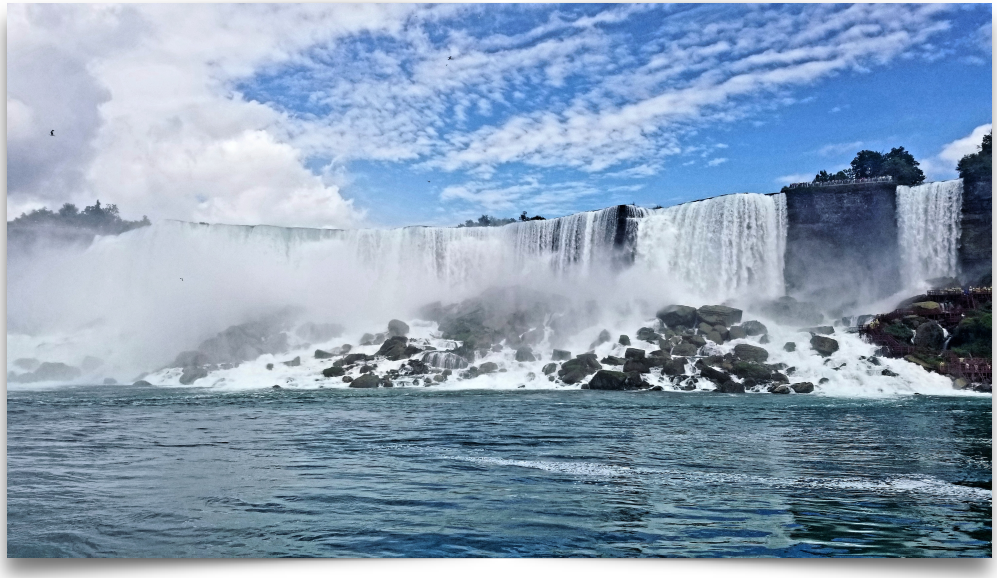
MEASURING JETS AT THE LHC

Christine McLean,
on behalf of the CMS and ATLAS collaborations

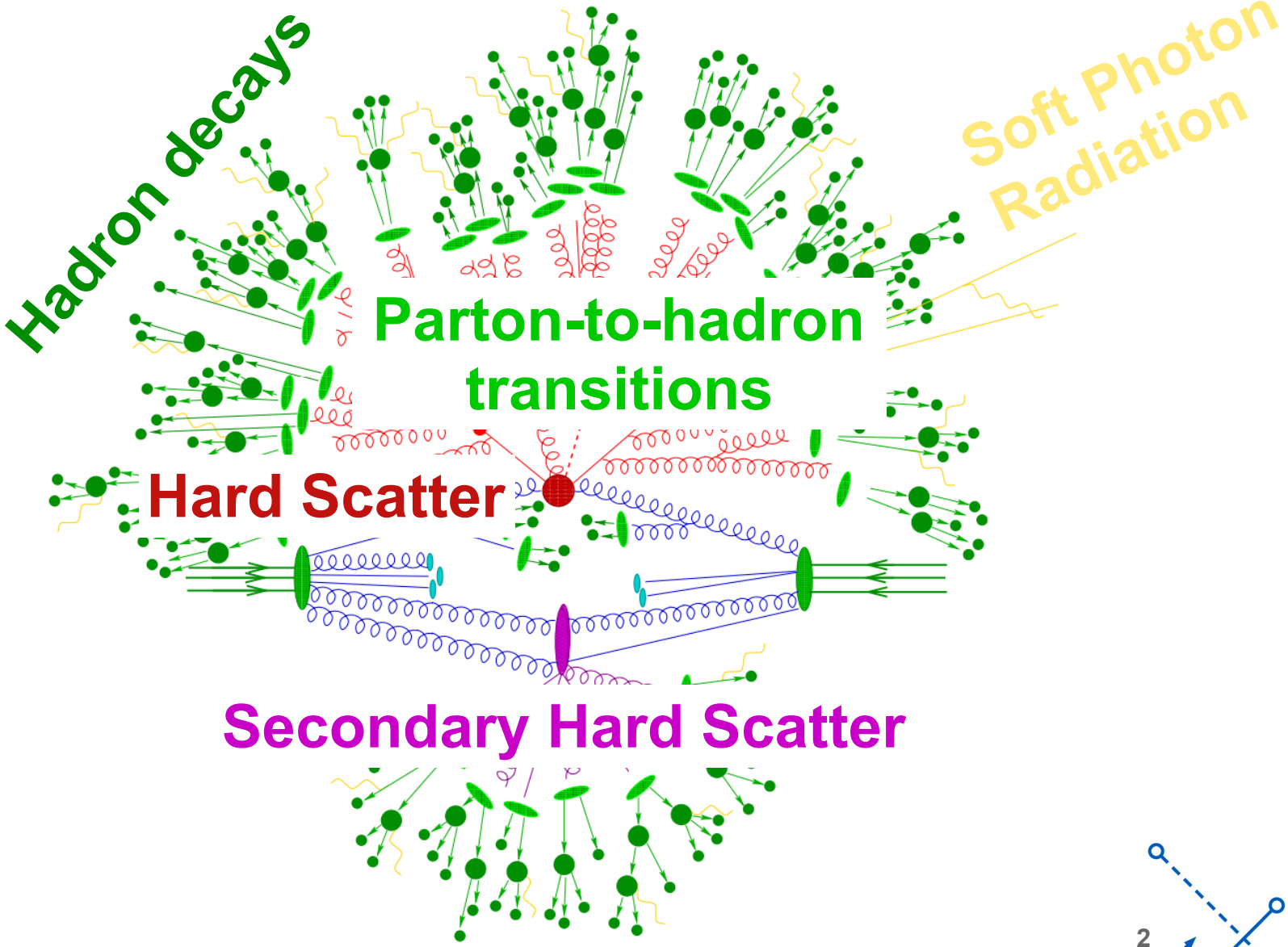
QCD@LHC 2019
July 19, 2019



University at Buffalo The State University of New York

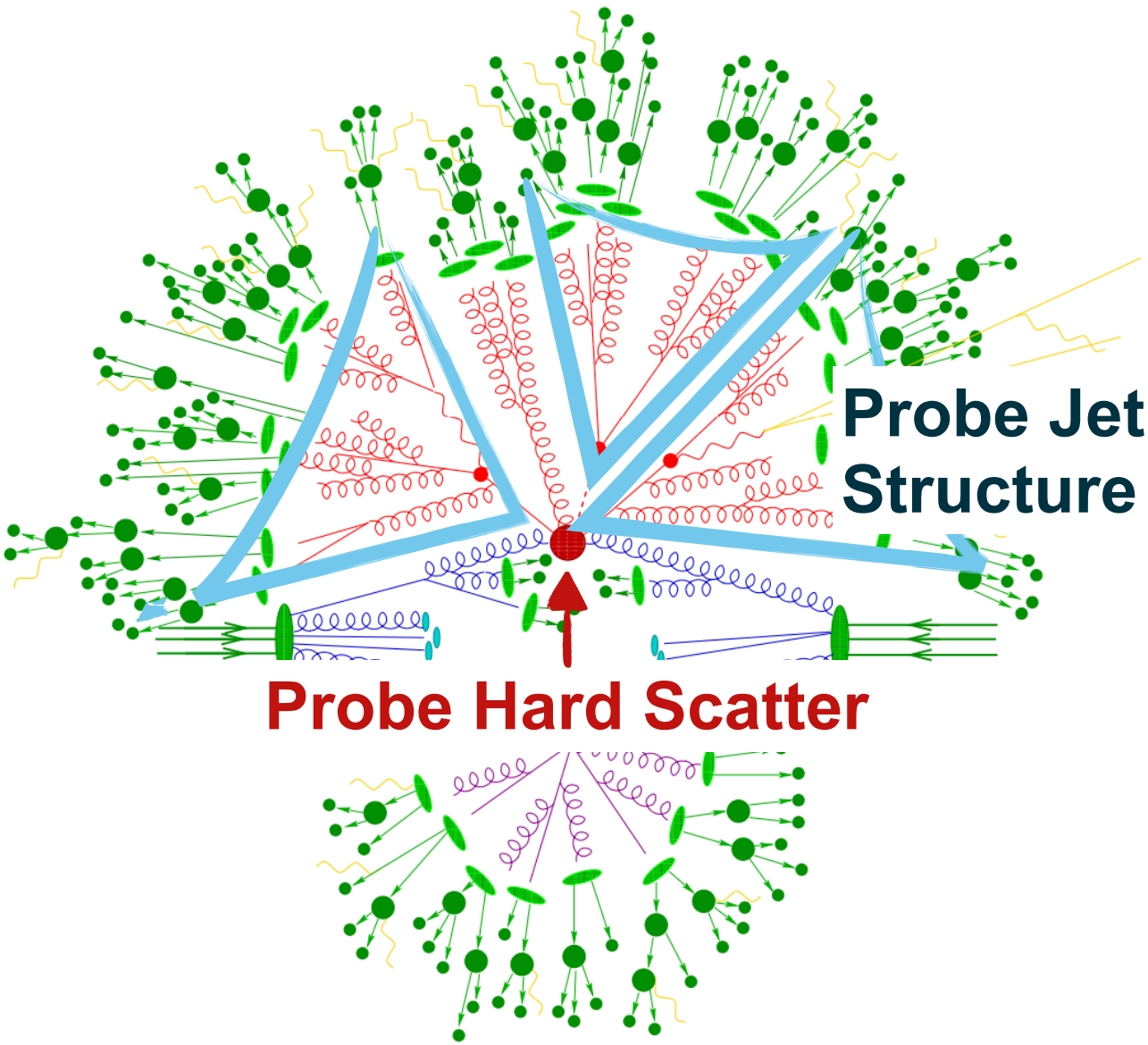
QCD

1411.4085

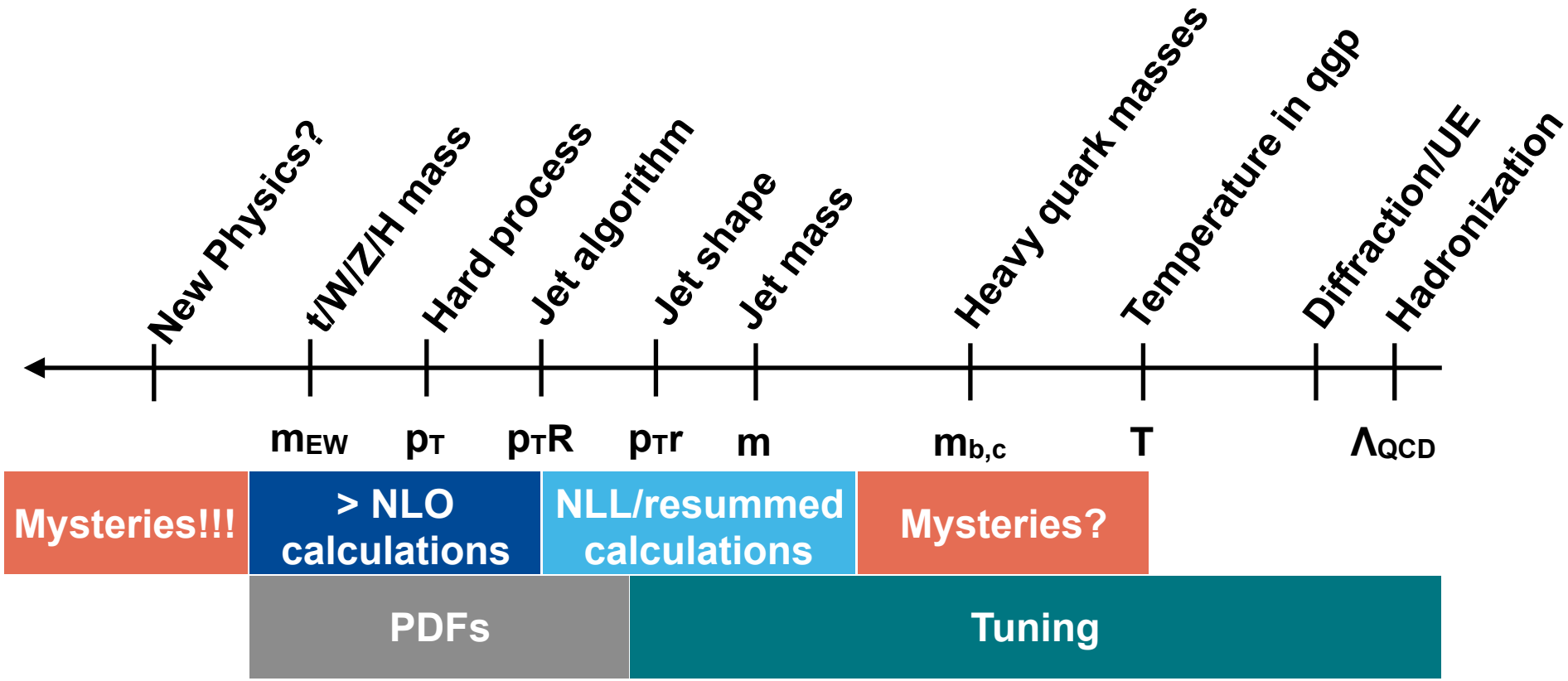


This Talk: Jets

1411.4085



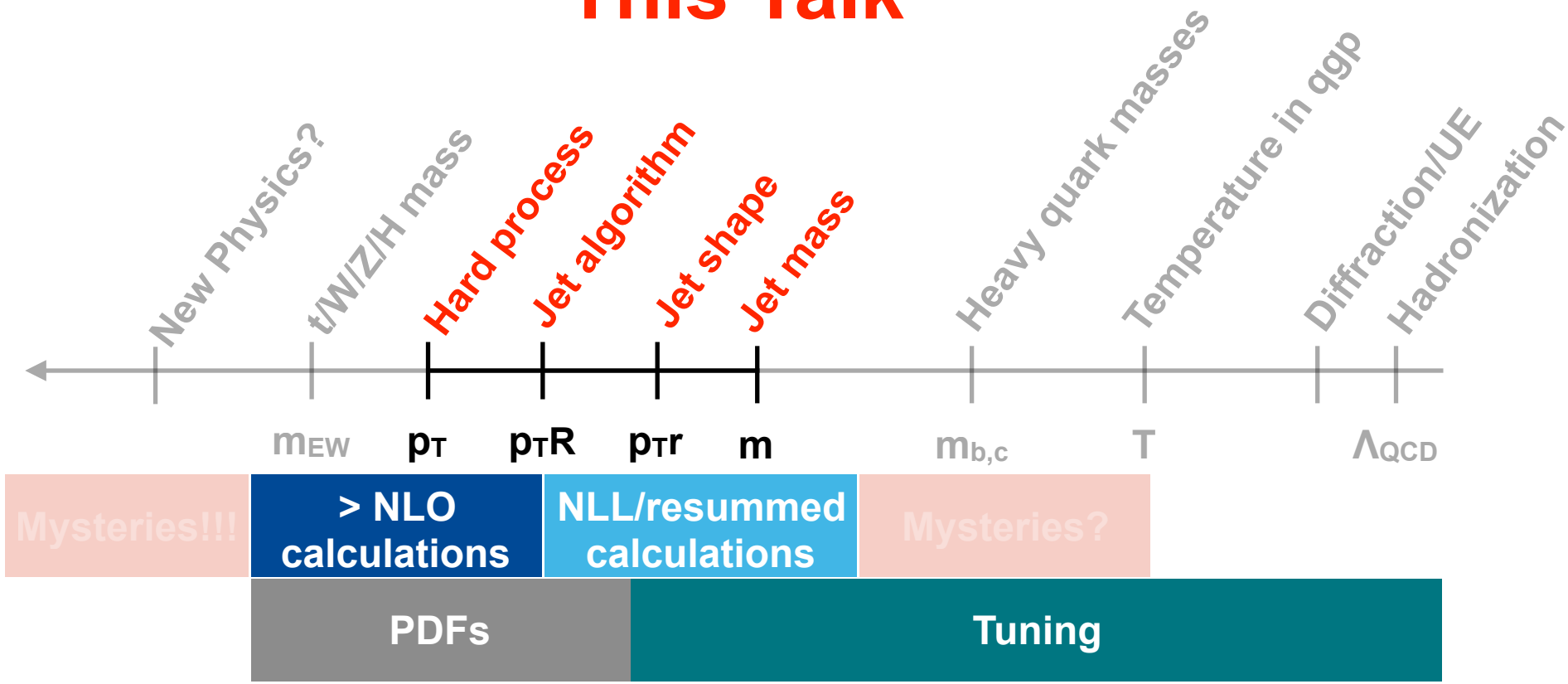
QCD@LHC



H/T Y.-T. Chien, S. Rappoccio

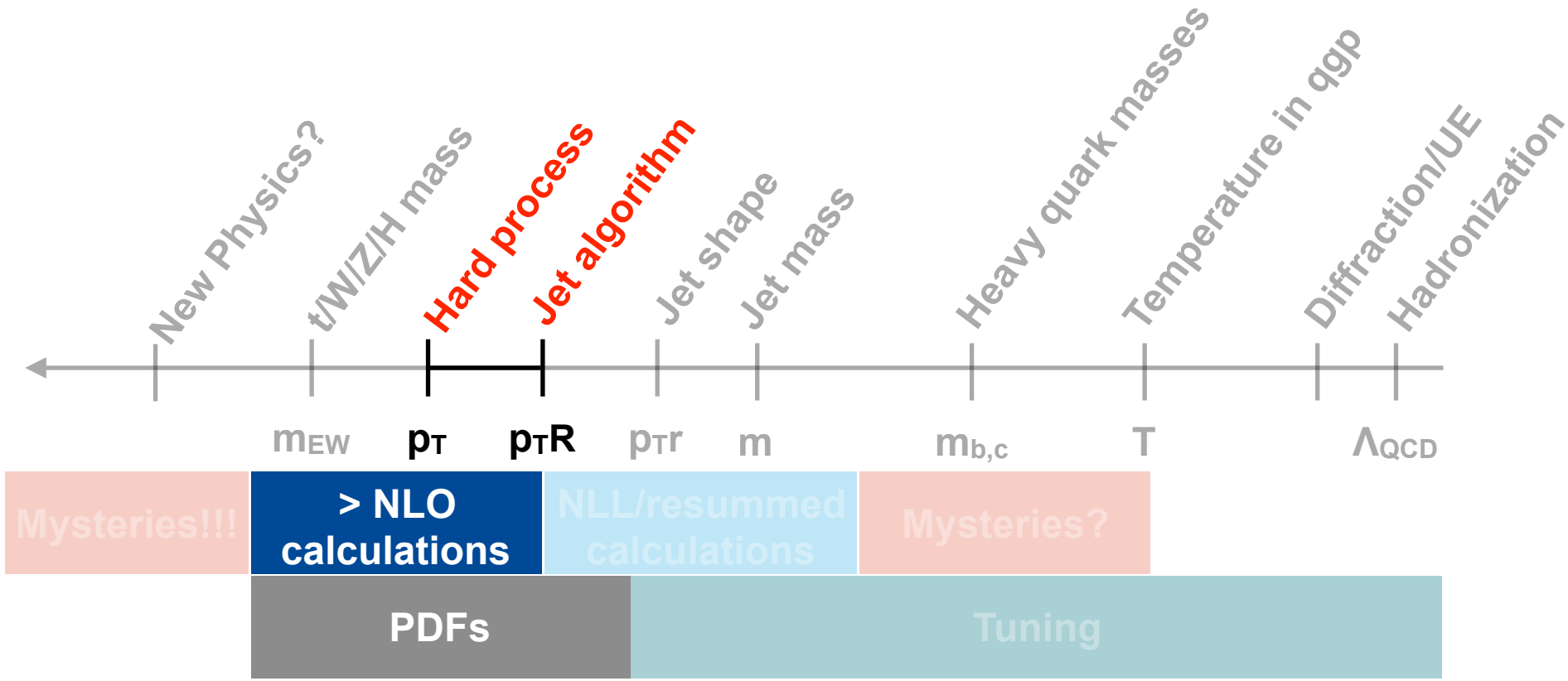
Jet Measurements at the LHC

This Talk



Caveat: not covering γ+jets, V+jets, top quark measurements

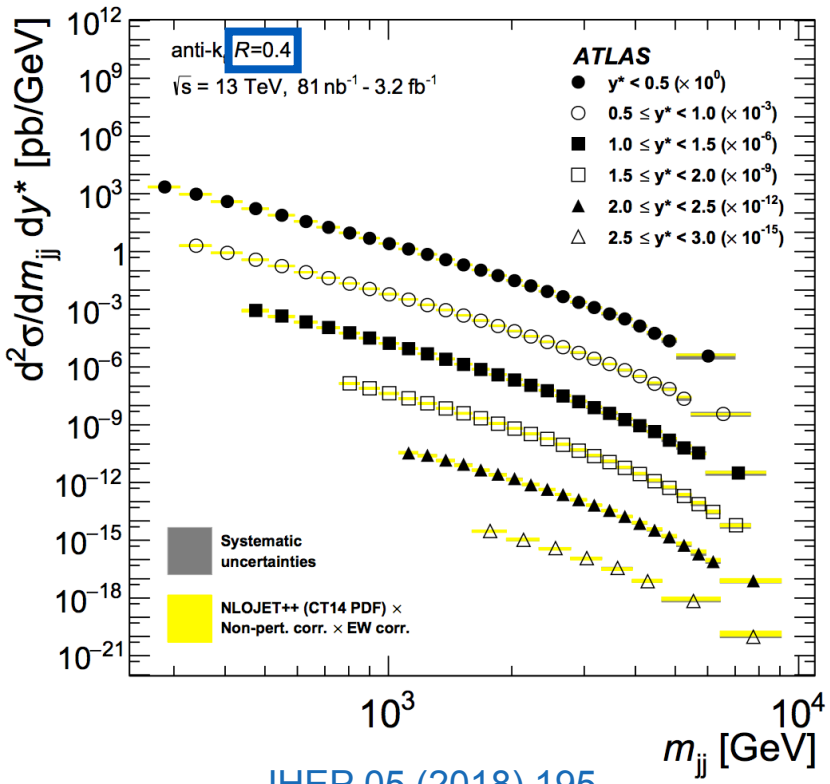
Jet Production Cross Sections



Dijet Cross Section

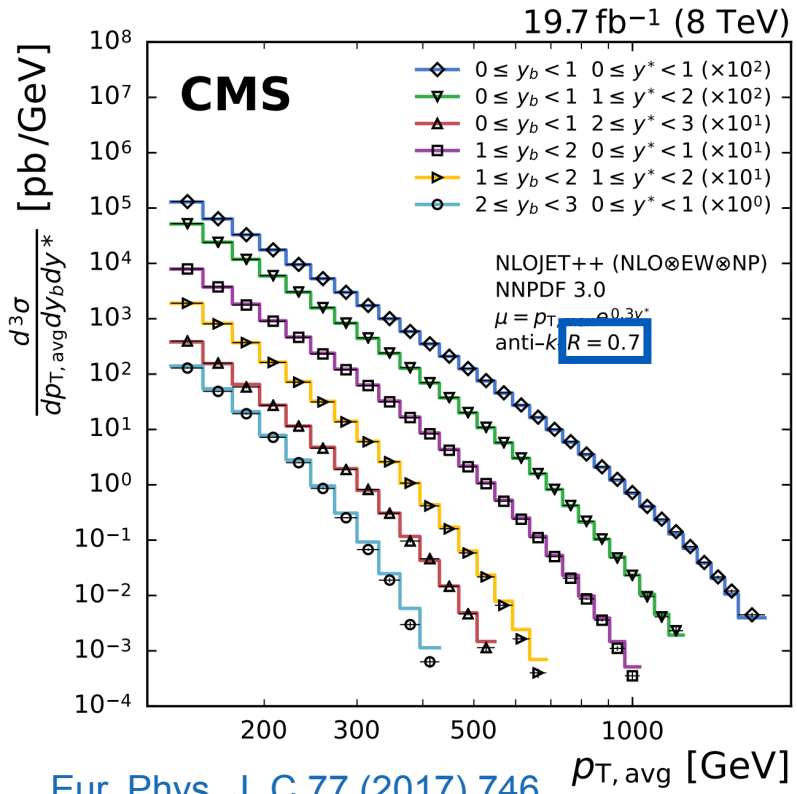
Test predictions of pQCD at high energy

ATLAS: 13 TeV double differential xs



JHEP 05 (2018) 195

CMS: 8 TeV triple differential xs



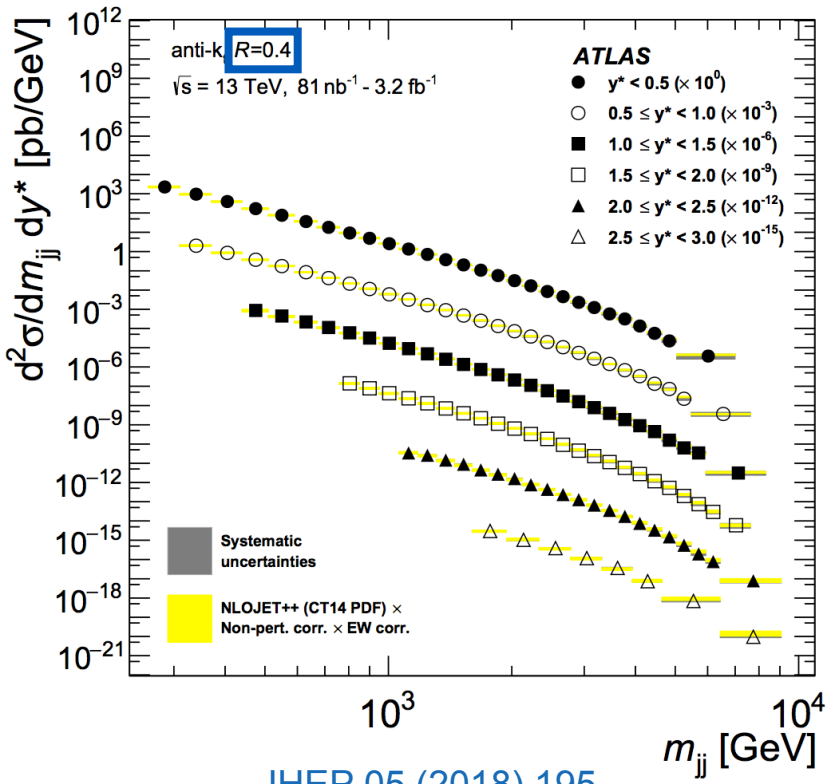
Eur. Phys. J. C 77 (2017) 746

$y^* = |y_1 - y_2|/2$ $\quad p_{T,avg} = (p_{T,1} + p_{T,2})/2$ $\quad y_b = |y_1 + y_2|/2$

Dijet Cross Section

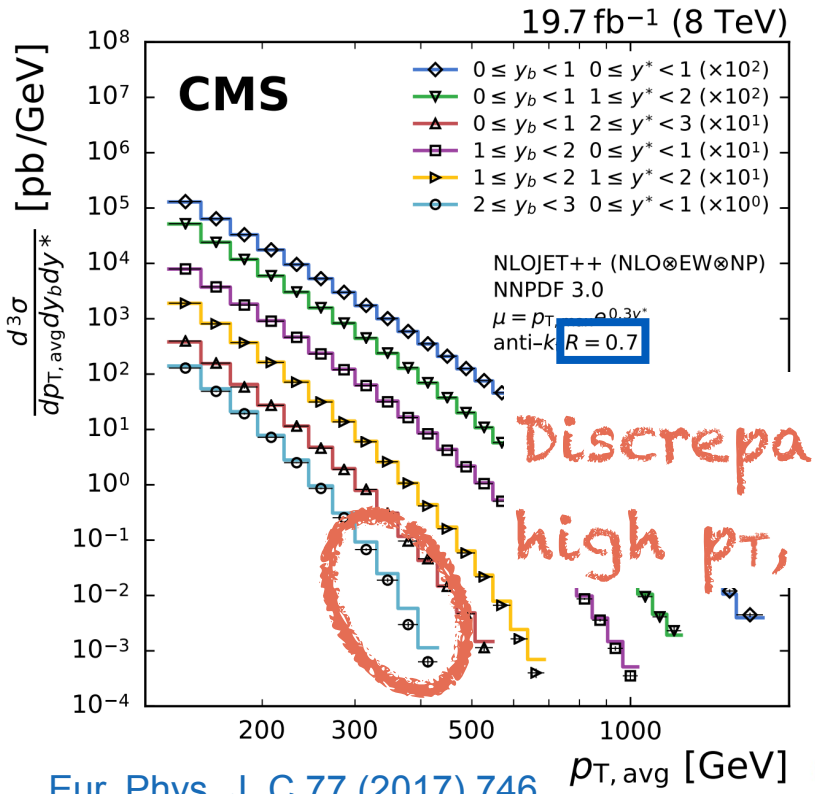
Test predictions of pQCD at high energy

ATLAS: 13 TeV double differential xs



JHEP 05 (2018) 195

CMS: 8 TeV triple differential xs



Discrepancy at high p_T, boost

Eur. Phys. J. C 77 (2017) 746

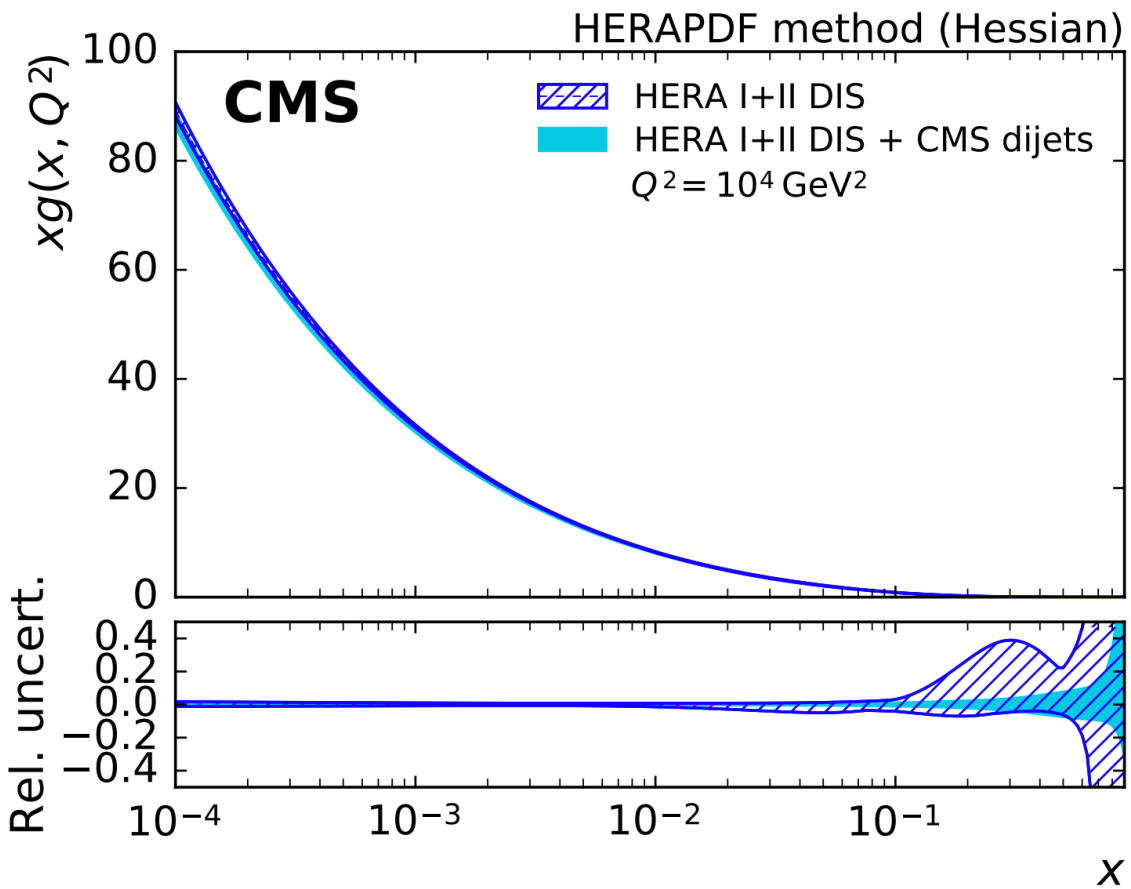
$y^* = |y_1 - y_2|/2$ $\quad p_{T,avg} = (p_{T,1} + p_{T,2})/2$ $\quad y_b = |y_1 + y_2|/2$

Dijet Cross Section

Eur. Phys. J. C 77 (2017) 746

Constrain PDFs, measure α_S

See talks by J. Pekkanen, S. Pflitsch, P. Starovoitov

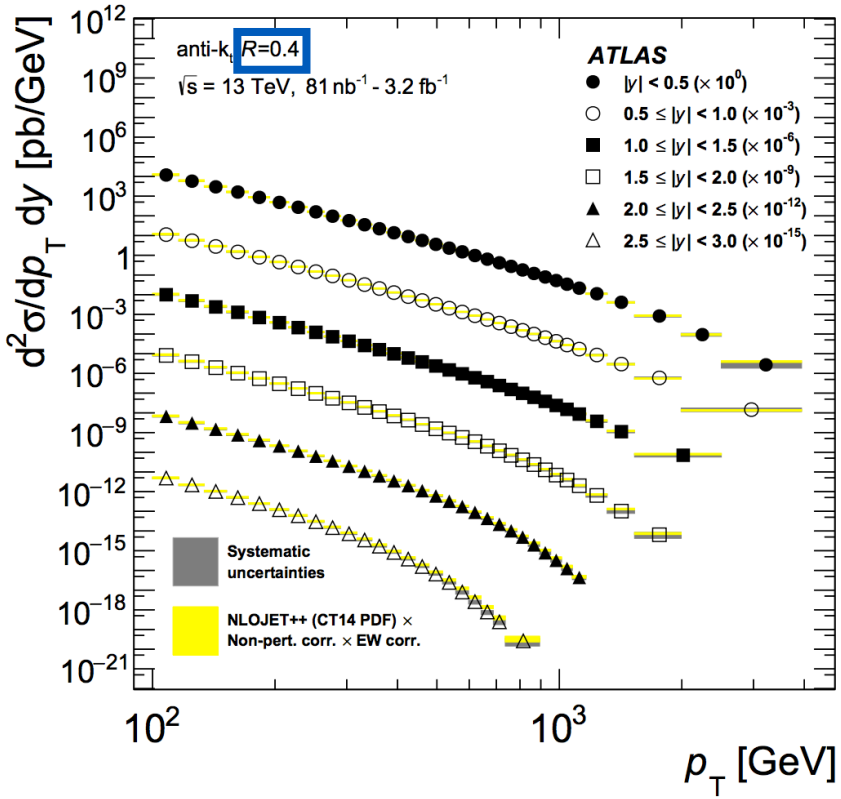


CMS dijet data reduces gluon PDF uncertainty at high x

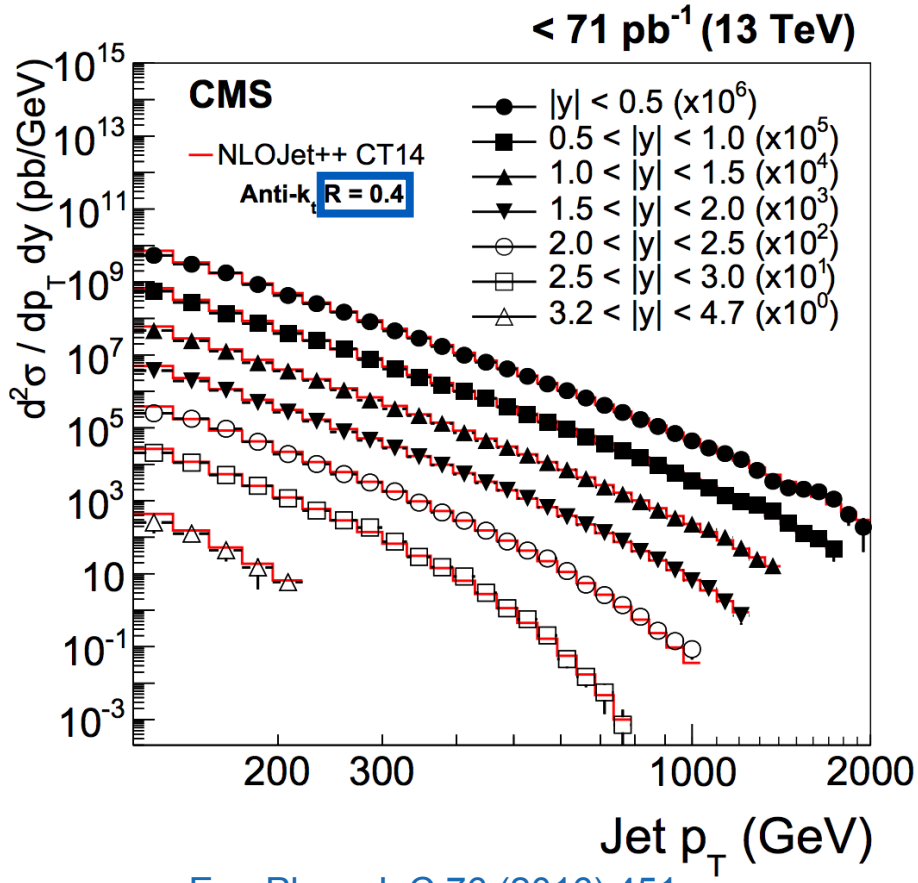
$$\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp})\,^{+0.0031}_{-0.0020}\,(\text{theo})$$

Inclusive Jet Cross Section

ATLAS, CMS: 13 TeV double differential xs



JHEP 05 (2018) 195



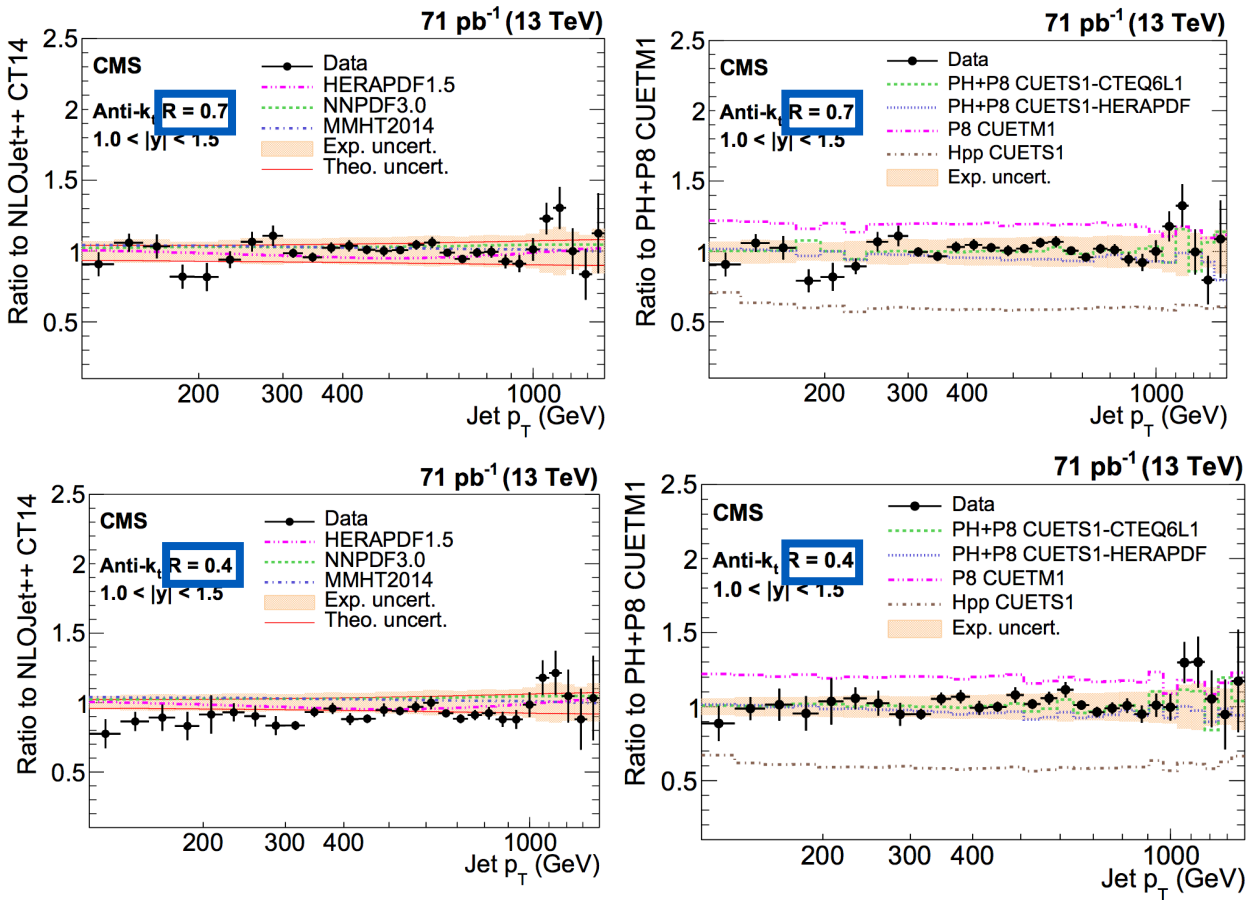
Eur. Phys. J. C 76 (2016) 451

Data/prediction appear to agree relatively well

Eur. Phys. J. C 76 (2016) 451

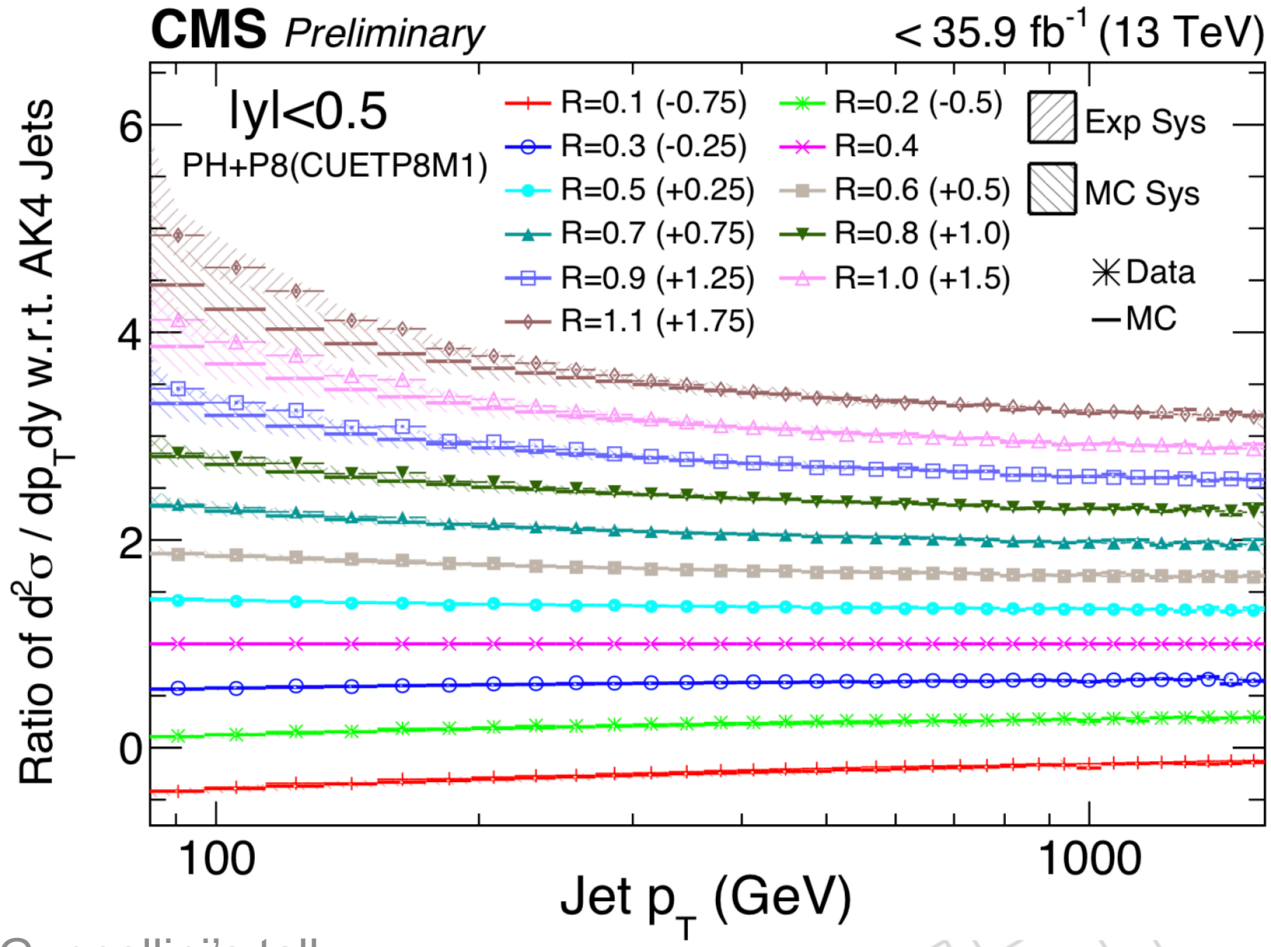
Inclusive Jet Cross Section

- **Closer look at CMS results**
  - Fixed-order NLO predictions + NP, EW corrections (NLOJet++)
    - Overestimates R=0.4 due to missing PS, soft-gluon resummation contributions
  - NLO predictions matched to parton showers (PH+P8) more effective overall



Radius Scan

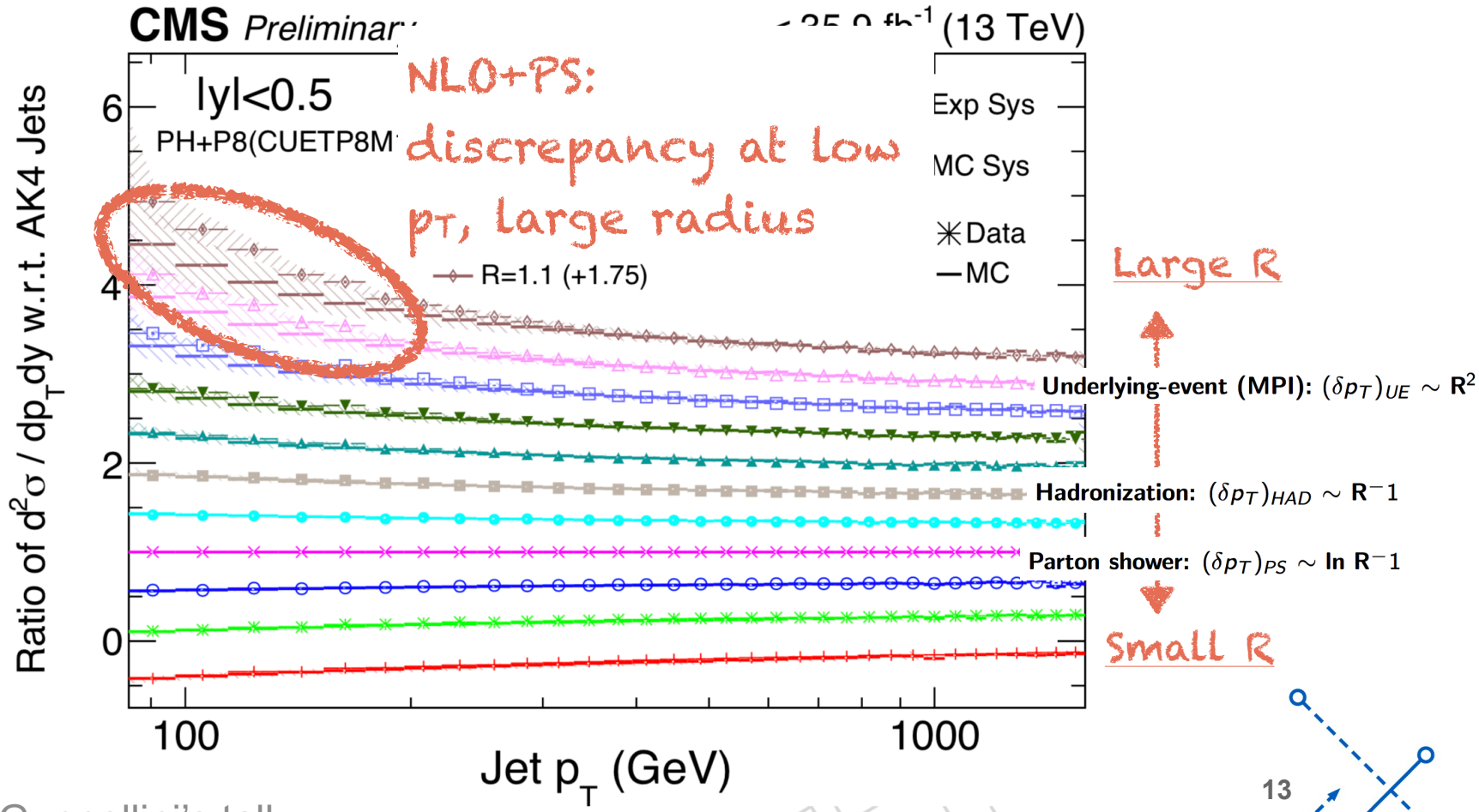
Test dependence of jet production xs on anti-k_T distance parameter



See P. Gunnellini's talk

Radius Scan

Test dependence of jet production xs on anti-k_T distance parameter



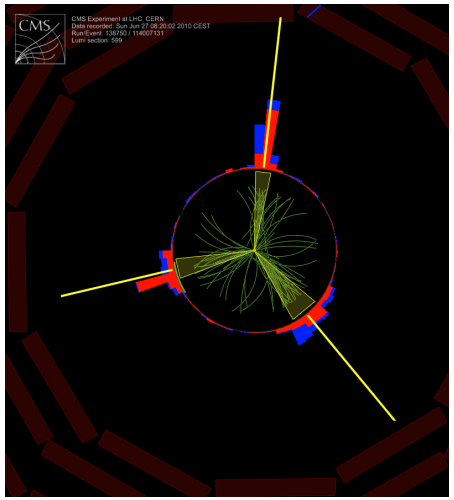
See P. Gunnellini's talk

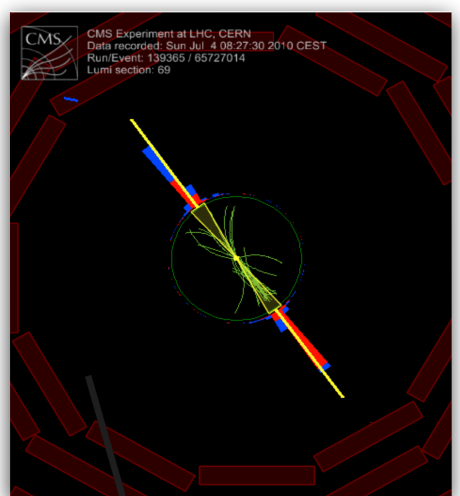
JHEP 12 (2018) 117

Event Shape Variables

ESVs sensitive to flow of energy in hadronic states

$\tau_\perp$





Transverse thrust

$$T_\perp \equiv \max_{\hat{n}_\mathrm{T}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_\mathrm{T}|}{\sum_i p_{\mathrm{T},i}}$$

Complement to $T_\perp$

$$\tau_\perp \equiv 1 - T_\perp$$

sensitive to hard-scattering

Jet mass

$$\rho_\mathrm{X} \equiv \frac{M_\mathrm{X}^2}{P^2}$$

Sensitive to hadronization, NP effects

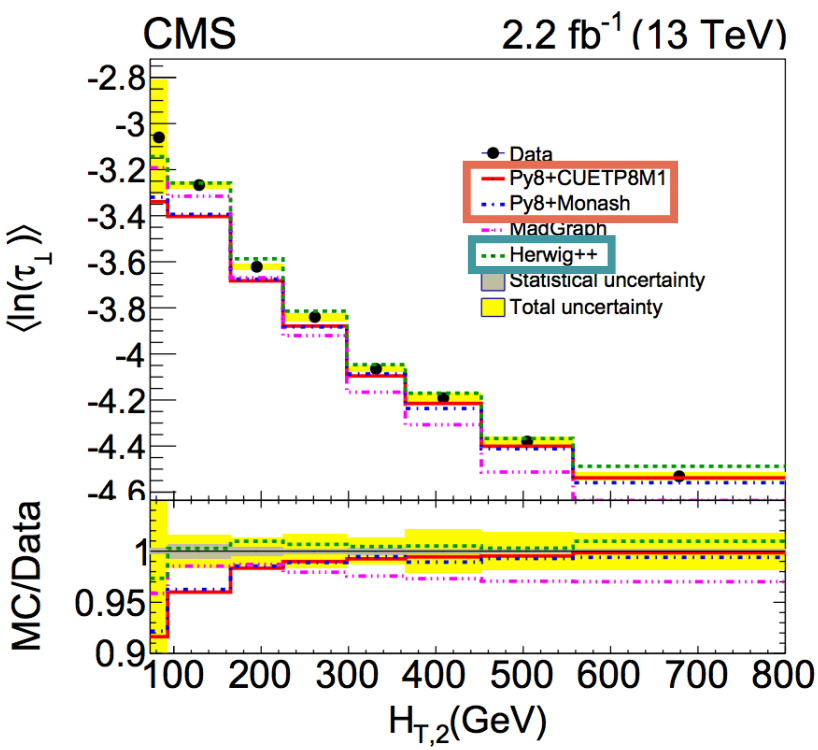
Jet broadening

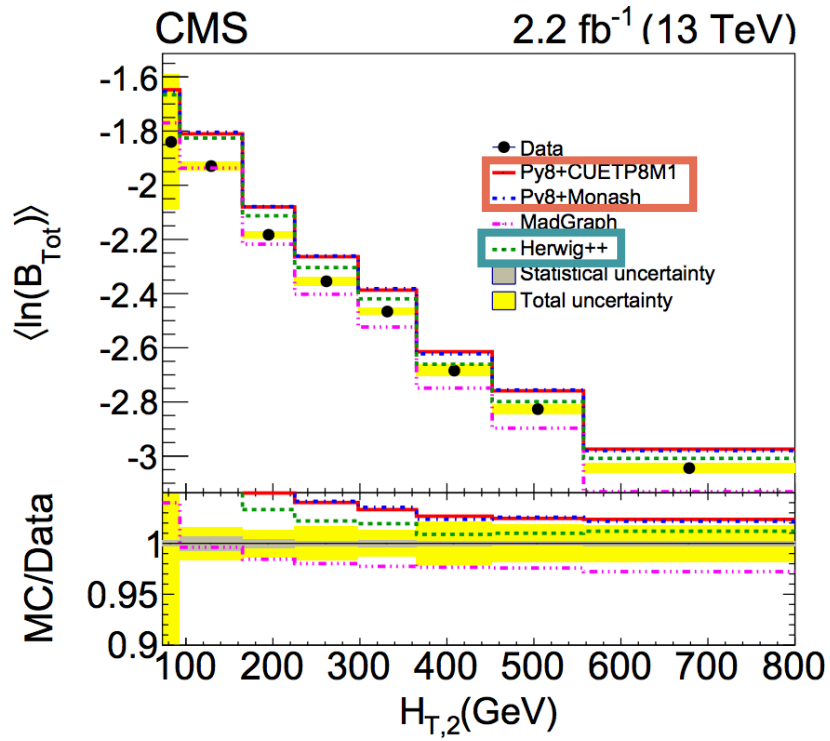
$$B_\mathrm{X} \equiv \frac{1}{2\,P_T} \sum_{i \in \mathrm{X}} p_{\mathrm{T},i} \sqrt{(\eta_i - \eta_\mathrm{X})^2 + (\phi_i - \phi_\mathrm{X})^2}$$

JHEP 12 (2018) 117

Event Shape Variables

- **Best ESV data/MC agreement at higher energy**
  - Partons more boosted, less spherical events
  - α_s decreases, less hard gluon emission





Pythia8 models energy flow in transverse plane well

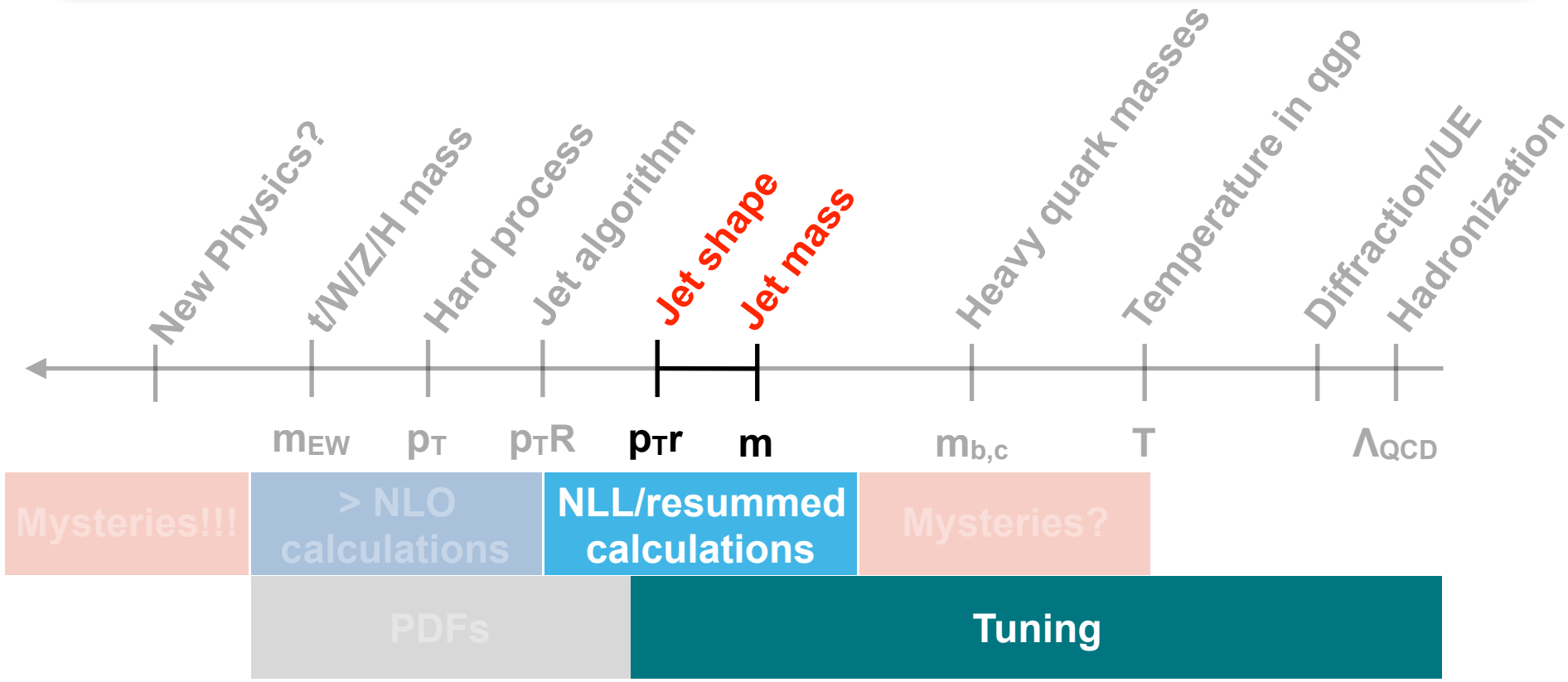
(string fragmentation + p_T-ordered shower)

Herwig++ performs well

(cluster fragmentation
+ angular-ordered shower)

Jet Substructure

Jet Substructure has emerged as a primary way to look for new physics, and probe QCD at the LHC. I. Moult

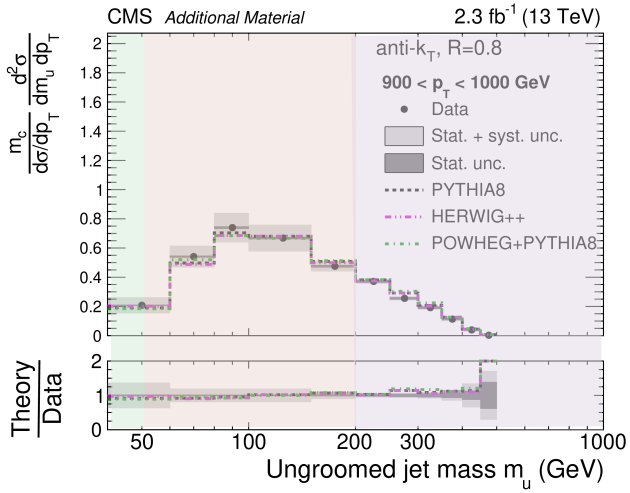


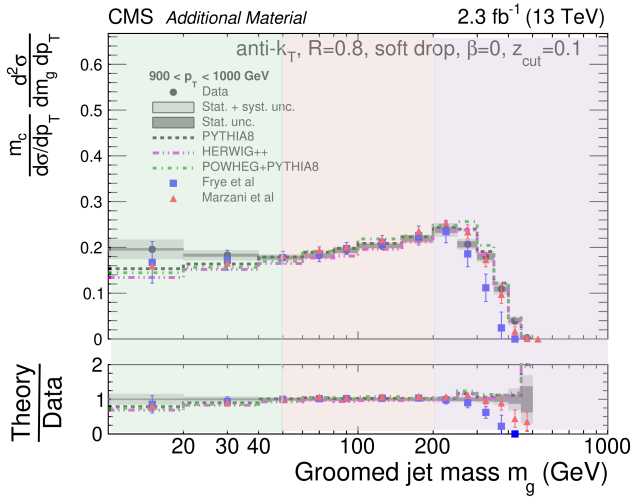
Jet Mass: Dijets

- **Groomed vs ungroomed mass: handle on the soft part of the jet (NP regime)**
  - Investigate multiple soft drop parameters

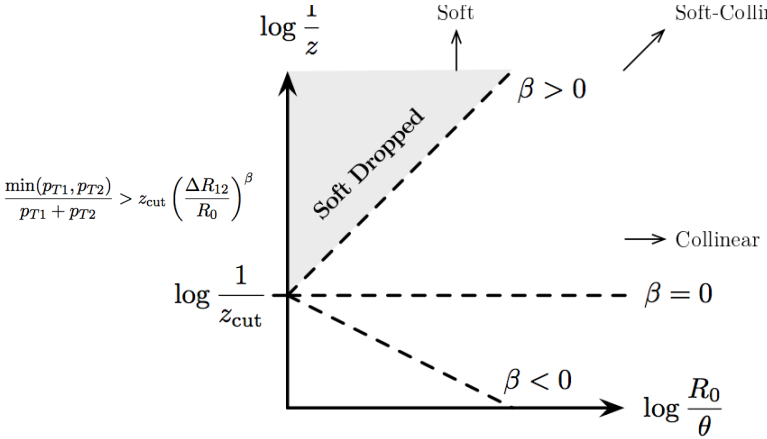
See A. Parker's talk

JHEP11(2018)113

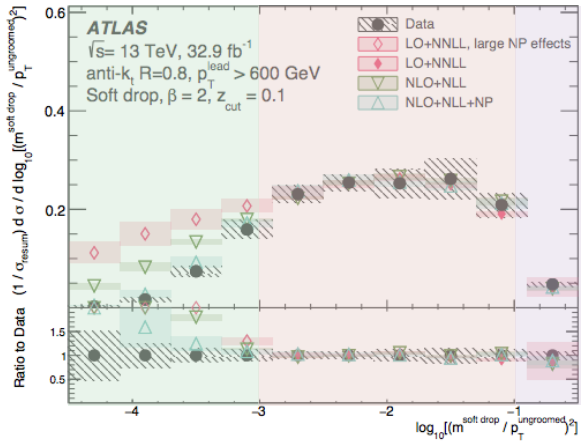




JHEP11(2018)113



JHEP09(2013)029

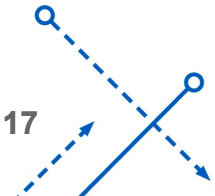


Phys. Rev. Lett. 121, 092001 (2018)

Non-perturbative

Resummation

Fixed-order

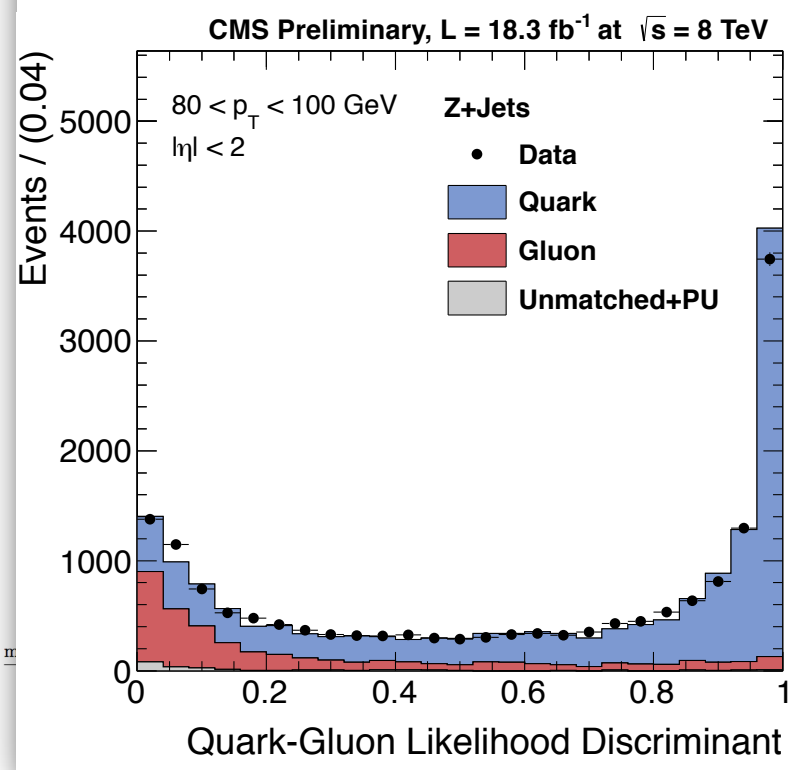


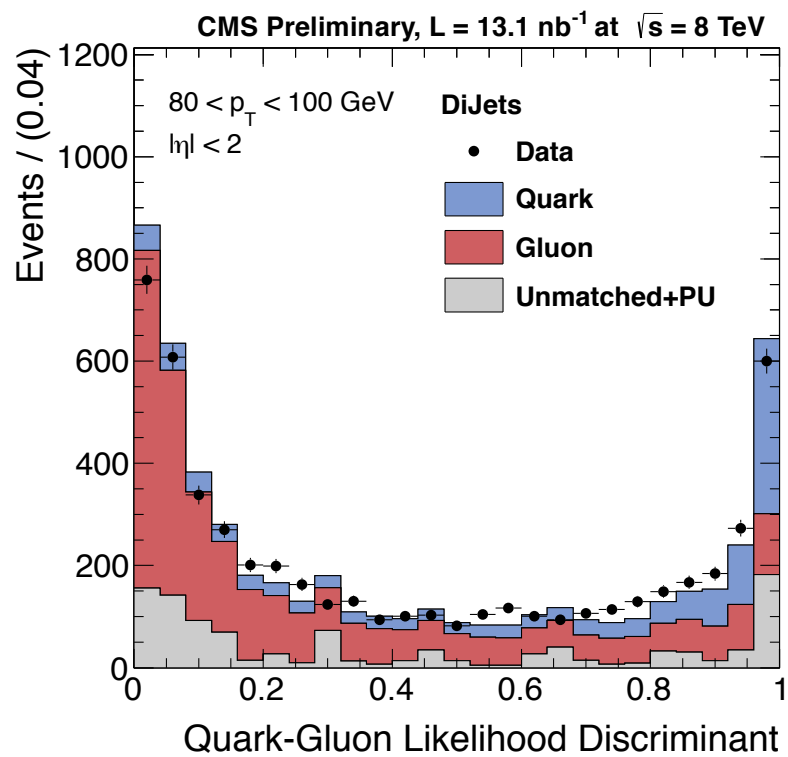
Jet Mass: Dijets

- Groomed vs ungroomed mass: handle on the

Gluon contribution needs tuning!

→ CMS Z+jets measurement ongoing





CMS PAS JME-13-002

arXiv:1906.09254

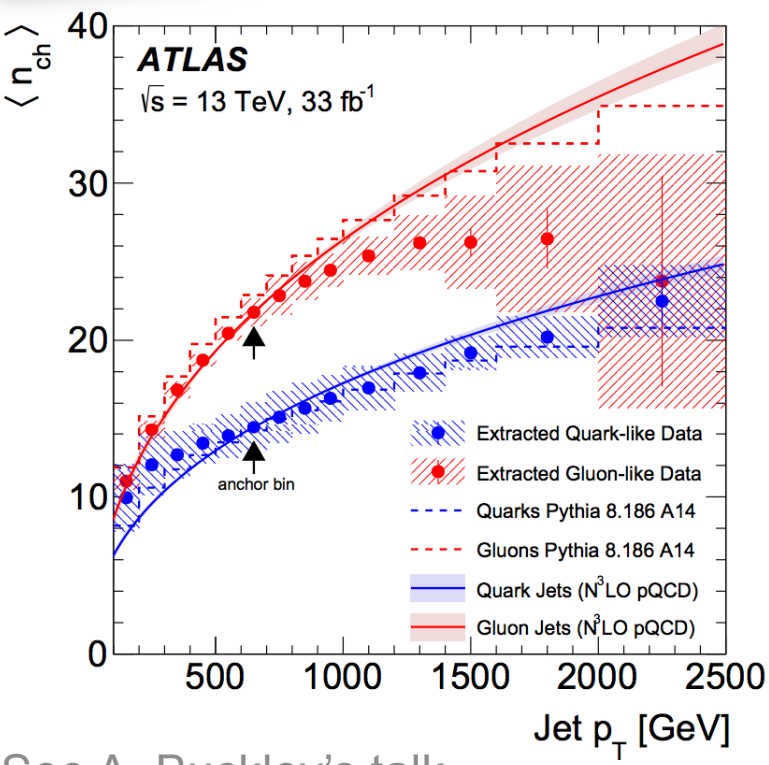
Jet Fragmentation

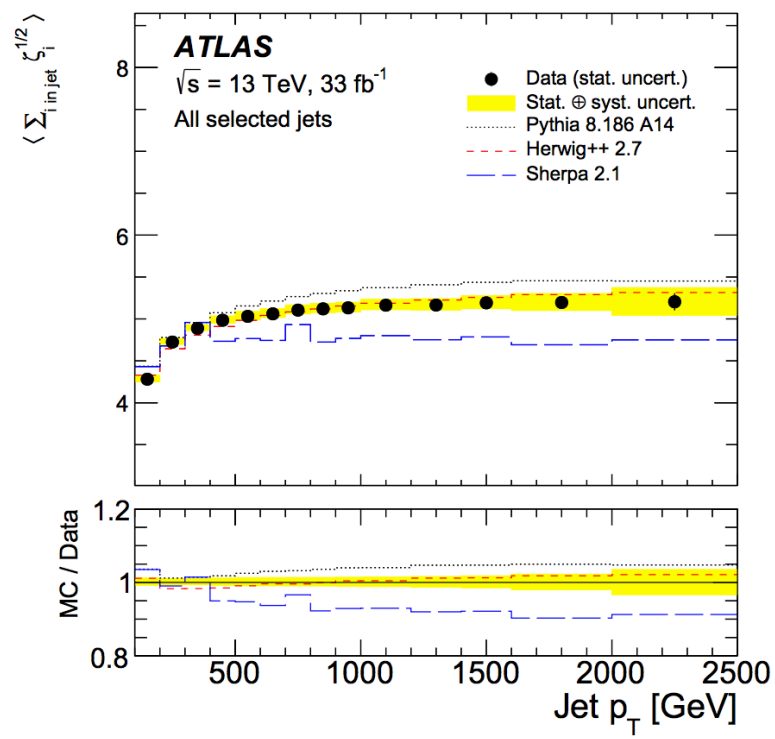
- **Measure track-based jet fragmentation functions**
  - Charged-particle multiplicity, relative momentum, angular properties of radiation pattern

Measuring jet fragmentation means understanding the emergence of jet structure A. Buckley

$$\langle n_{\rm ch}\rangle(p_{\rm T}^{\rm jet}) = \sum_p f_p(p_{\rm T}^{\rm jet}) \sum_{h\ \rm charged} \int_{\rm threshold/p_T^{jet}}^{1} d\zeta\, D_p^h(\zeta, p_{\rm T}^{\rm jet})$$

$$\zeta = p_{\rm T}^{\rm particle}/p_{\rm T}^{\rm jet}$$





See A. Buckley's talk

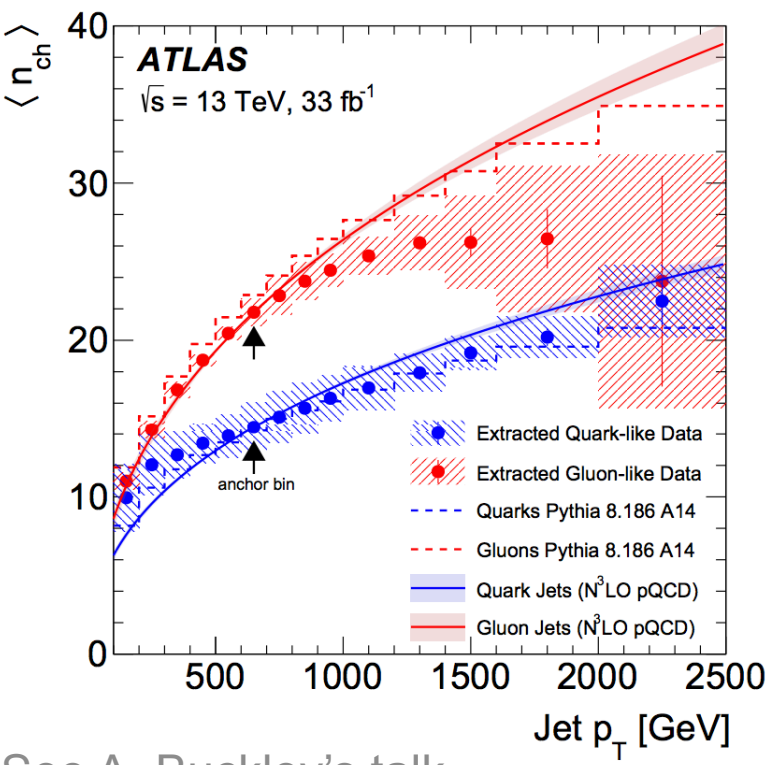
arXiv:1906.09254

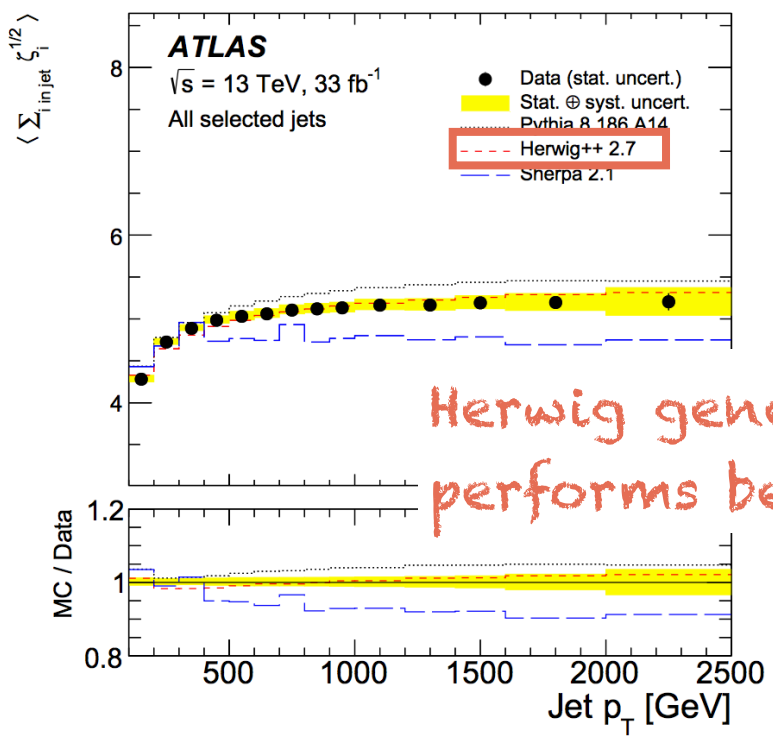
Jet Fragmentation

- **Measure track-based jet fragmentation functions**
  - Charged-particle multiplicity, relative momentum, angular properties of radiation pattern

Extraction of quark-like fragmentation function components more performant than for gluons

$$\zeta = p_{\mathrm{T}}^{\mathrm{particle}} / p_{\mathrm{T}}^{\mathrm{jet}}$$





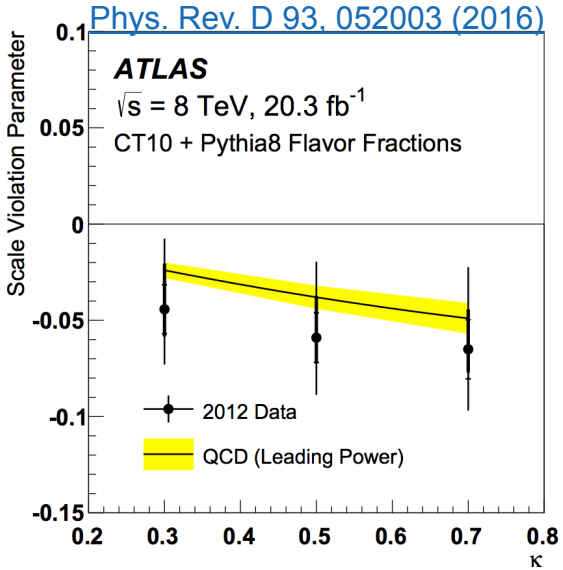
Herwig generally performs best here

See A. Buckley's talk

Jet Charge

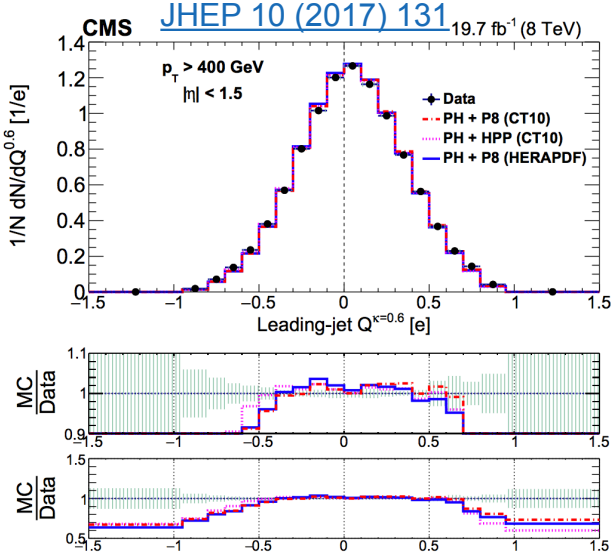
- **Measure momentum-weighted sum of the charges of the particles in the jet**
- **Jet charge probes hadronization, parton shower**

Phys. Rev. D 93, 052003 (2016)



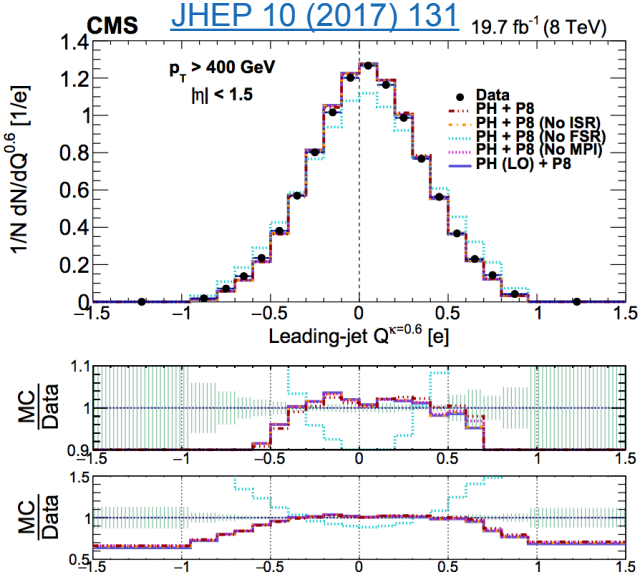
Measurements agree with pQCD

JHEP 10 (2017) 131



Sensitive to hadronization, fragmentation models in Pythia8 and Herwig++

JHEP 10 (2017) 131



Sensitive to FSR

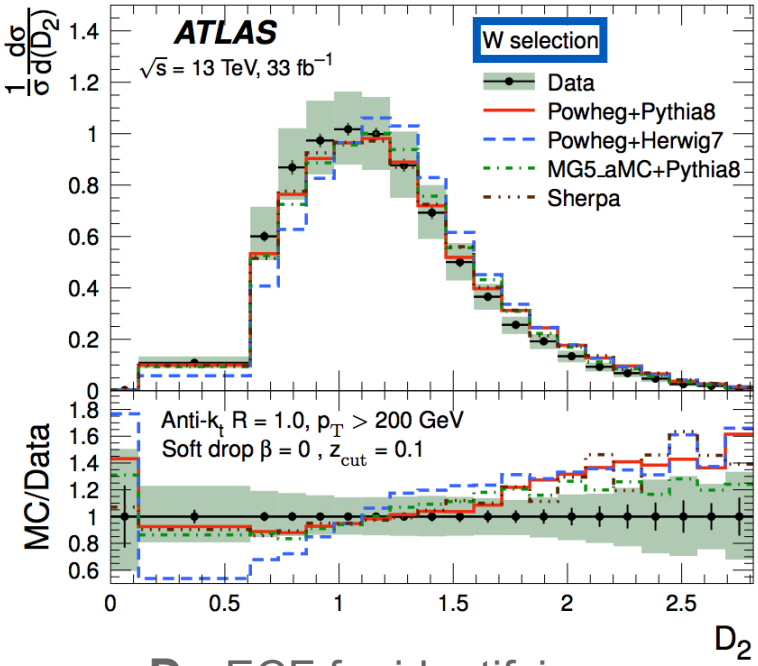
$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_i Q_i (p_{\mathrm{T}}^{i})^{\kappa}$$

arXiv:1903.02942

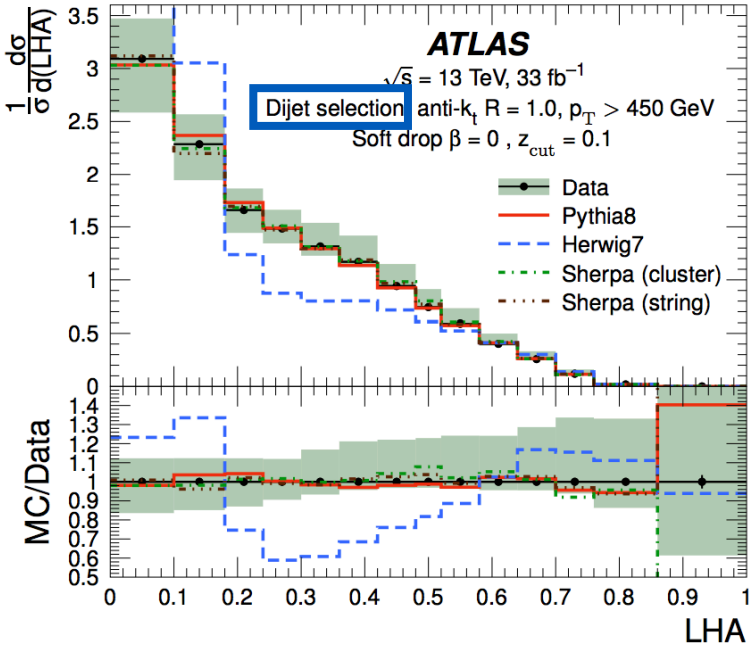
Jet Substructure Observables

- **Jet substructure variables used in BSM searches**
- **Measure in large-R soft drop jets**
  - Dijet (quark/gluon), W jets, top jets
  - Goal: improve modeling in MC

See I. Bertram's talk



D$_2$: ECF for identifying two-body structures

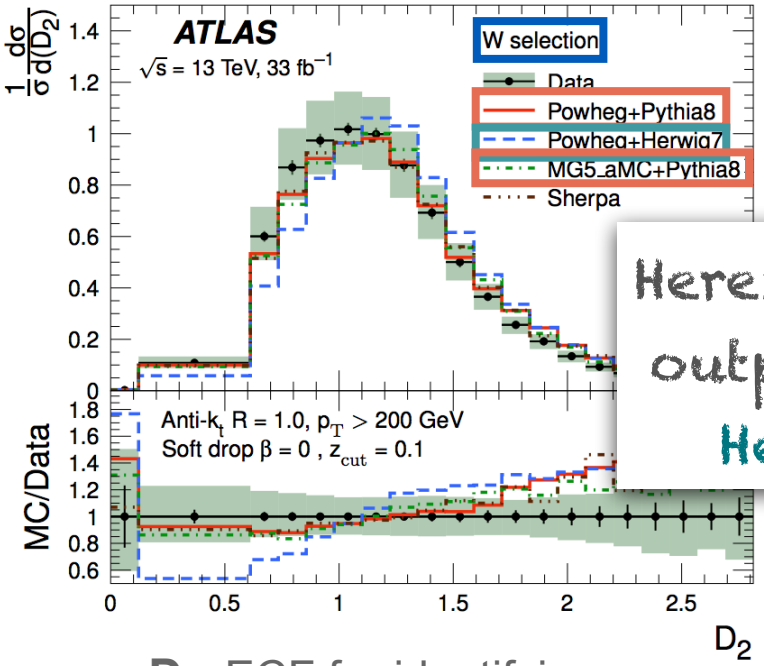


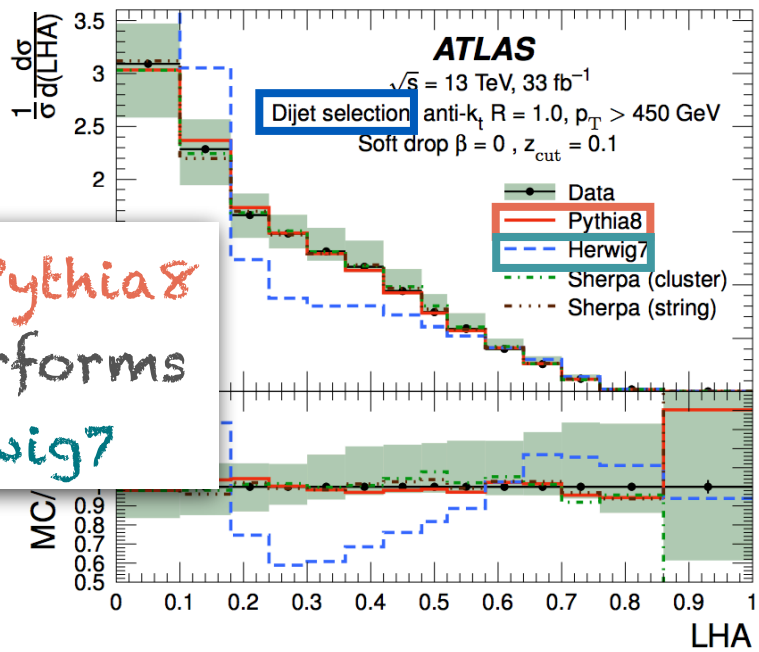
LHA: provides a measure of jet broadness

Jet Substructure Observables

arXiv:1903.02942

- **Jet substructure variables used in BSM searches**
- **Measure in large-R soft drop jets**
  - Dijet (quark/gluon), W jets, top jets
  - Goal: improve modeling in MC





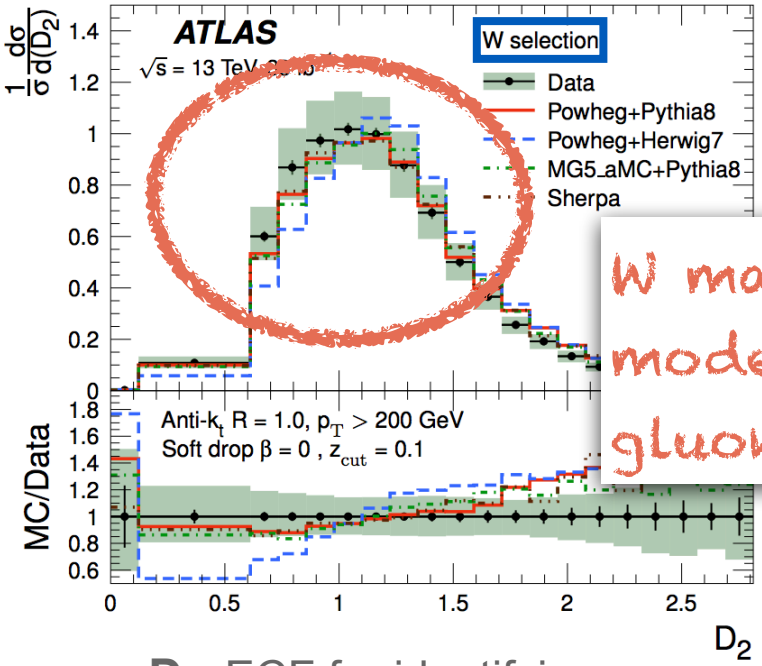
Here: Pythia8 outperforms Herwig7

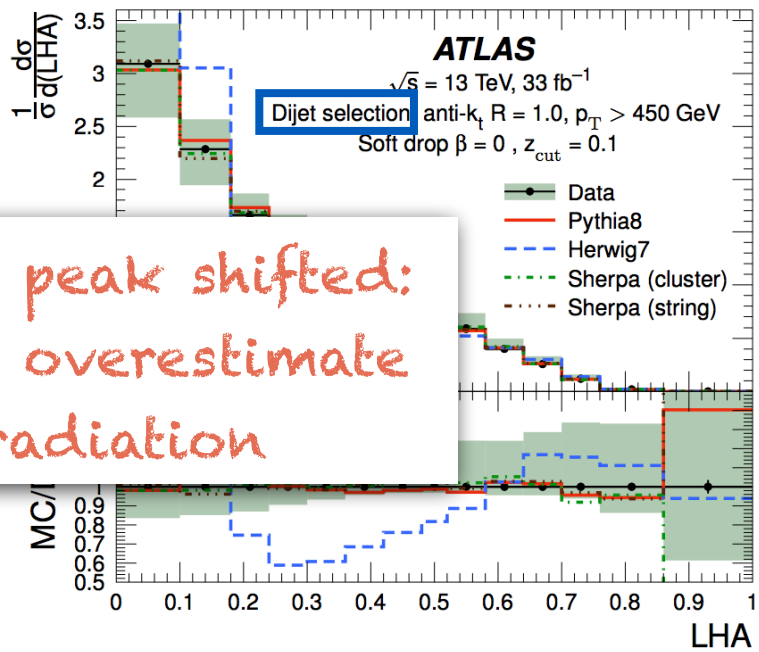
D_2: ECF for identifying two-body structures

LHA: provides a measure of jet broadness

Jet Substructure Observables

- **Jet substructure variables used in BSM searches**
- **Measure in large-R soft drop jets**
  - Dijet (quark/gluon), W jets, top jets
  - Goal: improve modeling in MC





W mass peak shifted: models overestimate gluon radiation

D$_2$: ECF for identifying two-body structures

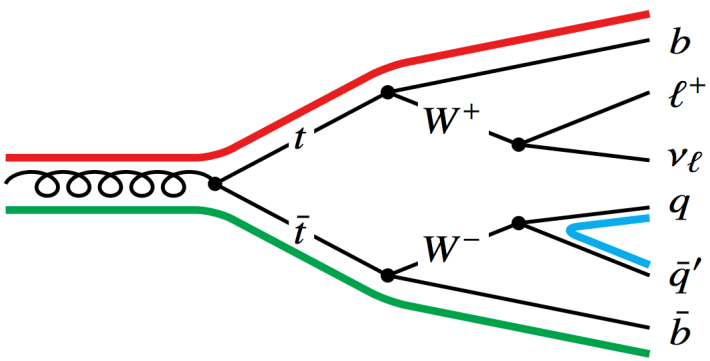
LHA: provides a measure of jet broadness

Eur. Phys. J. C 78 (2018) 847

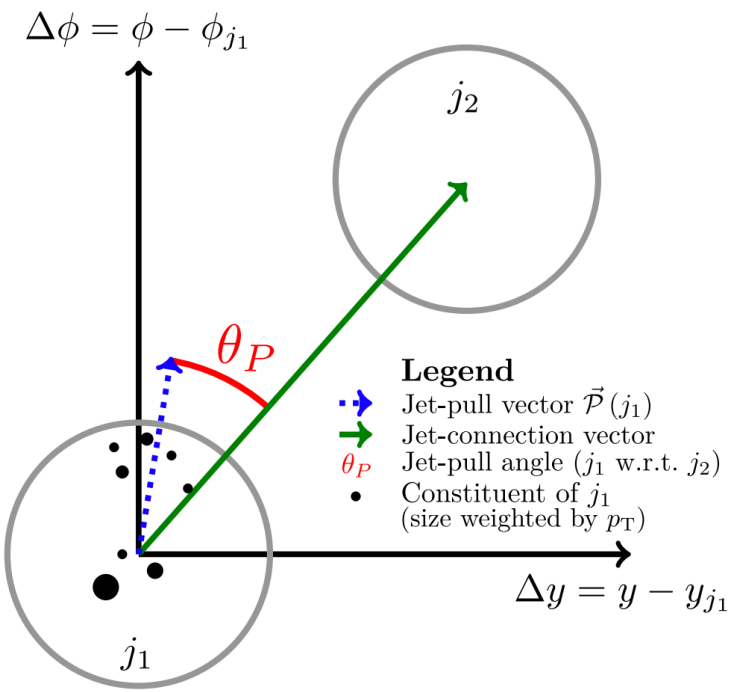
Color Flow in Jet Pull

- **Jet pull encodes parton color connections**
  - Poorly constrained area of QCD
  - Potentially useful for distinguishing event topologies

$$\vec{\mathcal{P}}(j) = \sum_{i \in j} \frac{\left|\vec{\Delta r}_i\right| \cdot p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{j}} \vec{\Delta r}_i$$



ATLAS measurement at 13 TeV

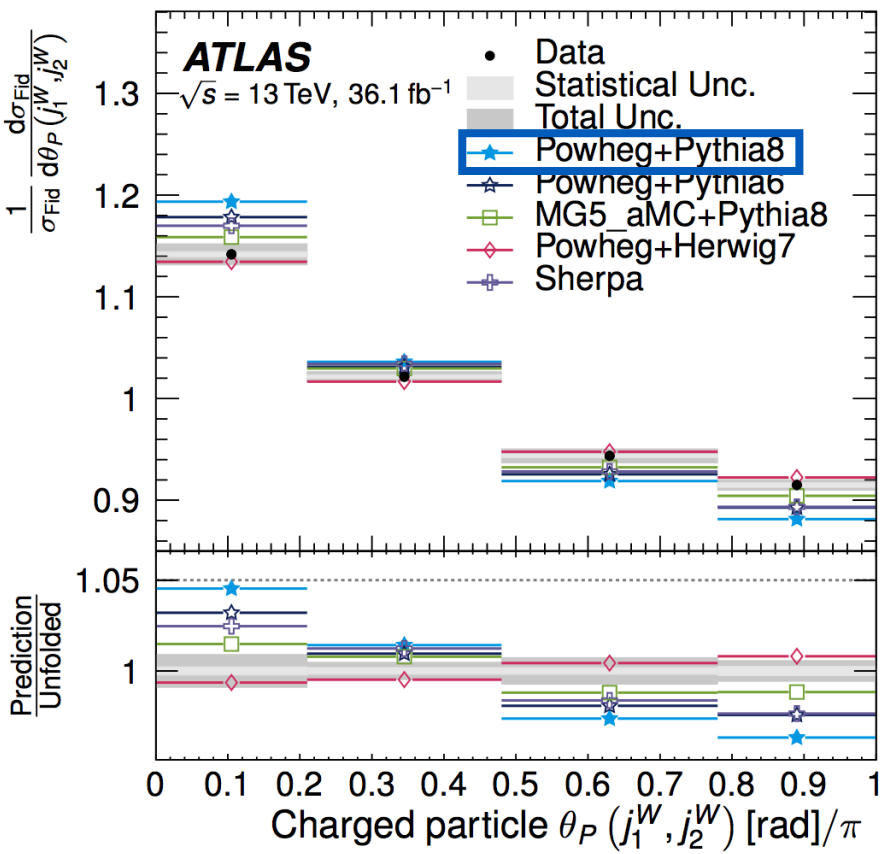


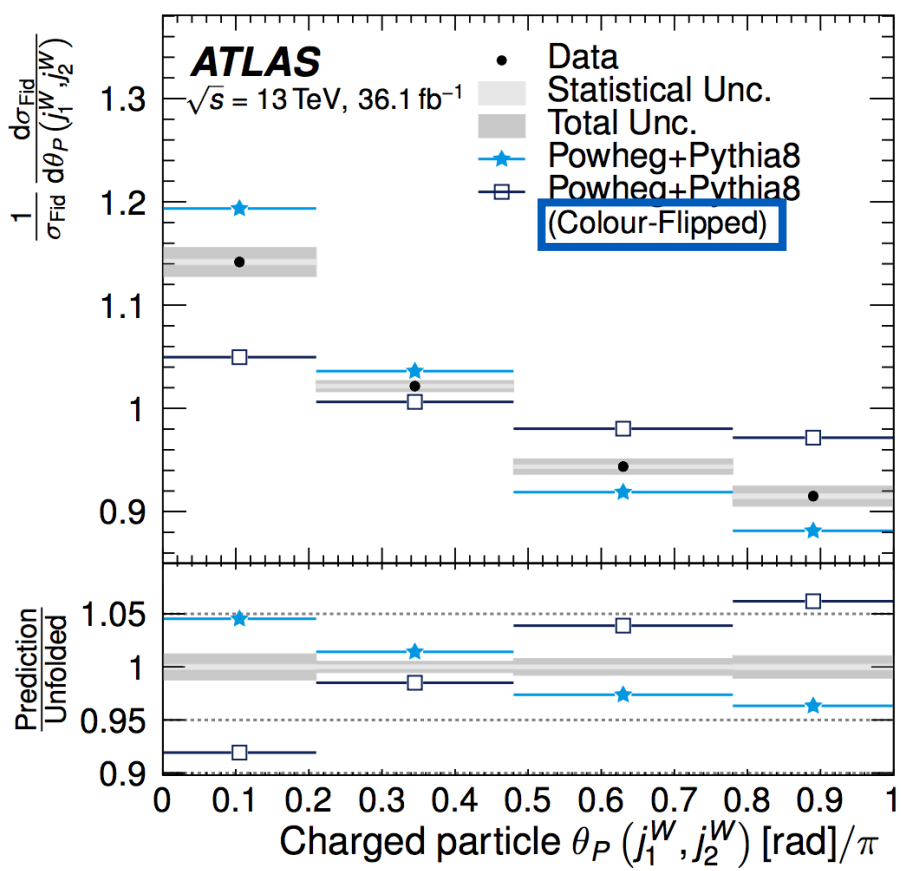
See S. Marzani's talk

Eur. Phys. J. C 78 (2018) 847

Color Flow in Jet Pull

Default generator does not agree well with data!



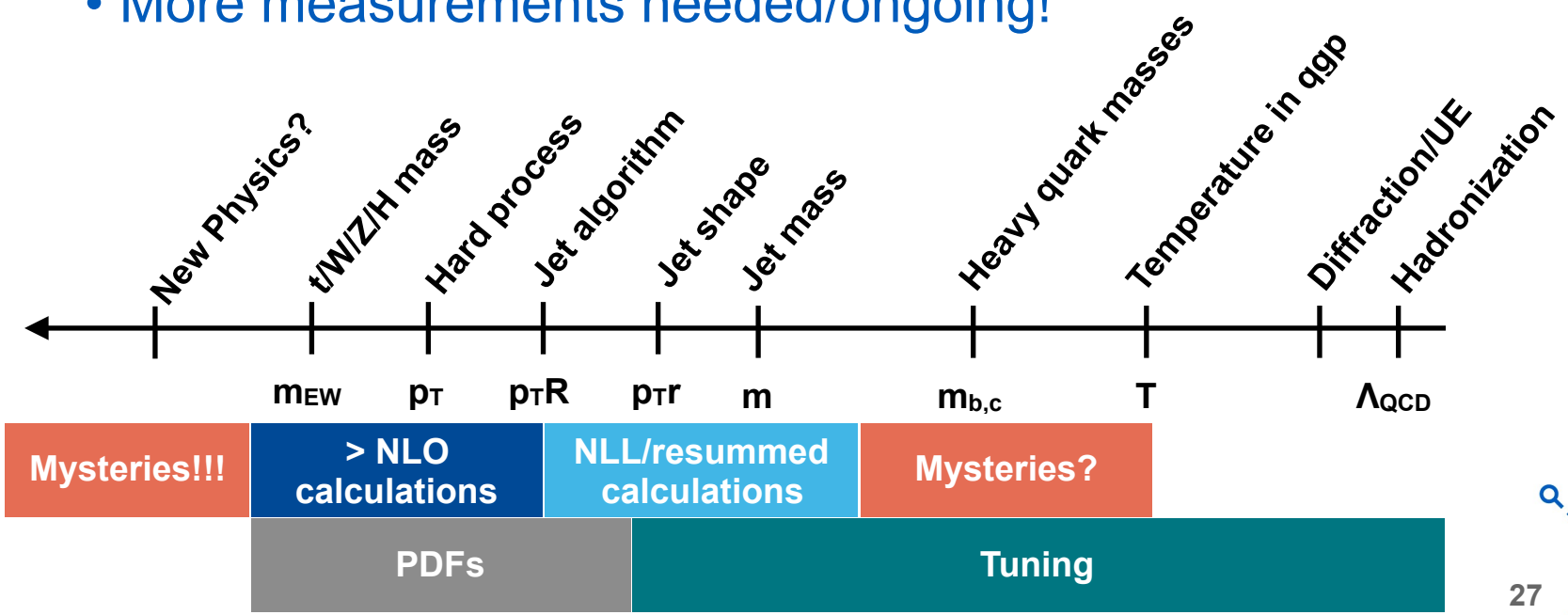


Data slightly favors SM over exotic color flow

See S. Marzani's talk

Jets at the LHC

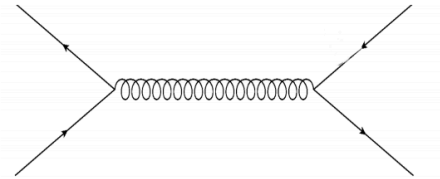
- **Jet measurements give us a handle on QCD**
- **Which generator is best? Depends on the observable!**
  - Can we combine the existing measurements to make MC work for everything?
- **Gluon jets not well-understood**
  - More measurements needed/ongoing!



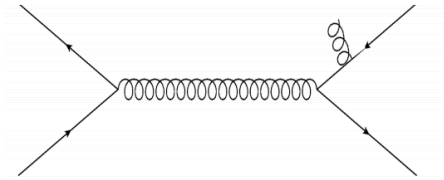
Additional Material

Generators

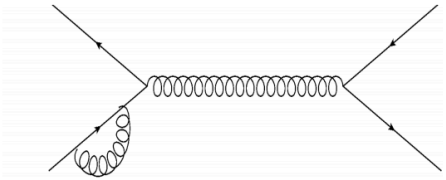
- PYTHIA8: 2→ 2 parton production @ LO + PS and UE
- HERWIG++ 2.7: 2→ 2 parton production @ LO + PS and UE
- HERWIG 7: 2→ 2 parton production @ NLO + PS and UE
- MADGRAPH_AMC@NLO+PYTHIA8: 2→ 2+n (with n<3) parton production @ LO + PS and UE
- POWHEG+PYTHIA8: 2→ 2 parton production @ NLO + PS and UE
- POWHEG+HERWIG++: 2→ 2 parton production @ NLO + PS and UE
- NLOJET++: 2→ 2 dijet production @ NLO



Leading order process

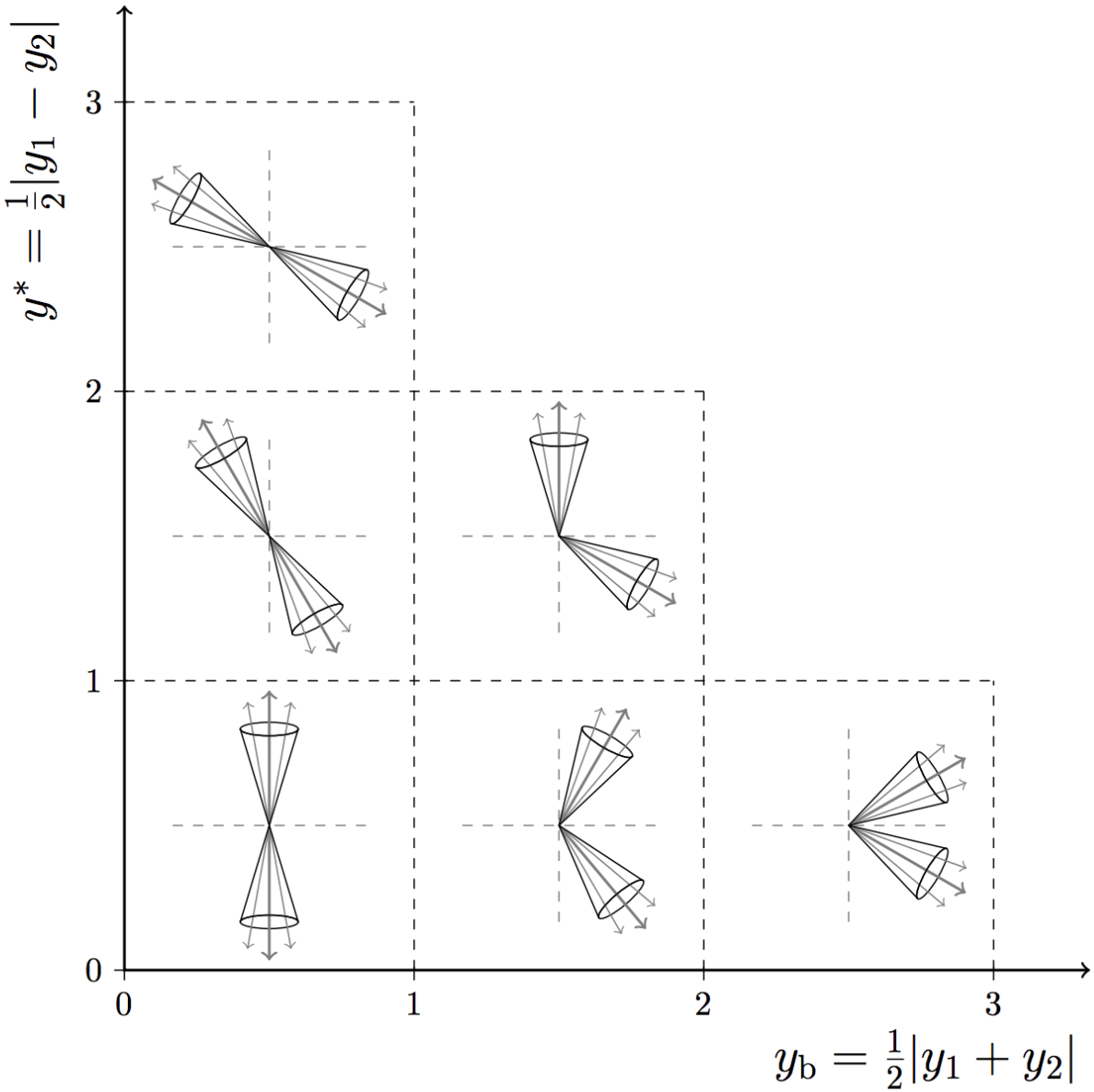


Real correction

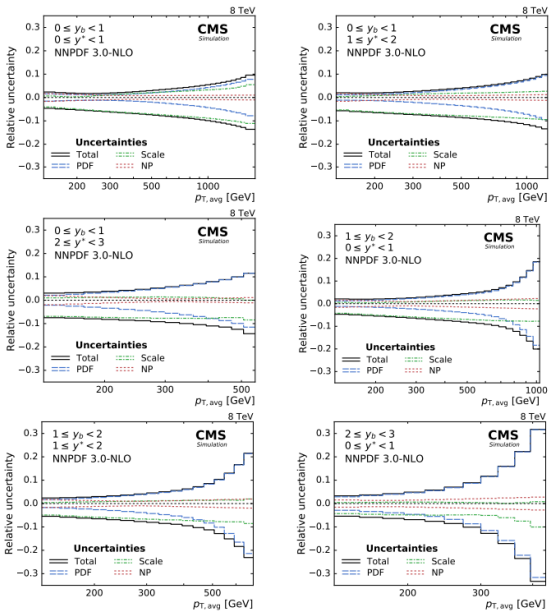


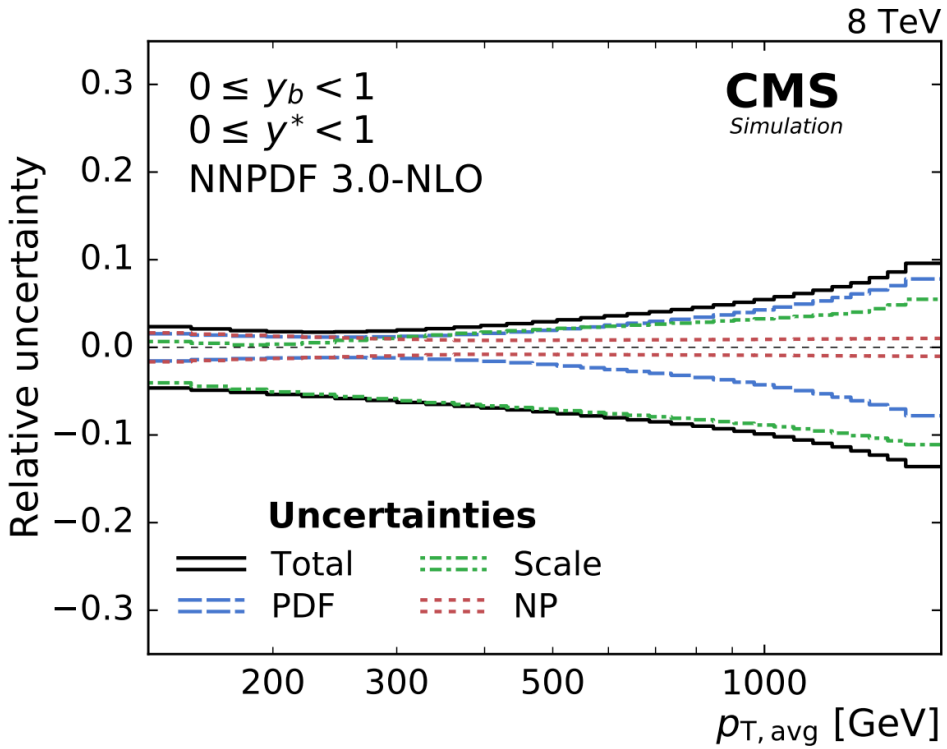
Virtual correction

CMS Dijet Cross Section



3D dijets: Theoretical uncertainties

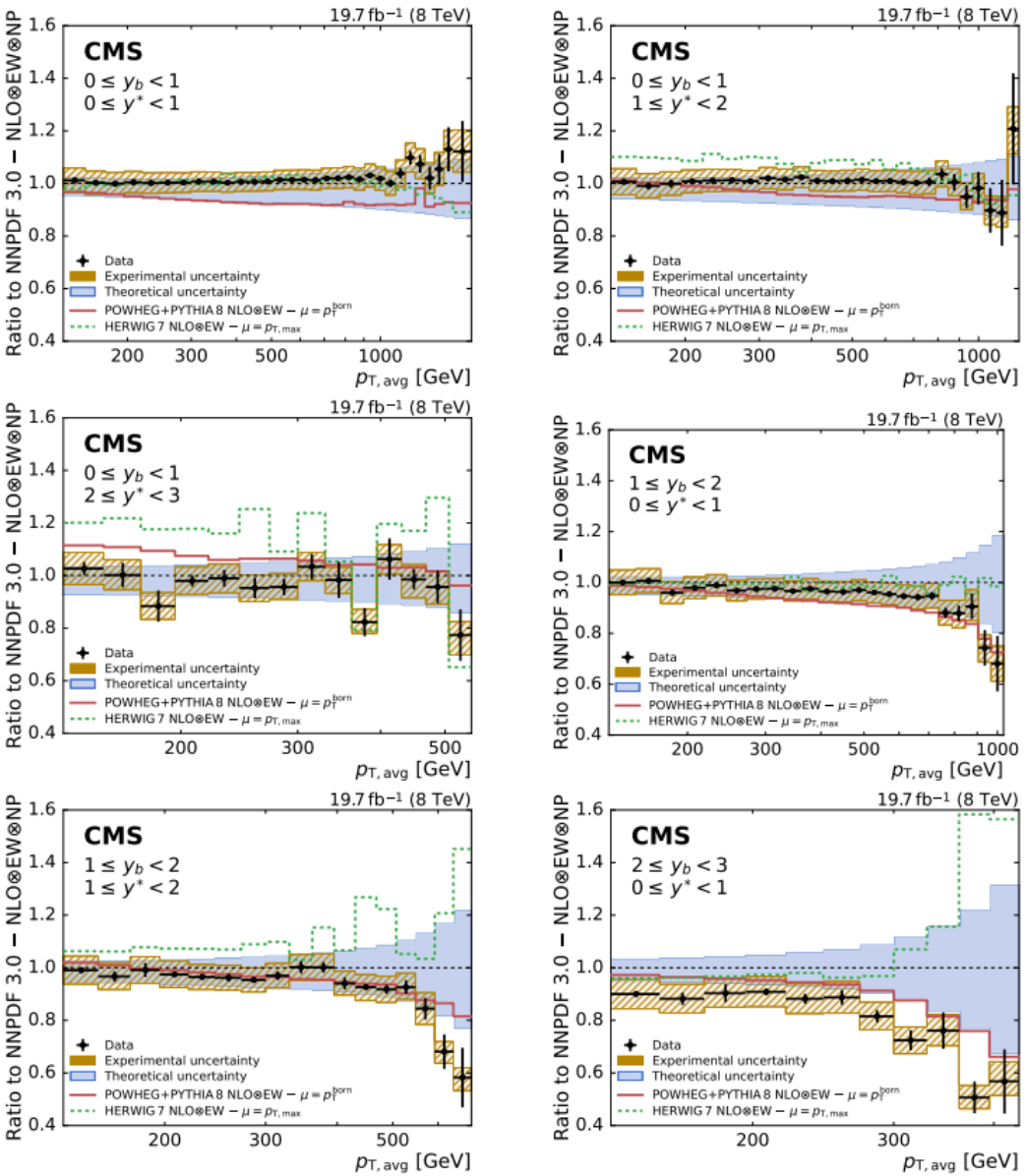




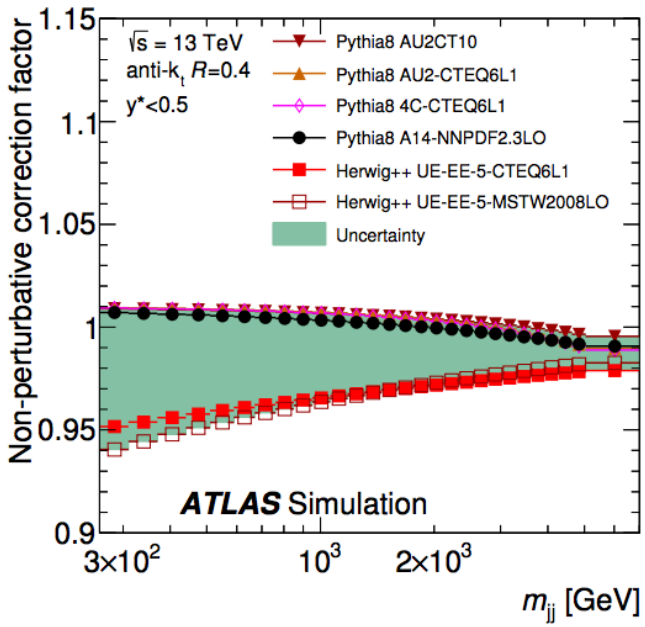
- no uncertainties in the EW corrections are assigned

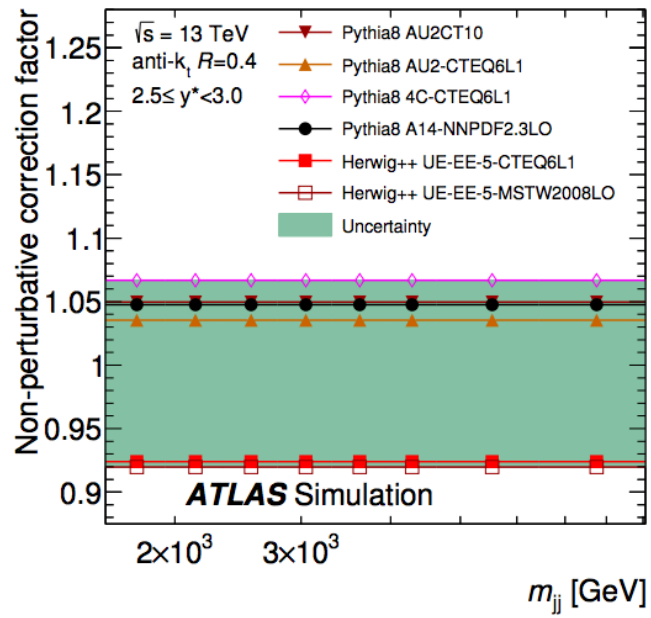
EPJ C 77(2017)746

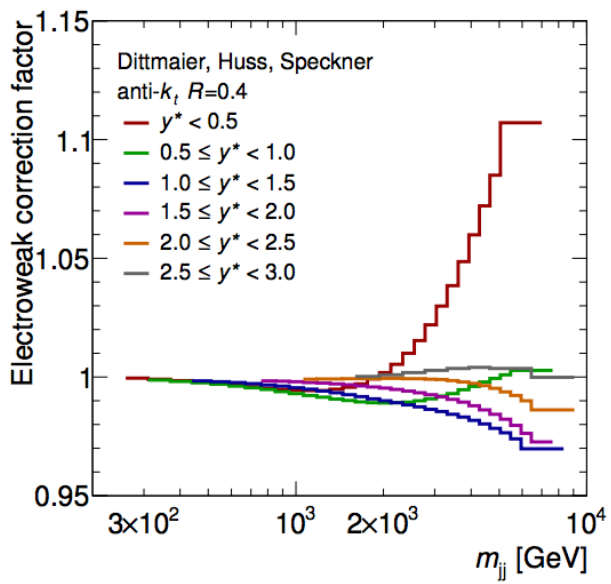
CMS Dijets: PDF Uncertainties



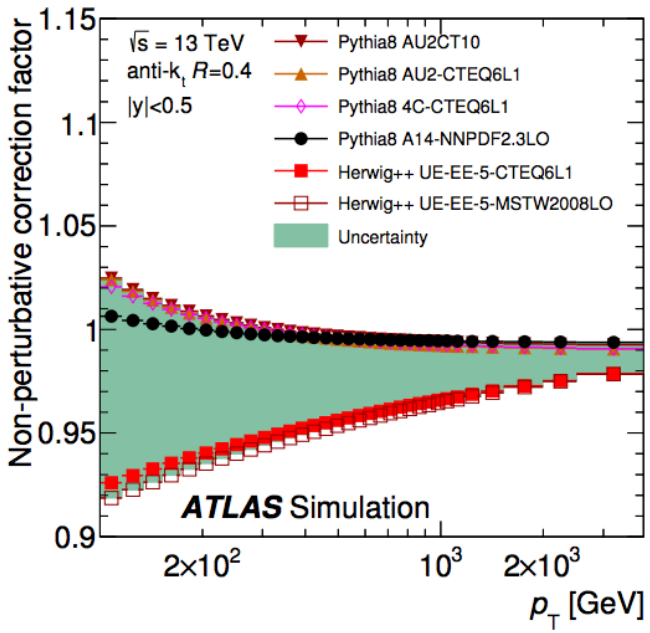
ATLAS Dijets: Theory Corrections

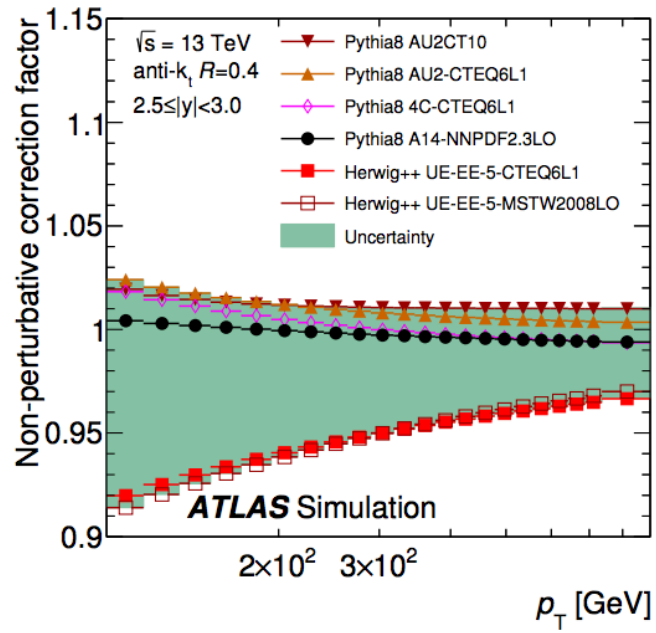


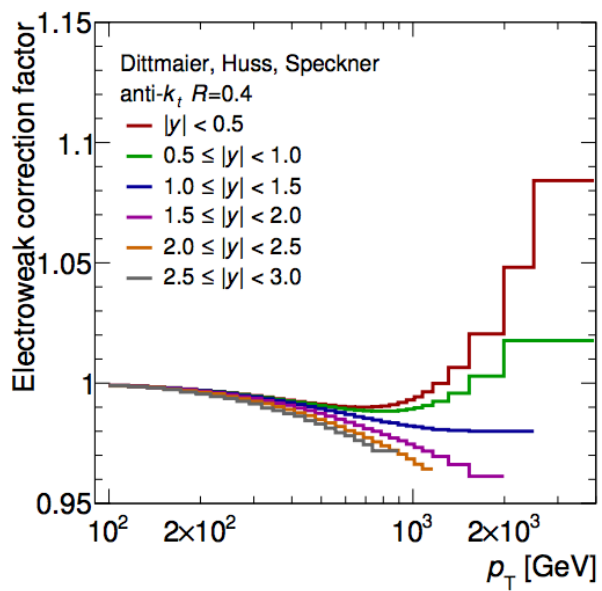




ATLAS Inclusive: Theory Corrections

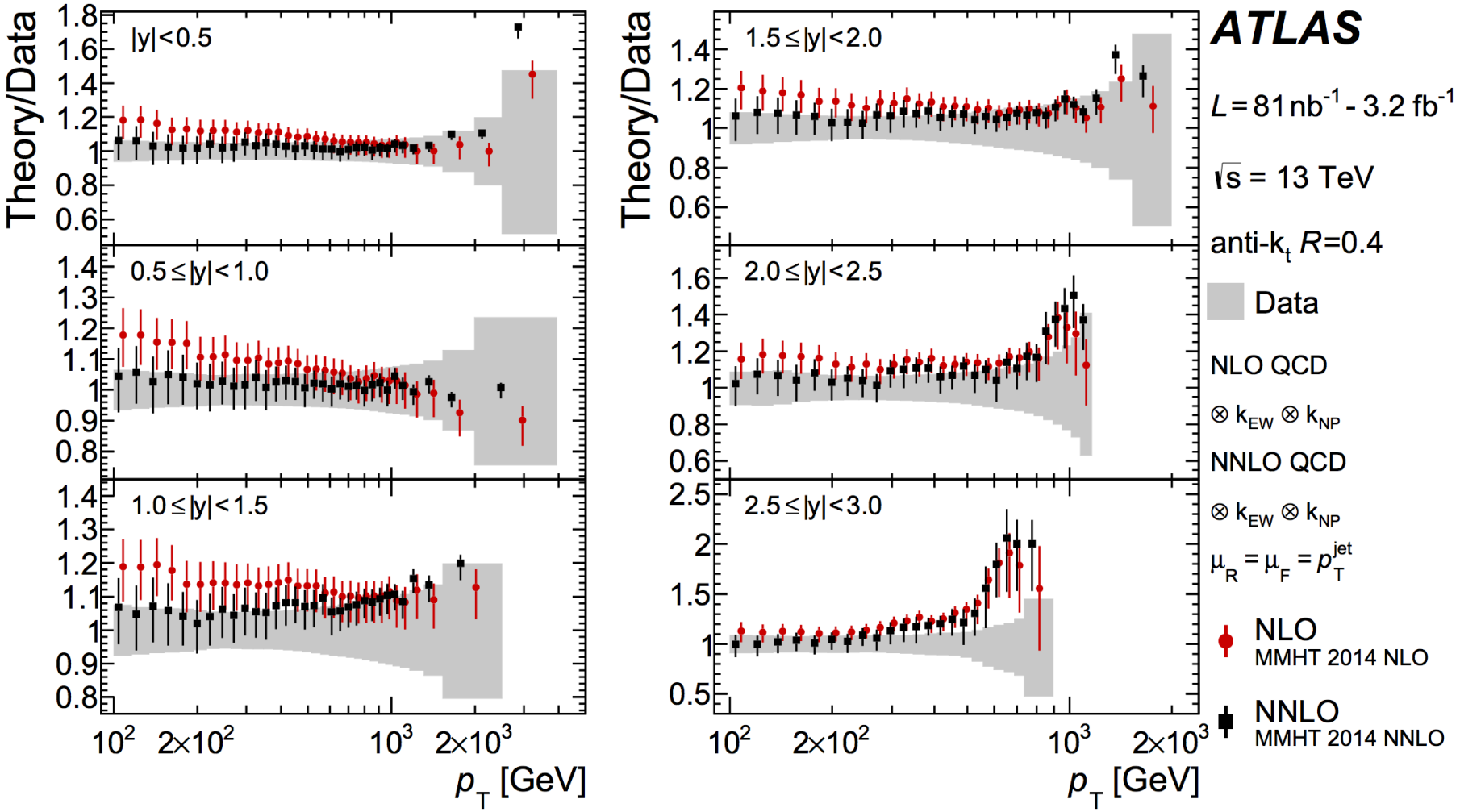






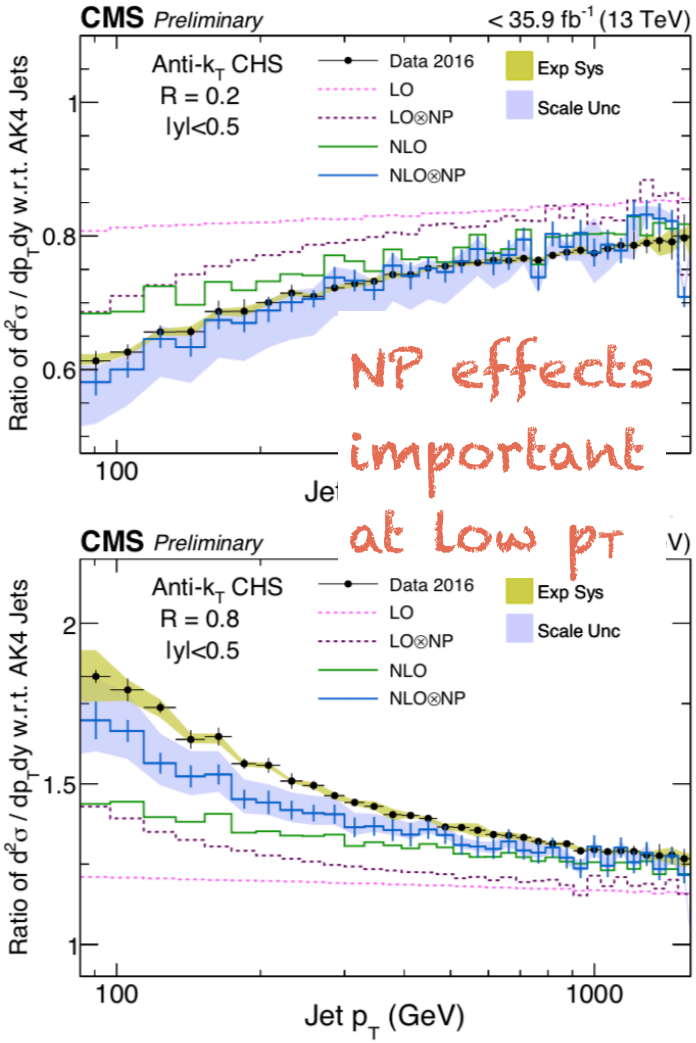
JHEP 05 (2018) 195

Jet Cross Sections



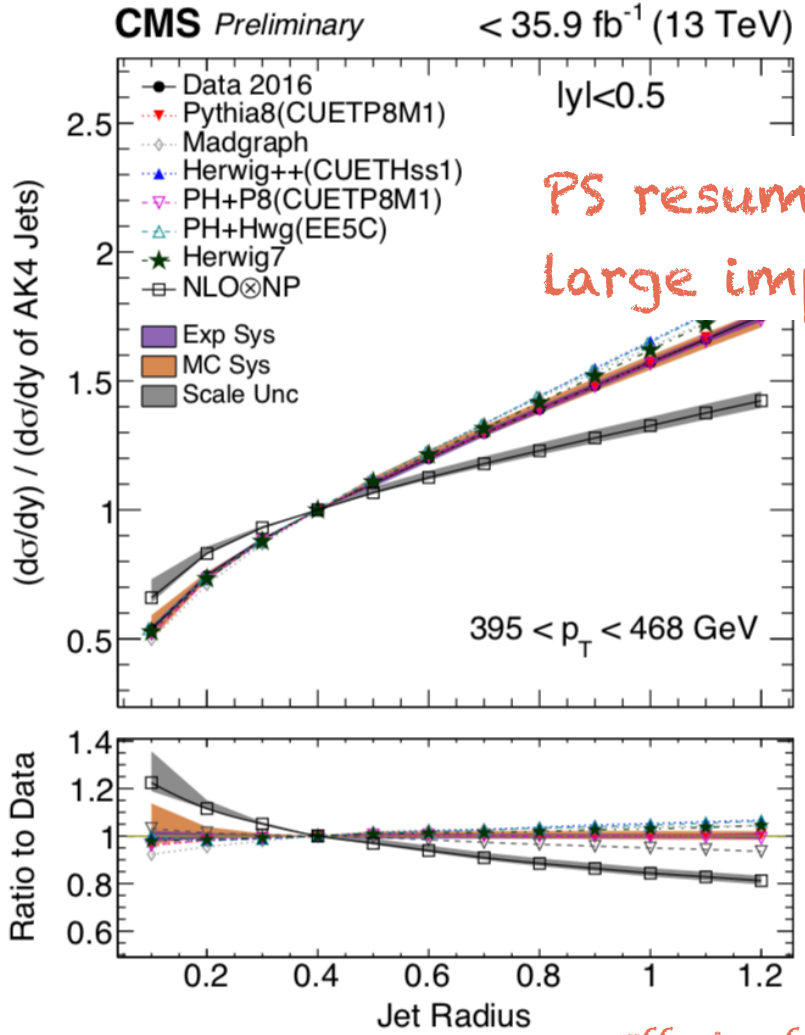
Radius Scan

Fixed order



NP effects important at low p_T

Fixed order vs MC with PS resummation



PS resummation: large impact

Soft radiation effects ⟷ Effects of hadronization, out-of-cone radiation

Jet Fragmentation

Observables

Fragmentation function D defined as p_T fraction of hadron h wrt its containing jet p_T, from parton p.
⇒ DGLAP pQCD evolution; mirror image of PDFs

$$\mu\frac{\partial}{\partial\mu}D_p^h(\zeta,\mu)=\sum_{p'}\int_\zeta^1\frac{d\zeta'}{\zeta'}\frac{\alpha_S(\mu)P_{p'\leftarrow p}(\zeta',\mu)}{\pi}D_{p'}^h\left(\frac{\zeta}{\zeta'},\mu\right)$$

This paper uses charged hadrons, but full (calo) jet
⇒ $\langle n_{ch}\rangle$ and differential $1/N_{jet}\, dN_{jet}/d\langle n_{ch}\rangle$

$$\langle n_{ch}\rangle(p_T^{jet})=\sum_p f_p(p_T^{jet})\sum_{h\ \text{charged}}\int_{\text{threshold}/p_T^{jet}}^1 d\zeta\, D_p^h(\zeta,p_T^{jet})$$

+ **summed fragmentation function:**
  differential in p_T fraction ζ *and* jet p_T ⇒ extract partial fractions, moments & weighted sums

$$F(\zeta,p_T^{jet})=\sum_p f_p(p_T^{jet})\sum_{h\ \text{charged}}D_p^h(\zeta,p_T^{jet})$$

+ Relative transverse momentum
  Radial profile (non-p_T-weighted)

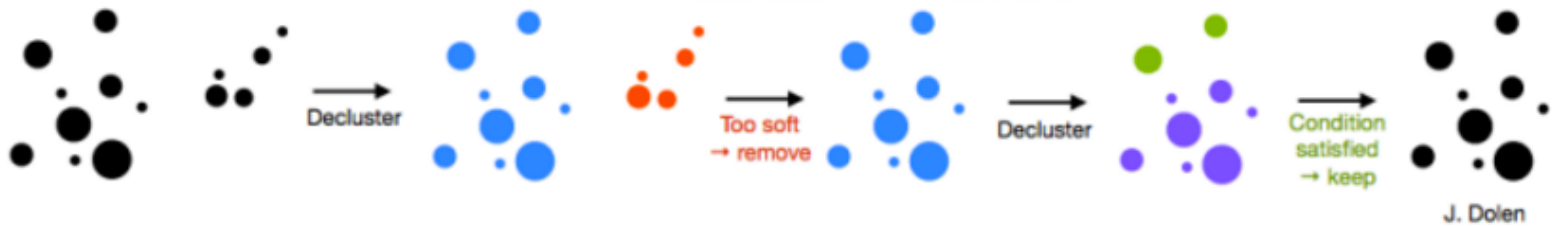
$$p_T^{rel}\equiv p_T^{\text{charged particle}}\sin\Delta\phi$$

$$\rho_{ch}(r,p_T^{jet})=(1/N_{jet})dn_{ch}/2\pi r\,dr$$

Soft Drop

- Recursively decluster jet. Remove the softer component unless the soft drop condition is satisfied.

Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



- Soft wide angle radiation fails the condition
  - As z_{cut} ↑ ⇒ more aggressive grooming
  - As β ↓ ⇒ more aggressive grooming
- Example (z_{cut} = 0.1) :
  - If β = 0, remove softer subjet if p_T fraction < 0.1 (~equivalent to MMDT)
  - If β > 0, remove softer subjet if p_T fraction < x, where x increases with ΔR and has maximum value 0.1
  - β → ∞ no grooming
  - β <0 soft drop becomes a tagger instead of a groomer (finds jets with hard, large angle subjets)