Higgs Boson Width

SM expectation Γ_{tot}= 4.15 MeV for M_H=125 GeV

- The **event yield** for each production × decay mode:

$$(\sigma \cdot \mathcal{B})\,(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{\mathrm{tot}}}$$

Γ_{ff} - Partial decay width into *ff* final state (ZZ, WW, bb, γγ, ττ, …)

- Direct measurement of the width is limited by the resolution of the detector response to photons, electrons, muons, jets, ..

H->γγ: 5.0 GeV 95% CL upper limit on width from observed mass spectrum

- assumes no interference with background

H->ZZ* 2.6 GeV 95% CL upper limit

- measurement resolution different for each lepton.

For each event 4-lepton mass is obtained by convolution of detector response with Breit-Wigner function.

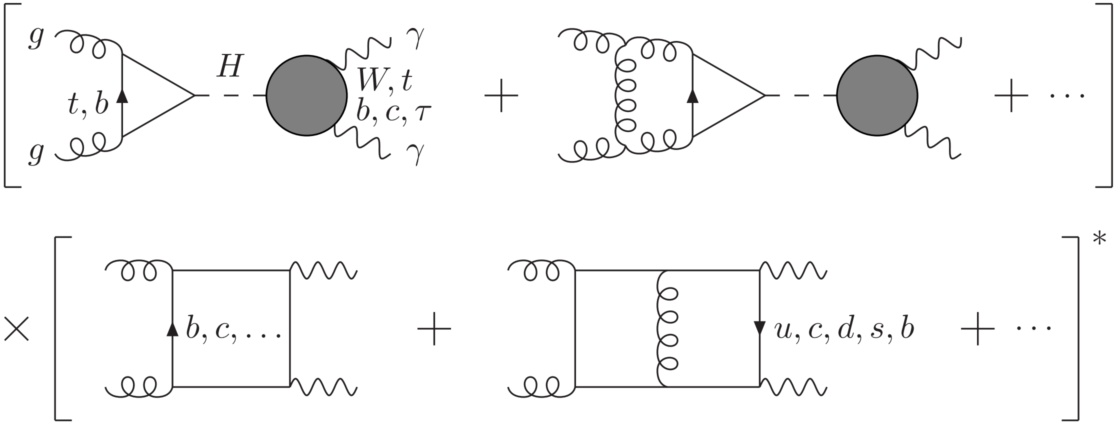
No Z-mass constraint applied.

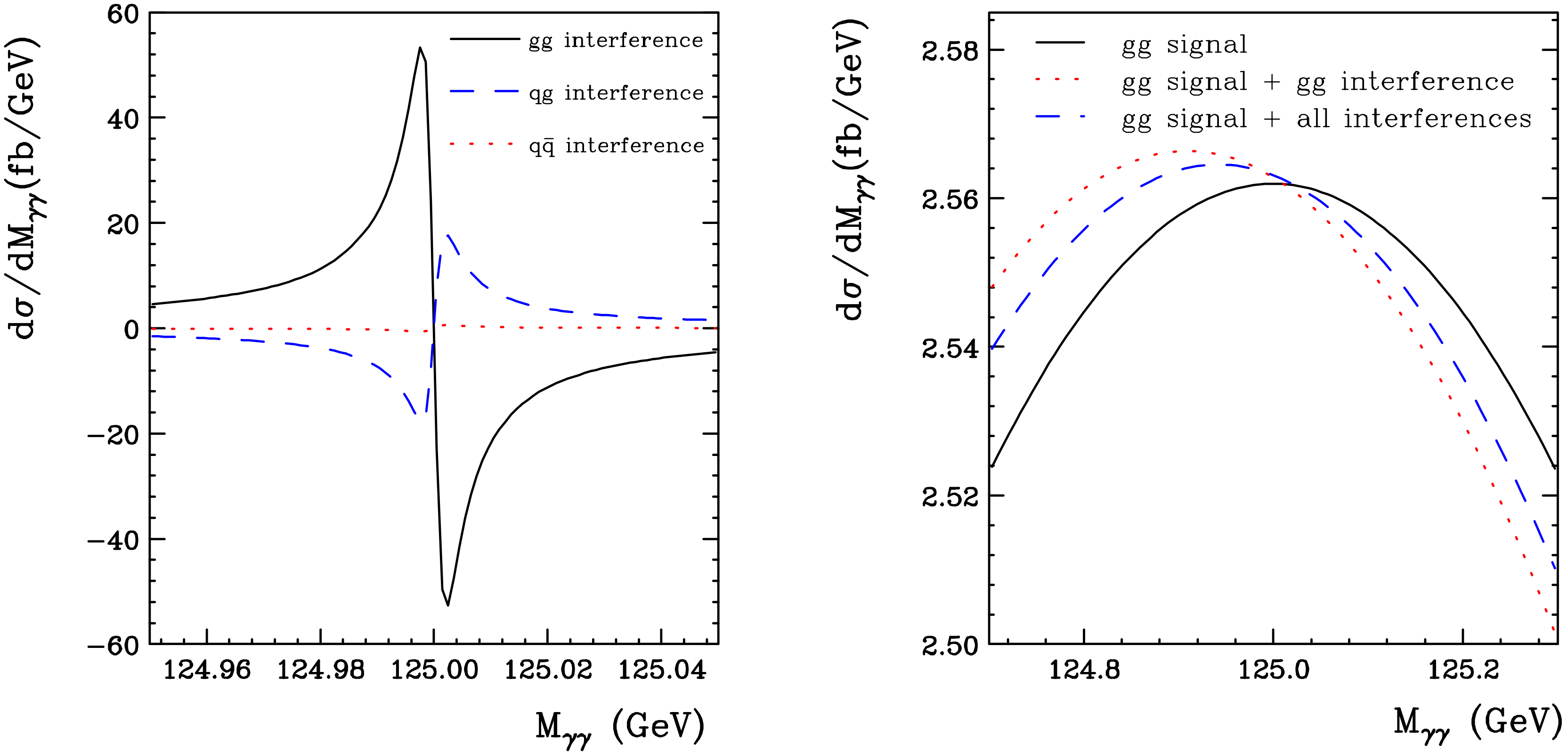
New idea – interference between Higgs signal and SM background

Interference for Higgs -> γγ

S.P. Martin, arXiv:1208.1533(2012)
L.J.Dixon,Y.Li, arXiv: 1305.3854(2013)
F.Coradeschi et al., arXiv:1504.05215(2015)

- Destructive interference between H->γγ signal and continuum background induces a shift of the mass peak.
- Mass shift depends on Higgs p_T, $\Delta M_{\gamma\gamma}$= -120 MeV at LO and -70 MeV at NLO





De Florian et al., EPJ **C73** (2013) 2387

Experimental result – shift of -35 MeV

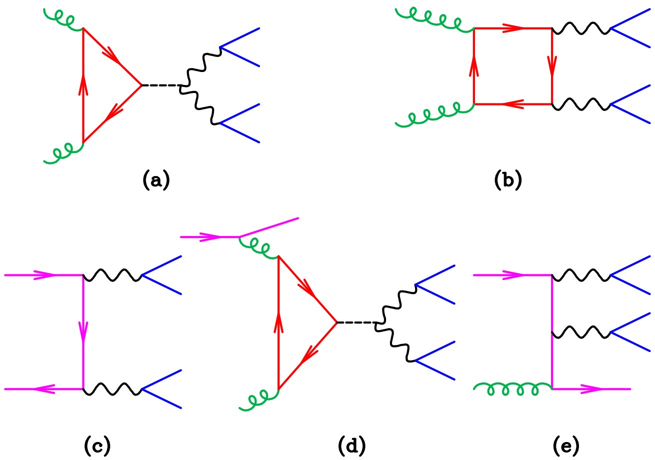
Interference for H -> 4l

- F.Caola, K.Melnikov, Phys.Rev.D88(2013)054024
- N.Kauer, G.Passarino, JHEP08(2012) 116
- J.M.Campbel, R.K.Ellis, C. Williams, JHE04 (2014) 060, FERMILAB-PUB-13-508-T

Off-shell Higgs boson signal strength is independent of the width,
while on-shell cross section is proportional to $1/\Gamma_{tot}$

$$\frac{d\sigma(pp \to H \to ZZ)}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

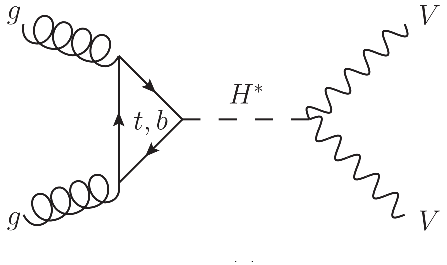
On-resonance $M^2_{4l} \cong m_H$ and $\sigma \approx 1/\Gamma_H$
Off-resonance the term $(M^2_{4l} - m^2_H)$ in denominator is large -> width can be neglected.



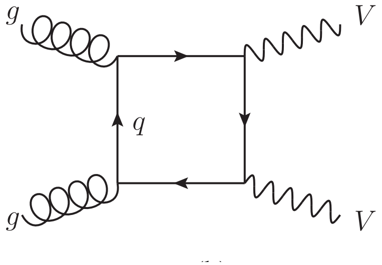
Use the ratio of signal and background cross sections on and off resonance to estimate width.

Interference for H -> 4l

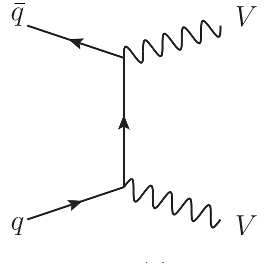
- ATLAS: arXiv1503.01060 (2015)



signal



background



background

For zero-width approximation

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

κ_j - scale factor of the Higgs coupling to particles j, for SM $\kappa_j = 1$
For off-shell measurement assume non-running coupling strength

$$\sigma^{off}(i \to H^* \to f) \sim \kappa_{i,off}^2 \cdot \kappa_{f,off}^2$$

Interference effects (signal-background) due to real part of the amplitudes are negative throughout whole mass region > $2M_V$.

Interference for H -> 4l

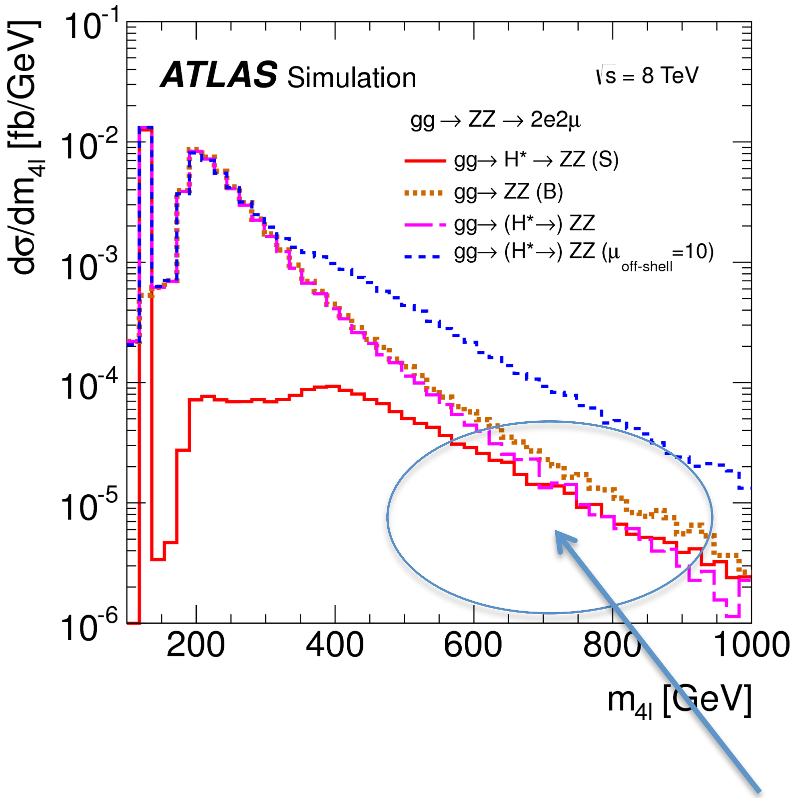
$$\mu_{off-shell} \equiv \frac{\sigma_{off-shell}^{gg\to H^*\to VV}}{\sigma_{SM,off-shell}^{gg\to H^*\to VV}} = \kappa_{goff-shell}^2 \cdot \kappa_{Voff-shell}^2$$

$$\mu_{on-shell} \equiv \frac{\sigma_{on-shell}^{gg\to H\to VV}}{\sigma_{SM,on-shell}^{gg\to H\to VV}} = \frac{\kappa_{g,on-shell}^2 \cdot \kappa_{V,on-shell}^2}{\Gamma_H / \Gamma_H^{SM}}$$

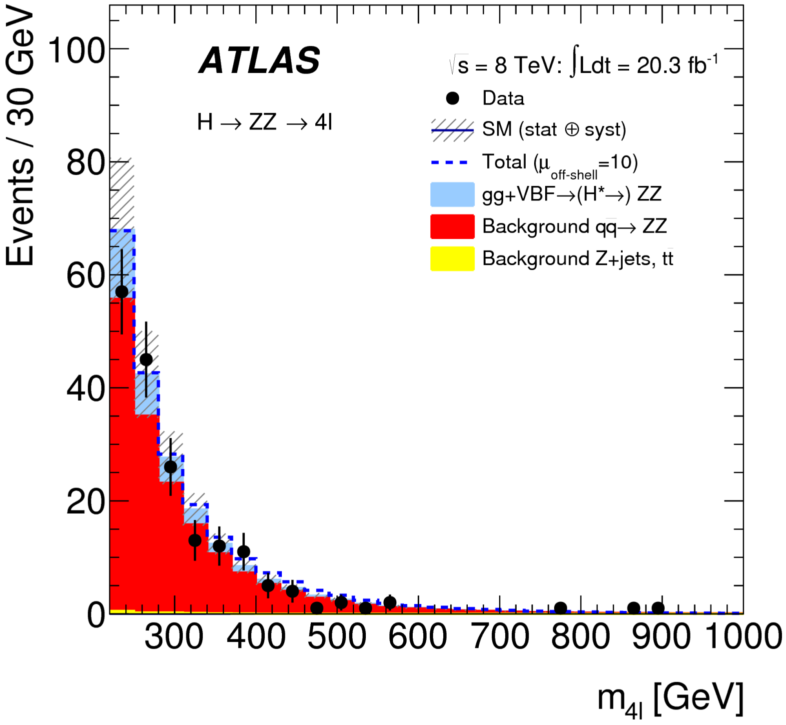
$$\frac{\mu_{off-shell}}{\mu_{on-shell}} \cong \frac{\Gamma_H^{SM}}{\Gamma_H}$$

Interference for H -> 4l

Simulation: gg -> H -> ZZ and gg -> ZZ



Data: 4 lepton invariant mass



Region of expected interference

Higgs decays to 4 leptons including 2 neutrinos

2 neutrino present in the final state -> no reconstruction of the 4 lepton mass

- for ZZ use transverse mass m_T^{ZZ} reconstructed from p_T^{ll} and E_T^{miss}

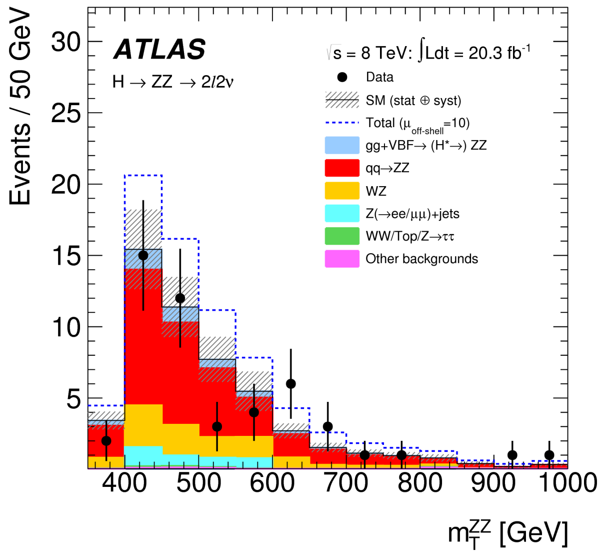
$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2+\left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}\right|^2}+\sqrt{m_Z^2+\left|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}\right)^2-\left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}+\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2},$$

- for WW use m_T^{WW} to form a variable R_8 with $p_T^{\nu\nu}$ is p_T^{miss} obtained from tracks only

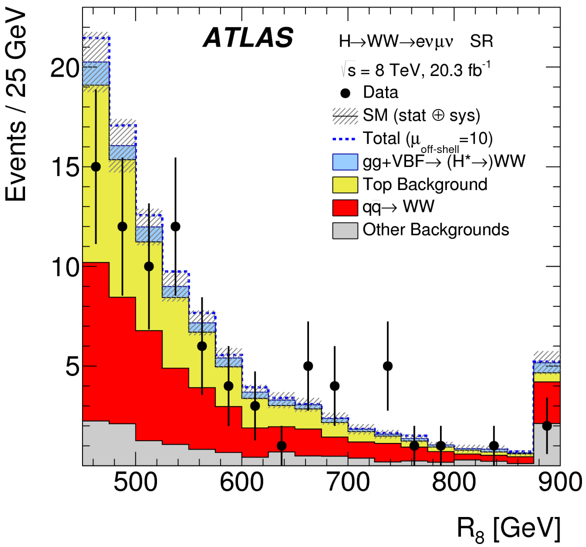
$$m_{\mathrm{T}}^{WW} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell}+p_{\mathrm{T}}^{\nu\nu}\right)^2-\left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}+\boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\right|^2}, \text{ where } E_{\mathrm{T}}^{\ell\ell} = \sqrt{(p_{\mathrm{T}}^{\ell\ell})^2+(m_{\ell\ell})^2}$$

$$\mathrm{R}_8 = \sqrt{m_{\ell\ell}^2+\left(a\cdot m_{\mathrm{T}}^{WW}\right)^2}.$$

H → ZZ → 2l2ν



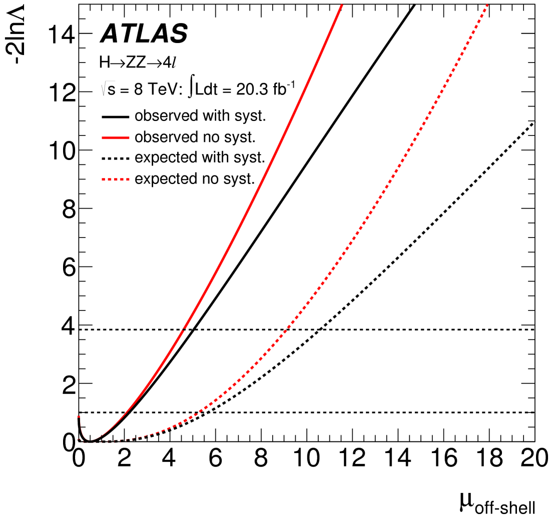
H → WW → eνμν



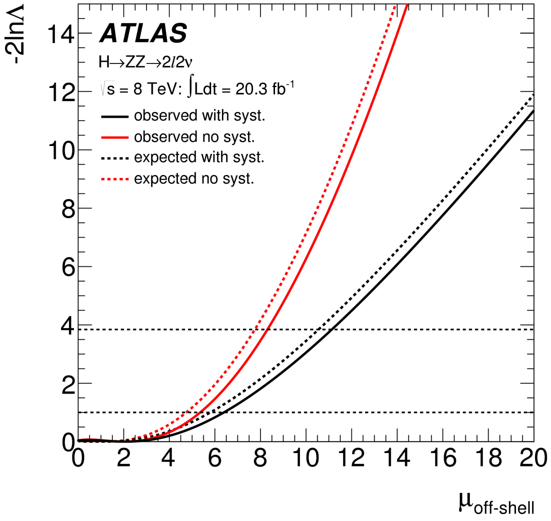
arXiv:1503.01060

Interference for H -> 4l: Likelihood fits

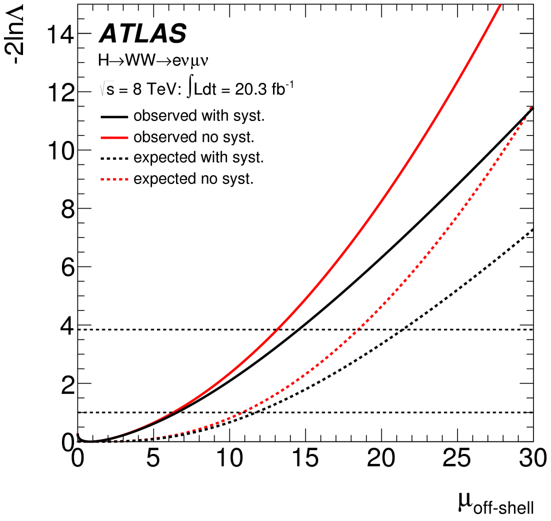
H->ZZ->4l

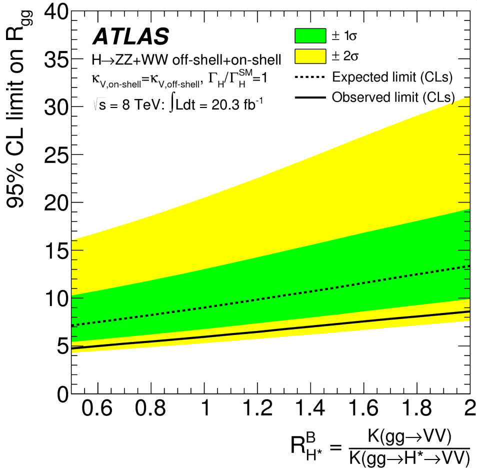


H->ZZ->2l2ν



H->WW->eνμν





ATLAS

Γ_H < 22.7 MeV (observed)

Γ_H < 33.0 MeV (expected)

Combined observed and expected 95% upper limits

Interference for H →4l - comments

- Similar results for ATLAS and CMS
- Similar sensitivity for Higgs decays to 4 charged leptons and to llνν
- Assumption - couplings are independent of energy scale
  - on-shell coupling and off-shell couplings are the same

ATLAS

$\Gamma_H < 22.7$ MeV (observed)

$\Gamma_H < 33.0$ MeV (expected)

CMS

$\Gamma_H < 22$ MeV (observed)

$\Gamma_H < 33$ MeV (expected)

-> 7÷8 times Standard Model expectation

Question to theory experts: Do we understand phases of the amplitudes involved here ?

Physics studies organization in ATLAS (not everything is about Higgs)

Groups

Standard Model
B Physics
Top Physics
Higgs
Supersymmetry
Exotics
Heavy Ions
Monte Carlo

Combined Performance Simulation and Statistics

e/gamma
muon
tau
jet/Etmiss
tracking
flavor tagging
simulation
statistics
astroparticles

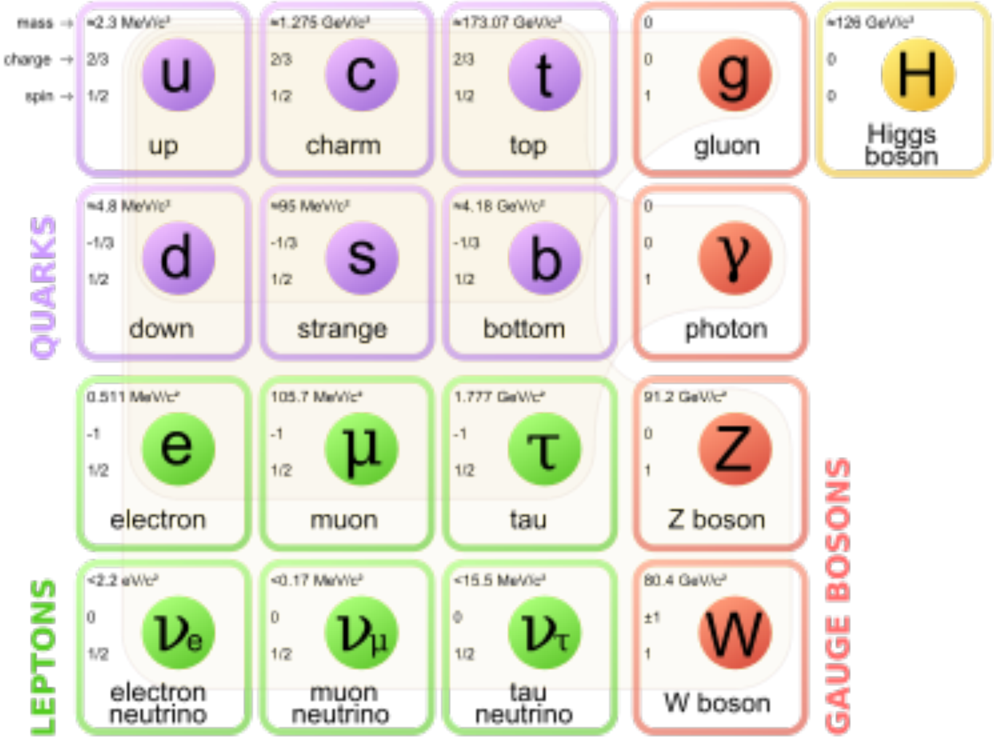
Detector systems computing, luminosity

Overall ATLAS
Pixel tracker
Semiconducter tracker (SCT)
Transition radiation tracker (TRT)
Inner detector combined
LAr calorimeter
Tile calorimeter
Muon spectrometer
Forward detectors
Trigger
Data acquisition
Detector control and safety
Luminosity
Event display

Standard Model

Theory of electromagnetic, weak and strong interactions that also includes the classification of all known subatomic particles.

Matter content



fermions
- 6 quarks x 3 colors
- 3 neutrinos
- 3 charged leptons

x 2

antiparticles

gauge bosons
- 8 gluons
- W+, W-, Z
- photon

Higgs boson

Total: 61 distinct fundamental objects

Theoretical aspects of SM

Quantum Field Theory - Lagrangian controls the kinematics and dynamics

- start by postulating symmetry
- write down the Lagrangian from particles and fields that observe these symmetries

All quantum filed theories satisfy **global** Poincare symmetry: translational symmetry, rotational symmetry and invariance of inertial reference frame.
Poincare symmetry gives us the momentum, energy and angular momentum conservation laws.

Standard Model also has an internal – **local** – symmetry SU(3) x SU(2) x U(1)
The three factors give rise to strong, electromagnetic and weak interactions.

Quantum chromodynamics - symmetry group SU(3)

QCD – describes interactions between quarks and gluons with the Lagrangian

$$L_{QCD} = i\overline{U}(\partial_\mu - ig_s G_\mu^a T^a)\gamma^\mu U + i\overline{D}(\partial_\mu - ig_s G_\mu^a T^a)\gamma^\mu D$$

G is the SU(3) gauge field containing the gluons
D and U are the Dirac spinors associated with up and down type quarks
γ are the Dirac matrices
g is the strong coupling constant
T generates SU(3) symmetry

Electroweak sector – symmetry group U(1) x $SU(2)_L$

$$L_{EW} = \sum_\psi \overline{\psi}\gamma^\mu (i\partial_\mu - g'\frac{1}{2}Y_W B_\mu - g\frac{1}{2}\overrightarrow{\tau_L}\overrightarrow{W_\mu})\psi$$

B is the U(1) gauge field
Y is the weak hypercharge generating U(1) group
W is the three component SU(2) gauge field
τ are the Pauli matrices generating SU(2) group and acting only on left-handed fermions
g are coupling constants

Higgs sector (SM)

Higgs is a complex scalar of the group $SU(2)_L$

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix}$$

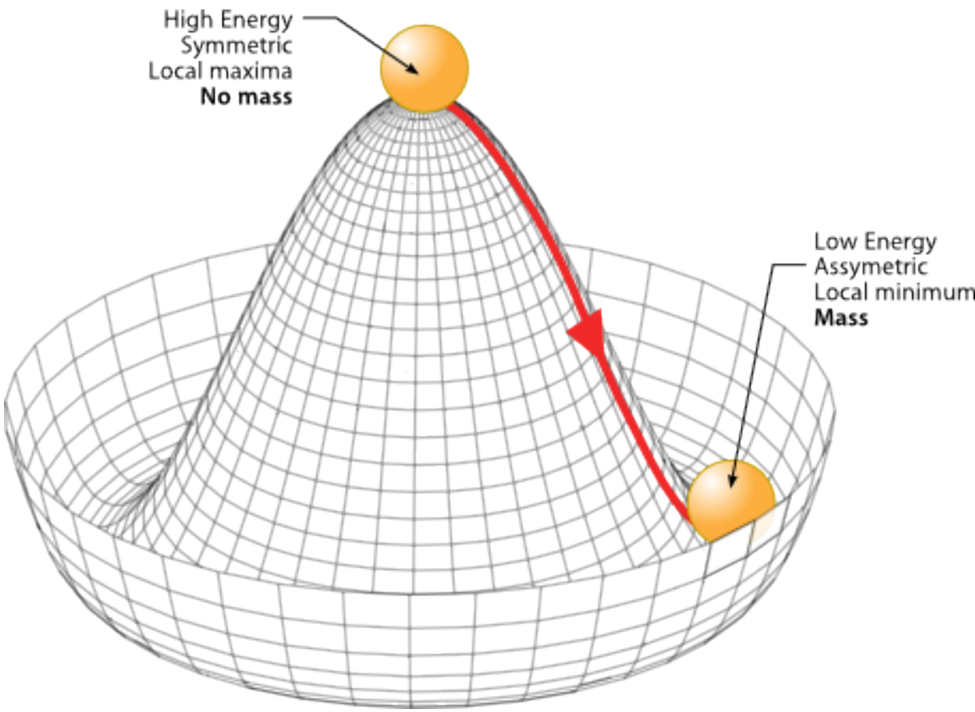
Before the symmetry breaking the Higgs Lagrangian is

$$L_H = \varphi^{\otimes}\left(\partial^{\mu} - \frac{i}{2}\left(g'Y_W B^{\mu} + g\vec{\tau}\vec{W}^{\mu}\right)\right)\left(\partial_{\mu} + \frac{i}{2}\left(g'Y_W B_{\mu} + g\vec{\tau}\vec{W}_{\mu}\right)\right)\varphi - \frac{\lambda^2}{4}\left(\varphi^{\otimes}\varphi - \upsilon^2\right)^2$$

The electroweak symmetry would lead to all gauge bosons being massless.
Contrary to observation → W+, W- and Z are massive.
Spontaneous symmetry breaking generates massive W and Z bosons while the photon remains massless.
Spontaneous braking – Lagrangian obeys symmetry but the lowest-energy solutions do not exhibit that symmetry

Higgs mechanism

- In the standard model, the Higgs field is an SU(2) doublet, a complex scalar with four real components (or equivalently with two complex components).
- Its weak hypercharge U(1) is 1. (electric charge is 0)
- It transforms as a spinor under SU(2).
- Under U(1) rotations it is multiplied by a phase that mixes real and imaginary parts of the complex spinor.



Recent Standard Model results from ATLAS
Miami December 2015

$B^\pm$ mass reconstruction at 13 TeV

Elegant test of the quality of tracking and momentum calibration at low p_T.

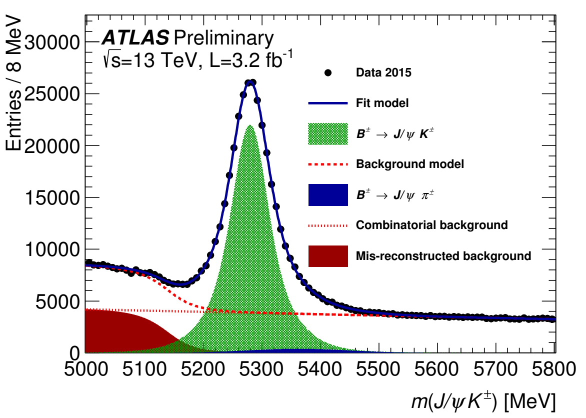
$$B^\pm \rightarrow J/\psi(\mu^+\mu^-)\ K^\pm$$

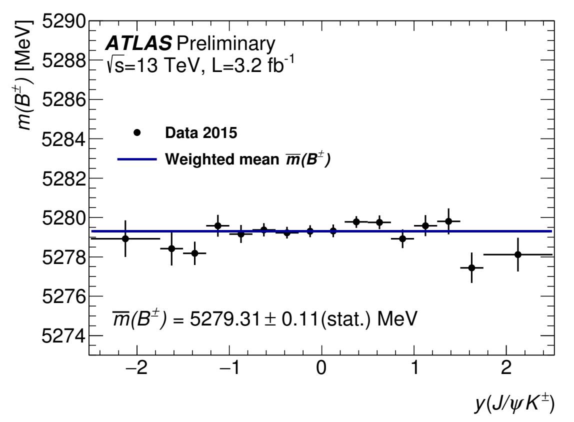
Muon momentum determined by inner detector, $p_T > 4$ GeV.

Mass of opposite-sign muon pairs in mass range 2.6 – 3.6 GeV fixed to J/ψ mass.

Third track with $p_T > 3$ GeV is added with K mass assumption.

Track triplet fitted with unbinned maximum-likelihood function including background due to π/K misidentification in 16 intervals of η.





ATLAS	**$m(B^\pm) = 5279.38 \pm 0.11$ (stat) ± 0.22 (fit syst) MeV**
LHCb	**$m(B^\pm) = 5279.38 \pm 0.11$(stat) ± 0.33 (syst) MeV**
World Average	**$m(B^\pm) = 5279.29 \pm 0.15$ (stat) MeV**

ATLAS-CONF-2015-064

SM Higgs Boson

Hint in 2011, Discovery publication in 2012

Scene repeated in hundreds of places

Spring 2015 - Completion of analyses of Run1 data at 7/8 TeV

H->4l $m_H = 124.51 \pm 0.52$ (stat) ± 0.04 (syst) GeV

H->γγ $m_H = 126.02 \pm 0.43$ (stat) ± 0.27 (syst) GeV

ATLAS + CMS combination

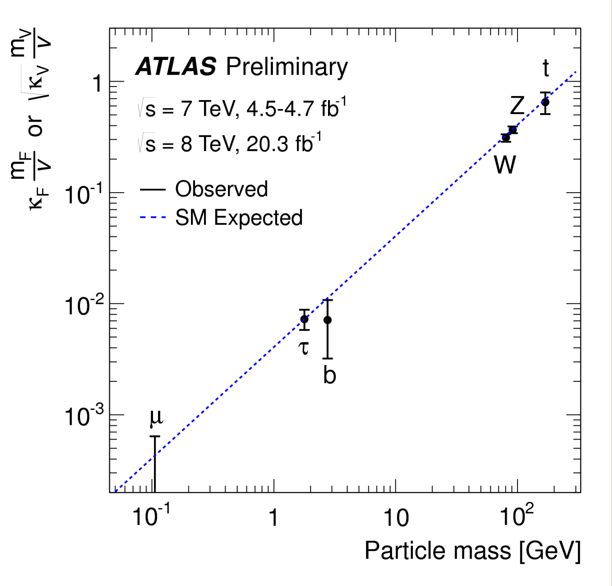
$m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV

Spin/Parity - consistent with $J^P = 0^+$

Cross Section/Couplings – many tests carried out

->Consistent with mass dependence expected in the Standard Model

Differential cross section p_T distributions have been measured



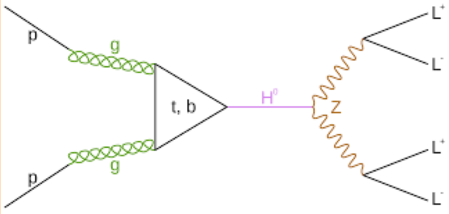
ATLAS-CONF-2015-044

H-ZZ*->4l fiducial cross section (low mass)

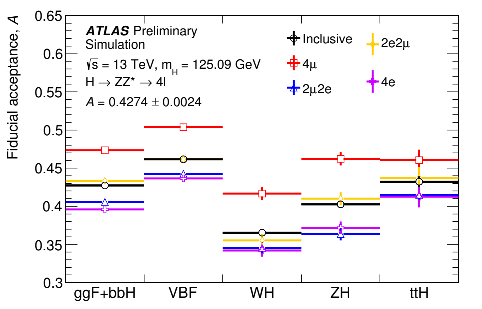
4 final states: 4μ, 2e2μ, 2μ2e, 4e
Largest backgrounds: ZZ*, Z+jets, ttbar

Event selection – main cuts

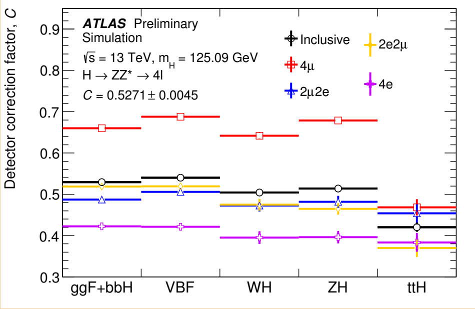
muons: $p_T > 6$ GeV, $|\eta| < 2.7$
electrons: $p_T > 7$ GeV, $|\eta| < 2.47$
leading lepton: $p_T > 20$ GeV
masses: $50 < m_{12} < 106$ GeV ; $12 < m_{34} < 115$ GeV
$118 < m_{4l} < 129$ GeV



Acceptance



Detector correction factor



Background estimates
- ZZ* continuum from simulation
- reducible background from fit to data in control regions enriched in Z + heavy/light flavor or ttbar.

$$\sigma_{4\ell}^{\mathrm{fid}} = \frac{N_{\mathrm{s}}}{C \cdot \mathcal{L}_{\mathrm{int}}}$$

Production modes

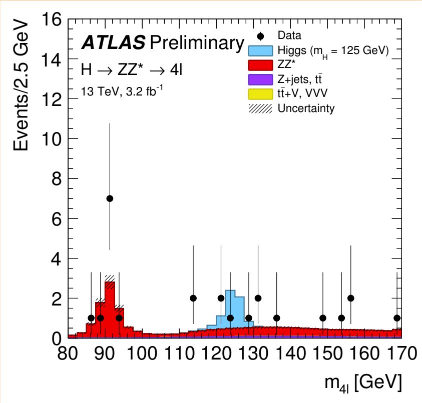
ATLAS-CONF-2015-059

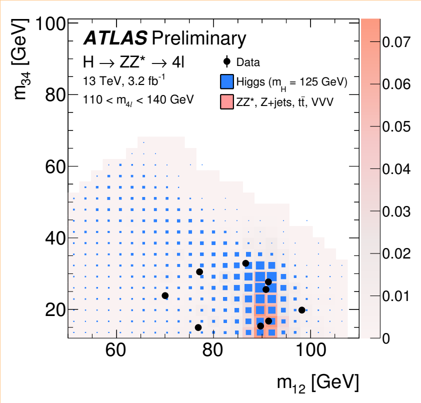
H-ZZ*->4l fiducial cross section (low mass)

Measurement statistically limited: 4 events in 118 < m_{4l} < 129 GeV (6.8 expected)

Data

Fit



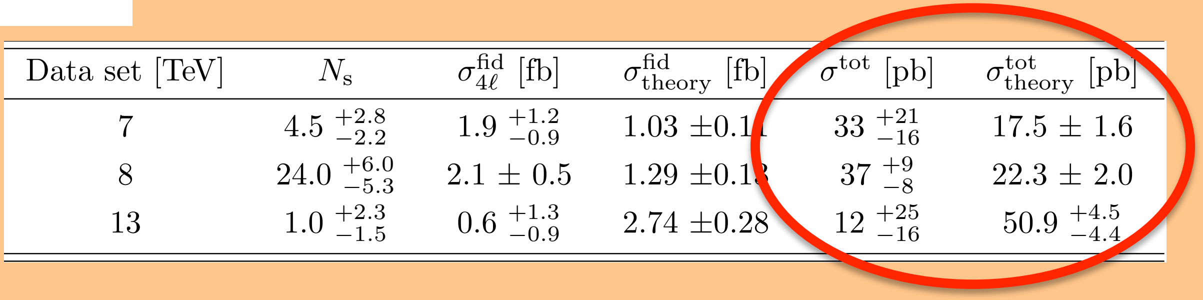


- **Likelihood fit to m_{4l} distribution**
- **Poisson probability of observing events in all four final states and the estimates of corresponding backgrounds assuming Higgs mass of 125.09 GeV**

$$\sigma^{\mathrm{tot}} = \frac{1}{\mathcal{A} \cdot \mathcal{BR}} \cdot \sigma^{\mathrm{fid}}_{4\ell} = \frac{N_{\mathrm{s}}}{\mathcal{A} \cdot \mathcal{C} \cdot \mathcal{BR} \cdot \mathcal{L}_{\mathrm{int}}},$$

Results

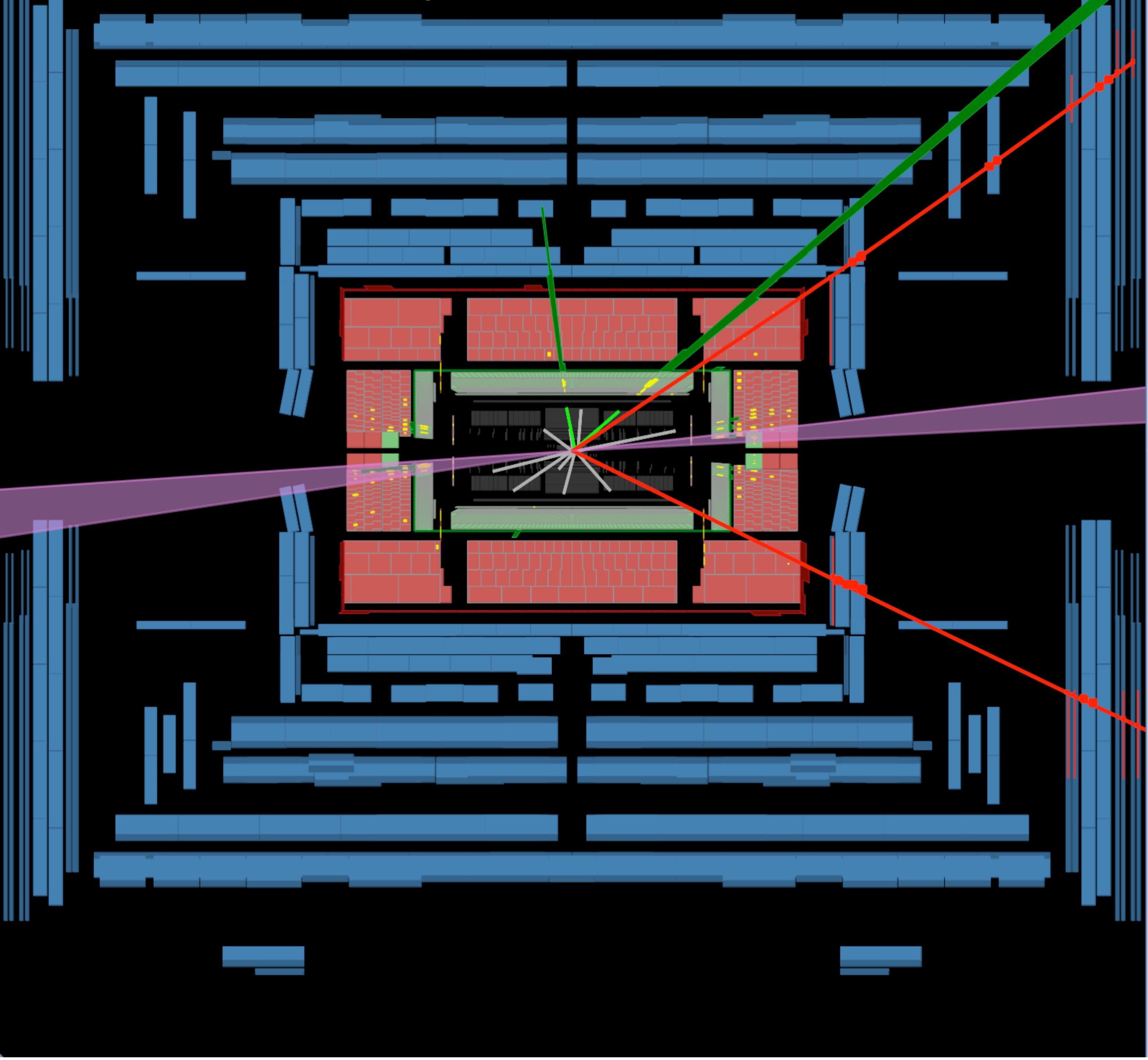
New ->



Data set [TeV]	N_{s}	$\sigma^{\mathrm{fid}}_{4\ell}$ [fb]	$\sigma^{\mathrm{fid}}_{\mathrm{theory}}$ [fb]	σ^{tot} [pb]	$\sigma^{\mathrm{tot}}_{\mathrm{theory}}$ [pb]
7	$4.5^{+2.8}_{-2.2}$	$1.9^{+1.2}_{-0.9}$	1.03 ± 0.11	33^{+21}_{-16}	17.5 ± 1.6
8	$24.0^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ± 0.13	37^{+9}_{-8}	22.3 ± 2.0
13	$1.0^{+2.3}_{-1.5}$	$0.6^{+1.3}_{-0.9}$	2.74 ± 0.28	12^{+25}_{-16}	$50.9^{+4.5}_{-4.4}$

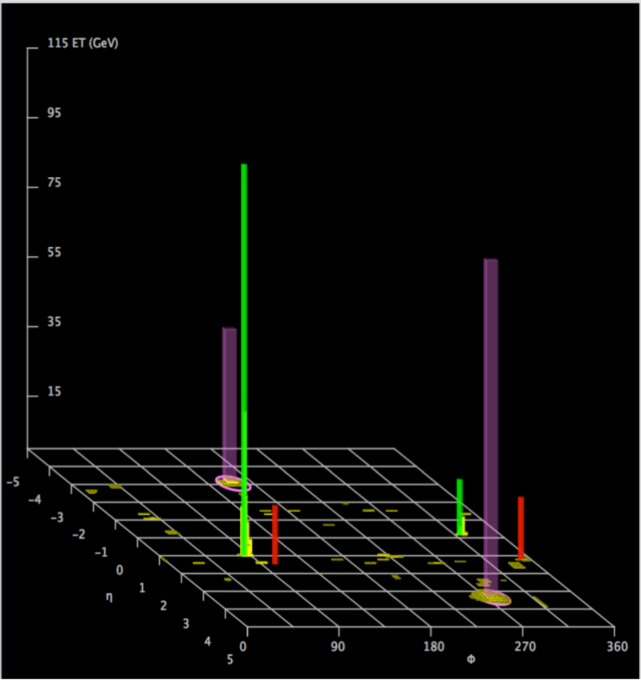
13 TeV: Low statistics and low cross section value -> consistent with SM

VBF H->2e2μ



Run Number: 280862, Event Number: 53564866

Date: 2015-10-02 16:24:44 CEST

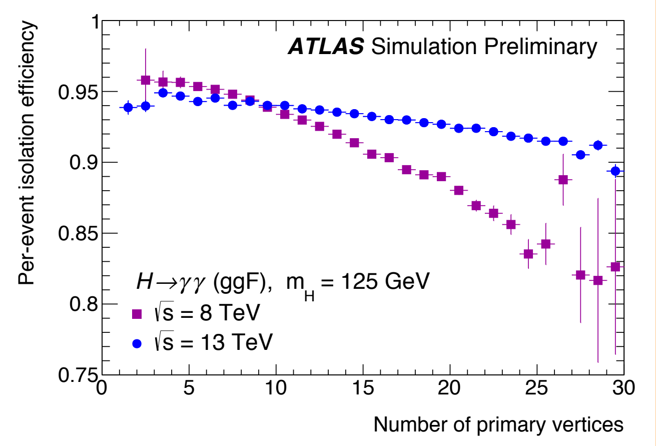


13 TeV SM Higgs cross section measurements

H -> γγ

Event Selection	
Two highest-p_T photons:	$\lvert\eta^\gamma\rvert < 2.37$
Relative-p_T:	$E^\gamma_{T,1}/m_{\gamma\gamma} \geq 0.35, E^\gamma_{T,2}/m_{\gamma\gamma} \geq 0.25$
Mass window:	$105 \leq m_{\gamma\gamma} < 160$
Photon isolation:	$E_{T,\mathrm{iso}} < 0.1 \times E^\gamma_T + 1\,\mathrm{GeV}$

- **Overall analysis strategy same as that for 8 TeV**
- **Two good quality isolated photons**
- **Use 3.2 fb^{-1} at 13 TeV**
- **Several detail changes**
  - **- Improved photon identification based on shower shape, isolation and pointing**
  - **- Increased selection efficiency for Httbar events**
  - **- Reduced sensitivity to pileup**
  - **- Improved MC simulation of the backgrounds**
    - **- continuum diphoton production (γγ)**
    - **- energetic π^0's from jet fragmentation (γ+jet)**
    - **- photon misidentification from Drell-Yan (j-j)**
- **Consistent re-analysis of 7 and 8 TeV data (same cuts, m$_H$ =125.09 used in simulations)**



ATLAS-CONF-2015-060

H -> γγ Fiducial cross section (low mass)

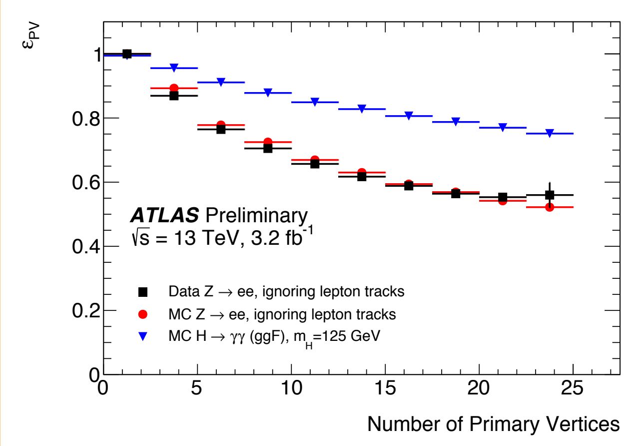
Fit

Signal shape: CB+Gauss
Background shape Exp (2nd order polynomial)
Fit range: $110 < m_{\gamma\gamma} < 160$ GeV
Fix mass in the fit $m_H = 125.09$ GeV

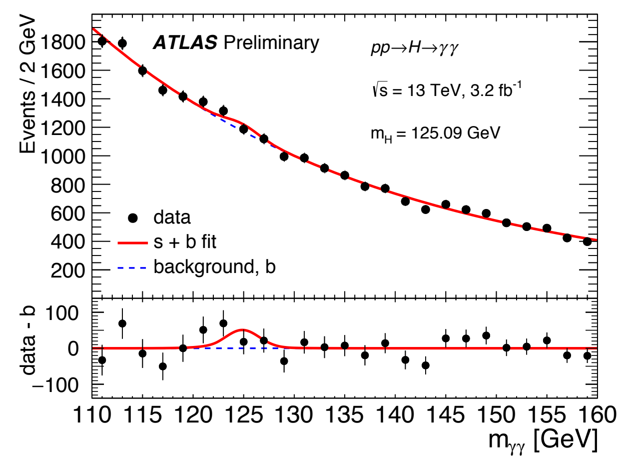
Main systematic uncertainty:

- photon energy resolution

γγ vertex selection efficiency



Data + fit



ATLAS-CONF-2015-060

Signal yield (expected and extracted)

$$\nu^{\text{exp}} = 146 \pm 72\,(\text{stat.})\,^{+35}_{-12}\,(\text{syst.})$$

$$\nu^{\text{sig}} = 114 \pm 74\,(\text{stat.})\,^{+42}_{-28}\,(\text{syst.})$$

Exotics search results (high mass) → talk by V. Jain

H -> γγ: Fiducial and Total Cross Sections

Corrections factors dependent on phase space, photon isolation and photon identification efficiency for different production mechanisms are similar

Fiducial cross section (within detector acceptance):

$$\sigma = \frac{\nu^{\mathrm{sig}}}{c \int L dt}$$

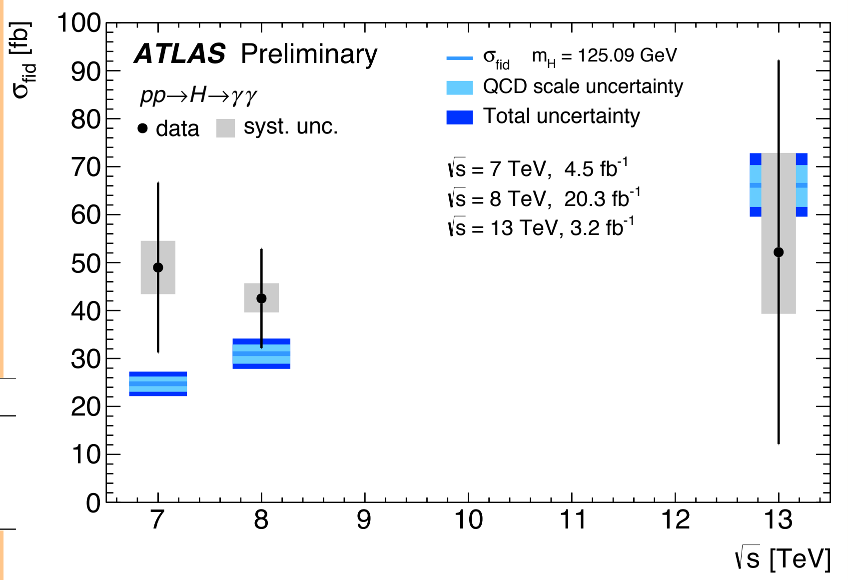
$\sqrt{s}$	Measured fiducial cross section [fb]	LHC-XS prediction [fb]
7 TeV	49 ± 17 (stat.) ± 6 (syst.) ± 1 (lumi.)	24.7 ± 2.6
8 TeV	42.5 ± 9.8 (stat.) $^{+2.9}_{-2.7}$ (syst.) ± 1.2 (lumi.)	31.0 ± 3.2
13 TeV	52 ± 34 (stat.) $^{+21}_{-13}$ (syst.) ± 3 (lumi.)	$66.1\ ^{+6.8}_{-6.6}$

Total cross section

(extrapolated to full phase space and corrected for branching fraction)

Theory: NNLO in QCD with NNLL+NO in EW

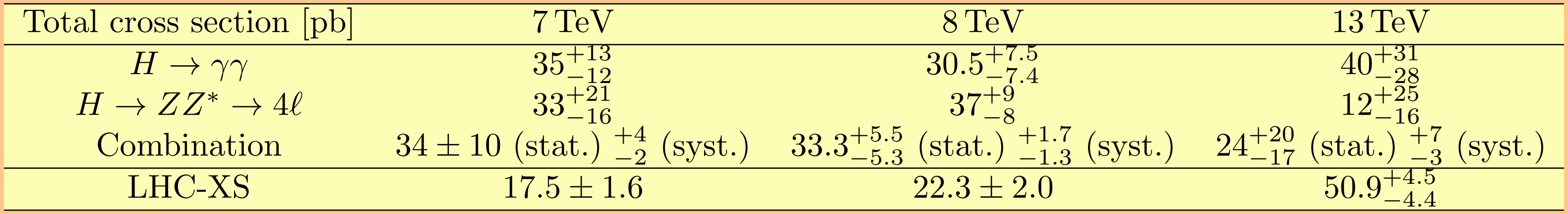
$\sqrt{s}$	Measured total cross section [pb]	LHC-XS prediction [pb]
7 TeV	35 ± 12 (stat.) ± 4 (syst.) ± 1 (lumi.)	17.5 ± 1.6
8 TeV	30.5 ± 7.1 (stat.) $^{+2.6}_{-2.5}$ (syst.) ± 0.9 (lumi.)	22.3 ± 2.0
13 TeV	40 ± 26 (stat.) $^{+16}_{-10}$ (syst.) ± 2 (lumi.)	$50.9\ ^{+4.5}_{-4.4}$



ATLAS-CONF-2015-060

Cross section combination

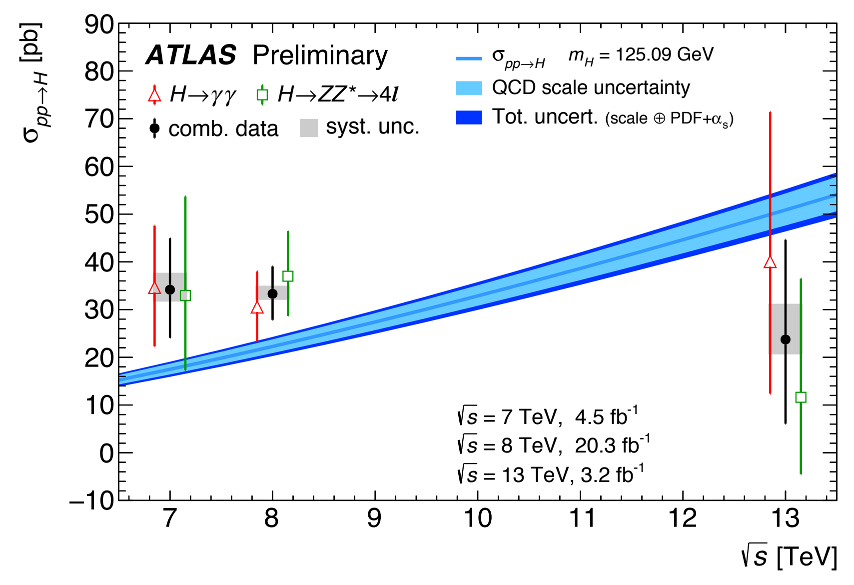
H->γγ and H->ZZ*->4l fiducial cross sections combined to obtain inclusive cross section (m_H = 125.09 GeV). Corrected for acceptance and detector effects. Use SM branching fractions and relative rates for production modes. differences



Total cross section [pb]	7 TeV	8 TeV	13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	40^{+31}_{-28}
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16}	37^{+9}_{-8}	12^{+25}_{-16}
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.)	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.)	24^{+20}_{-17} (stat.) $^{+7}_{-3}$ (syst.)
LHC-XS	17.5 ± 1.6	22.3 ± 2.0	$50.9^{+4.5}_{-4.4}$

All systematic uncertainties small
in comparison to statistical uncertainty
1.4σ – compatibility with SM
2.8σ – expected compatibility with SM

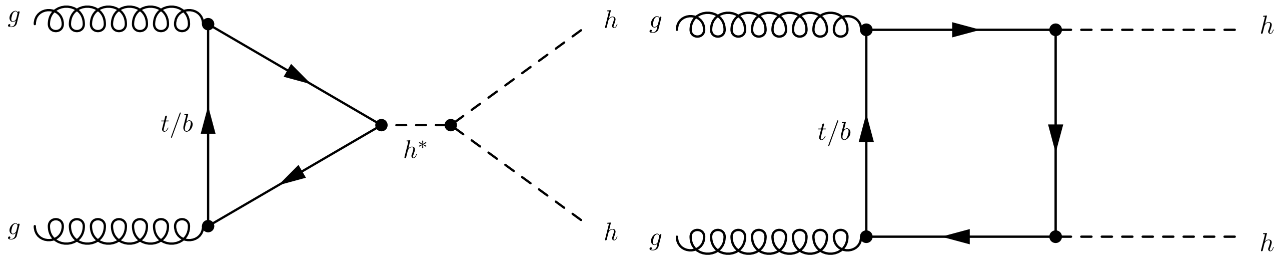
Theory:
ggF: NNLO + NNLL in QCD + NLO in EW
VBF: NNLO in QCD +NLO in EW
t+H: NLO in QCD
b+H: NNLO in QCD (5 flavor scheme)



ATLAS-CONF-2015-059; ATLAS-CONF-2015-069

Search for Higgs pair production

SM processes with
destructive interference
Sensitive to self coupling



Search done for **bbbb, bbττ, γγbb, γγWW*** final states

Decay branching fractions: 32.6% 7.1% 0.26% 0.10%

Signal MC generated with NLO MadGraph5 + Pythia8

Backgrounds include single Higgs boson (ggF and VBF, VH, ttH), V+jets, Wt, VV

Data analysis scheme (20.3 fb^{-1} at 8 TeV) same as in single H discovery papers .

Profile likelihood ratio test statistics used to measure compatibility with background only hypothesis

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Upper limit on the cross section [pb]					
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
Upper limit on the cross section relative to the SM prediction					
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

→ Search will continue with larger data sample and improved analysis !

Phys.Rev. D92, 092004 (2015)

Top-pair production cross section at 13 TeV

Top-pair production cross section calculations are challenging.
They are sensitive to gluon distribution function of the proton, α_s, m_t and possible new physics
At LHC top quarks are mostly produced in ttbar pairs.
Within Standard Model top quark decays almost exclusively to W and b quark
The identification of ttbar events depends on the choice of particular decay modes.
Three analyses with initial data at 13 TeV:

- **e-μ with b-tagged jets using 78 pb^{-1} of data at 13 TeV : ATLAS-CONF-2015-033**

$$t\bar{t} \to W^+bW^-\bar{b} \to e^+\mu^-\nu\bar{\nu}b\bar{b}$$

- **e-e (μ-μ) with b-tagged jets using 85 pb^{-1} of data at 13 TeV: ATLAS-CONF-2015-049**

$$t\bar{t} \to W^+bW^-\bar{b} \to e^+e^-\nu\bar{\nu}b\bar{b}, \mu^+\mu^-\nu\bar{\nu}b\bar{b}$$

- **lepton-plus-jets using 85 pb-1 of data at 13 TeV: ATLAS-CONF-2015-049**

$$t\bar{t} \to W^+bW^-\bar{b} \to l^+\nu q\bar{q}'b\bar{b}$$

Top-pair production cross section at 13 TeV

opposite flavor dilepton channel

Events selection

must have opposite sign eμ from W decays and exactly one or two b-tag jets

Main background: associated Wt production, Z -> τ τ, and diboson production

$$
\begin{aligned}
N_1 &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1-C_b\epsilon_b)+N_1^{\mathrm{bkg}}\\
N_2 &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b{\epsilon_b}^2+N_2^{\mathrm{bkg}}
\end{aligned}
$$

ε_b – acceptance x efficiency for b-quark jet

$C_b = \varepsilon_{bb}/\varepsilon_b^2$ - correlation coefficient from MC

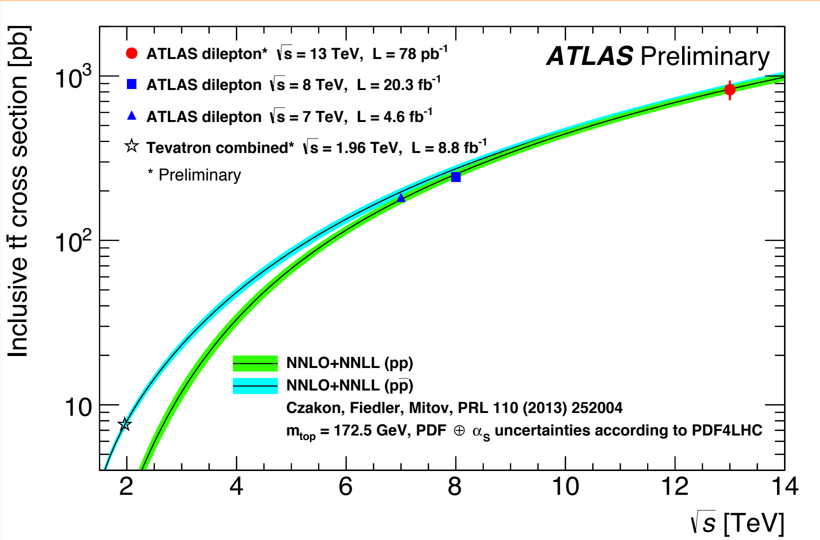
Backgrounds estimated from NLO MC

Result with $L = 78\ \mathrm{pb}^{-1}$

σ_{tt} = 825 ± 49 (stat) ± 60 (syst) ± 83 (lumi) pb

Good agreement with NNLO+NNLL calculation

$\sigma t_t = 832\,^{+40}_{-46}$ pb for m_t =172.5 GeV



ATLAS-CONF-2015-033

Top-pair production cross section at 13 TeV

Event selection

Same-flavor dilepton channel

Must have e^+e^- or $\mu^+\mu^-$ with $m(l^+l^-) > 60$ GeV, not coming from Z decays and exactly one or two b-tag jets

Background estimates as for eμ channel

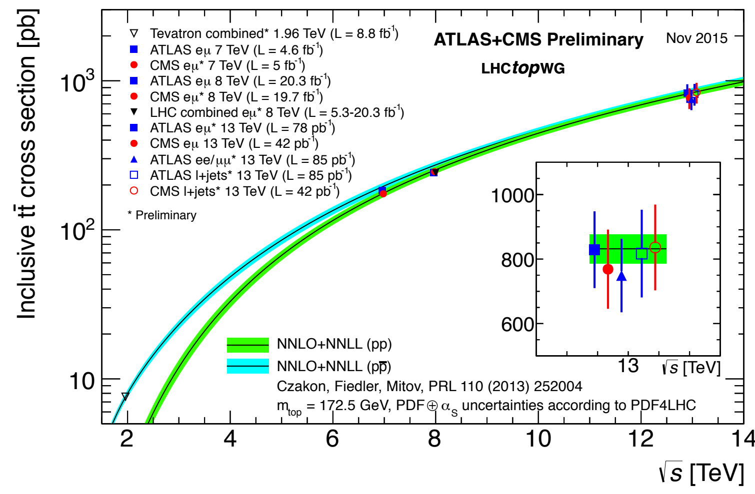
Lepton-plus-jets channel

Must have exactly one e or μ and at least 4 jets.

W suppressed by requiring large E_T^{miss} and large m_T^W

Cross section extracted from the number of events after the selection requirements

Channel	Cross-section measurement
ee	824 ± 88 (stat) ± 91 (syst) ± 82 (lumi) pb
$\mu\mu$	683 ± 74 (stat) ± 76 (syst) ± 68 (lumi) pb
ee and $\mu\mu$ combined	749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb
e+jets	775 ± 17 (stat) ± 123 (syst) ± 85 (lumi) pb
μ+jets	862 ± 18 (stat) ± 93 (syst) ± 94 (lumi) pb
e+jets and μ+jets combined	817 ± 13 (stat) ± 103 (syst) ± 88 (lumi) pb

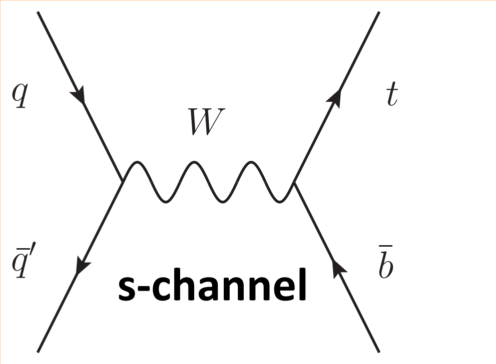


Results are consistent with each other and with theory

ATLAS-CONF-2015-049

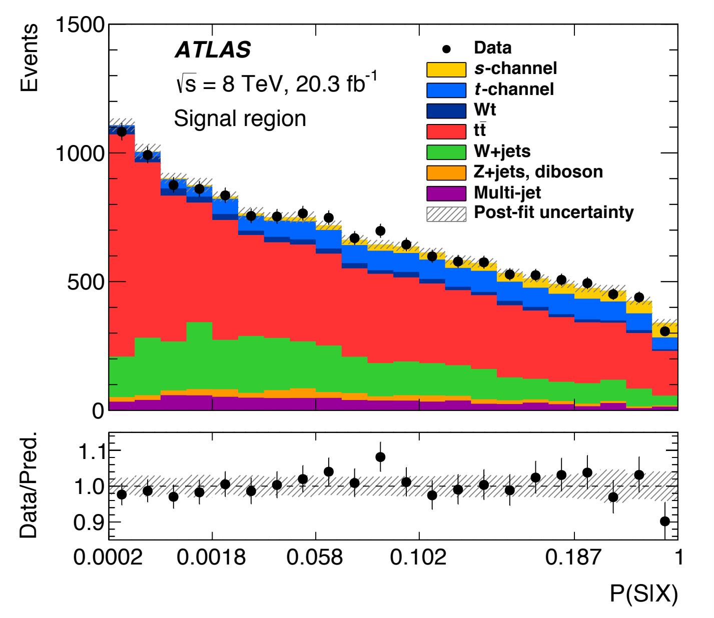
Single top quark production at 8 TeV (s channel)

- **Event selection:**
  - one isolated electron or muon with p_T > 30 GeV
  - exactly 2 b-jets with pT > 40, 30 GeV
  - $E_T$miss > 35 GeV
- **Main background: W+jets, t-tbar**
- **Maximum Likelihood fit using Matrix Element method to calculate per-event signal probability**



$\sigma = 4.8 \pm 0.8(\text{stat})^{+1.6}_{-1.3}(\text{syst})$ pb

Consistent with SM expectations
Observed significance 3.2 σ
Expected significance 3.9 σ



First evidence for this process at the LHC

arXiv:1511.05980

Single top quark production at 13 TeV (t channel)

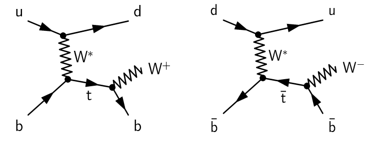
Virtual W exchange sensitive to properties of Wtb vertex (vector-axial vector structure of SM)

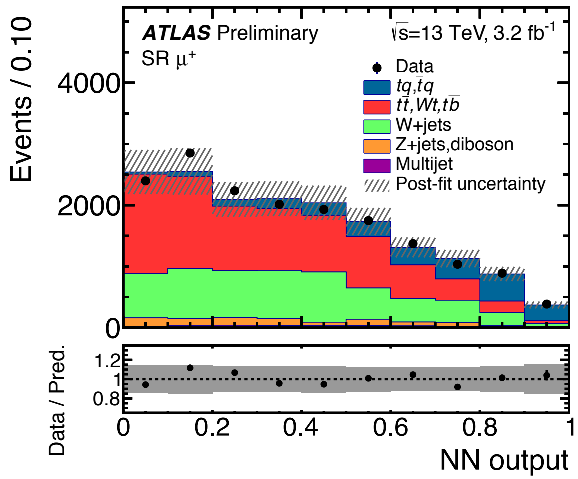
Coupling ~ V_{tb} × f_{LV}

V_{tb} - CKM matrix element; f_{LV} – left-handed formfactor

u-quark density in a proton ~ 2 x d-quark density

-> expect top production cross section ~2 x tbar





Dominant backgrounds: – ttbar, W+jets, heavy favor decays

Signal and backgrounds modeling ~NLO

Event selection: muon, E_t^{miss} , + and 2 jets (one b-jet)

Signal extraction with Neural Network fit using 10 discriminants, m_t = 172.5 GeV

Cross sections

σ(tq) = 130.3 ± 19.1 pb

σ(tbarq) = 90.2 ± 19.9 pb

Formfactor

Assume: Br (t-bW)=1; left-handed weak cplg

$|f_{LV}V_{tb}|$ = σ(tq) measured/σ(tq) NLO prediction

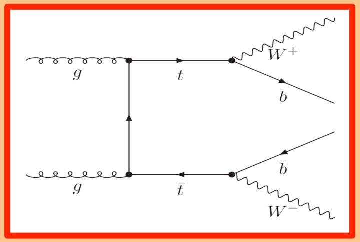
= 0.98 ± 0.08

ATLAS-CONF-2015-079

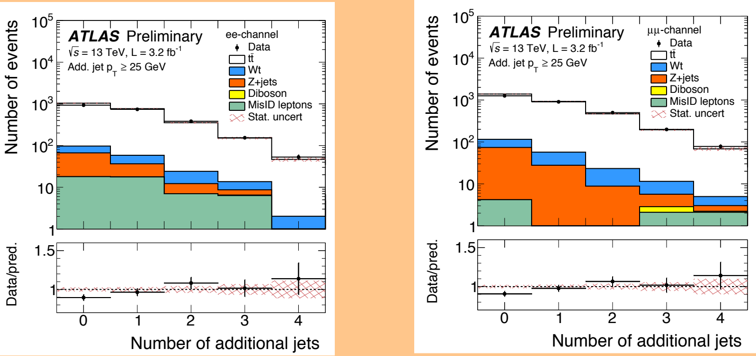
ttbar + jets at 13 TeV

Production of additional jets in ttbar events is sensitive to higher-order perturbative QCD. The p_T dependence of additional jets probes spectrum of hard-gluon emission.

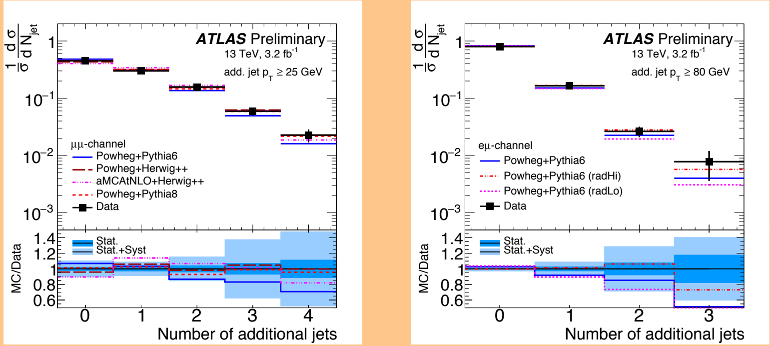
Signal - leptonic decays of both top quarks
opposite-sign lepton pair (ee, eμ, μμ) +two tagged b-jets
Background - Z boson suppressed by m(ee) m(μμ) cuts



data decomposition



unfolded distribution



Monte Carlo – NLO Powheg + Pythia6 for ttbar
ISR/FSR studied with tunes with different renormalization scale sensitive to radiation
Background subtraction + unfolding to particle level + correction for jet migration.

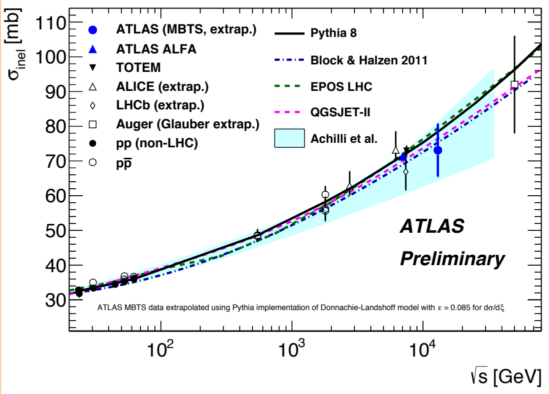
Results –Good description for 0,1,2 additional jets for all p_T range. Study of effects at higher p_T and higher jet multiplicity needs larger data sample.

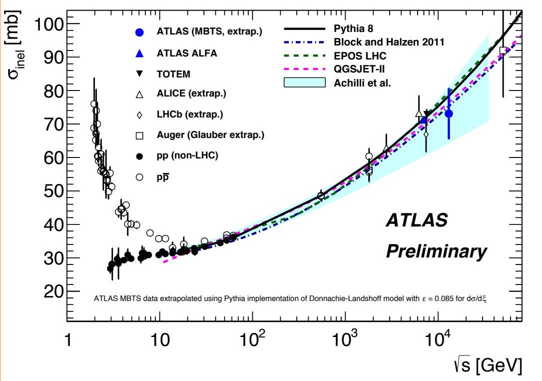
ATLAS-CONF-2015-065

QCD – basic properties of pp collisions

Early studies address global characteristics of events at 13 TeV

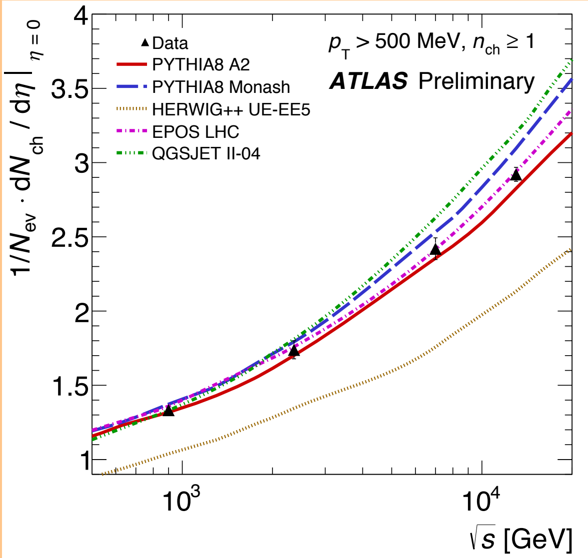
Inelastic cross section





ATLAS-CONF-2015-038

Charged particle multiplicity



ATLAS-CONF-2015-028

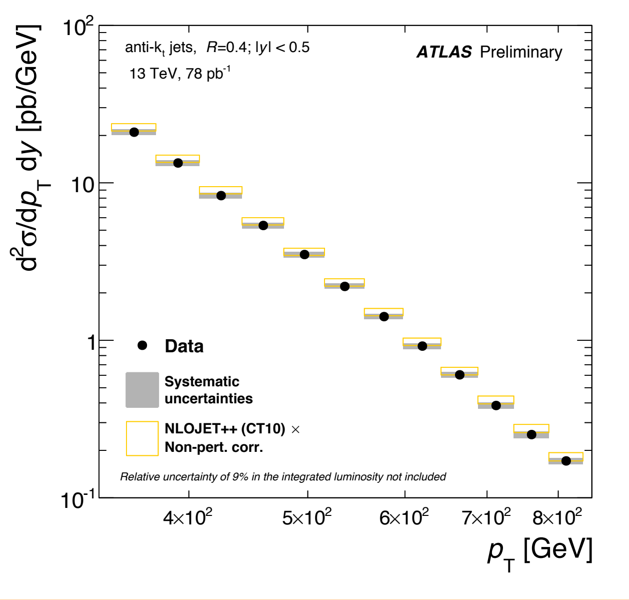
EPOS provides best description

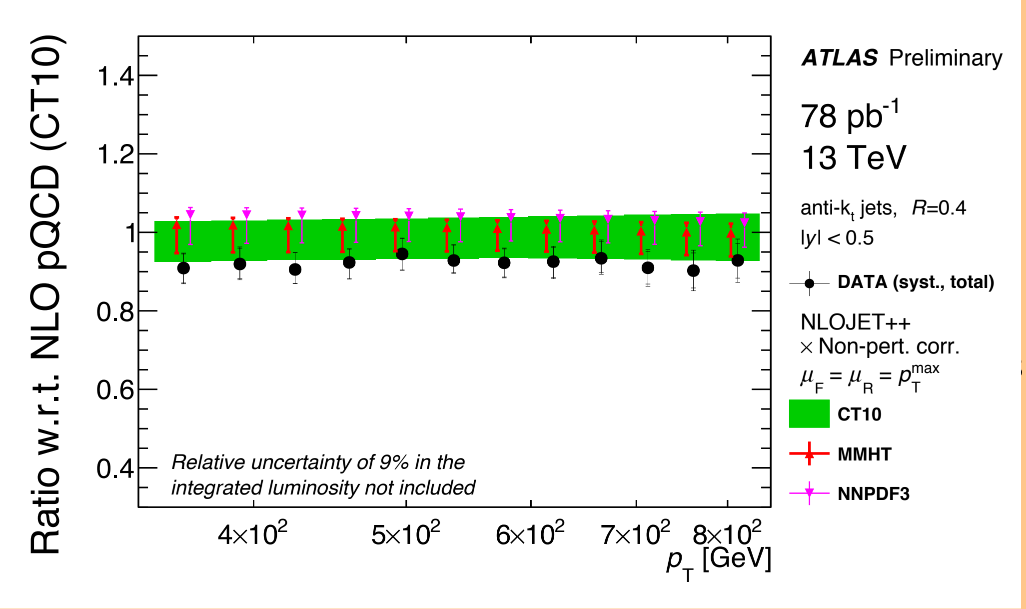
σ_{TOT}(13 TeV) = 73.1 ± 0.9 (exp) ± 0.9 (lum) ± 3.8 (extr) mb

Inclusive Jet Cross Sections at 13 TeV

Jet defined by anti-kt algorithm with radius R = 0.4 in rapidity range |y | < 0.5

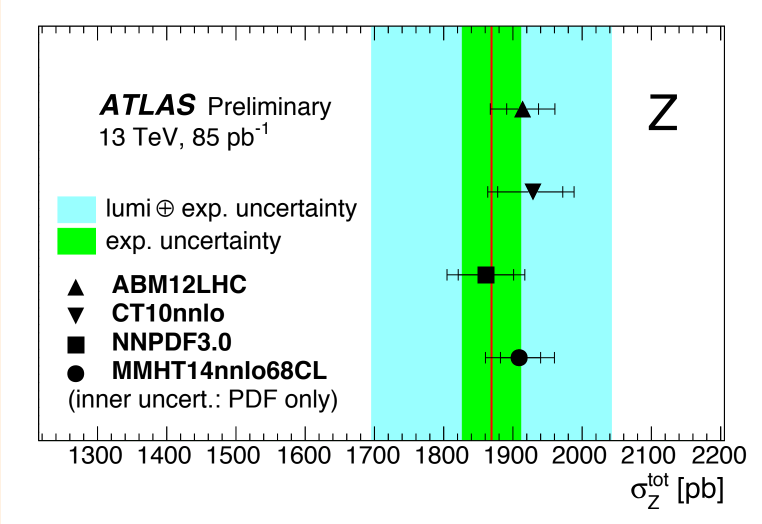
Jet p_T distribution

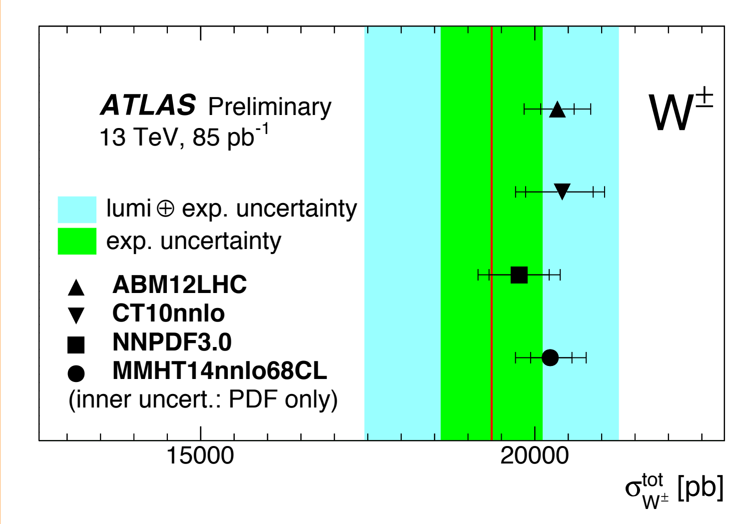


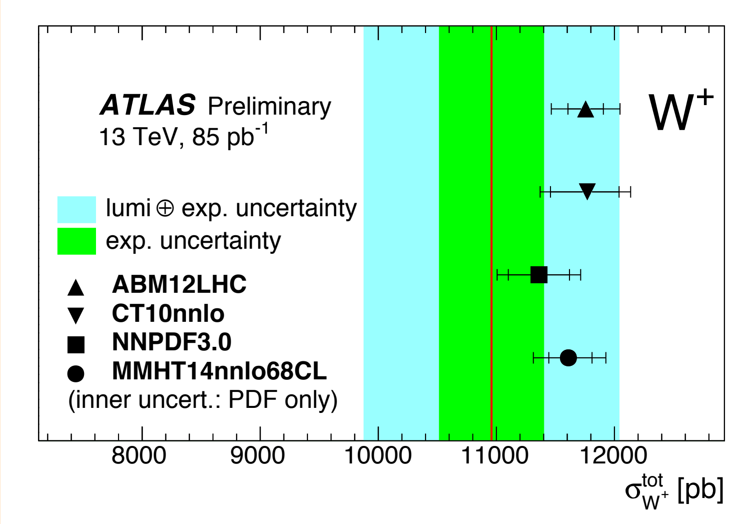


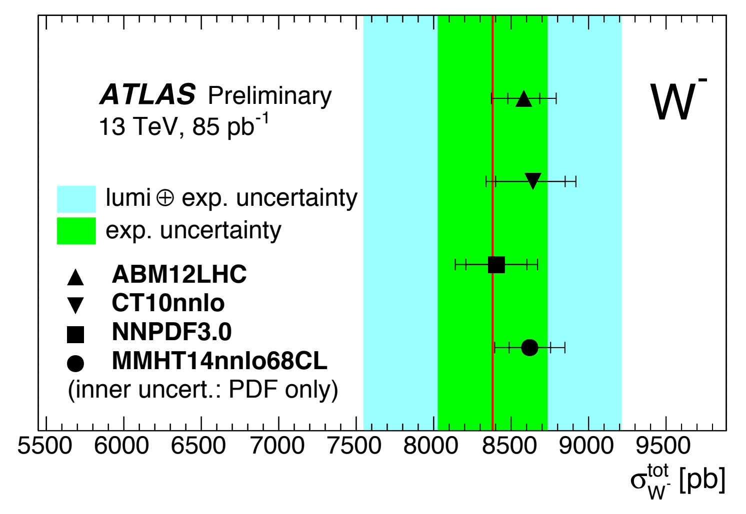
ATLAS-CONF-2015-034

Vector Boson Cross Sections at 13 TeV









ATLAS-CONF-2015-039

ZZ production Cross Section at 13 TeV

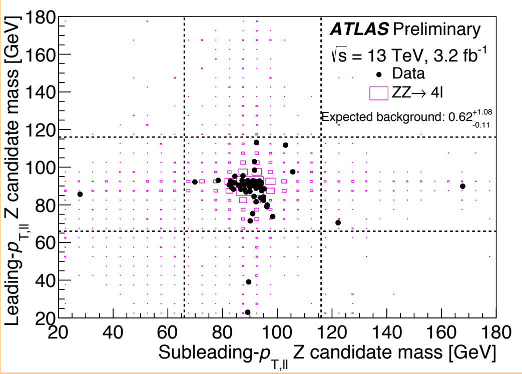
Test of the electroweak sector + Background for H->ZZ*

Two pairs of opposite-charged same-flavor leptons with $p_T > 20$ GeV

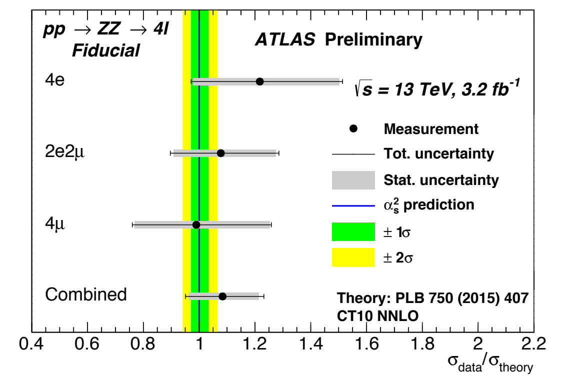
→ 62 events in three channels: $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$

On-shell Z requirements, total expected background $0.64^{+1.08}_{-0.12}$ events

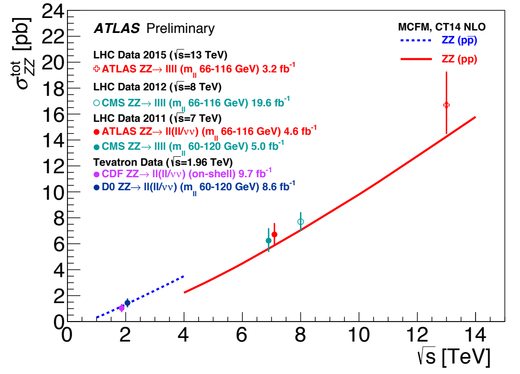
Data events

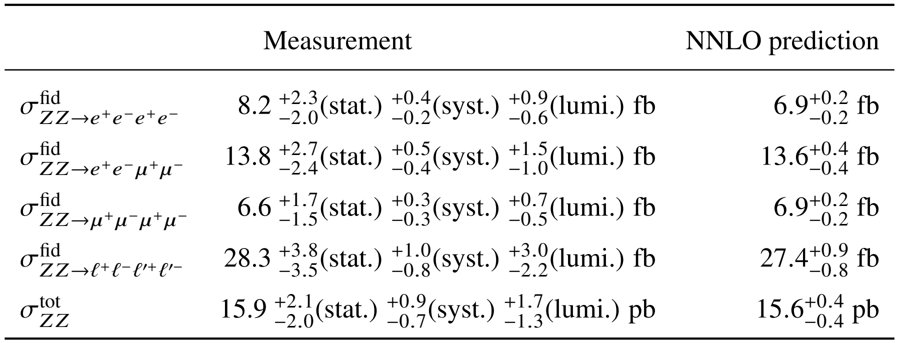


Consistency with theory (NNLO)



Energy dependence

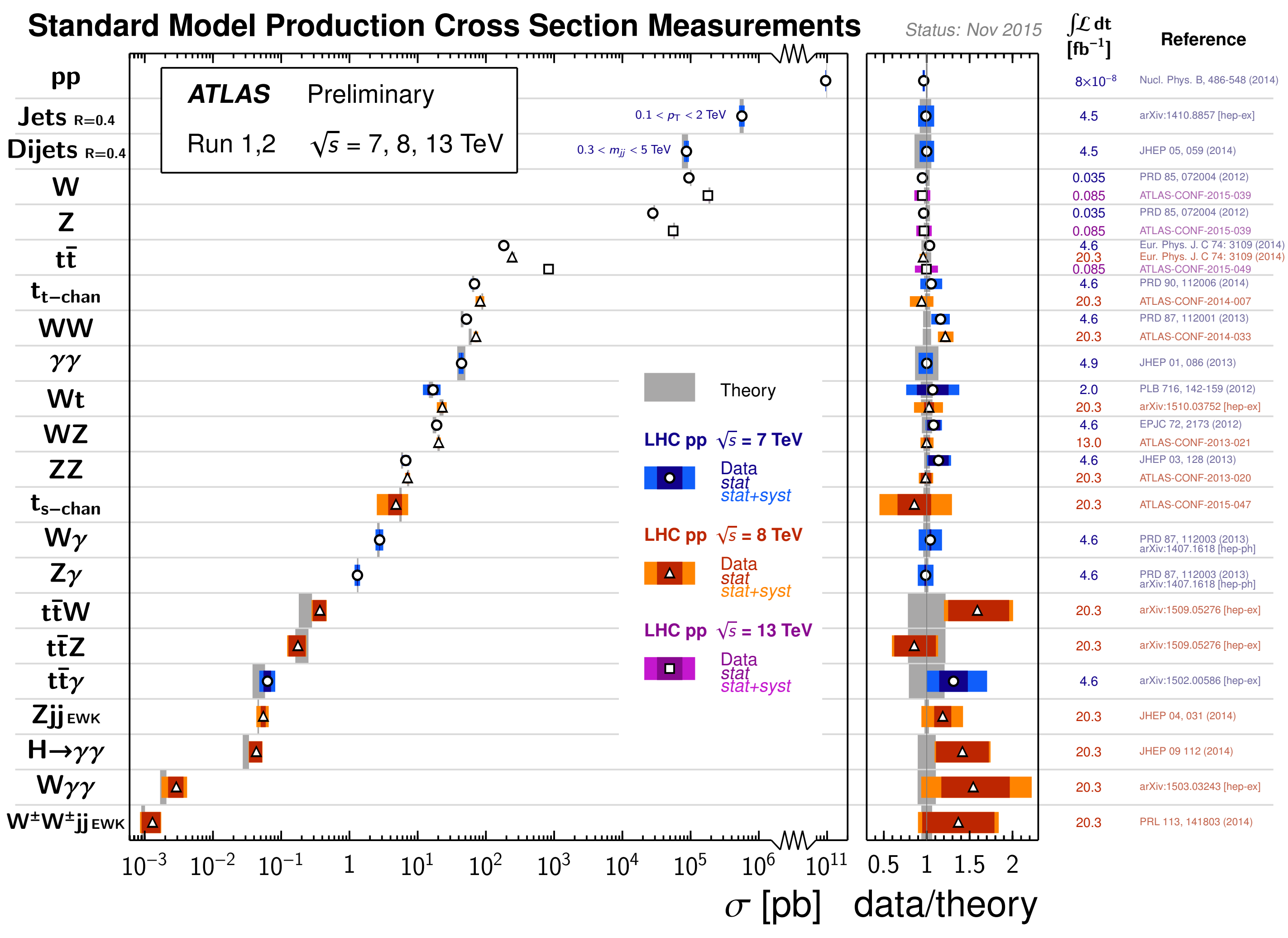




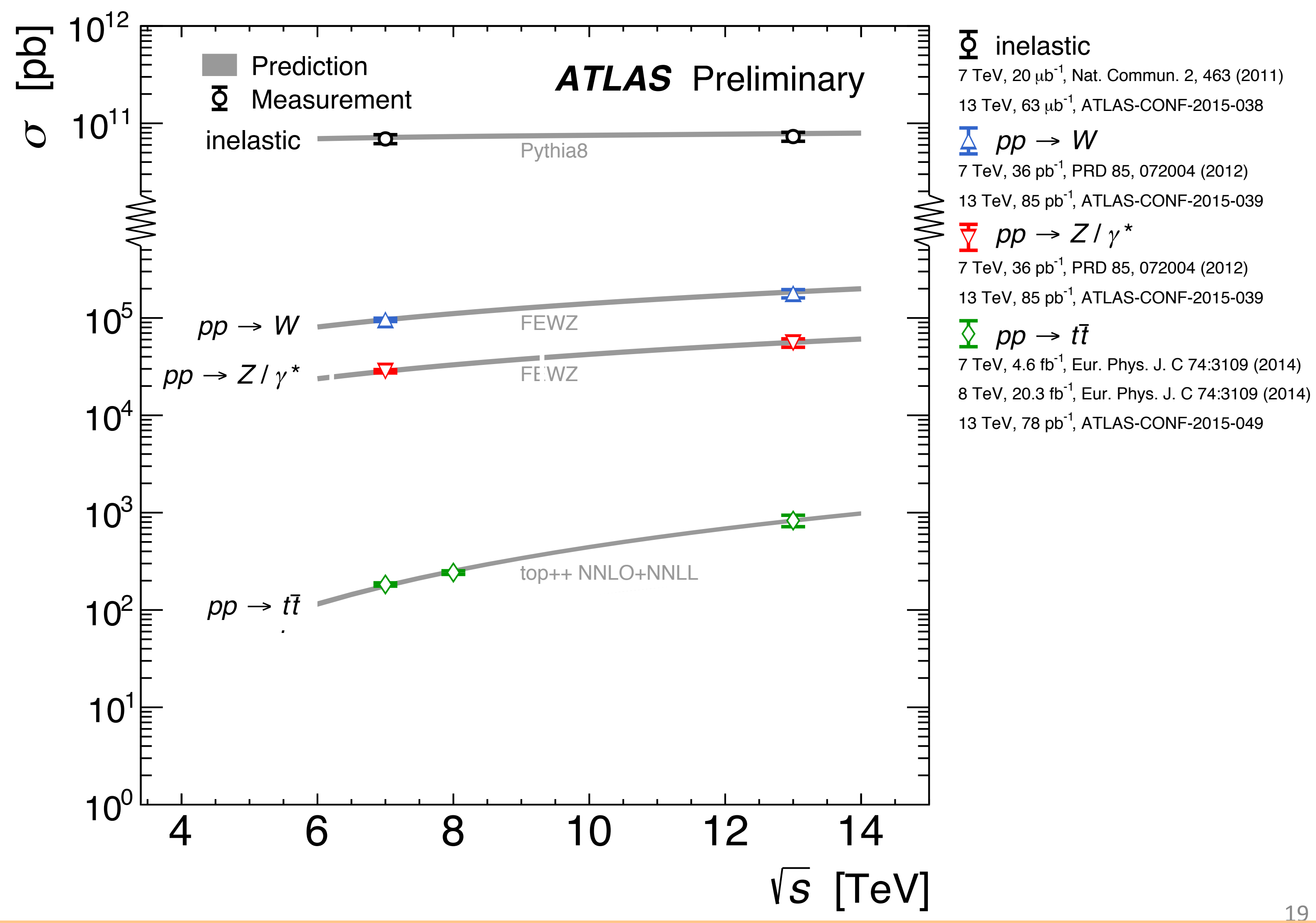
	Measurement	NNLO prediction
$\sigma^{fid}_{ZZ\to e^+e^-e^+e^-}$	$8.2\ ^{+2.3}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to e^+e^-\mu^+\mu^-}$	$13.8\ ^{+2.7}_{-2.4}(\text{stat.})\ ^{+0.5}_{-0.4}(\text{syst.})\ ^{+1.5}_{-1.0}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{fid}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.6\ ^{+1.7}_{-1.5}(\text{stat.})\ ^{+0.3}_{-0.3}(\text{syst.})\ ^{+0.7}_{-0.5}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$28.3\ ^{+3.8}_{-3.5}(\text{stat.})\ ^{+1.0}_{-0.8}(\text{syst.})\ ^{+3.0}_{-2.2}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$15.9\ ^{+2.1}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.7}_{-1.3}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb

arXiv:1512.05314

Standard Model Cross sections



Run-2 Total Cross Section Measurements

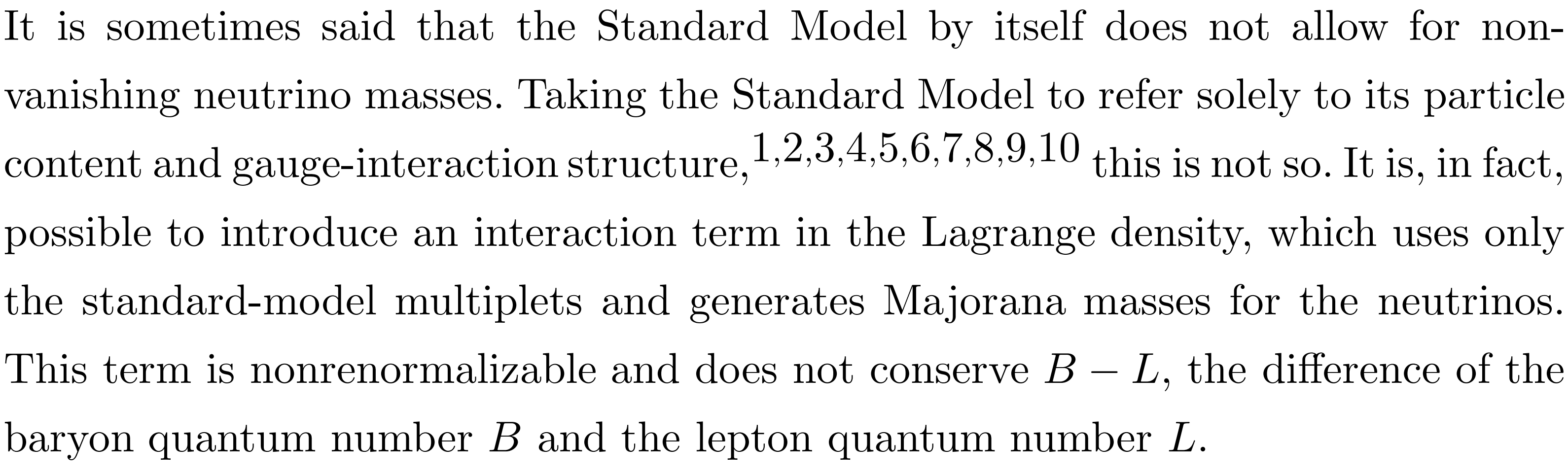


Challenges to Standard Model

Many observable effects are not described in Standard Model

Baryon-antibaryon asymmetry in the universe (observed)
Dark matter – possible explanation for observation
Dark energy – no explanation
Gravitational waves – observed once
Neutron electric dipole moment - measured
Neutrino masses – must be non-zero to satisfy observed mixing

Particle physics has Standard Model - an extensive theoretical framework that describes most of the observation of the structure of matter. It is natural to try to attach the explanations for the observables that we do not quite understand to an extension of Standard Model.



It is sometimes said that the Standard Model by itself does not allow for non-vanishing neutrino masses. Taking the Standard Model to refer solely to its particle content and gauge-interaction structure,[1,2,3,4,5,6,7,8,9,10] this is not so. It is, in fact, possible to introduce an interaction term in the Lagrange density, which uses only the standard-model multiplets and generates Majorana masses for the neutrinos. This term is nonrenormalizable and does not conserve $B - L$, the difference of the baryon quantum number B and the lepton quantum number L.

F.R. Klinkhamer **Mod.Phys.Lett. A28 (2013) 1350010**

These days most of the extensions are based on introduction of additional symmetry

The most popular case: **Supersymmetry**
Introduce symmetry between fermions and baryons i.e., there must be quarks and leptons with integer spin 1 and gauge particles with spin ½.
A perfect supersymmetry would have new partner particles with spin differing by ½ and with equal masses. Since they have not been seen, the symmetry must be spontaneously broken with the new particles expected to have much larger masses.

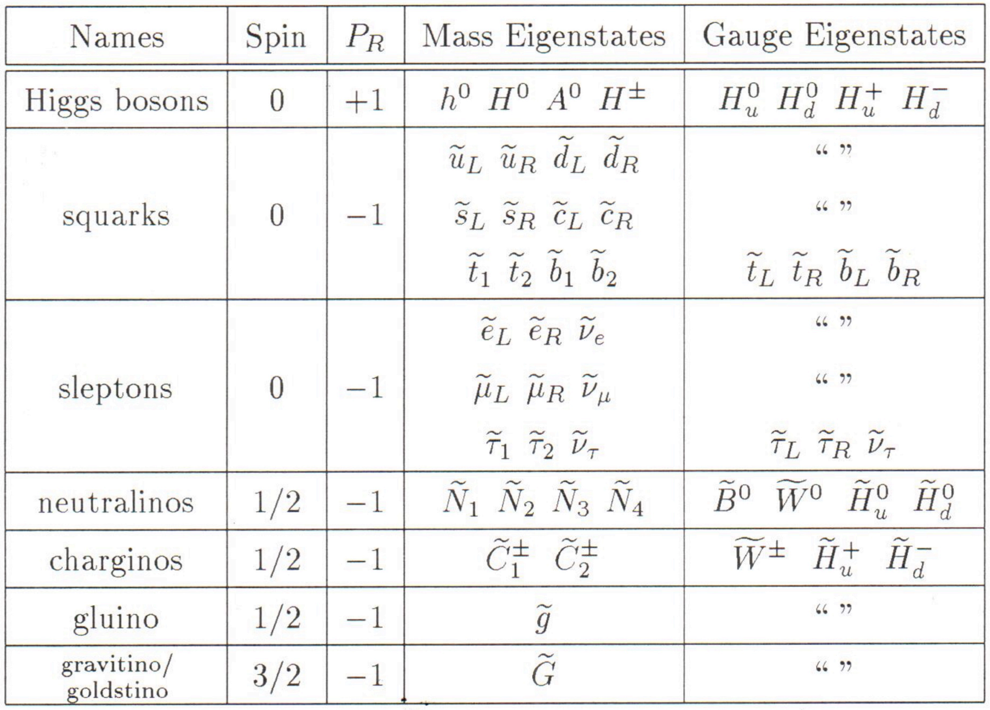
The naming convention for supersymmetric partners of fermions is to add letter s at the beginning of the name: e.g.squarks -- selectron, smuon, sbottom,…
the superpartners of gauge bosons are called gauginos - gluino, photino, Wino, Higgsino…→ these are somewhat more complicated since spontaneously symmetry breaking generate changes among the standard gauge particles.

In general there is a huge number of ways that the symmetry can be broken leading to over 100 free parameters.
The most tested is the MSSM – Minimal Supersymmetric Standard Model with just a few free parameters in the theory.

The attraction of supersymmetry for theorists is that provides candidates to solve several major problems.
Since there is no mixing between Standard Model particles and their supersymmetric partners, the lowest mass sparticle is stable. The neutral stable sparticle would be a candidate for dark matter.

In the MSSM there are 32 distinct masses corresponding to undiscovered particles not counting gravitino and two complex Higgs doublets.

Table 3: Undiscovered particles in the Minimal Supersymmetric Standard Model



Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	+1	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	" "
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	" "
			$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	" "
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	" "
			$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$	$\tilde{B}^0\ \widetilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$
charginos	1/2	−1	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$	$\widetilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$
gluino	1/2	−1	$\tilde{g}$	" "
gravitino/ goldstino	3/2	−1	$\tilde{G}$	" "

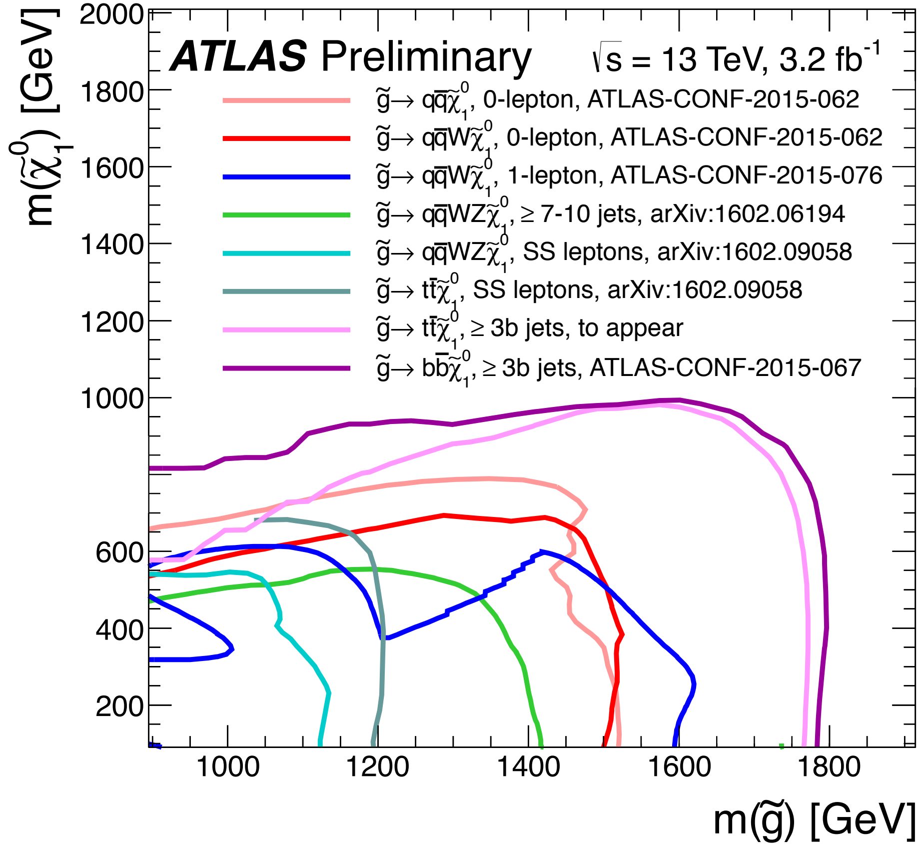
In MSSM the heavy sparticles would decay to the lighter ones in processes analogous to the Standard Model particles, but their connection to the Standard Model world would be weak . Thus they earned the nickname of WIMPs – Weakly Interacting Massive Particles.

The signatures of the supersymmtery are either processes that are forbidden in the Standard Model but that can proceed via loops involving virtual sparticles e.g., $\mu \rightarrow e\gamma$, enhanced rates for other rare process due to the virtual loops, etc

At LHC we also look for direct production of supersymmetric particles whose decay chain ends with a lowest mass, neutral sparticle. Such particle would interact only weakly with regular matter and thus it would leave the detector without producing detectable signal. The signature of such particle is, therefore, missing energy or more precisely in ATLAS – missing transvesre energy MET.

Another consequence of supersymmetry is that there are 4 Higgs particles: 2 charged and two neutral. In such scenario the object that has been discovered 3 years ago is only one of the two neutral Higgses

Exclusion limits at 95% CL for **13 TeV** in the (gluino, lightest neutralino) mass plane for different simplified models featuring the decay of the gluino to the lightest neutralino either directly or through a cascade chain featuring other SUSY particles with intermediate mass. For each line, the gluino decay mode is reported in the legend and it is assumed to proceed with 100% branching ratio. The limits might depend on additional assumptions on the mass of the intermediate states, as described in the references provided in the plot.

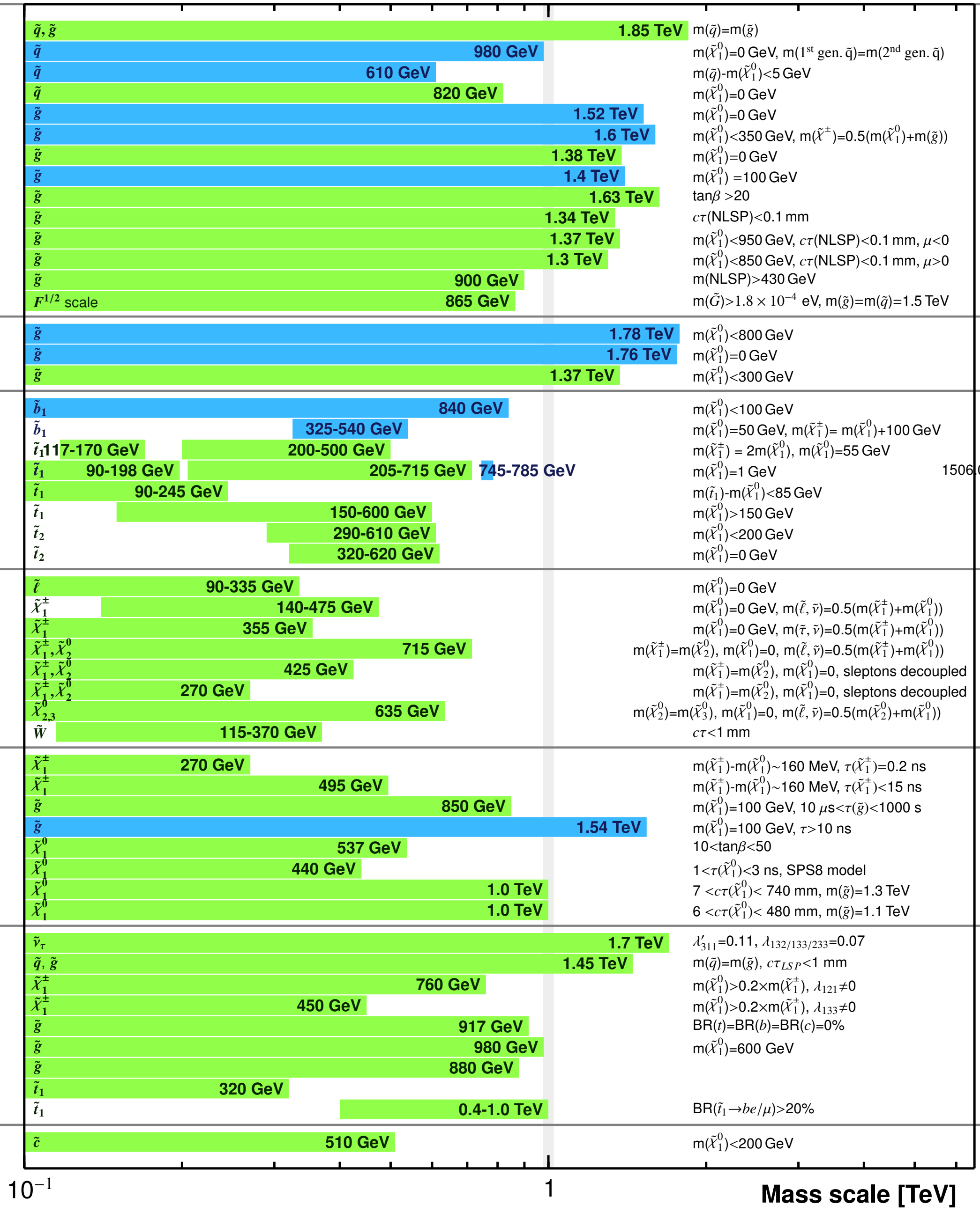


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

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



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	🟦 $\tilde{q}$ 980 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2015-062
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 610 GeV	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$<5 GeV	*To appear*
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ (off-Z)	2 jets	Yes	20.3	🟩 $\tilde{q}$ 820 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	🟦 $\tilde{g}$ 1.52 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	2-6 jets	Yes	3.3	🟦 $\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}^0_1)$<350 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}^0_1)$+$m(\tilde{g})$)	ATLAS-CONF-2015-076
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	🟩 $\tilde{g}$ 1.38 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-10 jets	Yes	3.2	🟦 $\tilde{g}$ 1.4 TeV	$m(\tilde{\chi}^0_1)$ =100 GeV	1602.06194
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	🟩 $\tilde{g}$ 1.63 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	🟩 $\tilde{g}$ 1.34 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}^0_1)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	🟩 $\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	3.3	🟦 $\tilde{g}$ 1.78 TeV	$m(\tilde{\chi}^0_1)$<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	3.3	🟦 $\tilde{g}$ 1.76 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	*To appear*
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}^0_1)$<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	3.2	🟦 $\tilde{b}_1$ 325-540 GeV	$m(\tilde{\chi}^0_1)$=50 GeV, $m(\tilde{\chi}^\pm_1)$= $m(\tilde{\chi}^0_1)$+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7/20.3	🟩 $\tilde{t}_1$ 117-170 GeV 🟩 200-500 GeV	$m(\tilde{\chi}^\pm_1)$ = 2$m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	🟩 $\tilde{t}_1$ 90-198 GeV 🟩 205-715 GeV 🟦 745-785 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	🟩 $\tilde{t}_1$ 90-245 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}^0_1)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_2$ 290-610 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 140-475 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 355 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 715 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 425 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 270 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$ 635 GeV	$m(\tilde{\chi}^0_2)$=$m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^0_2)$+$m(\tilde{\chi}^0_1)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 270 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^\pm_1$ 495 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.54 TeV	$m(\tilde{\chi}^0_1)$=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$ 440 GeV	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	6 <$c\tau(\tilde{\chi}^0_1)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	🟩 $\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 760 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 450 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde{g}$ 980 GeV	$m(\tilde{\chi}^0_1)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{g}$ 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	🟩 $\tilde{t}_1$ 320 GeV		1601.07453
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325

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

Exotics – experimental approach

Magnetic monopole
Highly ionizing particles
Long-lived (~10-8 s) particles
mini black holes
sequential gauge bosons Z’ W’

God Only Knows

Typical approach – assume existence of a new particle of a particular mass and width
model new particle decay to eg., bbγγ
search for it in the data
if not found – estimate production cross section limit
change the mass parameter and repeat the search.

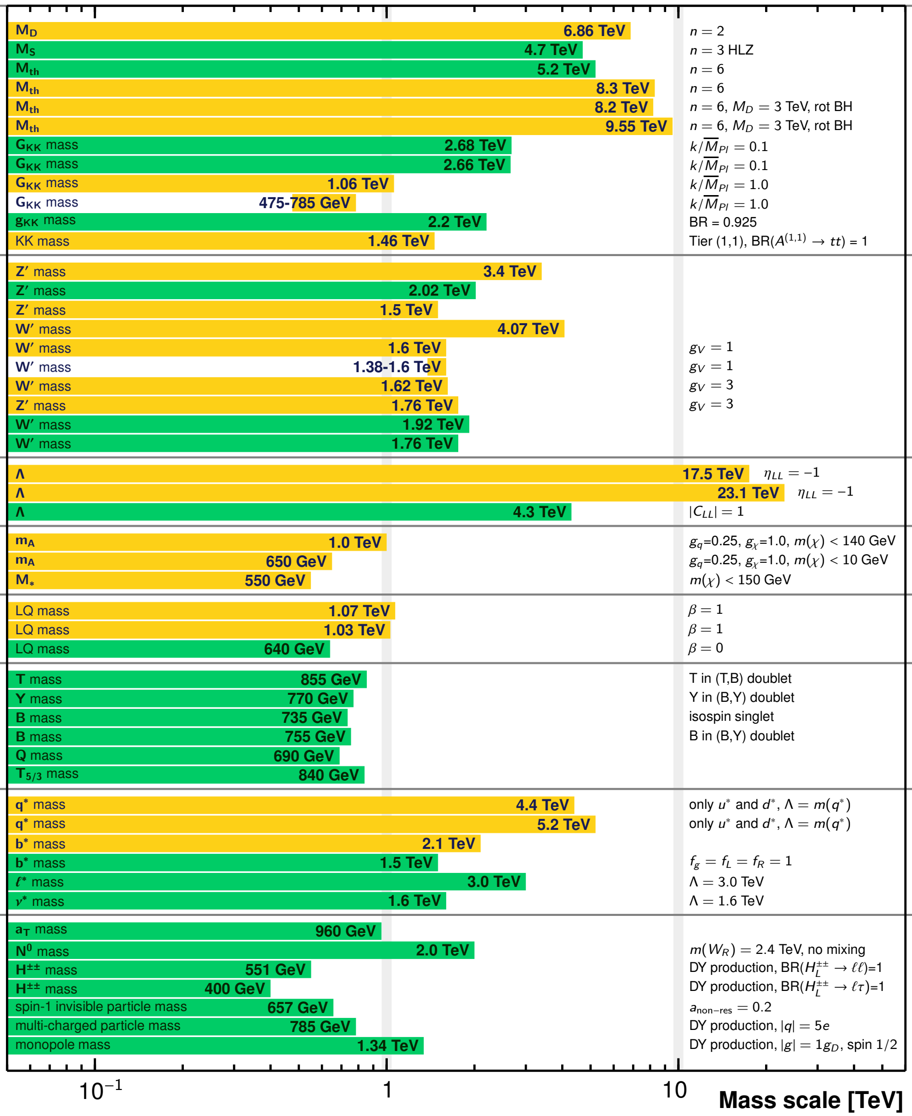
ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 - 20.3) fb^{-1}

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



	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.86 TeV	$n=2$	Preliminary
	ADD non-resonant $\ell\ell$	2 e,μ	–	–	20.3	🟩 M_S 4.7 TeV	$n=3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e,μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n=6$	1311.2006
	ADD QBH	–	2 j	–	3.6	🟨 M_{th} 8.3 TeV	$n=6$	1512.01530
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	ATLAS-CONF-2016-006
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\rightarrow\ell\ell$	2 e,μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl}=0.1$	1405.4123
	RS1 $G_{KK}\rightarrow\gamma\gamma$	2 γ	–	–	20.3	🟩 G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl}=0.1$	1504.05511
	Bulk RS $G_{KK}\rightarrow WW\rightarrow qq\ell\nu$	1 e,μ	1 J	Yes	3.2	🟨 G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK}\rightarrow HH\rightarrow bbbb$	–	4 b	–	3.2	🟨 G_{KK} mass 475-785 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2016-017
	Bulk RS $g_{KK}\rightarrow tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)}\rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z'\rightarrow\ell\ell$	2 e,μ	–	–	3.2	🟨 Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z'\rightarrow\tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z'\rightarrow bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		Preliminary
	SSM $W'\rightarrow\ell\nu$	1 e,μ	–	Yes	3.2	🟨 W' mass 4.07 TeV		ATLAS-CONF-2015-063
	HVT $W'\rightarrow WZ\rightarrow qq\nu\nu$ model A	0 e,μ	1 J	Yes	3.2	🟨 W' mass 1.6 TeV	$g_V=1$	ATLAS-CONF-2015-068
	HVT $W'\rightarrow WZ\rightarrow qqqq$ model A	–	2 J	–	3.2	🟨 W' mass 1.38-1.6 TeV	$g_V=1$	ATLAS-CONF-2015-073
	HVT $W'\rightarrow WH\rightarrow\ell\nu bb$ model B	1 e,μ	1-2 b, 1-0 j	Yes	3.2	🟨 W' mass 1.62 TeV	$g_V=3$	ATLAS-CONF-2015-074
	HVT $Z'\rightarrow ZH\rightarrow\nu\nu bb$ model B	0 e,μ	1-2 b, 1-0 j	Yes	3.2	🟨 Z' mass 1.76 TeV	$g_V=3$	ATLAS-CONF-2015-074
	LRSM $W'_R\rightarrow tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R\rightarrow tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	🟨 Λ 17.5 TeV	$\eta_{LL}=-1$	1512.01530
	CI $qq\ell\ell$	2 e,μ	–	–	3.2	🟨 Λ 23.1 TeV	$\eta_{LL}=-1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e,μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	🟩 Λ 4.3 TeV	$\lvert C_{LL}\rvert=1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e,μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi)<140$ GeV	Preliminary
	Axial-vector mediator (Dirac DM)	0 e,μ, 1 γ	1 j	Yes	3.2	🟨 m_A 650 GeV	g_q=0.25, g_χ=1.0, $m(\chi)<10$ GeV	Preliminary
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi)<150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.07 TeV	$\beta=1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.03 TeV	$\beta=1$	Preliminary
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta=0$	1508.04735
Heavy quarks	VLQ $TT\rightarrow Ht+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY\rightarrow Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB\rightarrow Hb+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB\rightarrow Zb+X$	2/≥3 e,μ	≥2/≥1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ\rightarrow WqWq$	1 e,μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	$T_{5/3}\rightarrow Wt$	1 e,μ	≥ 1 b, ≥ 5 j	Yes	20.3	🟩 $T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^*\rightarrow q\gamma$	1 γ	1 j	–	3.2	🟨 q^* mass 4.4 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1512.05910
	Excited quark $q^*\rightarrow qg$	–	2 j	–	3.6	🟨 q^* mass 5.2 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1512.01530
	Excited quark $b^*\rightarrow bg$	–	1 b, 1 j	–	3.2	🟨 b^* mass 2.1 TeV		Preliminary
	Excited quark $b^*\rightarrow Wt$	1 or 2 e,μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g=f_L=f_R=1$	1510.02664
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	LSTC $a_T\rightarrow W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\rightarrow\ell\ell$	2 e,μ (SS)	–	–	20.3	🟩 $H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm}\rightarrow\ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm}\rightarrow\ell\tau$	3 e,μ,τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm}\rightarrow\ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

**Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.*

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