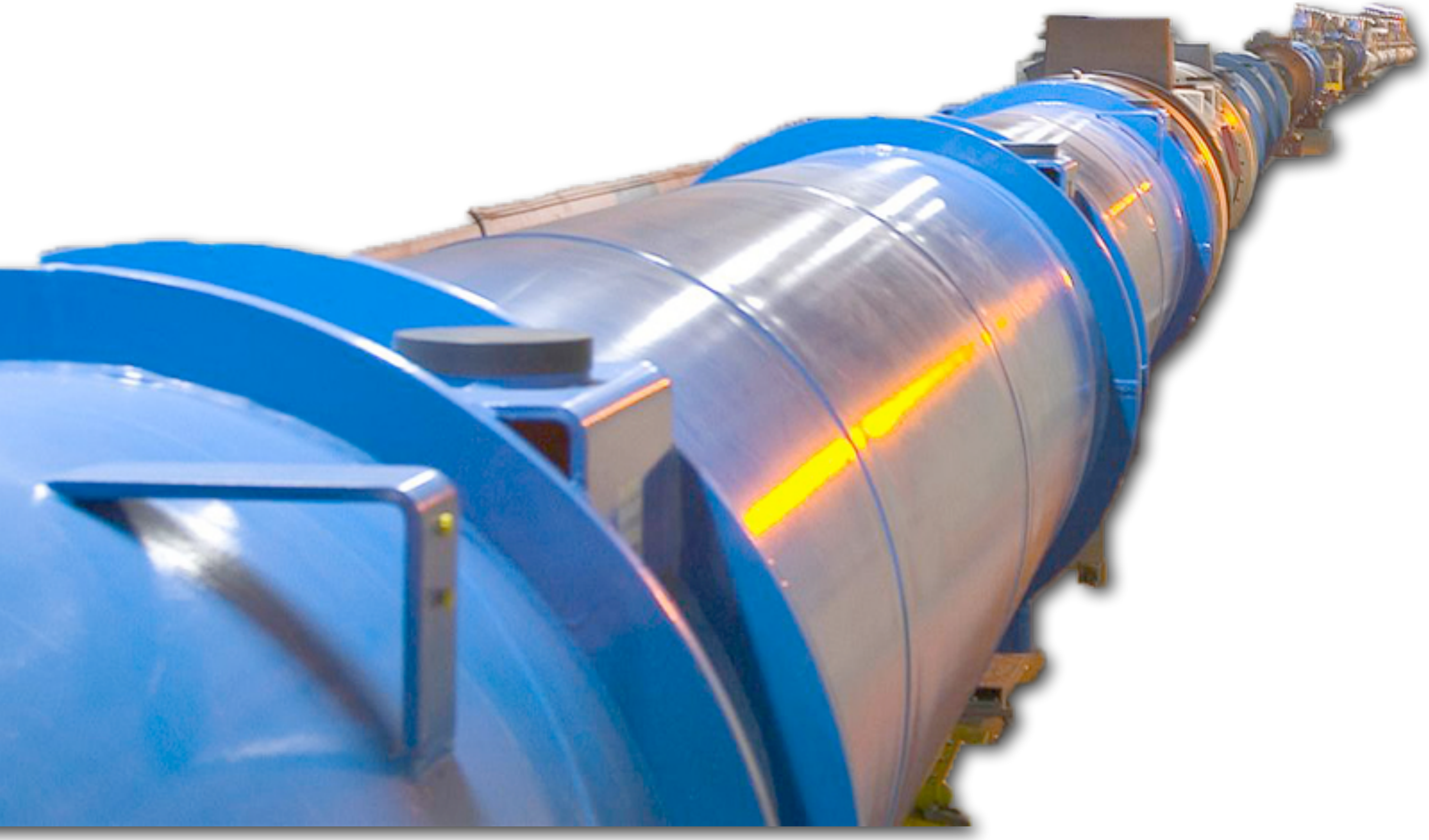
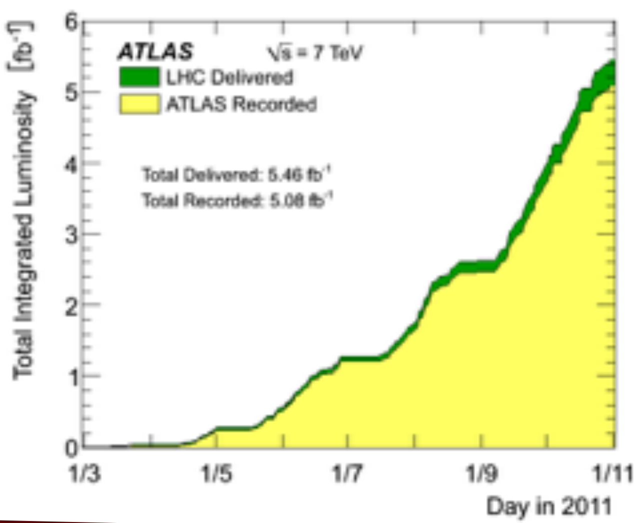


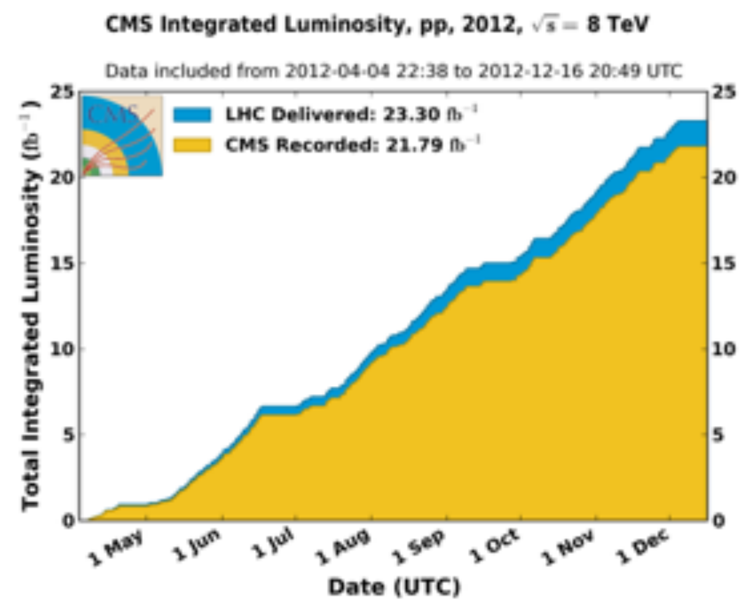
Standard Model Tests at the LHC

A. Salzburger, CERN on behalf of the ATLAS and CMS collaborations

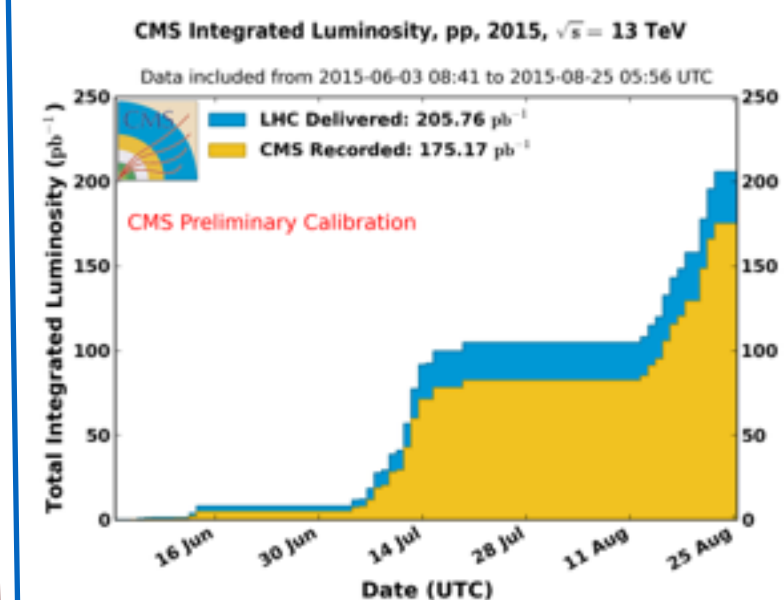
LHC Run-1 and Run-2

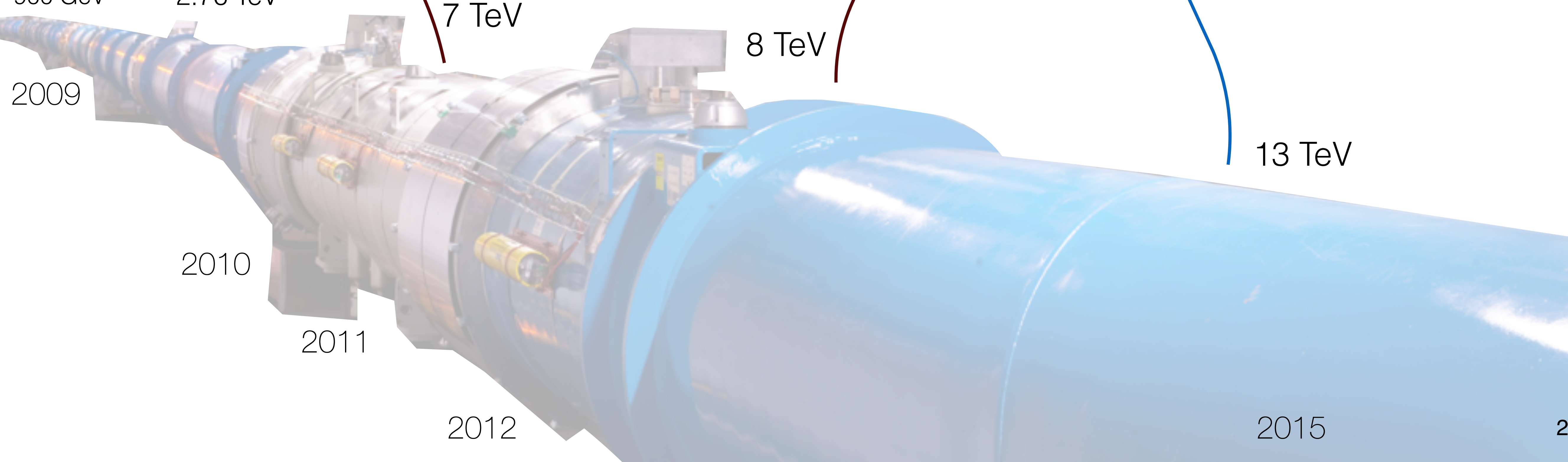
main Run-1 dataset





Run-2 has started

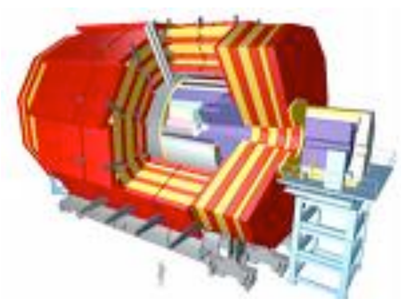




LHC - The main experiments

A **T**oroidal **L**HC **A**pparatu**S** **+ ALFA**

length ~40 m, height ~22 m, weight ~7000 tons
Inner Tracker embedded in 2 T solenoid, sampling EM calorimeter,
MS tracker/spectrometer within a toroidal magnetic system



Compact **M**uon **S**olenoid

length ~ 22 m, height ~ 12.5 m, weight ~12500 tons
Full Silicon Inner Tracker embedded 5 T solenoid, crystal EM calorimeter

A **L**arge **I**on **C**ollider **E**xperiment

dedicated for Pb-Pb collisions,
high particle identification capability

LHCb

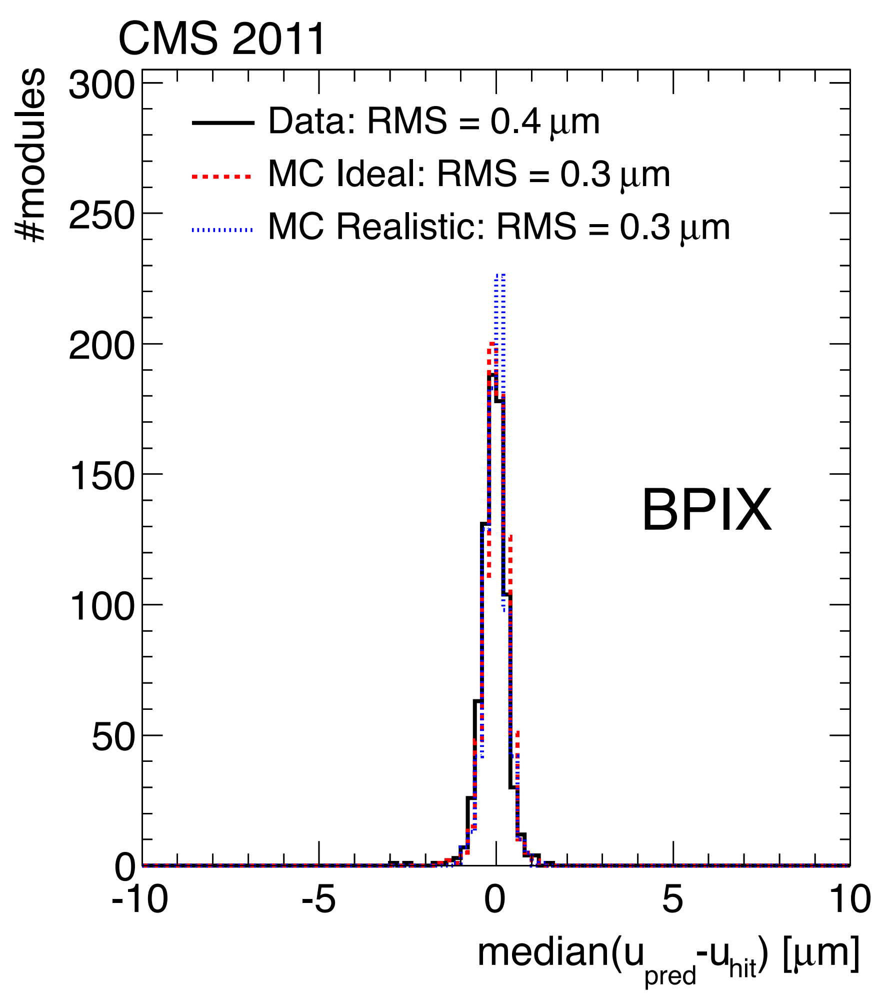
dedicated for studying properties of the B-mesons,
movable precision silicon pixel detector very close to the interaction region

TOTEM

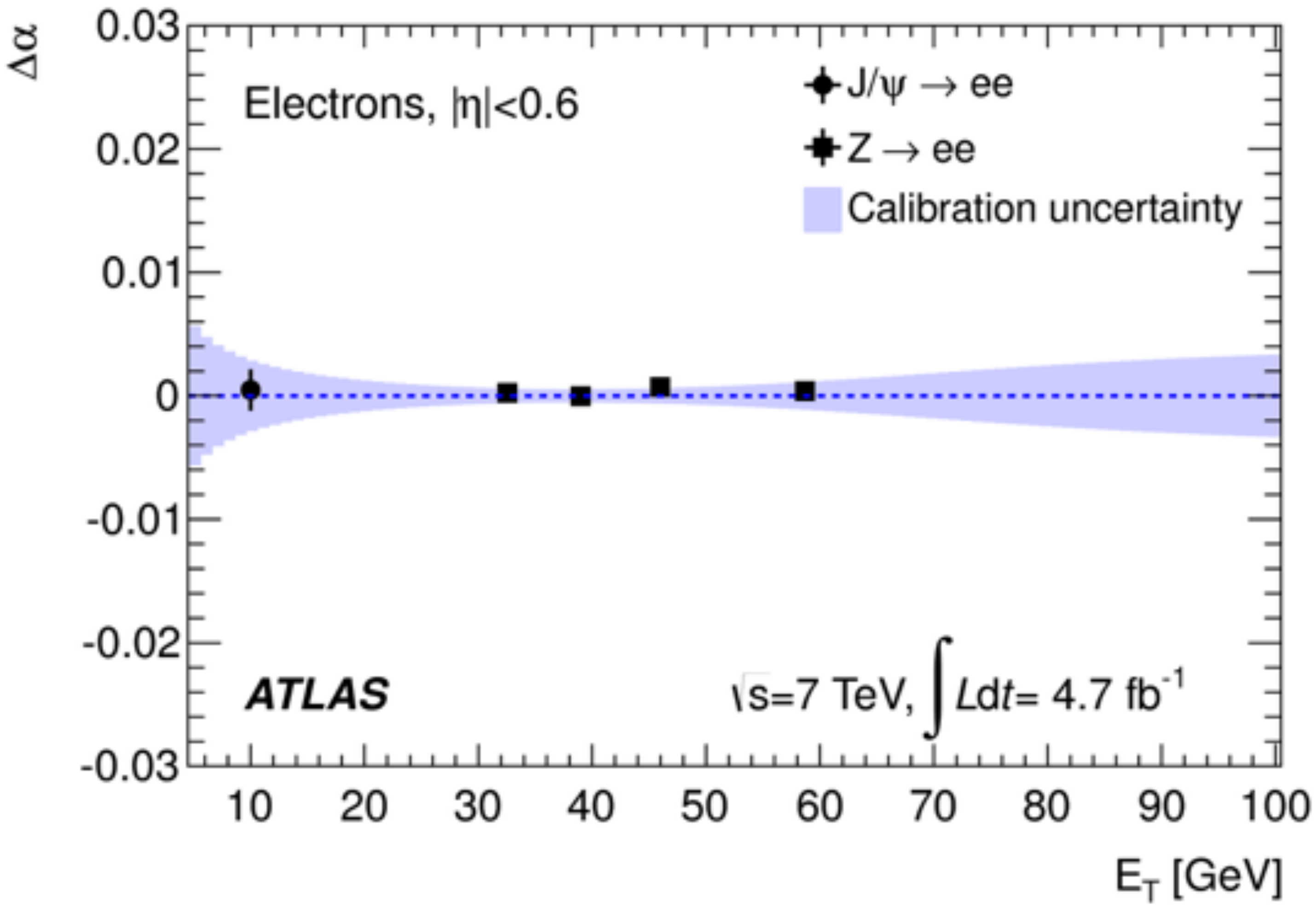
roman pot detectors located 150/220 m from the CMS interaction point

Foundation - detector performance

- presented results rely on a very deep understanding and precise modelling of the experimental setups
  - impressive results from the performance/physics objects groups
  - in general, exceptional Monte Carlo detector modelling of the data



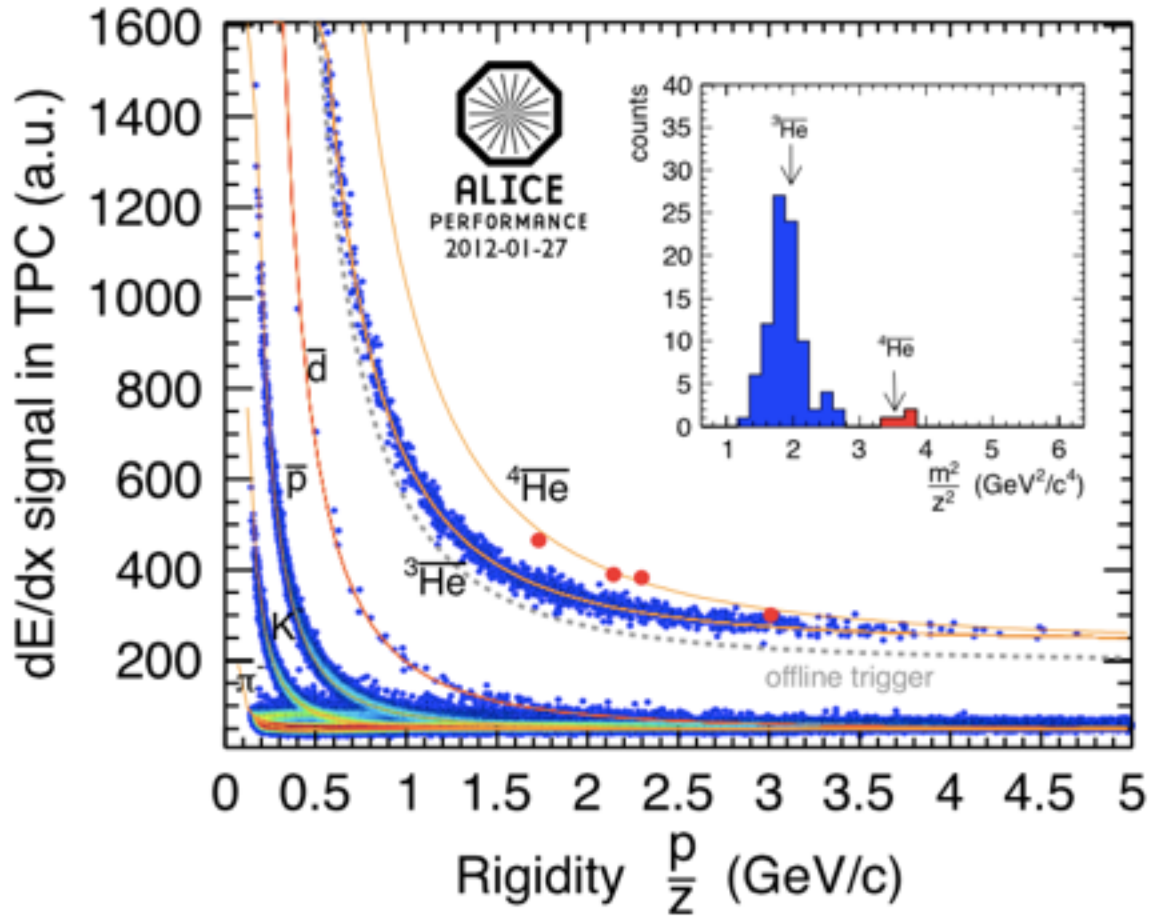
CMS Tracker alignment



ATLAS EM electron scale

Detector performance & data taking efficiency

- presented results would not have been possible without
  - excellent performance of the LHC
  - very high data taking efficiency and stable detector operation of the LHC experiments
- gives a lot of confidence for Run-2

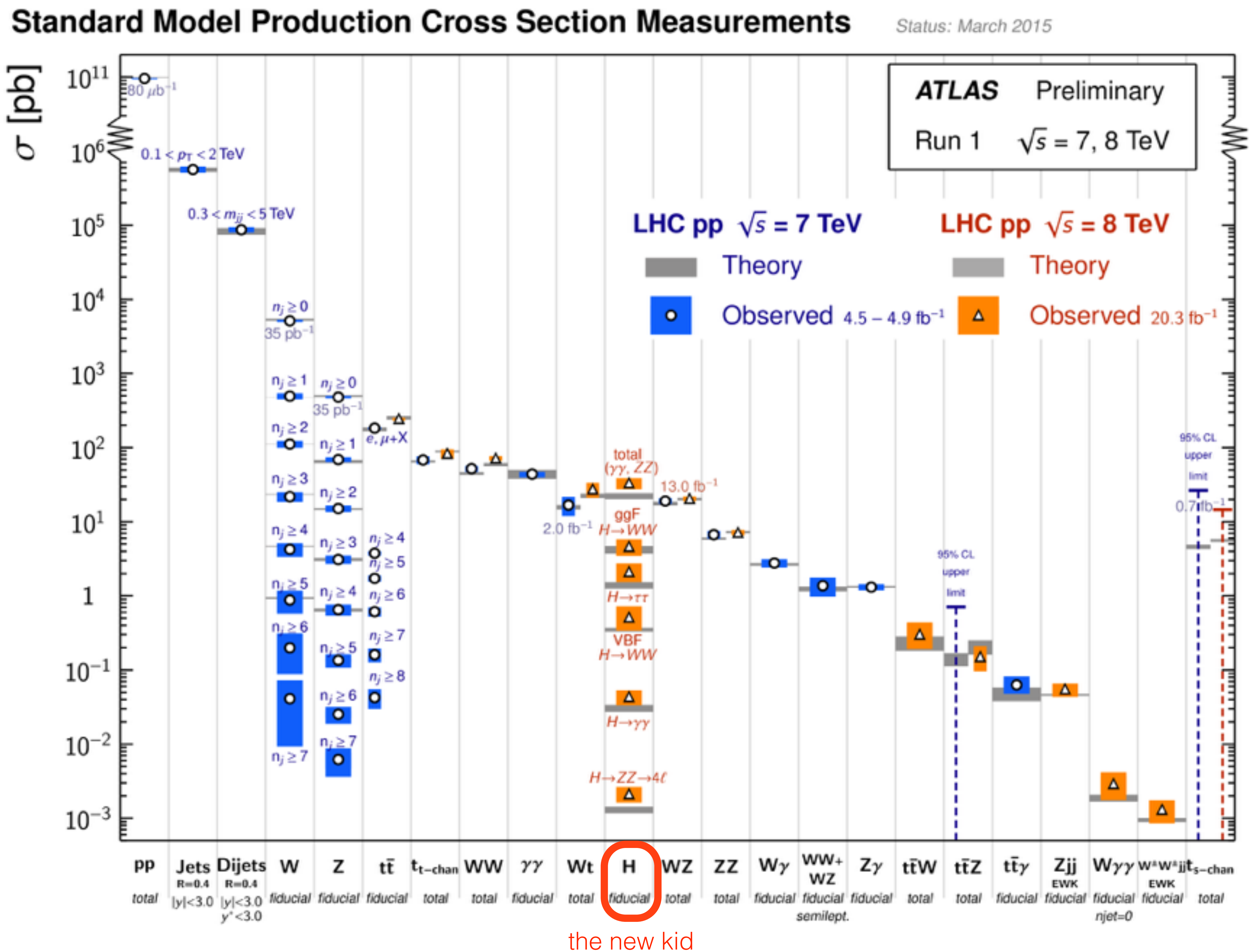


ALICE dE/dx in TPC

ATLAS Run-1 Detector Status (from Oct. 2012)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%

Very similar numbers for all experiments


Standard Model Production Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Theory
Observed 20.3 fb⁻¹
σ [pb]
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ fiducial
t t-chan total
WW total
γγ fiducial
Wt total
H fiducial
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial semilept.
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial
t s-chan total
total (γγ, ZZ)
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
95% CL upper limit
the new kid

All spot-on - all done ?

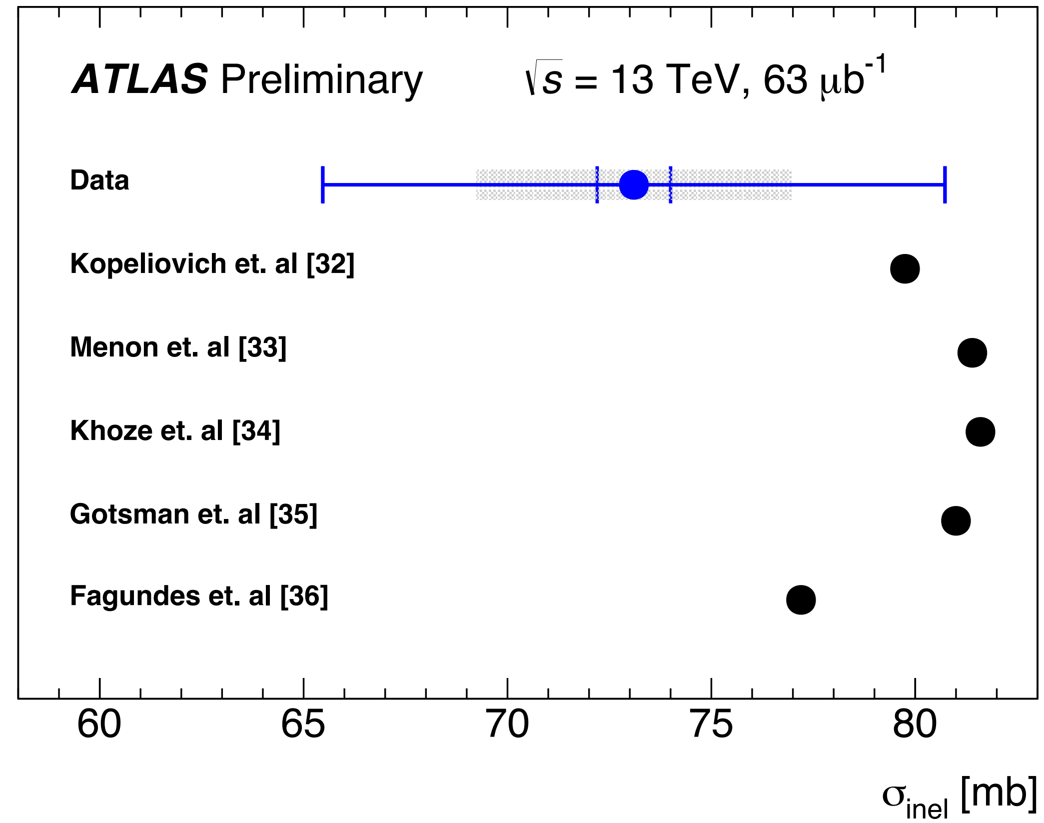
- Run-1data has still a lot of interesting physics
  - **QCD** - become more and more precision measurements
    - Soft QCD*: minimum bias, underlying event measurements necessary in pp conditions*
    - Hard QCD: *test of high order pertubative QCD (inclusive, multiple-jet production cross-sections V+jets production)*
    - *precision measurement of fundamental parameters* α_s
    - *constraining the parton density functions (PDFs)*
  - **EWK** observables and processes
    - *Z* A_{fb}
    - *VBF/VBS results (observation and evidence)*
  - precision measurements to come, such as m_W
- Run-2: 13 TeV measurements are on the way
  - back to the start, do it again and confirm (or not)
  - will show some hot-of-the-press results, many more to follow in the next months

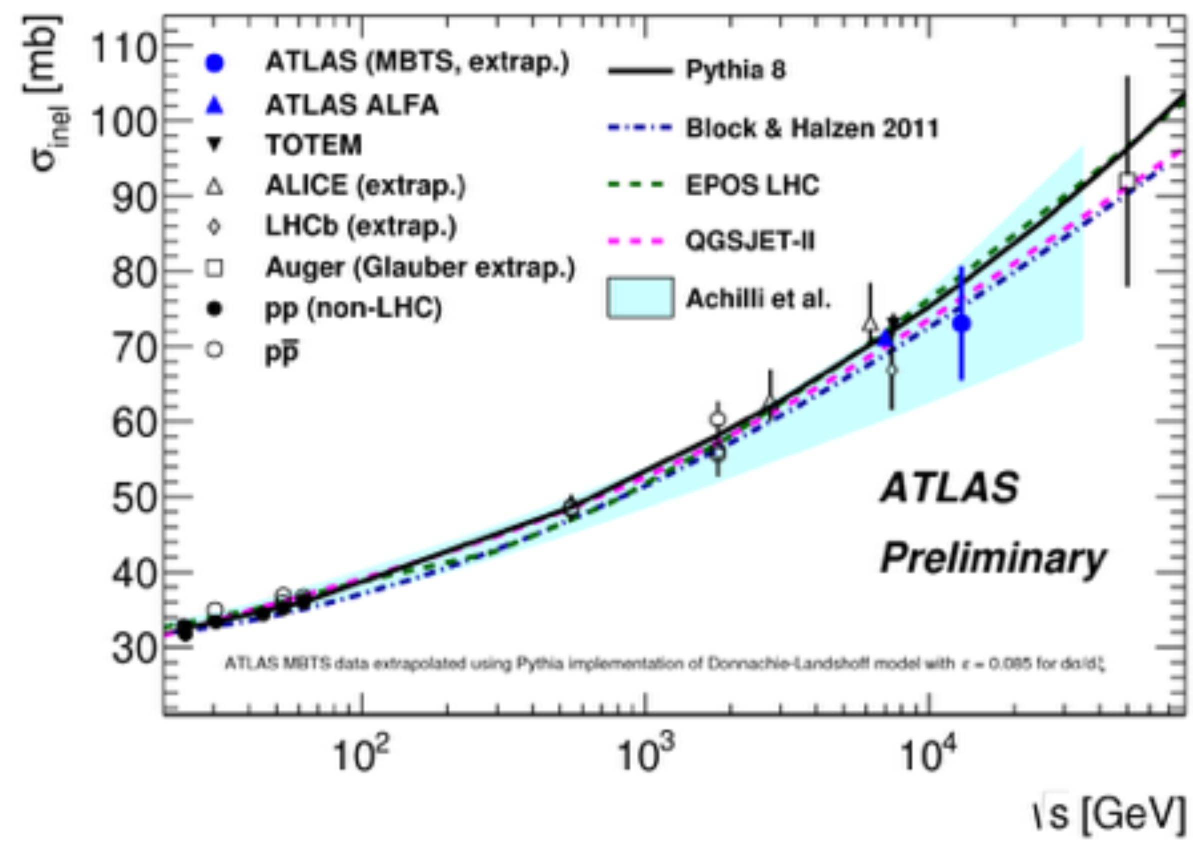
Total inelastic cross section

- inelastic cross section measurements are essential

- very precise measurements for 7 TeV and 8 TeV
  - supplemented by TOTEM measurement

- first 13 TeV result from ATLAS
  - using Minimum Bias Scintillator detectors and extrapolated to total cross section
  - ratio measurement single sided counter/ inclusive counters



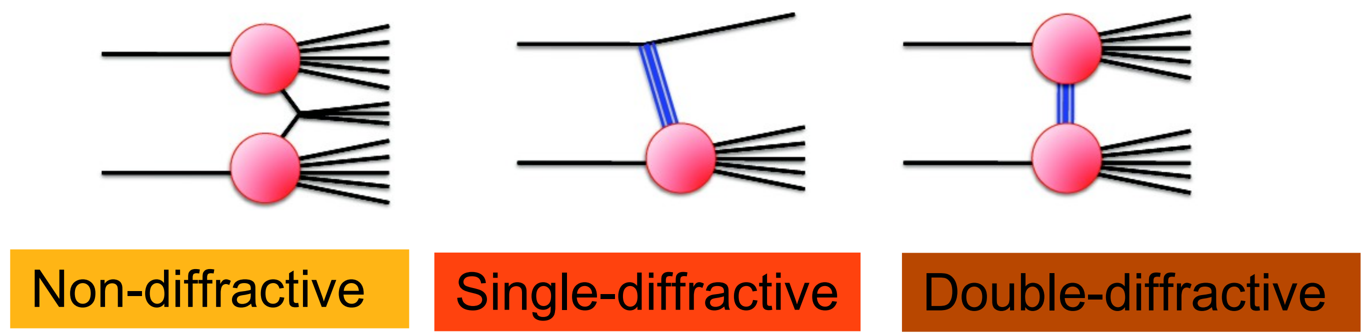


73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (extr.) mb.

ATLAS-CONF-2015-038

Soft QCD - Minimum bias measurements

- Why measuring the charged particle multiplicities ?
  - pertubative QCD describes only hard-scatter partons, rest described by phenomenological models



- ND component
  - QCD motivated models with many parameters
  - these parameters have impact when extrapolated to high Q (e.g. color reconnection)
- SD & DD component not well constraint and little data available
- Measure primary charged particle distribution to constrain models
  - model independent (e.g. no SD/DD/ND splitting), corrected to particle level

dN_{ev}/dn_{ch}, $\langle p_T \rangle$ vs. n_{ch}, $dN_{ch}/d\eta$, $d^2N_{ch}/d\eta dp_T$

Minimum bias measurement - CMS/TOTEM

- charged particle measurement
  - track counting measurement with corrections

    track reconstruction efficiency (dominant)

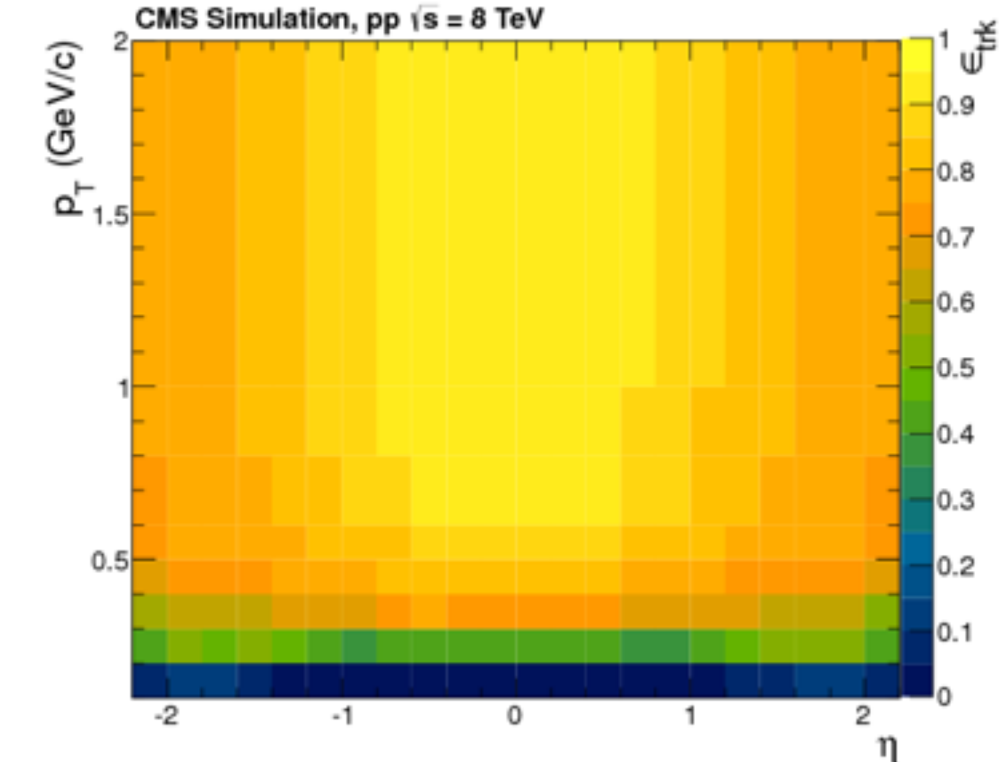
    fake/ghost tracks (not an issue in μ=0)

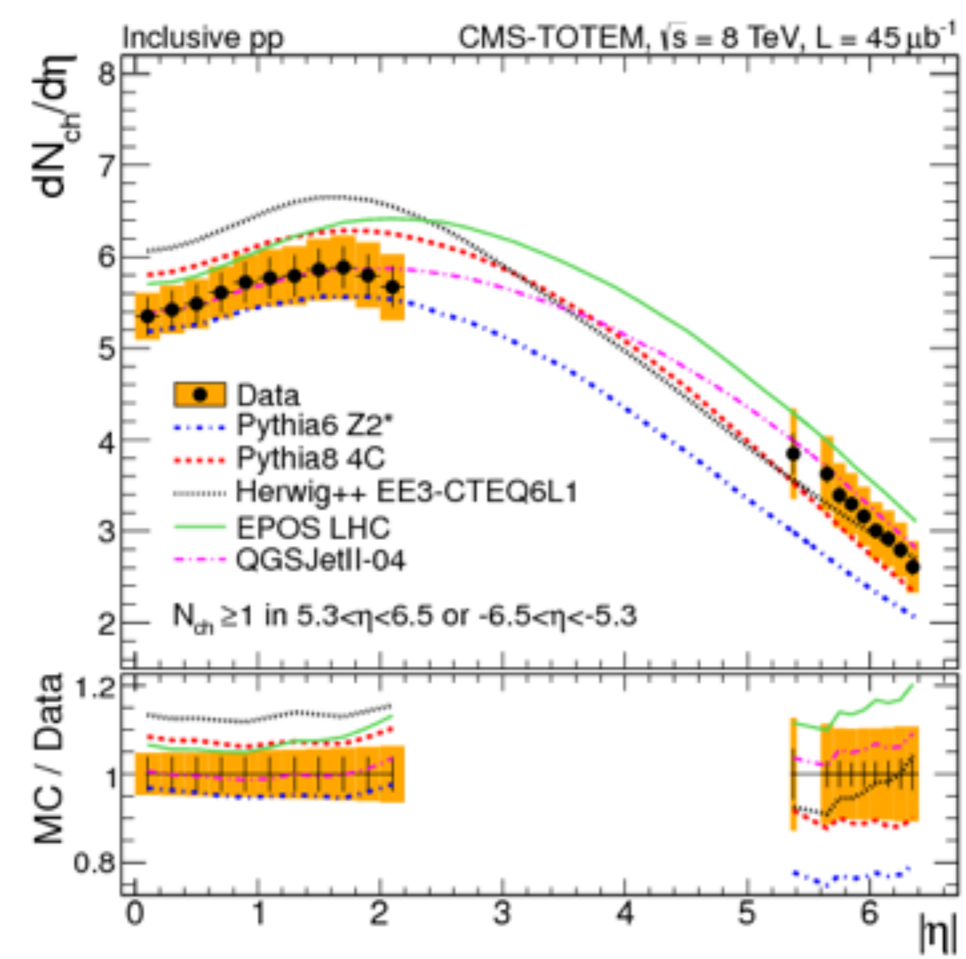
    trigger, vertex, selection efficiency

    contamination of pile-up events
  - unfolding to particle level

    usually done using a Bayesian unfolding

- CMS combined with TOTEM
  - test model dependence up to |eta| ~ 6.5
  - good modelling with QGSJetII-04 up to large pseudo-rapidity



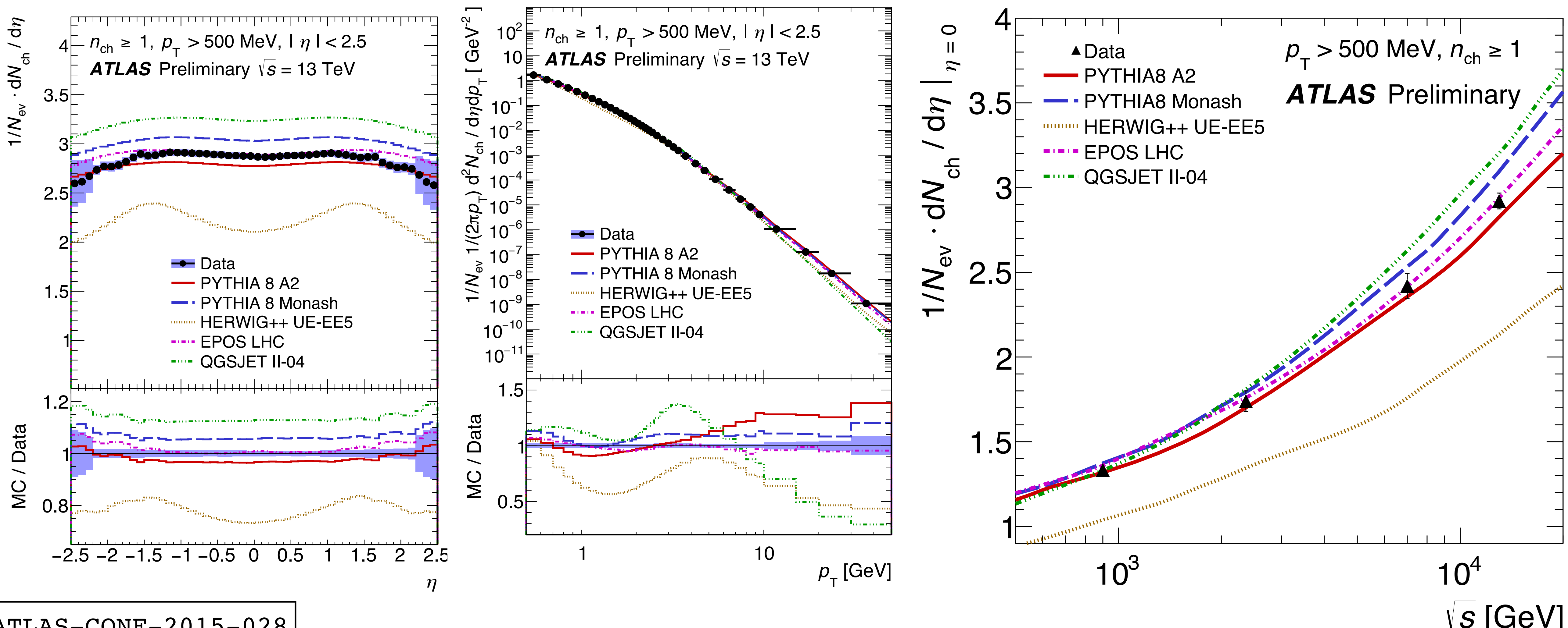


Eur. Phys. J. C 74 (2014) 3053

Minimum bias measurement - ATLAS

- recent 13 TeV measurement of ATLAS
  - challenging due to newly installed innermost pixel detector (IBL)
    many checks needed to understand the material budget of new detector
  - phase-space: $N_{ch} \geq 1$, $p_T > 500$ MeV, $|\eta| < 2.5$

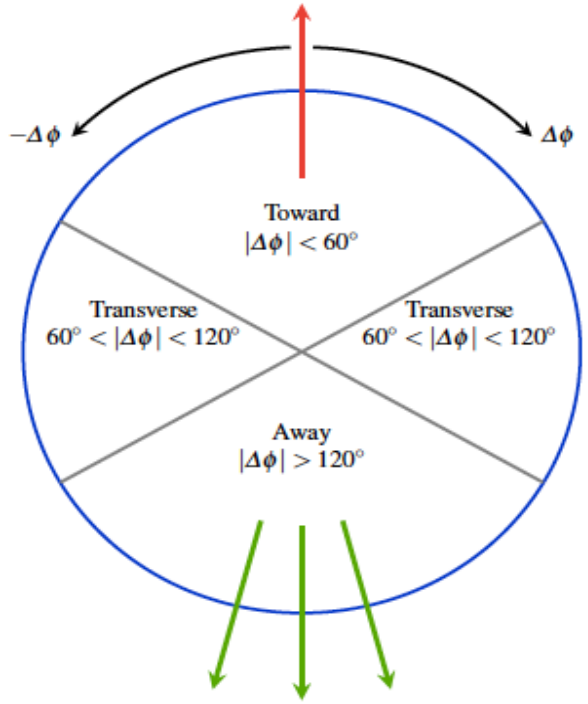
- Good modelling by EPOS (LHC tune) and PYTHIA8 (A2 tune)



ATLAS-CONF-2015-028

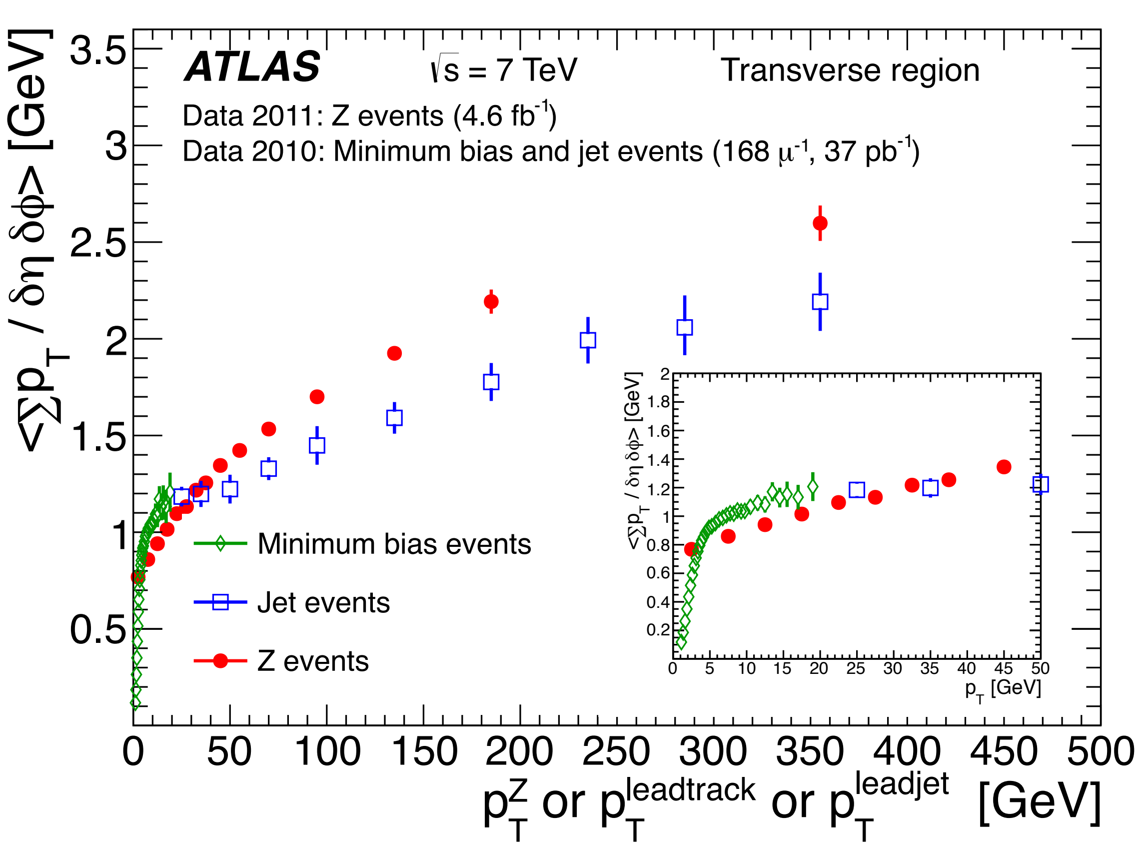
Soft QCD - Underlying event analyses

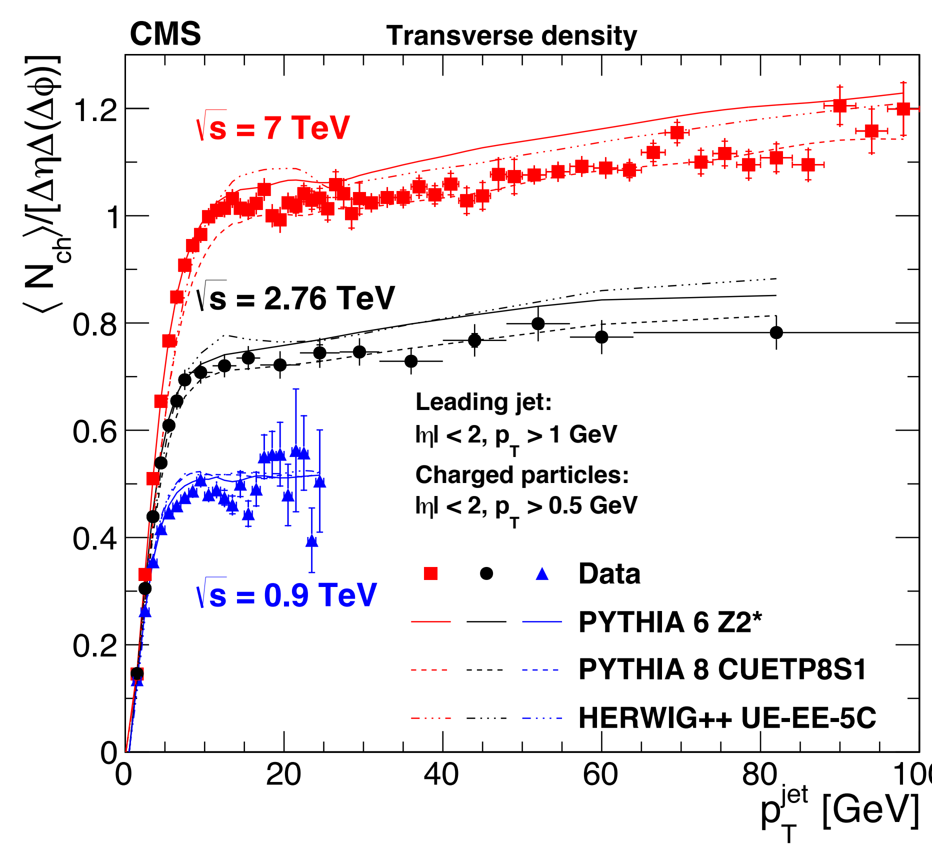
- Z Boson
- Leading Track
- Leading Jet



- Underlying event (UE) comprises all particles except those from the hard process of interest
  - performed within different azimuthal regions
  - Studying the UE at different processes and energies

- Modern tunes describe energy dependence very well
  - UE consistent between different processes within known selection biases



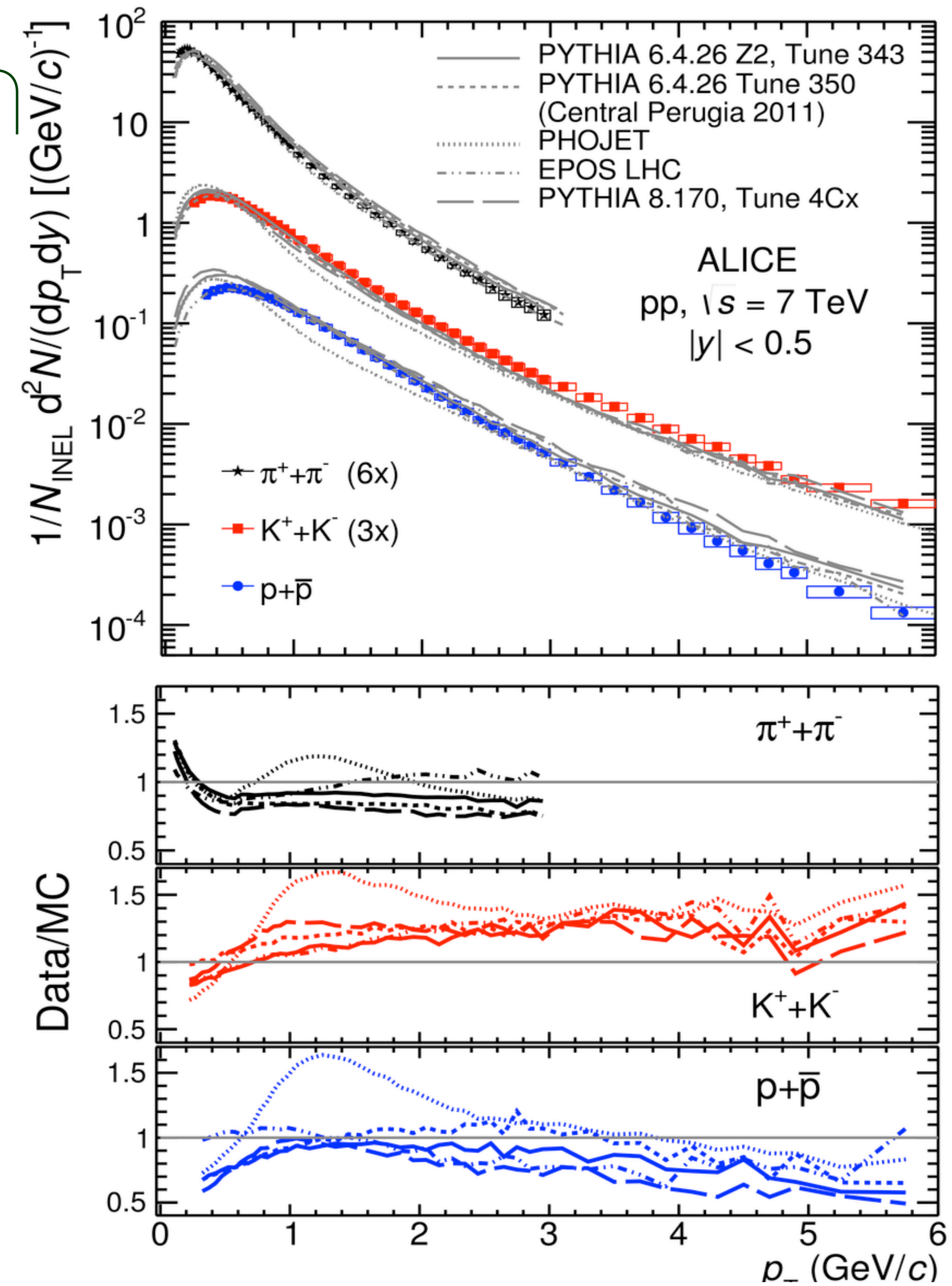


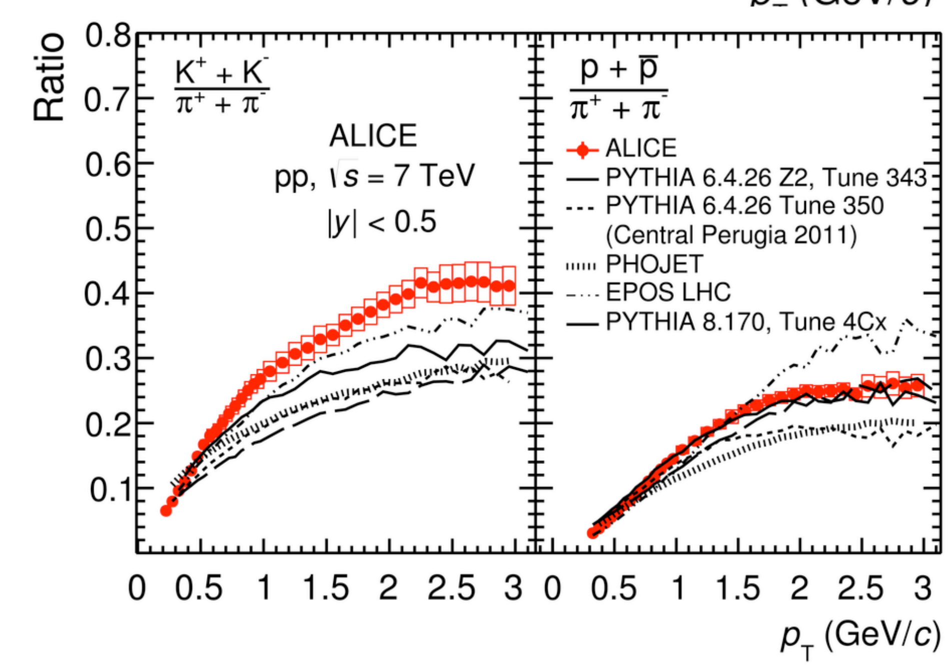
Eur. Phys. J.C(2014)74:3195

CERN-PH-EP-2015-176

Soft QCD - particle production

- Measurement of particle spectra and species give additional input to understand/ constraint the modelling
  - soft parton interactions
  - hadronisation process
- ALICE measurement of prompt hadrons ($\pi^{\pm}$,$K^{\pm}$,p,$\bar{p}$) at 7 TeV
  - combination of 5 techniques (sub-detectors) for particle identification
- Shapes of spectra are reasonably well described by most modules
  - no model can simultaneously describe the yield of the different particle types

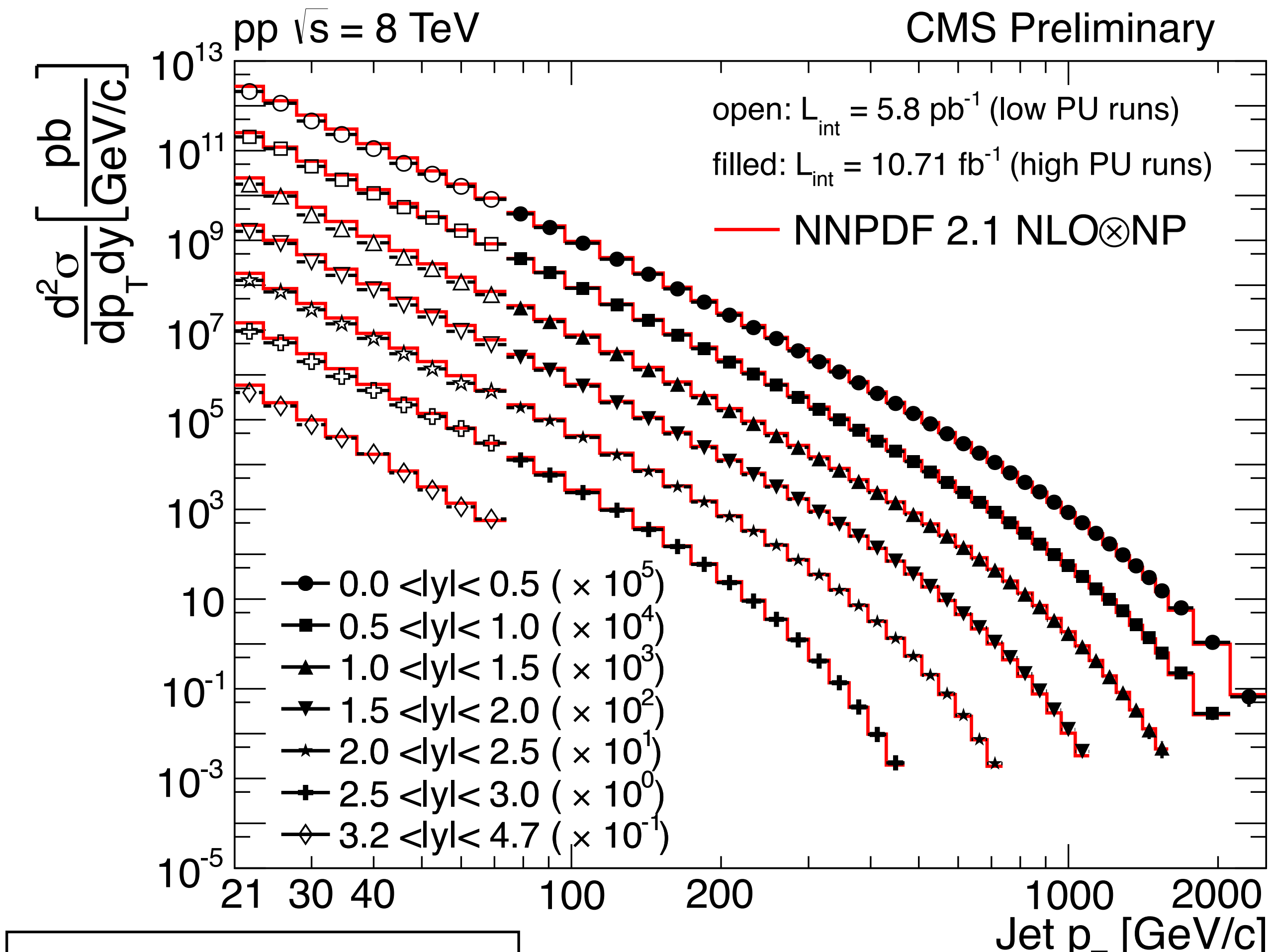


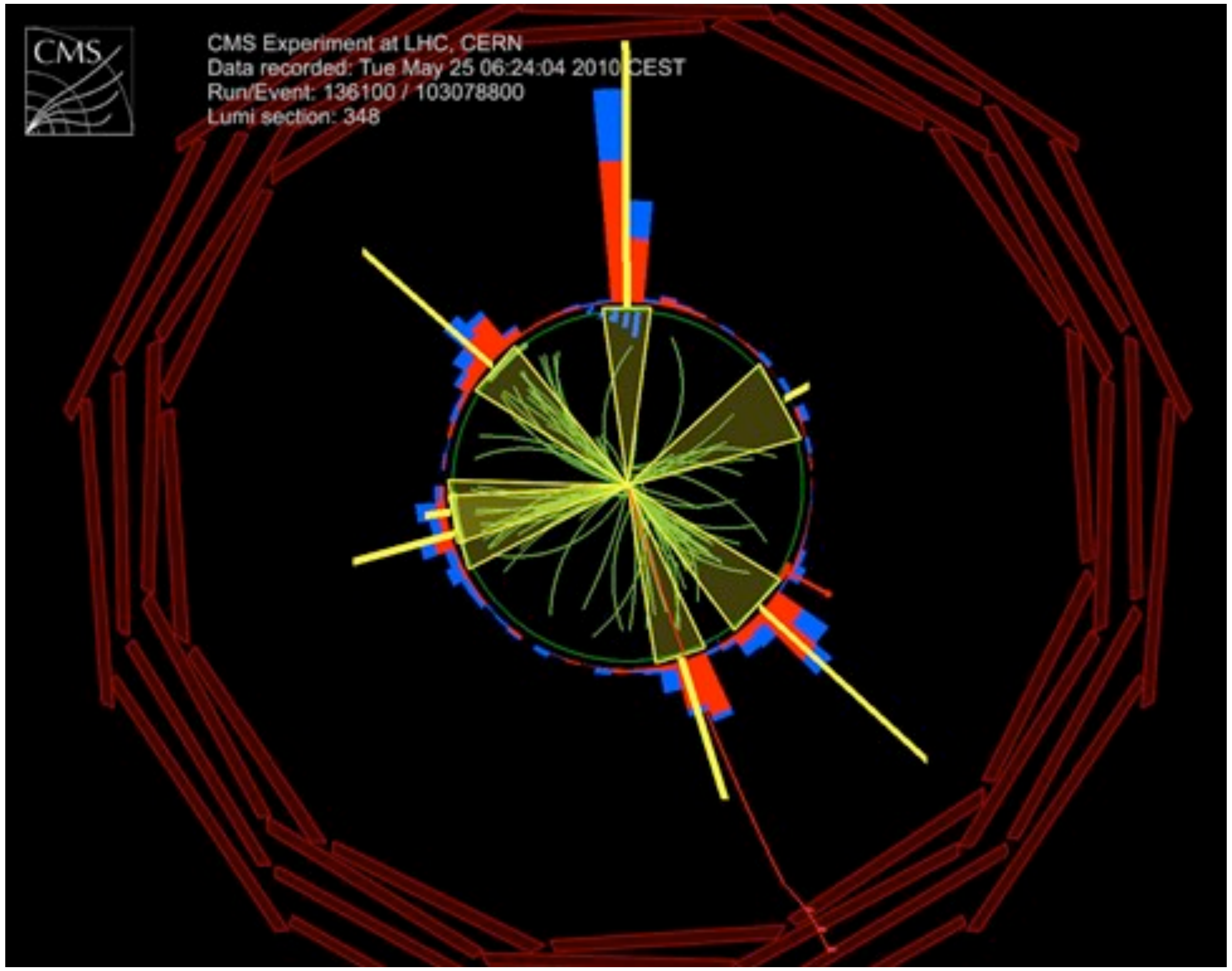


arXiv:1504.0024

Hard QCD - Jet production cross section

- Jet production cross section is a very good probe of QCD dynamics
  - over many orders of magnitudes, combines test of perturbative QCD with non-pertubative effects, LHC experiments cover 20 GeV to 2 TeV !
  - sensitive to as, PDF and multi-parton interactions
  - accuracy of better than 5% achieved, very good agreement with NLO predictions

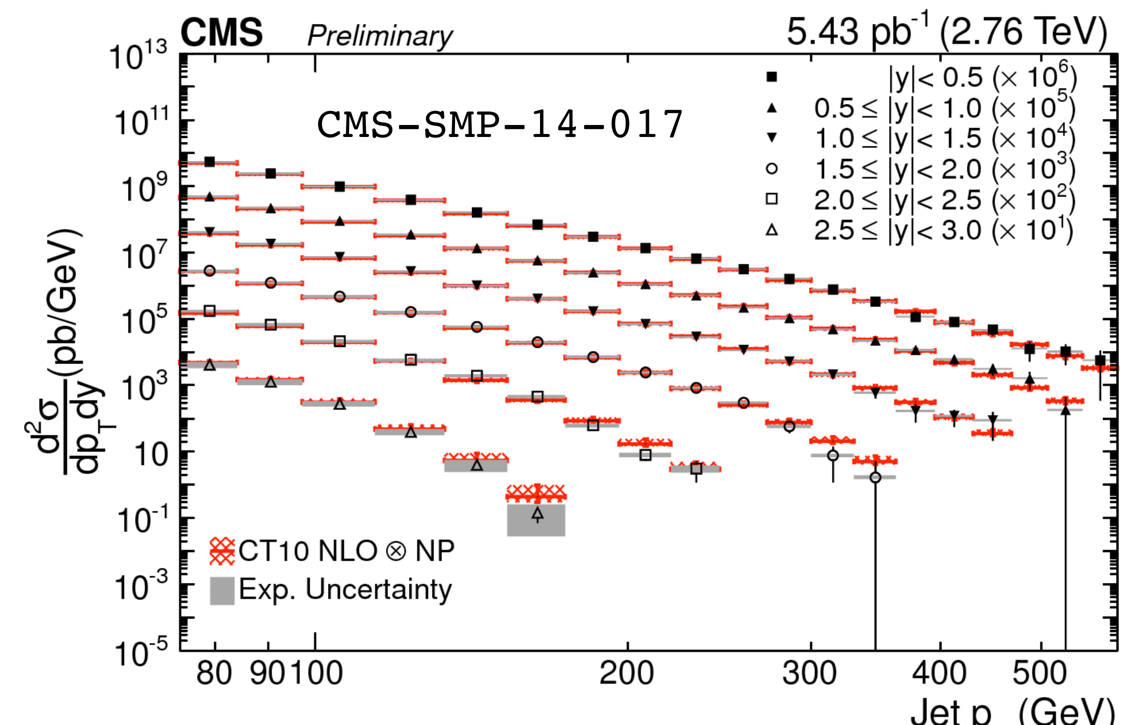




CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

Jet production cross section - ratios

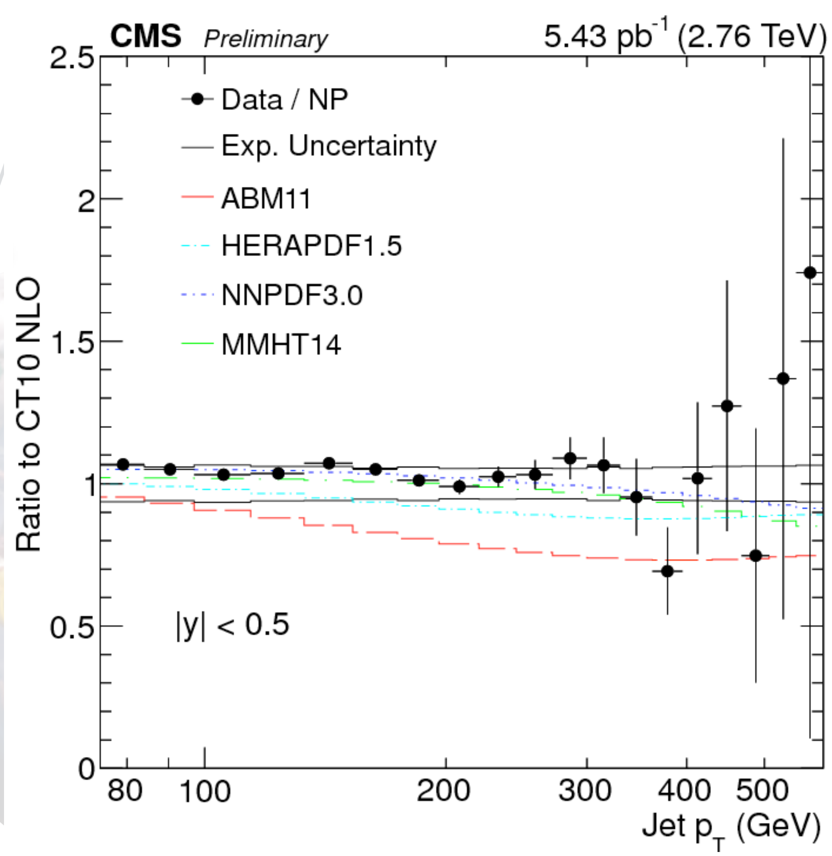
- use different beam energies to build ratios
  - allows cancellation of certain systematic energies
  - results in a higher sensitive to PDFs

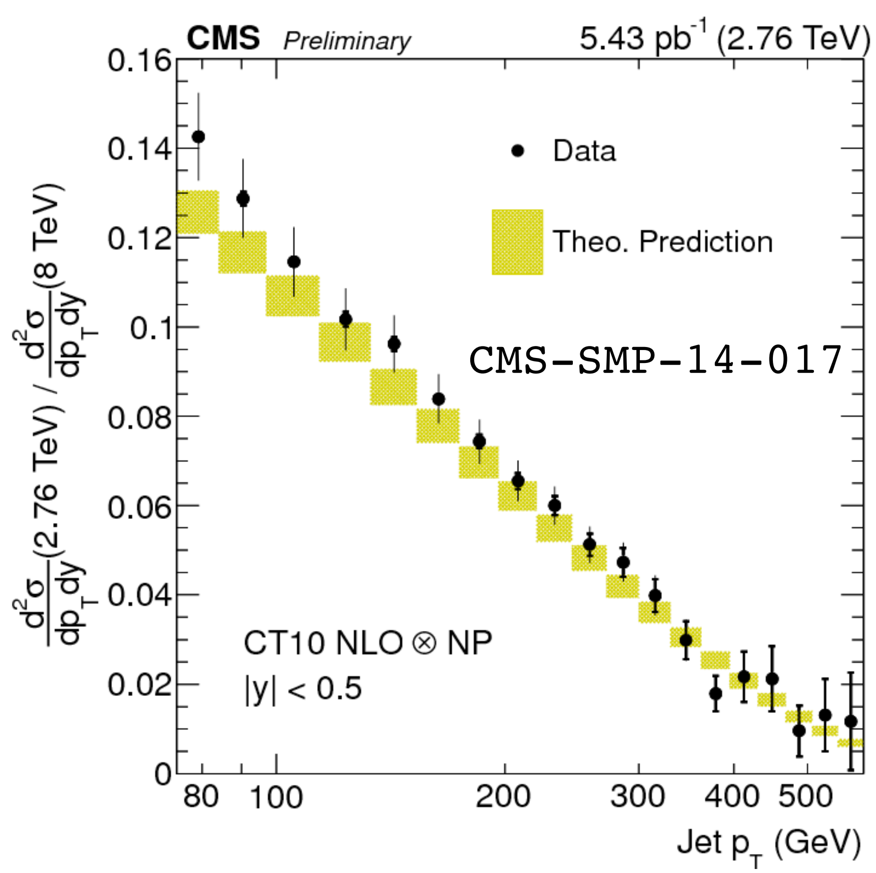


Six |y| bins (0.0-3.0), p_T range 74-592 GeV

- new result of CMS at 2.76 TeV

- Ratio 2.76/8 TeV
  - error range of 0.1 to 14 % with more precision at higher jet pT

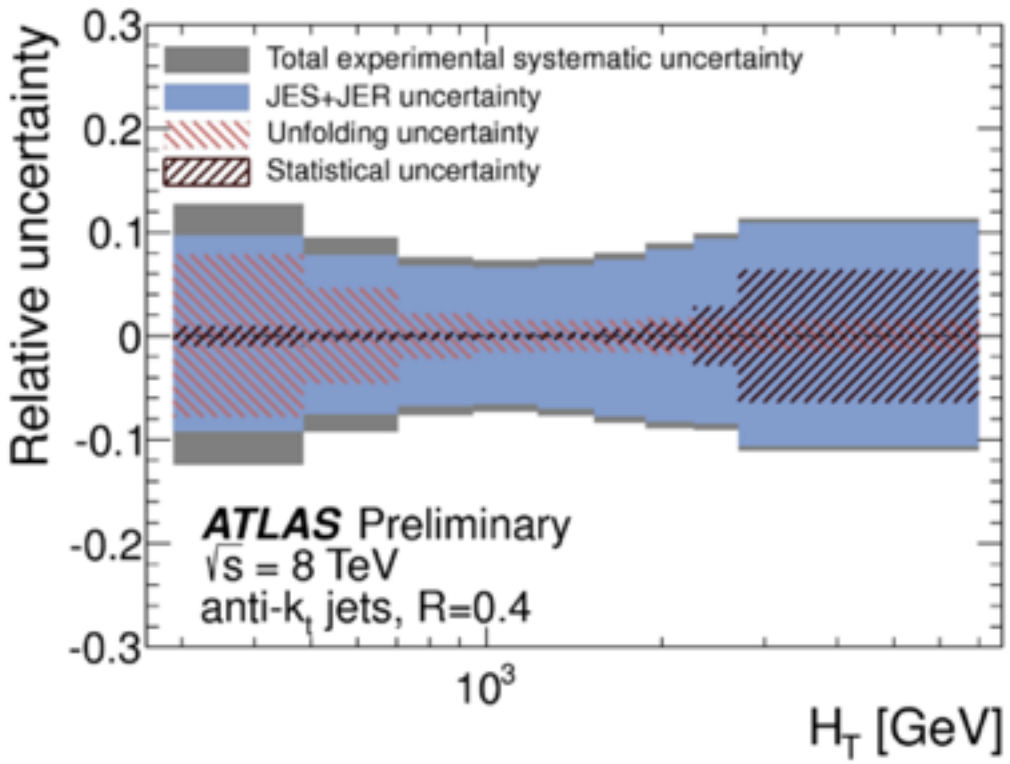


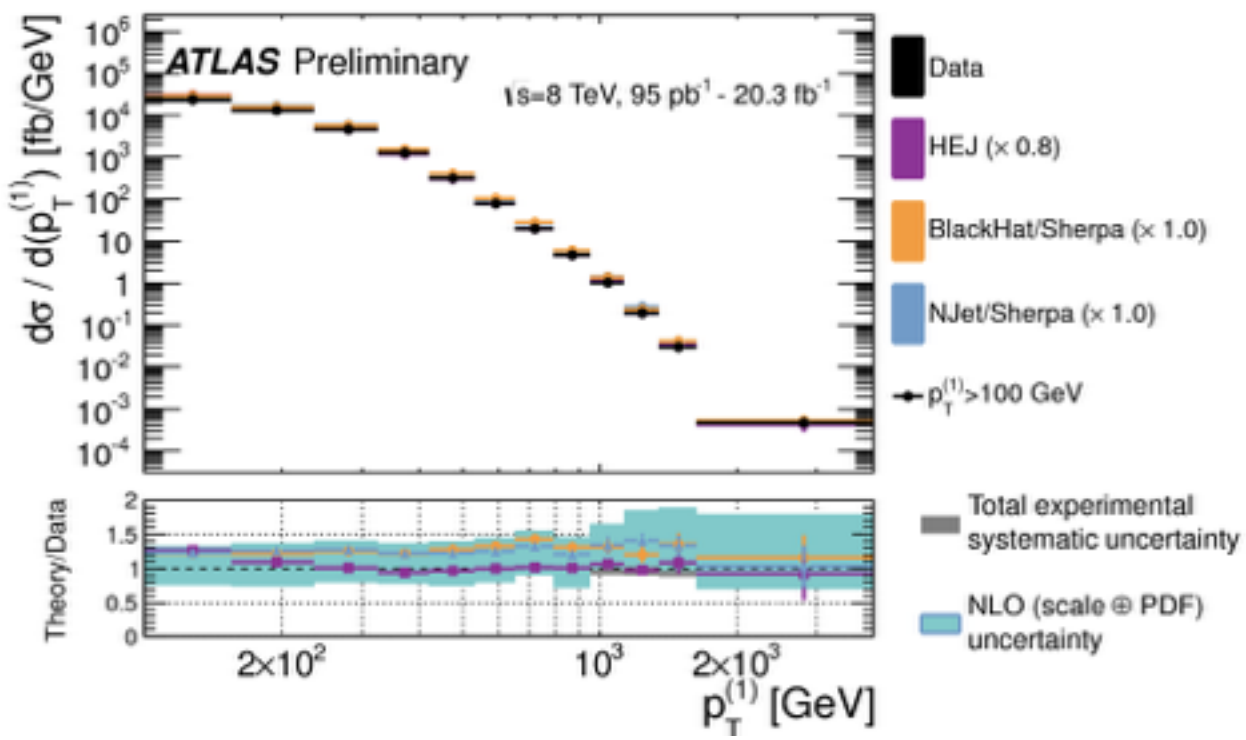


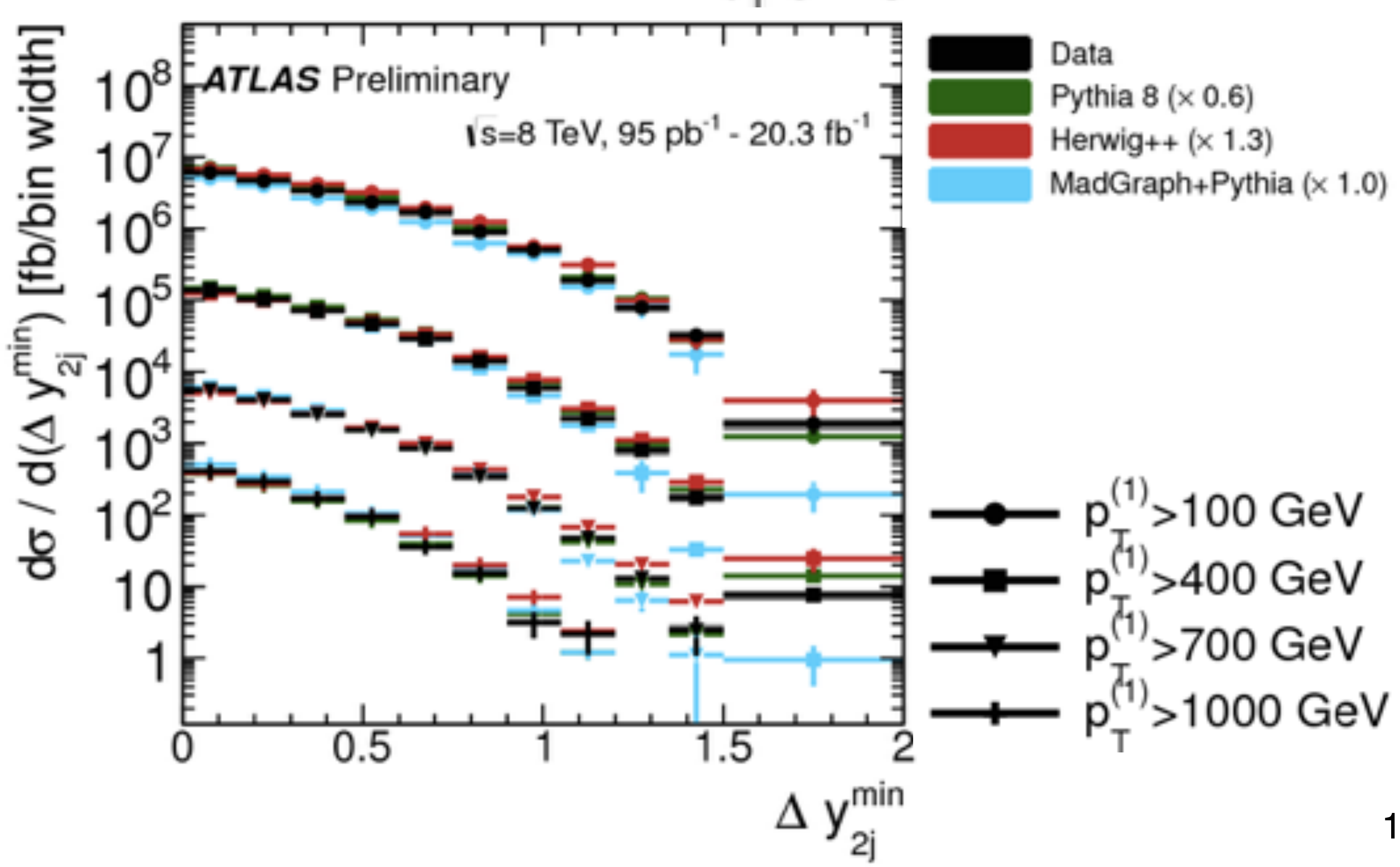
CMS-SMP-14-017

4-jet cross section measurement

- differential measurement of 4-jet cross section of ATLAS at 8 TeV







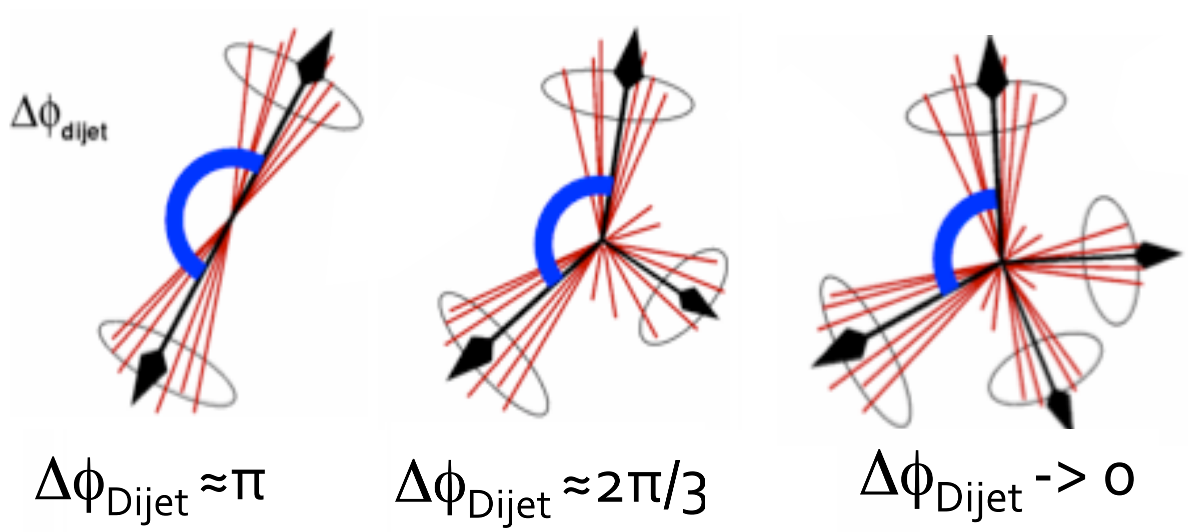
  - measured differentially w.r.t to different variables, e.g. angular distributions, jet momenta, event topologies

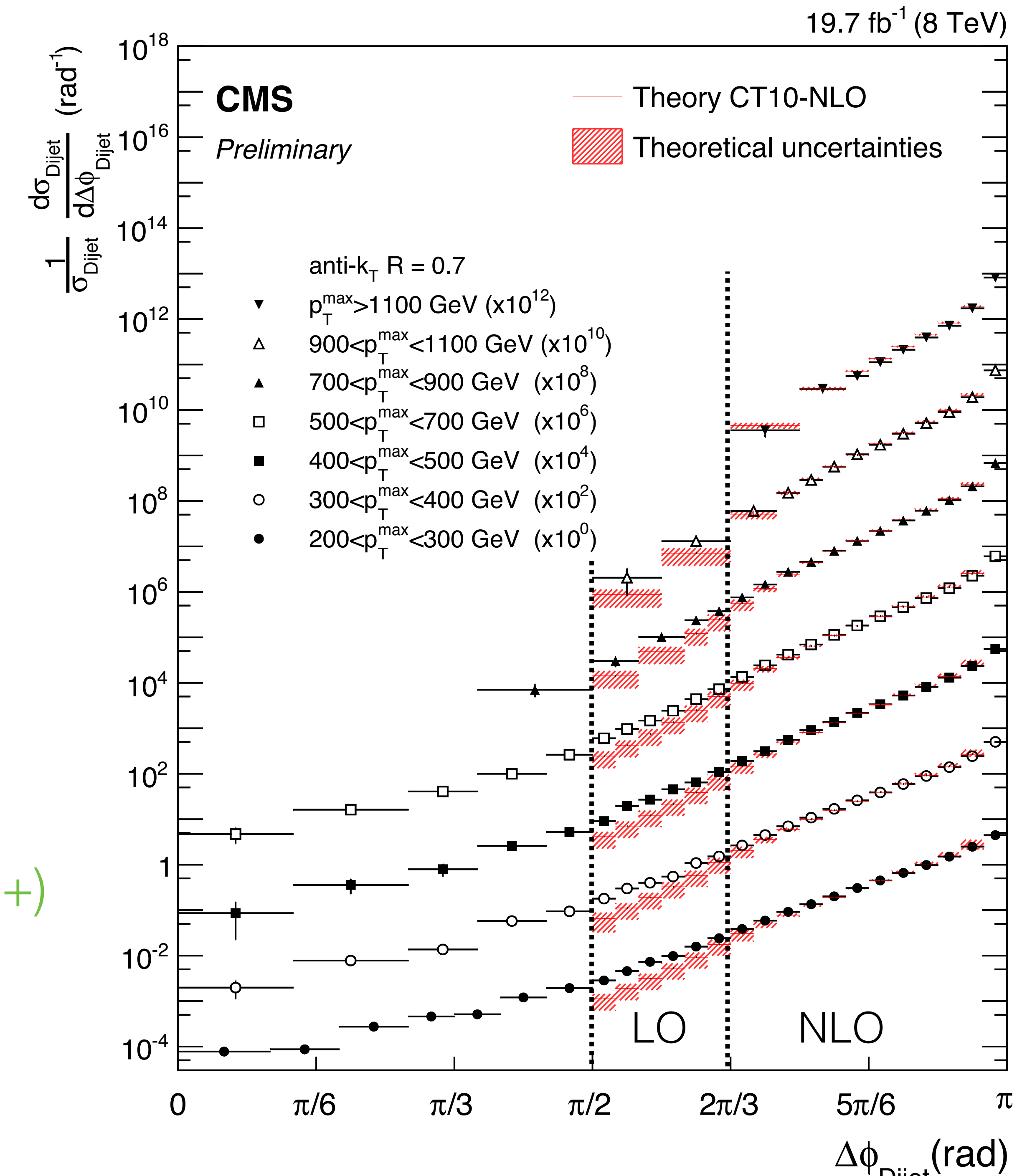
    test of PS and PS+ME

ATL-STDM-2014-14

Jet production cross section - decorrelation

- Dijet azimuthal decorrelation measurement - complementary to multi-jet
  - insight on multi-jet prodcution without measuring jets beyond leading two
  - experimental uncertainty on normalised distribution reach percent level for back-to-back jets





- Allows to test LO/NLO region
  - good agreement in NLO region (NLOJet++)
  - Multijet 2-> 4 provides best description (Madgraph + Pythia6)

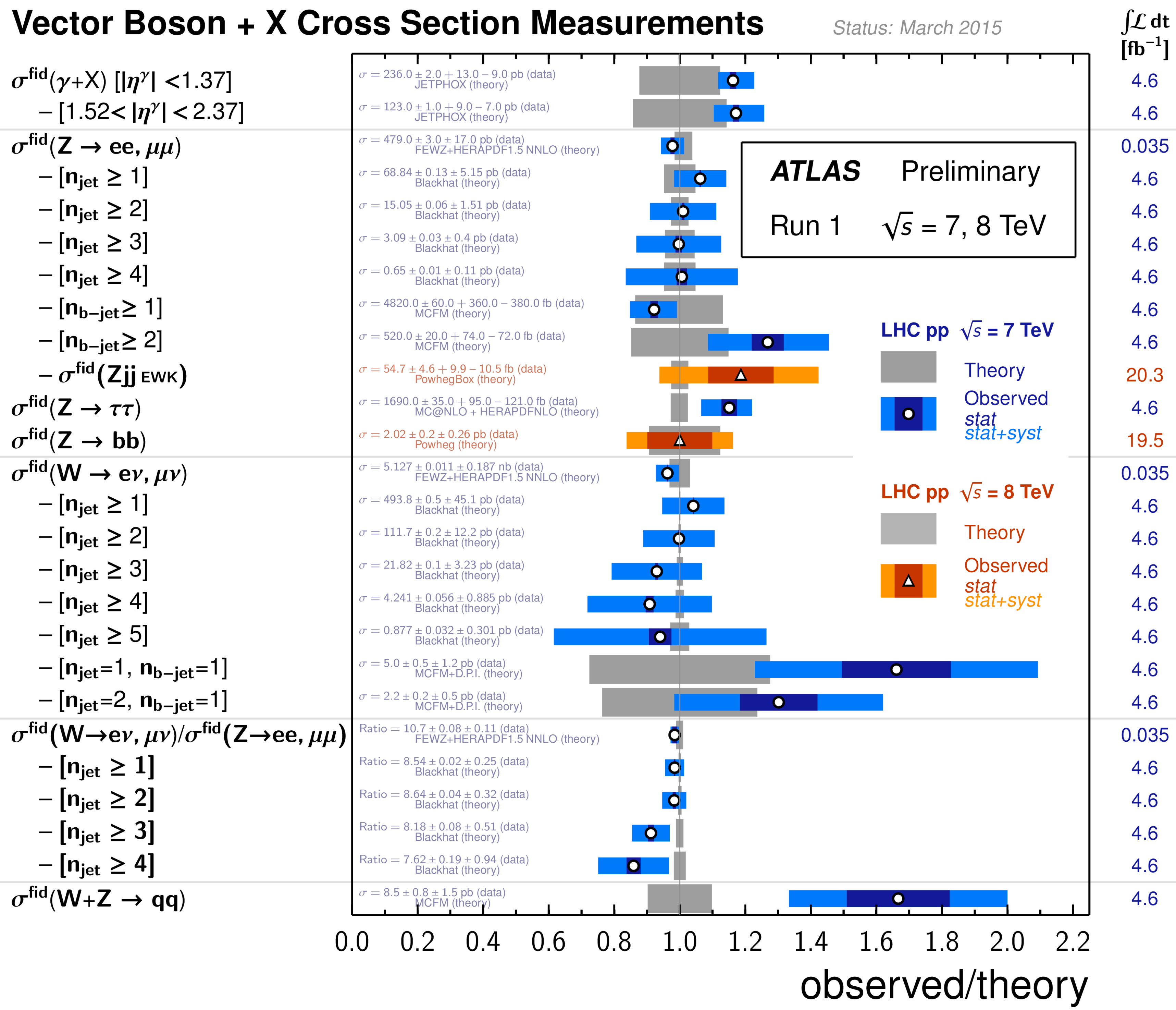
CMS-PAS-SMP-14-015

Pertubative QCD - V + jets

- In general, very good agreement over many orders of magnitudes

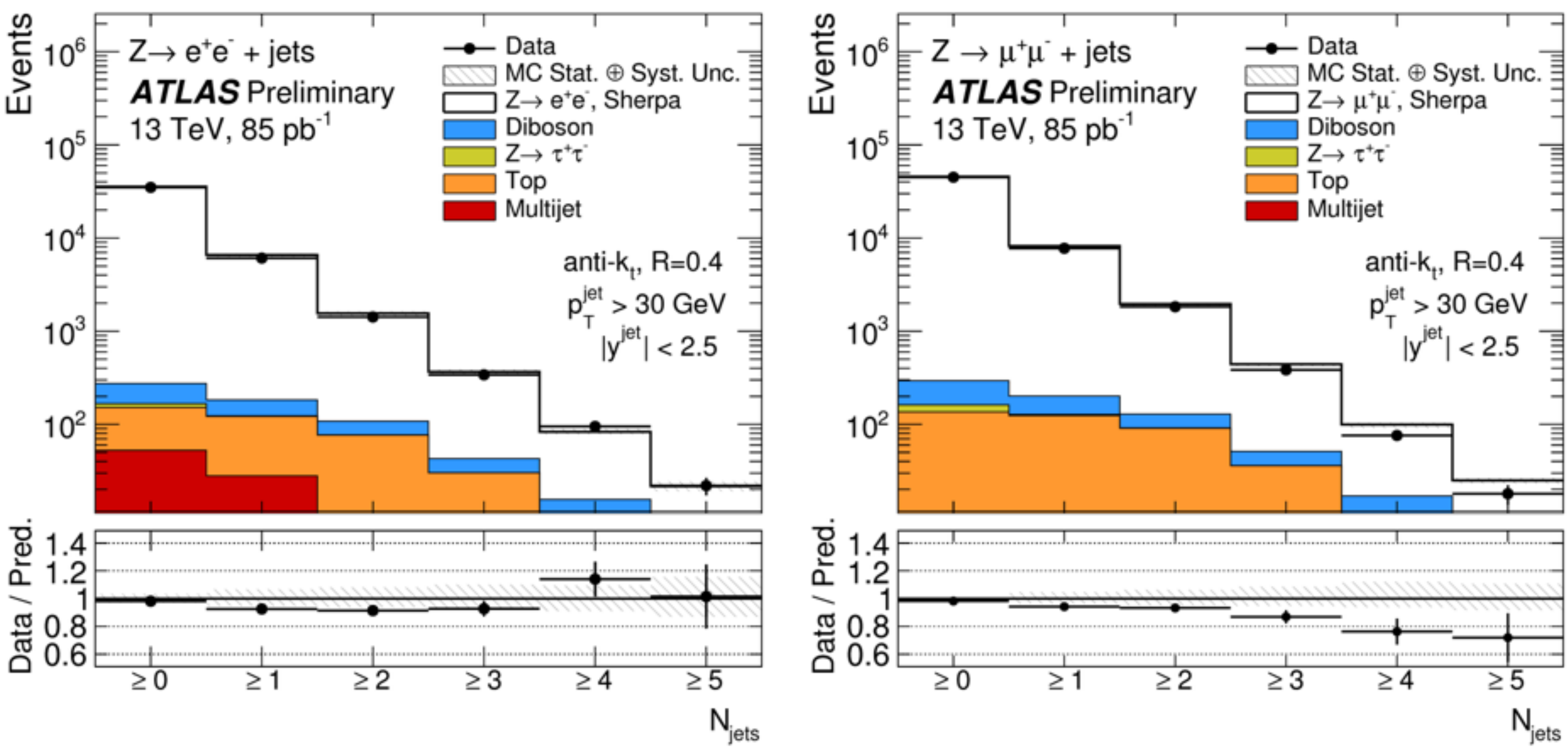
- High accuracy of measurements allow to access discrepancies to predictions

- V+jets is a very good tool as it allows to test many processes



V + jets

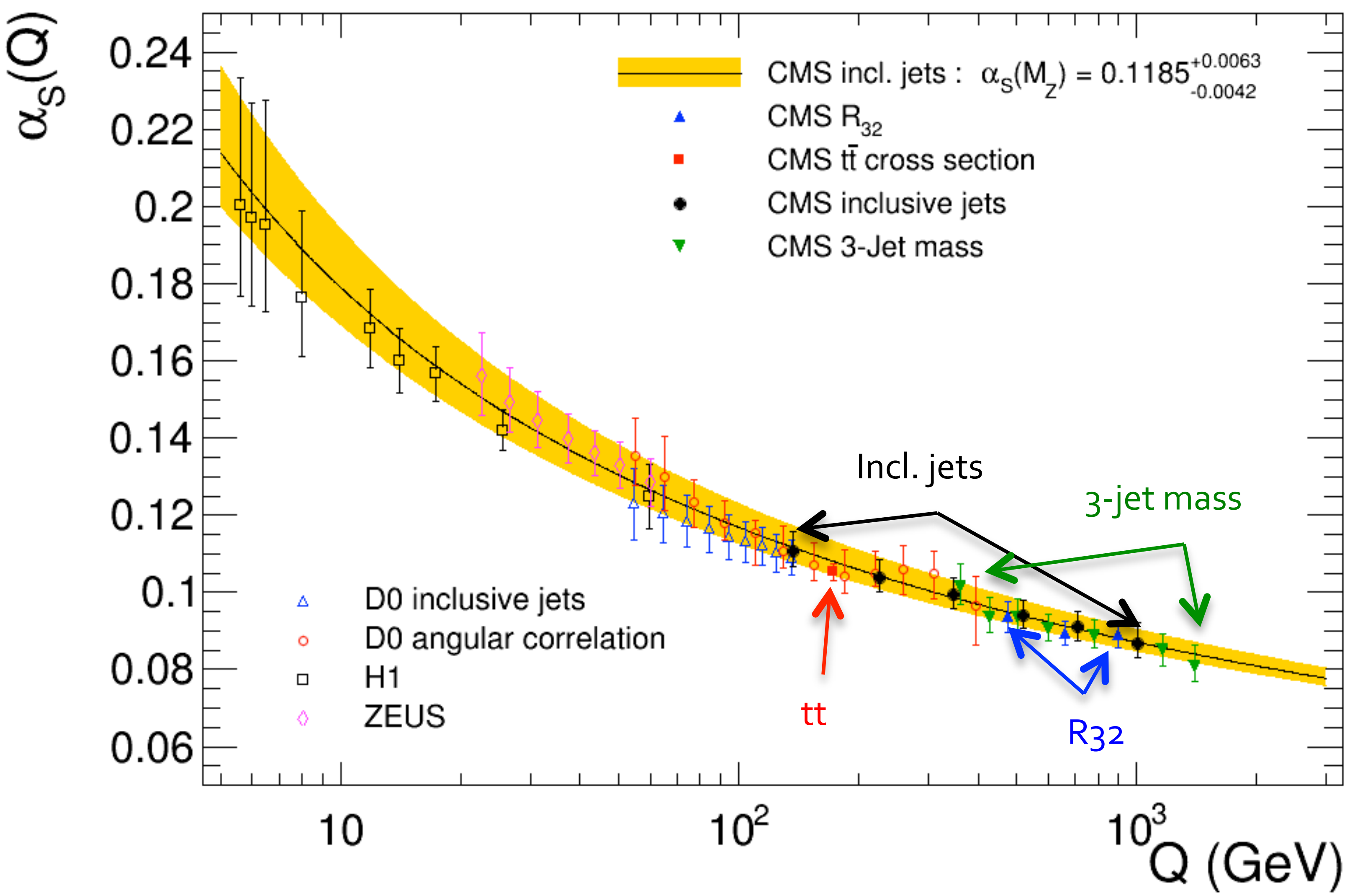
- New results coming in with 13 TeV - good agreement with MC
  - using integrated luminosity of 85 pb^{-1}
  - MC: O and NLO matrix elements supplemented by parton showers



ATLAS-CONF-2015-041

Strong coupling - α_s measurement

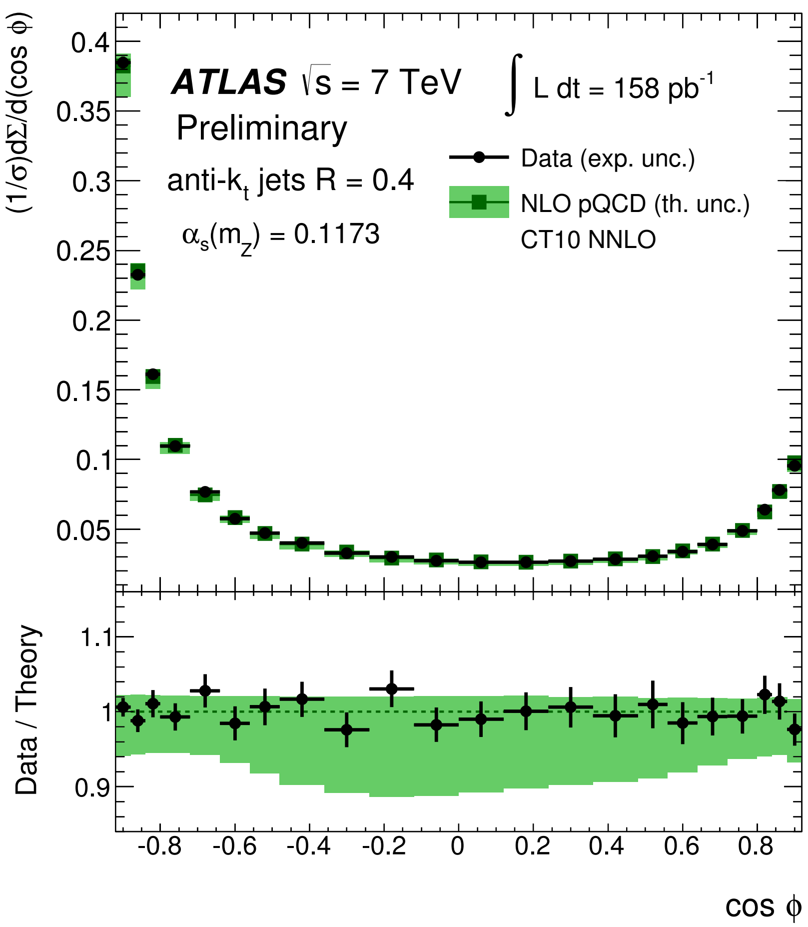
- α_s is fundamental QCD parameter, many measurements sensitive to it
  - measured via inclusive jet cross section, ratio 3-jet to 2-jet events (R_{32}), tt cross section, event shapes, etc.
  - CMS results demonstrate consistency of different processes
  - has sensitivity to new physics

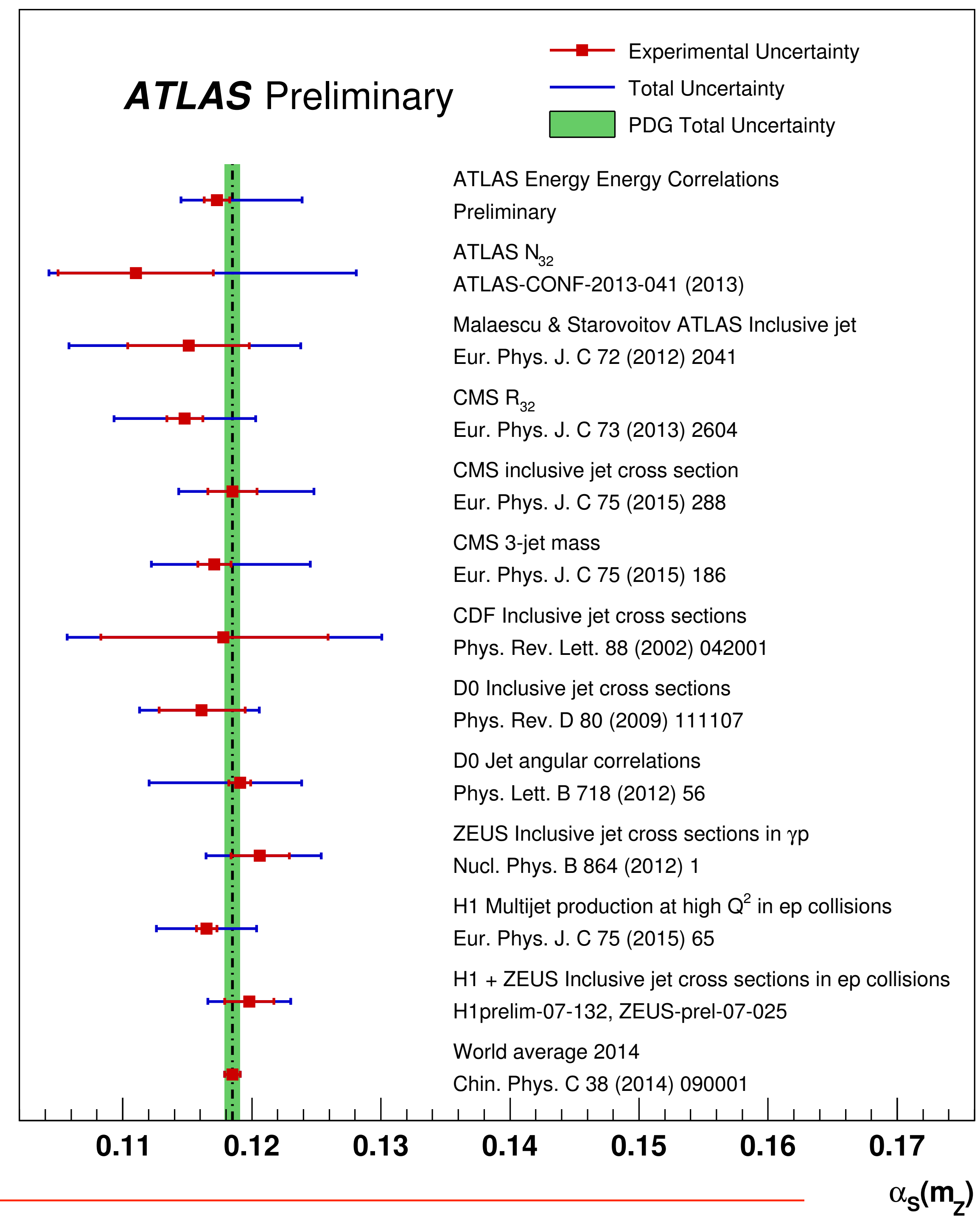


Good agreement with 2-loop solution of RGE as function of the scale Q up to TeV

Strong coupling - α_s measurement

- New measurement from ATLAS using event shapes





- extracting α_s at m_Z from jet-based transverse energy correlation

$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

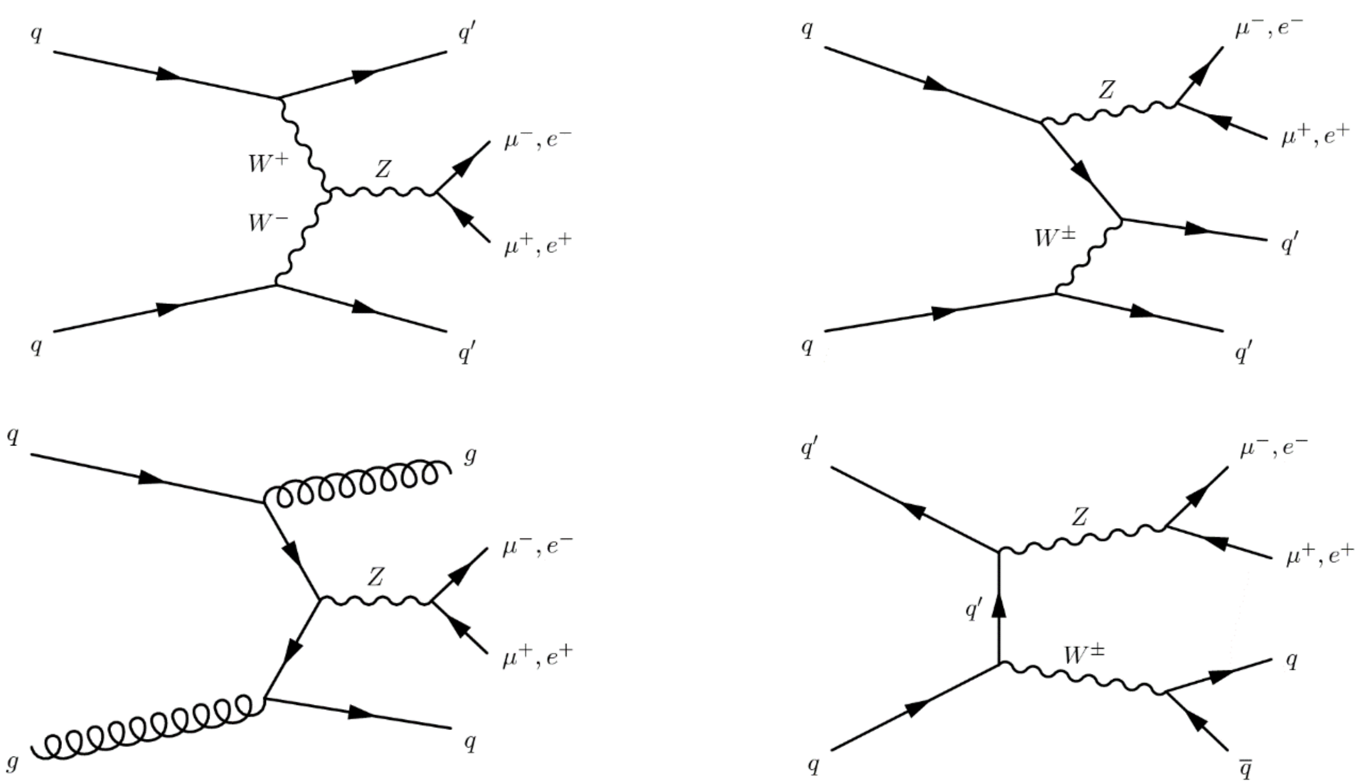
$$x_{Ti} = E_{Ti}/E_T \qquad E_T = \sum_i E_{Ti}$$

$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\ {}^{+0.0063}_{-0.0020}\,(\text{scale})\ \pm 0.0017\,(\text{PDF})\ \pm 0.0002\,(\text{NPC})$$

EWK - Electroweak production of W/Z : VBF Z

- Very complex and detailed analyses from ATLAS and CMS
  - First result from ATLAS, significance above 5σ: observation of VBF production
  - Excellent agreement data/MC demonstrated – will be “VBF reference analysis”.

- Z+2-jet final state, separate EWK (t-channel exchange of W/Z) and non-EWK contributions. EWK dominantly VBF + Z-bremsstrahlung diagrams:

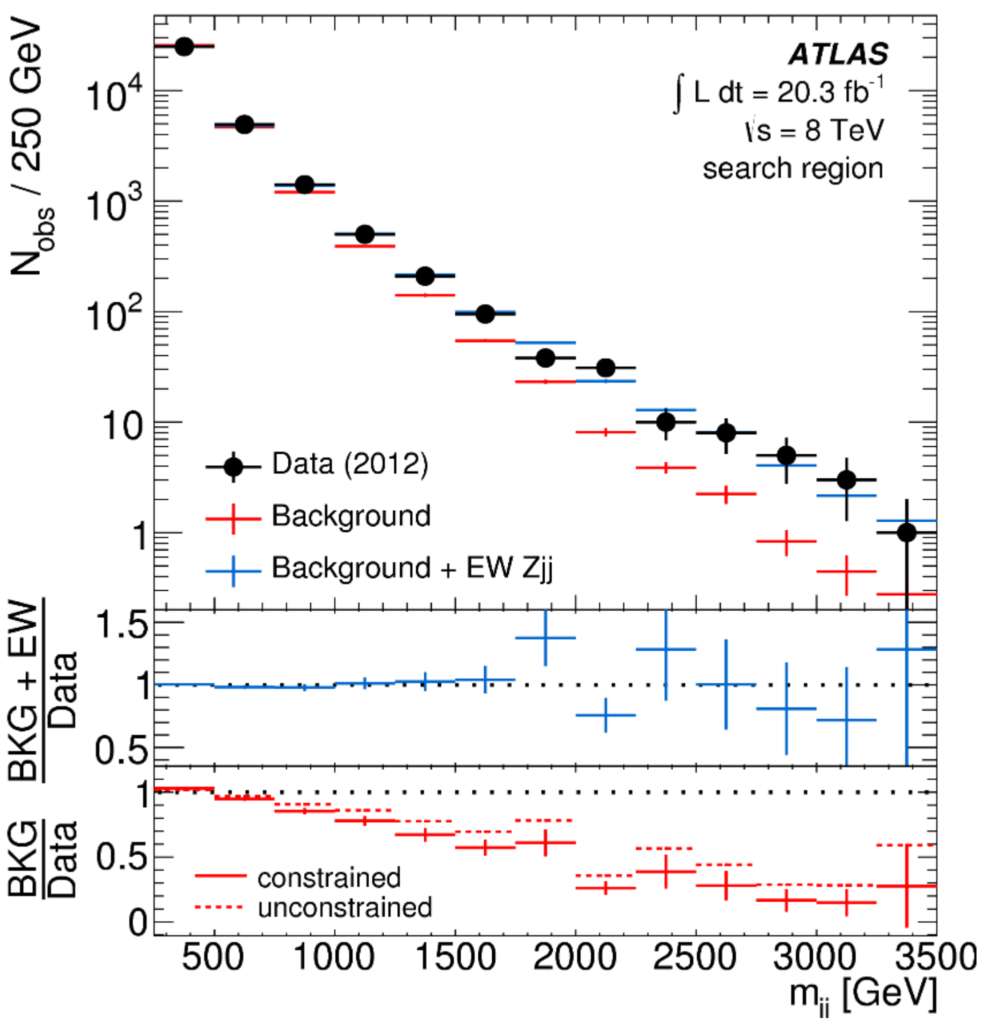


EWK

typical non-EWK

EWK - VBF Z production

- ATLAS analysis based on 5 fiducial regions
  - baseline, high-mass, search, control & high-p_T
- cut-based analysis, MC templates & control region to extract signal
  - SHERPA (LO multi-leg) and POWHEG (NLO) used for signal modelling



The “search” region (plot, m(jj) > 250 GeV): EWK is 5% of total Z+jets signal.

$\sigma_{EWK} = 54.7 \pm 4.6(\text{stat})\ ^{+9.8}_{-10.4}\ (\text{syst}) \pm 1\ (\text{lumi})$ fb

$\sigma_{Powheg} = 46.1 \pm 1.0$ fb

similar agreement for m(jj) > 1000 GeV region

significance estimated using Toys for search and control regions.

extract aTGC limits (compare to others)

EWK - VBF *W* production

- CMS analysis
  - MVA based after cutting on BDT discriminat, likelihood fit to the m_{jj} distribution to extract signal
  - Madgraph+PYTHIA used for signal modelling
  - data/MC agreement for distribution of BDT discriminant values not ideal

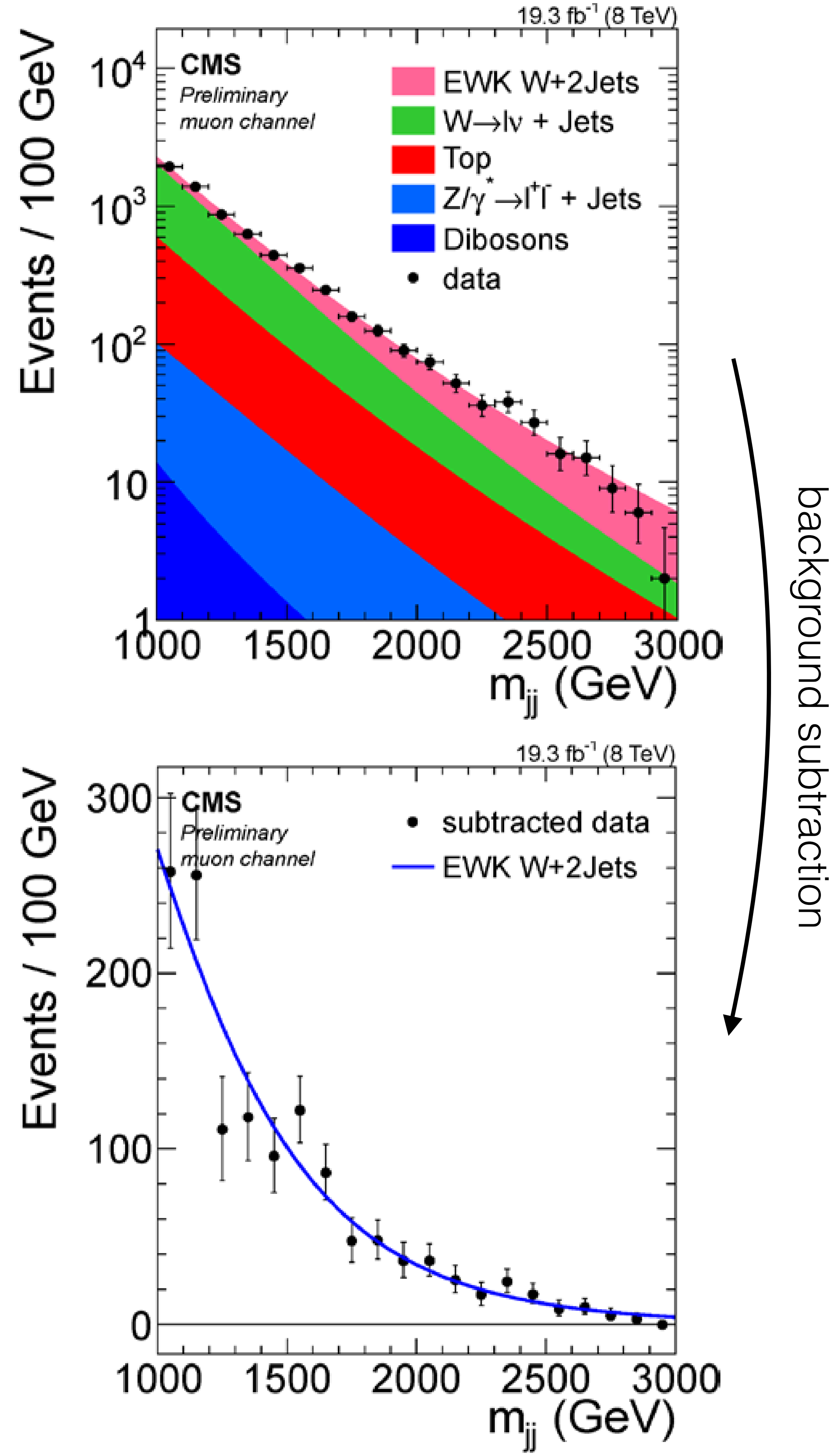
    -> results in systematic uncertainty
  - muon/electron channels very similar

    in terms of uncertainty & accuracy

- Well within prediction

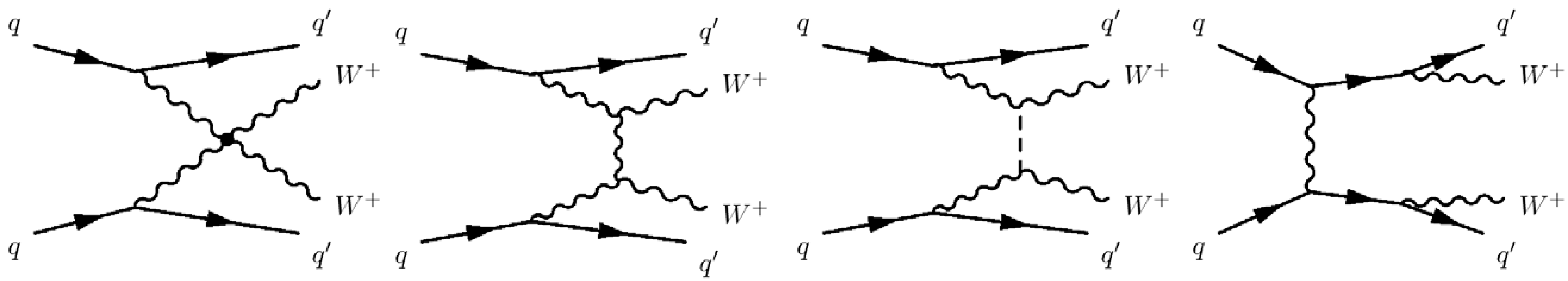
Event category	Measured cross section
μjj	0.43 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.01 (lumi.) pb
ejj	0.41 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
combined μjj and ejj	0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

predicted: $\sigma = 0.50 \pm 0.03$ pb

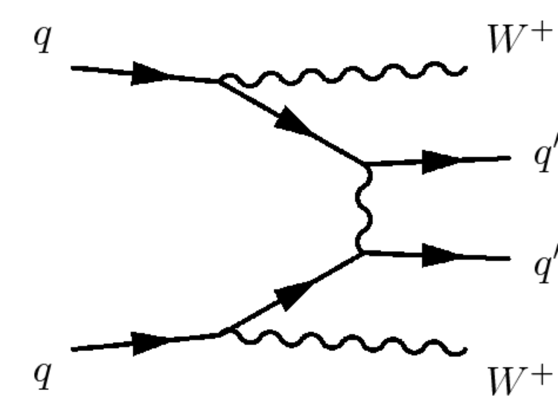


EWK - production of *W*: VBS *ssWW*

- First evidence (3σ) of VBS reported by ATLAS in same-sign WW channel
  - QCD and EWK contribution about the same size

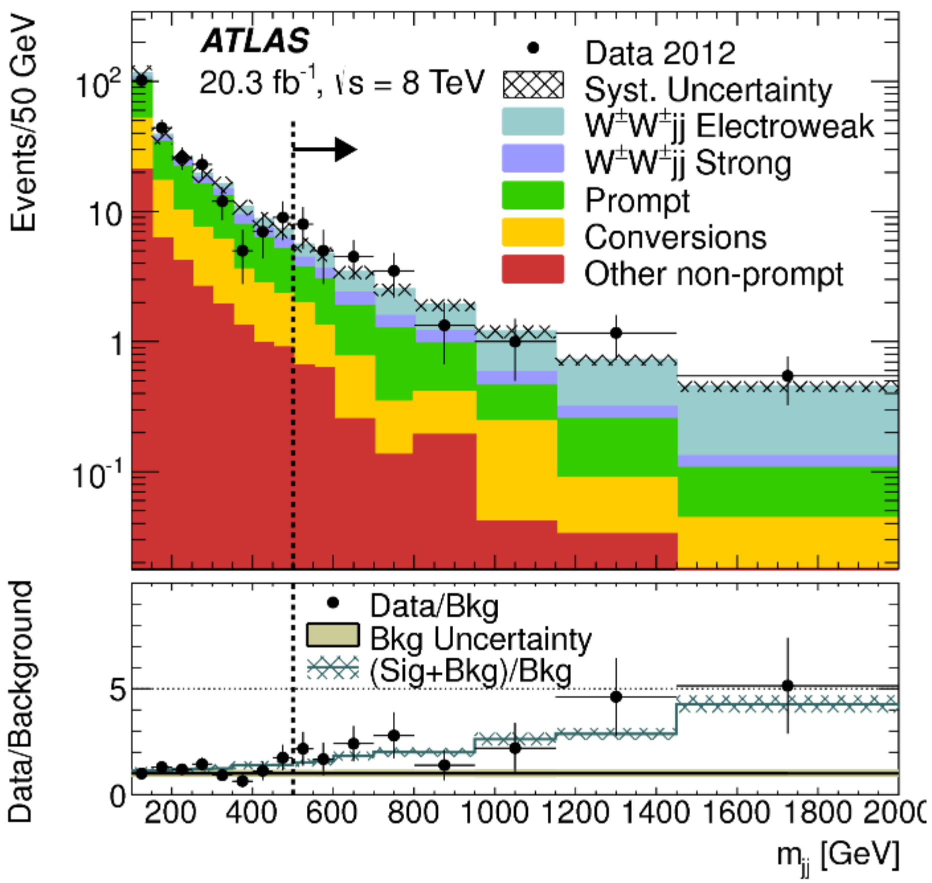


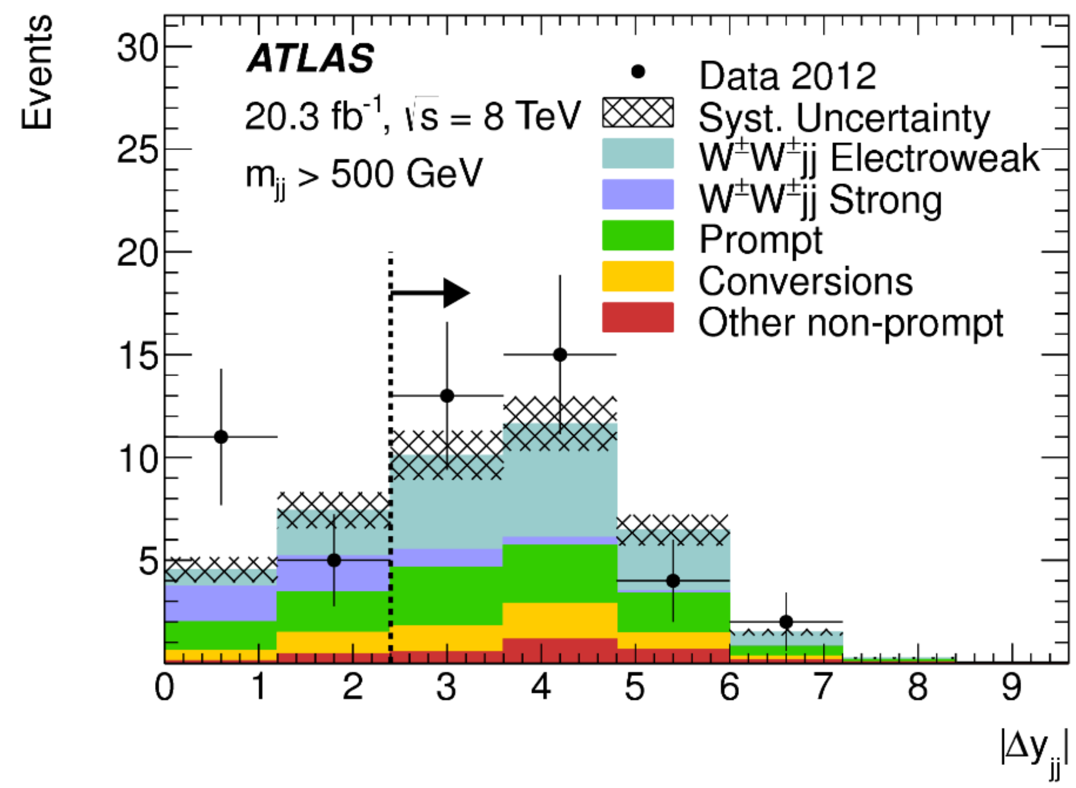
- 2-lepton with di-jet + MET final state
  - separate QCD with $O(\alpha_s^2 \alpha_{EW}^4)$ contribution from EWK with $O(\alpha_{EW}^6)$
  - ATLAS signal modelling: Sherpa with Powheg for NLO normalisation

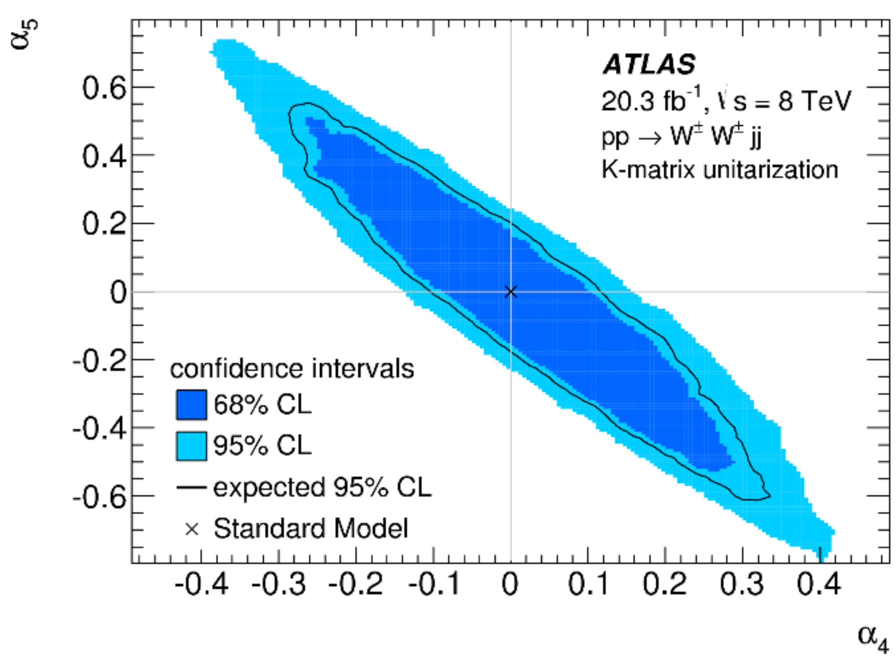


- Two analyses: inclusive *ssWW* and the (subset) VBS EWK

EWK - VBS *ssWW* production







Set first limits on anomalous quartic gauge couplings (aQGC) parameters relevant for WWWW couplings: α_4 and α_5

Use WHIZARD and K-matrix regularization and set limits using data in "EWK" analysis region.

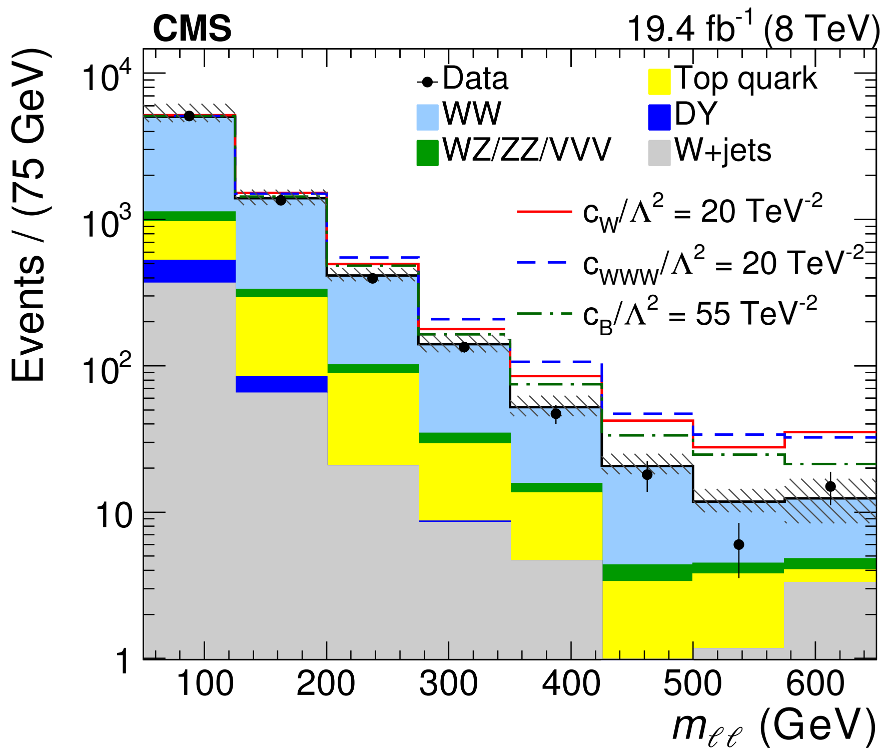
σ(incl) = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb
σ(pred) = 1.52 ± 0.11 fb

σ(EWK) = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb
σ(pred) = 0.95 ± 0.06 fb

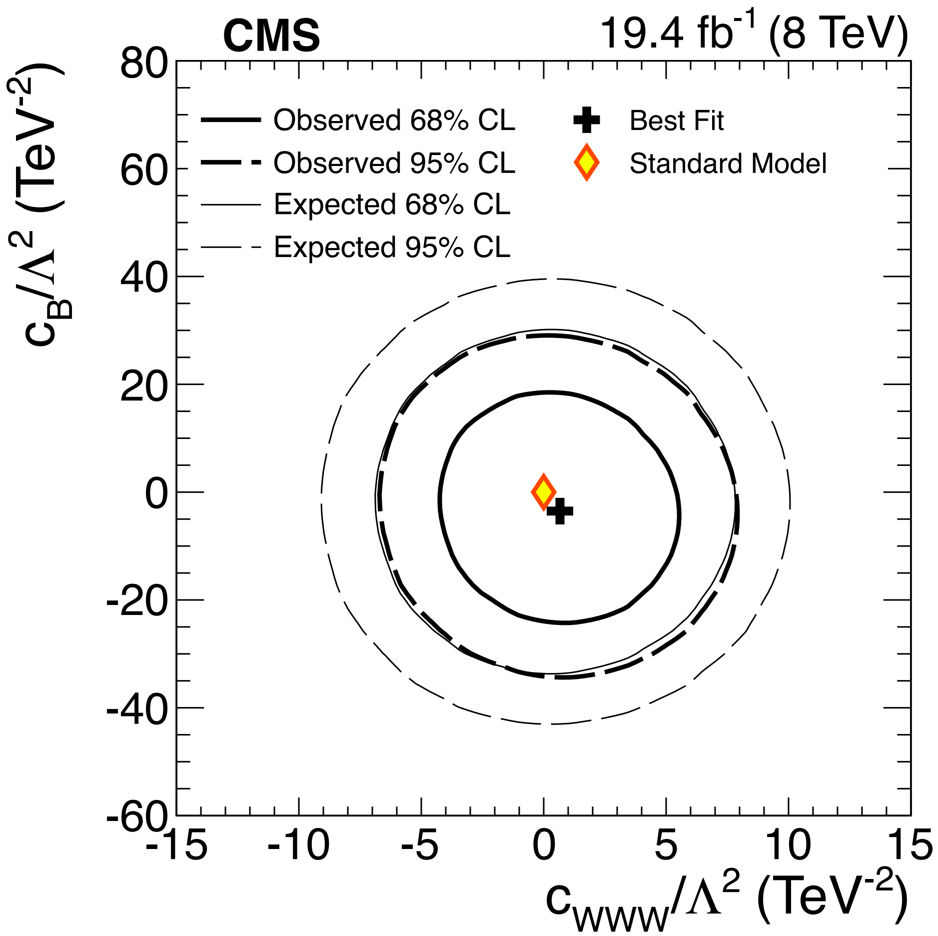
CERN-PH-EP-2014-079

EWK - Di-boson production **WW**

- Remove **H→WW** contribution (~8% effect)
- Evaluate limits for anomalous trilinear gauge couplings (aTGC)
- In this analysis only CP-conserving operators for aTGCs tested



Coupling constant	This result (TeV^{-2})	Its 95% CL interval (TeV^{-2})	World average (TeV^{-2})	
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8	(from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$	(from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$	(from κ_γ and g_1^Z)



σ(fid) = 60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1 (theo) ± 1.6 (lumi) pb

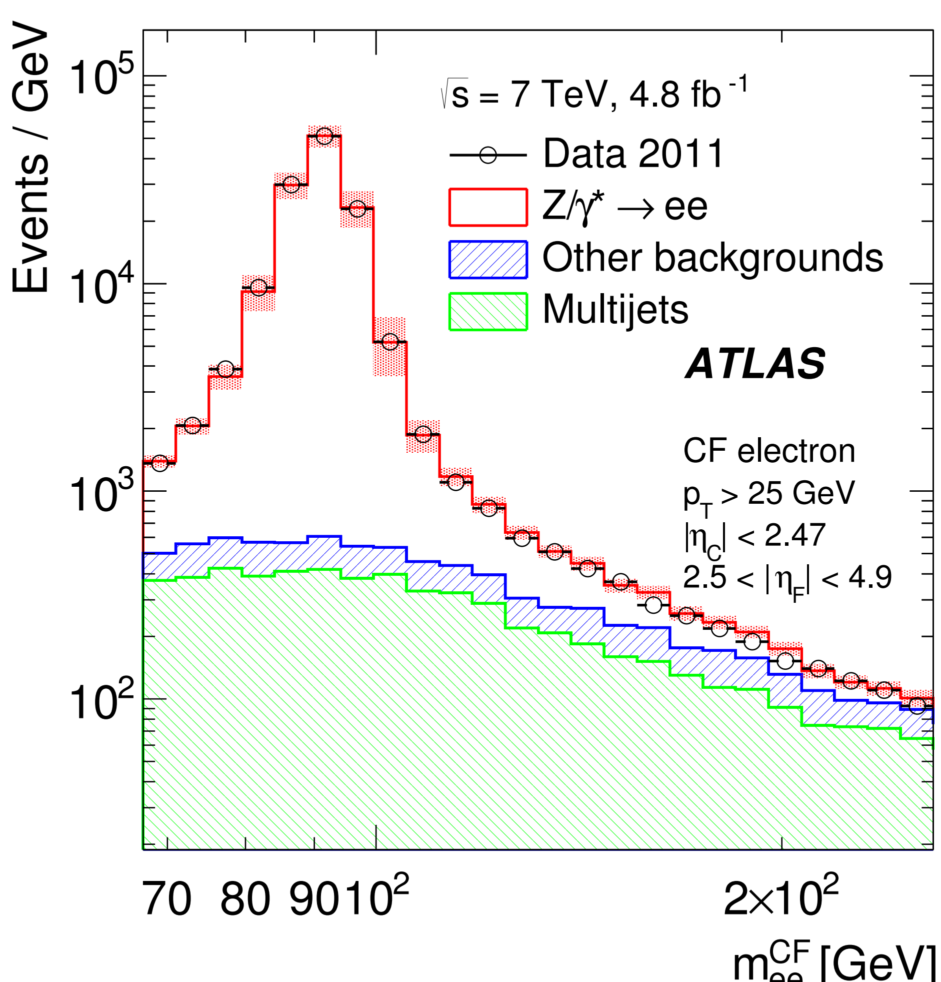
σ(NNLO) = 59.8 ± 1.2 pb

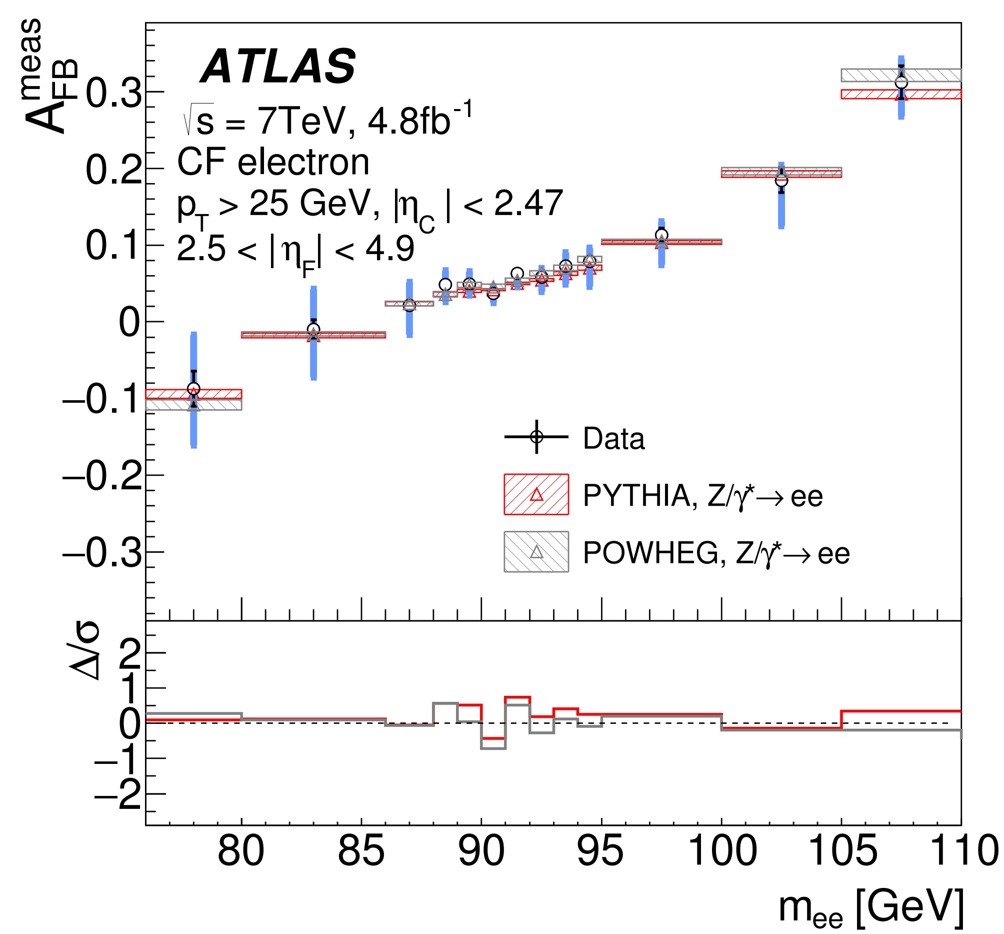
CERN-PH-EP-2015-122

Forward-backward asymmetry *Z* A_{fb}

- ATLAS result from 7 TeV most precise of LHC
  - use 3 categories: μμ, ee with central-forward (CF), ee with central-central (CC)
  - convert to $\sin^2\theta_{eff}^{lept}$ EWK mixing parameter
    use PYTHIA (LO) to extract EWK contribution, POWHEG as a crosscheck

    reasonable good modelling of A_{fb} distribution

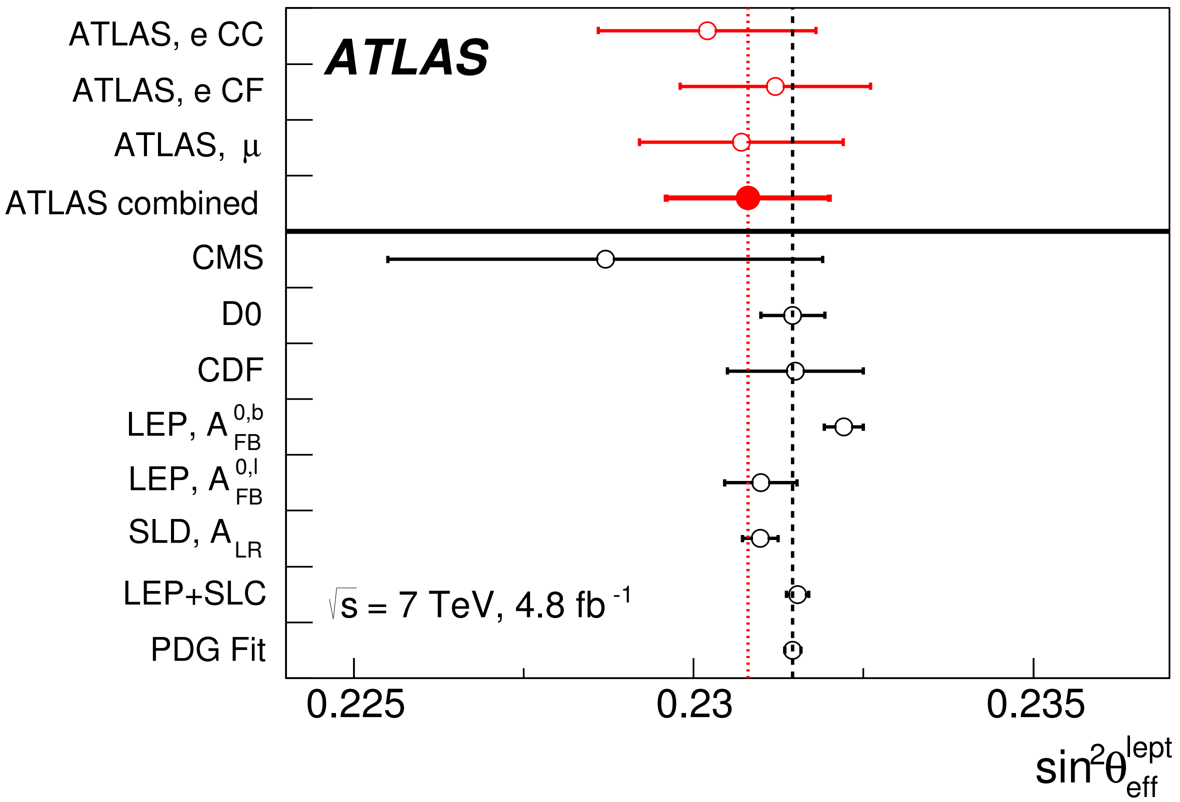




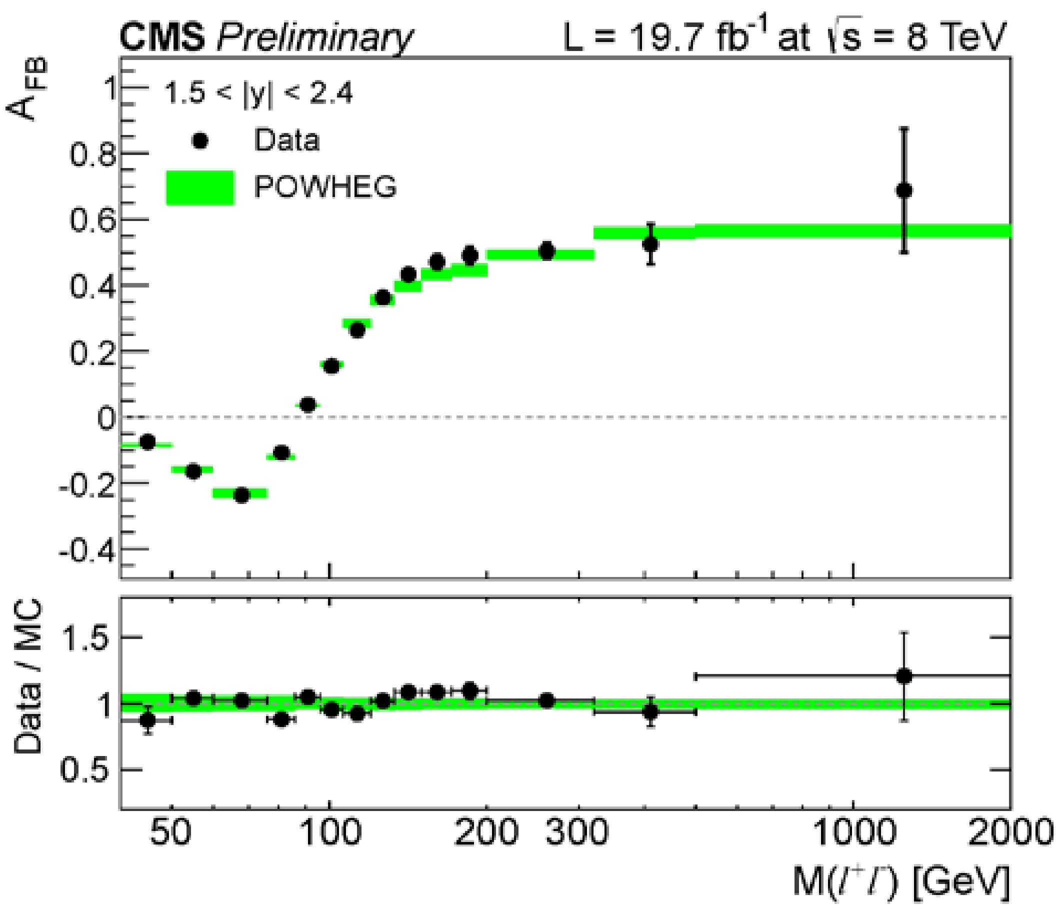
CERN-PH-EP-2014-259

EWK - Forward-backward asymmetry *Z* A_{fb}

- Overview table for $\sin^2\theta_{eff}^{lept}$
  - Tevatron is reaching LEP precision
  - LHC not yet competitive (more statistics and more elaborated analyses needed)

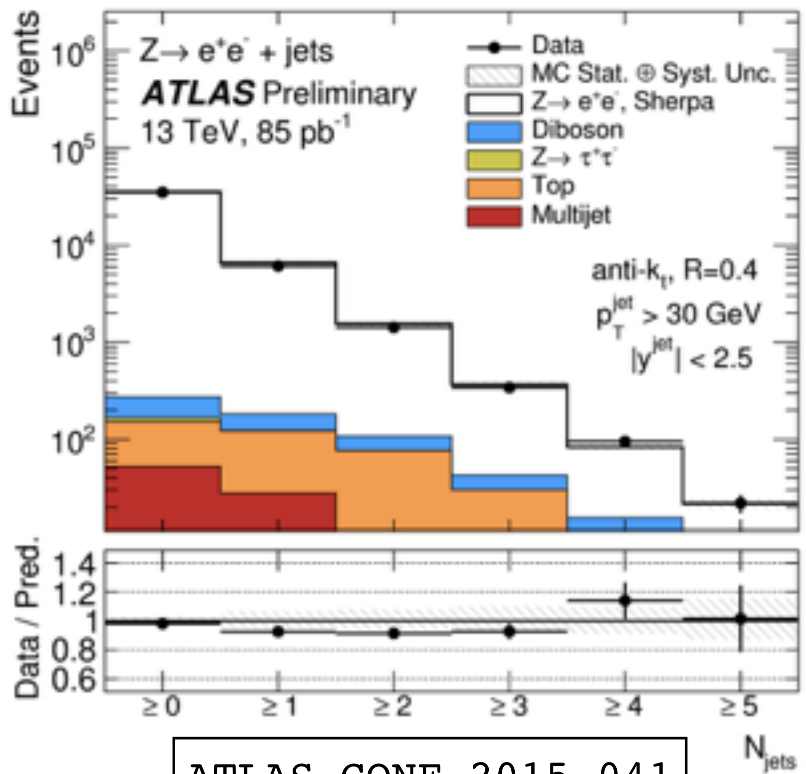


- Preliminary CMS results using full 8 TeV dataset
  - excellent modelling with POWHEG



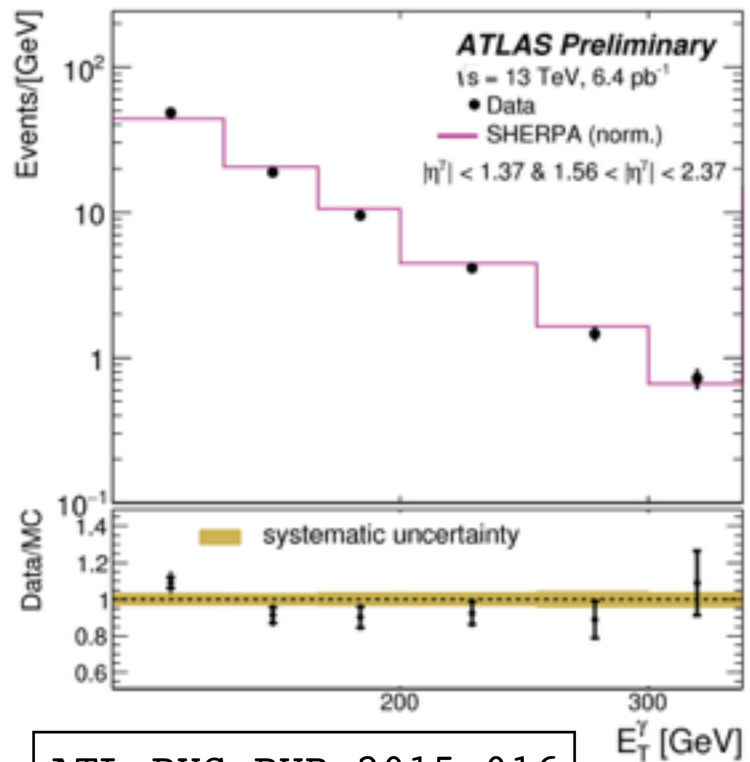
A first look on 13 TeV results

Z+jets measurement



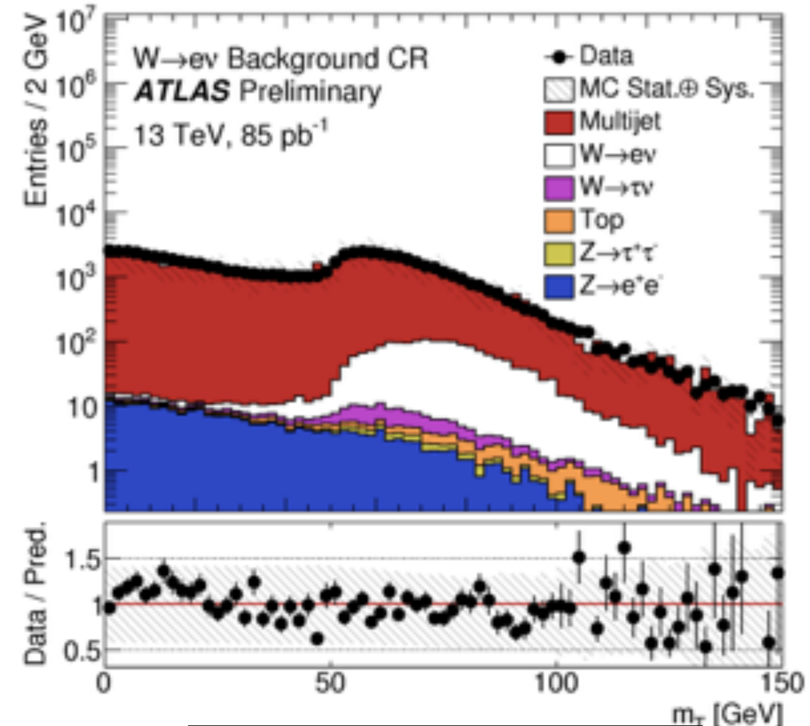
ATLAS-CONF-2015-041

Isolated photon production



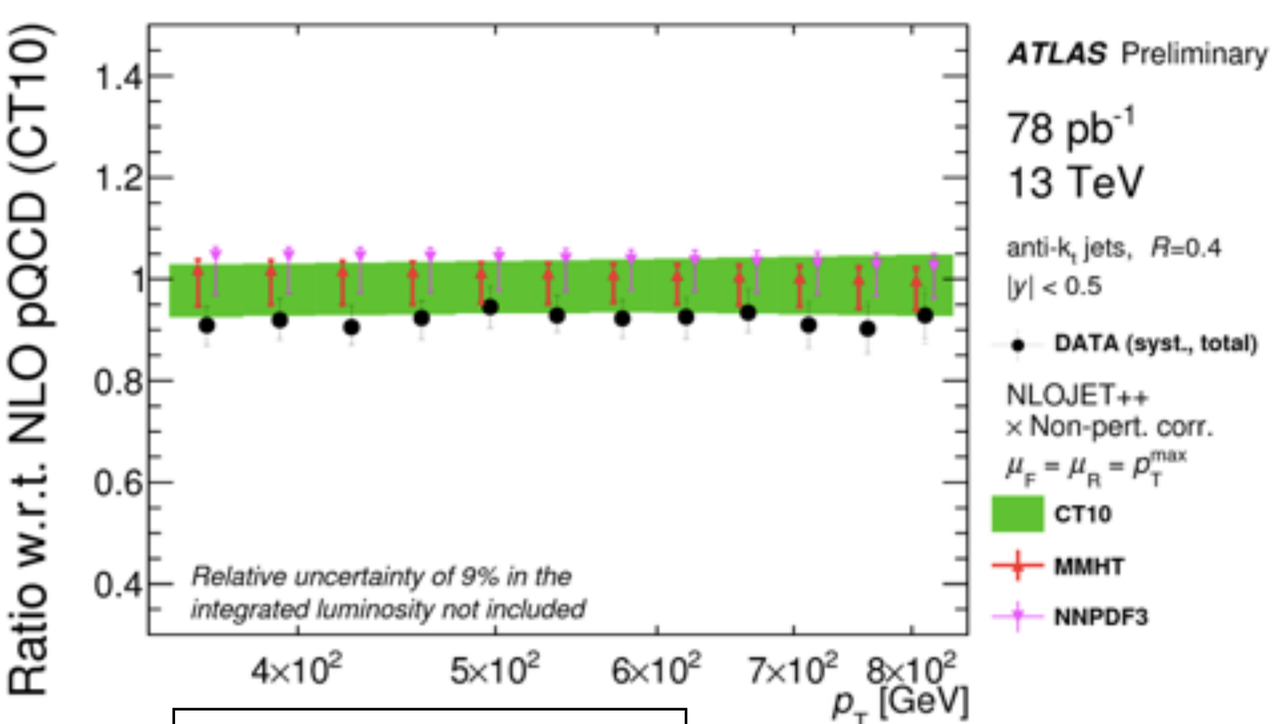
ATL-PYS-PUB-2015-016

W cross section measurement



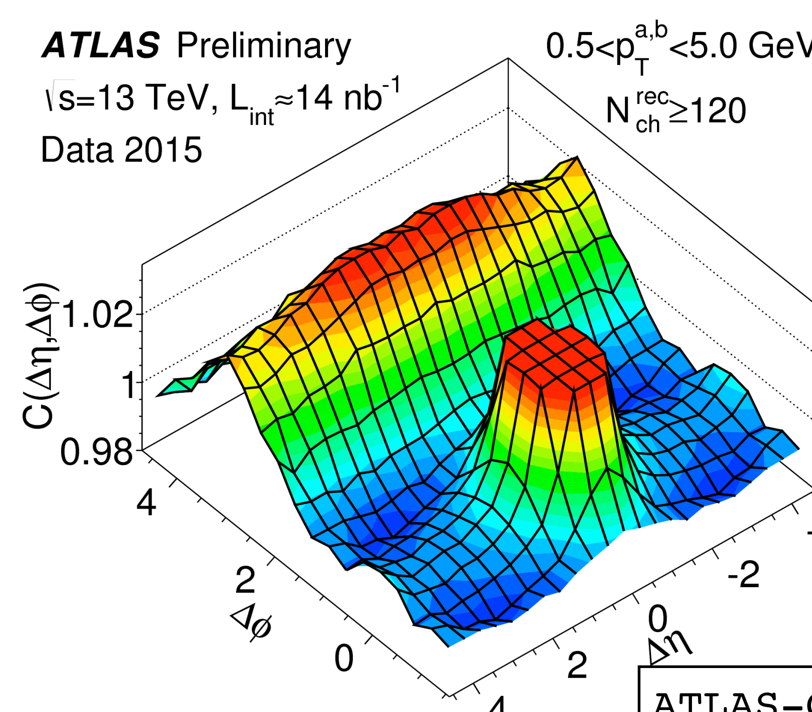
ATLAS-CONF-2015-039

jet cross section measurement



ATLAS-CONF-2015-034

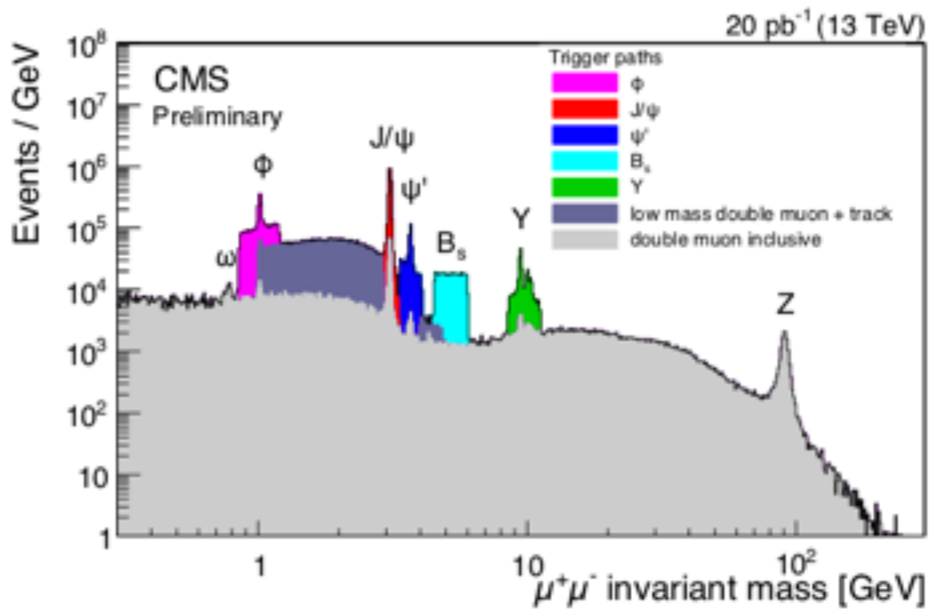
ridge in p-p collisions



ATLAS-CONF-2015-027

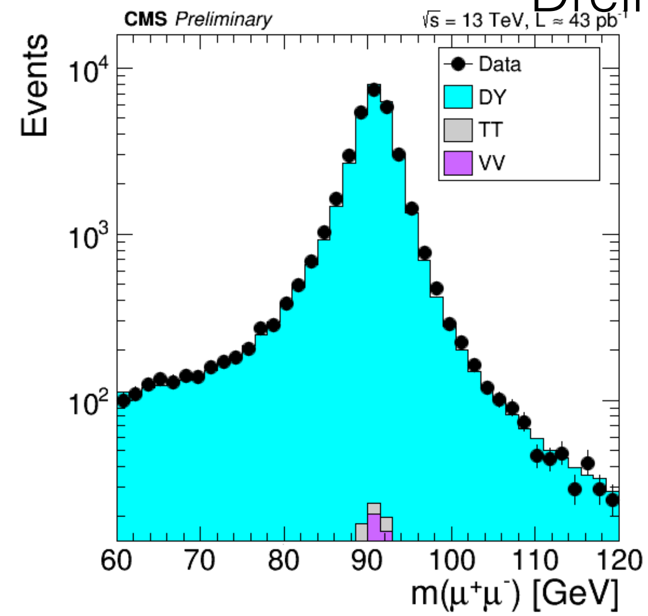
A first look on 13 TeV results

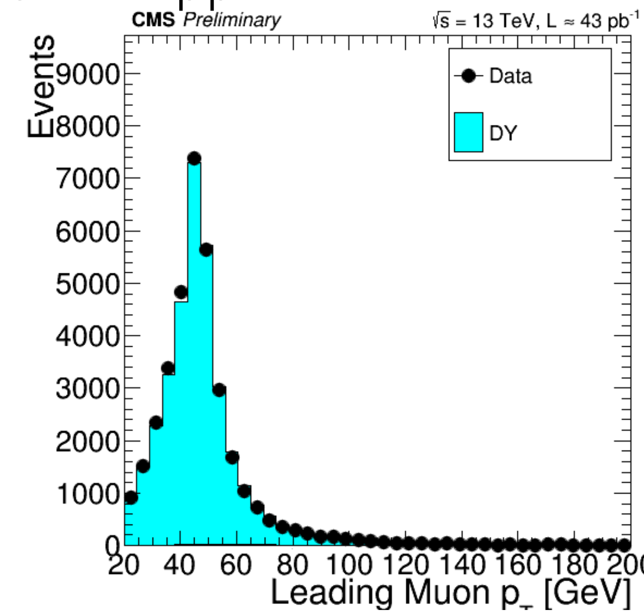
Di-muon invariant mass spectrum



CMS-DP-2015-001

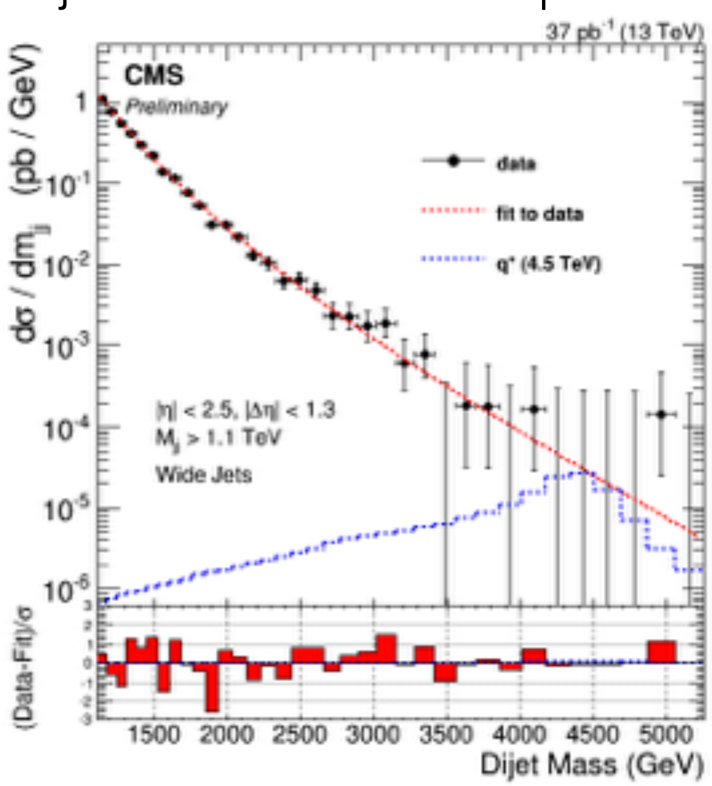
Drell-Yan Z->μμ





CMS-DP-2015-015

Di-jet invariant mass spectrum



CMS-DP-2015-017

- Many more physics and performance studies in the pipeline
- Exciting times ahead with Run-2
  - SM tests at the new energy frontier

Conclusion & Outlook

- Run-1 data campaign was a very successful test of the SM
- This would not have been possible without the excellent modelling and understanding of the detectors
- In general very good agreement of the measurements with predictions
- More detailed Run-1 data analyses are on the way
  - e.g. m_W precision measurements
- Run-2 data taking has started
  - first results are being prepared

Appendix

BSM tests

Tuesday, 15 September 2015	
07:30	--- Breakfast ---
09:00	**Morning session** (until 12:55)
09:00	Searches of physics/particles beyond the Standard Model at the LHC - Piotr Zalewski (CMS, National Centre for Nuclear Research, Warsaw)

- Testing the SM is testing beyond the SM

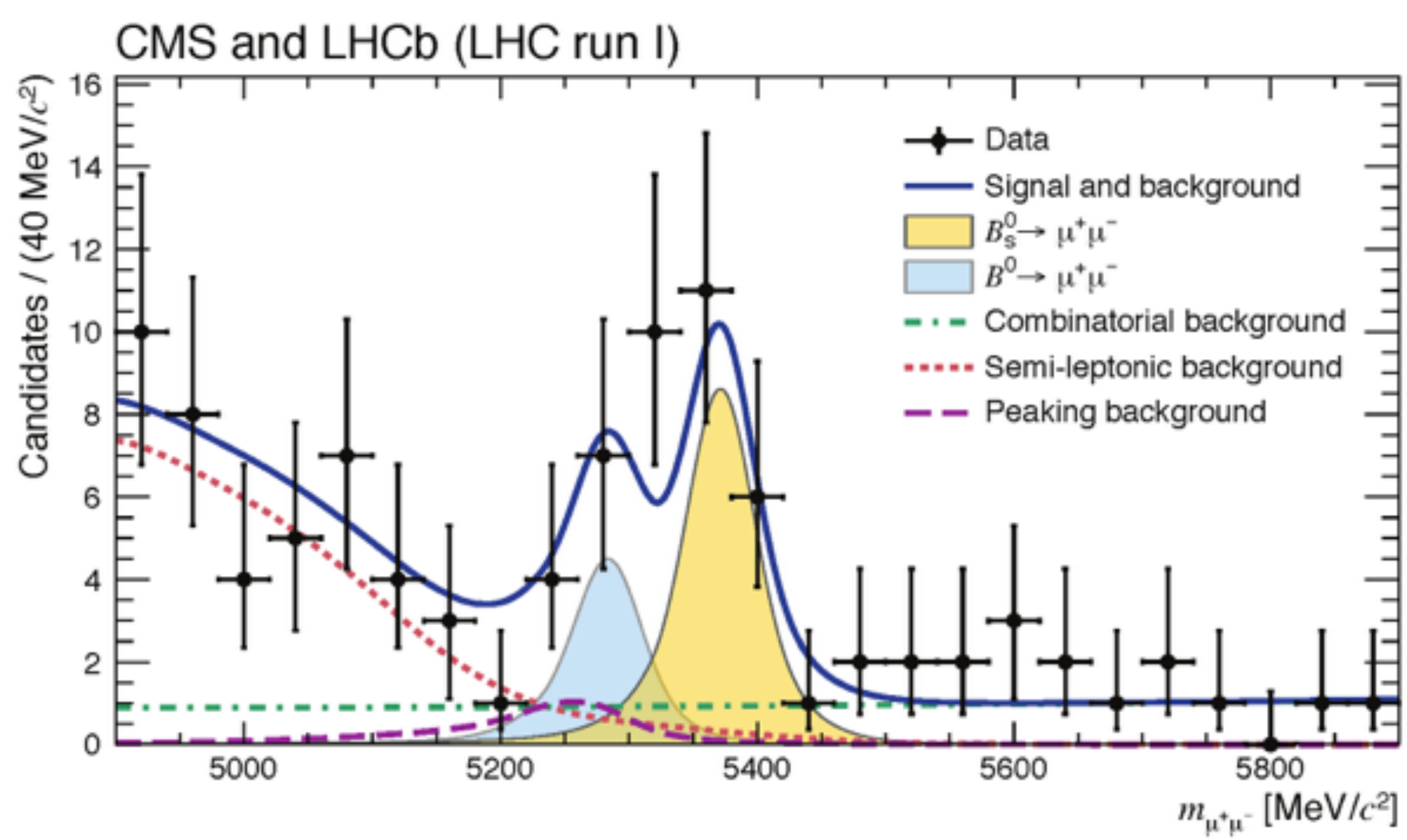
- Combined results of CMS and LHCb on B^0_S -> μμ

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

(Buras et al, JHEP 1009 (2010) 106)

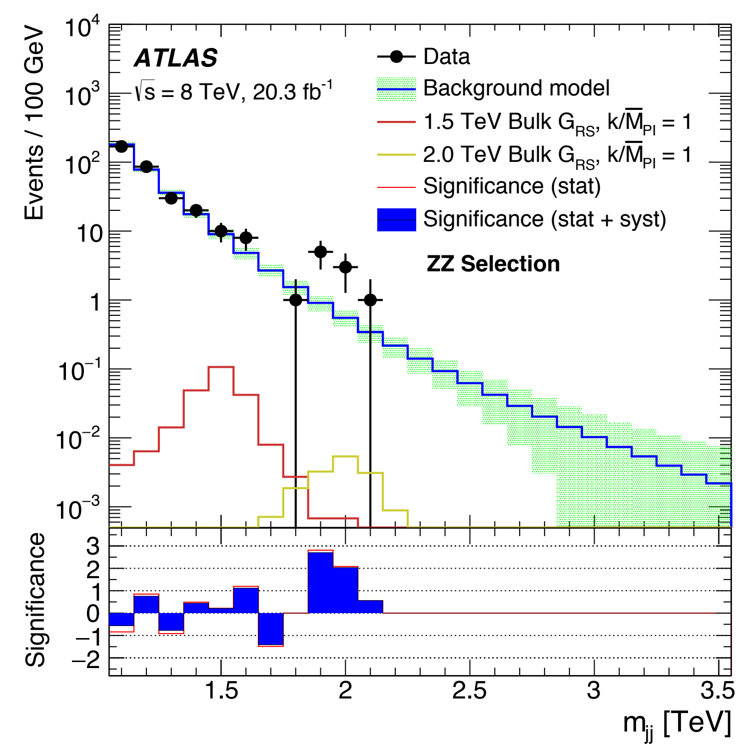
- Branching ratio is sensitive to BSM effects

- Very rare decay
  - challenging analysis



All good - no tension at all ?

- Overwhelming majority of measurements are consistent with SM model prediction
  - precision of the LHC measurements allow to test SM predictions over many orders of magnitudes
  - QCD measurements start turning into precision measurements
- Very little tension in SM measurements & EWK Higgs mechanism fits in like the perfect cindarella shoe
- Or is there something we’ve missed?
  - ATLAS slight excess in high-mass di-boson production



09:30	Di-boson production at high transverse momenta beyond NLO QCD - Francisco Campanario (Karlsruhe Institute of Technology)