Science & Technology Facilities Council
Rutherford Appleton Laboratory

WARWICK
THE UNIVERSITY OF WARWICK

Moriond QCD: March 2017

Bill Murray
Warwick University /
RAL, STFC

RENCONTRES DE MORIOND 50 since 1966

A selection of personal Highlights

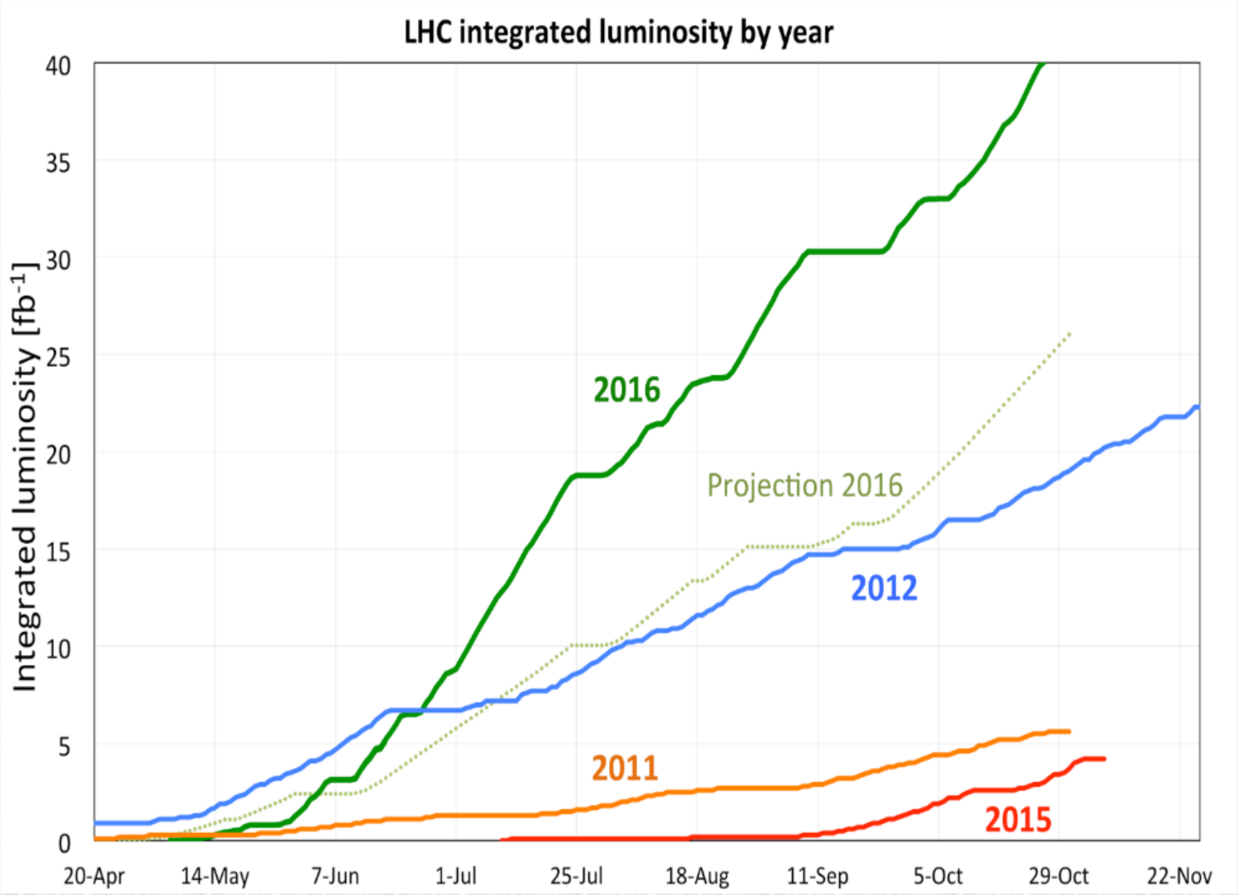
Most is left out , see
<u>Full Programme</u>

Venue: La Thuile

Isolated
not
spartan

LHC

- LHC dominates the conference
  - F. Bordry reviewed status
- 2016:
  - $L=1.4x10^{34}$, passing design
  - Great uptime
- Total $40fb^{-1}$ delivered pp
  - Passing sum of previous
- 2017 goal: $45fb^{-1}$



- But only a handful of results are from $>30fb^{-1}$ 2016 pp
- e.g. LHCb, Alice major roles

Top precision with diphotons at the LHC

Moriond 2017 QCD, La Thuile, Italy (Mar. 29)

Hyung Do Kim (Seoul National University)

with D Chway, R Dermisek, T H Jung (+W Cho, D Lee)

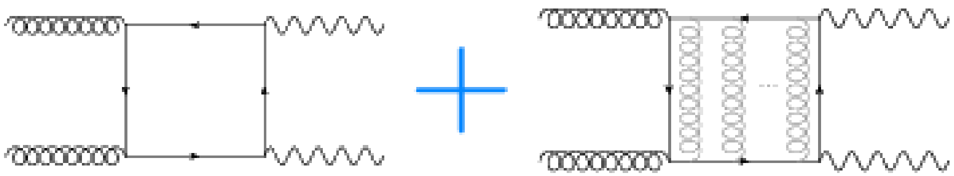
PRL 117 (2016) 061801

arXiv:1612.05031 submitted to PRD

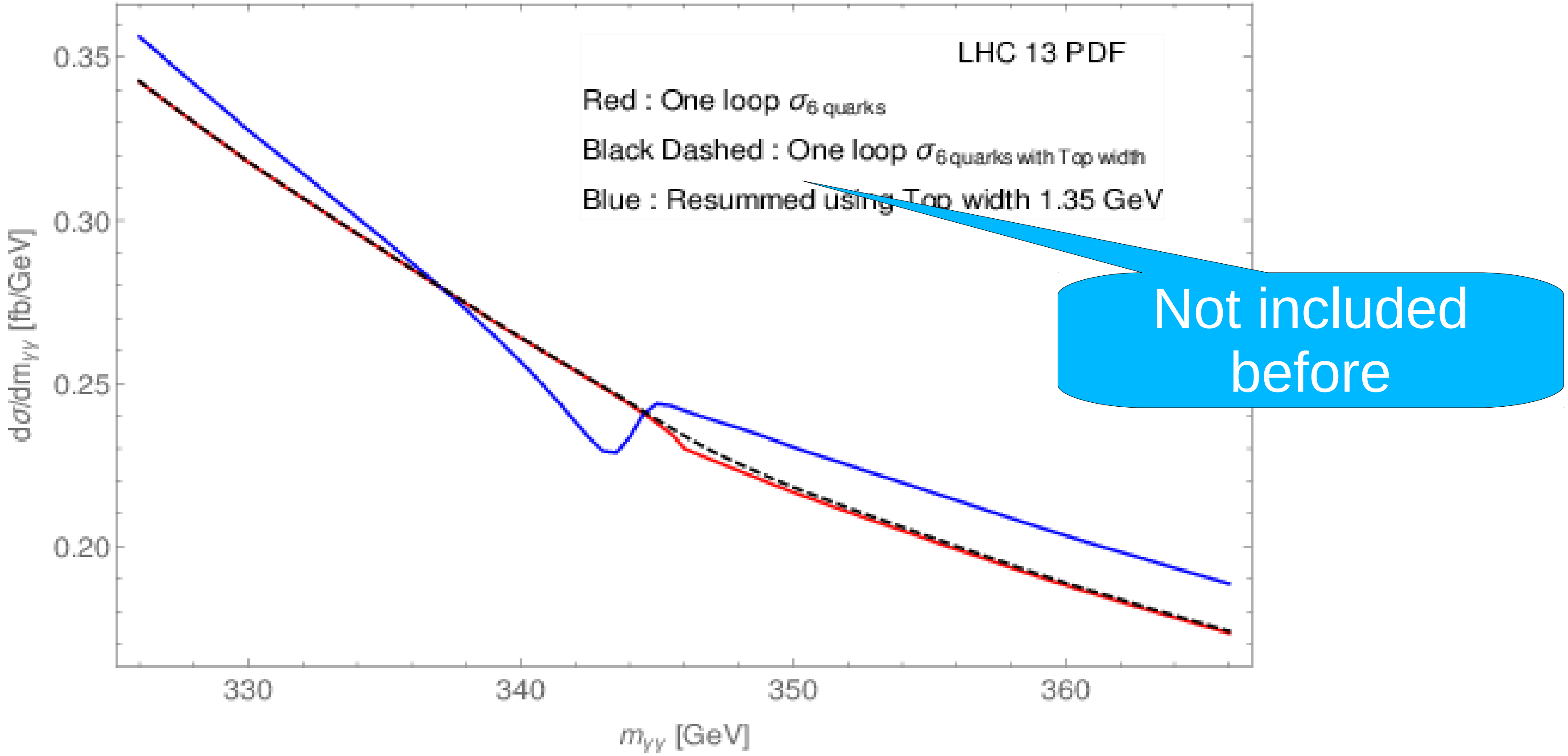
arXiv:1704.yyyyy

fat toponium

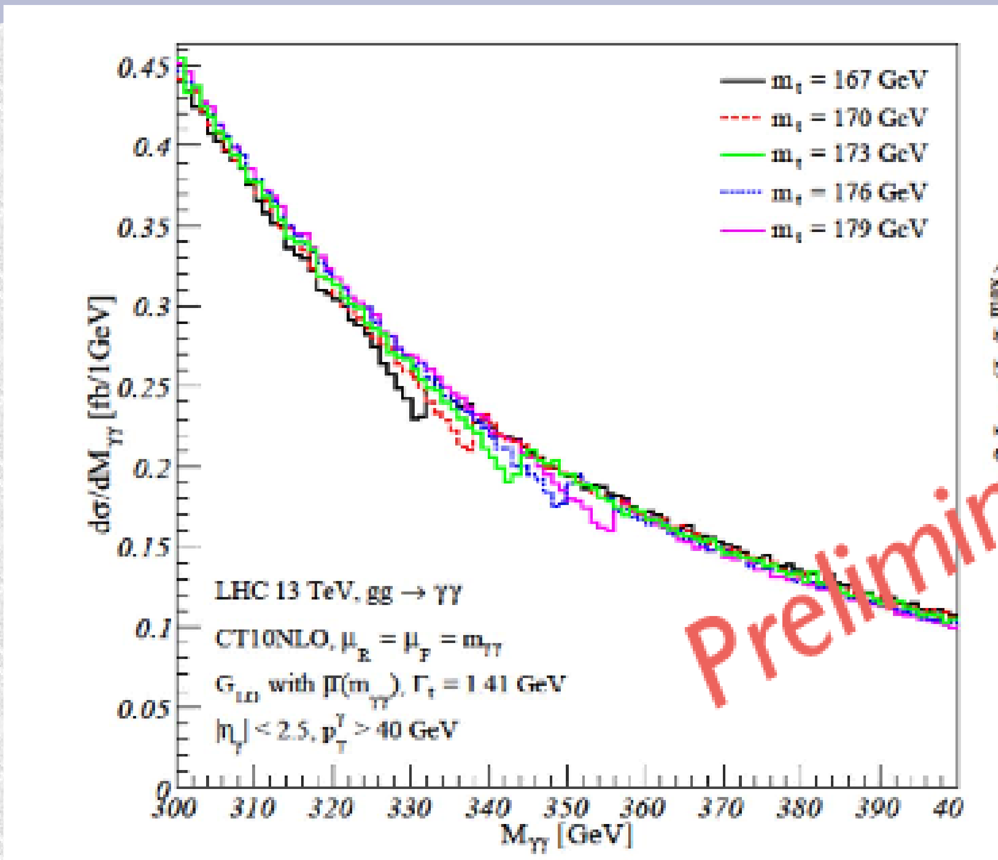
u,d,s,c,b + top

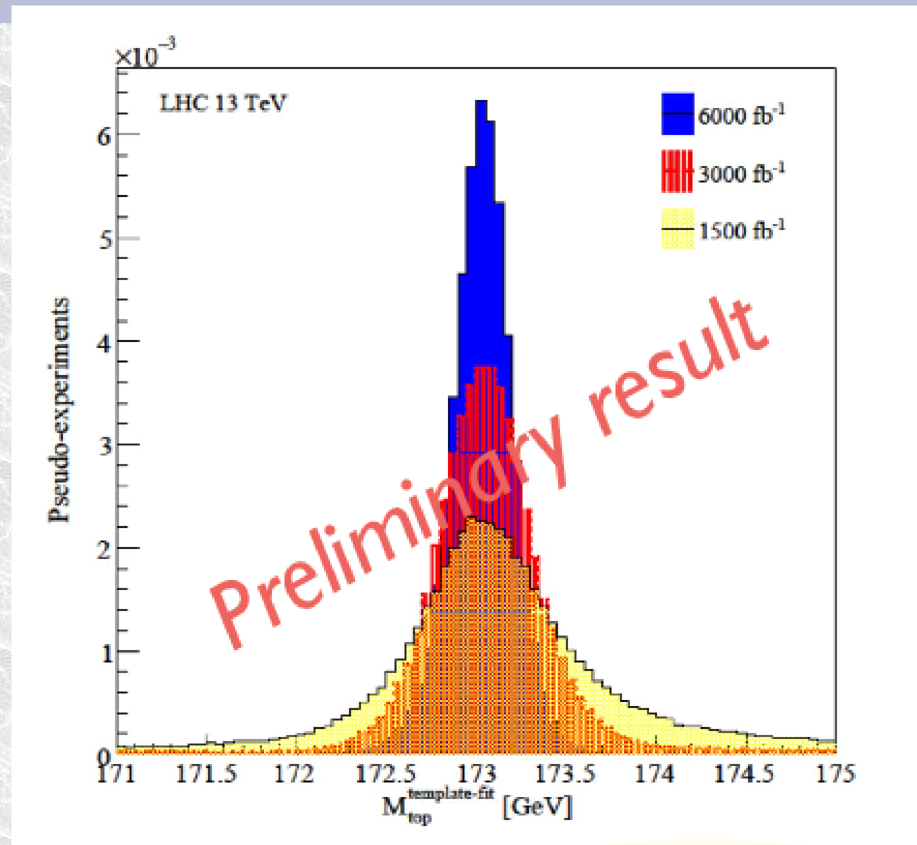


At LHC, top quark can show 2~3% effects in di-photon invariant mass spectrum from interference with 5 light quarks



Visible spectrum





- 3000 fb^{-1} gives <500MeV error on m_{top}
  - Very useful addition to the picture
- But the author admits his work is controversial

Measuring the leading hadronic contribution to the muon g-2 anomaly via μe scattering

Expt proposal

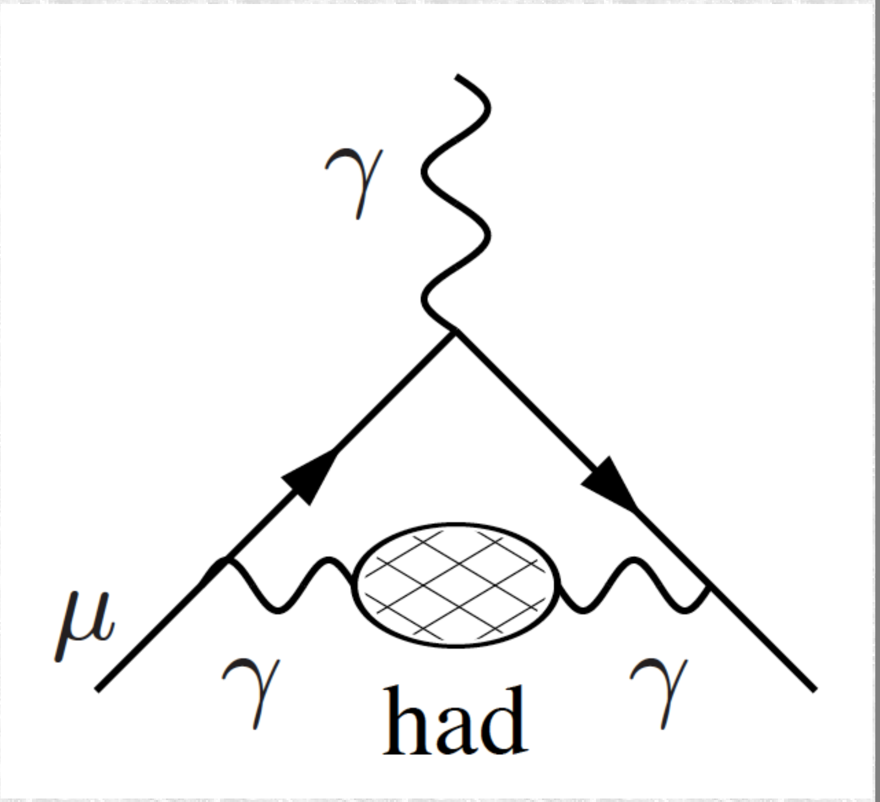
Umberto Marconi
INFN Bologna (IT)

Rencontres de Moriond
QCD and High Energy Interactions
LA THUILE, MARCH 25 - APRIL 1, 2017

Eur. Phys. J C (2017) 77:139

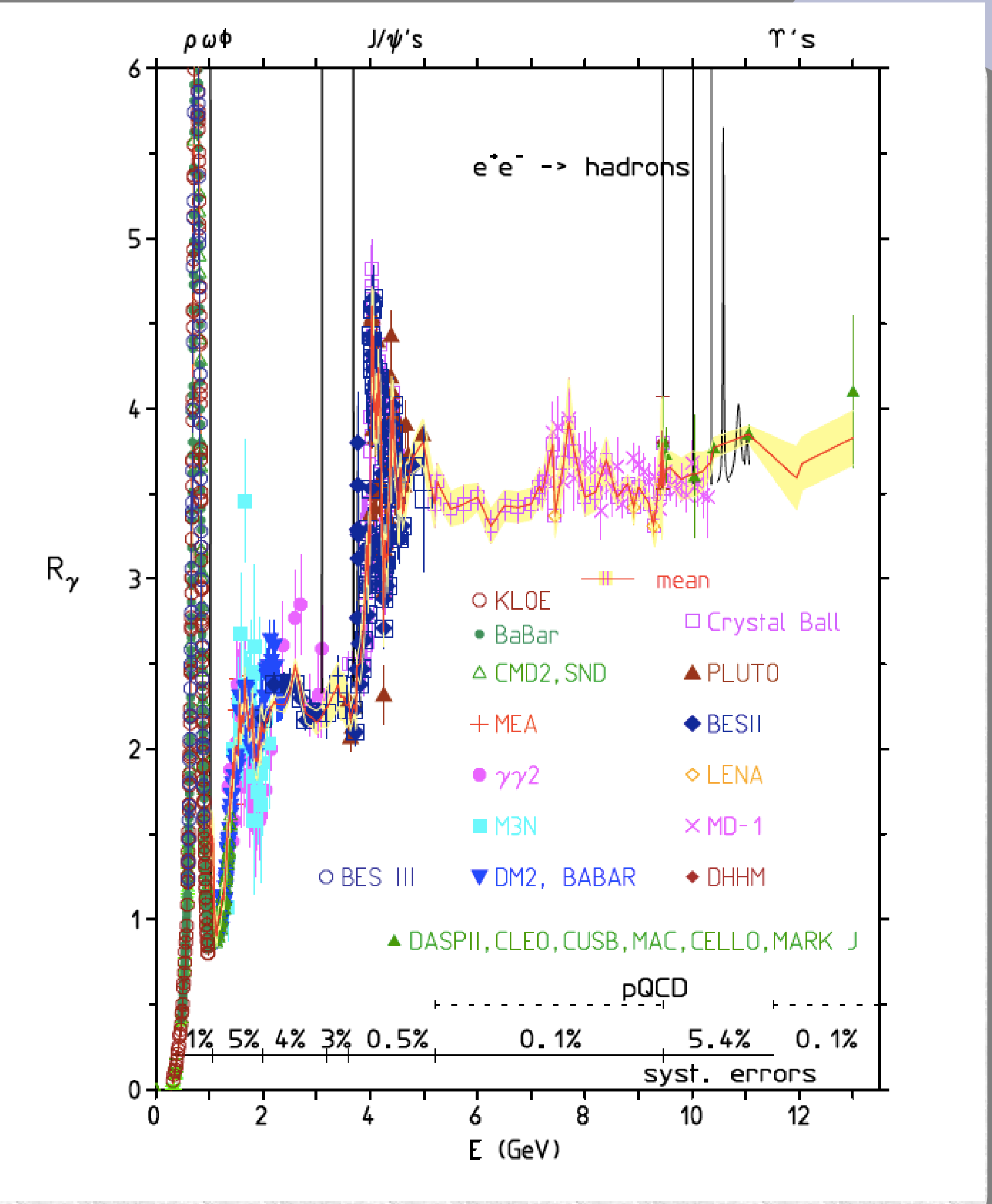
Recall: g-2

- Muon anomalous magnetic moment
- E821 (Brookhaven) found $a_\mu=(11659208.9\pm6.3)\times10^{-10}$
- SM predicts $a_\mu=(11659180.2\pm4.9)\times10^{-10}$
- deviation: $\delta a_\mu=(28\pm8)\times10^{-10}$
- Theory limited by contribution from a_μ^{HLO}, as shown right



Hadronic contribution to g-2

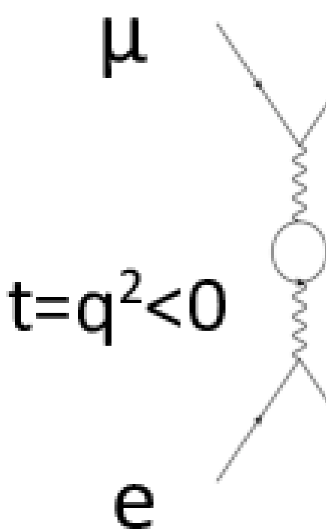
- Low energy e+e- annihilation gives $\gamma \rightarrow$ had part of the diagram
- Optical theorem allows extraction of a_{μ}^{HLO} from integral
- But messy integral
  - Needs factor 2 improvement to keep up with next generation g-2 experiments.



The elastic scattering μ + e → μ + e

α(t) through:

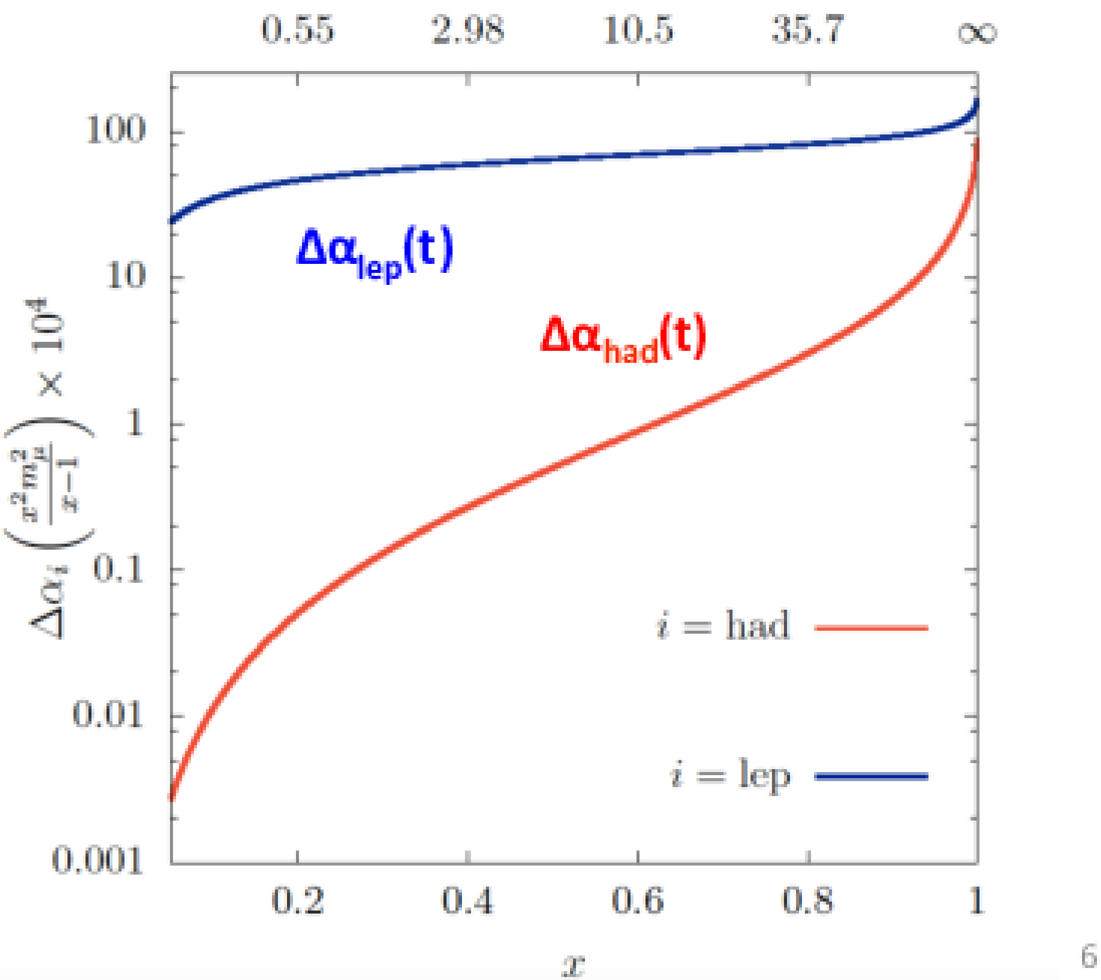
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$$



$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}$$

$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$

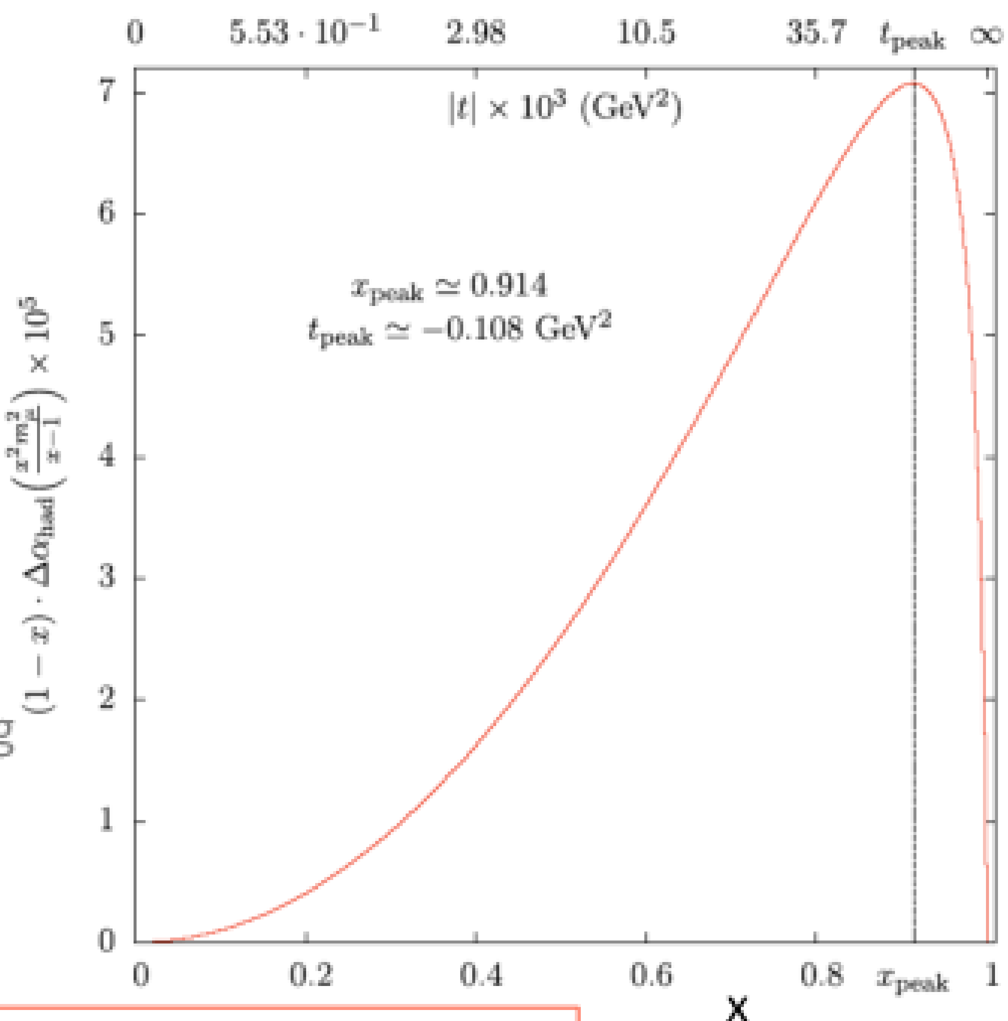
$$t = -m_\mu^2 \frac{x^2}{1-x} \; (10^{-3} GeV^2)$$



a_μ^{HLO} space-like approach

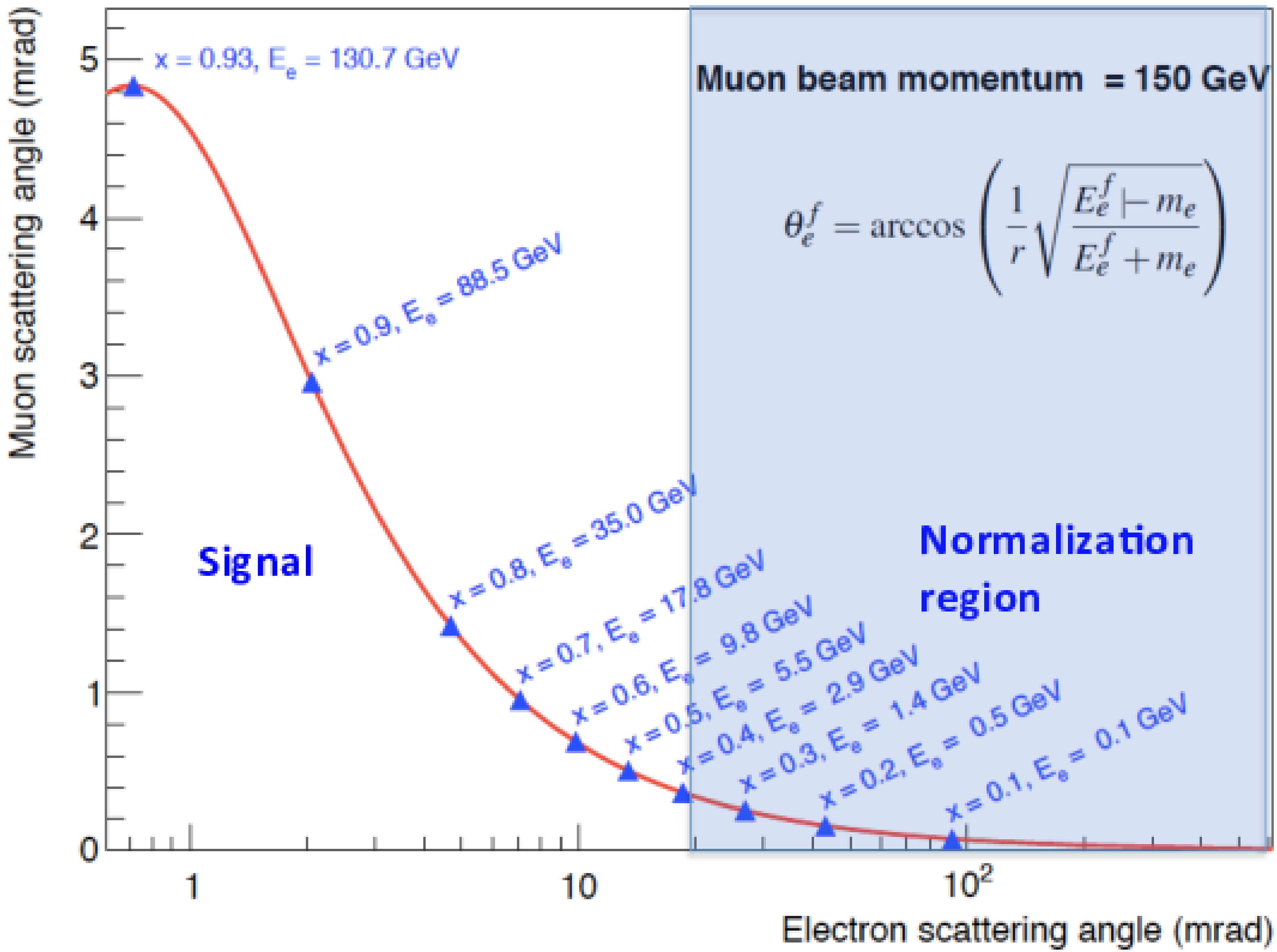
- **It requires just the single process**
  μ + e → μ + e elastic
  High intensity CERN muon beam of
  E_μ ~ 150 GeV colliding on atomic
  electrons at rest.
- **Highly boosted final state:**
  $0 < -t < 0.161$ GeV^2
  $0 < x < 0.93$ (peak is at $x = 0.914$)
  The range covers **87%** of the integral.
- Beyond the kinematics limit the integral (13%) can be determined using pQCD & time-like data, and/or lattice QCD results.

The expected shape of integral function



$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$

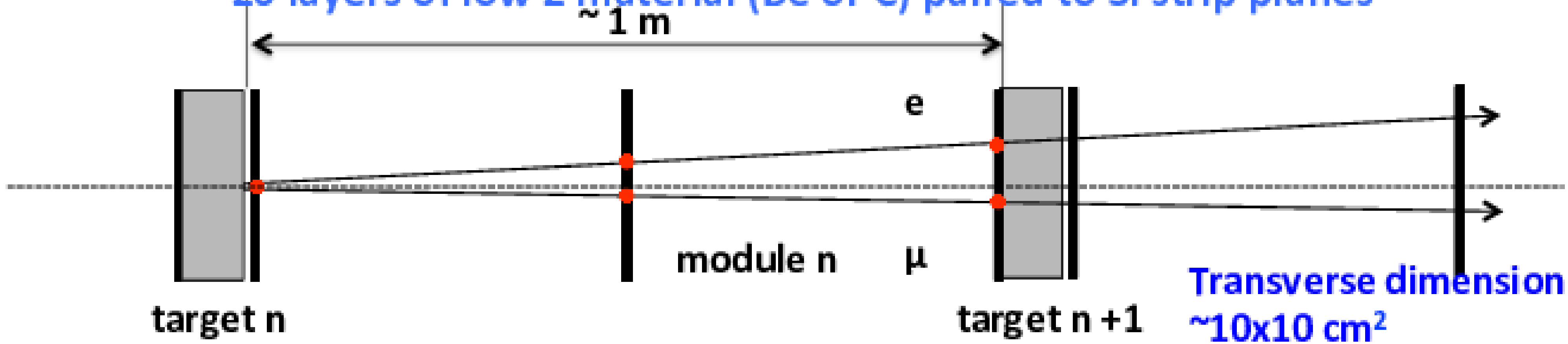
Elastic scattering in the (θ_e , θ_μ) plane



Detection technique

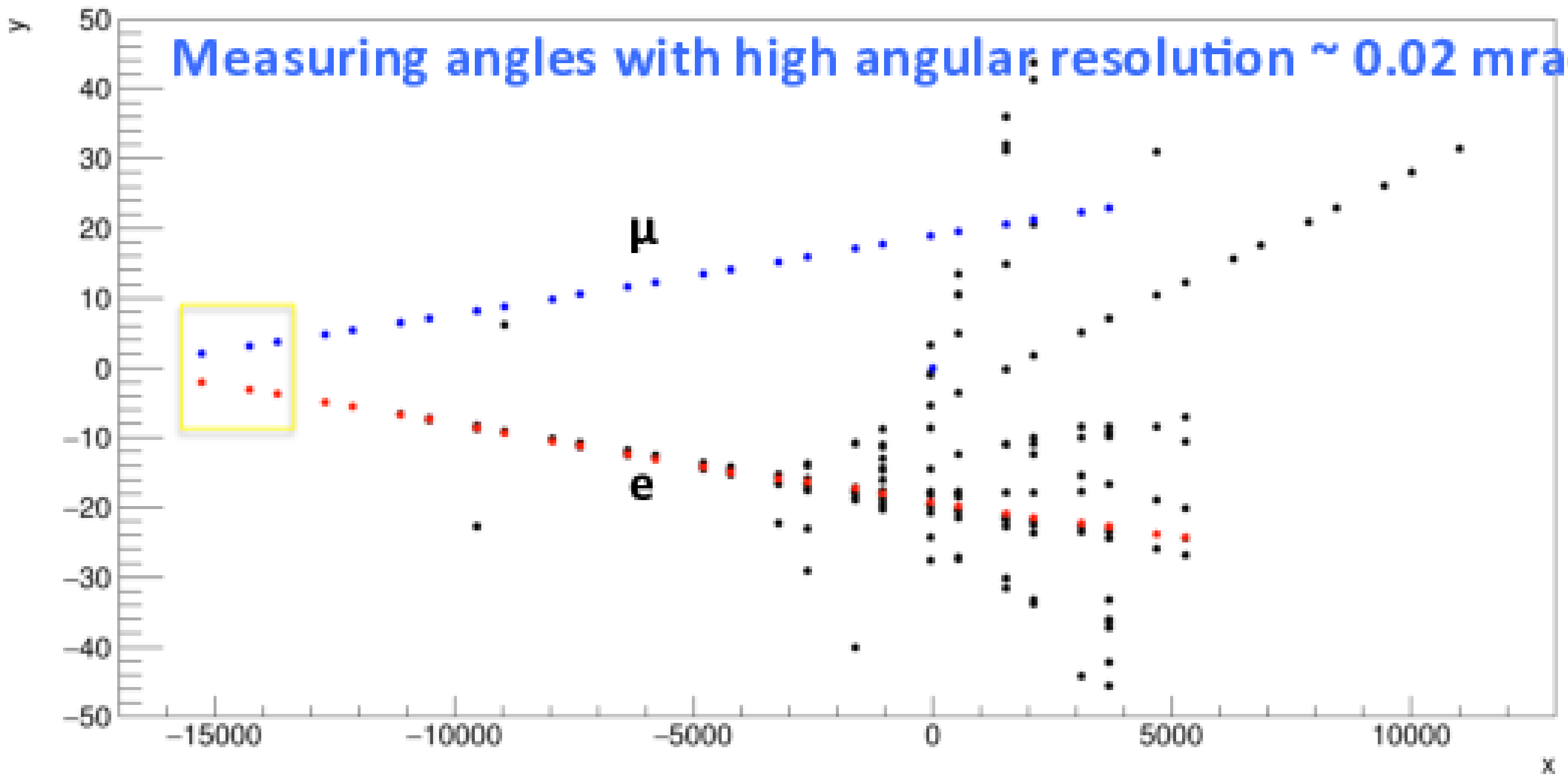
Modular apparatus covering the full angular acceptance with high uniformity.

20 layers of low Z material (Be or C) paired to Si strip planes



Transverse dimension $\sim 10 \times 10\ cm^2$

Measuring angles with high angular resolution ~ 0.02 mrad



Beam requirements:

- 150 GeV muon beam
- Use 20 Be layers, each 3cm thick
- 1.3×10^7 μ/s
- 4×10^7 s (2 years?) gives required event count
- Give statistical measure of a_μ^{HLO} of 0.3%, as required for g-2.

- I thought the detector sounded like Mice
  - I wasn't paying enough attention
  - 30 multiple targets in there, not just one
  - And high rate
- But maybe an interesting experiment?

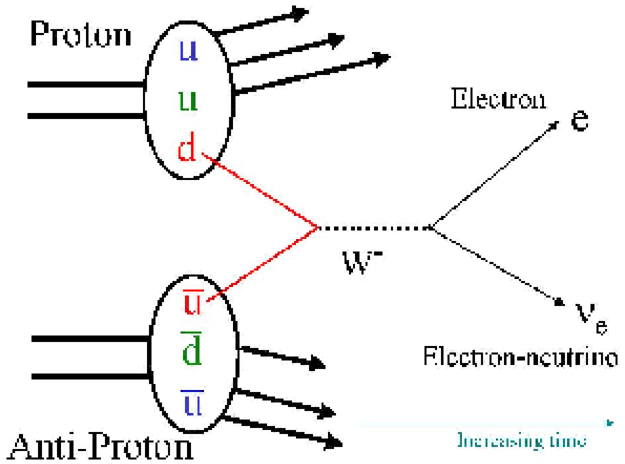
W mass

- Huge W samples at LHC give high hopes for W mass measurement
  - Even Z mass!
- Fun fact: To measure m_Z at LEP precision in ATLAS would require knowing the (average) silicon position to about 10 nm
  - W precision is only 1 order of magnitude less

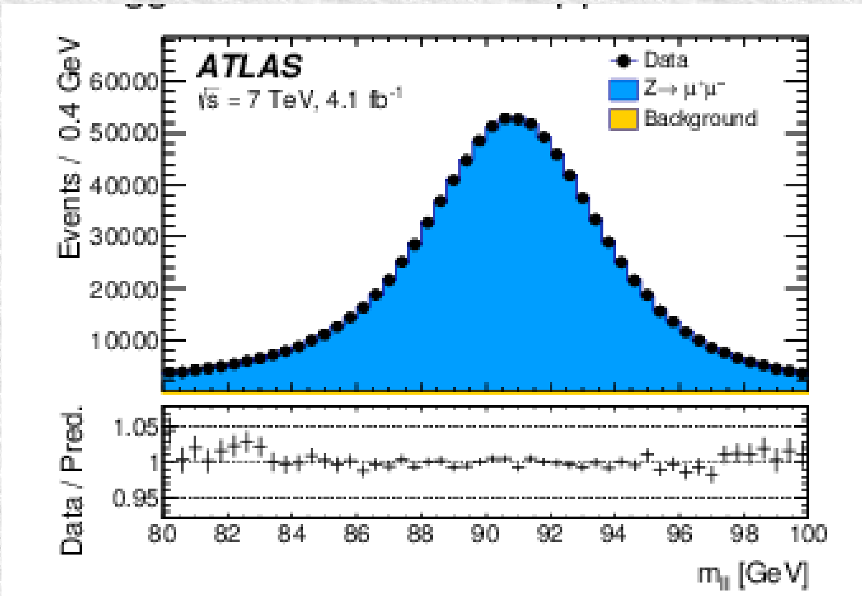
W mass

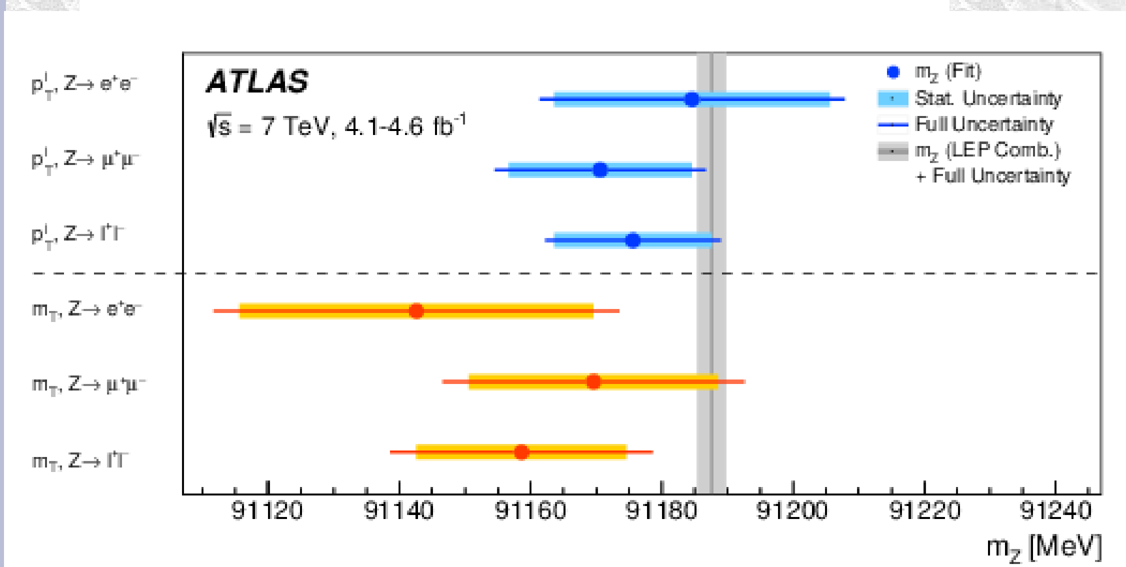
LHC versus Tevatron

- Tevatron: W^+/W^- production is symmetric, dominated by interactions with at least one valence quark
- W^+/W^- production at the LHC is asymmetric $\rightarrow$ Charge-dependent analysis
- The sea-quark PDFs play a larger role at the LHC
- W-mass measurement sensitive to s and c PDFs (implications in the W p_T distributions): 25% of the W-boson production is induced by at least one second generation quark at the LHC, only 5% at Tevatron
- Very challenging to achieve at the LHC an experimental precision similar to Tevatron



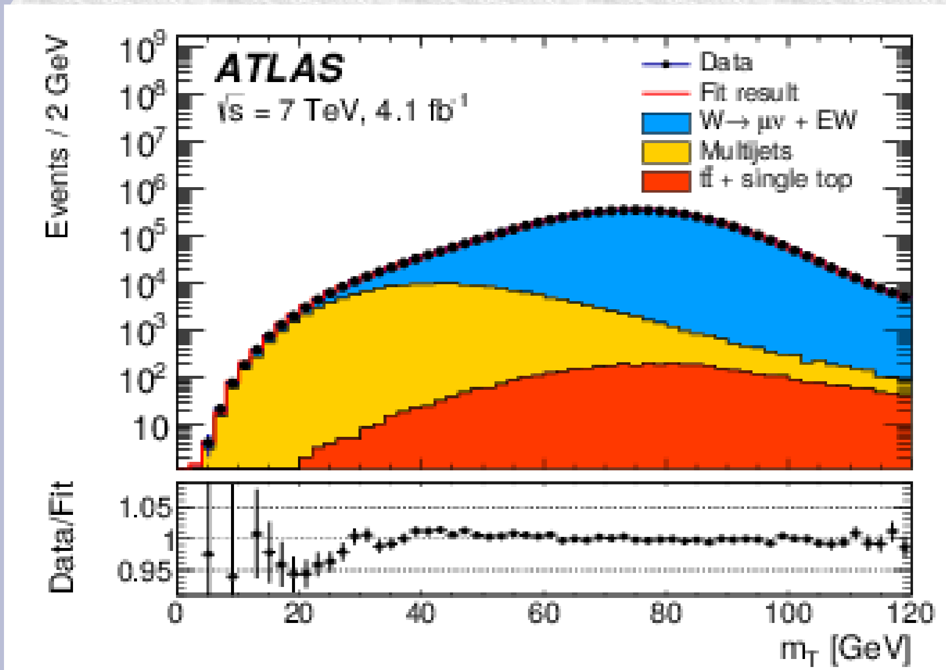
Calibration tests on Z





- Build accurate model of detector to reproduce Z peak with 1.2M Z→ μμ (left)
- Similar in ee
- Then ‘hide’ one lepton and fit p_T or m_T to measure Z mass
  - Tests recoil model, eta etc.
  - 10 MeV precision

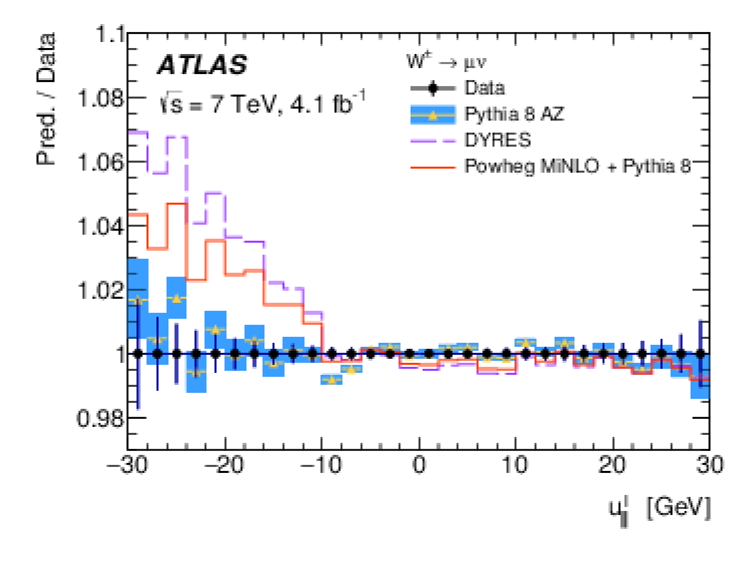
Model backgrounds



- $Z\rightarrow ll$ is dominant background
  - Up to 4% in e mode
  - Up to 6% in muon mode
- Yellow (multijet) measured in data
  - Template fits of lepton isolation sidebands
- Red (top) taken from simulation
- Backgrounds are not limit on analysis

Physics modelling

- Much is controlled and checked
- e.g. Hadronic recoil to W
  - Use $u^{l}_{||}$ i.e. the summed hadronic p_T in the lepton direction.
  - Pythia beats DYRES and Powheg
    - Both resummed calculation
- Finally the PDFs dominate
  - Controlled via W+ W- studies versus eta



W-boson charge Kinematic distribution	W^+ p_T^ℓ	 m_T	W^- p_T^ℓ	 m_T	Combined p_T^ℓ	 m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

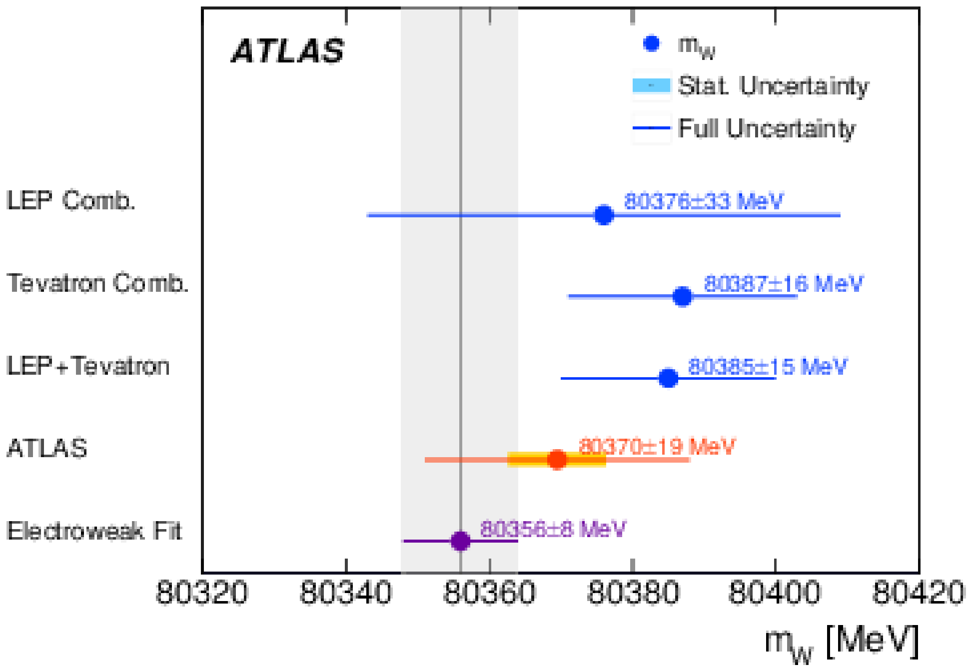
Final results

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

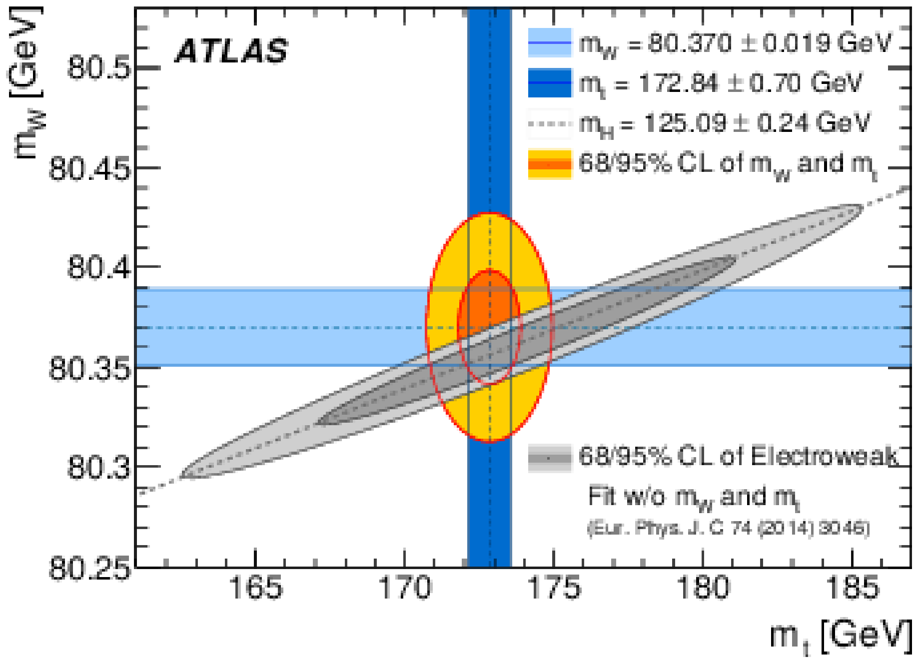
⇒ Result consistent with the SM expectation ($m_W = 80358 \pm 8$ MeV) and compatible with the PDG world average ($m_W = 80385 \pm 15$ MeV)

⇒ Result sits in between the Tevatron measurement and the SM prediction reducing the tension and shrinking the space for new physics

SM prediction of m_W from the global electroweak fit using:
$m_t = 172.84 \pm 0.70$ GeV
$m_H = 125.09 \pm 0.24$ GeV



Indirect determination of m_W and m_t from the global electroweak fit assuming $m_H = 125.09 \pm 0.24$ GeV compared to the ATLAS measurements

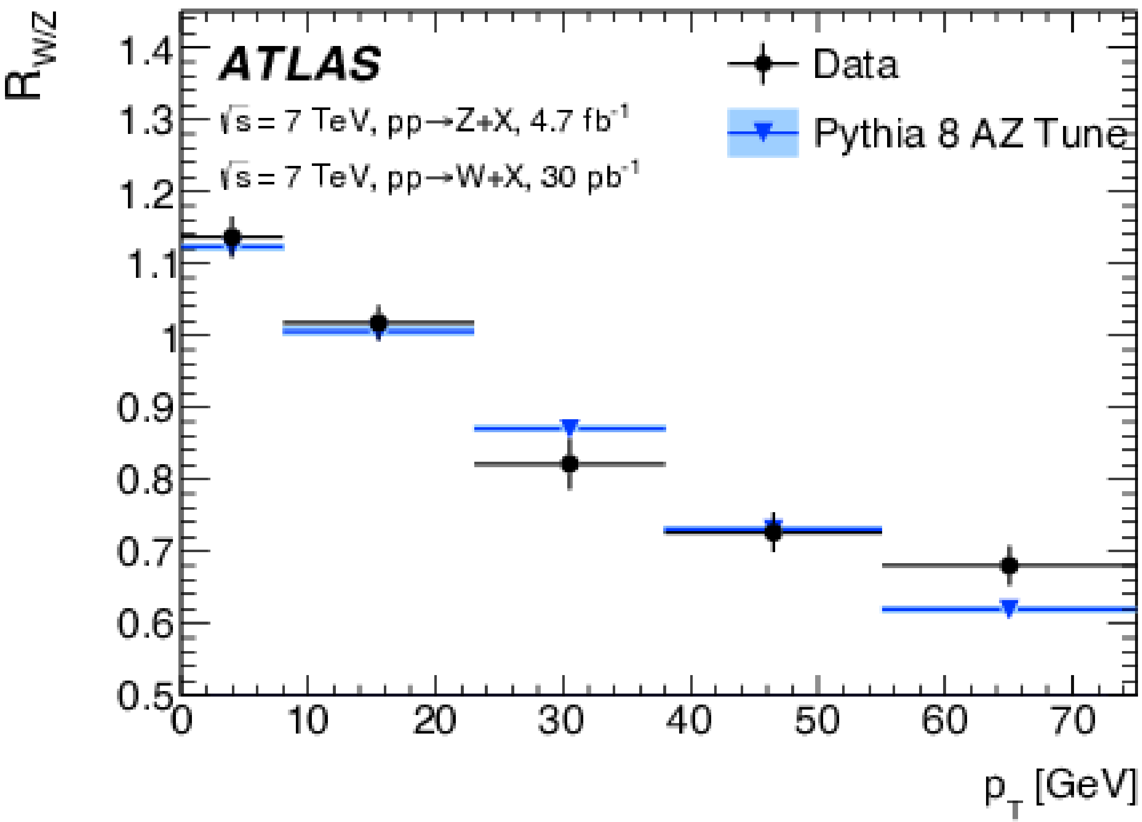


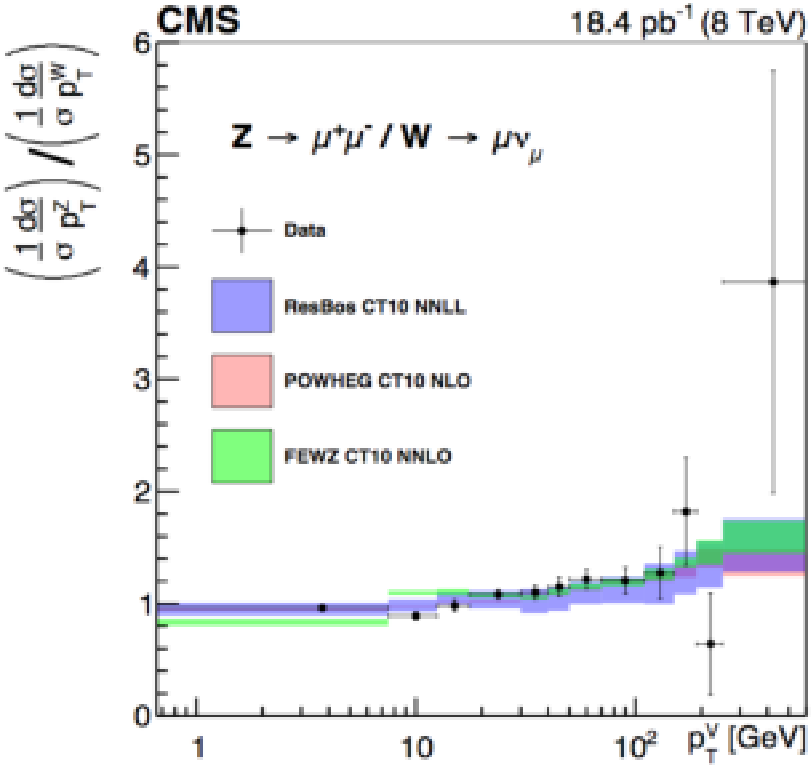
QCD at LHC

Ruiz-Martinez, Pasztor

W/Z production vs. p_T

- ATLAS and CMS have both made measurements; see also QCD section
  - ATLAS R(W/Z), linear scale – just showing range relevant for m_W measurement here
  - CMS R(Z/W), log scale

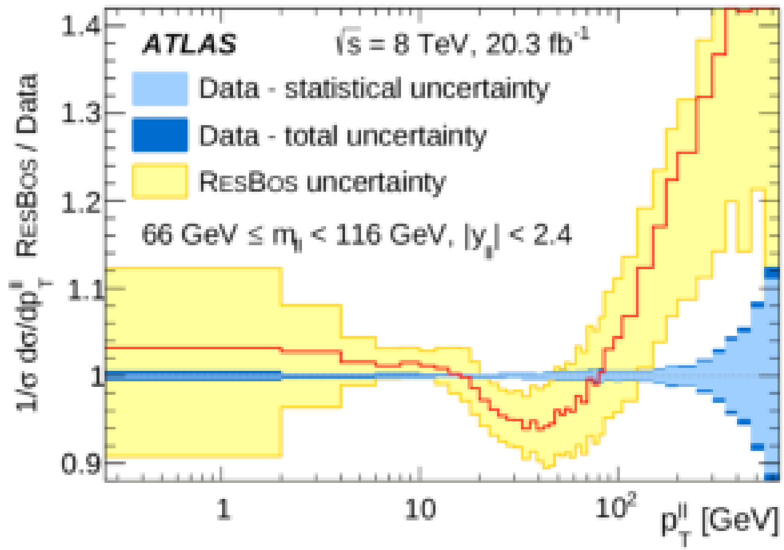


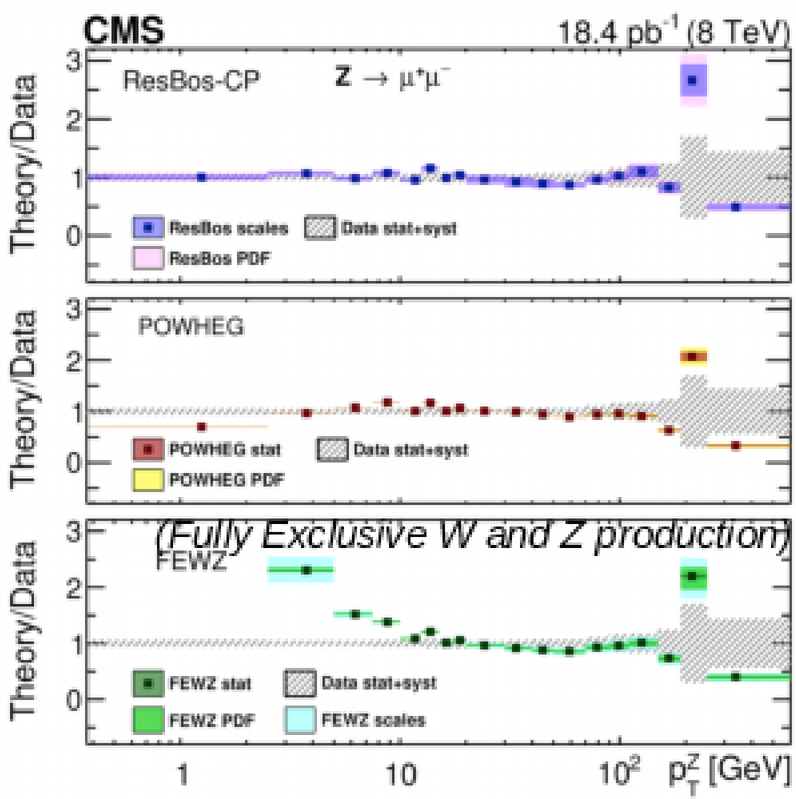


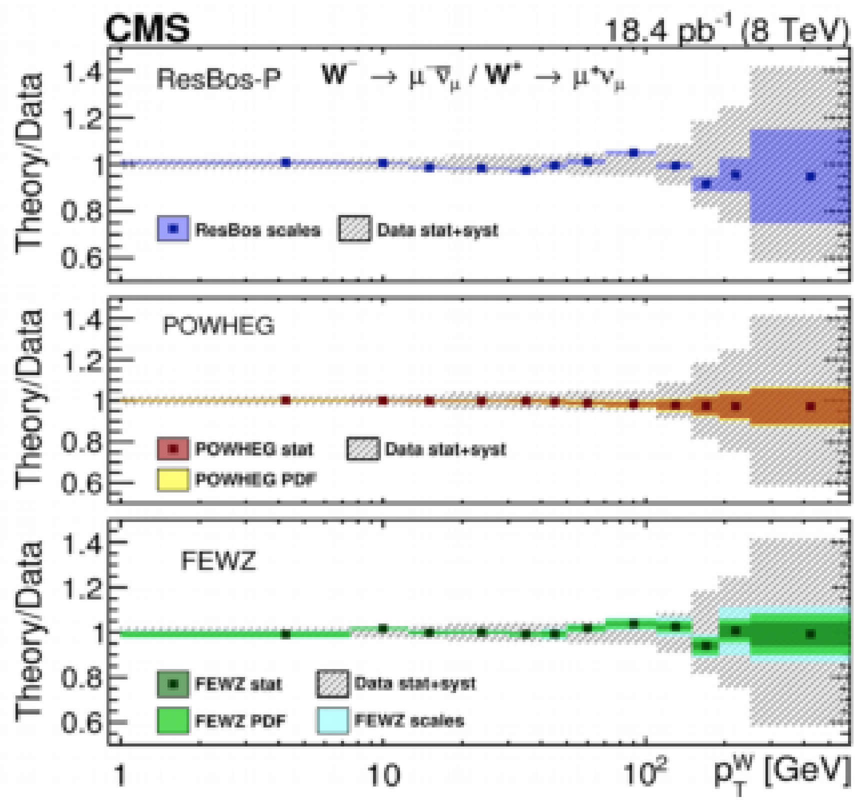
Wolter

W/Z transverse momentum

- W/Z transverse momentum spectrum (cf. W mass measurement)
- ATLAS: RESBOS/data – agreement for low $p_T(Z)$
- CMS: Theory/data in special low pileup run at 8 TeV



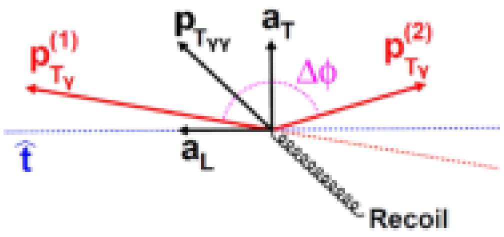




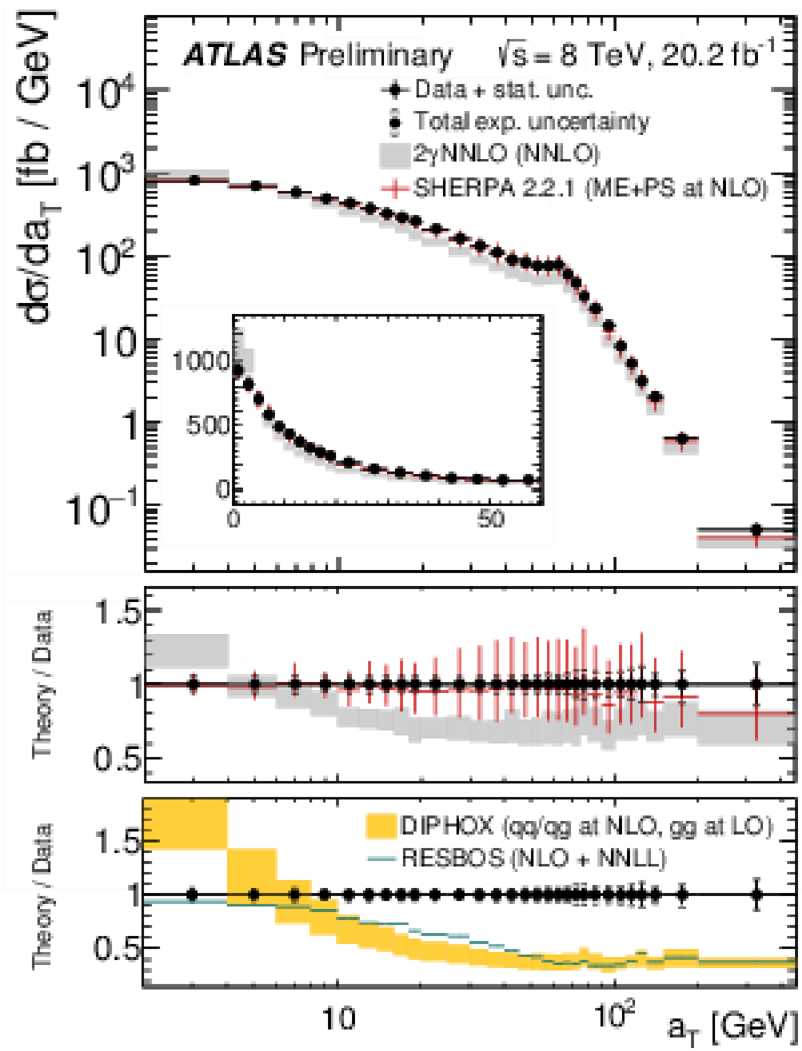
Saimpert

Photon pair production at 8 TeV in ATLAS

- Fiducial and differential cross section measurements
- Example, a_T



- RESBOS good description at low a_T (infra-red emissions)
- RESBOS and DIPHOX missing α_S corrections
- SHERPA 2.2.1 in good agreement

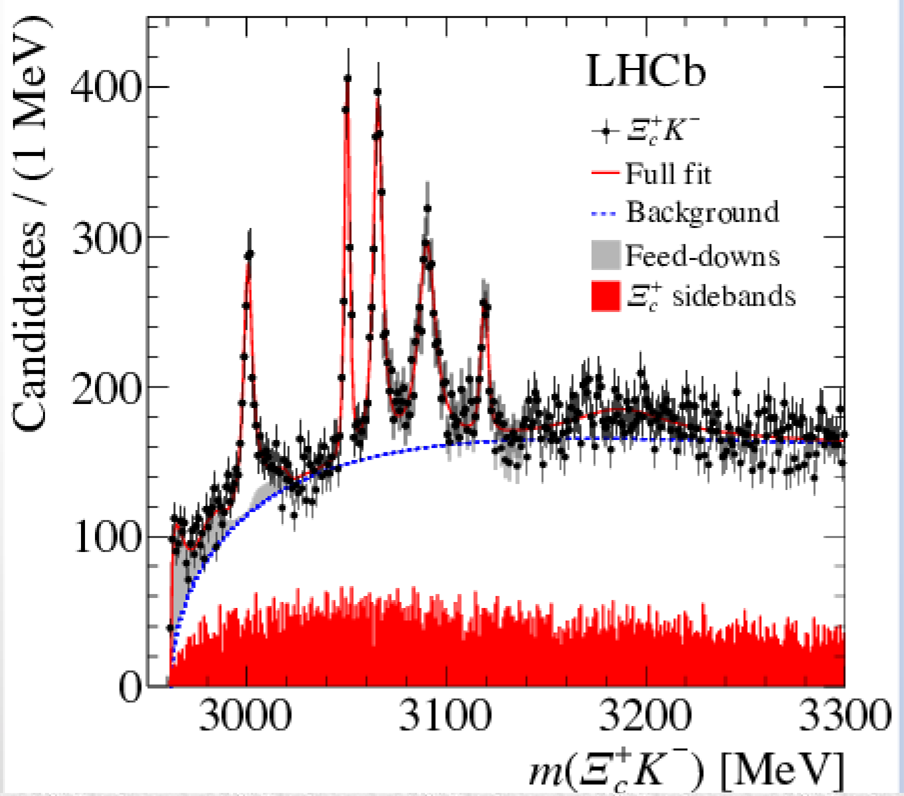


Spectroscopy

LHCb: $\Xi_c^+K^-$ mass spectrum

[arXiv:1703.04639]

- Very pretty spectrum observed
  - Fitted with 6 BW peaks
  - Plus background from like sign
  - And feed-downs, $\Xi_c^{+\prime} \to \Xi_c^+\gamma$
- 5 *new* Ω_c^0 states seen, mass and width measured
  - No surprise they exist
  - But it <u>is</u> a surprise they are so narrow



D0: $B_s \pi$ resonance

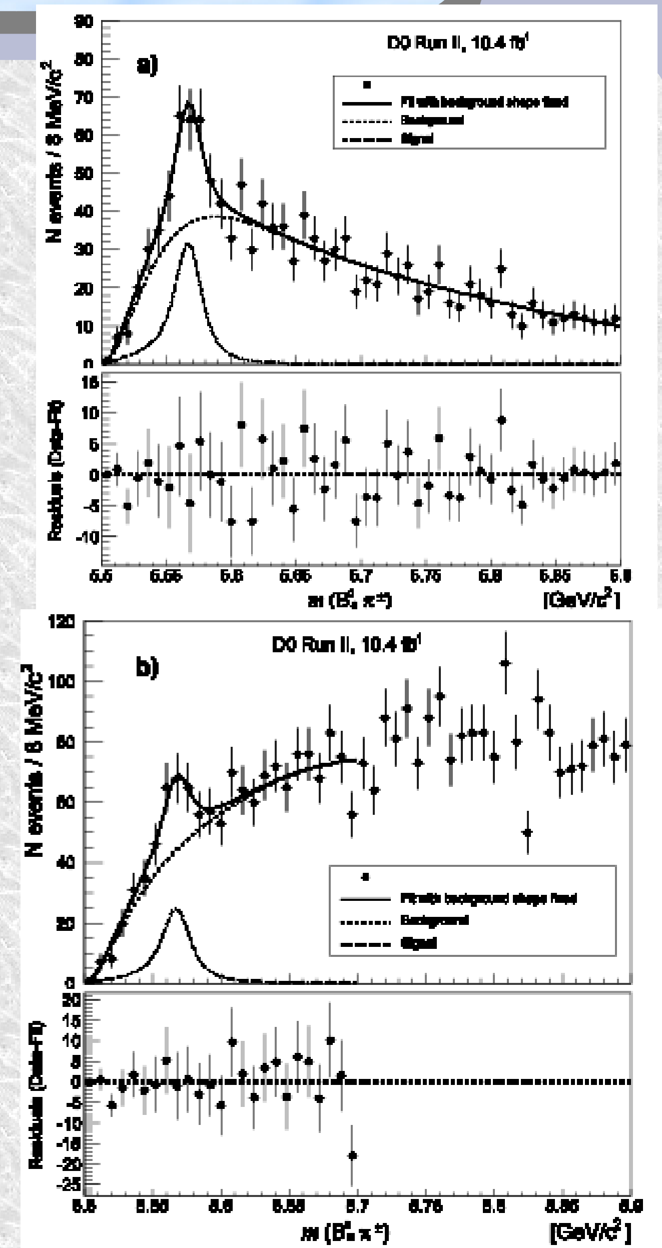
- Observed by D0 last year
- Phys. Rev. Lett. 117, 022003 (2016)
- Using Bs to J/Ψ φ modes
  - Top: With a (controversial) dR cut on the pion angle
  - Bottom: without that cut
- Significance of 5.1σ
  - For the top analysis, as released

X(5568)

$$M = 5567.8 \pm 2.9(\text{stat})^{+0.9}_{-1.9}(\text{syst})\,\text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})\,\text{MeV}/c^2$$

$$\rho(X(5568)/B_s) = 8.6 \pm 1.9(\text{stat}) \pm 1.4(\text{syst})\%$$



SEARCH FOR X(5568)$^{\pm}$ AT LHCb

[PRL 117 (2016) 152003]

Claimed observation/evidence of an exotic state ($\overline{b}s\overline{u}d$) by DØ collaboration

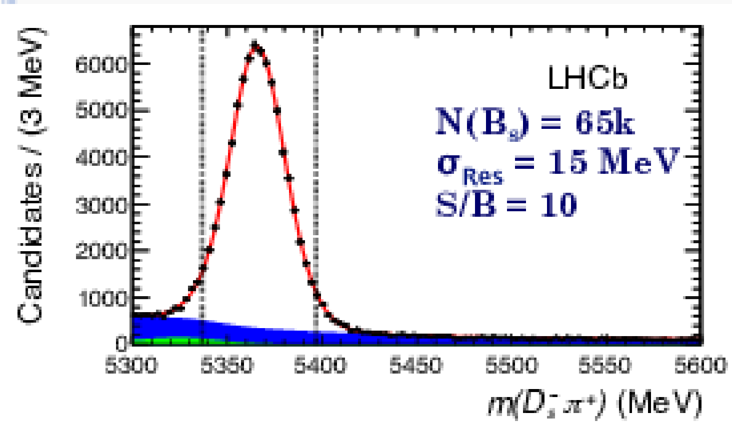
- ✓ $X(5568)^{\pm} \rightarrow B_s^0 \pi^{\pm}$, $B_s^0 \rightarrow J/\psi\, \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$

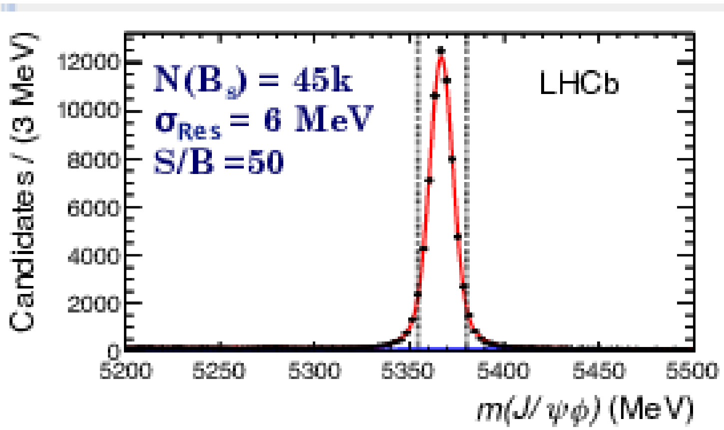
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$

N.B. $m(\Xi_b)$ ~ 5790 MeV

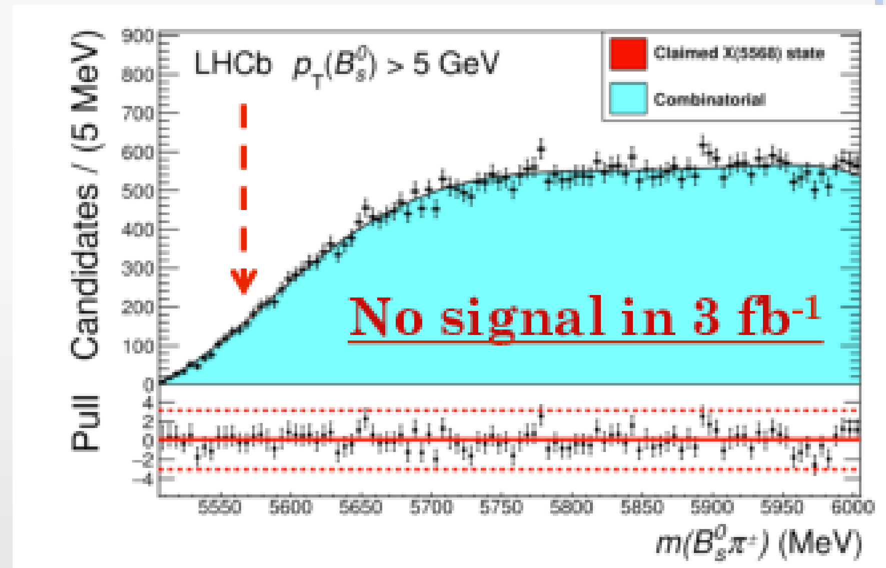
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

- ✓ Fraction of B_s^0 from $X^{\pm}$ decay: $\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)\ \%$





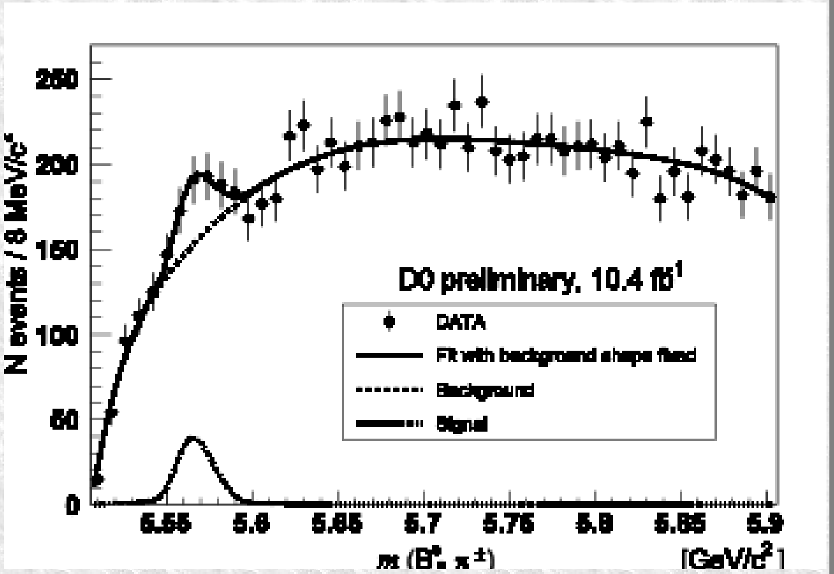
$B_s + \pi^{\pm}$



$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 5\ \mathrm{GeV}/c) < 0.011\ (0.012)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 10\ \mathrm{GeV}/c) < 0.021\ (0.024)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 15\ \mathrm{GeV}/c) < 0.018\ (0.020)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$

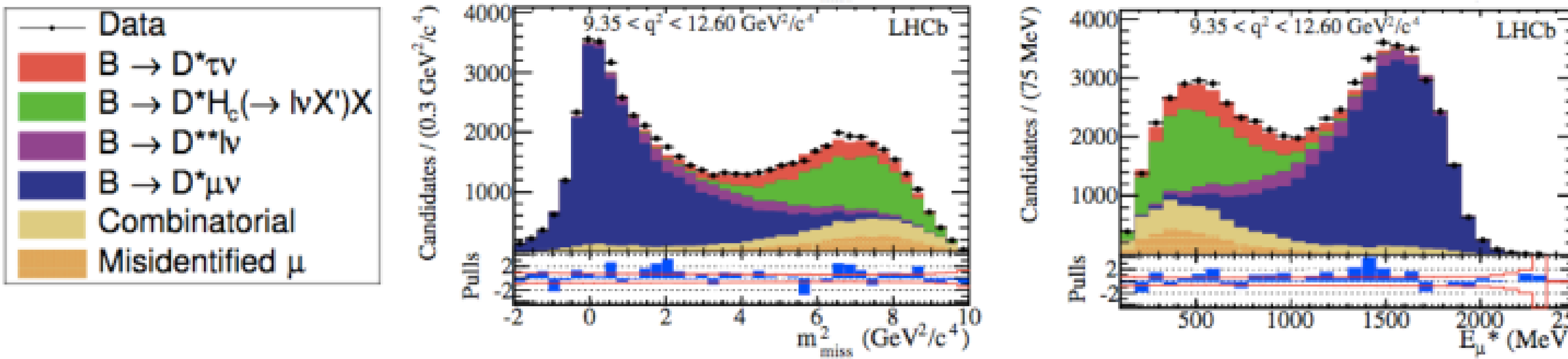
D0: $B_s\pi$ resonance II

- Repeat search using different mode: $B_s \rightarrow Ds\ \mu\nu$
  - Require large mass to minimise neutrino contribution
  - Decent mass resolution on $B_s\pi$ possible
- Significance of 3.2σ
- Mass is 5566±3.5
- Width is 6GeV, c/f 21 before
  - But compatible given errors
- So the story is not over...



Schune

LHCb lepton flavour universality tests

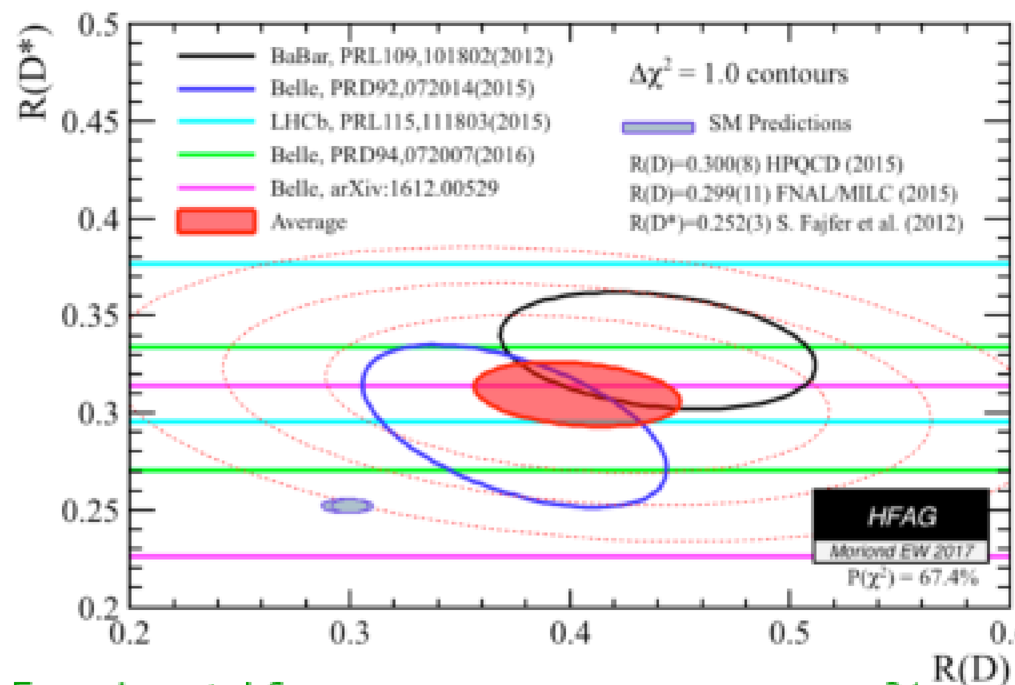


$$\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$

$$R(D^*) = \frac{B \to D^* \tau \nu}{B \to D^* \mu \nu}$$

In agreement with other measurements and 2.1 σ away from the SM

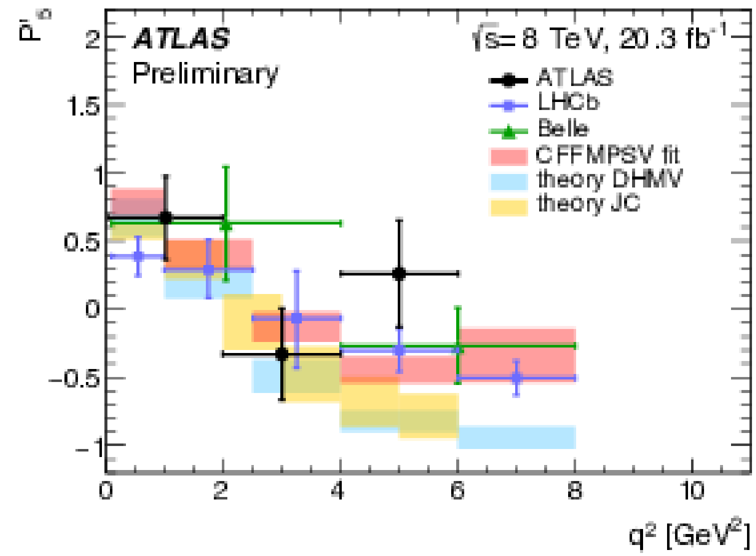
- R(SM) = 0.252 ± 0.003
- LHCb [PRL 115 (2015) 111803]
- In total ~3.9σ away from SM
- Present analysis uses τ→μνν; systematics cancel
- Coming soon - τ_{had} analysis

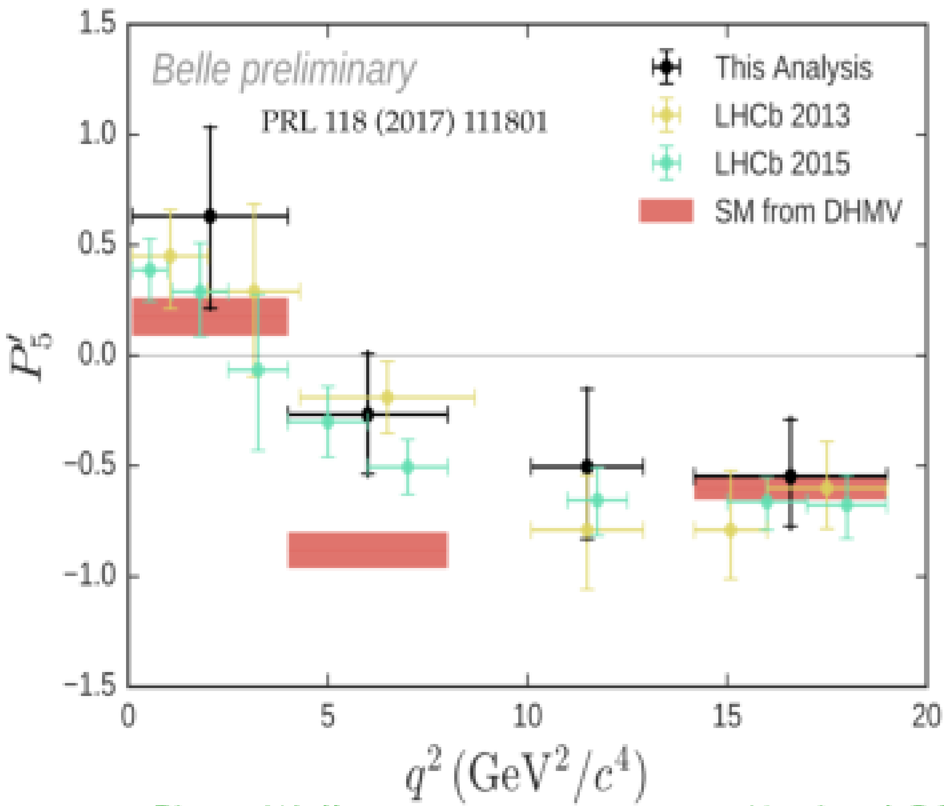


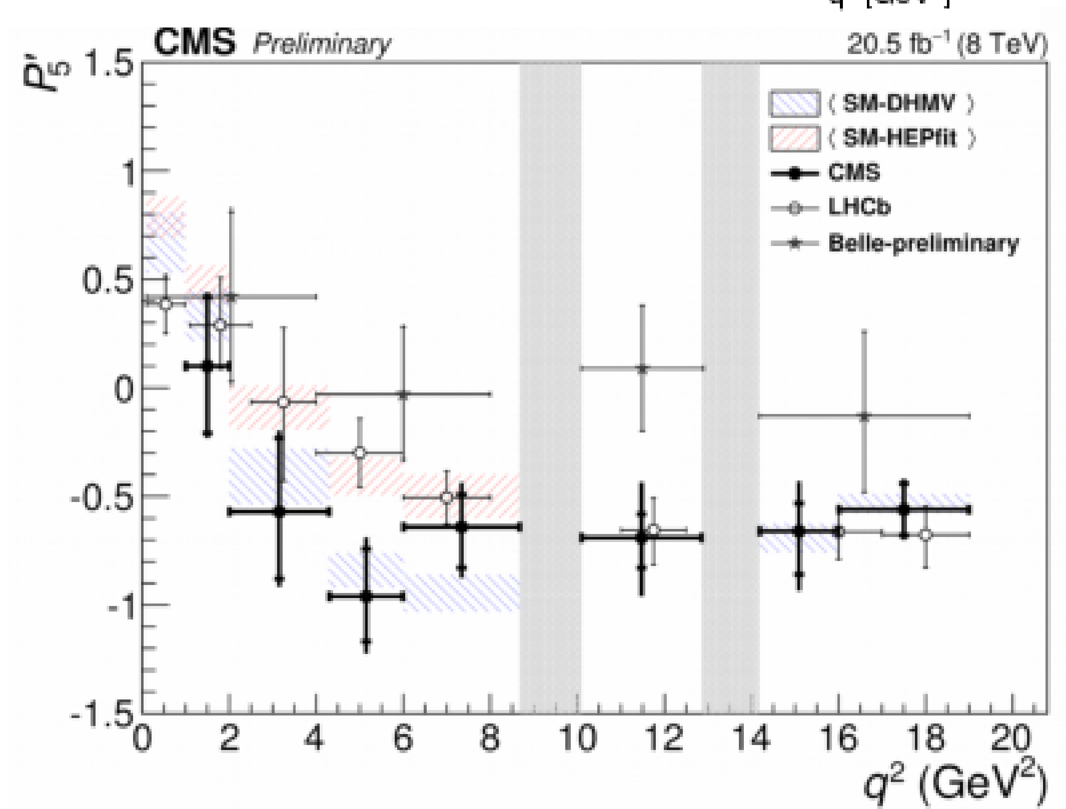
B→K*μμ angular analysis

Galanti, Neubert

- New results from ATLAS (q^2<8), Belle and CMS
- Belle also has a Kee result. LHCb looking into this.



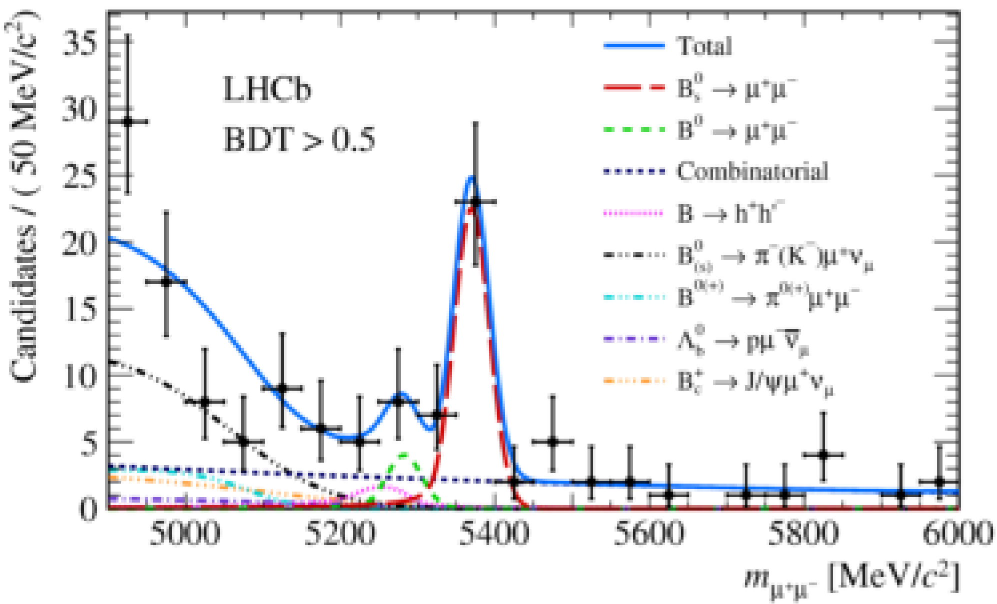


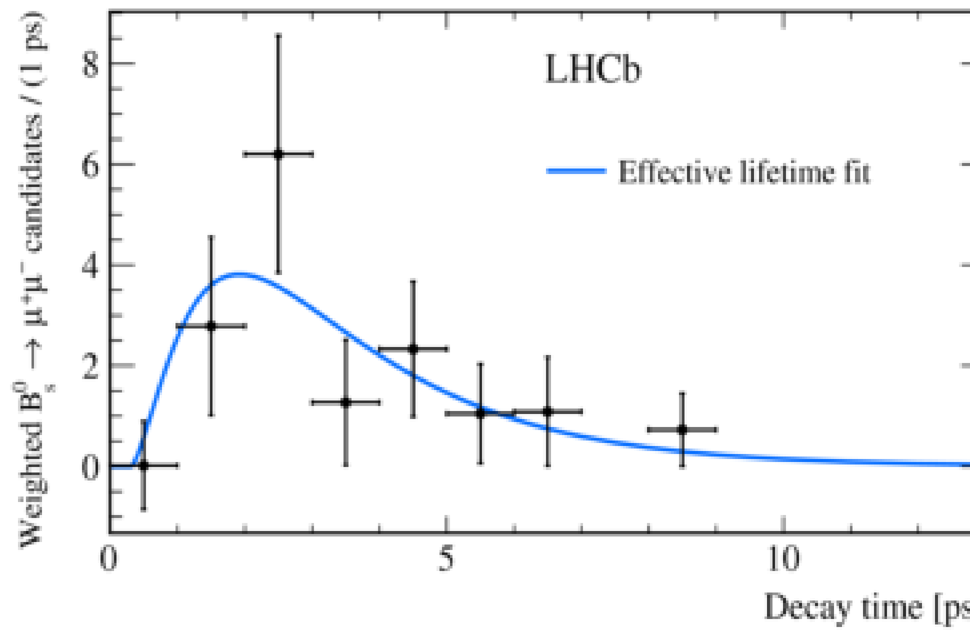


Bettler

LHCb rare decays - $B_s \rightarrow \mu\mu$ and $B \rightarrow \mu\mu$

3/fb Run 1 + 1.4/fb Run 2, improved analysis [LHCb-PAPER-2017-001]





First single-experiment observation of the B_s mode!

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

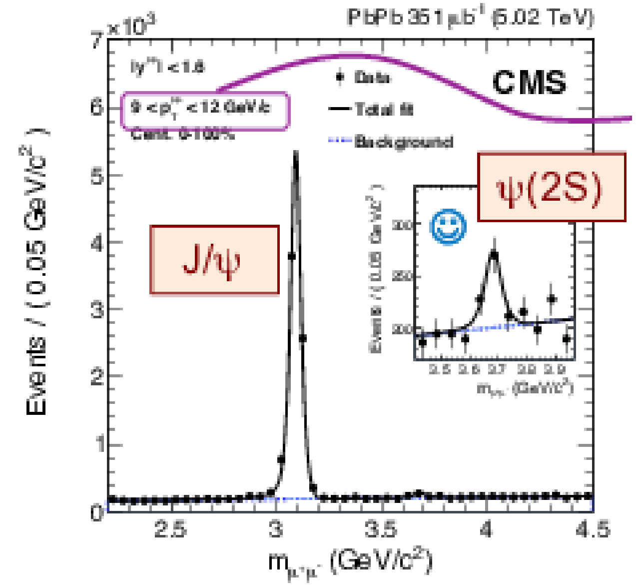
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,(\text{stat})\,^{+0.2}_{-0.1}\,(\text{syst})) \times 10^{-10} \qquad (1.6\sigma)$$

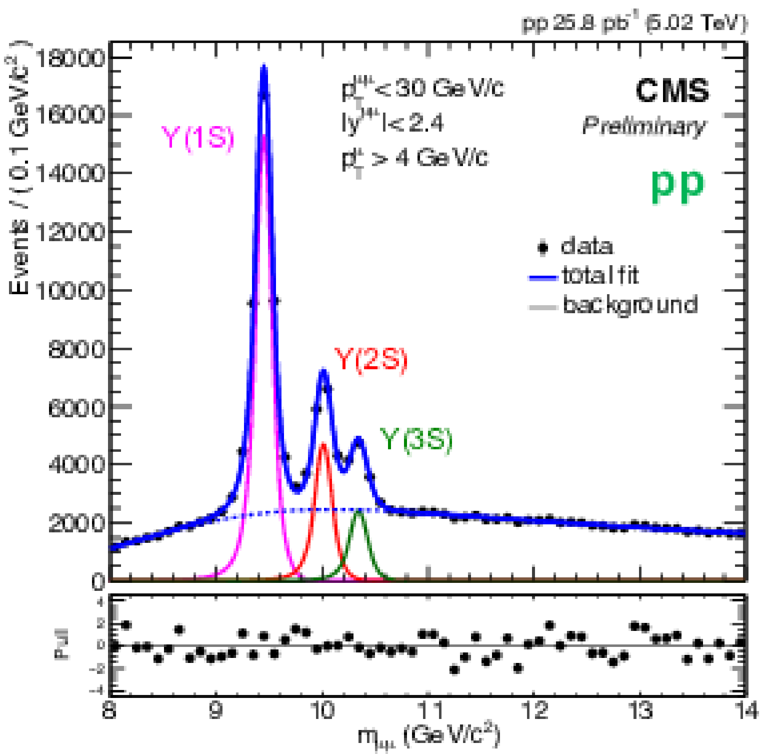
$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44\,(\text{stat}) \pm 0.05\,(\text{syst})\ \text{ps}$$

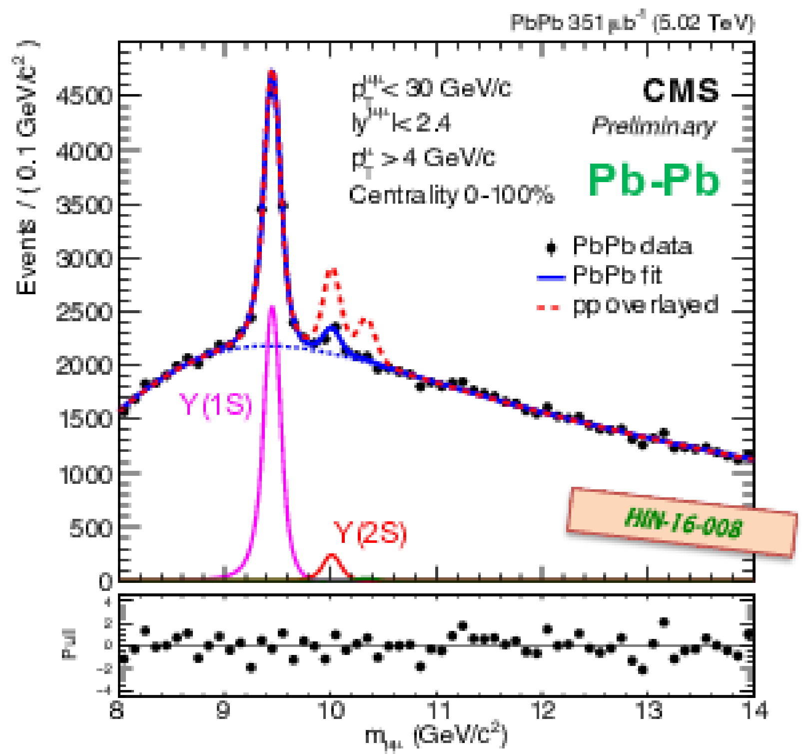
Heavy Ions+

Quarkonia at CMS

- QCD screening “melts” QQ bound states.
  - Different binding energies → measure of temperature
  - Random ccbar pairs in medium can recombine. Much less likely for bbbar
  - ψ(2S) melting seen even in most peripheral collisions



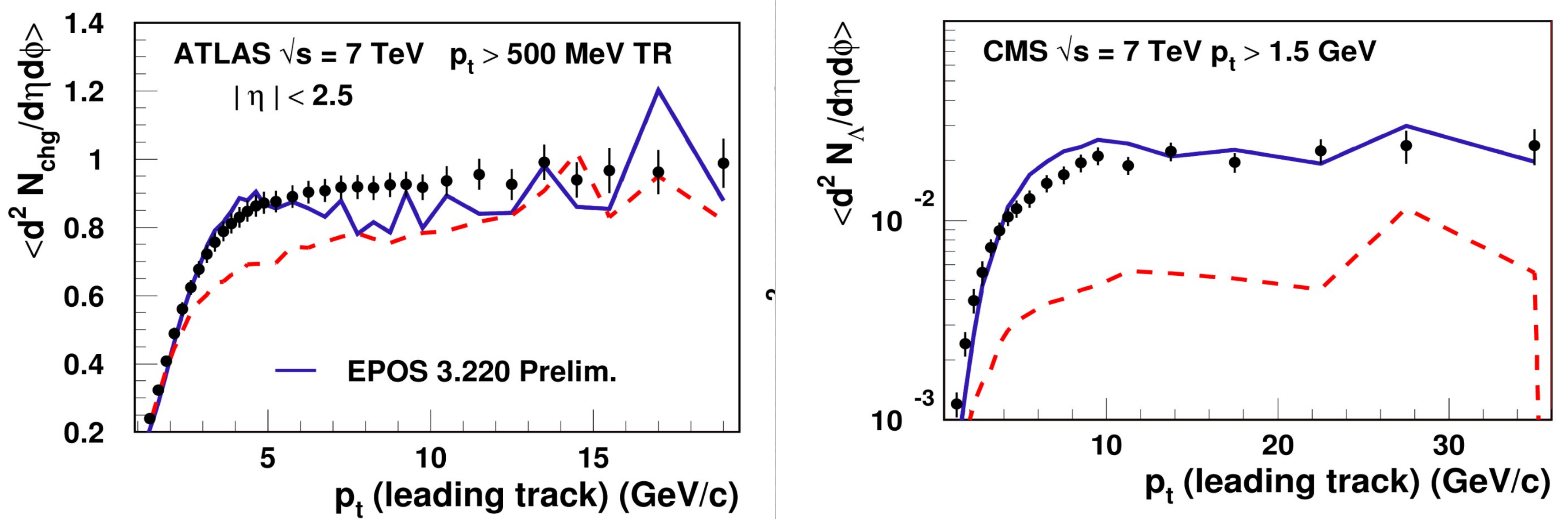




EPOS 3.2

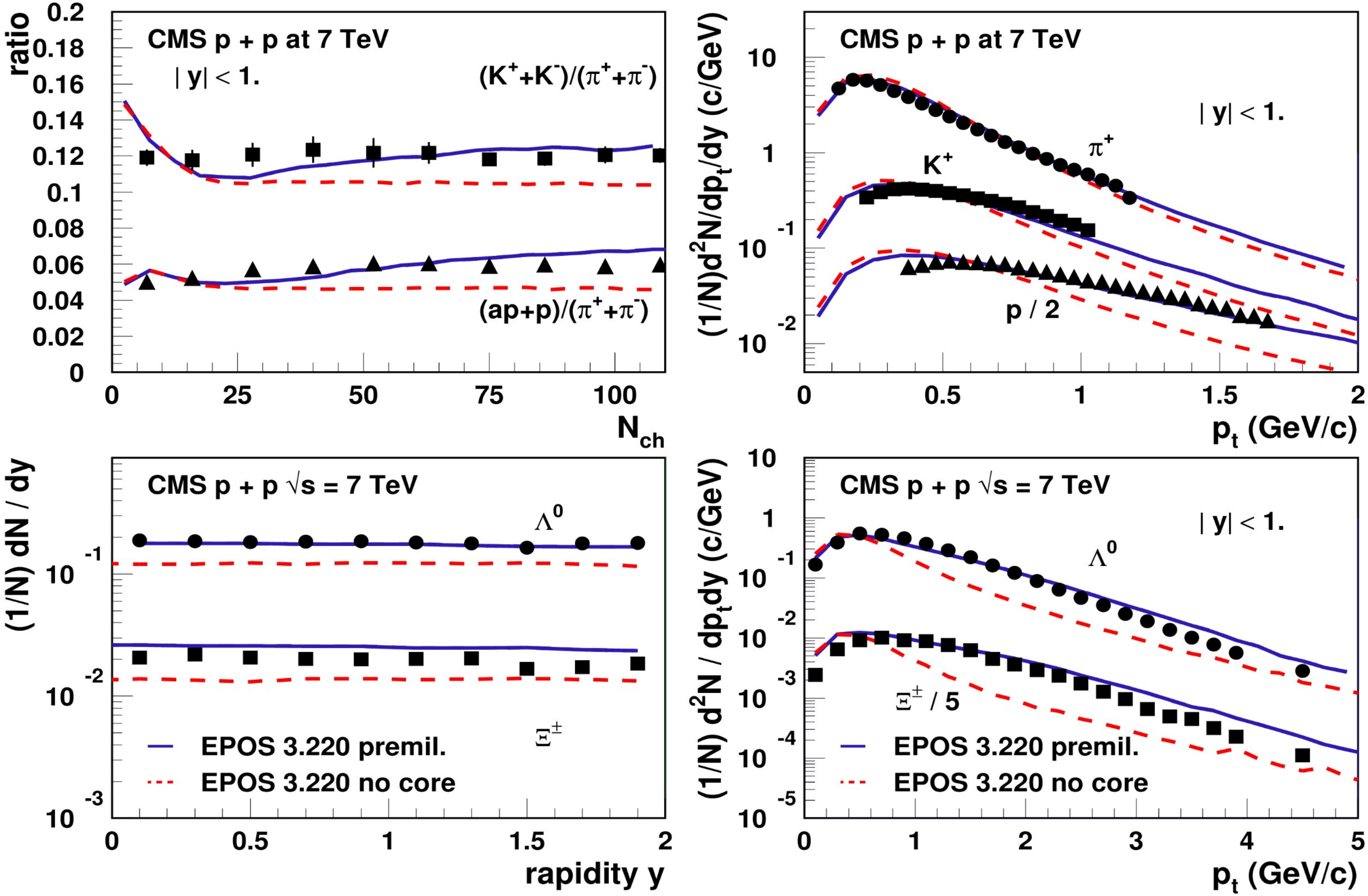
- EPOS is minbias generator
  - Parton based Gribov-Regge theory
- Designed for pp, pA and AA collisions
- Used modified string fragmentation in high-density regions "core"
  - Roughly corresponds to QGP
- Discussed by T.Pierog
- Tuned using at least:
  - LEP, Hera, ATLAS, CMS, Alice (and probabaly others)
- EPOS 3.220 is available for testing, better than ever
  - But still a work in progress

EPOS 3.2 with(out) core



- Cannot describe charged particle multiplicity fluctuations I pp without core
- Even more essential for lambda (right)

EPOS 3.2


CMS p + p at 7 TeV
| y| < 1.
(K⁺+K⁻)/(π⁺+π⁻)
(ap+p)/(π⁺+π⁻)
ratio
N_ch
CMS p + p at 7 TeV
| y| < 1.
π⁺
K⁺
p / 2
(1/N)d²N/dp_t/dy (c/GeV)
p_t (GeV/c)
CMS p + p √s = 7 TeV
Λ⁰
Ξ^±
EPOS 3.220 premil.
EPOS 3.220 no core
(1/N) dN / dy
rapidity y
CMS p + p √s = 7 TeV
| y| < 1.
Λ⁰
Ξ^± / 5
EPOS 3.220 premil.
EPOS 3.220 no core
(1/N) d²N / dp_tdy (c/GeV)
p_t (GeV/c)

Summary

Difficult to describe min bias and hard scale events at the same time

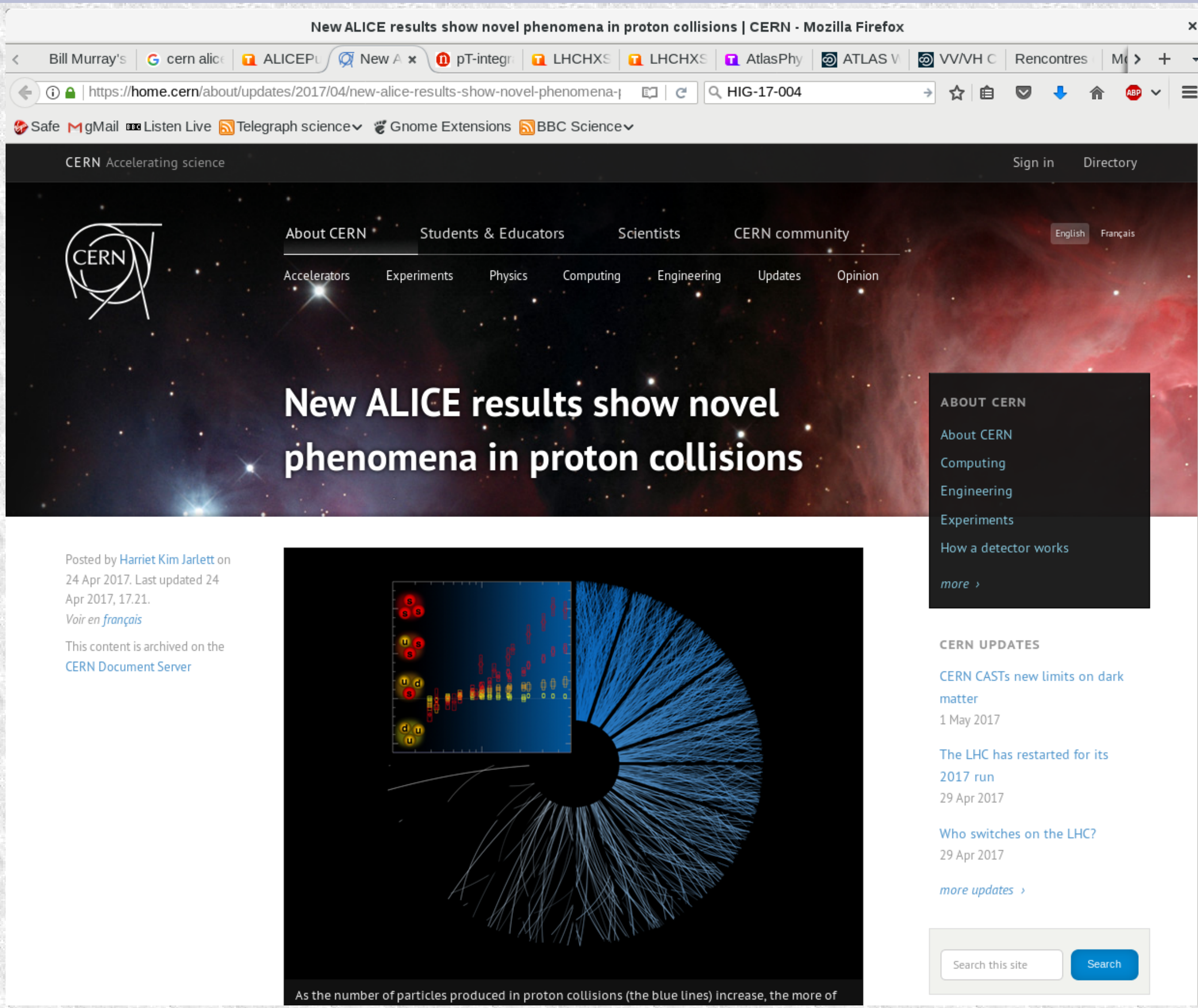
- UE require large mutliplicity
- transverse momentum distributions depend on event multiplicity even at high p_t (to high for flow effect)

EPOS 3

- introduce non-perturbative scale Q_0^2 GENERATED Pomeron-by-Pomeron and dependent on the number of MPI event-by-event.
- non perturbative N-pdf generation coupled with N independent DGLAP evolutions to get N hard partons event-by-event
- recover factorization and binary scaling for inclusive hard processes above Q_0^2
- hydro expansion require higher MPI than imposed by multiplicity that reflects on UE and other variables (like charm production (See B. Guiot MPI 2016)
- improve underlying event description in p-p but real hydro still to be tried for final results

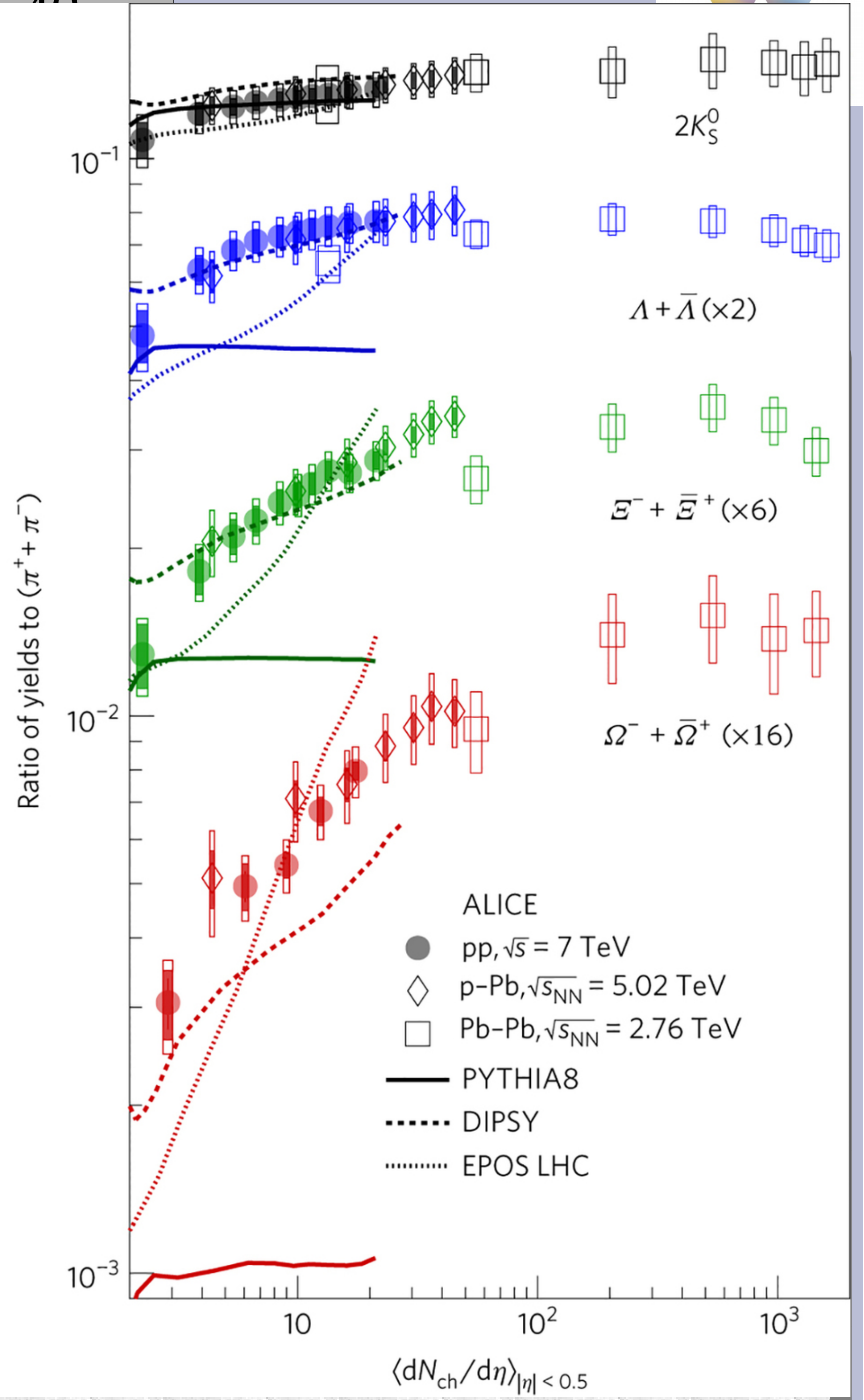
To reconcile minimum bias (MB) and underlying events (UE) in pp, we need both collective effects and variable non-pertub. scale.

Alice shock result!



Alice shock result!

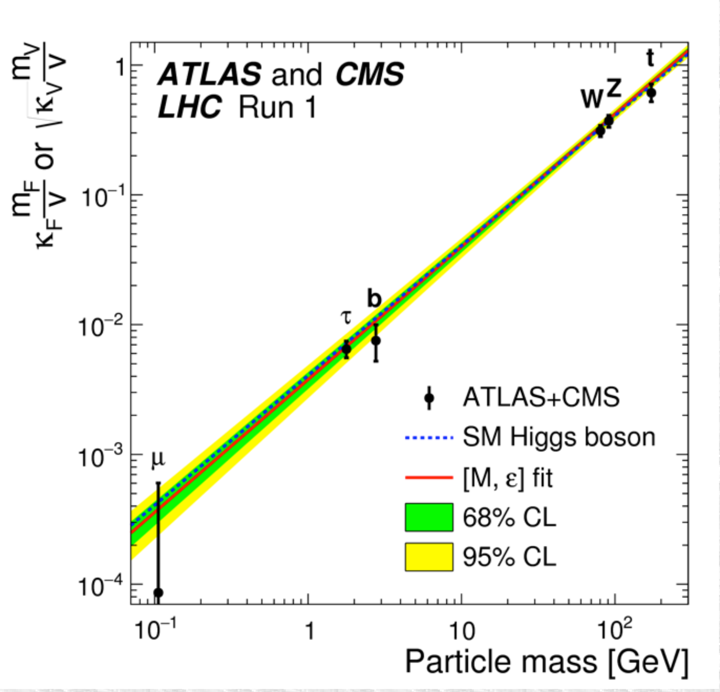
- ALICE nice measurement shows pp blending into pPb and PbPb
- Charged particle yields versus event activity
- Comparison with three MC:
  - all fail
  - DIPSY comes closest, and has interacting strings
- Collective effects <u>needed</u>
- But I think we knew that
  - Near side ridge? EPOS 3.22?



Higgs

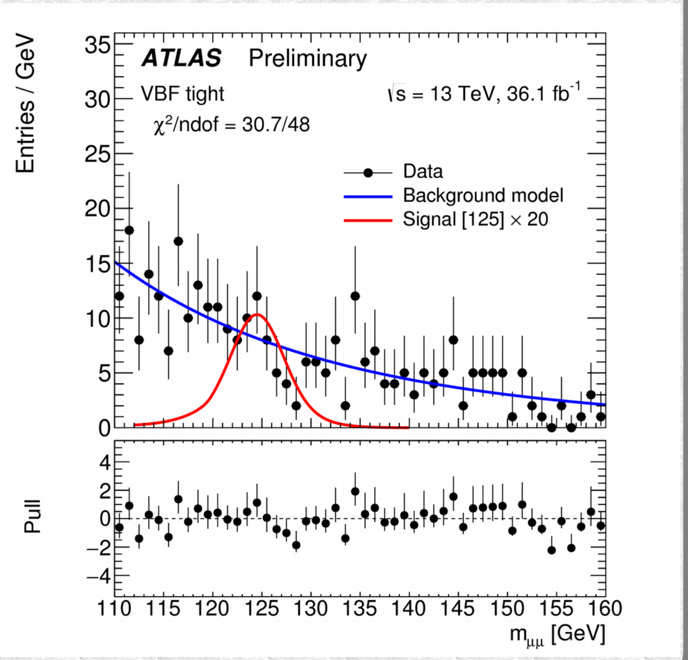
Higgs: ATLAS

- Several results exist from ~13fb-1
  - H→γγ, H→ZZ, ttH, H→bb etc.
- ATLAS released only two 36fb^{-1} Higgs results
- (H→ γγ) + E_t^{miss}
  - Search for H+Dark matter: no sign
- H→μμ
  - Best bet for a second generation H coupling at LHC
  - Run 1 starting to be sensitive



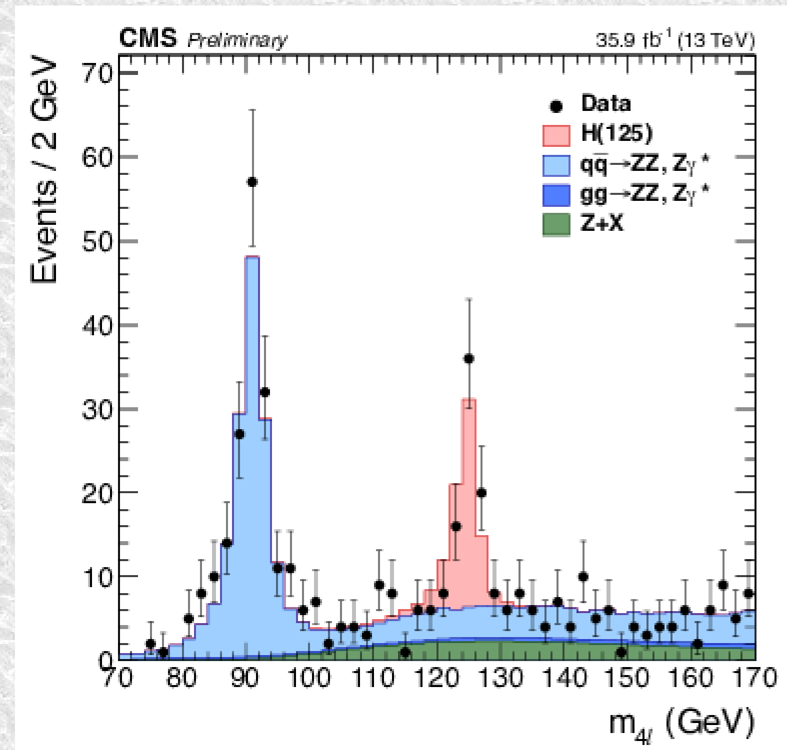
H→μμ with ATLAS

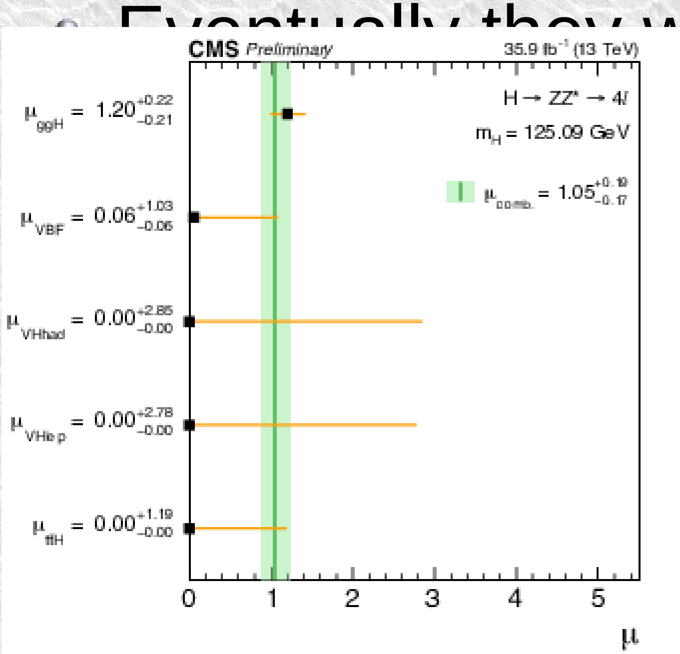
- Approach like H→γγ
  - Look for narrow peak on smooth background
  - Fit in eight 1D categories
  - Use BDT to separate VBF categories
- Expected Signal rate similar to H→ZZ→llll
  - Br 2×10^{-4}
- Drell-Yan background is large
- Cleanest category is VBF tight
- No sign of signal
- μ=-0.1 ±1.5
  - More than factor 2 better than run 1.
    - -0.6±3.6
- Good progress….



H→ZZ CMS

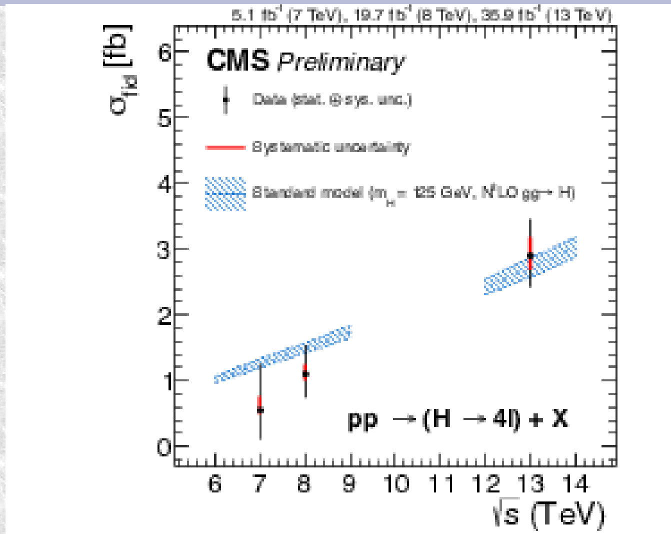
- Beautiful H→ZZ peak
  - Unquestionably clear
- Analyse production modes
  - Statistically limited for these
    - WW, γγ maybe better
  - Eventually they will be good

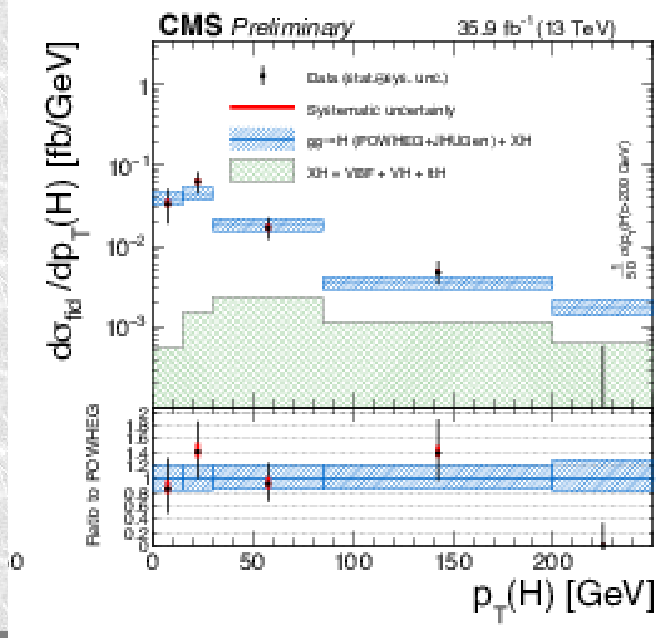




H→ZZ production CMS

- Fiducial cross-section extracted
  - See HIG-16-041 for definition & nos.
  - Good agreement with N^{3}LO
  - Consistent with growth of cross-section with E_{CM}
- Differential properties released too
  - e.g. Higgs p_T, Njets, jet p_T…
  - No significant anomalies
    - Unlike 2012 ATLAS p_T distributions





$H \rightarrow ZZ \rightarrow 4\ell$: mass

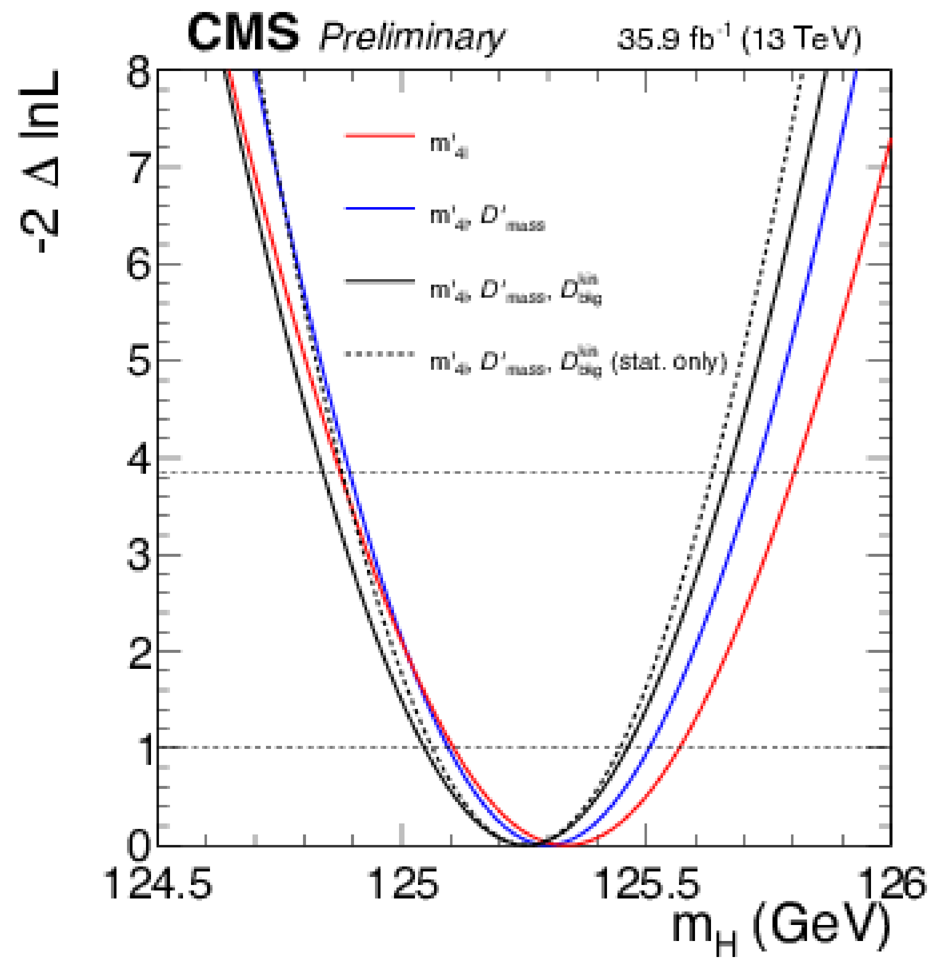
- 3D analysis: m'_{4l}, D_{bkg}^{kin}, m_{4l} error
  - Kinematic fit to constrain m_Z, $m_{4l} \rightarrow m'_{4l}$
  - 8% gain $m_{4l} \rightarrow m_{4l'}$ in 3D
  - 21% gain w.r.t 1D m_{4l}

$m_H = 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})$ GeV

Compared to

$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})$ GeV from Run1 ATLAS+CMS (4l+ γγ) combination

Also: Width less than 1.1 GeV



HIG-17-015 H → ZZ couplings CMS

- Fit for anomalous couplings in VVH vertex:

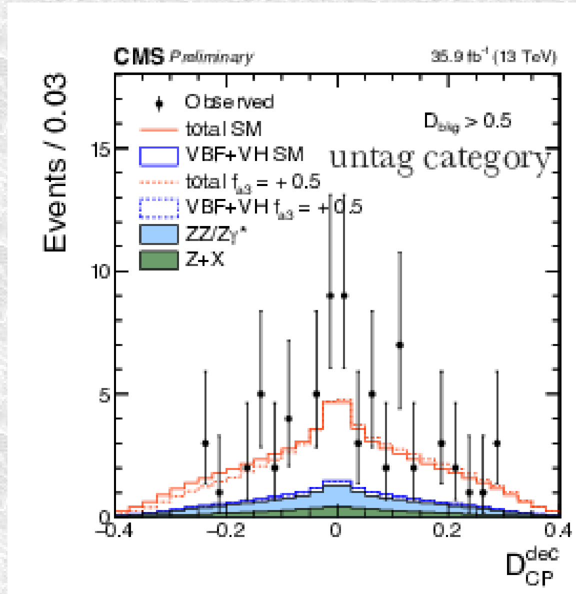
SM — leading momentum expansion — higher order cp-even — cp-odd

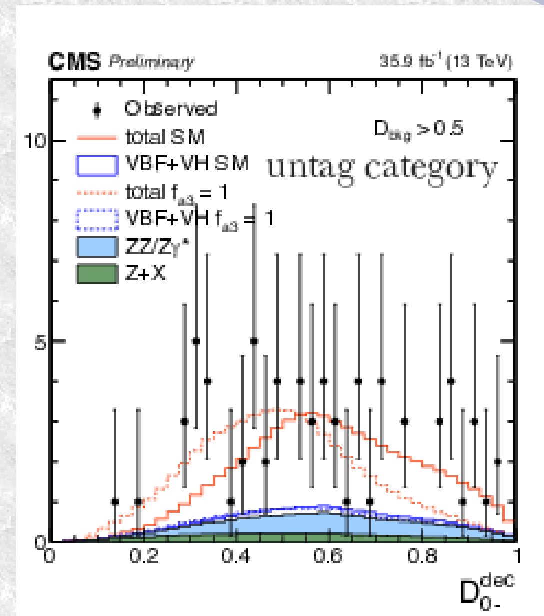
$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

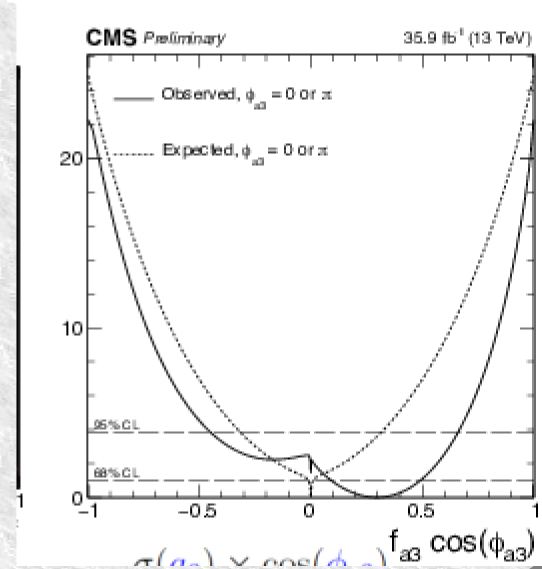
  - a1 is SM, a2, a3 and Λ are all BSM terms
- Fermion couplings held to SM value
- Using total information:
  - Decay kinematic a la Run 1
  - Production angles for VH, VBF too
- Analyse using MELA approach
  - Calculate event-by-event matrix elements for each parameter value tested
- In 3D: for sig-v-back, BSM, and interference

H→ZZ couplings CMS

- Many distributions
- CP even/odd decay
  MELA shown
  - 3D Hard to visualise
- Precision beats run 1
  HWW and HZZ
  combined
- All compatible with 0: SM
  - a3 has small offset
  - Note also dip in LR at 0
    - Comes from VBF production angles
    - Very precise but not proven to exist!

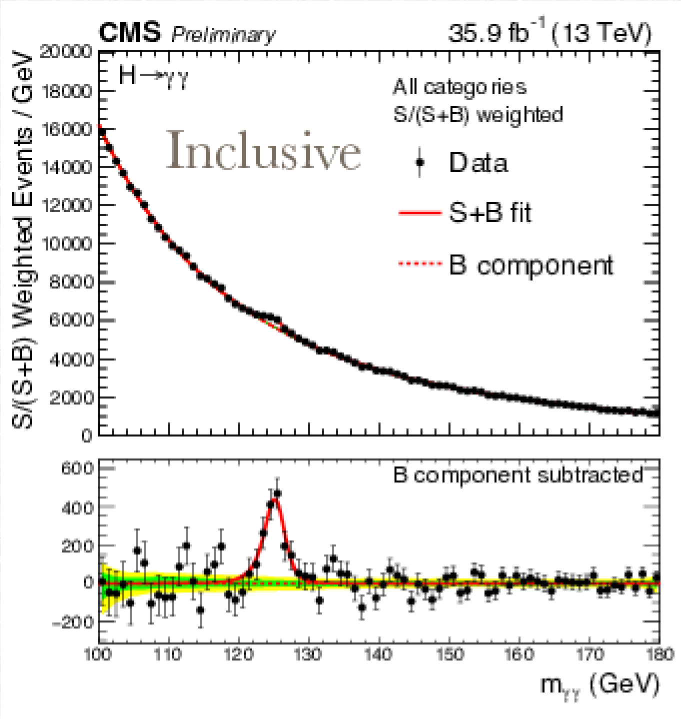


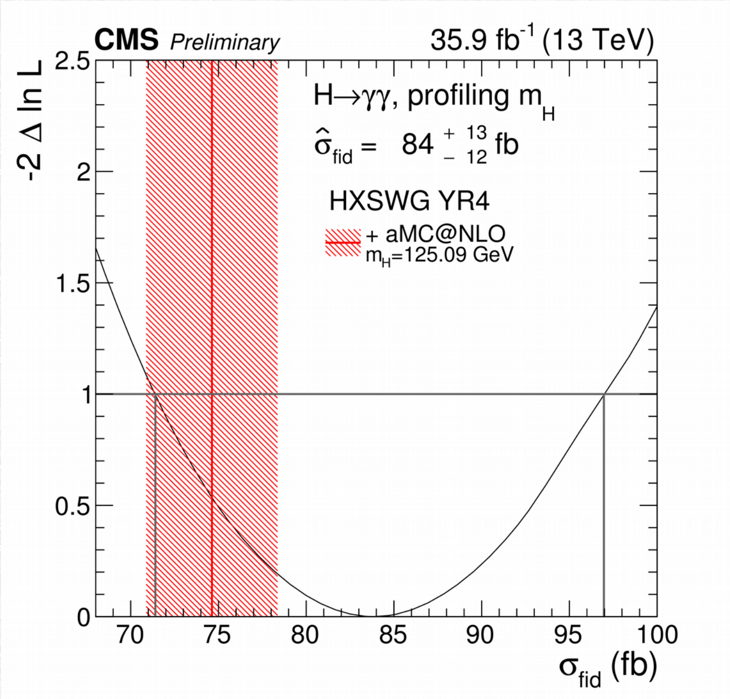




H→ γγ CMS

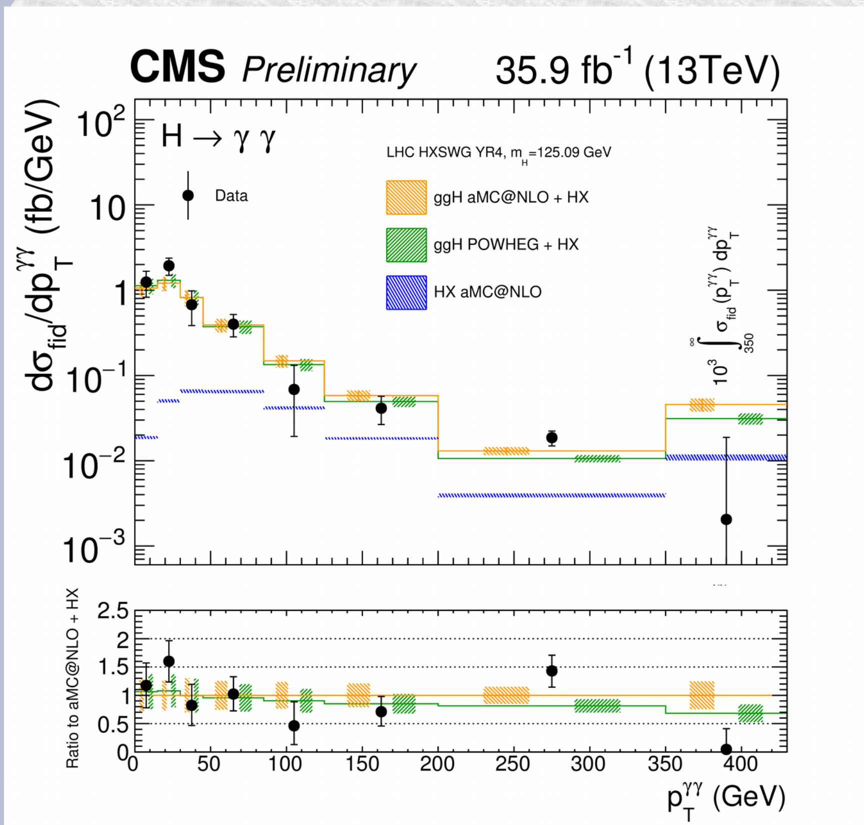
- Di-photon spectrum also shows an unambiguous signal
  - Here analysed simply in 3 bins of resolution

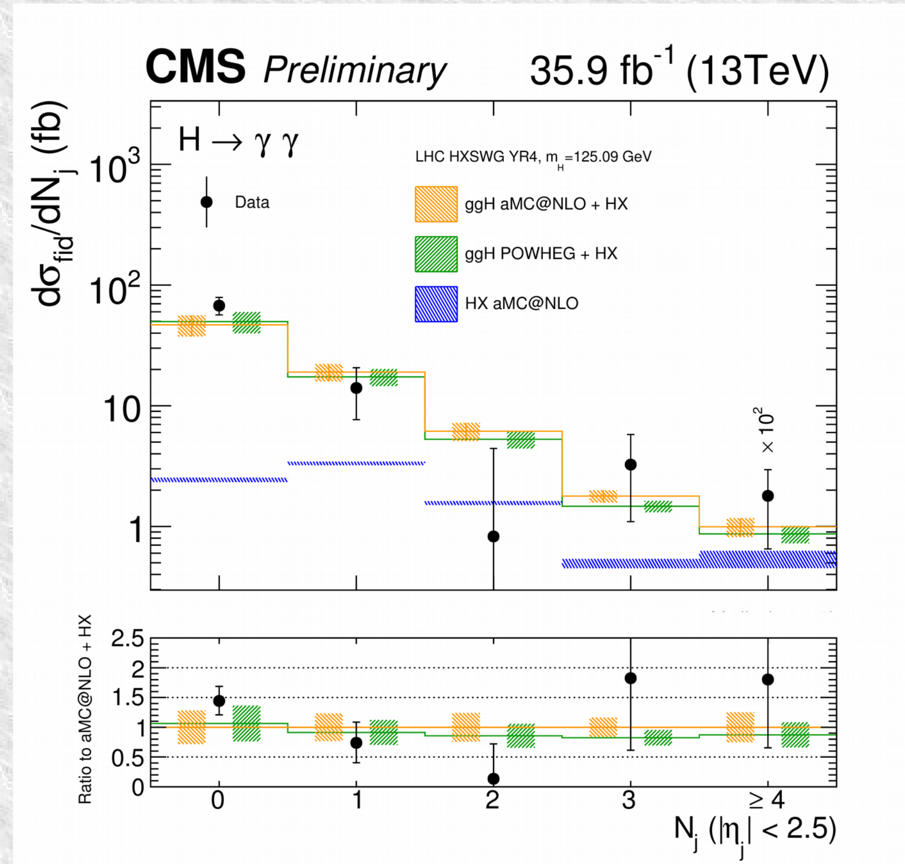




- Fiducial cross-section is shown (left)
  - The most precise fiducial Higgs cross-section yet

$H \rightarrow \gamma\gamma$ CMS



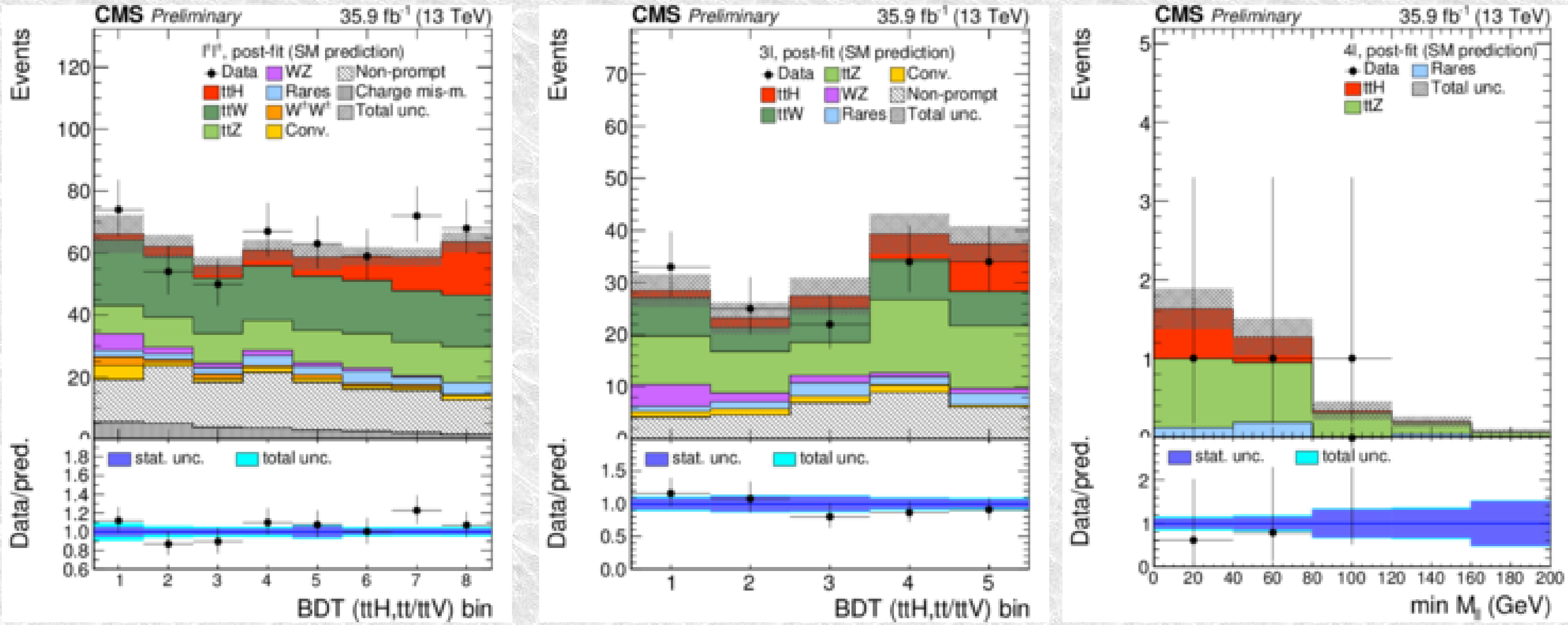


- p_T (left) and N jets (right)
  - Both in good agreement with predictions

ttH multileptons, CMS

- ttH into multileptons analyses H→WW, ZZ, ττ
- showed excess in Run 1 in ATLAS and CMS
  - Also true in summer partial results
- CMS have full-2016 data analysis ready
- Many modes used:
  - ll same-sign dilepton
  - 3l
  - 4l (Z veto)
  - 1l+2τ
  - 2l+1τ
  - 3l+1τ

ttH multileptons, CMS



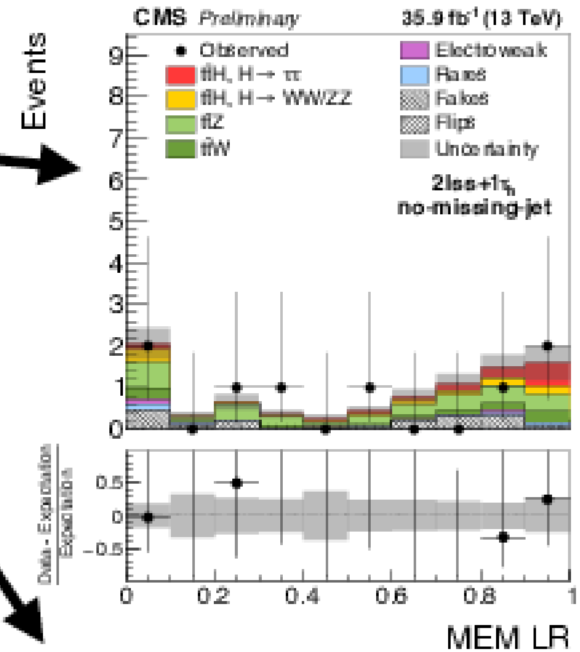
- The non tau categories show reasonable agreement with SM expectation
  - But there is a hint of overproduction in same-sign ll

$t\bar{t}H, H\rightarrow\tau\tau$ discriminants

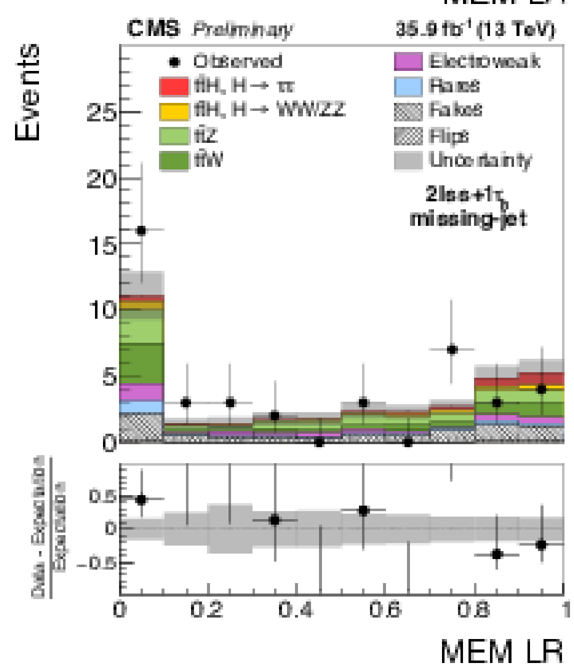
CMS HIG-17-003

$2\ell ss+1\tau_h$
- **MEM** likelihood ratio with ttH vs ttZ and ttbar hypotheses

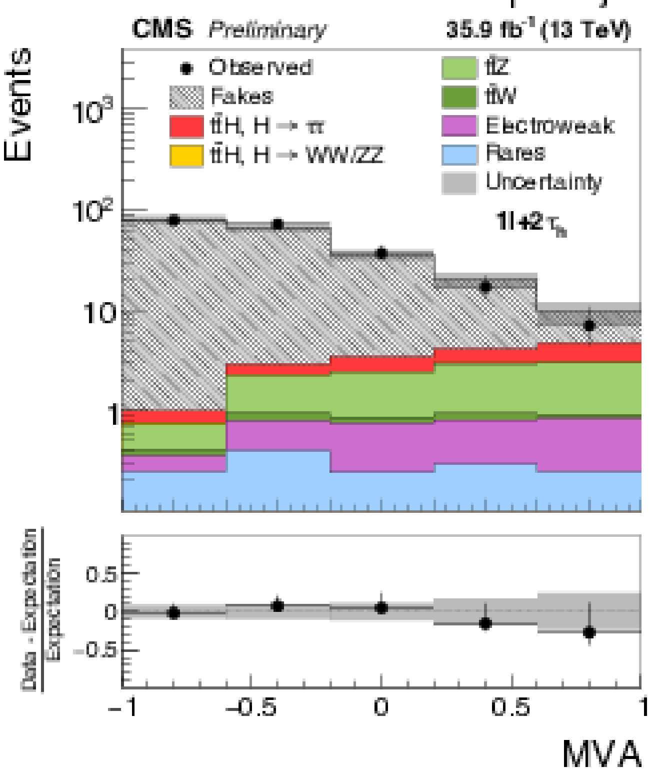
no missing jet



with missing jet

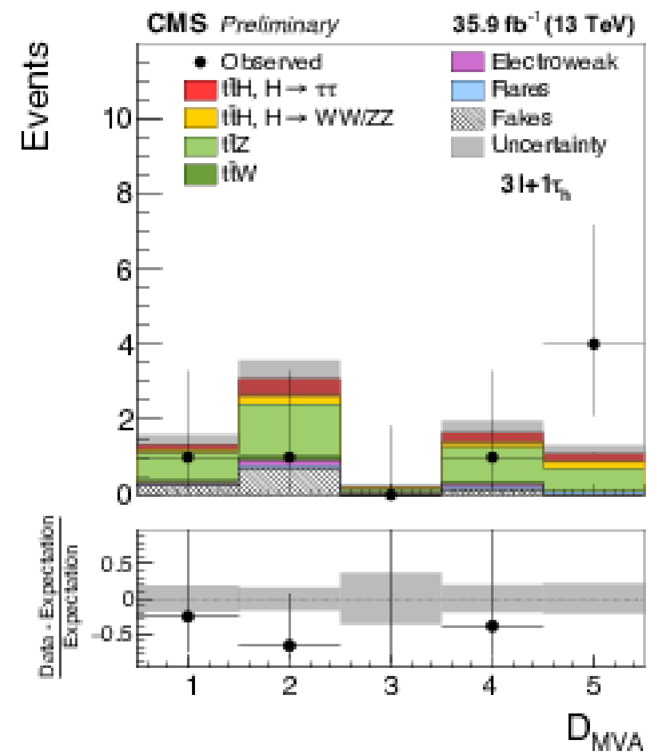


$1\ell+2\tau_h$
- **BDT** trained against ttbar
- **jets faking τ_h :** fake rate measured in ttbar eμ+1jet data



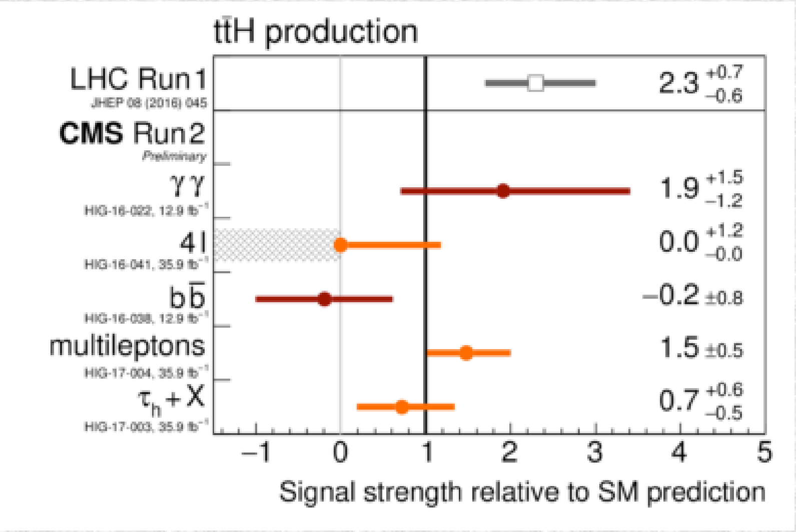
$3\ell+1\tau_h$

2BDTs: against ttV and ttbar + 1D mapping



ttH → multileptons CMS

- Two new measurements of ttH in multilepton
- Scatter around μ=1
  - Perfect agreement with SM
- Each of them more sensitive than the total LHC combination from Run 1
  - Achieved by attention to detail
- The fakes background is large in these analyses
  - Good: if it can be reduced
  - But a real problem to control if it cannot

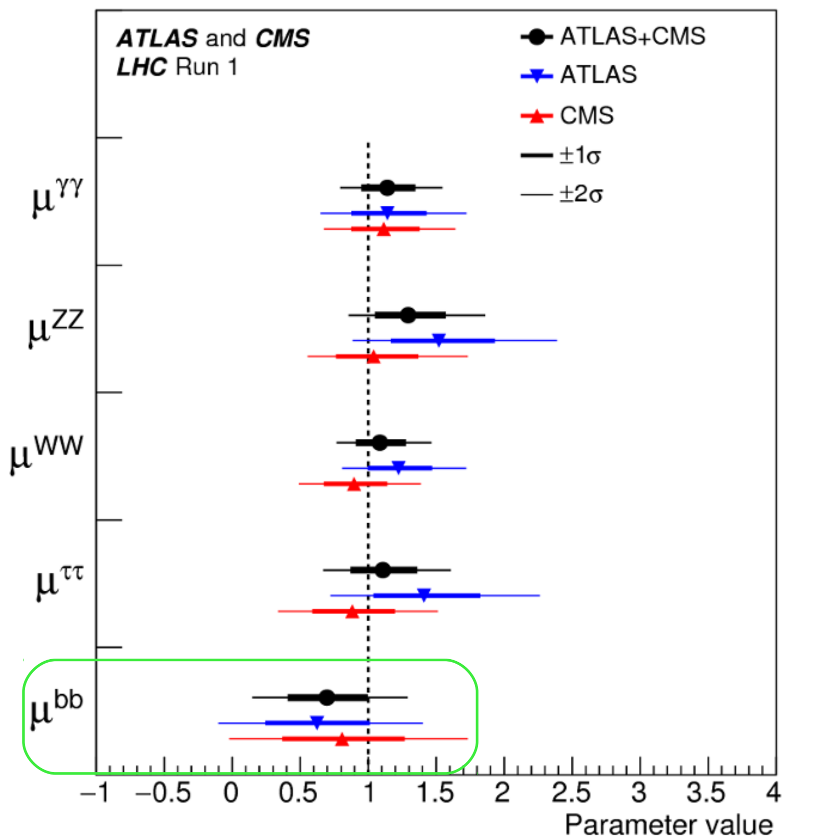


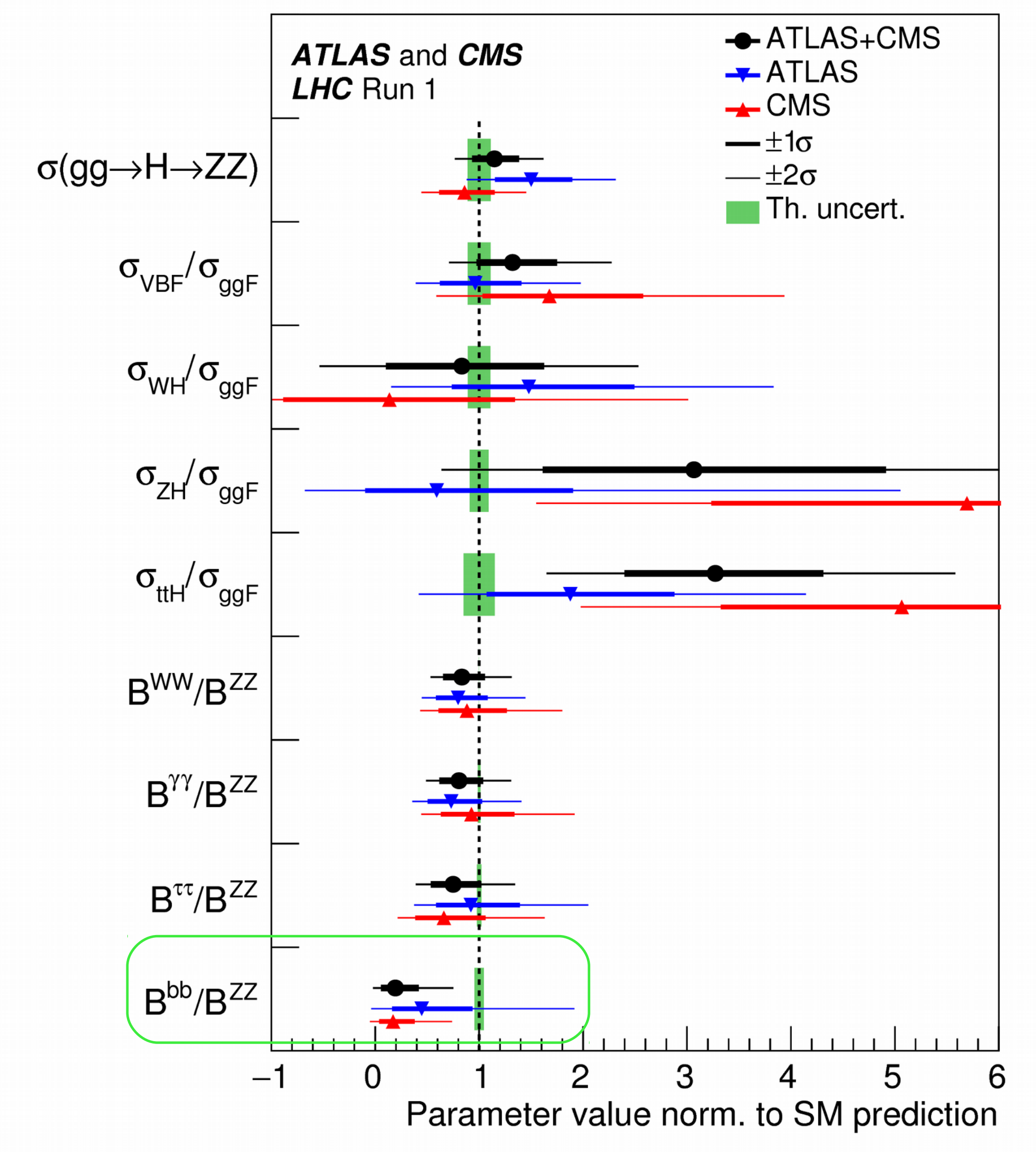
Science & Technology Facilities Council
Rutherford Appleton Laboratory

WARWICK
THE UNIVERSITY OF WARWICK

H→bb: Run 1 ATLAS+CMS

- $\mu = 0.70^{+0.29}_{-0.27}$
- $B^{bb}/B^{ZZ} = 0.20^{+0.20}_{-0.12}$
- Is all well?





H→bb in Run 2

- Analyses considered:

	ATLAS All results	CMS papers and preliminary
ttH	ATLAS-CONF-2016-080 13.2fb^{-1}	CMS-PAS-HIG-16-038, 12.9fb^{-1}
~~tH~~		~~CMS-PAS-HIG-16-019, 2,3fb^{-1}~~
VBF	ATLAS-CONF-2016-063 Hγ, 12.6fb-1	CMS-PAS-HIG-16-03, 2.3fb^{-1}
VH	ATLAS-CONF-2016-09113.2fb^{-1}	

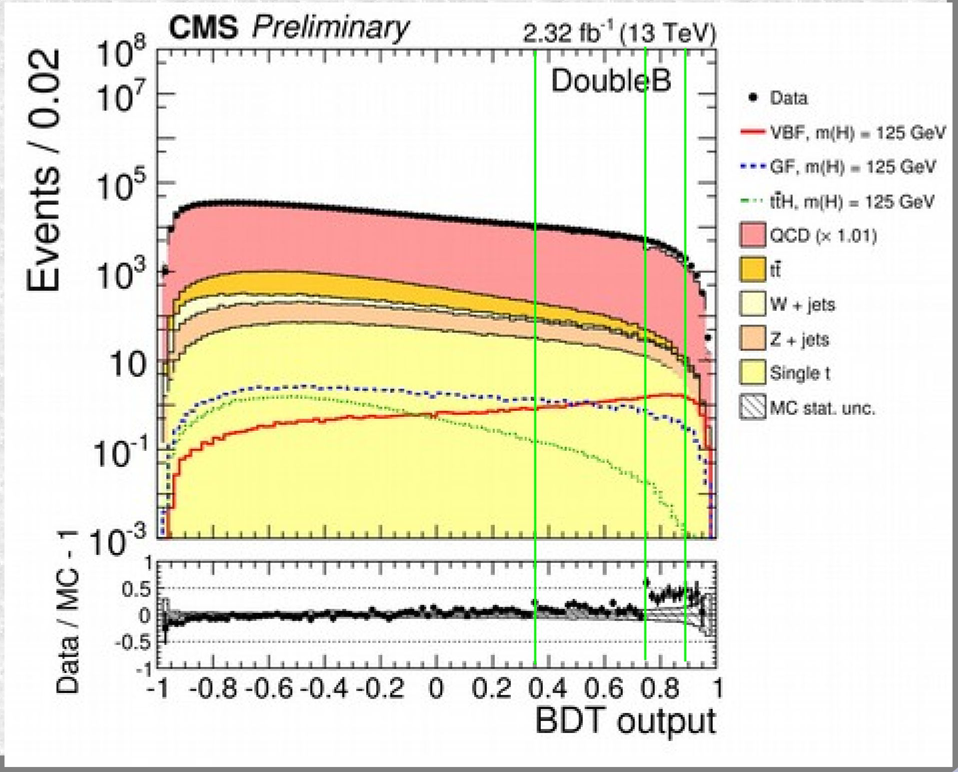
- (tH is in backup for time reasons)
- None use full 2016 dataset
- But Higgs sample far exceeds Run 1 in ttH

VBF H→bb

- CMS results from 2.3 fb^{-1}
- Highest rate analysis attempted...problem is background.
- Trigger is critical. Two strategies
  - L1 (common), 3 jets, one of them can have $|\eta| > 2.6$
  - HLT (common): 4 jets, p_T> 92, 76, 48 & 15 GeV
  - Either 1b, 2 others m > 460 GeV
  - Or 2b, 2 others m > 200 GeV
- Total trigger efficiency 6.2%, (3.9% from 2b)
- Analysis preserves 2 channel, adds angular cuts

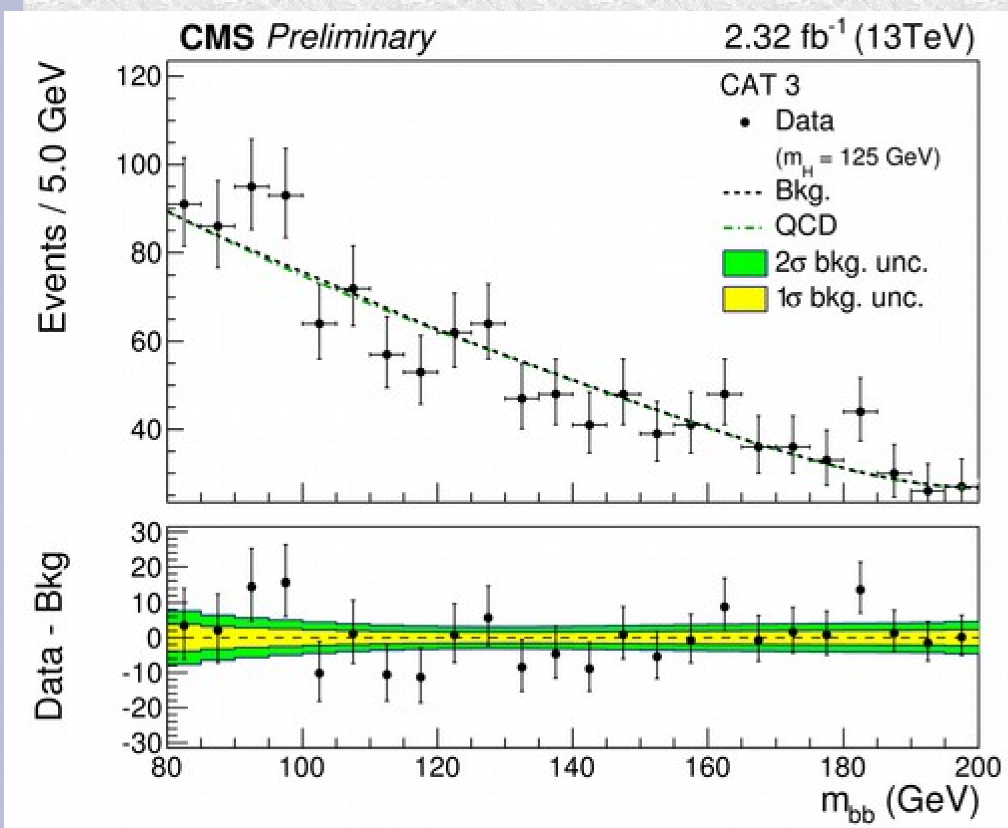
VBF H→bb

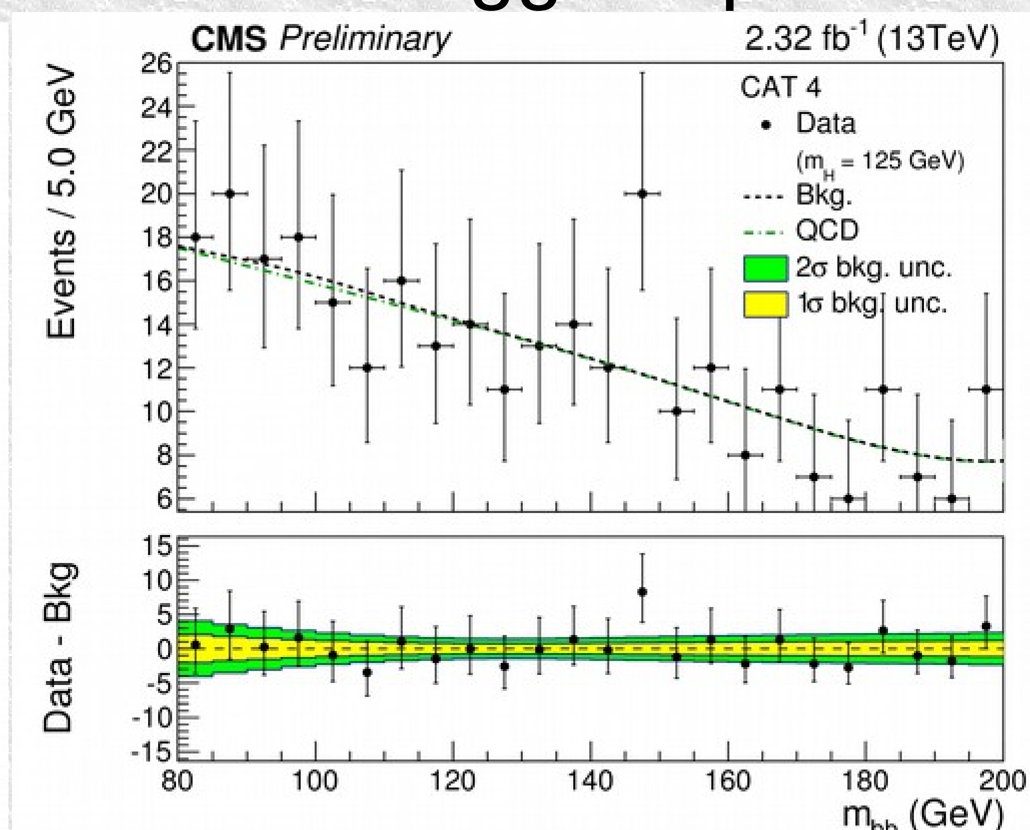
- BDT used to separate H from background
  - Dynamics of VBF system
  - B-jet content of event
  - Minor RMS of q-jet candidates (q/g separation)
  - Gap activity (no. jets above 5 GeV, pT of 5th jet)
  - H production angles
  - p_T,p_L of 4-jet system
- Classifier output for 2b shown right
- Multiple signal regions:
  - 1b has 4
  - 2b has 3 → shown



VBF H→bb fit

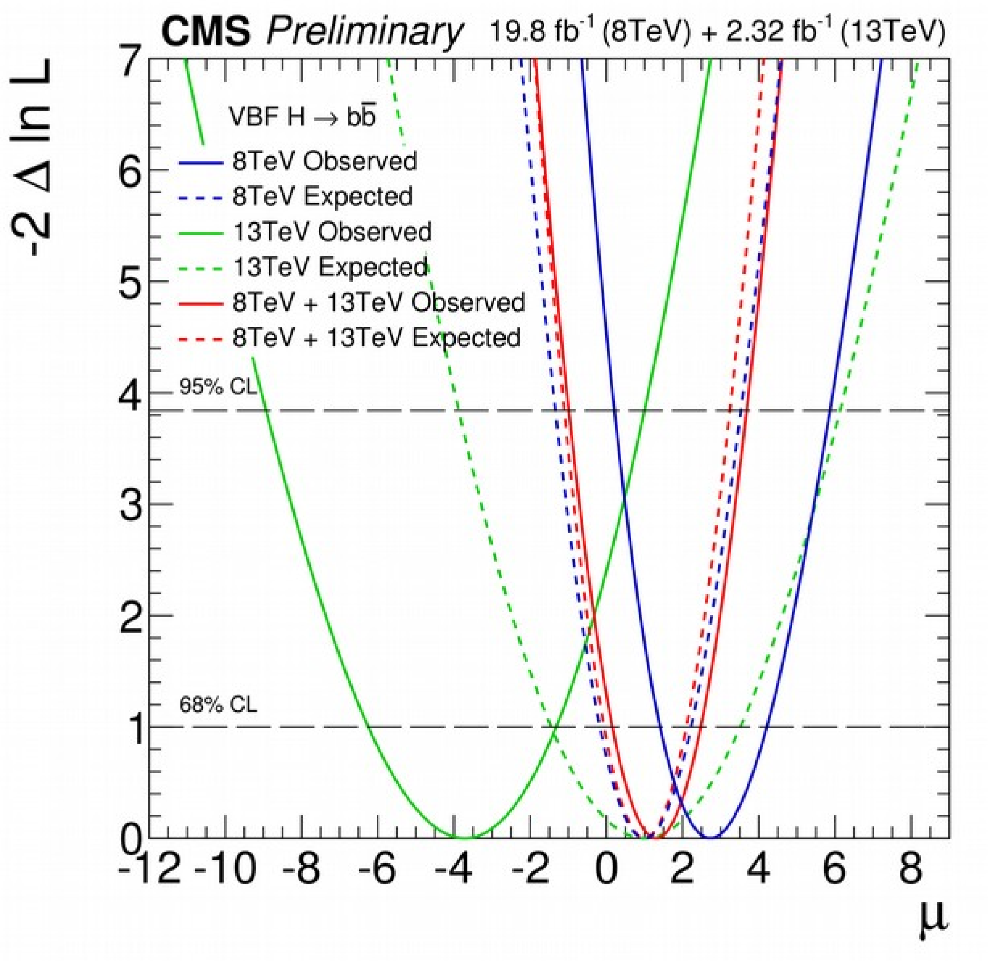
- 7 signal regions, from 300 to 70000 events
- 98% of background or more is multijets (QCD)
  - QCD polynomial constrained between categories
- Best 2 regions shown, 7.8 and 4.4 Higgs expected



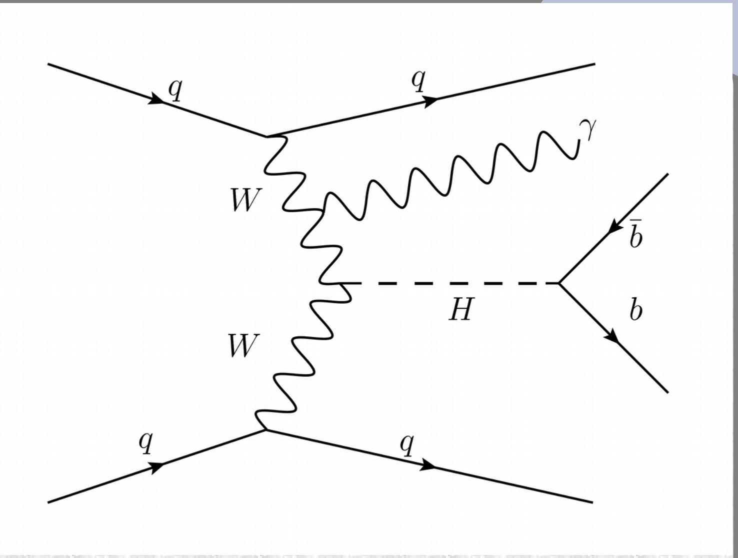


VBF H→bb results

- Systematics small as background mostly from fit
  - Though delicate inter-region fixing
- $\mu=-3.7^{+2.4}_{-2.5}$
  - Compatibility 3% with SM
- Note that combination with 2012 gives $\mu=1.3^{+1.2}_{-1.1}$



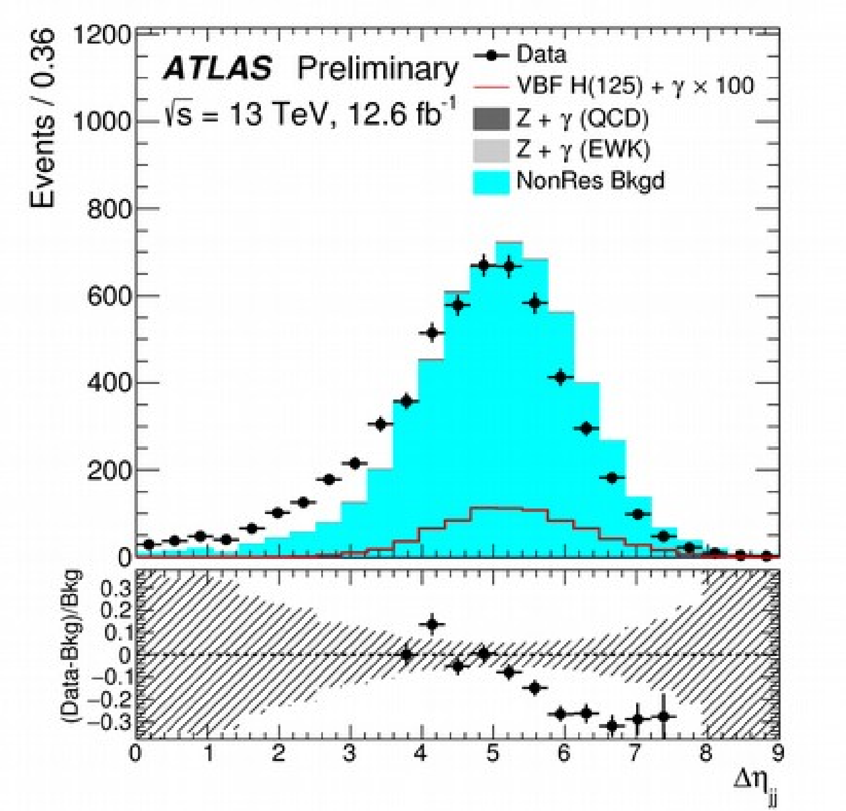
VBF γH→γbb

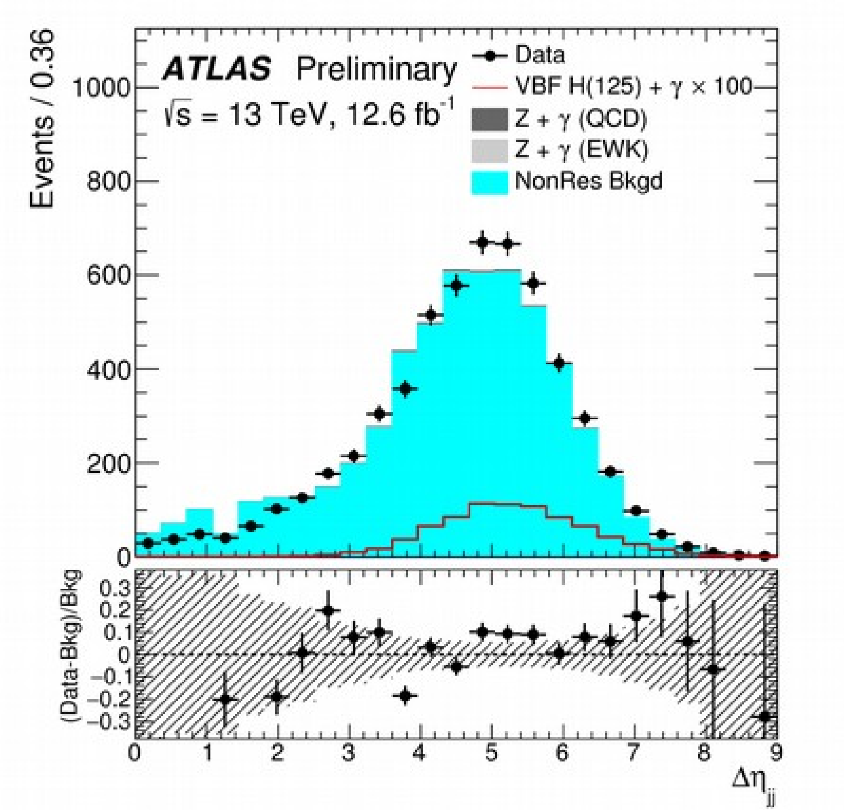


- ATLAS search for same channel, but use photon as a tag
  - Rate much reduced
  - But s/b enhanced as gluons not charged & interference in backrnd.
- Trigger is simpler
  - L1: Photon 22 GeV E_T
  - HLT: γ, 4j p_T>35, m_{jj}>700 GeV
- No b's, but p_T & mass tighter than CMS…
- This is complementary to VBF H→bb

VBF γH → γbb

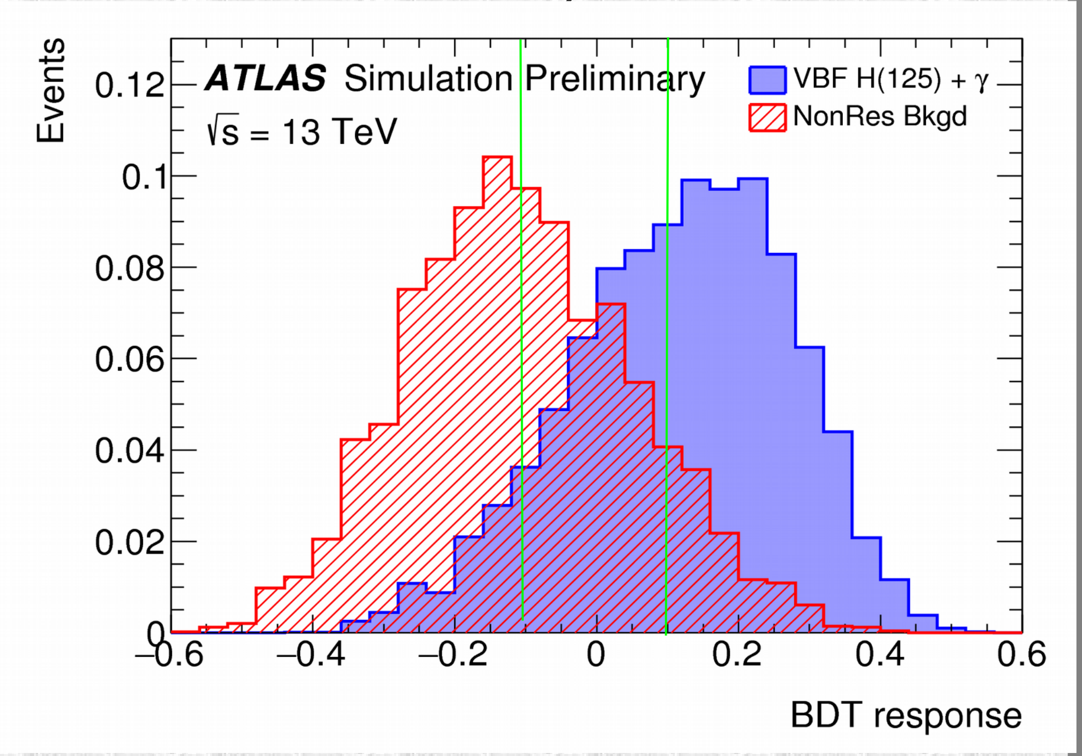
- BDT filled with similar variables to CMS
  - 7 variables, less than CMS but in same areas.
  - $\Delta\eta_{jj}$, between tag jets, is badly modeled,
    - reweighted using m_{jj} sideband data





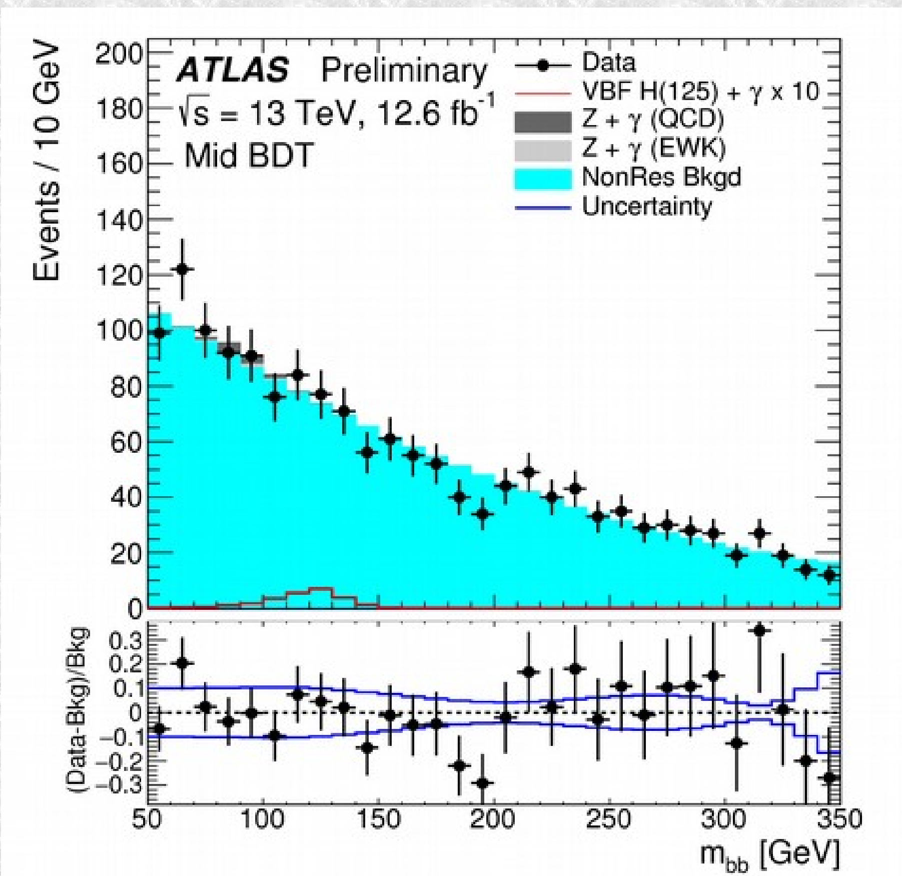
VBF γH → γbb

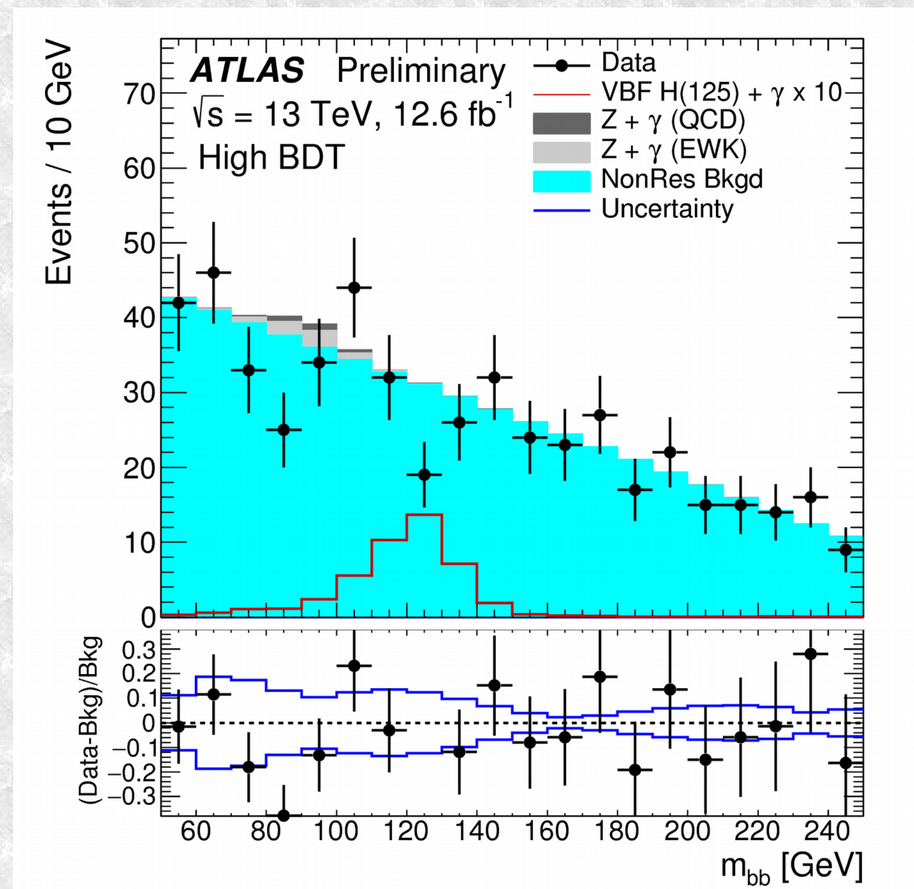
- BDT data distribution is not shown by ATLAS
- Signal and background simulations are, below
  - Three regions are used
- Best has 4.4 Higgs expected,
  - Same as CMS best
    - Bkg density similar too
  - But other regions poorer
  - And this analysis has 4x the luminosity…
  - (In 2012 ATLAS VBF similar to CMS result)



VBF γH→γbb results

- Fitted signal strength $\mu = -3.9^{+2.8}_{-2.7}$
- Upper limit is at 4 x SM rate





VH→(ll/lν/νν)bb

- ATLAS results from 13.2 fb^{-1}
- 3 channels: Z→ll, W→lν, Z→νν
  - ll has low rate, but clean
  - lν maximum rate, but large top background
  - νν best overall – slightly.
- Vector boson provides trigger
  - Leptonic triggers, with isolated e/μ 20-24 GeV lowest
  - Most problematic in νν channel;
    - Threshold ~90 GeV (2016) 70 GeV in 2015
- Analyse in two jet bins: 2jets or 3 jets (3+ in ll)
  - 2 b jets

VH→(ll/lν/νν)bb channels

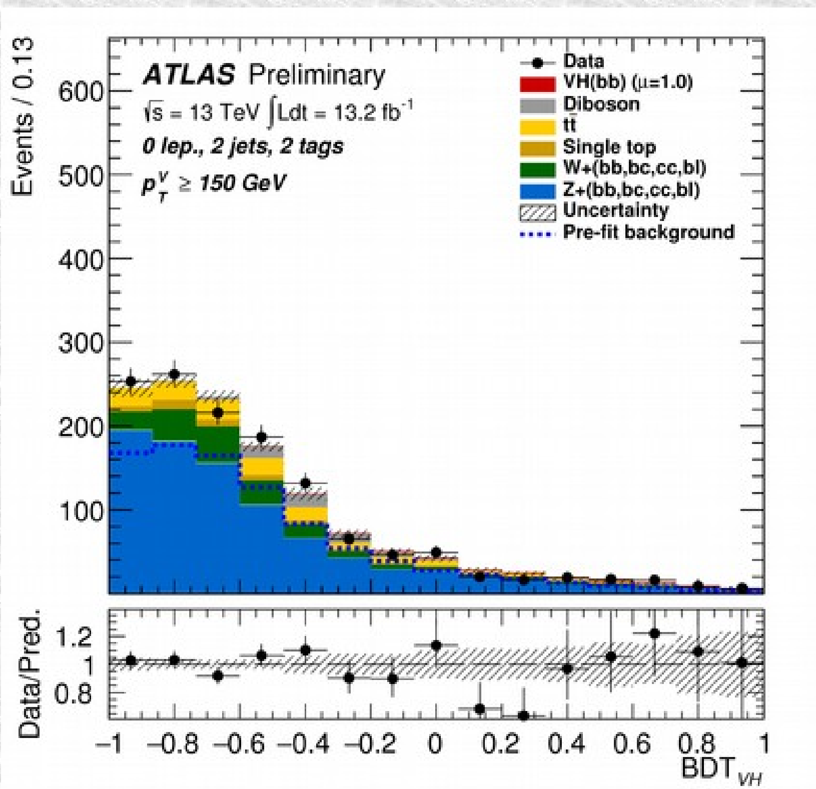
- All 3 channels are analysed with $p_{T,V}$ > 150 GeV
  - ll has additional region, $p_{T,ll}$<150 GeV
  - Thus there are 8 channels in all, marked 'BDT' below:

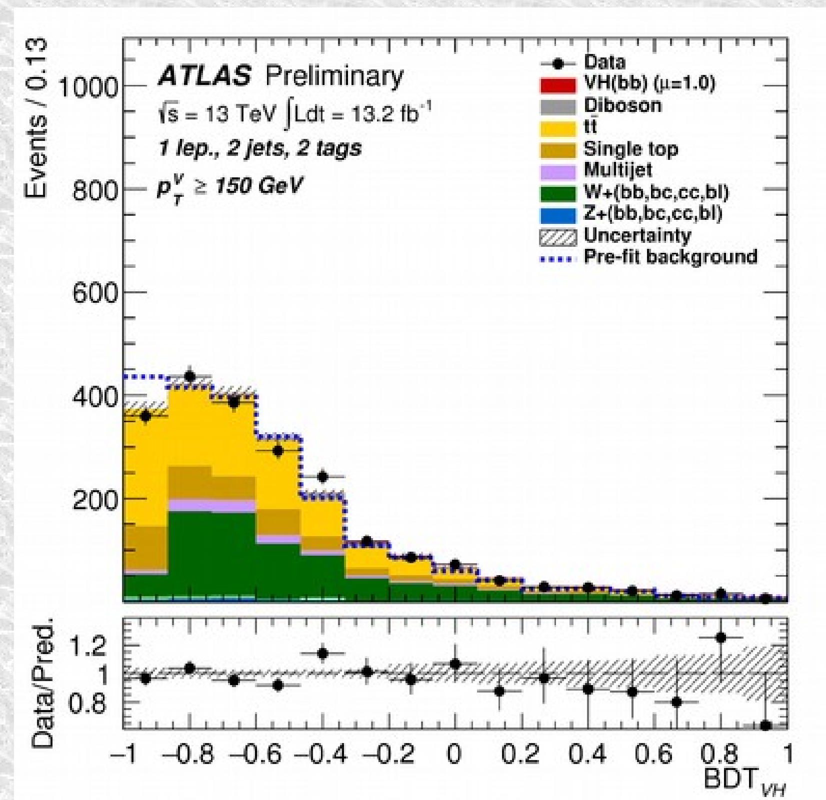
Channel	Categories					
	2 b-tagged jets					
	$p_T^V < 150$ GeV			$p_T^V > 150$ GeV		
	2 jets	3 jets	≥ 3 jets	2 jets	3 jets	≥ 3 jets
0 lepton	-	-	-	BDT	BDT	-
1 lepton	-	-	-	BDT	BDT	-
2 lepton	BDT	-	BDT	BDT	-	BDT

- Several channel-specific selections used
  - e.g. on angles in the 0-lepton analyses
- All channels have statistical sensitivity within a factor 3 of the best

VH→(ll/lν/νν)bb BDT

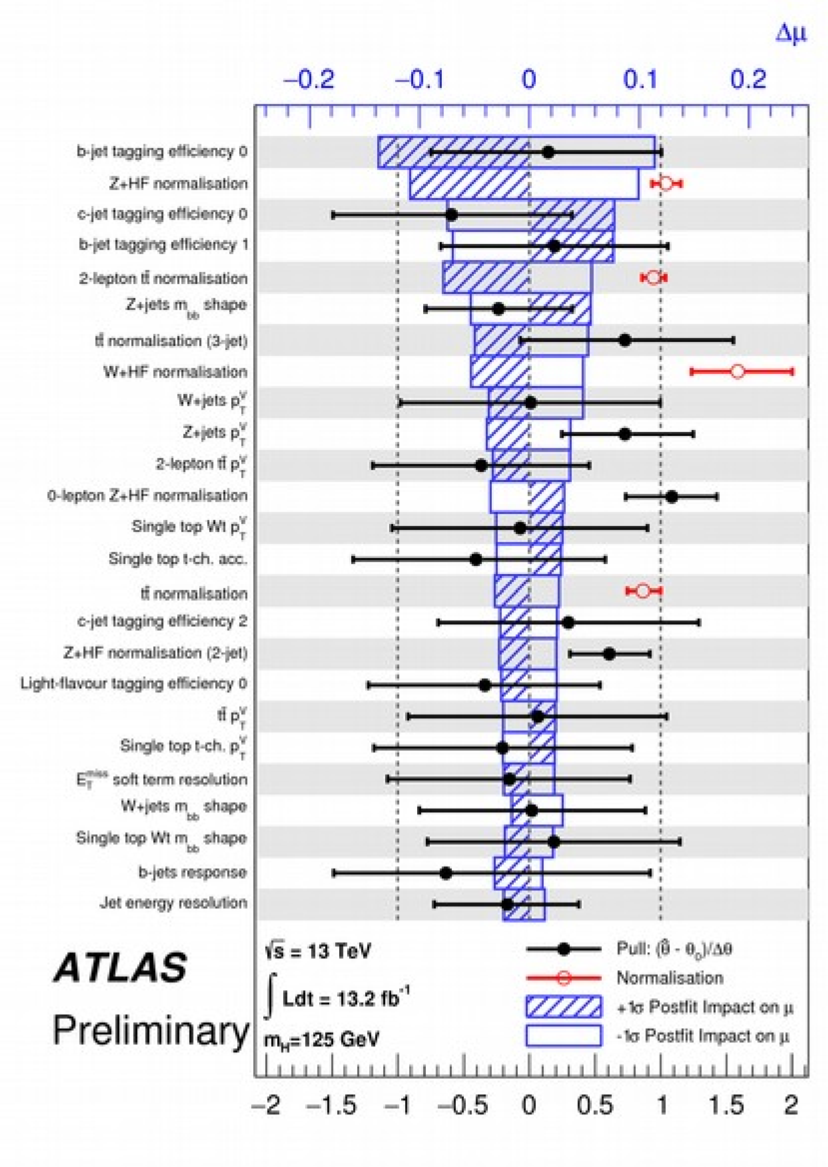
- As usual, a BDT characterizes signal
  - Using b-jet p_T, m_{bb}, E_T^{miss}, kinematics, lepton m/m_T etc.
- BDT approaching 1 is the signal region
  - background composition in 0-lep, 1-lep visible below





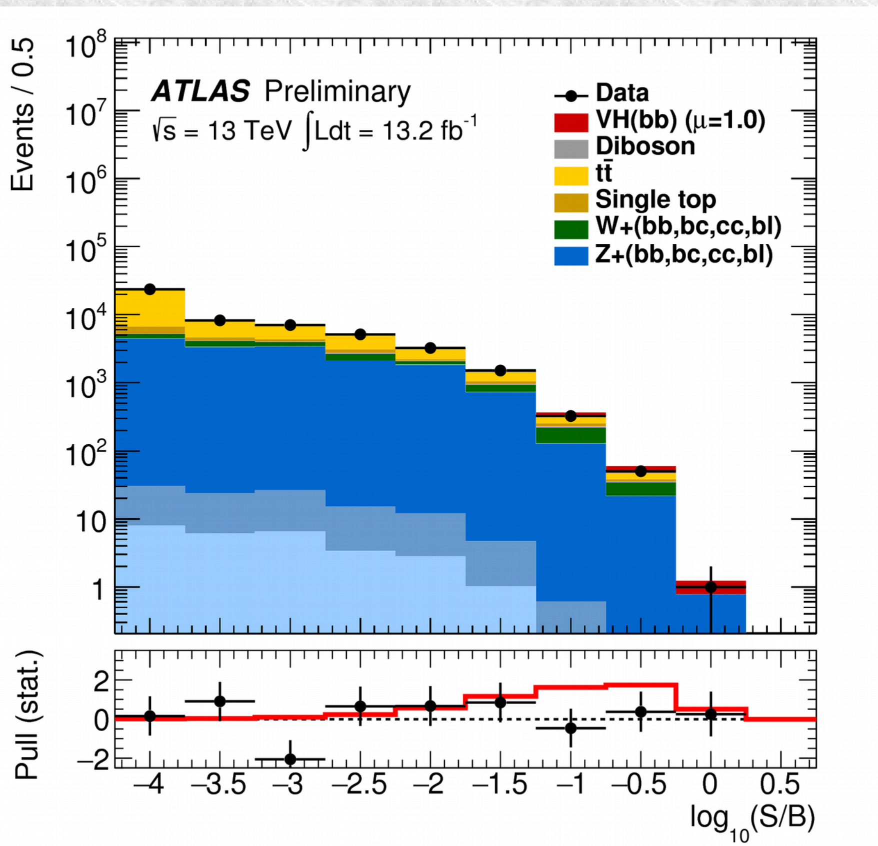
VH → (ll/lν/νν)bb systematics

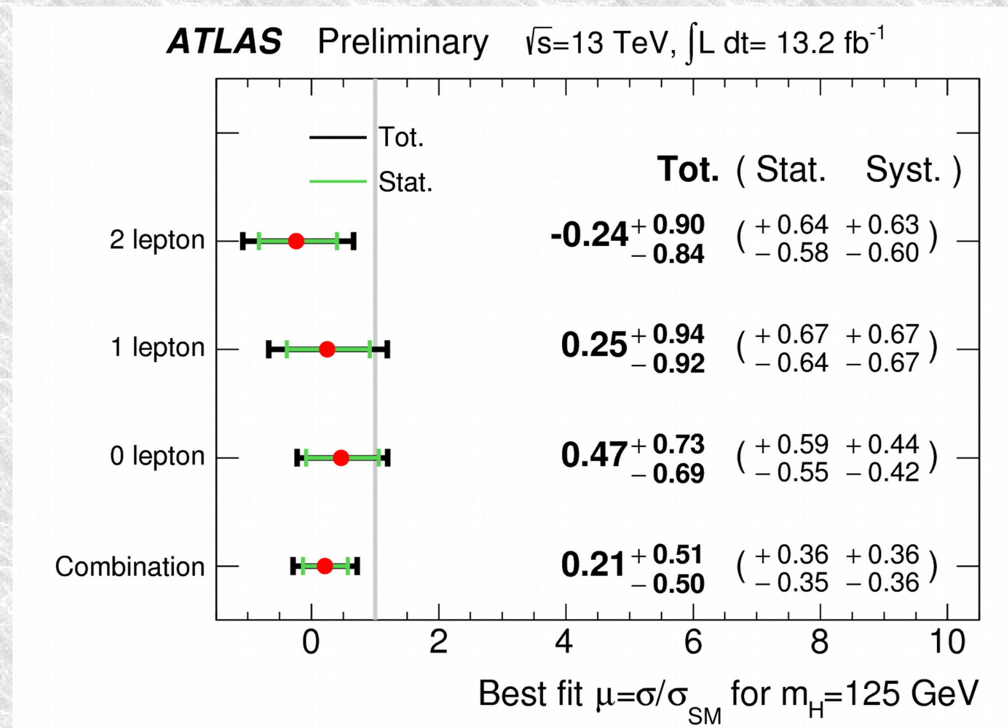
- The pull plot describes the systematics & their impact
- Blue shows the change in signal from 1σ change in systematic
- Red shows fitted strength of free parameters (where 1 is SM expectation)
- Black the post-fit pull of constrained parameters
- b/c tag takes 3/4 top slots
- Z+hf normalization 2nd



VH→(ll/lν/νν)bb results

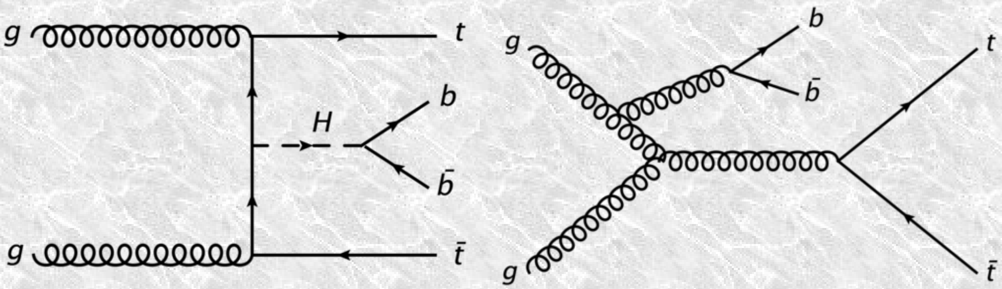
- Fitted signal 0.21±0.51
- Stat and sys errors comparable
- Check: same on VZ yields 0.91±0.17(stat)±0.3(sys)





ttH, H→bb

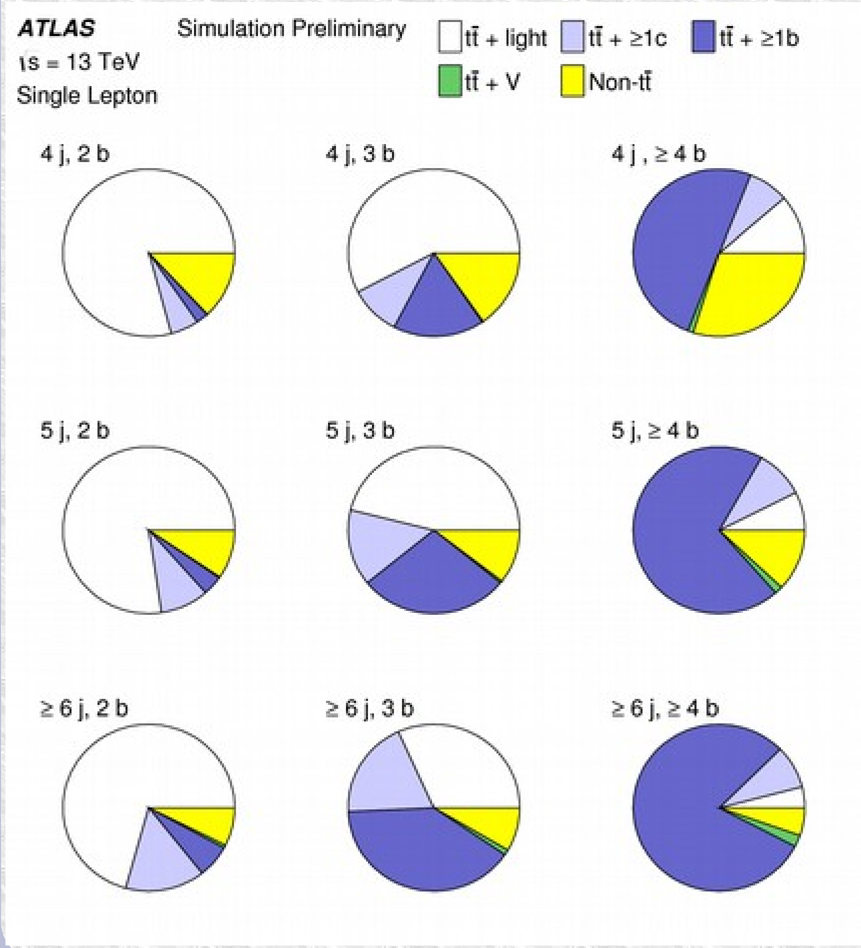
- ATLAS and CMS have results with ~13fb^{-1}
- ttH cross-section increased factor 3.8 w.r.t 8 TeV
  - Good expectations…
  - But complex state

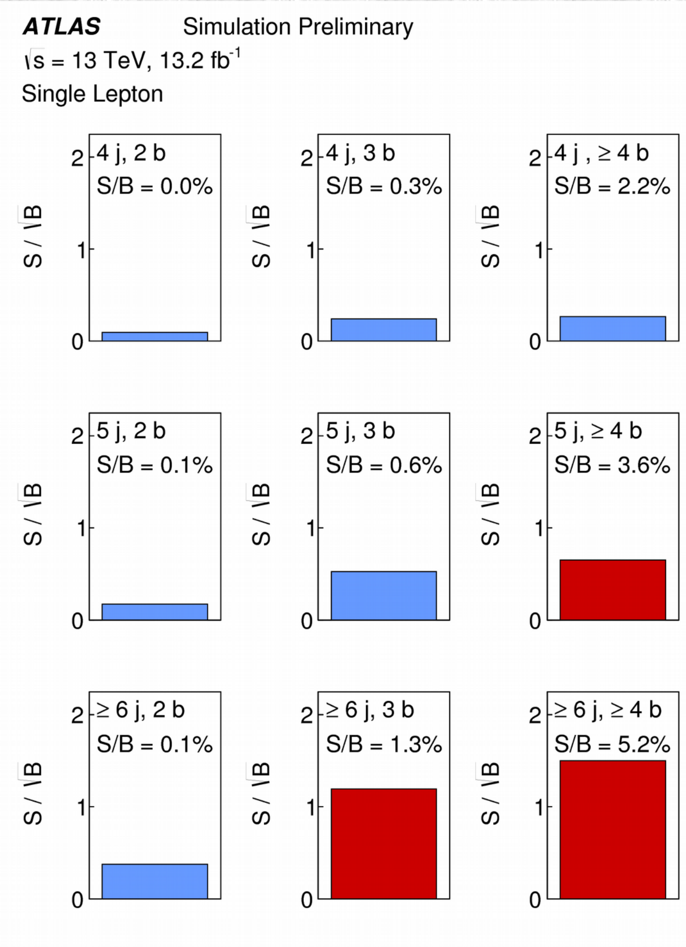


- Analysis two paths:
  - Leptonic, (6 quarks, 4b)
  - Dileptonic (4 quarks, all b)
- Signal to backgrounds are not great
  - ttbb ‘irreducible’ far exceeds signal
- Complex distributions & assignment confusion make bump-hunt impractical
- CMS used boosted region in 2015 – it will be back!
- ►Fully BDT/ME driven analysis

ttH, H→bb analysis

- Each channel (l,ll) is divided by N_{jets} and N_b
- Background composition & s/√b (ATLAS) below:



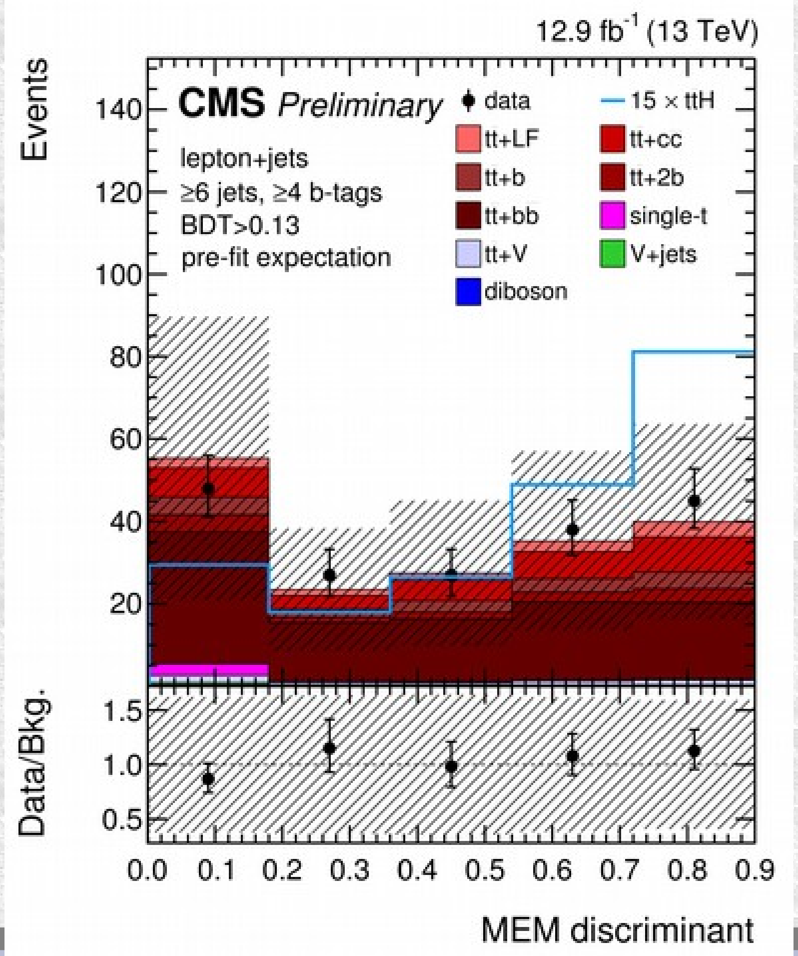


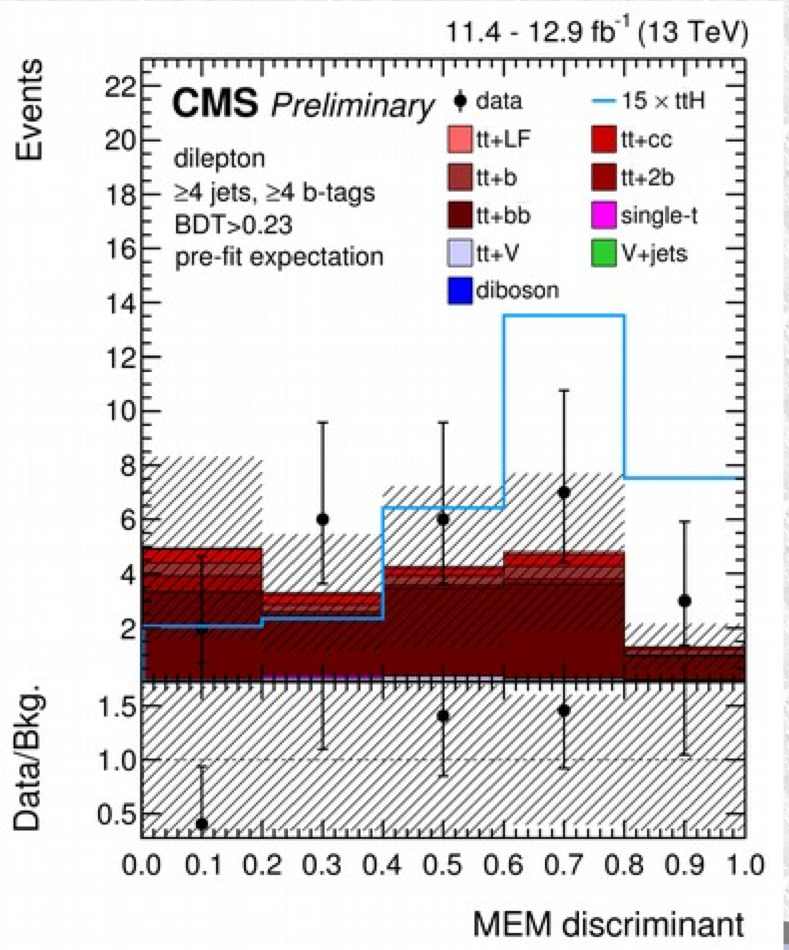
ttH, H→bb background

- The signal regions have large tt+b background
  - Both ATLAS and CMS simulate with PowHeg v. 2
- CMS use NNPDF3.0
  - Underlying event custom Pythia tune, from CUETP8M1
  - Fixes α_s^{ISR} and h_{damp} using 8 TeV data
- ATLAS use CT10
  - h_{damp} set to m_t, p_T of tops and $t\bar{t}$ reweighted to NNLO
  - Parton shower: Pythia 6.428, CTEQ 6L1 and Perugia 2012 UE
- Each define $t\bar{t}+b\bar{b}$, $t\bar{t}+b$, $t\bar{t}+2b$, $t\bar{t}+c\bar{c}$, $t\bar{t}$+light, $t\bar{t}$+V,t
  - ATLAS fits overall b,c,l rates, with b classes modelled
  - CMS adds 50% *additional* uncertainty to each rate
    - report 10% degradation in mean limit from this

ttH, H→bb analysis

- Each subchannel then has a BDT applied
  - CMS (below) used MEM on data split by BDT first
    - Gets to good s/b in highest bin

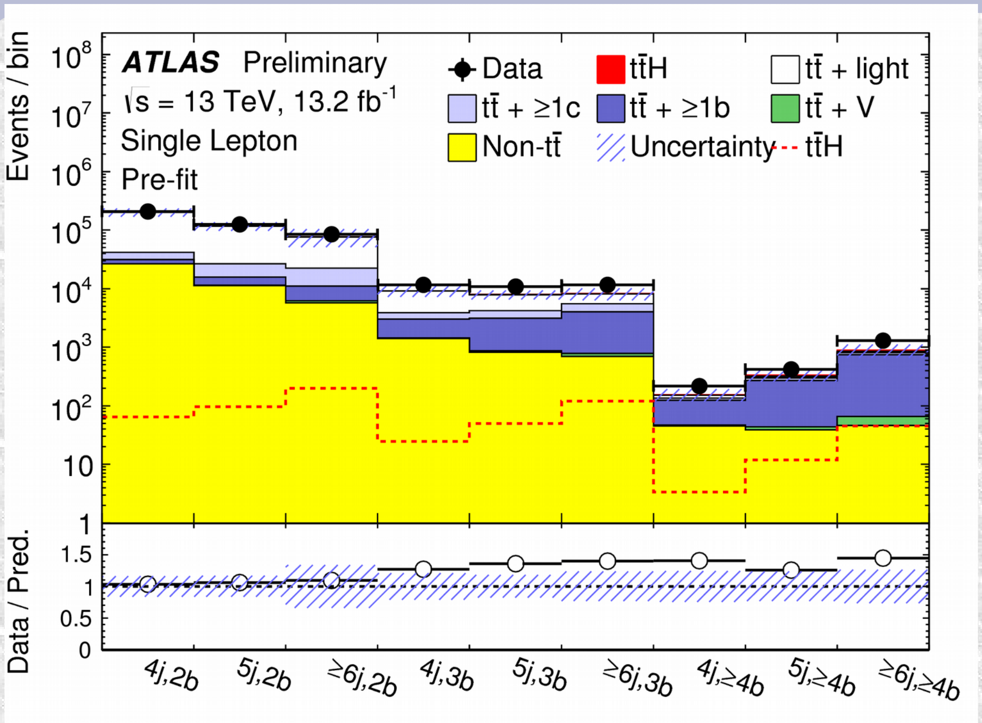


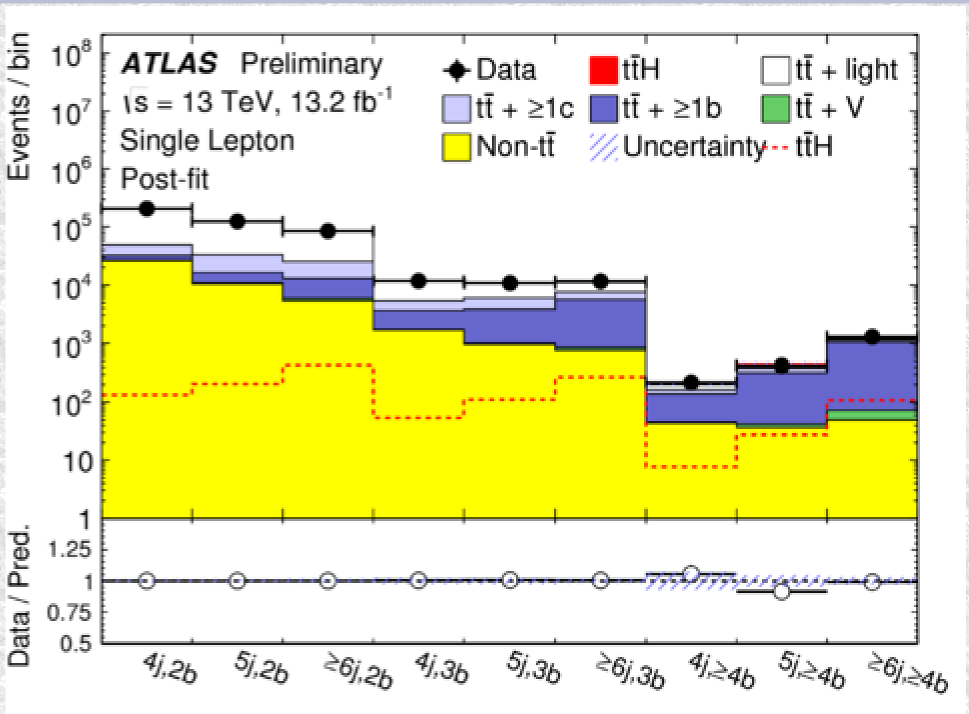


Top modelling

- Top modelling needs (and is getting) attention
  - Both theoretically and experimentally
- Overall we have to be impressed at how good it is
- But with > 30M top in 2016 it is challenging
- ATLAS ttH in 2016 showed about a factor 1.5 mismodelling of event numbers in 6j4b
  - C/f Powheg+Pythia 6 (CMS better)
- 890 expected (80% tt+>=1b), 1285 observed
  - Had been factor 2 in 2015.
  - ttbb and ttcc cross-section predictions were not used
    - Fitted from data: ttbb 1.33±0.18 (c/f 3% error on bin 6j4b)
    - While using NNLO calculations of shapes & uncertainties
      - ttbb is Sherpa+OL, NLO+massive b quarks

The effect of fitting



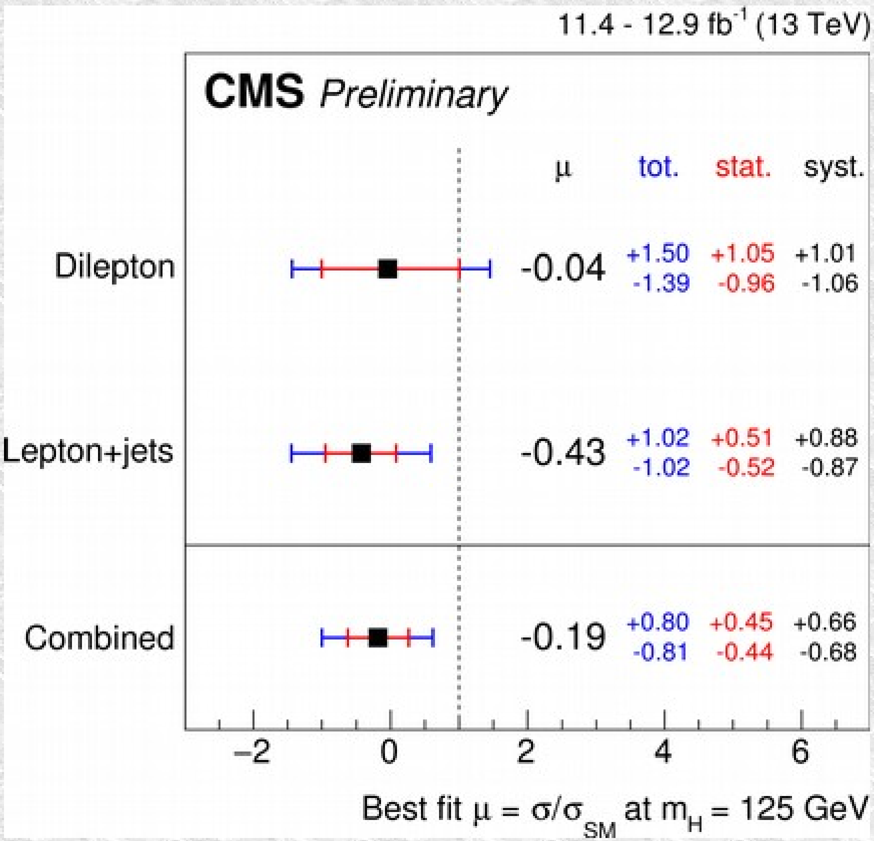


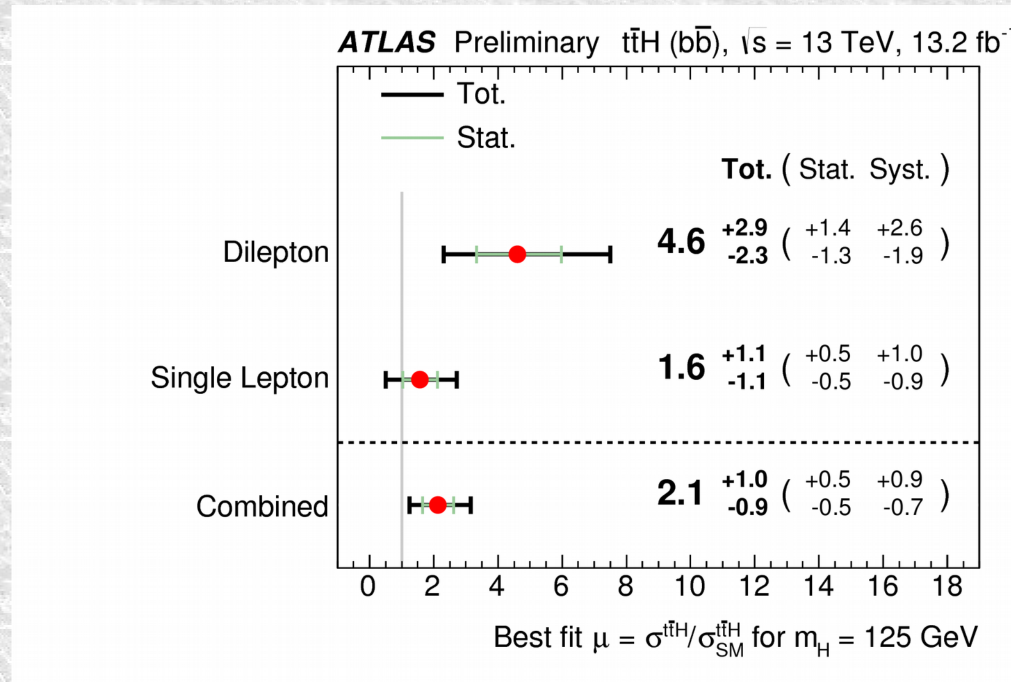
- Pre-fit shows modelling issue
- Post-fit agreement looks good
  - But this is largely by construction
  - Pulls on nuisance parameters need to be understood

Science & Technology Facilities Council
Rutherford Appleton Laboratory

WARWICK
THE UNIVERSITY OF WARWICK

ttH, H→bb results





Conclusions

	Luminosity, fb^{-1}	μ
ATLAS ttH	13.2	$2.1^{+1}_{-0.9}$
CMS ttH	12.9	-0.19±0.80
ATLAS VH	13.2	0.21±0.51
CMS VBF	2.3	$-3.7^{+2.4}_{-2.5}$
ATLAS VBF+γ	12.6	$-3.9+^{2.8}_{-2.7}$

- The first 3 have systematics ≥ statistics
- Last two lag in sensitivity but may catch up?
- There is a pattern of low rates of H→bb
  - Naive average 0.2±0.4
- Full statistics analyses urgently awaited!

New physics searches

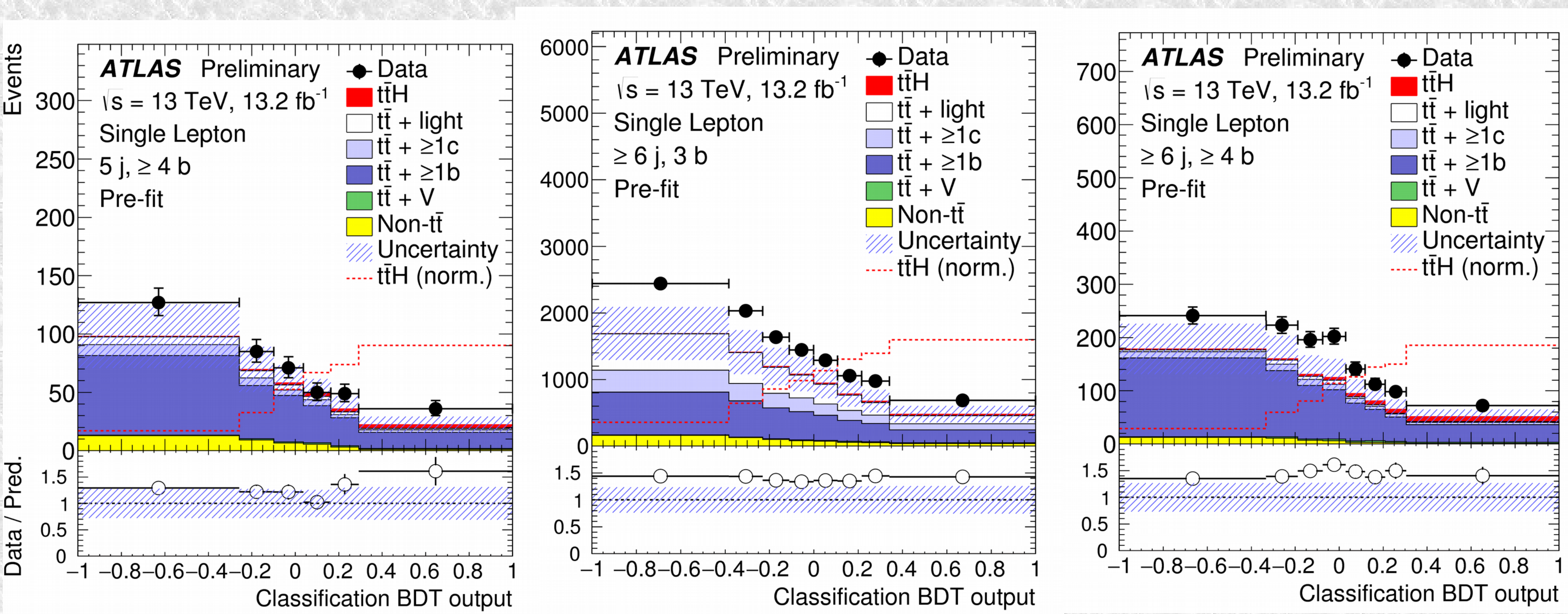
- Dozen of full 35fb results
  - SUSY
  - Exotica
  - Dark matter
  - Higgs resonances
  - Higgs decay modes
- We didn’t see anything worth mentioning.

Conclusions

- Fantastic experimental data
  - Many, many directions are being probed
  - Precision measurements and precision eory advance hand in hand
- Intriguing discoveries
  - Charm spectroscopy
- The range and variety of this conference is excellent
  - And the venue and environment does encourage interaction
  - Though the sheer density of results means time for formal discussion is limited

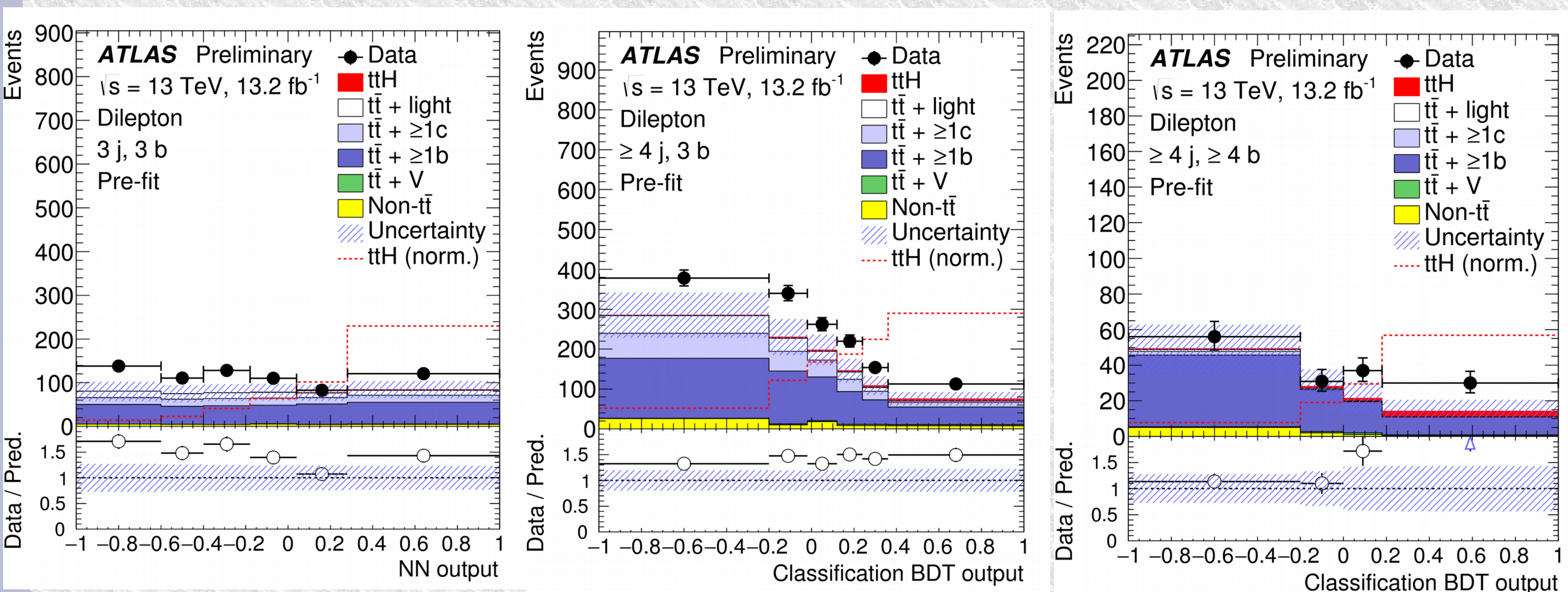
ATLAS signal: 1l

- Prefit



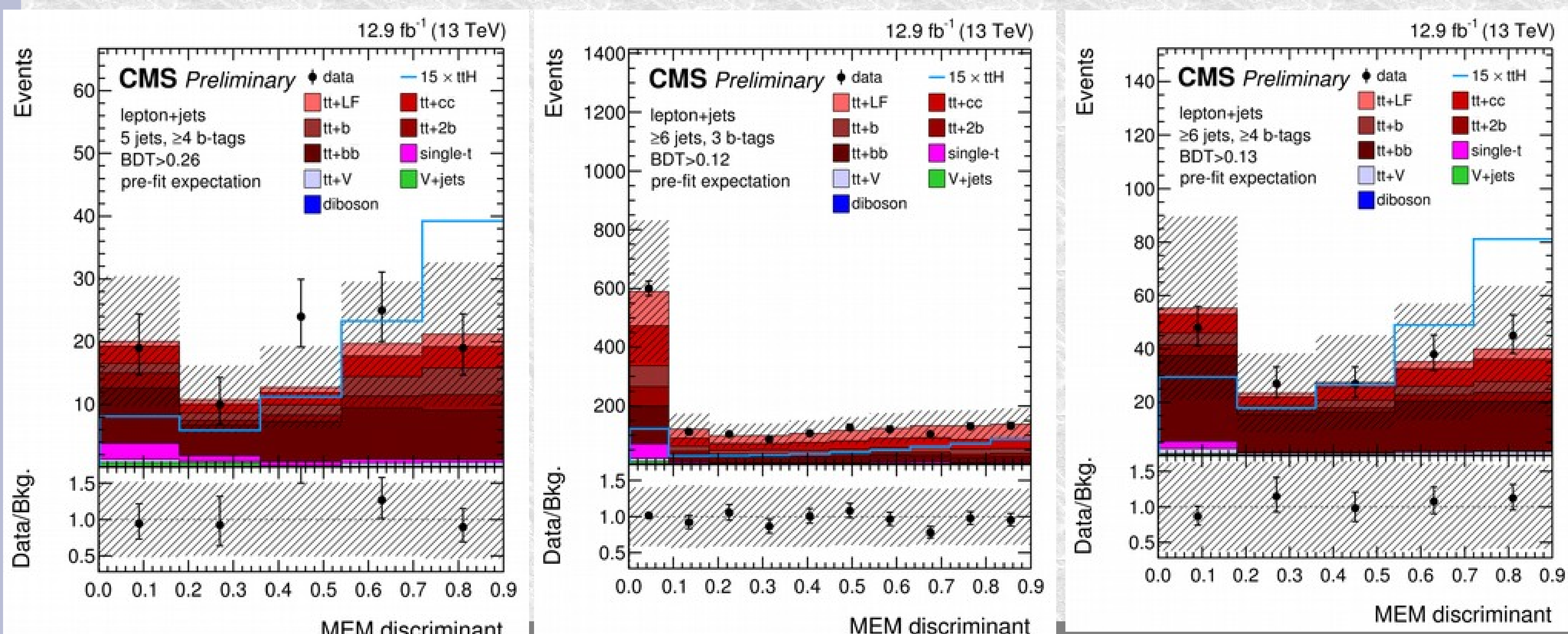
ATLAS signal: 2l

- Prefit



CMS signal region: 1l

- Pre-fit

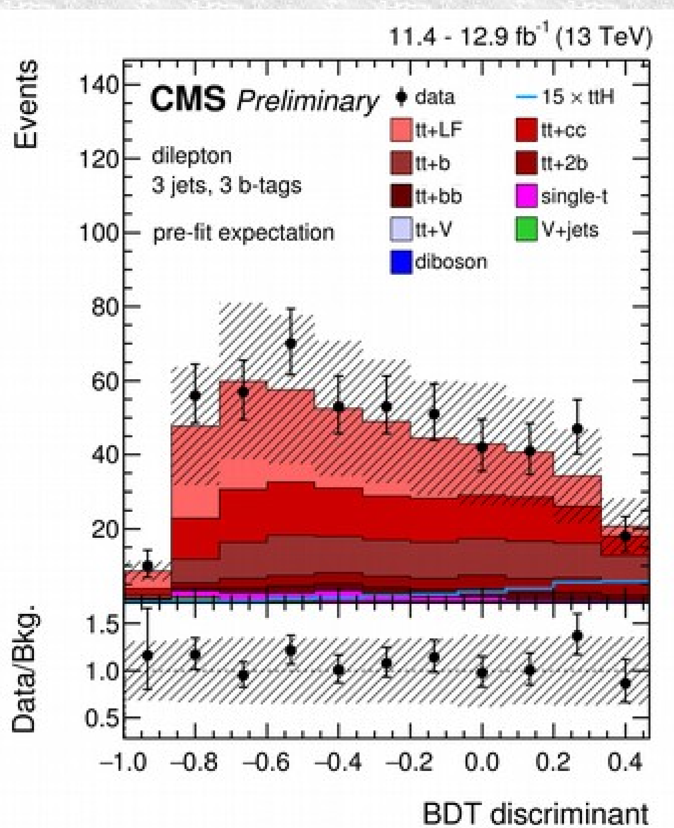


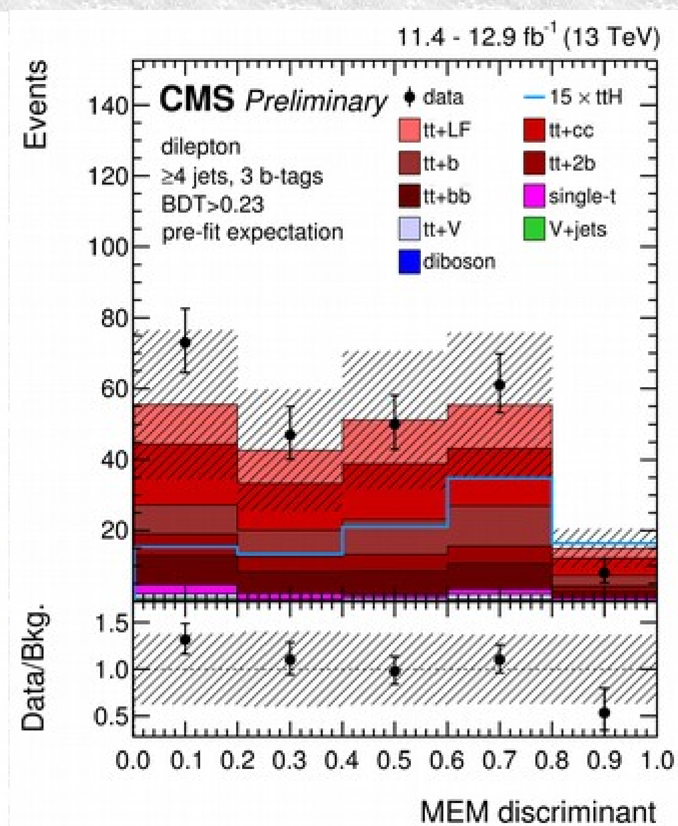
Science & Technology Facilities Council
Rutherford Appleton Laboratory

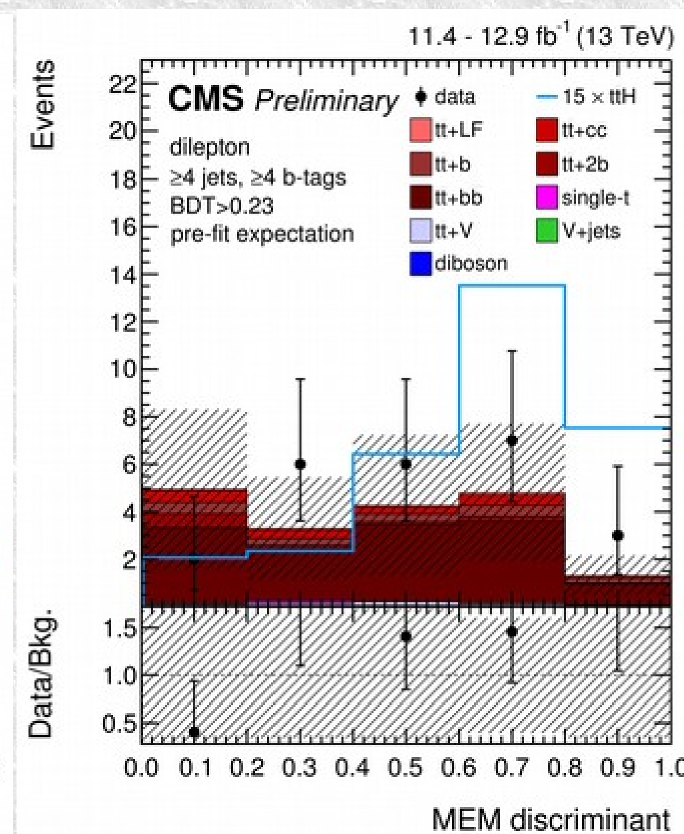
WARWICK
THE UNIVERSITY OF WARWICK

CMS signal region: 2l

- Pre-fit

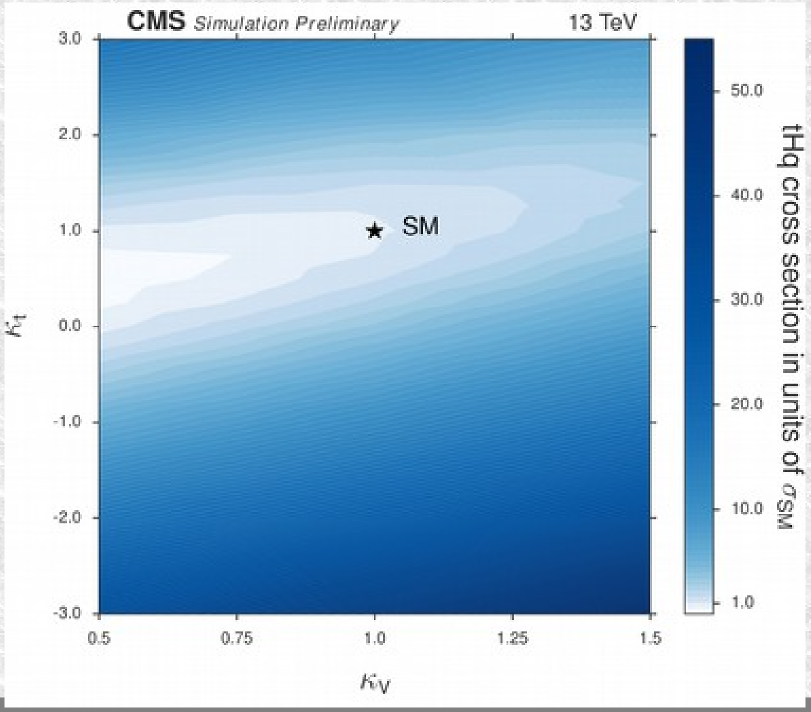


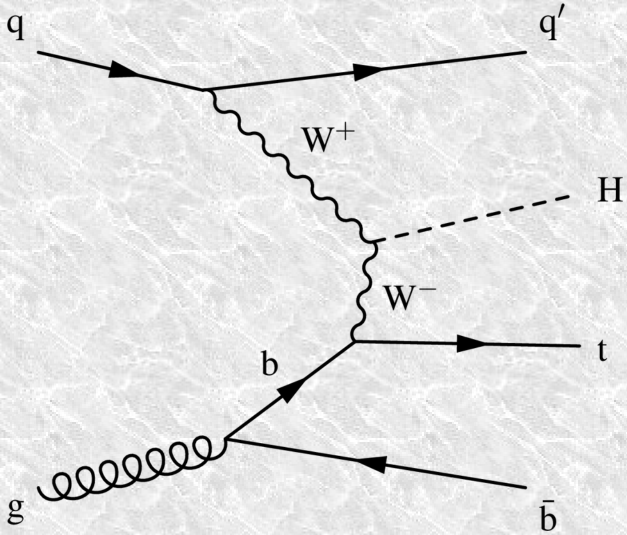


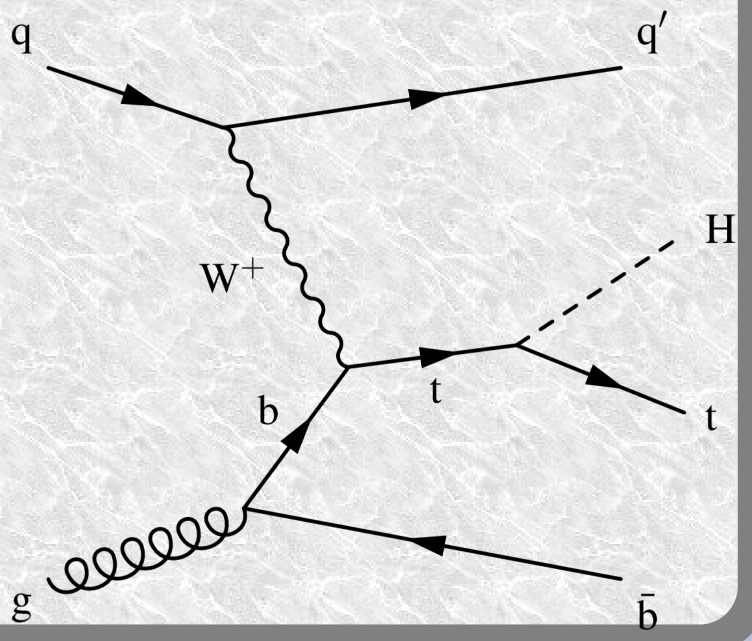


tH: motivation

- Two main modes: tH and tWH
  - Each suffers from cancellations between diagrams, right:
- Flip phase of k_t and cancellation disappears, below:

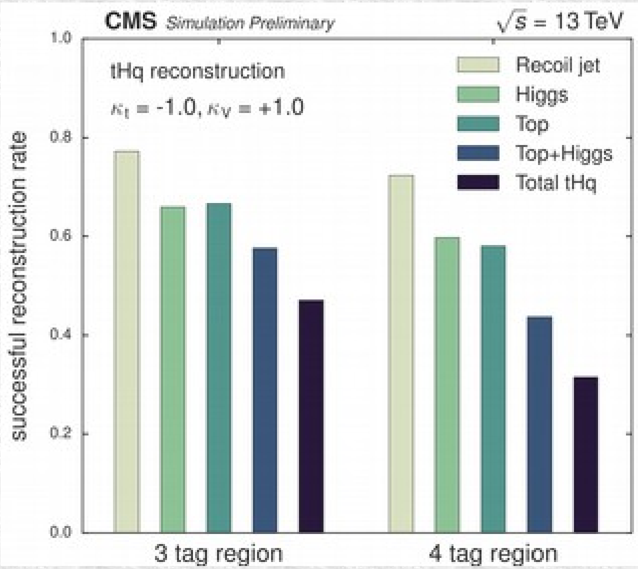


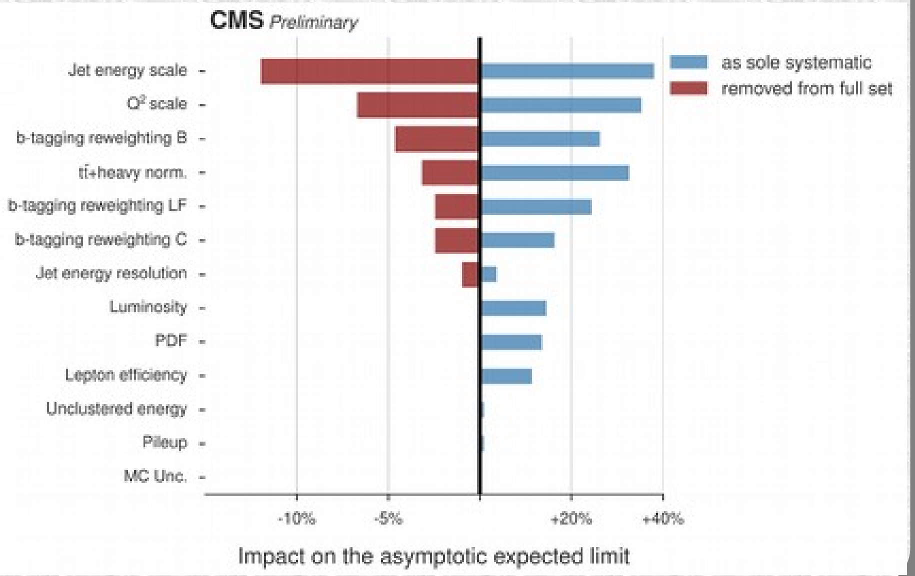




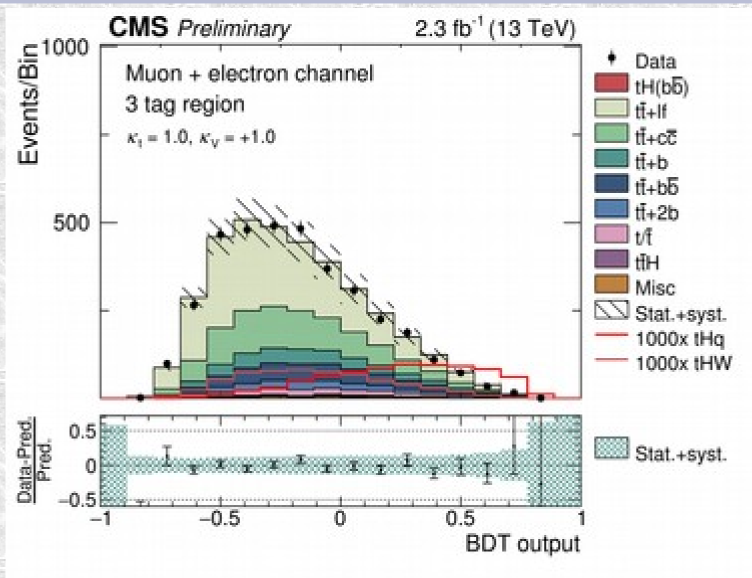
tH analysis

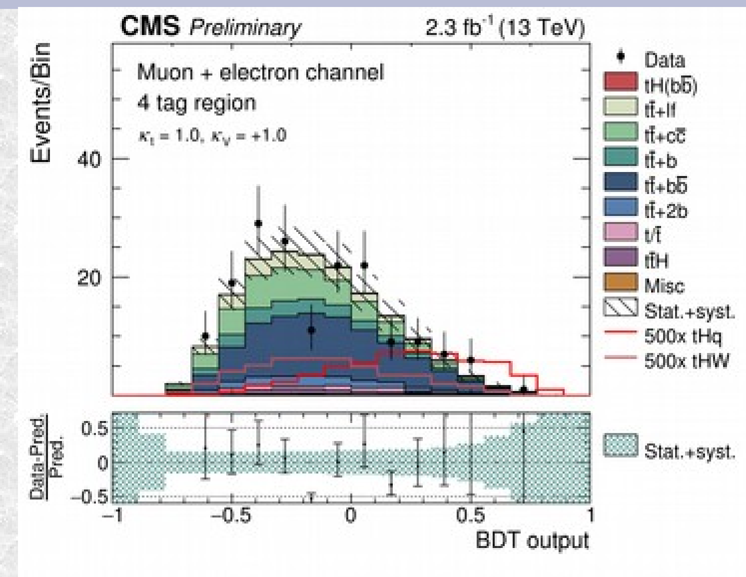
- CMS analysis, 2.3 fb^{-1}
- Identification of correct jets not easy
  - BDTs used to select
  - With a variety of kinematic information
- Use 2-tag events to validate
- Separate 3 and 4 btag signals
- Full efficiency 30-50%
- Systematics mix detector (JES) and theory (Q^2)





tH results





- Data in signal regions match background
- Limit 114 x SM (K_t=+1)
  - Or 6.0 x pred (K_t=-1)
- Sensitivity to -ve coupling not so far away