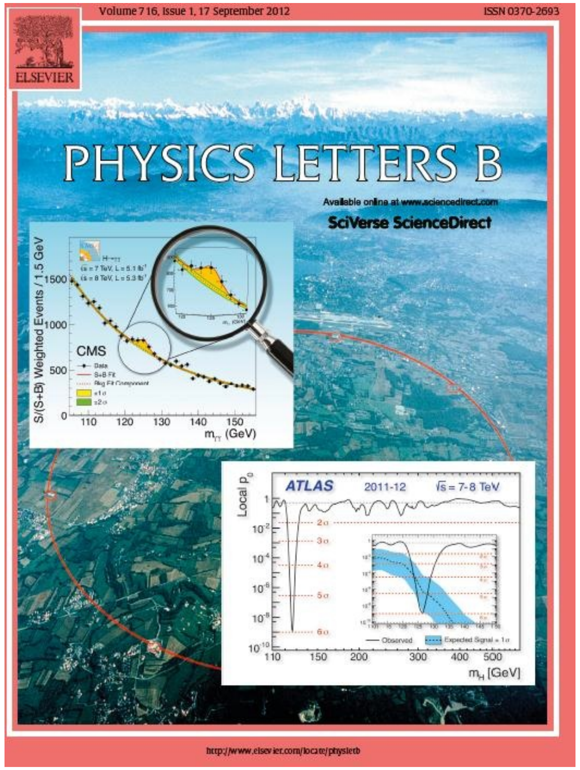
Physics at the LHC and future outlook

Dimitris Varouchas (LPNHE)

FRIF retreat meeting, 24 January 2014

Higgs boson discovery

- **Summer 2012:** **Historic observation of Higgs boson particle with a mass of $m_H \simeq 125.5$ GeV from ATLAS and CMS**



- **Autumn 2013:**

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Photo: A. Mahmoud

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Outline

- **Higgs** boson physics
  - Decay channels
  - Mass measurement
  - Spin CP properties
  - Status of rare decays searches

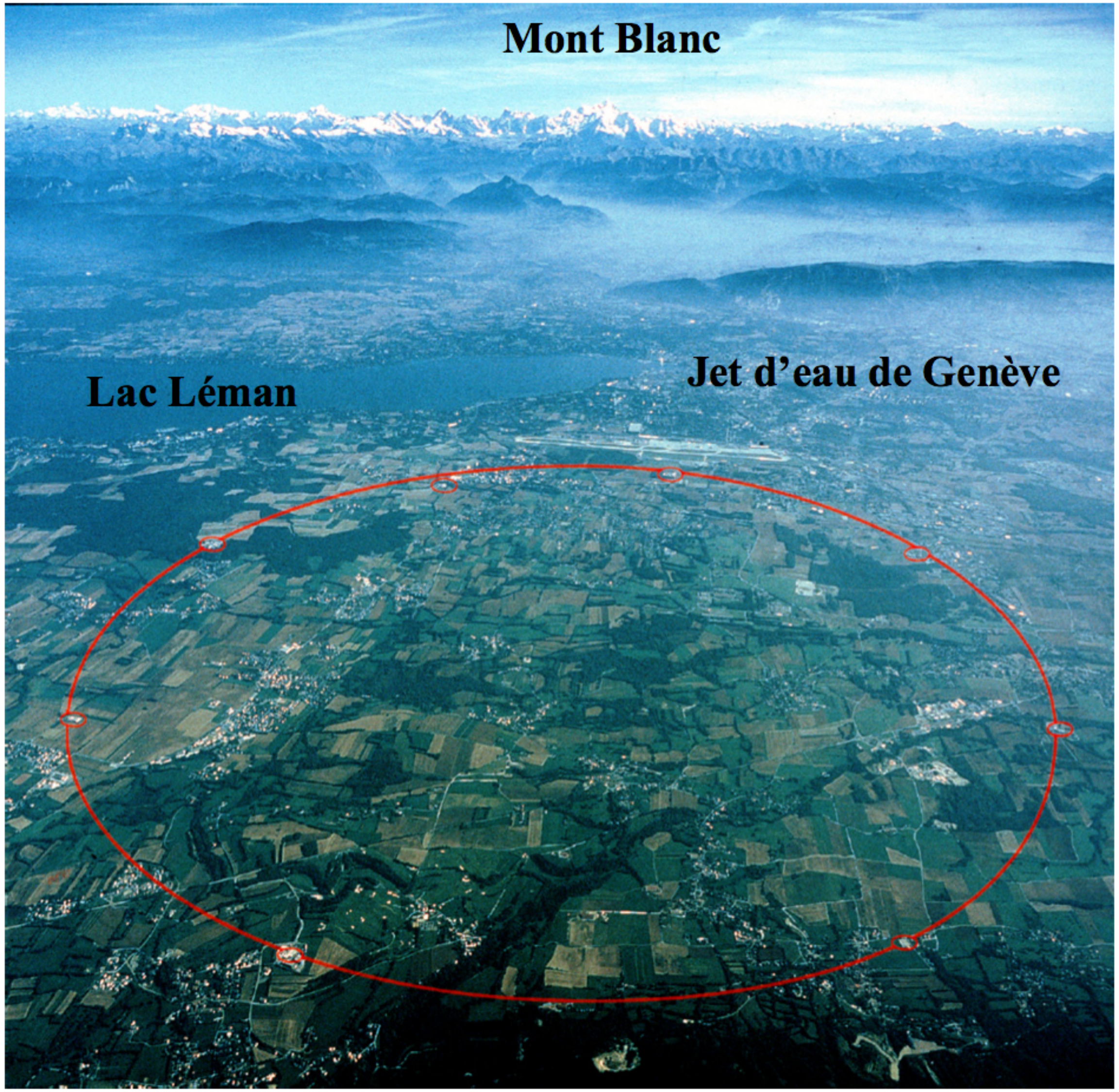
Outline

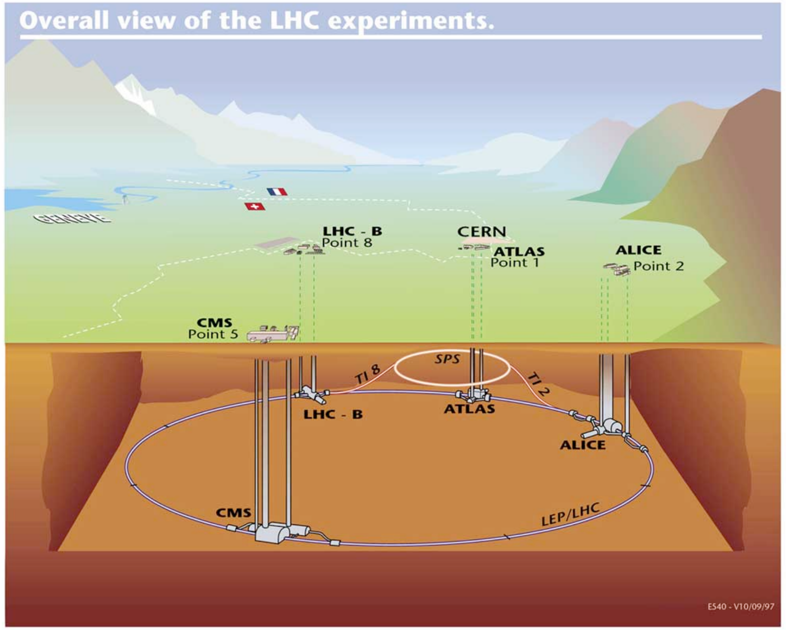
- **LHC**
  - **ATLAS** / CMS detectors
- A few SM (non-Higgs) results
- **Higgs** boson physics
  - Decay channels
  - Mass measurement
  - Spin CP properties
  - Status of rare decays searches
- SUSY
- Exotics
- **ATLAS**/CMS potential in the future LHC runs

LHC

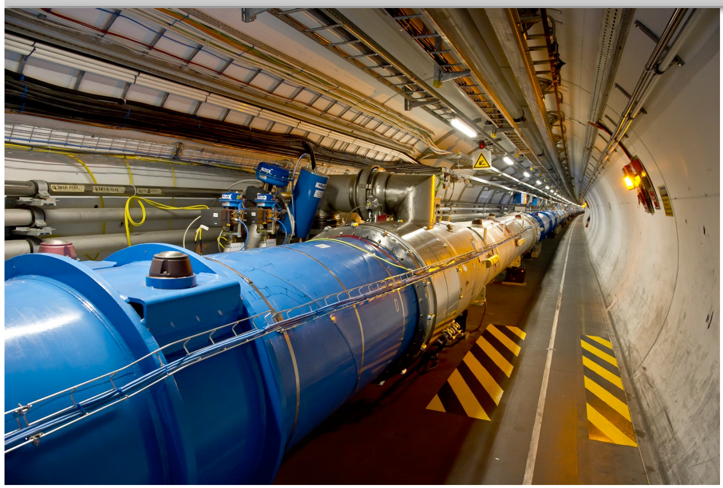
LHC is a (mainly) pp collider of 27 km long in a tunnel ~ 100 m underground close to Geneva (tunnel already used by LEP) which should work with a *design* centre-of-mass energy of 14 TeV Although, 2011: 7TeV

2012: 8TeV

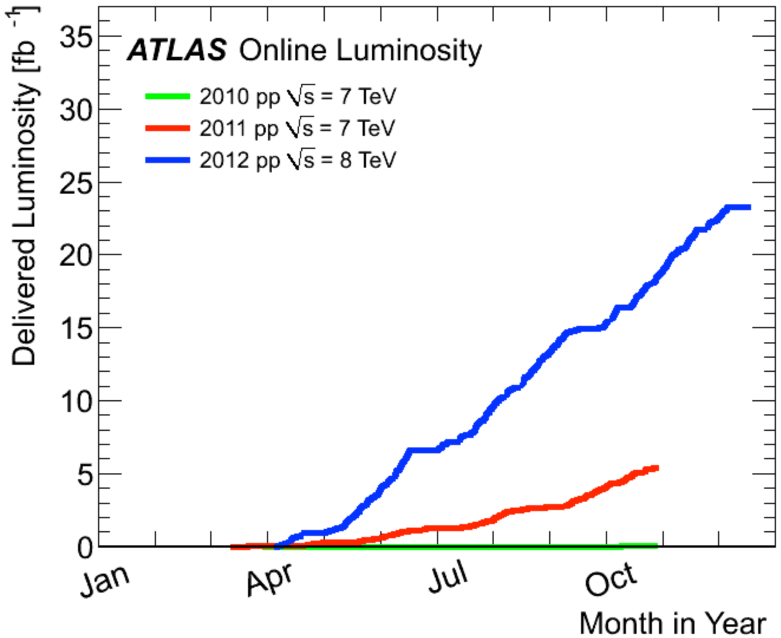


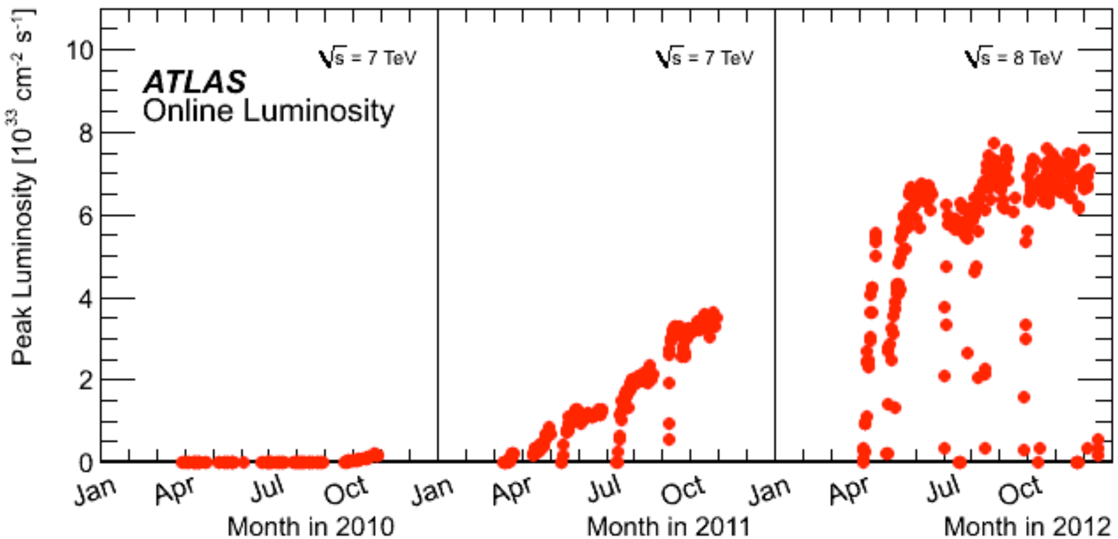


LHC and Luminosity



$$N_{events} = \sigma \times L$$



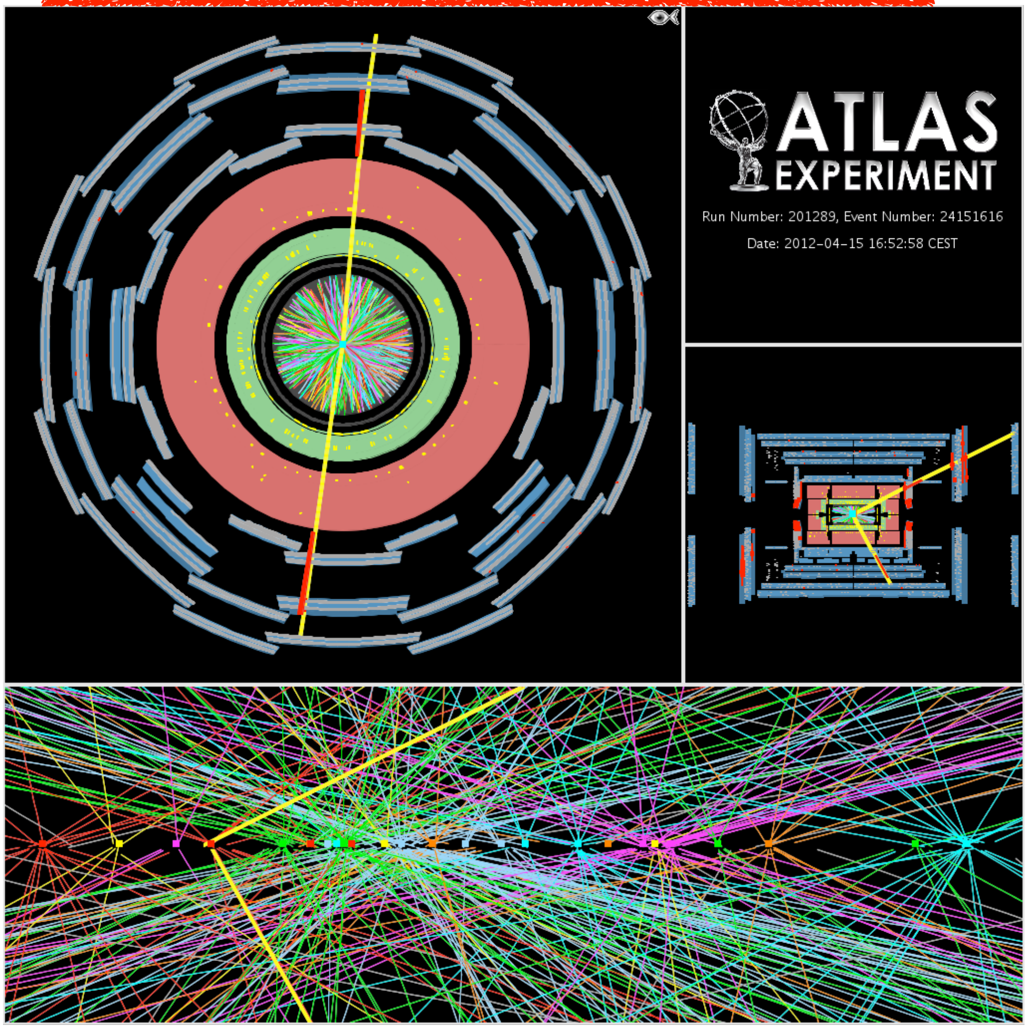


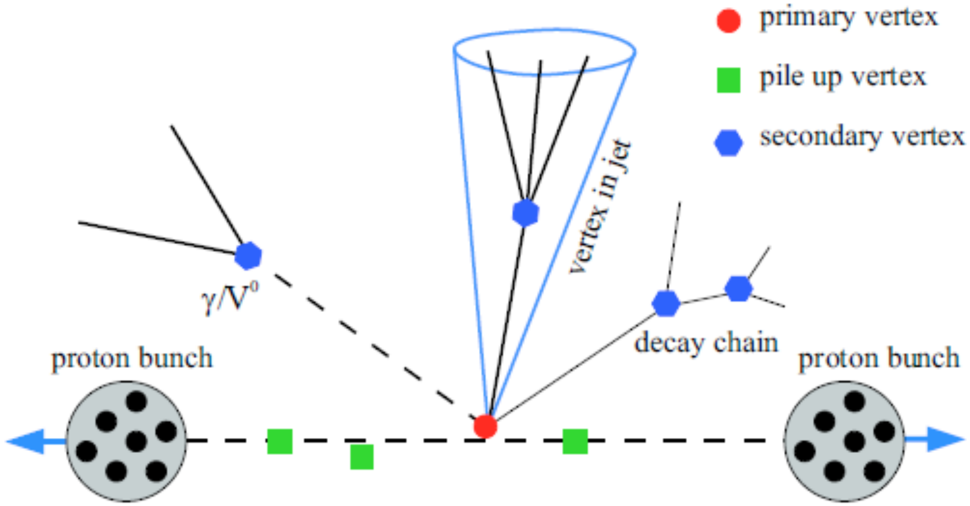
Outstanding LHC performance!!!

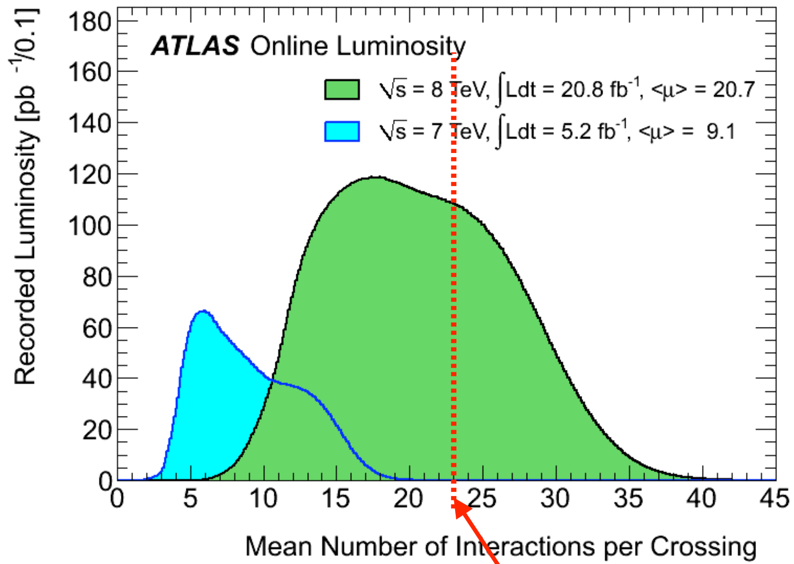
2012 peak luminosity 7.9nb^{-1}/s: ~95 W->lν events/s

The price of high Luminosity: Pileup

Z->μμ candidate event with 25 reconstructed vertices

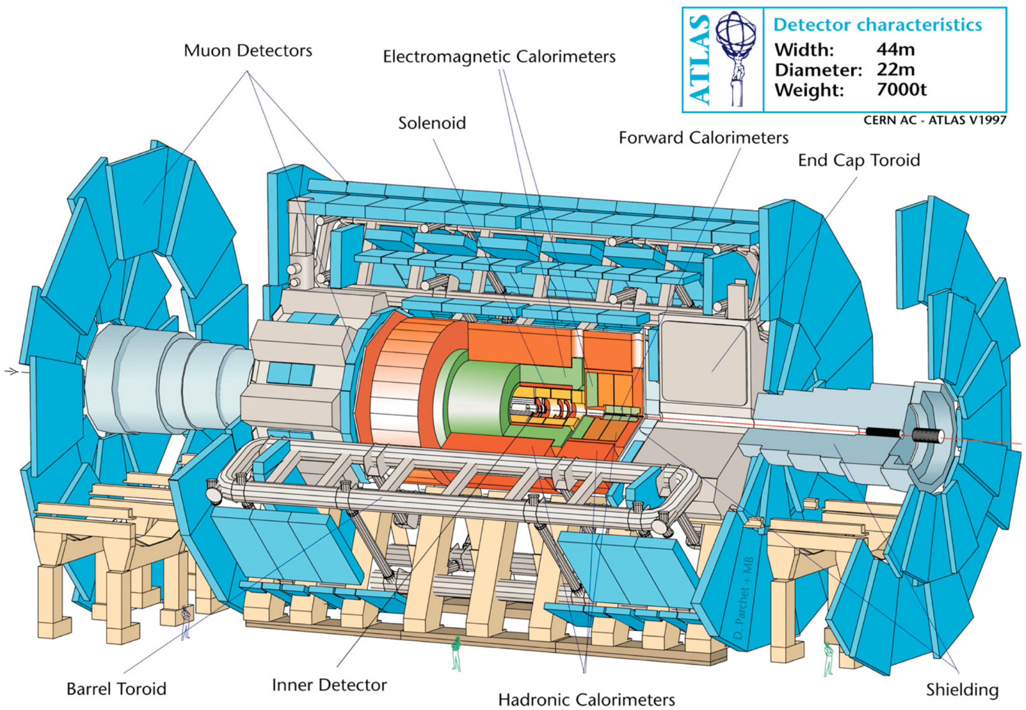


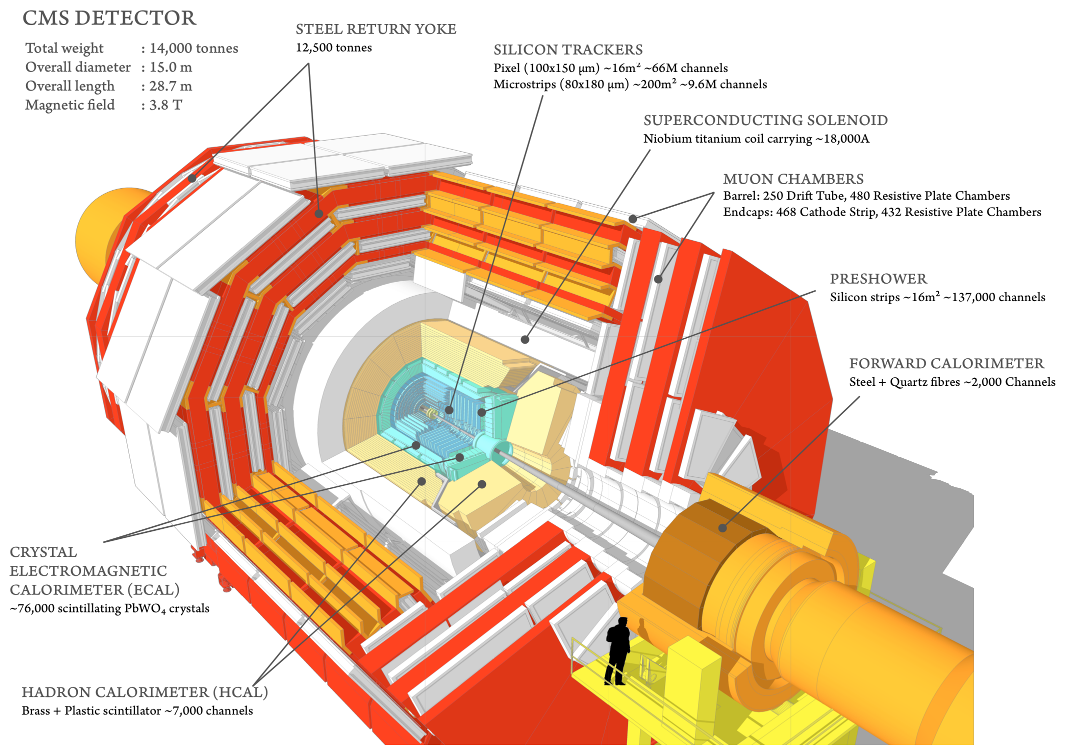




We're dealing with pileup, already greater than design!!

ATLAS - CMS

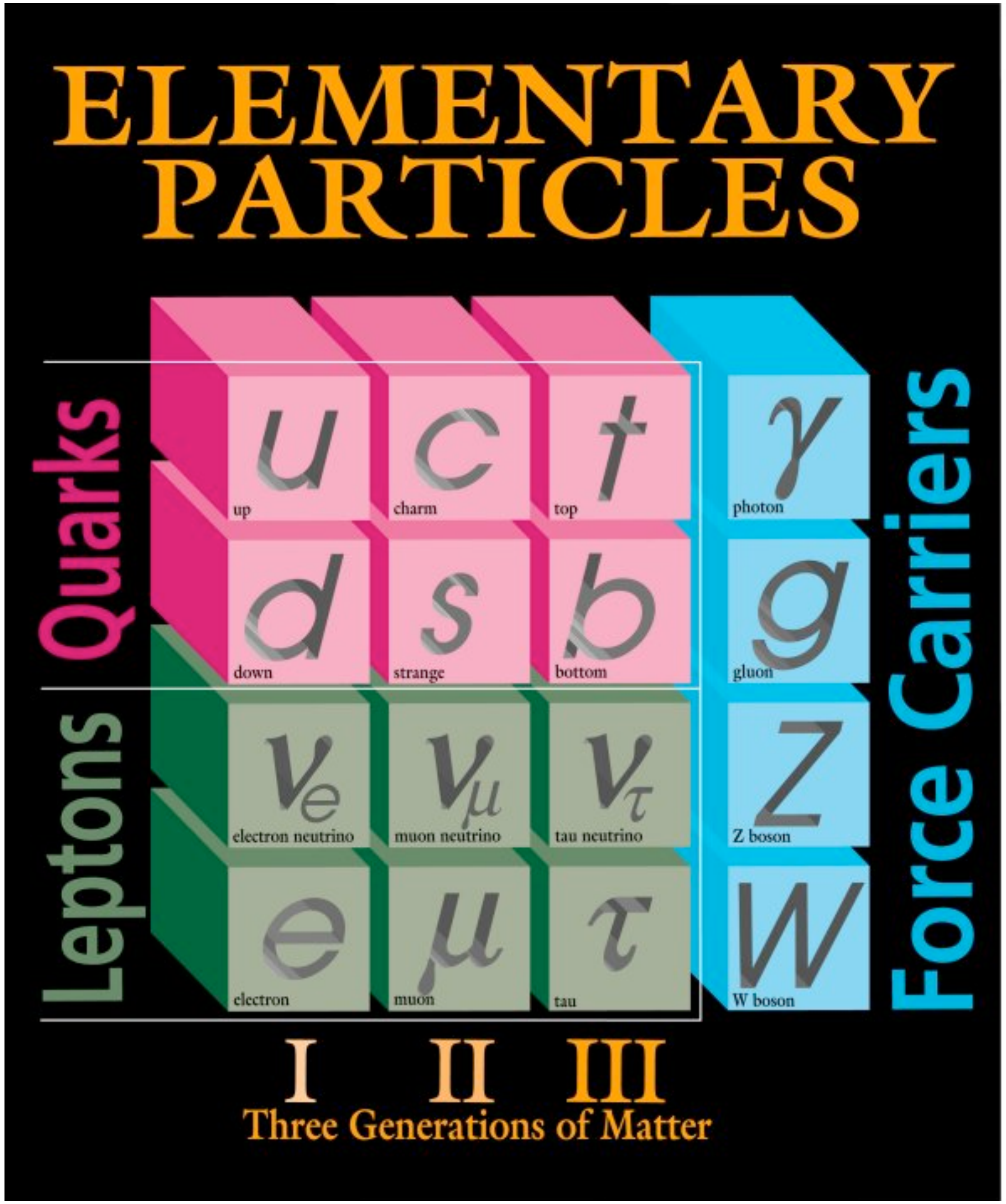




- **Designed for Higgs boson discovery and New Physics searches**
- Excellent vertex and tracking system
  - ✦ **Our best handle against pileup**
- Excellent calorimetry with extended coverage to enable accurate jet and missing energy measurements
- Large coverage of muon detection

I will mainly focus on ATLAS results

Why still look for SM?

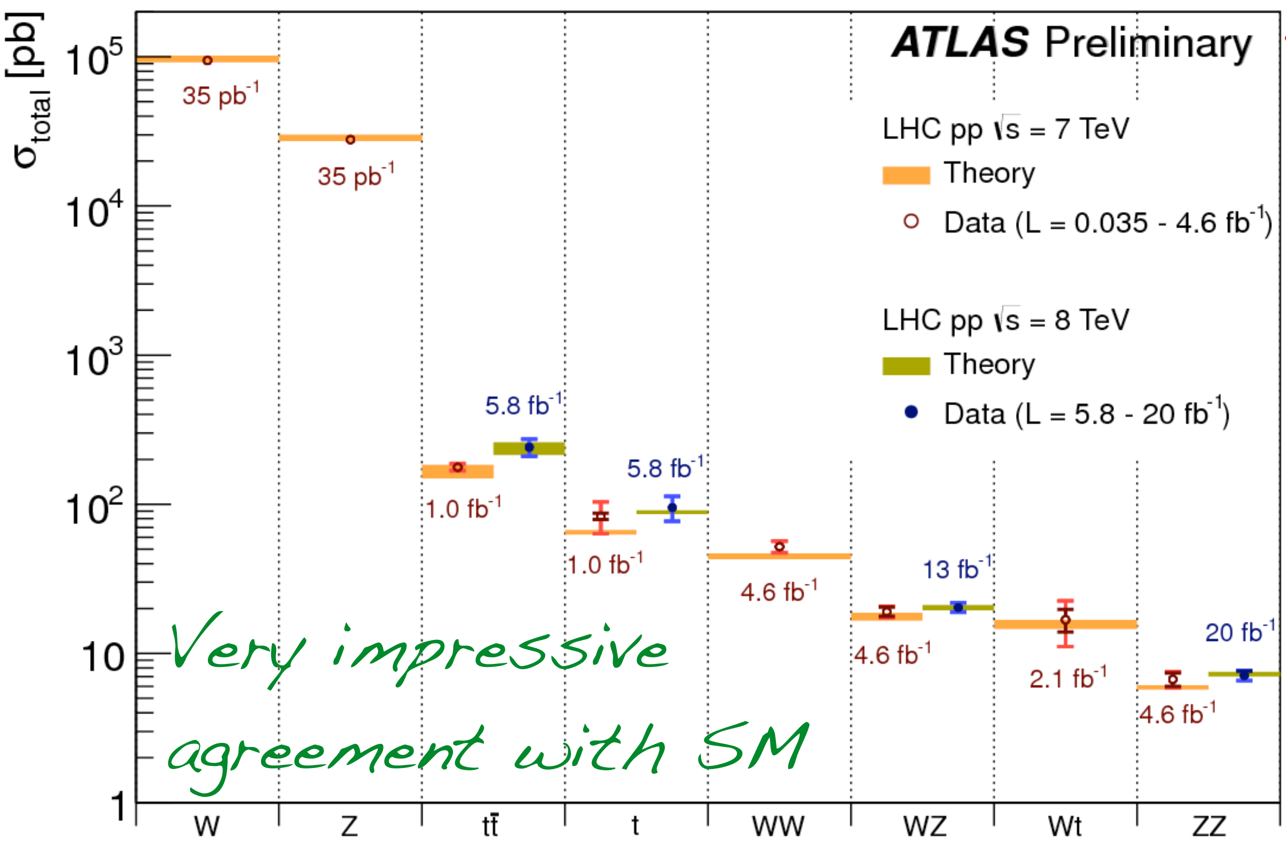


- Do the experiments perform as designed?
- Is known physics correctly observed?
- Then look for new physics

- We can claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model

➡ **Make sure we understand what we measure**

Standard Model: Inclusive cross-sections



In 2012, ~22 fb^{-1} @ 8TeV

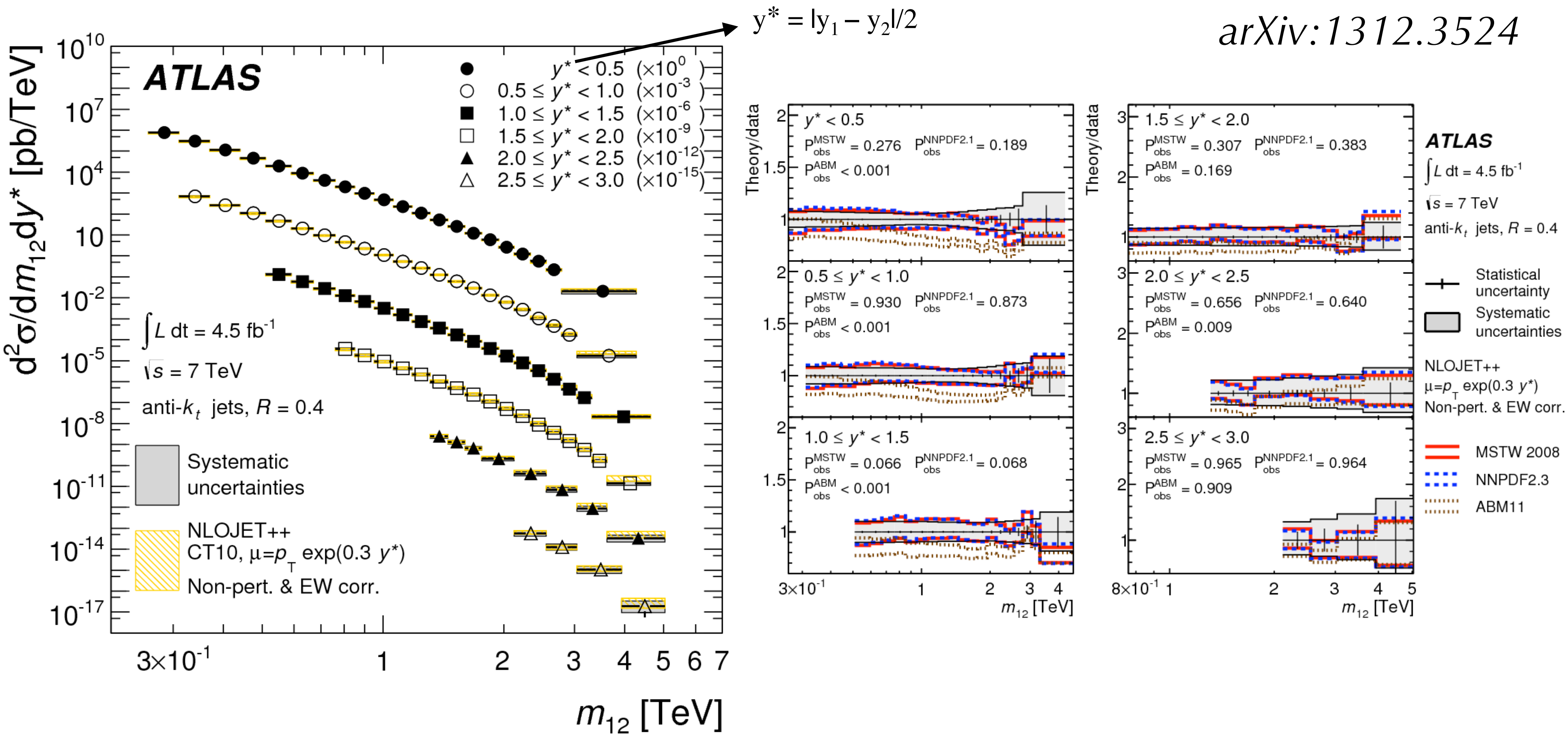
- 1.5 quadrillion (10^{15}) pp inelastic collisions
- 3 billions (10^9) recorded including pileup

After selections

- 100M W->lv
- 10M Z->ll
- 400k ttbar->lX
- hundreds of H(125)

- In general, make **measurements** fully **corrected to fiducial acceptances**, which can be easily **reproduced in MC generators**, extrapolate to total cross-sections
- More **complex topologies** are important **backgrounds** for **Higgs** and **BSM** searches
- Beyond inclusive cross-sections: plenty of **high precision measurements** -can only flash a few examples here-

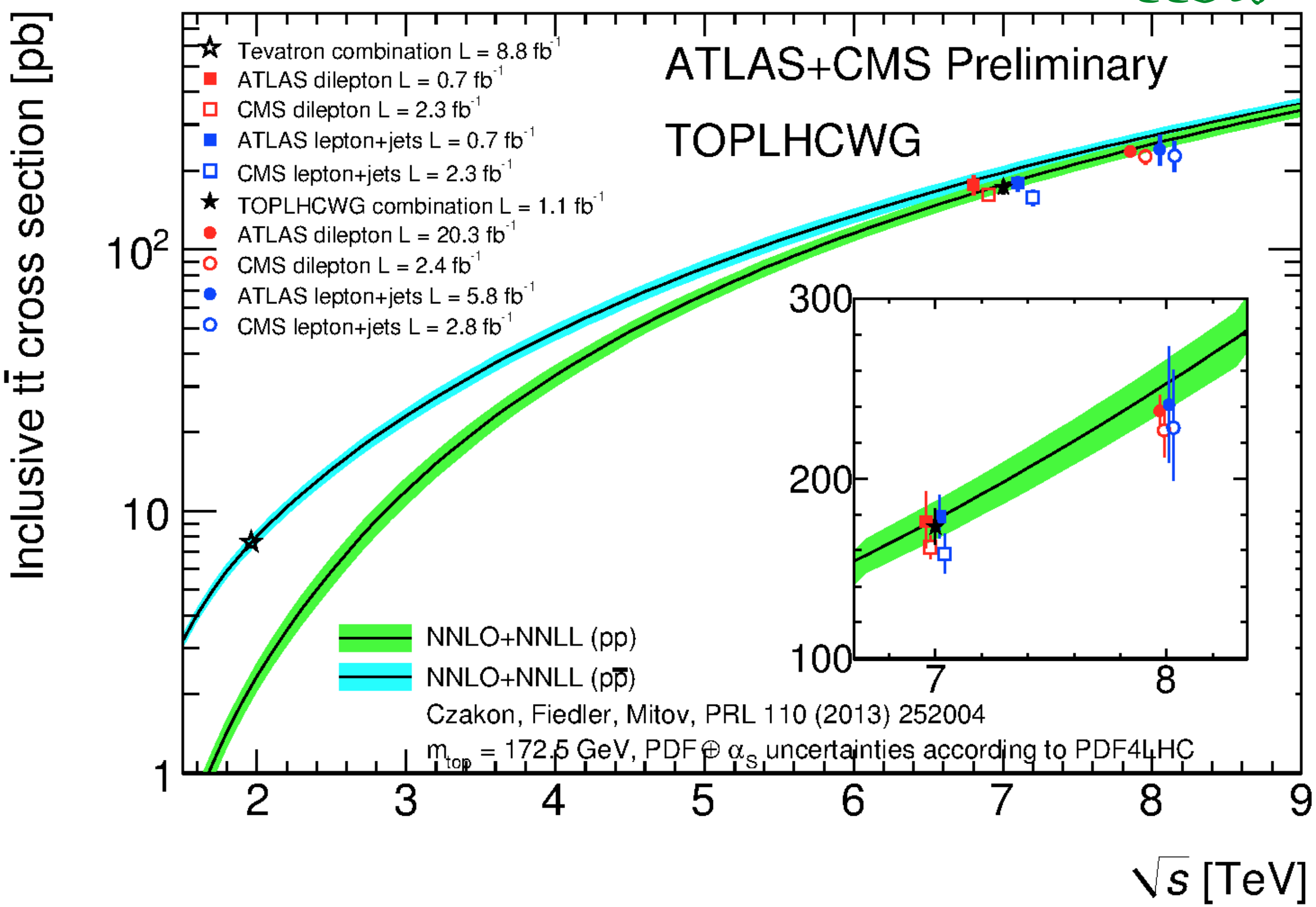
Standard Model: Dijets



- **Dijet differential** cross-section as a function of **m_{jj}**
- Superb **QCD agreement**
- Precision high enough, to **test different PDF's**
- All necessary info is public: People can easily test their models

Top quark physics

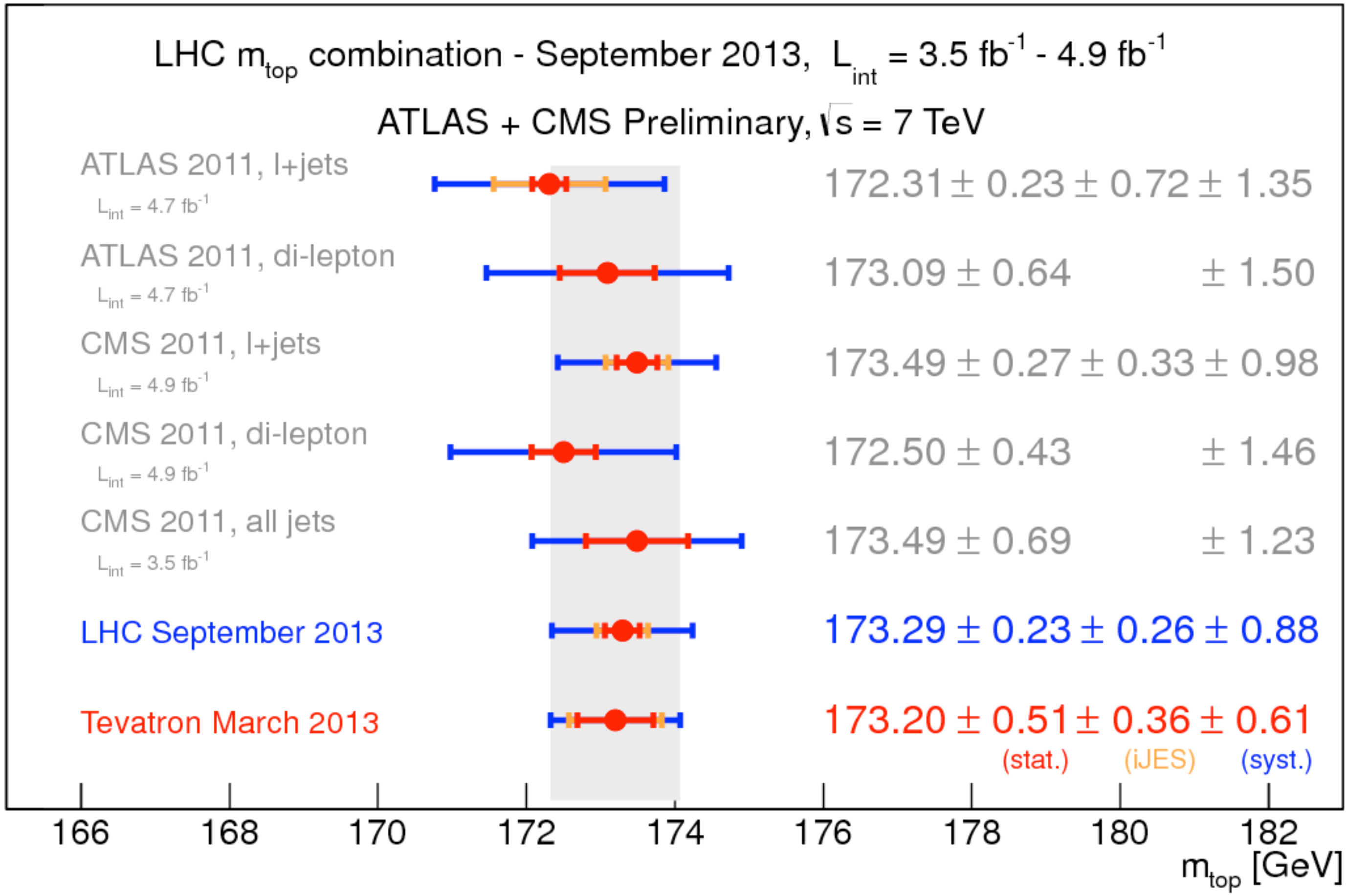
ttbar



- **Excellent description** by NNLO+NNLL
- Top quark measurements are **systematics-limited**. Ongoing efforts on reducing systematic uncertainties

Top quark physics

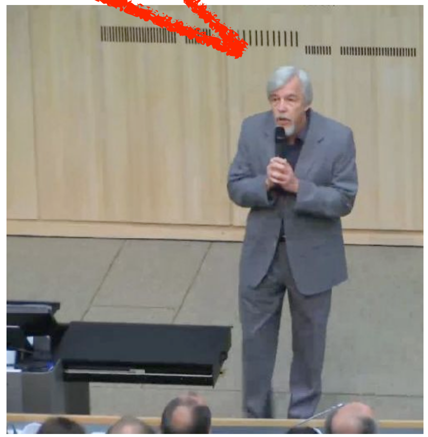
mass of the top



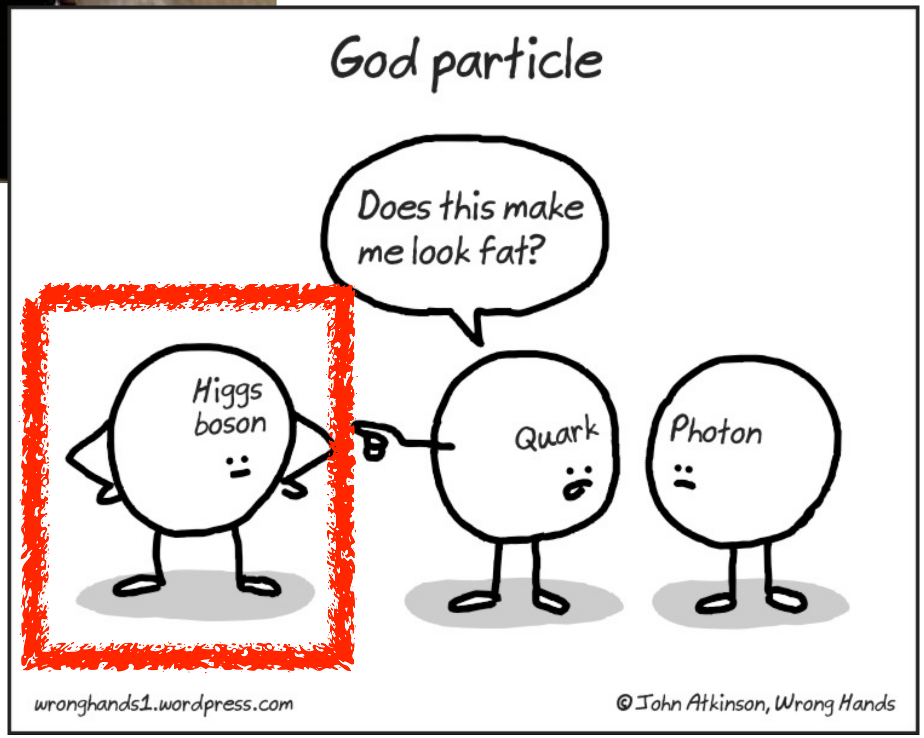
- ATLAS-CMS combination of 2011 results, for $\mathbf{m_{top}}$
  - Uncertainty of **0.95 GeV** comparable to Tevatron measurement
    - Dominated by **systematic uncertainties** due to **jet calibration**
  - 2012 updates are on going: **$\mathbf{m_{top}}$ higher precision to be reached soon**

"I think we have it!!"

- ***July 4 2012, "Discovery!"***

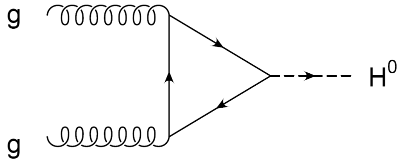


CERN DG, Rolf Heuer
on the 4th of July 2012

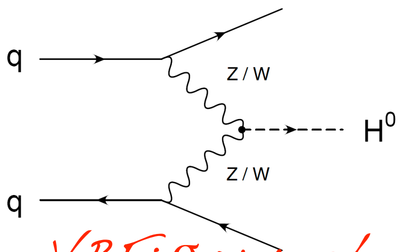


Higgs phenomenology @ LHC

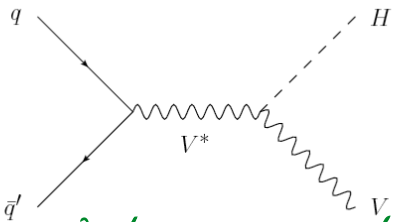
LHC Higgs Xsec WG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
(arXiv:1307.1347)



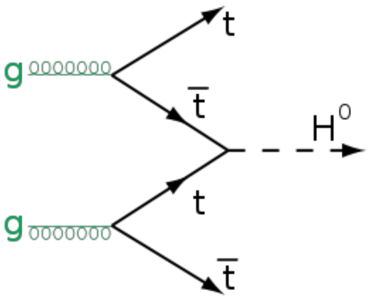
ggF: σ =19.2 pb



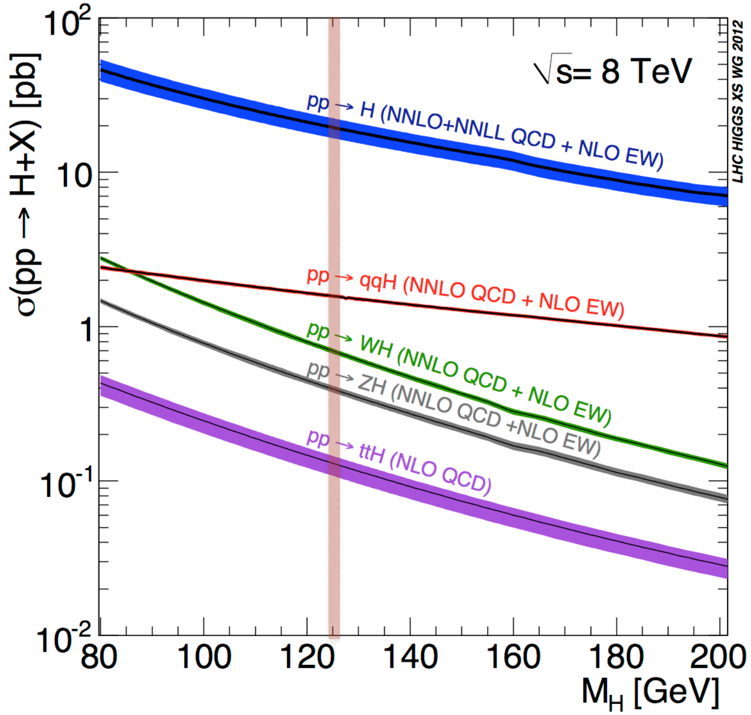
VBF: σ =1.6 pb

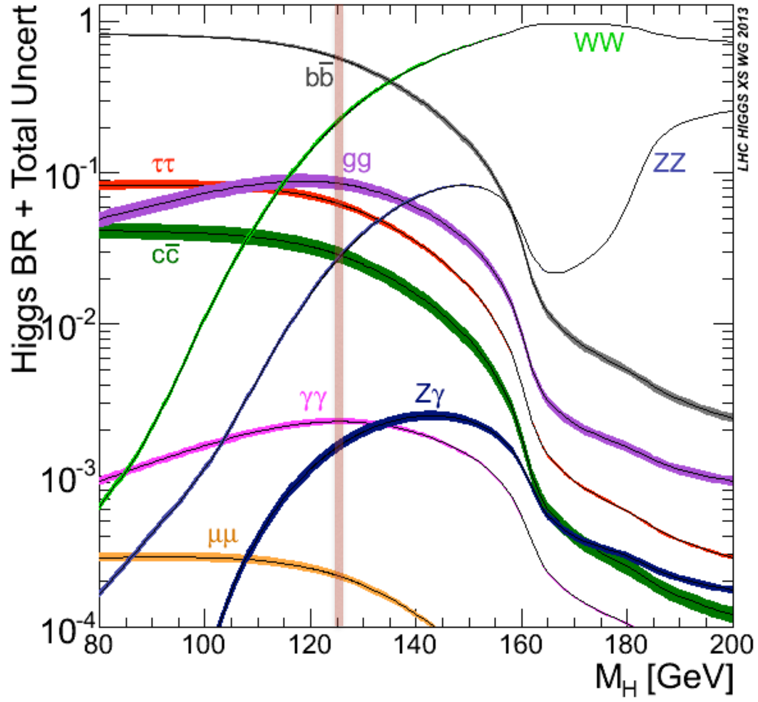


WH: σ =0.7 pb
ZH: σ =0.4 pb



ttH: σ =0.13 pb



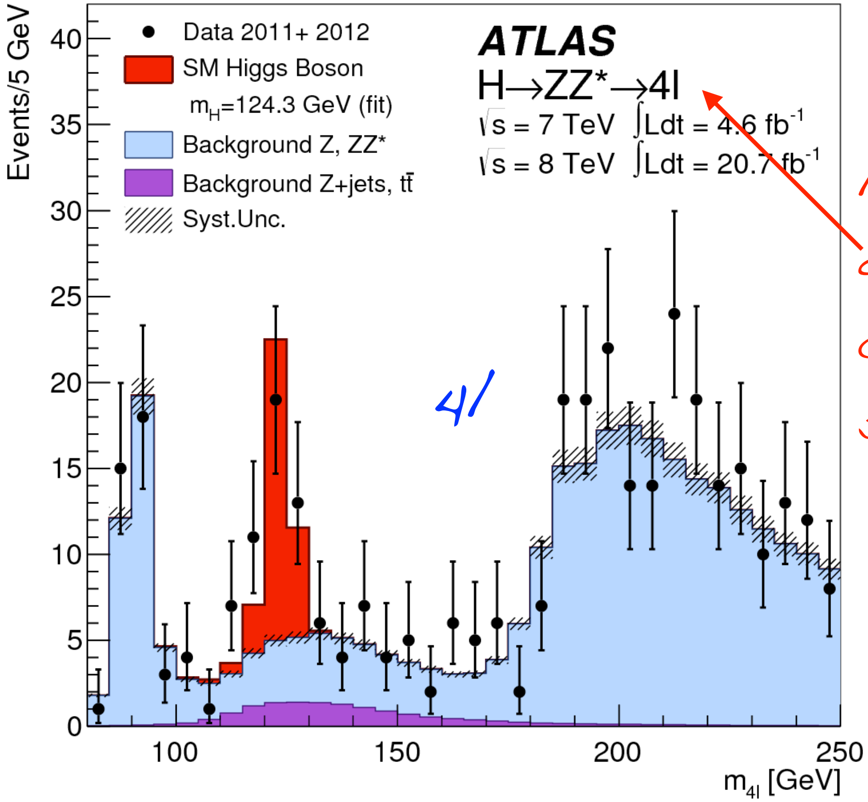


Br(H—>WW): 22%   Br(H—>bb): 57%
Br(H—>ZZ): 2.8%   Br(H—>ττ): 6.2%
Br(H—>γγ): 0.23%

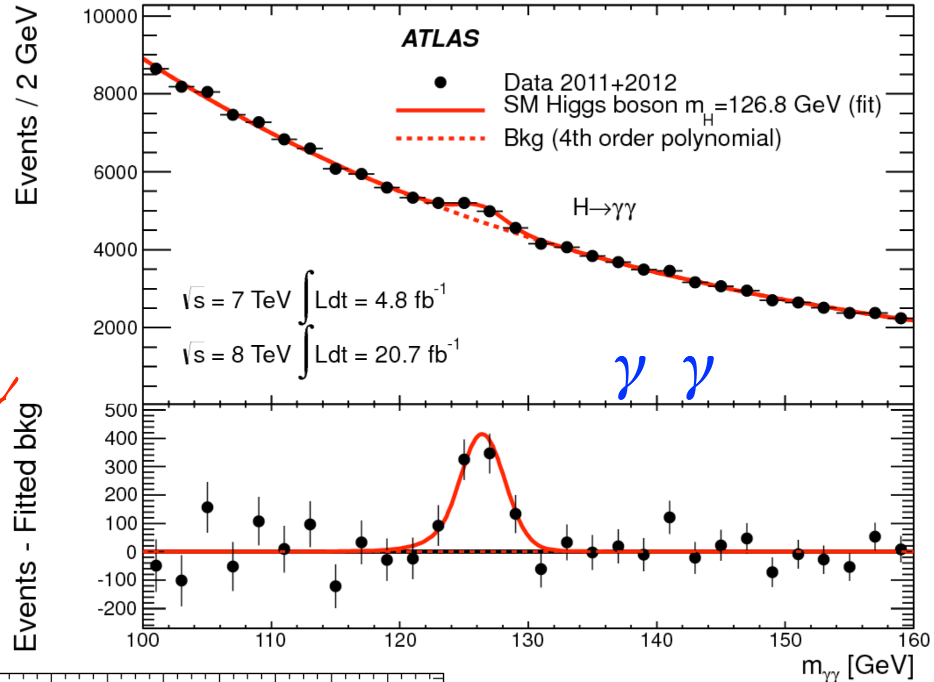
- Measure all possible combinations of production modes and decay channels
- Nature is being kind, giving us a Higgs boson with a m_H~125 GeV, perfect mass point to measure all measurable decay channels

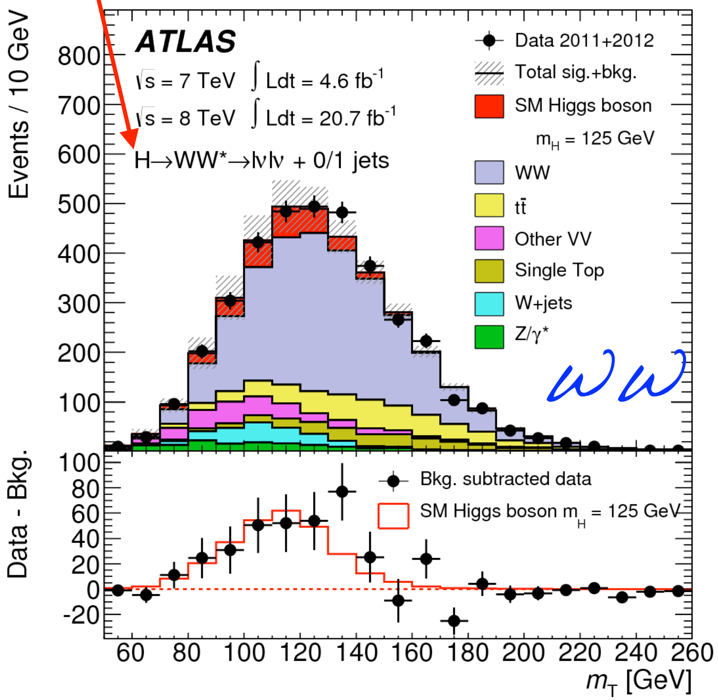
Higgs to bosons

arXiv:1307.1427



leptonic
decays only
cleaner
signature





- **Higgs mass peaks visible to the naked eye!!**
- **4l and γγ excellent mass resolution: 1-2%**

Higgs to bosons

- We fit the Background + μ×Signal model to the data
  - μ: the parameter of interest, signal strength: $\mu = \frac{\sigma_{measured}}{\sigma_{SM}}$
  - The value **μ=0 (μ=1)** corresponds to the **absence (presence)** of a Higgs boson signal with the SM production cross section.

μ	**ATLAS**	**CMS**
H—>γγ	1.5 ± 0.3	0.8 ± 0.3
H—>ZZ*	1.4 ± 0.4	0.9 ± 0.3
H—>WW*	1.0 ± 0.3	0.7 ± 0.2
Combined	1.3 ± 0.2	0.8 ± 0.2

Consistent with SM Higgs boson predictions !

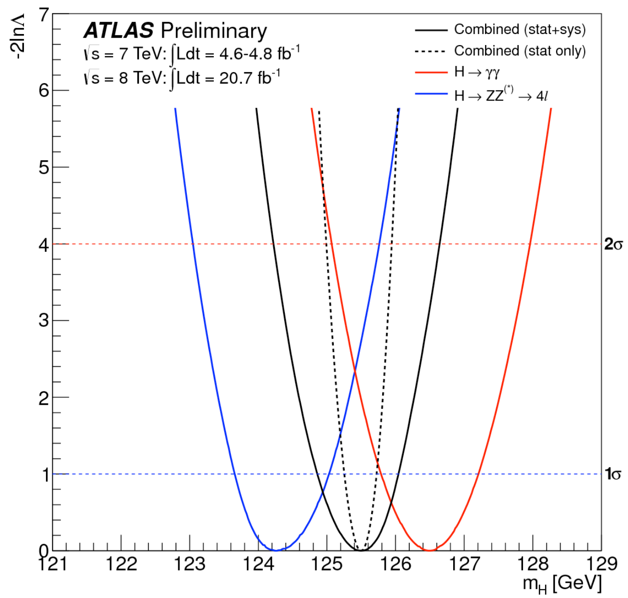
ATLAS combined mass measurement

ATLAS-CONF-2013-014

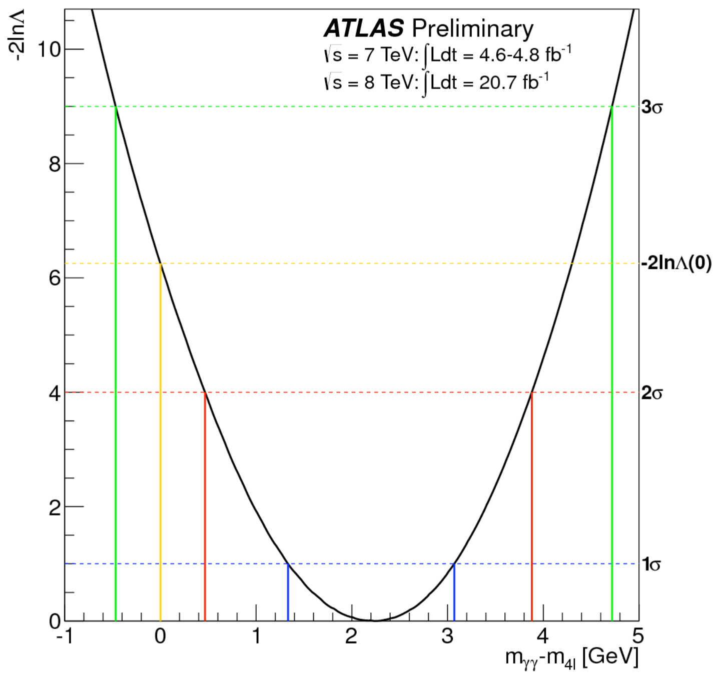
$m_H^{\gamma\gamma}$ = 126.8 ± 0.2 (stat.) ± 0.7 (sys) GeV

m_H^{4l} = 124.3 ± 0.6 (stat.) ± 0.5 (sys.)

- Combined mass measurement
  - **m_H = 125.5 ± 0.2 (stat.) ± 0.6 (syst.) GeV**



- Mass difference, $m_{\gamma\gamma}$ - m_{4l} :
  - Test the assumption that both come from a common mass, parameter of interest $\Delta m_H = m_{\gamma\gamma} - m_{4l}$
  - Δm_H = 2.3 ± 0.7 (stat) ± 0.6 (sys) GeV
  - Consistency of $\Delta m_H = 0$:
    - **2.4σ** away from $\Delta m_H = 0$ (p-value=**1.5**%)



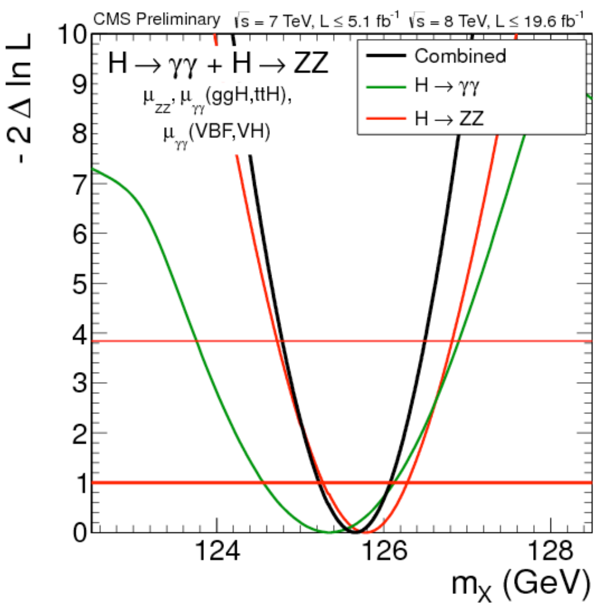
CMS combined mass measurement

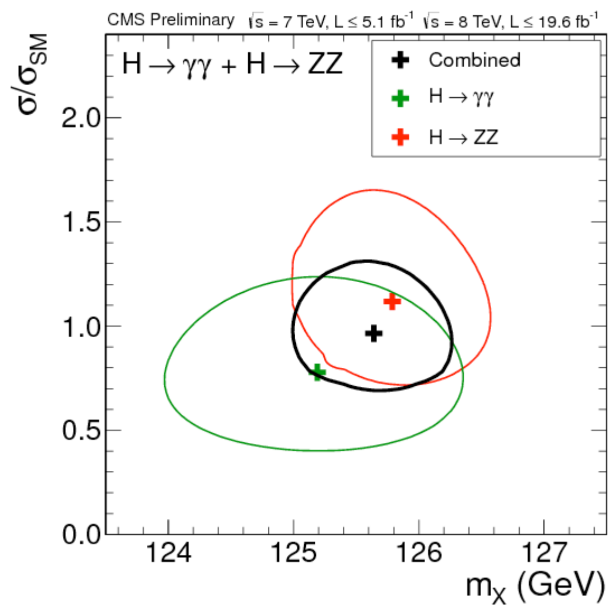
CMS-PAS-HIG-13-005.

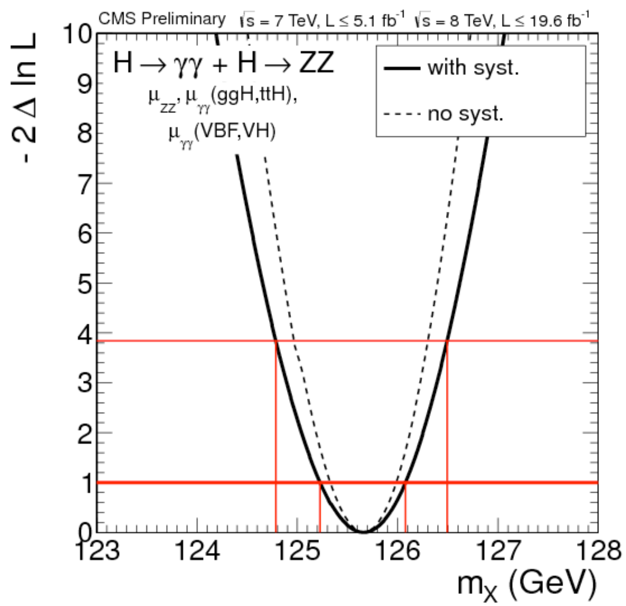
$m_H^{\gamma\gamma}$ = 125.4 ± 0.5 (stat.) ± 0.6 (syst.) GeV

m_H^{4l} = 125.8 ± 0.5 (stat.) ± 0.2 (syst.) GeV

- CMS Combined mass measurement
  - **m_H = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV**



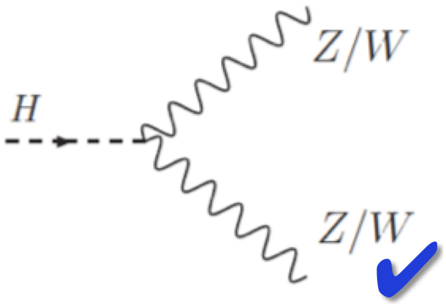


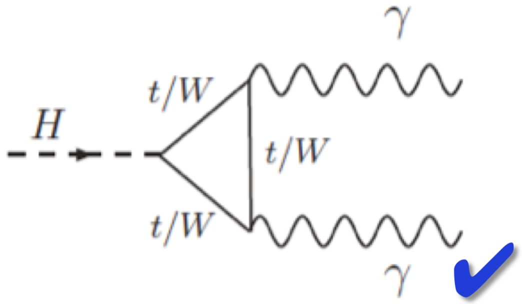


- **ATLAS: m_H = 125.5 ± 0.2 (stat.) ± 0.6 (syst.) GeV**

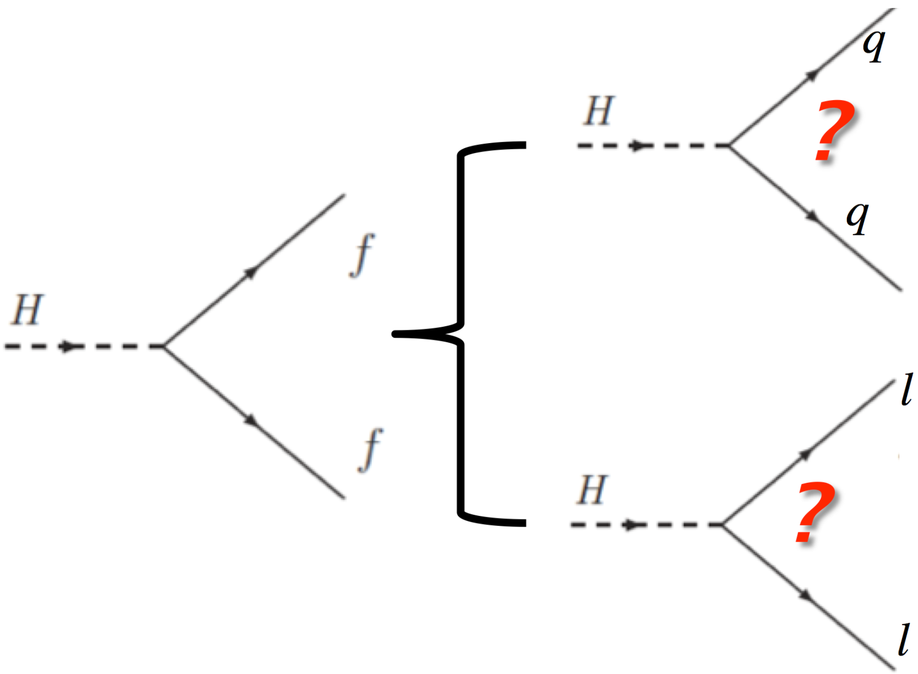
Higgs to fermions

- Observation via ZZ*, WW* and γγ decay modes





- Is the discovered Higgs boson coupling to fermions?



- quarks?

Most likely yes, because of the quark loop in gg-fusion/photon decay. Nevertheless a direct measurement to quarks is necessary (**H→bb**)

- leptons?

This is the question that the **H→ττ/μμ** analyses are addressing

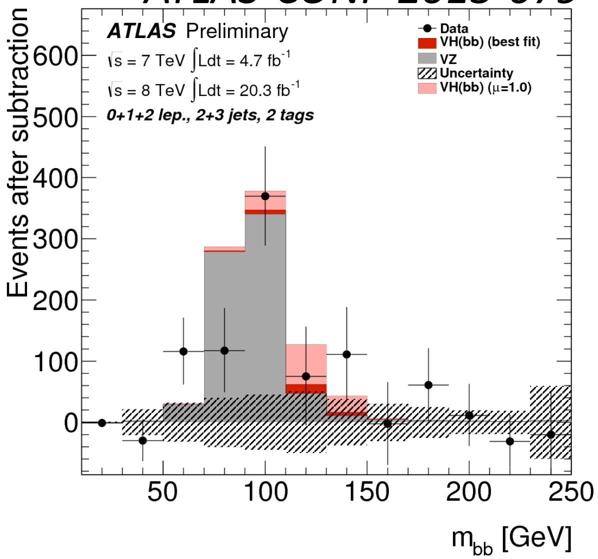
NEW!

ATLAS & CMS updated ττ results from December 2013!!

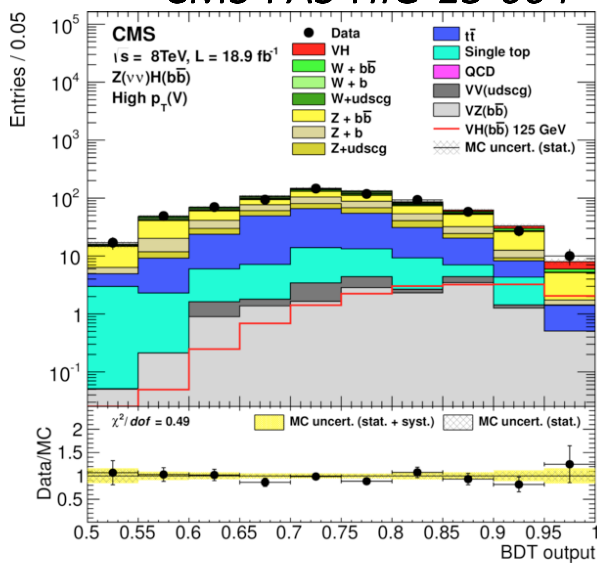
Higgs to fermions (bb)

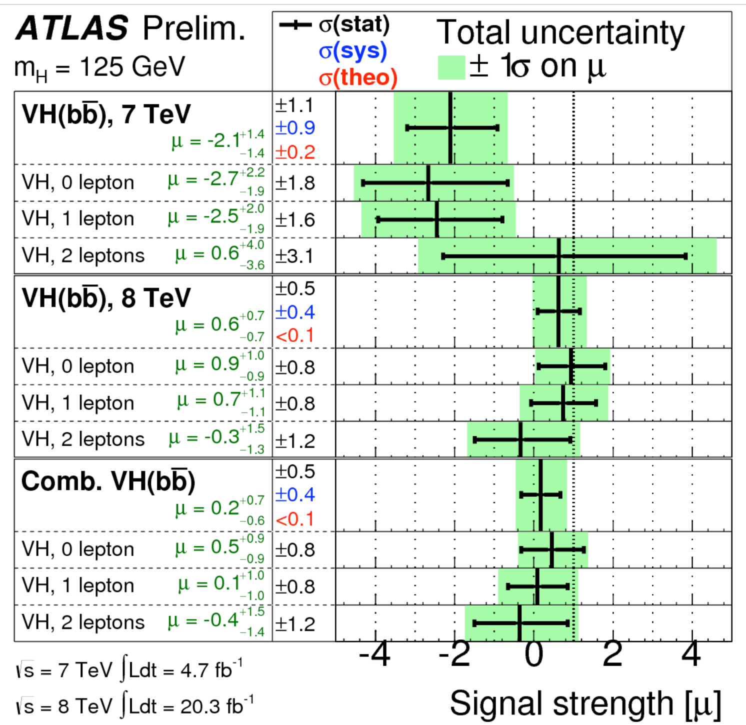
- VH, H—>bb
  - *V*: W—>lν, Z—>ll,νν
- ATLAS: μ=0.2 ± 0.7
- CMS: μ=1.0 ± 0.5
  - ATLAS observes downward fluctuation (?) originating from 7TeV. Re-analysis ongoing

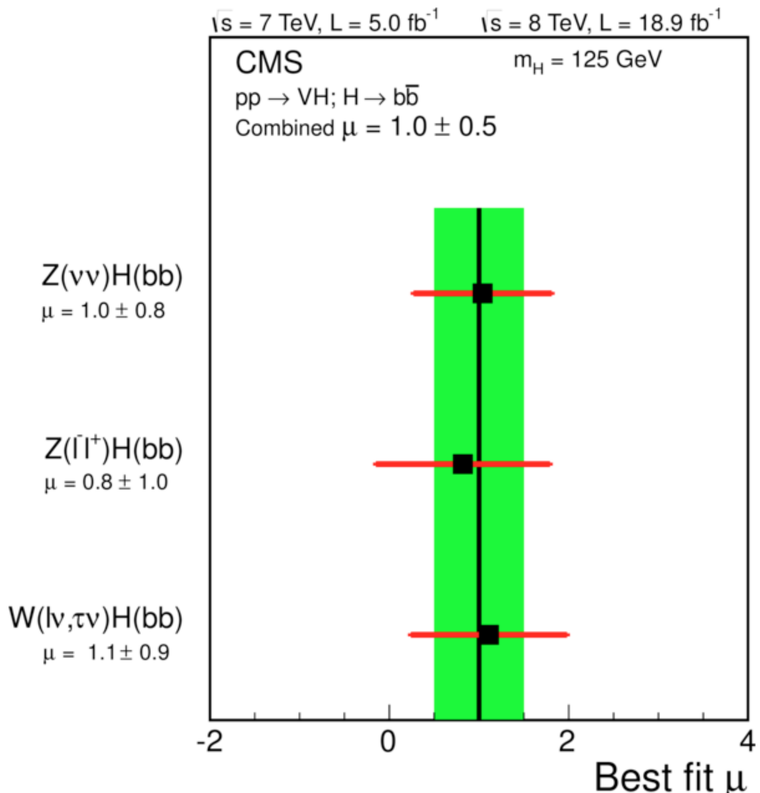
ATLAS-CONF-2013-079



CMS-PAS-HIG-13-004

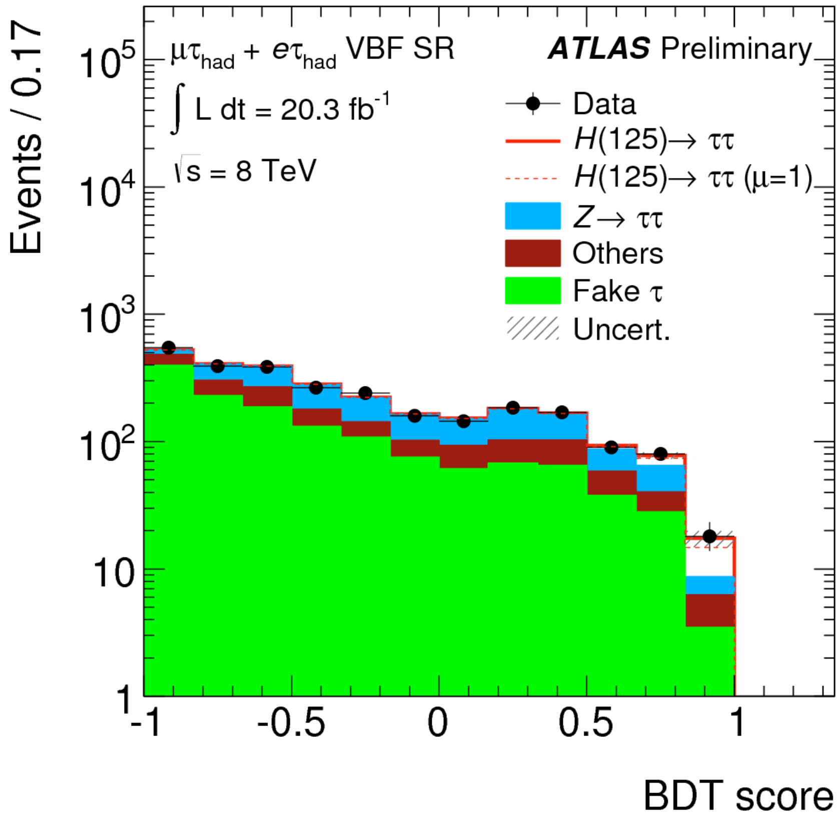






H→ττ significant excess observed

ATLAS-CONF-2013-108



Number of events in highest BDT-score bin

Signal	8.7±2.5
Bckgr.	8.7±2.4
Data	19

Measured signal strength: **μ = 1.4 ± 0.5**

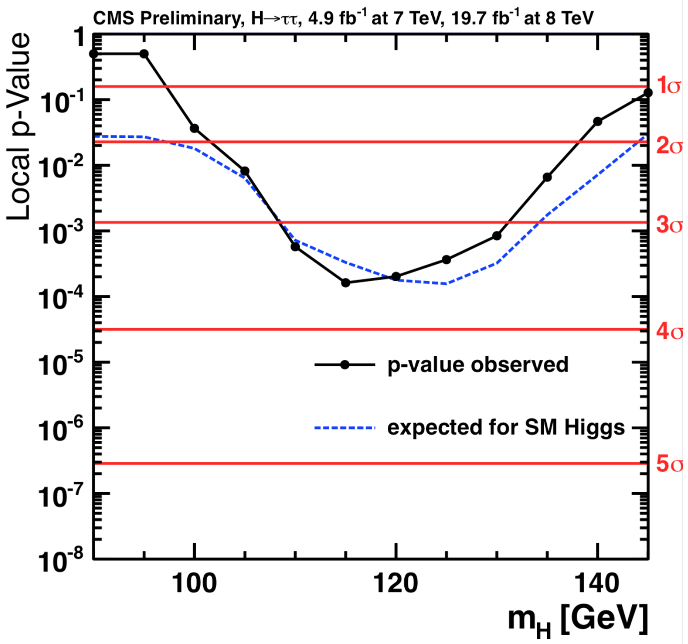
Consistent with SM Higgs boson predictions !

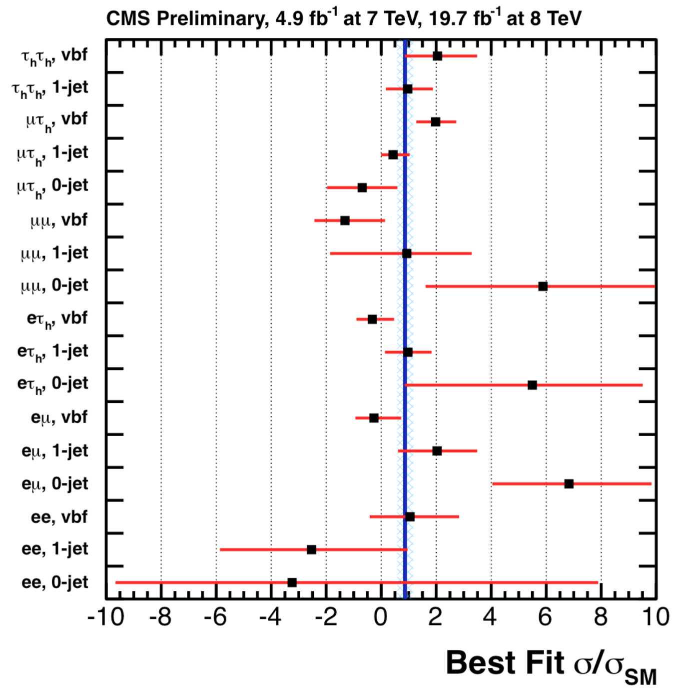
- ATLAS observes significant excess of data events in high S/B region
  - ✦ **Expected** significance @ m_H=125 GeV : **3.2σ** (Probability: **6.6×10^{-4}**)
  - ✦ **Observed** significance @ m_H=125 GeV : **4.1σ**
    - ✳Probability that the observed excess is due to a background fluctuation: **2×10^{-5}**
- **H→ττ (strong) evidence, observed by ATLAS**

$H \to \tau\tau$ in CMS

- **$\tau\tau$ Evidence confirmed by CMS as well!!**

arXiv:1401.5041





At m_H= 125 GeV:

3.4σ observed excess!

3.6σ expected

$\mu = \sigma/\sigma_{SM} = 0.87 \pm 0.29$

- **4σ strong evidence, when CMS combines fermionic channels bb and ττ**

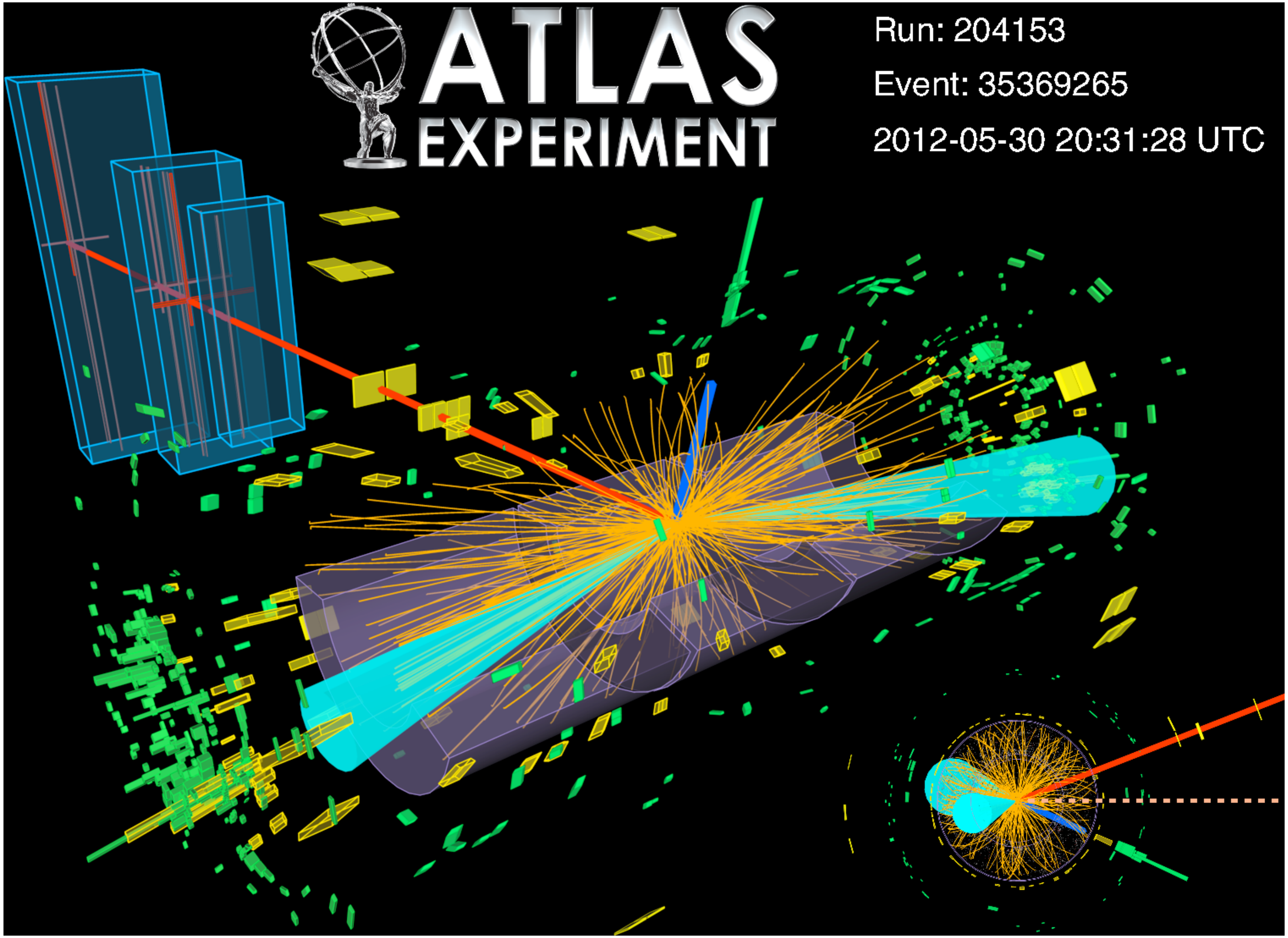
Channel M_H= 125 GeV	Significance		μ
	Expected	Observed	
VH→bb	2.1 σ	2.1σ	1.0±0.5
H→ττ	3.6σ	3.4σ	0.87±0.29
Combination	4.2σ	4.0σ	0.90±0.26

A VBF H—>ττ event

- Event from May 2012

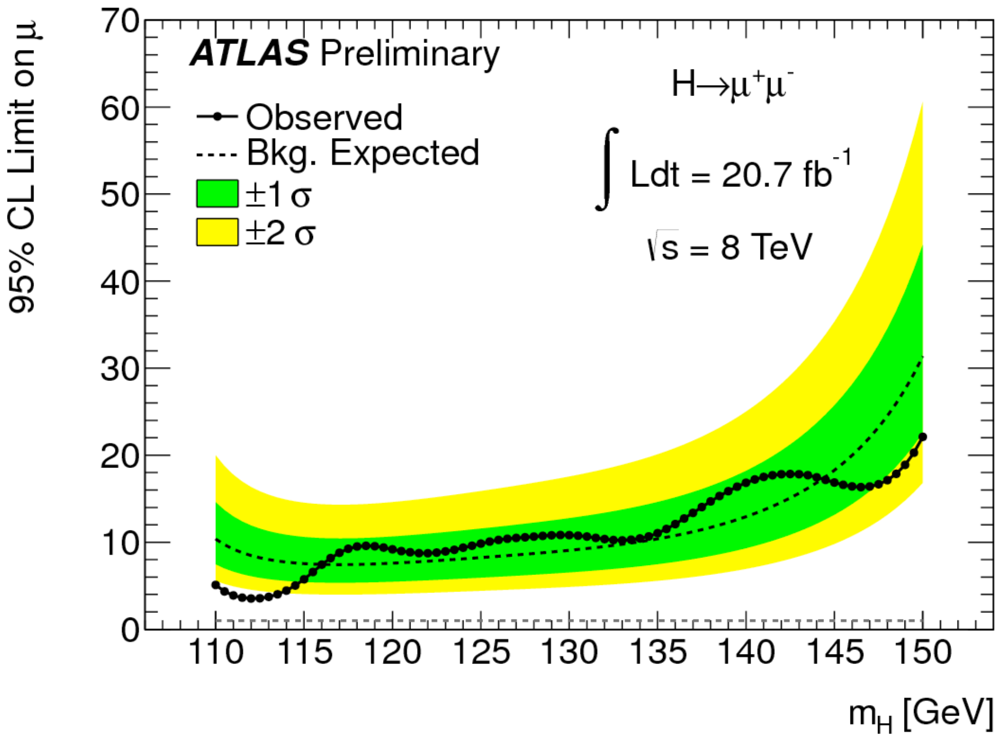
- mu p_T=53 GeV
- el p_T=34 GeV
- E_T^{miss}=102 GeV

- m=127 GeV
- BDT=0.99

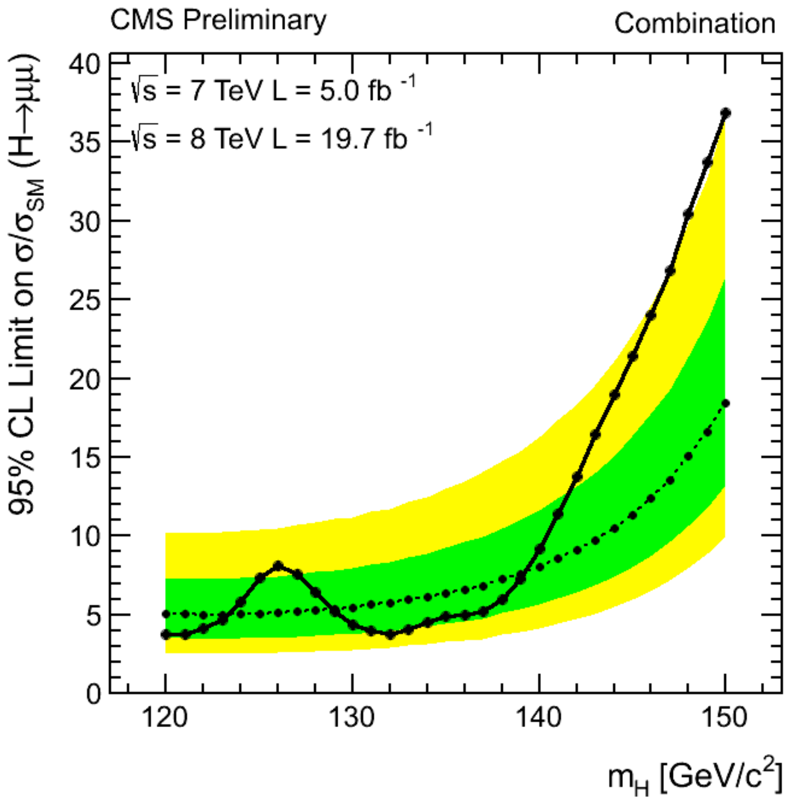


H—>μμ

ATLAS-CONF-2013-010

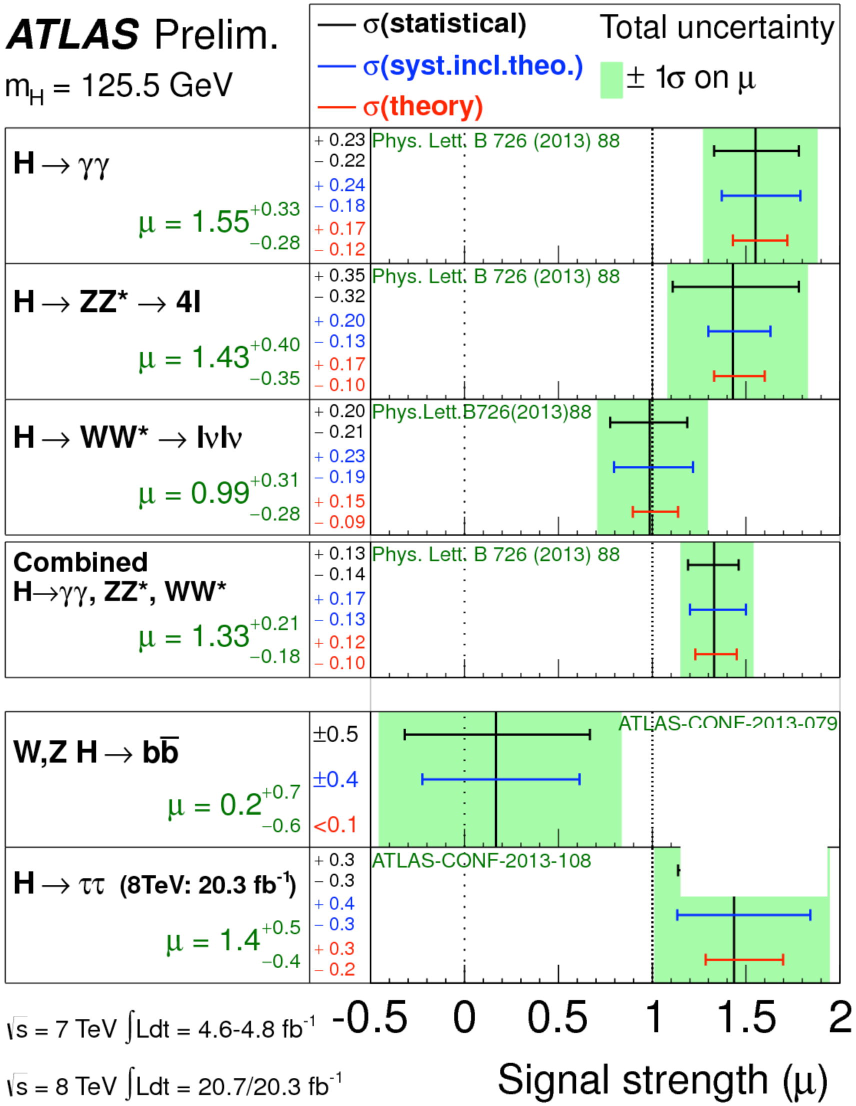


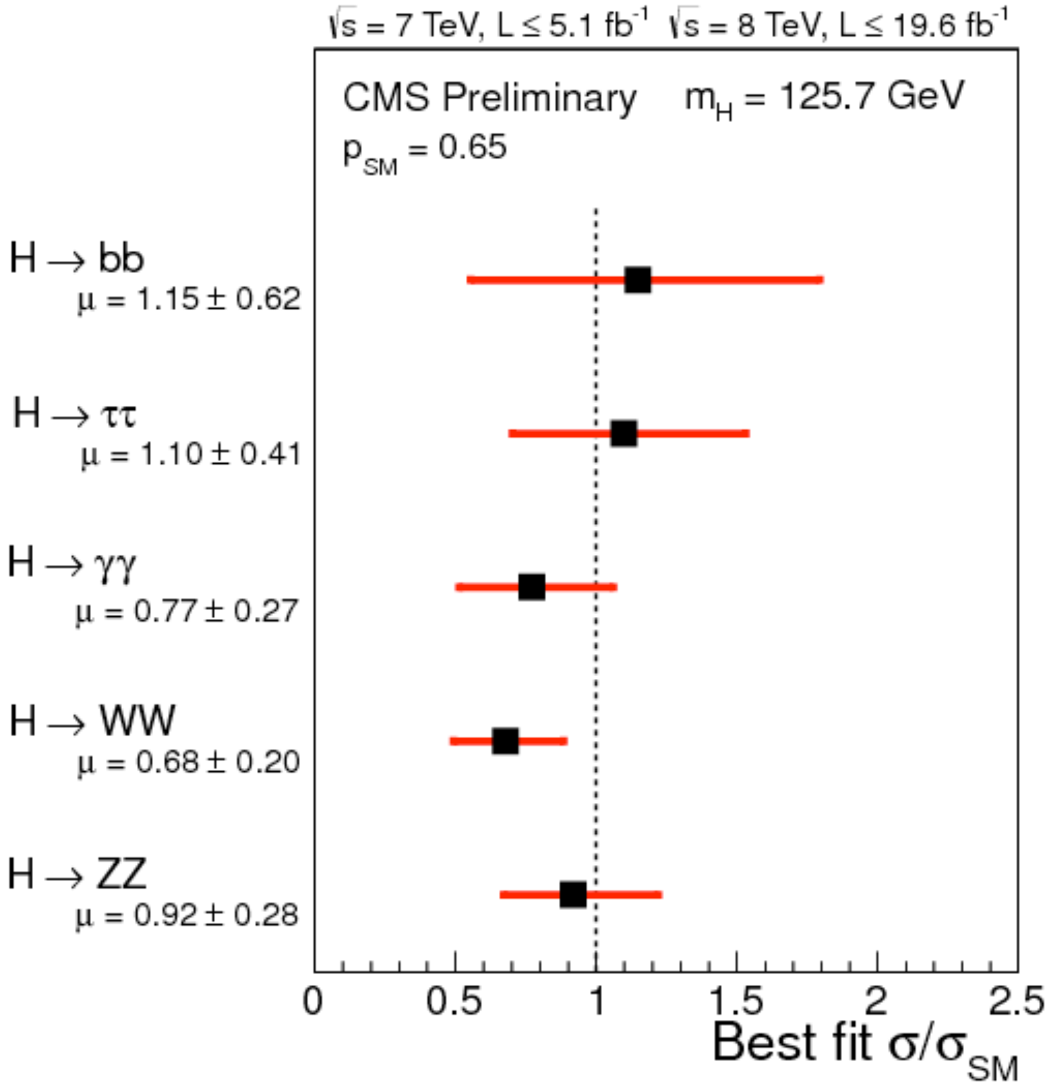
CMS PAS HIG-13-007



- **BR (H—>μμ) very small** ~2.2×10^{-4} (~10 times smaller than γγ)
- Fit $m_{\mu\mu}$ with analytic signal+background shape
- Current sensitivity **not sufficient** for **conclusive statement**
- **ATLAS**: 95% CL limit @ 125 GeV: **expected(observed) 8.2(9.8)**×SM
- **CMS**: 95% CL limit @ 125 GeV: **expected(observed) 5.1(8.2)**×SM

Signal strength: probe production rate





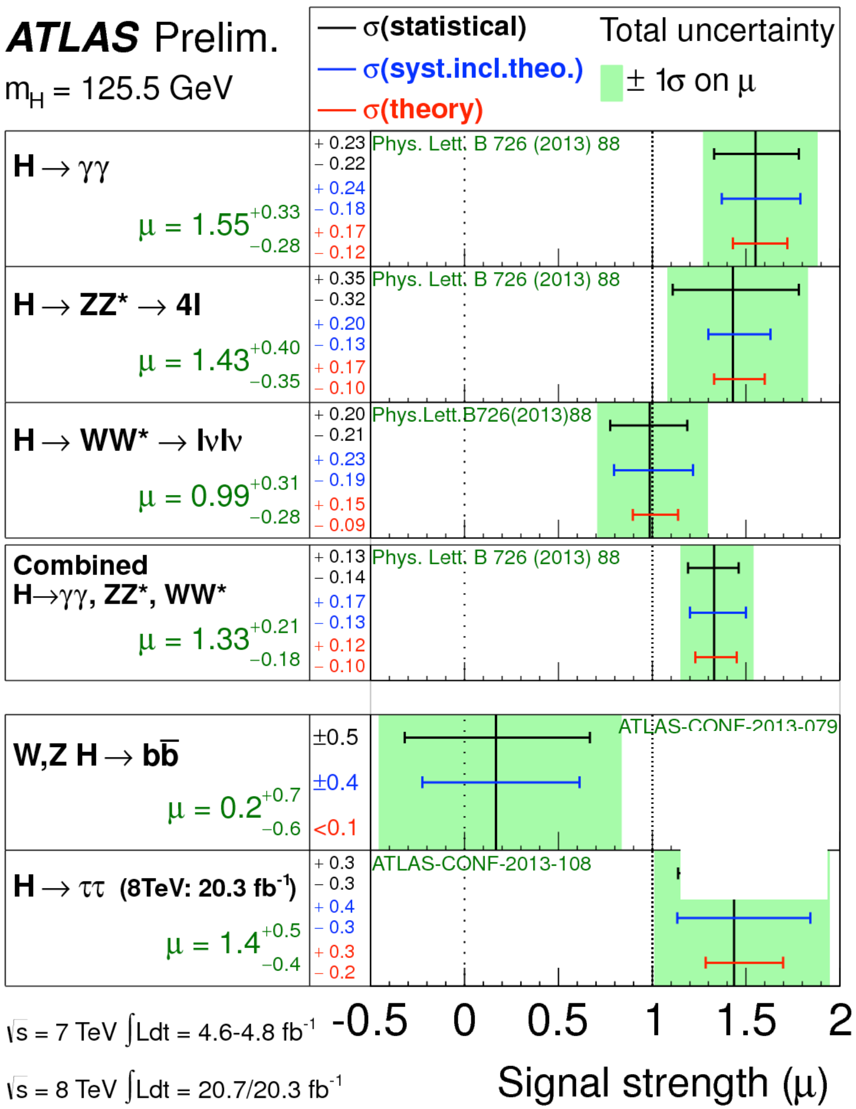
$\mu = 1.33 \pm 0.20$

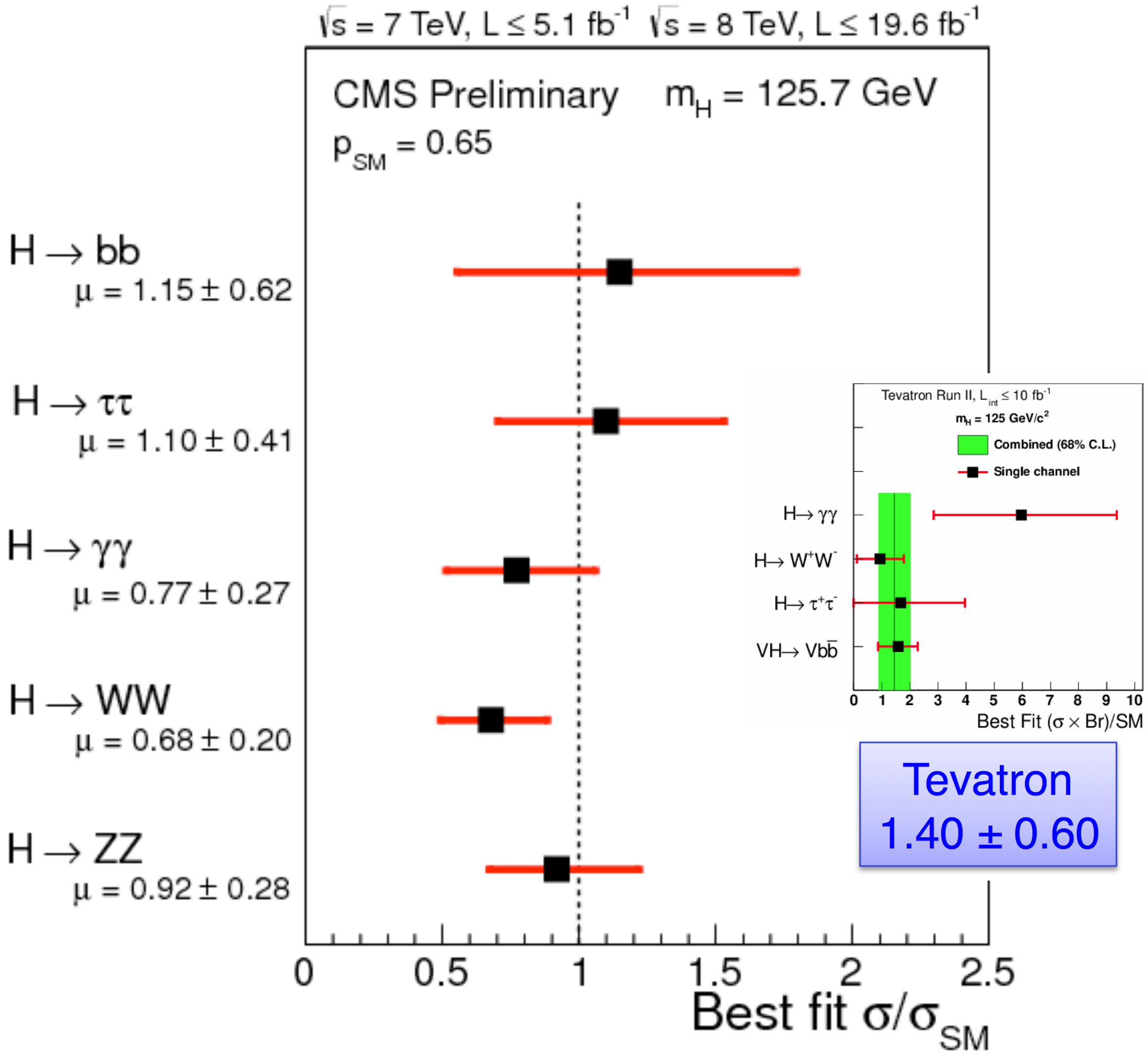
arXiv:1307.1427v1

$\mu = 0.80 \pm 0.14$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Signal strength: probe production rate





$\mu = 1.33 \pm 0.20$

arXiv:1307.1427v1

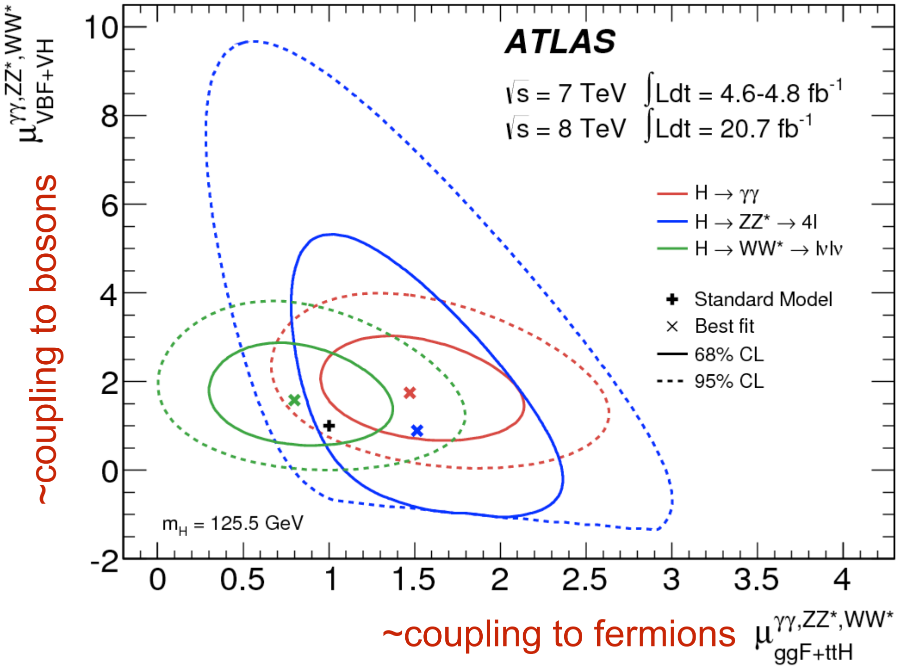
$\mu = 0.80 \pm 0.14$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

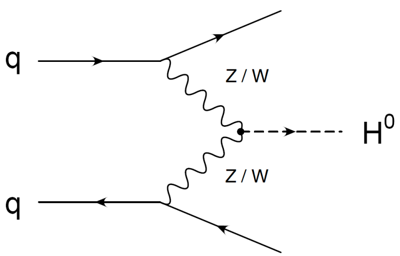
Production processes

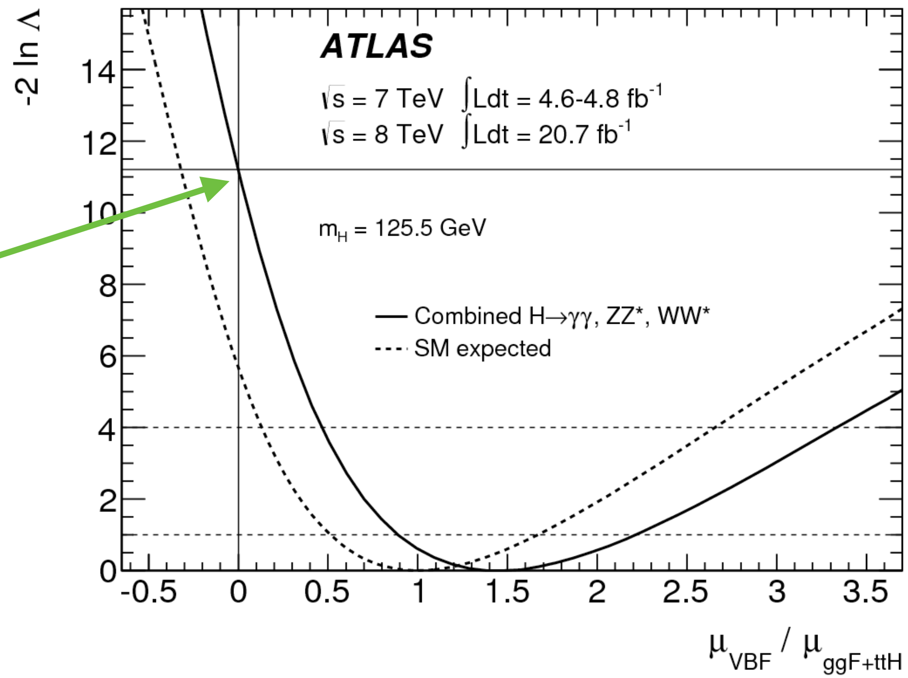
arXiv:1307.1427, Phys. Lett. B 726 (2013), pp. 88-119

- Coupling strength to vector bosons Vs that to fermions
- Compatible with SM=(1,1) within 68% CL contour



- Ratio of vector-boson mediated production compared to gluon (top)-initiated production
  - ✦ **$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.7}_{-0.5}$**
- Looking purely for vector-boson fusion production

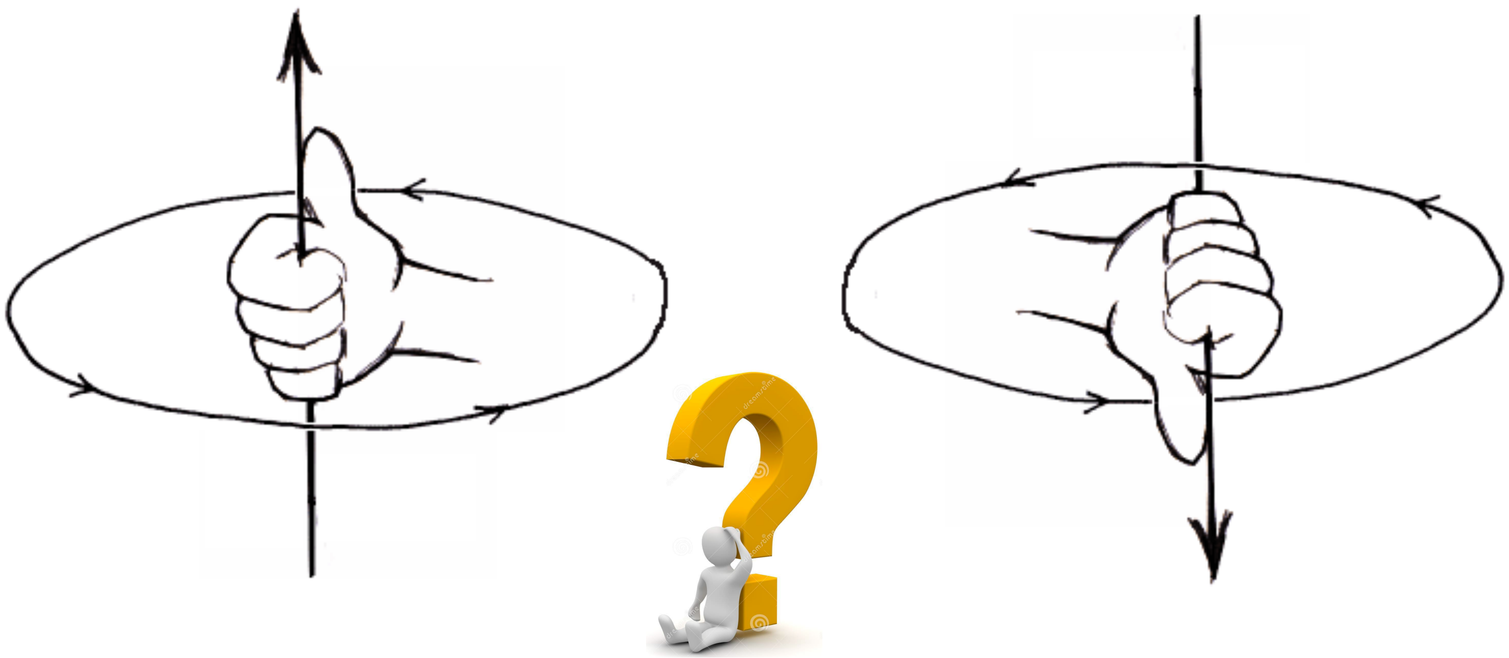




More than 3σ evidence for VBF!

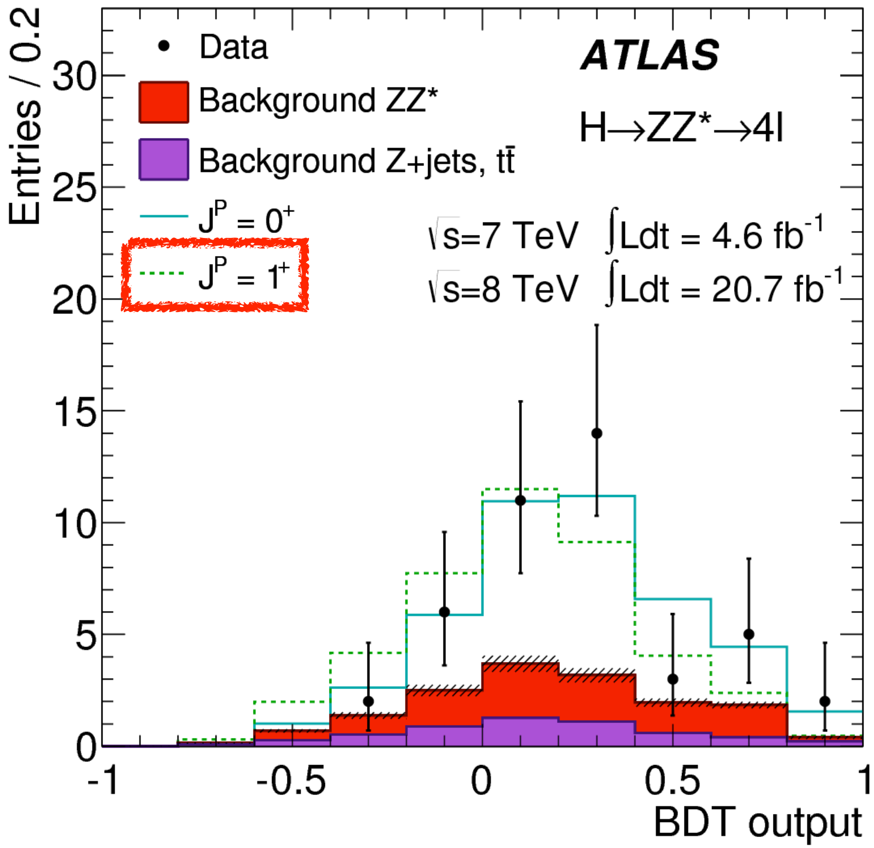
Higgs boson properties

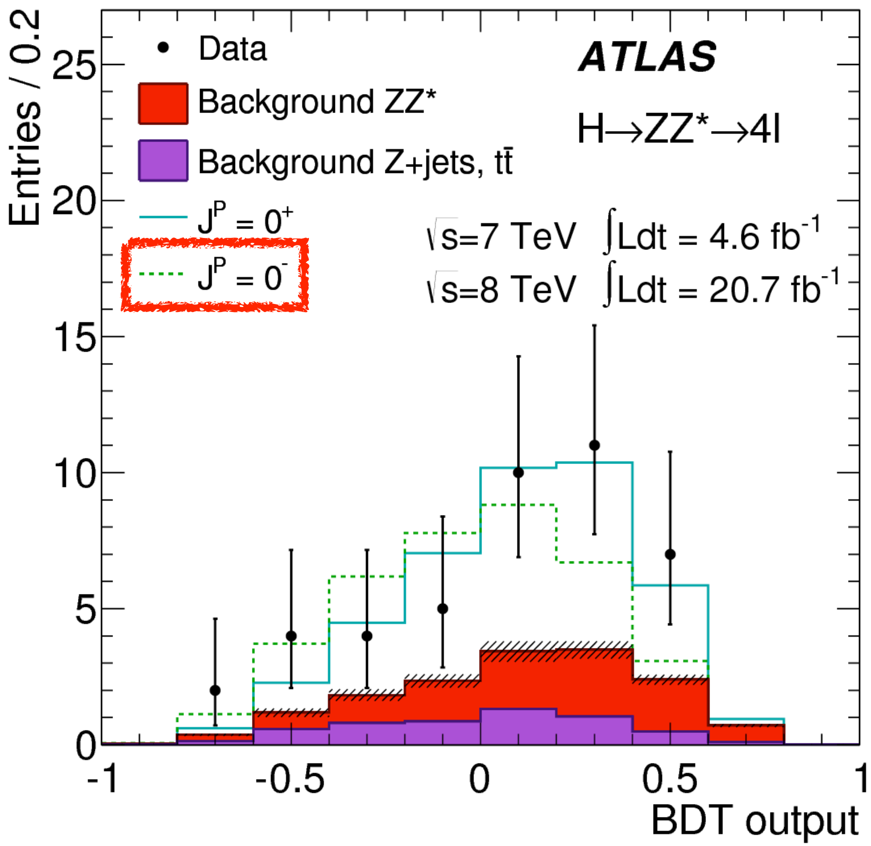
- **SM Prediction: $J^P=0^+$**
- It decays into two photons, so not spin-1 particle (Landau-Yang theorem)
- Use angular distributions of the decay products in the H rest frame. Use MVA to distinguish different scenarios
  - ✦ 0^-, 1^+, Spin 2^+ (Graviton inspired models)



Higgs boson spin

arXiv:1307.1432



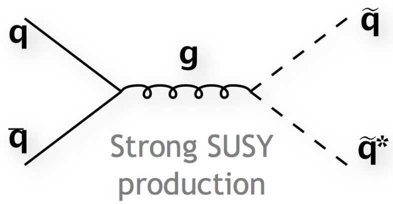


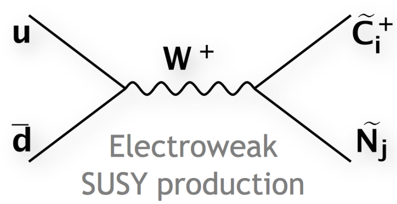
- H—>ZZ* alone excludes non SM spin scenarios @ 95%
- 3 channels (ZZ*, WW*, γγ) combined exclude 2^+ @ 99.9% CL, independent of production mode

Data compatible with the SM 0^+ hypothesis

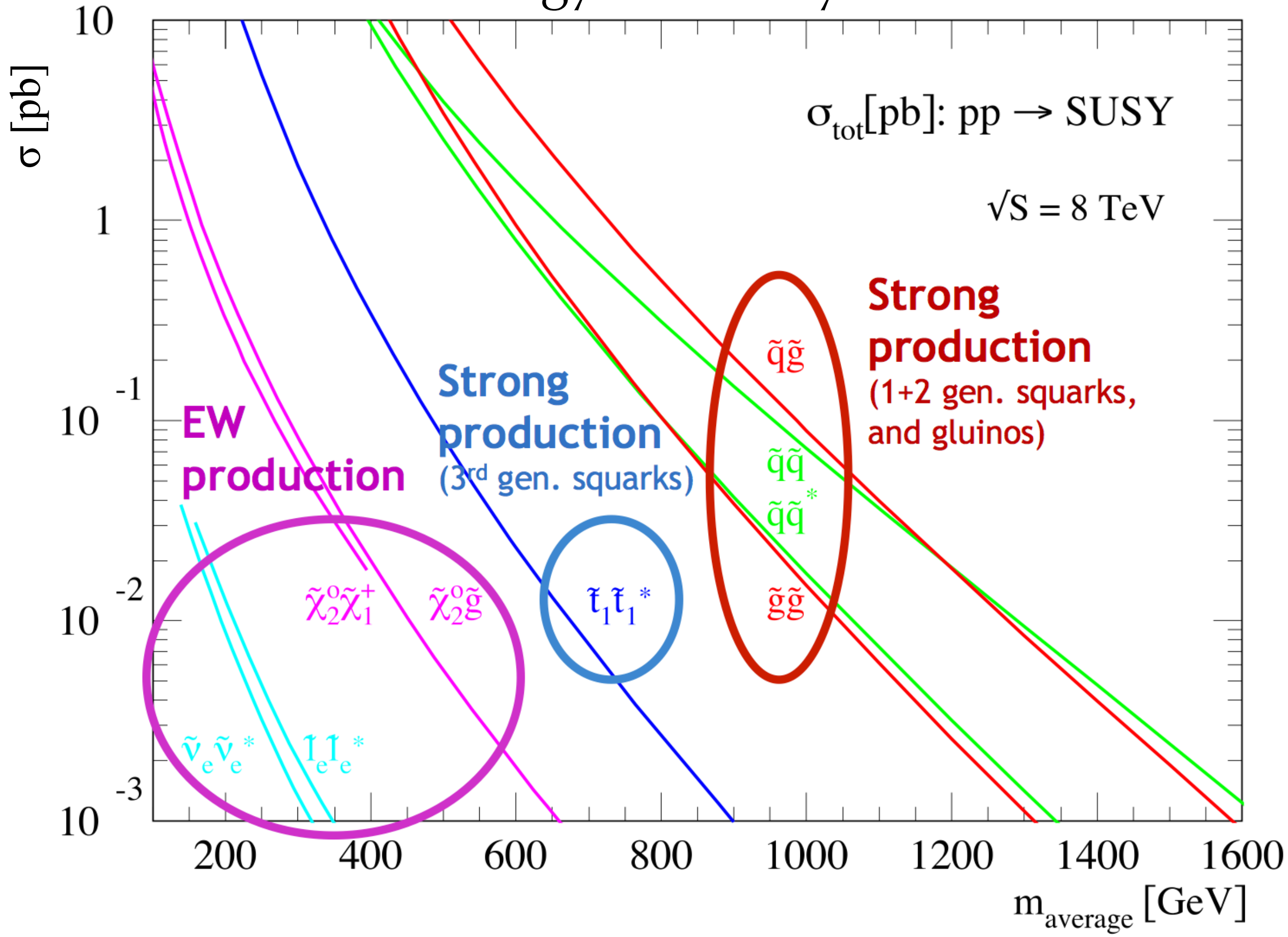
Supersymmetry

- Where to start?
- Huge parameter space, but guiding principals





- SUSY searches strategy driven by cross-section and luminosity



- Early analyses dominated by broad and inclusive searches for **gluino** and **squark** production

- Increasing luminosity gave access to rarer production channels.
  eg charginos, neutralinos

- It was quickly realised that dedicated searches had to be developed to adequately cover the rich decay spectrum
  mSUGRA, CMSSM, GMSB, Gravitino LSP, R-Parity violating,…

➡ **Typically searches probing signatures with energetic jets and large Missing Energy, and 0,1,2 leptons**

mSUGRA/CMSSM limits

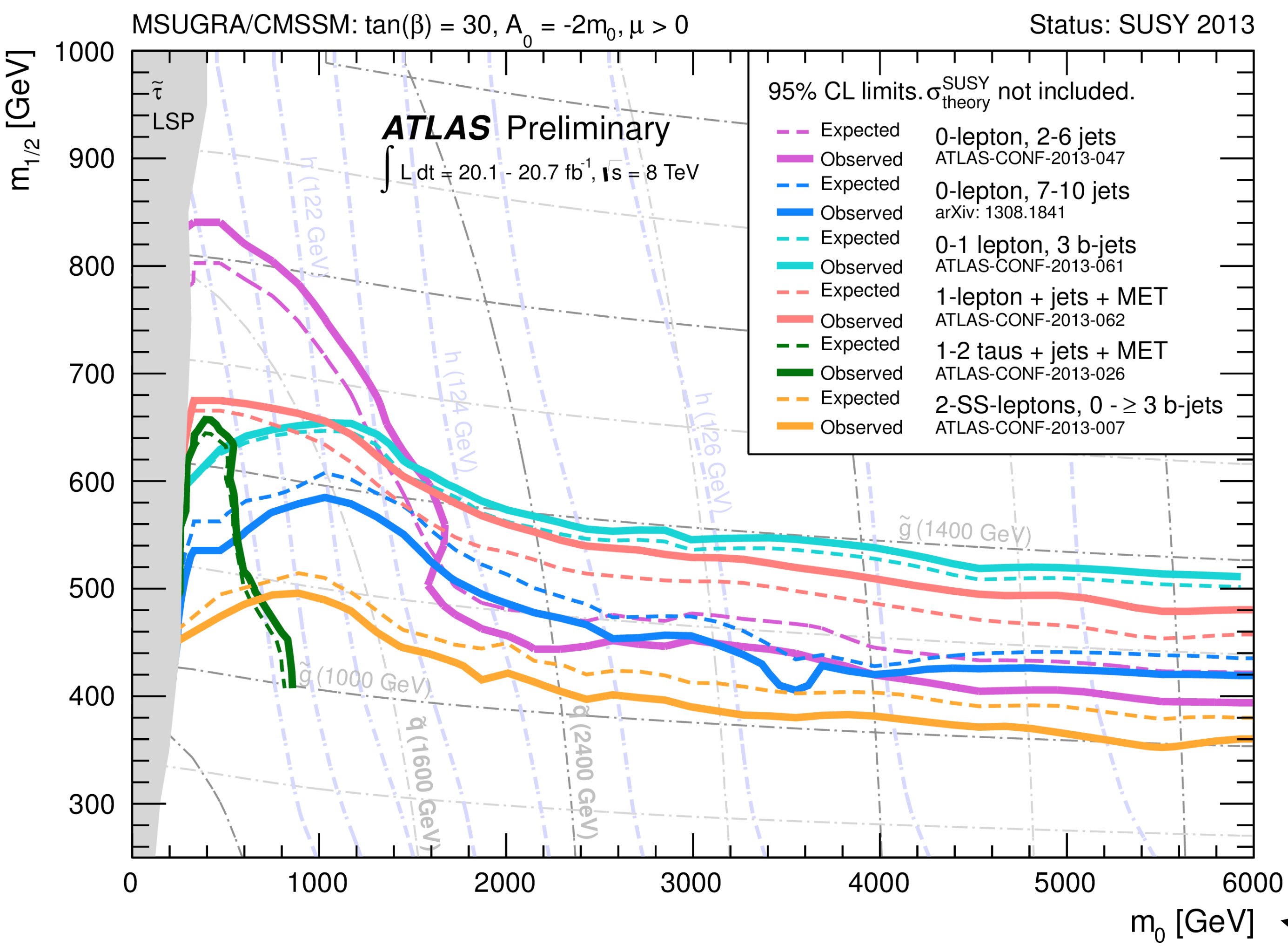
universal gaugino mass

$\tan(\beta)=30,$

$A_0=-2m_0,$

$\mu>0$

sign of Higgsino mass parameter

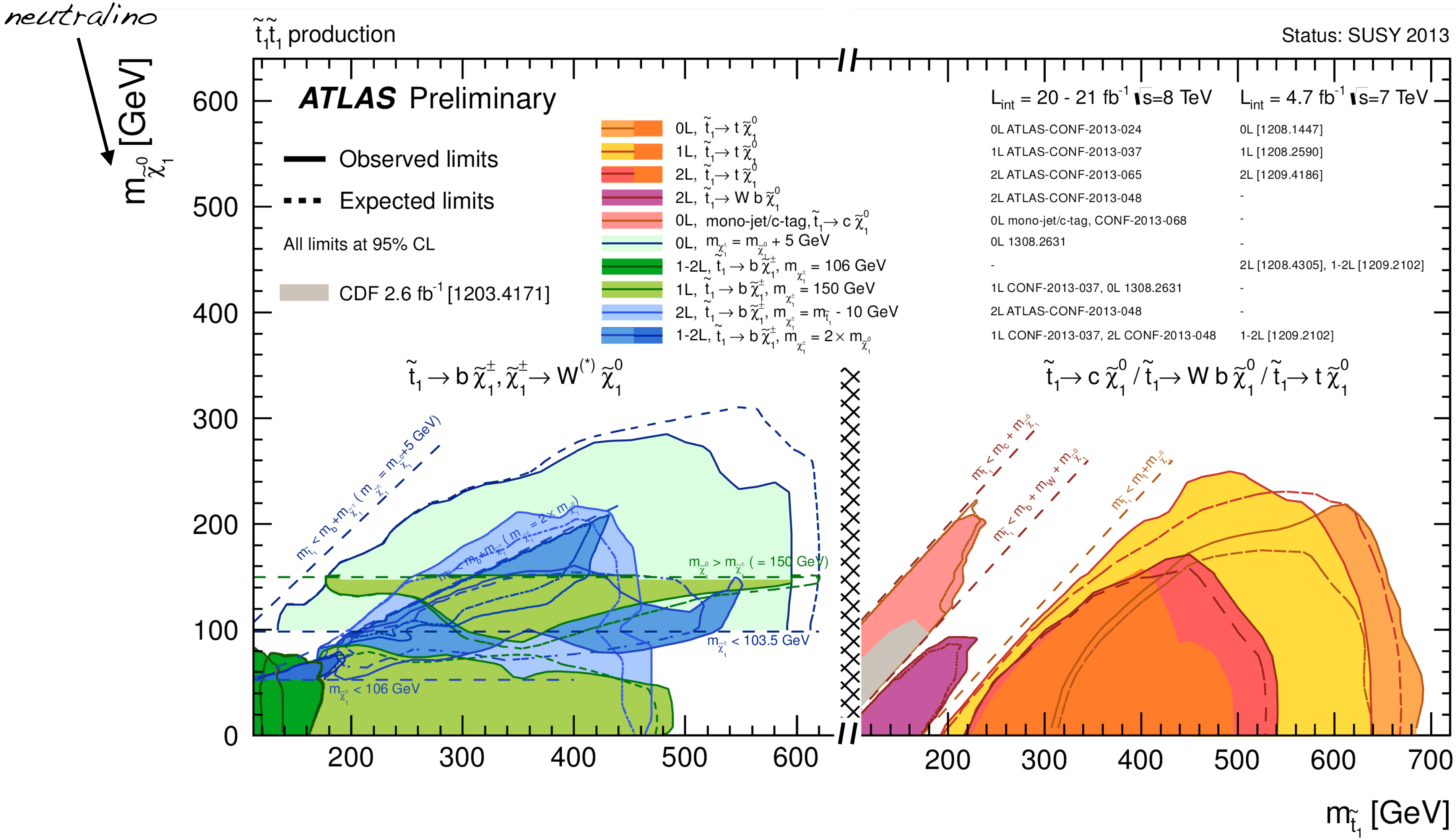


universal scalar mass

- Gluino mass > **1.3 TeV**
  - limit at large m_0 from 0-1l+3b-jet analysis
- Squark mass > **1.7 TeV**
  - limit from untagged 0-lepton analysis

Searches for direct stop production

- Dedicated program for **stop** and **sbottom** searches ongoing
- Maximum **stop** exclusion of **680 GeV**, but it can be significantly lowered depending on mass and mixing parameters



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

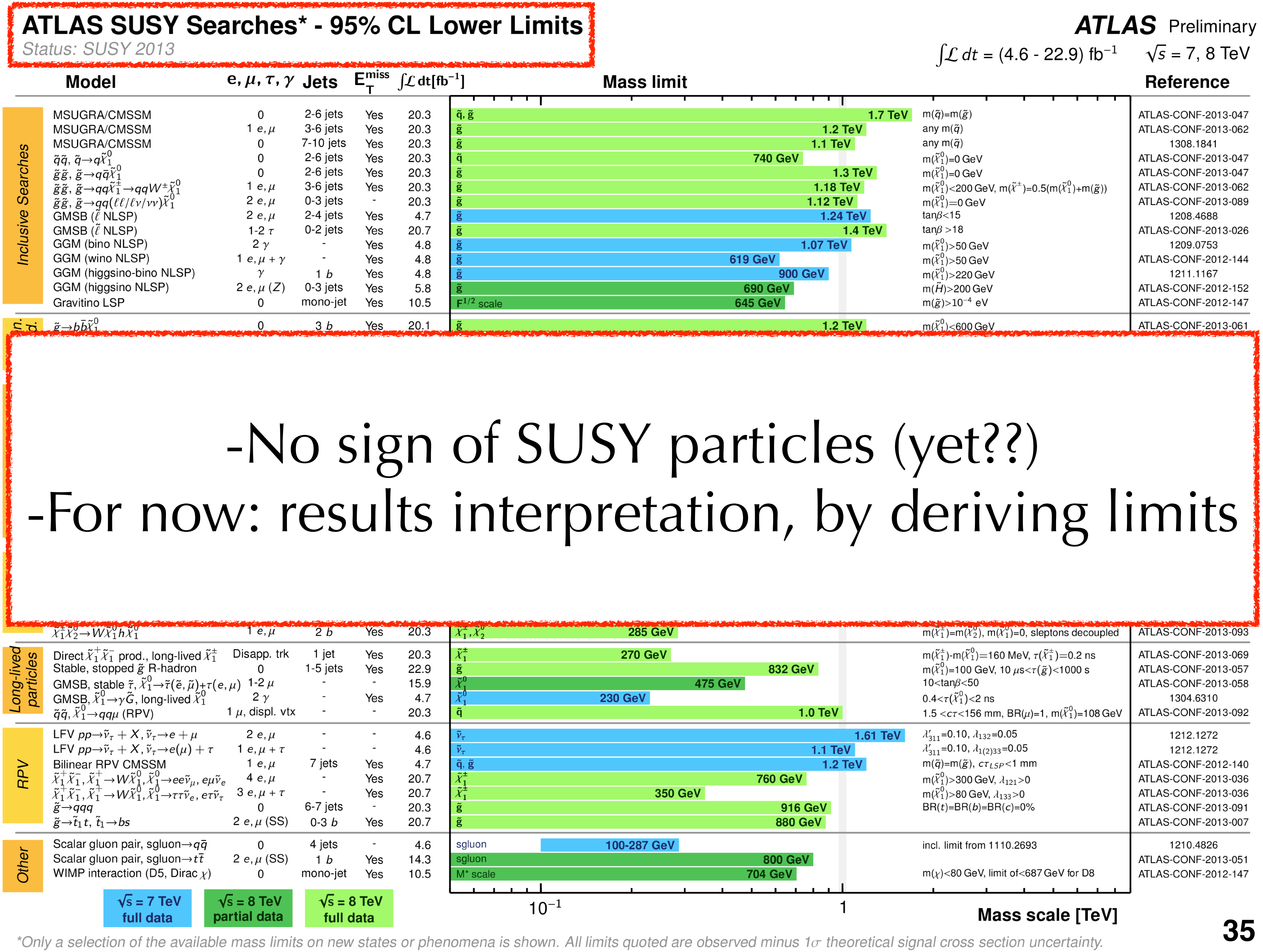
$\int \mathcal{L}\, dt = (4.6 - 22.9)$ fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}^0_1)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}^0_1)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}^0_1)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}^0_1)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}^0_1)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}^0_1)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}^\pm_1)$=2 $m(\tilde{\chi}^0_1)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}^0_1)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}^0_1)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}^\pm_1)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}^0_1$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}^0_1)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}^0_1)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}^0_1)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$	125-450 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}^\pm_1$	180-330 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-028
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$	600 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	3 e, μ	0	Yes	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$	315 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$	285 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$	270 GeV	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$=160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}^0_1$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	4.7	$\tilde{\chi}^0_1$	230 GeV	0.4<$\tau(\tilde{\chi}^0_1)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}^0_1)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}^\pm_1$	760 GeV	$m(\tilde{\chi}^0_1)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}^\pm_1$	350 GeV	$m(\tilde{\chi}^0_1)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

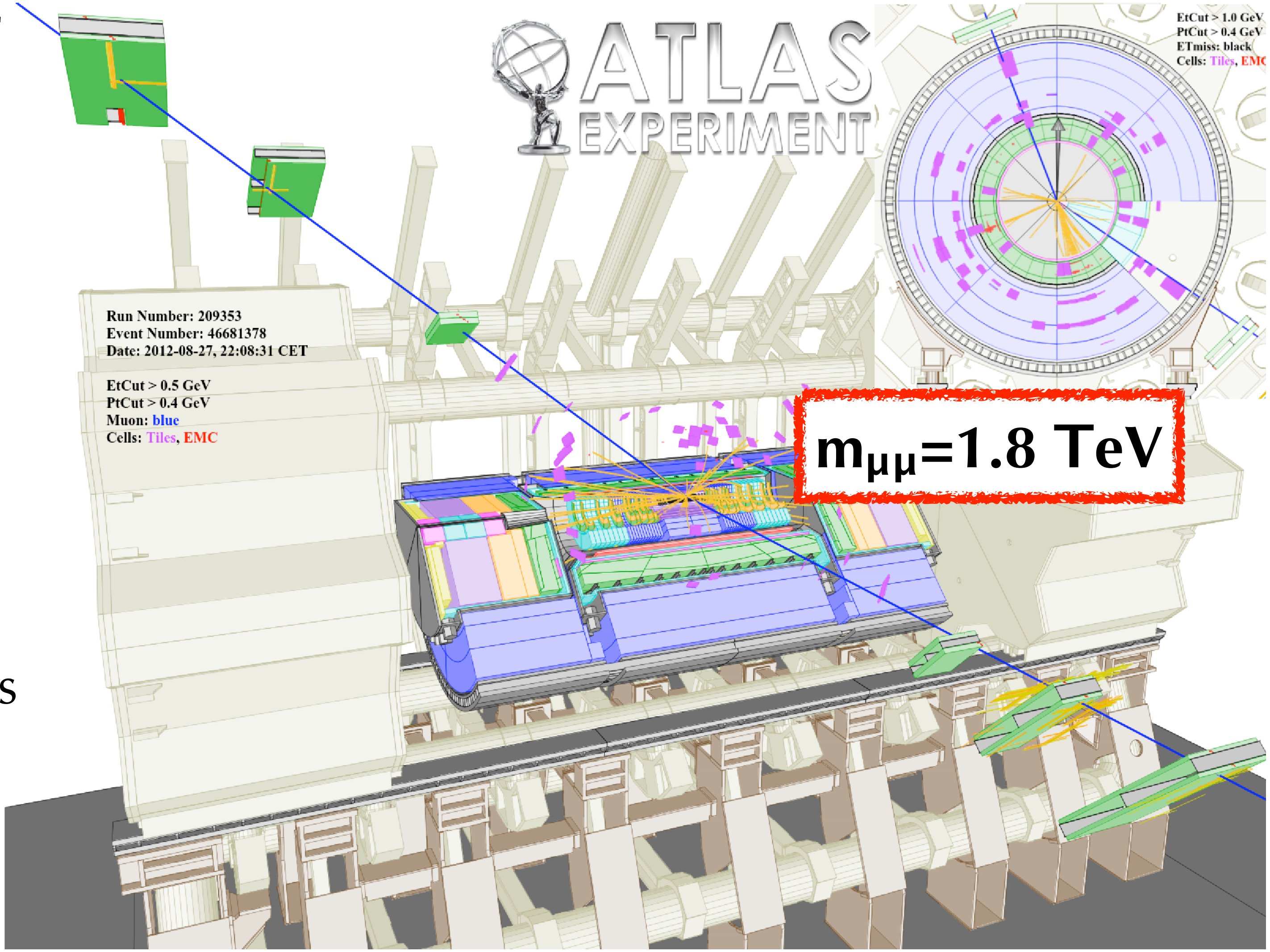


-No sign of SUSY particles (yet??)

-For now: results interpretation, by deriving limits

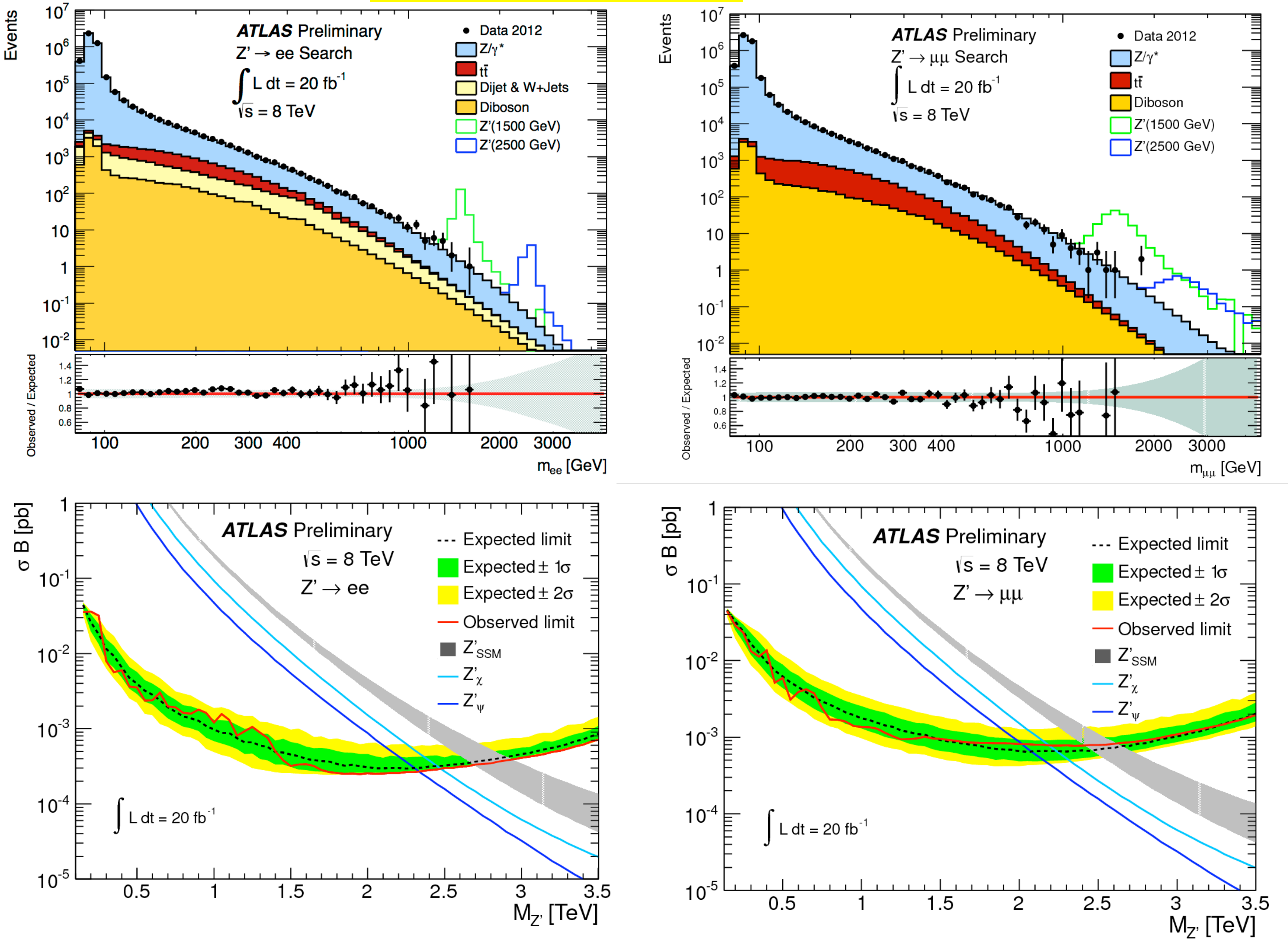
Exotics

- Many extensions of the SM other than SUSY have been developed
  - **GUT, Extra dimensions**
    - Heavy resonances (eg Z′)
  - **Dark matter**
    - Monojet signatures
  - **Vector like quarks**
    - Same sign di-leptons and b-jets signatures
  - ...



Exotics: ee, μμ

ATLAS-CONF-2013-017



Z'_{SSM}: Benchmark model, Z' same couplings to fermions as SM Z

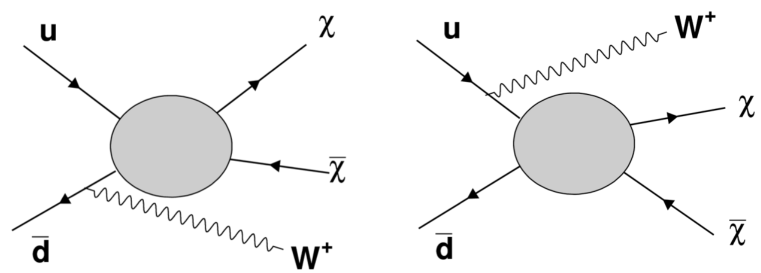
Z'_χ, Z'_ψ: Neutral gauge bosons from E_6 gauge group GUT

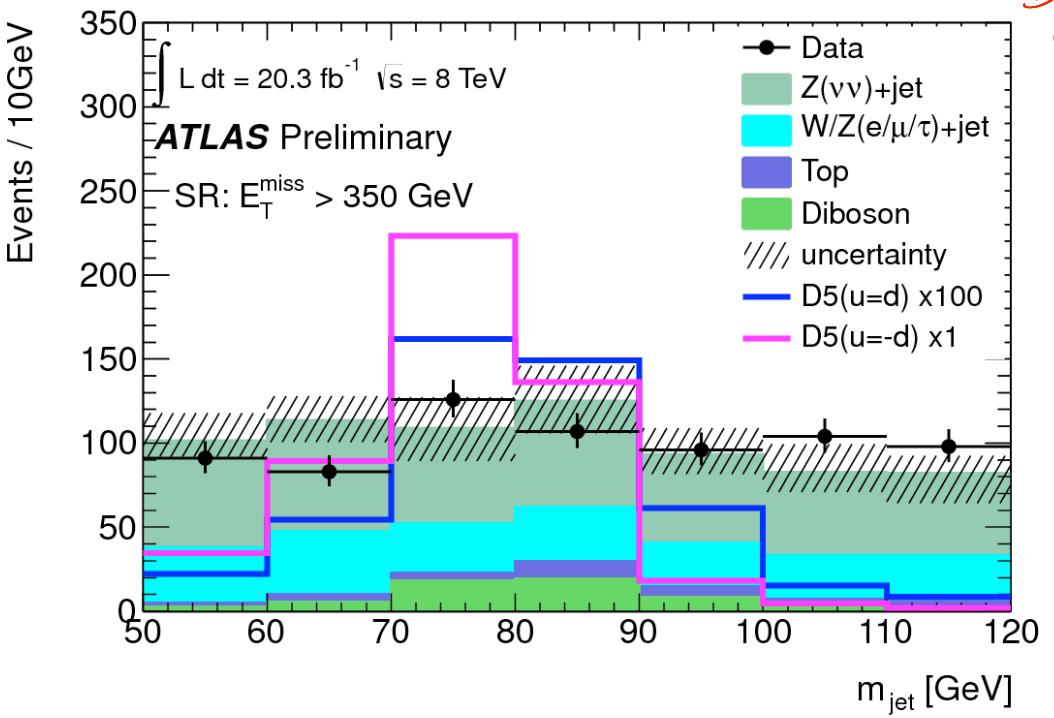
Limits (95% CL): M(Z')>2.8 TeV (ee); M(Z')>2.5 TeV (μμ)

Dark matter searches

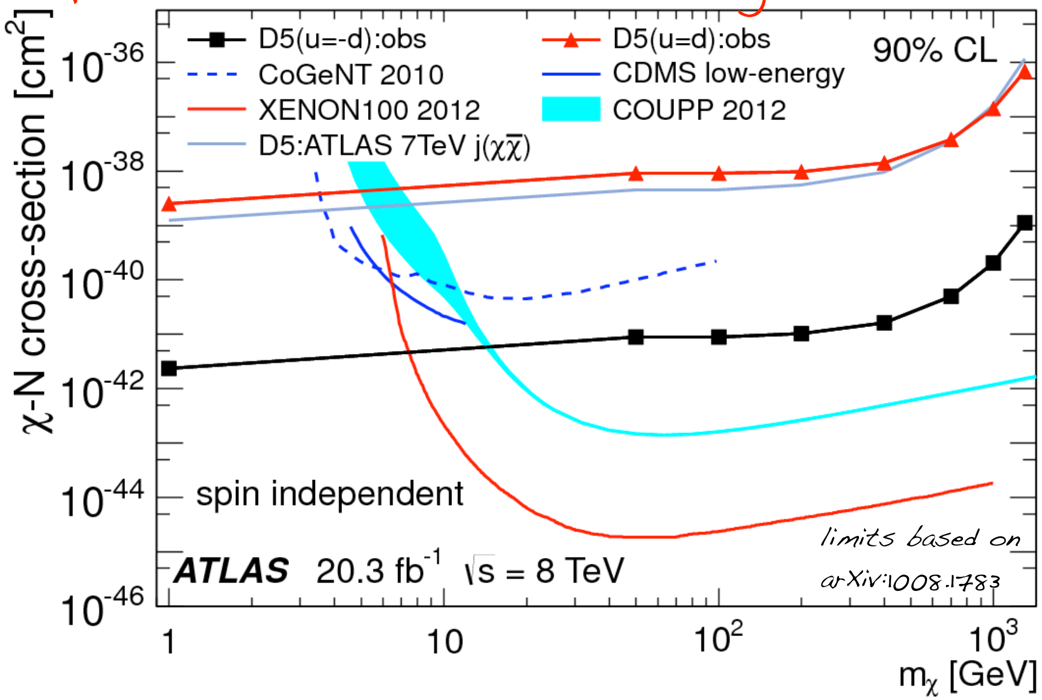
arXiv:1309.4017

- Search for **Weak Interacting Massive Particle**
- pp—>χχ+X
  - X: jet, photon, W, or Z produced in Initial State Radiation
- ATLAS WIMP searches where **W/Z** decay hadronically: **events with large jet and MissingE_T**



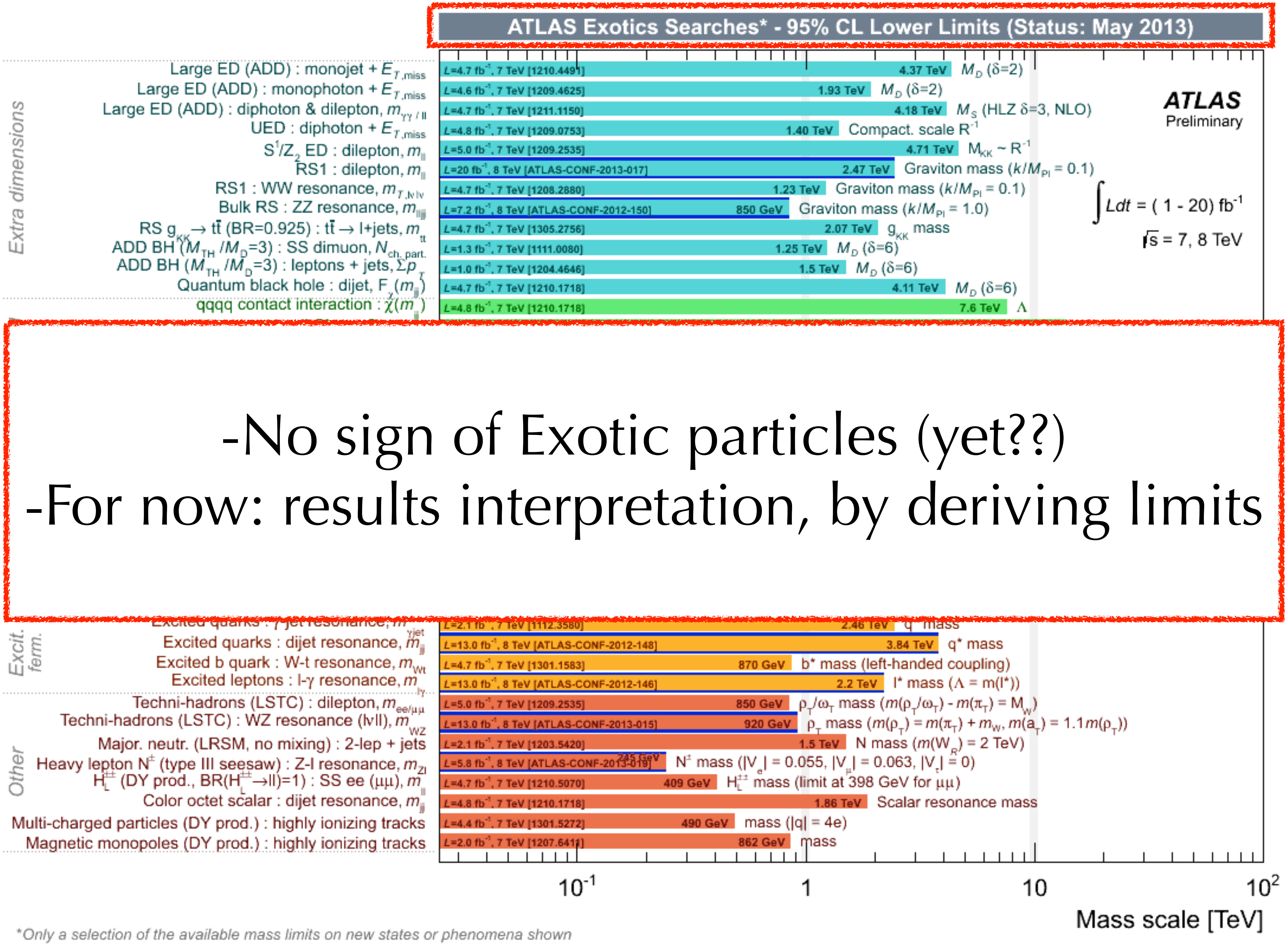


Dark matter-nucleon scattering x-section



- **DM-nucleon scattering cross section:** ATLAS contributes to region **m_X<10 GeV**, where the direct detection experiments have less sensitivity

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



-No sign of Exotic particles (yet??)

-For now: results interpretation, by deriving limits

What to expect from the future LHC?

LHC planning

(updated by CERN: Dec. 2nd 2013)

2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
…
…
2035

Run 1: $\sqrt{s}$**=7-8 TeV**, $\int$**Ldt=25 fb^{-1}**, pileup **μ≈20**
$L^{peak}=0.7\times10^{34}\ cm^{-2}s^{-1}$

→ 25 fb^{-1}

LS1: **phase 0** upgrade

new

Run 2: $\sqrt{s}$**≈13-14 TeV**, $\int$**Ldt≈120 fb^{-1}**, pileup **μ≈43**
$L^{peak}=1.6\times10^{34}\ cm^{-2}s^{-1}$

→ ~120 fb^{-1}

LS2: **phase 1** upgrade

Run 3: $\sqrt{s}$**≈14 TeV**, $\int$**Ldt≈350 fb^{-1}**, pileup **μ=50-80**
$L^{peak}\approx2\text{-}3\times10^{34}\ cm^{-2}s^{-1}$

→ ~350 fb^{-1}

LS3: **phase 2** upgrade

HL-LHC: $\sqrt{s}$**≈14 TeV**, $\int$**Ldt≈3000 fb^{-1}**, pileup **μ≈140-200**
$L^{peak}=20\times10^{34}\ cm^{-2}s^{-1}$ leveled to $L^{peak}=(5\text{-}7.5)\times10^{34}\ cm^{-2}s^{-1}$

→ ~3000(?) fb^{-1}

LHC machine in 2015

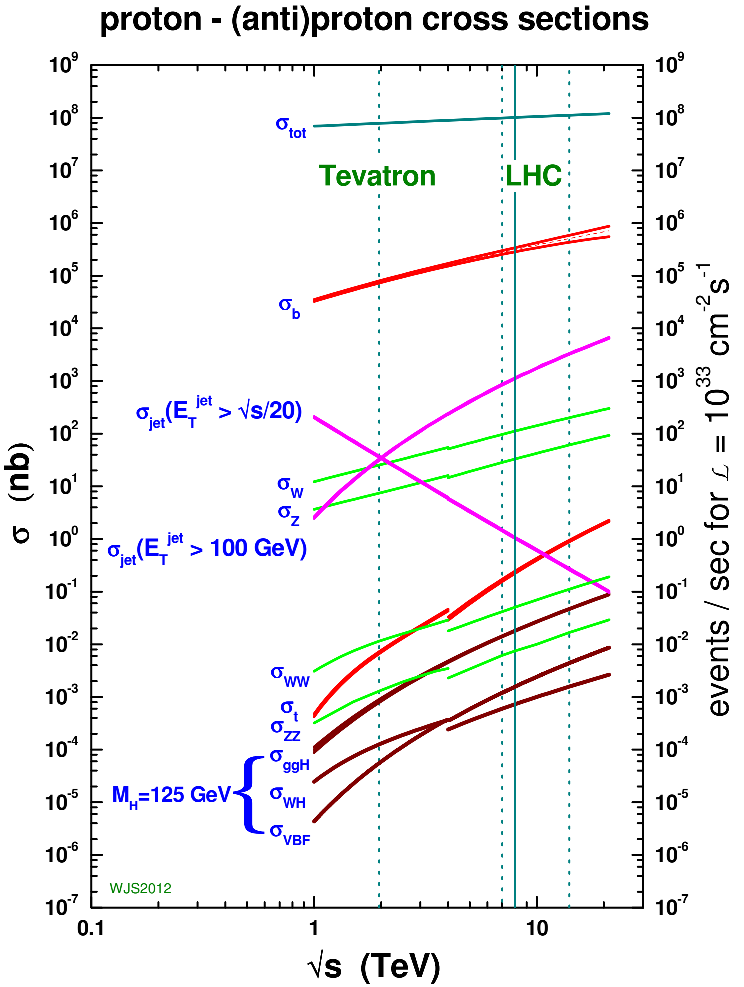
- LHC will start again in 2015 for the Run 2

Expectation	2015	2016-2017
CM energy [TeV]	13	13-14
Integrated L [fb^{-1}]	15-30	80-120
Bunch spacing [ns]	25	25
Pileup <μ>	~25	~40

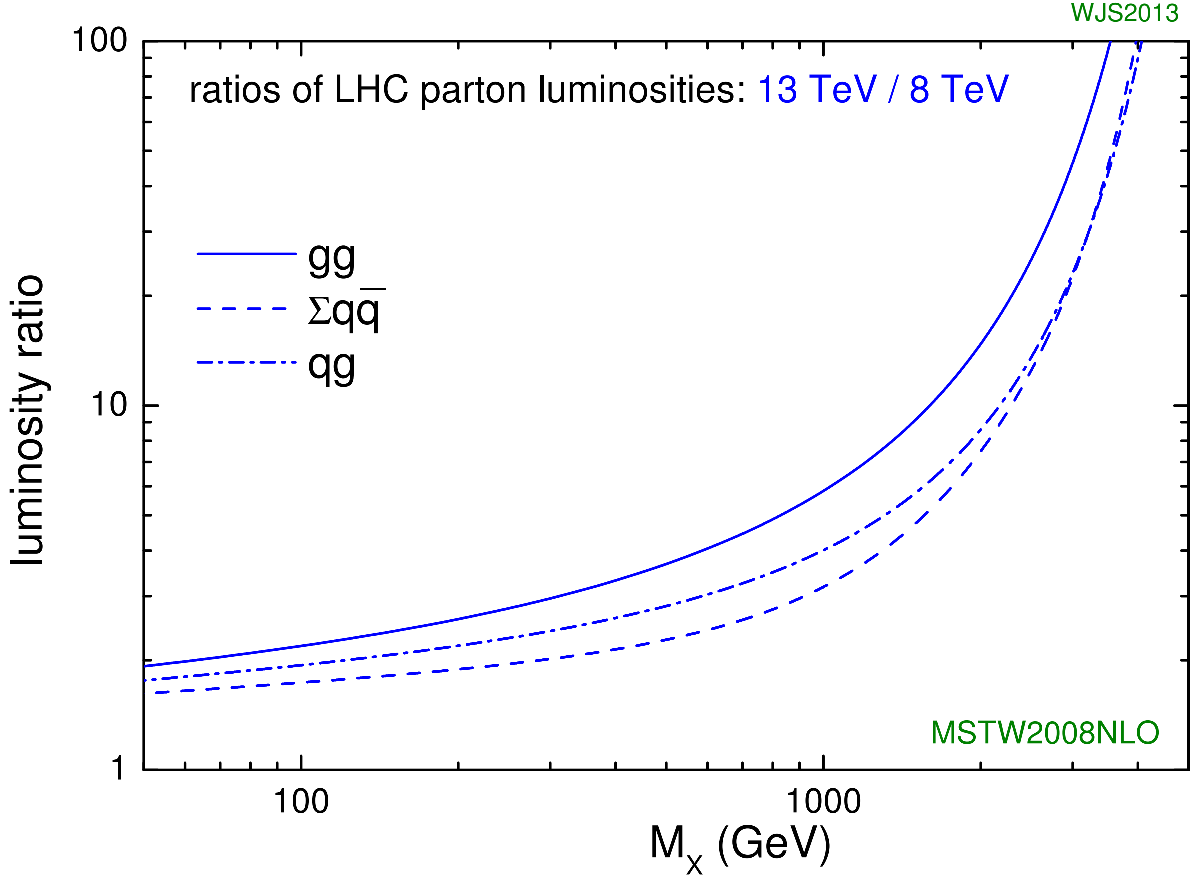
- 2015
  - ❖ $\sqrt{s}$ energy expected to be 13 TeV and average pileup at 25
- 2016-2017
  - ❖ LHC likely to reach its design energy: $\sqrt{s}$ = 14 TeV

Cross sections increase

- Physics reach, largely driven by increase in partonic luminosities

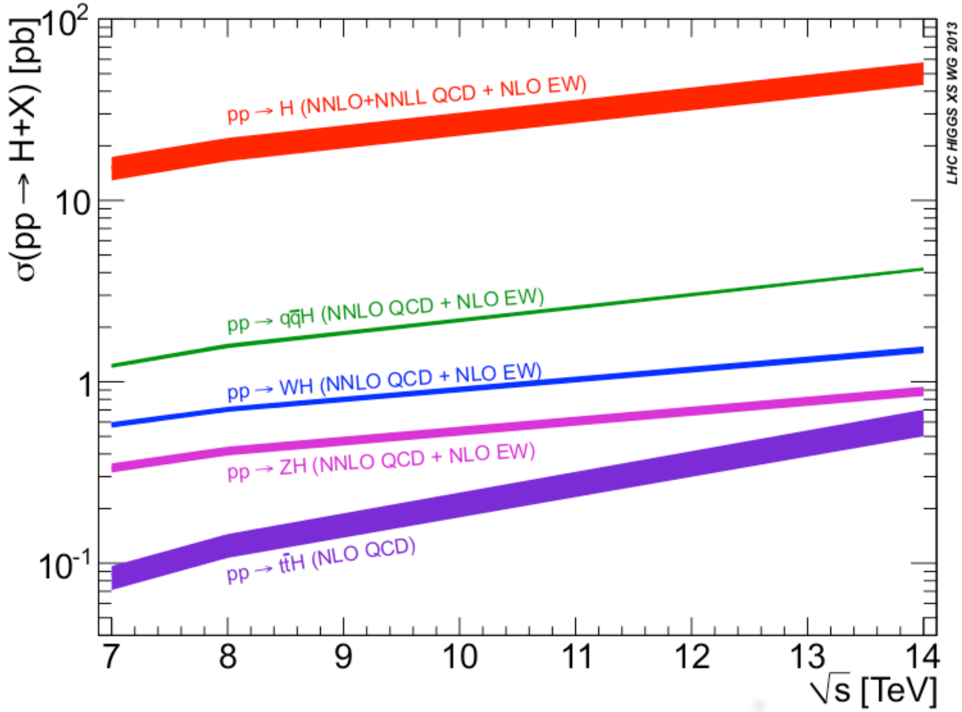


http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



- Significant cross-section as mass, M_X, grows
- Backgrounds will increase as well, though. Fortunately not with the same rate

Higgs @ 13-14 TeV

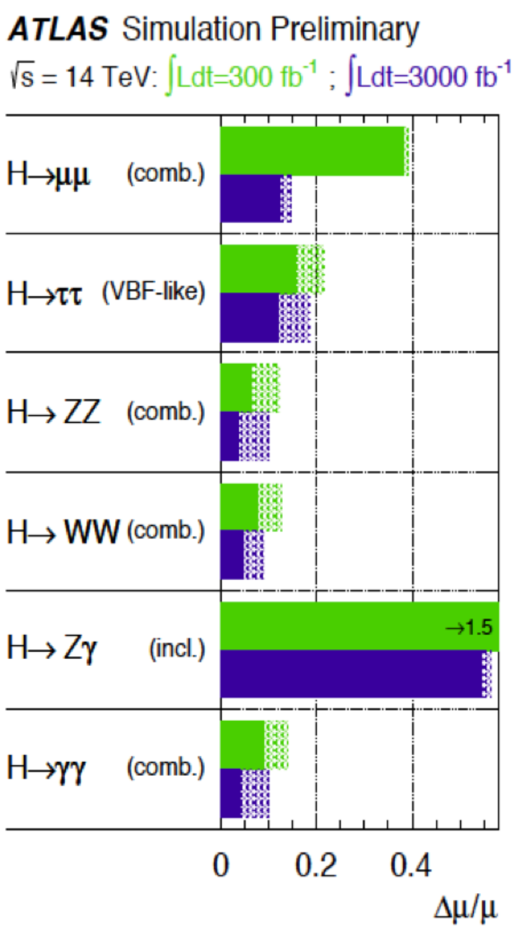


- **bbH** might be relevant too
- **Total cross section** for 14 TeV is **~2.5 times** that for 8TeV (dominated by ggF)
- All very similar except for **ttH**, which shows a larger increase : **factor of 5** for 14 TeV
- Expect in **2015** alone alone to be **2×Run-1** statistics.
- **Full Run-2: 10-15 × Run-1 statistics**

Higgs boson coupling measurements

Relative precision on Higgs cross section

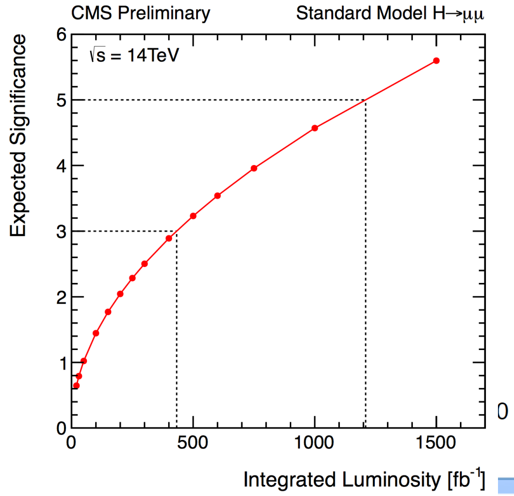
ATLAS-PHYS-PUB-2013-014

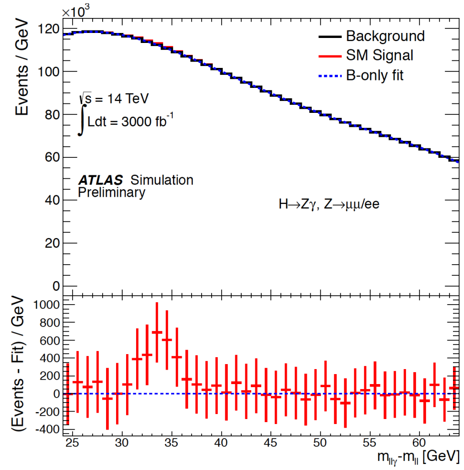


Access to rare decays:

- H→μμ: How does it couple to 2nd generation?
- H→Zγ: Is there new physics in loops?

arXiv:1401.6081





CMS projections for coupling precision (*arXiv:1307.7135*) in %

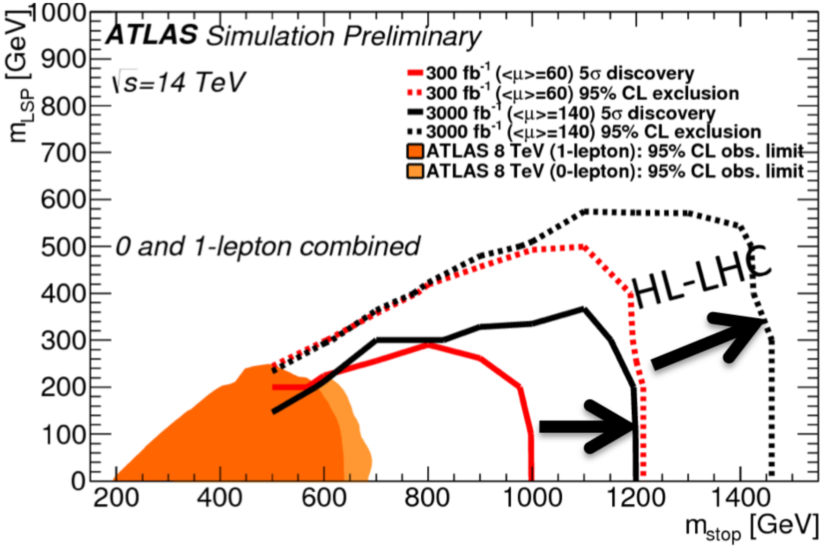
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

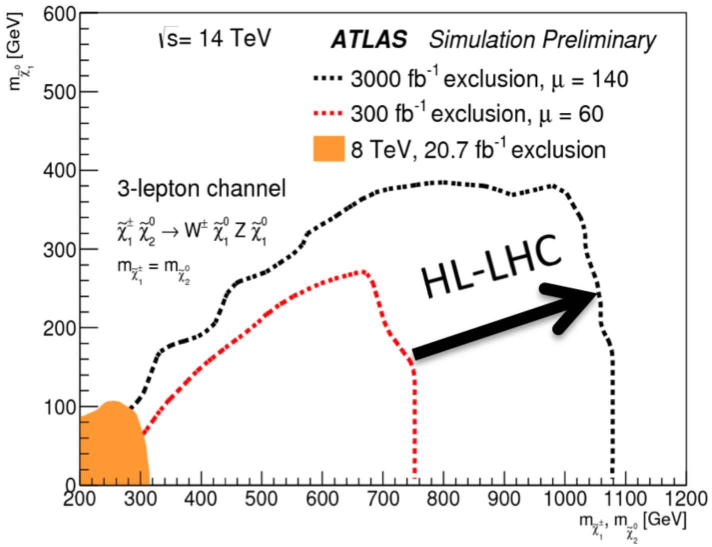
HL-LHC will enable precision Higgs physics:

- probe most couplings with **2-8%** precision
  - factor ~3 improvement compared to 300 fb^{-1} LHC
- Access to important rare decays

Higgs self-coupling HHH? Ongoing studies for very challenging analyses
Estimate: ~20-30% precision

SUSY prospects towards HL-LHC



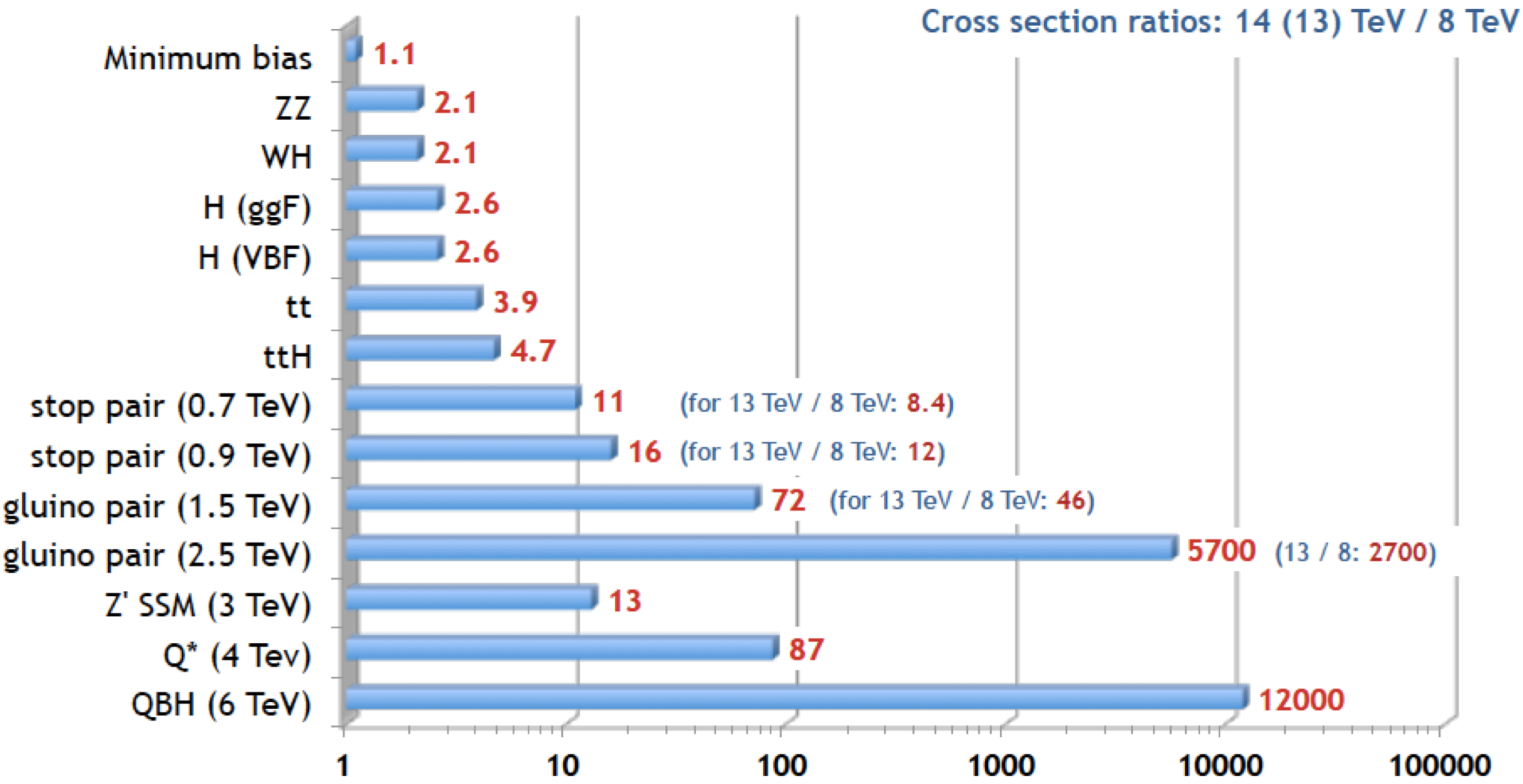


- **HL-LHC enables characterization of any new particles found in runs 2 and 3**
- **HL-LHC significantly extends discovery reach**
  - Probe stop masses up to M~1.5 TeV
  - Probe chargino/neutralino masses up to M~1 TeV
  - Probe gluino masses well beyond 2 TeV

ATLAS-PHYS-PUB-2013-011

13-14 TeV running

- Hugely increased potential for discovery of heavy particles at 13-14 TeV



LHC Run 2 and Run 3

2015–2018	**Run 2**: $\sqrt{s}\approx$**13-14 TeV**, $\int Ldt\approx$**120 fb^{-1}**, pileup **$\mu\approx$43** $L^{peak}=1.6\times10^{34}$ cm^{-2}s^{-1} $\rightarrow$ ~120 fb^{-1}
2018–2019	LS2: **phase 1** upgrade
2020–2023	**Run 3**: $\sqrt{s}\approx$**14 TeV**, $\int Ldt\approx$**350 fb^{-1}**, pileup **μ=50-80** $L^{peak}\approx2\text{-}3\times10^{34}$ cm^{-2}s^{-1} $\rightarrow$ ~350 fb^{-1}
2023–2024	LS3: **phase 2** upgrade

- Run 2: Need a few (~5) inverse fb^{-1} to exceed currents limits
  - Expected for summer 2015
    - Stay tuned for Moriond 2016
- Limits will improve by a factor of ~2 end of Run 2
- Run 2 is critical for searches
- BSM searches benefit a lot by the increase of $\sqrt{s}$ energy
  - If nothing new is seen then
    - Slower increase in limits during Run 3
    - Run 3 basically more a measurement programme than a search program

Epilogue

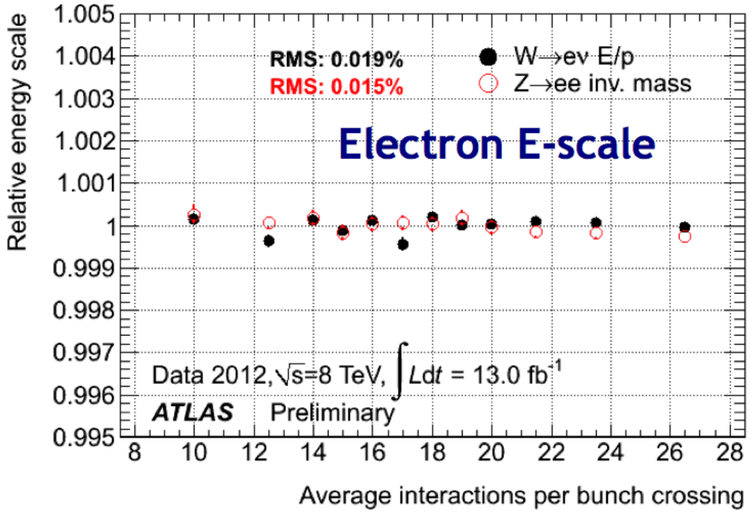
- **Fantastic delivery from LHC during exciting Run-I**
- Detectors maintained excellent performance despite beyond design pileup
- **Higgs boson discovered @ m_H=125.5 GeV !!**
  - Move beyond observation
    - **$J^P=0^+$ strongly favoured**
  - Higgs analyses are now part of the measurement programme
    - Coupling measurements
- Wide range of searches explore more challenging parts of SUSY space, and complex BSM signatures ➜ **No sign yet of a second discovery**

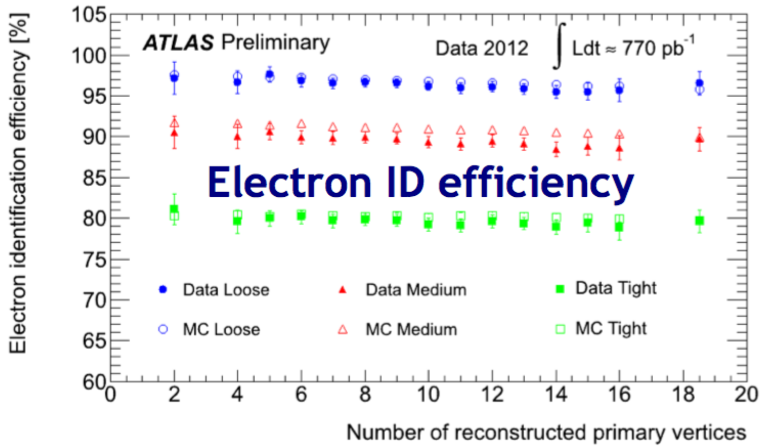
- What to expect in Run-II starting in 2015?
  - Higgs (more) precise measurement programme
    - ttH evidence/observation
  - **SUSY and BSM searches will benefit a lot from the LHC energy increase**
    - A few fb^{-1} are enough to exceed current limits ➜ **Stay tuned**

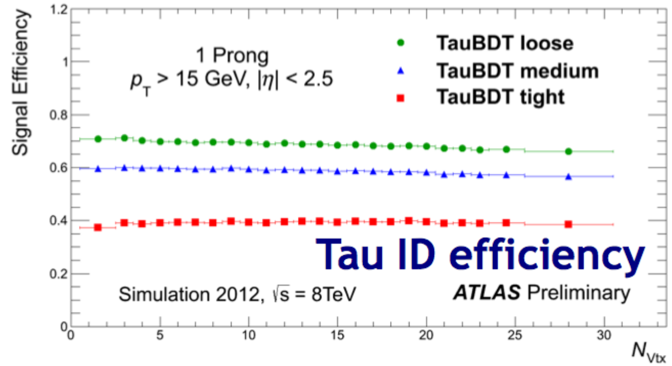
Back-up slides

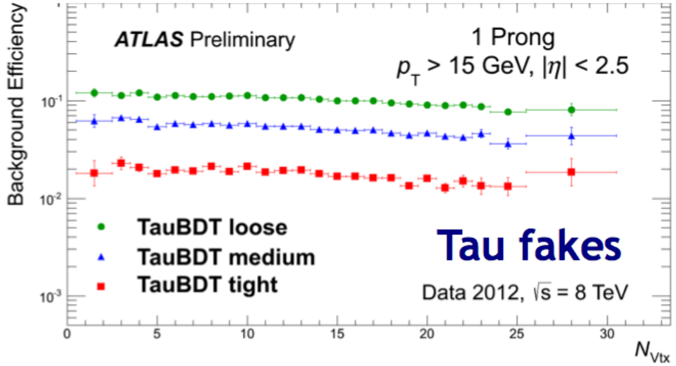
Handling pileup

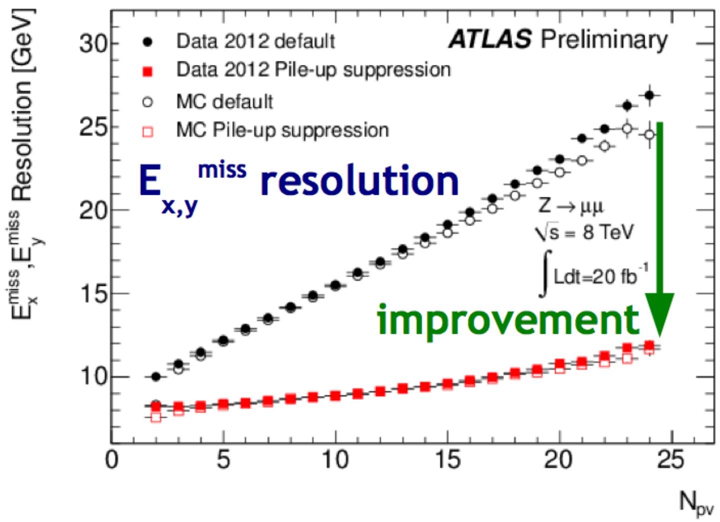
Handling pileup







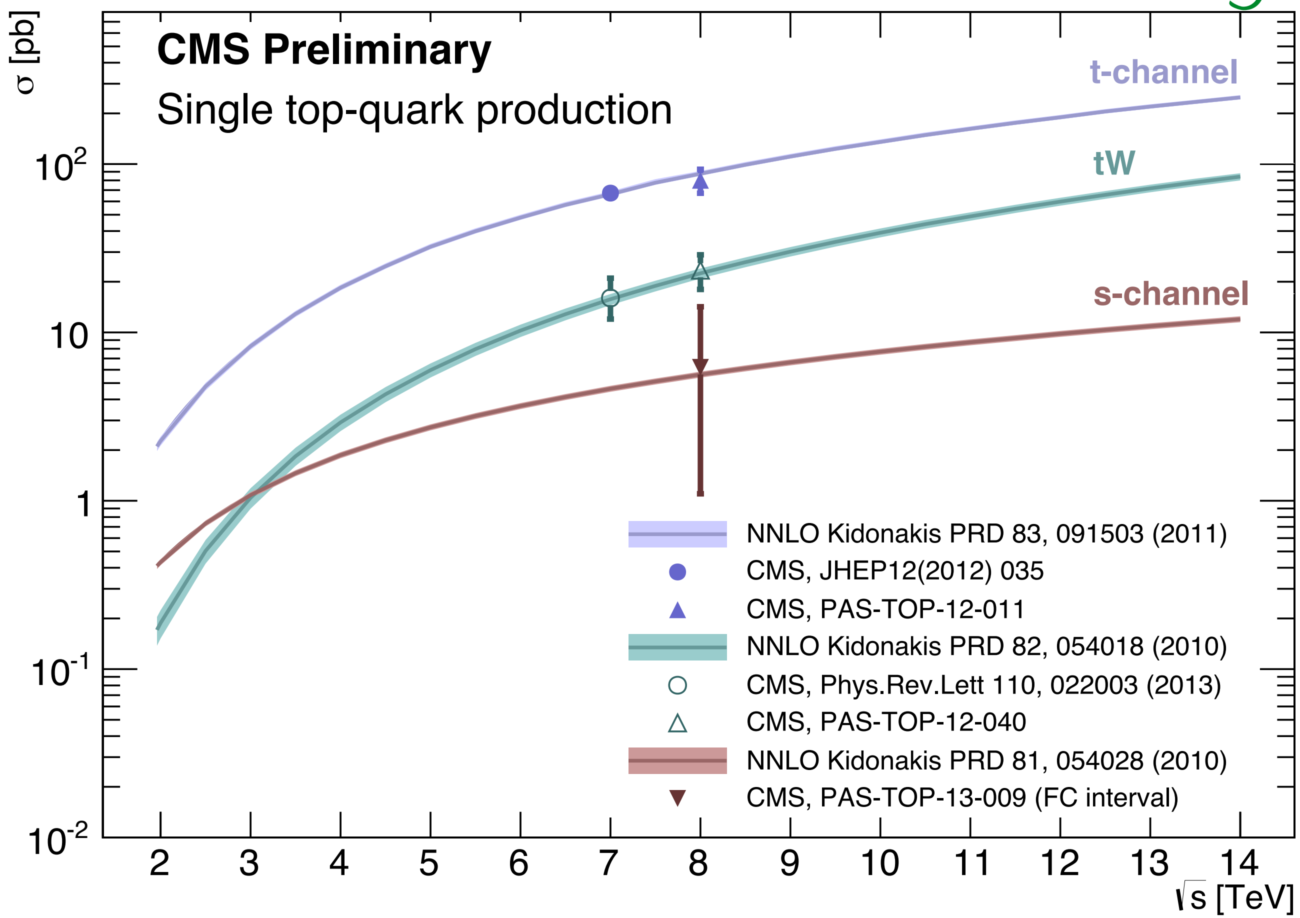




After intense work, impact of pileup can be much reduced, even beyond the design maximum of μ~25

Top quark physics

single top



- Excellent description by NNLO+NNLL
- Top quark measurements are systematics-limited. Ongoing efforts on reducing systematic uncertainties

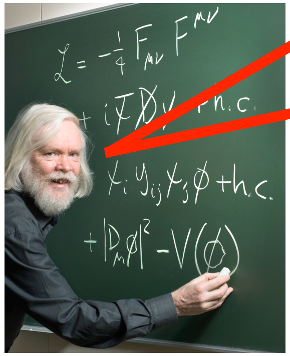
What about Higgs boson mass?

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

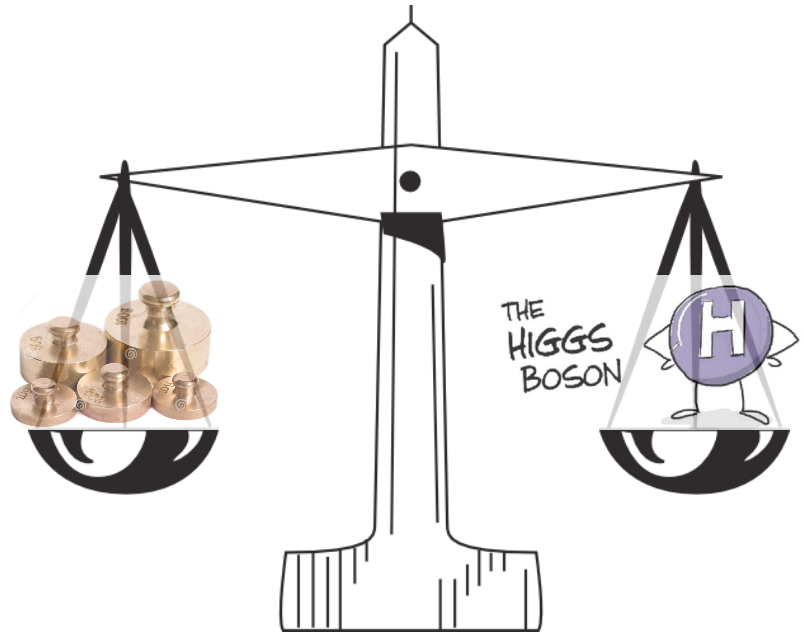
Received 7 November 1975

Review of H decay modes and status searches in **1975**



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

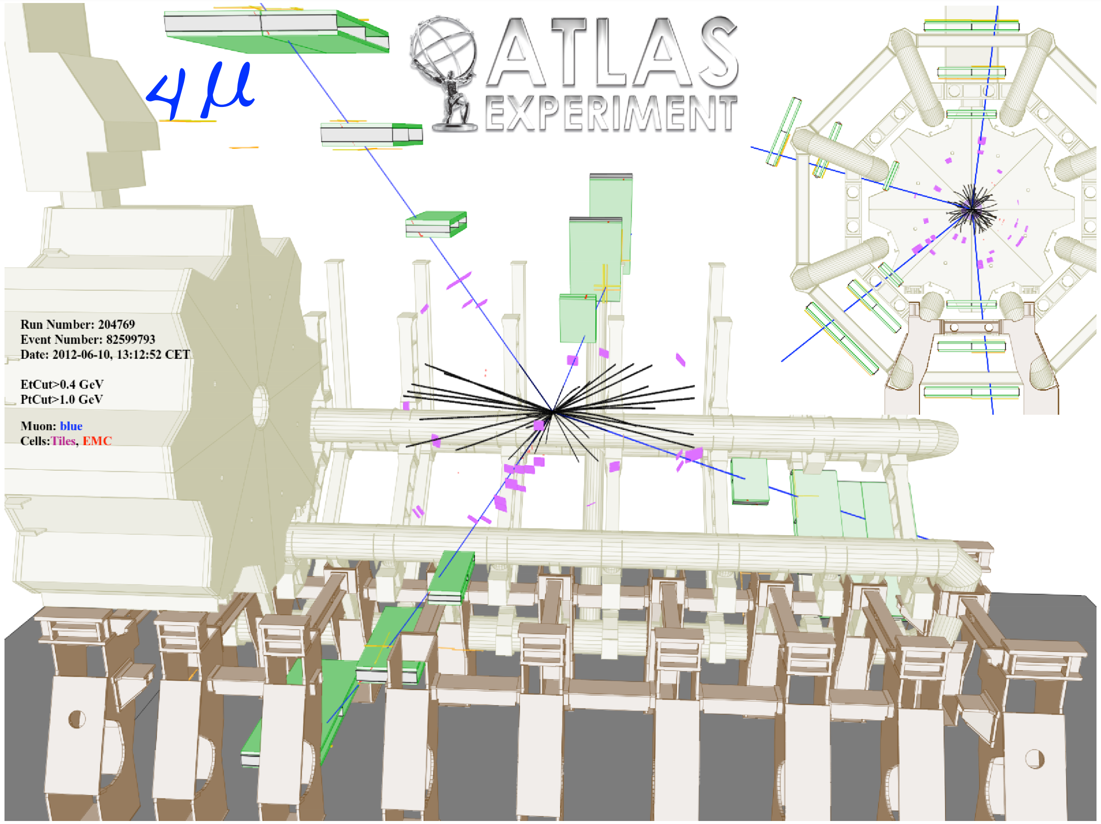
How many of these?

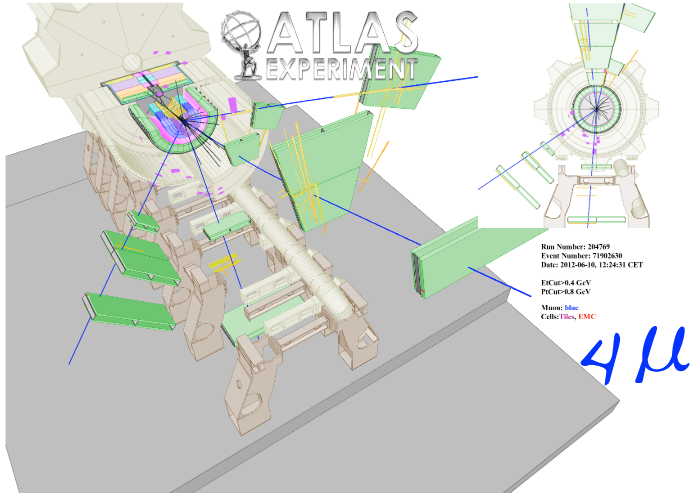


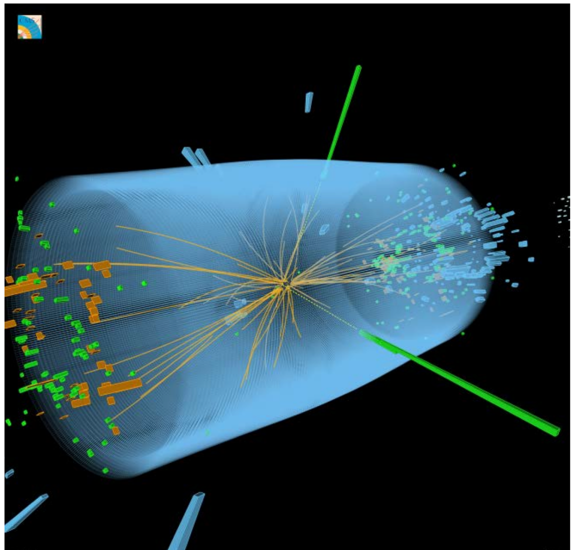
2013:

Mass is measured with the high mass resolution (1-2 %) channels: $\gamma\gamma$ - 4l

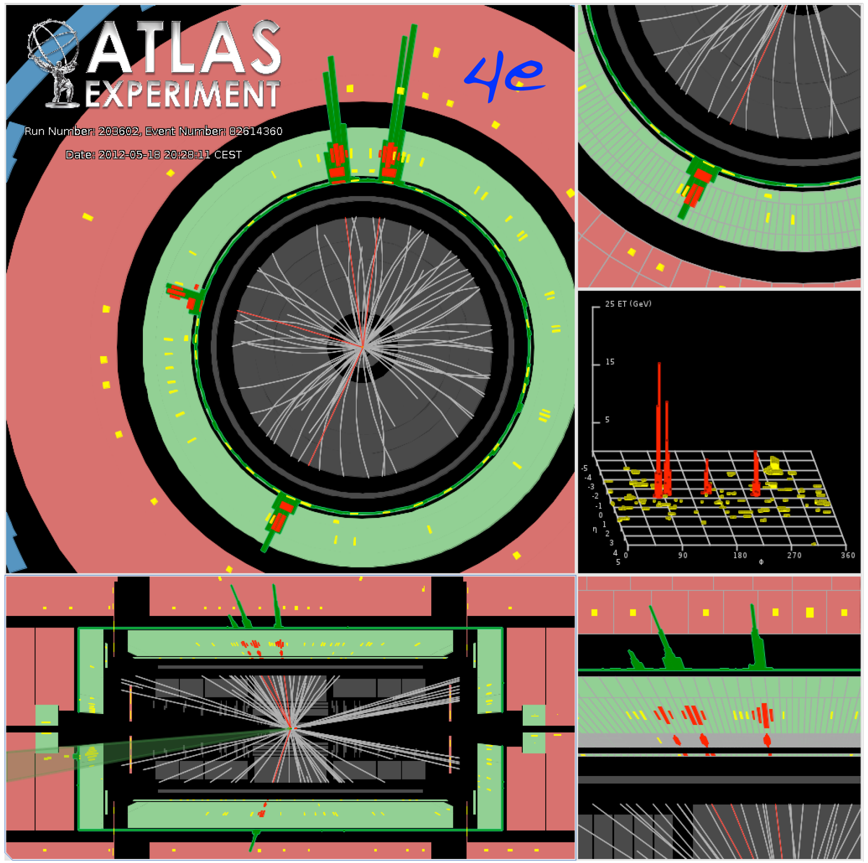
Higgs events candidates in ATLAS & CMS







2γ

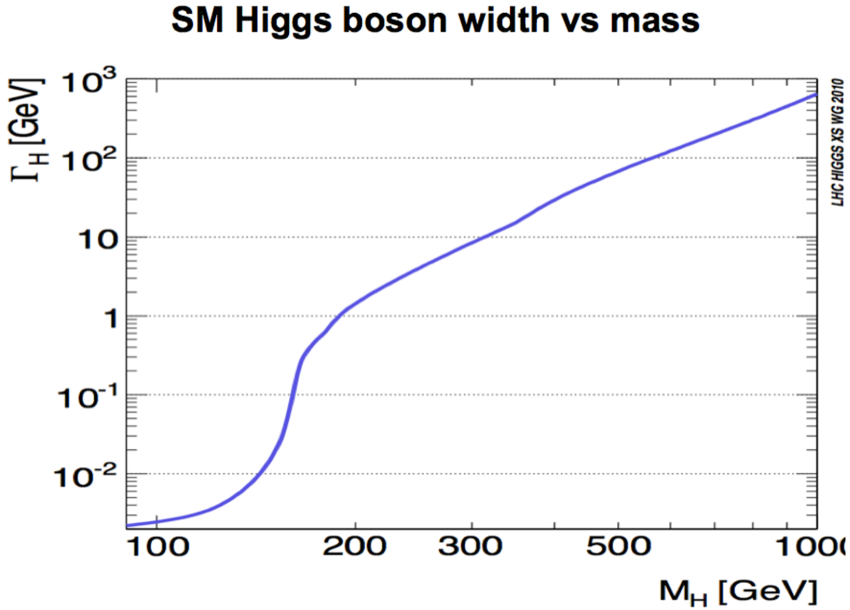


CMS Higgs width measurement

Width measurement :

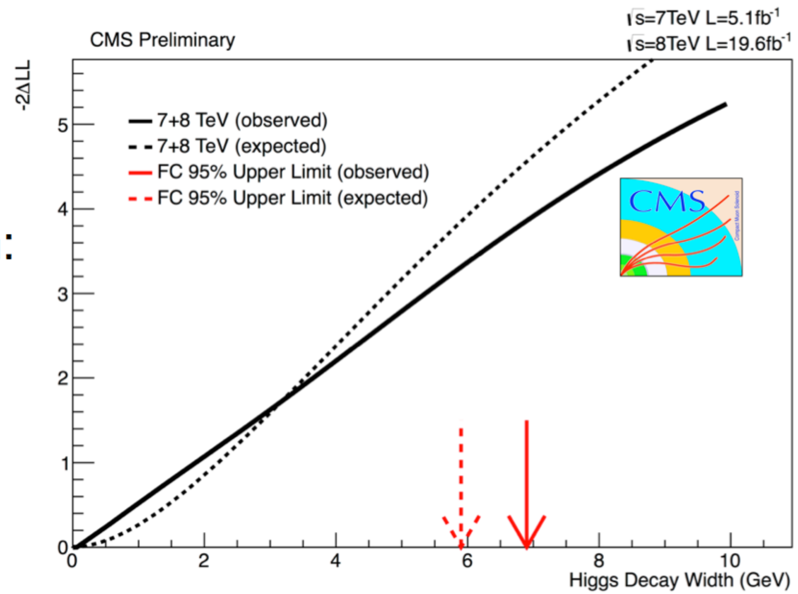
- Very narrow resonance at low mass:
  ~4 MeV at **125 GeV**

- Signal modeling:
  analytic convolution of a :
  Breit-Wigner distribution
  (modeling a **non-zero decay width**)
  Gaussian distribution
  (modeling the **non-zero detector resolution**)

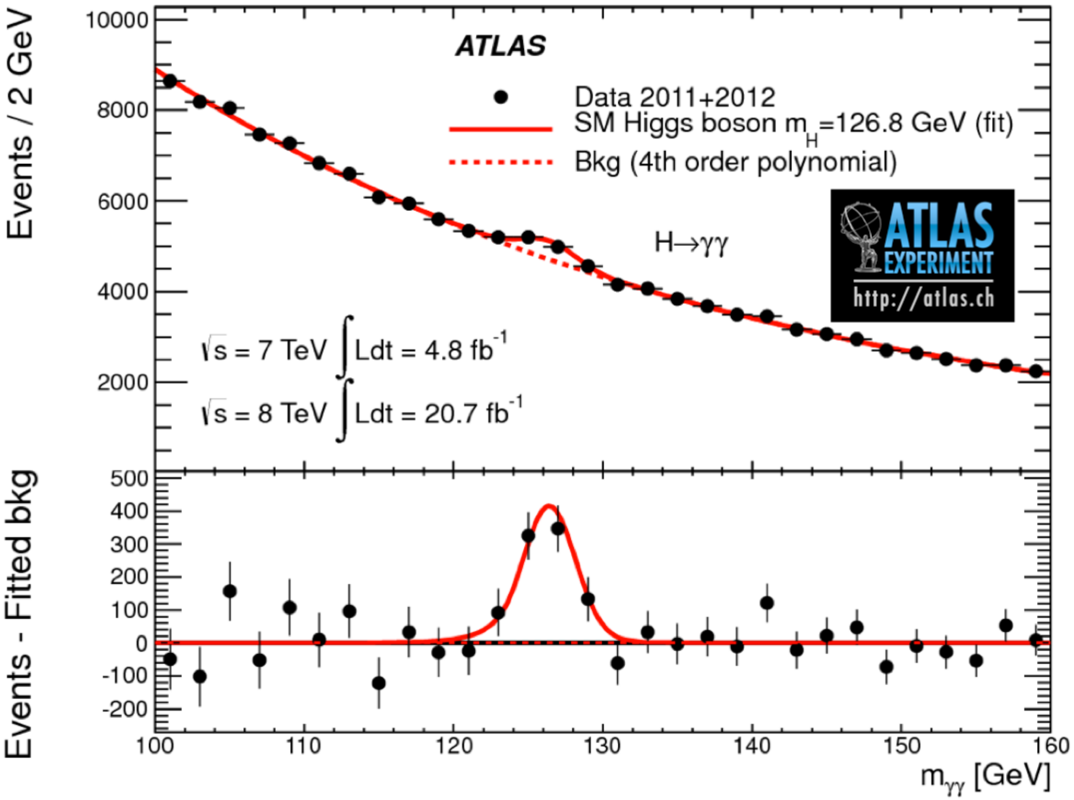


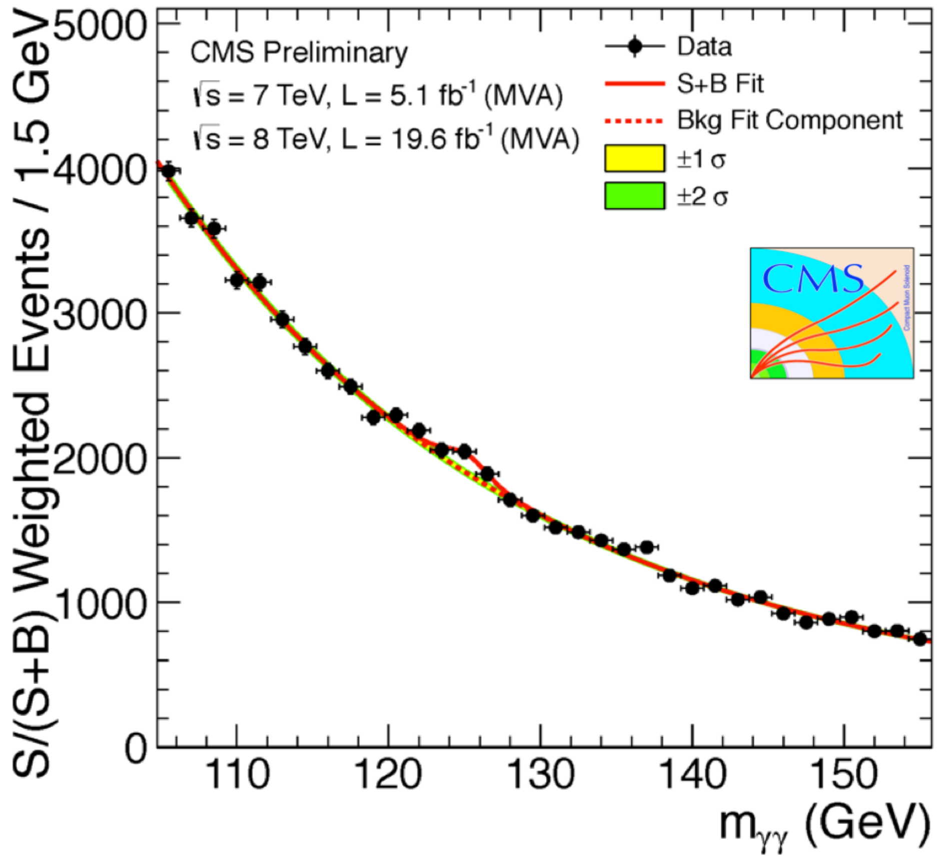
- Method:
  profile likelihood estimator is used to calculate **upper limits** on the **width**

- **First** direct **upper limit** on the Higgs boson **width**:
  an upper limit on the natural width of the Higgs boson:
  - **6.9 GeV** at 95% CL (observed)
  - **5.9 GeV** at 95% CL (expected)



Mass measurement with H—>γγ



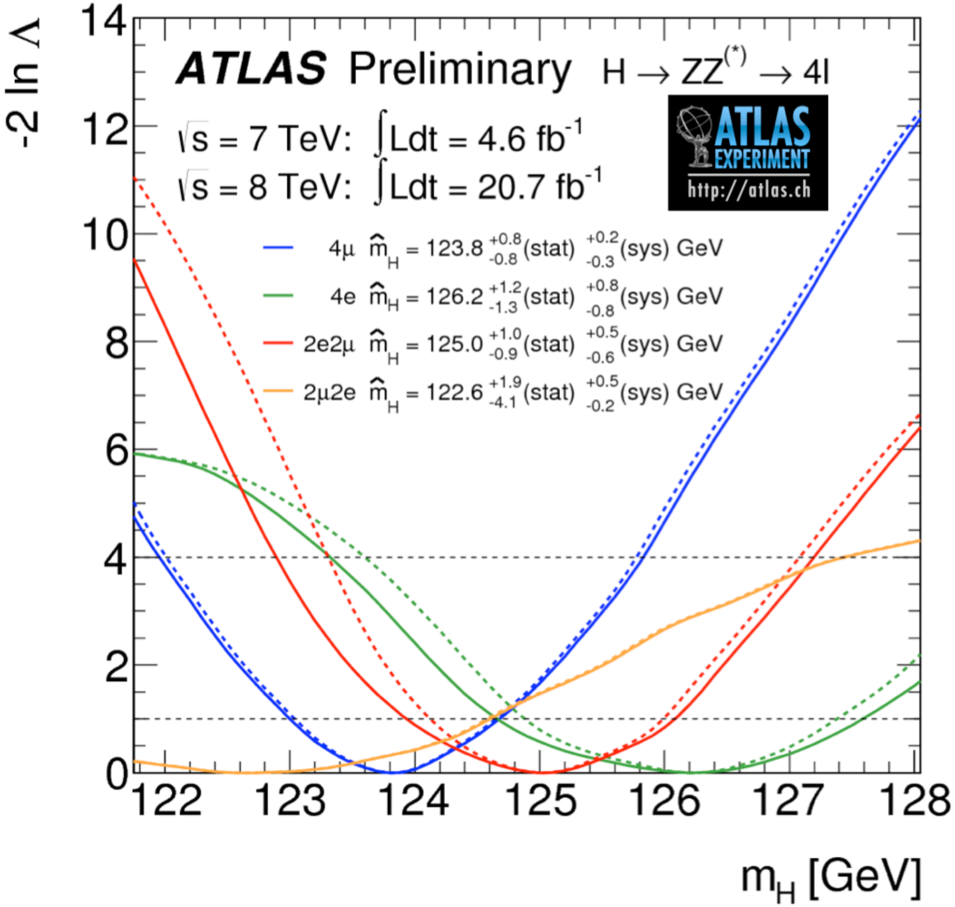


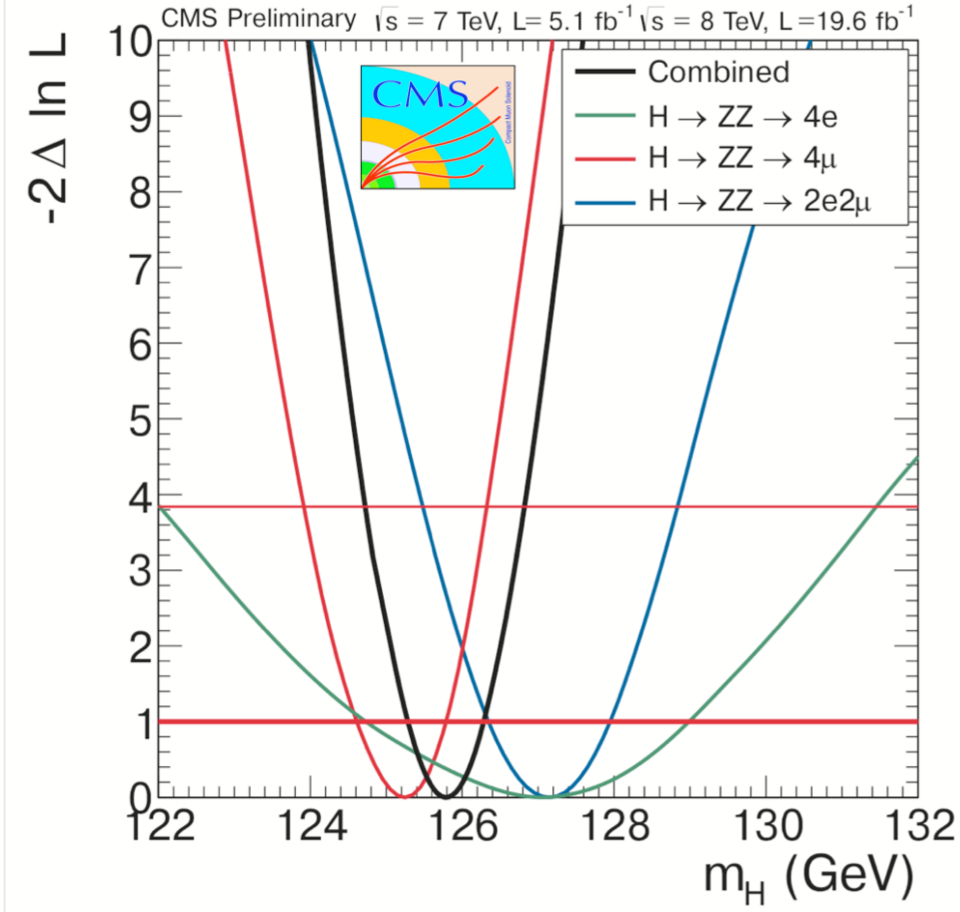
m_{Higgs} = 126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV

m_{Higgs} = 125.4 ± 0.5 (stat.) ± 0.6 (syst.) GeV

larger statistical uncertainty in CMS, is mostly coming from the lower observed signal yield wrt ATLAS

Mass measurement with H—>ZZ*





m_{Higgs} = 123.4 ± $^{+0.6}_{-0.5}$ (stat.) ± $^{+0.5}_{-0.3}$ (syst.) GeV

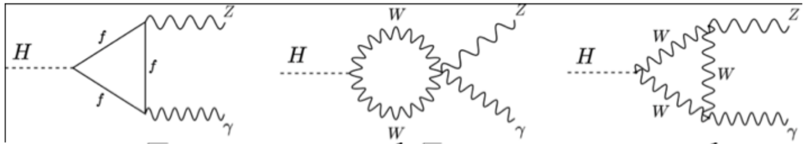
m_{Higgs} = 125.8 ± 0.5 (stat.) ± 0.2 (syst.) GeV

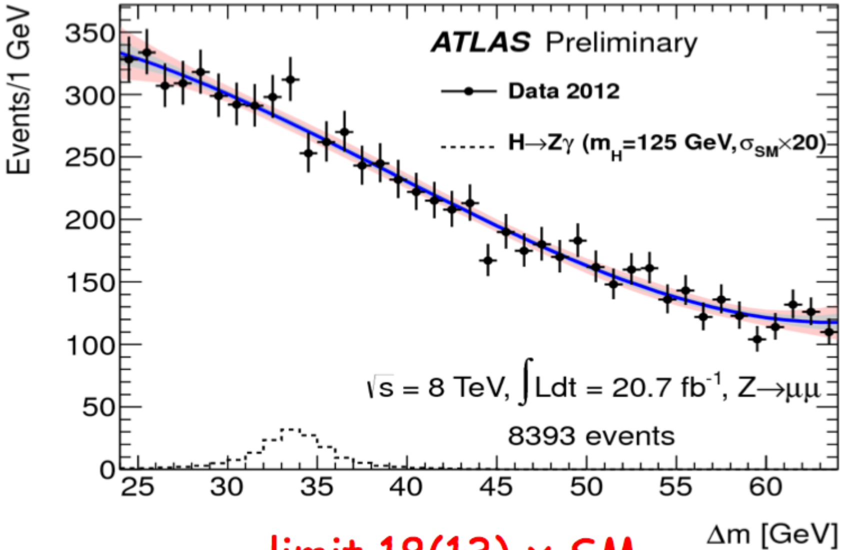
H—>Zγ

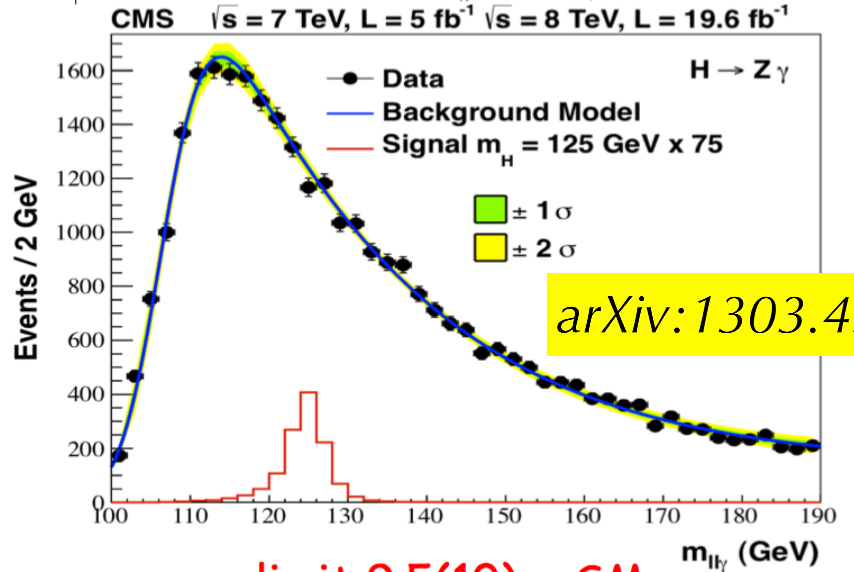
ATLAS-CONF-2013-009

Sensitive to new physics

H to Zγ



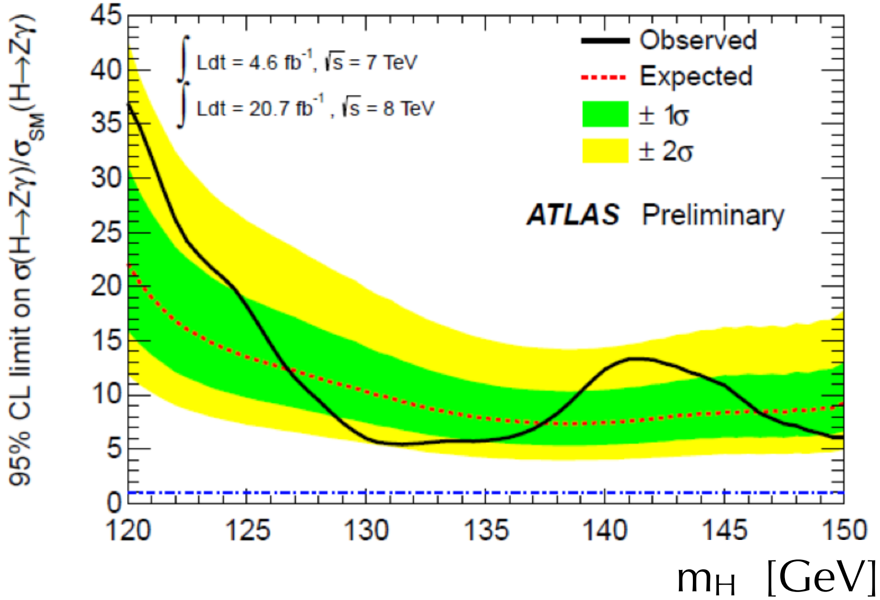


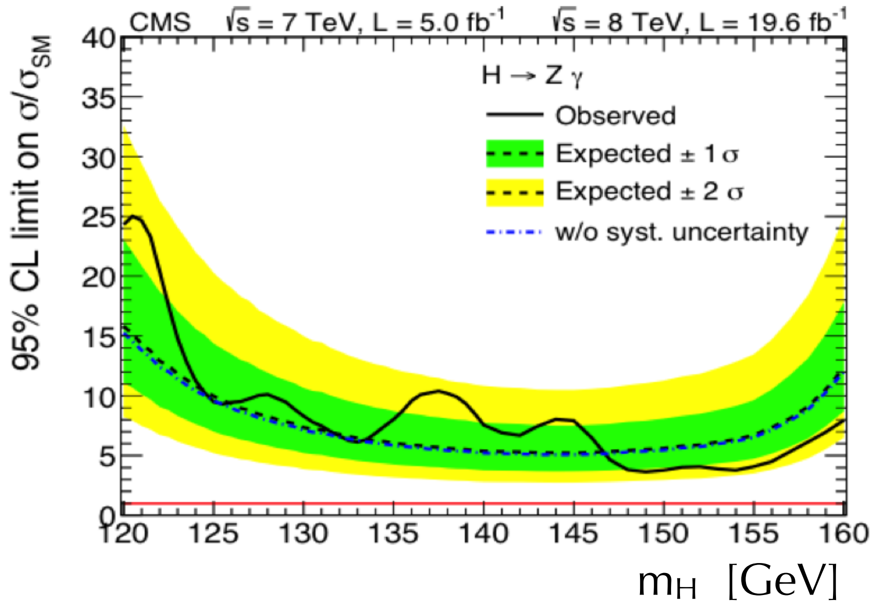


arXiv:1303.4571v2

limit 18(13) x SM

limit 9.5(10) x SM

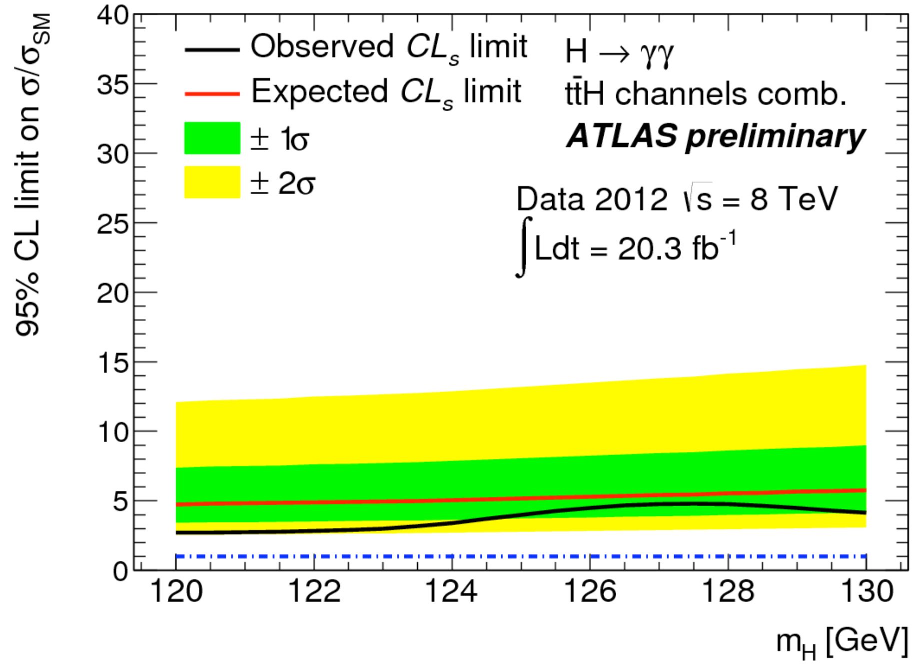




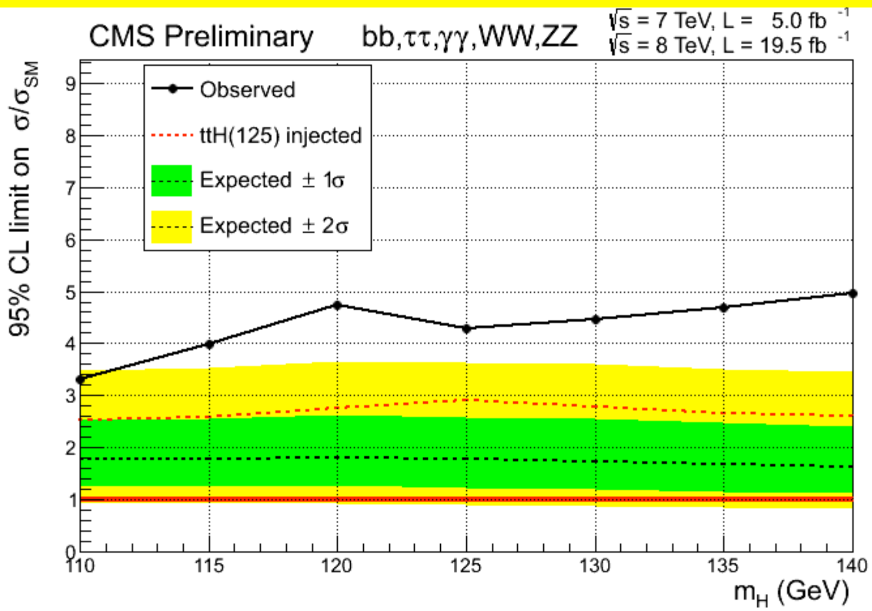
ttH

- Very challenging mode
  - Low rate
  - Complex final state
  - Enormous background
- Direct access to top Yukawa coupling
- ttH(γγ)
  - Run-I ATLAS: 5.3 (6.4) × SM
  - Run-I CMS: 5.4 (5.3) × SM
- ttH(bb)
  - 7 TeV ATLAS: 13.1 (10.5) × SM
  - Run-I CMS: 5.2 (4.1) × SM
- CMS combination of bb, γγ, ττ, WW, ZZ
  - Run-I CMS: 4.3 (1.8) × SM

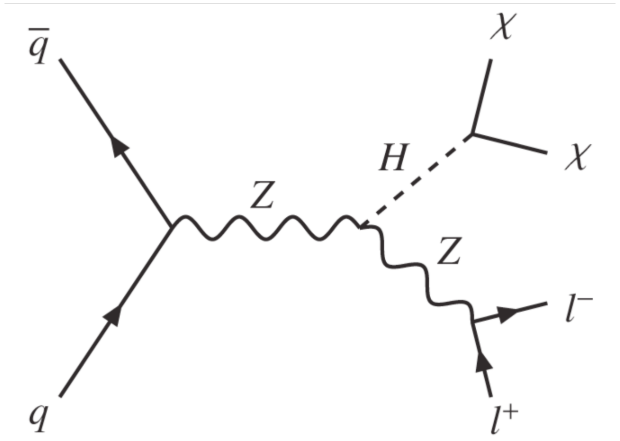
ATLAS-CONF-2013-080

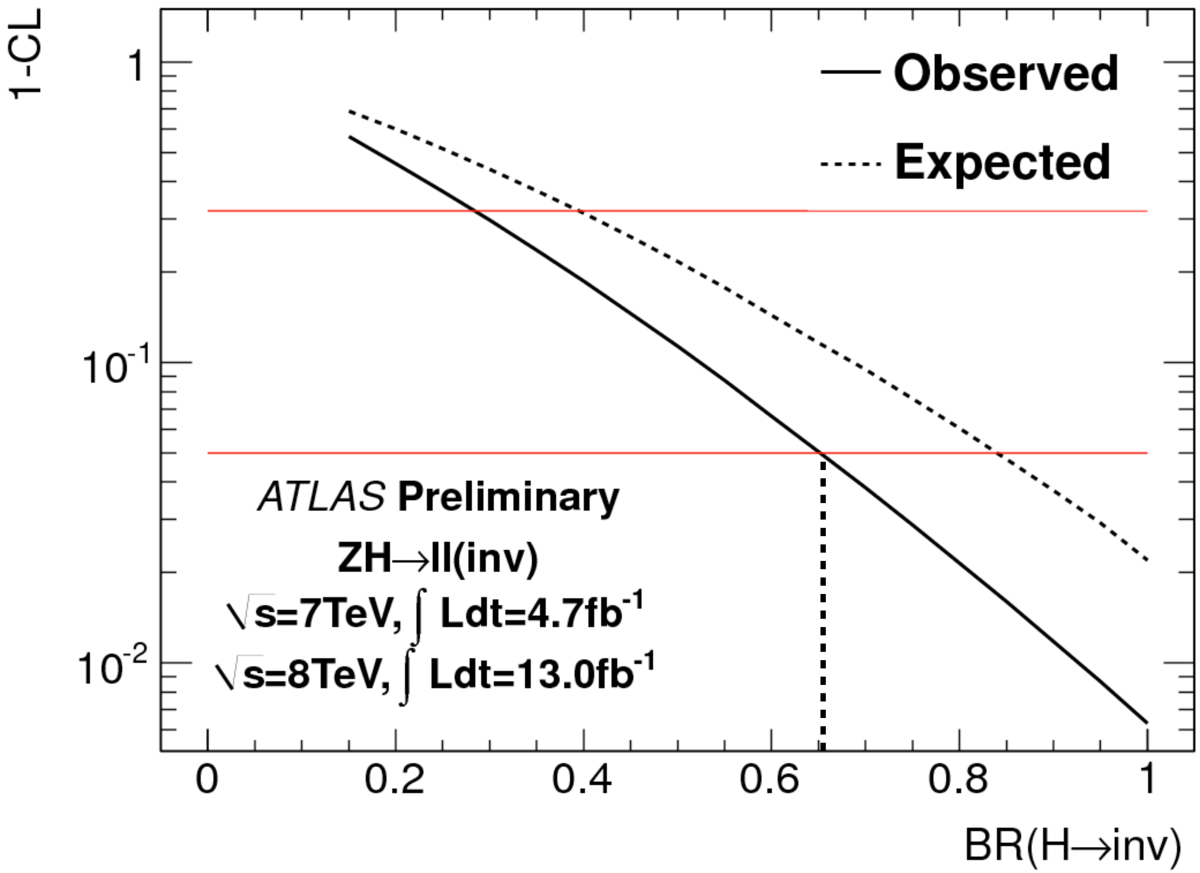


https://twiki.cern.ch/twiki/bin/view/CMSPublic/ttHCombinationTWiki



Higgs invisible decays



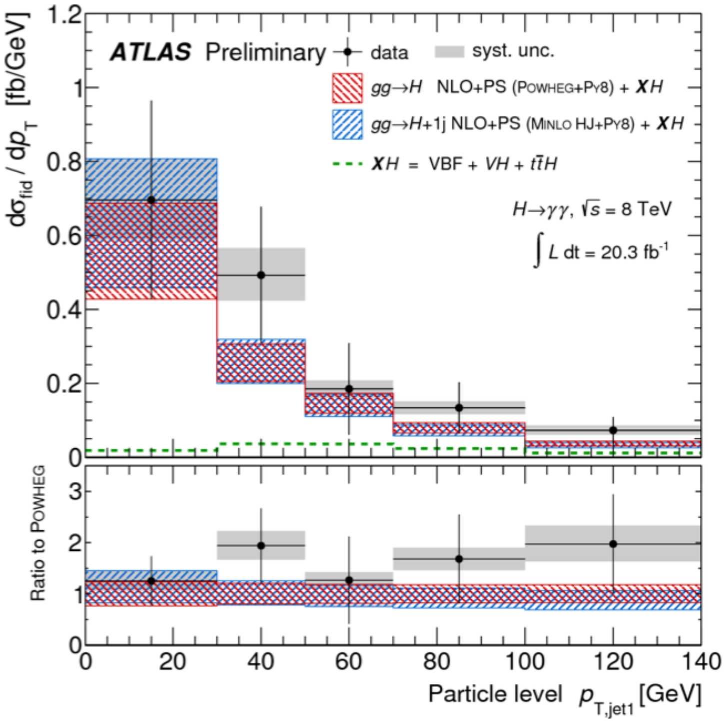


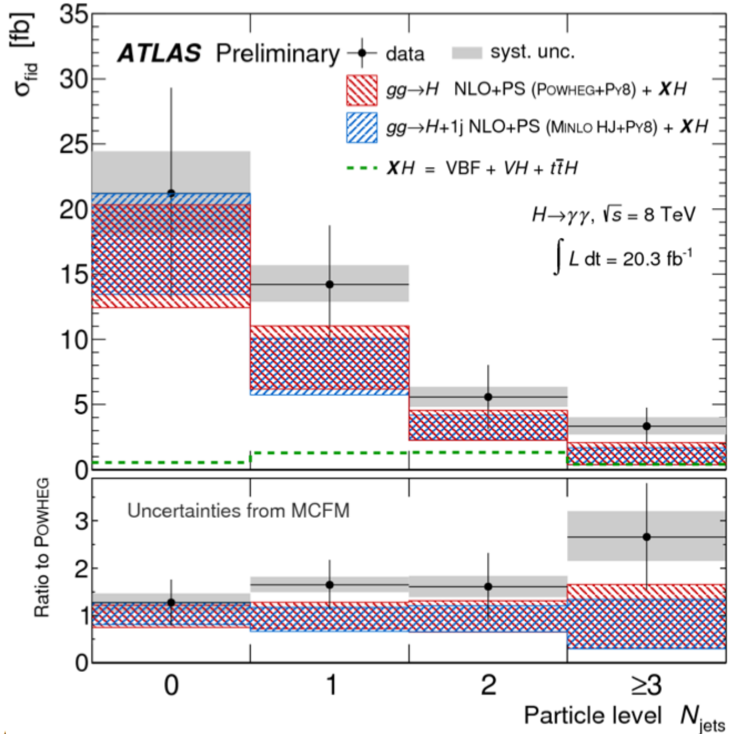
Higgs differential cross section

Differential cross section

atlas-conf-2013-072

- The clear signal in $H\rightarrow\gamma\gamma$ allows the measurement of a differential cross section
- The analysis is done inclusively and dominated by ggF
- Results are presented at the particle level
- There is good agreement with the prediction $P(\chi^2)>0.3$





mSUGRA/CMSSM

A particular mSUGRA/CMSSM model point is specified by five parameters:

the universal scalar mass m0,

$\tan(\beta)=30$, the universal gaugino mass m1/2,

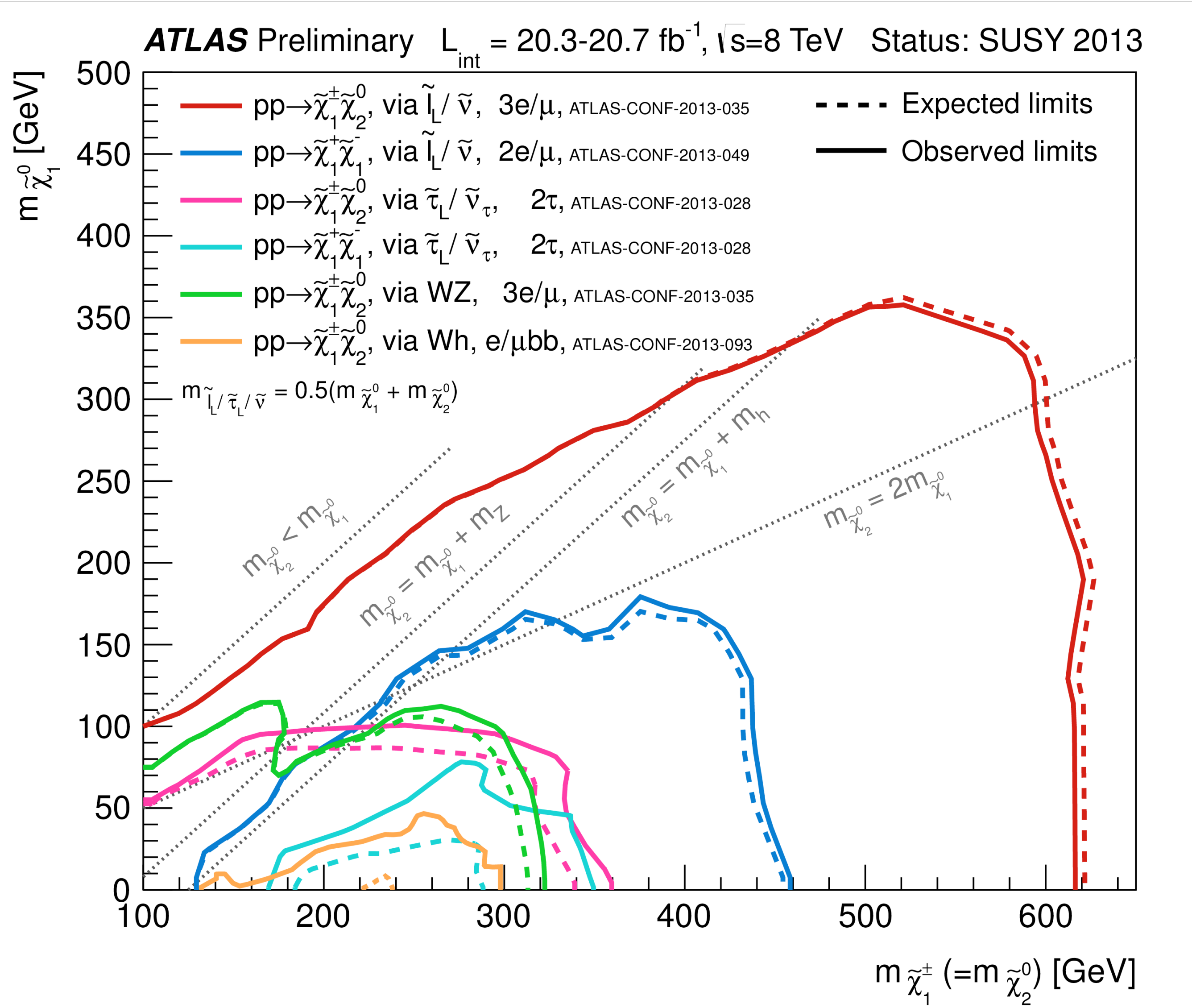
$A_0=-2m_0$, the universal trilinear scalar coupling A0,

$\mu>0$

the ratio of the vacuum expectation values of the two Higgs fields tanβ,

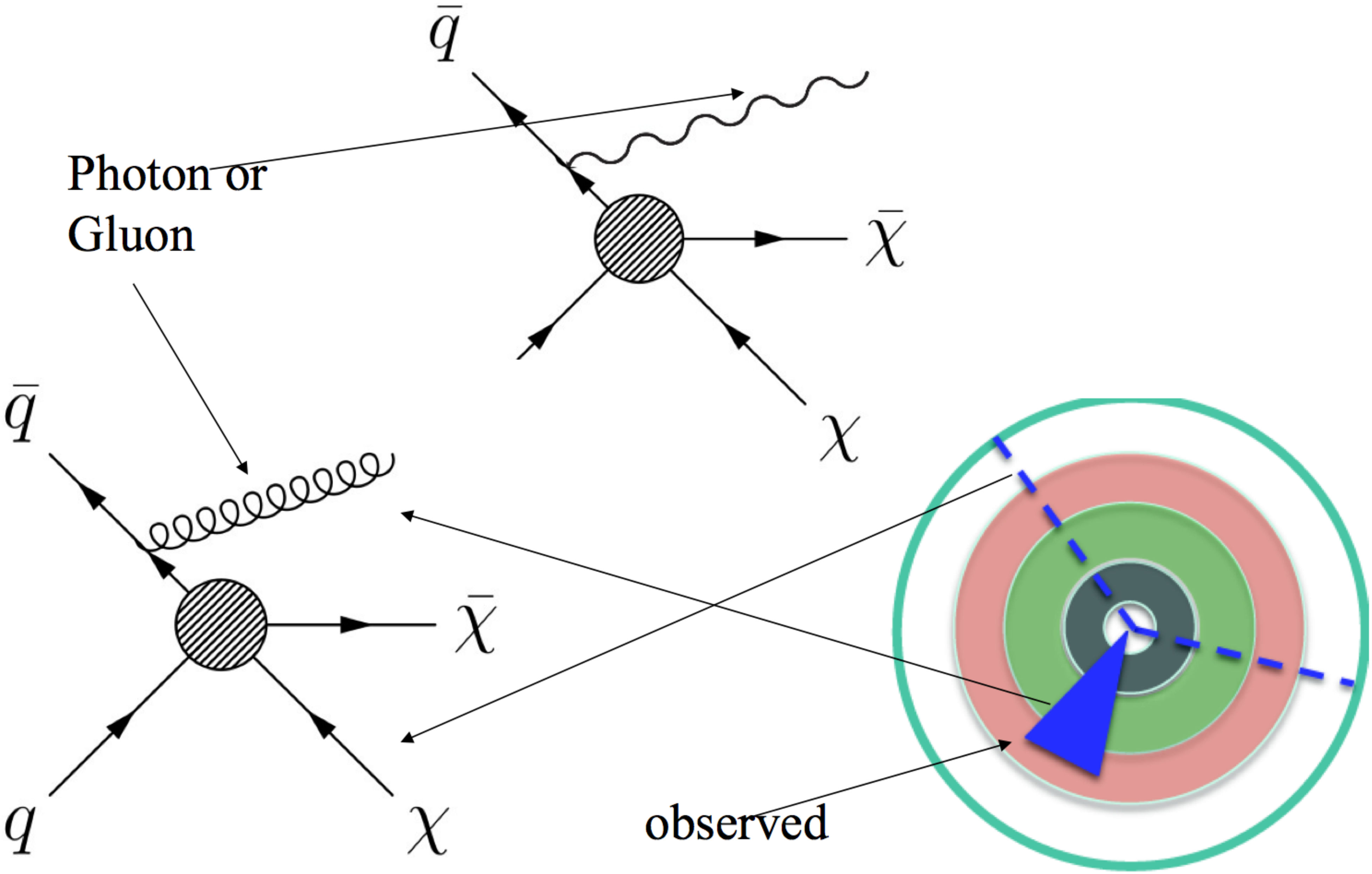
and the sign of the higgsino mass parameter μ.

SUSY Electroweak production



- Limits at the electroweak produced chargino, neutralino mass plane

DM associated production



Direct dark matter searches

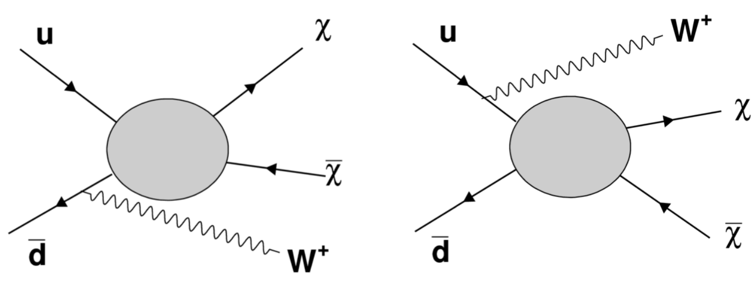
arXiv:1309.4017

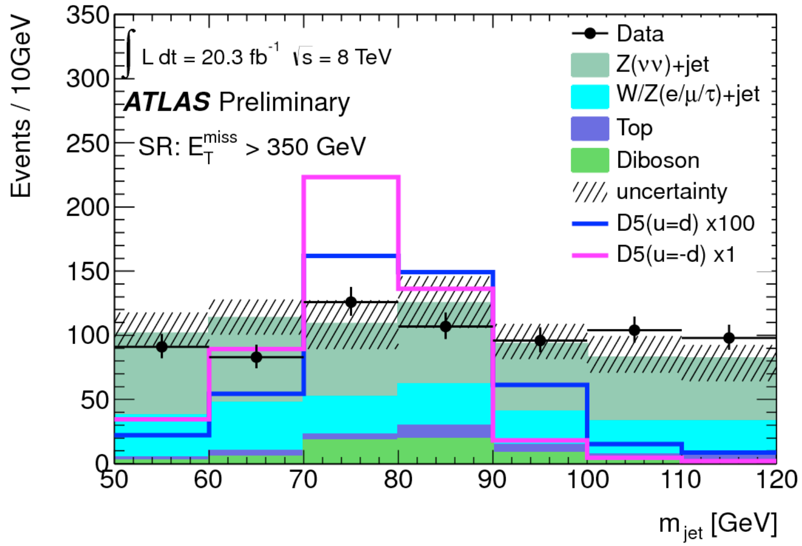
The operators studied in these mono-jet and mono-photon searches assume equal couplings of the dark matter particles **to up-type and down-type quarks (C(u) = C(d))**.

For W boson radiation there is **interference between the diagrams in which the W boson is radiated from the u-quark or the d-quark.**

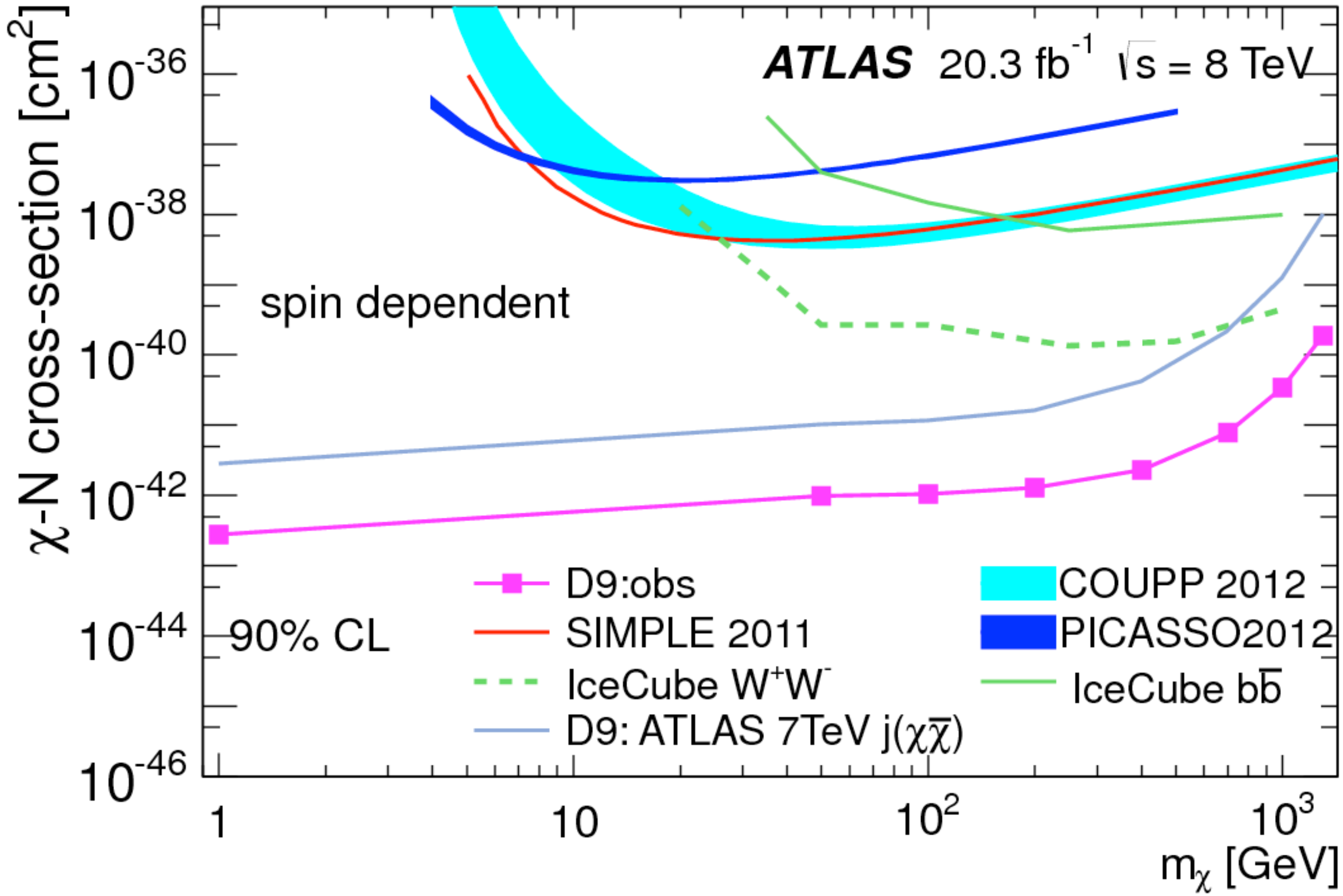
In the case **of equal coupling**, the interference is destructive and gives a small W boson emission rate.

If, **however, the up-type and down-type couplings have opposite signs** (C (u) = −C (d)) to give constructive interference, the relative rates of gluon, photon, W or Z boson emission can change dramatically, such that mono-W-boson production is the dominant process

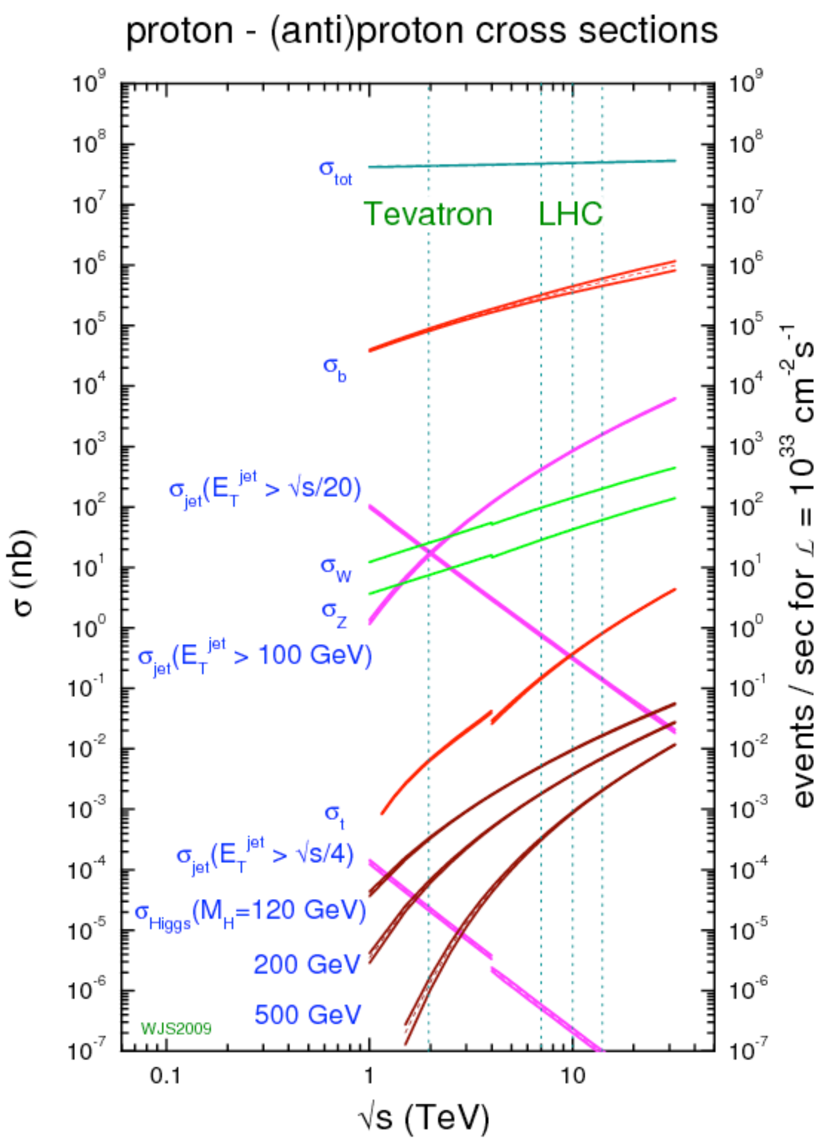


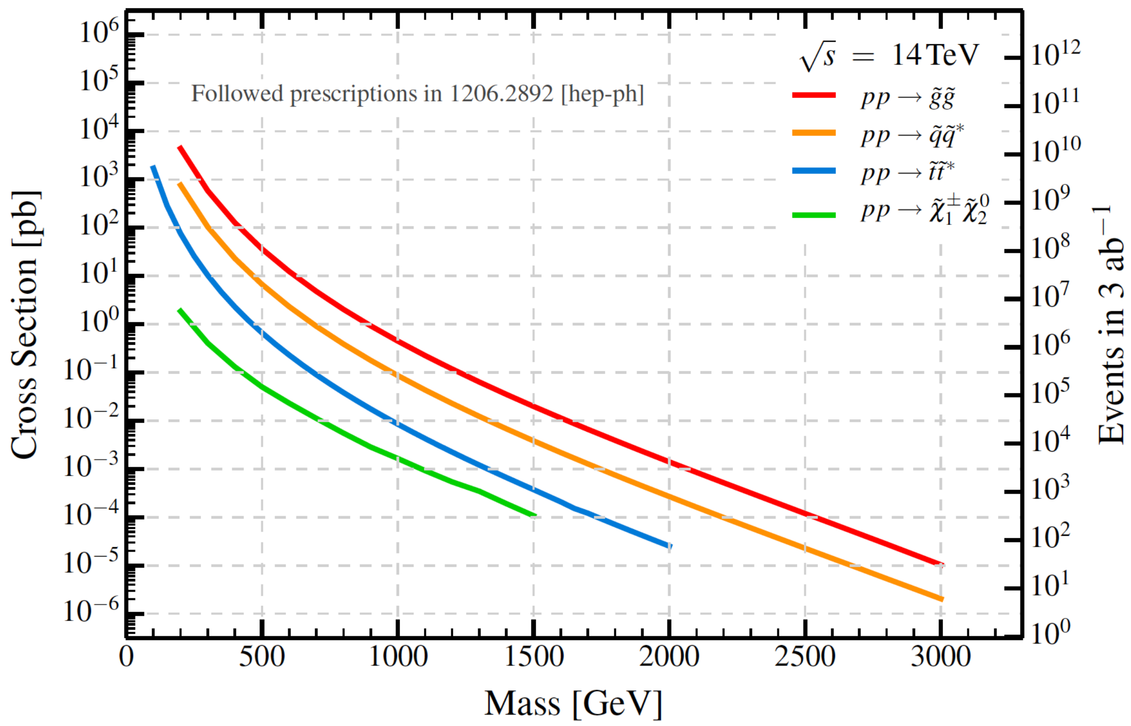


Direct dark matter searches

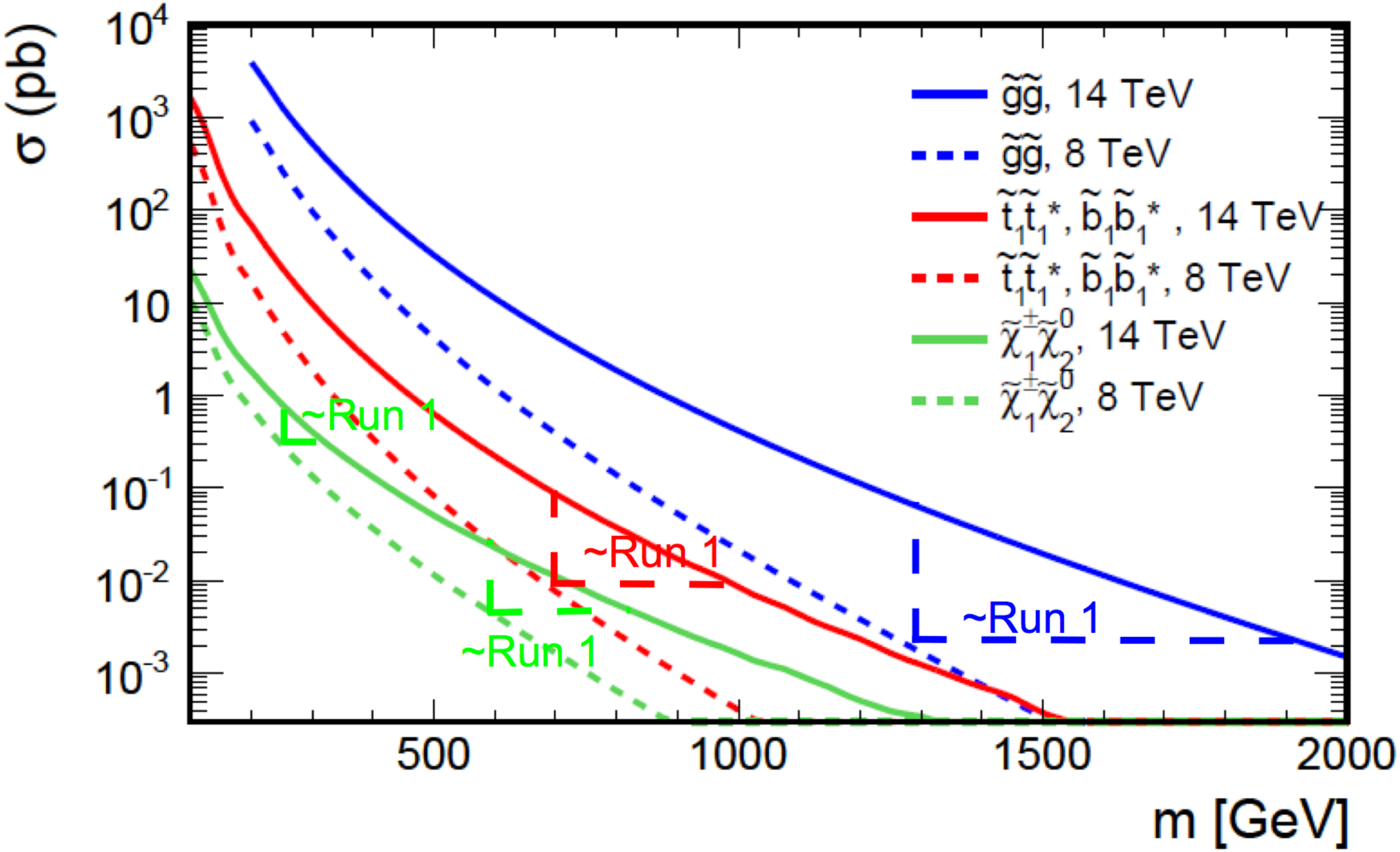


Some cross-sections



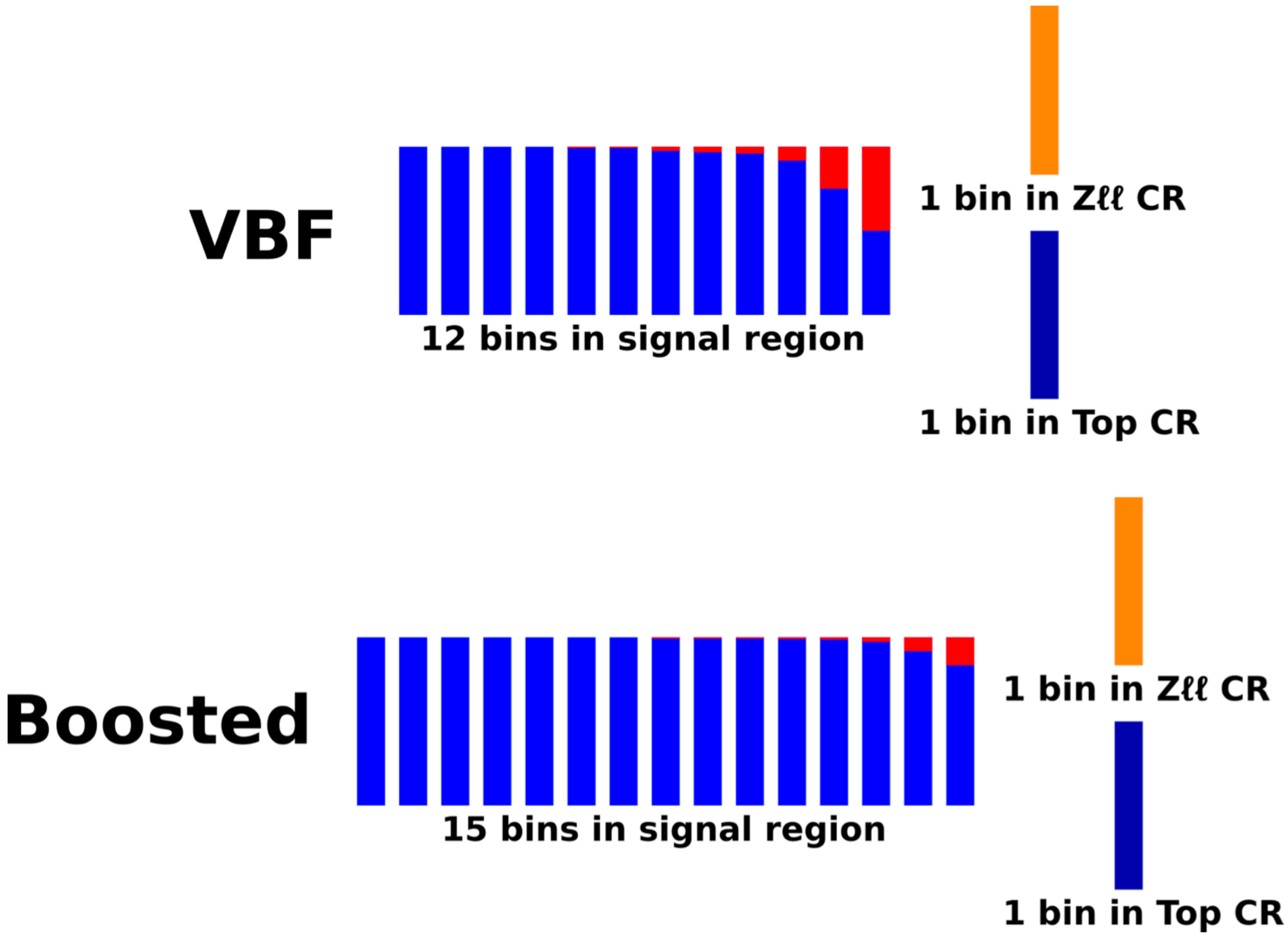


SUSY prospects



- Significant increase in cross-section for SUSY particles as well
- Specially going to higher masses, where the improvement can reach even 3 orders of magnitude

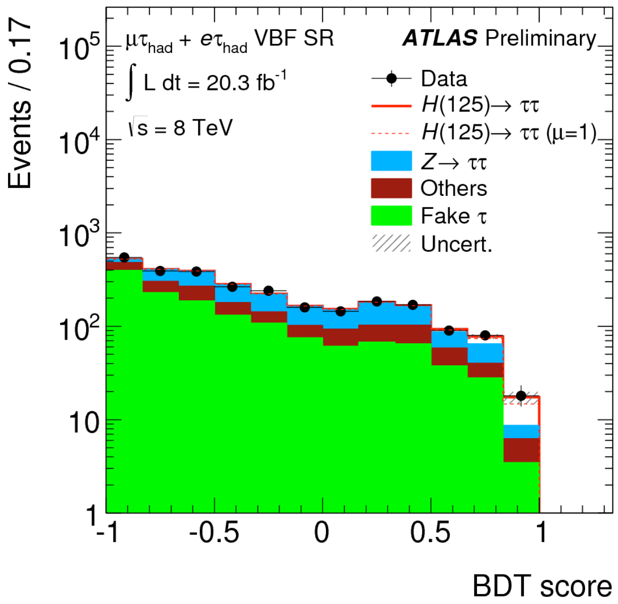
Fit model

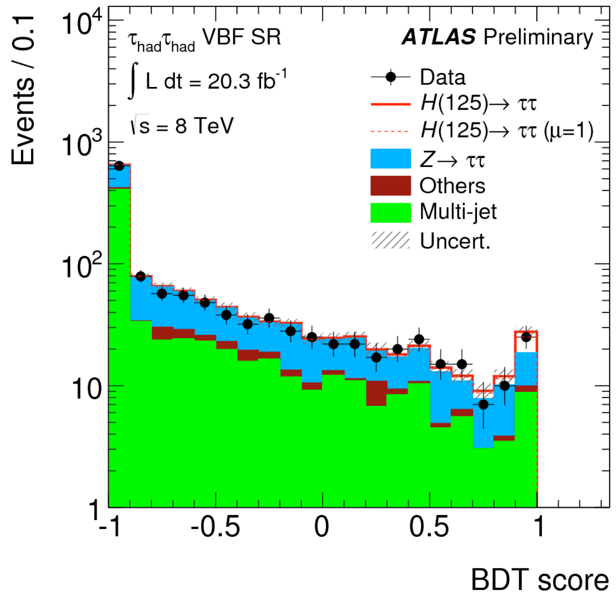


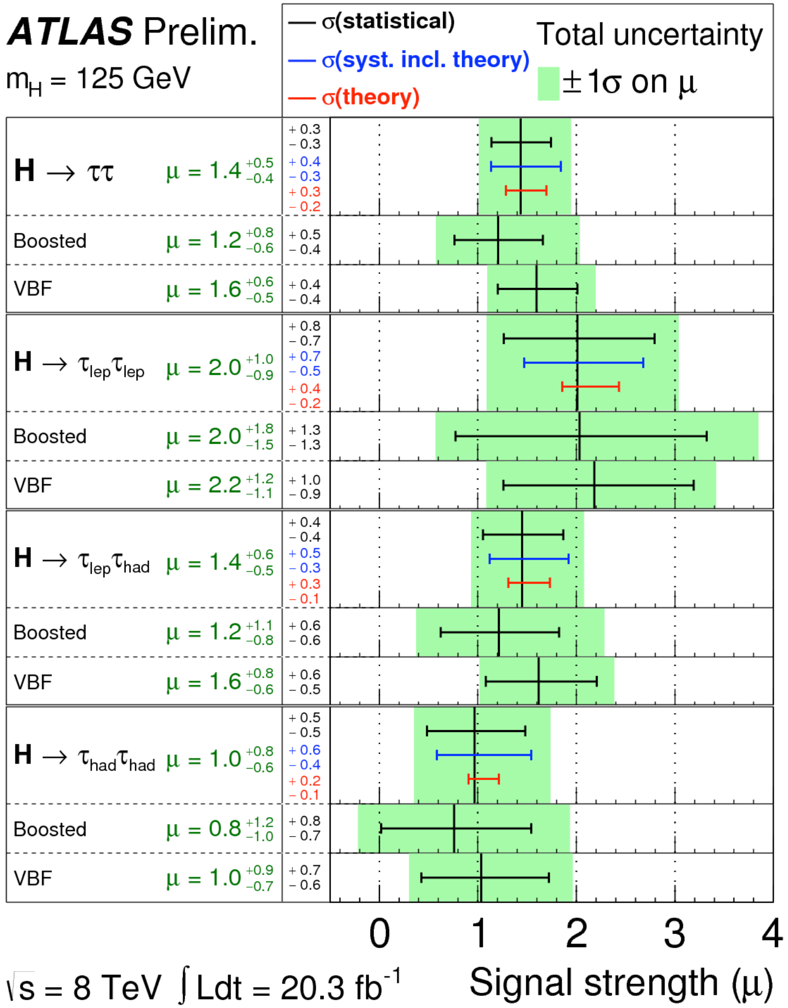
We run a simultaneous fit on all these (along with the bins from $\tau_{\rm had}\tau_{\rm had}$ and $\tau_{\rm lep}\tau_{\rm lep}$)

Higgs to fermions (ττ)

ATLAS-CONF-2013-108





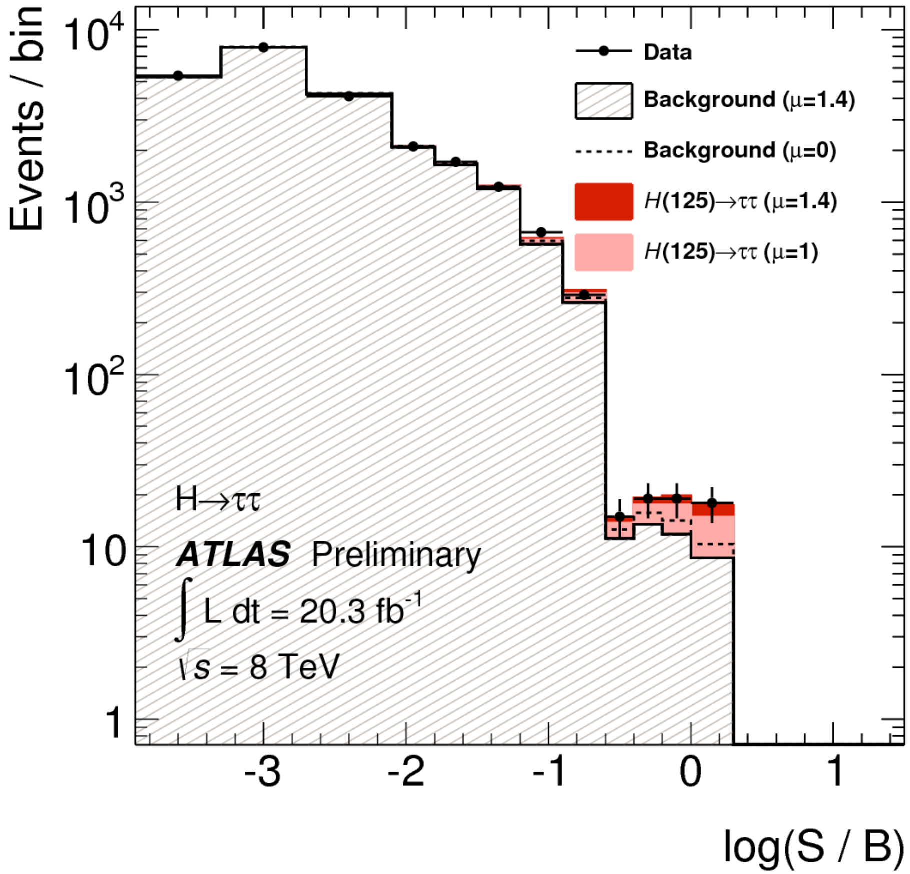


- Measured signal strength
  - ✦ **μ = 1.4 ± 0.5**

Consistent with SM Higgs boson predictions !

H→ττ significant excess observed

ATLAS-CONF-2013-108



Number of events in highest BDT-score bin

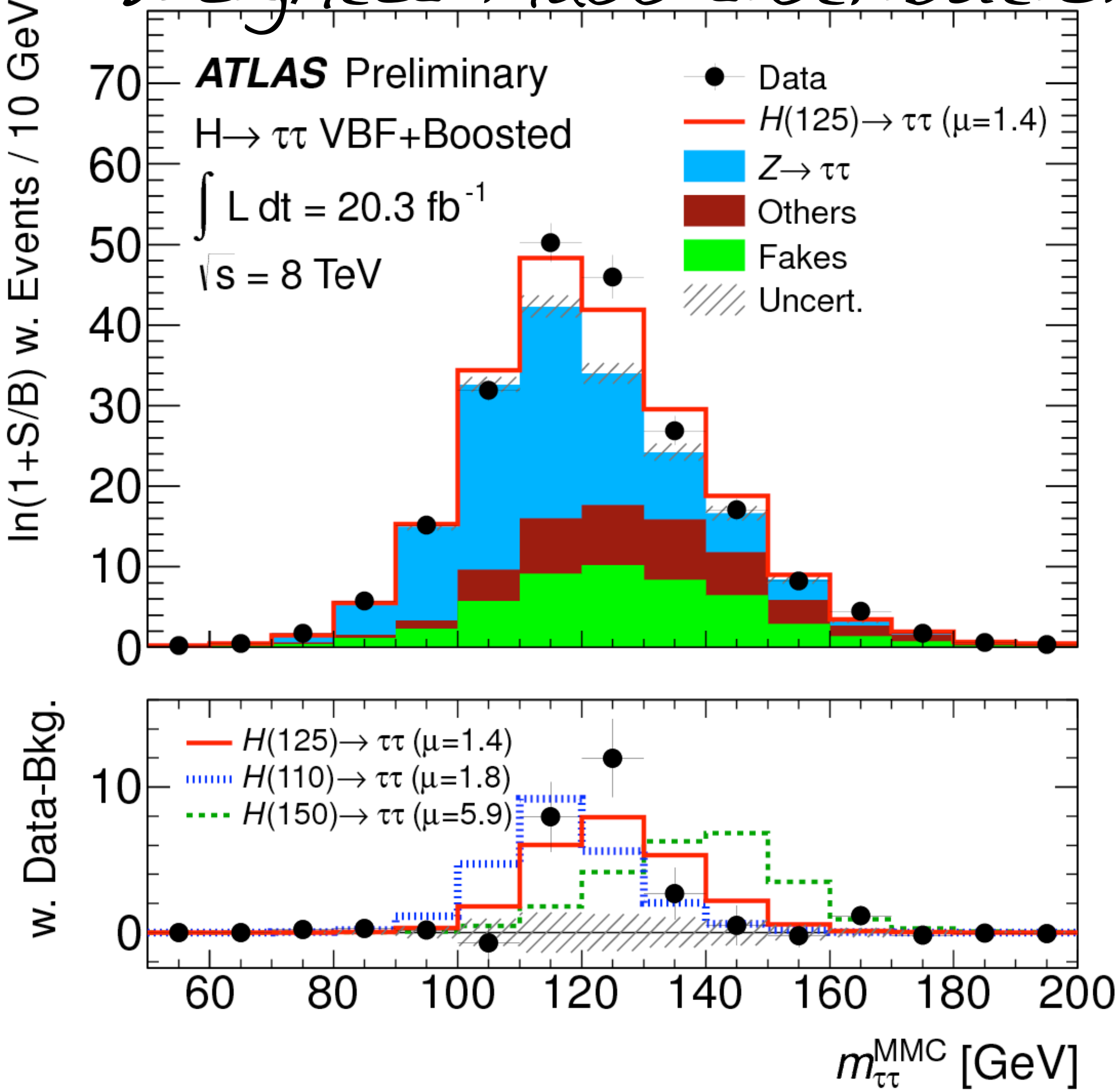
	LepLep	LepHad	HadHad
Signal	5.7±1.7	8.7±2.5	8.8±2.2
Bckgr.	13.5±2.4	8.7±2.4	11.8±2.6
Data	19	19	19

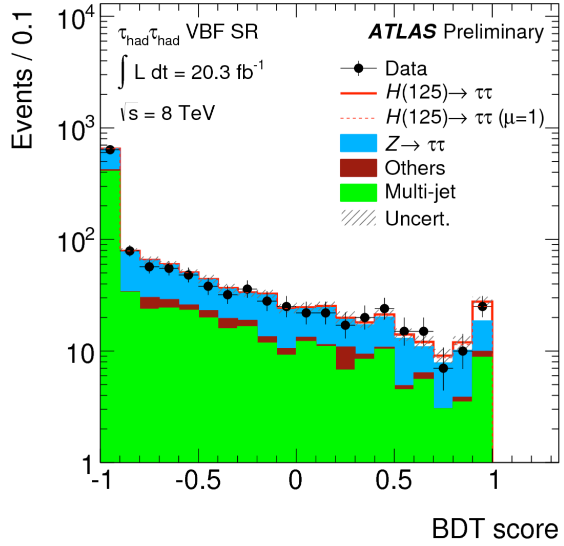
Signal	2.6±0.8	8.0±2.5	3.6±1.1
Bckgr.	20.2±1.8	32±4	11.2±1.9
Data	20	34	15

- ATLAS observes significant excess of data events in high S/B region
  - ✦ **Expected** significance @ m_H=125 GeV : **3.2σ** (Probability: **6.6×10^{-4}**)
  - ✦ **Observed** significance @ m_H=125 GeV : **4.1σ**
    - ✳Probability that the observed excess is due to a background fluctuation: **2×10^{-5}**
- **H→ττ (strong) evidence, observed by ATLAS**

Is the excess compatible with a m_H=125 GeV Higgs boson?

Weighted mass distribution



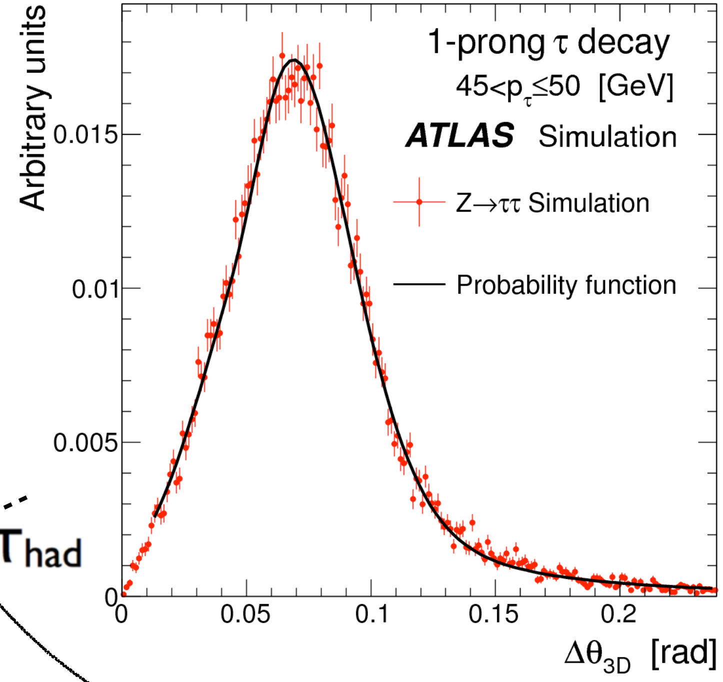


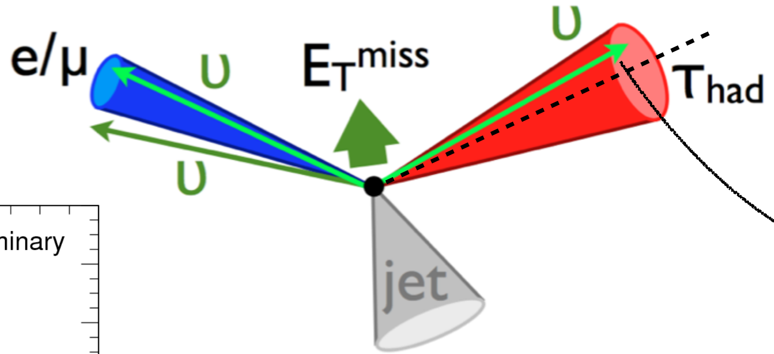
- Each event is weighted by ***ln(1 + n_S/n_B)***, given the bin of the BDT-Score, in which it is contained to

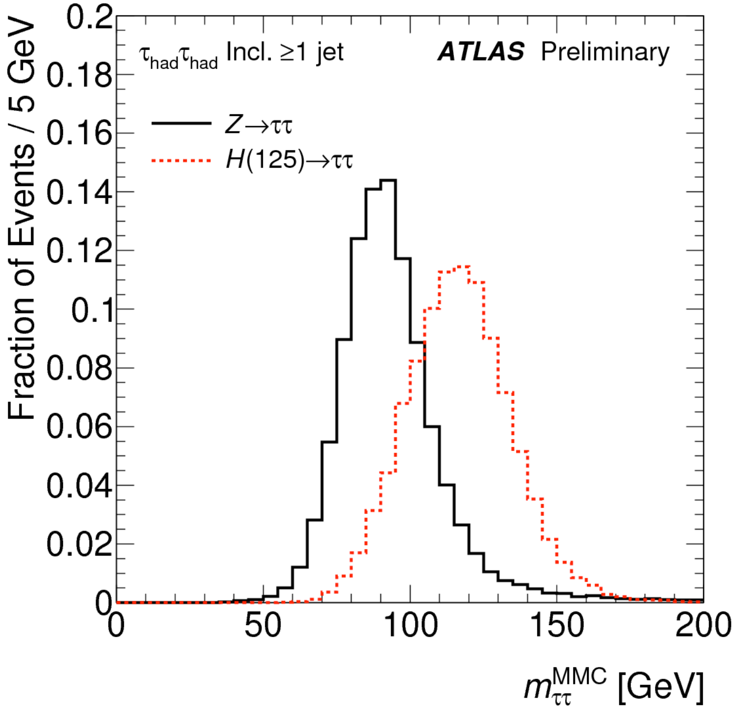
- **Observed signal compatible with m_H=125 GeV**

DiTau mass reconstruction: MMC

- MMC: Mass reconstruction of original ττ system despite the presence of undetectable neutrinos
  - ✦ Solve under-constrained system of kinematic equations by selecting the most likely solution given a parameterisation of 3D angle of tau visible and invisible decay products







- Correct peak position, reduced tails
- Resolution **14%-22%** depending on channel and category

The role of the MMC mass in the analysis

- Typically Higgs searches analyses have been using the mass distribution to fit the model to data

- We made a decision to include the MMC mass as an input variable to the BDT and fit the BDT score distribution

  - ✦ Mass resolution cannot be compared with the 4l or γγ, channels that provide the Higgs boson mass measurement

  - ✦ Take advantage of the MMC mass correlations which differ for signal and backgrounds

  - ✦ **Boost the analysis sensitivity to answer the question wether the Higgs boson recently discovered directly couples to τ's**