XXIX IFT Christmas Workshop
12-14 December 2018 Madrid

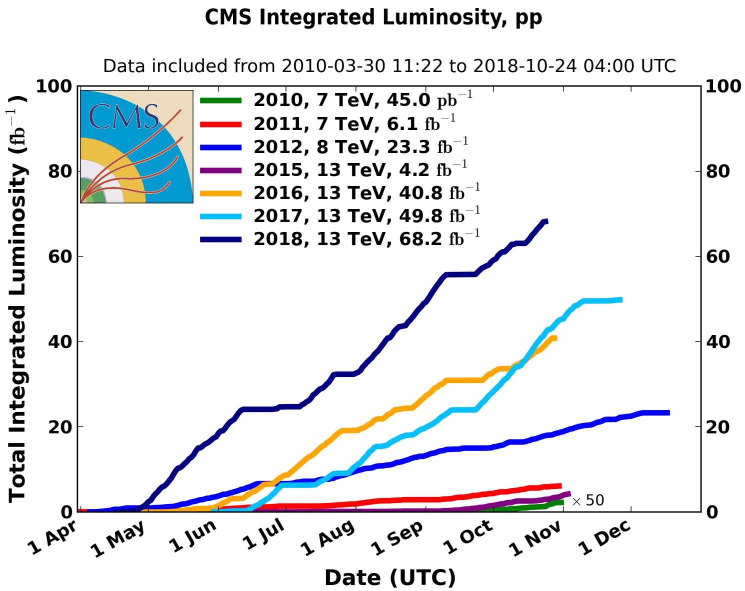
Highlights from LHC

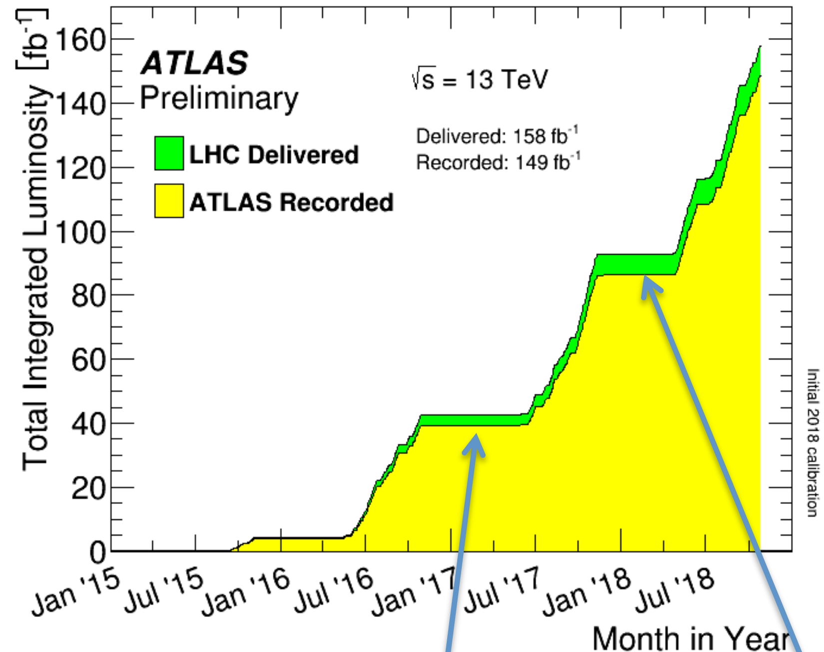
Martine Bosman

Reference talks – ICHEP2018

- ATLAS + ALICE highligths T. Carli
- CMS + LHCb highlights S. Rahatlou
- Higgs experimental summary G. Piacqadio
- EW/SM/Top summary L. Skinnari
- SUSY summary S. Strandberg
- EXOTICS at the LHC D. del Re
- CKM& CPV (Quark Flavour) Ph. Urquijo
- etc.

LHC performance and recorded data

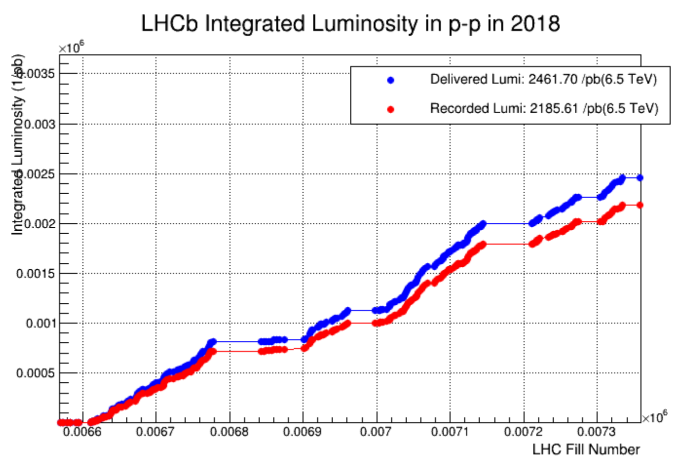




2015-17 data ~80 fb-1

2015-16 data ~36 fb-1

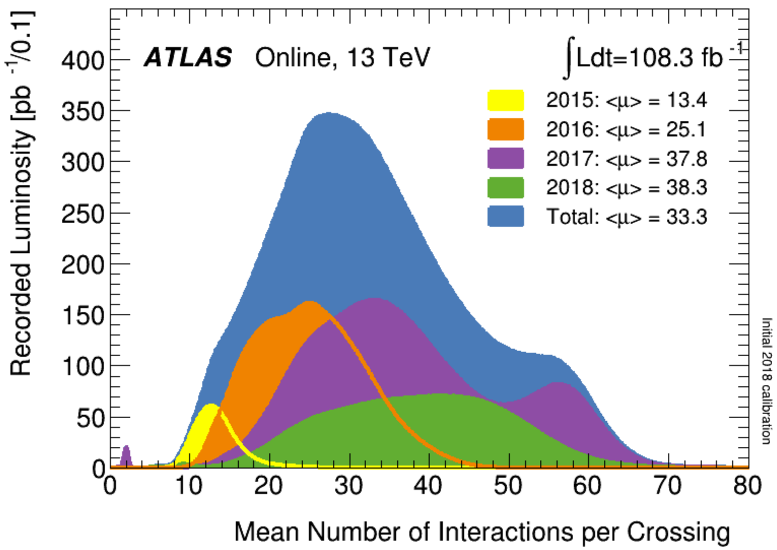
Instantaneous luminosity reached $2.10^{34} cm^{-2}s^{-1}$ in ATLAS and CMS



LHCb collected in

- Run1 3 fb^{-1}
- Run2 6 fb^{-1}

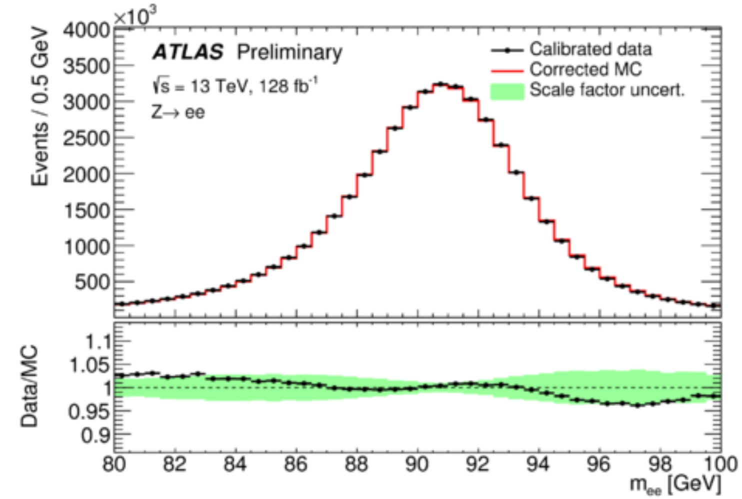
Running conditions & detector performance

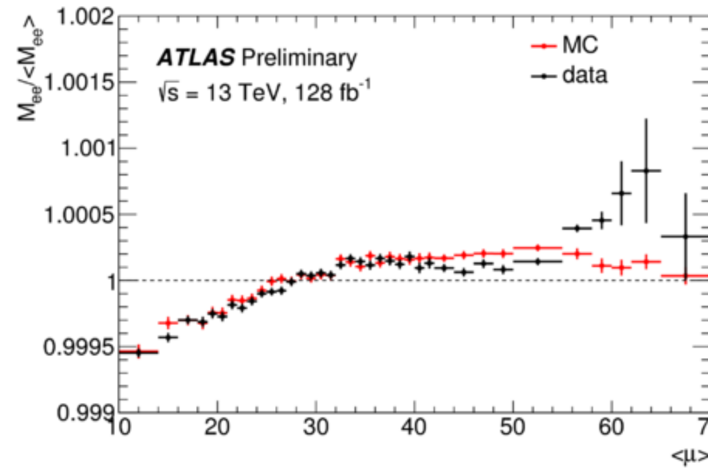


- mitigate the effect of pile-up
- MC should describe the impact on data with high precision

example: $Z \rightarrow e^+e^-$

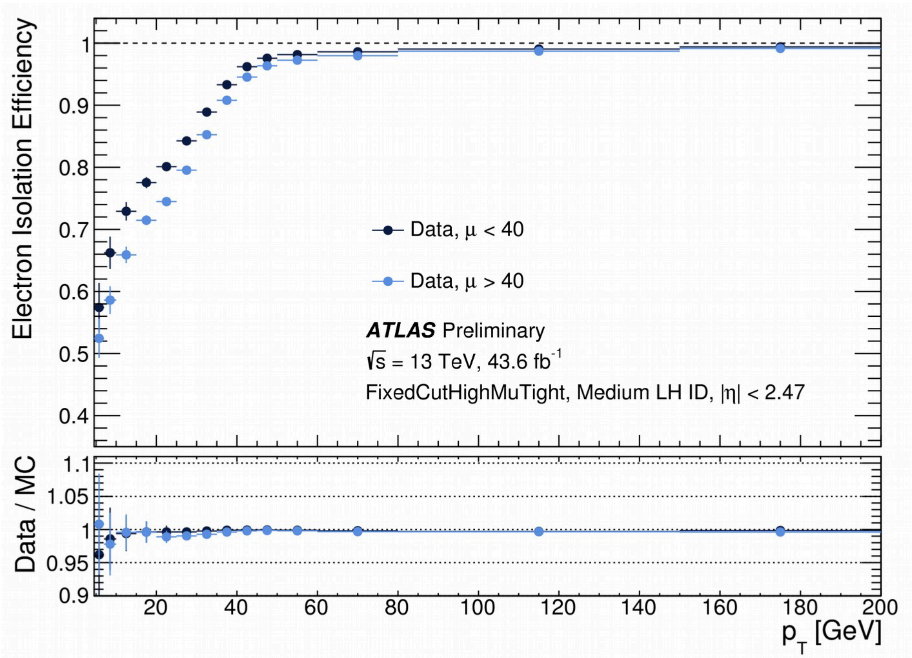
[electron calibration]



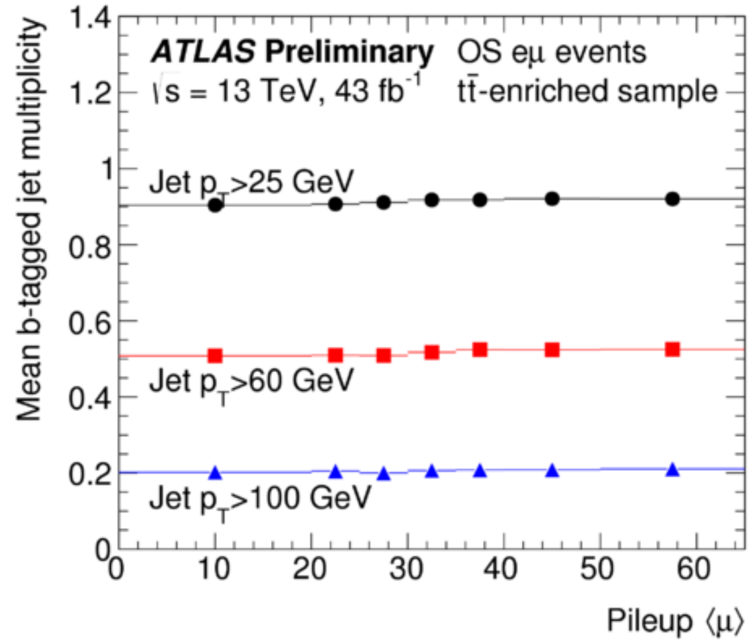


per mil effect well described by MC

Running conditions & detector performance



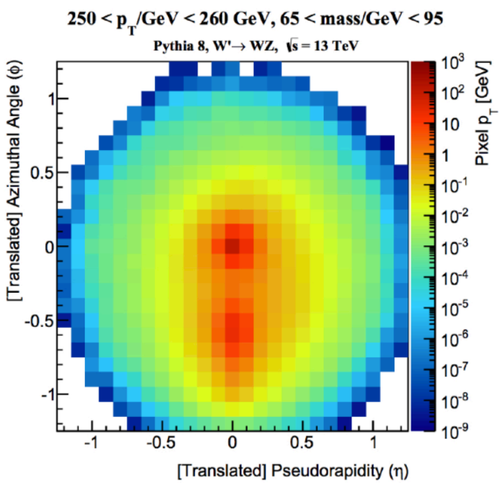
electron isolation



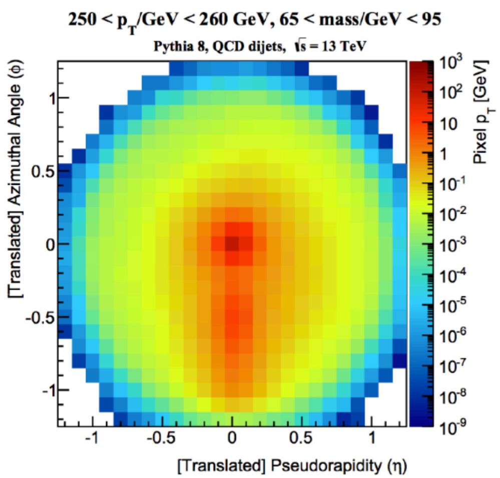
Number of b-tagged jets in a high purity ttbar sample

new analysis techniques, jet substructure

Boosted jet variables (substructures and flavor tagging) with images, deep learning and more detailed algorithms



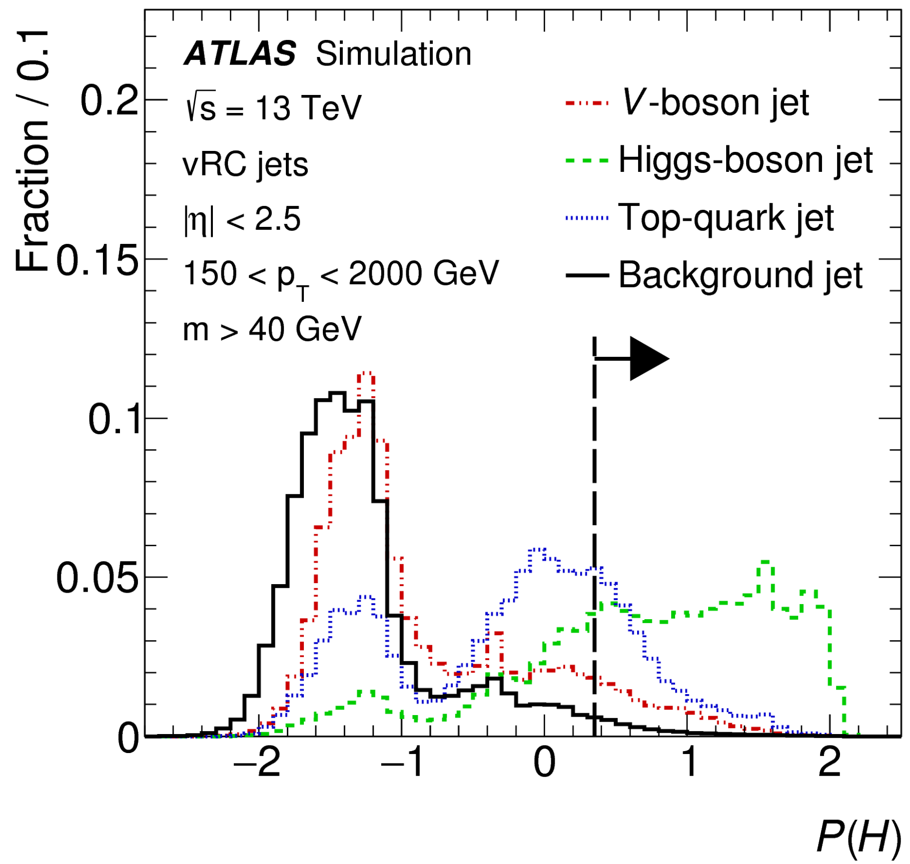
W jets



QCD jets

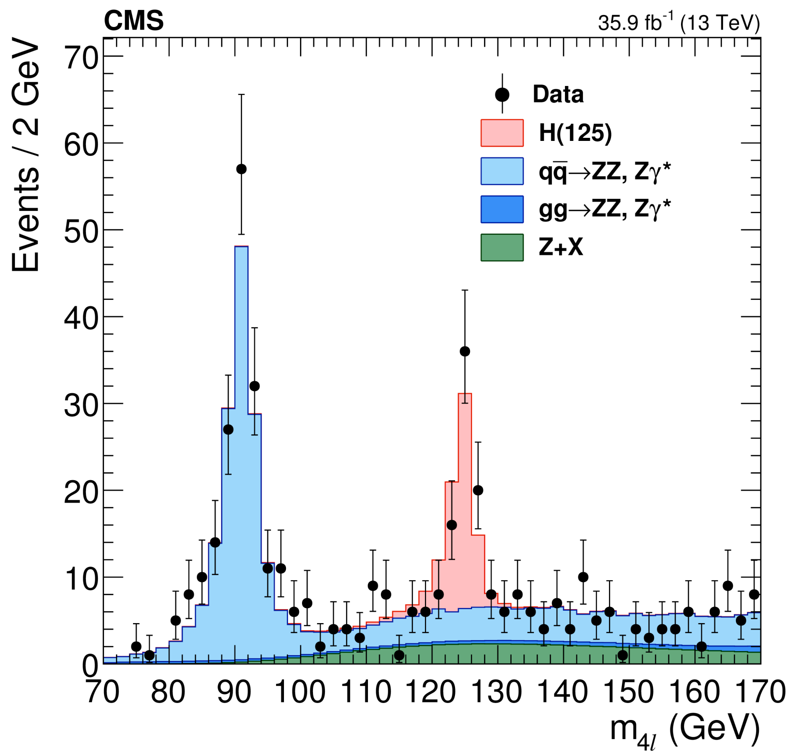
Luke de Oliveira, et al, JHEP 07 (2016) 069

some examples: Phys. Rev. D 98, 092005

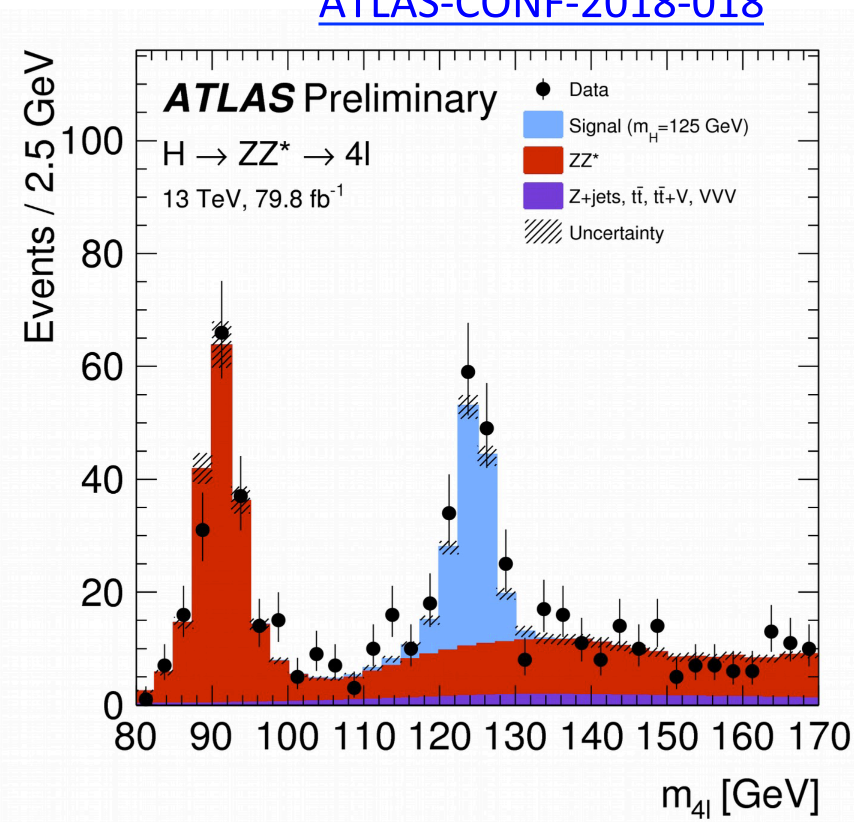


Higgs physics

Phys.lett.B 775 (2017) 1



ATLAS-CONF-2018-018



Time to study the properties of the new fundamental scalar!

Is it a Standard Model Higgs boson?

Standard Model Higgs boson

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

describes experimental data until 2012 discovery

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs sector

$+ \mathcal{L}_{new}$?

Yukawa coupling with new scalar new type of interaction	Gauge boson interaction with new scalar (known for fermions)	Higgs potential $\mu^2\phi^2+\lambda^2\phi^2$ to be explored at HL-LHC

LHC Run 1 legacy

- Higgs boson mass measured to ~0.2%
  (fixes the SM predictions!)
- Higgs boson couplings measured to ~10-25%
  (H $\rightarrow$ invisible constrained to < 25-30%)
- First studies of spin, CP eigenstate/ admixtures, differential distributions, all compatible with the SM

More precision is needed

- Coupling to fermions not fully established yet in Run-1
  coupling to top and bottom quarks not directly observed
- Generic size of (inclusive) Higgs couplings modifiers expected for new physics (BSM) at ~O(TeV)

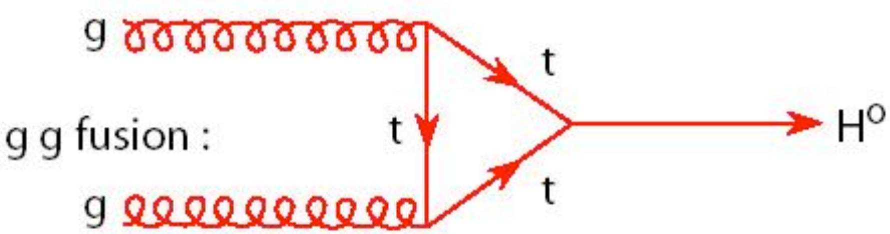
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

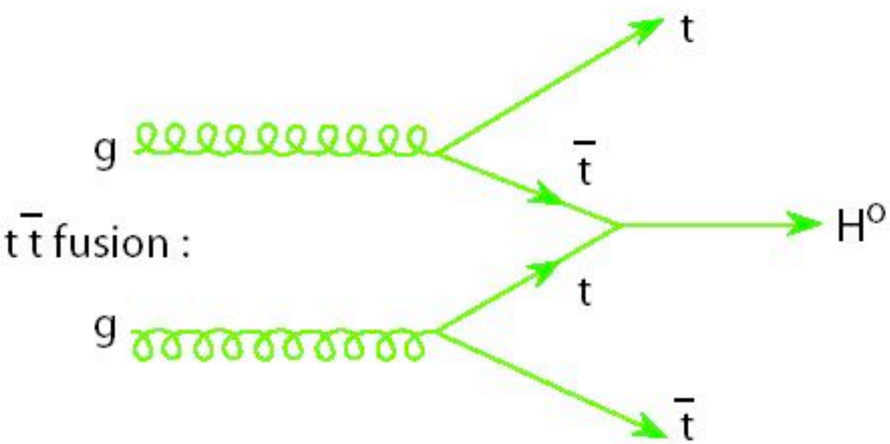
[Snowmass 2013 study, https://arxiv.org/pdf/1310.8361.pdf]

N.B. BSM effects may be enhanced at high transverse momentum, in tails of distribution

Higgs production modes

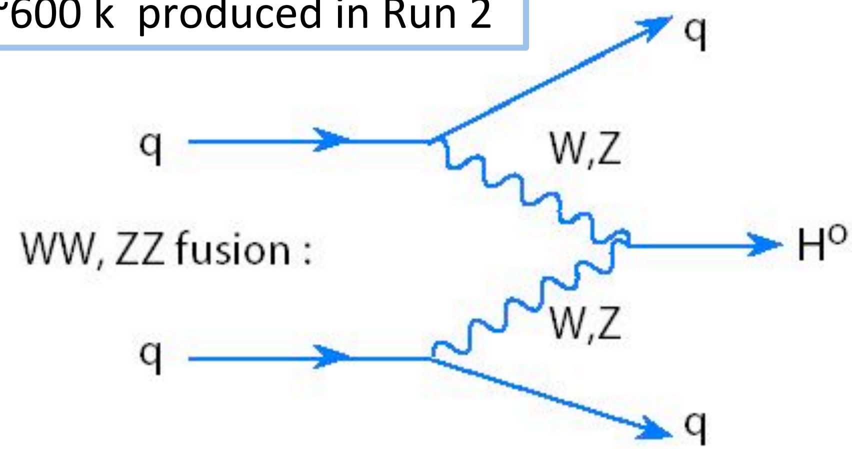
~8 M produced in Run 2

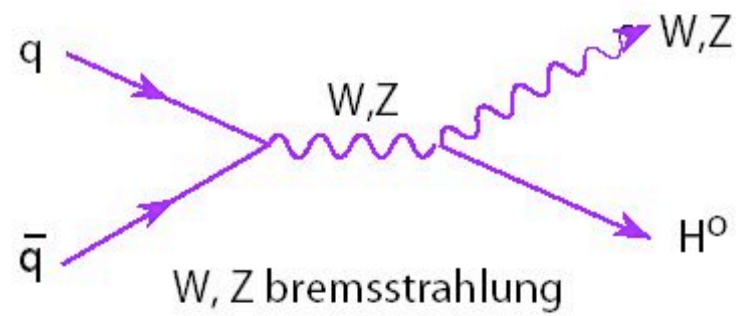




~40k produced in Run 2

~600 k produced in Run 2





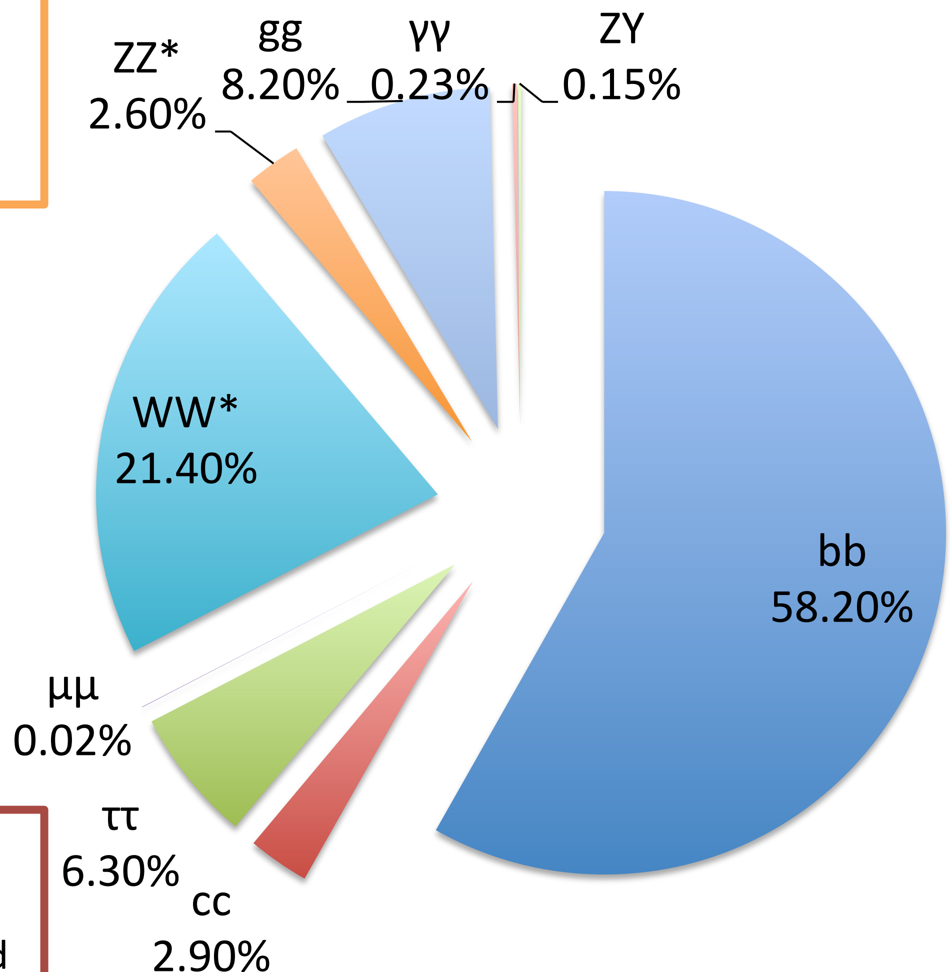
~400 k produced in Run 2

Higgs decay modes

ZZ*, γγ
high mass resolution
→ mass and precise differential measurements

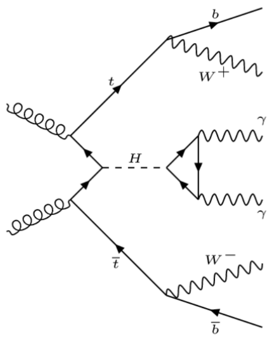
WW*
high BR, low mass resolution

μμ
very small BR
access coupling to 2nd generation fermions



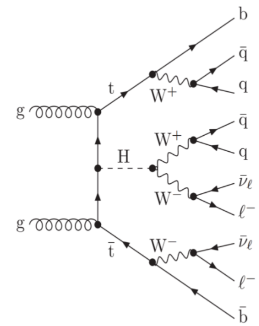
bb, ττ
high BR, low S/B,
→ important as direct probe of Higgs coupling to fermions

measurement of ttH production

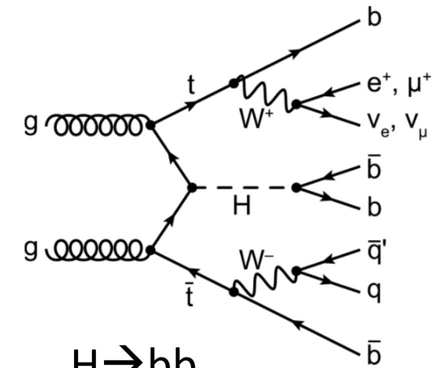


H→γγ

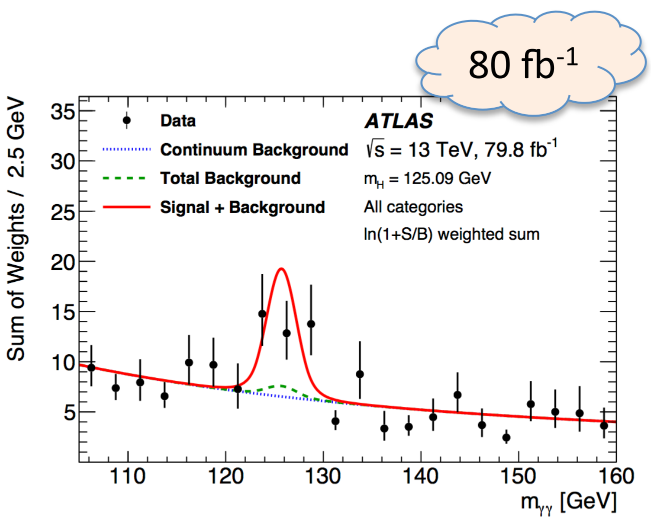
H→ZZ*→4l

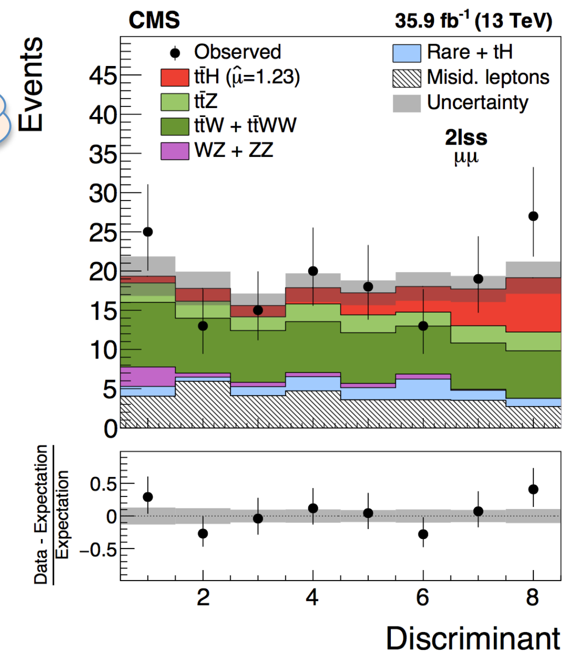


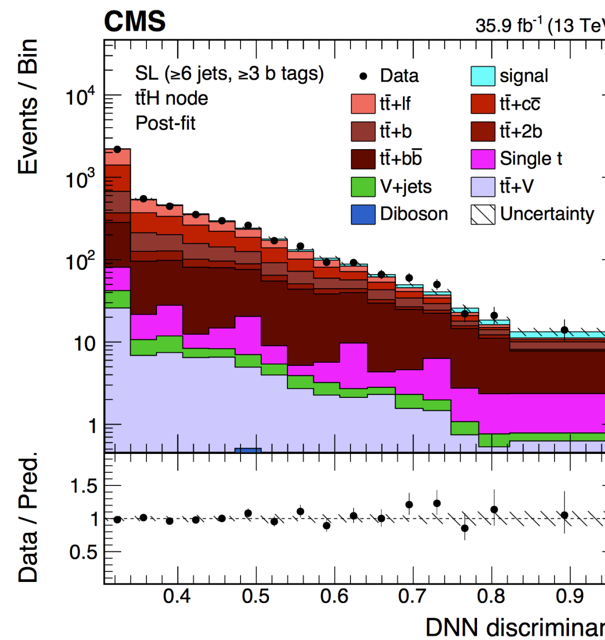
H→WW*→lνlν; H→ττ



H→bb







ATLAS 4.1σ (3.7σ exp.)

Phys. Lett. B 784 (2018) 173

CMS 3.2σ (2.8σ exp.)

[JHEP 08 (2018) 066]

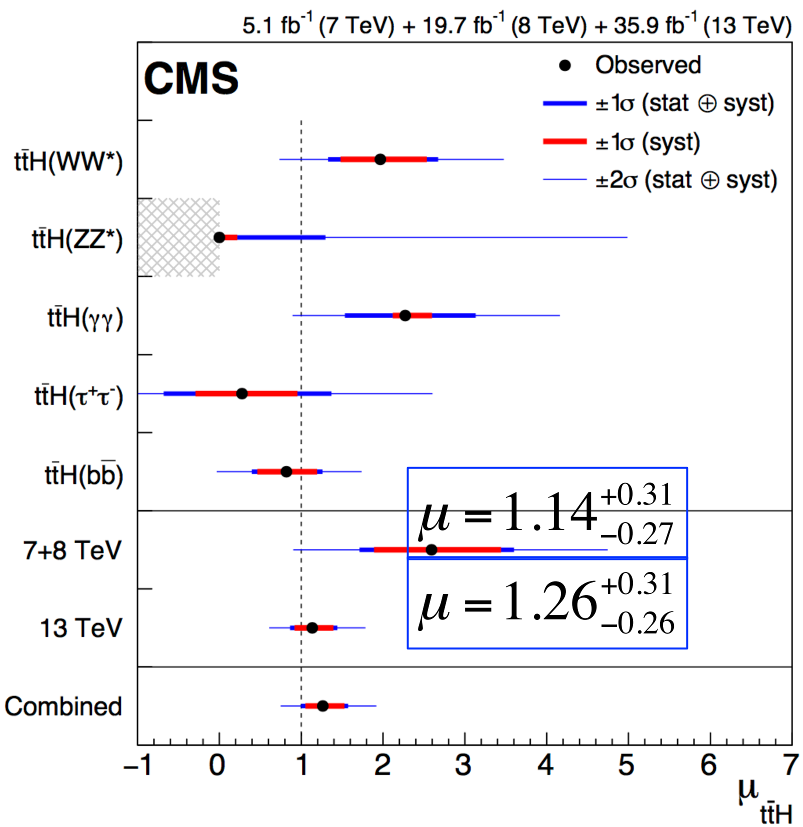
CMS 1.6σ (2.2σ exp.)

[arxiv 1804.03682]
[subm. JHEP]

Combination of ttH measurements

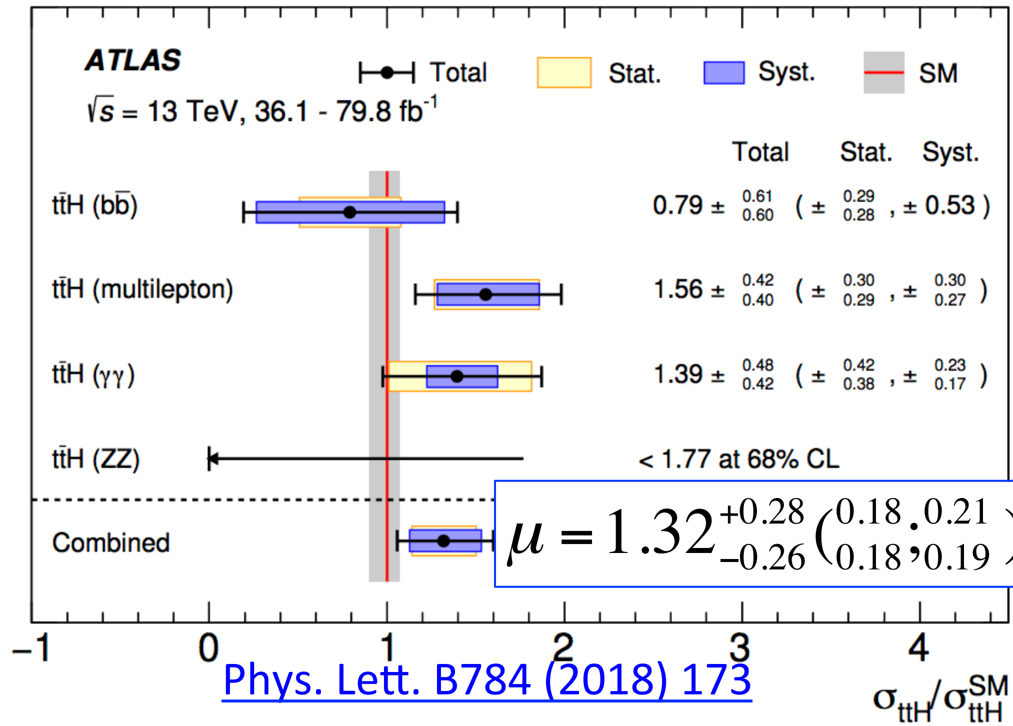
CMS 5.2σ (4.2σ exp.)

ATLAS 6.5σ (5.3σ exp.)



$\mu = 1.14^{+0.31}_{-0.27}$

$\mu = 1.26^{+0.31}_{-0.26}$



$\mu = 1.32^{+0.28}_{-0.26} \left({}^{0.18}_{0.18} , {}^{0.21}_{0.19} \right)$

[Phys. Lett. B784 (2018) 173](#)

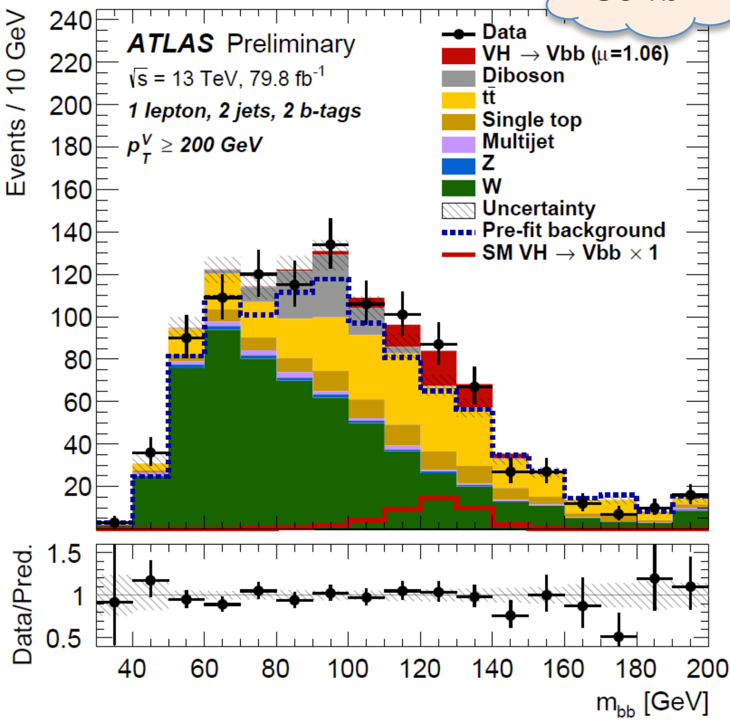
[Phys. Lett. B 779 (2017) 283](#)

[Phys. Lett. B 780 (2017) 501](#)

Direct observation of top Higgs coupling.
Confirmation of Yukawa coupling to fermions

Associated VH production and H→bb

80 fb^{-1}



H→bb highest branching ratio: Br=58%

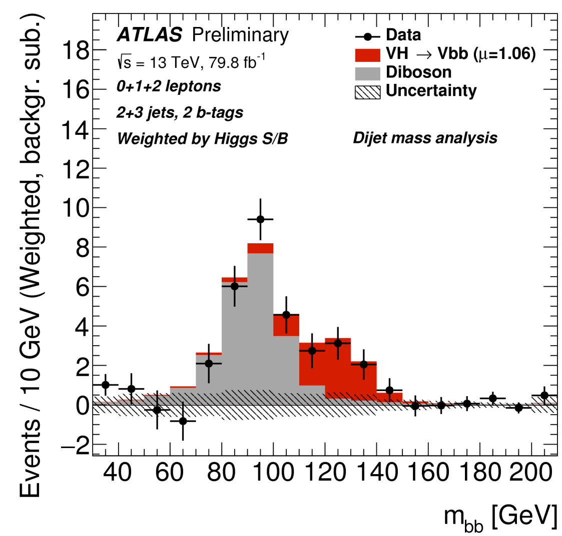
Associated WH or ZH production (VH)

- Br(H→bb) constrains invisible Higgs decays
- Tests Higgs Yukawa coupling to fermions

Analysis with large background:

- Use high-pT boson region
- Multi-variate analysis in 0, 1 and 2 lepton channels

ATLAS 5.4σ (5.5σ exp.)



Example: One input to di-jet mass analysis global fit – 1 lepton channel

[ATLAS-CONF-2018-036]

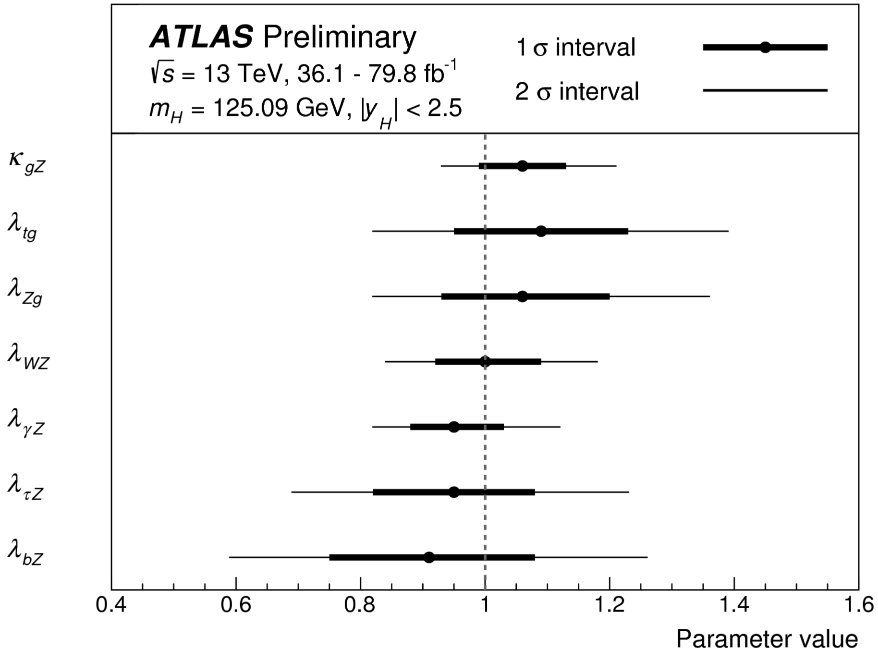
Dijet mass analysis as cross-check

Higgs couplings & decays

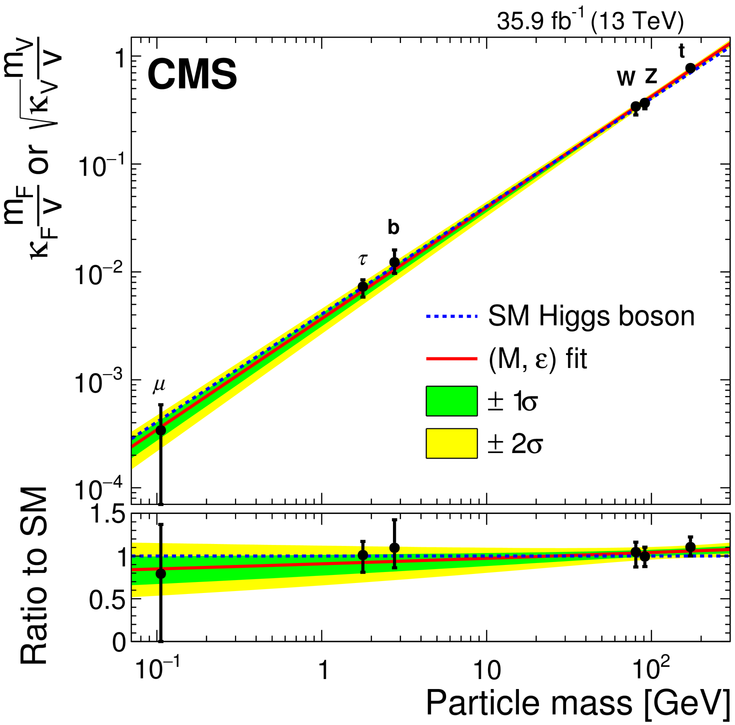
ATLAS-CONF-2018-031

CMS-PAS-HIG-17-031

ratio of couplings



mass dependence of couplings



- All couplings to high mass particles measured.
- Next challenge, second generation: muon, c-quark…

H→μμ getting close to SM

CMS-HIG-17-019 (Acc. Phys.Rev.Lett.)

CMS (36fb^{-1}) : $\mu_{\mu\mu}$=0.7±1.0
$\mu_{\mu\mu}$<2.6 (2.1 exp.)

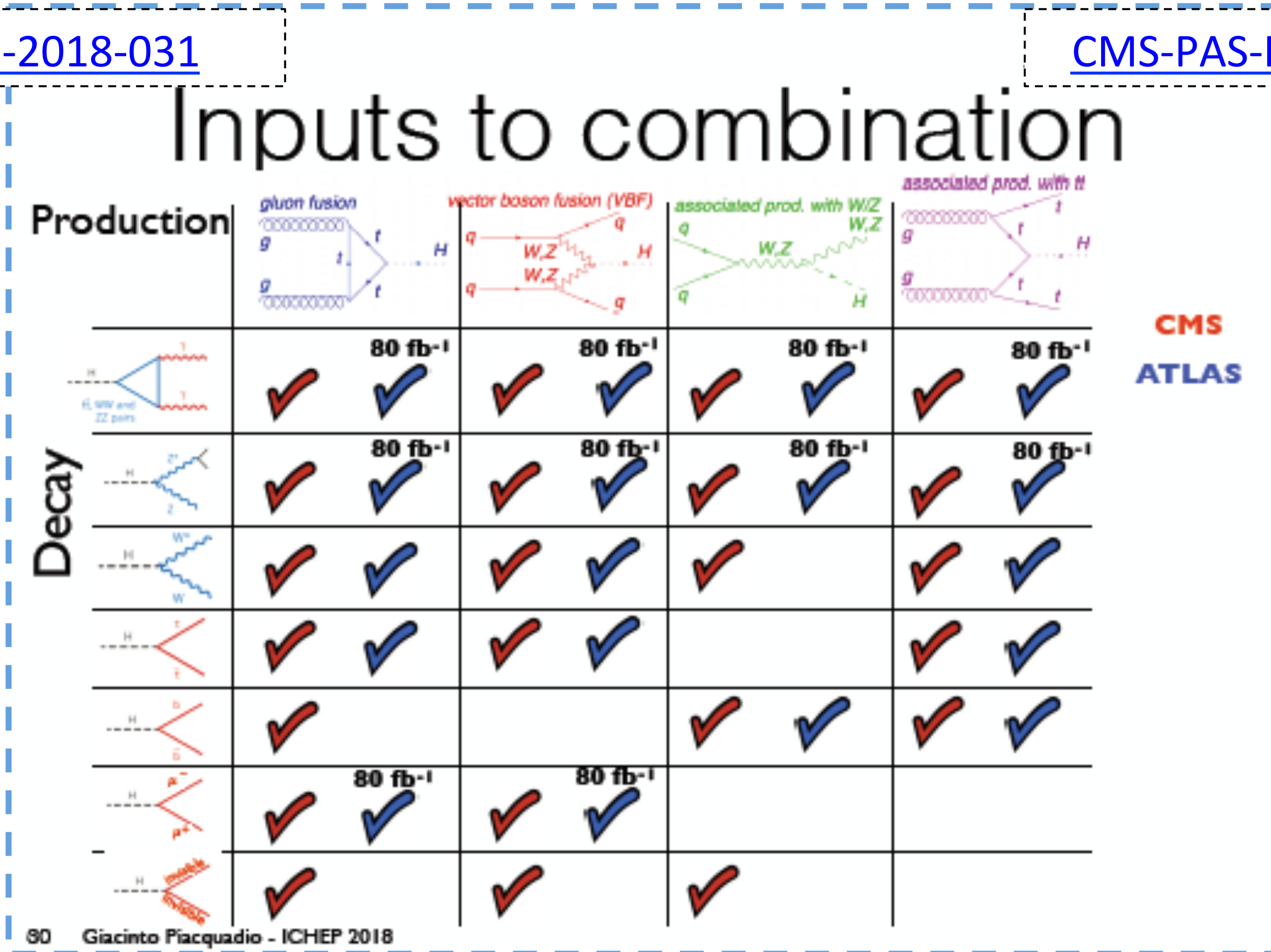
ATLAS-CONF-2018-026

ATLAS (80fb^{-1}) ; $\mu_{\mu\mu}$=0.1+1.0-1.1
$\mu_{\mu\mu}$<2.1 (2.0 exp.)

Combining measurements

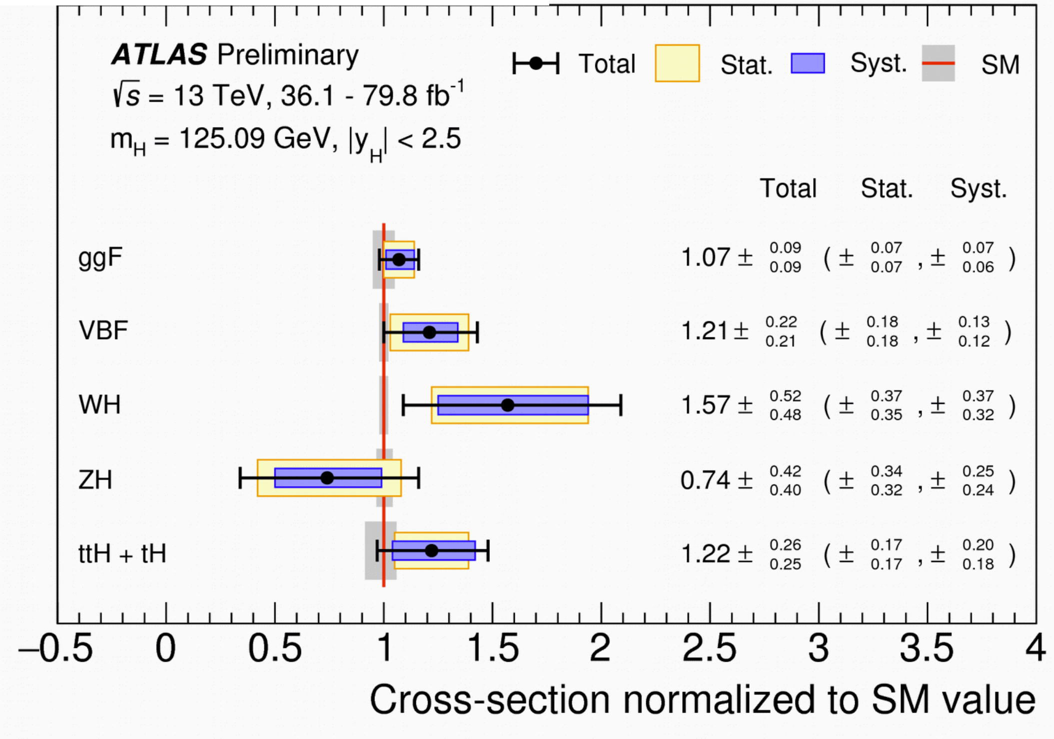
ATLAS-CONF-2018-031

[CMS-PAS-HIG-17-031](CMS-PAS-HIG-17-031)

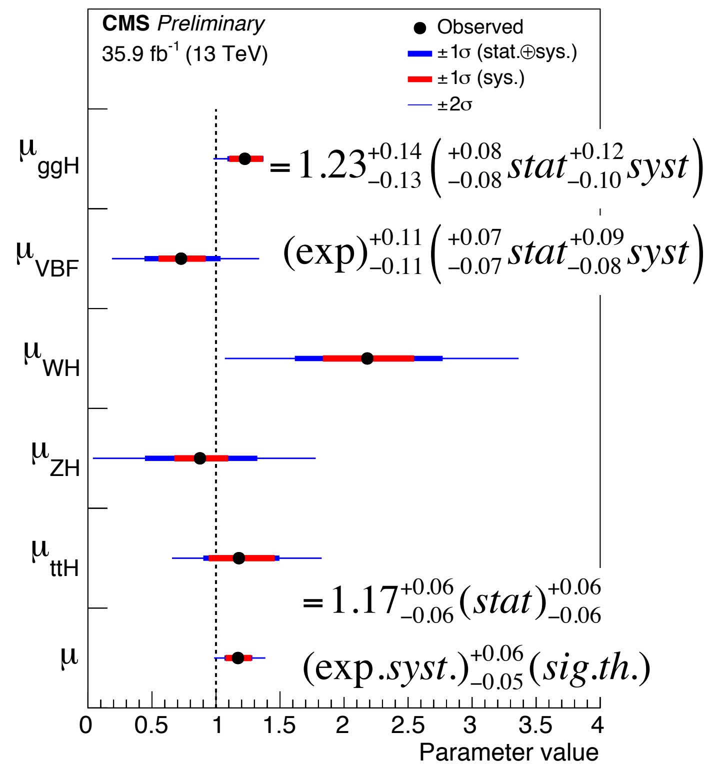


Higgs production modes

ATLAS-CONF-2018-031



CMS-PAS-HIG-17-031



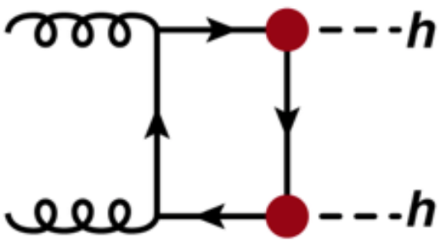
- **9-11% precision** on gg fusion per **experiment**
- **~5% uncertainty** state-of-the-art **theory** prediction (N3LO QCD+NLO EW [JHEP 1605 (2016) 058]),

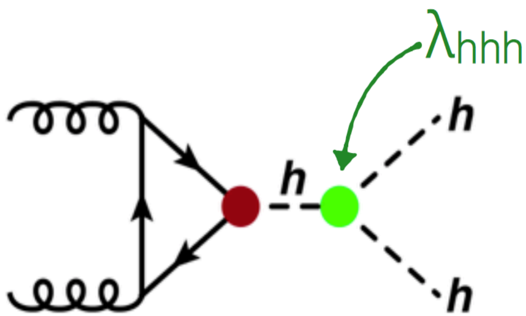
265 categories
5500 nuisance parameters in the fit

$$BF(H \rightarrow \text{inv.}) < 22\% \,@\, 95\%\ \text{C.L.}$$

combination of indirect and direct measurement

Di-Higgs production





σ (gg→h) = 48.5 pb

1/1500

σ (gg→hh) = 33.4±5.9 fb
[Higgs Xsec WG Report 4]

- ATLAS bbττ: σ_{HH} → bbττ < 13 x SM (15 exp.)
- CMS full combination : 95%CL

  σ_{HH} comb < 22 x SM (13 exp.)

  $K_\lambda=\lambda/\lambda_{SM}$ $-11.8<K_\lambda<18.8$ ($-7.1<K_\lambda<13.6$ exp.)

Phys. Rev. Lett.121 (2018) 191801

CERN-EP-2018-269

CERN-EP-2018-292

Getting close to 10 x SM rate for Di-Higgs production
Should reach SM sensitivity by the end of HL-LHC

Higgs mass

- **Run 1** Combination ATLAS + CMS: Phys.Rev.Lett. 114 (2015) 191803

  m_H = 125.09 ± 0.24 GeV (0.19%)

- **Run 2**

  ATLAS 36 fb^{-1} H→γγ, ZZ*→4l Phys. Lett. B 784 (2018) 345

  m_H =124.86 ± 0.27 GeV (0.21%) (stat. limited)

  CMS 36 fb^{-1} H→ZZ*→4l JHEP 11 (2017) 047

  m_H = 125.26 ± 0.21 GeV(0.17%) (stat. limited)

Will improve with full Run 2

Higgs width

SM Higgs boson width: 4 MeV

→ too small for a precise direct measurement

- best direct limit CMS H→ZZ*→4l   JHEP 1711 (2017) 047

  Γ_H < 1.10 GeV @ 95% CL

- ratio of on-shell to off-shell cross section   Phys.Lett. B786 (2018) 223

  recent ATLAS measurement H → ZZ*→4l,2l2ν   13 TeV 36 fb^{-1}

  Γ_H < 14.4 MeV (15.2 MeV exp.)

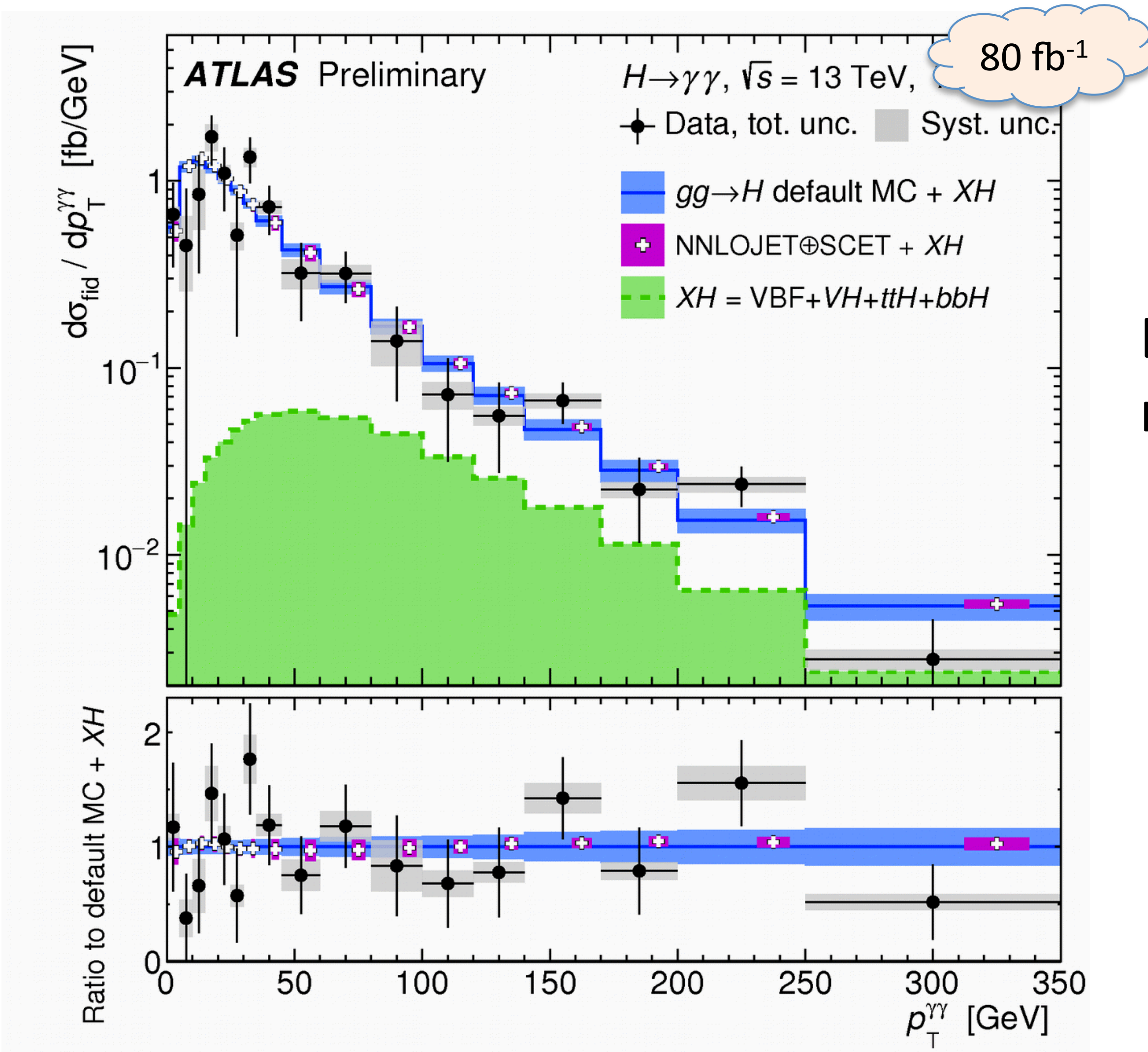
  (NLO K_g,K_Z factor with some assumptions $K_{on\text{-}shell} = K_{off\text{-}shell}$)

  x2 better than ATLAS, CMS Run 1 results

  further improvements expected with full Run 2

Differential cross-section with gauge bosons decays

ATLAS-CONF-2018-028



Data well described by recent SM predictions.

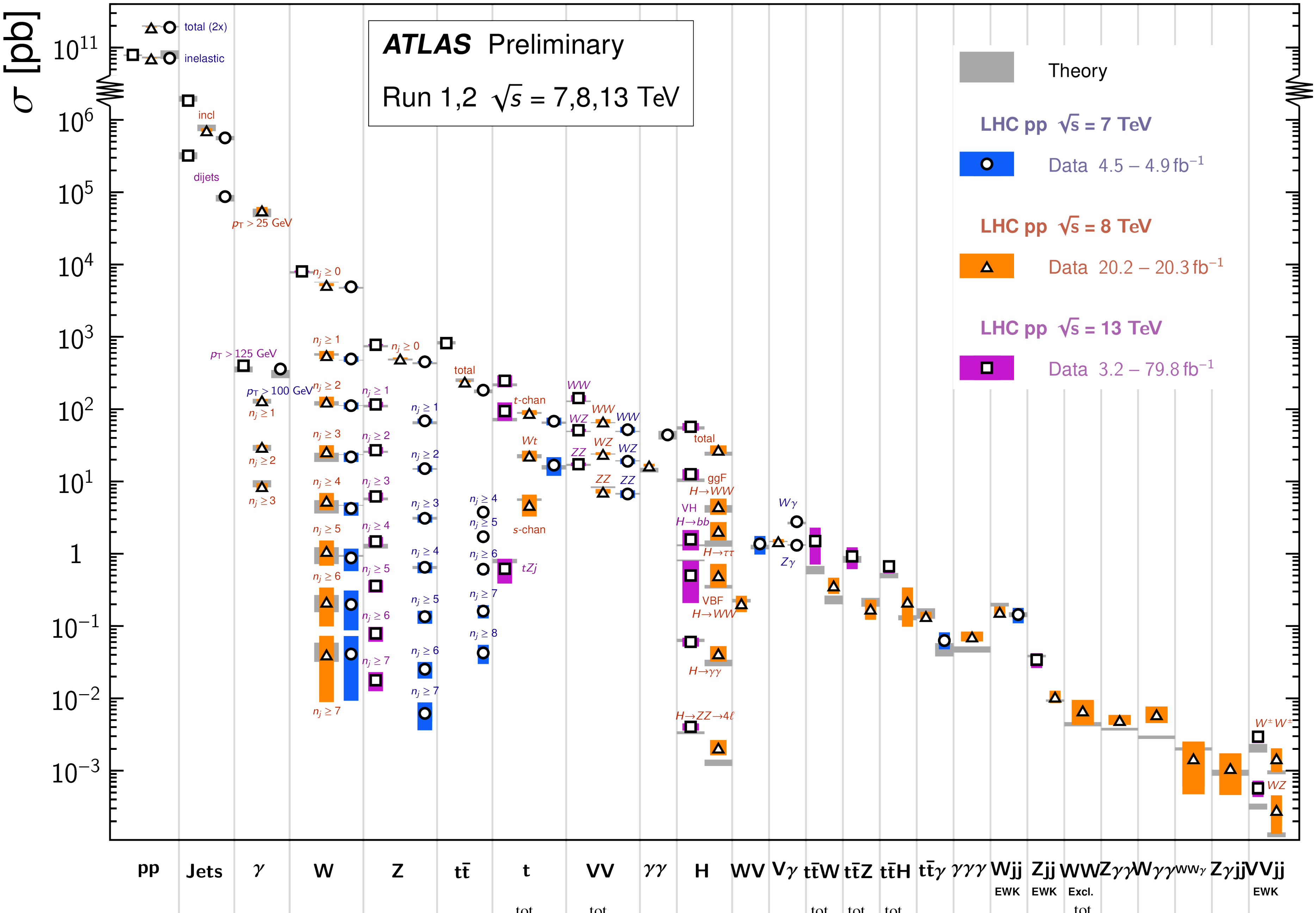
Precision SM measurements

- Standard Model widely studied but need to
  - probe in so far inaccessible regions
    - High energy, rare processes
    - Difficult modeling: high-order/EW corrections
  - tune MC generators, constrain PDFs,
- Run 2 data = opportunity to look for BSM
  - Rare production processes
  - Processes sensitive to anomalous couplings
- Measure backgrounds for Higgs measurements and direct BSM searches

ICHEP2018 overview [EW/SM/Top summary L. Skinnari]

Standard Model Production Cross Section Measurements

Status: July 2018



Electroweak measurements

- W/Z/γ high-statistics samples
  extract SM parameters & test self-consistency:
  - W boson mass
  - Weak mixing angle

- Multi-bosons
  sensitive probe of BSM gauge interactions:
  - cross-section measurements
  - probe anomalous triple/quartic gauge couplings: aTGC, QGC
  - vector boson scattering (VBS)

W boson mass

Key test of SM consistency

- Extract m_W using fits to lepton p_T & transverse mass

- Requires precise lepton energy/ momentum calibration

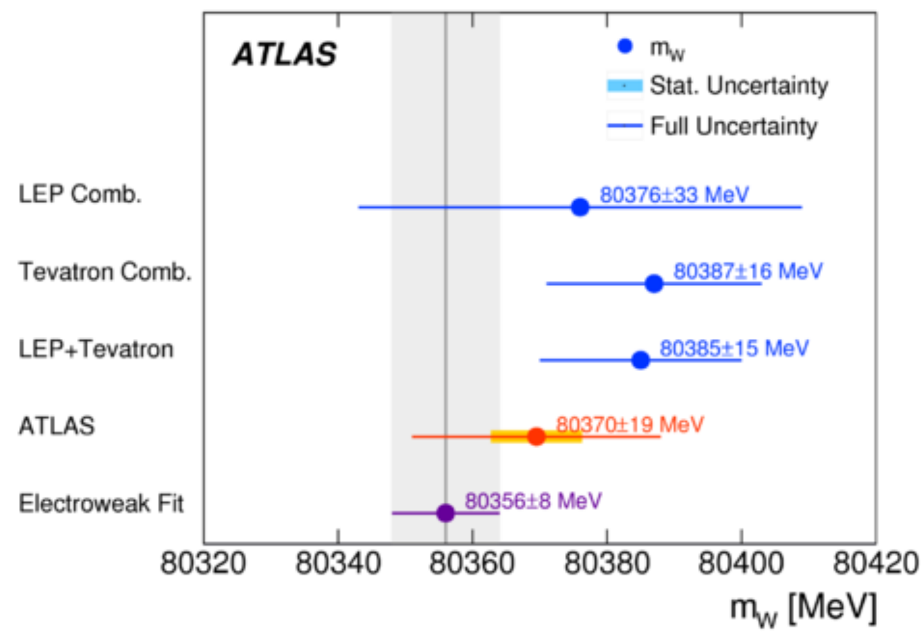
- about 12 MeV systematic uncertainty from W boson kinematic (PDF)

  new LHC low pile-up data sample recently recorded

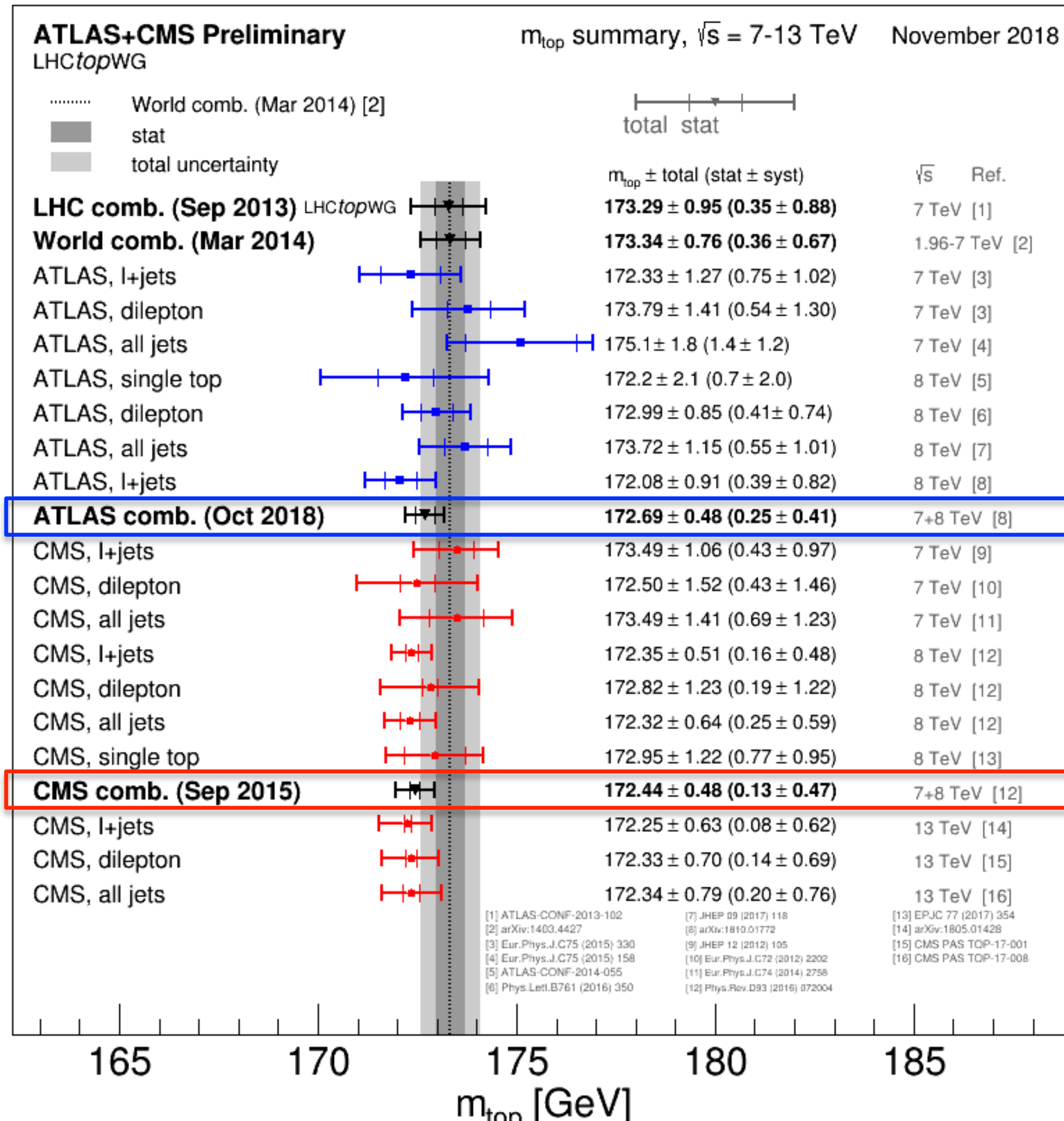
[Eur. Phys. J. C 78 (2018) 110]

m_W = 80370 ± 19 MeV

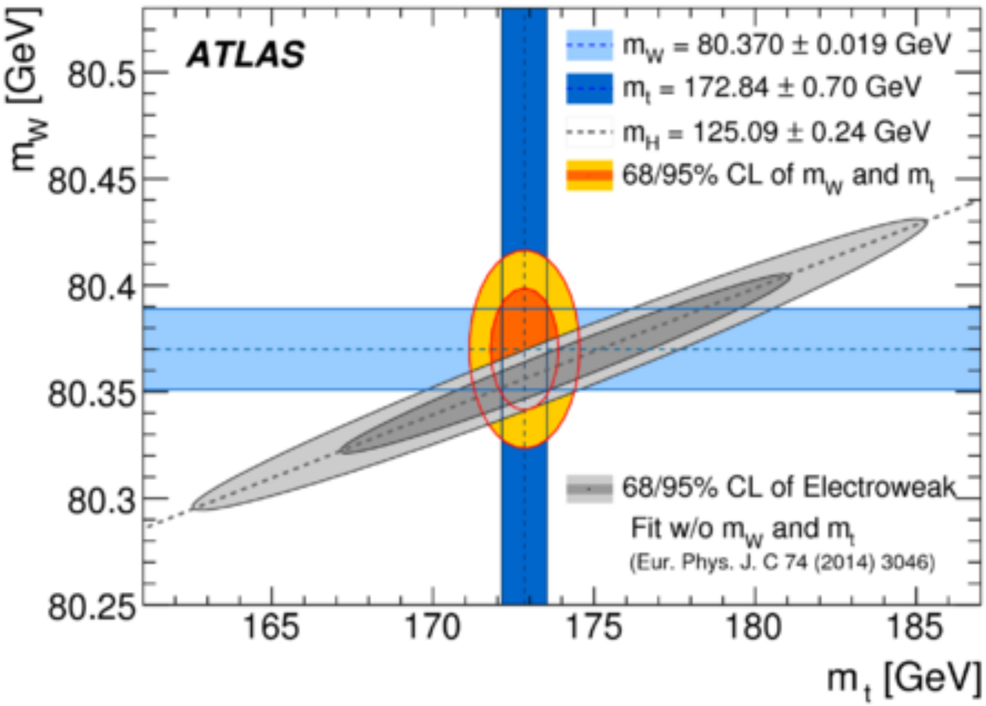
±7 (stat) ±11 (exp. syst) ±14 (mod. syst) MeV



Top quark mass



Consistency of SM



W-mass: 80370 +- 19 MeV **~0.02%** Eur. Phys. J. C 78 (2018) 110

Higgs mass: 124970 +- 240 MeV **~0.2%** Phys. Lett. B 784 (2018) 345

(will improve with Run 2)

Top-mass: 172510 +- 500 MeV **~0.3%** ATLAS-CONF-2017-071

similar results by CMS

Weak-mixing angle

Drell-Yan cross section qq→Z→ll: spin correlation between the initial-state spin-1/2 partons and the final-state spin-1/2 leptons mediated by a spin-1 intermediate state (mostly Z). In LO QCD:

$$\frac{d\sigma}{dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{\ell\ell}\, dm^{\ell\ell}}\left\{(1+\cos^2\theta) + A_4 \cos\theta\right\}.$$

ATLAS-CONF-2018-037

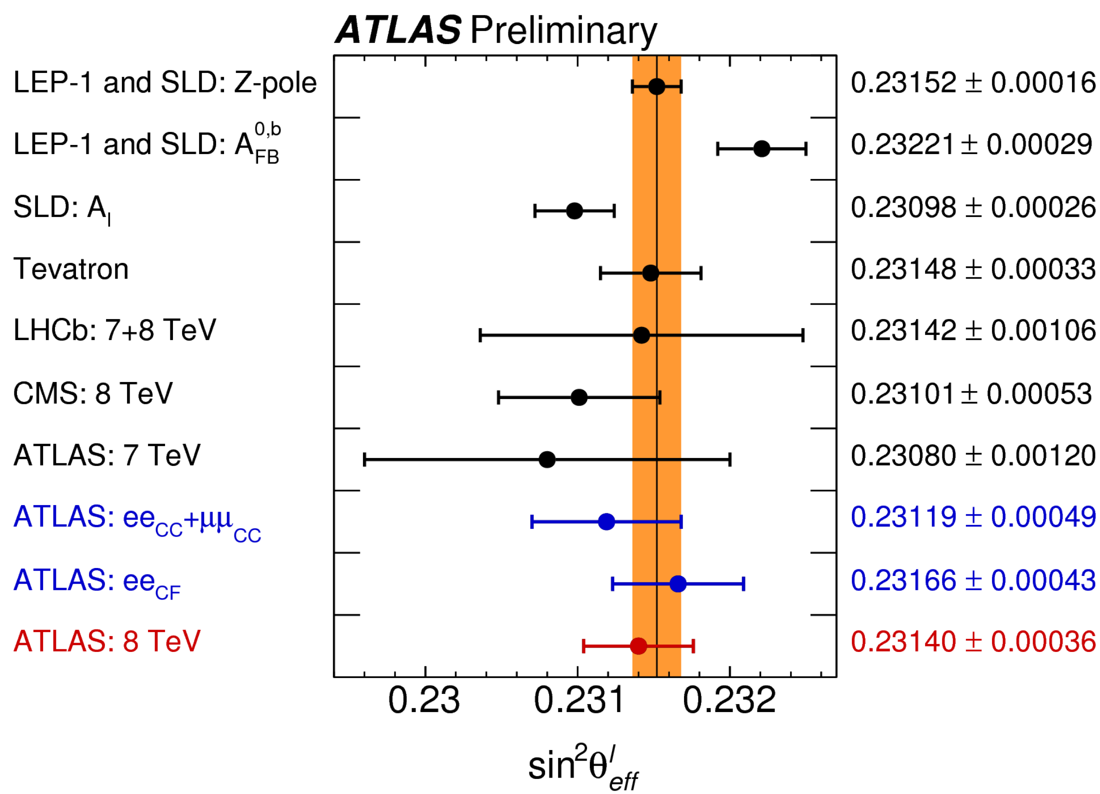
8 TeV data: A4 measured
- two leptons |η|<2.4 (cc)
- at least one forward electron 2.5<|η|<4.6 (cf).

$$\sin^2\theta^l_{eff} = 0.23140 \pm 0.00036$$

Uncertainty break-down:

$$0.00021(stat) \pm 0.00024(PDF) \pm 0.00036$$

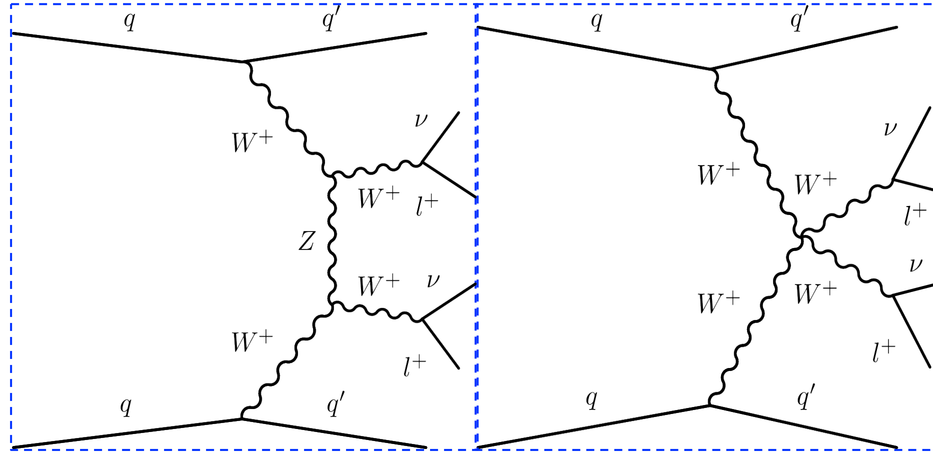
Main limitation PDF knowledge initial quark direction.



global EW fit 0.23149 ± 0.00007

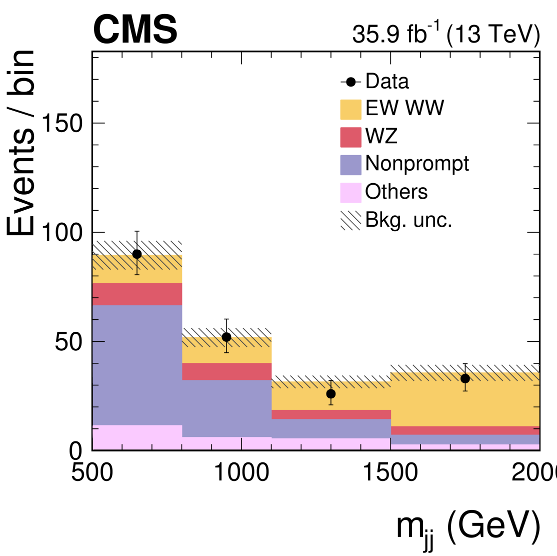
Vector Boson Scattering: same-sign WWjj

- Key test of EWSB
  restoration of unitarity of the WW scattering cross-section
- Sensitive to anomalous QGC
- Enhanced in BSM scenarios (e.g. modified Higgs sector or new resonances)



1st observation CMS 2017

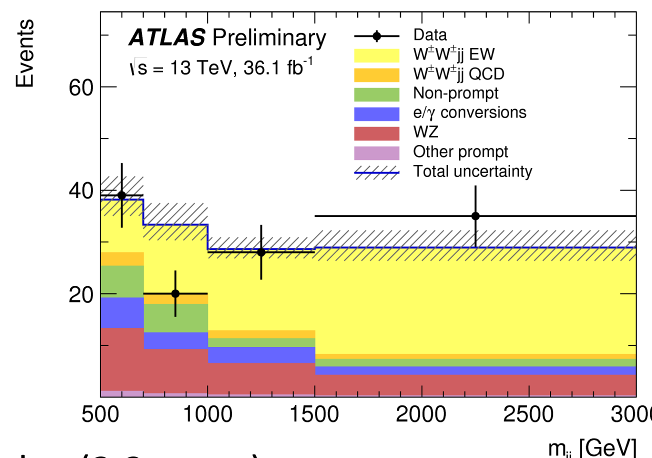
Phys.Rev.Lett.120(2018)081801



5.5σ obs.
(5.7σ exp.)

observation ATLAS 2018

ATLAS-CONF-2018-030/



6.9σ obs.
(4.6σ exp.)

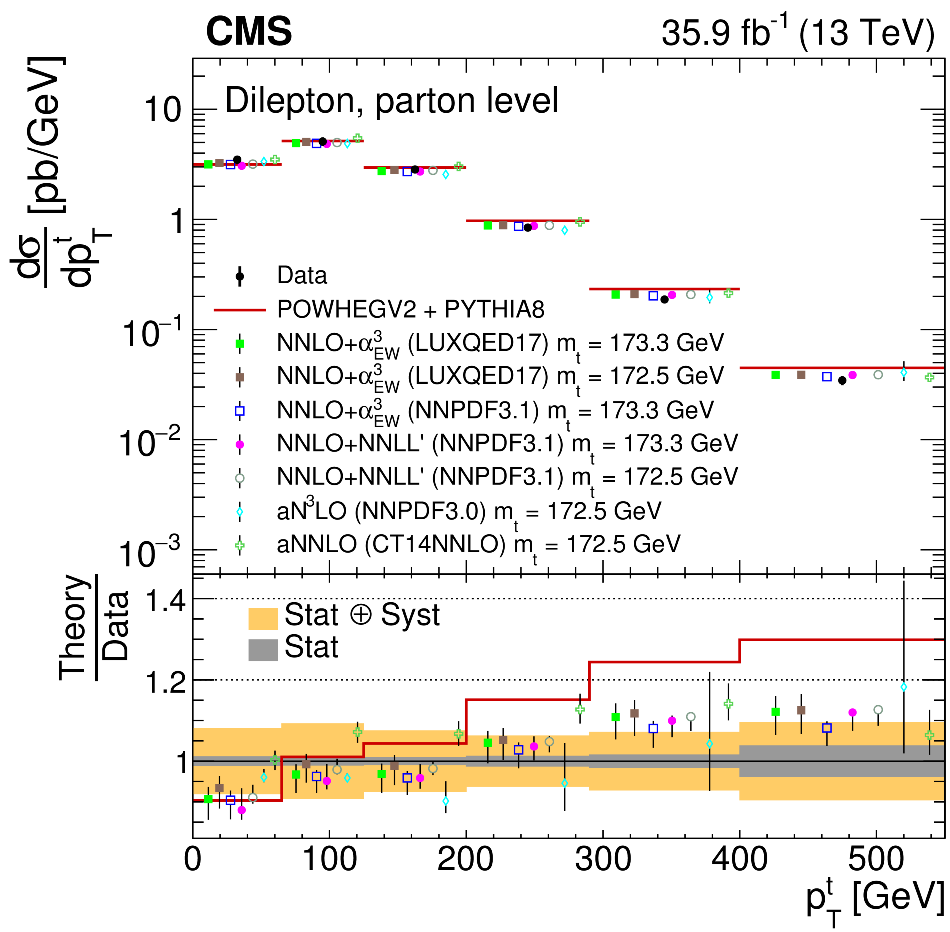
ATLAS WZ 5.6σ obs. (3.3σ exp.)

CMS WZ 1.9σ obs. (2.7σ exp.) ZZ 2.7σ obs. (1.6σ exp.)

$t\bar{t}$ differential cross-section

- large effort in measuring multi-differential cross-sections
- Overall good modeling of $t\bar{t}$ production provided by NLO generators
  but tend to produce p_T top spectra harder than the measured one
- Signal modeling among the largest systematic uncertainties
- new era of NNLO calculations & EW corrections: mis-modeling in top p_T spectrum improved, but not solved

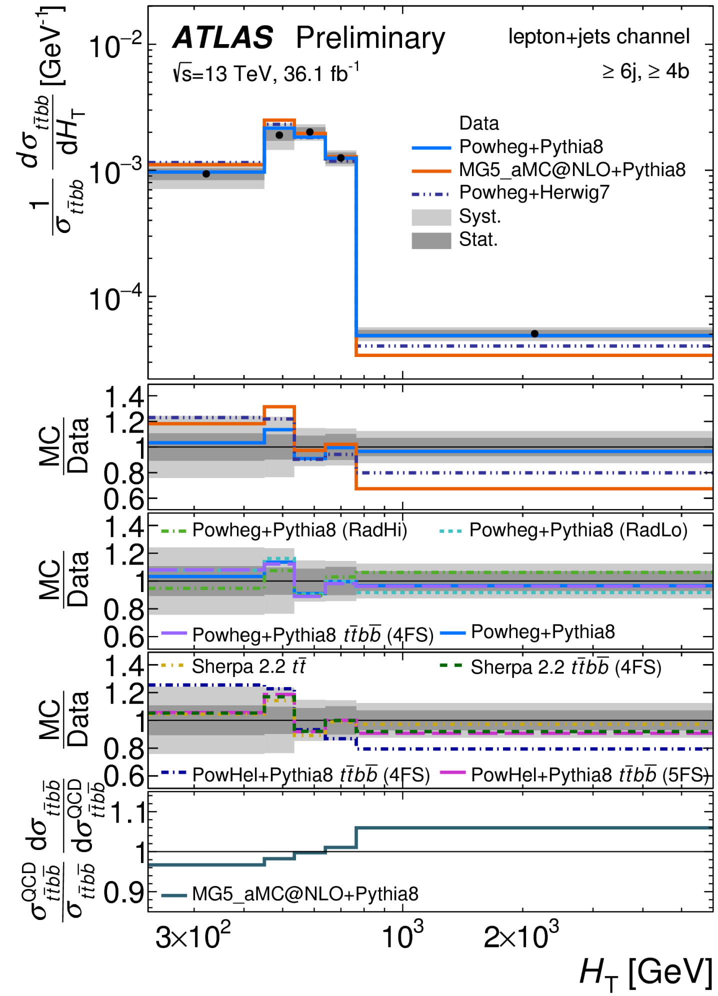
arXiv:1811.06625 subm. JHEP



$t\bar{t}$ + $b\bar{b}$ differential cross-section

CERN-EP-2018-276

- Modeling of tt+HF essential for ttH, H→bb measurements (dominant uncertainty!)
- Challenging for QCD calculations due to massive b's
- Some discrepancies observed -valuable input for MC tuning
- Dominant uncertainties from b-tagging & signal modeling



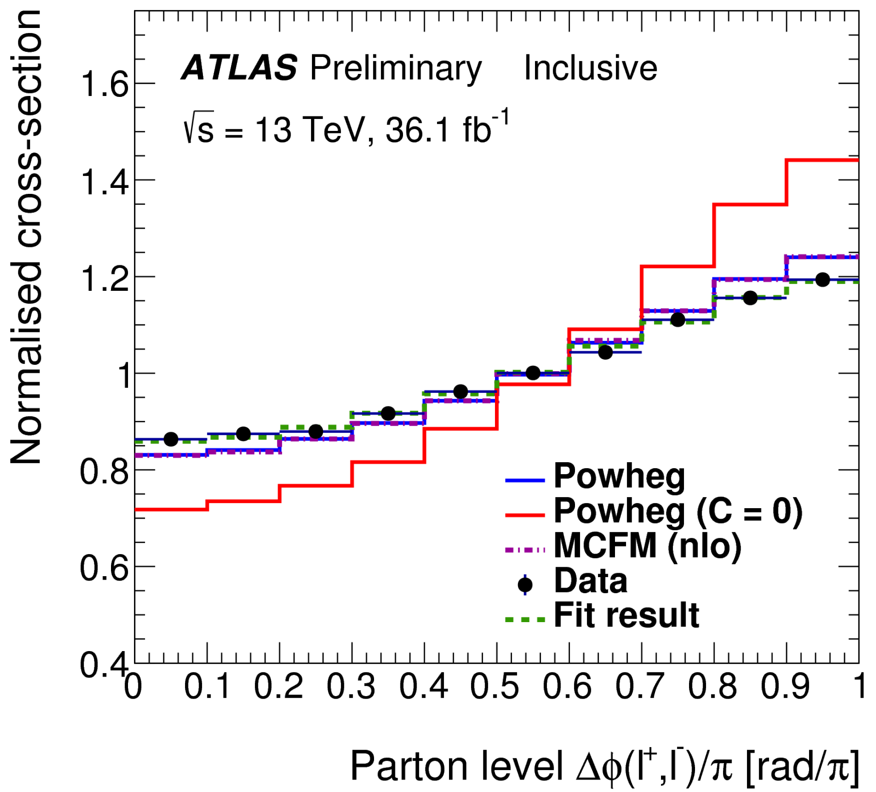
top spin correlation

Correlation of spin for pp→tt→eμbb measured between the top decay products and a spin axis with a sensitive variable ΔΦ(eμ)

Stronger spin correlations observed than expected by NLO QCD.

Fit result: f=1.250+-0.026+-0.063
3.2σ discrepancy with NLO QCD

ATLAS-CONF-2018-027

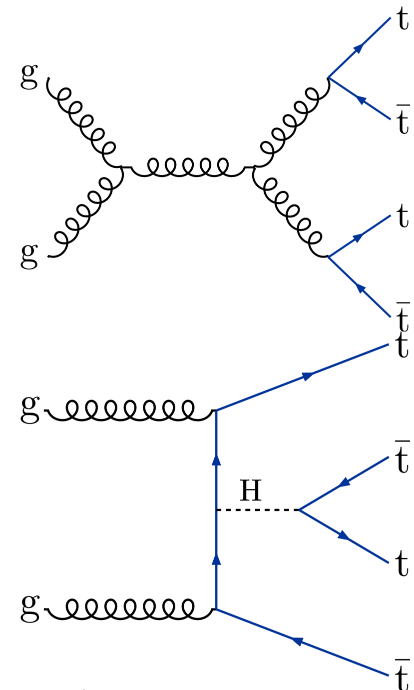


But impact of NNLO calculations ?
Rene Poncelet et al.

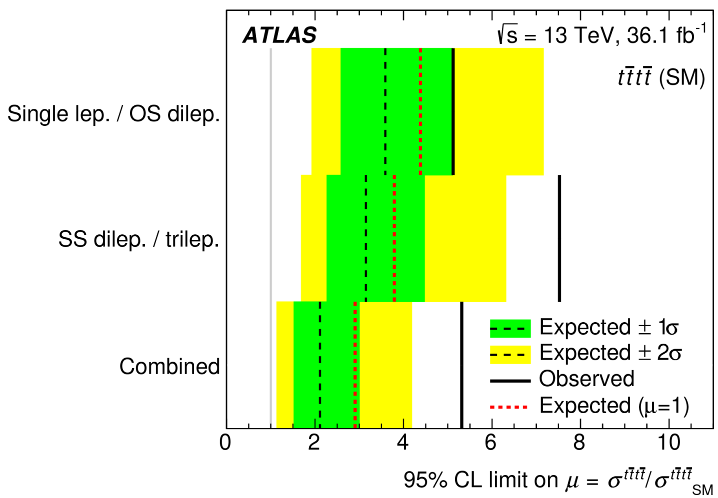
TOP2018 Rene Poncelet NNLO QCD top quark production & decay

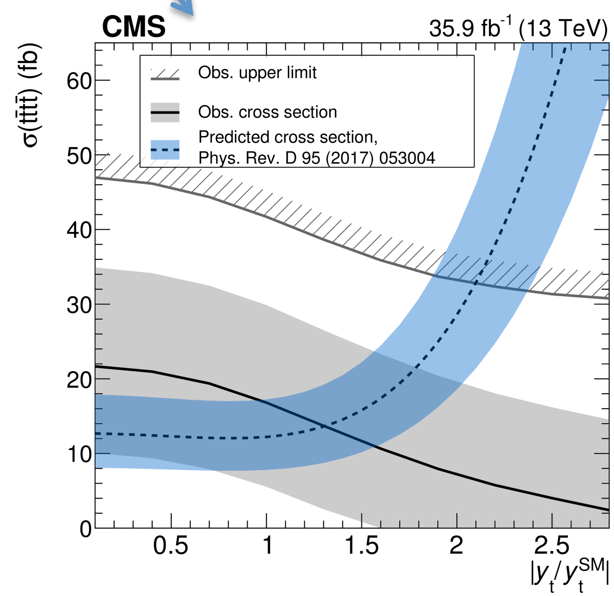
4 tops production

- $\sigma_{tttt,SM} \approx 10^{-5} \times \sigma_{tt,SM}$ @ 13 TeV
- Sensitive to new physics (e.g. high mass scalars, top Yukawa coupling)



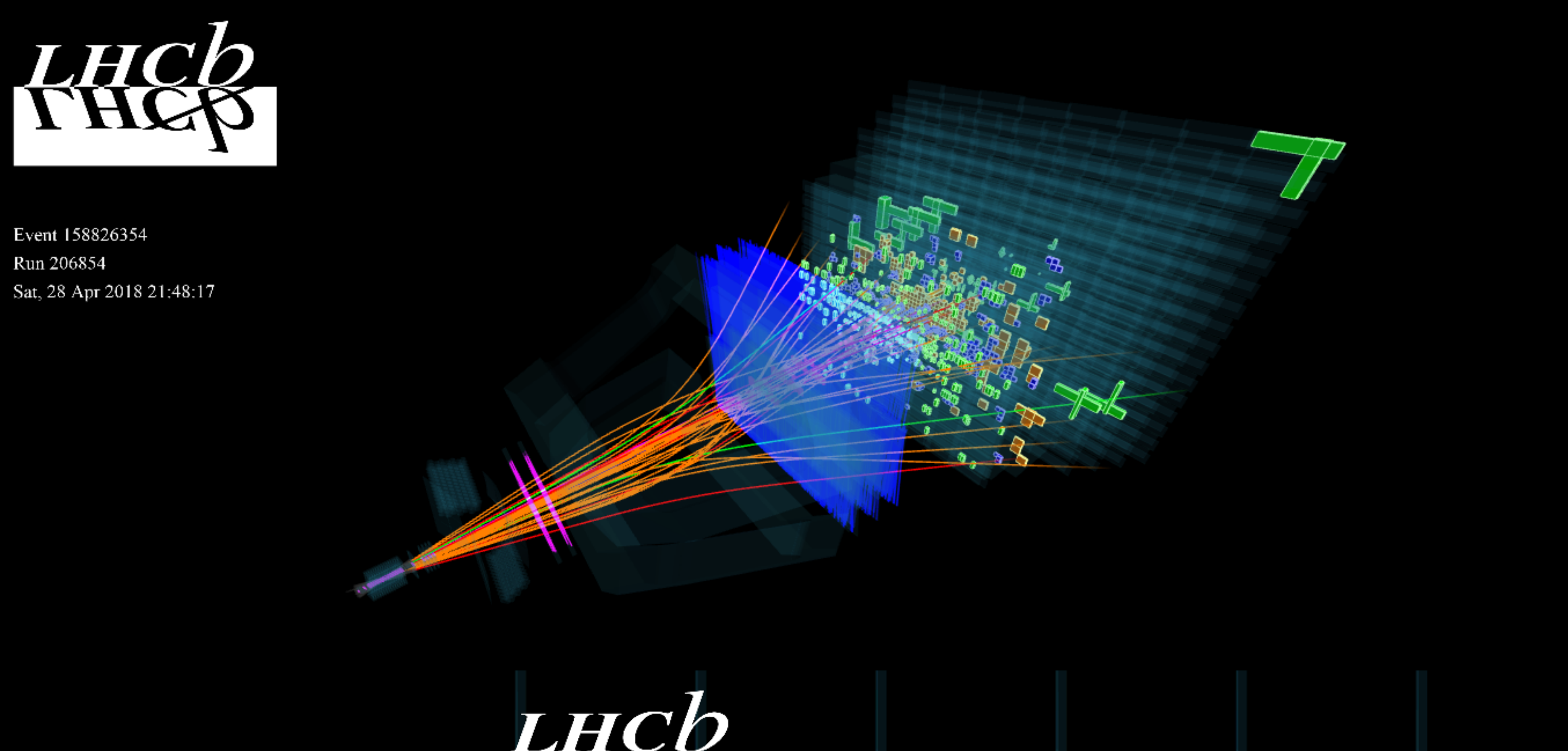
ATLAS: 2.8σ (2.0σ) SS/OS dileptons, l+jets
CMS : 1.6σ (1.0σ) SS/trileptons

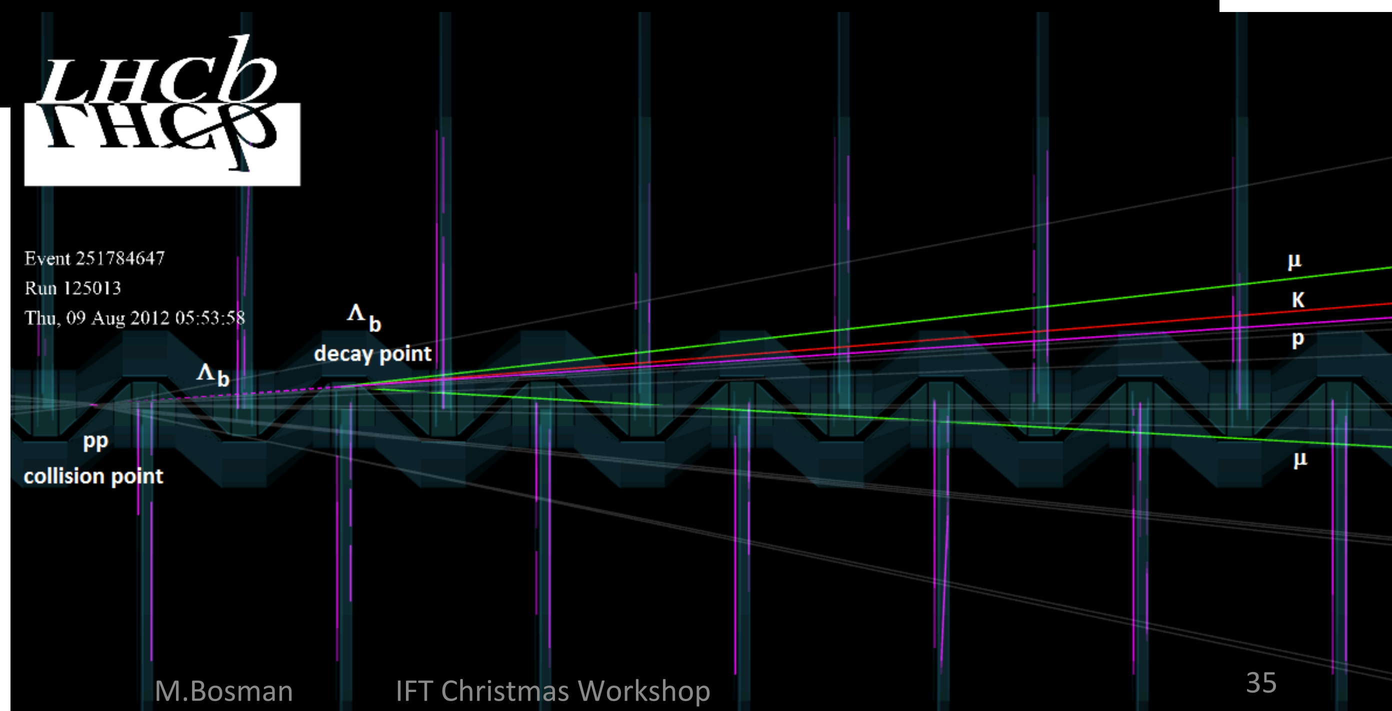




ATLAS: arXiv:1811.02305, subm. Phys.Rev.

CMS: EPJC 78 (2018) 140

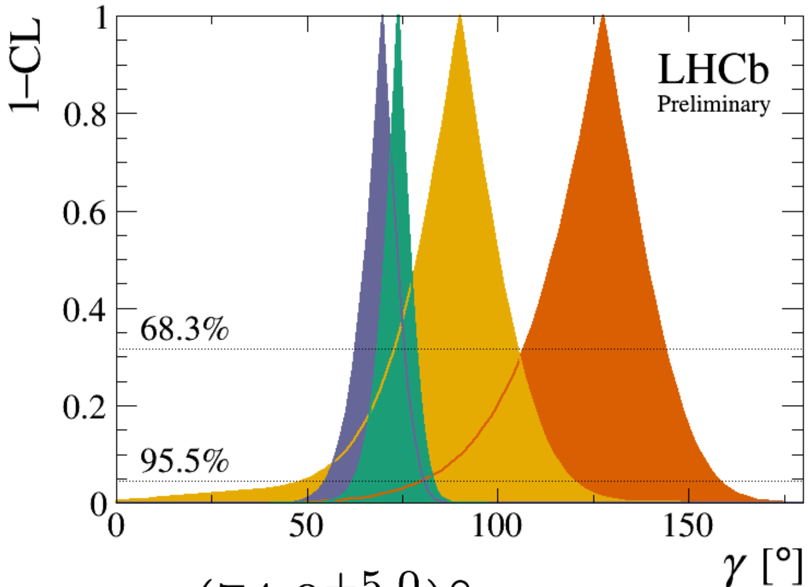

LHCb
Event 158826354
Run 206854
Sat, 28 Apr 2018 21:48:17

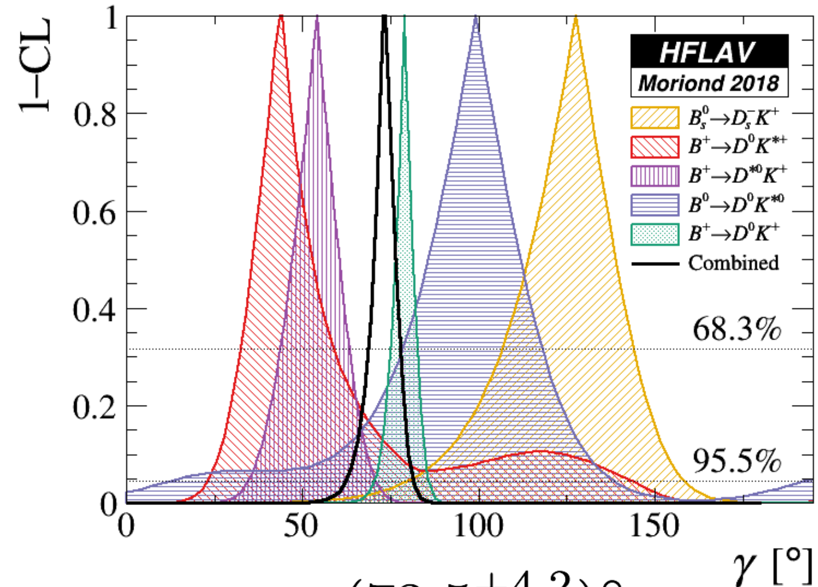

LHCb
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λb
decay point
Λb
pp
collision point
μ
K
p
μ

LHCb angle γ

LHCB-CONF-2018-002

HFLAV Moriond2018





$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

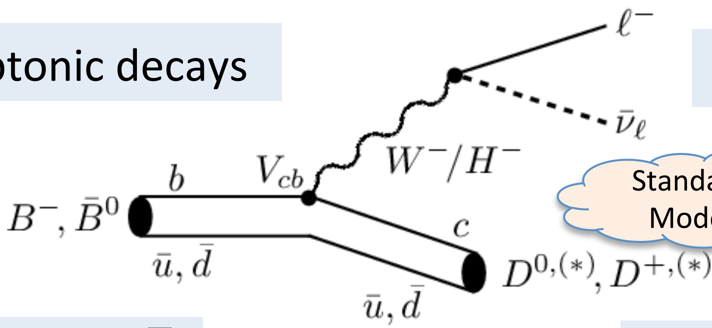
- B_s^0 decays
- B^0 decays
- B^+ decays
- Combination

- Combination of 16 measurements from LHCb
- 98 observables with 40 free parameters
- some tension between different decay modes

Lepton Flavor Universality

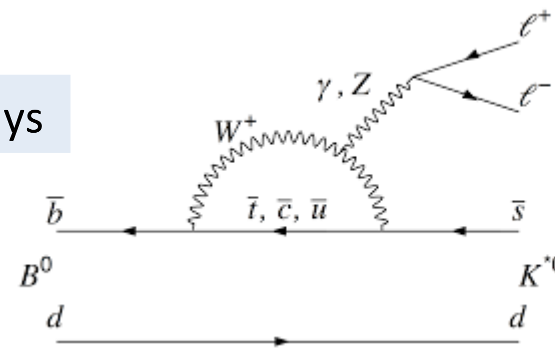
Differences in ratios of decays in leptons should originate only in different masses
Clean probe for NP

b→c semileptonic decays



Standard Model

b→sll decays

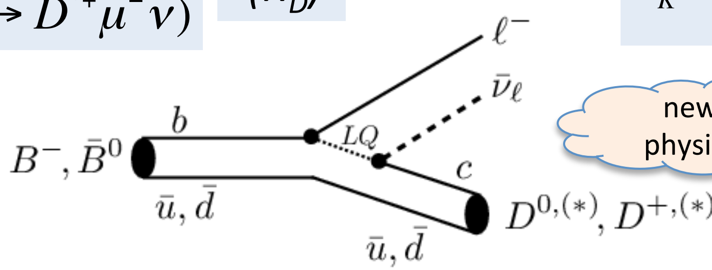


$$R_{D^*} = \frac{BR(B^0 \to D^{*+}\tau^-\bar{\nu})}{BR(B^0 \to D^{*+}\mu^-\bar{\nu})}$$

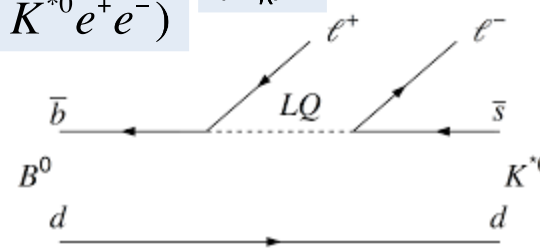
(R_D)

$$R_{K^*} = \frac{BR(B^0 \to K^{*0}\mu^+\mu^-)}{BR(B^0 \to K^{*0}e^+e^-)}$$

(R_K)



new physics



also

$$R_{J/\psi} = \frac{BR(B_c^+ \to J/\psi\tau^-\bar{\nu})}{BR(B_c^+ \to J/\psi\mu^-\bar{\nu})}$$

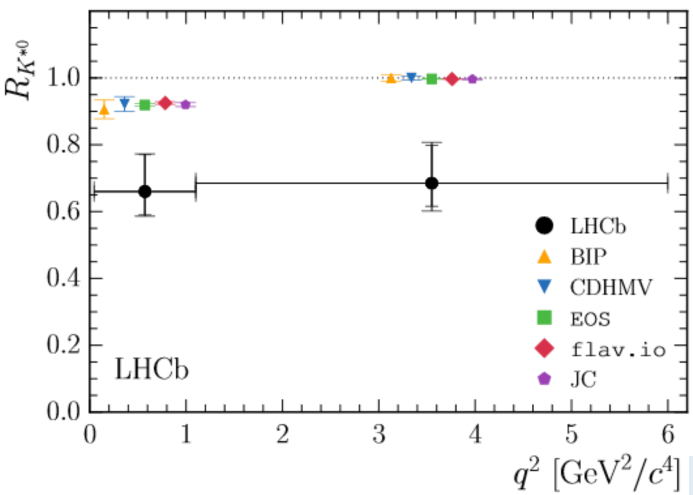
and

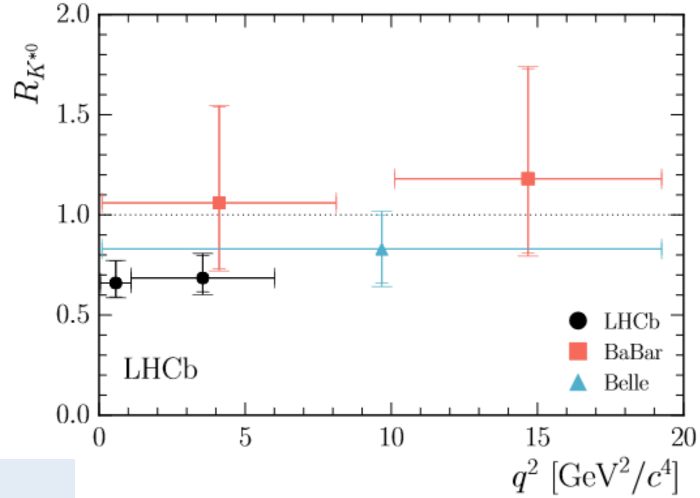
R_{D*} with hadronic τ decays

also

anomalies in angular distributions of $B \to K^{(*)}\mu^+\mu^-$

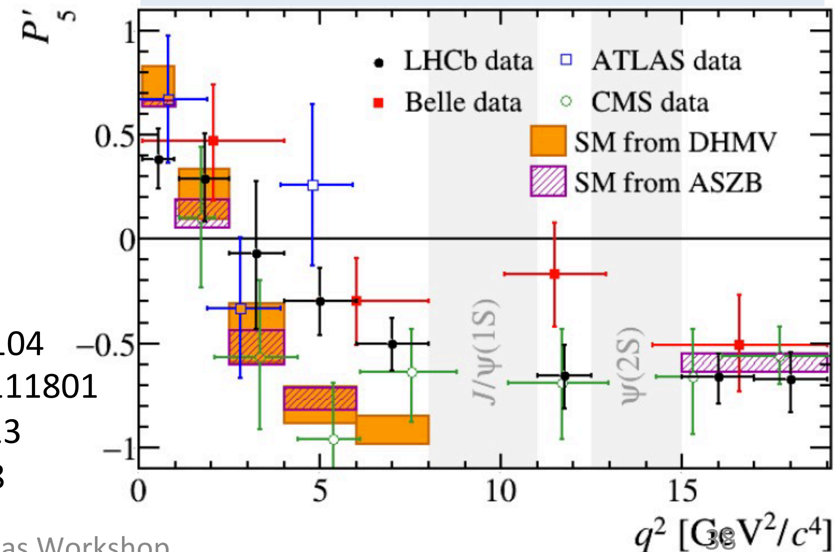
Lepton Flavor Universality b→sll decays





R_{K^*}

optimised angular variable



R_{K^*} consistent, but lower than the SM:

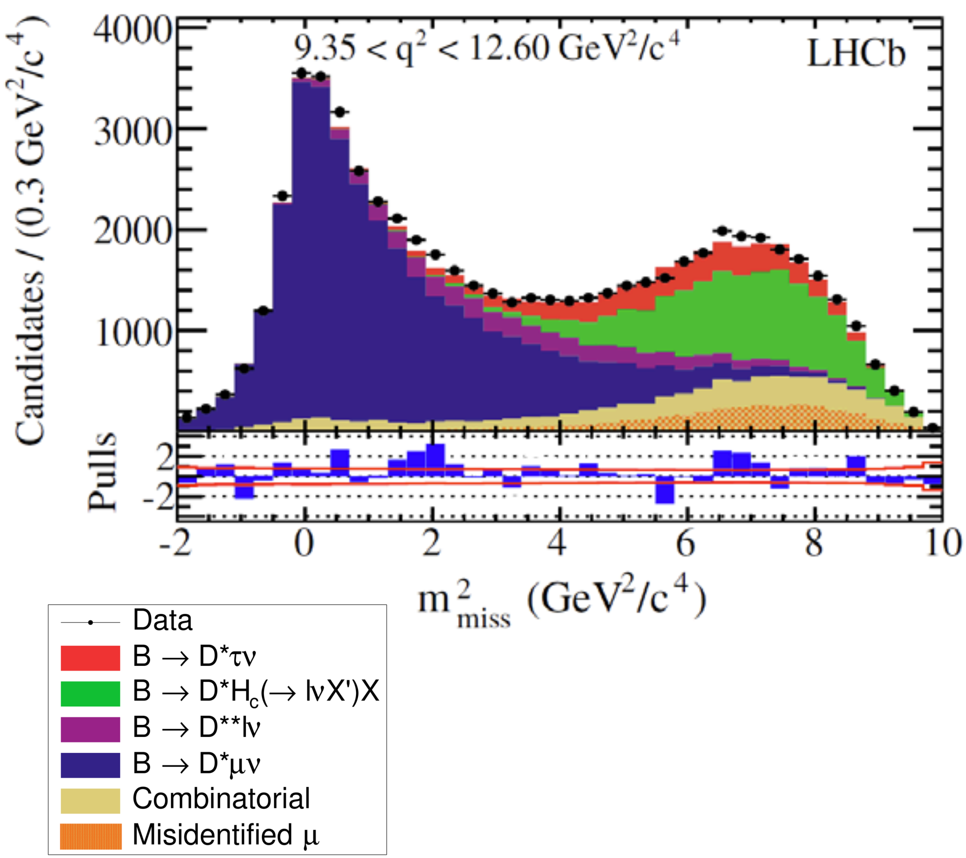
- **2.1-2.3**σ (low q^2)
- **2.4-2.5**σ (central q^2)

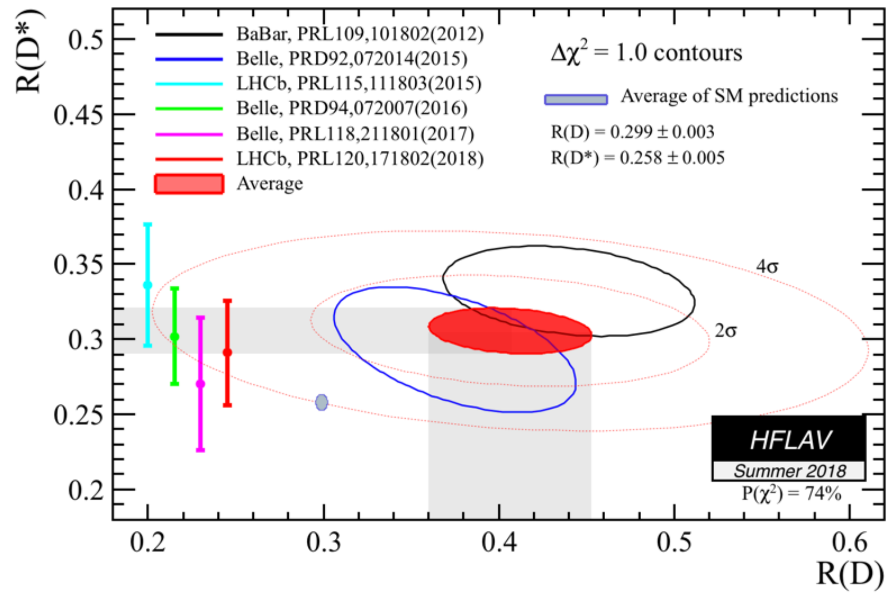
- LHCb JHEP 02 (2016)104
- Belle PRL 118 (2017)111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

Lepton Flavor Universality R_D, R_{D*}

Signal separated in ML fit with 3D templates in kinematic variables:

- missing mass: mmiss2=$(P_B - P_{D*} - P\mu)^2$
- muon energy





HFLAV summer 2018

All measurements above SM prediction

- R_{D*} exceeds SM by 3.4σ
- R_D by 2.3σ
- Combination: close to 4σ

B anomalies - future

measurements still statistically limited and not always experimentally or theoretically “clean”

BUT

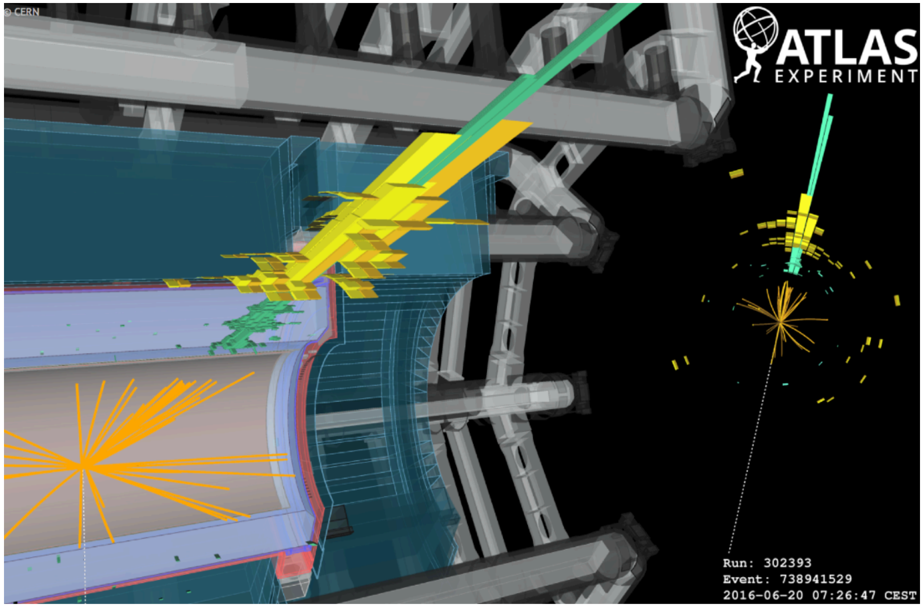
- Factor 3 of statistics of LHCb already on tape, being analysed
- Belle 2 starting to take data
- Run 3 new improved software trigger: much more similar between electron and muon

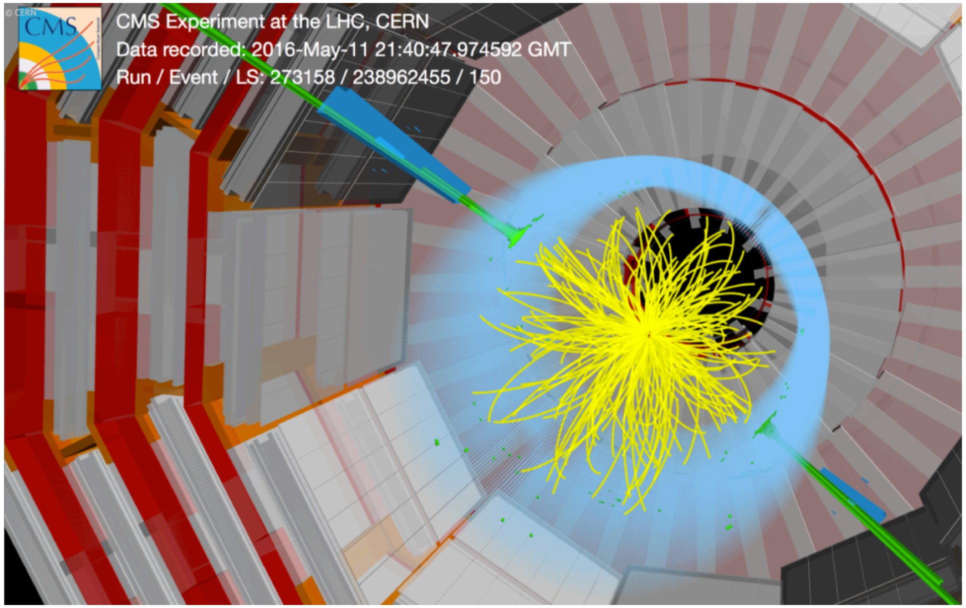
more channels, more cross-checks, etc.

Direct searches for new physics

- broad spectrum of models
  - new gauge bosons, new heavy fermions
  - Leptoquarks, vector-like quarks
  - SUSY
  - etc…
- broad spectrum of signatures
  - very heavy resonances
  - unconventional signatures (long-lived particles)
  - weakly interacting particles, large Missing ET, monojet searches

high energy events at LHC





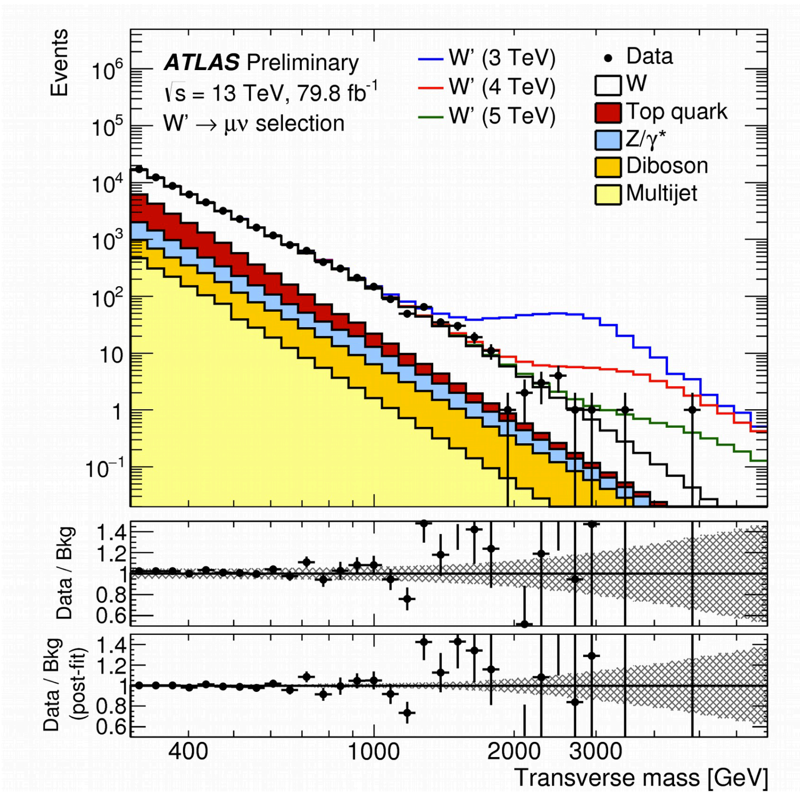
1.5 TeV monojet

8 TeV dijet

Resonance search

In general 2-body final states, robust signal, many channels explored

ATLAS-CONF-2018-017



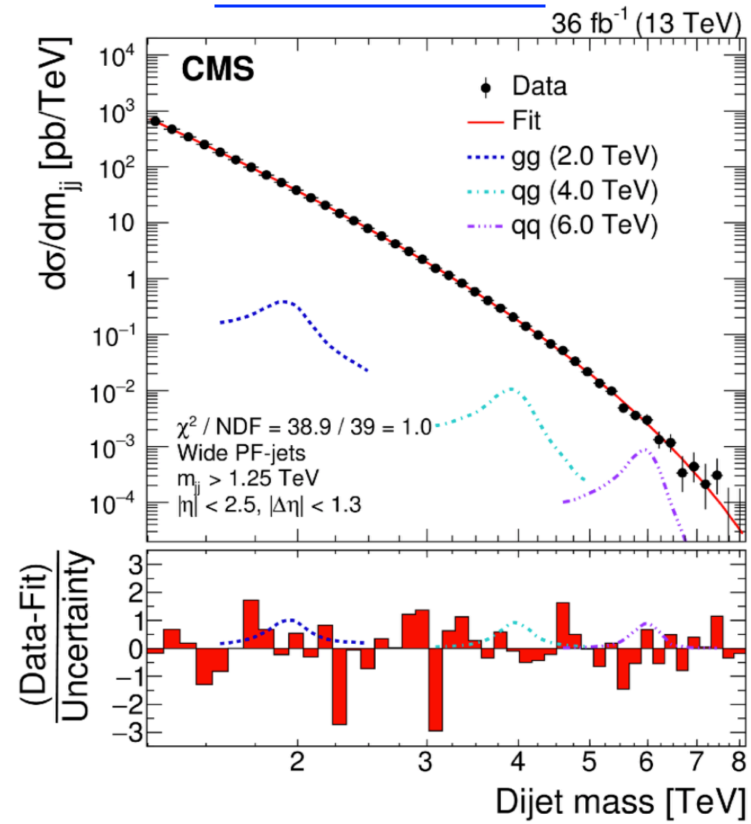
New **electro-weak gauge boson (W')**

(80 fb^{-1}) assuming SM coupling:

M < 5.6 TeV excluded at 95%CL

was 5.2 TeV with 36fb^{-1} (arXiv:1706.04786)

CMS EXO-16-056



String resonance (jj) M< 8 TeV

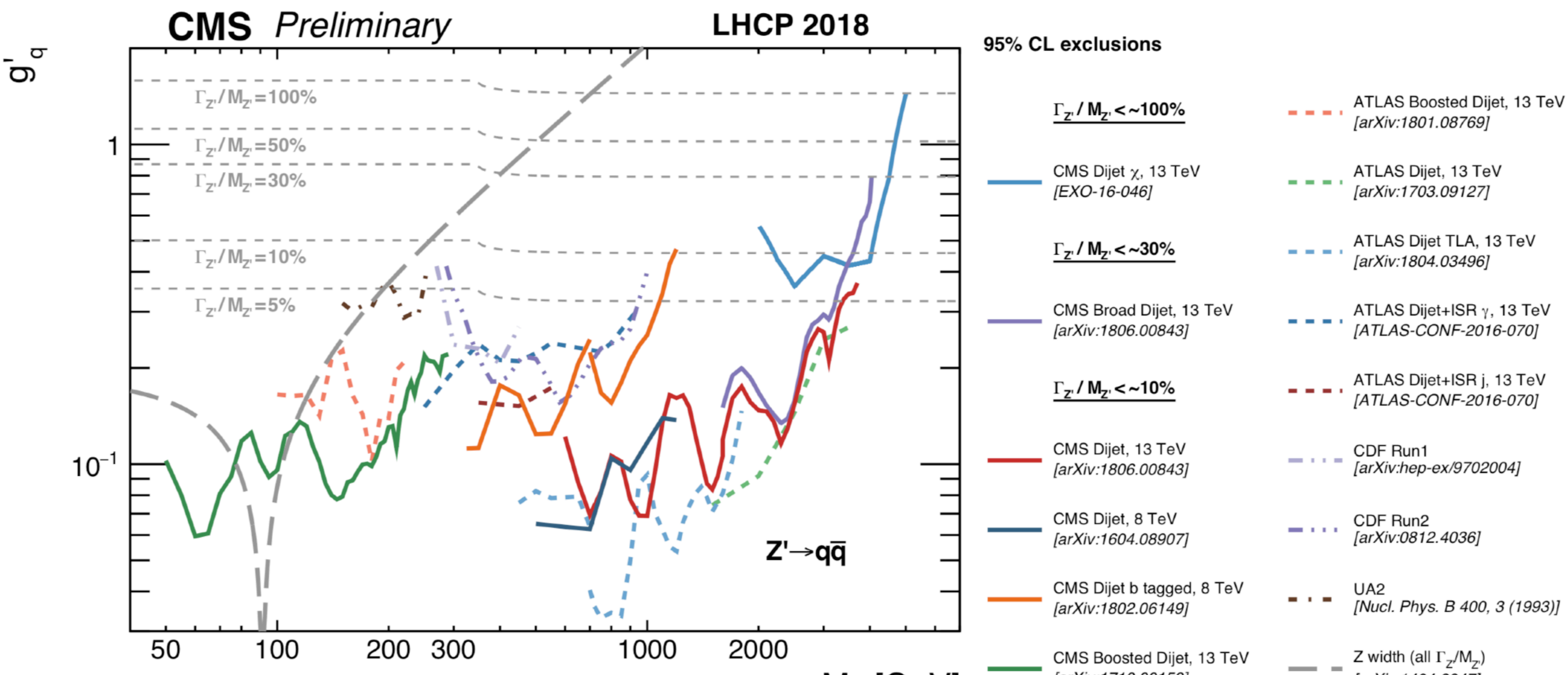
Excited quark (jj) < 6 TeV

increase of statistics, slow improvement

Dijet resonance search

Also covering low and intermediate range: lower trigger with reduced event info; "ISR jet" trigger (for boosted jet with substructure)

ATLAS and CMS limits on g_q ($\sigma \propto g_q^4$)



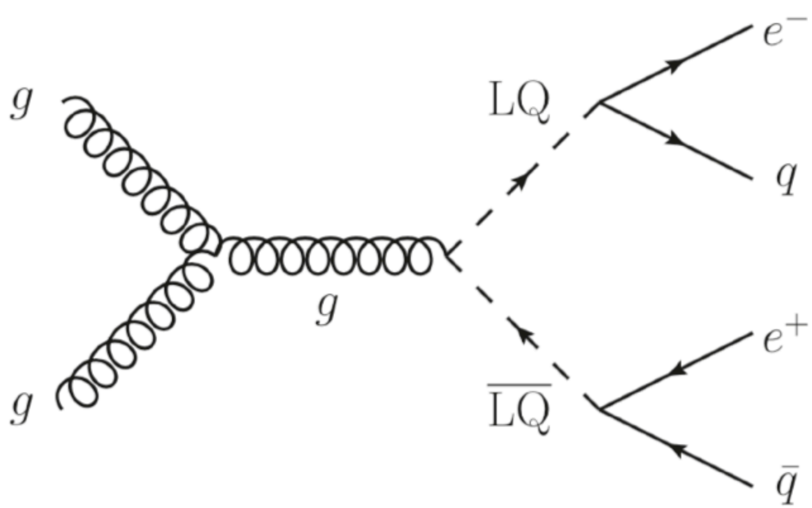
Dijet_summary_plots

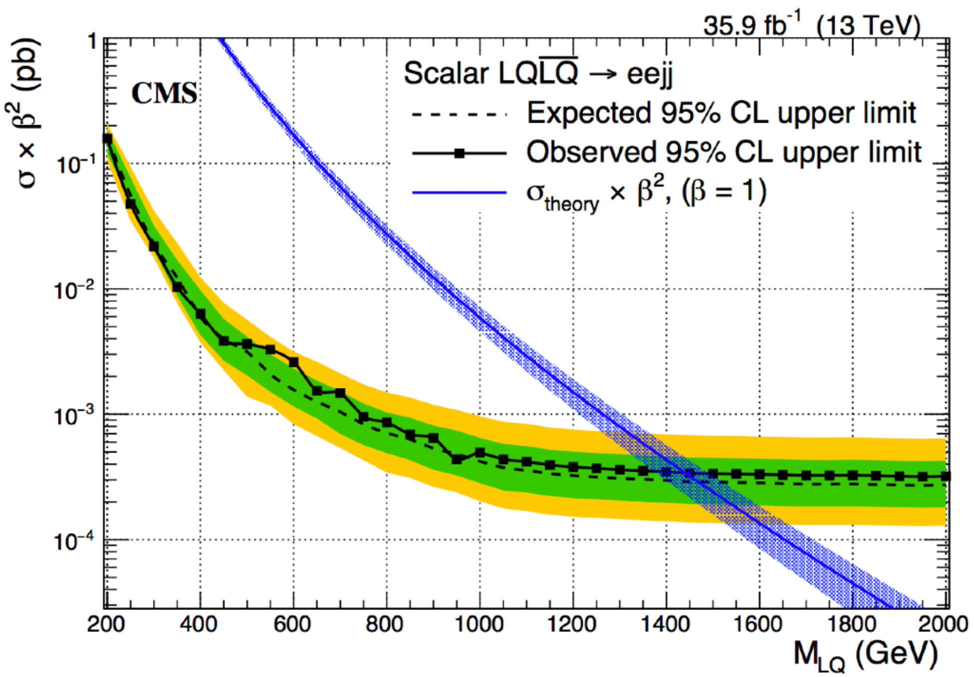
LeptoQuark

explain B anomalies: R_{D*}, R_{K*}

CMS-EXO-17-009

produced in pairs





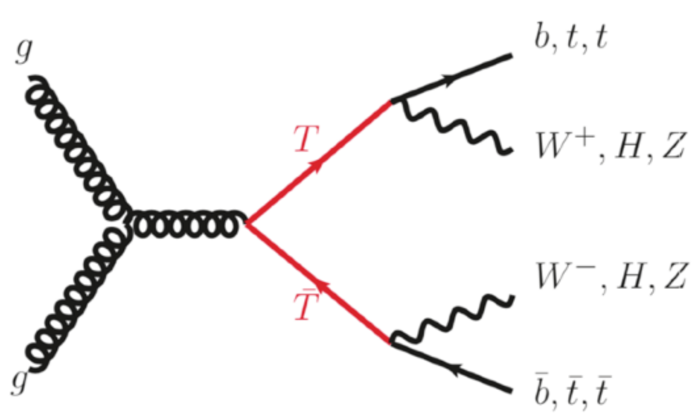
2e2j, ev2j final states

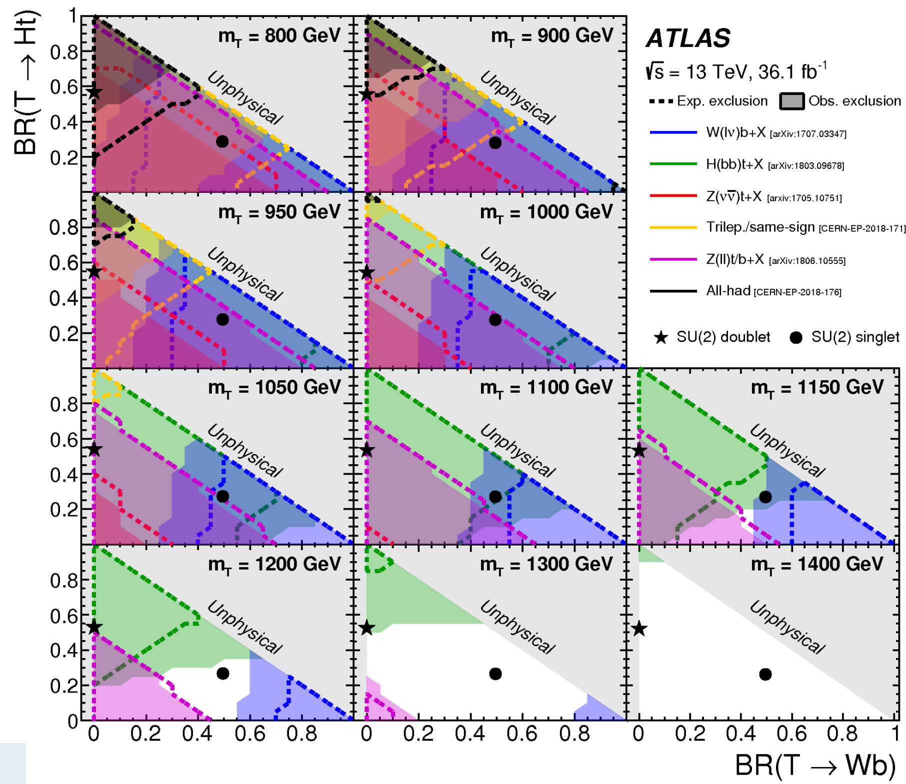
typical limits: 1.2 - 1.45 TeV

Vector Like Quark

Vector-like T quark models solve hierarchy problem
→ new heavy partner of top in loop

Phys.Rev.Lett. 121 (2018) 211801

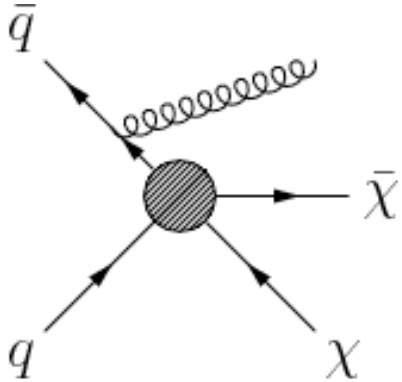




Search of T (q=2/3) and B (q=-1/3) VLQ
- decaying to W,H,Z and t,b
- produced in pairs

Limits at the level of 1.3-1.4 TeV

Observed (filled area) and expected (dashed line) 95% CL exclusion in the plane of BR(T → Ht) versus BR(T → Wb), for different values of the vector-like T quark mass



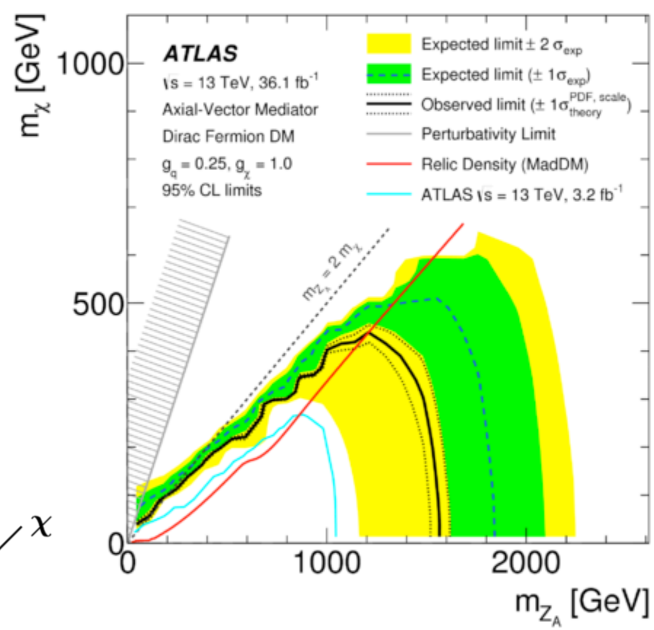
Dark matter

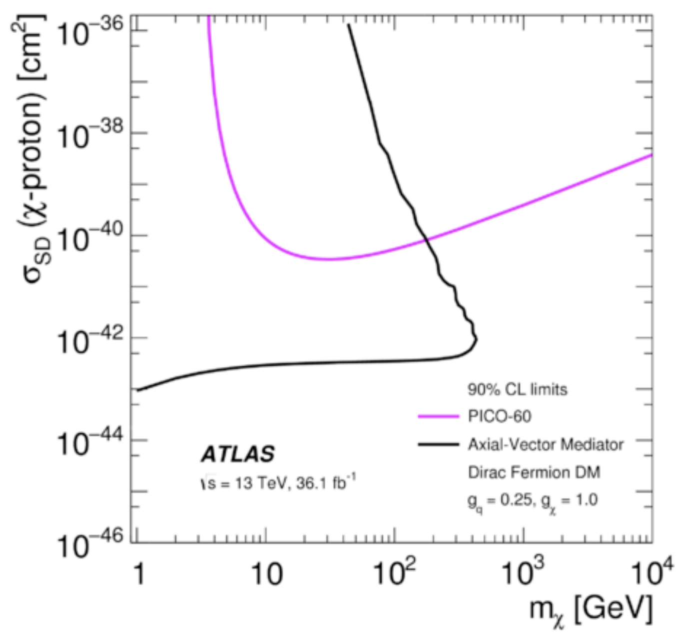
EW bosons and gluons can be radiated by initial partons

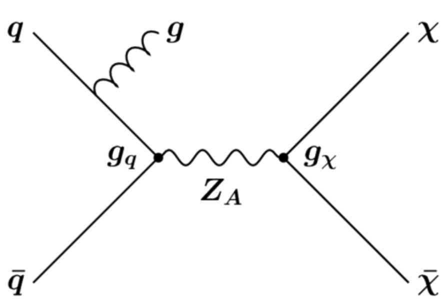
search for mono-jet (-photon, -W, -Z, -H) + large ETmiss

JHEP 1801 (2018) 126

most sensitive monojet





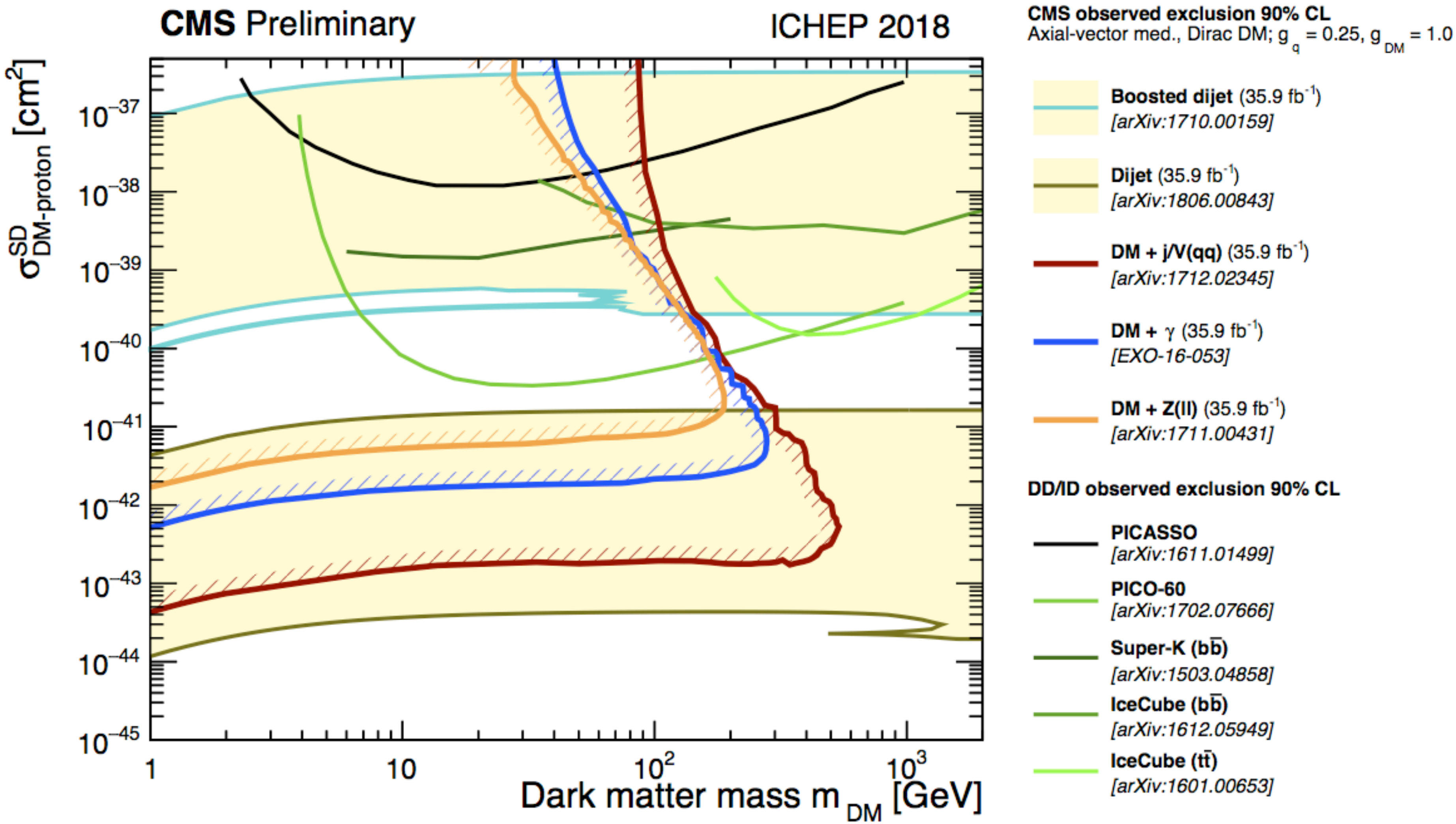


$$\sigma = K' \frac{g_q^2 g_{DM}^2}{M^4 \Gamma_{med}}$$

Dark matter

Fixing couplings limits on mediators cross section translated into DM production cross section
N.B. dependence on coupling & model

CMS preliminary ICHEP 2018



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 − 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= 1/ $\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-XXX
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

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

10^{-1} 1   10   Mass scale [TeV]

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

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

Exotics summary

- Many signatures and models are tested
- Expect moderate improvements for extremely high mass with higher statistics
- Several new approaches and analysis techniques target low/intermediate mass region and new signatures

SUSY

- Experiments have covered a huge set of scenarios and final states:
  - Strong production.
  - Electroweak production.
  - R-parity conserved and violated.
- Driven by simplified models.
  - Masses of non-relevant SUSY particles put very high.
  - 100% BR to single final state.

  used for model dependent exclusion limits.
- Produce large scans for pMSSM

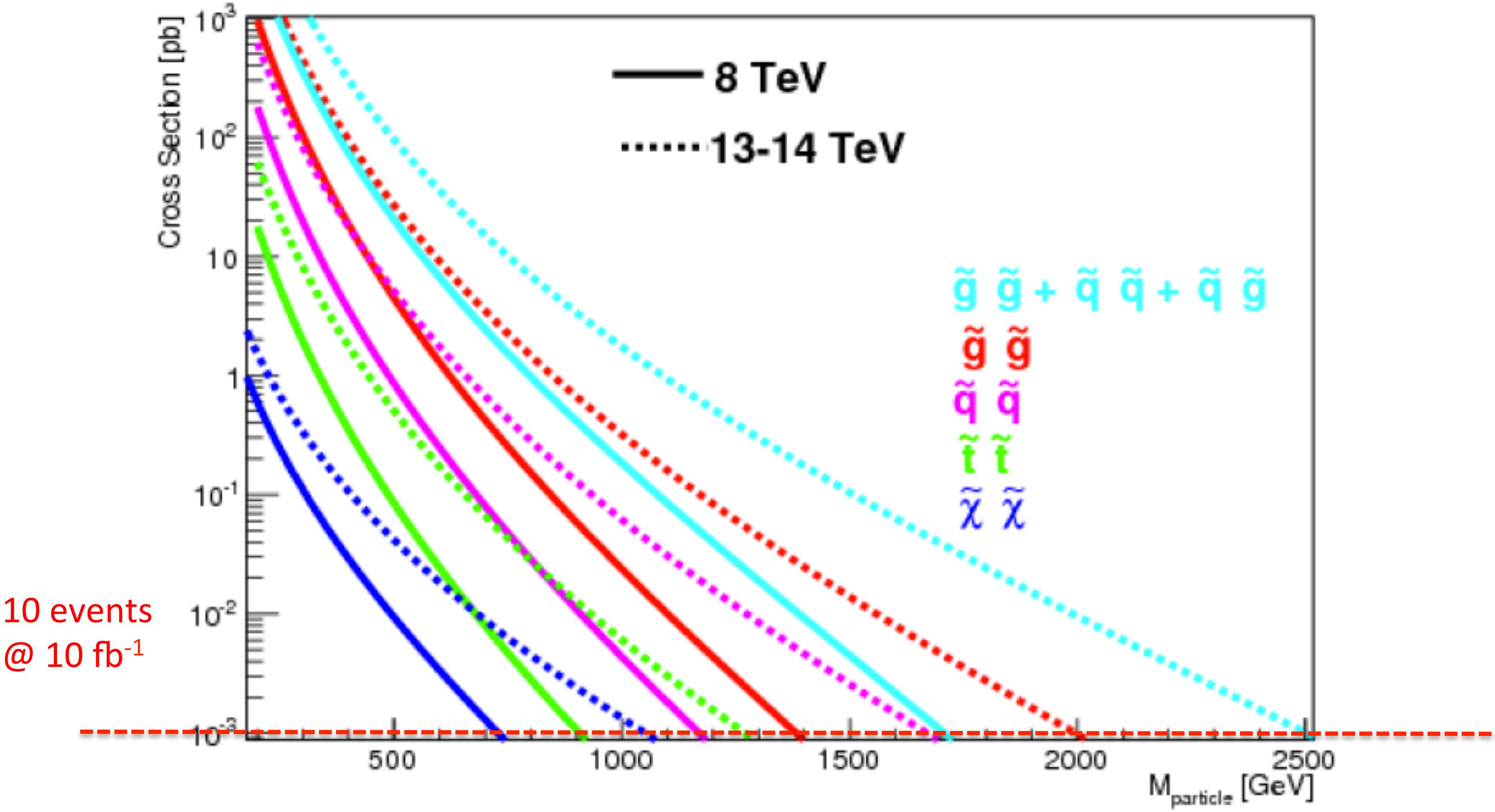
  MSSM (Minimal new particle content; No assumption on SUSY breaking)

  → 120 free parameters.

  pMSSM (imposing phenomenological and experimental constrains)

  →19 free parameters

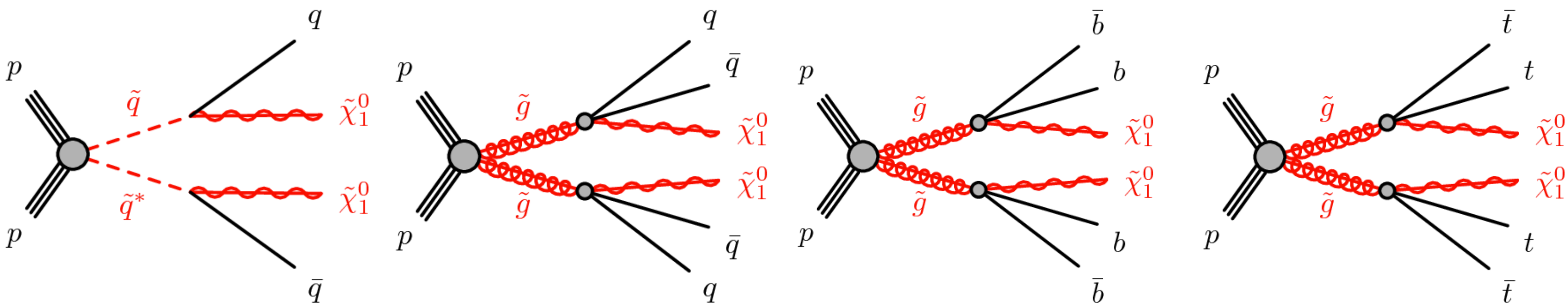
SUSY cross-section



PDG 2017 NLL-FAST, Prospino

E. Halkiadakis, G. Redlinger, and D. Shih, Ann. Rev. Nucl. and Part. Sci. 64, 319 (2014).

Searches for squarks and gluinos

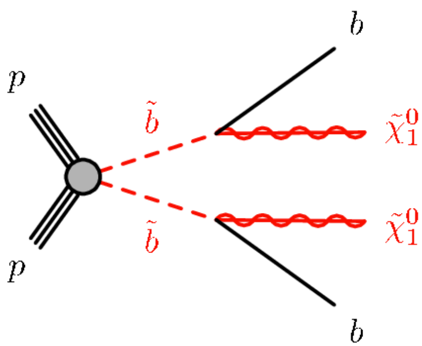


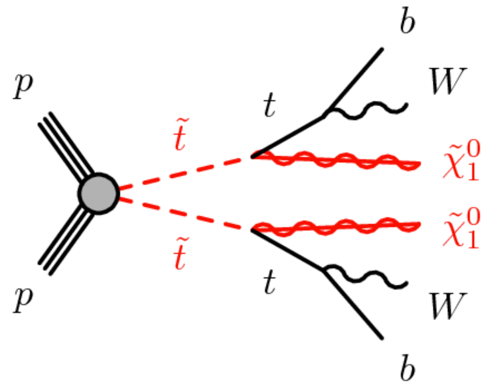
ETmiss, (b) jets, (leptons)

Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55 $\tilde{q}$ [1×, 8× Degen.] 0.43 0.71
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0 $\tilde{g}$ Forbidden 0.95-1.6
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ $ee,\mu\mu$	4 jets 2 jets	- Yes	36.1 36.1	$\tilde{g}$ 1.85 $\tilde{g}$ 1.2
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 3 e,μ	7-11 jets 4 jets	Yes -	36.1 36.1	$\tilde{g}$ 1.8 $\tilde{g}$ 0.98
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ 3 e,μ	3 b 4 jets	Yes -	36.1 36.1	$\tilde{g}$ 2.0 $\tilde{g}$ 1.25

ATLAS EXPERIMENT

Searches for sbottom and stops



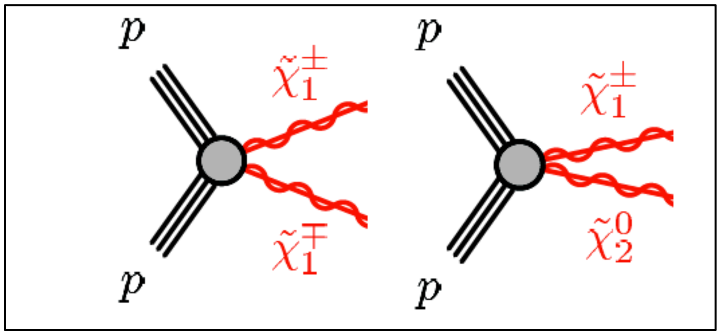


Light stops needed for natural SUSY
0/1/2 leptons, (b) jets and ET

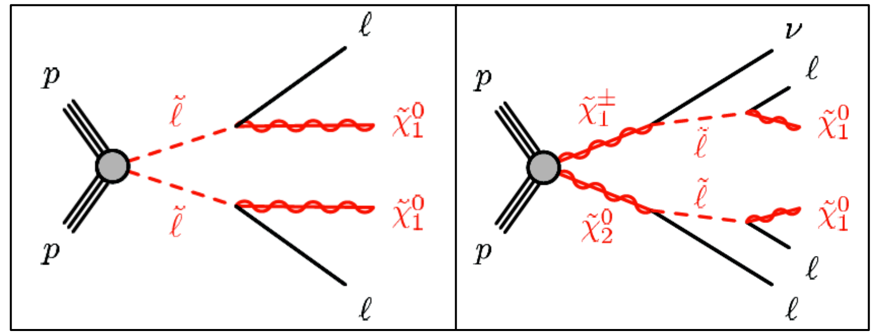
3^{rd} gen. squarks direct production

$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden	0.9
		Multiple		36.1	$\tilde{b}_1$	Forbidden	0.58-0.82
		Multiple		36.1	$\tilde{b}_1$	Forbidden	0.7
$\tilde{b}_1\tilde{b}_1$, $\tilde{t}_1\tilde{t}_1$, $M_2 = 2 \times M_1$		Multiple		36.1	$\tilde{t}_1$		0.7
		Multiple		36.1	$\tilde{t}_1$	Forbidden	0.9
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$		1.0
$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$		0.4-0.9
		Multiple		36.1	$\tilde{t}_1$	Forbidden	0.6-0.8
$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$		0.48-0.84
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	$2c$	Yes	36.1	$\tilde{t}_1$		0.85
					$\tilde{t}_1$		0.46
	0	mono-jet	Yes	36.1	$\tilde{t}_1$		0.43
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$		0.32-0.88

Searches for EW processes



Chargino/neutralino production



Slepton production

Lower cross sections → important search in case squarks and gluinos are heavy

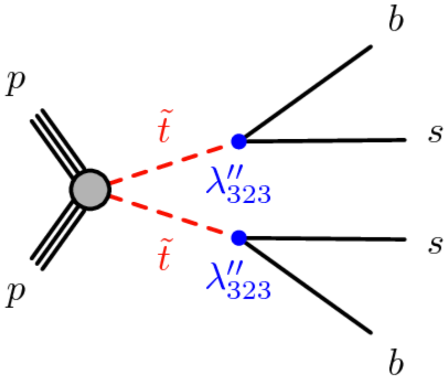
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.6
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.17
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.26
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^{+}\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	$2\ \tau$	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.76
						$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.22
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18
	$\tilde{H}\tilde{H}$, $\tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3

ATLAS EXPERIMENT

Searches for RPV SUSY and long-lived particles

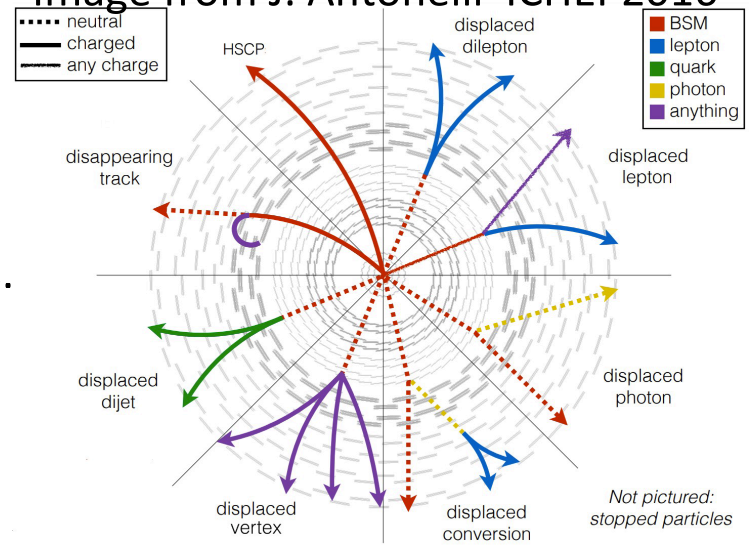
Many viable RPV scenarios.

LSP decays → no large ETmiss



Can also yield long lifetimes.
Many topologies

Image from J. Antonelli ICHEP2016



	Model	Signature	Jets	E_T^{miss}	$\int L\,dt$ [fb^{-1}]	Mass limit [TeV]
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46; $\tilde{\chi}_1^\pm$ 0.15
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6, 2.4
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82, 1.33
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3, 1.9
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05, 2.0
	$\tilde{g}\tilde{g}$, $\tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8, 2.1
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55, 1.05
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42, 0.61
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45

SUSY summary

- broad and diverse search program
  - Completing the program with 36 fb^{-1} (2015+2016) dataset
  - first results with 80 fb^{-1} dataset (2015+2016+2017)
- Simplified signatures covered to high masses

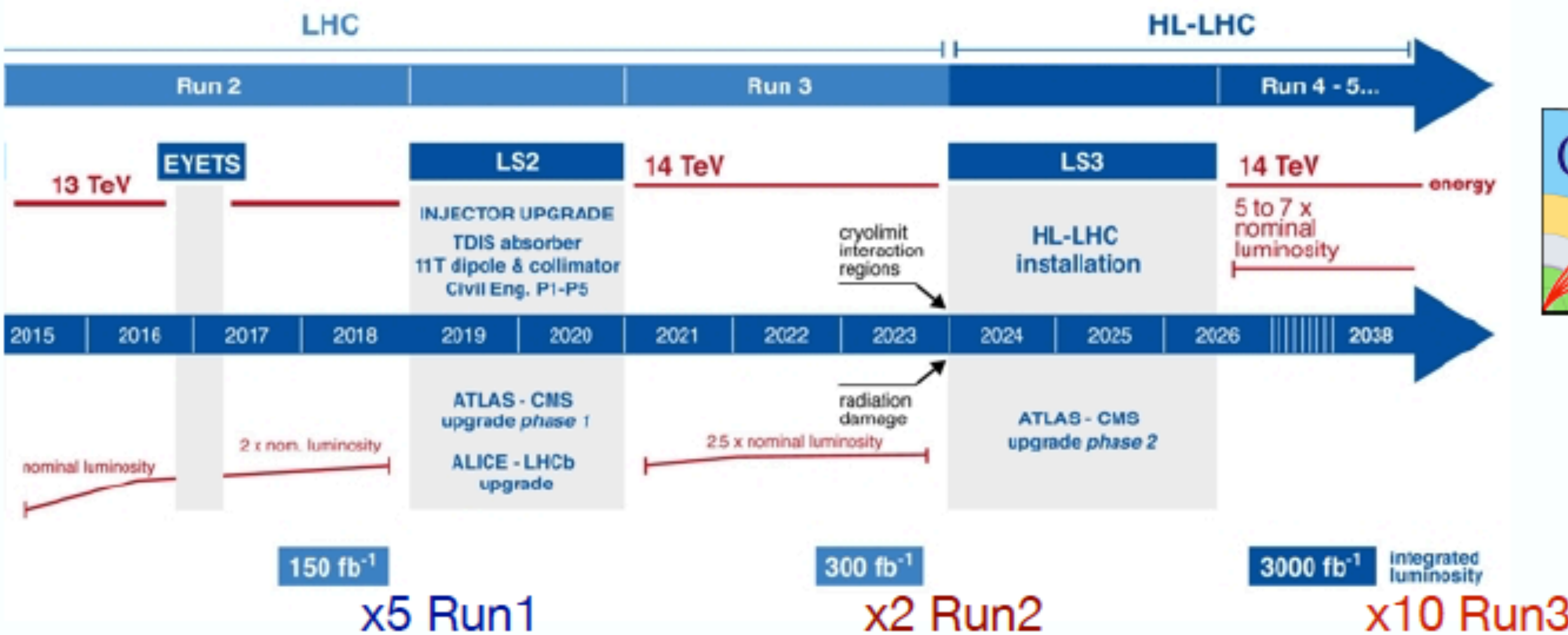
  but plenty of low mass unexplored model space.
- the improvement in sensitivity will largely have to come from
  - the larger statistics
  - evolution of trigger and analysis techniques

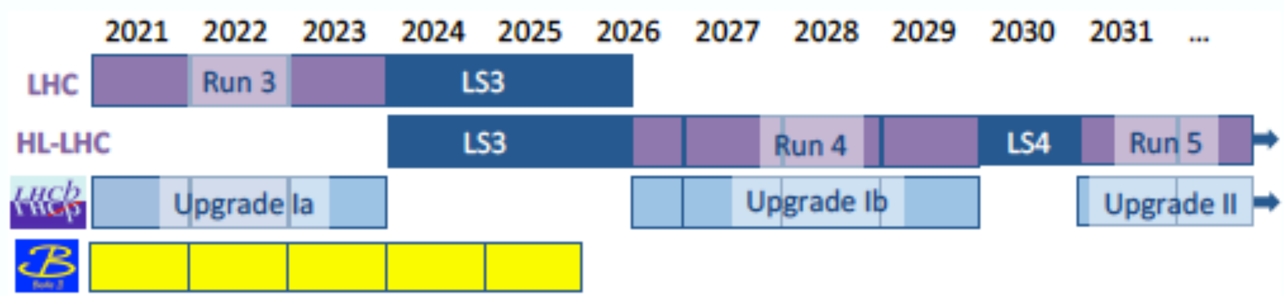
  since there will be no significant energy increase at the LHC anymore
- larger statistics will be most beneficial in case of electroweak processes, compressed scenarios, R-parity violating scenarios, etc.

SUSY summary S. Strandberg

LHC in the future

Credit Shahram Rahatlou CMS & LHCb Highlights ICHEP2018





Conclusion

- The LHC has worked fantastically
- The experiments took data with very high efficiency and detectors are well understood
- High precision measurements are possible at the LHC, even with high pile-up conditions
- Many measurements are still statistically limited and the full Run 2 data will bring them to an interesting level of precision
- New analysis techniques will also bring improvements
- We need increasingly precise theoretical predictions to keep up with the experimental precision
- Many estimates of future sensitivity are being prepared in the context of the European strategy process, based on our current better understanding of the performances

Stay tuned …