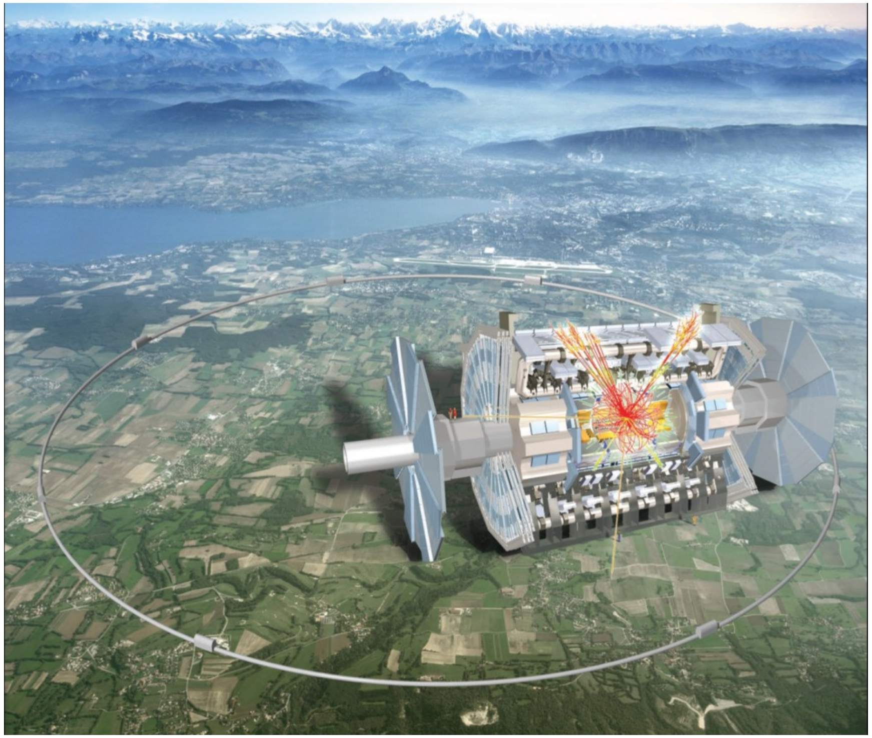
July 4 2018

[CN-FR Summer School]

ATLAS detector and its physics : a selection



Physics for both infinities : L'École d'été France Excellence

针对两个无穷的物理研究：硕士法国暑期学校

Laurent Vacavant

The introduction…

Particle Physics ?

The ambitious goals of Particle Physics: answer some of the most fundamental questions in science:

- nature of matter ?
- nature of mass ?
- nature of energy ?
- how these are linked to cosmology and the evolution of the Universe

Huge progresses towards this aim made over the last decades, through interleaved contributions from:

- theory work
- experimental work

➔ the two sides of the research in Particle Physics

Our best friend (so far) in this quest:

The Standard Model of Particle Physics

Its Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

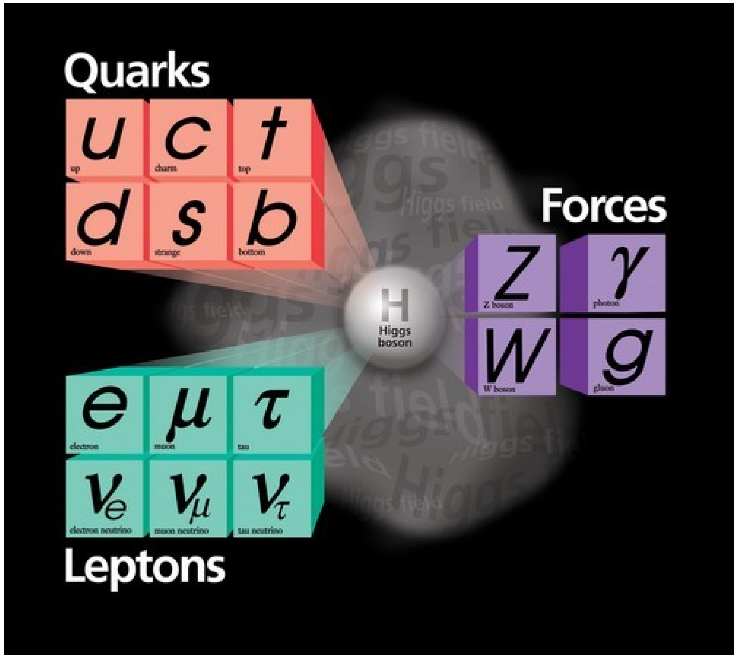
$$+ i \bar{\psi} \not{D} \psi$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

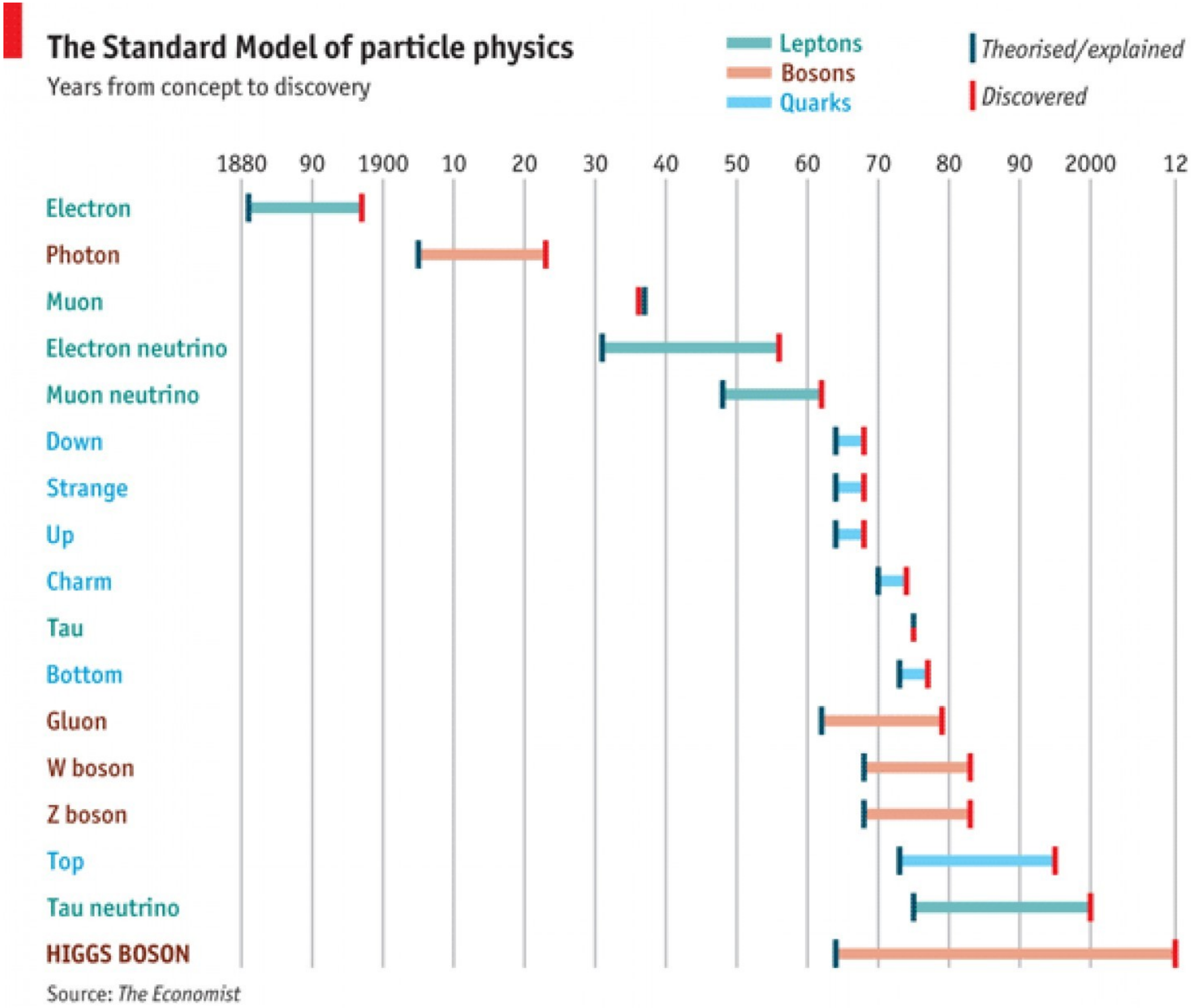
$$+ |D_\mu \phi|^2 - V(\phi)$$

simple and elegant…

Particle contents:

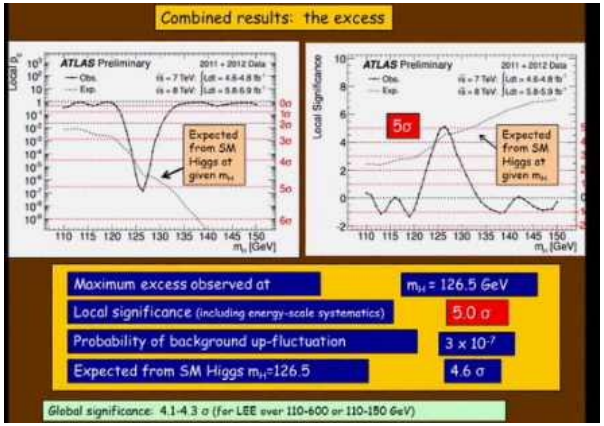


The (triumphant) long reign of SM



Source: *The Economist*

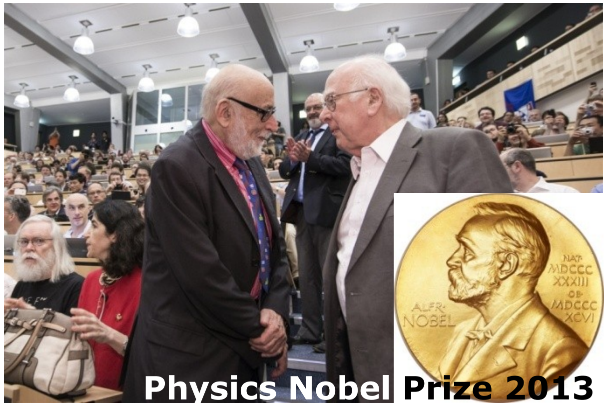
Crowning of SM !! 4th of July, 2012



Combined results: the excess

Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)



Physics Nobel Prize 2013

Le Monde.fr

Mise à jour à 10h02 – Paris

INTERNATIONAL POLITIQUE SOCIÉTÉ ÉCONOMIE CULTURE IDÉES SPORT SCIENCES TECHNO

EN CE MOMENT Nicolas Sarkozy Mali Boson de Higgs 1962 : l'indépendance algérienne Microsoft

Le boson de Higgs découvert avec 99,9999 % de certitude

Voici la confirmation tant attendue : une nouvelle particule a été découverte au Centre européen de recherche nucléaire (CERN), près de Genève.

SCIENCES ET AVENIR

BOSON de HIGGS

La découverte du siècle

LES MYSTÈRES DU TEMPS

Gazeta.pl Wiadomości

Naukowcy z CERN niemal pewni, że złapali "boską cząstkę". Jest zgodna z bozonem Higgsa

Libération

Physique des particules

La masse est dite

Le Cern a réussi à mettre en évidence le boson de Higgs qui résout une énigme fondamentale

The New York Times

Wednesday, July 4, 2012

New Particle Could Be Physics' Holy Grail

vk.nl

Higgs of niet, het is een spectaculaire ontdekking

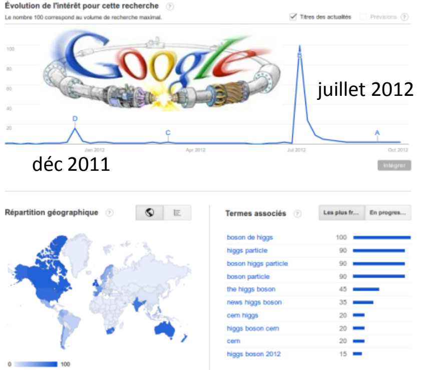
miércoles, 4 julio 2012 | Actualizado 09:52 CET

EL PAÍS

Los científicos del CERN anuncian el descubrimiento de una partícula que podría ser Higgs.

llada "la más sólida evidencia" de existencia del bosón de Higgs

"Puedo confirmar que se ha descubierto una partícula que es consistente con la teoría del bosón de Higgs", dicen los científicos. El descubrimiento de la partícula ayudaría a explicar el origen de la masa. Los físicos del CERN explican en estos momentos sus hallazgos



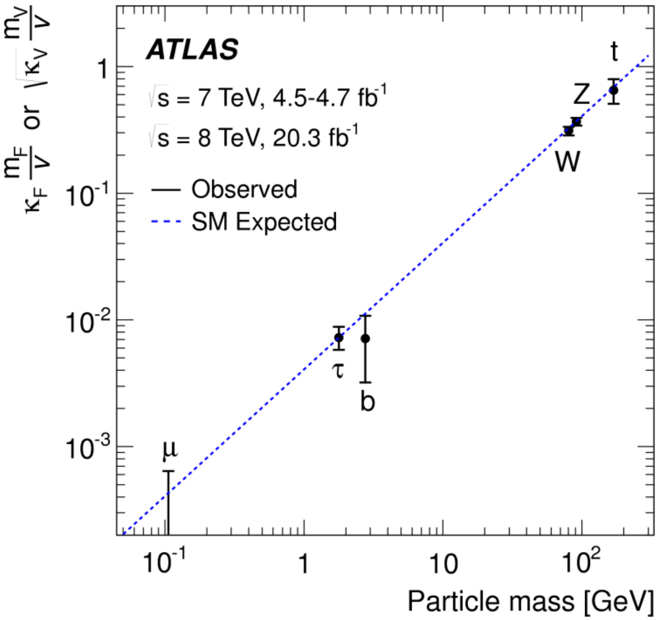
Exciting times for you as well !

The discovery of the Higgs boson, 40 years after the prediction of its existence, is a major achievement for science !

It’s not the end of our discipline, rather a new era opening up:
➔precise measurements of the Higgs boson property !!
➔search for new particles arising in theories beyond the SM !!

Higgs properties:

production: WH, ttH
decays: bb, WW



New physics beyond the SM:

- several good reasons for going BSM
  - neutrino masses
  - dark matter ?
  - matter/antimatter asymmetry
  - “fine-tuning” problems

- no clear/favored solution from theor

➔ **the ball is in the experimental**

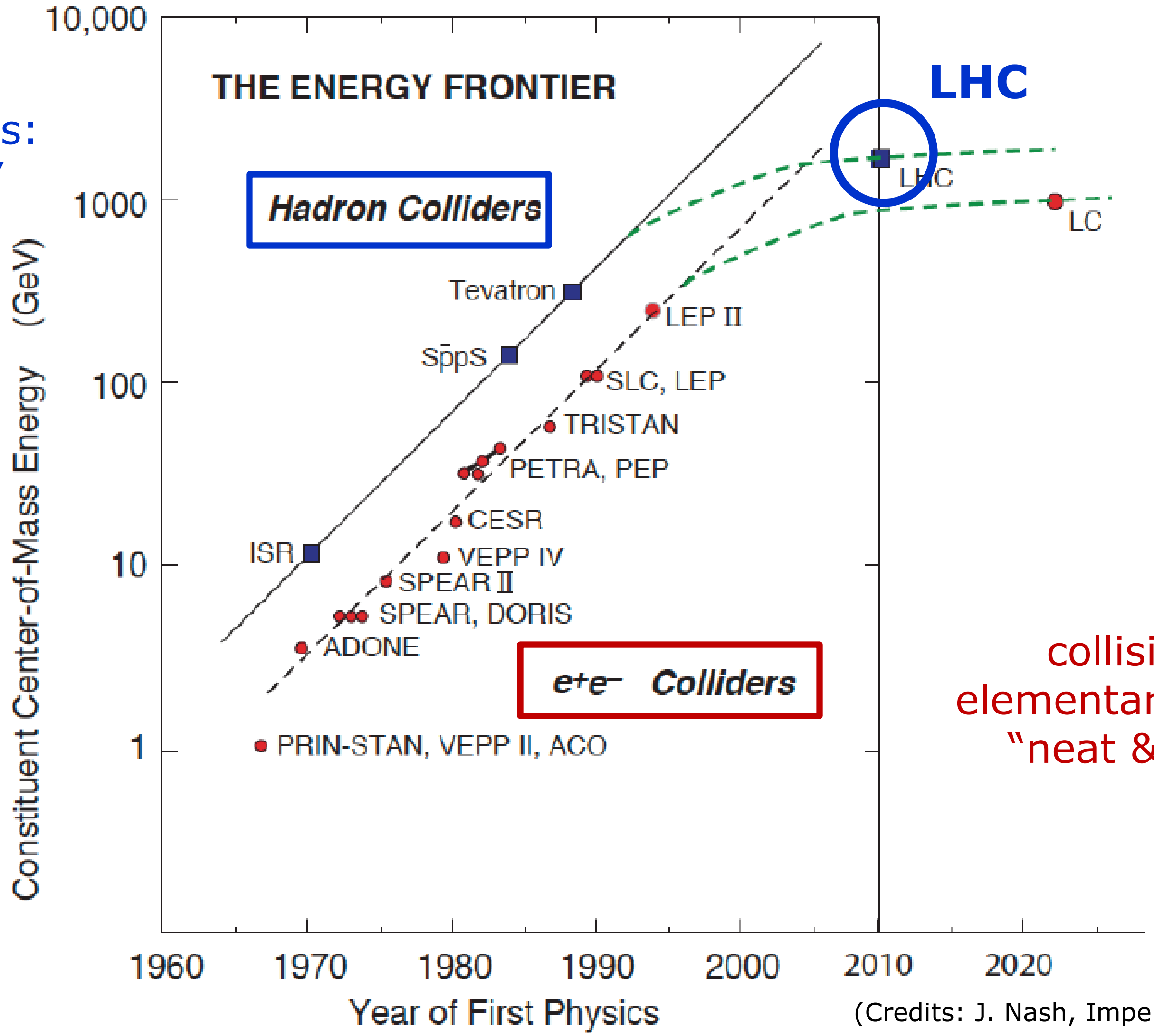
- possible theoritical models:
  - supersymmetry ?
  - extra-dimensions ?

➔ **we have the tool to explore the region: new run of LHC at 13 TeV just started**

The collider… LHC

The Energy Frontier

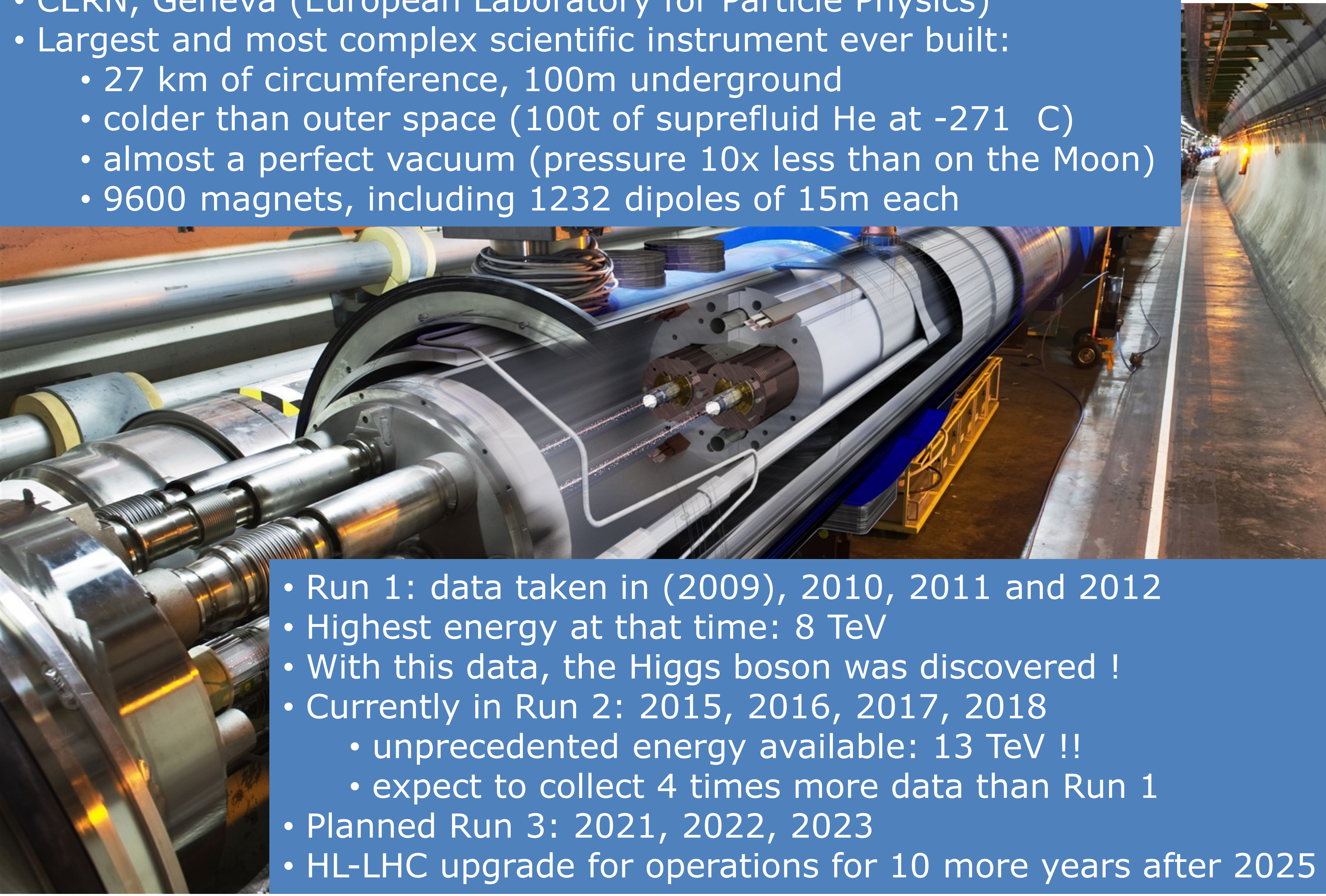
collisions of
composite particles:
“messy & crude”



collisions of
elementary particles:
“neat & precise”

(Credits: J. Nash, Imperial College London)

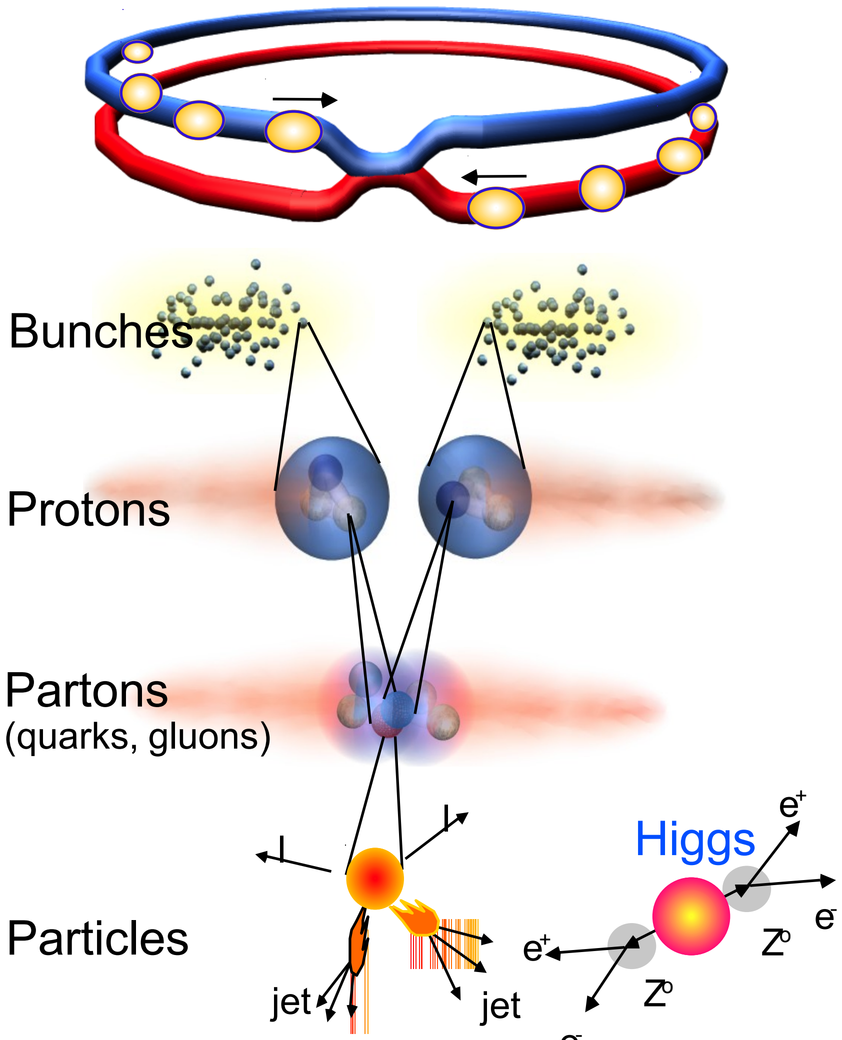
The Large Hadron Collider (LHC)



- CERN, Geneva (European Laboratory for Particle Physics)
- Largest and most complex scientific instrument ever built:
    - 27 km of circumference, 100m underground
    - colder than outer space (100t of suprefluid He at -271 C)
    - almost a perfect vacuum (pressure 10x less than on the Moon)
    - 9600 magnets, including 1232 dipoles of 15m each

- Run 1: data taken in (2009), 2010, 2011 and 2012
- Highest energy at that time: 8 TeV
- With this data, the Higgs boson was discovered !
- Currently in Run 2: 2015, 2016, 2017, 2018
    - unprecedented energy available: 13 TeV !!
    - expect to collect 4 times more data than Run 1
- Planned Run 3: 2021, 2022, 2023
- HL-LHC upgrade for operations for 10 more years after 2025

A challenging machine !



- Chasing very rare phenomena:
  - e.g. tt+H: 1 / 1,500,000,000,000

➔ solution: a lot of collisions !!

- For instance in 2012:
  - up to 1308+1308 bunches of protons
  - each bunch with 10^{11} protons inside
  - 4 TeV per beam
  - 15 millions of bunch crossing / sec.
  - up to 600 millions of proton-proton collisions per second !

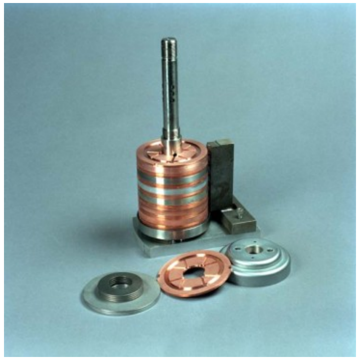
- In 2017-2018:
  - 7.5 TeV per beam
  - 2556 bunches per beam (25 ns i.e. 7cm separation)

- Head-on collisions created in four points of the ring: the 4 experiments of LHC, recording what's happening during the collisions (ATLAS, CMS, LHCb, ALICE)

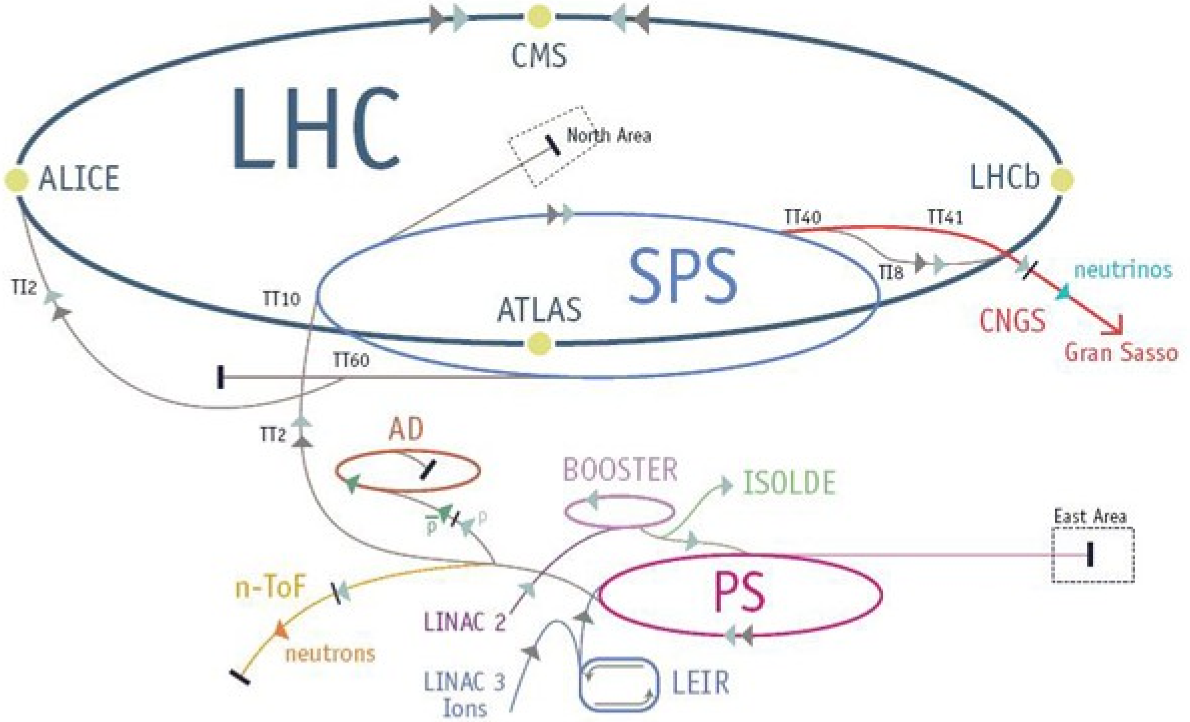
Why using protons in the LHC ?

- Synchrotron radiation: energy loss ∝ $(1/R)*(E/m)^4$
  - m(p) ~ 2000 m(e)
  - for a 100 GeV electron in LEP2: 3 GeV lost per turn
  - for a 7 TeV proton in LHC (same radius of curvature): 10 keV
  - to get 200 GeV electron requires a machine 16 times bigger !
  - ➔ protons: the avenue to the high energies (or go linear?)

- Proton-proton or proton-antiproton (like Tevatron) ?
  - p-pbar XS higher than p-p, but difference vanishes at high E
  - antiproton production is inefficient
  - p + A → p + p + pbar + A
  - at Tevatron, 10^6 protons on target to get 20 antiprotons
  - not enough to reach high luminosity target for LHC
  - → pp collisions
  - → 2 accelerators in one !



The accelerator complex



- H_2 bottle !
- duoplasmatron → protons
- Linac 2 → 50 MeV (to be replaced in 2019 by Linac 4 at 160 MeV)
- Booster & PS → 25 GeV
- SPS → 450 GeV
- before entering the LHC, a proton has traveled already ~6M km !

Luminosity: ∝ rate of collisions

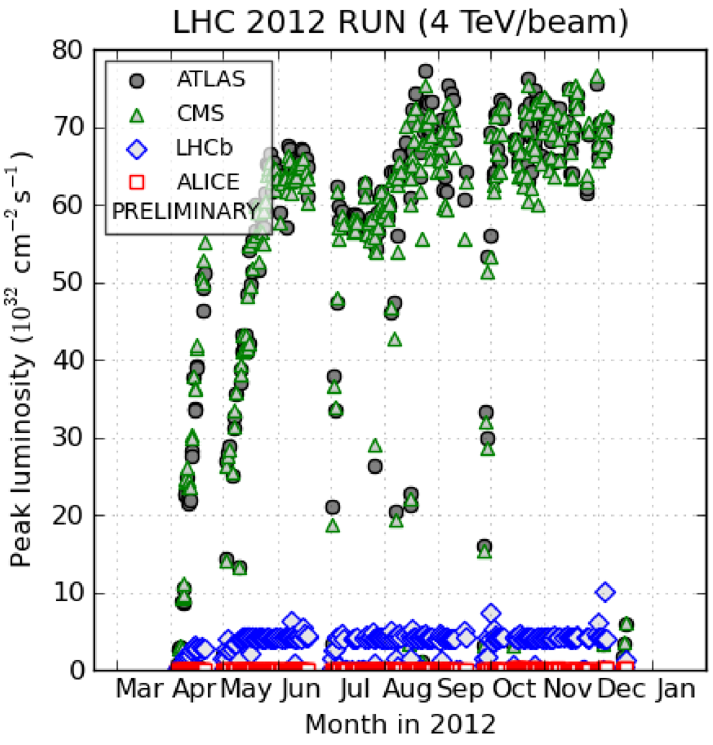
$$\mathcal{L} = f n_p \frac{n_1 n_2}{4\pi\sigma_x\sigma_y} F = f n_p \frac{\gamma n_1 n_2}{4\beta^* \epsilon_N} F.$$

Rate of events: L σ
\# of events: Int(L)×σ

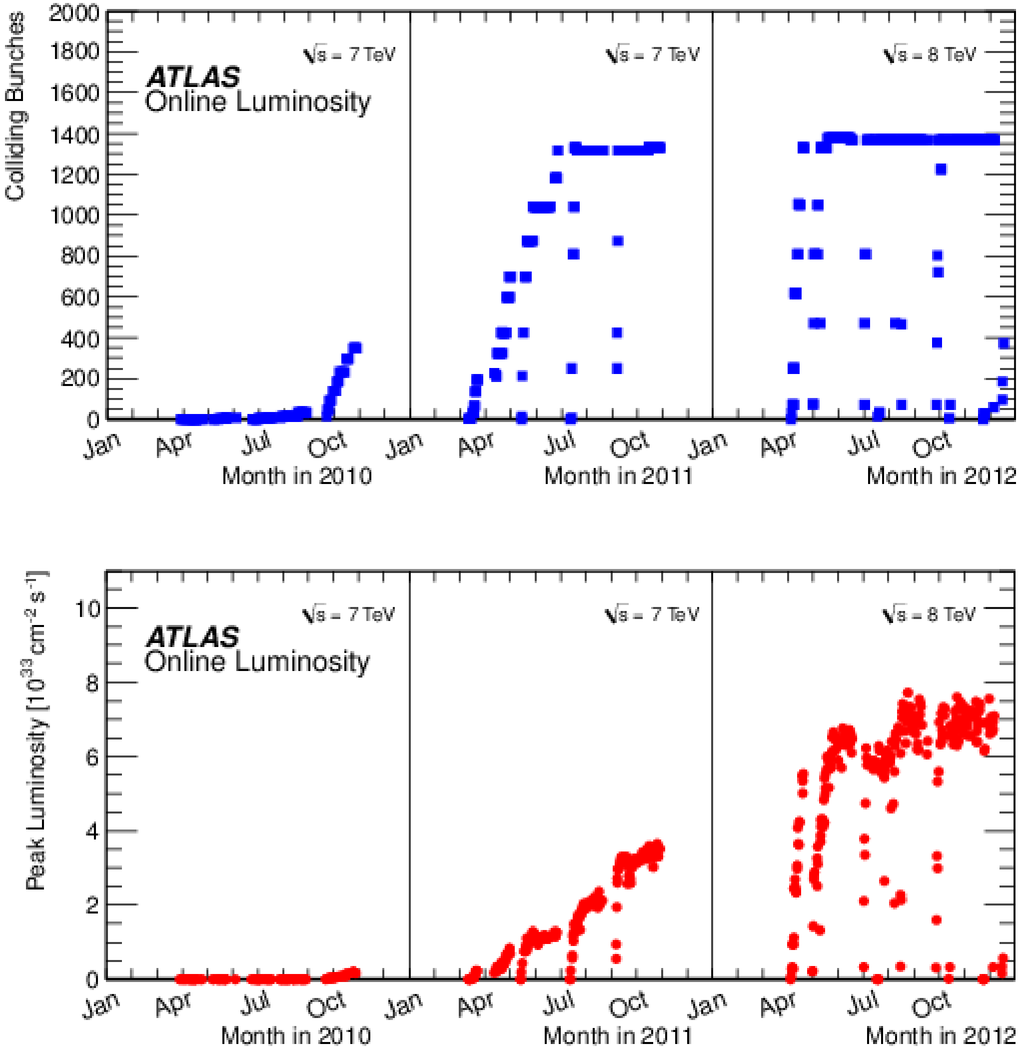
- f: number of turns in LHC per second : 11245 Hz
- n_p: number of bunches of protons. Nominal: 2808 . In 2012: 1380
- n_1, n_2: number of protons in the colliding bunches. Nominal: 1.15 10^{11}, in 2012 up to 1.5 10^{11}
- $\sigma_x=\sigma_y=16$ µm : transverse size of beam at collision point
- ε: beam emittance (=πσσ’), $\varepsilon_N=\varepsilon\gamma$ (normalized emittance)
- σ’: emittance in $x'=p_x/p_z$
- F: factor for crossing angle ~ 0.8 (Θ=285 µrad)
- β=σ/σ’, to be minimized at IP. Typically 55cm for LHC.

- Design luminosity for 14 TeV operations: 10^{34} $cm^{-2}s^{-1}$

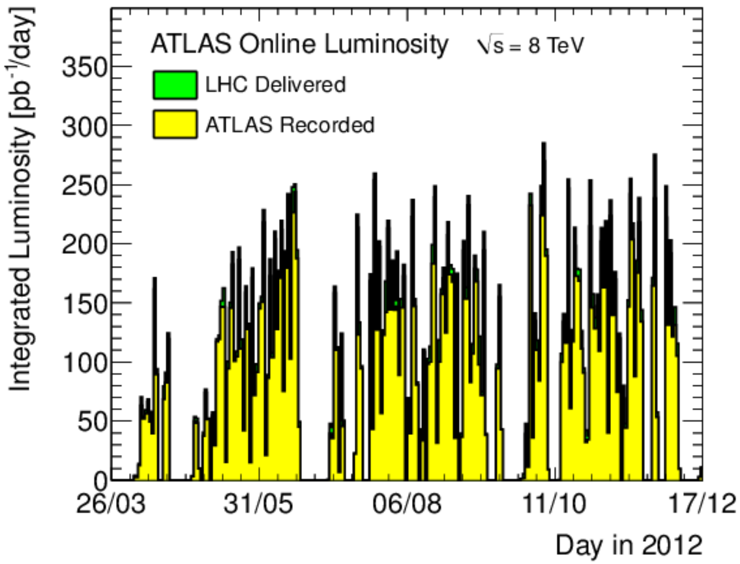
LHC luminosity for Run 1

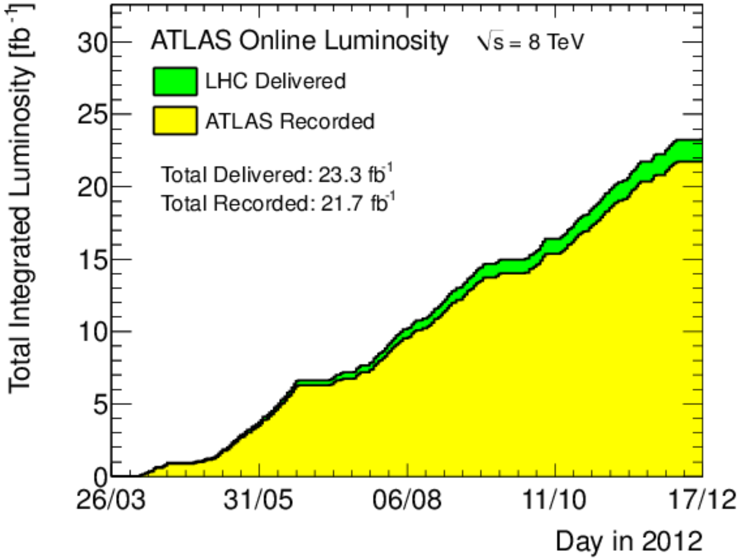


(generated 2013-01-29 18:28 including fill 3453)

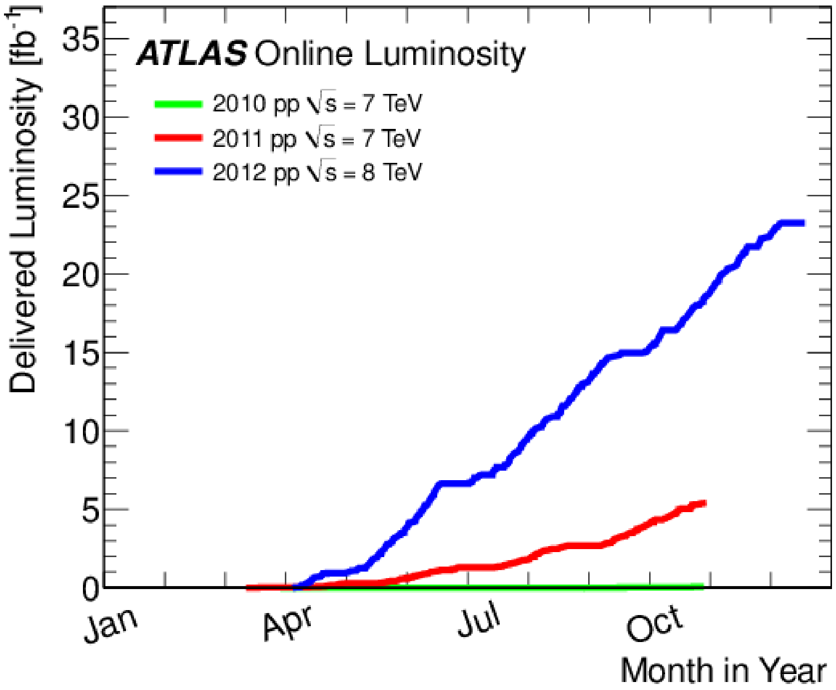


Integrated luminosity in Run 1





LHC Run 1 (2010-2012)

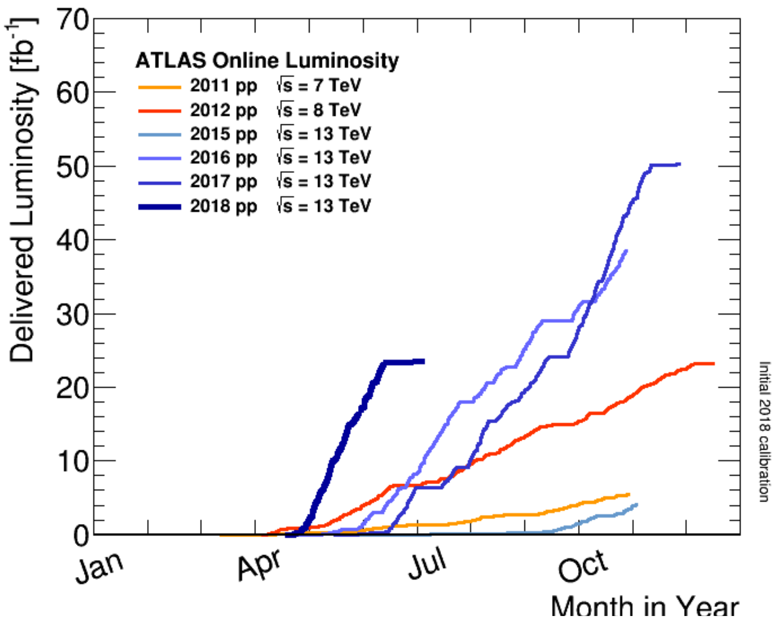


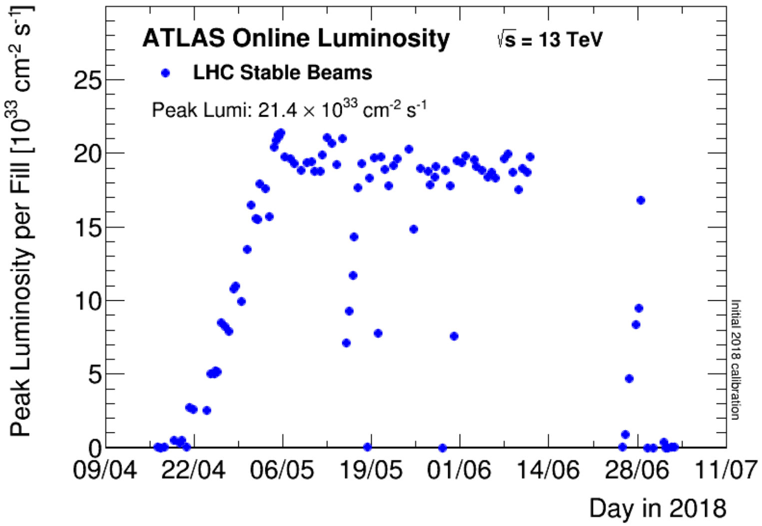
Integrated luminosity recorded per experiment

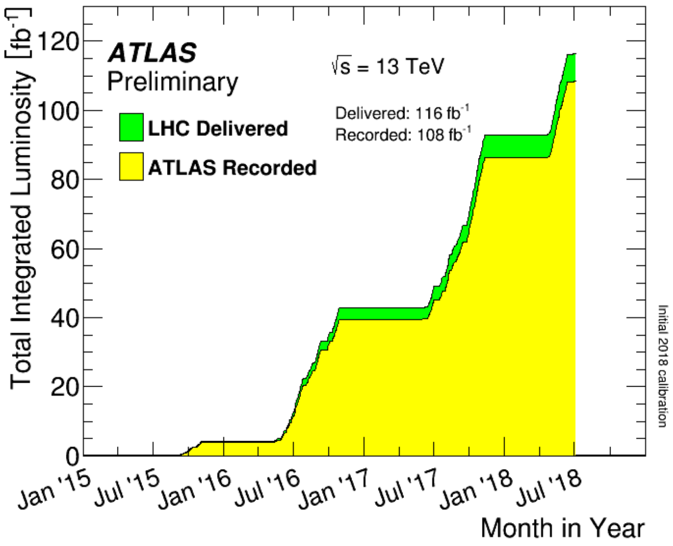
(similar for ATLAS and CMS):

- ~22 fb^{-1} in 2012
- ~5 fb^{-1} in 2011
- ~45 pb^{-1} in 2010

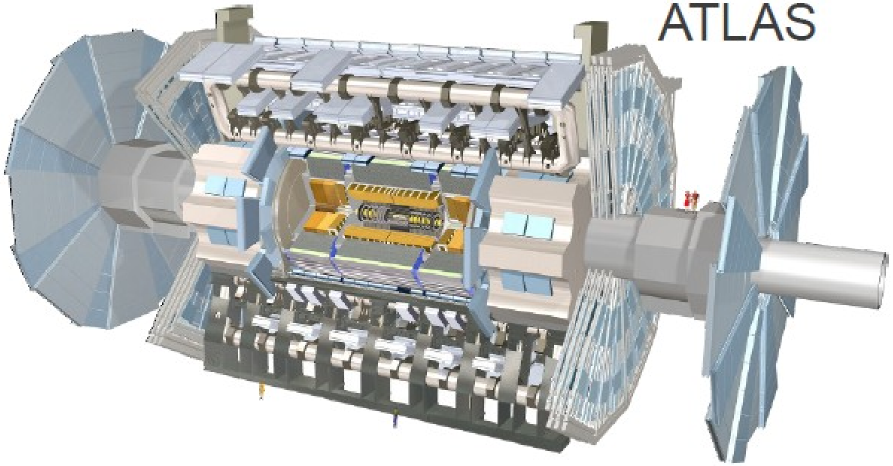
Run 2 and 2018 Data-Taking

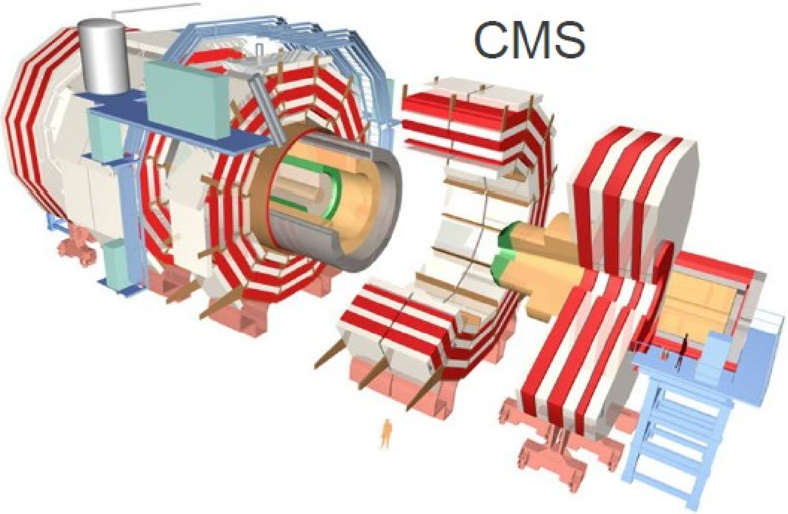


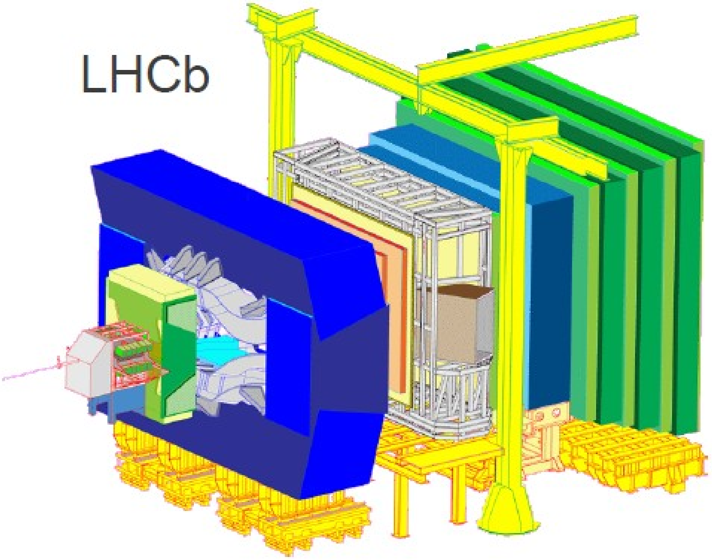


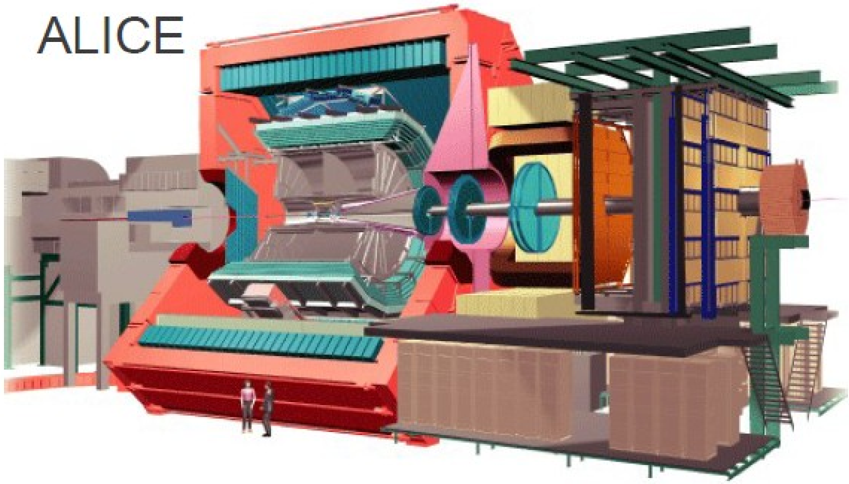


Gigantic cameras to catch particles !


ATLAS

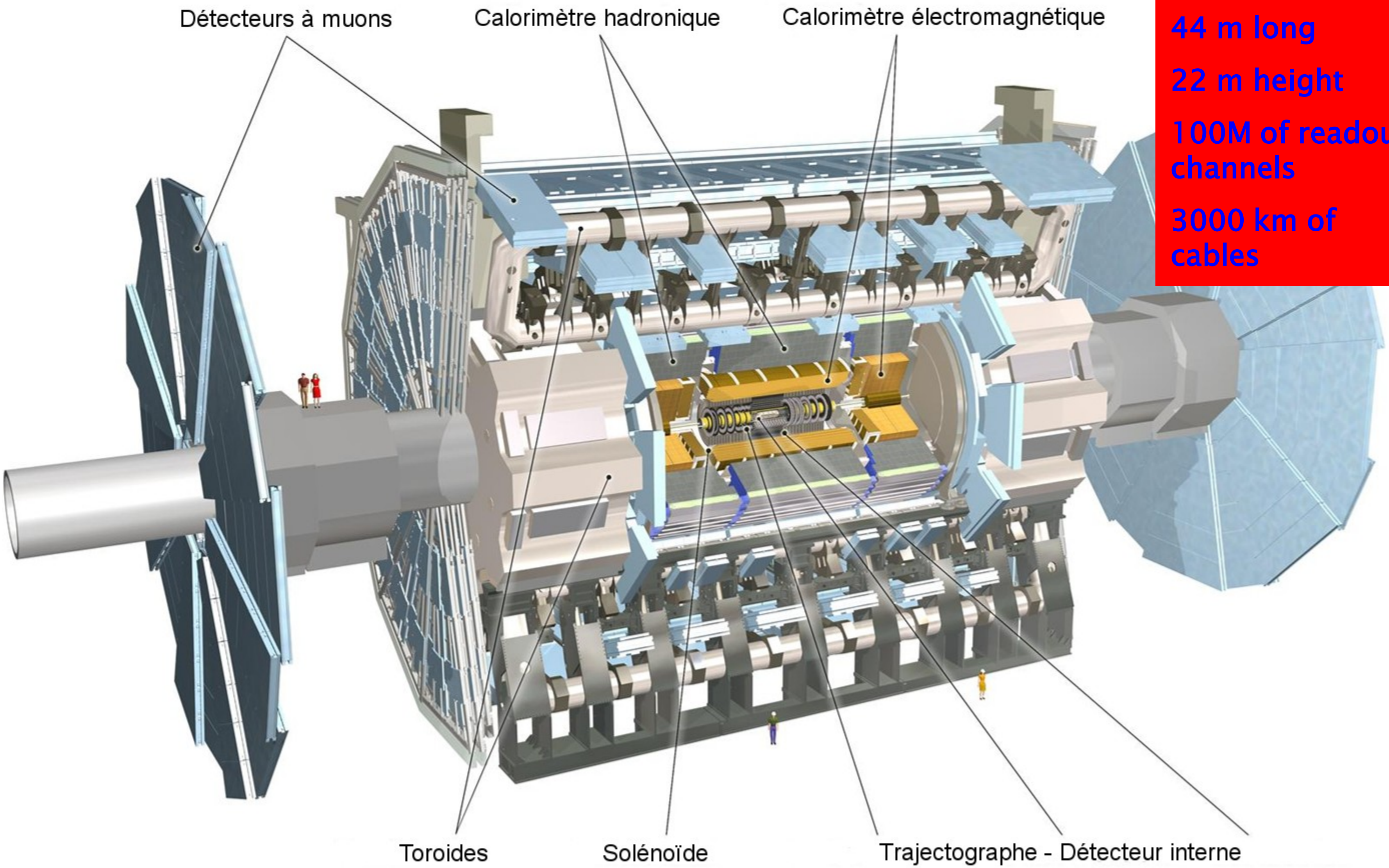

CMS


LHCb


ALICE

The detector… ATLAS

ATLAS



7000 tons

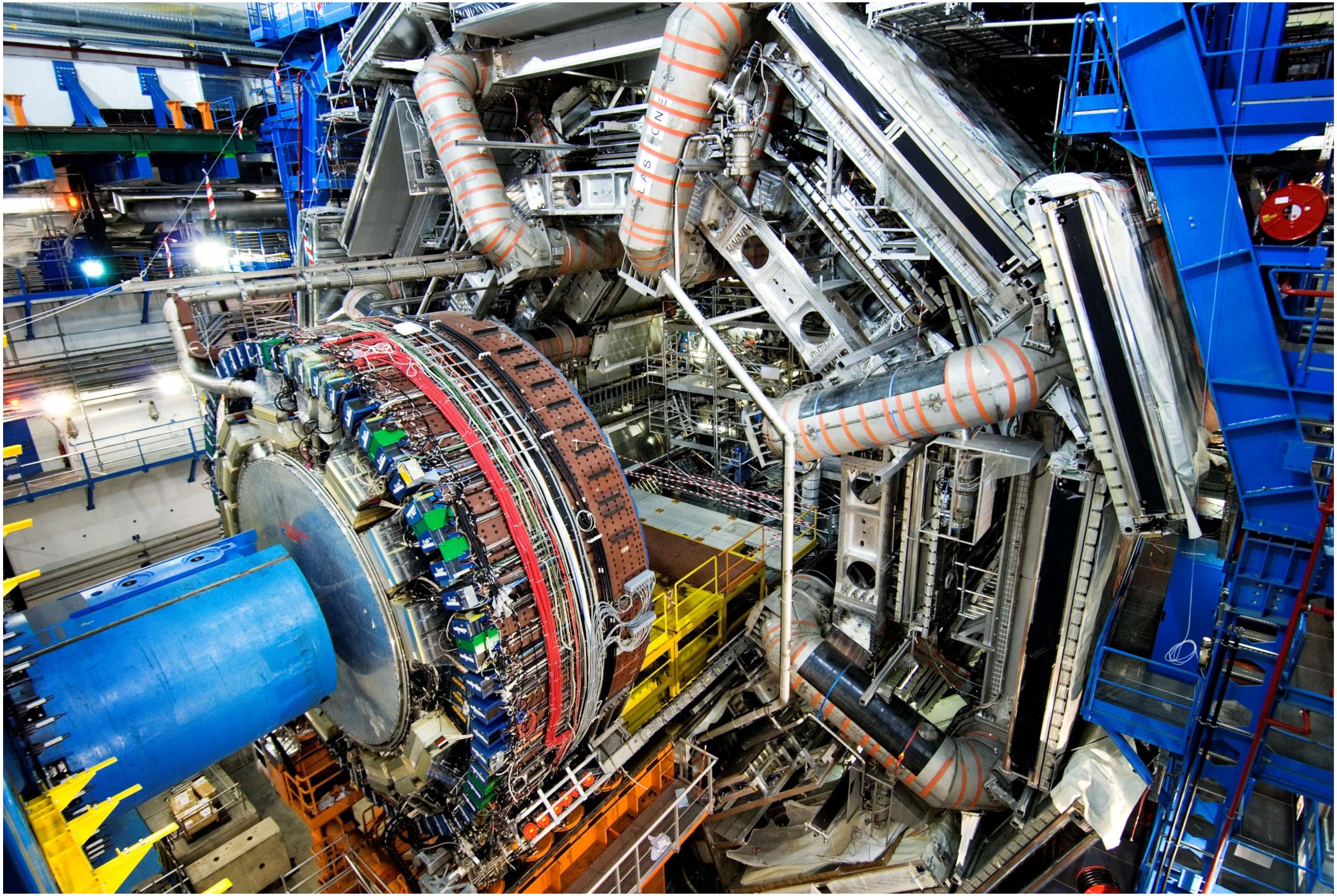
44 m long

22 m height

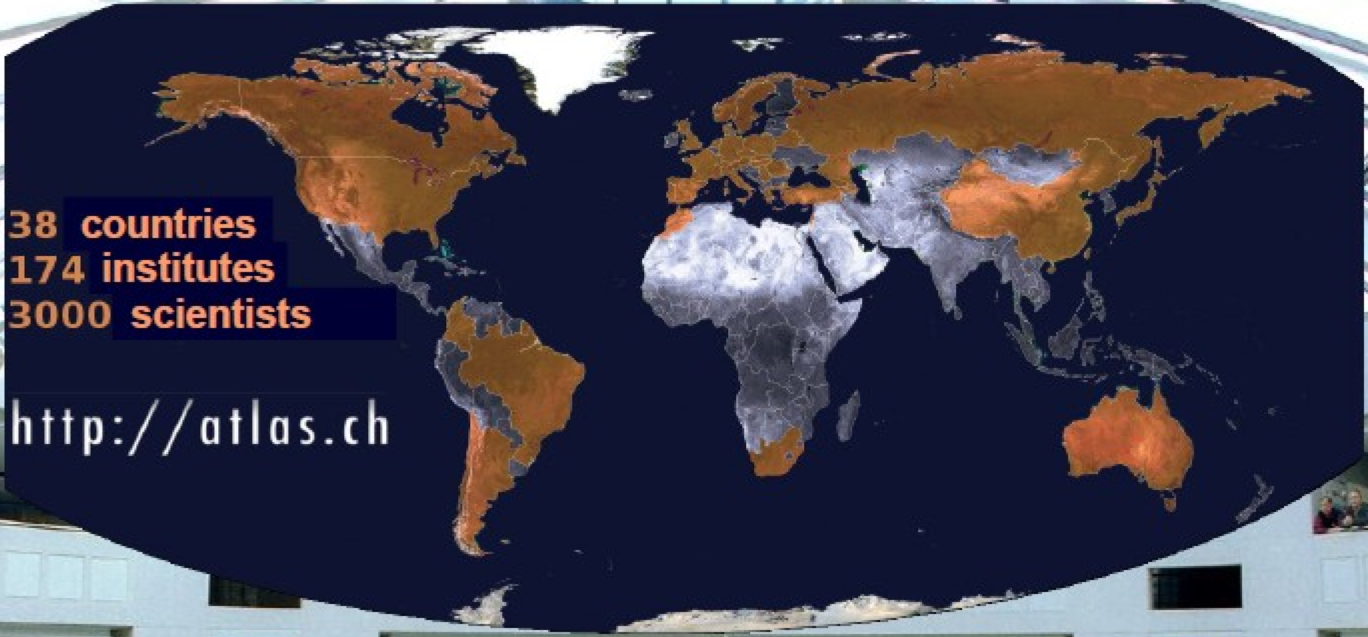
100M of readout channels

3000 km of cables

ATLAS



The ATLAS collaboration



ATLAS in France:

- 6 laboratories CNRS/IN2P3+Universities: Annecy, Clermont-Ferrand, Grenoble, Marseille, Orsay, Paris
- 1 laboratory CEA in Saclay

ATLAS in Marseille: ~45 people

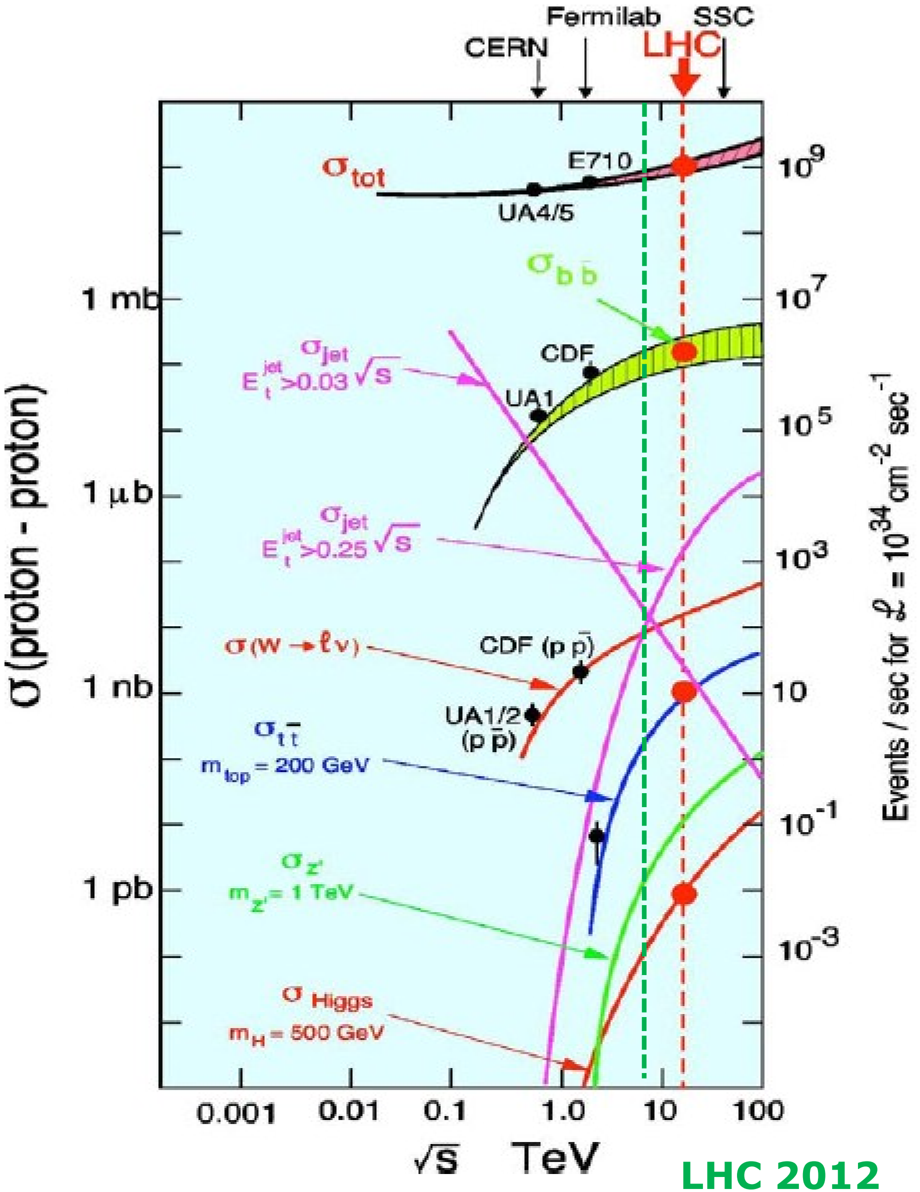
Experimental challenges

- Signal cross-sections very small compared to QCD background
  - important to identify and measure very precisely leptons, ɣ
  - measure also precisely jets from quarks/gluons !
  - need to identify b-jets and tau hadron (particles w/ lifetime)
  - ability to trigger is crucial !!!!
    - in 2012, 15 millions of bunch crossings per second in ATLAS and CMS, which means 600 millions of p-p collisions per second !
    - need to select only ~100 Hz of collisions

- Significant pile-up at LHC
  - high-granularity detectors
  - detectors with small integration time

- Radiation hardness of detectors
  - huge flux of particle → 10 Gy/y to 20000 kGy/y
  - most difficult: low radius, pixel vertex detectors

Typical cross-sections at LHC



LHC 2012

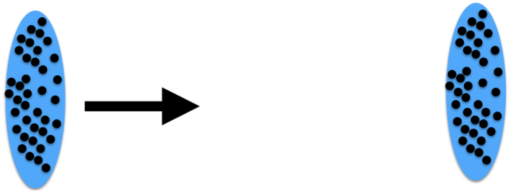
Production rates at nominal luminosity and design energy:

- inelastic pp: 10^9 Hz
- bb: 2.10^6 Hz
- tt: 8 Hz
- W→μν: 150 Hz
- Z→μμ: 15 Hz
- H(125 GeV): 0.2 Hz
- gluino/squark (1 TeV): 0.03 Hz

Large rates for interesting physics, but overwhelming backgrounds !

High-luminosity and pile-up

Major drawback with large # of protons / bunch:
→ extra collisions in same time window (25 ns) !

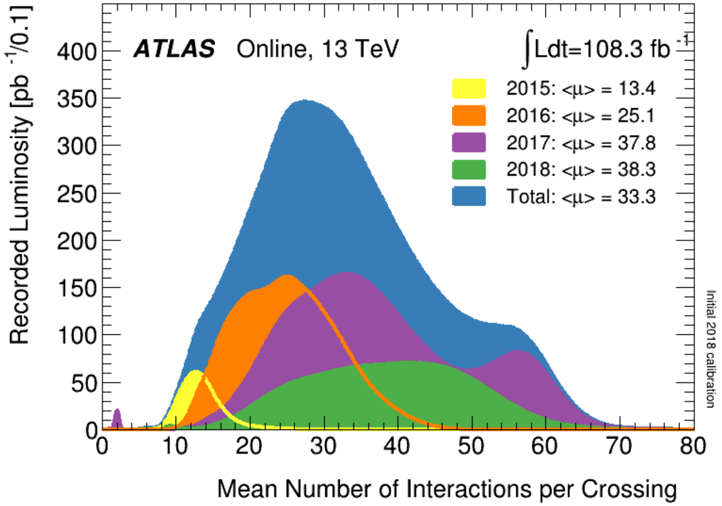


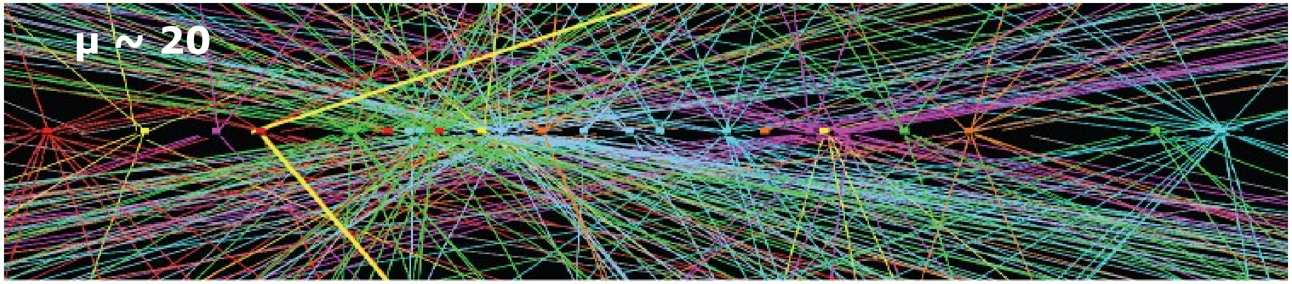
μ = mean number of minimum bias events piled-up in the same bunch crossing

$\mu = L_i \quad \sigma_{inel} / f$

σ_{inel} ~73 (80) mb for 8 (13) TeV

Design: μ~25, μ~40 these days !!





2010:
150 ns spacing
O(2) pile-up events

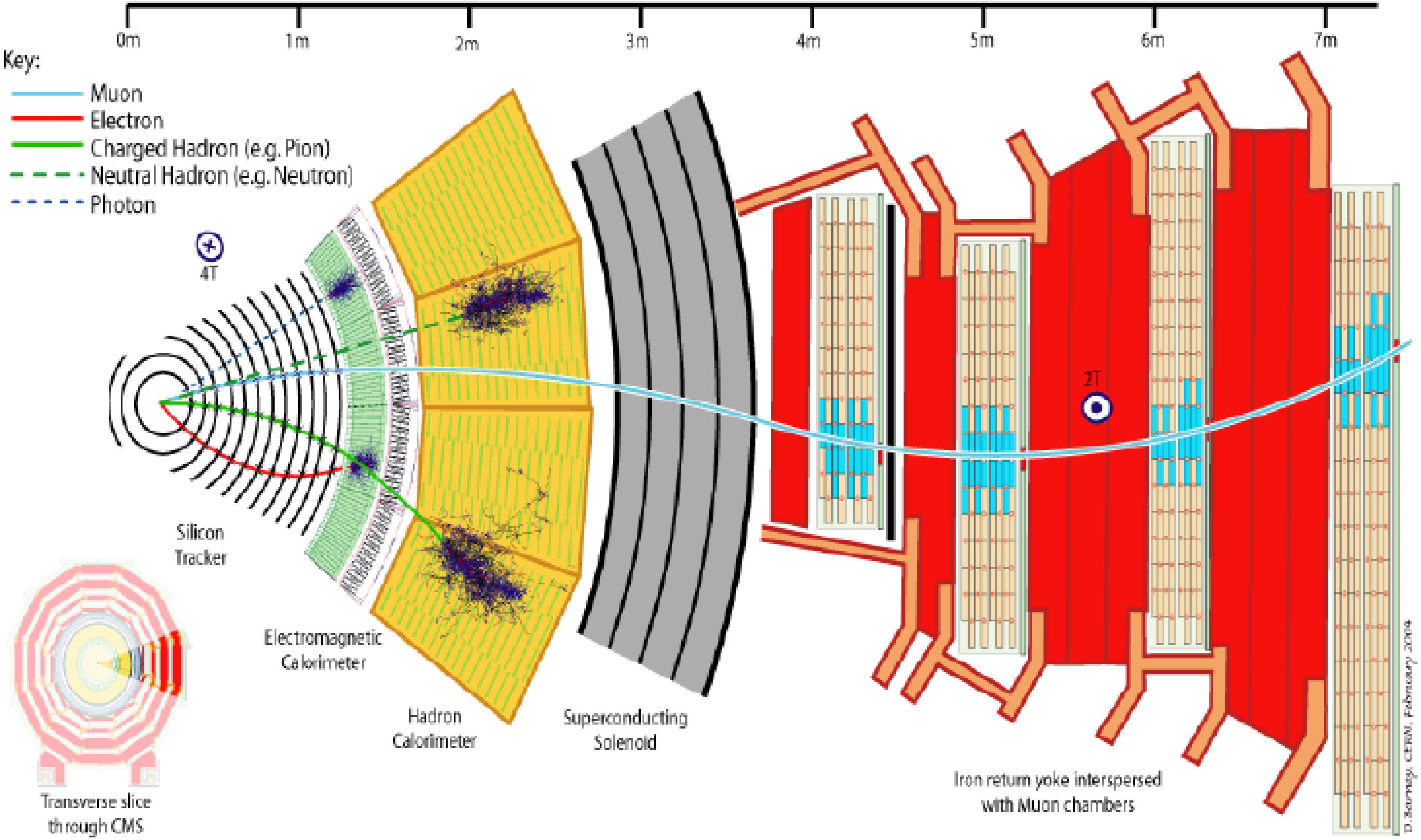
2011:
50 ns spacing
O(10) pile-up event

2012:
50 ns spacing
O(20) pile-up events

2017-2018:
25 ns spacing
O(40) pile-up events

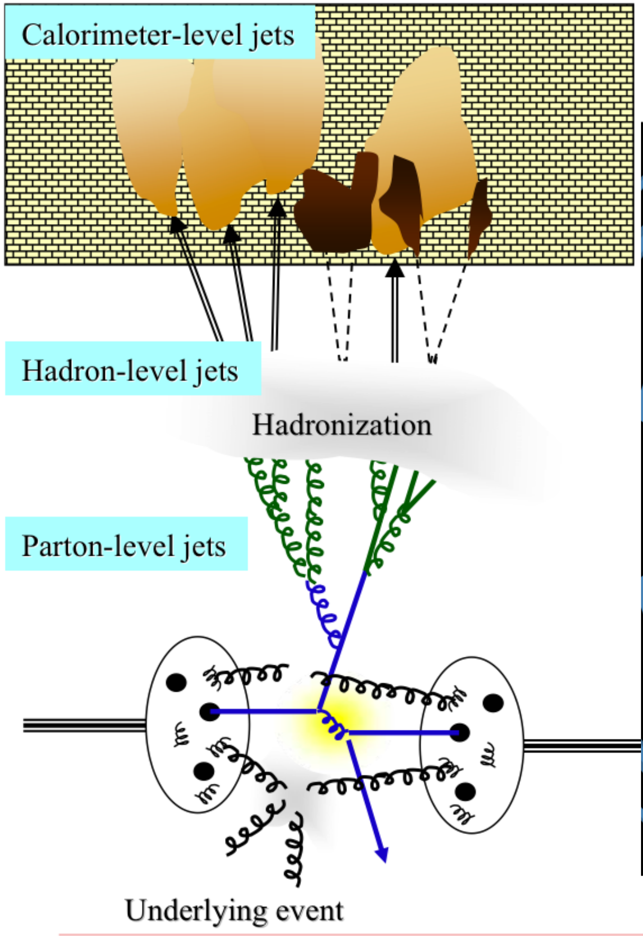
How to measure & identify particles ?

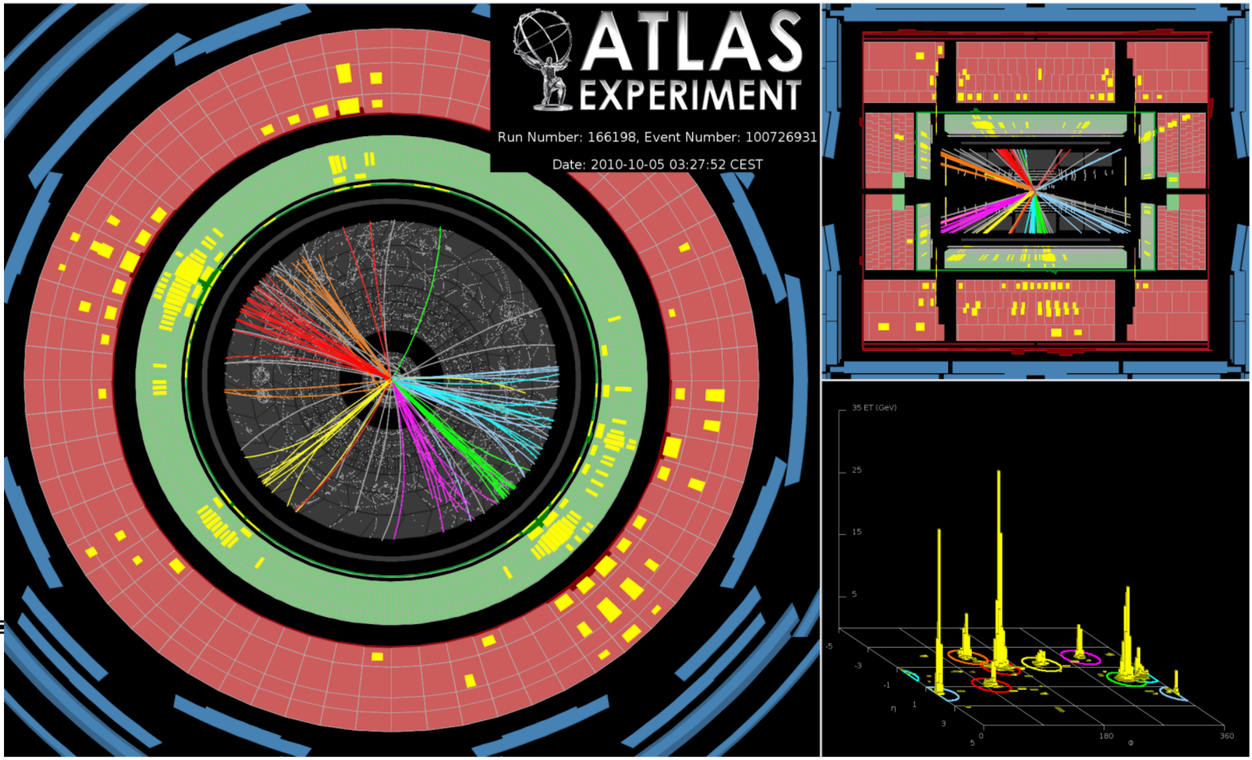
This is CMS !



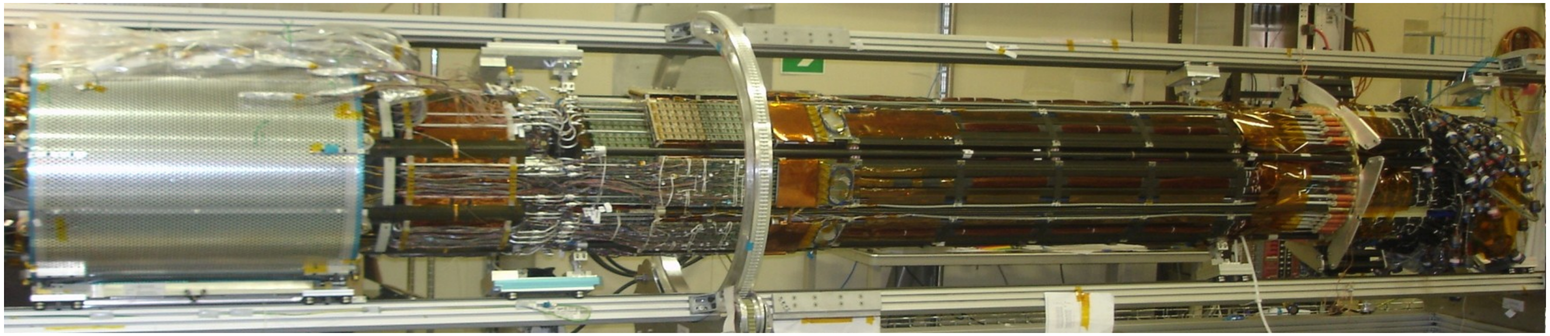
Typical objects in HEP, and jets

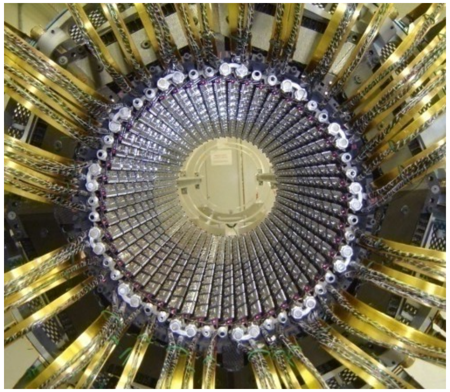
- Relatively-well defined: electron, muon, photon
- More delicate: jets from the hadronization of quark or gluon

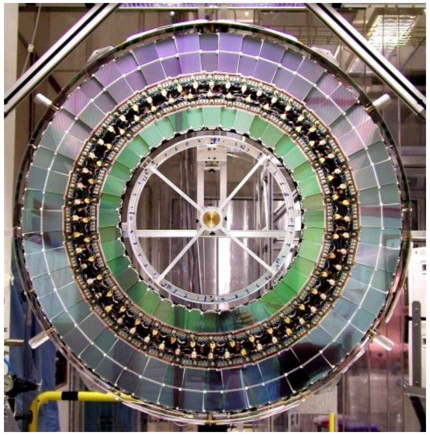


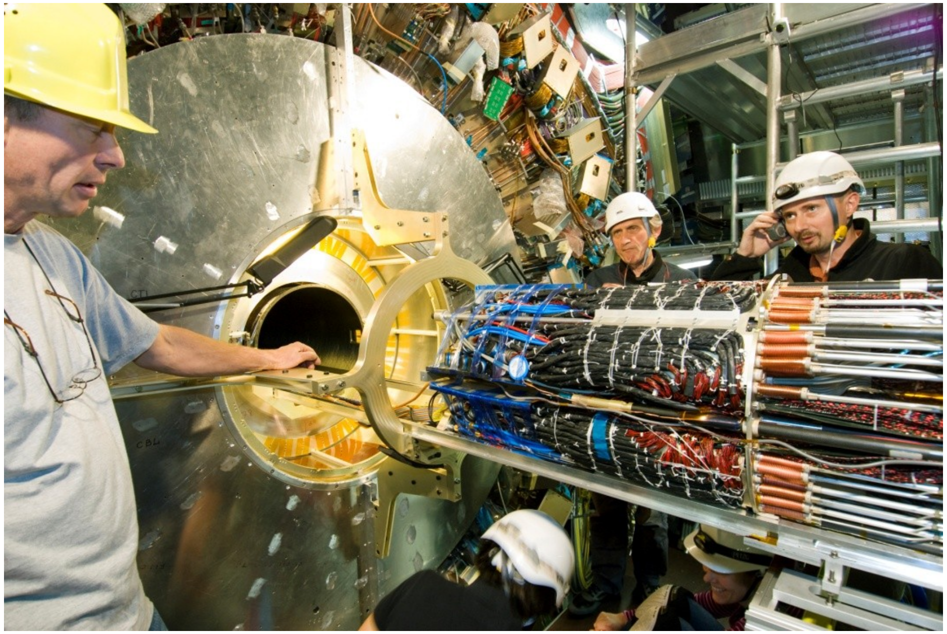


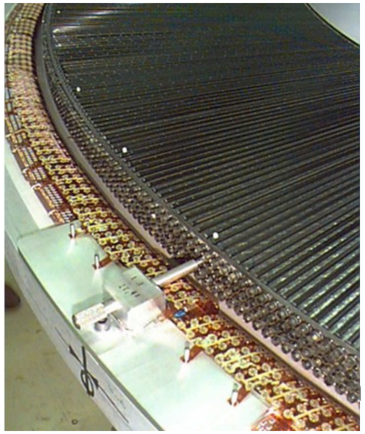
The ATLAS Inner Detector



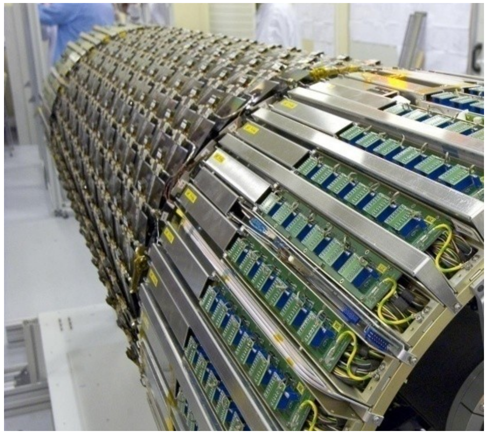




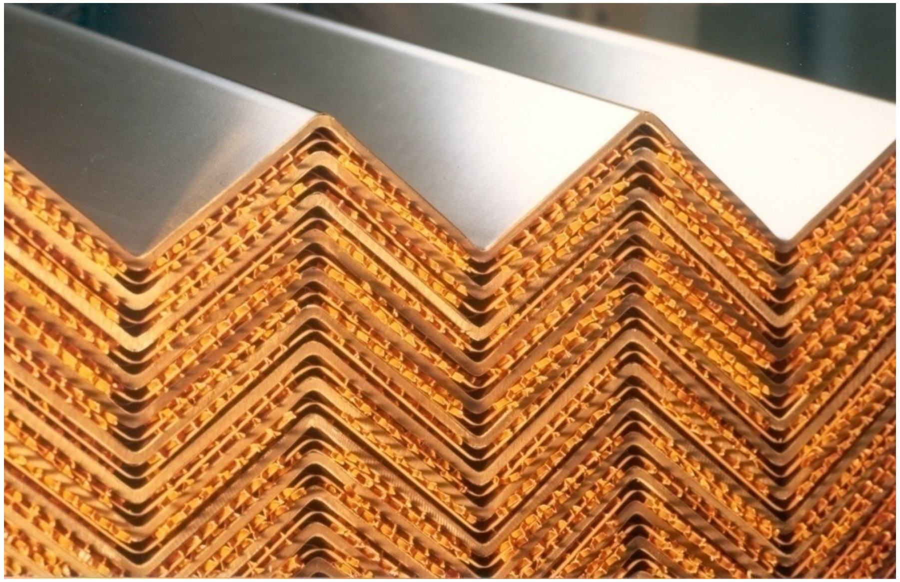


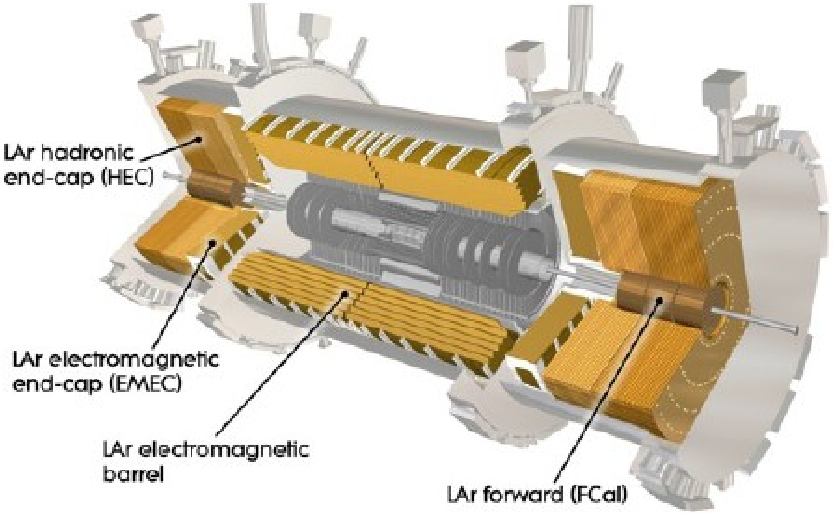


nt



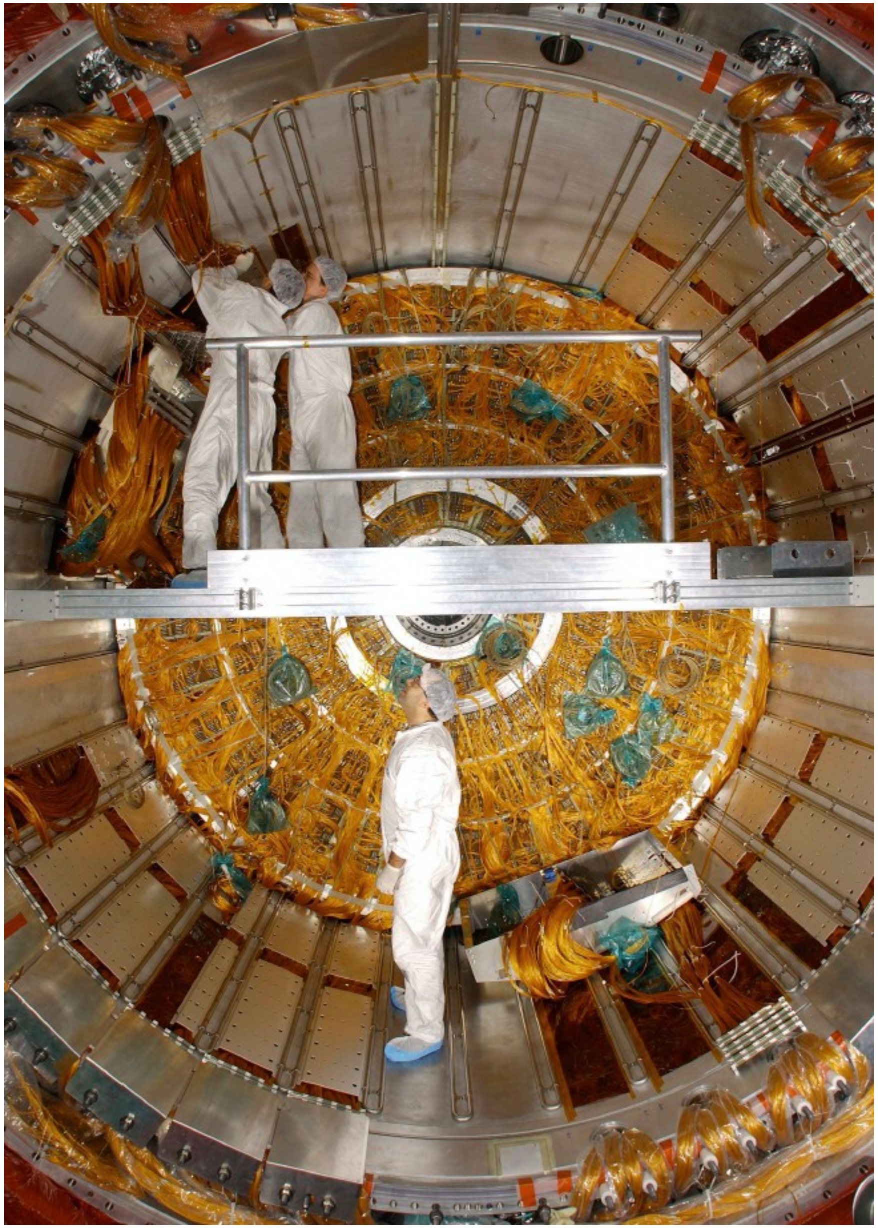
LAr calorimeters





Cryostat and muon chambers

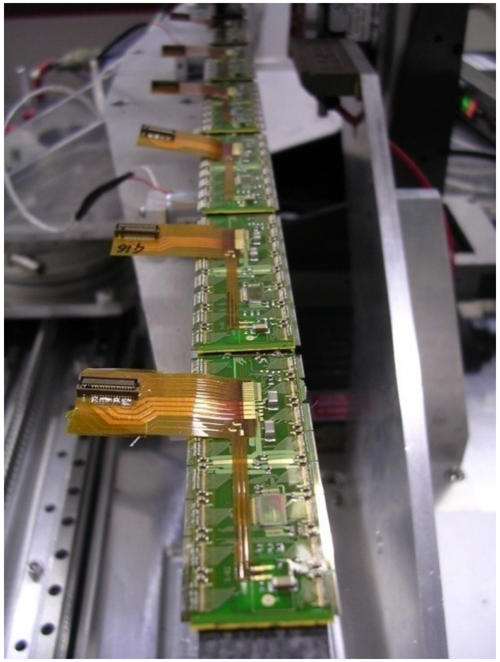
ATLAS: contributions from CPPM



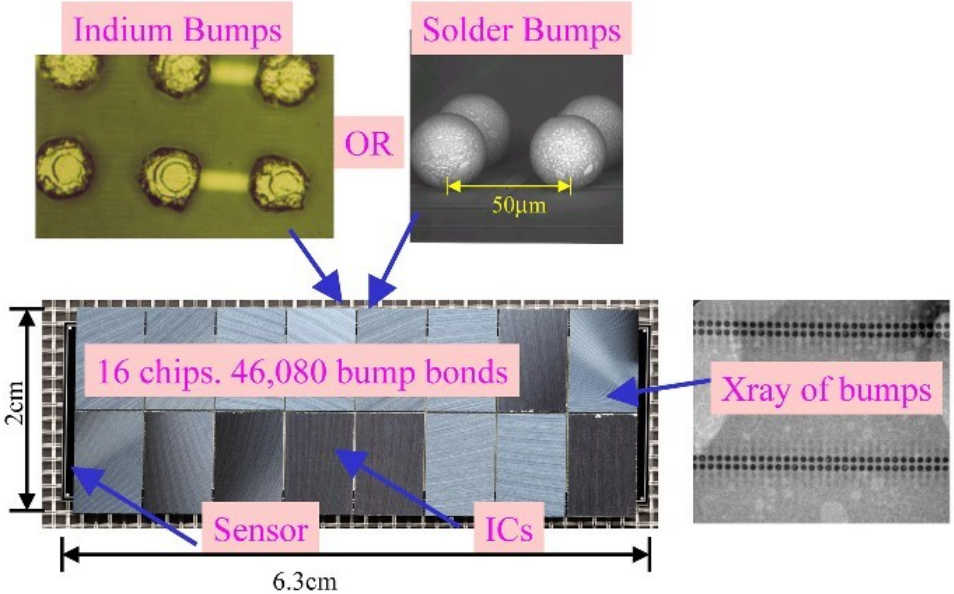
LAr calorimeter (endcaps)

Trigger L3

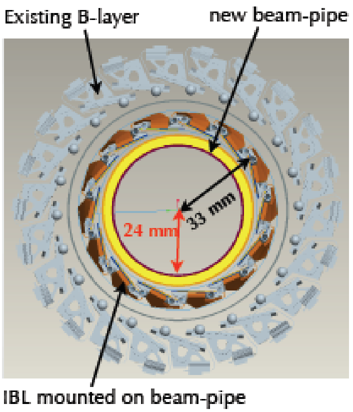
(no picture here)

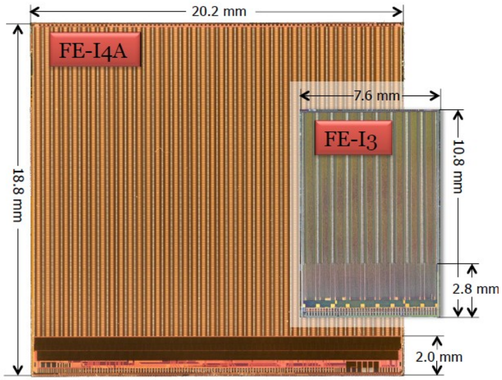


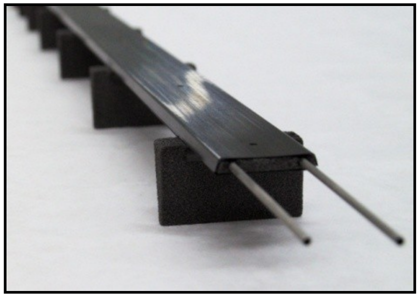
Pixel detectors:

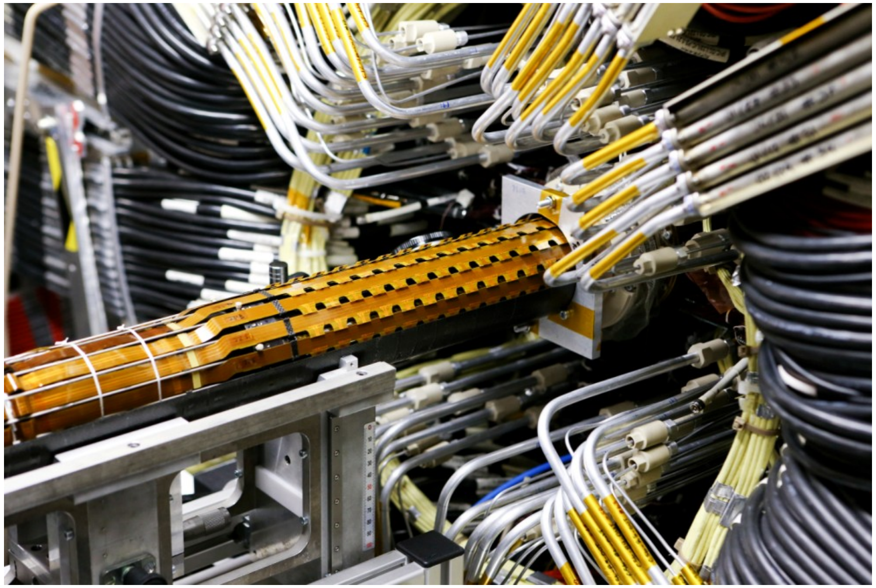


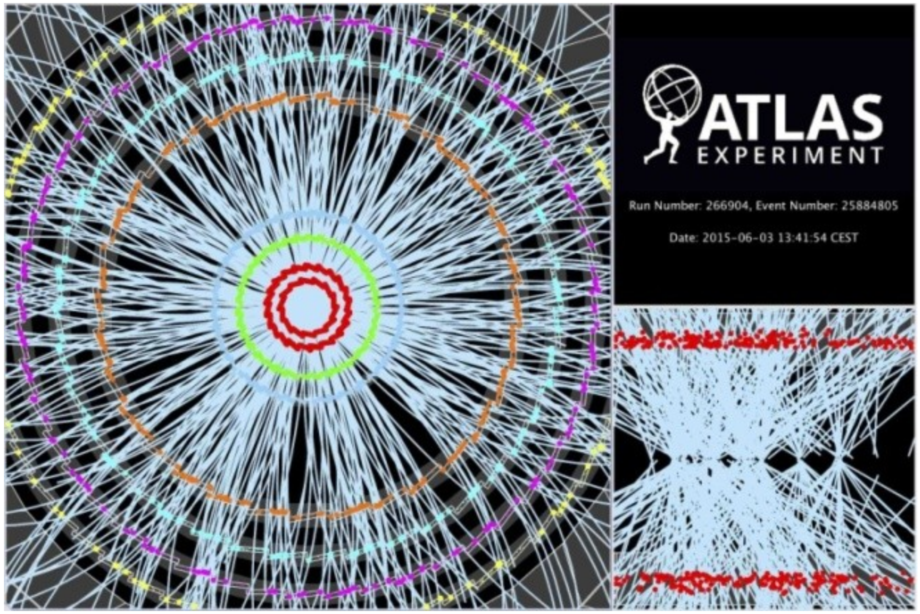
New for Run 2: 4th pixel layer IBL





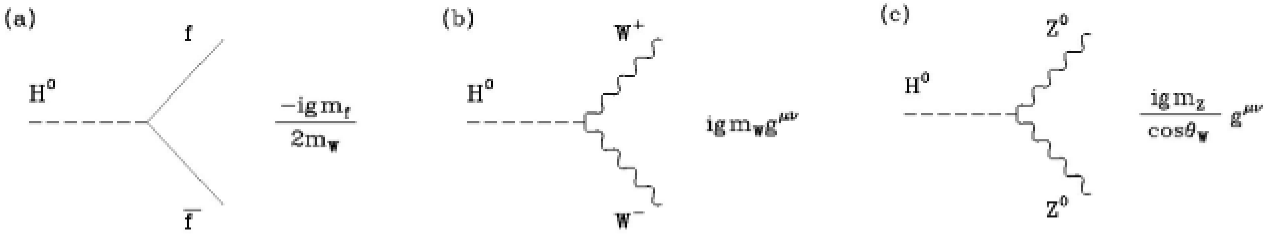






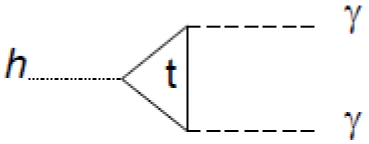
What you need for the Higgs boson discovery…

Knowledge about its couplings



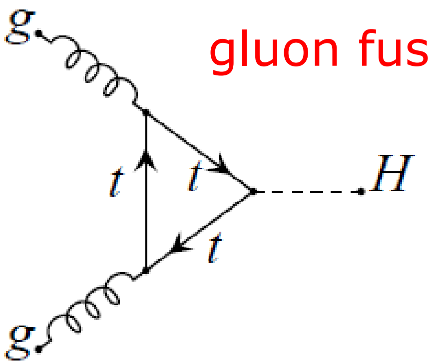
- Higgs boson couplings proportional to mass of the particles

- coupling to massless particles realized via loops of massive particles:
  - important for production at LHC: gluon fusion
  - important for decays at LHC: ɣɣ decay

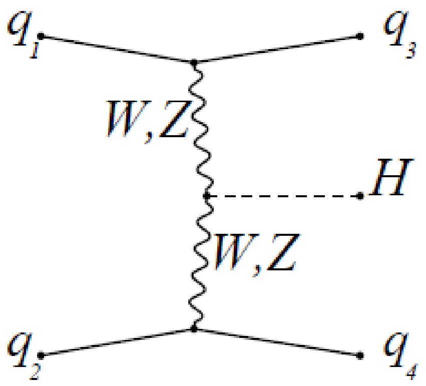


Higgs production at LHC

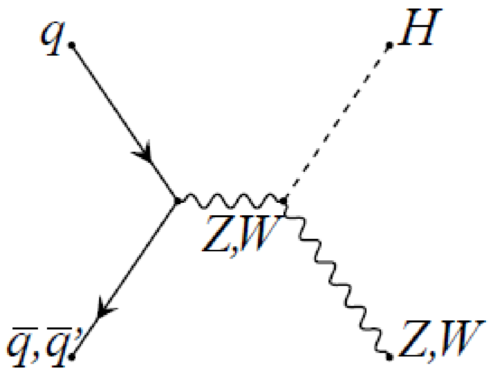
gluon fusion



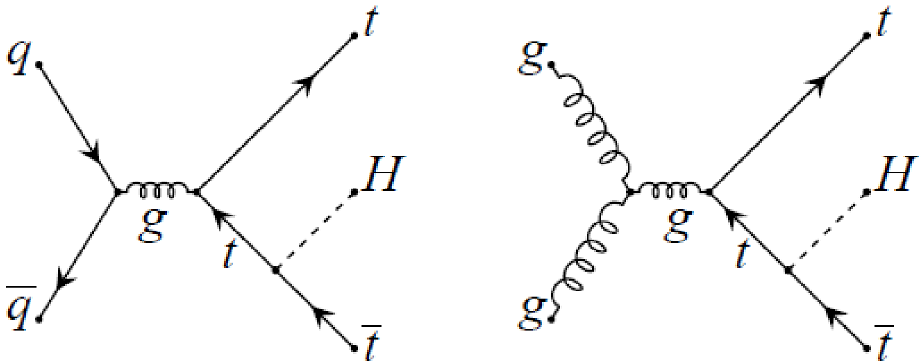
vector boson fusion



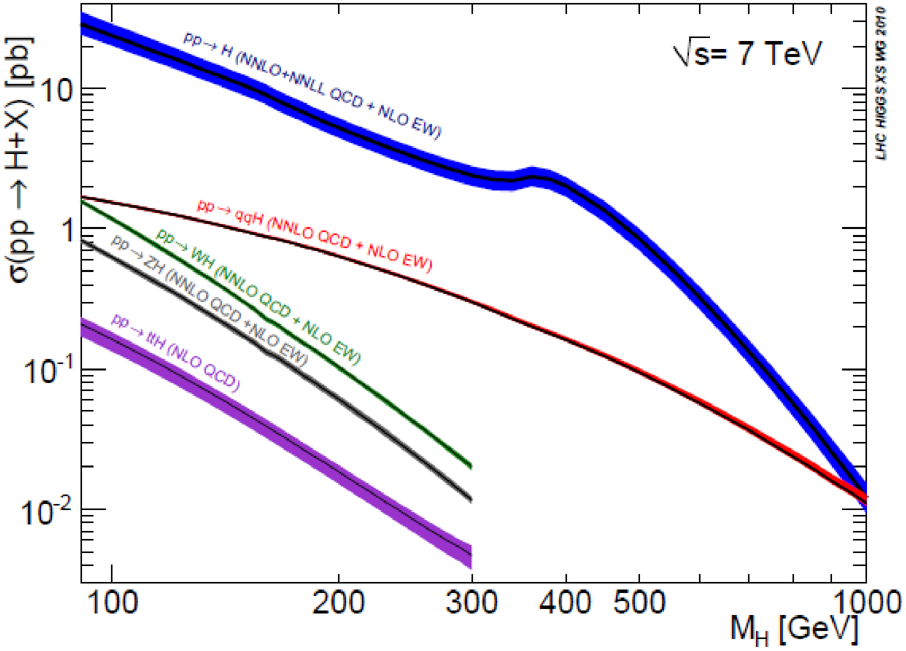
association with vector boson

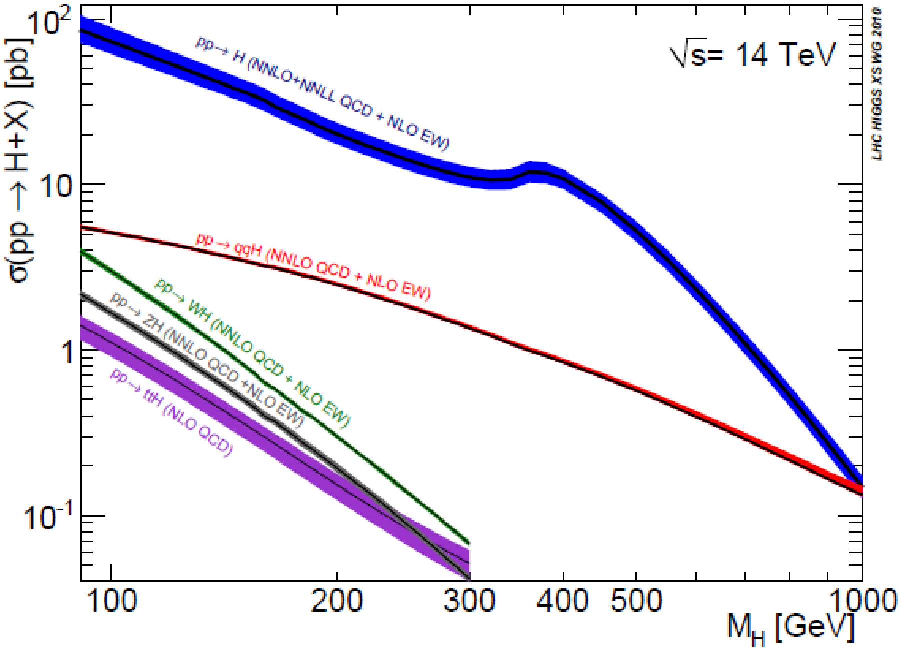


association with top quark pair



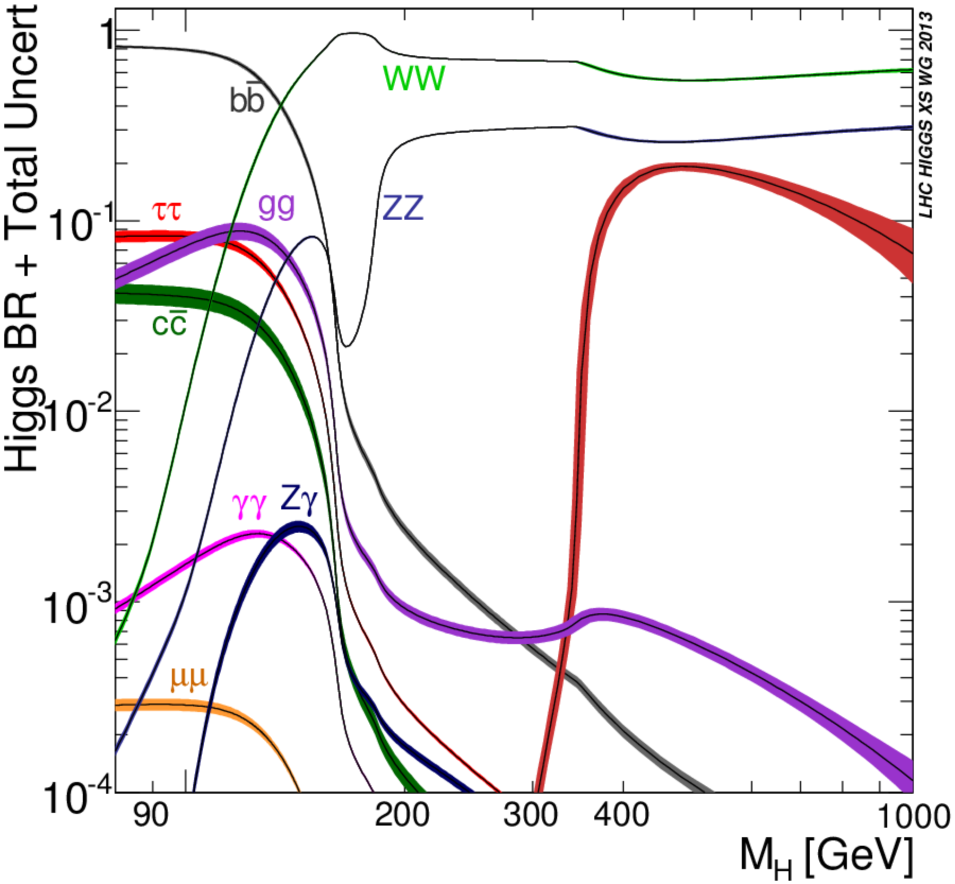
Production cross-sections at LHC

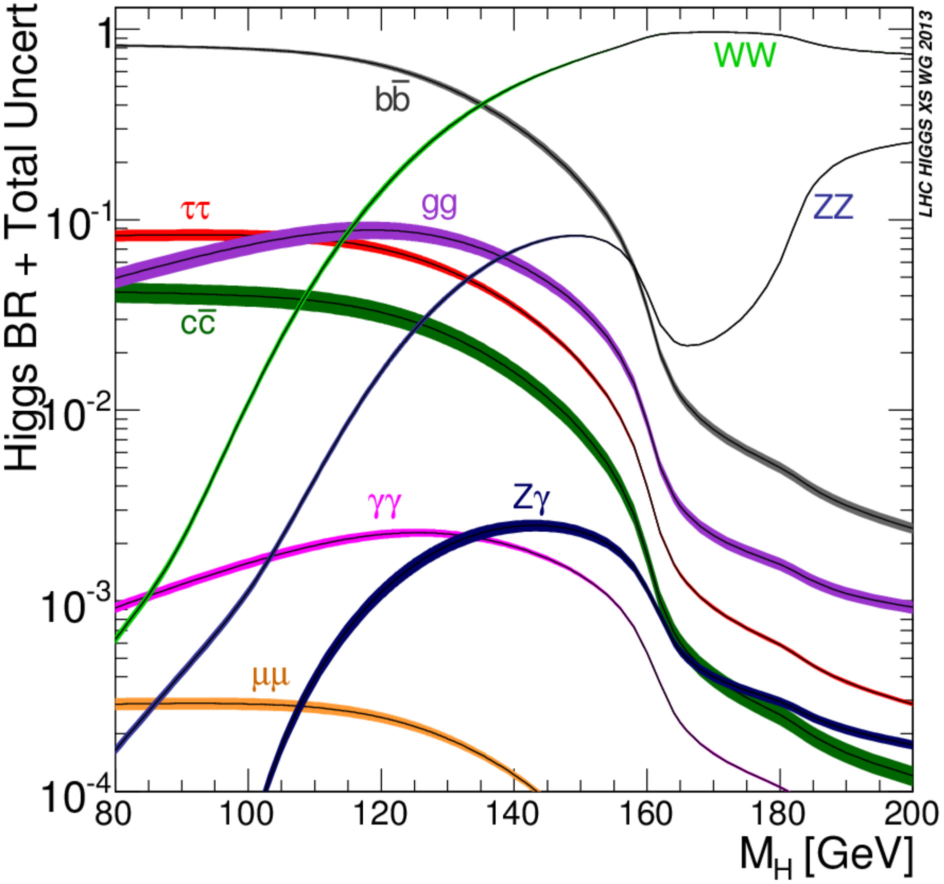




- gluon fusion vastly dominant (parton luminosities)
- VBF second largest production
- associated production costly
- significant increase of cross-section with √s (NB: true for bckgd also!)

SM Higgs decays

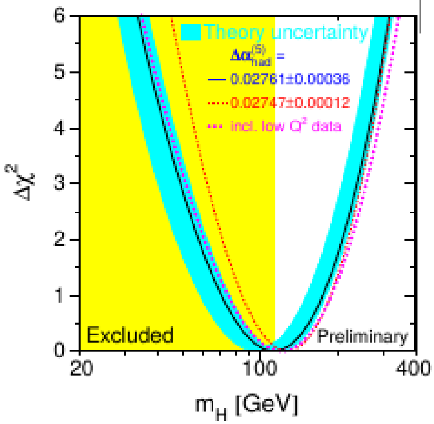




NB: the rate is not the whole story !

Some indications about its mass ?

Pré–LHC constraints on the SM Higgs sectior and on the Higgs mass:



- **Experimental constraints:**

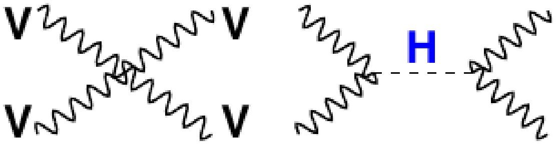
– indirect from global fit of EW precision data:

$\rm M_H = 92^{+34}_{-26}$ **GeV** $\Rightarrow \rm M_H \lesssim 160$ **GeV@95% CL**

– Direct searches at LEP and the Tevatron:

$\rm M_H > 114$ **GeV@95%CL and** $\neq 160-175$ **GeV**

- **Constraints from unitarity at high energies:**

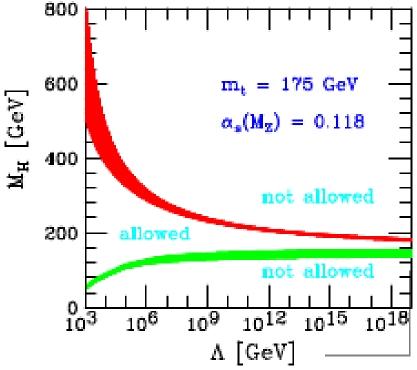


without Higgs: $|\rm A_0(vv \to vv)| \propto E^2/v^2$

including H with couplings as predicted:

$|\rm A_0| \propto M_H^2/v^2 \Rightarrow$ **the theory is unitary but needs** $\rm M_H \lesssim 700$ **GeV...**

- **Constraints from triviality and stability@high scale:**



coupling $\lambda = 2\rm M_H^2/v$ **evolves with energy**

– $\rm M_H$ **too large: coupling non perturbative**

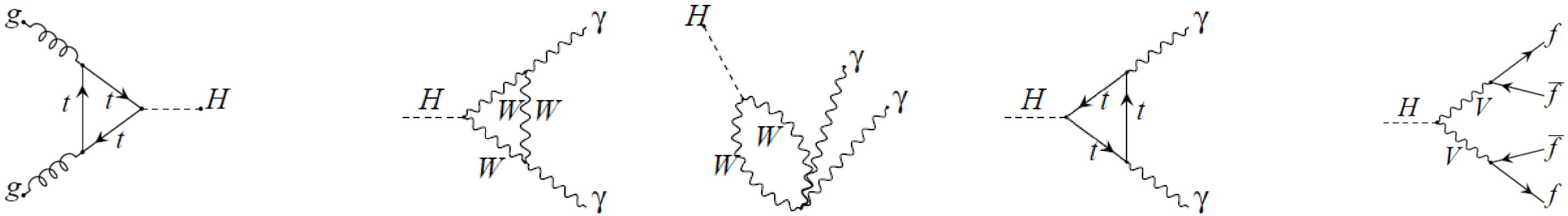
– $\rm M_H$ **too small: stability of the EW vaccum**

$\Lambda_{\rm C} \approx 1\ \rm TeV \Rightarrow 70 \lesssim M_H \lesssim 700\ GeV$

$\Lambda_{\rm C} \approx \rm M_{Pl} \Rightarrow 130 \lesssim M_H \lesssim 180\ GeV$

Finally, a search strategy:

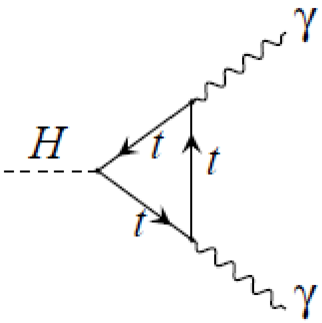
- Main channels to search for the Higgs boson at LHC:
  - mostly direct production, decay to $\gamma\gamma$
  - mostly direct production, decay to ZZ* then 4 leptons (golden channel)
  - mostly direct production, decay to WW*



- Other channels, important to confirm its nature:
  - other production modes (VBF, associate productions with W/Z and tt)
  - decays to fermions: tau-tau, bb, μμ

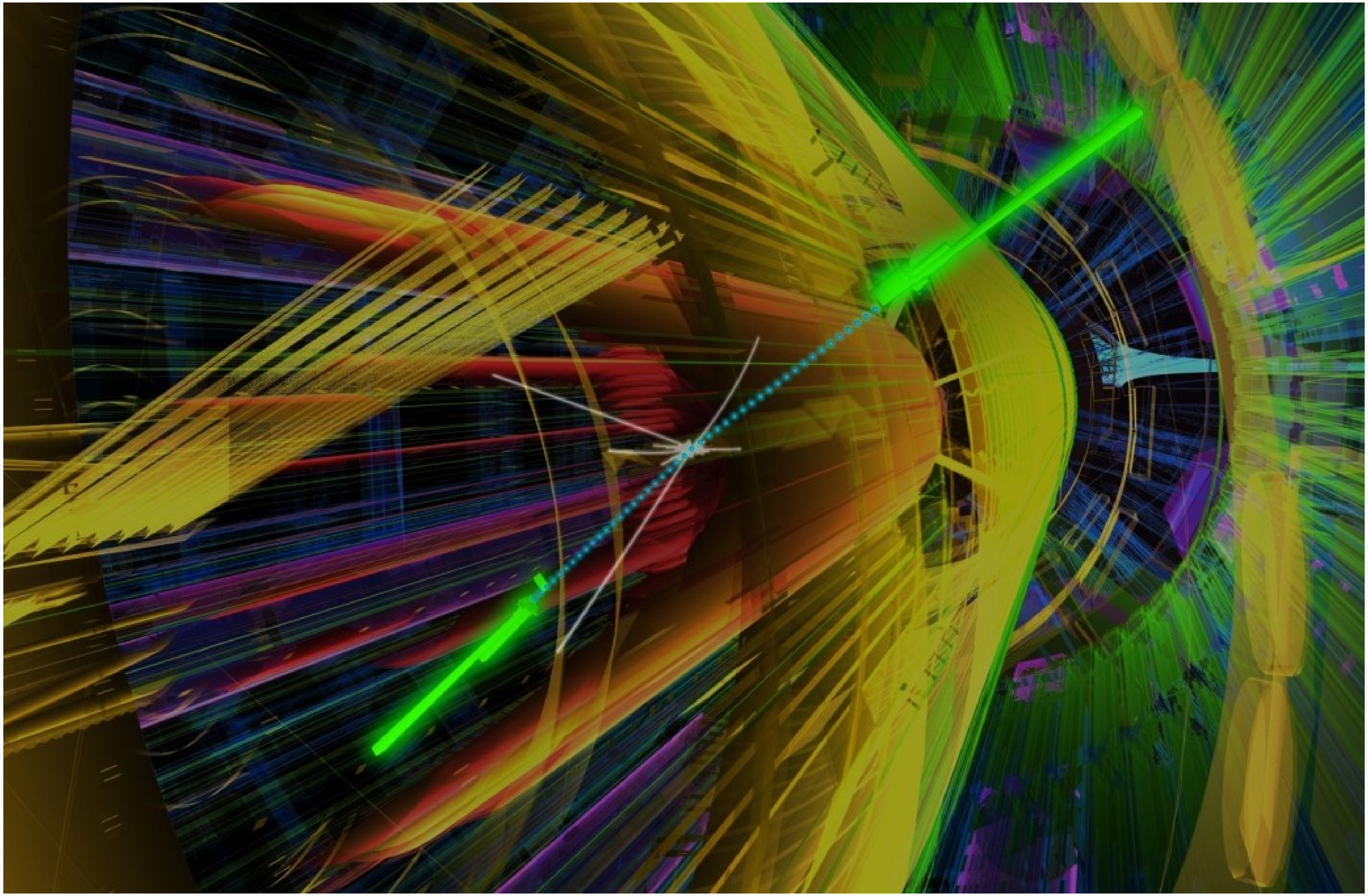
(discussed further today)

The H→ γγ case



H→γγ: strategy

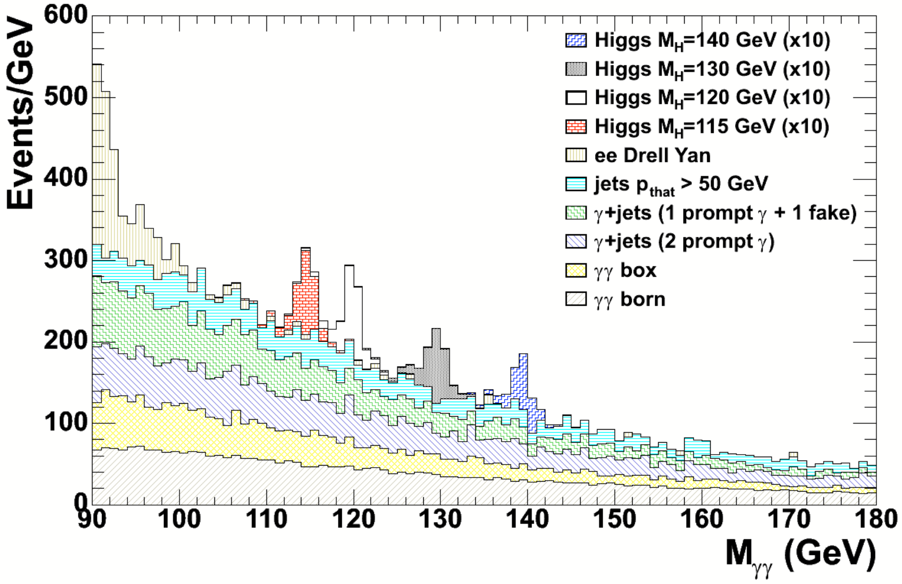
striking signature: look for 2 isolated photons in the detector



H→γγ: strategy

look for 2 photons

$m_{\gamma\gamma}^2 = m_H^2 = 2E_1E_2\,(1-\cos\alpha)$

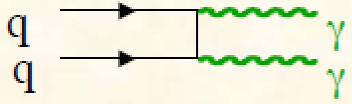


- rare mode: 0.2% for m_H=120 GeV
- narrow resonance: ~100 MeV (natural width: 4 MeV)
- precise reconstruction of diphoton invariant mass
- large non-resonant background

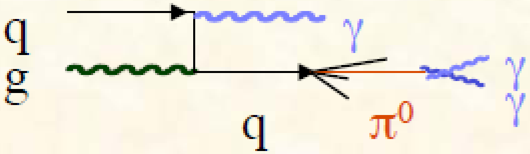
➔observation of a peak above continuous background

Main backgrounds:

γγ irreducible background



γ-jet and jet-jet (reducible)



$\sigma_{\gamma j+jj} \sim 10^6\,\sigma_{\gamma\gamma}$ with large uncertainties

→ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

Main exp. tools for background suppression:

- photon identification
- γ / jet separation (calorimeter + tracker)

Requirements on photon ID

Photon energies

Di-photon opening angle

$$M_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}\left(1-\cos(\alpha)\right)$$

$$\frac{\delta M}{M} = \frac{1}{2}\left(\frac{\delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\delta\alpha}{\tan(\alpha/2)}\right)$$

Photon energy resolution

Angular resolution

Requirements for the Higgs search:

- precise reconstruction of the photon energy
- precise reconstruction of the photon direction
- very good discrimination between photons and jets

Electromagnetic Calorimetry in 2mn

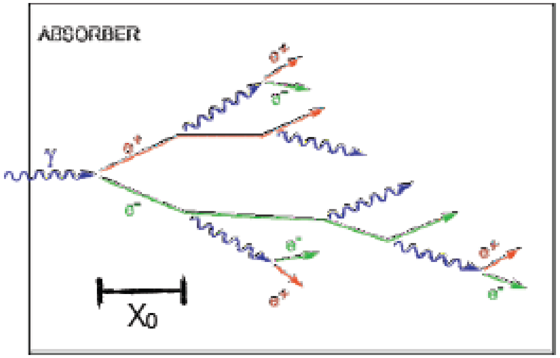
Calorimetry:

- energy measurement via total absorption of particles (signal $\propto$ E)
- energy deposited: heat, ionization, Cherenkov light, atom excitation
- homogeneous calorimeters (CMS): absorber = active medium
- sampling calorimeters (ATLAS): sandwich absorber/active medium

Electromagnetic showers:

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung



Pair production:

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm²]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

Bremsstrahlung:

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\, \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]

Sampling calorimetry

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

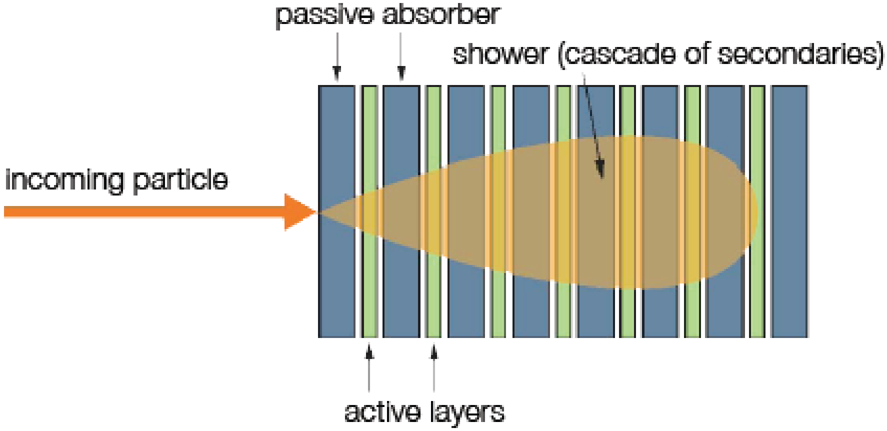
Absorber materials:
[high density]

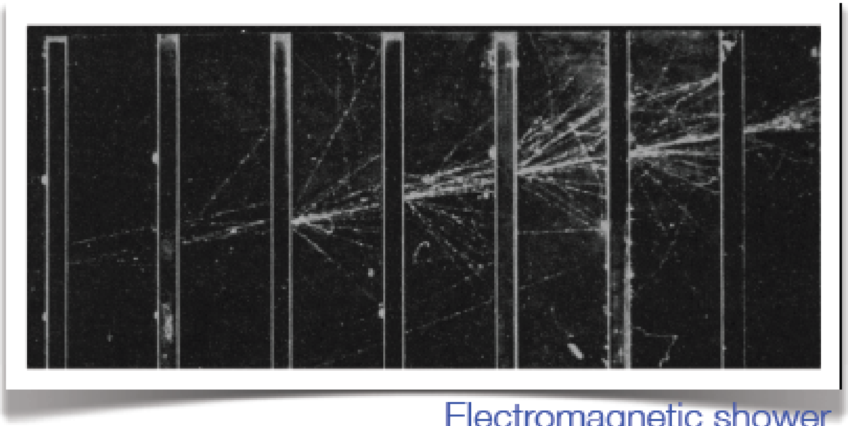
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

Active materials:

- Plastic scintillator
- Silicon detectors
- Liquid ionization chamber
- Gas detectors

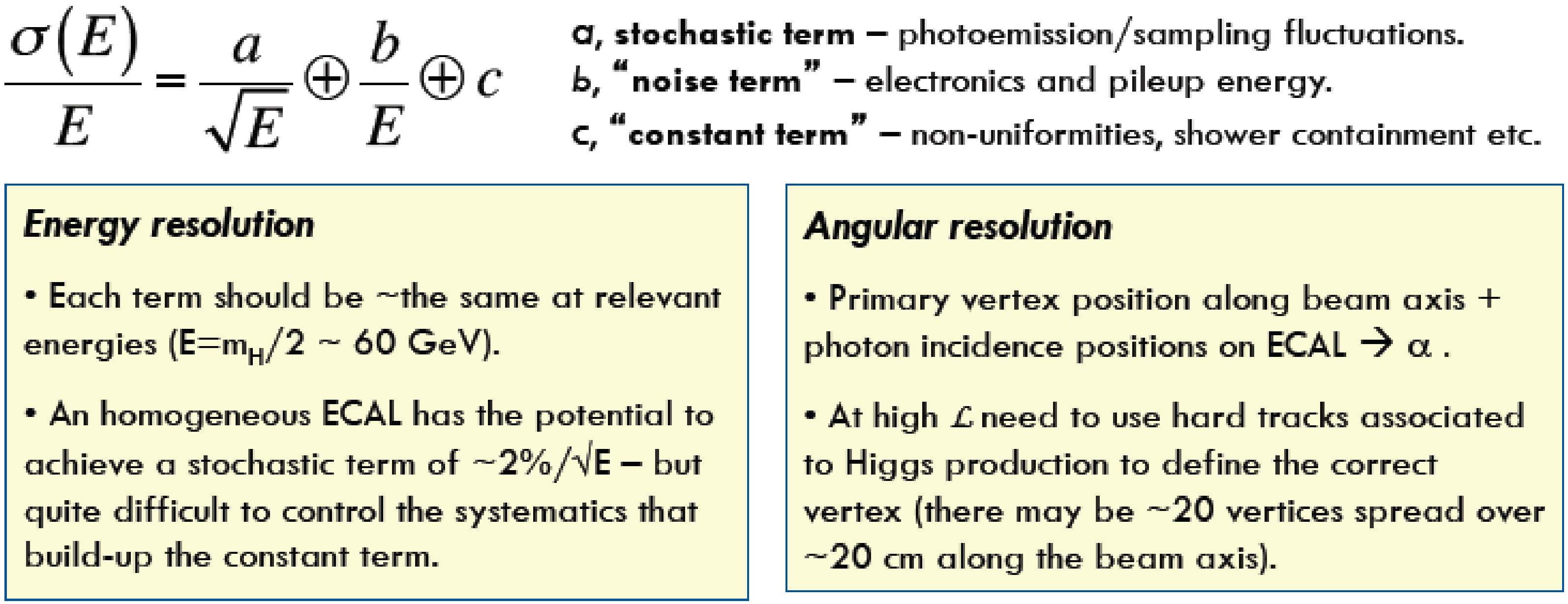
Scheme of a sandwich calorimeter





Electromagnetic shower

Energy and angular resolution



$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a, stochastic term – photoemission/sampling fluctuations.
b, **"noise term"** – electronics and pileup energy.
c, **"constant term"** – non-uniformities, shower containment etc.

Energy resolution

- Each term should be ~the same at relevant energies ($E=m_H/2$ ~ 60 GeV).
- An homogeneous ECAL has the potential to achieve a stochastic term of ~2%/√E – but quite difficult to control the systematics that build-up the constant term.

Angular resolution

- Primary vertex position along beam axis + photon incidence positions on ECAL → α .
- At high $\mathcal{L}$ need to use hard tracks associated to Higgs production to define the correct vertex (there may be ~20 vertices spread over ~20 cm along the beam axis).

Goals for ATLAS:

- a ~ 10%
- b ~ 300 MeV
- c ~ 0.7%

Goals for CMS:

- a ~ 2.5% (5.7% in endcap)
- b < 200 MeV (800 in endcap)
- c ~ 0.55%

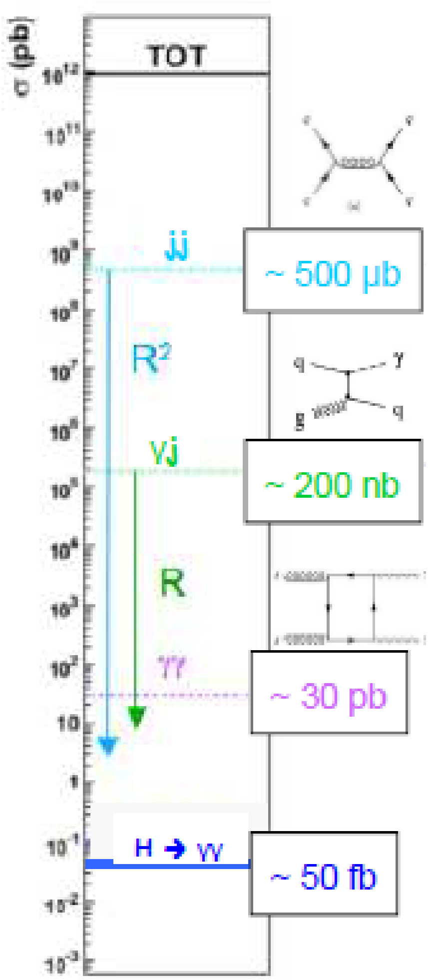
Angular resolution (similar): ~ 50 mrad / √E

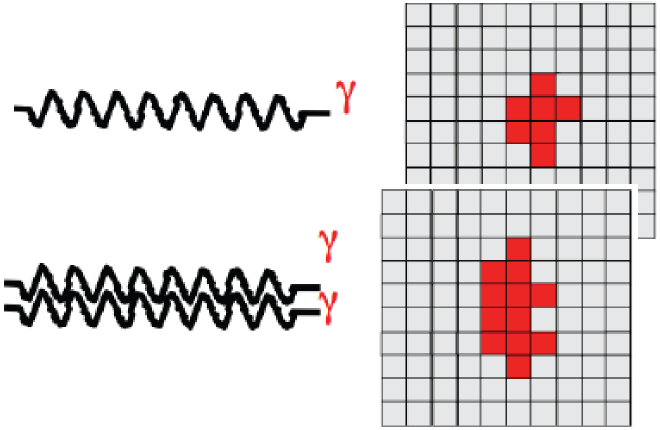
Photon ID with ATLAS

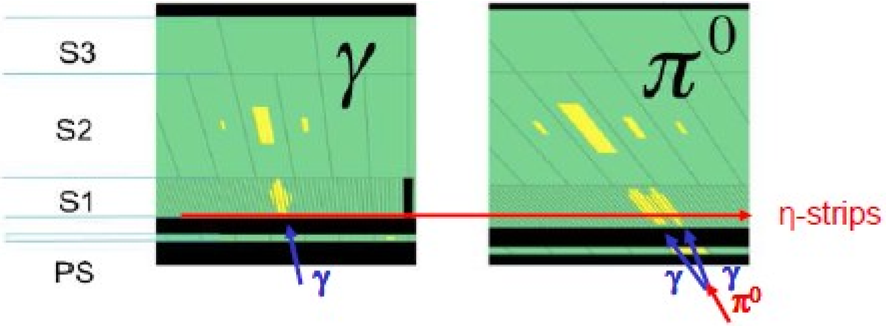
- Large jet-jet and ɣ-jet backgrounds
- Cross-section not well known

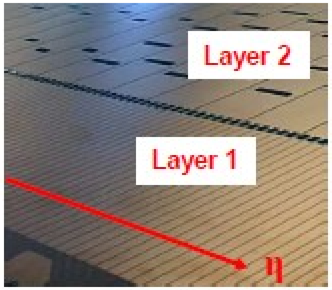
- Rejection needed: R ~10^4
- Main problem: π^0 versus ɣ

➔ high granularity for calorimeter 1st layer



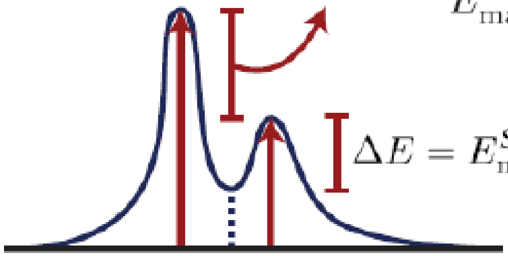




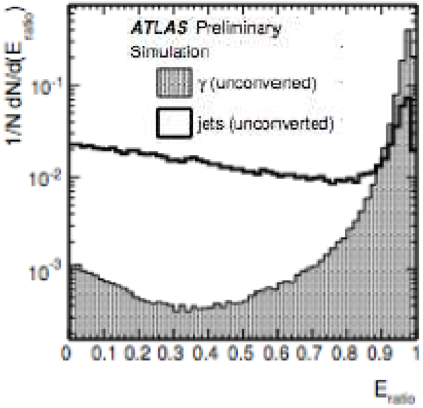


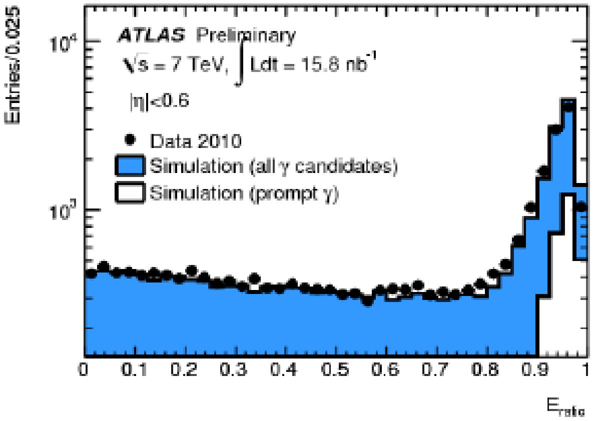
Photon ID performance

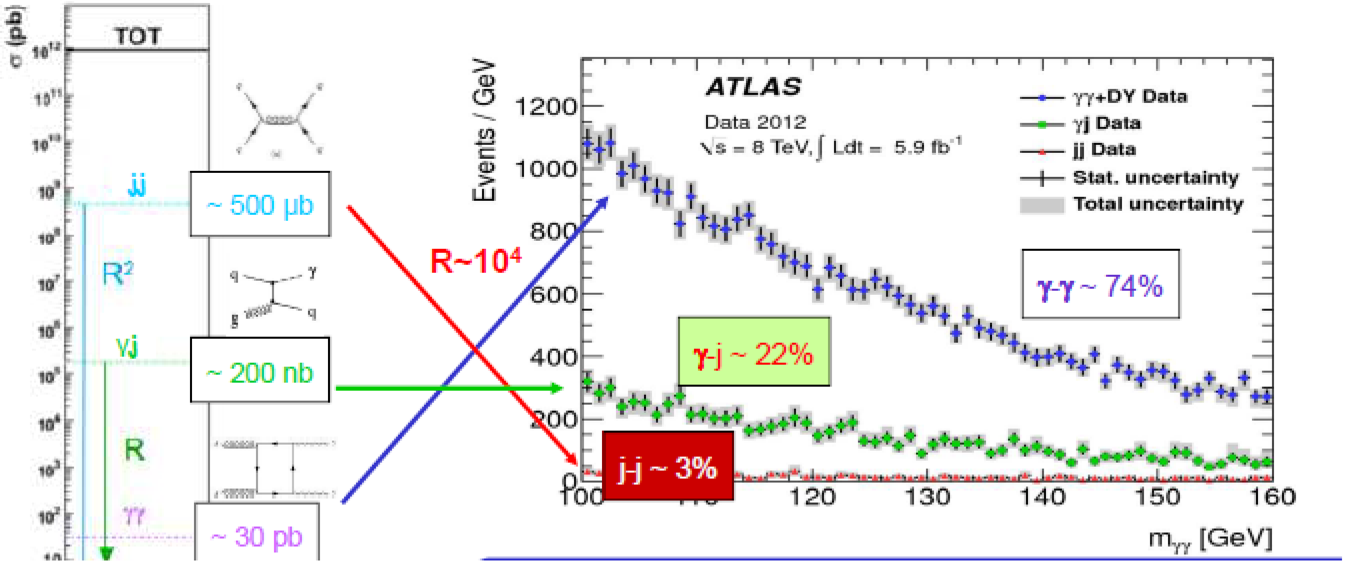
$$E_{\rm ratio} = \frac{E^{S1}_{\max,1} - E^{S1}_{\max,2}}{E^{S1}_{\max,1} + E^{S1}_{\max,2}}$$



$$\Delta E = E^{S1}_{\max,2} - E^{S1}_{\min}$$



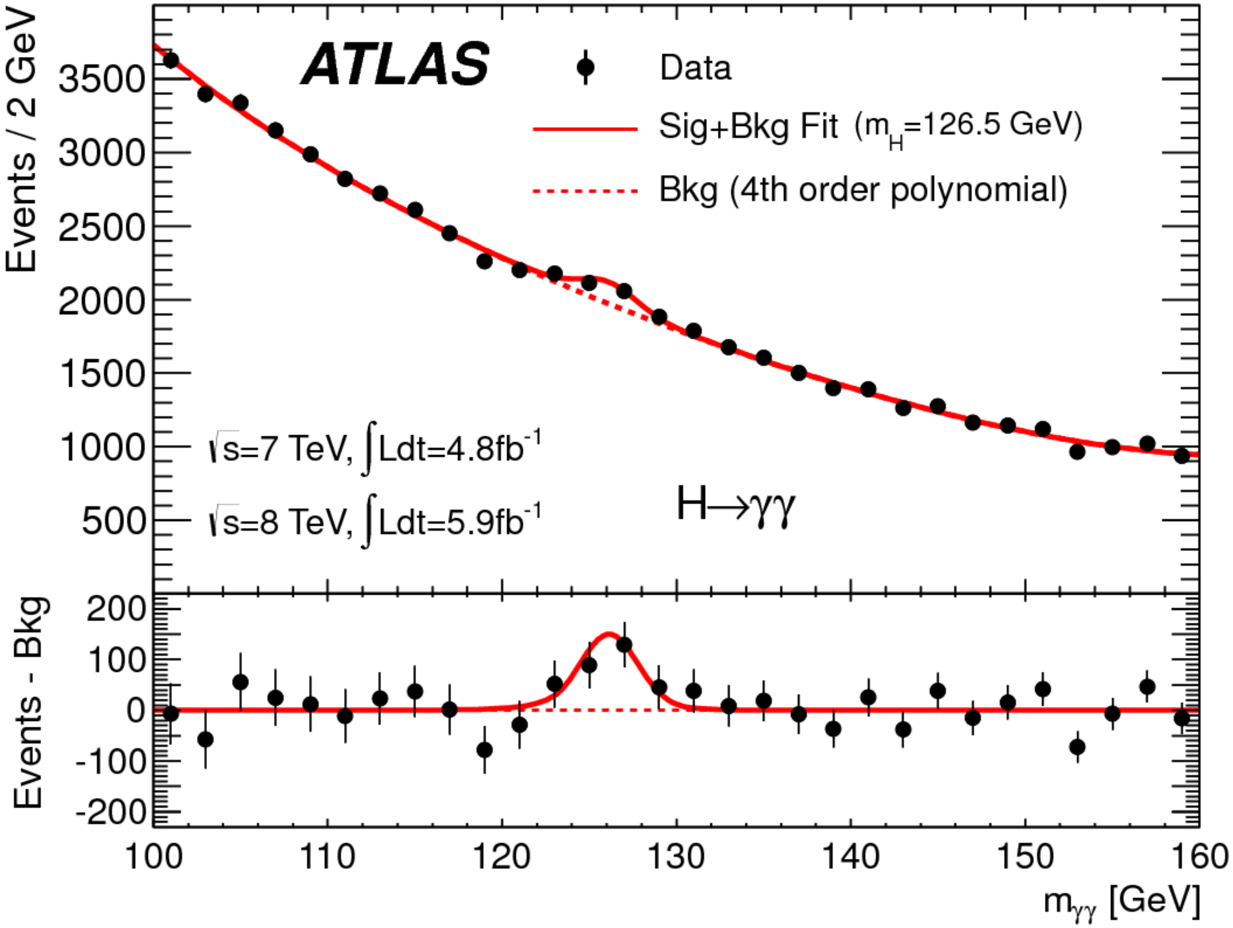




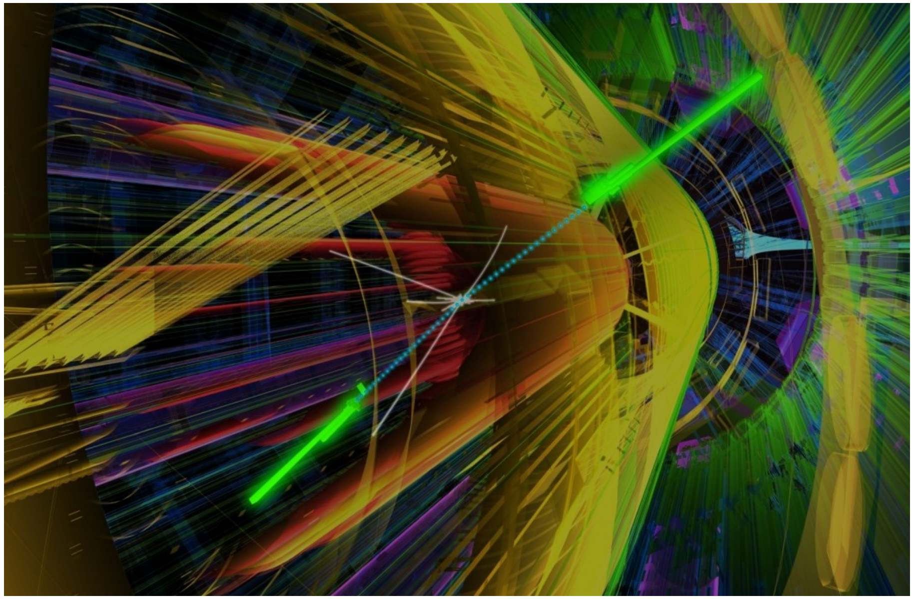
Excès dans le canal H→γγ

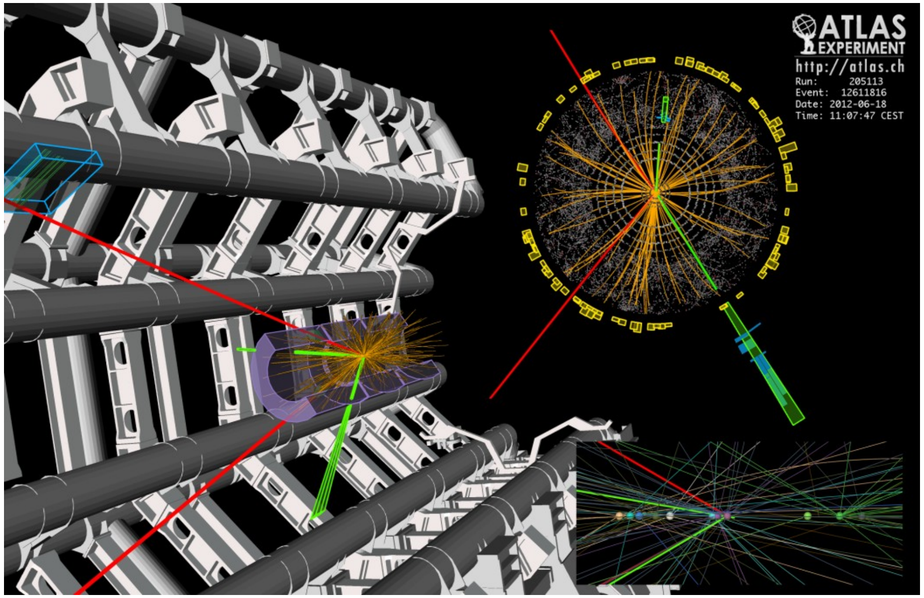
$$m_{\gamma\gamma} = \sqrt{2 E_1 E_2 (1 - \cos\theta)}$$

July 2012

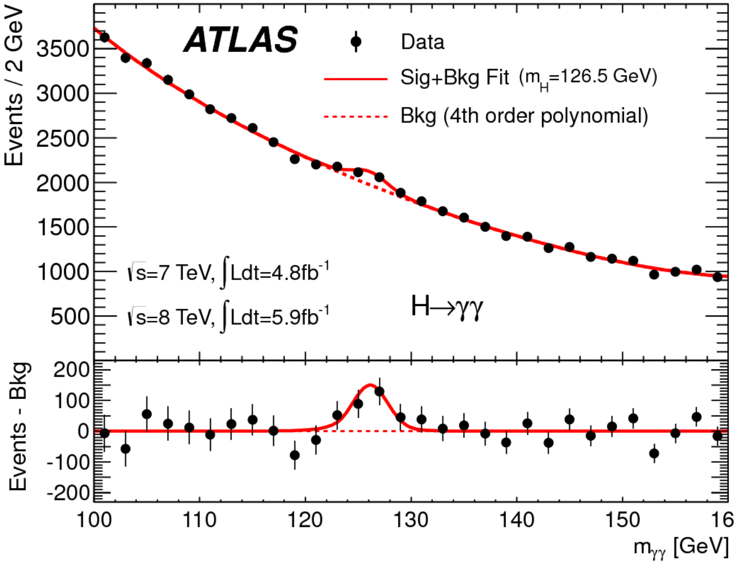


Discovery of the Higgs boson

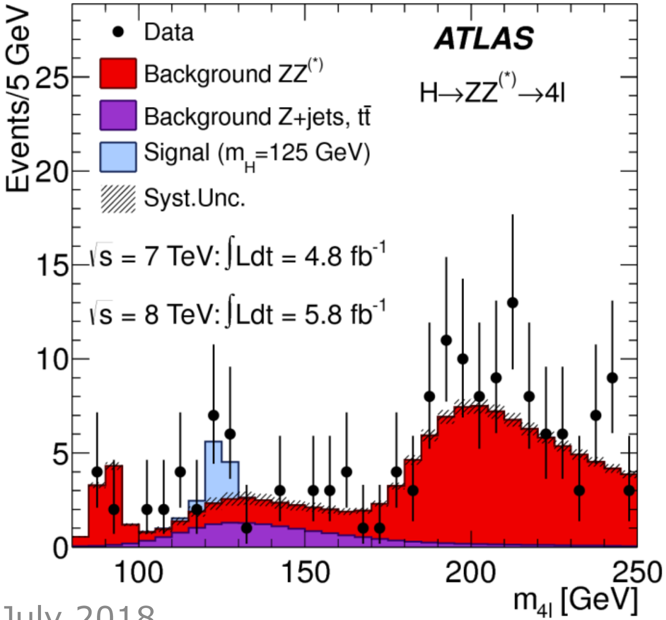




H→γγ

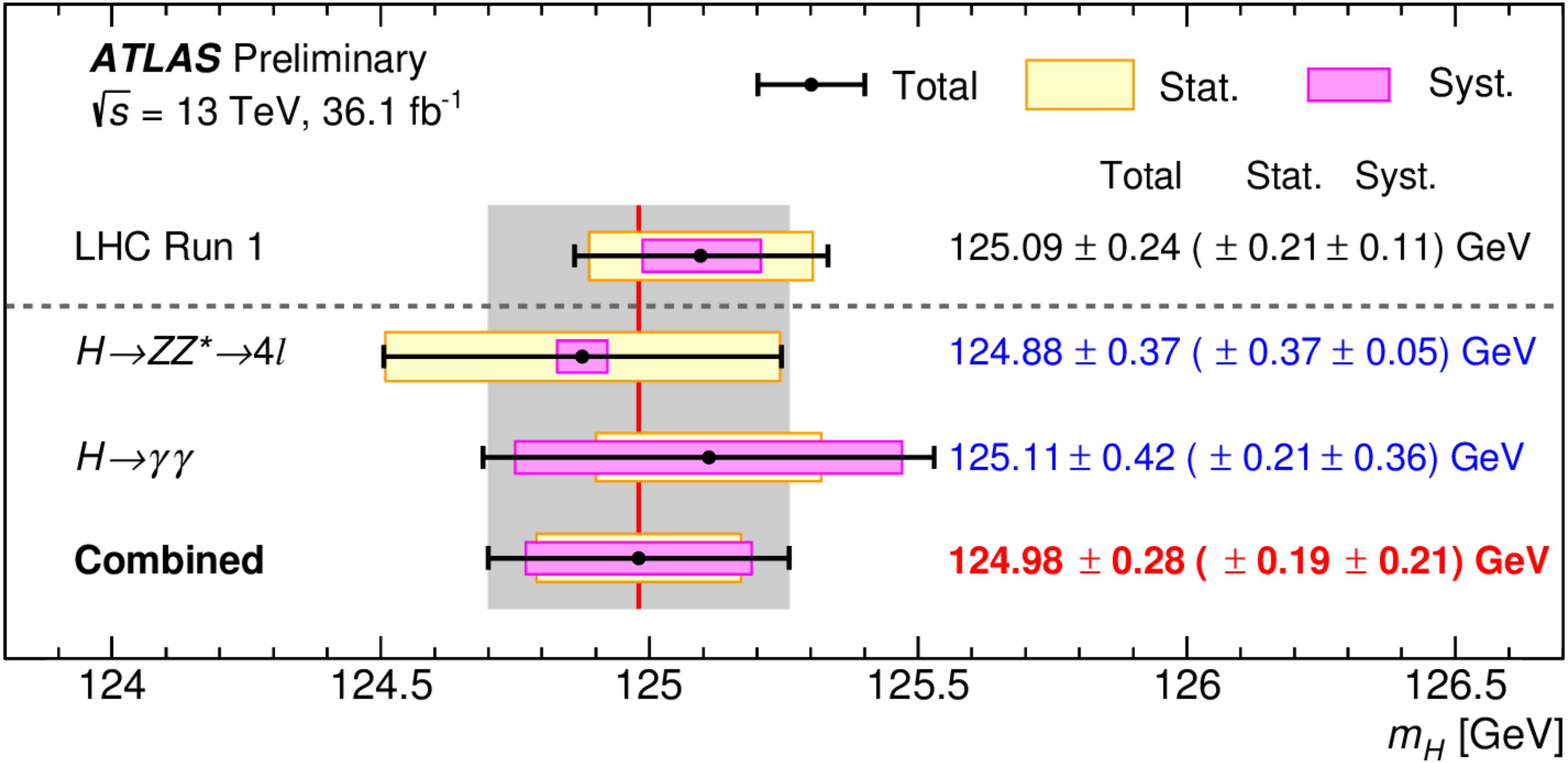


H→ZZ*→4(e/μ)



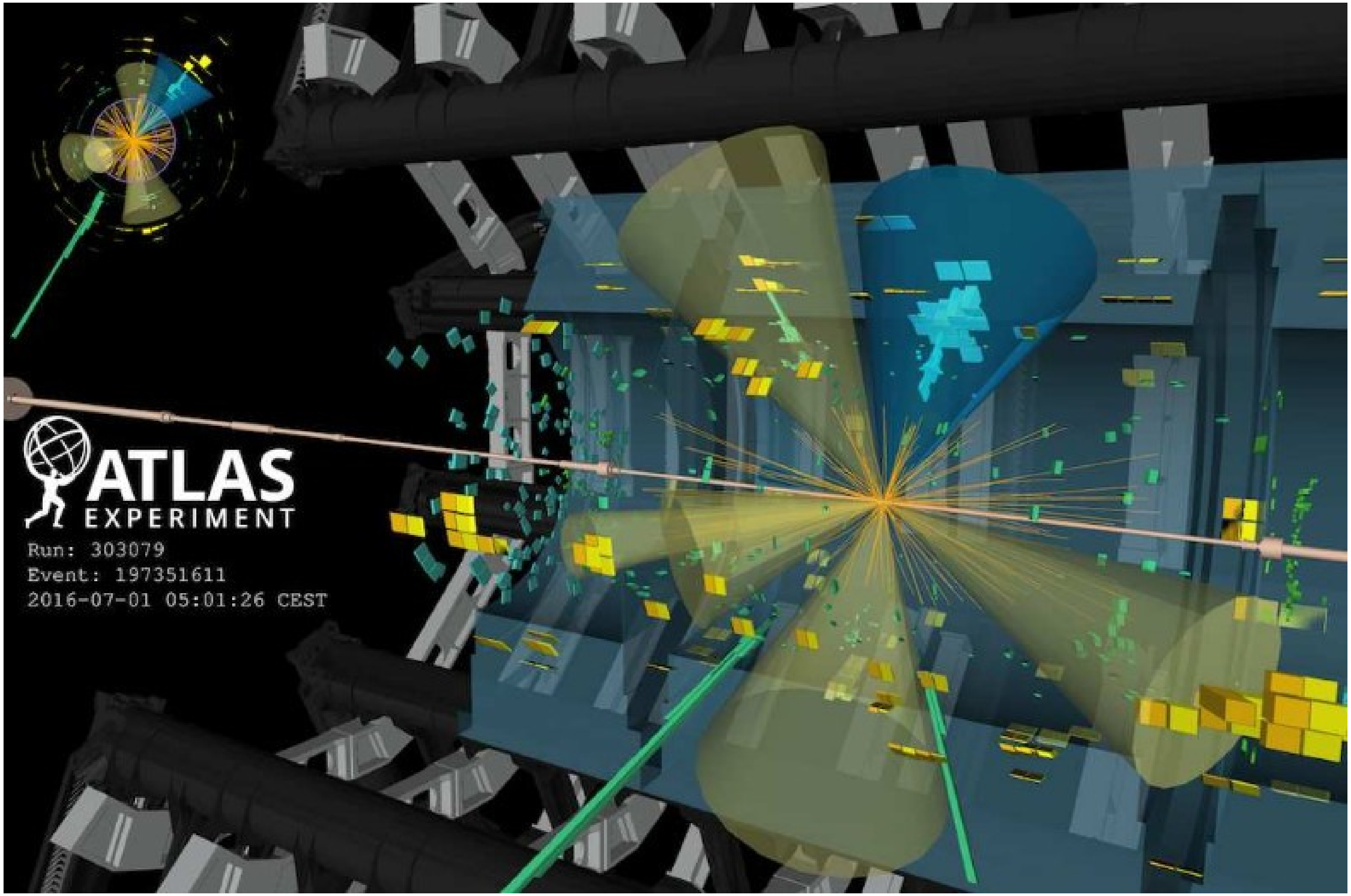
& also H→WW*

Higgs mass measurements



The ttH case

t(bW[→jj]) t(bW[→jj]) H($\gamma\gamma$)
6 jets, 1 or 2 identified as b-jets, 2 photons

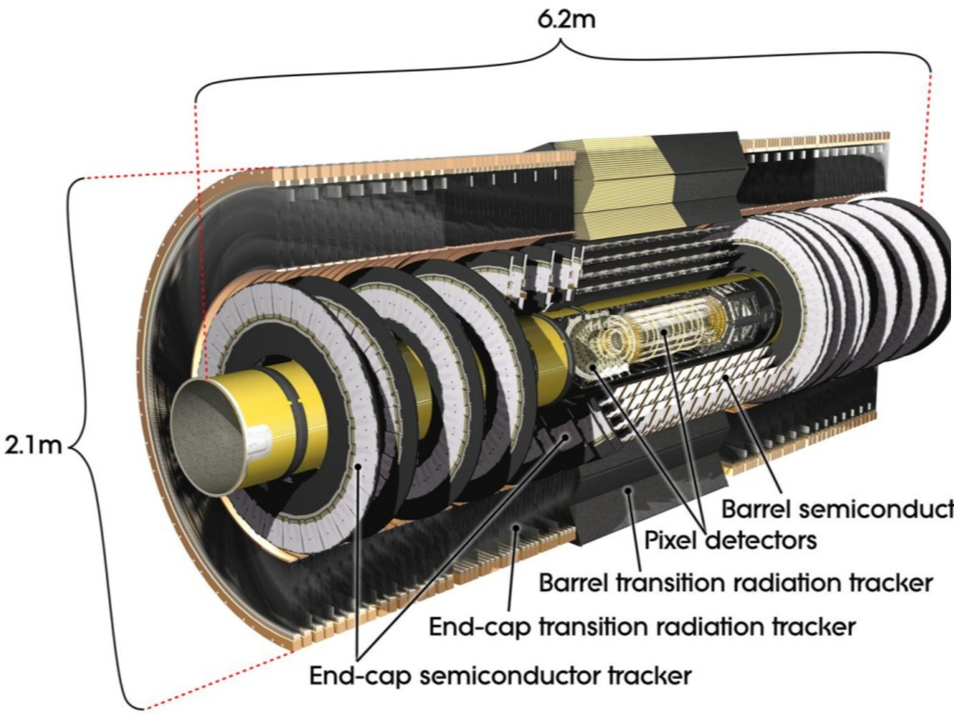


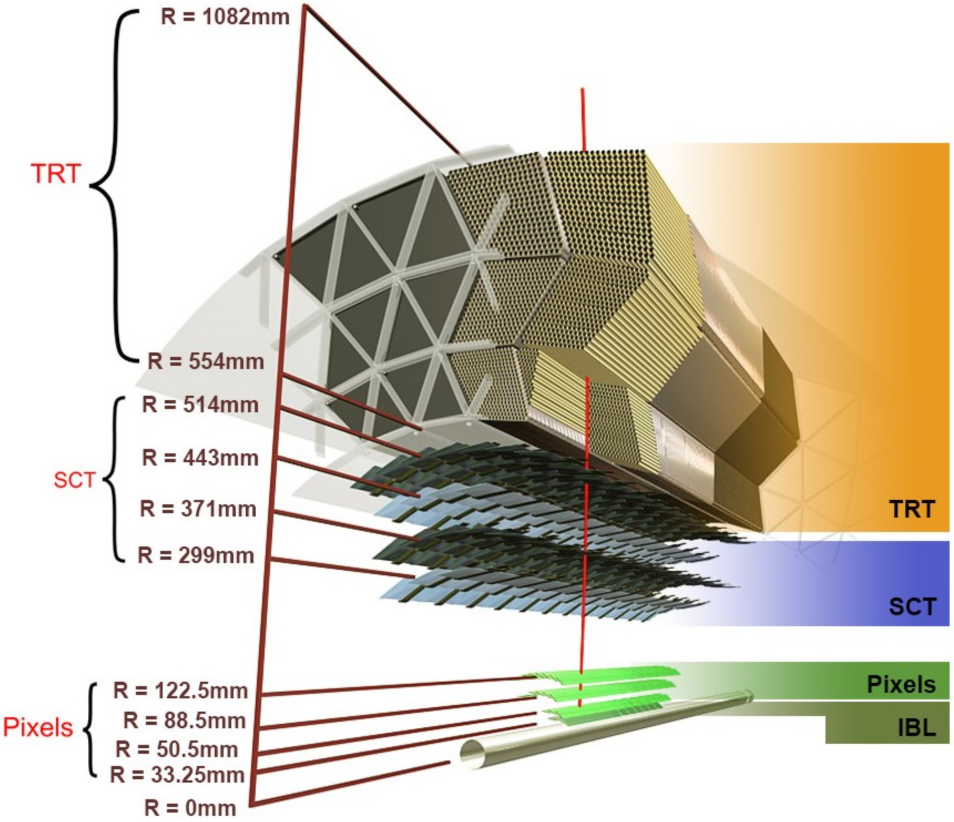
Layout of the Inner Detector

Covers |η|<2.5, in 2T B-field

Granularity:

- pixels:
  - 80M (50x400 μm^2)
  - Run2: +10M from IBL (50x250 μm^2)
- strips: 6.3M (~80μm, stereo 40mrad)
- TRT straws: 400k (4mm)



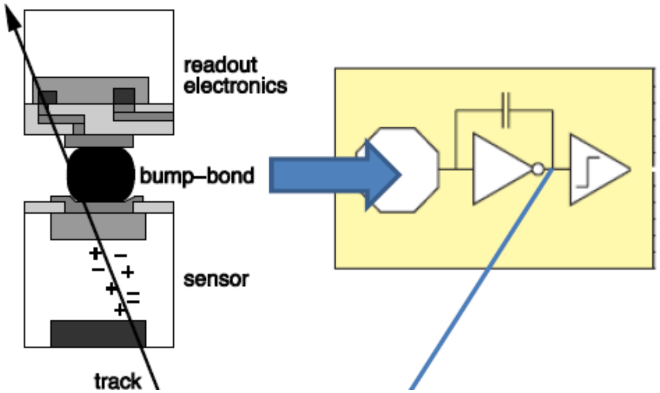


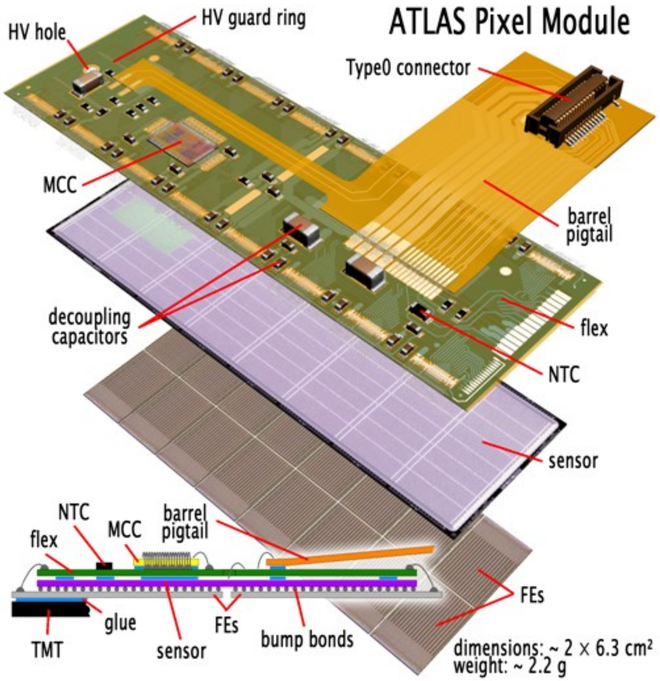
Typical track contains:

- 4 pixel hits
- 4x2 strip hits
- 36 TRT hits
- momentum resolution:

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% \, p_T \oplus 1\%$$

ATLAS Pixel Detector





Requirements:

- resolution: 10 (115) µm
- ε > 99%
- radiation hardness (160 kG/y @ 10^{34})

Sensors (3 initial layers, not IBL):

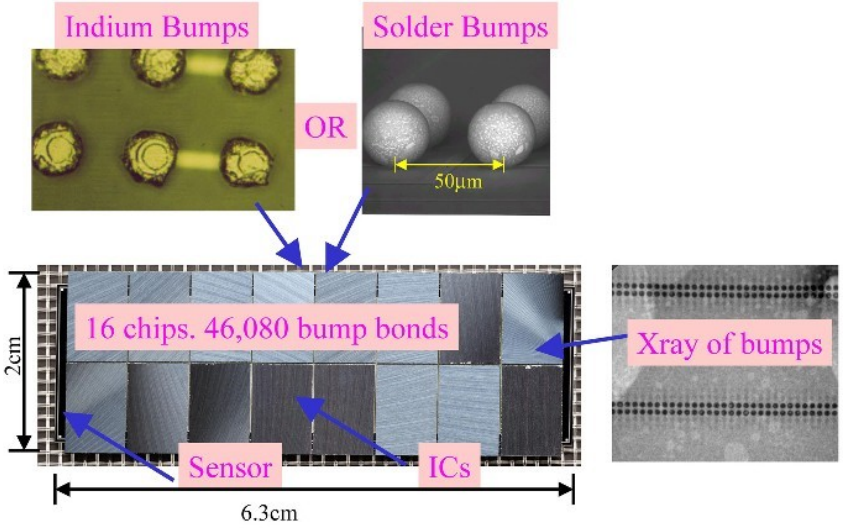
- n^+-in-n, 256 µm-thick Si
- module: 16 FEs, 2880 pixels on each
- FE: 18 col x 160 rows , cell: 50x400 μm^2

Read-out:

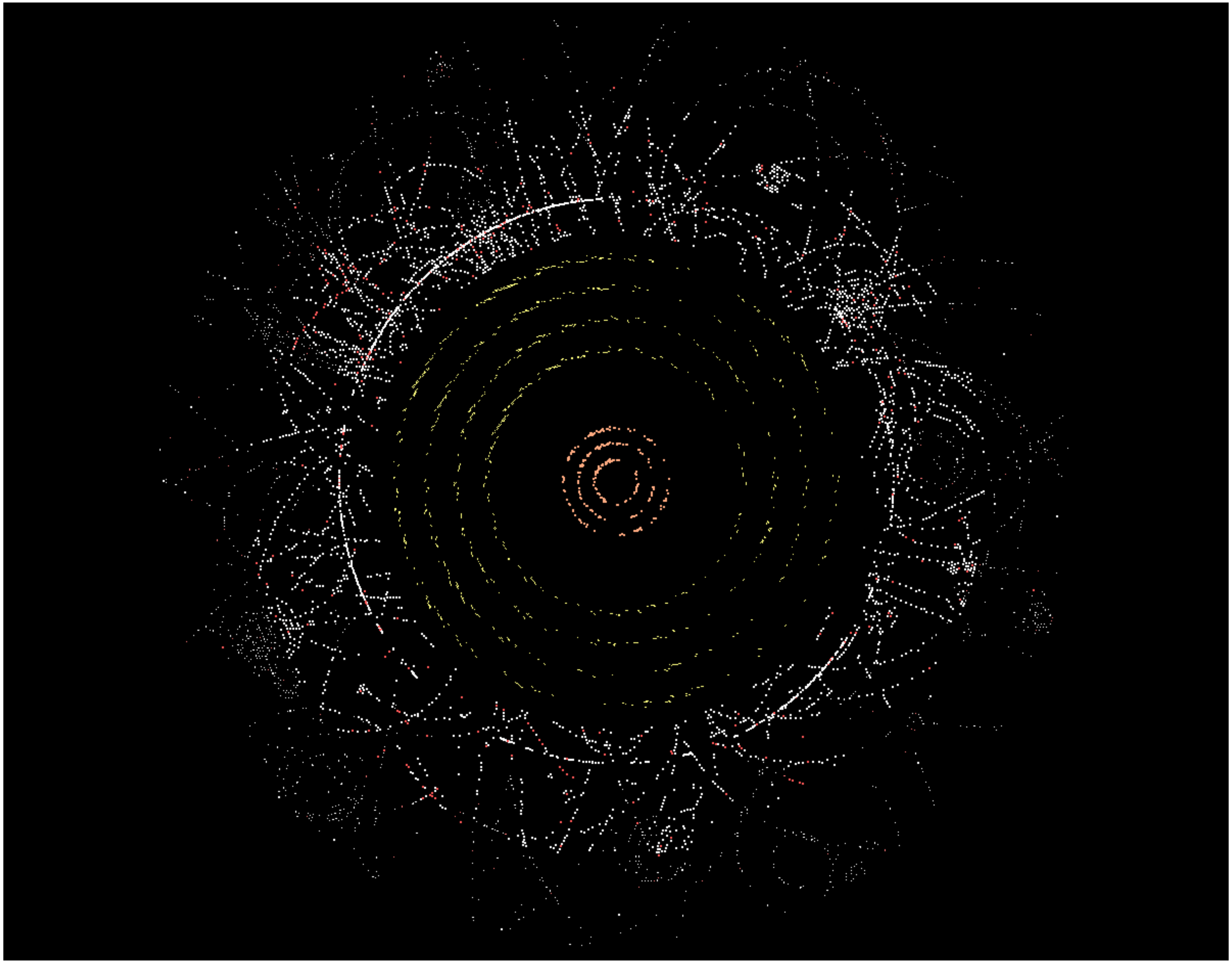
- per pixel + MCC
- binary readout + ToT
  - threshold: tunable
  - # BCOs: tunable

Operation conditions:

- reverse bias: 150 → 600 V
- sensor operation temp.: -20^{o} C

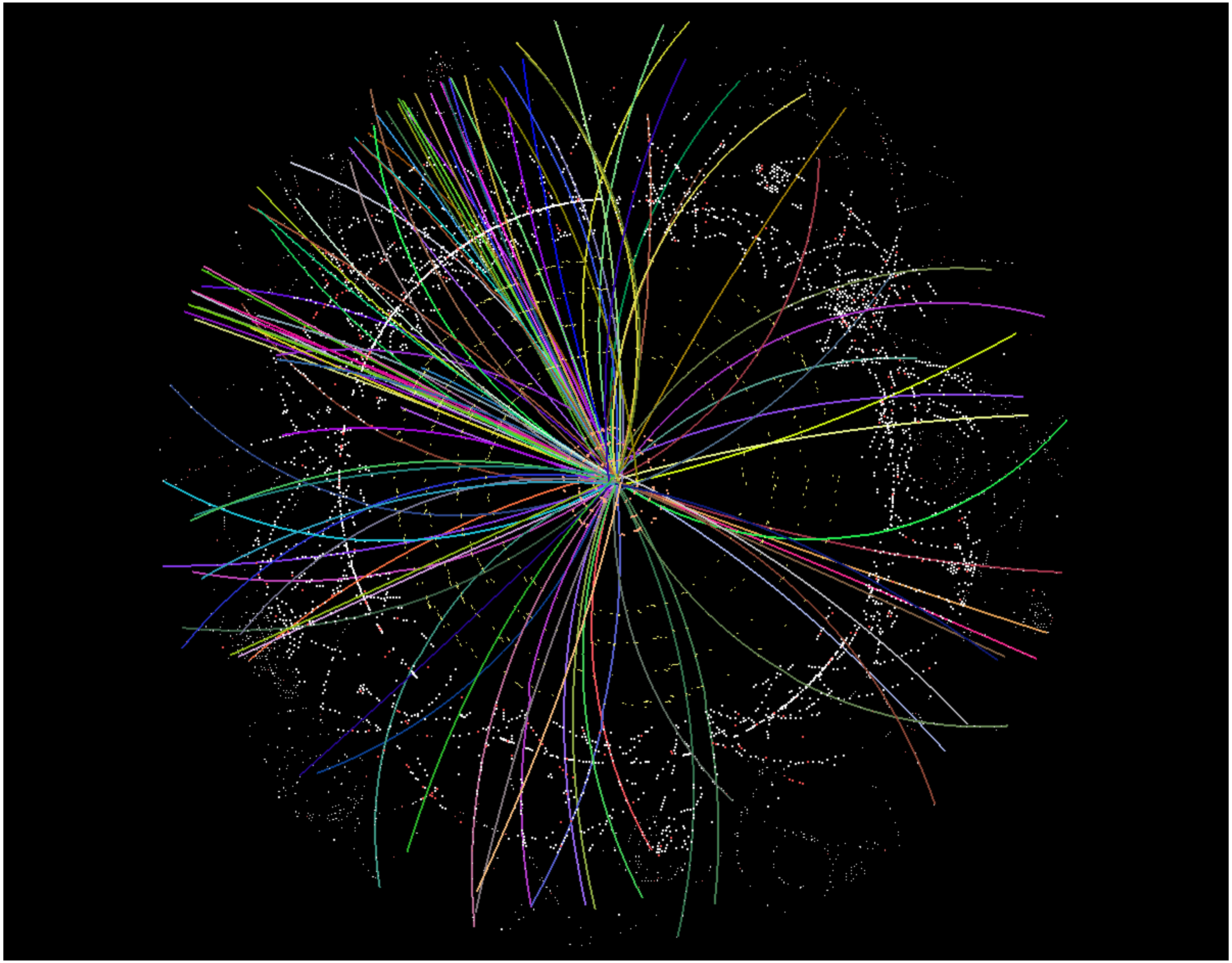


Pattern-recognition for track-finding



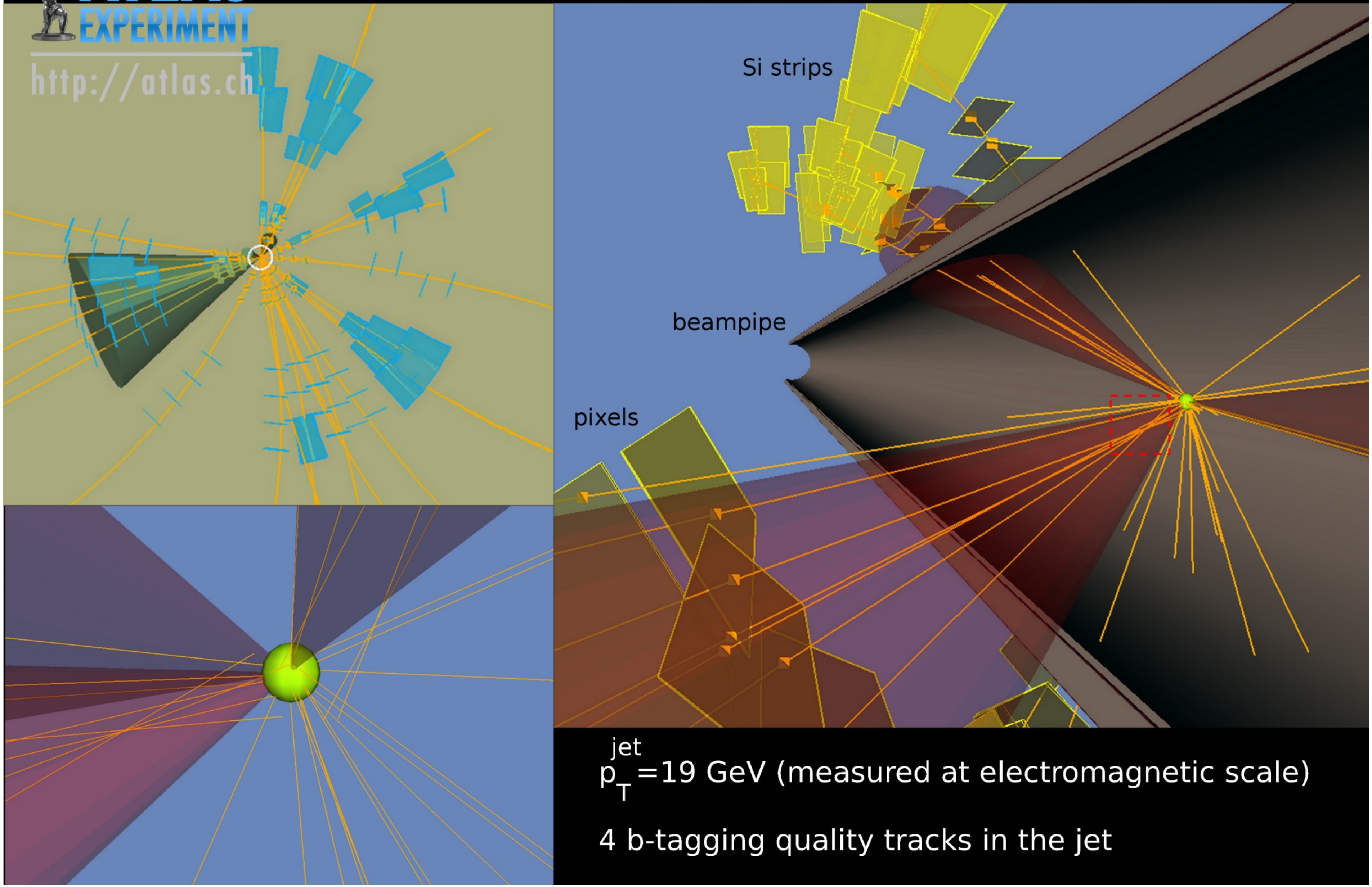
(Credits: D. Rousseau)

Pattern-recognition for track-finding



Run 152166
Event 817271

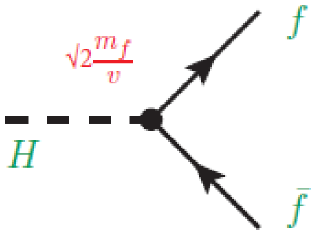
b-tagged jet in 7 TeV collisions



p_T^{jet}=19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

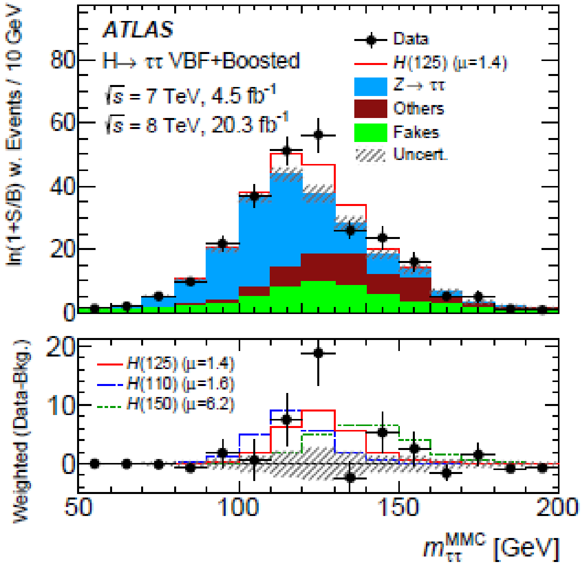
Higgs couplings to fermions

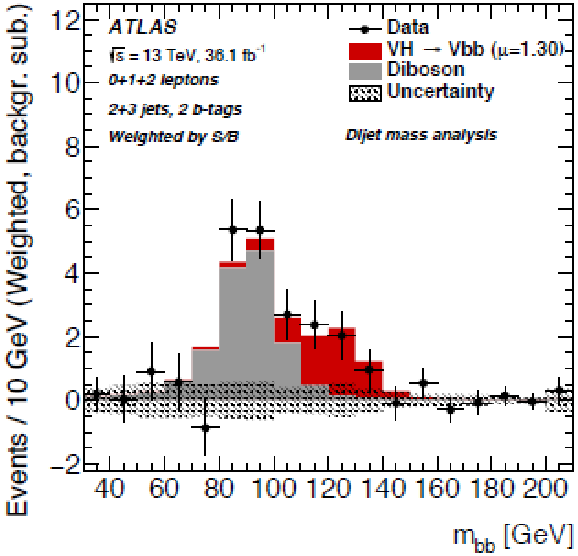


- All current measurements of the Higgs boson properties are consistent with the SM
- Fermion masses are a consequence of the EWSB with the Higgs coupling to the fermions through Yukawa interactions

- Yukawa coupling: proportional to fermion mass
  - ○ Top is heaviest fermion in the SM → Largest Yukawa coupling: $\lambda_t = \sqrt{2} m_t / v \approx 1$
- Experimentally observed so far:
  - ○ Tau Yukawa coupling observed in $H \to \tau\tau$ decays
  - ○ Evidence for the b-quark Yukawa coupling through $H \to b\bar{b}$ decays

LHC seminar on 26/11/2013
JHEP 04 (2015) 117





arXiv:1708.03299
LHC seminar on 27/07/2017

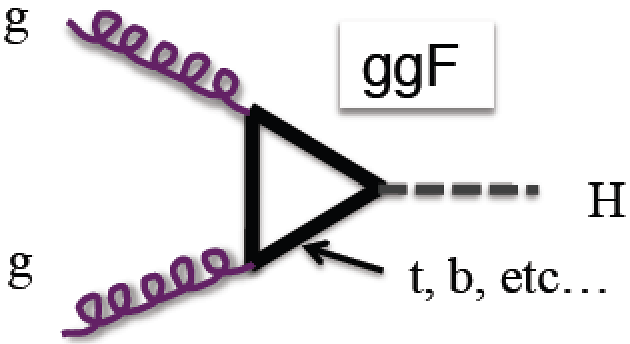
(Ximo Poveda)

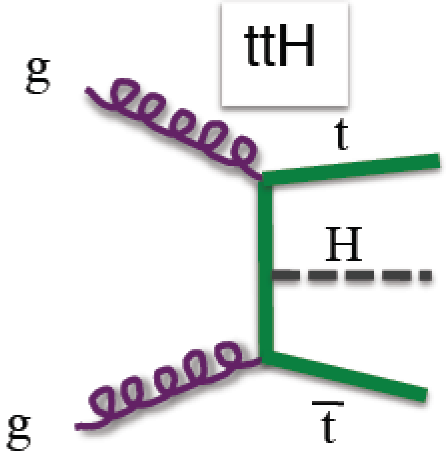
Interest of measuring Y_{top}

- le couplage top-Higgs intervient en fait dans le mécanisme principal de production du boson de Higgs (90% des cas)
- et également dans la désintégration en 2 photons

➔ contributions à des diagrammes en boucle

90%





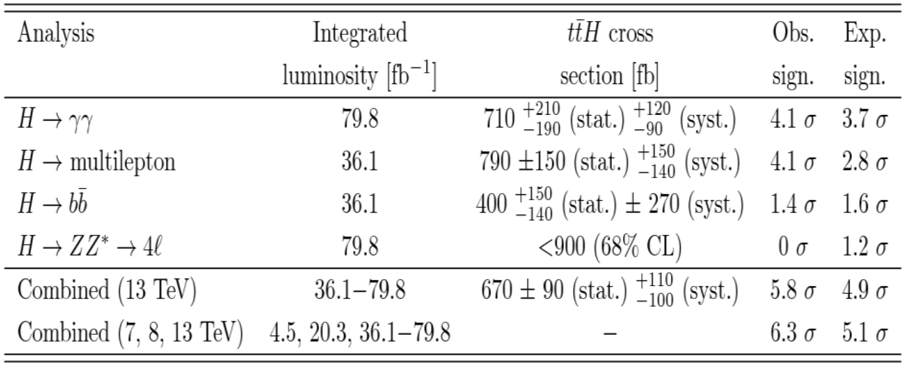
1%

- mais il y a d'autres particules qui interviennent, y compris peut-être des particules non-prévues par le Modèle Standard !!

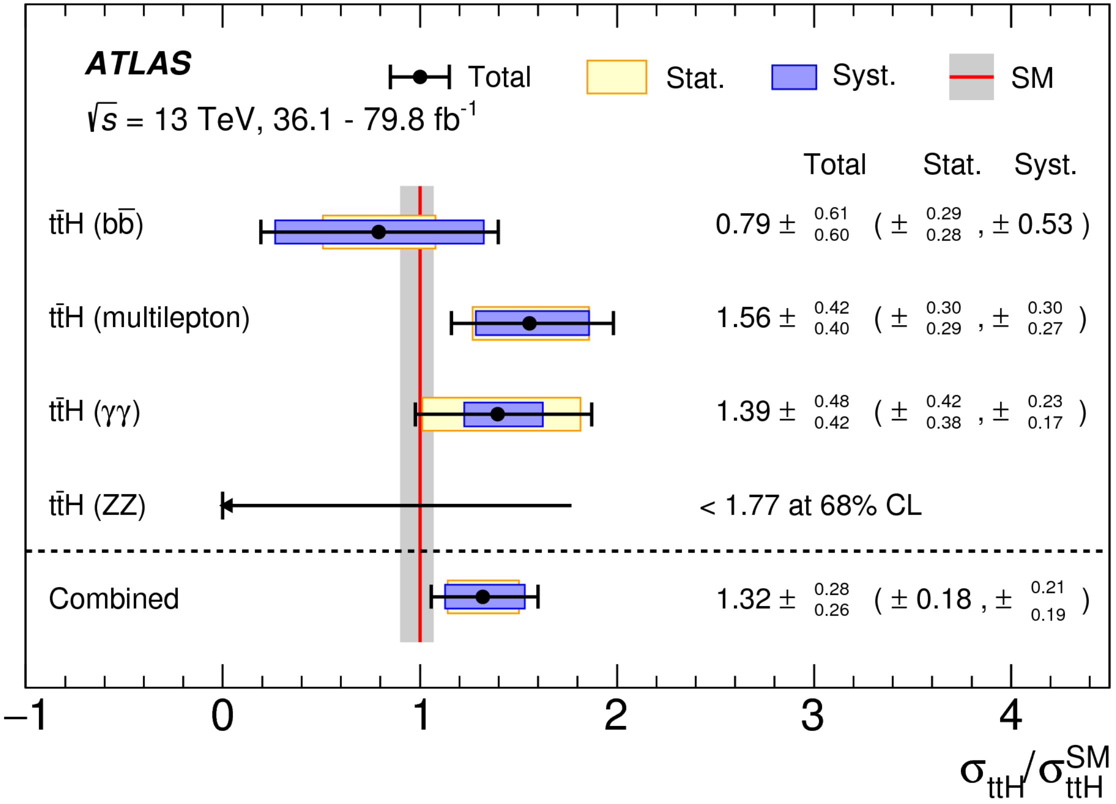
➔mesurer ttH permet de quantifier de façon non-ambigue la composante ttH (mesure à l'arbre, directement ∝ Y^2_{top}), et donc de sonder de la nouvelle physique potentielle

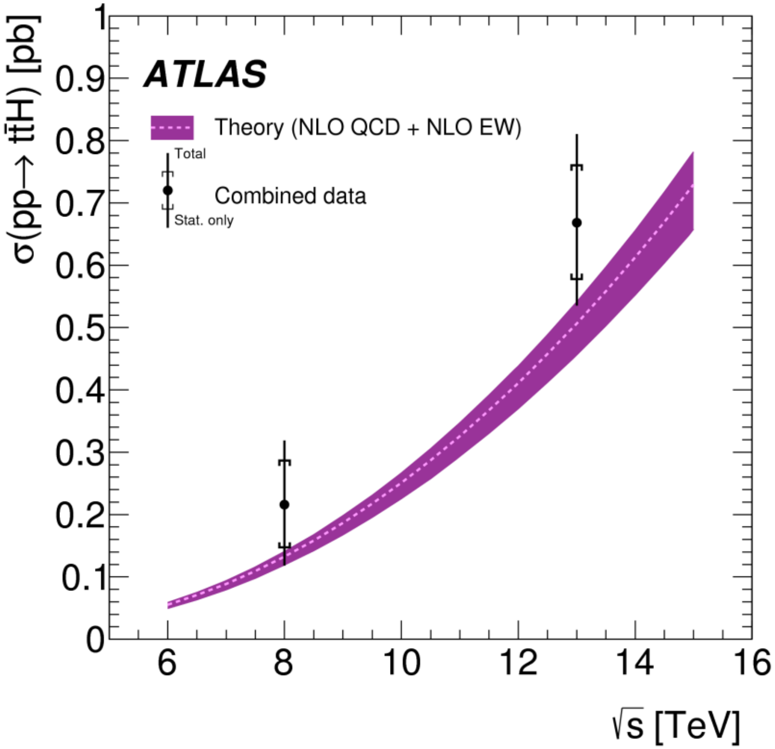
Fresh result: observation of ttH!

- production ttH observée au Run 2
- compatible avec le MS
- évidence directe du couplage intense entre top et Higgs
- première observation du couplage aux quarks



Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1 σ	3.7 σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1 σ	2.8 σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4 σ	1.6 σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0 σ	1.2 σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3 σ	5.1 σ





Higgs boson measurements to do

- Mass:
  - done
  - (understand differences between ɣɣ and ZZ measurements)
  - improved accuracy really needed ? (already at ~0.2% level)

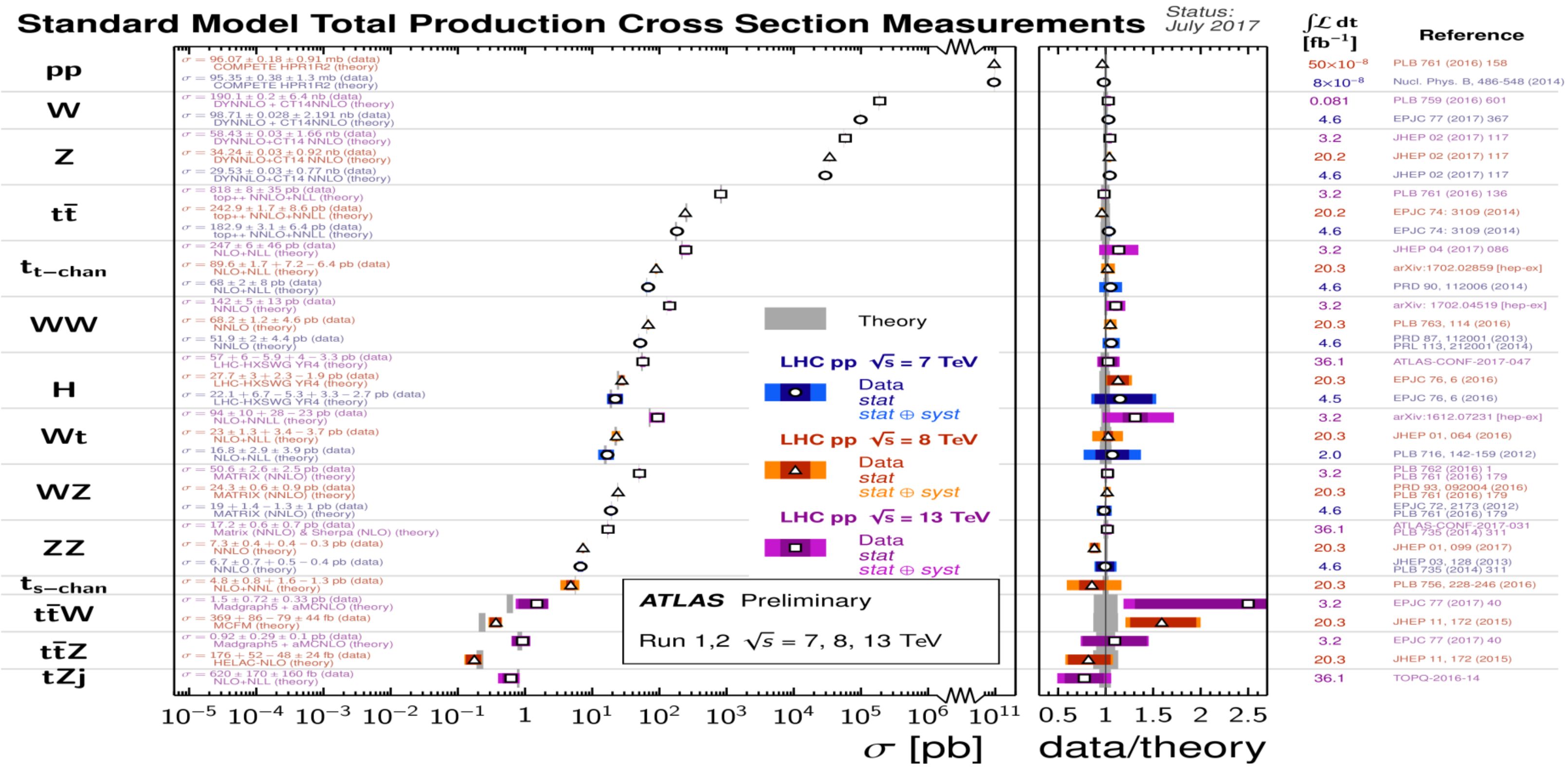
- Couplings:
  - to bosons: under control (10-20%) for ɣɣ and ZZ channels
  - to fermions: evidence for H→bb for now, and confirmation (observation) of H→ττ as well
  - major goal of Run 2: coupling to top via ttH ➔ just observed (4/06/2018)
  - check full consistency of coupling patterns !!
  - self-coupling: HL-LHC !!(?)

- Spin/parity:
  - more data needed for precise determination, is it interesting ?

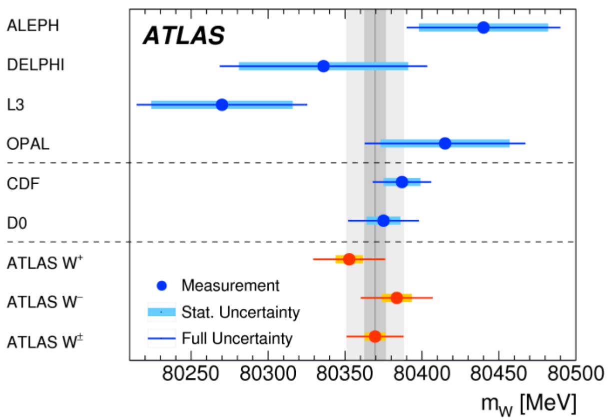
Quite some interesting work to do in the next years !!

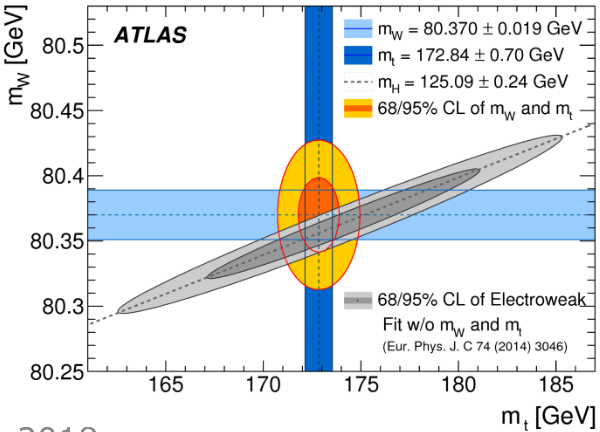
More precision measurements…

Precise measurements/tests of SM



Recent
most precise
measurement
of m(W):





Looking for the unknown…

Beyond the Standard Model

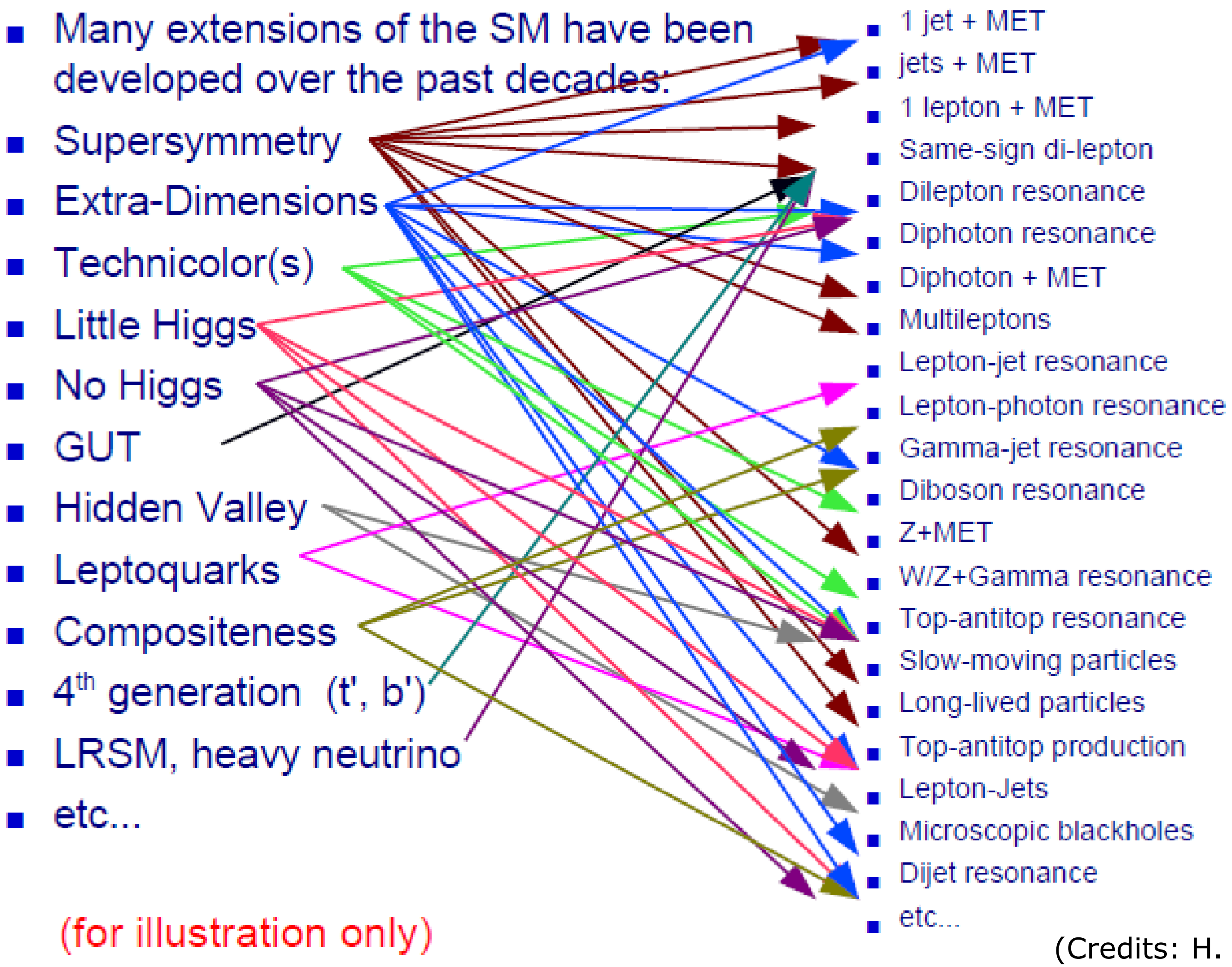
A large variety of theories/(mostly) models:

- Supersymmetry:
  - addresses hierarchy problem well (if at relatively low scale)
  - provides naturally a Dark Matter candidate
- Technicolor:
  - explain underlying EWSB through strong interaction
  - used to be popular, but difficult to reconcile with H(125)
- Extra-dimensions:
  - address hierarchy problem by bringing the Planck scale down to the TeV scale (in other words, explain why gravity is so weak)
- 4th generation models:
  - can provide an additional source of CP-violation to explain Matter-Antimatter asymmetry
  - chiral models in trouble with H(125), Vector-Like Quarks still OK
- Etc….

Where to look ?

- BSM particles must somehow couple to SM particles
  - otherwise would not help to explain anything…
  - usually also implies (severe) constraints from SM measurements
  - new massive particles decaying to SM (electrons, muons, quarks…) ?
  - long-lived particles produced ? explain Dark Matter ?
  - if new interactions: how to compute rates ?
- Where to look:
  - direct production of these new particles (ATLAS, CMS, …)
    - on top of SM processes ? specific (striking) signatures ?
    - maybe out of reach for LHC (or even future colliders) ?
  - indirect effects of them through quantum loops:
    - B-physics sector (LHCb)
    - look where SM breaks: change in cross-section, interferences, etc
- Remember:
  - not much BSM theories available, mostly (and to many) models
  - none of them is so compelling that everybody believes it is *the* model to look for (SUSY was close to this but…)
  - a very interesting time for working on HEP experiments, since only them can (hopefully) shed light on New Physics

Models ⊗ Signatures: a jungle !!



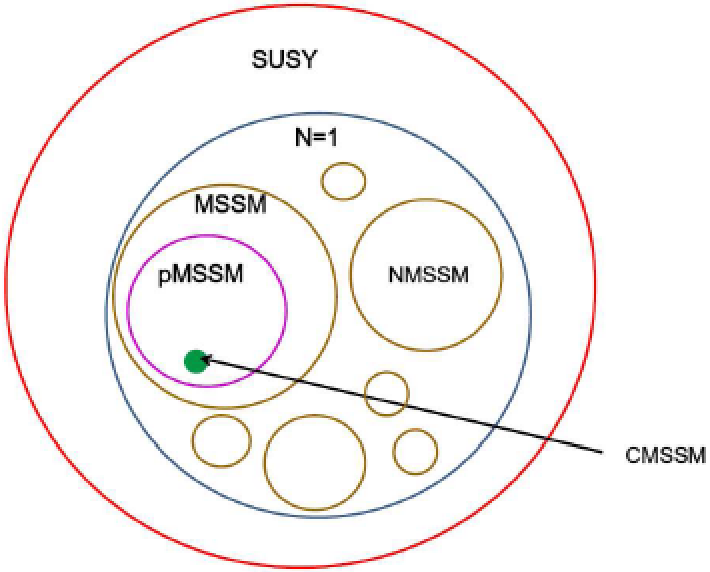
- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

(Credits: H. Bachacou)

The infinite realm of SUSY



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

SUSY

N = 1

N > 1

Minimal SUSY SM (MSSM)
2 Higgs doublets
105 free parameters

Ex: scalar gluon search

R-parity cons.
LSP is Dark Matter candidate

R-parity violation
add 48 free parameters
Lepton/Baryon # violation
Resonances
Long-lived particles

Constrained models. 5 free parameters:
- Minimal SUperGRAvity / CMSSM
- Gauge-Mediated SUSY-breaking
Cascades with large missing energy
- AMSB: long-lived particles

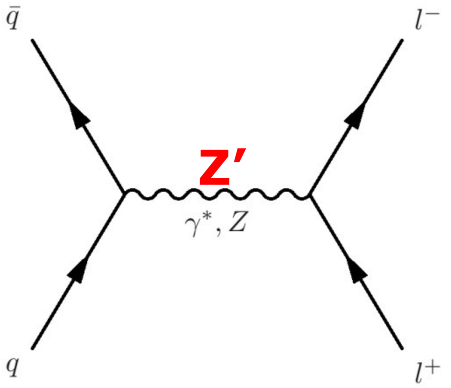
Split SUSY
Long-lived Particles

Stealth SUSY: compressed spectrum
No missing energy
Long-lived Particles

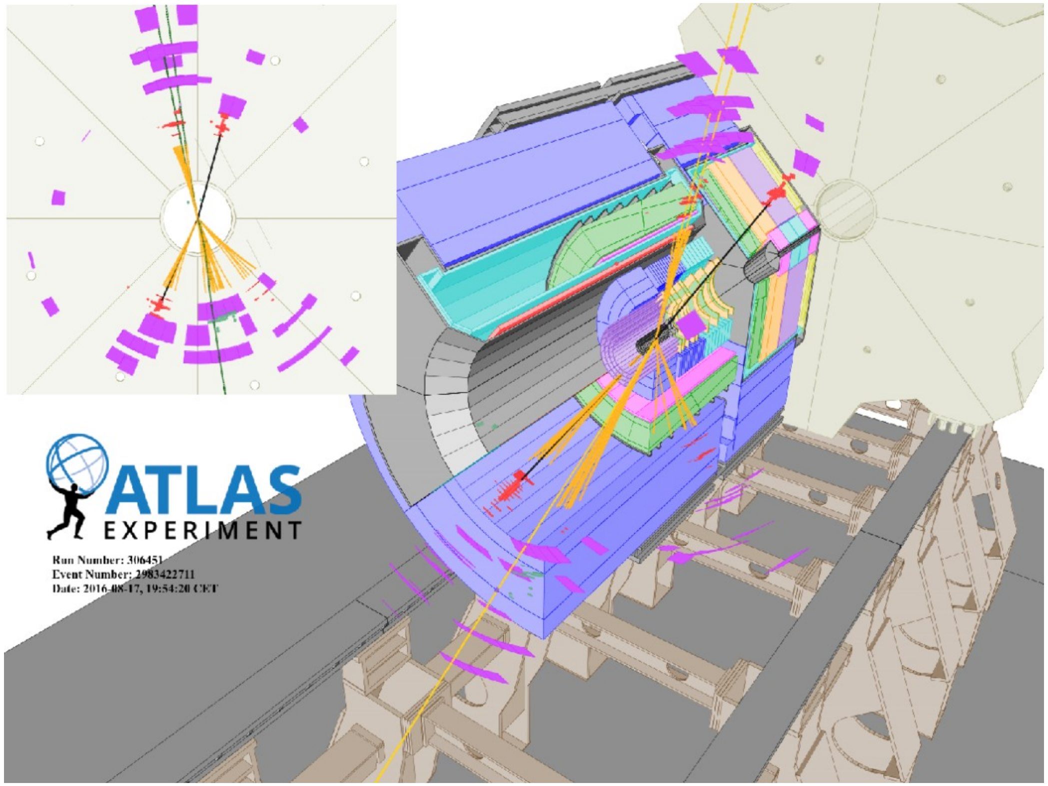
Search for heavy resonances

Models: SSM Z’, RS graviton, GU E6, minimum walking technicolor,…

Search: looking for ‘bumps’ on top of (tails of) SM Drell-Yan background in **m(ll)** distribution



- clean signature: 2 high-p_T leptons (of opposite charge)
- triggering on one of them



Run Number: 306451
Event Number: 2983422711
Date: 2016-08-17, 19:54:20 CET

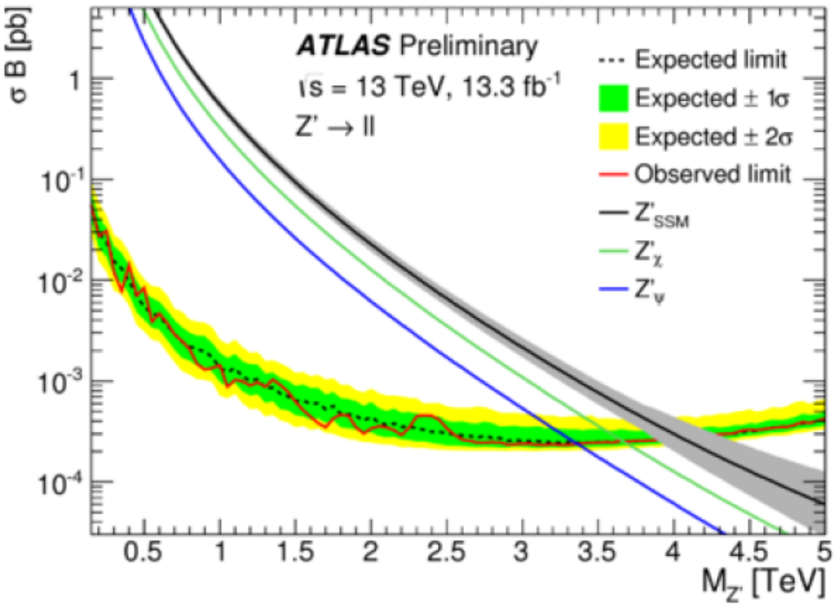
μμ vs **ee:**

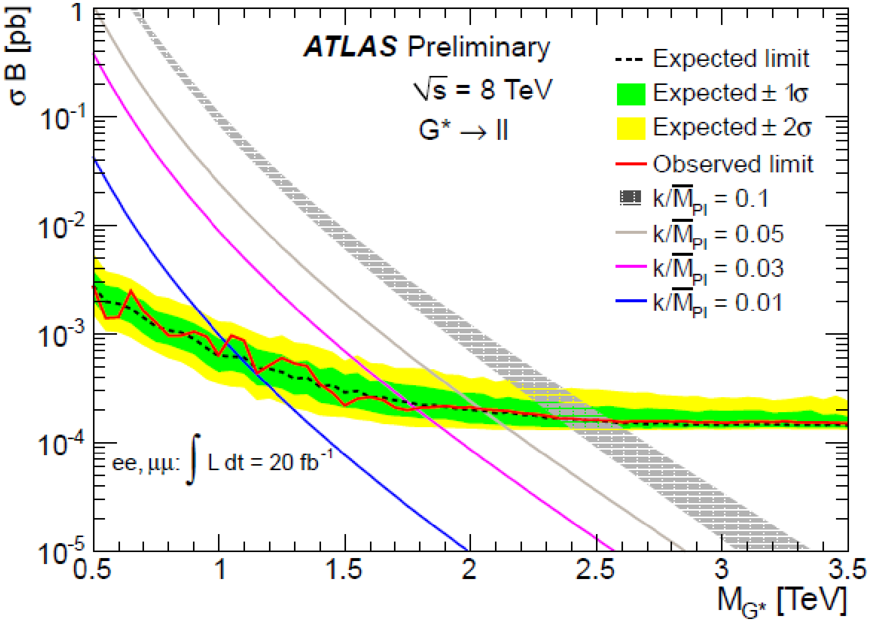
- low **μ** fake level vs jet background for **e**
- easier charge ID for **μ**
- ≳2 better energy/mass resolution for **e**

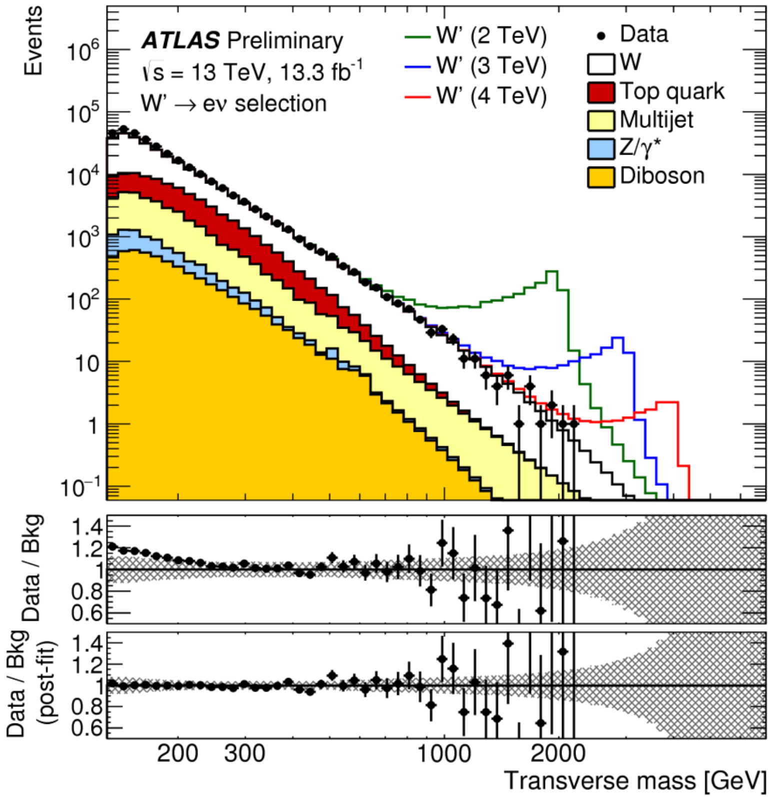
Highest dielectron invariant mass event in ATLAS (2017): **m(ee)=2.90 TeV**

$E_T(e_1)$=841 GeV, $E_T(e_2)$=655 GeV

Heavy resonances in dileptons





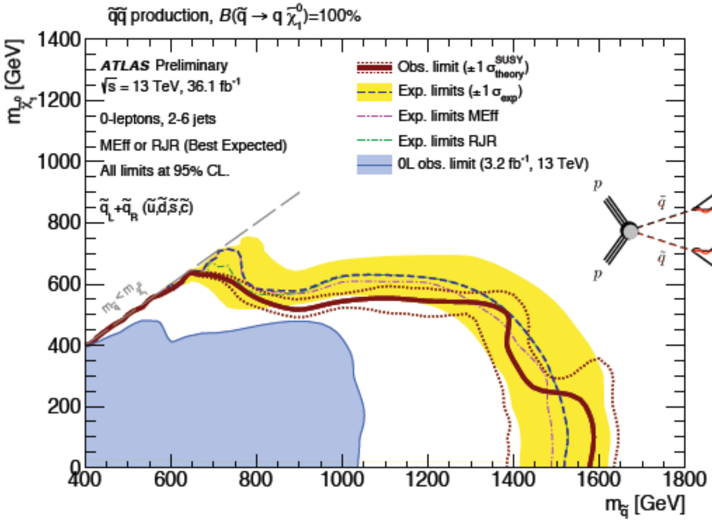


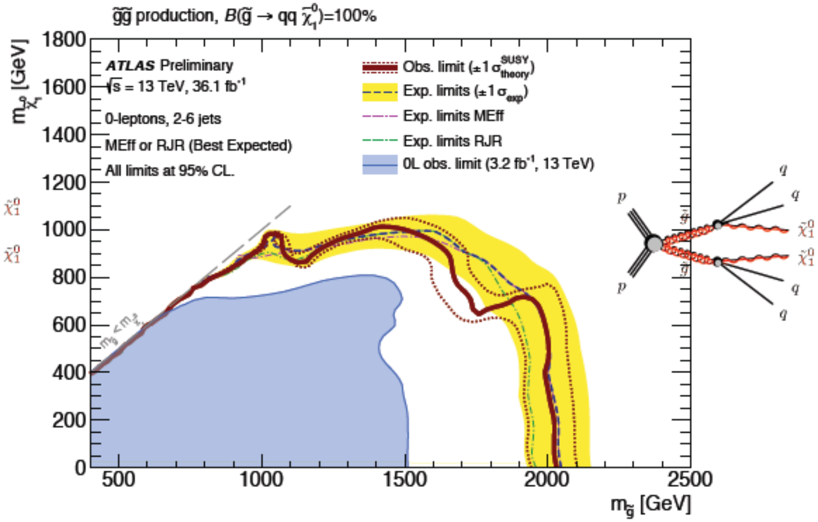
Observed lower limits (TeV) at 95% CL:

Model	√s=8 TeV	13 TeV
SSM Z'	2.86	4.05
E6 Z'_ψ	2.38	3.36
RS G* (spin 2) k/M_{Pl}=0.1	2.47	

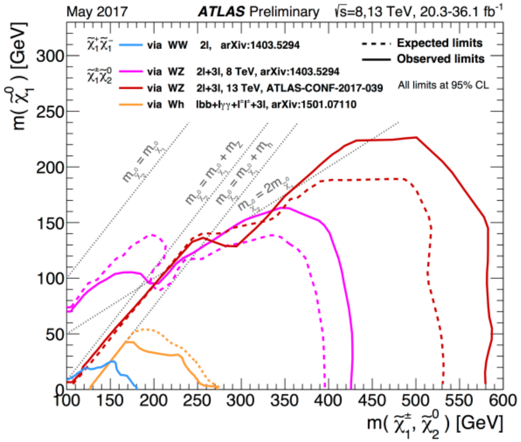
The 1 slide on SUSY…

- Classic searches for strongly produced SUSY: m(~q) > 1.6 TeV, m(~g) > 2 TeV

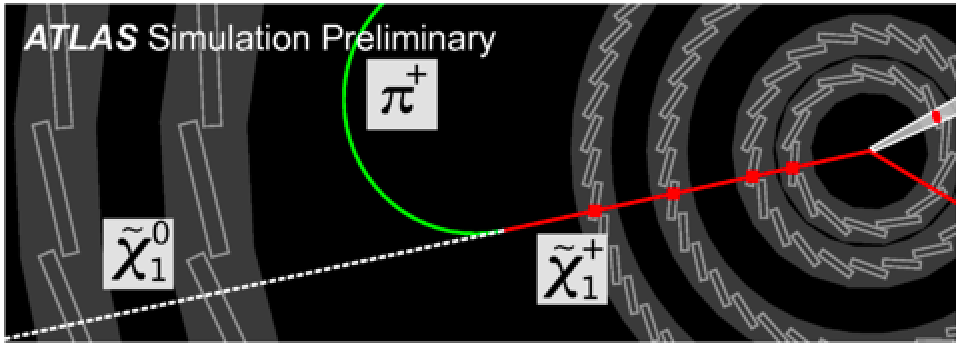




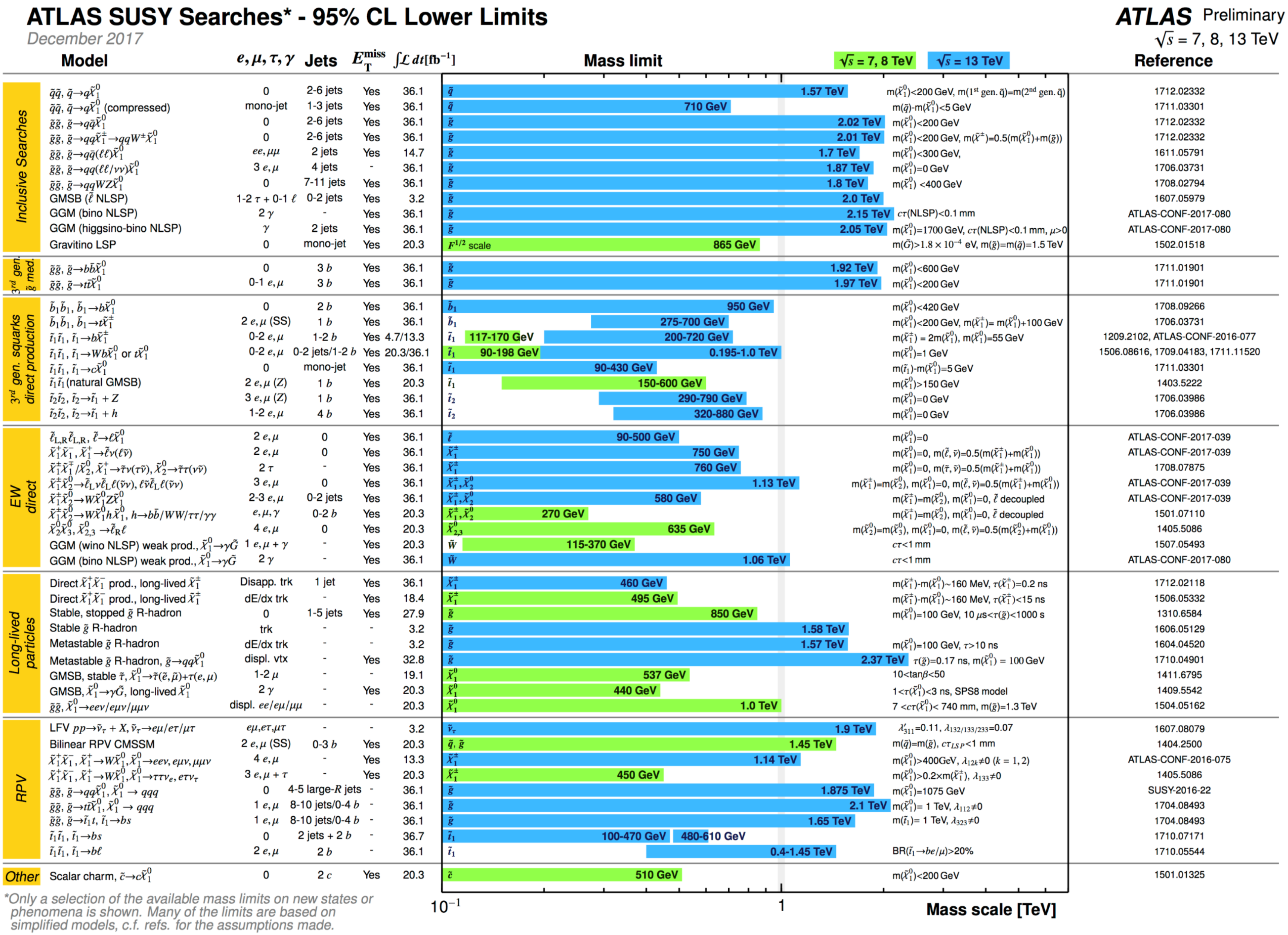
- EW production (lower XS):



- New experimental challenges (RPV, etc
  - displaced vertices, disappearing tracks,…



Summary of searches ☹



ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

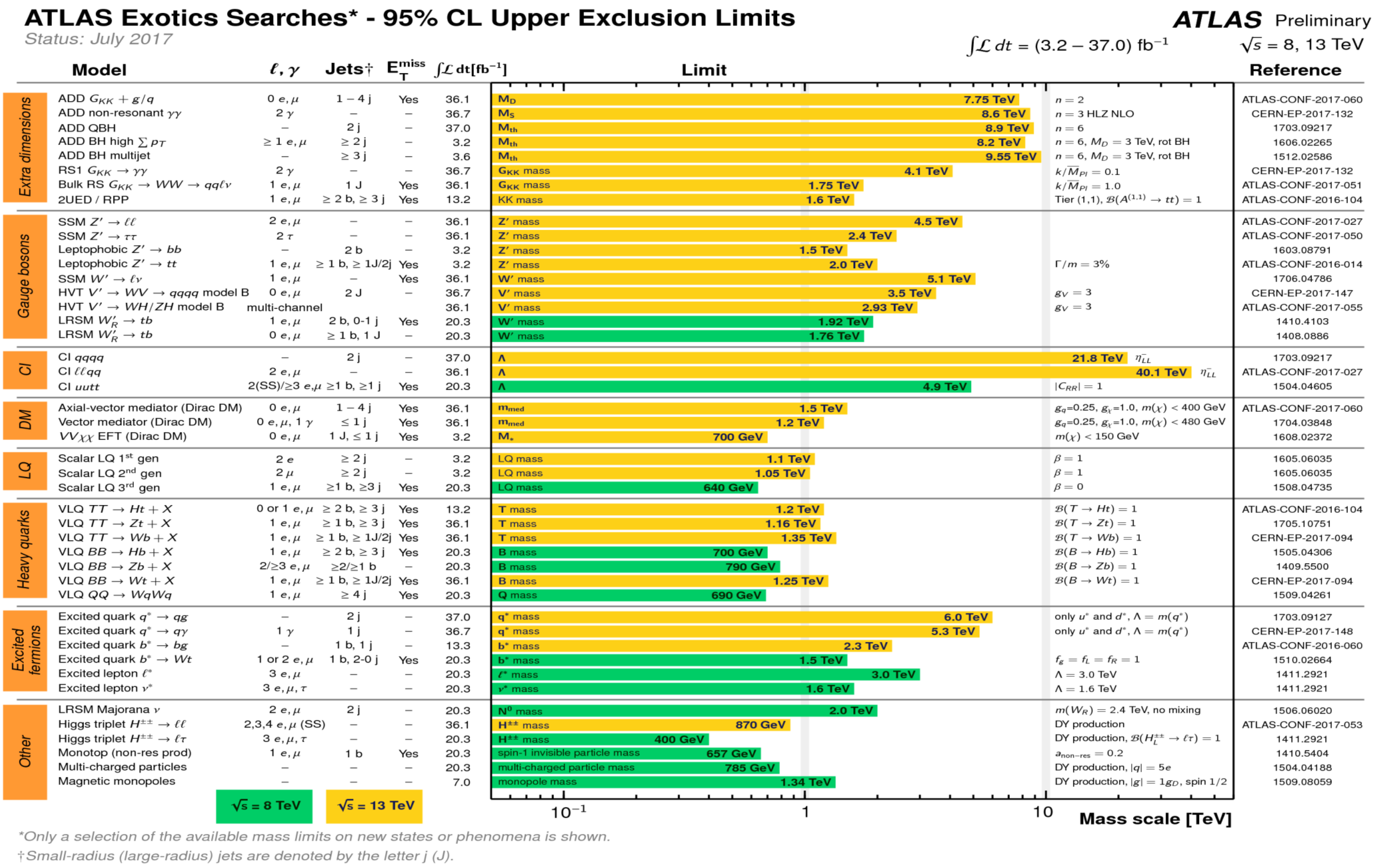
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 🟦 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ 🟦 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$ 🟦 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 🟦 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 🟦 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$ 🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$ 🟦 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 🟩 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$ 🟦 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 🟦 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$ 🟦 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 🟩 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 🟦 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 🟦 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 🟦 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 🟦 1.13 TeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 🟦 580 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 🟩 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$ 🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 460 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 🟩 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 🟦 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$ 🟦 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_{\tau} + X$, $\tilde{\nu}_{\tau}\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_{\tau}$ 🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}$, $\tilde{g}$ 🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 🟦 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_{\tau}$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ 🟦 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ 🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Summary of searches ☹



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

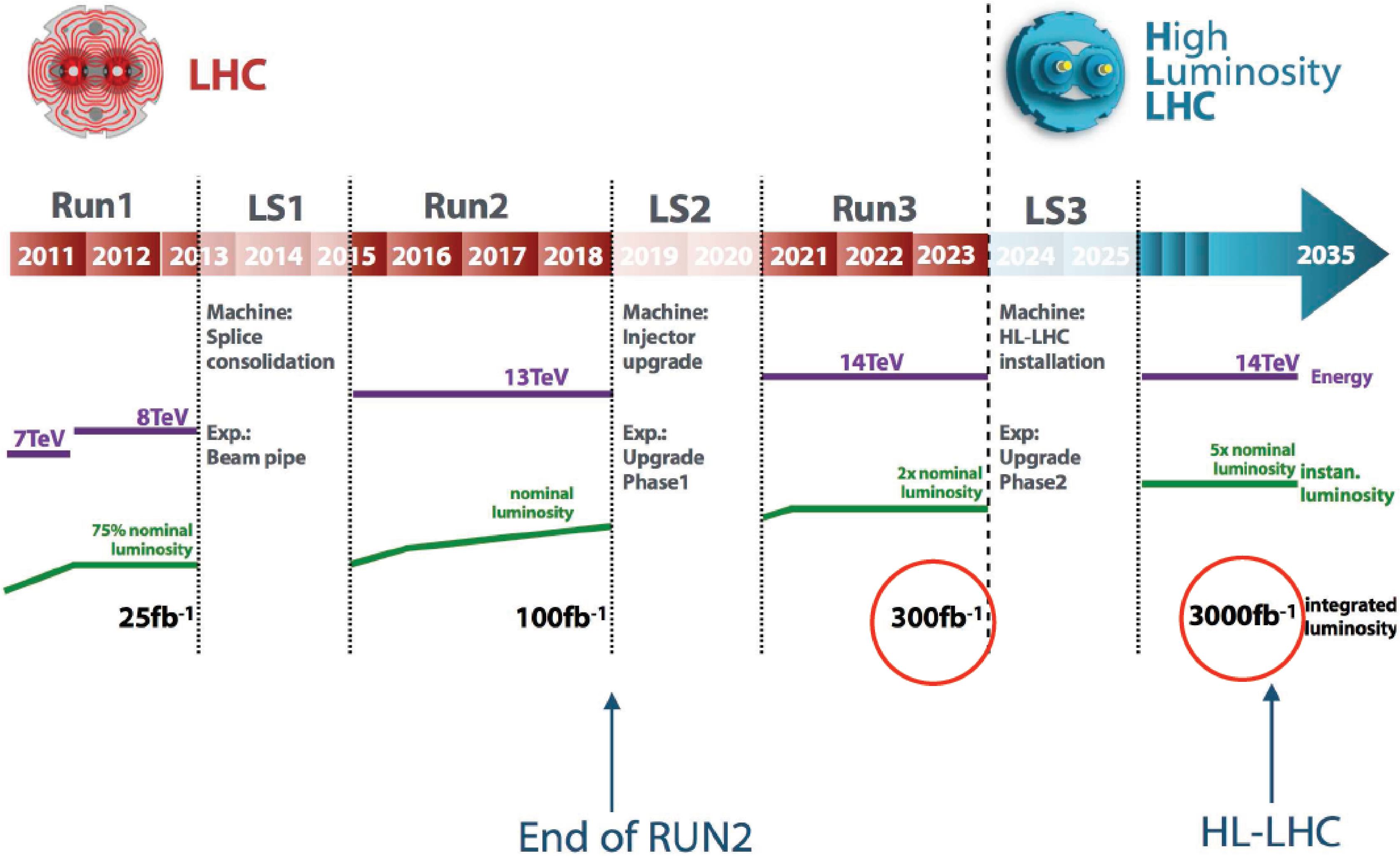
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV η_{LL}^-		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Future: HL-LHC



End of RUN2

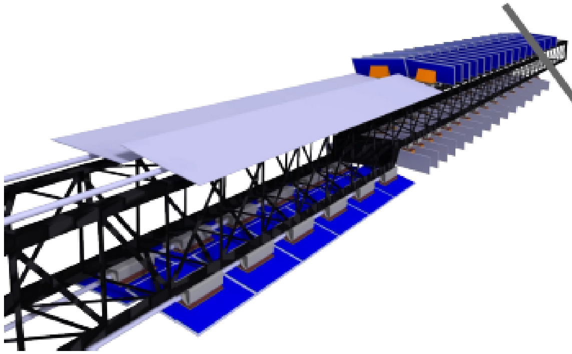
HL-LHC

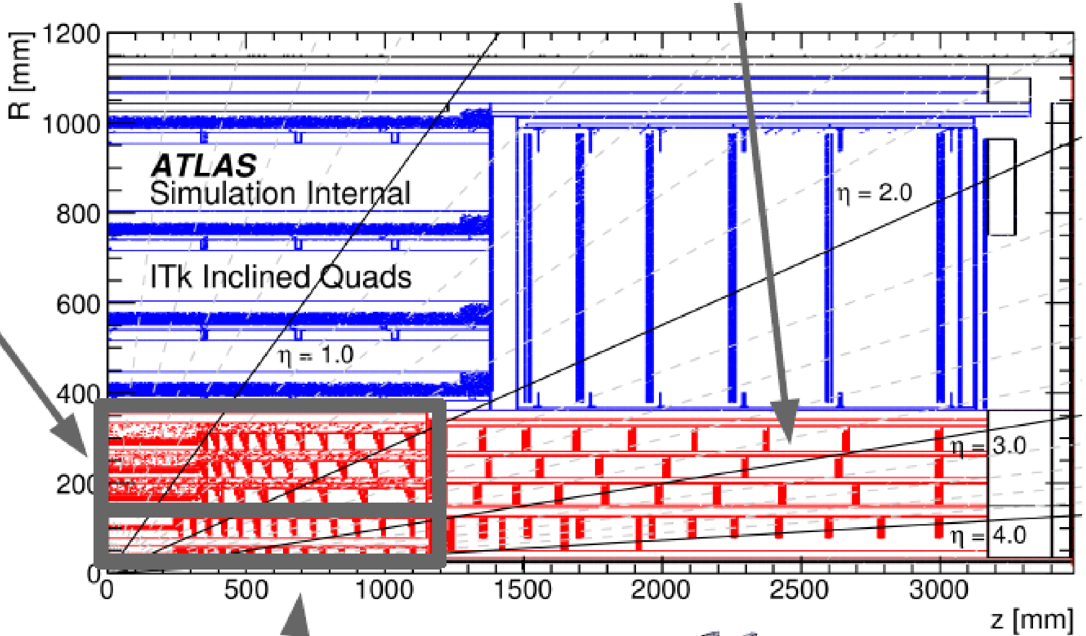
➔ on-going work to upgrade detectors already started !!

Replacement of the ATLAS Tracker

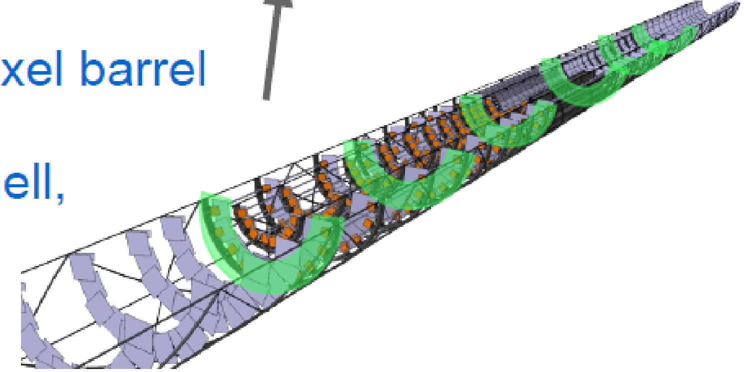
- Outer three layers of the pixel barrel (layers outside IST) are modelled on Slim Demonstrator staves,

- Pixel end-caps are modelled on UK half-rings,





- Inner two layers of the pixel barrel (layers inside the IST) are modelled on truss shell,



Conclusion

- Impressive results from LHC so far
  - Higgs boson discovery !
  - many of its properties measured ! just fresh: ttH observation !
  - Standard Model explored and measured in many corners
  - including very high precision measurements ! m_W=80370±19 MeV/c^2
- Still a lot of data to collect for Run 2, then Run 3
  - pursue searches for new physics
  - more investigation of the Higgs sector
  - measurements in the SM

- Path well-defined with HL-LHC till ~2035
  - opportunities to learn about detector design, construction, operations
  - physics prospects with HL-LHC:
    - precise measurements of the Higgs boson couplings
    - including its self-coupling
    - rare decays of the Higgs
    - extended reach for searches for New Physics

- Exciting time and perspective for you !

More information

ATLAS general public	atlas.ch
ATLAS live	atlas-live.cern.ch
ATLAS on	twitter.com/ATLASexperiment
ATLAS on f	www.facebook.com/ATLASexperiment
ATLAS on g+	www.google.com/+ATLASexperiment
ATLAS on YouTube	www.youtube.com/theATLASExperiment
French site for LHC	www.lhc-france.fr
CPPM	atlas.cppm.in2p3.fr
CERN	cern.ch
CERN on	twitter.com/cern