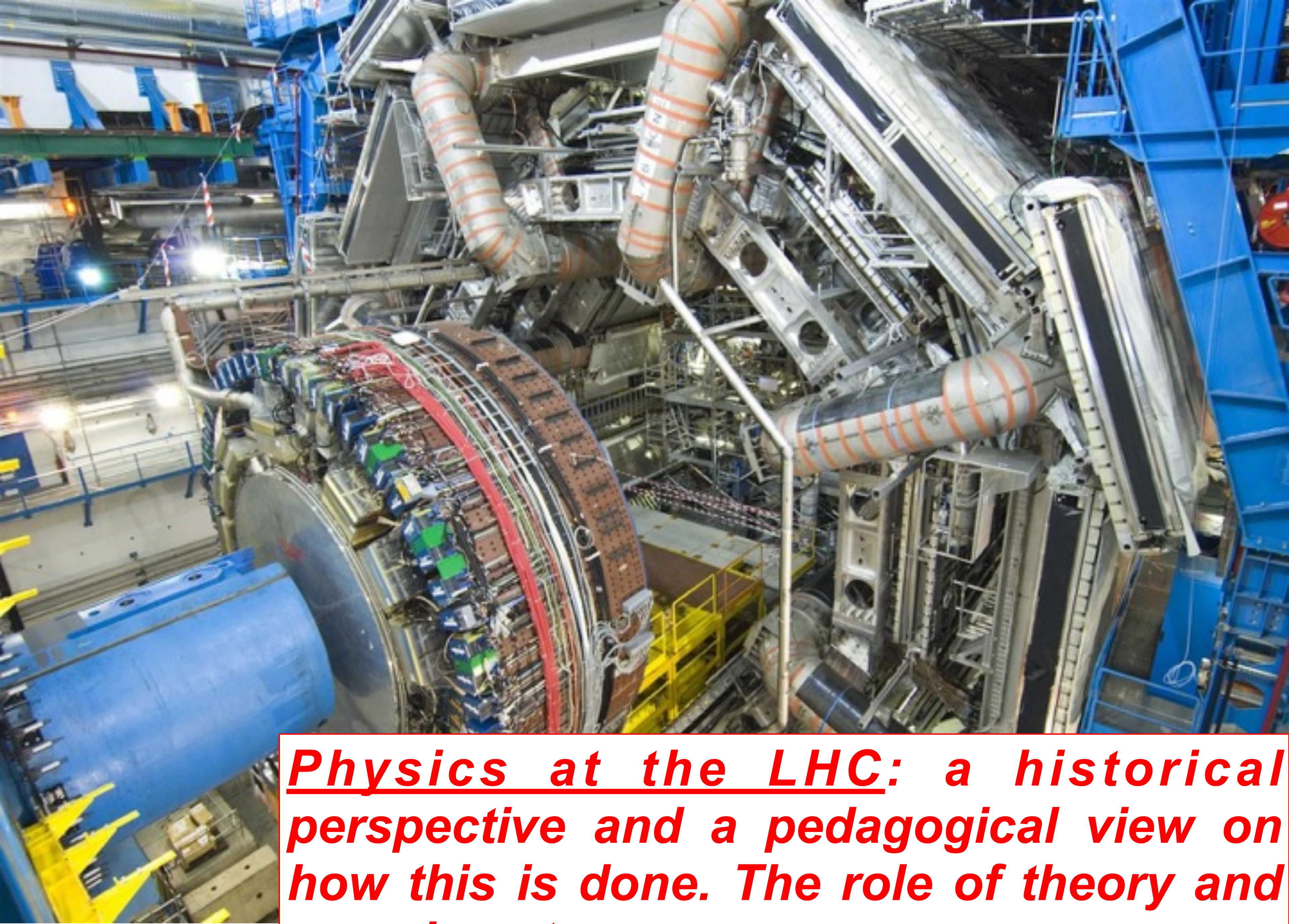
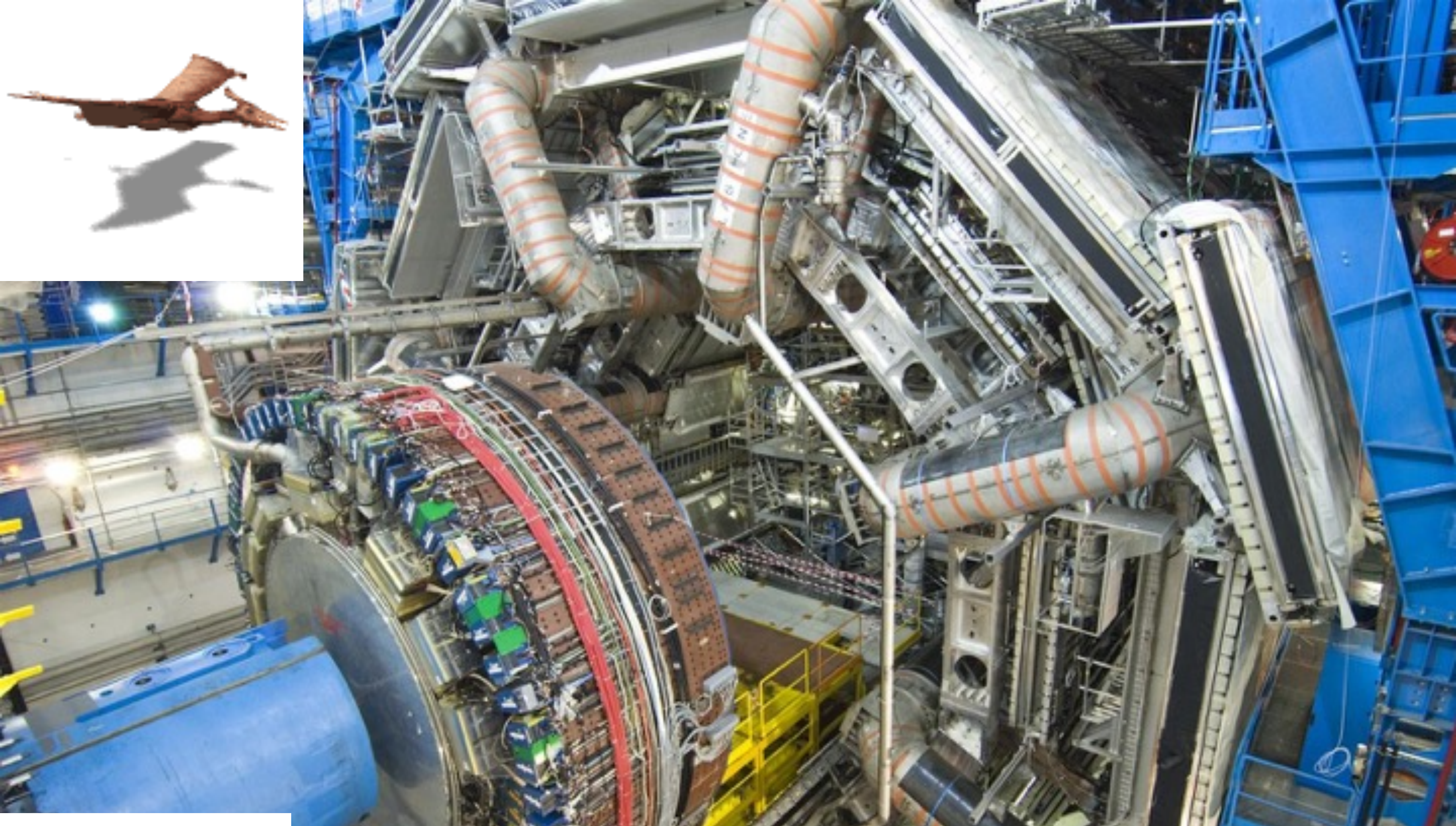


# Physics at the LHC: a historical perspective and a pedagogical view on how this is done. The role of theory and experiment

D. Froidevaux (CERN)

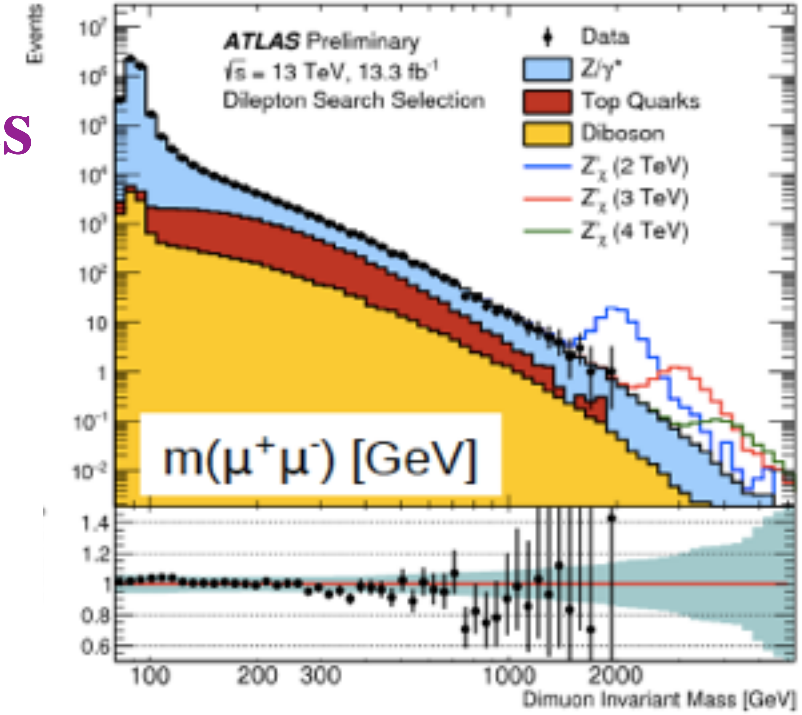


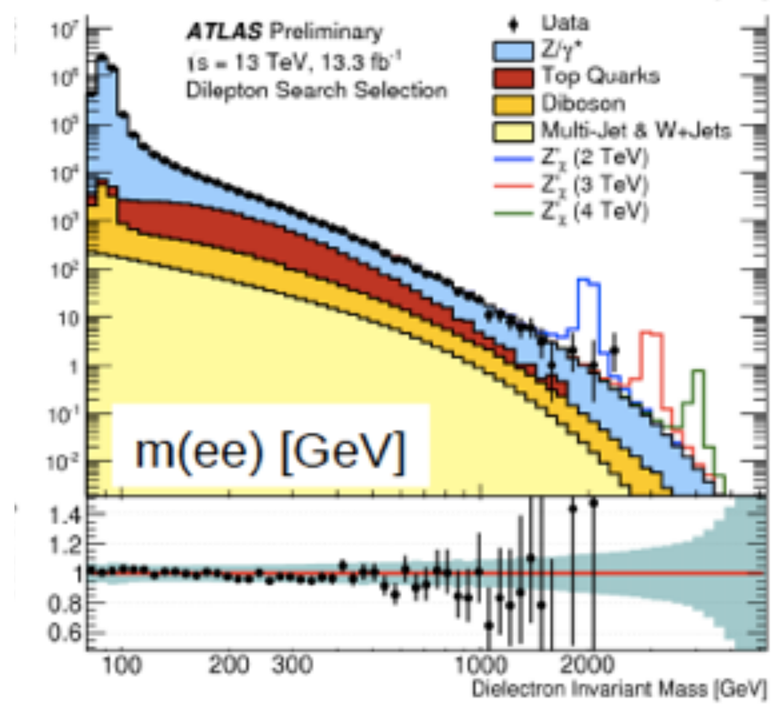
# Physics at the LHC: a historical perspective and a pedagogical view on how this is done. The role of theory and experiment

D. Froidevaux (CERN)

# Search for high-mass resonances decaying to leptons

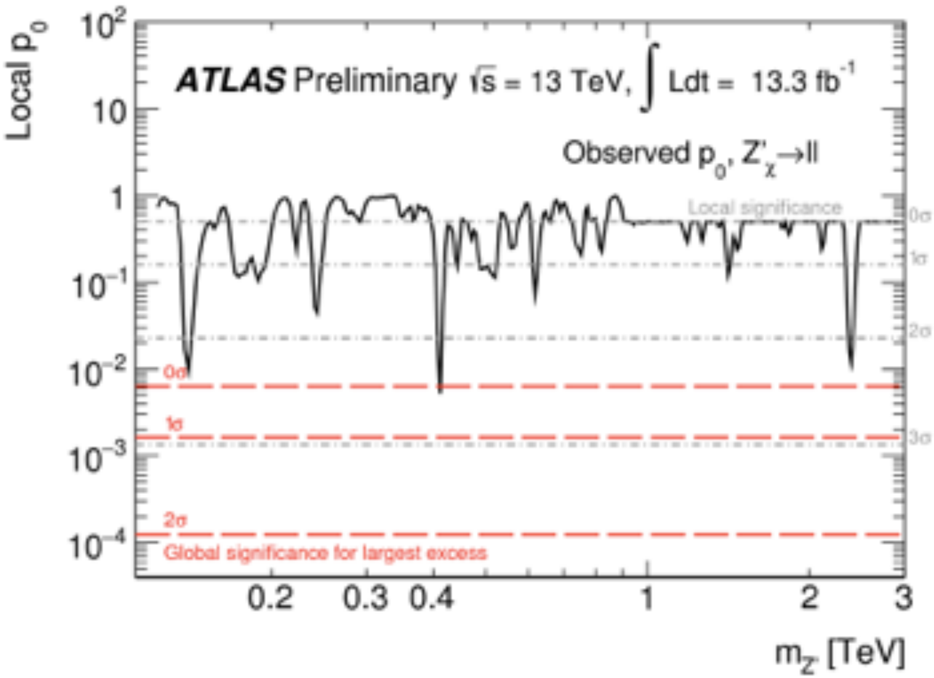
- Dimuon channel:
  - → 30 μm muon spectrometer alignment critical (ATLAS)
  - → Resolution 10-15% at $p_T$ = 1 TeV
- Dielectron channel:
  - → Excellent resolution: < 2% at high momentum
  - → Poor charge measurement → no charge requirement
- Fit of the entire dilepton spectrum, incl. Z peak.

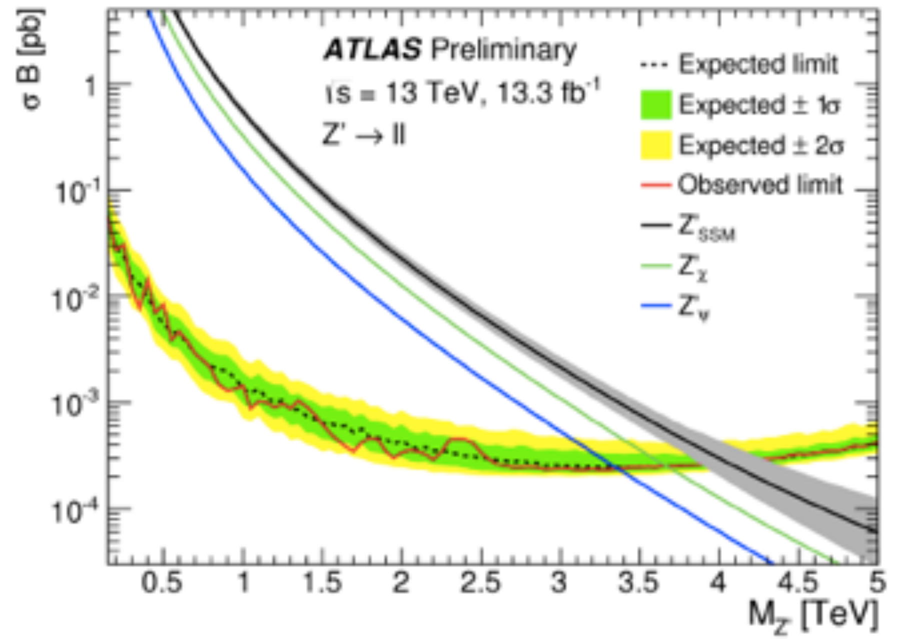


# Search for Heavy Resonance: dilepton channel

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

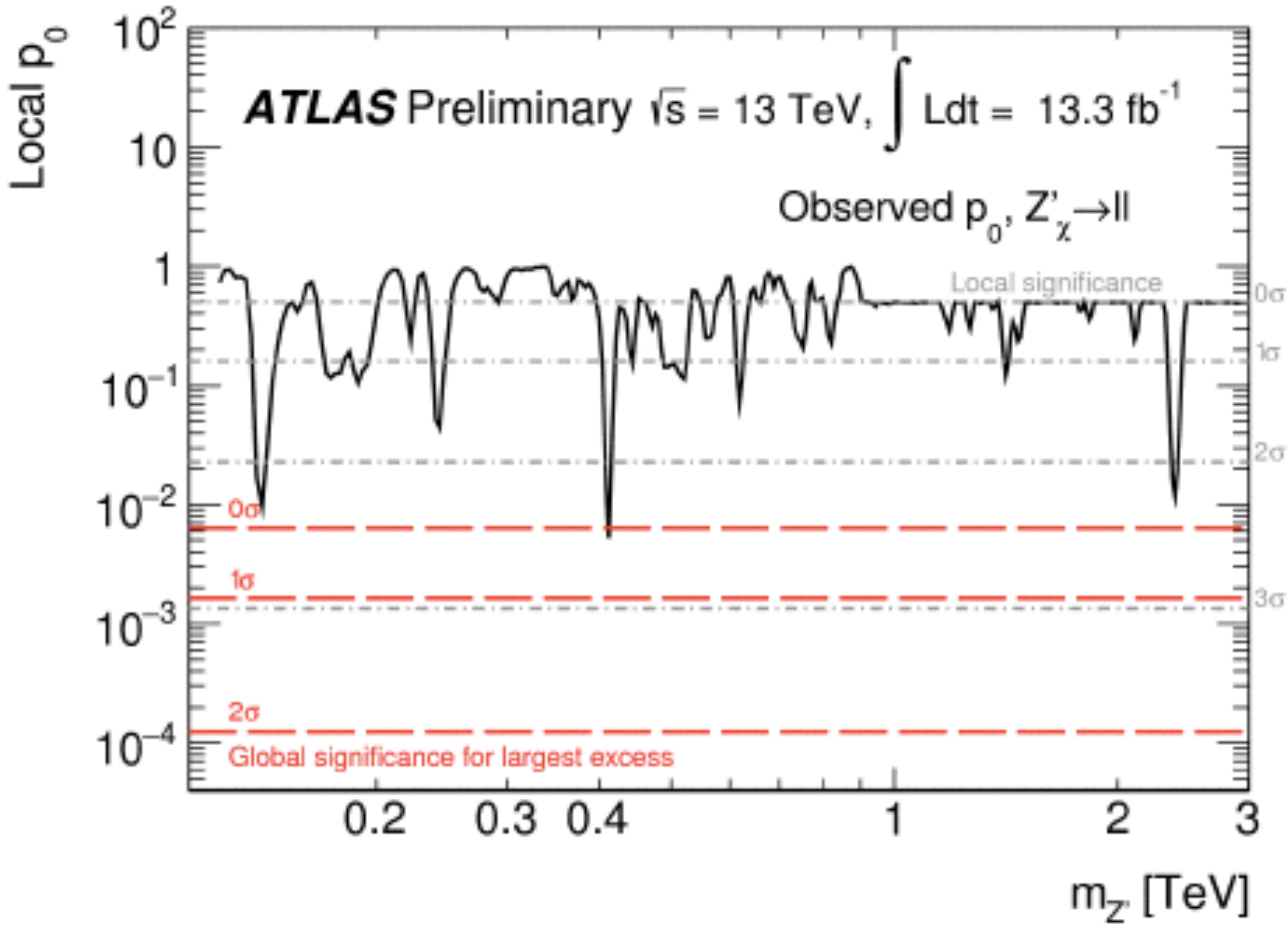



Observed lower limit (TeV) at 95% CL:
m(SSM Z') > 4.05 TeV

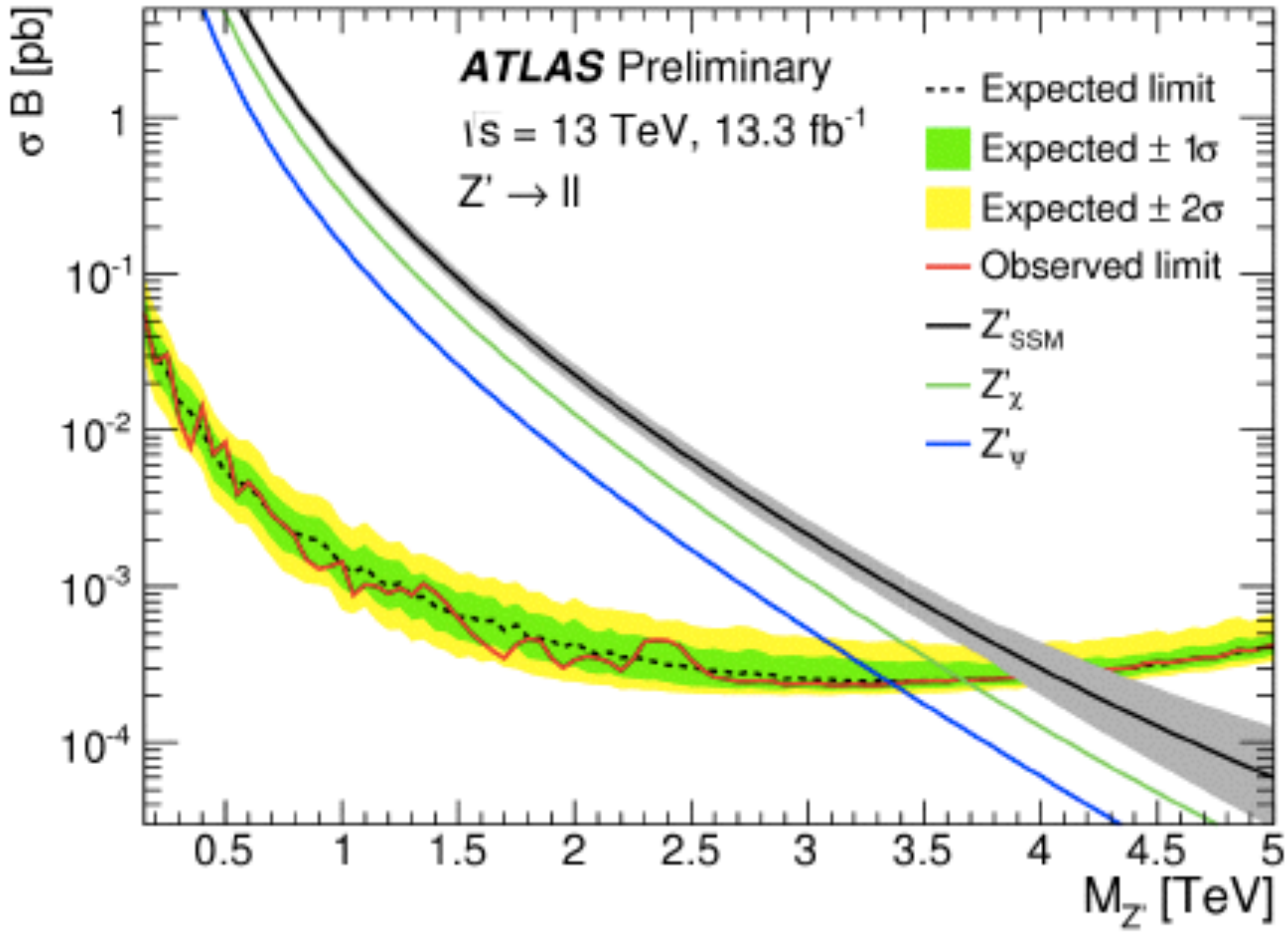
# Search for Heavy Resonance: dilepton channel

# Search for Heavy Resonance: dilepton channel



# Search for Heavy Resonance: dilepton channel

# Search for Heavy Resonance: dilepton channel

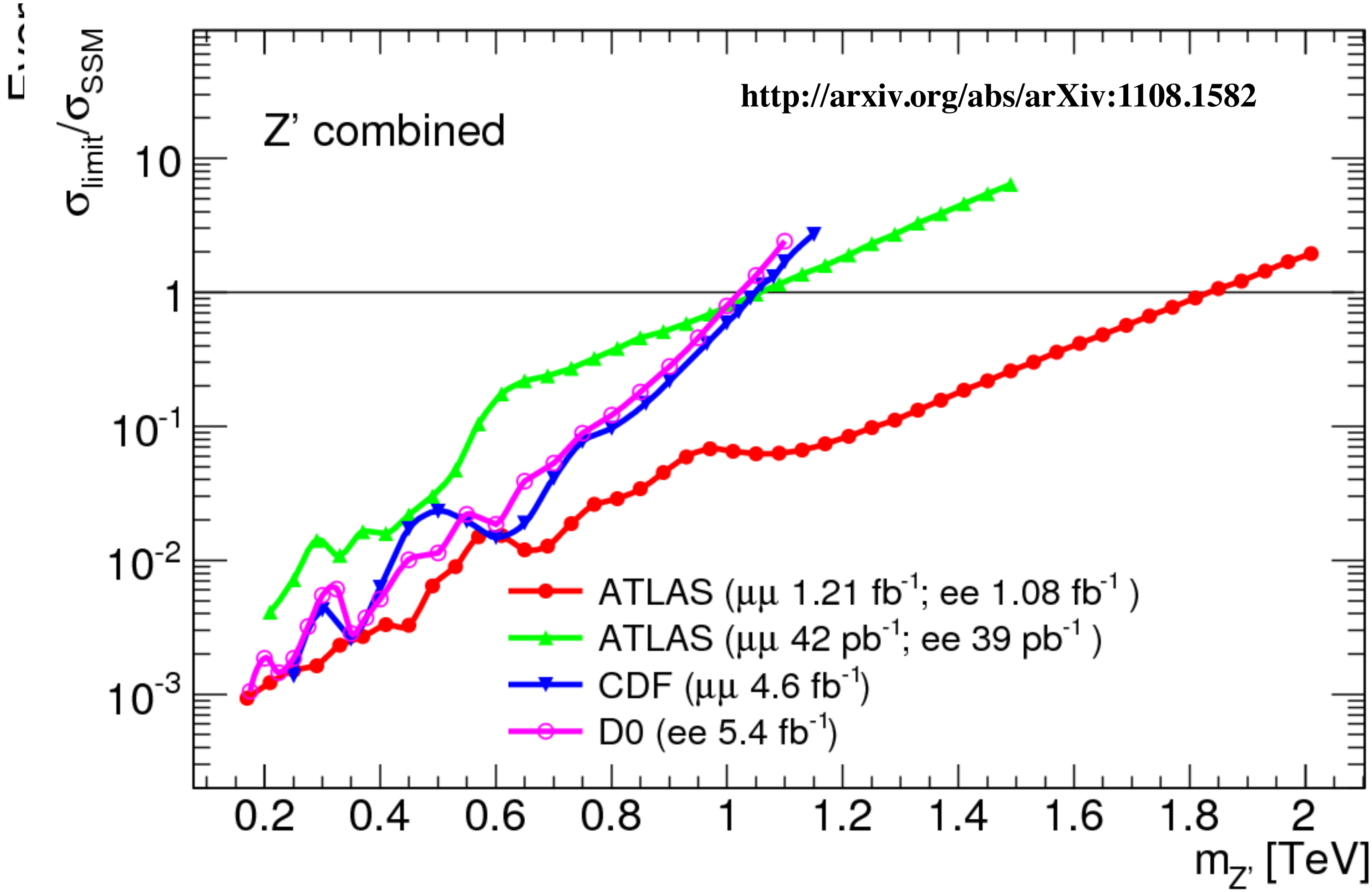



Observed lower limit (TeV) at 95% CL:
m(SSM Z') > 4.05 TeV

# 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

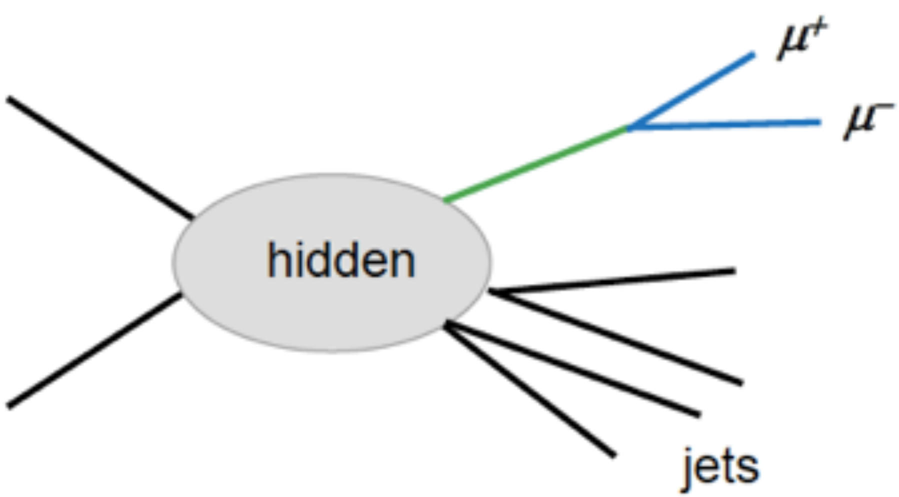


# Physics Hidden in Inclusive Distributions

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

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

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




Rare, prompt, light dilepton resonance along with hard jets

# Physics Hidden in Inclusive Distributions

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

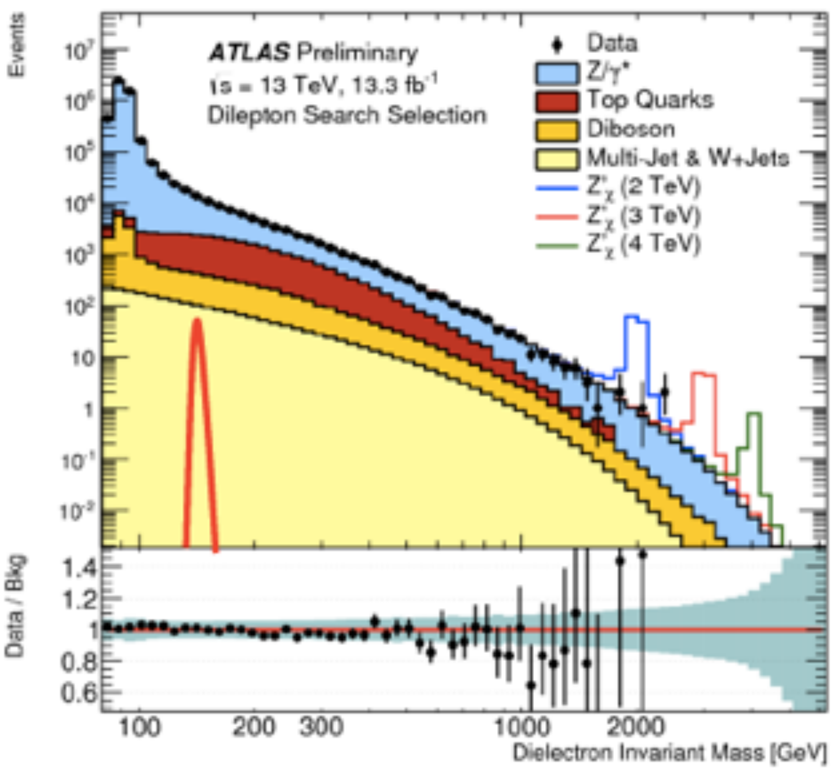
- Rare or unusual production of new neutral particle
- Bump, edge, endpoint, dip, wiggle is present
  - but swamped in inclusive background

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

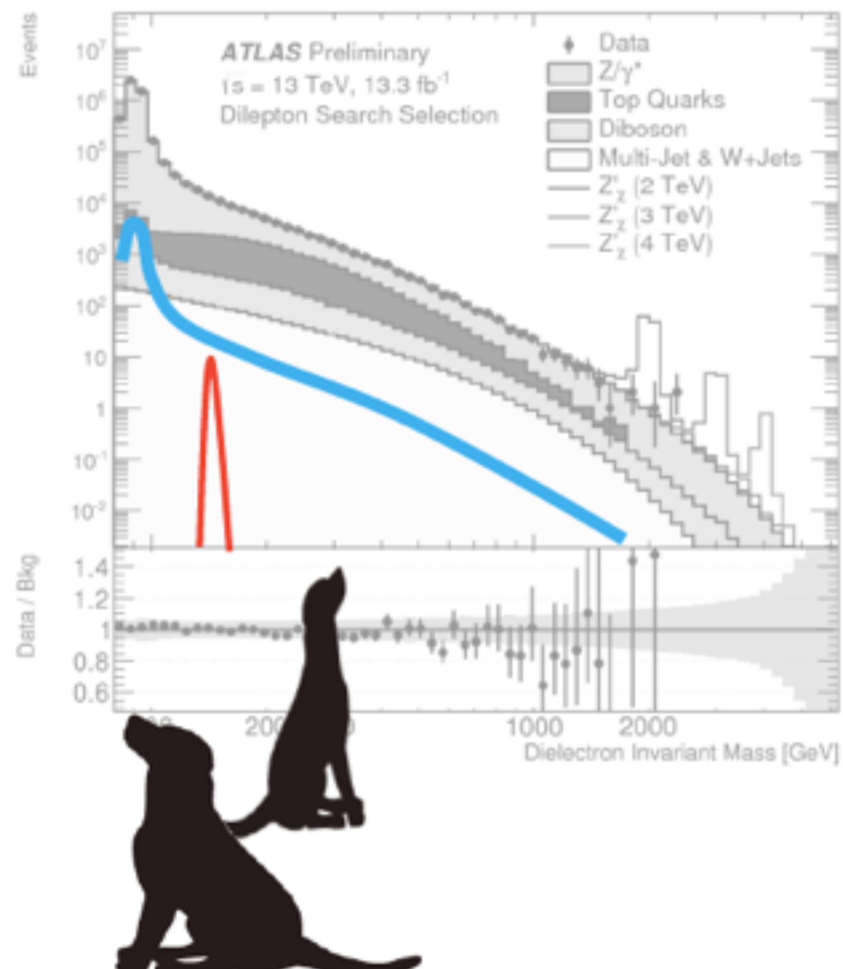
- We should do this for other resonance searches as a matter of course!

# Inclusive is not Conclusive

## Inclusive



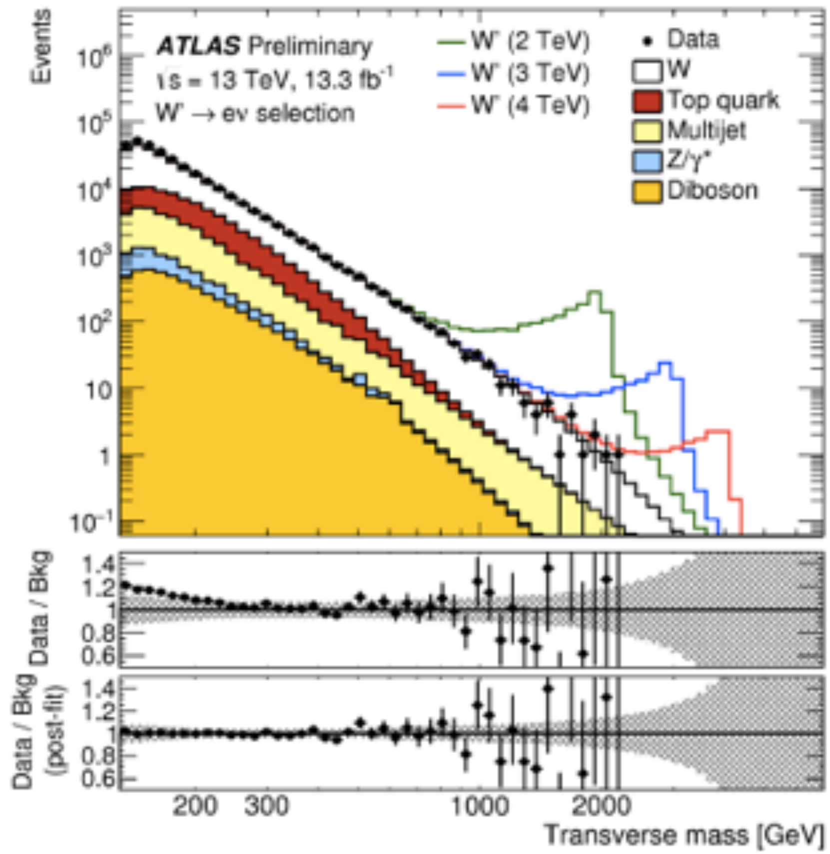

## Require 4 jets and high HT and… presto!



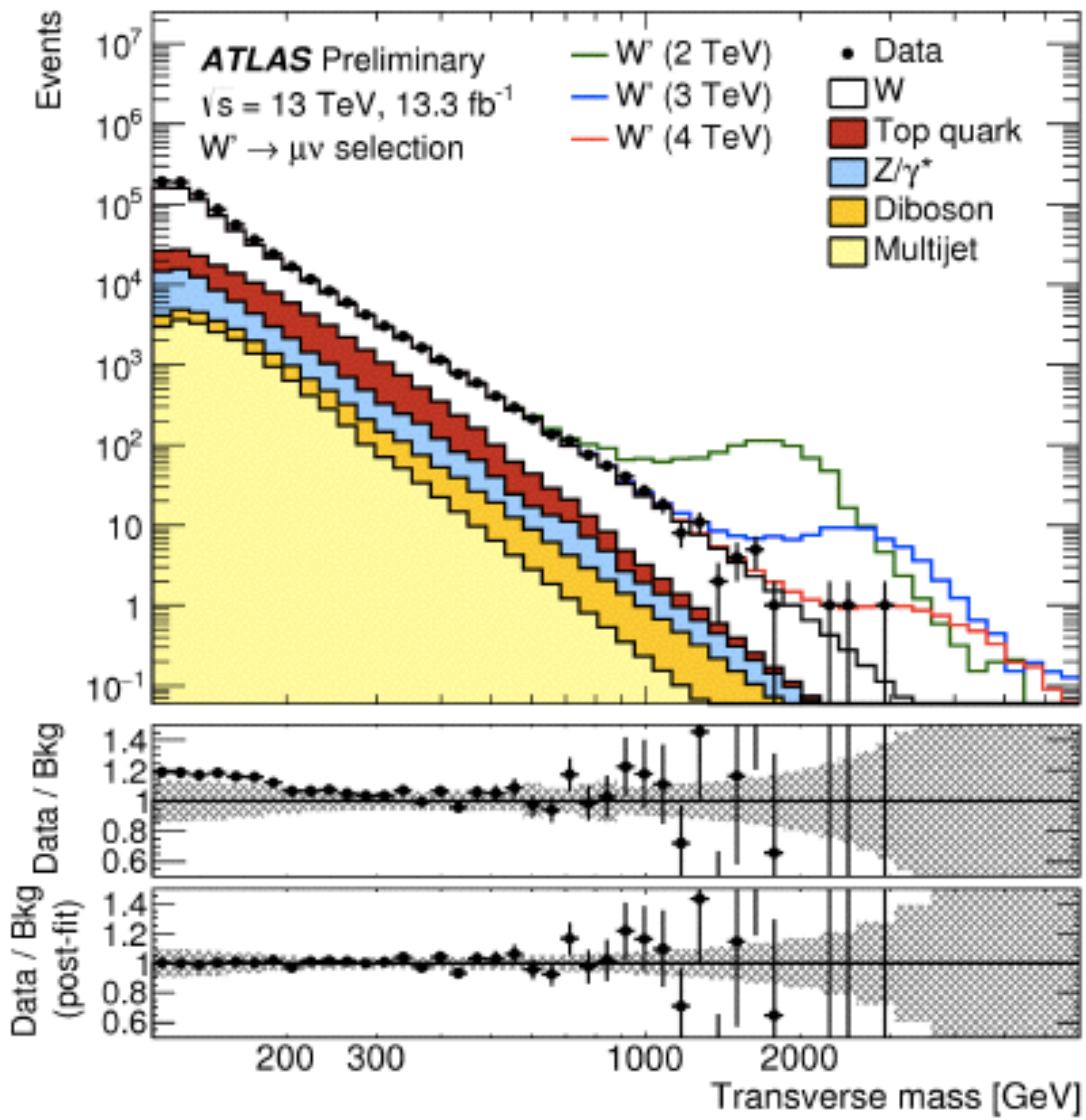
# Search for Heavy Resonance: W' → lν

- 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:

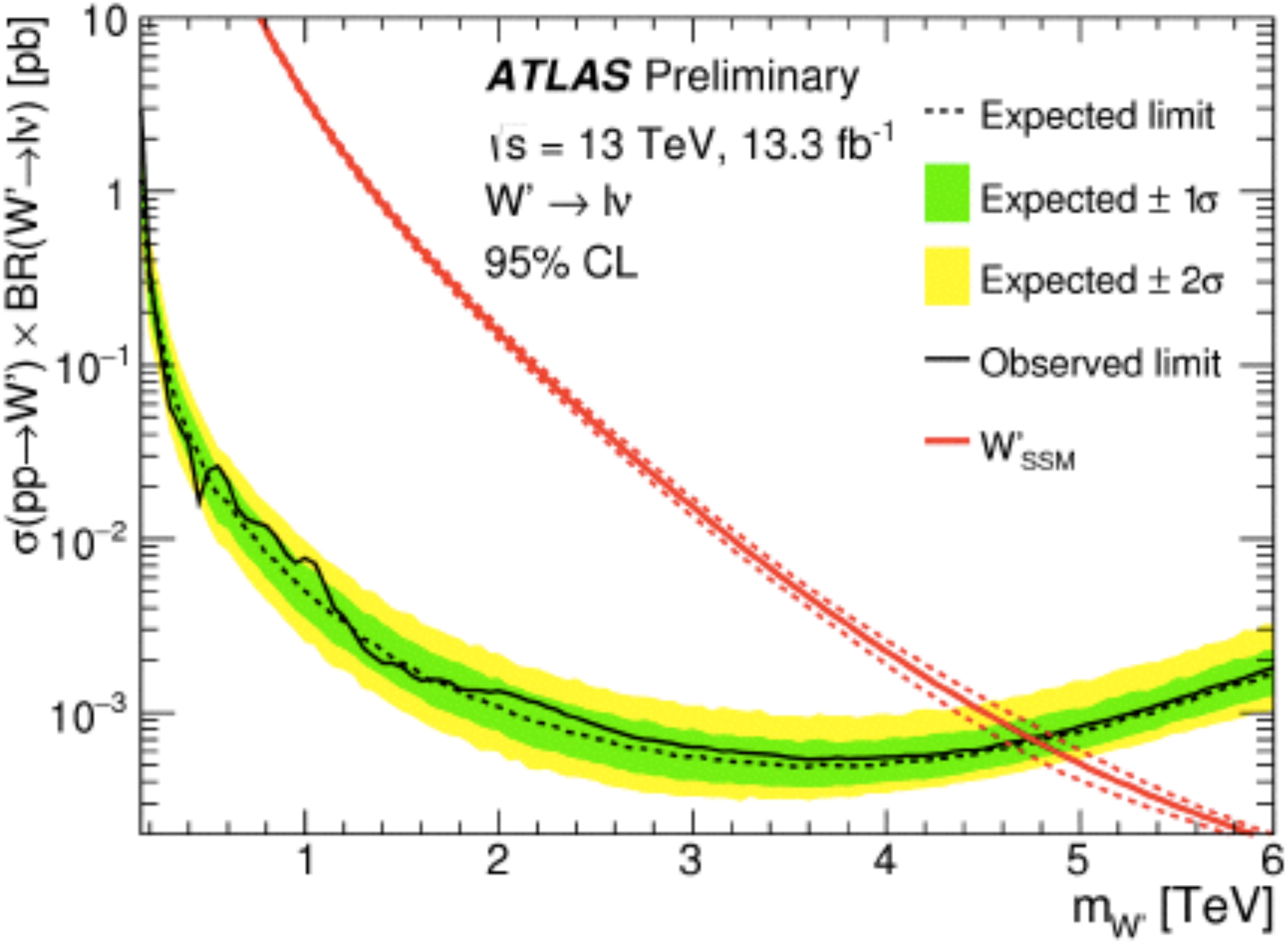
$$m_T = \sqrt{2 p_T \not{E}_T (1 - \cos\Delta\phi_{\ell,\not{E}_T})}$$




Electron channel




# Muon channel

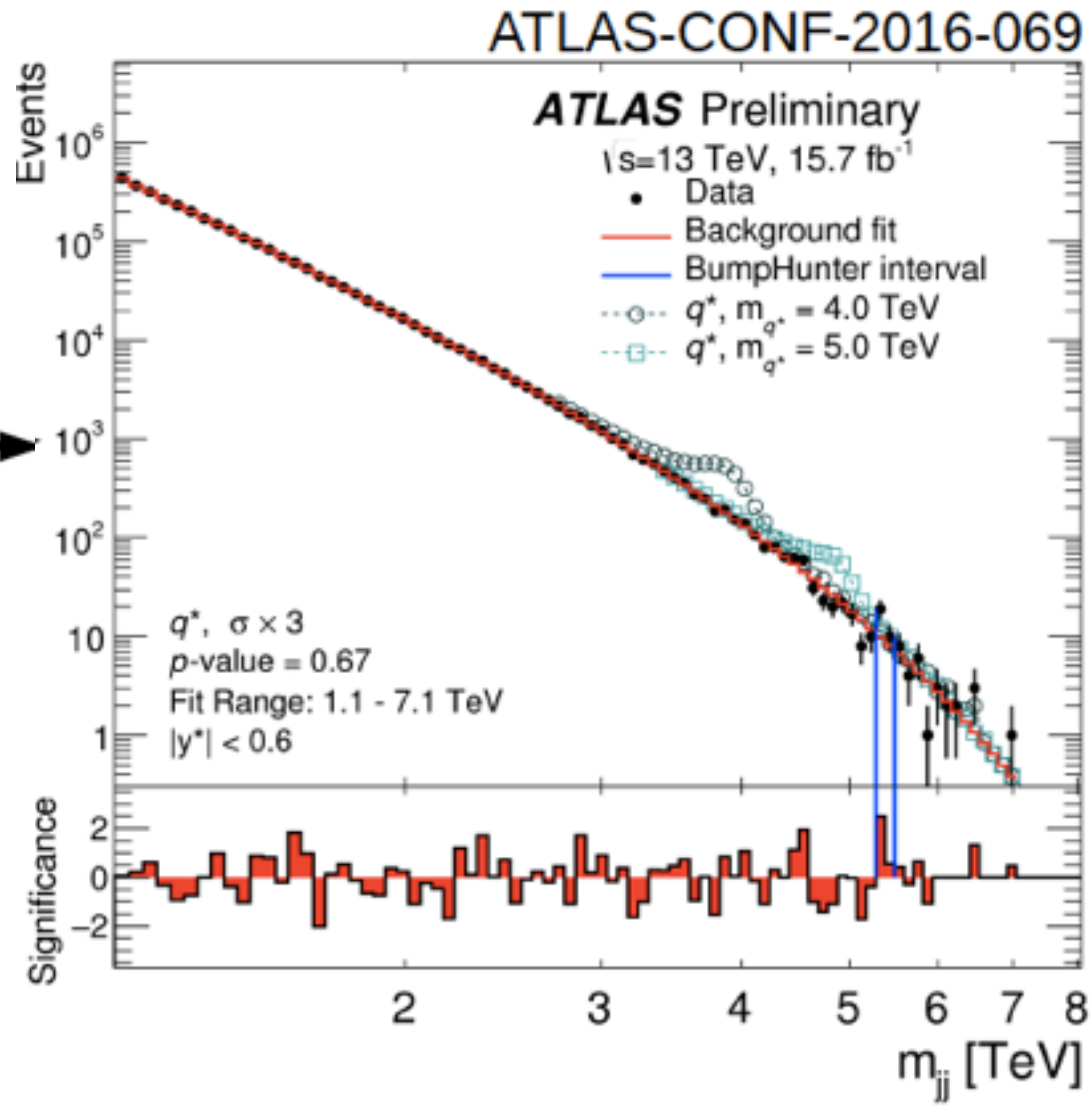



Sequential SM:

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

# Search for high-mass resonances decaying to jets

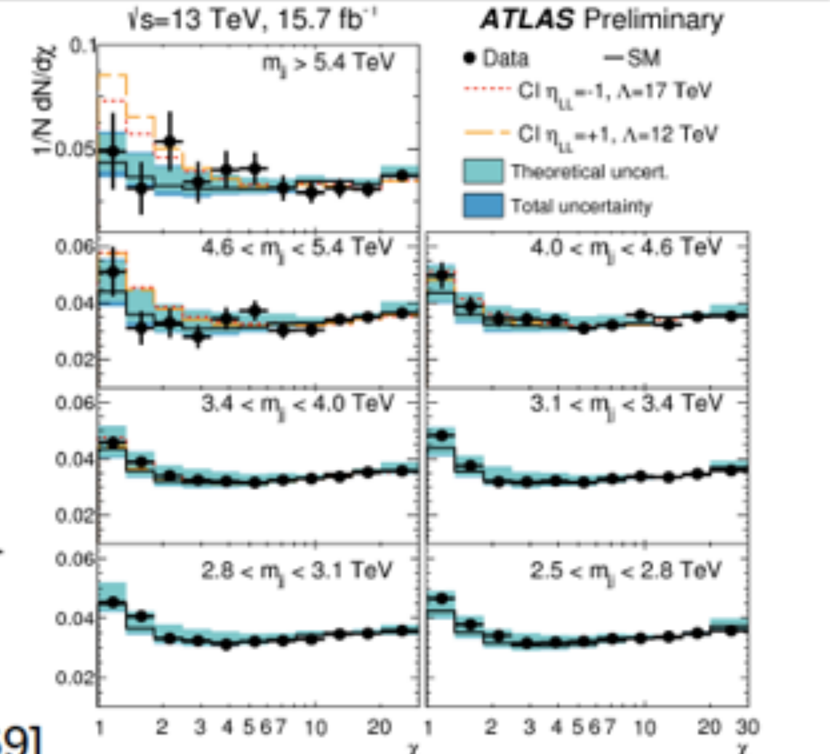
- W'/Z', excited quarks, strong gravity, DM-mediator
- Look for resonance above phenomenological fit of the data
- High-mass analysis [ATLAS-CONF-2016-069] limited by trigger
- To reach sensitivity at low-mass:
  - → ISR photon or jet [ATLAS-CONF-2016-070]
  - → Trigger-Level Analysis [ATLAS-CONF-2016-030]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



# Search for Heavy Resonance: Dijet High-mass

- **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

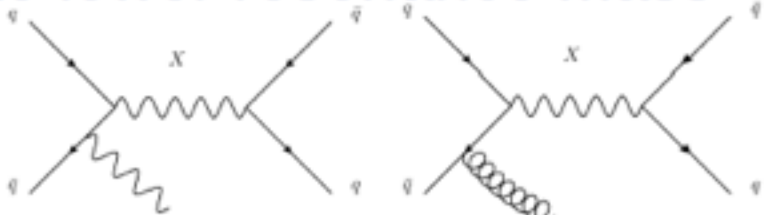
| Model | 95% CL exclusion limit Observed | Expected |
|---|---|---|
| Quantum black holes, ADD (BlackMax generator) | 8.7 TeV | 8.7 TeV |
| Excited quark | 5.6 TeV | 5.5 TeV |
| $W'$ | 2.9 TeV | 3.3 TeV |
| $W^*$ | 3.3 TeV | 3.3 TeV |
| Contact interactions ($\eta_{LL}$ =+1) | 12.6 TeV | 13.7 TeV |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

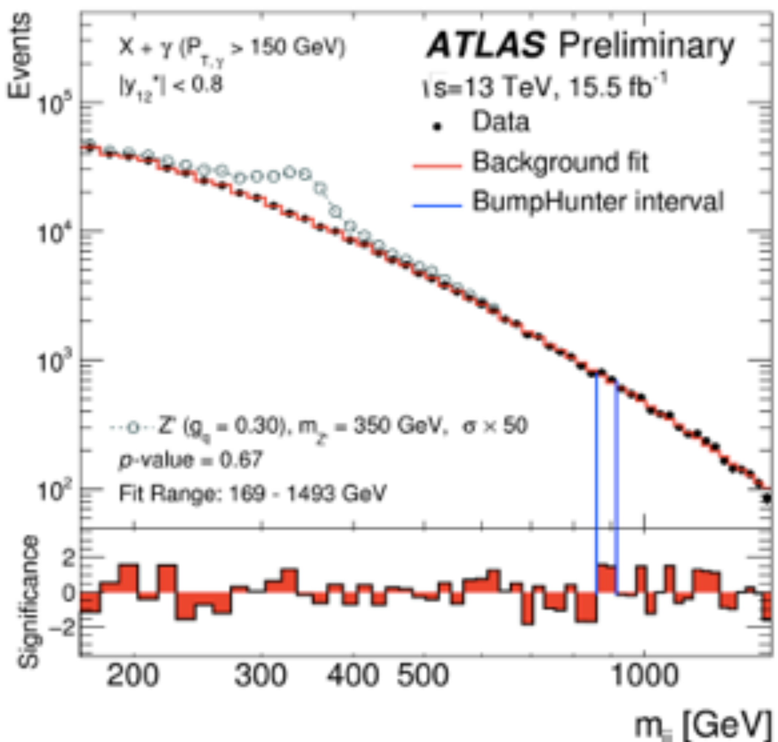


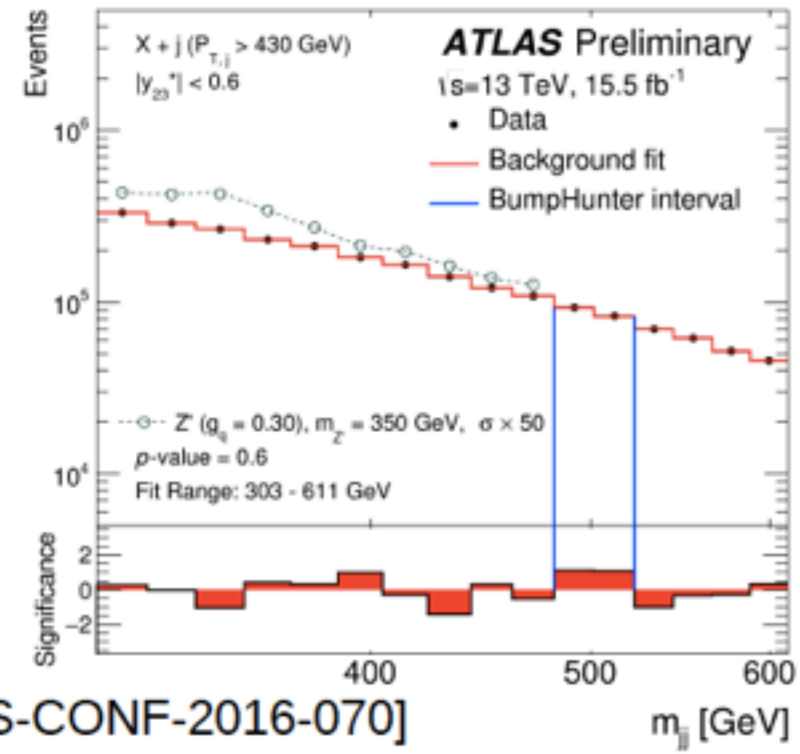

[ATLAS-CONF-2016-069]

# 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)





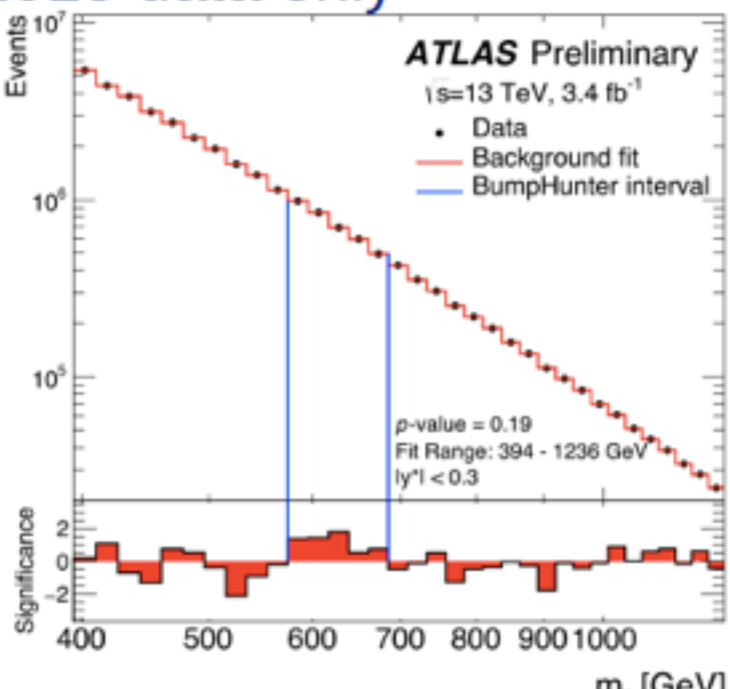



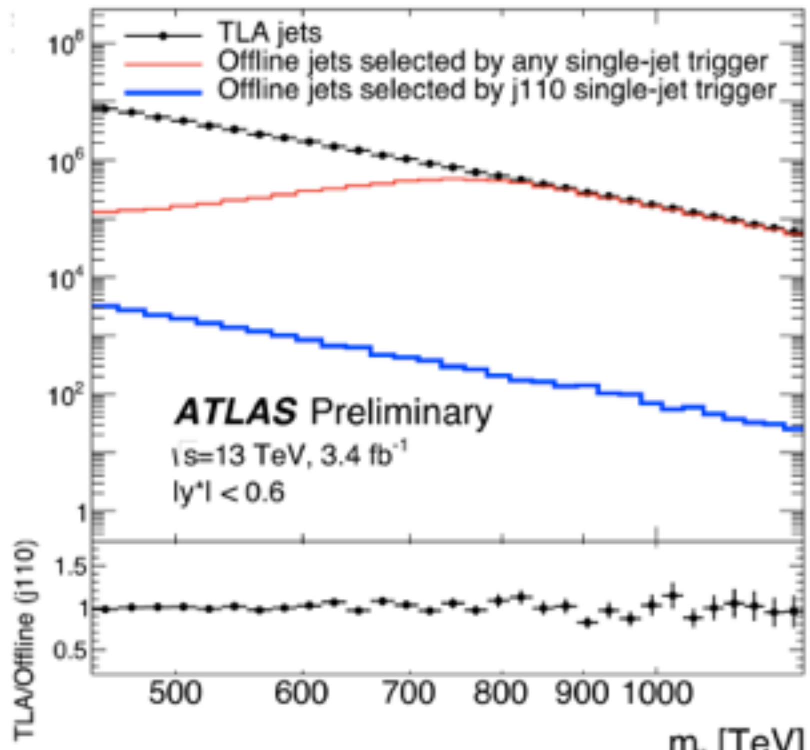

[ATLAS-CONF-2016-070]

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

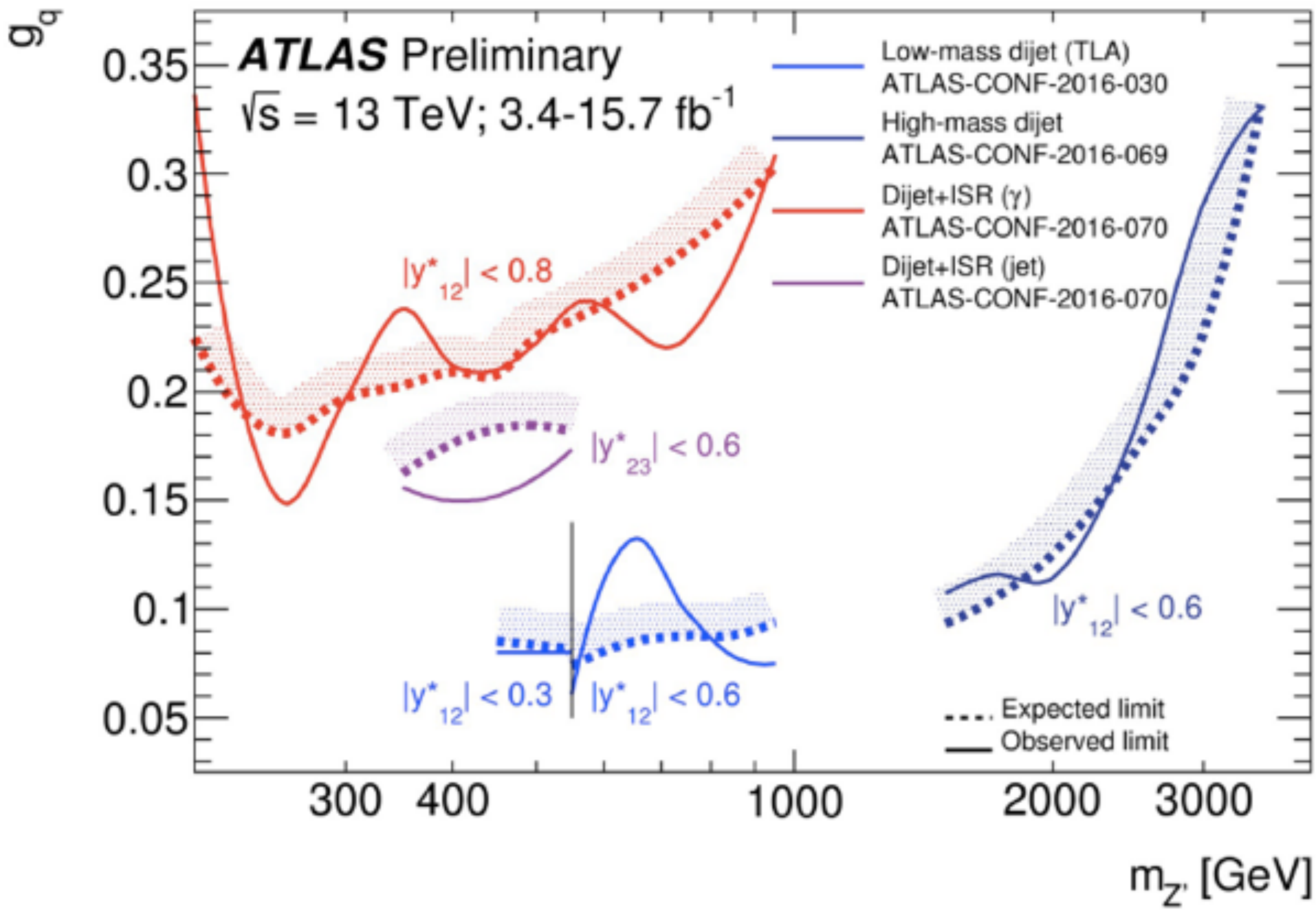
- Lower trigger-threshold by keeping only partial information of the event
- Addition jet calibration and cleaning applied online
- 2015 data only

[ATLAS-CONF-2016-030]

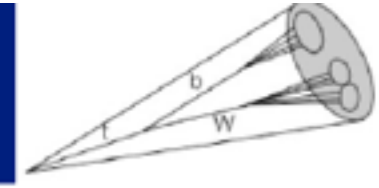


# Dijet searches: a summary



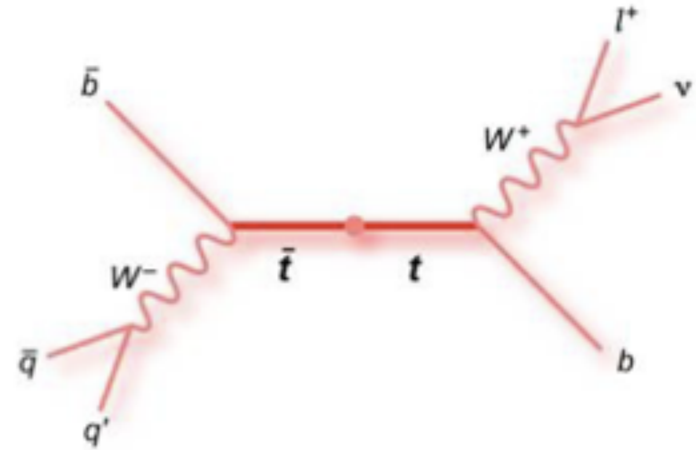
# Top-antitop Resonance




- Event Topology:

  t-tbar → Wb Wb

- Final state depends on W decays:




Larger Branching Ratio but more background

→ All-hadronic final state:

2 W → jj

2 b-jets + 4 light jets (+0ν)

→ Lepton+Jets final state:

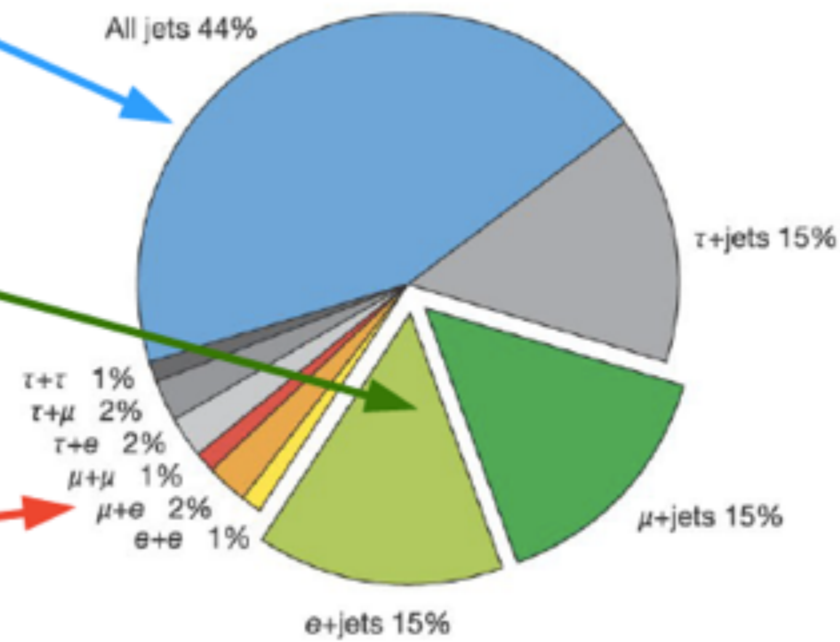
1 W → lν, 1 W → jj

1l + 2 b-jets + 2 light jets (+1ν)

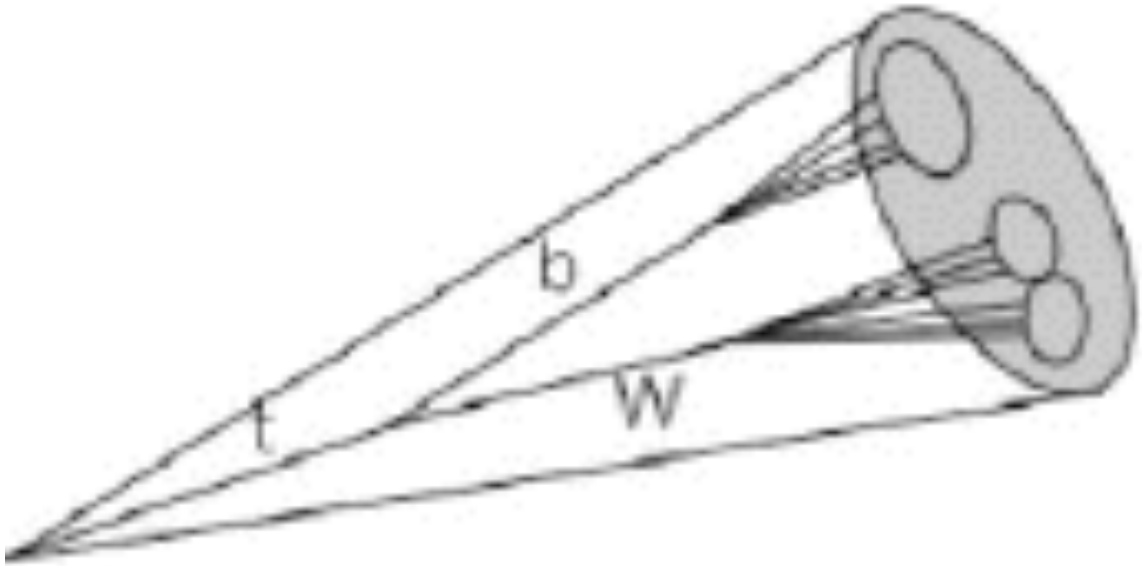
→ Dilepton final state:

Both W → lν (l = e or μ)

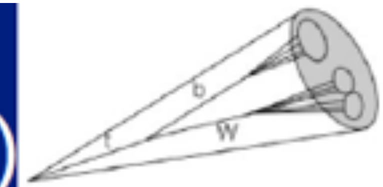
2l + 2 b-jets (+2 neutrinos)



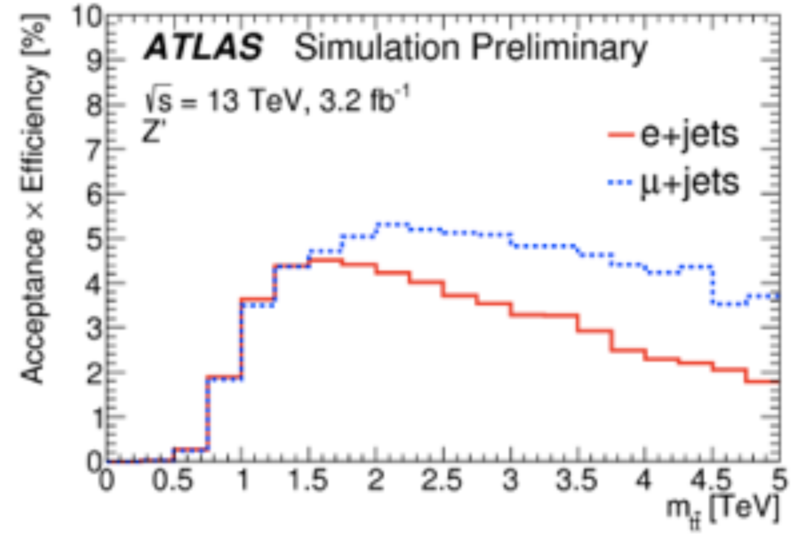
# Top-antitop Resonance

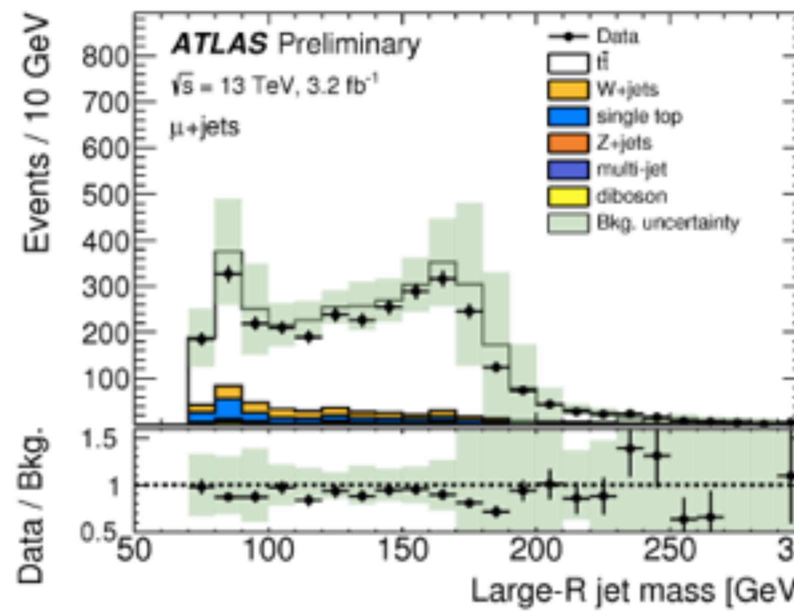


# Top-antitop Resonance Lepton+Jets Channel (ATLAS)



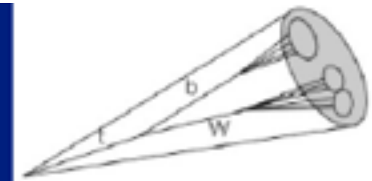

- First 13 TeV result, boosted channel only:
  - → anti-kT R=1.0, $p_T$>300 GeV, $|\eta|$<2
  - → Top-tagging (80% efficiency working point) using jet mass and n-subjettiness ratio $\tau_{32}$
- Improve efficiency at high t-tbar mass with:
  - → Lepton "mini-isolation":
    - smaller isolation cone at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



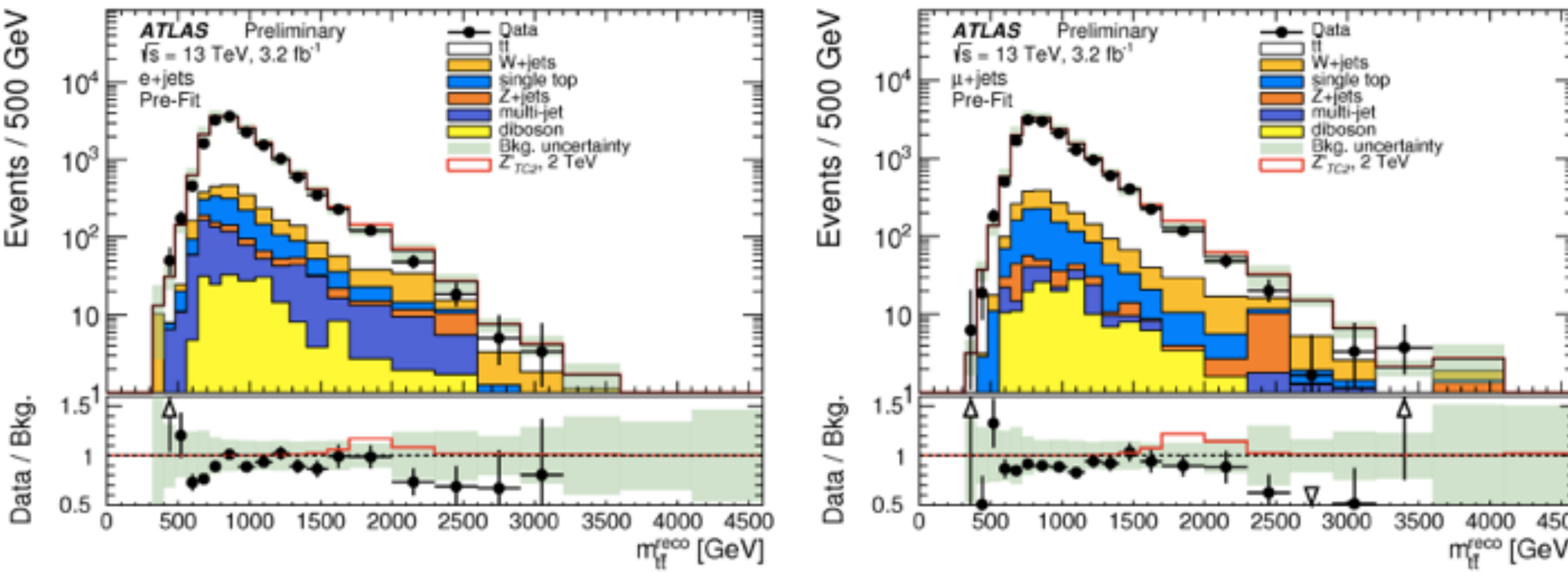




[ATLAS-CONF-2016-014]

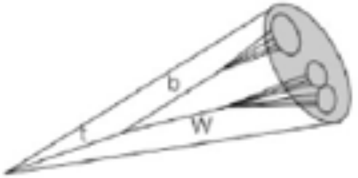
# Top-antitop Resonance
# L+Jets Channel

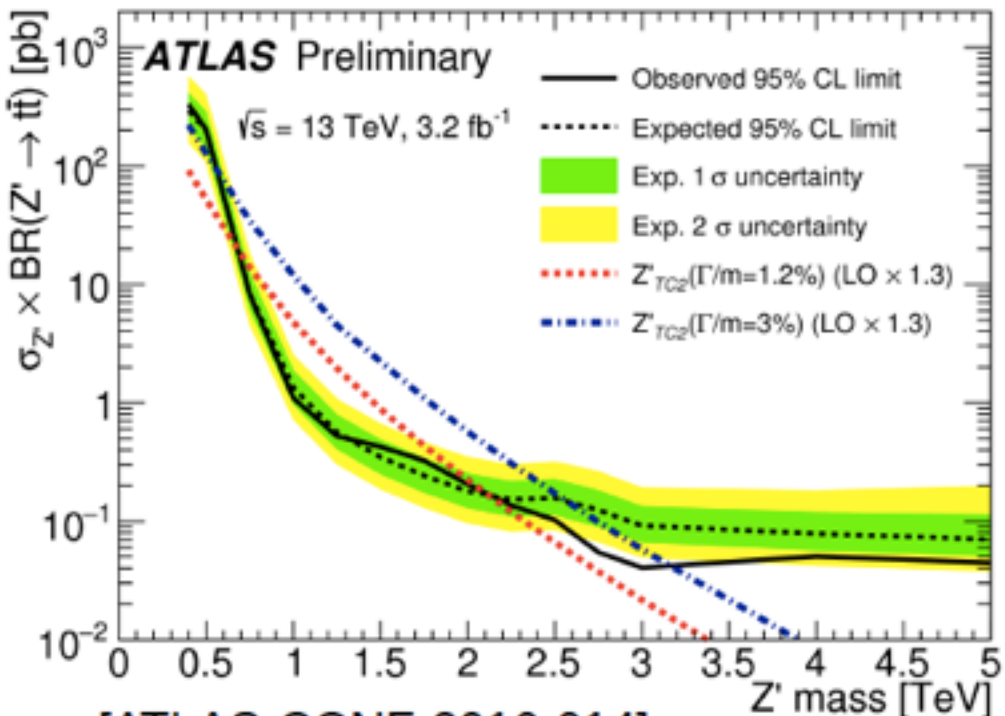



- Top-antitop mass spectrum at 13 TeV:

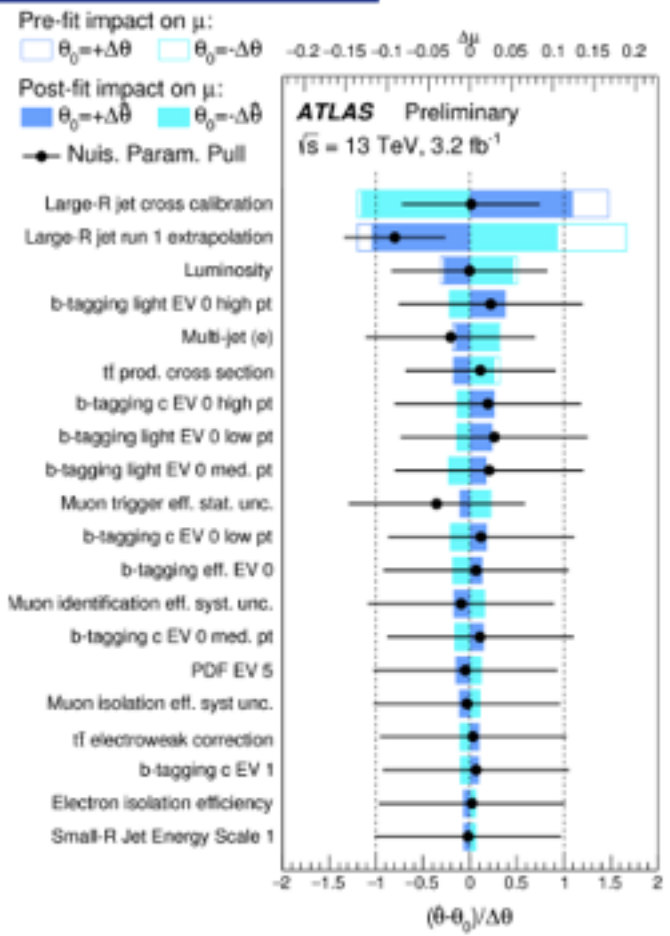


# Top-antitop Resonance L+Jets Channel




[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

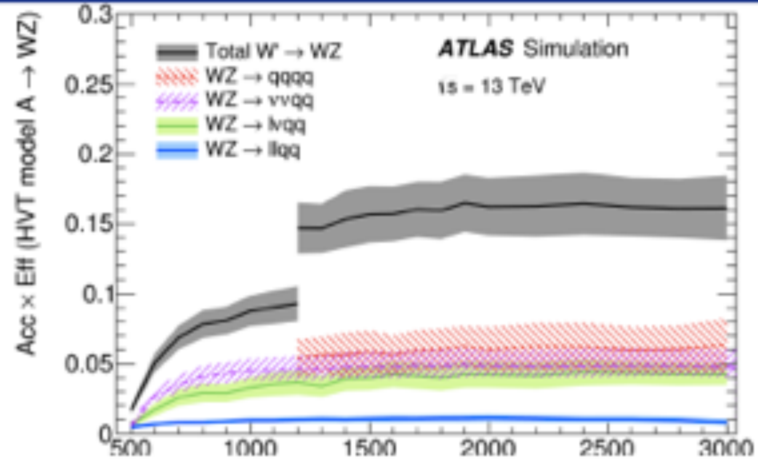
- Heavy resonance searches benefit the most (and the fastest) from increase in center-of-mass energy
- Corollary: future improvements will take a lot more time!

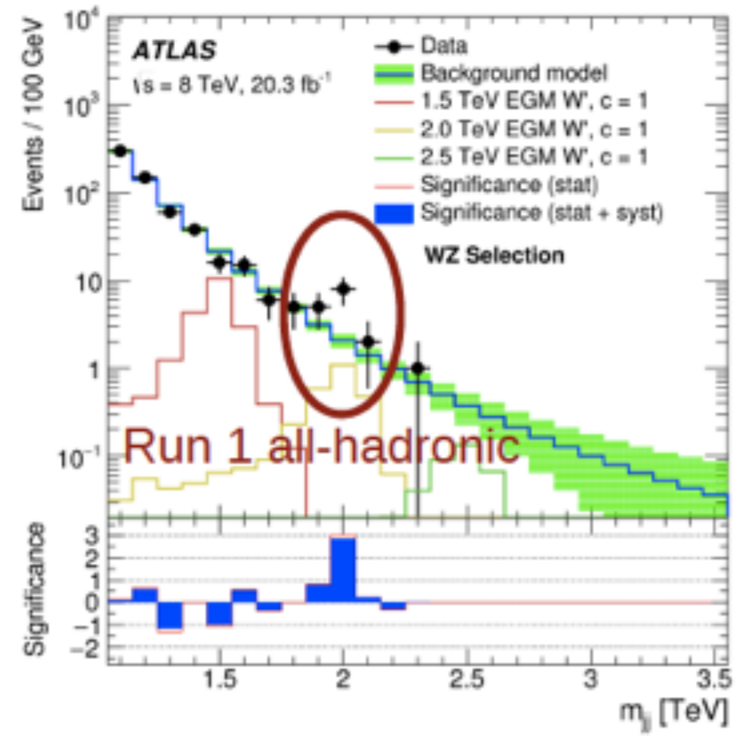
| 95% CL limit (TeV) | CDF | Run 1 '12 | Moriond '15 | ICHEP '16 | 300 $fb^{-1}$ 14 TeV | 3000 $fb^{-1}$ 14 TeV |
|---|---|---|---|---|---|---|
| $Z' \rightarrow ll$ | 1.1 | 2.9 | 3.4 | 4.1 | 6.5 | 7.8 |
| $q^* \rightarrow$ dijet | 0.9 | 4.1 | 5.2 | 5.6 | 7.4 | 8 |
| $Z' \rightarrow tt$ | 0.9 | 1.8 |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

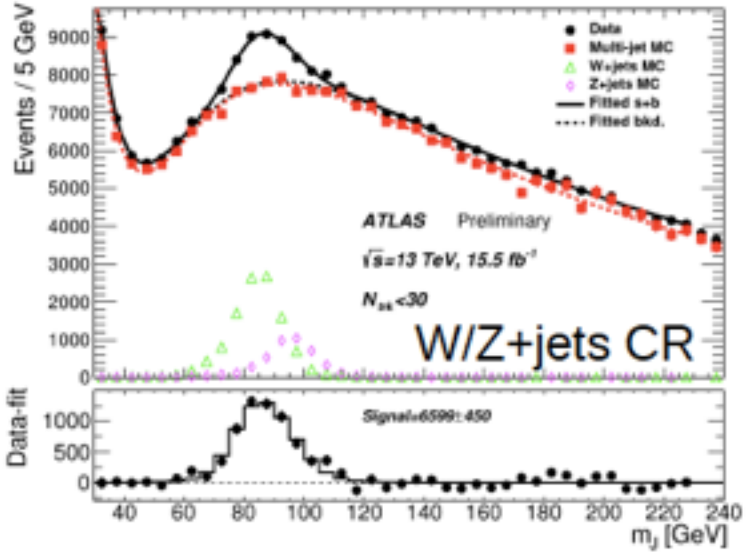
- Many channels:
  - → WW → lvlv or lvqq or (qq)(qq)
  - → WZ → lvll or lvqq or llqq or (qq)(qq)
  - → ZZ → (ll)(ll) or (ll)(vv) or llqq or (qq)(qq)
  - → (qq) can be either resolved into two jets, or merged into one fat jet
- Interpretation in terms of HVT W'/Z', bulk RS graviton, and 2HDM
- Got some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



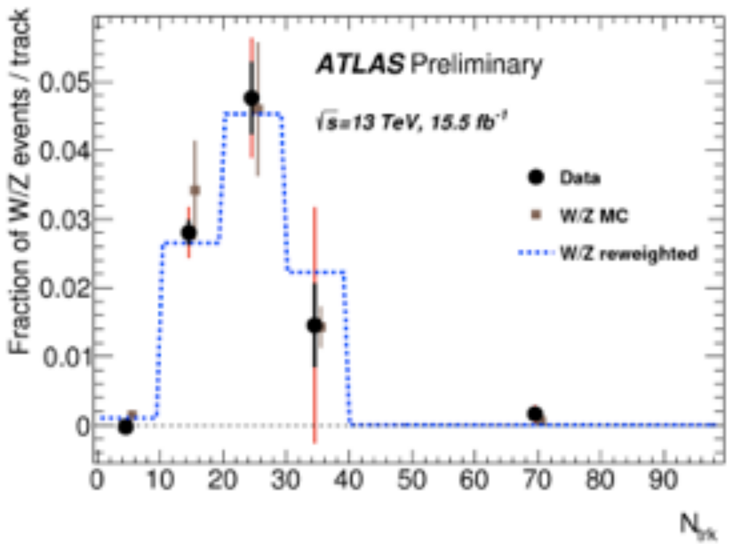



# Diboson all-hadronic channel

- 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

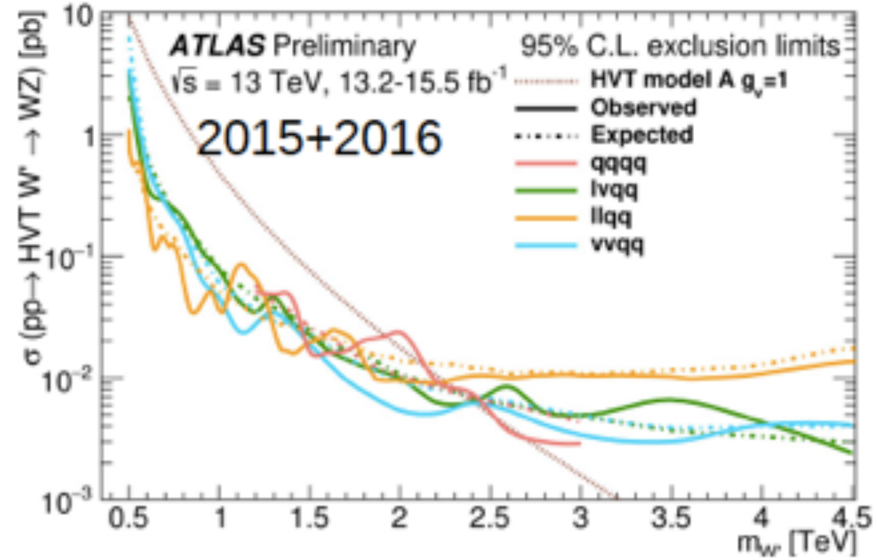
- Full combination only with 2015 data currently
- Combine channels with lepton-multiplicity from 0 to 4:

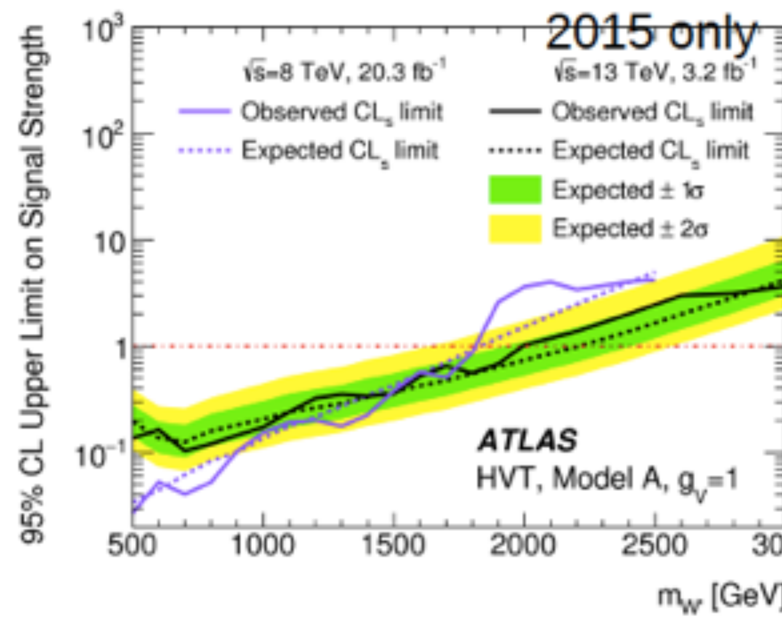
  (qq)(qq)  (lν)(qq)

  (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

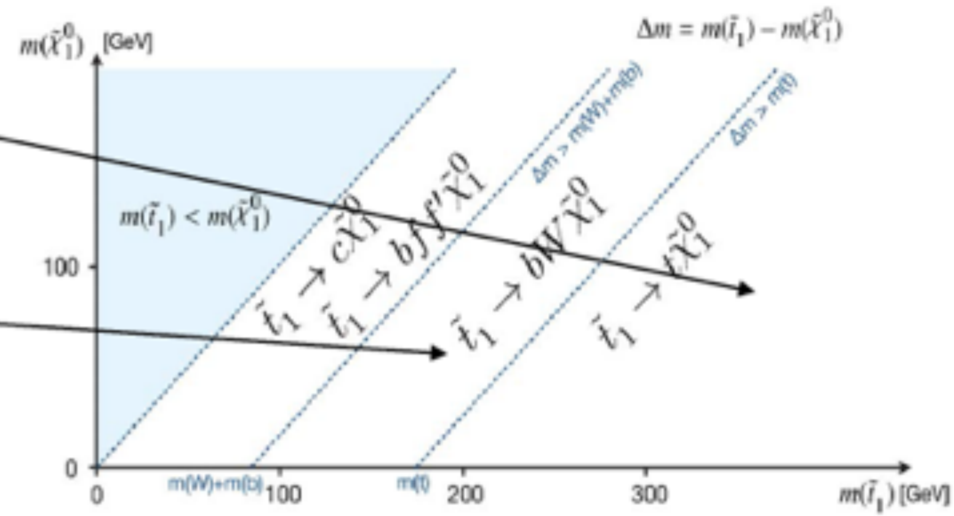
> stop -> bottom + Chargino

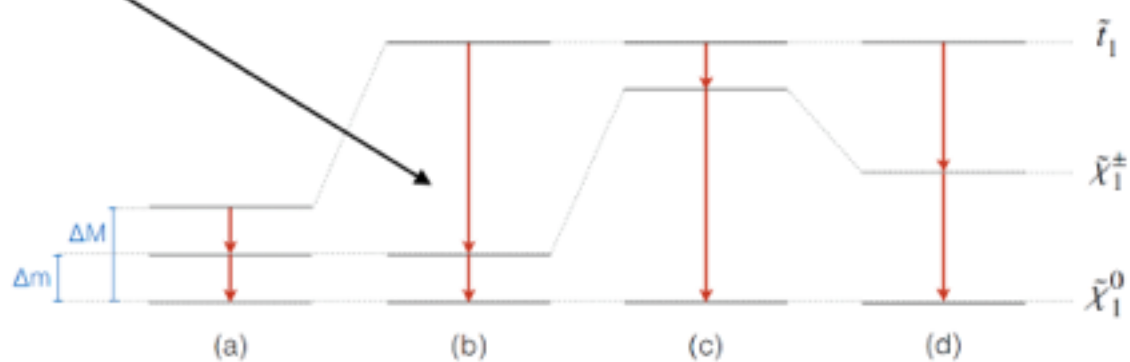
> stop2 production

> stop GMSB / stau

> Stop RPV

> sbottom production



Using this analysis also to explain the general analysis procedure

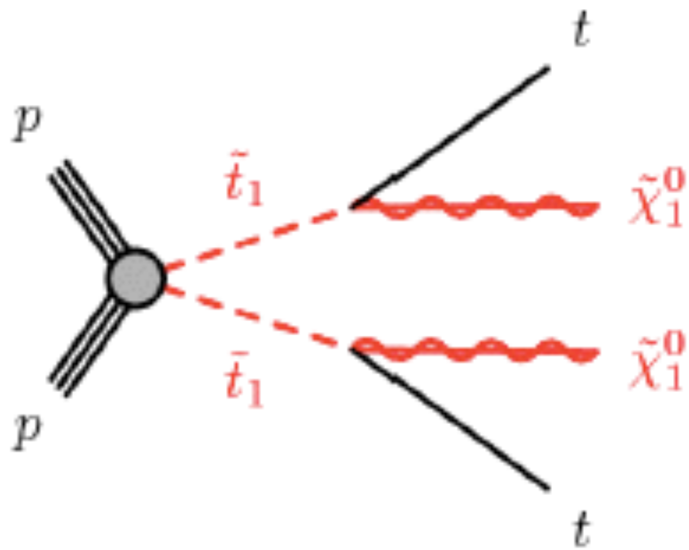
# stop -> top + neutralino (stop 1L)

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

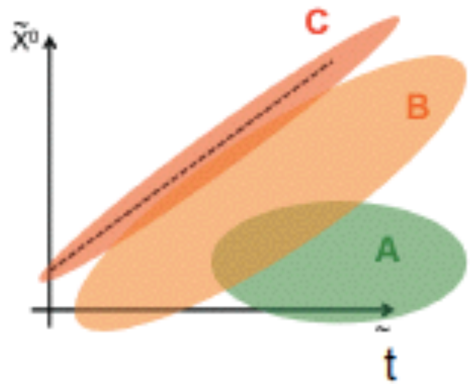
# Using this analysis also to explain the general analysis procedure

**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)

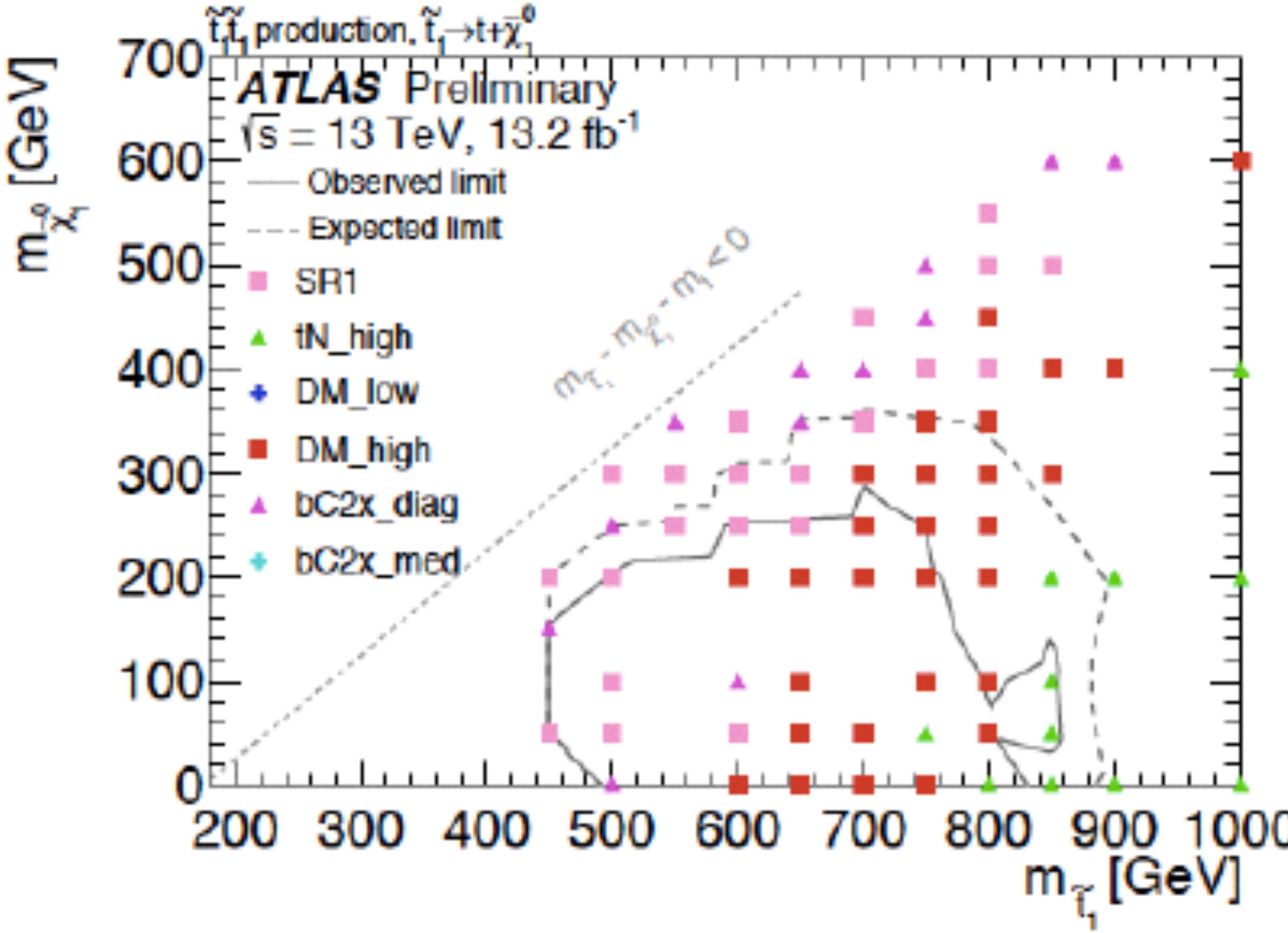
ATLAS-CONF-2016-050 (13.3 fb-1)

arxiv:1606.03903 with 3.2 fb-1

Using this analysis also to explain the general analysis procedure

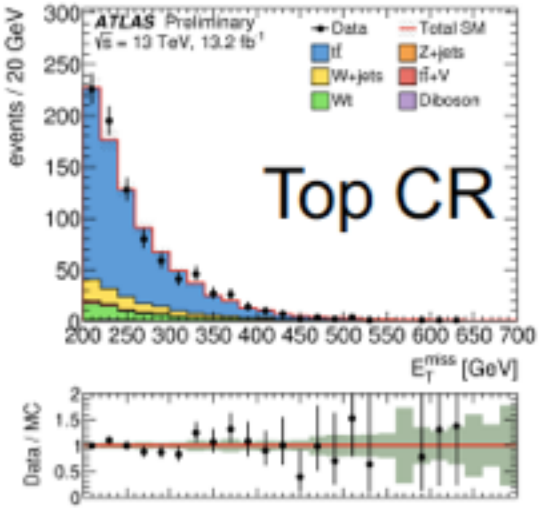
st

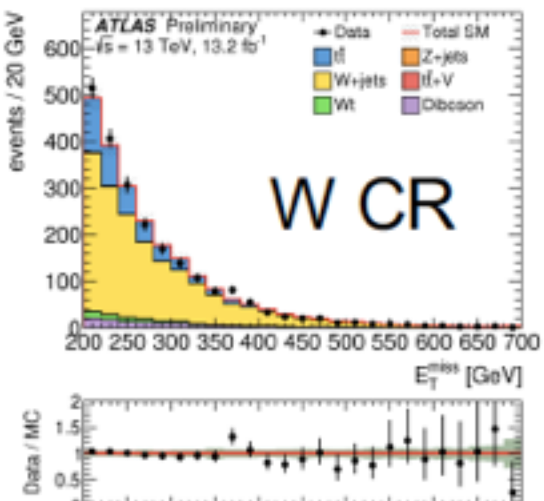
ATL

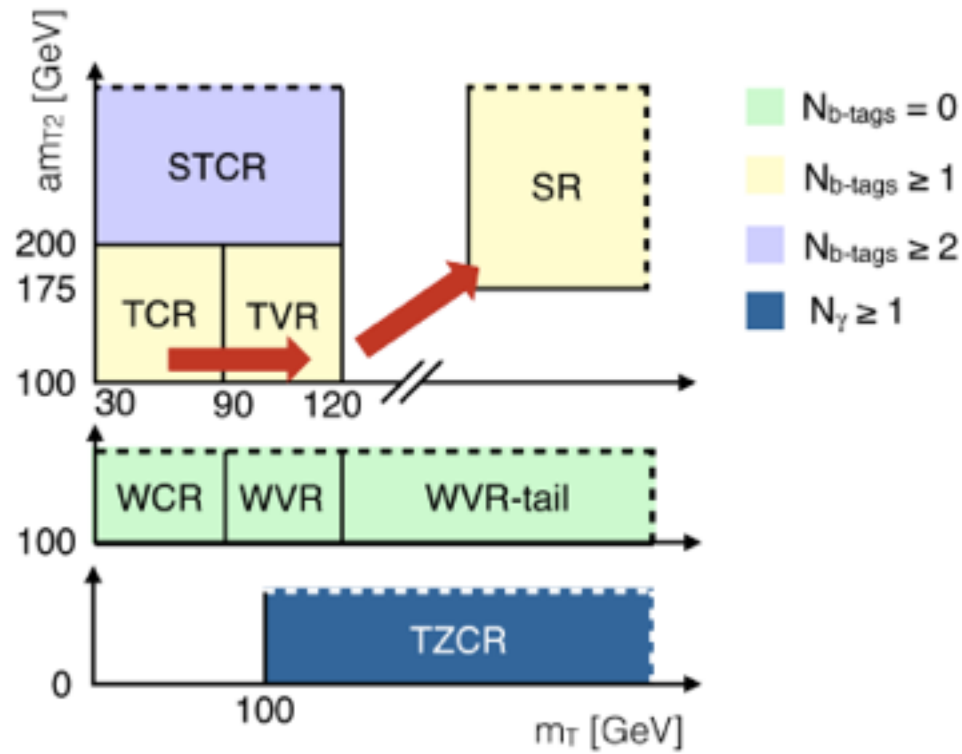


# Control regions (normalization)

# 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

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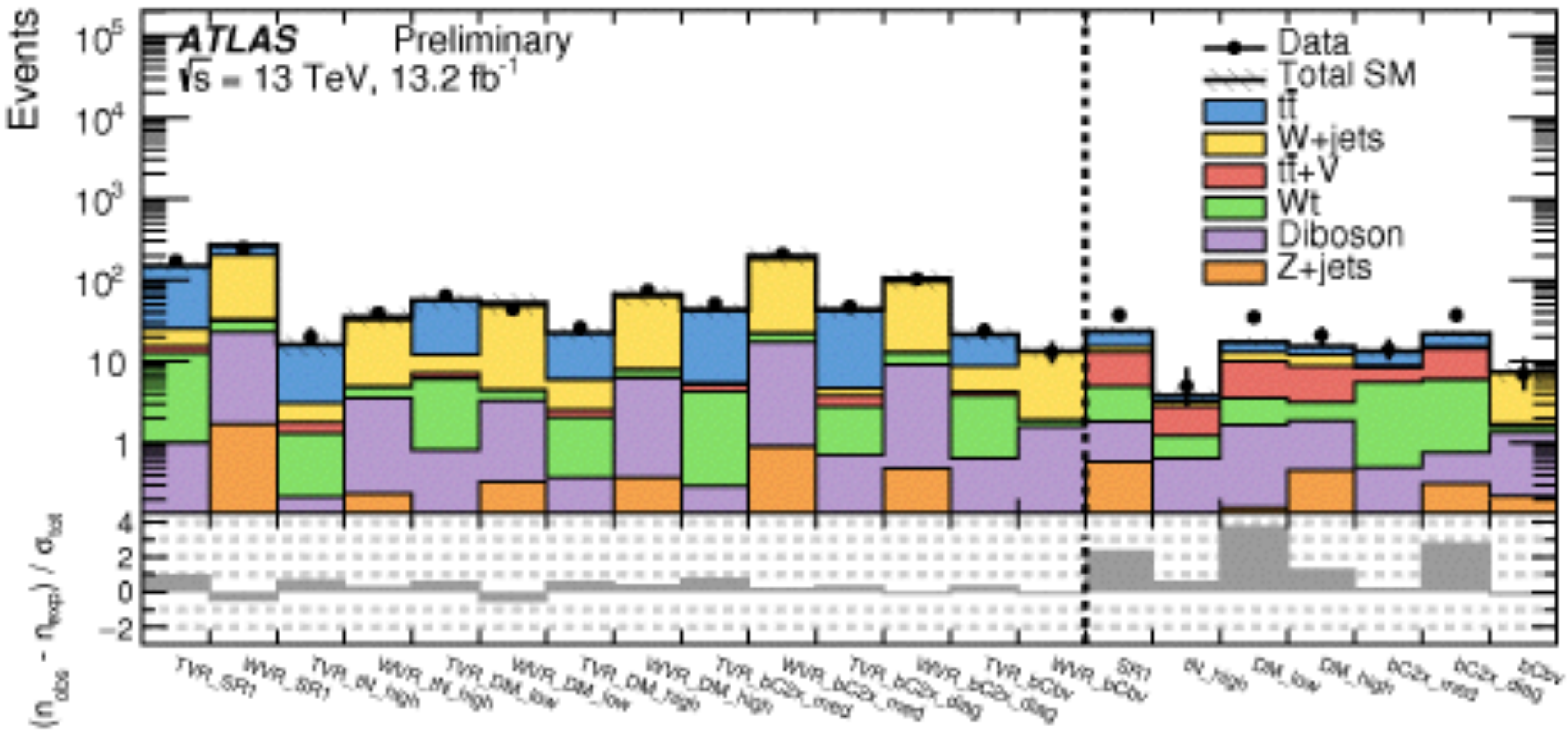

# Signal region and limits stop 1L

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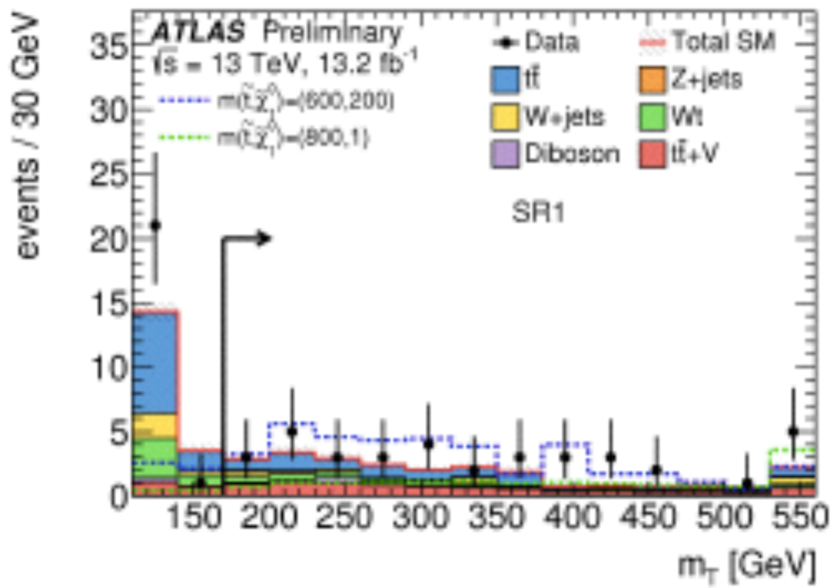
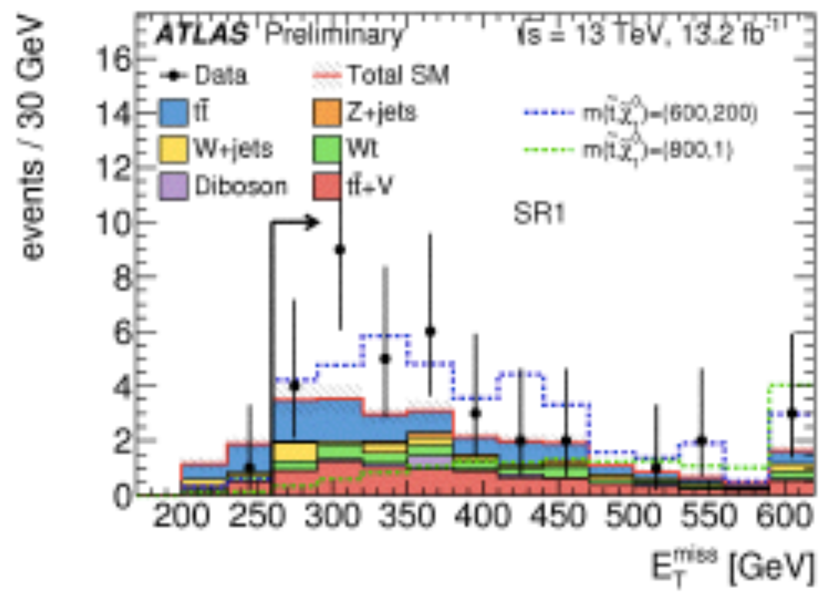
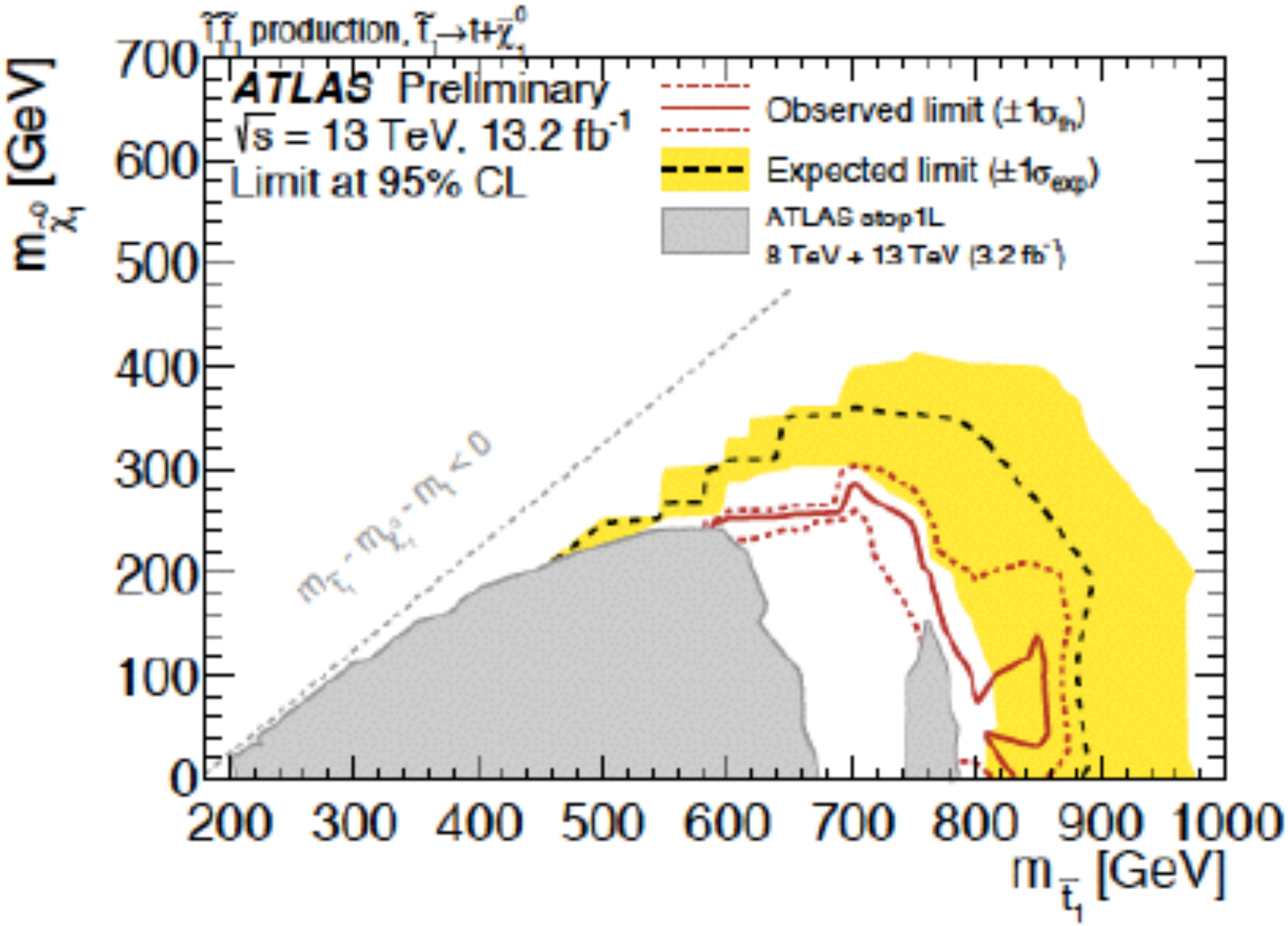


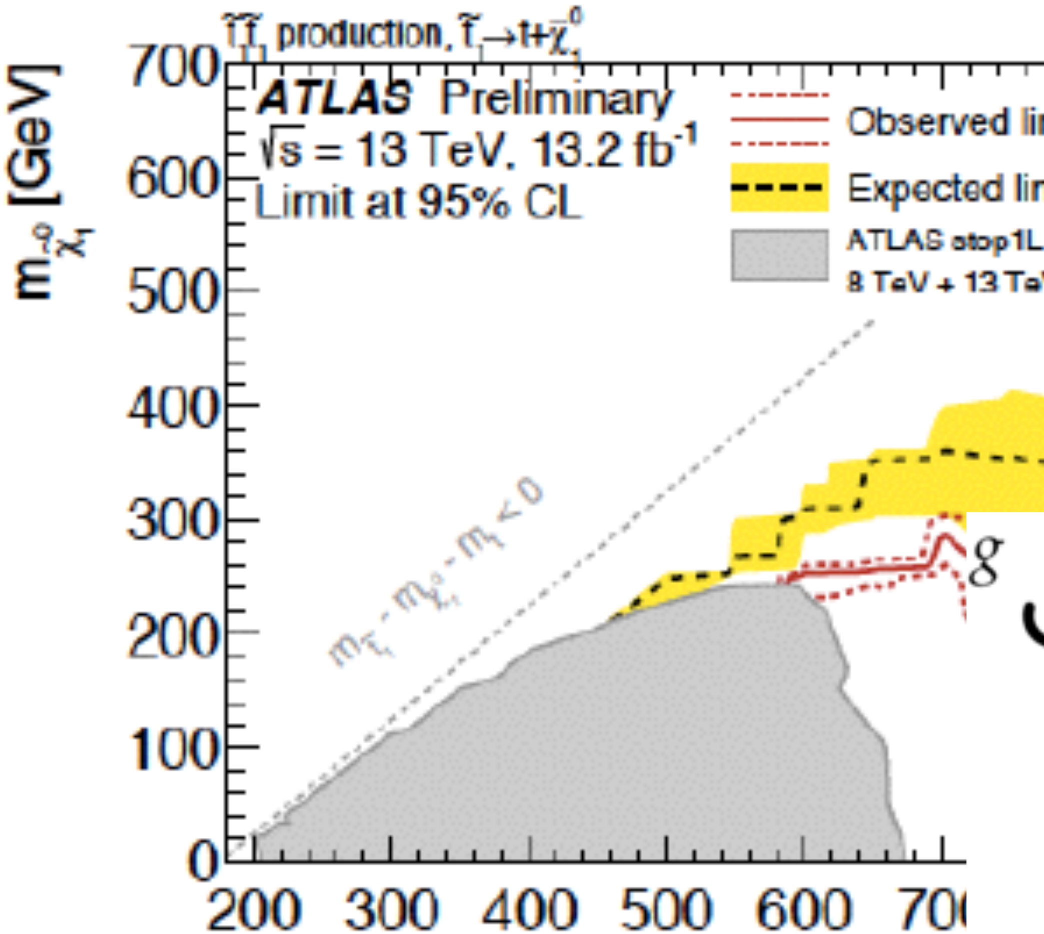



# Signal region and limits stop 1L

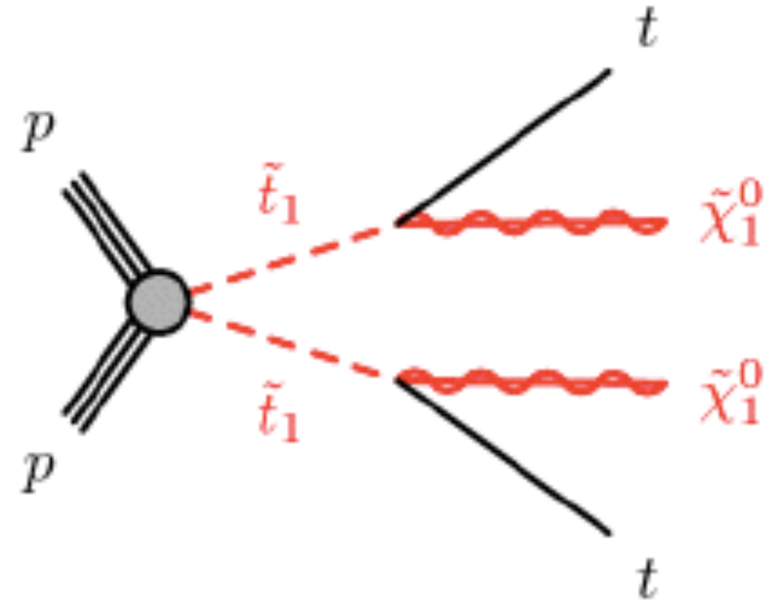
# 1L



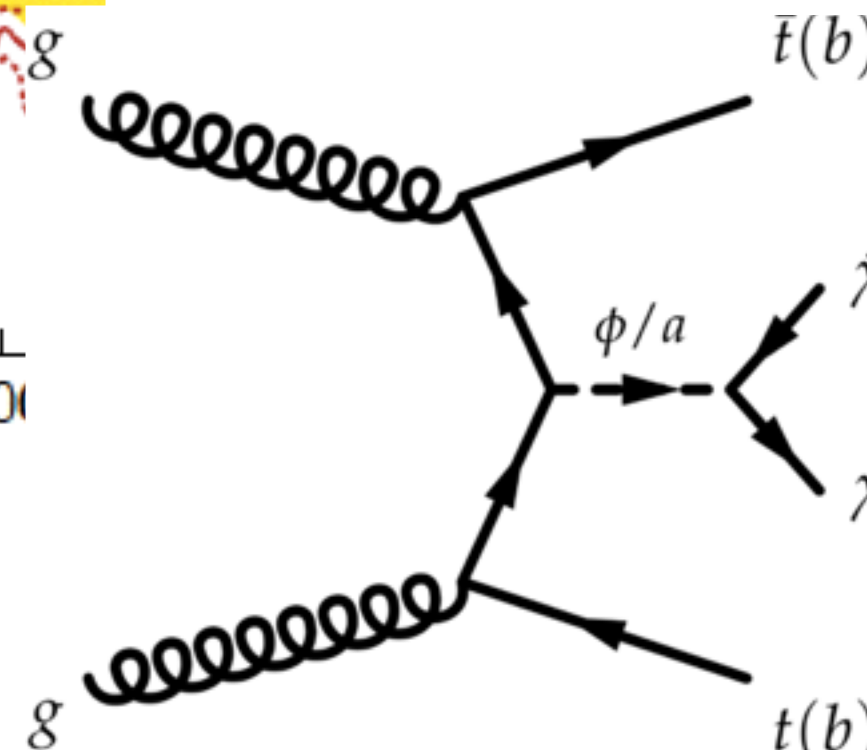
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to t + \tilde{\chi}_1^0$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.2 fb$^{-1}$
Limit at 95% CL
Observed limit ($\pm 1\sigma_{th}$)
Expected limit ($\pm 1\sigma_{exp}$)
ATLAS stop1L
8 TeV + 13 TeV (3.2 fb$^{-1}$)
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}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



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t+\tilde{\chi}_1^0$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.2 fb$^{-1}$
Limit at 95% CL
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t < 0$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
600
700
200
300
400
500
600

$p$
$p$
$\tilde{t}_1$
$\tilde{t}_1$
$t$
$t$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

$g$
$g$
$\bar{t}(b)$
$t(b)$
$\phi/a$
$\bar{\chi}$
$\chi$

# Why Supersymmetry?

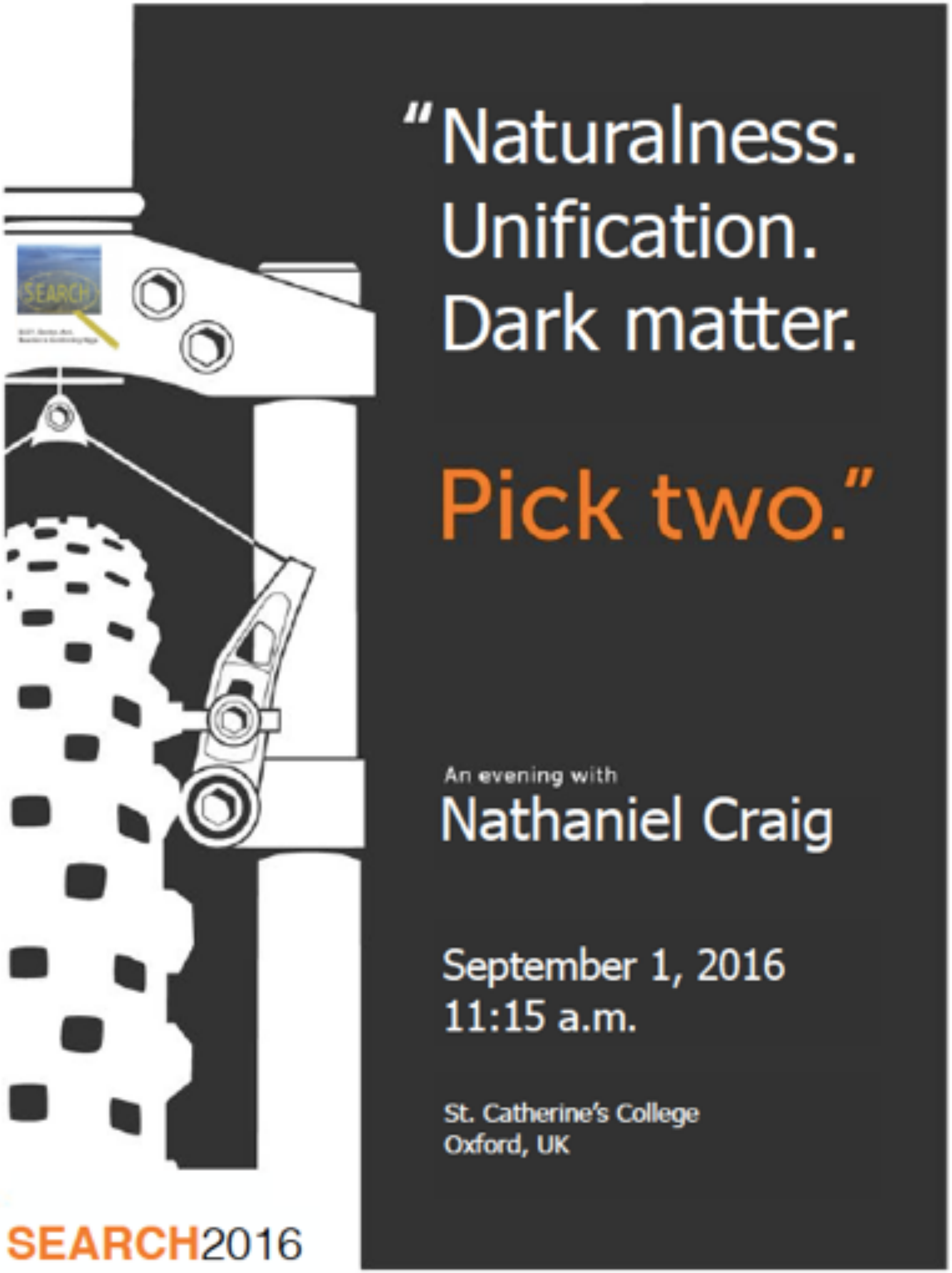
- ☑ Hierarchy problem
- ☑ Gauge coupling unification
- ☑ WIMP dark matter

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.*


Famous truism in the MTB industry:

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

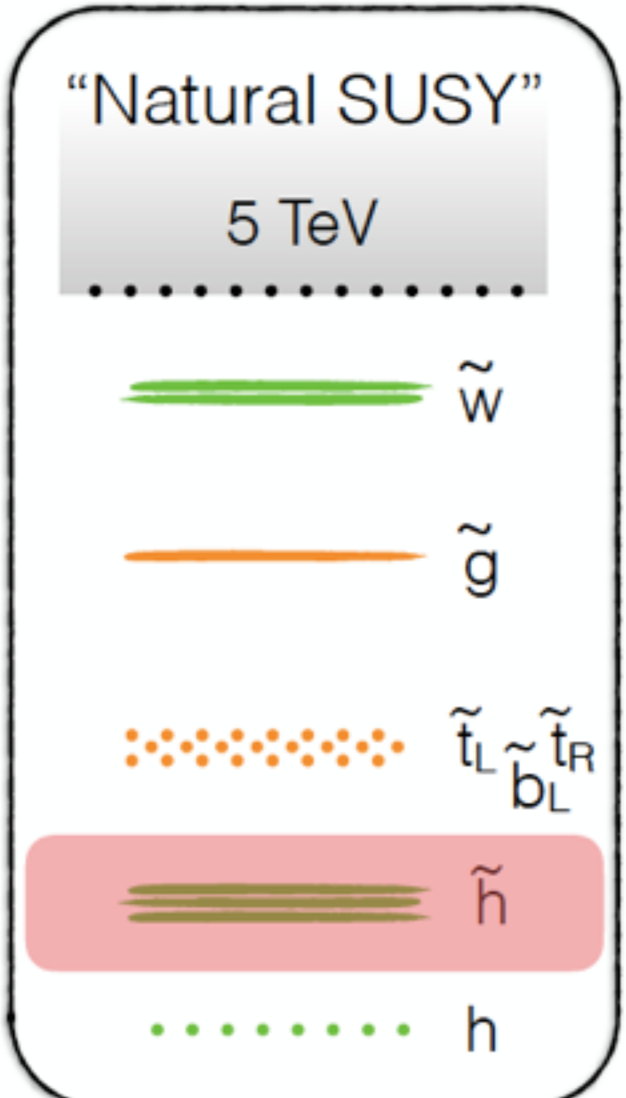



Supersymmetry in light of data:

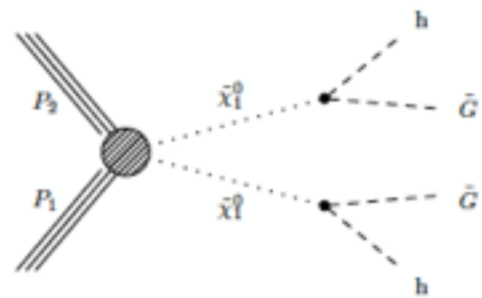
Impossible to have a simple theory that is natural, unifies, and gives WIMP DM.

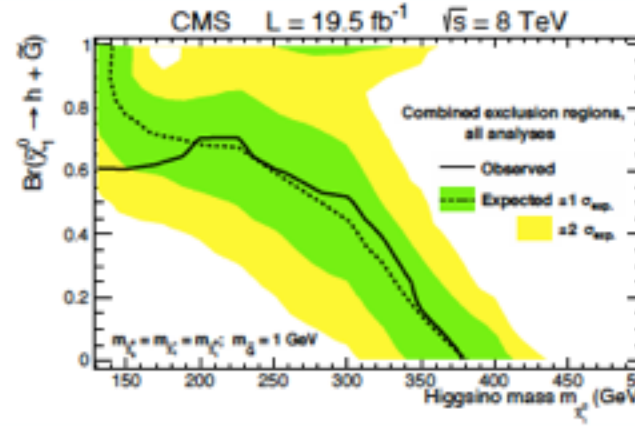
Picking two is a useful guide.

# Where we are now: Higgsinos



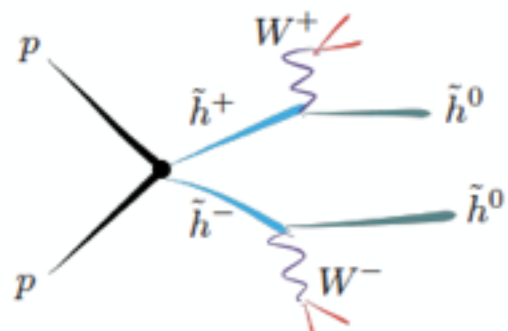

Lots of searches…

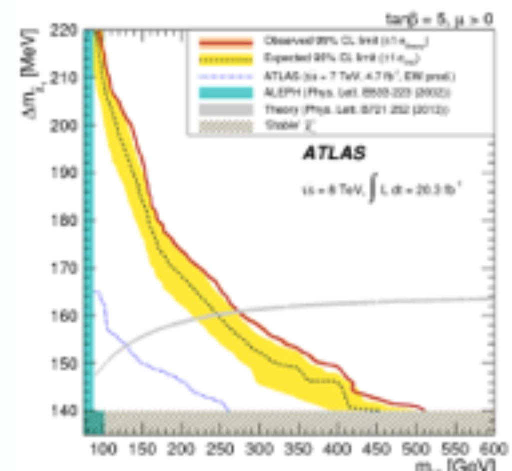


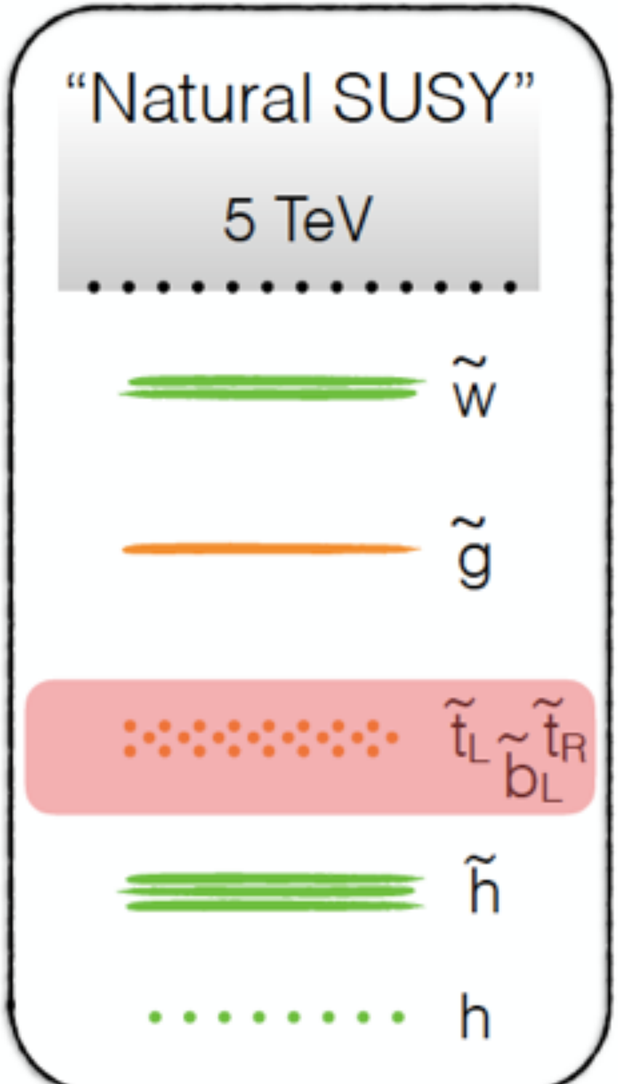

…but no irreducible limits

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

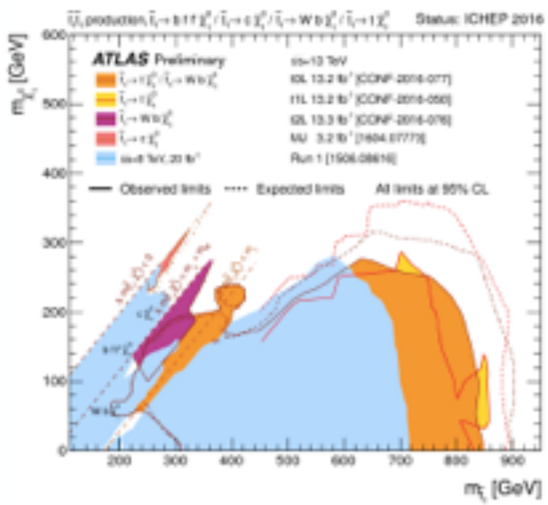


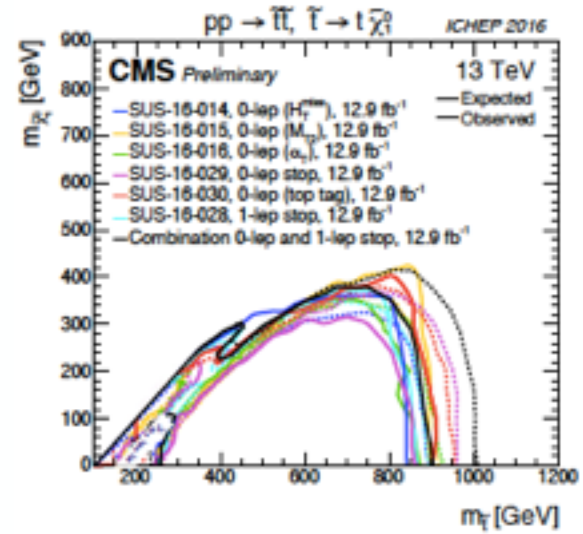



# Where we are now: Stops




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



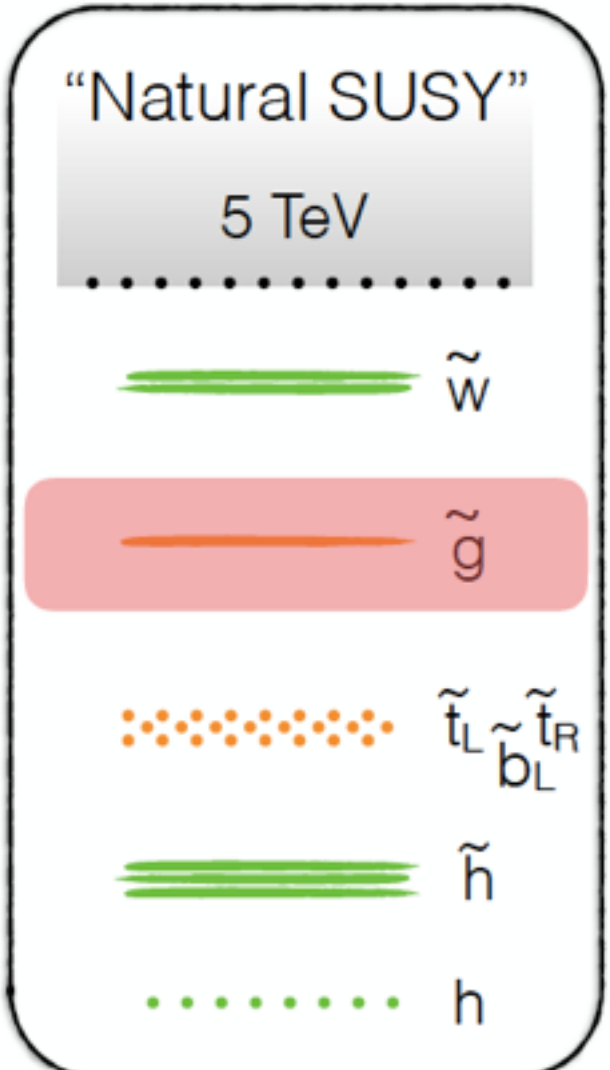




Generic limit > 800 GeV (both stops)

→ **Δ~90 (1% tuning)**

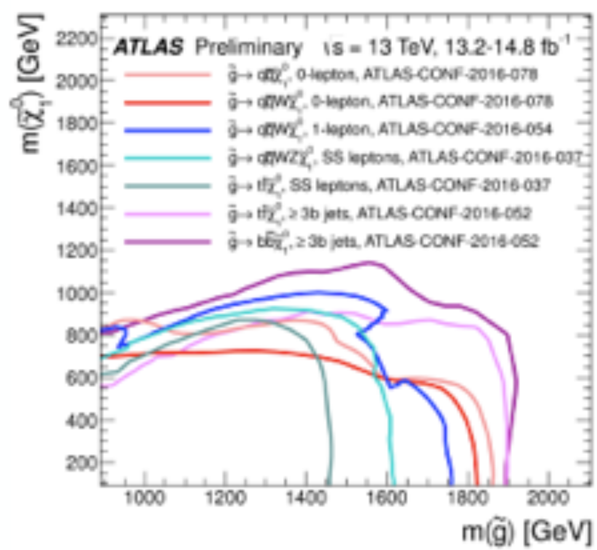
(Λ = 100 TeV)*

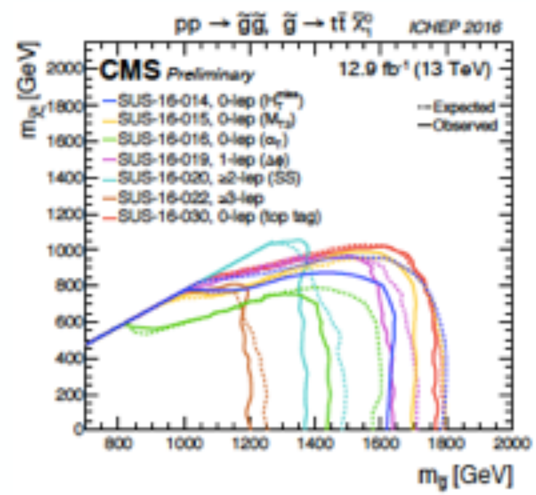
# Where we are now: Gluinos




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

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




Generic limit > 1800 GeV

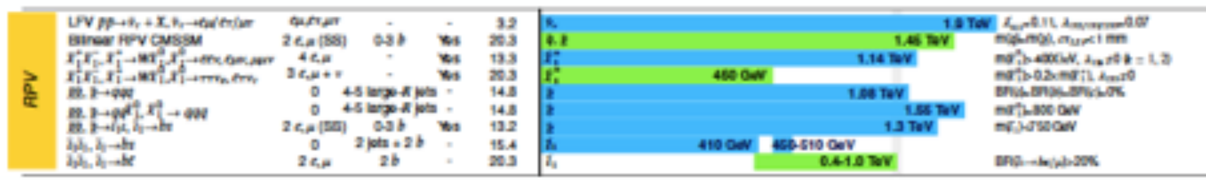
→ **Δ~57 (2% tuning)**

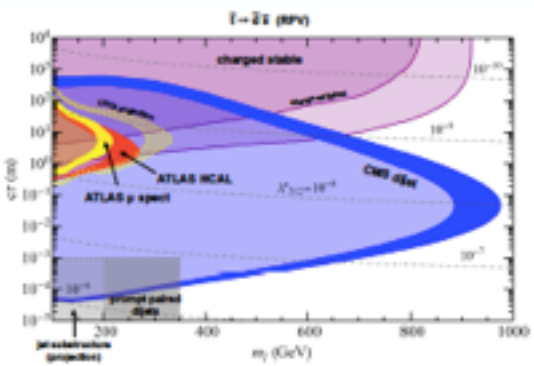
(Λ = 100 TeV)

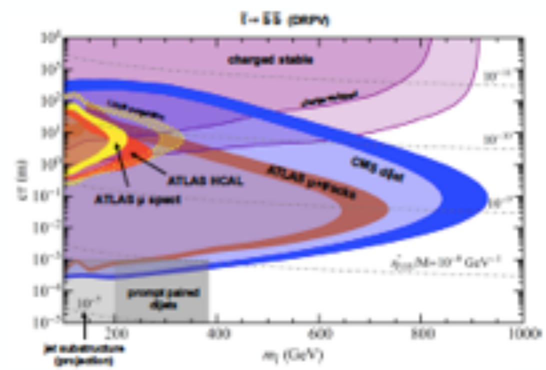
# Naturalness & Unification

*Violate the parity that gave you DM (RPV).*

**Lesson 1**: Leptonic RPV kills you quickly.

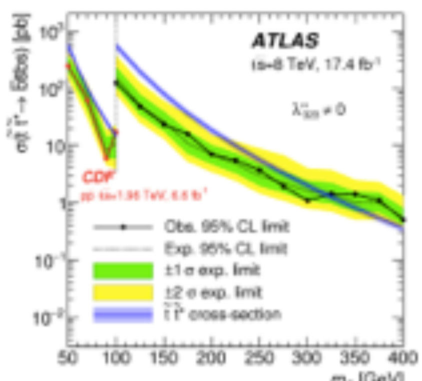


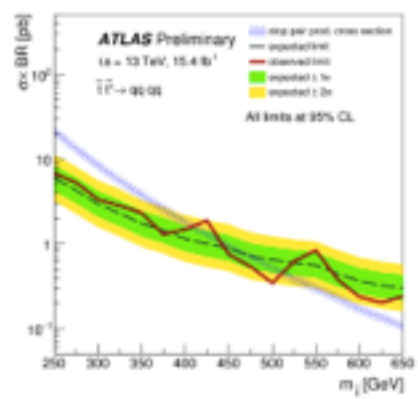



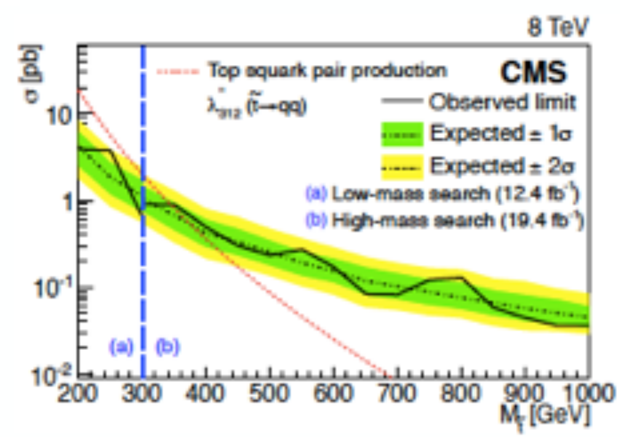




**Lesson 2**: Displacement kills you quickly. [Liu, Tweedie 1503.05923]

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



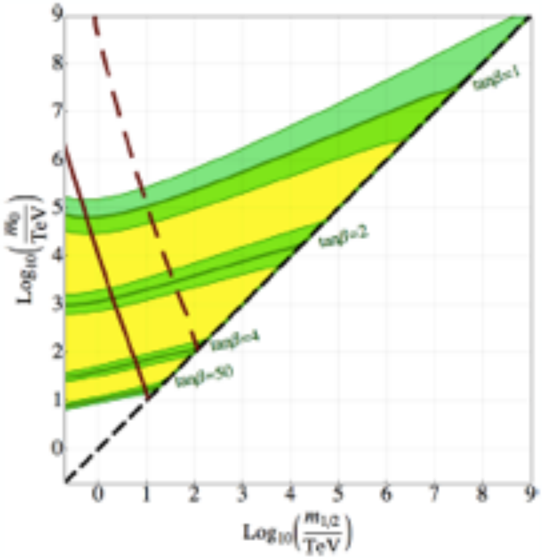



# Unification & Dark Matter

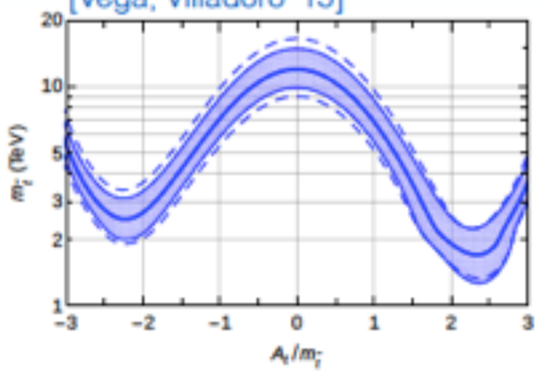
*Forget the scalars, keep the fermions at a TeV.*

[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]



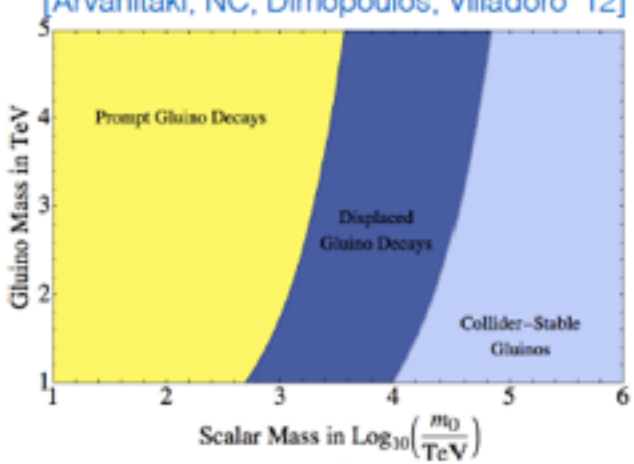

Pressure from unification & DM to keep higgsinos & gauginos beneath ~10 TeV

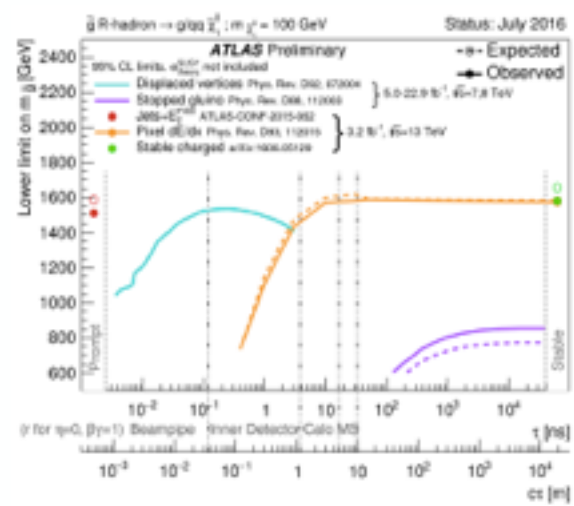
"Split / mini-split"

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

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

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

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

$$\mathcal{G} \to \mathcal{H}$$

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

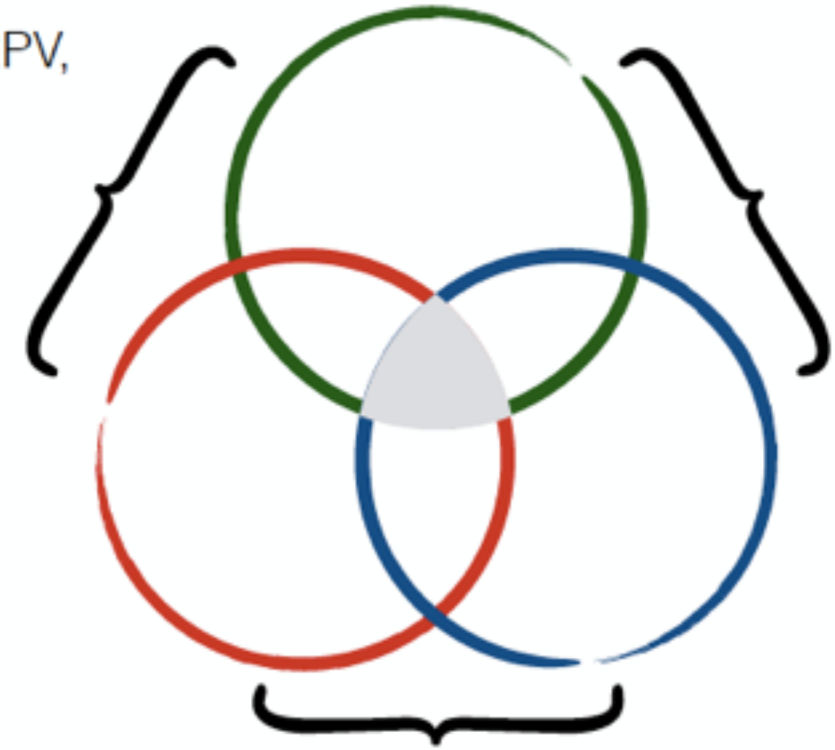
*Look for the new stuff. Often large cross sections or resonantly produced.*

**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>

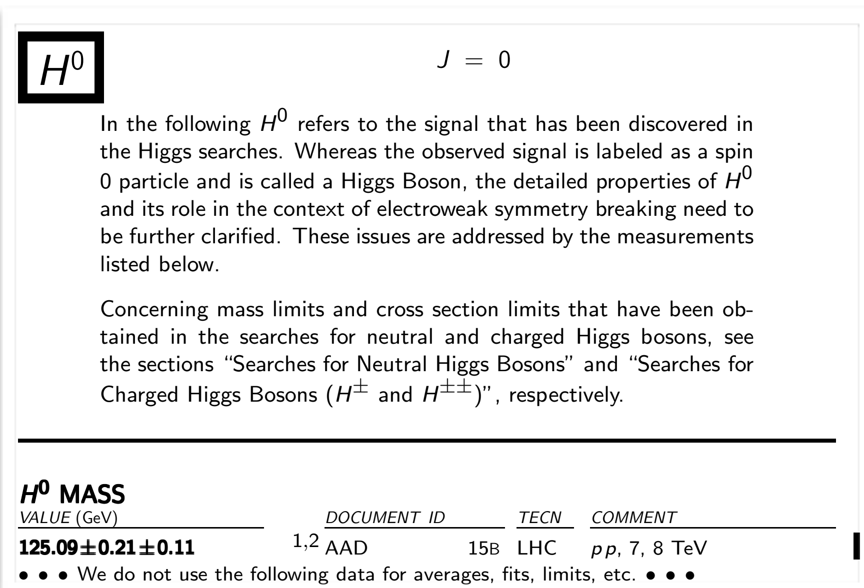
# Getting to know the new particle

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):

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

- Measure **couplings** (including self-coupling)



$H^0$

$J = 0$

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.

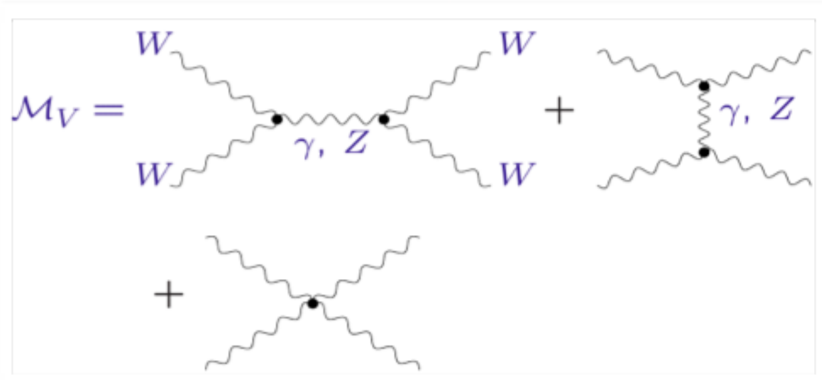
**$H^0$ MASS**

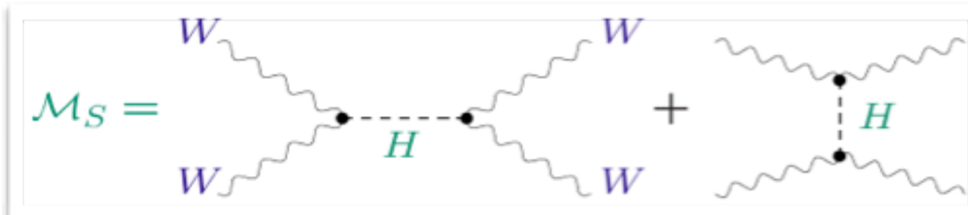
| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **125.09±0.21±0.11** | [1,2] AAD | 15B | LHC | $pp$, 7, 8 TeV |

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

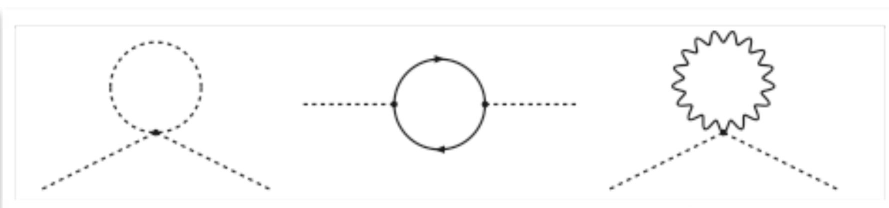
# The Hierarchy Problem

- 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




LEP/LIBRARY

ps

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 !

$H^0$ $J = 0$

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.

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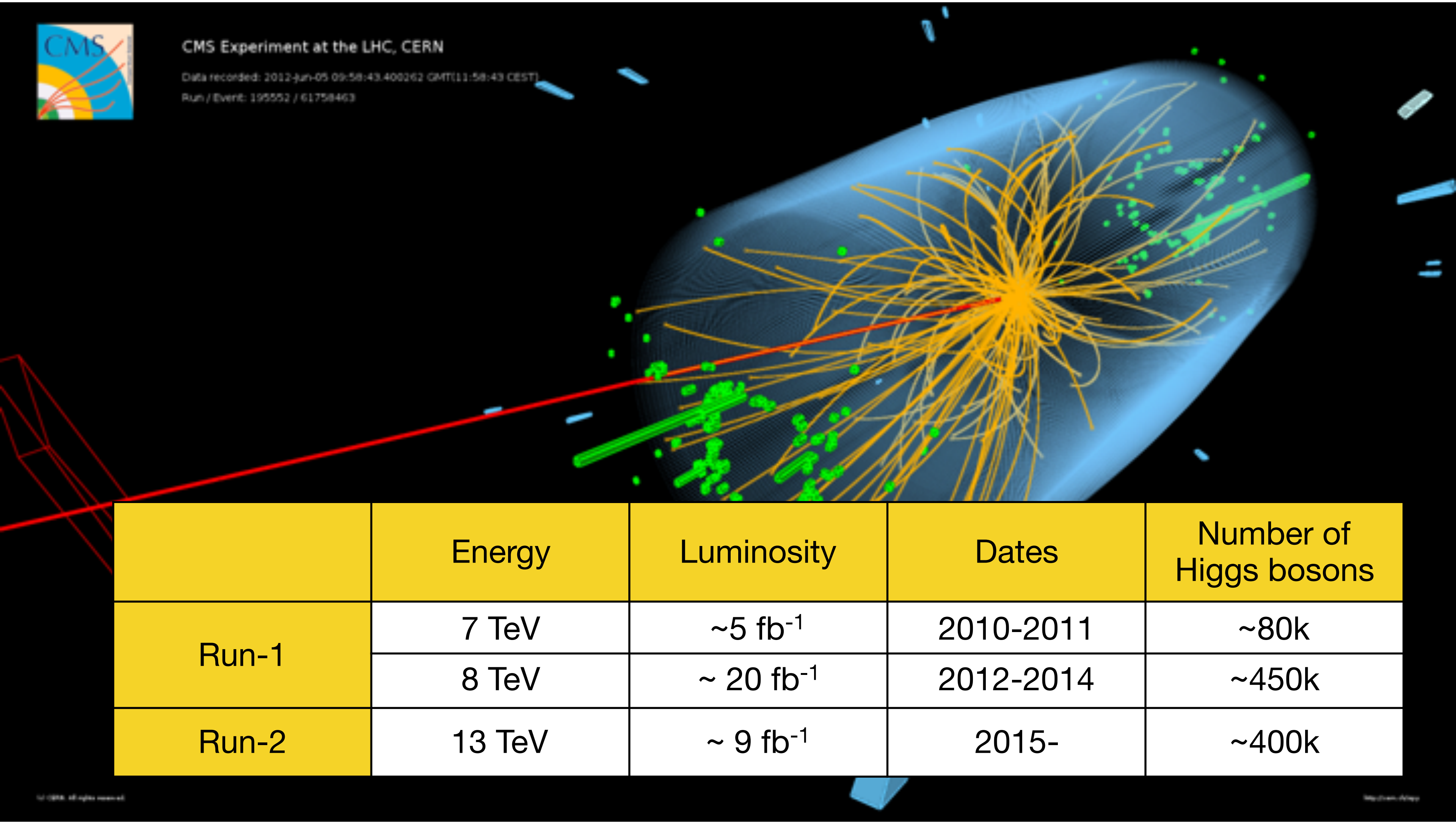
|---|---|---|---|---|
| **125.09±0.21±0.11** | [1,2] AAD | 15B | LHC | $pp$, 7, 8 TeV |

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

# It's real … it's in the PDG

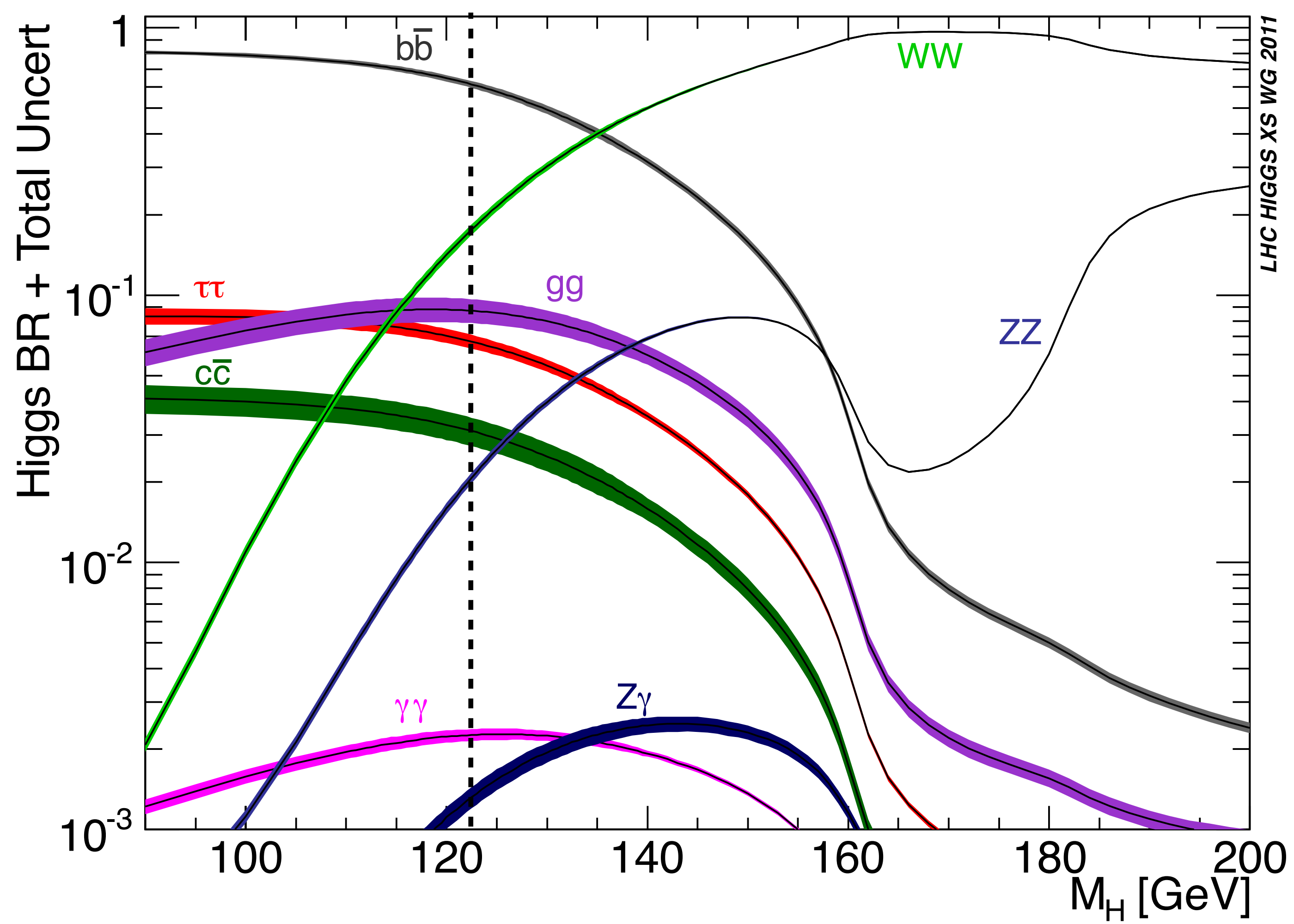
# How many Higgs' ?




| | 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?*

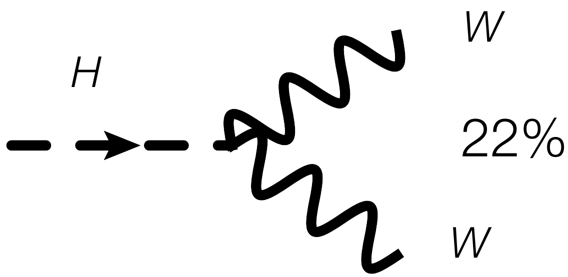
# Incredibly Lucky?

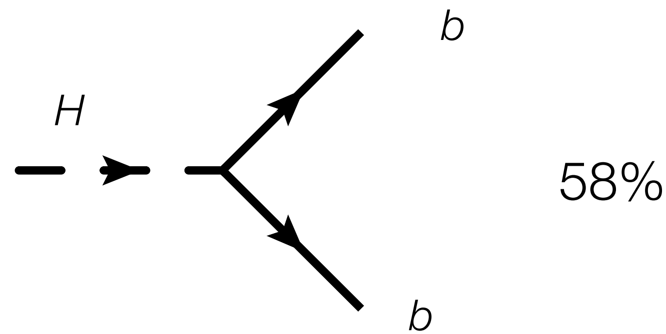


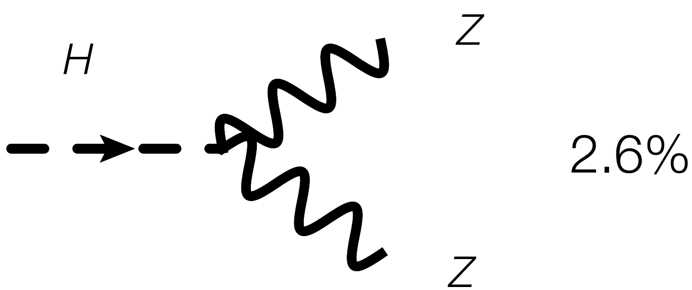

Nature just happened to choose a Higgs mass for which almost all experimental channels are accessible

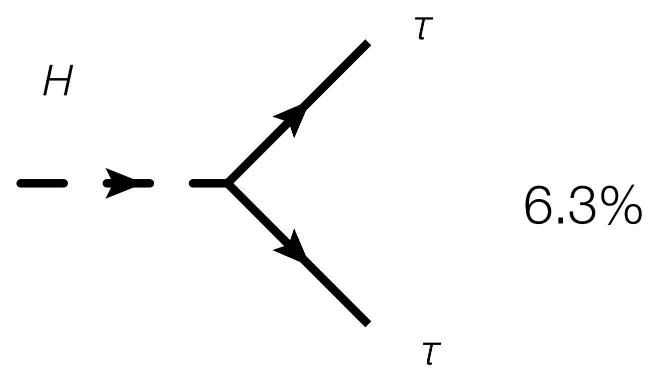
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

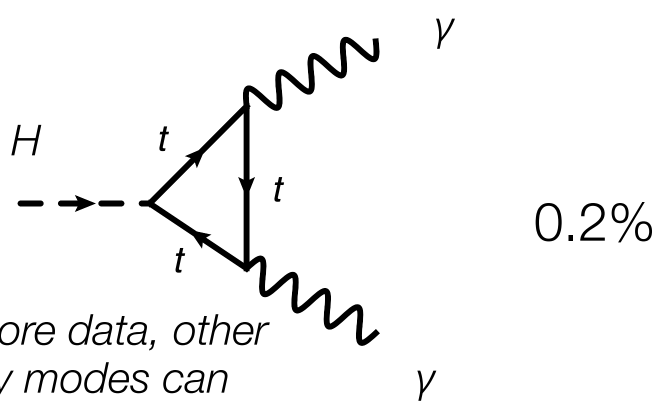
# Higgs Decays: The Big 5



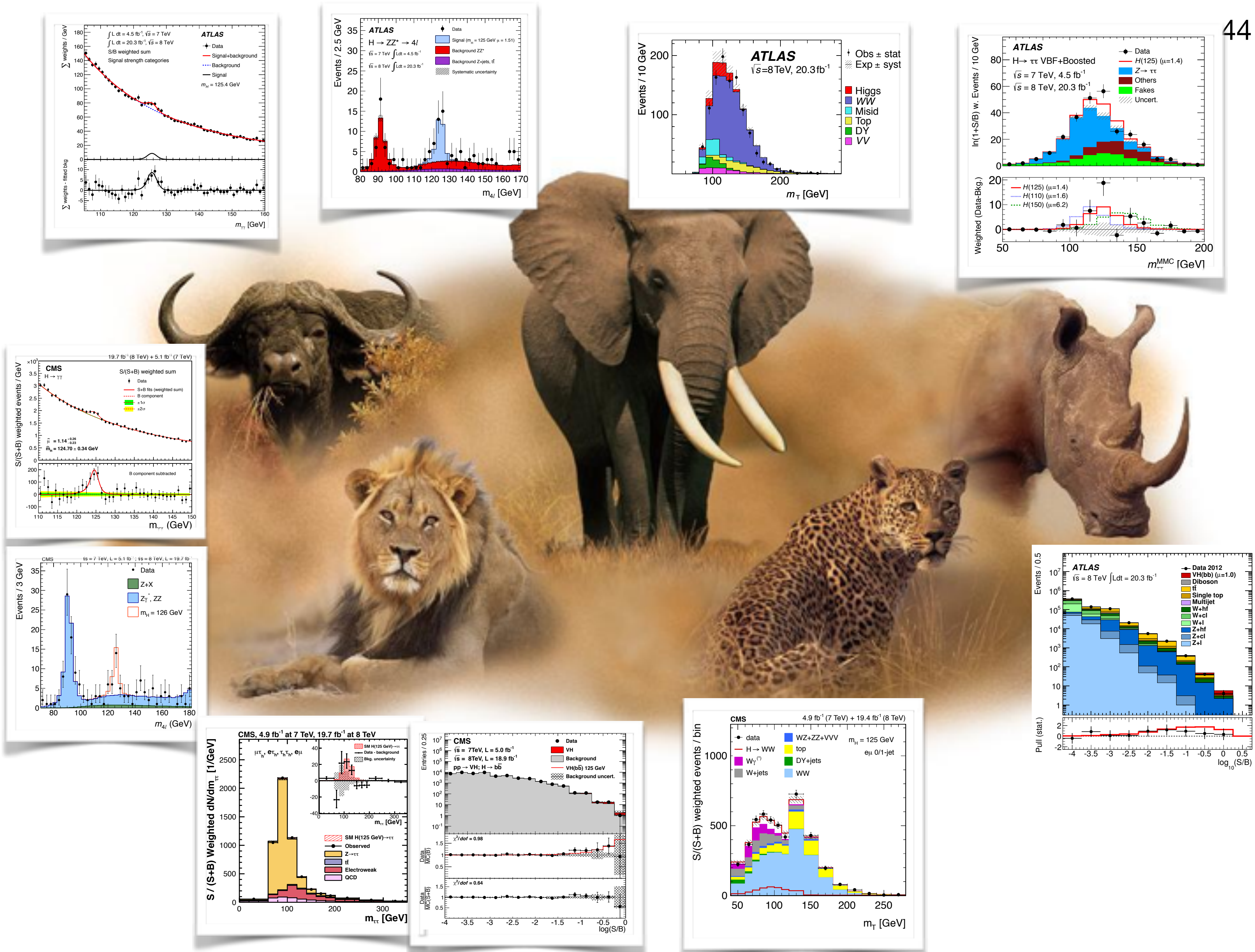




| Decay channel | Mass resolution |
|---|---|
| $H \to \gamma\gamma$ | 1-2% |
| $H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ | 1-2% |
| $H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ | 20% |
| $H \to b\bar{b}$ | 10% |
| $H \to \tau^+\tau^-$ | 15% |

*With more data, other decay modes can also be studied*


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
Background ZZ*
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(110) (μ=1.6)
H(150) (μ=6.2)
Weighted (Data-Bkg.)
$m_{\tau\tau}^{MMC}$ [GeV]
CMS
H → γγ
S/(S+B) weighted sum
Data
B component subtracted
$m_H$ = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
$m_{\gamma\gamma}$ (GeV)
CMS
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
tt
Single top
Multijet
W+hf
W+cl
W+l
Z+hf
Z+cl
Z+l
Events / 0.5
Pull (stat.)
$\log_{10}$(S/B)
CMS, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
tt
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 → bb
Data
VH
Background
VH(bb) 125 GeV
Background uncert.
Entries / 0.25
log(S/B)
CMS
4.9 fb⁻¹ (7 TeV) + 19.4 fb⁻¹ (8 TeV)
data
H → WW
Wγ(*)
W+jets
WZ+ZZ+VVV
top
DY+jets
WW
$m_H$ = 125 GeV
eμ 0/1-jet
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 | | | | |

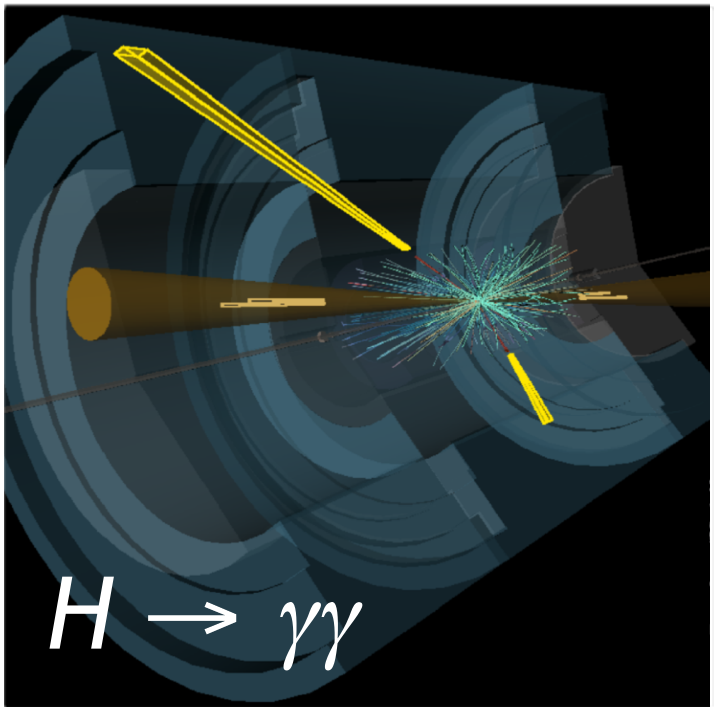
*Searches for almost every* decay modes and production channels*

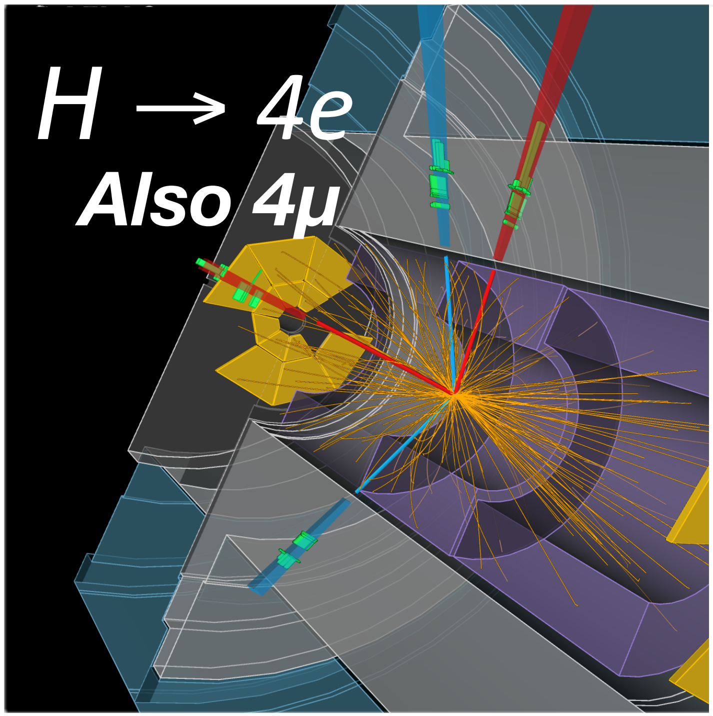
*of course, there are some more exotic production and decay modes

# Discovery Channels

An excellent channel for
$m_H$ = 125 GeV

Golden channel over a
wide mass range




$N_S \sim 500$

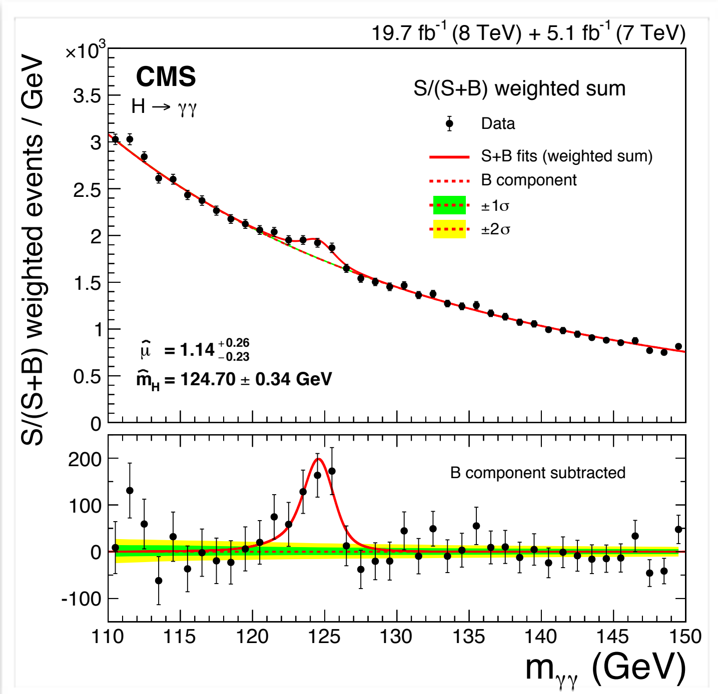
$N_S \sim$ 20-30

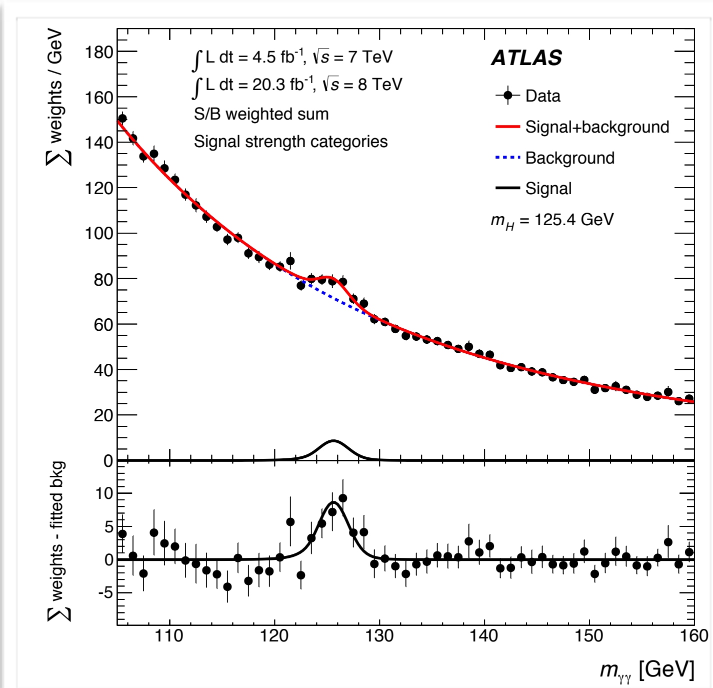
Simple channels with excellent mass resolution

# Higgs to two photons ($H \to \gamma\gamma$)

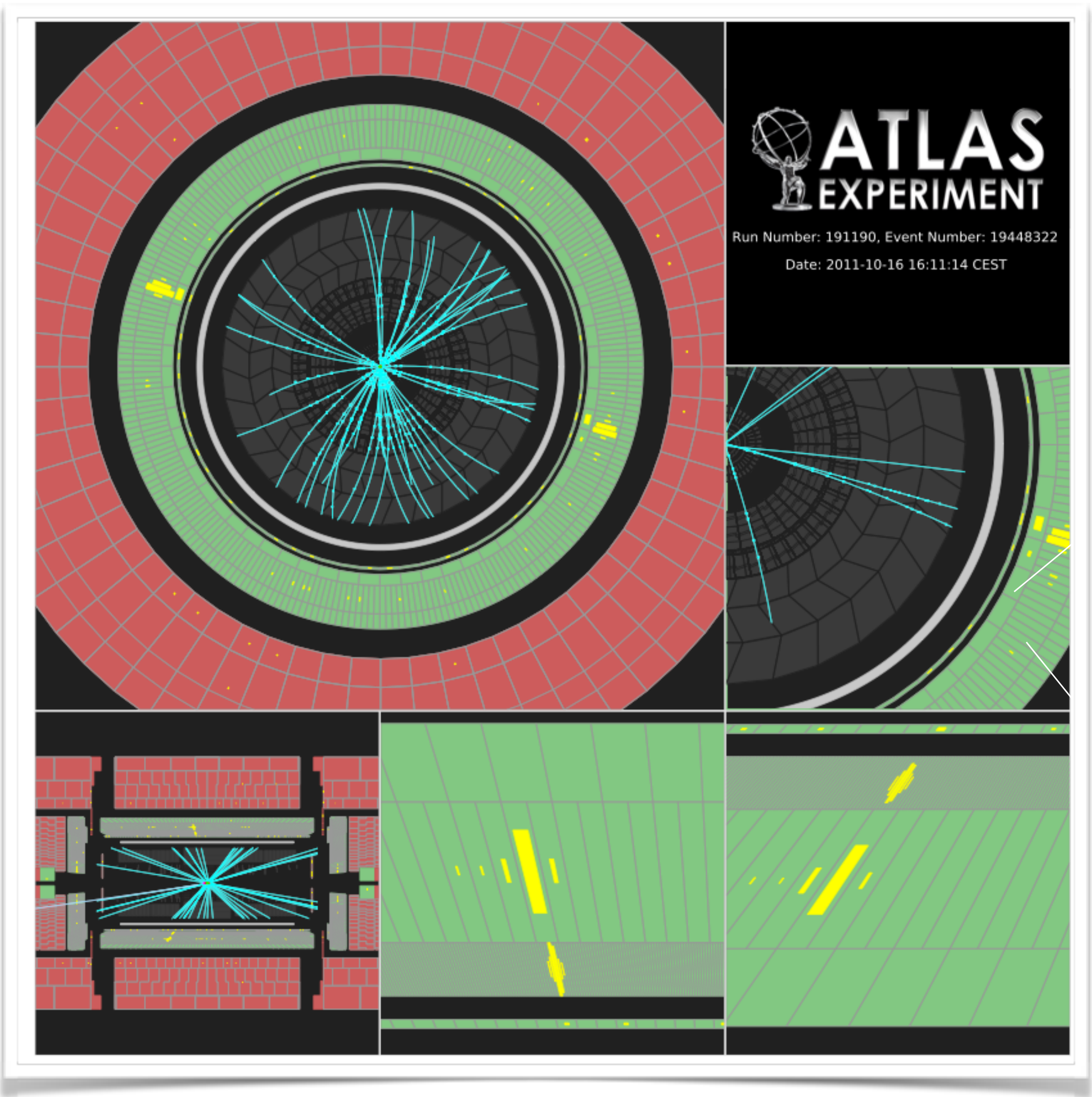
HIGG-2013-08
HIG-13-001

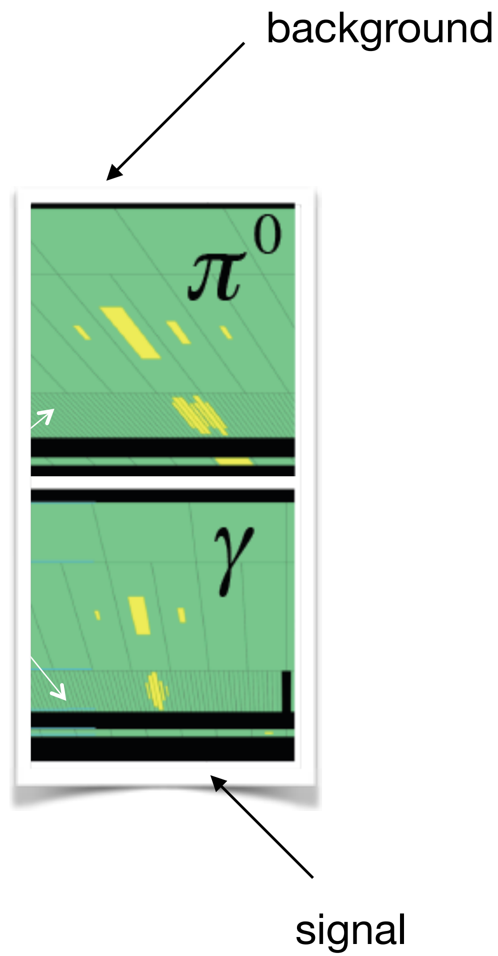
- A good **discovery** final state
  - Resonance on top of a **smooth background**
  - Excellent Higgs mass **resolution**
- Large backgrounds: need good **photon identification**
  - Key consideration in calorimeter design



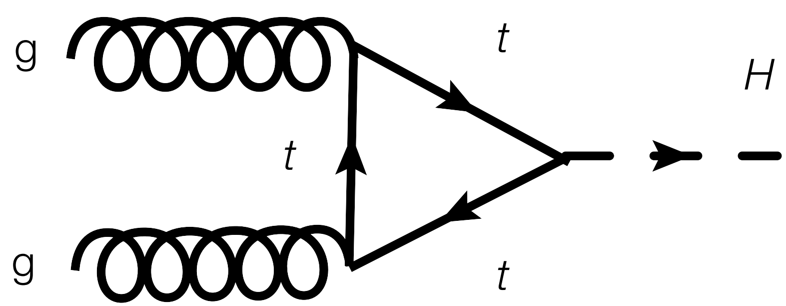
# H→γγ: Signal and Background

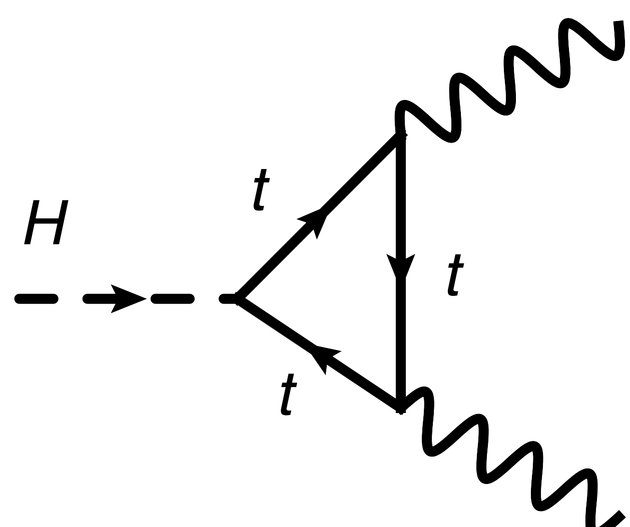


# Production and Decay

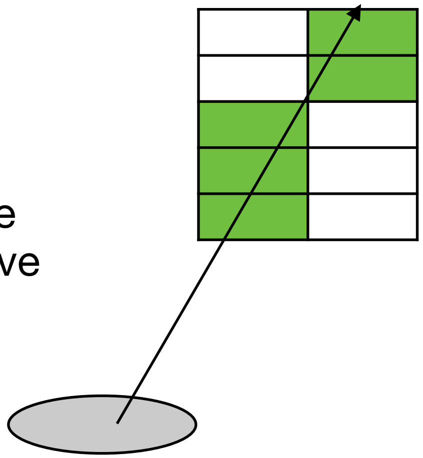
- No coupling of Higgs to gluons
  - Main **production** through a loop containing top (and bottom) quarks
    - Cross-section depends on Higgs coupling to **top**
- **No coupling of the Higgs to photons**
  - Decay through loops containing tops and W bosons
    - Decay depends on coupling to **top**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



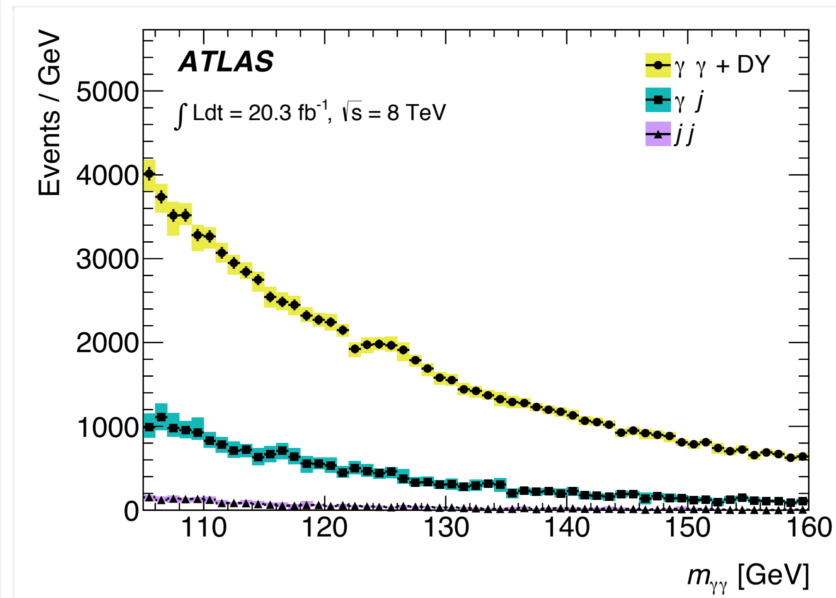



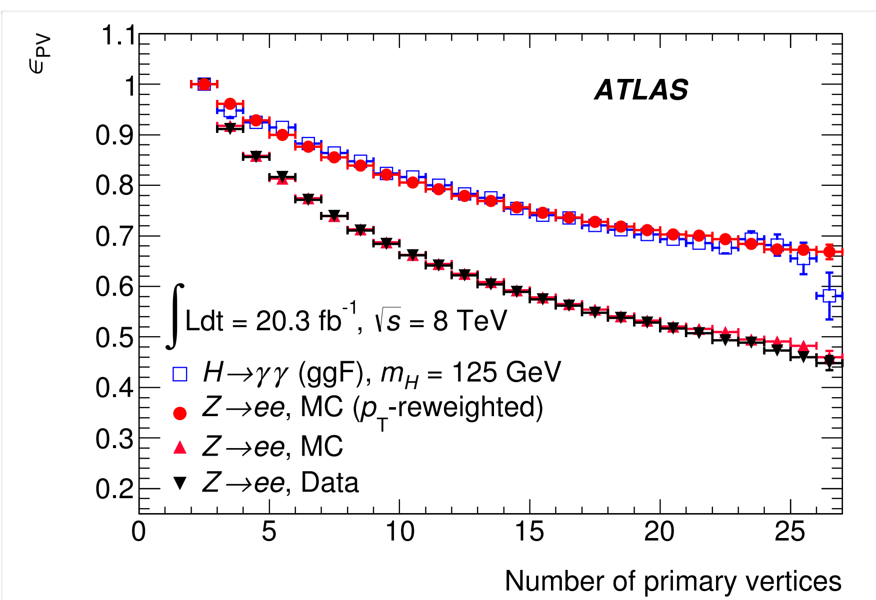
# Backgrounds: pile up and jets

ATLAS uses longitudinal segmentation of the calorimeter to improve vertex resolution



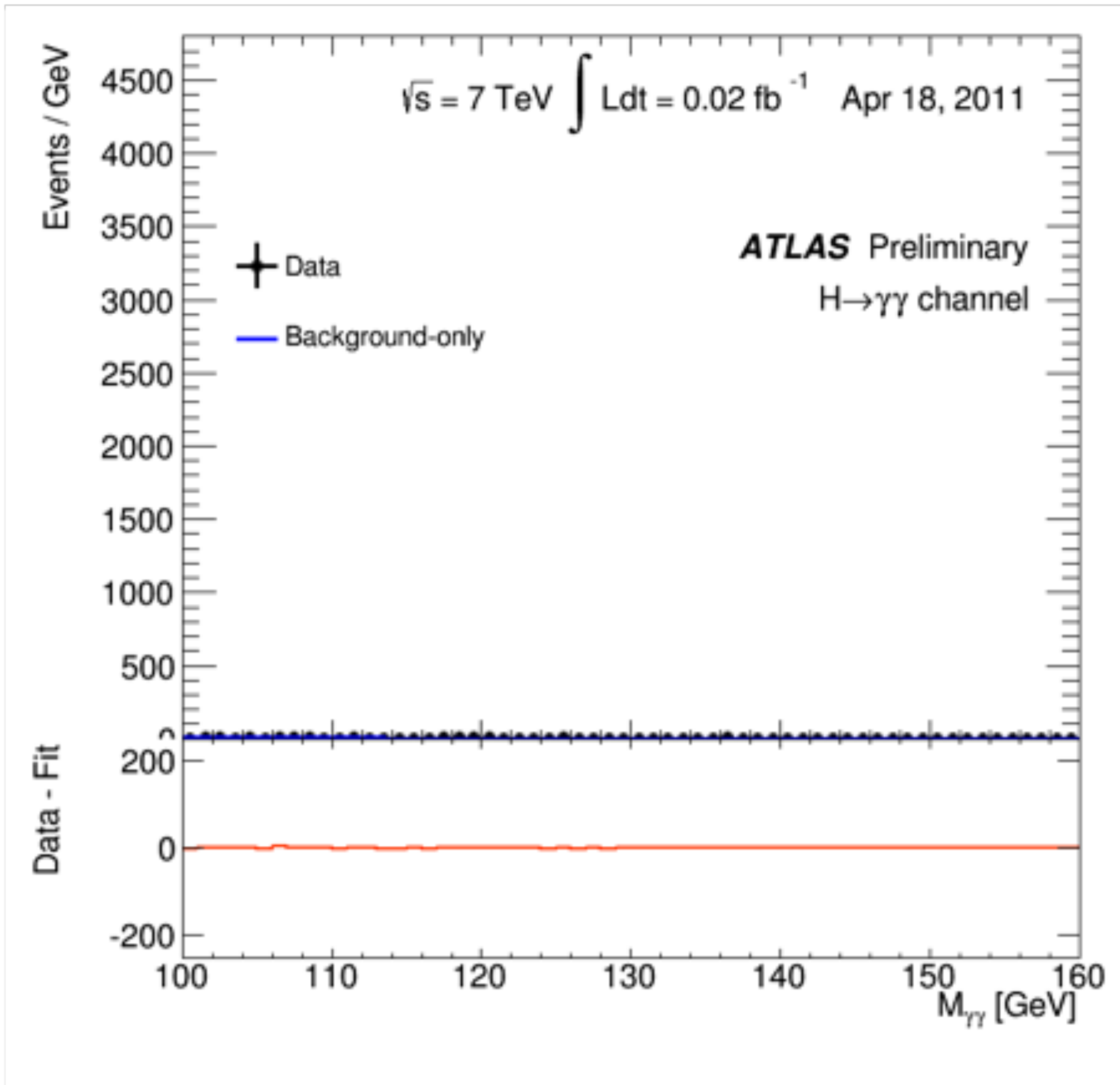
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$



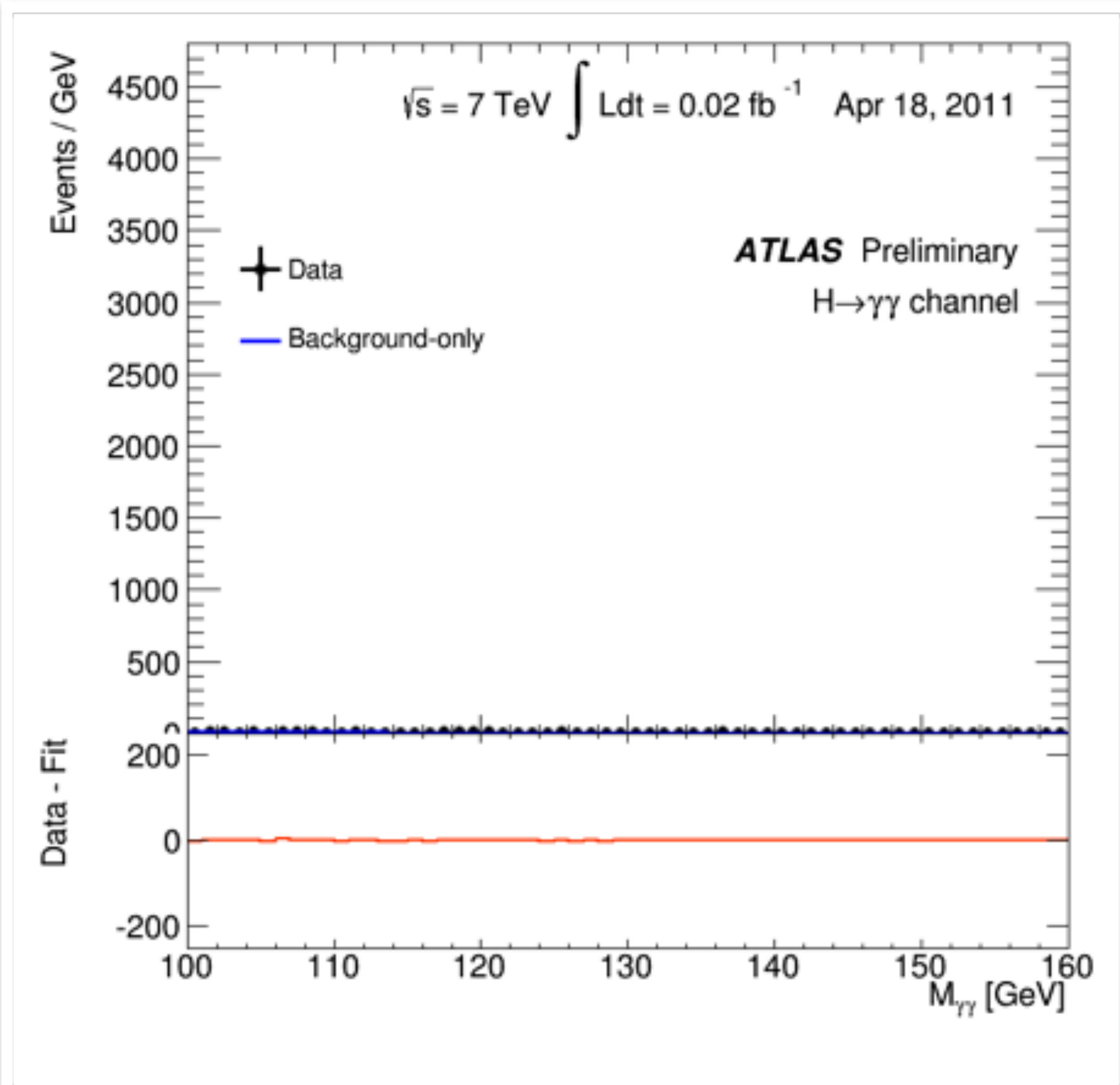




Main background from real photons
Small contribution from jets faking photons

# Higgs to two photons (H→γγ)



# Higgs to two photons (H→γγ)



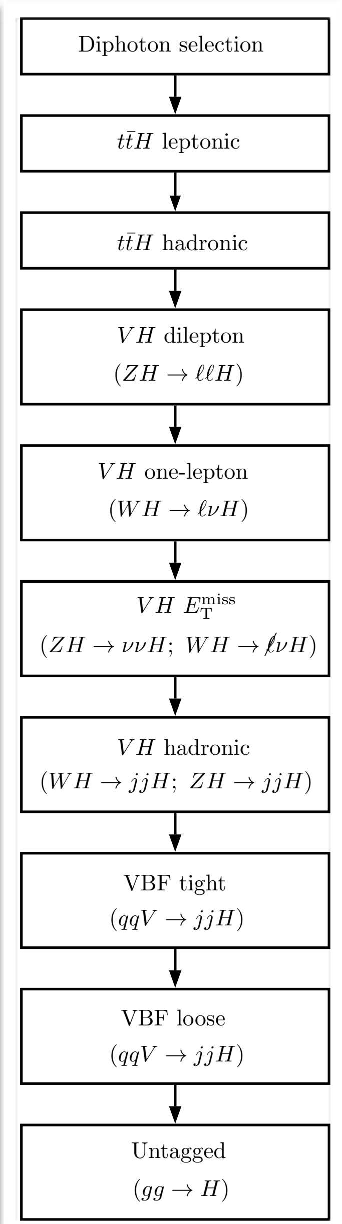
# Why Categories ?

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

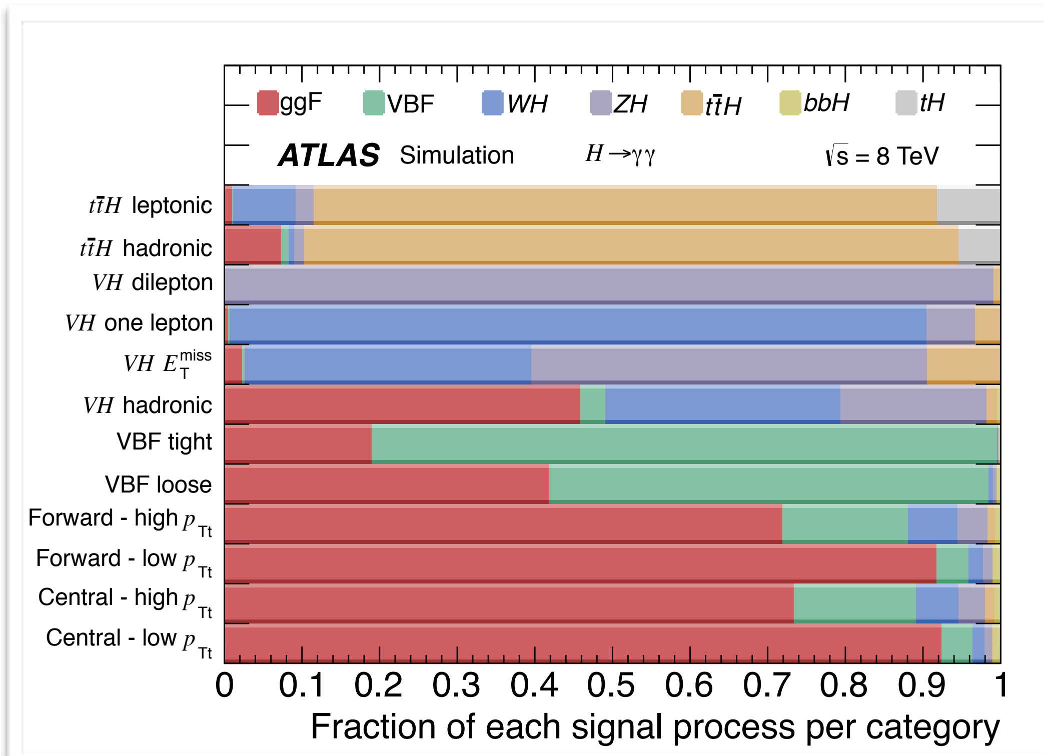
- Take a simple example with two categories:
  - C1: s=12 and b=60
  - C2: s=18 and b=40
- Inclusively we have
  - s = 30
  - b = 100
  - Significance of $3\sigma$
- Now calculate for the two categories
  - C1: $2.85\sigma$
  - C2: $1.55\sigma$
  - Combined significance: 3.24

Improved significance!

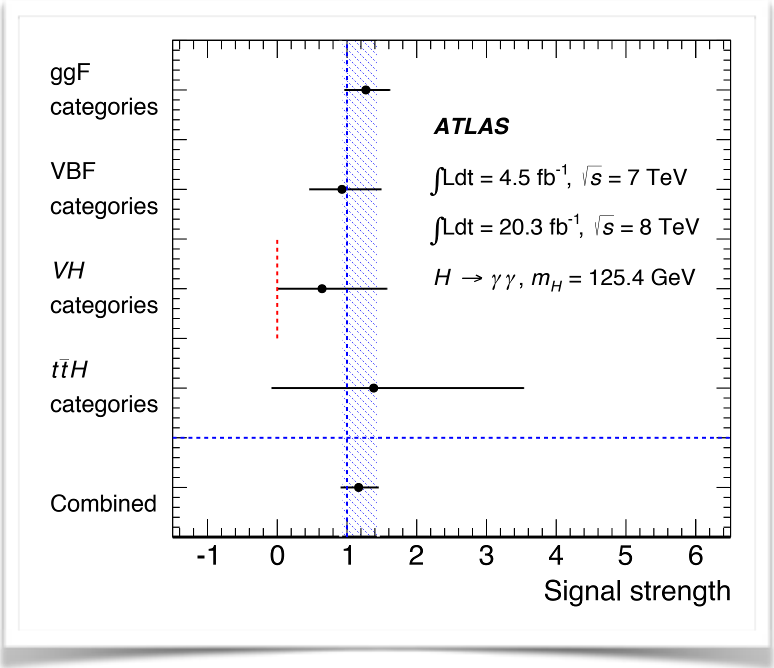
# Improving Sensitivity: Categories

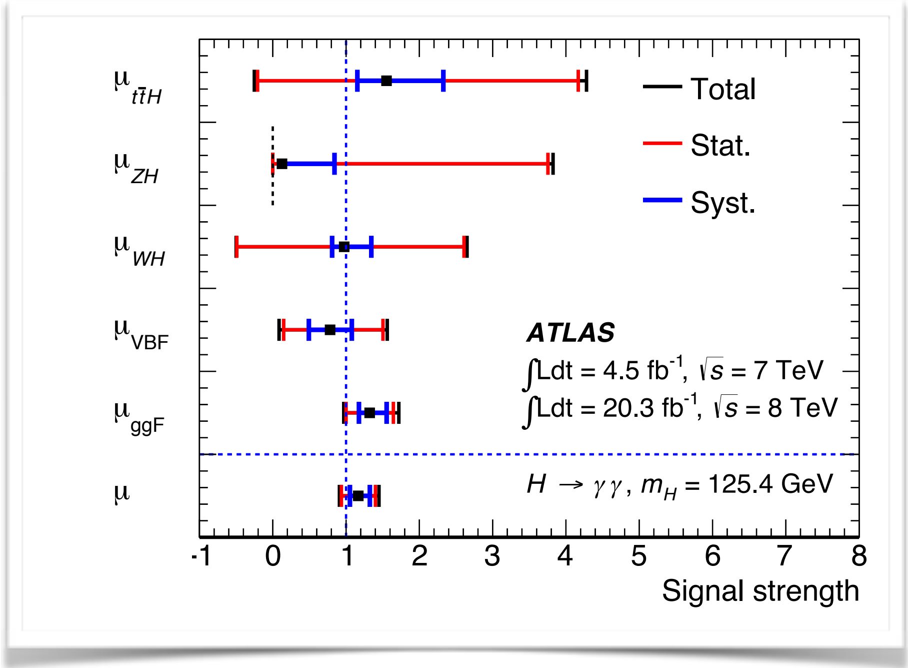



- For γγ, categories are also used to improve sensitivity to the different production modes
- Define categories with higher or lower purity of a specific production mode



# Why Categories? (2)



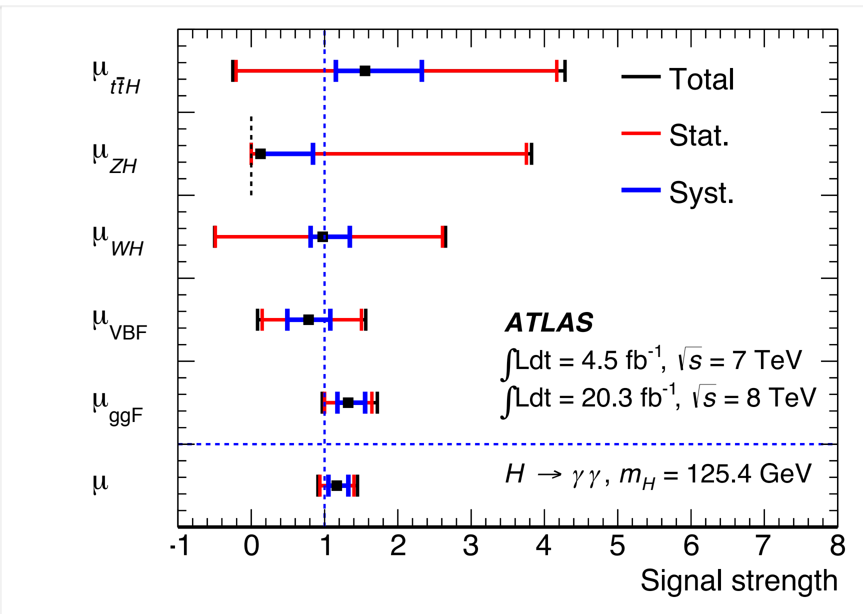



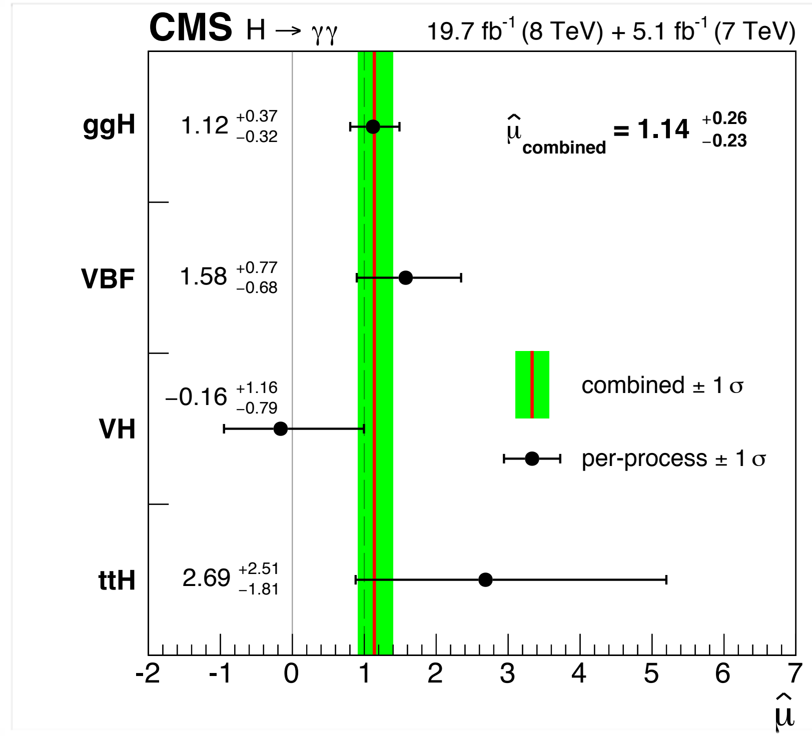

$$\begin{pmatrix} n_s^1 \\ \vdots \\ n_s^N \end{pmatrix} = \begin{pmatrix} \varepsilon_{ggF}^1 A_{ggF}^1 L^1 & \varepsilon_{VBF}^1 A_{VBF}^1 L^1 & \varepsilon_{VH}^1 A_{VH}^1 L^1 & \varepsilon_{ttH}^1 A_{ttH}^1 L^1 \\ \vdots & \vdots & \vdots & \vdots \\ \varepsilon_{ggF}^N A_{ggF}^N L^N & \varepsilon_{VBF}^N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

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

Extract measurements of all production modes

# Final Run-1 γγ Results




$$\mu = 1.18 \pm 0.27$$

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

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

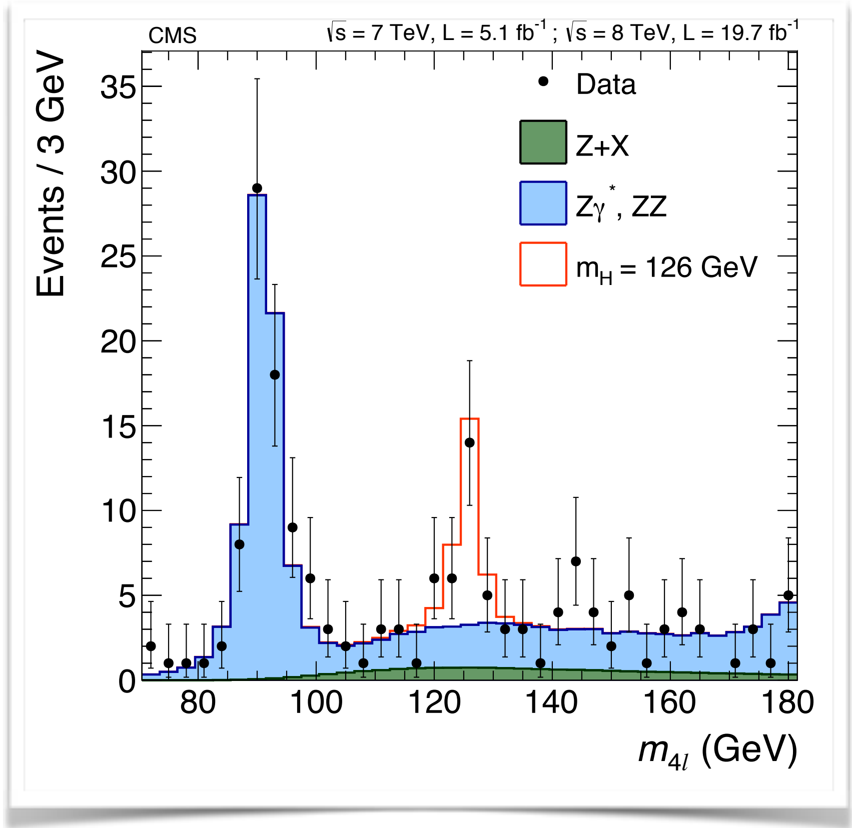
$$\mu = 1.14 \pm 0.26$$

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

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

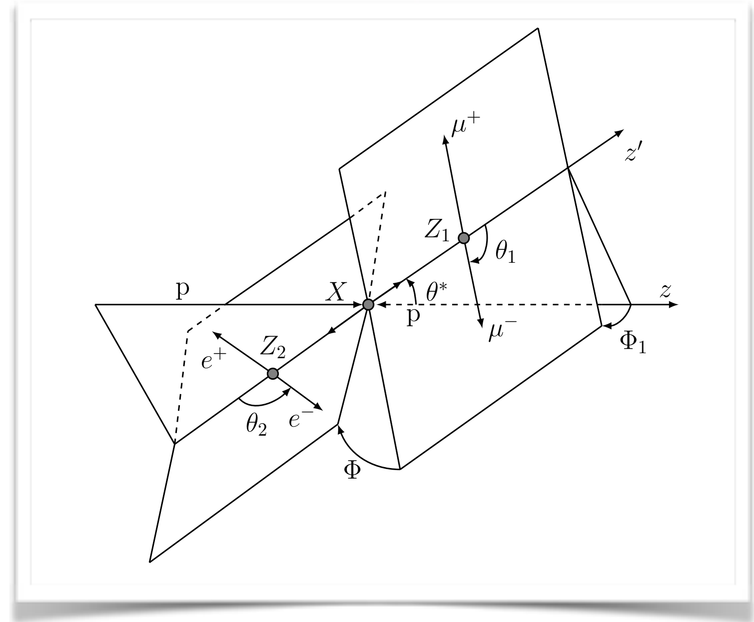
# Higgs to 4 leptons (H→ZZ*→llll)

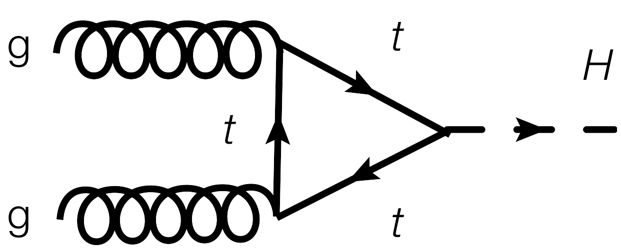
- A good **discovery** final state
  - Low backgrounds
    - S/B: 1.5 - 10
  - Very good Higgs mass **resolution**
  - Requires good lepton reconstruction efficiencies
    - Muon spectrometers designed specifically for this channel
  - Clear and robust signal of Higgs coupling to weak bosons
- Select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

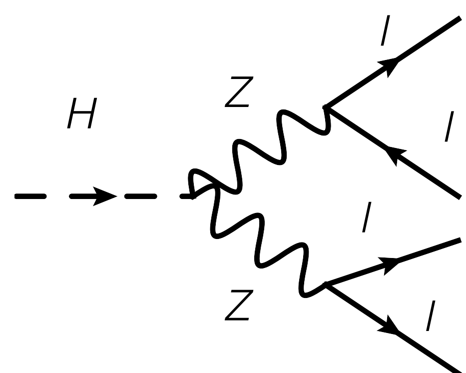


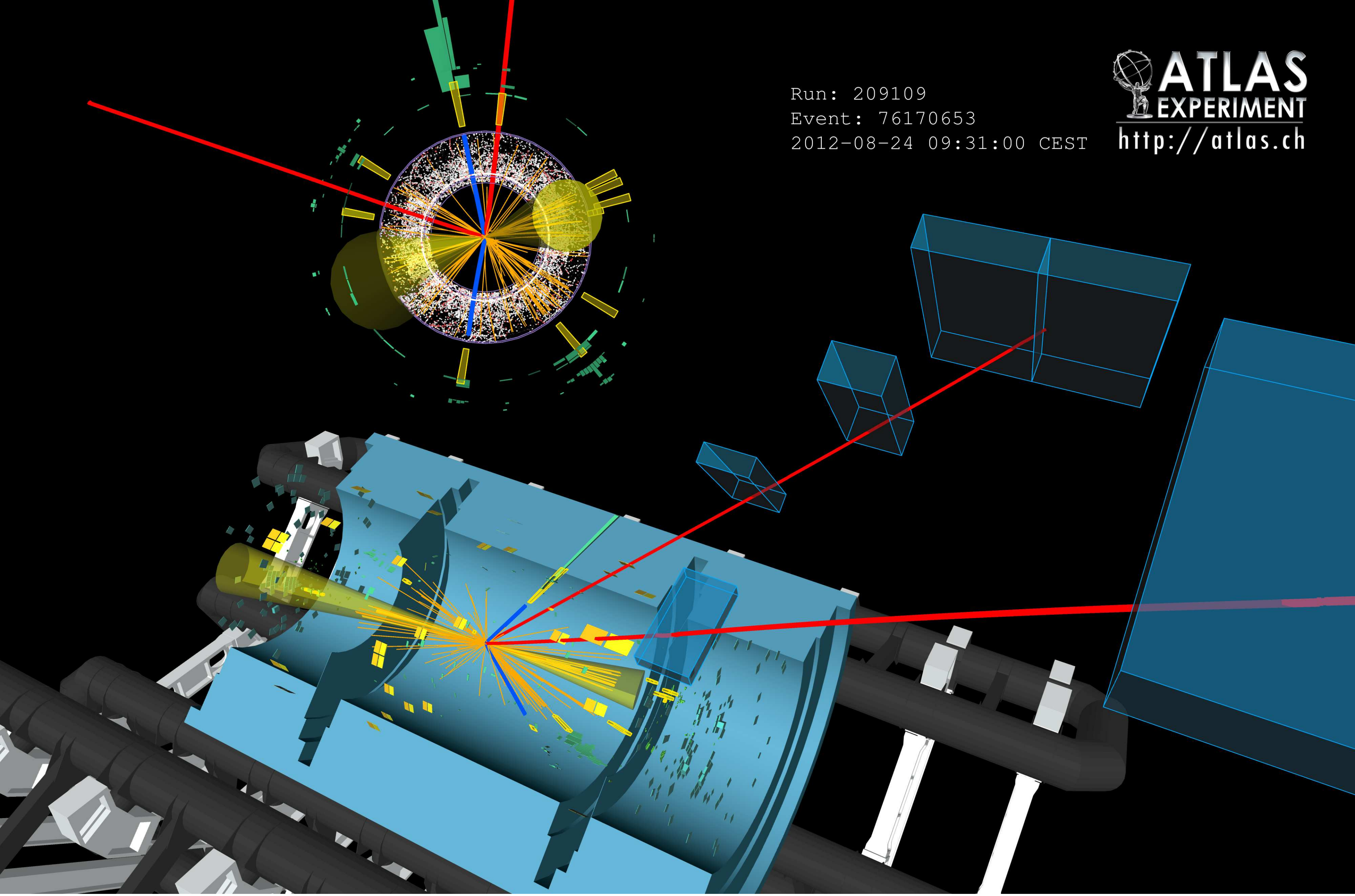
# Production and Decay

- 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



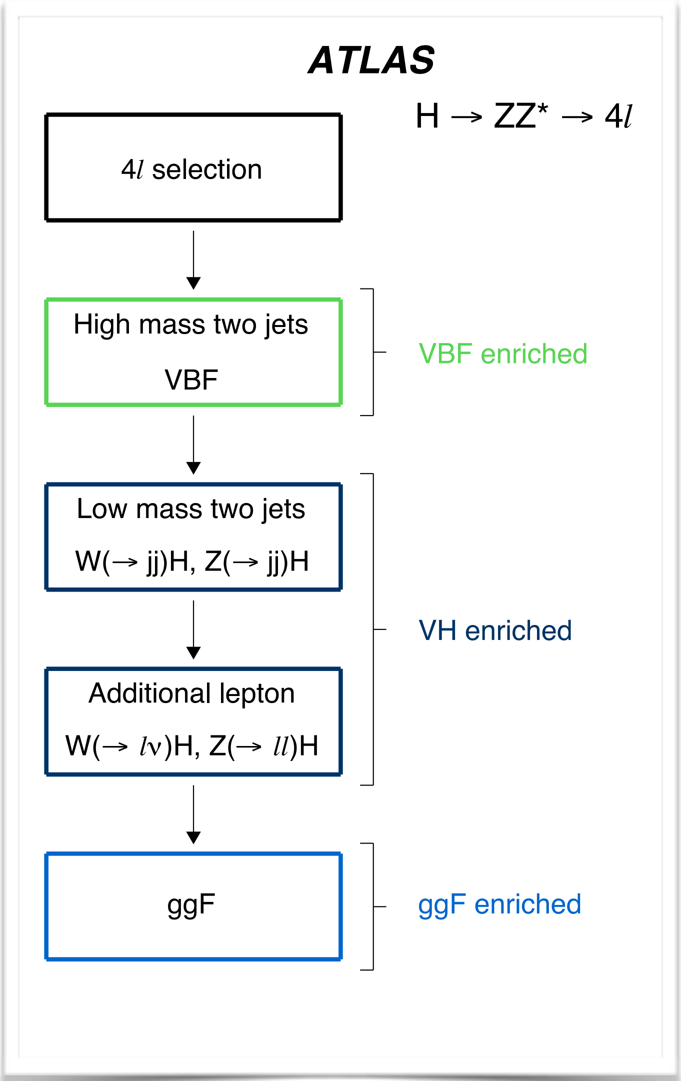



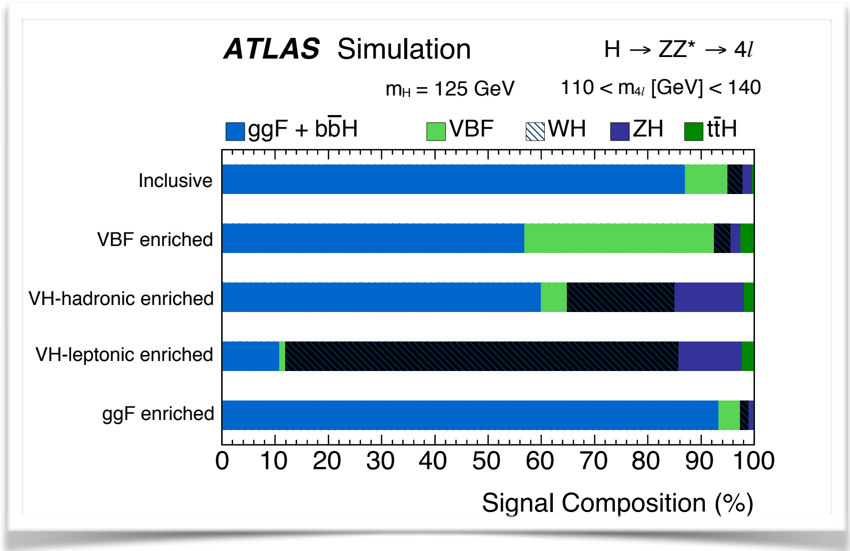



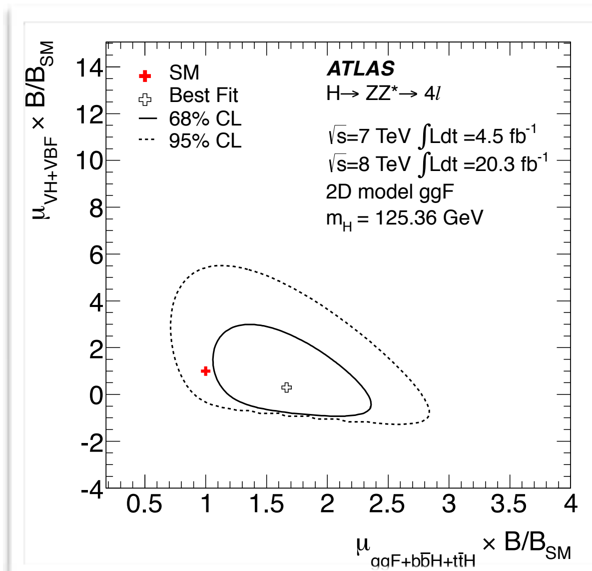



EventNumber : 76170653 RunNumber : 209109 $m_{4\ell}$=123.4 GeV. The $BDT_{VBF}$ value is 0.7. Six jets in total, and the two leading jets have $p_T$ = 180 and 150 GeV, $\Delta\eta_{jj}$ = 3.4, and $p_{Tjj}$ = 200 GeV. The missing $E_T$ = 40 GeV.

# Categories

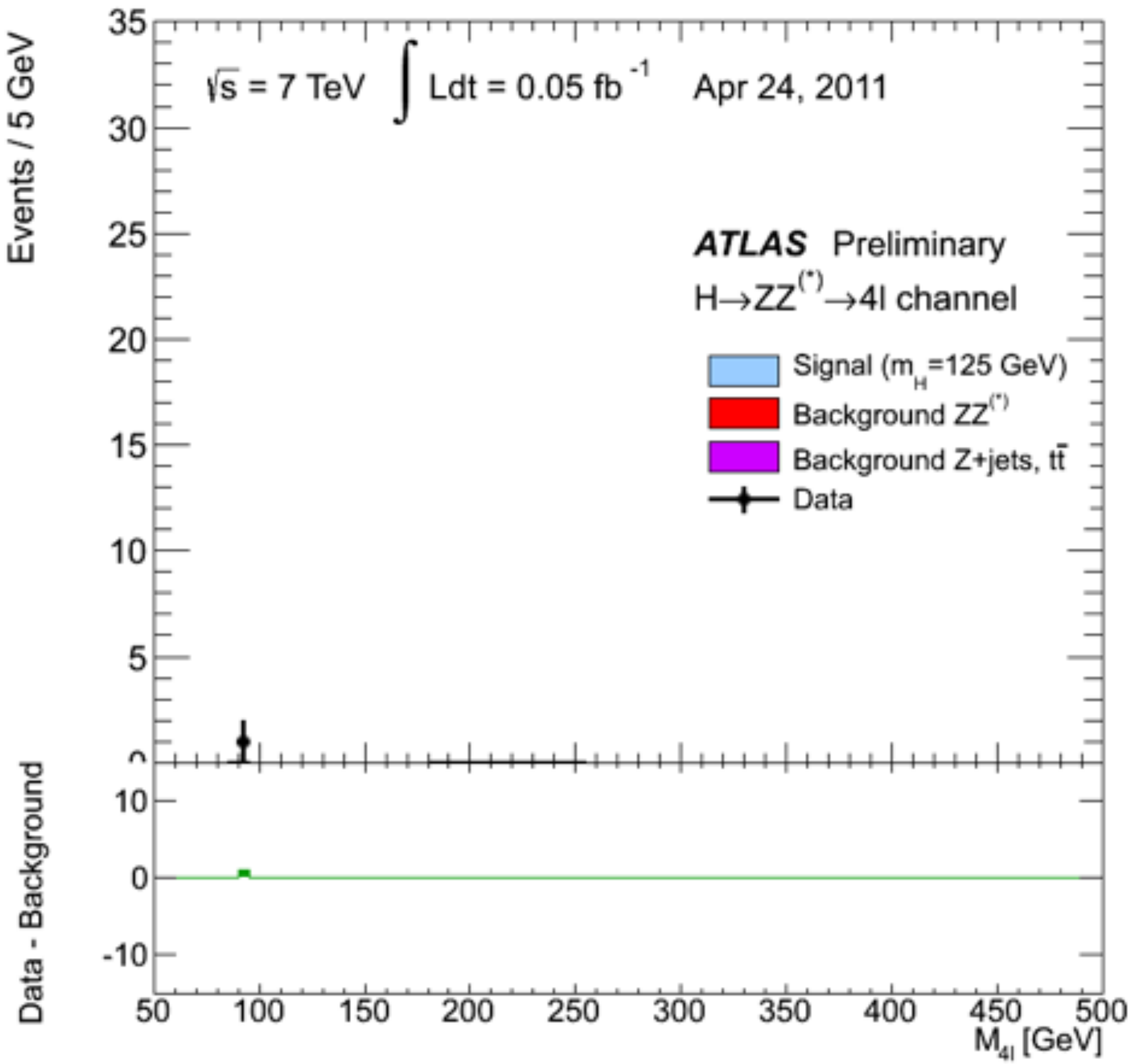


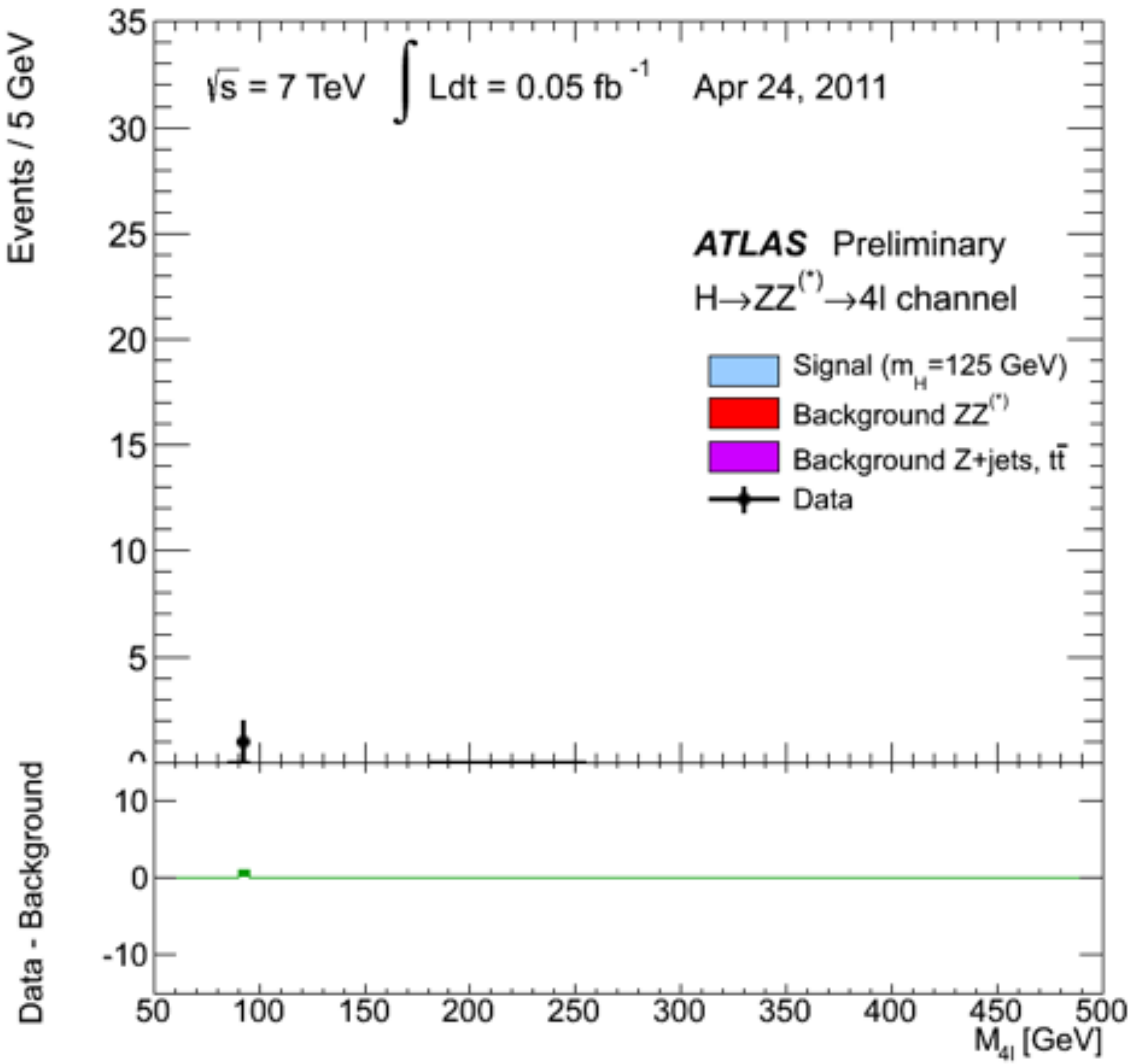

*Limited by statistics so will improve quickly with more data*

# Higgs to 4 leptons (H→ZZ*→llll)




**4 July 2012**

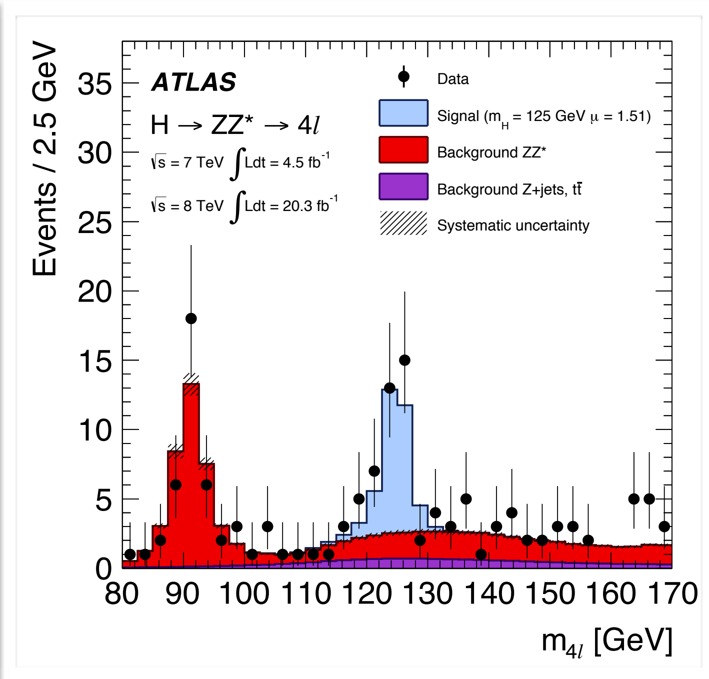
# Higgs to 4 leptons (H→ZZ*→llll)

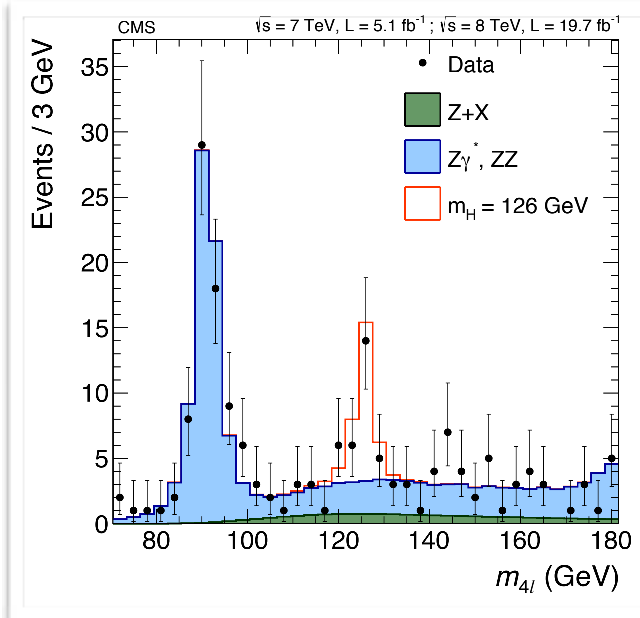



**4 July 2012**

# Final Run-1 ZZ Results

HIG-13-002
HIGG-2013-21




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

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

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

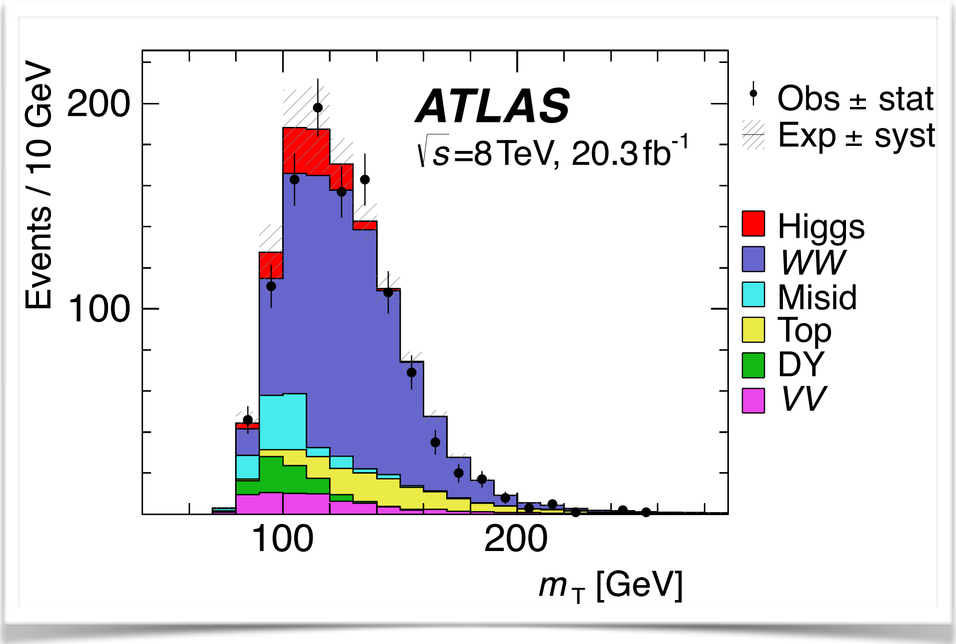
$$\mu = 0.93 \pm 0.29$$

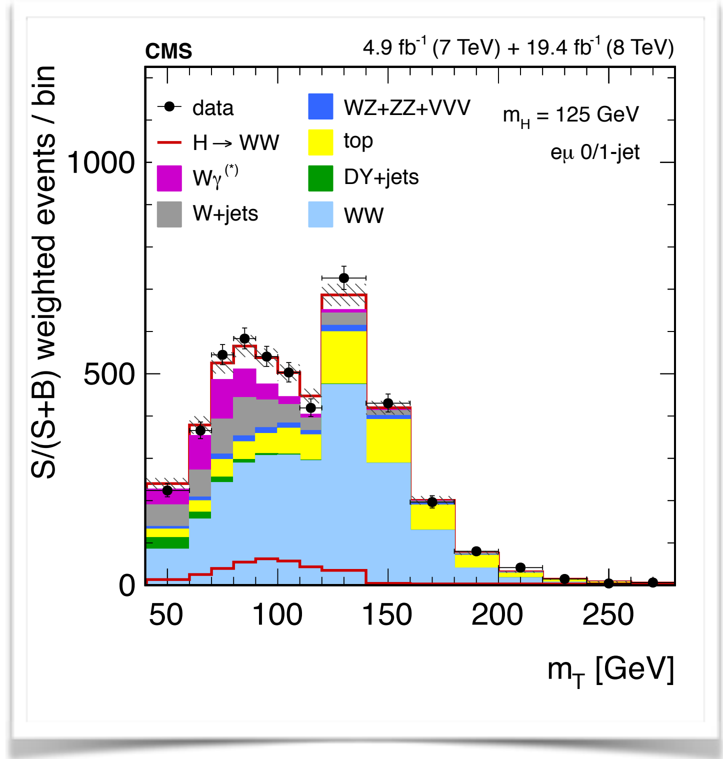
$$m_H = 125.6 \pm 0.45 \text{ GeV}$$

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

# H→WW

HIGG-2013-13
HIG-13-023




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

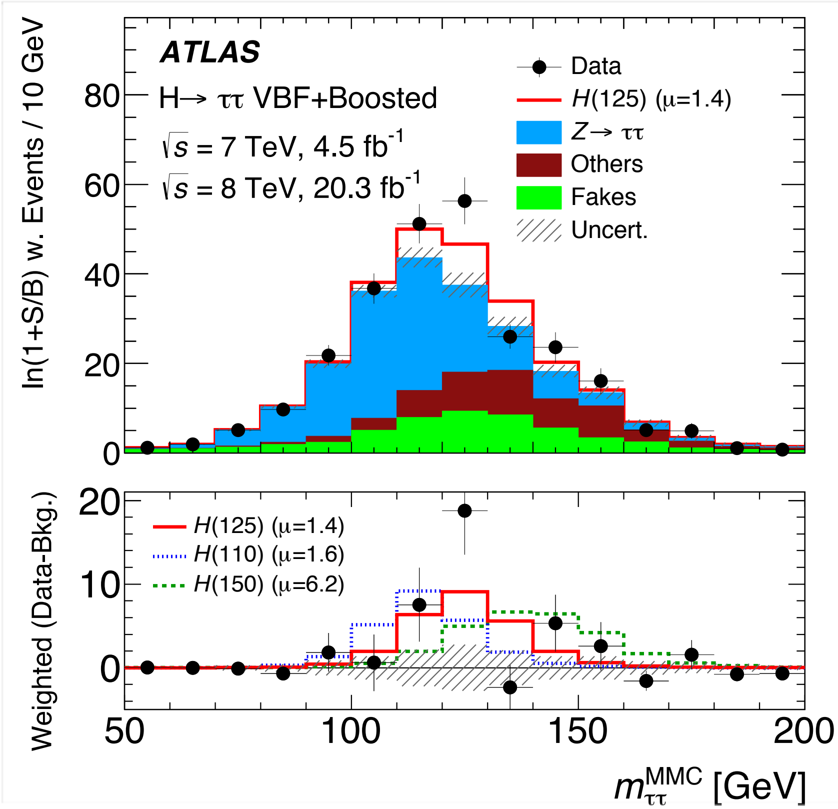
$$Z = 6.8(5.8)\sigma$$

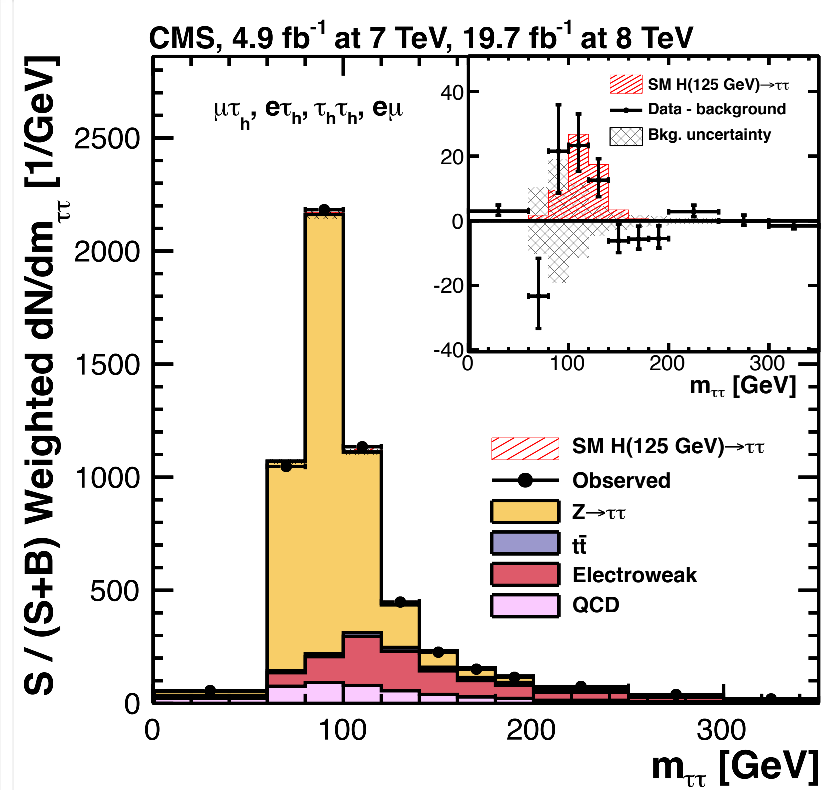
$$\mu = 0.90^{+0.23}_{-0.21}$$

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

# H→ττ

HIG-13-004
HIGG-2013-32




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

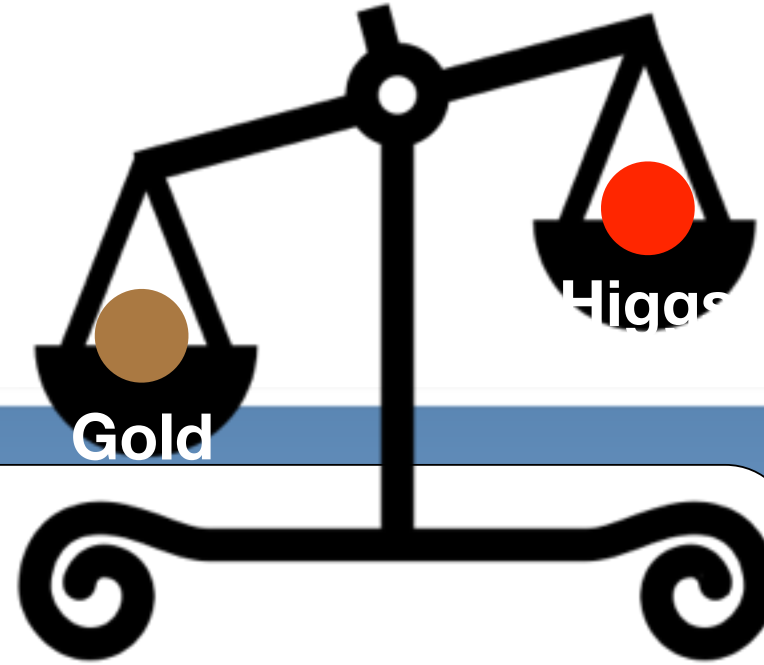
$$Z = 4.4(3.3)\sigma$$

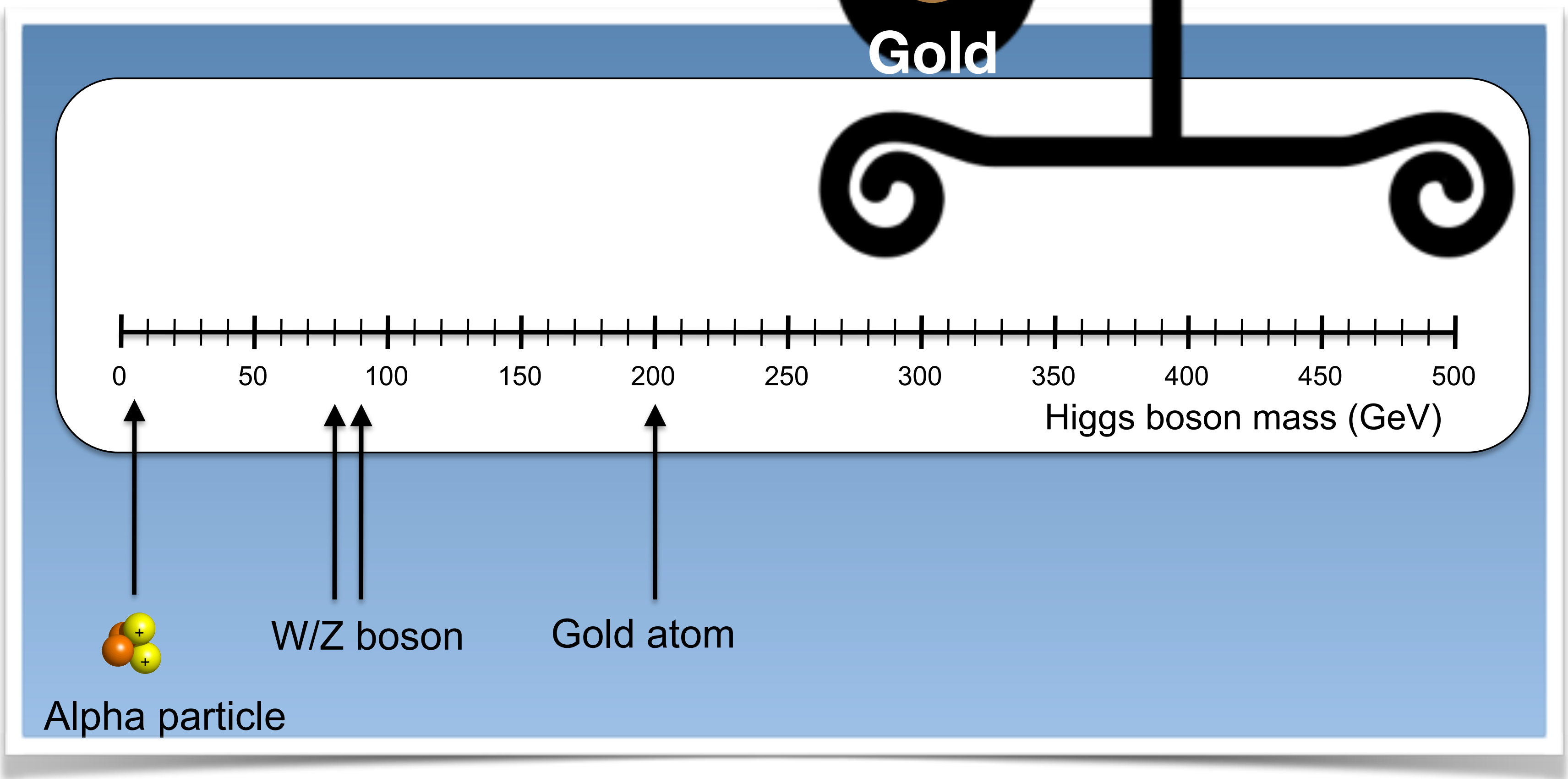
$$\mu = 0.88^{+0.30}_{-0.28}$$

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

# Mass

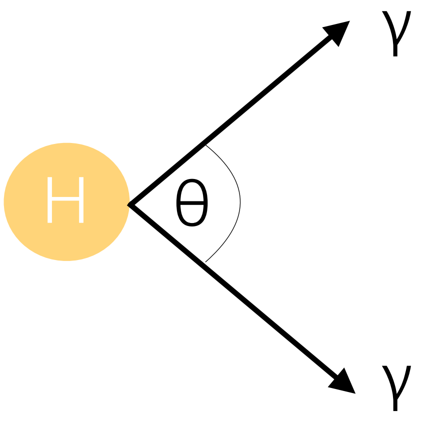
*Higgs boson is almost as heavy as a gold atom*



# 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 $m^2 = 2|P^1||P^2| . (1 - \cos\theta)$

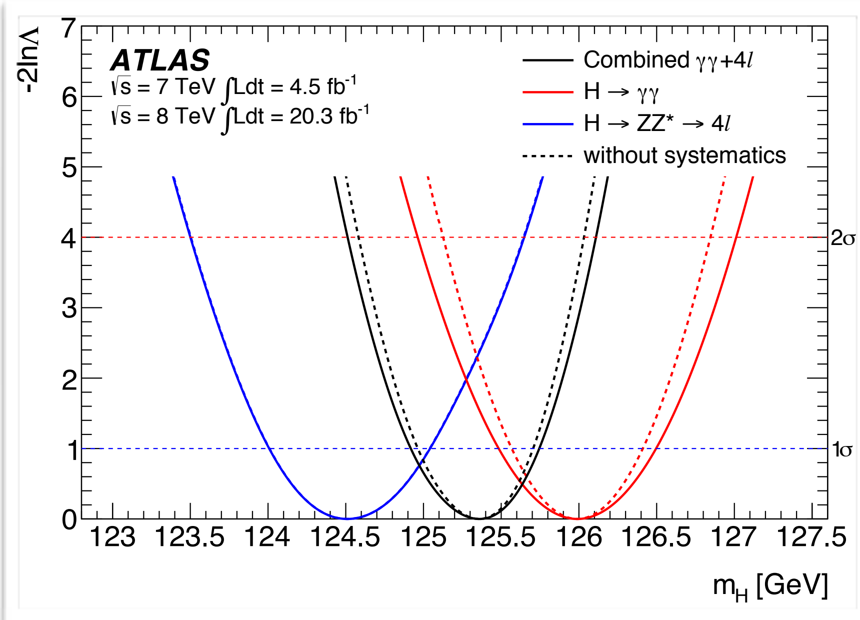
# ATLAS Mass Measurement

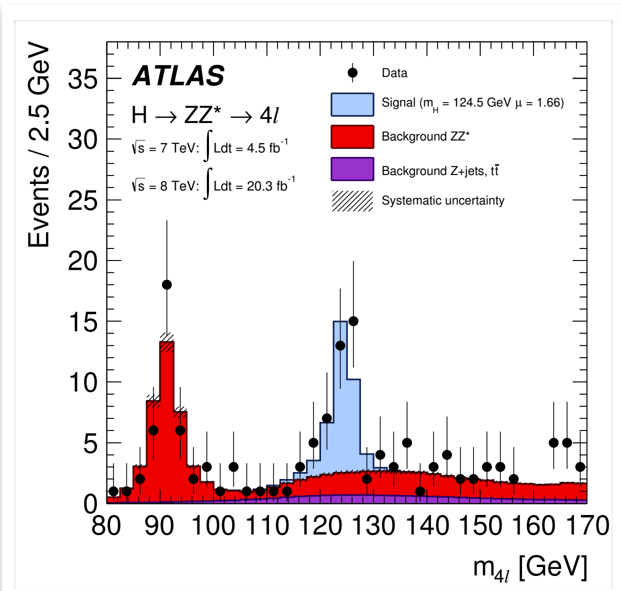
Phys. Rev. D. 90, 052004 (2014)

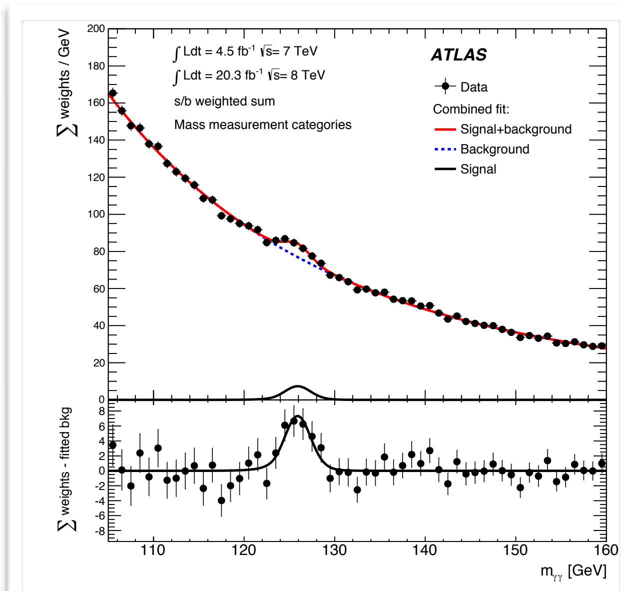
ZZ: 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV

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

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



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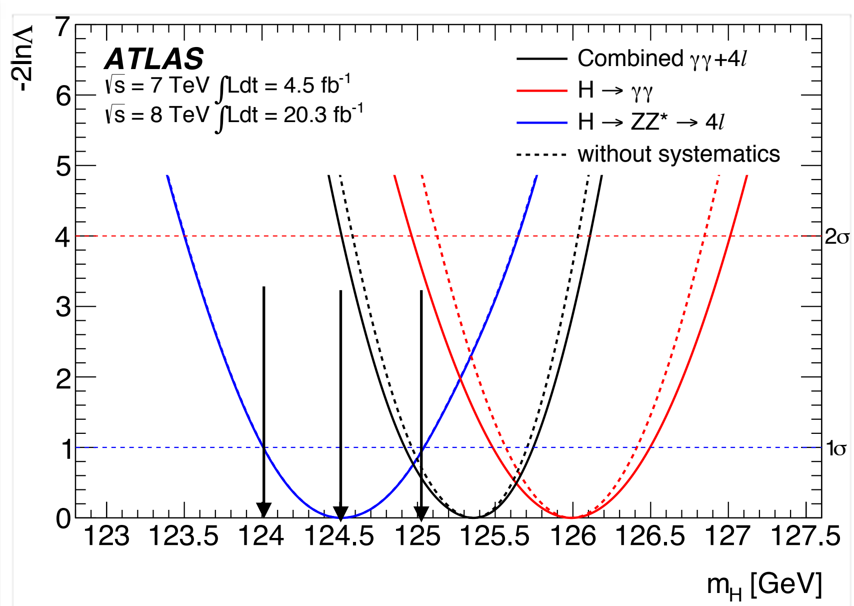
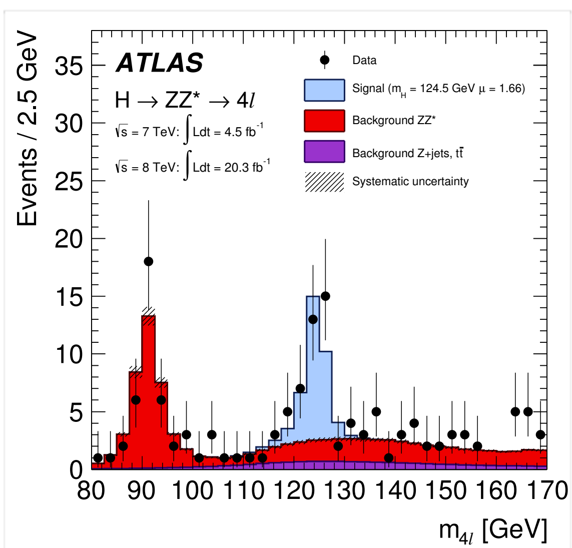
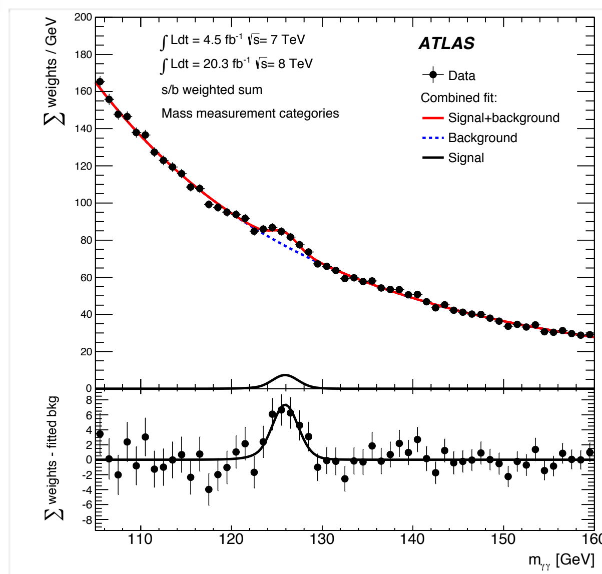
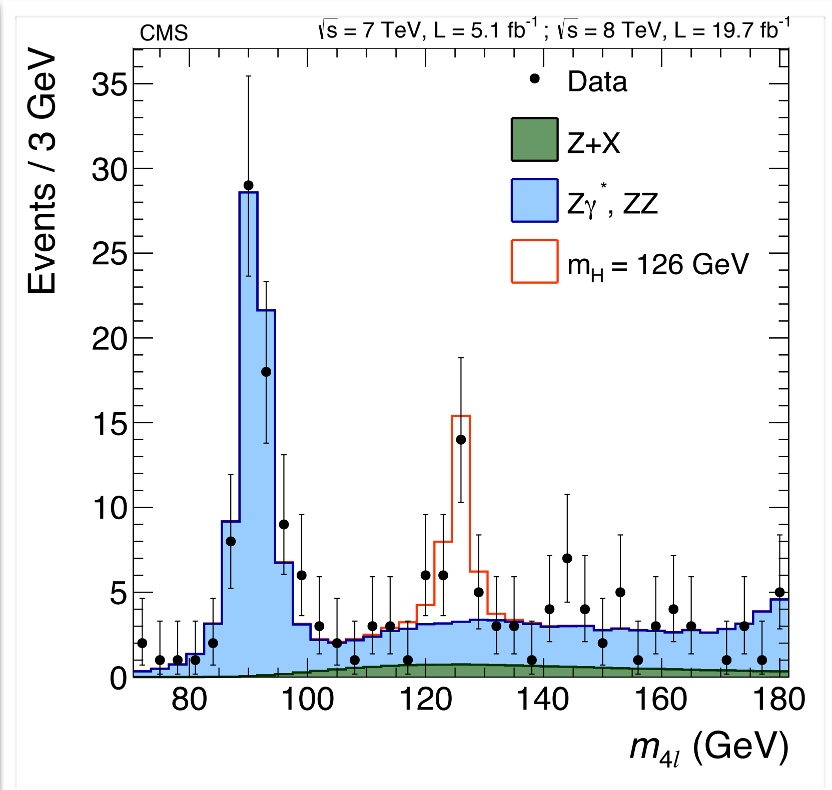
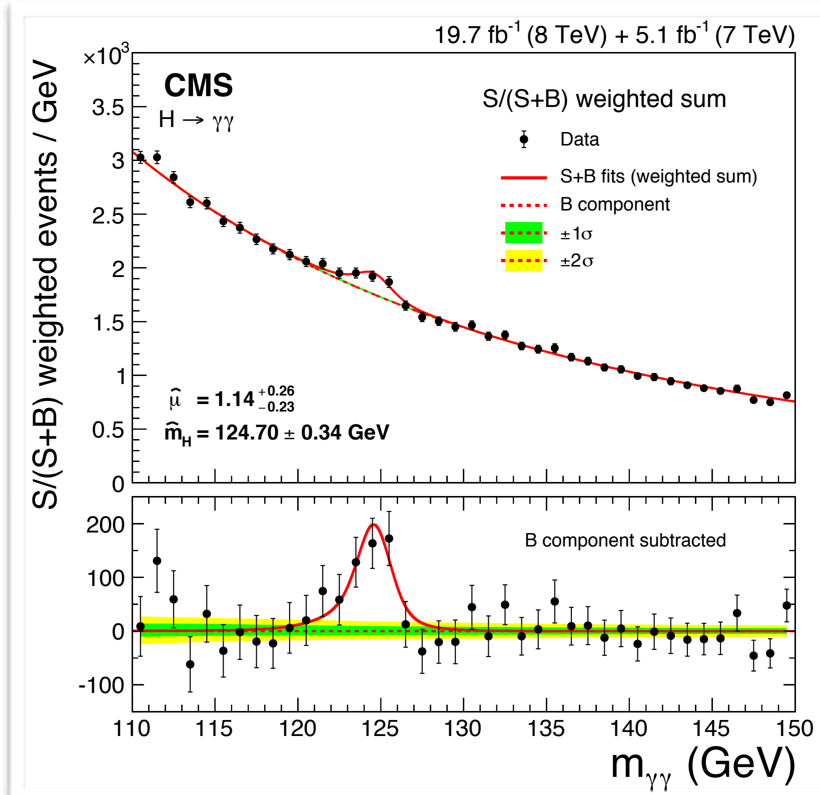


# CMS Mass Measurement



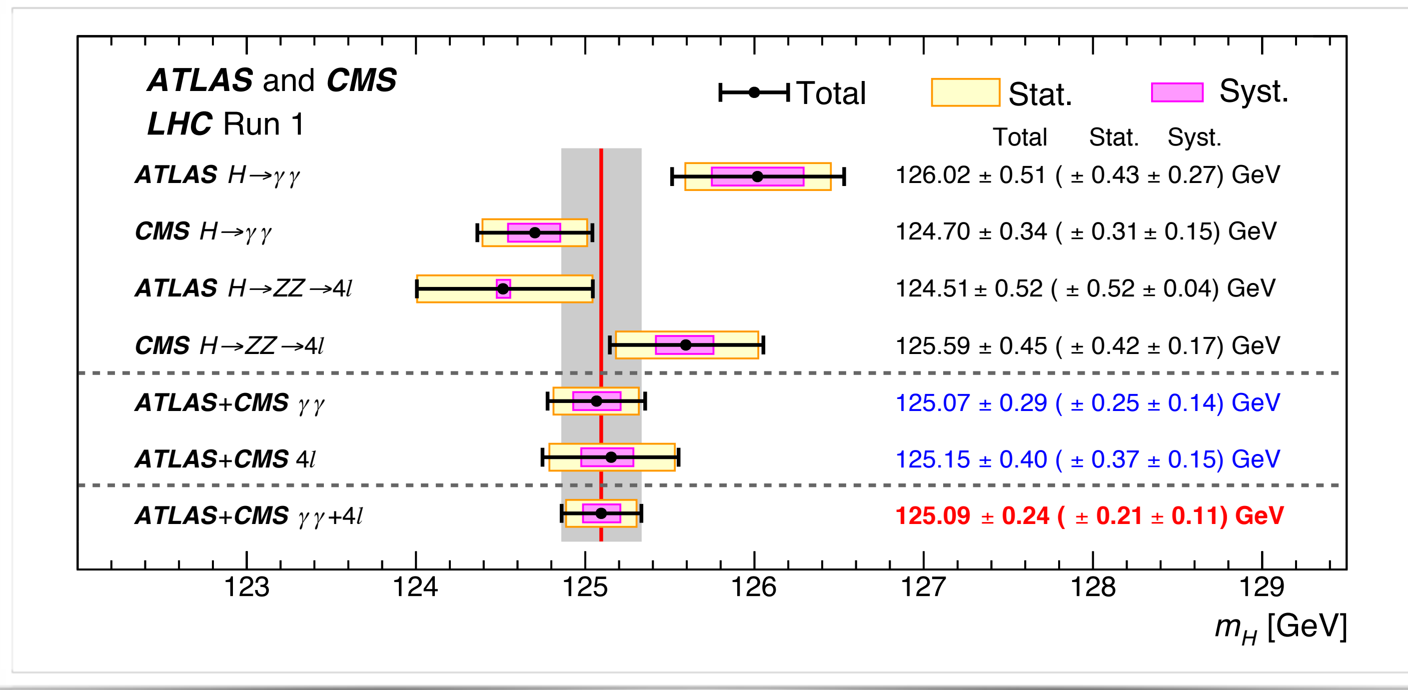



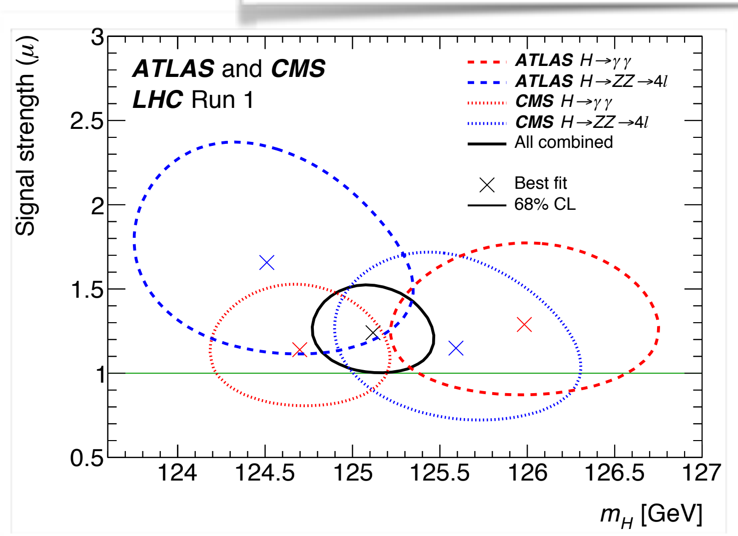

ZZ: 125.59 ± 0.42 (stat) ± 0.17 (syst) GeV

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

# Combined Higgs Mass Measurement

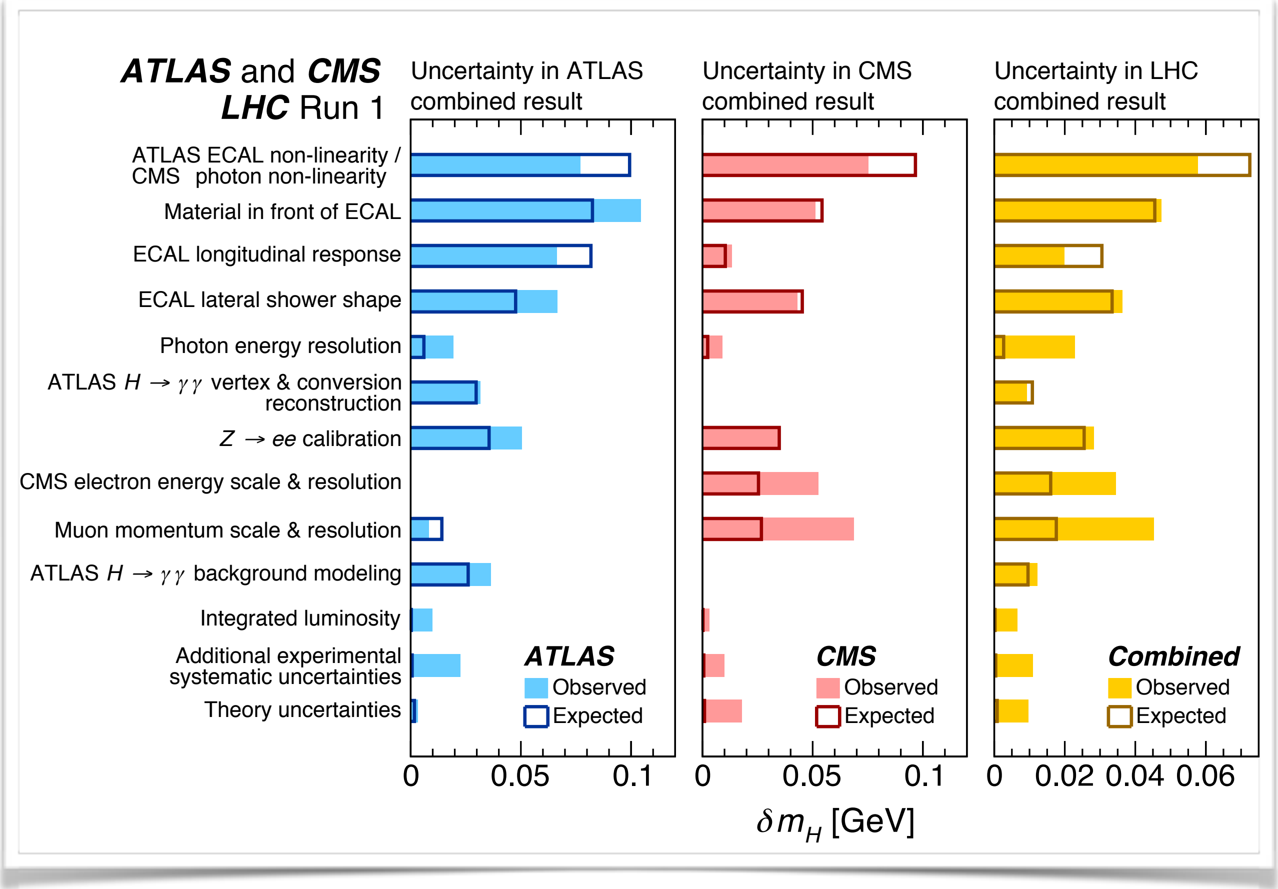
HIGG-2014-14




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

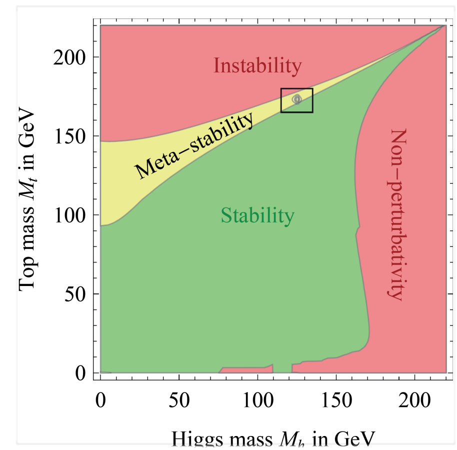
# Uncertainties on the Mass Measurement

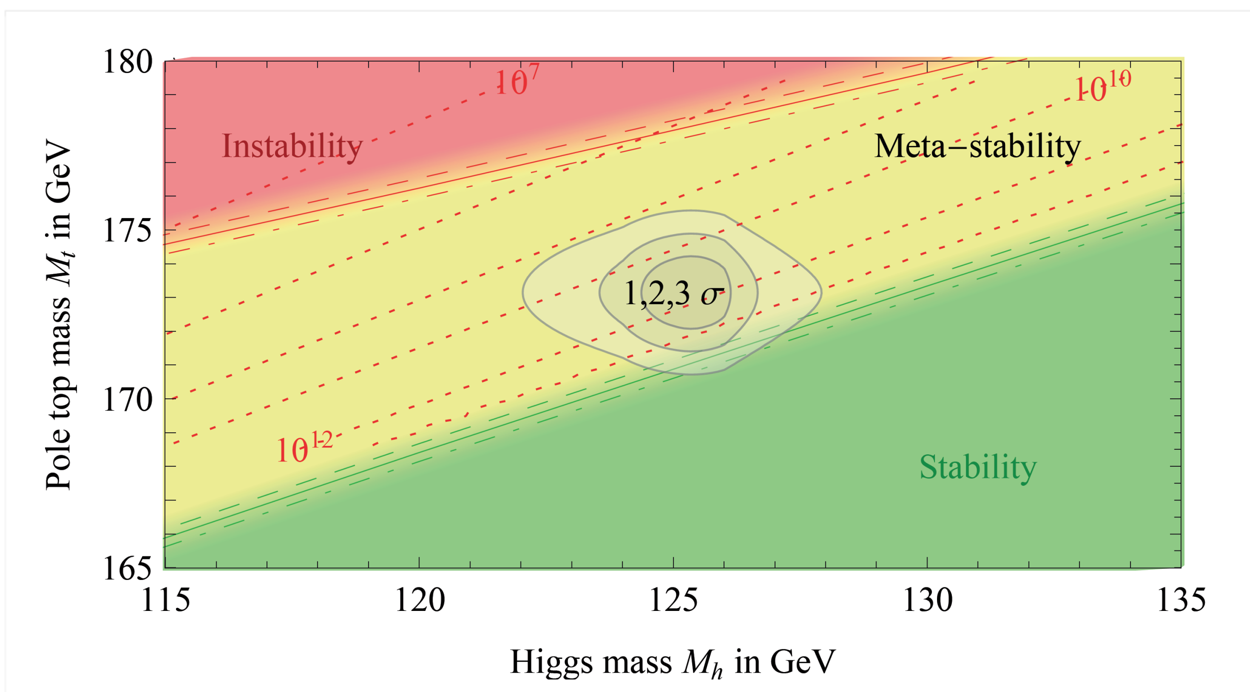



Largest systematic uncertainties are those from the calibration of the calorimeter

# Mass Measurement Implications

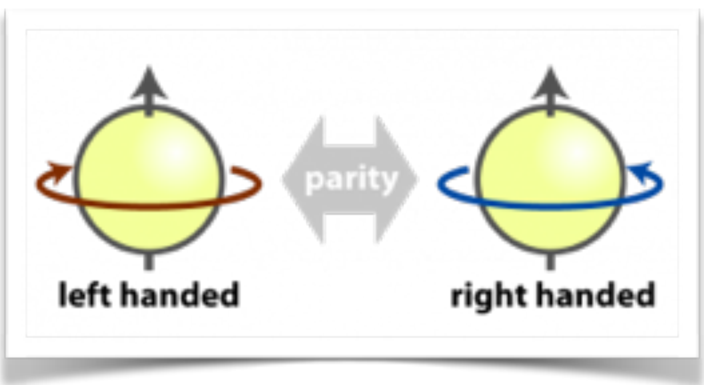
- $m_H$ = 125 GeV → our universe lies on the boundary between instability and stability
- No need to panic: metastability means that the universe is unlikely to end tomorrow
    - But intriguing, nonetheless

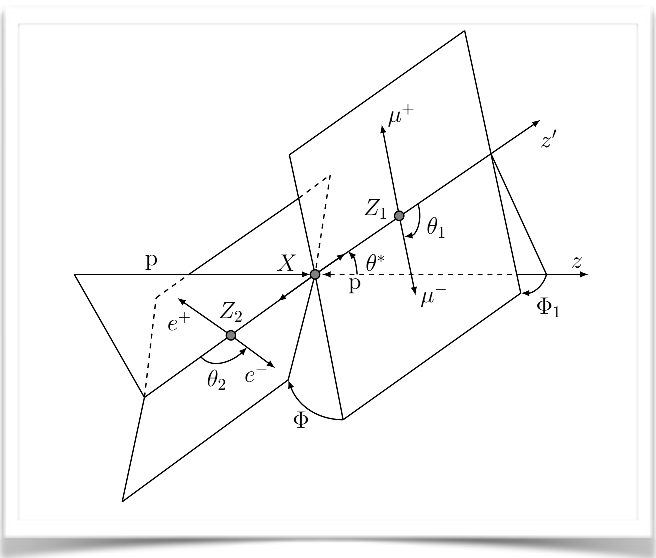


# Spin/Parity

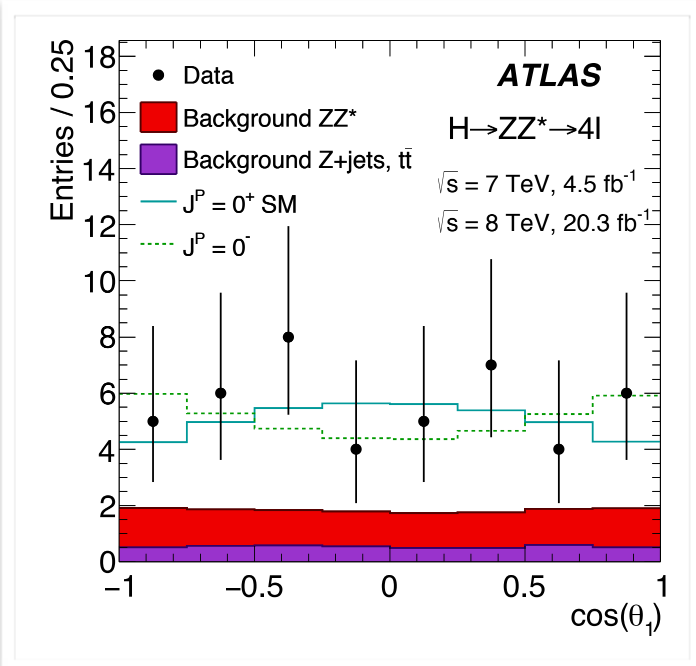
- Only elementary particle with spin-0
- Spin and parity determine angular distributions of decay products
    - Use γγ, ZZ and WW
- Don't forget, though, that the γγ observation implies
    - does not originate from spin 1 : Landau-Yang theorem
    - charge conjugation is +1 (assuming C and P separately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

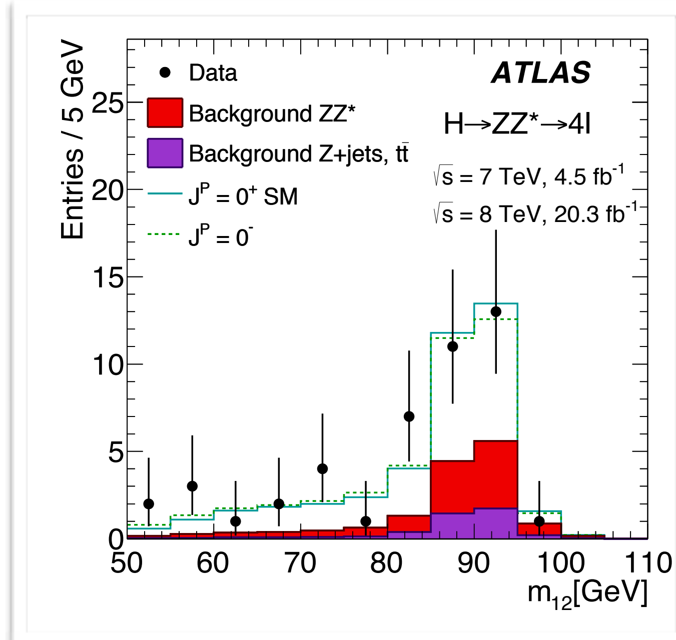


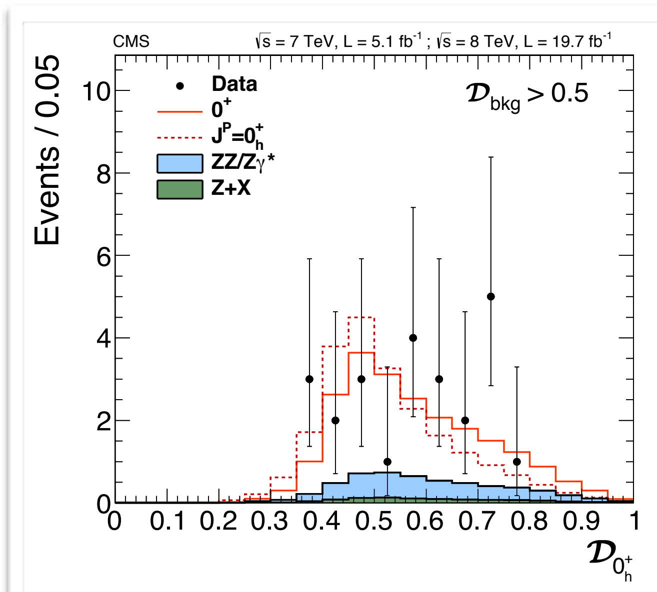



# Variables sensitive to spin

HIG-13-002
HIGG-2013-17

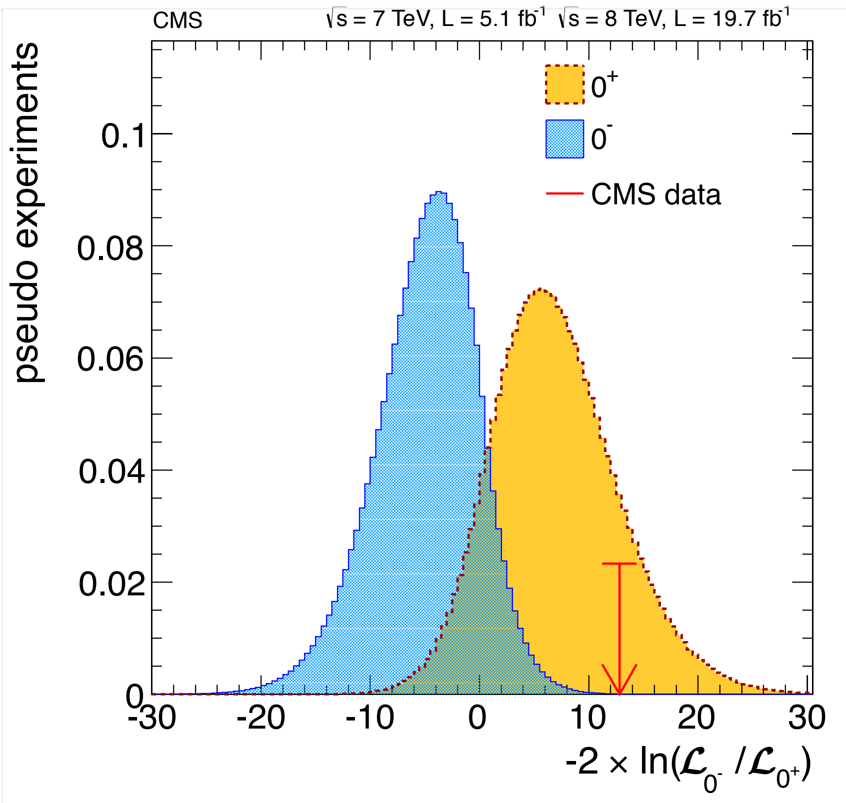


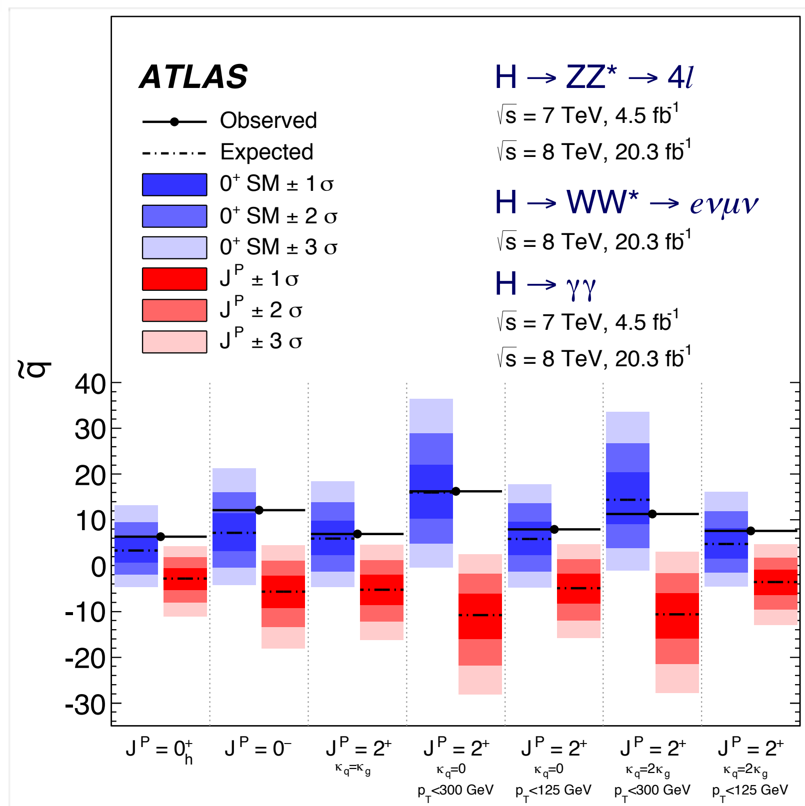




- Study a number of angular variables sensitive to spin and parity
- Combine into a single discriminant using an MVA or theory-based matrix element technique

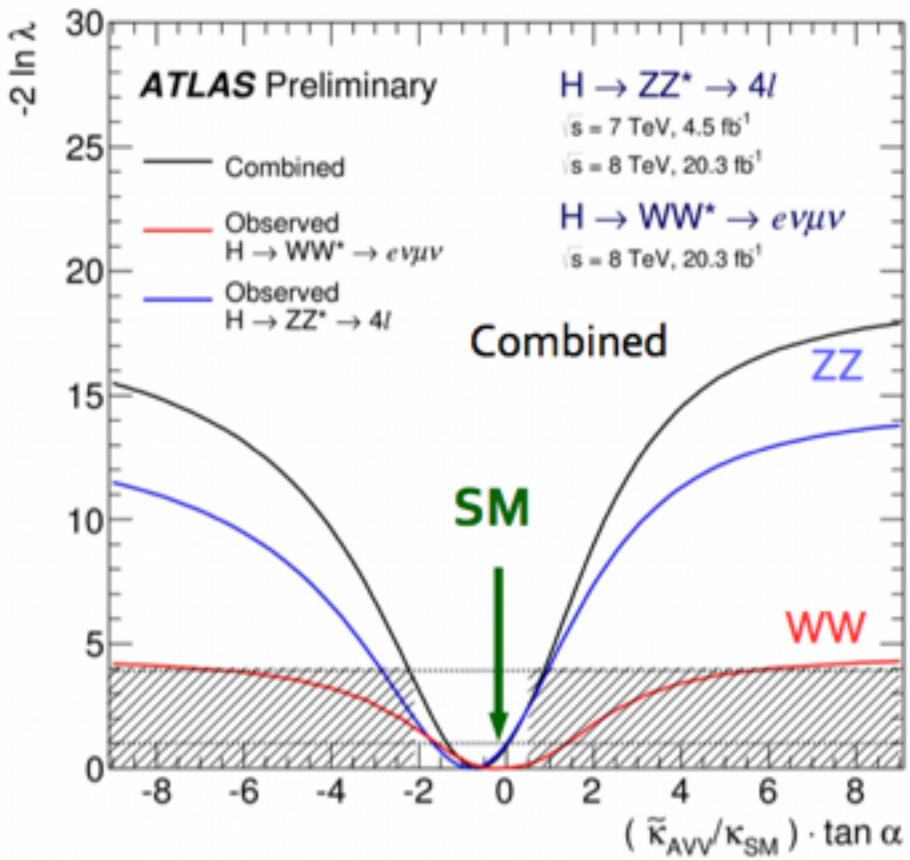
# Spin/Parity Results

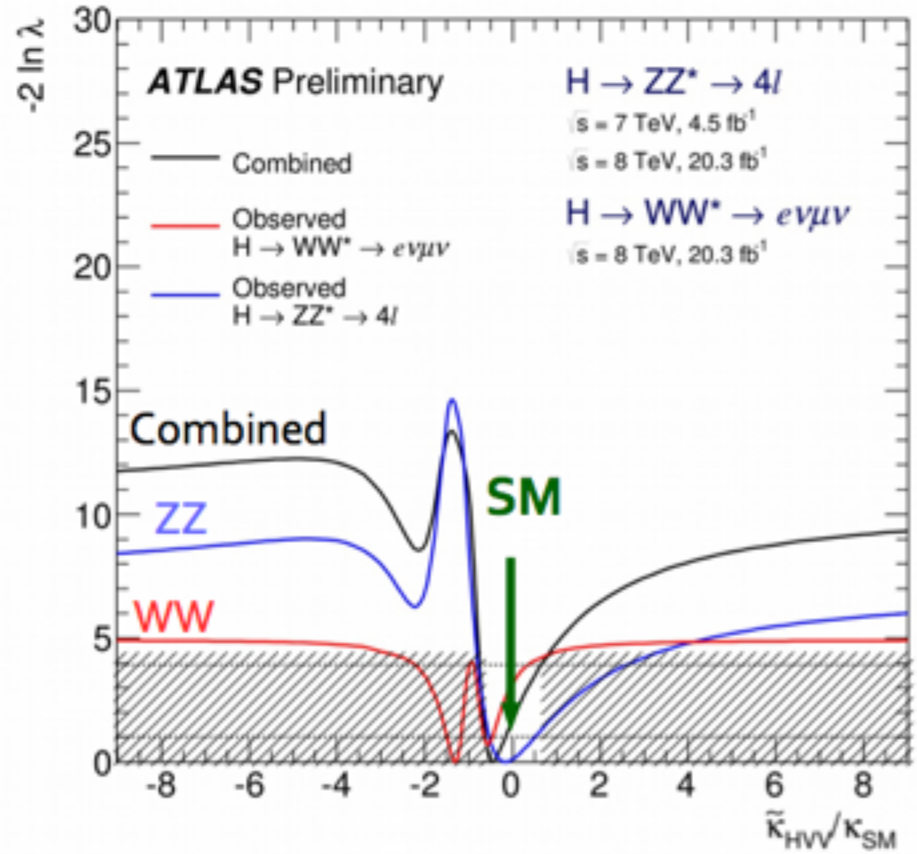



Strong evidence that the Higgs is 0+ as predicted by the Standard Model

# CP Mixing

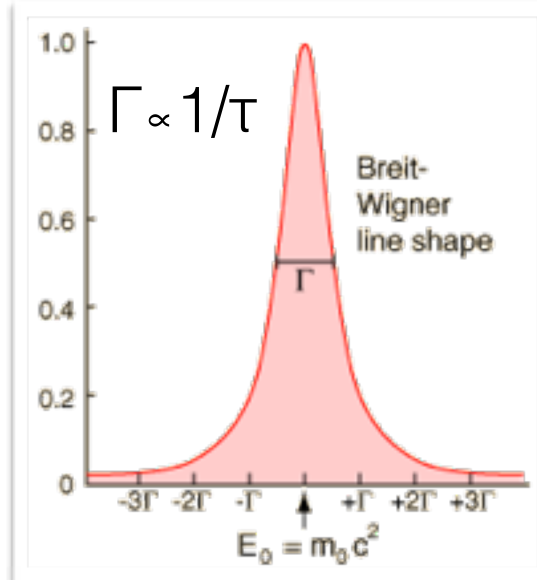


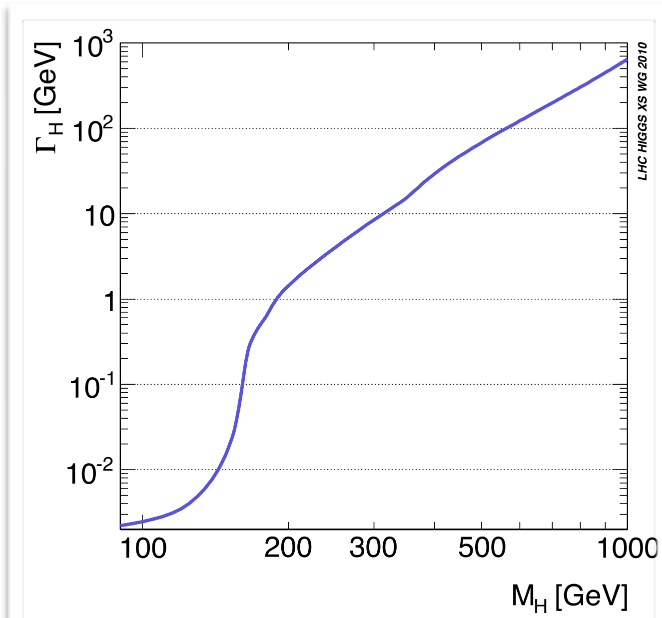




Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even

# Width

- As an highly unstable elementary particle, the **lifetime** of the Higgs is **very short**
- For $m_H$ = 125 GeV
  - $\Gamma$=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

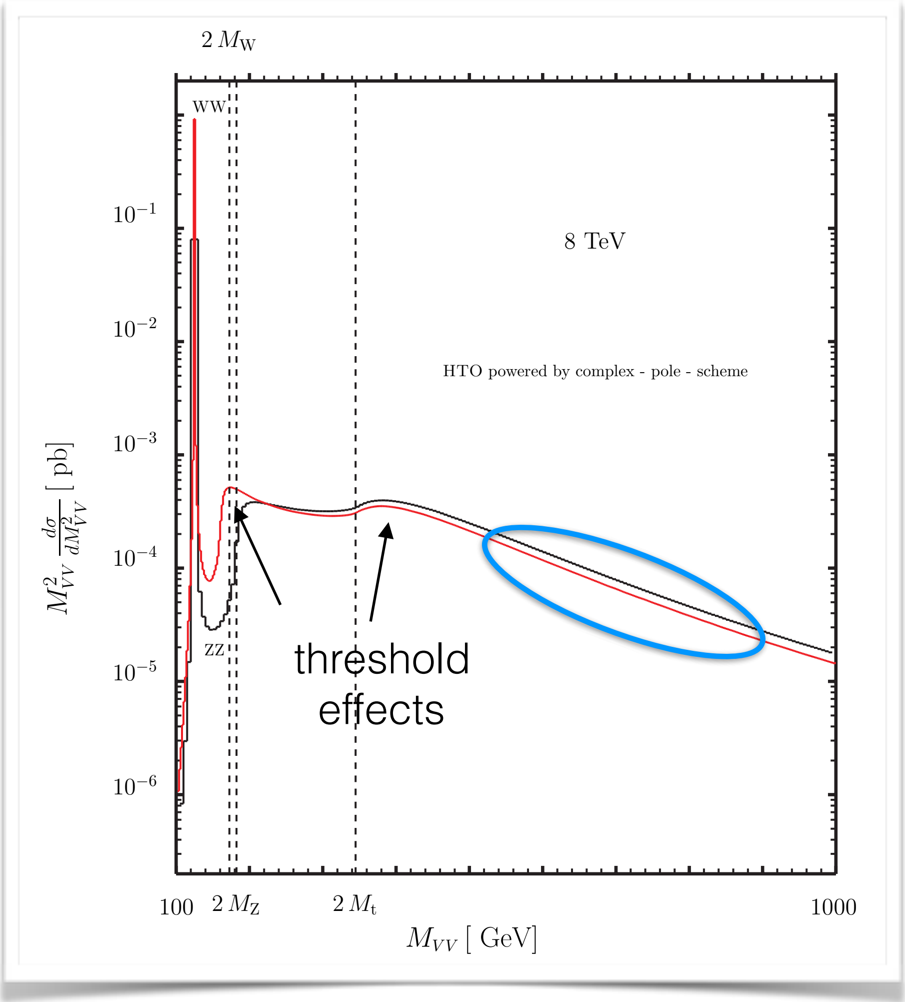
N. Kauer and G. Passarino, JHEP 08 (2012) 116

- 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

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

- 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 |



# 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

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

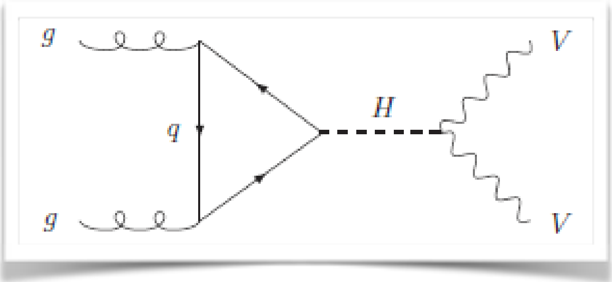
$$\frac{d\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2 \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

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

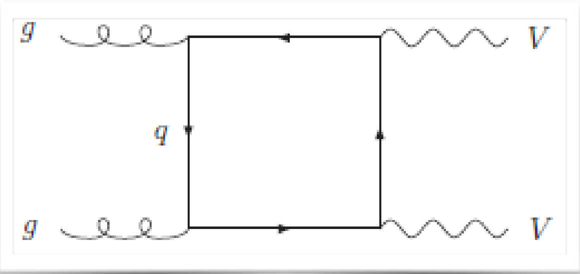
$$\kappa_Z = g_{HZZ}/g^{\mathrm{SM}}_{HZZ},$$

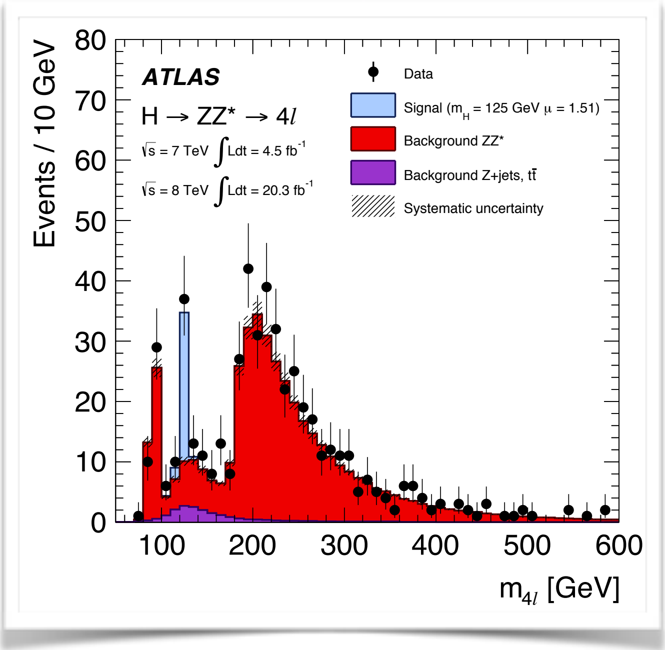
$$\boxed{r = \Gamma_H/\Gamma_H^{\mathrm{SM}}}$$

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



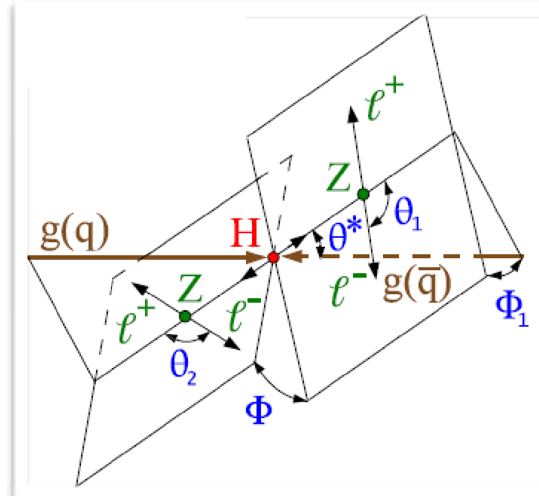

Significant interference with the SM VV background at high mass

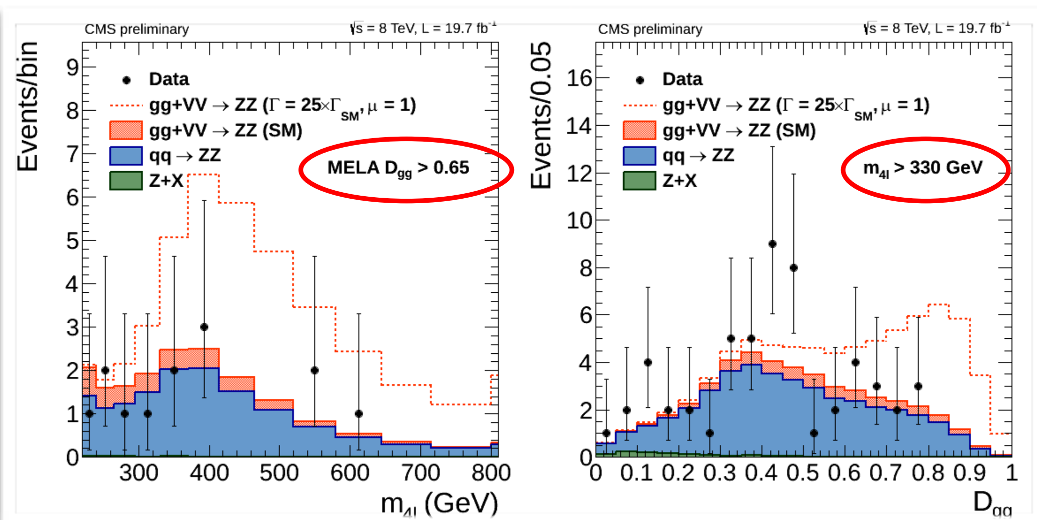


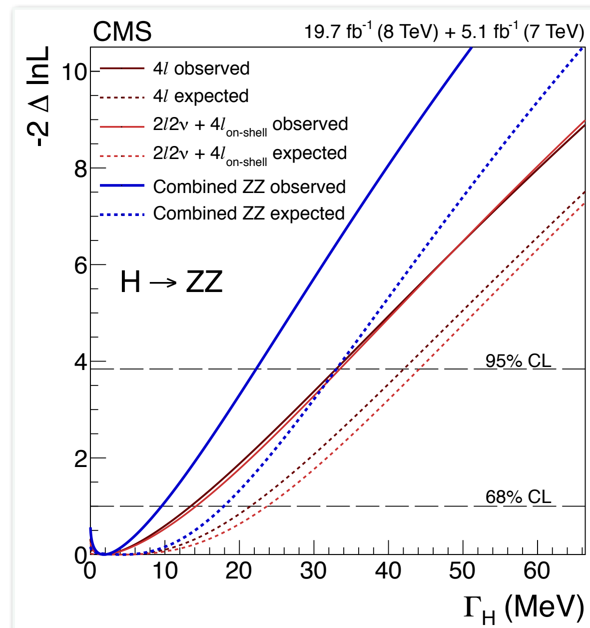



# CMS measurement of the width

- 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



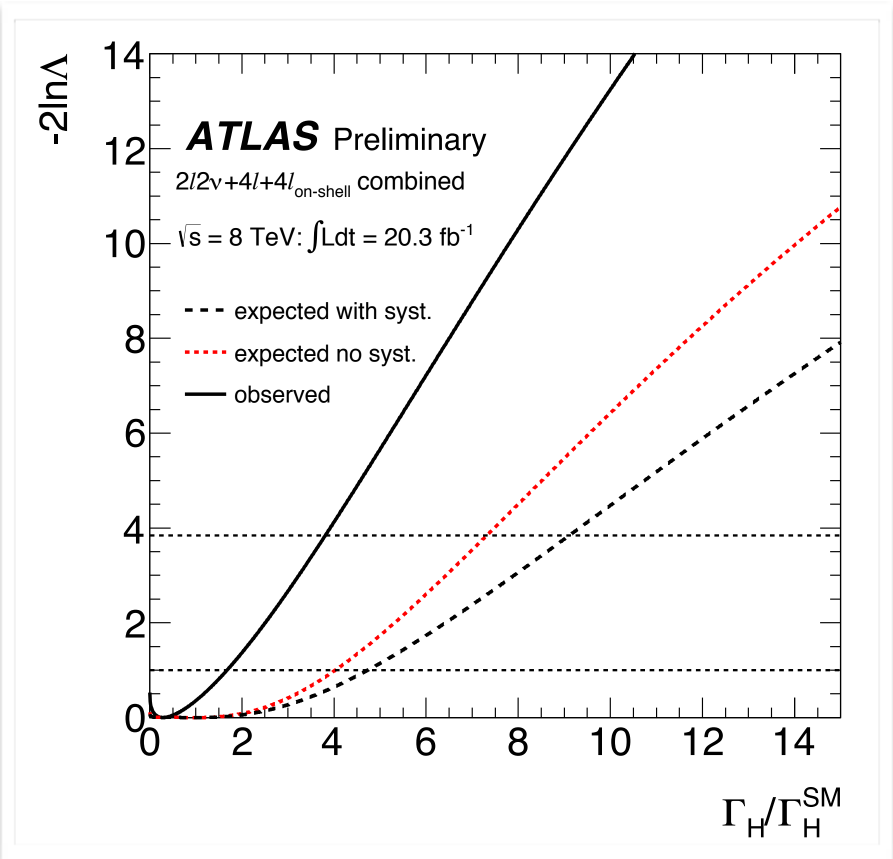



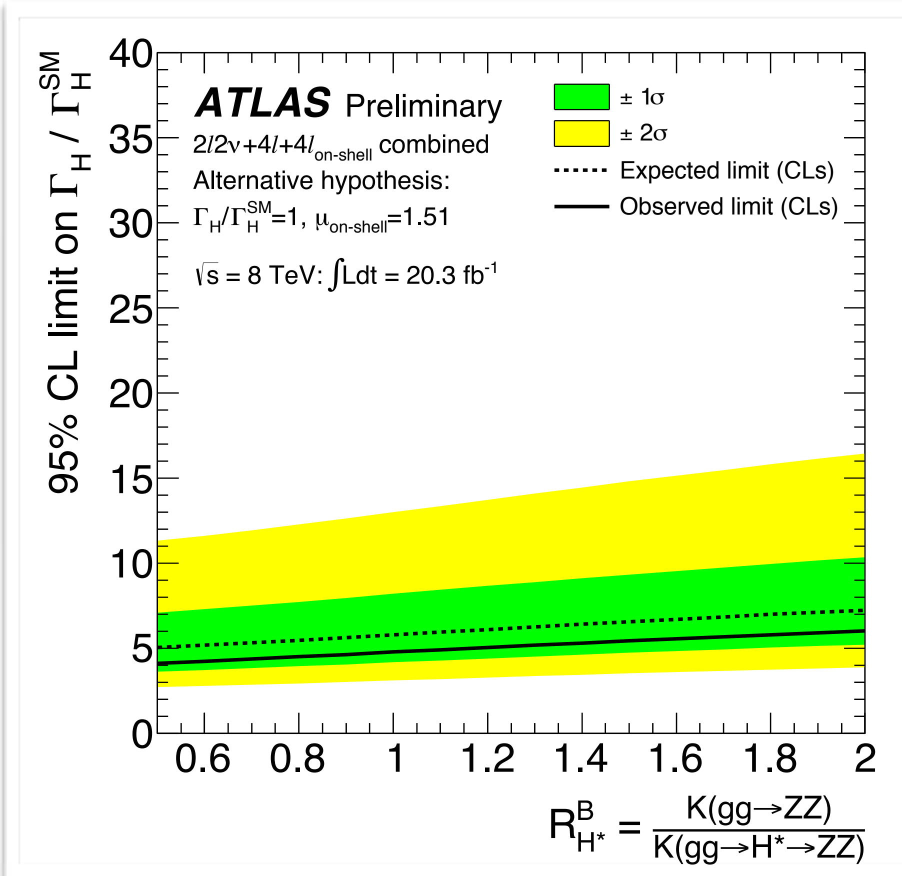



# ATLAS width result

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



# Higgs 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

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# 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 [$\mu$] from results in this paper (Section 5.2) | | Signal significance [$\sigma$] 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 | | | | |
|---|---|---|---|---|---|
| | $H \to \gamma\gamma$ | $H \to ZZ$ | $H \to WW$ | $H \to \tau\tau$ | $H \to bb$ |
| $gg$F | $(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{gg\mathrm{F}}$ | $(\sigma \cdot \mathrm{B})^{ZZ}_{gg\mathrm{F}}$ | $(\sigma \cdot \mathrm{B})^{WW}_{gg\mathrm{F}}$ | $(\sigma \cdot \mathrm{B})^{\tau\tau}_{gg\mathrm{F}}$ | – |
| VBF | $(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VBF}}$ | $(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{VBF}}$ | $(\sigma \cdot \mathrm{B})^{WW}_{\mathrm{VBF}}$ | $(\sigma \cdot \mathrm{B})^{\tau\tau}_{\mathrm{VBF}}$ | – |
| $WH$ | $(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{WH}$ | $(\sigma \cdot \mathrm{B})^{ZZ}_{WH}$ | $(\sigma \cdot \mathrm{B})^{WW}_{WH}$ | $(\sigma \cdot \mathrm{B})^{\tau\tau}_{WH}$ | $(\sigma \cdot \mathrm{B})^{bb}_{WH}$ |
| $ZH$ | $(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ZH}$ | $(\sigma \cdot \mathrm{B})^{ZZ}_{ZH}$ | $(\sigma \cdot \mathrm{B})^{WW}_{ZH}$ | $(\sigma \cdot \mathrm{B})^{\tau\tau}_{ZH}$ | $(\sigma \cdot \mathrm{B})^{bb}_{ZH}$ |
| $ttH$ | $(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{ttH}$ | $(\sigma \cdot \mathrm{B})^{ZZ}_{ttH}$ | $(\sigma \cdot \mathrm{B})^{WW}_{ttH}$ | $(\sigma \cdot \mathrm{B})^{\tau\tau}_{ttH}$ | $(\sigma \cdot \mathrm{B})^{bb}_{ttH}$ |

No measurement

Insufficient precision

Take SM values

23 parameter fit

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

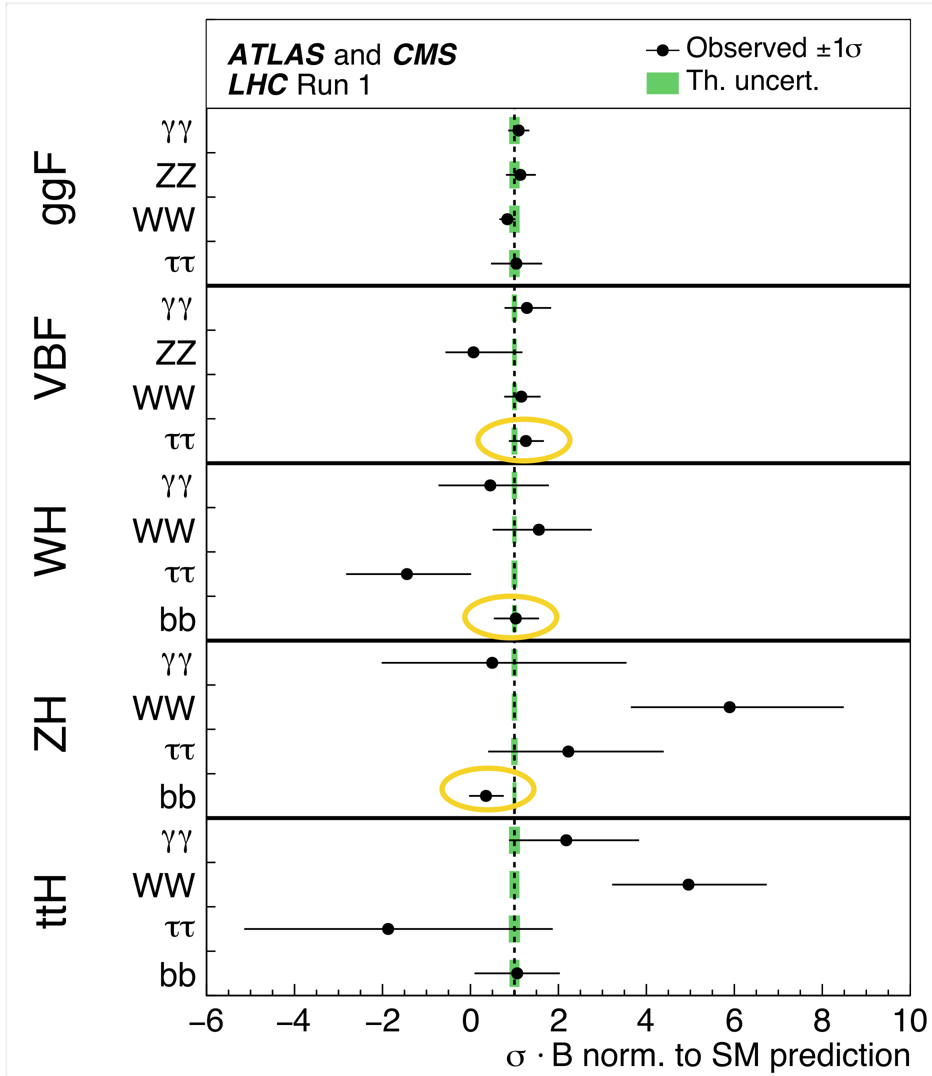
# Independent cross-section and BR Results

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