Highlights from the LHC (I)

Selected results from ATLAS and LHCb

38th ICHEP, Chicago, USA

8 August 2016

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University of Birmingham

On behalf of ATLAS and LHCb

For more details, see the plenary talks:

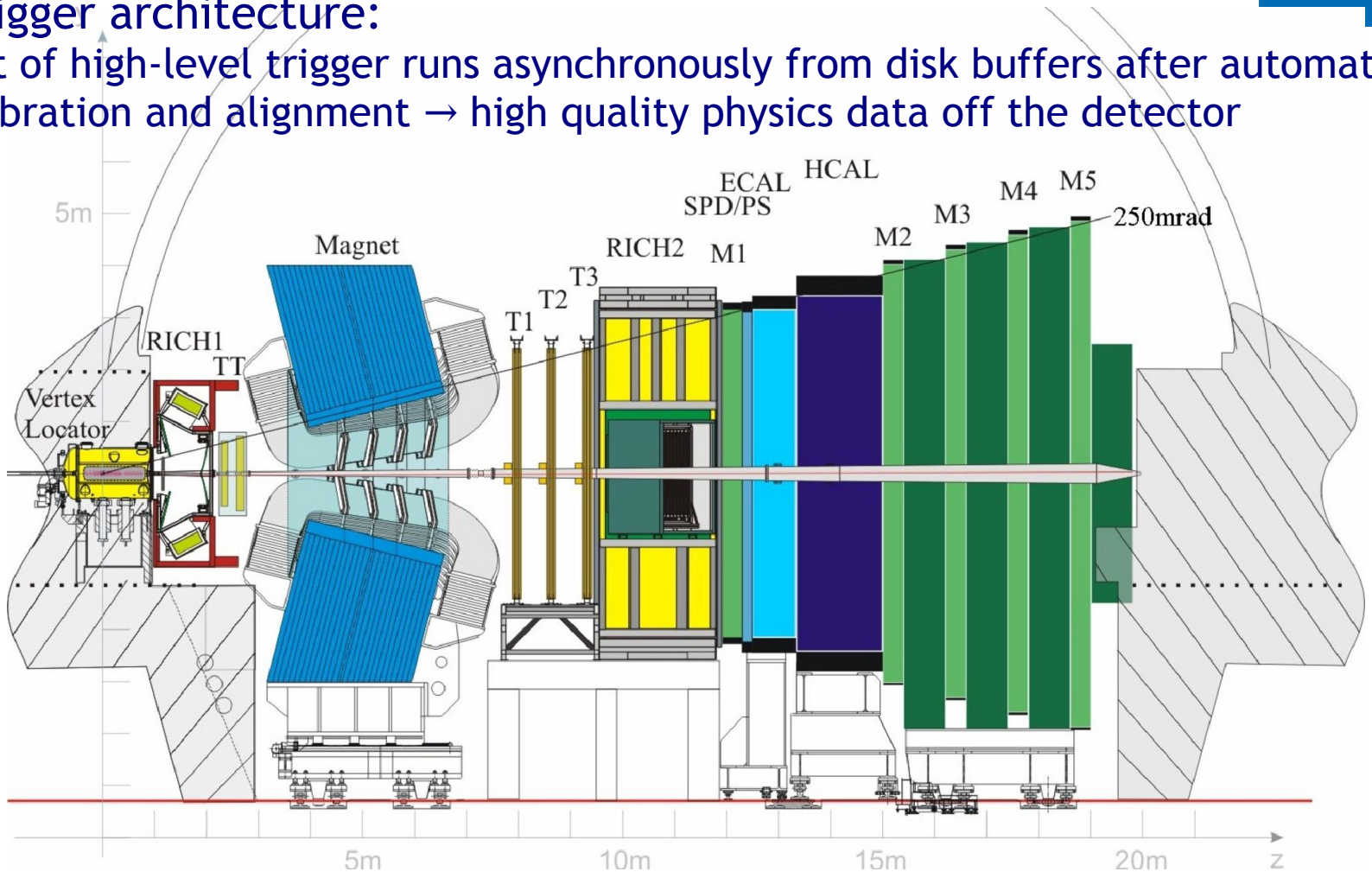
- *Higgs Measurements - Florencia Canelli*
- *Top and Electroweak Measurements - Ulla Blumenschein*
- *Searches for SUSY - Wolfgang Adam*
- *Exotica Searches - Shih-Chieh Hsu*
- *Results and Prospects on Bottom Physics - Vincenzo Vagnoni*
- *Hadron Physics Overview - Beijiang Liu*
- *Strong Interactions Expt Overview - Halina Abramowicz*

...and the many many parallel talks and posters

LHCb in Run-2

New trigger architecture:

- Part of high-level trigger runs asynchronously from disk buffers after automated calibration and alignment → high quality physics data off the detector



New Run-2 subdetector:

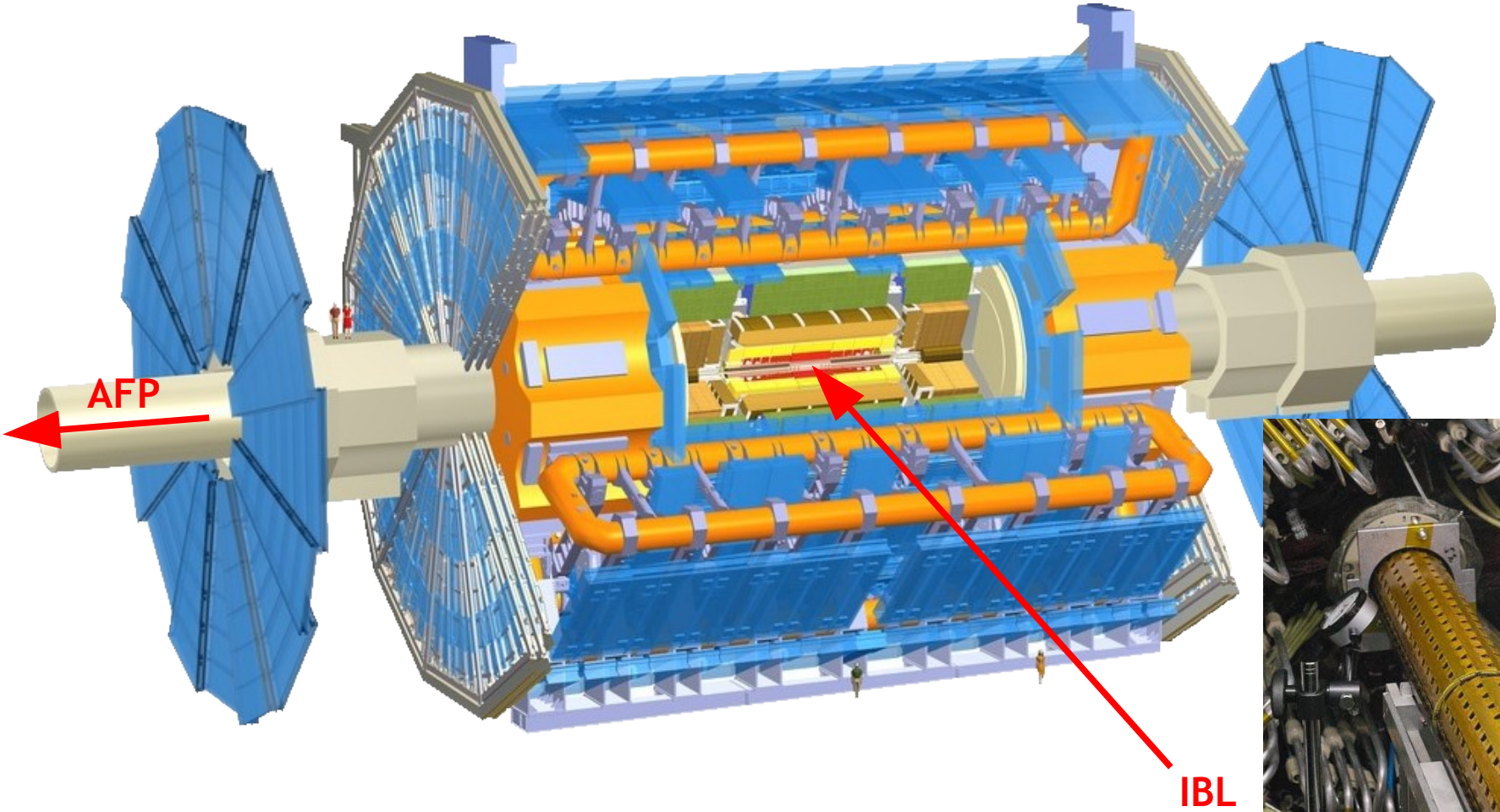
- "Herschel" scintillators along the beam directions up to 114m away from IP

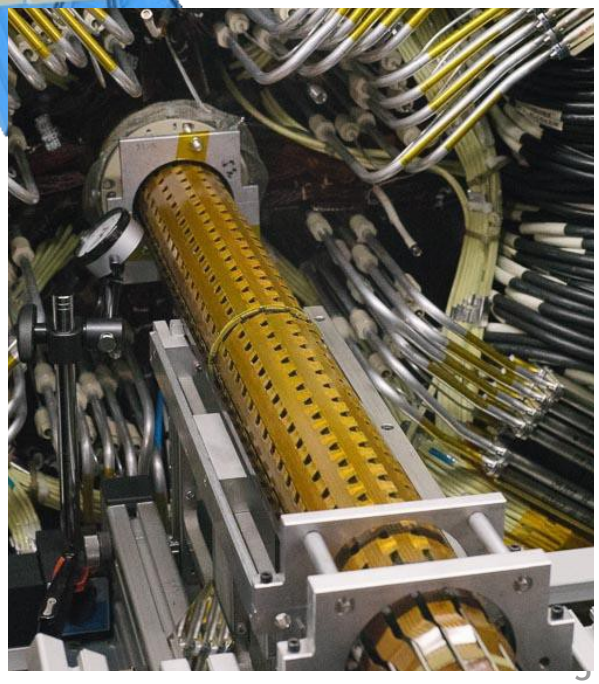
LHCb data samples: 3 fb^{-1} in Run-1 (7+8 TeV), so far ~1.2 fb^{-1} in Run-2 (13 TeV)

ATLAS in Run-2

New detectors in Run-2:

- Innermost pixel layer IBL, 3.4cm from interaction point
- Forward proton detectors (one arm in 2016, 210m from IP)

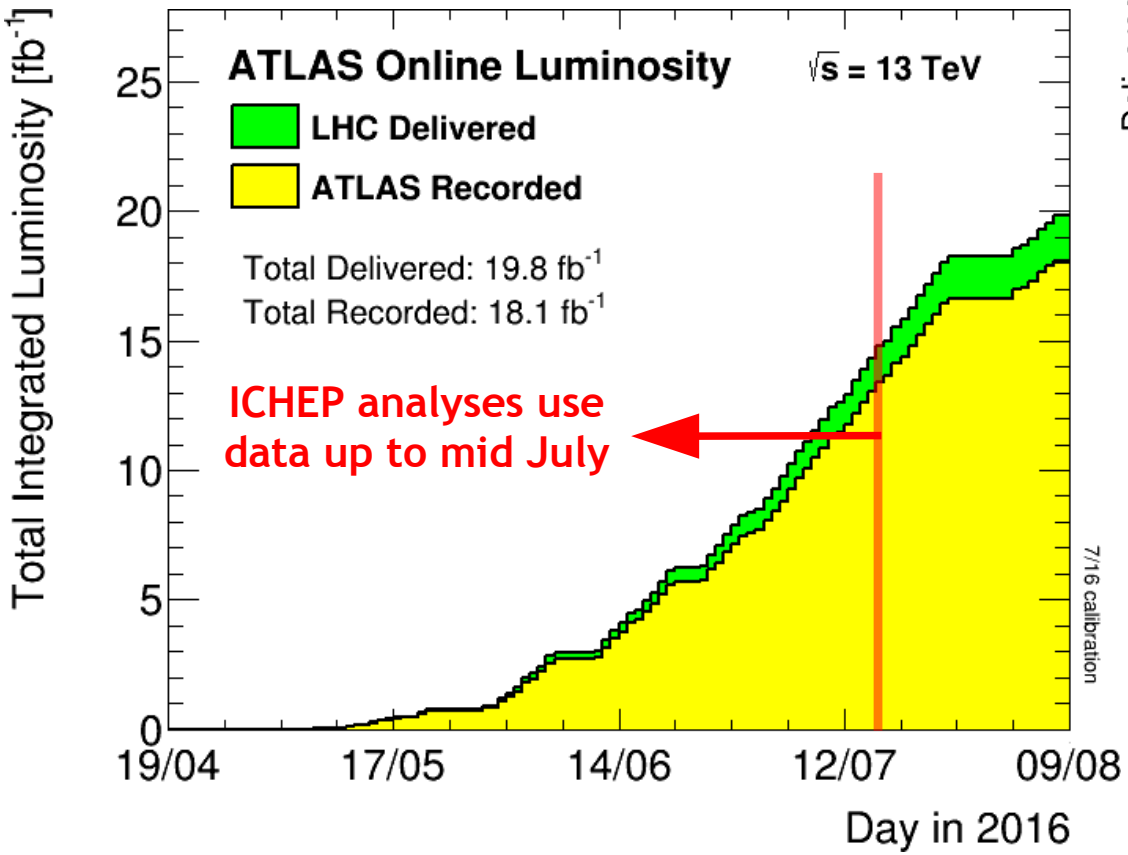


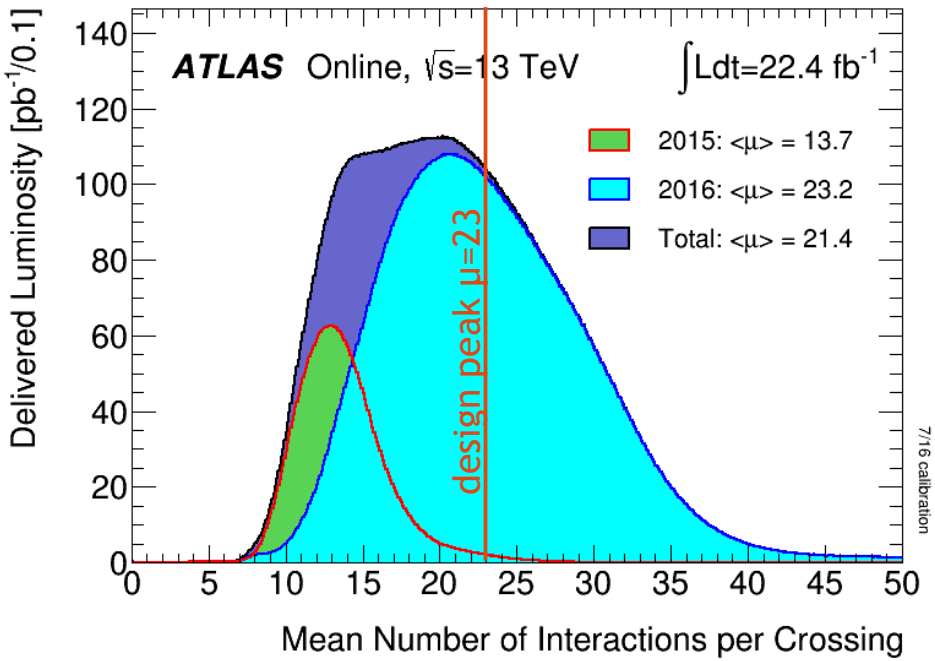


In addition, various consolidations provide improved running at high luminosities and rates

Data Samples

Exceptional LHC performance in 2016 following 13 TeV commissioning in 2015
(2015: 4.2 fb^{-1} delivered, 3.9 fb^{-1} collected)
Results reported with 3-15 fb^{-1}





Pileup often above LHC design in 2016

Luminosity uncertainty
- ±2.1% (2015)
- ±3.7% (2016, preliminary)
- ±2.9% (2015+2016, prel)

Data quality in 2016:
- >90% of data collected usable for analysis

Data Samples

Exceptio
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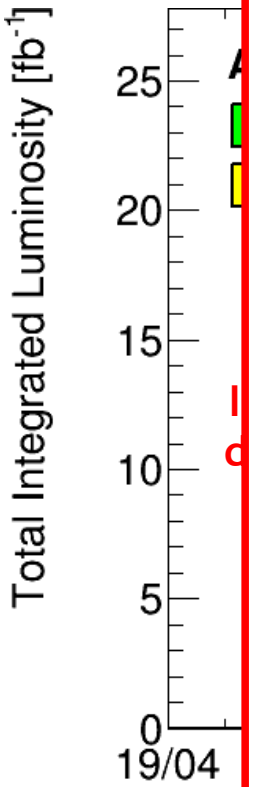
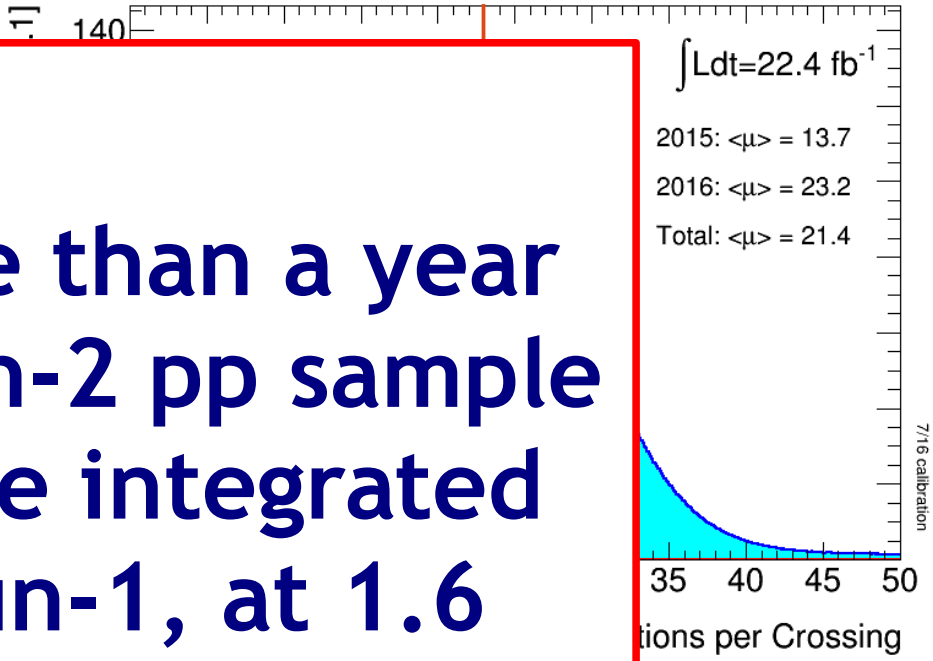
Results





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- >90% of data collected usable for analysis

After a little more than a year the ATLAS/CMS Run-2 pp sample is approaching the integrated luminosity of Run-1, at 1.6 times higher √s

Major new-physics sensitivity has opened up

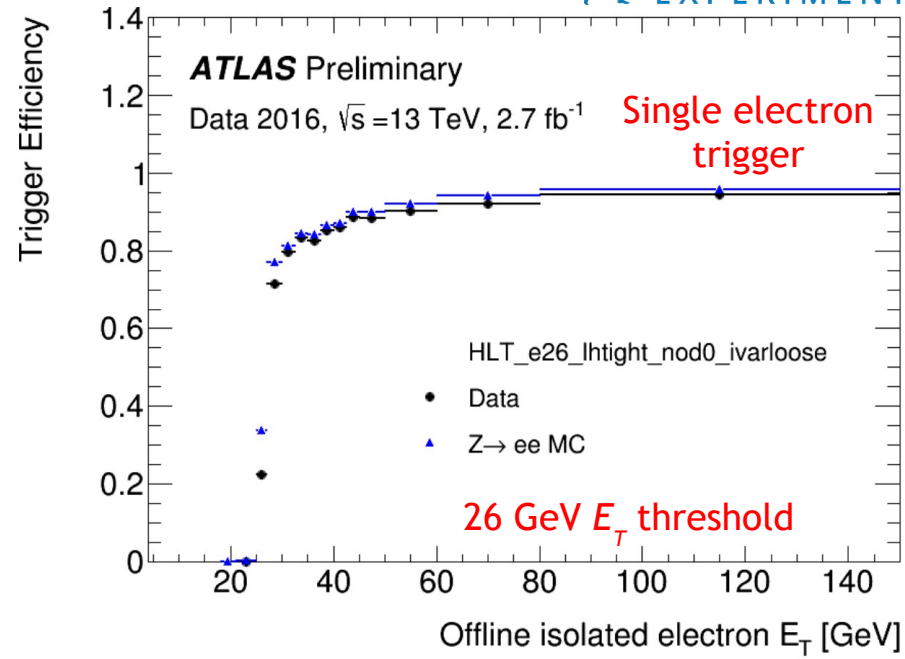
The Trigger Challenge

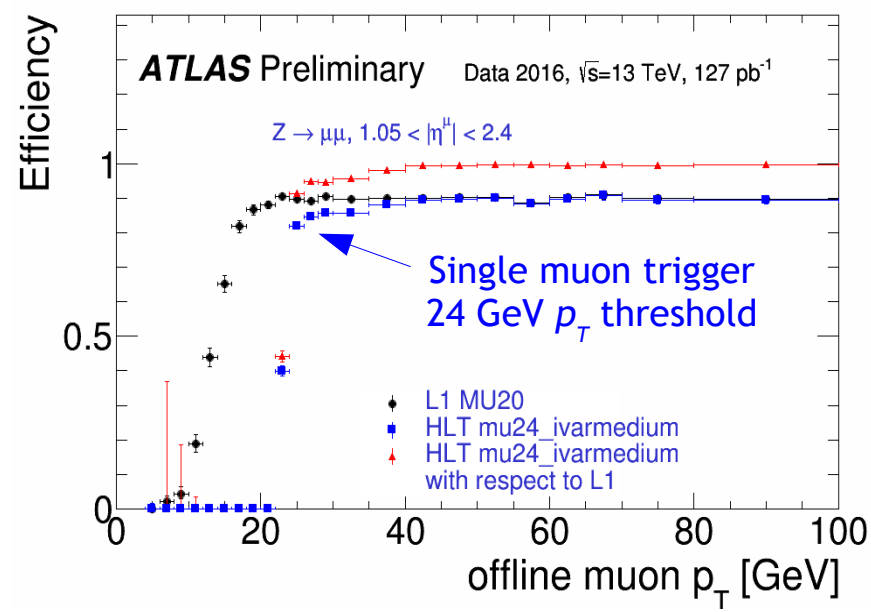
Complex trigger menu designed to meet varied physics, monitoring and performance requirements

- Typically ~2000 active menu items
- Stable main primary triggers
- Level-1 running at ~85 kHz
- Average physics output rate ~1kHz

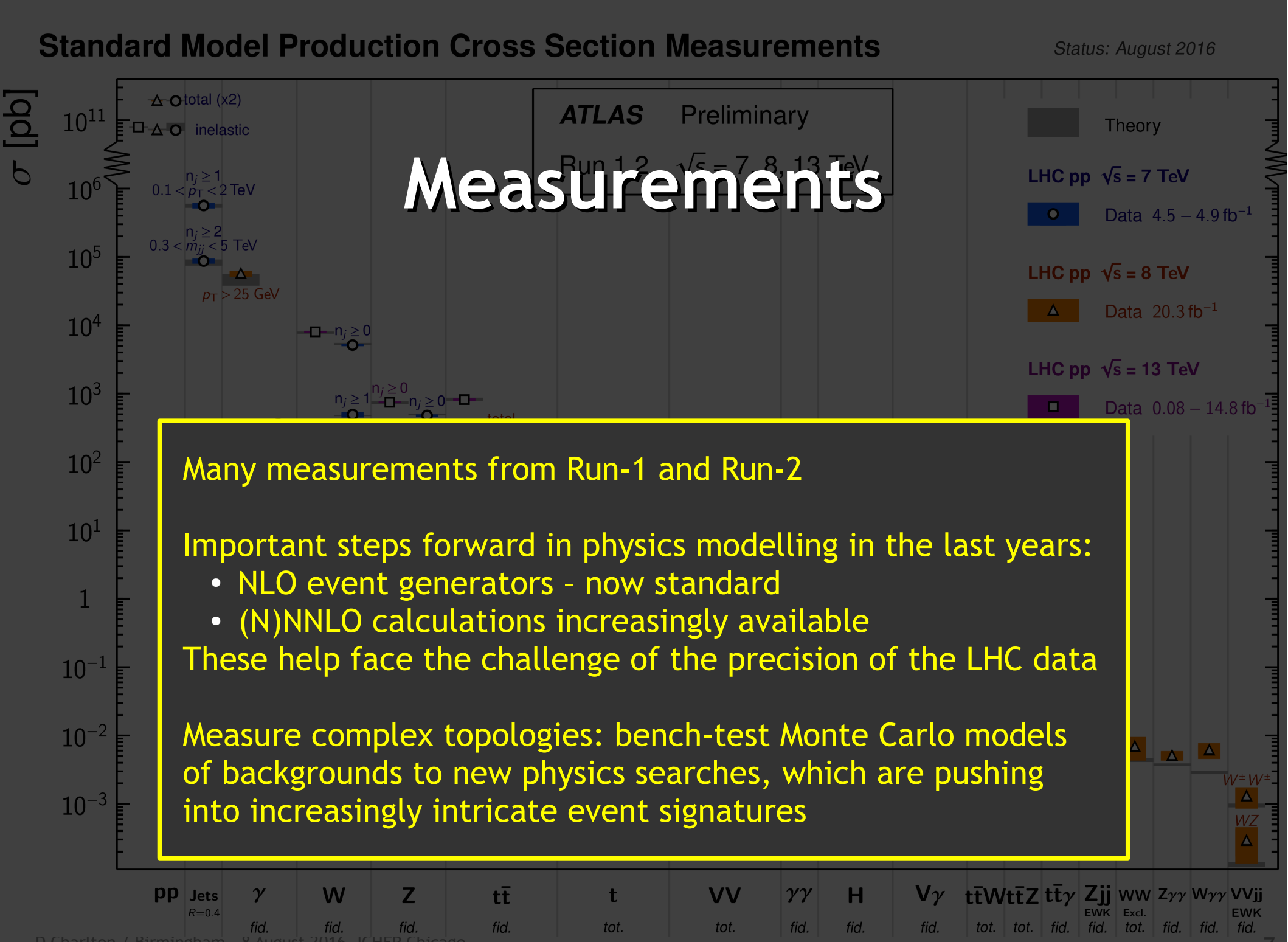
A few, example, trigger thresholds (GeV)

- E_T(e) > 24-26
- p_T(μ) > 24-26
- E_T^{miss} > 90-110
- E_T(jet) > 380
- E_T(γ) > 140
- p_T(μ1,μ2) > 6,6 + topo/mass selections
- E_T(γ1,γ2) > 35,25





Measurements



Many measurements from Run-1 and Run-2

Important steps forward in physics modelling in the last years:

- NLO event generators – now standard
- (N)NNLO calculations increasingly available

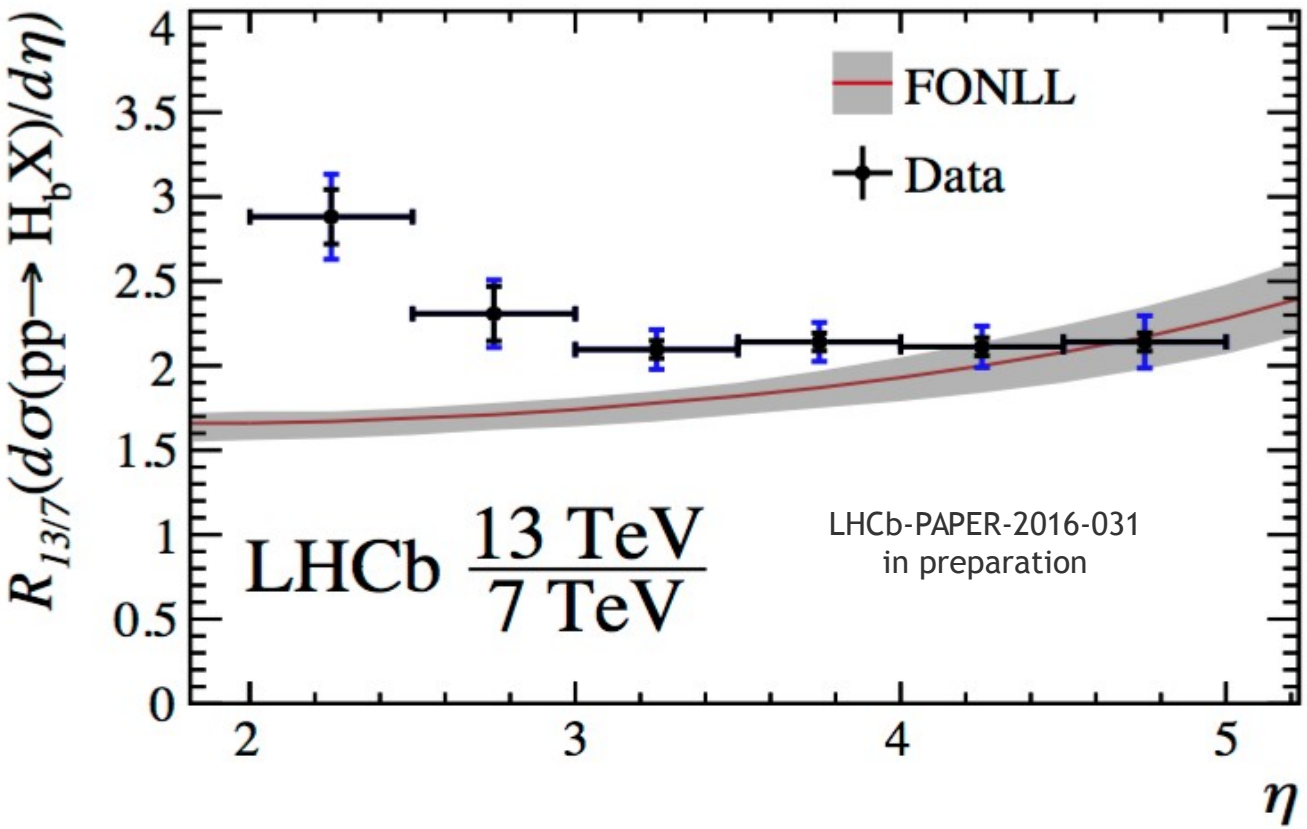
These help face the challenge of the precision of the LHC data

Measure complex topologies: bench-test Monte Carlo models of backgrounds to new physics searches, which are pushing into increasingly intricate event signatures

$b\bar{b}$ Cross-Section at 7 and 13 TeV

LHCb has measured the cross-section for the process $pp \to b\bar{b}X$ at both 7 and 13 TeV centre-of-mass energies, in the pseudorapidity range $2 < \eta < 5$

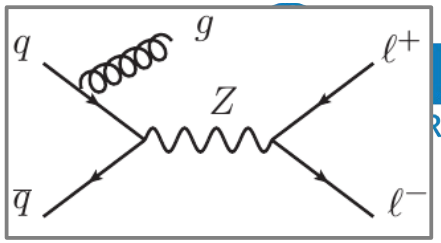
- The measurement is made using semileptonic decays of b-hadrons



The ratio of 13 to 7 TeV cross-sections appears to depart from FONLL theory predictions at low η

- Calls for further theoretical progress

Z+Jets

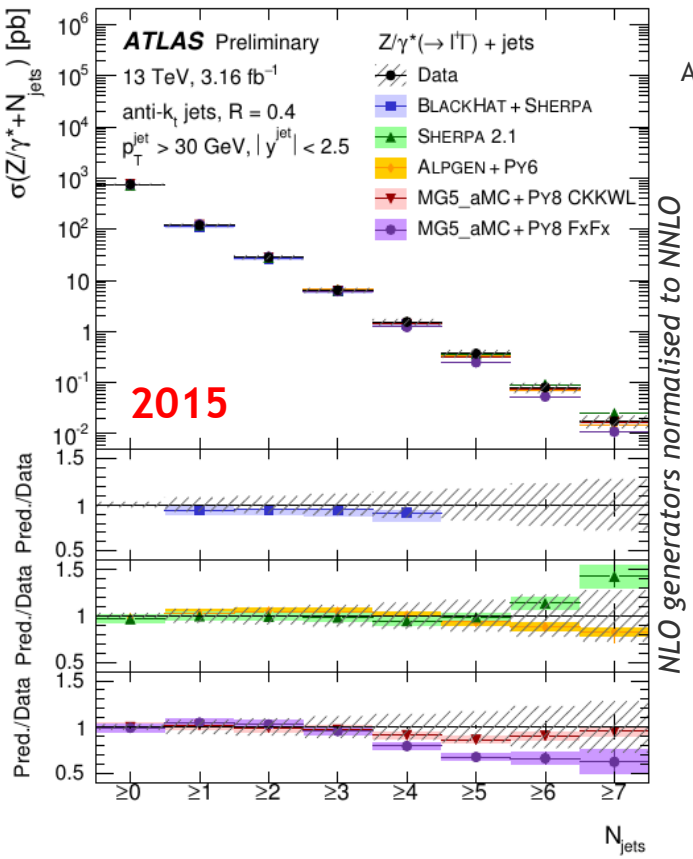


Access and measure high jet multiplicities in 13 TeV data

- Test NLO generators on easily triggered events with high jet multiplicities
- Vector-boson plus jet events are a major background in searches

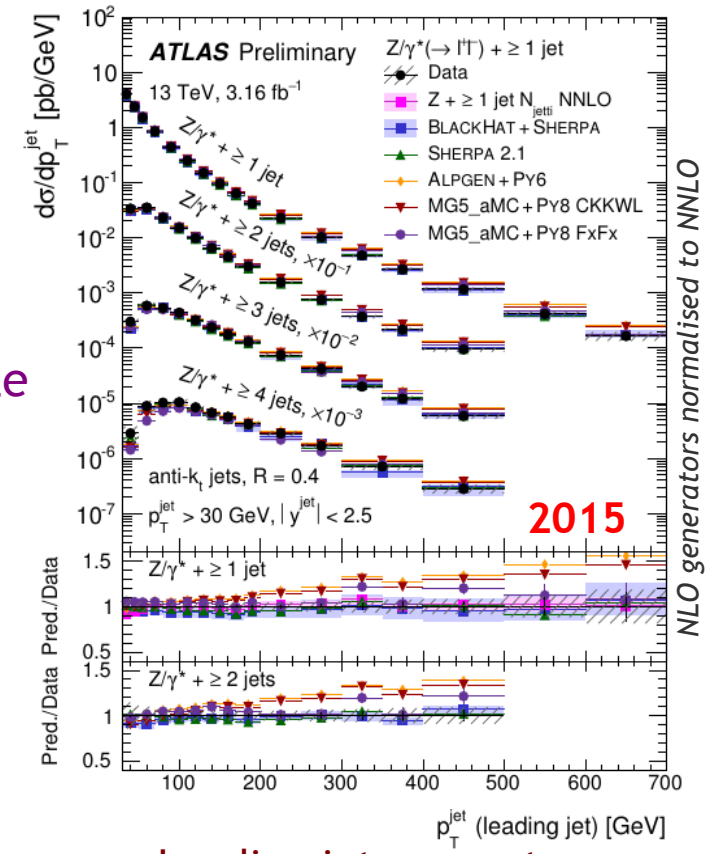
Fully corrected fiducial and differential cross-sections

- Z with up to 7 additional jets measured



ATLAS-CONF-2016-046

~6M Z→ℓℓ event sample (3.2 fb^{-1})



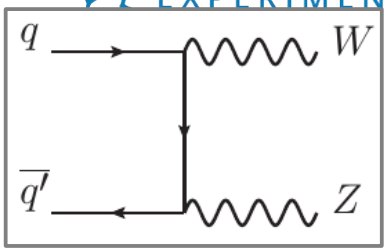
Jet multiplicity: main NLO generators do a good job, at least up to 6 jets

Leading jet p_T spectra:

LO generators over-predict high-p_T tail

NLO generators provide better description

Massive Diboson Production



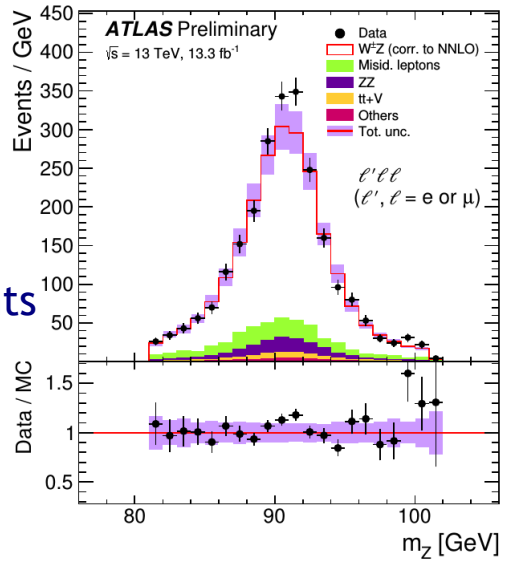
Run-1 puzzle to describe inclusive diboson cross-sections

- Measurements tended to lie above NLO calculations

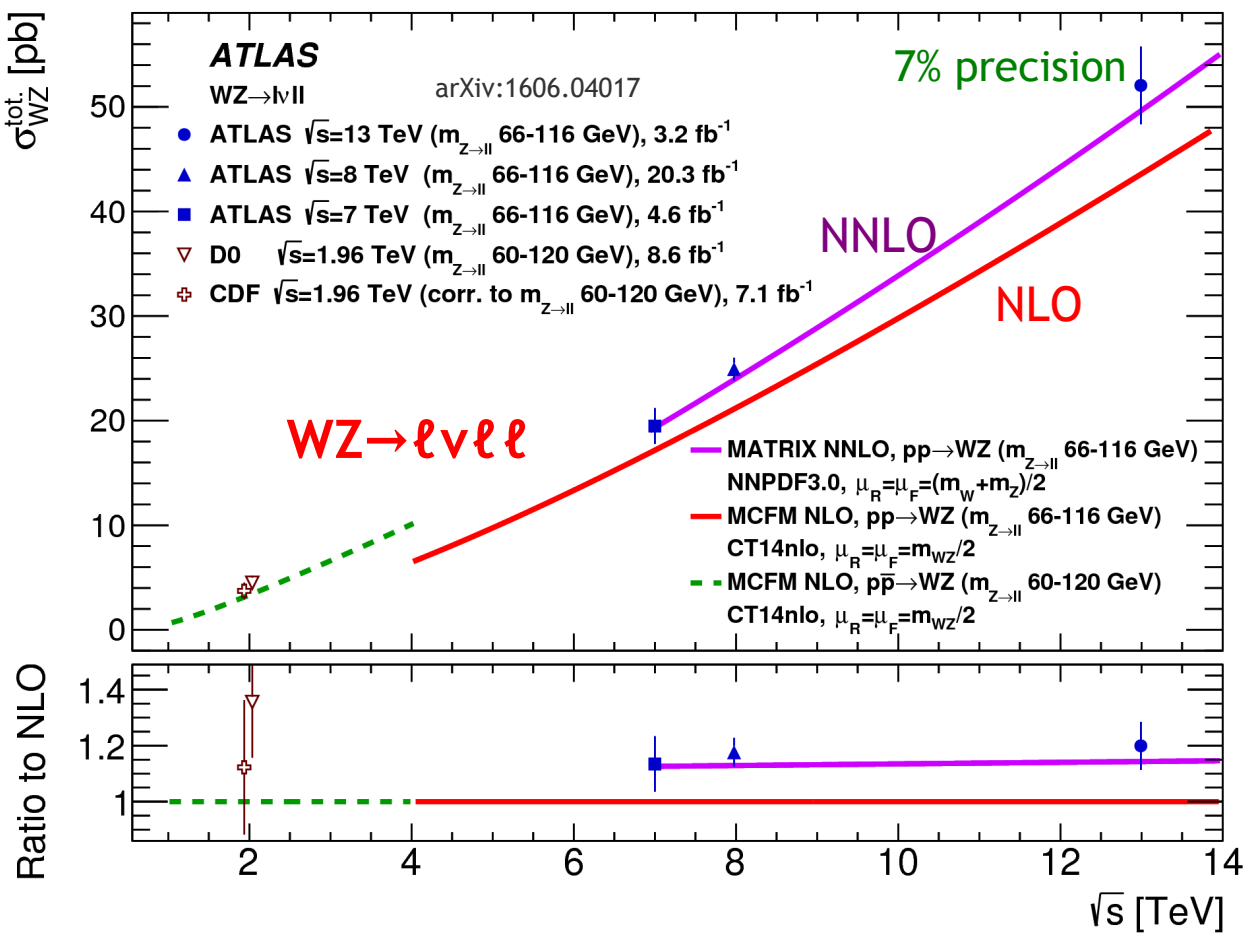
NNLO calculations → ~20% corrections and better agreement

Presented measurements at 13 TeV of WW, WZ, ZZ leptonic channels

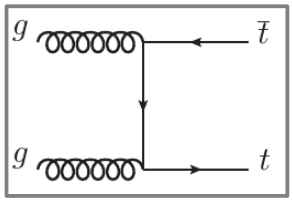
Z→ℓℓ in selected WZ events

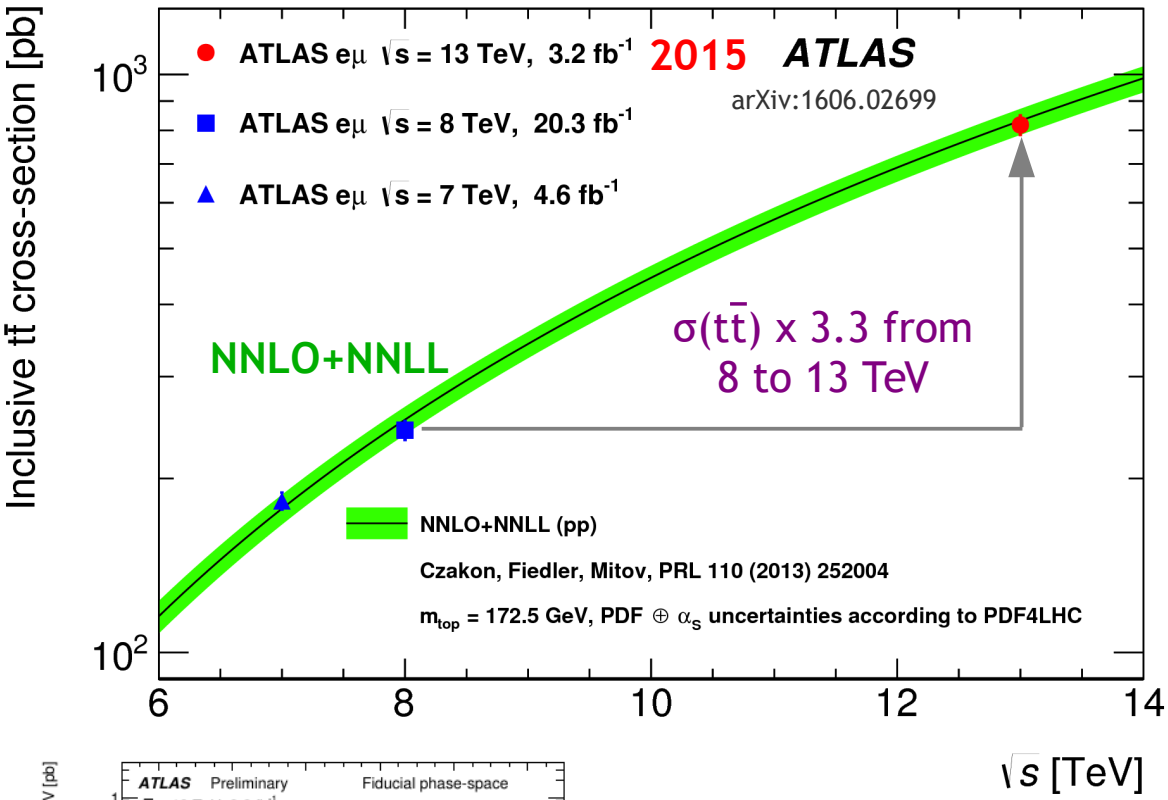


Example:
WZ leptonic decays
NNLO calculations describe data much better than NLO



$t\bar{t}$ Production

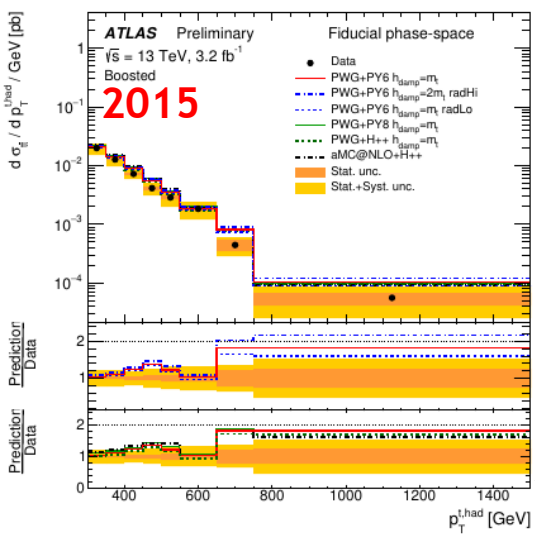




Single and double b-tagged $t\bar{t}\rightarrow be\nu\bar{b}\mu\bar{\nu}$ events allow to measure $t\bar{t}$ cross-section and b-tagging efficiency simultaneously

Precision ±(3.9-4.4)% (7-13 TeV) betters NNLO+NNLL predictions (~5%)

High $t\bar{t}$ statistics → detailed studies of production properties



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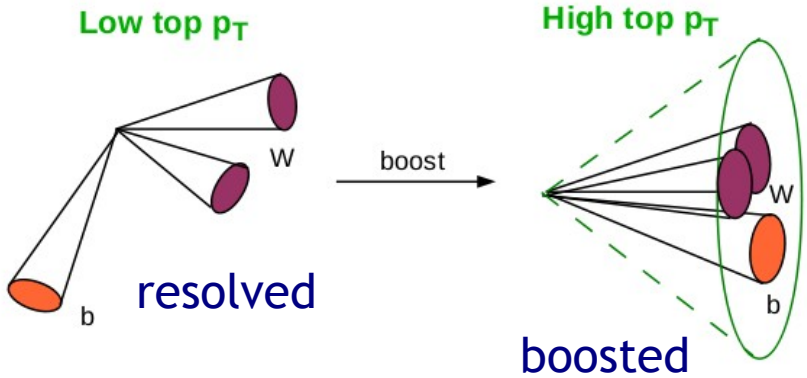
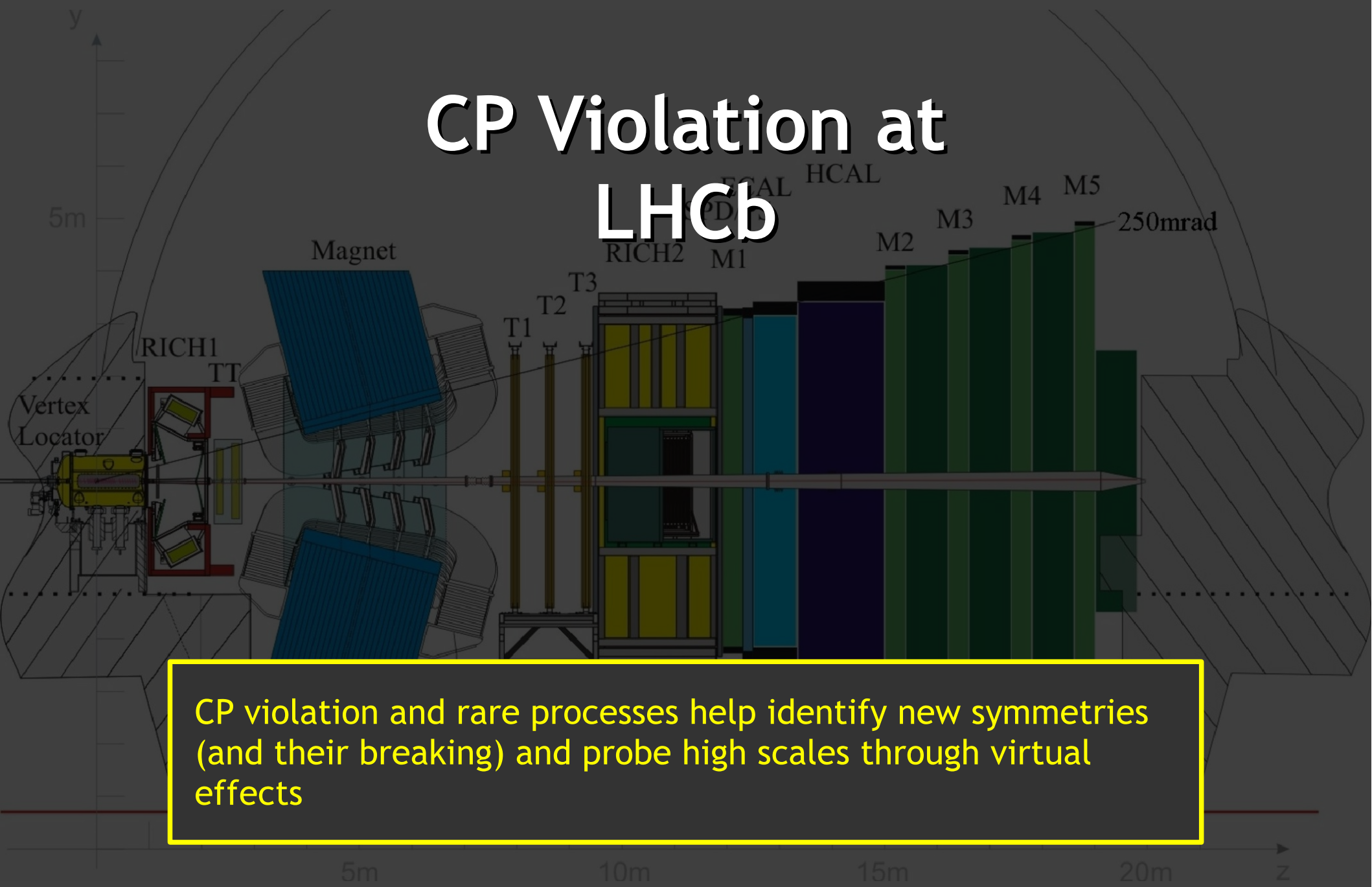
ℓ+jet channel high-p_T differential cross-section from boosted analysis (also resolved)



CP Violation at LHCb



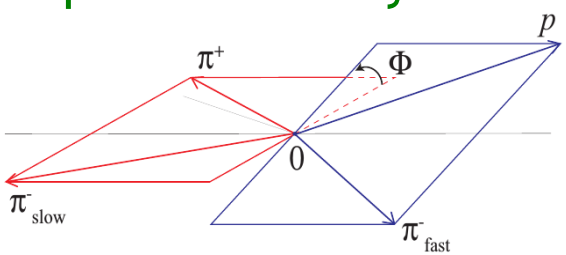
CP violation and rare processes help identify new symmetries (and their breaking) and probe high scales through virtual effects

CP Violation at LHCb - Λ_b Decays

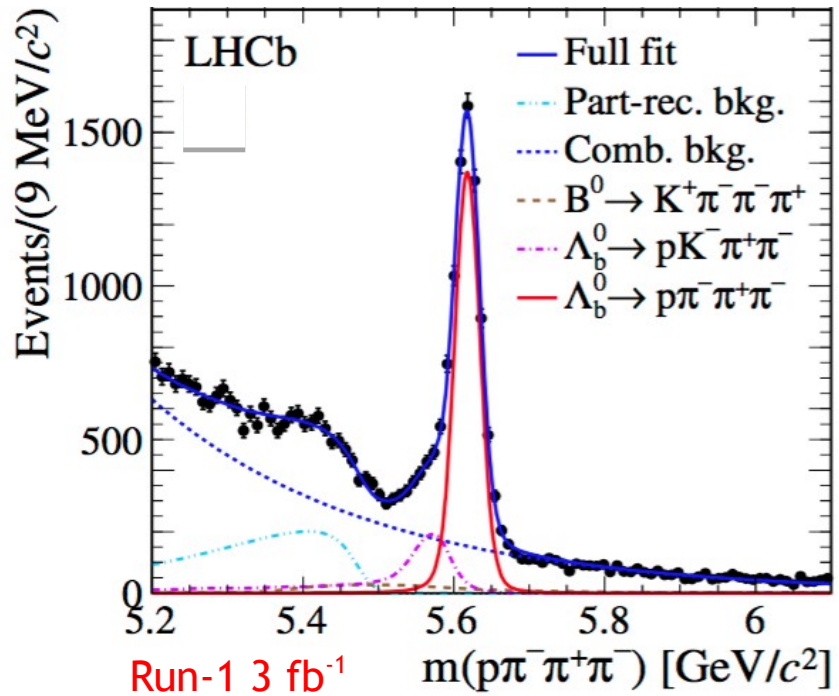
In the flavour sector, LHCb has a wealth of measurements, and is probing CP violation in new processes

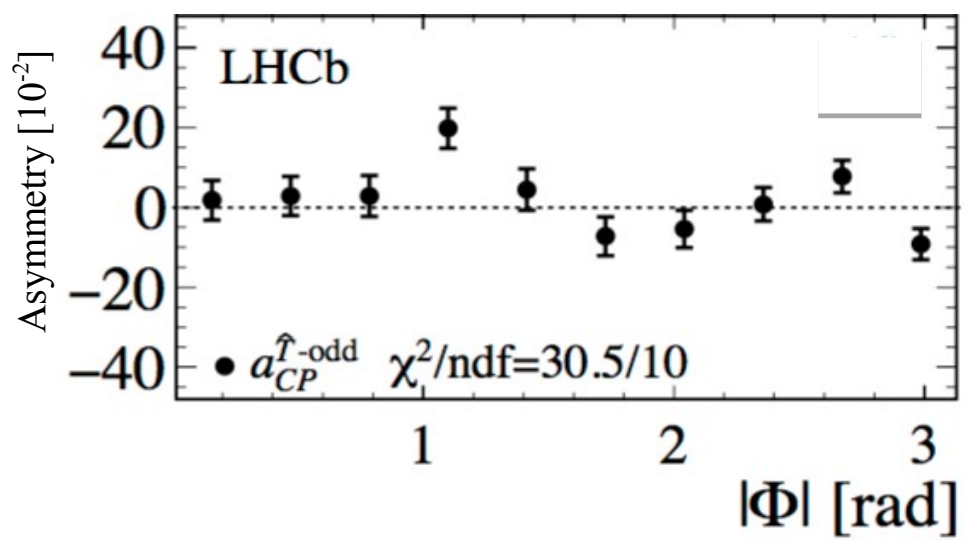
First evidence for CP violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$

- Searching for local CP-violating effects in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays as a function of the relative orientation between the decay planes formed by the $p\pi^-$ and $\pi^+\pi^-$ systems (Φ)



- Evidence is found for CP violation at the 3.3σ level





First evidence of CP violation in the baryon sector

LHCb-PAPER-2016-030 in preparation

Search for CP Violation in Charm Decays

CP violation in the charm sector is expected to be very small in the SM, but can be enhanced by new physics

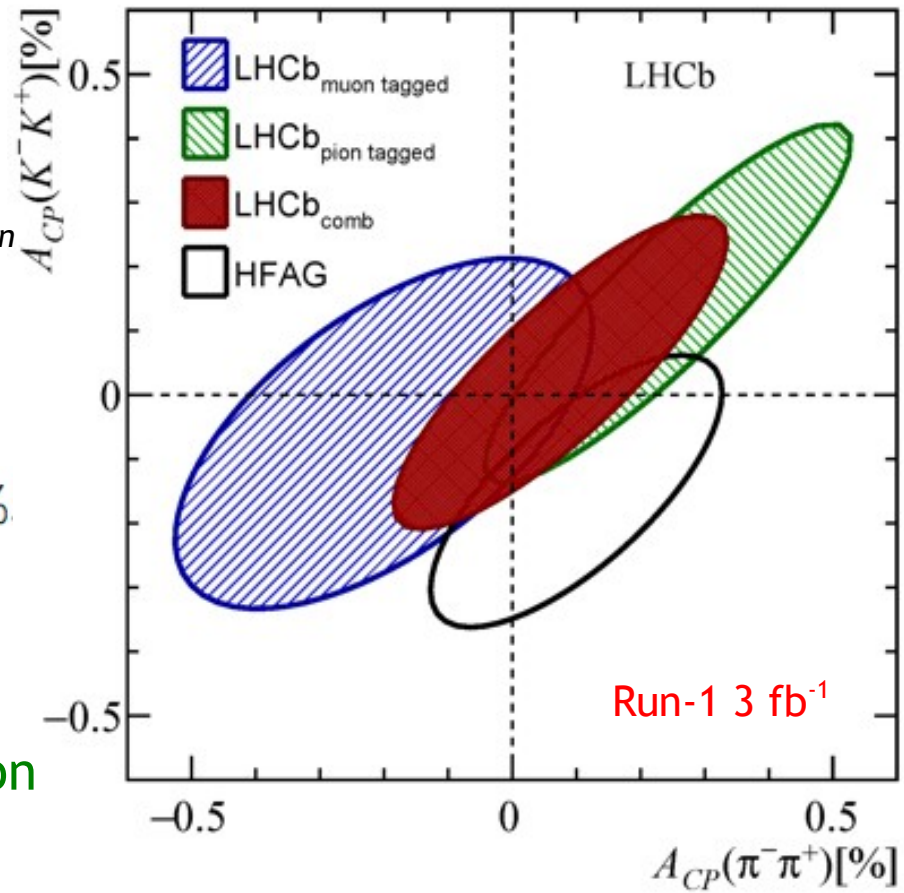
- Most precise measurement of $A_{CP}(D^0 \to K^+K^-)$

$$\frac{N(D^0 \to f) - N(\overline{D}^0 \to \overline{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \overline{f})}$$ with $f = K^+K^-$

Experimental and production nuisance effects need to be pinned down

- Flavour of D^0 is tagged using the $\pi^\pm$ charge from $D^{*+} \to D^0(K^+K^-)\pi^+$ decays

$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

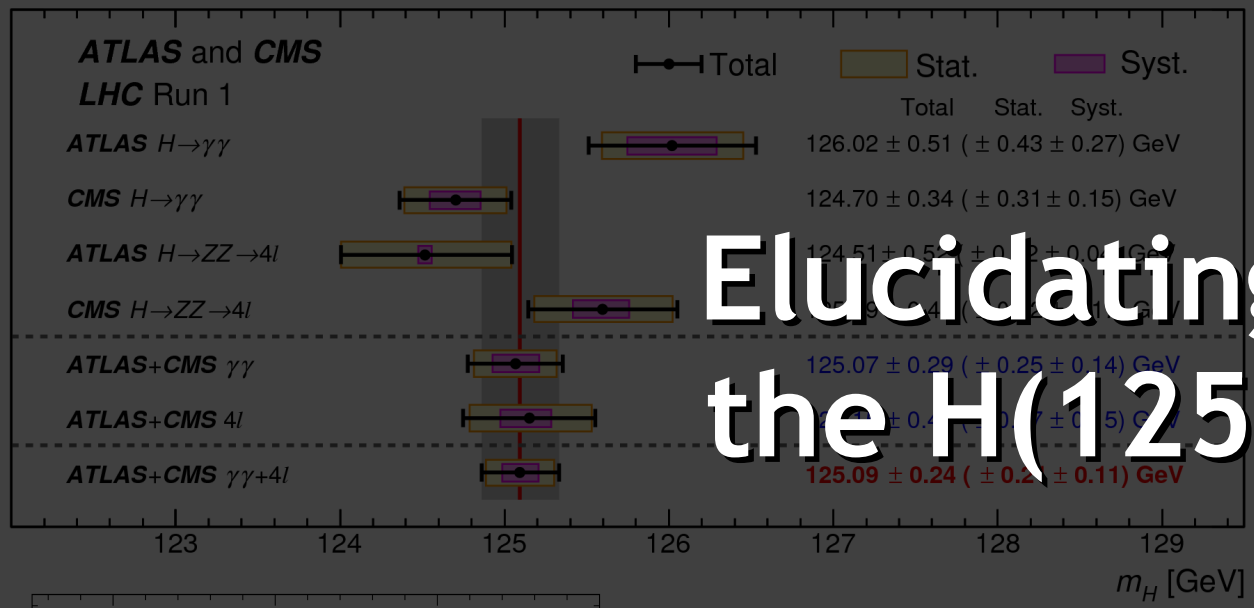


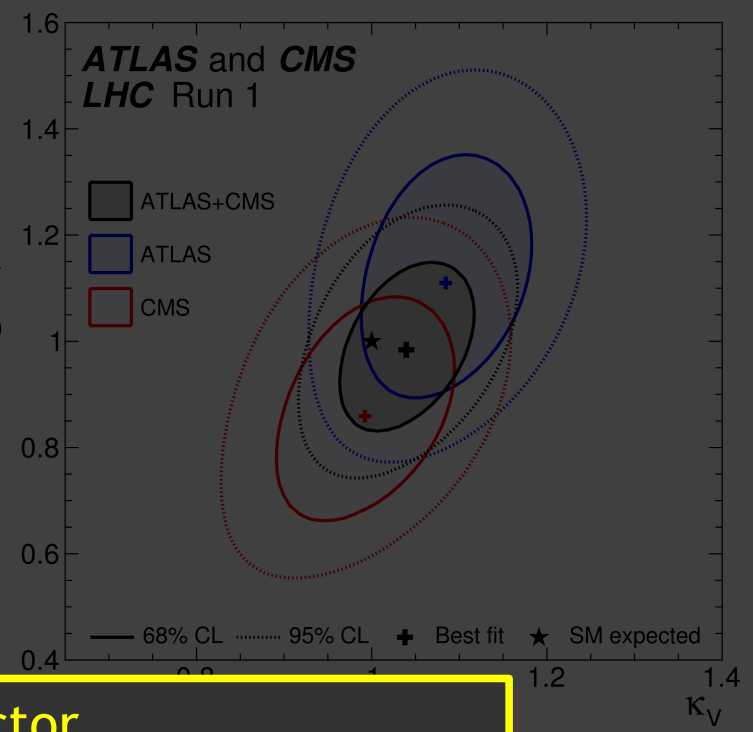
LHCb-PAPER-2016-035 in preparation

Combining this with a previous LHCb result using muon charge in semileptonic B→DμX decays as a tag, the most precise CP violation measurement from a charm meson decay from an individual experiment is obtained:

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

Elucidating the H(125)





H discovery opened the door on the scalar sector

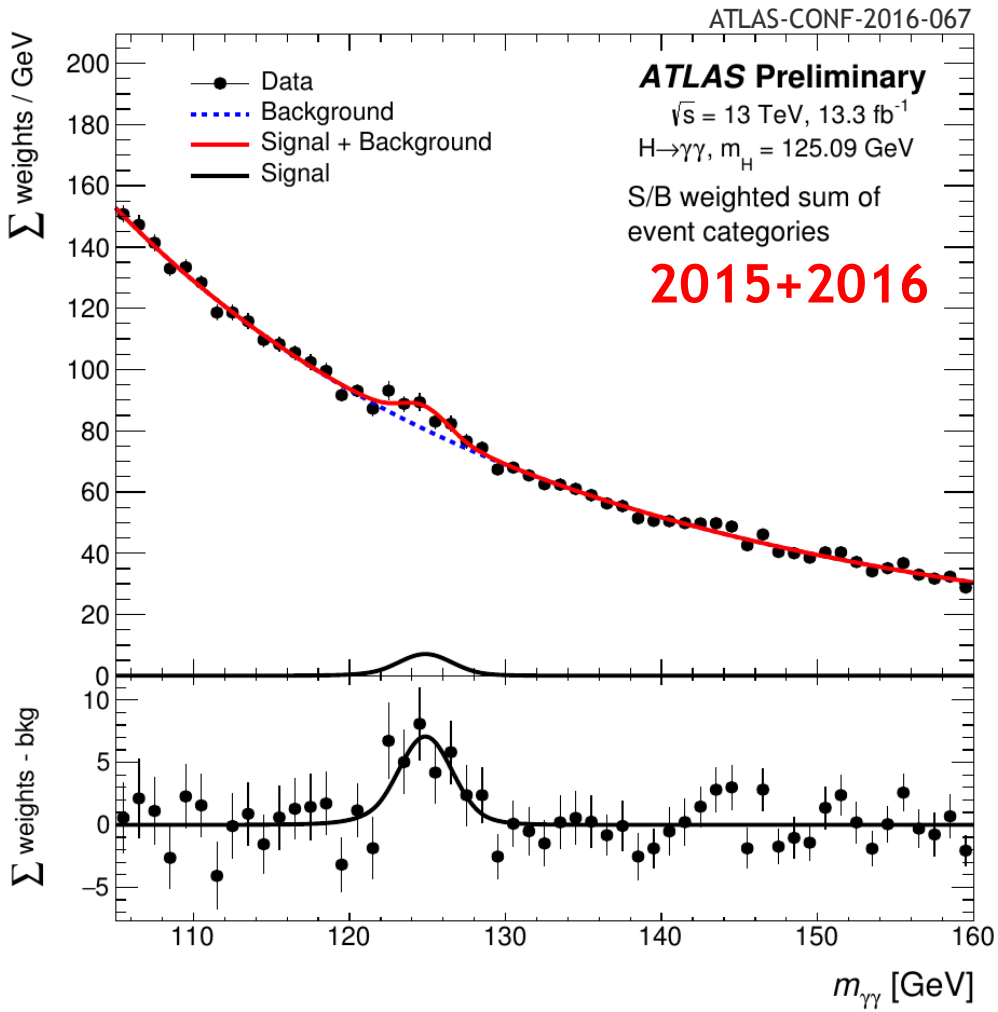
In Run-1 we measured:

- Its spin-parity, and its mass precisely (±0.2%)
- Production via gluon-fusion, vector-boson fusion, and with a W or Z
- The decays to γγ, WW, ZZ, and the fermionic decay to ττ

Run-2 priorities:

- Establish and measure at 13 TeV
- Search for ttH production to probe ttH vertex directly
- Search for H → bb decays
- Search for rare decays
- Refine measurements of couplings, mass, etc
- Expand use of H as a tool to find new physics

H→γγ

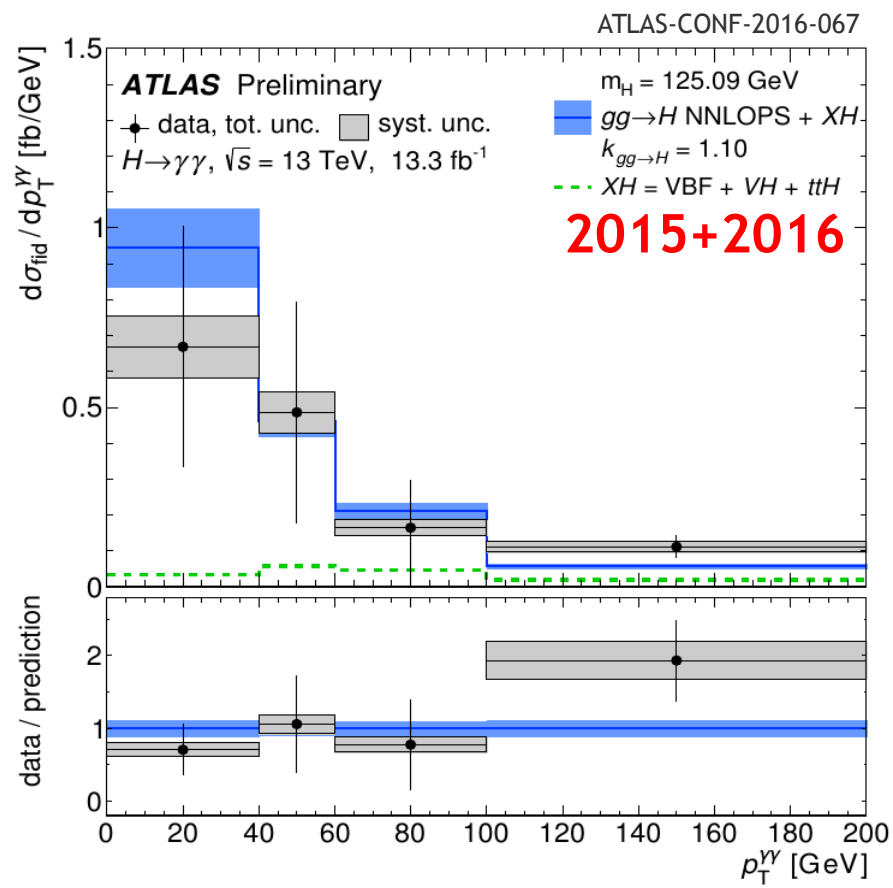


$$\sigma_{\text{fid}} = 47.0 \pm 13.9\,(\text{stat.}) \pm 5.4\,(\text{syst.})\ \text{fb}$$

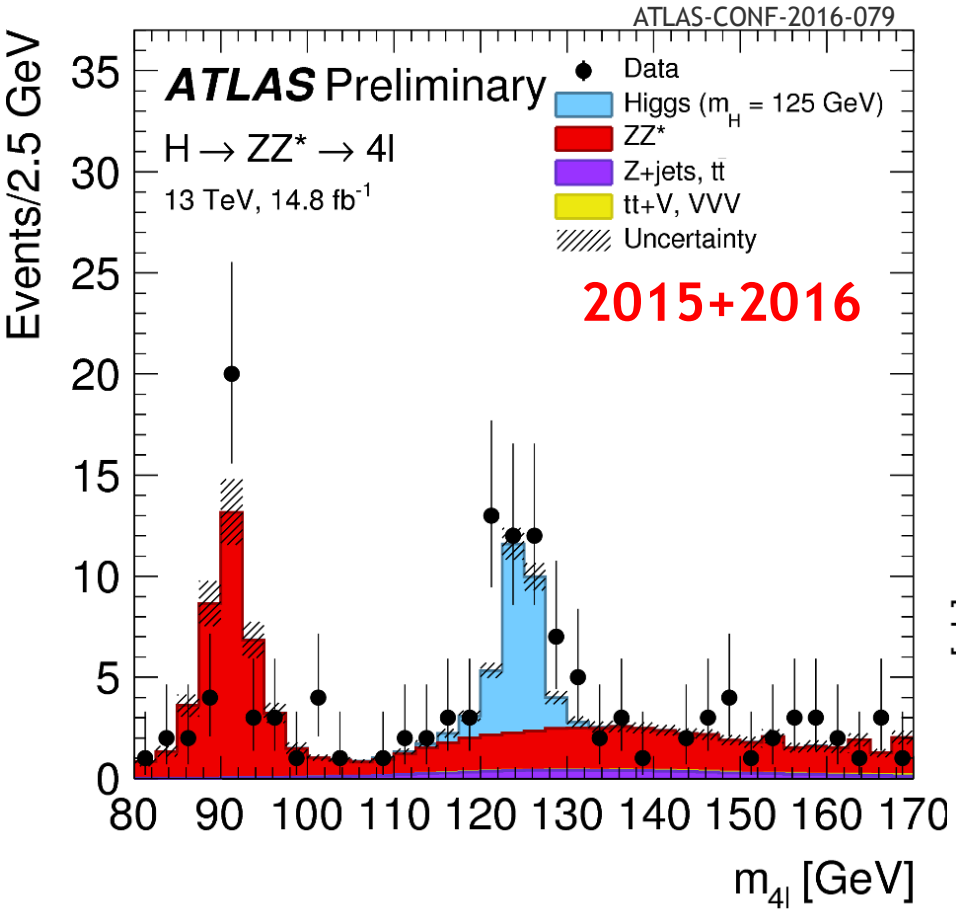
SM prediction $62.8^{+3.4}_{-4.4}$ fb

Event categories enhance sensitivity and help separate production modes

- Clear signal, rate consistent with SM H expectation
- Fiducial and differential cross-section measurements



H→4ℓ & Cross-Section Combination



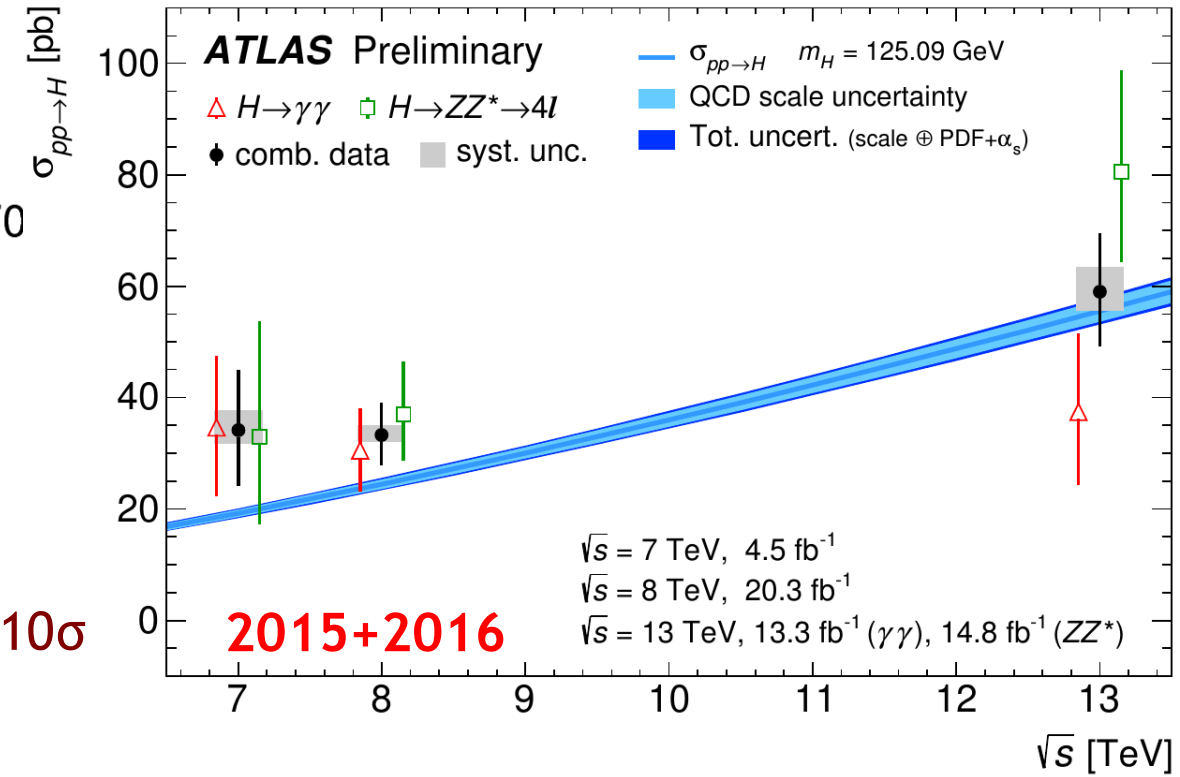
H→ZZ*→4ℓ: event categories again used

- Clear re-observation, rate consistent with SM H expectation (1.6σ high)

Combining γγ+4ℓ channels

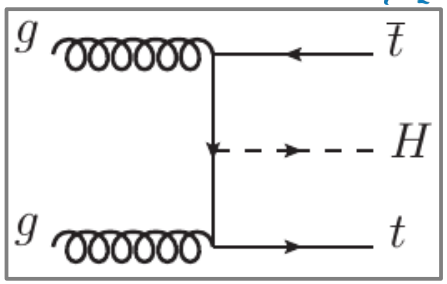
σ(pp→H+X,13 TeV) = $59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb

SM prediction $55.5^{+2.4}_{-3.4}$ pb



Overall significance at 13 TeV ~10σ

Search for ttH production



Direct probe of top Yukawa coupling
Cross-section at 13 TeV ~4 times that at 8 TeV
Results presented with 2015+2016 data for

- ttH, H→bb
- ttH, multilepton final states (contributions from several decay chains)
- ttH, H→γγ through H→γγ event categorisation

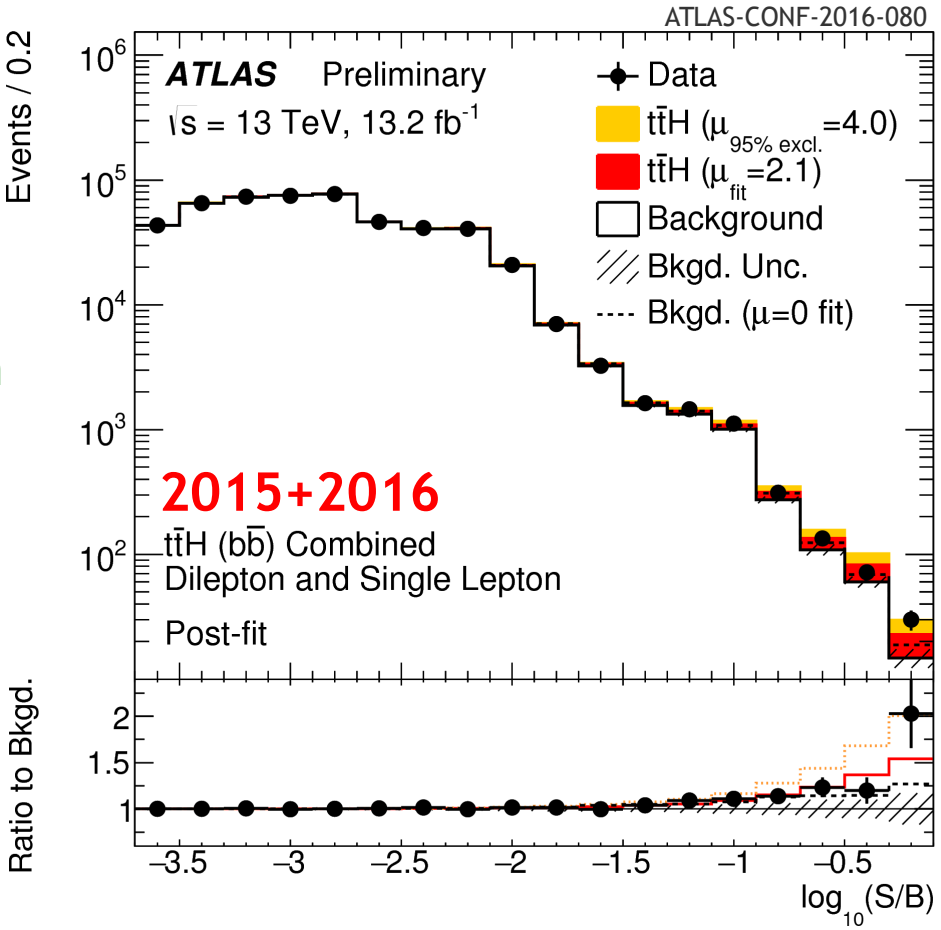
ttH, H→bb analysis

Complex final states

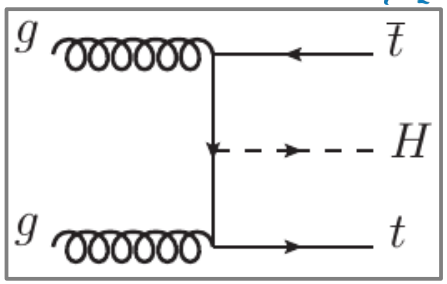
- 1ℓ + 6jets (4 b-jets)
- 2ℓ + 4jets (4 b-jets)

Multiple selection regions help to constrain $t\bar{t}$+HF production and systematic uncertainties

Plot shows events from 16 selection categories, with events ordered in signal/bkgd ratio



Search for ttH production



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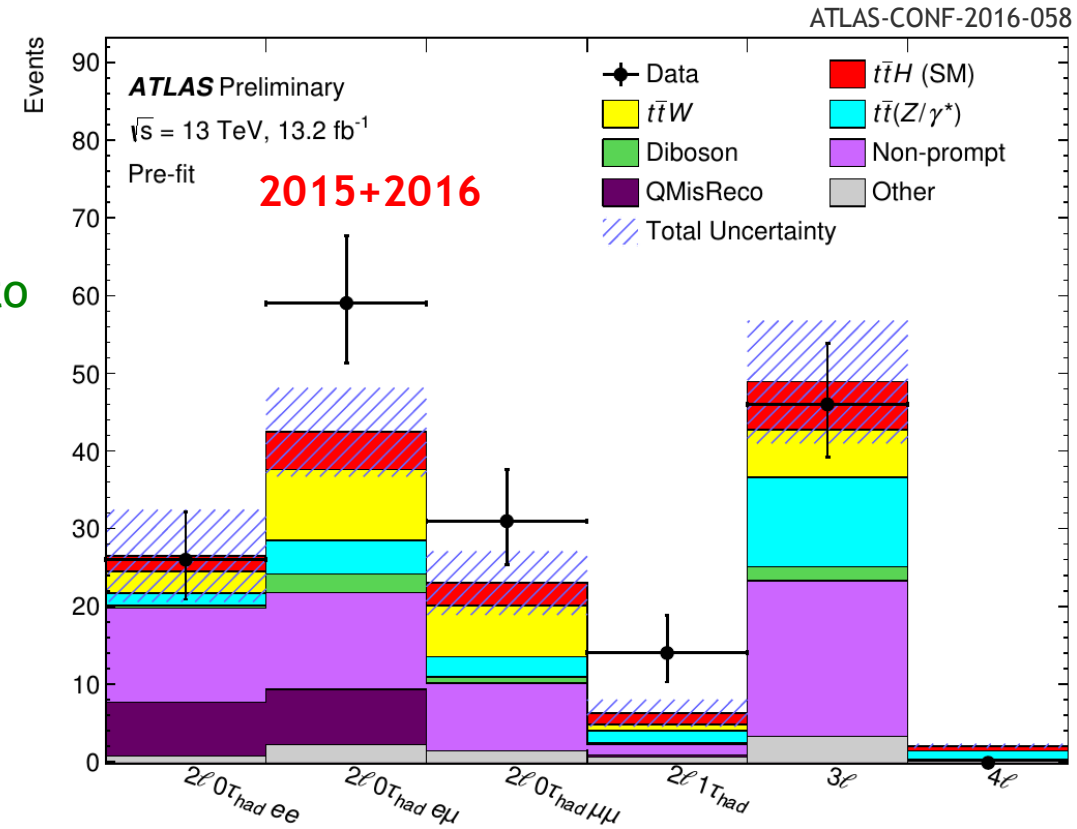
ttH multilepton analysis

Primarily targets

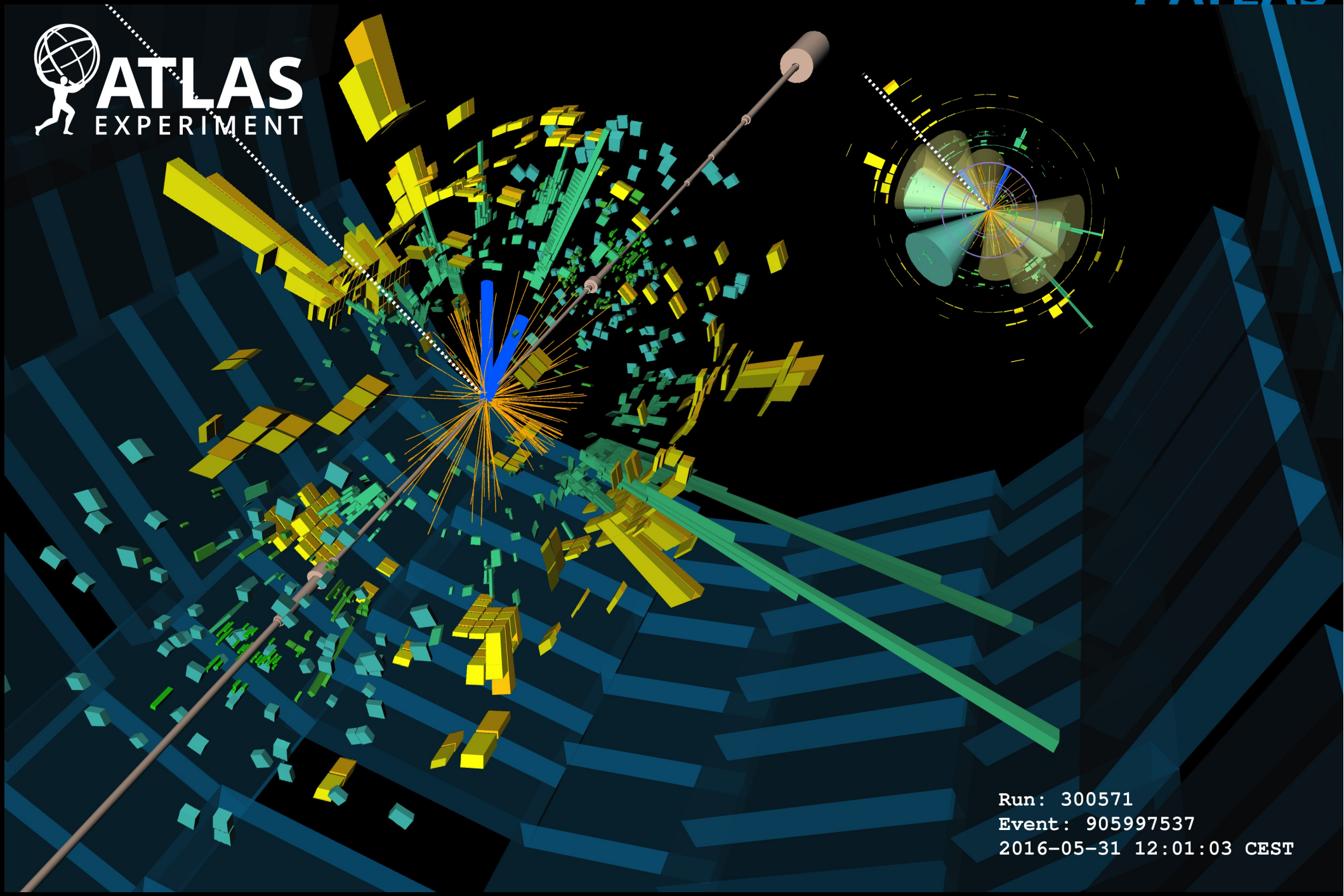
- H→WW*, H→ττ

Multiple selection regions according to ℓ and τ multiplicities

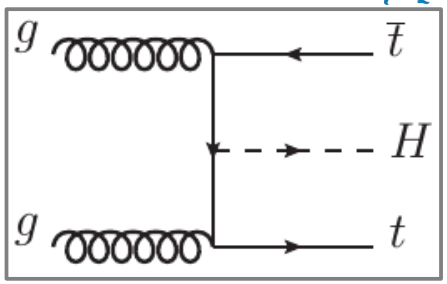
Dominant backgrounds from tt(W/Z) and non-prompt leptons/fakes



Event selected in ttH multilepton analysis



Search for ttH production



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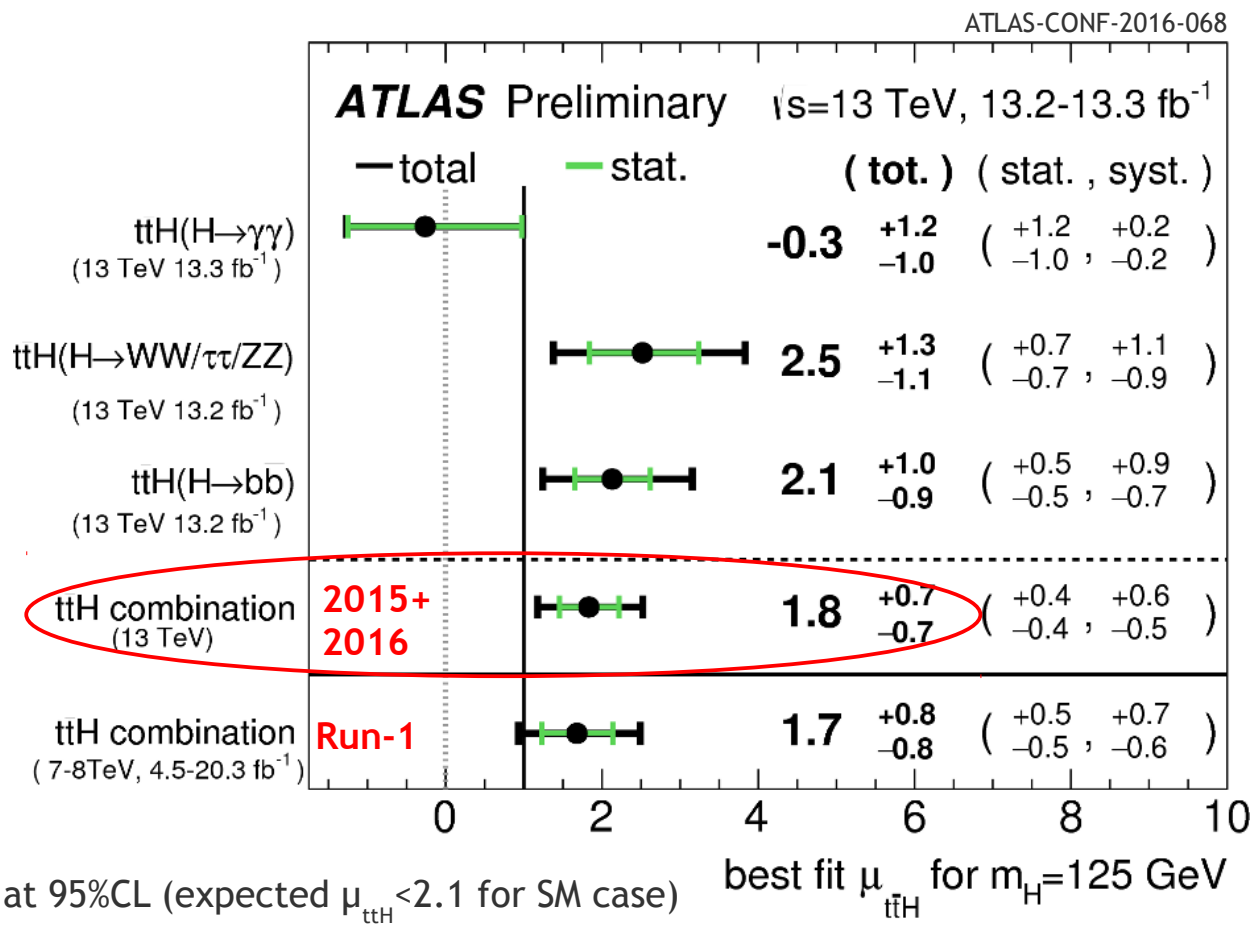
- ttH, H→γγ through H→γγ event categorisation

ttH combination

Combine all three 13 TeV analyses

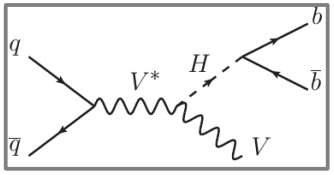
Signal strength μ expressed relative to SM expectation

Observed significance 2.8σ (expect 1.8σ)
Cf Run-1 expected 1.5σ



Upper limit on signal strength: μ_{ttH}<3.0 at 95%CL (expected μ_{ttH}<2.1 for SM case)

H→bb in (W/Z)H production



ATLAS EXPERIMENT

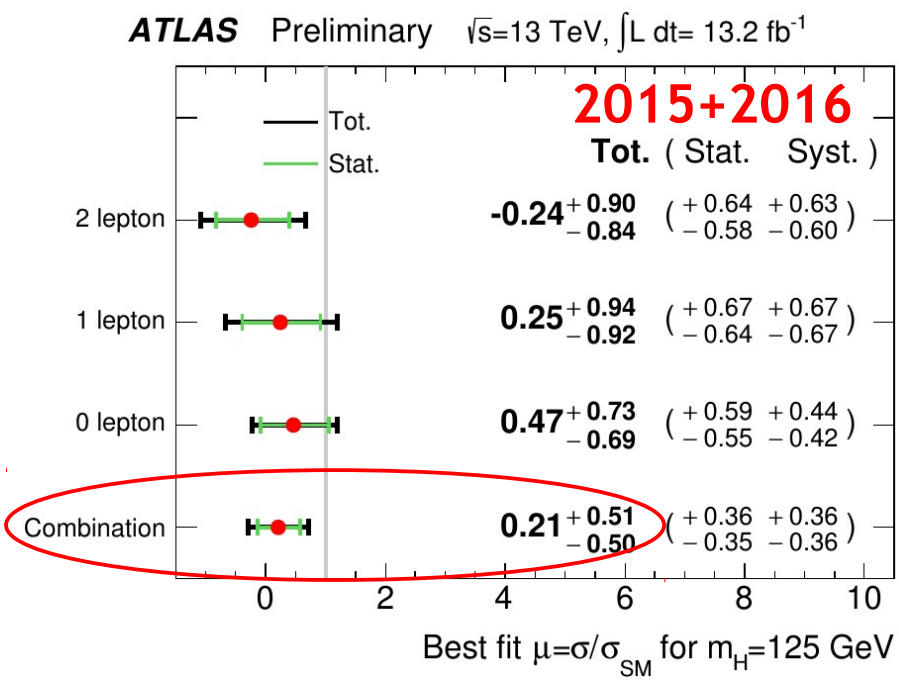
ATLAS-CONF-2016-091

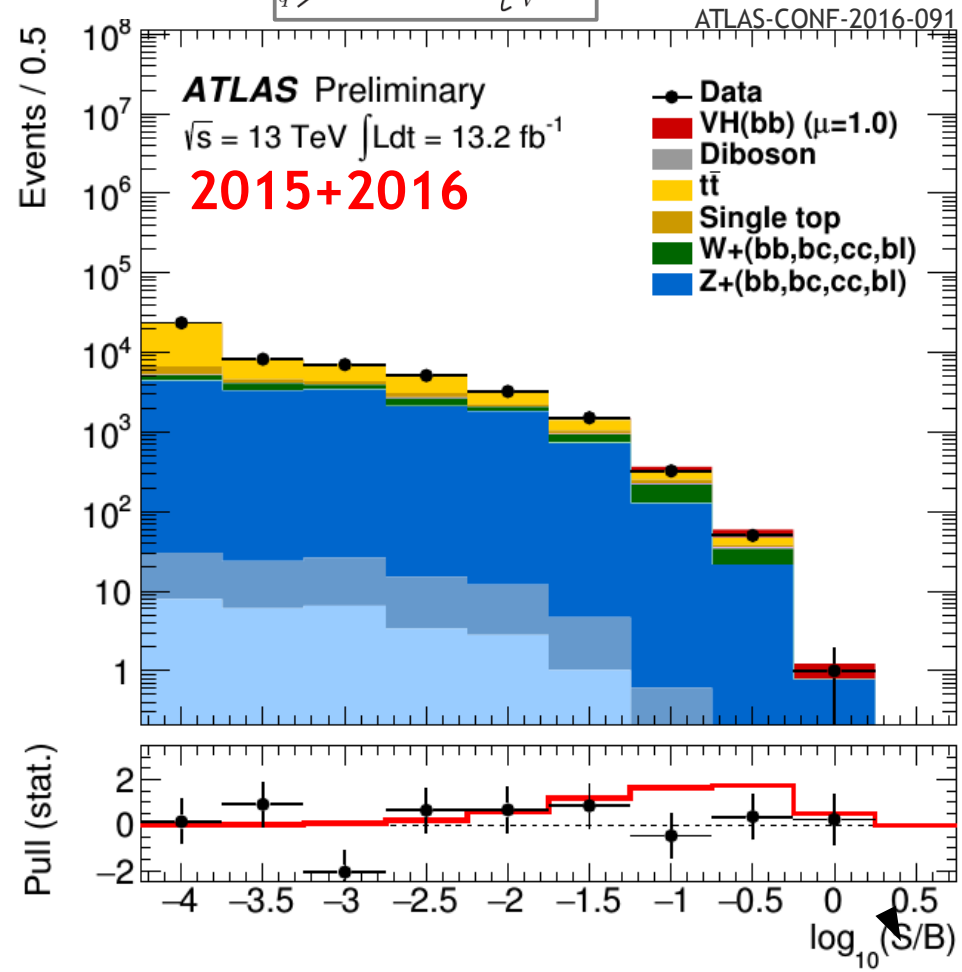
Run-1: H→bb "evidence" at 2.6σ (3.7σ expected), combining ATLAS+CMS Run-1

- Dominant H decay mode (BR~58%) remains to be observed!

Analysis with 2015+2016 13 TeV data:

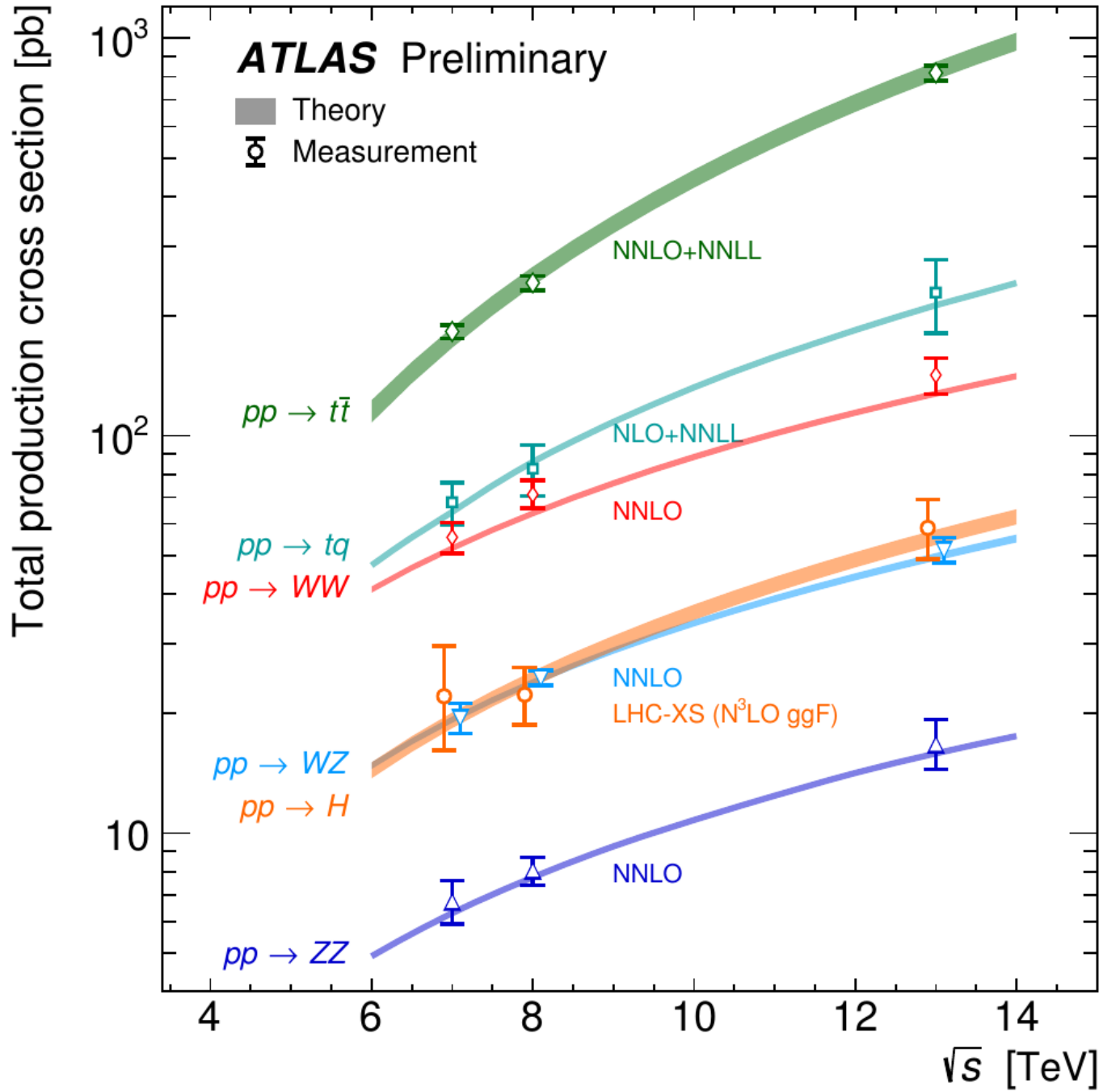
- 2ℓ(Z→ℓℓ), 1ℓ(W→ℓν), 0ℓ(Z→νν) channels
- VZ, Z→bb validation: 3.0σ, expect 3.2σ





Significance 0.42σ cf. expected 1.94σ

Can convert to upper limit on signal strength: μ < 1.2 at 95%CL



$pp \to t\bar{t}$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb^{-1}, arXiv:1606.02699

$pp \to tq$
7 TeV, 4.6 fb^{-1}, PRD 90, 112006 (2014)
8 TeV, 20.3 fb^{-1}, ATLAS-CONF-2014-007
13 TeV, 3.2 fb^{-1}, ATLAS-CONF-2015-079

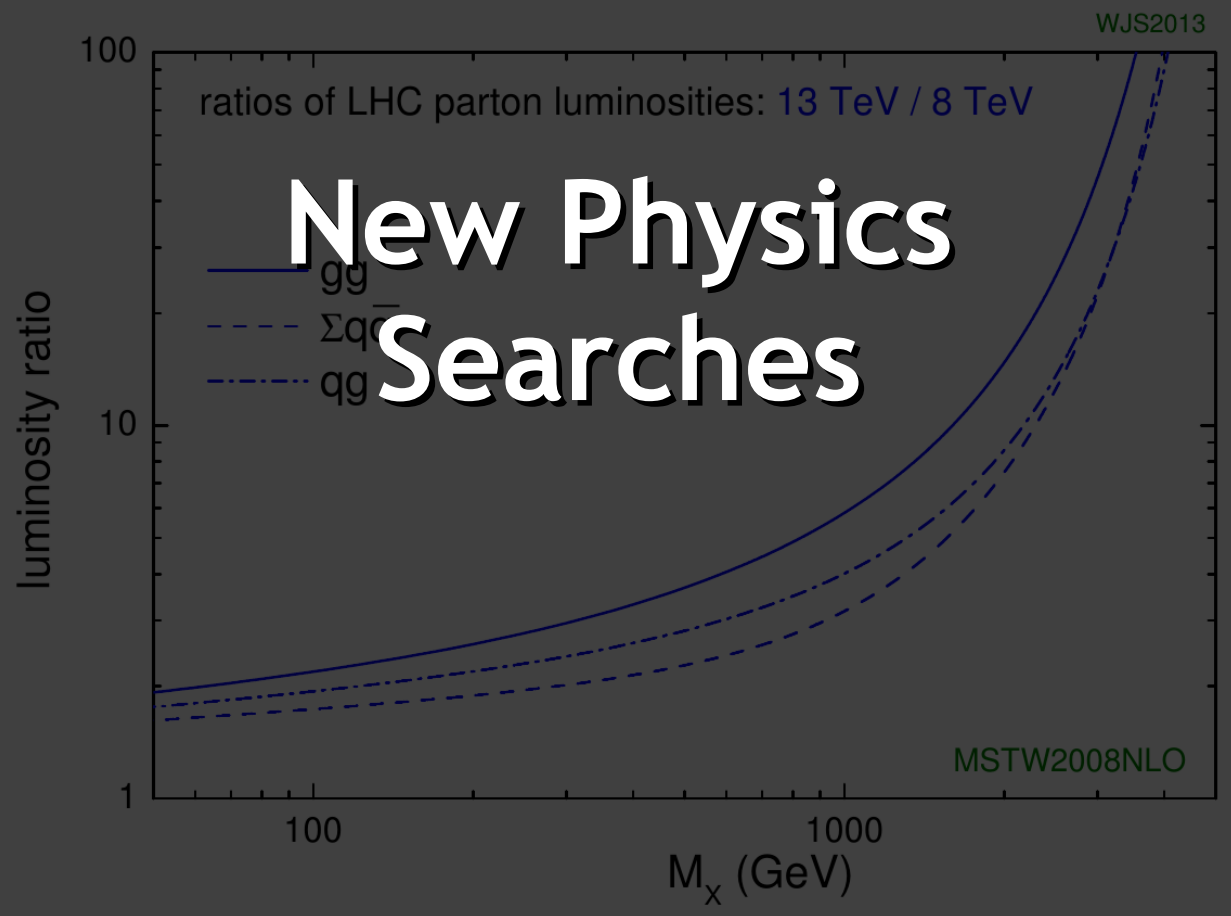
$pp \to WW$
7 TeV, 4.6 fb^{-1}, PRD 87, 112001 (2013)
8 TeV, 20.3 fb^{-1}, CERN-EP-2016-186
13 TeV, 3.2 fb^{-1}, ATLAS-CONF-2016-090

$pp \to WZ$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb^{-1}, PRD 93, 092004 (2016)
13 TeV, 3.2 fb^{-1}, arXiv:1606.04017

$pp \to H$
7 TeV, 4.5 fb^{-1}, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C76 (2016) 6
13 TeV, 13.3 fb^{-1}, CONF-HIGG-2016-28

$pp \to ZZ$
7 TeV, 4.6 fb^{-1}, JHEP 03, 128 (2013)
8 TeV, 20.3 fb^{-1}, ATLAS-CONF-2013-020
13 TeV, 3.2 fb^{-1}, PRL 116, 101801 (2016)

New Physics Searches



Major extension of reach compared to Run-1

All results shown here include 2016 data

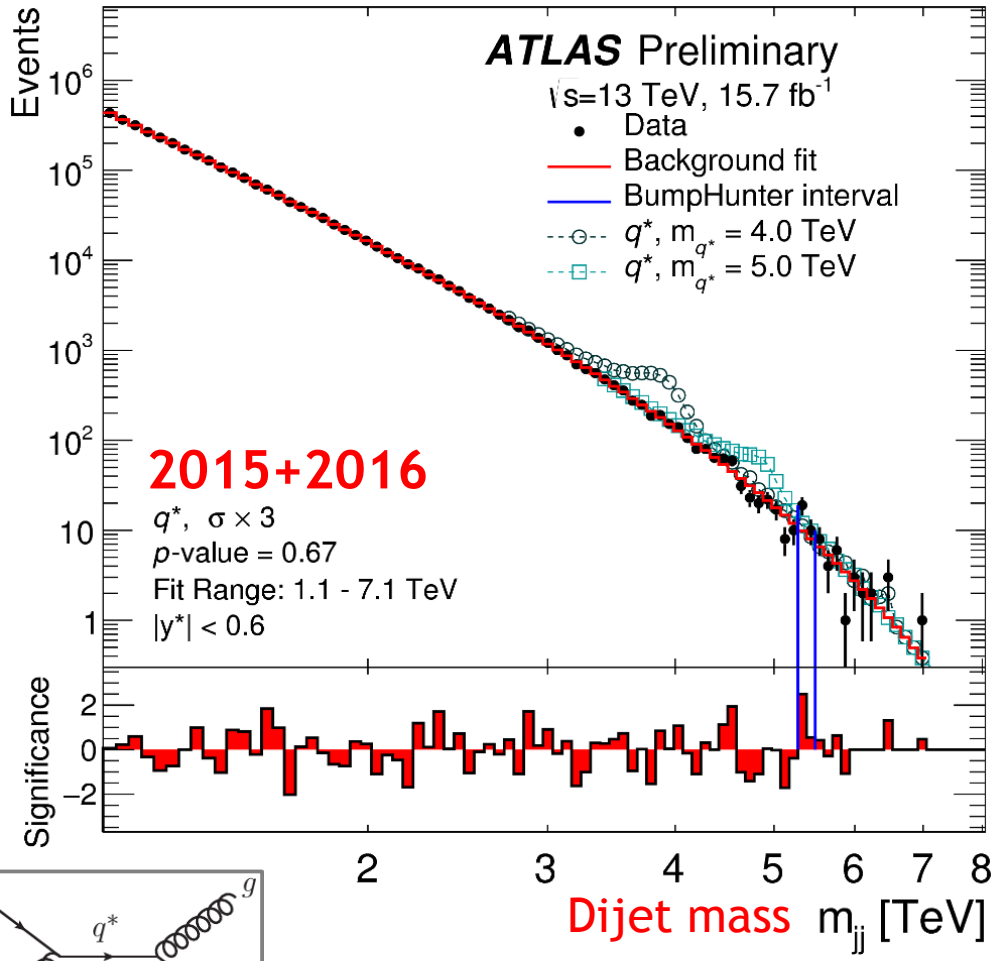
They probe well into the TeV, even multi-TeV, mass scale range

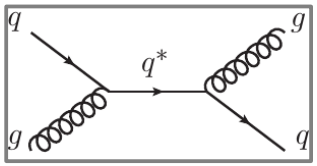
Many more searches will yet come with the 2016 dataset

Dijet Search

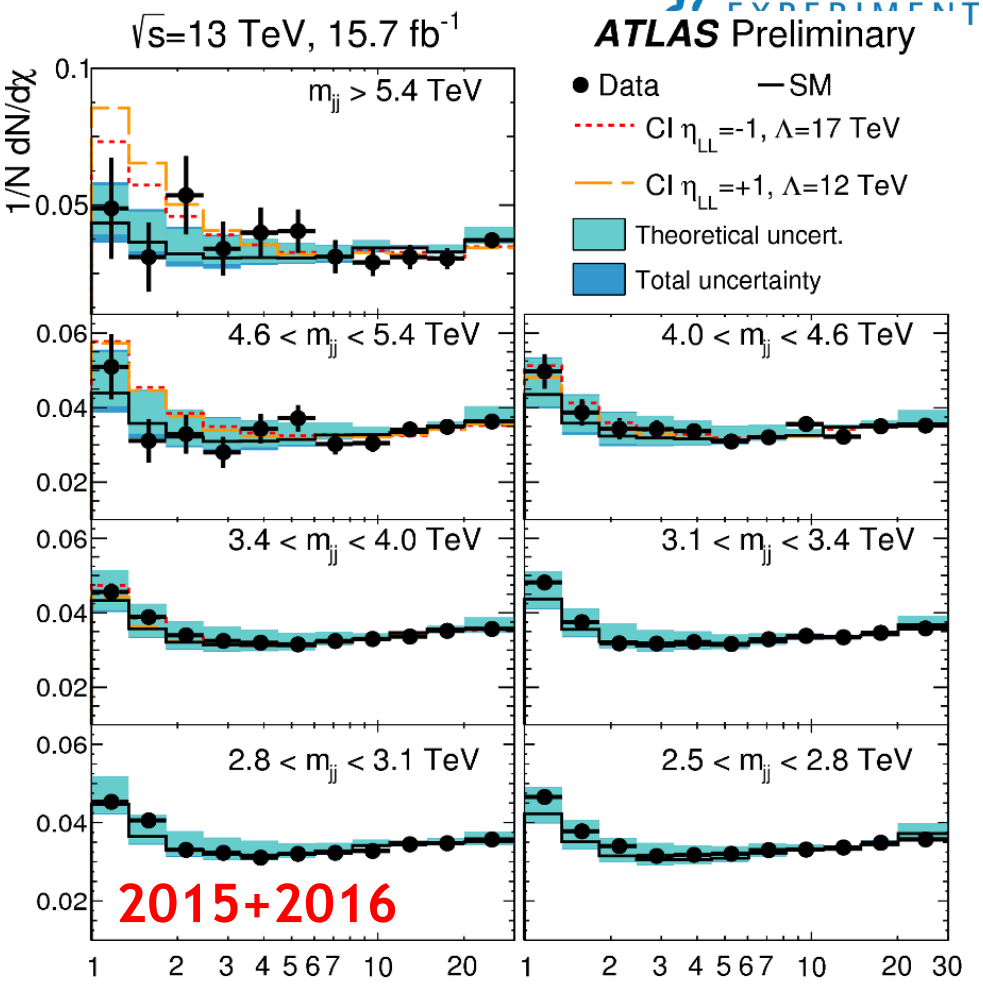
Search for new physics in dijet mass spectrum and angular distributions

ATLAS-CONF-2016-069





Examples (@95% CL):
m(q*) > 5.6 TeV
(ATLAS Run-1: 4.1 TeV)



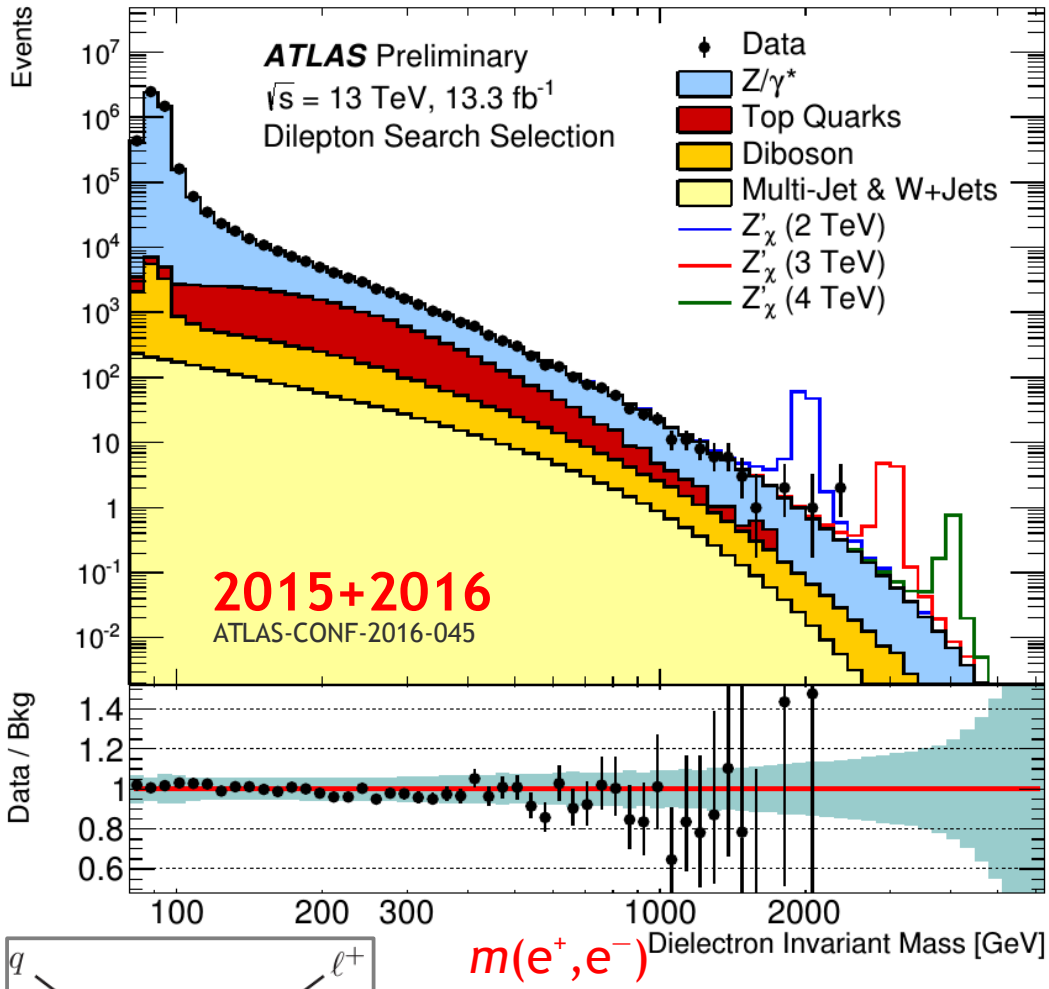
$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

Scattering angle

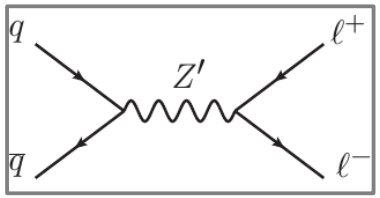
$$L_{qq} = \frac{2\pi}{\Lambda^2}\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$$

- Contact interaction scale (η_{LL}=+1/-1)
  Λ > 12.6 / 19.9 TeV (8.1/12.0 TeV)

Dilepton Resonance Searches

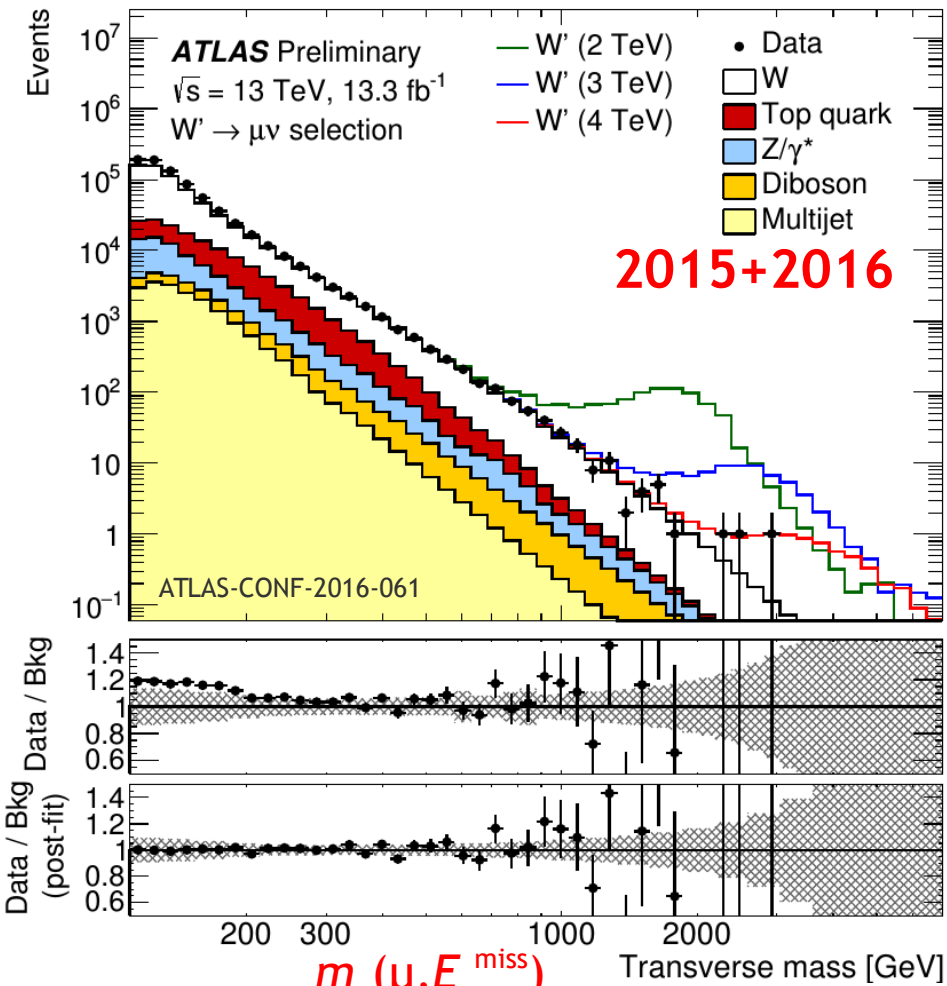


$m(e^+,e^-)$



Z'_{SSM} (@95%CL): m > 4.05 TeV

(Run-1 m>2.90 TeV)



$m_T(\mu,E_T^{miss})$

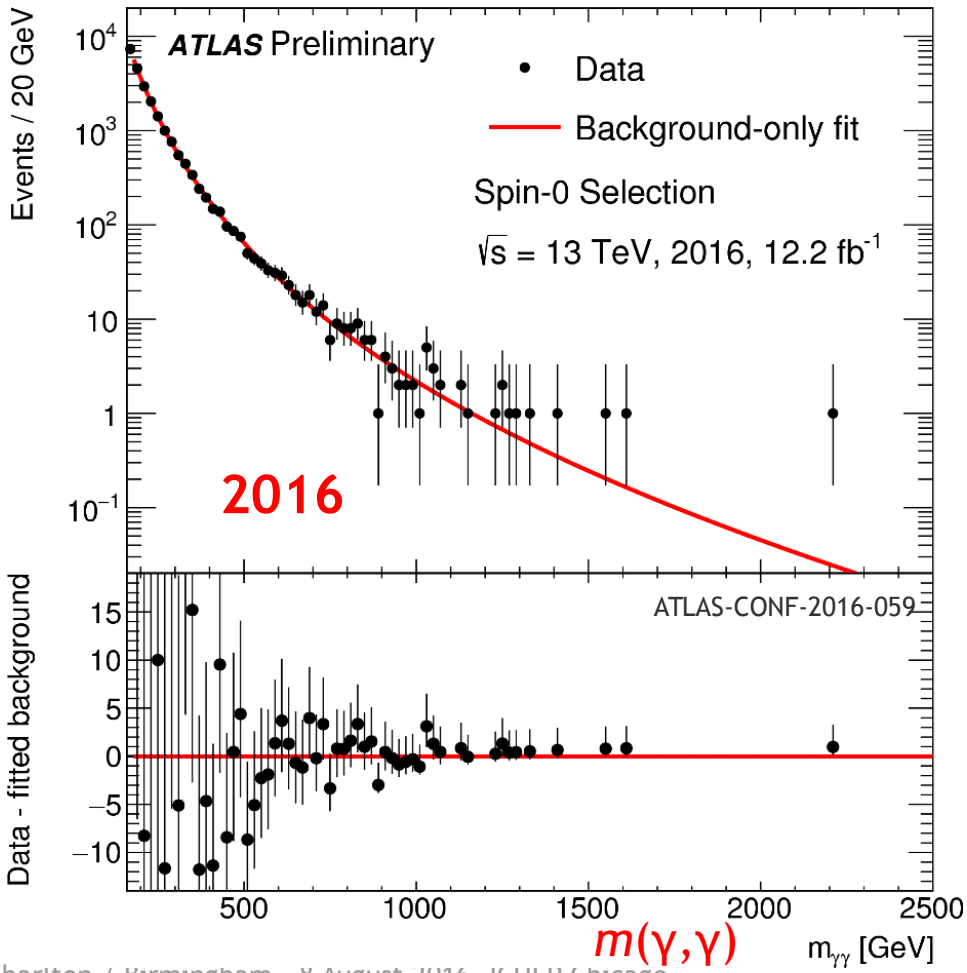
W' (@95%CL): m > 4.74 TeV

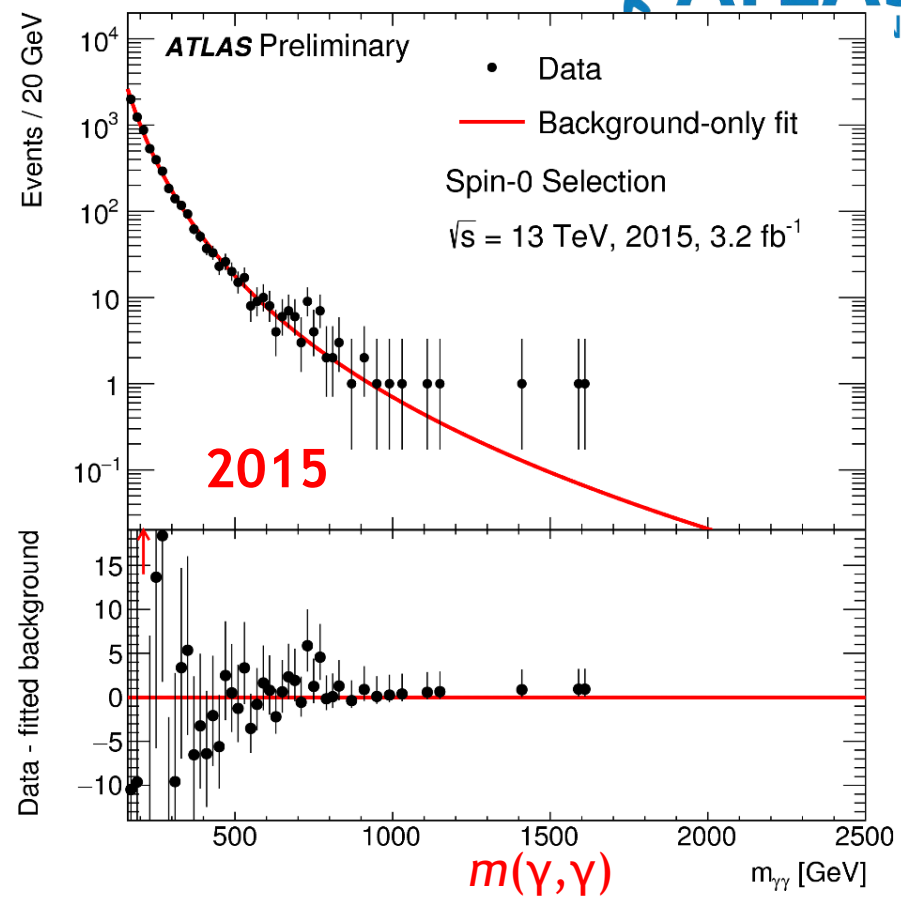
(Run-1 m>3.24 TeV)

Diphoton Searches

Localised excess seen in 2015 ATLAS data

- 2.1σ global (3.9σ local) significance at 750 GeV (spin-0 search), width ~50 GeV
- After reprocessing, new 2016 reconstruction → 3.4σ local, at ~730 GeV

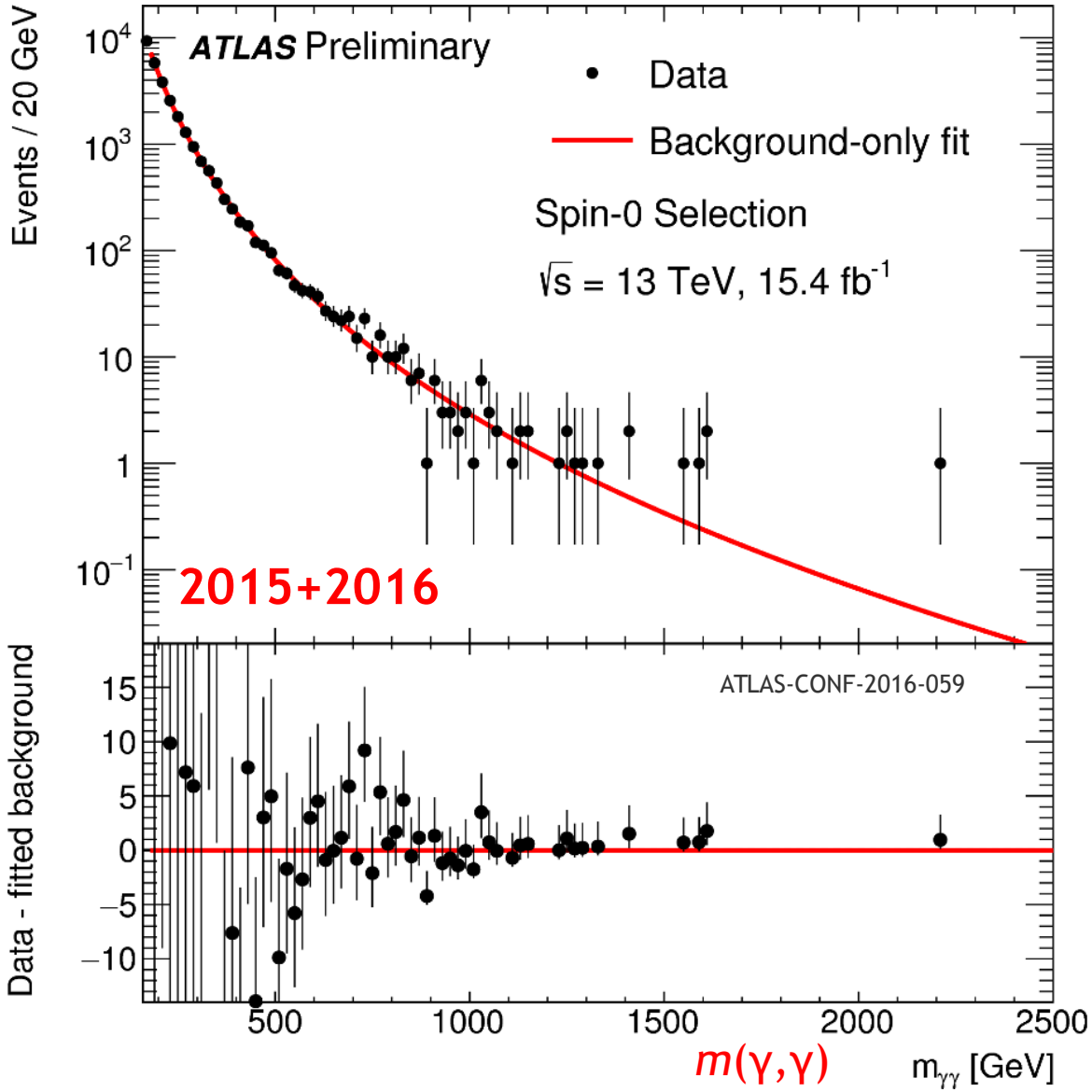




2016 data: no clustering around 730-750 GeV, and 3.8x more data

- 2016 data consistent with 2015 at the 2.7σ level
- Appears that the 2015 excess was a statistical fluctuation

Diphoton Searches



With 2015+2016 data:

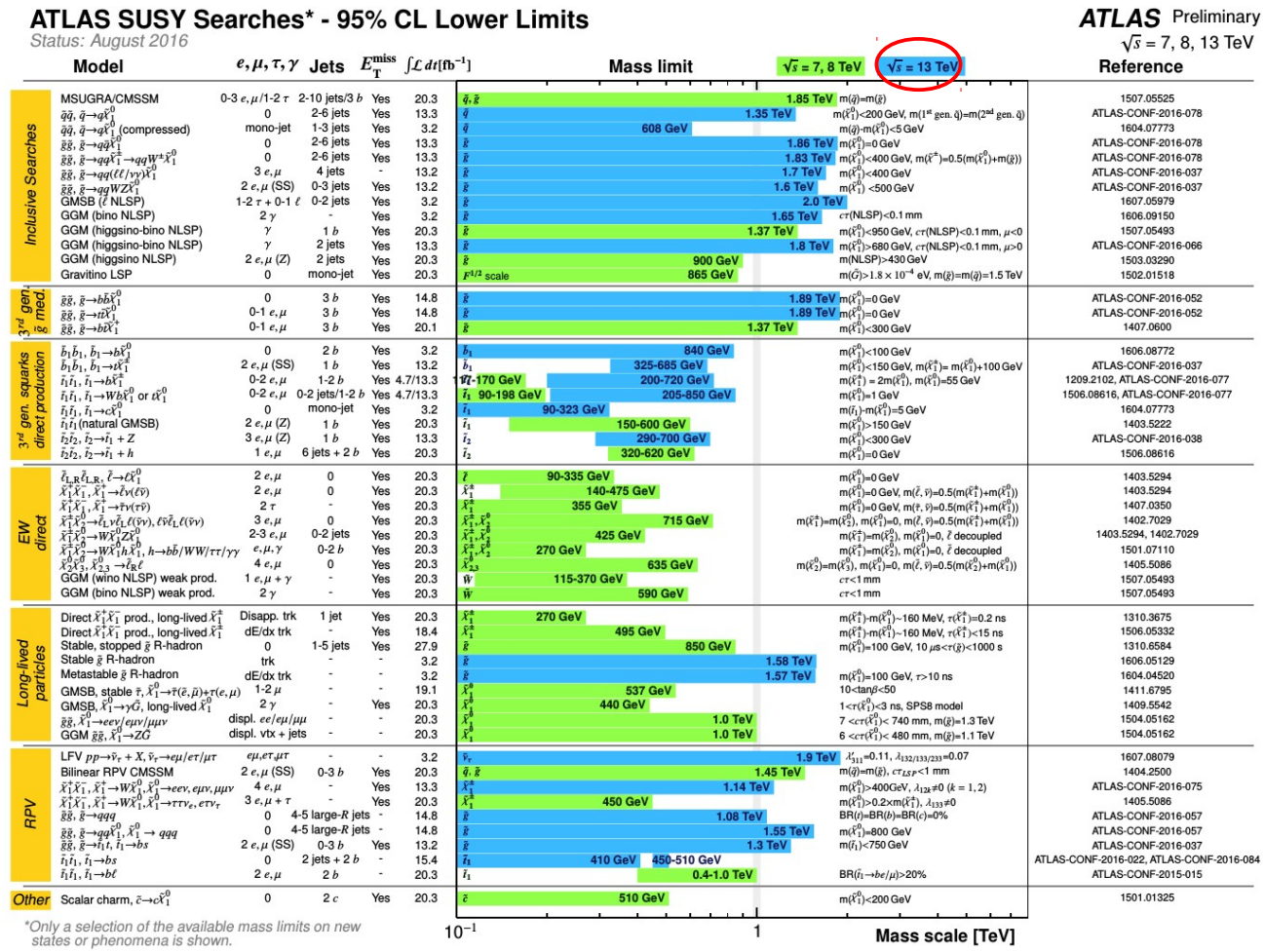
- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

SUSY Searches

Very broad set of SUSY search results reported with 2015+2016 data

Just a couple of examples here

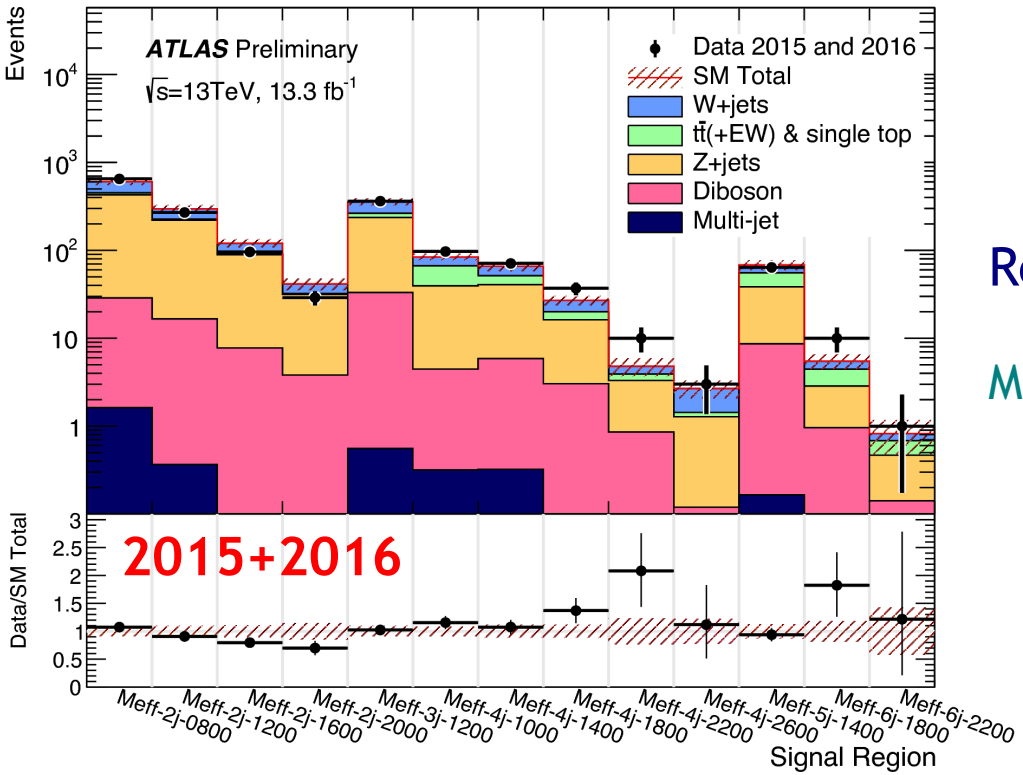
- $\tilde{g}/\tilde{q}$ search with jets+E_T^{miss}
- $\tilde{t}$ searches

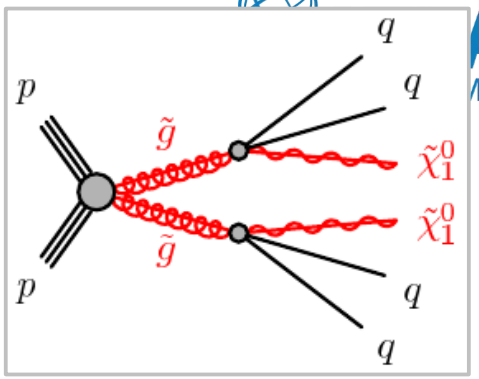


Standard ATLAS approach in many searches:

- Focus on specific signatures, simplified models guide optimisation
- Data-driven backgrounds: multiple control regions to constrain MC predictions and systematic uncertainties
- Validation regions: verify background descriptions
- Signal regions: sensitivity!

Jets + E_T^{miss} (0ℓ)





Require 2-6 jets and veto isolated leptons

- Sensitive to $\tilde{g}$ and $\tilde{q}$ production

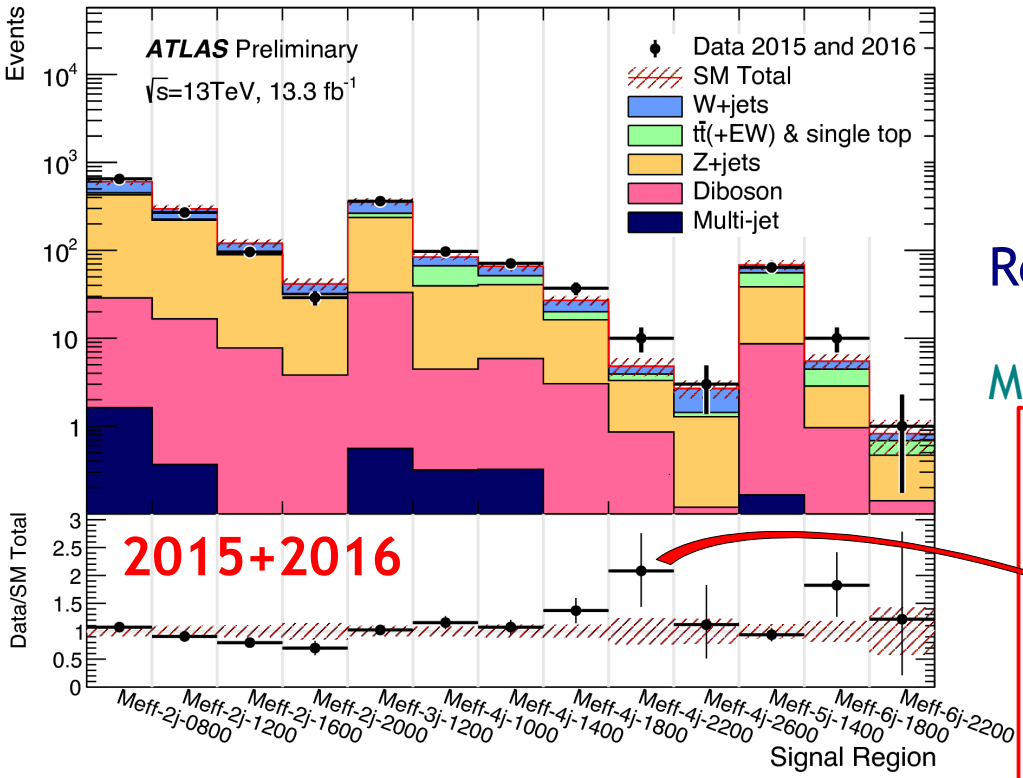
Main backgrounds Z/W+jets and $t\bar{t}$

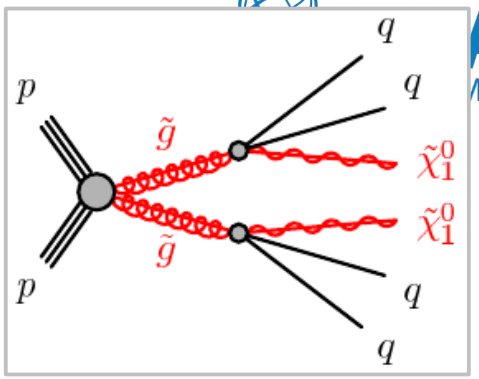
Total of 30 signal regions:

- 13 shown with different m_{eff} cuts
- Largest excess 1.6σ
- No significant excesses overall

$$m_{eff} = E_T^{miss} + \Sigma\ |p_T(\text{jet})|$$

Jets + E_T^{miss} (0ℓ)





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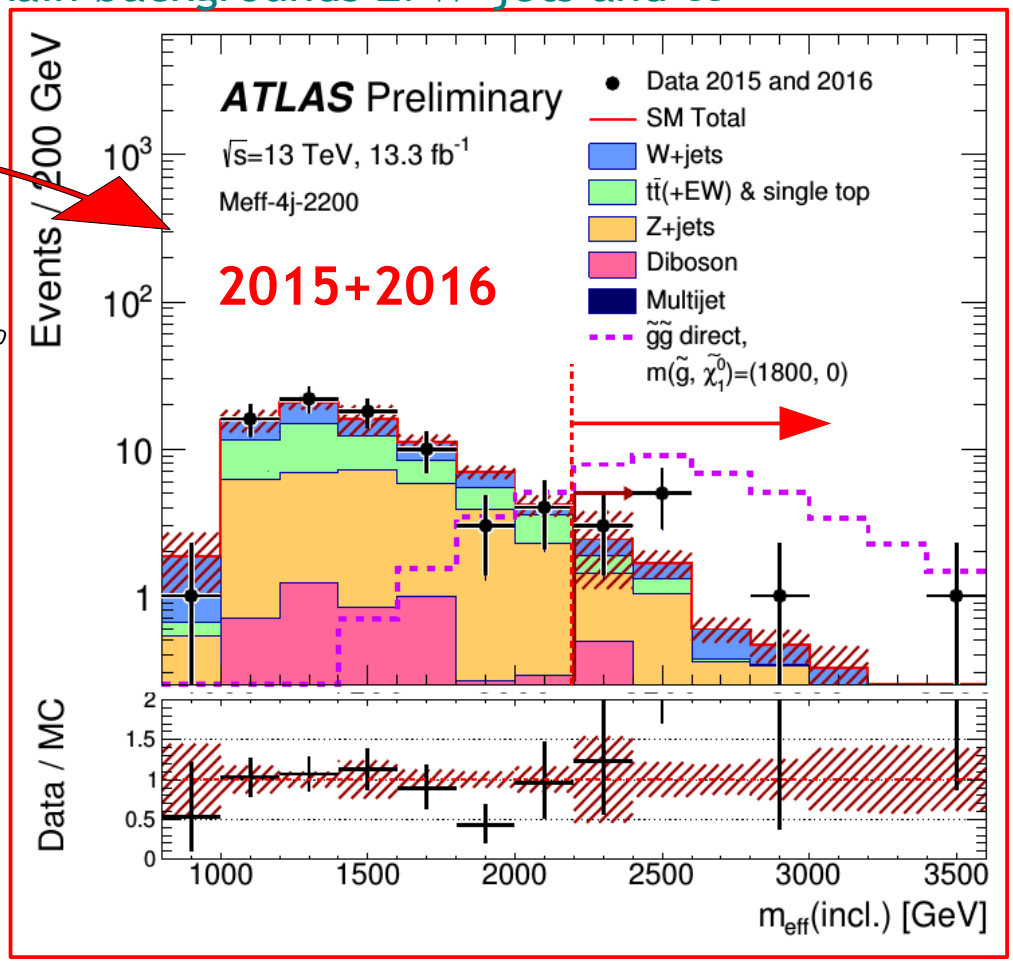

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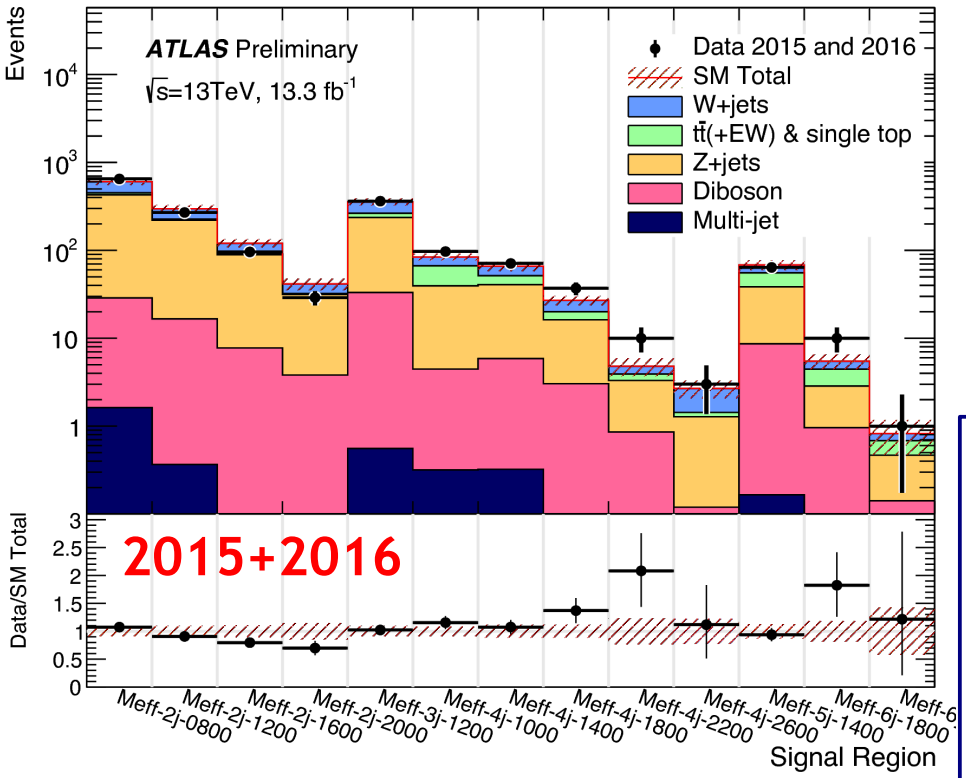
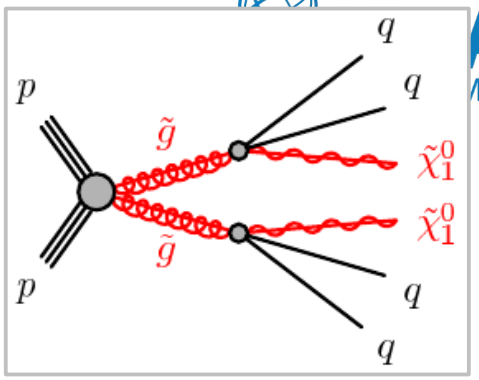
Jets + E_T^{miss} (0ℓ)





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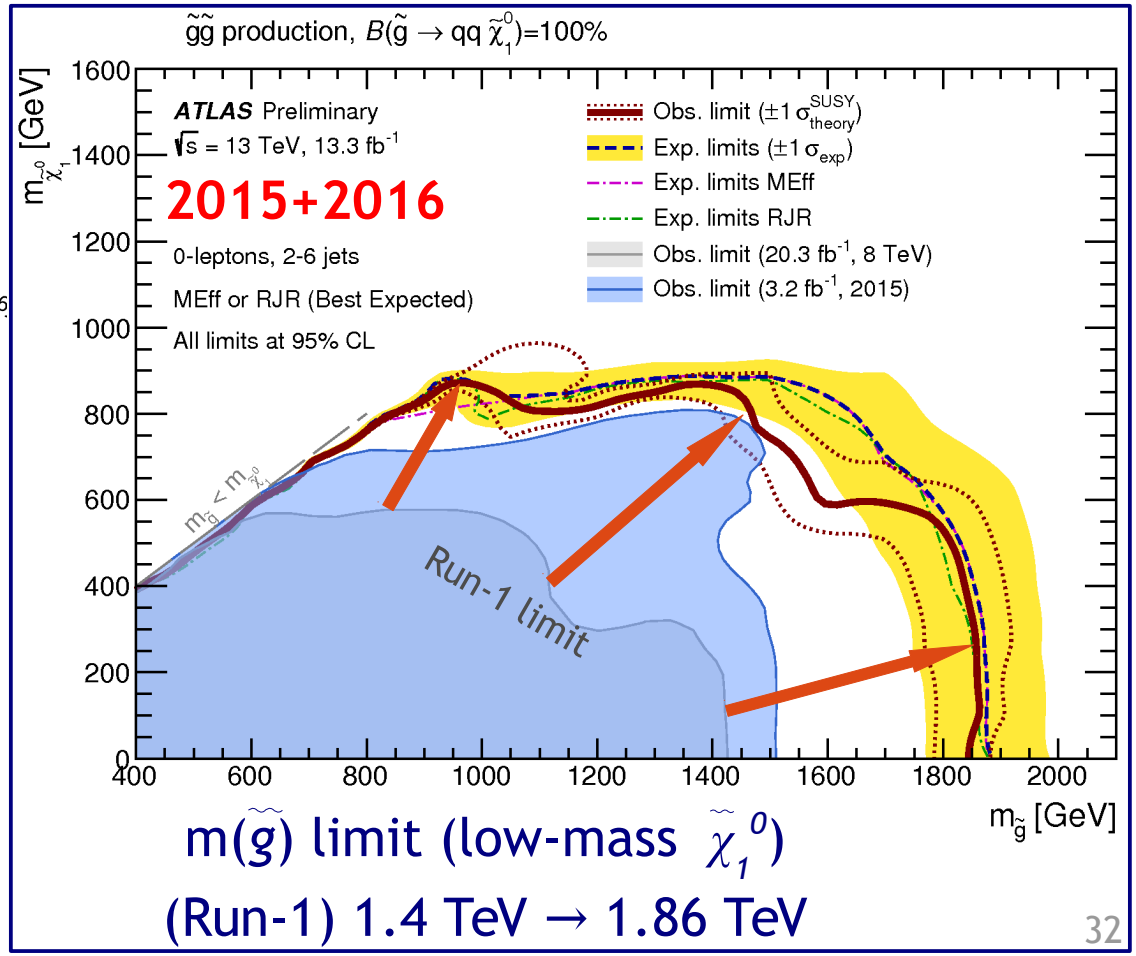


m($\tilde{g}$) limit (low-mass $\tilde{\chi}_1^0$)

(Run-1) 1.4 TeV → 1.86 TeV

Total of 30 signal regions:

- 13 shown with different m_{eff} cuts
- Largest excess 1.6σ
- No significant excesses overall

$$m_{eff} = E_T^{miss} + \Sigma\, |p_T(\text{jet})|$$

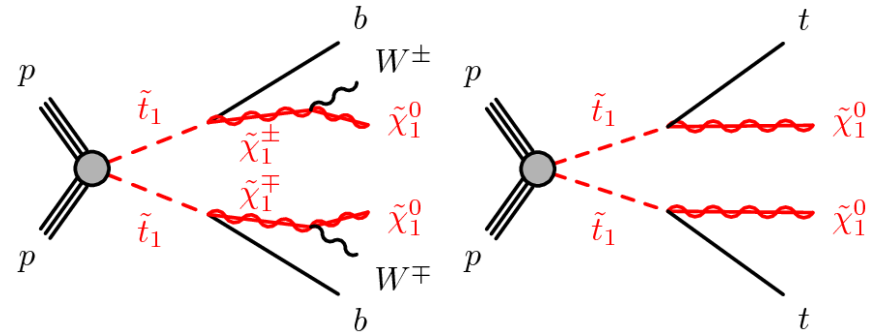
Stop Search: $\tilde{t}\to bW\tilde{\chi}_1^0$, $\tilde{t}\to t\tilde{\chi}_1^0$

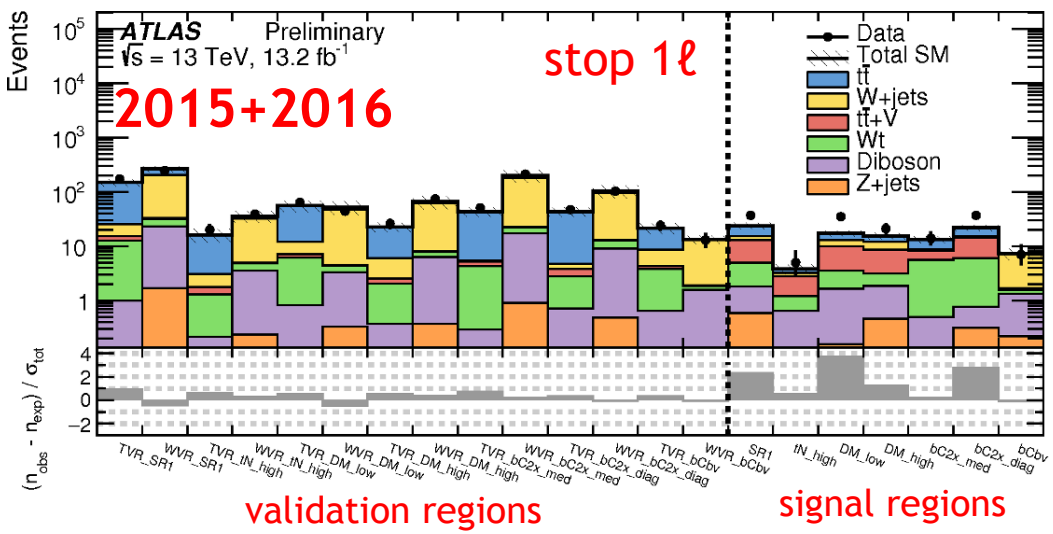
Event topology: WbWb+E_T^{miss}(+jets)

- Divide according to W decays: 0ℓ, 1ℓ, 2ℓ, τ

In total, 35 signal regions

- Aiming to cover $m(\tilde{\chi}_1^0)$ vs $m(\tilde{t})$ plane
- Largest excess 3.3σ





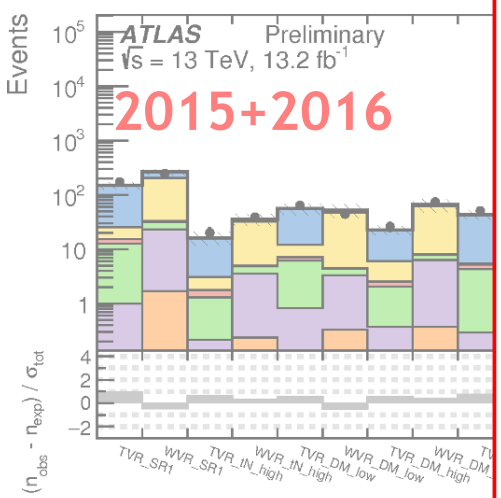
Stop Search: $\tilde{t}\to bW\tilde{\chi}_1^0$, $\tilde{t}\to t\tilde{\chi}_1^0$

Event topology: W

- Divide accordin

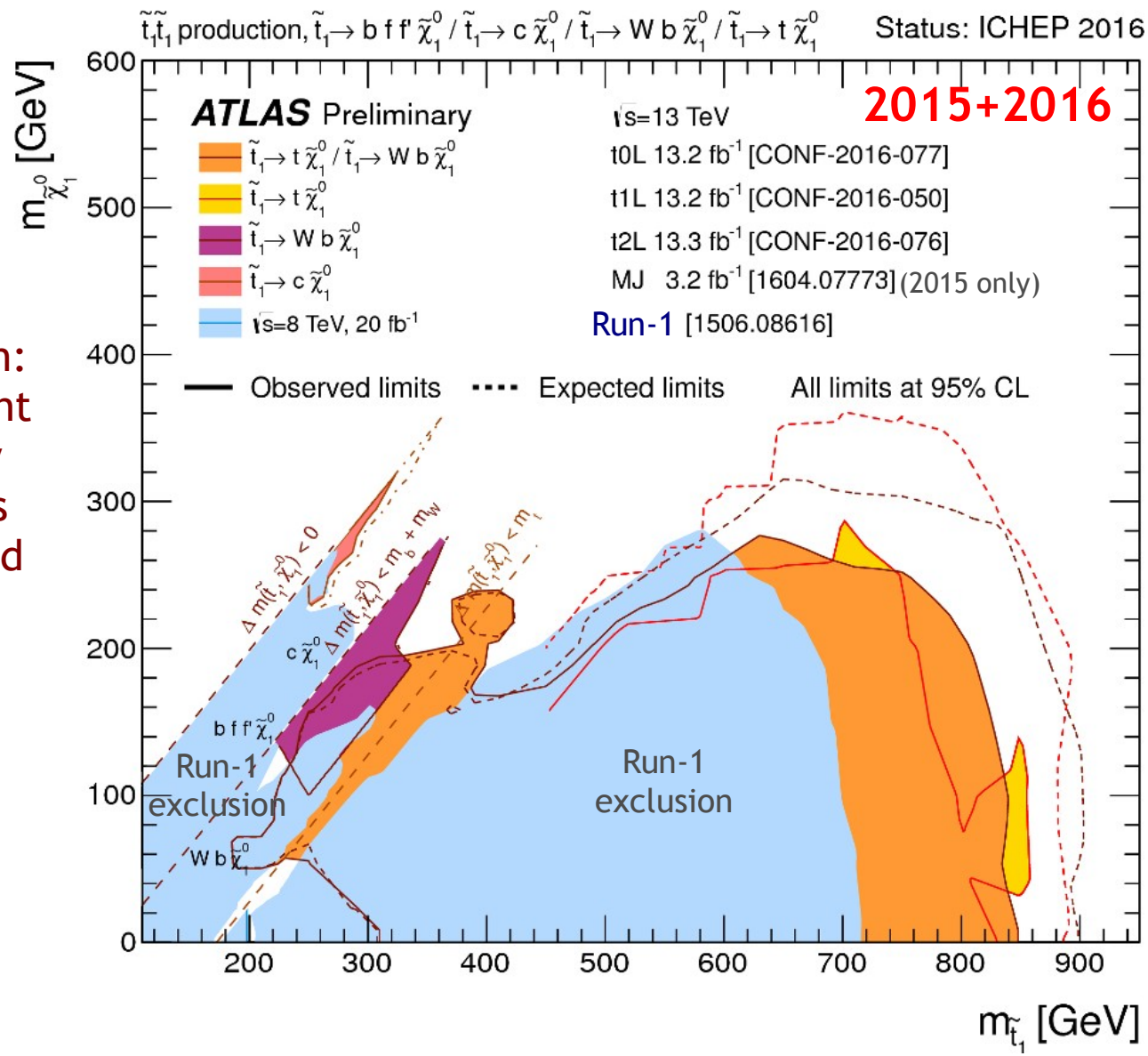
In total, 35 signal

- Aiming to cove
- Largest excess



validation regi

Caution: different decay modes overlaid



Stop Search: $\tilde{t}\to bW\tilde{\chi}_1^0$, $\tilde{t}\to t\tilde{\chi}_1^0$

Event topology: W

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- Aiming to cove
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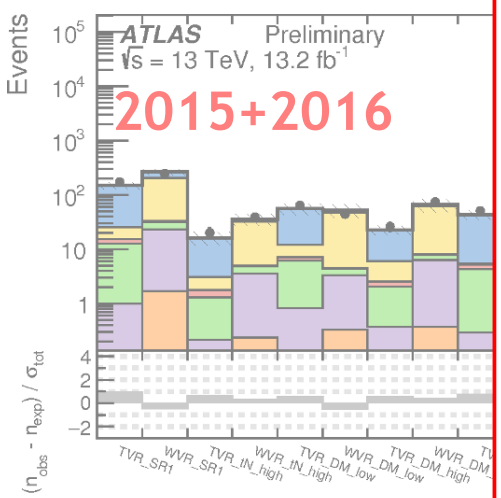

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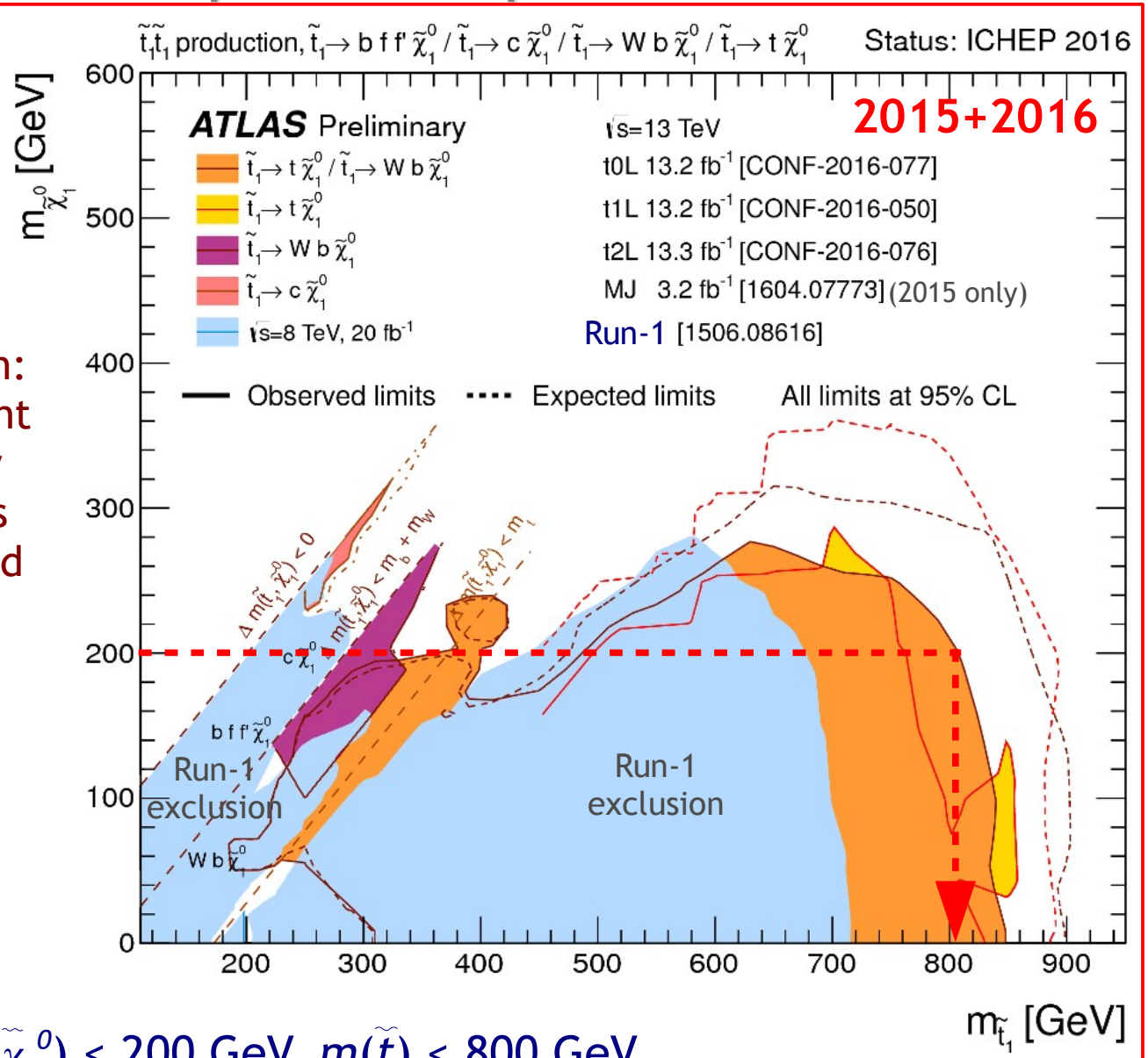
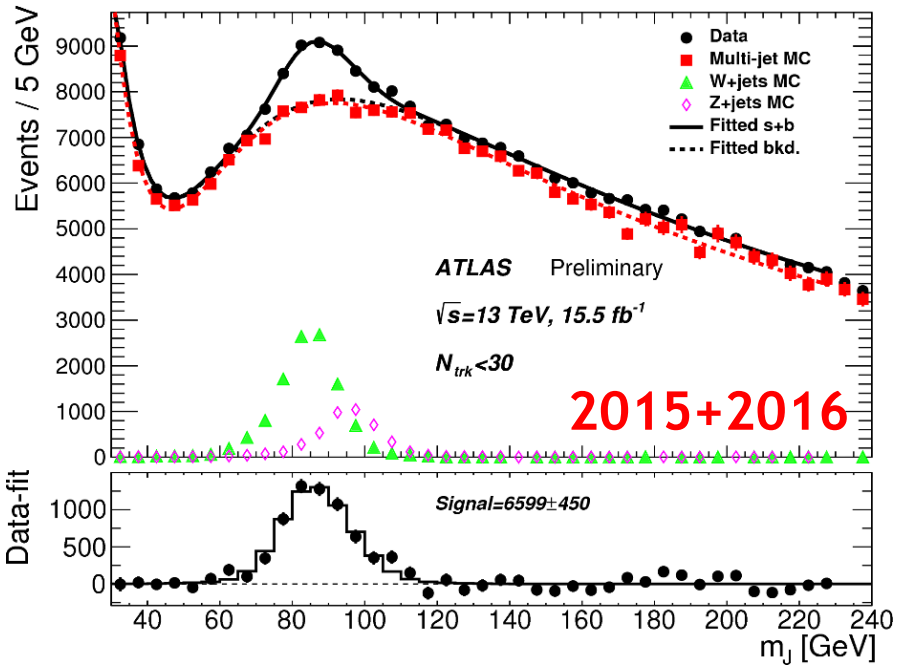


For $m(\tilde{\chi}_1^0)$ < 200 GeV, $m(\tilde{t})$ < 800 GeV excluded except in rather small regions

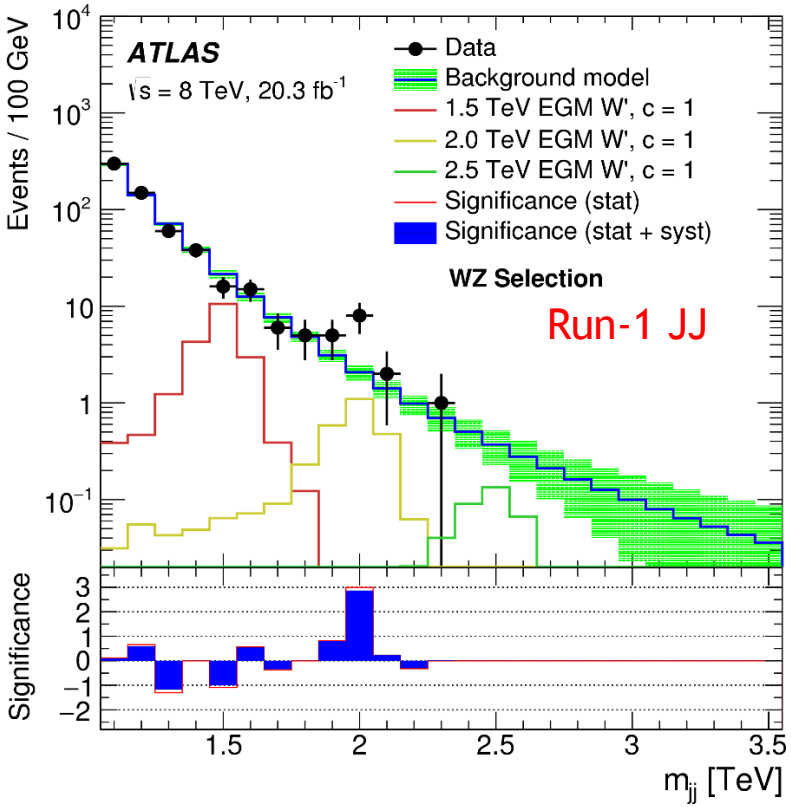
Massive Diboson Searches

Search for resonant di-boson production

- Boosted ("fat jet") selections vital at high-p_T
- Explored *many* channels with 2016 data



In-situ validation of performance:
Preselected fat jets with p_T(J)>500 GeV



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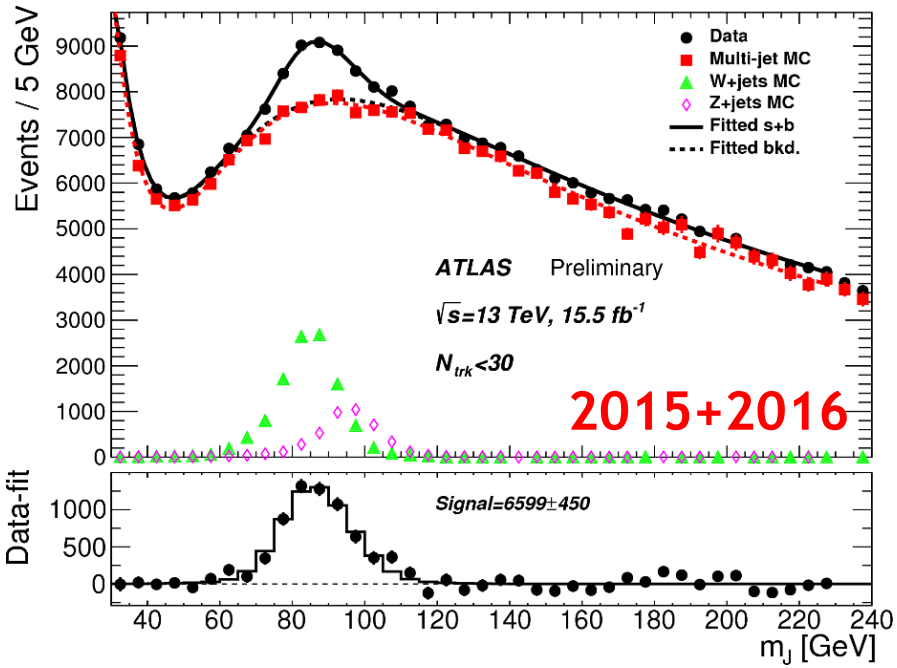

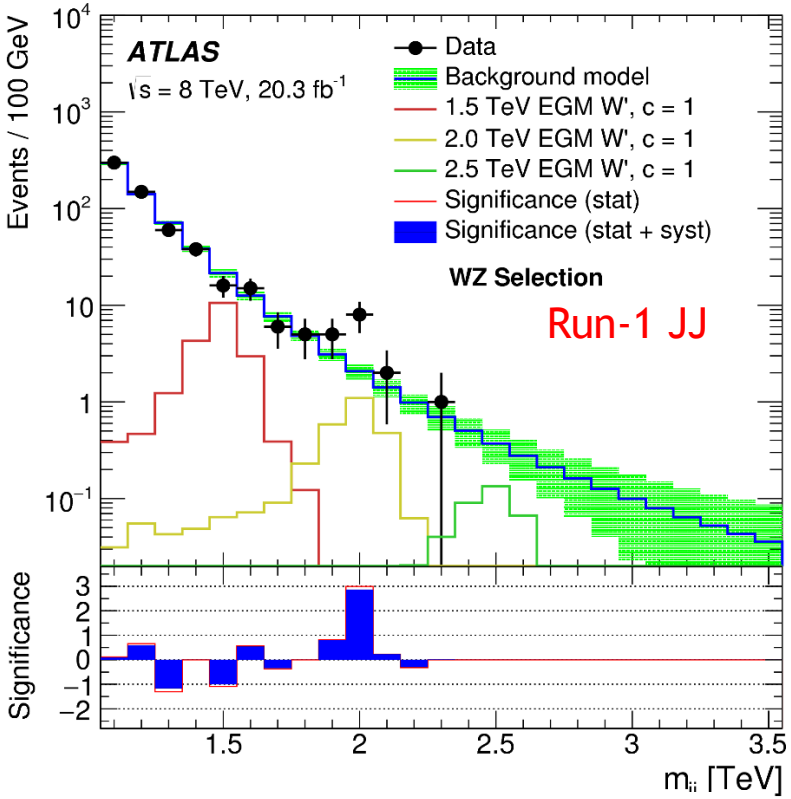

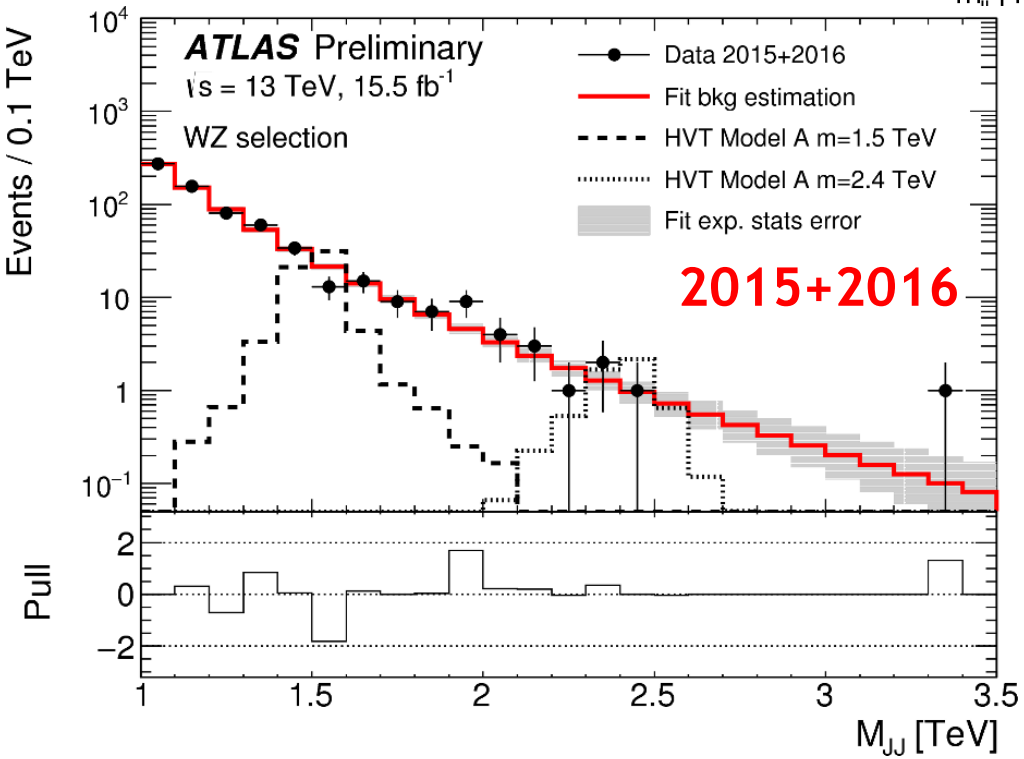

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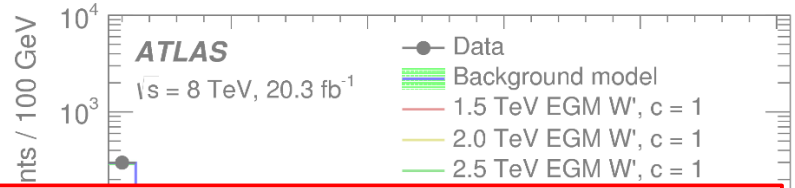
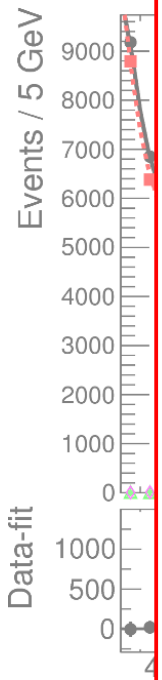
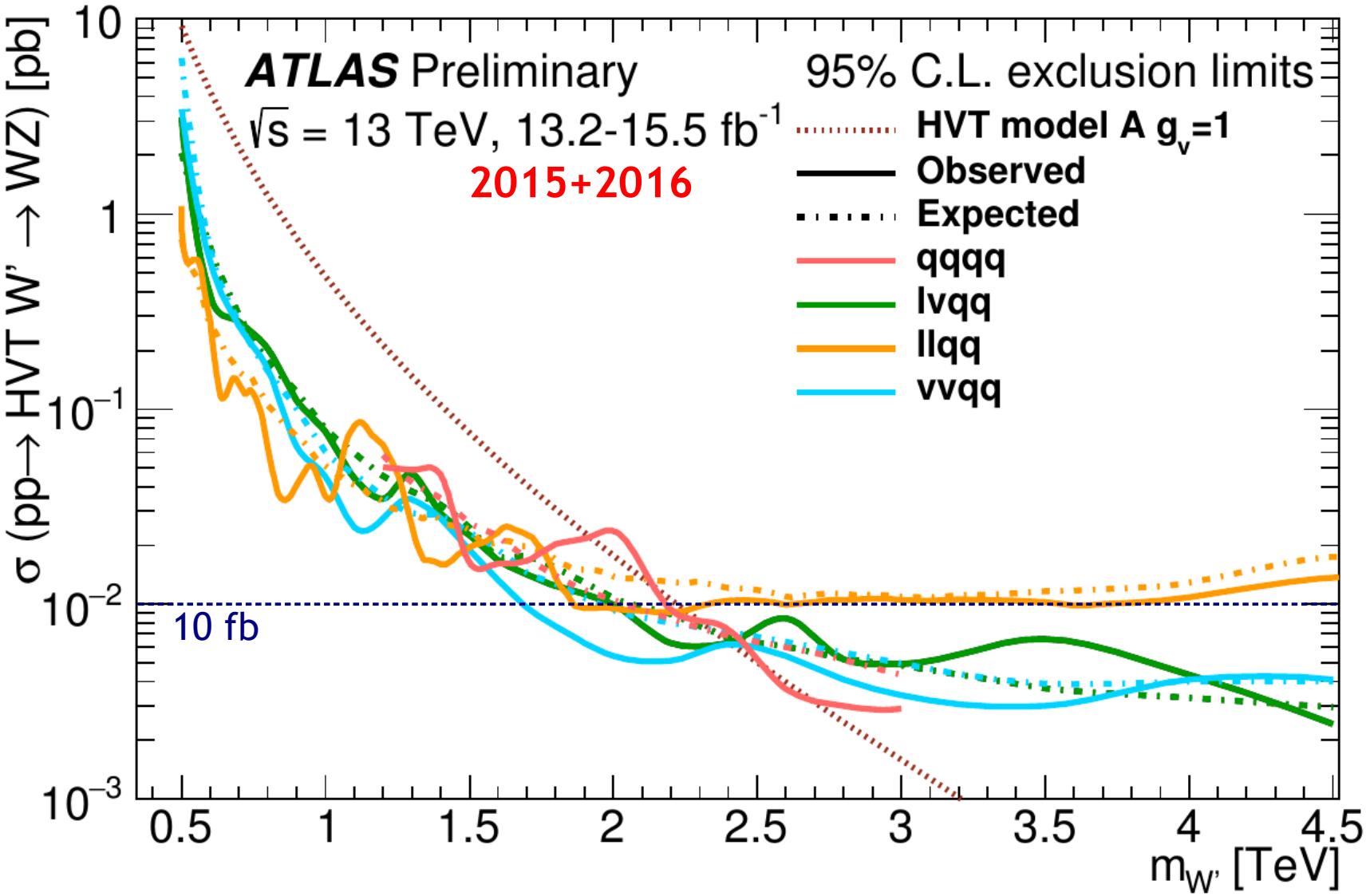


Sea

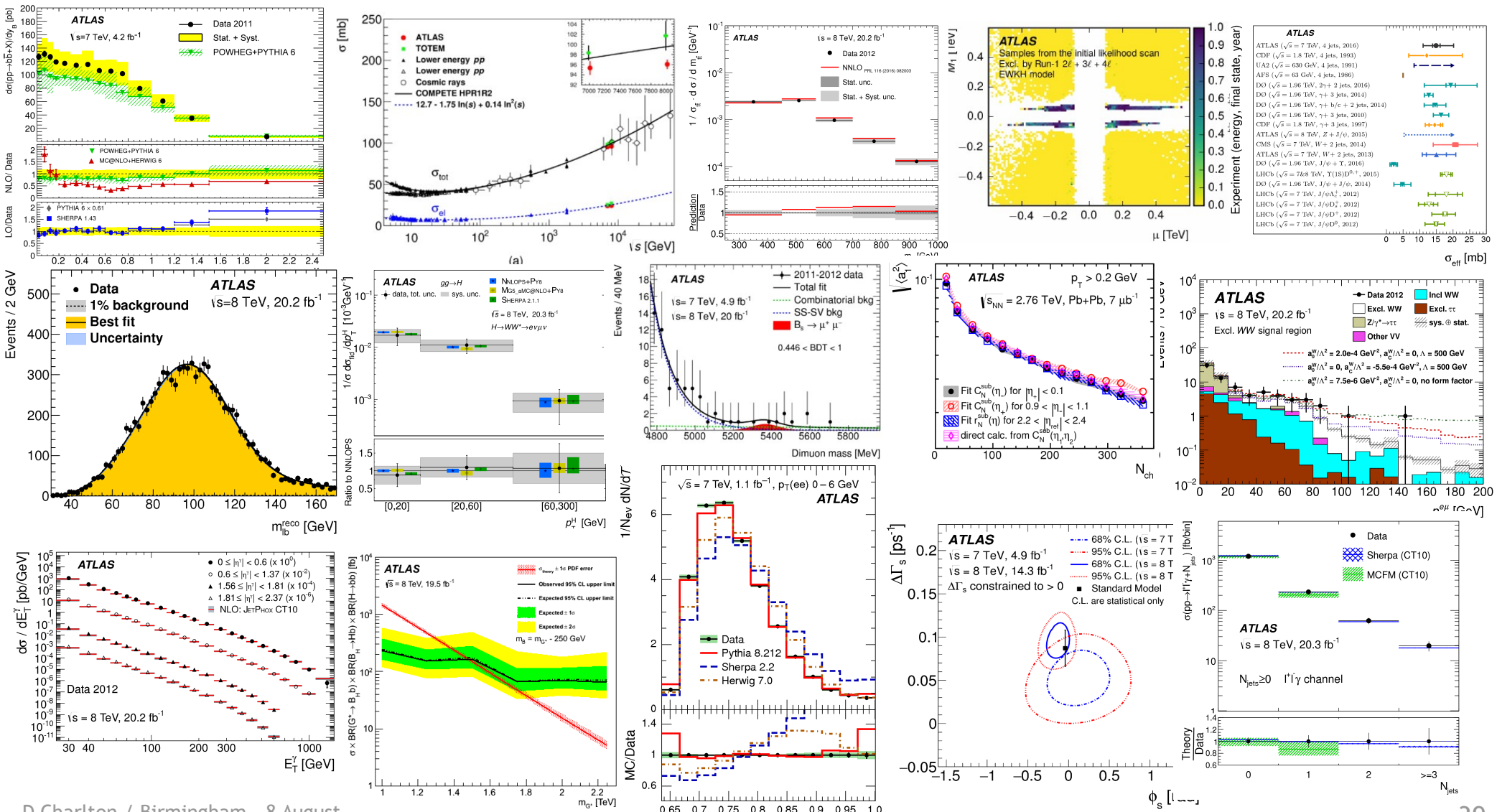




Overlaying limits from all WZ searches – no persistent excesses

A Small Selection

In total **64** new results prepared for ICHEP, **56** using 13 TeV data and **45** with 2015+2016
ATLAS has now submitted **40** papers with Run-2 data (**576** total with collision data)
The flood-tide of Run-1 results has not yet ebbed



Summary

LHC Run-2 is storming ahead!

Enhanced detectors and trigger systems working very well
- ATLAS coping well with pileup levels approaching twice design
- LHCb revised trigger system provides high-quality data very fast

Wealth of measurements already from 13 TeV data
- Simple and complex final-states
- Inclusive cross-sections to multi-boson, top, b-physics
- New probes of CP violation from LHCb
- Starting precise measurements of H(125) at 13 TeV
- Closing in on Standard Model ttH sensitivity

Exploring the 2016 data in many topologies
- Many complex searches with multiple signal regions probed
- No significant excesses, though some ~2-3σ effects ~ *as expected*
  - More data will tell which, if any, will remain

Huge thanks to the LHC and injector teams who are delivering this extraordinary 2016 data sample

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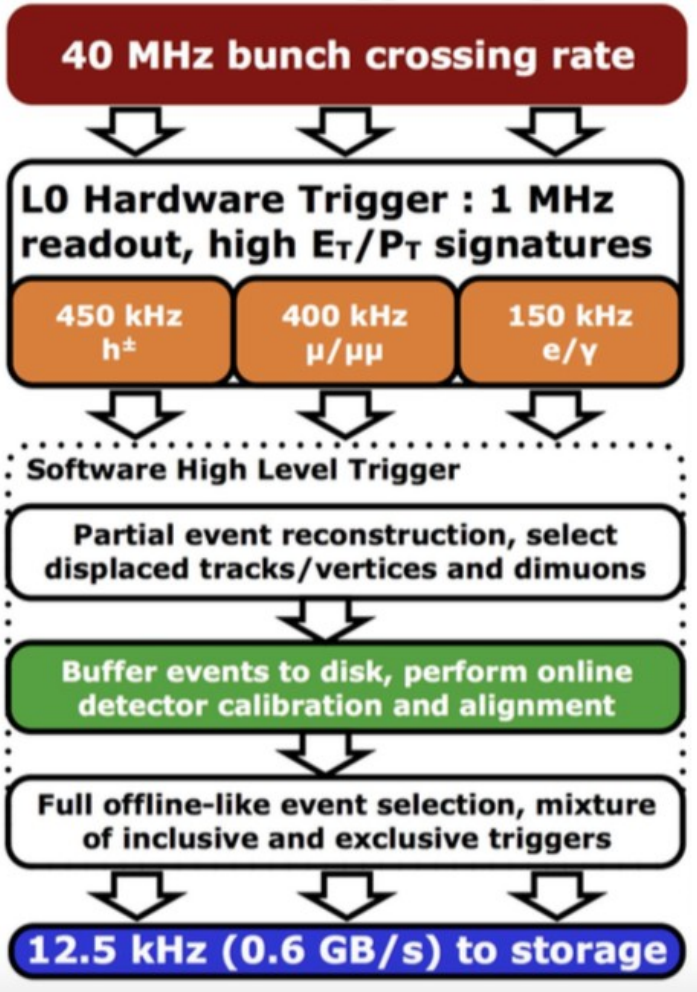
Bonus

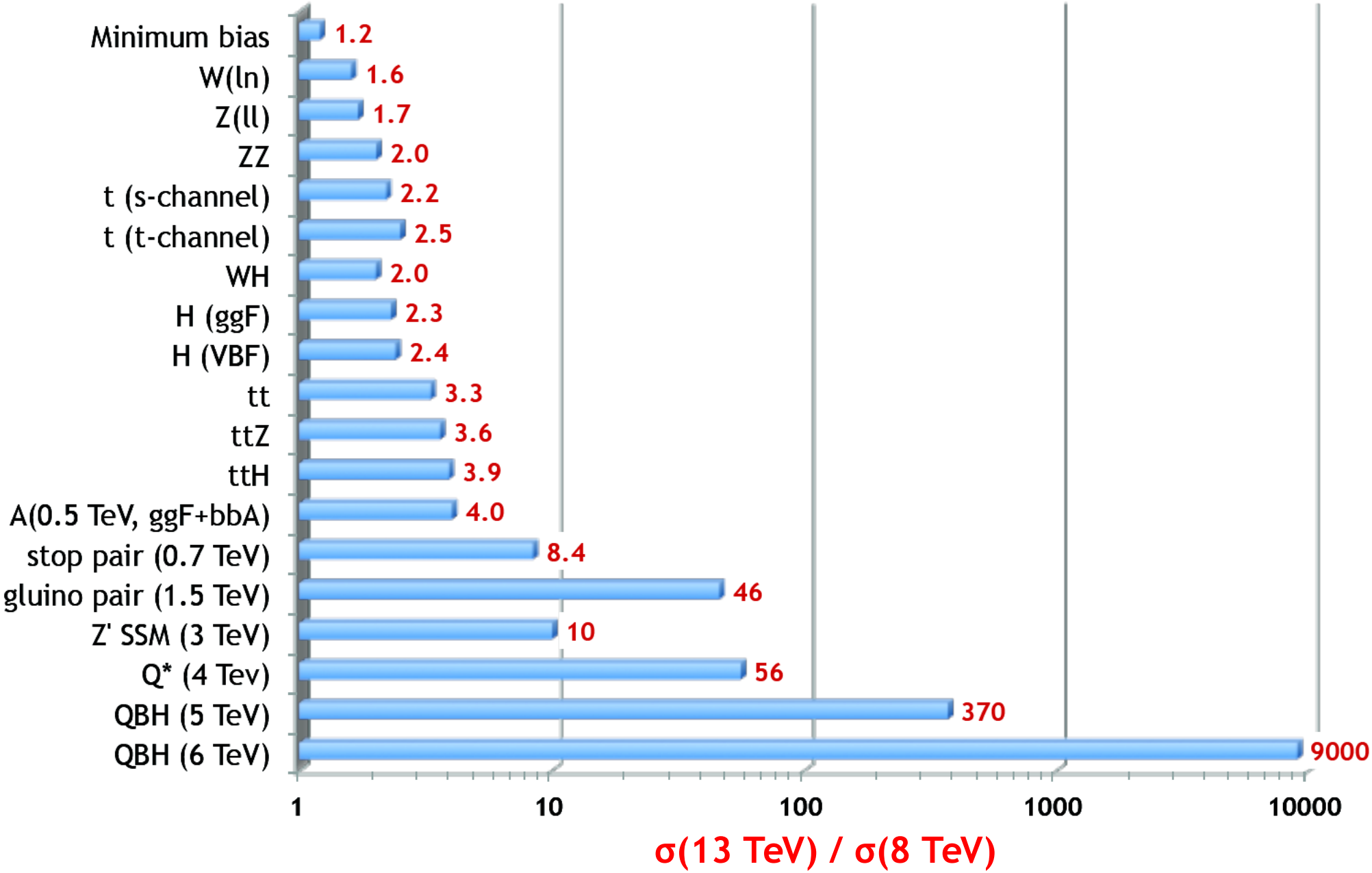
Improvements to LHCb in Run-2

- Radical changes to software trigger strategy
  - splitting the HLT into HLT1 and HLT2 steps
- HLT1 runs synchronously with data taking and performs a first looser selection
  - Events are then stored onto the local disks of the online computing farm (10 PB disk buffer)
- Automatic online calibration and alignment are performed and more selective HLT2 step is (mostly) run asynchronously in interfill/MD/TS periods
  - The new scheme leads to take high-quality data directly from the trigger output
- A further novelty is the Turbo trigger stream
  - Writes out a compact summary of "physics" objects containing all information necessary for analyses
  - Allows for an increased output rate and thus higher trigger efficiencies

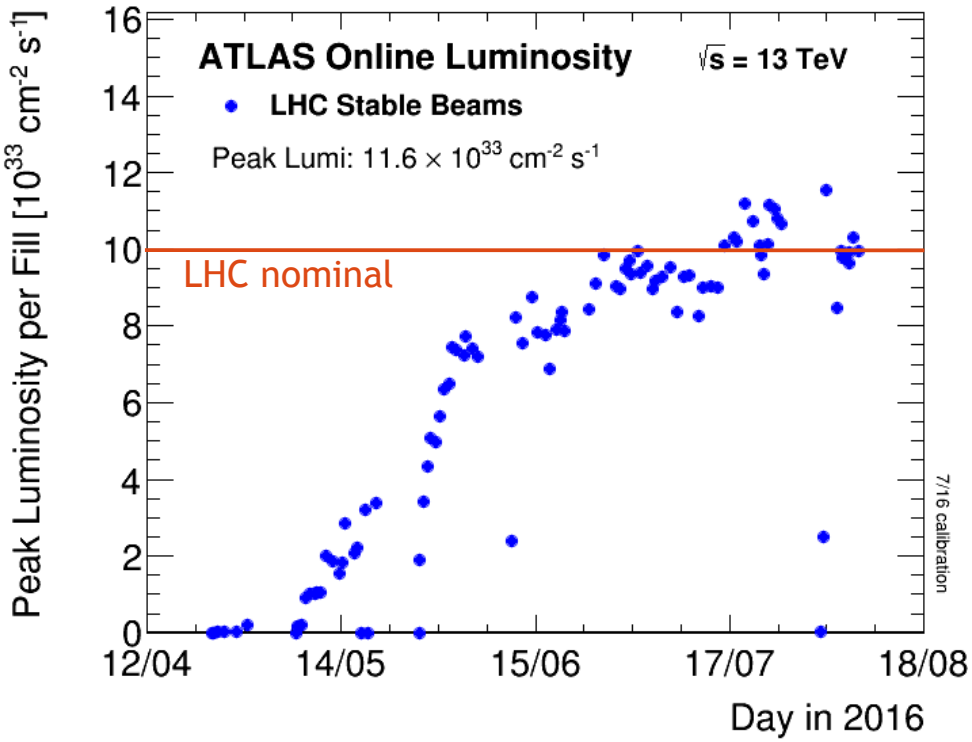


- New "Herschel" subdetector
  - System of forward shower counters (5 stations) located in the LHC tunnel up to maximum distance of ~114m in either side of the luminous region
  - Extends the rapidity coverage of the LHCb experiment in the high rapidity regions
  - Crucial for studies of diffractive physics and central exclusive production

Cross-section Increase 8→13 TeV

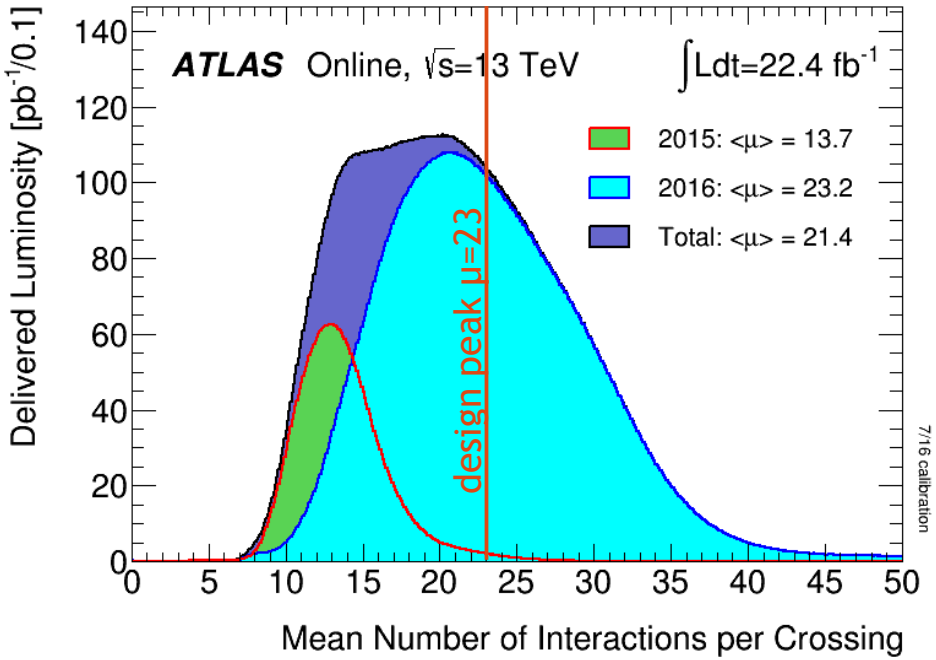


More than Nominal Luminosity



LHC design: $L = 10^{34}\ cm^{-2}\ s^{-1}$

Achieved: $L = 1.2 \times 10^{34}\ cm^{-2}\ s^{-1}$



Pileup often above LHC design in 2016

Many challenges

- Detectors (occupancies, SEUs ...)
- Trigger (thresholds, rates)
- Readout (bandwidth)
- Offline (Tier-0, Grid)

ATLAS has risen to meet these challenges!

Data Quality

Detector operational channel fractions remain at Run-1 levels

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	98.2%
SCT Silicon Strips	6.3 M	98.7%
TRT Transition Radiation Tracker	350 k	97.2%
LAr EM Calorimeter	170 k	100%
Tile calorimeter	5200	100%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.7%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	383 k	99.8%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	357 k	99.7%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Chambers	383 k	96.6%
TGC Endcap Muon Chambers	320 k	99.6%
ALFA	10 k	99.9 %
AFP NEW for 2016	188 k	98.8 %

Data quality good, with occasional short toroid-off periods (power glitches)

ATLAS pp 25ns run: April-July 2016

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
98.9	99.9	100	99.8	100	99.6	99.8	99.8	99.8	99.7	93.5

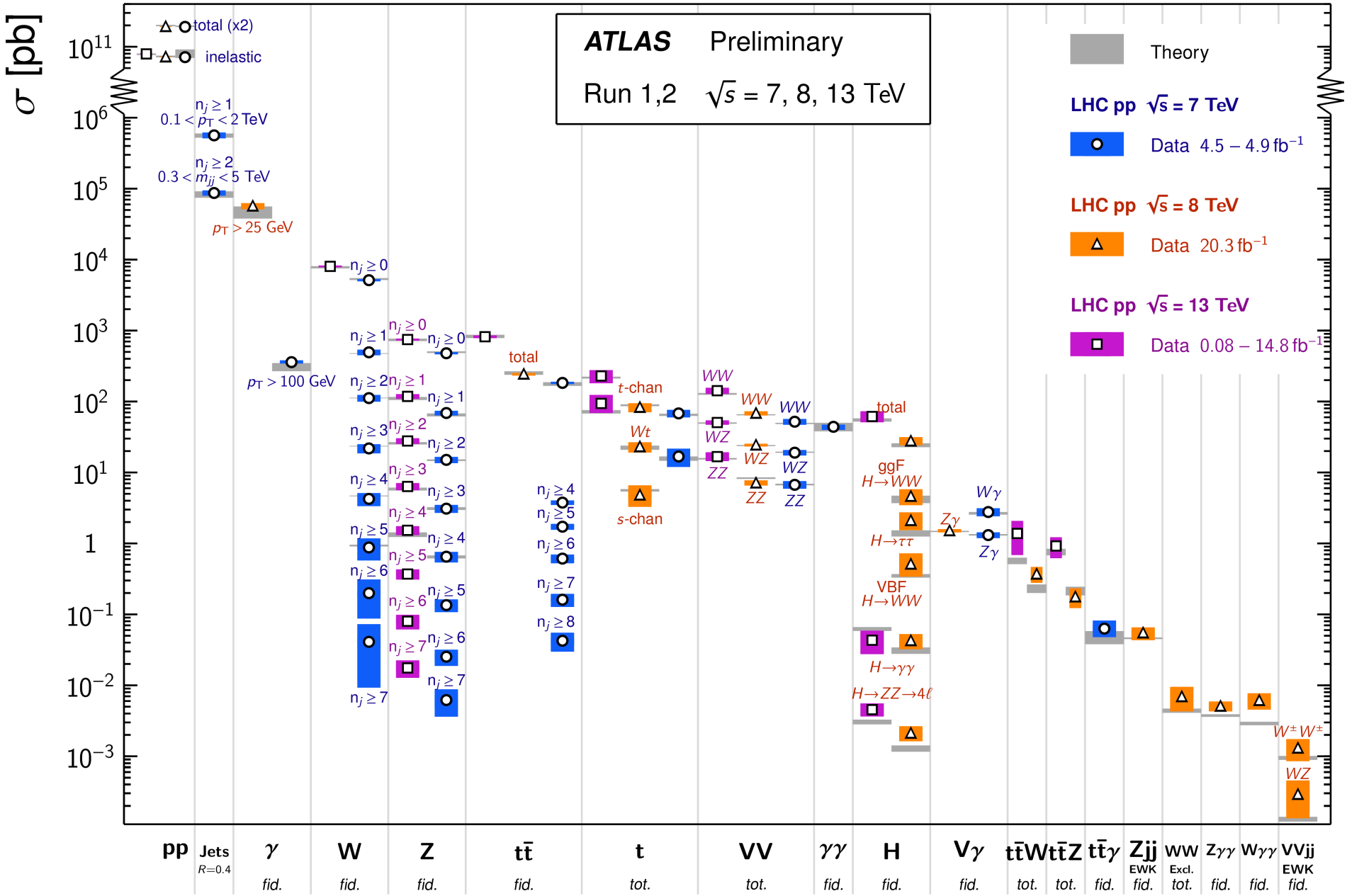
Good for physics: 91-98% (10.1-10.7 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between 28th April and 10th July 2016, corresponding to an integrated luminosity of 11.0 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

Inclusive Cross-Sections

Standard Model Production Cross Section Measurements

Status: August 2016



Massive Diboson Production

Run-1 puzzle to describe inclusive diboson cross-sections

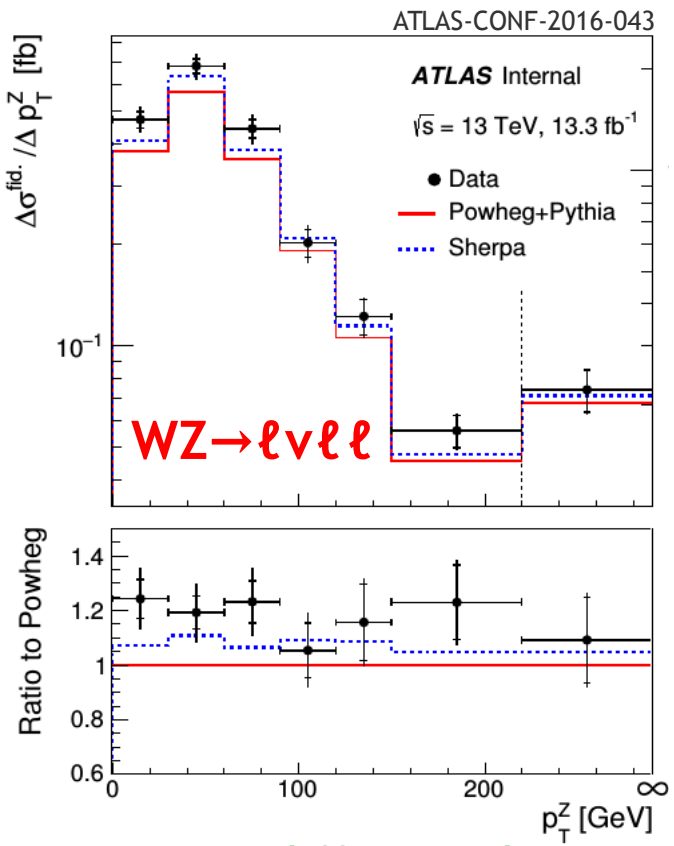
- Measurements tended to lie above NLO calculations

NNLO calculations → ~20% corrections and better agreement

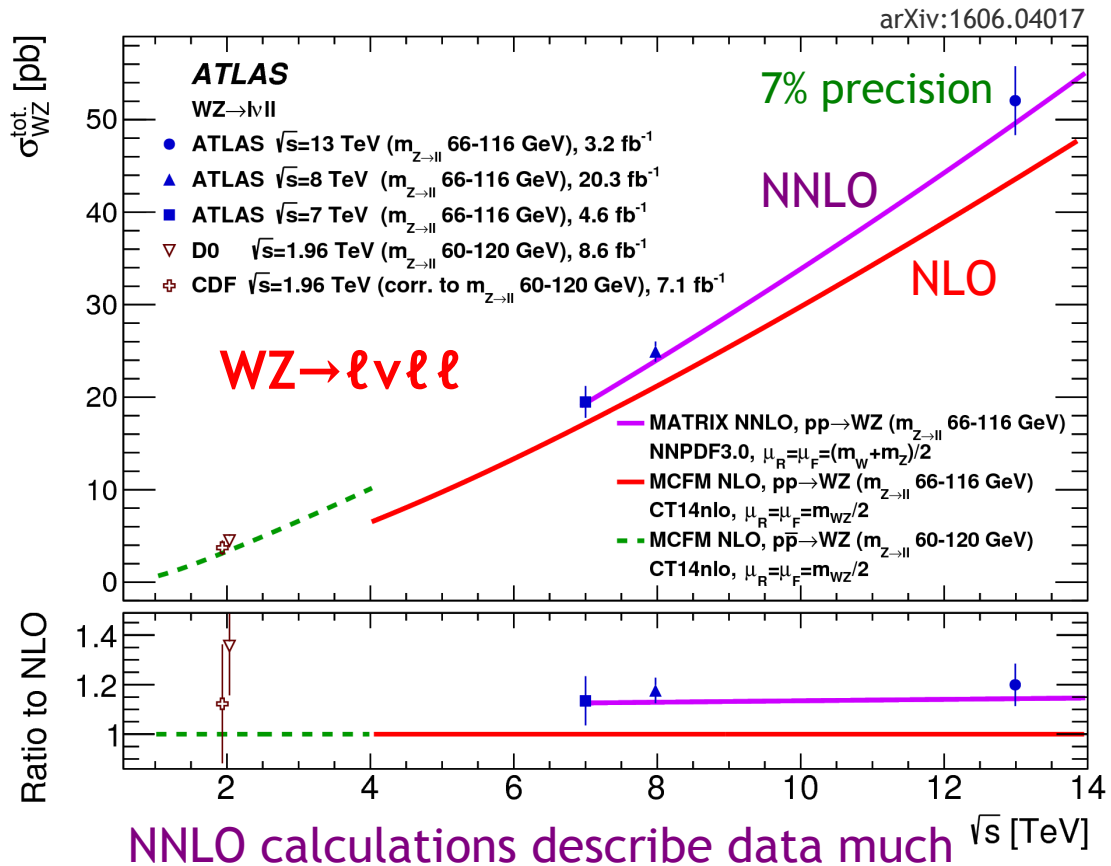
Presented measurements at 13 TeV of WW, WZ, ZZ leptonic channels

One example: WZ→ℓνℓℓ

(inclusive, differential cross-section measurements, triple gauge coupling limits)



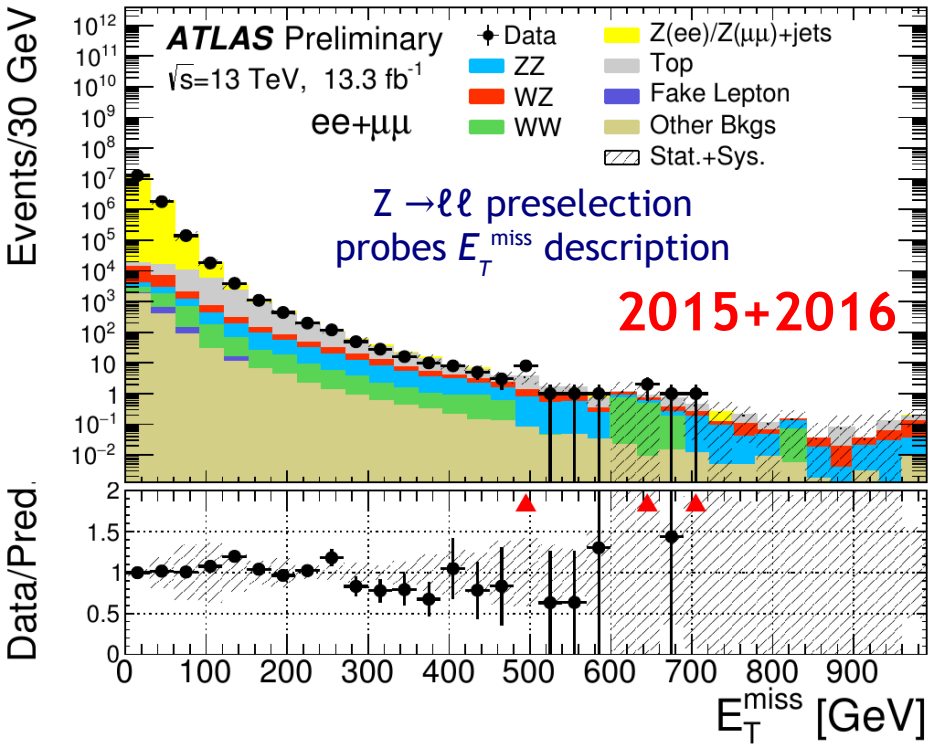
Cross-section differential in $p_T(Z)$

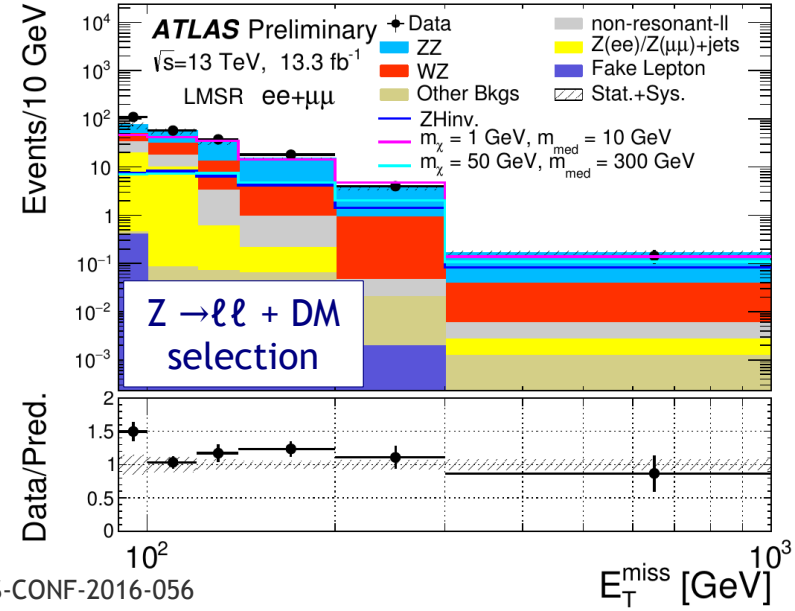


NNLO calculations describe data much better than NLO

Dark Matter Searches

Range of searches for weakly-interacting dark matter production in association with other identified particles, including SUSY-search derived analyses





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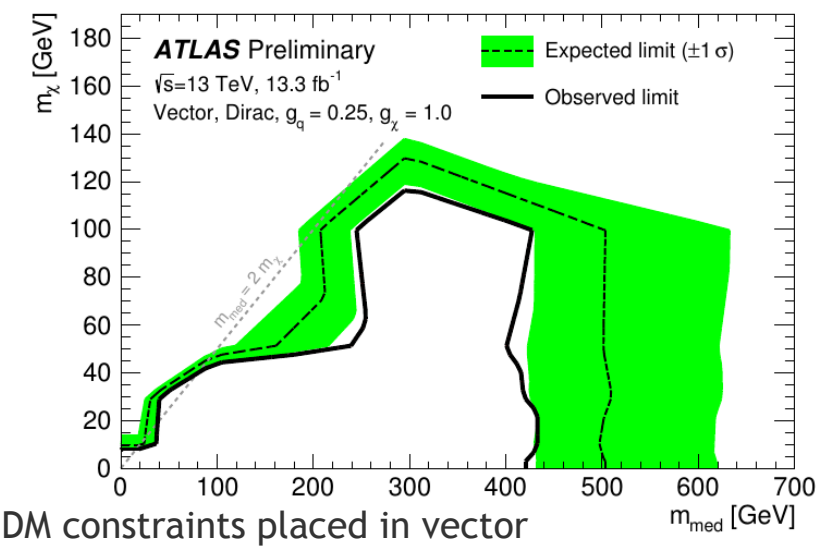


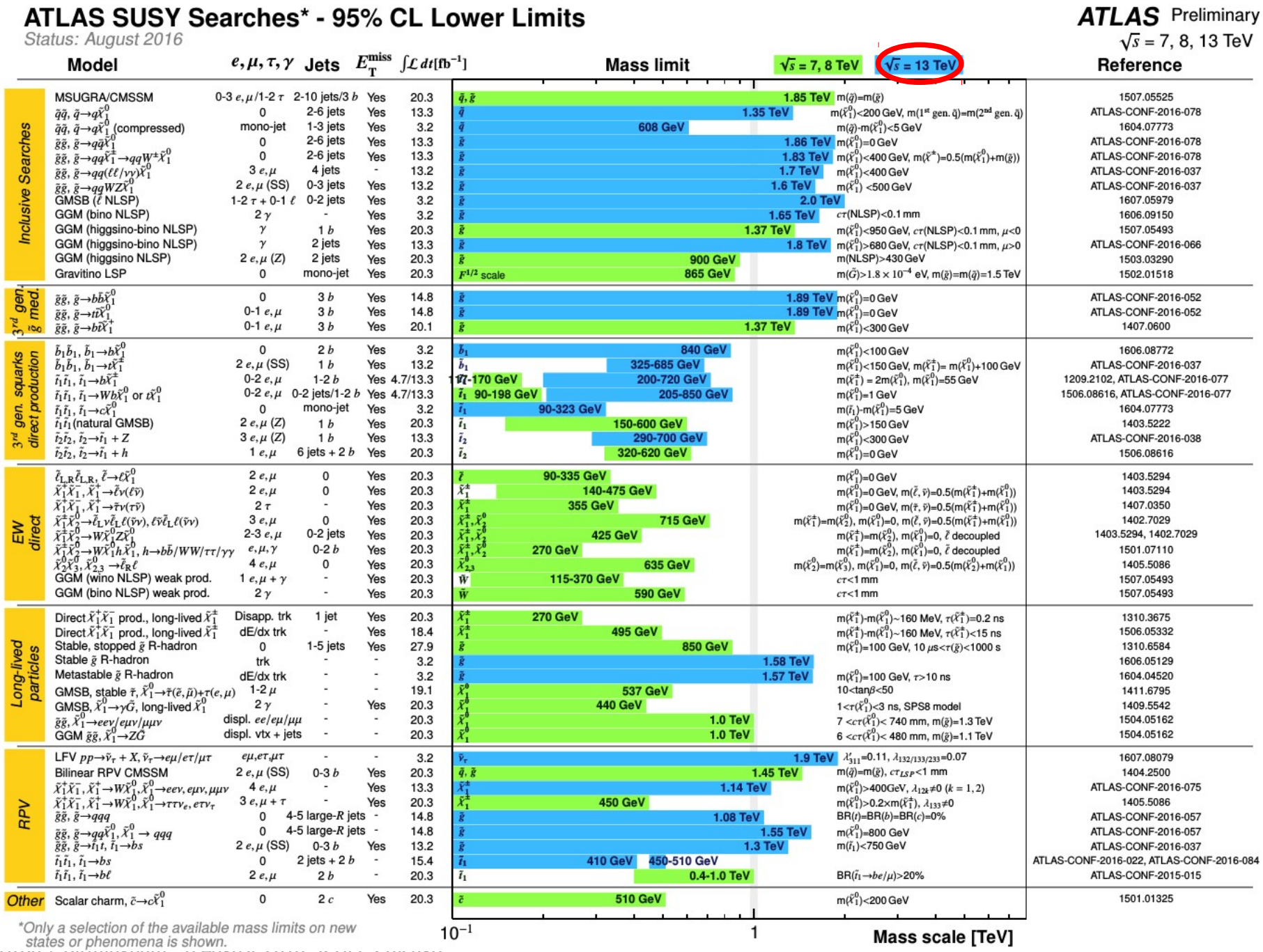
DM constraints placed in vector mediator model from arXiv: 1507.00966

$(Z \to \ell\ell) + E_T^{miss}$ analysis sensitive to

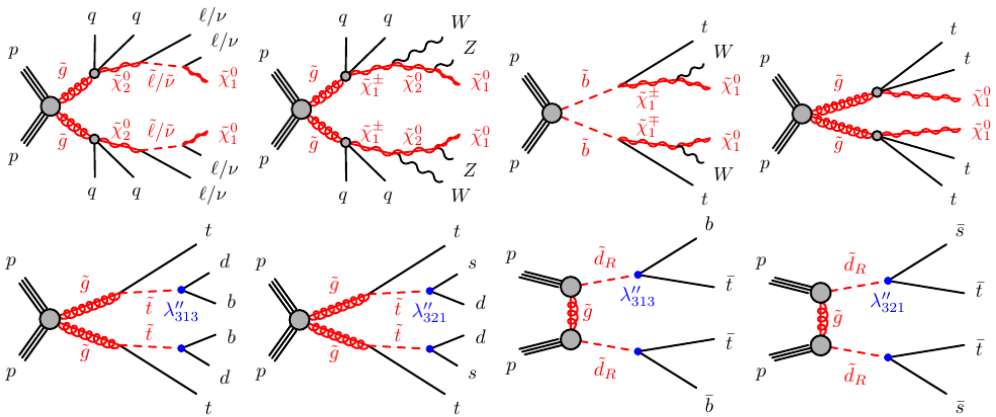
- Z+DM production
- ZH production with H→invisibles
- Resonant ZZ→ℓℓνν

Main SM background ZZ →ℓℓνν

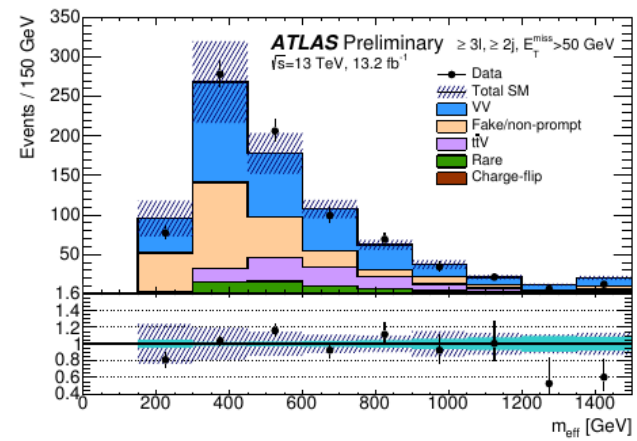
SUSY Summary (selection)

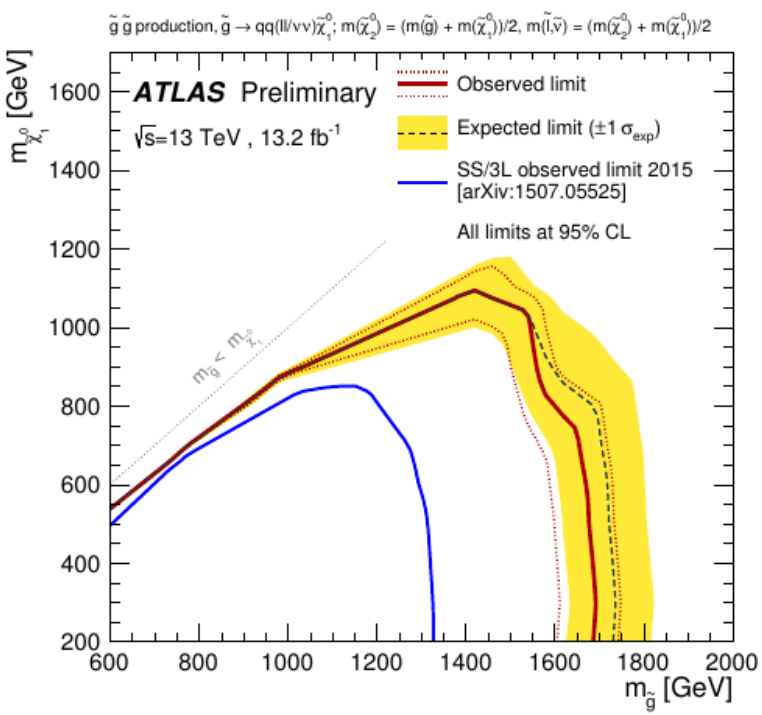


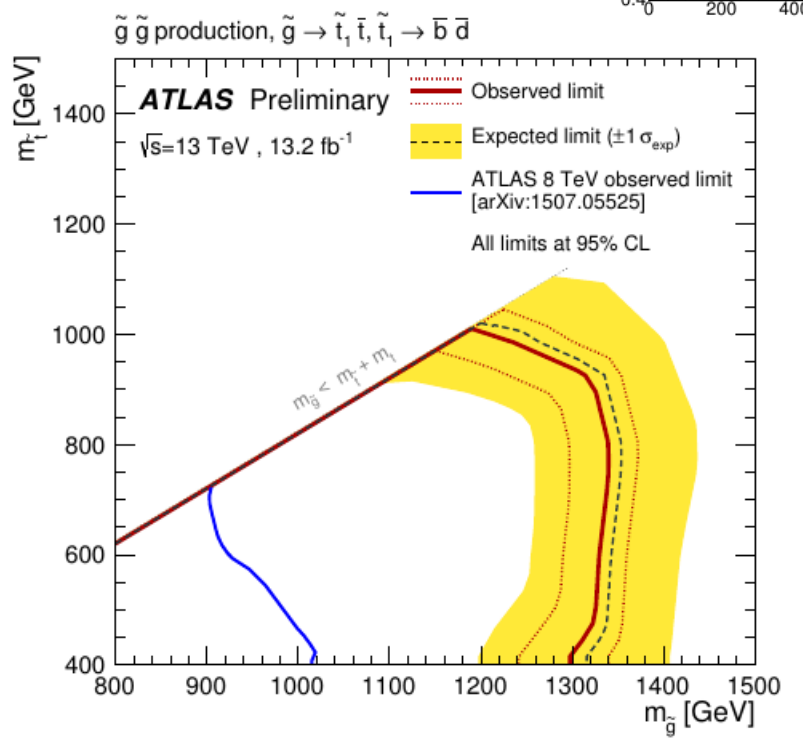
SUSY ℓ±ℓ± / 3ℓ



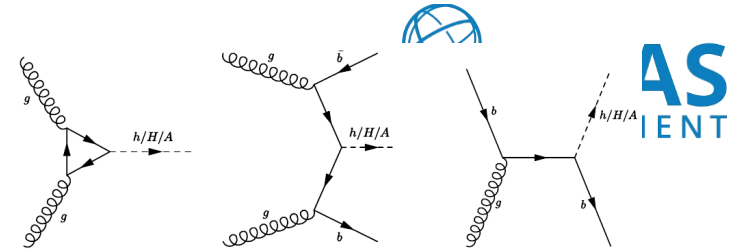
Large number of signal regions aiming at strong production and both RPC and RPV models





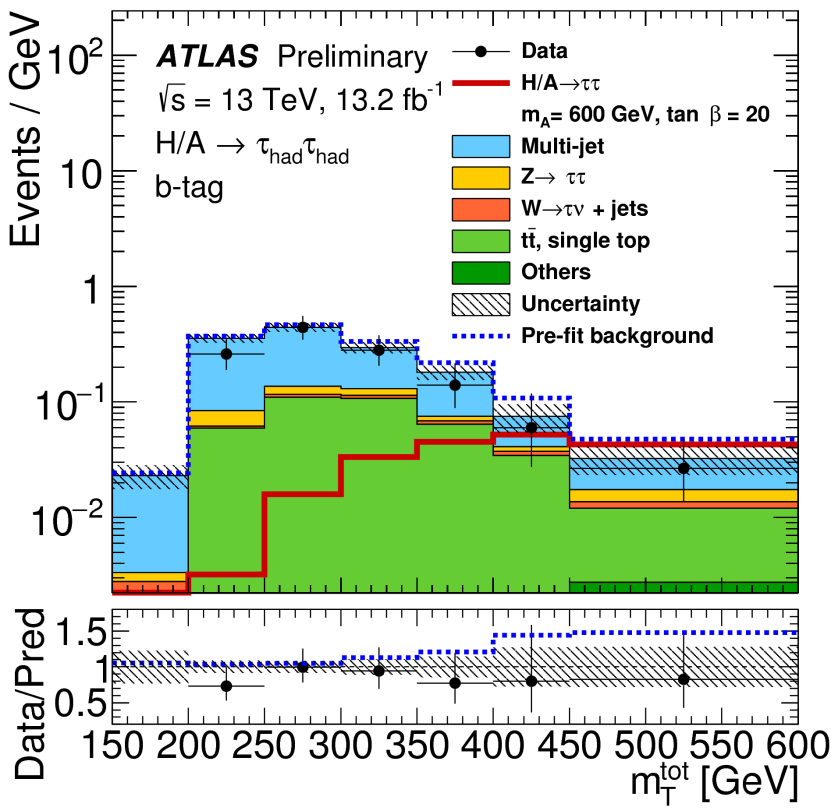


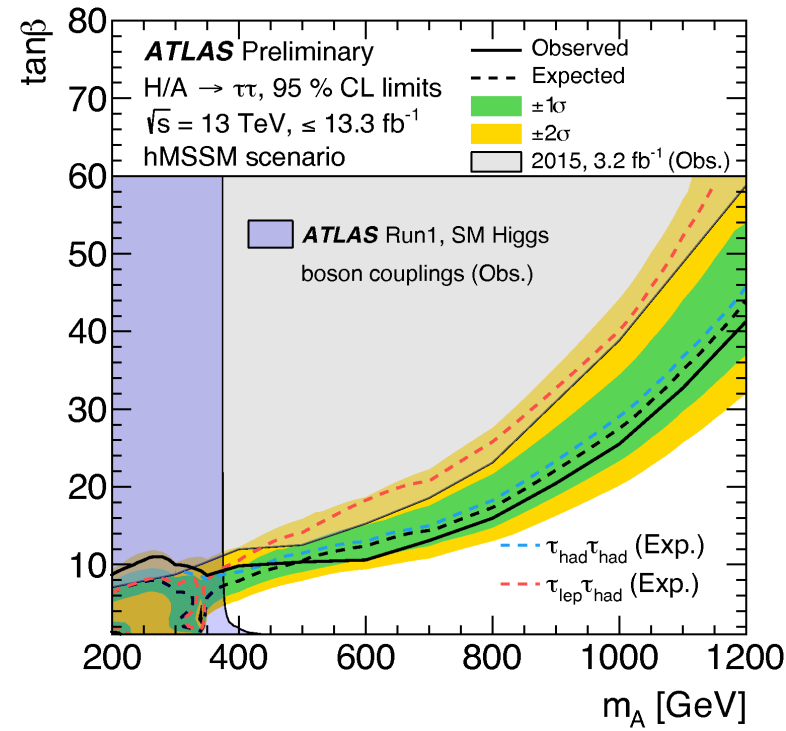
H/A → ττ



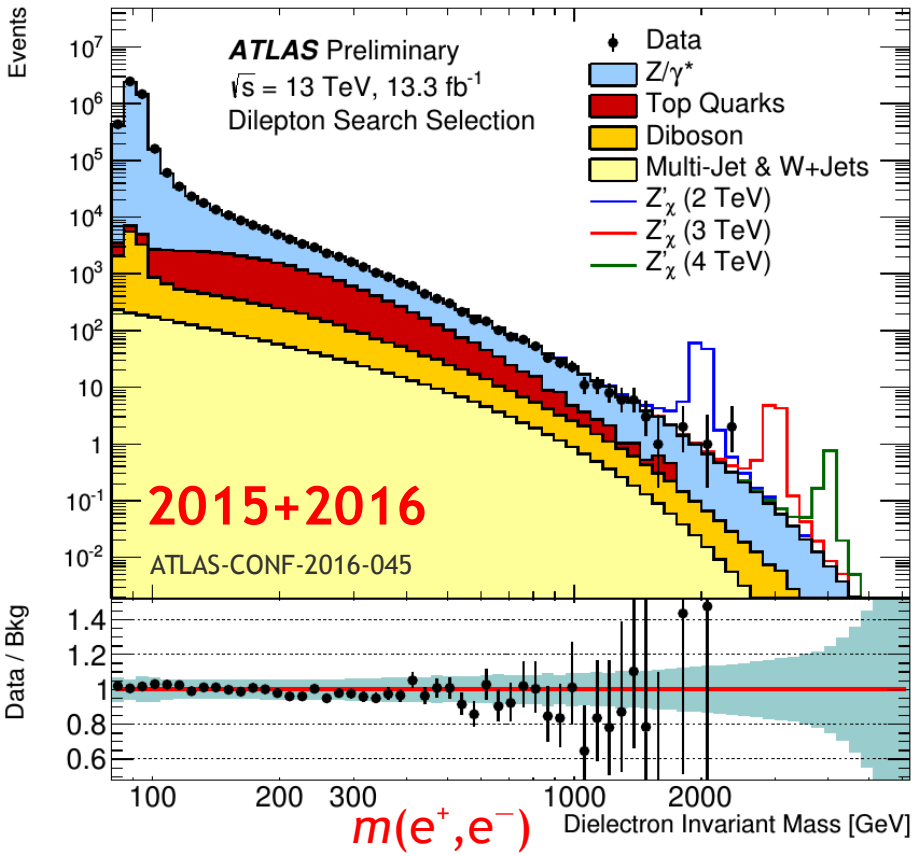
Search for anomalous high mass ττ production from additional high-mass scalar in various MSSM models

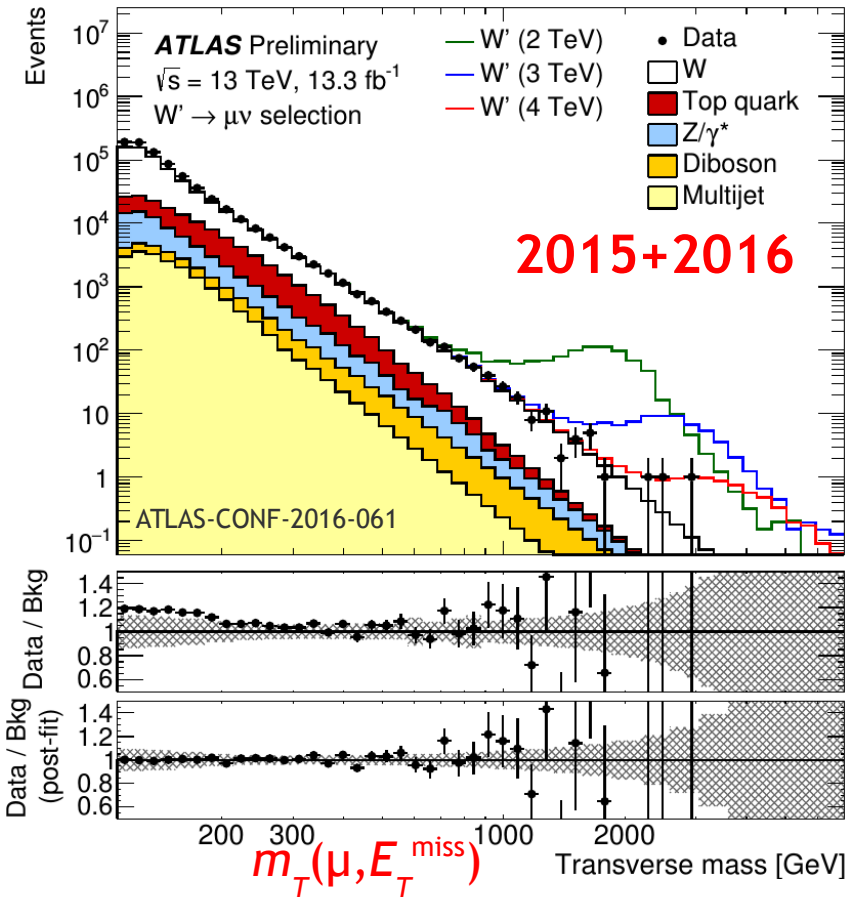
- Lepton+hadron and hadron-hadron tau-tau decay modes
- Signal regions with/without b-tags, and high-Etmiss in l-h modes

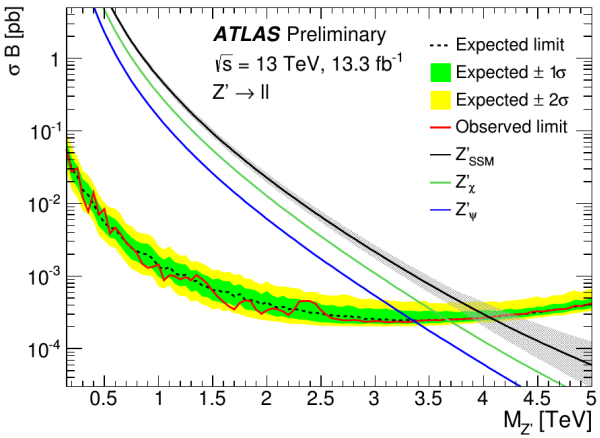




Dilepton Resonance Searches

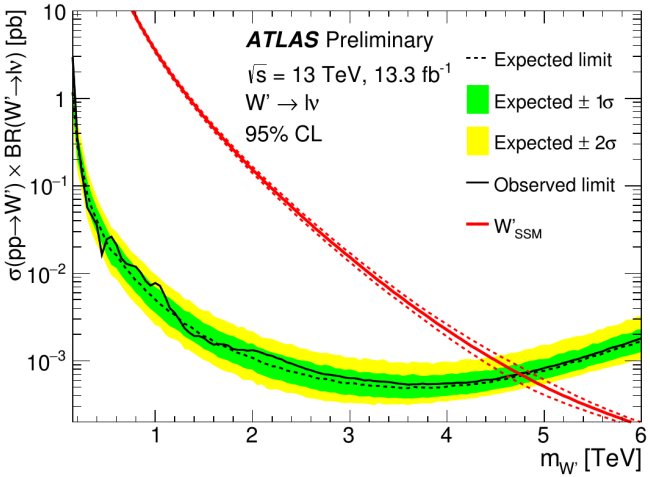




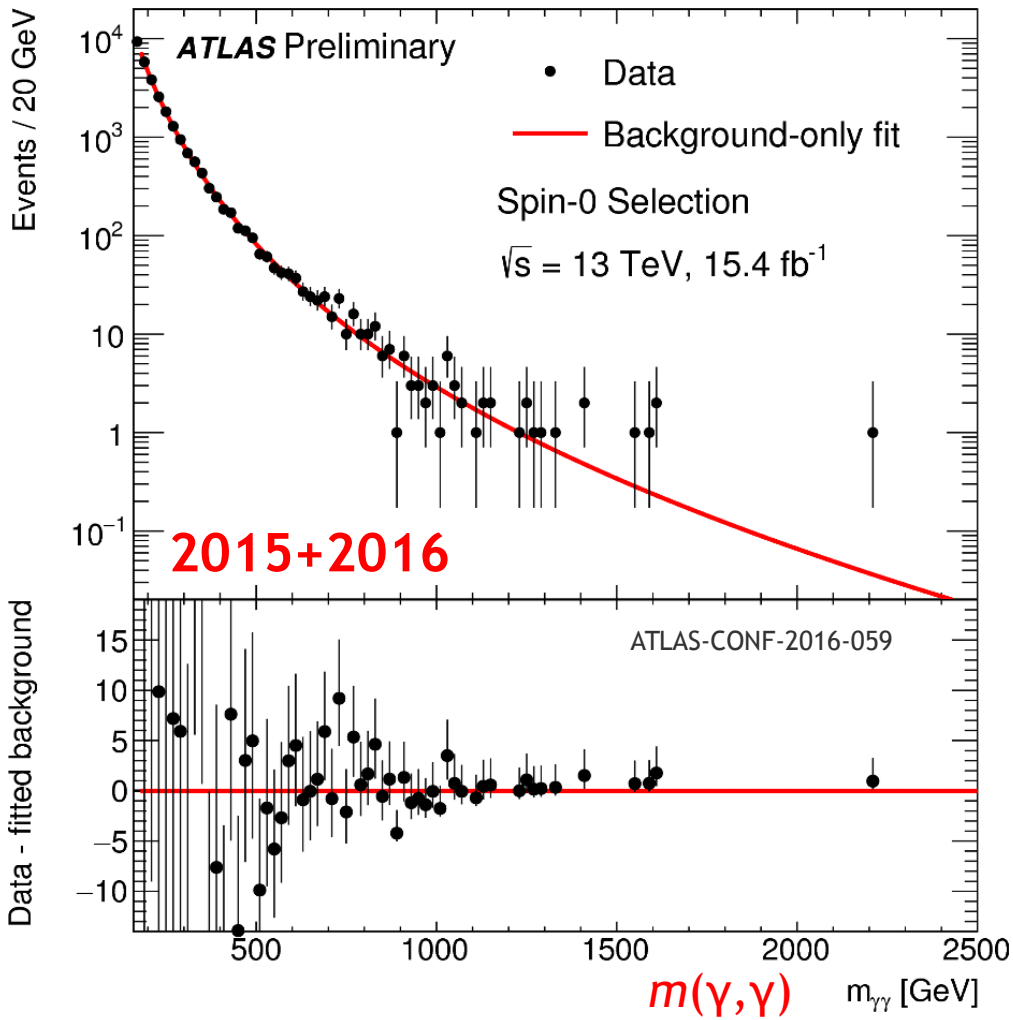


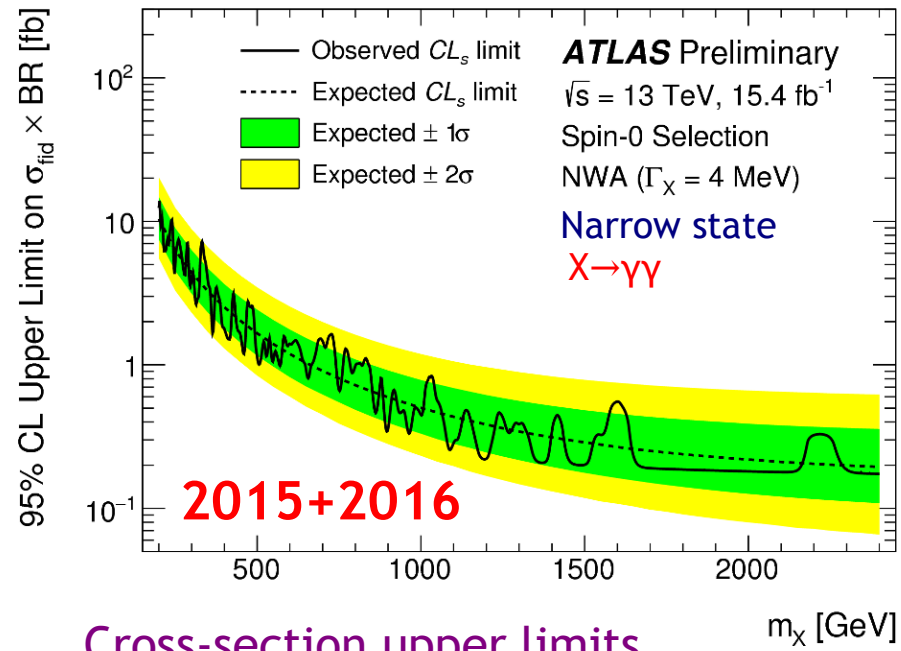
Z'$_{SSM}$ (@95%CL)
m > 4.05 TeV
(Run-1 m>2.90 TeV)

W' (@95%CL)
m > 4.74 TeV
(Run-1 m>3.24 TeV)

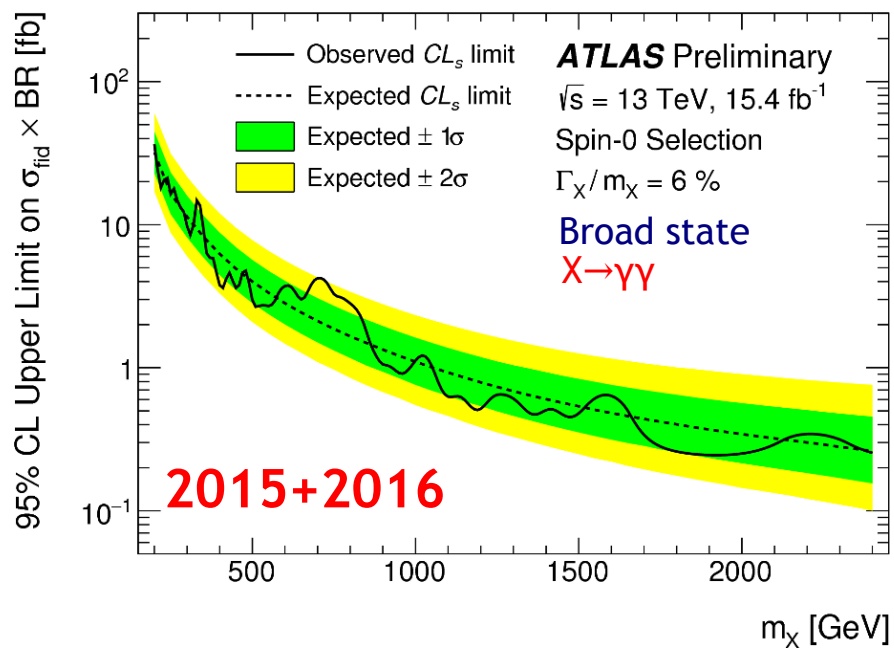


Diphoton Search Limits





Cross-section upper limits



With 2015+2016 data:

- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

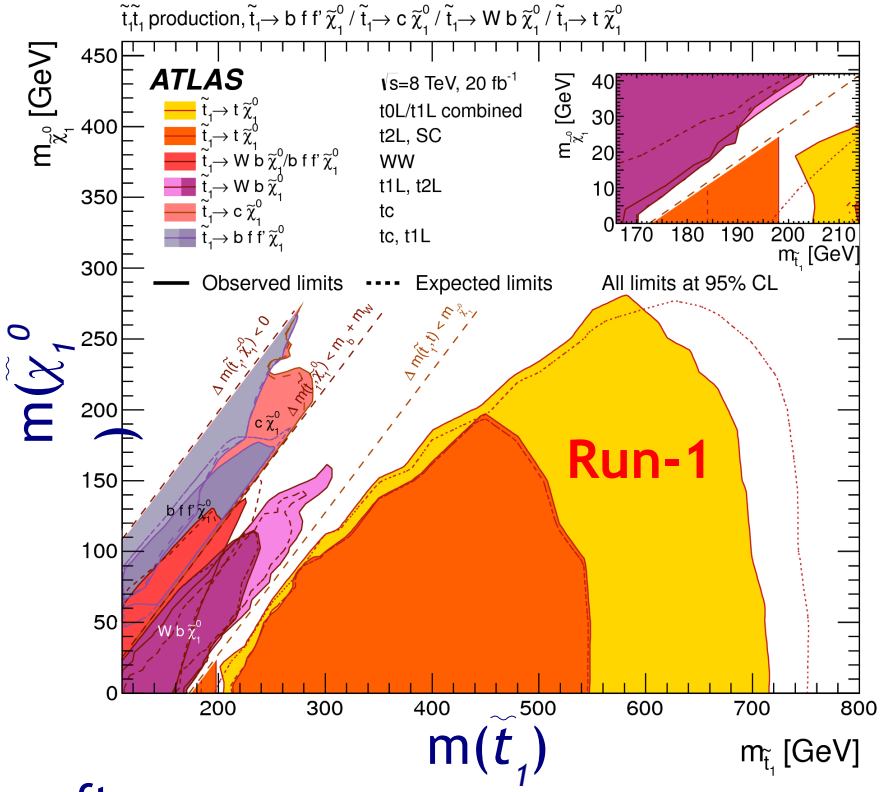
SUSY Searches

The case for SUSY is well known

- Natural DM candidate in $\tilde{\chi}_1^0$
- Can solve the fine-tuning problem – if $\tilde{t}$ and $\tilde{g}$ are light

From Run-1

- $m(\tilde{g})$ > 1.4 TeV for low mass $\tilde{\chi}_1^0$
- $m(\tilde{t}_1)$ > 700 GeV if $m(\tilde{\chi}_1^0)$ < 100 GeV



Major goals for the Run-2 data:

- Extend mass reach (√s)
- Fill "kinematic holes" where particles are soft
- "Leave no stone unturned" - displaced decays, heavy massive particles …

Standard ATLAS approach in many searches:

- Focus on specific signatures, using simplified models to guide optimisation
- Data-driven backgrounds: multiple control regions to normalise MC predictions, help constrain systematic uncertainties
- Validation regions: verify background descriptions
- Signal regions: sensitivity!