ATLAS and CMS: The Current Physics Landscape at the LHC

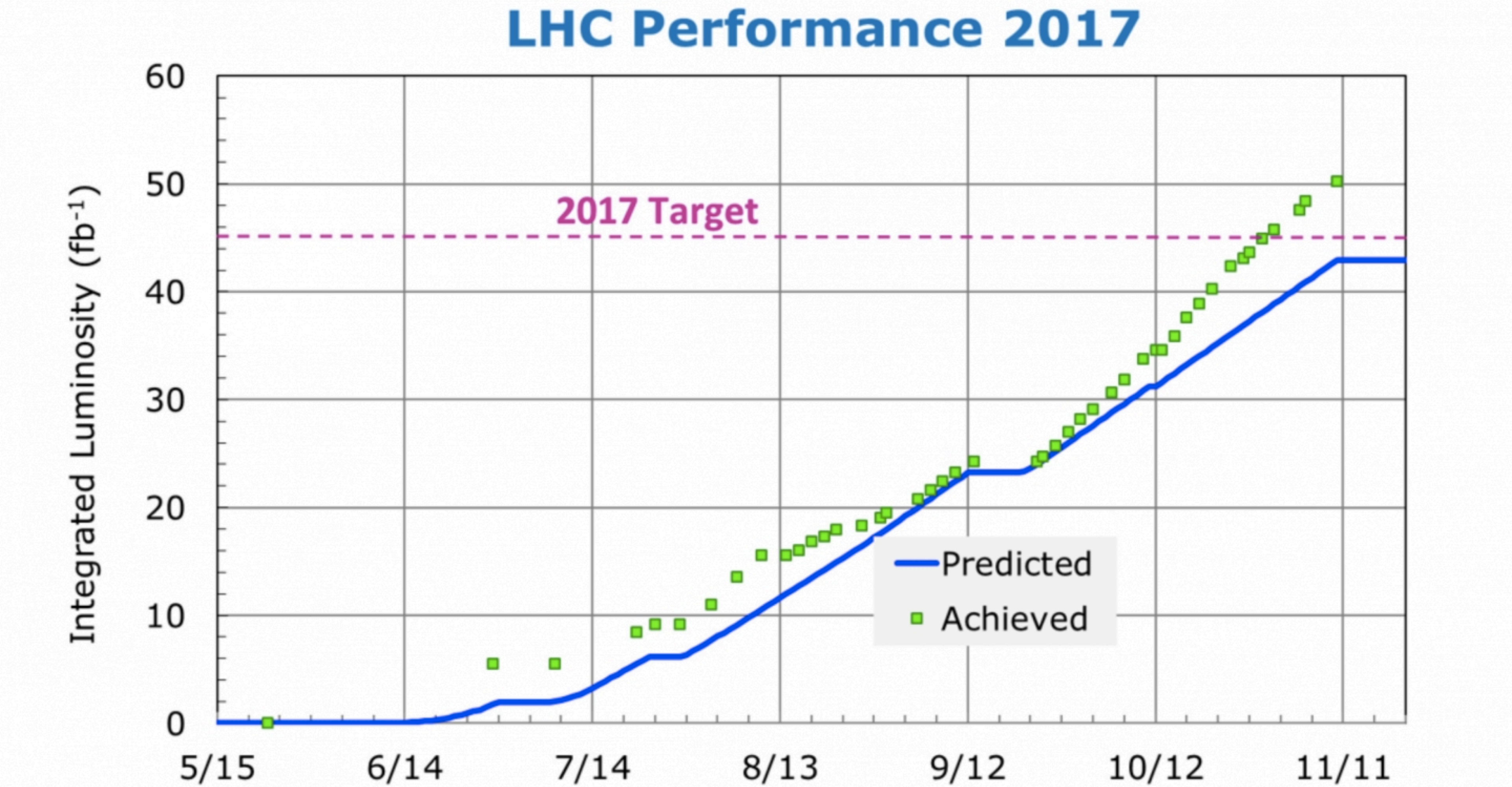
Lake Louise Winter Institute
January 19, 2018

Sarah Demers, Yale University
On behalf of ATLAS and CMS

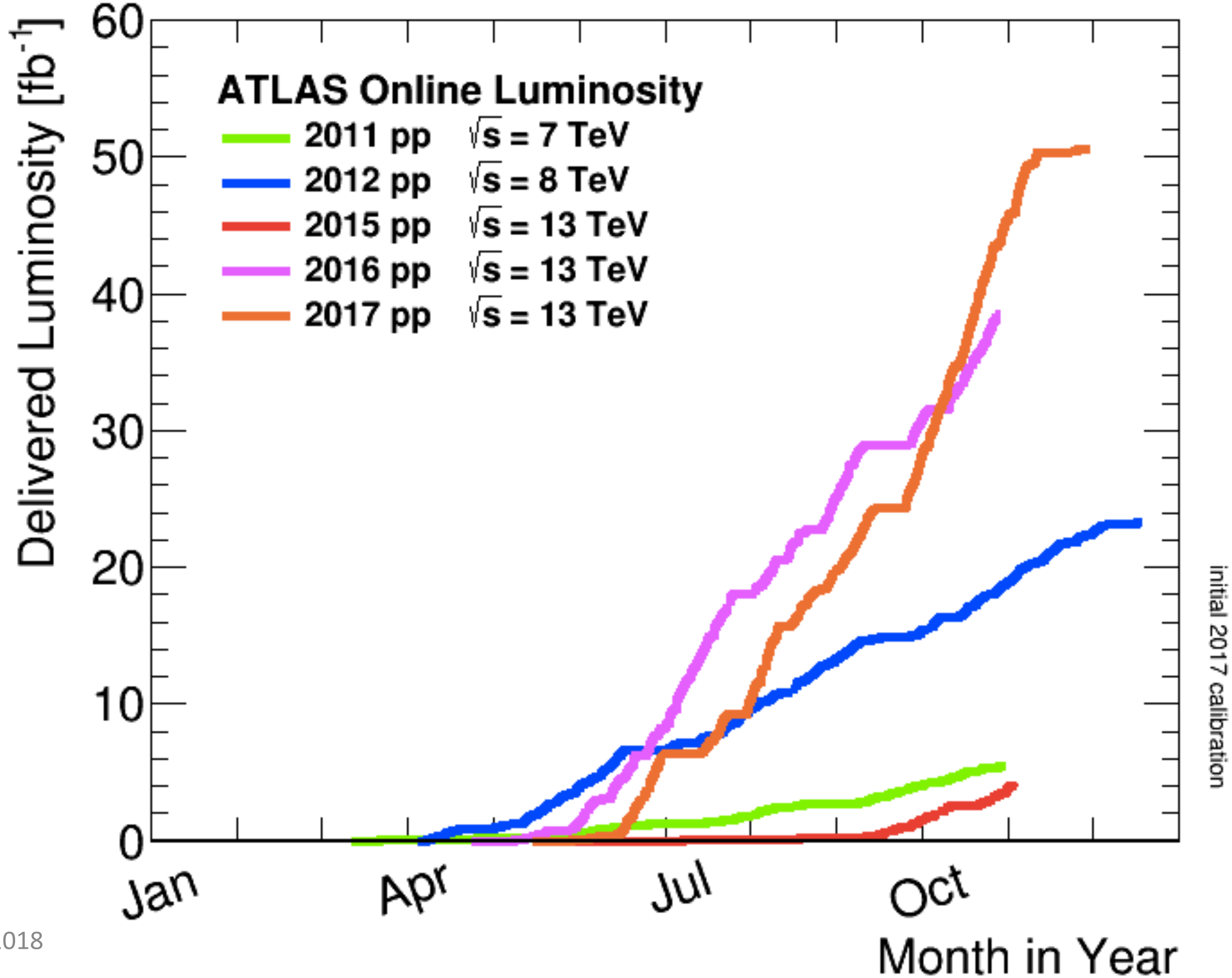
Outline

- **LHC, ATLAS, and CMS Performance**
  - *how much data and under what conditions*
- The Searches
  - *fueled by a jump in energy and luminosity*
- The Measurements
  - *precision measurements, and measurements as searches*
- The Higgs
  - *improved sensitivities and new channels*

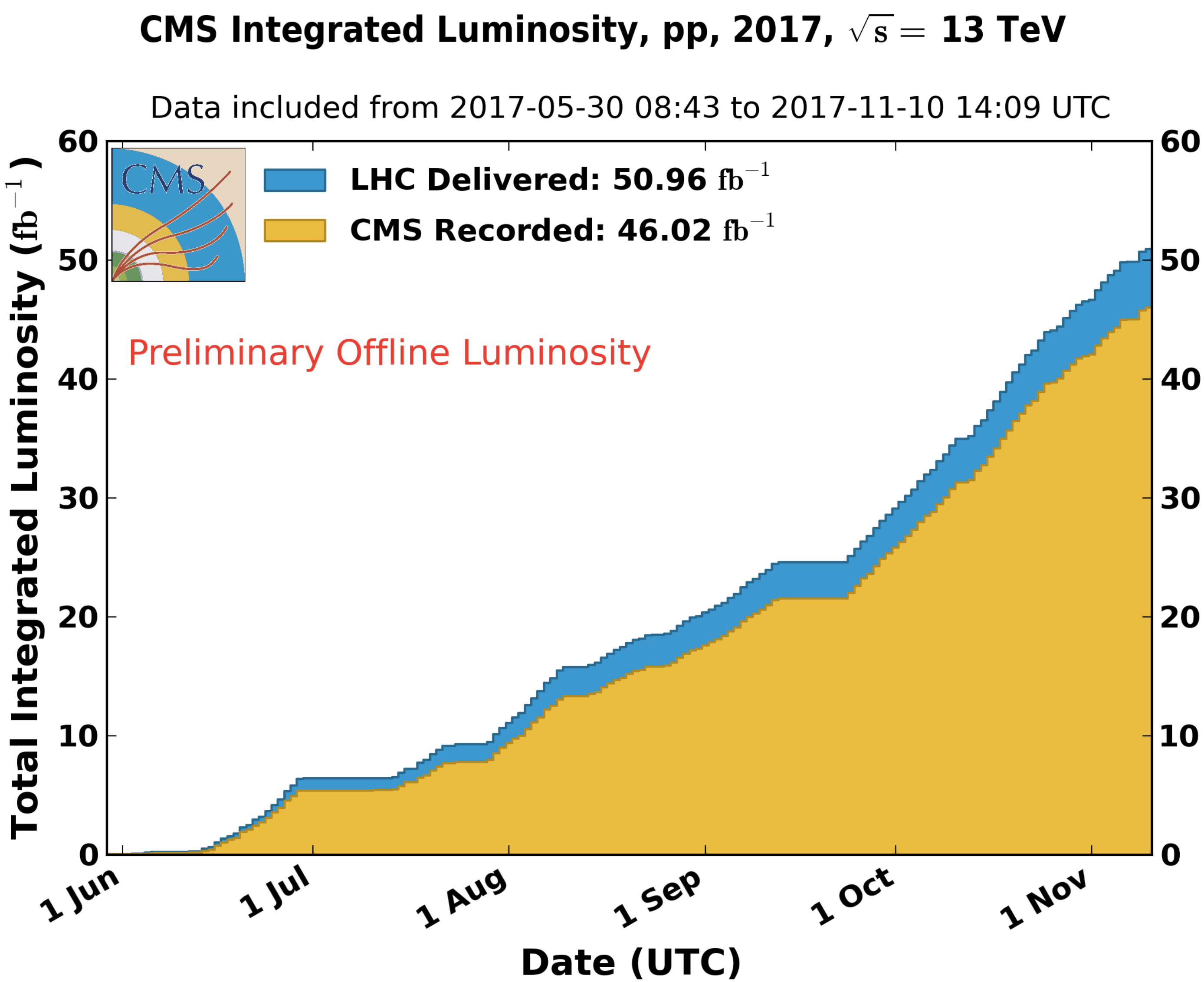
The LHC delivered 50 fb^{-1} to ATLAS and CMS in 2017



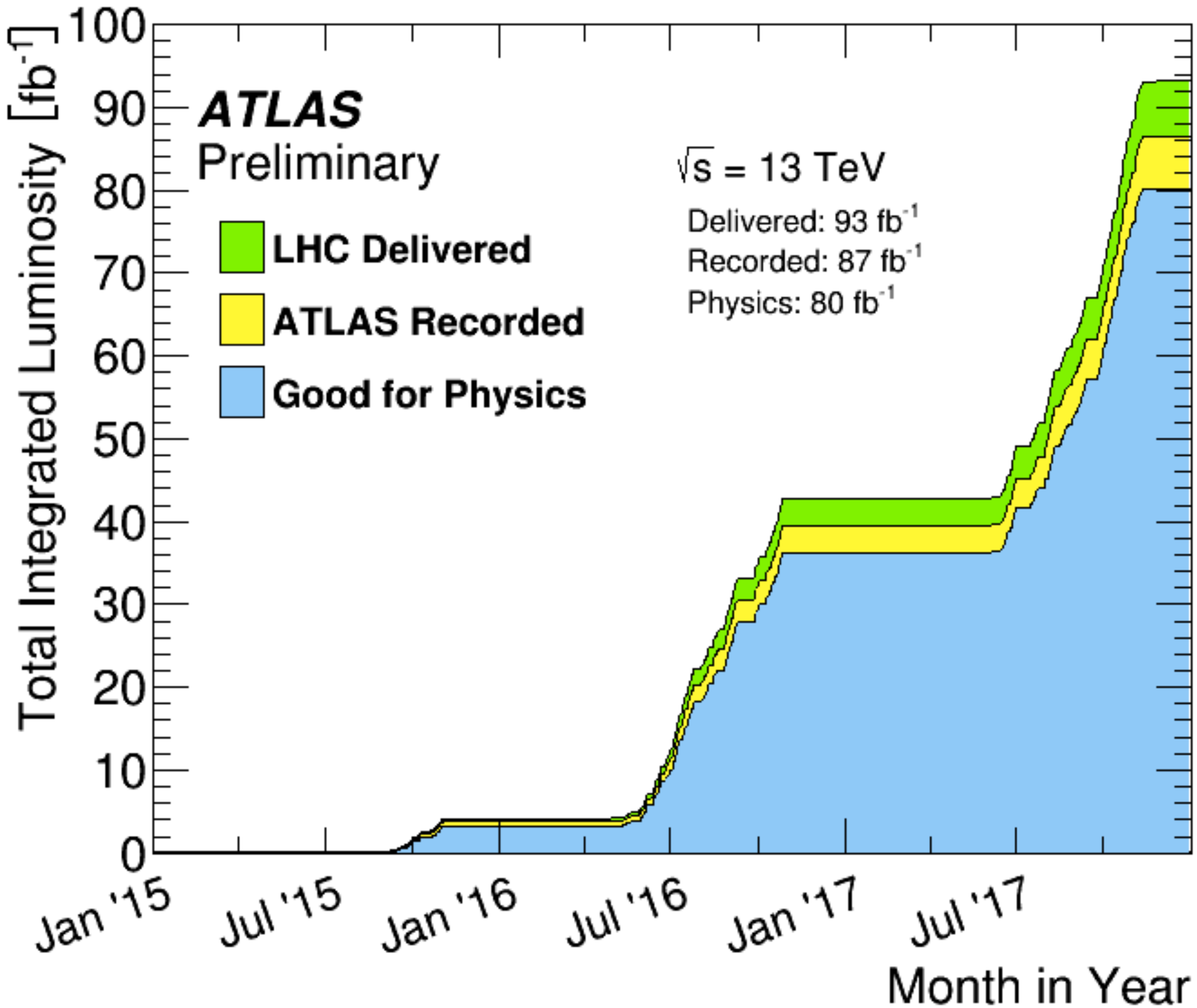
2017 was a Banner Year



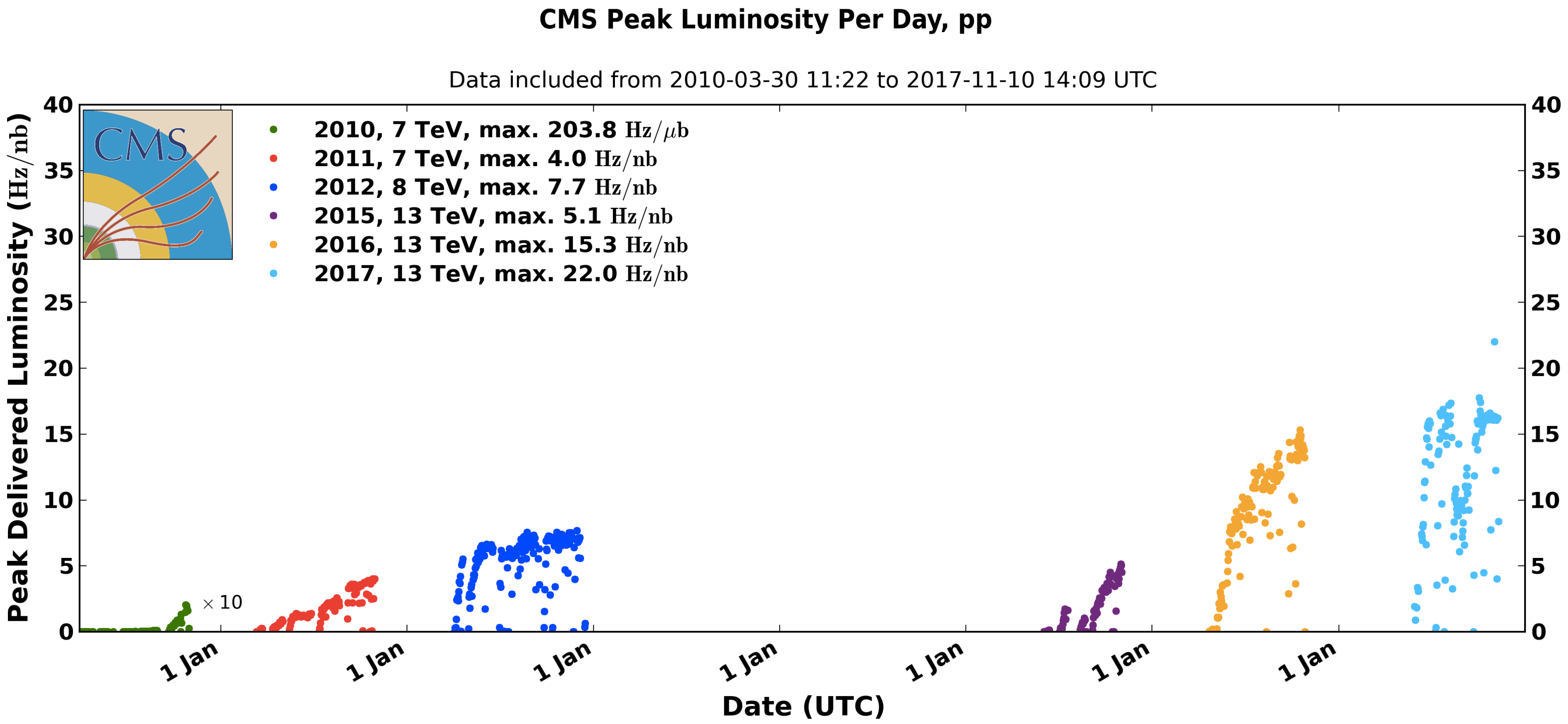
CMS and ATLAS recorded a high fraction of the delivered data



Much of the data we record passes our strict requirements for physics analysis

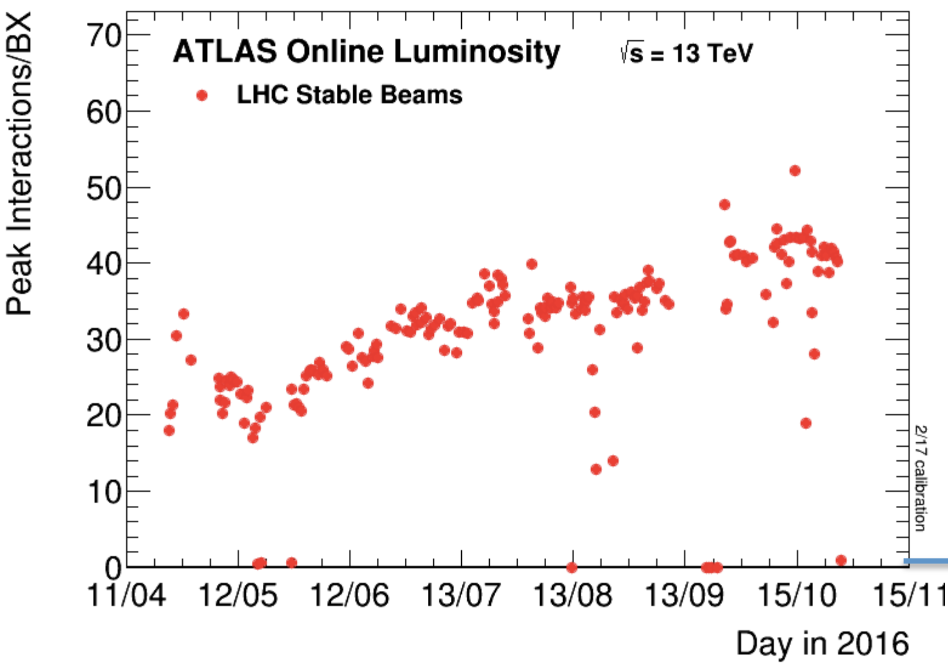


Experimental conditions are quite challenging, as we are operating above our design luminosity

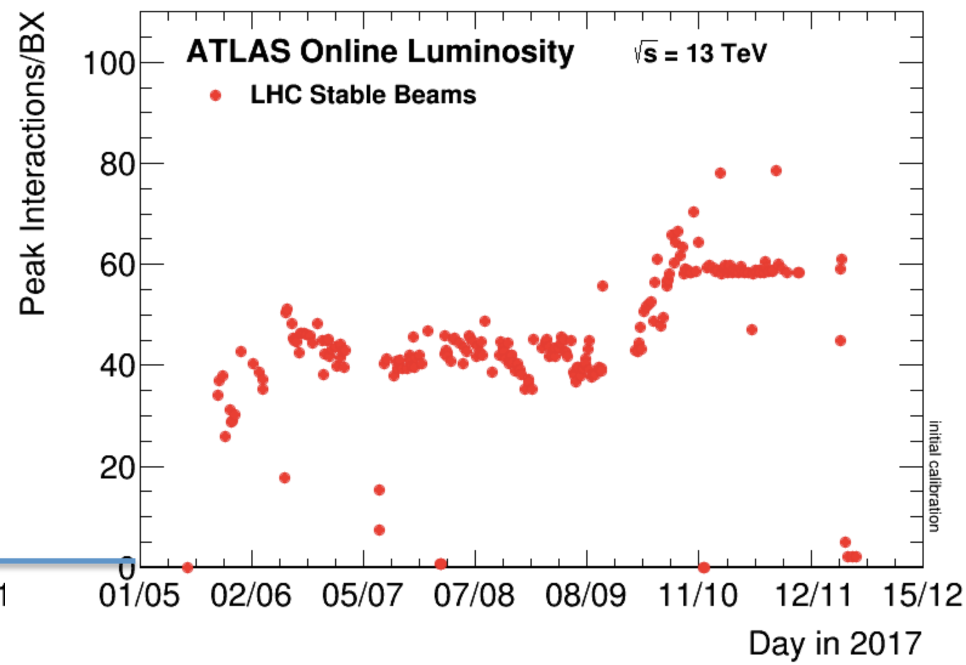


This translates into events with many (~60 in 2018) overlapping simultaneous interactions in our detectors

2016



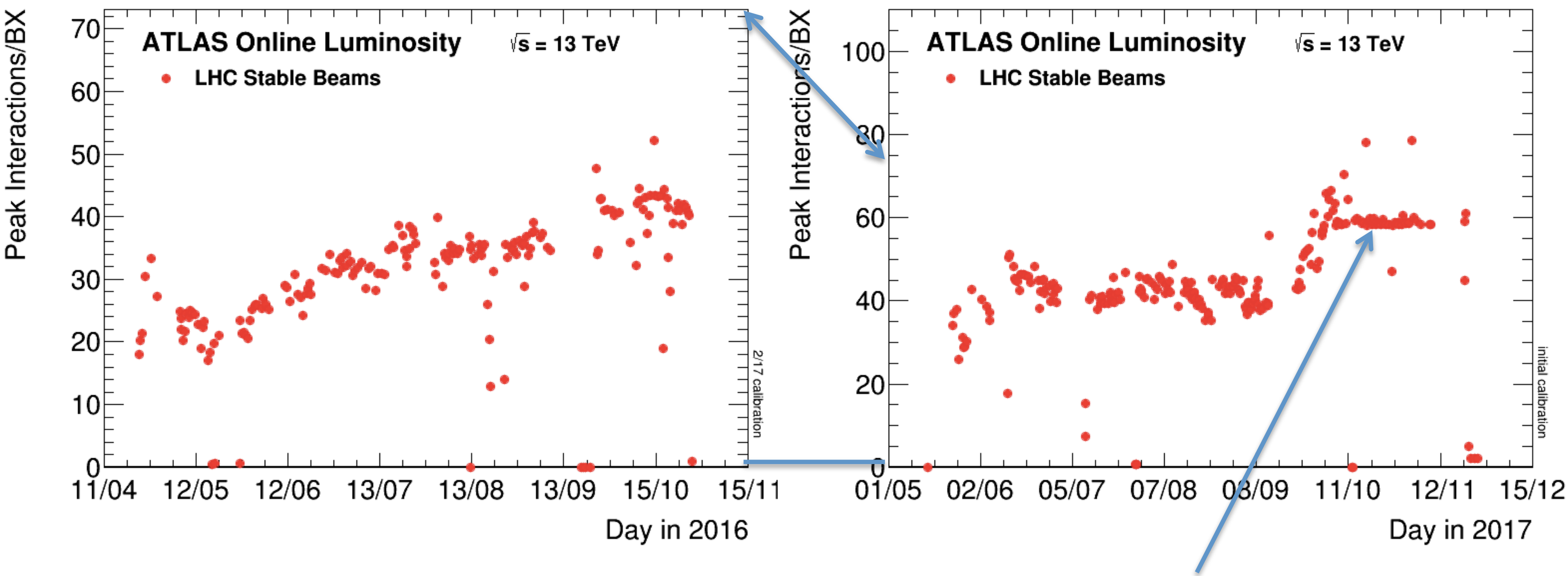
2017



From 2556 bunches to 1920 (8b4e structure)

This translates into events with many (~60 in 2018) overlapping simultaneous interactions in our detectors

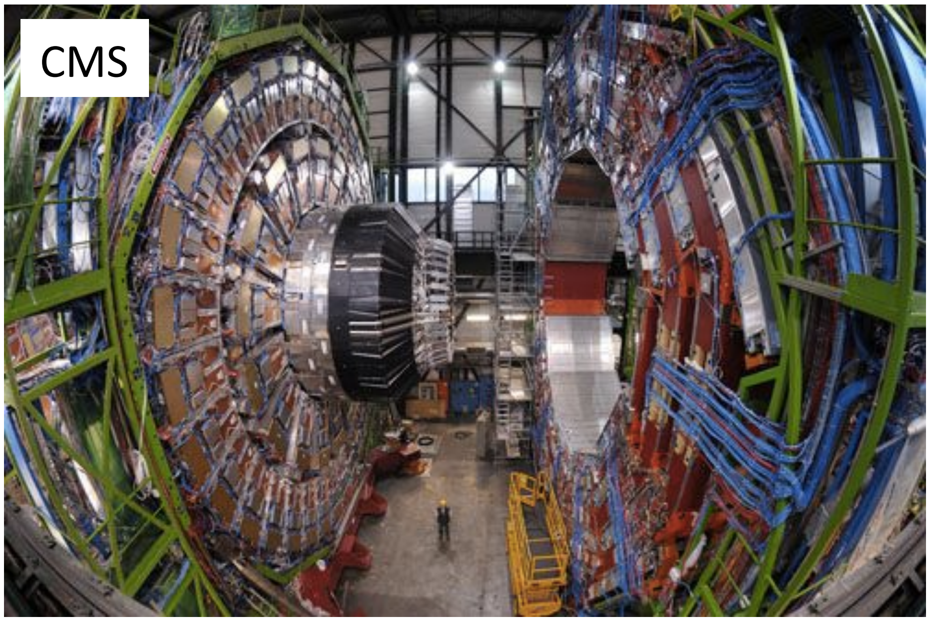
2016 2017

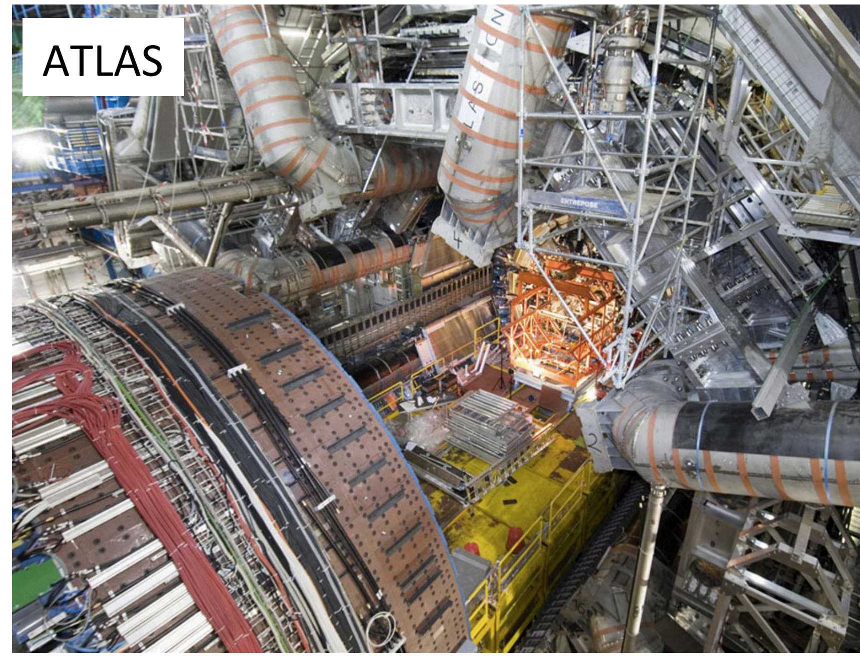


From 2556 bunches to 1920 (8b4e structure)

Our Detectors and DAQ

- Radiation hard precision tracking using silicon near the beampipe
- High granularity calorimeters
- Muon chambers surrounding interaction region





Many techniques have been developed to maintain performance in the face of high pile-up

Some of our best techniques use tracking information, where the extent of the interaction region enables separating vertices. We do not have access to tracking information at our first level trigger. Isolation requirements can become inefficient in high-pileup environments

Physics Organization

ATLAS

B Physics and Light States
Standard Model
Top
Higgs
Supersymmetry
Exotics
Heavy Ions

CMS

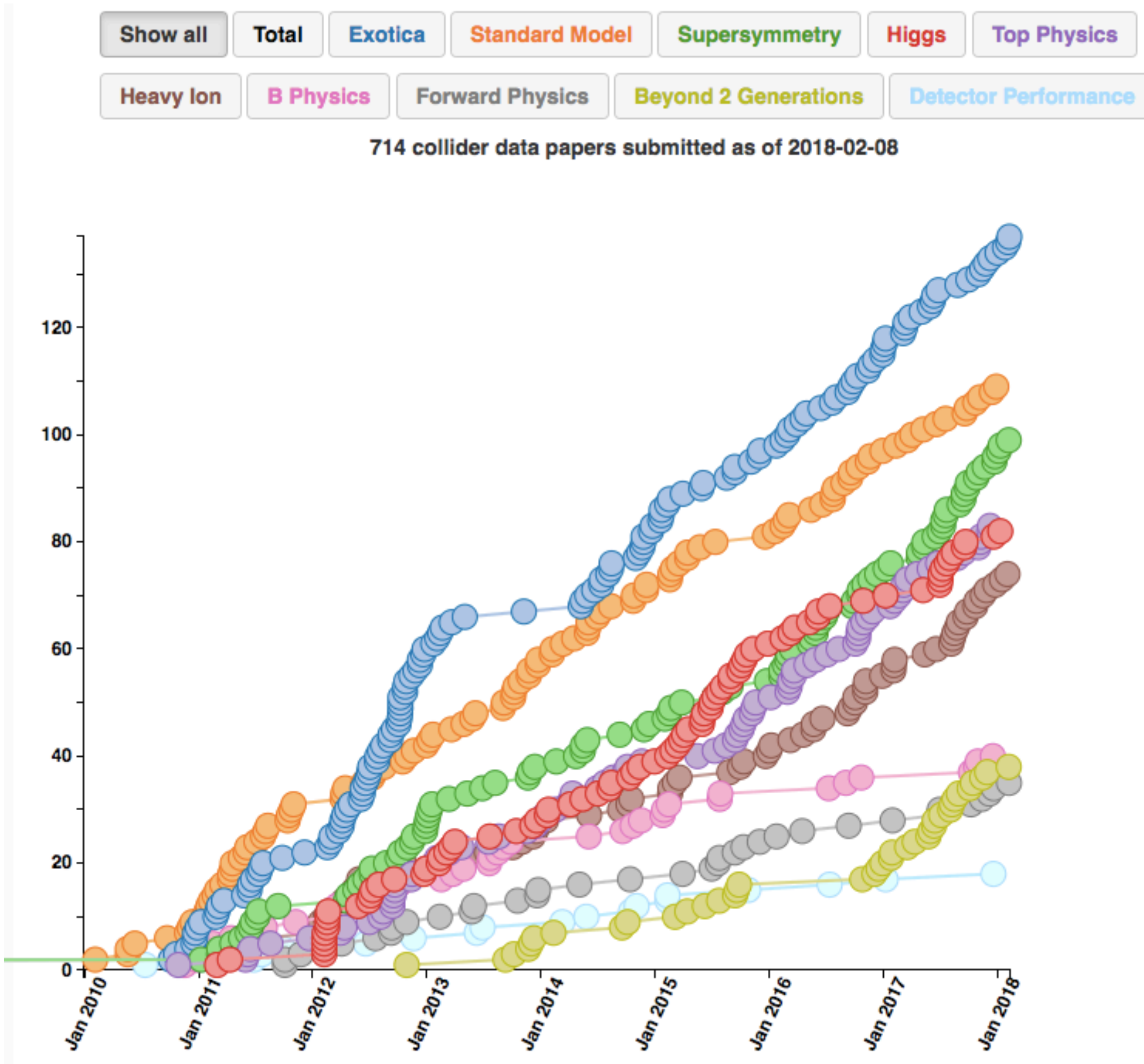
Forward Physics
B Physics and Quarkonia
Standard Model Physics
Top Physics
Higgs Physics
Supersymmetry
Exotica
Beyond 2 Generations
Heavy-Ion Physics

There are hundreds of exciting analyses I could discuss.
I have chosen highlights that give you a sense of our current capabilities.
There are many talks this week that will go into greater detail.

ATLAS Public Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS Public Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/

Analyzers have been busy…



an interactive plot from CMS:
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

What's New?

It's instructive to take a look at the most recently published papers coming out of the LHC… There are exciting searches with new data and some beautiful measurements from $\sqrt{s}$ = 7 and $\sqrt{s}$ = 8 TeV!

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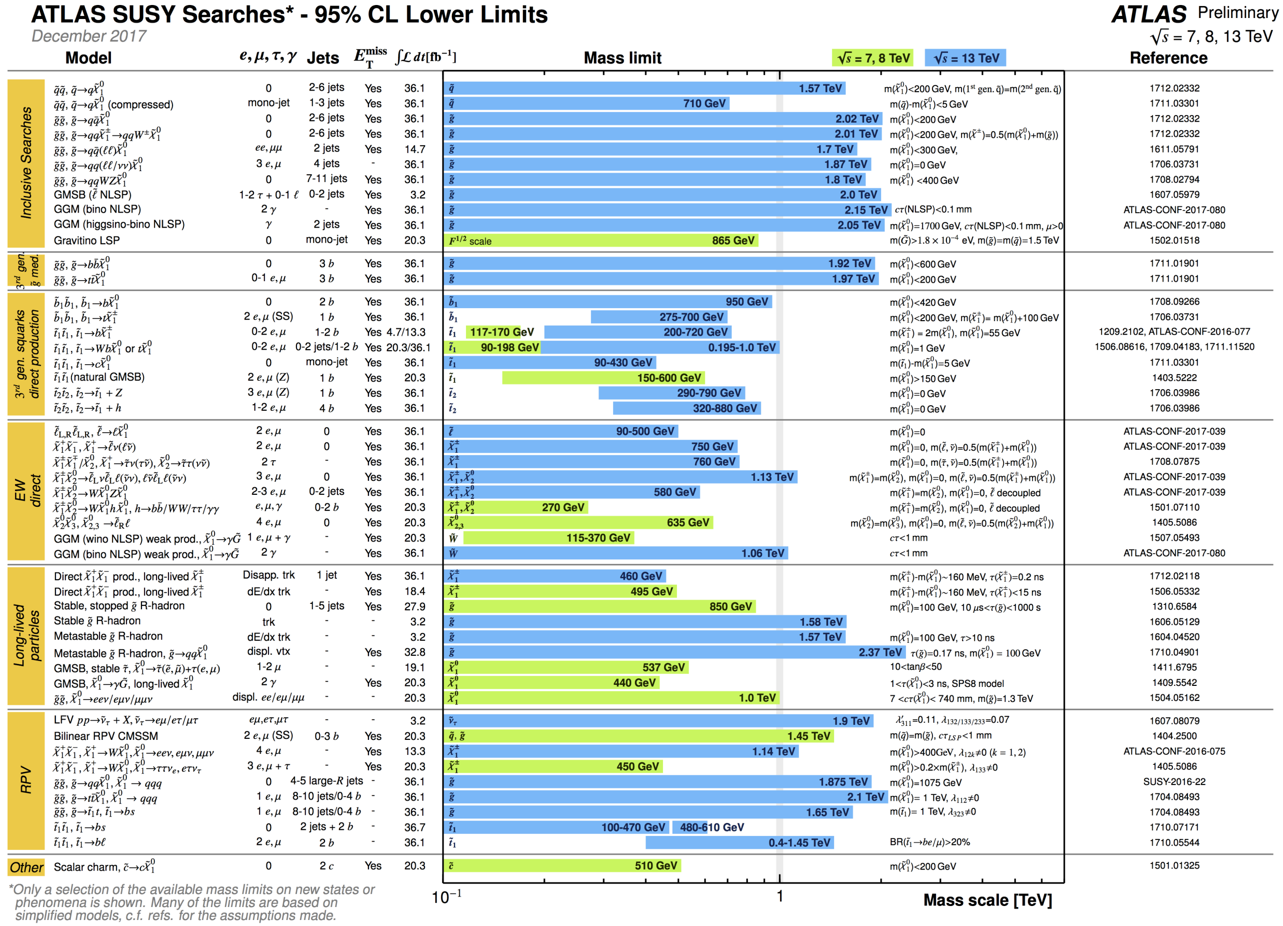
Strong production

Naturalness and stops

Electroweak production

Relax assumptions
(R parity violating)



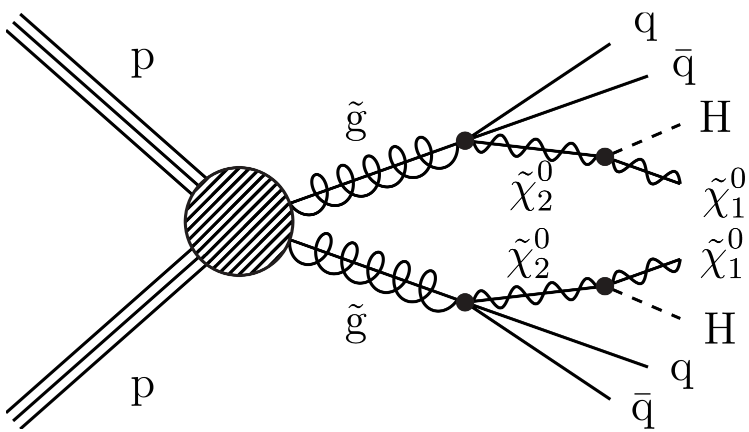
SUPERSYMMETRY RESULTS

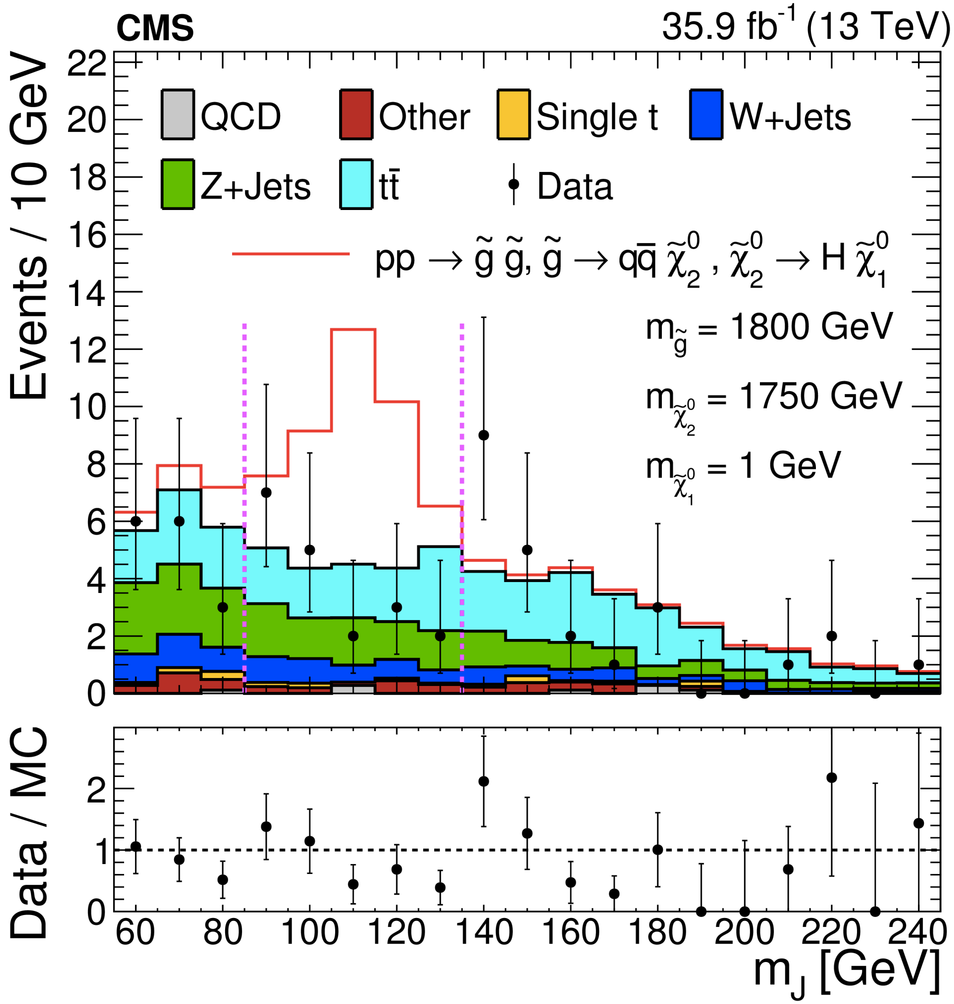
ATLAS Supersymmetry Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS Supersymmetry Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

High transverse momentum Higgs bosons + missing transverse energy

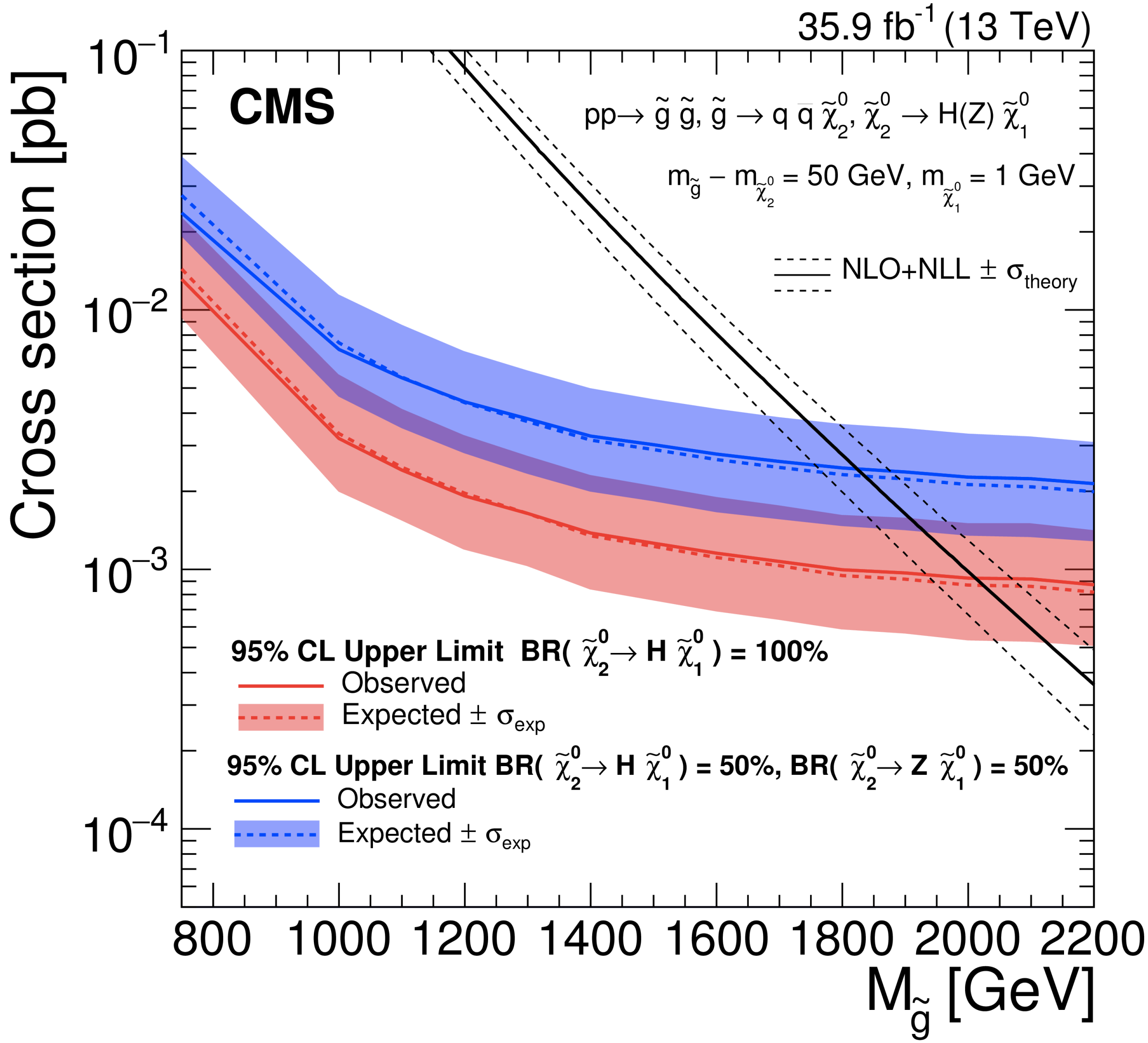
Higgs Bosons produced via gluino pair production





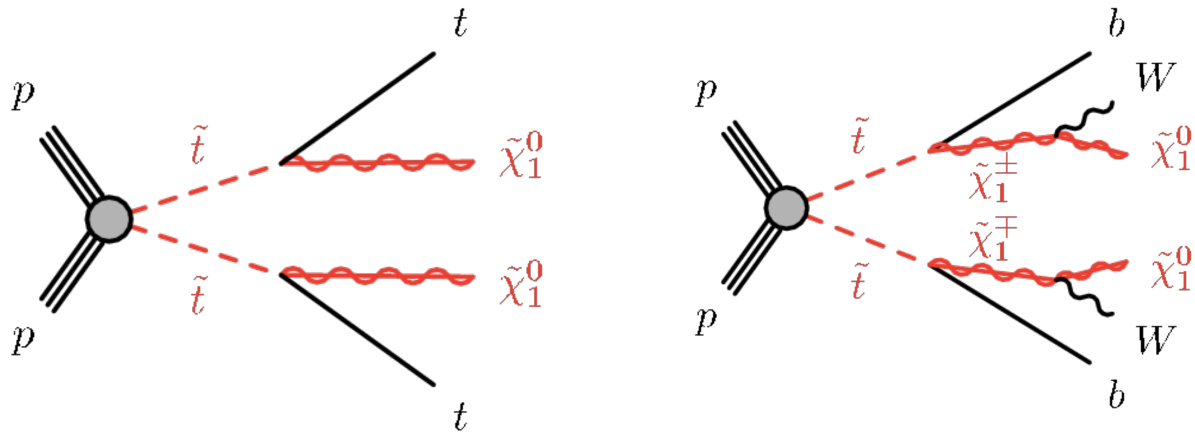
https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-17-006/index.html

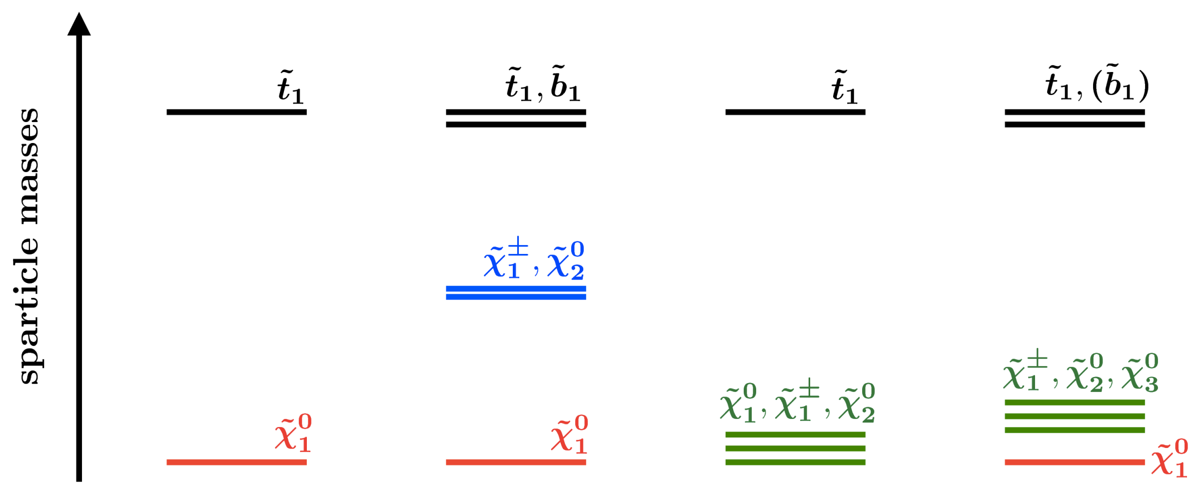
High transverse momentum Higgs bosons + missing transverse energy



https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-17-006/index.html

Top squark pair production with one lepton, jets and missing transverse energy

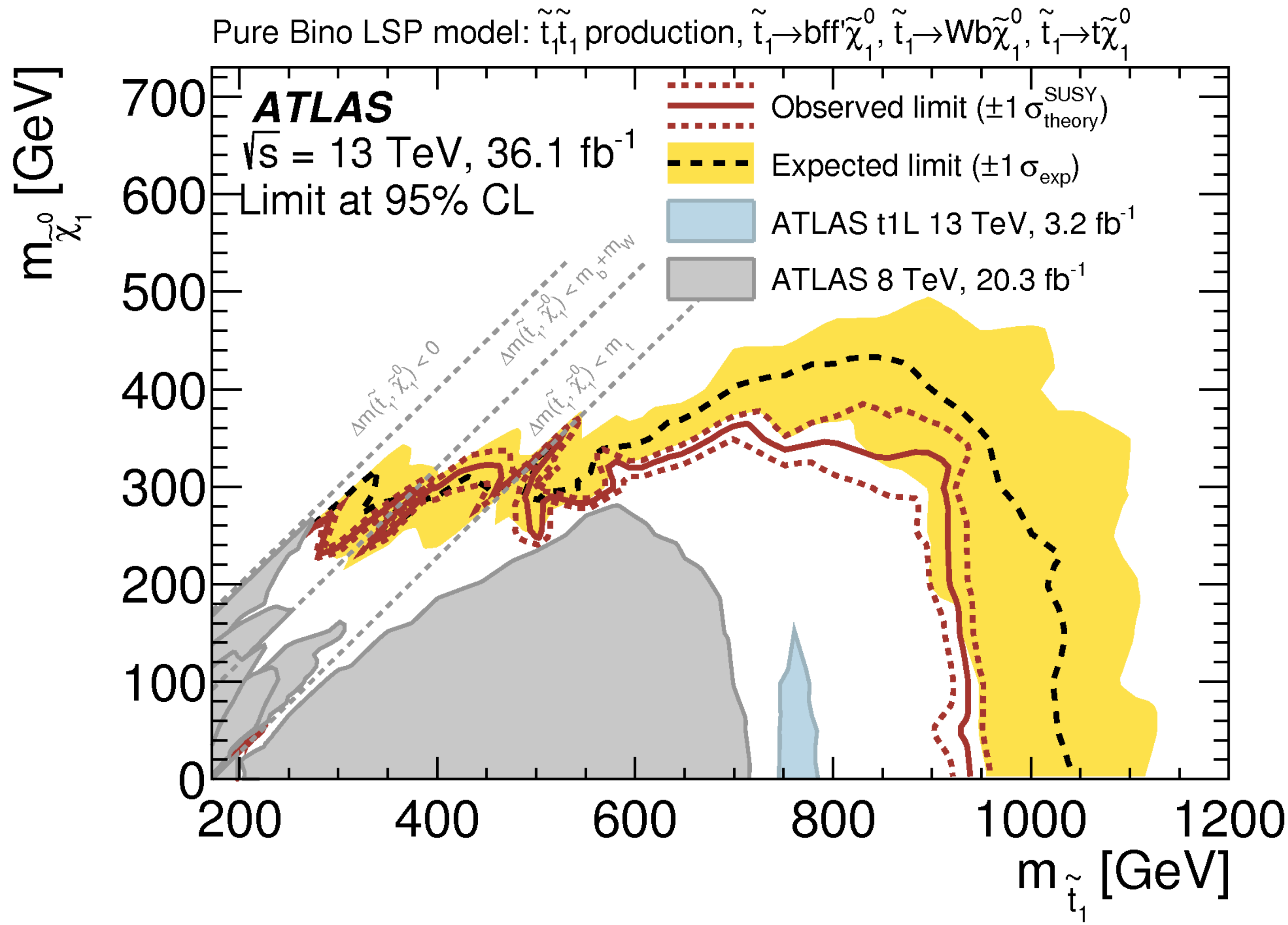




a) pure bino LSP b) wino NLSP c) higgsino LSP d) bino/higgsino mix

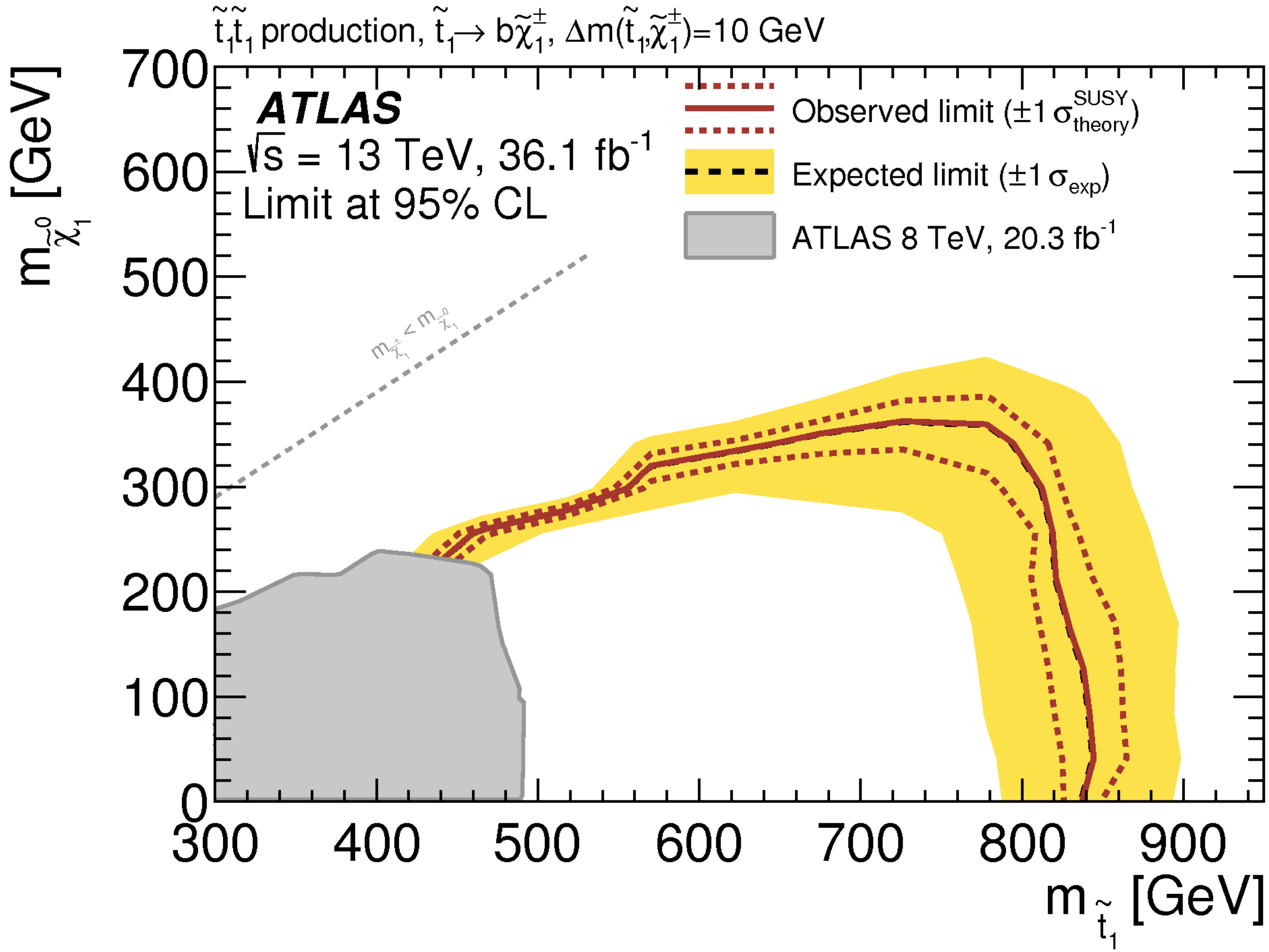
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-16/

Top squark pair production with one lepton, jets and missing transverse energy



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-16/

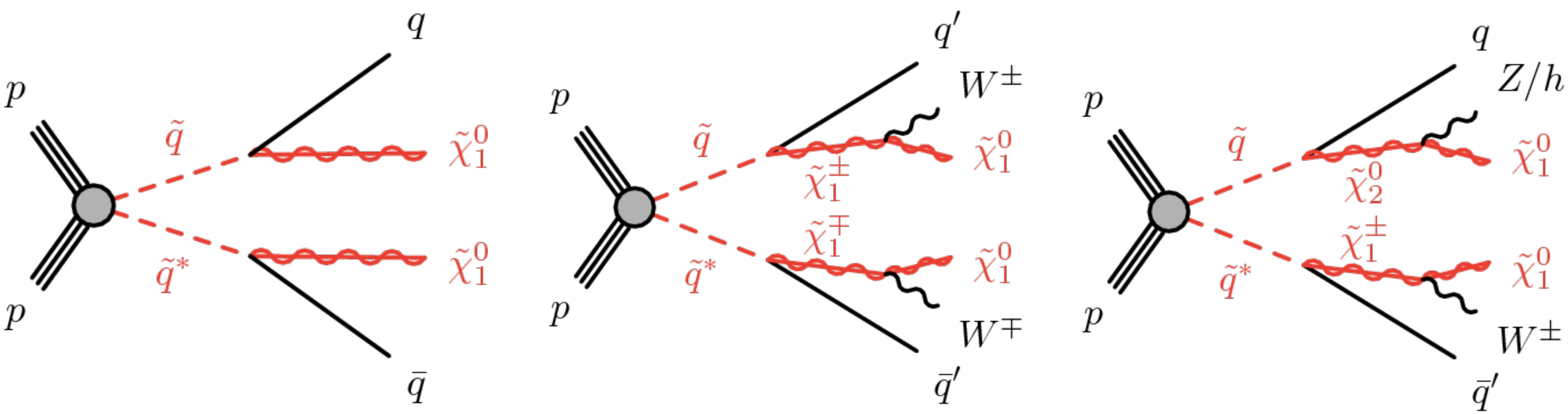
Top squark pair production with one lepton, jets and missing transverse energy



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-16/

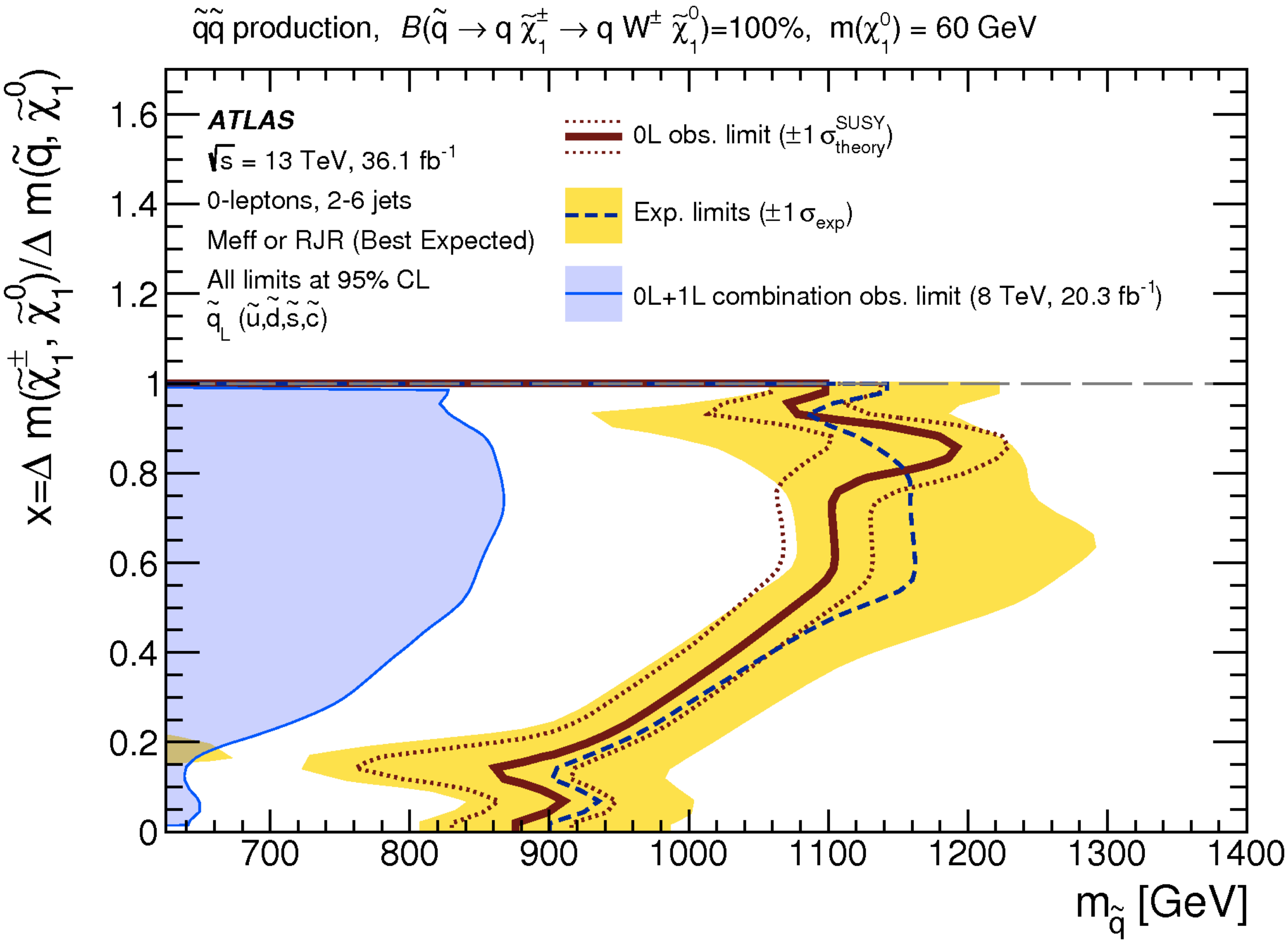
squark and gluino search with jets and missing transverse energy and no leptons

squark pair production



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-07/

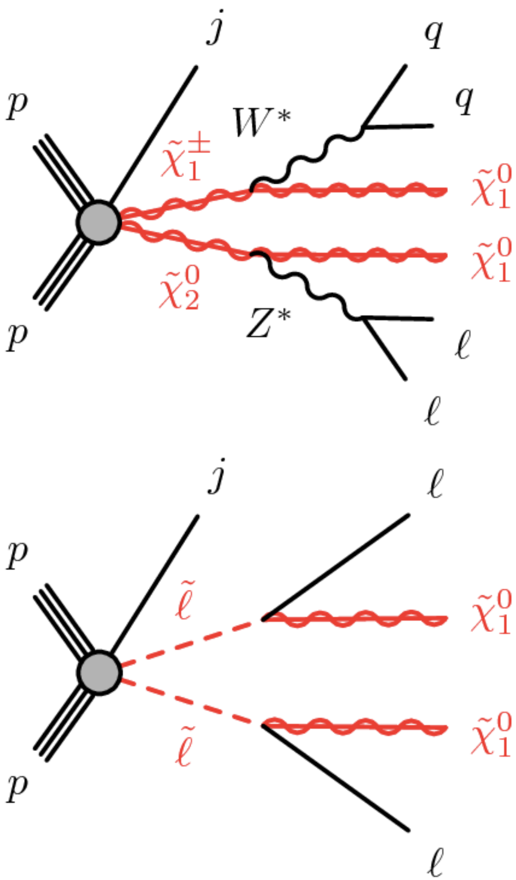
squark and gluino search with jets and missing transverse energy and no leptons



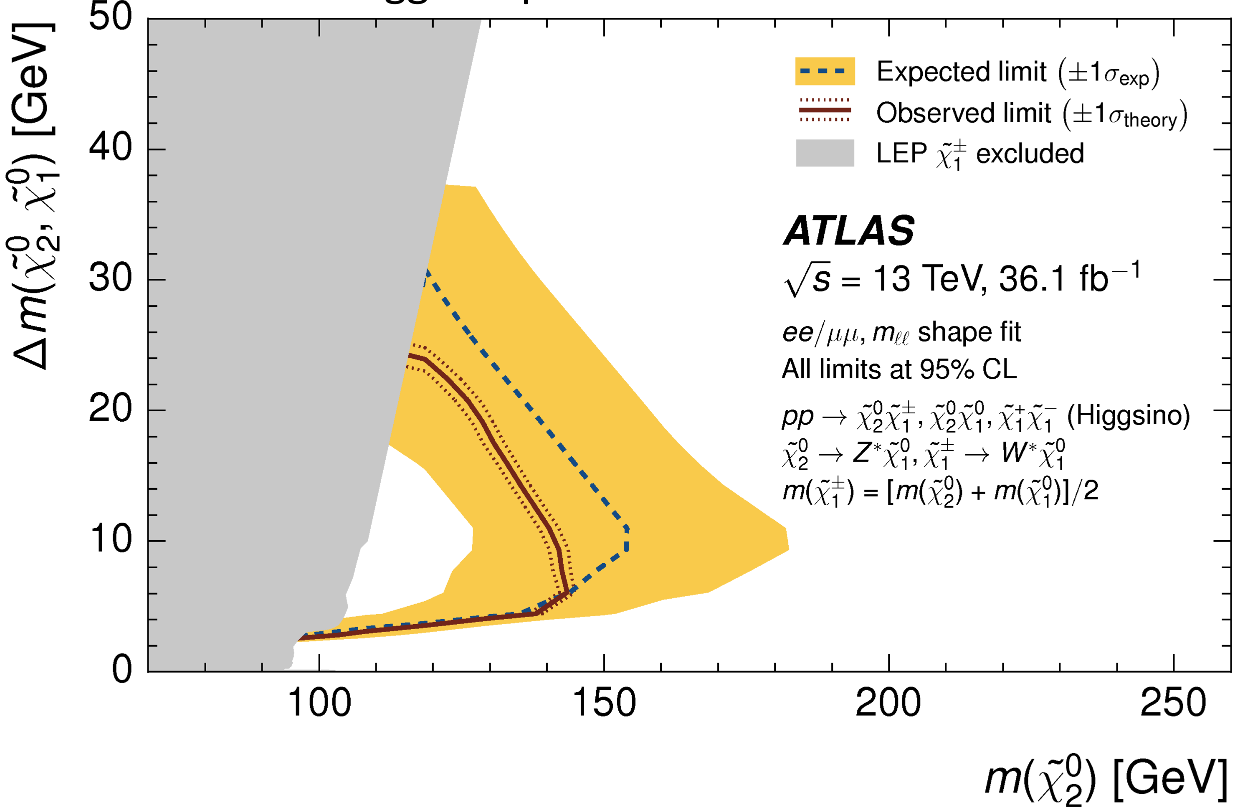
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-07/

Electroweak production w/ compressed mass spectra

Two lepton final state Feynman diagrams for electroweakino and slepton pair production

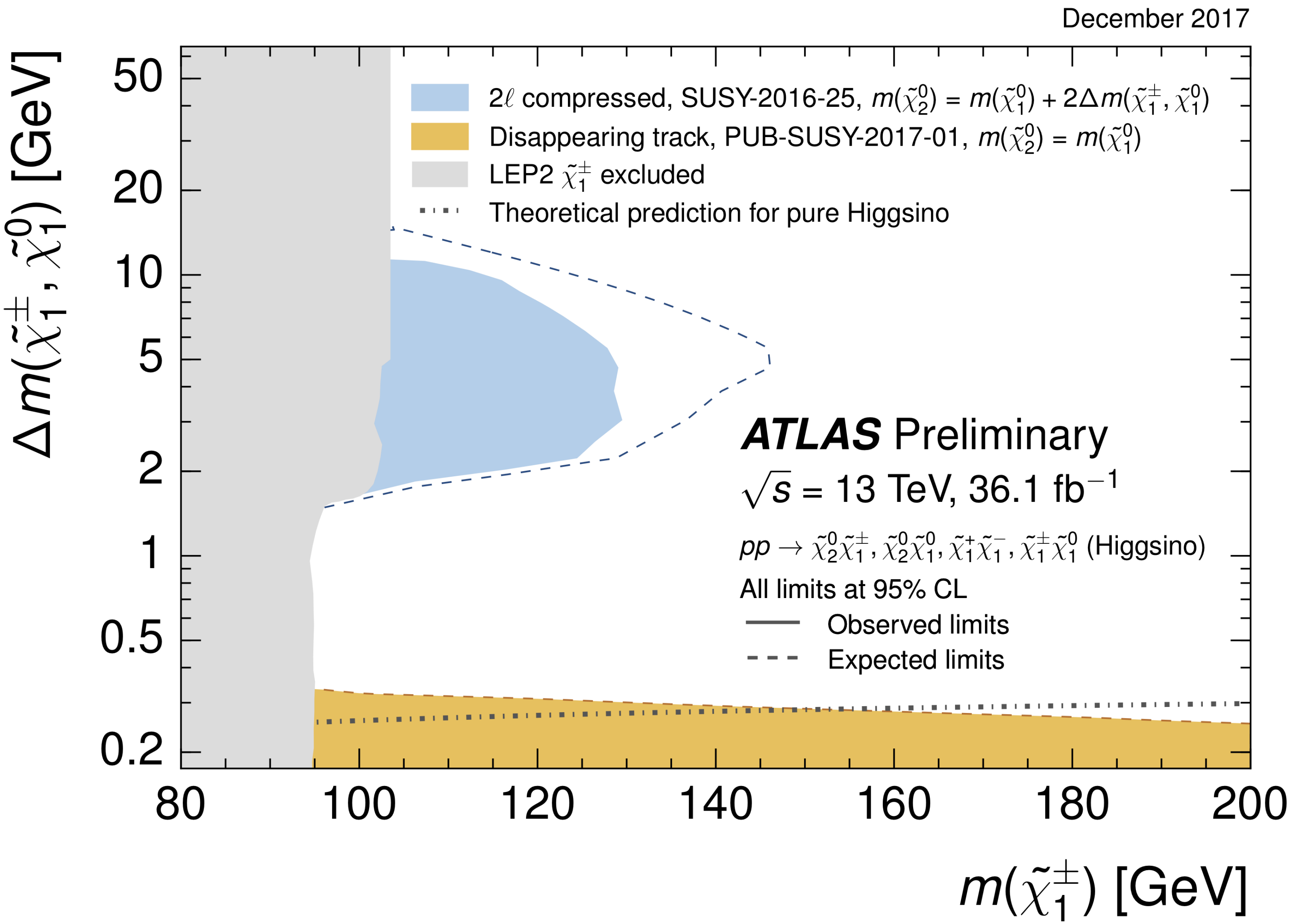


Higgsino production exclusion limit

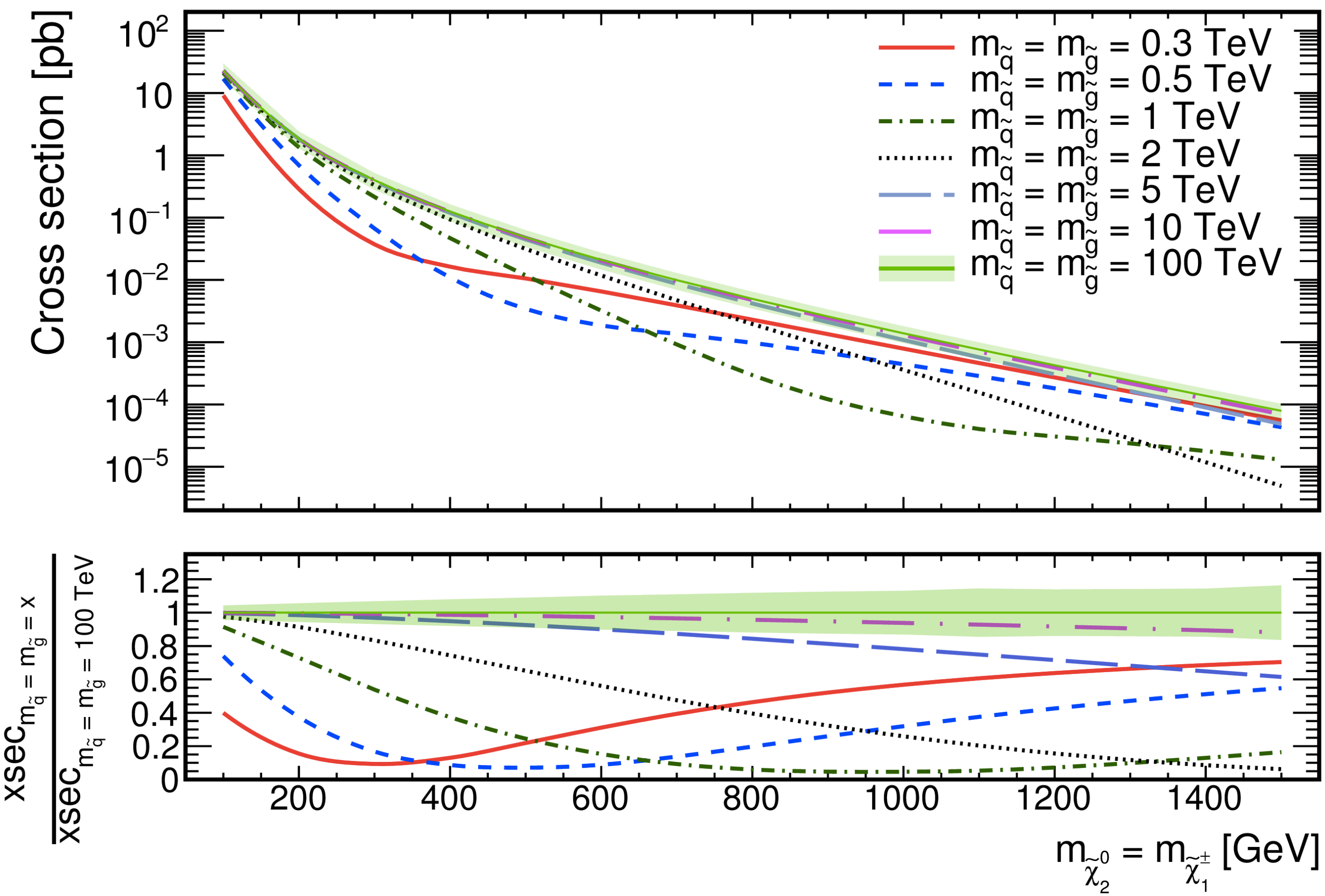


 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-25/

Combination Exclusion Limits (two lepton and disappearing track analyses)



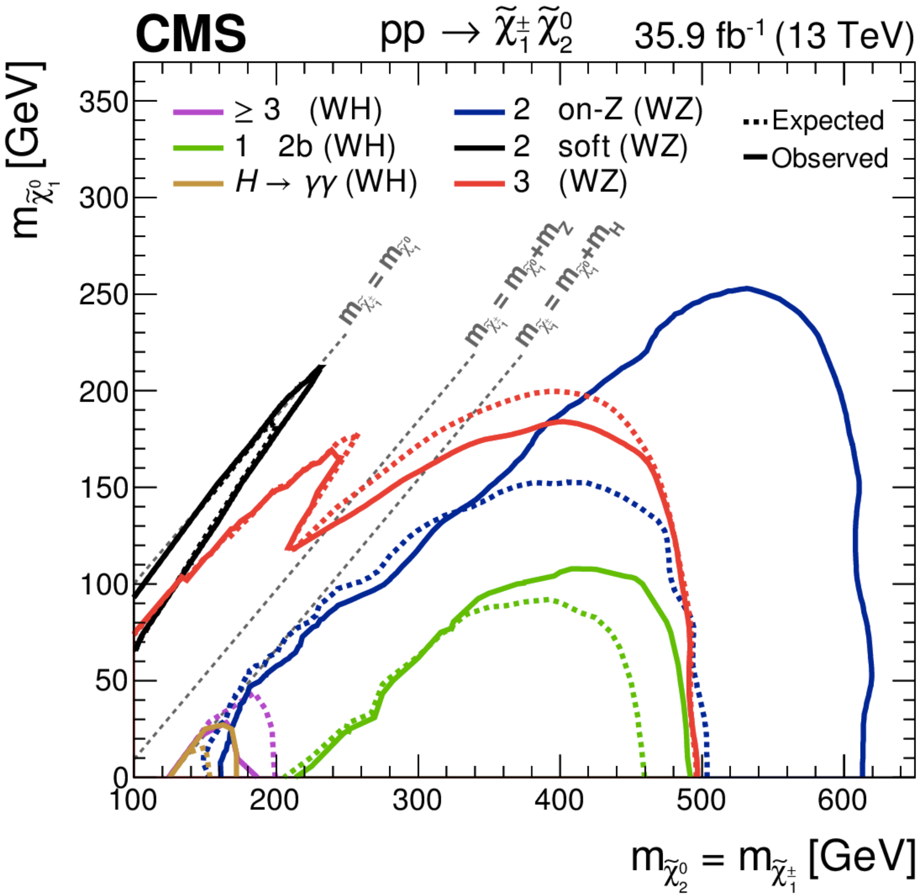
EW production of charginos and neutralinos at √s = 13 TeV



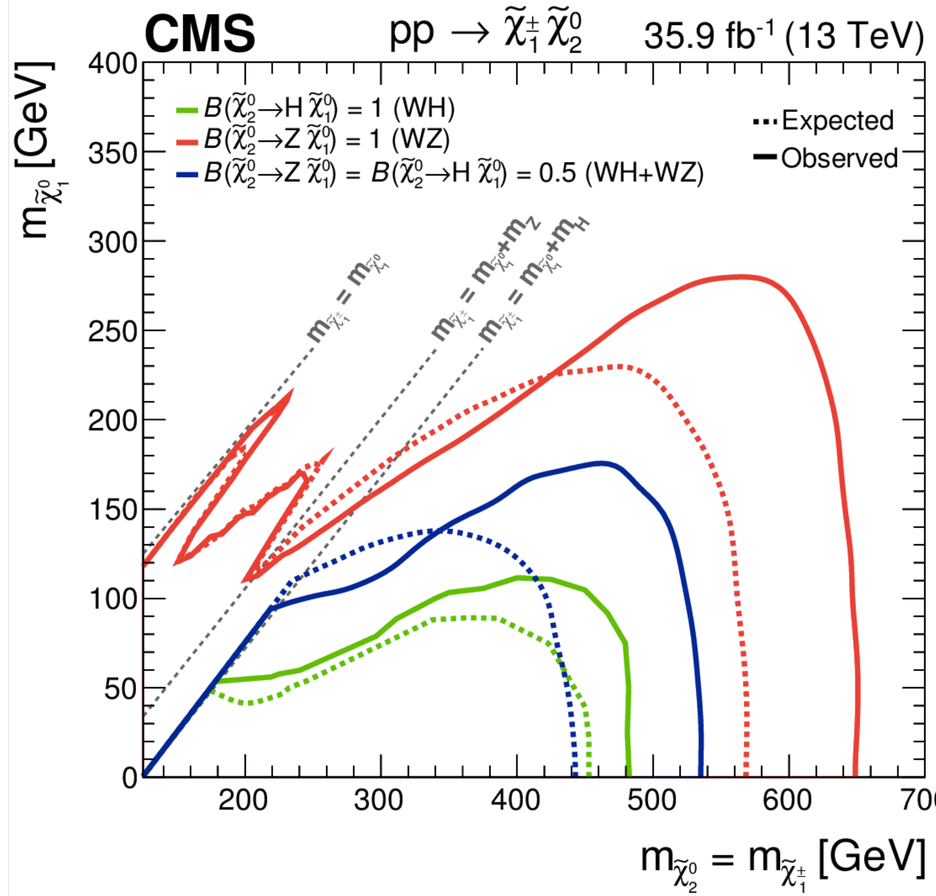
https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-17-004/index.html

EW production of charginos and neutralinos at √s = 13 TeV

Individual channels



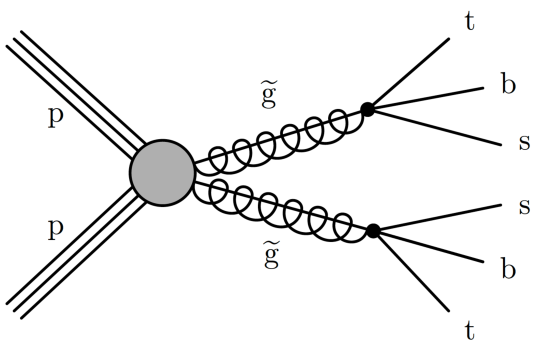
Combination

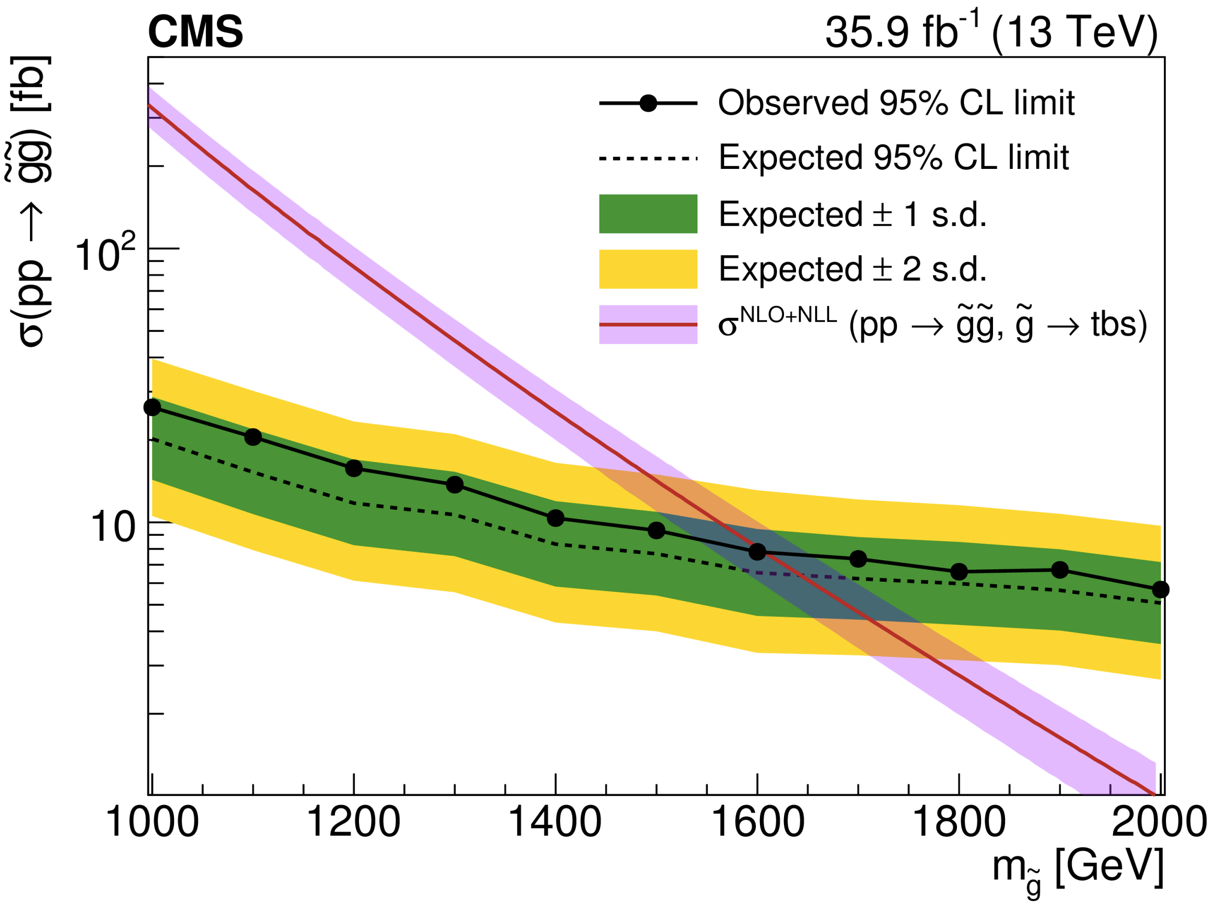


https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-17-004/index.html

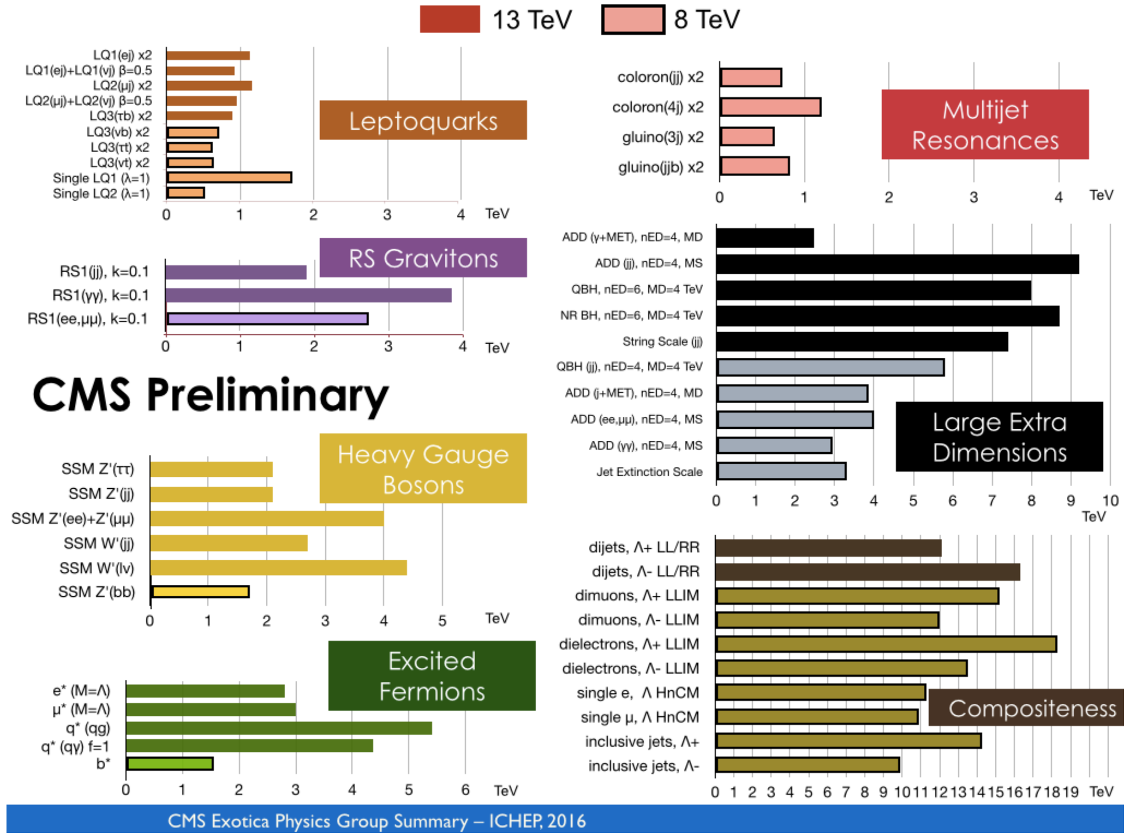
Search for R-parity violating SUSY with one lepton, bjets and high sum of large radius jet masses

Simplified Model Diagram





https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-040/index.html

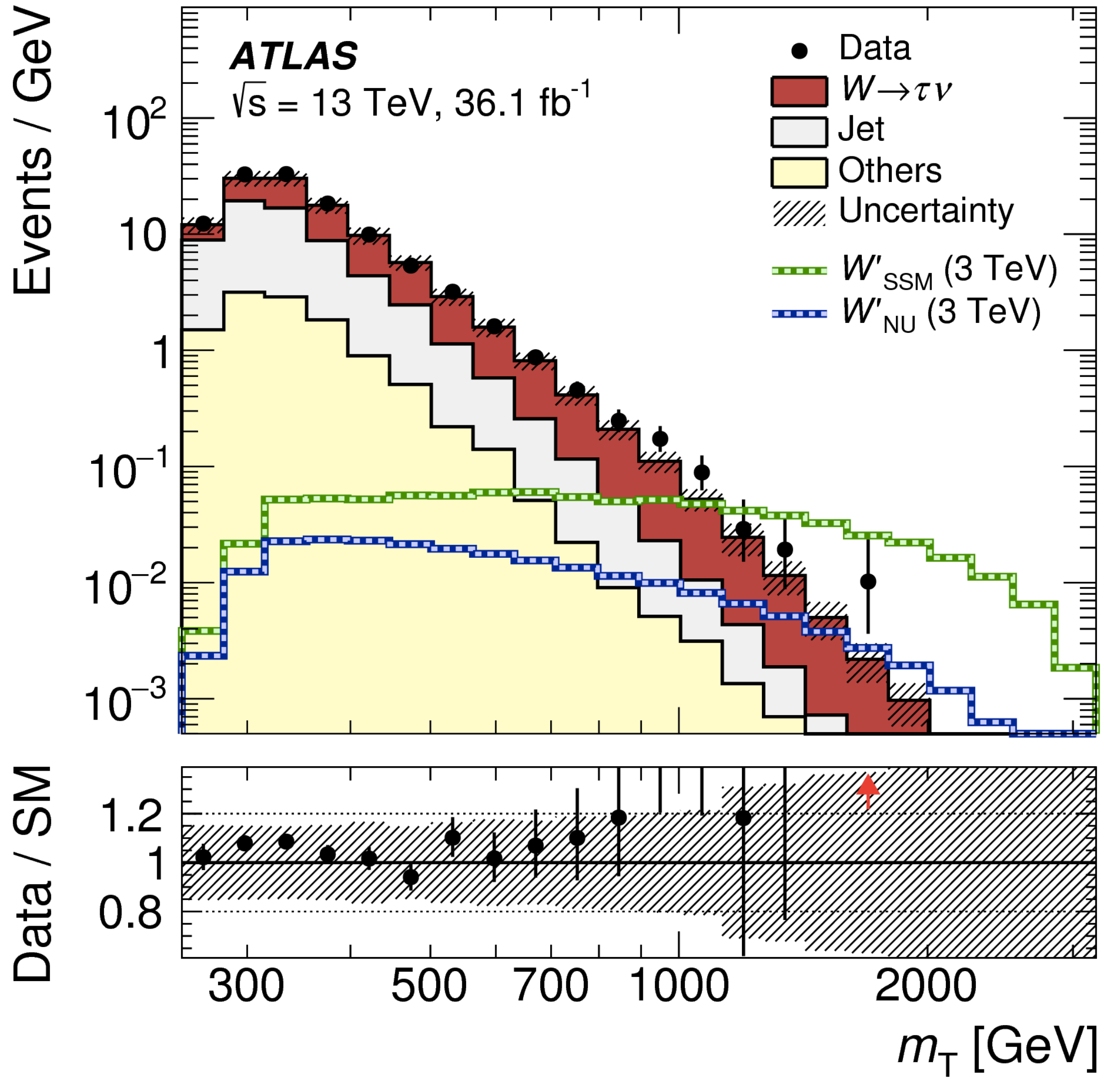


EXOTICS RESULTS

ATLAS Exotics Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

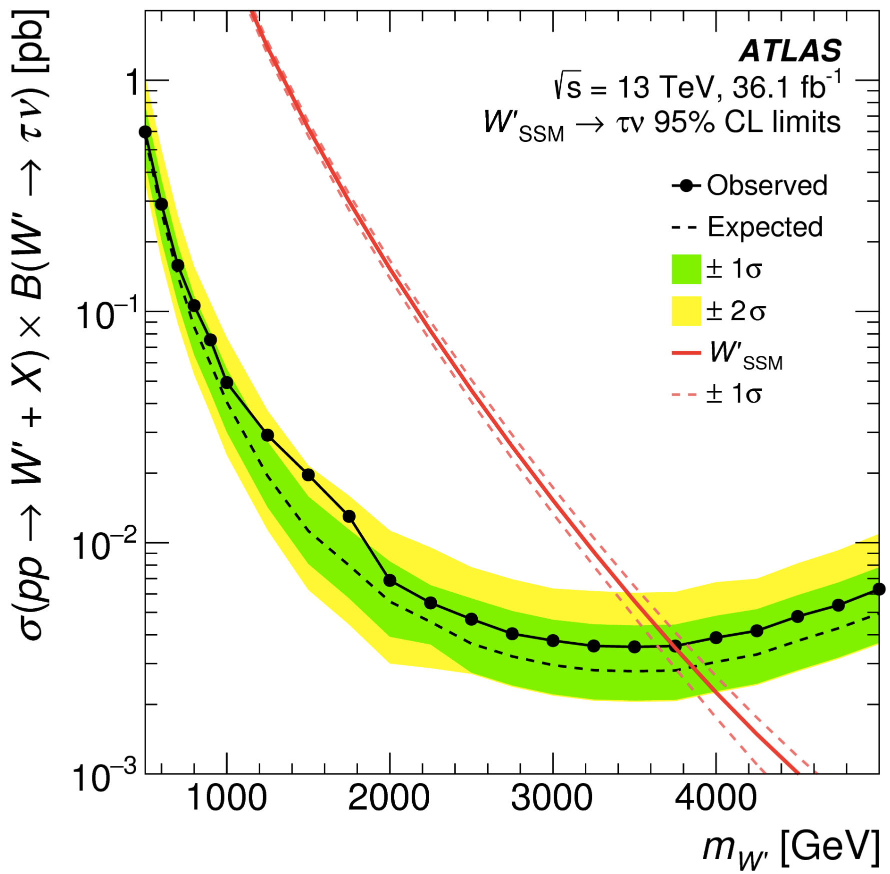
CMS Exotics Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

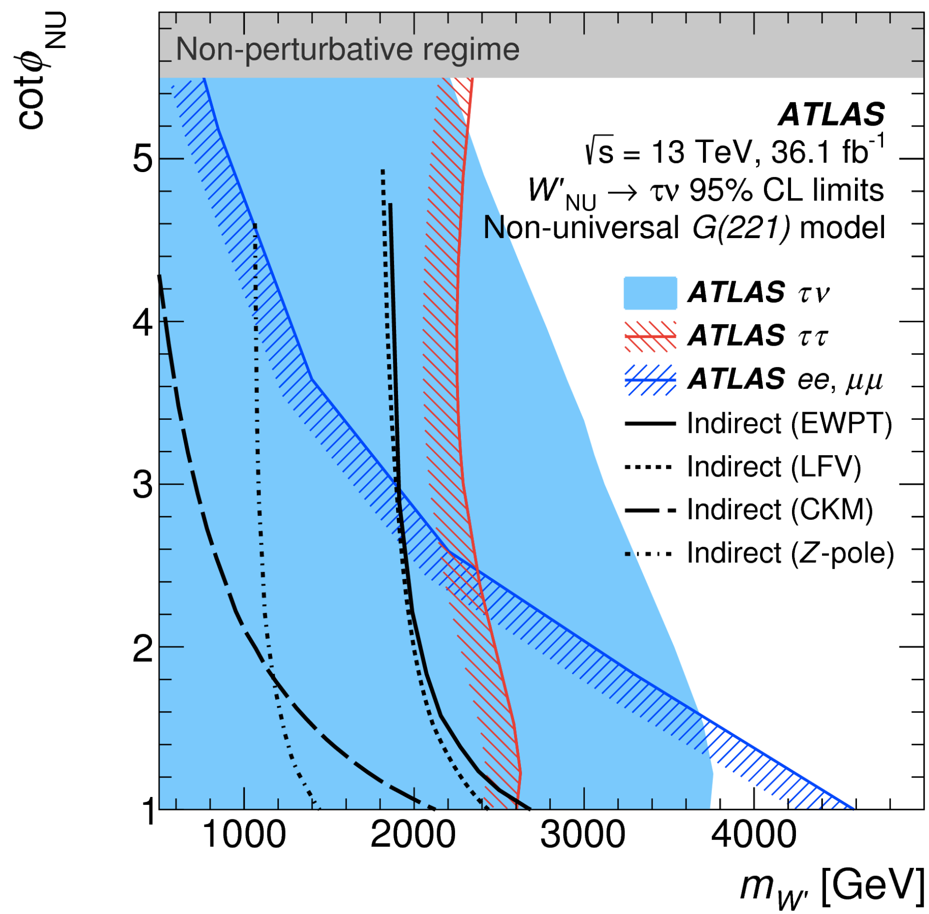
high mass resonances decaying to τν



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2017-06/

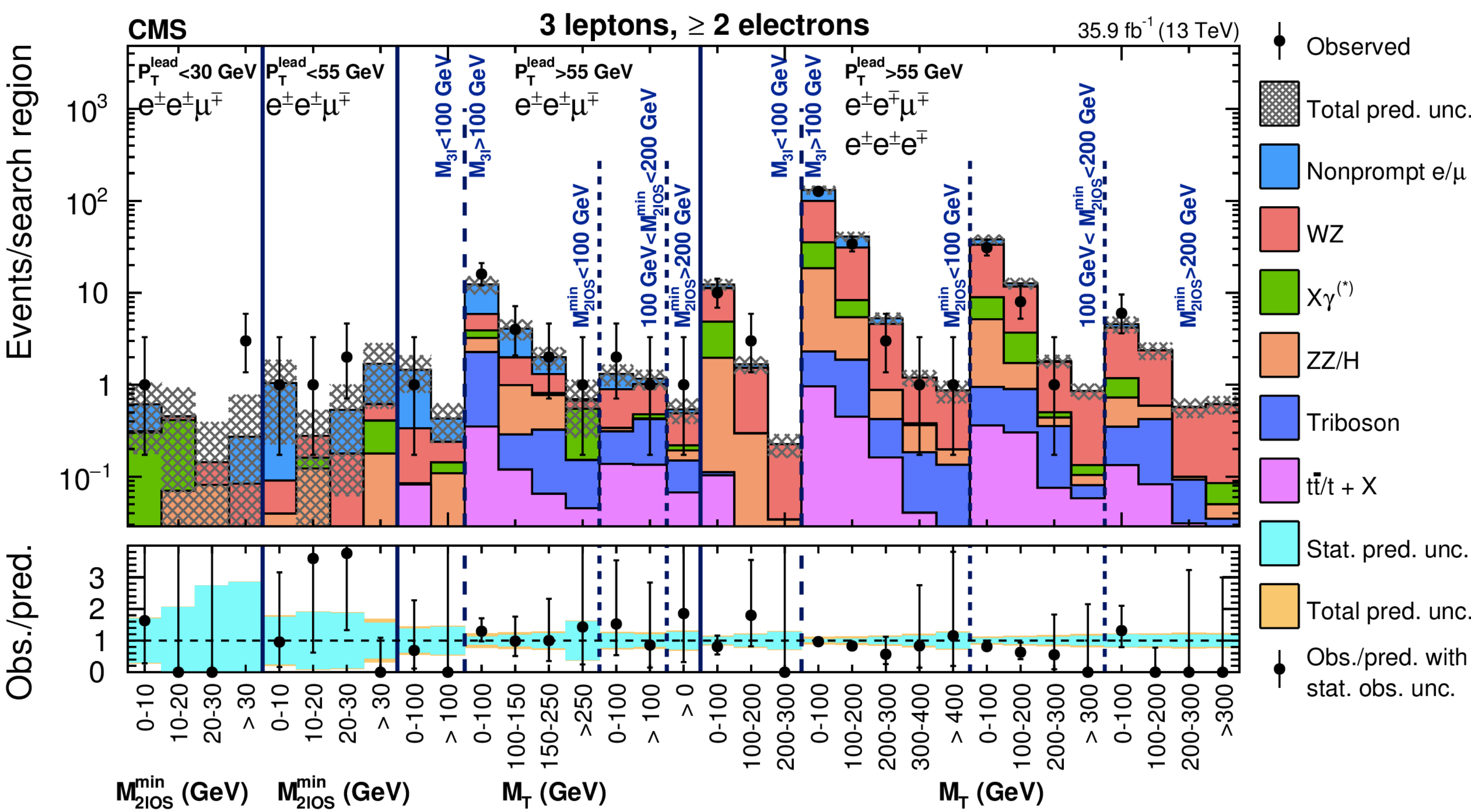
high mass resonances decaying to $\tau\nu$





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2017-06/

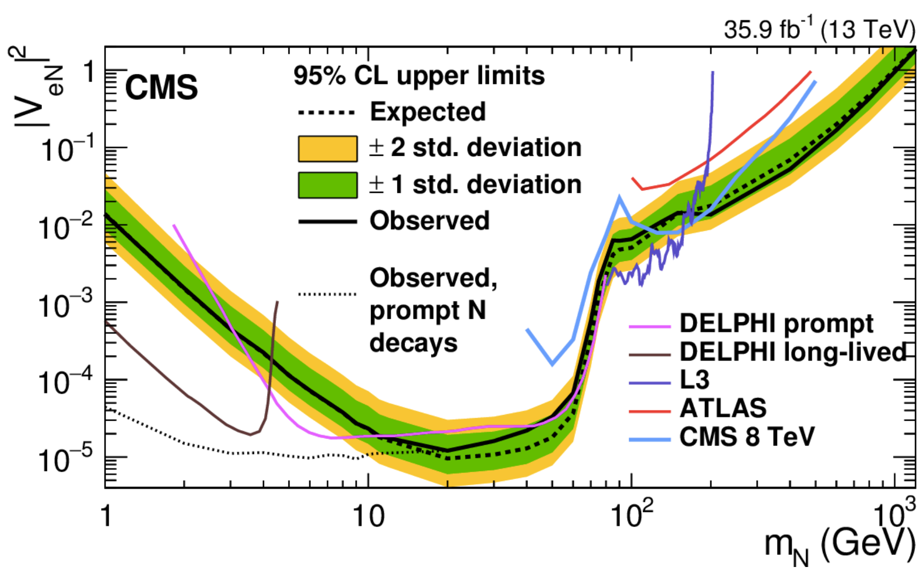
heavy neutral lepton search with at least three leptons

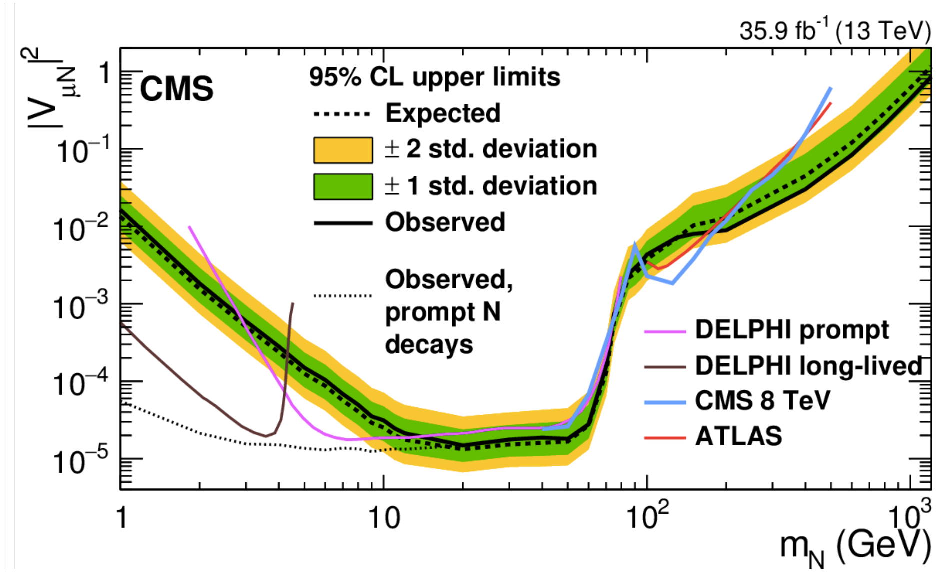


https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-17-012/index.html

heavy neutral lepton search with at least three charged leptons

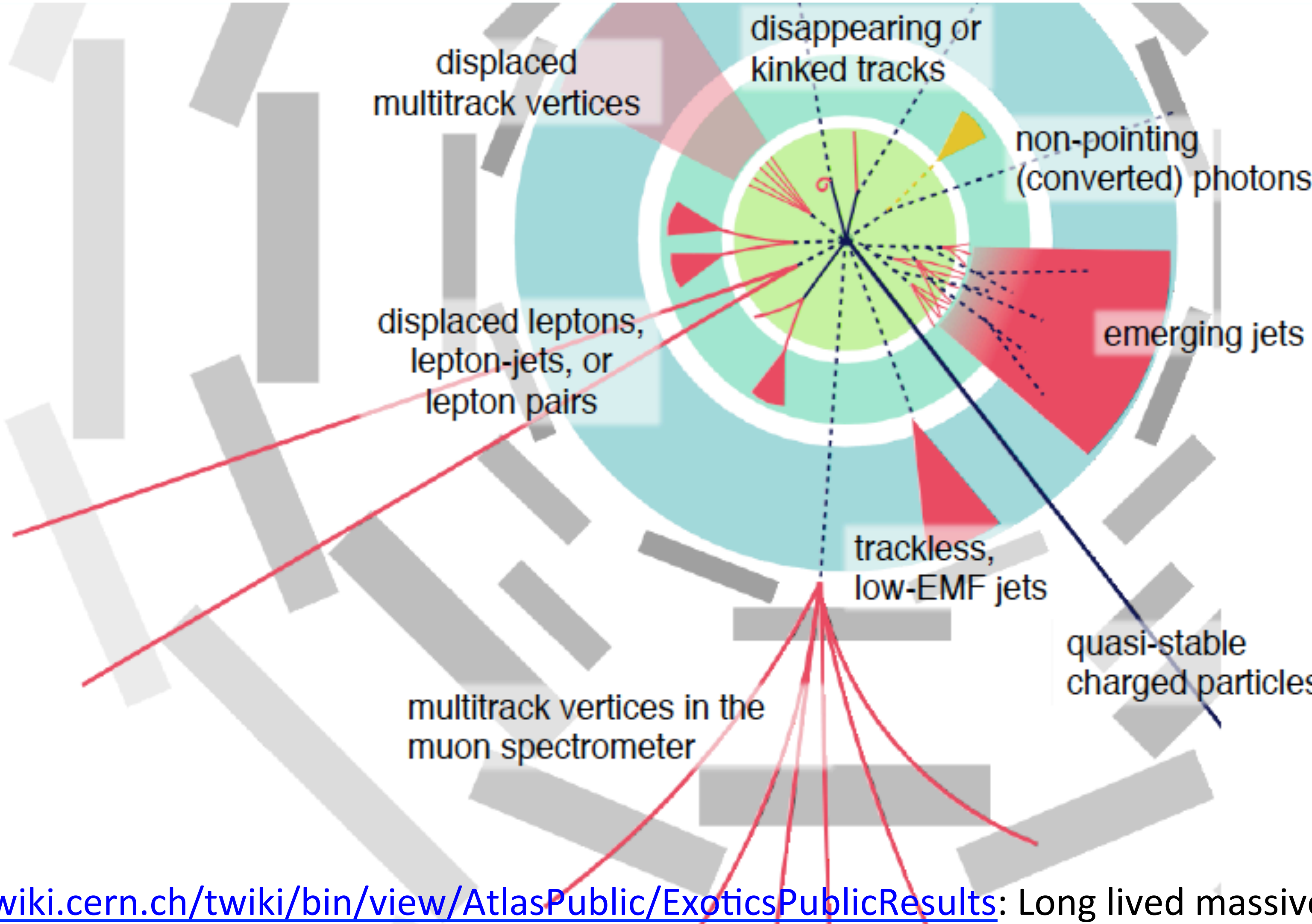
Upper limits are set on the mixing parameters $|V_{eN}|^2$ and $|V_{\mu N}|^2$
This are the first direct limits at high mass (m_N > 500 GeV) and the first LHC probes at very low mass (m_N < 40 GeV)



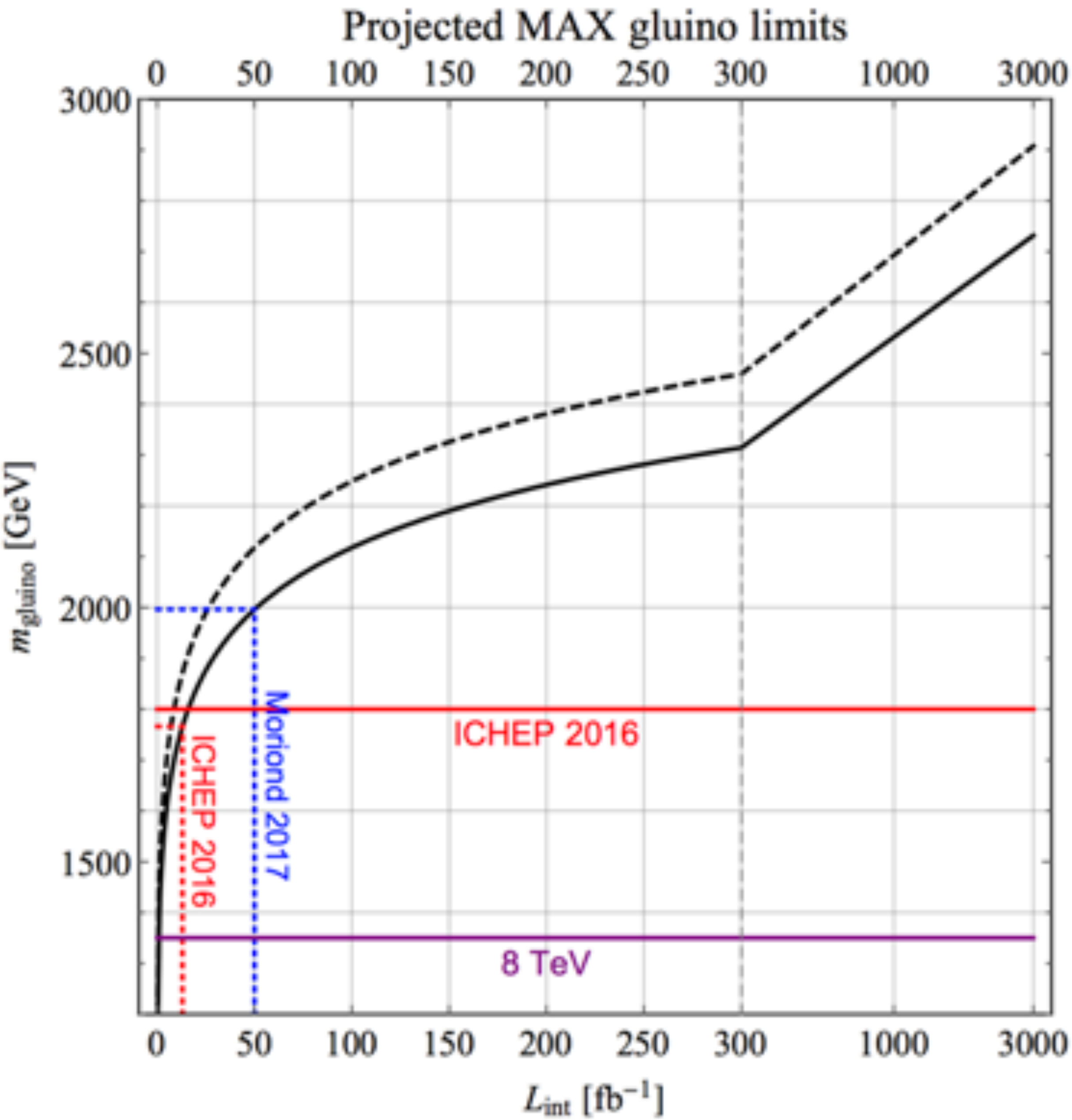


https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-17-012/index.html

Many other searches are on-going…
Long-lived particles are a particularly interesting category



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults: Long lived massive particle
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LLP.html



Projected MAX gluino limits
0
50
100
150
200
250
300
1000
3000
3000
2500
2000
1500
m_{gluino} [GeV]
ICHEP 2016
ICHEP 2016
Moriond 2017
8 TeV
L_{int} [fb^{-1}]

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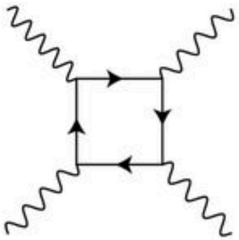
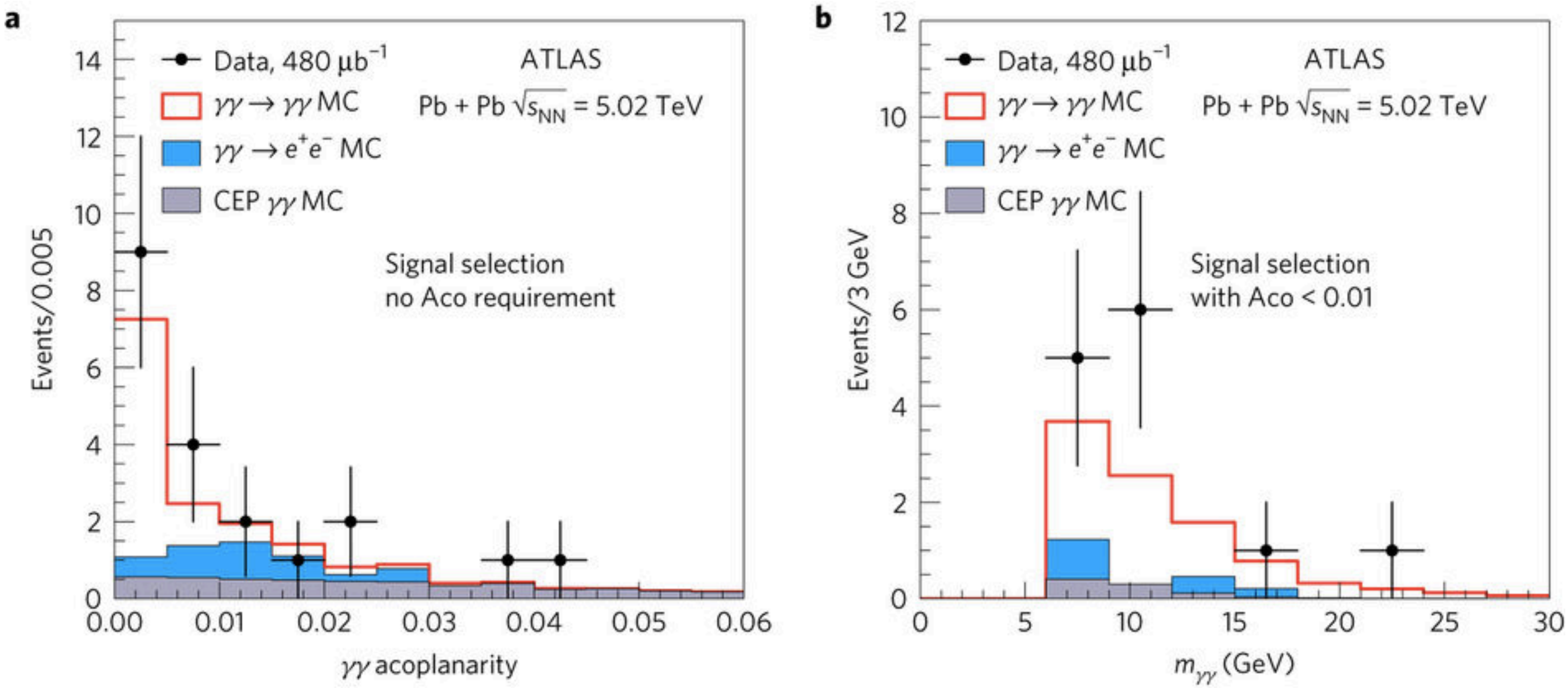
Heavy Ions: Light-by-Light Scattering



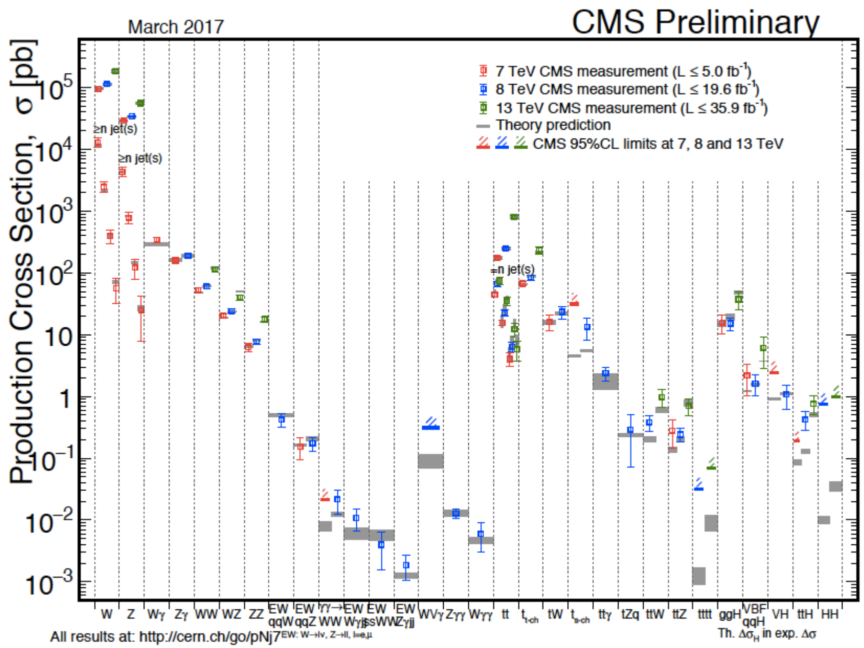
Maxwell's equations, relying on superposition, do not allow light-by-light scattering, which is purely a quantum mechanical effect



https://www.nature.com/nphys/journal/v13/n9/fig_tab/nphys4208_F3.html

With time to analyze comes great power, and with great power comes great responsibility.

Every measurement is a search.

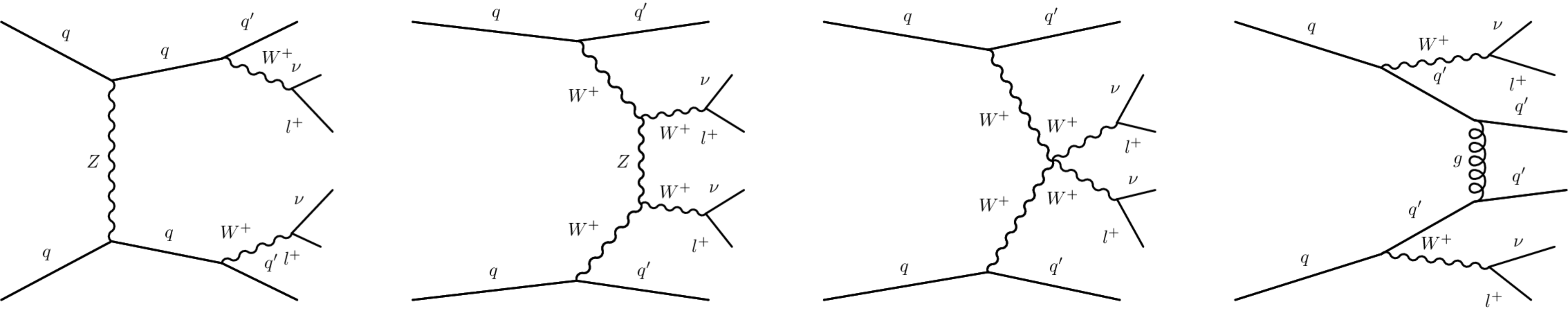


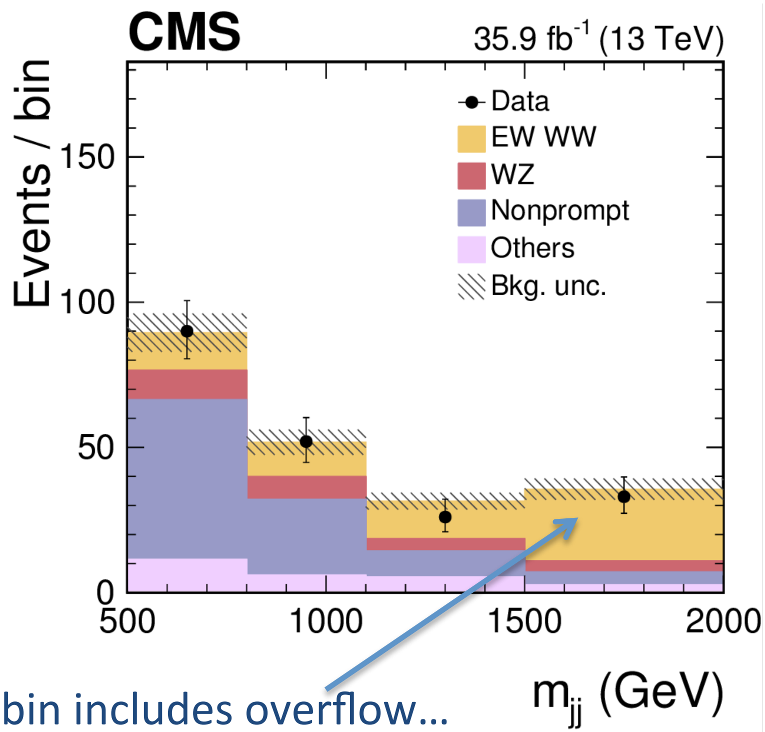
STANDARD MODEL RESULTS

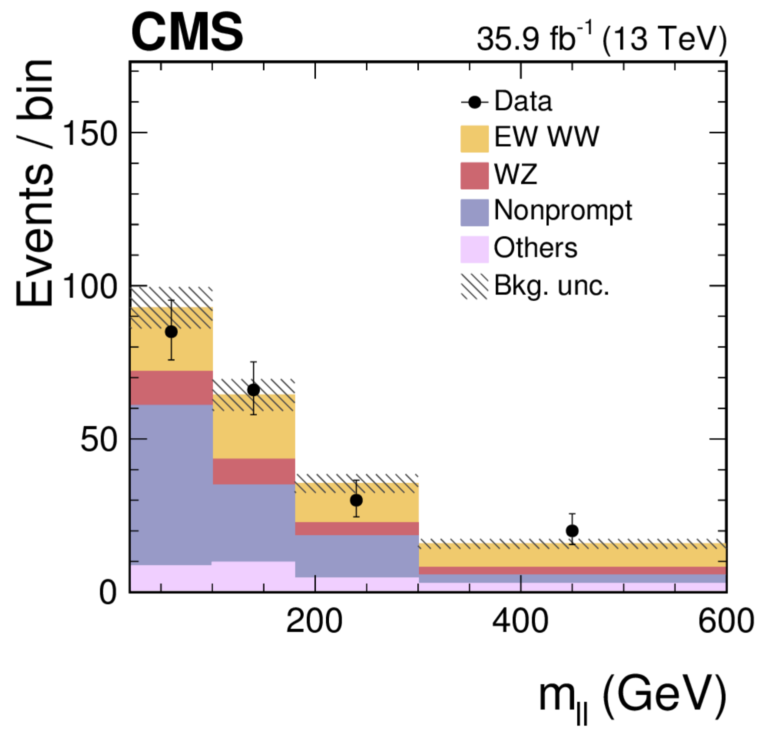
ATLAS SM Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

CMS SM Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Observation of same-sign WW





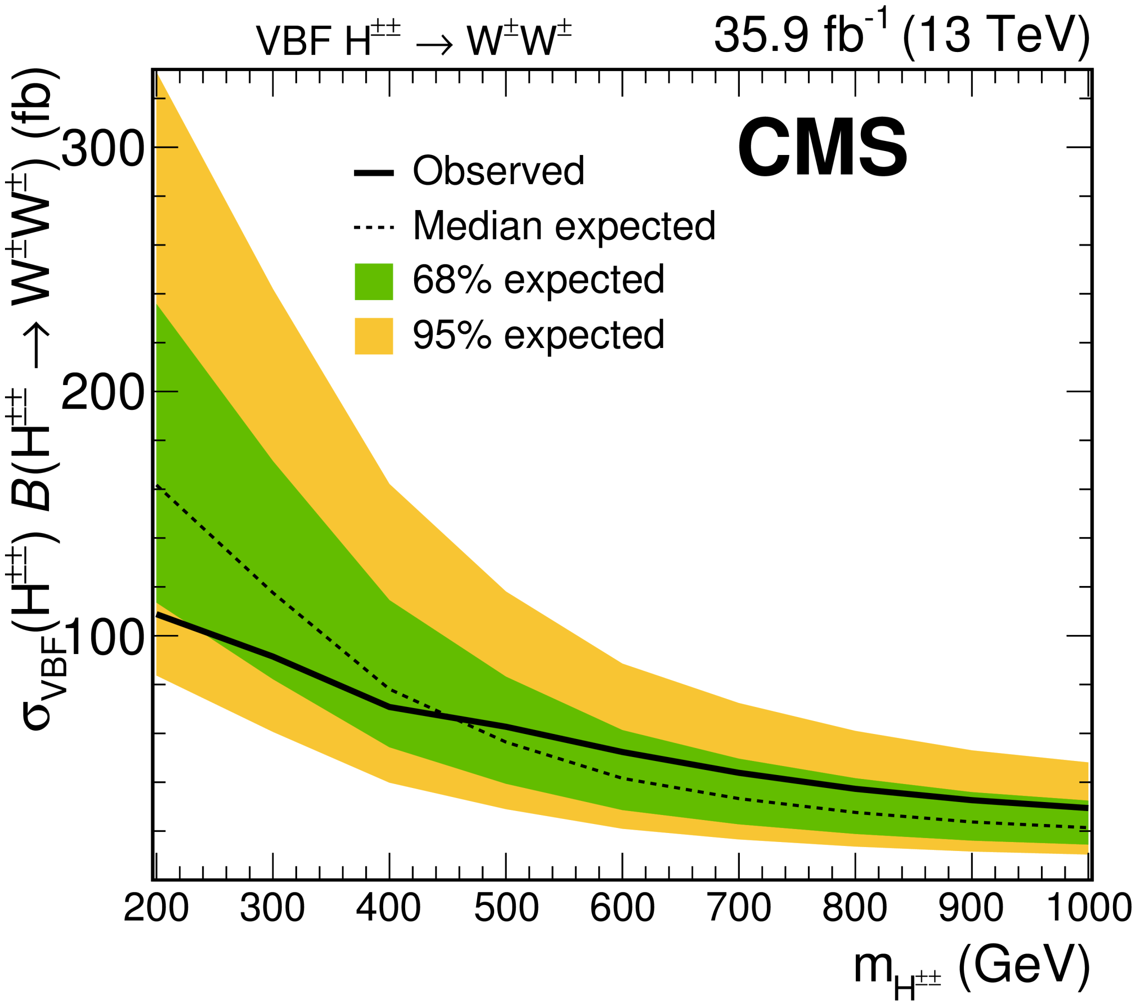


last bin includes overflow...

https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-17-004/index.html

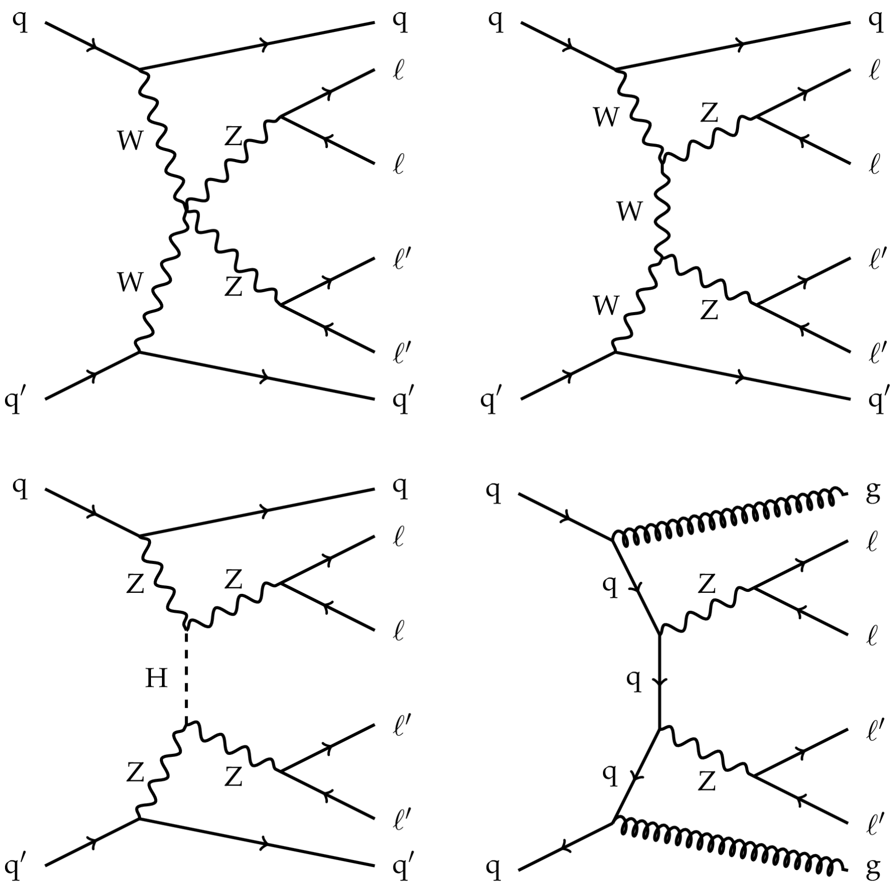
Observation of same-sign WW

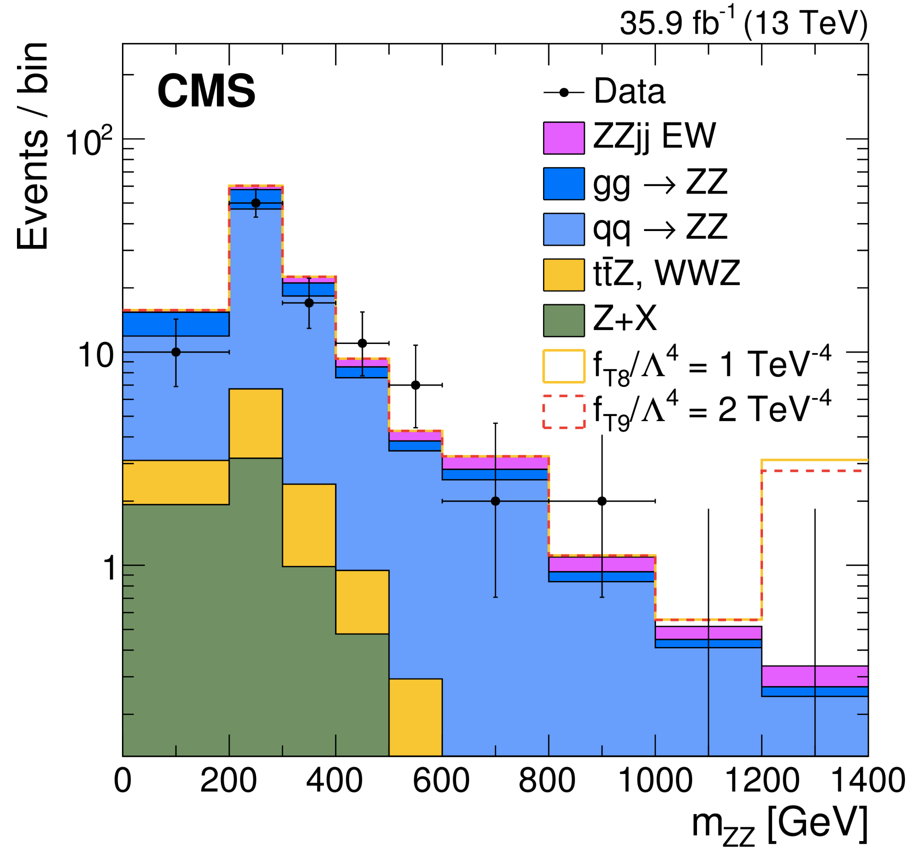
Limits can be placed on the $H^{\pm\pm}$ allowed cross section, here for VBF production



https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-17-004/index.html

Vector Boson Scattering



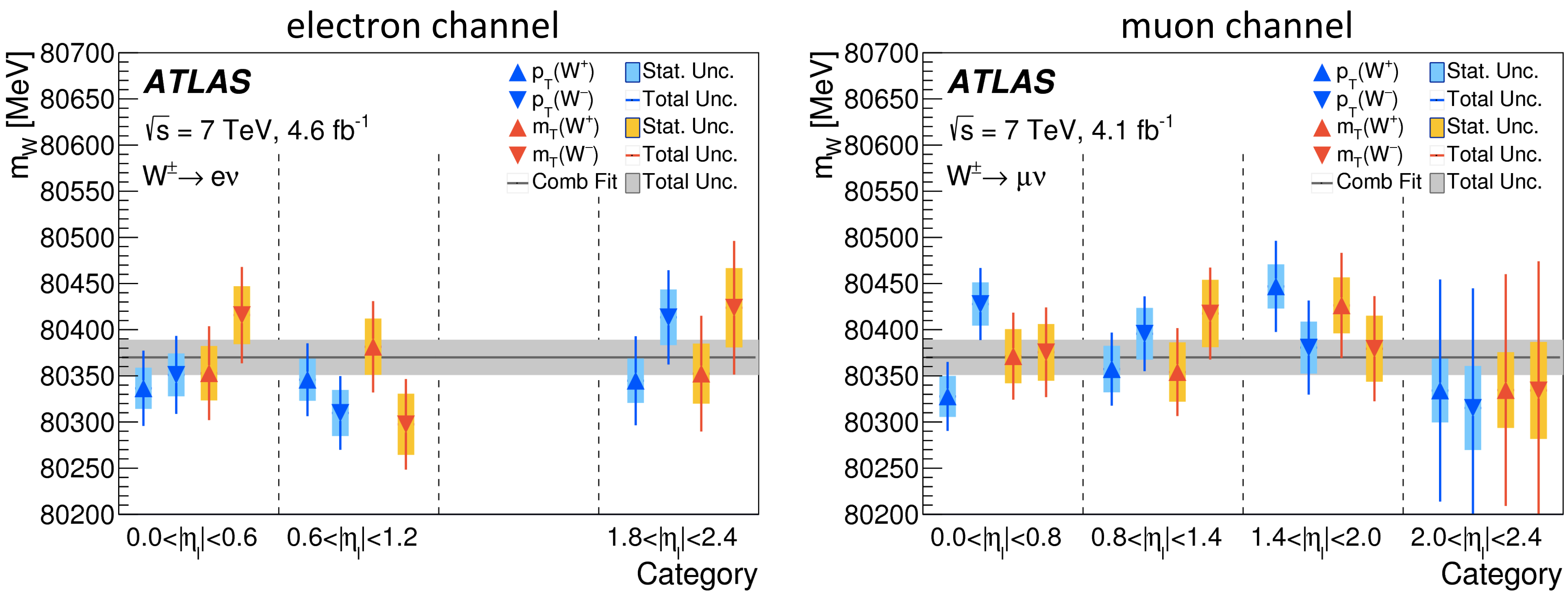


First LHC results for electroweak production of two Z bosons plus jets.
Most stringent limits on the T0, T1, T2, T8, and T9 anomalous quartic gauge couplings to date.

Phys. Lett. B 774 (2017) 682

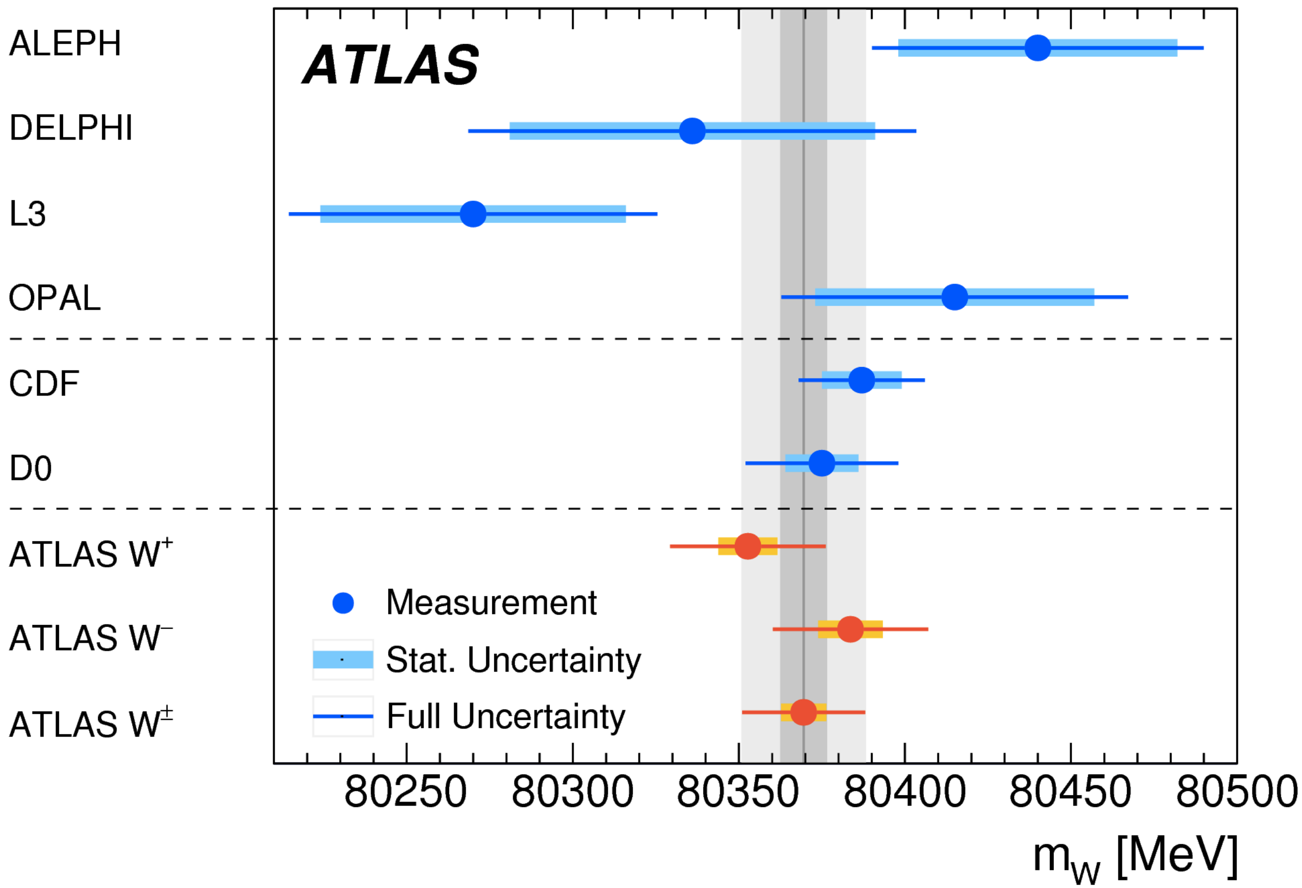
W Boson Mass Measurement, √s = 7 TeV

Measurements done using both transverse momentum and transverse mass distributions, for W^+ and W^- in bins of eta.



Eur. Phys. J. C 78 (2018) 110

W Boson Mass Measurement



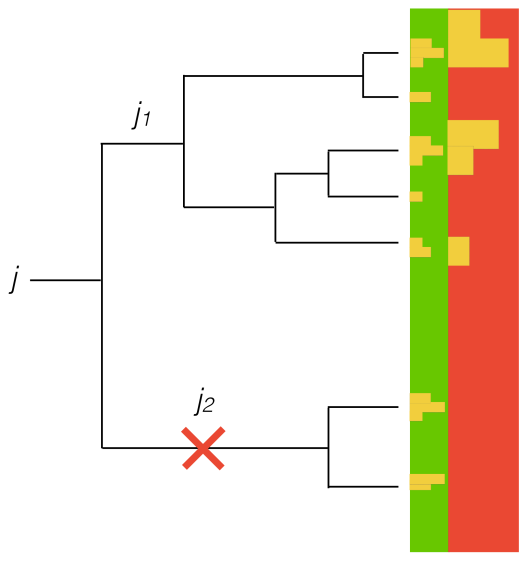
$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\text{MeV}$$
$$= 80370 \pm 19\text{MeV},$$

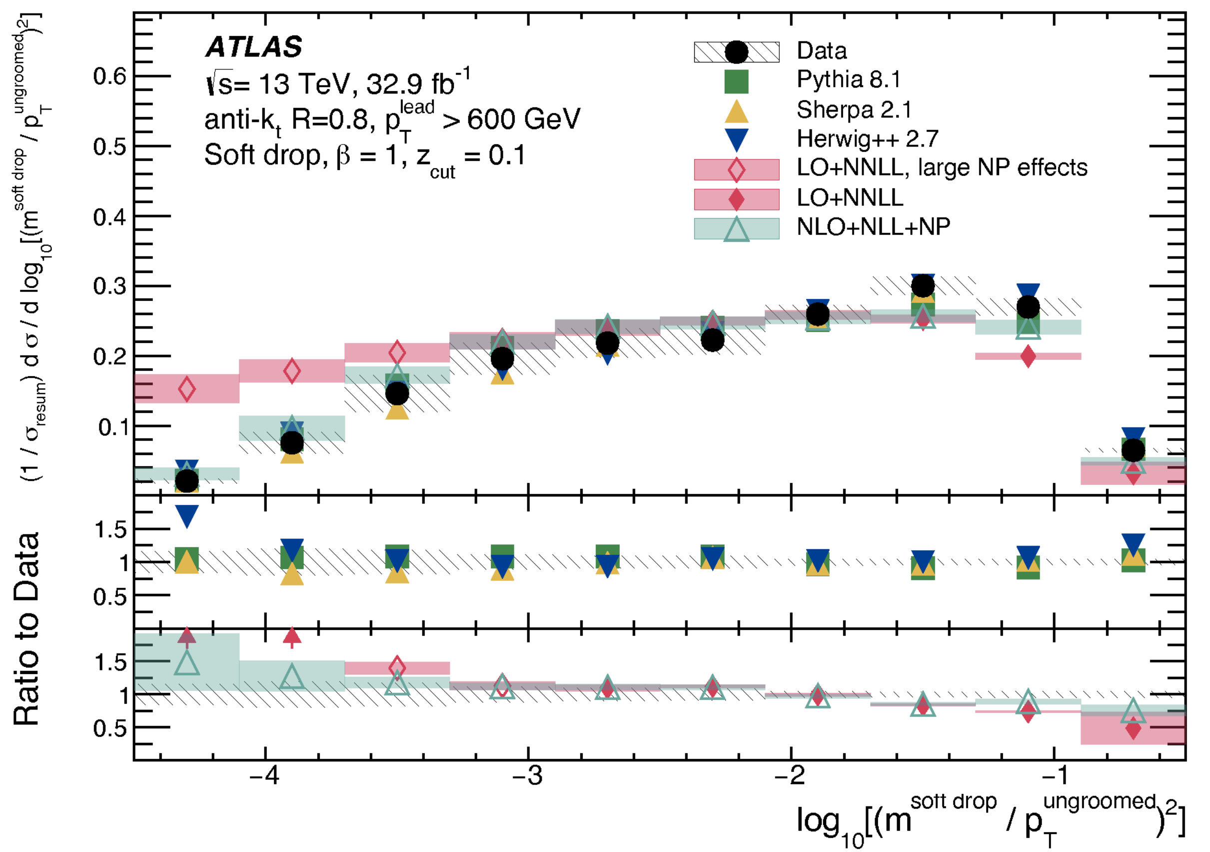
[*Eur. Phys. J. C 78 (2018) 110*]

Understanding jet substructure

Jet "soft drop" mass, a jet substructure technique being used in analyses

$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-04/

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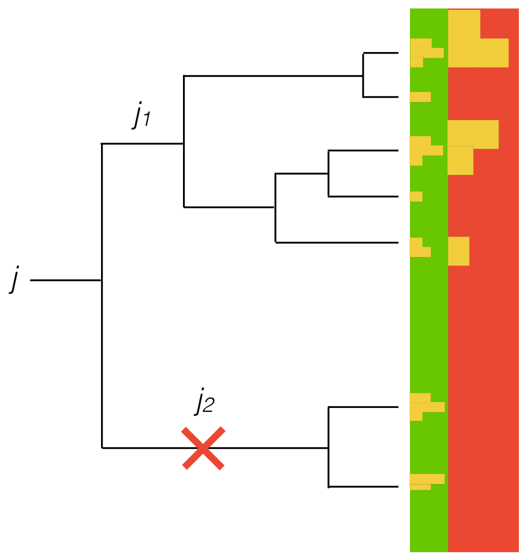
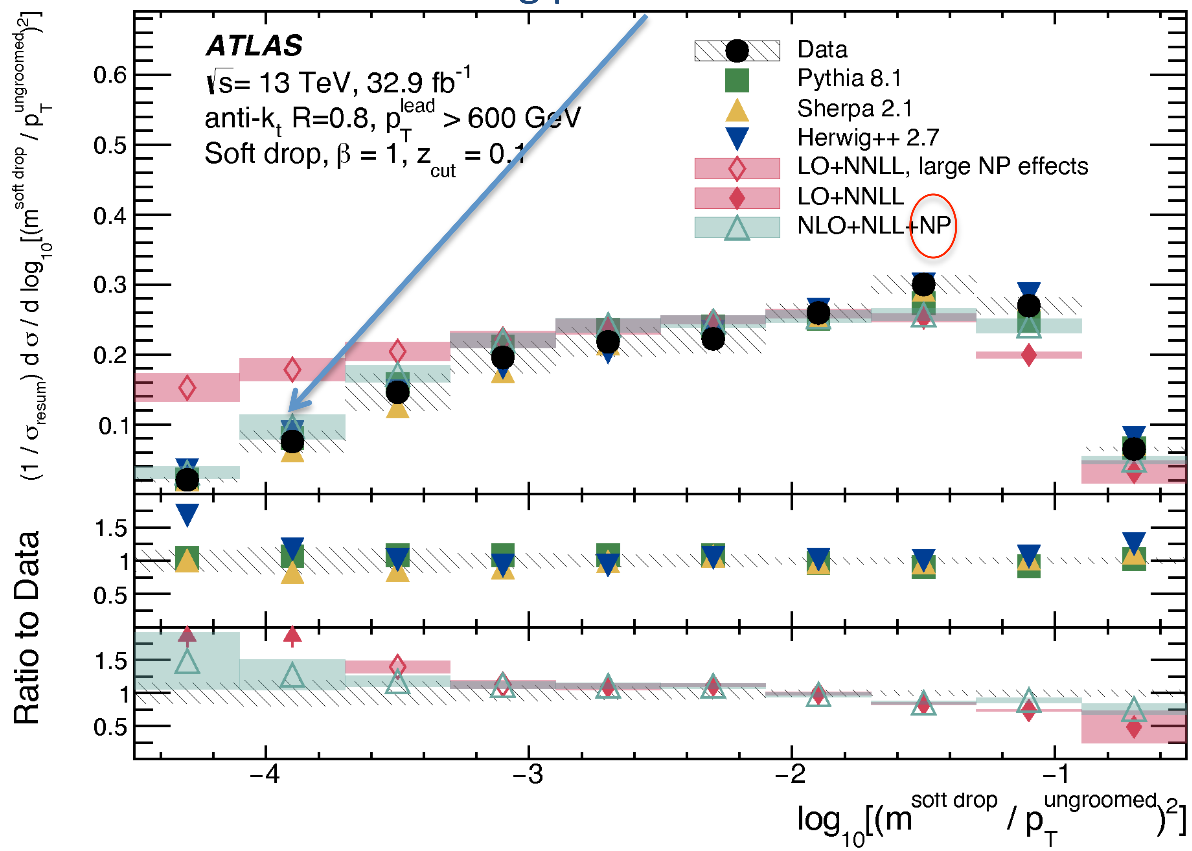
Jet “soft drop” mass, a jet substructure technique being used in analyses

$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$



a first for using perturbative calculations



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-04/

So massive, so promising, so well-behaved…

There are many new cross section results out

There are new properties measurements (mass)

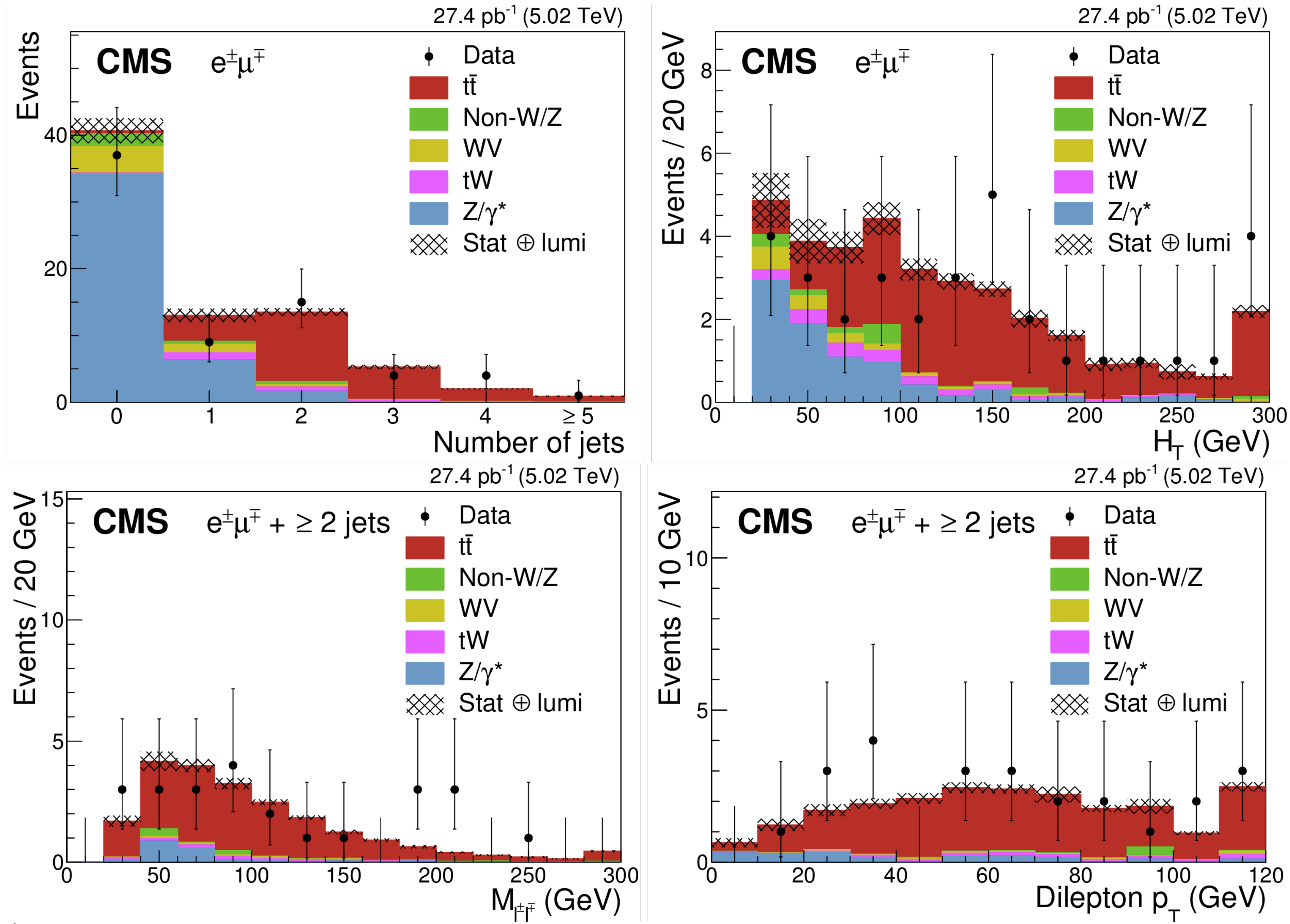
There are searches for new physics using top

TOP PHYSICS RESULTS

ATLAS Top Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

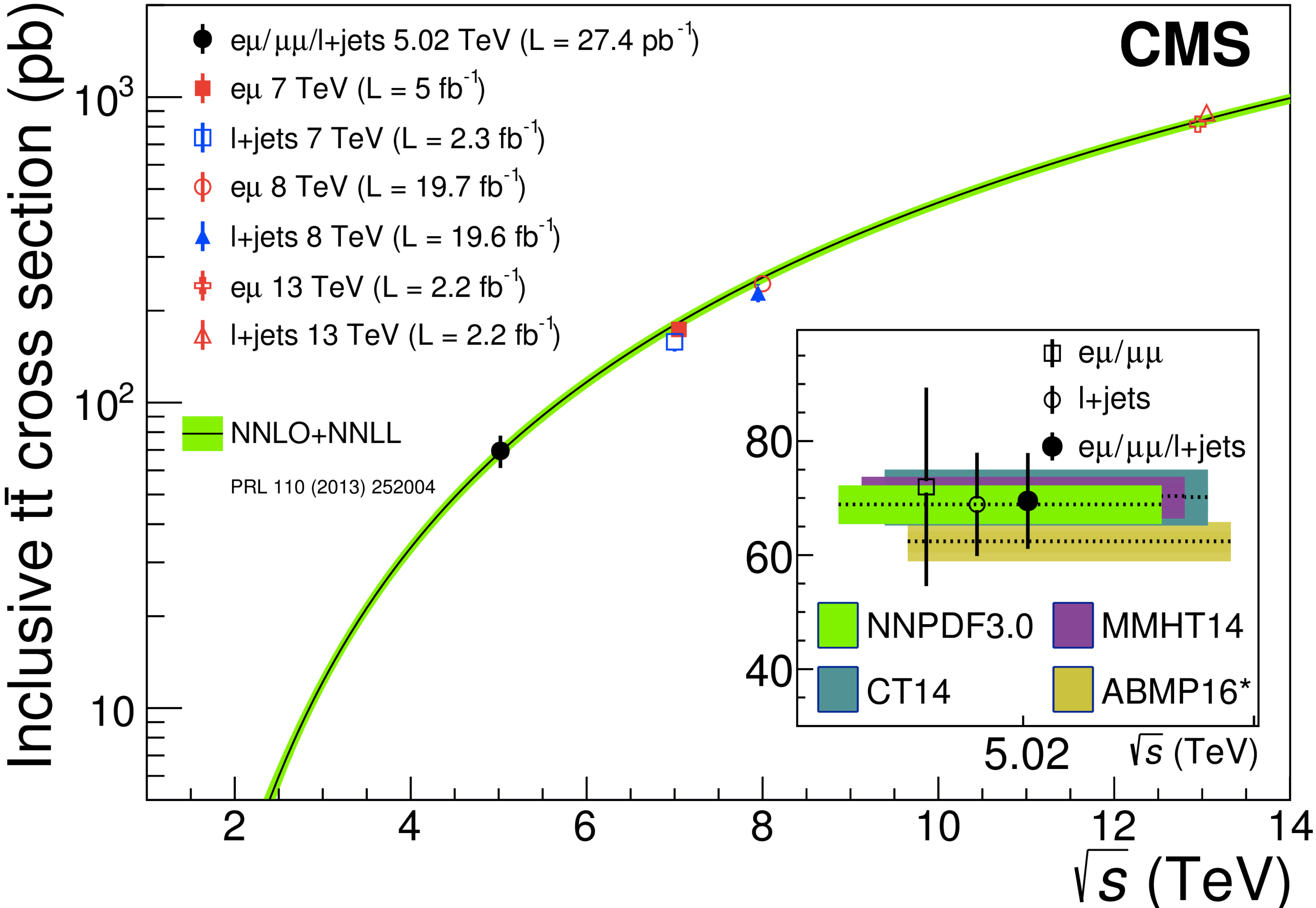
CMS SM Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

First ttbar cross section at √s = 5.02 TeV



https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-16-023/index.html

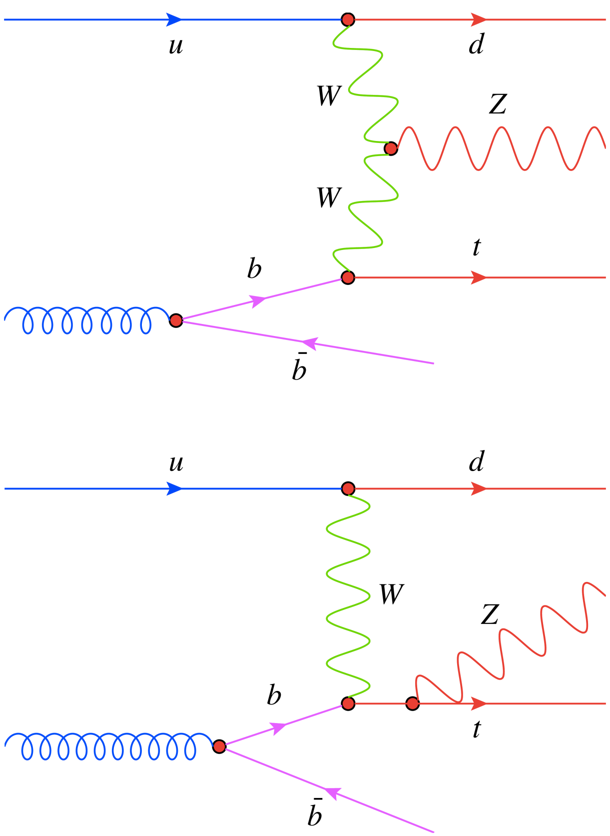
First ttbar cross section at √s = 5.02 TeV



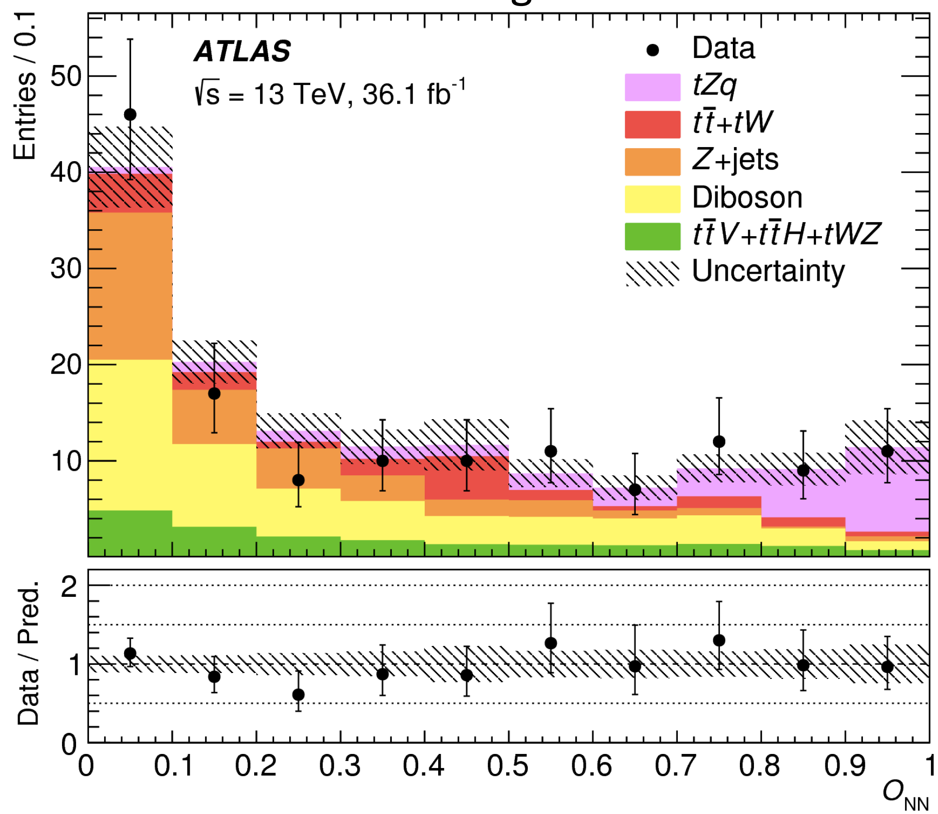
https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-16-023/index.html

tZ cross section at √s = 13 TeV

example lowest order
Feynman diagrams



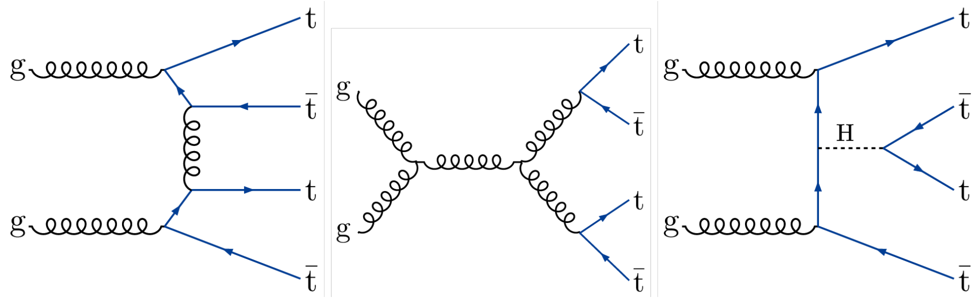
measurement significance: 4.2 σ



The measured cross-section for tZq production is $600 \pm 170(\text{stat.}) \pm 140(\text{syst.})$fb

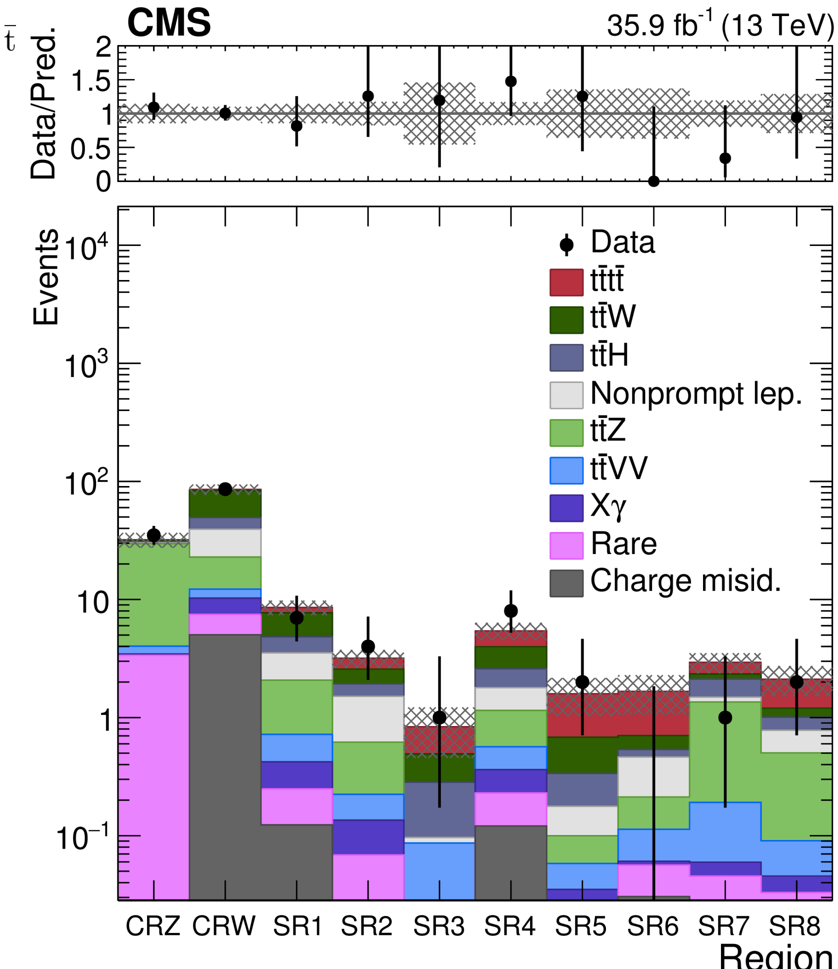
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2016-14/

Search for four t SM production



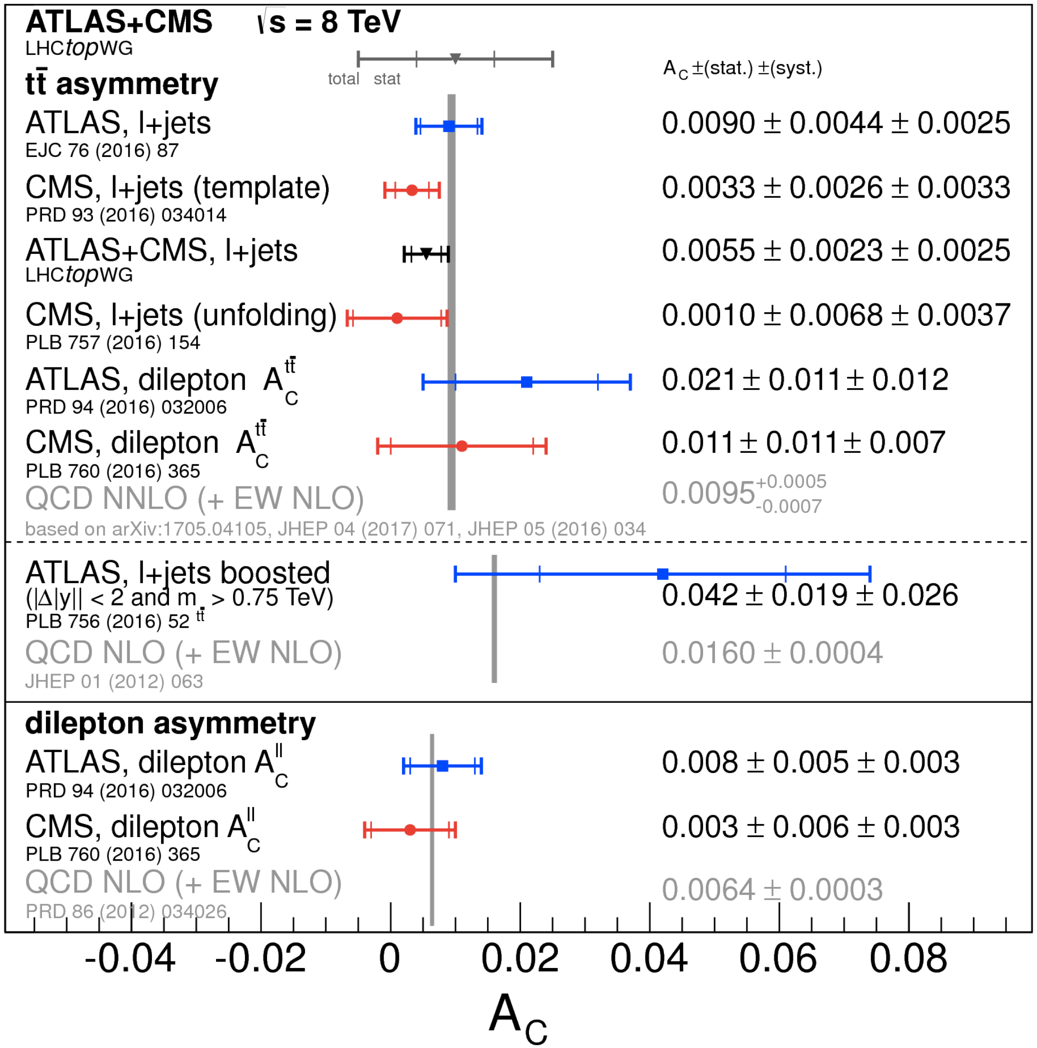
Results in agreement with SM, constrain Yukawa coupling between t and H to less than 2.1 times SM

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ



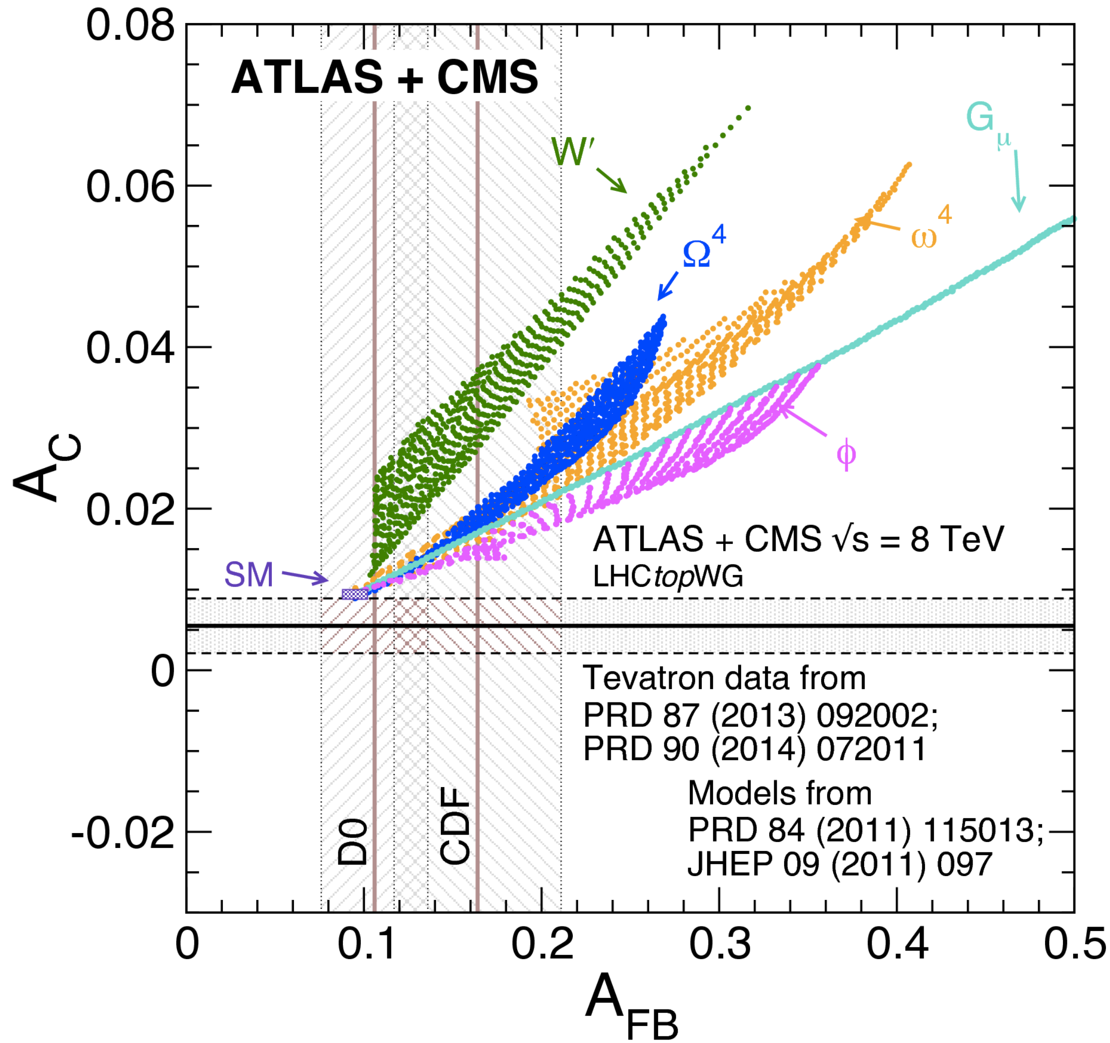
https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-17-009/index.html

ATLAS and CMS Combination: Inclusive and Differential Charge Asymmetry



 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2016-16/

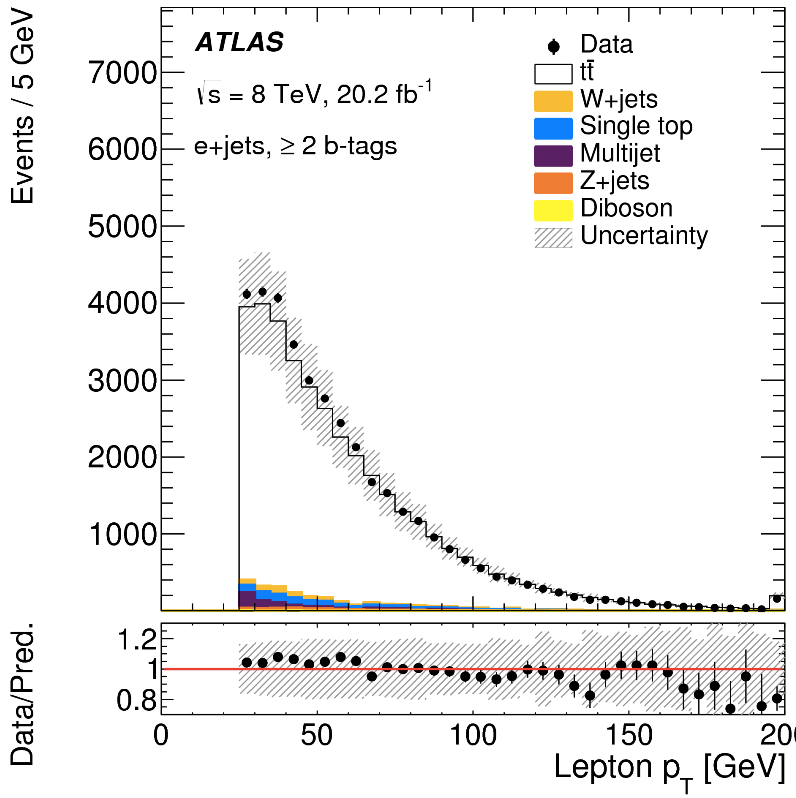
ATLAS and CMS Combination: Inclusive and Differential Charge Asymmetry



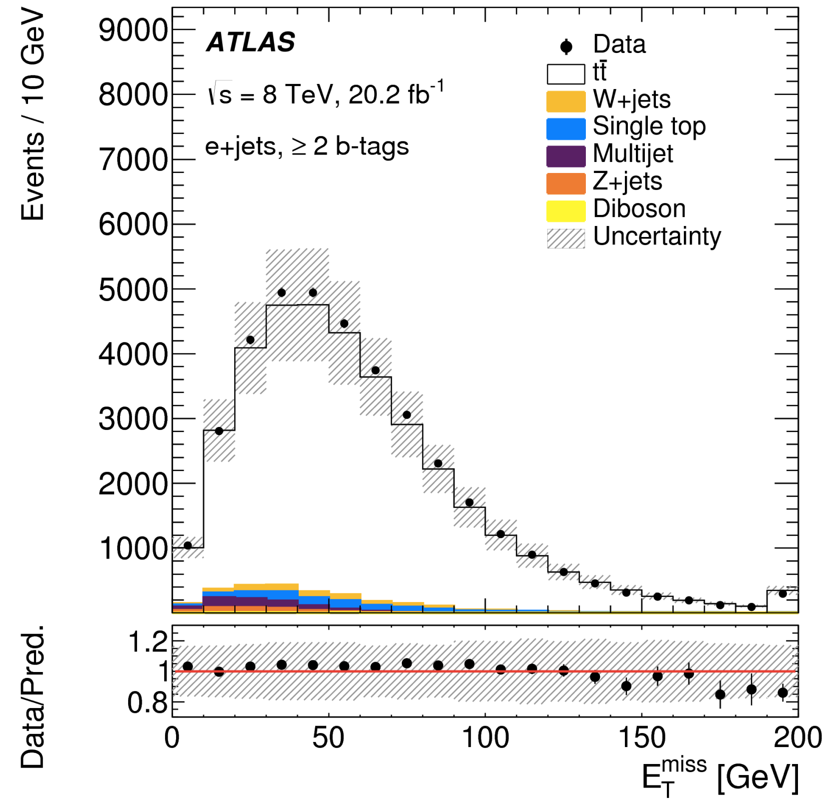
 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2016-16/

Decay Width at √s = 8 TeV using template fit with kinematic variables

leading lepton transverse momentum



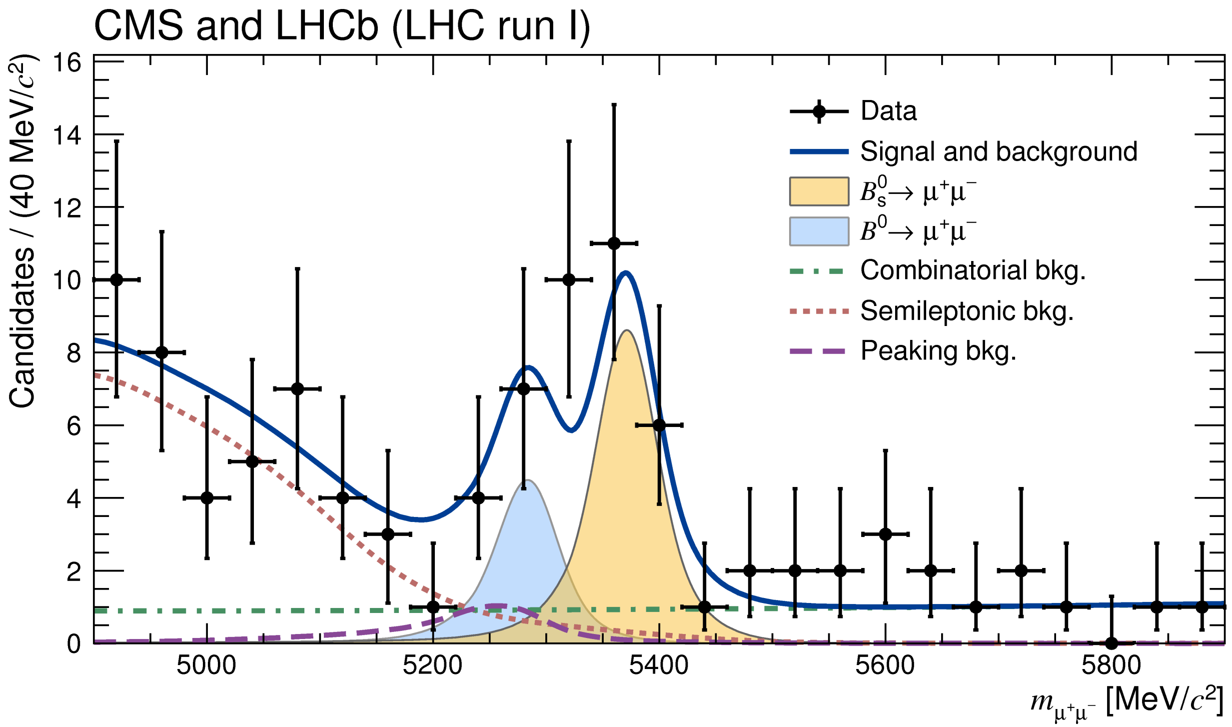
missing transverse momentum



$$\Gamma_t = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})\text{GeV}$$

The result is consistent with the SM theory prediction of 1.322 GeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-02/



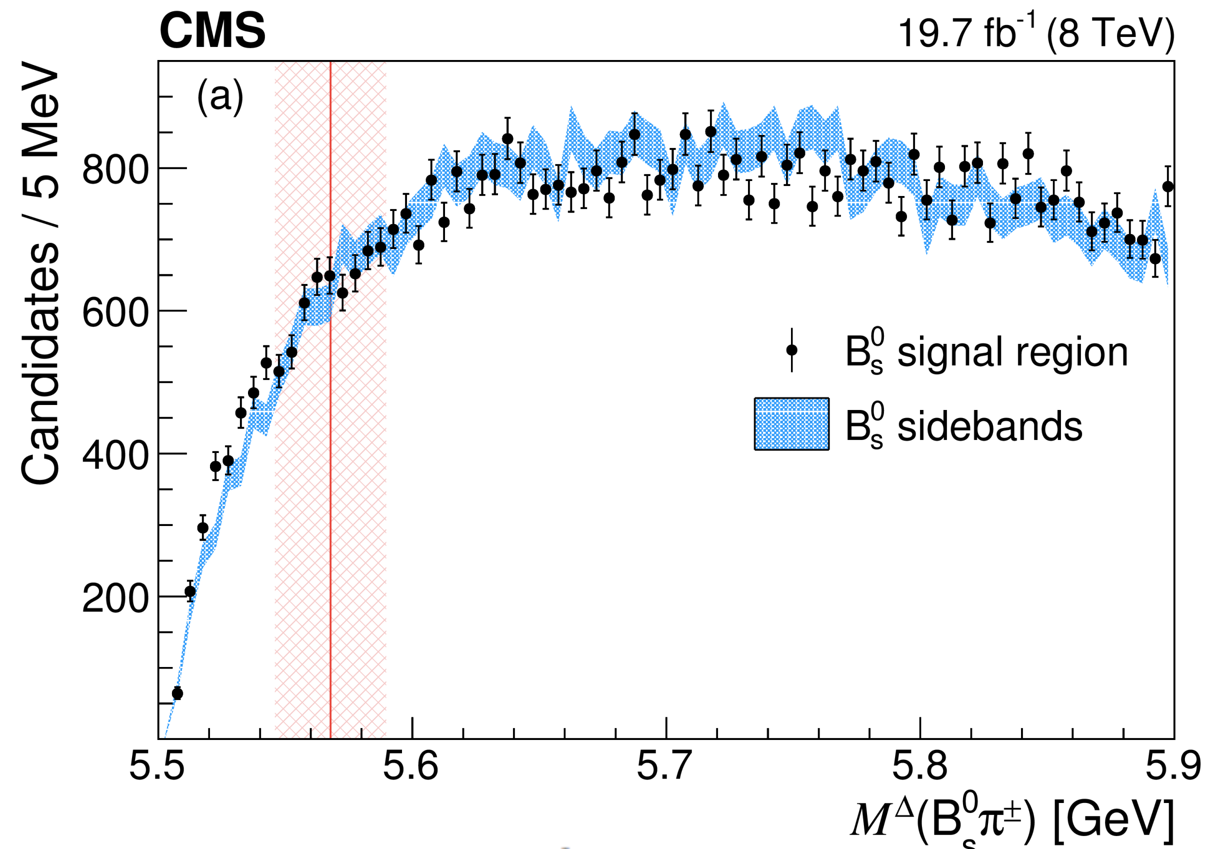
B PHYSICS RESULTS

ATLAS b Physics Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

CMS b Physics Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html

Search for X(5568) $B_s^0\pi^\pm$

An unexpected observation from D0 of a narrow resonance, named X(5568), prompted a search at LHCb that returned a null result. This CMS measurement has limits a factor of two more stringent.

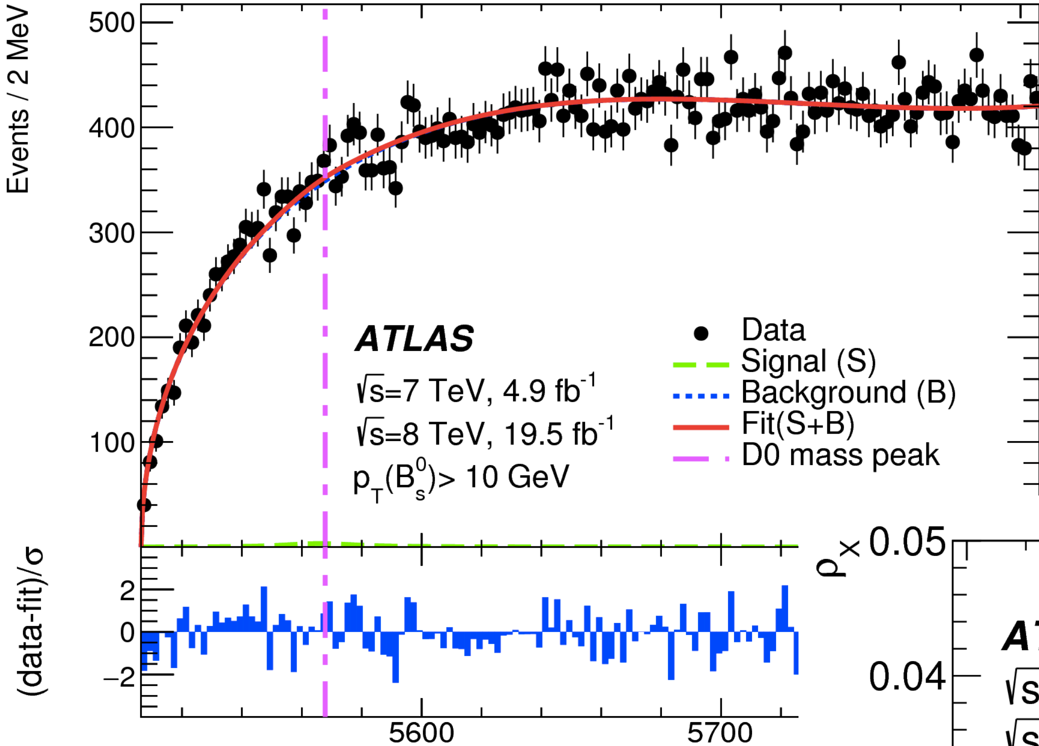


Upper limits on relative production rates of X(5568) and B_s^0 states:

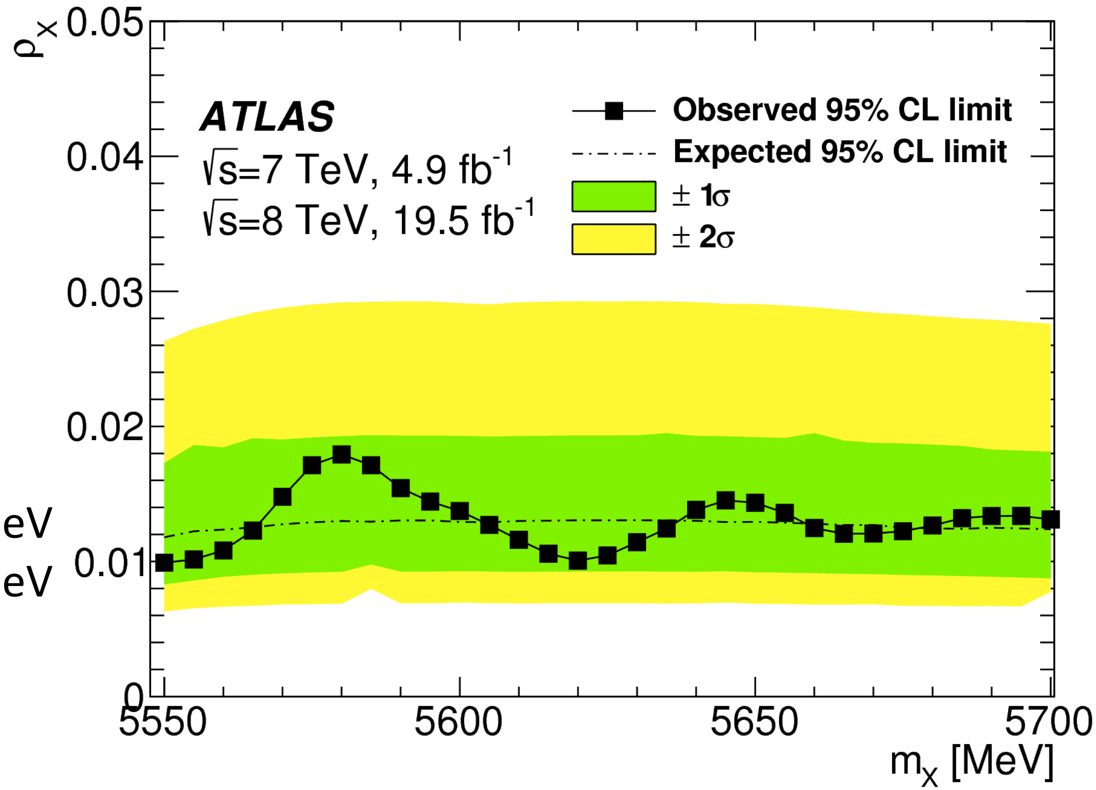
$\rho_X < 1.1\%$ at 95% CL for $p_T(B_s^0) > 10$ GeV and

$\rho_X < 1.0\%$ at 95% CL for $p_T(B_s^0) > 15$ GeV.

https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-16-002/index.html



Search for X(5568) $B_s^0\pi^\pm$



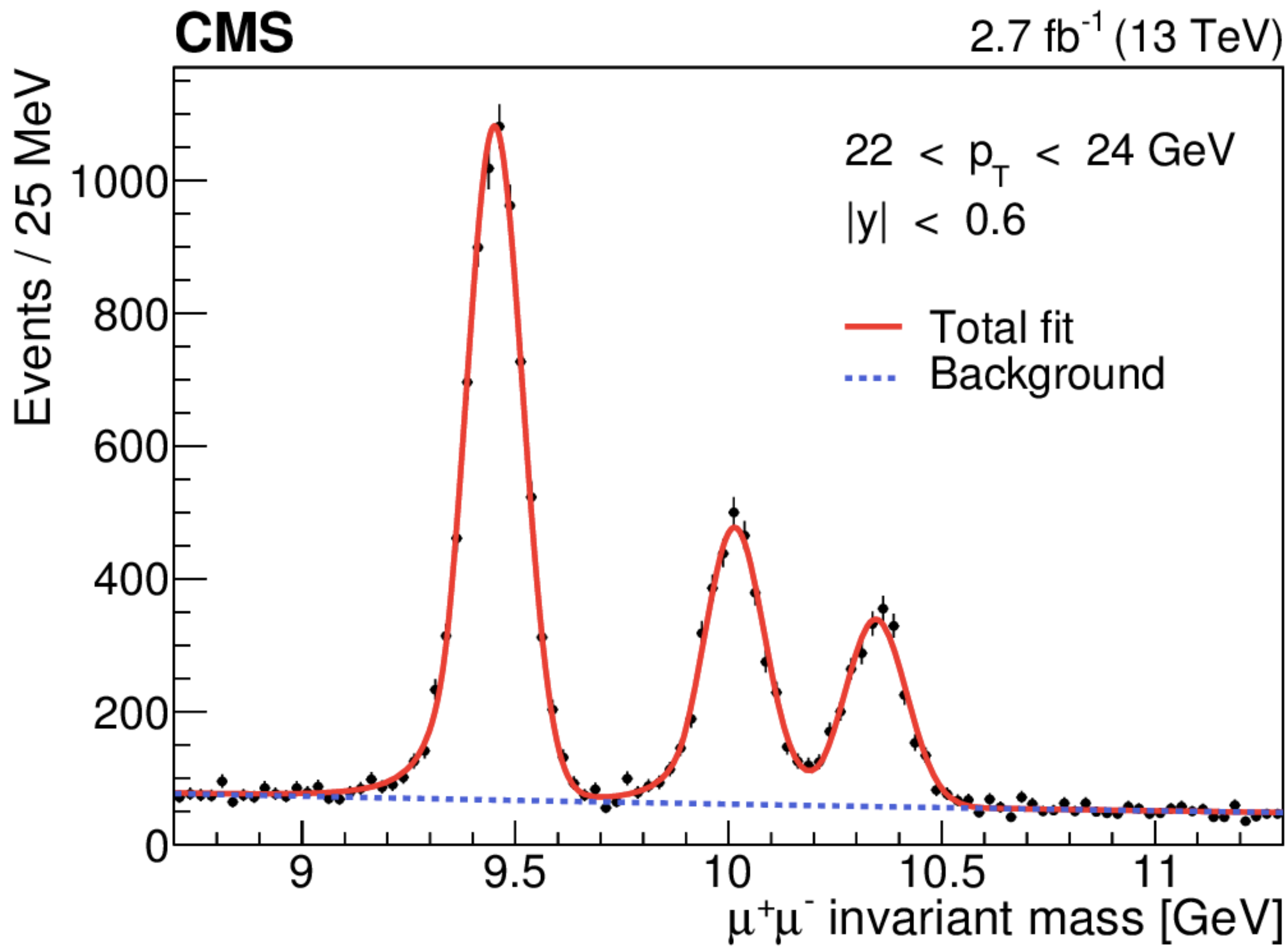
Results are compatible with CMS:

ρ_x < 1.5% for B_s^0 mesons with p_T> 10 GeV

ρ_x < 1.6% for B_s^0 mesons with p_T> 15 GeV

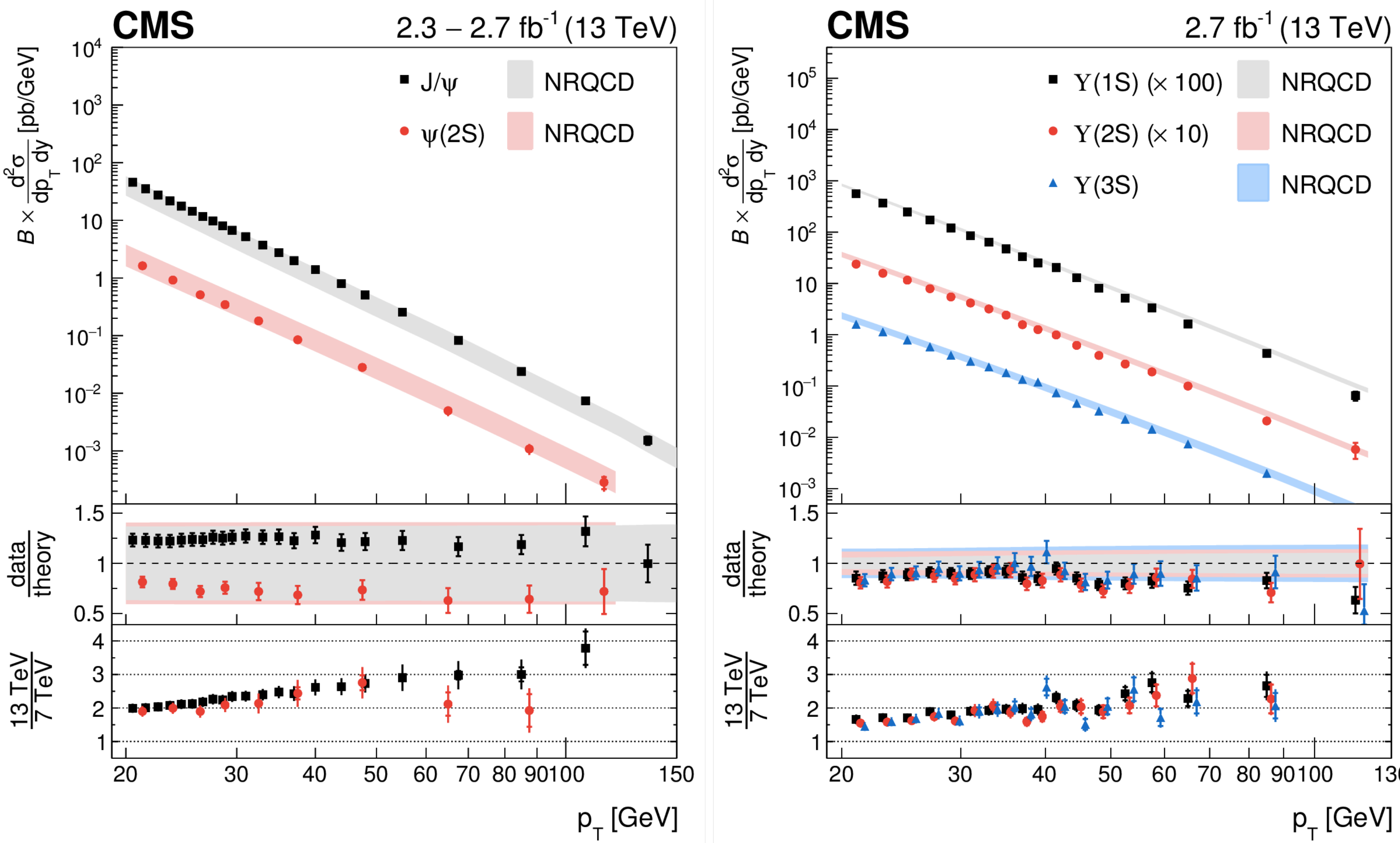
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/BPHY-2017-02/

Measurements of Quarkonia Production



Measurements of Quarkonia Production

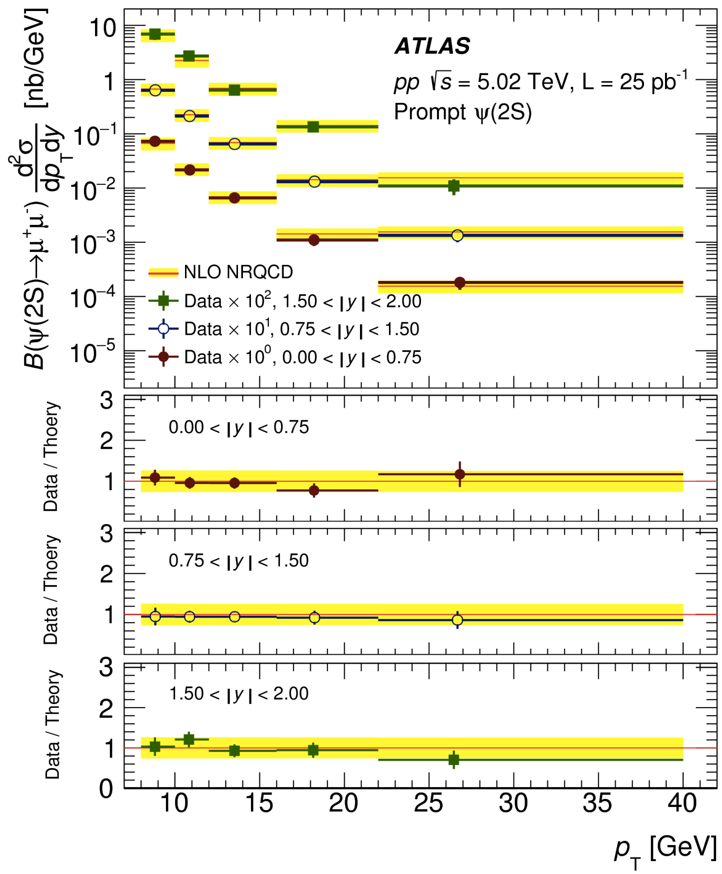
Double Differential Cross Sections central in eta



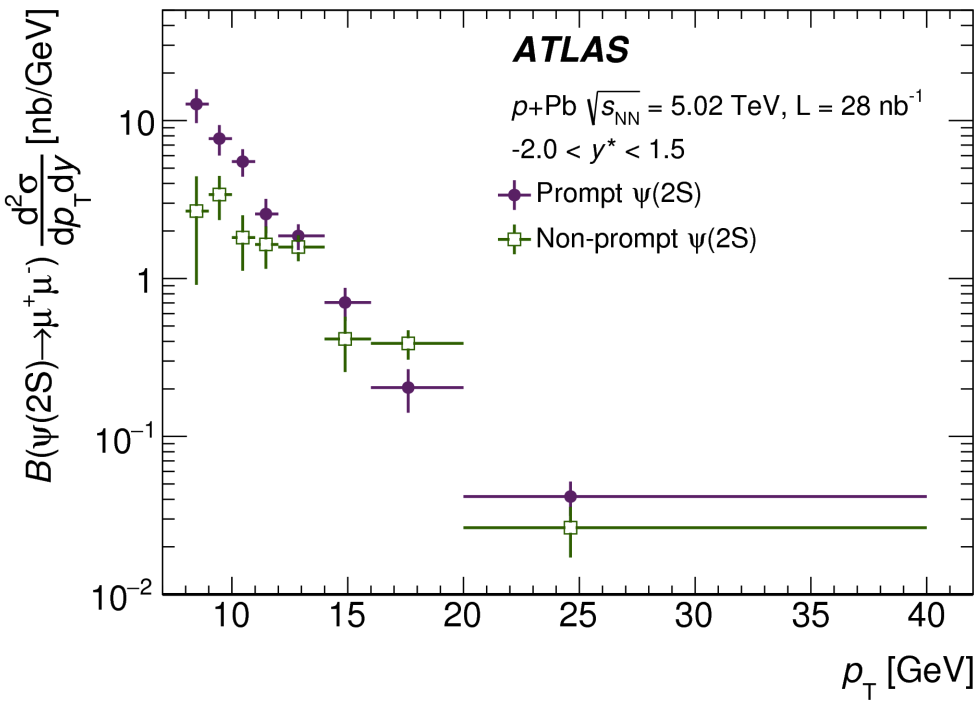
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-15-005/index.html

Quarkonia production in pp, p+pb

differential cross sections in pp



differential cross sections in p + pb

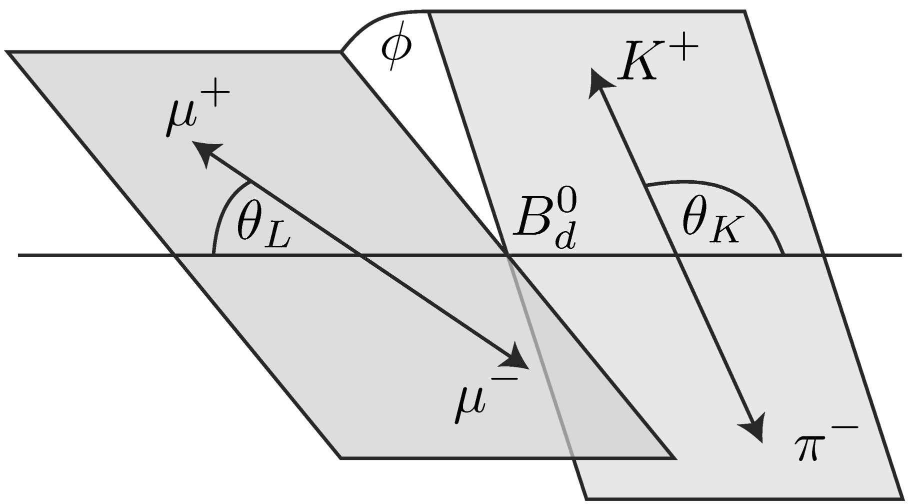


No significant modification of the J/ψ production

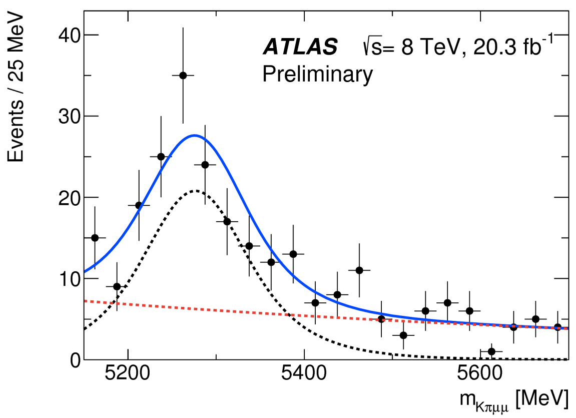
$\Upsilon(1S)$ production is found to be suppressed at low transverse momentum in p+Pb collisions relative to pp

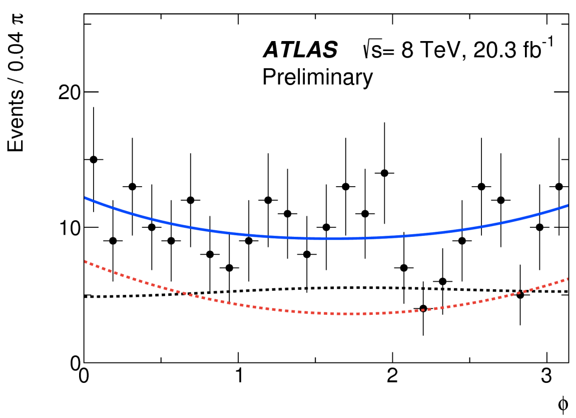
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2014-05/

Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ at $\sqrt{s}$ = 8 TeV at ATLAS



BLACK: signal
RED: background
BLUE: total



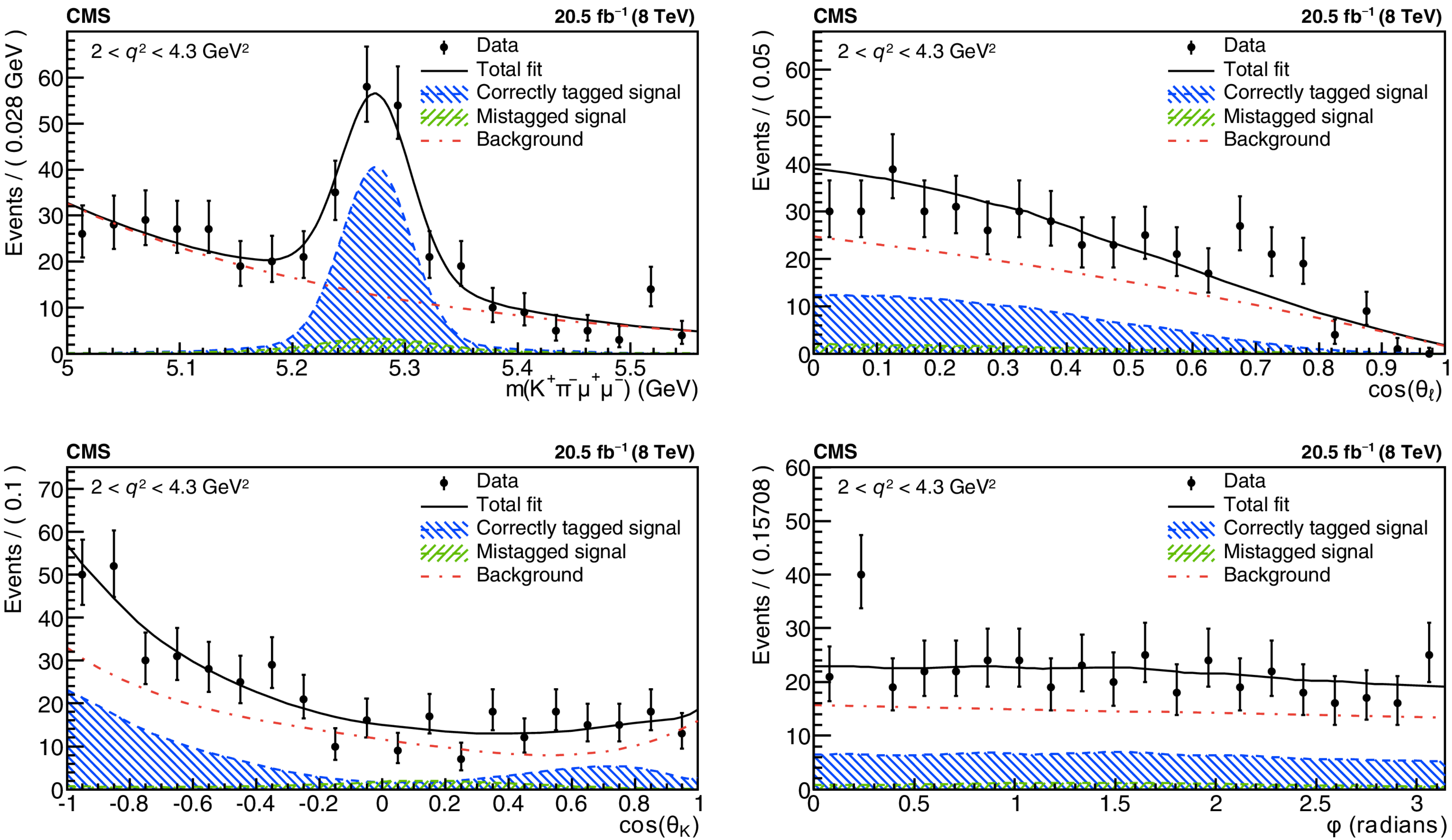


Measurements are sensitive to heavy new particles contributing to FCNC decay amplitudes.

Results are compatible with theoretical predictions

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-023/

Angular analysis of $B_d^0 \to K^*\mu^+\mu^-$ at √s = 8 TeV at CMS

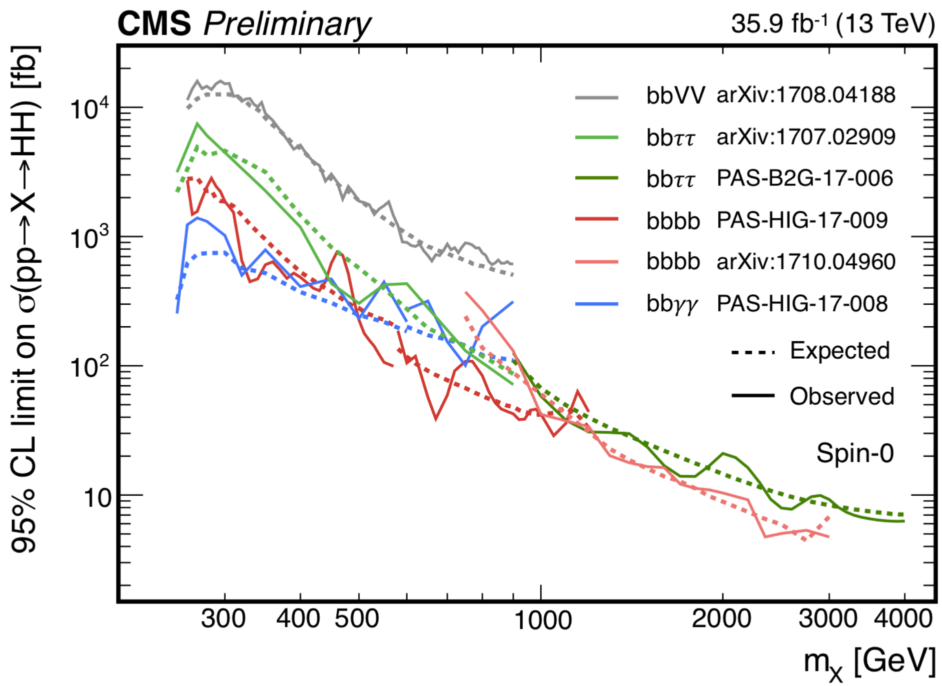


https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-15-008/index.html

Outline

- LHC, ATLAS, and CMS Performance
  - *how much data and under what conditions*
- The Searches
  - *fueled by a jump in energy and luminosity*
- The Measurements
  - *precision measurements, and measurements as searches*
- **The Higgs**
  - *improved sensitivities and new channels*

We have a long road ahead of us still…

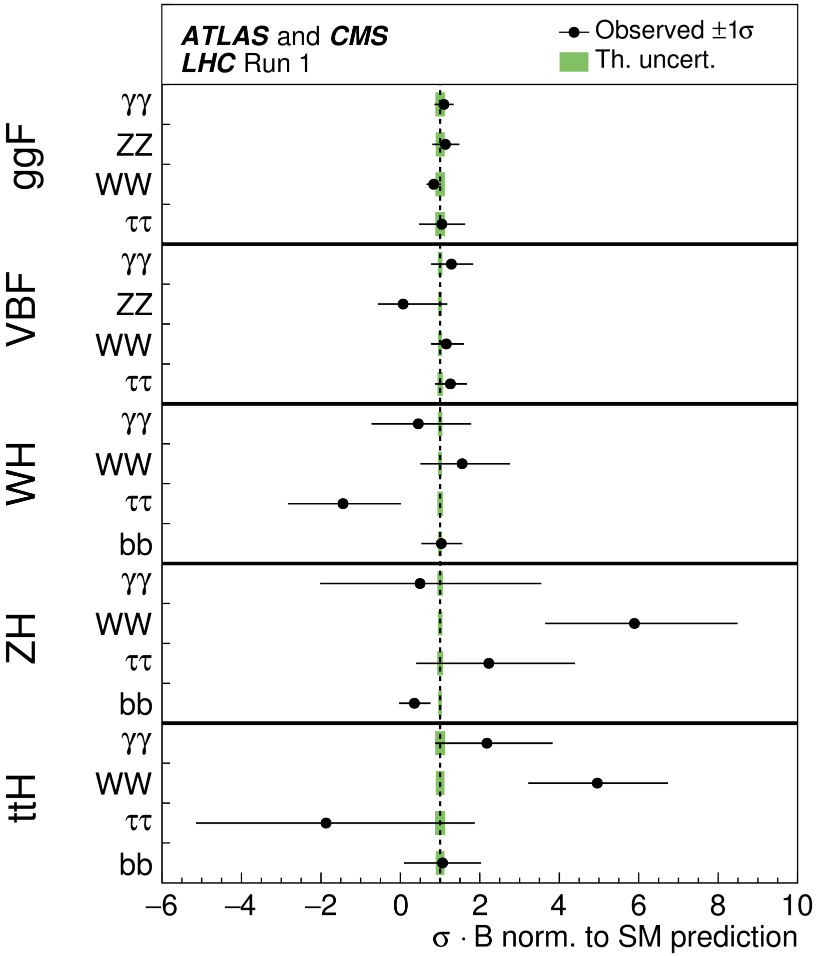


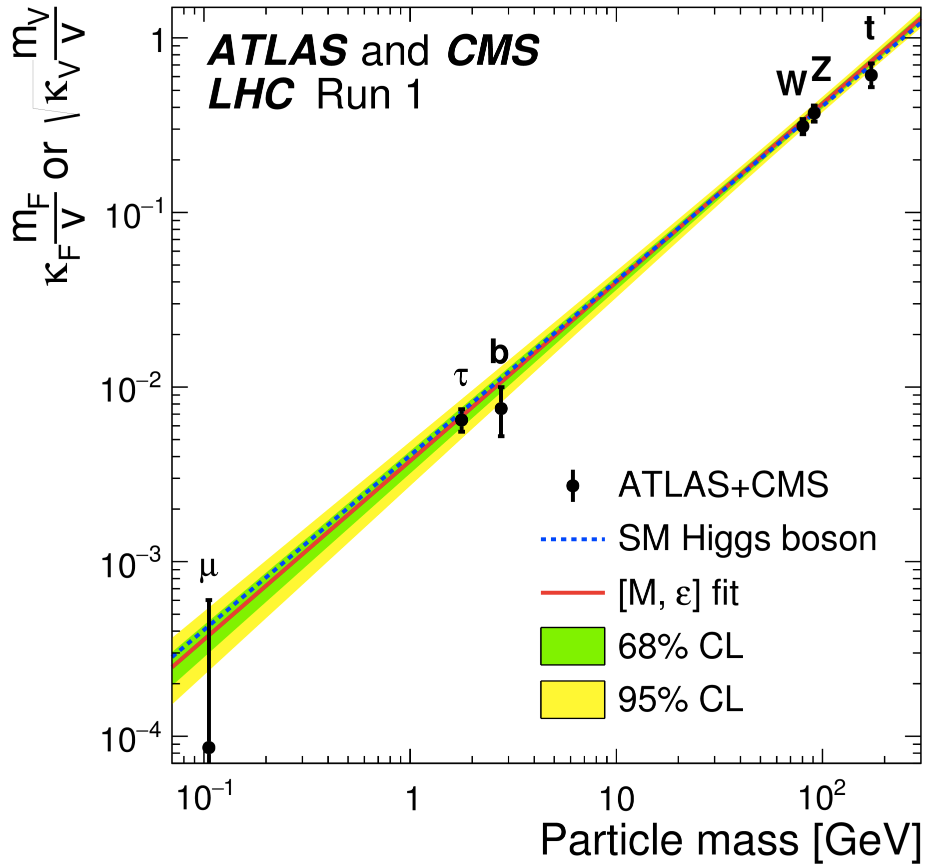
HIGGS RESULTS

ATLAS Higgs Results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

CMS Higgs Results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

The Higgs boson is looking SM-like



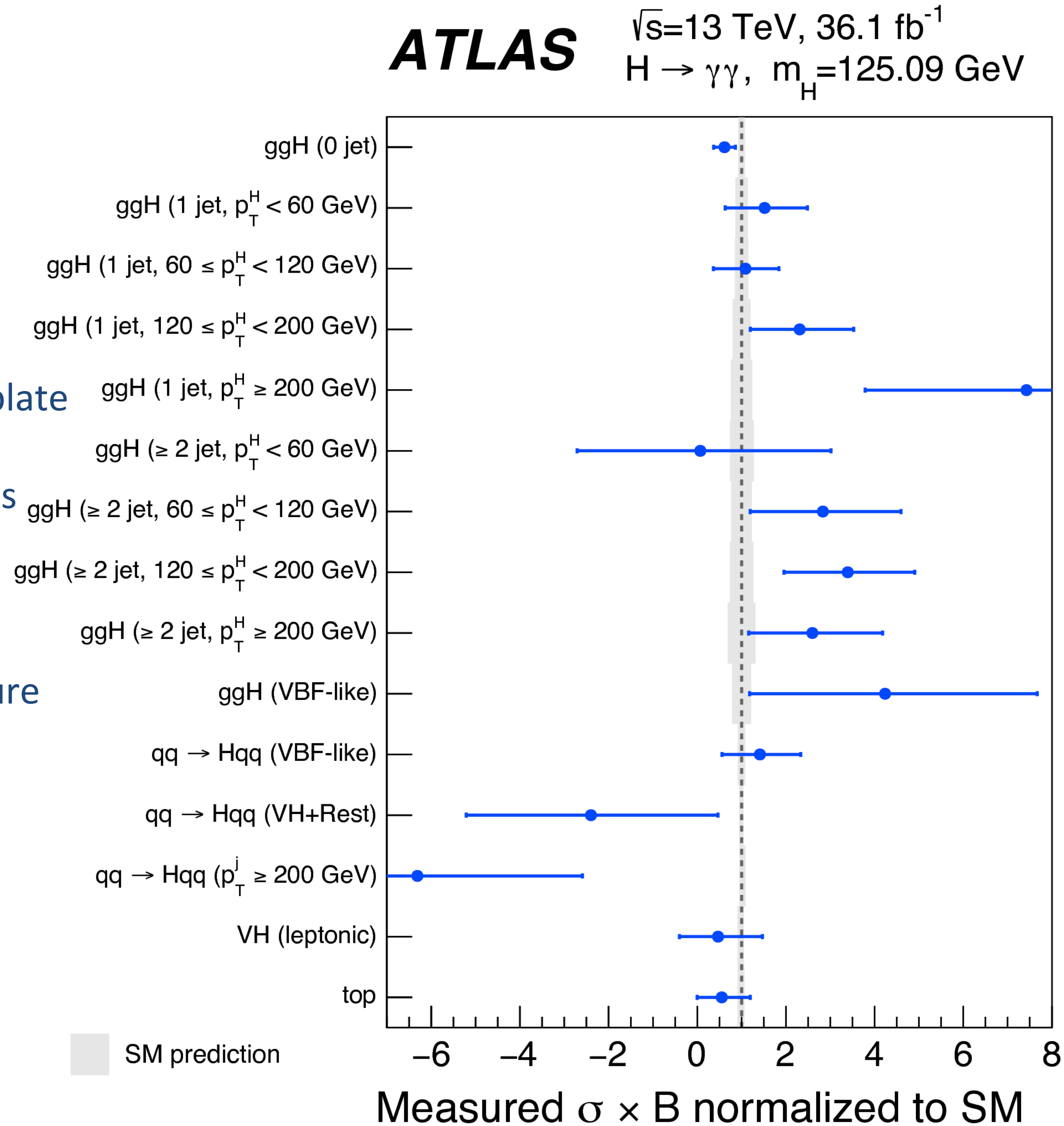


Run 2 Program: Increase precision, finding missing production and decay modes, and model independent measurements to characterize deviations from SM

H->γγ

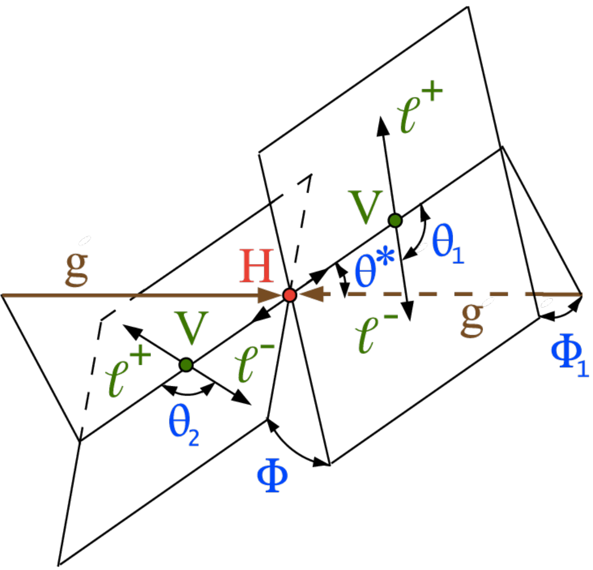
Differential and simplified template cross sections are sensitive to
- higher order QCD corrections
- Higgs spin and CP
- couplings

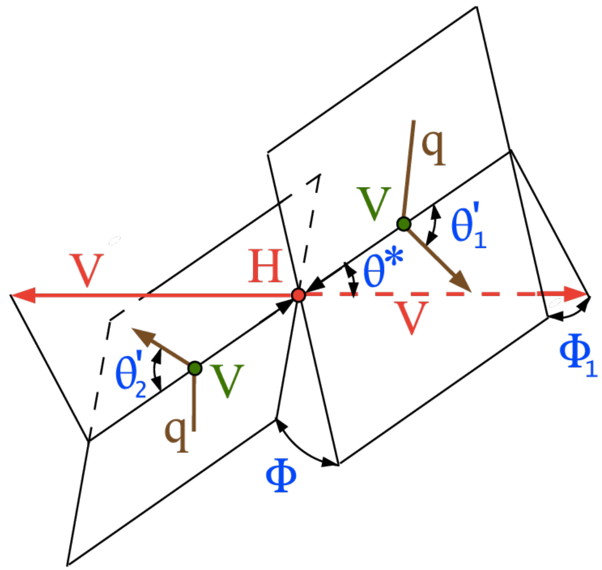
The strength and tensor structure of interactions are investigated with an effective Lagrangian in model independent ways.
No significant deviations from SM are found.

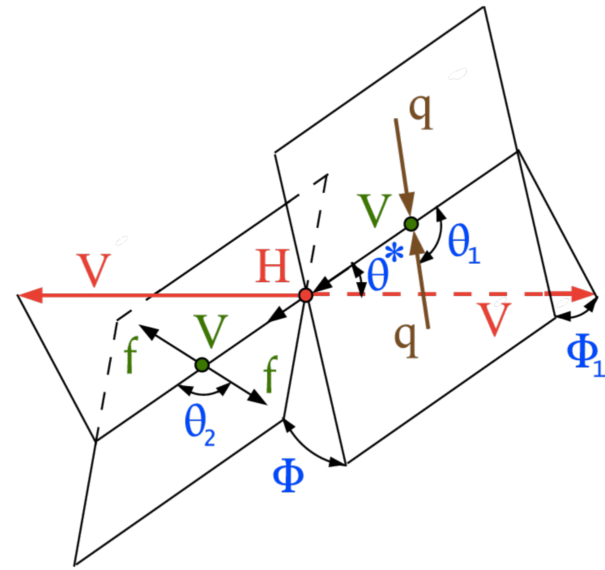


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-21/

H->ZZ->llll : Constraints on anomalous couplings







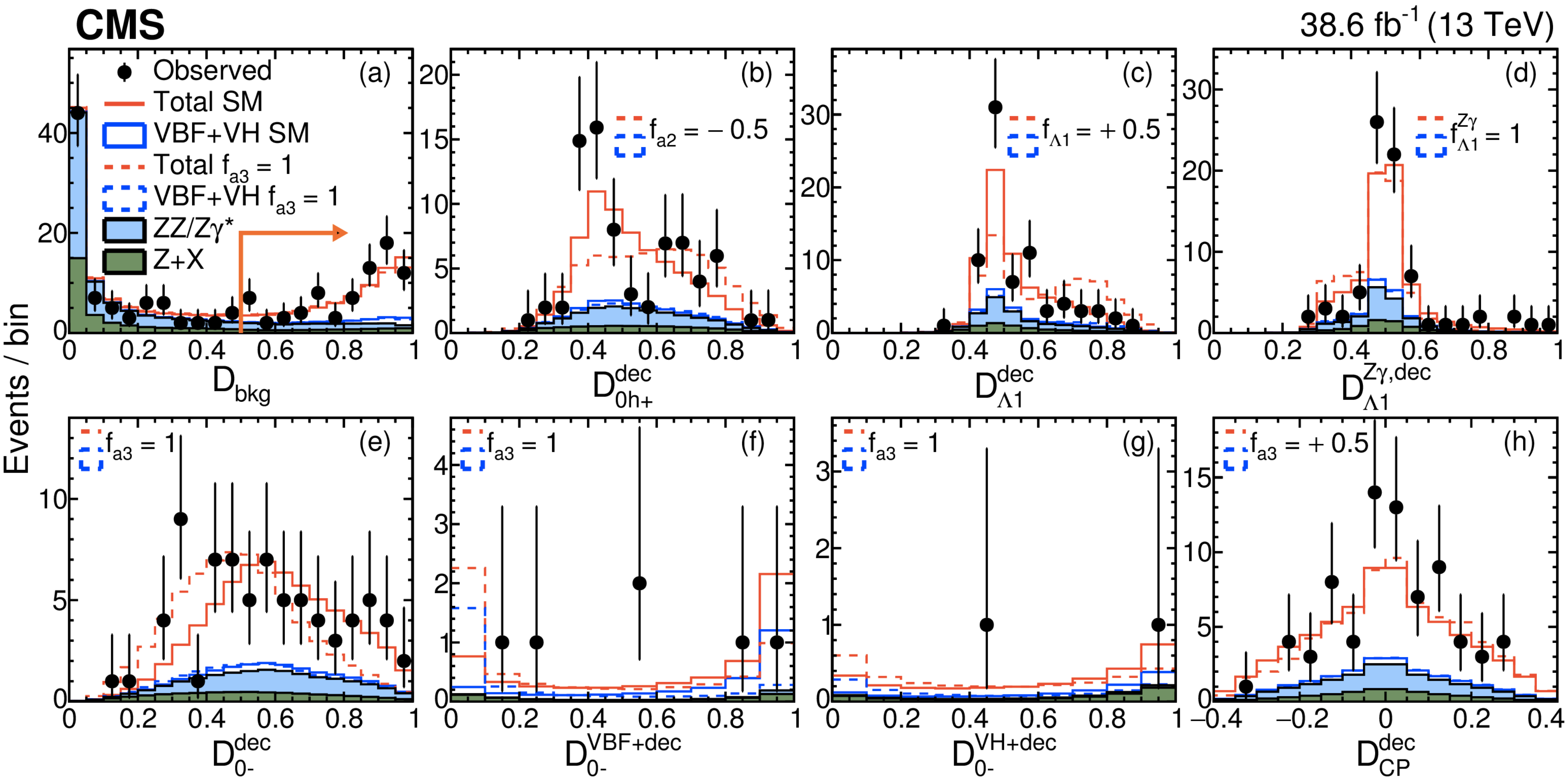
gluon-gluon fusion
5 decay angles
two invariant masses

vector boson fusion
5 decay angles
two invariant masses
decay of V to 4l not shown

associated production (VH)
5 decay angles
two invariant masses
decay of V to 4l not shown

[*Phys. Lett. B 775 (2017) 1*]

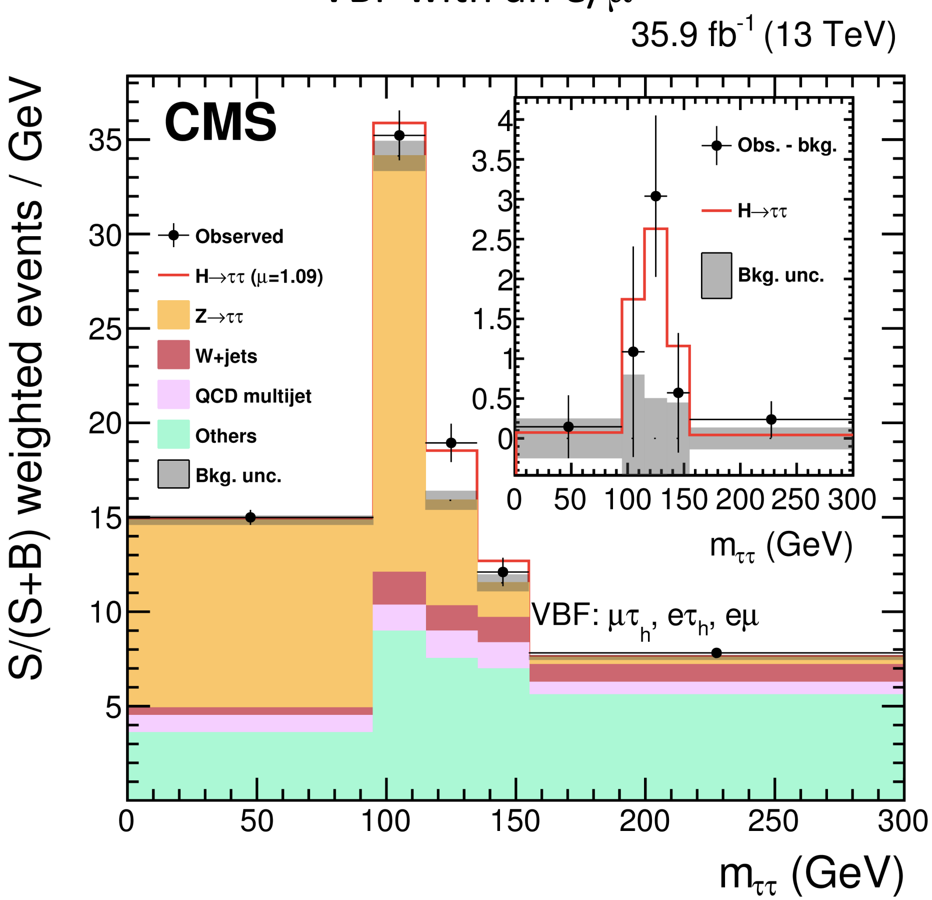
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$



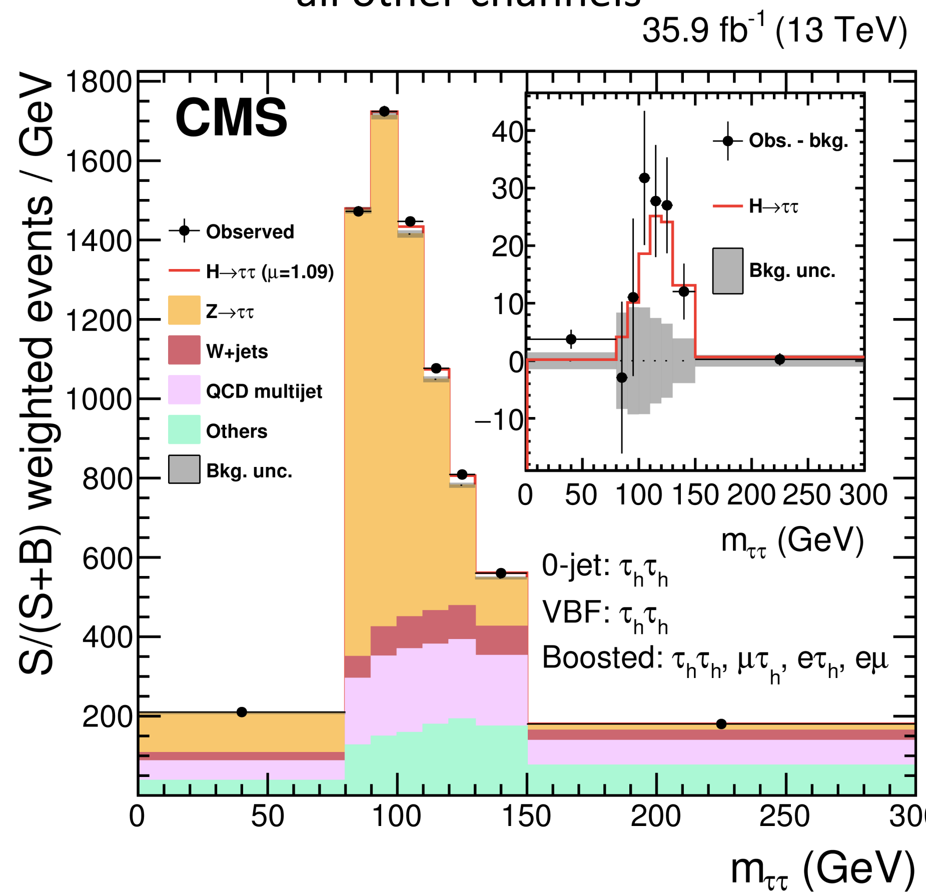
Phys. Lett. B 775 (2017) 1

H->ττ

VBF with an e/μ



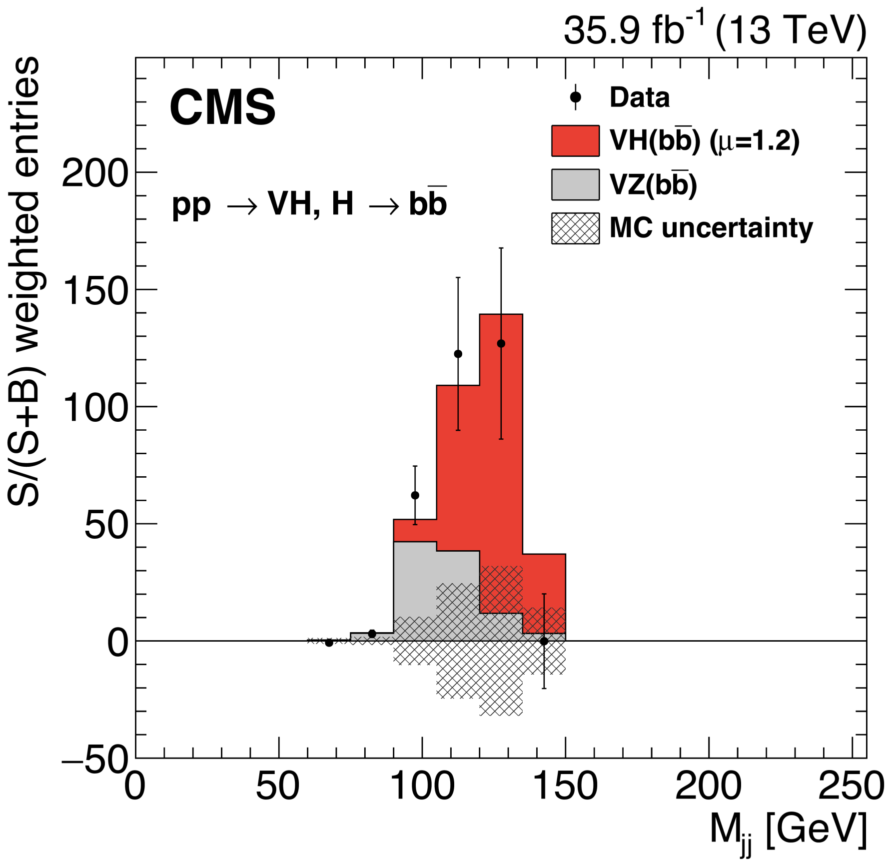
all other channels

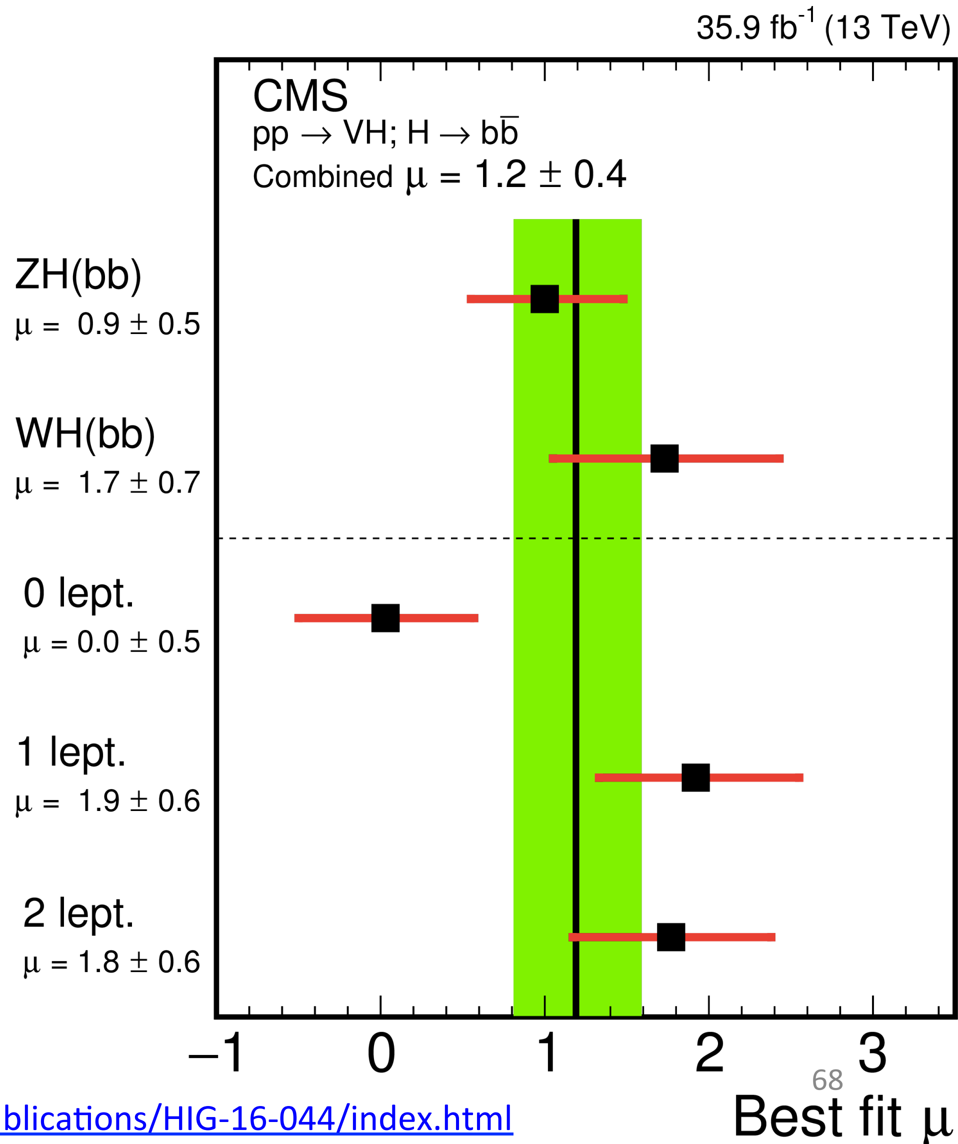


When combined with lower COM energy measurements, 5.9σ

https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-043/index.html

Higgs decays to b quarks at CMS

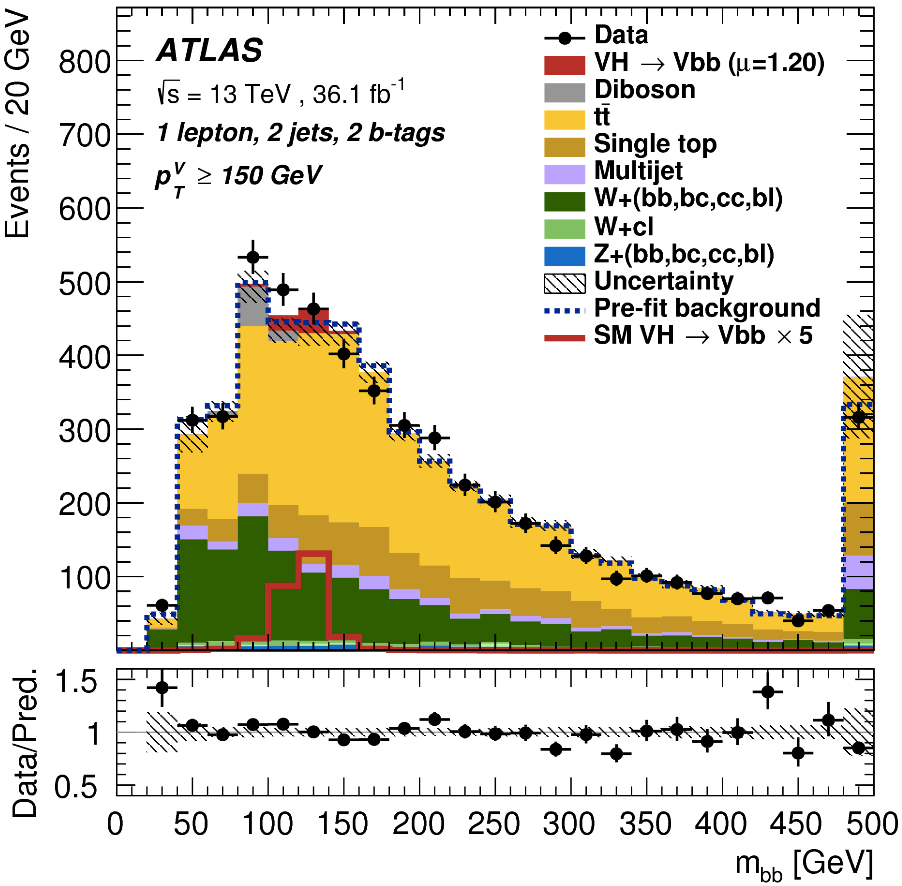


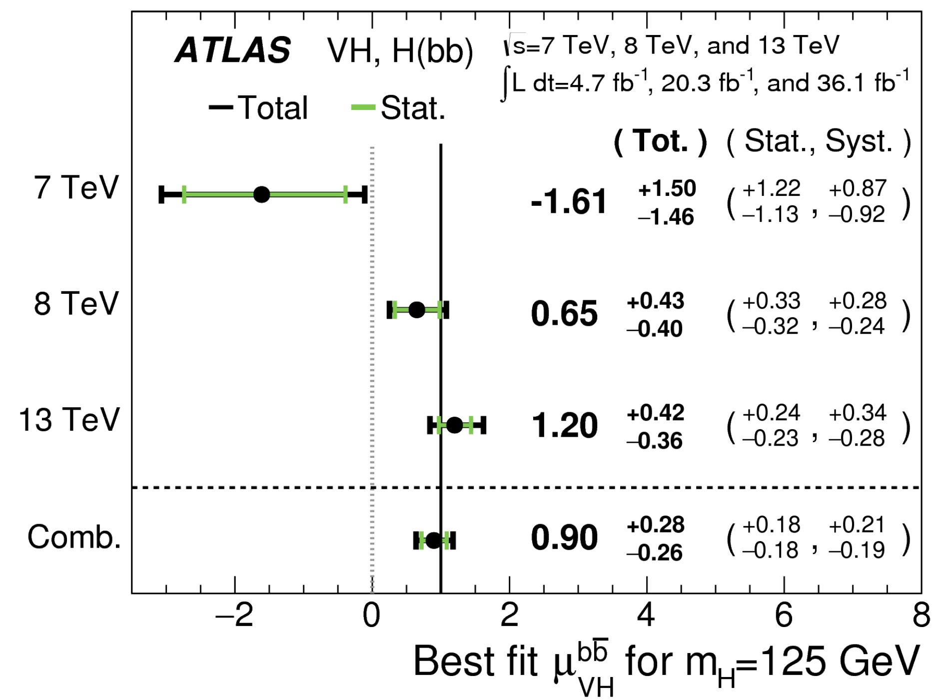


When combined with Run 1, 3.8σ

https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-044/index.html

Higgs decays to b quarks at ATLAS

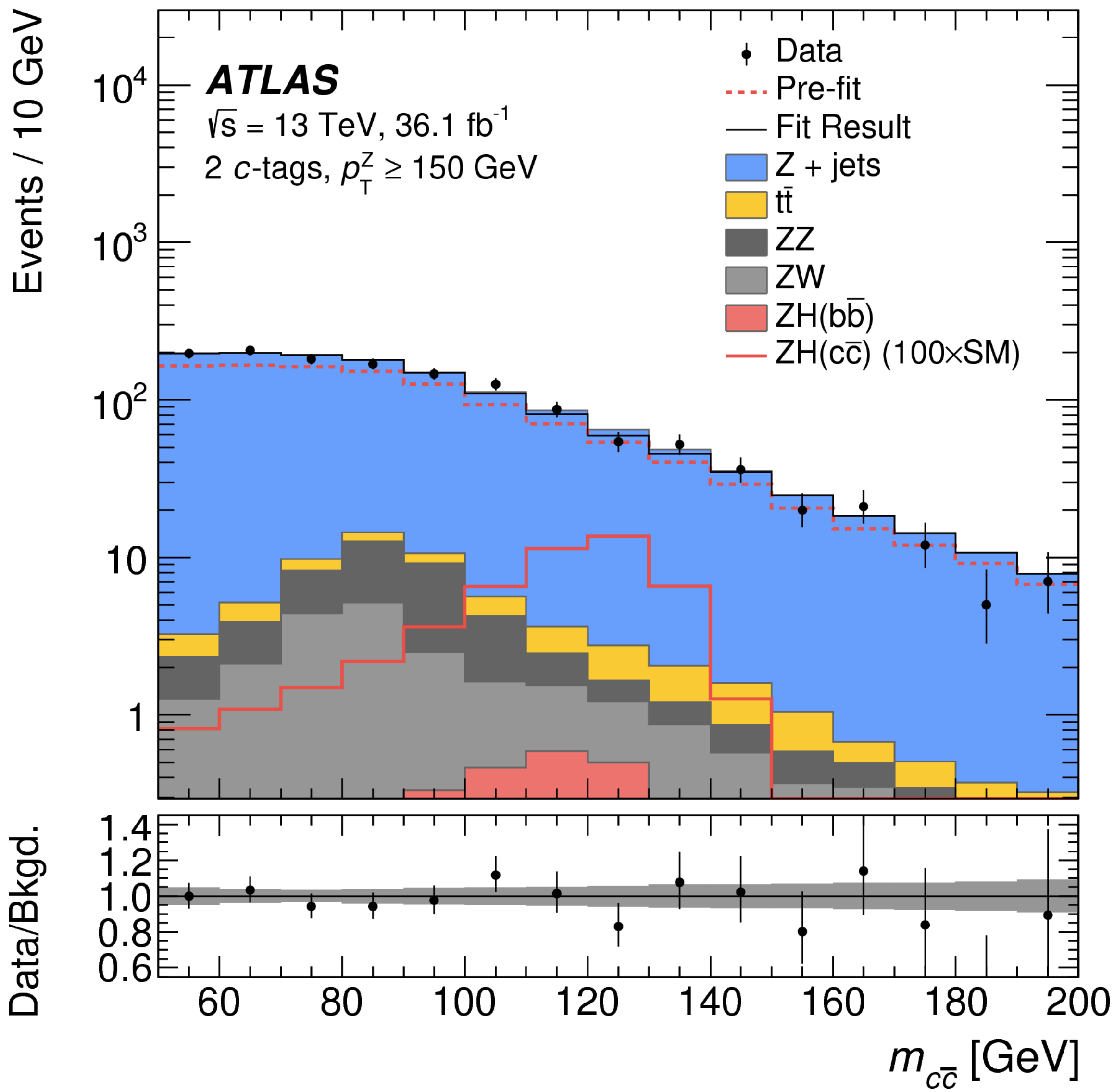




Run 2 observed significance: 3.5 σ

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-29/

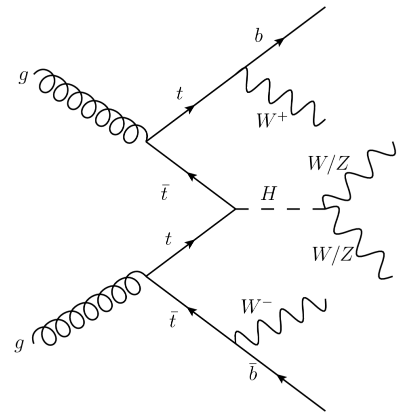
Search for Higgs decays to charm quarks

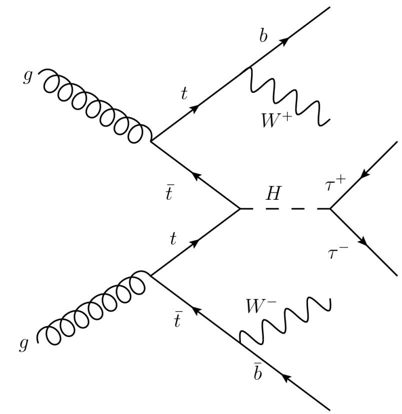


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2017-01/

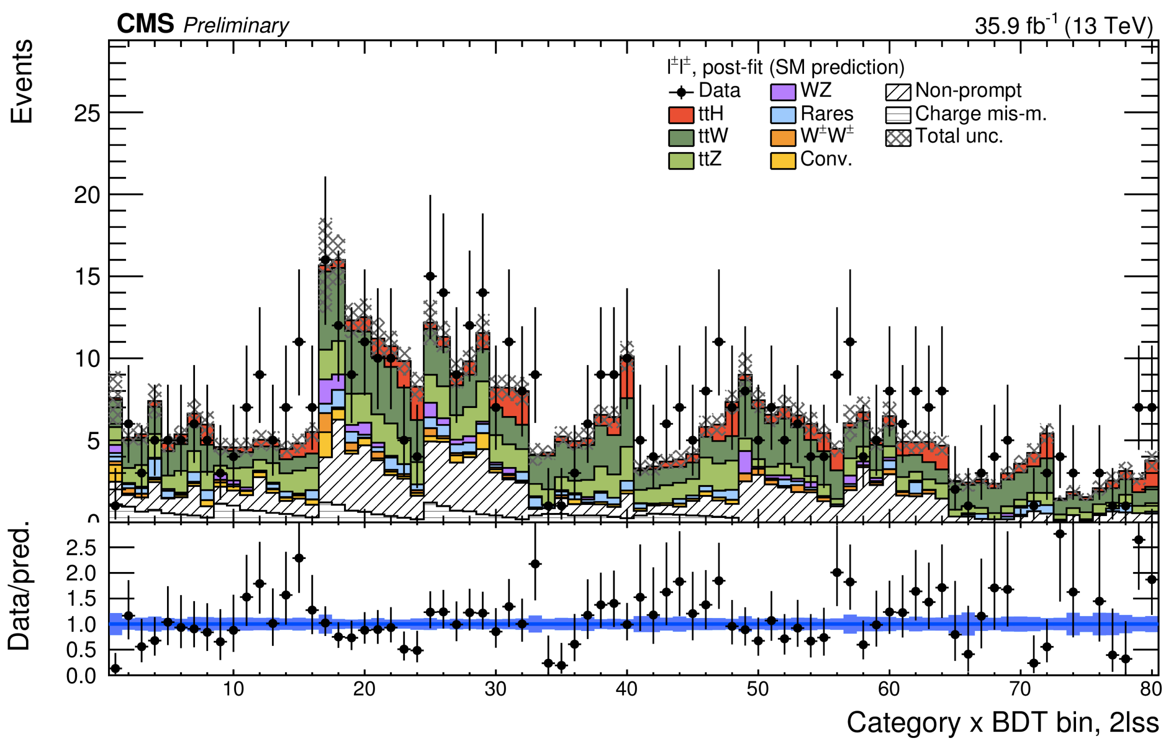
ttH at CMS

using H->WW, H->ZZ and H->ττ

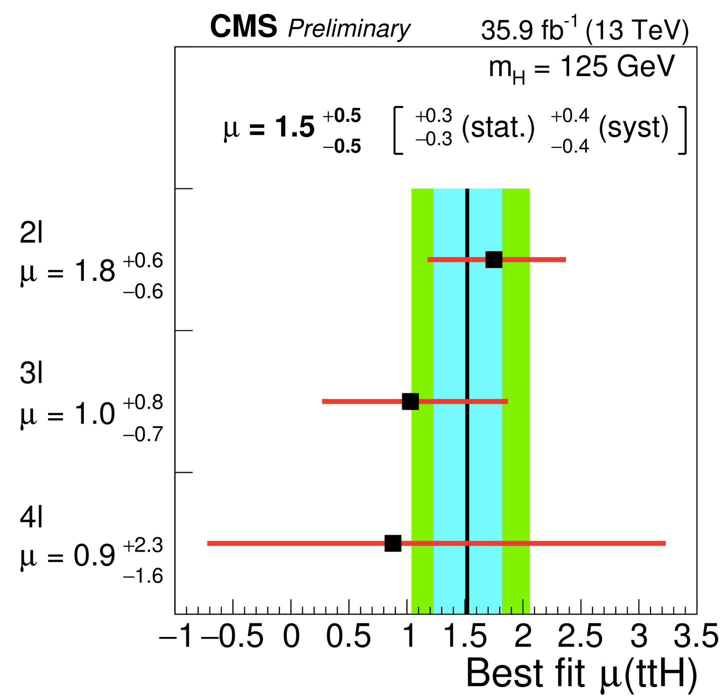




Output of classifiers for the 2 lepton, same-sign channels



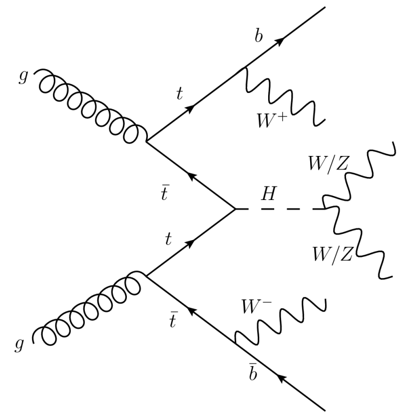
significance of 3.3 σ

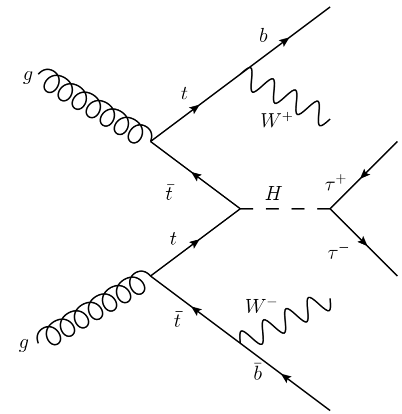


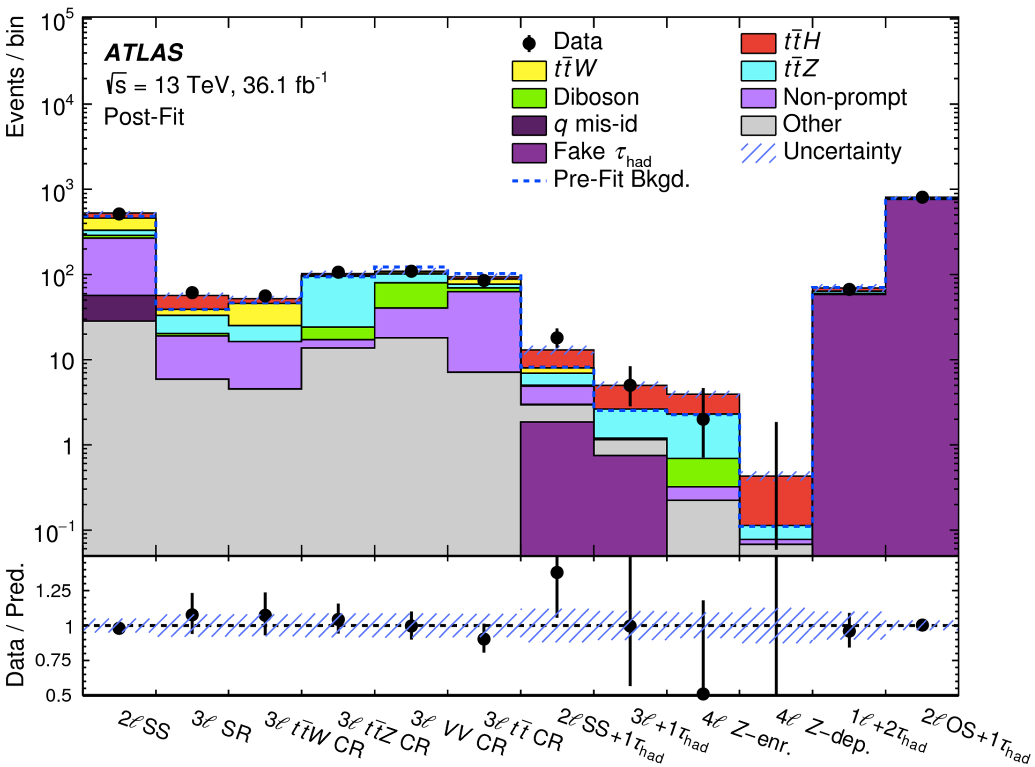
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-17-004/index.html

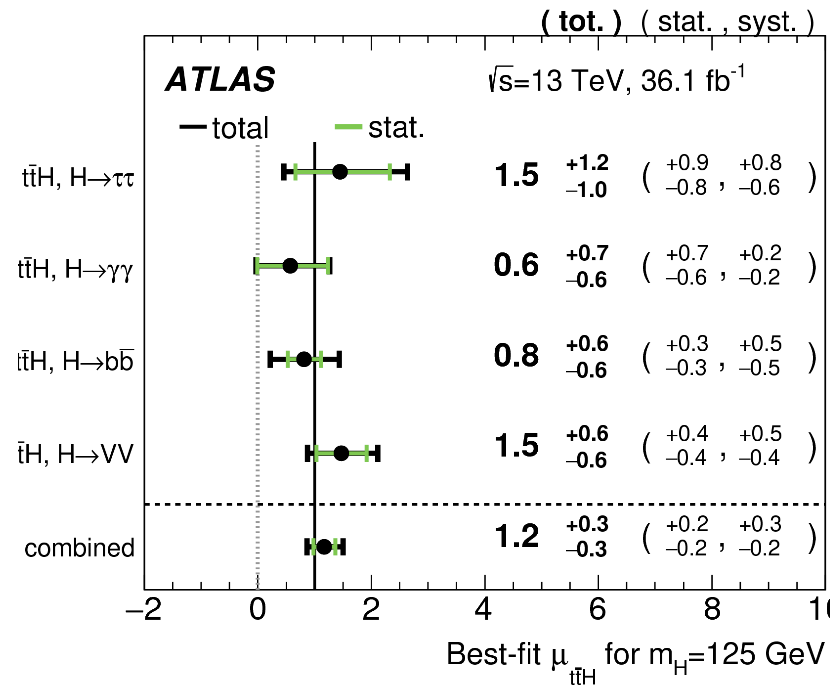
ttH at ATLAS

using H->WW, H->ZZ and H->ττ









significance of 4.2 σ

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2017-02/

Conclusions

- A diverse and aggressive program is moving ahead with full steam at the LHC.
- We continue to push forward with searches as our datasets grow, while simultaneously developing new techniques and making precision measurements.
- With orders of magnitude more data on our horizon, the best is yet to come.
- Thanks for your attention!