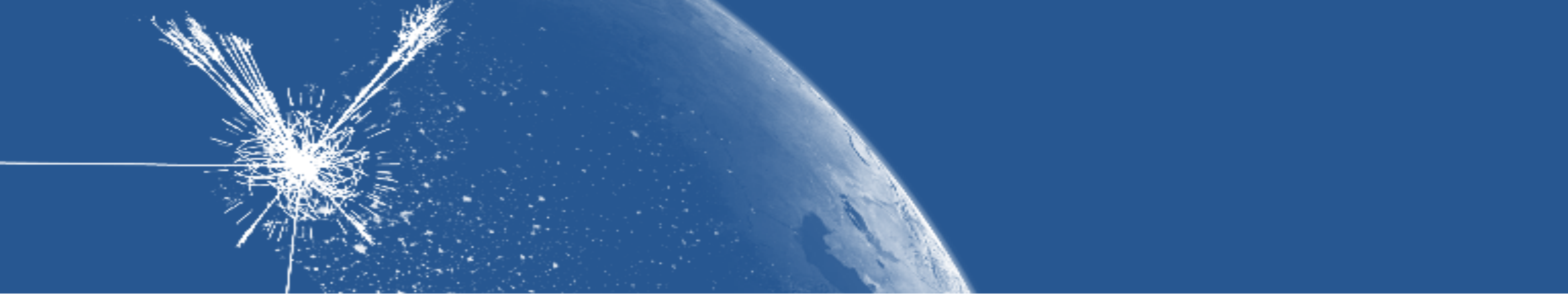


New Results from the LHC (3)

Andreas Hoecker (CERN)

September 26–28, 2016 in Freudenstadt, Germany

Outline

[3 × 1h lectures]

Before yesterday:

- Basic introduction
- Overview of the LHC experimental programme and methods

Yesterday:

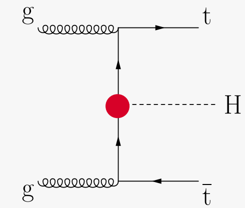
- A review of Run-1 physics highlights
- SM results from the LHC Run-2

Today

- Higgs and BSM searches from the LHC Run-2
- Digression on precision measurements
- Short outlook to HL-LHC

First search for ttH production at 13 TeV by CMS

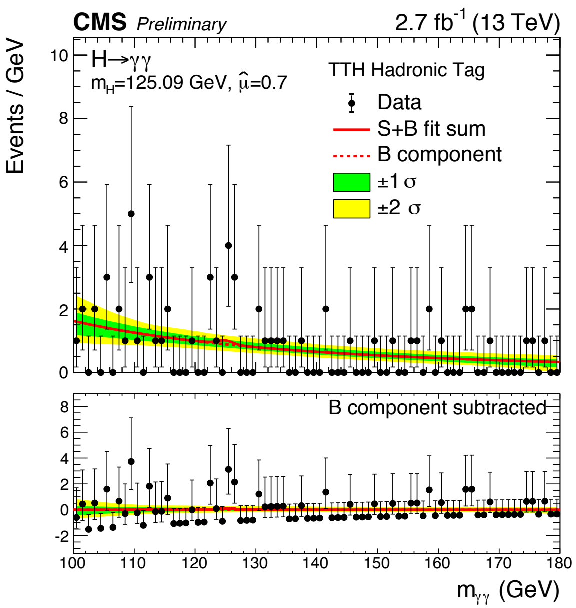
Most interesting of the SM Higgs channels at current luminosity



CMS showed preliminary results for ttH in all major Higgs decay channels: **$H \to \gamma\gamma$, multi-leptons, bb**

Highly complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)

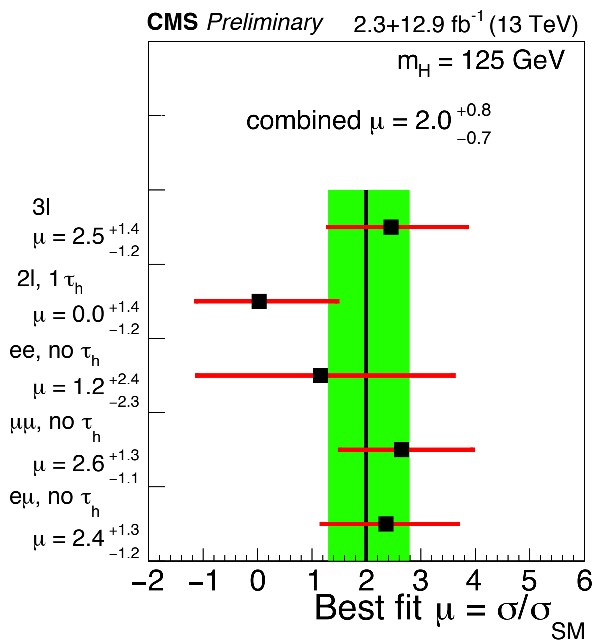
$H \to \gamma\gamma$,
tt → 0 & 1 leptons



$\mu = 3.8^{+4.5}_{-3.6}$

CMS-PAS HIG-15-005

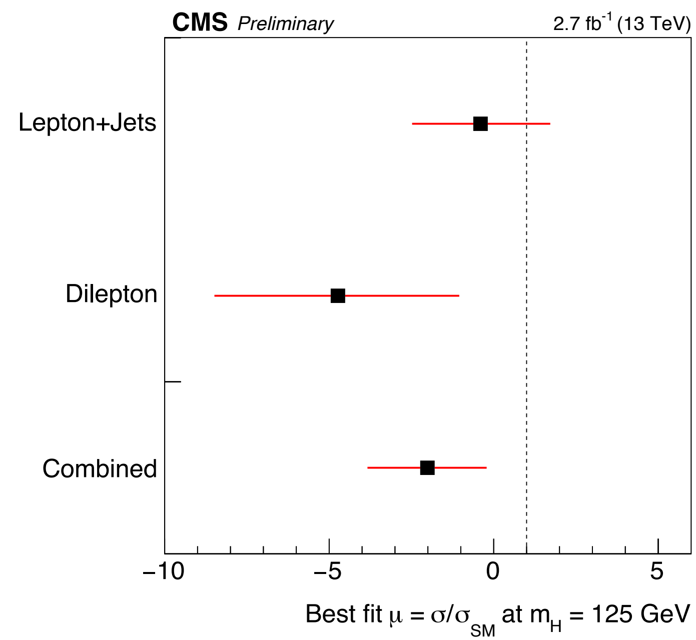
ttH → multi-leptons
2 same charge (+ τ) / 3 leptons



$\mu = 2.0^{+0.8}_{-0.7}$

CMS-PAS-HIG-16-022

H → bb
tt → 1 & 2 leptons

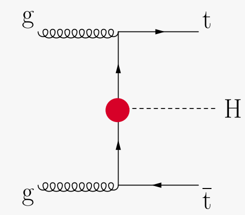


$\mu = -2.0 \pm 1.8 < 2.6$ (95% CL)

CMS-PAS HIG-16-004

First search for ttH production at 13 TeV by ATLAS

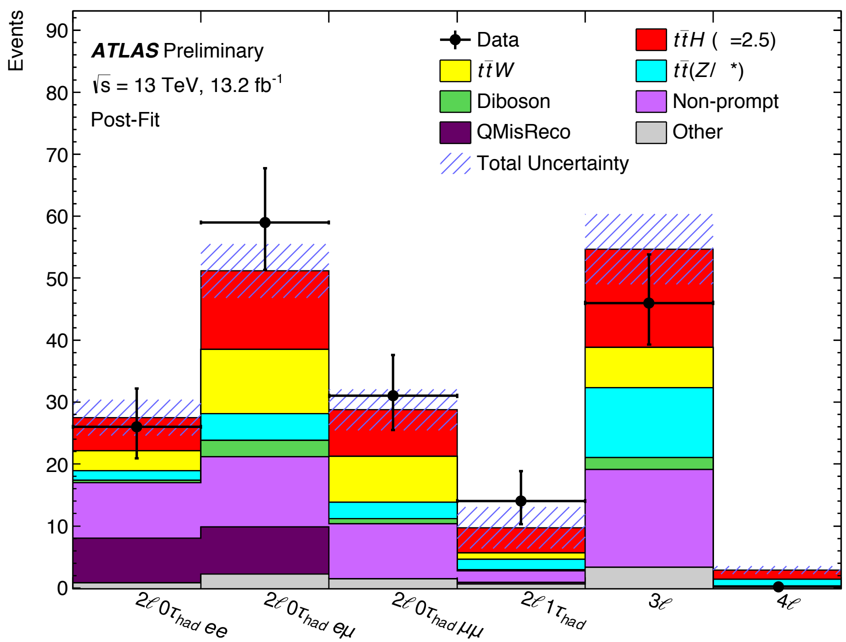
Most interesting of the SM Higgs channels at current luminosity



ATLAS showed preliminary results for ttH in all major channels and their combination at ICHEP 2016

ttH → multi-leptons

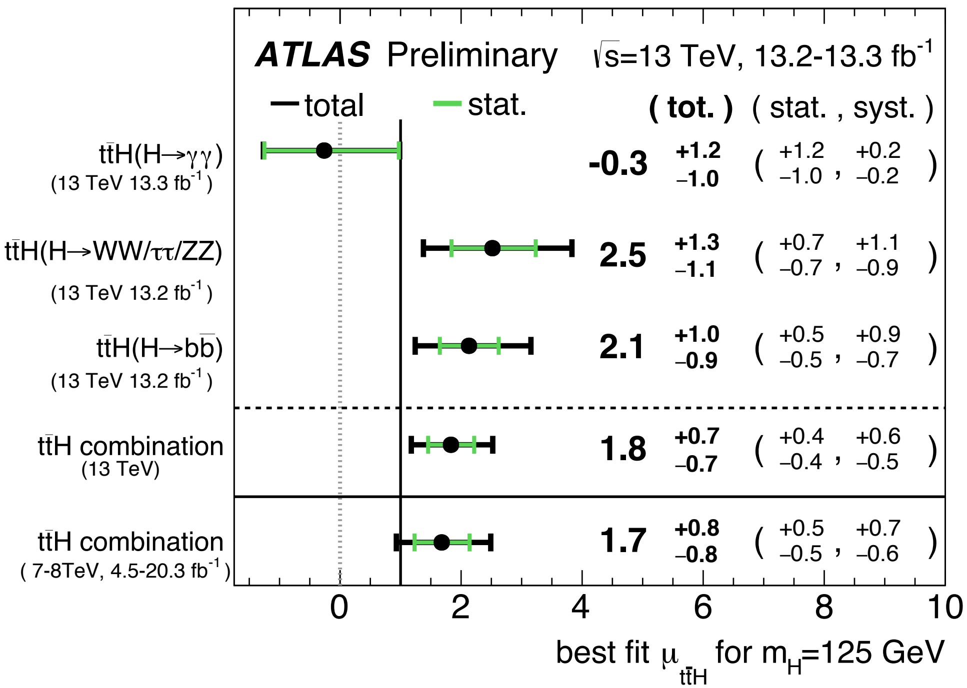
ATLAS-CONF-2016-058



$$\mu = 2.5^{+1.3}_{-1.1}$$

Individual channels and combination

ATLAS-CONF-2016-068



BSM searches — a fresh start

Will cover:

- BSM Higgs (briefly)
- Heavy resonances
- Supersymmetry
- Long-lived particles
- Dark matter (WIMPs)

Heavy resonance searches benefit the most and fastest from increase in centre-of-mass energy. Slow improvement with increasing luminosity

Beyond the Standard Model Higgs physics

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

Diverse search programme:

BSM Higgs searches

- **Light or heavy neutral Higgs bosons**
- **Charged Higgs boson**
- **Lepton flavour violating Higgs decays**
- **Di-Higgs production (resonant or not)**
- **Exotic Higgs decays**
- **Higgs as portal to hidden sector**
- **Higgs in BSM decay chains**
- **BSM constraint from coupling measurements**

Taken from: Thibault Guillemin @ SEARCH 2016

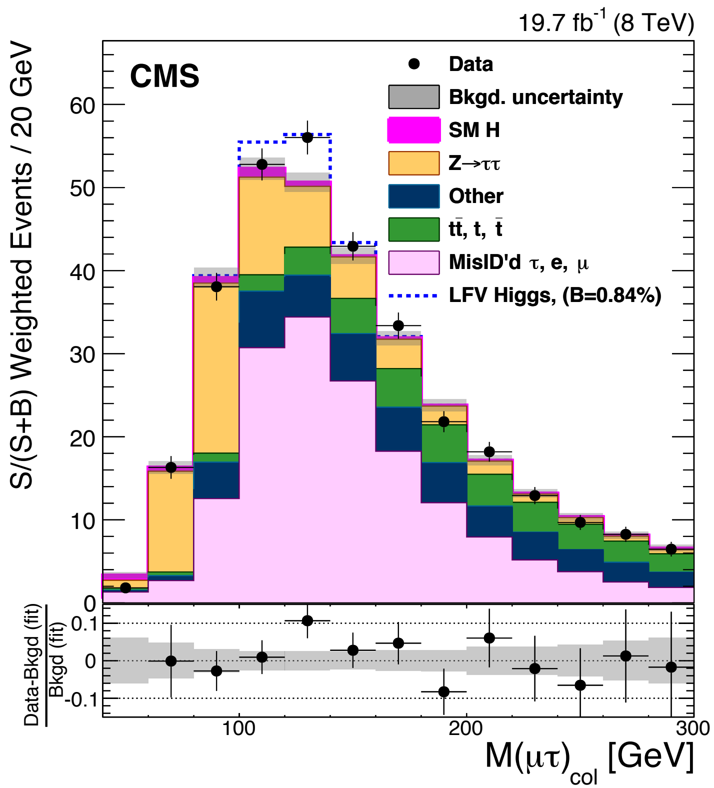
One word on lepton flavour violation in Higgs decays

Both experiments have finalised their Run-1 LFV analyses

While H → μe is severely constrained from flavour physics, H → τμ, τe are not (~10% limits)

CMS released early 2015 a H → τμ search finding a slight (2.4σ) excess

Not confirmed by ATLAS in the full Run-1 analysis



H → τμ:

ATLAS:

BR = 0.53 ± 0.51% < 1.43% (95% CL)

CMS:

BR = $0.84^{+0.39}_{-0.37}$ % < 1.51% (95% CL)

H → τe:

ATLAS:

BR = –0.3 ± 0.6% < 1.04% (95% CL)

One word on lepton flavour violation in Higgs decays

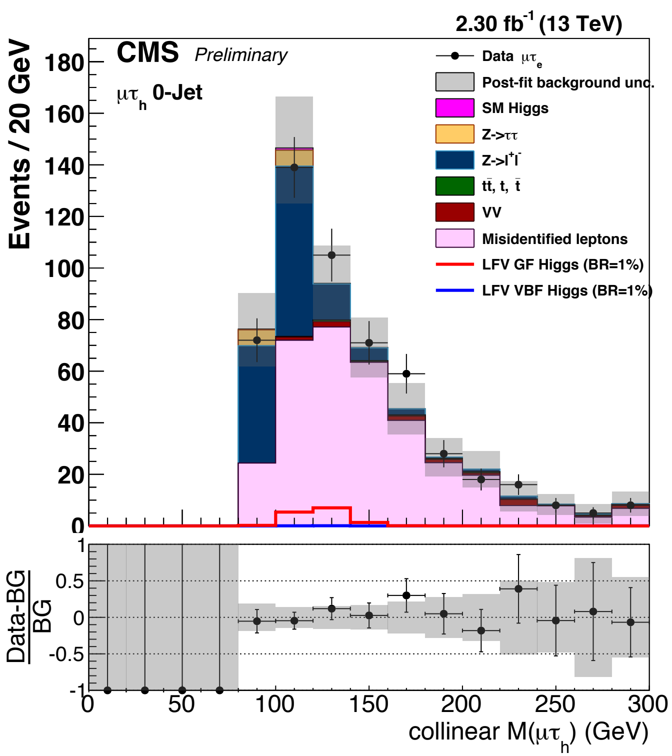
Both experiments have finalised their Run-1 LFV analyses

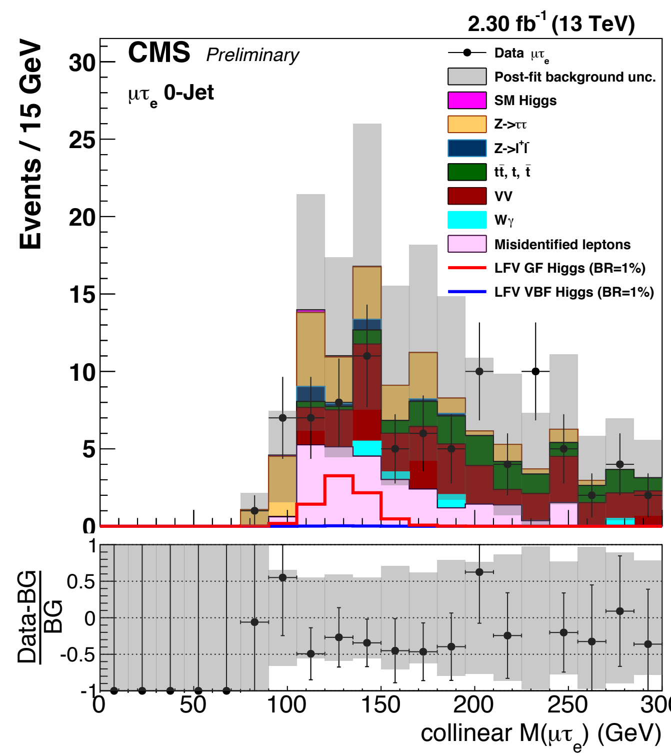
New preliminary result with 13 TeV from CMS [CMS-PAS-HIG-16-005]

Six categories considered: $(\mu\tau_h, \mu\tau_e) \times (0,1,2 \text{ jets})$

No significant excess, combined limit: BR = –0.8 ± 0.8 % (<1.2% at 95%CL, expected: < 1.6%)

Limit on non-diagonal Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$





BSM Higgs boson searches

Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

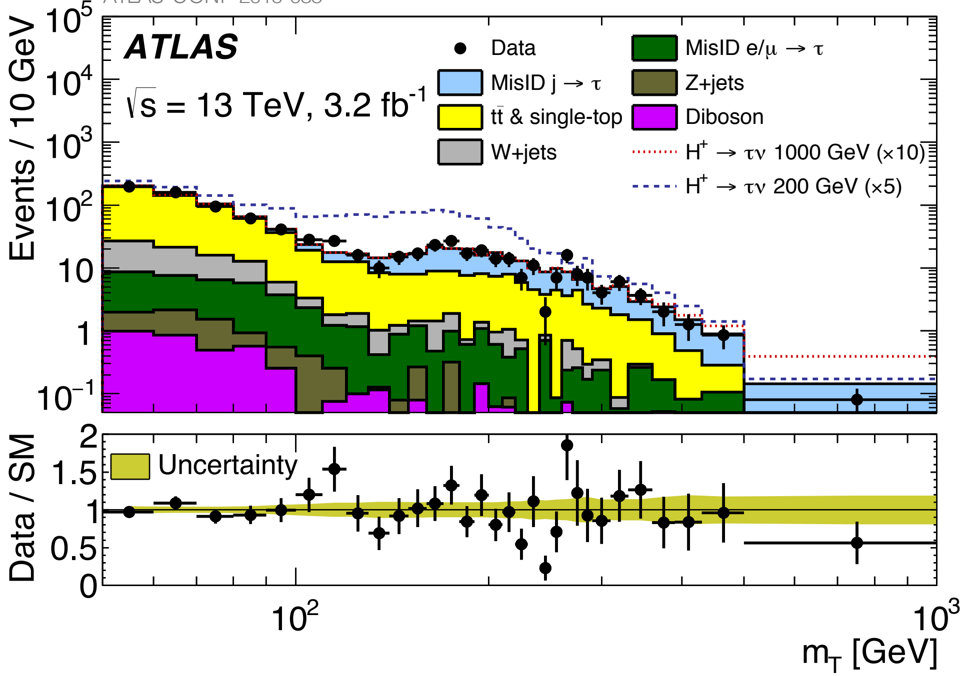
Beyond the SM “Higgs zoo”

[Will Davey, LHCP 2014]

Higgs coupling to mass, look for decays to tau leptons or weak bosons, for example:

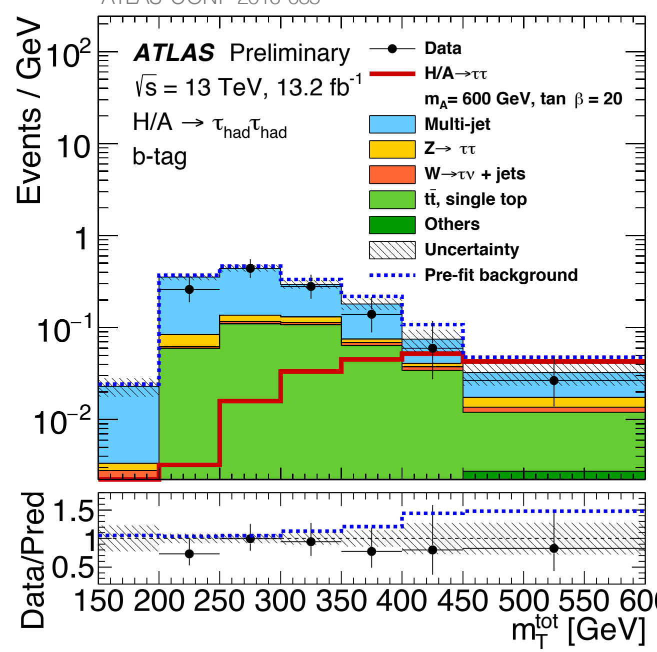
ATLAS-CONF-2016-088

$H^+ \to \tau\nu$

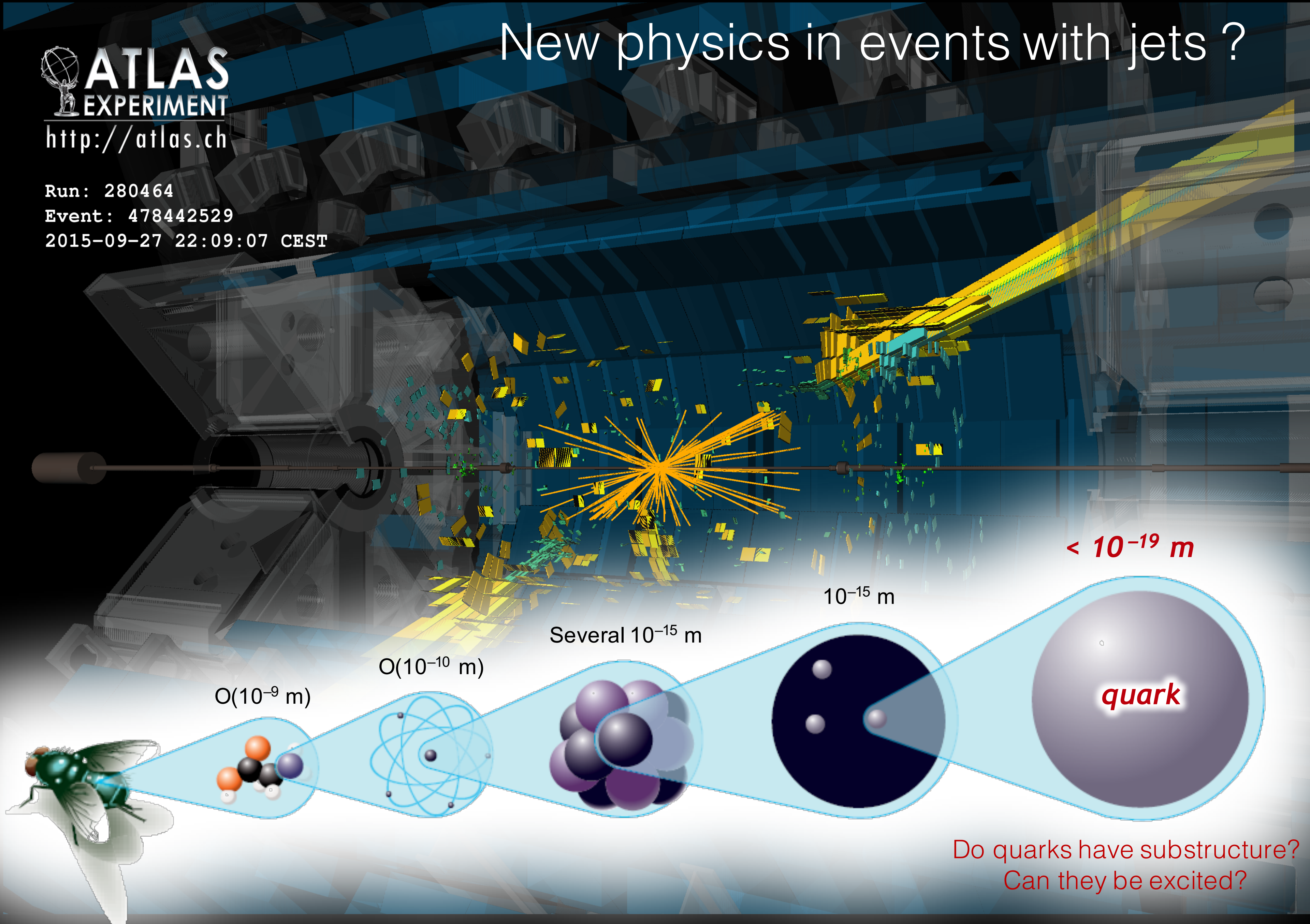


ATLAS-CONF-2016-085

$H / A \to \tau\tau$



New physics in events with jets ?



Do quarks have substructure?
Can they be excited?

Searches in high-p_T multijet final states at 13 TeV

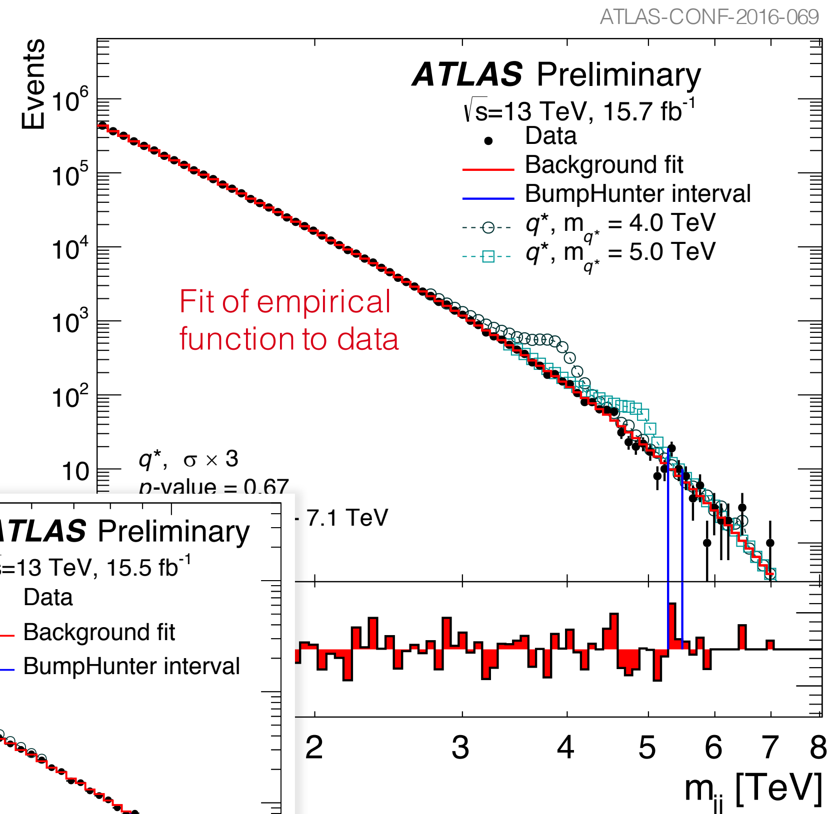
Processes with large cross-sections, sensitivity to highest new physics scales

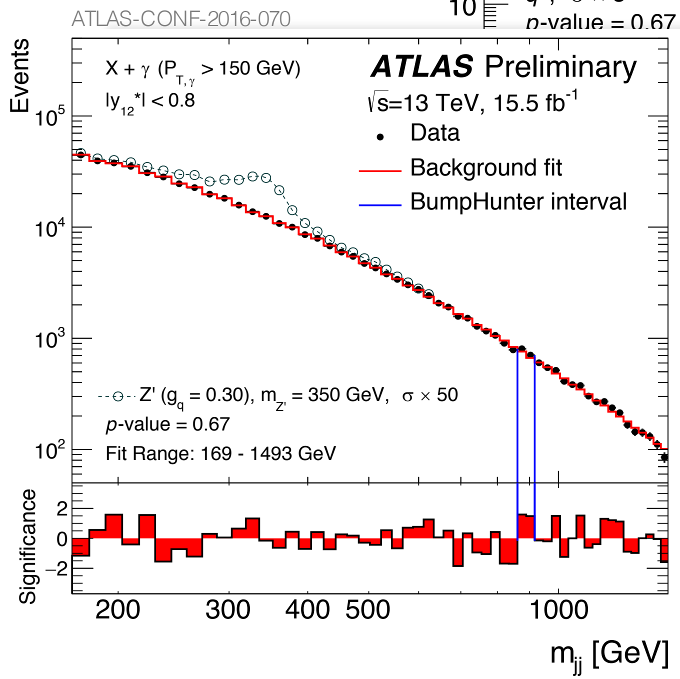
High priority early 13 TeV searches

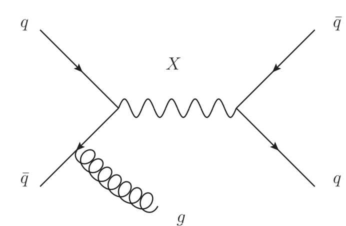
- Dijet resonance and angular distribution (incl. lower mass via ISR)
- High-p_T multijets produced, eg, by strong gravity
- High-p_T lepton + jets (strong gravity)
- Second generation scalar lepto-quark pair production (μq-μq final state, excl. < 1.2 TeV)

None of these searches showed an anomaly so far

Limits on excited quarks (for example) at 5.6 TeV



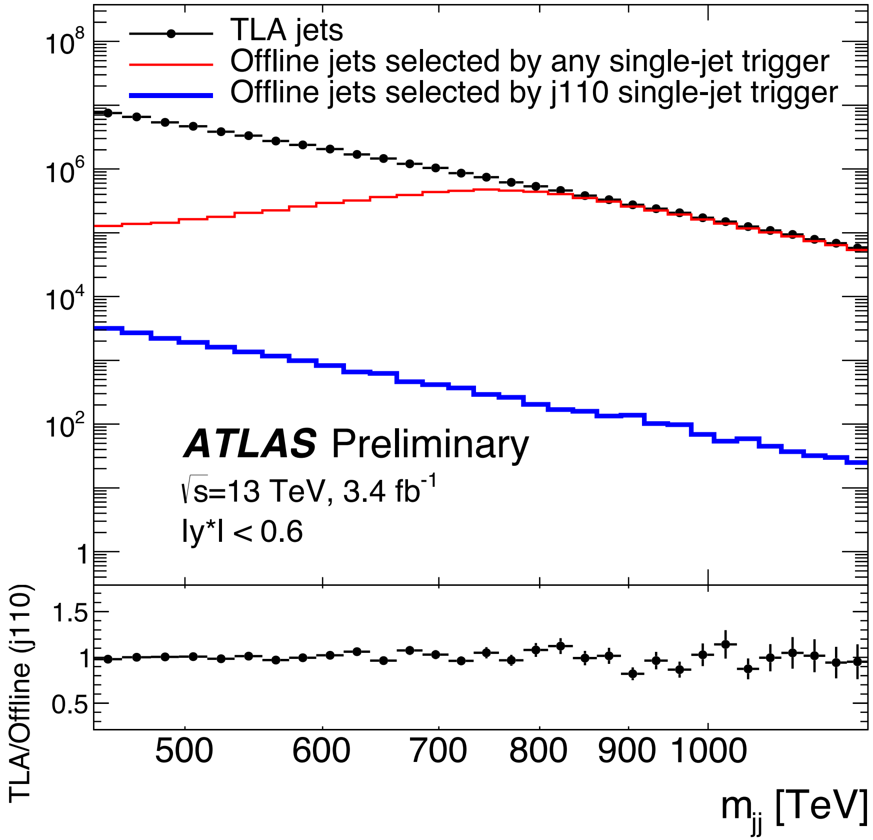




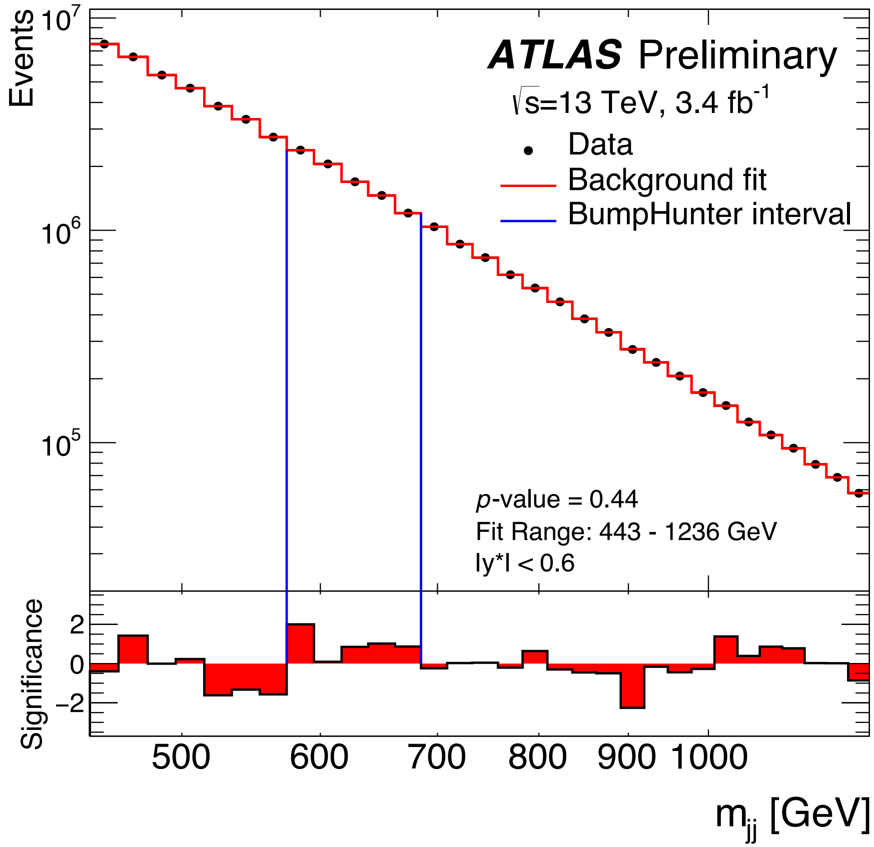
Searches in high-p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

A “trigger level analysis” allows to reduce trigger threshold



ATLAS-CONF-2016-030

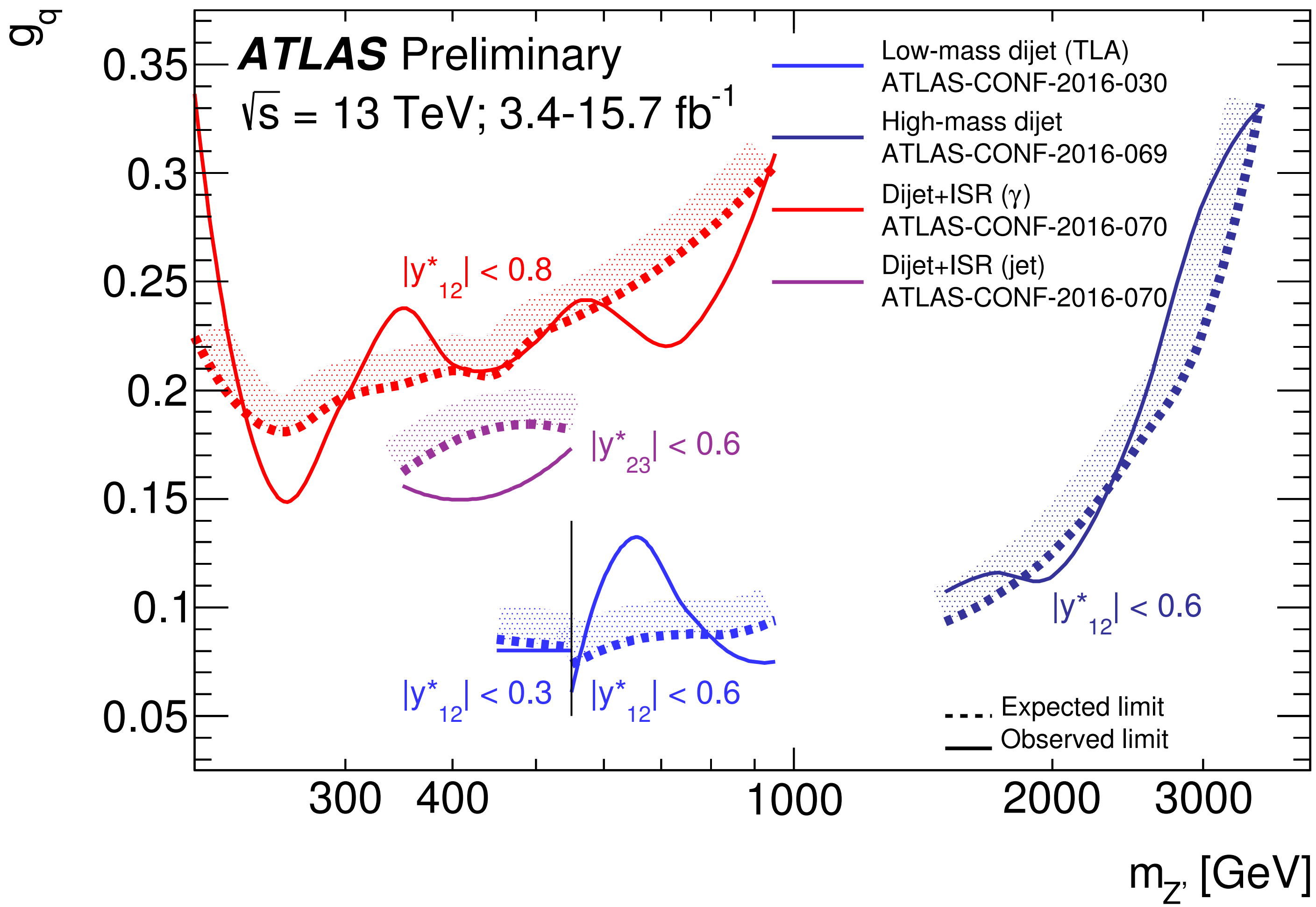


$$y^* = \frac{1}{2}(y_1 - y_2)$$

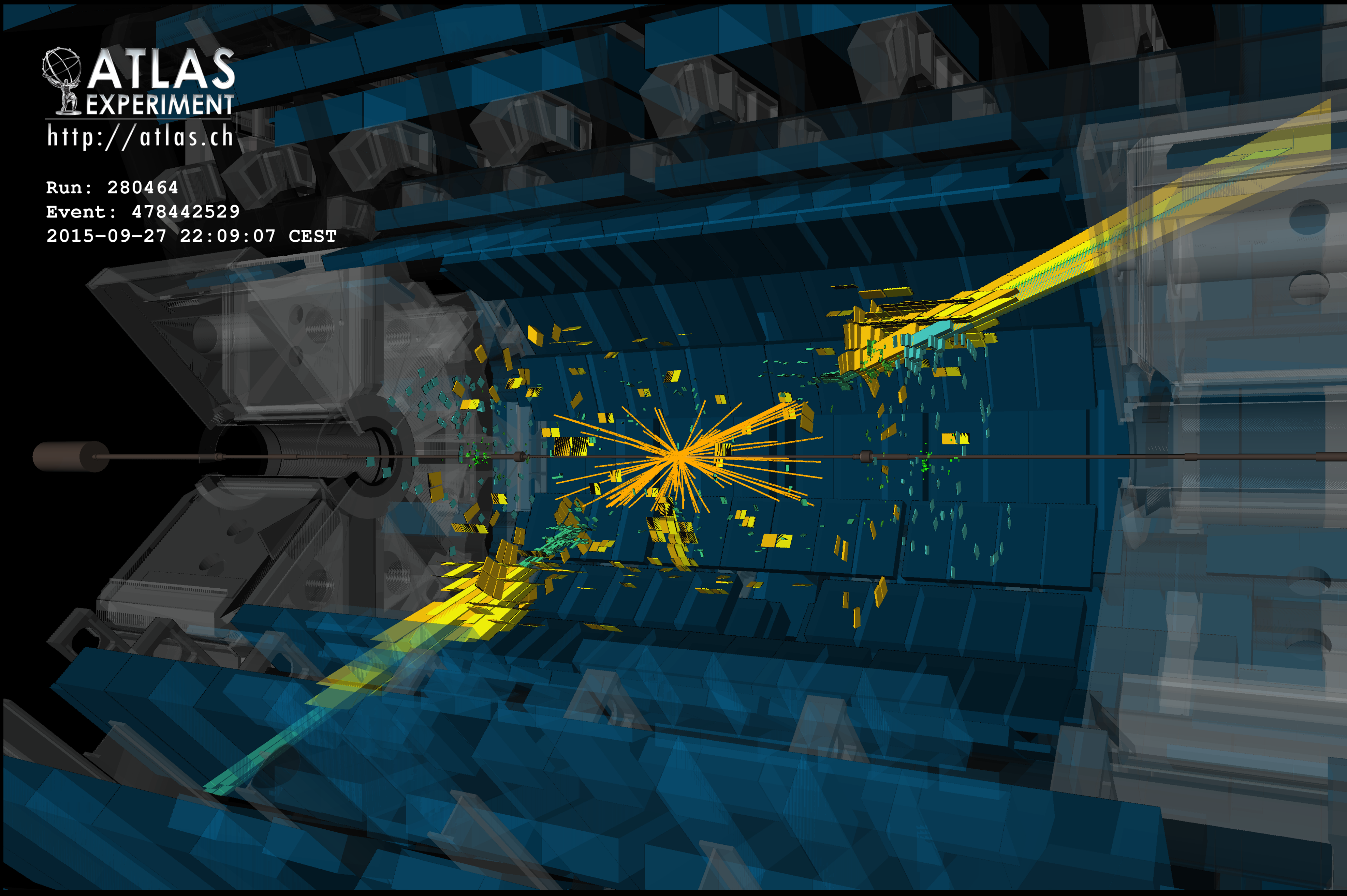
Searches in high-p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

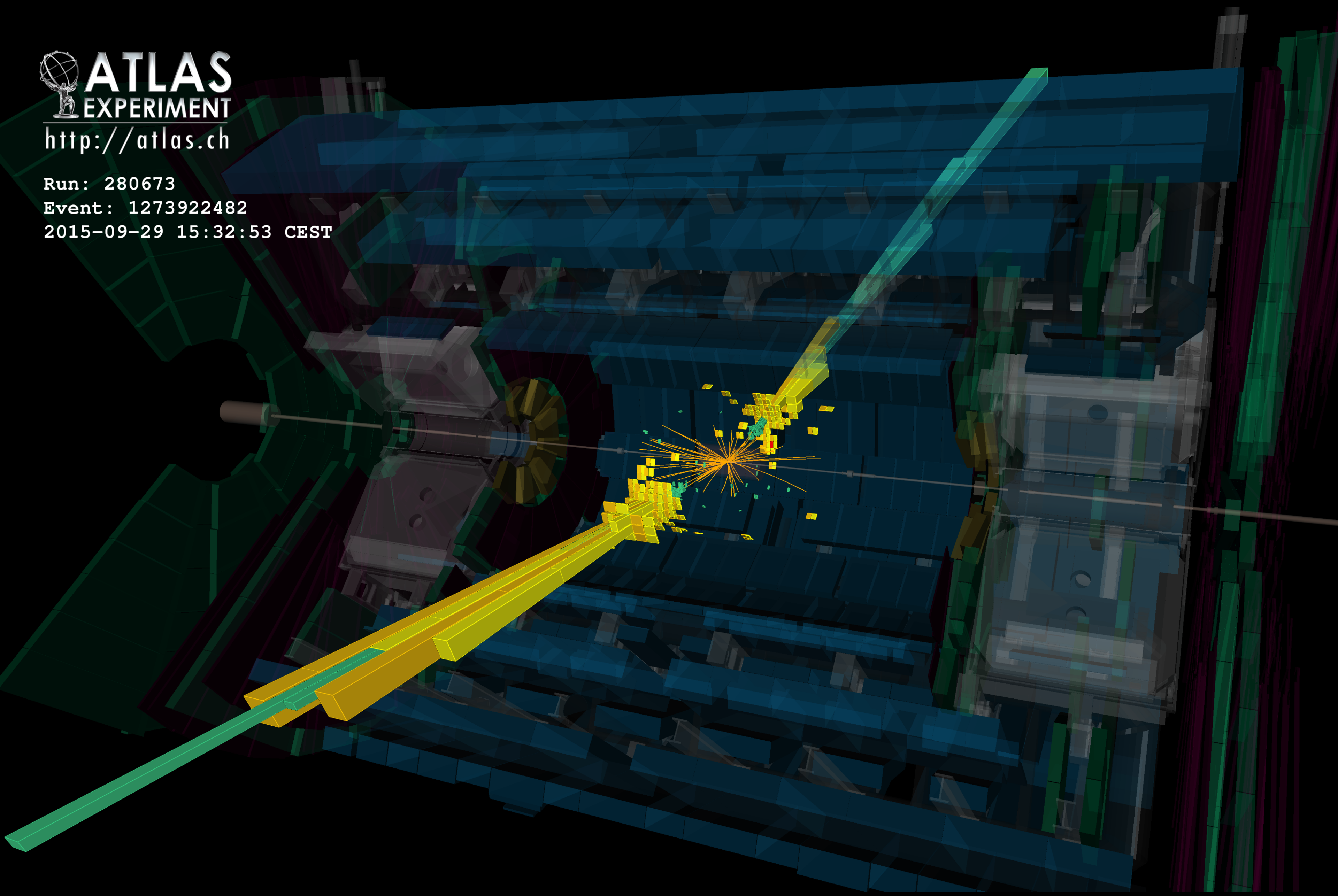
ATLAS bounds in the coupling-vs-mass plane for leptophobic Z' model from dijet searches



Highest mass dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 7.9 TeV



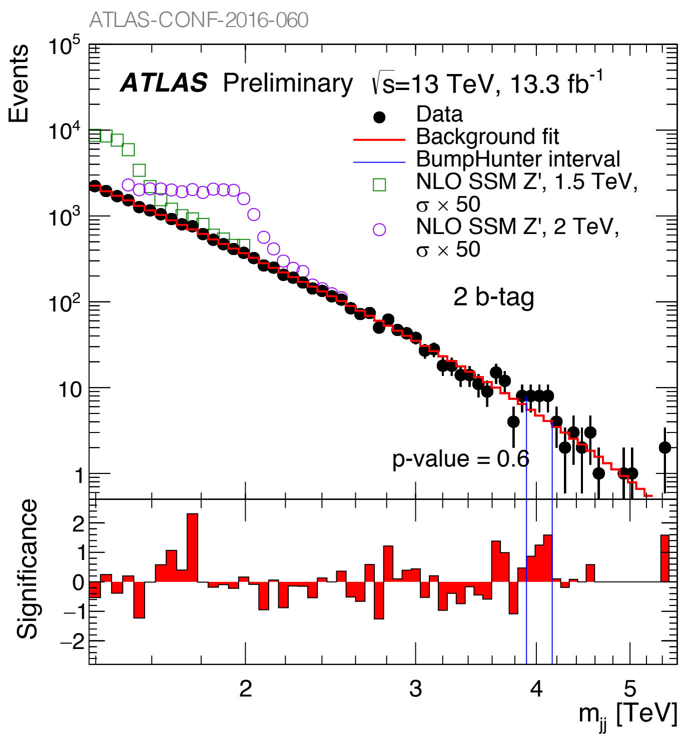
Highest mass *central* dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 6.9 TeV

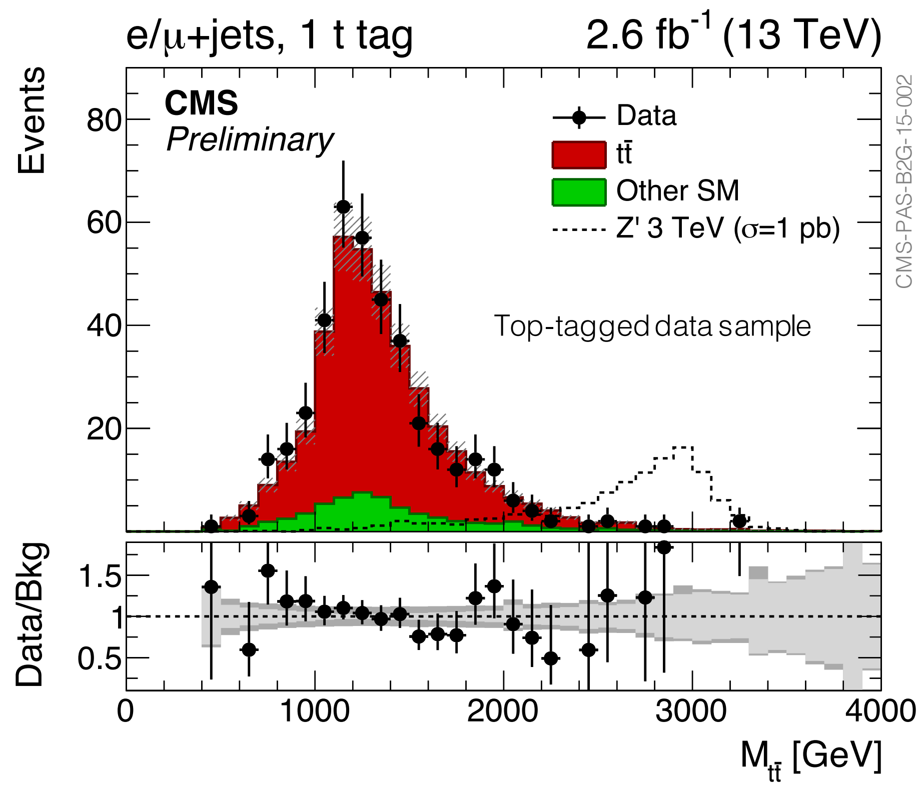


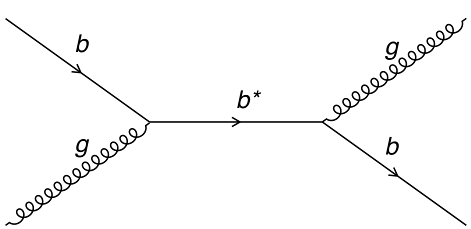
Searches in high-p_T heavy-flavour final states at 13 TeV

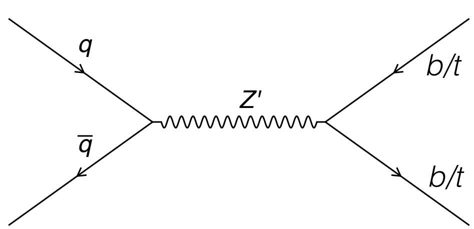
Processes with large cross-sections, sensitivity to highest new physics scales

Also searches for a b-anti-b and top-antitop resonance









Need to understand detector performance at highest momentum scales with practically no control samples

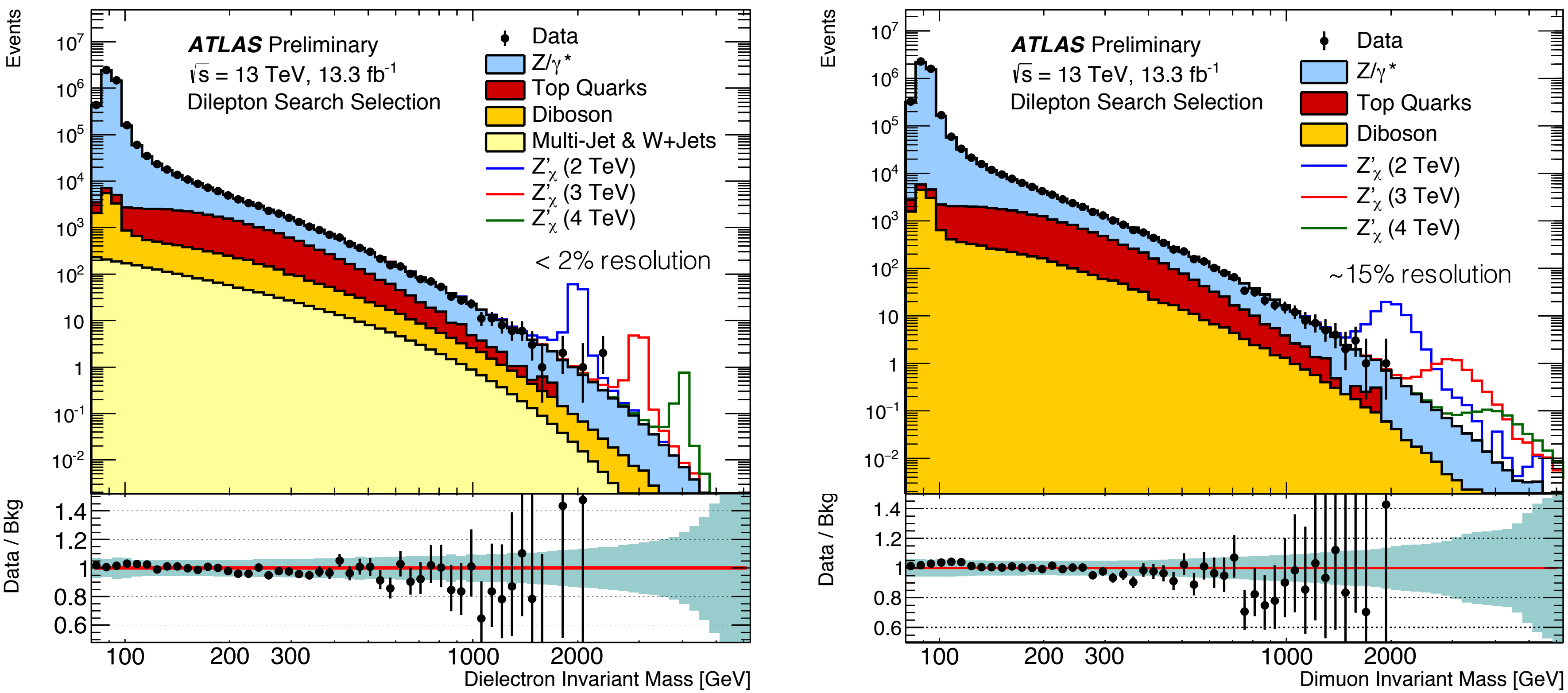
Searches in leptonic final states

Canonical searches for new physics in high-mass Drell-Yan production (Z' → $\ell^+\ell^-$ / W' → $\ell\nu$)

Good Drell-Yan modelling crucial → SM diff. cross-section measurements paired with searches

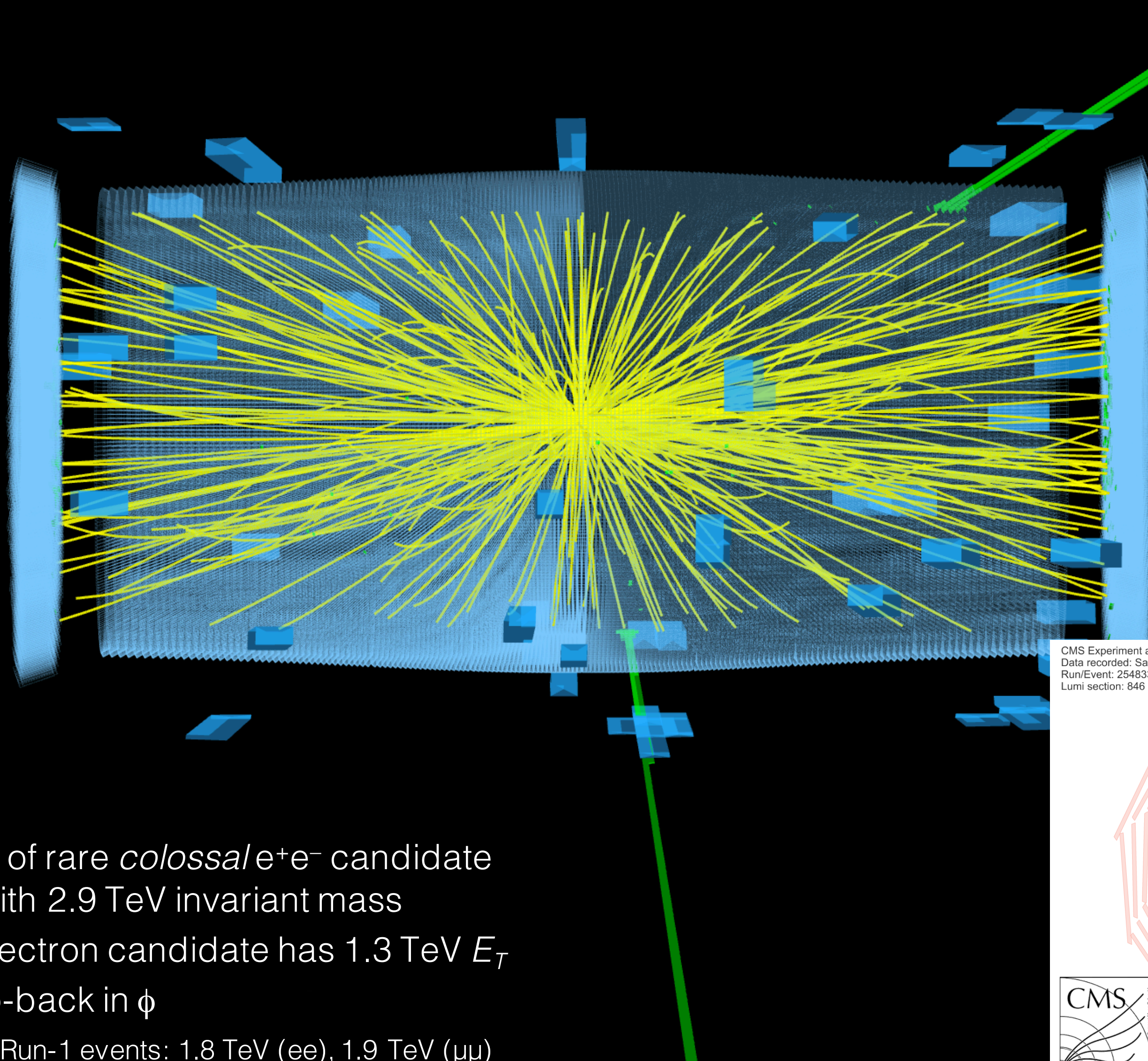
High-p_T muons challenge detector alignment (30 μm in ATLAS), ~no charge information from electrons

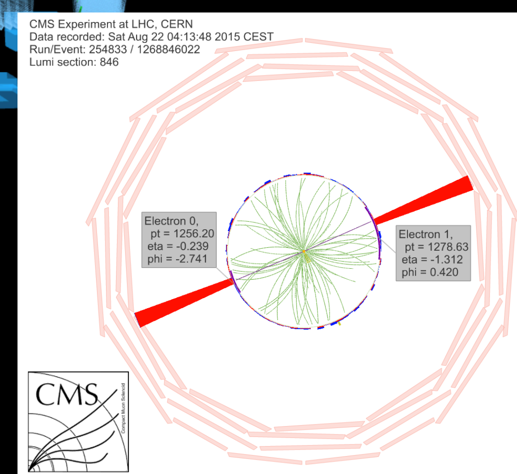
No anomaly found. SSM Z' / W' benchmark limits set at 4.0 / 4.7 TeV (2.9 / 3.3 TeV at 8 TeV)



ATLAS & CMS also looked into high-mass eμ (LFV) production. Main background here: top-antitop.

CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846





- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV (μμ)

Heavy resonance searches

Corollary: future improvements in reach will take more time

Historical data and future extrapolation (lower limits given in TeV):

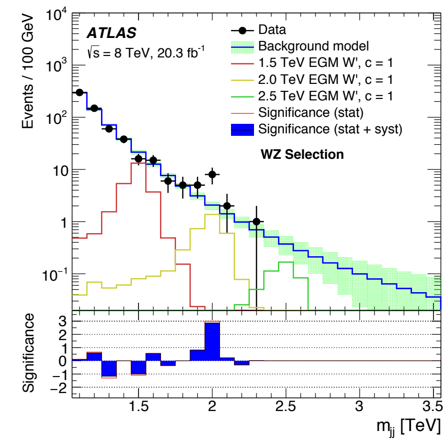
95% CL limit (TeV)	CDF	Run-1 '12	Moriond '16	ICHEP '16	300 fb^{-1} 14 TeV	3000 fb^{-1} 14 TeV
$Z' \to \ell\ell$	1.1	2.9	3.4	4.1	6.5	7.8 (?)
$q^* \to qg$	0.9	4.1	5.2	5.6	7.4	8
$Z' \to tt$ (1.2% width)	0.9	1.8	2.0		3.3	5.5

ATLAS upgrade:
ATL-PHYS-PUB-2013-003,
ATL-PHYS-PUB-2015-004

CDF:
http://arxiv.org/abs/1101.4578 (4.6 fb^{-1})
http://journals.aps.org/prd/abstract/10.1103/PhysRevD.83.031102 (5.3 fb^{-1})
http://prd.aps.org/abstract/PRD/v79/i11/e112002 (1.1 fb^{-1})
http://arxiv.org/abs/1211.5363 (9.5 fb^{-1})

Searches for diboson resonances (hh, Vh, VV)

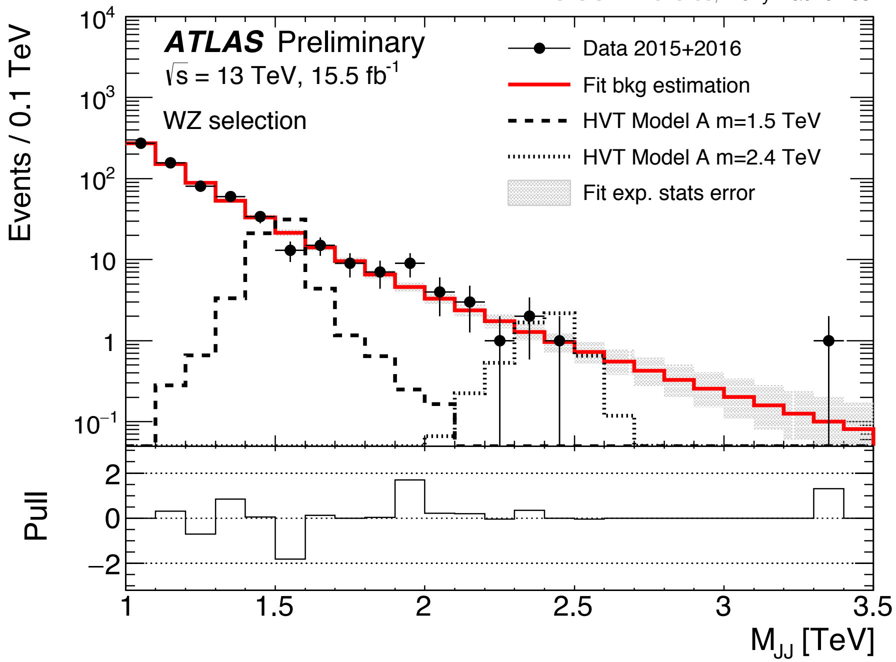
High-p_T of bosons boosts hadronic decay products into merged jets



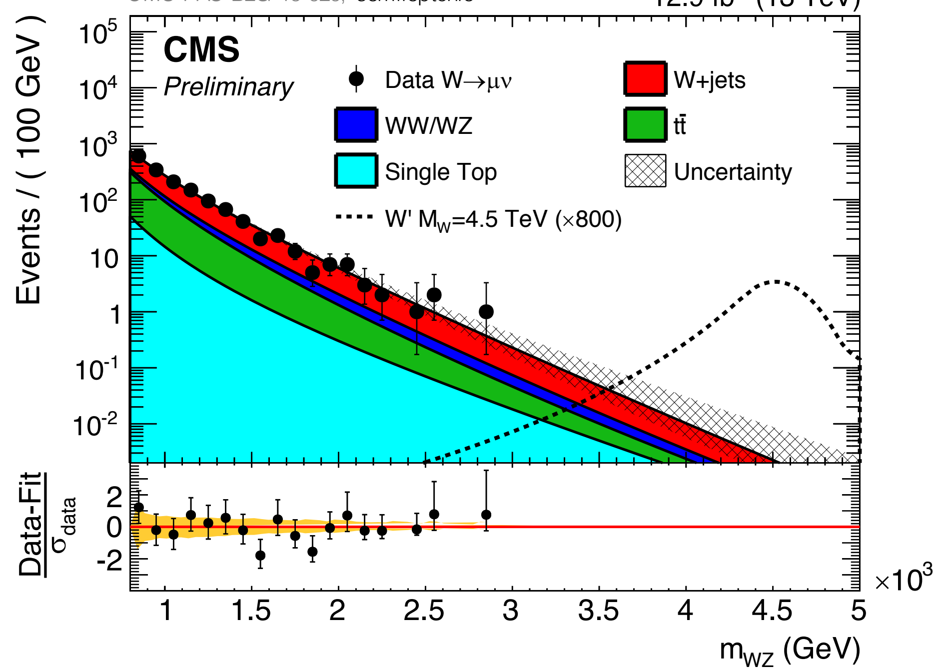
Hadronic decay modes use jet substructure analysis to reconstruct bosons. Important strong interaction backgrounds

Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen at 8 TeV in VV in fully hadronic channel, not seen in the other decay channels (eg, lνqq)

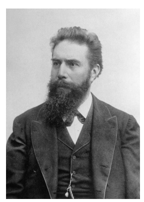
ATLAS-CONF-2016-05, fully hadronic5



CMS-PAS-B2G-16-020, semileptonic



Light quanta



First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand, Nov 1895
[First Nobel price of physics, 1901]

Used since forever
as detection probe

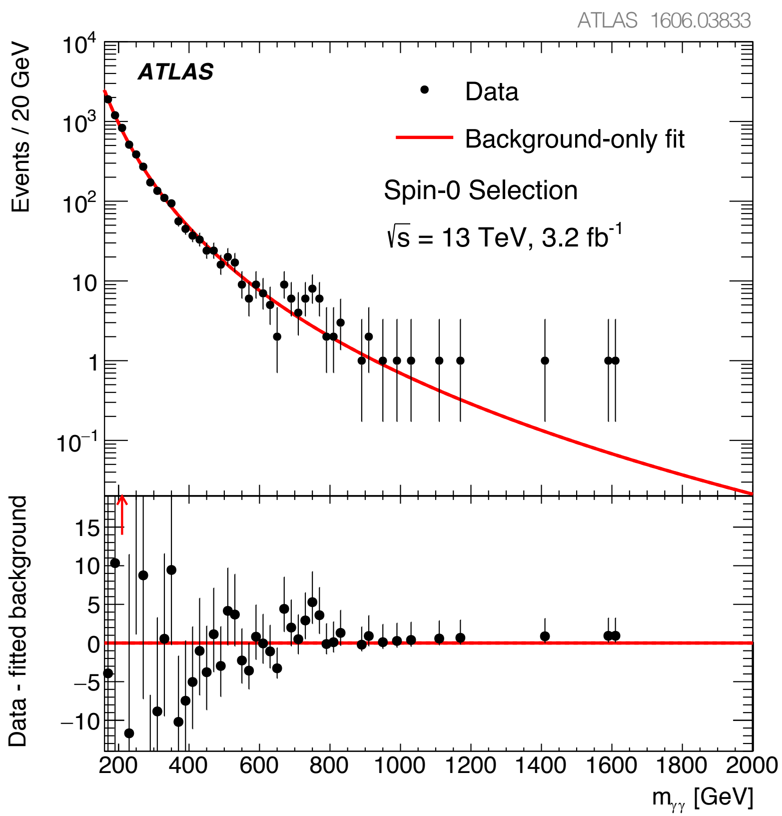
Recent example: H → yy
Other example:

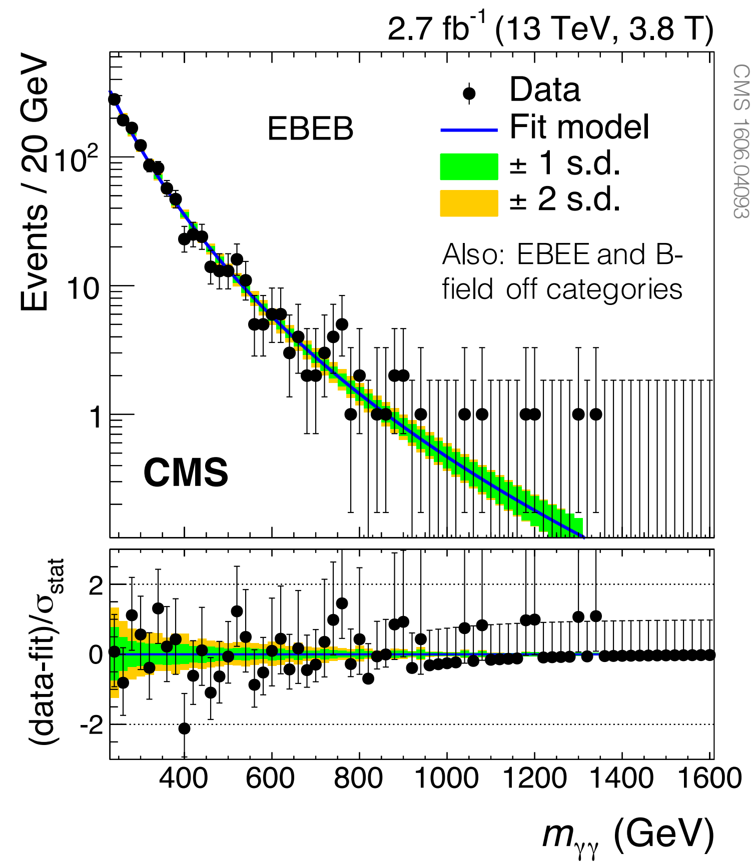
Picture of a mirage

Diphoton resonance searches, the 2015 data

Dedicated searches for a spin-0 and a spin-2 diphoton resonance

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)





Lowest p-value at ~750 GeV, Γ ~ 45 GeV (6%)

Local / **global Z** = 3.9 / **2.1σ**

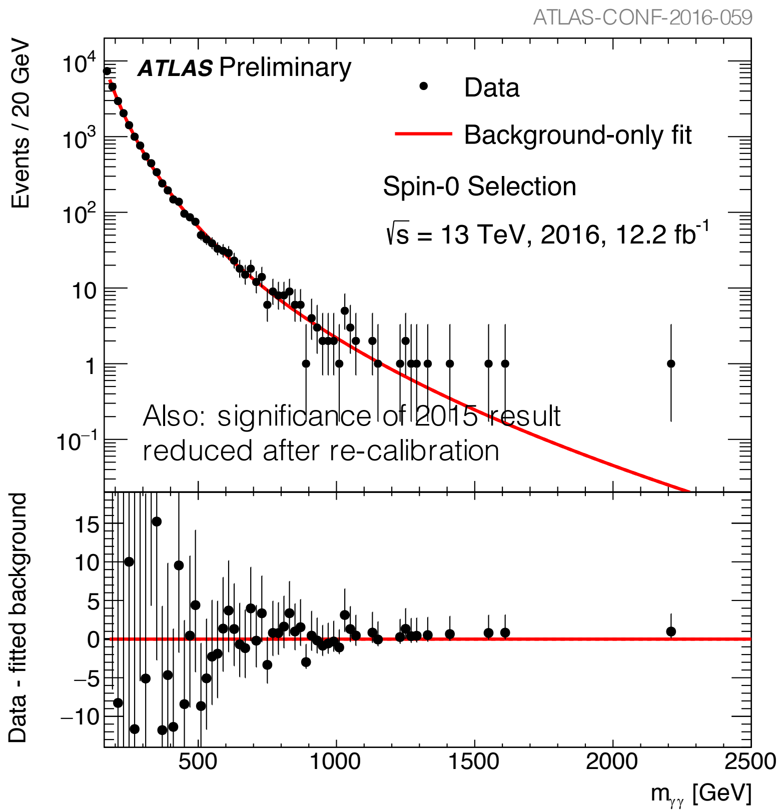
Lowest p-value at ~750 GeV, narrow width

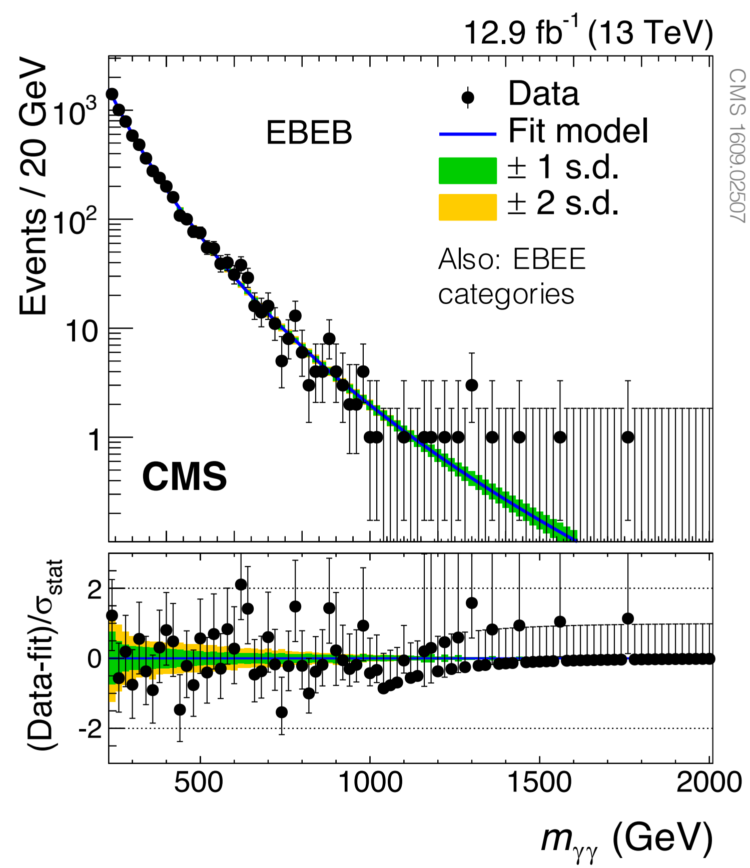
Local / **global Z** = 3.4σ / **1.6σ** (Run-1+2 combination)

Diphoton resonance searches, the 2016 results

Repeated ~unchanged analyses with 2016 data

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)



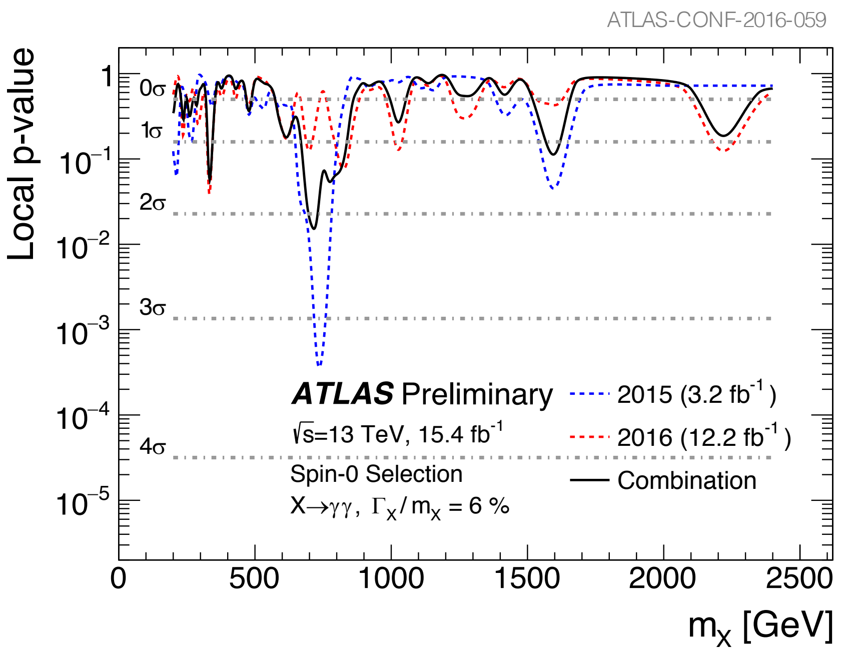


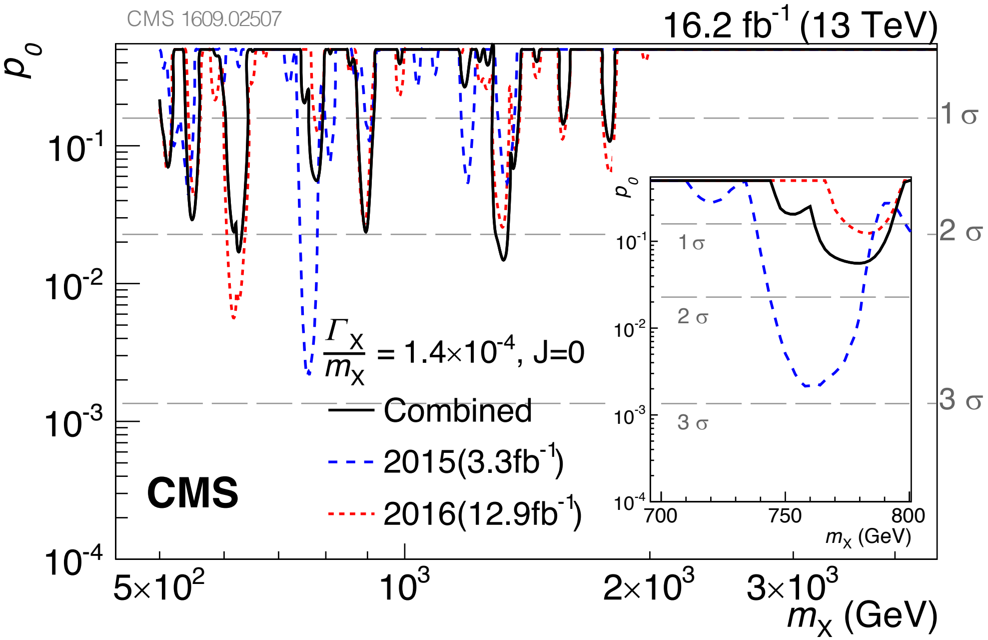
No noticeable excess in 2016 data

Diphoton resonance searches, the 2016 results

Comparison of 2015 and 2016 p-values

Resulting background-only p-values





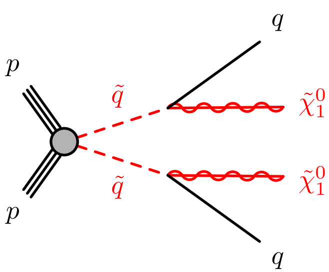
Lesson? Statistical fluctuation. Can happen, nothing wrong.

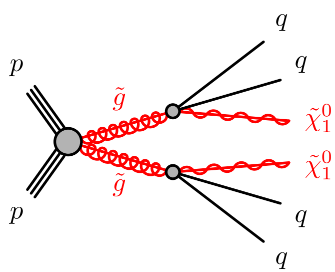
Actual trials factor larger than global factor quoted, as very many signatures probed by experiments (hard to estimate, but keep in mind!). Having a second experiment with a similar non-significant excess does not remove trials factor if you keep both. Removing 2015 data, and looking at 750 GeV in 2016 does remove trials factor.

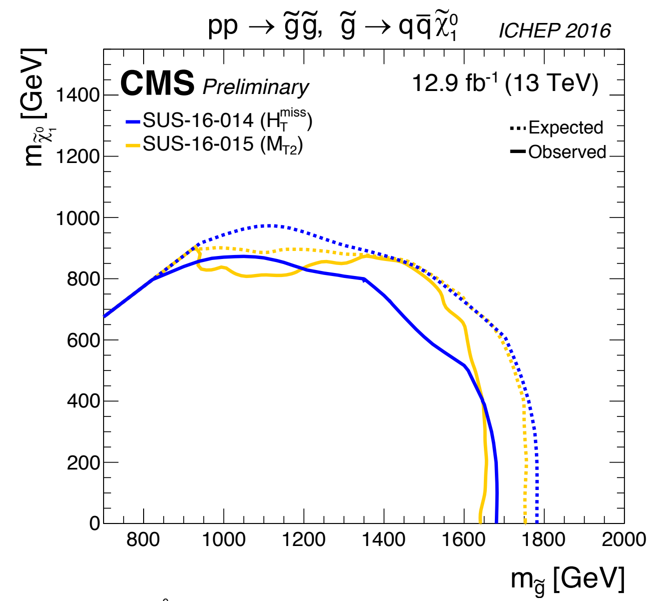
Supersymmetry

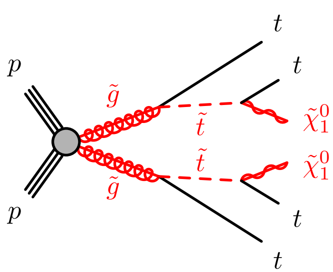
Still among the most popular SM extensions: hierarchy problem, unification, dark matter

Very diverse signatures. Highest cross-section events produce gluino / squark pairs with decays to jets and missing transverse momentum

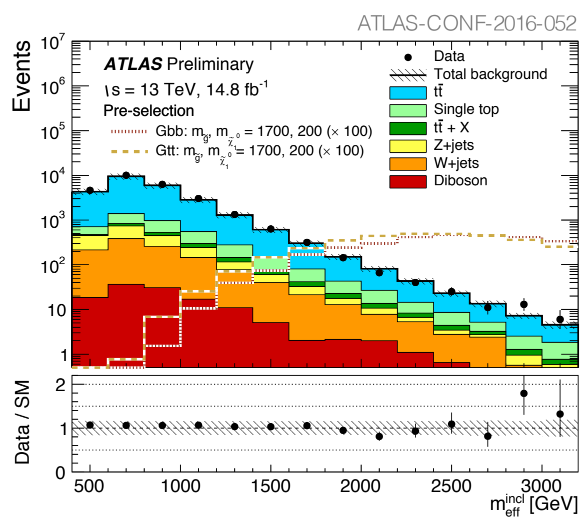


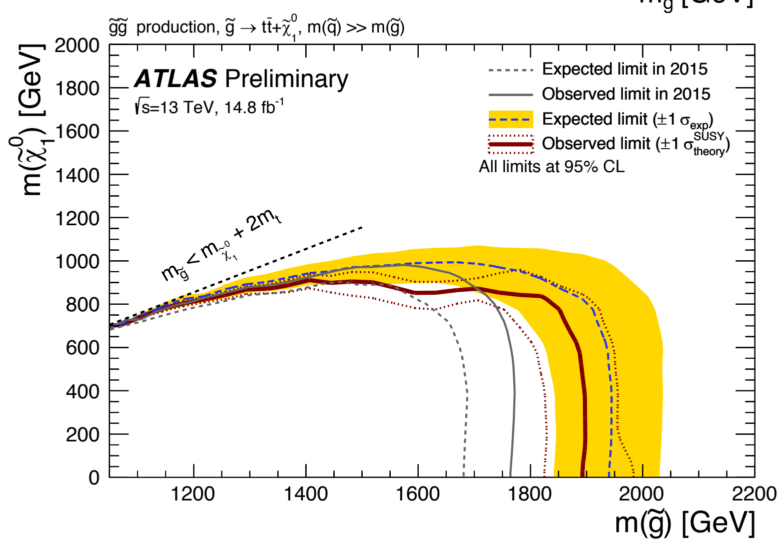






No significant anomaly seen in many different analyses



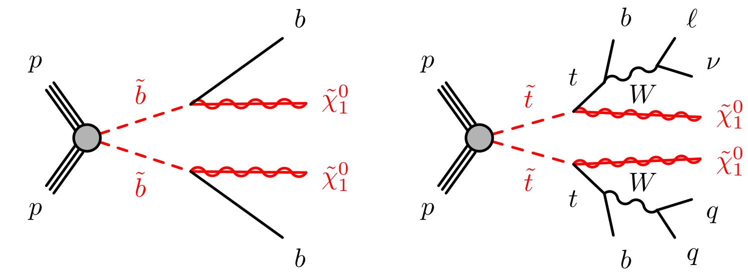


Third generation quark partners

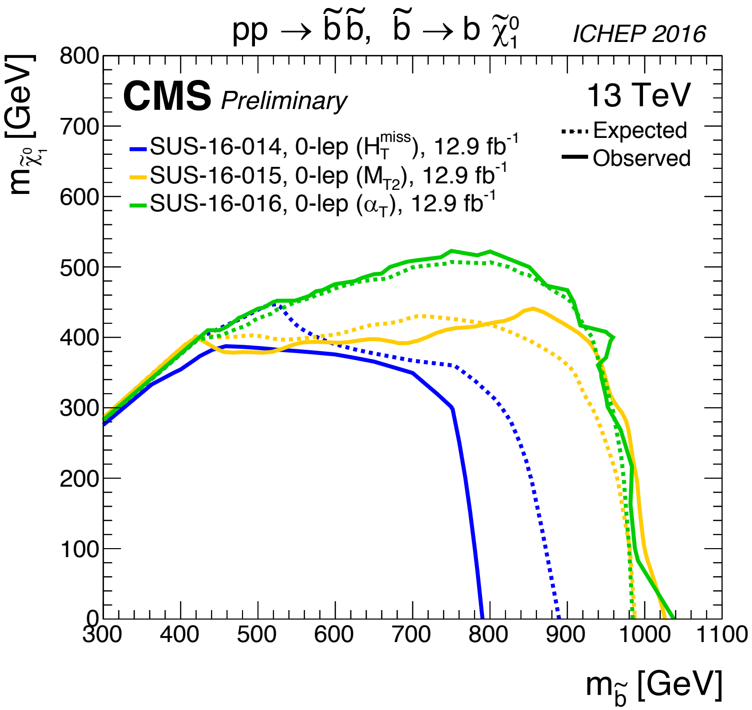
Searches for direct production

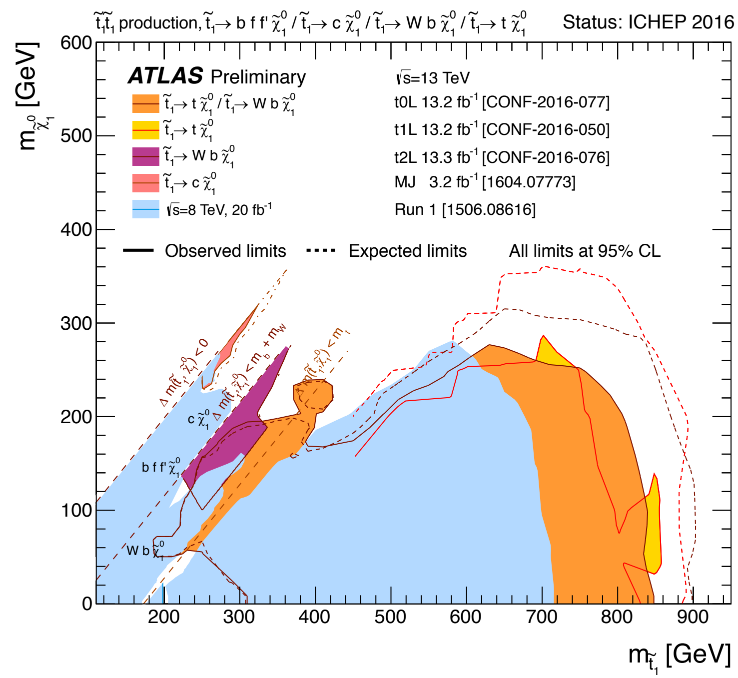
SUSY stop and sbottom may be the lightest sfermions. They have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Vector-like quarks* (VLQ) singly or pair produced decay to bW, tZ or tH. Also exotic $X_{5/3} \rightarrow tW$ possible



Signatures are b-jets, jets, possibly leptons and MET





No anomaly seen

Sensitivity improved over Run-1

Similar for VLQ searches

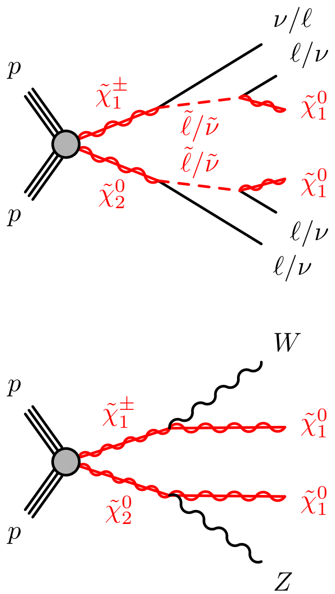
*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Electroweak supersymmetry production

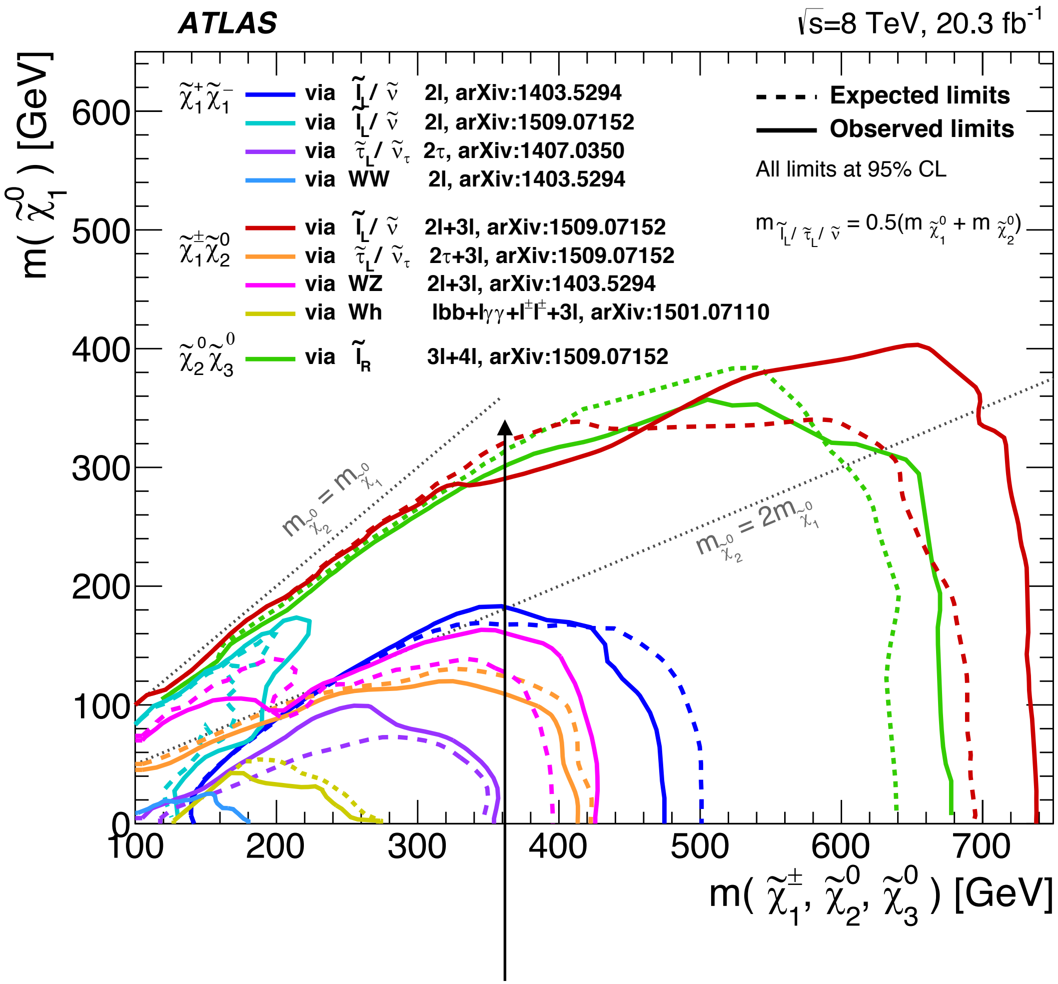
Searches for direct production

“Electroweak-inos” may be the lightest fermions. They also have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Signatures are leptons, few or no jets, MET



Example diagrams

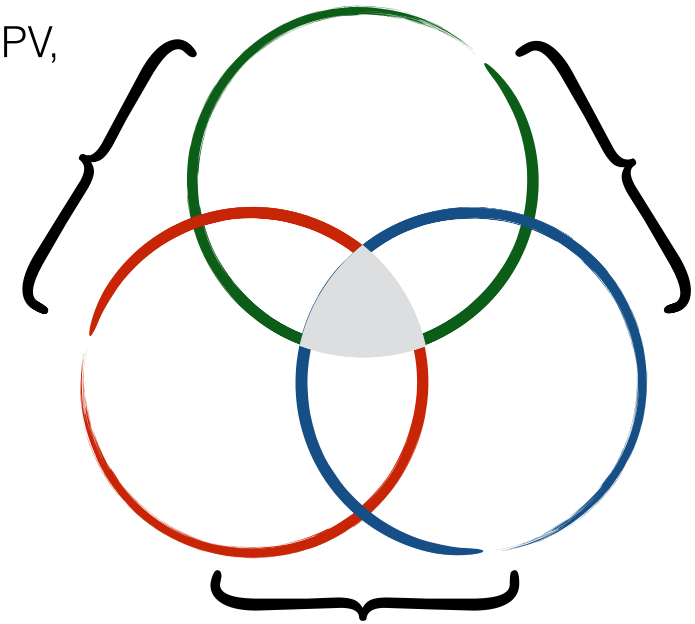


Compressed region (“higgsino” case)

Nathanial Craig @ SEARCH 2016: **PICK TWO**

Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>



Naturalness & Dark Matter

- Additional states near weak scale (sgluon, KK resonances, …)
- Higgs properties
- <Your idea here>

Unification & Dark Matter

- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Good idea ?

Long-lived particles predicted in many new physics models

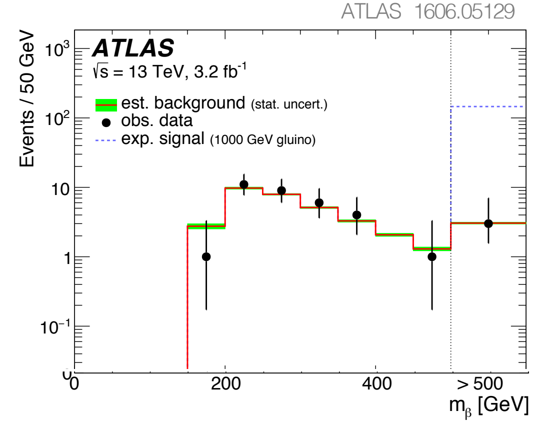
Reason: large virtuality in decay, low coupling, or mass degeneracy

Multitude of signatures depending on lifetime, charge, decay: highly ionising, slow, out-of-time decay, displaced vertex, kinked or disappearing track, lepton-jets, …

Some signatures require dedicated triggers, most requiring dedicated analysis strategies.

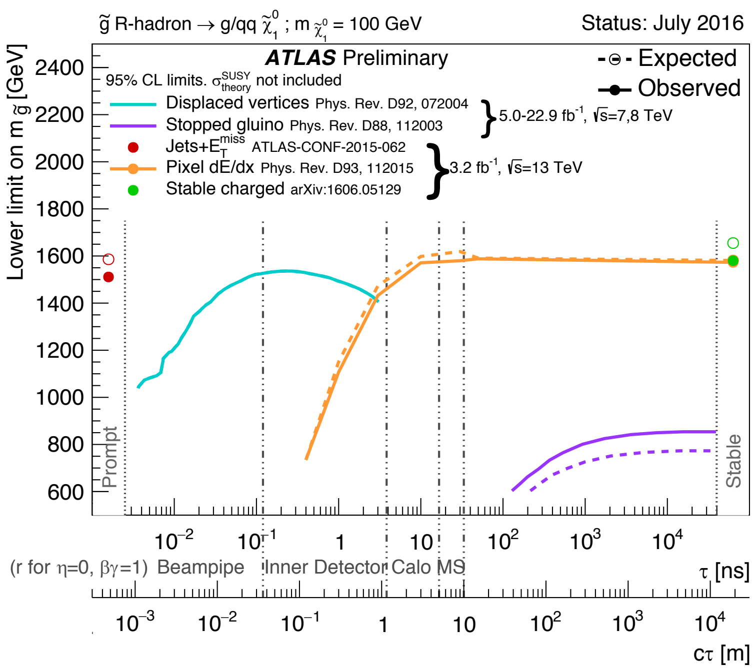
Standard searches sometimes sensitive to signatures with long-lived particles as well

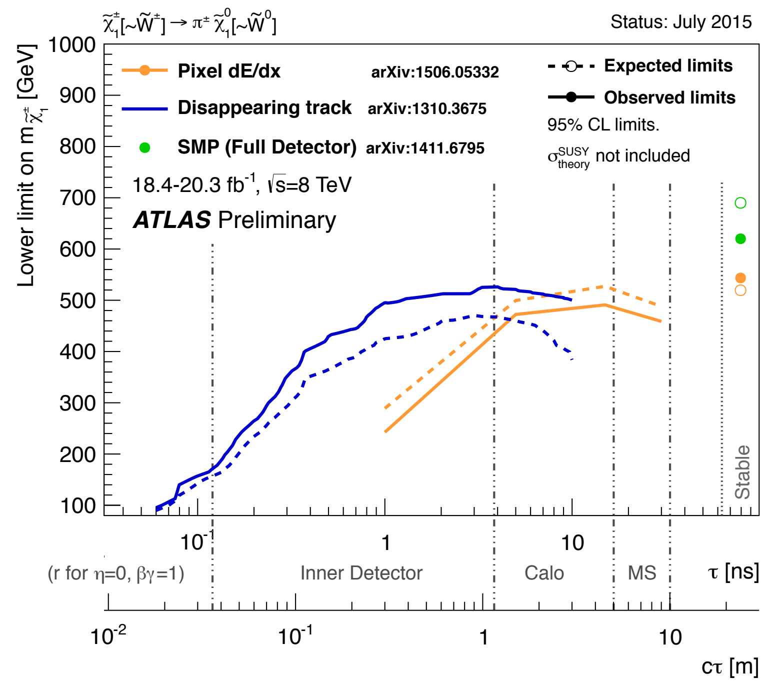
ATLAS 1606.05129



Particle mass from velocity via time-of-light measured in Tile calorimeter

Similar analysis from CMS uses tracker dE/dx and TOF from muon system





Summaries of mass limits versus lifetime of new particle

Searches for dark matter production at the LHC

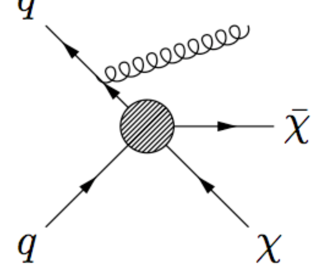
Canonical signature is ‘X+MET’ with large variety of ‘X’

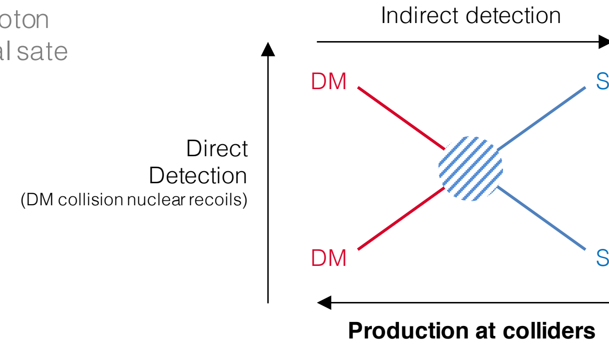
May not be able to prove at LHC that a signal is dark matter

Direct dark matter production at the LHC
Requires boost for triggering. Depending on coupling it can be made by different objects.

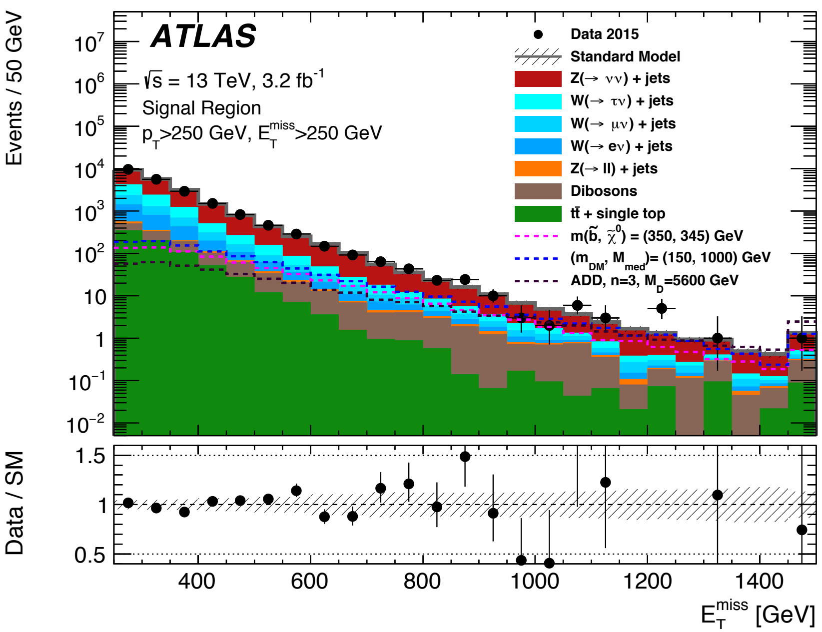
Experimentally challenging to control Z/W+jets background. Theory input needed.

Energetic gluon/photon radiation in the initial sate

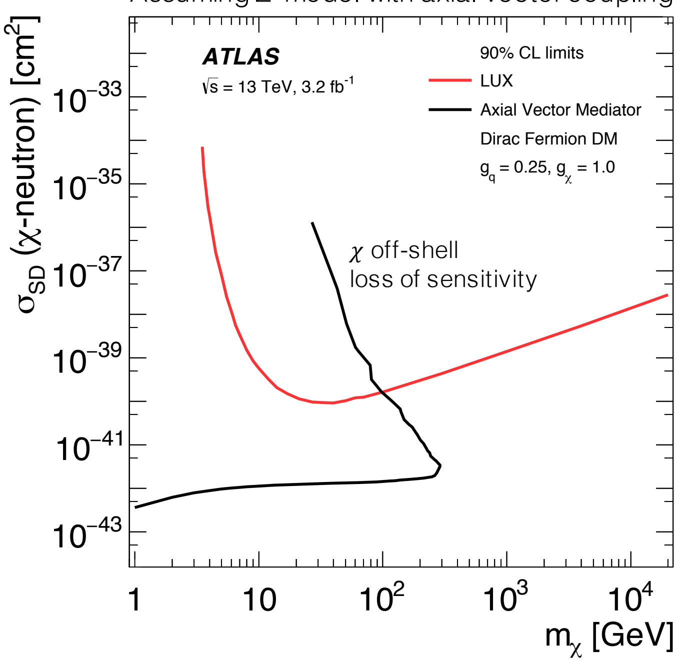




ATLAS 1604.07773



Assuming Z’ model with axial-vector coupling

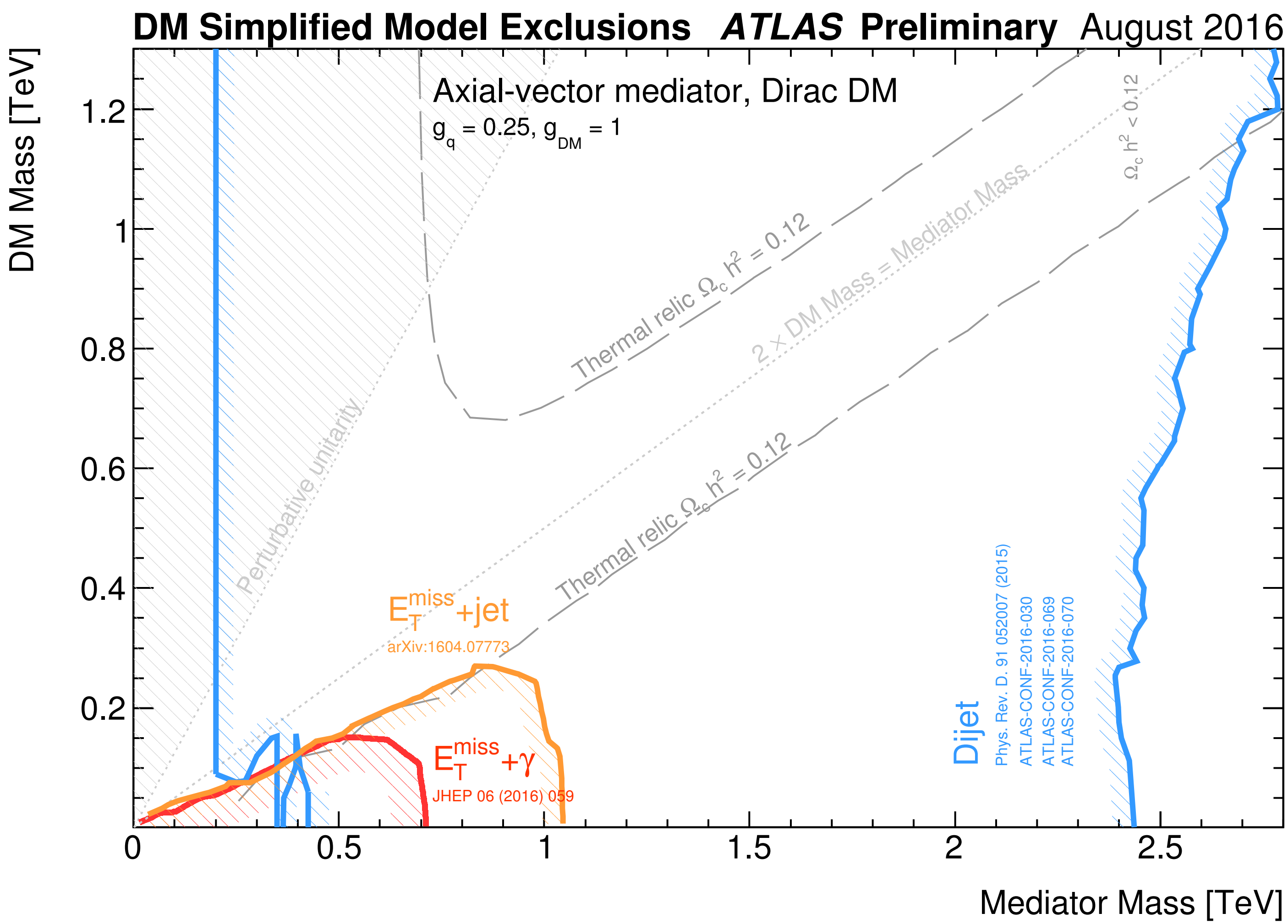


Many other 13 TeV results available:

- jets + MET
- γ + MET
- V + MET
- bb/tt + MET

No anomaly seen so far

Exclusion regions for simplified models with heavy particle mediating interaction between initial state quarks and final state WIMPs

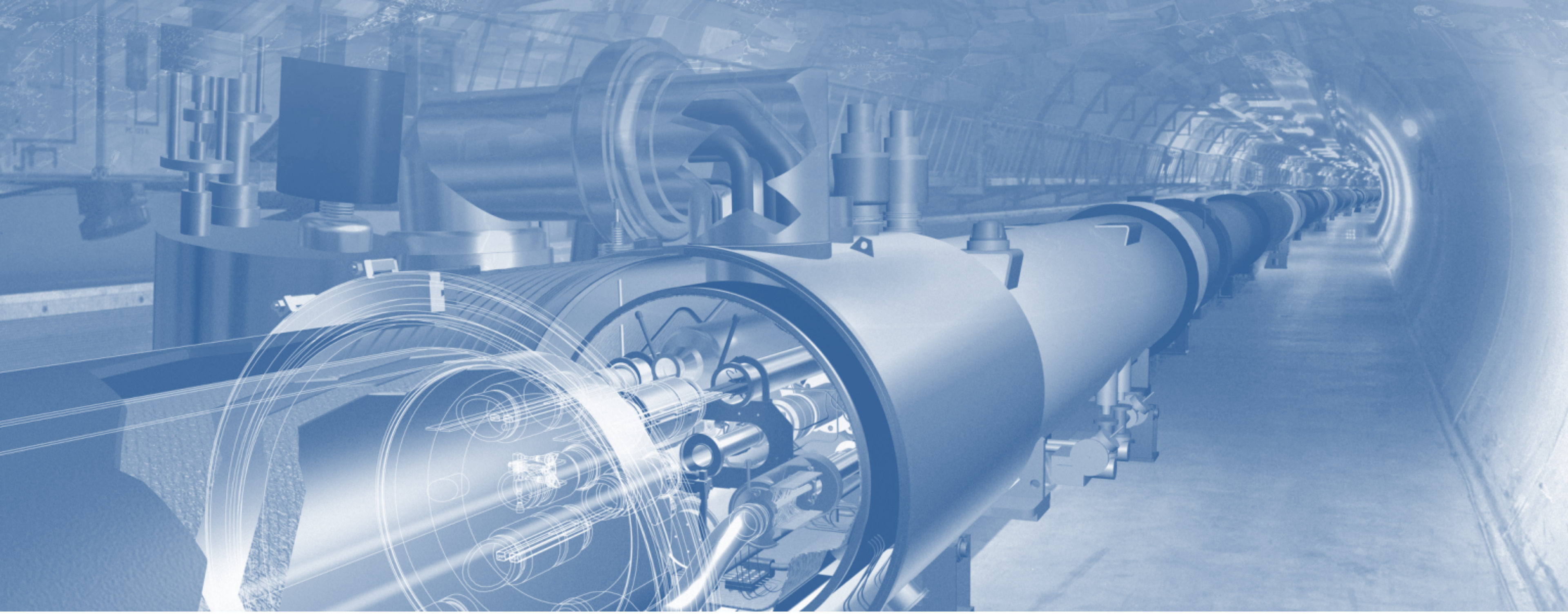


Since the mediator is produced via quark annihilation (g_q), it can also decay to quarks

For full explanation, see: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary

This was a very incomplete extraction of all the available 13 TeV searches only

The return of the limits …

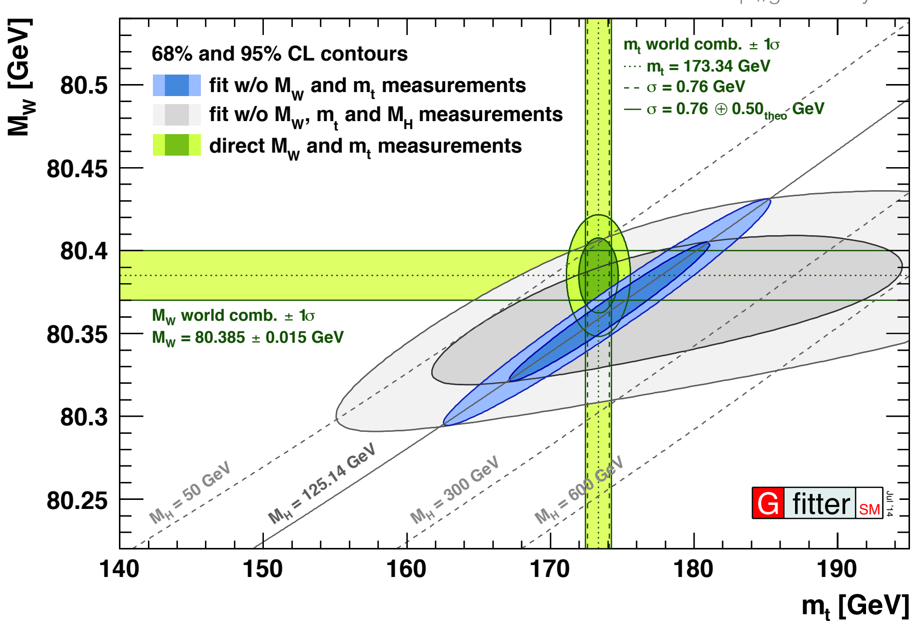


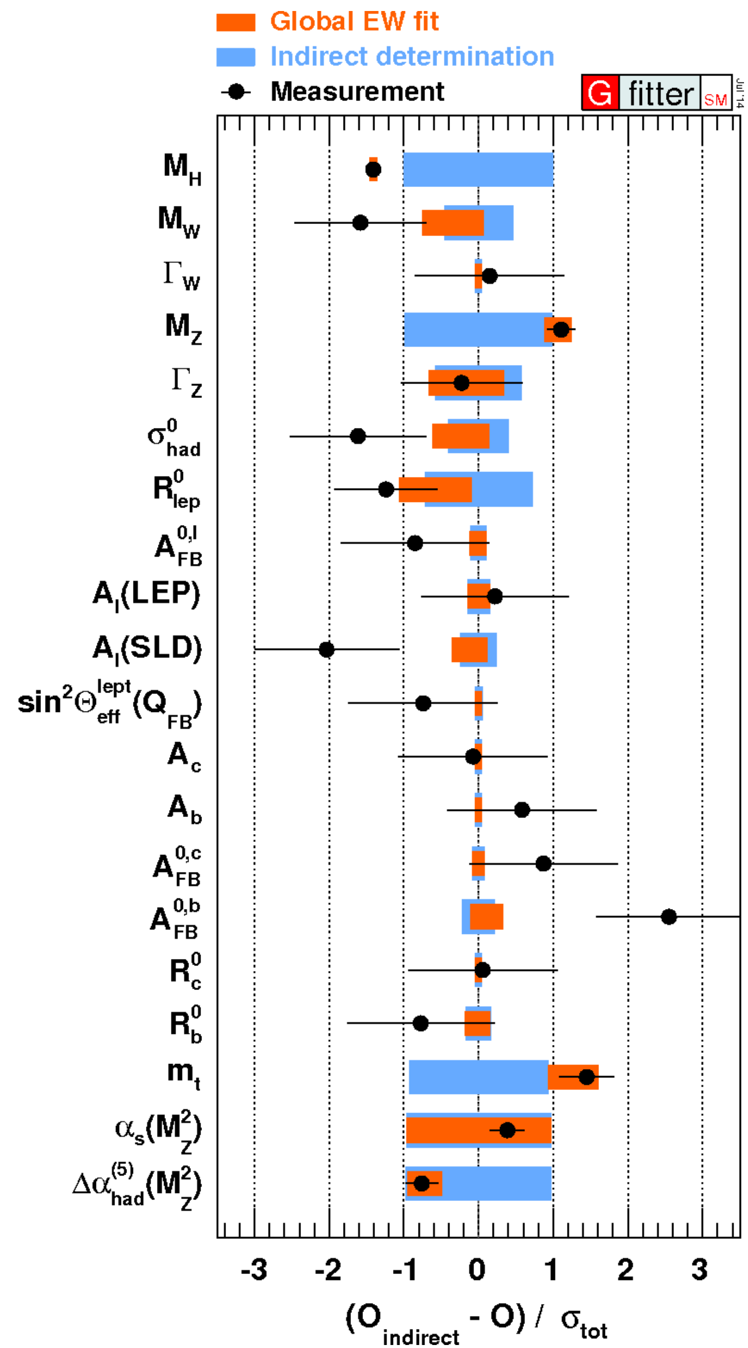
Digression on Precision Measurements

Electroweak precision physics

Global electroweak fit was masterpiece of LEP/SLD era. Discovery of Higgs over-constrains the fit and dramatically improves predictability

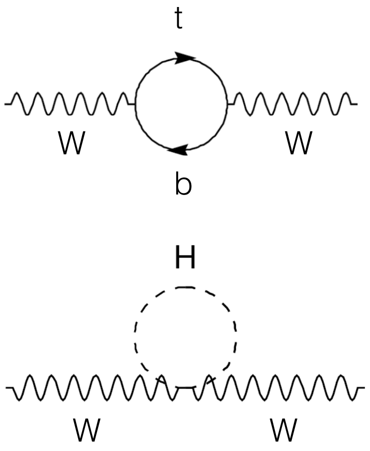
http://gfitter.desy.de





Electroweak sector relates M_W to α, G_F, M_Z

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\,\pi\alpha(1-\Delta r)}{G_F M_Z^2}}\right)$$



$\sim m^2_{top}$

$\sim \ln(m^2_H)$

SM Predictions [1407.3792, EW fit]

$$\begin{aligned} M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \text{GeV}\,, \\ &= 80.358 \pm 0.008_{\rm tot}\ \text{GeV}\,. \end{aligned}$$

[exp WA: σ = 15 MeV]

$$\begin{aligned} \sin^2\theta^\ell_{\rm eff} &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\rm theo} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\rm theo} \sin^2\theta^f_{\rm eff}}\,, \\ &= 0.23149 \pm 0.00007_{\rm tot}\,, \end{aligned}$$

[exp WA: σ = 0.00016]

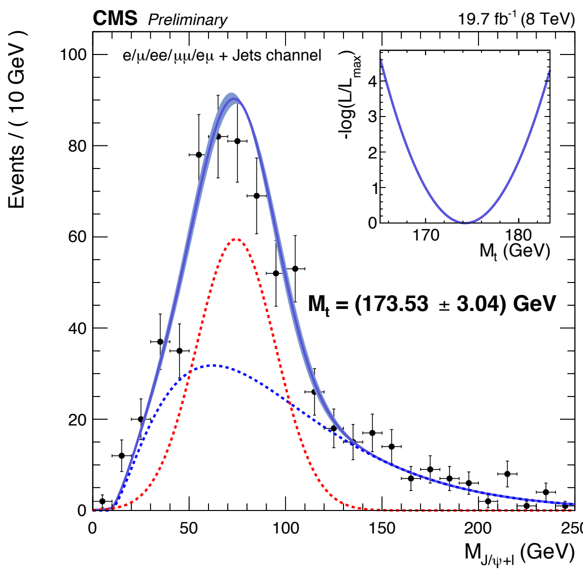
Electroweak precision measurements

Best top mass from LHC: 172.44 ± 0.13 ± 0.47 GeV (CMS), 172.84 ± 0.34 ± 0.61 GeV (ATLAS, not yet all 8 TeV)

Traditional kinematic top mass measurement method approaches systematic limit of *b* modelling

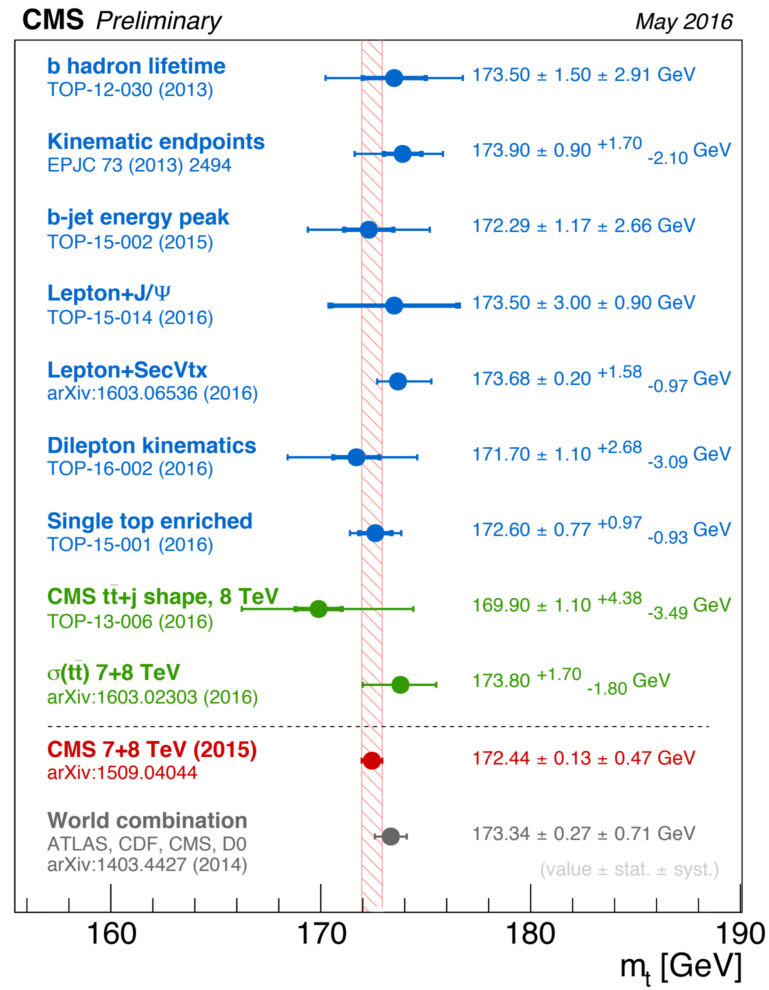
Possible ways to improve (a lot of pioneering work by CMS):

- Choose more robust observables (eg, wrt. b fragmentation)
- Select charmed mesons (rare but very clean signature)
- Use dilepton kinematic endpoint (clean but large theoretical uncertainties)
- Use cross-sections or differential variables (promising but difficult to achieve competitive precision



Currently best result (CMS): 1.7 GeV uncertainty

CMS alternative top mass measurements:



Electroweak precision measurements

$\sin^2\theta_W$ and Z asymmetries from hadron colliders

CDF, D0, and also LHC have extracted weak mixing angle from Z/γ* asymmetry measurements

Uncertainties at Tevatron dominated by statistical uncertainties, LHCb equally, ATLAS & CMS by PDF uncertainties.

Data-driven "PDF replica rejection" method applied by CDF

Complex measurements (in particular physics modelling) that are important to pursue, but precision of hadron colliders not yet competitive with LEP/SLD

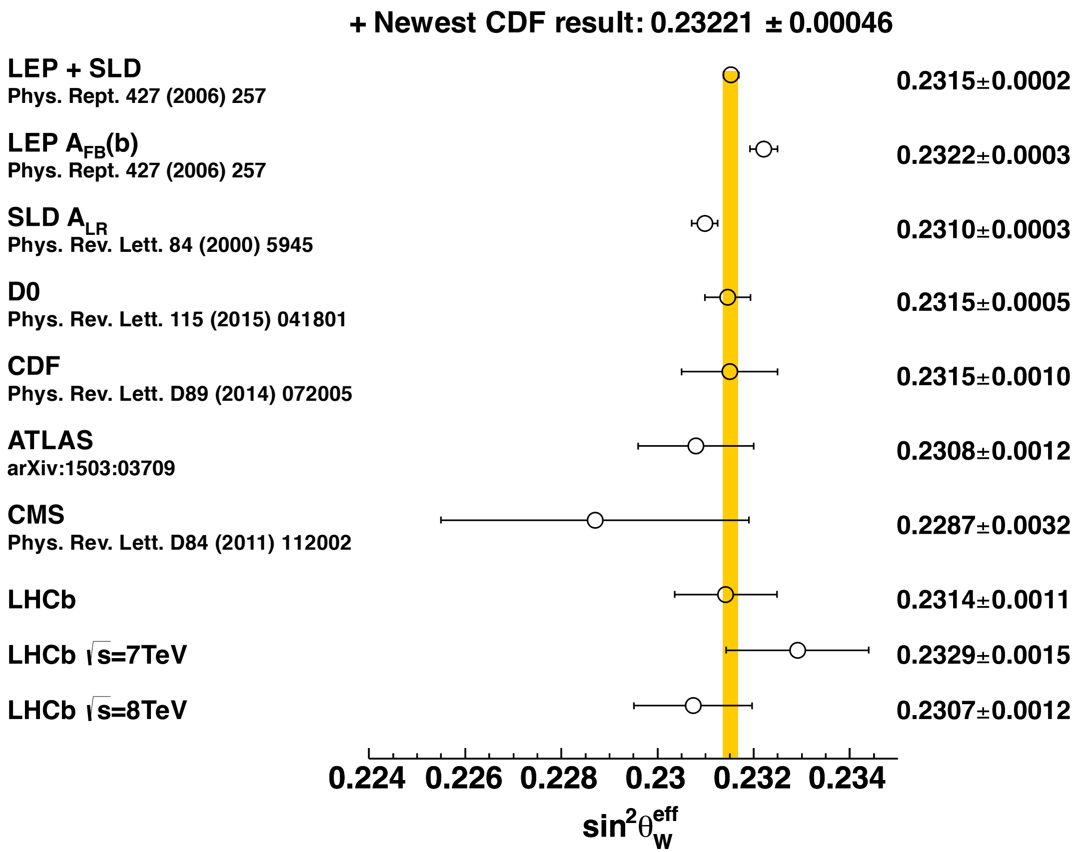


Figure from LHCb 1509.07645