51st Rencontre de Moriond

Electroweak Interactions & Unified Theories

— Experimental Summary —

Andreas Hoecker (CERN)

La Thuile, 19 March 2016

This Moriond EW & UT conference featured — as is tradition — a vibrant snapshot of newest results and trends in the fields of neutrino physics, astrophysics & cosmology, gravitational waves (!), dark matter and collider physics (it became the promised LHC feast).

Beautifully prepared talks! 53 on experimental results. We live in data-driven times.

I also found the YSF talks very interesting and well prepared.

Many thanks, indeed, to all the speakers!

Attempt for a summary …

Warning: in case *you* are asked next time, consider :

You won't have this:

Warning: in case *you* are asked next time, consider :

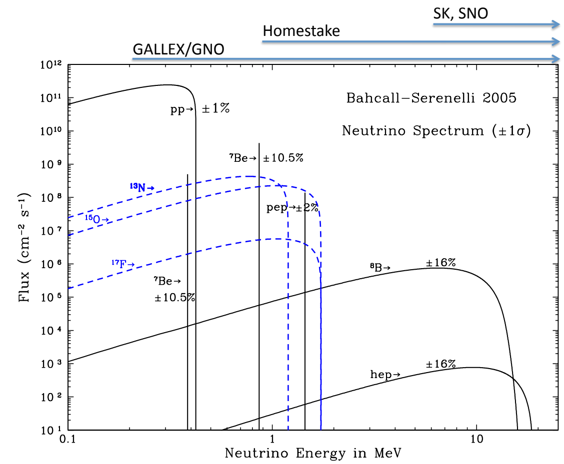
You won't have this:

But rather…

Views from a hotel room…

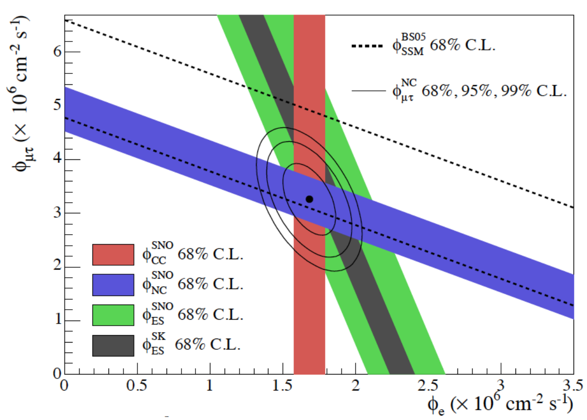
Wednesday, Mar 16: great

Friday, Mar 18: bad

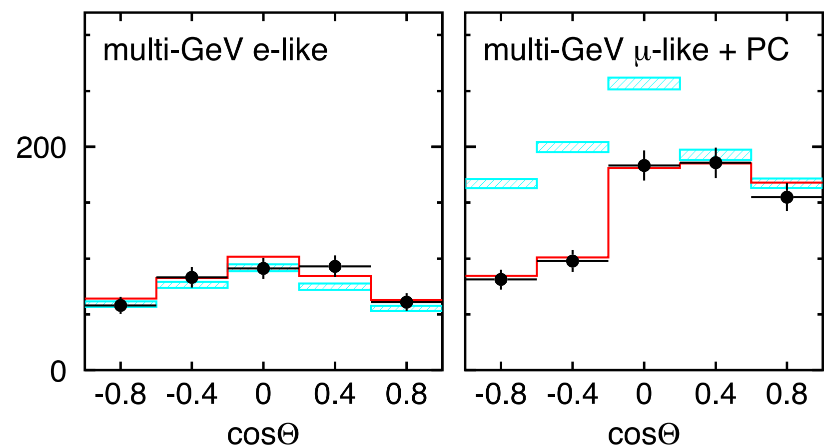


Neutrino physics

Another **Nobel Price*** for particle physics in 2015, and another one for **neutrino oscillation** !



Fluxed of ^{8}B solar neutrinos measured by SNO and SK



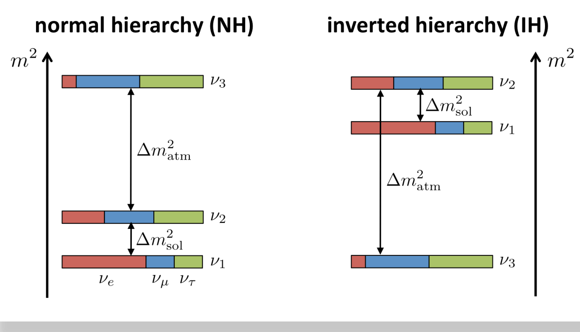
Zenith angle distribution in SK for e-like and μ-like events above 1.35 GeV. Boxes show expectation without oscillation

*Awarded jointly to T. Kajita and A.B. McDonald

What do we know

- Neutrinos are massive fermions
- Three active neutrino flavours
- Neutrino mass eigenstates are mixed flavour states, governed by PMNS matrix

Neutrino physics



Critical ν questions:

- Neutrino nature: Majorana fermions?
- Δm^2 (2.5%) and angles (3–7%) pretty well known
- Neutrino masses: absolute values & hierarchy
- CP violation in neutrino sector (δ_{CP} in flavour-changing PMNS elements)
- Are there sterile neutrinos, can we observe heavy additional neutrinos ?
- *But also:* neutrino cross section and flux measurements and predictions

A very exciting experimental programme !

Neutrino physics

The tools

- Neutrino oscillation measurements (short / long baseline)
- Single beta decay
- Neutrinoless double beta decay
- Cosmology (Graziano Rossi: $\Sigma m_\nu < 0.12$ eV with Ly-α, CMB, BAO combined)
- *And also neutrinos as messengers in astronomy, Sun & geo science, as well as for GUT, lepto/baryogenesis and physics beyond the SM*

Sarah Lockwitz

Neutrinos from short-baseline accelerators: MicroBooNE

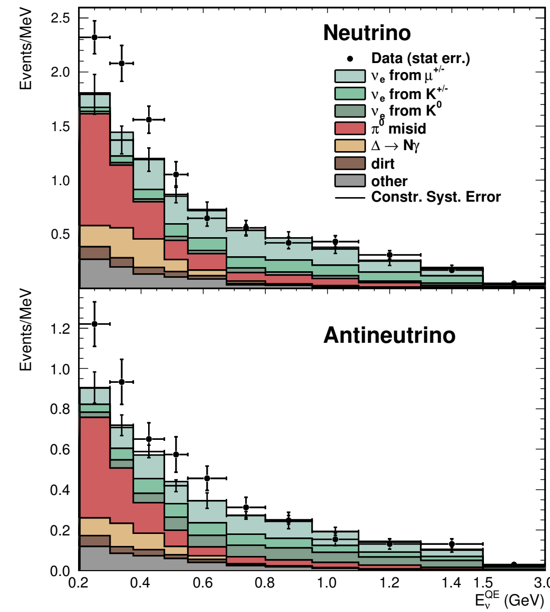
170 ton LAr TPC neutrino experiment at FNAL that started data taking in October 2015

MicroBooNE ~500m from BNB ~ν_μ beam, dedicated to low-energy neutrino cross sections to investigate the excess seen by MiniBooNE in $\nu_\mu \rightarrow \nu_e$ (and anti-…) appearance

Also step towards kiloton LAr TPC: DUNE (far detector) at LBNF (up to 2.4 MW beam power)

Principle: charged particle interacts with Ar: wire planes detect drifting ionisation electrons (→ tracks), PMTs detect scintillation light, use dE/dx to separate between e/γ

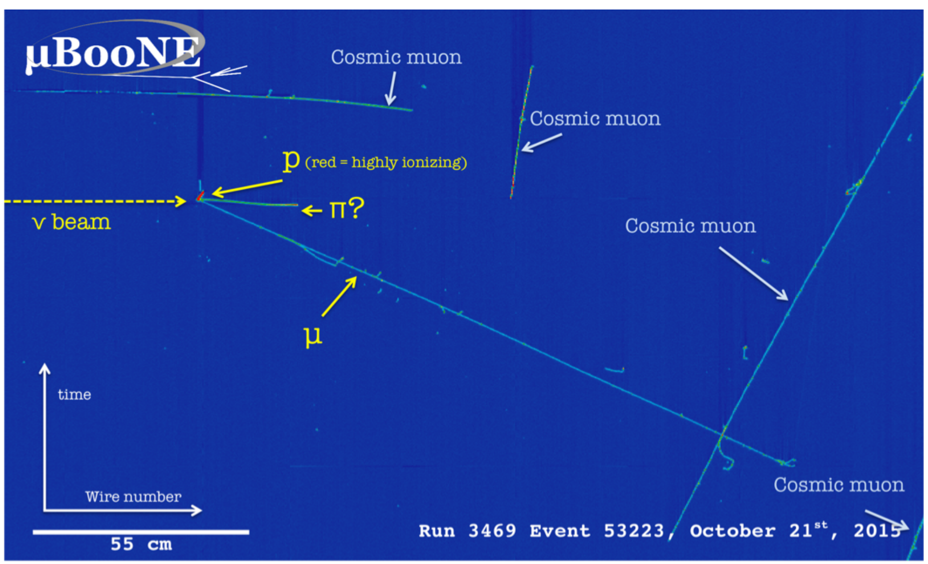
MiniBooNE, PRL 110, 161801 (2013)



~3σ excess of electron-like events in Cherenkov detector

Electrons or photons ?

There is also the LSND anti-ν_e excess



MicroBooNE event display

Daniel Rutherbories

Neutrinos from short-baseline accelerators: MINERvA

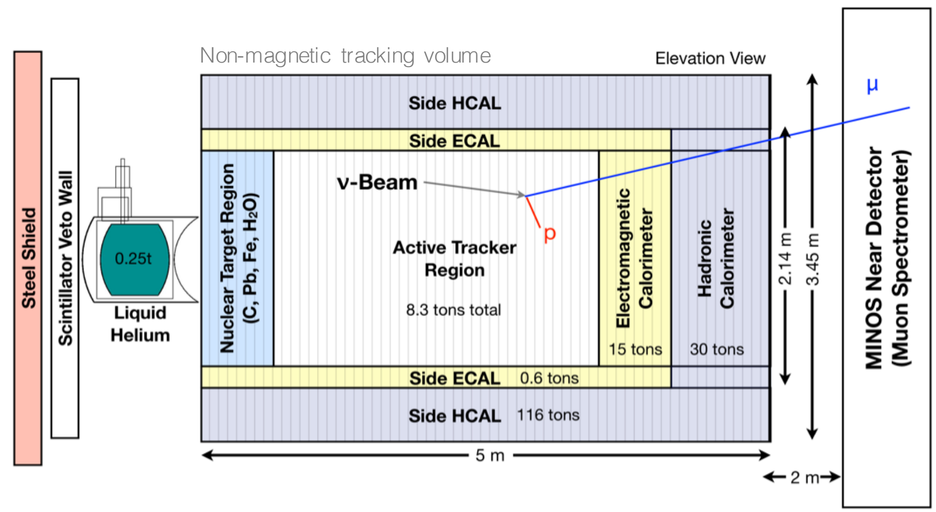
Detailed study of neutrino interactions in varying nuclear targets (C, Pb, Fe, H_2O)

MINERvA at NuMI, ~1km after NuMI target, 3.1 GeV peak ν_μ energy (low-energy beam flux).

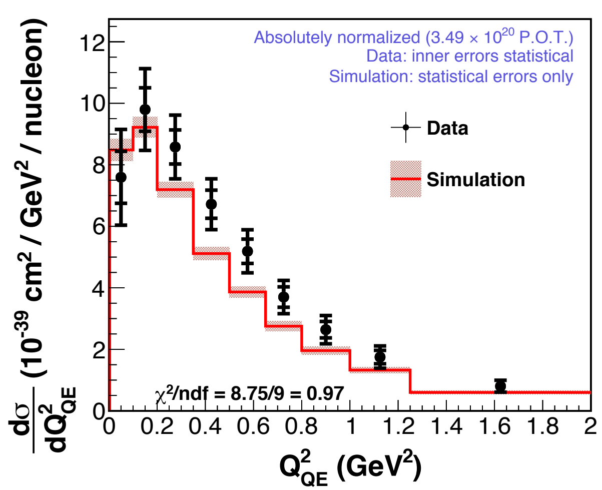
Detector features charged particle and em & had energy reconstruction, PID, uses MINOS (ND) as μ spectrometer

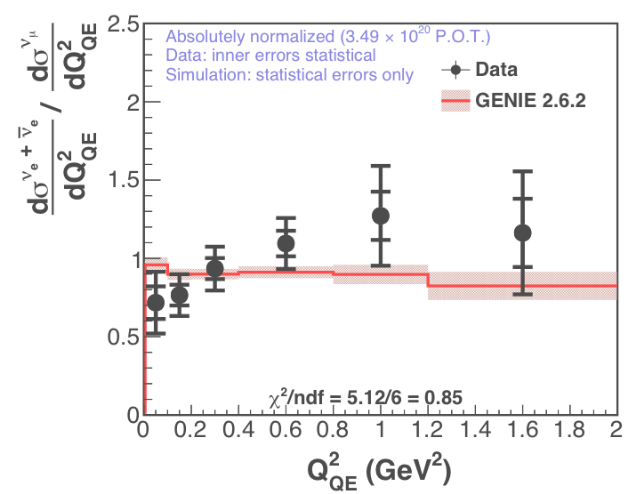
Test and improve ν–N interactions modelling

For example, ν_e CCQE is oscillation signal, but little low-energy cross-section data available.
Can $\nu_\mu \rightarrow \nu_e$ cross-sections be trusted universally ?



ν_e n → e⁻ p (dominant) and ν_e p → e⁺ n in hydrocarbon target





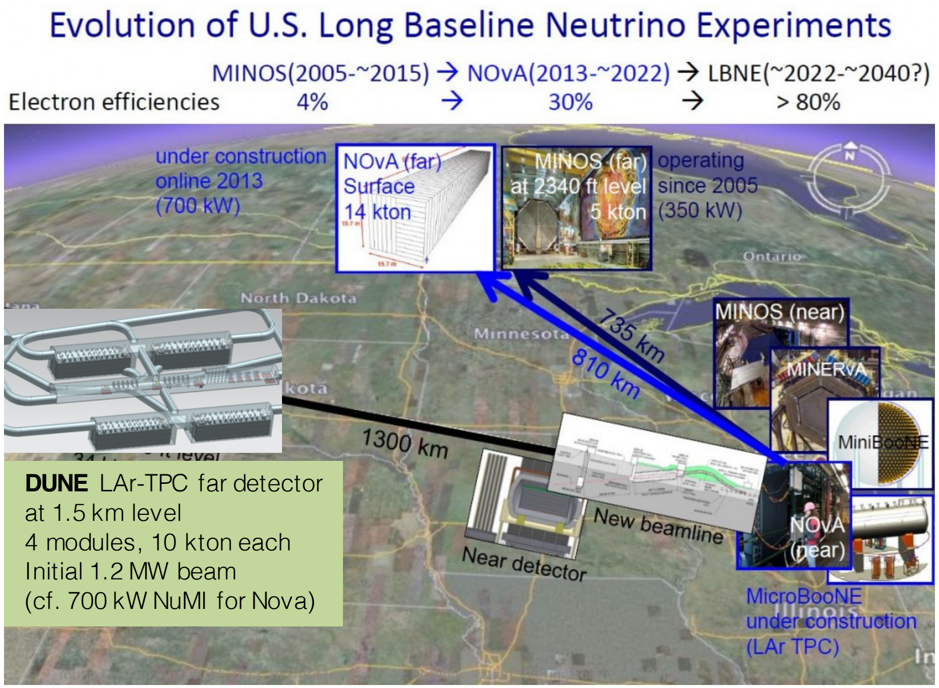
Exclusive measurement of flux-integrated differential cross section for ν_e CCQE-like interactions

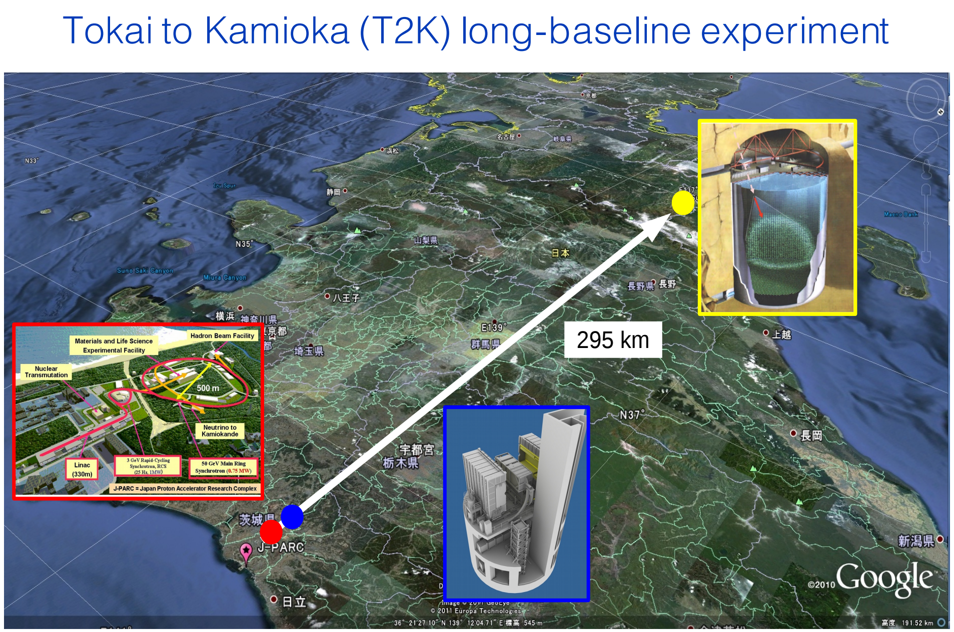
Sufficiently good description for current experiments

Next steps: higher beam *E*

Long-baseline neutrino experiments

Extremely rich present and future long-baseline neutrino programme





Long-baseline experiments look at ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance
+ their anti processes

Probabilities depend on $\sin^2(2\theta_{13})$, well measured and large, on $\sin^2(\theta_{23})$, on δ_{CP} ($\rightarrow$ CP violation), and on the sign of Δm^2_{31} ($\rightarrow$ mass hierarchy)

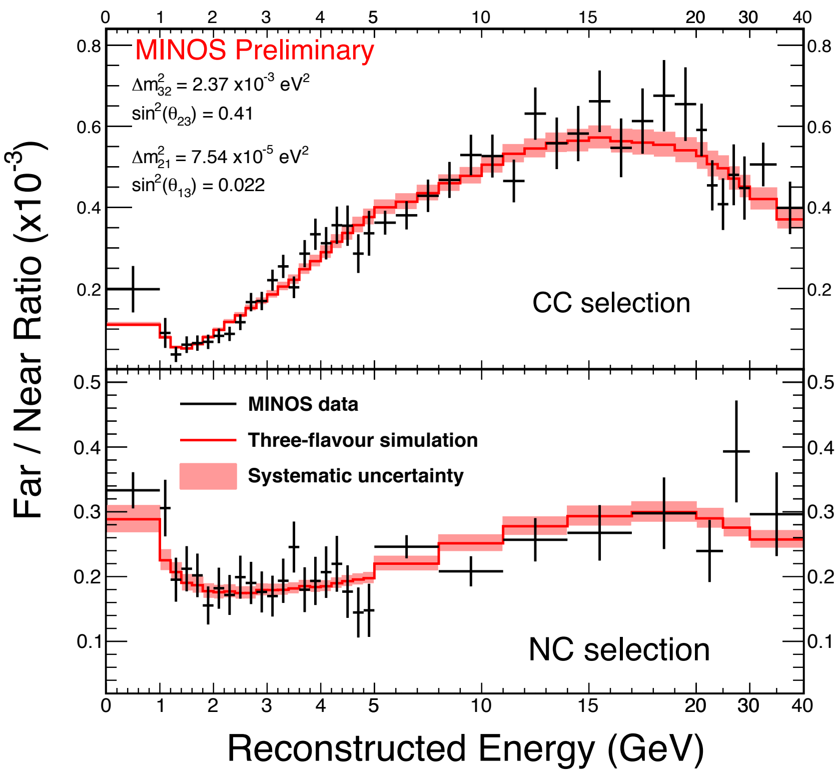
$\rightarrow$ *All these properties can be experimentally addressed*

Long-baseline neutrino experiments: MINOS

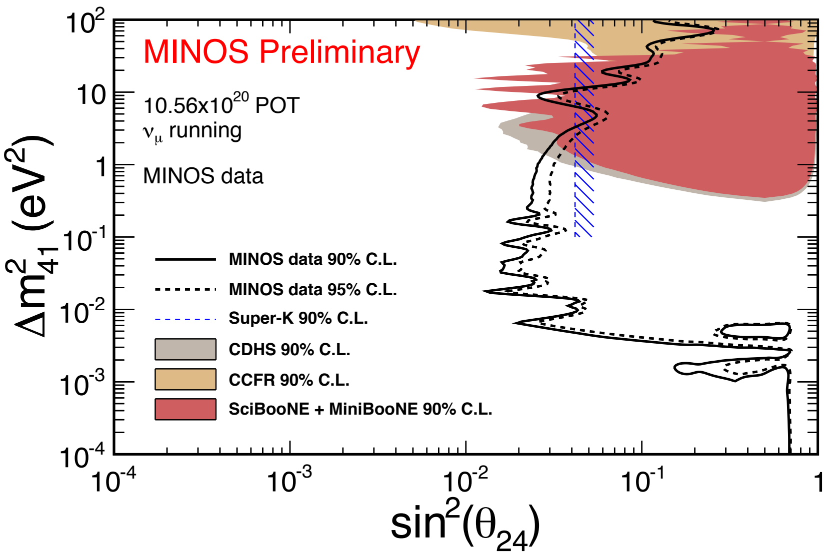
ND 24 ton, ~1 km on target; FD 4.2 kton (ND+FD magnetised), 735 km in Soudan mine, 705 m deep

MINOS released in May 2014 a combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance data

Talk this week reported search for sterile neutrino using ν_μ beam: 1 $\nu_{sterile}$ introduces 6 new parameters.
For simplicity set CP phases and $\theta_{14} = 0$, fit: Δm^2_{32}, Δm^2_{41}, θ_{23}, θ_{24}, θ_{34}



$\nu_{active} - \nu_{sterile}$ mixing may affect ND reference. Thus: combined fit of FD / ND ratio. Find agreement with 3-flavour model → limits



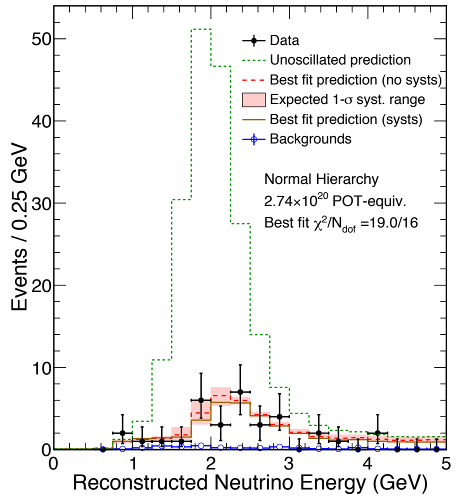
Long-baseline neutrino experiments: NOvA

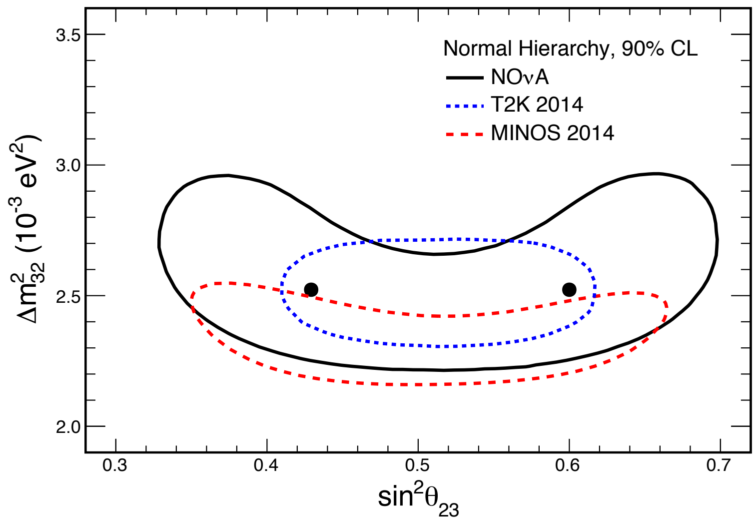
14 kton FD (810 km, on surface), 0.3 kton ND, both are fine-grained tracking calorimeters

NOvA ~0.8° off-axis from the NuMI beam → narrow $E(\nu_\mu)$ ~ 2 GeV, ~maximum of ν_μ disappearance and ν_e appearance, ν_e ID

First results using 11/2014–6/2015 data (< 500 kW beam power):

- ν_e cross-section (a bit higher than T2K & Gargamelle → GENIE)
- ν_μ disappearance gives first measurement of Δm^2_{32} and $\sin^2\theta_{23}$:





With magnetic horns focusing on positive mesons NuMI beam composed of 97.6% ν_μ, 1.7% anti-ν_μ, 0.7 ν_e + anti-ν_e for neutrino energies between 1 and 3 GeV.

Beautifully simple detector technology

Also first $\nu_\mu \rightarrow \nu_e$ appearance result: 6/11 (LID/LEM) events observed in FD for ~1 expected background event (based on ND measurement). 3.3/5.3σ excess, LEM result less compatible with inverted hierarchy

Results with twice larger dataset expected this year. 700 kW running this year

Christine Nielsen

Long-baseline neutrino experiments: T2K

295 km baseline, far detector SK (water), near detectors $\text{INGRID}_{\text{on}}$ / $\text{ND280}_{\text{off}}$ (different target materials)

T2K 2.5° off beam axis giving narrow $E(\nu_\mu)$ ~ 0.6 GeV. ND280 target so far carbon, not same as SK

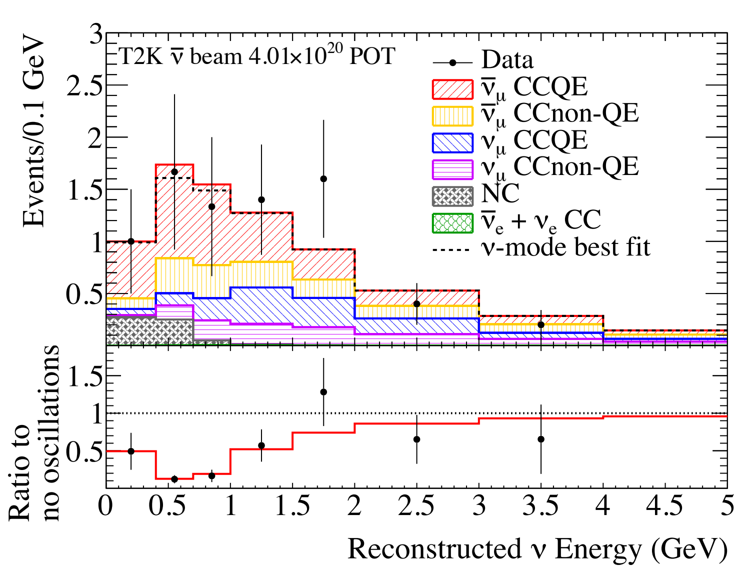
[Combined $\nu_\mu \rightarrow \nu_\mu$ / ν_e analysis (2010–2013, !2011 data) provided world's best Δm^2_{32}, θ_{23} measurements]

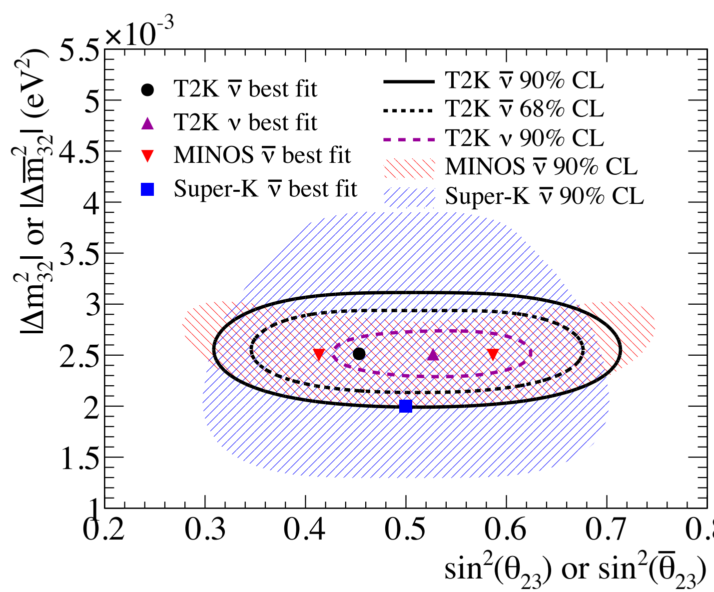
Anti-ν_μ mode during Run 5–6 (2014/15): 11×10^{20} POT (cf. NOνA: 2.7×10^{20}), 390 kW max beam power

Larger wrong-sign background, must measure in near detector: ~10% flux and cross-section uncertainties: improve by combined fit of model together with external and ND280 data as input to oscillation fit

→ Anti-ν_μ disappearance: 34 μ events observed. Anti-ν_e appearance: 3 events seen, not yet significant

Clear evidence of oscillation in anti-ν_μ disappearance





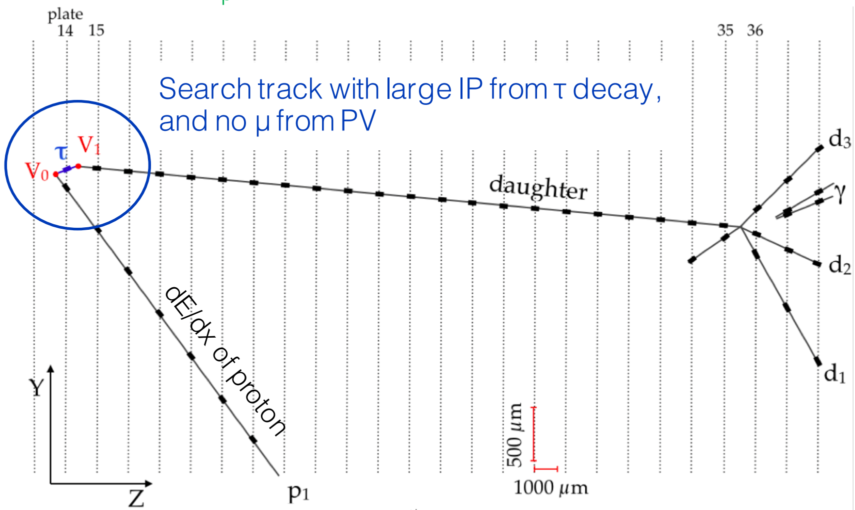
Long-baseline neutrino experiments: OPERA

Breakthrough in July 2015 with > 5σ observation of tau neutrino appearance (5 ν_τ candidates)

OPERA exploits 732 km (2.5 ms) CNGS ν_μ beam to search for ν_τ appearance

Charged-current neutrino interactions are recorded in detectors (bricks) of lead and emulsion film with sub-micron resolution. Total target of 150k bricks. Additional target trackers & muon spectrometers.

$(\nu_\mu \rightarrow)\ \nu_\tau + N \rightarrow \tau^- (\rightarrow e,\mu,h) + X$



Event display of 5th ν_τ candidate in emulsion

Data between 2008 and 2012 were analysed, corresponding to 18×10[19] POT giving 20k neutrino interactions in detector (6.7k analysed)

Channel	Expected background				Expected signal	Observed
	Charm	Had. reinterac.	Large μ scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01			0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

→ 5.1σ

Also limits on sterile neutrinos

Short-baseline (reactor) neutrino experiments: Daya Bay

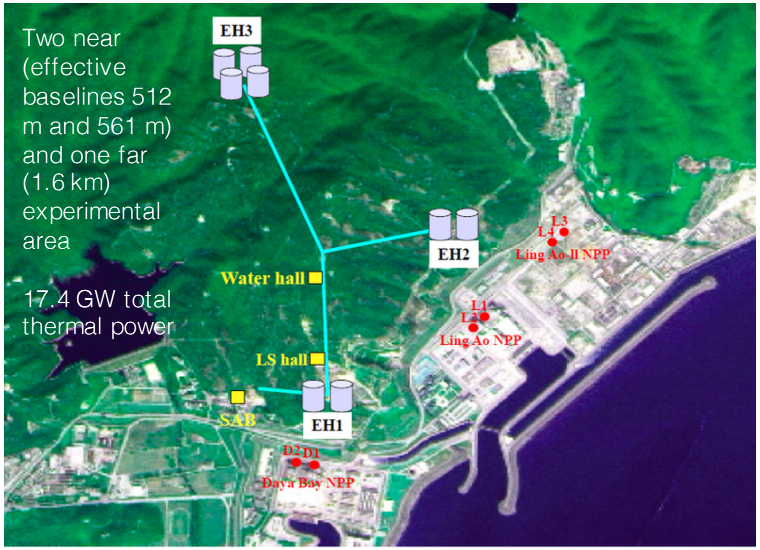
Powerful anti-ν_e source from ß-decay of reactor fission products, detector now completed

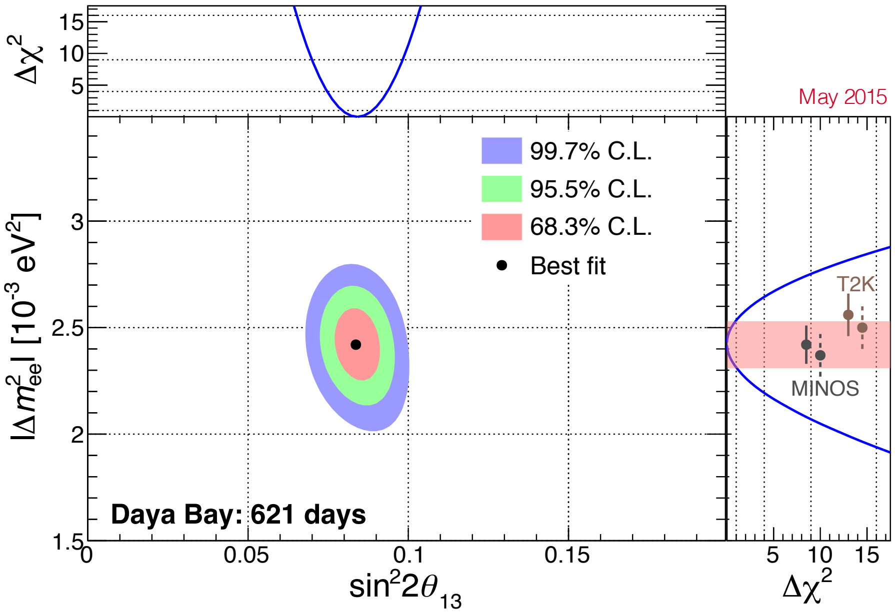
Daya Bay measures θ_{13} from anti-ν_e survival probability O(km) away from reactors, dominated by Δm^2_{32} term

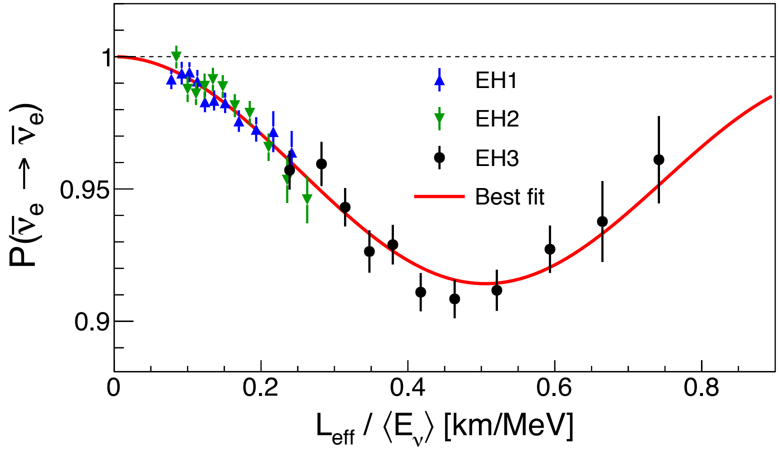
Detection through anti-ν_e + p → e^+ + n reaction (IBD) in Gd doped liquid scintillators. Prompt e^+ annihilation γ + delayed 8 MeV γ's from neutron capture. Flux uncertainty eliminated by measuring at 3 different detector sites

→ $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$ (10/2012–11/2013 data, 2/3rd 8 ADs)

Layout of China-based Daya Bay experiment







Yiming Zhang

Short-baseline (reactor) neutrino experiments: Daya Bay

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Daya Bay measures θ_{13} from anti-ν_e survival probability *O*(km) away from reactors, dominated by Δm^2_{32} term

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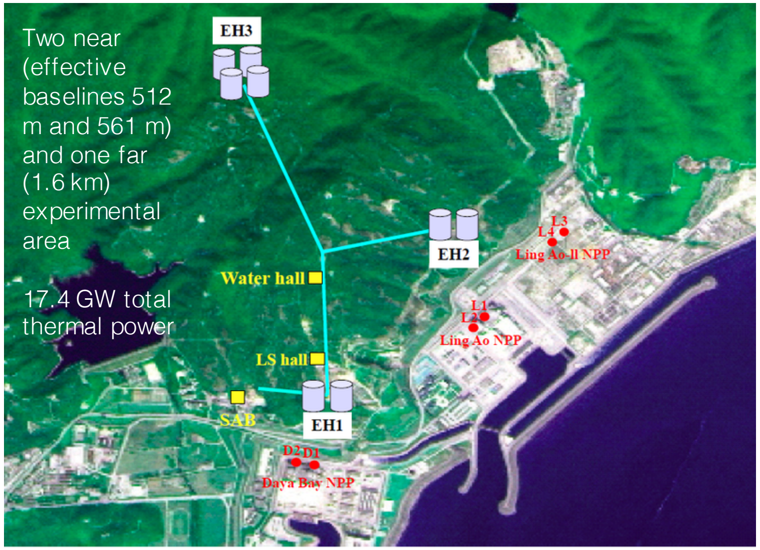
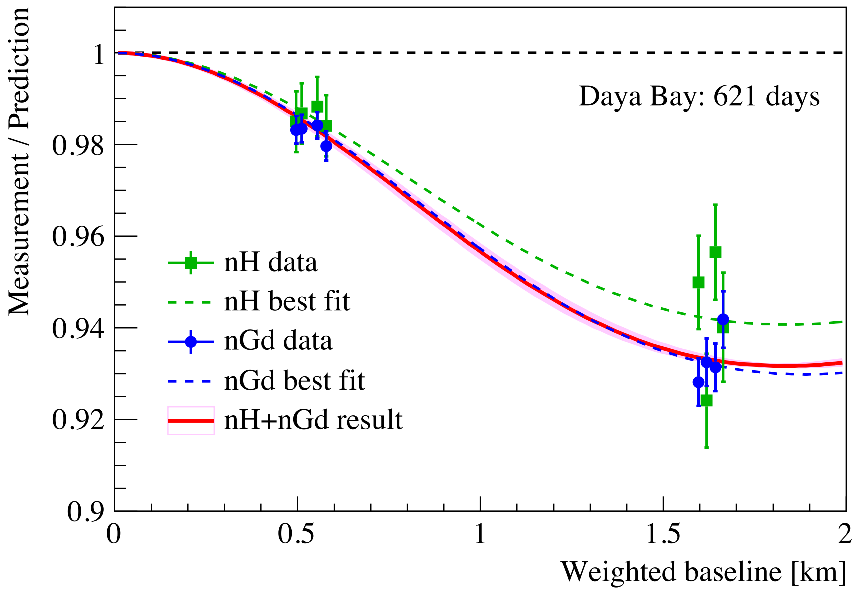




Brand new analysis using neutrons captured by hydrogen (instead of gadolinium). Independent data sample, different systematics

→ $\sin^2(2\theta_{13})$ =0.071 ± 0.011 (nH)

→ $\sin^2(2\theta_{13})$ =0.082 ± 0.004 (nGd & nH combined)

Short-baseline (reactor) neutrino experiments: Double Chooz

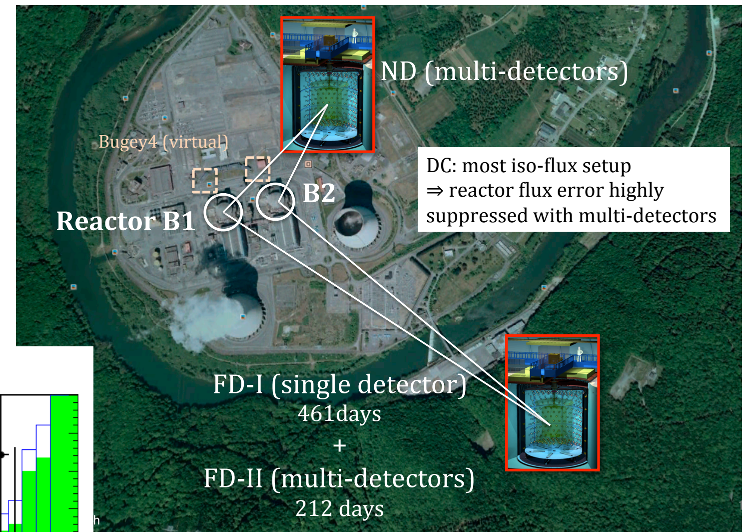
Multi-detector setup with ND (0.4 km, since 2015) & FD (1.1 km, since 2011)

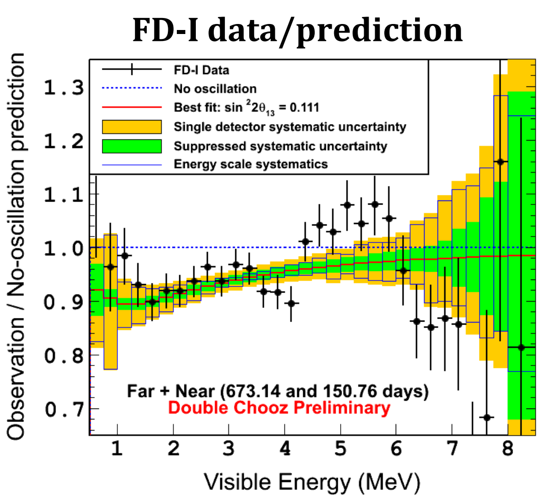
Masaki Ishitsuka

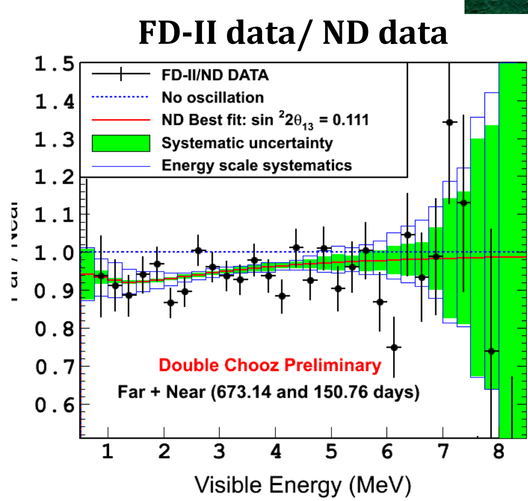
New preliminary Double Chooz θ_{13} measurement with multi-detectors. Nearly iso-flux setup reduces flux uncertainty to < 0.1%. Uncorrelated detection systematic < 0.3%

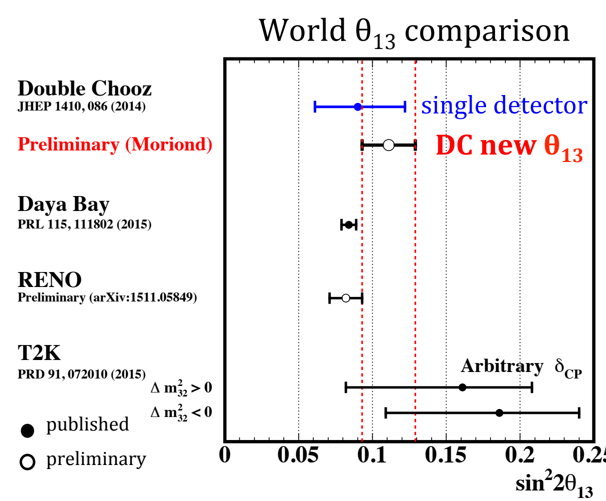
Combined fit of parameters to FD-I, FD-II, ND data (reactor-off data also used for bkg constraint)

Layout of France based Double Chooz experiment









→ $\sin^2(2\theta_{13})$ =0.111 ± 0.018 (stat + syst, 5.8σ from zero)

Anna Hayes, Nick van Remortel

A word on reactor flux anomalies

Cannot currently follow-up new physics claims based on absolute reactor flux comparisons

Daya Bay reports recent measurement of anti-ν_e flux using 340k candidates, better than 1% energy calibration, and comparison with model prediction: ~2.5σ overall deviation, ~4σ local deviation at $E(\nu_e)$ ~ 5 MeV (shown to be due to reactor ν). While an overall deficit may look like disappearance to sterile neutrino, the bump does not!

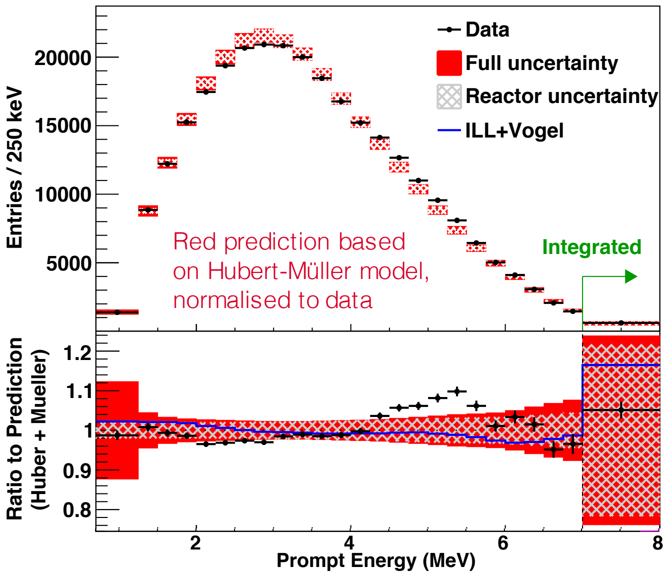
Consistent with "**reactor neutrino anomaly**" picture from earlier short baseline measurements (Daya Bay, Reno, Double Chooz): measured / expected anti-ν_e flux ~ 0.94

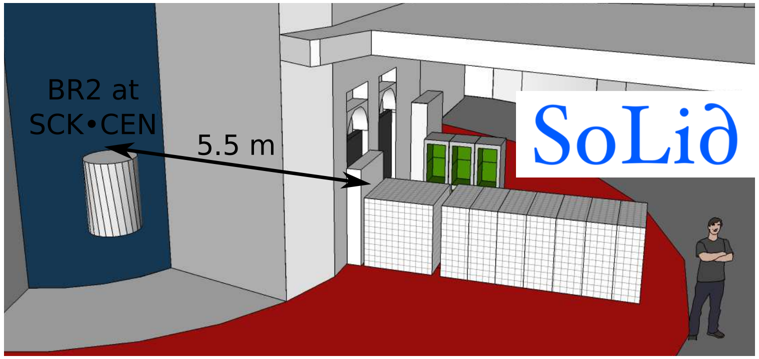
Anna Hayes explained us that much caution is needed as various uncertainties may in total cover the deficit.

The ~5 MeV bump may be due to prominent fission daughter isotopes (eg, ^{238}U or Plutonium)

In any case, new experiments needed: ~10 very-short baseline experimental projects, among which: SoLid →

Prompt energy spectrum, Daya Bay, 1508.04233, Aug 2015



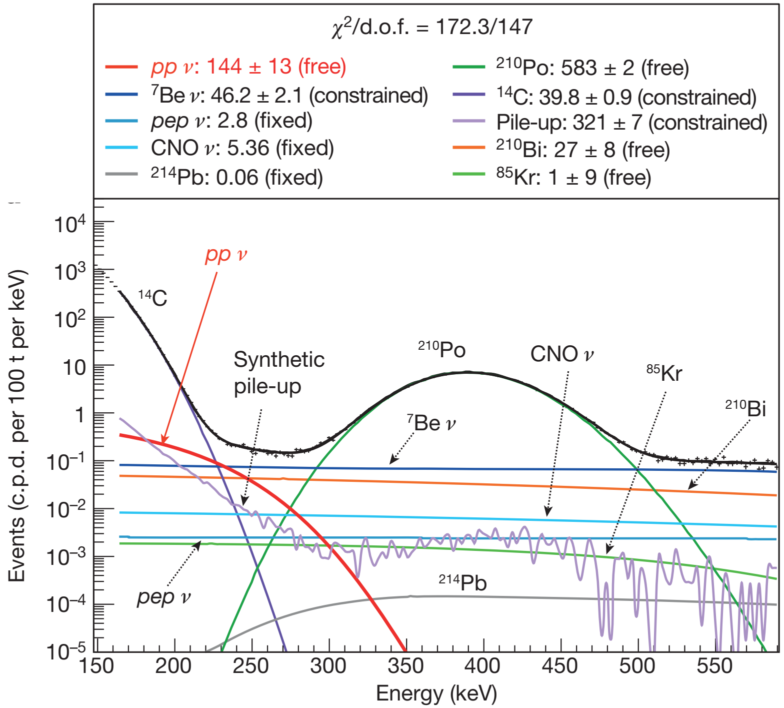


3 ton SoLid experiment deployed 5.5 m from the BR2 reactor core

Neutrinos from the Sun: Borexino (LNGS)

New measurements after the 2014 breakthrough evidence for primary pp fusion neutrinos

Borexino initially designed for measurement of 0.86 MeV Be-7 solar ν_e's via ν-e scattering and electron recoil measurement (also IBD)



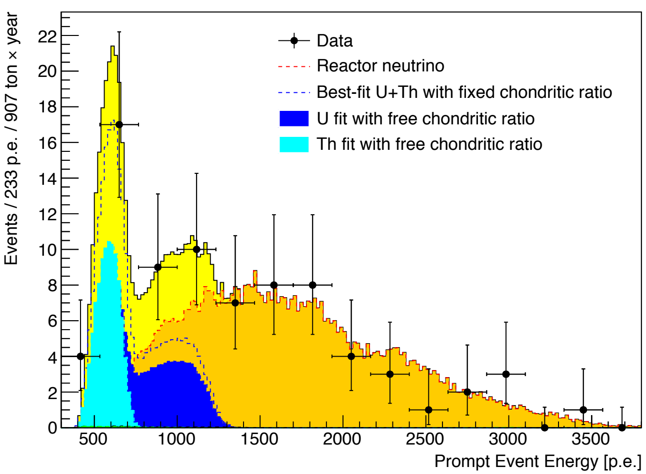
"Money" plot published in 2014. Resulting pp neutrino flux consistent with photon luminosity within 10% precision

270 t liquid scintillator, surrounded by 890 t buffer fluid;
Installed in 9.5 m diameter nylon vessel, 1.3km underground

Extremely high radiopurity allows 250 keV threshold

Since that measurement Borexino focused on:

- Detection (proof) of "CNO" cycle in Sun
- Tests of e-charge conservation ($e \to \gamma\nu$, $\nu\nu\nu$), giving $\tau_e > 6.6\times10^{28}$ years
- Detection of geo-anti-ν_e (largest bkg reactors)



5.9σ observation

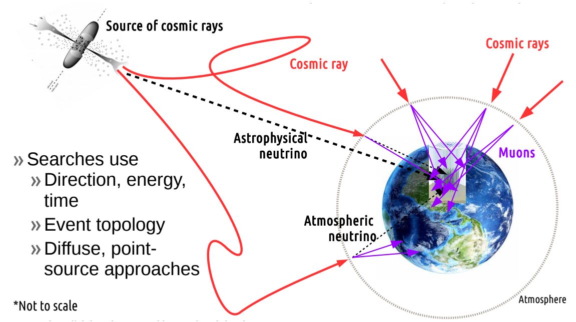
Jan Auffenberg

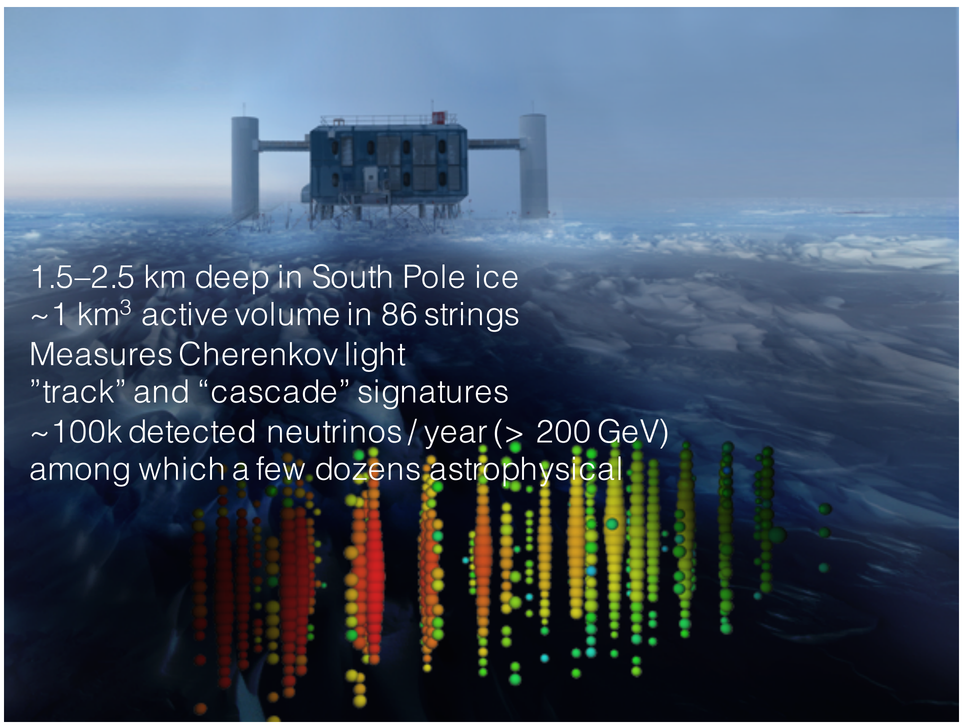
Neutrino astronomy with IceCube

IceCube studies astrophysical neutrino properties (and through atmospheric neutrinos also oscillation phenomena)

Cosmic rays: measured over 11 orders of magnitude, but highest energy sources not well known

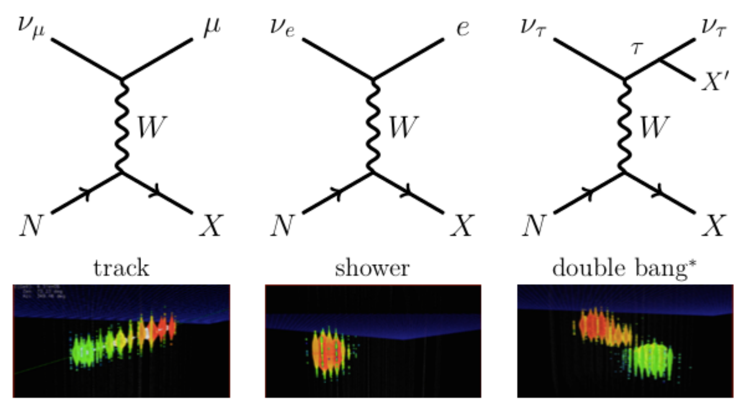
Neutrinos point back to their sources:





TeV-scale muon ("track") neutrino event superimposed on view of IceCube Lab

Characteristic signatures:



Direction ☺	Direction ☹	Direction ☺
Energy res ☹	Energy res ☺	Energy res ☺

Large atmospheric μ and ν_μ backgrounds

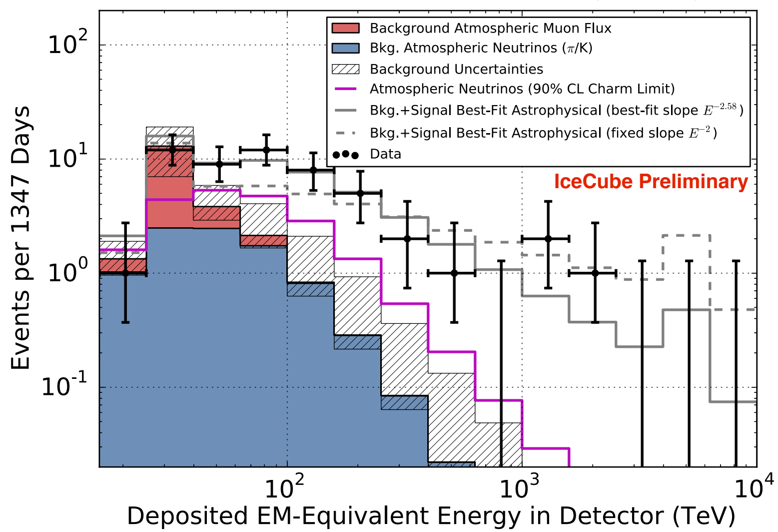
Jan Auffenberg

Neutrino astronomy with IceCube

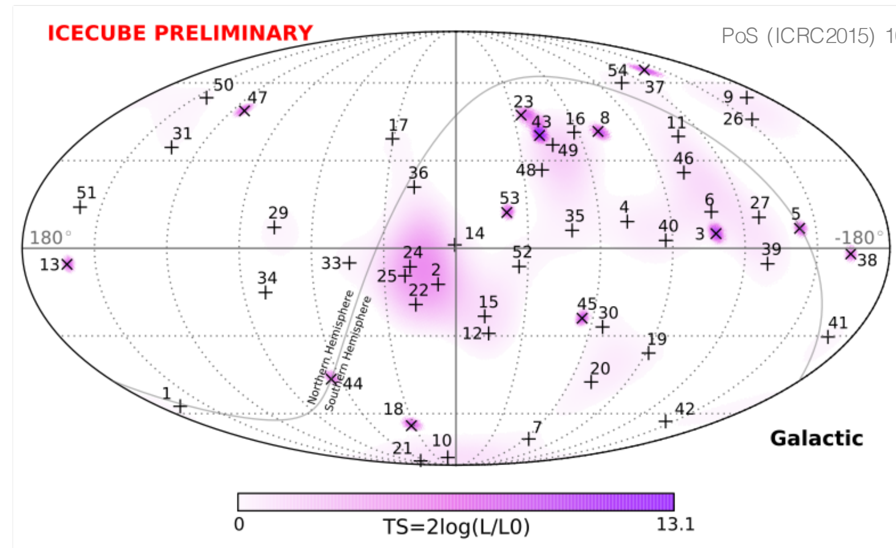
Highest energy neutrinos have lowest atmospheric neutrino background

Energy spectrum > 60 TeV after 4 years of data
53 good events, up to ~2 PeV, 6.5σ signal
Hard spectrum. E^{-2} model may be too simple

PoS (ICRC2015) 1081



No significant clustering found



Shower-like events are marked with + and those containing tracks with ×

- IceCube also sees 5.9σ excess of up-going ν_μ (CC only) 0.2–8.3 PeV energy over atmospheric background (normalised at 100 TeV)
- Possible pattern in spectral index vs energy
- No significant point source

Jan Auffenberg, Gwenhaël de Wasseige

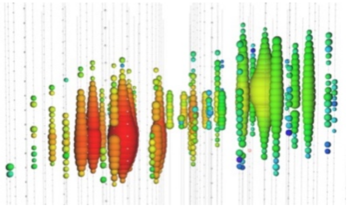
Neutrino astronomy with IceCube

Flavour decomposition

Measurement of neutrino flavour can give hints about source of astrophysical neutrinos

- Pion decay should produce $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ (at earth)
- If muons suppressed (eg, due to large *B* fields): 1 : 1.8 : 1.8 (earth)
- If from neutron decay: 2.5 : 1 : 1 (earth)

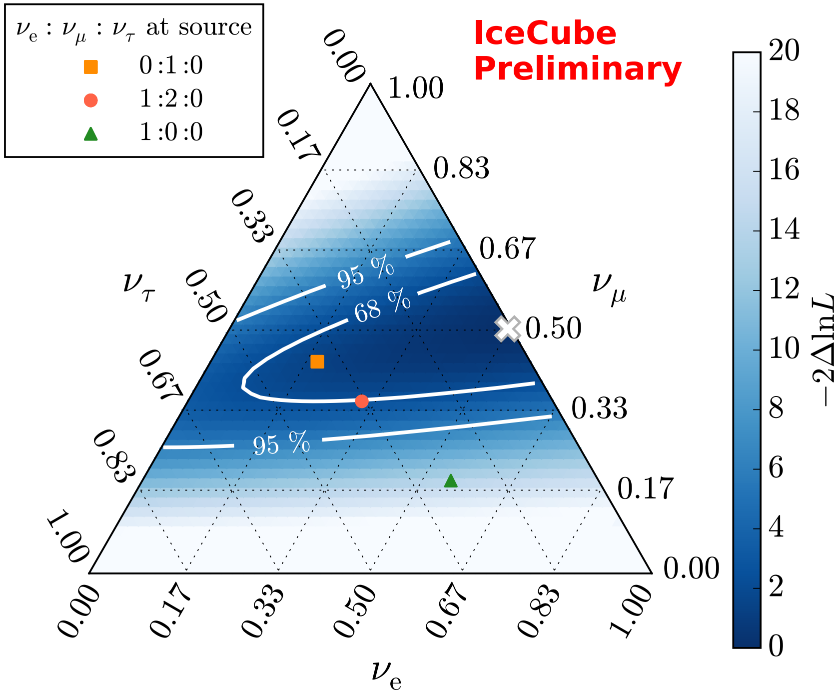
But: no hint for ("double-bang") tau neutrinos yet



IceCube also now belongs to elite of experiments who have observed ν oscillation through ν_μ disappearance: compatible Δm^2_{32}, θ_{23} measurements

Interesting, but insufficient data yet

→ Next generation IceCube-Gen2: ~10 km^3 (R&D)



Also search for sterile neutrinos, heavy WIMP annihilation, solar flares

Paolo Gorla, Yung-Ruey Yen

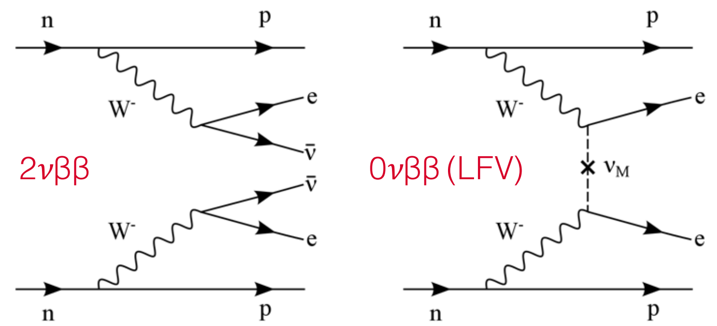
Of which quantum nature are neutrinos ?

Search for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{136}Xe (EXO200) and ^{130}Te (CUORE)

$\Gamma_{0\nu\beta\beta} \propto |M_{0\nu\beta\beta}|^2 \, m^2_{\beta\beta} \rightarrow$ observation would indicate:

- Non-zero Majorana mass term
- (Heavy right-handed N might be responsible)
- Infer information on mass & hierarchy (theory input)

Experiments require: • large mass • high isotopic abundance • good energy resolution • high efficiency • low background



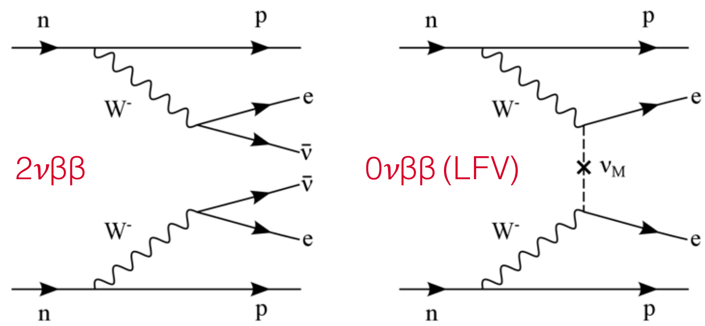
Paolo Gorla, Yung-Ruey Yen

Of which quantum nature are neutrinos ?

Search for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{136}Xe (EXO200) and ^{130}Te (CUORE)

$\Gamma_{0\nu\beta\beta} \propto |M_{0\nu\beta\beta}|^2\ m^2_{\beta\beta} \rightarrow$ observation would indicate:

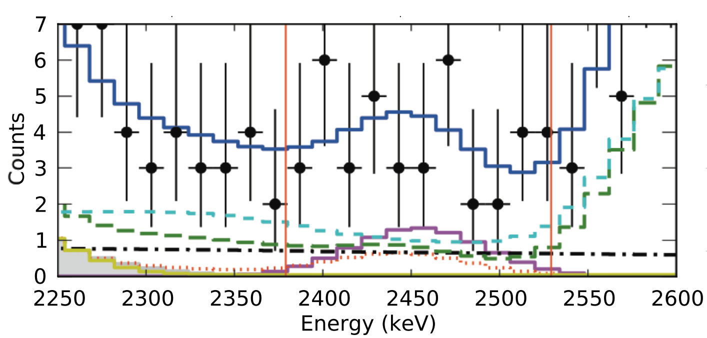
- Non-zero Majorana mass term
- (Heavy right-handed N might be responsible)
- Infer information on mass & hierarchy (theory input)



Experiments require: • large mass • high isotopic abundance • good energy resolution • high efficiency • low background

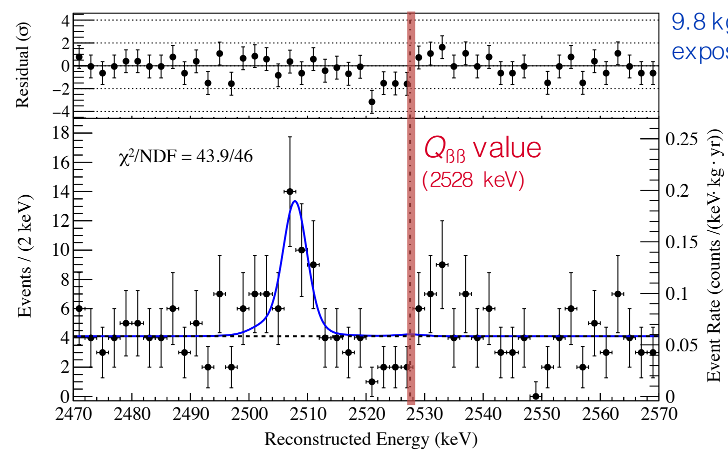
EXO-200 enriched (~81%) liquid-Xe TPC ($^{136}Xe \rightarrow {}^{136}Ba + 2e^-$) installed in nuclear waste isolation plant in New Mexico, US.

2014 result using 100 kg·yr: $\langle m_{\beta\beta} \rangle < (190–470)$ meV



Presented here new search for $2\nu\beta\beta$ to excited ^{136}Ba, which de-excites via 2 γ's → MV analysis

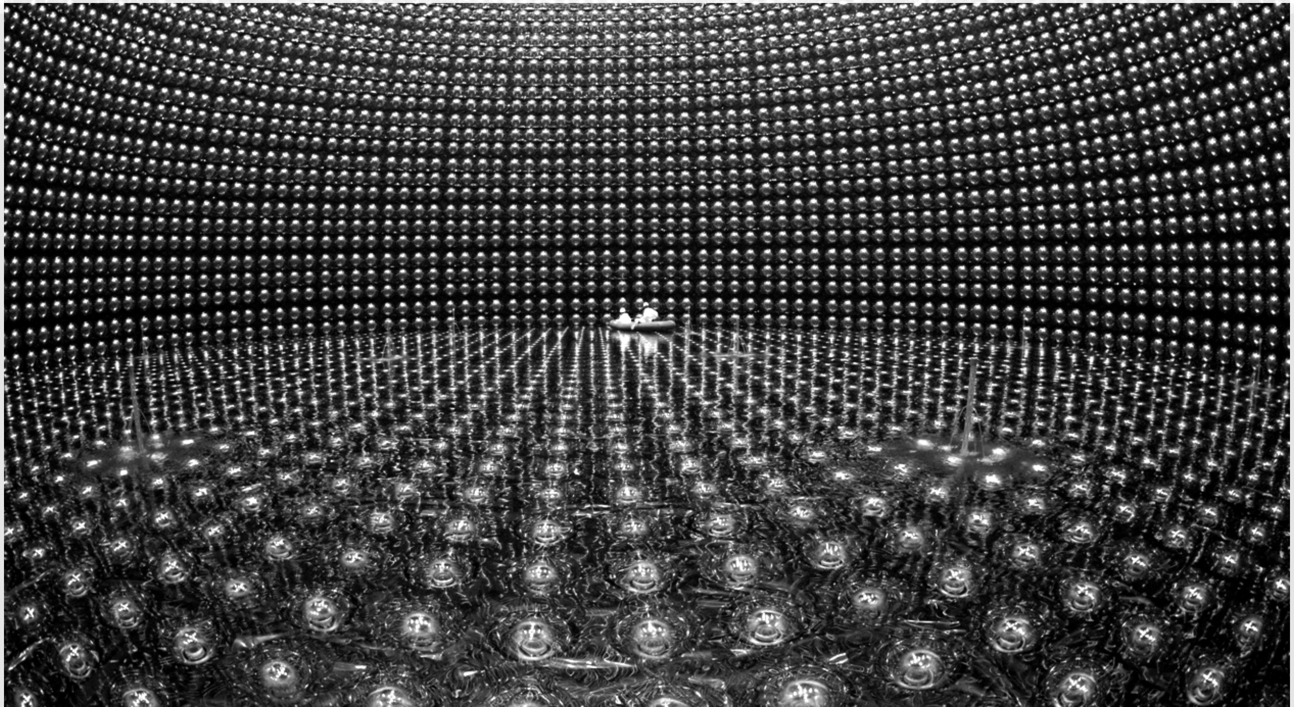
CUORE-0 bolometric technique using array of tellurium dioxide crystals ($^{130}Te \rightarrow {}^{130}Xe + 2e^-$) cooled to ~10 mK! Good E resolution, no PID



9.8 kg·yr ^{130}Te exposure

CUORE-0 + Cuoricino: $\langle m_{\beta\beta} \rangle < (270–650)$ meV

Nucleon decay — GUT messengers



Cannot reach expected GUT energy in Lab. Even Enrico Fermi's *Globatron* (that was to be built in 1994) would with LHC technology "only" reach 20,000 TeV CM energy

Messengers from GUT: baryon decay

Remember: KamiokaNDE stands for *Kamioka Nucleon Decay Experiment*

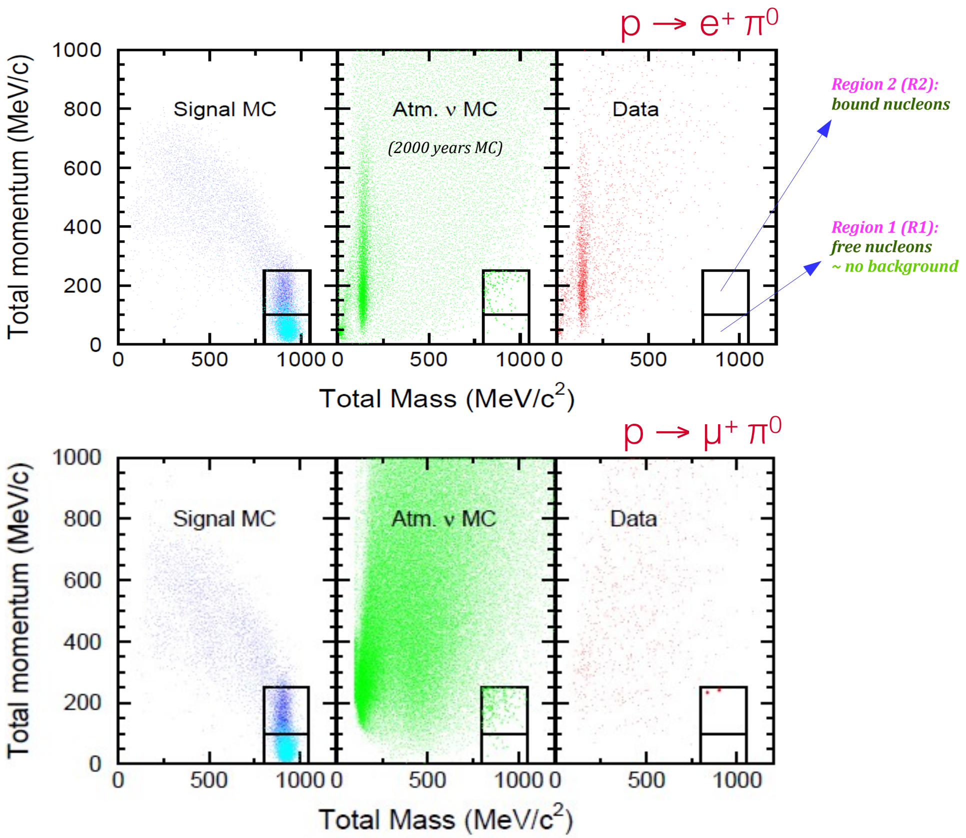
Super-Kamiokande presented new proton decay limits combining all SK I–IV data (1996–now)

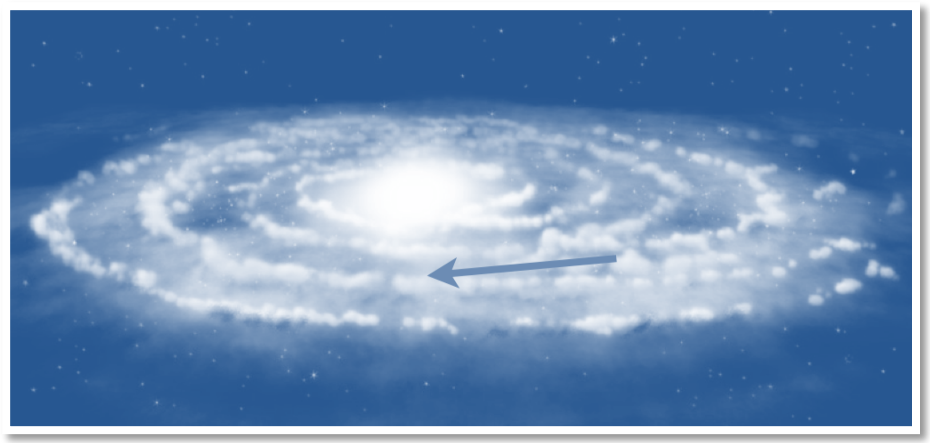
No significant excess found, strong new limits:

- $\tau(p \to e^+ \pi^0) > 1.7 \times 10^{34}$ years
  (no events seen in R1/2, 0.07/0.54 expected)
- $\tau(p \to \mu^+ \pi^0) > 7.8 \times 10^{33}$ years
  (less sensitive because μ^+ through decay to e^+, 0/2 events seen in R1/2, 0.05/0.82 expected, two events background like properties)
- $\tau(p \to K^+ \nu) > 6.6 \times 10^{33}$ years
  (K+ below Ch. threshold, detect through decays, no events seen in SB/C, 0.39/0.56 expected)

Looked also for more exotic phenomena.

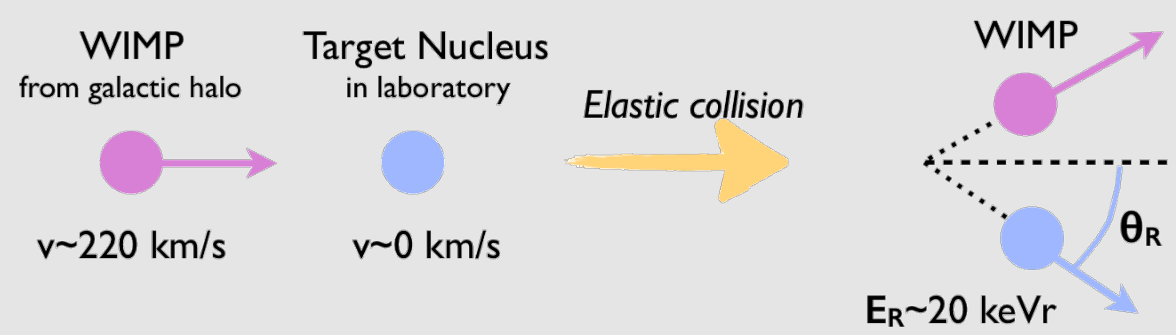
Order of magnitude sensitivity gain on $p \to e^+ \pi^0$ expected from Hyper-K





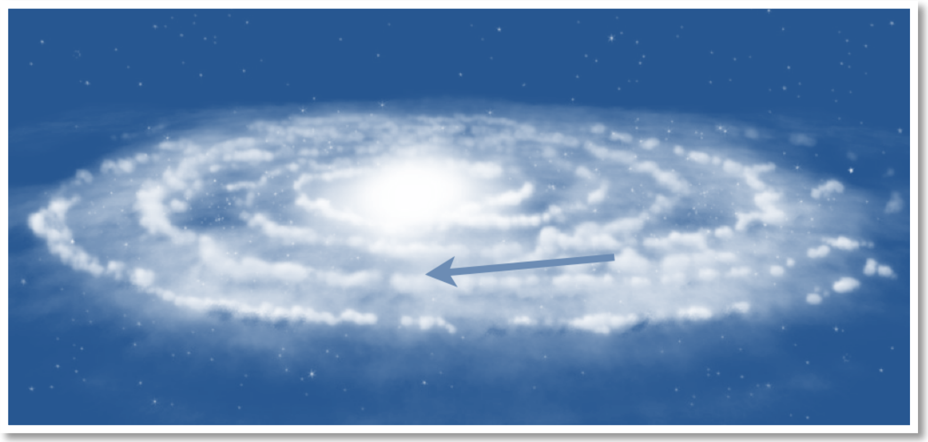
Direct Dark Matter Searches

Direct
Detection
(DM collision nuclear recoils)



Effective scattering Lagrangian may have scalar (SI $\propto A^2$) or axial-vector (SD $\propto$ nuclear spin, no coherence) terms

Dominant background from electrons recoiling after X-ray or γ-ray interactions



Direct Dark Matter Searches

Similar experimental challenges as for the elusive neutrinos

- Deep underground
- Excellent radio-purity
- Shielding around active volume
- Redundancy in signal detection

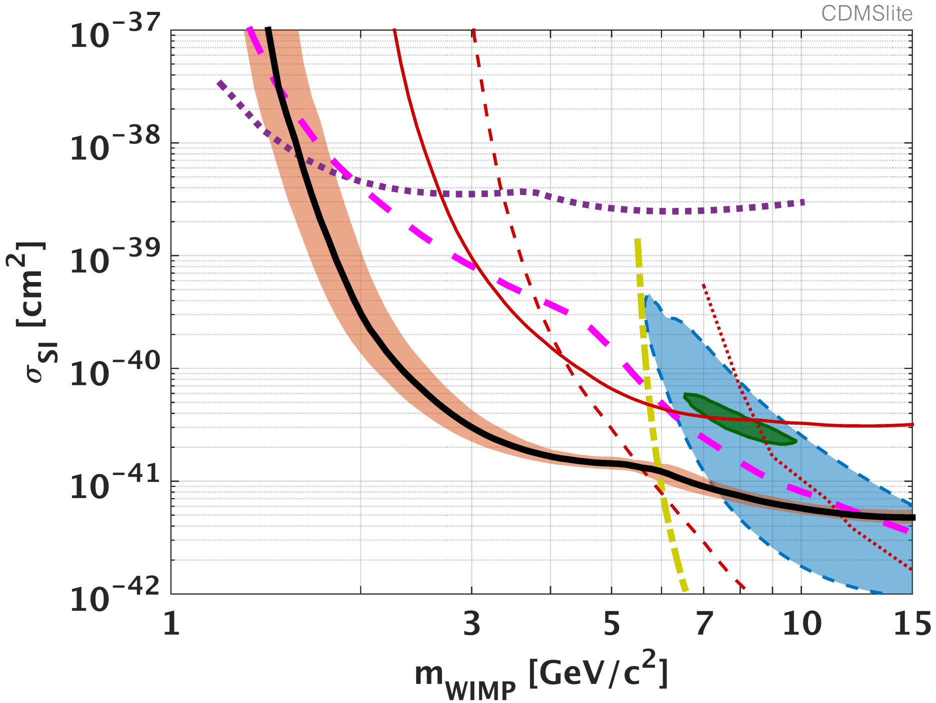
Elias Lopez Asamar

Direct dark matter searches: CDMSlite

High bias voltage signal amplification to gain sensitivity to lower WIMP masses

CDMS looks for keV-scale recoils from elastic scattering of WIMPs off target nuclei. Uses up to 19 Ge and 11 Si detectors placed in Soudan mine. Ionisation charges & phonons (heat) are measured and used to discriminate electron (ER*) from nuclear recoils (NR).

- CDMSlite: operate 1 Ge detector at higher bias voltage to amplify the phonon signal.
- Two runs. Second run had reduced acoustic noise (→ lower threshold) and increase exposure



New parameter space excluded between 1.6–5.5 GeV DM mass

SuperCDMS now ended. Follow-up programme: SuperCDMS SNOLAB (2.1 km deep)

Exclusion limit assumes all events in signal region are WIMPs

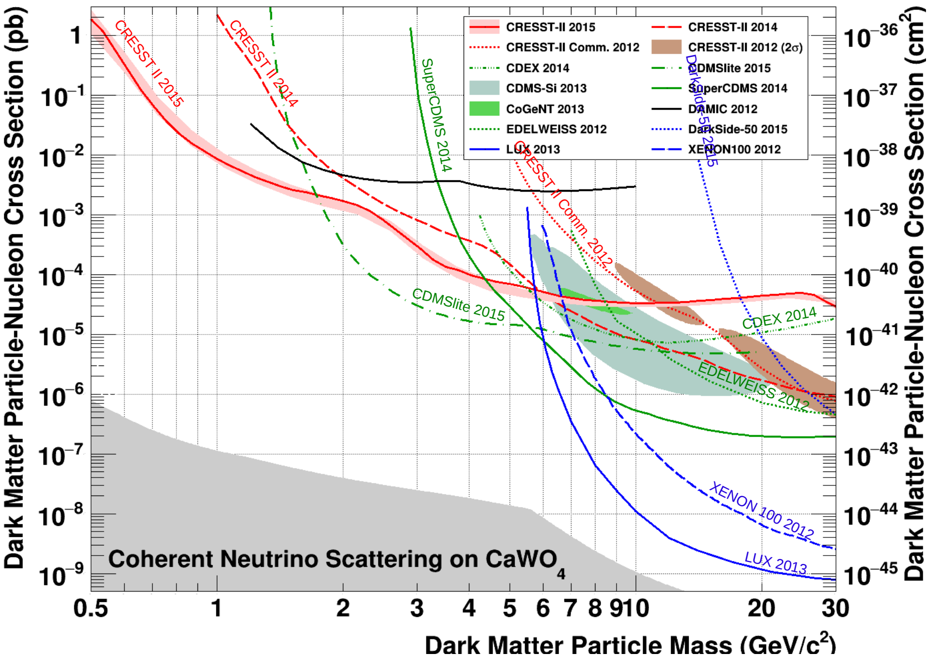
*ER from Compton scatters due to radioactive detector components, intrinsic ß decays, solar ν scattering off electrons

Direct dark matter searches: CRESST–II

Improved sensitivity to low-mass WIMPs: threshold is key

CRESST–II at LNGS uses cryogenic calcium tungstate ($CaWO_4$) crystals to measure scintillation light and phonons to separate ERs from NRs. TES (~15 mK) and SQUID signal measurement & amplification.

- Sub-keV energy thresholds and a high-precision energy reconstruction.
- Combined with the light target nuclei, CRESST-II has potential to explore < 1 GeV dark matter particle



Extends searches to sub-GeV range

Systematic studies still ongoing. Follow-up programme with 50–100 eV threshold starts in Apr 2016

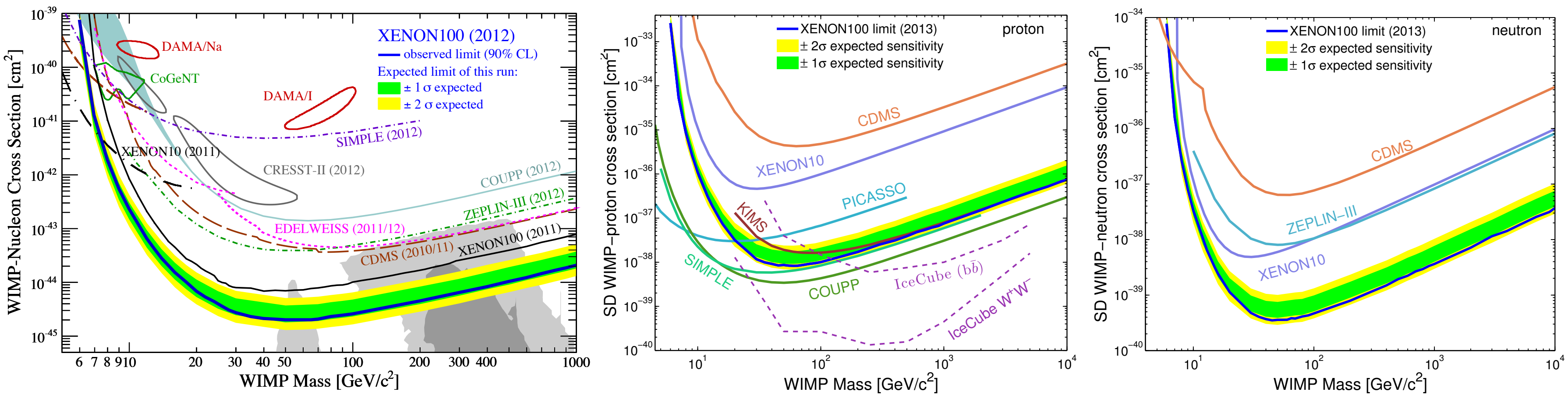
Constanze Hasterok

Direct dark matter searches: XENON100

2nd phase of XENON DM experiment at LNGS running since 2009, predecessor of XENON1T

XENON100 uses 61 (100) kg target (active veto) liquid-gas xenon filled TPC. High-density, high atomic number, sensitivity to spin-dependent interactions through ~50% odd isotopes, low threshold due to high ionization and scintillation yield, low backgrounds, self-shielding target. LXe scintillation light measured by PMTs. Light from prompt scintillation (S1) and delayed ionization (S2) allows to discriminate ER from NR.

2012/2013 results:



Recent result (2015) addresses DAMA's periodic signal: XENON100 does not find significant periodicity, DAMA phase & amplitude excluded at 4.8σ; DAMA-like DM models excluded to at least 3.6σ

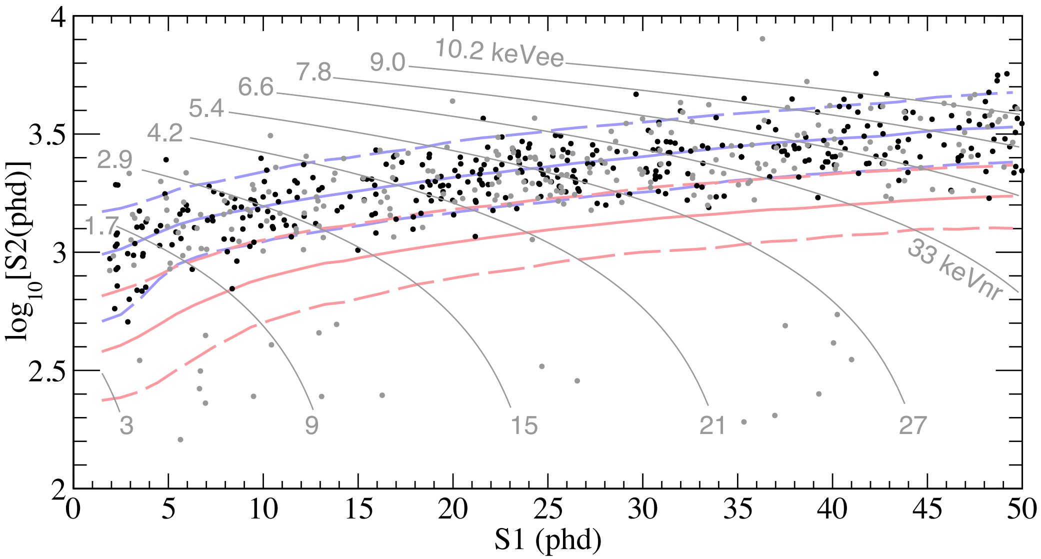
Follow-up programme XENON1T commissioning almost completed, first results expected this year

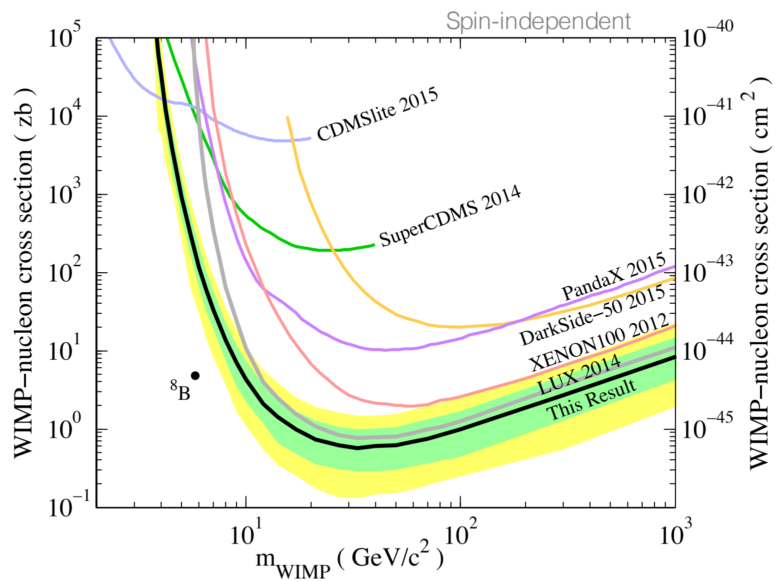
Direct dark matter searches: LUX

Liquid-Xe experiment at Sanford, South Dakota, US, 1.5 km underground

LUX is very similar as XENON100 based on a dual-phase Xe target. LUX has larger active target and lower threshold (3 keV vs. 6.6 keV), ie, sensitivity to lower WIMP masses.

- Reanalysis of 2013 data (95 live days, 145 kg fiducial mass) with improved calibration, event reconstruction and background modelling improving the sensitivity especially at low WIMP masses





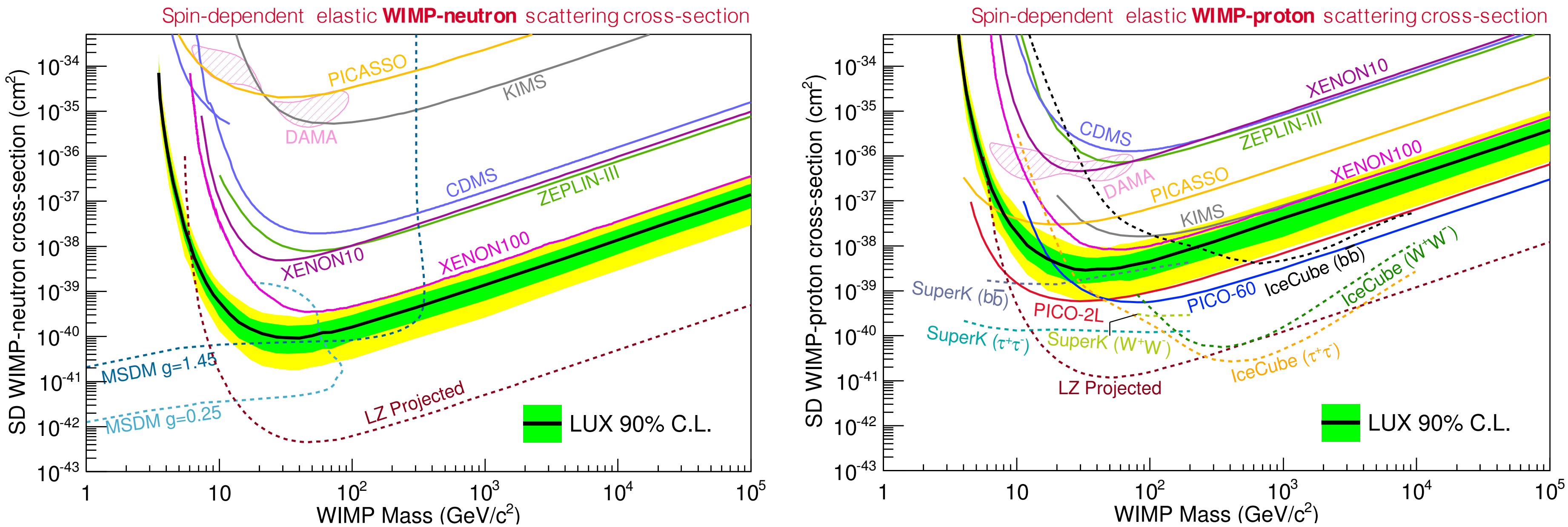
Paolo Beltrame

Direct dark matter searches: LUX

Liquid-Xe experiment at Sanford, South Dakota, US, 1.5 km underground

LUX is very similar as XENON100 based on a dual-phase Xe target. LUX has larger active target and lower threshold (3 keV vs. 6.6 keV), ie, sensitivity to lower WIMP masses.

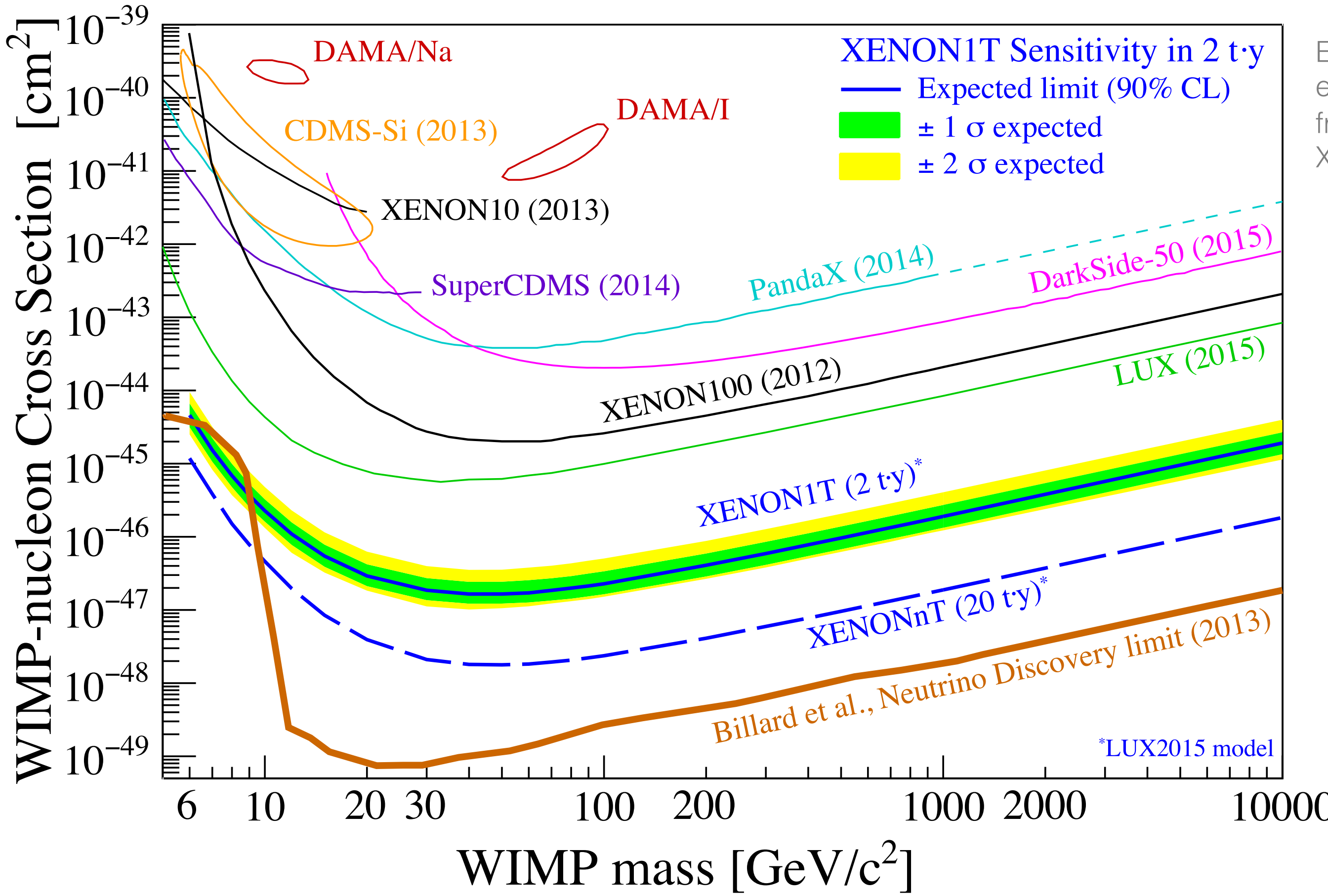
- LUX has also recently published spin-dependent limits using the same dataset



Follow-up programme LZ = LUX + ZEPLIN entering CD-2 review, start foreseen for 2025

Direct dark matter searches: Outlook

Healthy experimental programme in preparation with orders of magnitude improved sensitivity



Example extrapolation from XENONnT

Next generation experiments may reach irreducible coherent ν–N scattering background limit

Gravitational Waves

A new **Popstar**
in science

Gravitational Waves

LIGO Hanford site (Washington, US)

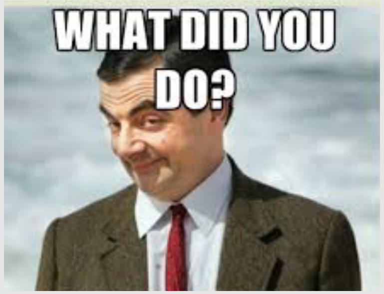

LIGO Livingston (Louisiana, US)


VIRGO (Cascina, Italy)
— not operating in Sep 2015

… reporting on Feb 11th, 2016 an *earthshattering* measurement

Gravitational Waves

REMEMBER ?



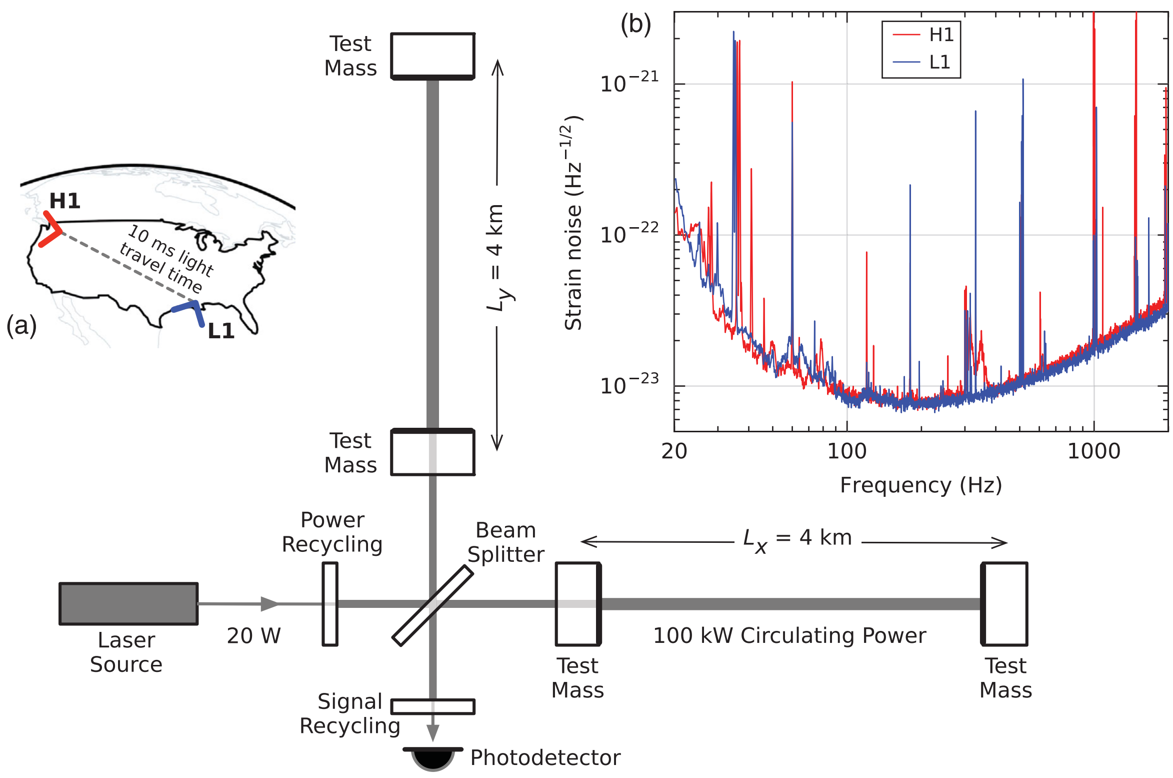
... ON SEP 14, 2015 AT 09:51 UTC (11:51 AM CEST)

Alessio Rocchi

Gravitational Waves: LIGO / VIRGO

Huge signal of binary black hole merger in LIGO, first noticed by online burst detection system

LIGO's measurement is an example of scientific perseverance



Two (better three!) detectors to localise GW and measure polarisation

Spin-2 GW lengthens one arm while shortening other and vice versa in laser interferometer

$\Delta L = \delta L_x - \delta L_y = h(t)\, L$

Optical signal measured proportional to strain $h(t)$

Enhancements to basic Michelson interferometer:

- Test mass mirrors multiply effect of GW on light phase by ~300
- Power recycling mirror on input amplifies laser light
- Output signal recycling broadens bandwidth

Isolation of test masses from seismic noise, low thermal noise. Vibration isolation of all components and vacuum to reduce Raleigh scattering

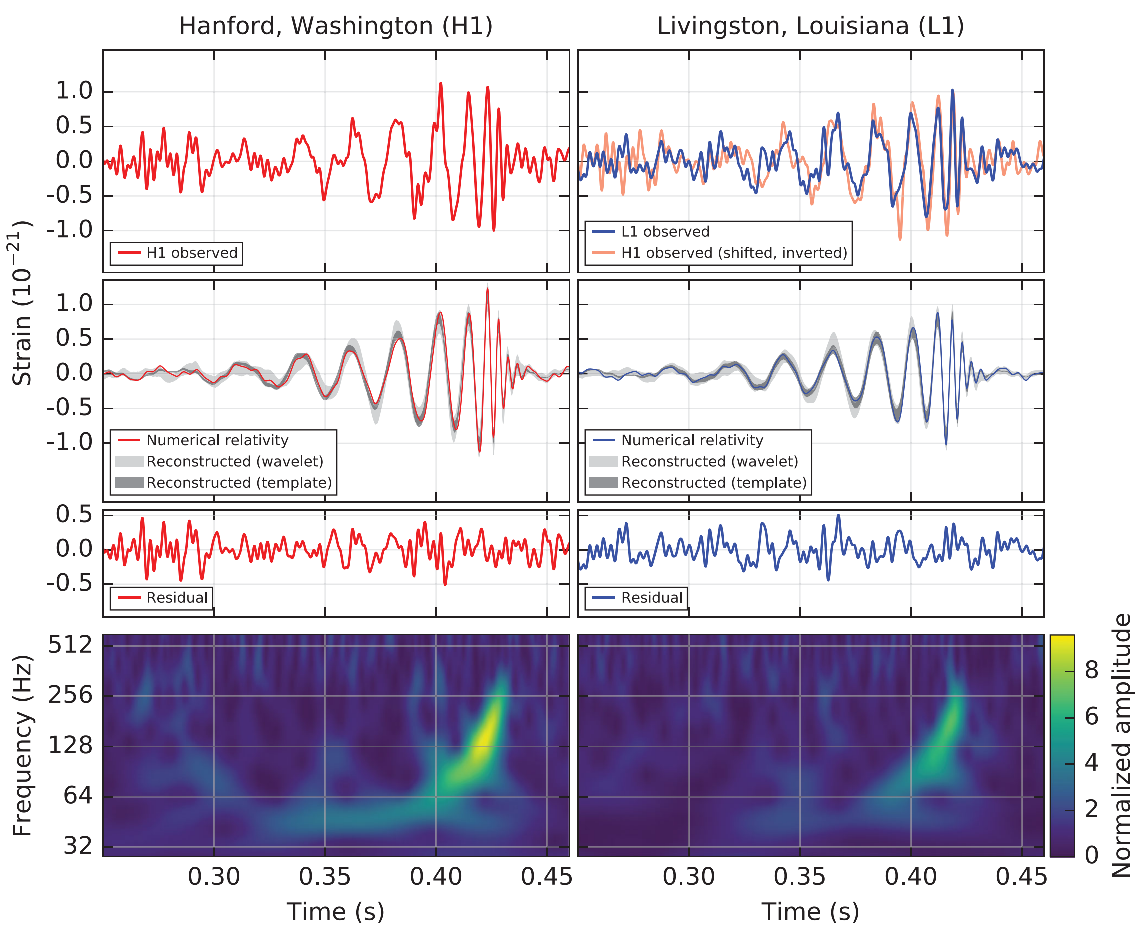
System of calibration lasers and array of environmental sensors

Alessio Rocchi

Gravitational Waves: LIGO / VIRGO

Huge signal of binary black hole merger in LIGO, first noticed by online burst detection system

Then, on Sep 14, 2015 at 09:51 UTC (11:51 am CEST) [total 16 days of simultaneous two-detector observational data]



H1 data shifted by 6.9 ms

Extremely loud event (ρ_c = 23.6)

Maximum strain (10^{-21}) times 4 km gives length deformation: 4×10^{-18} m ~ 0.5% size of proton

Measured spectrum well reproduced by GW calculation after fitting parameters

→ **GW150914** (> 5.1σ over bkg)

Time series filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen on previous page

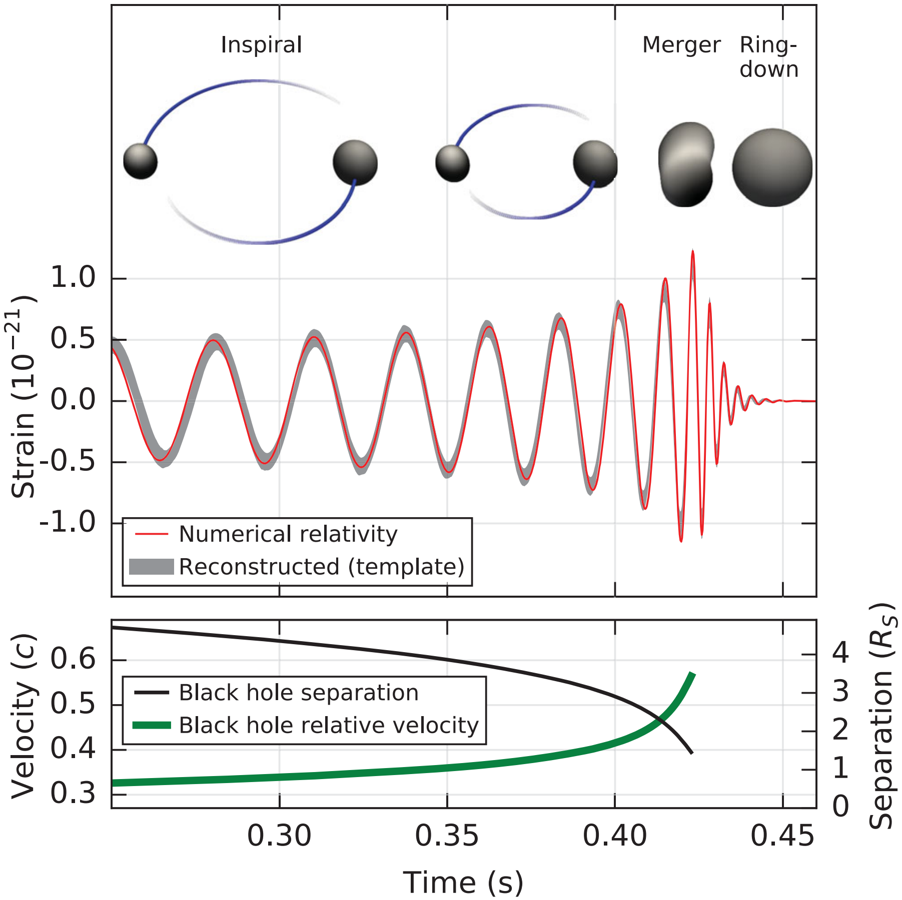
Times shown are relative to Sep 14, 2015 at 09:50:45 UTC

Alessio Rocchi

Gravitational Waves: LIGO / VIRGO

Huge signal of binary black hole merger in LIGO, first noticed by online burst detection system

1.3 (± 0.5) billion years (410 Mpc) ago in a galaxy far away….



GW150914

- Over 0.2 s, frequency and amplitude increase from 35 to 150 Hz (~8 cycles)
- To reach 75 Hz orbital frequency, objects need to be very close ~350 km and massive (→ black holes)
- Two black holes of initially 36 and 29 solar masses ($M_\odot$) inspiral with ~half c
- The black holes merge within tens of ms
- Inspiral, merging and ringdown leave characteristic amplitude and frequency gravitational wave pattern
- Total radiated GW energy 3.0 ± 0.5 $M_\odot$
- It's direct observation follows upon the demonstration of GW from energy loss in binary pulsar systems (1982)

Gravitational Waves: LIGO / VIRGO

Huge signal of binary black hole merger in LIGO, first noticed by online burst detection system

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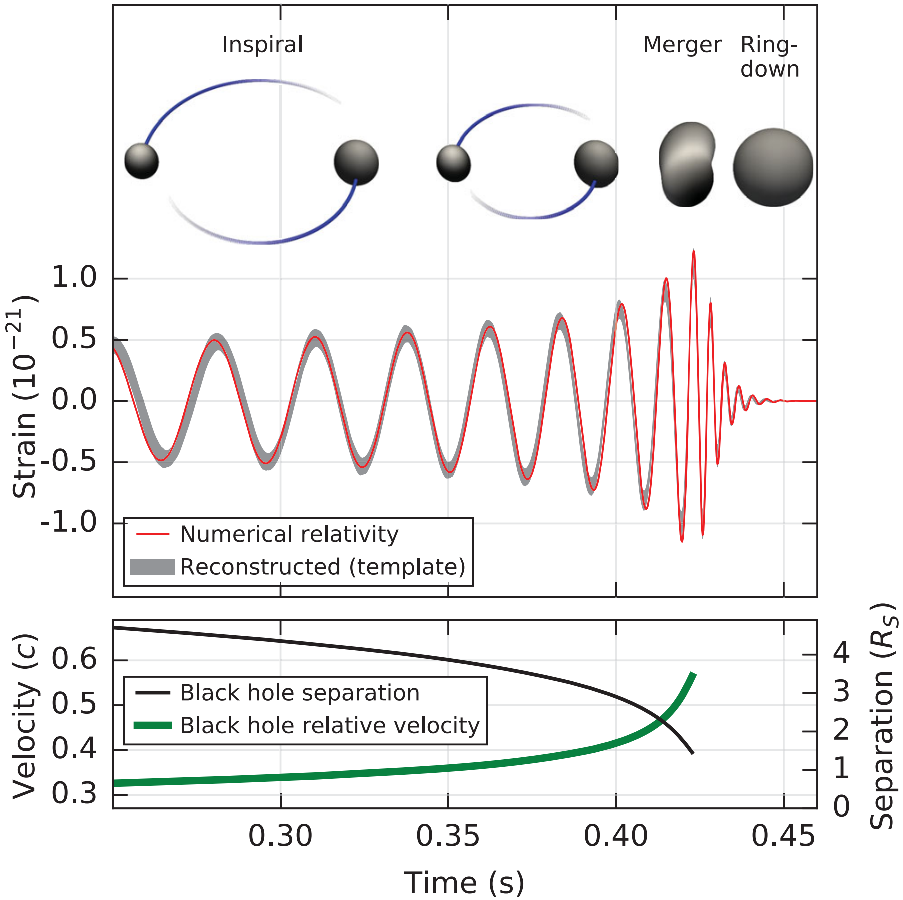

Observation of GW150914 bundles several discoveries:

- First direct detection of GWs
- First observation of binary black hole merger
- Relatively heavy stellar-mass black holes ($> 25\ M_{\odot}$) exist in nature
- Observation of ”no-hair-conjecture”
- Most relativistic binary event seen ($v/c \sim 0.5$)
- Limit on graviton mass ($< 1.2\times10^{-22}$ eV)

Likely not a unique BBH event: inferred rate 2–400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ at higher end of predictions

Adding VIRGO will improve localisation of GW; new interferometers upcoming in India & Japan

EM and high-$E\,\nu$ follow-up programme (no HEN coincidence seen by ANTARES and IceCube)

Alessio Rocchi

Gravitational Waves: LIGO / VIRGO

Huge signal of binary black hole merger in LIGO, first noticed by online burst detection system

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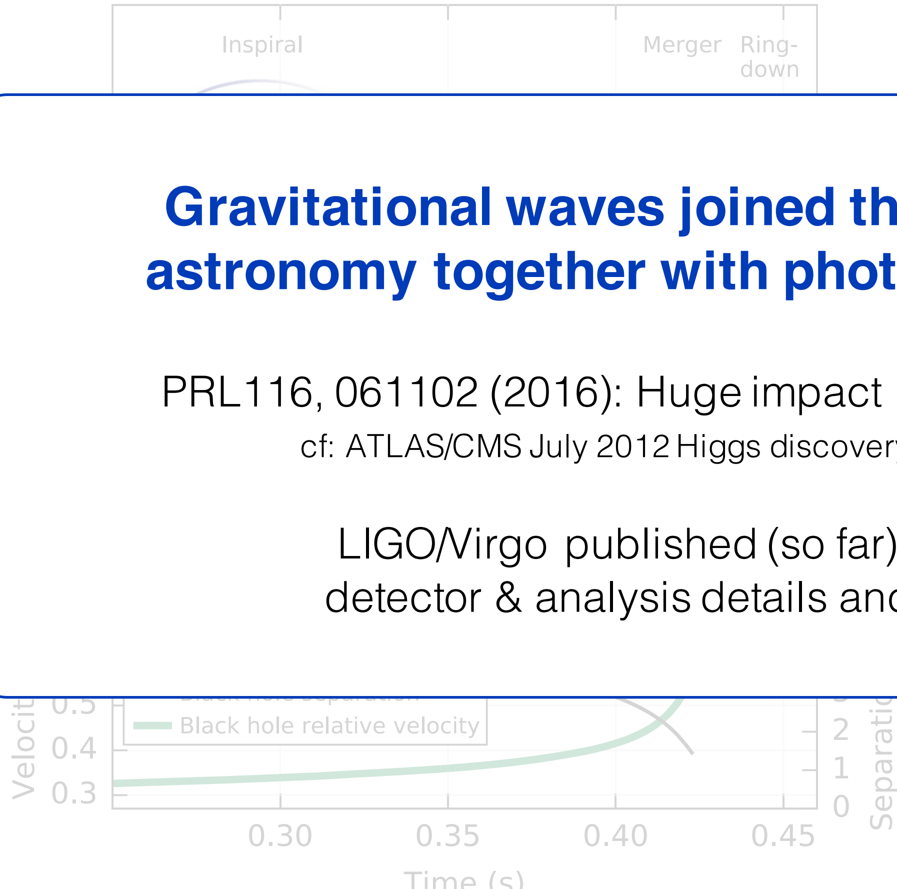


Observation of GW150914 bundles several discoveries:

Gravitational waves joined the club for multi-messenger astronomy together with photons, cosmic rays, neutrinos

PRL116, 061102 (2016): Huge impact paper: >100 citations within 1 month

cf: ATLAS/CMS July 2012 Higgs discovery papers have > 5600 citations by now

LIGO/Virgo published (so far) 12 follow-up papers about detector & analysis details and implications of GW150914

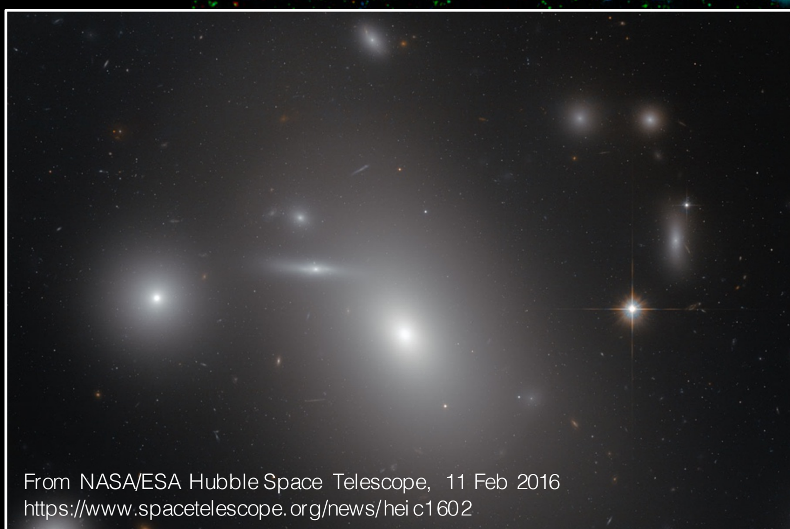
observation; new interferometers upcoming in India & Japan

EM and high-E ν follow-up programme (no HEN coincidence seen by ANTARES and IceCube)

Talking about black holes … there are gargantuan black holes

Every galaxy is expected to host supermassive black holes with > 1M sun masses in its centre, formed during galaxy creation process

NGC 4889, the brightest elliptical galaxy in the Coma cluster (94 Mpc ~ 300 Mly from earth), hosts a record BH of 21 billion times mass of Sun, event horizon diameter of ~130B km (Sun: 1.4M km)



From NASA/ESA Hubble Space Telescope, 11 Feb 2016
https://www.spacetelescope.org/news/heic1602

(Heavy) flavour physics

- Study flavour mixing & CP violation in all its aspects
- Look for new physics far beyond the current energy frontier in rare and forbidden processes
- By these measurements we hope to get insight into the mystery of the observed flavour structure (which is related to Higgs sector)

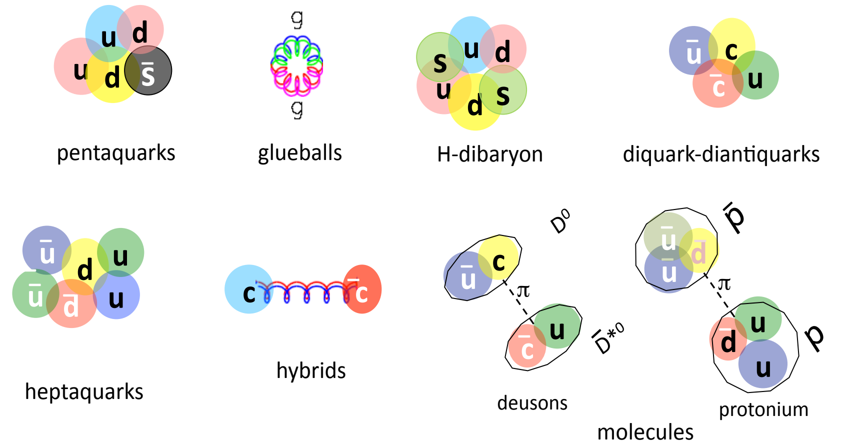
Flavour Physics

The cavern in the North Area shortly before the NA62/2 run in autumn 2014

Jeroen van Tilburg

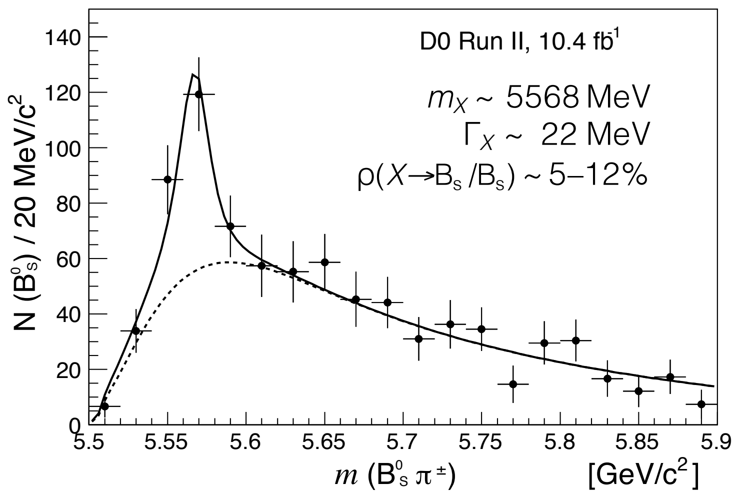
Hadron zoo: XYZ mesons

Topic of Moriond QCD, only this much…

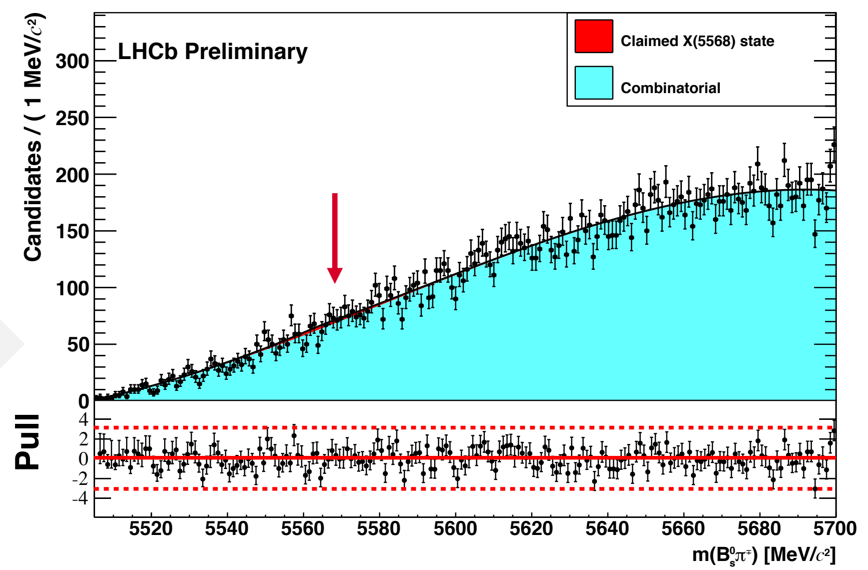


Picture from Stephen Lars Olsen, La Thuile 2016

D0 announced new state in $m(B_s(\rightarrow J/\psi\,\phi)\,\pi^{\pm})$ spectrum which may be a tetra-quark ($bsud$) [1602.07588, Feb 2016]



Prompt cross-check by LHCb did not confirm the observation in 20 times larger B_s sample.
Upper limit on $\rho \sim 1\%$, but this may depend on beam/energy/analysis. No public material yet, but more information expected this week.



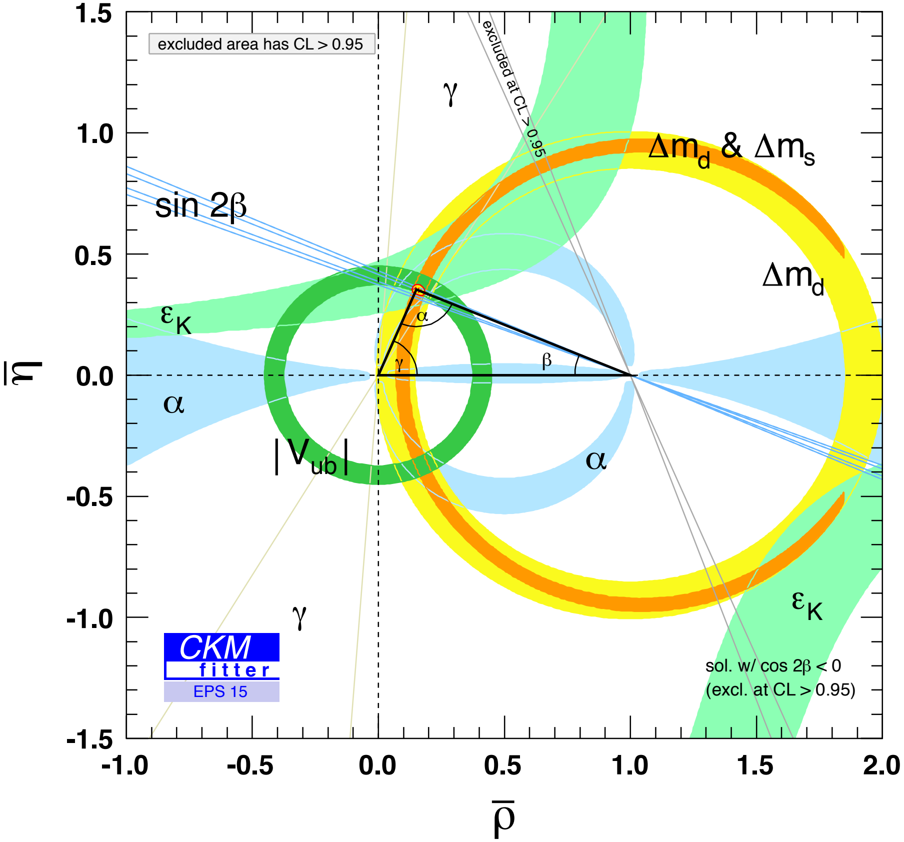
Other experiments are also looking

Jeroen van Tilburg

The CKM matrix and more

Long-term effort to overconstrain CKM matrix continues. Huge contributions from LHCb

A precise measurement of γ (tree) together with sin(2β) (mix) or $|V_{ub}|$ (tree), fixes the unitarity triangle. All other measurements probe these two.

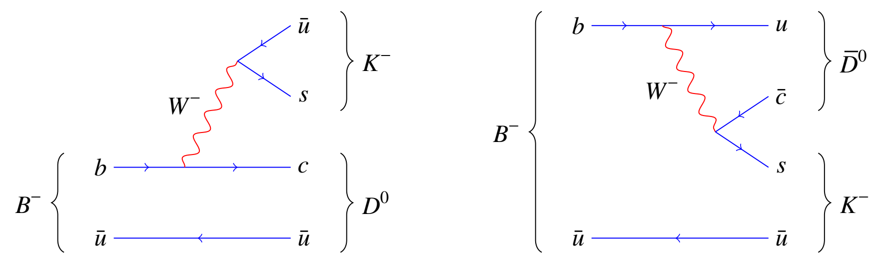


LHCb reported:

- $|V_{ub} / V_{cb}|$ from $\Lambda_b \rightarrow p\mu\nu$ at 5% precision (closer to exclusive B-factory result)
- World's best single Δm_d measurement: $0.5050 \pm 0.0021 \pm 0.0010\ \mathrm{ps}^{-1}$ (B-factories: $\sigma_{ave} = 0.005\ \mathrm{ps}^{-1}$)
- Precision on sin(2β) approaches that of B-factories: $0.73 \pm 0.04 \pm 0.02$
- World's best constraints on CP violation in $B^0_{(s)}$ mixing (a_{sl}^s, a_{sl}^d) in agreement with SM (D0 sees 3.6σ deviation)
- Search for CPT violation (difference in mass or width) in $B^0_{(s)}$ system, measurement of sidereal phase dependence of CPT violating parameter

The CKM matrix and more

Huge LHCb effort on CKM angle γ

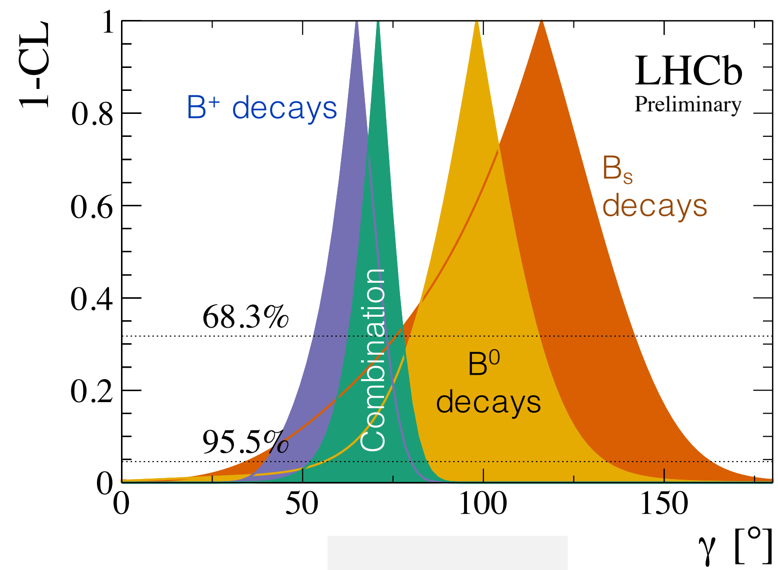


The CKM angle γ ~ arg(–V_{ub}*) can be measured through interference of b → u with b → c tree transitions

Hadronic parameters are: r_B and strong FSI phase δ_B

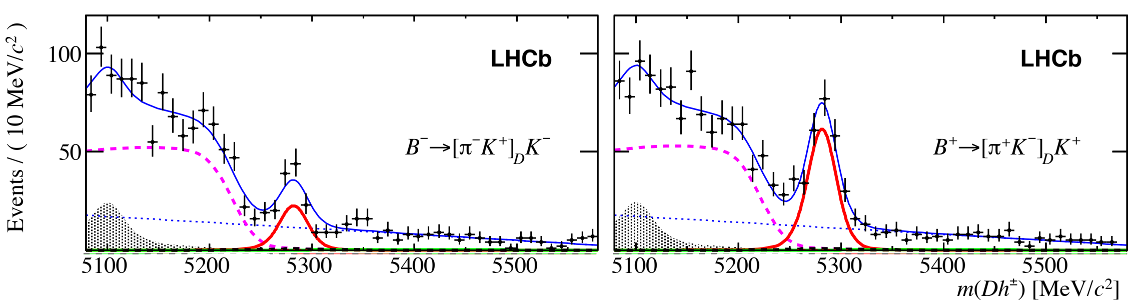
Theoretically clean measurement, but large statistics needed due to CKM suppression of amplitudes.

Hence use B±, B⁰, B_s, and many D decay modes requiring different techniques; also DK* and D^{s}K used. Some modes show large CP asymmetries (*example below*)



ADS: ***B±→ Dh±, D→ π⁺K⁻***

$$\boxed{A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \quad \pm 0.056 \quad \pm 0.011}$$



$\gamma_{\mathrm{combined}} = 71^{+7}_{-8}$ deg

CKM fit: 68 ± 2 deg

(γ measurement not in fit)

Alex Pearce

Charm @ LHCb: CP violation and mixing

Exploiting huge recorded charm sample from Run-1

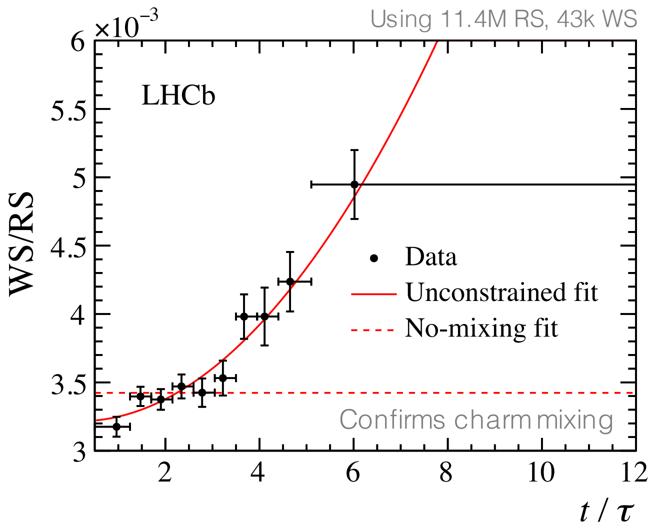
Charm: mixing frequency extremely low, challenging high-statistics measurement, CP violation small in SM

New mixing analysis using $D^0 \to K^- \pi^+ \pi^- \pi^+$.
Sensitive to strong phase difference needed for γ measurement via $B^+ \to D^0K^+$ (with $D^0 \to K^- \pi^+ \pi^- \pi^+$)

$$\frac{\mathrm{WS}}{\mathrm{RS}}(t) = \frac{D^0 \to K^+ \pi^- \pi^+ \pi^-}{D^0 \to K^- \pi^+ \pi^- \pi^+}(t) = R(t) \approx \left(r_D^{K3\pi}\right)^2 - r_D^{K3\pi} R_D^{K3\pi} \cdot y'_{K3\pi} \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

sensitive to mixing, to ratio of CF to DCS amplitudes and their interference (strong phase δ)

Using 11.4M RS, 43k WS



Taking x, y from WA, allows to measure $r_D^{K3\pi}$ & $R_D^{K3\pi} \cdot y'_{K3\pi}$

New results were shown for CP violation in charm:

$$\Delta A_{CP} = A_{CP}(D^0/\bar{D}^0 \to K^+K^-) - A_{CP}(D^0/\bar{D}^0 \to \pi^+\pi^-)$$

D^0 flavour inferred from soft pion charge in: $D^{*+} \to D^0 \pi^+$

Earlier 0.6 fb^{-1} result exhibited 3.5σ discrepancy with SM, not confirmed with larger data sample.

New, full 3 fb^{-1} result:

$$\Delta A_{CP} = -0.10 \pm 0.08_{stat} \pm 0.03_{syst}\ \%$$

Johannes Albrecht, Sanjay Kumar Swain

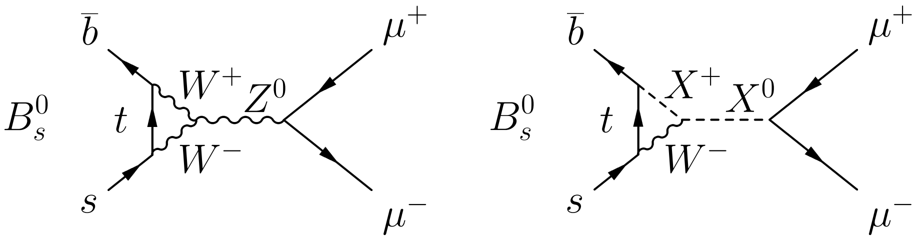
Rare B decays

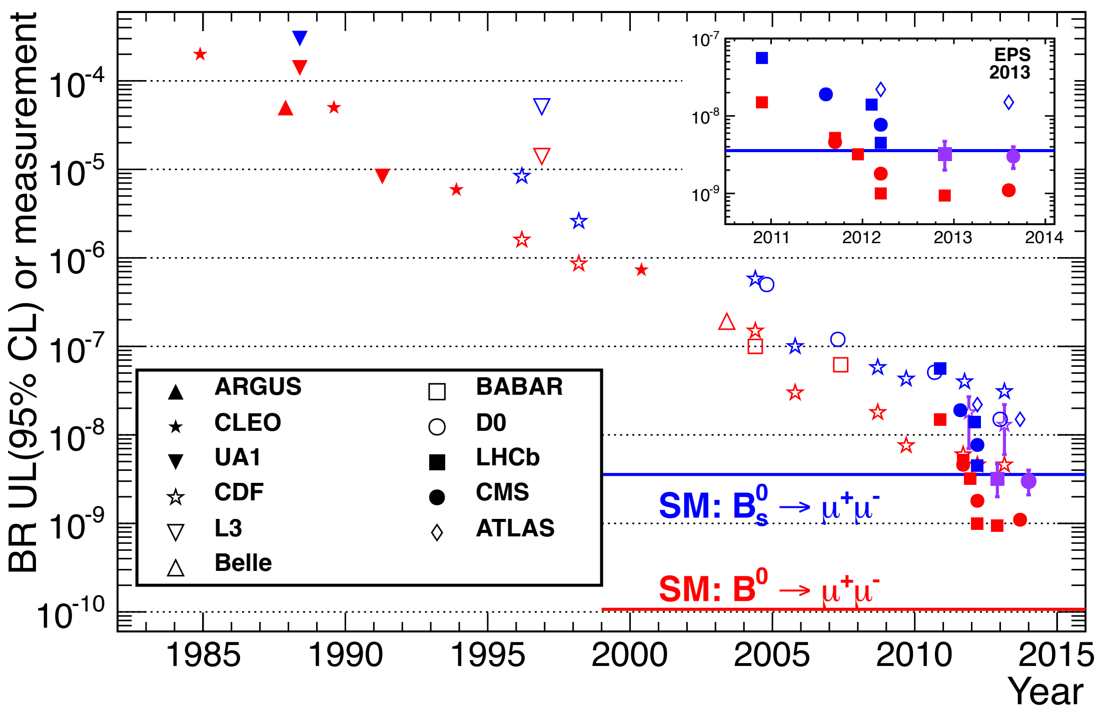
$B_s \to \mu\mu$ decay unambiguously observed by CMS & LHCb in Nov 2014 using Run-1 dataset

Beautiful channel to look for new physics

Relatively precise SM prediction, measurable branching fraction

Long search before it was finally observed





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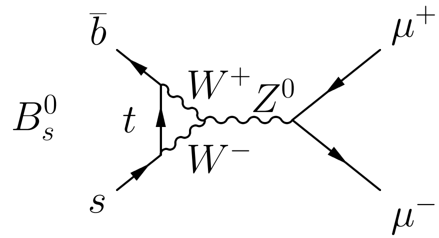
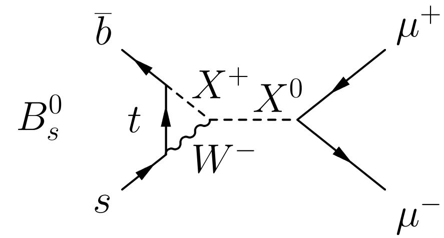
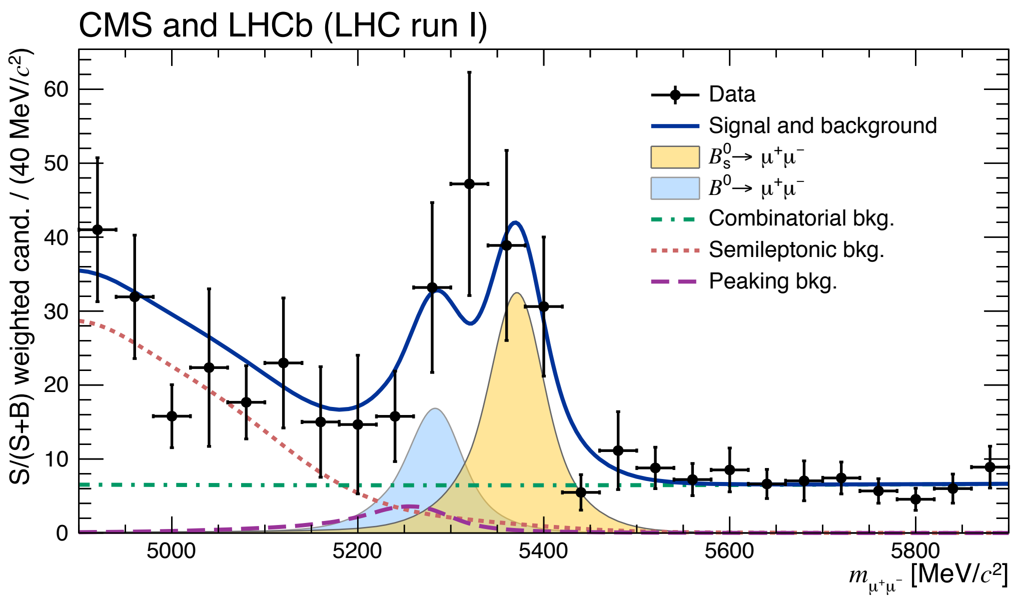
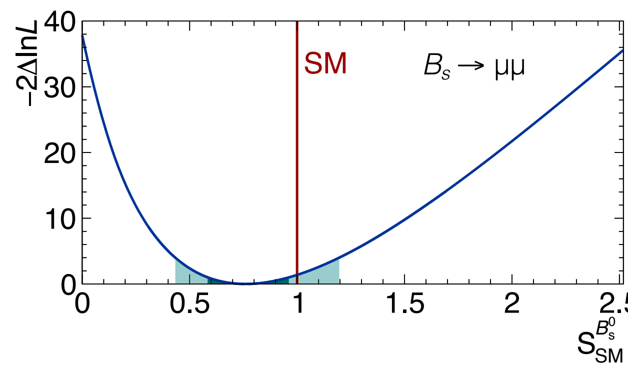
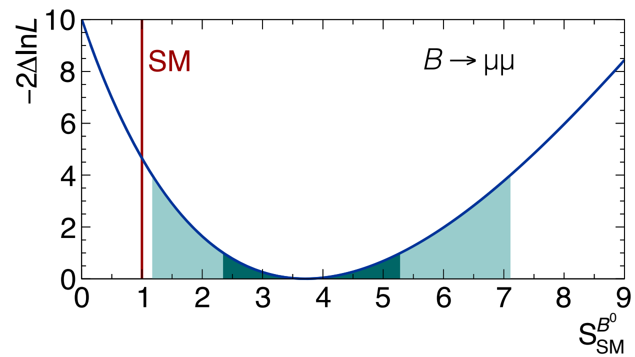
Relatively precise SM prediction, measurable branching fraction











CMS & LHCb combined:

$\mathcal{B}(B_s \to \mu\mu) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$ (6.2σ) | SM: $3.7 \pm 0.2 \times 10^{-9}$

$\mathcal{B}(B \to \mu\mu) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$ (3.2σ) | SM: $1.1 \pm 0.1 \times 10^{-10}$

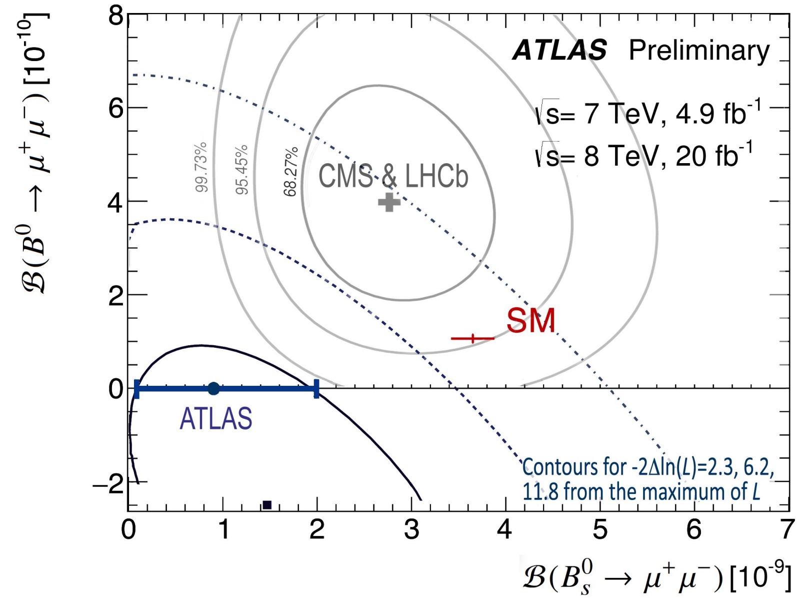
Rare B decays

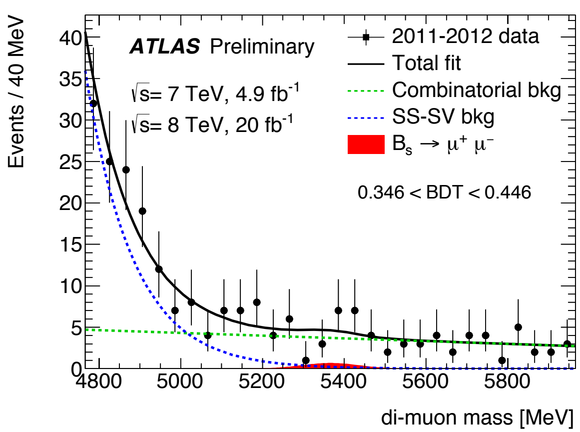
Preliminary Run-1 $B_s \to \mu\mu$ search presented at this conference by ATLAS

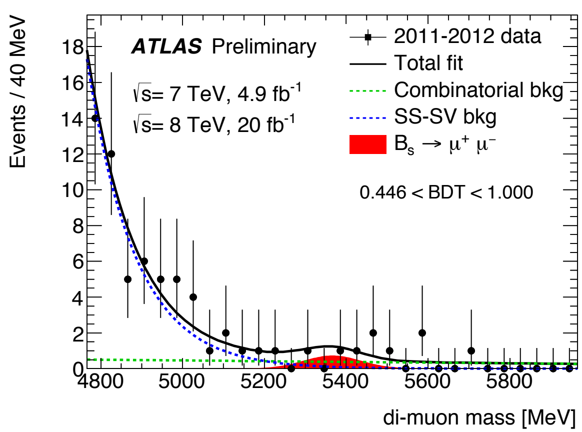
Similar analysis approach as CMS & LHCb

Features:

- BDT to suppress hadrons faking muons (fight peaking backgrounds)
- BDT to suppress continuum background
- 2D fit to cont. BDT bins & $m(\mu\mu)$ (unbinned)
- Event yield normalised to $B^+ \to J/\psi\, K^+$ (input: f_s/f_d)
- Control channels: $B^+ \to J/\psi\, K^+$ and $B_s \to J/\psi\, \phi$
- 3.1σ expected significance for $B_s \to \mu\mu$ [SM]







$$\mathrm{BR}(B_s \to \mu\mu) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$$
$$< 3.0 \times 10^{-9} \text{ (95\% CL)}$$

$$\mathrm{BR}(B \to \mu\mu) < 4.2 \times 10^{-10} \text{ (95\% CL)}$$

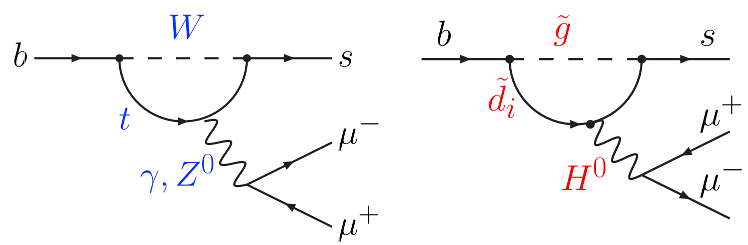
Compatibility with SM: 2.0σ

Flavour anomalies

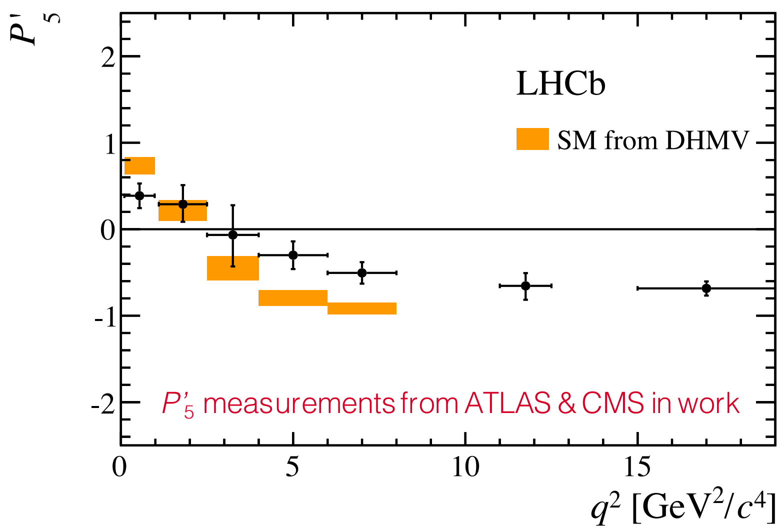
$b \to s\, \mu^+\mu^-$ continues to produce interesting results, more channels added

LHCb showed results with full angular analyses for $K^*\mu\mu$ (8 independent CP-averaged observables).
Best experimental precision on A_{FB}, F_L, …

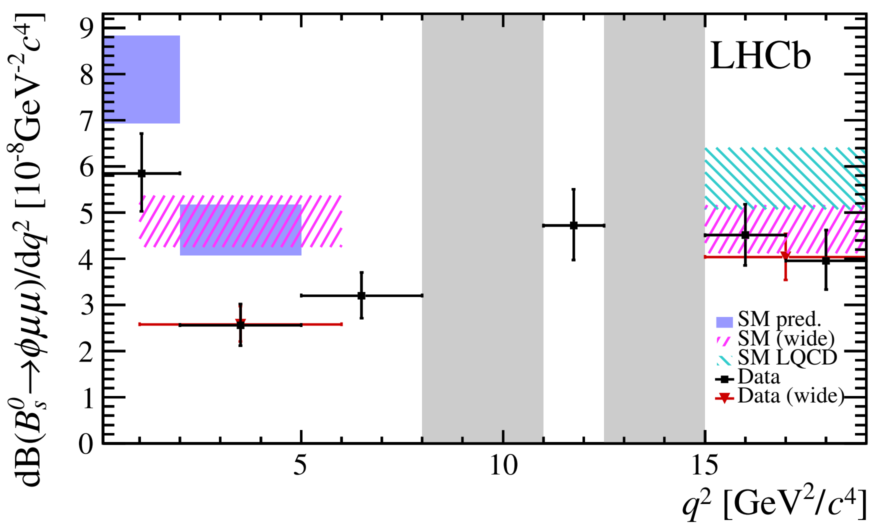
Also angular and diff. BR analysis of $B_s \to \phi\mu\mu$, and diff. BR analysis of $B^+ \to K^+\mu\mu$



Use ratio to cancel FF dependence: $P_5' = S_5/\sqrt{F_L(1-F_L)}$
Full Run-1 dataset and new analysis confirms discrepancy



Differential branching ratio of $B_s \to \phi\mu\mu$ decay



Global fit with new physics parameterisation (C_9^{NP}, C_{10}^{NP}) seems to reproduce observed discrepancy pattern

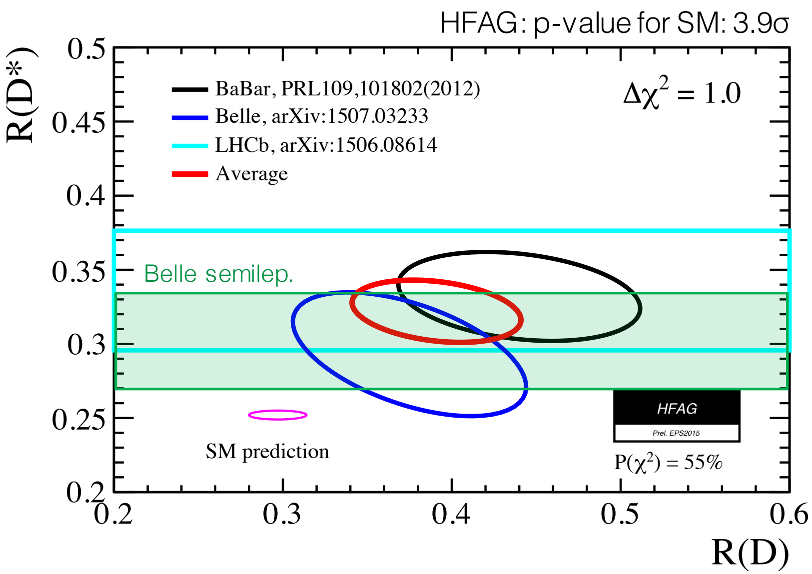
Johannes Albrecht, Pablo Goldenzweig

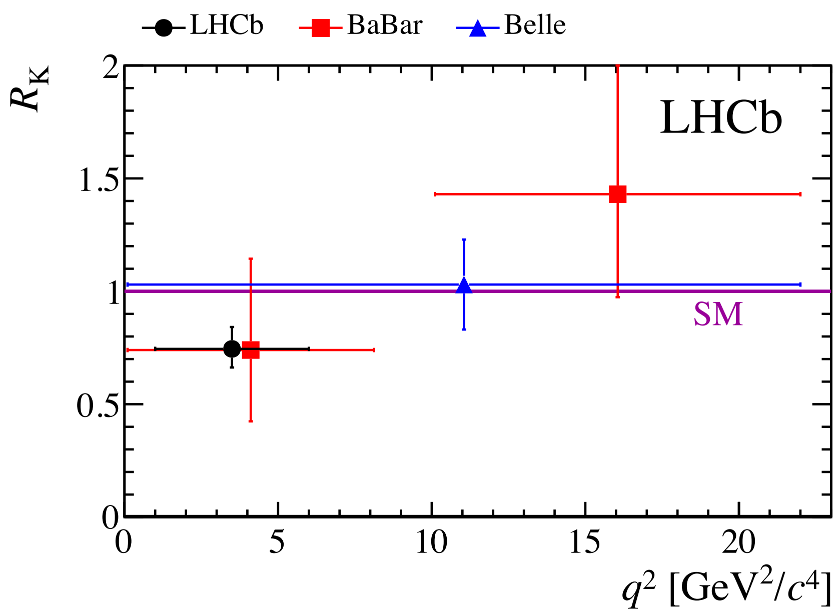
Flavour anomalies

Less plagued by hard to estimate theoretical uncertainties are lepton universality tests

The B-factories and LHCb measure ratios of semileptonic B decays. Robust SM predictions

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B^0 \to D^{(*)}\tau\nu)}{\mathrm{BR}(B^0 \to D^{(*)}\ell\nu)} \qquad R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu\mu)}{\mathrm{BR}(B^+ \to K^+ee)}$$





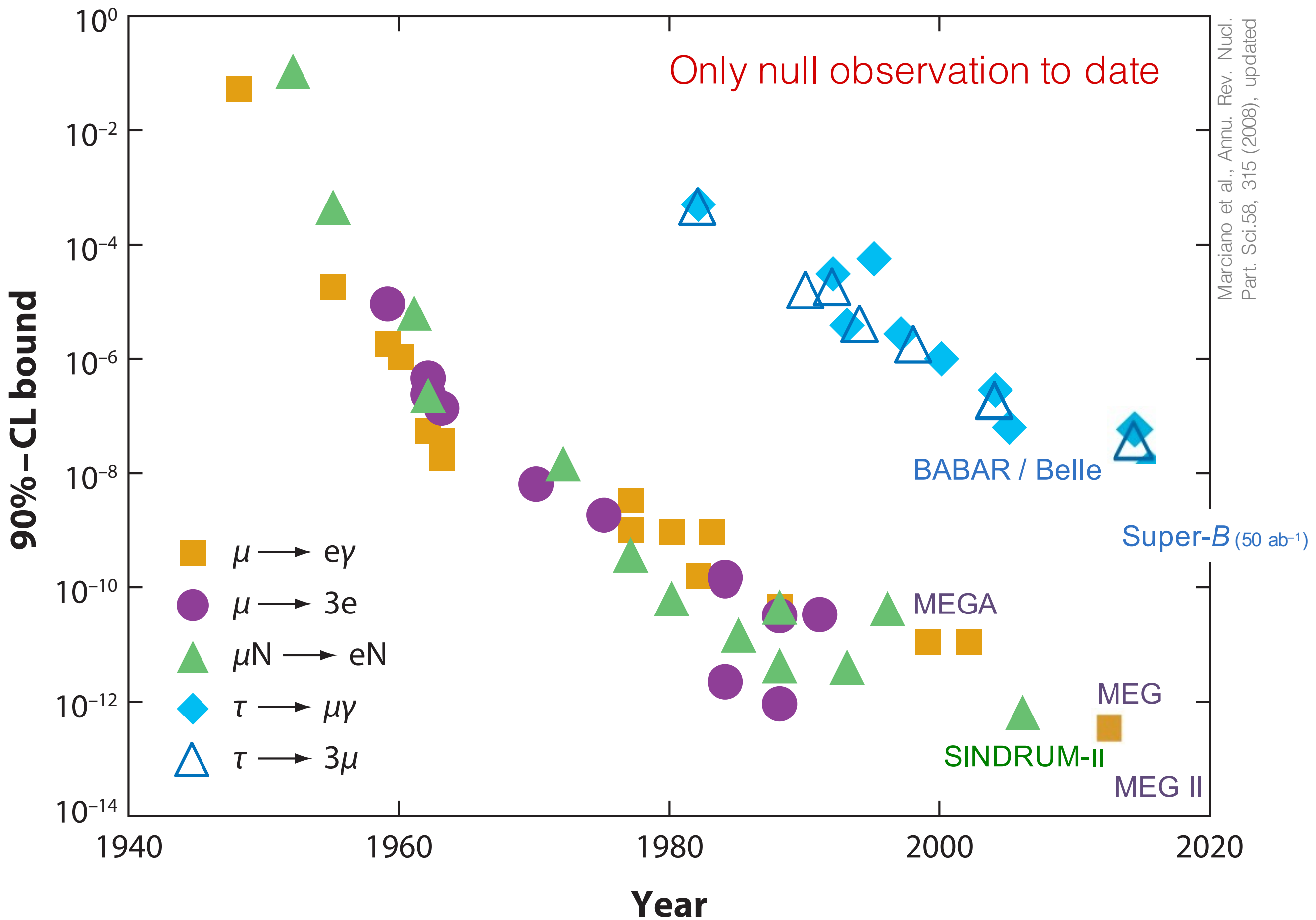
New measurement by Belle using semileptonic tagging of recoil B:

$R_{D^*} = 0.302 \pm 0.030_{stat} \pm 0.011_{syst}$ [SM: 0.252 ± 0.003, 1.6σ]

Also studied kinematic distributions (additional NP sensitivity)

Charged lepton flavour violation: SM-free signals!

A very active field of BSM searches



Spectacular perspectives: Mu2e / COMET
PRISM / PRIME

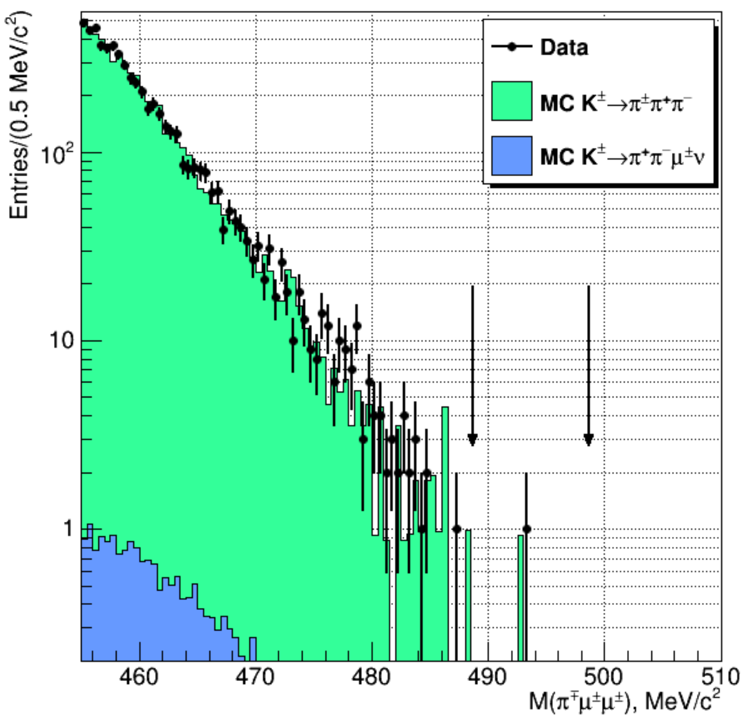
Charged lepton flavour violation

New analysis of NA48/2 2003–2004 data sample to search for lepton number violation

NA48/2 looked for the decay: $K^+ \to \pi^- \mu^+ \mu^+$ (negligible contribution from SM or neutrino oscillation expected)

Main background from $K^+ \to \pi^- \pi^+ \pi^+$ with $2\,\pi^+ \to \mu^+\nu$ decays

Total of $2{\times}10^{11}$ $K^\pm$ decays in fiducial detector volume



No excess observed. Strong 90% CL limit:

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$$

Also looked into di-muon invariant mass of opposite sign $K^+ \to \pi^+ \mu^+ \mu^-$ sample for resonances. None seen.

Outlook for NA62: expect to reach 10^{-12} LFV sensitivity (and 10^{-11} for $\pi^0 \to e\mu$)

Rare kaon decays: NA62

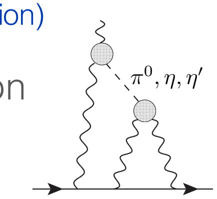
New result on 2007 dataset and /2 is ramping up

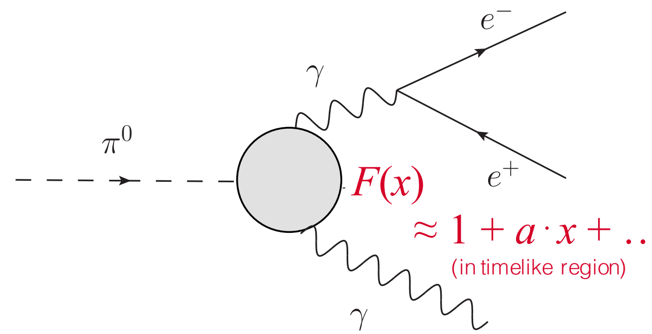
NA62 presented new measurement on 2007 dataset:

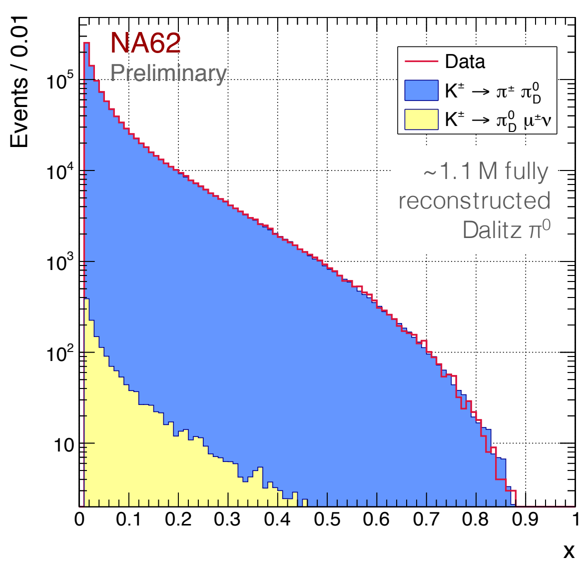
Measurement of timelike transition form-factor (TFF) slope with $\pi^0 \to e^+e^-\gamma$ Dalitz decays (1.2% BR) using ~5B triggered π^0 from $K^\pm \to \pi^\pm\pi^0$ (~20B $K^\pm$ in decay region)

TFF important to model muon g–2 LBLS contribution
(other experimental information from spacelike measurements of $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ by CELLO, CLEO, BABAR)

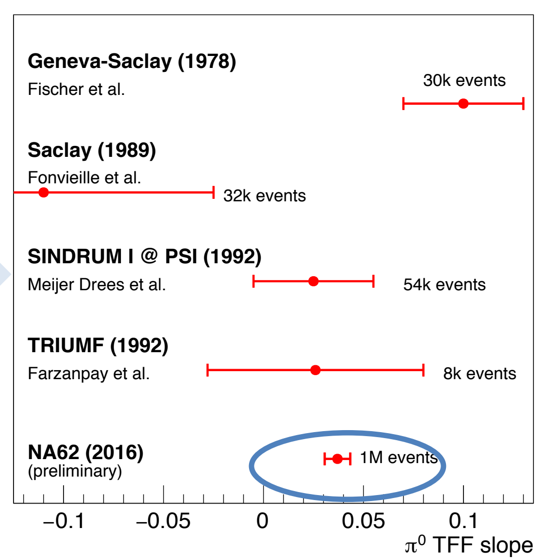
Challenge for $F(x)$ extraction: rad. corrections (included in MC)







$F(x)$ fit using MC templates



$a_{NA62} = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$

Rare kaon decays: NA62/2

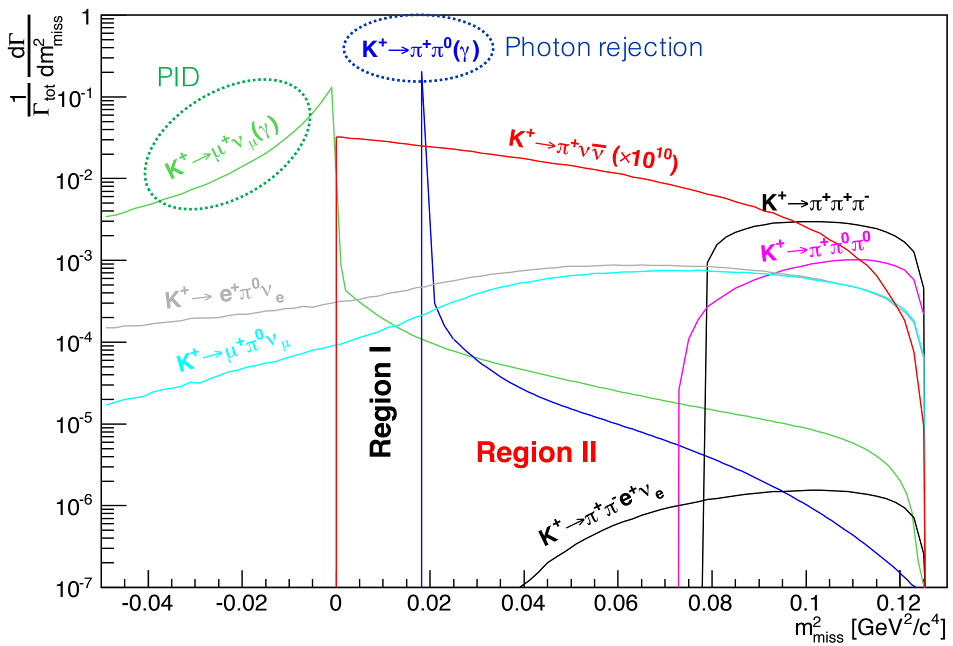
Eagerly awaited results on $K^+ \to \pi^\pm \nu\nu$ are on their way. 2014/15 data for commissioning

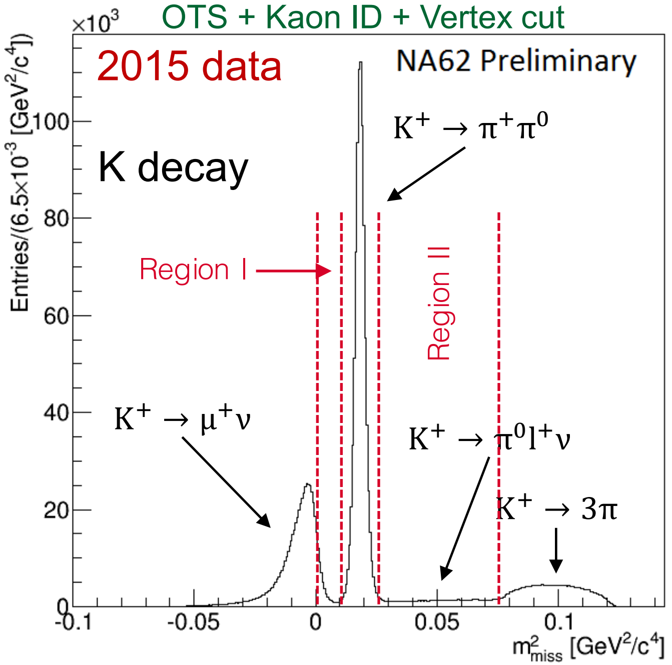
NA62 towards a measurement of $K^+ \to \pi^\pm \nu\nu$ (SM: $(8.4 \pm 1.0) \times 10^{-11}$, BNL E949: $(17 \pm 11) \times 10^{-11}$)
Additional physics goals: standard kaon physics and new physics searches

Goal: 10% $K^+ \to \pi^\pm \nu\nu$ BR measurement

Requirements: 5 trillion K^+ decays (~50 signal events) / year (possibly already in 2016)
similar order for background suppression (< 10 events / year, dominated by $K^+ \to \pi^\pm \pi^0$)

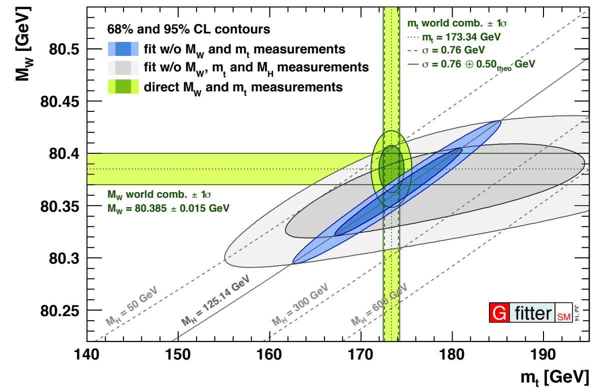
Most sensitive variable: $m^2_{miss} = (p_{K+} - p_{\pi+})^2$





Close to design performance

The LHC Run-1 is not over yet: high-quality, extremely well understood data sample for precision measurements



Global electroweak fit was masterpiece of LEP/SLD era. Discovery of Higgs over-constrains the fit and dramatically improves predictability

Electroweak precision physics

The LHC experiments — as do D0 & CDF since long, and continuing — are investing efforts into precision measurements of EW observables: m_W, m_{top}, $\sin^2\theta_W$

All are **very** challenging

SM Predictions [1407.3792, EW fit]

$$\begin{aligned} M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\text{had}}} \\ &\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W}\ \text{GeV}\,, \\ &= 80.358 \pm 0.008_{\text{tot}}\ \text{GeV}\,. \end{aligned}$$

[exp WA: σ = 15 MeV]

$$\begin{aligned} \sin^2\theta^{\ell}_{\text{eff}} &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\text{had}}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2\theta^f_{\text{eff}}}\,, \\ &= 0.23149 \pm 0.00007_{\text{tot}}\,, \end{aligned}$$

[exp WA: σ = 0.00016]

Benjamin Stieger

Electroweak precision measurements

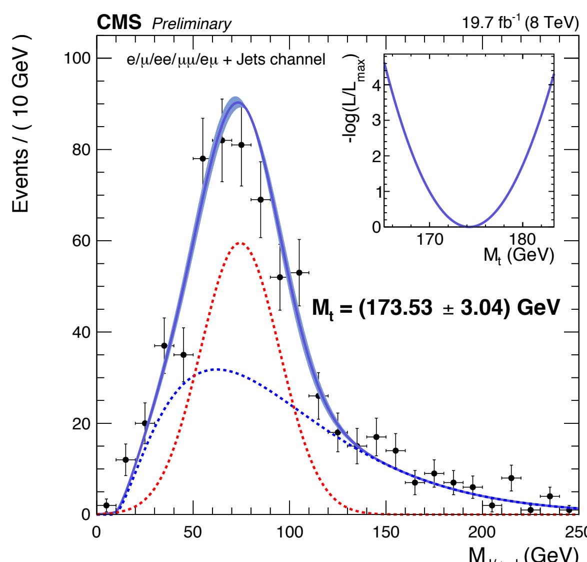
Top mass from LHC and Tevatron

We heard a beautiful talk about alternative methods to measure the top mass

Traditional kinematic top mass measurement method approaches systematic limit of b-quark hadronisation

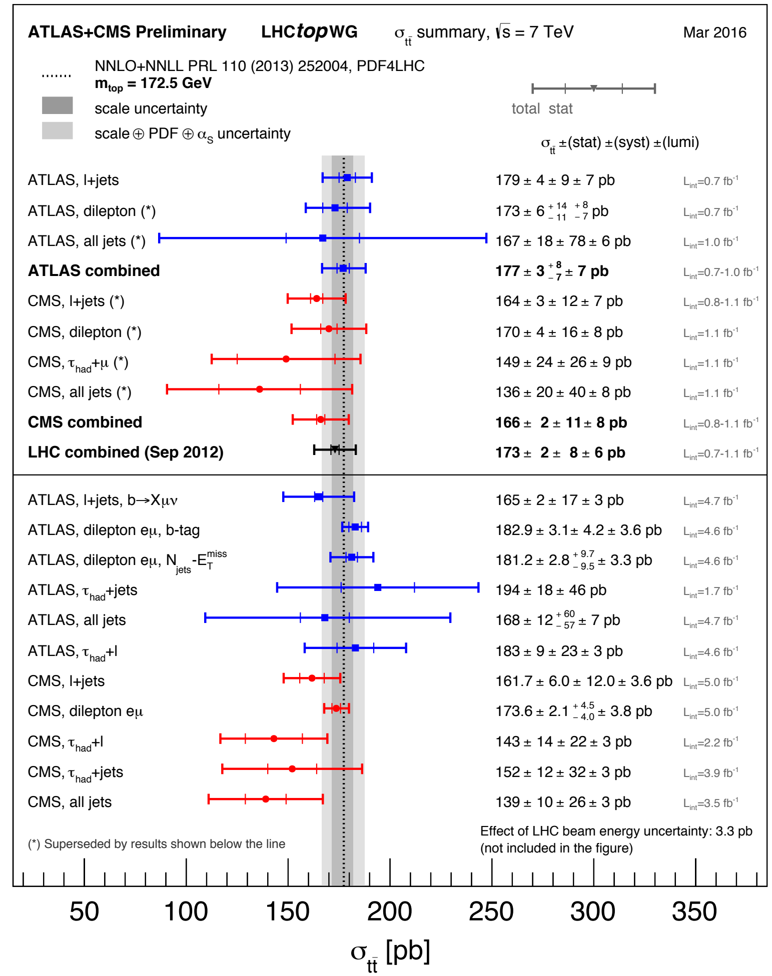
Ways to improve (lot of pioneering work by CMS):

- Choose more robust observables (eg, wrt. b fragmentation)
- Select charmed mesons (rare but very clean signature)
- Use dilepton kinematic endpoint (clean but large theoretical uncertainties)
- Use cross-sections or differential variables (promising but difficult to achieve competitive precision



Currently best result (CMS): 1.7 GeV uncertainty

LHC kinematic top mass measurements:



Arie Bodek, William James Barter

Electroweak precision measurements

$\sin^2\theta_W$ and Z asymmetries from hadron colliders

CDF, D0, and also LHC have extracted weak mixing angle from Z/γ* asymmetry measurements

Uncertainties at Tevatron dominated by statistical uncertainties, LHCb equally, ATLAS & CMS by PDF uncertainties.

Data-driven “PDF replica rejection” method applied by CDF

Complex measurements (in particular physics modelling) that are important to pursue, but precision of hadron colliders not yet competitive with LEP/SLD

+ Newest CDF result: 0.23221 ± 0.00046

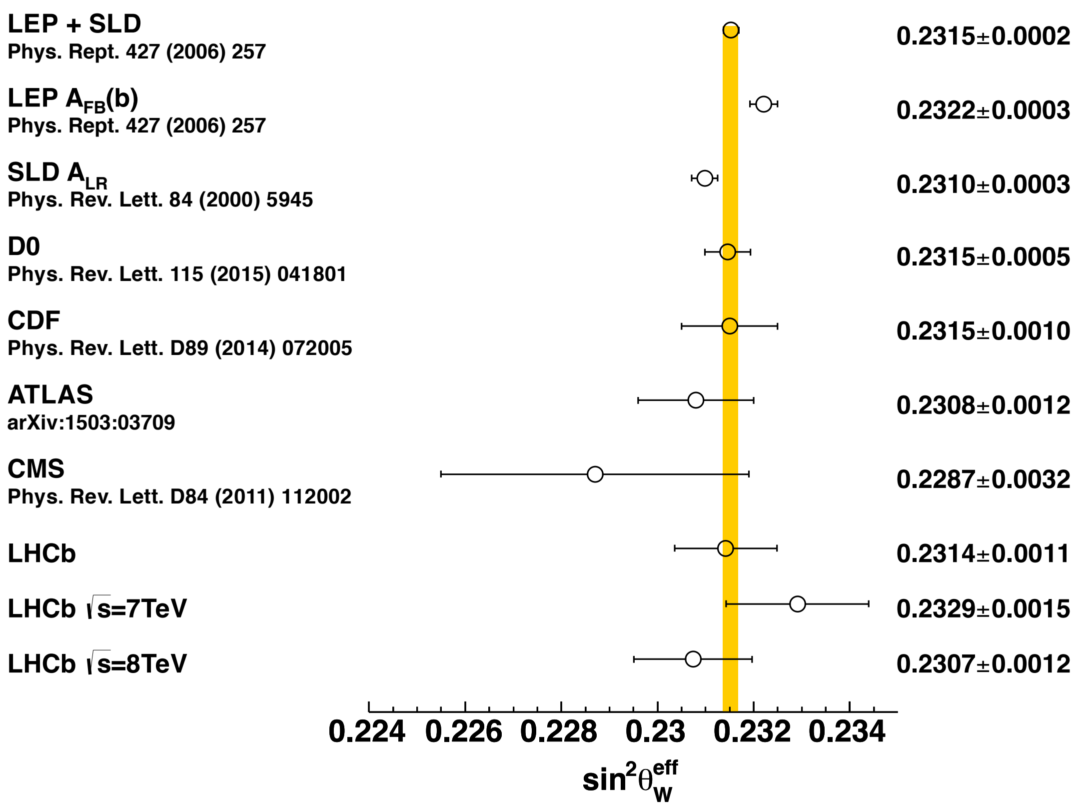


Figure from LHCb 1509.07645

Mariarosaria D'Alfonso

Electroweak precision measurements

W mass: towards a first measurement at the LHC via decay to lepton + neutrino

ATLAS, CMS & LHCb have presented progress towards the (challenging) m_W measurement at the LHC

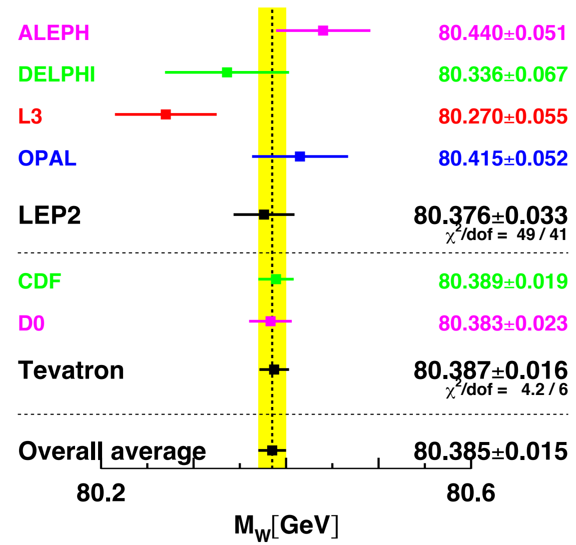
Measurement relies on excellent understanding of final state

Observables: $p_{T,\ell}$, $p_{T,\nu}$, m_T as probes of m_W

Challenges, high-precision:

- Momentum/energy scale (incl. had. recoil) calibration: Z, J/ψ, Y
- Signal efficiency and background modelling
- Physics modelling:
  - Production governed by PDF & initial state interactions (pert & non-pert): use W^+, W^-, Z, W+c data for calibration, and NNLO QCD calculations + soft gluon resummation
  - EW corrections well enough known
  - Probes very sensitive to W polarisation (and hence to PDF, including its strange density)

Current experimental picture for m_W



Project: Experiments are in a vigorous process of addressing the above issues. Many precision measurements (differential Z, W + X cross sections, polarisation analysis, calibration performance, …) produced on the way. Also theoretical developments mandatory. **Long-term effort.**

Electroweak precision measurements

W mass: towards a first measurement at the LHC via decay to lepton + neutrino

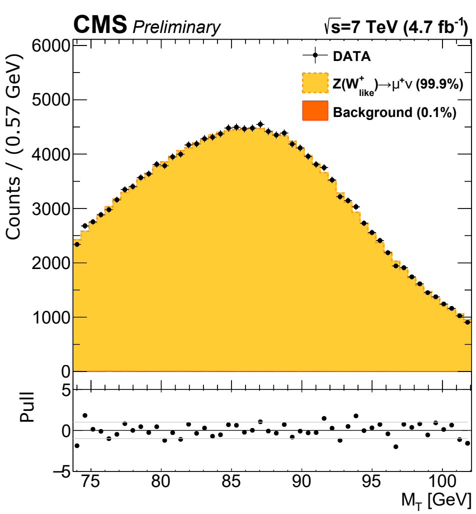
CMS presented a new m(Z) measurement using a W-like Z → μμ analysis (replacing one μ by recomputed MET)

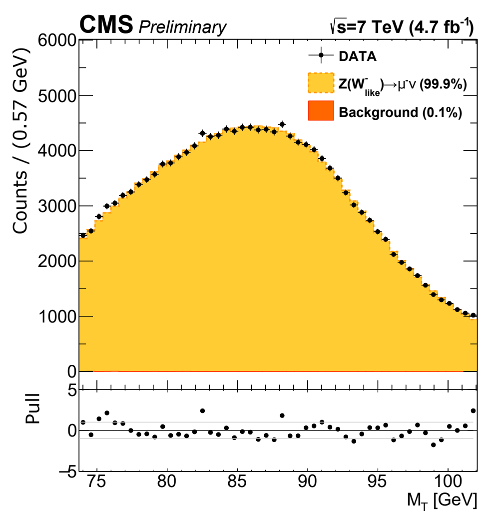
Proof-of-principle analysis, but differences with full m(W) analysis remain: event selection, background treatment and of most of the theory uncertainties, …

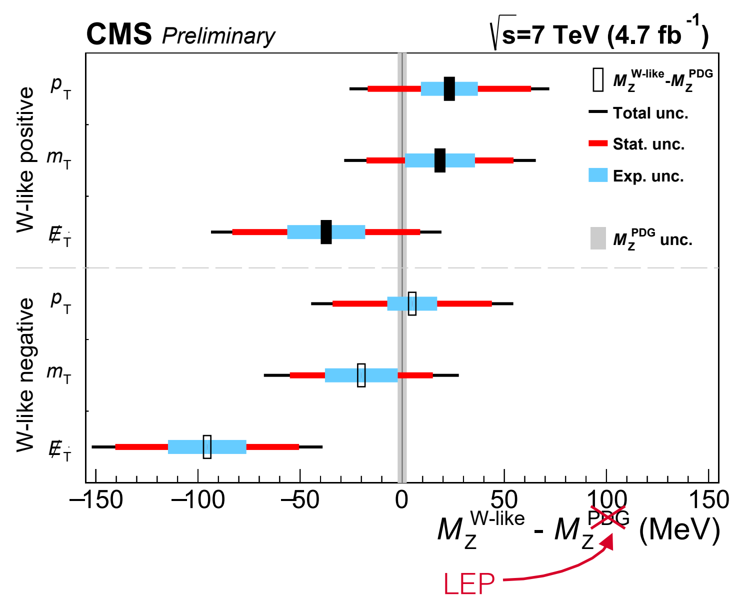
- 7 TeV dataset used (lower pileup)
- Scale and resolution calibration relies on J/ψ & Y
- Track-based MET
- W transverse recoil calibrated using Z+jets events

Results (depending on observable used):

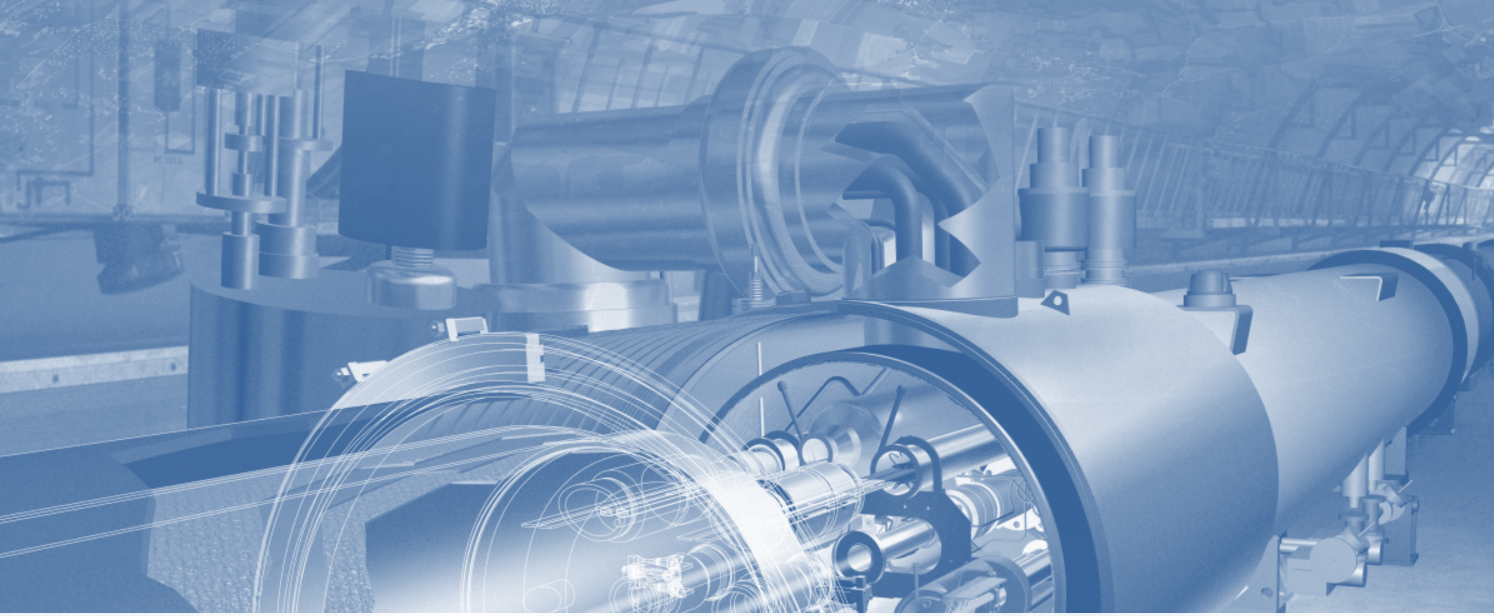
- Statistical errors: 35–46 MeV
- Total systematics: 28–34 MeV
- QED radiation: ~23 MeV (dominant)
- Lepton calibration: 12–15 MeV



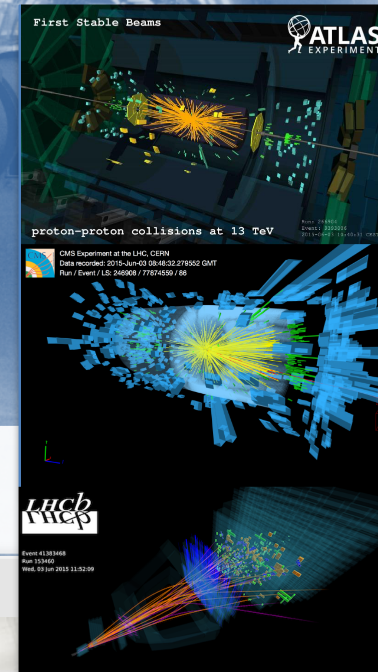




Jörg Wenninger



The LHC at 13 TeV



Huge milestone achieved in 2015 with record proton–proton collision energy of 13 TeV

After a rocky start, the LHC delivered
$L_{\mathrm{int}} = 4.2\ \mathrm{fb}^{-1}$, $L_{\mathrm{peak}} = 5.0\times10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

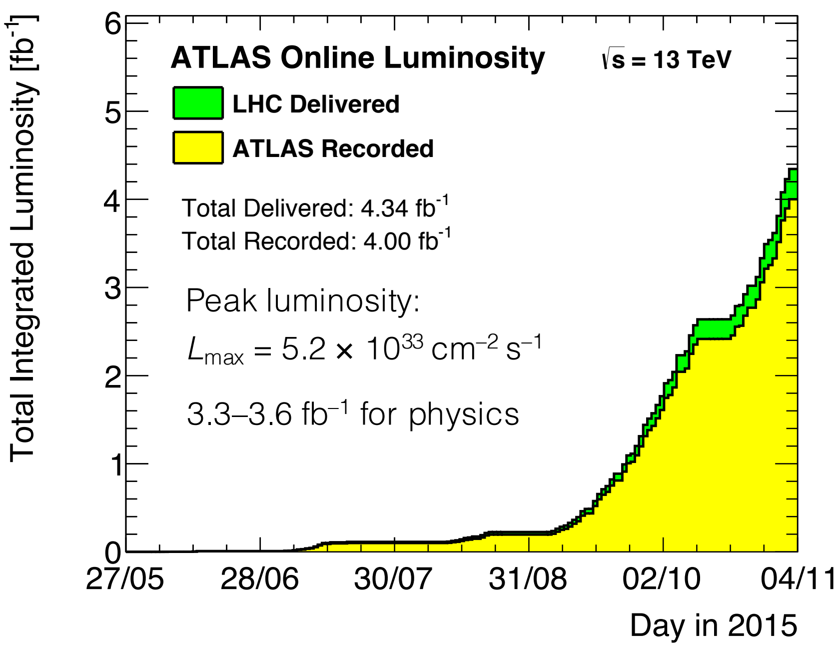
This luminosity already increase the new physics reach for many searches

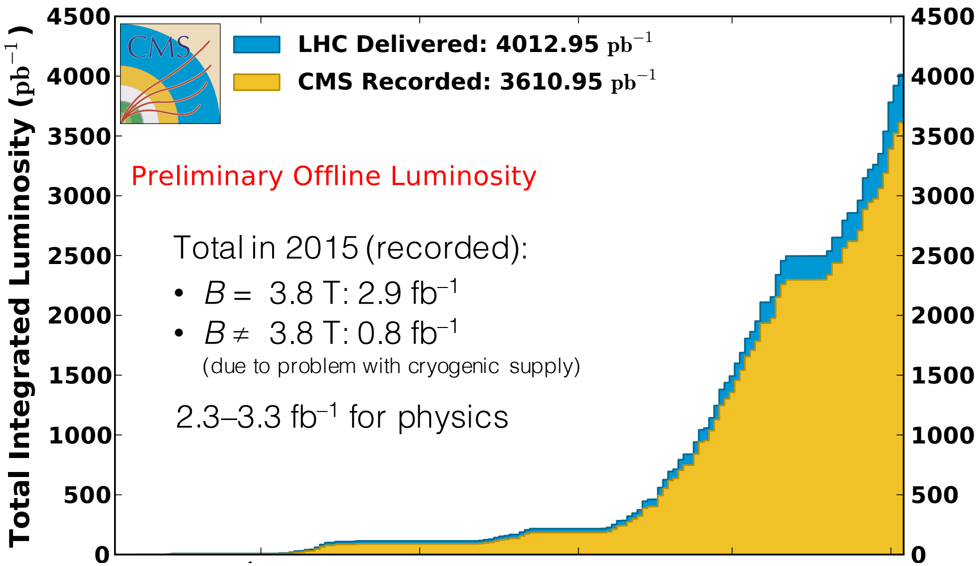
Great year for experiments with many results available for the summer conferences, and a huge amount for the end-of-year jamboree, and **much more at this conference**

Expect $1\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and $\sim30\ \mathrm{fb}^{-1}$ in 2016

2015 LHC proton–proton luminosities

Most results reported at this conference use total 2015 datasets



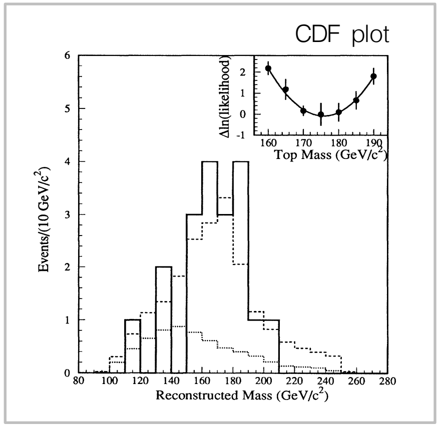


LHCb after luminosity levelling: 0.32 (0.36) fb^{-1} recorded (delivered)

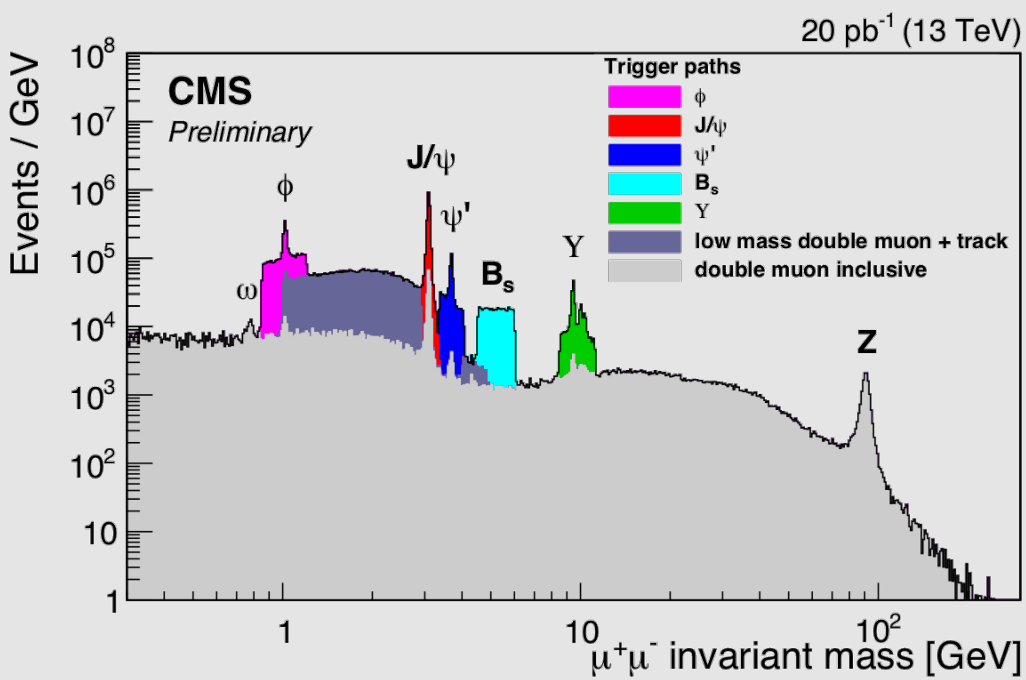
Luminosity monitors calibrated with beam-separation scans.
Current precisions: 5.0% (ATLAS), 2.7% (CMS), 3.8% (LHCb)

Pileup profiles: ATLAS/CMS: $\langle\mu\rangle_{50\,ns}$ = 20, $\langle\mu\rangle_{25\,ns}$ = 13 ($\langle\mu\rangle_{8TeV}$ = 21), LHCb: $\langle\mu\rangle \sim 1.7$

Celebrated last year at Moriond EW the 20th anniversary of the top discovery at the Tevatron



SM and Top Physics



Dimuon mass distribution collected with various dimuon triggers by CMS

William James Barter

Inclusive W and Z production

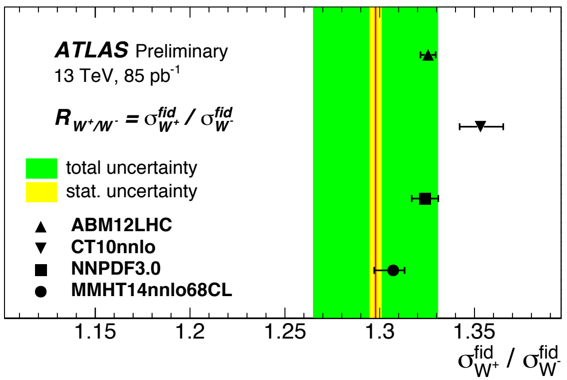
Very rich physics: strong PDF dependence, probes for QCD, precision electroweak physics

ATLAS, CMS & LHCb studied single gauge boson production at 7, 8, 13 TeV, LHCb covers complementary phase space in x, Q^2

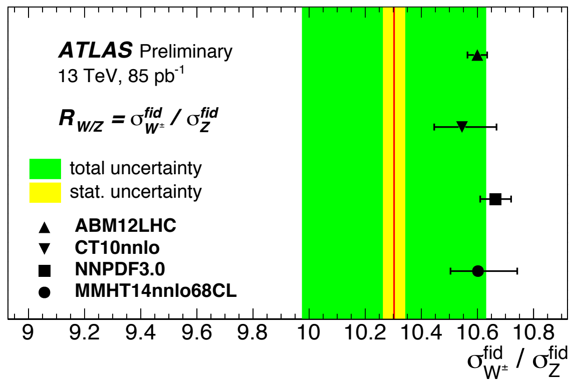
Leptonic decays of Z & W are also standard candles to verify and calibrate e/μ performance

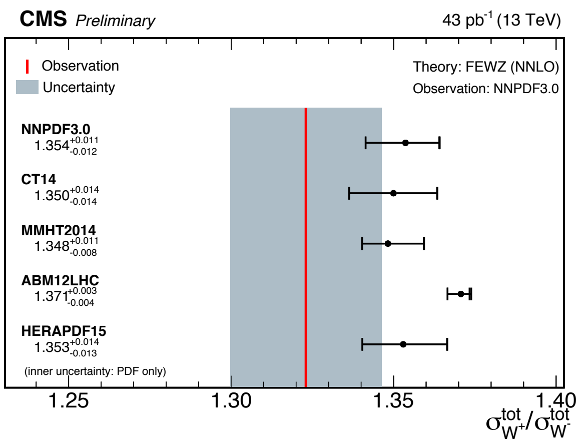
- 13 TeV W/Z cross section measurements (→ right plots)
- $p_T(Z)$ @ 8 TeV from ATLAS shows resummation needed at low p_T to describe data, NNLO below data at high p_T
- Charge asymmetry results by CMS and LHCb rather well predicted by theory
- LHCb high-rapidity cross sections well predicted with NNLO and PDFs
- 8 TeV $Z \rightarrow \mu\mu$ angular analysis by CMS, sensitive to Z polarisation and decay structure

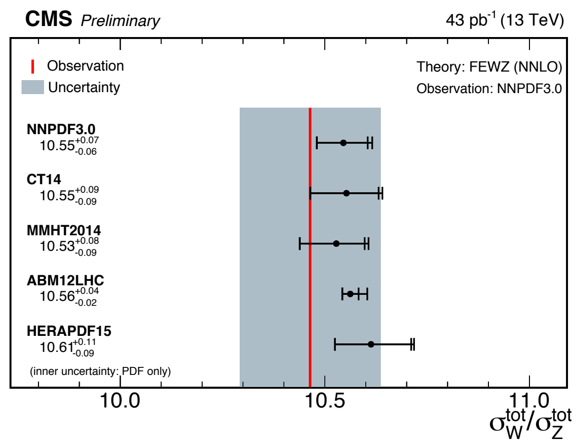
Note: fiducial cross-section ratios



Note: fiducial cross-section ratios







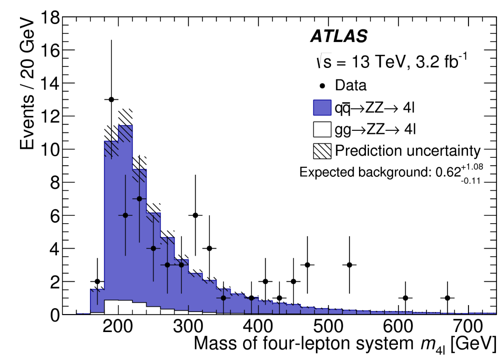
Also: LHCb σ_Z ($2.0 < \eta < 4.5$) in agreement with SM (PDFs)

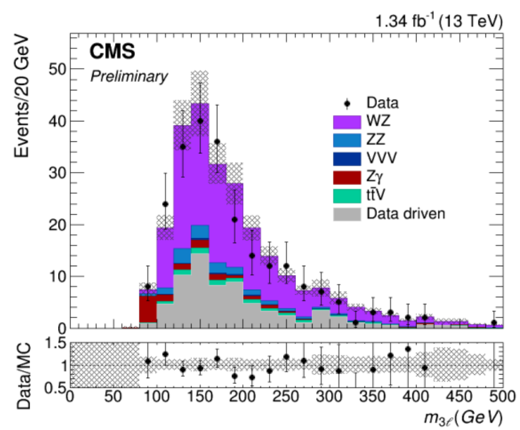
Diboson production

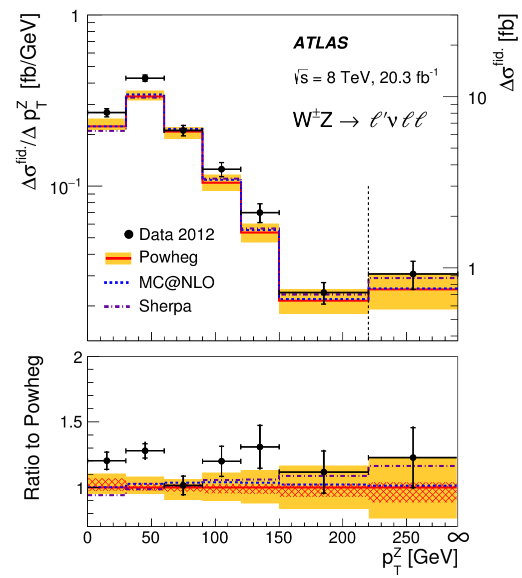
Highly important sector of LHC physics, intimately related to electroweak symmetry breaking

ATLAS & CMS studied diboson production at 7, 8, 13 TeV. Detailed inclusive, fiducial and differential cross-section analyses at 8 TeV. First 13 TeV results. Theoretical predictions at NNLO needed to match data.

- ZZ @ 13 TeV measured by ATLAS & CMS, WZ by CMS: all agree with SM
- WW @ 8 TeV cross-sections agree with SM NNLO + p_T resummation
- WZ @ 8 TeV by ATLAS shows deviations from SM (NLO only)
- Zγ @ 8 TeV by ATLAS & CMS, matched by NNLO SM predictions
- VBS: evidence in W^+W^+qq channel, new 8 TeV results on (W/Z)γqq (CMS), and WZqq (ATLAS), no observation yet
- Tri-boson process Wγγ & Zγγ observed by CMS, evidence for Wγγ by ATLAS
- Large set of anomalous coupling limits







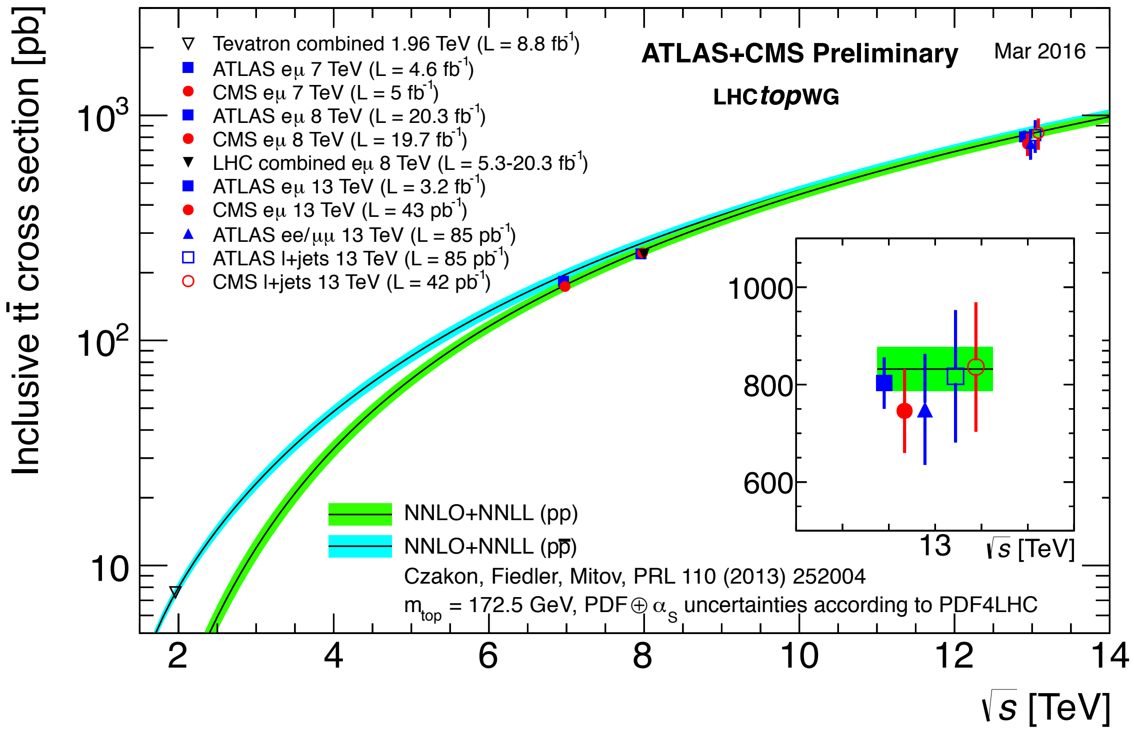
Each of these measurements in an experimental **tour de force**

Pedro Ferreira da Silva

Top-antitop production at 13 TeV

Increase of cross section by factor of 3.3 over 8 TeV

ATLAS & CMS studied top production in many ways at 13 TeV → very prompt analyses turn around



Robust eμ final state gives most precise inclusive results at all CM energies

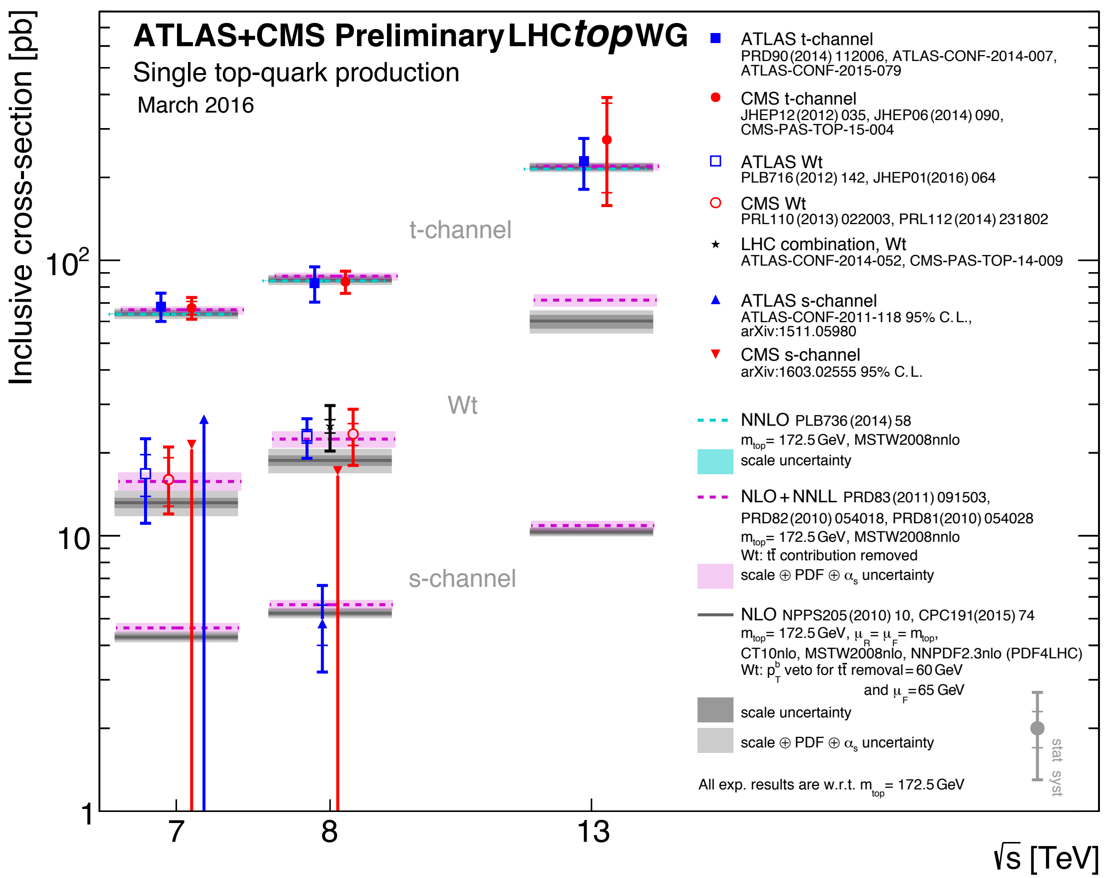
Differential cross-section measurements at 13 TeV show reasonable modelling, though some deviations at large jet multiplicity

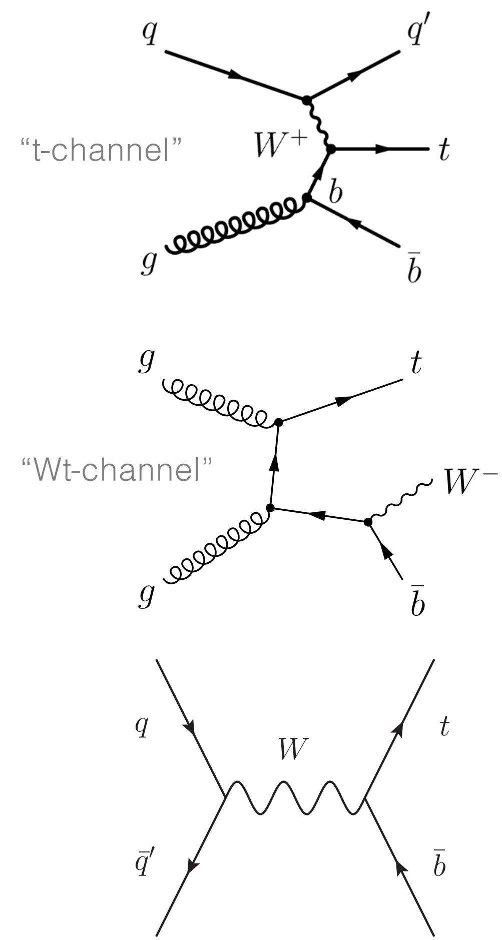
Pedro Ferreira da Silva

Single top quark production

Increase of cross section by factor of 2.5 (t-channel) over 8 TeV

ATLAS & CMS have so far released t-channel measurement at 13 TeV





"s-channel"
(not easier at 13 TeV)

Tevatron: 6.3σ, ATLAS Run-1: 3.2σ

Emmanuel Monnier

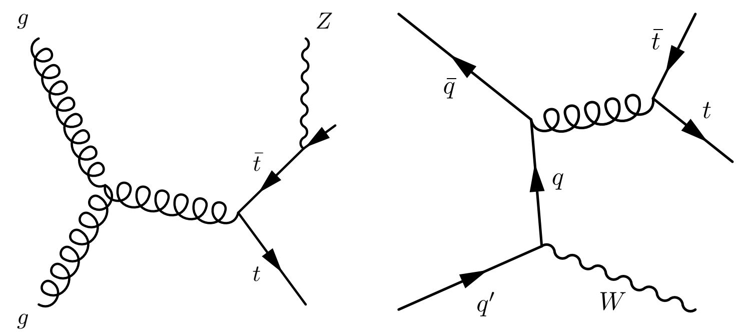
Top-antitop production and a vector boson at 13 TeV

First results on important ttV process, in it's own right, and as background to ttH and searches

ATLAS & CMS showed new 13 TeV results

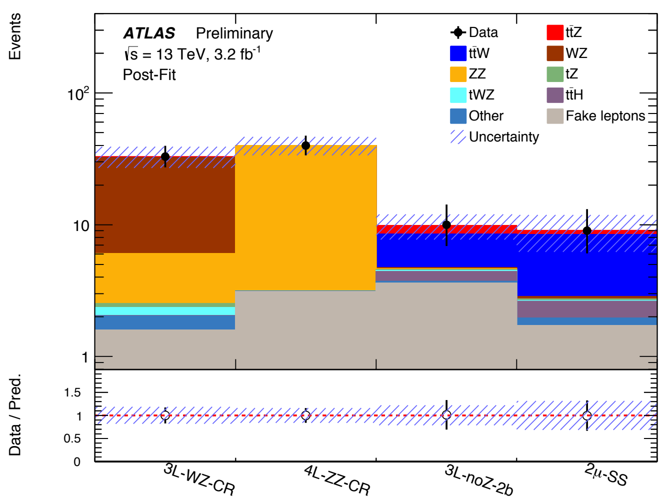
Analyses combine several multilepton final states, difficult mis-ID background

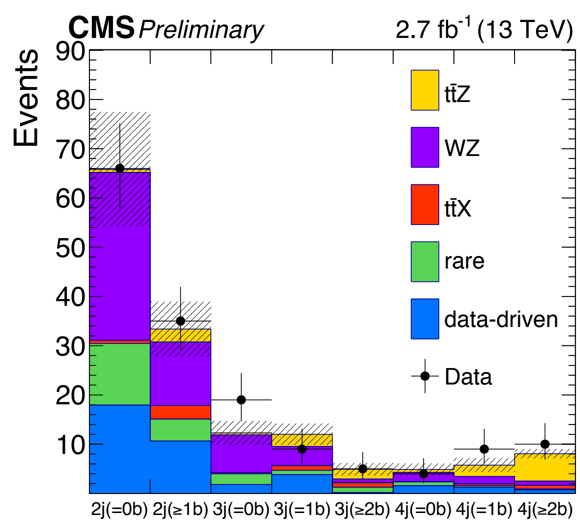
At 8 TeV, both processes observed, and found to agree with SM prediction
(ttW ~1σ up in both ATLAS & CMS)



Different production processes and thus 13/8 TeV cross-section ratios for ttZ & ttW: 3.6 & 2.4

Preliminary ttW/Z results from ATLAS, ttZ from CMS:





ATLAS:
ttW: 1.38 ± 0.70 ± 0.33 pb
ttZ: 0.92 ± 0.30 ± 0.11 pb

CMS:
ttZ: $1.07\,^{+0.35}_{-0.31}\,^{+0.17}_{-0.14}$ pb

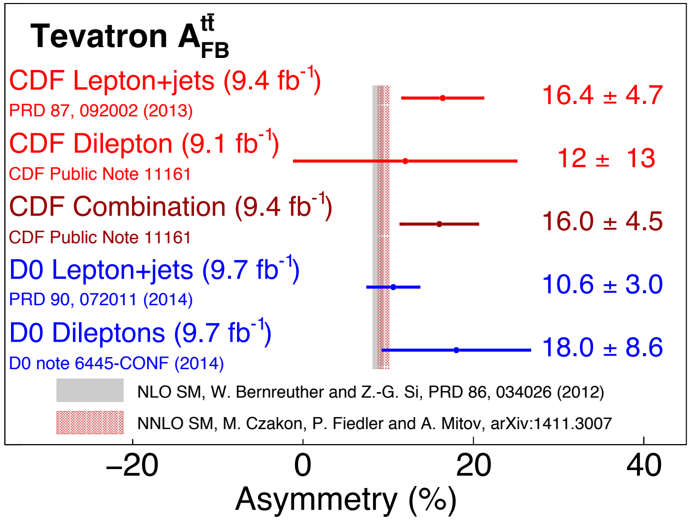
SM (NLO):
ttW: 0.57 ± 0.06 pb
ttZ: 0.76 ± 0.08 pb

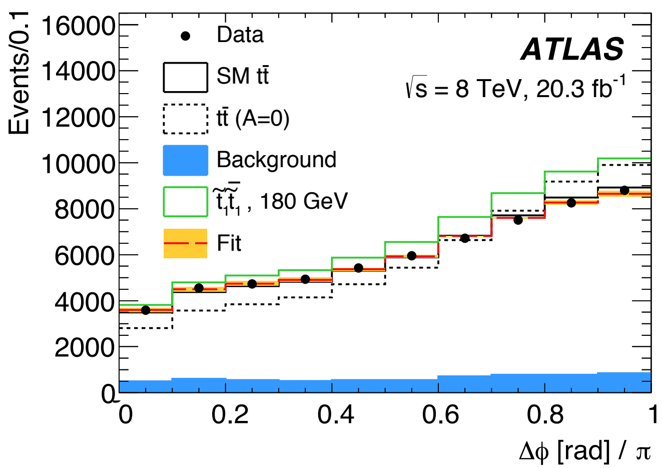
Top property measurements

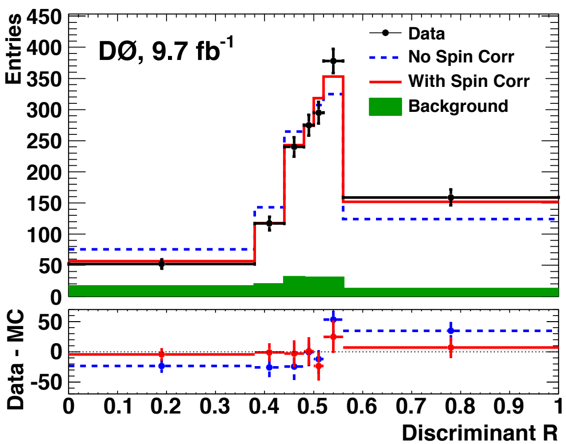
This is a huge field of research, studying polarisation, asymmetries, P/CP violation, FCNC

New LHC (8 TeV) and Tevatron results

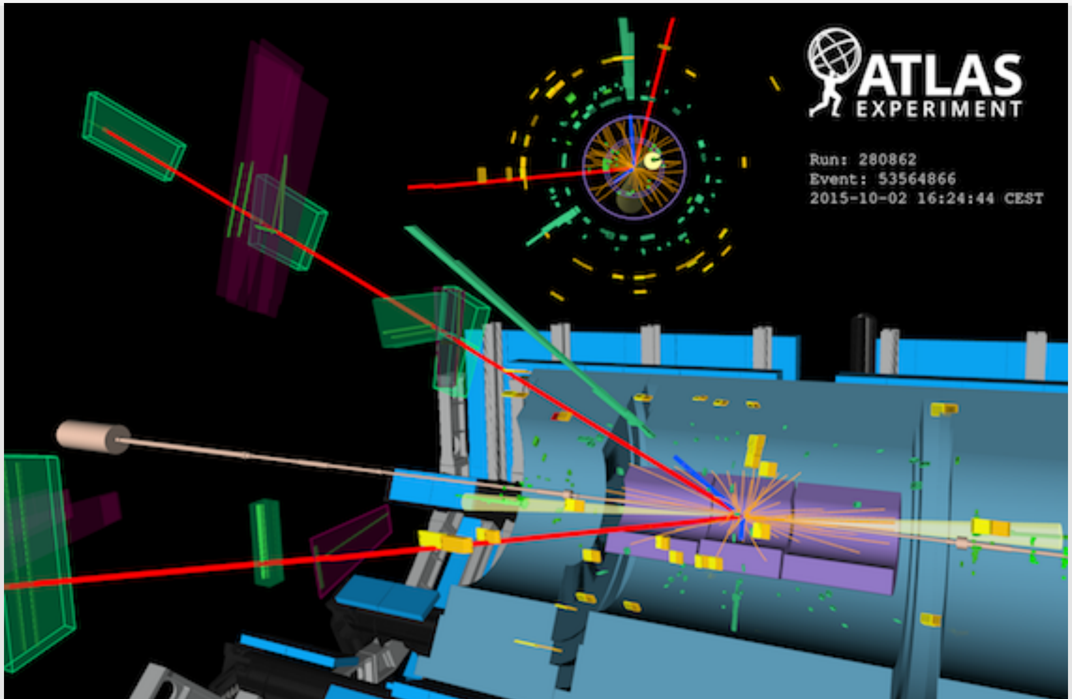
- Tevatron A_{FB}(tt) and NNLO SM prediction have converged towards each other
- Charge asymmetries at LHC in agreement with SM
- D0 has beautiful new measurement of P and CP-odd observables (CP-odd one found compatible with zero)
- Top-antitop spin correlations established at LHC, used by ATLAS to look for "stealth stop". First 4.2σ evidence for spin correlations by D0.
- FCNC processes $t \rightarrow qg, Zq, Hq$ probed by ATLAS & CMS, no signal







Higgs boson Physics



Display of $H \to ee\mu\mu$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the di-electron invariant mass is 91 GeV, the di-muon invariant mass is 29 GeV, the pseudorapidity difference between the two jets is 6.4 while the di-jet invariant mass is 2 TeV. **This event is consistent with VBF production of a Higgs boson decaying to four leptons.**

In 2015 ATLAS & CMS achieved full Run-1 Higgs combination

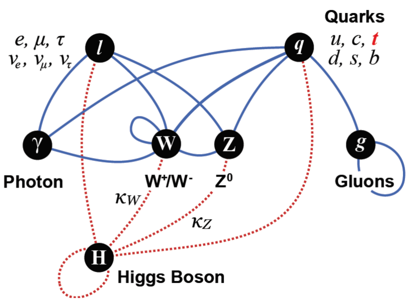
As by product: combined observation of H → ττ decay and VBF production mode

Lidia Dell'Asta

ATLAS & CMS
combinations of Higgs mass and coupling measurements

Also:

- Differential cross-section measurements
- Limit on invisible Higgs branching ratio of < 25%
- Constraints on anomalous off-shell coupling, spin/CP, LFV, forbidden decays (FCNC) and other scalar particles (BSM Higgs)

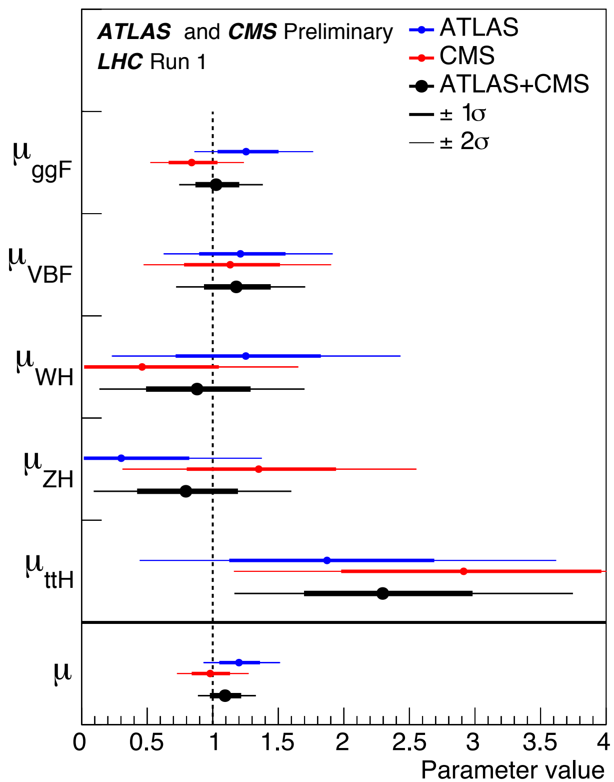


m_H = 125.09 ± 0.24 GeV

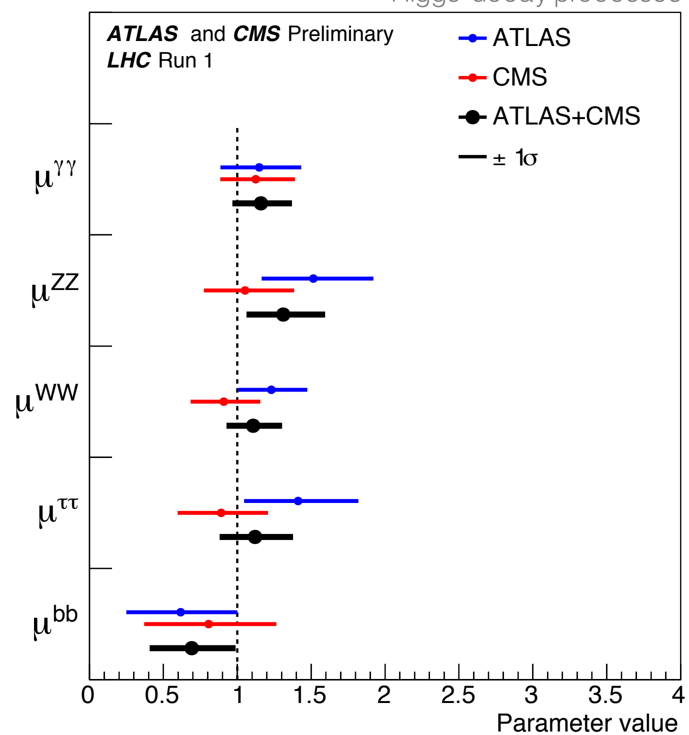
13/8 TeV cross section ratios of 2~2.4 for VH, ggH, VBF, but 3.9 for ttH

→ $K_{13/8}$ ~ 0.8 for $ttH_{3.3/fb}$

Higgs production processes



Higgs decay processes



One word on lepton flavour violation in Higgs decays

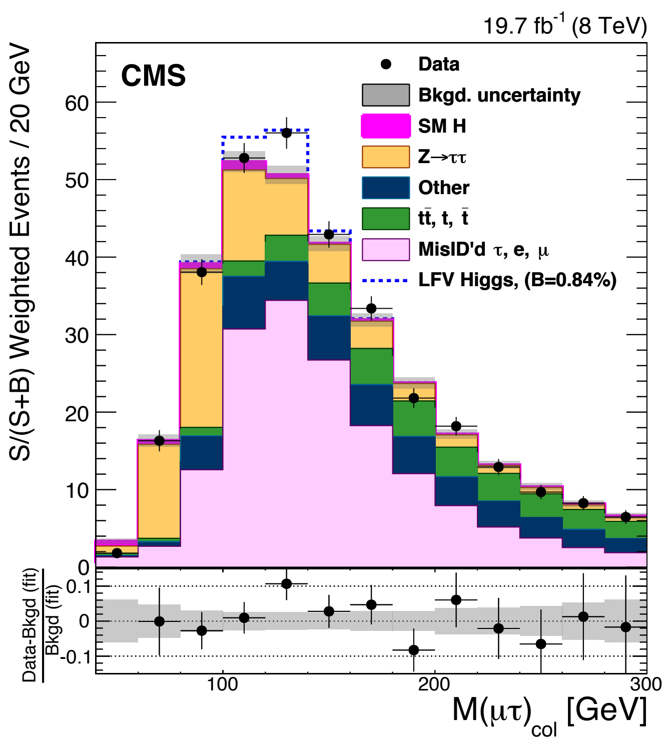
Both experiments have finalised their Run-1 LFV analyses

Lidia Dell'Asta, Joachim Kopp

While H → μe is severely constrained from flavour physics, H → τμ, τe are not (~10% limits)

CMS released early 2015 a H → τμ search finding a slight (2.4σ) excess

ATLAS has completed full analysis (including H → τe) for this conference



H → τ*μ*:

ATLAS:

BR = 0.53 ± 0.51% < 1.43% (95% CL)

CMS:

BR = $0.84^{+0.39}_{-0.37}$ % < 1.51% (95% CL)

H → τe:

ATLAS:

BR = –0.3 ± 0.6% < 1.04% (95% CL)

*Meant to be examples of flavour **violation**?*

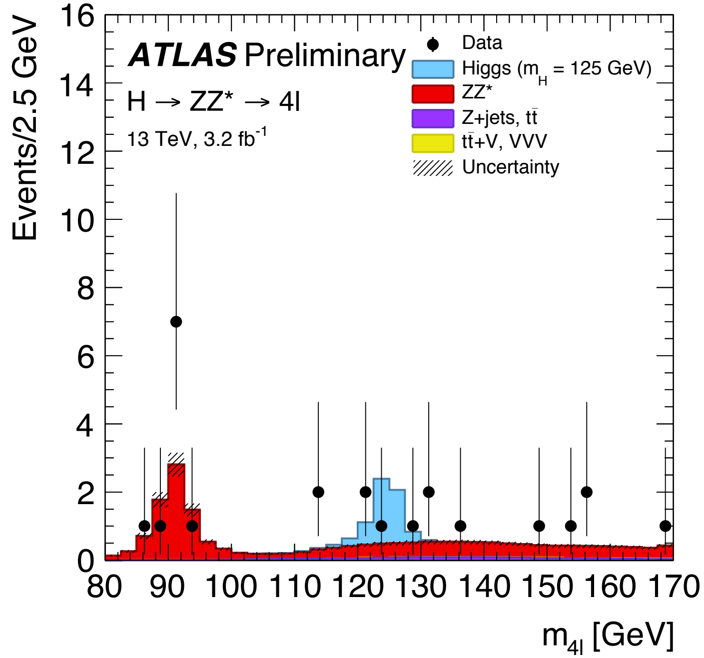
Seth Zenz

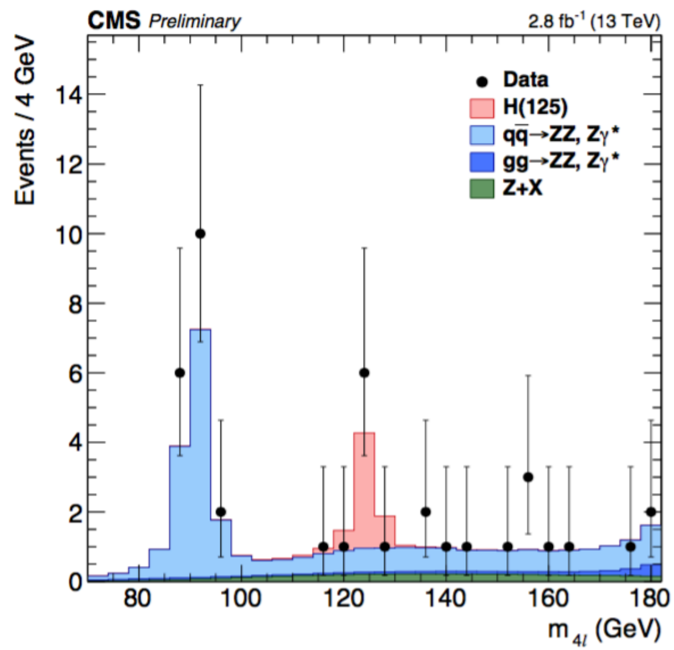
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

$H \to ZZ^* \to 4\ell$





$$\sigma_{tot,data} = 12^{+25}_{-16} \text{ pb}$$

$$\sigma_{tot,SM} = 51 \pm 5 \text{ pb}$$

Expected significance (SM): 2.8σ

$$\mu = \sigma_{data} / \sigma_{SM} = 0.82^{+0.57}_{-0.43}$$

Expected significance (SM): 3.4σ

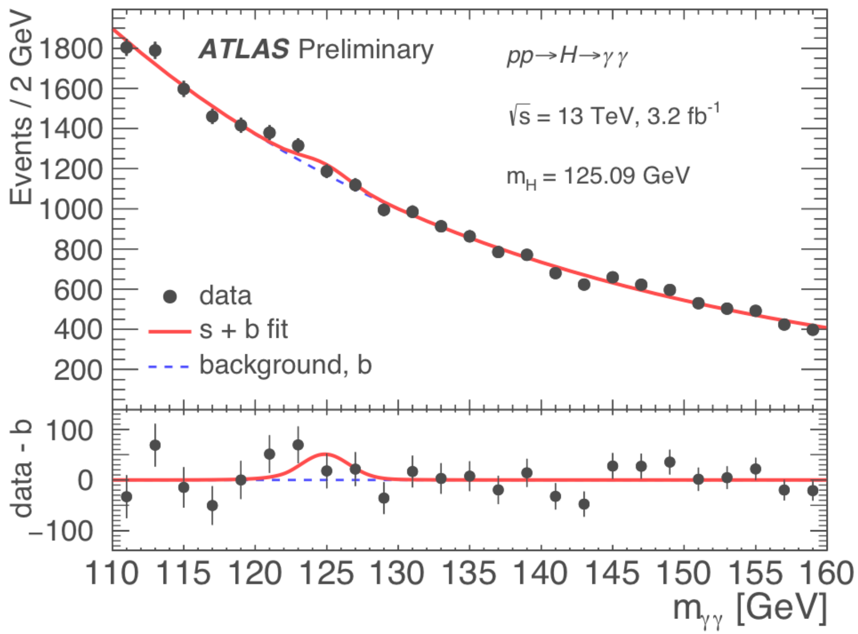
Seth Zenz

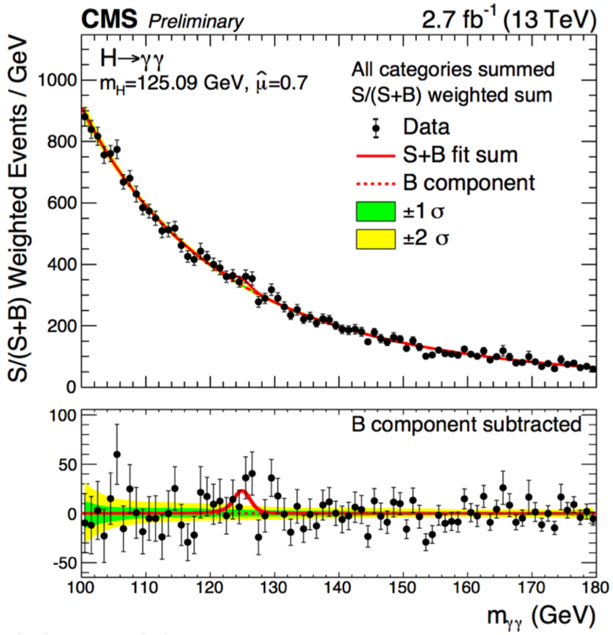
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

H → γγ





$\sigma_{tot,data} = 40 \pm 26\ ^{+16}_{-10} \pm 2_{lumi}$ pb

$\sigma_{tot,SM} = 51 \pm 5$ pb

Expected significance (SM): 1.9σ

$\mu = 0.69\ ^{+0.47}_{-0.42}$

Expected significance (SM): 2.7σ

Seth Zenz

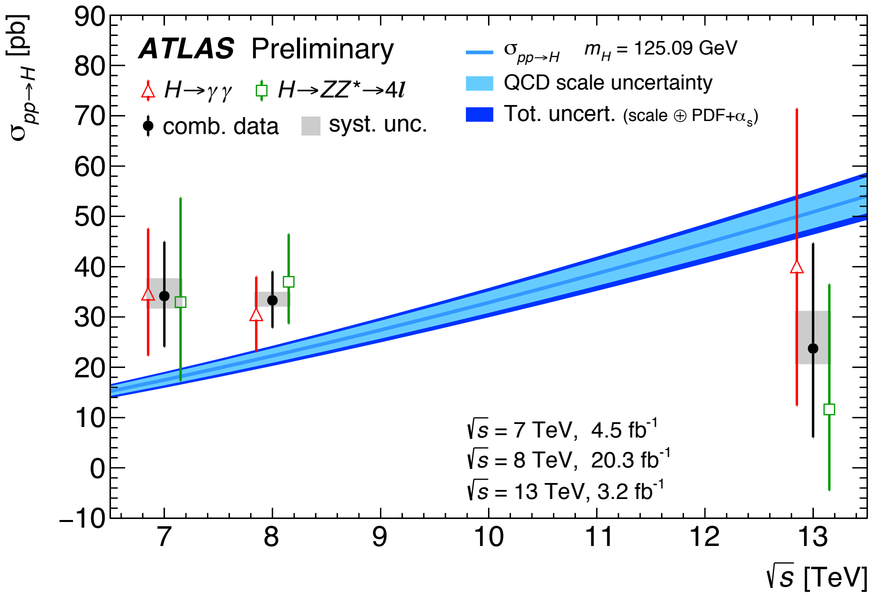
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

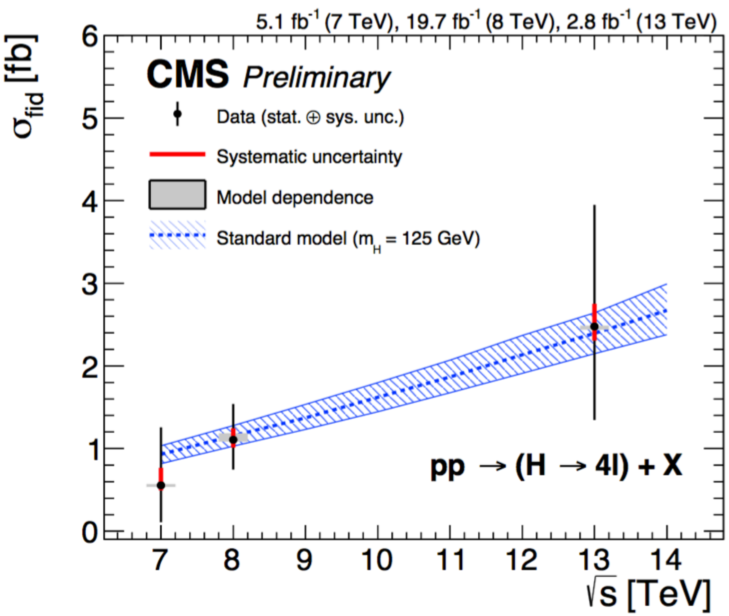
ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

Extracted cross sections vs CM energy

Combined H → 4ℓ, γγ



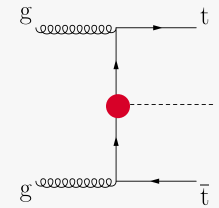
H → 4ℓ, *fiducial* cross section



First search for ttH production at 13 TeV by CMS

Most interesting of the SM channels at current luminosity

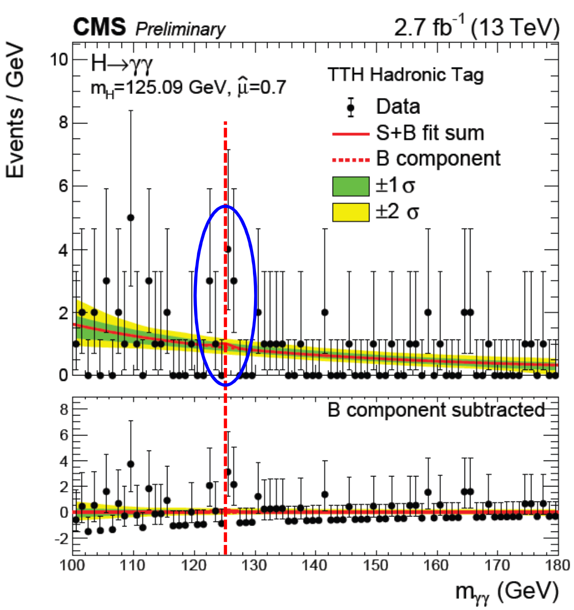
Johannes Hauk



CMS showed preliminary results for ttH in all major Higgs decay channels: **H → γγ, multi-leptons, bb**

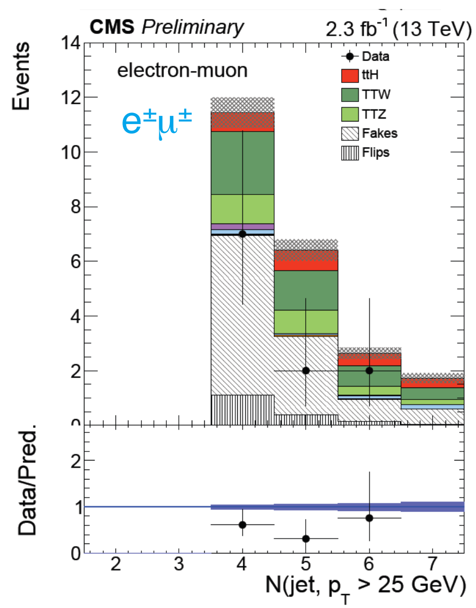
Highly complex analyses, huge effort to get these done so quickly after data taking

H → γγ,
tt → 0 & 1 leptons



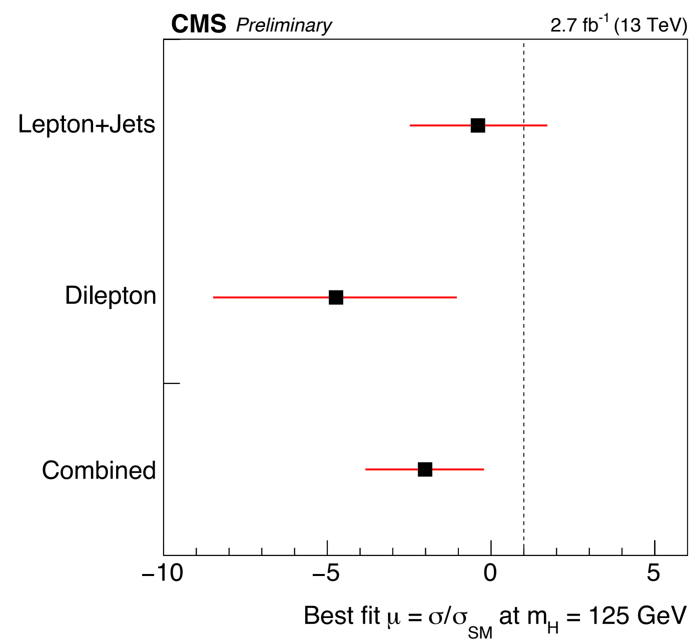
$\mu = 3.8\,^{+4.5}_{-3.6}$

ttH → multi-leptons
2 same charge / 3 leptons



$\mu = 0.6\,^{+1.4}_{-1.1}$

H → bb
tt → 1 & 2 leptons



$\mu = -2.0 \pm 1.8 < 2.6$ (95% CL)

*A few anomalies from Run-1
are to be followed up in Run-2

LHC-13

Searches — a fresh start*

Allison McCarn

BSM Higgs boson searches

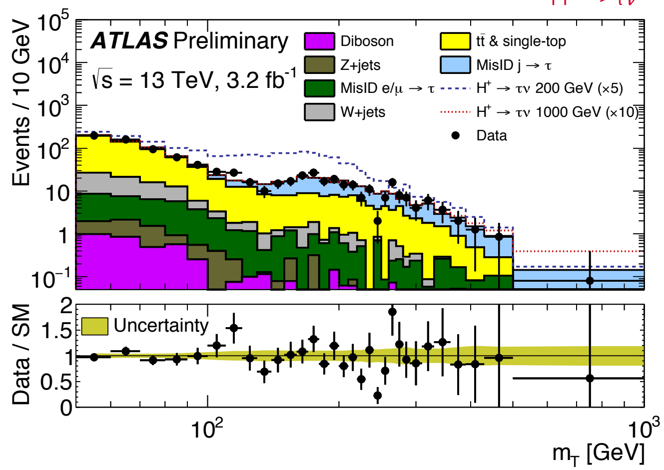
Single BEH doublet and form of potential simple but Nature may be more complex

At 13 TeV (only results recalled here, more shown by Allison) mainly heavy BSM searches interesting

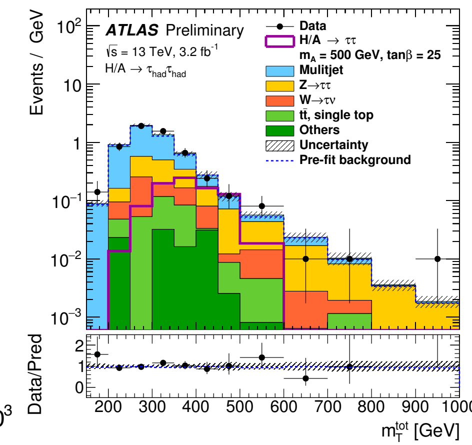
- $H^+ \to \tau\nu$: sensitivity better than Run-1 at mass > 250 GeV
- H / A → ττ: similarly, improved sensitivity at mass > 700 GeV
- $A \to Z(\to \ell\ell, \nu\nu)\, h_{125}(\to bb)$: improved sensitivity > 800 GeV
- $H \to ZZ(\to \ell\ell qq, \nu\nu qq, 4\ell)$ / $WW(\to \ell\nu qq)$: searches addressed 1–3 TeV mass range with boosted bosons
- X → hh → bbγγ: small excess in Run-1 at m_X~300 GeV, not yet excluded at 13 TeV
- X → hh → bbττ resonant (and non-resonant) search

None of these **many** searches showed anomaly so far

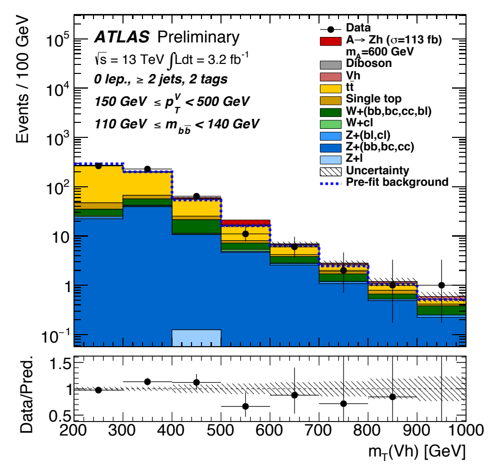
$H^+ \to \tau\nu$



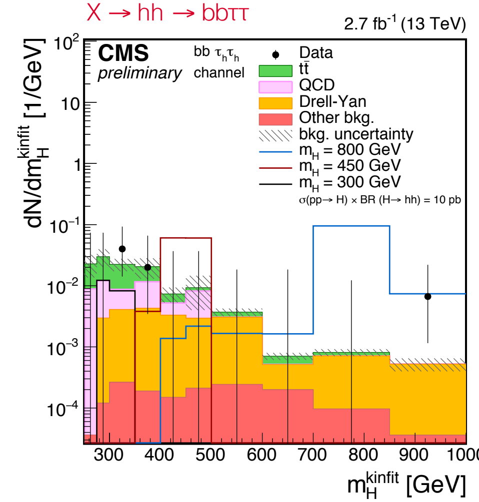
H / A → ττ



A → Zh



X → hh → bbττ



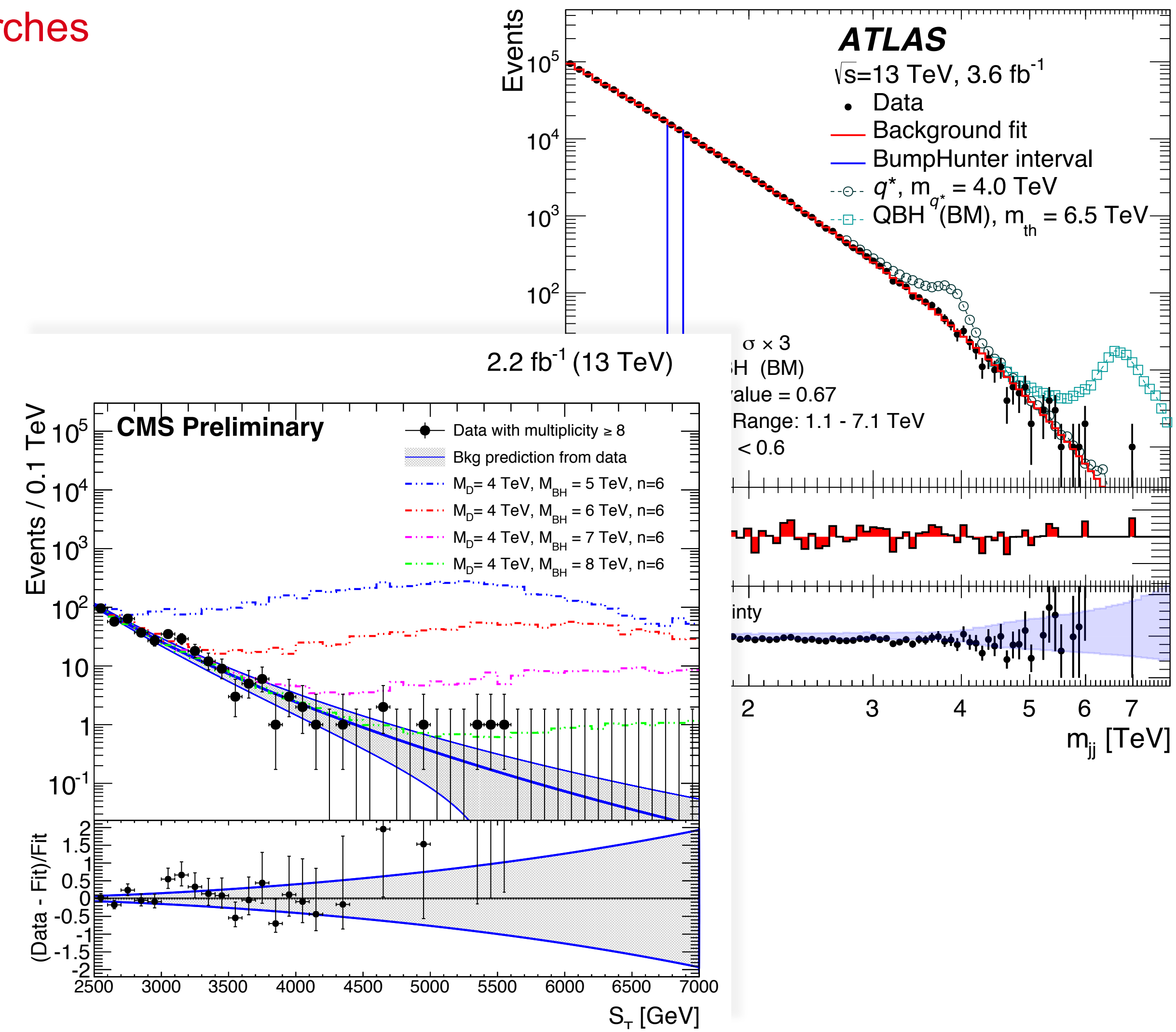
Searches in high-p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

High priority early 13 TeV searches

- Dijet resonance and angular distribution
- High-p_T multijets produced, eg, by strong gravity
- High-p_T lepton + jets (strong gravity)
- Second generation scalar lepto-quark pair production (μq-μq final state, excl. < 1.2 TeV)

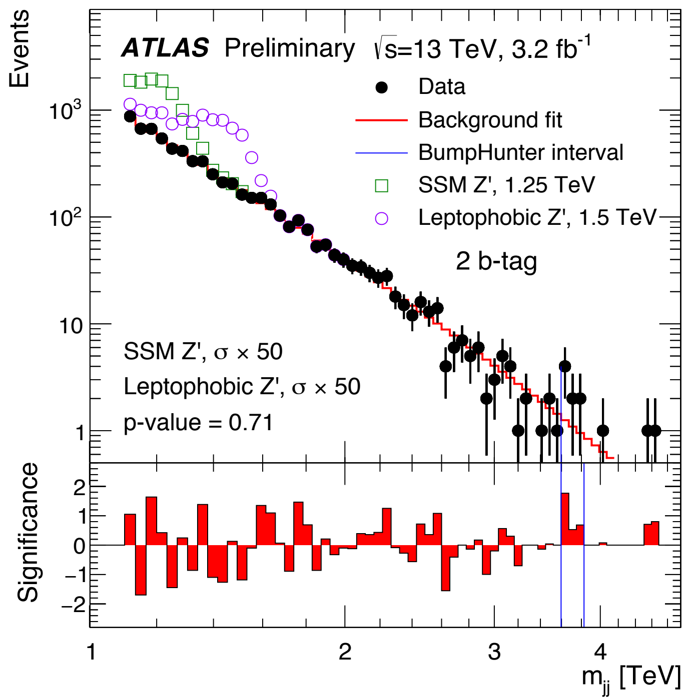
None of these searches showed an anomaly so far

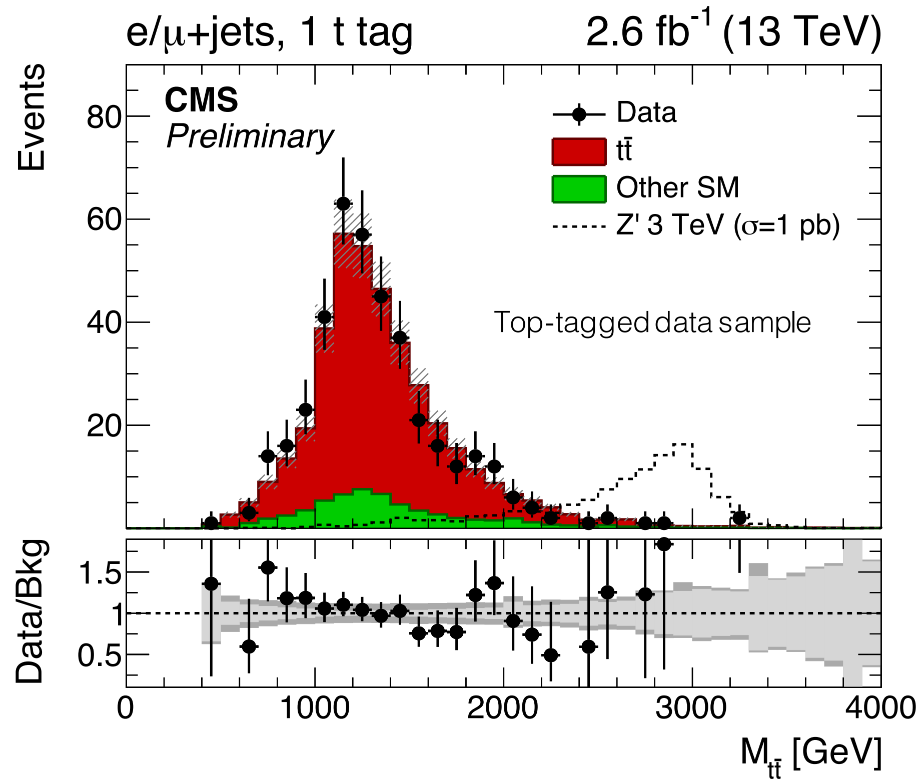


Searches in high-p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

Also searches for a b-anti-b and top-antitop resonance





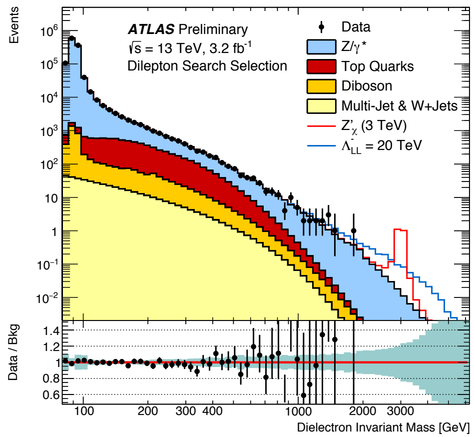
None of these searches showed an anomaly so far

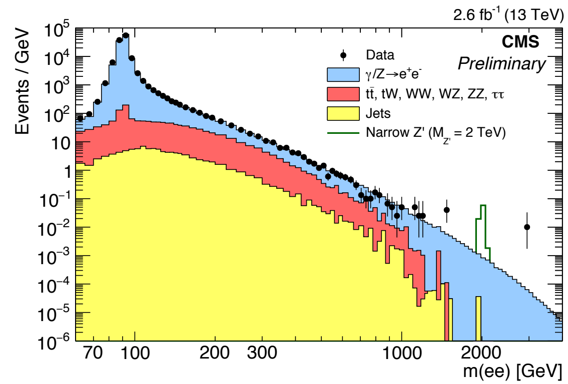
James Catmore

Searches in leptonic final states (I)

Canonical searches for new physics in high-mass Drell-Yan production (Z', W')

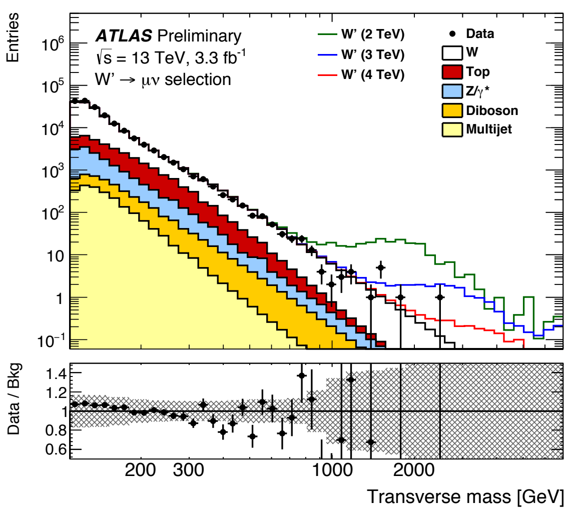
ATLAS & CMS have analysed their full 2015 dataset and presented results for $\ell^+\ell^-$ and $\ell\nu$ final states

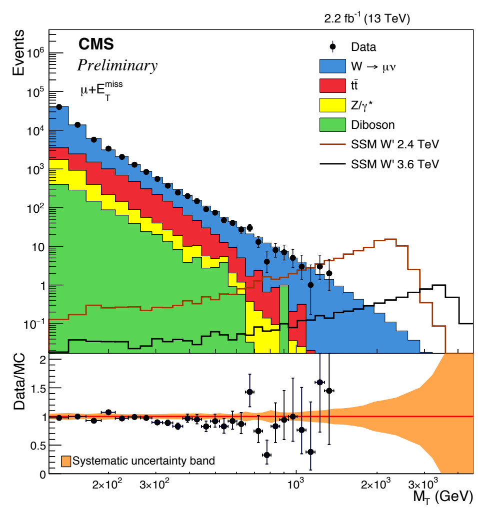




Good high-mass Drell-Yan modelling crucial → SM diff. cross-section measurements paired with searches

High-p_T muon reconstruction challenges detector alignment

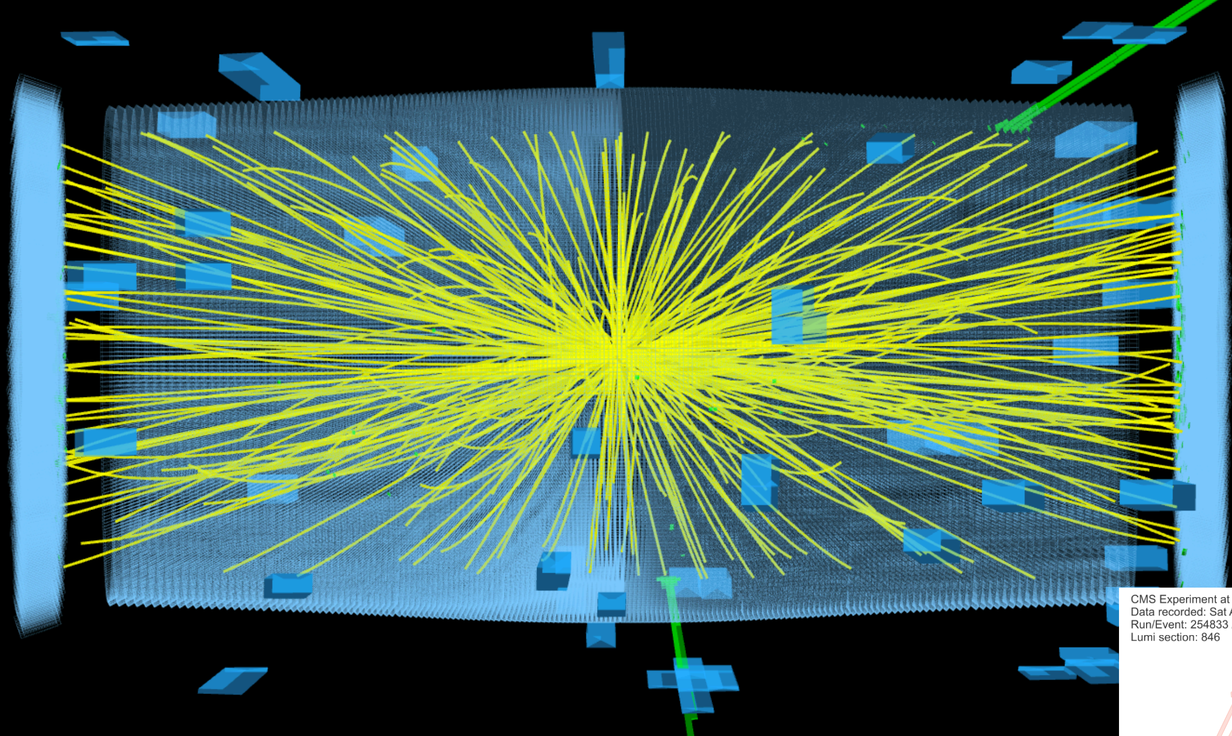


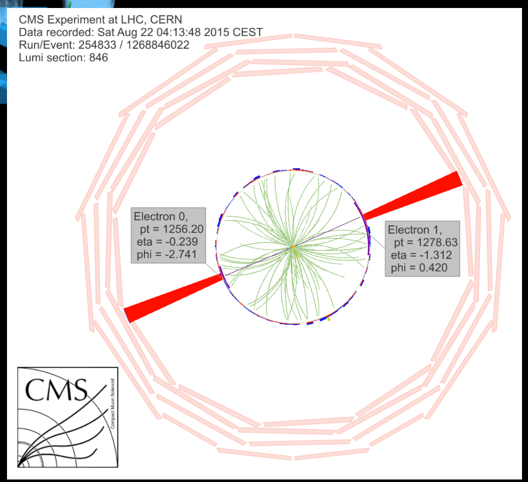


No anomaly found. SSM Z' / W' benchmark limits set at 3.4 / 4.4 TeV (2.9 / 3.3 TeV at 8 TeV)

ATLAS also looked into high-mass eμ (LFV) production. Main background top-antitop. No anomaly seen

CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846





- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV ($\mu\mu$)

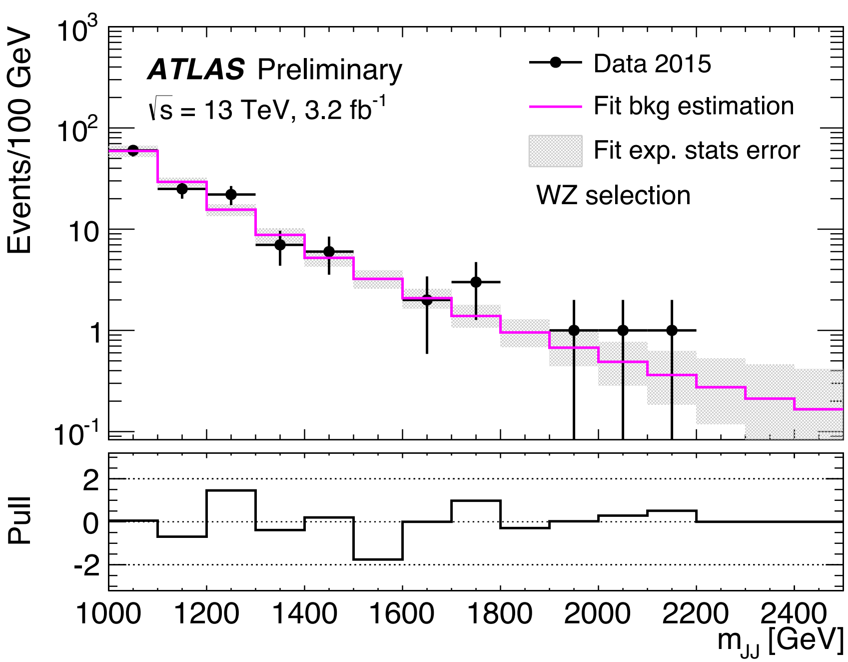
Max Bellomo, Maurizio Pierini

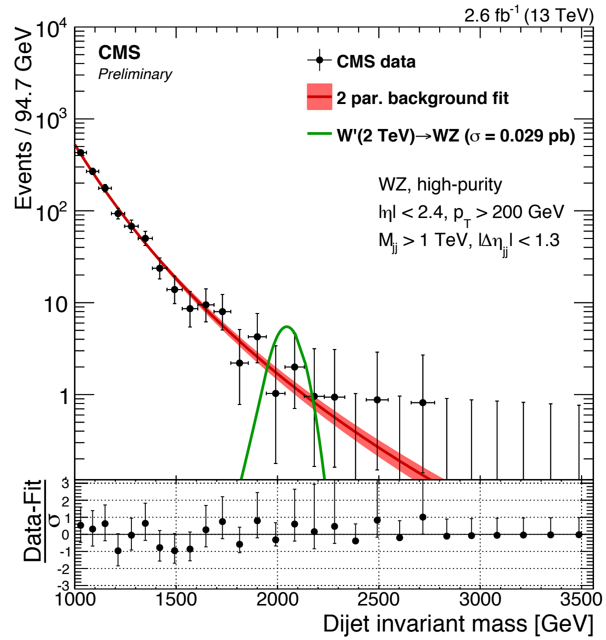
Searches for diboson resonances (hh, Vh, VV)

High p_T of bosons boosts hadronic decay products giving merged jets

Fast 13 TeV analysis turn around as in the other searches: 10 Run-2 analyses presented. Hadronic decay modes use jet substructure analysis to reconstruct bosons. Important strong interaction backgrounds

Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen in WZ mode at 8 TeV in fully hadronic channel, not seen in the other decay channels

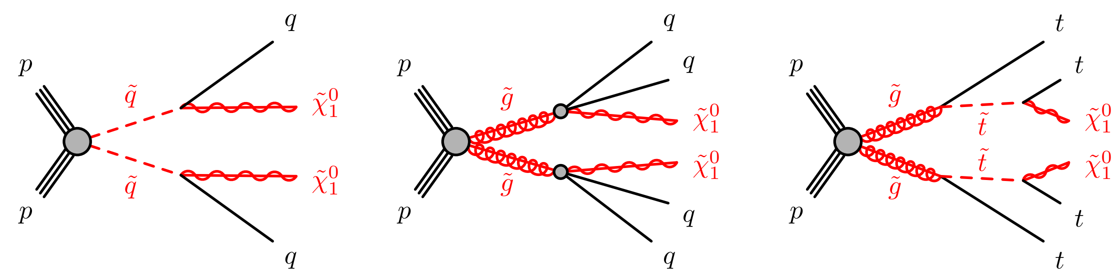




So far no excess in 13 TeV data around 2 TeV, also other diboson searches do not show anomaly

Supersymmetry (I)

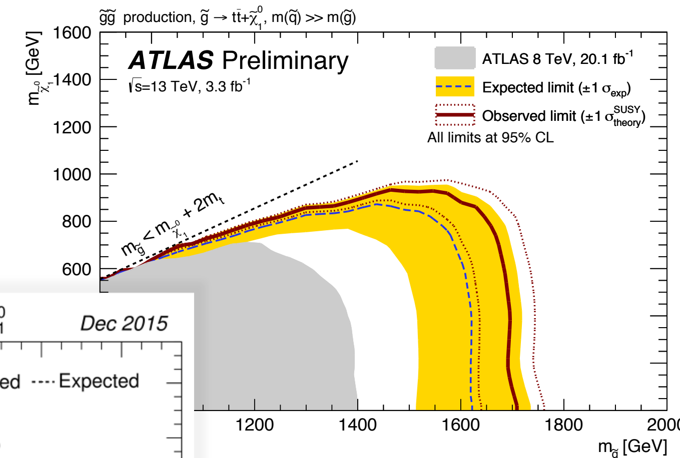
With jets & MET

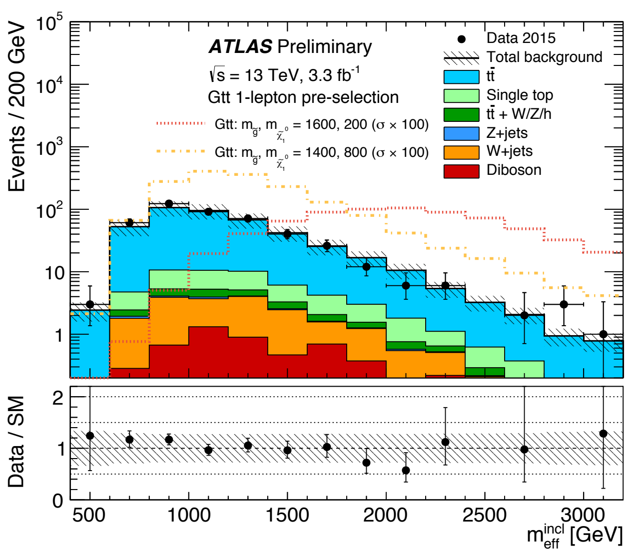


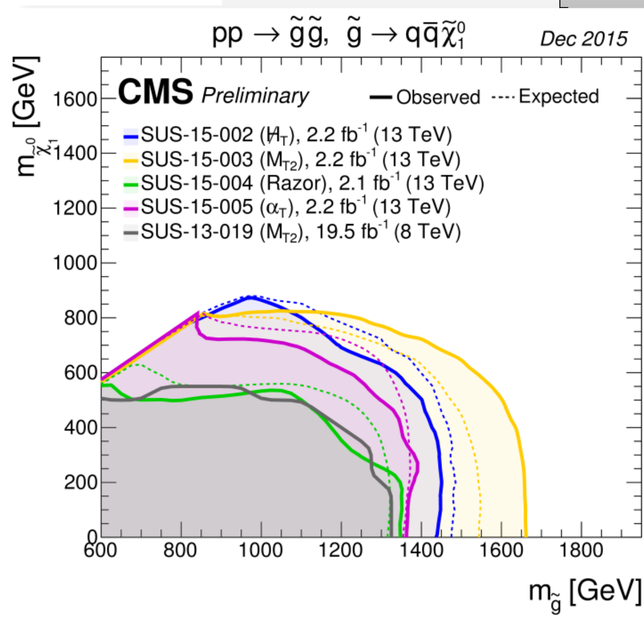
ATLAS & CMS have updated their most sensitive SUSY searches using (b-)jets and MET

Benefit from improved background modelling (better generators & theory, better tuning), but can still find large scale factors from control region normalisation of SM processes in extreme corners of phase space

Personal remark: need to make sure our analyses are optimised for discovery (not limits)







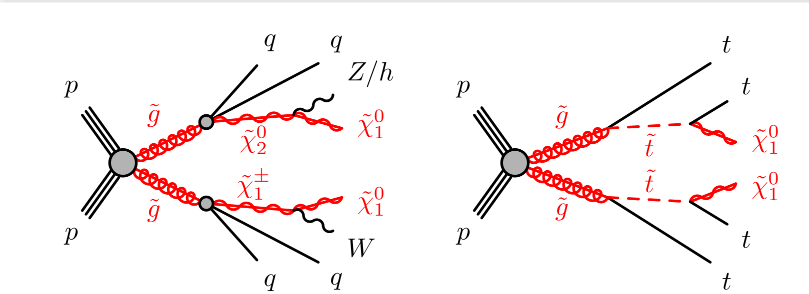
No significant anomaly seen in 7 different jets + MET analyses presented

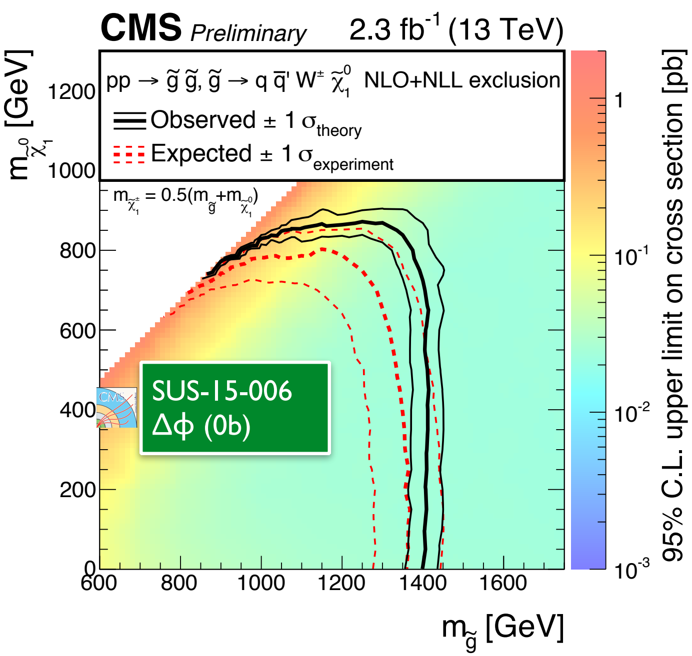
Supersymmetry (II)

With leptons, jets & MET

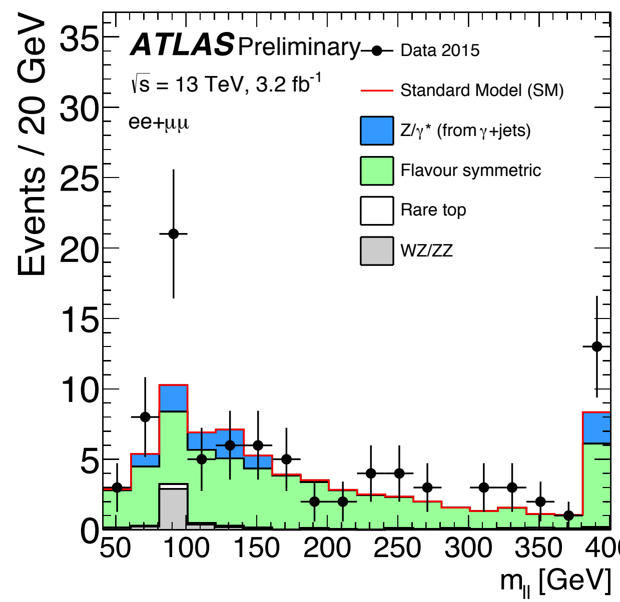
Leptonic searches target production of W/Z + jets + MET, as well as top through gluino decay (via stop)

Lower backgrounds than in jets + MET studies, but also lower signal





Opposite sign dilepton search (here on-Z)



Small excess (2.2σ) observed, 3σ excess was seen by ATLAS in that channel at 8 TeV

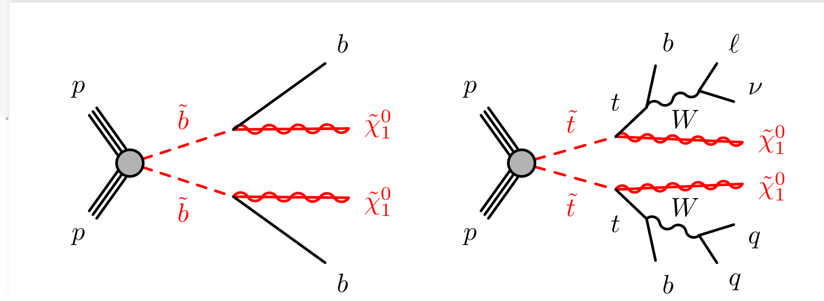
Excess was not confirmed by CMS/8 TeV, neither at 13 TeV

A small CMS/8 TeV excess (2.6σ) off-Z was not confirmed

9 searches presented, including two looking for same-charge lepton pairs and 3 leptons. No anomalies (apart from Z+MET)

Third generation quark partners

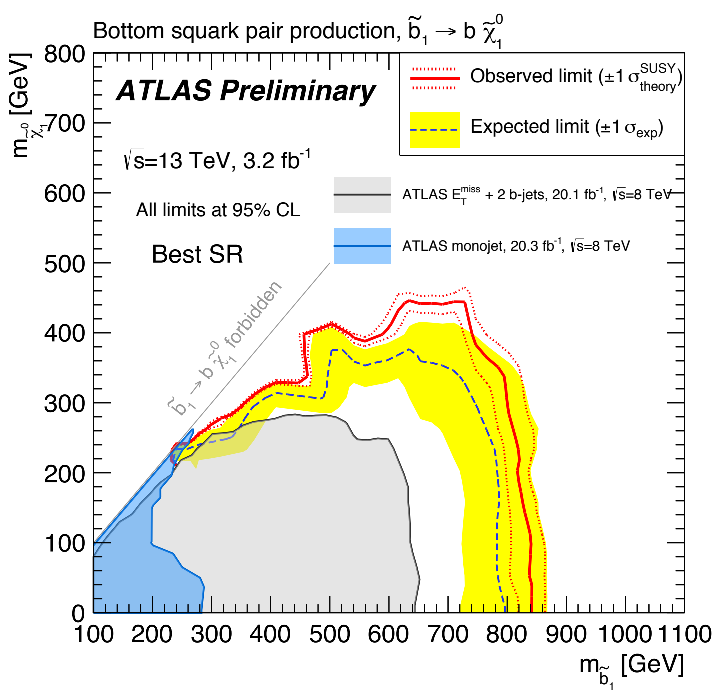
Searches for direct production

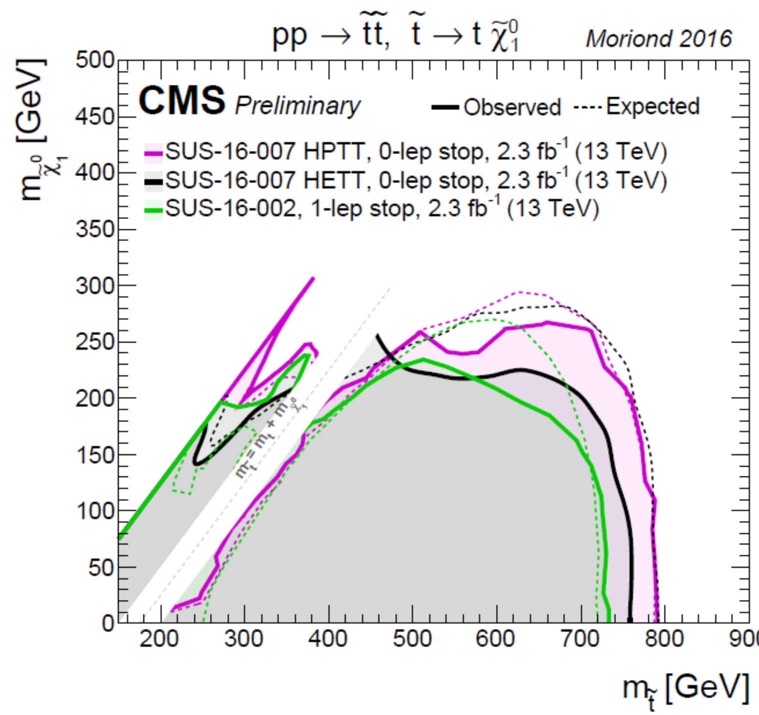


SUSY stop and sbottom may be the lightest sfermions. They have low cross-sections, so run-2 luminosity just enough to increase sensitivity

Signatures are b-jets, jets, possibly leptons and MET

Vector-like quarks* (VLQ) singly or pair produced decay to bW, tZ or tH. Also exotic $X_{5/3} \rightarrow tW$ possible





Total of 10 Run-2 analyses

No anomaly seen

Sensitivity improved over Run-1

Similar for VLQ searches

*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Revital Kopeliansky

Searches in unconventional final states

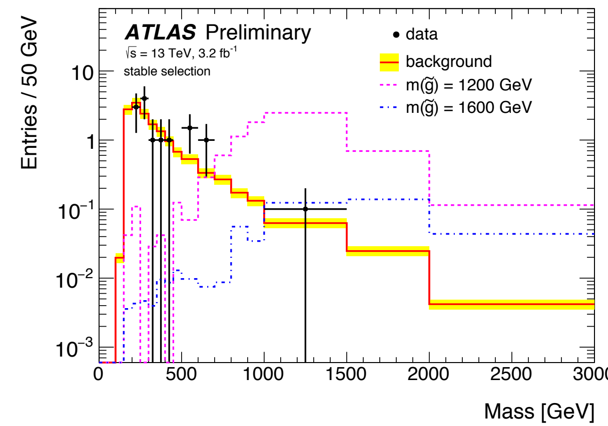
ATLAS & CMS also started to look for long-lived massive particle at 13 TeV

Long-lived particles in many new physics models

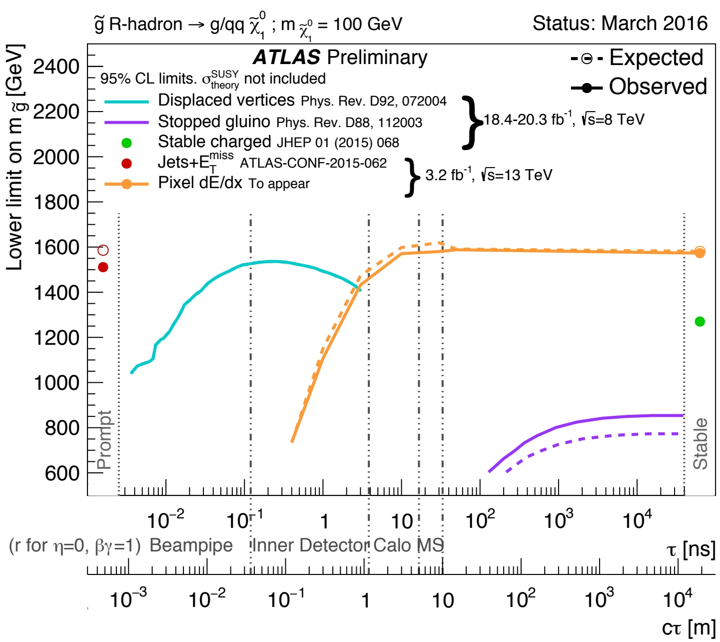
(due to: large virtuality, low coupling, mass degeneracy, eg, scale-suppressed colour triplet sclar from *unnaturalness* by Tony Gherghetta).

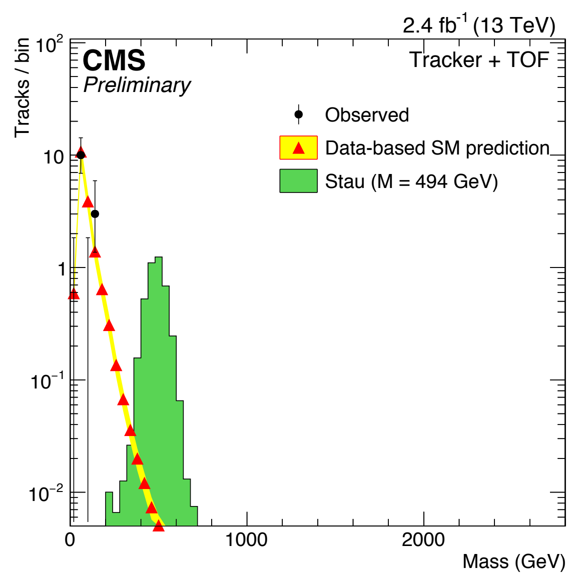
Multitude of signatures, some requiring dedicated triggers, most requiring dedicated analysis strategies.

ATLAS and CMS have so far looked into heavy long-lived SUSY particles at 13 TeV



Mass from dE/dx measured in Pixel only (sensitivity to metastable particles)





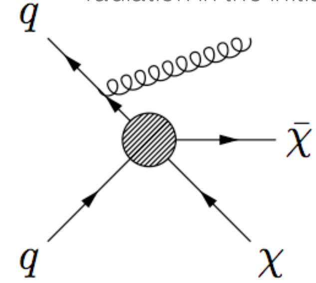
Analysis uses tracker dE/dx and TOF from muon system

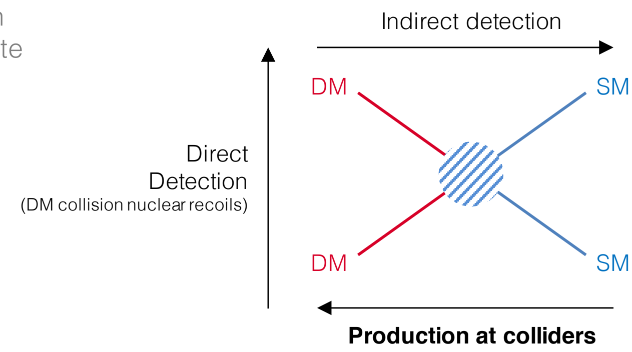
Searches for dark matter production at the LHC

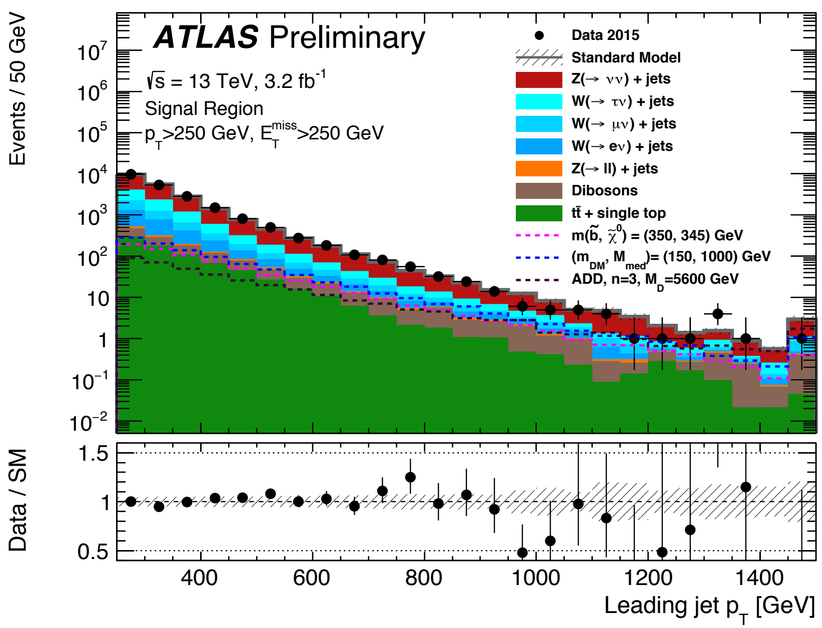
Canonical signature is 'X+MET' with large variety of 'X'

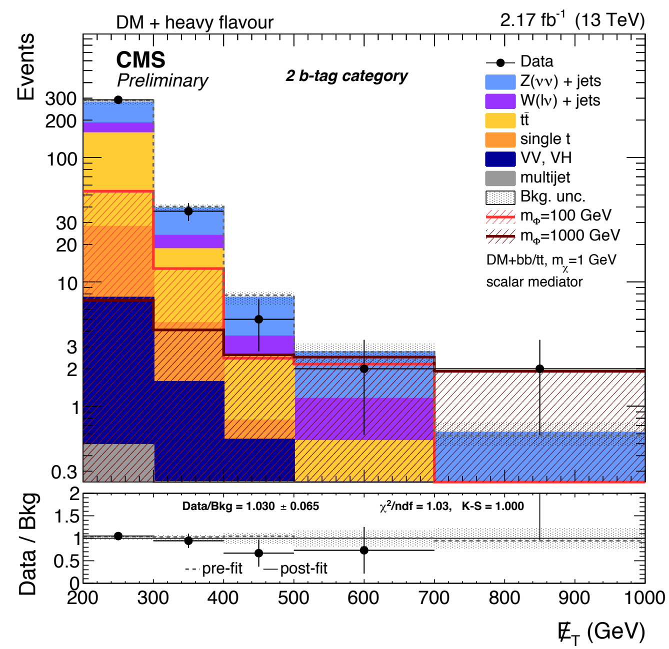
Direct dark matter production at the LHC
Requires boost for triggering. Depending on coupling it can be made by different objects.

Experimentally challenging to control Z/W+jets background. Theory input needed.









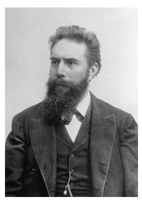
Several 13 TeV results already available:

- jets + MET
- γ + MET
- V + MET
- bb/tt + MET

No anomaly seen so far

The return of the limits …

Light quanta



First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand, Nov 1895
[First Nobel price of physics, 1901]

Used since forever
as detection probe

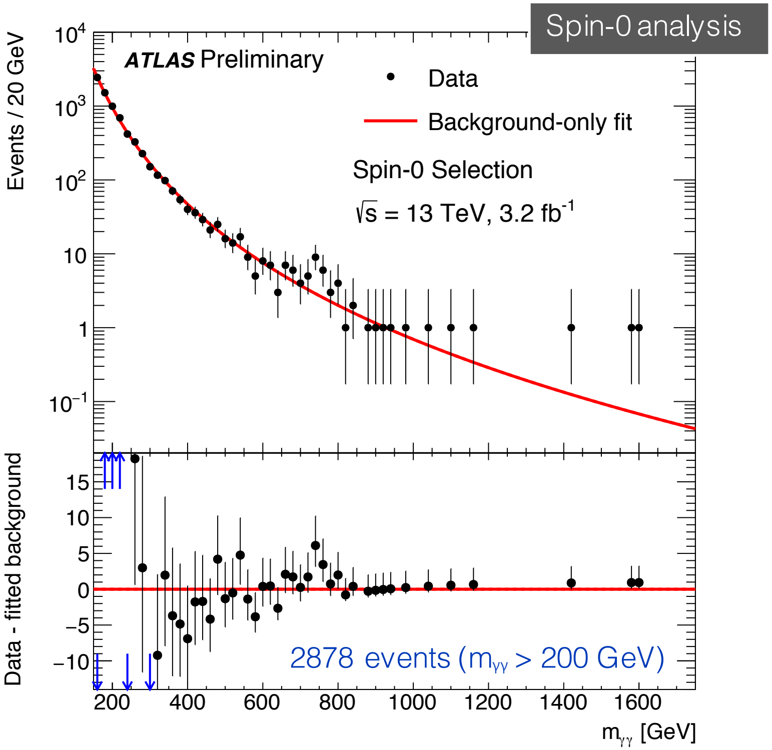
Recent example: $H \to \gamma\gamma$

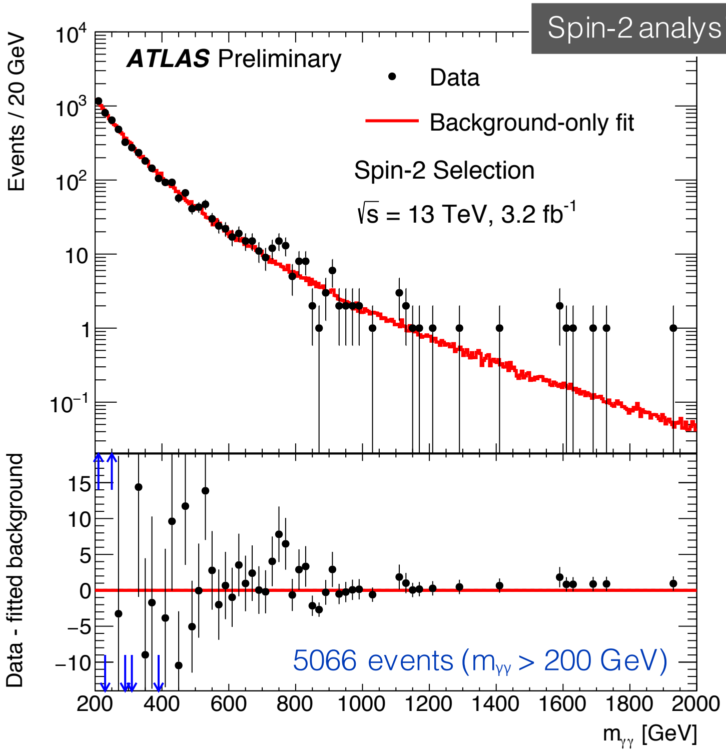
Diphoton resonance searches: ATLAS

Updated preliminary results presented this week

ATLAS showed dedicated searches for a spin-0 and a spin-2 diphoton resonance.

- Main difference is acceptance: spin-0: $E_T(\gamma_1) > 0.4 \cdot m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \cdot m_{\gamma\gamma}$, spin-2: $E_T(\gamma_{1/2}) > 55$ GeV
- Photons are tightly identified and isolated. Typical purity ~94%
- Background modelling empirical in spin-0, and (mainly) theoretical in spin-2 case (for high-mass search)



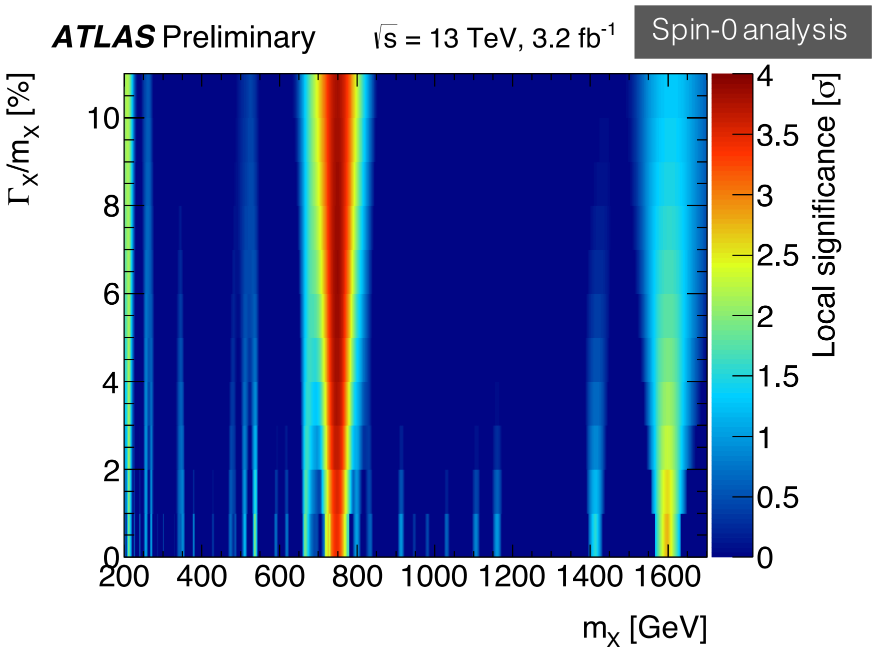


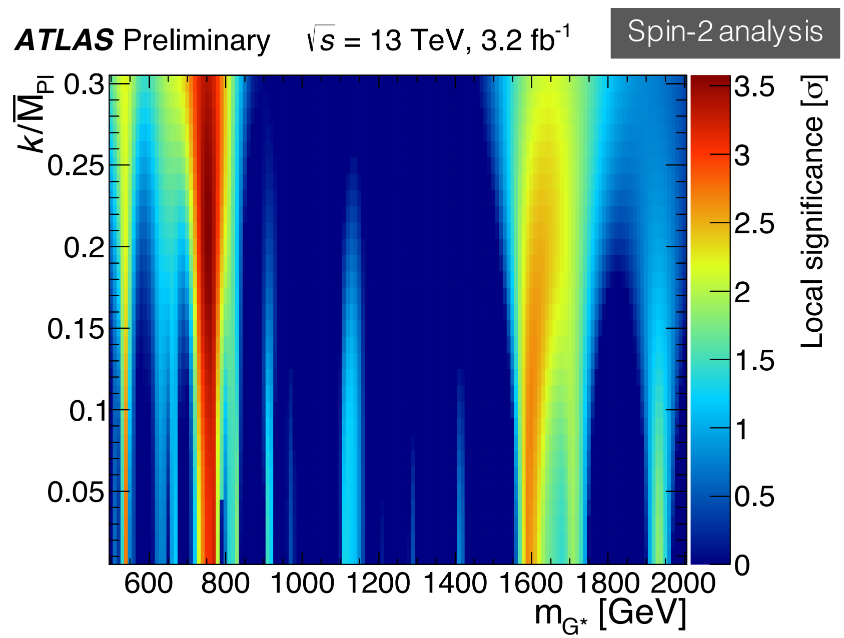
Diphoton resonance searches: ATLAS

Updated preliminary results presented this week

Event properties in signal region appear similar to those in sidebands, within large statistical uncertainties

Background-only p-value scan versus resonance mass and width:





Lowest p-value at ~750 GeV, Γ ~ 45 GeV (6%)

Local / global Z = 3.9 / 2.0σ

Lowest p-value at ~750 GeV, Γ ~ 7% of mass

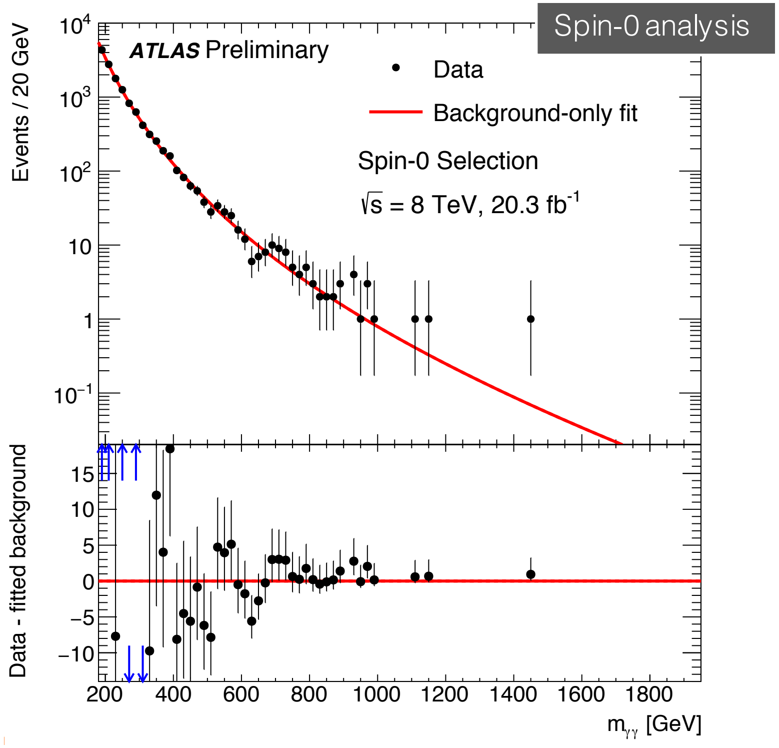
Local / global Z = 3.6 / 1.8σ

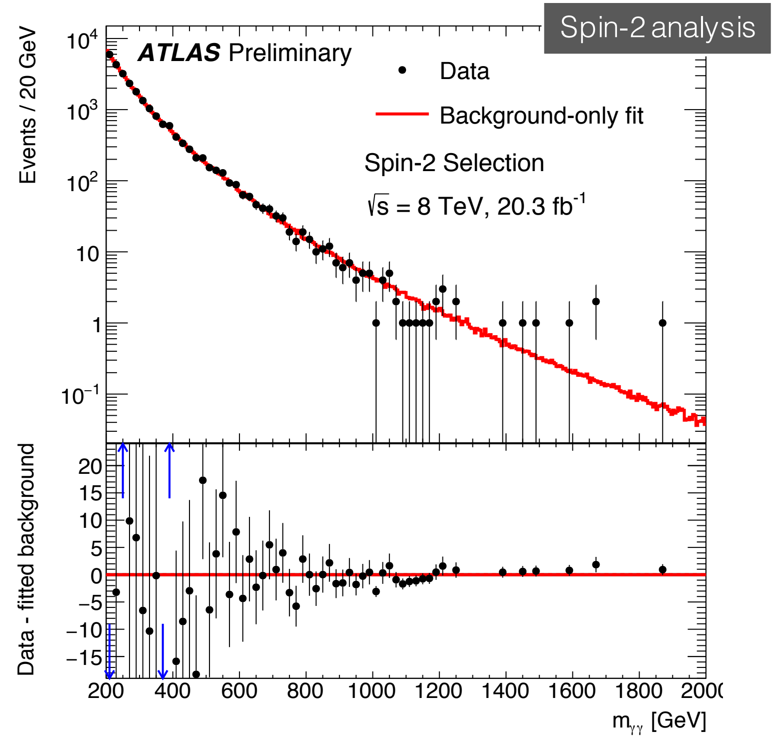
Global p-values derived with respect to scan planes

Diphoton resonance searches: ATLAS

Updated preliminary results presented this week

Compatibility with 8 TeV result (slight reanalysis: latest e/γ calibration, 13 TeV analysis method)





P-value at 750 GeV, Γ ~ 6% of mass: 1.9σ

Compatibility: gg = 4.7 / qq = 2.7 scaling: 1.2σ / 2.1σ

No excess at 750 GeV

Compatibility: gg / qq scaling: 2.7σ / 3.3σ

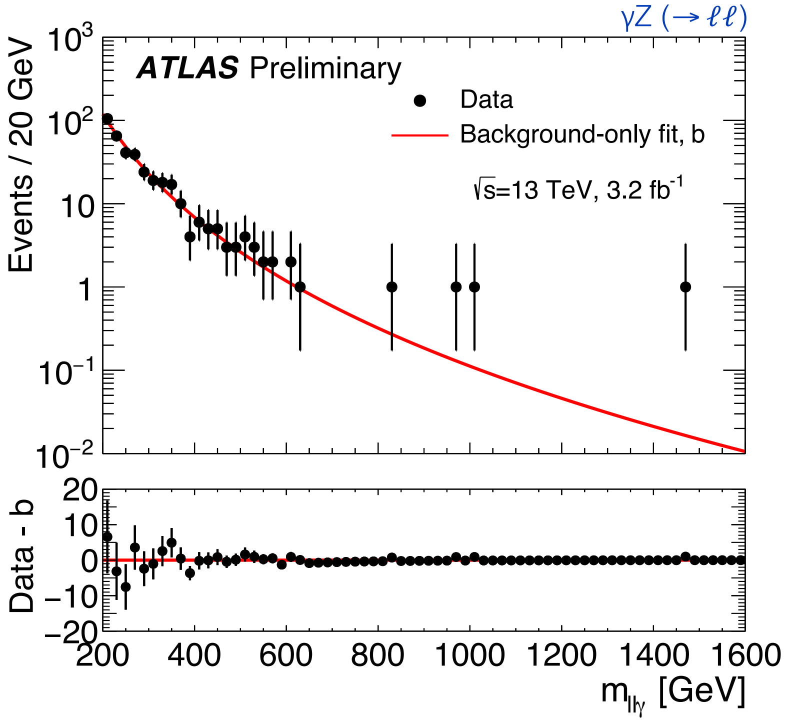
Global p-values derived with respect to scan planes

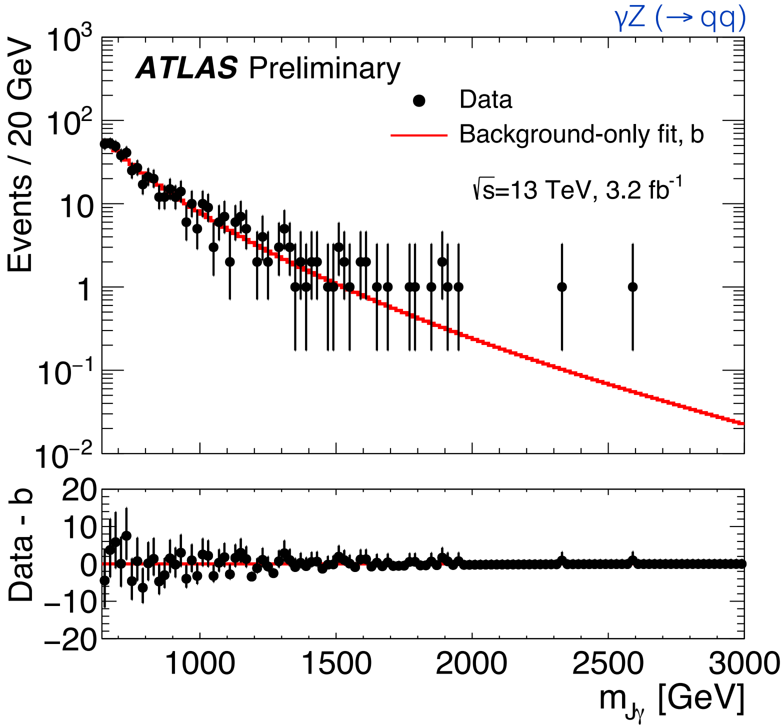
Diphoton resonance searches: ATLAS

Digression: ATLAS also presented 13 TeV Zγ searches this week

Narrow resonance search, split into $Z \to \ell\ell$ and $Z \to qq$ final states (qq dominant at high mass).

Background from empirical function





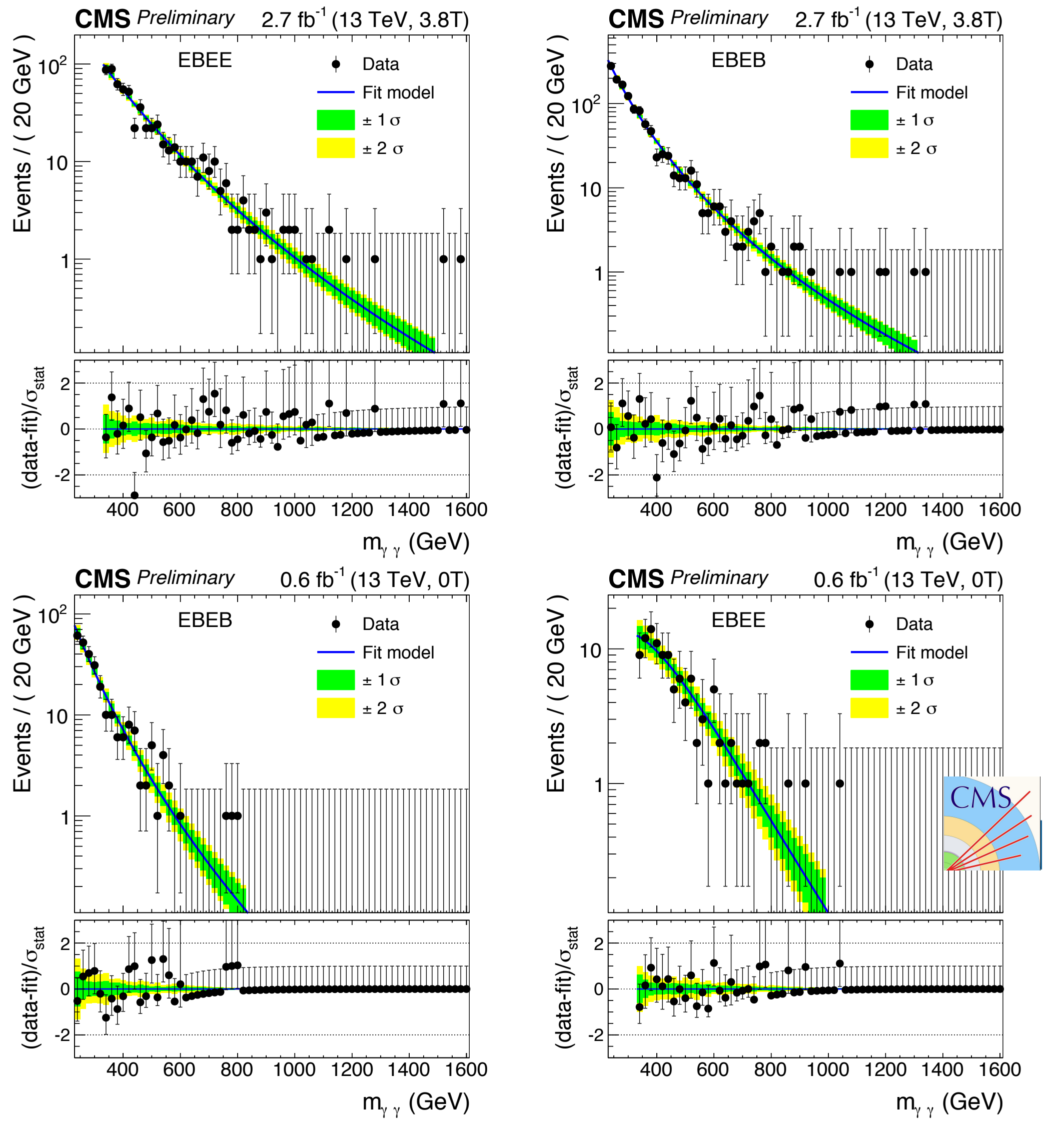
No excess in spectra, limits following expectation

Diphoton resonance searches: CMS

Updated preliminary results presented this week

CMS searches agnostically for spin 0 and 2 bosons. Updated 13 TeV analysis with improved ECAL calibration (~30% improved resolution above $m_{\gamma\gamma}$ ~ 500 GeV), and including 0.6 fb^{-1} of B-field off data

- Acceptance: $E_T(\gamma_{1/2})$ > 75 GeV, at least one γ with $|\eta|$ < 1.44 (barrel), split EB-EB, EB-EE
- Dedicated calibration of B-field-off data, slightly lower γ-ID efficiency, better resolution, harder PV finding
- Empirical background modelling



Pasquale Musella

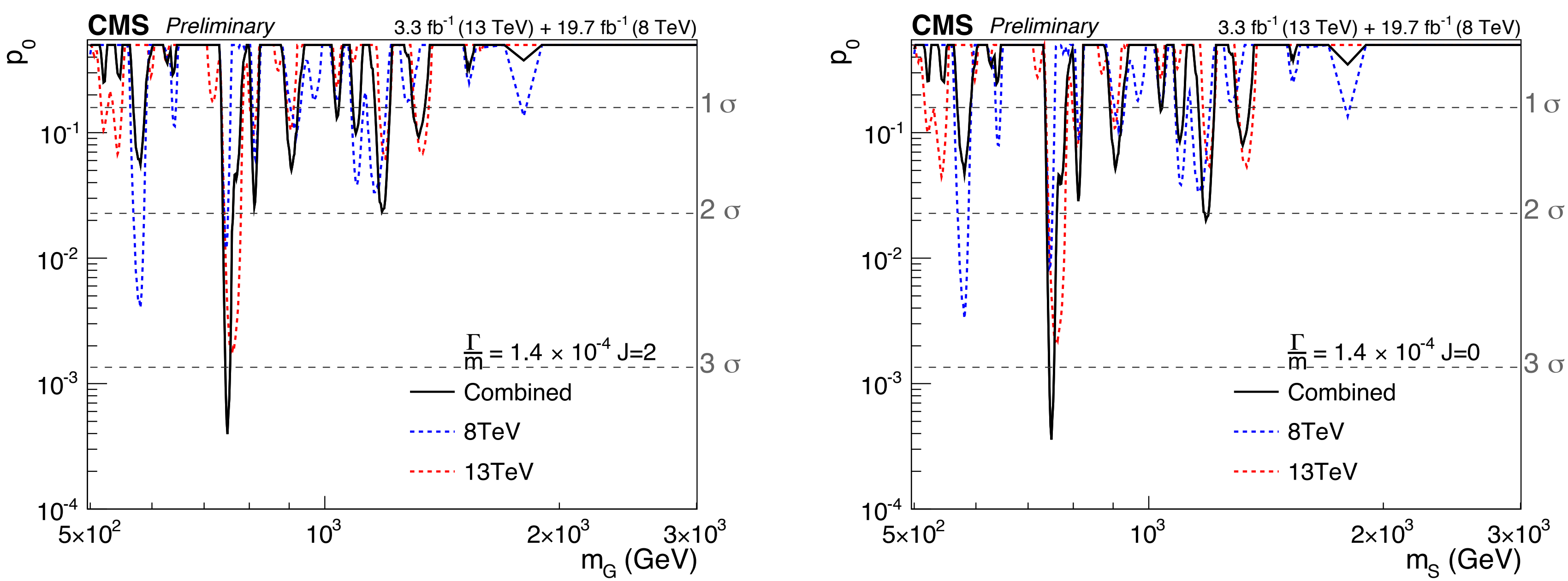
Diphoton resonance searches: CMS

Updated preliminary results presented this week

CMS has also looked into event properties of excess region and found them consistent with sidebands

CMS combines 13 TeV with spin-0 and 2 searches from 8 TeV data. Results found to be compatible.

Resulting p-value scans (lowest width models, giving largest excess at 750 GeV, shown here):



Lowest p-value at ~750 GeV (760 for 13 TeV data only), narrow width

Local / global Z = 3.4σ / 1.6σ (2.9σ / < 1 for 13 TeV data only)

Alessandro Strumia:

Today it could be everything, including nothing.

Alessandro Strumia:

Today it could be everything, including nothing.

Soon we shall know more.

Moriond EW (51st edition) has been memorable

It exhibited once again the challenges today's experimental physics takes on and overcomes

- The discovery of the Higgs boson required the construction of a huge accelerator and ultra-sophisticated particle detectors to find the events buried under 10^{12} times larger backgrounds
- The direct observation of gravitational waves required to measure over 4 km a relative length deformation two hundred times smaller than the size of a proton.
- Similar things can be said about neutrino physics, dark matter searches, etc. It is breathtaking.
- Accomplishing these measurements requires great ideas, visionary leadership, long-term support by governments & society, innovative & highest quality hardware and software, computing resources, operational & maintenance support, precise & unbiased analysis — and above all: dedication
- Given what we have seen this week, I have no worry. We live in an extraordinary period for fundamental experimental research in physics

Congratulations to the 50th anniversary of Moriond EW & UT.

There will be ample material for an exciting next half a century !

Spare slides

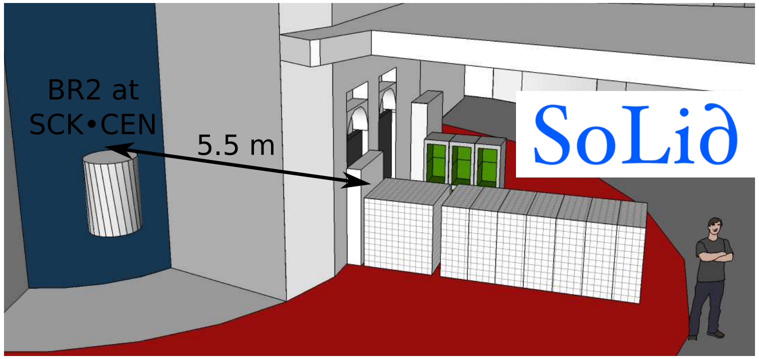
Very short-baseline (reactor) neutrino experiments : SoLid

Put neutrino experiment closer to the source to test anti-neutrino flux models

Nick van Remortel

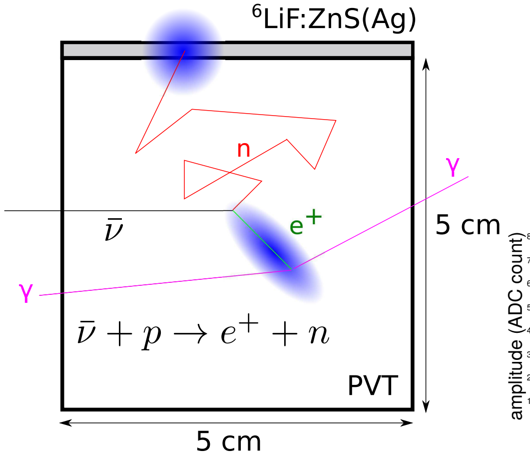
SoLid: highly segmented plastic scintillation detector coated with Lithium-6, designed to measure flux and energy of anti-ν_e at very short baseline distances between 6–10 m from the *compact* BR2 test reactor with highly-enriched uranium core in Mol (Belgium).

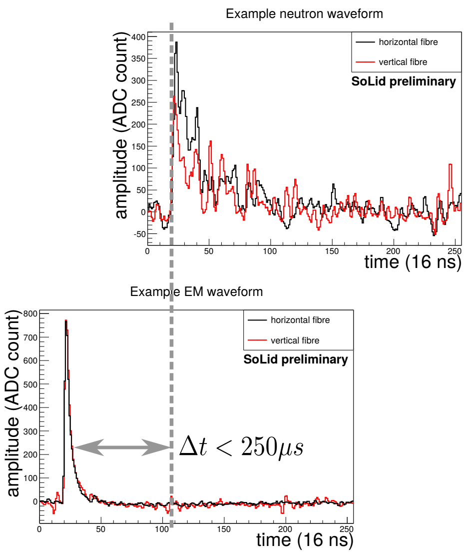
Challenge is background suppression in proximity of reactor (high captured neutron–e/γ separation) and precise location of IBD products: not only time difference, but also spatial information used to reconstruct IBD events



3 ton SoLid experiment deployed 5.5 m from the BR2 reactor core

$$n + {}^6\text{Li} \rightarrow {}^3\text{H} + \alpha + 4.78\ \text{MeV}$$





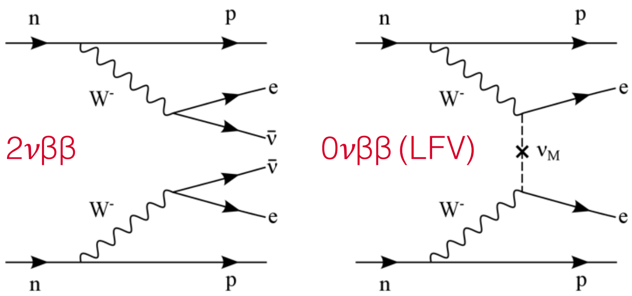
Long-term goal: run experiment for three years to resolve reactor neutrino anomaly w/o relying on theoretical calculations. Results with 290 kg prototype presented.

Of which quantum nature are neutrinos ?

EXO-200 showed new limits on neutrinoless double beta decay ($0\nu\beta\beta$) in $^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

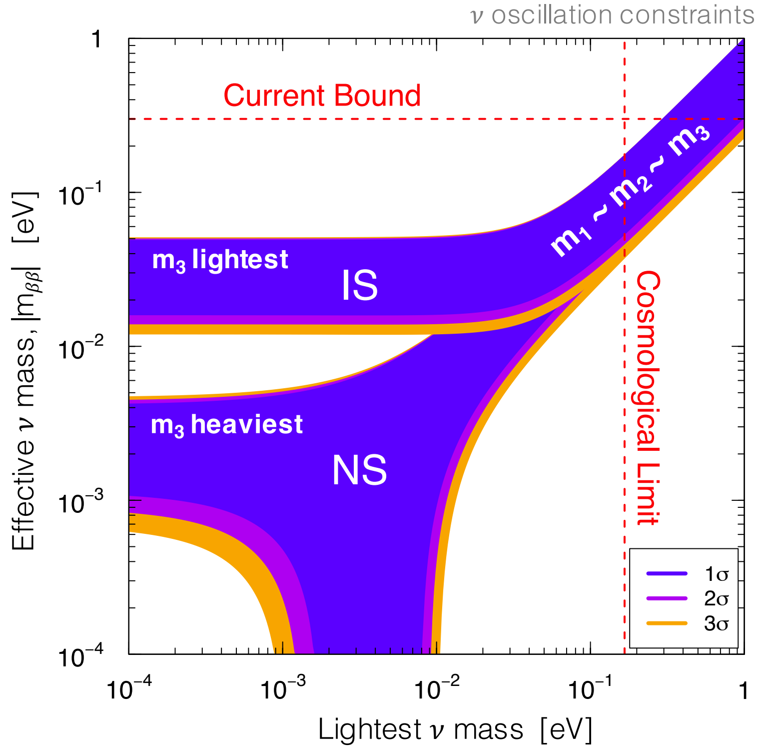
EXO-200 enriched (~81%) liquid-xenon TPC (shielded + active muon veto) is installed in nuclear waste isolation plant in New Mexico, US.

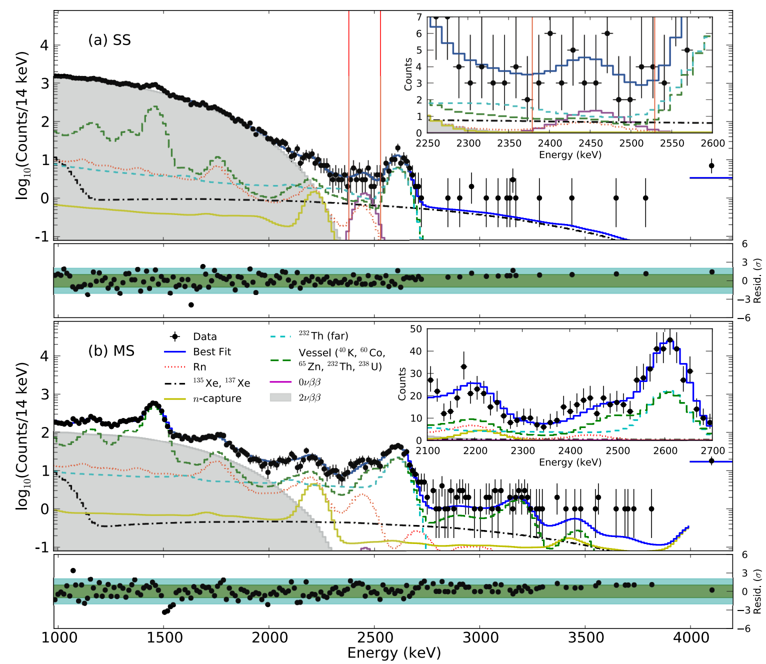
Experiments require: • large mass • high isotopic abundance • good energy resolution • high efficiency • low background



Requires non-zero Majorana ν mass term

$\Gamma_{0\nu\beta\beta} \propto |m_{\beta\beta}|^2$





100 kg·yr ^{136}Xe exposure:

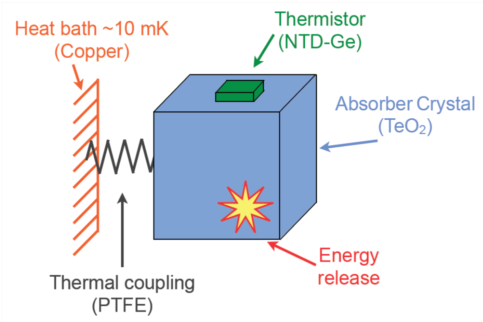
Lower limit on $m_{Maj}(\nu)$ = 0.2–0.4 eV (90% CL)

Dominant uncertainty from nuclear matrix element

Of which quantum nature are neutrinos ?

CUORE (“heart”) at LNGS is one of several next generation $0\nu\beta\beta$ experiments

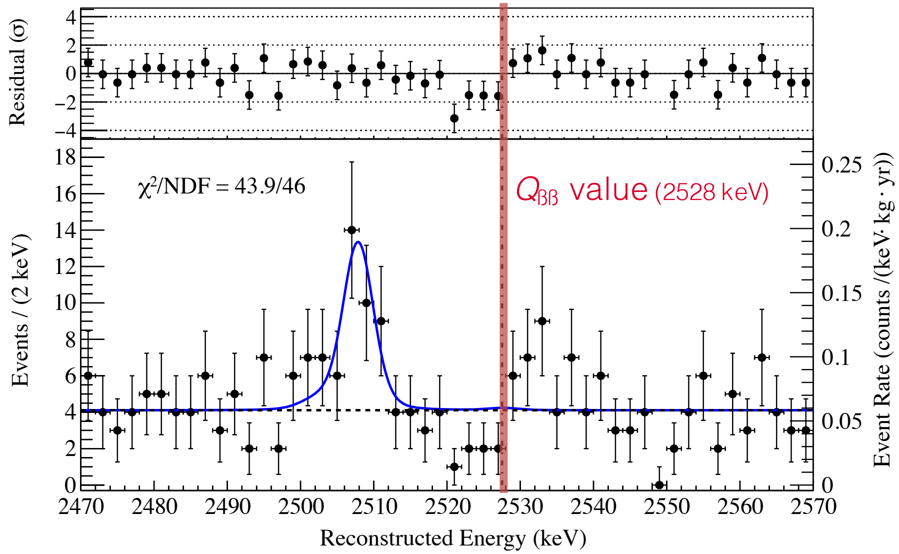
CUORE bolometric technique using array of tellurium dioxide crystals ($^{130}Te \rightarrow {}^{130}Xe + 2e^-$) cooled to ~10 mK → low heat capacity: single particle interaction produces measurable rise in temperature



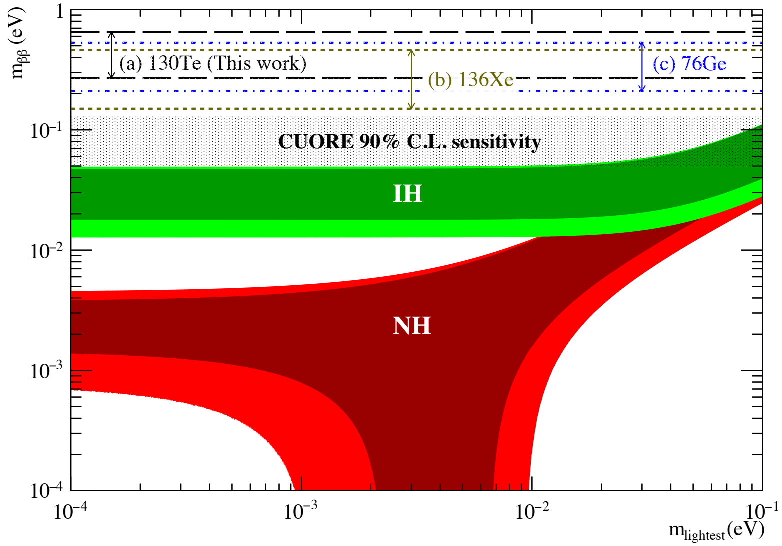
CUORE-0 (2013–2015): 11 kg ^{130}Te || CUORE (2016–…): 206 kg ^{130}Te

Sensitivity ∝ (detector mass)$^{1/2}$

9.8 kg·yr ^{130}Te exposure (CUORE-0):



Lower limit on $m_{Maj}(\nu)$ = 0.3–0.8 eV (90% CL)



CUORE-0 + Cuoricino: $T_{1/2}^{0\nu\beta\beta} > 4.0\ 10^{24}$ yr

Cosmological neutrinos: Baryonic Acoustic Oscillations

Neutrino physics in the Lyman-α forest ($2 < z < 5$) using BOSS data

Graziano Rossi

Cosmology offers laboratory with sensitivity to the neutrino mass: free-streaming primordial neutrinos leave their imprint into large-scale structure (LSS) observables:

- Set expansion rate at BBN
- Suppression of power on small scales probed, eg, by Lyman-α forest BAO data
- Slow down growth of structure

Reproduce numerically using hydrodynamical models large-structure formation using different neutrino masses.

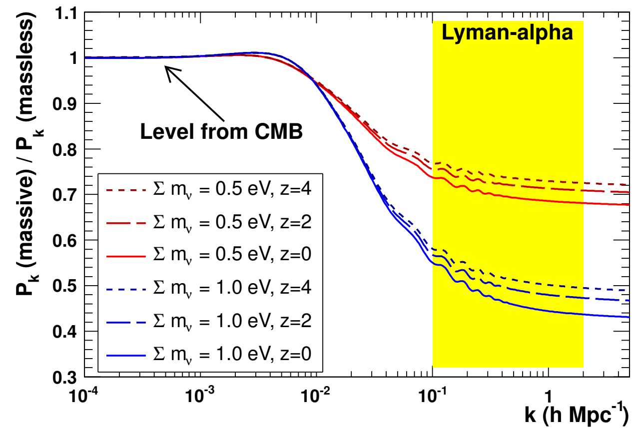
Combine results on Lyman-α forest with CMB (Planck, WMAP, ACT, SPT)

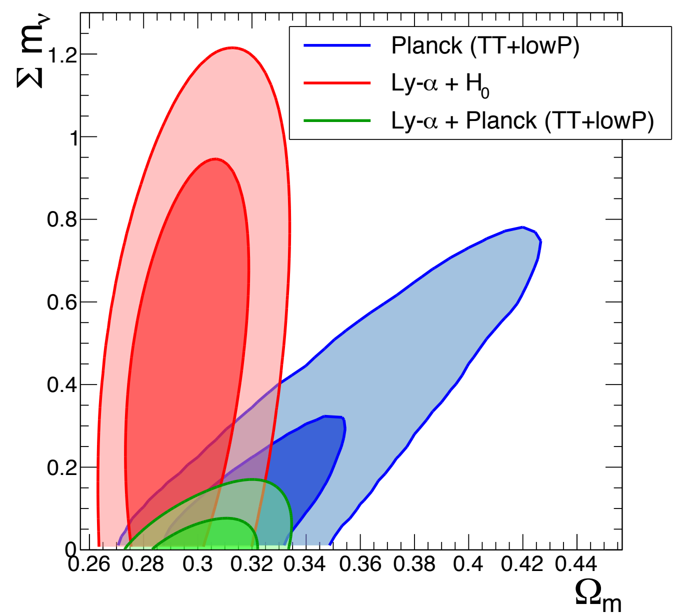
Σm_ν < 1.1 eV (Ly-α alone)

< 0.23 eV (CMB, Planck)

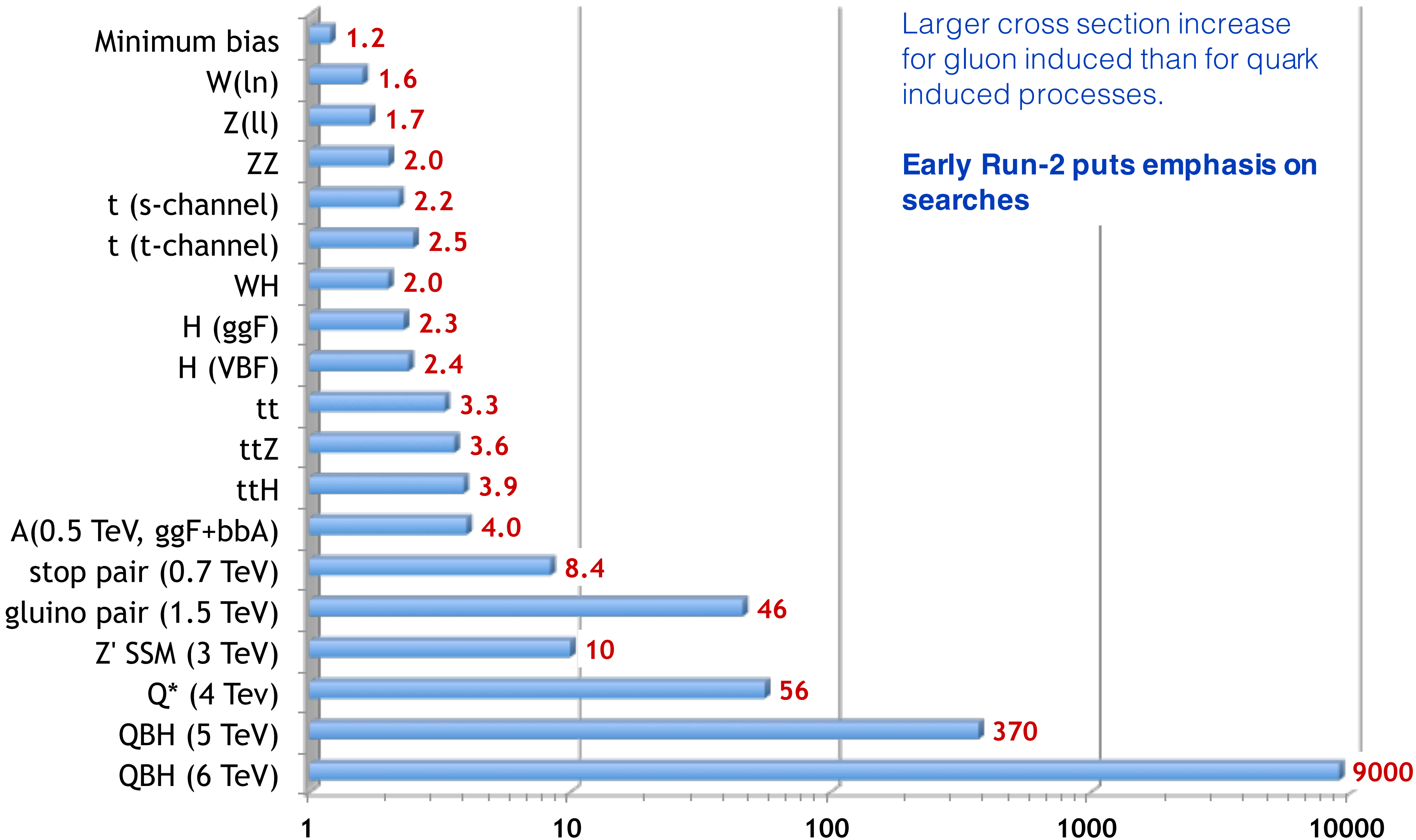
< 0.12 eV (Ly-α & CMB & BAO combined)

Large list of possible systematic uncertainties





Life in 2015: 13 TeV / 8 TeV inclusive *pp* cross-section ratio



Larger cross section increase for gluon induced than for quark induced processes.

Early Run-2 puts emphasis on searches

Sean Benson

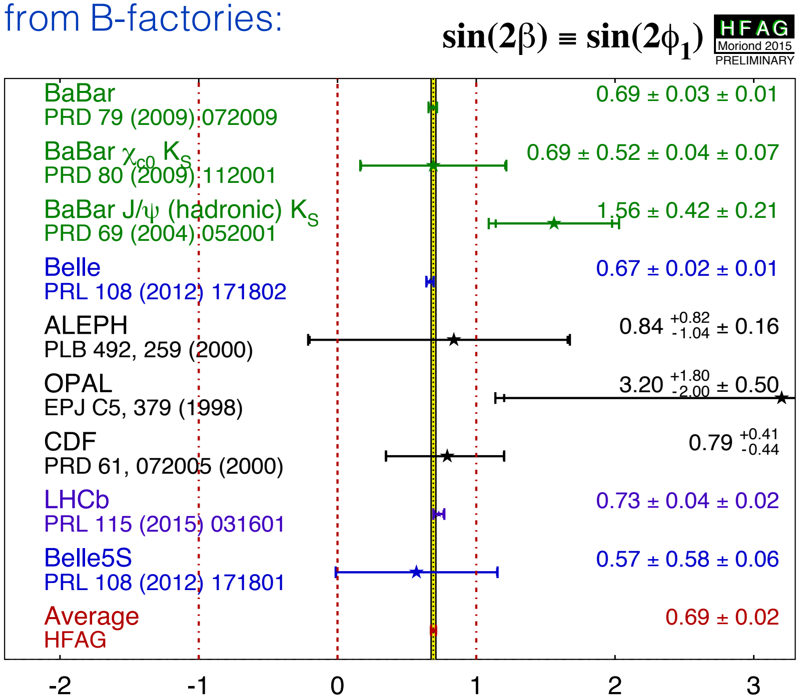
New CP violation results in b-hadrons from LHCb

Apart from the results shown below, new measurements in Lb sector

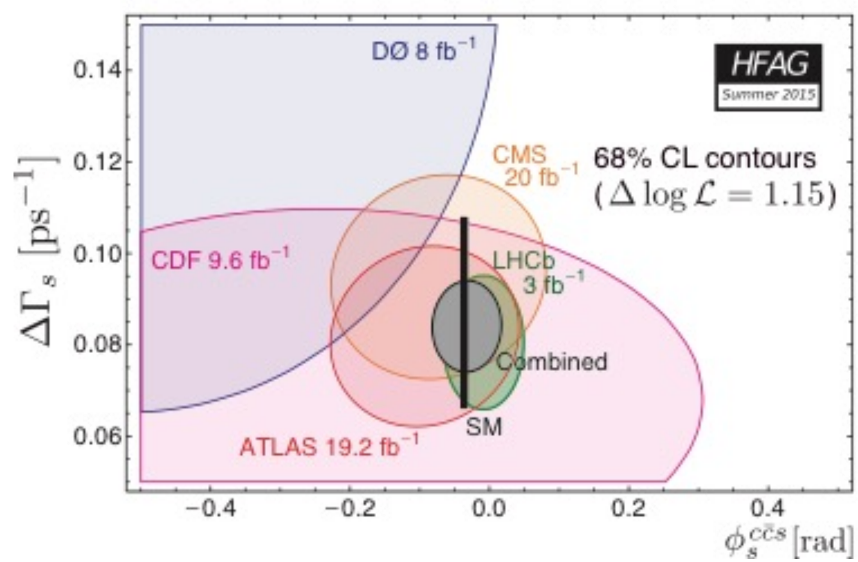
LHCb contributes to vanilla CKM CP physics through various B_d meson measurements

For example: world's best Δm_d from LHCb: $0.5050 \pm 0.0021 \pm 0.0010\ ps^{-1}$ (B-factories: $\sigma_{ave} = 0.005\ ps^{-1}$)

LHCb approaches precision on sin(2β) from B-factories:



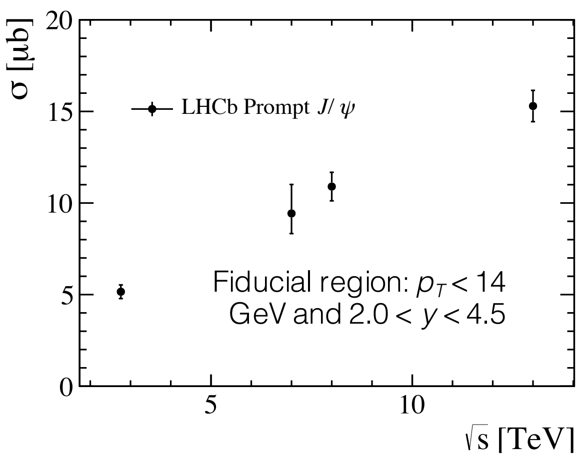
Current picture of corresponding ϕ_s measurements fully consistent with SM

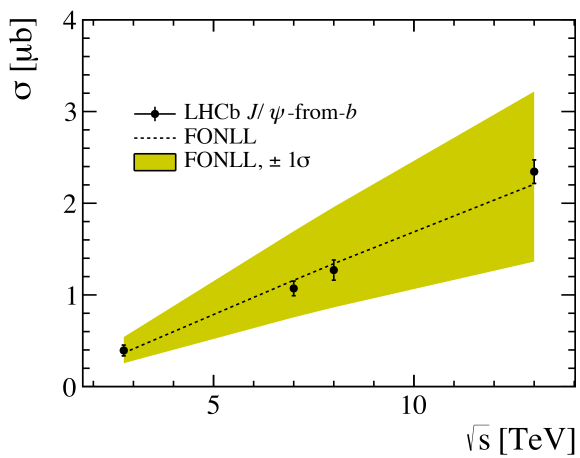


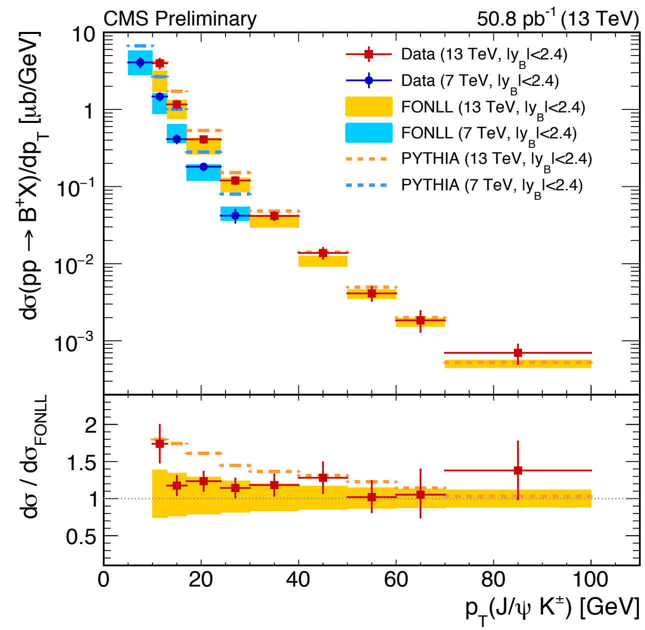
Data-driven studies of penguin pollution using $B_s \rightarrow J/\psi\ K^*$ together with SU(3). Excellent experimental precision of < 0.015 on $\Delta\phi_s(J/\psi\ \phi)$

Heavy flavour production at 13 TeV

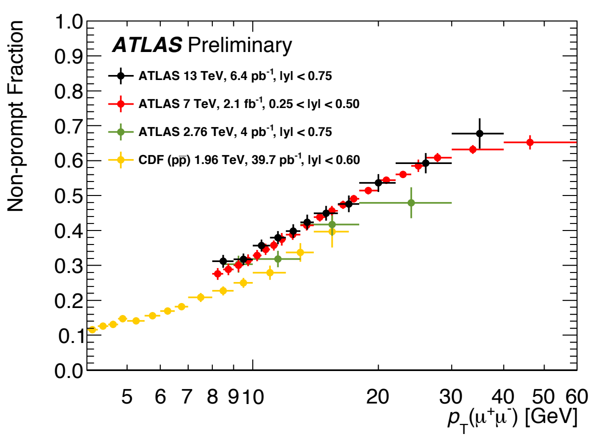
ATLAS, CMS & LHCb measured heavy flavour production processes, such as prompt & non-prompt J/ψ, and $B^+(\rightarrow J/\psi\ K^+)$ cross-sections. In agreement with predictions.







Diff. cross section for $|y_B| < 2.4$ and $\sqrt{s}$ = 7, 13 TeV



Cross-sections rise mostly due to CM energy; harder p_T spectrum at 13 TeV than at 8 TeV

Total $\sigma(pp \rightarrow bb+X)$ = 515 ± 2 ± 53 μb

Non-prompt contribution to total rate rises rise from approximately 25% at $p_{T,\mu\mu}$ of 8 GeV to 65% at 40 GeV

LHC / HL-LHC Plan