Lawrence Berkeley National Laboratory

Highlights from the ATLAS experiment at the LHC

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on behalf of the ATLAS Collaboration

Brookhaven Forum 2017

In search of New Paradigms

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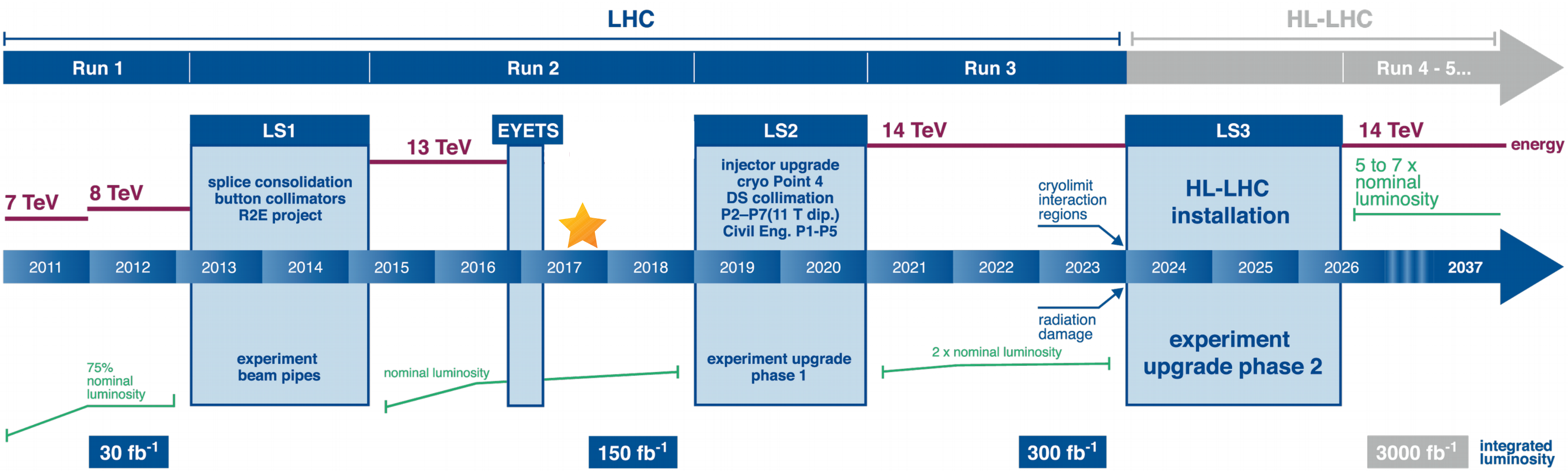
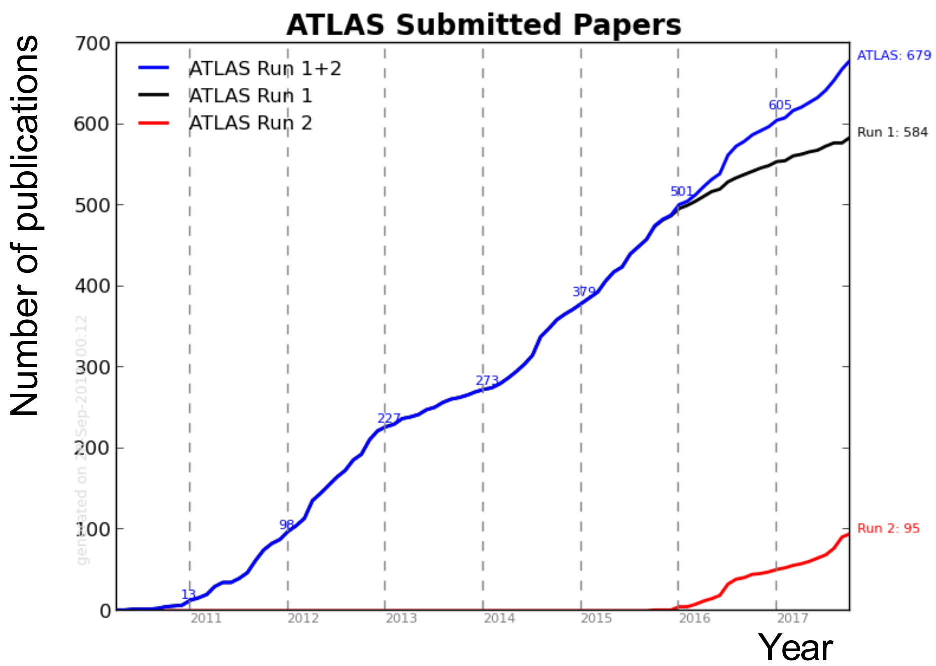
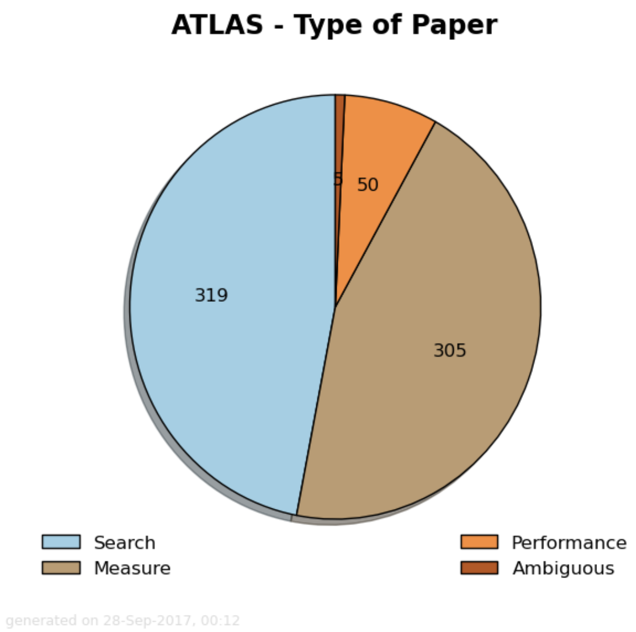
Outline

- The ATLAS experiment: overview
  - Challenges and recent highlights
- Physics results highlights
  - Standard Model and Higgs measurements
  - Search for physics beyond the Standard Model
- A look into the future: High-Luminosity LHC physics reach



- Large scientific output
  - > 600 papers submitted for publication
  - > 100 papers + preliminary results released only in 2017

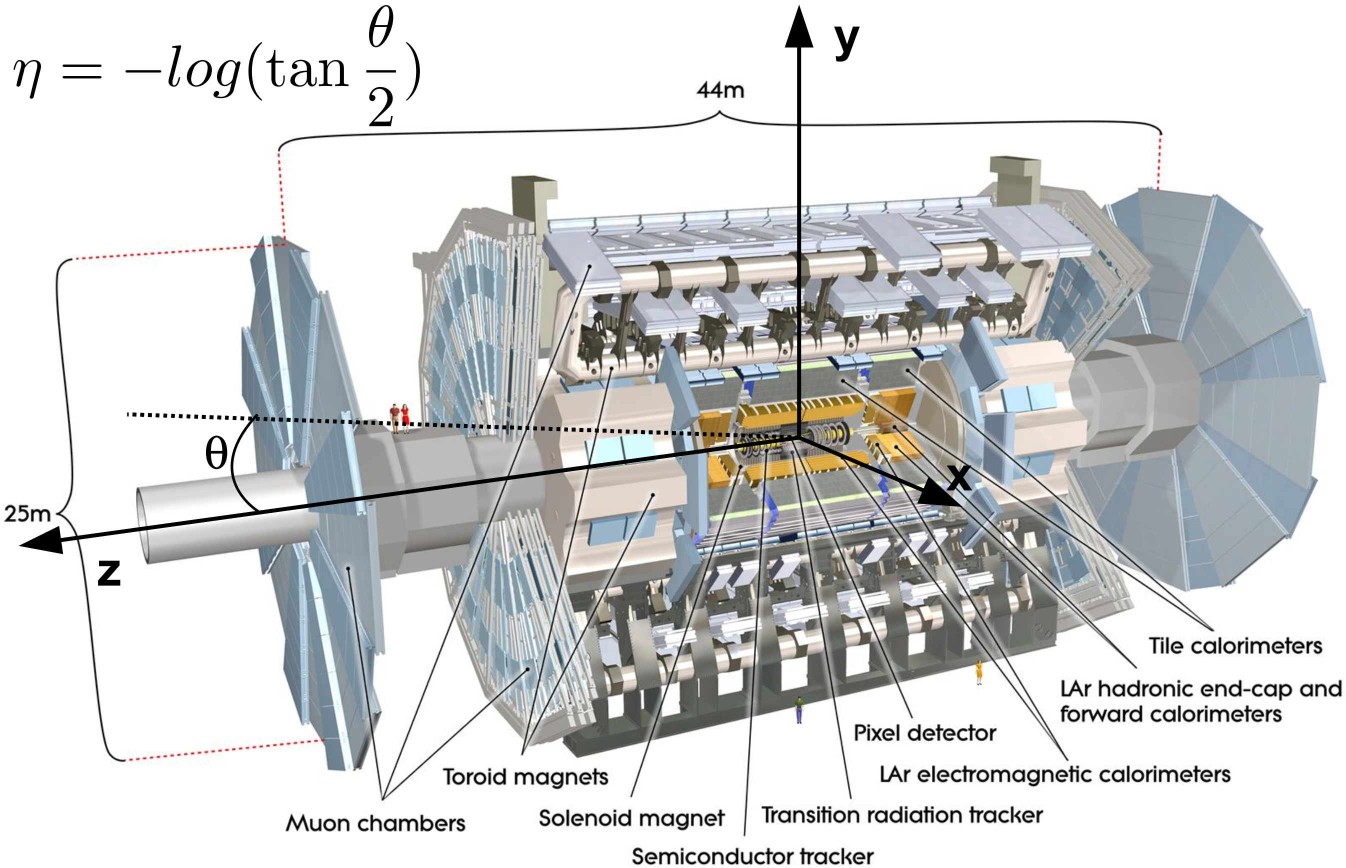




- Will present an overview of the physics program highlighting a selection of the most recent results
  - main focus on high-p_T p-p collision data

The ATLAS experiment

$$\eta = -log(\tan\frac{\theta}{2})$$



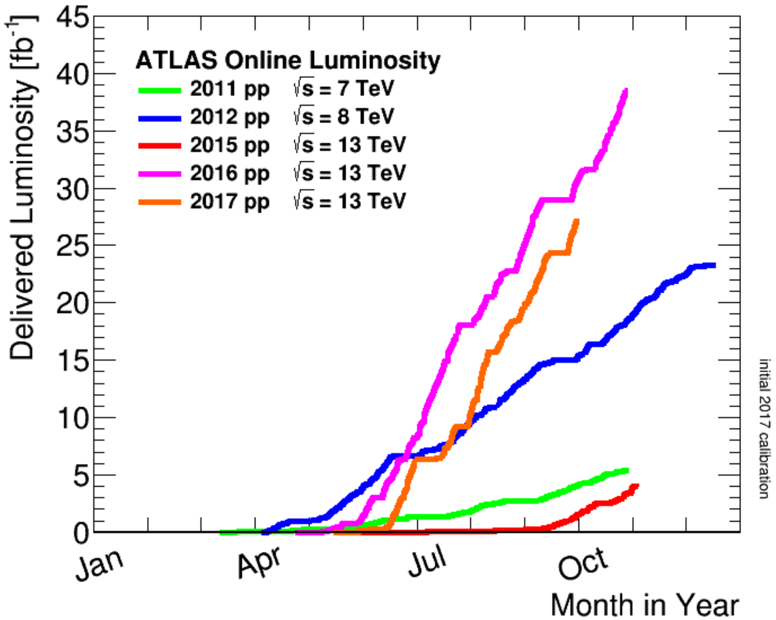
Muon system
$|\eta| < 2.7$ (164.2°)
Strong bending power (air-core toroid)
Trigger chambers

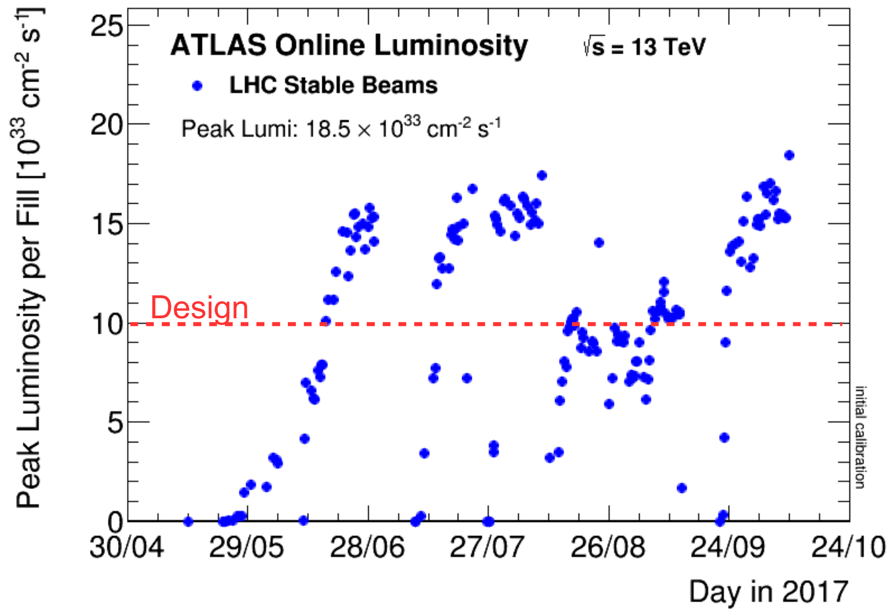
Calorimeters
$|\eta| < 4.9$ (178.4°)
Electromagnetic ($>22X_0$)
Hadronic ($>10\lambda_0$)

Tracking system
$|\eta| < 2.5$ (161.2°)
Si Pixels, Strips, Transition-Radiation Tracker
2T magnetic field

- Two-level triggering system
  - Reduce 40 MHz event rate down to ~1kHz for disk/tape storage
  - Typically ~2000 active menu items

Dataset



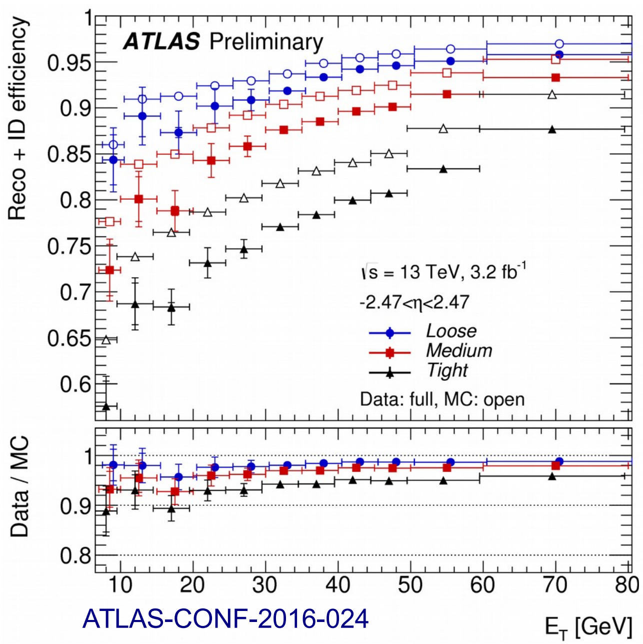


- About 70 fb^{-1} ($\sim 5 \cdot 10^{15}$) of 13 TeV pp collisions data delivered by LHC
  - Most of results shown use 2015+2016 dataset: ~ 36fb^{-1} of recorded data
- Instantaneous peak luminosity above design already in 2016; up to ~70! inelastic pp interactions per bunch crossing in 2017
- Excellent performance by experiments, with > 90% data-taking efficiency (good for physics)

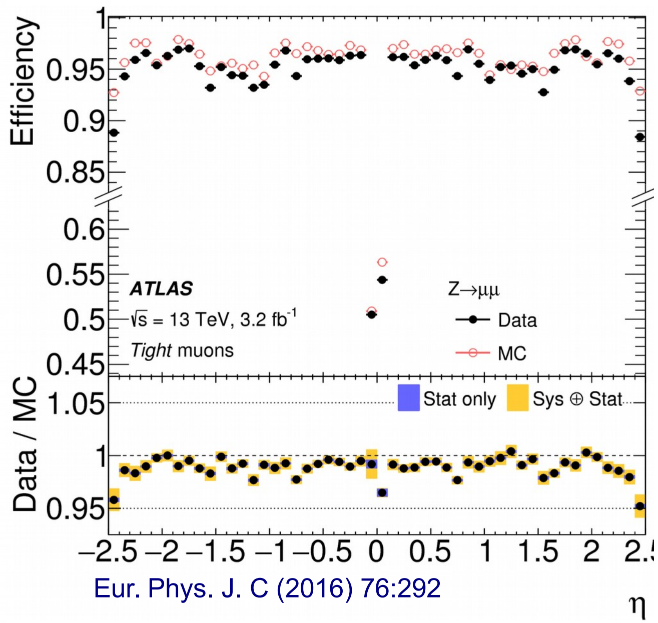
Performance – leptons

- Excellent lepton reconstruction and identification efficiency
  - well modeled by detailed ATLAS detector simulation
- Single e,μ triggers un-prescaled with p_T > ~25 GeV

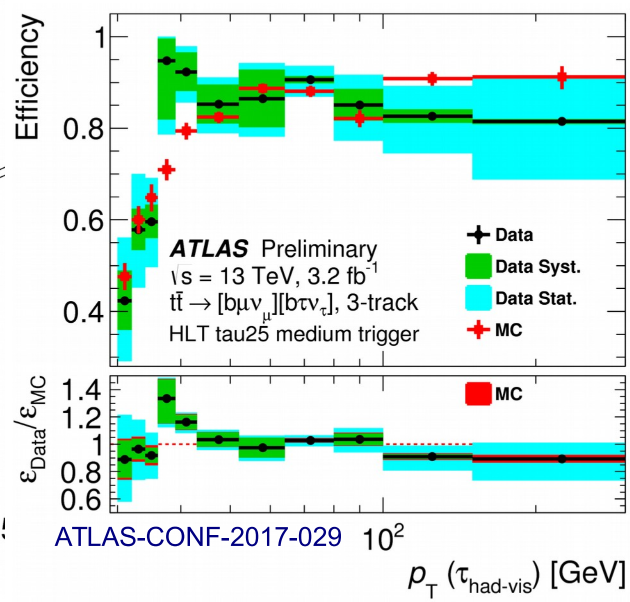
Electrons



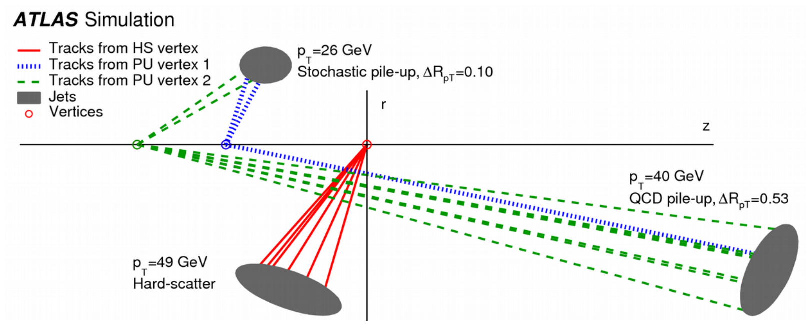
Muons

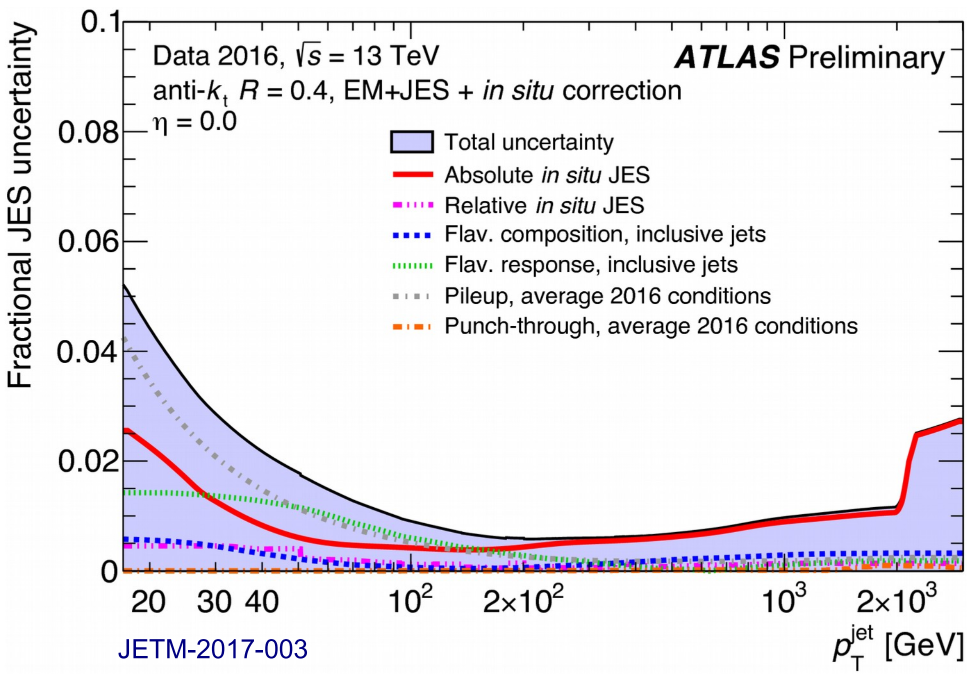


Taus



- Excellent jet energy scale calibration to within few %
- Large effort to mitigate effects of pile-up p–p interactions
  - Recently: improved rejection of (forward) pile-up jets





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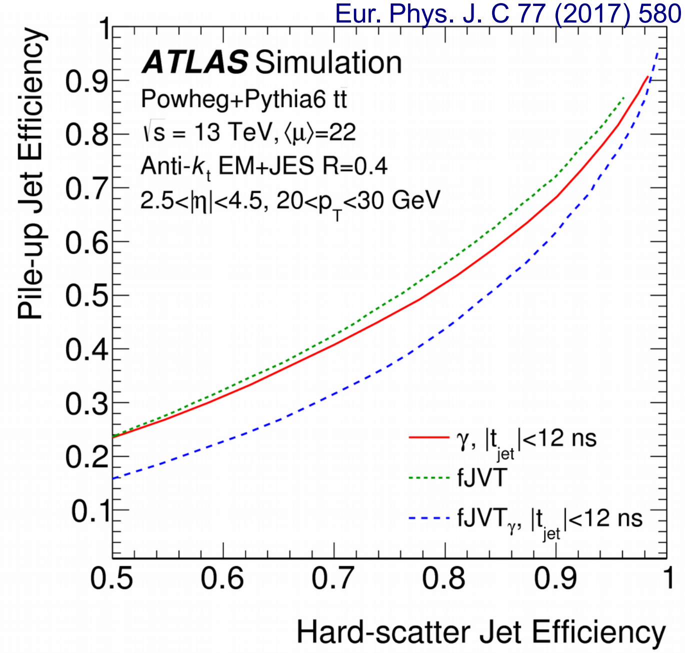
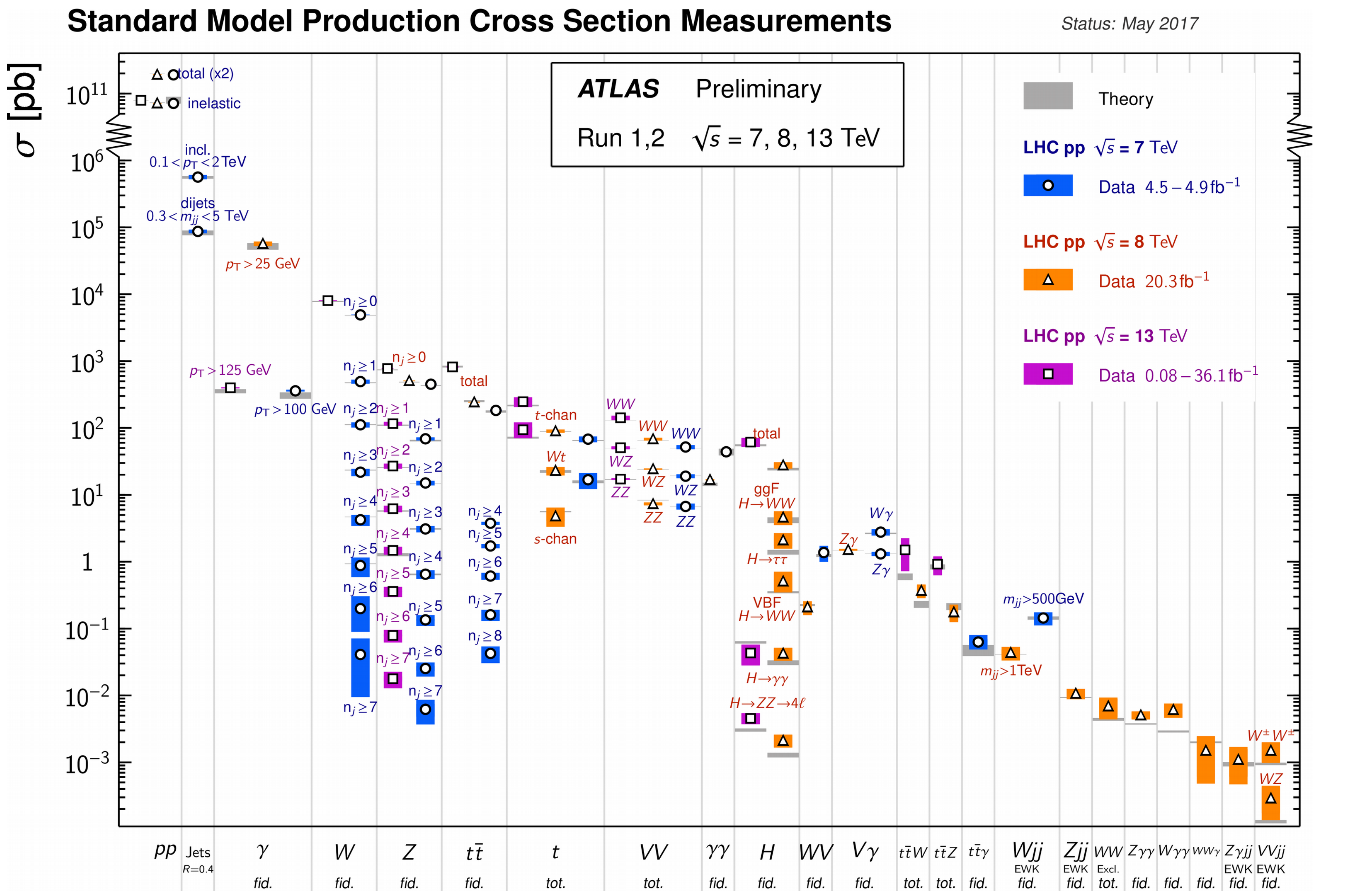
Eur. Phys. J. C 77 (2017) 580

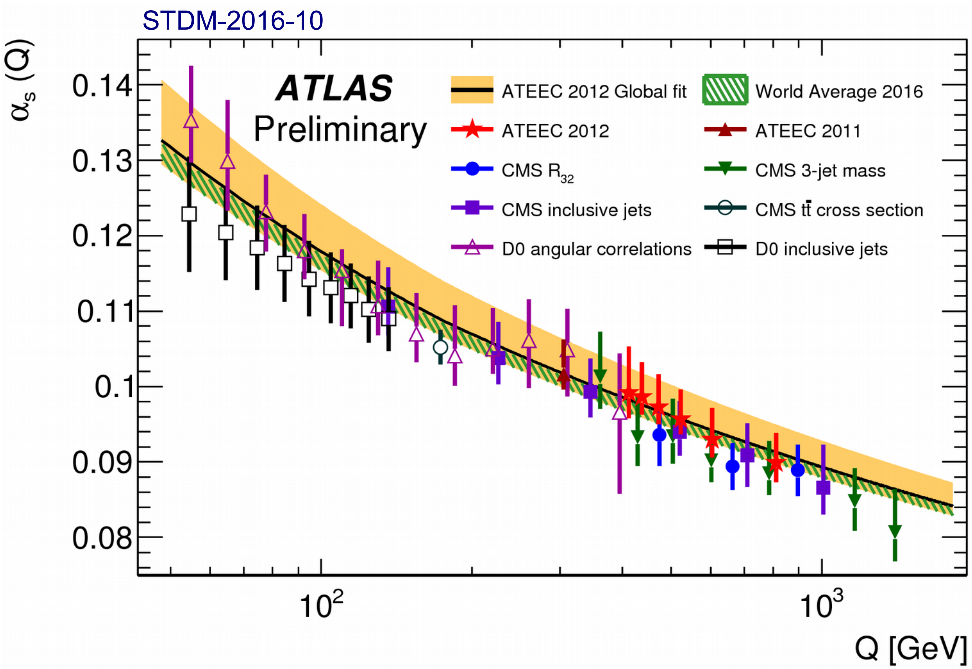


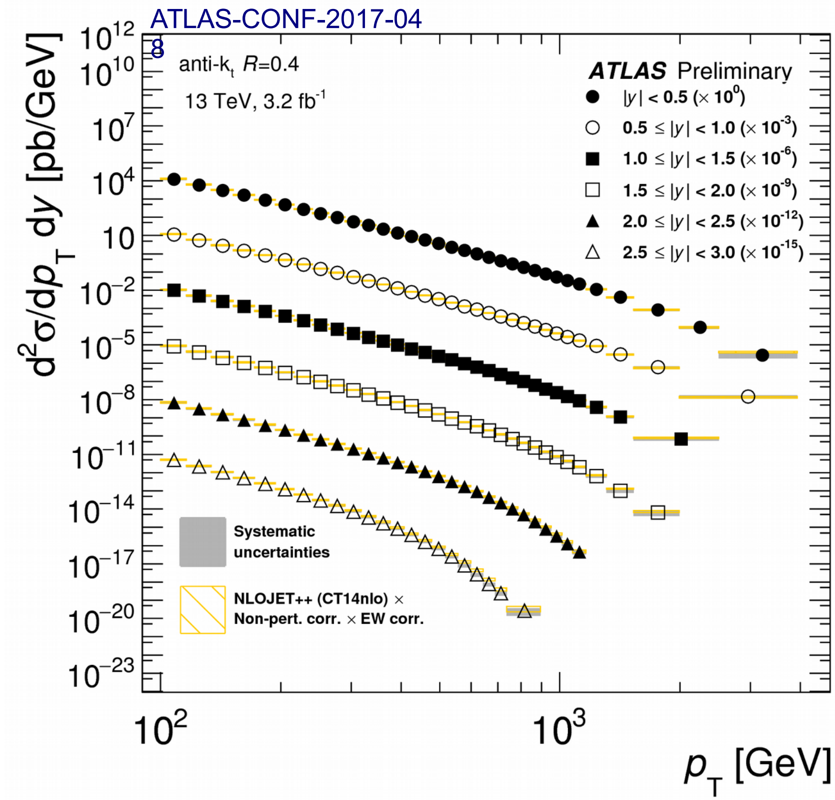
Standard Model measurements



Jet production

- Differential cross section for single and multi-jet production
- Strong coupling constant from energy-energy correlations and asymmetries





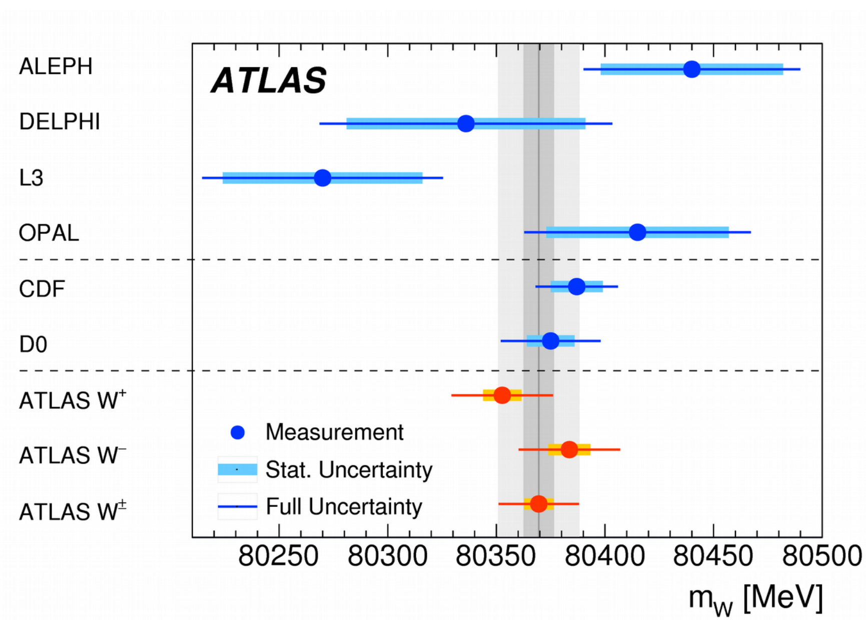
Ref.	$\alpha_s(M_Z)$ measurement
ATLAS	$0.1196 \pm 0.0013(\text{exp.})^{+0.0075}_{-0.0045}(\text{theory})$
W.A.	0.1181 ± 0.0011

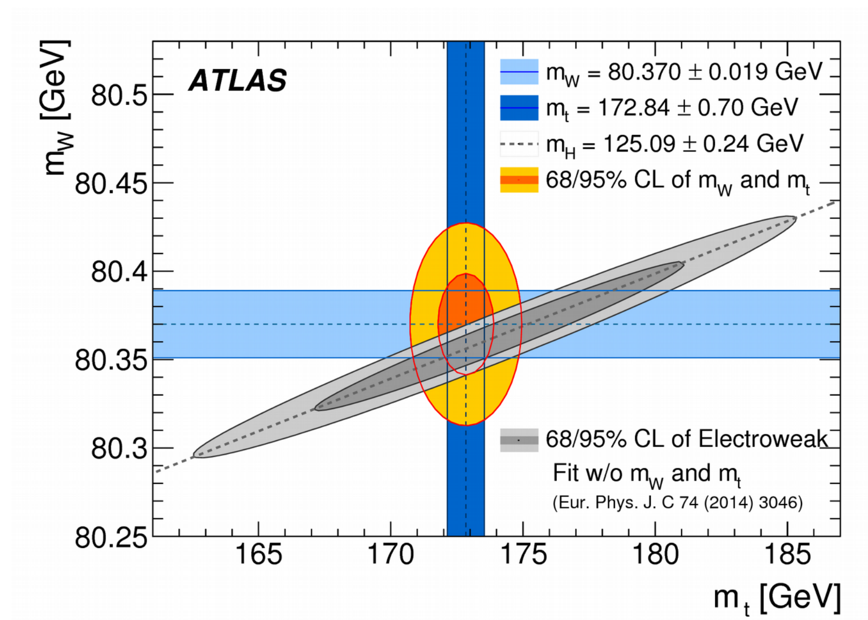
- Using low pile-up $\sqrt{s}$ = 7 TeV data
  - Huge work in detector understanding
- Uncertainty similar to previous best measurement from CDF

m(W) = 80370±19 MeV
±7 (stat.)
±11 (exp. syst.)
±14 (mod. syst.)

arxiv:1701.07240

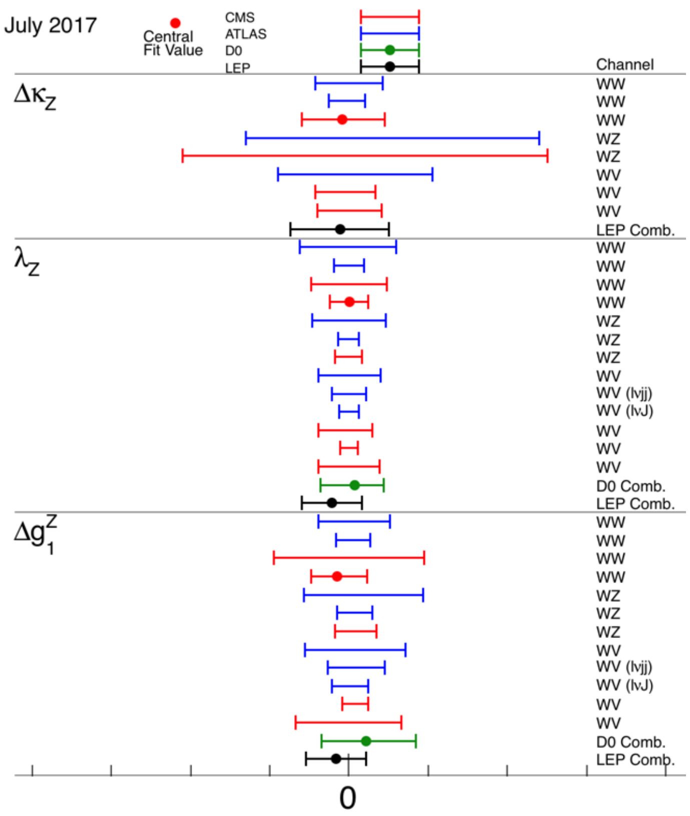
- Expect improvements from theory modeling and larger statistics sample to reduce experimental uncertainties



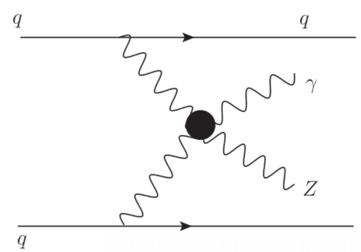


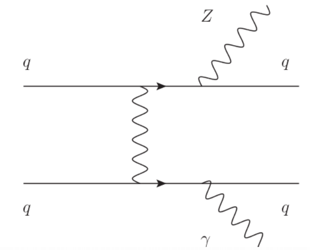
EWK Gauge couplings

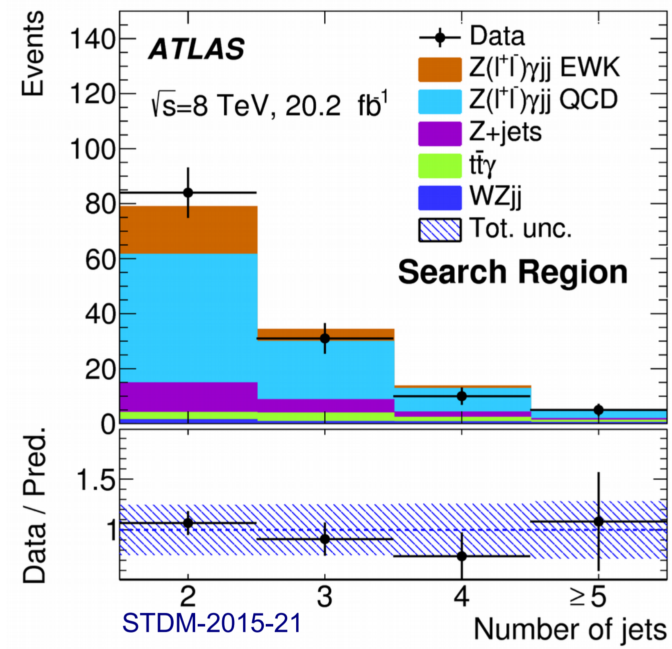
- Extensive studies of diboson and W/Zjj processes
  - constraints on anomalous trilinear gauge couplings beyond LEP limits
- Vector-boson scattering measurements are a milestone in the study of the EWK sector



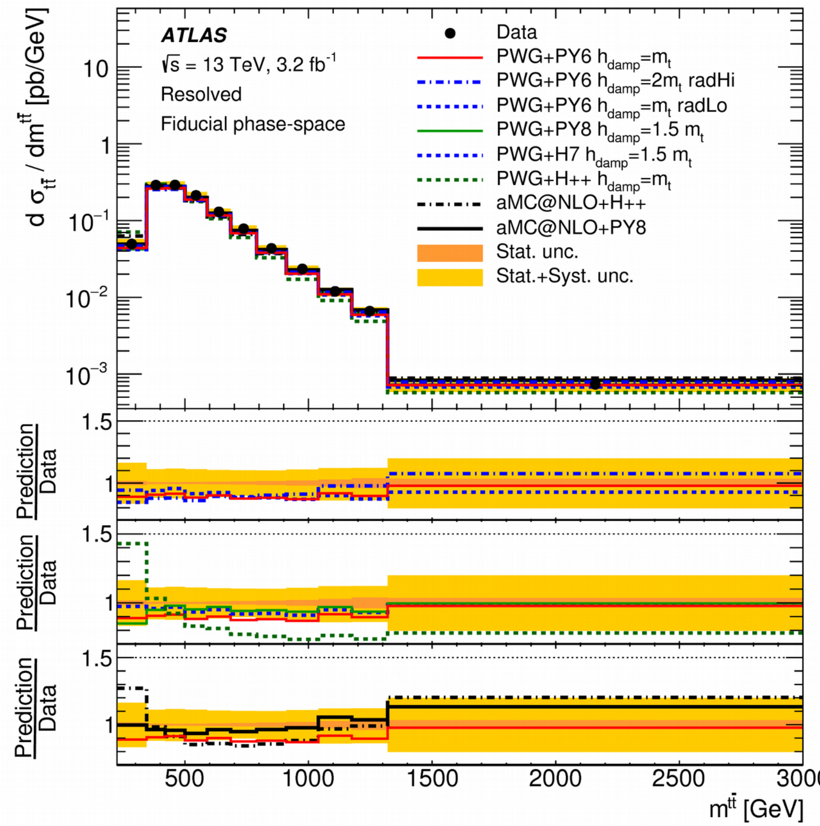
WWZ aTGC Limits @ 95%C.L.

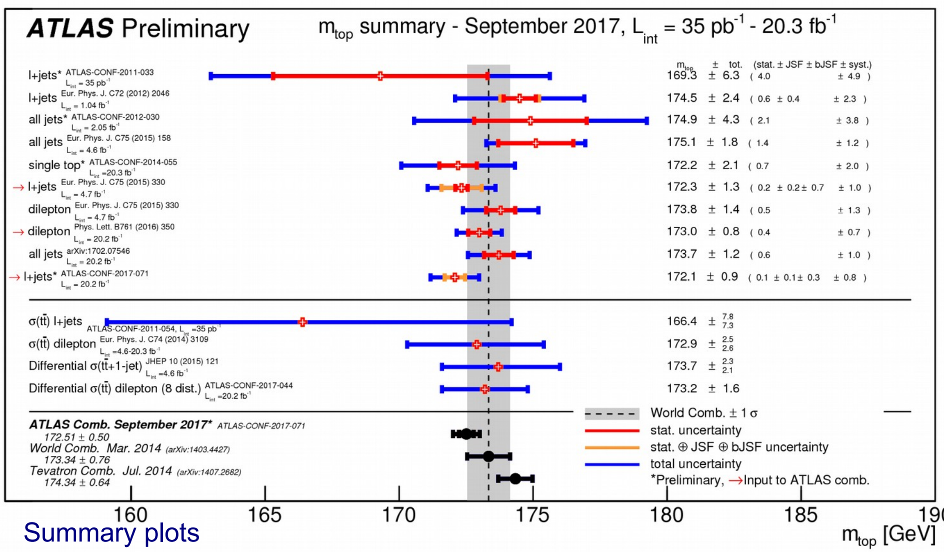






- Detailed studies of the heaviest fundamental particle known
  - strong indirect probe for New Physics
- Differential cross section meas. to refine theory calculations in extreme phase-space





Summary plots

top mass (Sep. 2017):
ATLAS Combination: 172.51 ± 0.50 GeV
Tevatron Combination: 174.34 ± 0.64 GeV

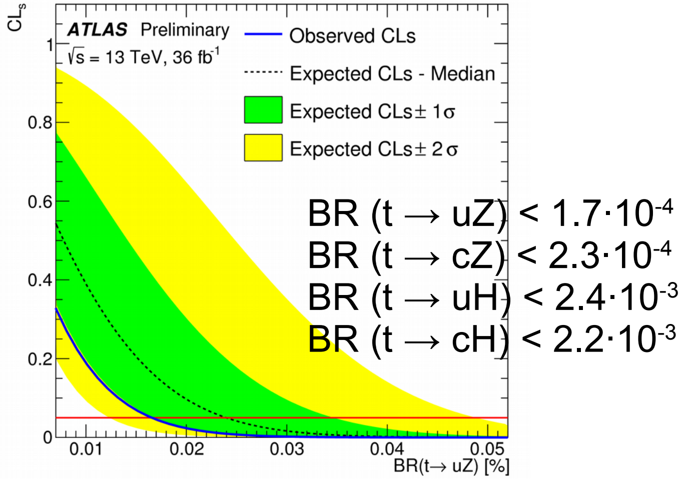
Recent results extracting top *pole** mass
m(top) = 173.2 ± 0.9 ± 0.8 ± 1.2(th.) GeV
* mass definition corresponding to that of a free particle
and directly measuring top width
Γ(top) = 1.76 ± 0.33 +0.79-0.68 GeV
using kinematic information of final state
TOPQ-2015-02, TOPQ-2017-02

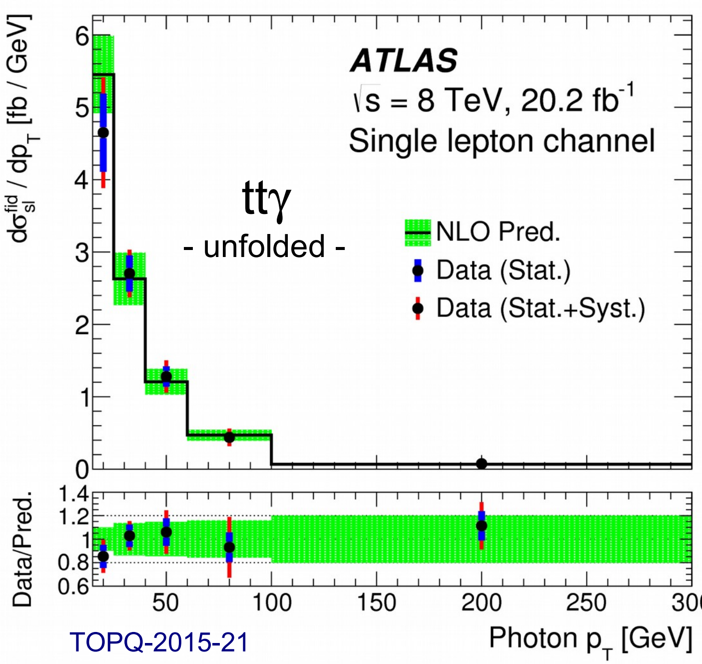
Rare top processes

- Rare top decay offer excellent probes for Flavor-Changing-Neutral-Current processes beyond SM
  - $t \to qZ$, $t \to qH$ (q = u, c)
- Measurement of rare processes in association with top

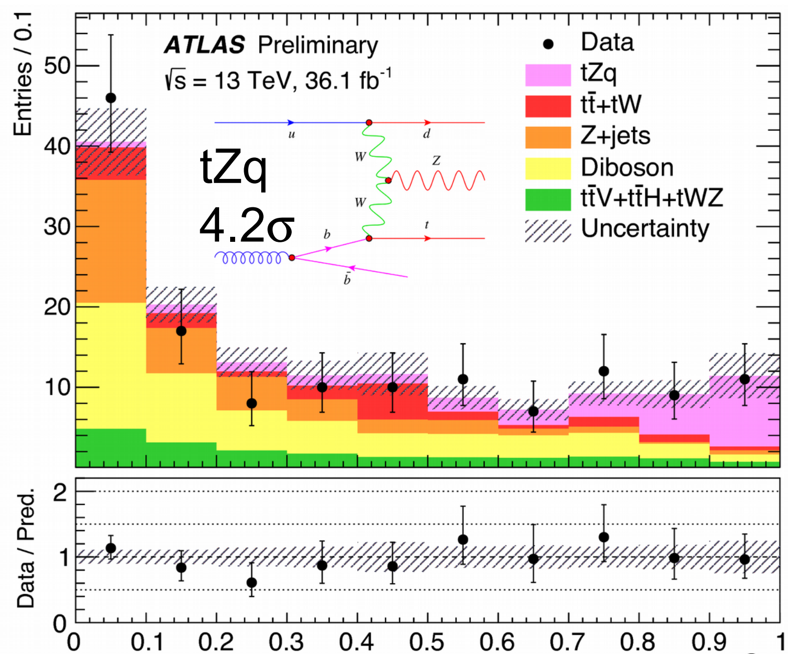
ATLAS-CONF-2017-070

HIGG-2016-26



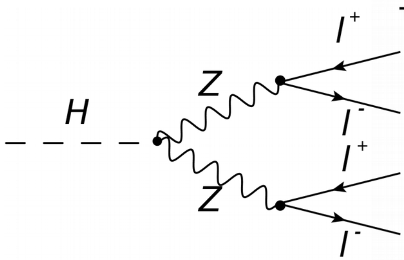


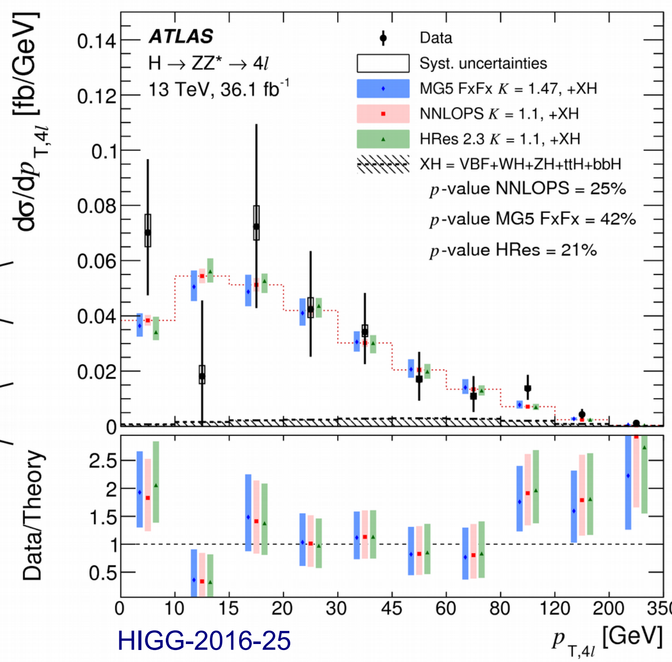
TOPQ-2015-21



ATLAS-CONF-2017-052

- The only fundamental scalar in the Standard Model
- Test (differential!) cross section prediction in various decay channels

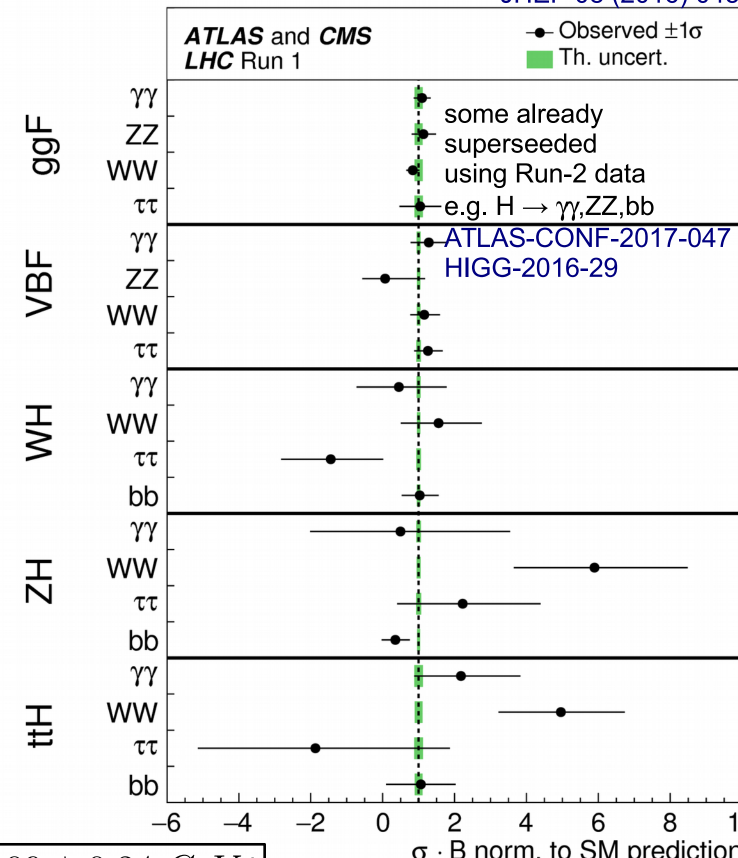




HIGG-2016-25

Combined ATLAS+CMS result:

JHEP 08 (2016) 045



- Measure mass, spin/CP and indirect constraints on width

$m_H = 124.97 \pm 0.28 GeV$ (Run 1: $125.09 \pm 0.24\ GeV$)

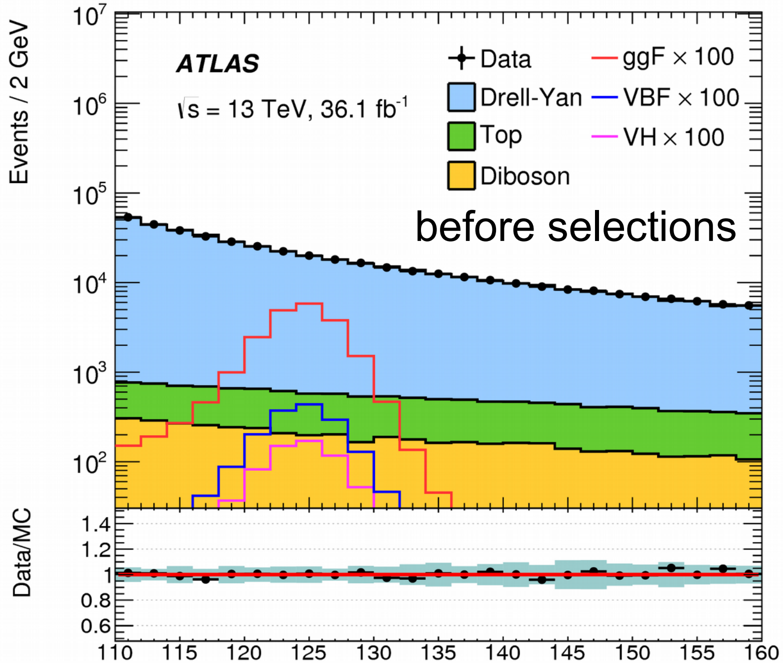
$\Gamma_H < 22.7\ MeV (SM \sim 4.1\ MeV)$

ATLAS-CONF-2017-046, Eur. Phys. J. C (2015) 75:335

Rare decay modes

$H \rightarrow \mu\mu$

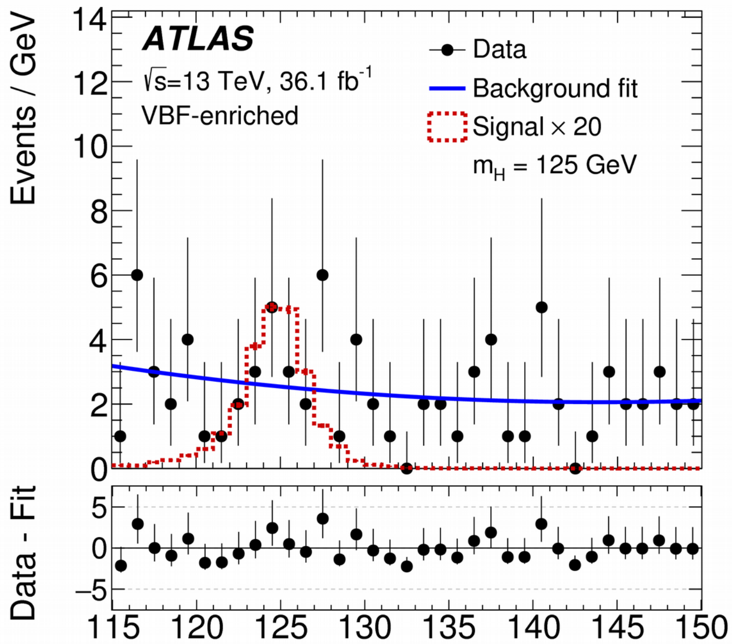
- Expected BR ~ $2 \cdot 10^{-4}$
- $(\sigma \cdot BR)^{95\%CL}/SM < 2.8$ (2.9 exp.) combining 7,8,13 TeV data
  - BR < 0.6% assuming SM $\sigma(pp \rightarrow H)$



Phys. Rev. Lett. 119 (2017) 051802

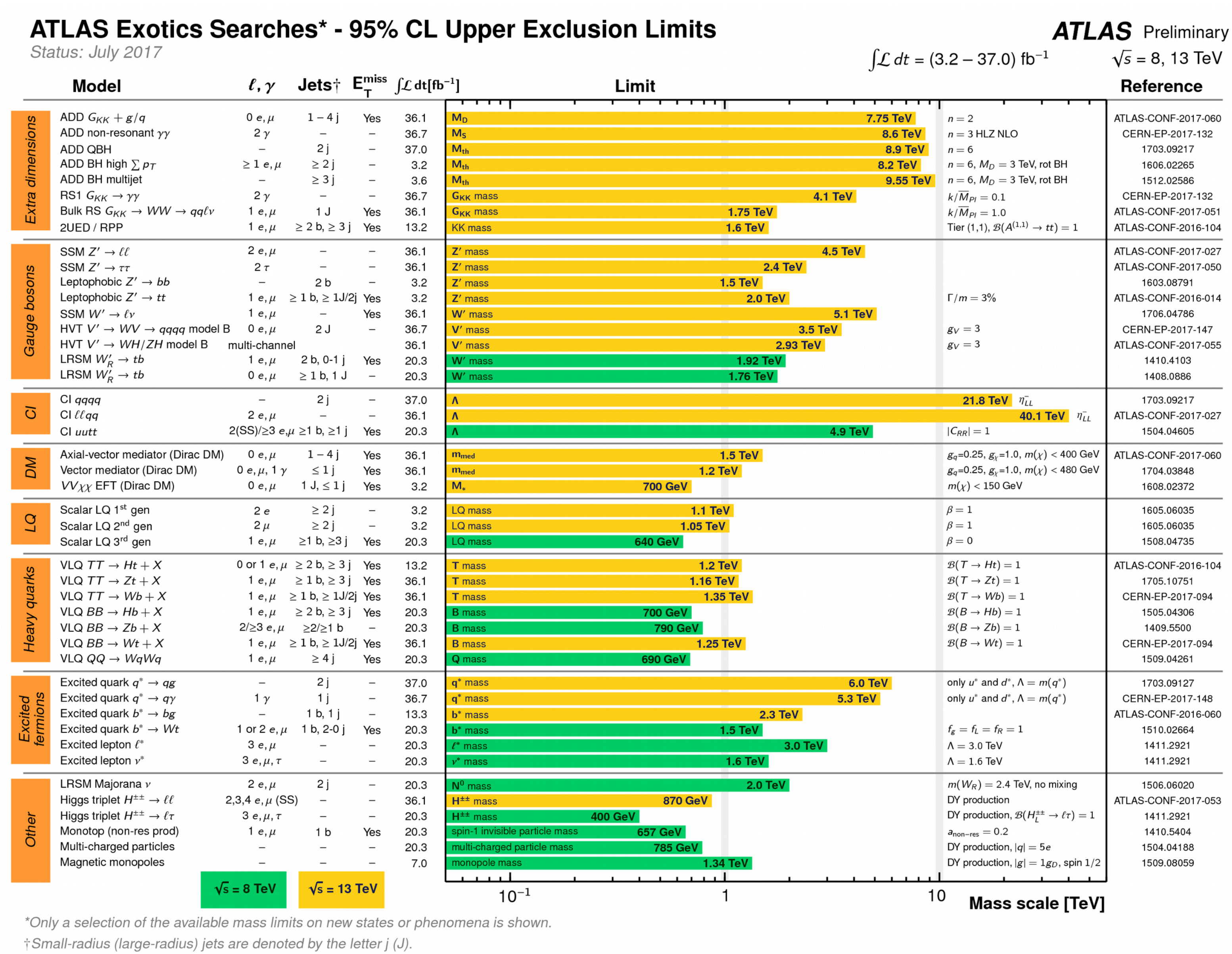
$H \rightarrow Z\gamma$

- Suppressed w.r.t. WW/ZZ or $\gamma\gamma$
- $(\sigma \cdot BR)^{95\%CL}/SM < 6.6$ (5.2 exp.)
  - BR < 1.0% assuming SM $\sigma(pp \rightarrow H)$
- Additionally search for heavier resonances



HIGG-2016-14

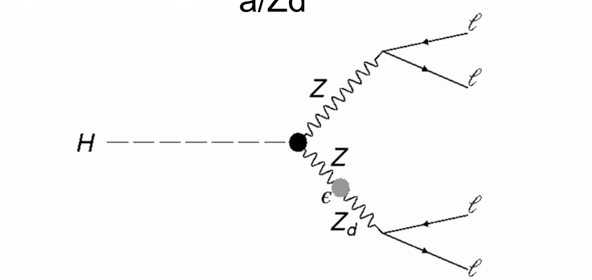
Beyond SM searches

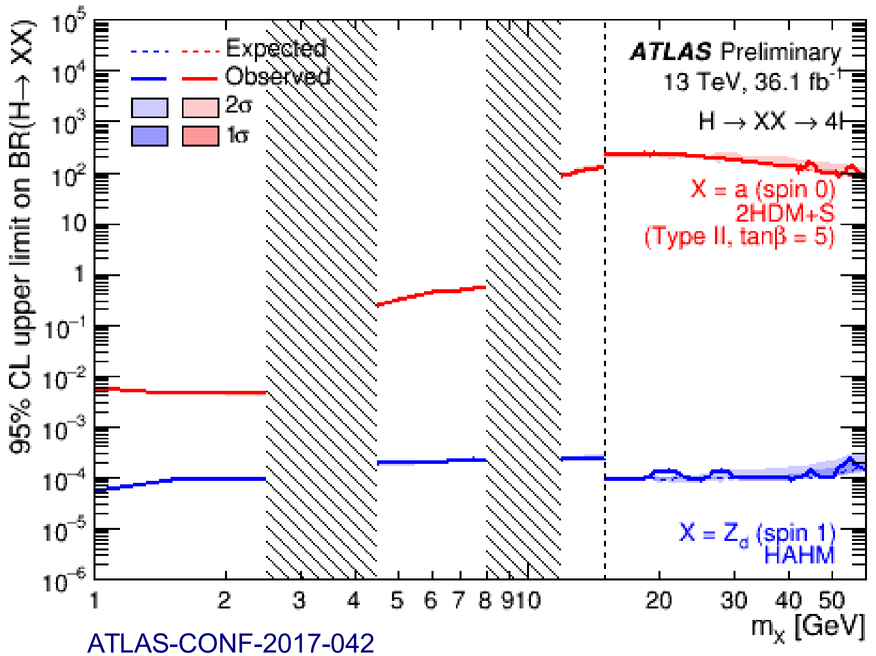


Higgs as portal to new physics

H → aa (or ZZ_d) → 4 leptons

- Light ($m_{a/Zd} < m_Z$) boson pair
- Explore $1 < m_{a/Zd} < 60$ GeV mass

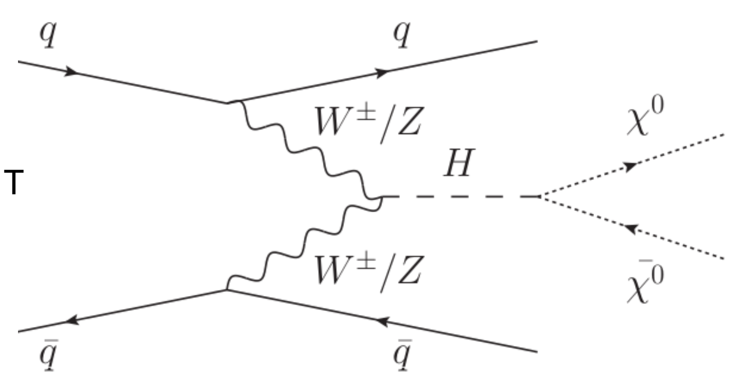




ATLAS-CONF-2017-042

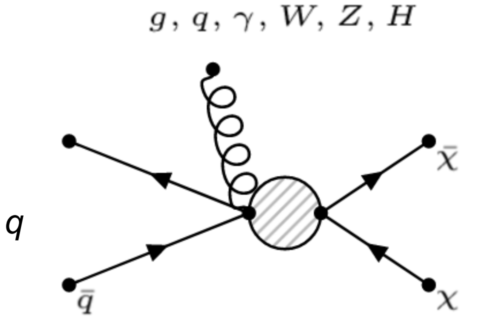
H → invisible

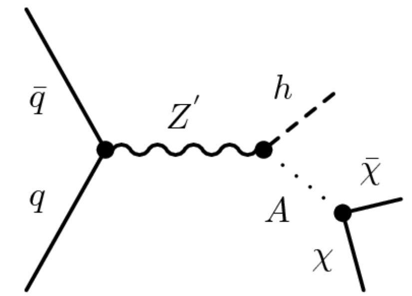
- Associated Higgs production and Missing transverse energy ($E\!\!\!/_T$)
- Most recent result: ZH → 2 leptons + $E\!\!\!/_T$
  HIGG-2016-28
- Best constraint when combined with VBF H → 2 jets + $E\!\!\!/_T$
  JHEP 01 (2016) 172
- Run-1 combination: BR < 23% JHEP11(2015)206



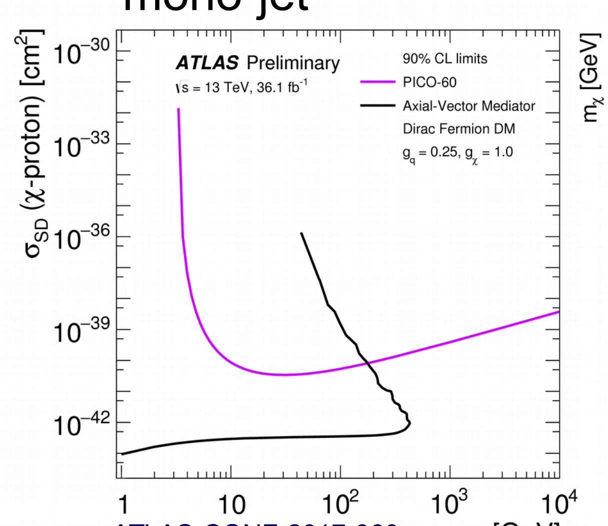
Dark Matter hunt

- LHC in excellent position to test Dark Matter production at EWK scale
- Searches for DM giving Missing Transverse Energy when recoiling against identified object
- Comparison with direct detection only possible in specific models



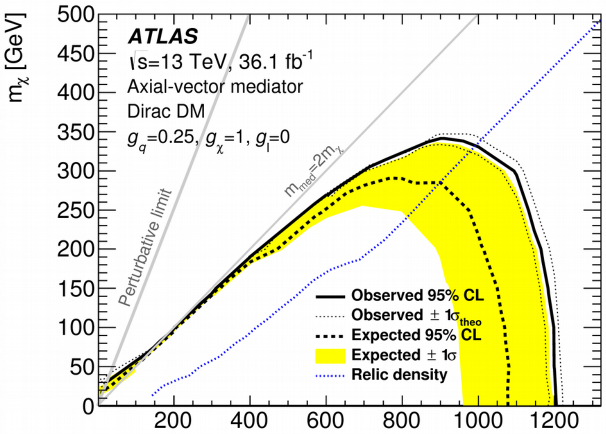


mono-jet



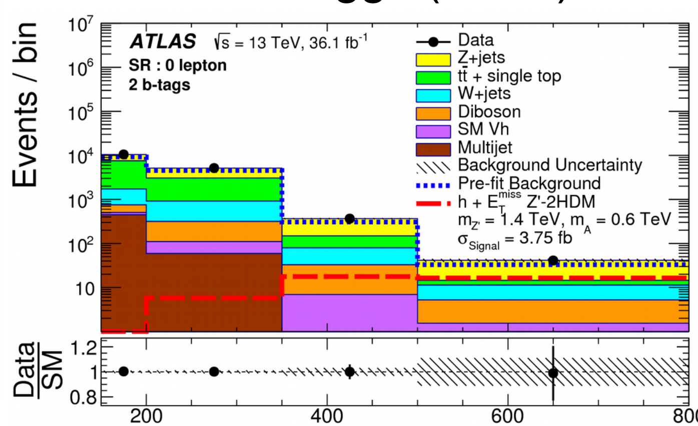
ATLAS-CONF-2017-060

mono-photon



Eur. Phys. J. C 77 (2017) 393

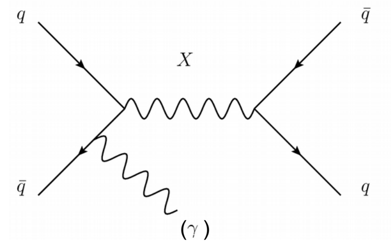
mono-Higgs (→ bb)

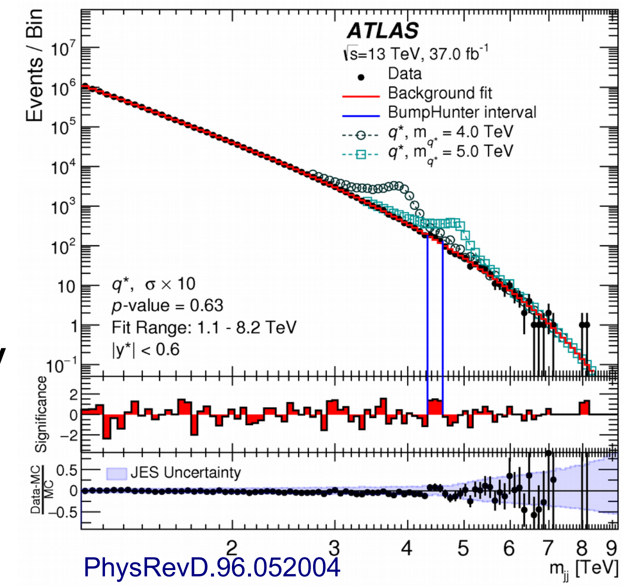


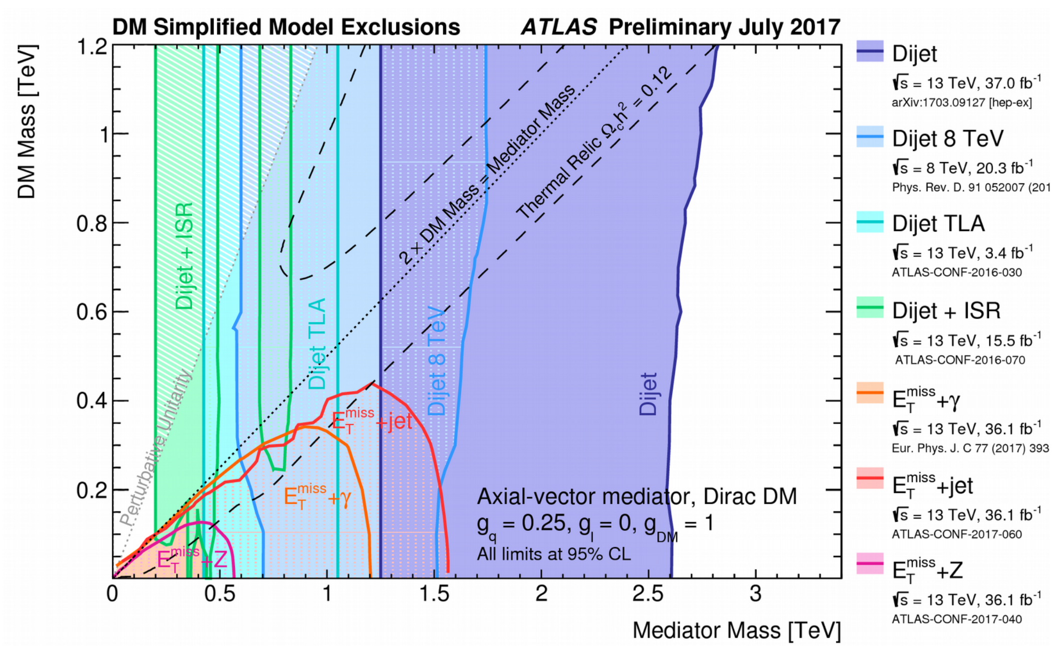
EXOT-2016-25

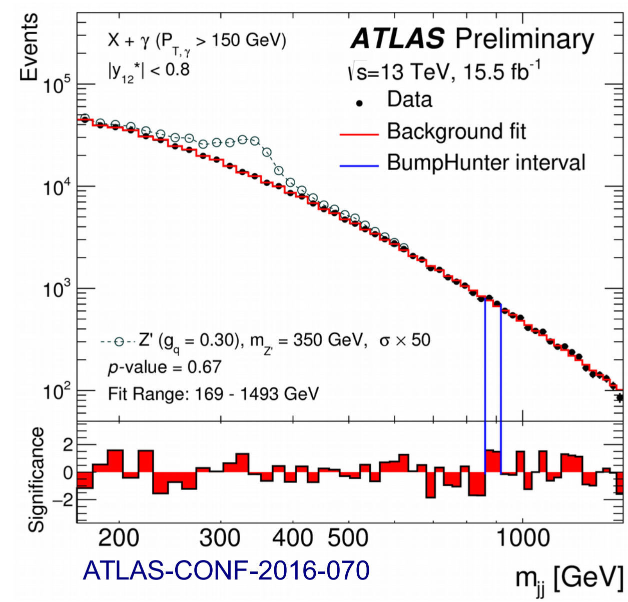
Di-jet resonances

- Di-jet resonance search also sensitive to DM production
- Synergy between different strategies
  - high-mass di-jet resonance and angular study
  - trigger-level analysis
  - Initial State Radiation + di-jet resonance



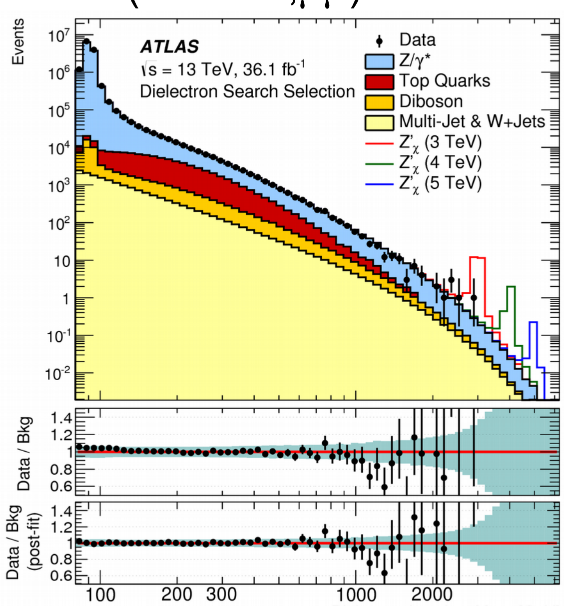






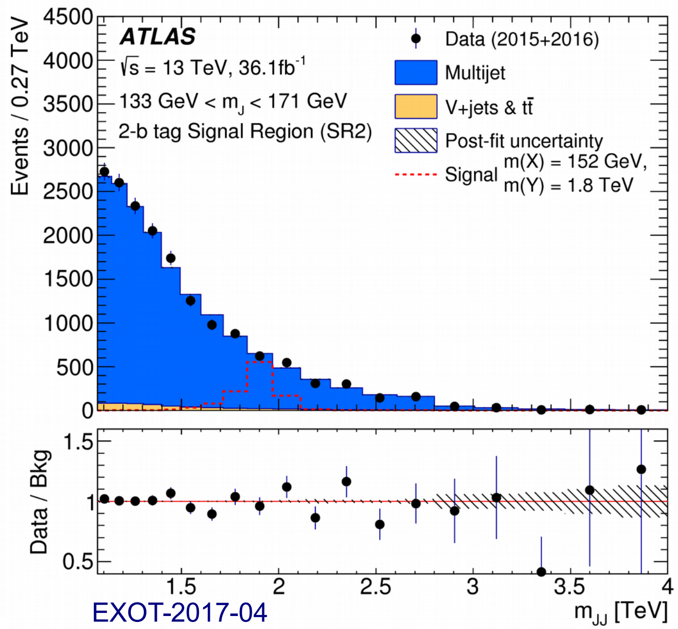
- Comprehensive searches for high-mass resonances
- Hadronic final states in boosted regimes for vector-boson final states
- Limits extend to several TeV in mass and 10fb – 0.1fb in cross section for benchmark models

m(Z' → ee,μμ) > 4.1 TeV



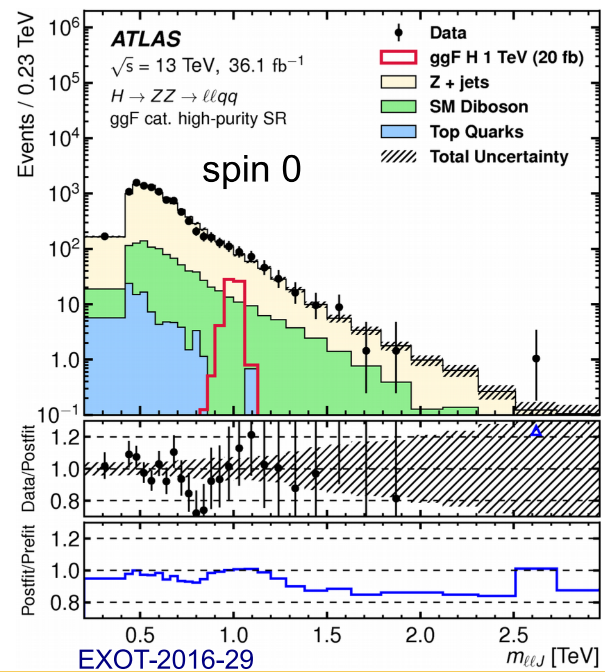
EXOT-2016-05

Y → XH → qq'bb



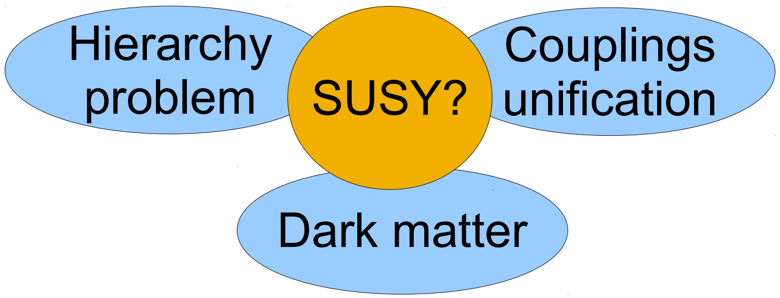
EXOT-2017-04

ZZ/ZW resonances



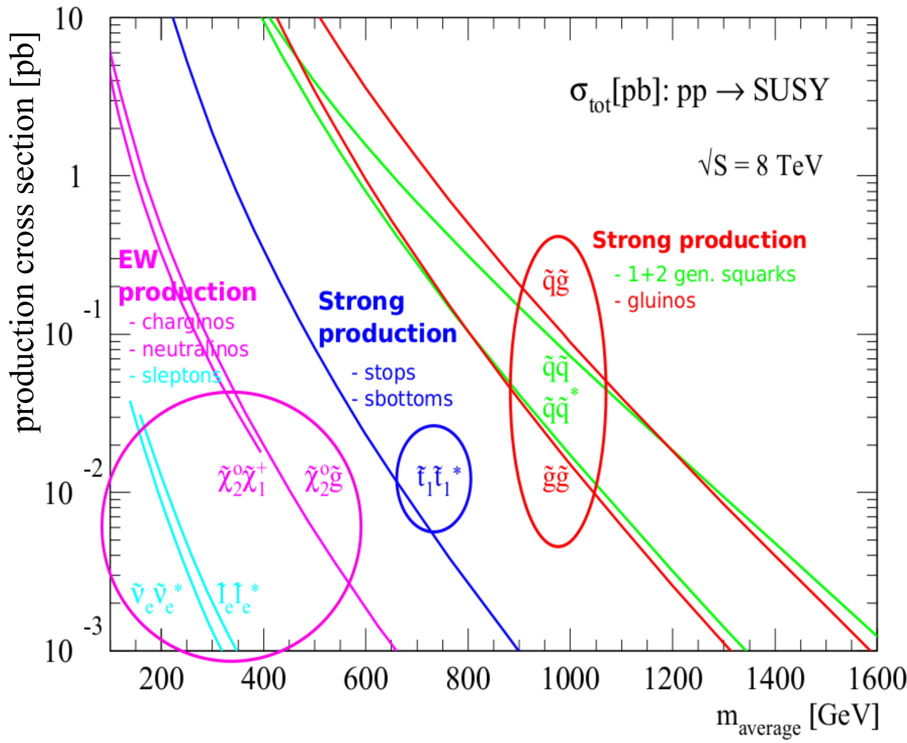
EXOT-2016-29

- SUSY represents an attractive solution to three main present questions
- Rich phenomenology depending on details of SUSY breaking



- Large improvements compared to Run-1:
  - energy jump (8 → 13 TeV)
  - increased luminosity
  - targeted search techniques

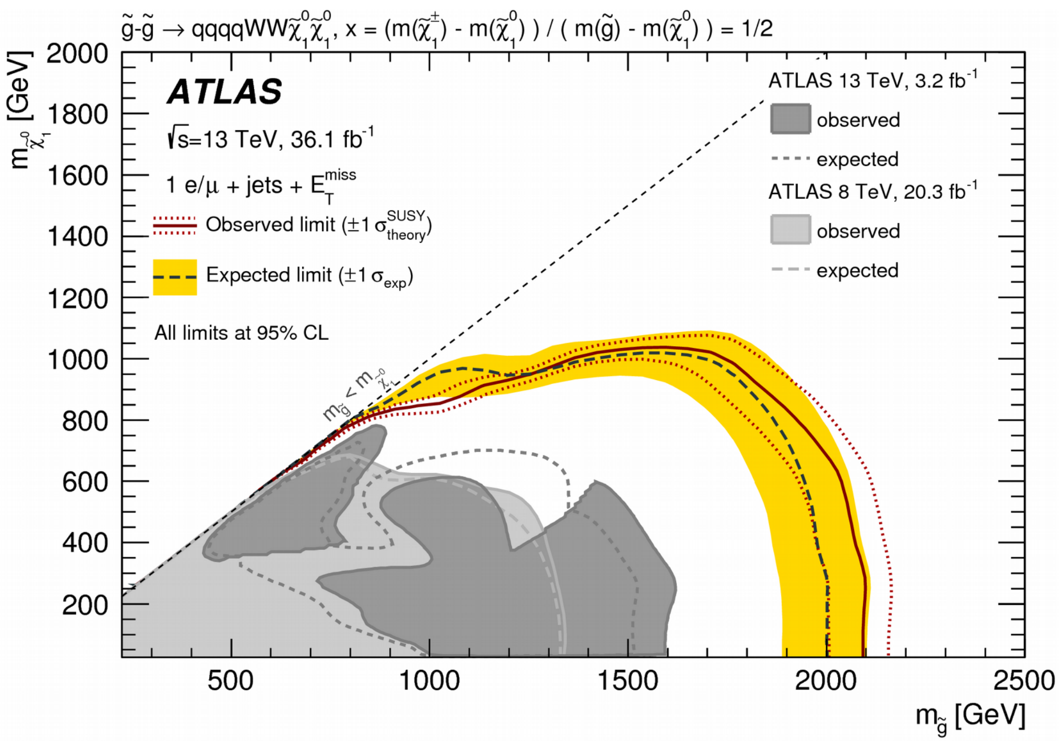
Process	$\frac{\sigma(13\ \mathrm{TeV})}{\sigma(8\ \mathrm{TeV})}$
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}} \approx 1.5$ TeV)	30
$\tilde{t}\tilde{t}$ ($m_{\tilde{t}} \approx 0.7$ TeV)	8
$\tilde{\chi}^{\pm}\tilde{\chi}^{\pm}$ ($m_{\tilde{\chi}^{\pm}} \approx 0.5$ TeV)	4

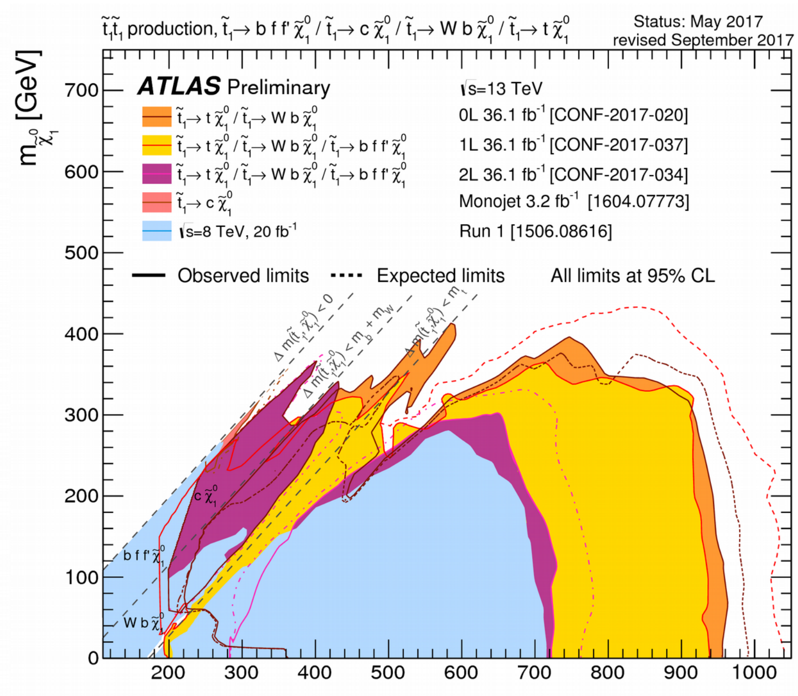


- Almost 40 null results using Run-2 data, and counting

SUSY Strong production

- In simplified models with light χ^0_1
  - stop excluded up to ~ 1 TeV
  - gluino excluded up to ~ 2 TeV
- In particular scenarios even e.g. a light stop is still allowed!
  - although current searches are constraining it more and more





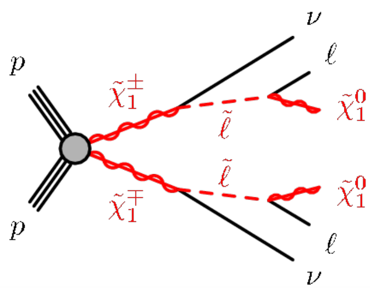
SUSY Summary plots

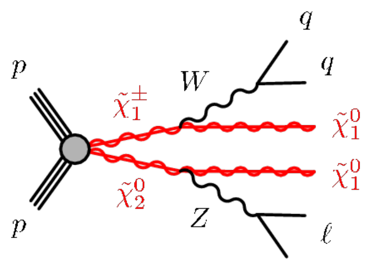
Low expected cross section → need luminosity

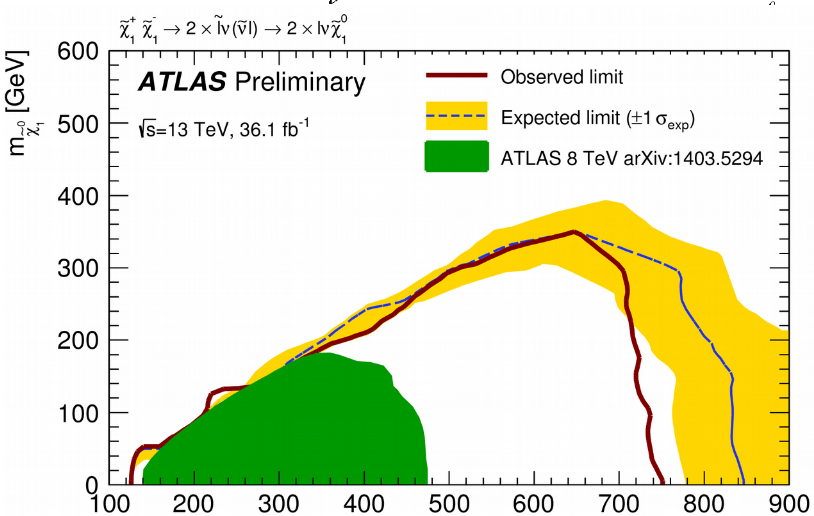
Light staus and Higgsinos are a primary target

2/3 leptons + E_T^{miss} (+jets)

- search for $\tilde{\chi}_1^{\pm}\tilde{\chi}^0, \tilde{\chi}^+\tilde{\chi}^-, \tilde{l}\tilde{l}$



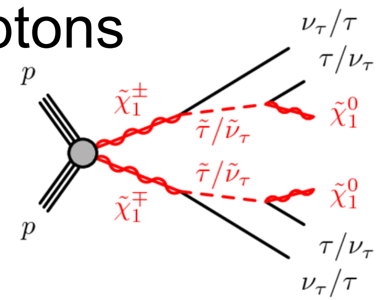


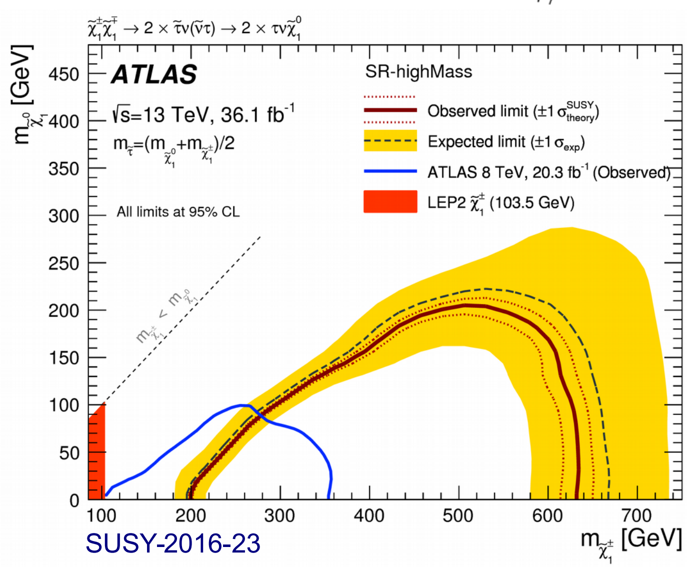


ATLAS-CONF-2017-039

ττ+E_T^{miss}

- Well motivated in presence of light sleptons



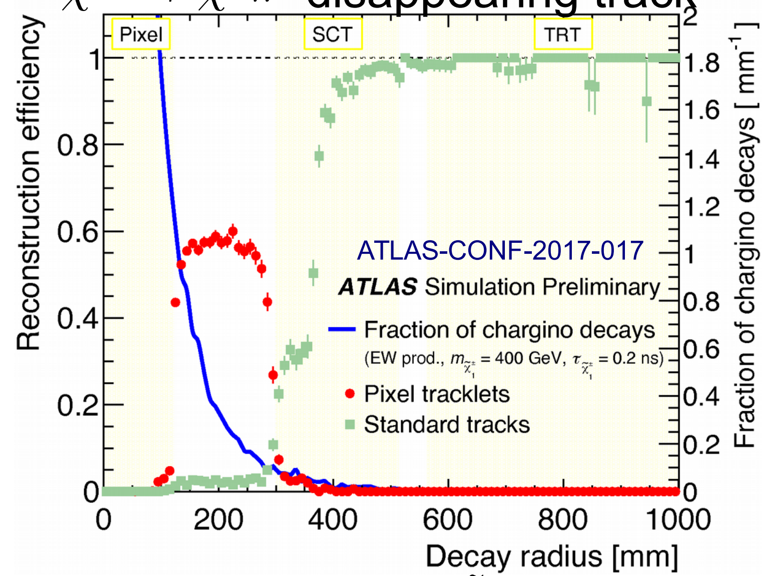


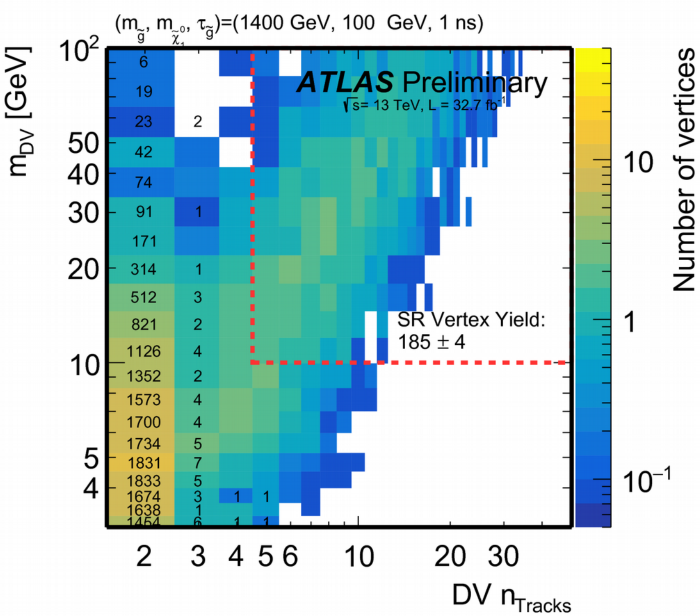
SUSY-2016-23

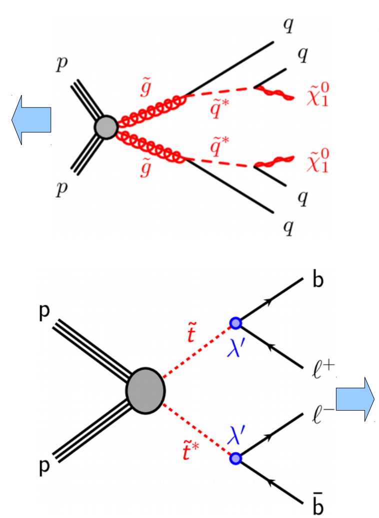
RPV SUSY and Long-lived particles

- Relax common assumptions
  - SUSY partners can easily acquire significant lifetime
  - R-parity violation can lead to unexpected signatures
- Often require dedicated event reconstruction strategies

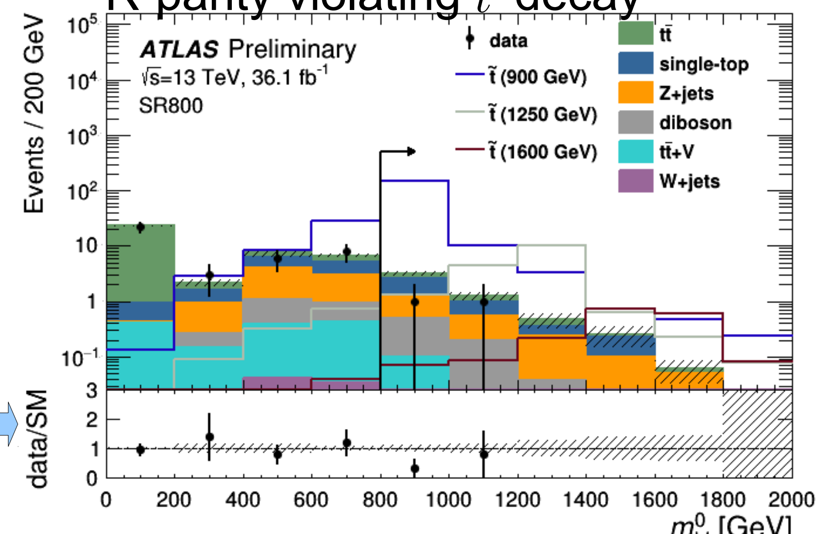
$\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0}\pi$ "disappearing track"







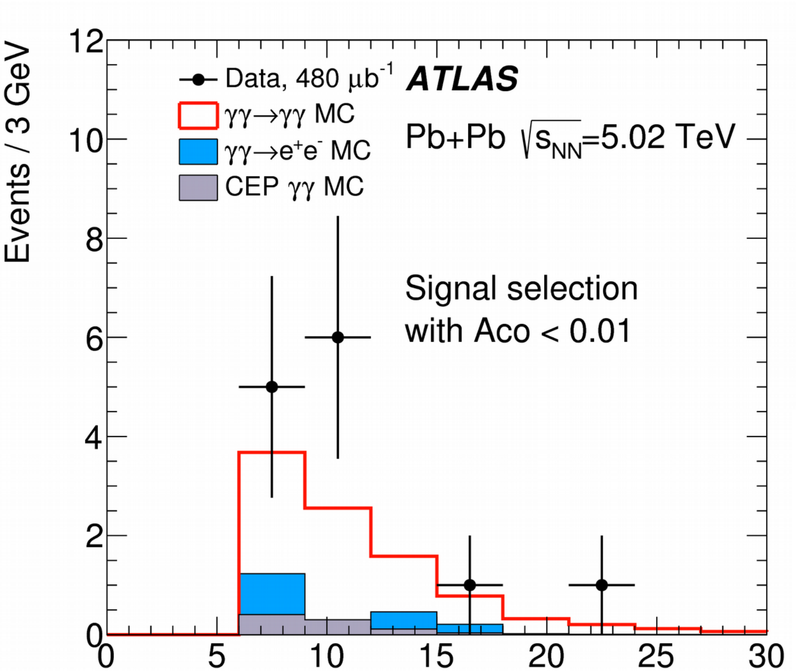
R-parity violating $\tilde{t}$ decay



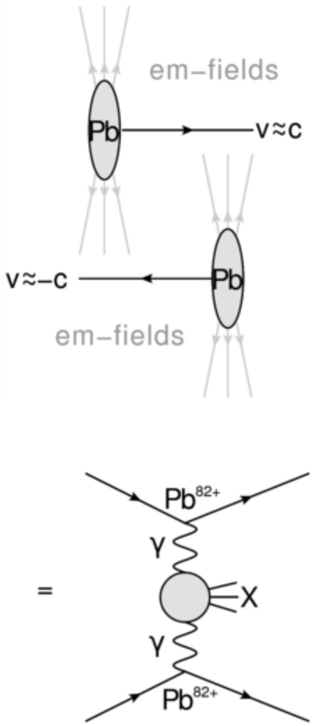
ATLAS-CONF-2017-036

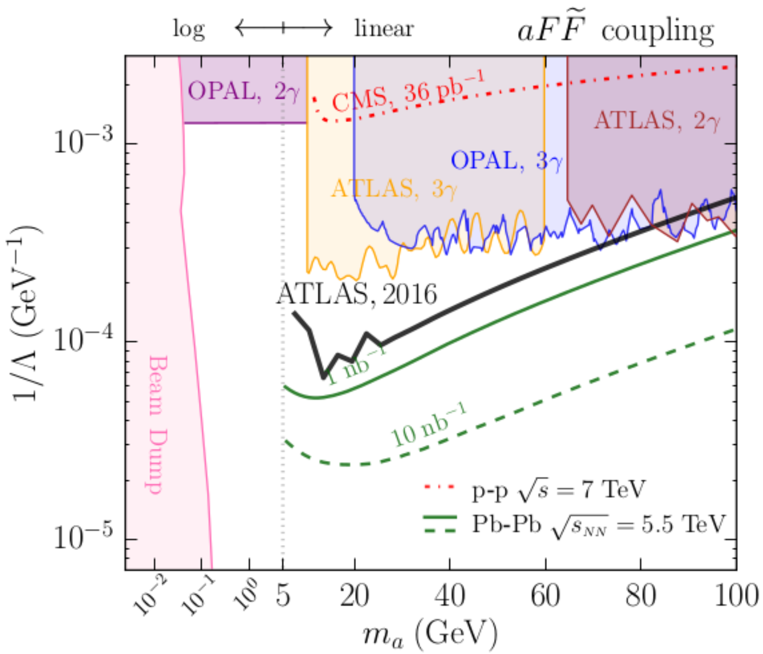
Heavy-Ion program

- Vibrant Heavy-Ion (Pb) collision program, Pb-Pb, p-Pb, Pb-p
- Recent highlight: observation of light-light scattering
  - can also constrain axion models (thanks to large ion electric charge)



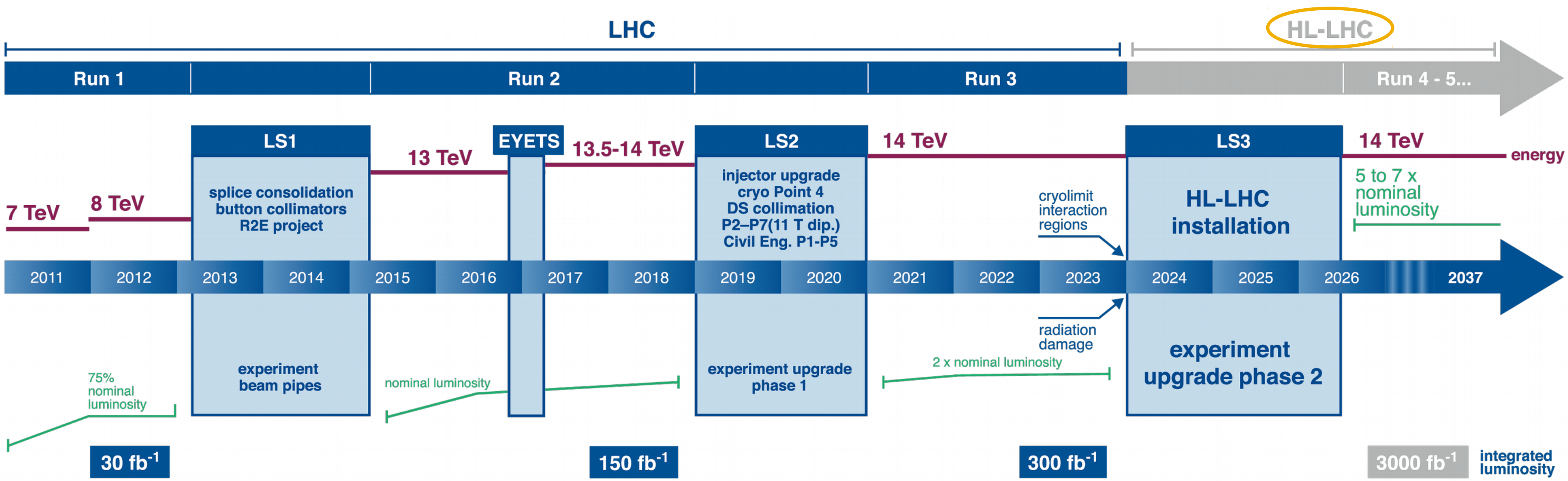
Nature Physics 13 (2017) 852





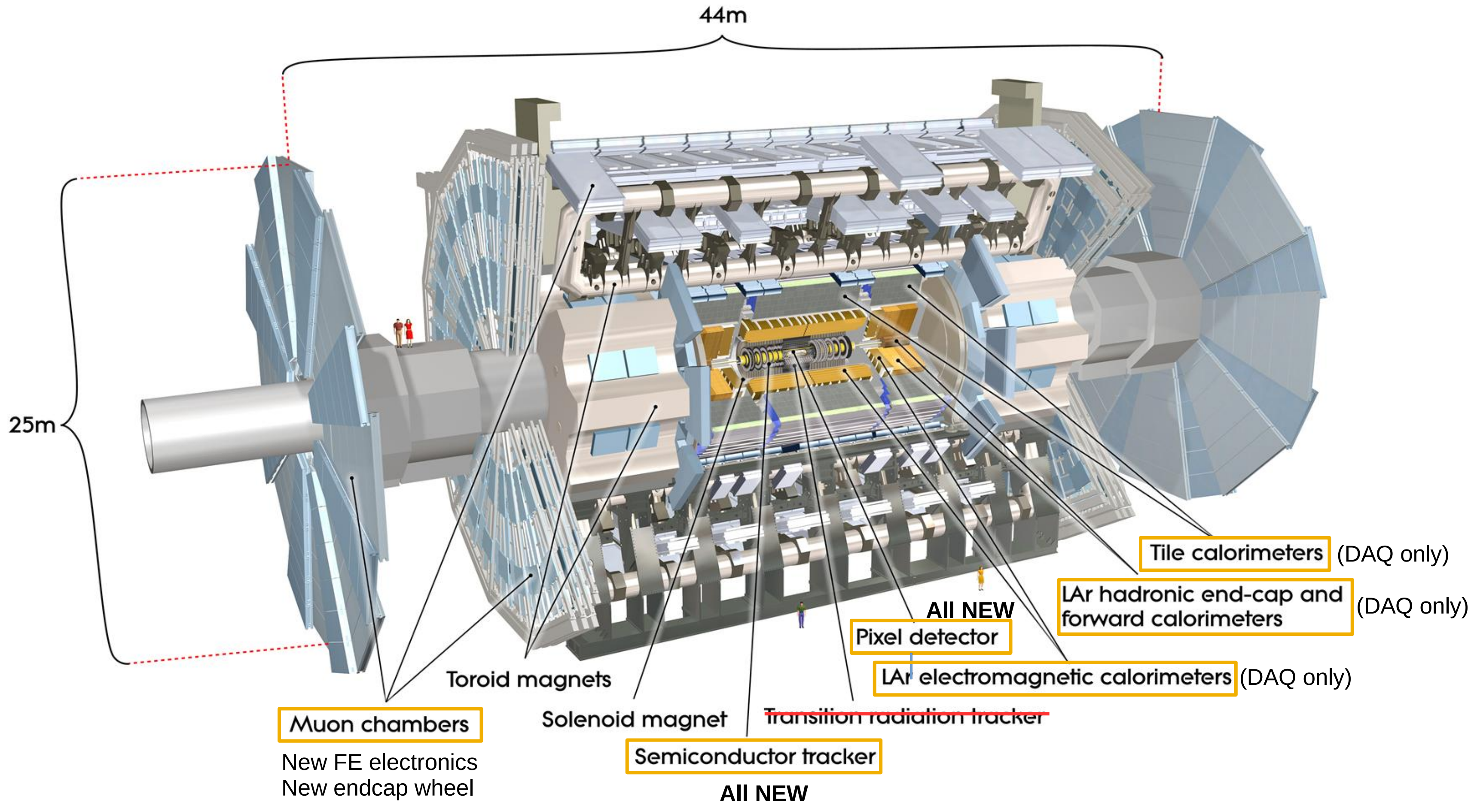
Knapen et al. arXiv:1709.07110

High Luminosity LHC



- To maximize physics output in the long-term, a major upgrade to the accelerator is planned, aiming to increase the instantaneous luminosity and deliver a total of 3000/fb by the end of the HL-LHC
- The ATLAS detector will also be upgraded to cope with the higher instantaneous luminosity expected (up to 200 interactions / bunch crossing)

Systems planning upgrade

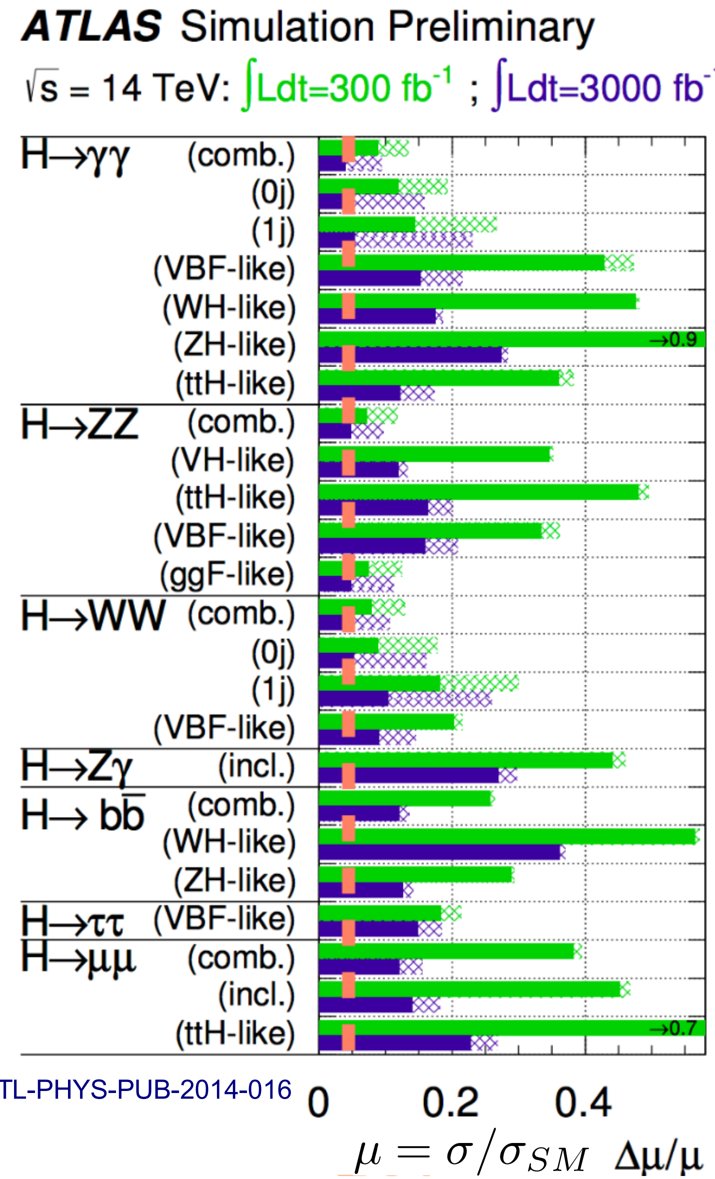


Completely new inner tracking system, extending up to $|\eta| \sim 4$

+ Trigger system, Computing, possibly new forward timing detectors

Higgs physics

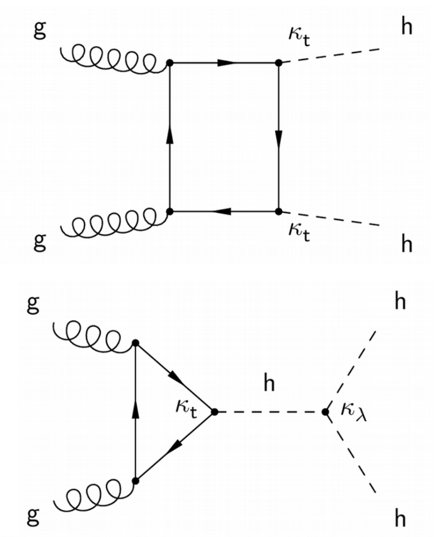
- Precision measurement of main couplings: WW, γγ, bb
- Strengthen evidence of couplings with fermions / leptons (τ, b, t)
- Test couplings to 2nd generation (μ, c)
- Indirect measurement of Higgs width
  - For $\Gamma_H = \Gamma_H^{SM}$
    $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV with 3000 fb^{-1}
    Run-1 limit: Γ_H < 22.7 MeV @ 95% C.L.

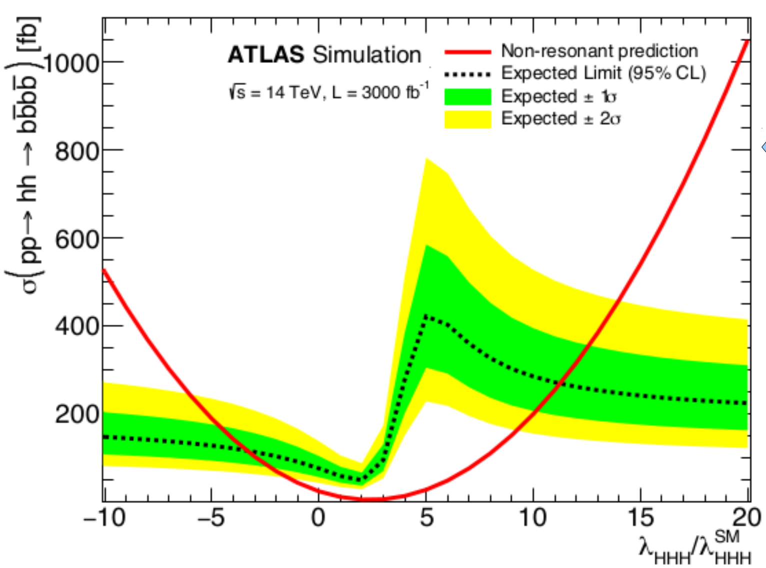


ATL-PHYS-PUB-2014-016

Higgs self-coupling

- Critical to test Higgs self-coupling in the SM
- Very low cross-section
  - small couplings + destructive interference: ~40 fb
- Full HL-LHC dataset and combination of channels needed for SM sensitivity
  - upgraded detector critical to maintain e.g. low jet p_T trigger thresholds and b-tagging capabilities



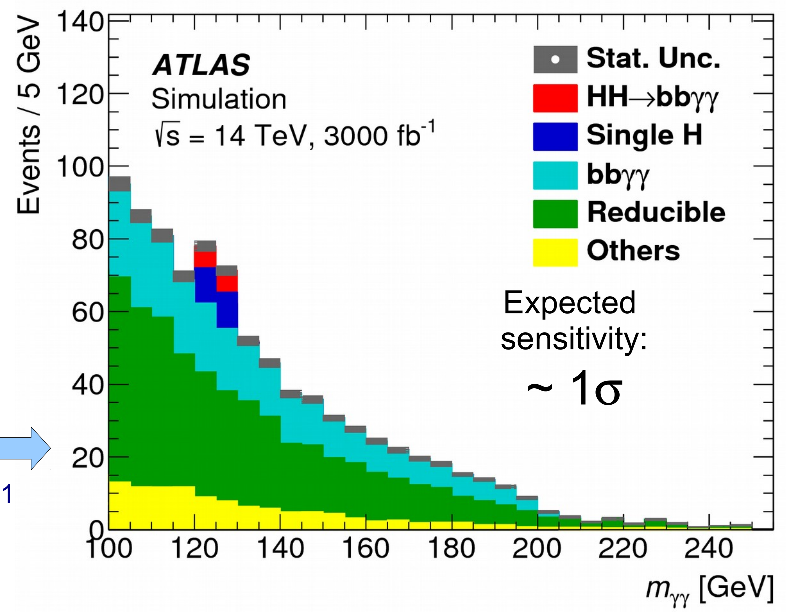


HH → bbbb

ATLAS-TDR-025

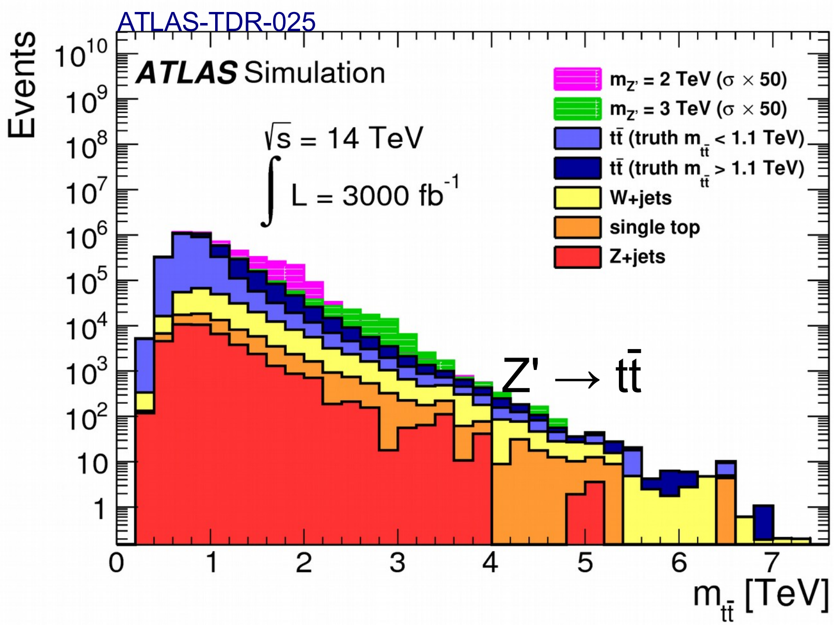
HH → bbγγ

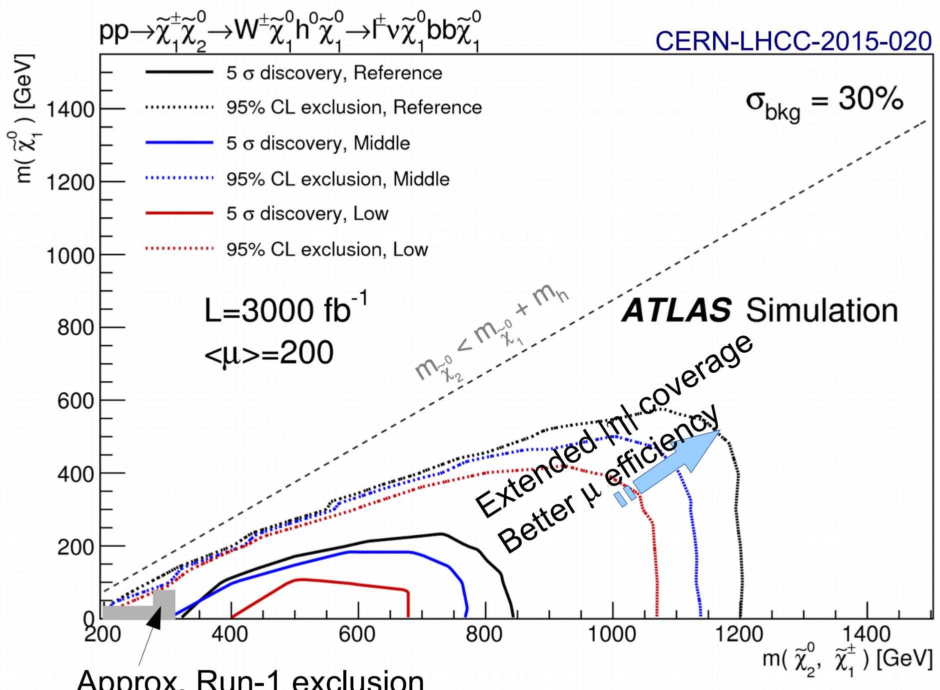
ATL-PHYS-PUB-2017-001



Beyond the Standard Model

- Increase mass reach for resonant states
  - e.g. Z' → tt reach increases from ~2TeV (2015) to ~4 TeV (HL-LHC)
- Large dataset increase sensitivity to rare processes
  - EWK SUSY partners reach extends from few hundreds of GeV to above 1 TeV in standard simplified models





Conclusions

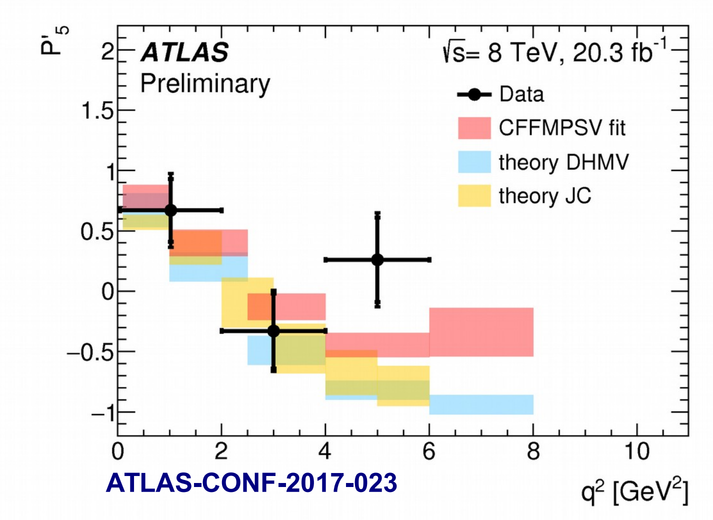
- LHC has been performing remarkably well
  - e.g. instantaneous luminosity beyond design value
- ATLAS is collecting and analyzing data efficiently
  - continuous improvements to detector and analysis technique to cope with increasingly challenging conditions
- Vast physics program to test the Standard Model
  - accurate measurement of known processes
  - direct search of beyond-SM physics in a variety of final states
- The Standard Model remarkably reproduces observations
- The current dataset is ~2% of what expected by end of HL-LHC
  - More luminosity will allow us to explore new ways to test theory

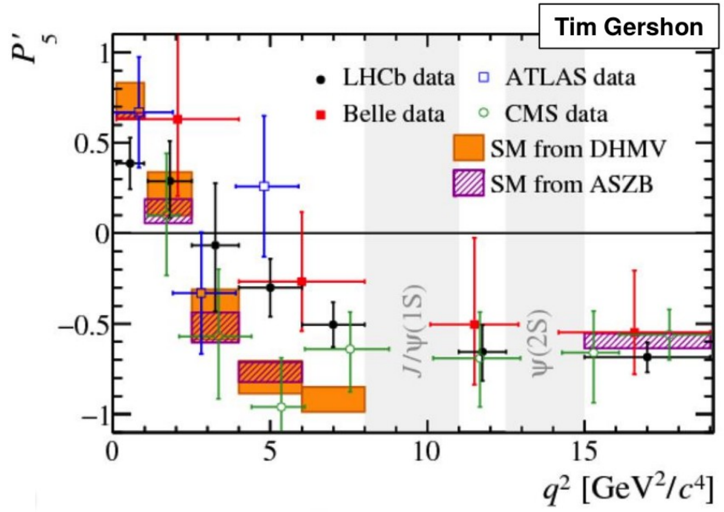
BACKUP

- Heavy flavor physics is a robust probe of new physics through loop contributions

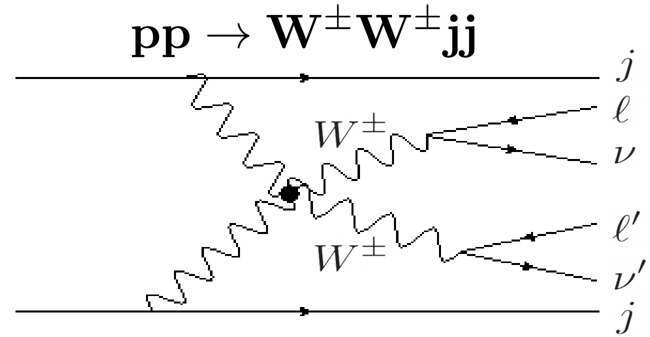
Angular analysis of $B_d \rightarrow K^* \mu\mu$

- P5' amplitude parameter measured to exceed SM expectation at moderate $q^2 = m(\mu\mu) \sim 5$ GeV^2 by LHCb and Belle
- ATLAS analysis with 8 TeV Run-1 data consistent with SM but also with LHCb and Belle measurements

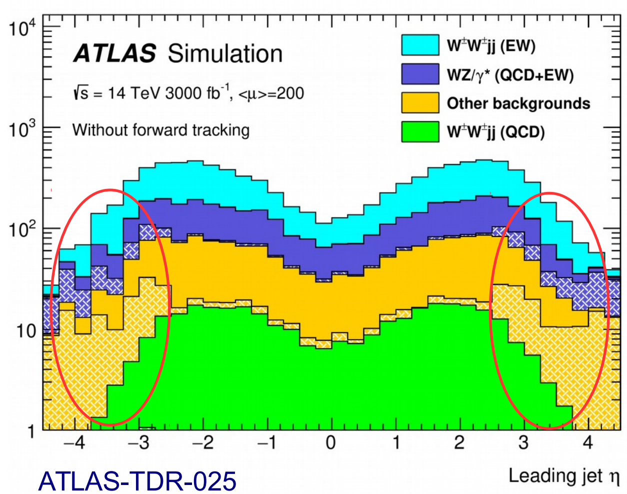




- Golden channel: pp → $W^\pm W^\pm$ jj
- First evidence from Run-1 data
  - σ ~1 fb @ 8 TeV, Δσ / σ ~ 30%

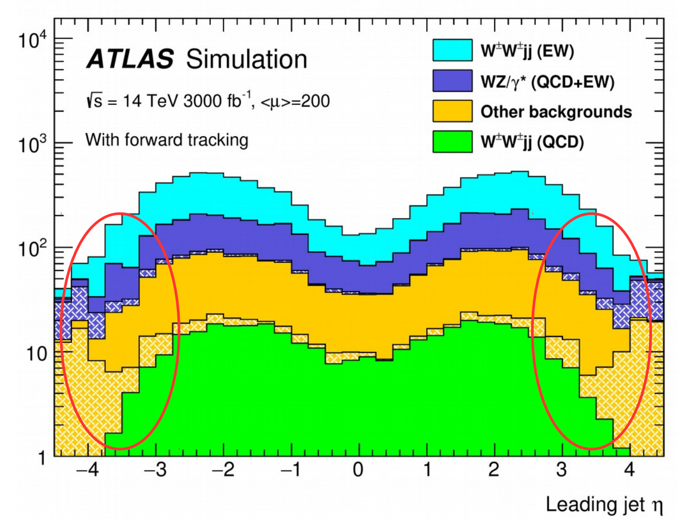


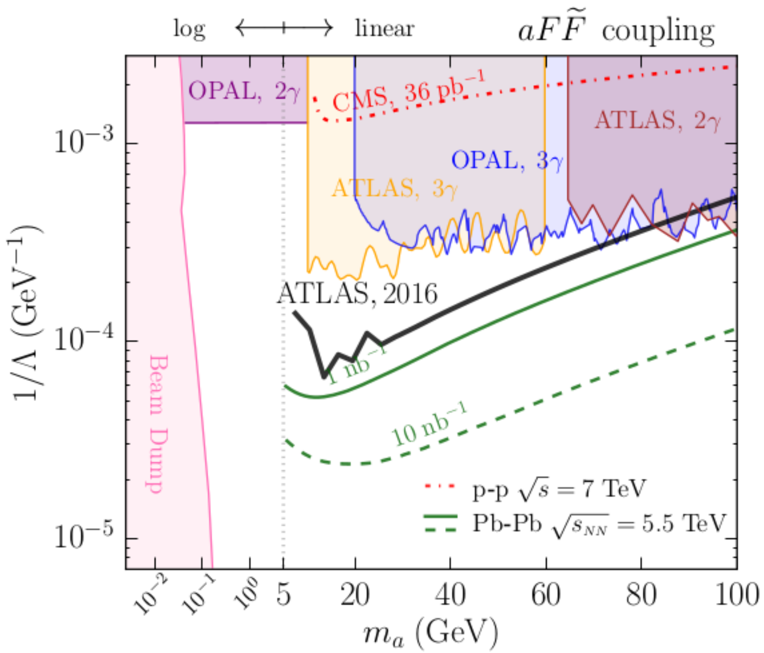
- Greatly profit from large dataset and extended tracker coverage
- Expect Δσ / σ ~ 4% by end of HL-LHC
  → differential cross section measurements become possible
  → Sensitivity to higher mass resonances 2-3 TeV → 4-6 TeV



|η| tracking coverage

2.5 → 4.0




log ⟷ linear
$aF\widetilde{F}$ coupling
OPAL, 2γ
CMS, 36 pb^{-1}
ATLAS, 2γ
OPAL, 3γ
ATLAS, 3γ
ATLAS, 2016
1 nb^{-1}
10 nb^{-1}
Beam Dump
p-p $\sqrt{s} = 7$ TeV
Pb-Pb $\sqrt{s_{NN}} = 5.5$ TeV
$1/\Lambda$ (GeV^{-1})
m_a (GeV)