Measurements of event properties with jets in CMS

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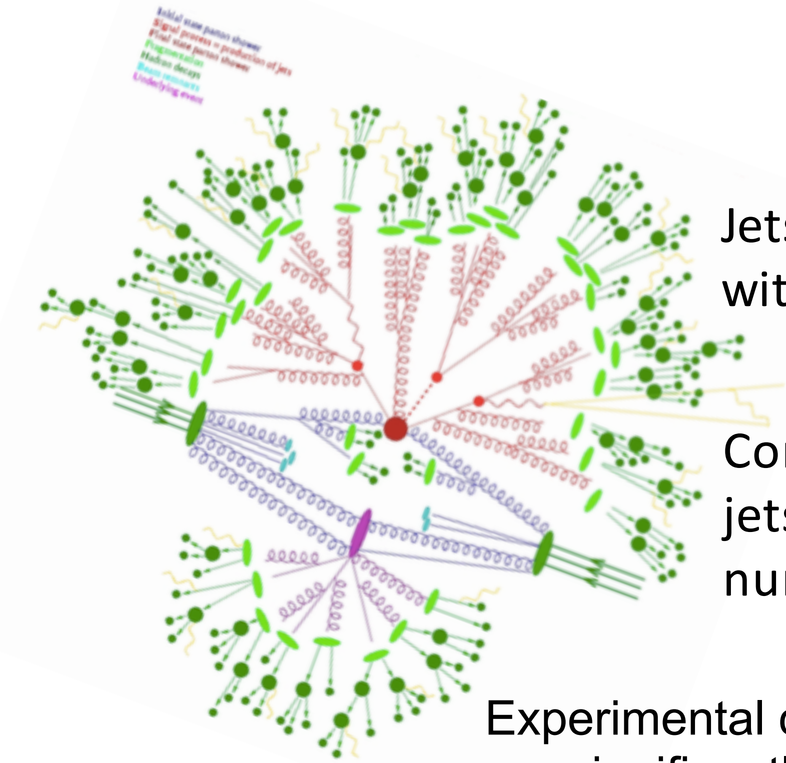
On behalf on the CMS Collaboration

EPS Venezia – July 7, 2017

LCH: a jet factory



Jets produced in a phase space never probed before, with several TeV transverse momentum

Complex final states containing multiple hadronic jets are produced copiously at LHC and enter in a number of new particle discovery processes

Experimental capabilities to disentangle signal from background are significantly enhanced if the **detailed structure of jets** can be used as a diagnostics for potential new physics effects, e.g. in decays of highly boosted massive state

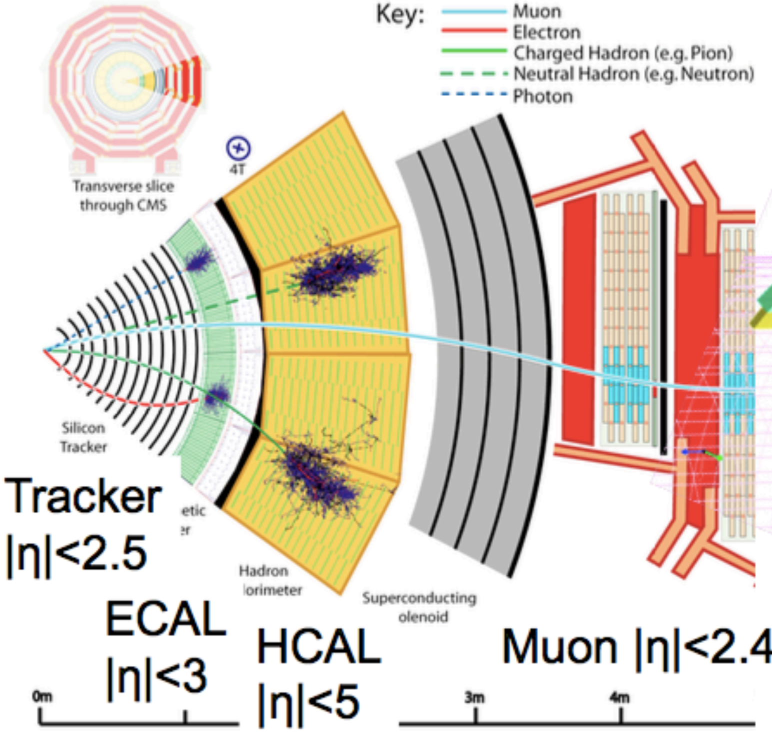
The interpretation of experimental data for such multi-particle final states relies both on **perturbative multi-jet calculations** and on realistic event simulation by **parton-shower Monte Carlo generators**.

Outline

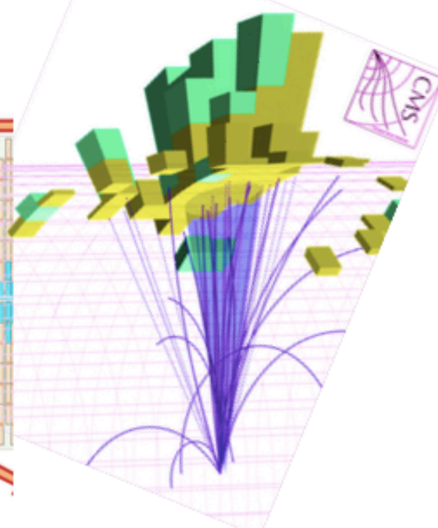
- Jet Reconstruction and Calibration in CMS
- Inclusive jet cross section at 8 and 13 TeV (**P. Kokkas talk)**
- Jet charge observables in dijet events at 8 TeV
- Differential jet poduction cross section as function of jet mass and transverse momentum in dijet events at 13 TeV
- Comparison to Montecarlo event generators at LO and NLO with different PDFs (**E. Eren talk)**
- Conclusions

Jet reconstruction

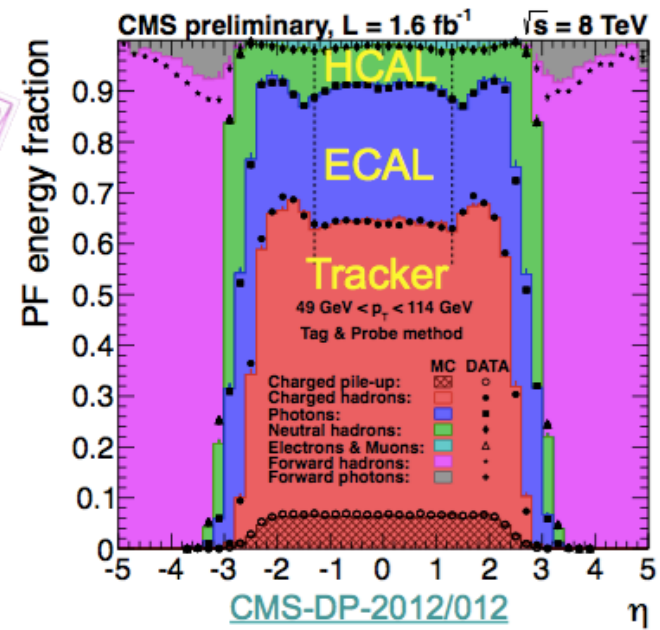
Particle flow reconstruction



Jet clustering (anti-k_T)



Jet energy fractions



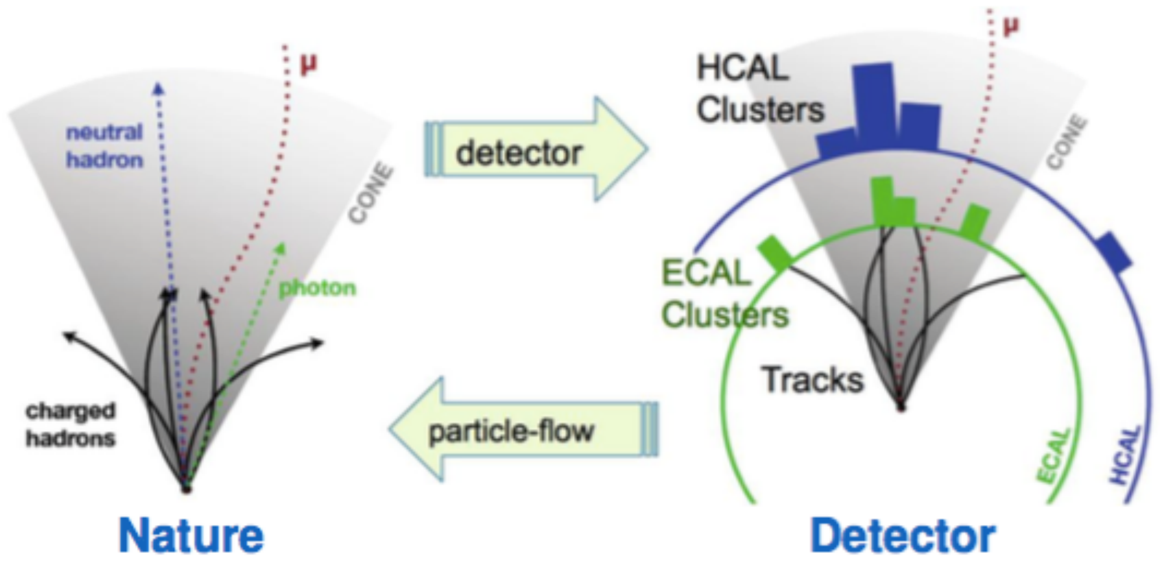
CMS-DP-2012/012

Particle Flow algorithm benefits from sub-detectors with best spatial+energy resolution

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (|η|<1.48)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (|η|<1.74) 0.175 x 0.175 (|η|>3)

Particle flow paper arXiv:1706.04965

Particle Flow and Jet reconstruction



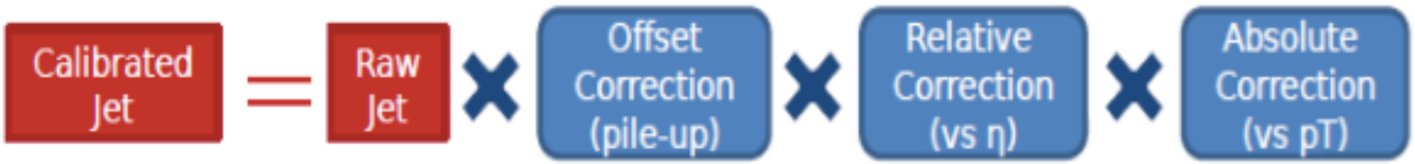
- **Particle Flow Jets (PF Jets)**: Combining information from all sub-detectors to reconstruct and identify all stable particles to be clustered in jets ➔ jet substructure

PF jets: up to 5x less sensitive to calorimetry than calo-jets

- **Anti-k_T clustering algorithm**: input particle flow objects infrared and collinear safe. Used with various values of $R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$

Jet energy calibration

Factorized JEC approach in CMS

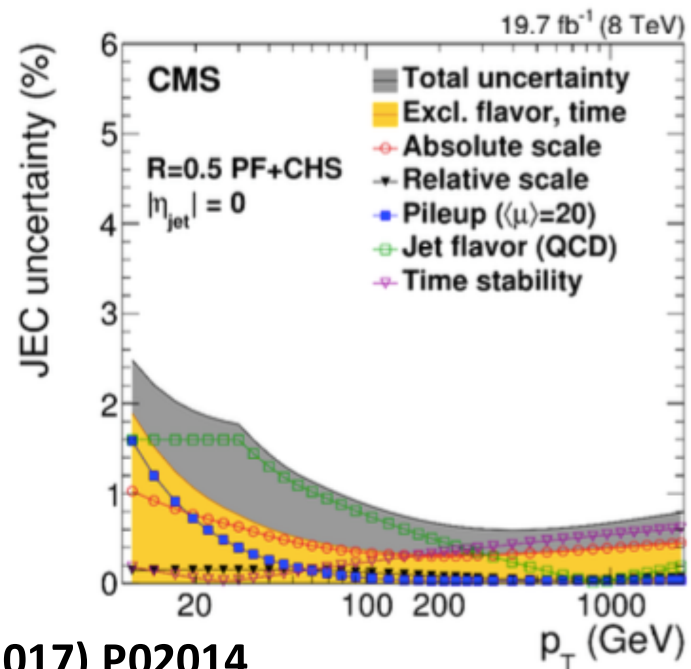


Pileup increases jet mass and distorts jet substructure observables

Pile-up corrections applied:

- charged hadron subtraction (CHS) algorithm charged pileup (60%, decreasing at high p_T) removed reconstructing secondary vertices
- neutral pileup component (40%) weighted with pileup probability (PUPPI)

Jet energy corrections with small uncertainties: less than 2% in the region $p_T > 100$ GeV

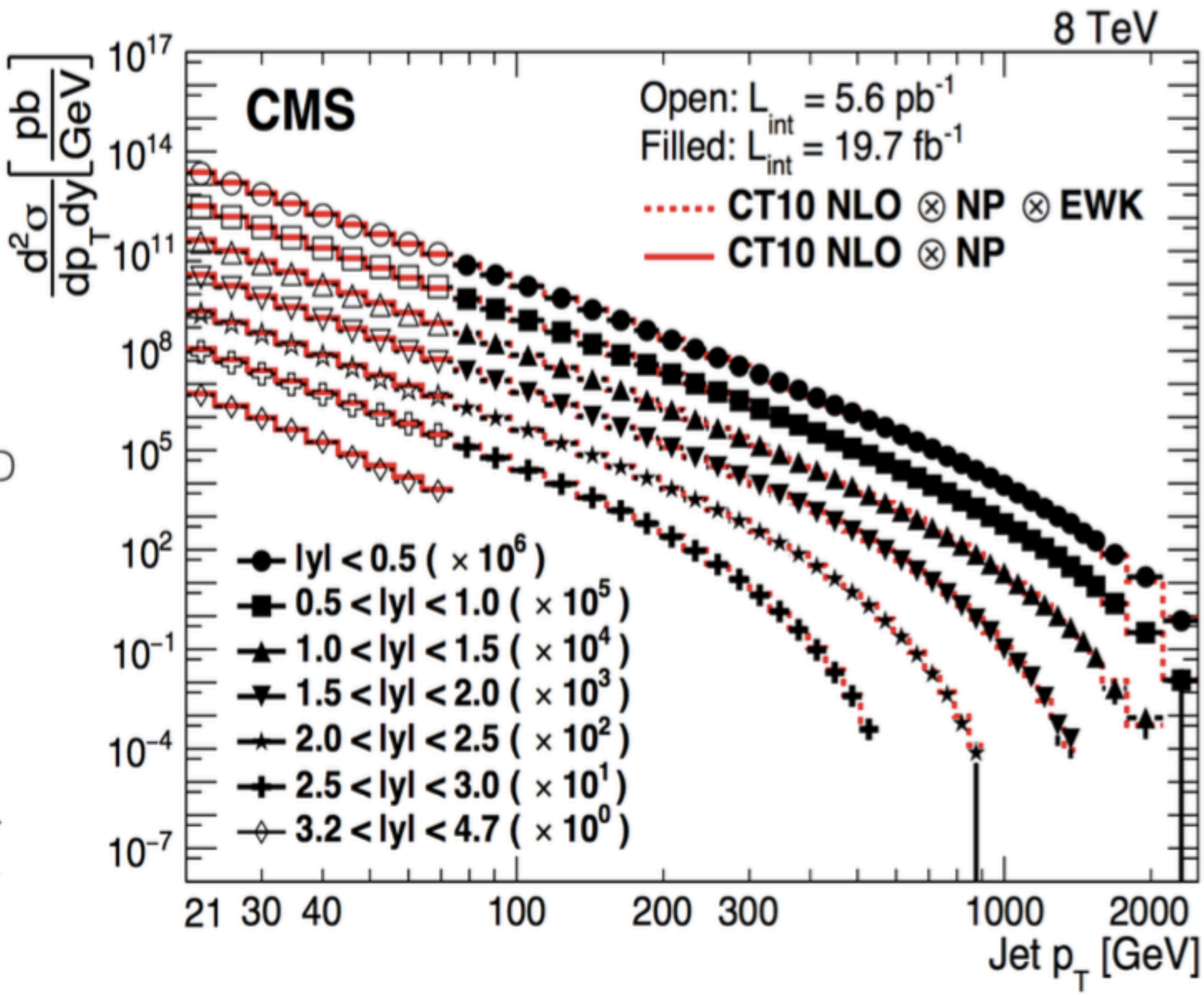


JINST 12 (2017) P02014

Inclusive jets @ 8TeV

- Inclusive jets within $0 < |y| < 4.7$ and $p_T \geq 21\ GeV$
- QCD benchmark
  - used to constrain collinear PDF
  - used to measure α_s
  - benchmark for all QCD MC generators at LO and NLO !
- sets the level of experimental uncertainties
  - JES uncert. leads to ~ 2-4% at low, up to ~ 20 % at highest p_T

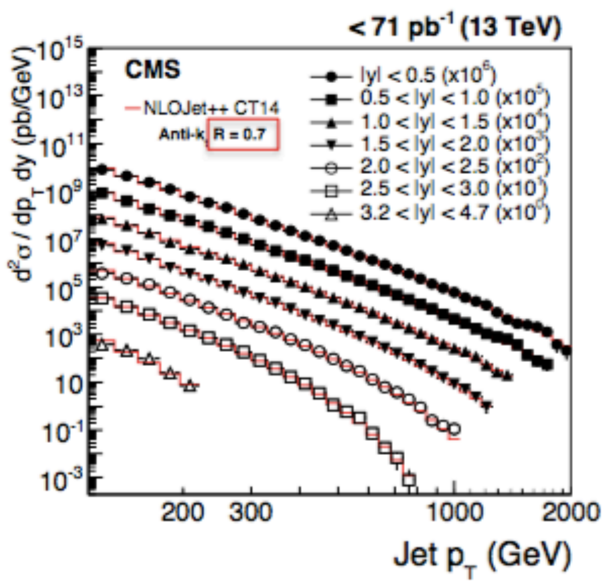
CMS JHEP 1703, 156 (2017)

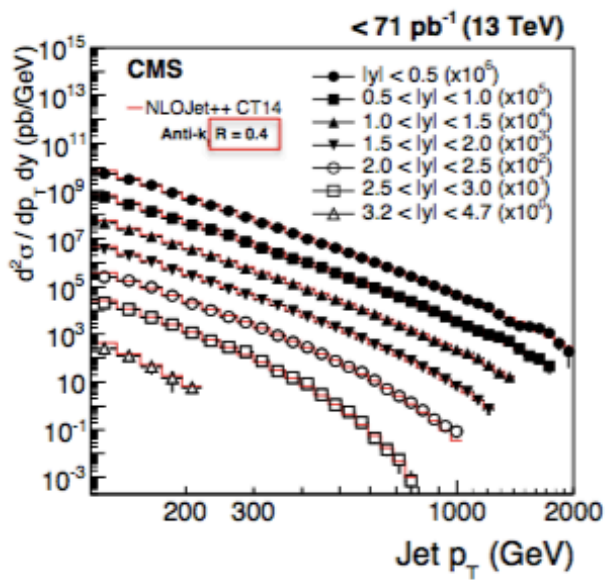


Inclusive cross section @ 13 TeV

EPJC 76 (2016) 451

- first indication that jet physics is as well understood at 13 TeV as at smaller centre-of-mass energies
- double-differential inclusive jet cross section with 71 pb^{-1} data extends to $|y|$=4.7, p_T=2TeV (similar reach as with 20 fb^{-1} of 8 TeV data)
- jets are reconstructed with the anti-*k*T clustering algorithm for two jet sizes: 0.4, 0.7
- compared to predictions of pQCD at NLO precision, complemented with EWK and nonperturbative (NP) corrections and NLO + PS
- data in good agreement with NLO calculations

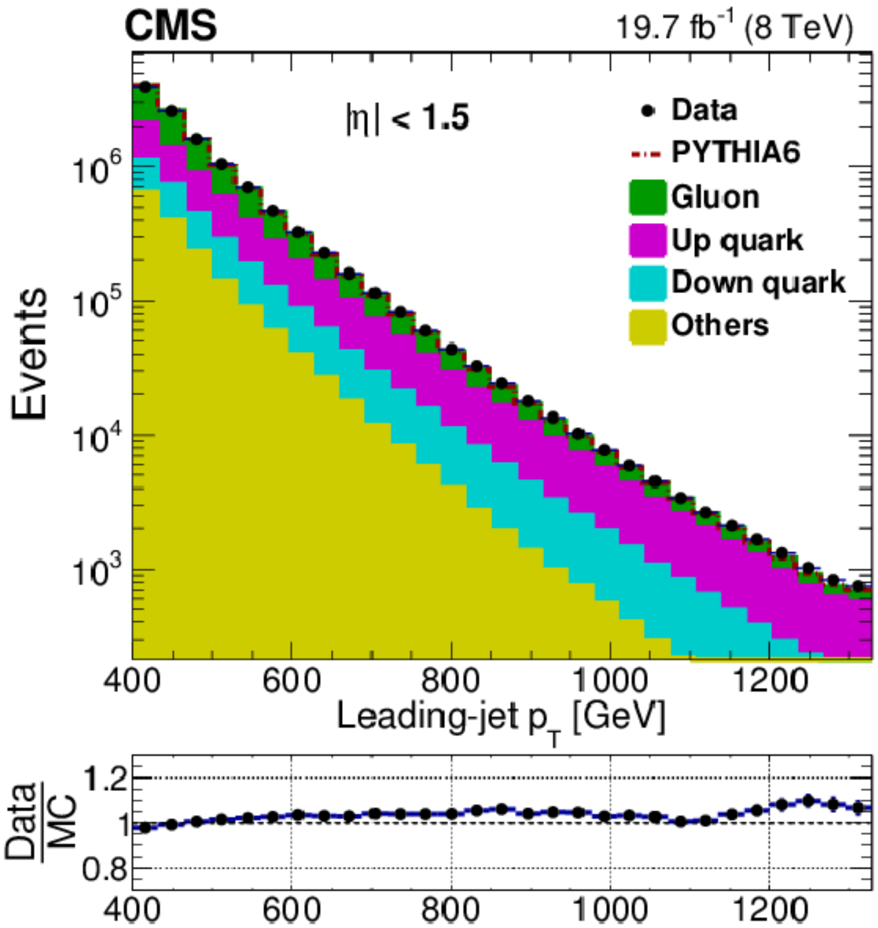




POWHEG+Pythia8 gives a good agreement both for R 0.4 and 0.7

Leading-jet p_T distribution @8 TeV

arXiv:1706.05868



The jet parton type composition of the selected dijet sample depends on the leading-jet *p*T

The filled histograms show the contributions from different types of initiating partons, identified by means of a matching algorithm

The "others" category represents those jets that are initiated by parton types, the up antiquark, the down antiquark, the charm, strange, and bottom quarks and antiquarks, and any unmatched jets.

Data (points) compared to PYTHIA6 simulation

Only statistical uncertainties are shown

Jet charge definition

arXiv:1706.05868

Estimator for the electric charge of a quark, antiquark or gluon initiating a jet, based on the momentum-weighted sum of the measured electric charges of the jet constituents

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

Three different charge observables of the leading jet

$$Q_L^{\kappa} = \sum_i Q_i \left(p_{\parallel}^i\right)^{\kappa} \Big/ \sum_i \left(p_{\parallel}^i\right)^{\kappa}$$

$$Q_T^{\kappa} = \sum_i Q_i \left(p_{\perp}^i\right)^{\kappa} \Big/ \sum_i \left(p_{\perp}^i\right)^{\kappa}$$

19.7 fb^{-1} proton-proton collisions at $\sqrt{s}$ = 8 TeV
dijet events with HLT trigger requiring at least one jet with transverse momentum $p_{\mathrm{T}} > 320$ GeV

$$p_{\parallel}^i = \vec{p}^{\,i} \cdot \vec{p}_{\mathrm{jet}} / |\vec{p}_{\mathrm{jet}}| \text{ and } p_{\perp}^i = |\vec{p}^{\,i} \times \vec{p}_{\mathrm{jet}}| / |\vec{p}_{\mathrm{jet}}|$$

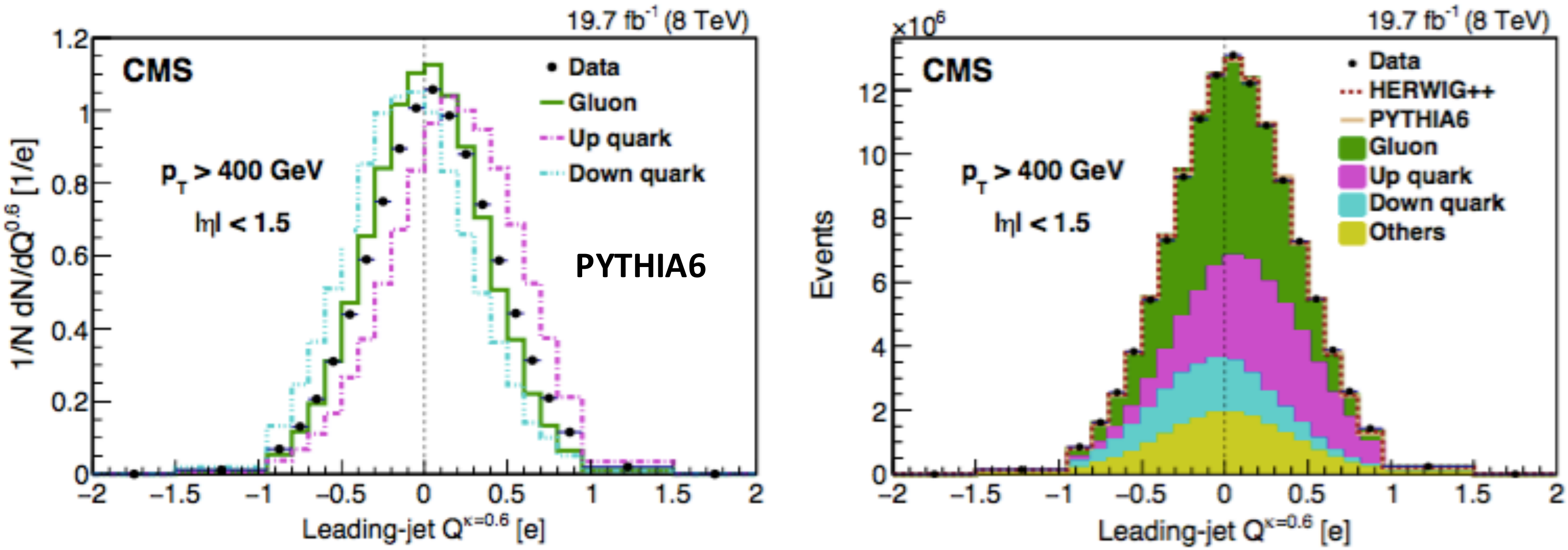
The sums are over all color-neutral (electrically charged and neutral) particles *i* in the jet that have $p_{\mathrm{T}} > 1$ GeV. ➔ dependence on # of pileup interactions negligible

The κ parameter in the exponent of the particle momenta controls the relative weight given to low and high momentum particles contributing to the jet charge. Three values of κ are investigated: 0.3, 0.6, and 1.0

Jet charge: comparison with LO MC generators

It is important to identify the object initiating a jet by means of the properties of the reconstructed particles that define the jet.
The type of partons that initiate jets – **quark jets, antiquark jets, or gluon jets** – are distinguished at leading order (LO) in QCD

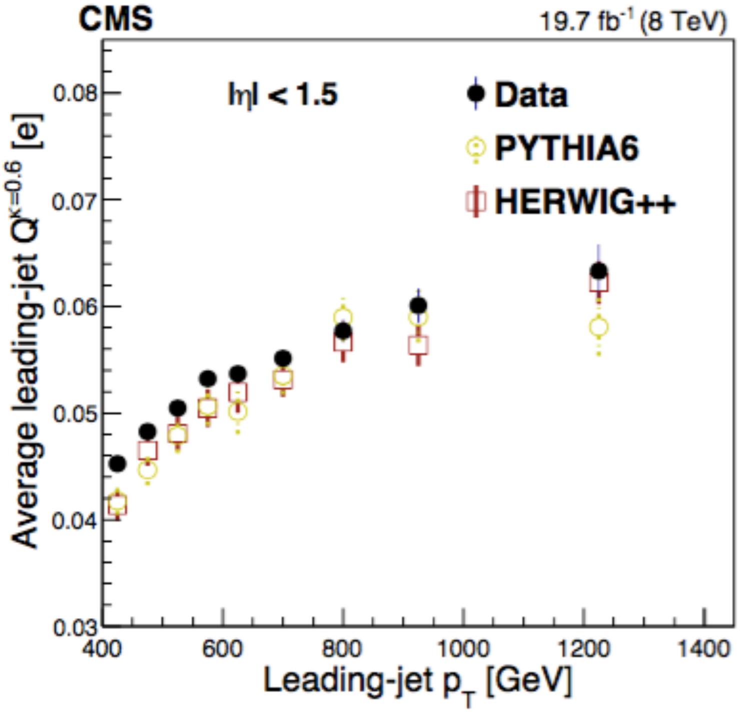
arXiv:1706.05868v1



jet charge data UNCORRECTED distribution compared with multijet predictions from PYTHIA6 and HERWIG++

≈55% of the down quark jets and ≈45% of the gluon jets can be rejected at a selection efficiency of 70% for up quark jets

Jet charge vs leading-jet p_T



Estimated uncertainty in the jet energy scale 1–2.5% depending on the jet p_T and η

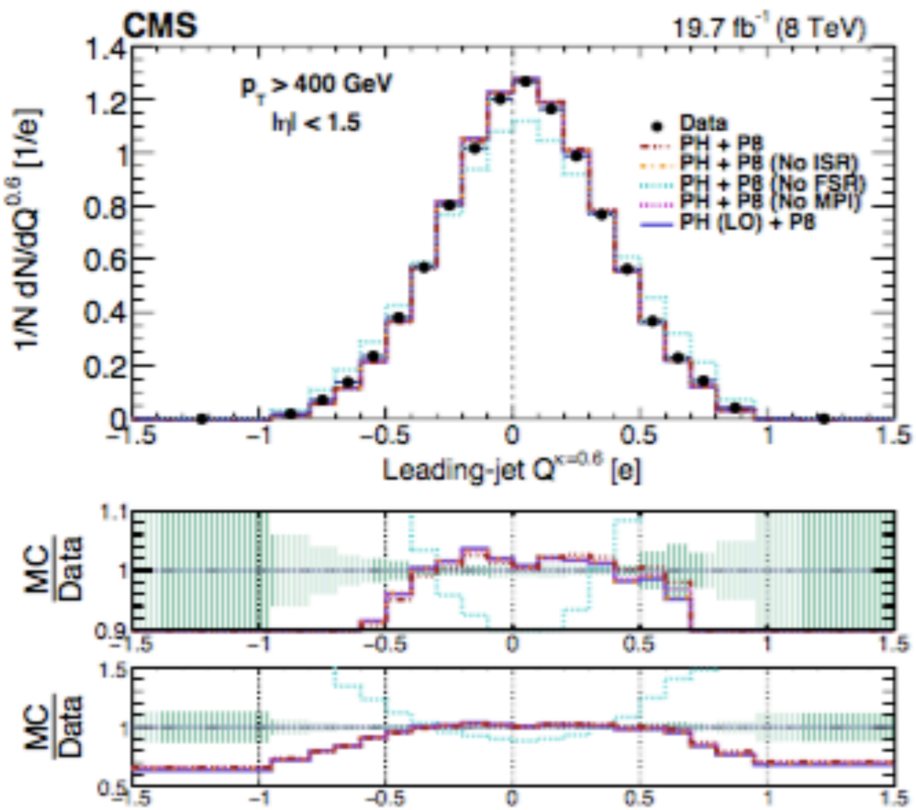
Gluon jets dominate the lower part of the p_T spectrum, while up quarks become progressively more relevant at high p_T

Difference between jet charge distributions at the generator level and the reconstructed level in PYTHIA6 increases with decreasing κ values, because the definition of jet charge for small values of κ gives more weight to low-p_T particles, which have a track reconstruction efficiency of about 90%.

3 definitions of jet charge ➔ sensitive to parton fragmentation
3 choices of κ parameter ➔ sensitive to the softer and harder particles in jet

Jet charge (κ = 0.6) vs NLO predictions

To compare with other measurements or theoretical predictions, the measured jet charge distributions must be unfolded from the resolution at the detector level to the final-state particle level.



POWHEG + PYTHIA8 ("PH+P8")

NLO POWHEG with the NLO CT10 PDF set compared with disabled in PYTHIA8:

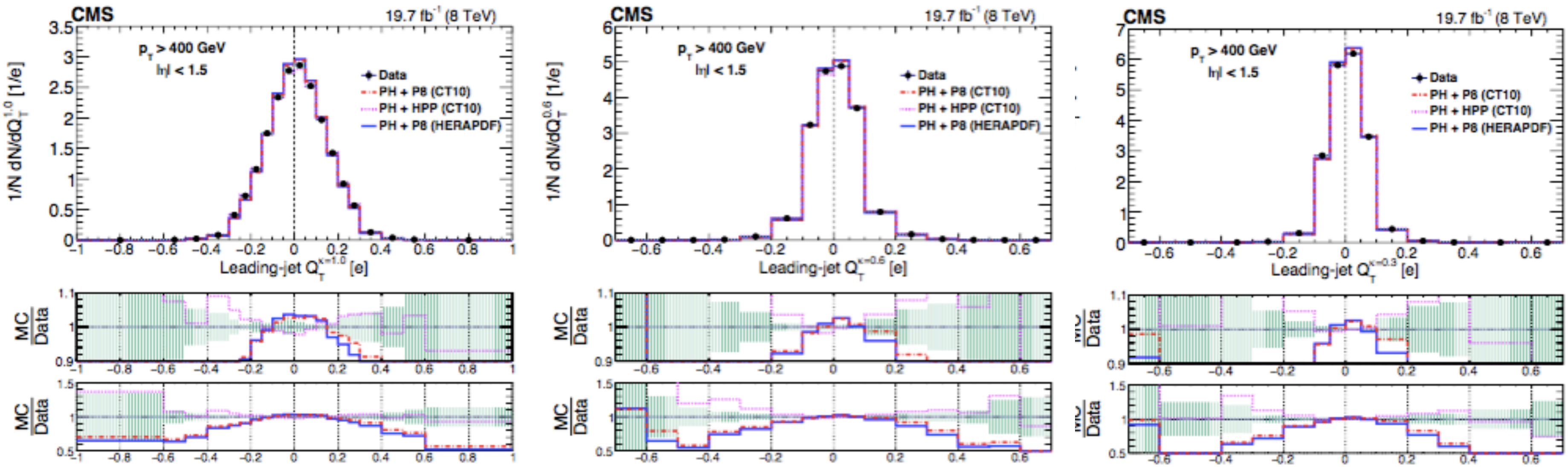
initial-state radiation ("No ISR")
final-state radiation ("No FSR")
multiple-parton interactions ("No MPI")

LO POWHEG using LO CTEQ6L1 PDF set ("LO")

Final state PS makes the dominant effect on the jet charge

Hashed uncertainty bands include both statistical and systematic contributions in data, added in quadrature.

Transverse jet charge (κ = 1, 0.6, 0.3)



POWHEG + PYTHIA8 with:
NLO CT10 PDF "CT10"
NLO HERA- PDF 1.5 "HERAPDF"

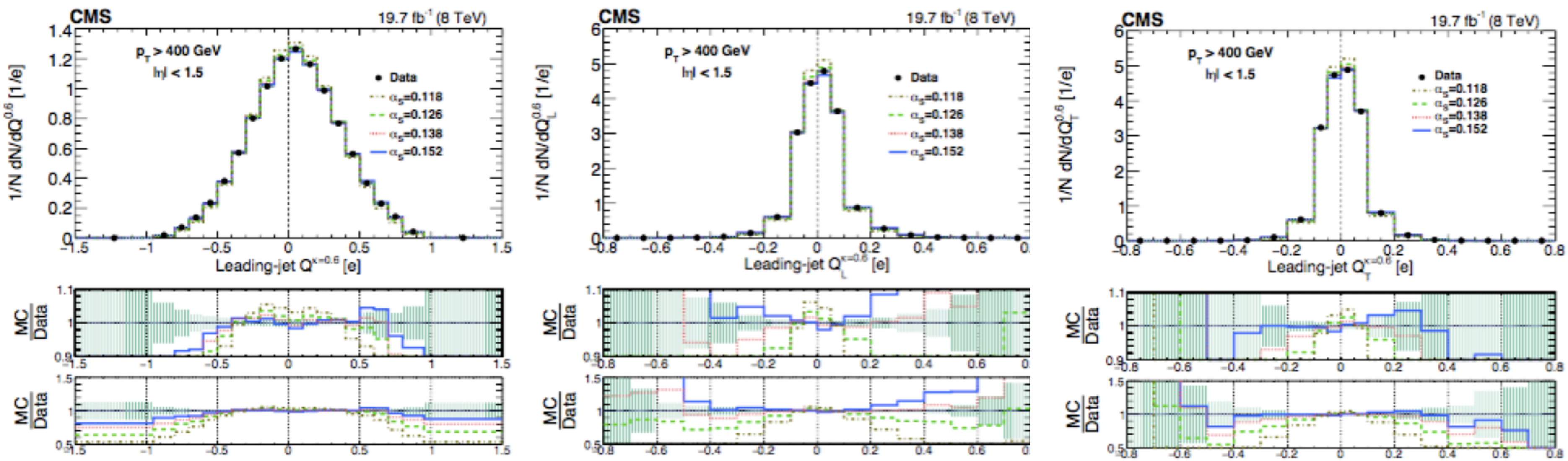
POWHEG + HERWIG++ "PH+HPP"

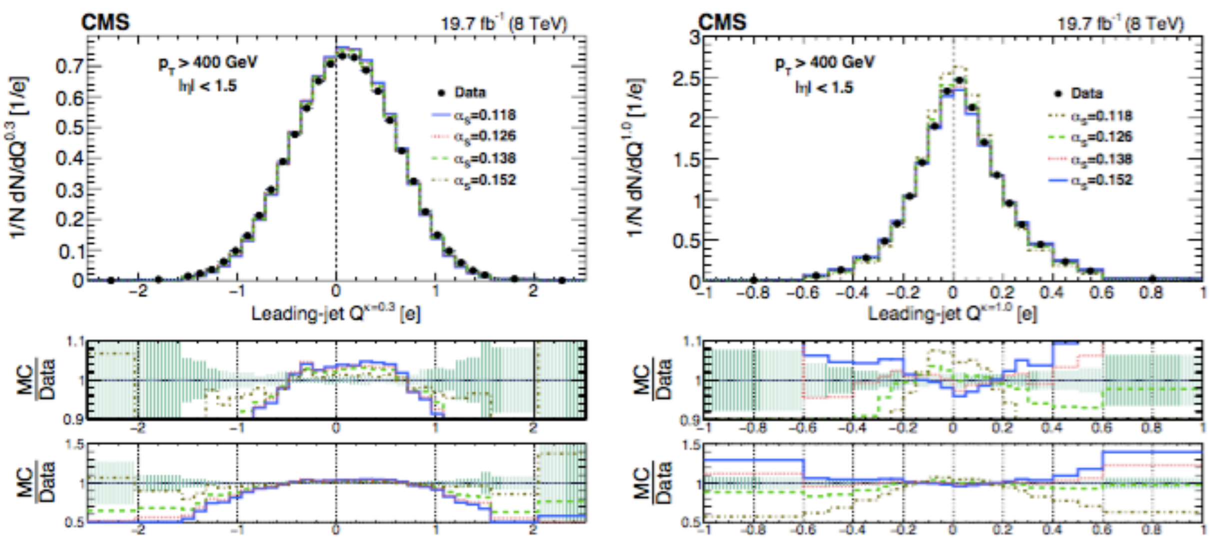
Experimental uncertainties are generally larger for small values of κ as well as for $Q_{\kappa T}$ because of the larger weights given to soft particles.

For $Q\kappa$ and $Q\kappa L$ POWHEG + PYTHIA8 and POWHEG + HERWIG++ show similar levels of agreement.
For $Q\kappa T$ both generators diverge significantly from data in most of the range.

The two generators differ systematically for the three definitions of jet charge
➔ this measurement can constrain such modeling predictions

Jet charge (κ=1, 0.6, 0.3) vs α_S parameter





NLO POWHEG + PYTHIA8
NLO CT10 PDF set

α_S parameter for final-state radiation in PYTHIA8 is varied from its default value of 0.138

The same α_S parameter cannot be used for all the jet charge distributions ➔ test aspects of the model that cannot be accommodated by a single parameter

Differential jet production cross section

as a function of the jet mass and transverse momentum

CMS PAS SMP-16-010 **pp collisions @ 13 TeV**

dijet topology R=0.8 at least two jets, without an explicit third jet veto
p_T asymmetry satisfies $(p_{T1} - p_{T2})/(p_{T1} + p_{T2}) < 0.3$
$\Delta(\varphi_1 - \varphi_2) > \pi/2$ to reduce the number of jets from detector noise

with and without a jet grooming algorithm ➔ separates hard and soft portions of the jet
"soft drop" grooming algorithm used

ungroomed jets: all MC event generators predict jet mass spectrum within uncertainties in the data for intermediate masses of about 10-30% of the jet transverse momentum
Outside of this range, some disagreement is observed.

groomed jets: jet mass peak suppressed and precision in the low and intermediate regions improved, since portions of the jet from soft radiation that are difficult to model cancelled

Experimental uncertainties: JES, JER, JMS, JMR, pileup
Theoretical uncertainties: physics model (parton shower and tuning) and PDFs

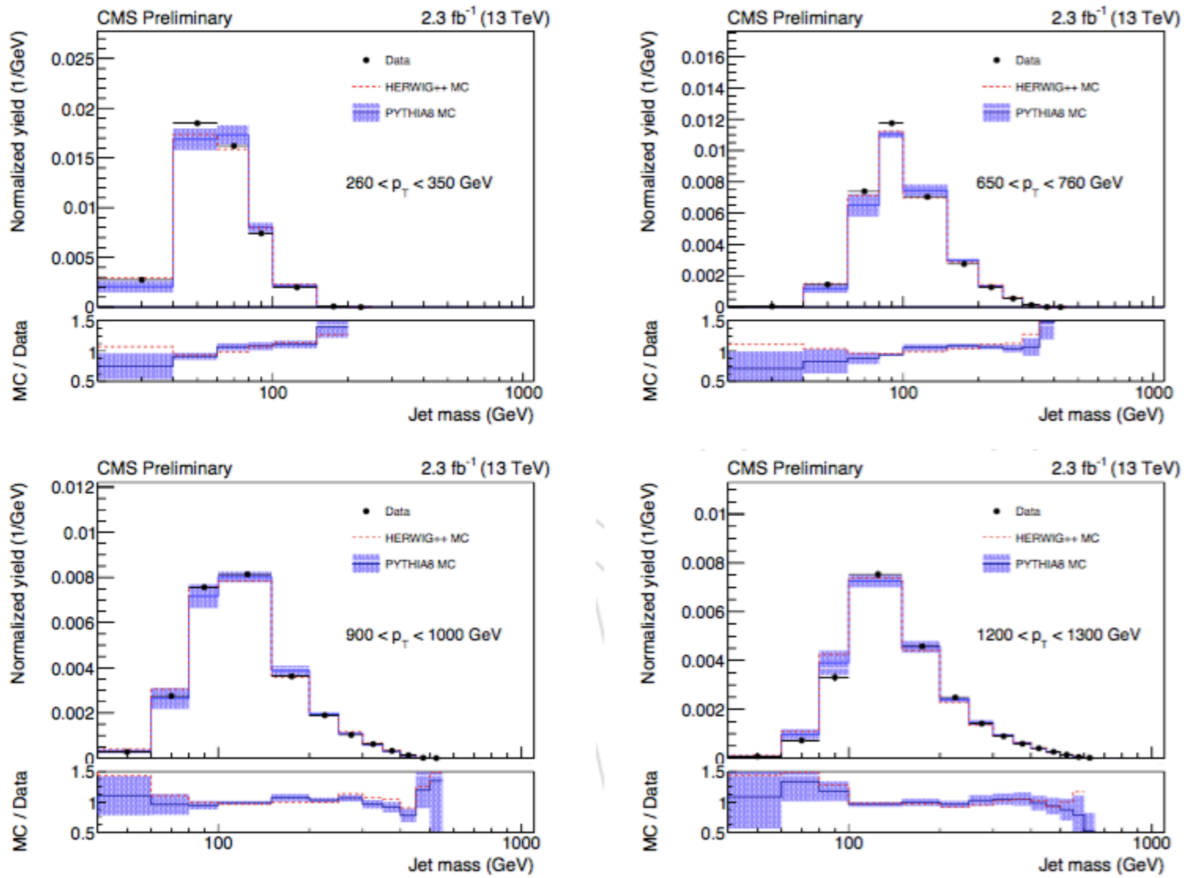
Jet mass

Mass is more sensitive to the internal structure of jets, theoretically described by QCD PS

Predicting jet mass is complicated ➔ singularities from emissions at very low energies ("soft") or at very small angles ("collinear") compared to the momentum of the original quark or gluon (the "hard" component). At NLL the phase space available to the decay is restricted in the collinear and soft regimes, suppressing the singularities.

$m/p_T \approx 0.1$ "Sudakov peak" ➔sensitive to soft QCD effects and to pileup

Above $m/p_T \approx 0.3$ jet splitting threshold



CMS-PAS-16-010

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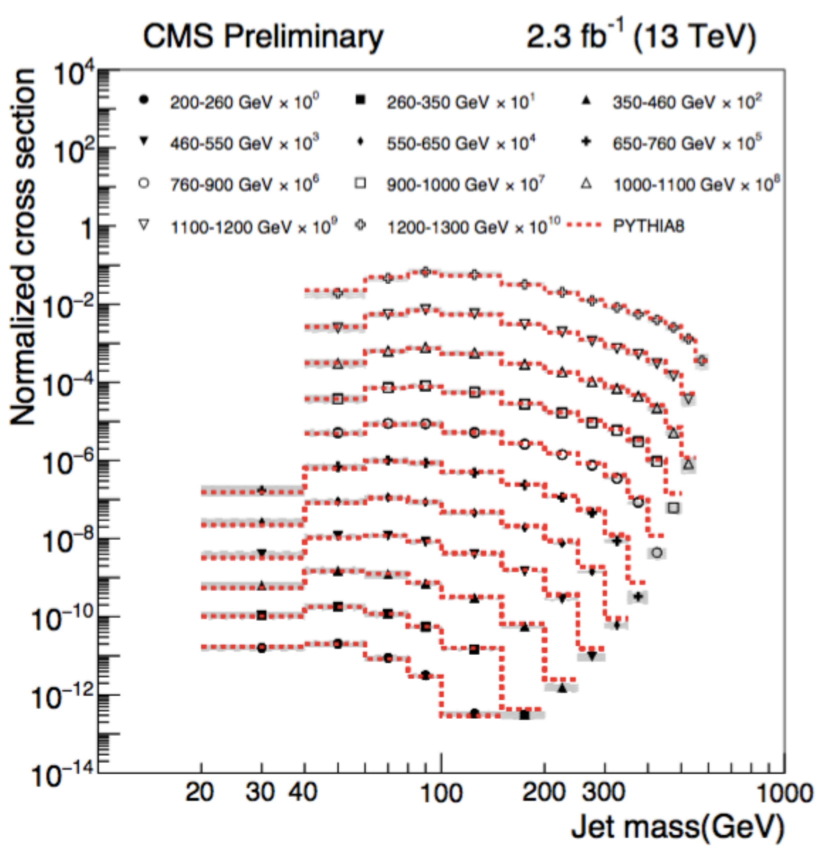
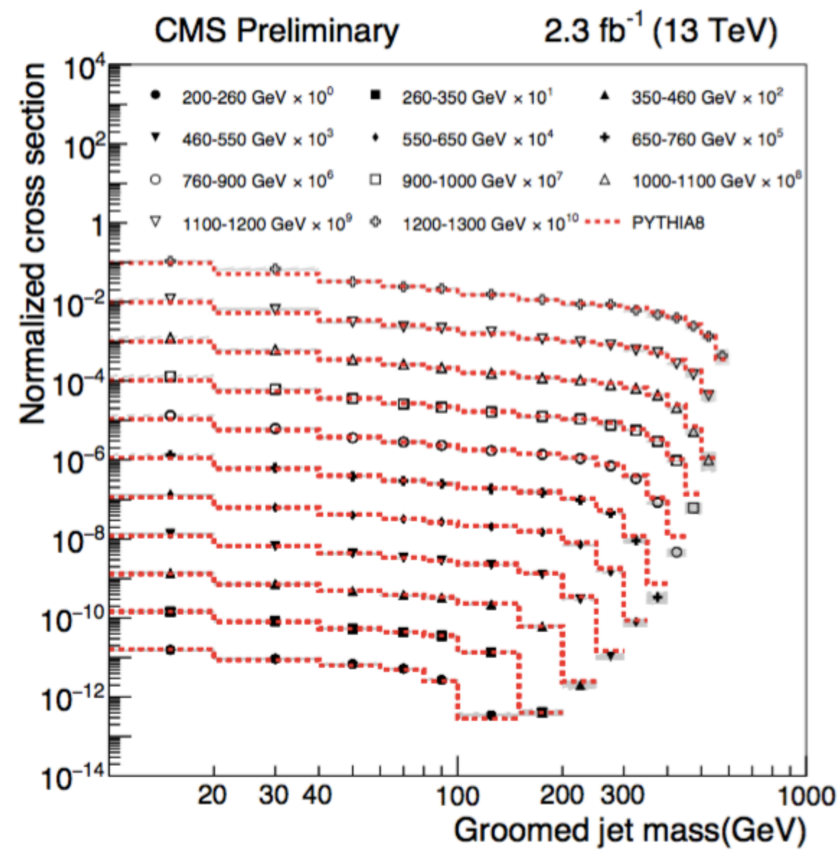
Normalized double differential cross section

The jet masses after unfolding for all p_T bins for the ungroomed and groomed jet
unfolding in both transverse momentum and mass





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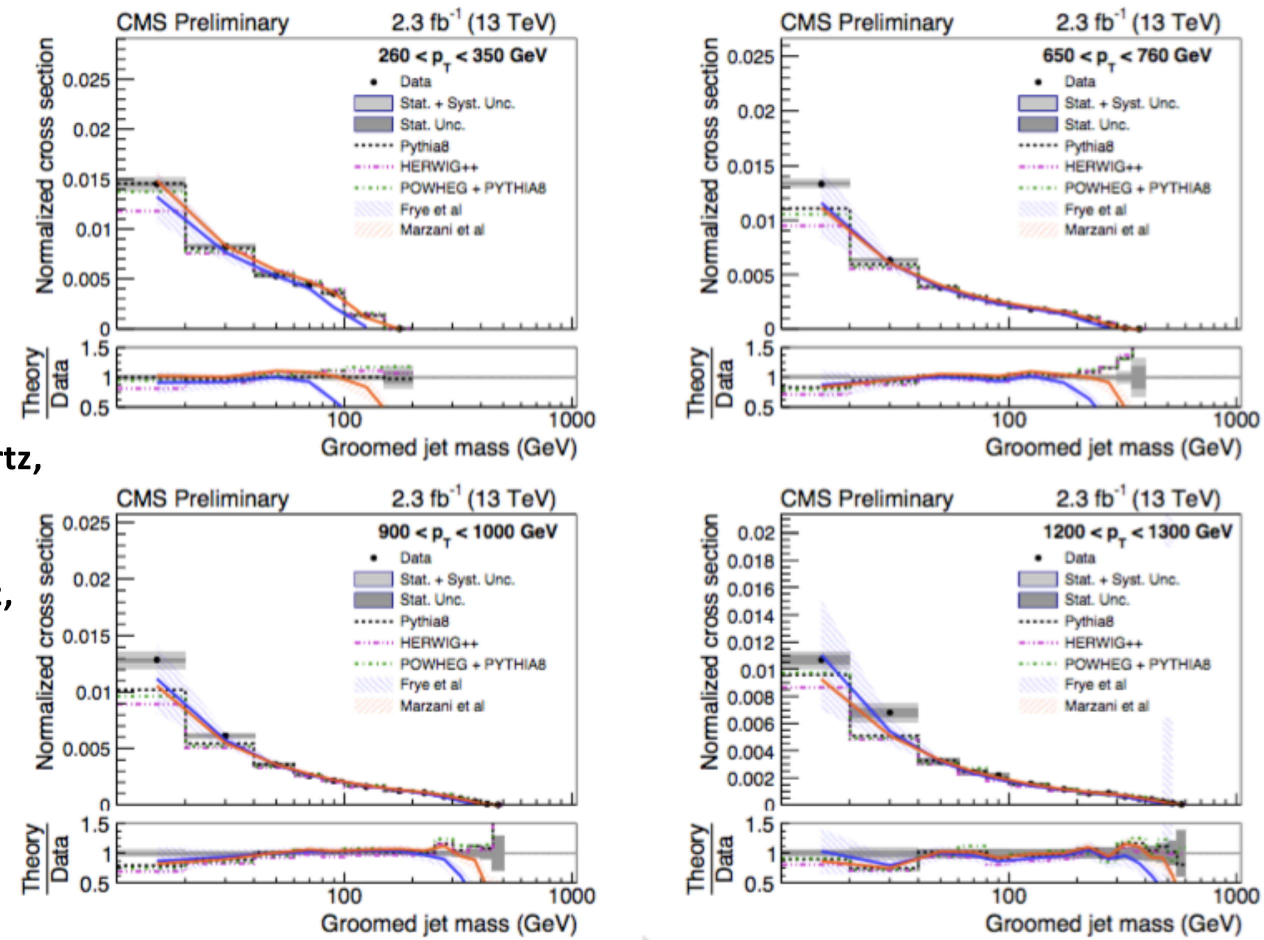
Jet mass after unfolding groomed jet

Sudakov peak suppressed and improved precision in $0.1 < m/p_T < 0.3$ region (soft radiation removed)

$m/p_T < 0.1$ disagreement between PYTHIA8 (better prediction) and HERWIG++ as for ungroomed jets

Semi-analytical calculations beyond NLL agree with each other, and predict the data at $m/p_T < 0.3$ where wide jets start to be split into two

CMS PAS SMP-16-010



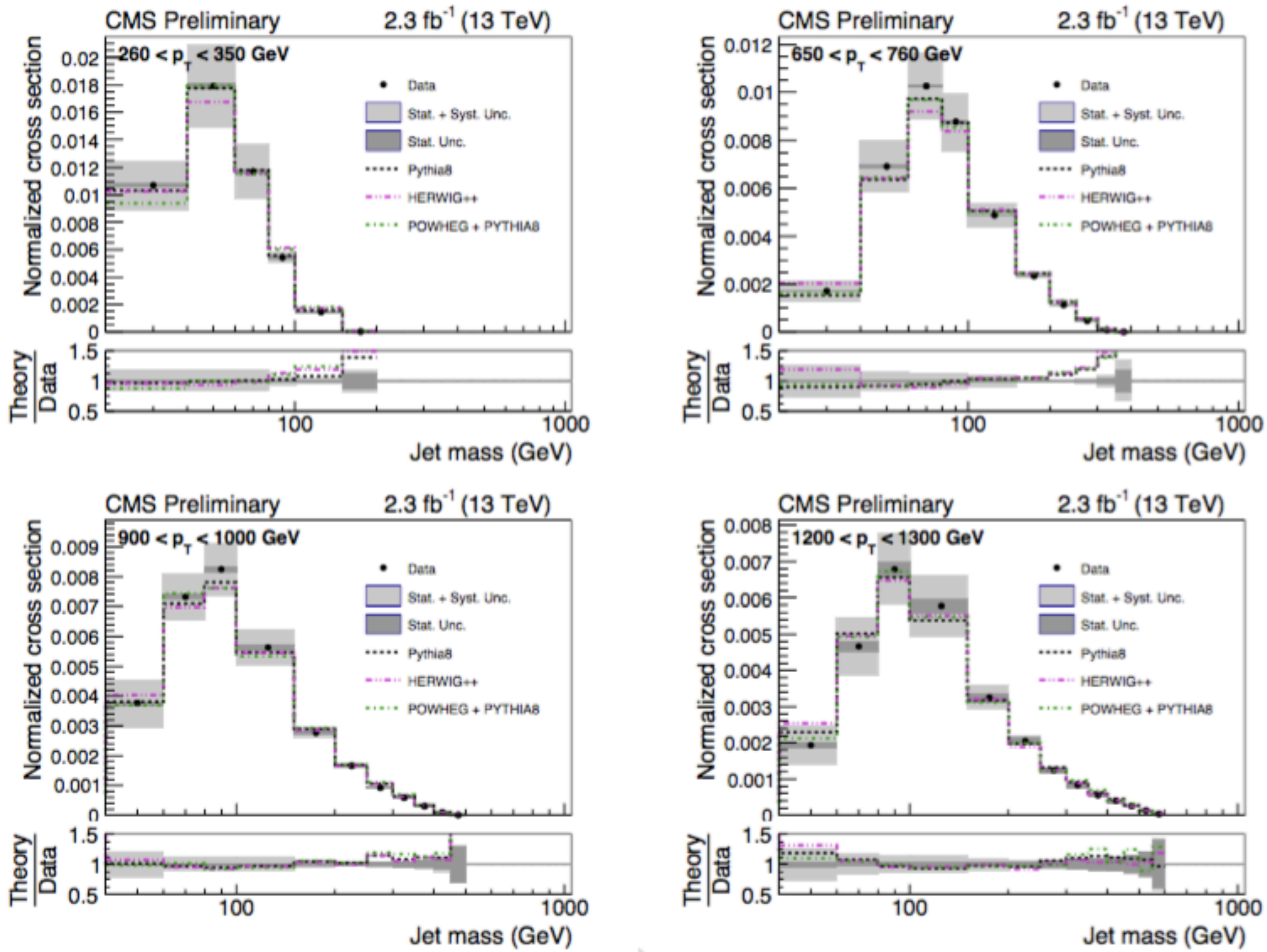
C. Frye, A. J. Larkoski, M. D. Schwartz, and K. Yan, *JHEP* 07 (2016) 064

S. Marzani, L. Schunk, and G. Soyez, arXiv:1704.02210.

Jet mass after unfolding ungroomed jet

***m/p*$_T$ < 0.1** large variations (> 20%) between the predictions from PYTHIA8 and HERWIG++
***m/p*$_T$ > 0.3** predictions from PYTHIA8 and HERWIG++ agree but overpredict by 20–50%
no significant difference when POWHEG+PYTHIA8 is used compared to PYTHIA8 alone.

CMS-PAS-16-010



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Conclusions

- Entering a new region never reached before: jets with p_T>3 TeV

➔ **Precision measurements in the medium to high p_T range**

- Excellent understanding of jet reconstruction and calibration
- Various jet measurements improve our understanding of QCD

➔ **Theory comparison in good agreement with measurement in the new phase space**

- Comparison with physics modeling to improve BSM searches

➔ **Semi-analytical calculations beyond next-to-leading logarithmic accuracy of groomed jet mass compared to the data for the first time at a hadron collider**

The study of jets and QCD is a key component to extend our understanding of the SM and for searches beyond the SM

Exciting times ahead with improved calculations and more data !!