Production of top quarks, jets and photons

Javier Llorente Merino,
on behalf of the ATLAS and CMS Collaborations

Simon Fraser University

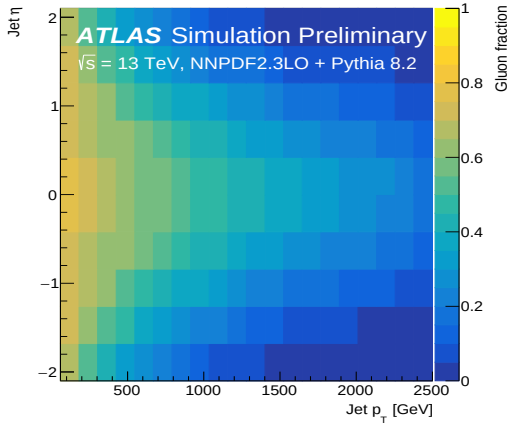
LHCP 2019. Puebla, México

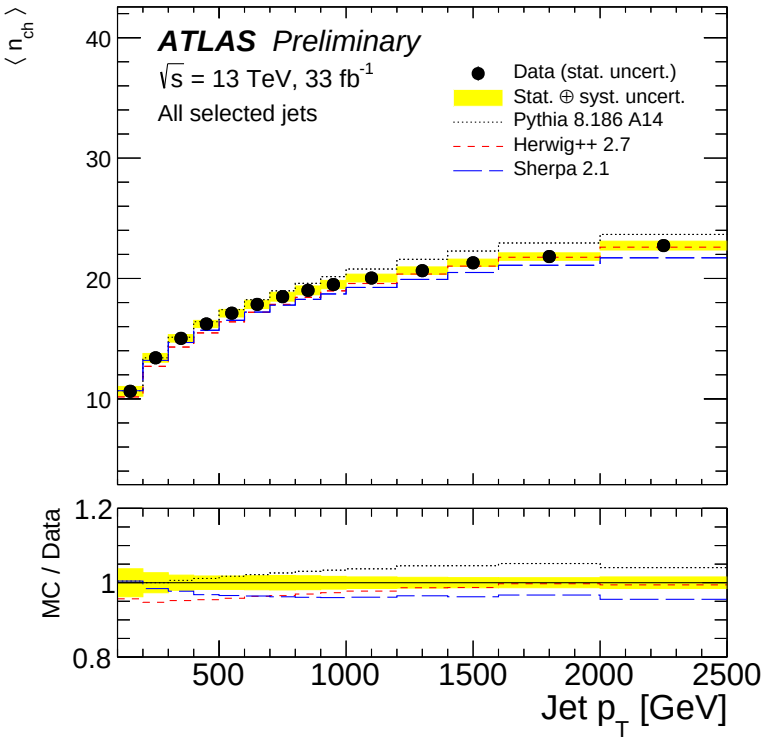
Jet analyses

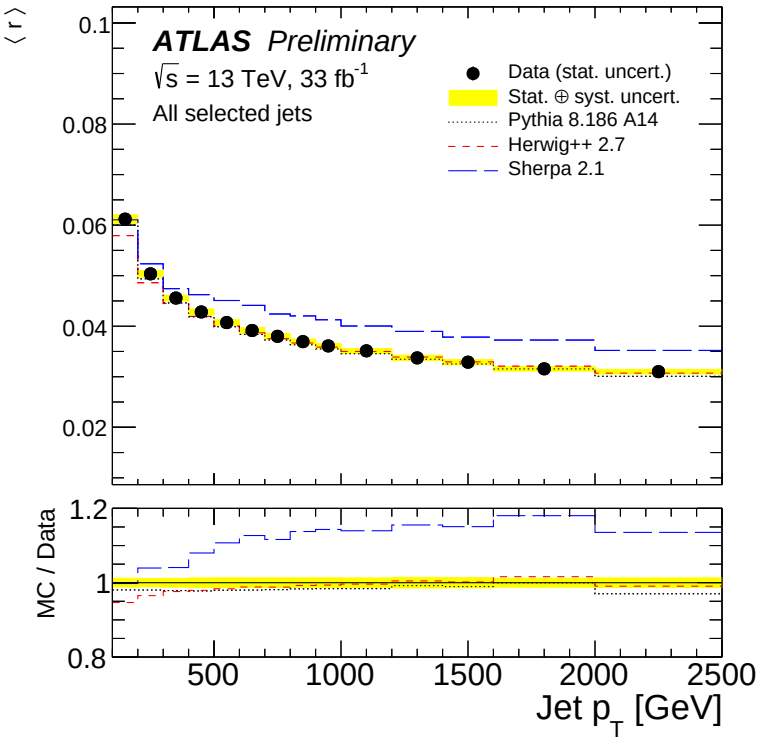
Properties of jet fragmentation at ATLAS [STDM-2017-16]

Measurement of observables sensitive to fragmentation functions $D^h_{q,g}(\zeta, \mu)$.

- Number of charged particles $\langle n_{\rm ch} \rangle$ in jet.
- Momentum fraction $\zeta = p_T^{\rm ch} / p_T^{\rm jet}$.
- Transverse profile $p_T^{\rm rel} = p_T^{\rm ch} \sin\theta_{jc}$.
- Radial profile $\rho = 1/(2\pi r N_{\rm jet}) dn_{\rm ch}/dr$; $r = \Delta R_{jc}$.
- Extraction of quark and gluon profiles from data.







Properties of jet fragmentation at ATLAS [STDM-2017-16]

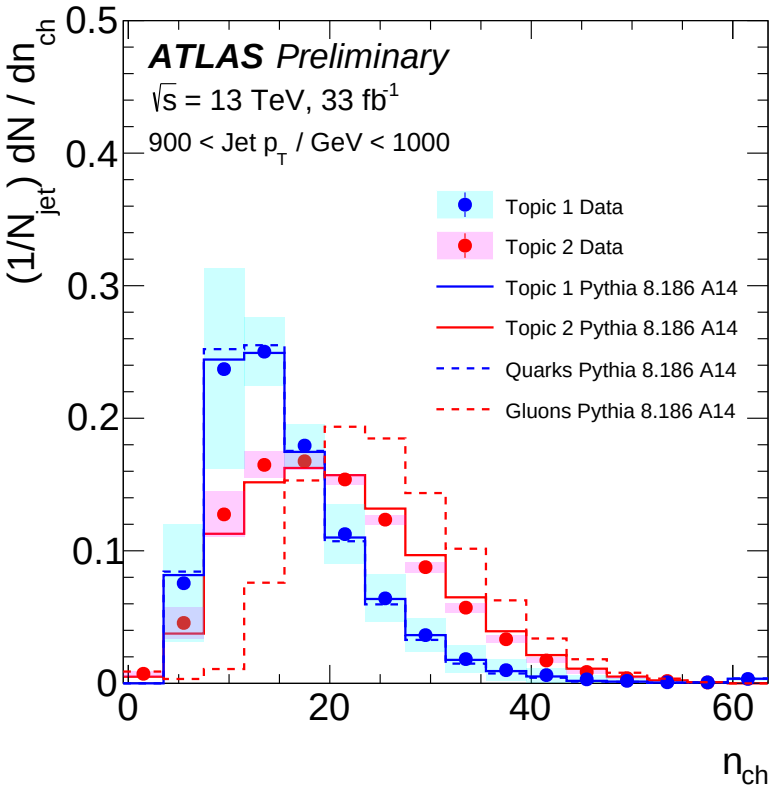
Quark and gluon-like distributions obtained using two different methods

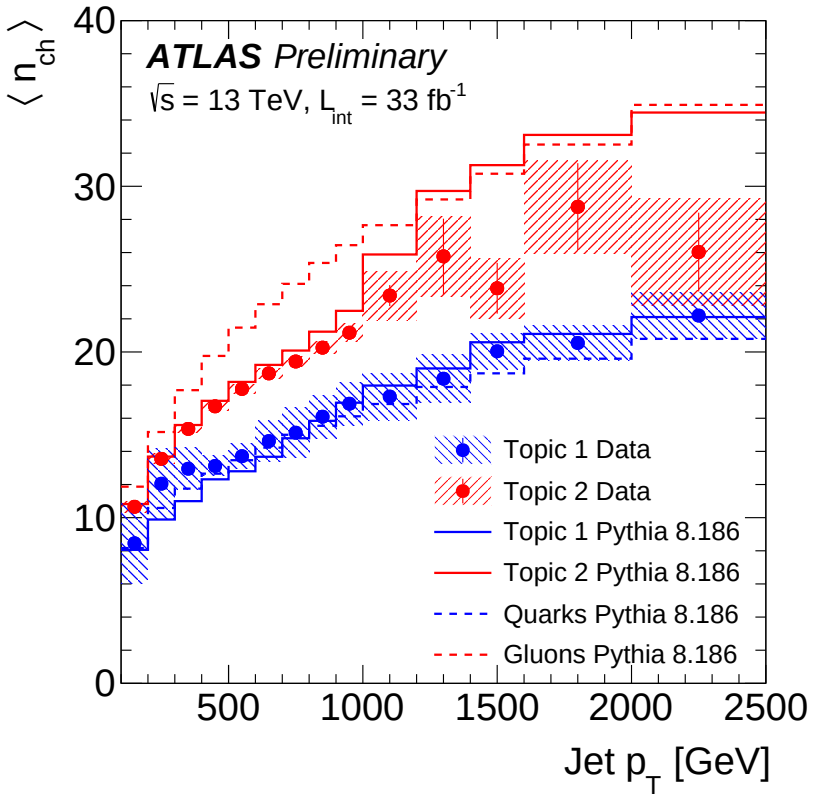
- Solve the system of equations for bin i of each observable:

$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g; \quad h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g$$

- Determine distributions for topics T_1 (q-like) and T_2 (g-like)

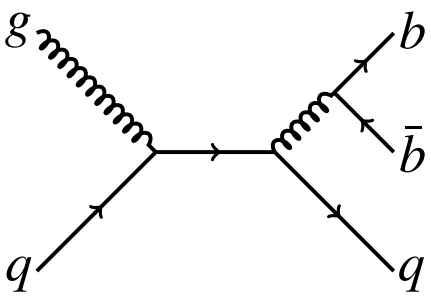
$$h_i^{T_1} = \frac{h_i^f - \min_j\{h_j^f / h_j^c\} \times h_i^c}{1 - \min_j\{h_j^f / h_j^c\}}; \quad h_i^{T_2} = \frac{h_i^c - \min_j\{h_j^c / h_j^f\} \times h_i^f}{1 - \min_j\{h_j^c / h_j^f\}}$$

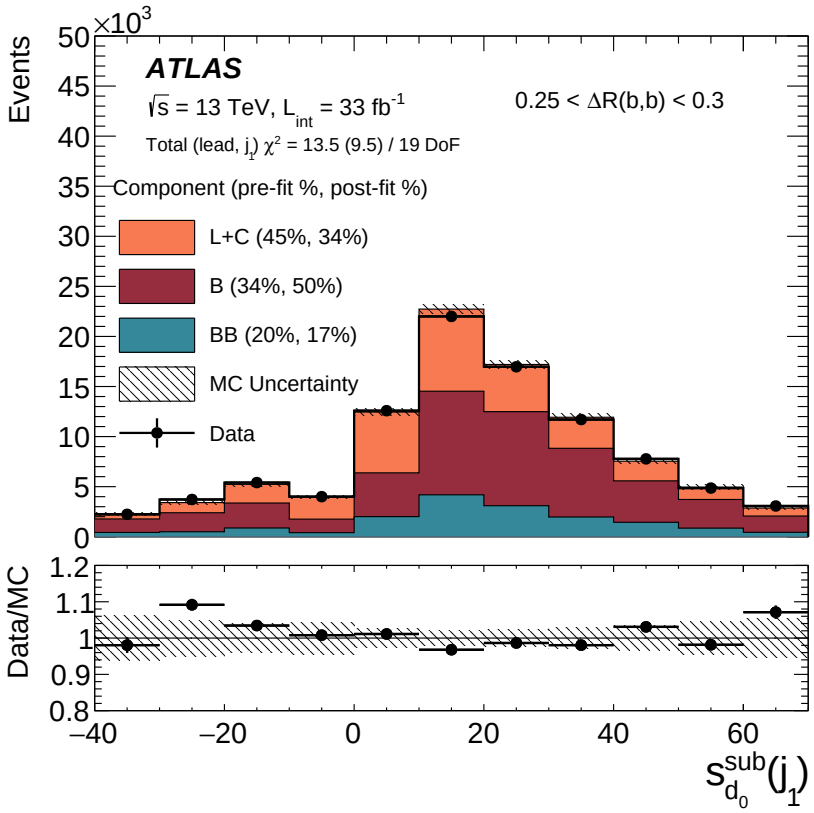


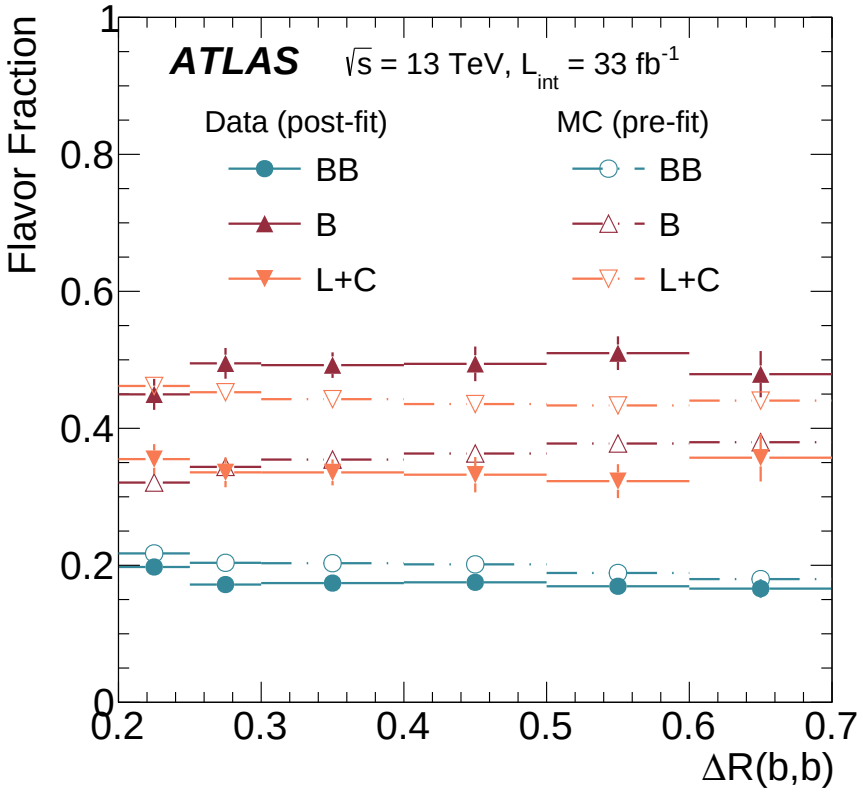


$g \to b\bar{b}$ at small angles in ATLAS [Phys. Rev. D 99, 052004 (2019)]

- Measurement of topology of the $b\bar{b}$ system.
- Trimmed anti-k_t jet with $R = 1.0$ as a proxy for the gluon.
- Anti-k_t track jets with $R = 0.2$ as proxies for b-quarks.
- Flavour fractions extracted from fits to signed impact parameter of tracks in both b-jets with respect to jet axis.



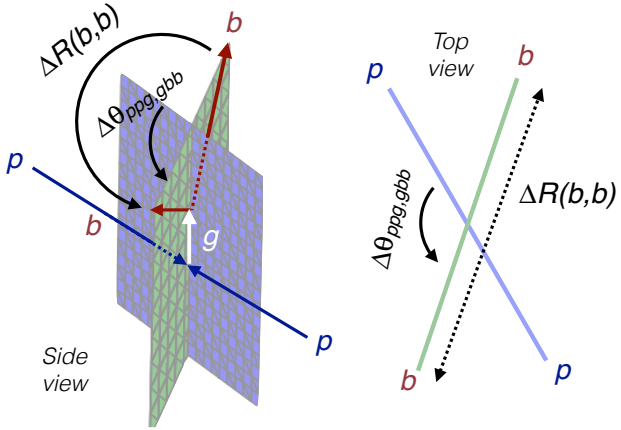


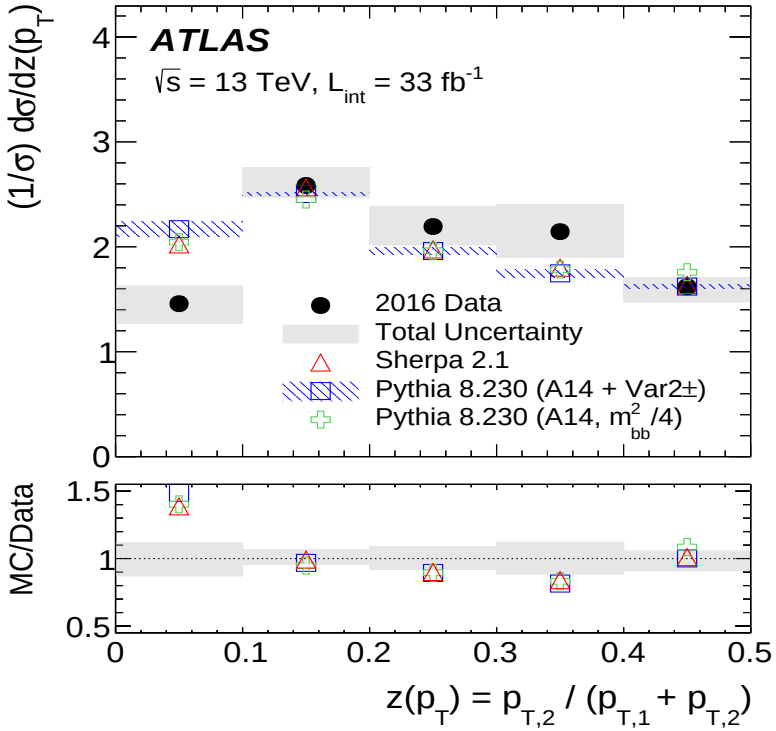


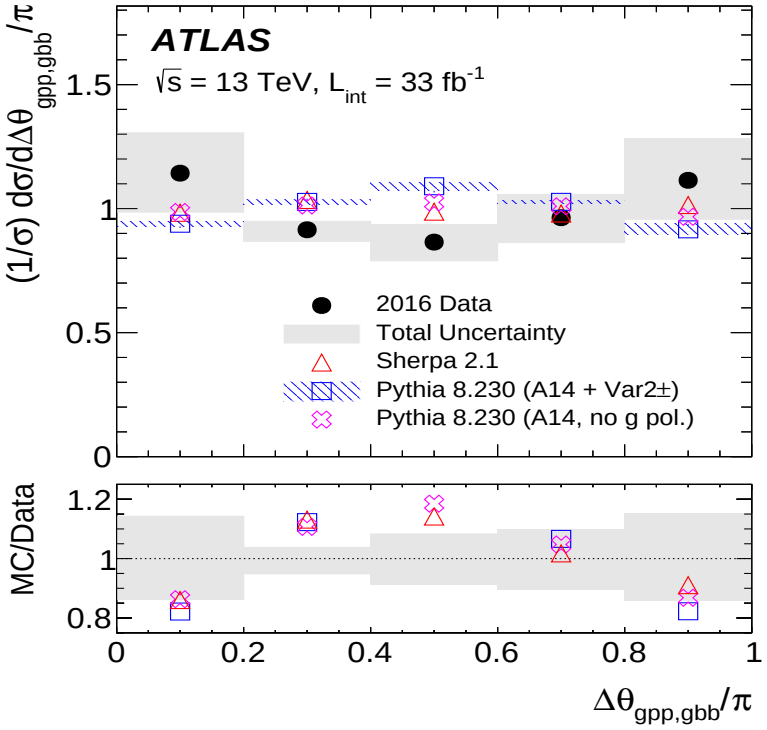
$g \to b\bar{b}$ at small angles in ATLAS [Phys. Rev. D 99, 052004 (2019)]

Measured observables include:

- Angular distance $\Delta R_{bb} = \sqrt{(\Delta\eta_{bb})^2 + (\Delta\phi_{bb})^2}$
- Momentum sharing $z = p_{T2}/(p_{T1} + p_{T2})$
- Dimensionless mass $\rho = m_{bb}/p_T$
- Angle $\Delta\theta_{ppg,gbb}$ between jet-beam and bb planes.





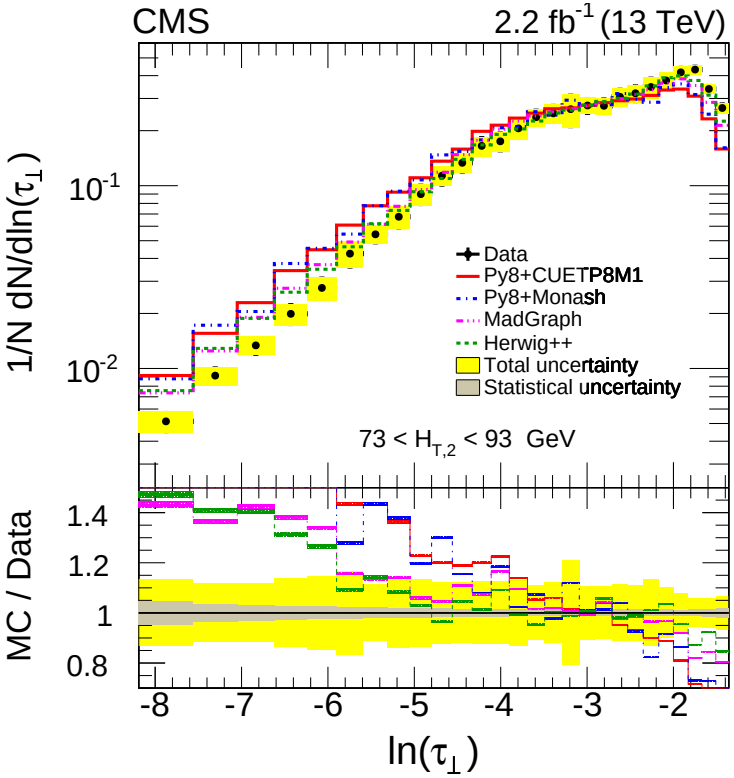


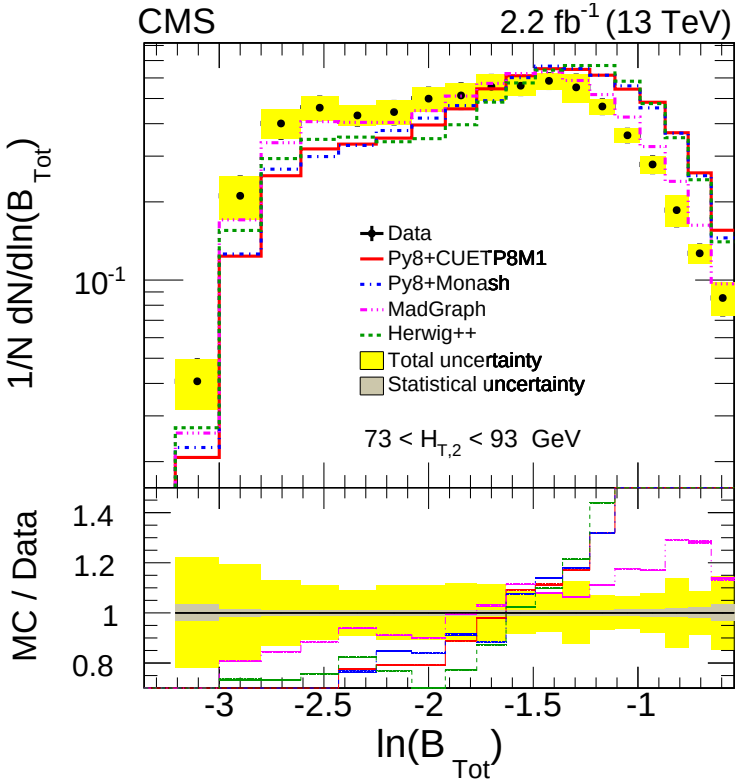
Significant disagreement at low z, "less polarization" is preferred.

Event shapes at CMS [JHEP 12 (2018) 117]

- Transverse thrust and thrust axis $\hat{n}_T$: $\tau_\perp = 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{Ti} \cdot \hat{n}_T|}{\sum_i p_{Ti}}$
- U and L hemispheres: $\vec{p}_{Ti} \cdot \hat{n}_T > 0$ (< 0).

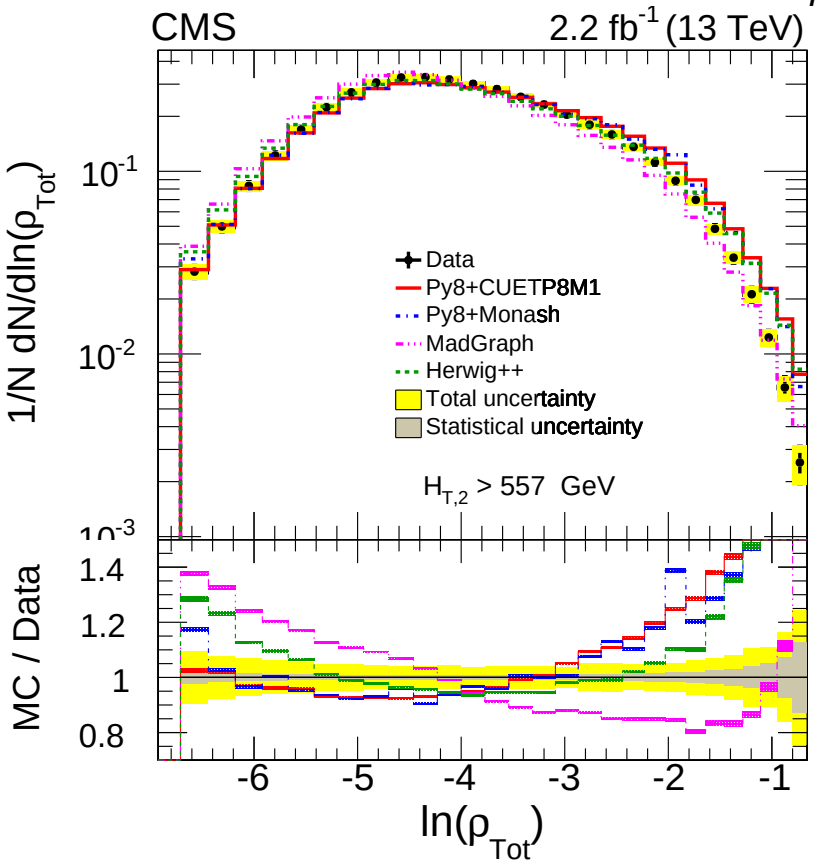
  Define hemisphere coordinates: $\eta_X = \frac{\sum_{i \in X} p_{Ti} \eta_i}{\sum_{i \in X} p_{Ti}}$; $\phi_X = \frac{\sum_{i \in X} p_{Ti} \phi_i}{\sum_{i \in X} p_{Ti}}$
- $B_X = \frac{1}{2P_T} \sum_{i \in X} p_{Ti} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$; $B_{\text{tot}} = B_U + B_L$

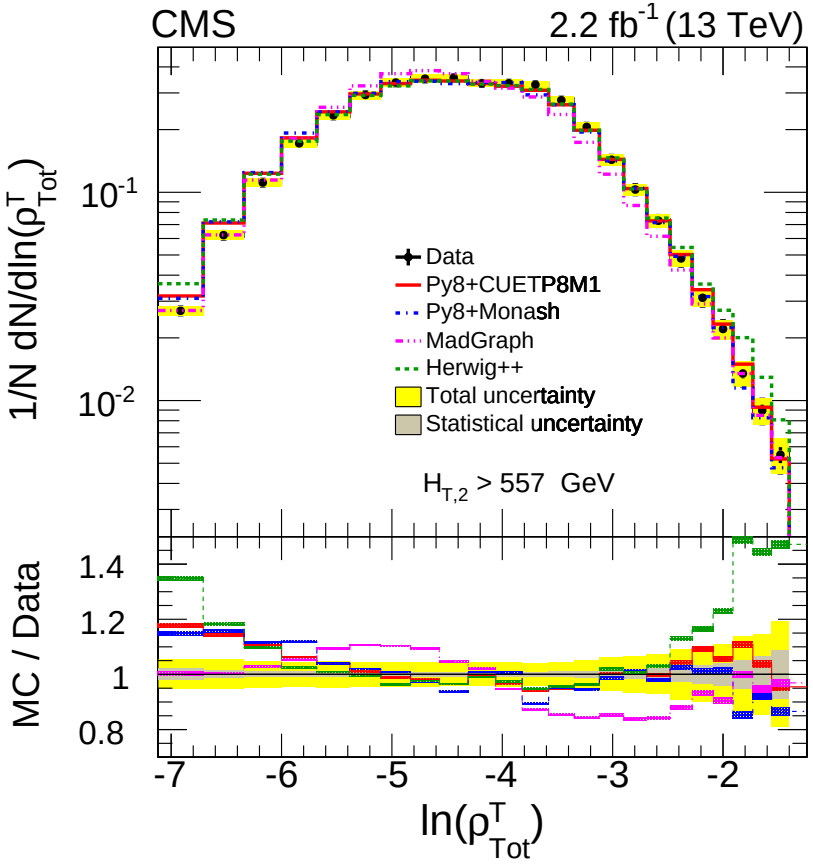




Event shapes at CMS [JHEP 12 (2018) 117]

- Total jet mass: $\rho_X = \frac{M_X^2}{P^2}$; $\rho_{\rm tot} = \rho_U + \rho_L$
- Total transverse jet mass: $\rho_X^T = \frac{M_X^2}{P_T^2}$; $\rho_{\rm tot}^T = \rho_U^T + \rho_L^T$

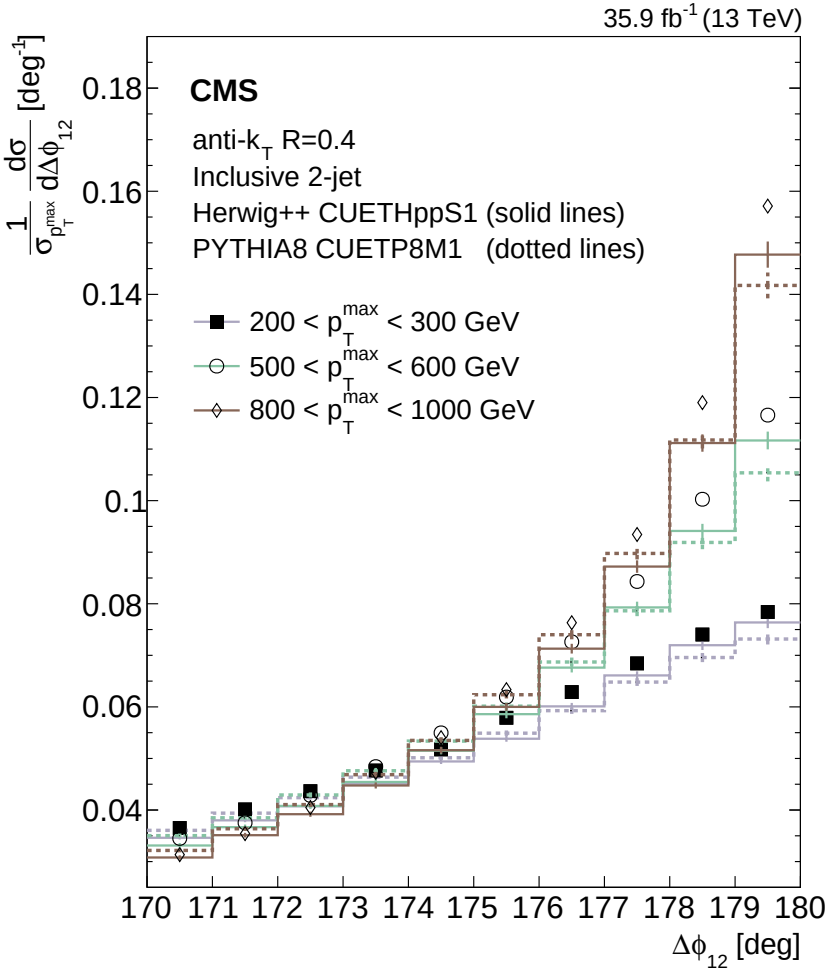


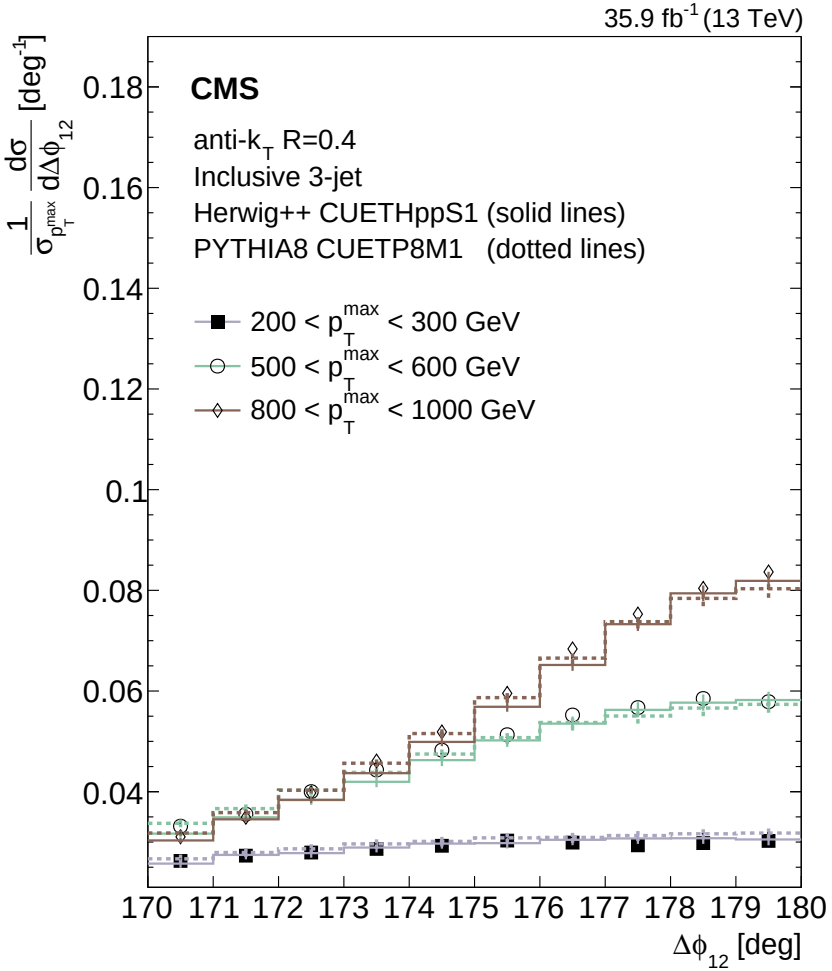


- Important test of the back-to-back and collinear regime (low thrust).
- Significant discrepancies observed in all variables across p_T bins.

$\Delta\phi_{12}$ in back-to-back topologies at CMS [arXiv:1902.04374 (hep-ex)]

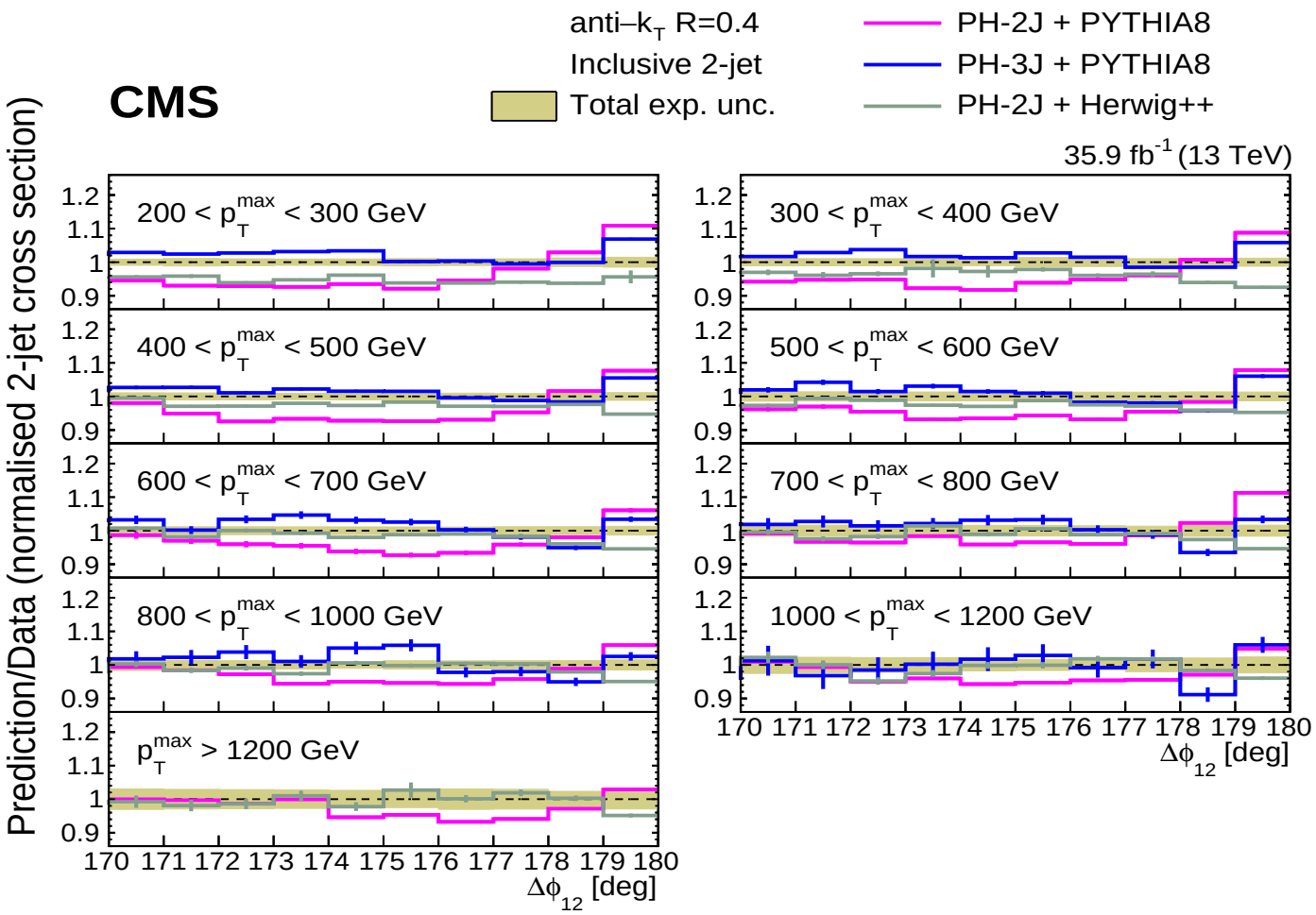
- Test of QCD at angles $\Delta\phi \lesssim \pi$, sensitive to resummation details.
- Two and three jet events studied ($p_{T1} > p_{T2} > 100$ GeV, $p_{T3} > 30$ GeV).
- Measurement of the normalized distribution of azimuthal difference $\Delta\phi_{12}$.





$\Delta\phi_{12}$ in back-to-back topologies at CMS [arXiv:1902.04374 (hep-ex)]

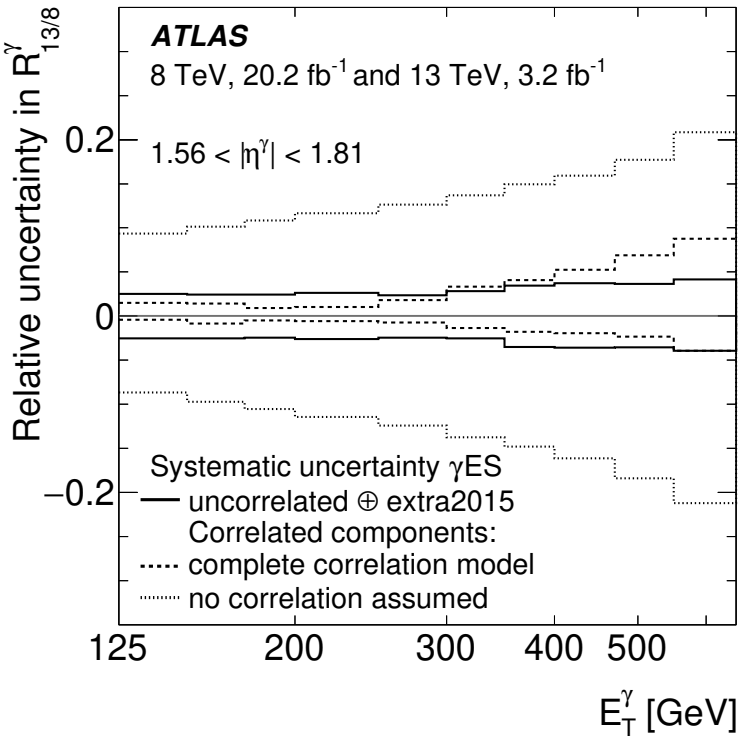
- Comparison to LO+PS and NLO+PS are provided.
- In particular, Powheg ($2 \to 2$ and $2 \to 3$) are studied.
- 2 and 3-jet measurements not simultaneously described by any model.

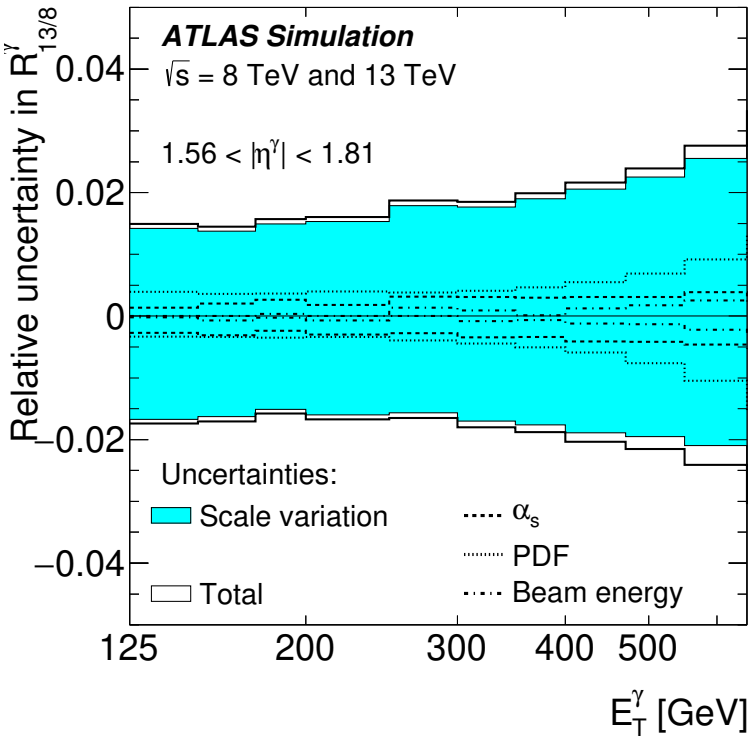


Photon analyses

Photon cross section ratios 13 / 8 TeV [JHEP 04 (2019) 093]

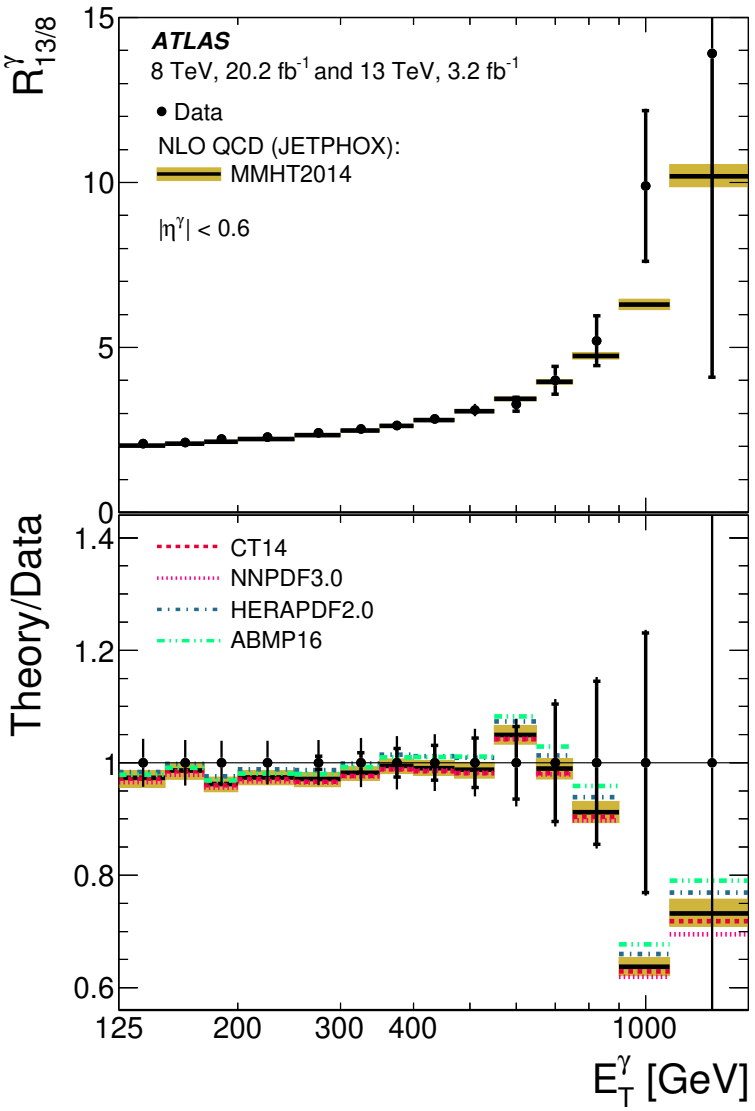
- Ratio of two measurements: [JHEP 08 (2016) 005, PLB 770 (2017) 473]
- Reduction of uncertainties by considering their correlations:
  - Experimental uncertainties below 5% in the full E_T^γ range (γES).
  - Theoretical uncertainties below 2% in the full E_T^γ range (scale).
- Ratios come in two flavours:
  - Ratio of double-differential cross sections: $R^\gamma_{13/8}$ versus E_T^γ and $|y^\gamma|$
  - Double ratio to Z fiducial cross sections $D^{\gamma,Z}_{13/8} = R^\gamma_{13/8}/R^{Z,\mathrm{fid}}_{13/8}$.

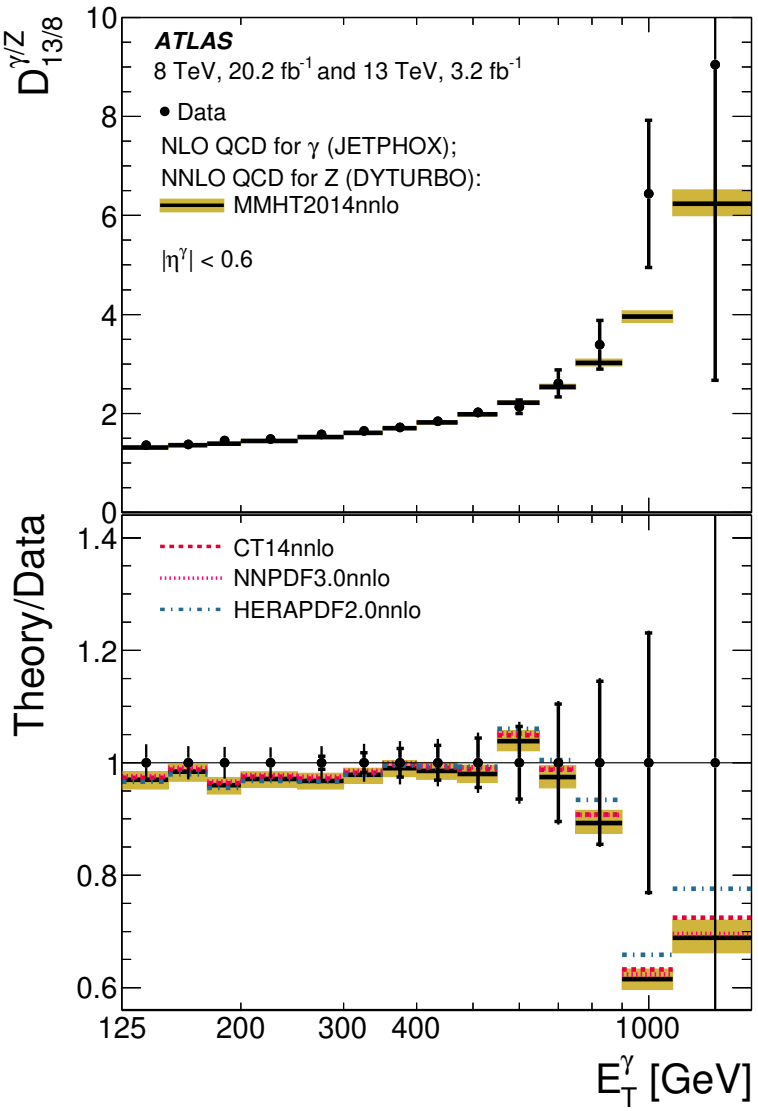




Photon cross section ratios 13 / 8 TeV [JHEP 04 (2019) 093]

Comparison of ratios to NLO QCD (+NNLO for Z)



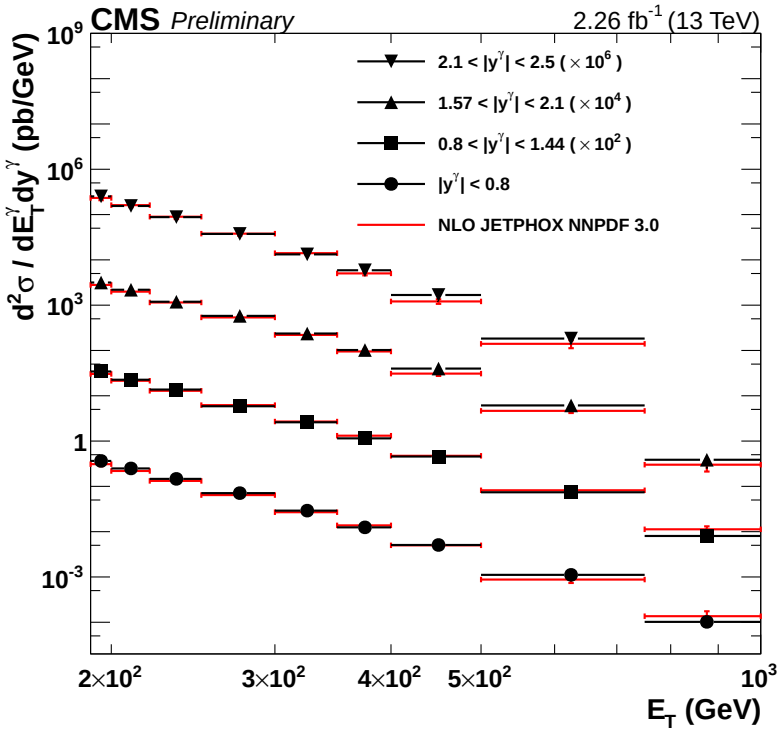


Recent NNLO predictions for γ production [arXiv:1904.01044 (hep-ph)]

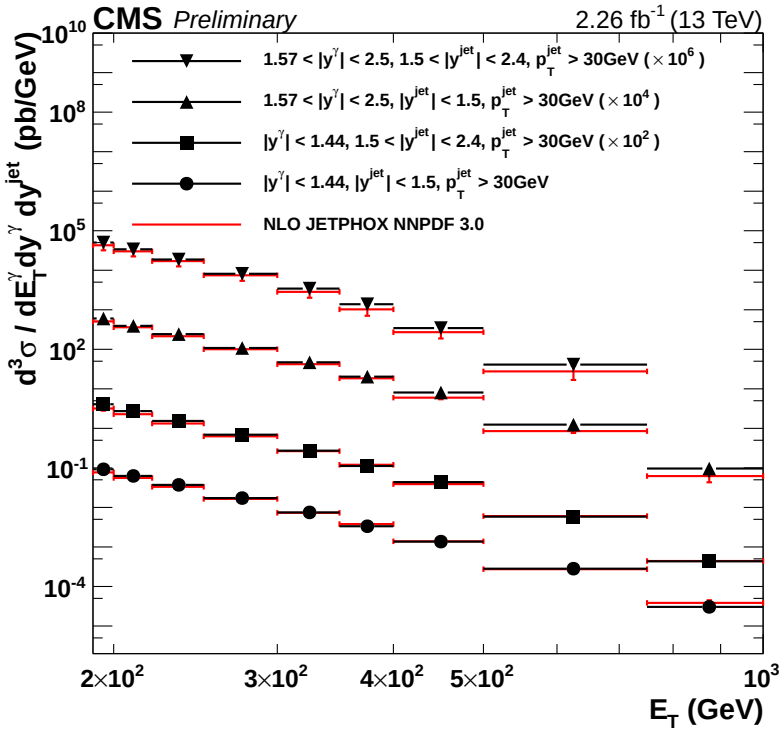
Inclusive photon and photon + jets in CMS [Eur. Phys. J. C 79 (2019) 20]

- Measurement of isolated photons inclusively and in association with jets
- $E_T^\gamma > 190$ GeV and $|y^\gamma| < 2.5$.
- $p_T^{\mathrm{jet}} > 30$ GeV and $|y^{\mathrm{jet}}| < 2.4$.
- BDT to discriminate from background, validated with isolation sidebands.

Inclusive γ

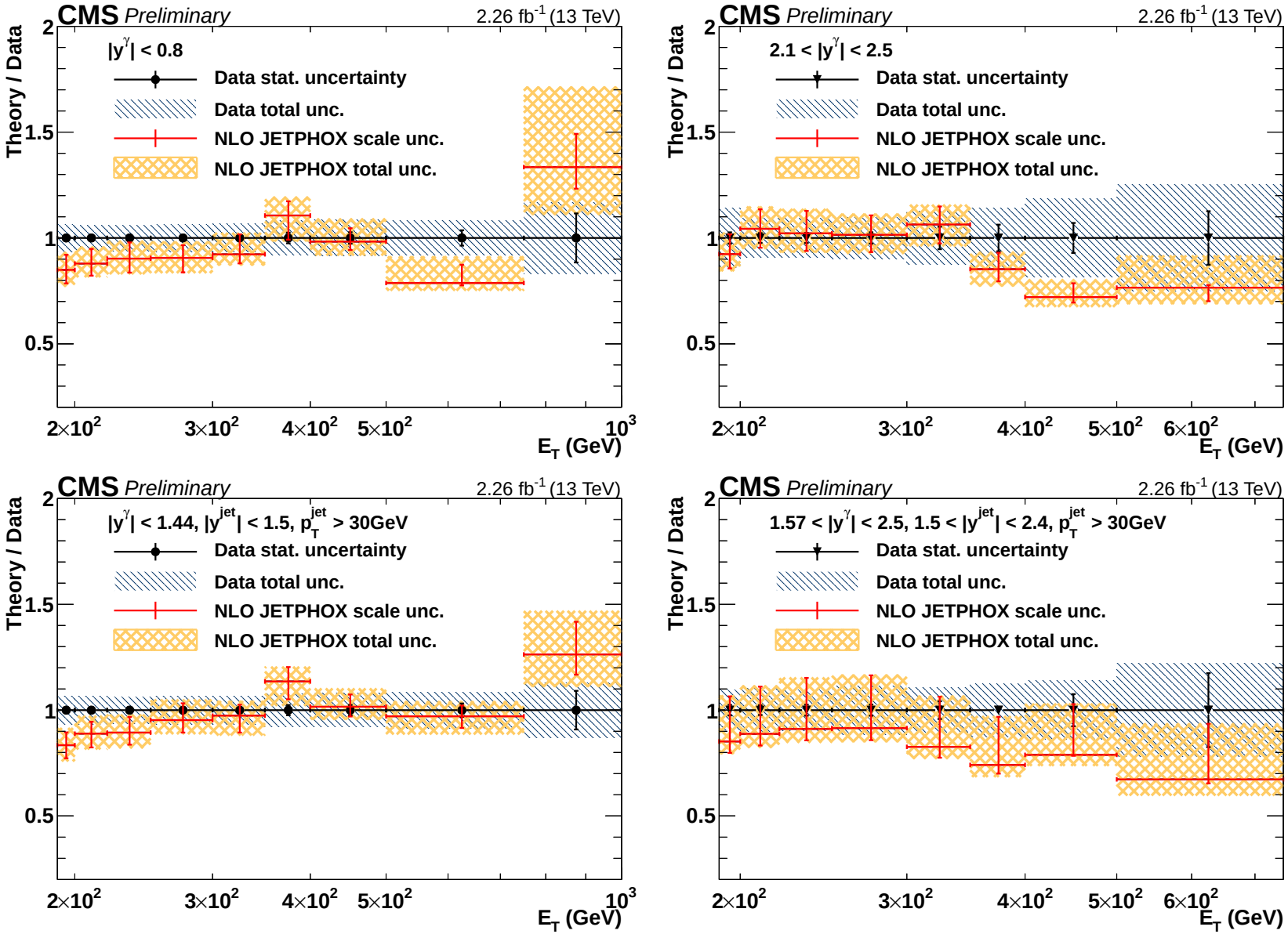


γ+jets



Inclusive photon and photon + jets in CMS [Eur. Phys. J. C 79 (2019) 20]

Comparison of inclusive γ (top) and γ+jet (bottom) to NLO pQCD (JetPhox)

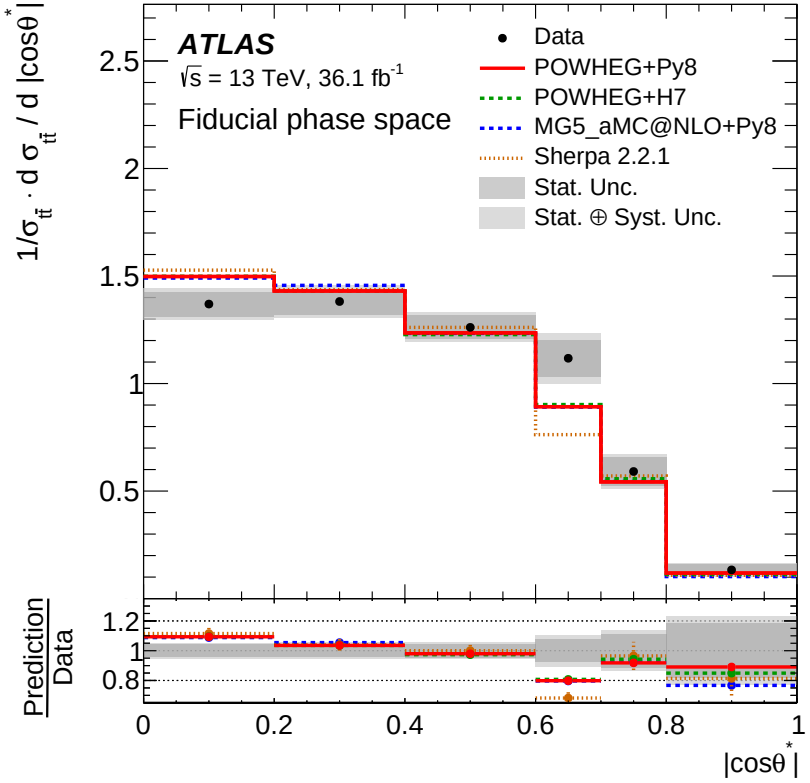


Top quark analyses

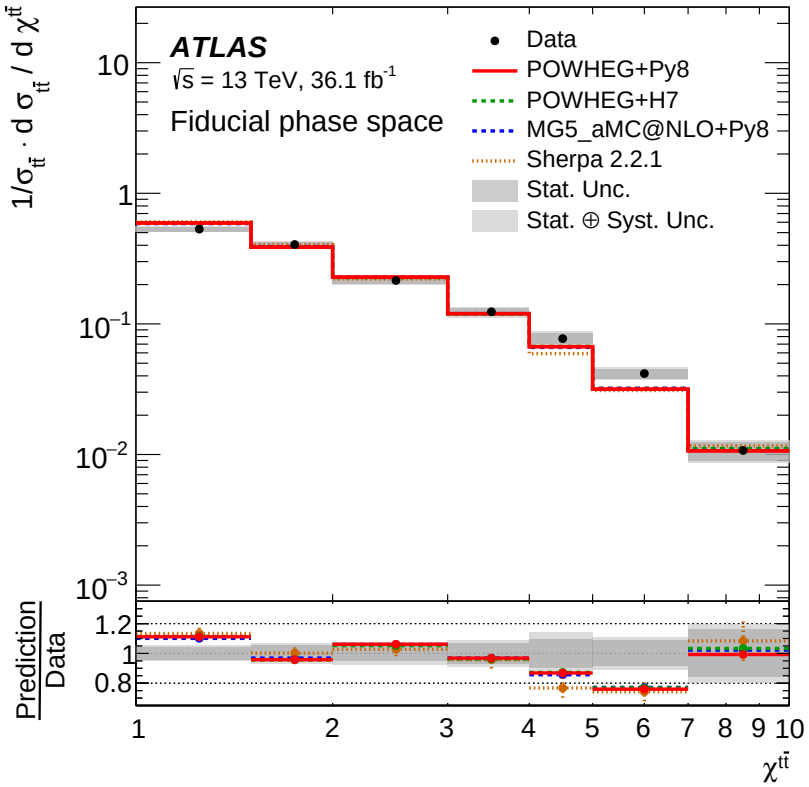
Boosted, fully hadronic $t\bar{t}$ at ATLAS [Phys. Rev. D 98 (2018) 012003]

- Fully hadronic $t\bar{t}$ events in boosted regime
- Two $R = 1.0$ jets with $p_T > 350$ GeV, $|\eta| < 2.0$, $|m_J - m_t| < 50$ GeV.
- Both jets are associated to a small ($R = 0.4$) b-tagged jet ($\Delta R_{jJ} < 1.0$)
- Multijet background estimated in a data-driven way.

Collins-Soper angle $\cos\theta^*$



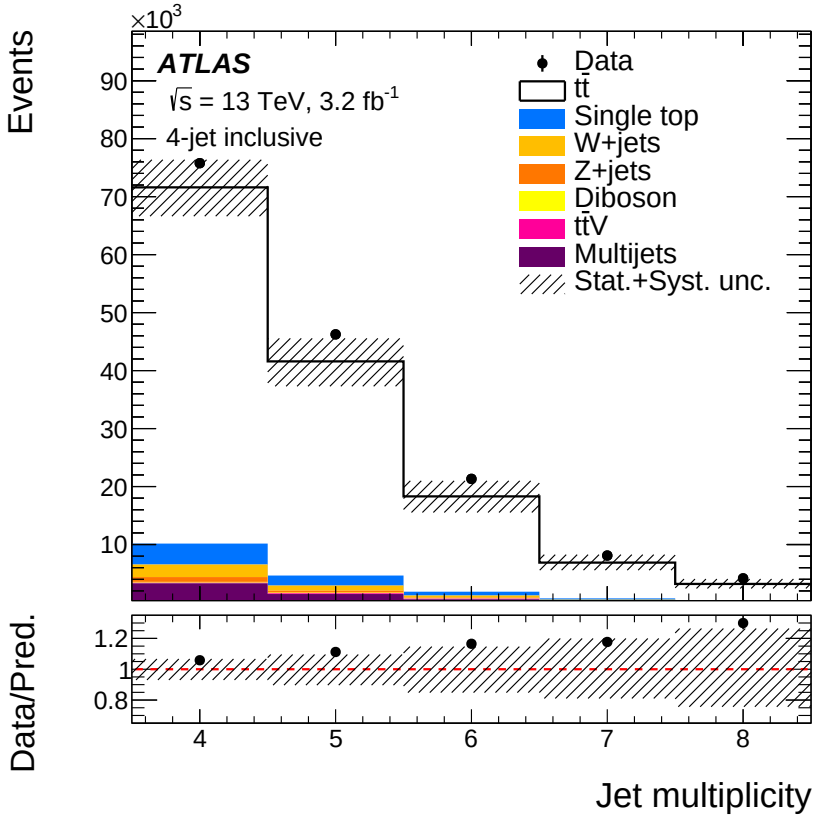
Angular distance $\chi = e^{|y_t - y_{\bar{t}}|}$

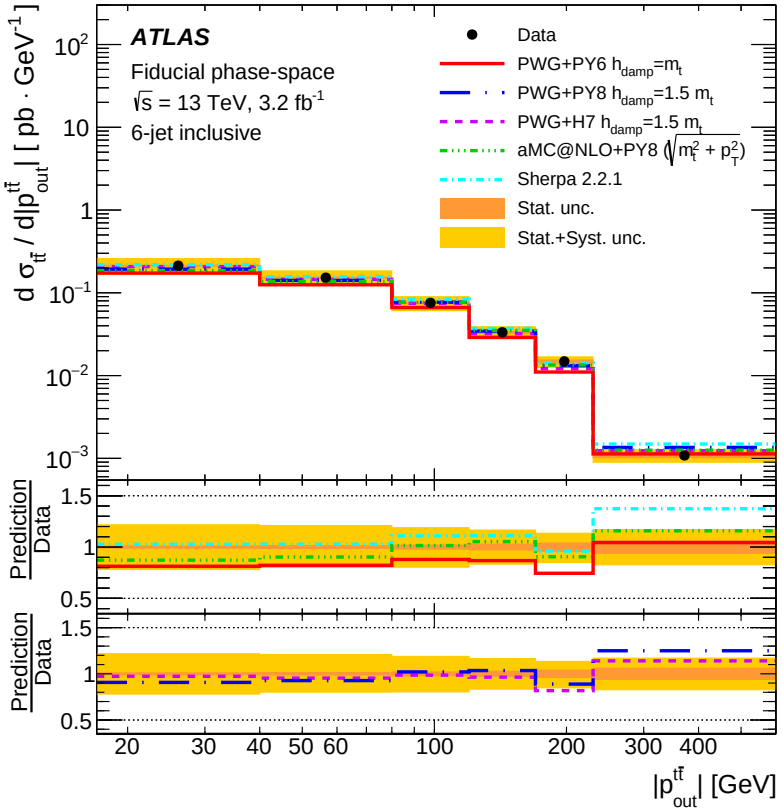


$t\bar{t}$+jets differential cross sections at ATLAS [JHEP 1810 (2018) 159]

- Single lepton channel e or μ with $p_T > 25$ GeV, $|\eta| < 2.5$.
- Jets reconstructed with $R = 0.4$, $p_T > 25$ GeV and $|\eta| < 2.5$

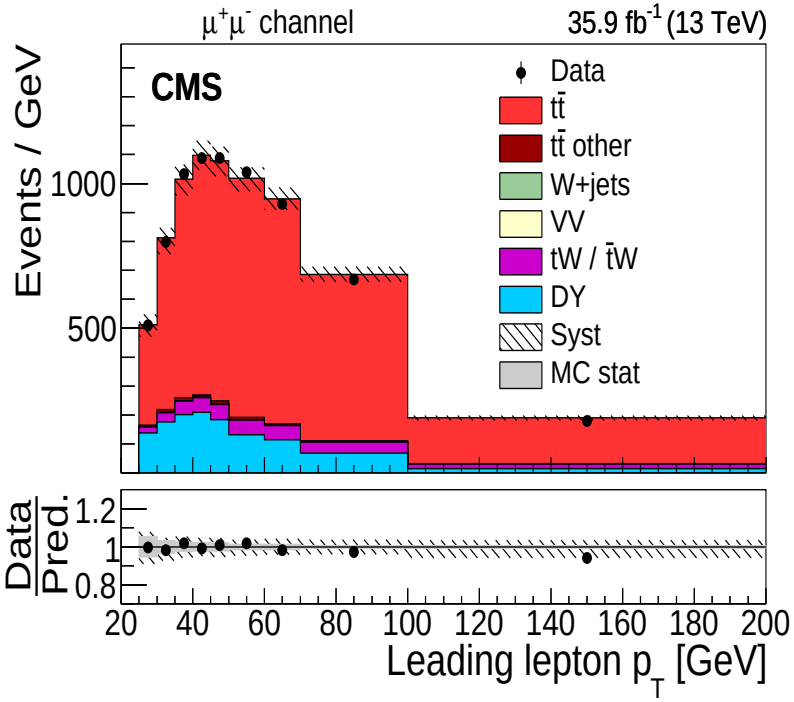
$$\text{Out-of-plane momentum: } |p^t_{\text{out}}| = \left| \vec{p}^{\,t}_{\text{had}} \cdot \frac{\vec{p}^{\,t}_{\text{lep}} \times \hat{z}}{|\vec{p}^{\,t}_{\text{lep}} \times \hat{z}|} \right|$$

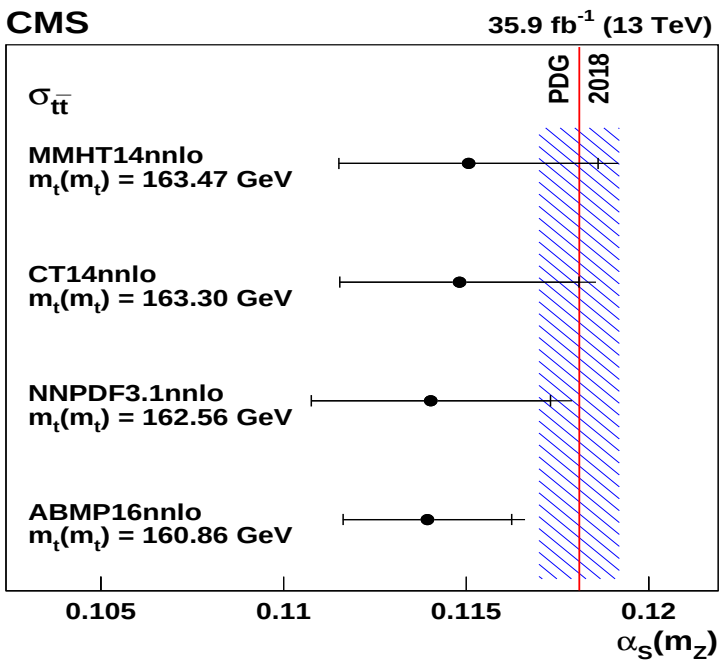




$t\bar{t}$ cross section, α_s and m_t at CMS [Eur. Phys. J. C 79 (2019) 368]

- Combined fit to e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ channels.
- Likelihood fit to extract $\sigma_{t\bar{t}}$, $\alpha_s(m_Z)$ and m_t.
- $\sigma_{t\bar{t}} = 815 \pm 2$ (stat.) ± 29 (sys.) ± 20 (lumi.) from m_t, σ simultaneous fit.



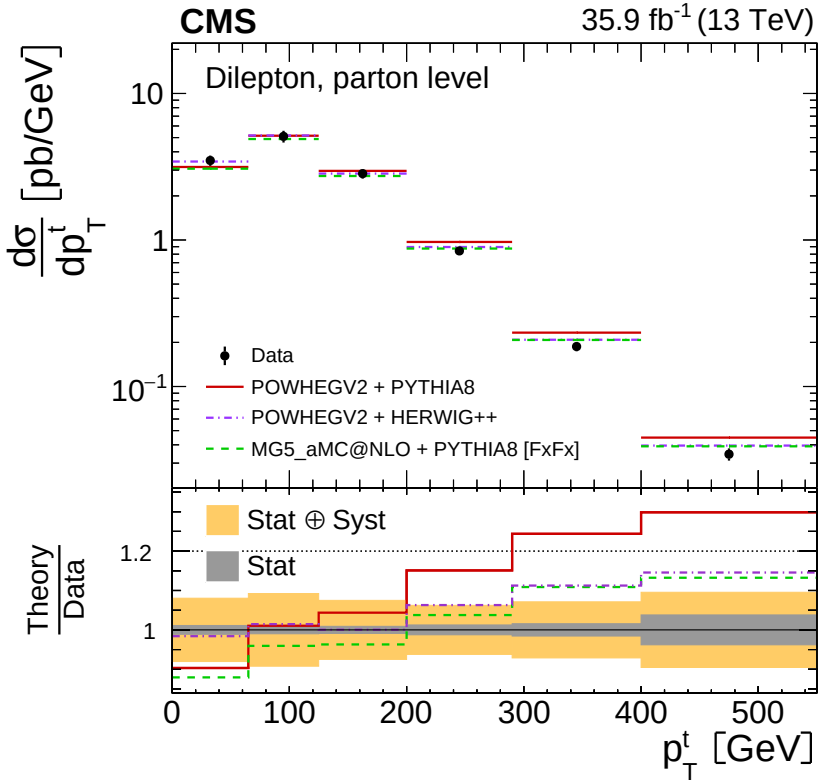


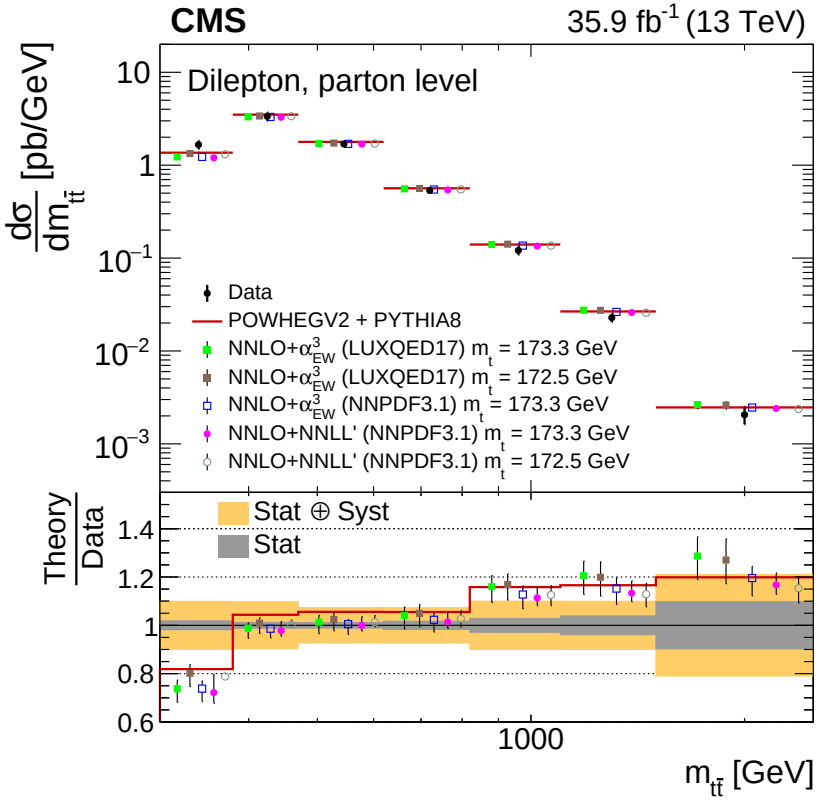
PDF set	$\alpha_S(m_Z)$
ABMP16	0.1139 ± 0.0023 (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	0.1140 ± 0.0033 (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	0.1148 ± 0.0032 (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	0.1151 ± 0.0035 (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

PDF set	m_t^{pole} [GeV]
ABMP16	169.9 ± 1.8 (fit + PDF + α_S) $^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	173.2 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.3}$ (scale)
CT14	173.7 ± 2.0 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)
MMHT14	173.6 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)

$t\bar{t}$ dilepton differential cross sections at CMS [JHEP 02 (2019) 149]

- Differential cross sections versus a large variety of observables.
- Comparison to high-order predictions in QCD
  - Full NNLO + α^3_{EW} (LUXQED17)
  - Full NNLO + double resummation (NNLO+NNLL')
  - Approximate N^{3}LO @ NNLL.
  - Approximate NNLO.



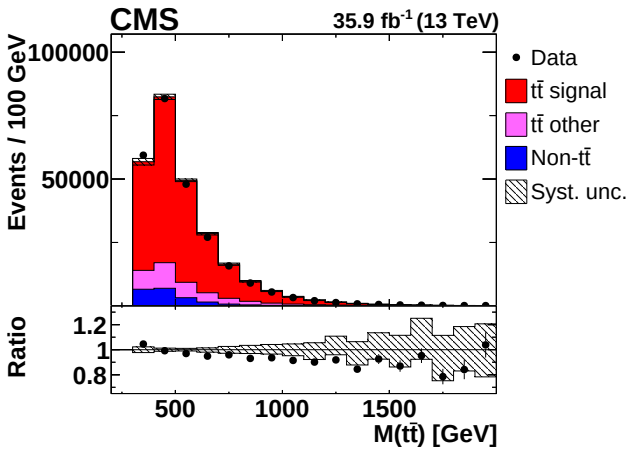


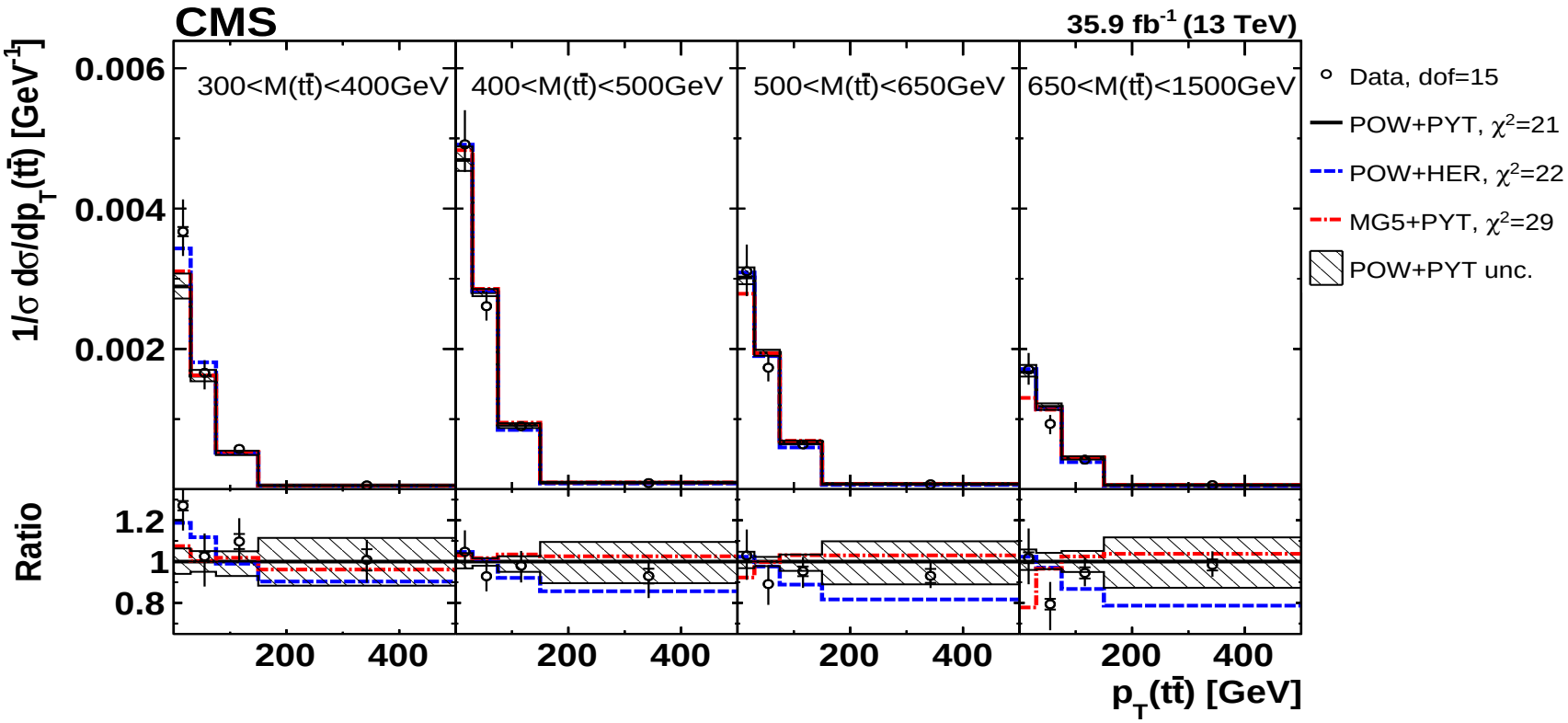
$t\bar{t}$ multi-differential cross sections at CMS [arXiv:1904.05237 (hep-ex)]

- Dilepton channels ee, $e\mu$, $\mu\mu$.
- Cross sections as a function of pairs of variables:

$$\{p_T(t), y_t, M_{t\bar{t}}, y_{t\bar{t}}, \Delta\eta_{t\bar{t}}, \Delta\phi_{t\bar{t}}, p_T(t\bar{t})\}$$

- Triple-differential cross sections of jet multiplicity N_{jet}
- Extraction of strong coupling α_s, top mass m_t and PDFs.



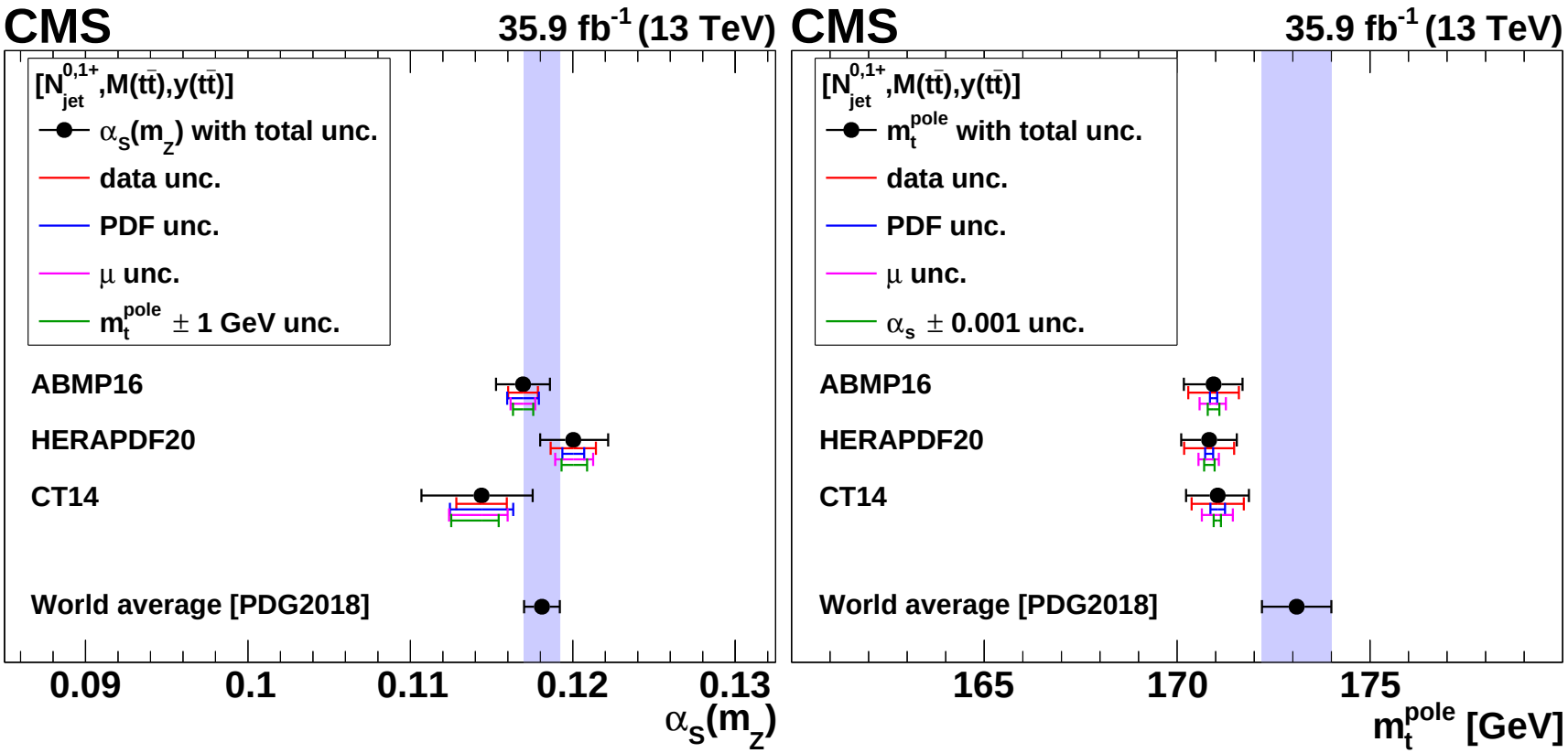


$t\bar{t}$ multi-differential cross sections at CMS [arXiv:1904.05237 (hep-ex)]

Values of strong coupling and top pole mass obtained from NLO QCD analysis:

- $\alpha_s(m_Z) = 0.1135 \pm 0.0016\ (\text{fit})\ ^{+0.0002}_{-0.0004}\ (\text{mod.})\ ^{+0.0008}_{-0.0001}\ (\text{par.})\ ^{+0.0011}_{-0.0005}\ (\text{scale})$
- $m_t^{\text{pole}} = 170.5 \pm 0.7\ (\text{fit})\ \pm 0.1\ (\text{mod.})\ ^{+0.0}_{-0.1}\ (\text{par.})\ \pm 0.3\ (\text{scale})$

Uncertainties estimated according to the general approach of HERAPDF2.0



Summary and conclusions

- New results on jet, photon and top quark production have been presented.
- Higher order theoretical predictions have been recently developed, in particular for photon and top production.
- In general, good qualitative agreement is observed with the state of the art theoretical predictions.
- Some significant discrepancies are also observed for some jet observables (event shapes)
- Huge ongoing effort from both ATLAS and CMS to provide new measurements. Stay tuned for future updates!
- See next talk by C. Pollard for another nice set of jet substructure and top measurements.