# Differential jet cross sections at CMS

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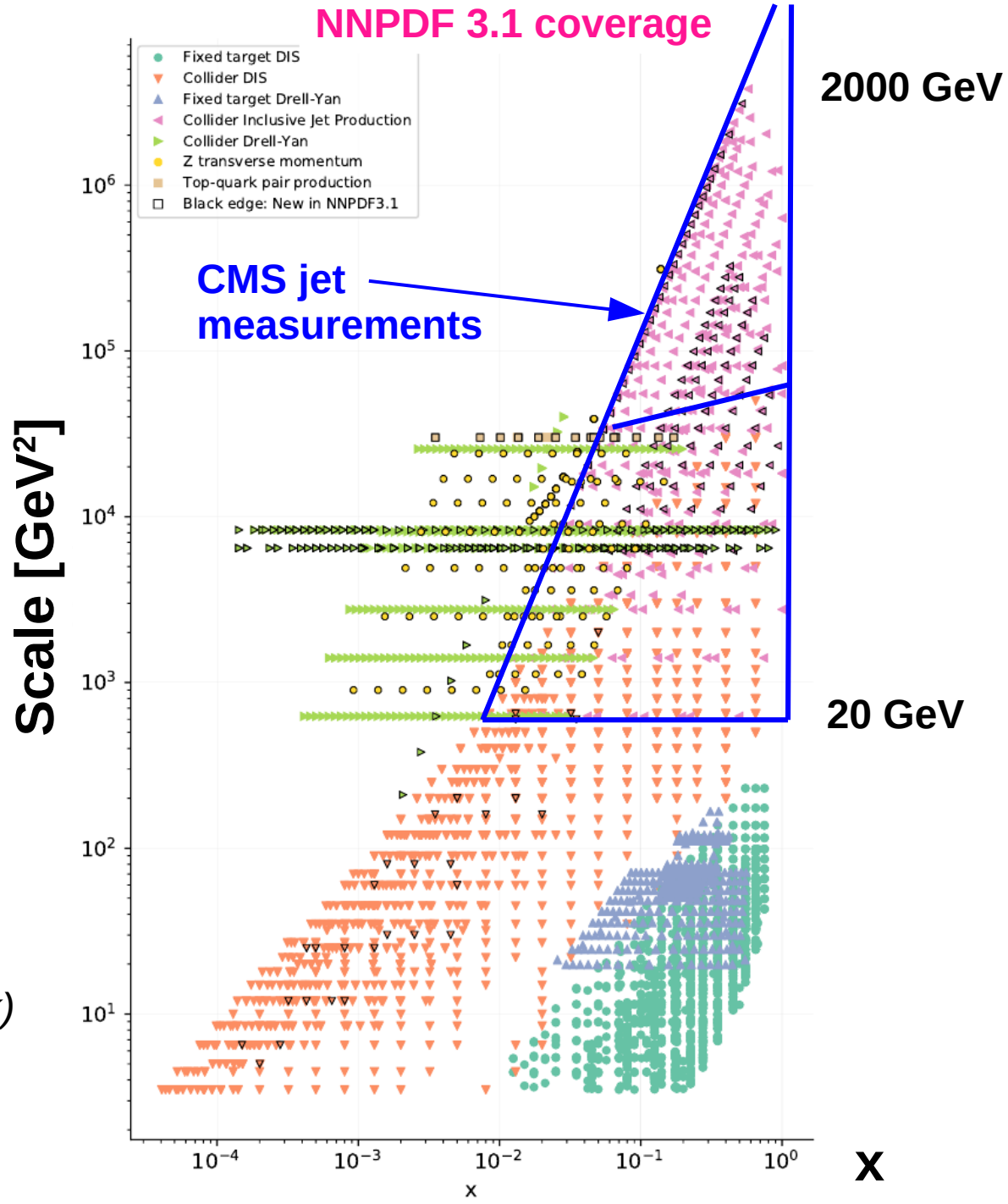
**on behlaf of the CMS Collaboration**

**Wednesday, April 10**
**DIS 2019, Torino**

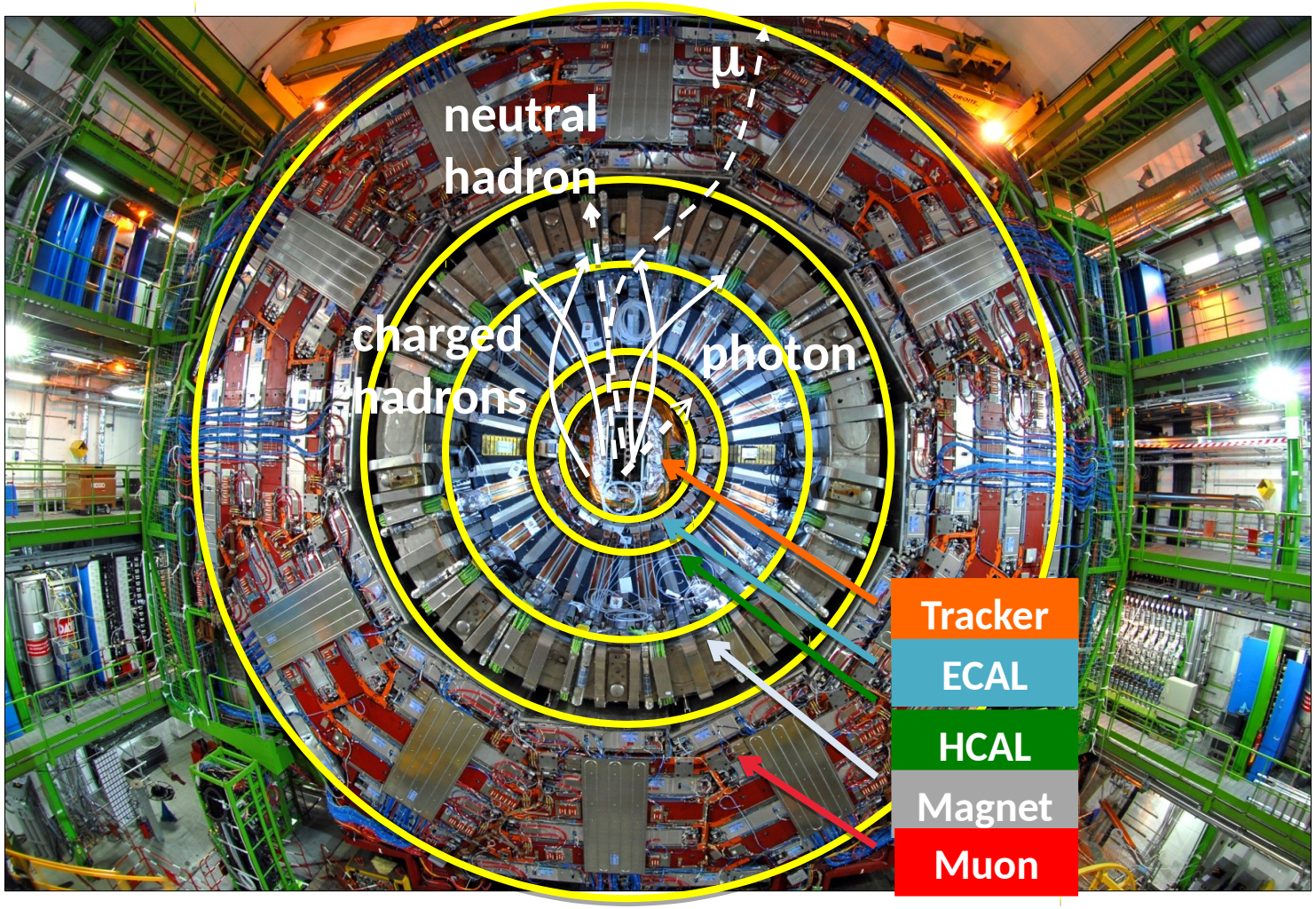
# Why jets?

- Jets allow to test perturbative predictions at the highest energy scales
  → the $\alpha_S$ running
- Jets allow to probe proton structure at the smallest distances (~$10^{-19}$ m)
  → PDFs *(Juan Rojo's talk)*
- Jets allow to test:
  Fixed order predictions
  Resummation effects
  ME + PS matching *(Simon Platzer's talk)*
  MPI + non. pert. effects

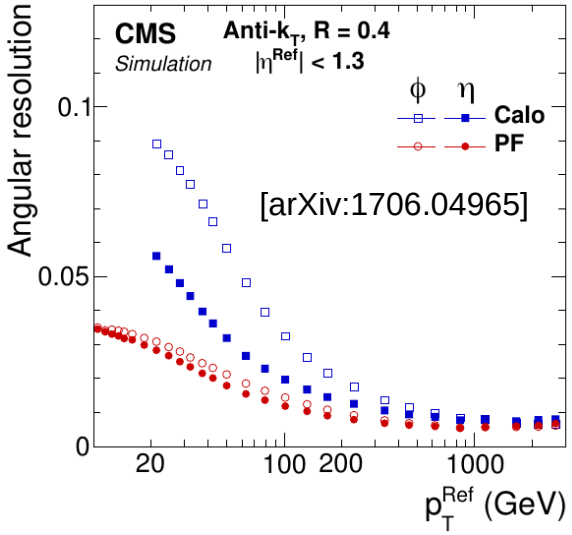


# Jet detection at CMS – Particle flow (PF) algo

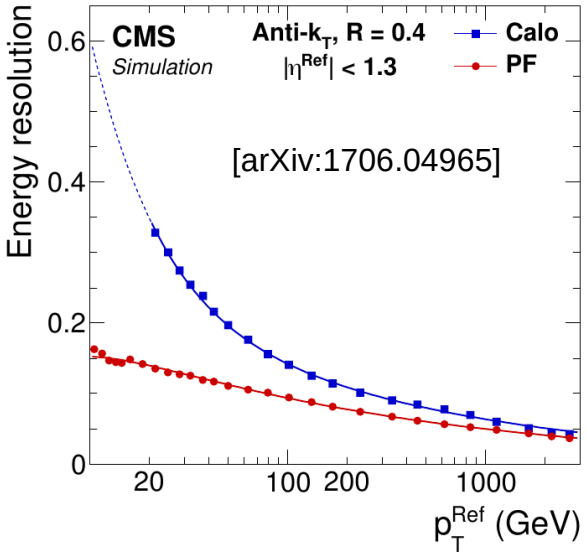
- Using all CMS components to reconstruct the jet kinematics




**Better angular resolution**




**Better energy resolution**



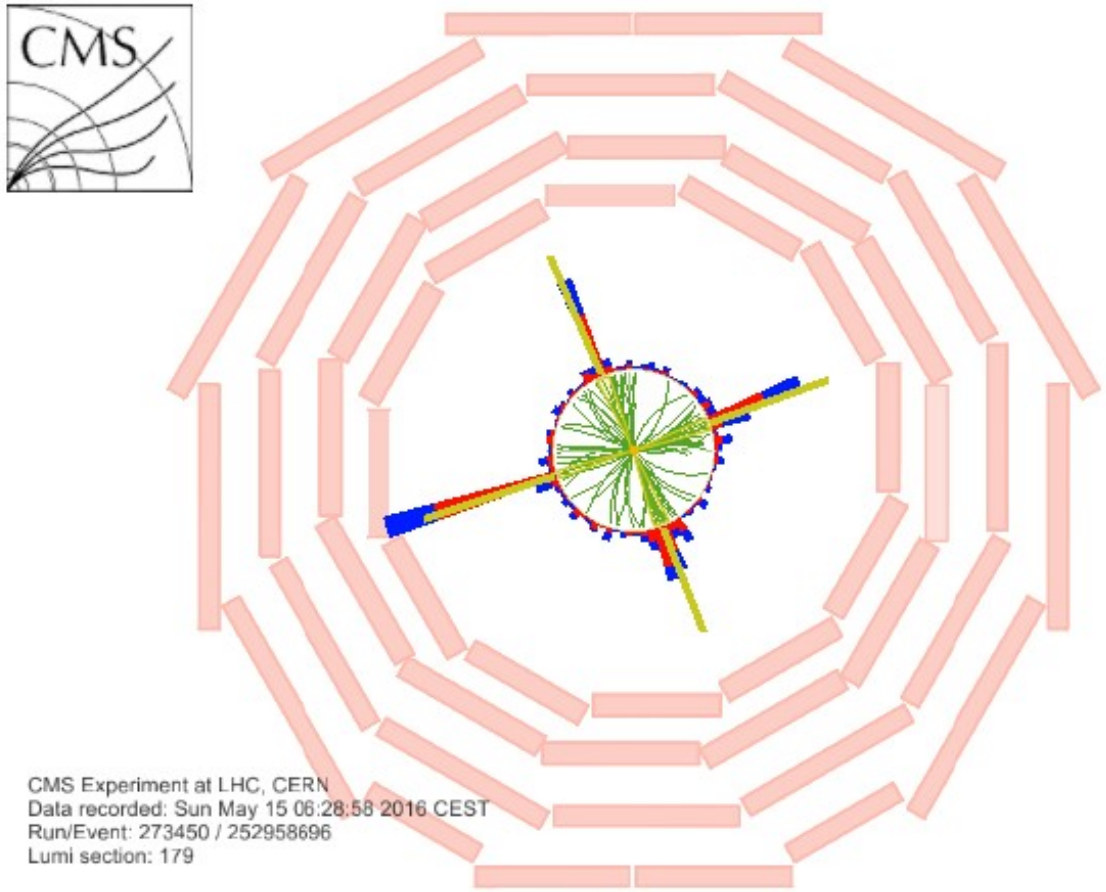
# The CMS jet analyses

- **Inclusive jets at 8 TeV (20 $fb^{-1}$)***
- Inclusive jets at 13 TeV (71 $pb^{-1}$)

- **Triple differential dijets at 8 TeV (20 $fb^{-1}$)***
- **$R_{32}$ at 8 TeV (20 $fb^{-1}$)***

- Azimuthal correlations at 13 TeV (36 $fb^{-1}$)
- Azimuthal correlations for back-to-back jets at 13 TeV (36 $fb^{-1}$), new!

4 jet event

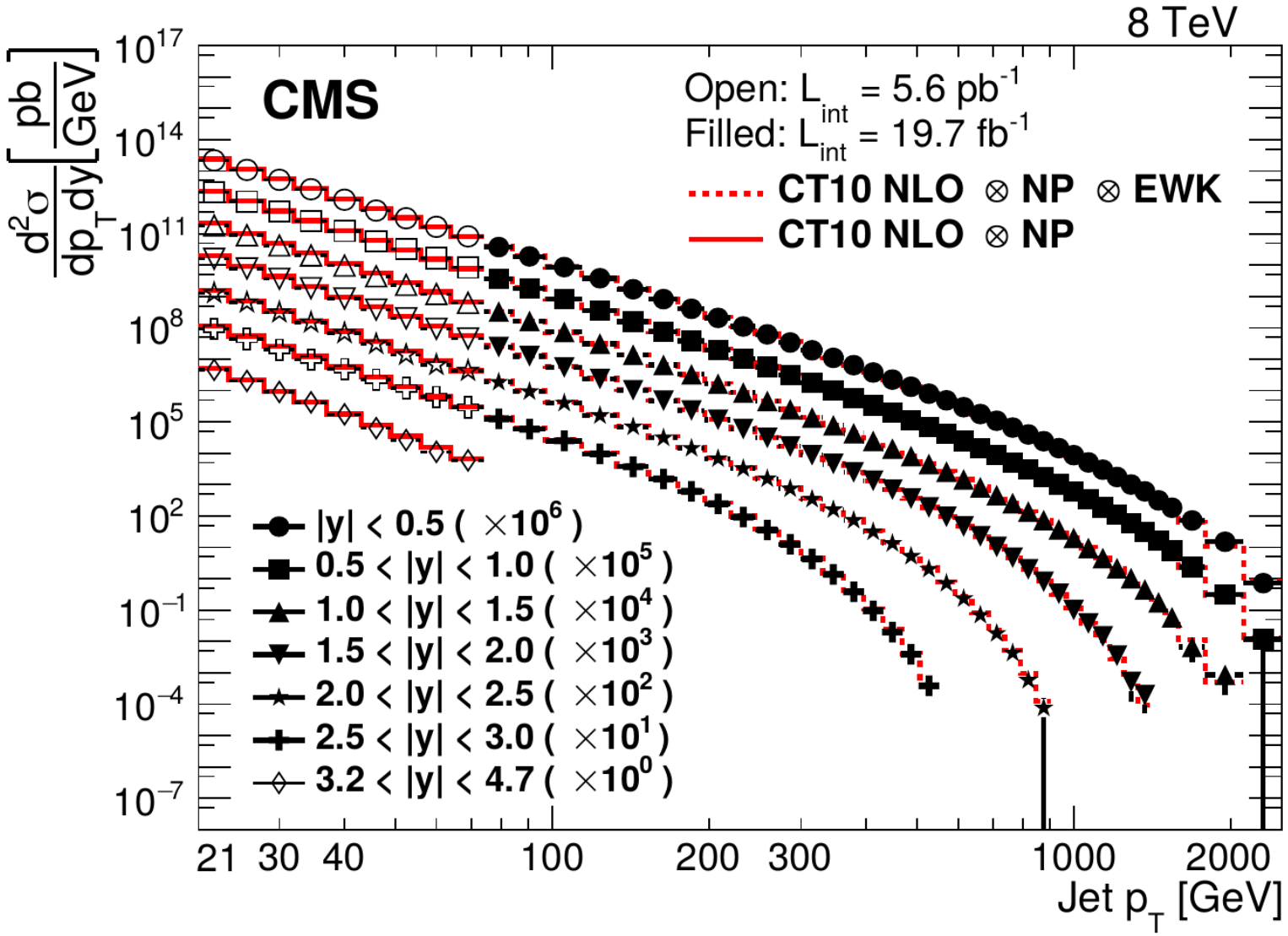



***Includes QCD analysis**

# Inclusive jets at 8 TeV

CMS Collaboration, JHEP 1703 (2017) 156
[arXiv:1609.05331]

- The jet (anti-$k_T$ R=0.7) spectrum between 20 GeV - 2000 GeV
- Forward region 3.2<|y|<4.7 only for low-$p_T$
- Compared to fixed order NLO predictions (by NLOJET++)

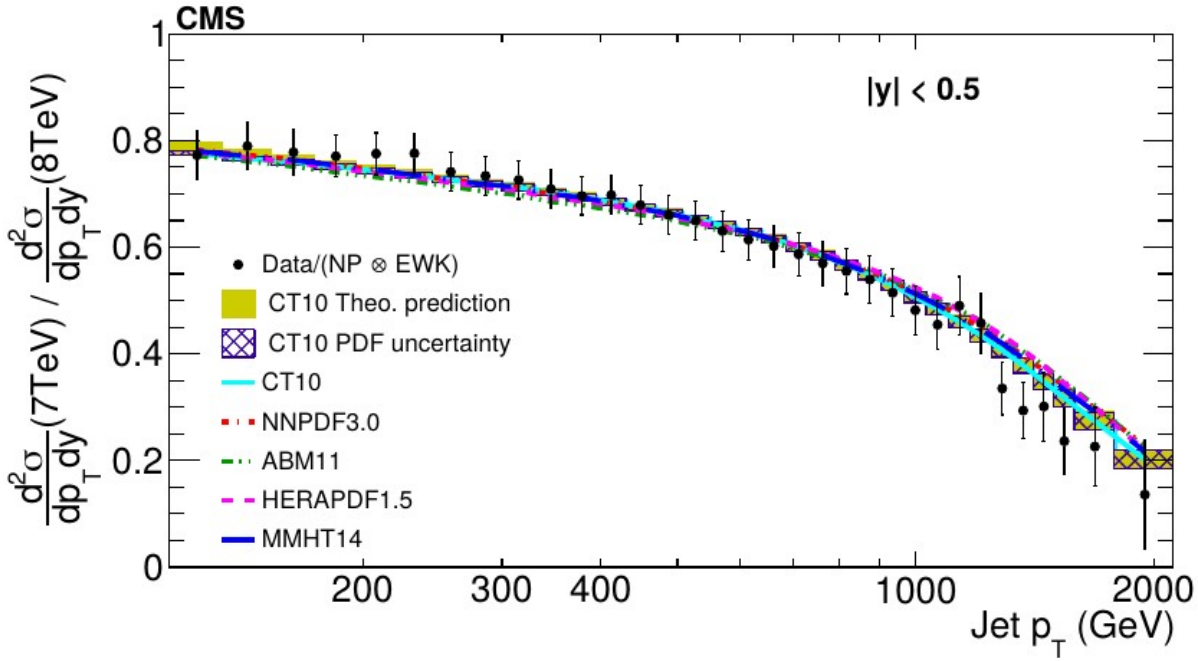


# Inclusive jets at 8 TeV – Power of Ratios

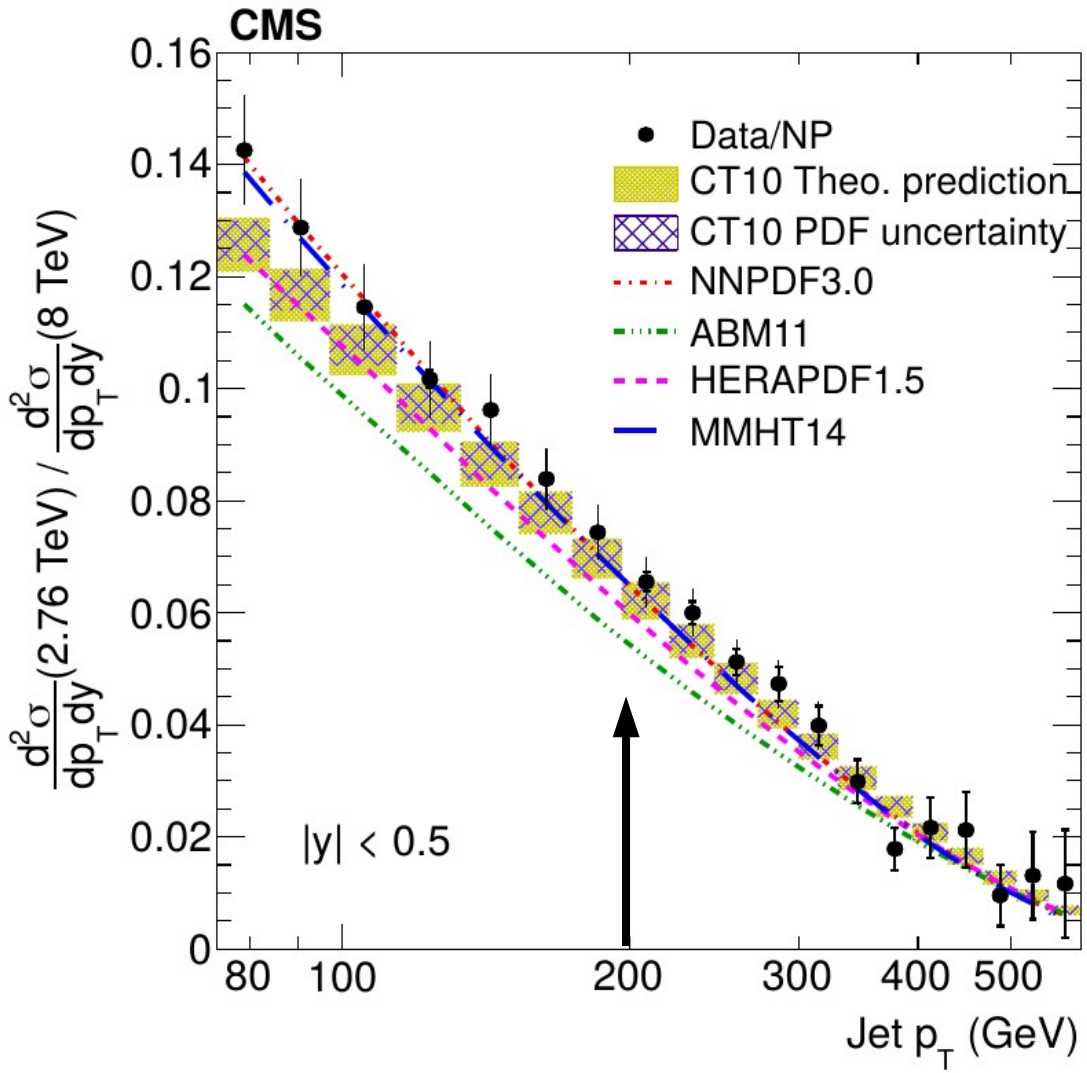
$$\propto \frac{g(x = 200/2760, \mu = 200)}{g(x = 200/8000, \mu = 200)}$$

- Partial cancellation of:
  - → Theoretical unc. (e.g. QCD scale)
  - → Exp. systematic unc.
- Improved PDF sensitivity

**7 TeV / 8 TeV**




**2.76 TeV / 8 TeV**

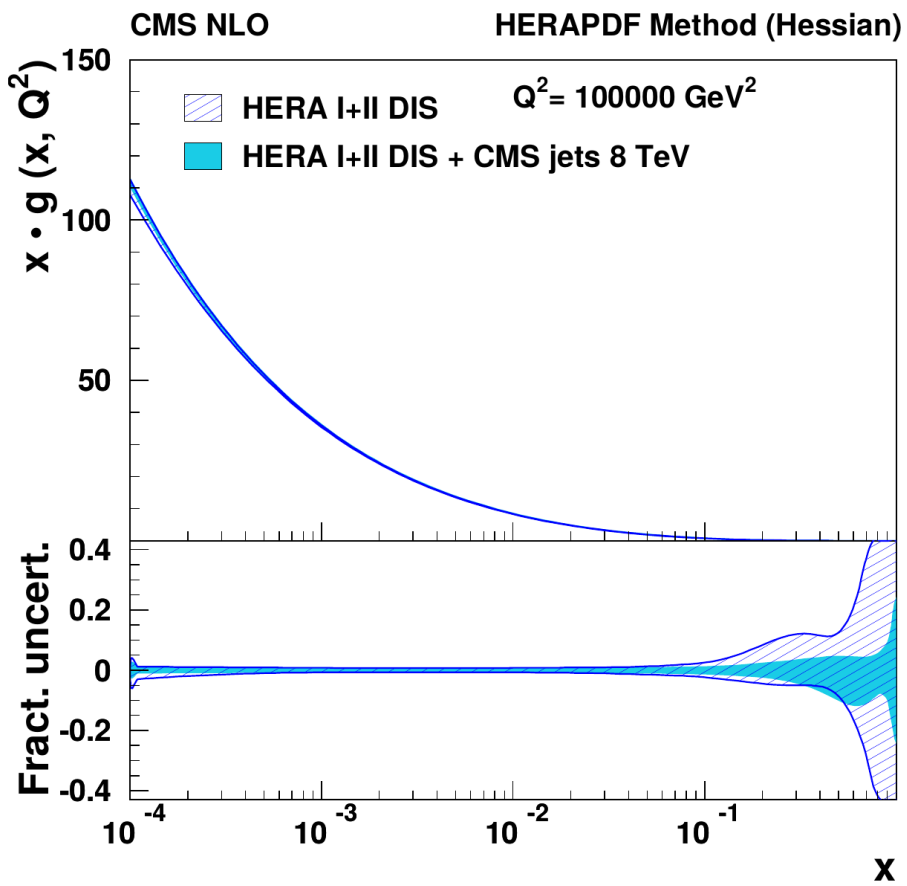


# Inclusive jets at 8 TeV – QCD Analysis

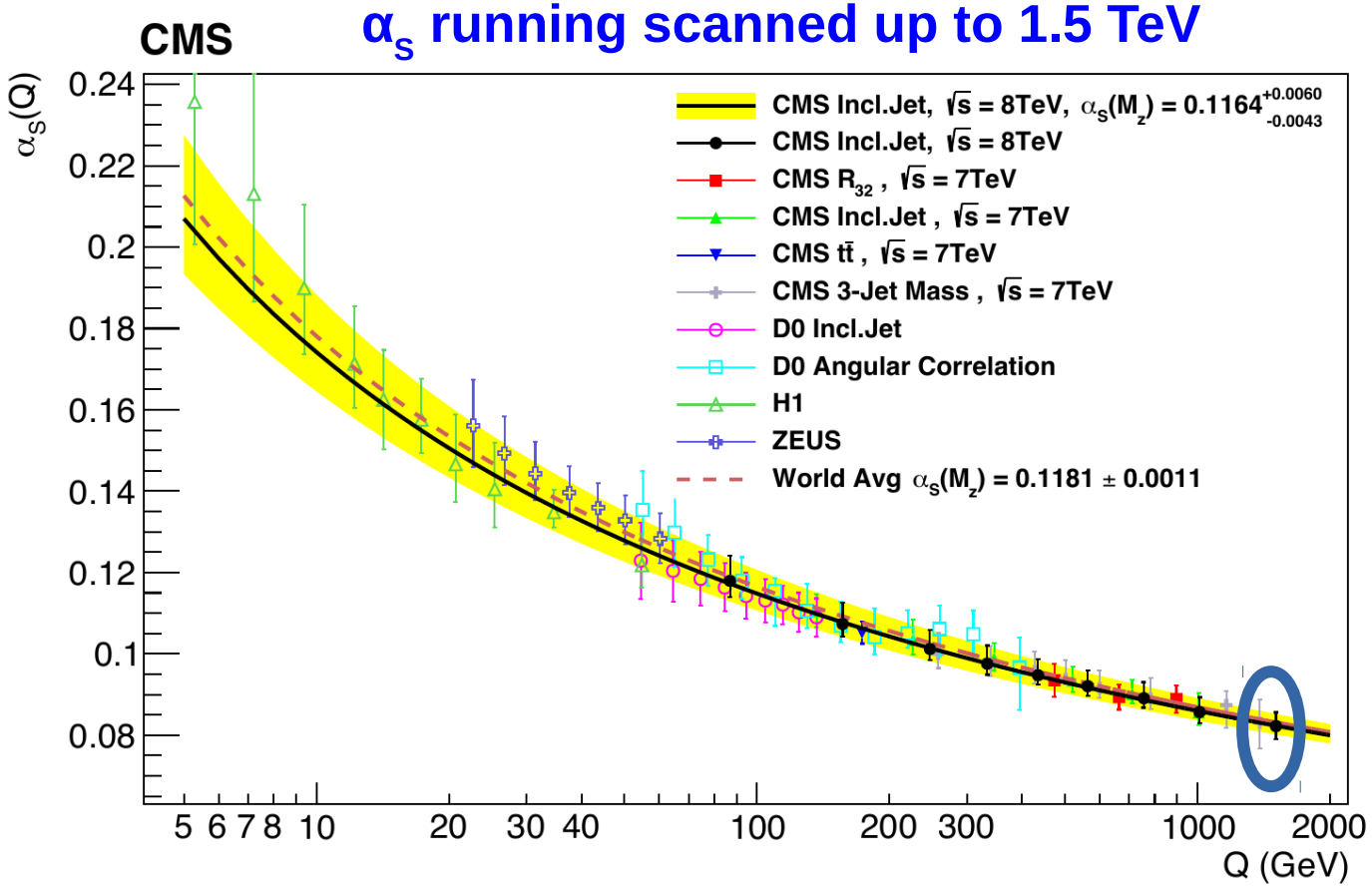
- A significant constrain of gluon PDF w.r.t. HERA-only fit
- $\alpha_s$ unc. dominated by scale

$$\alpha_S^{\mathrm{NLO}}(M_Z) = 0.116^{+0.006}_{-0.004}$$

**Gluon PDF at μ=320 GeV**




**$\alpha_s$ running scanned up to 1.5 TeV**



# Inclusive jets at 8 TeV – QCD Analysis

- Overall chi2/ndf ~ 1.2
- Slightly worse values for forward jets 1.5<|y|<2.5

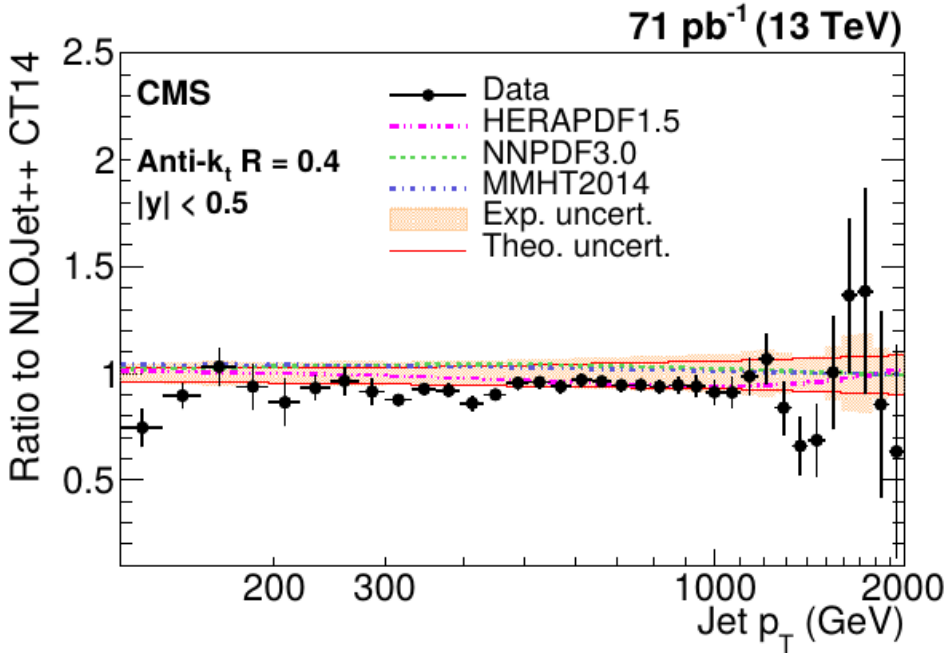
| Data sets | | Partial $\chi^2/N_{dp}$ |
|---|---|---|
| HERA I+II neutral current | $e^+p$, $E_p = 920$ GeV | 376/332 |
| HERA I+II neutral current | $e^+p$, $E_p = 820$ GeV | 61/63 |
| HERA I+II neutral current | $e^+p$, $E_p = 575$ GeV | 197/234 |
| HERA I+II neutral current | $e^+p$, $E_p = 460$ GeV | 204/187 |
| HERA I+II neutral current | $e^-p$ | 219/159 |
| HERA I+II charged current | $e^+p$ | 41/39 |
| HERA I+II charged current | $e^-p$ | 50/42 |
| CMS inclusive jets 8 TeV | $0 < y < 0.5$ | 53/36 |
| | $0.5 < y < 1.0$ | 34/36 |
| | $1.0 < y < 1.5$ | 35/35 |
| | $1.5 < y < 2.0$ | 52/29 |
| | $2.0 < y < 2.5$ | 49/24 |
| | $2.5 < y < 3.0$ | 4.9/18 |
| Correlated $\chi^2$ | | 94 |
| Global $\chi^2/N_{dof}$ | | 1471/1216 |

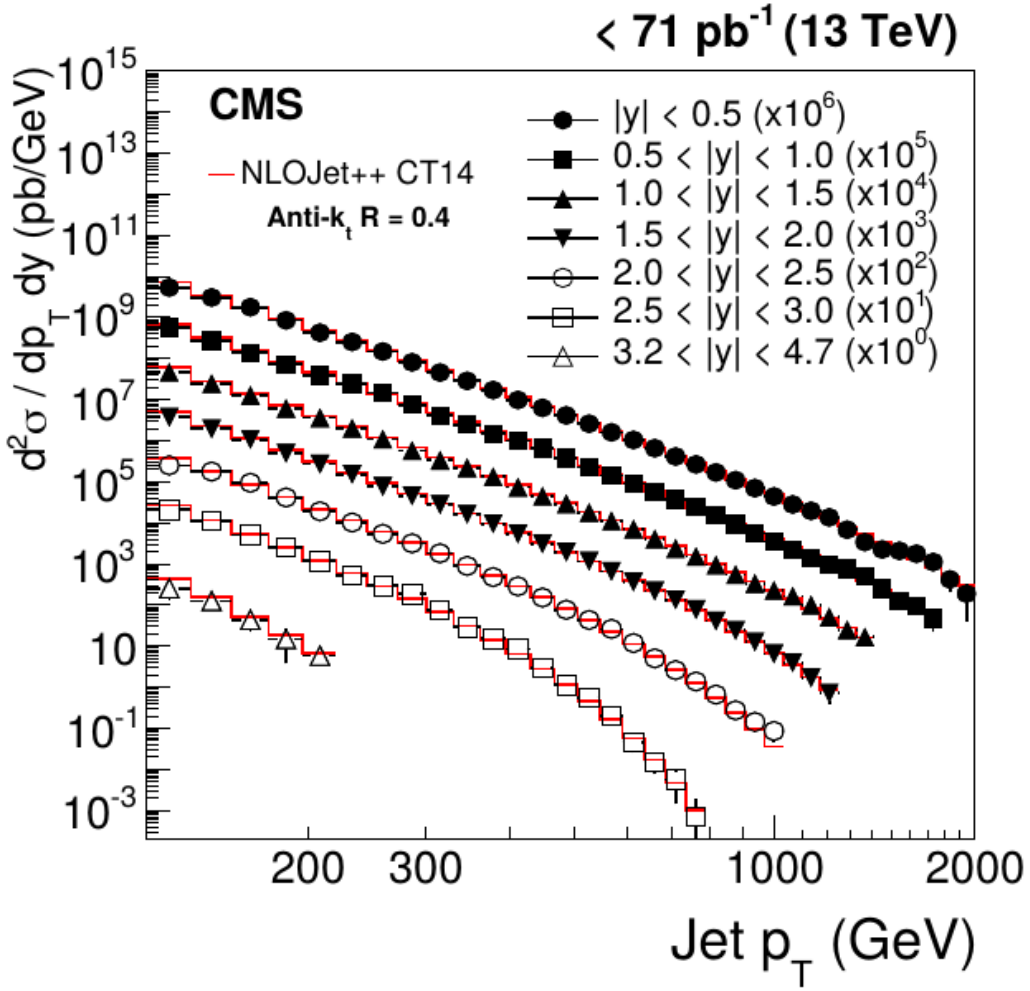
# Inclusive jets at 13 TeV

CMS Collaboration, Eur.Phys.J. C76 (2016) no.8, 451 [arXiv:1605.04436]

- Early 13 TeV jet data (anti-$k_T$ R=0.4, 0.7) from 2015 with limited lumi
- Data precision not sufficient for detailed QCD analysis

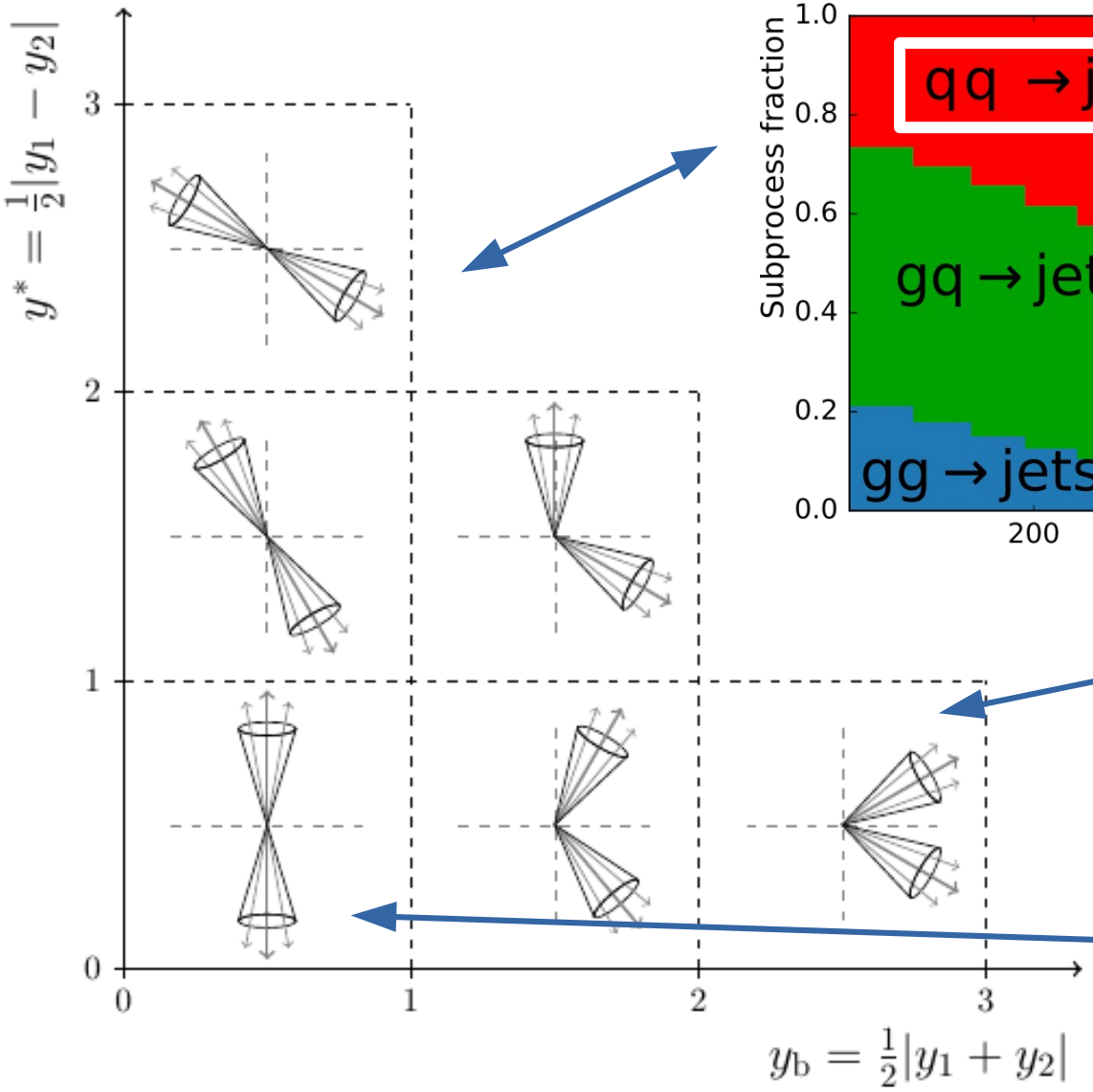
*A legacy analysis of 2016, 2017 & 2018 data (~140 fb$^{-1}$) in progress*

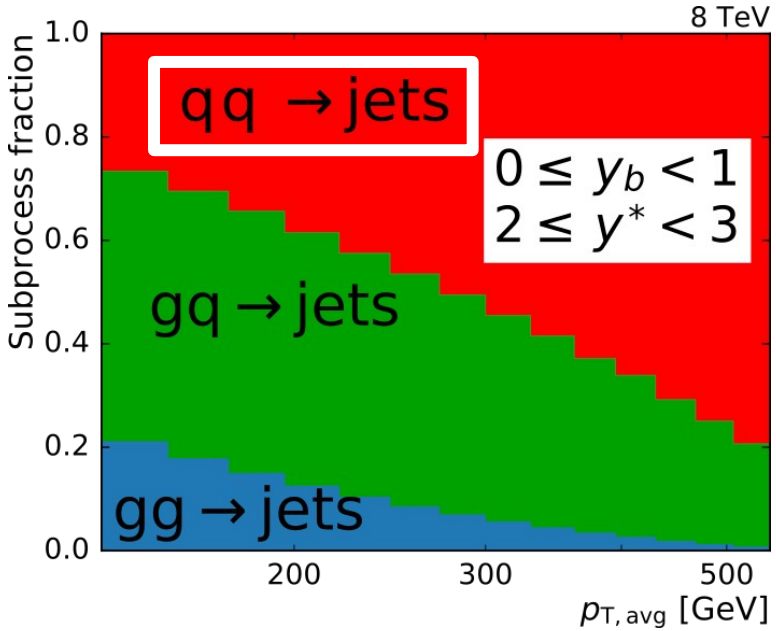


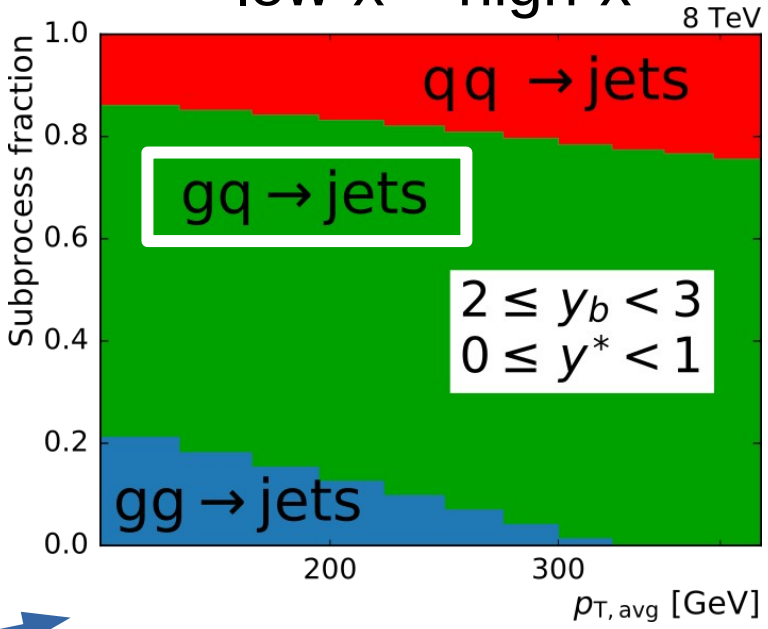
# 3D scan of the dijet events

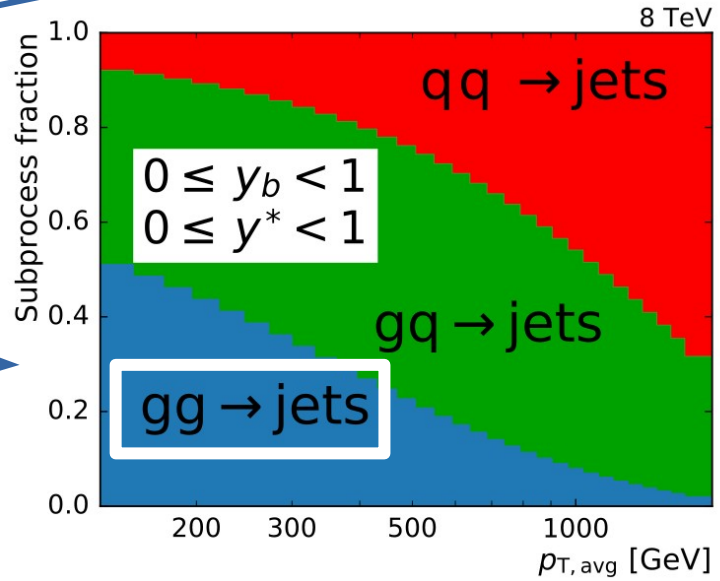
CMS Collaboration, Eur.Phys.J. C77 (2017) no.11, 746 [arXiv:1705.02628]




low-x + high-x

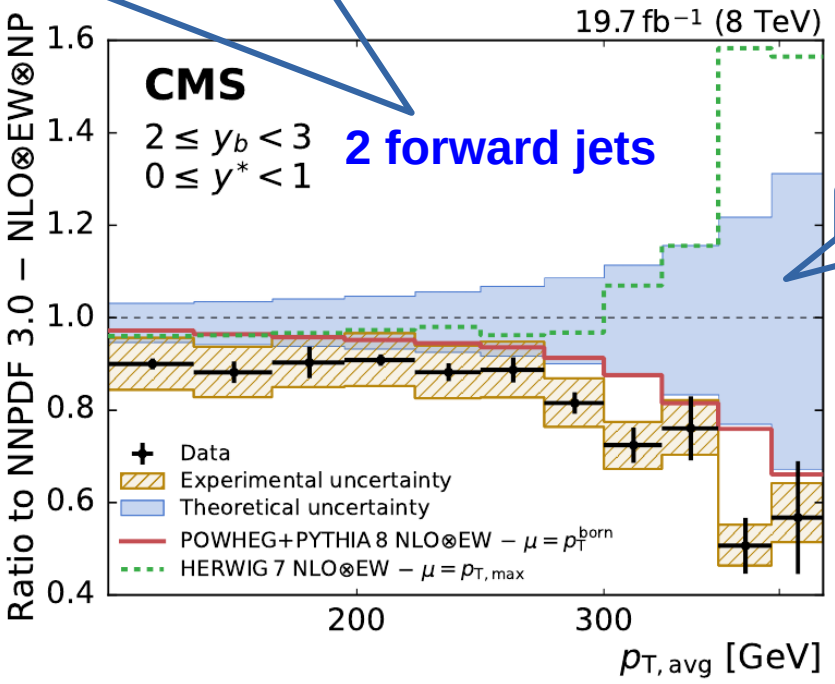


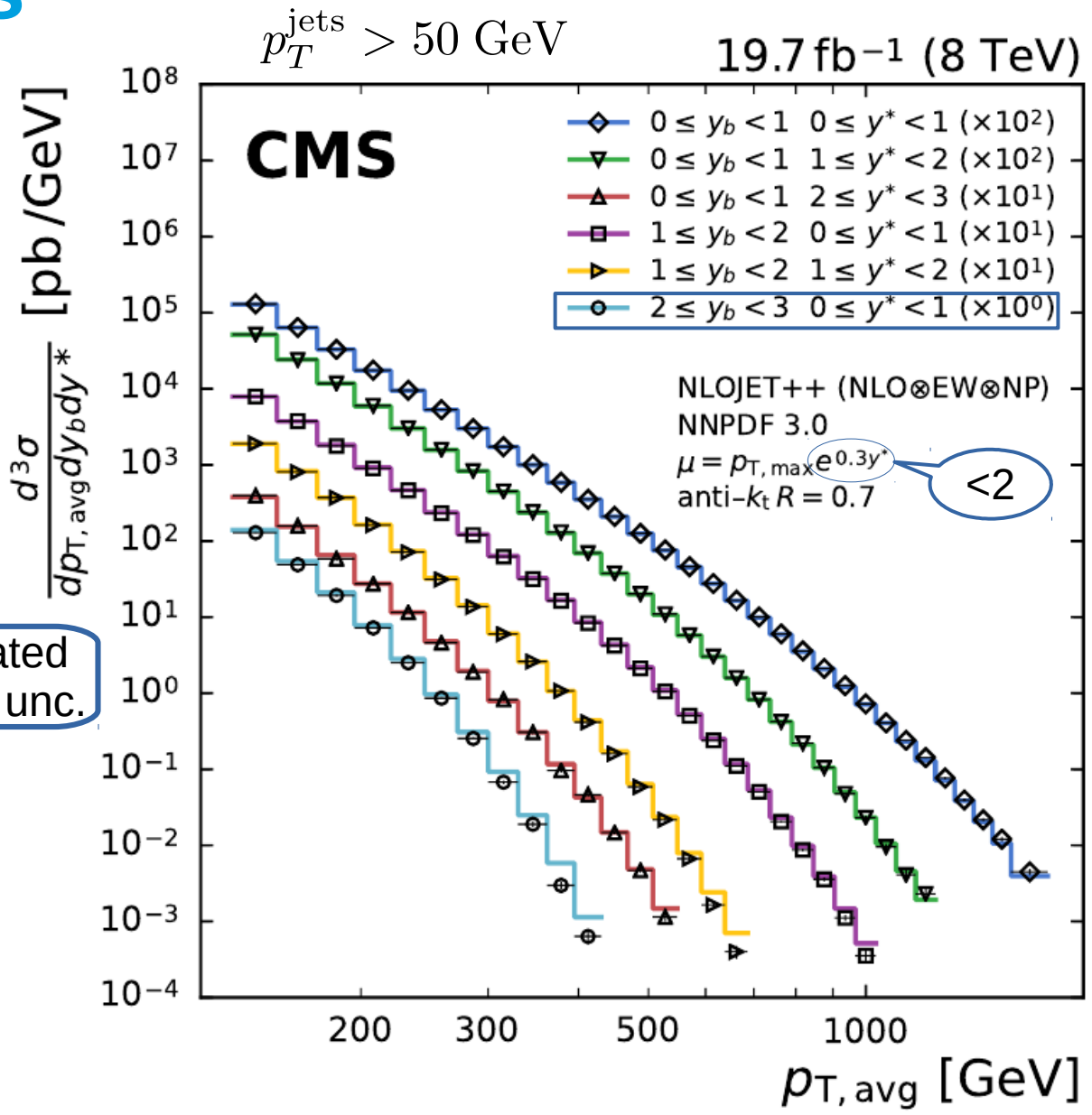
# 3D scan of the dijet events

- The 8 TeV jet data (anti-$k_T$ R=0.7) of lumi 20 $fb^{-1}$

PDF sensitivity
+ PS matching effects.
(POWHEG vs HERWIG7 vs NLOJET++)




dominated by PDF unc.

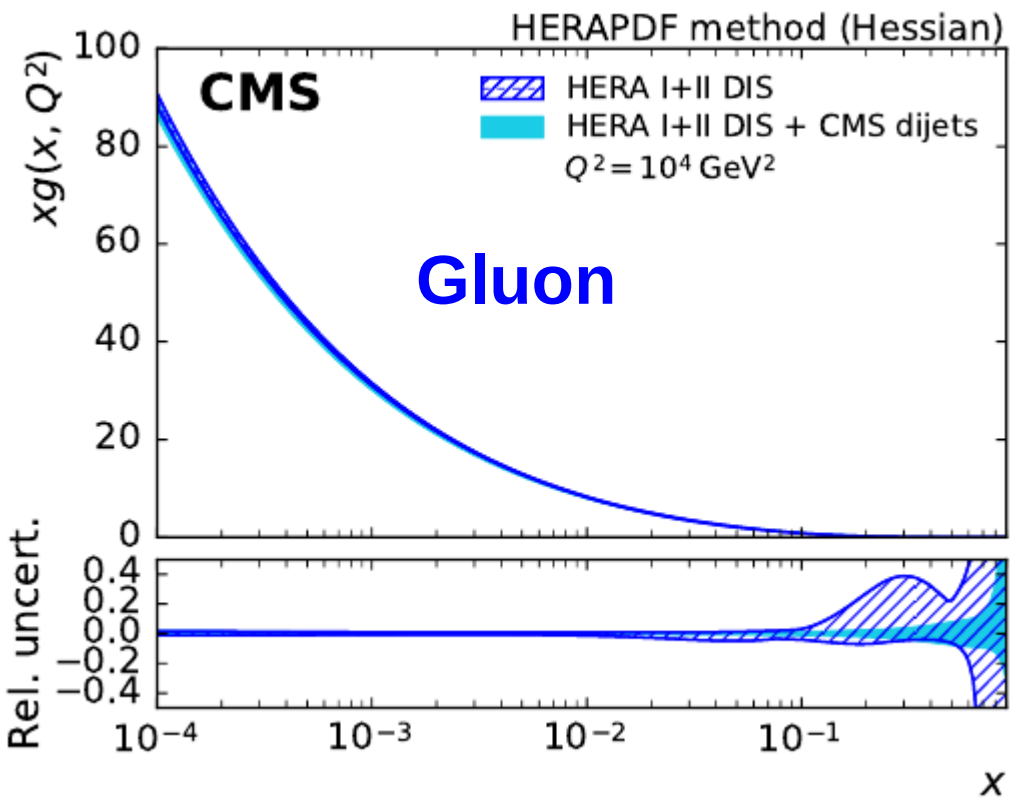


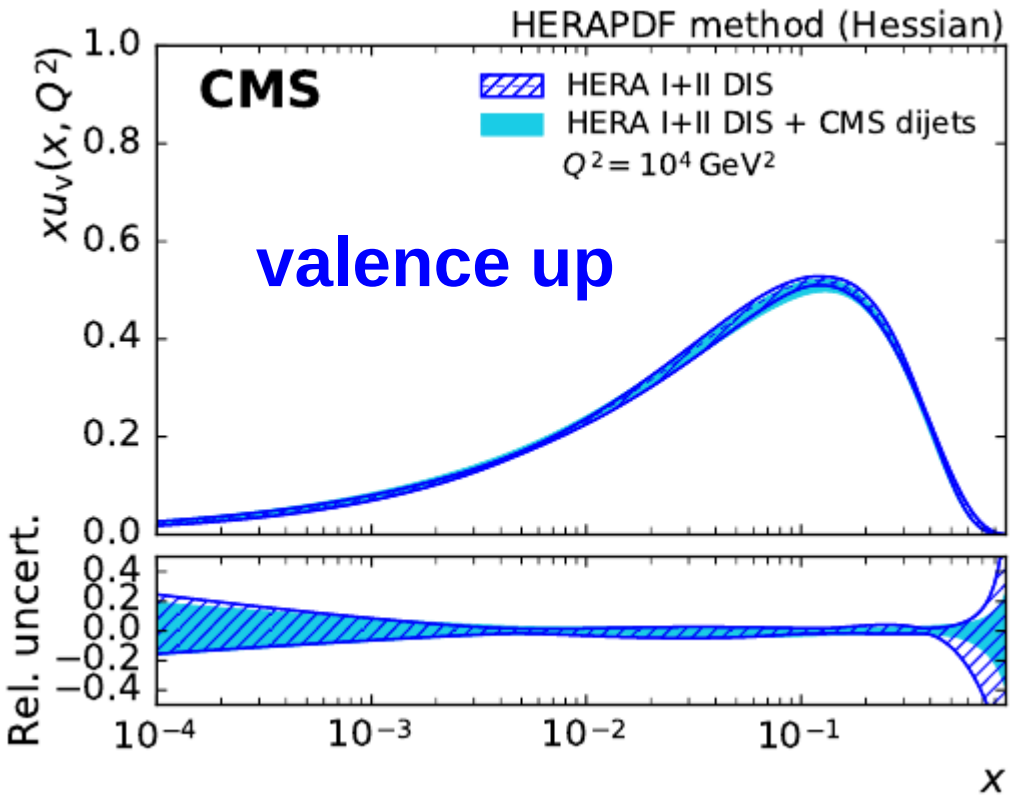
# 3D scan of the dijet events

- A reduction of PDF uncertainty at high-x

- $\alpha_s$ unc. dominated by scale

$$\alpha_S^{\mathrm{NLO}}(M_Z) = 0.120^{+0.004}_{-0.003}$$



# The $R_{32}$ measurement

- The $R_{32}$ is the fraction of dijet events where an extra jet is "emitted"
  → should be ~ $\alpha_s$

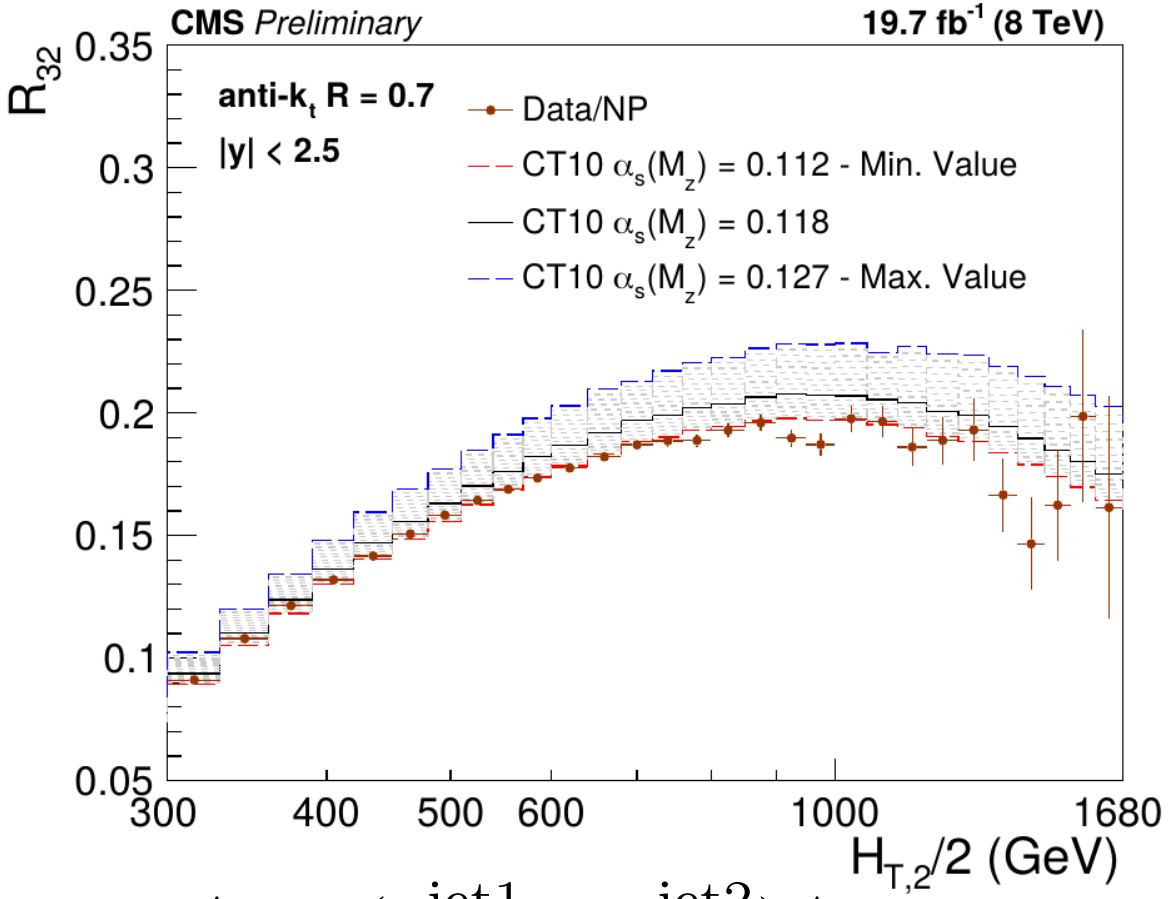
$$R_{32} = \frac{\mathrm{d}\sigma/\mathrm{d}(H_{T,2}/2)|_{N_{\mathrm{jets}}>3}}{\mathrm{d}\sigma/\mathrm{d}(H_{T,2}/2)|_{N_{\mathrm{jets}}>2}}$$

where $p_T^{\mathrm{jet}} > 150\,\mathrm{GeV}$

- Partial cancellation of the exp. & theor. uncertainties in the ratio

- $\alpha_s$ unc. dominated by scale

$$\alpha_S^{\mathrm{NLO}}(M_Z) = 0.115^{+0.005}_{-0.002}$$




$$H_{T,2}/2 = (p_T^{\mathrm{jet1}} + p_T^{\mathrm{jet2}})/2$$

# Jet-based Strong Coupling extractions

- All $\alpha_s$ jet extractions based on 8 TeV data and NLO fixed order predictions
- Uncertainty dominated by the QCD scale
  → NNLO predictions?

| | Energy | Lumi | $\alpha_s(M_Z)$ | exp. unc. | theor. unc. |
|---|---|---|---|---|---|
| Inclusive jets | 8 TeV | 20 $fb^{-1}$ | 0.116 | 0.001 | 0.005 |
| 3D dijets | 8 TeV | 20 $fb^{-1}$ | 0.200 | 0.002 | 0.003 |
| $R_{32}$ | 8 TeV | 20 $fb^{-1}$ | 0.115 | 0.001 | 0.004 |

All $\alpha_s(M_Z)$ values compatible with world average 0.118±0.001

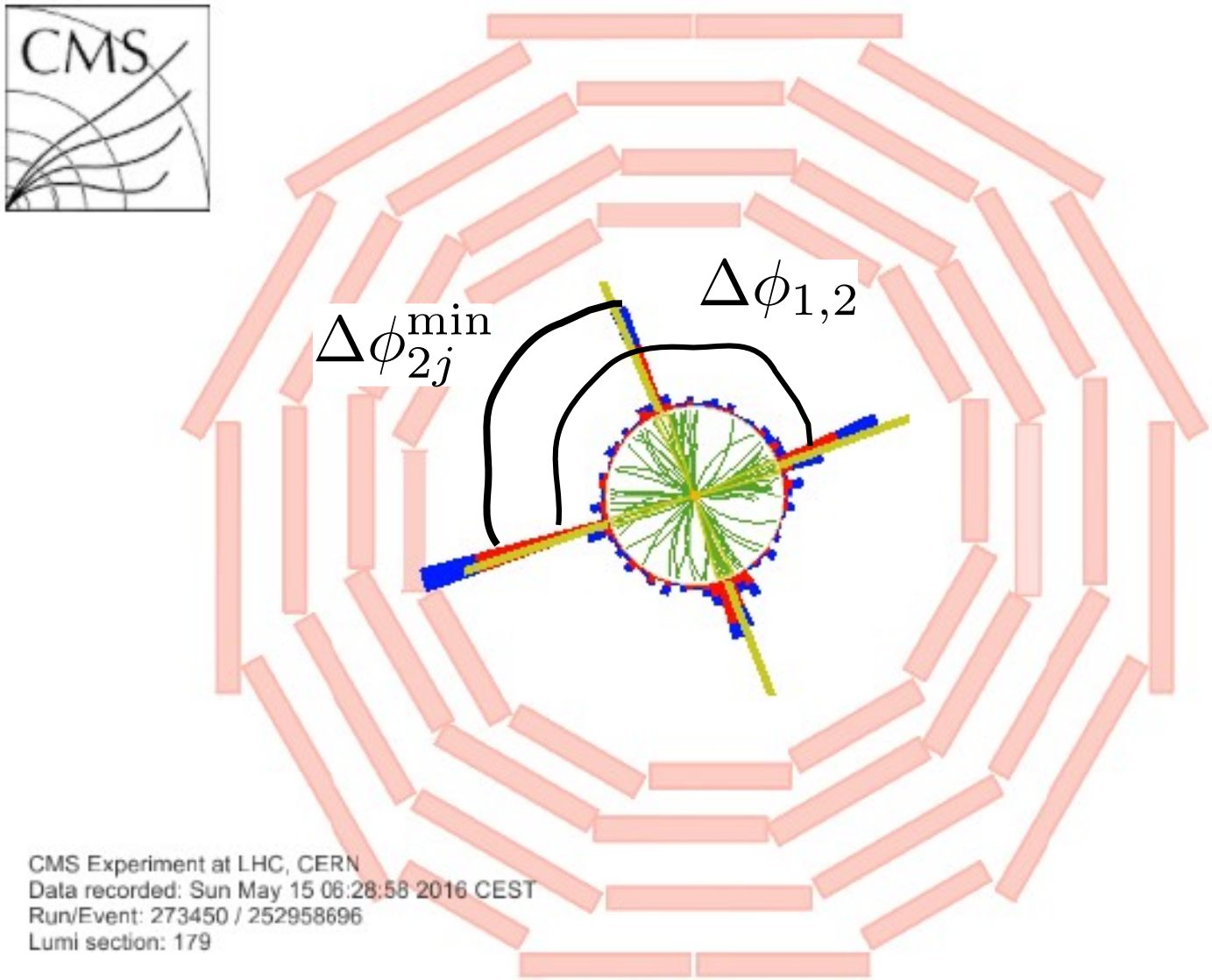
# Azimuthal correlations

- Azimuthal angle between leading and sub-leading jet in $p_T$

$$\Delta\phi_{1,2}$$

- The smallest azimuthal angle between any 2 jets

$$\Delta\phi_{2j}^{\min}$$

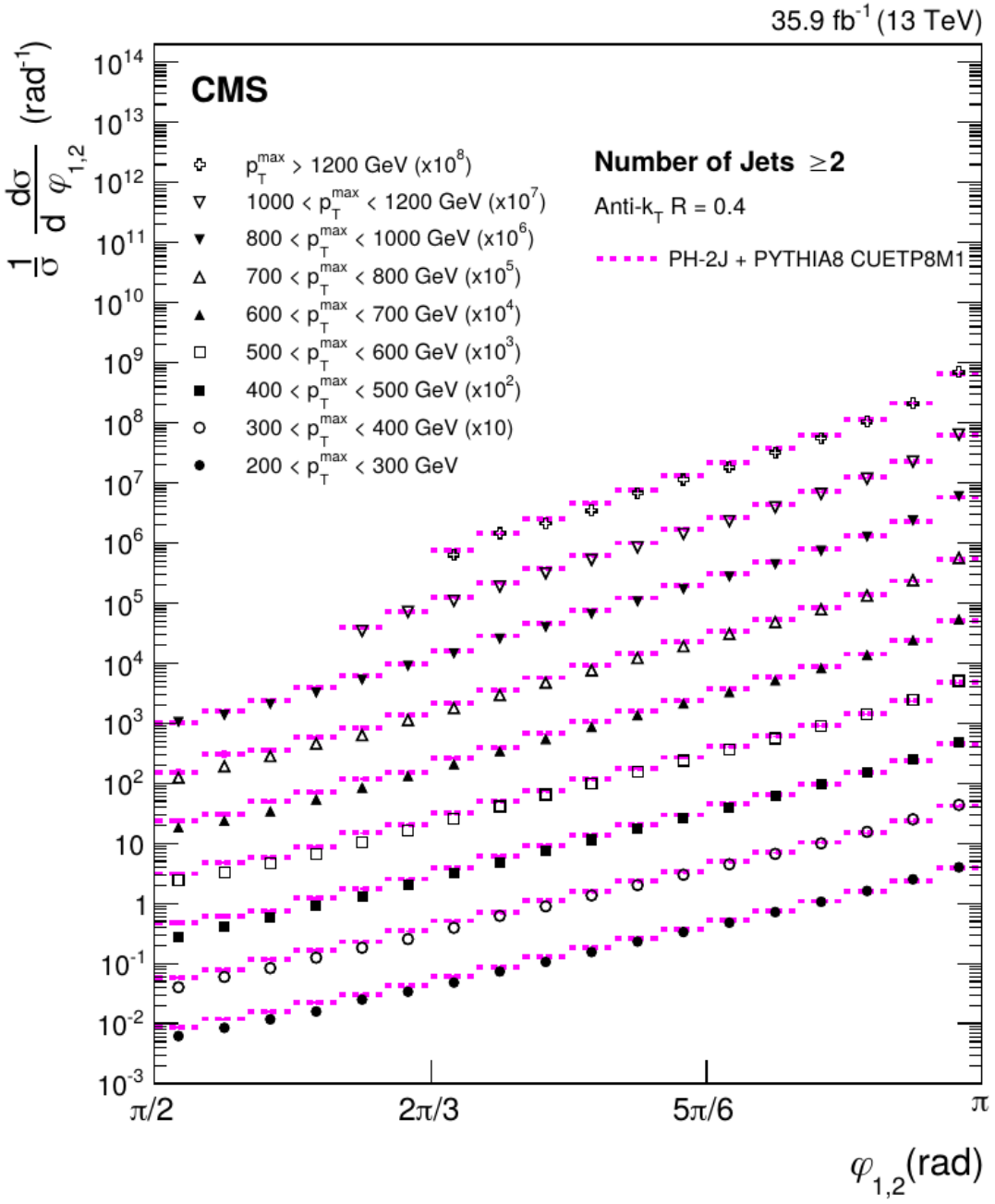


# Azimuthal correlations

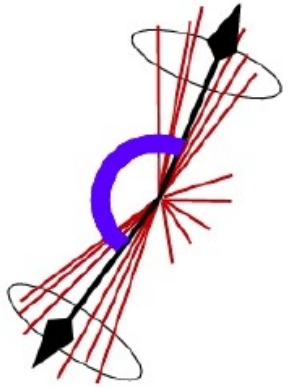
$$\frac{1}{d\sigma_{1,2}}\frac{\sigma_{1,2}}{d\Delta\phi_{1,2}}$$

- For inclusive 2-jet 3-jet and 4-jet events ( $p_T^{\mathrm{jet}} > 100\,\mathrm{GeV}$)
- 13 TeV 2016 data (R=0.4), 36 fb$^{-1}$
- Sensitive to the QCD resummation effects ($\Phi_{1,2}$ ~ 180°), as well as to higher orders & multi-leg ME (lower $\Phi_{1,2}$)

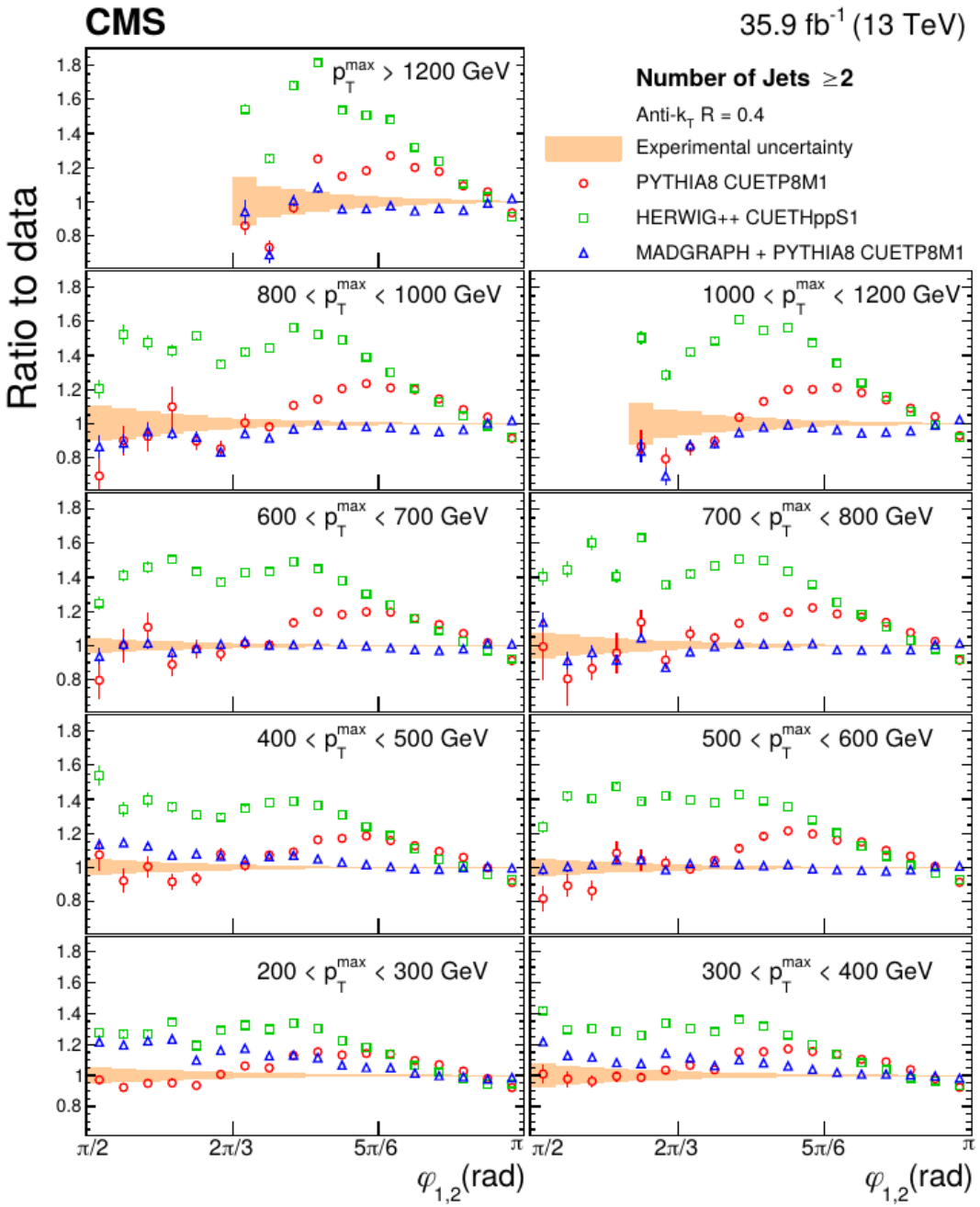
CMS Collaboration, Eur.Phys.J. C78 (2018) no.7, 566 [arXiv:1712.05471]



# Azimuthal correlations (>= 2 Jets vs LO)

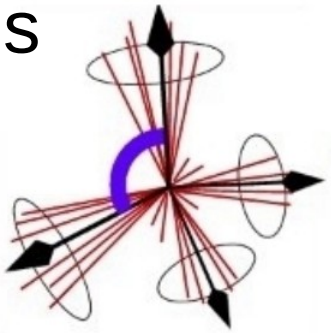


- Best description by **MadGraph + Pythia8** (CUETP8M1)
  up to 4 jets in ME, MLM matching
- **Pythia8** & **Herwig++** have both "flatter" spectrum than in data for $\Phi_{1,2} \sim \pi$
- At smaller dphi **Pythia8** agrees better than **Herwig++**

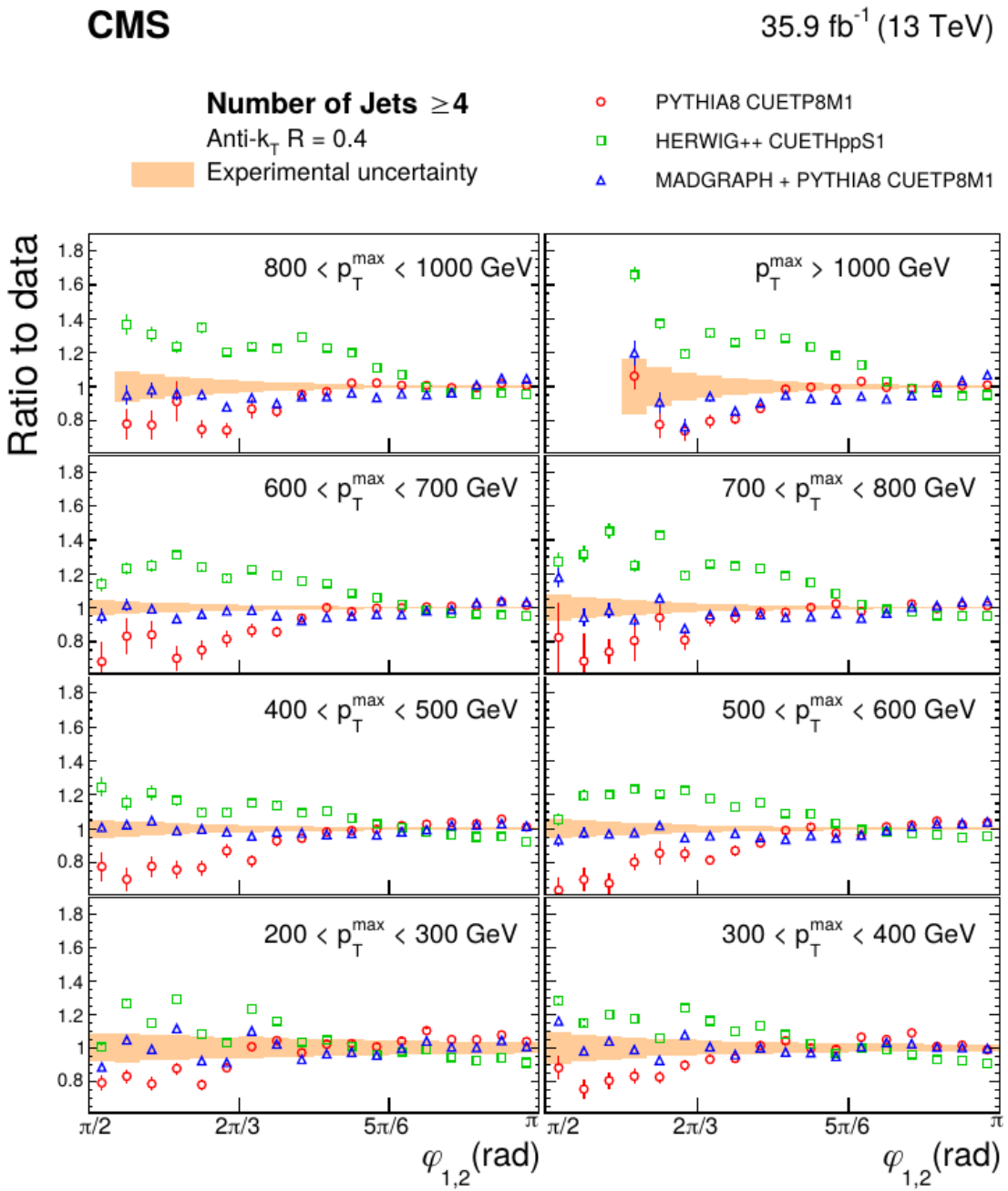


# Azimuthal correlations (>= 4 Jets vs LO)

- Best description again by **Madgraph + Pythia8** (CUETP8M1), where ME itself contains topologies $\Phi_{1,2} > 90°$

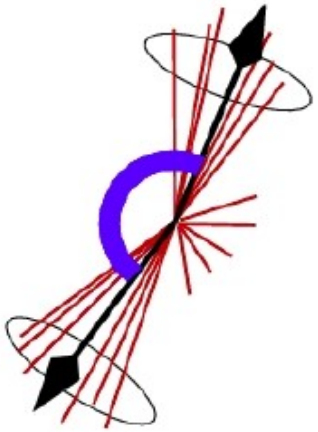


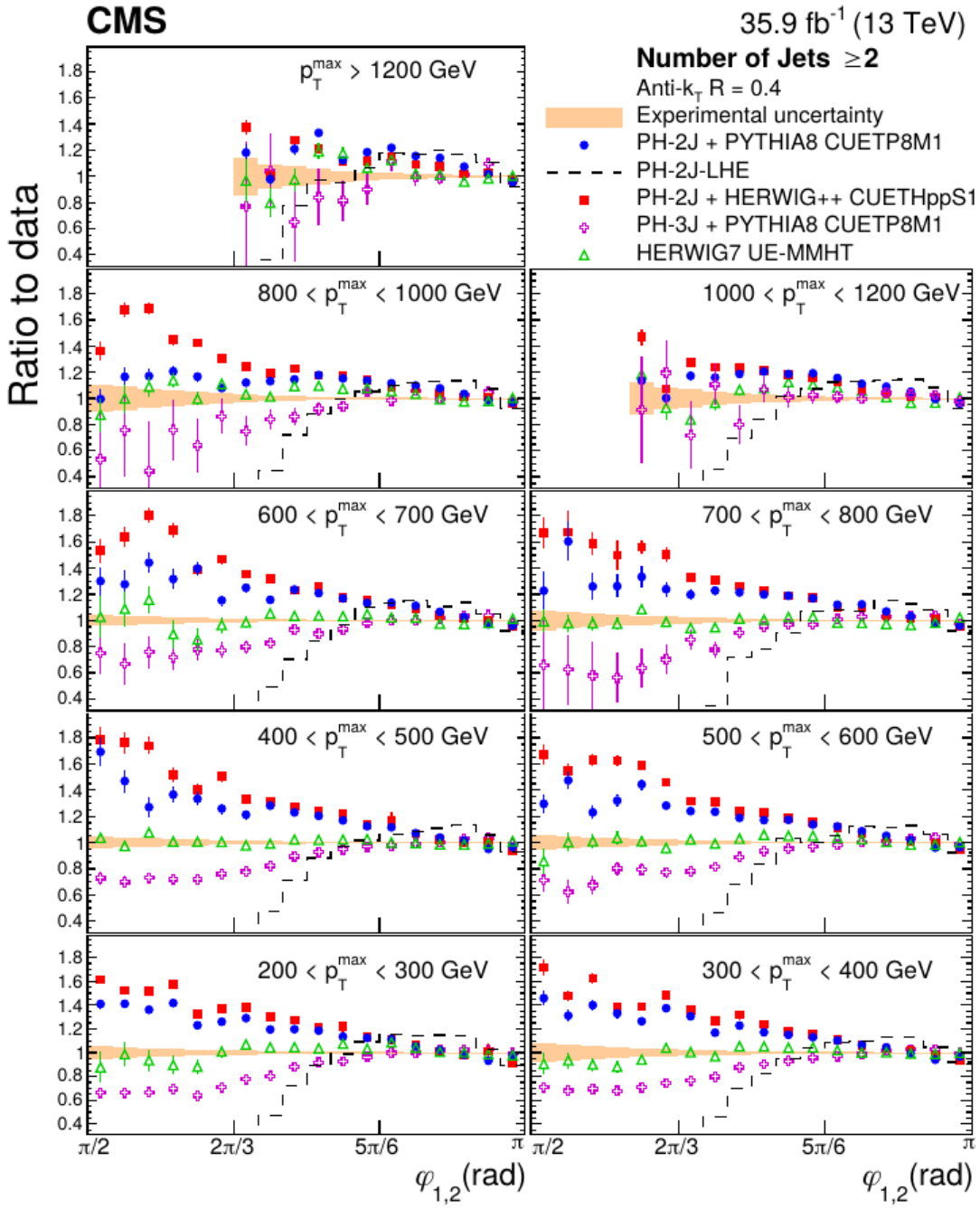
- **Pythia8** (**Heriwig++**) sightly below (above) data



# Azimuthal correlations (>= 2 Jets vs NLO)

- **HERWIG7 NLO** (MC@NLO like matching) provides the best description
- **Powheg-2J + Herwig++** performs significantly worse

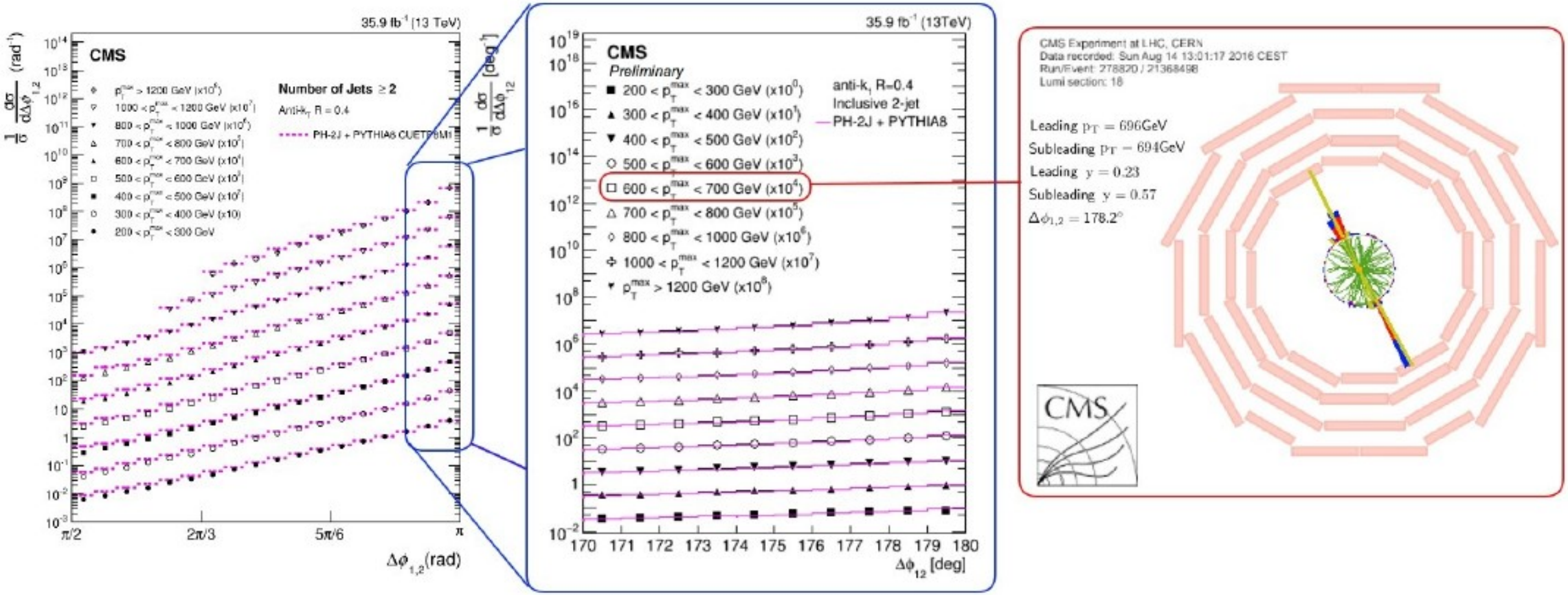




# Azimuthal correlations in back-to-back region

CMS Collaboration, SMP-17-009
[arXiv:1902.04374]

$170° < \Phi_{1,2} < 180°$

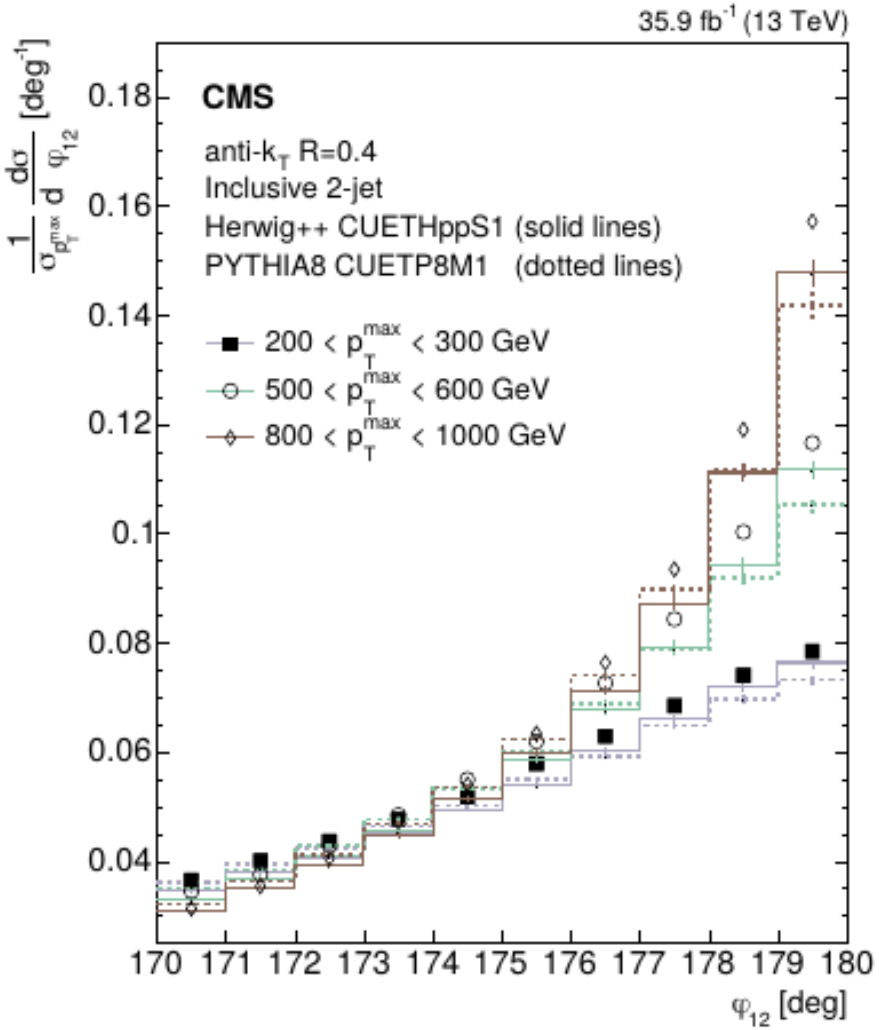


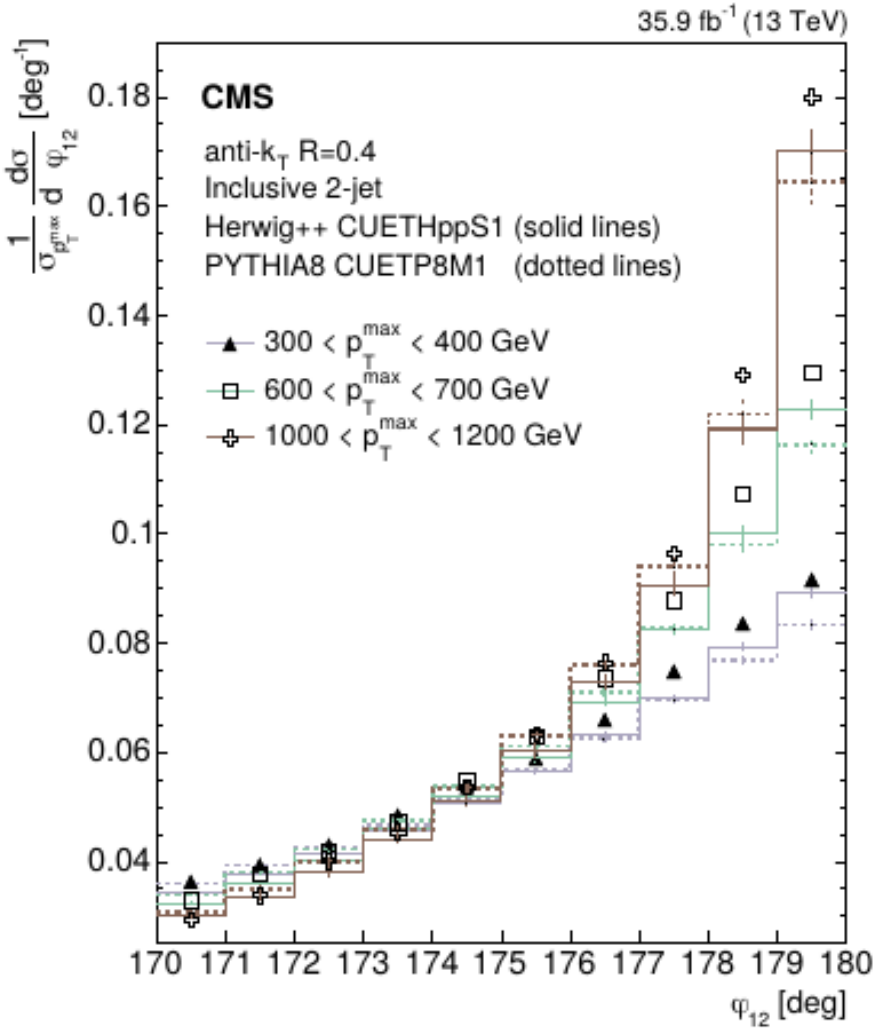
# Azimuthal correlations in back-to-back region

$$p_T^{\text{jet}} > 100\,\text{GeV}$$

$$170° < \Phi_{1,2} < 180°$$

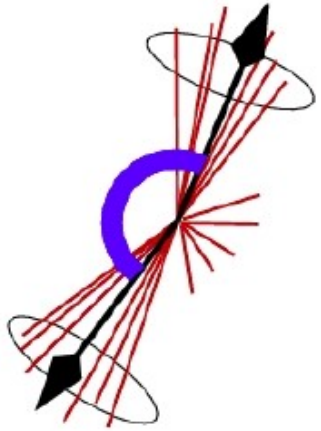
- The normalized spectra for various $p_T$ ranges differ mostly in the back-to-back region
- Higher $p_T$ enhances $\Phi_{1,2} \sim \pi$

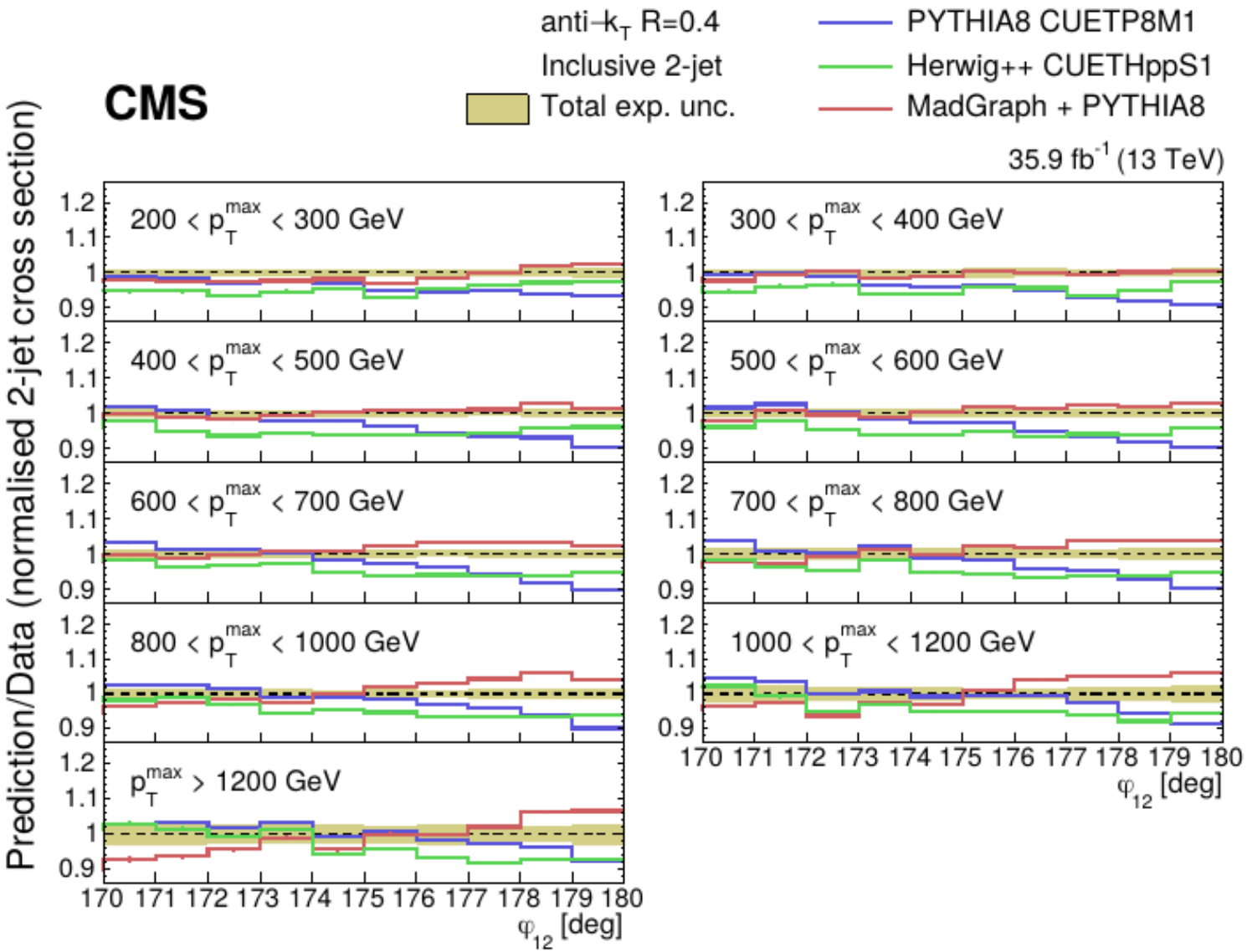


# Azimuthal correlations (>= 2 Jets vs LO)

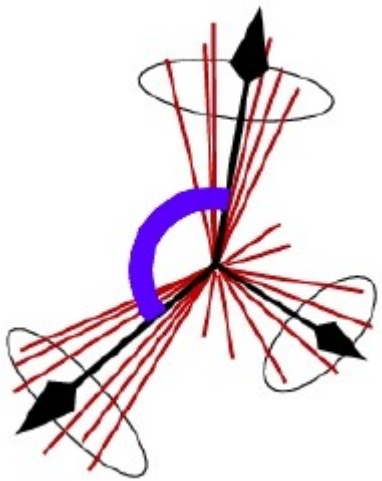
- **Best** description by **MadGraph + Pythia8** (CUETP8M1) up to 4 jets in ME, MLM matching
- **Pythia8** not steep enough

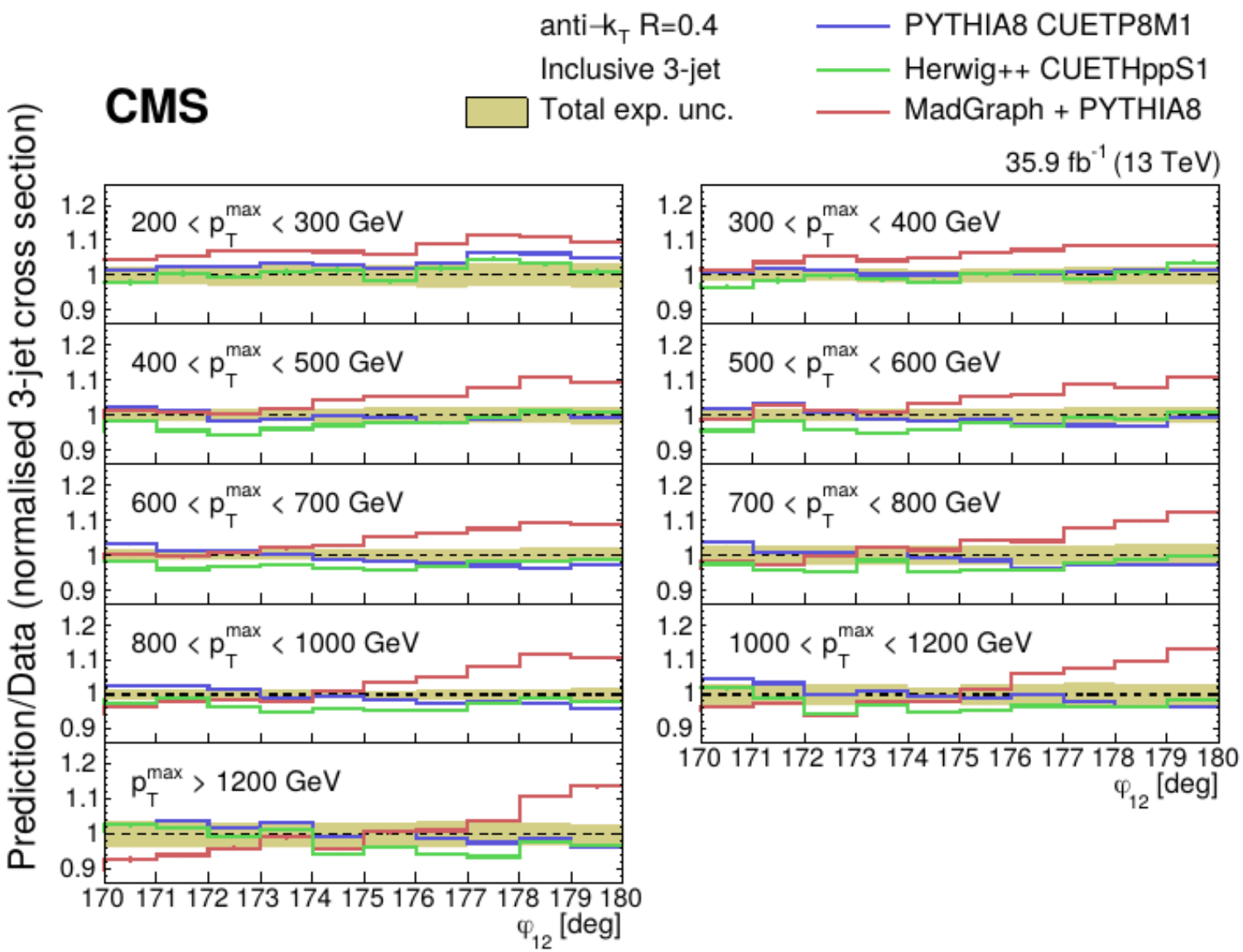




# Azimuthal correlations (>= 3 Jets vs LO)

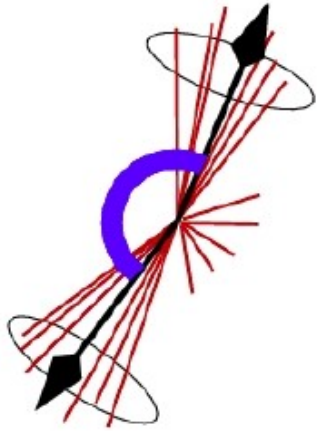
- **The worst** description by **MadGraph + Pythia8** (CUETP8M1)
  up to 4 jets in ME, MLM matching

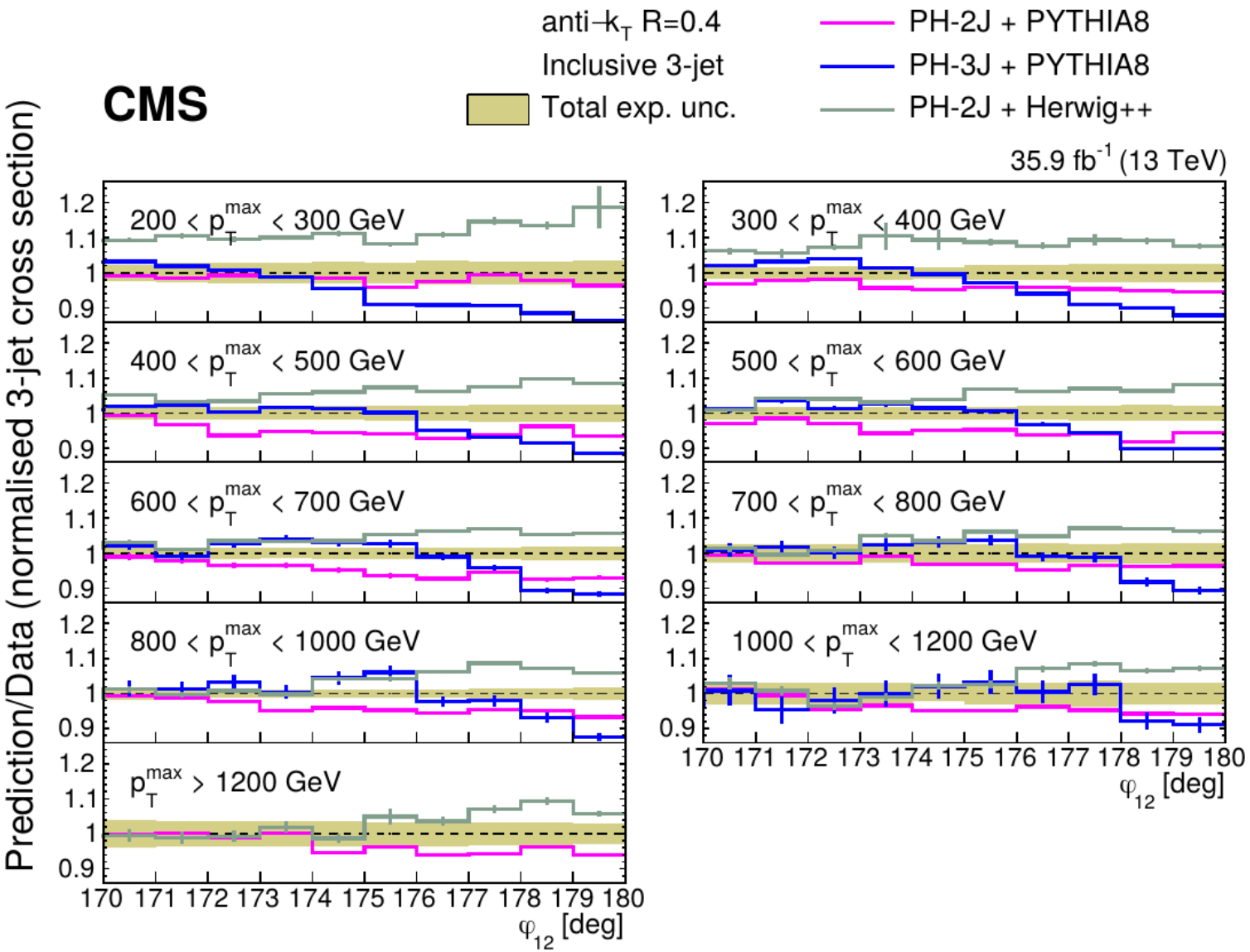




# Azimuthal correlations (>= 3 Jets vs NLO)

- **Worst** description by **POWHEG-3J+Pythia8** (CUETP8M1)
- **POWHEG-2J** performs better for 3-jet topologies!





# Conclusions

- Inclusive jet measurements at 8 and 13 TeV
  → Scan of $\alpha_S$ running up to the TeV-scale
  → Reduction of PDF unc. at high-x & scales
- Triple differential jet x-section & $R_{32}$ measurement
  → Enhance $\alpha_S$ + PDF sensitivity by going more differential
  (but lower statistics)
- Azimuthal correlations between leading jets
  → Testing PS & ME matching
  e.g. MC@NLO (Hg7) found to perform better than POWHEG

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/JETS.html