Standard Model results from ATLAS and CMS

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## On behalf of ATLAS and CMS

Why measuring the SM?

- Most successful theory ever, precision physics also at LHC, search for deviations, "legacy" measurements

- Conventionally, does not include:
  - top, Higgs, HF decays, HI

- Includes: Vector Boson production, Jets, Photons, soft QCD, EW:
  - Study and test QCD in corners of phase space
  - extract PDFs
  - tune MC
  - understand jet structure
  - precision measurements of SM constants (like α_s, M_W…)
  - place limits on Effective Field Theory extensions of the SM
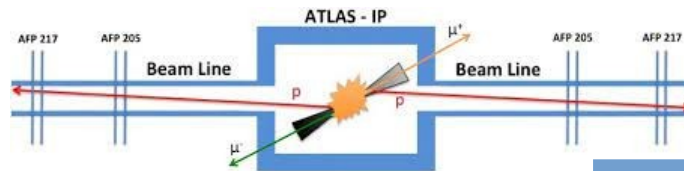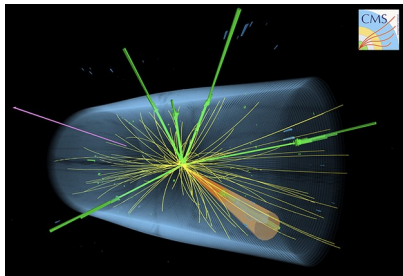
Many different experimental signatures

Soft QCD:
underlying event,
MC tuning, study of
hadronisation
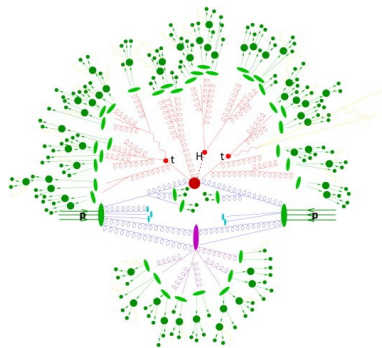
Jets and photons:
perturbative QCD, PDFs,
substructure, α_s
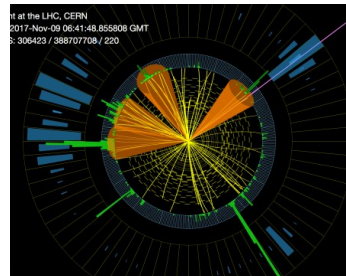
Vector bosons:
QCD, EW, PDFs,
$\sin\theta_W$, EFT, α_s

Intact protons: QCD,
EFT, invisible states

Will just give a few examples:
α_s determination from jets and Z bosons, W mass, jet substructure, EFT and ALP limits from
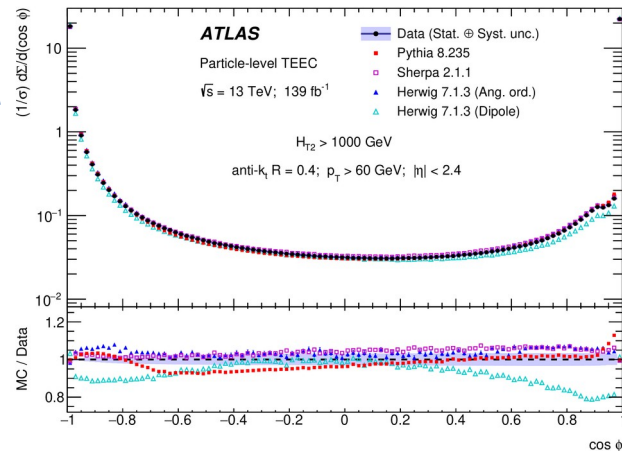intact protons

α$_s$ from jets: Transverse Energy-Energy Correlation (and Asymmetry)

- TEEC: Transverse-energy weighted distribution of azimuthal difference between jet pairs
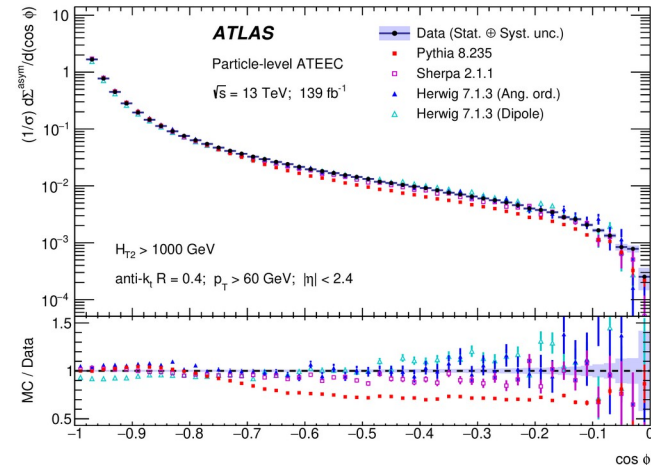
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int\frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^A E_{Tj}^A}{\left(\sum_k E_{Tk}^A\right)^2}\delta(\cos\phi - \cos\varphi_{ij}),$$

- ATTEC: difference between forward and backward part of TEEC

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}.$$

Back-to-back jets

Self-correlation of collinear jets

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Selection and systematics

- Use 139/fb of ATLAS data from 2015 to 2018 with $<\mu> = 33.6$

- At least 2 PFlow anti-kt 0.4 jets with pT>60 GeV and $\eta < 2.4$.

- $H_{T2} = p_{T1} + p_{T2} > 1$ TeV

- TEEC and ATEEC measured in 10 intervals of H_{T2}

- Results unfolded to particle level using iterative Bayesian method

- Main systematics from jet energy scale and resolution; reduced in asymmetry
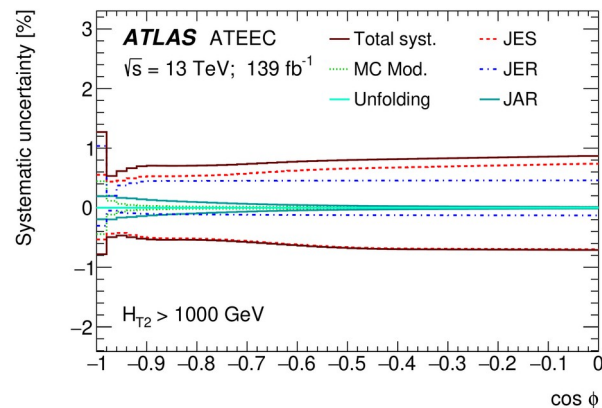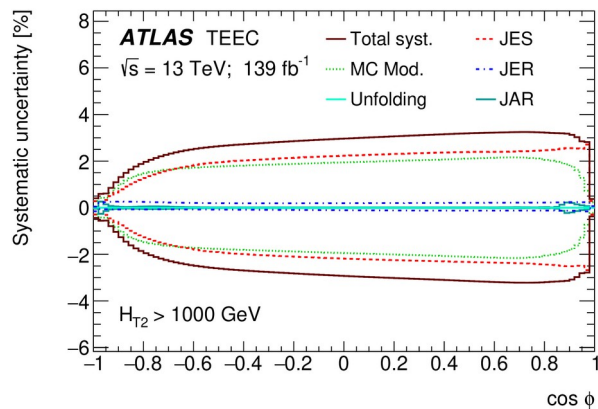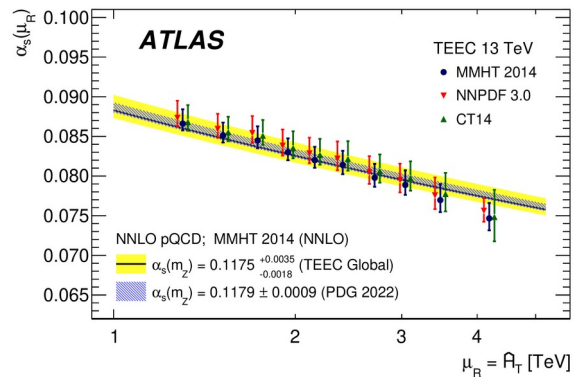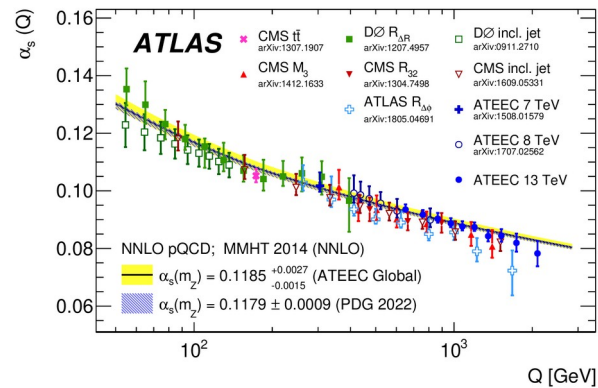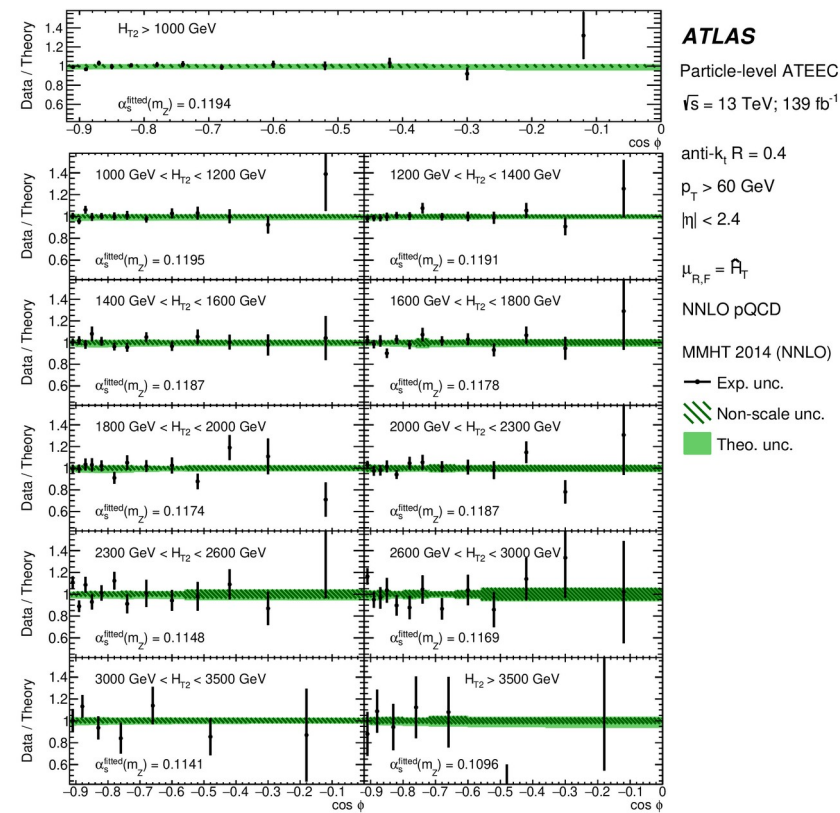
Unfolded results with fixed α_s
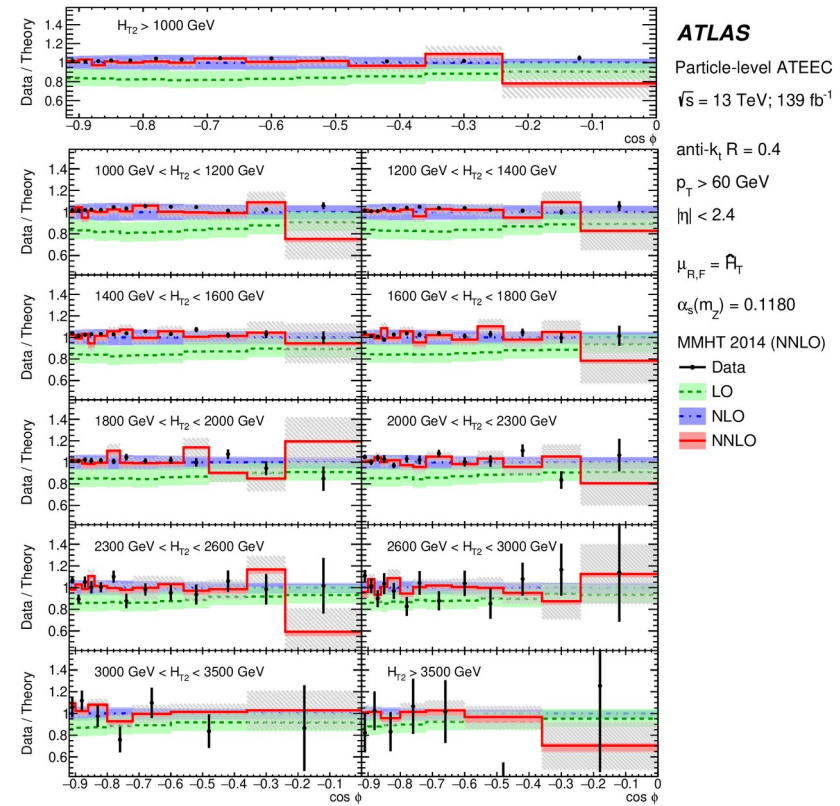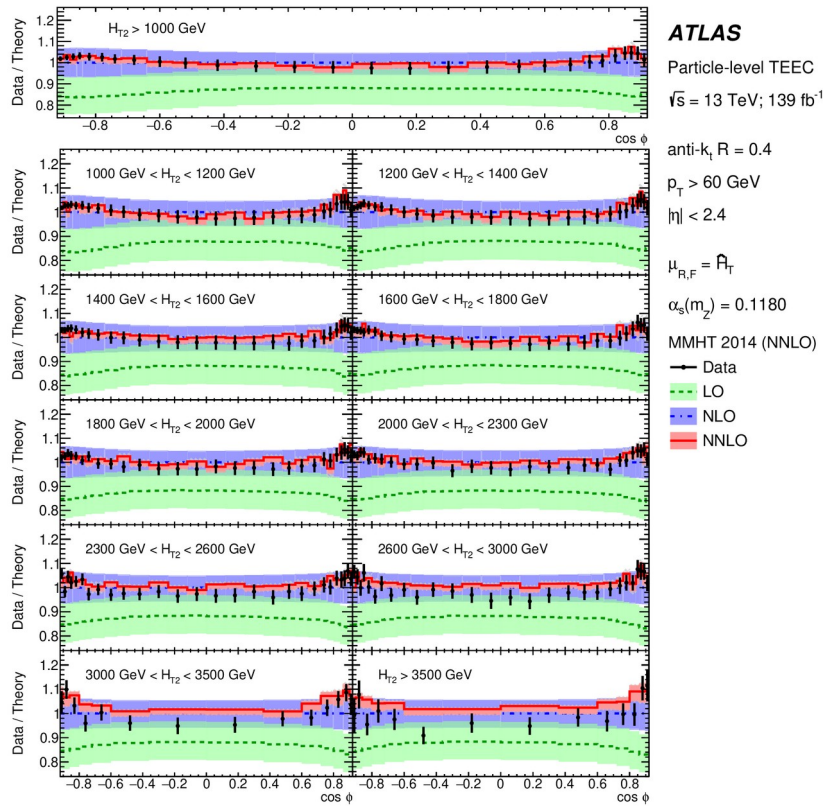
Compare with MMHT 2014, using its standard value of $\alpha_{s\,(MZ)} = 0.1180$

Observables sensitive to α_s since angle between jets sensitive to gluon emission.

First NNLO α_s extraction of from this observable (new NNLO predictions, big reduction in theory uncertainties)

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Determination and running of α_s

Leaving the value of α_s as a free parameter, it can be fitted as a function of HT (using Q = HT/2), show its running and obtain final combined values

$\alpha_s (M_{Z,\ TEEC}) = 0.1175 \pm 0.0006$ (exp.)$+0.0034-0.0017$ (theo.) and

$\alpha_s (M_{Z,\ ATEEC}) = 0.1185 \pm 0.0009$ (exp.)$+0.0025-0.0012$ (theo.)

# The most precise α_S: Z pT

New!

Possible because Z pT strongly depends on initial gluon emission.

Theory prediction from DYTurbo, interfaced to xFitter. Full N4LL in Sudakov, approximate in hard coefficient, corrected for QED ISR

Sudakov part not used in PDF determination, so fit limited to pT<29 GeV.

Measurement employs angular decomposition in full dilepton phase space to reduce theory uncertainties

Evaluate a χ2 that includes experimental and theory uncertainties, and at each value of α_S, a reweighting technique is used to get the PDFs that best fit the data. Expected sensitivity 0.05%.
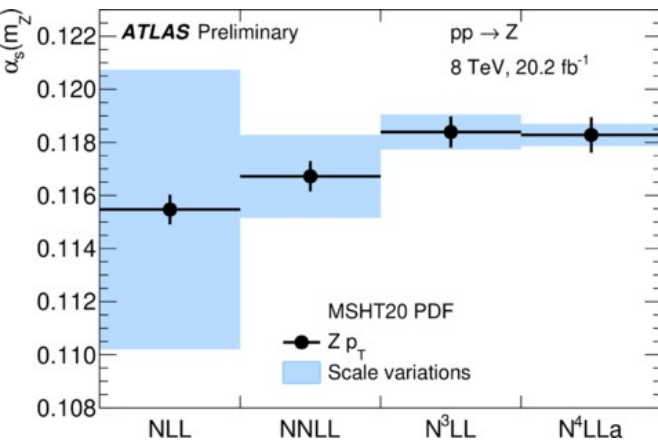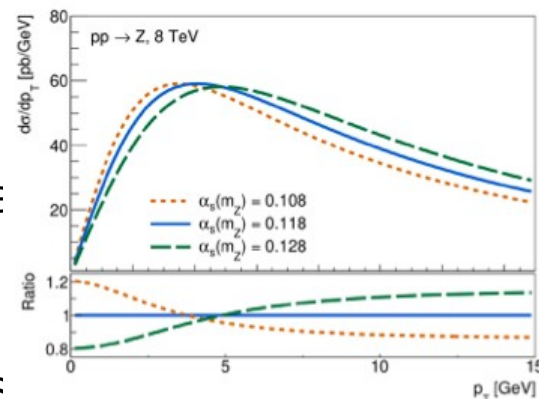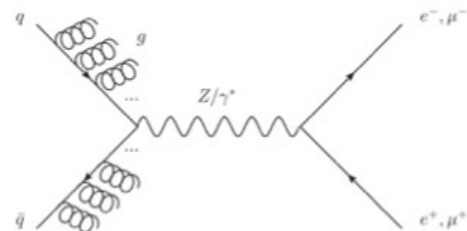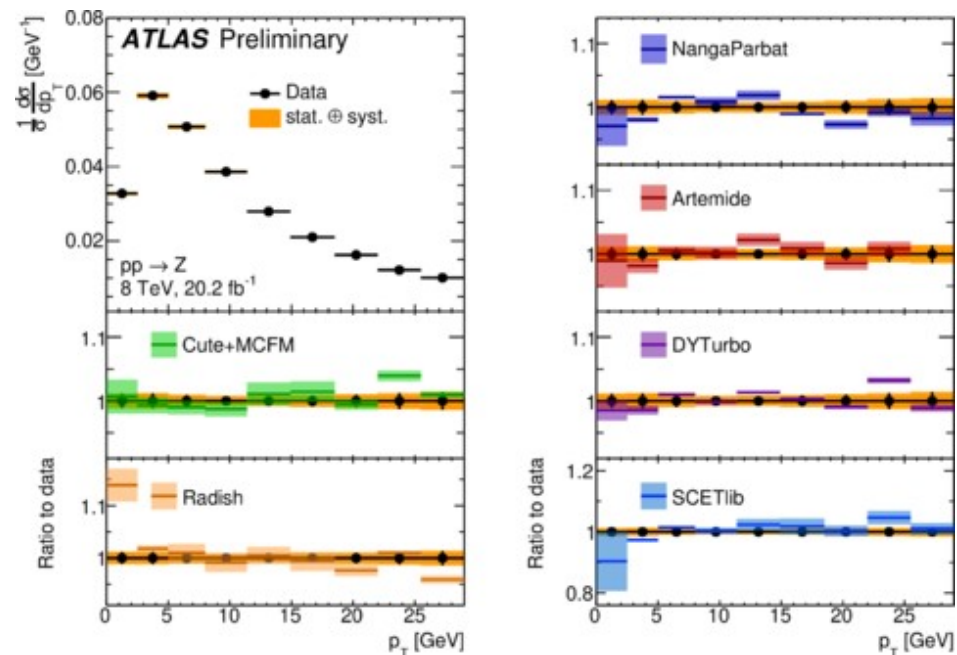
Final result is the midpoint of the (μ_R, μ_F) scale variation envelope

Nice convergence as we increase the perturbation order

$$\alpha_S = 0.11828 \ +0.00089 \ -0.00094$$

Comparison data/theory predictions

Pt distribution in data vs various resummation codes. They all include approximate N4LL resummation and (apart from Artemis) fixed order α_s^3 contributions. Good agreement with all predictions

Rapidity distribution compared to DYTURBO predictions, with experimental and theory uncertainties.
This distribution is very suitable to be included in PDF fits
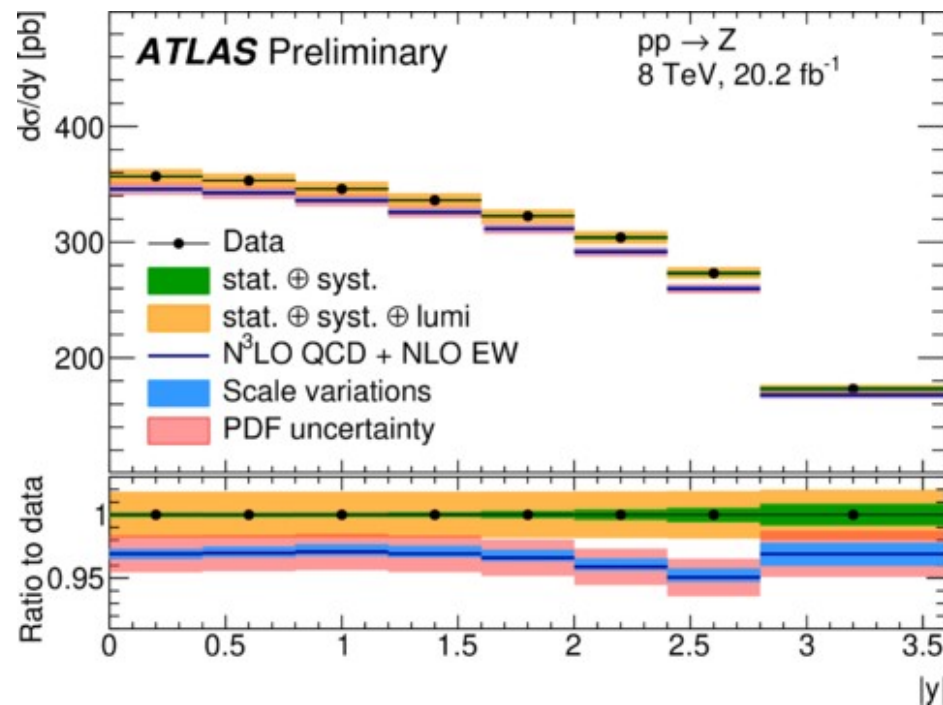
# Profiled PDFs, uncertainties
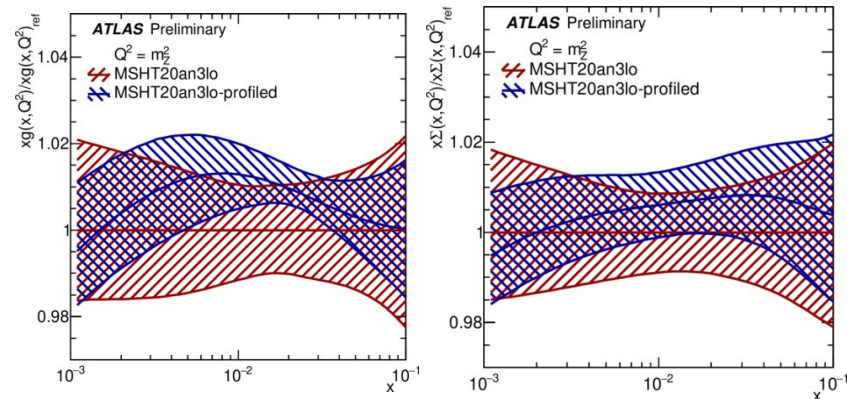
Being relatively orthogonal, result does not impact PDFs too much, but slightly decreases uncertainties for gluons and light quarks

Still, PDFs are the largest source of theory uncertainty. Experimental uncertainty matches with expectation. Performing a full N3LL fit to α_s and PDFs, using NNLO DGLAP evolution, uncertainty increases to 0.001

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088
Inflated total	+0.00089	-0.00094

Global picture
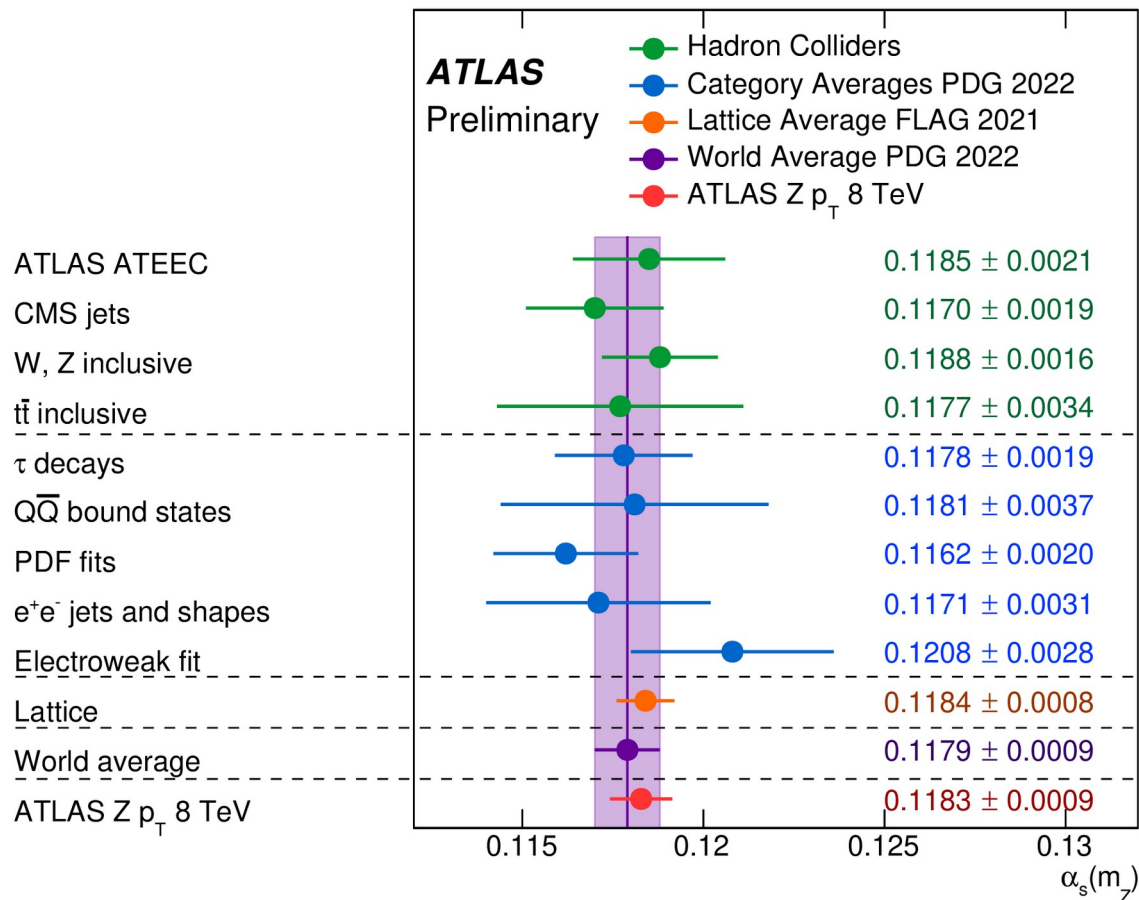
Measurement dominated by theory uncertainties, but most of them can be constrained with more precise cross-section measurements

PDFs and α_s from dijets (CMS PAS SMP 21-008)

Dijet events have a huge cross-section and are the typical QCD process. Sensitive to high-order perturbation, PDFs and α_s.

The two jet rapidities y1 and y2 define
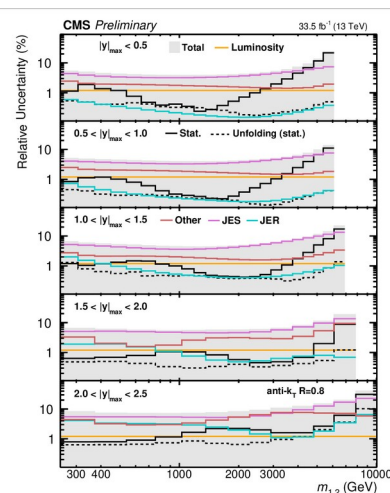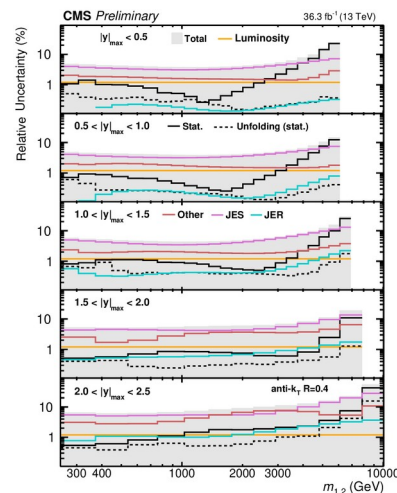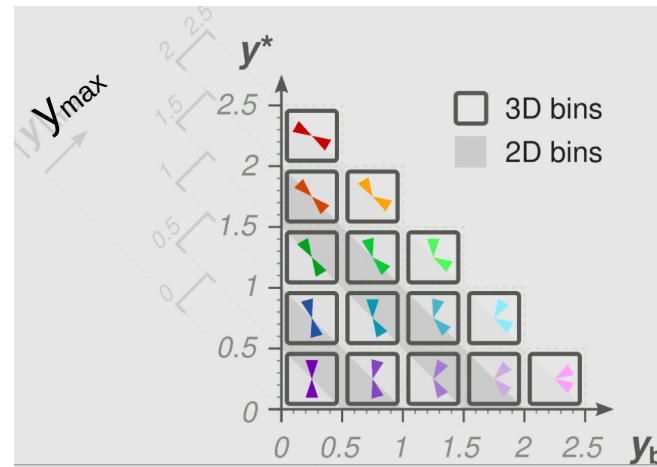
rapidity separation y* = |y1-y2|/2 and

boost y_b = |y1+y2|/2 together with invariant mass or average momentum, they allow 2D or 3D differential cross-section.

CMS measured on 36.3/fb of 13 TeV data Pflow dijets of R = 0.4 and 0.8 < |η| < 3 and pT > 100 and 50 GeV respectively

Events unfolded with Tunfold

As usual in this kind of measurements, uncertainty
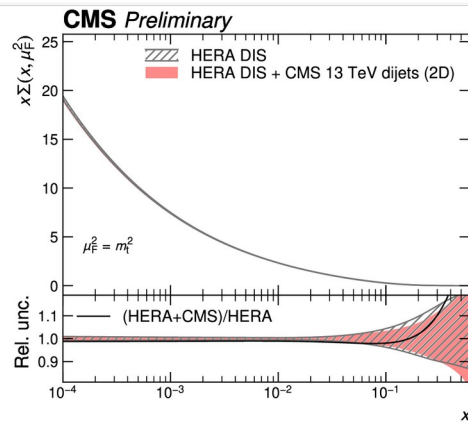
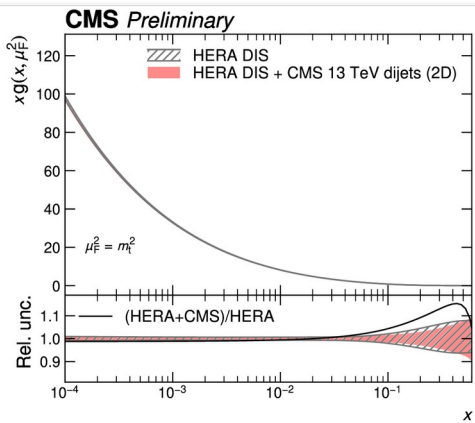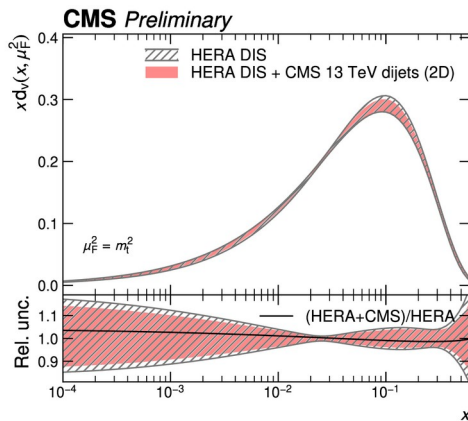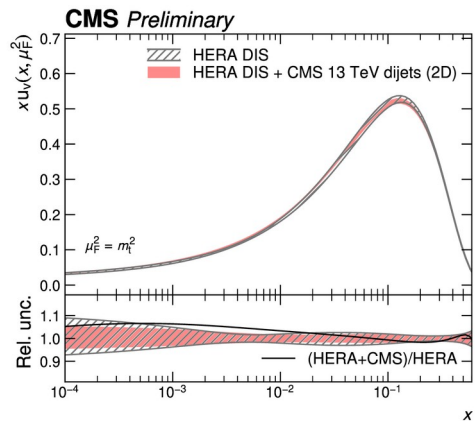dominated by JES and JER

1D, 2D and 3D results

Example the ratio of the <pT> distribution for the first rapidity region with various PDF sets
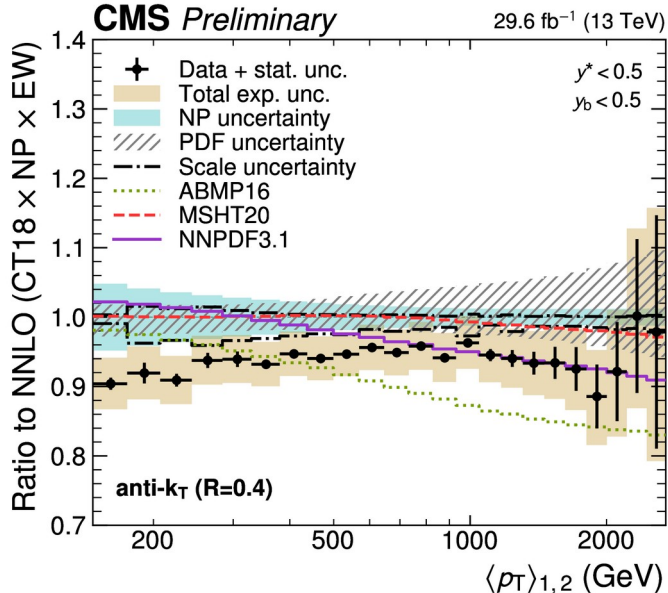
2D and 3D distributions using m12 and <pT> compared to CT10 NNLO
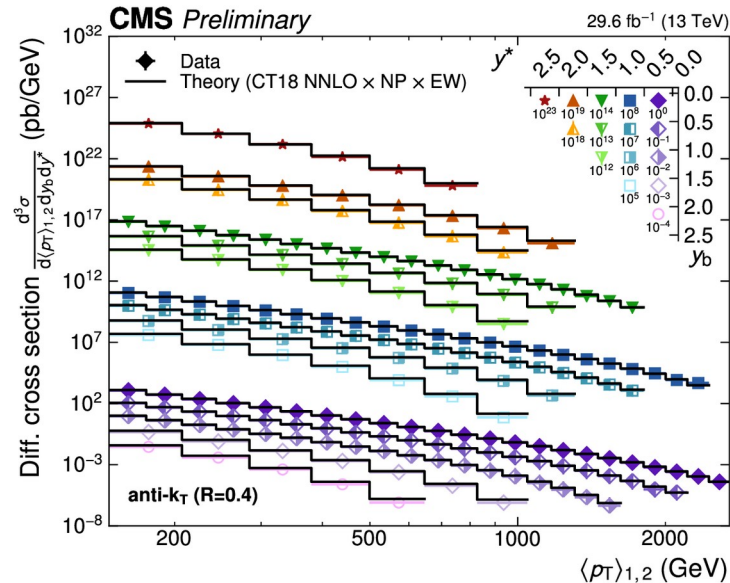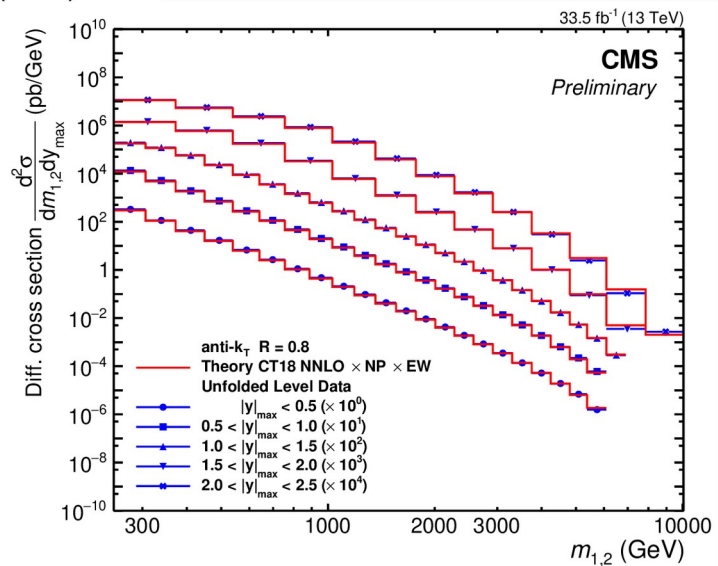
Impact on PDFs and α_s

Including this measurement in the HERAPDF set produces a small but visible improvement on low-x up and down, and high-x gluon. A common fit of the PDFs and of αs yields (for the 3D measurement)
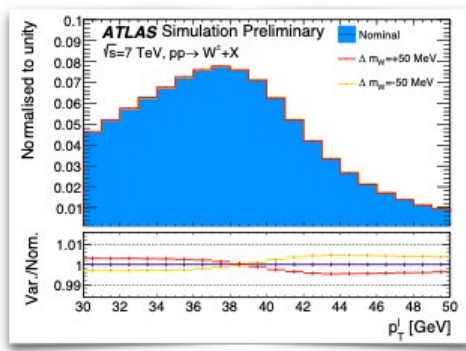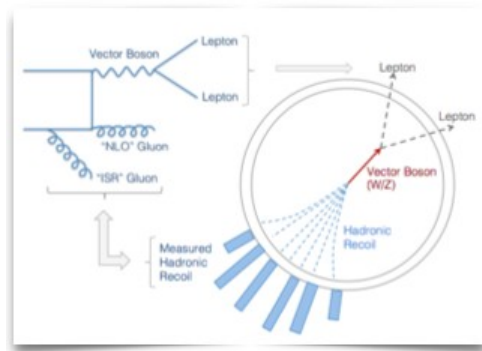
$$\alpha_s(m_Z) = 0.1201 \pm 0.0010 \,(\text{fit}) \pm 0.0005 \,(\text{scale}) \pm 0.0008 \,(\text{model}) \pm 0.0006 \,(\text{param.})$$
$$= 0.1201 \pm 0.0020 \,(\text{total}),$$

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ATLAS re-analysis of the Mw measurement

ATLAS-CONF-2023-004

- W mass in semileptonic (e, μ) channel comes from a fit of MT and lepton pT



- Already measured on 2011 data at Eur.Phys.J.C 78 (2018) with final result 80370 ±19 MeV. At the time (before CDF), world's best individual measurement

- A big effort went into re-analysis of these data, with an improved physics modelling and systematic treatment using Profile Likelihood (treating systematics as nuisance parameters, fitted with data)

Analysis recap: selection and calibration

- Isolated leptons: pT > 30, pT > 30
  - Electrons with $|\eta| < 1.2$, $1.8 < |\eta| < 2.4$
  - Muons with $|\eta| < 2.4$
- mT > 60 GeV, uT < 30 GeV
- Lepton energy (momentum) calibrated using mass form $Z \to ll$ events
- Lepton efficiency from Tag-and-Probe
- Hadronic recoil calibrated from $Z \to ll$ events

Projection of recoil on lepton pT
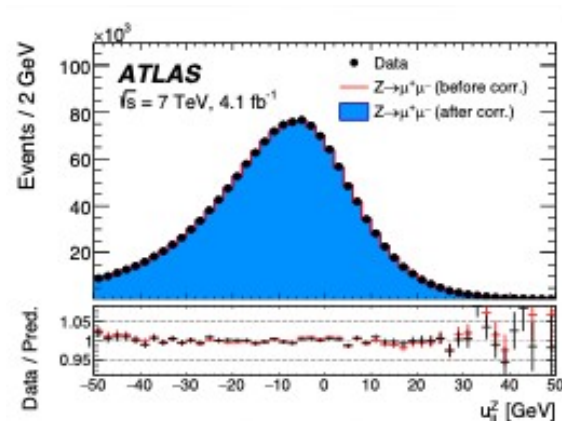
Improvements wrt previous analysis

- New baseline PDF set CT18

- Systematic shape variation of multijet BG using PCA (1000 NP reduced to 200) → 2 MeV improvement

- Detector level evaluation of EW uncertanties (1-2 MeV improvement)

- 1.5% more statistics in electron channel

- Add Γw as nuisance parameter

- Final likelihood:

$$L\left(\mu, \vec{\theta} | \vec{n}\right) = \prod_j \prod_i \text{Poisson}\left(n_{ji} | \nu_{ji}(\mu, \vec{\theta})\right) \cdot \text{Gauss}\left(\vec{\theta}\right)$$

$$\nu_{ji}(\mu, \vec{\theta}) = \Phi \times \left[S_{ji}^{\text{nom}} + \mu \times \left(S_{ji}^{\mu} - S_{ji}^{\text{nom}} \right) \right] + \sum_s \theta_s \times \left(S_{ji}^{P} - S_{ji}^{\text{nom}} \right)$$

$$+ B_{ji}^{\text{nom}} + \sum_b \theta_b \times \left(B_{ji}^{p'} - B_{ji}^{\text{nom}} \right),$$

Expected number of events per bin and distribution

Floating normalisation
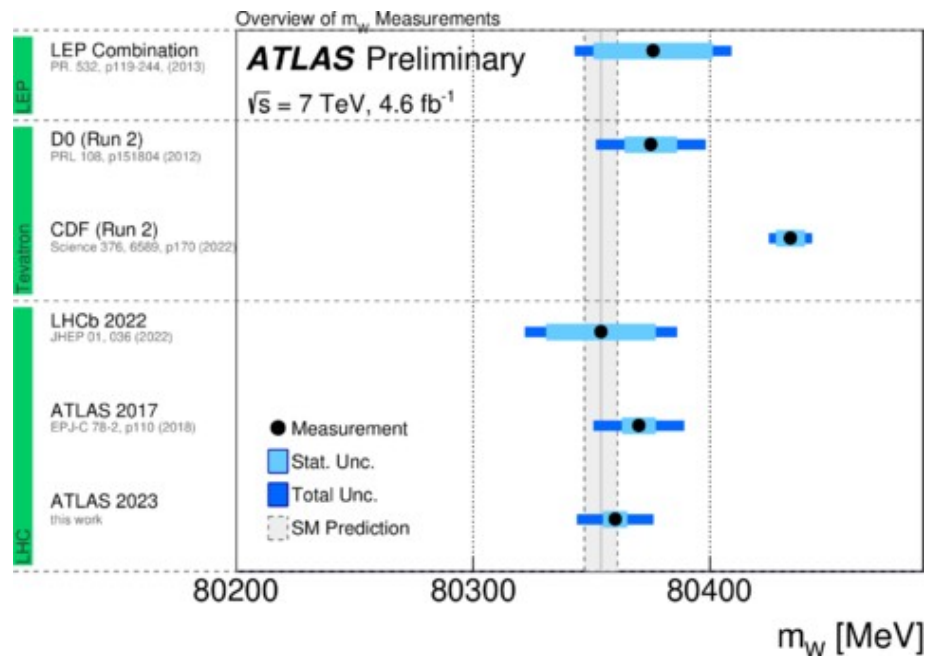
Nuisance parameters

Cross-checks of method

- Good closure found, and consistency between pT and mT fits (correlated by 0.6)

- Old result reproduced with stat errors only, but toys show that PL treatment shifts central value

- Agreement in post-fit distributions show an improved agreement
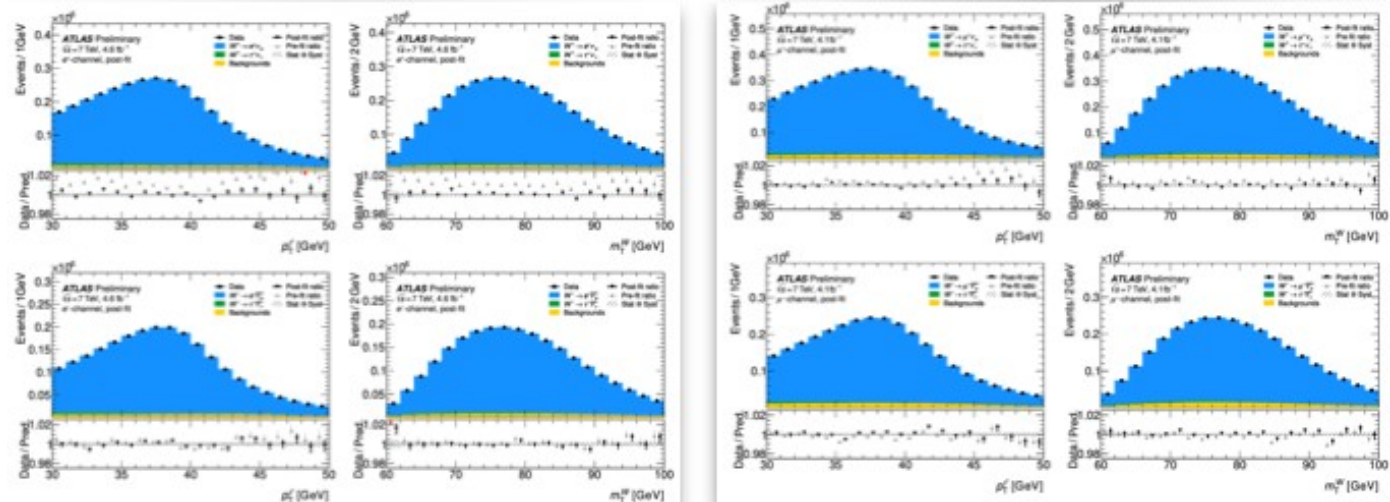
Pull distributions post-fit behave as expected
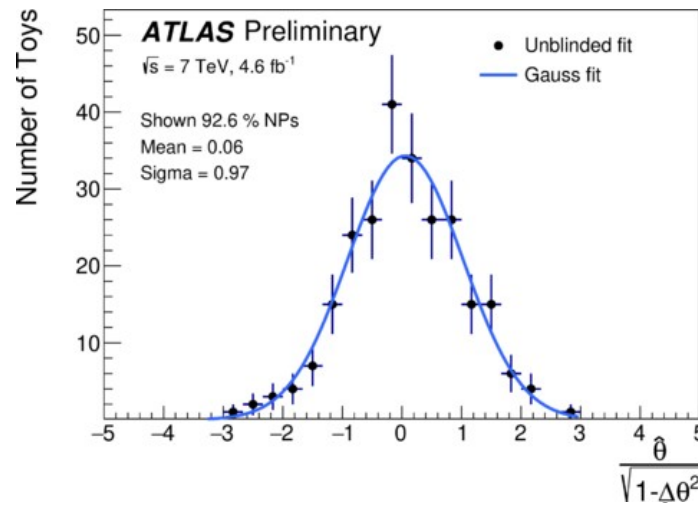
Results
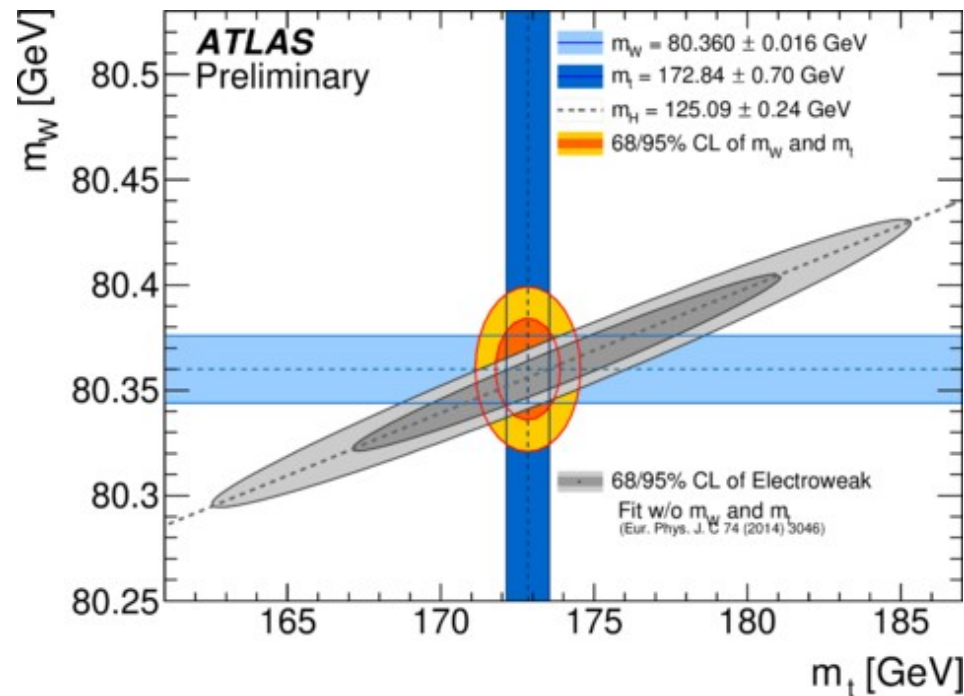
$$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16 \text{ MeV}$$

Final result shifted by 10 MeV, in better agreement with EW fits, and world average, uncertainty decreased from 19 to 16 MeV

Measuring the Lund Plane for inclusive jets

CMS PAS SMP-22-007

- The Lund Jet Plane is an abstract representation of the jet branching, where each step in the parton shower is represented by a point connected to its kT and ΔR

- Experimentally, the Lund Plane can be approximately reconstructed by running backward an angular-ordered clustering algorithm (Cambridge-Aachen)

- Its interest lies in the fact that the various regions of the plane are sensitive to phases of jet formation

  – Explore various aspects of QCD

  – MC tuning
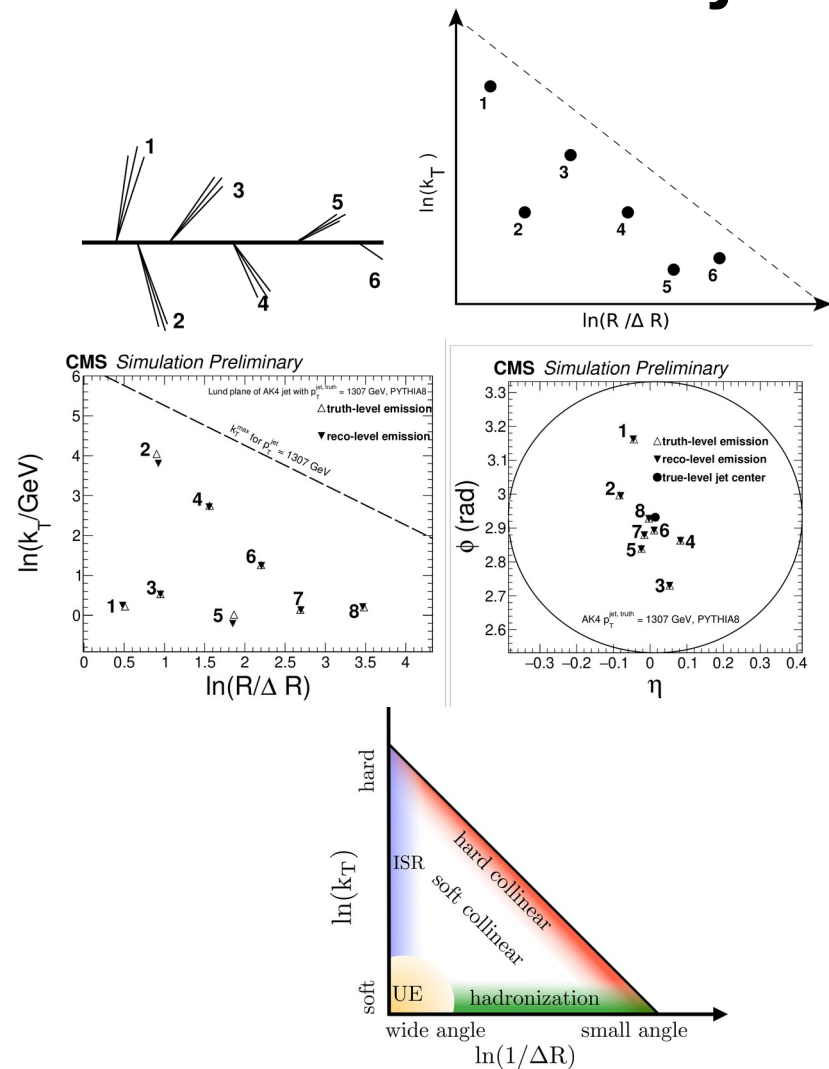
Selection and detector-level distributions

Inclusive jets (Akt 0.4 and Akt 0.8) with pT>700 GeV and |η| < 1.7.

Only constituents associated to charged particles with pT>1 GeV.

Already at detector level LJP slices show important differences between MC

2D iterative unfolding to correct to particle level, accounting for correlations of detector-level points.

Correlation is the largest at low kT and large ΔR (underlying event and residual pileup)
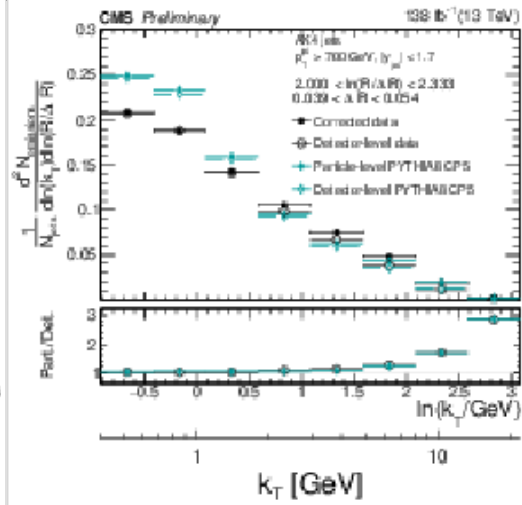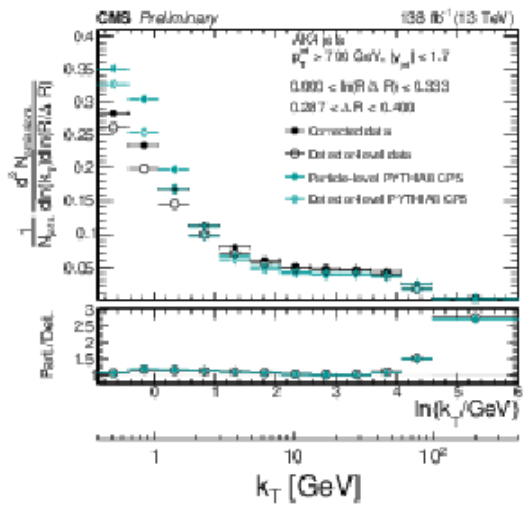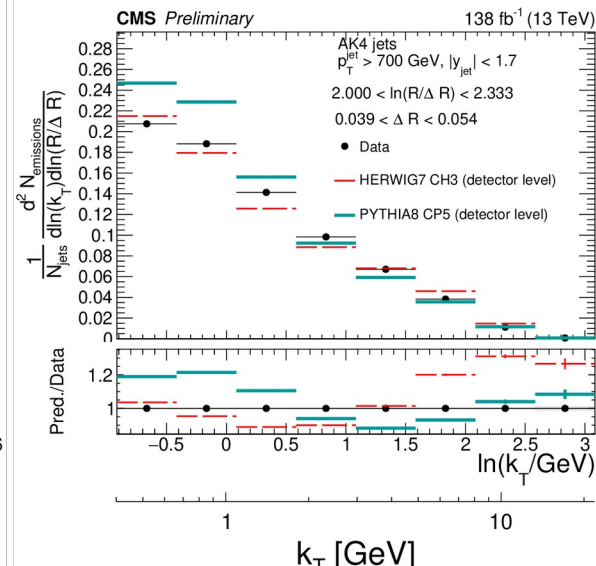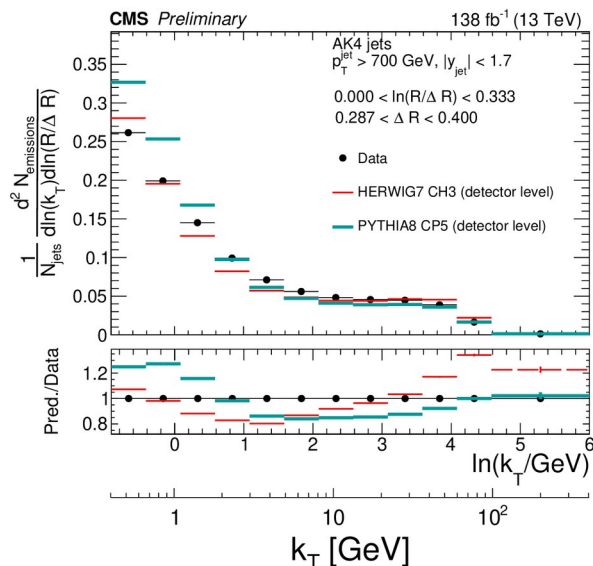
Particle-level results
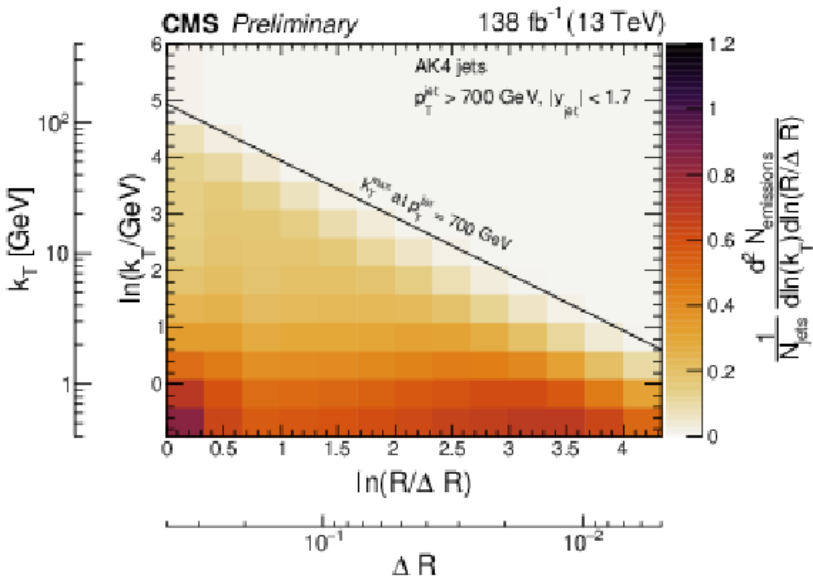
AKT 0.4 (strong hadronisation component)

Kinematic limit of emission (hard scattering region)
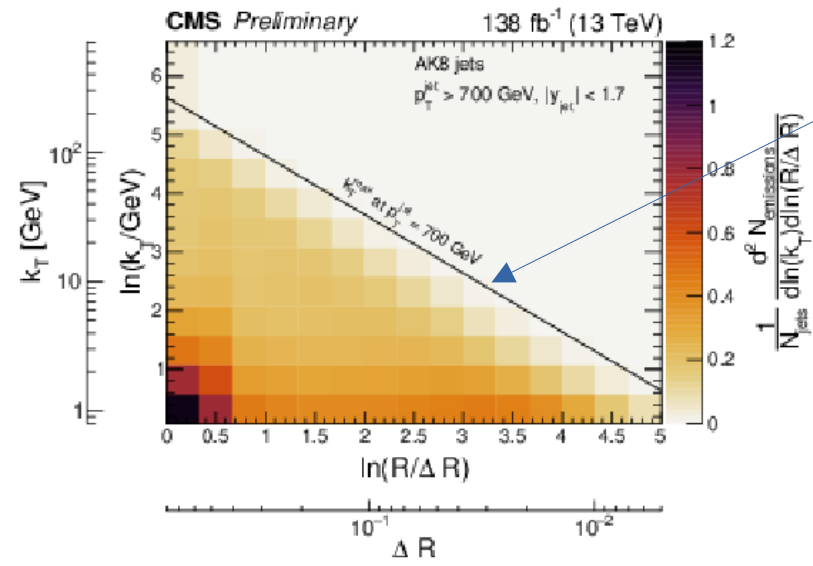
AKT 0.8 (dominated by UE)

Exploring modelling differences

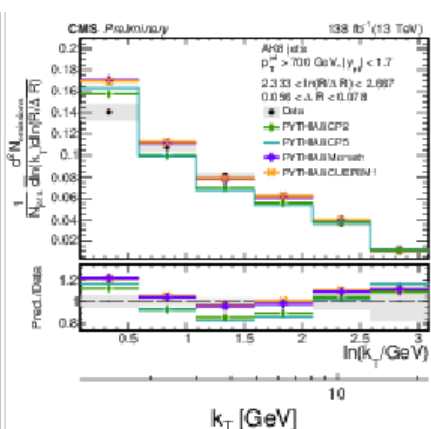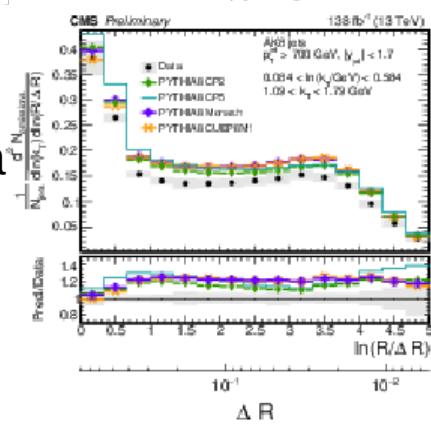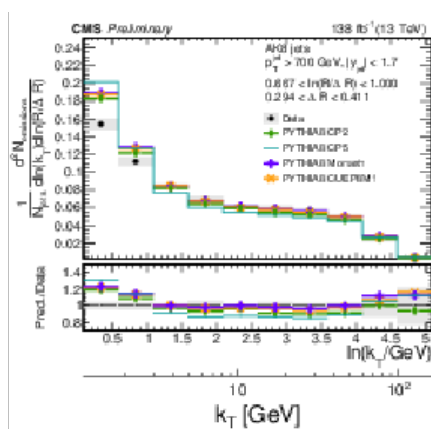Large angles   Small angles   Large angles   Small angles
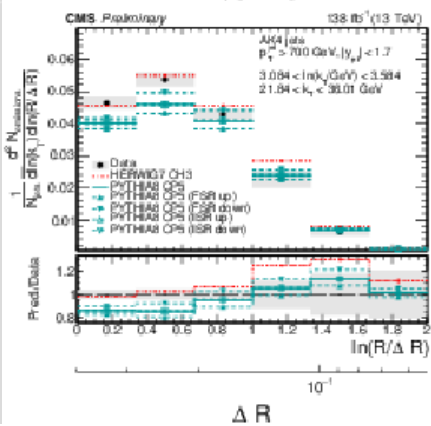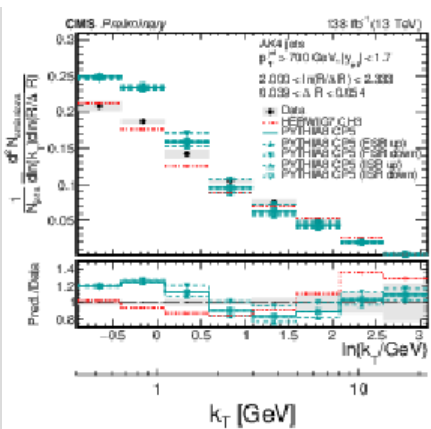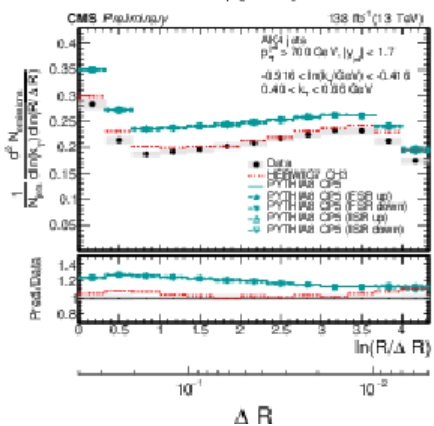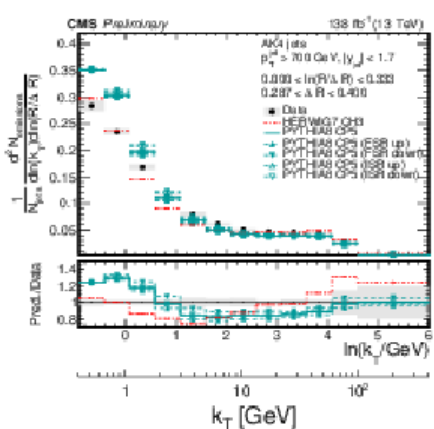
Pythia scales
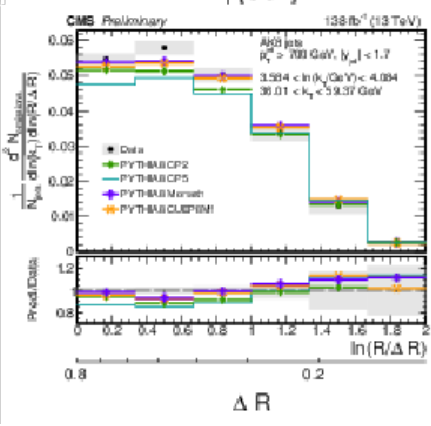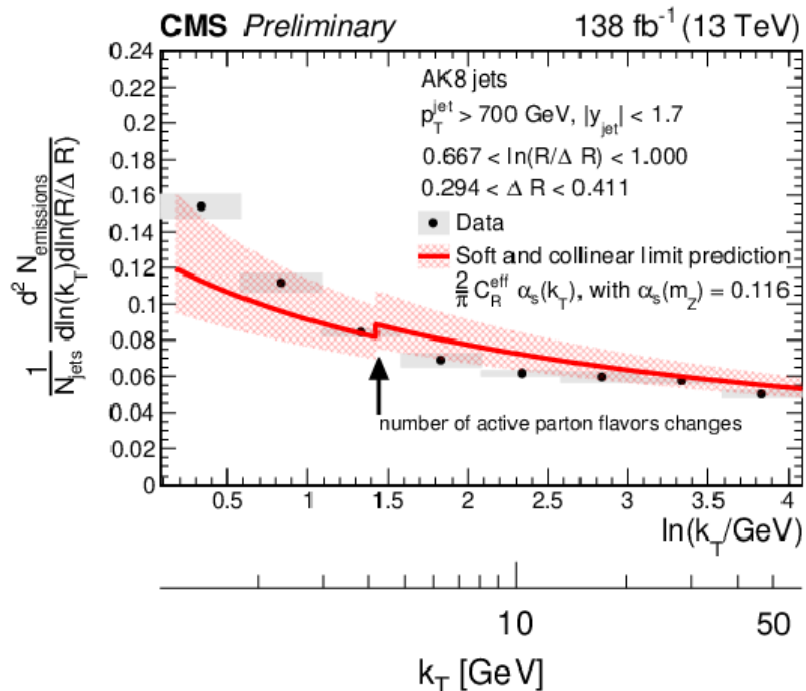
Pythia tunes
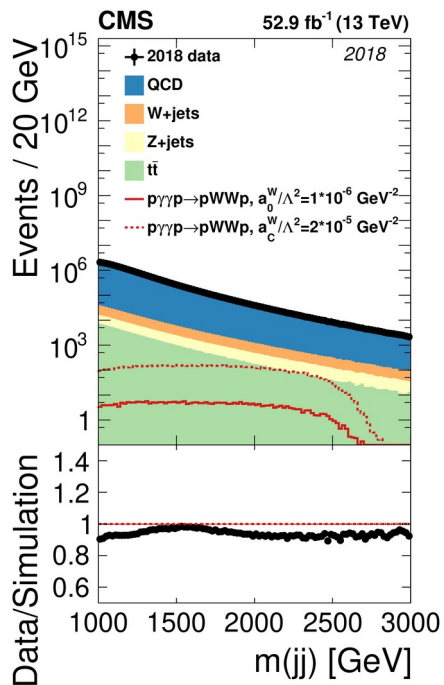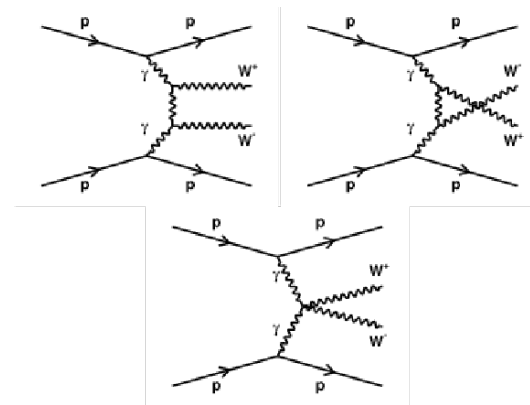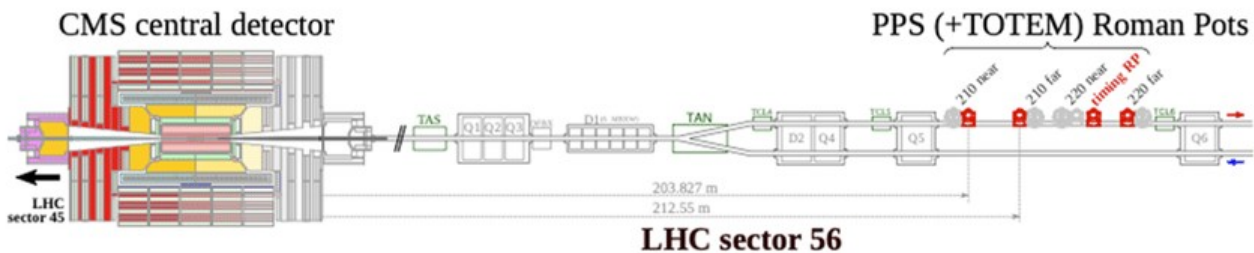
Low kT   High kT   Low kT   High kT

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Analytic predictions

- 1D projection compared to analytic predictions in the soft and collinear limit.

- Discontinuity when kT reaches the mass of the b quark

- Band is factor 2 renormalisation scale variation

# Search for WW, ZZ → jj and intact protons with CMS/TOTEM PPS

Dijets with Mjj > 1 TeV and two intact forward protons with fractional energy loss $0.04 < \zeta < 0.20$

SM signal very small, but can be enhanced in the presence of anomalous couplings (EFT)

Since conditions changed, data from 2016, 2017 and 1018 analysed independently

Central-forward matching

For well-matched signal, we expect invariant mass and rapidity from central detector match the prediction from the forward proton. Events in the diagonal have only one correctly assigned proton
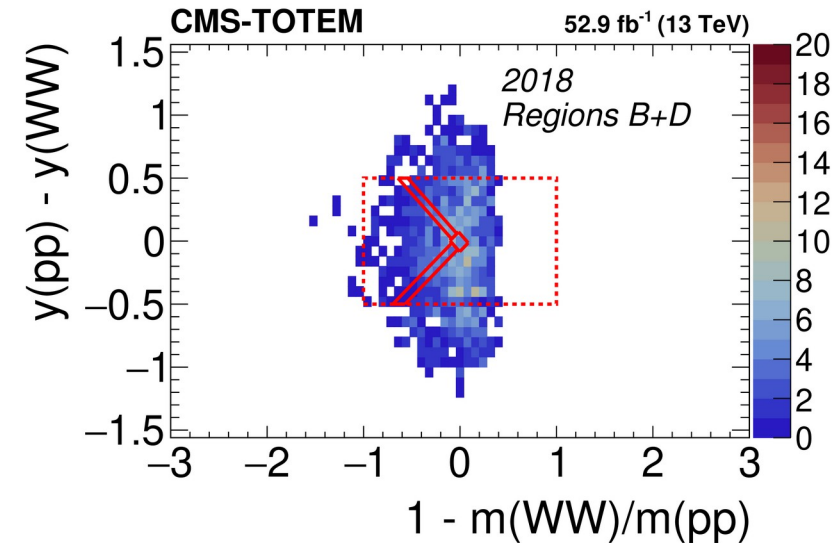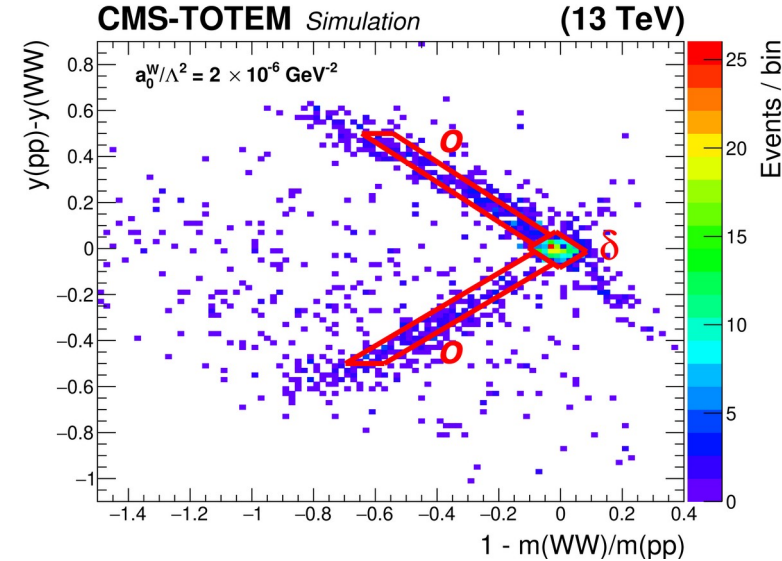
After requiring jets to have a substructure compatible with WW or ZZ, background estimated from data, by requiring acoplanarity > 0.1 (reversing the cut for signal).
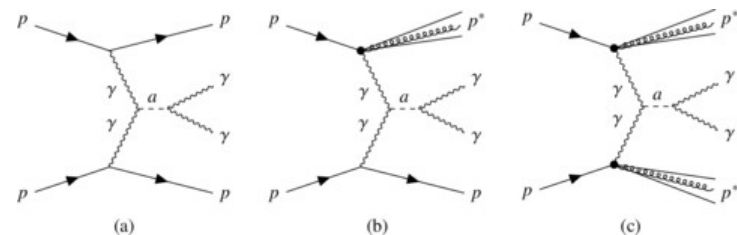
Results and limits

For all years considered and final states, data is compatible with data-driven background. No indication of anomalous coupling, translated into limits to EFT operators
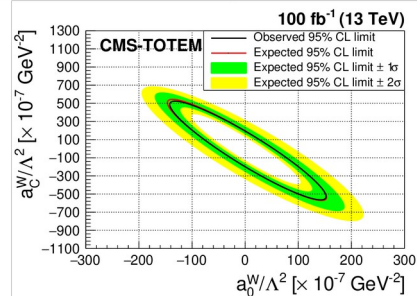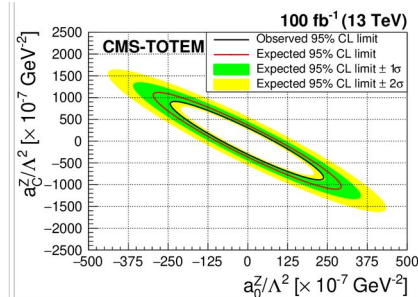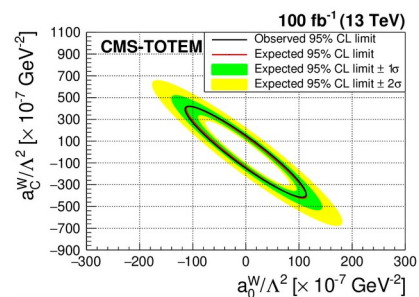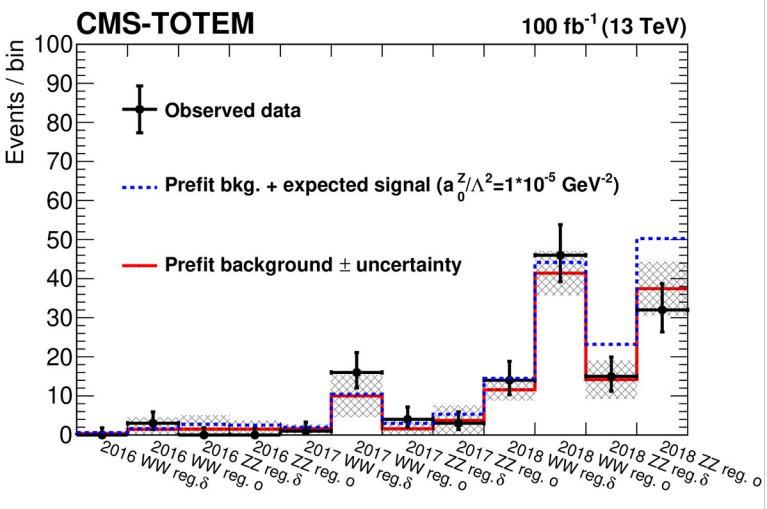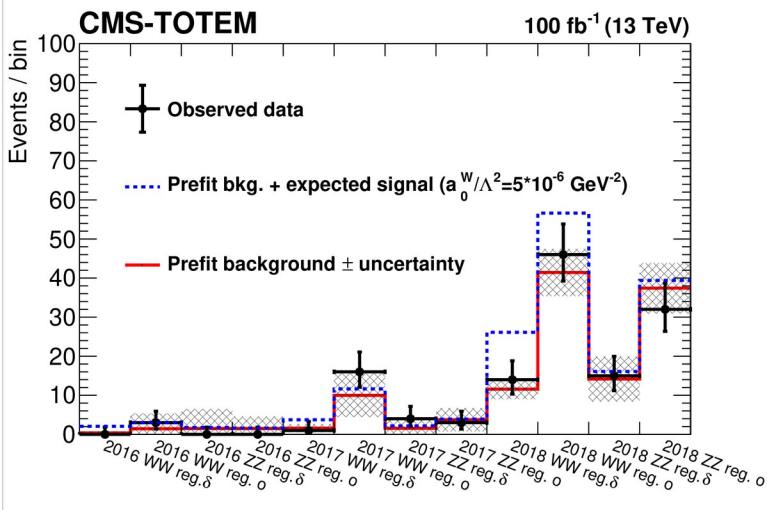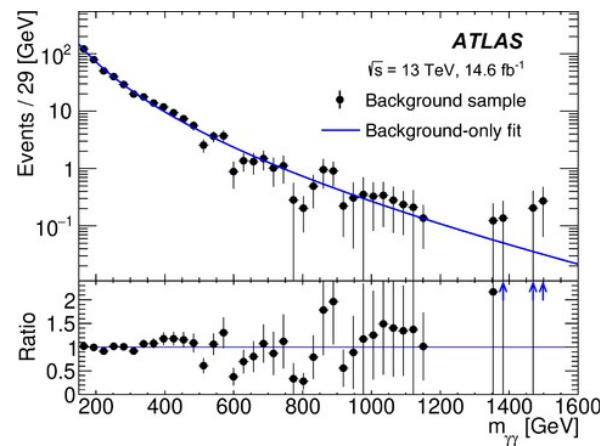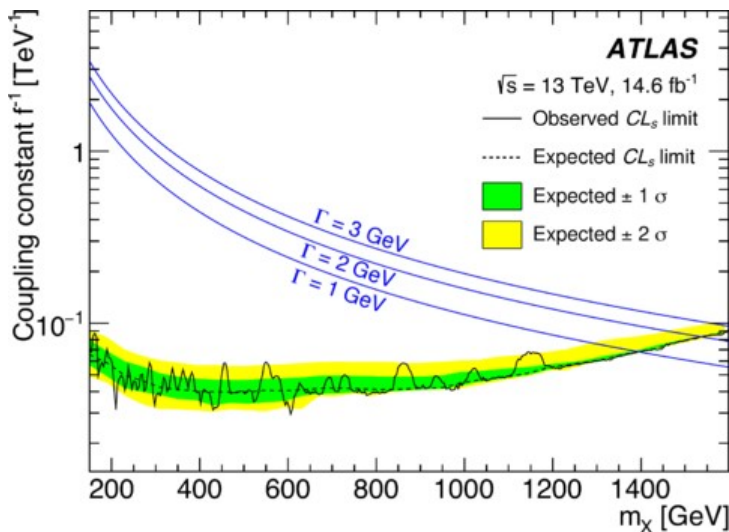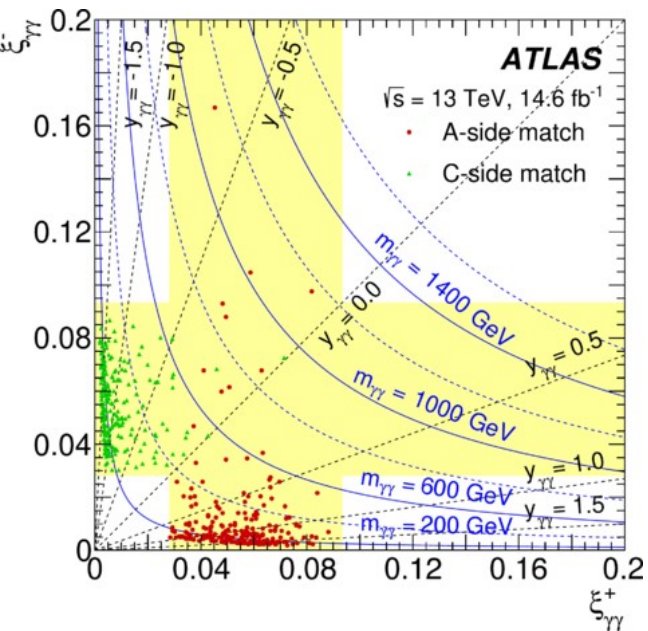
Forward protons + diphotons in ATLAS

arXiv:2304.10953

- It would be enhanced by the presence of Axion-Like Particles

Measure Myy for events with double proton forward tagging, matched to central detector mass

Lack of excess translated into limits of ALP coupling

Conclusions

- SM measurements are meant to stay as "legacy" results, require very careful analysis and can lead to high precision

- Many possible final states and physics aims

- Only gave a few examples

- Keep testing the most precise theory in science