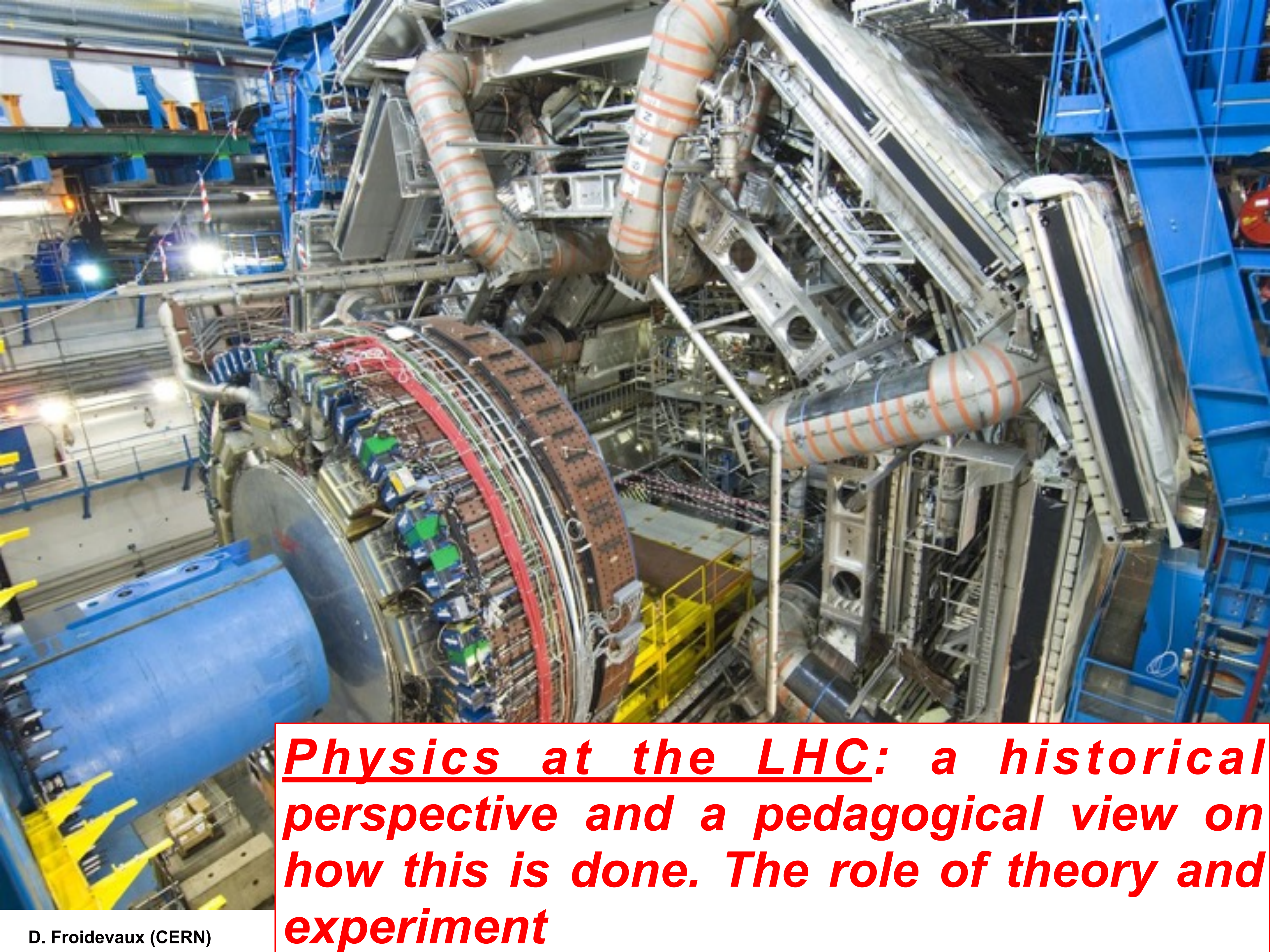
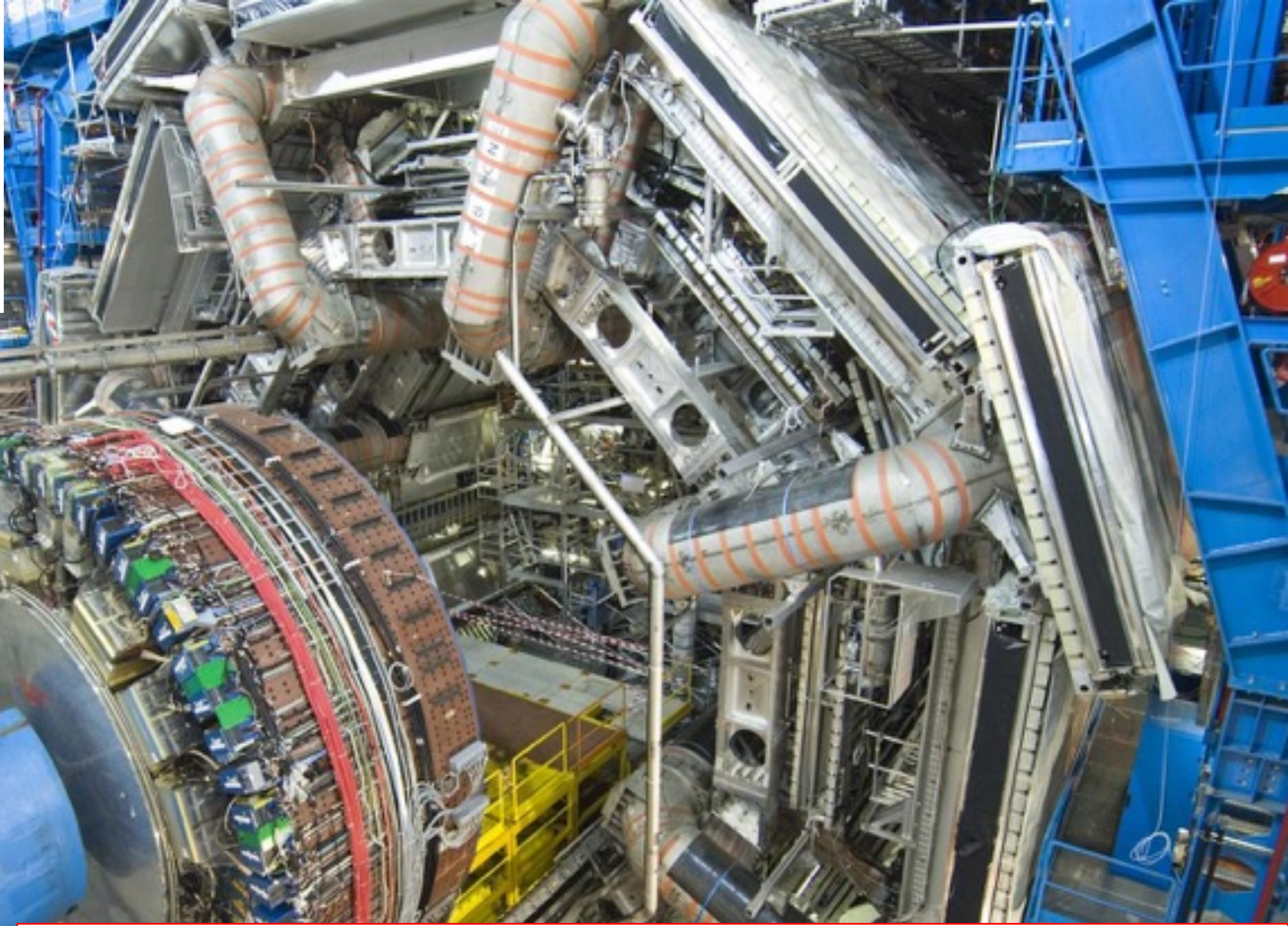


Physics at the LHC: a historical perspective and a pedagogical view on how this is done. The role of theory and experiment

D. Froidevaux (CERN)

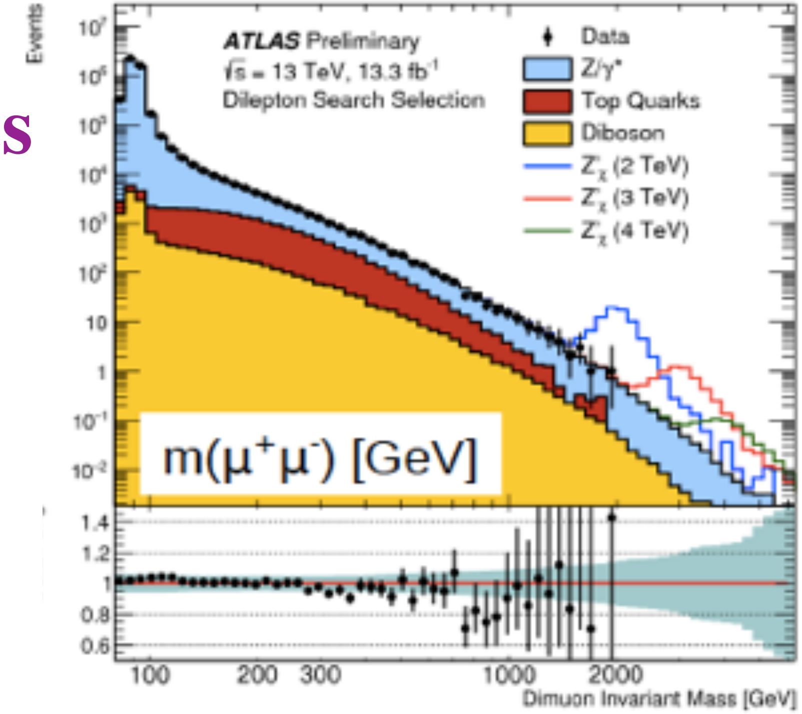


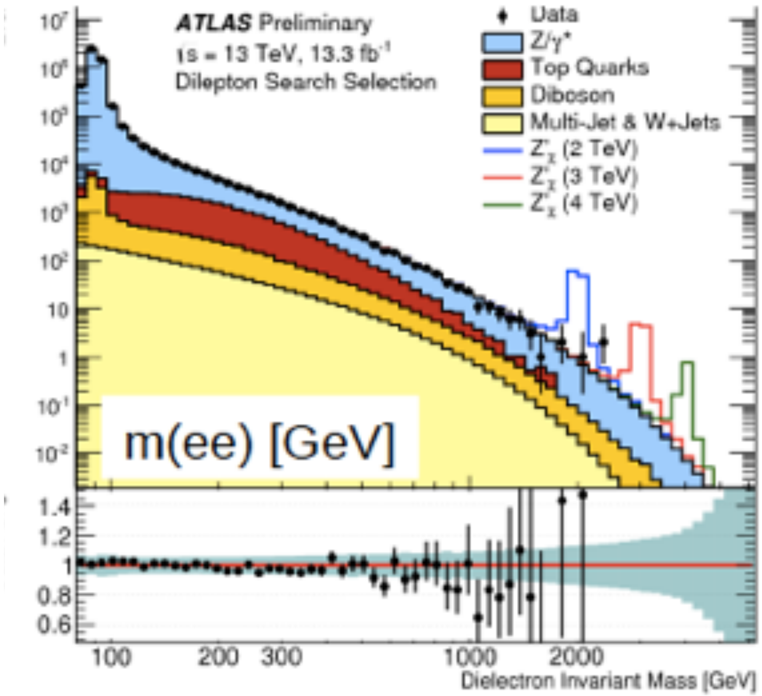
Physics at the LHC: a historical perspective and a pedagogical view on how this is done. The role of theory and experiment

D. Froidevaux (CERN)

Search for high-mass resonances decaying to leptons

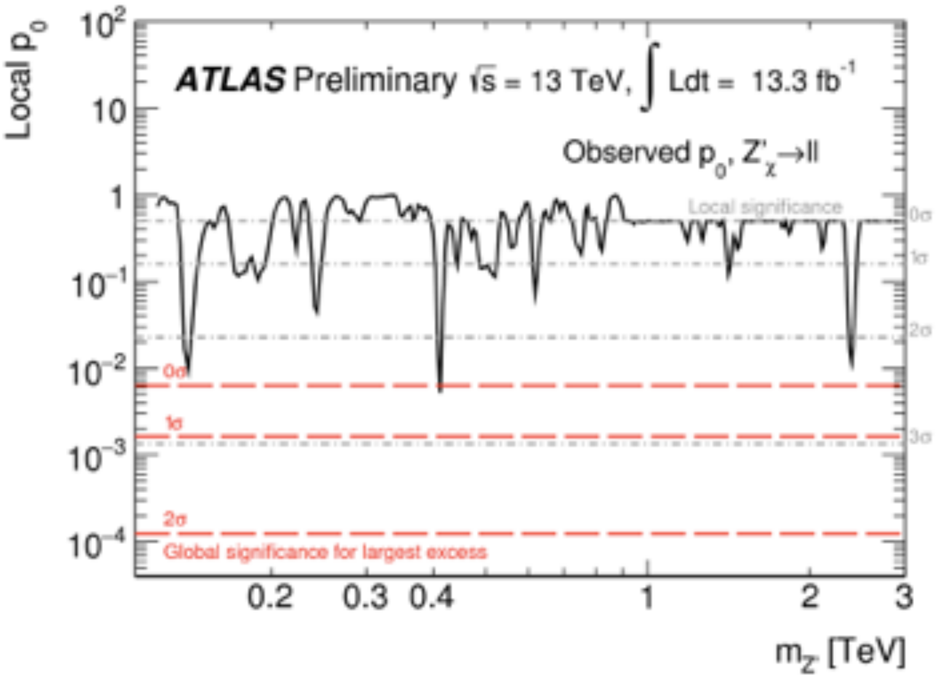
- Dimuon channel:
  - → 30 µm muon spectrometer alignment critical (ATLAS)
  - → Resolution 10-15% at $p_T = 1$ TeV
- Dielectron channel:
  - → Excellent resolution: < 2% at high momentum
  - → Poor charge measurement → no charge requirement
- Fit of the entire dilepton spectrum, incl. Z peak.

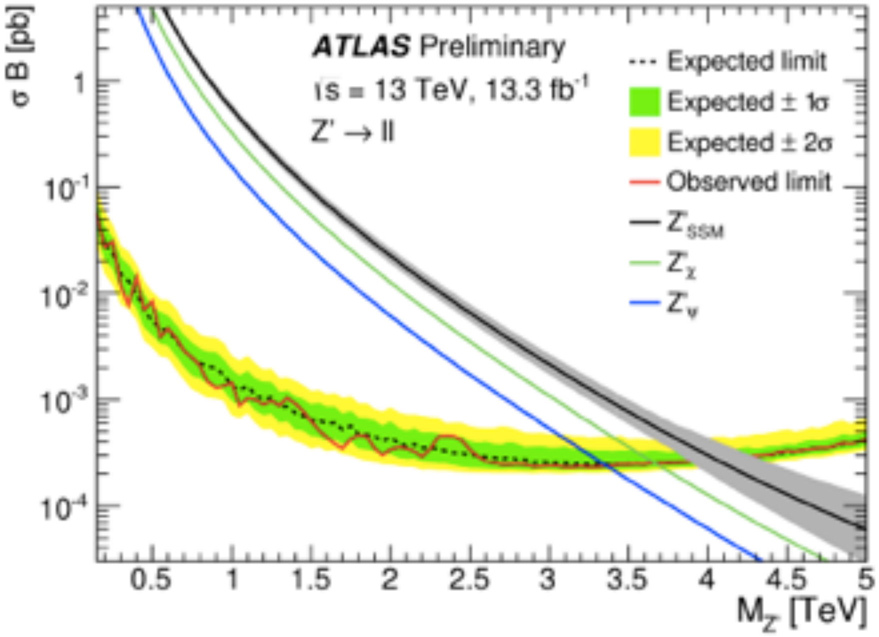




Search for Heavy Resonance: dilepton channel

- Search for narrow resonance with binning optimized wrt detector resolution from 120 GeV to 5 TeV

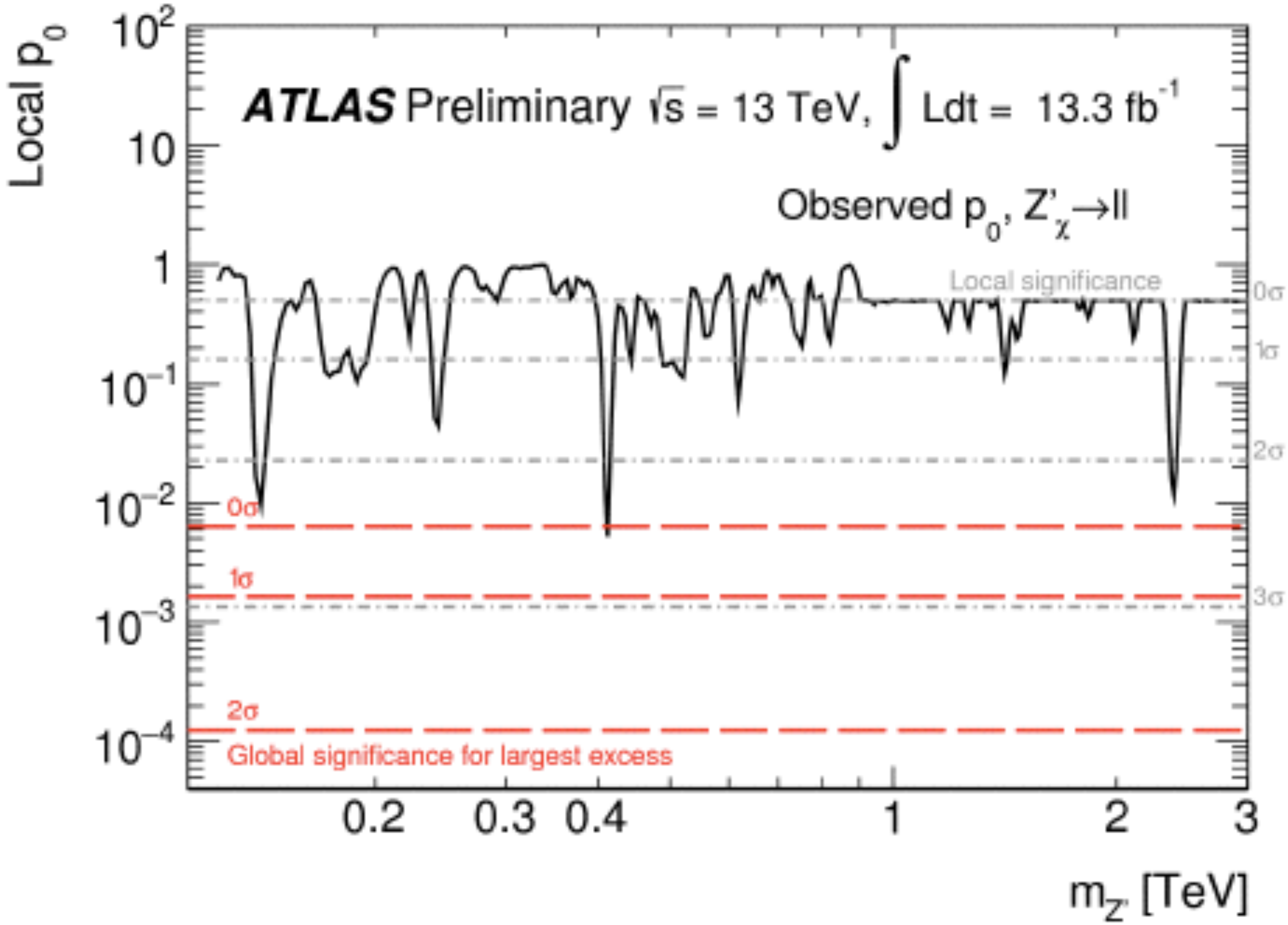




Observed lower limit (TeV) at 95% CL:
m(SSM Z') > 4.05 TeV

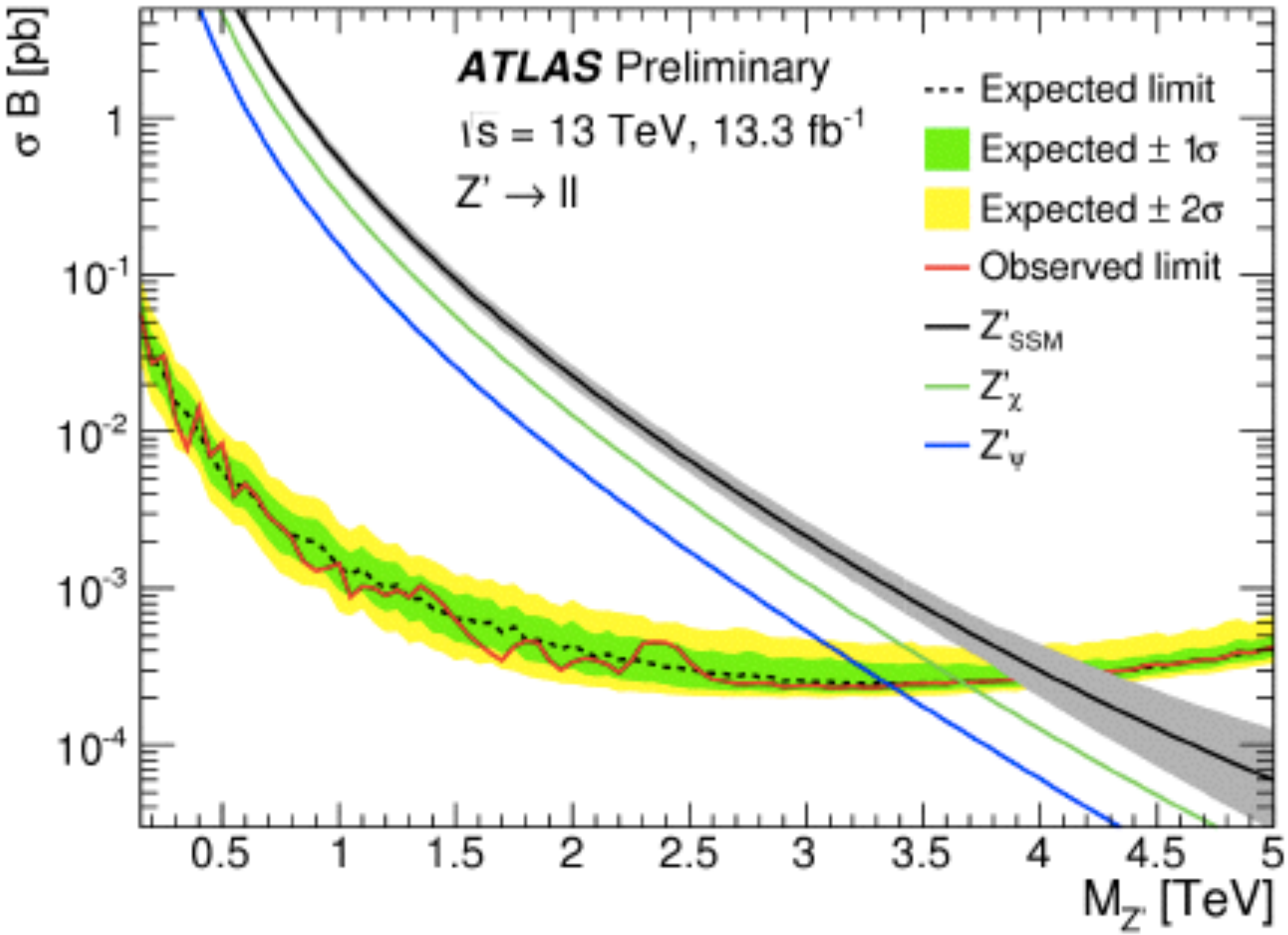
Search for Heavy Resonance: dilepton channel

Search for Heavy Resonance: dilepton channel



Search for Heavy Resonance: dilepton channel

Search for Heavy Resonance: dilepton channel

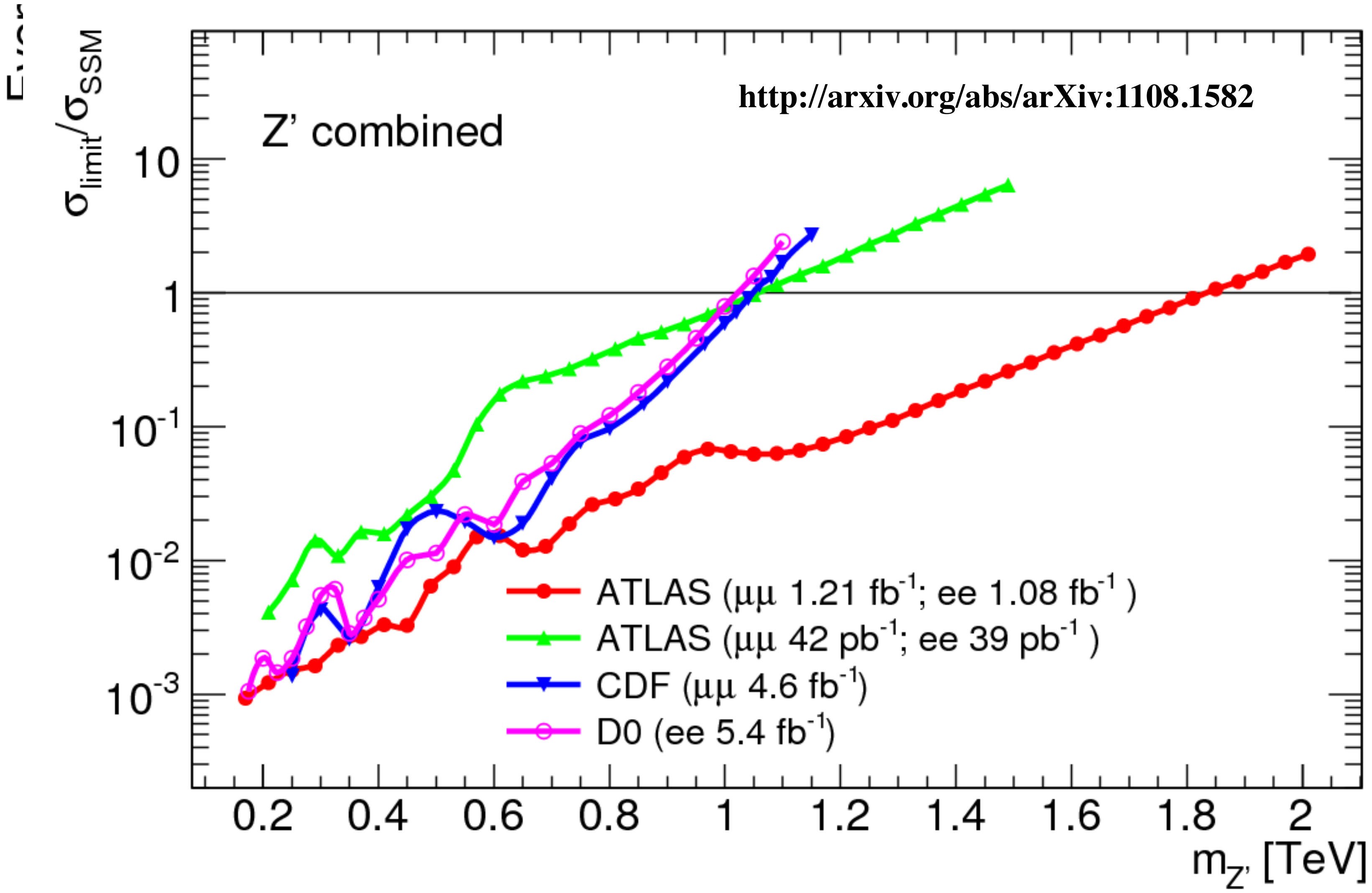


Observed lower limit (TeV) at 95% CL:
m(SSM Z') > 4.05 TeV

ATLAS status report

Now have covered a lot of phase space for many signatures

Search for dilepton resonances in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

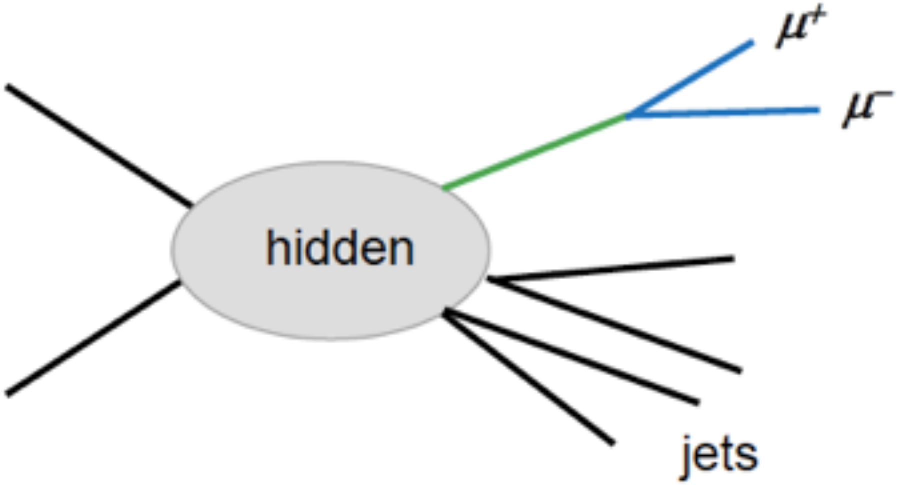


Physics Hidden in Inclusive Distributions

In various models *(common in hidden valleys/dark sectors)*

- Rare or unusual production of new neutral particle
- Bump, edge, endpoint, dip, wiggle is present
  - but swamped in inclusive background

MJS & Zurek '06
Han,Si,Zurek & MJS '07



Rare, prompt, light dilepton resonance along with hard jets

Physics Hidden in Inclusive Distributions

In various models *(common in hidden valleys/dark sectors)*

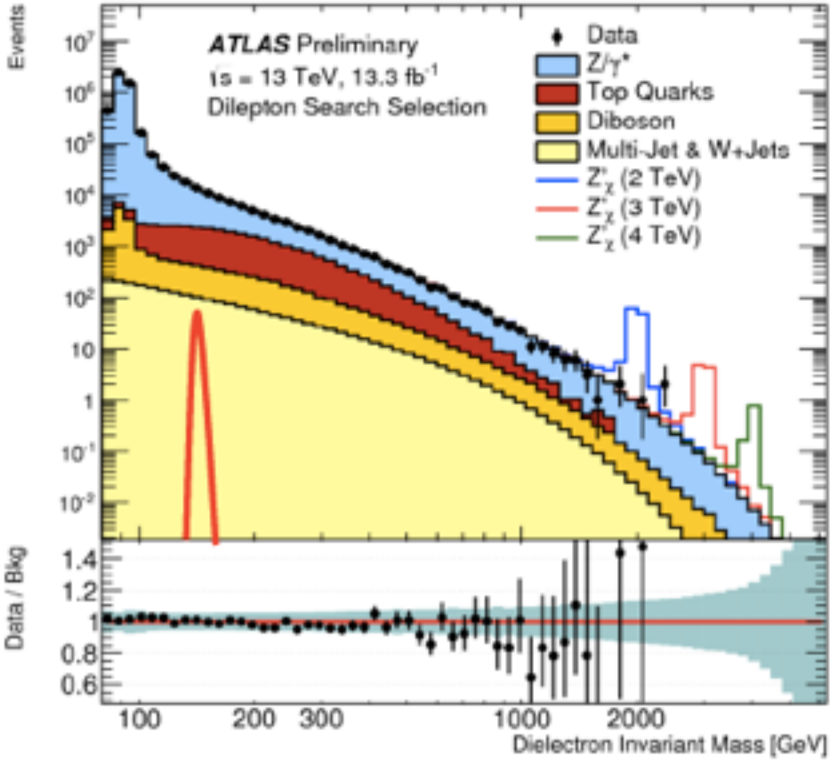
- Rare or unusual production of new neutral particle
- Bump, edge, endpoint, dip, wiggle is present
  - but swamped in inclusive background

- Point:
  - Higgs → bb resonance is invisible in inclusive production
  - But a semi-exclusive search can reveal it
    - The selection criterion reduces background, keeps signal

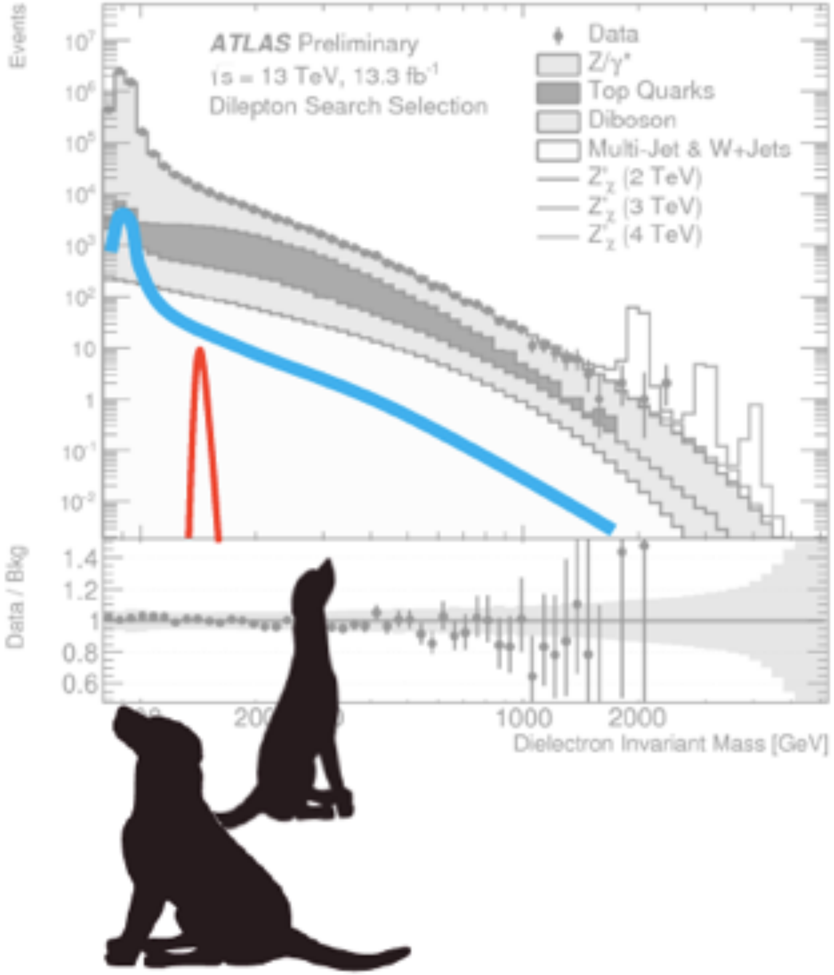
- We should do this for other resonance searches as a matter of course!

Inclusive is not Conclusive

Inclusive



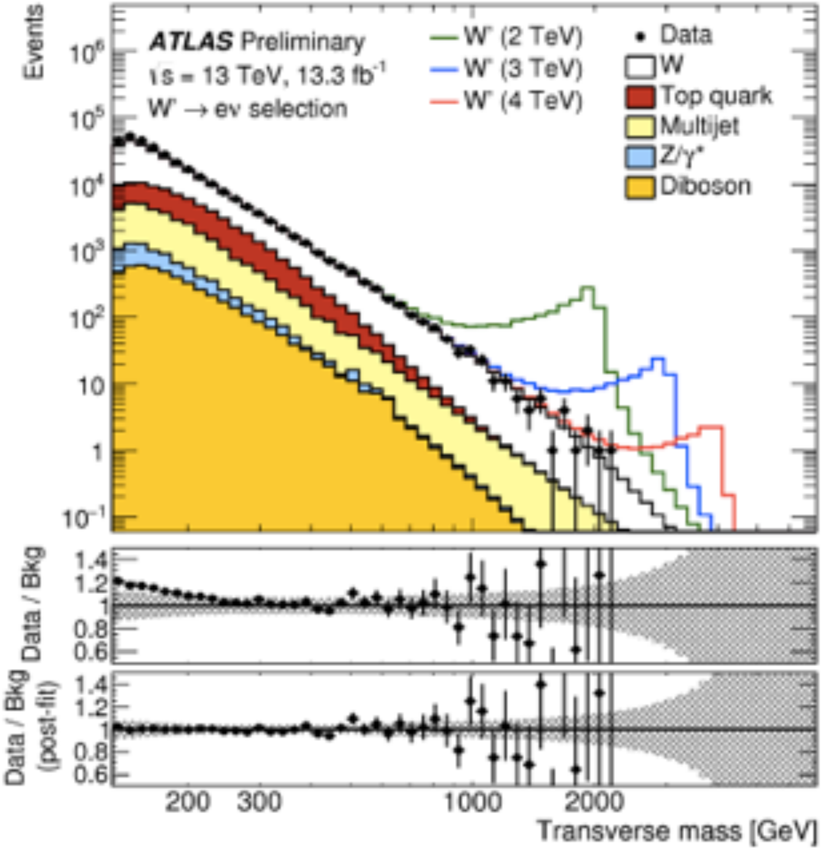
Require 4 jets and high HT and… presto!



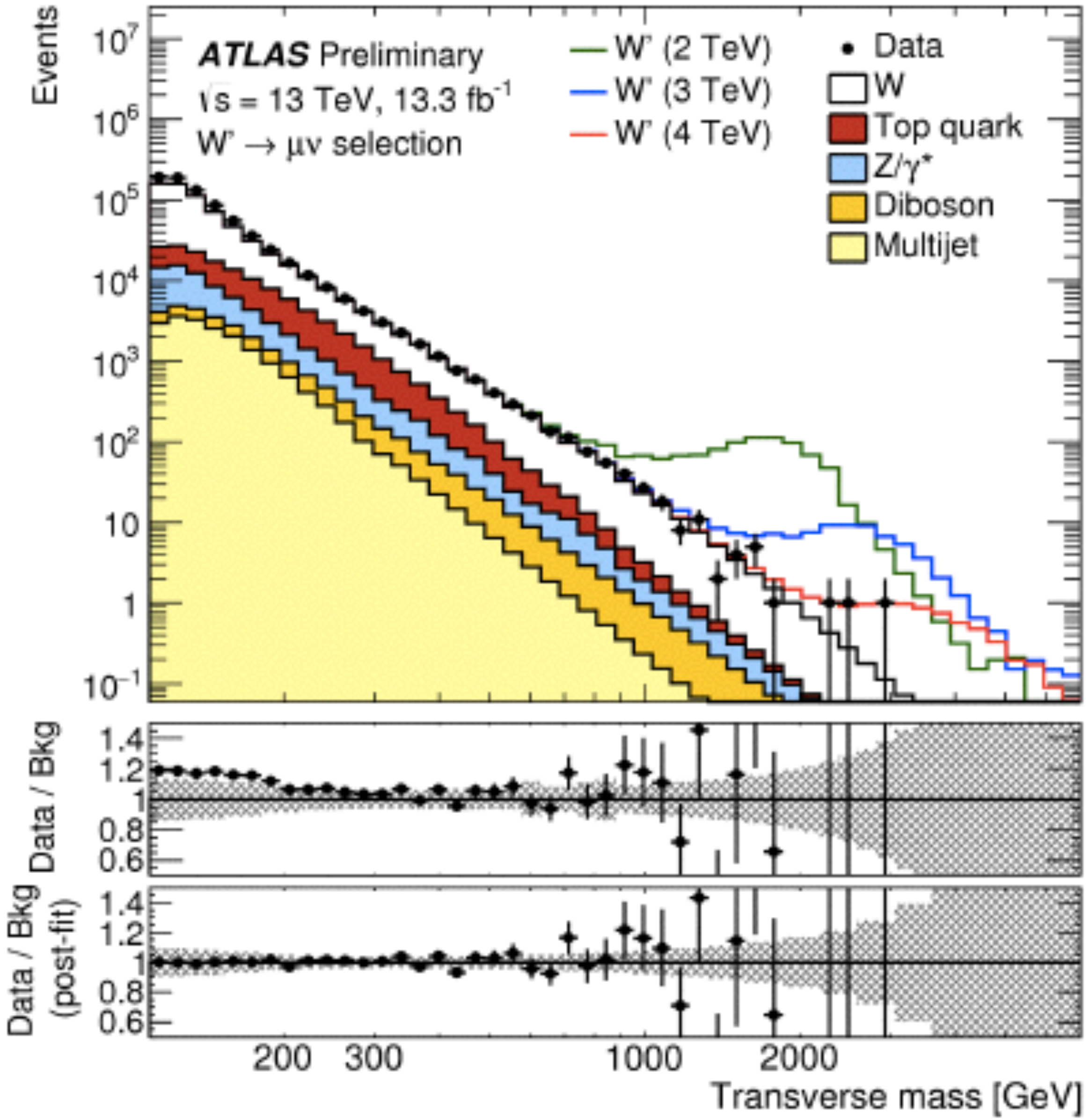
Search for Heavy Resonance: W' → lν

- W': the charged equivalent of the Z'
- Bulk-RS: excited KK W
- Final state: 1 lepton + Missing E_T
- Look for Jacobian peak in transverse mass:

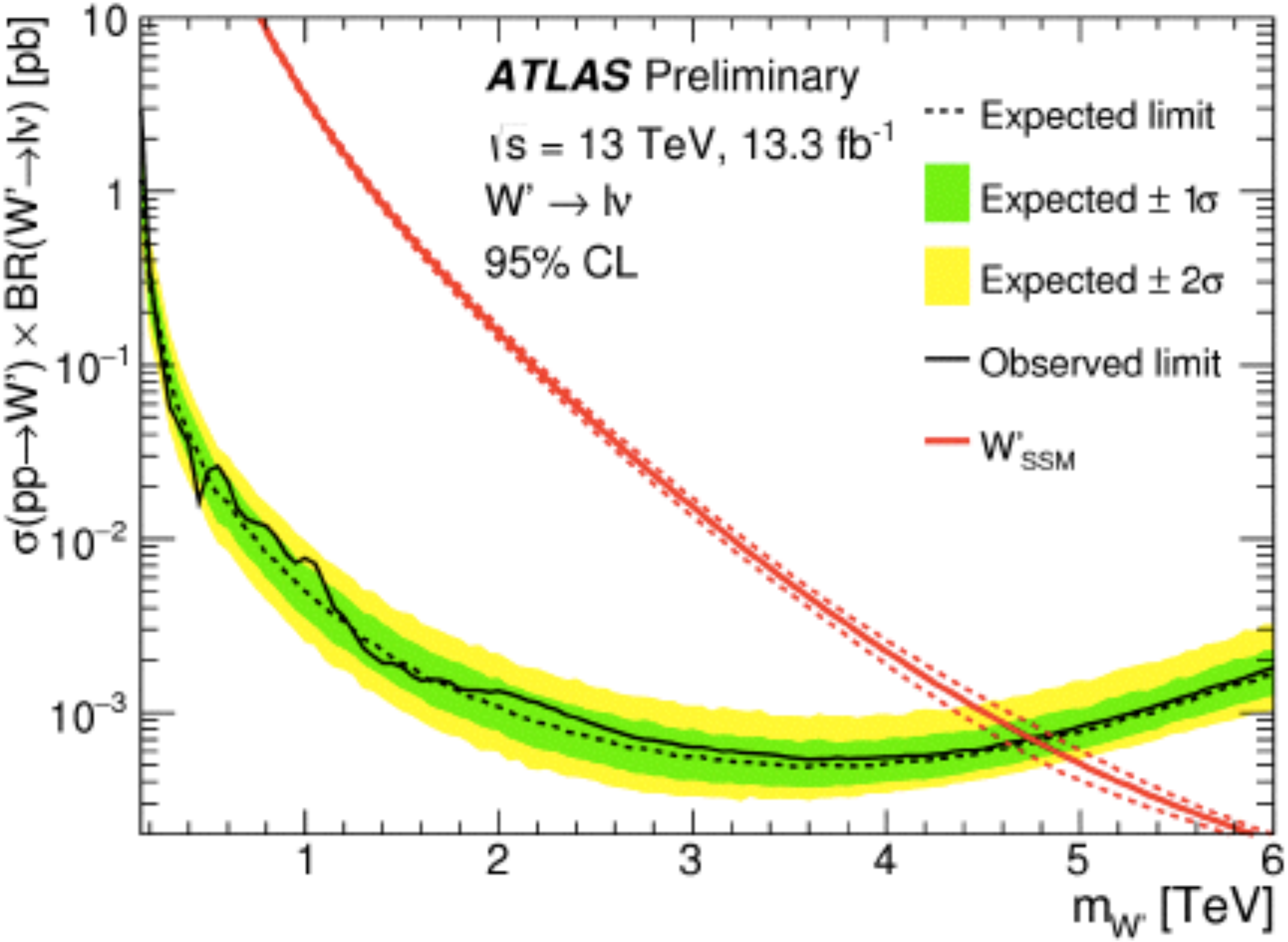
$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$



Electron channel



Muon channel



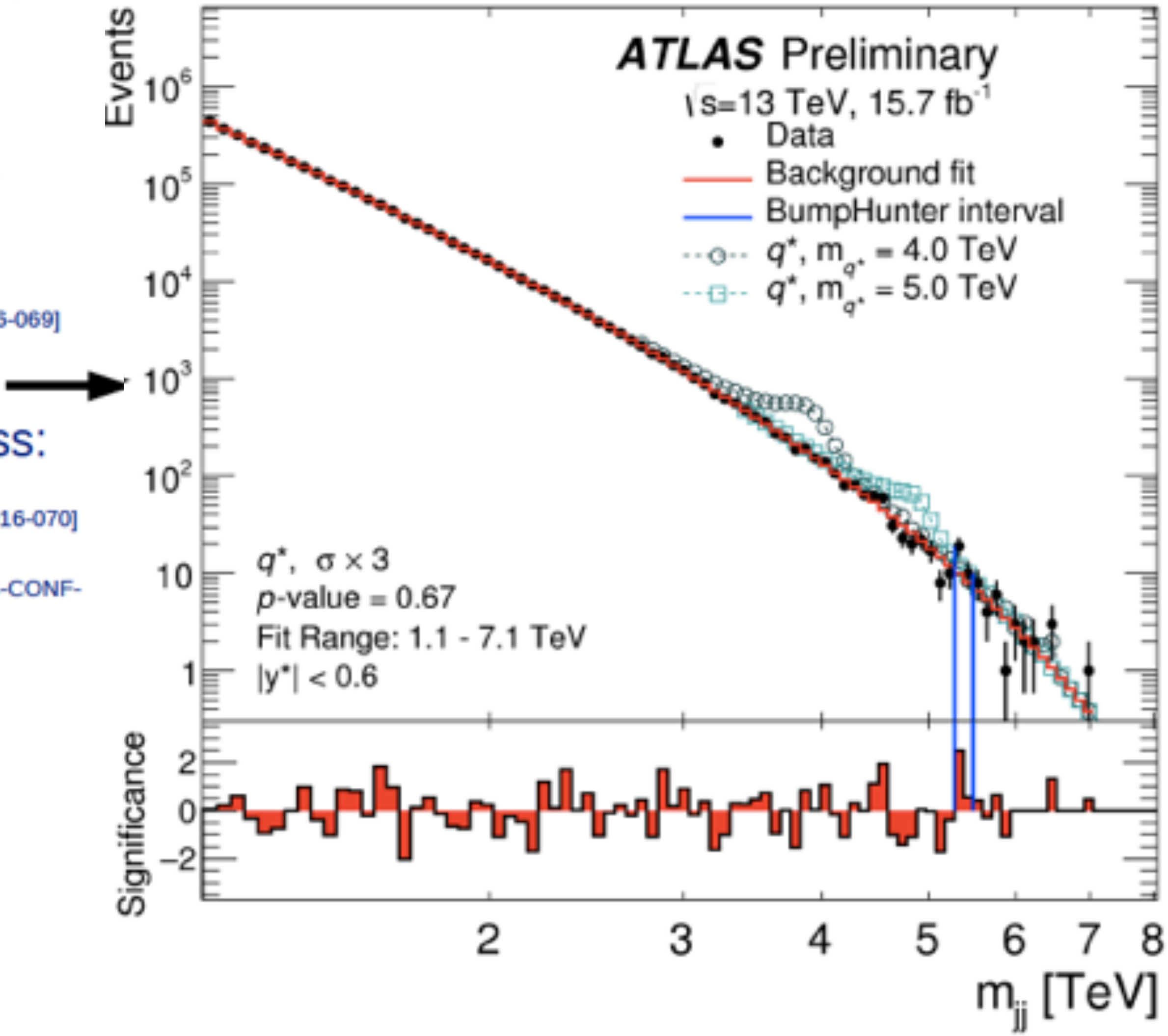
Sequential SM:

m(W') > 4.74 TeV at 95% C.L

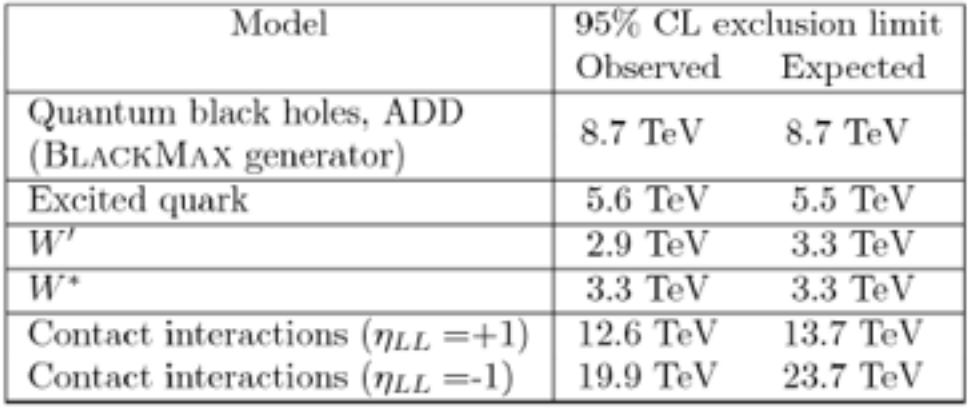
Search for high-mass resonances decaying to jets

- W'/Z', excited quarks, strong gravity, DM-mediator
- Look for resonance above phenomenological fit of the data
- High-mass analysis [ATLAS-CONF-2016-069] limited by trigger
- To reach sensitivity at low-mass:
  - → ISR photon or jet [ATLAS-CONF-2016-070]
  - → Trigger-Level Analysis [ATLAS-CONF-2016-030]
- To enhance heavy-flavor:
  - → B-tagging [ATLAS-CONF-2016-060]

ATLAS-CONF-2016-069

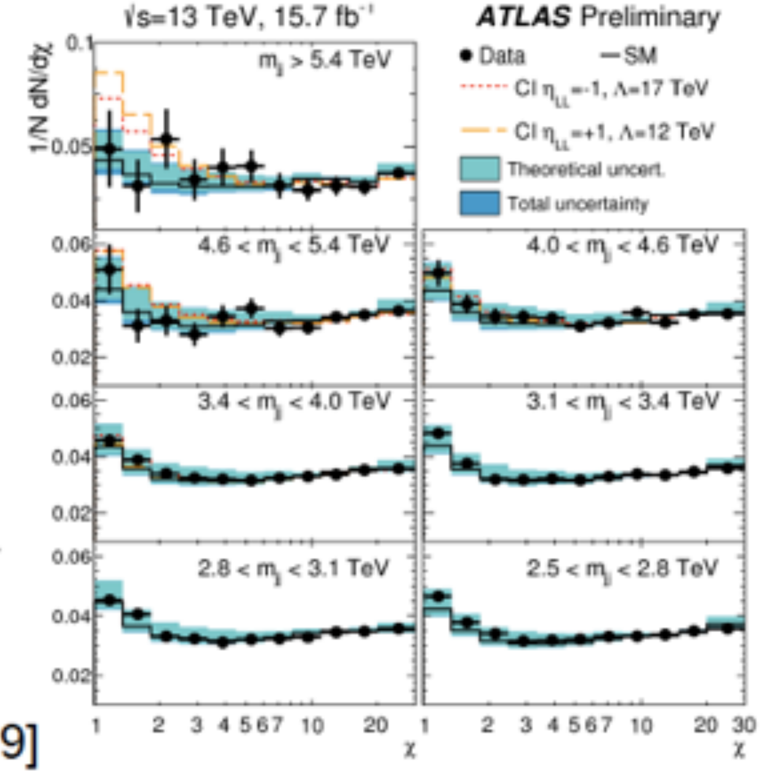


Search for Heavy Resonance: Dijet High-mass



Model	95% CL exclusion limit	
	Observed	Expected
Quantum black holes, ADD (BLACKMAX generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions (η_{LL} =+1)	12.6 TeV	13.7 TeV
Contact interactions (η_{LL} =-1)	19.9 TeV	23.7 TeV

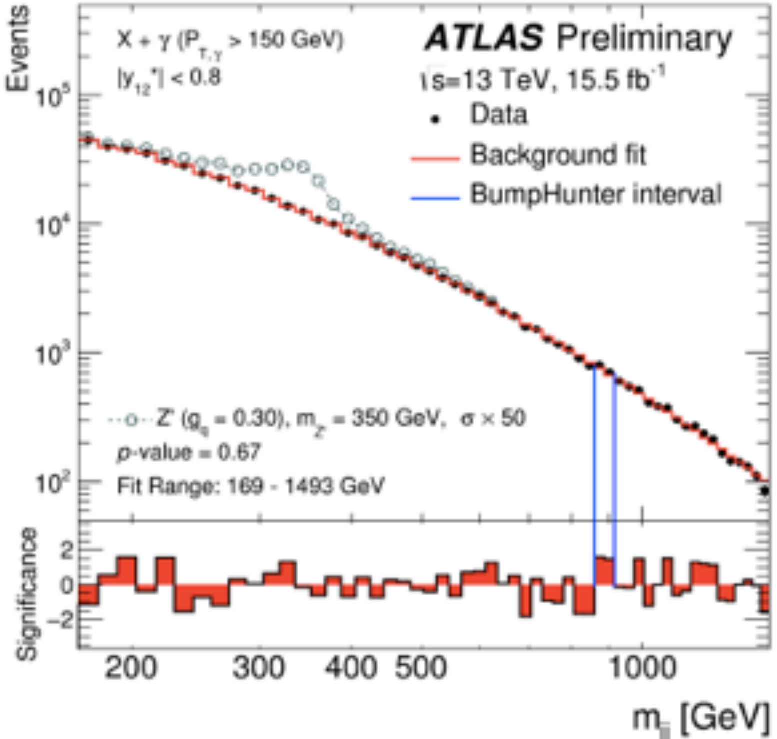
- **Trigger:**
  - → 1-jet trigger E_T~380 GeV (100% efficient)
- **Event selection:**
  - → anti-k_T R=0.4 jets
  - → Leading jet pT > 440 GeV, sub-leading pT > 60 GeV
  - → |y*| < 0.6 (or 1.2 depending on model)
- **Selection implies:**
  - → m(jj) ≳ 1.1 TeV
- **Angular analysis:** →
  - → |y*| < 1.7 and |yB| < 1.1
  - → m(jj) > 2.5 TeV

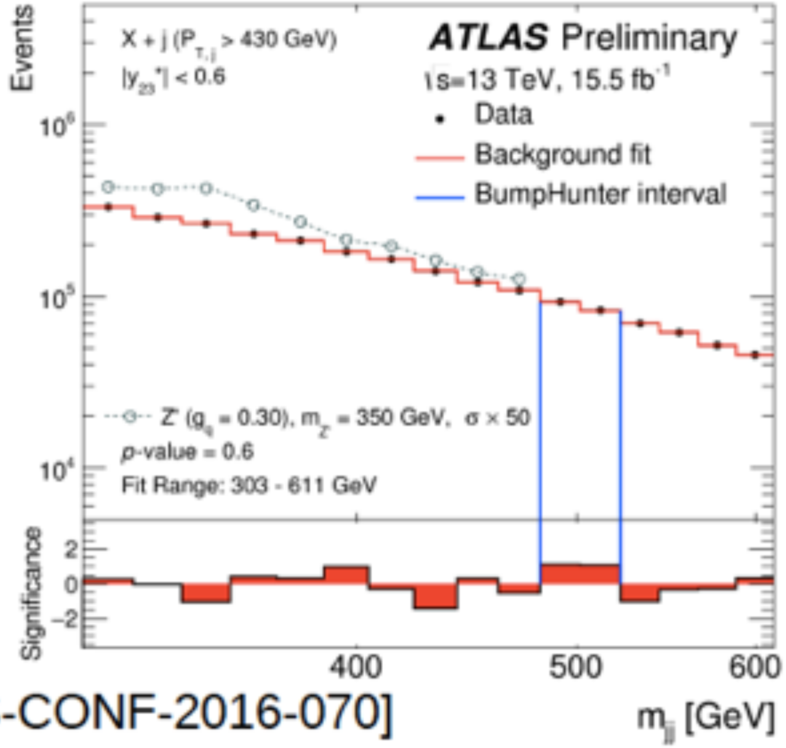


[ATLAS-CONF-2016-069]

Search for Low-mass Resonance: Dijet + ISR

- Same trigger and offline thresholds (380 → 440 for jets, 140 → 150 for photon), but reach to lower resonance mass by requiring ISR photon or jet
- Photon: 200-1500 GeV
- Jet: 300-600 GeV (fails above due to combinatorial issues)



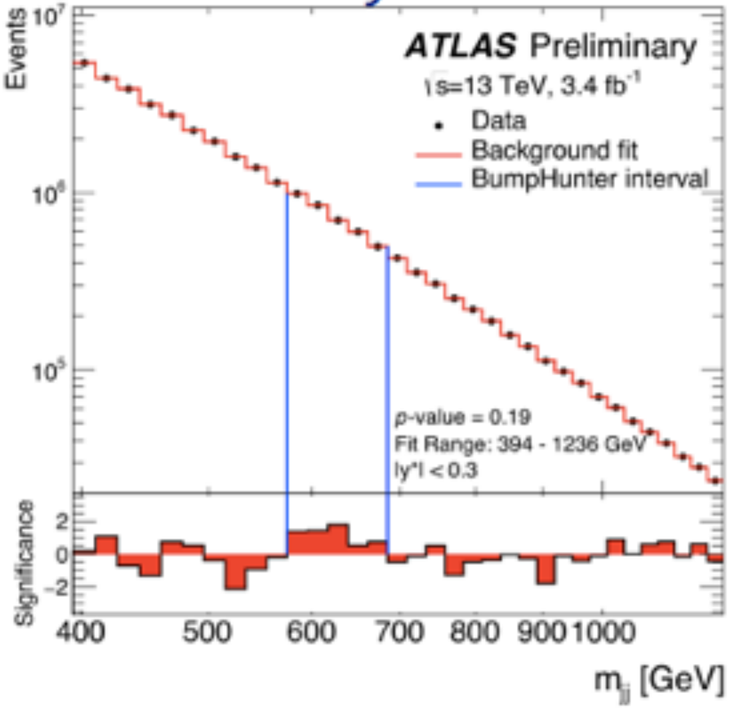


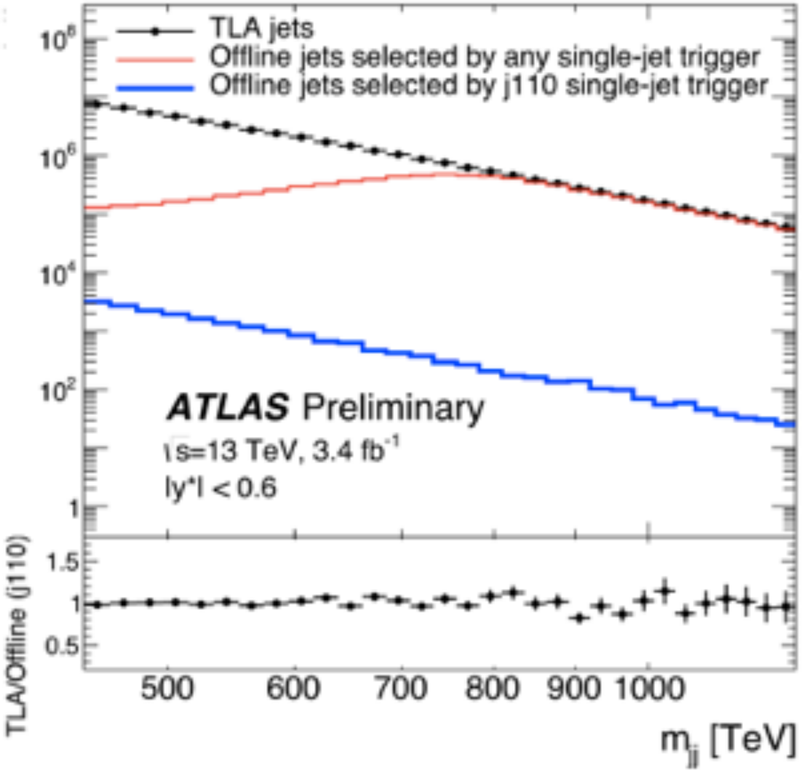
[ATLAS-CONF-2016-070]

Search for Low-mass Resonance: Dijet Trigger-Level Analysis

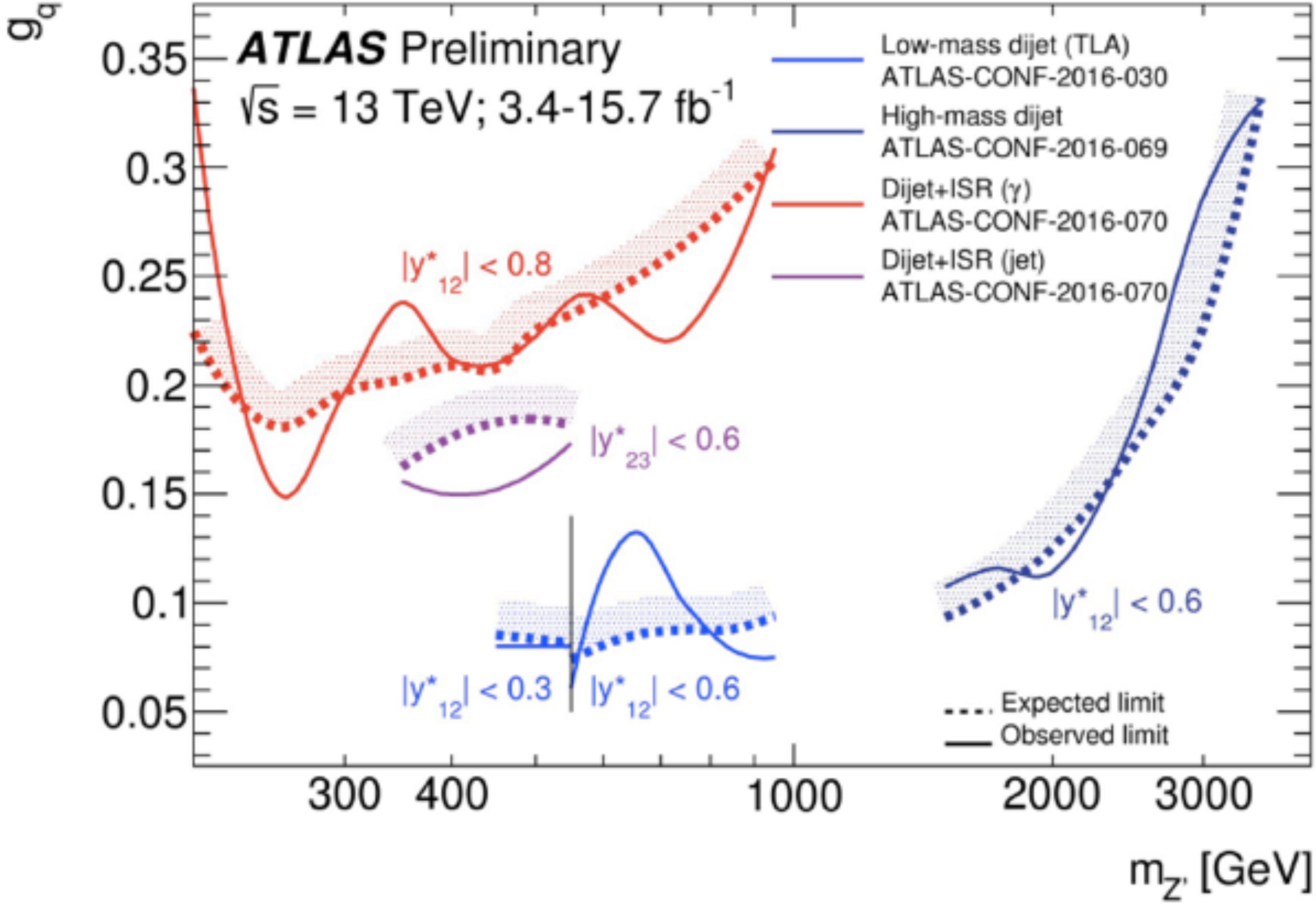
- Lower trigger-threshold by keeping only partial information of the event
- Addition jet calibration and cleaning applied online
- 2015 data only

[ATLAS-CONF-2016-030]

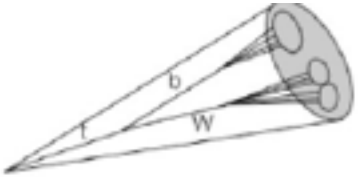




Dijet searches: a summary

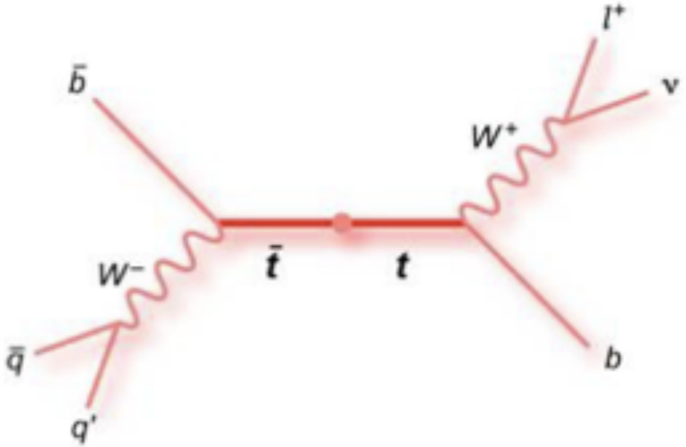


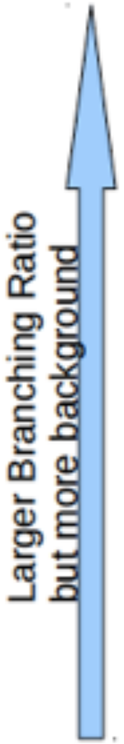
Top-antitop Resonance



- Event Topology:

  t-tbar → Wb Wb
- Final state depends on W decays:





  - → All-hadronic final state:

    2 W → jj

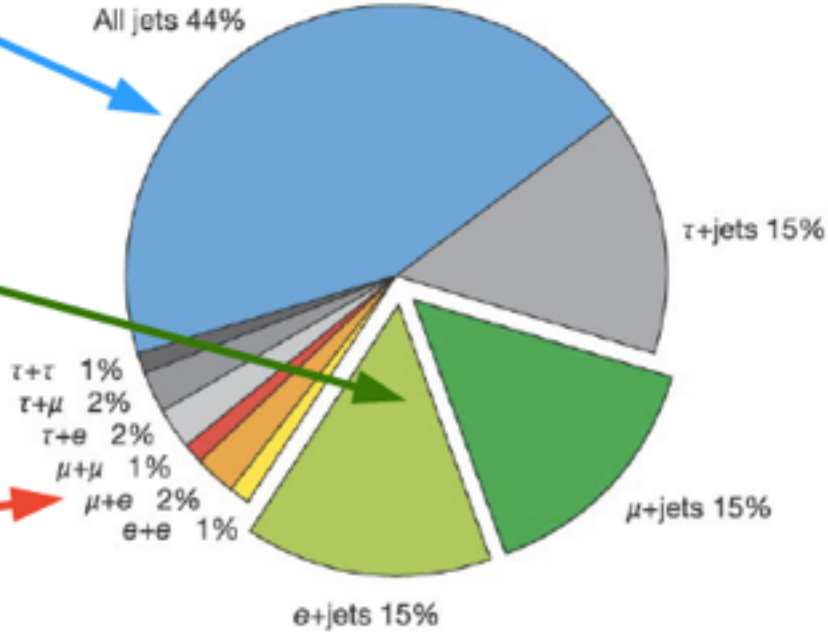
    2 b-jets + 4 light jets (+0ν)
  - → Lepton+Jets final state:

    1 W → lν, 1 W → jj

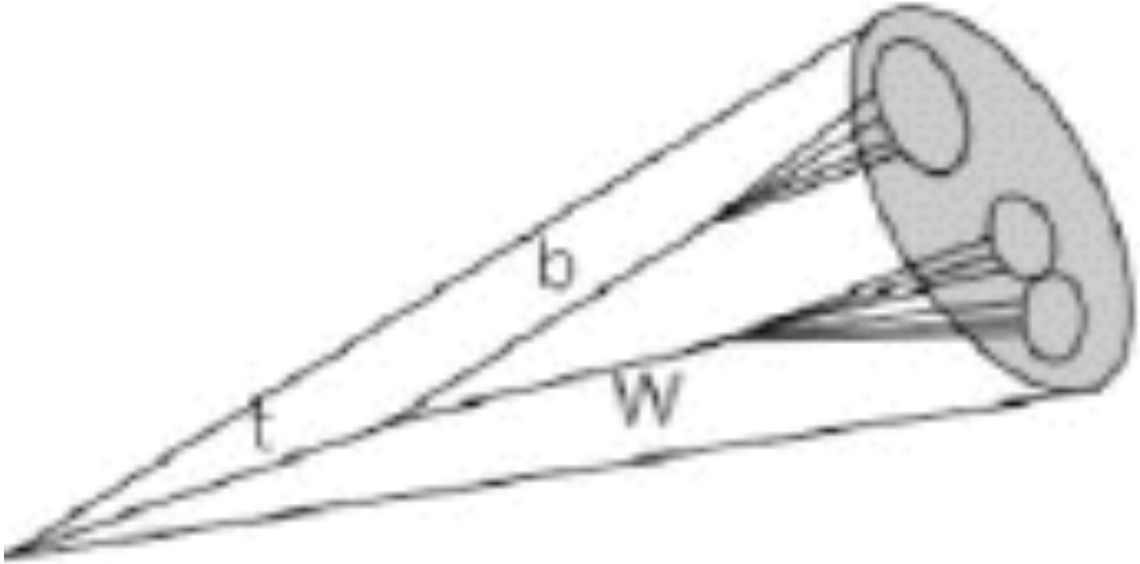
    1l + 2 b-jets + 2 light jets (+1ν)
  - → Dilepton final state:

    Both W → lν (l = e or μ)

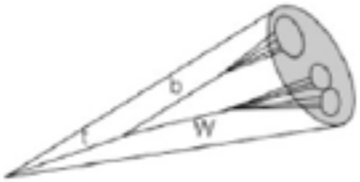
    2l + 2 b-jets (+2 neutrinos)



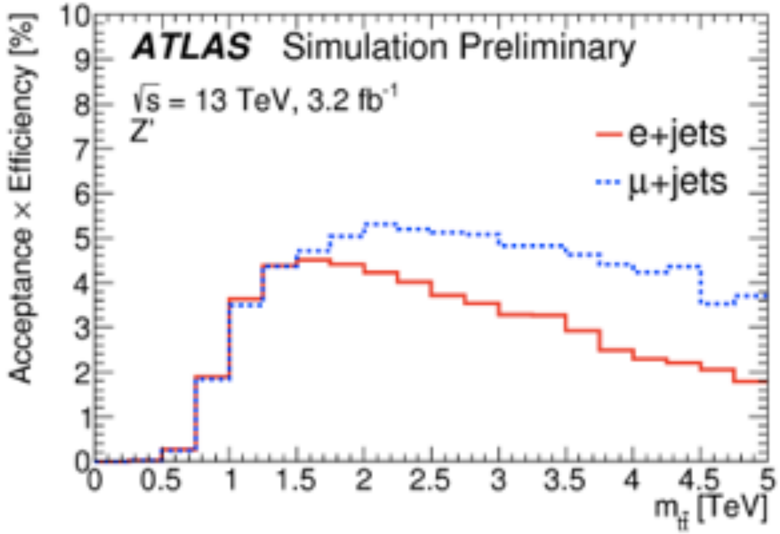
Top-antitop Resonance

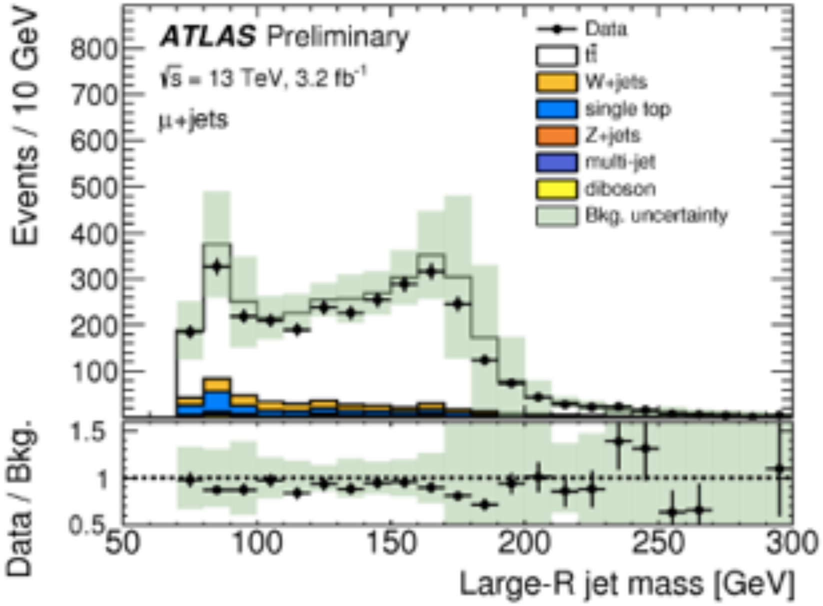


Top-antitop Resonance Lepton+Jets Channel (ATLAS)



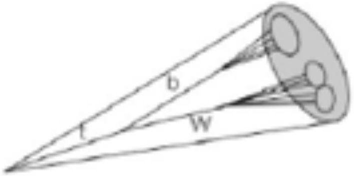
- First 13 TeV result, boosted channel only:
  - → anti-kT R=1.0, p_T>300 GeV, $|\eta|<2$
  - → Top-tagging (80% efficiency working point) using jet mass and n-subjettiness ratio τ_{32}
- Improve efficiency at high t-tbar mass with:
  - → Lepton "mini-isolation":
    - smaller isolation cone at high momentum
    - tolerate muons inside jets at high pT
  - → R=0.2 track-jet b-tagging (at least one b-tag)



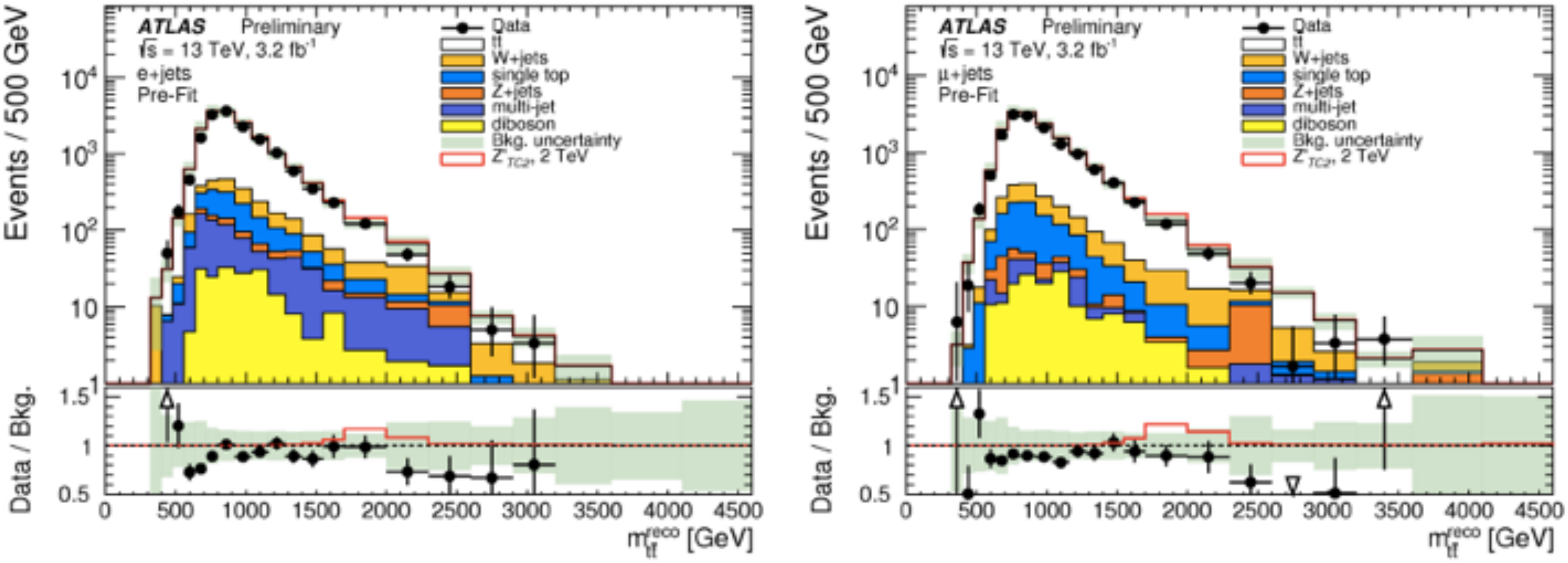


[ATLAS-CONF-2016-014]

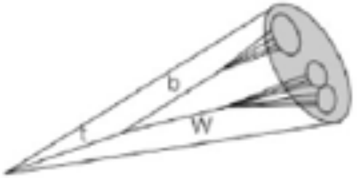
Top-antitop Resonance L+Jets Channel

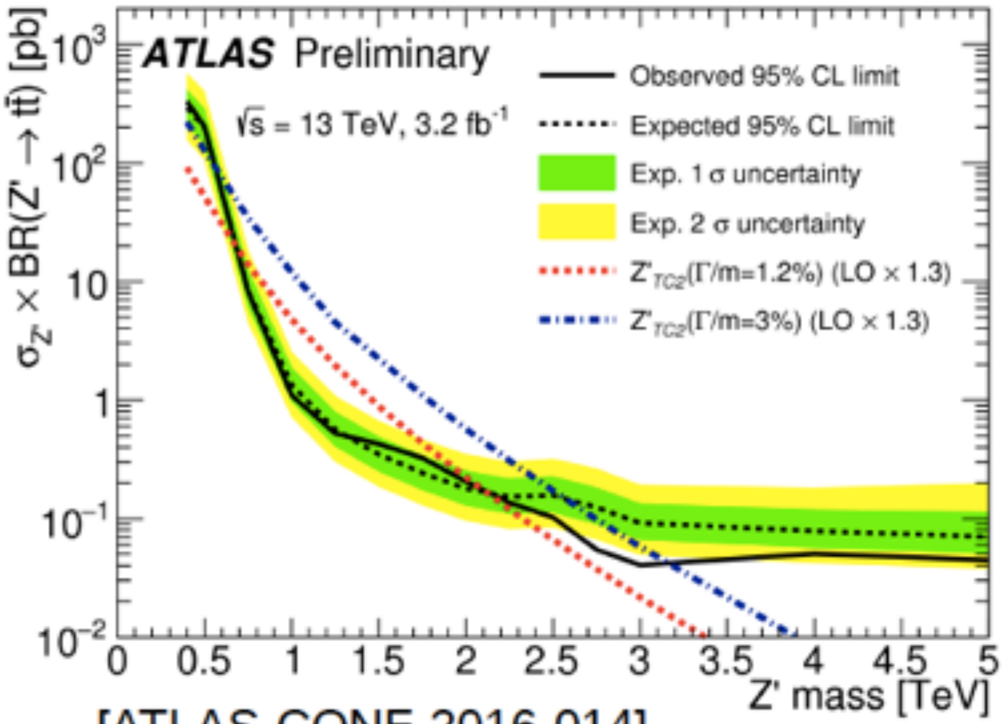


- Top-antitop mass spectrum at 13 TeV:

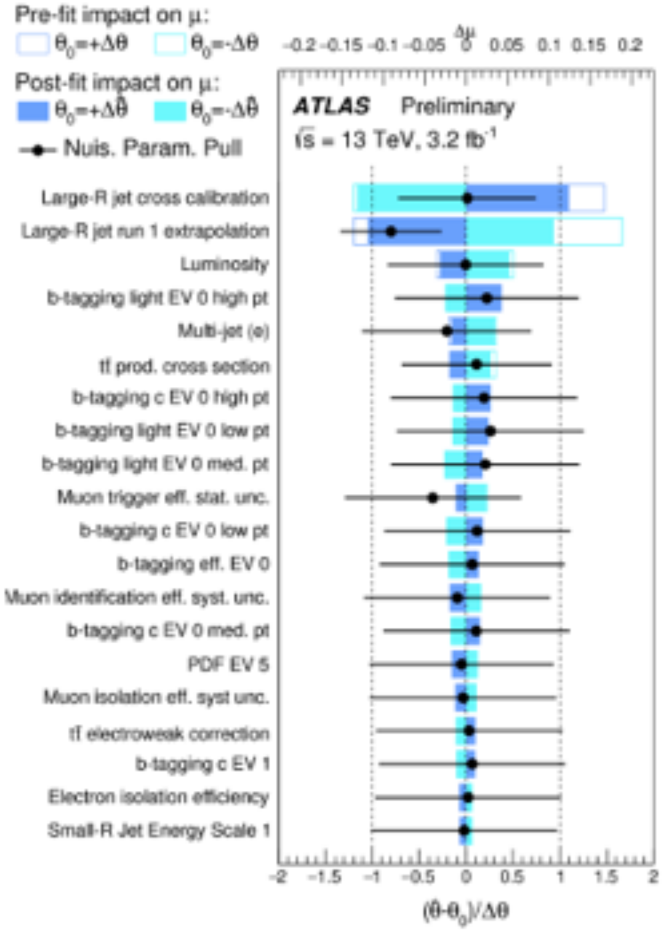


Top-antitop Resonance
L+Jets Channel





[ATLAS-CONF-2016-014]



- Limit with 3 /fb at 13 TeV:

  m(Z' 1.2% width) > 2.0 TeV

- Already surpassing recent ATLAS Run 1 paper: http://arxiv.org/abs/1505.07018

  m(Z' 1.2% width) > 1.8 TeV

Heavy Resonances: a summary

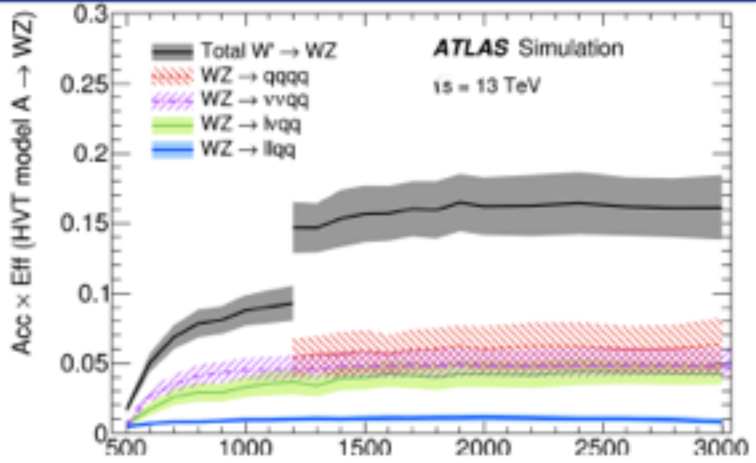
- Heavy resonance searches benefit the most (and the fastest) from increase in center-of-mass energy
- Corollary: future improvements will take a lot more time!

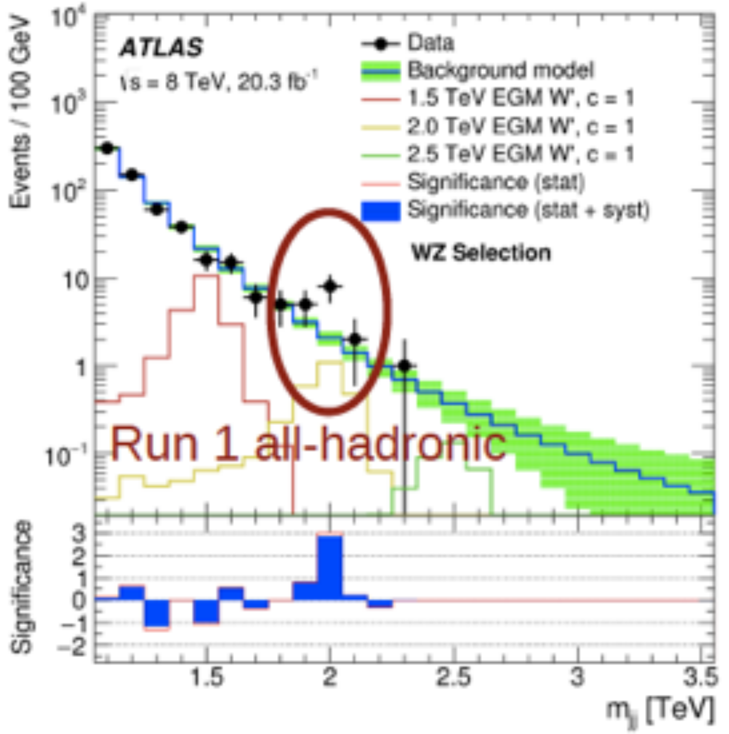
95% CL limit (TeV)	CDF	Run 1 '12	Moriond '15	ICHEP '16	300 fb^{-1} 14 TeV	3000 fb^{-1} 14 TeV
Z' → ll	1.1	2.9	3.4	4.1	6.5	7.8
q* → dijet	0.9	4.1	5.2	5.6	7.4	8
Z' → tt	0.9	1.8		2.0	3.3	5.5

ATLAS upgrade: ATL-PHYS-PUB-2013-003, ATL-PHYS-PUB-2015-004
CDF:
http://arxiv.org/abs/1101.4578 (4.6 fb^{-1})
http://journals.aps.org/prd/abstract/10.1103/PhysRevD.83.031102 (5.3 fb^{-1})
http://prd.aps.org/abstract/PRD/v79/i11/e112002 (1.1 fb^{-1})
http://arxiv.org/abs/1211.5363 (9.5 fb^{-1})

Search for WW/WZ/ZZ resonances

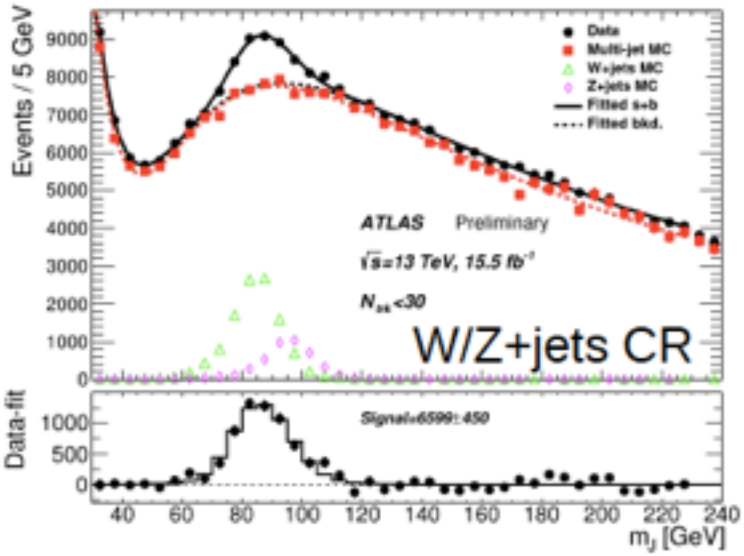
- Many channels:
  - → WW →lvlv or lvqq or (qq)(qq)
  - → WZ → lvll or lvqq or llqq or (qq)(qq)
  - → ZZ → (ll)(ll) or (ll)(vv) or llqq or (qq)(qq)
  - → (qq) can be either resolved into two jets, or merged into one fat jet
- Interpretation in terms of HVT W'/Z', bulk RS graviton, and 2HDM
- Got some attention between Run 1 and Run 2 due to the all-hadronic ATLAS result (although not seen in other channels)



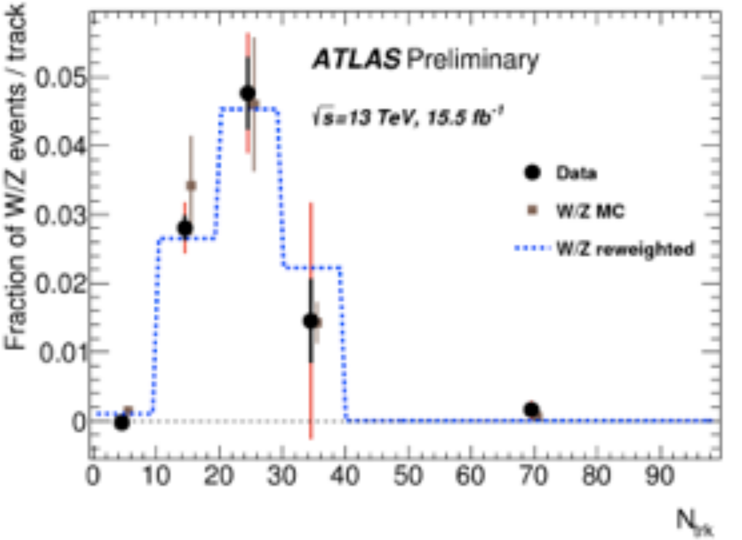


Diboson all-hadronic channel

- Look for pair of vector bosons, each decaying to pair of quarks:
  - → WW or WZ or ZZ → (qq) (qq)
- High-momentum → boosted topology:
  - → anti-kT R=1.0, |η|<2
  - → p_T >200 GeV, m > 30 GeV after trimming
  - → Boson-tagging:
    - mass window of 15 GeV around W or Z mass
    - pT-dependent cut on D2(beta=1)
  - → N(tracks) < 30



[ATLAS-CONF-2016-055]



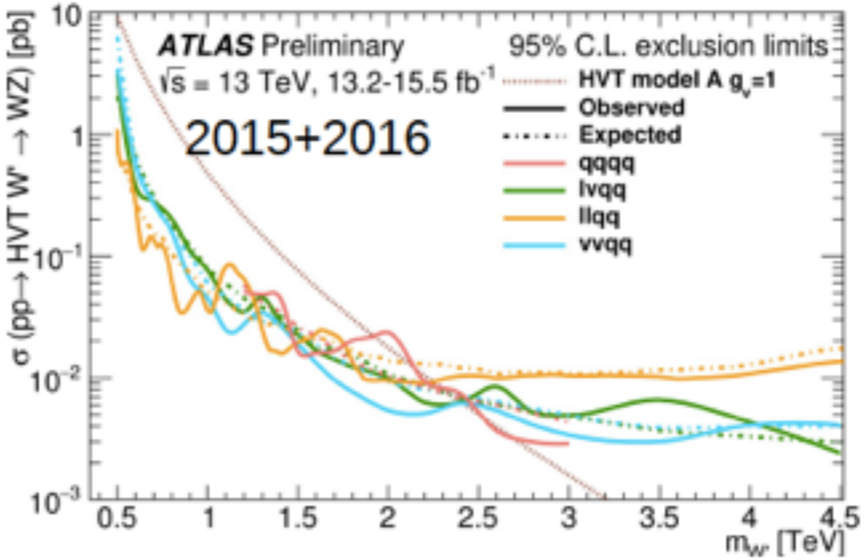
Diboson comparison of channels

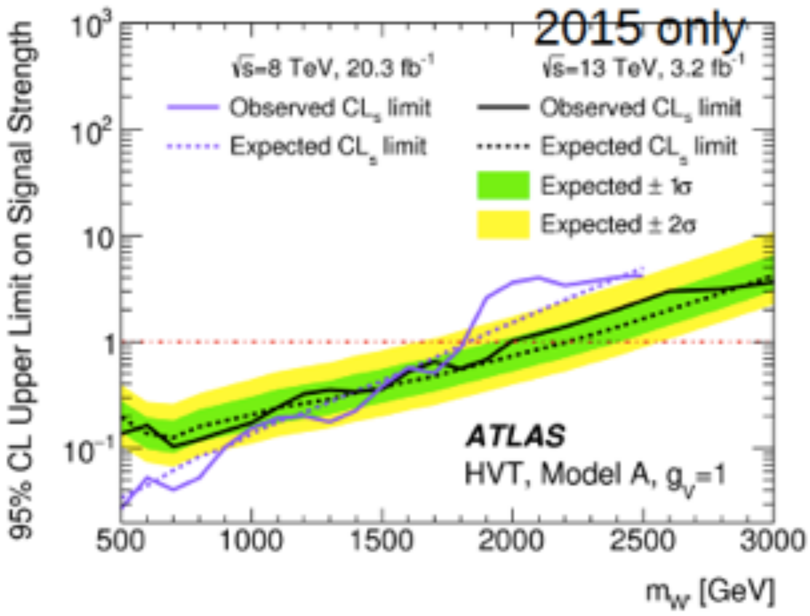
- Full combination only with 2015 data currently
- Combine channels with lepton-multiplicity from 0 to 4:

(qq)(qq) (lν)(qq)
(ll)(qq) (νν)(ll)

	vvqq	lvqq	llqq	qqqq (JJ)
WZ	X	X	X	X
WW		X		X
ZZ	X		X	X

- Run 1 excess is excluded by Run 2 (even with 2015 only)





SUSY is a class of models

SUSY breaking
Gravity, Gauge, Anomaly,
Dilaton/Moduli, Mirage,
Gaugino, D-term, Z-prime, …

R-Parity conservation

SUSY models possibly with extra matter/gauge bosons

NMSSM, USSM, μνSSM,
E6SSM, PQNMSSM,…

Various forms of SUSY spectra

Natural, Split, Compressed, Stealth, …

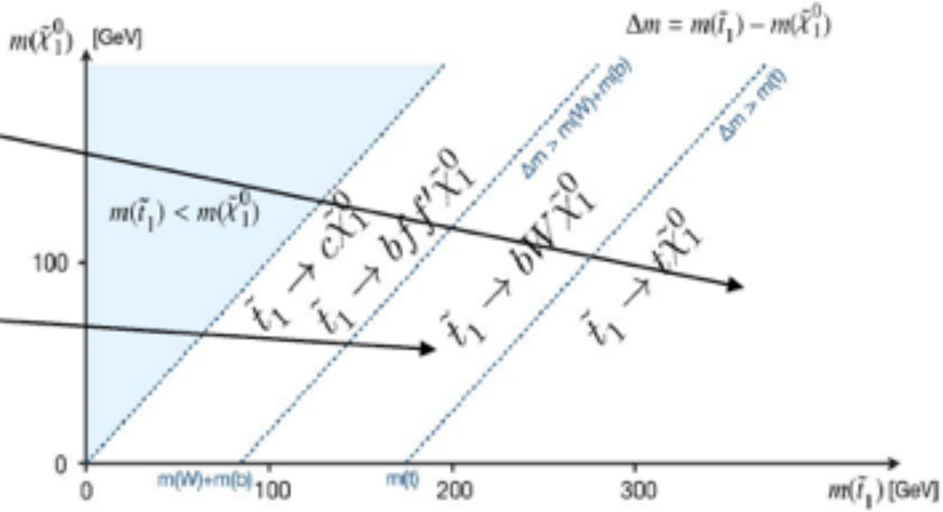
LSP?

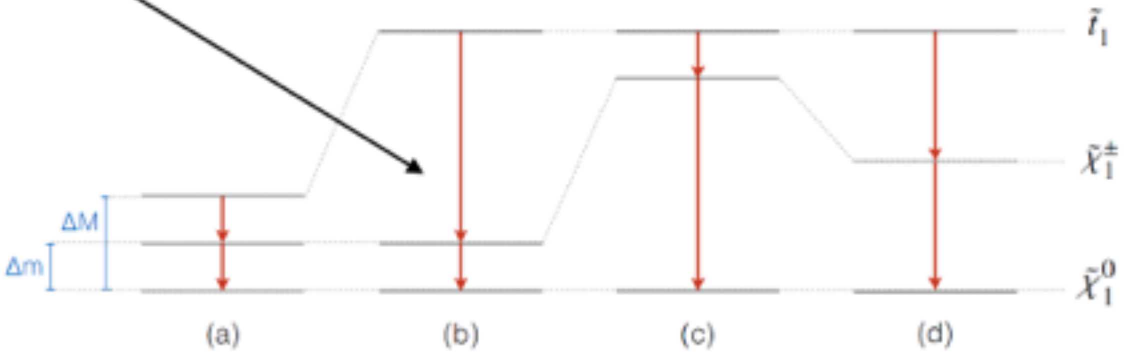
Neutralino, SM, Gravitino,
Axino, …

Strategy and outline

- Make blocks by “Naturalness”
  - 3rd generation
  - “Strong” gluino, squark
  - EW

- stop -> top + Neutralino
  - Analysis approach (general)
  - Show a search with one lepton[1] in the final state
- stop -> bottom + W-boson + Neutralino
- stop -> bottom + Chargino
- stop2 production
- stop GMSB / stau
- Stop RPV
- sbottom production





Using this analysis also to explain the general analysis procedure

stop -> top + neutralino (stop 1L)

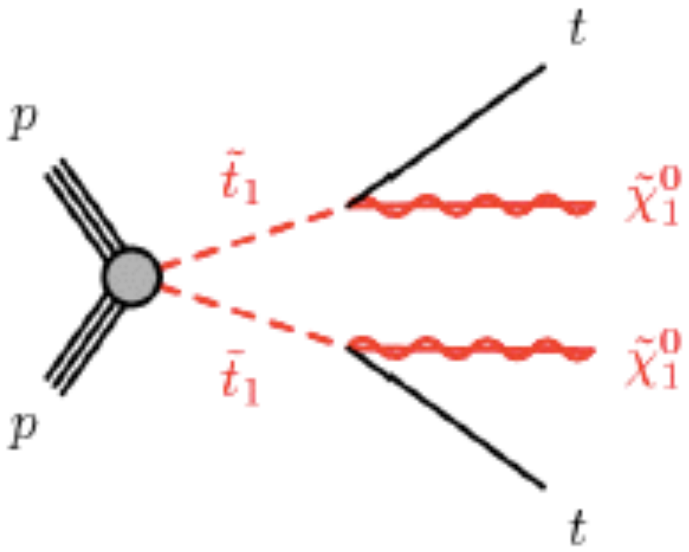
ATLAS-CONF-2016-050 (13.3 fb-1)

arxiv:1606.03903 with 3.2 fb-1

Using this analysis also to explain the general analysis procedure

stop -> top + neutralino (stop 1L)

ATLAS-CONF-2016-050 (13.3 fb-1)   arxiv:1606.03903 with 3.2 fb-1



Using this analysis also to explain the general analysis procedure

stop -> top + neutralino (stop 1L)

ATLAS-CONF-2016-050 (13.3 fb-1)

arxiv:1606.03903 with 3.2 fb-1

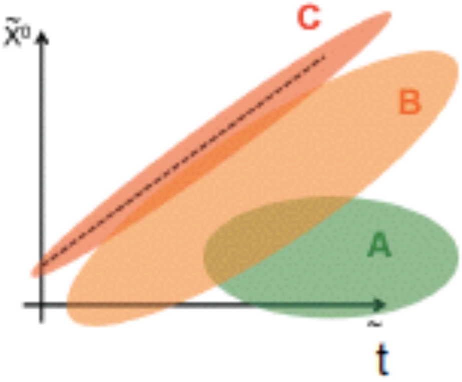
Using this analysis also to explain the general analysis procedure

stop -> top

ATLAS-CONF-2016-0

Specific regions in the m(N1)-m(stop) plane result in different experimental signatures and topologies (different phenomenology).

e.g.:



B: Small mass splitting, top decay products are resolved. Design specific “signal regions” (SR1 in this case) to target this region.

A: Large mass splitting, resulting in boosted top quarks (“tN_high” signal region)

Using this analysis also to explain the general analysis procedure

stop -> top + neutralino (stop 1L)

ATLAS-CONF-2016-050 (13.3 fb-1) arxiv:1606.03903 with 3.2 fb-1

Using this analysis also to explain the general analysis procedure

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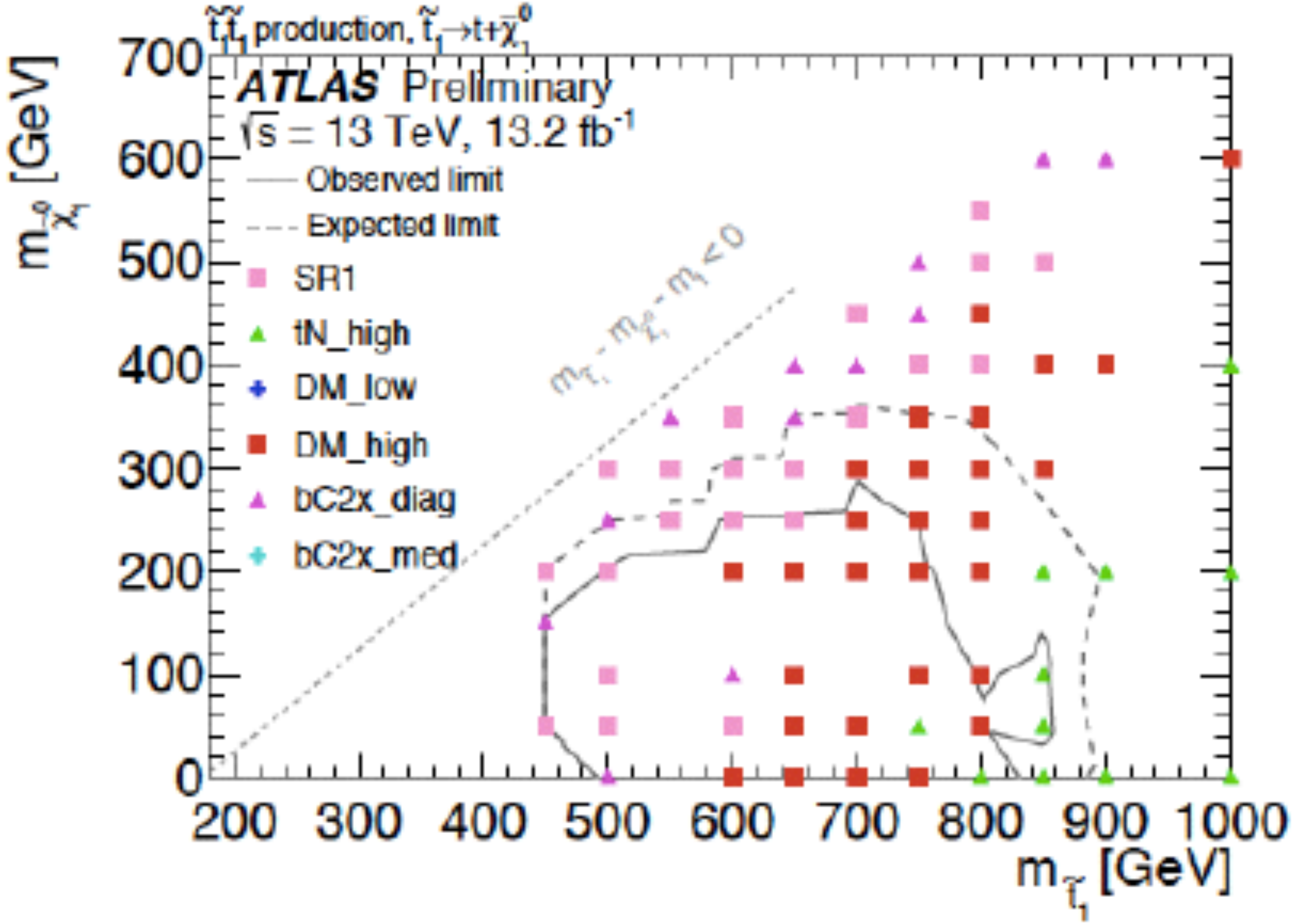
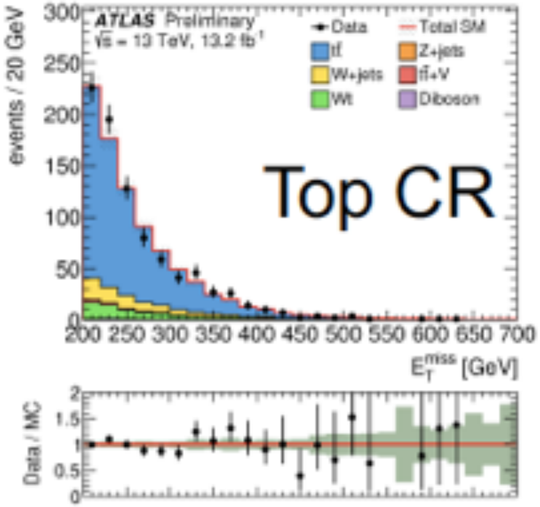
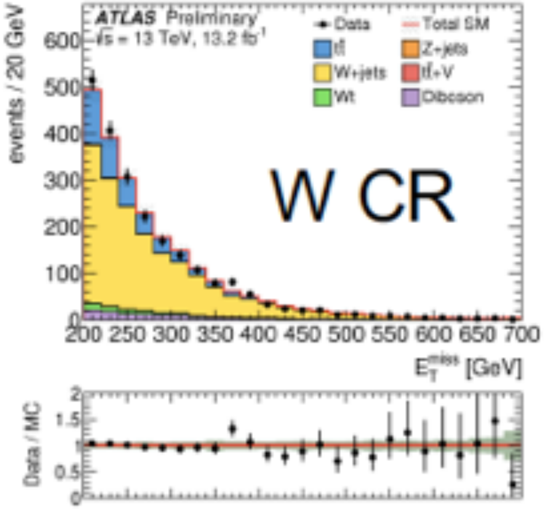
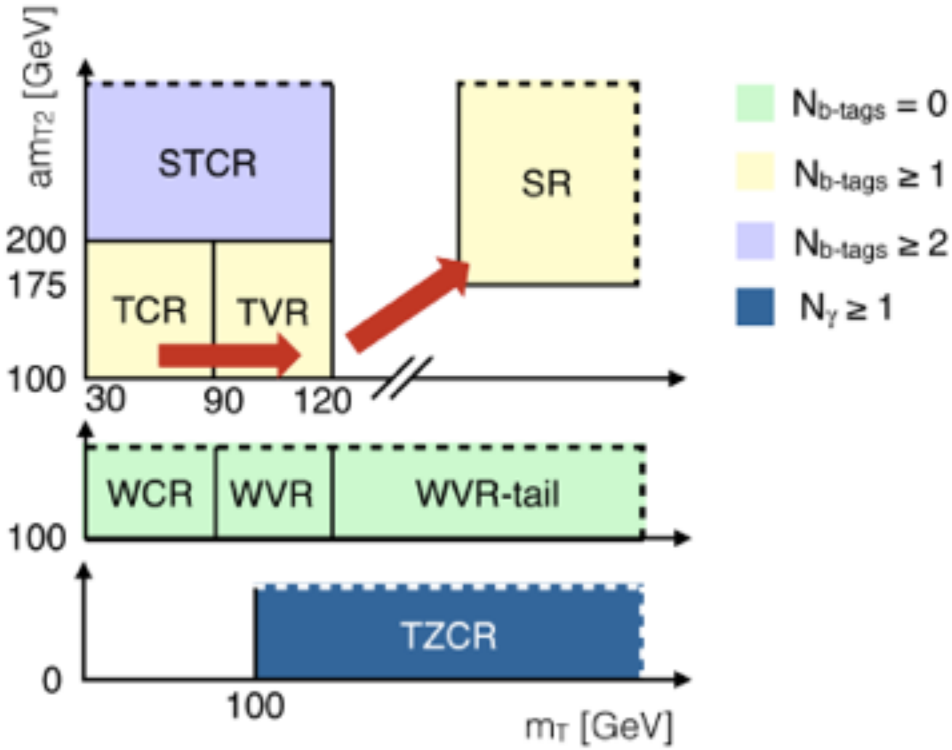


Control regions (normalization)

Data driven background





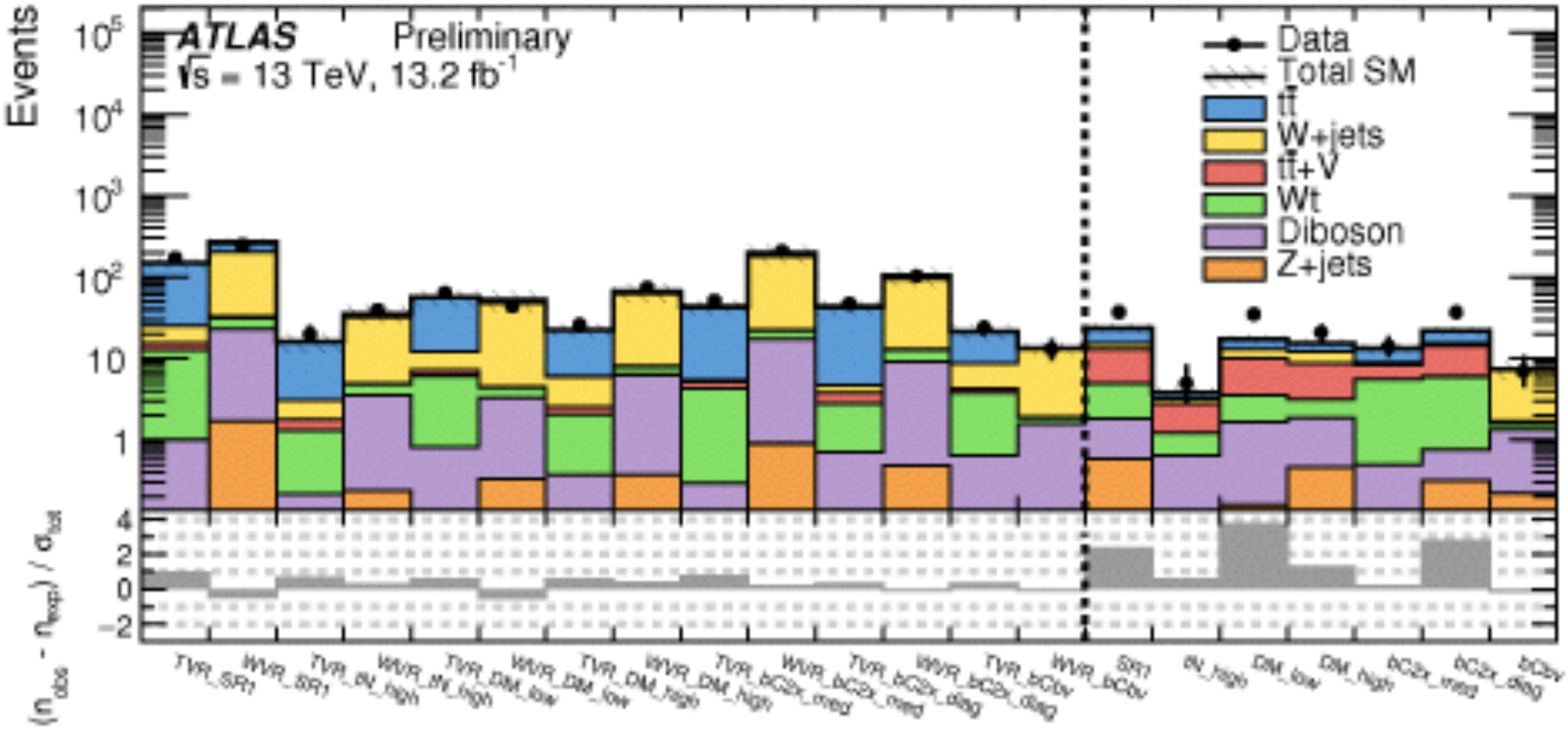


$$M_{T2}^2 \equiv \min_{\not{p}_1+\not{p}_2=\not{p}_T}\left[\max\left\{m_T^2(p_{Tl^-},\not{p}_1),\, m_T^2(p_{Tl^+},\not{p}_2)\right\}\right]$$

$$m_T^2 = 2p_T^{\mathrm{lep}}E_T^{\mathrm{miss}}[1-\cos(\Delta\phi)]$$

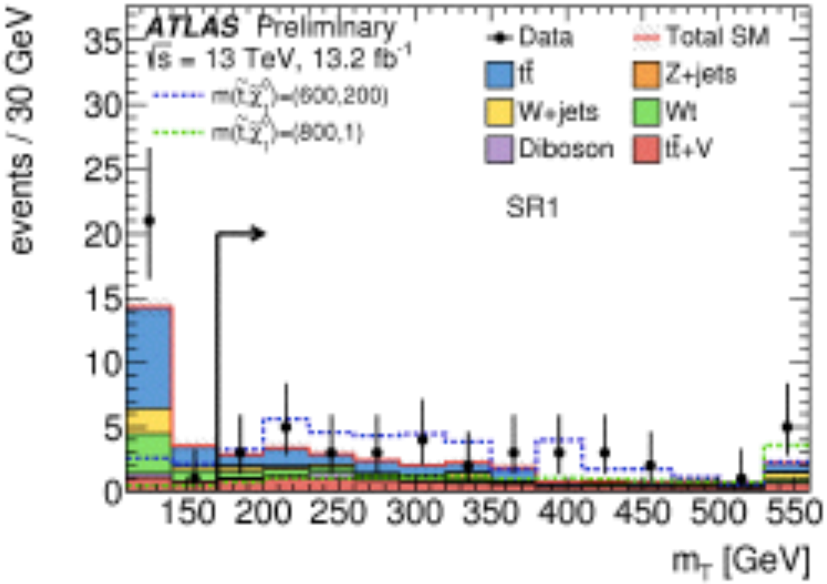
Signal region and limits stop 1L

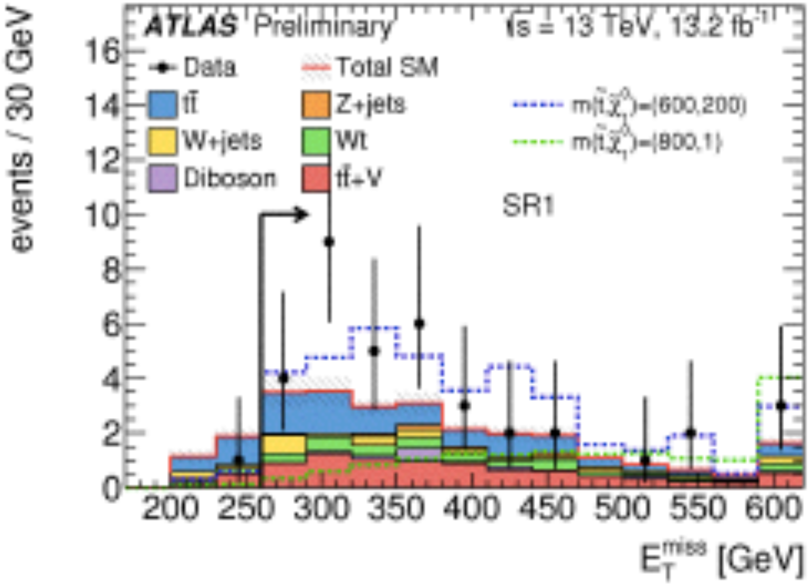
Signal region and limits stop 1L



Signal region and limits stop 1L

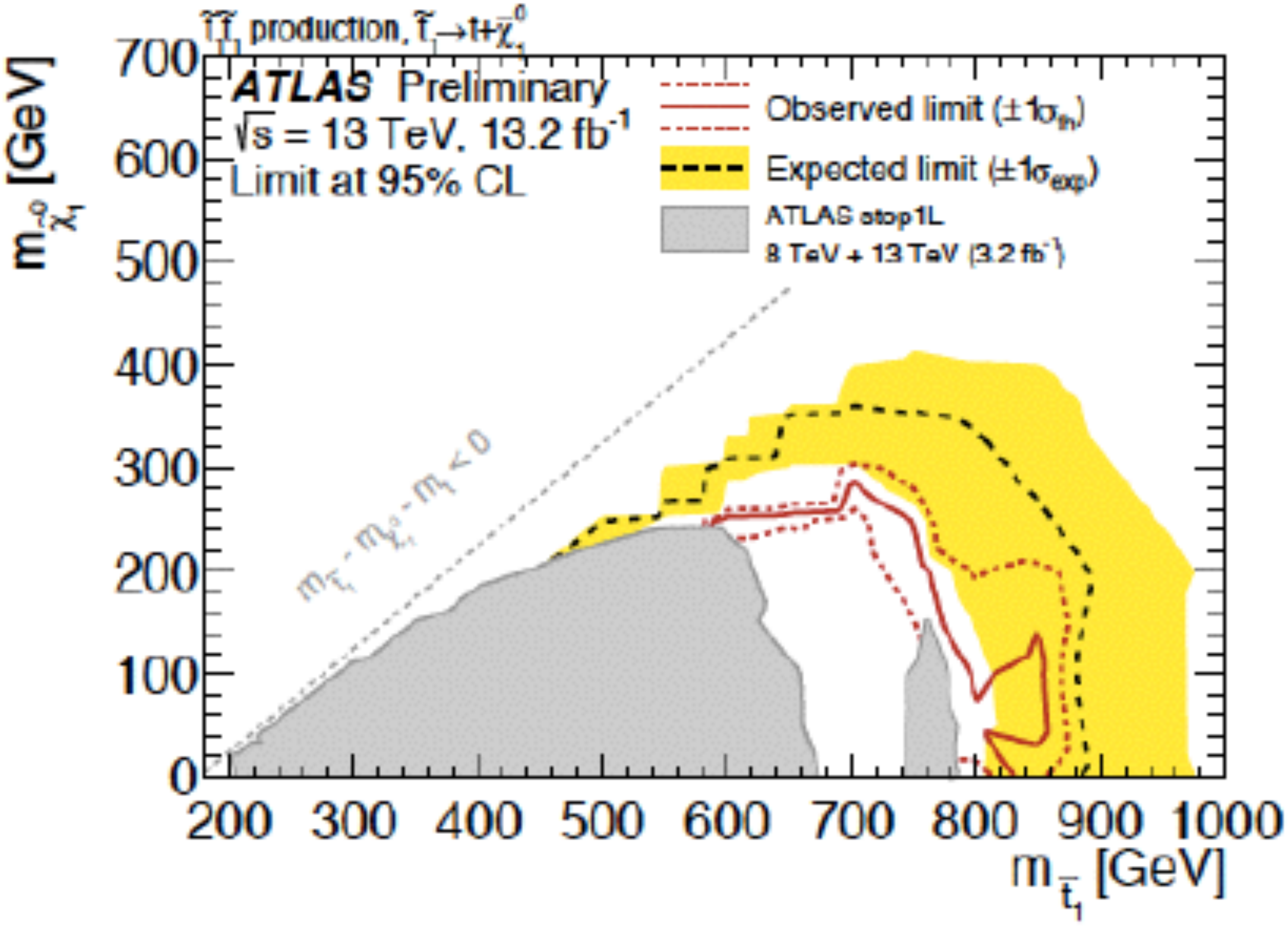
Signal region and limits stop 1L

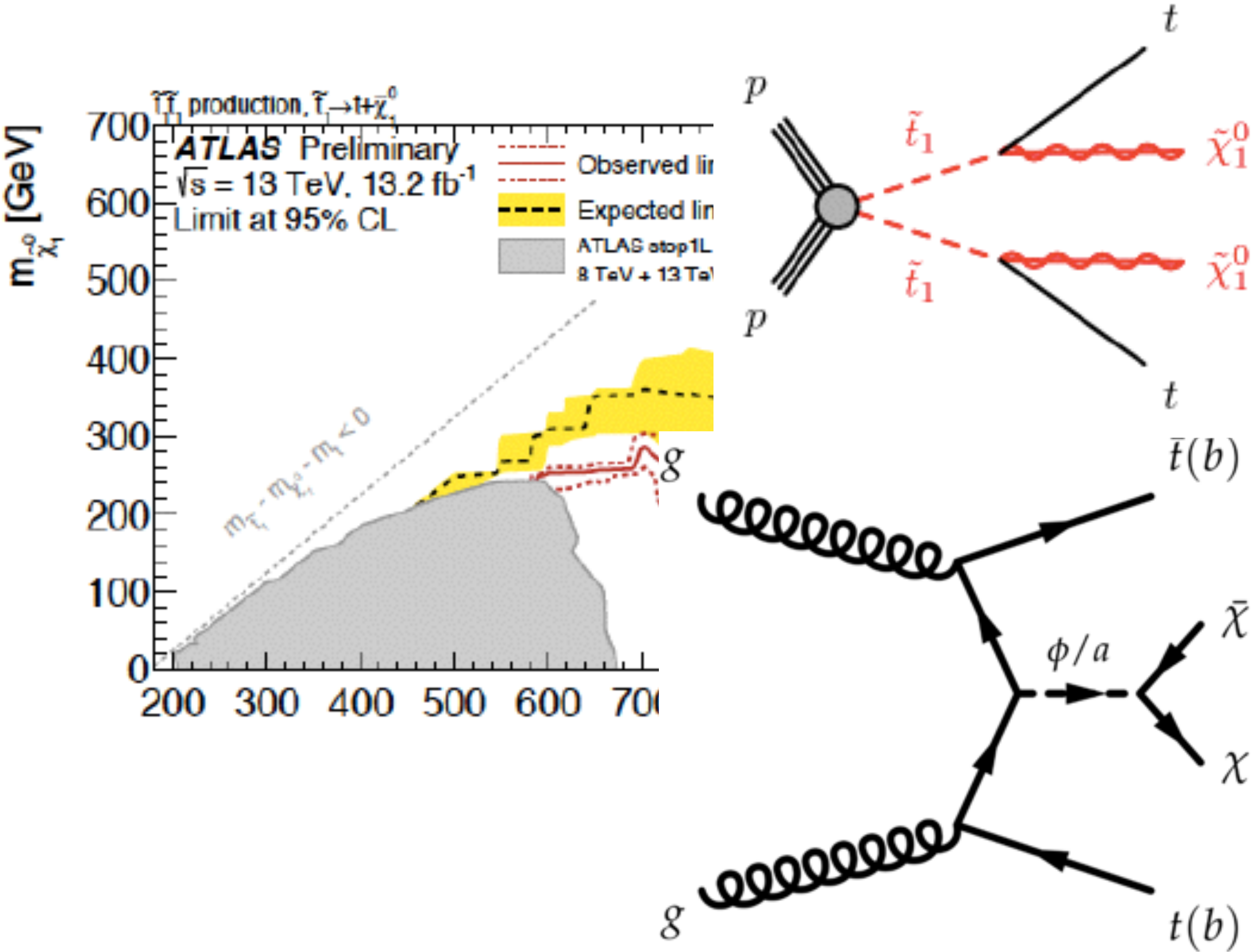




Signal region and limits stop 1L

1L


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t+\tilde{\chi}^0_1$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.2 fb^{-1}
Limit at 95% CL
Observed limit ($\pm 1\sigma_{th}$)
Expected limit ($\pm 1\sigma_{exp}$)
ATLAS stop1L
8 TeV + 13 TeV (3.2 fb^{-1})
$m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} - m_t < 0$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
100
200
300
400
500
600
700
200
300
400
500
600
700
800
900
1000
$m_{\tilde{t}_1}$ [GeV]


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to t+\tilde{\chi}_1^0$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.2 fb^{-1}
Limit at 95% CL
Observed li
Expected li
ATLAS stop1L
8 TeV + 13 Te
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t < 0$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
600
700
200
300
400
500
600
70
p
p
$\tilde{t}_1$
$\tilde{t}_1$
t
t
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
g
g
$\bar{t}(b)$
$t(b)$
ϕ/a
$\bar{\chi}$
χ

Why Supersymmetry?

- ☑ Hierarchy problem
- ☑ Gauge coupling unification
- ☑ WIMP dark matter

For 30 years, experiments testing these suggestive reasons were "right around the corner", and SUSY became the dominant BSM paradigm.

The experiments are now here.

"Strong.
Light.
Cheap.

Pick two."

An evening with

Keith Bontrager

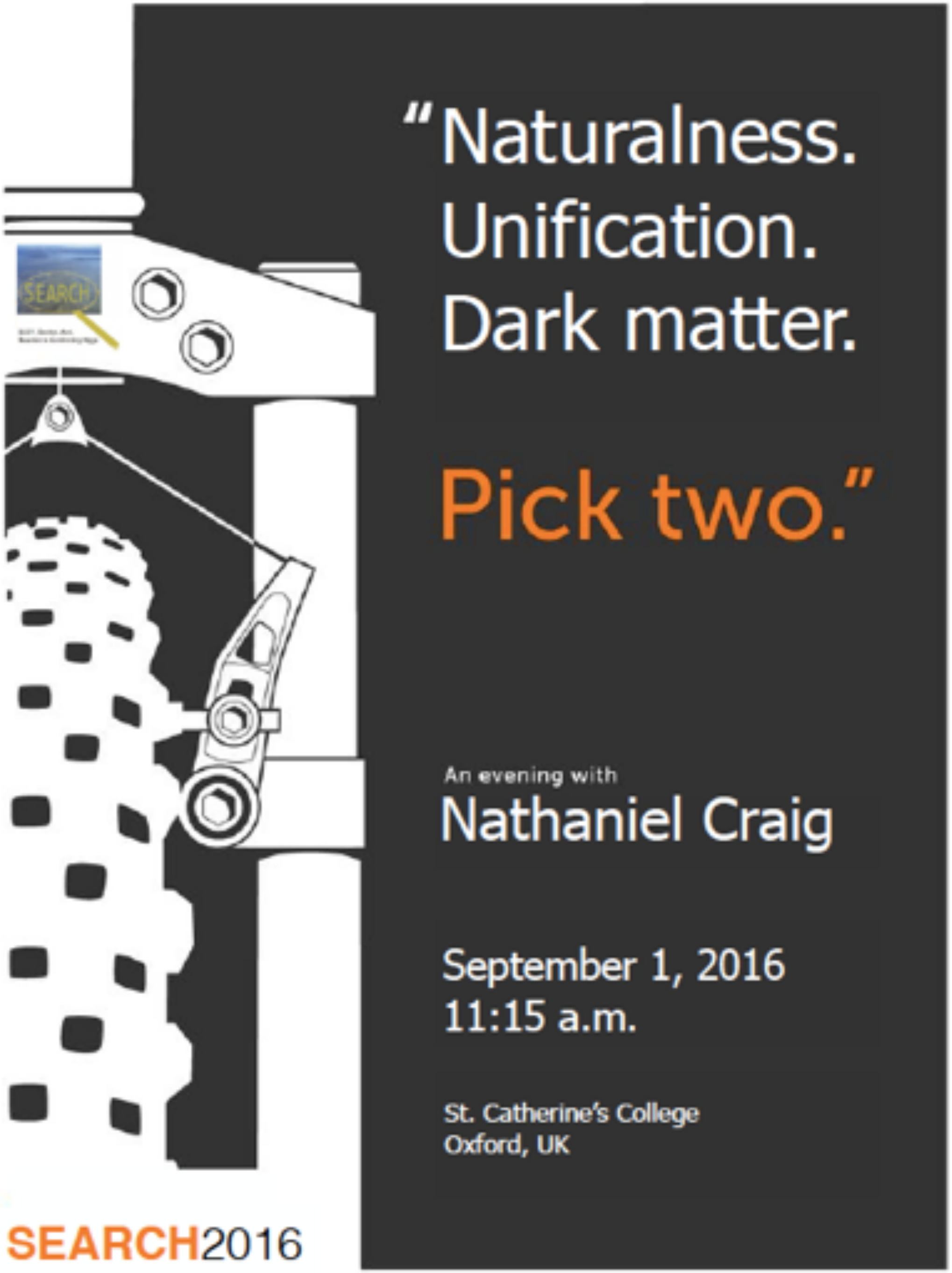
September 28, 2013
7:30 p.m.

801 Ridge Road
Wilmette, Illinois
847.920.9360
velosmith.com

velosmith
bicycle studio

Famous truism in the MTB industry:

Impossible to have simultaneously strong, light, and cheap components.



"Naturalness.
Unification.
Dark matter.

Pick two."

An evening with
Nathaniel Craig

September 1, 2016
11:15 a.m.

St. Catherine's College
Oxford, UK

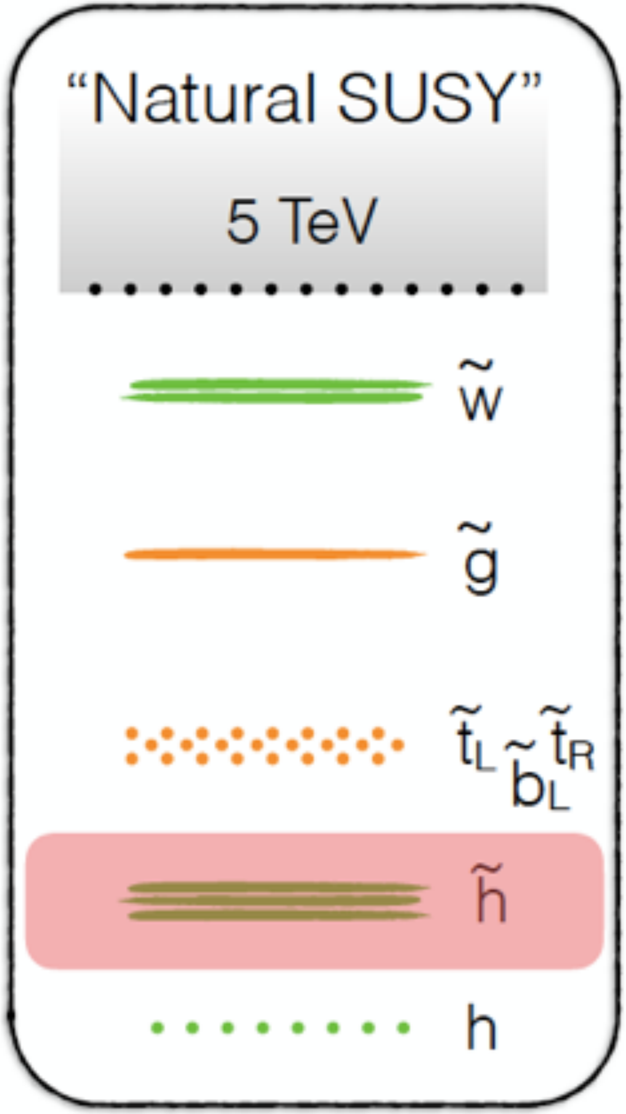
SEARCH2016

Supersymmetry in light of data:

Impossible to have a simple theory that is natural, unifies, and gives WIMP DM.

Picking two is a useful guide.

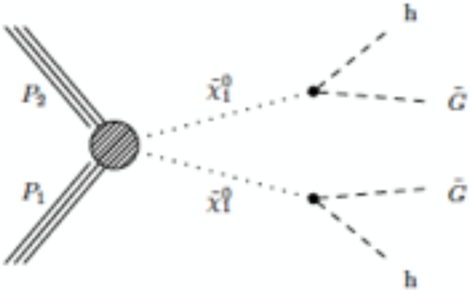
Where we are now: Higgsinos

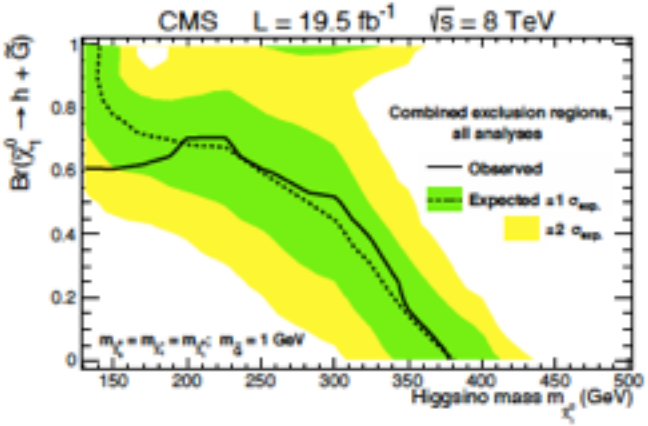


“Natural SUSY”

5 TeV

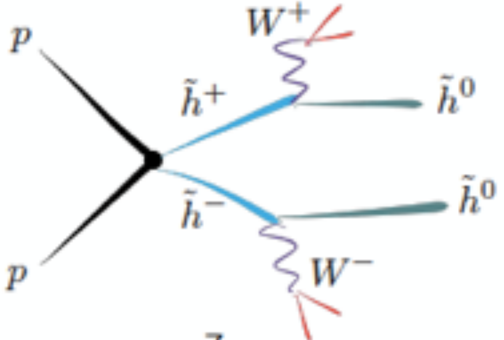
Lots of searches…

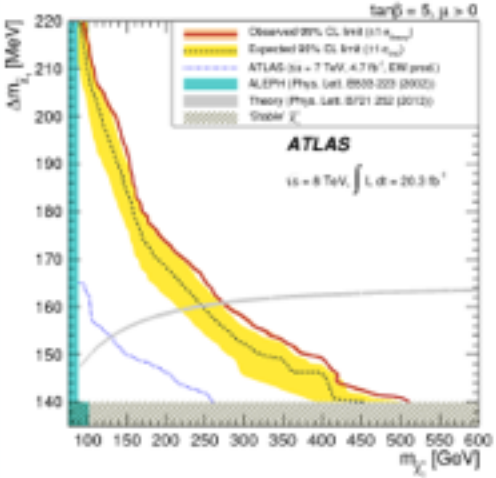




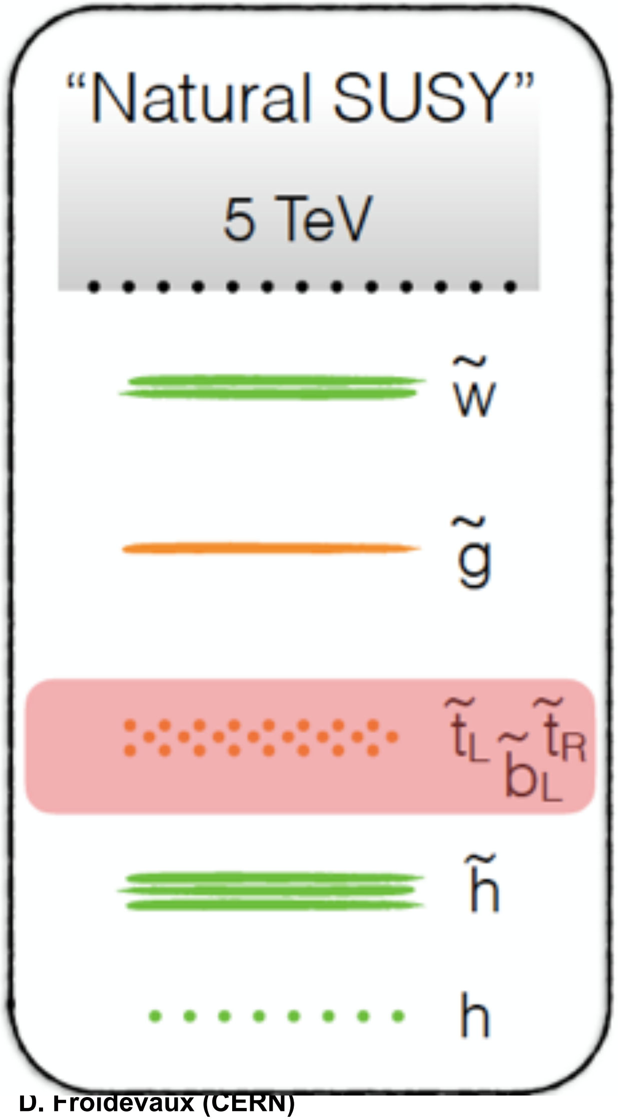
…but no irreducible limits

Chargino-neutralino splitting in pure higgsino multiplet: 355 MeV [Thomas, Wells ’98]

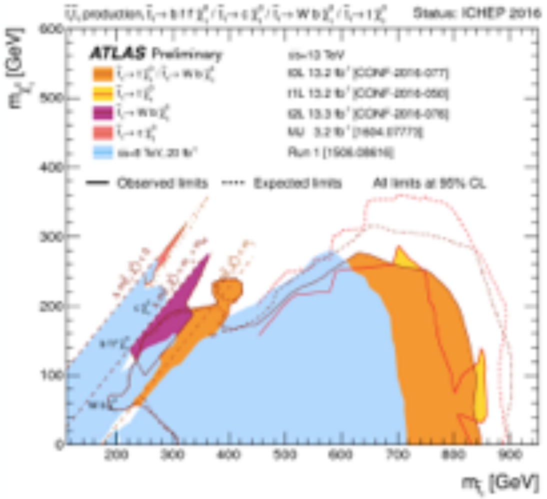


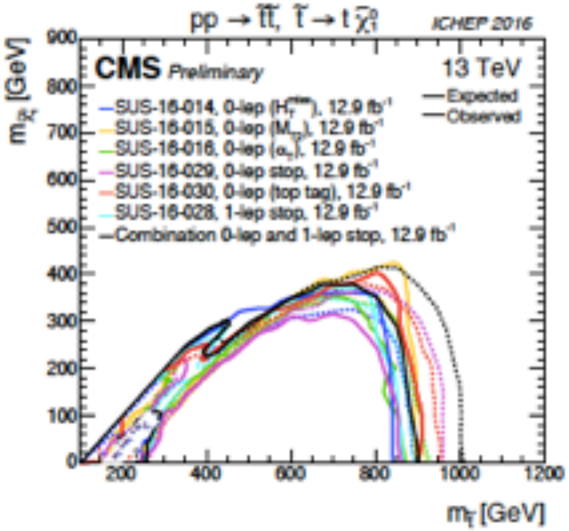


Where we are now: Stops



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log(\Lambda/\mathrm{TeV})$$



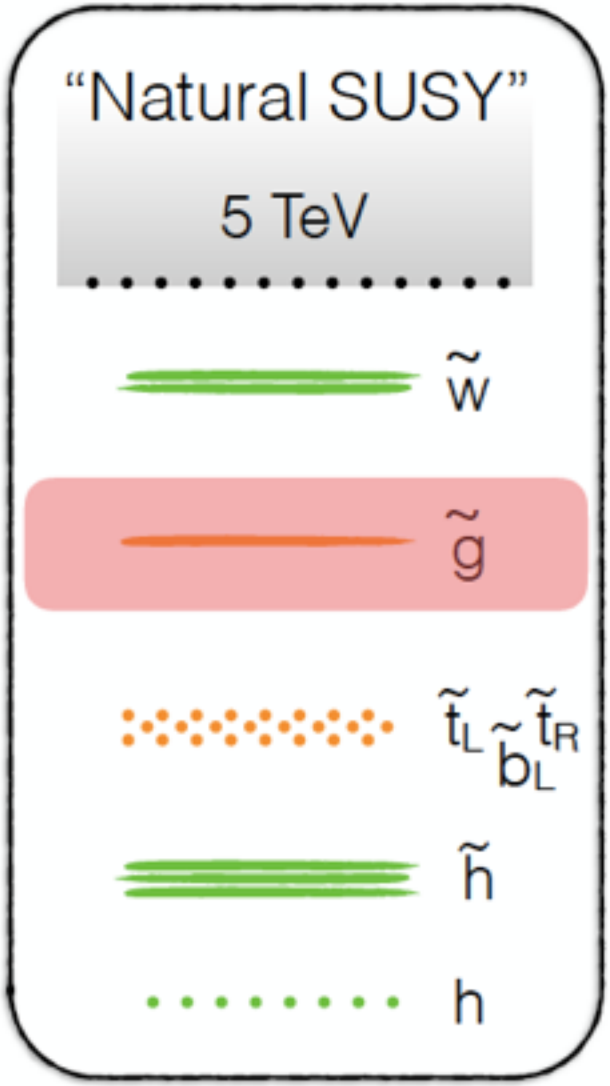


Generic limit > 800 GeV (both stops)

→ **Δ~90 (1% tuning)**

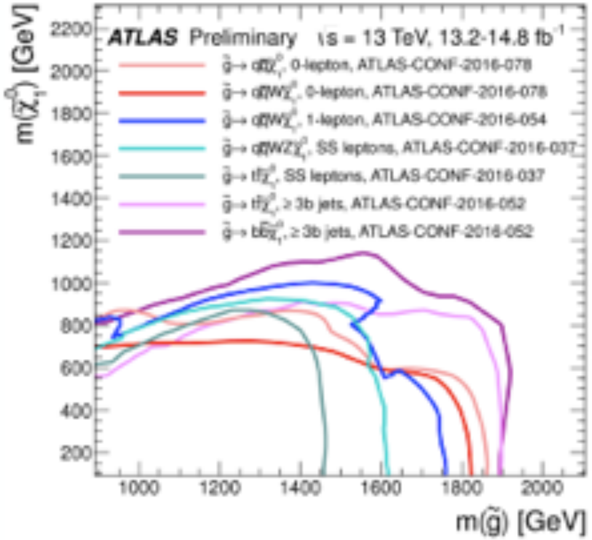
(Λ = 100 TeV)*

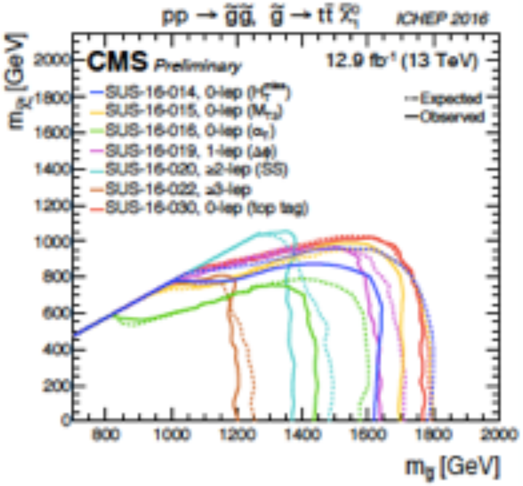
Where we are now: Gluinos



$$\delta m_H^2 \sim -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2(\Lambda/\text{TeV})$$

Leads to "$m_{\tilde{t}} \gtrsim M_3/2$"





Generic limit > 1800 GeV

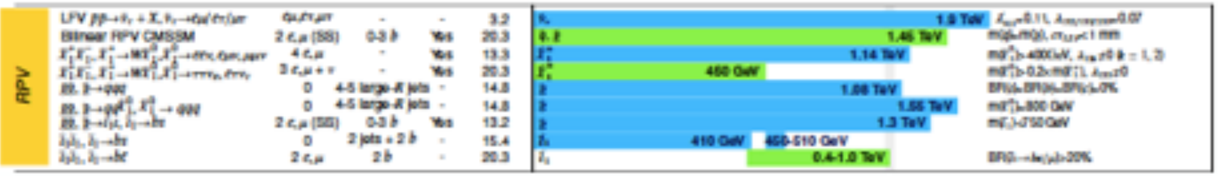
→ **Δ~57 (2% tuning)**

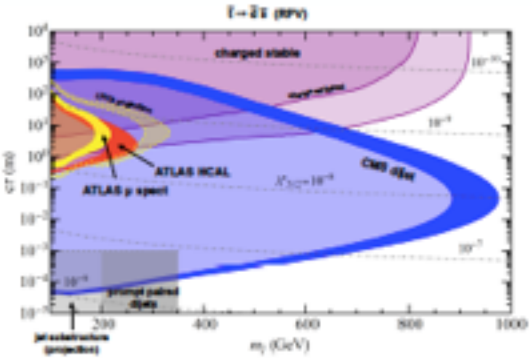
(Λ = 100 TeV)

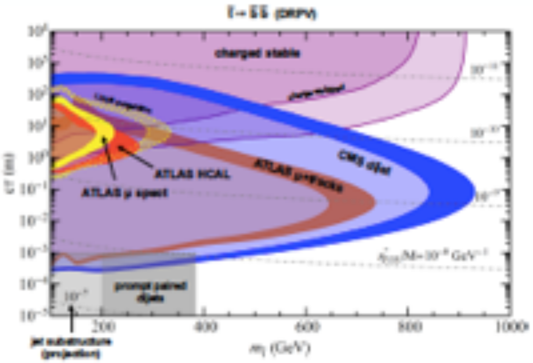
Naturalness & Unification

Violate the parity that gave you DM (RPV).

Lesson 1: Leptonic RPV kills you quickly.



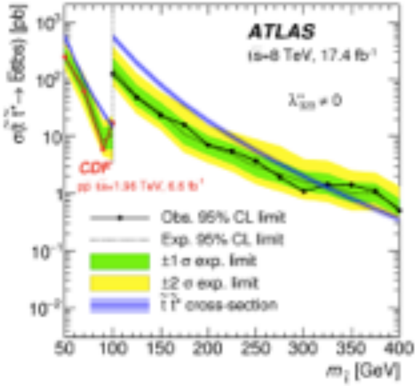


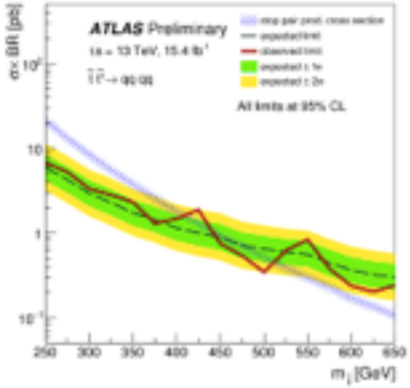


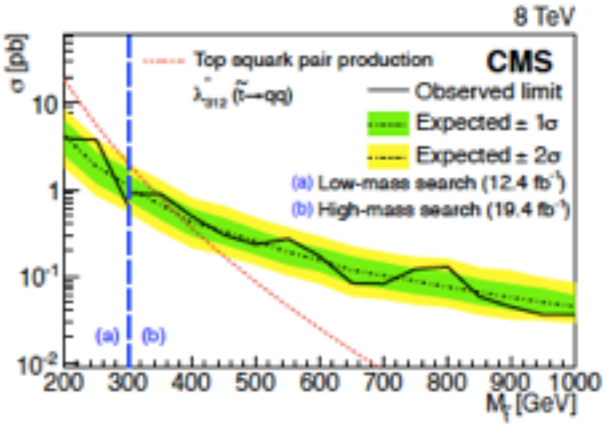
Lesson 2: Displacement kills you quickly.

[Liu, Tweedie 1503.05923]

Lesson 3: Even UDD RPV no longer gets you out of jail for free.



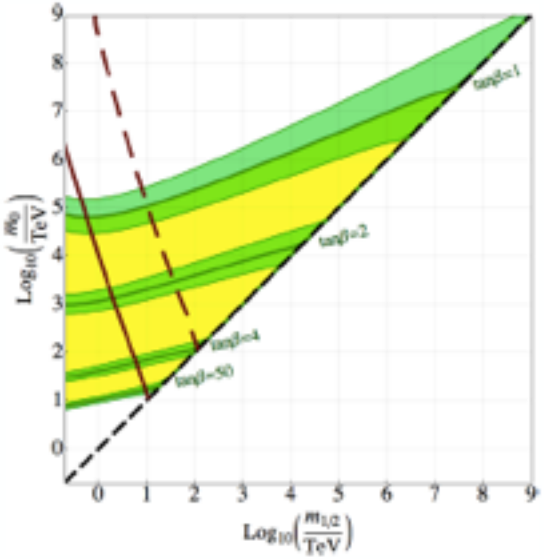




Unification & Dark Matter

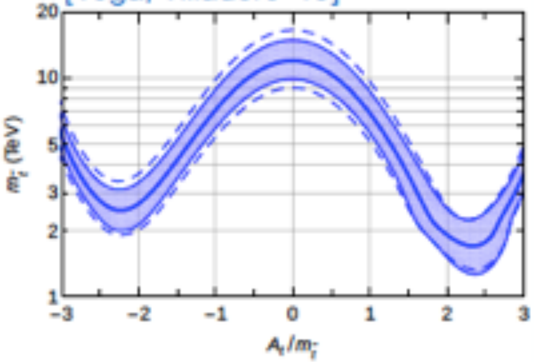
Forget the scalars, keep the fermions at a TeV.

[Arvanitaki, NC, Dimopoulos, Villadoro '12]



Use the MSSM Higgs mass as a guide; it was telling us that stops were above ~1 TeV all along.

[Vega, Villadoro '15]



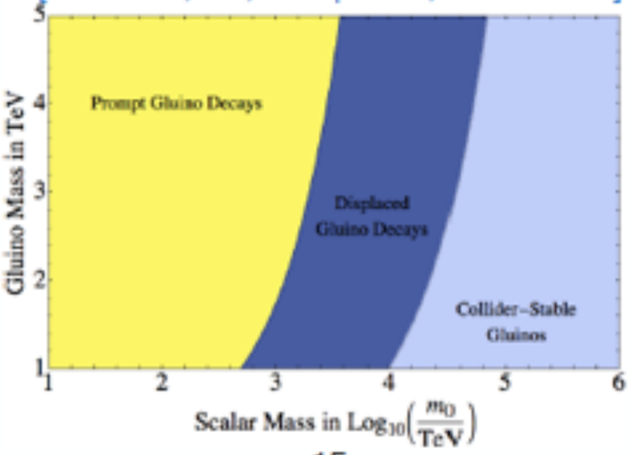
Pressure from unification & DM to keep higgsinos & gauginos beneath ~10 TeV

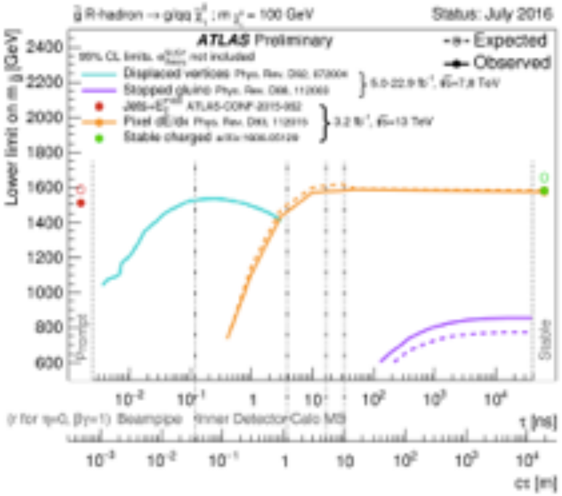
"Split / mini-split"

Canonical opportunity: search for gluinos. Opportunity, not guarantee; not required to be within kinematic reach

(*Request: what is the cτ reach of "prompt" searches?)

[Arvanitaki, NC, Dimopoulos, Villadoro '12]





Naturalness & Dark Matter

Bring in new charged states at the TeV scale.

Dirac gauginos

$$m_{\tilde{t}} \neq M_3/2$$

SUSY broken by a D-term

$$\mathcal{D} \equiv \frac{1}{8}\langle D^2 \bar{D}^2 V' \rangle > 0$$

$$W \supset \frac{W'_\alpha W^\alpha_j A_j}{M} \longrightarrow \mathcal{L} \supset \frac{\mathcal{D}}{M} \lambda \tilde{a}$$

Scalar masses radiative

$$\tilde{m}_i^2 \sim \frac{\alpha_i}{\pi} m_D^2 \log\left(m_a^2/m_D^2\right)$$

Minimally $m_a \sim 2m_D$

so $m_{\tilde{t}} \sim M_3/5$

Decouple gluinos! Predict new adjoint scalars

Global symmetry for Higgsinos

$$m_H^2 \neq \mu^2$$

[NC, Howe; Cohen, Kearney, Luty]

SUSY Higgs is a pNGB associated w/ spontaneously broken global symmetry

$$\mathcal{G} \rightarrow \mathcal{H}$$

μ term an invariant of

$$\mathcal{G}$$

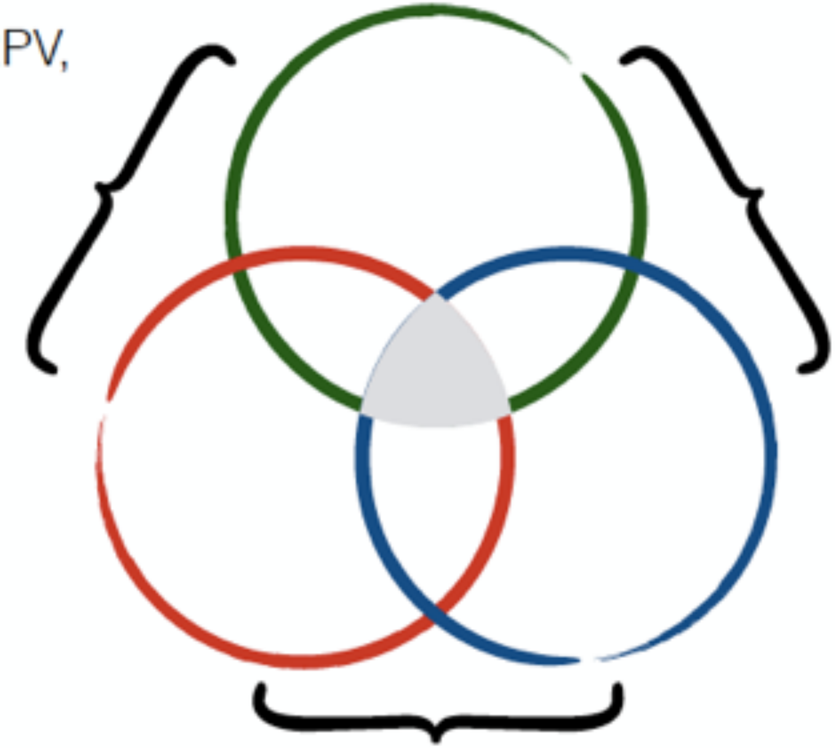
doesn't contribute to Higgs potential

No problem w/ higgsinos @ TeV, but predict new states associated w/ global symmetry.

No local 4D SUSY

- E.g. 5D SUSY on S_1/Z_2, SUSY broken by BCs.
- Spectrum finite, no large logs. (Often) dirac gauginos.
- Geography/localization can distinguish generations.
- Zero modes not supersymmetric ("hard breaking" for higgsino).
- Scale is 1/R ~ 5 TeV
- Analogous models in 4D

Look for the new stuff. Often large cross sections or resonantly produced.



Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>

Naturalness & Dark Matter

- Additional states near weak scale (sgluon, KK resonances, …)
- Higgs properties
- <Your idea here>

Unification & Dark Matter

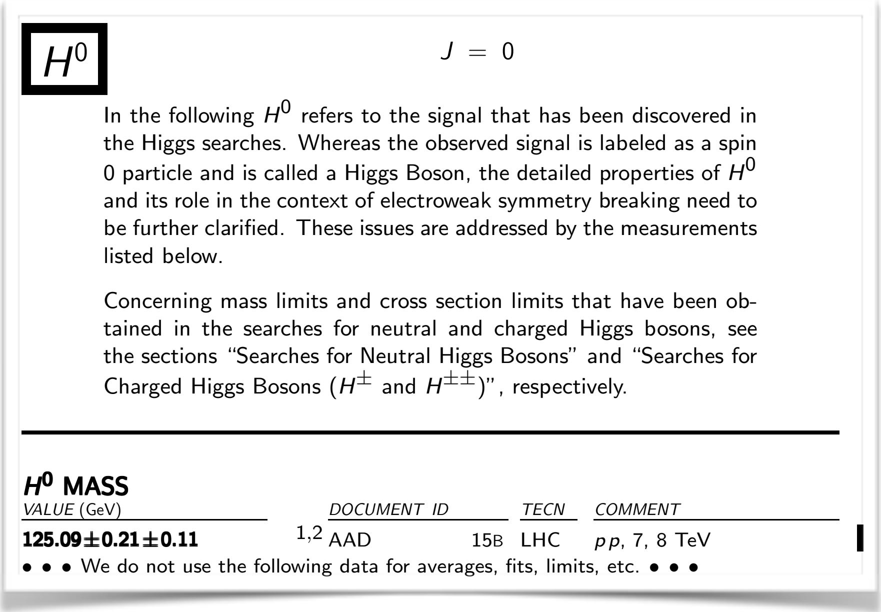
- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Getting to know the new particle

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002, PRL 114 (2015) 191803, EPJC 75 (2015) 212, Phys. Lett. B 726 (2013), pp. 120-144

- SM is highly **predictive** for the Higgs boson: Only free parameter is the mass
- Measure the **mass** and **width**
- Measure the **production** rate
- Measure **spin** and **parity** (only elementary scalar):
- Measure **couplings** (including self-coupling)

$$J^{PC} = 0^{++}$$



H^0

$J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

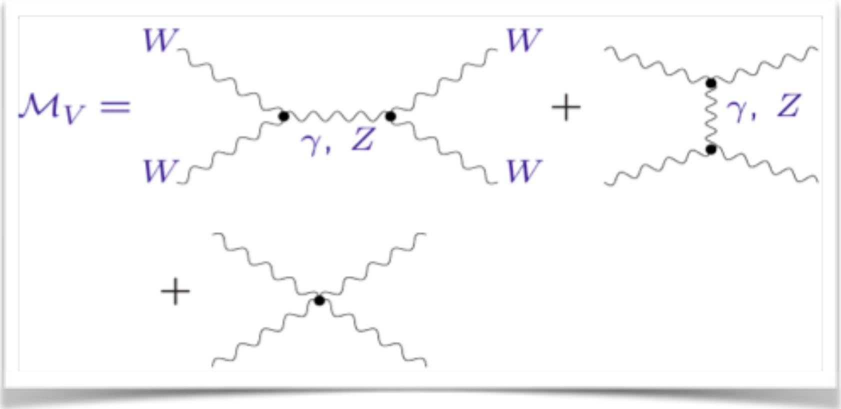
H^0 MASS

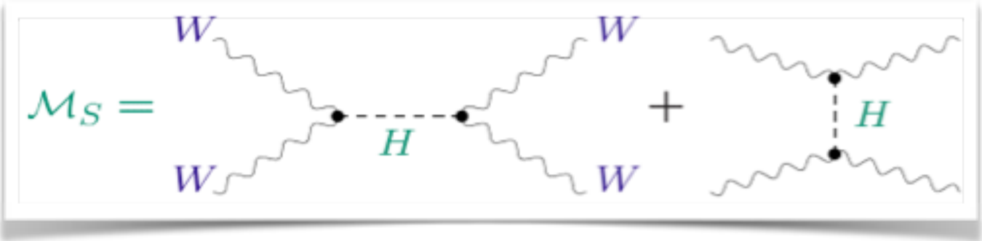
VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD	15B	LHC	*pp*, 7, 8 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

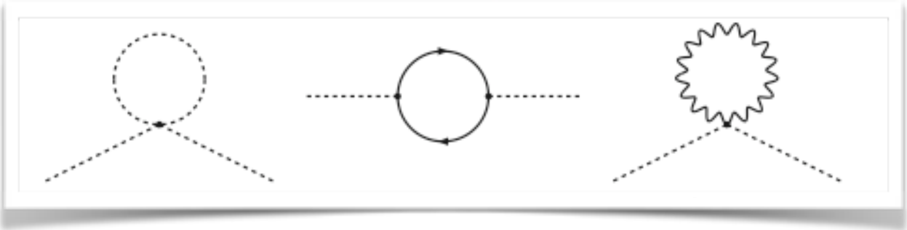
The Hierarchy Problem

- WW scattering violates unitarity above ~1 TeV
- New diagrams needed to regulate the cross section
- Adding diagrams with a scalar solves the problem





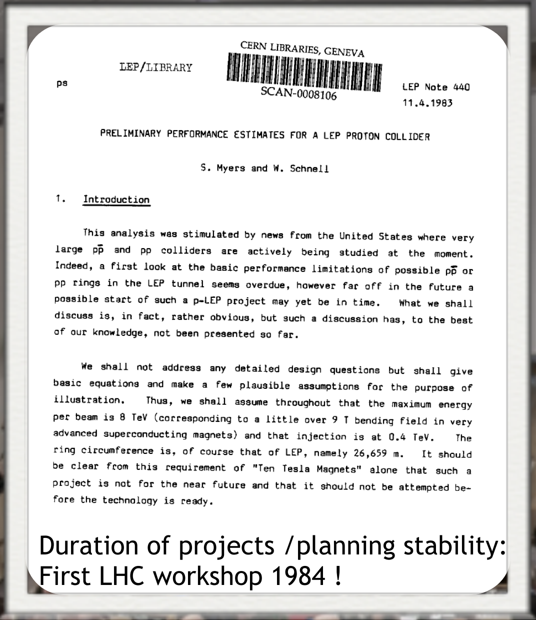
- BUT, the loop corrections to the Higgs boson mass are quadratically divergent, so although we've solved one problem, we're left with another



Planck scale

$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

4 July 2012: Higgs (In)dependence Day



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LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

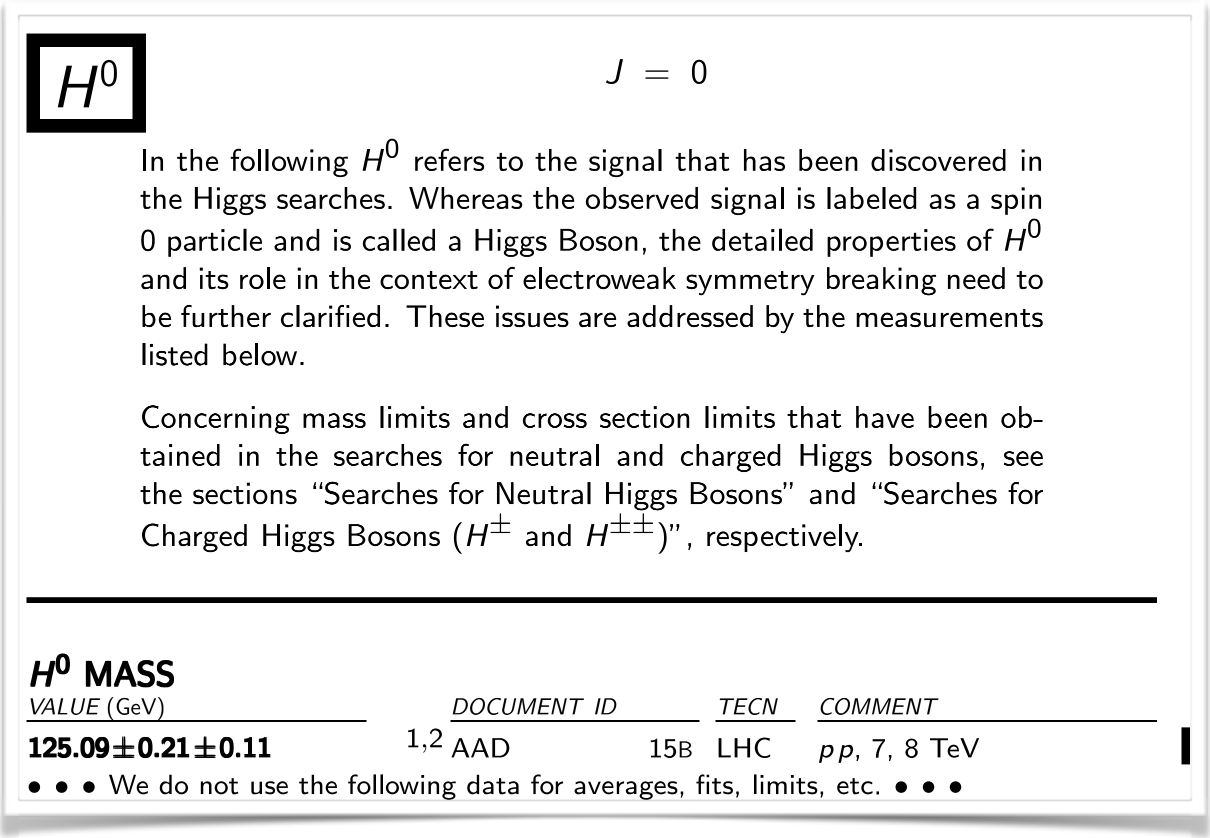
S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

Duration of projects /planning stability:
First LHC workshop 1984 !



H^0

$J = 0$

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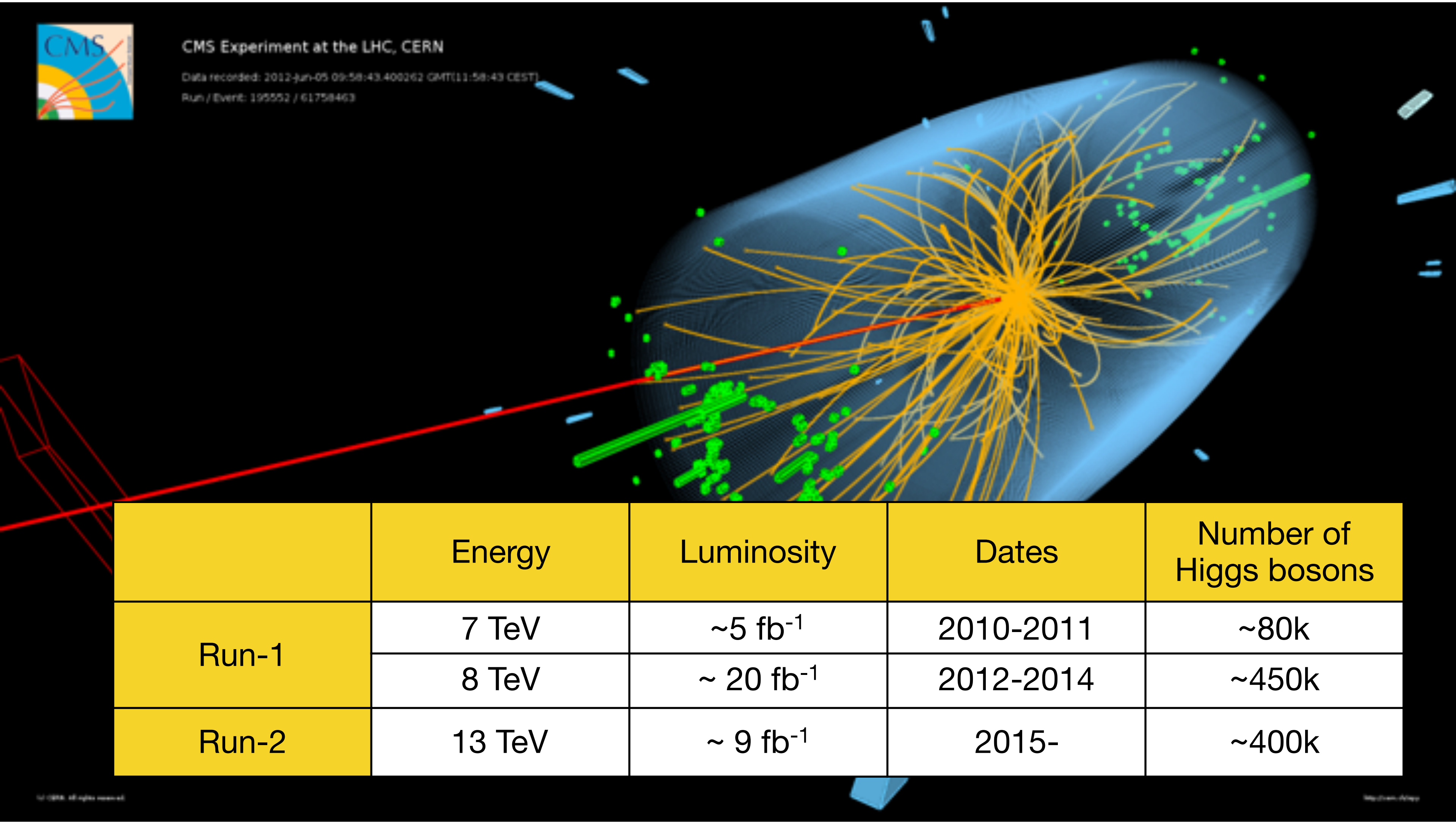
H^0 MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD 15B	LHC	pp, 7, 8 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

It's real … it's in the PDG

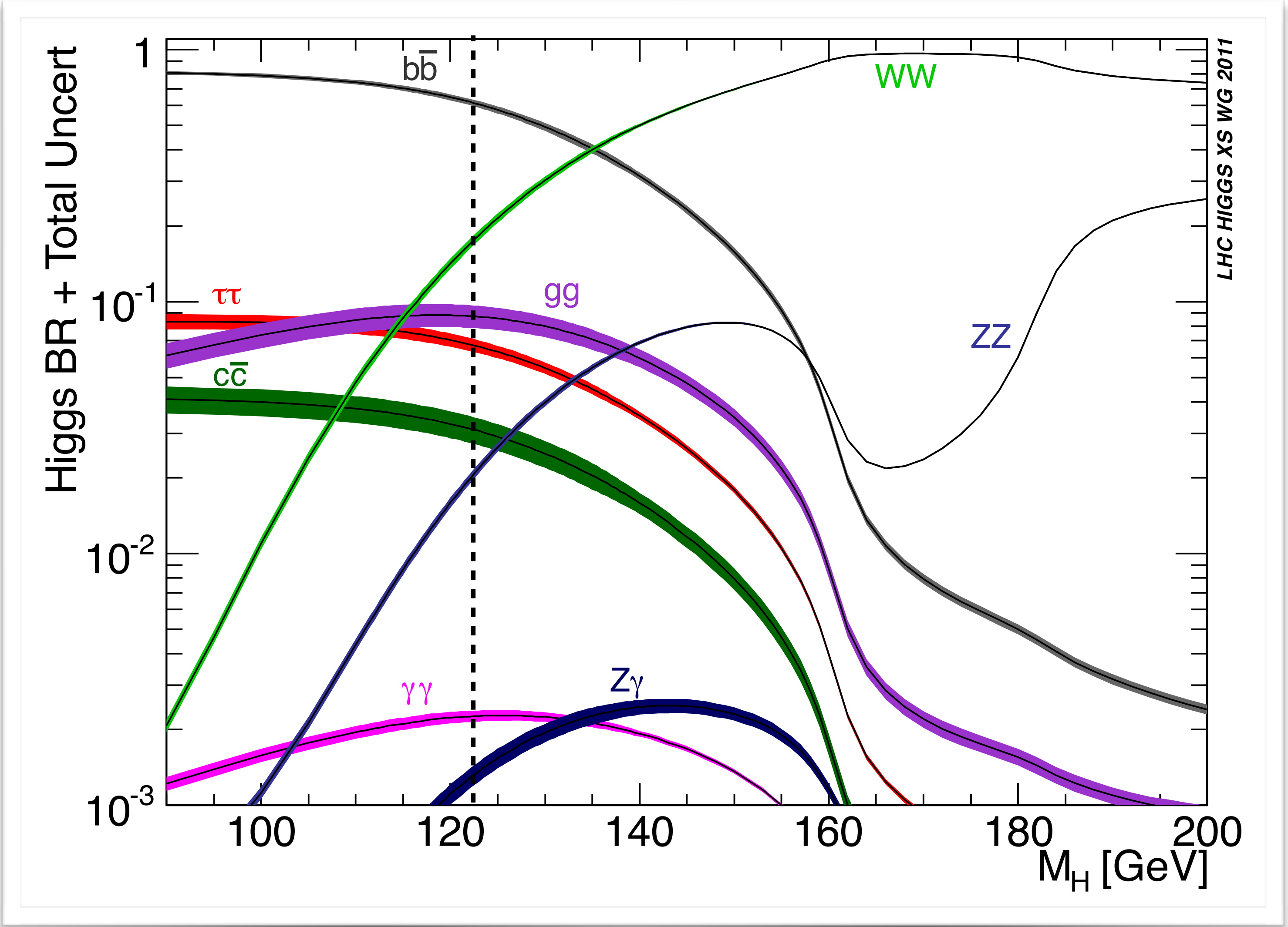
How many Higgs' ?



	Energy	Luminosity	Dates	Number of Higgs bosons
Run-1	7 TeV	~5 fb^{-1}	2010-2011	~80k
	8 TeV	~ 20 fb^{-1}	2012-2014	~450k
Run-2	13 TeV	~ 9 fb^{-1}	2015-	~400k

How hard can it be to find 500k particles?

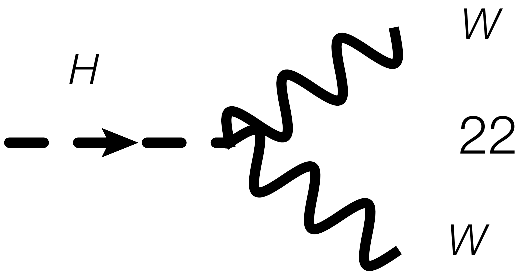
Incredibly Lucky?



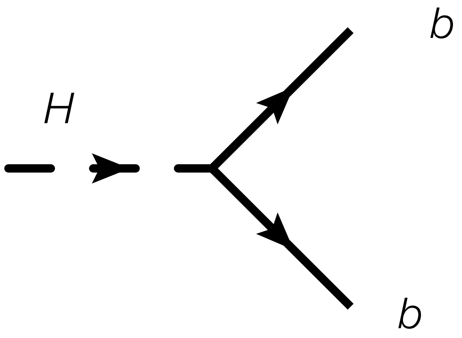
Nature just happened to choose a Higgs mass for which almost all experimental channels are accessible

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Higgs Decays: The Big 5



22%



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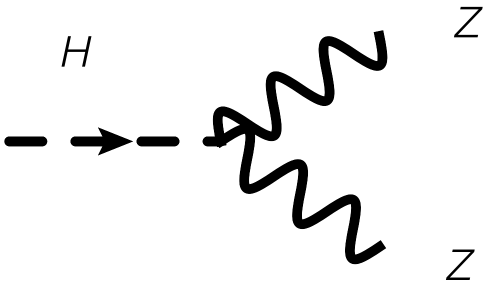

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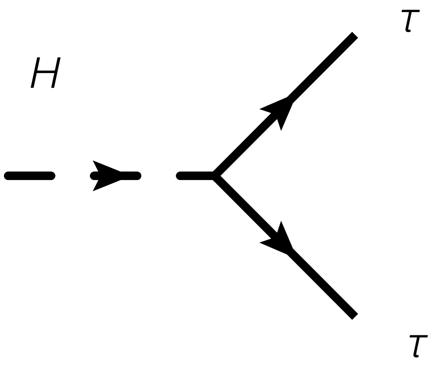

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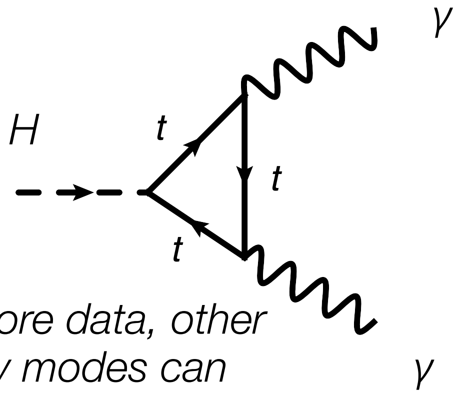

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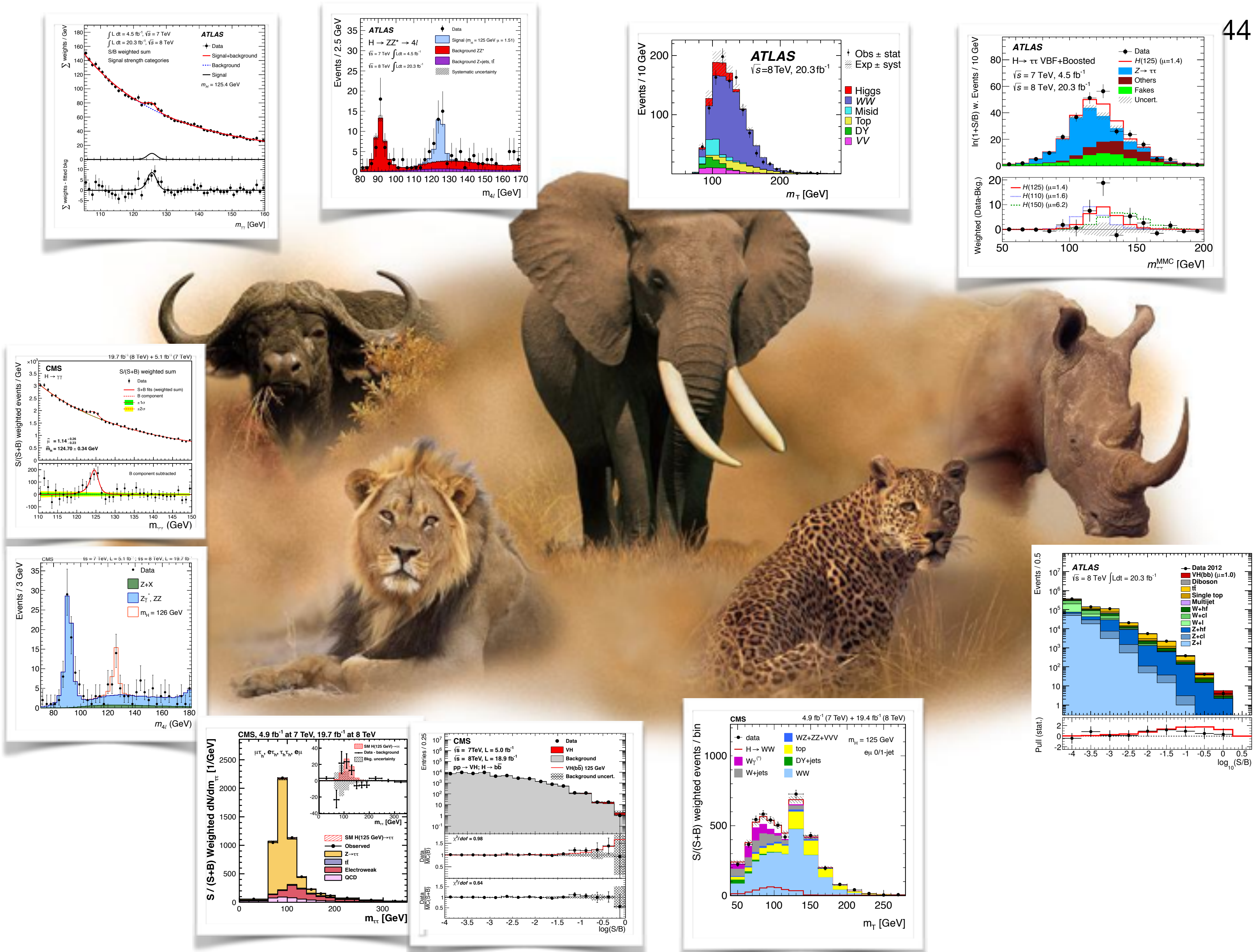
With more data, other decay modes can also be studied

Decay channel	Mass resolution
$H \to \gamma\gamma$	1-2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1-2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%


ATLAS
S/B weighted sum
Signal strength categories
Data
Signal+background
Background
Signal
m_H = 125.4 GeV
$m_{\gamma\gamma}$ [GeV]
ATLAS
H → ZZ* → 4l
Data
Signal (m_H=125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
m_{4l} [GeV]
Events / 2.5 GeV
ATLAS
√s=8 TeV, 20.3 fb⁻¹
Obs ± stat
Exp ± syst
Higgs
WW
Misid
Top
DY
VV
Events / 10 GeV
m_T [GeV]
ATLAS
H→ ττ VBF+Boosted
√s = 7 TeV, 4.5 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Data
H(125) (μ=1.4)
Z→ ττ
Others
Fakes
Uncert.
H(125) (μ=1.4)
H(110) (μ=1.6)
H(150) (μ=6.2)
ln(1+S/B) w. Events / 10 GeV
Weighted (Data-Bkg.)
$m_{\tau\tau}^{MMC}$ [GeV]
CMS
H → γγ
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m_H = 124.70 ± 0.34 GeV
B component subtracted
S/(S+B) weighted events / GeV
$m_{\gamma\gamma}$ (GeV)
CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Data
Z+X
Zγ*, ZZ
m_H = 126 GeV
Events / 3 GeV
m_{4l} (GeV)
ATLAS
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Data 2012
VH(bb) (μ=1.0)
Diboson
tt̄
Single top
Multijet
W+hf
W+cl
W+l
Z+hf
Z+cl
Z+l
Events / 0.5
Pull (stat.)
log₁₀(S/B)
CMS, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
$\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, eμ
SM H(125 GeV)→ττ
Data - background
Bkg. uncertainty
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
S / (S+B) Weighted dN/dm$_{\tau\tau}$ [1/GeV]
$m_{\tau\tau}$ [GeV]
CMS
√s = 7TeV, L = 5.0 fb⁻¹
√s = 8TeV, L = 18.9 fb⁻¹
pp → VH; H → bb̄
Data
VH
Background
VH(bb̄) 125 GeV
Background uncert.
Entries / 0.25
χ²/dof = 0.98
χ²/dof = 0.64
Data/MC(B)
Data/MC(S+B)
log(S/B)
CMS
4.9 fb⁻¹ (7 TeV) + 19.4 fb⁻¹ (8 TeV)
m_H = 125 GeV
eμ 0/1-jet
data
H → WW
Wγ(*)
W+jets
WZ+ZZ+VVV
top
DY+jets
WW
S/(S+B) weighted events / bin
m_T [GeV]

Studied Higgs Modes

	mass range [GeV]	Branching Ratio [%]	Mass Resolution [%]	ggF	VBF	VH	ttH
bb	110-135	58	10		🟩	🟩	🟩
WW	110-600	22	20	🟩	🟩	🟩	🟩
ττ	110-145	6,3	15	🟩	🟩	🟩	🟩
ZZ	110-1000	2,6	1-2	🟩	🟩	🟩	🟩
γγ	110-150	0,2	1-2	🟩	🟩	🟩	🟩

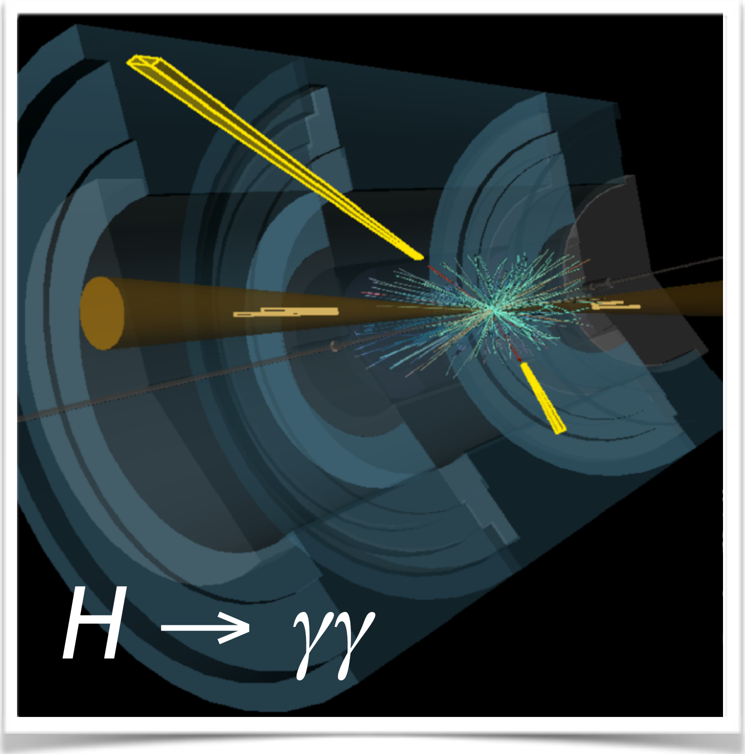
Searches for almost every decay modes and production channels*

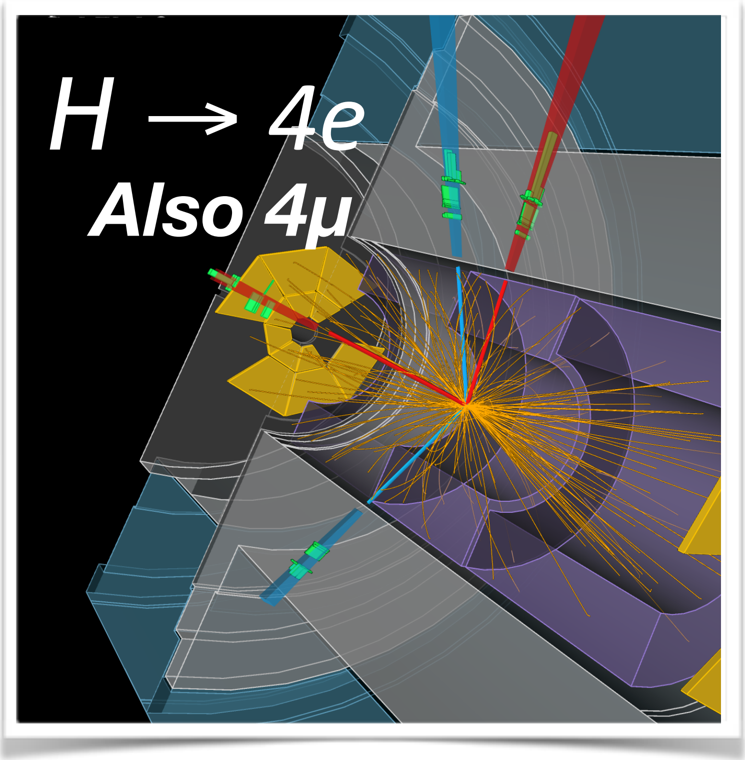
*of course, there are some more exotic production and decay modes

Discovery Channels

An excellent channel for
m_H = 125 GeV

Golden channel over a
wide mass range





N_s ~ 500

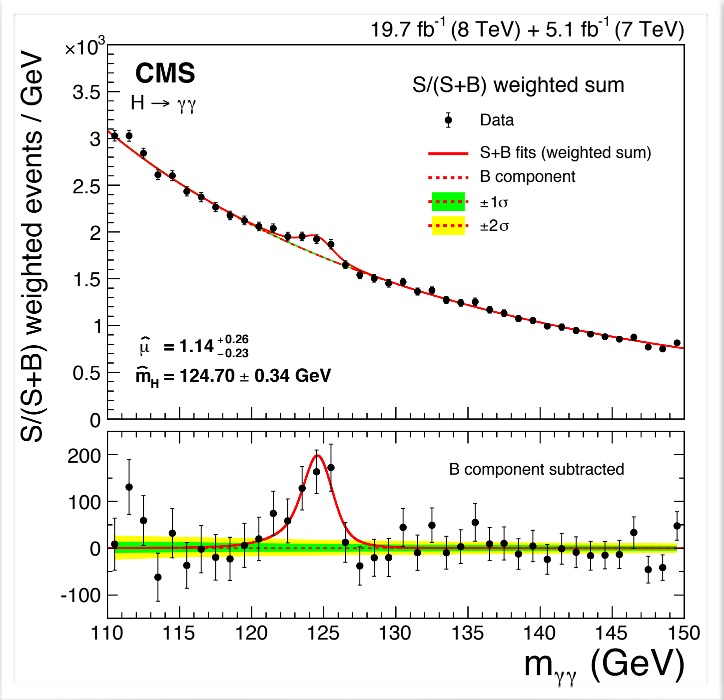
N_s ~ 20-30

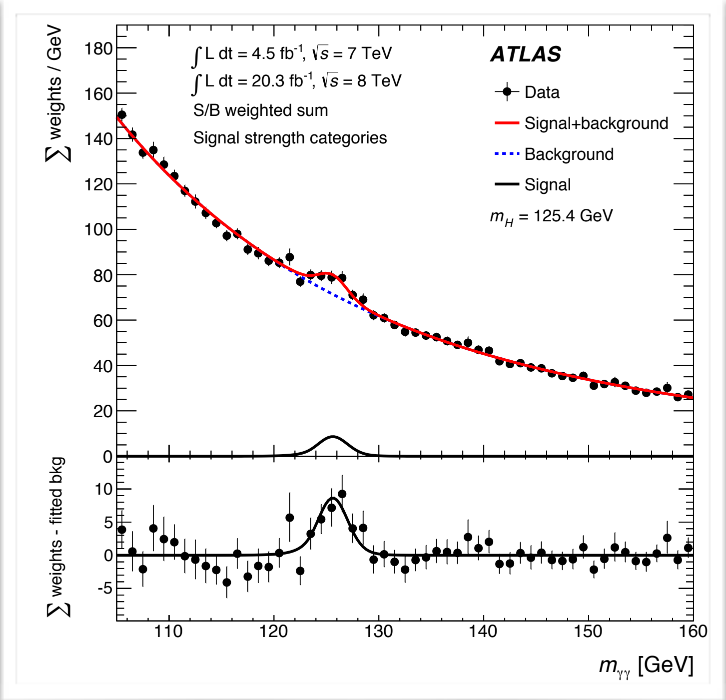
Simple channels with excellent mass resolution

Higgs to two photons (H→γγ)

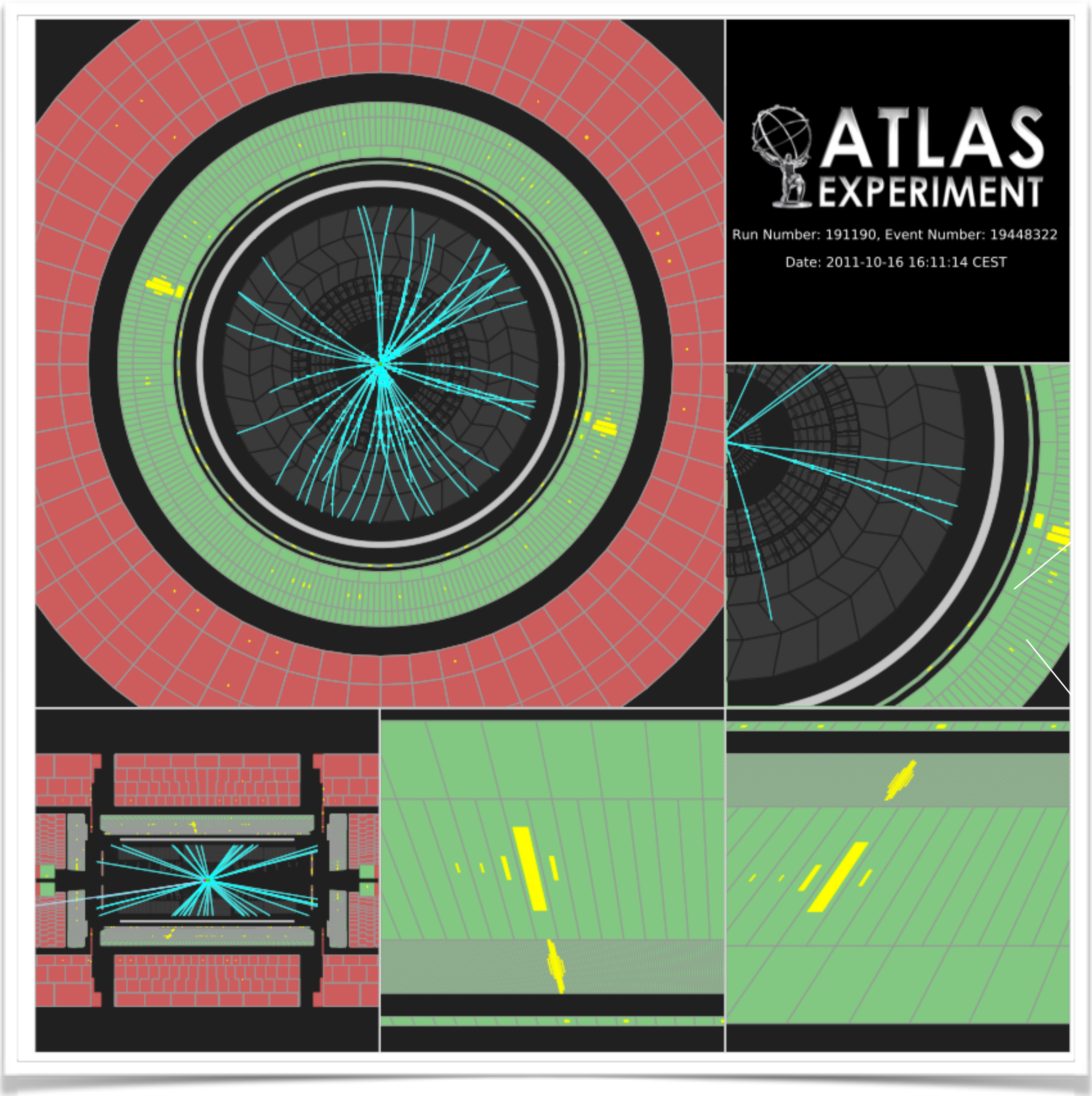
HIGG-2013-08
HIG-13-001

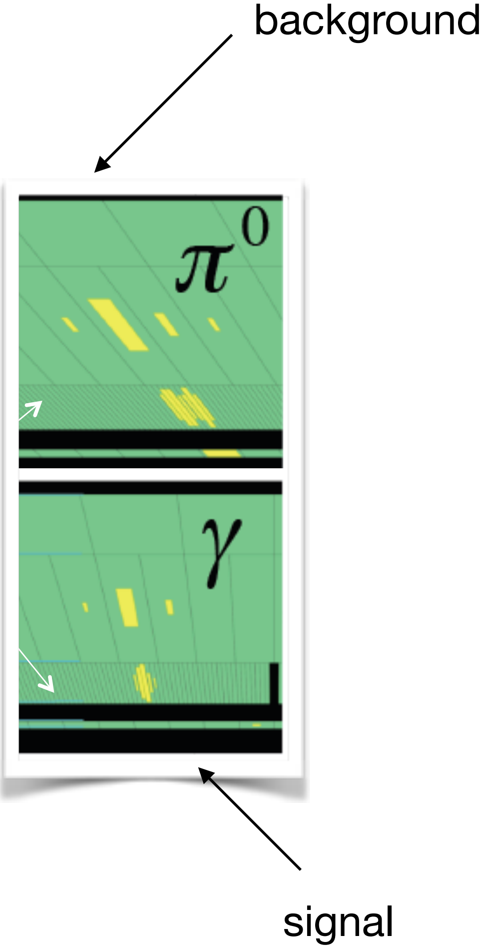
- A good **discovery** final state
  - Resonance on top of a **smooth background**
  - Excellent Higgs mass **resolution**
- Large backgrounds: need good **photon identification**
  - Key consideration in calorimeter design





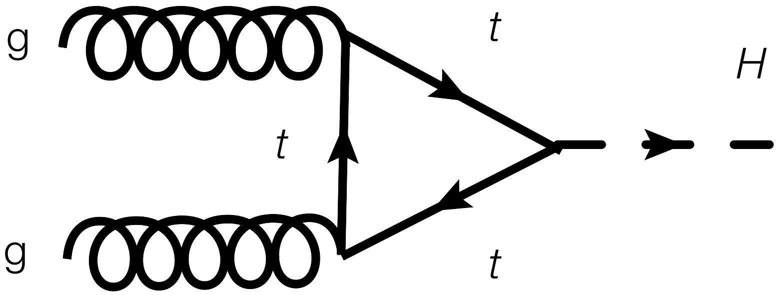
H→γγ: Signal and Background

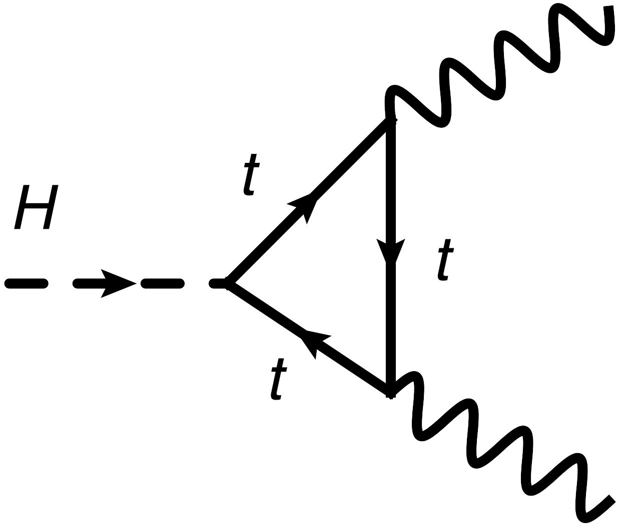




Production and Decay

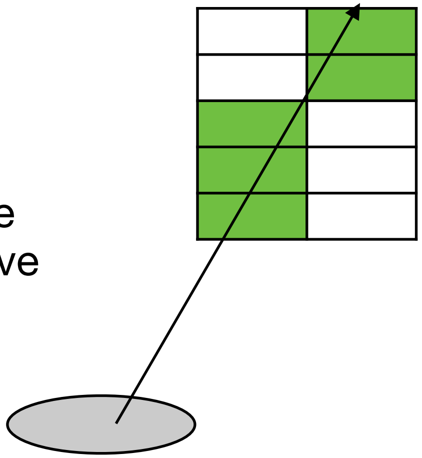
- No coupling of Higgs to gluons
    - Main **production** through a loop containing top (and bottom) quarks
        - Cross-section depends on Higgs coupling to **top**
- **No coupling of the Higgs to photons**
    - Decay through loops containing tops and W bosons
        - Decay depends on coupling to **top** and **W** boson
    - Small **branching ratio** (0.2%)



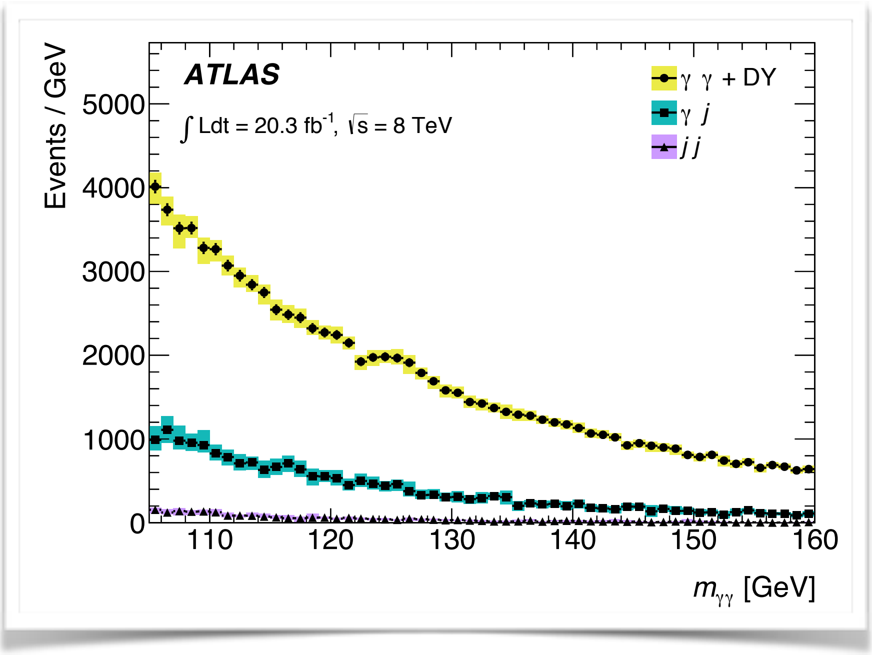


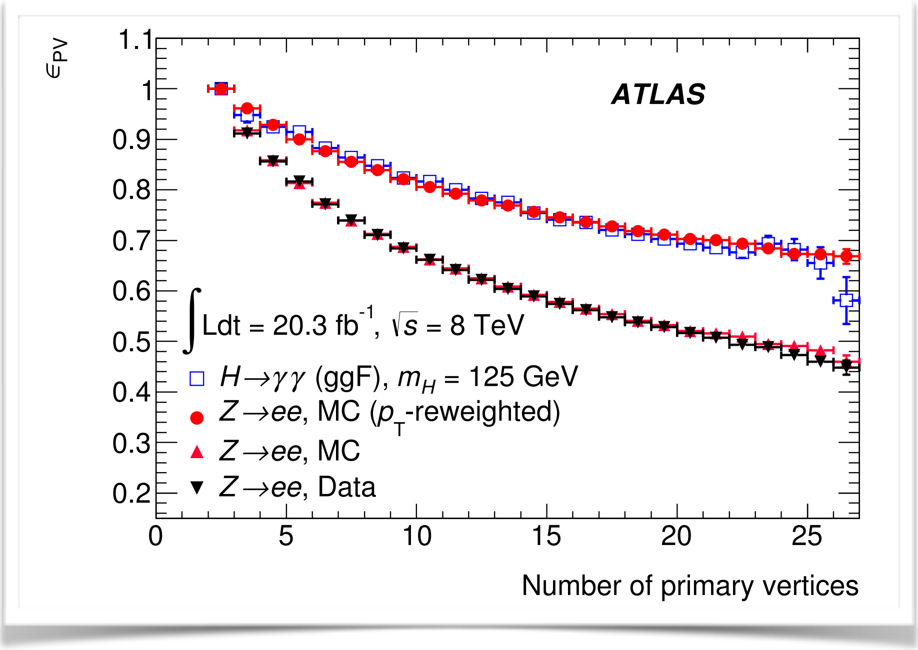
Backgrounds: pile up and jets

ATLAS uses longitudinal segmentation of the calorimeter to improve vertex resolution



$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$

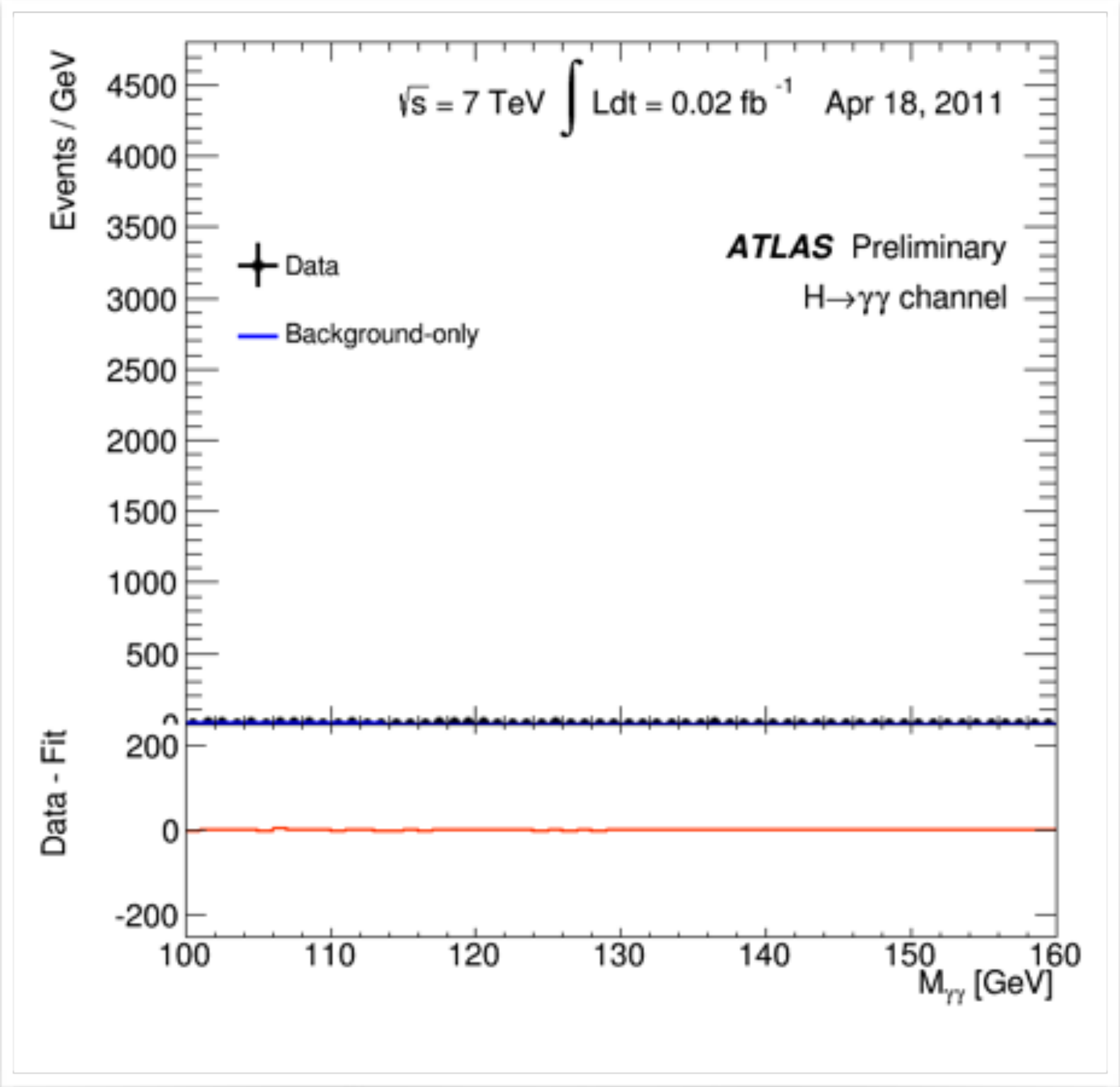




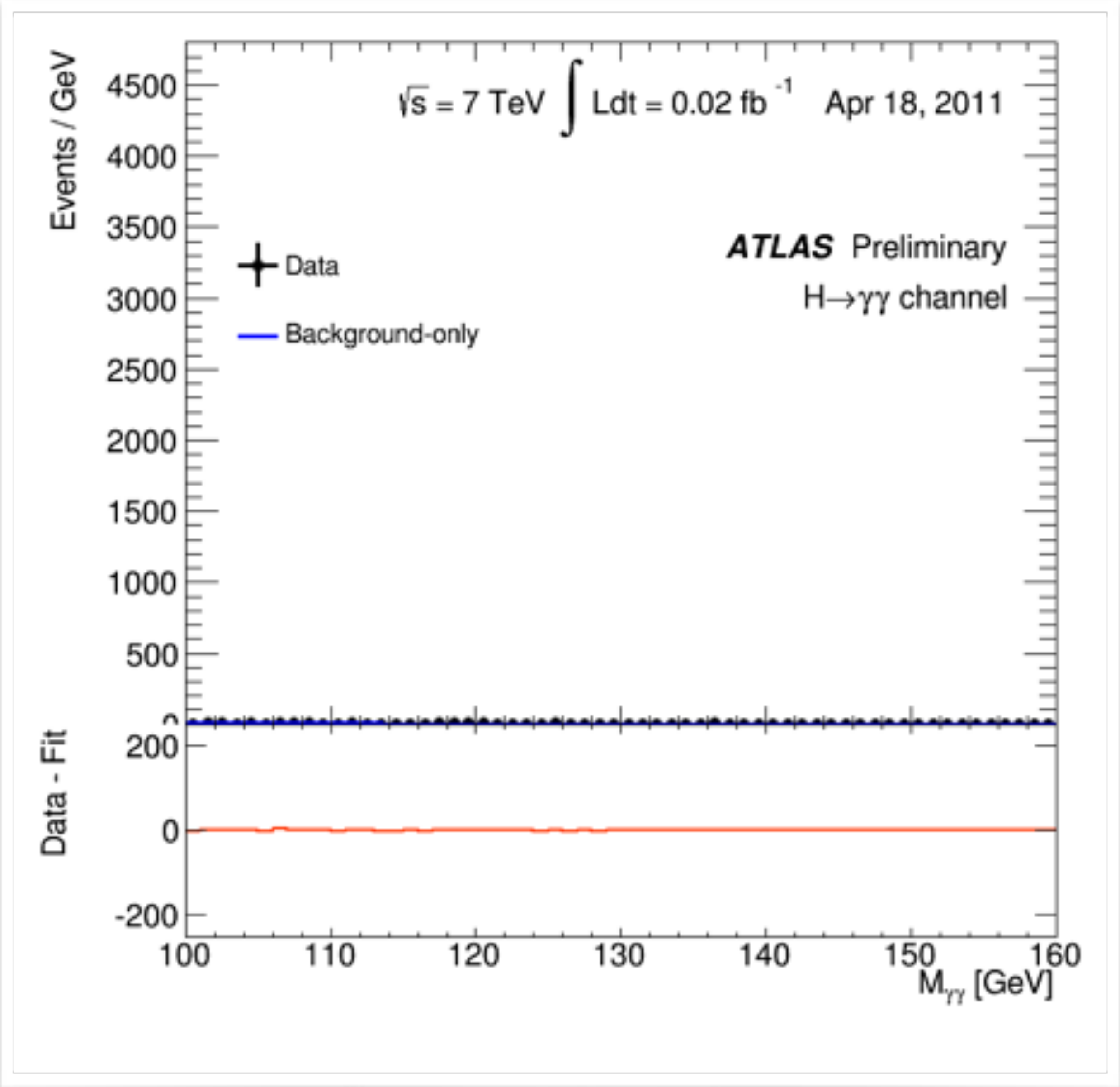
Main background from real photons

Small contribution from jets faking photons

Higgs to two photons (H→γγ)



Higgs to two photons (H→γγ)



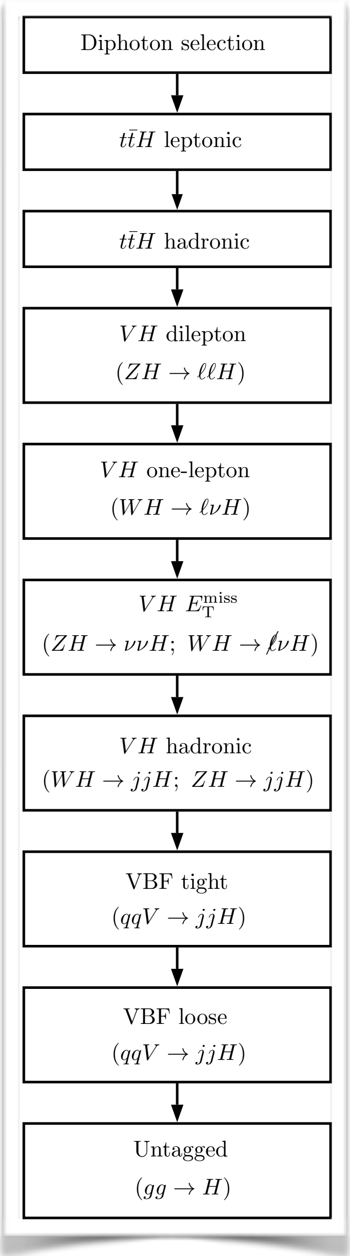
Why Categories ?

- Most LHC Higgs analyses use categories to improve sensitivity
- Main strategy is to separate events with different significance ~S/√B
- Differences can depend on resolution, background type or size, signal production mechanism or systematic uncertainties

- Take a simple example with two categories:
    - C1: s=12 and b=60
    - C2: s=18 and b=40
- Inclusively we have
    - s = 30
    - b = 100
    - Significance of 3σ
- Now calculate for the two categories
    - C1: 2.85σ
    - C2: 1.55σ
    - Combined significance: 3.24

Improved significance!

Improving Sensitivity: Categories



Diphoton selection

$t\bar{t}H$ leptonic

$t\bar{t}H$ hadronic

VH dilepton
$(ZH \to \ell\ell H)$

VH one-lepton
$(WH \to \ell\nu H)$

VH $E_{\mathrm{T}}^{\mathrm{miss}}$
$(ZH \to \nu\nu H;\ WH \to \not{\ell}\nu H)$

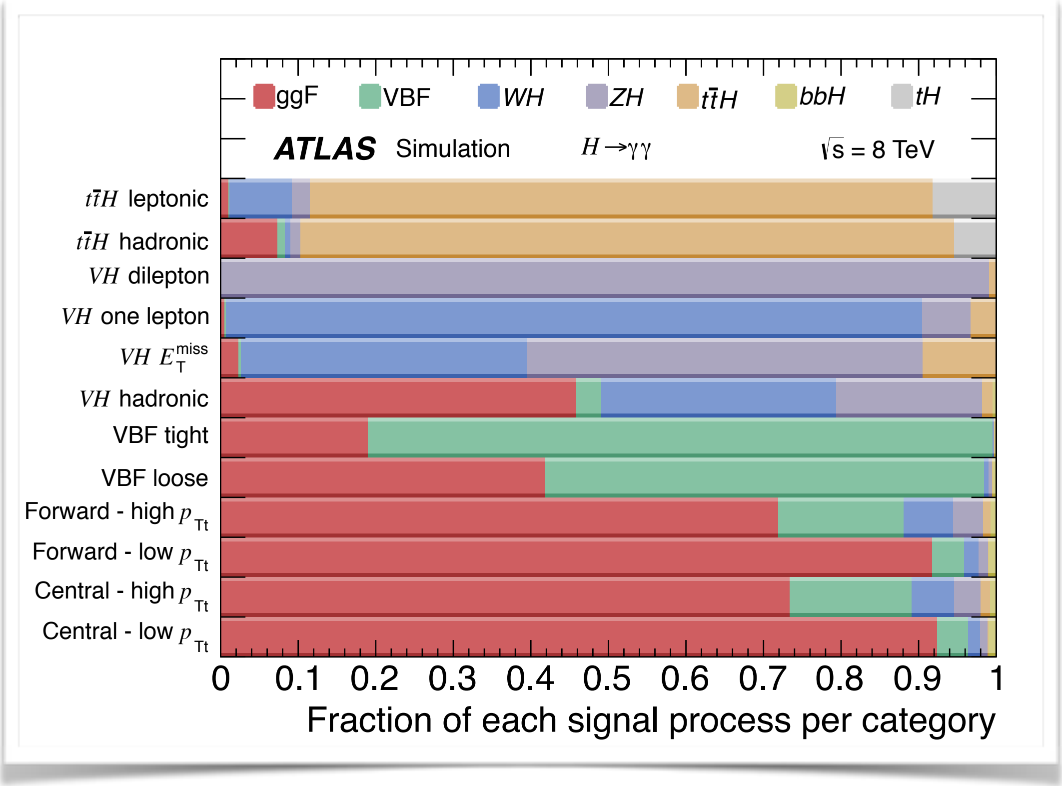
VH hadronic
$(WH \to jjH;\ ZH \to jjH)$

VBF tight
$(qqV \to jjH)$

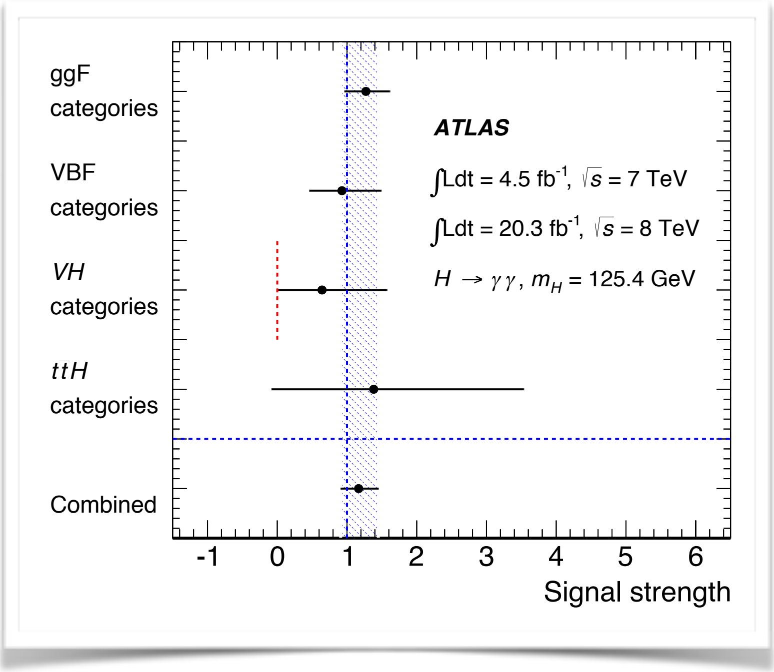
VBF loose
$(qqV \to jjH)$

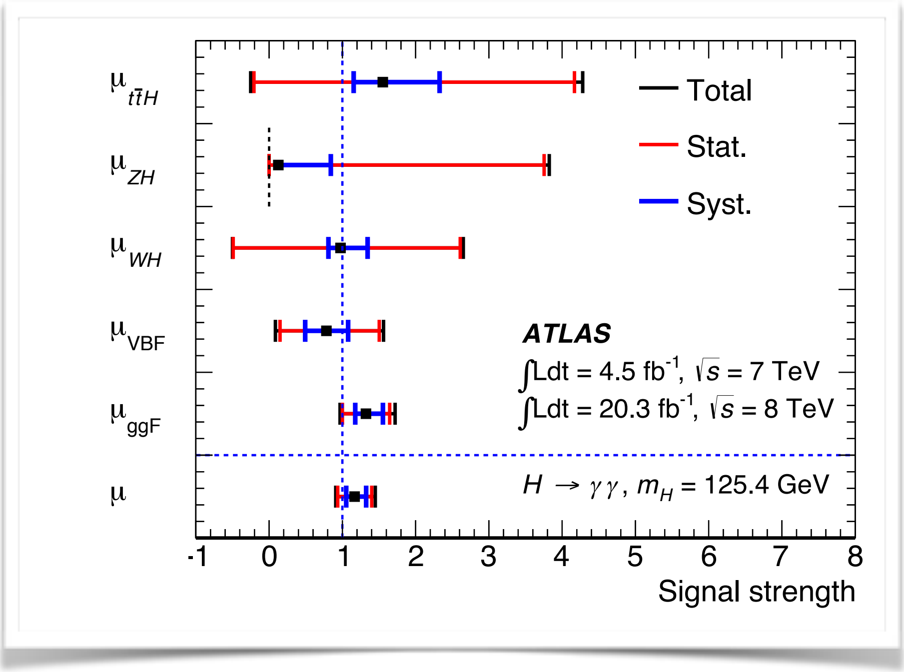
Untagged
$(gg \to H)$

- For ɣɣ, categories are also used to improve sensitivity to the different production modes
- Define categories with higher or lower purity of a specific production mode



Why Categories? (2)



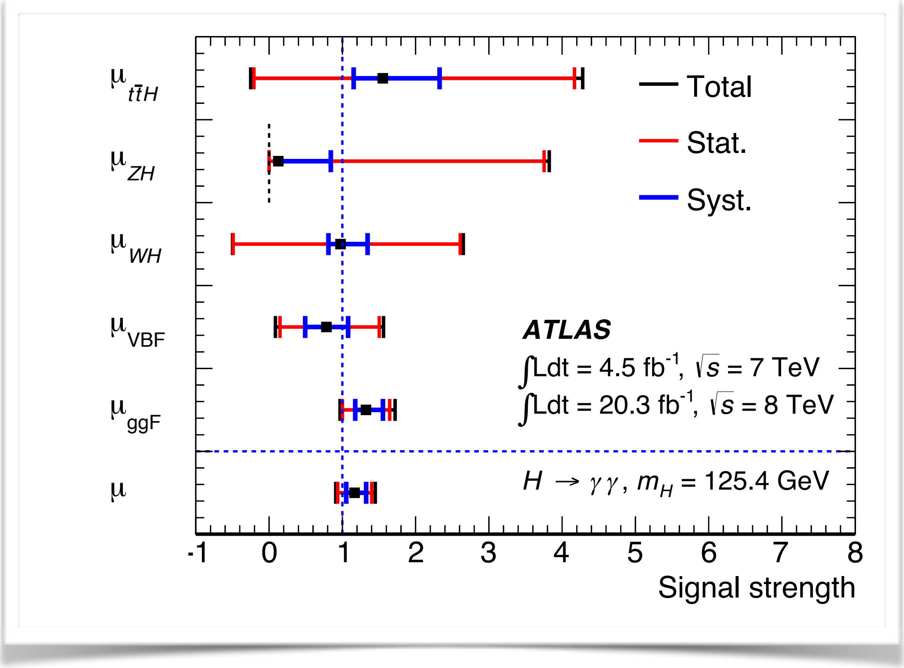


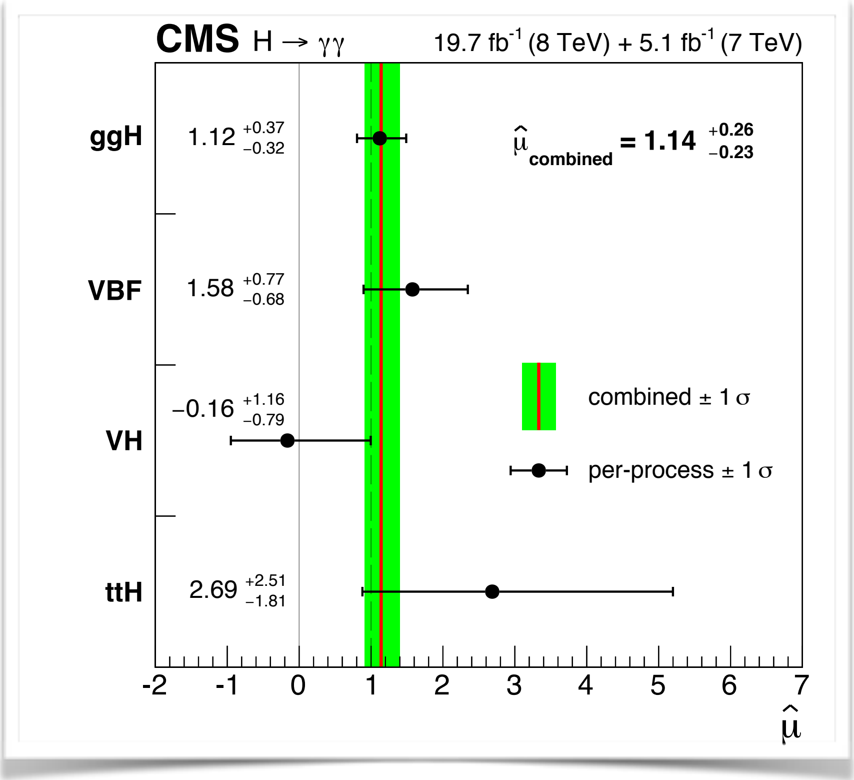
$$\begin{pmatrix} n_s^1 \\ \vdots \\ n_s^N \end{pmatrix} = \begin{pmatrix} \varepsilon_{ggF}^1 A_{ggF}^1 L^1 & \varepsilon_{VBF}^1 A_{VBF}^1 L^1 & \varepsilon_{VH}^1 A_{VH}^1 L^1 & \varepsilon_{ttH}^1 A_{ttH}^1 L^1 \\ \vdots & \vdots & \vdots & \vdots \\ \varepsilon_{ggF}^N A_{ggF}^N L^N & \varepsilon_{VBF}^N A_{VBF}^N L^N & \varepsilon_{VH}^N A_{VH}^N L^N & \varepsilon_{ttH}^N A_{ttH}^N L^N \end{pmatrix} \begin{pmatrix} \mu_{ggF}\sigma_{ggF}^{SM} \\ \mu_{VBF}\sigma_{VBF}^{SM} \\ \mu_{VH}\sigma_{VH}^{SM} \\ \mu_{ttH}\sigma_{ttH}^{SM} \end{pmatrix} B_{\gamma\gamma}^{SM}$$

$$\mu = \frac{\sigma}{\sigma_{tot}}$$

Extract measurements of all production modes

Final Run-1 γγ Results





$$\mu = 1.18 \pm 0.27$$

$$m_H = 125.4 \pm 0.27\ \text{GeV}$$

$$Z = 5.2(4.6)\sigma$$

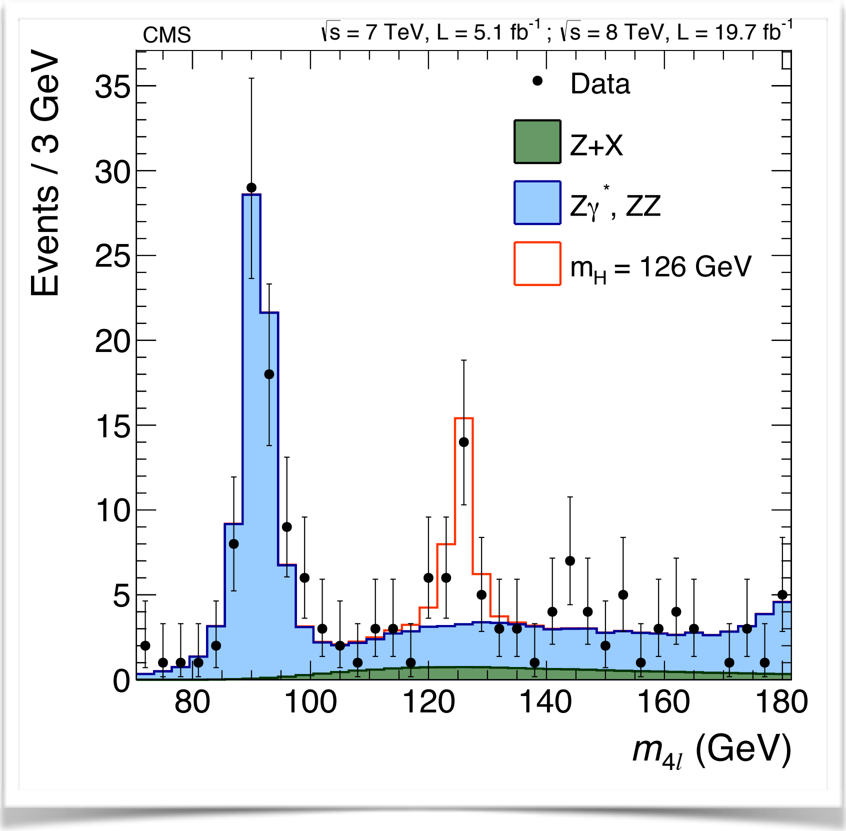
$$\mu = 1.14 \pm 0.26$$

$$m_H = 124.7 \pm 0.34\ \text{GeV}$$

$$Z = 5.7(5.2)\sigma$$

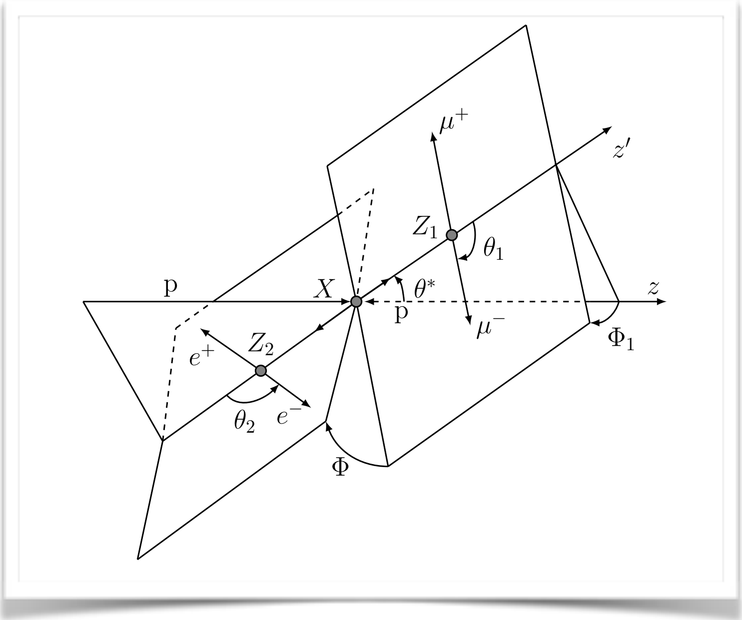
Higgs to 4 leptons (H→ZZ*→llll)

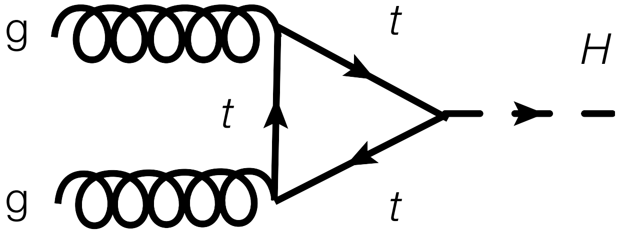
- A good **discovery** final state
  - Low backgrounds
    - S/B: 1.5 - 10
  - Very good Higgs mass **resolution**
  - Requires good lepton reconstruction efficiencies
    - Muon spectrometers designed specifically for this channel
  - Clear and robust signal of Higgs coupling to weak bosons
- Select 4 reconstructed leptons
  - 4e, 4μ, 2e2μ

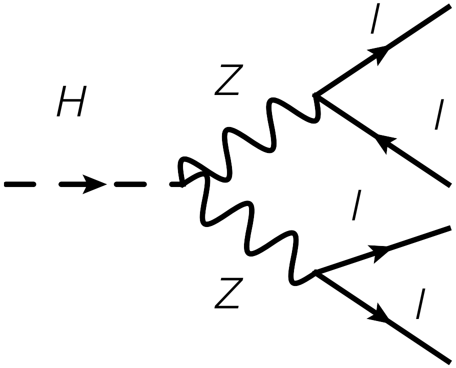


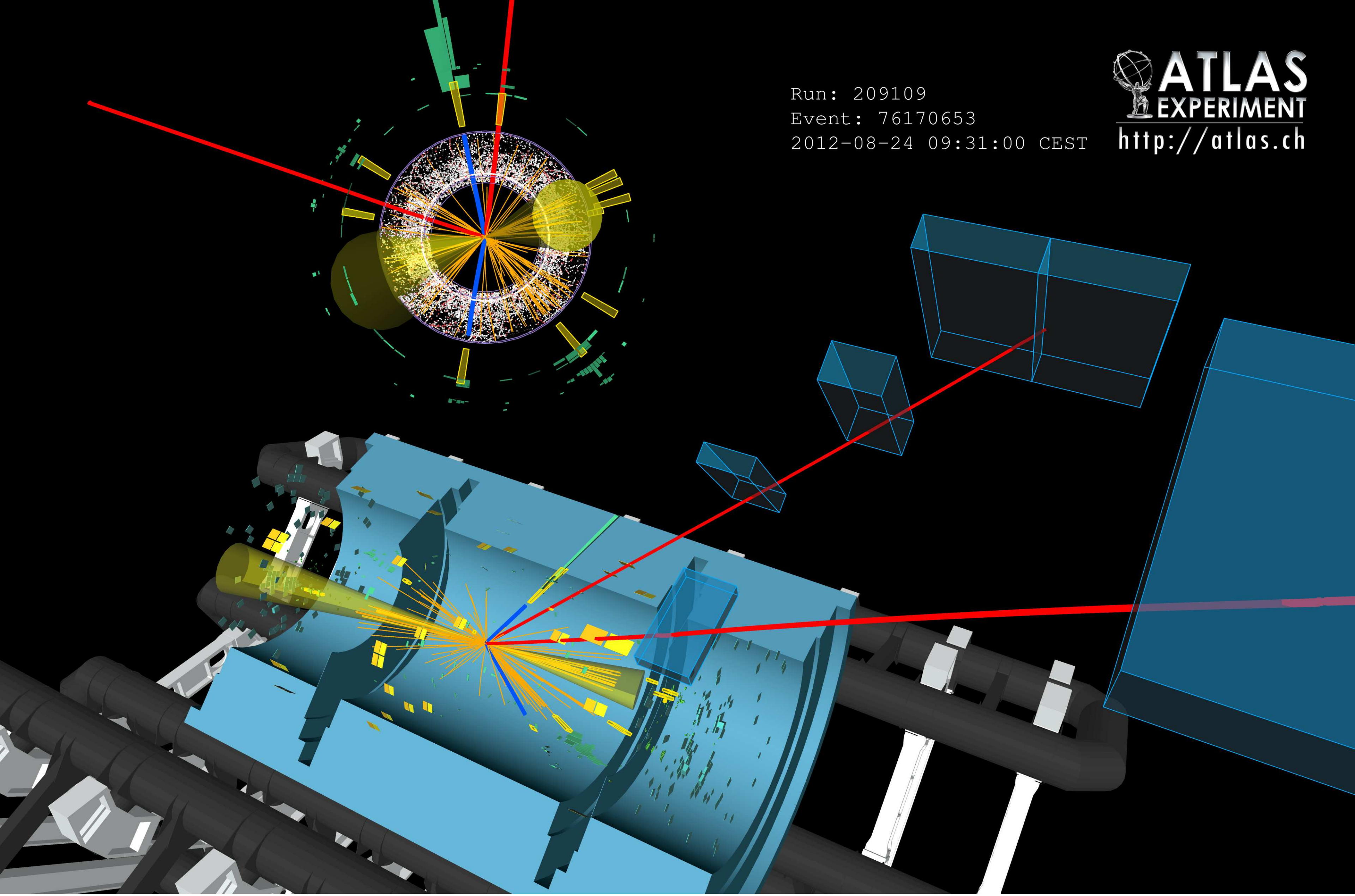
Production and Decay

- As for γγ, production through top loop
- Decay depends only on coupling to Z boson
- Small branching fraction to the 4-lepton final state (2.6%)
- Improve sensitivity by using full event information (e.g. in MVA)
    - 2 production and 3 decay angles
    - Z_1 and Z_2 masses



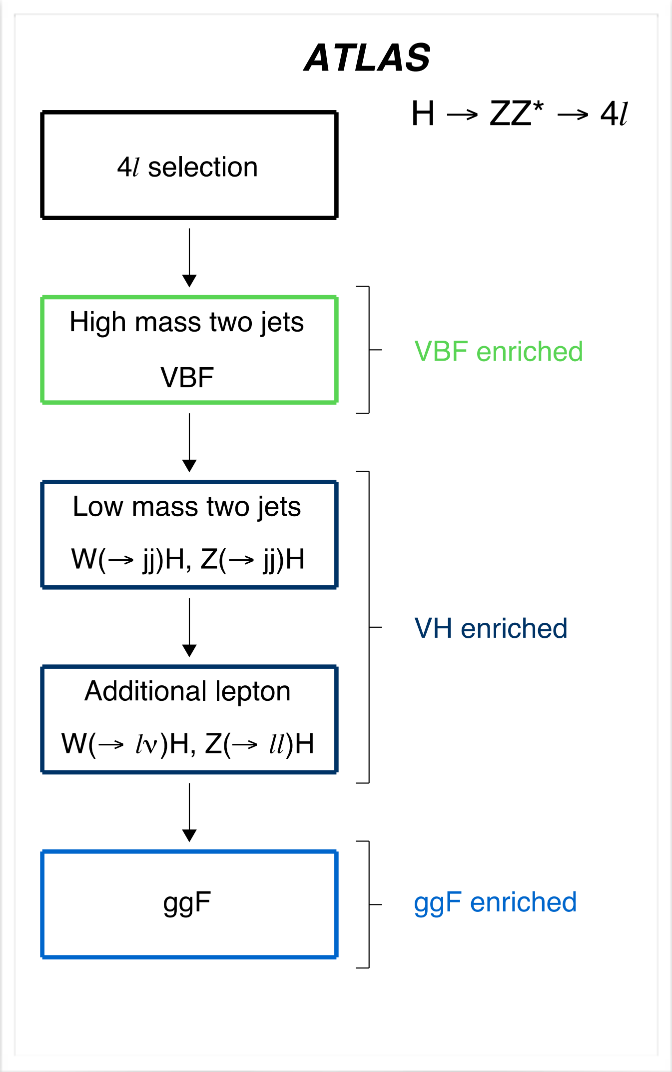






EventNumber : 76170653 RunNumber : 209109 $m_{4\ell}$=123.4 GeV. The $\mathrm{BDT}_{\mathrm{VBF}}$ value is 0.7. Six jets in total, and the two leading jets have p_T = 180 and 150 GeV, $\Delta\eta_{jj}$ = 3.4, and p_{Tjj} = 200 GeV. The missing E_T = 40 GeV.

Categories



ATLAS

H → ZZ* → 4*l*

4*l* selection

High mass two jets

VBF

VBF enriched

Low mass two jets

W(→ jj)H, Z(→ jj)H

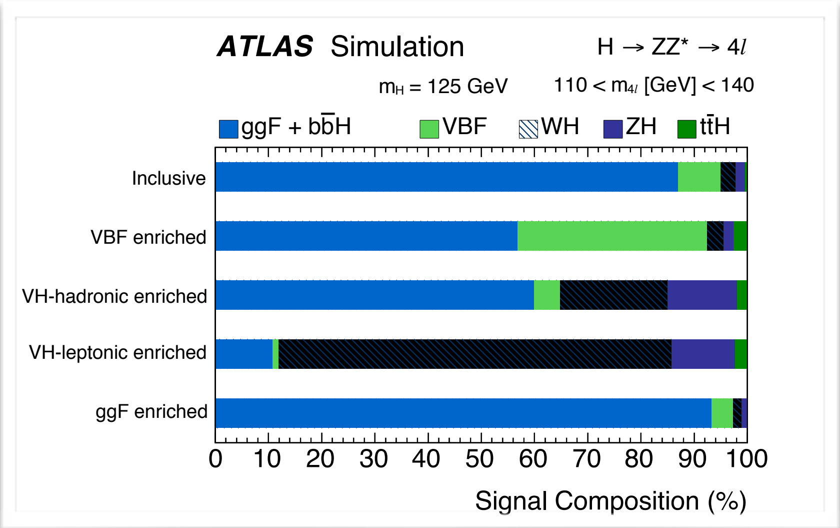
Additional lepton

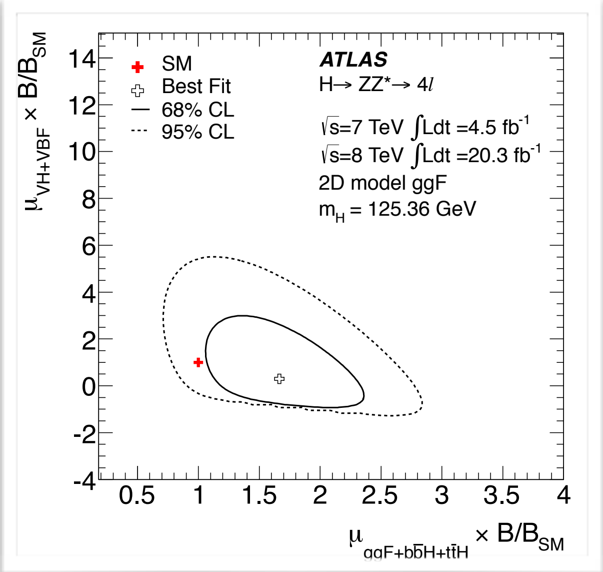
W(→ *l*ν)H, Z(→ *ll*)H

VH enriched

ggF

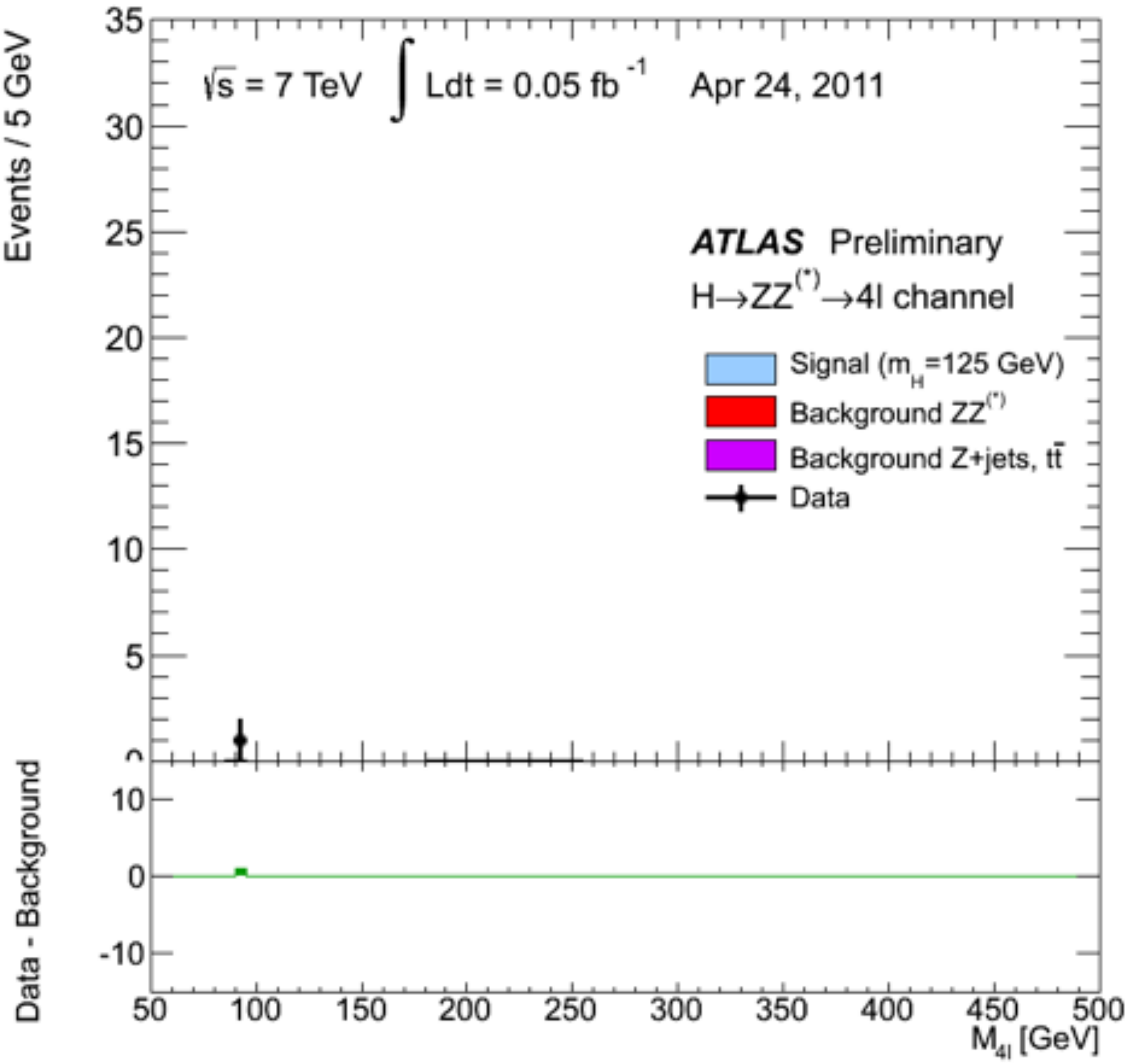
ggF enriched





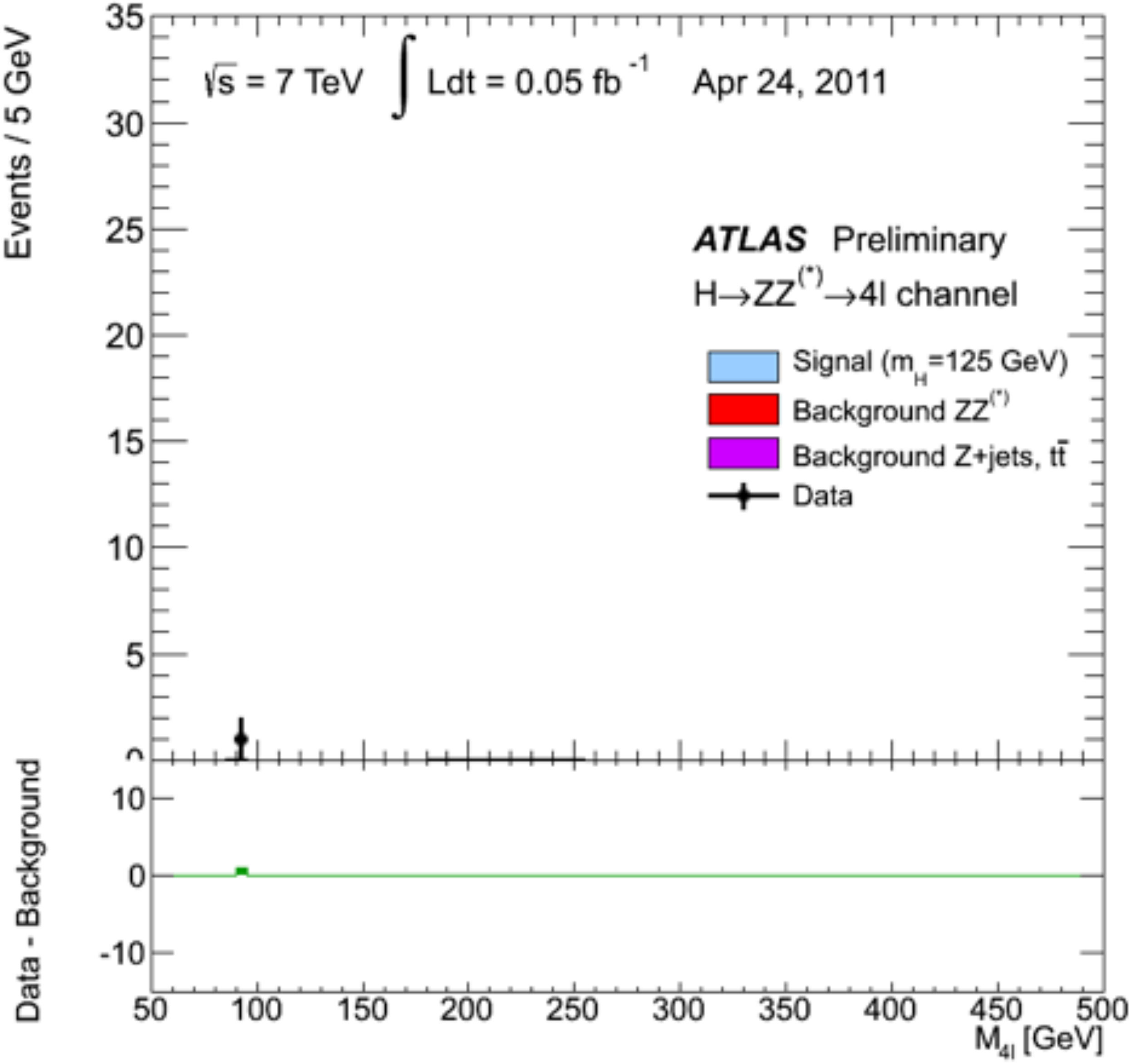
Limited by statistics so will improve quickly with more data

Higgs to 4 leptons (H→ZZ*→llll)



4 July 2012

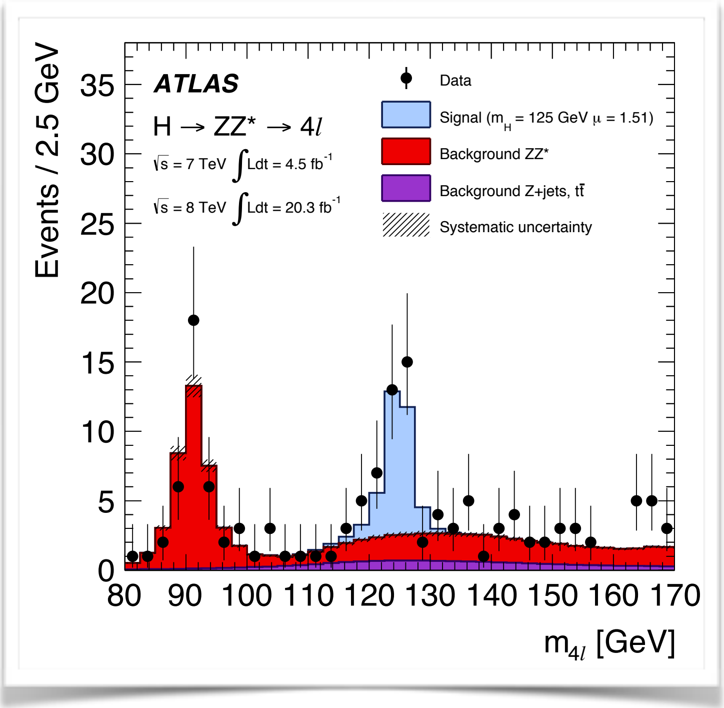
Higgs to 4 leptons (H→ZZ*→llll)

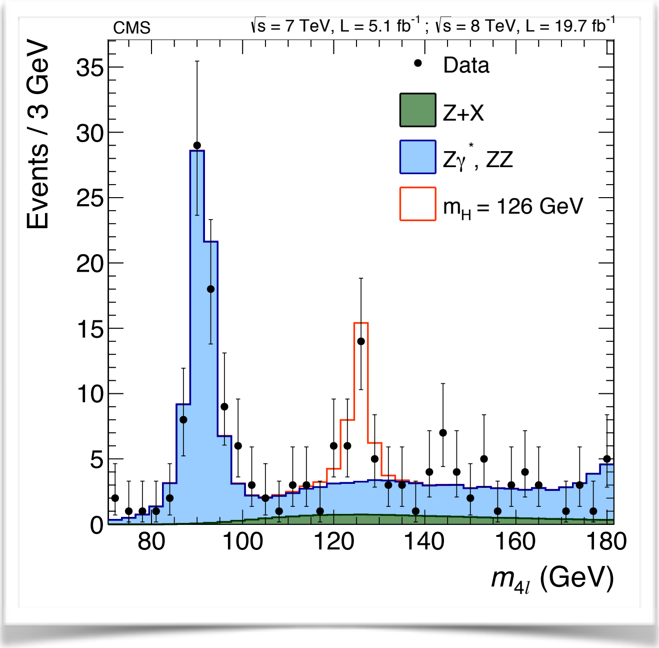


4 July 2012

Final Run-1 ZZ Results

HIG-13-002
HIGG-2013-21





$$\mu = 1.44^{+0.40}_{-0.33}$$

$$m_H = 125.4 \pm 0.27 \text{ GeV}$$

$$Z = 8.1(6.2)\sigma$$

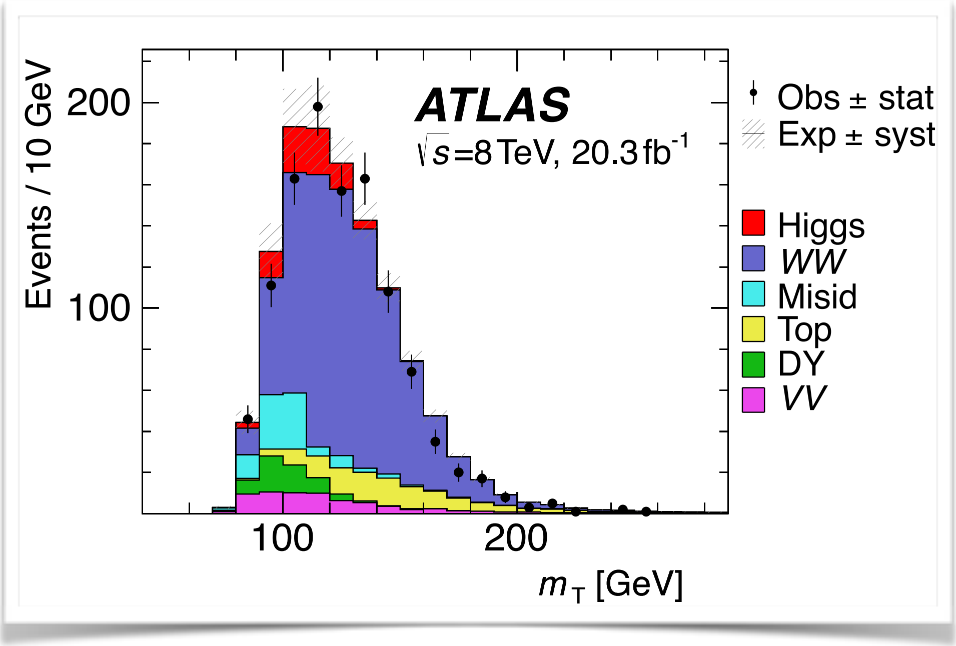
$$\mu = 0.93 \pm 0.29$$

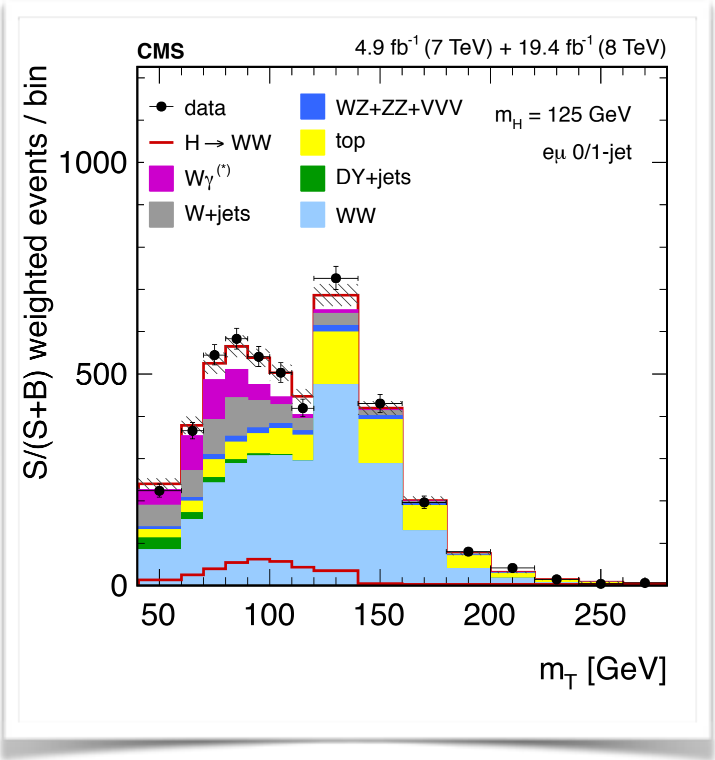
$$m_H = 125.6 \pm 0.45 \text{ GeV}$$

$$Z = 6.8(6.7)\sigma$$

H→WW

HIGG-2013-13
HIG-13-023





$$\mu = 1.22^{+0.23}_{-0.21}$$

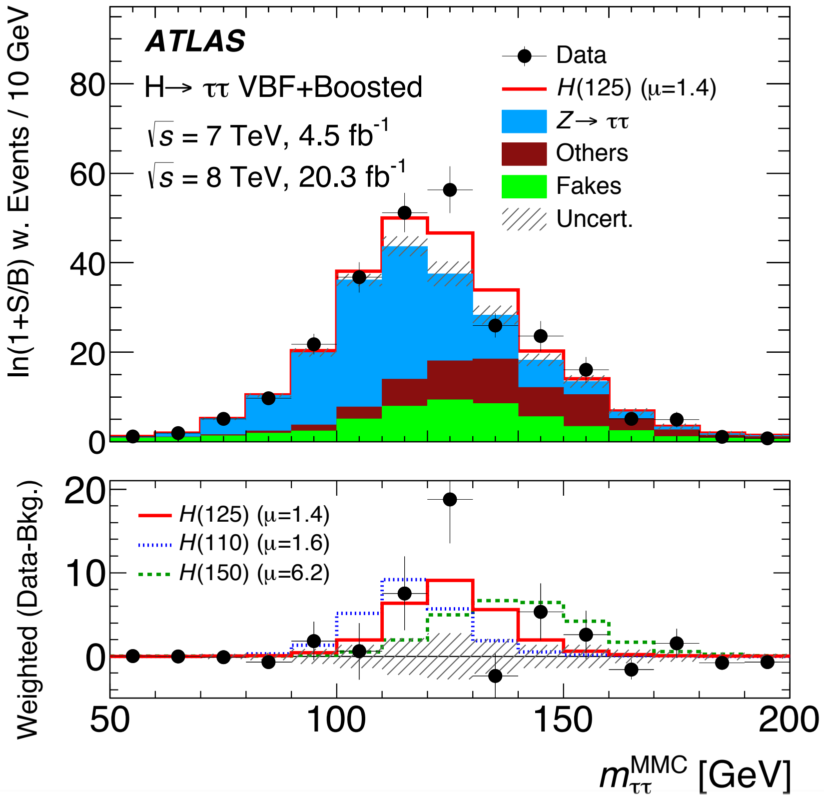
$$Z = 6.8(5.8)\sigma$$

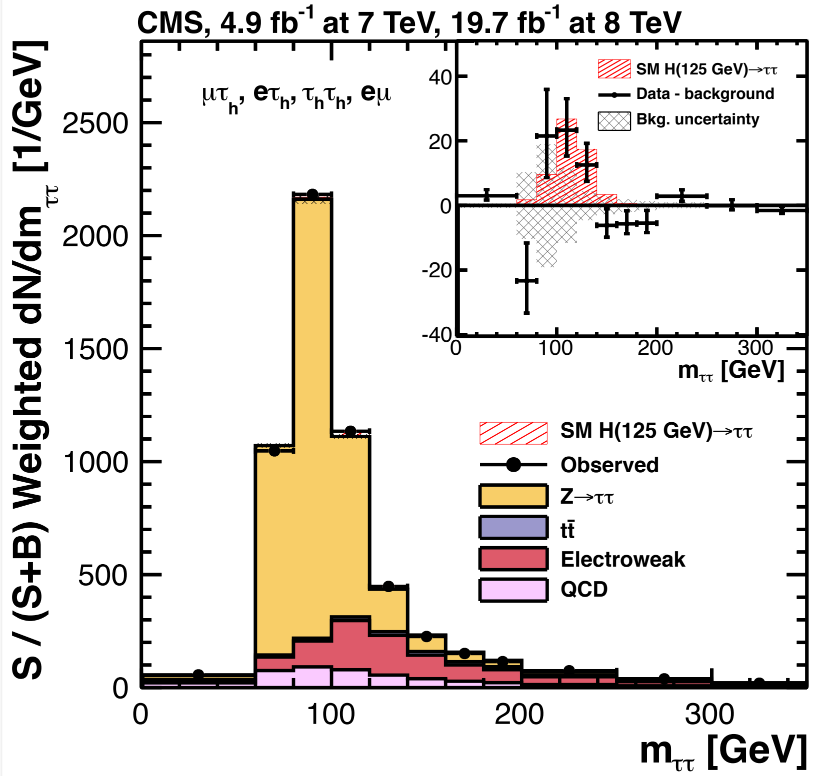
$$\mu = 0.90^{+0.23}_{-0.21}$$

$$Z = 4.8(5.6)\sigma$$

H→ττ

HIG-13-004
HIGG-2013-32





$$\mu = 1.41^{+0.40}_{-0.36}$$

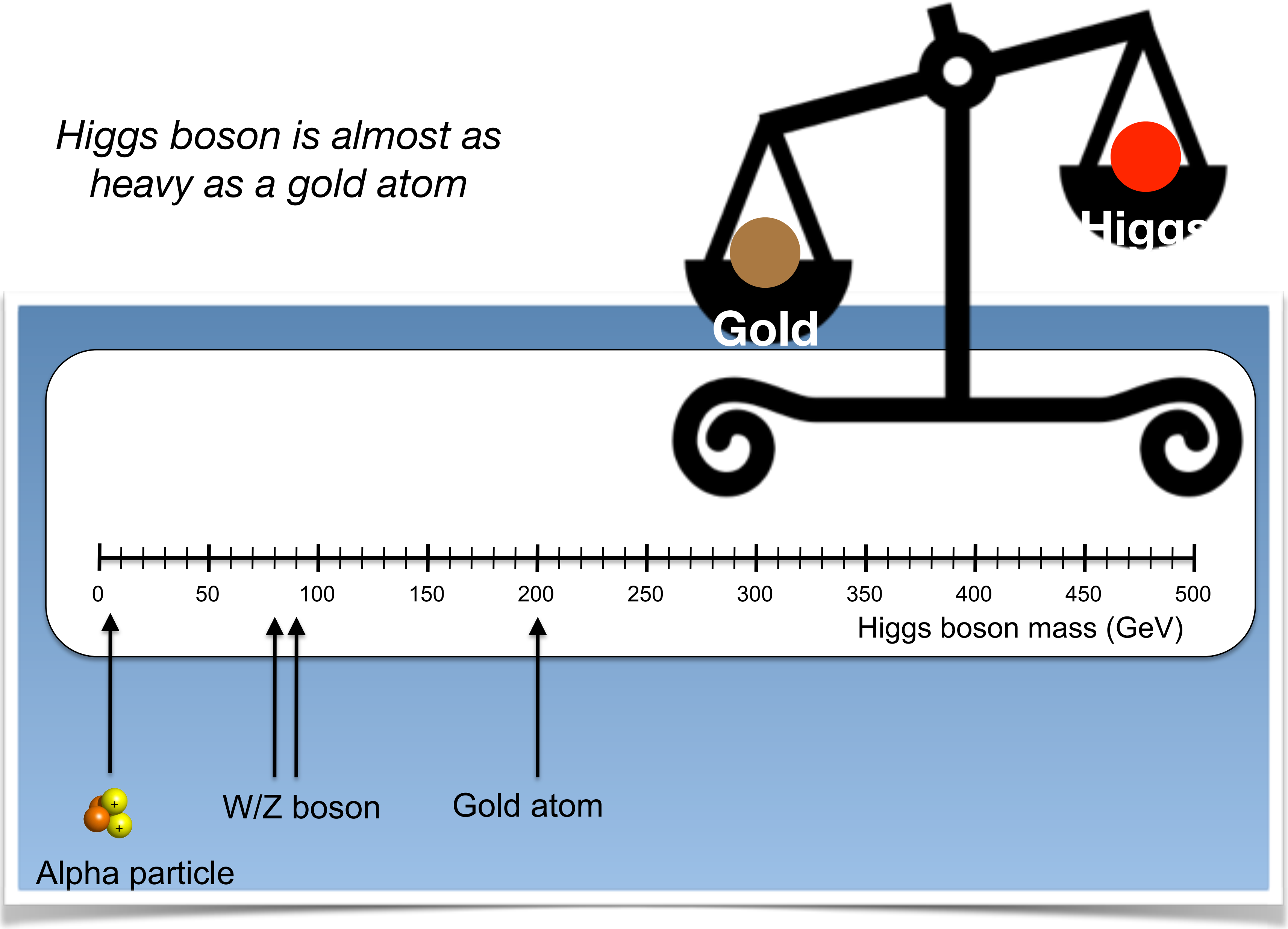
$$Z = 4.4(3.3)\sigma$$

$$\mu = 0.88^{+0.30}_{-0.28}$$

$$Z = 3.4(3.7)\sigma$$

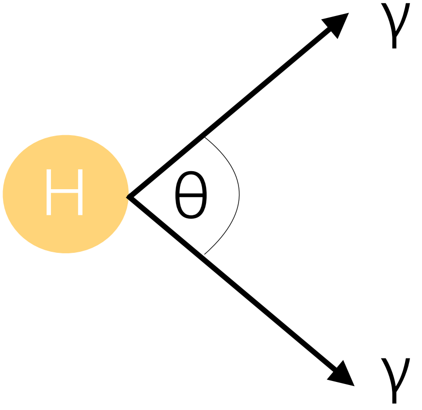
Mass

Higgs boson is almost as heavy as a gold atom



Measuring Particle Masses: An Example

- Higgs boson decays to photon 1 and photon 2
- Photons are reconstructed in the calorimeter
- Use the momentum (energy) of these photons to calculate the Higgs boson mass
- $(E, p_x, p_y, p_z) =$
  - $(|P_1|, p_{x1}, p_{y1}, p_{z1}) + (|P_2|, p_{x2}, p_{y2}, p_{z2})$
  - $= (|P_1| + |P_2|, p_{x1} + p_{x2}, p_{y1} + p_{y2}, p_{z1} + p_{z2})$



- Mass of Higgs boson: $m^2 = E^2 - p^2$
- Or $m^2 = 2|P^1||P^2| . (1 - \cos\theta)$

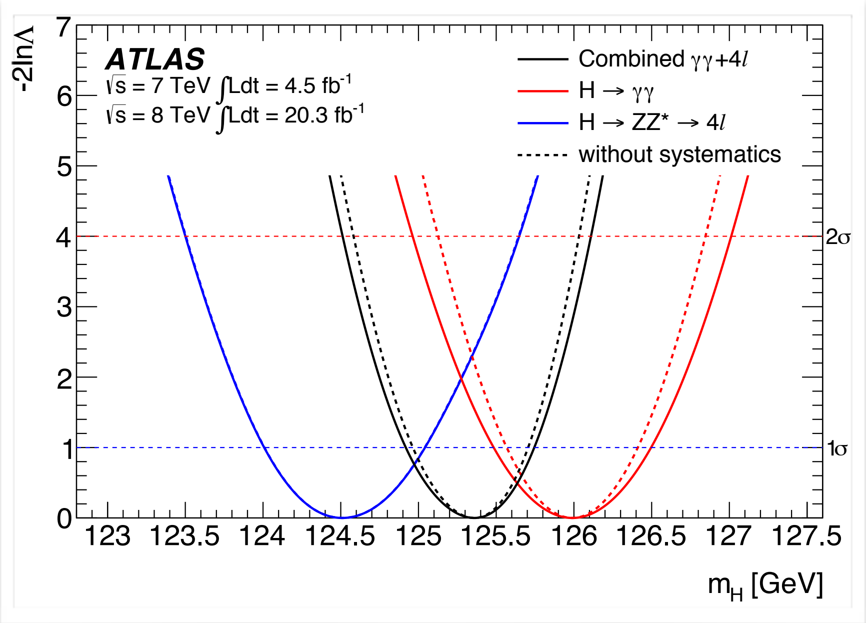
ATLAS Mass Measurement

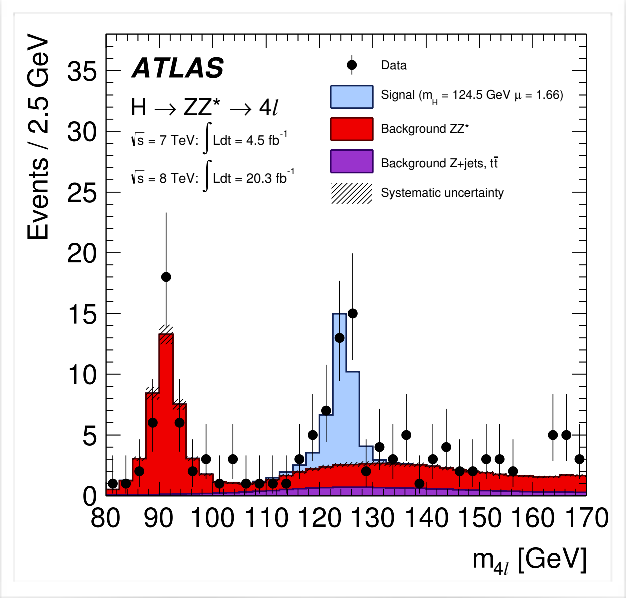
Phys. Rev. D. 90, 052004 (2014)

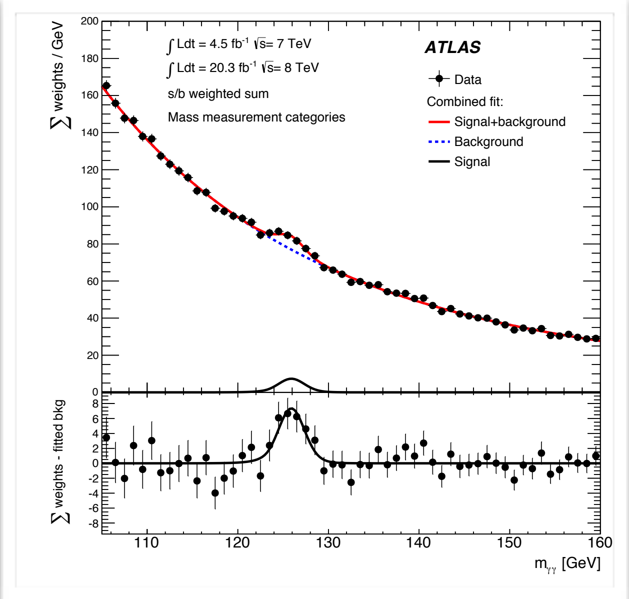
ZZ: 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV

γγ: 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

Combined: 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV







ATLAS Mass Measurement

Phys. Rev. D. 90, 052004 (2014)

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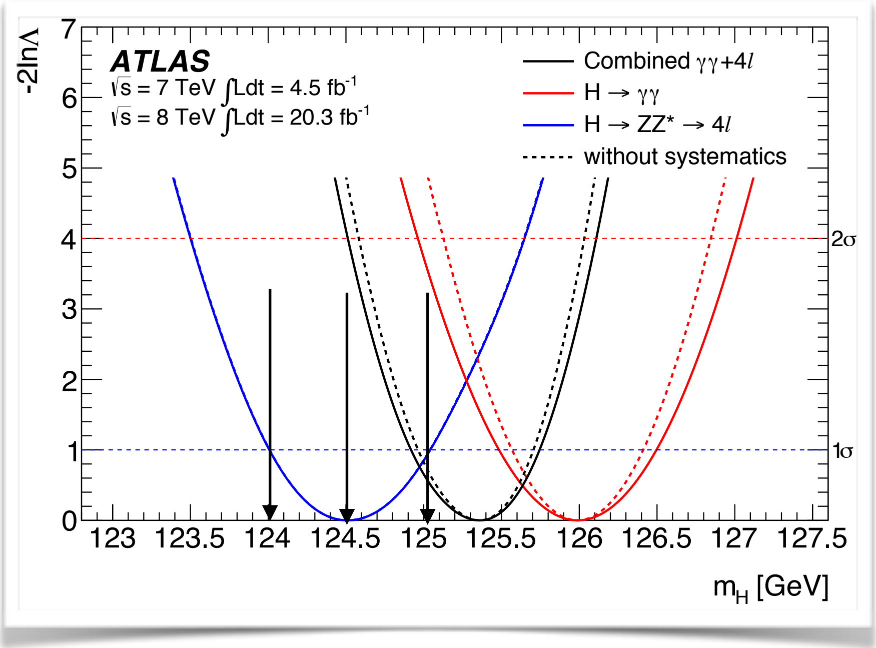
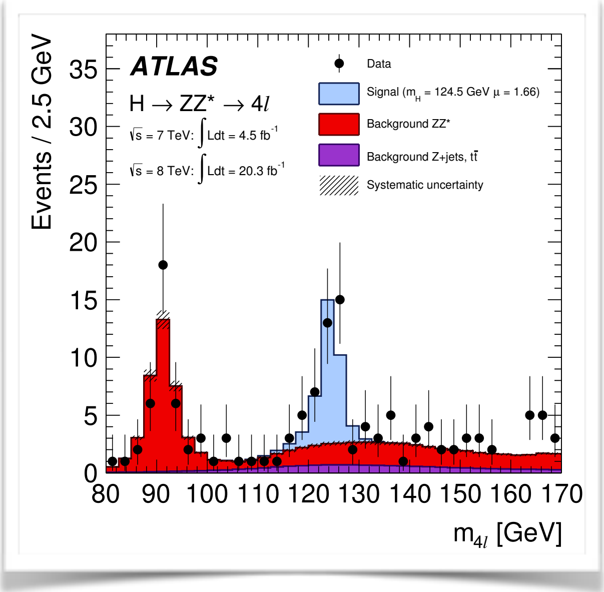
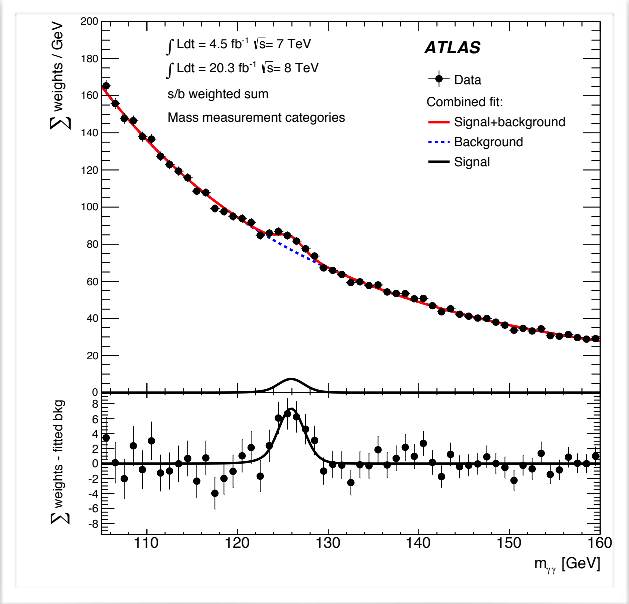
γγ: 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

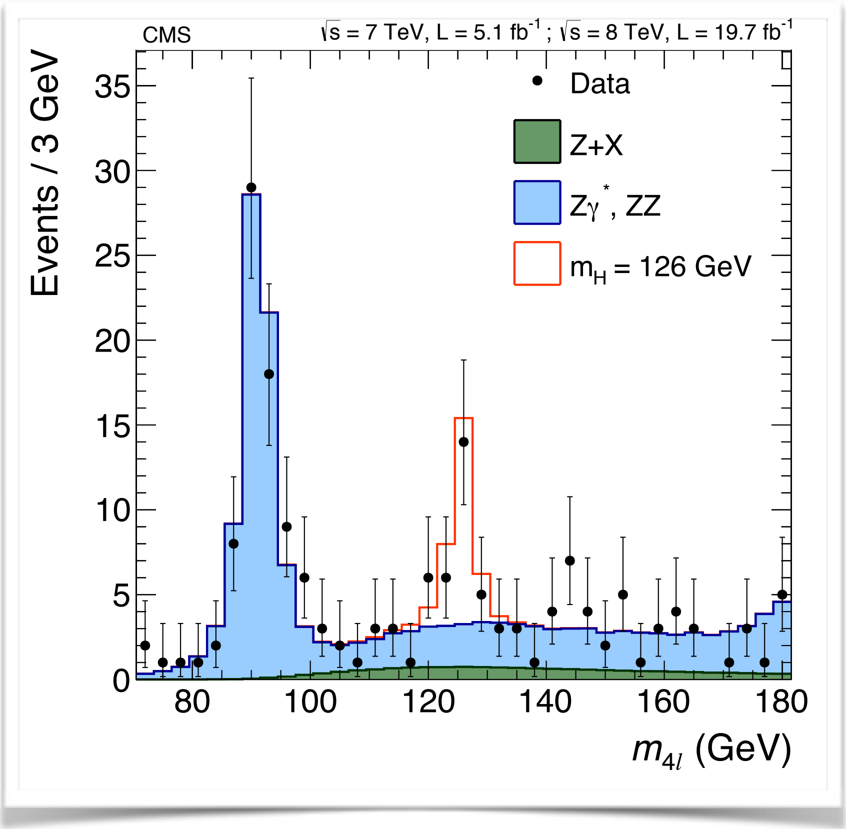
Combined: 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV

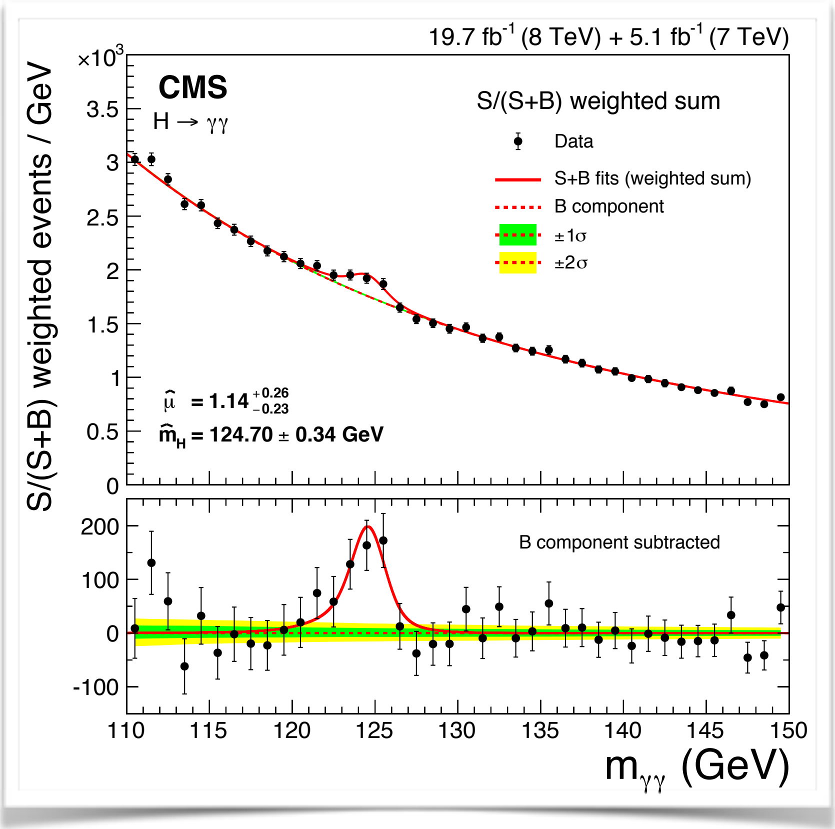






CMS Mass Measurement



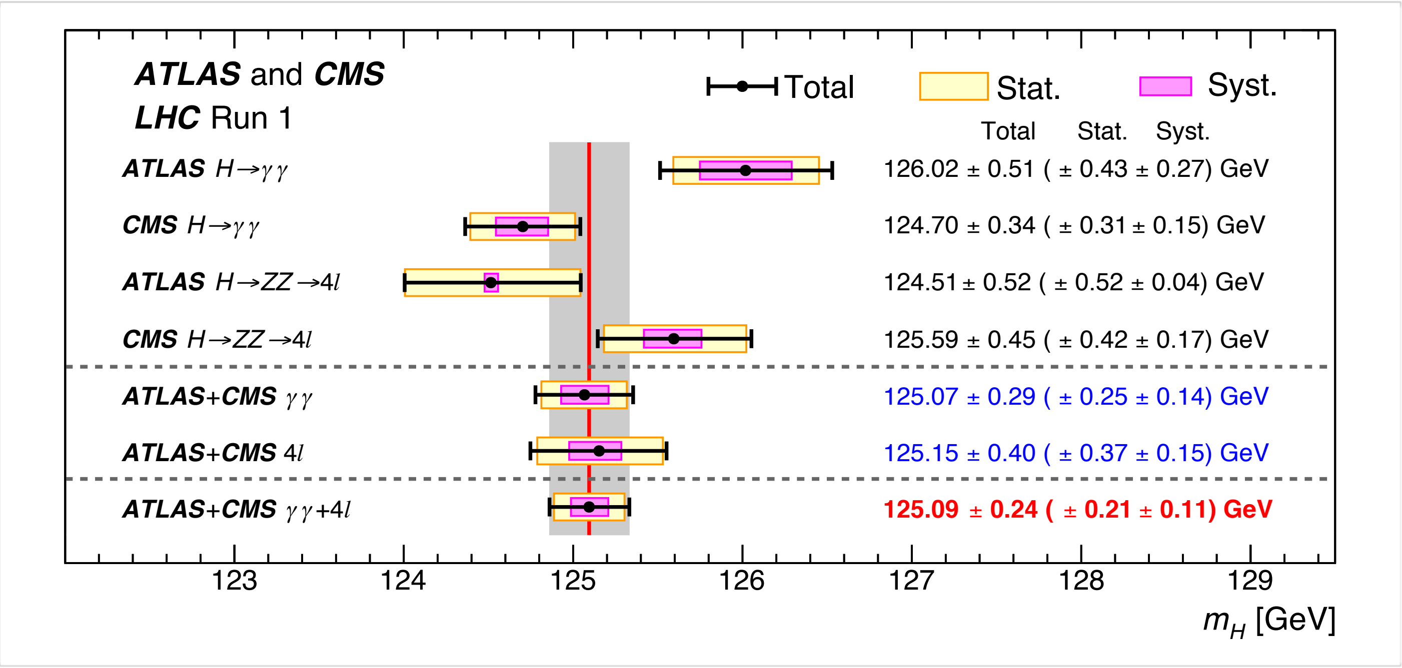


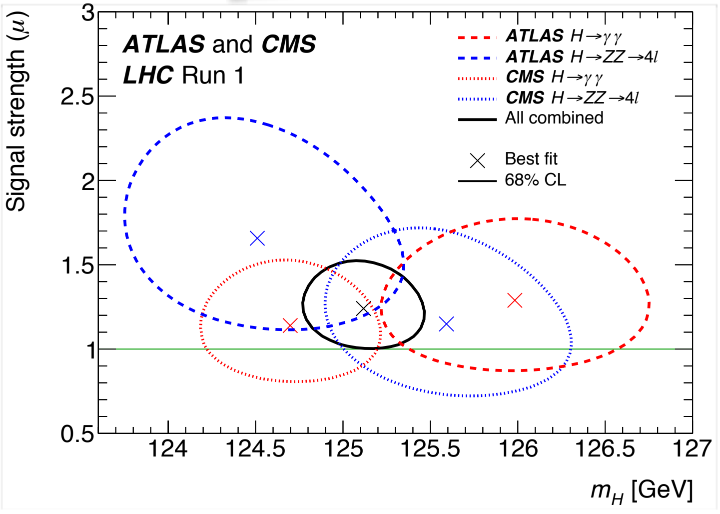
ZZ: 125.59 ± 0.42 (stat) ± 0.17 (syst) GeV

γγ: 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

Combined Higgs Mass Measurement

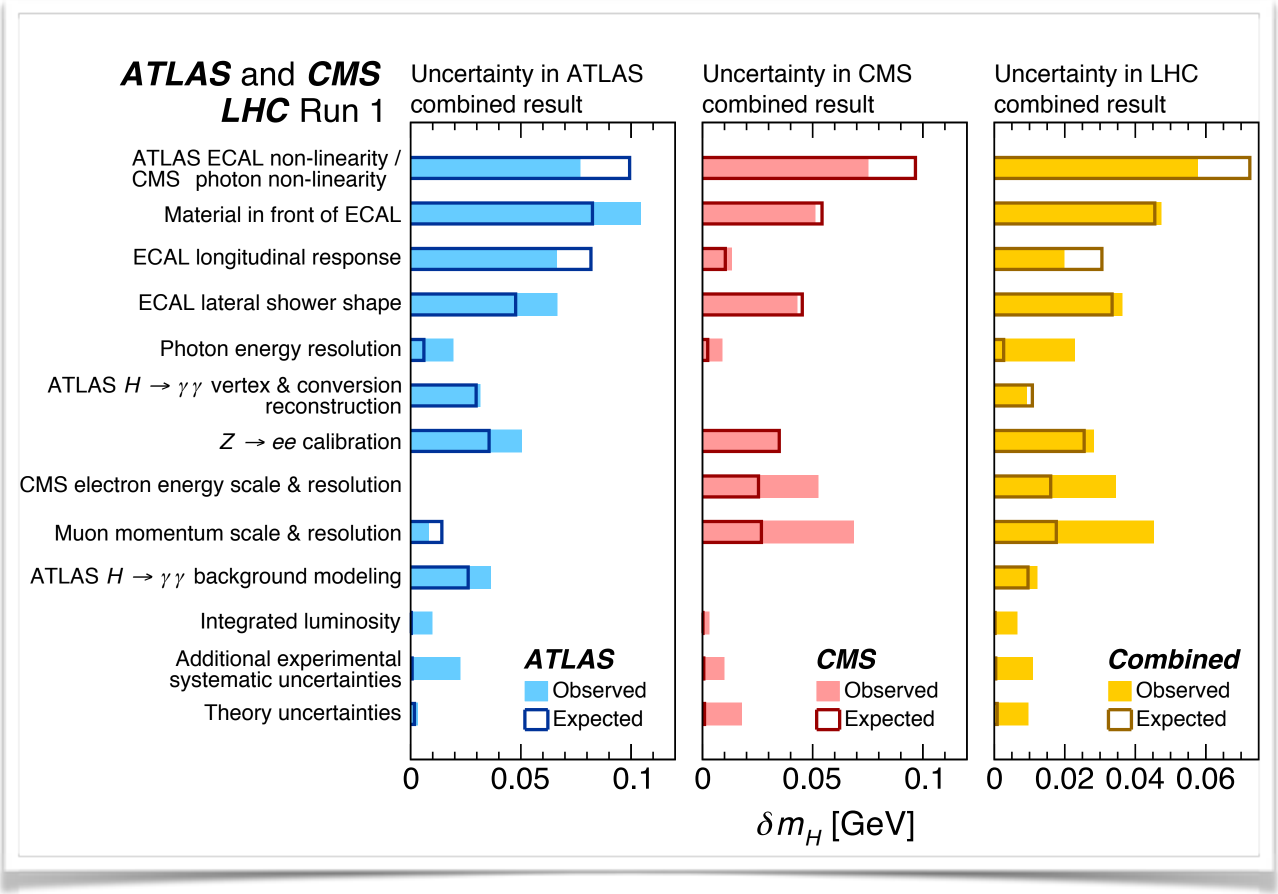
HIGG-2014-14





- Measurement dominated by statistics
- The compatibility of the four measurements is to within 10%
- Tension between ATLAS 4l and γγ ~2σ

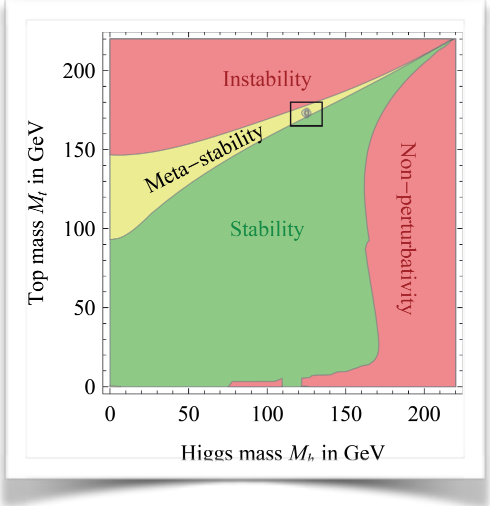
Uncertainties on the Mass Measurement

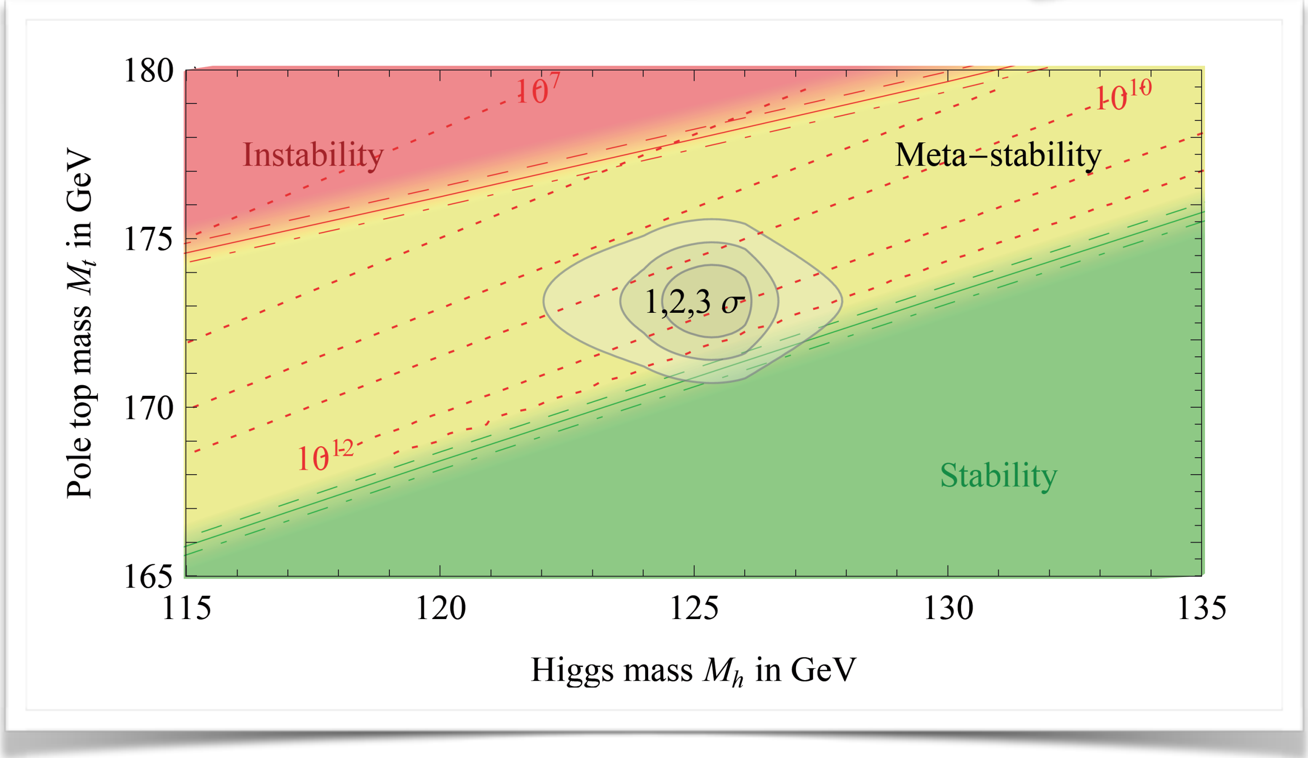


Largest systematic uncertainties are those from the calibration of the calorimeter

Mass Measurement Implications

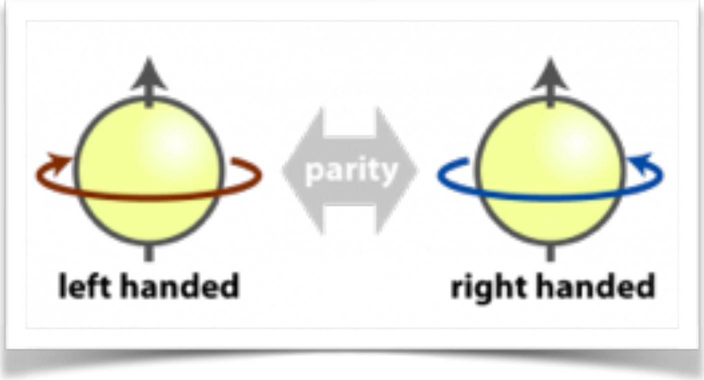
- m_H = 125 GeV → our universe lies on the boundary between instability and stability
- No need to panic: metastability means that the universe is unlikely to end tomorrow
    - But intriguing, nonetheless

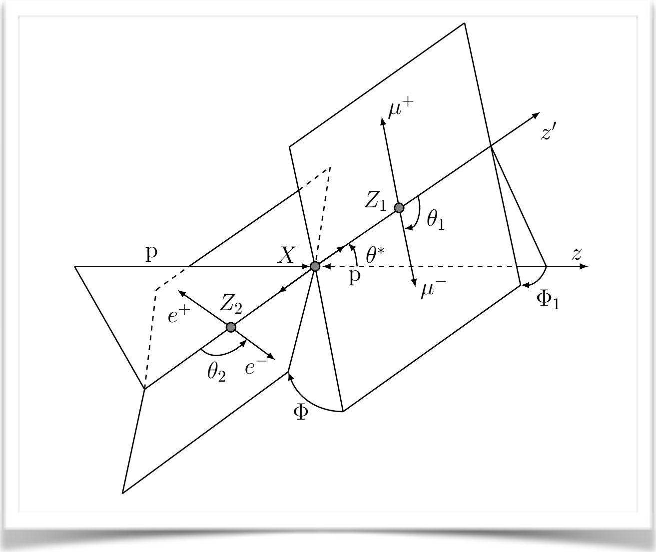




Spin/Parity

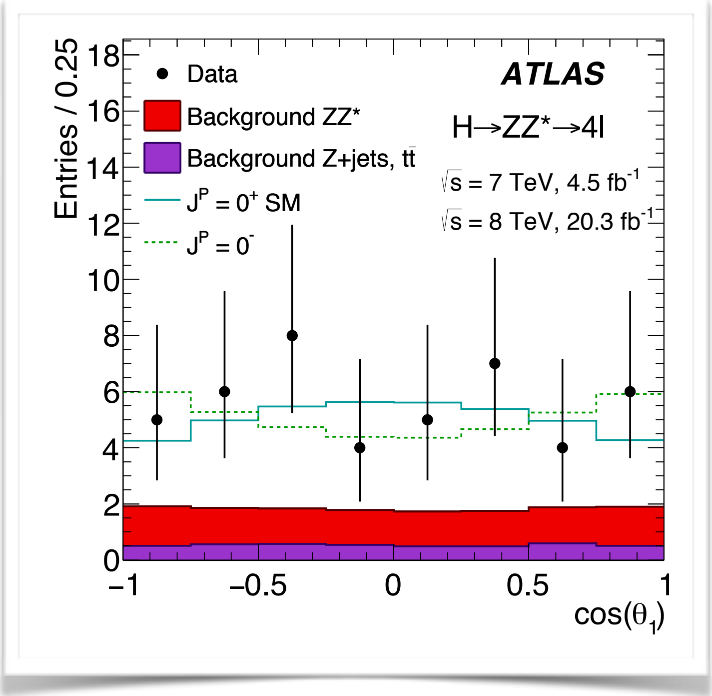
- Only elementary particle with spin-0
- Spin and parity determine angular distributions of decay products
  - Use γγ, ZZ and WW
- Don’t forget, though, that the γγ observation implies
  - does not originate from spin 1 : Landau-Yang theorem
  - charge conjugation is +1 (assuming C and P separately conserved)
  - WW/ZZ channels disfavour CP odd hypothesis (can occur through loops)

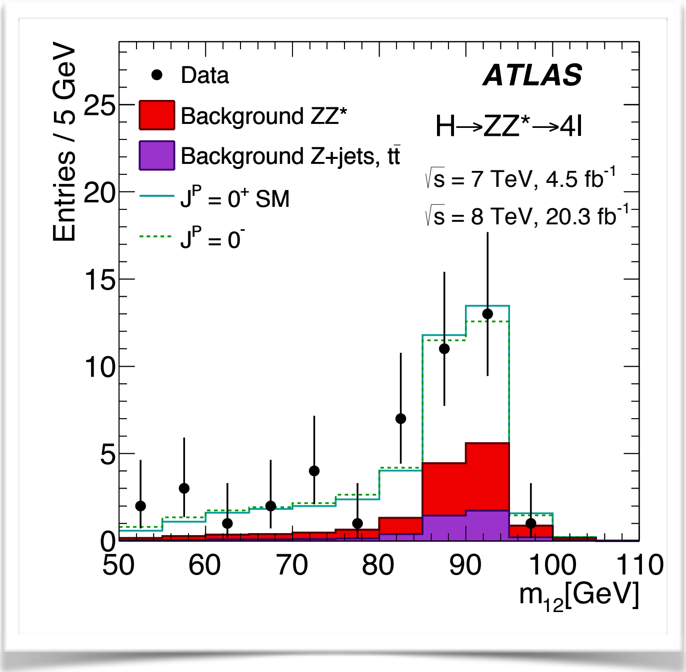




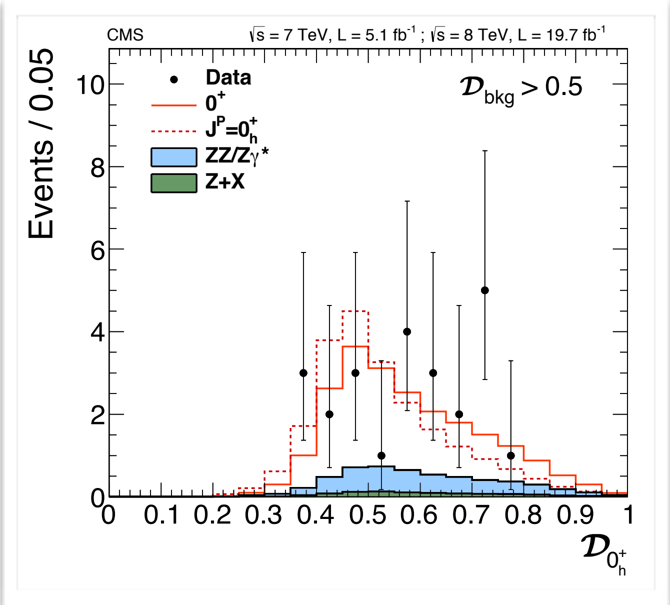
Variables sensitive to spin

HIG-13-002
HIGG-2013-17

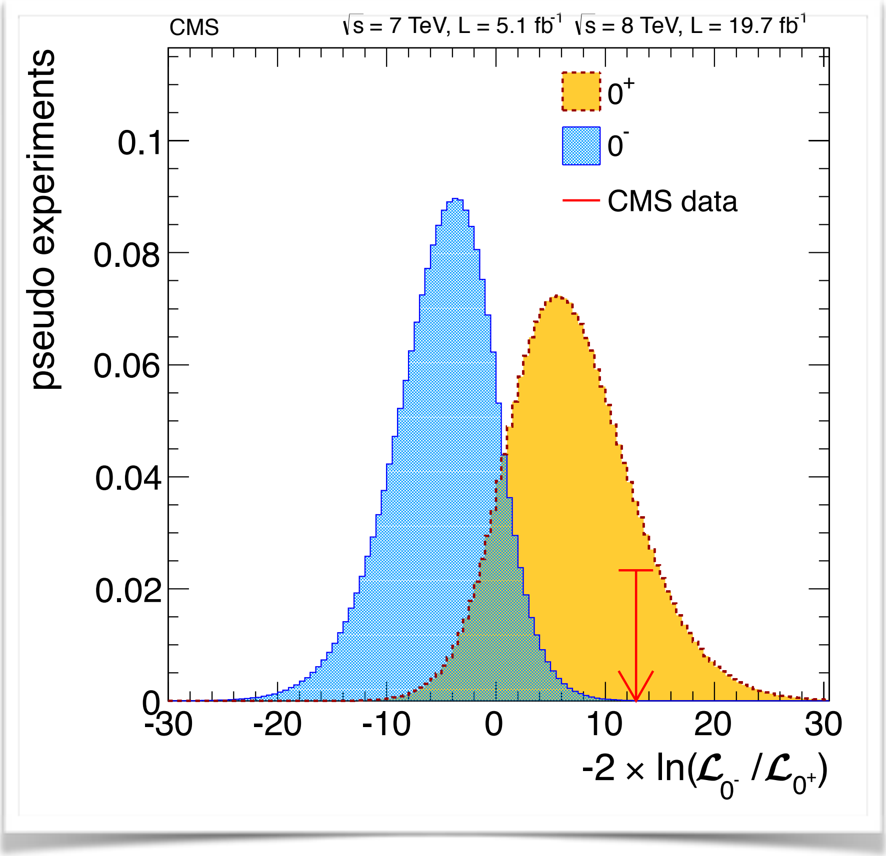


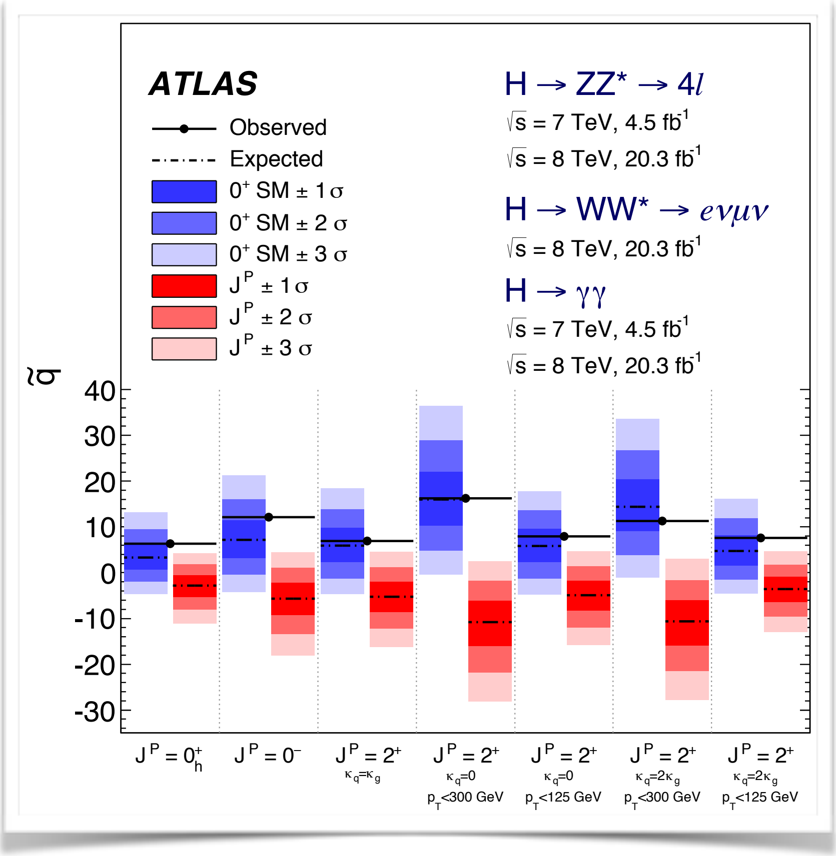


- Study a number of angular variables sensitive to spin and parity
- Combine into a single discriminant using an MVA or theory-based matrix element technique



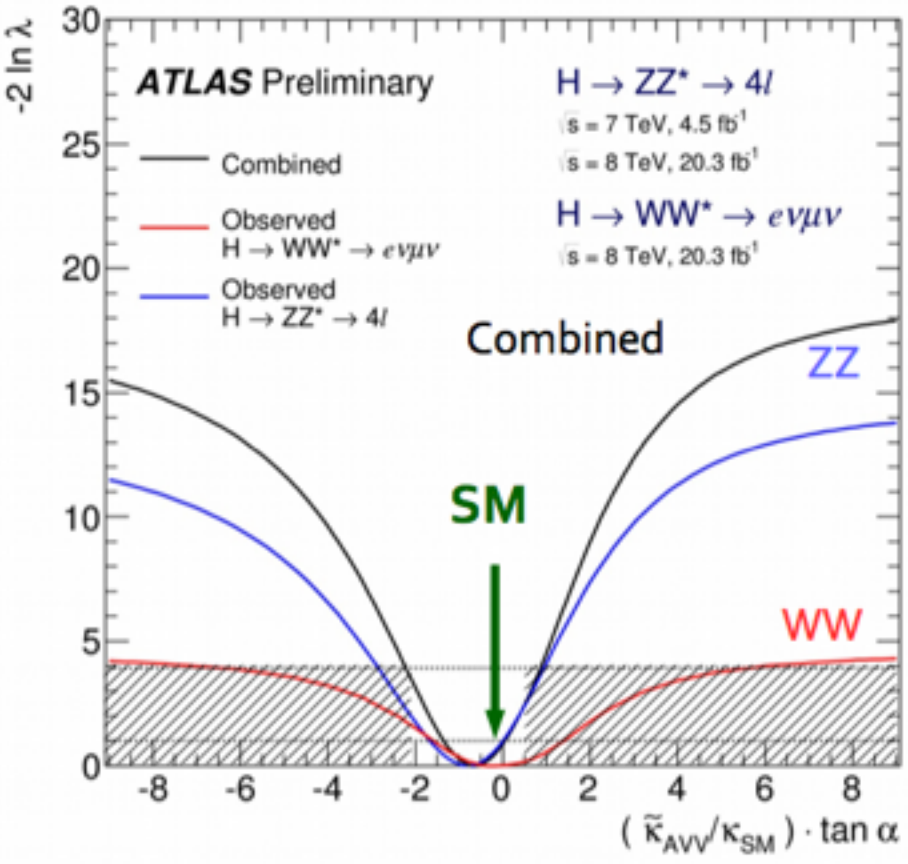
Spin/Parity Results

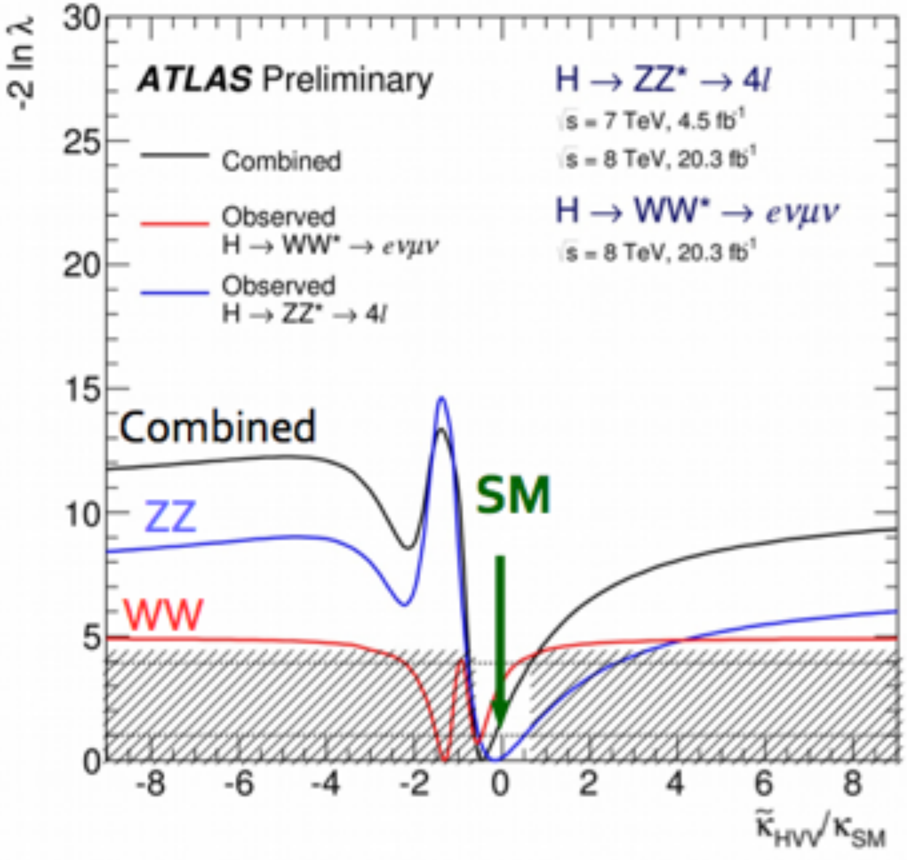




Strong evidence that the Higgs is 0+ as predicted by the Standard Model

CP Mixing

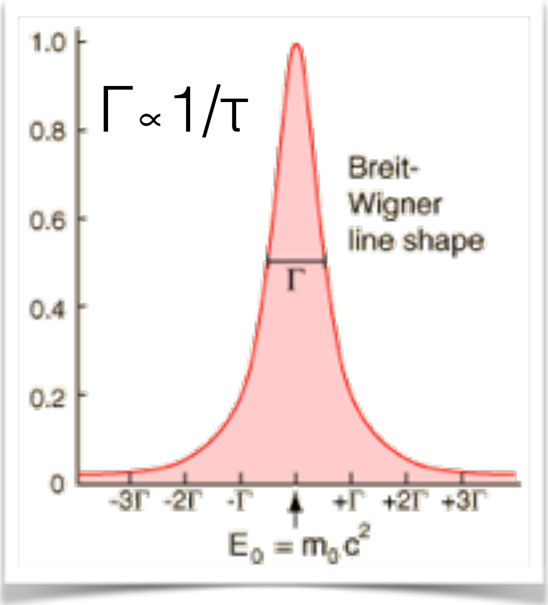


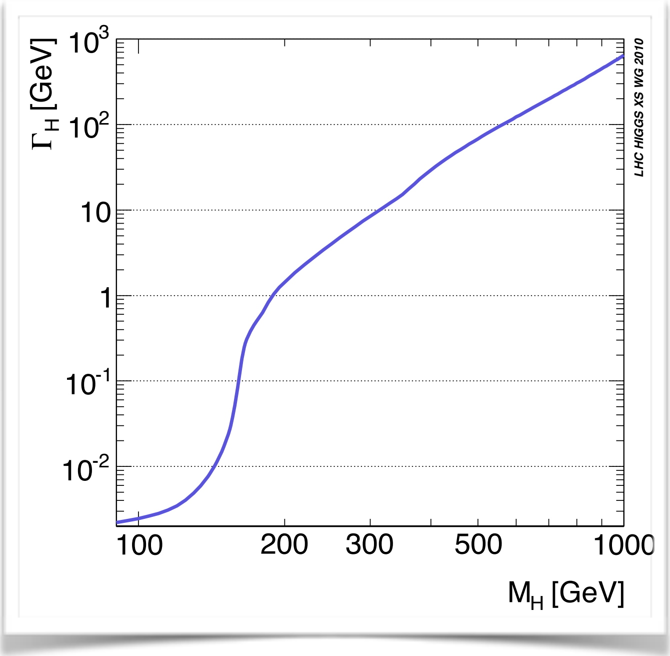


Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even

Width

- As an highly unstable elementary particle, the **lifetime** of the Higgs is **very short**
- For m_H = 125 GeV
    - Γ=4.07 x 10^{-3} GeV
- Direct experimental measurements probe widths **3 orders of magnitude larger** ~1.6 GeV (ATLAS, ZZ)
- Thought to be **impossible to measure the width** at a hadron collider





Off-shell Higgs Production

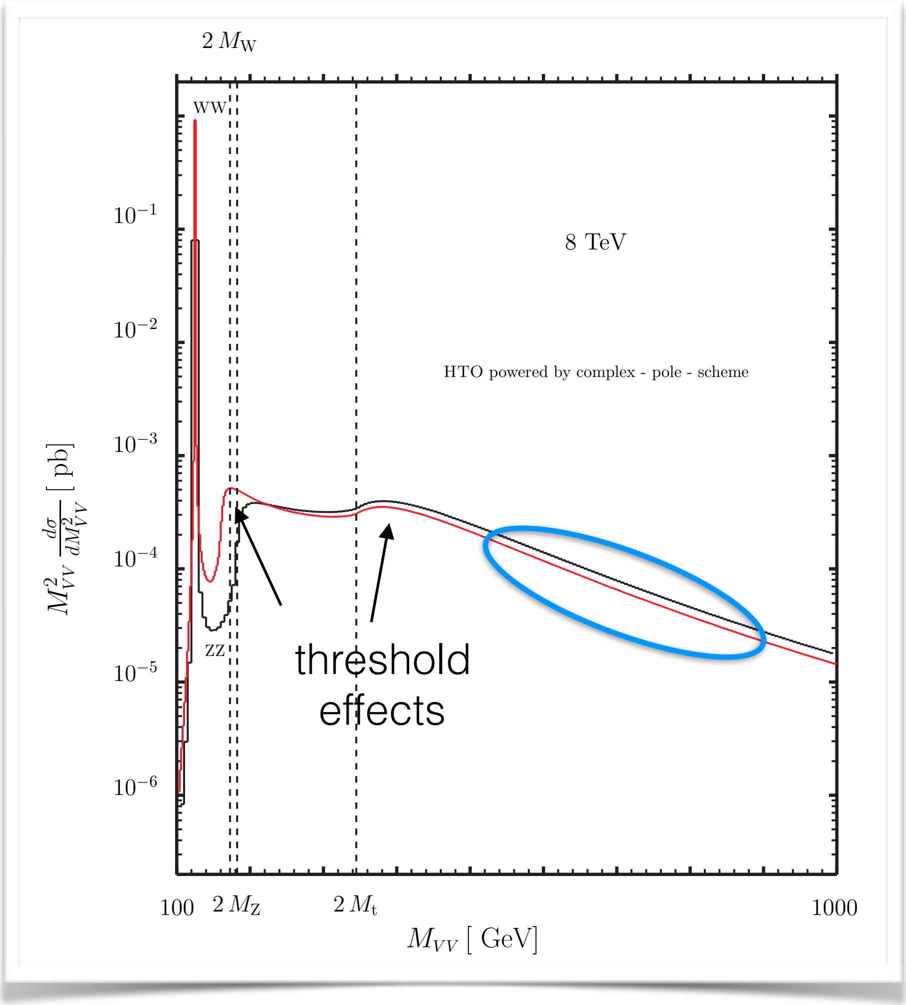
N. Kauer and G. Passarino, JHEP 08 (2012) 116

- A paper from Kauer and Passerino in 2012 pointed out a peculiar cancellation between the Breit-Wigner trend and the width as a function of m$_{VV}$ enhances the cross-section at high mass

$$\left(\frac{d\sigma}{dM_{VV}}\right)_{\rm ZWA} = \sigma_{H,\rm ZWA}\,\frac{M_H\Gamma_H}{\pi}\,\frac{2M_{VV}}{\left(M_{VV}^2-M_H^2\right)^2+(M_H\Gamma_H)^2}\,.$$

- For ZZ, ~7.6% of the total cross-section is at high mass

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6



threshold effects

Measuring the Width

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024)
J. Campbell et al. (arXiv:1311.3589)

- This can be used to set a constraint on the Higgs width as follows

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \mathrm{BR})_{\mathrm{SM}} \equiv \boxed{\mu}(\sigma\cdot \mathrm{BR})_{\mathrm{SM}}$$

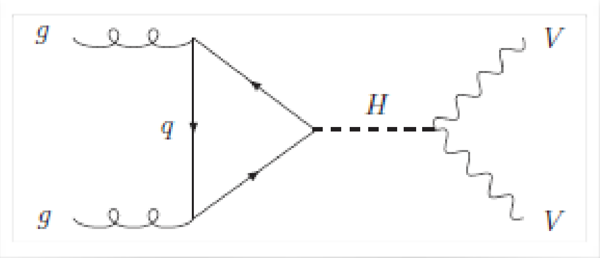
$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \boxed{\kappa_g^2\kappa_Z^2}\,\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} \equiv \boxed{\mu r}\,\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{\mathrm{SM}}_{ggH}$$

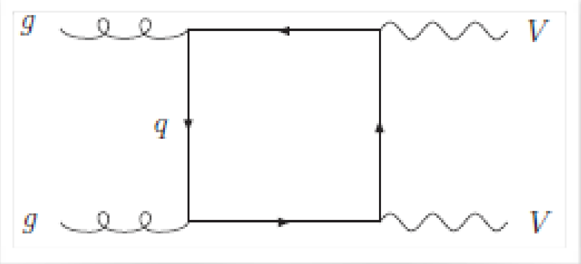
$$\kappa_Z = g_{HZZ}/g^{\mathrm{SM}}_{HZZ}$$

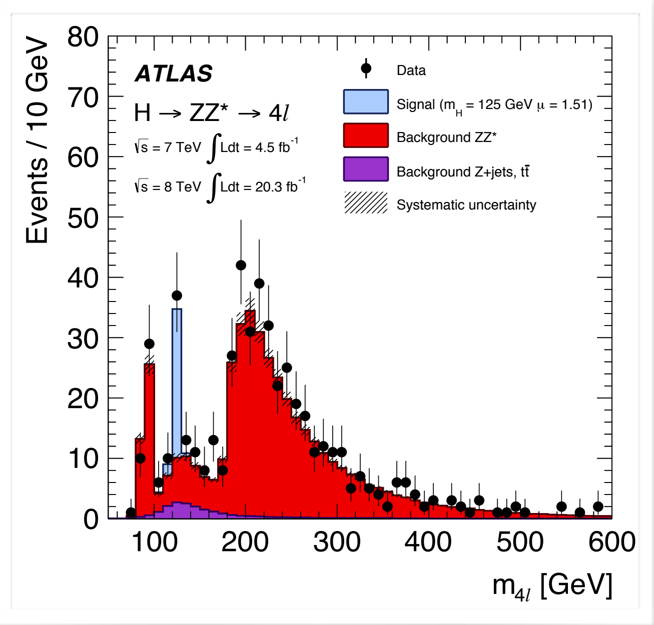
$$\boxed{r = \Gamma_H/\Gamma_H^{\mathrm{SM}}}$$

- Determine r by measuring ratio of off-peak to on-peak cross-section



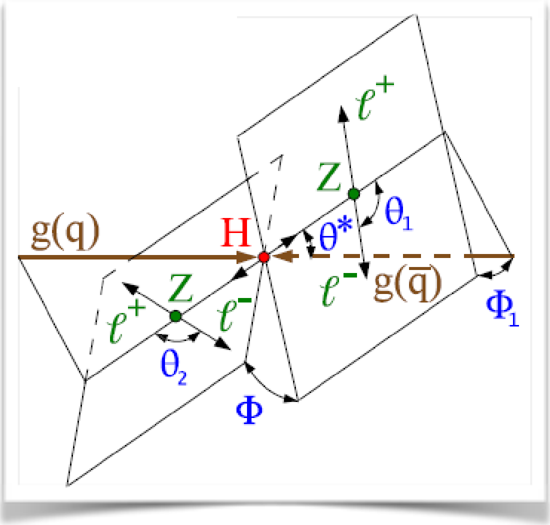
Significant interference with the SM VV background at high mass

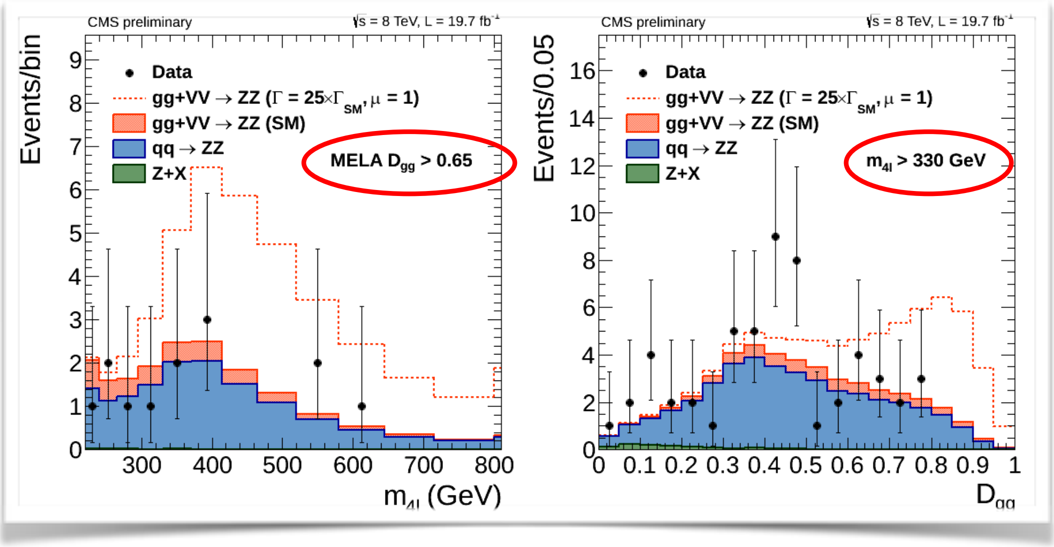


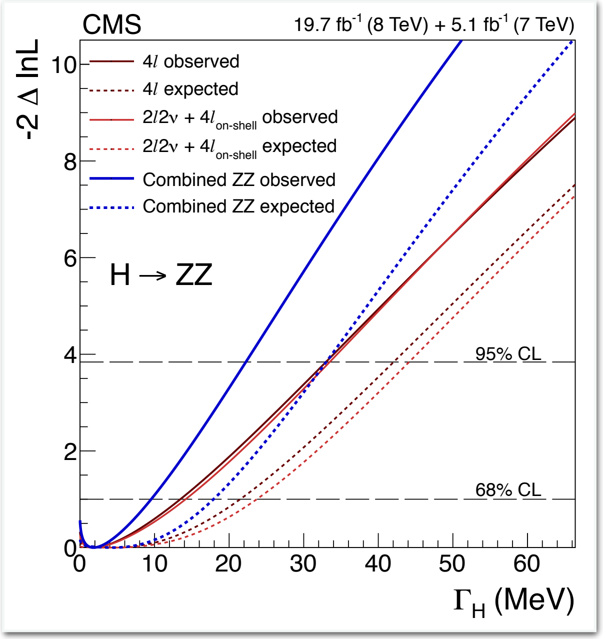


CMS measurement of the width

- First measured by CMS (Moriond 2014) using the 4l and 2l2v using a matrix element likelihood approach (MELA)
- Combined observed (expected) values
  - r < 4.2 (8.5) @ 96% CL
  - Γ < 17.4 (35.3) MeV)
- Two orders of magnitude better than direct measurements



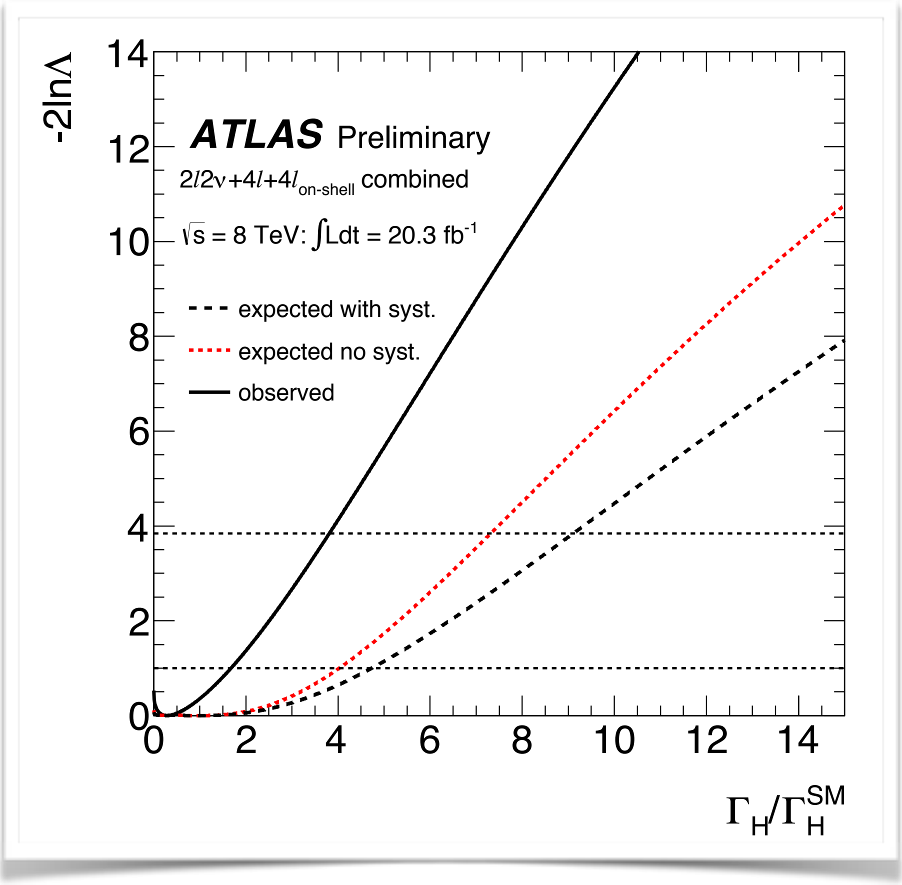


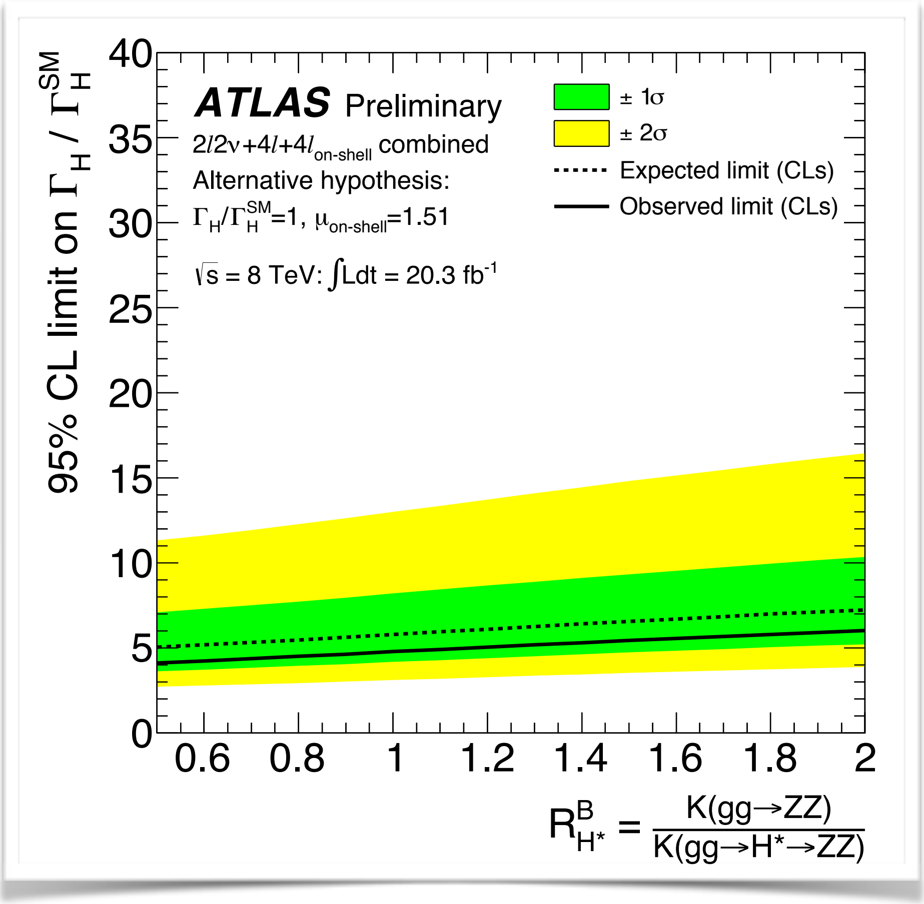


ATLAS width result

ATLAS-CONF-2014-042

- Similar result from ATLAS during 2014
- Additionally, showed the dependence on the k-factor for the ZZ background
    - No strong dependence observed





Couplings Combination

Combinations

- As we've only seen a small* amount of data from the LHC so far, we want to combine the results from ATLAS and CMS so that we get the most accurate measurements

$$\mu = 1.20 \pm 0.15 \qquad\qquad \mu = 0.97 \pm 0.14$$

Average: 1.08

But wait, what about the errors?

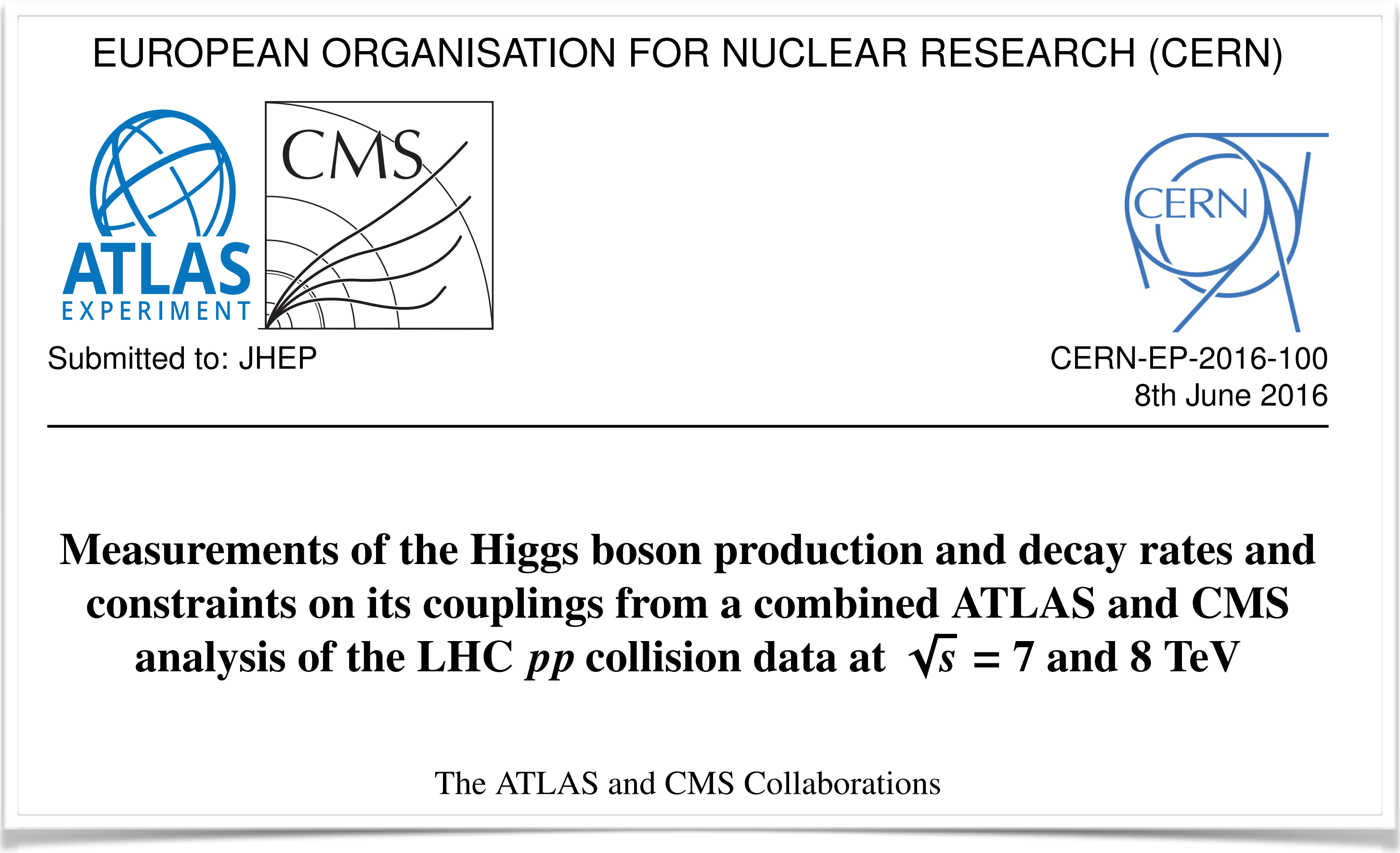
$$\bar{x} = \frac{\sum_{i=1}^{n} x_i \sigma_i^{-2}}{\sum_{i=1}^{n} \sigma_i^{-2}}$$

Weighted average: 1.07

Perhaps some of the errors should be correlated? e.g. the theoretical uncertainties

Full combination

2 years?



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

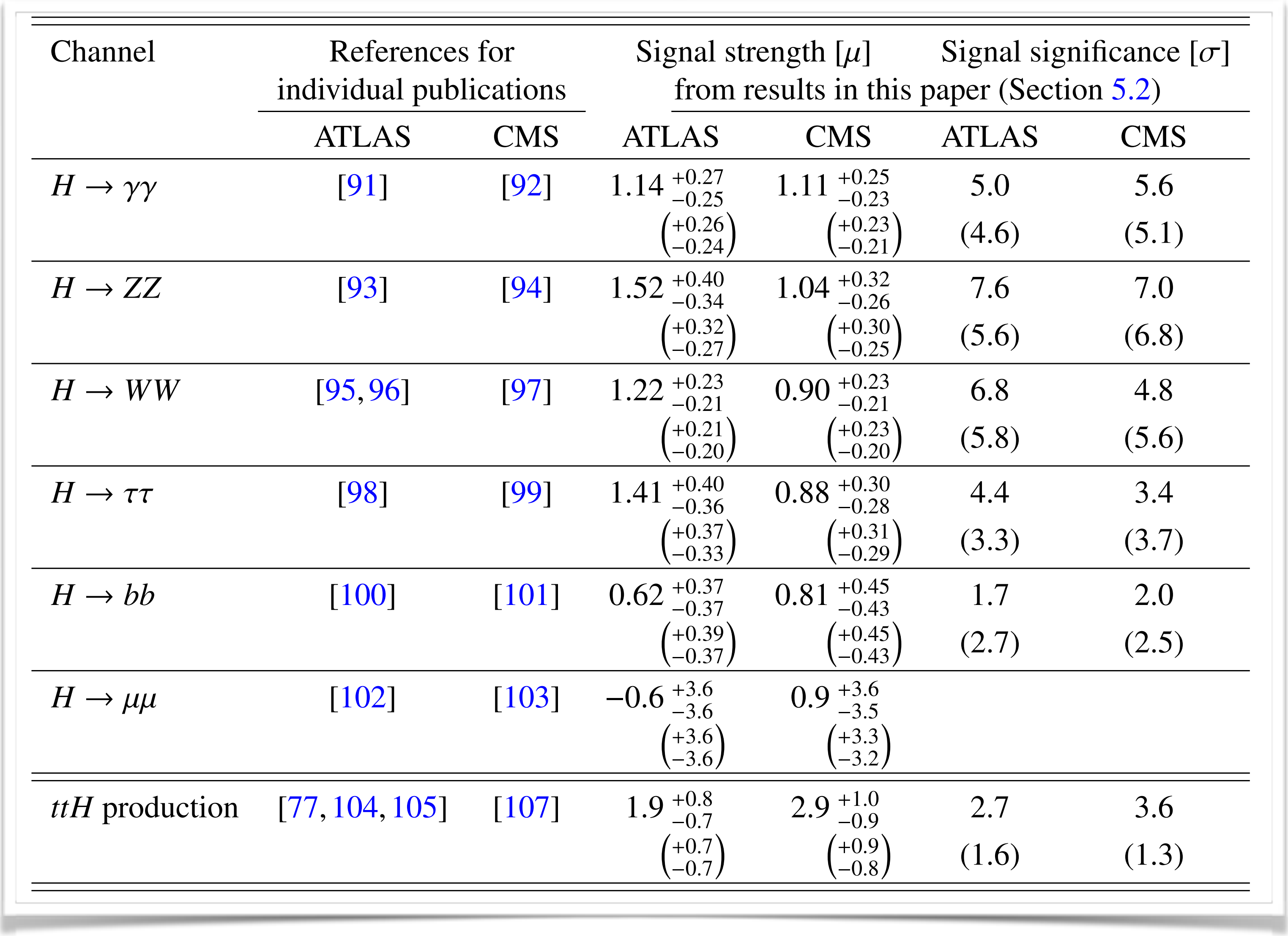
Submitted to: JHEP

CERN-EP-2016-100
8th June 2016

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV

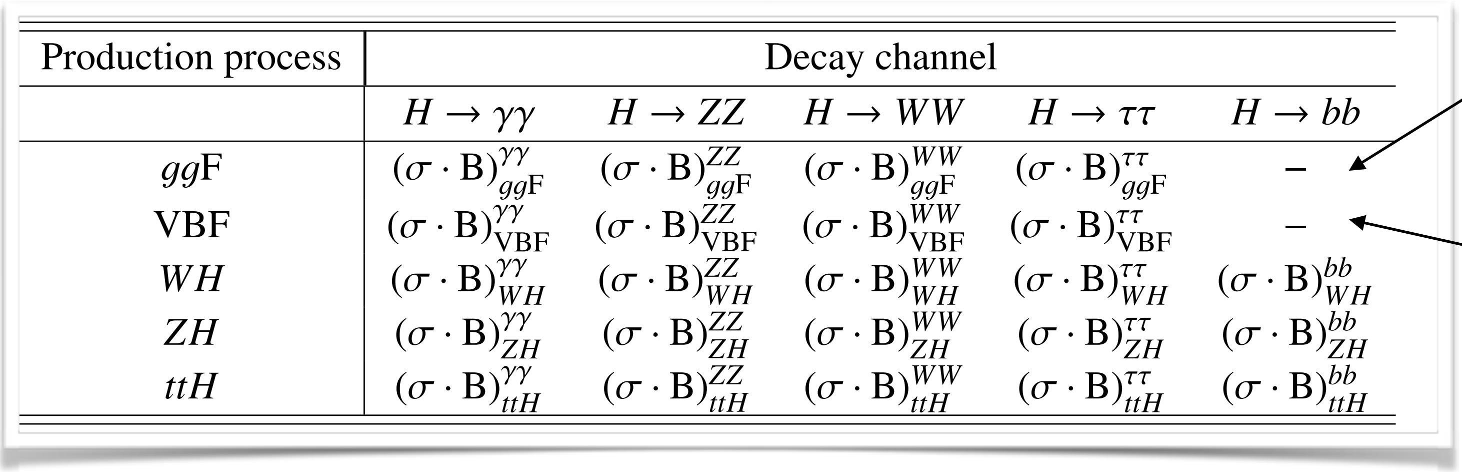
The ATLAS and CMS Collaborations

Combination Inputs



Channel	References for individual publications		Signal strength [μ]		Signal significance [σ]	
			from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[91]	[92]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95, 96]	[97]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77, 104, 105]	[107]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)

No theory assumptions, independent



Production process	Decay channel				
	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$(\sigma \cdot B)^{\gamma\gamma}_{ggF}$	$(\sigma \cdot B)^{ZZ}_{ggF}$	$(\sigma \cdot B)^{WW}_{ggF}$	$(\sigma \cdot B)^{\tau\tau}_{ggF}$	–
VBF	$(\sigma \cdot B)^{\gamma\gamma}_{VBF}$	$(\sigma \cdot B)^{ZZ}_{VBF}$	$(\sigma \cdot B)^{WW}_{VBF}$	$(\sigma \cdot B)^{\tau\tau}_{VBF}$	–
WH	$(\sigma \cdot B)^{\gamma\gamma}_{WH}$	$(\sigma \cdot B)^{ZZ}_{WH}$	$(\sigma \cdot B)^{WW}_{WH}$	$(\sigma \cdot B)^{\tau\tau}_{WH}$	$(\sigma \cdot B)^{bb}_{WH}$
ZH	$(\sigma \cdot B)^{\gamma\gamma}_{ZH}$	$(\sigma \cdot B)^{ZZ}_{ZH}$	$(\sigma \cdot B)^{WW}_{ZH}$	$(\sigma \cdot B)^{\tau\tau}_{ZH}$	$(\sigma \cdot B)^{bb}_{ZH}$
ttH	$(\sigma \cdot B)^{\gamma\gamma}_{ttH}$	$(\sigma \cdot B)^{ZZ}_{ttH}$	$(\sigma \cdot B)^{WW}_{ttH}$	$(\sigma \cdot B)^{\tau\tau}_{ttH}$	$(\sigma \cdot B)^{bb}_{ttH}$

No measurement

Insufficient precision

Take SM values

23 parameter fit

Only quote results of 20 parameters: ZH/WH and ttH have too low sensitivity

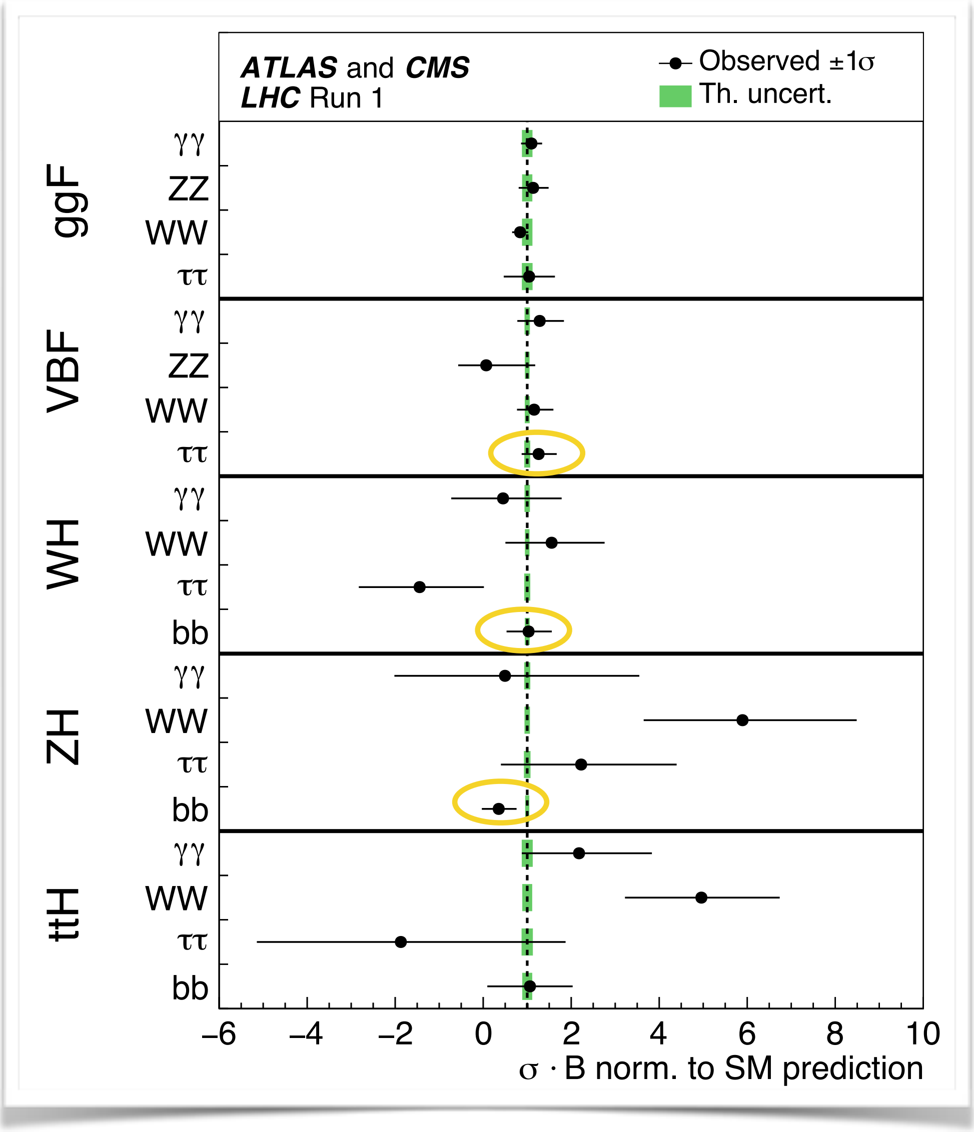
Independent cross-section and BR Results

Very generic: assume all cross-sections and BR to be independent

SM Higgs @ 1
No Higgs @ 0

Very good agreement

Larger errors, typically agreement at the 1 and 2σ level

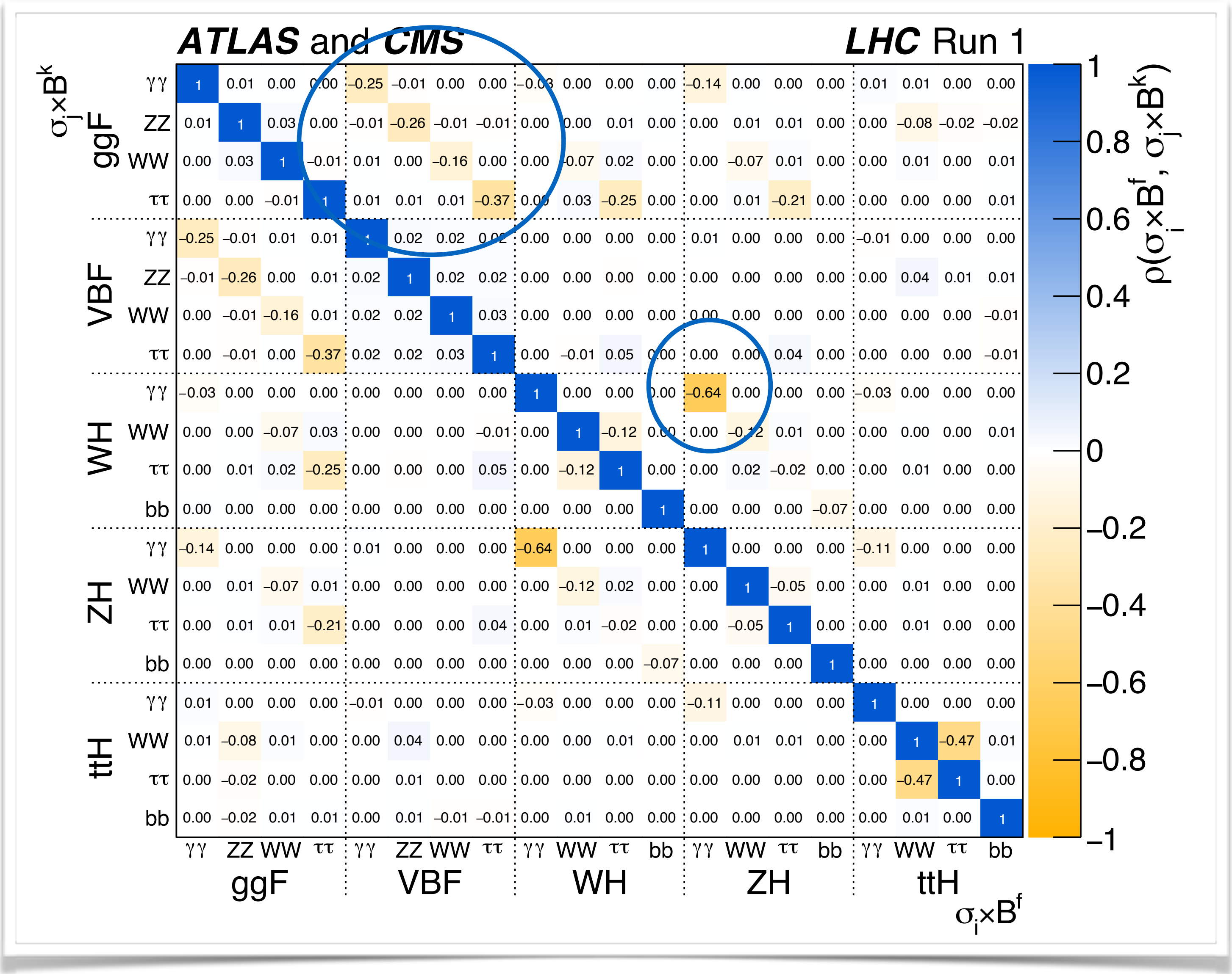


Statistical +systematic uncertainty as error bars

Very large scale!

Correlations

Significant anti-correlations



$\sigma_j \times B^k$ \ $\sigma_i \times B^f$	ggF γγ	ggF ZZ	ggF WW	ggF ττ	VBF γγ	VBF ZZ	VBF WW	VBF ττ	WH γγ	WH WW	WH ττ	WH bb	ZH γγ	ZH WW	ZH ττ	ZH bb	ttH γγ	ttH WW	ttH ττ	ttH bb
ggF γγ	1	0.01	0.00	0.00	–0.25	–0.01	0.00	0.00	–0.03	0.00	0.00	0.00	–0.14	0.00	0.00	0.00	0.01	0.01	0.00	0.00
ggF ZZ	0.01	1	0.03	0.00	–0.01	–0.26	–0.01	–0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	–0.08	–0.02	–0.02
ggF WW	0.00	0.03	1	–0.01	0.01	0.00	–0.16	0.00	0.00	–0.07	0.02	0.00	0.00	–0.07	0.01	0.00	0.00	0.01	0.00	0.01
ggF ττ	0.00	0.00	–0.01	1	0.01	0.01	0.01	–0.37	0.00	0.03	–0.25	0.00	0.00	0.01	–0.21	0.00	0.00	0.00	0.00	0.01
VBF γγ	–0.25	–0.01	0.01	0.01	1	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00
VBF ZZ	–0.01	–0.26	0.00	0.01	0.02	1	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01
VBF WW	0.00	–0.01	–0.16	0.01	0.02	0.02	1	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
VBF ττ	0.00	–0.01	0.00	–0.37	0.02	0.02	0.03	1	0.00	–0.01	0.05	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	–0.01
WH γγ	–0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.64	0.00	0.00	0.00	–0.03	0.00	0.00	0.00
WH WW	0.00	0.00	–0.07	0.03	0.00	0.00	0.00	–0.01	0.00	1	–0.12	0.00	0.00	–0.12	0.01	0.00	0.00	0.00	0.00	0.01
WH ττ	0.00	0.01	0.02	–0.25	0.00	0.00	0.00	0.05	0.00	–0.12	1	0.00	0.00	0.02	–0.02	0.00	0.00	0.01	0.00	0.00
WH bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.07	0.00	0.00	0.00	0.00
ZH γγ	–0.14	0.00	0.00	0.00	0.01	0.00	0.00	0.00	–0.64	0.00	0.00	0.00	1	0.00	0.00	0.00	–0.11	0.00	0.00	0.00
ZH WW	0.00	0.01	–0.07	0.01	0.00	0.00	0.00	0.00	0.00	–0.12	0.02	0.00	0.00	1	–0.05	0.00	0.00	0.01	0.00	0.00
ZH ττ	0.00	0.01	0.01	–0.21	0.00	0.00	0.00	0.04	0.00	0.01	–0.02	0.00	0.00	–0.05	1	0.00	0.00	0.01	0.00	0.00
ZH bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.07	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00
ttH γγ	0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	–0.03	0.00	0.00	0.00	–0.11	0.00	0.00	0.00	1	0.00	0.00	0.00
ttH WW	0.01	–0.08	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	1	–0.47	0.01
ttH ττ	0.00	–0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.47	1	0.00
ttH bb	0.00	–0.02	0.01	0.01	0.00	0.01	–0.01	–0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1