Low-x QCD

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on behalf of the CMS Collaboration

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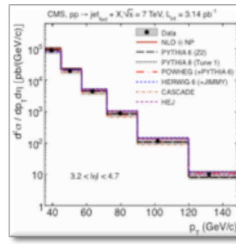
Outline

Motivation for small-x QCD studies at CMS

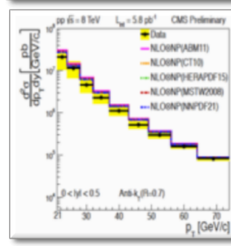
Apparatus:
CMS forward detectors

Measurement

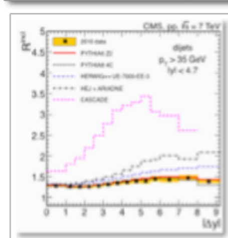
- Forward and forward-central jets spectrum (7 TeV)



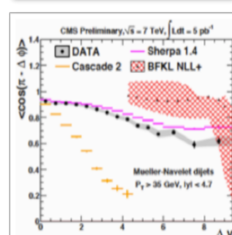
- Low p_t jets (8 TeV, 2012 data)



- Ratios of inclusive to exclusive cross-sections



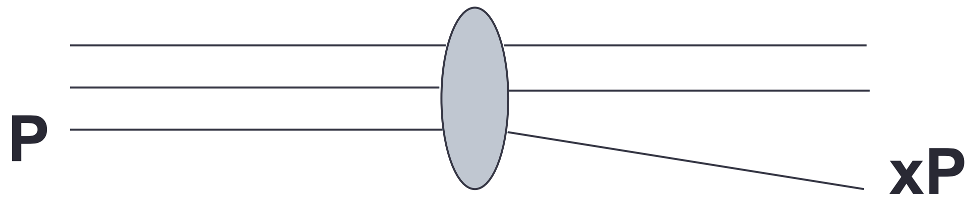
- Azimuthal angle decorrelations of Mueller-Navelet jets



Summary
Outlook

Small-x QCD (1)

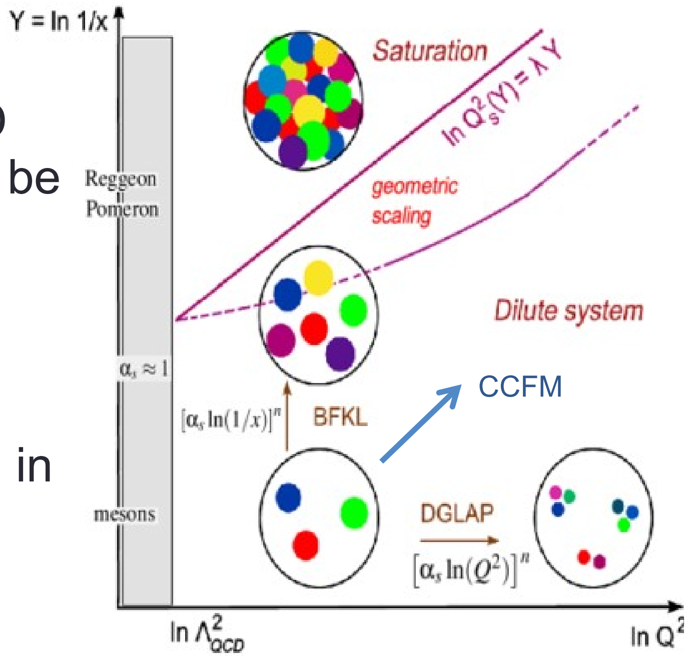
- Term „small-*x*" corresponds to a small fraction of proton momentum carried by an interacting parton (gluon or quark).



- Why interactions between small-*x* objects are so interesting? (it is not a full list, of course…)

1. In small-*x* region standard approach to NLO QCD perturbative calculations (DGLAP) is predicted to be not sufficient. An alternative is BFKL/CCFM.

2. Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data. We gain new region of phase space that can be used in tuning.



Small-x QCD (2)

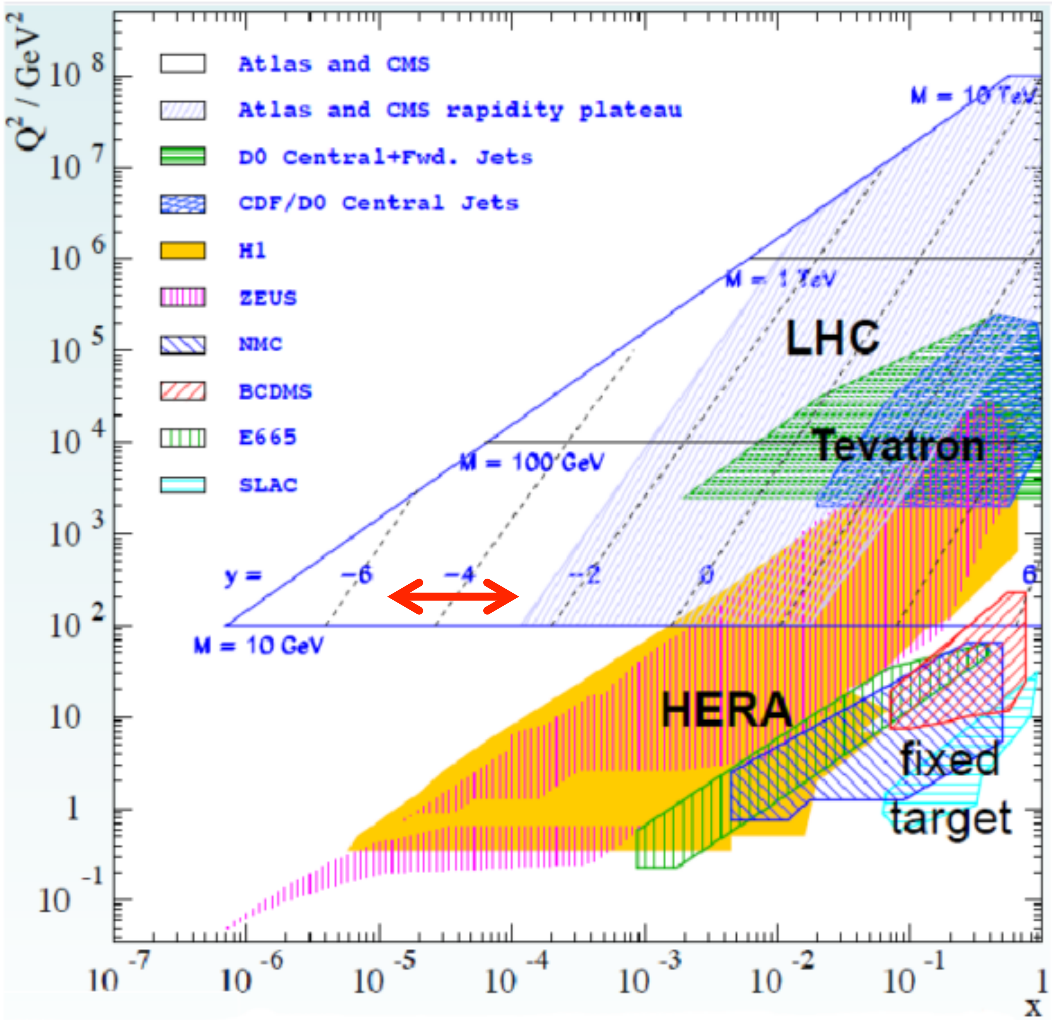
- A tool to study small-*x* QCD are forward jets – jets emitted at small angle with respect to the beam (large rapidity).

- Forward jets appear usually in asymmetric collisions $x_1 << x_2$.

$$x_1 = \frac{k_{1\perp}}{\sqrt{s}} e^{\eta_1} + \frac{k_{2\perp}}{\sqrt{s}} e^{\eta_2}$$

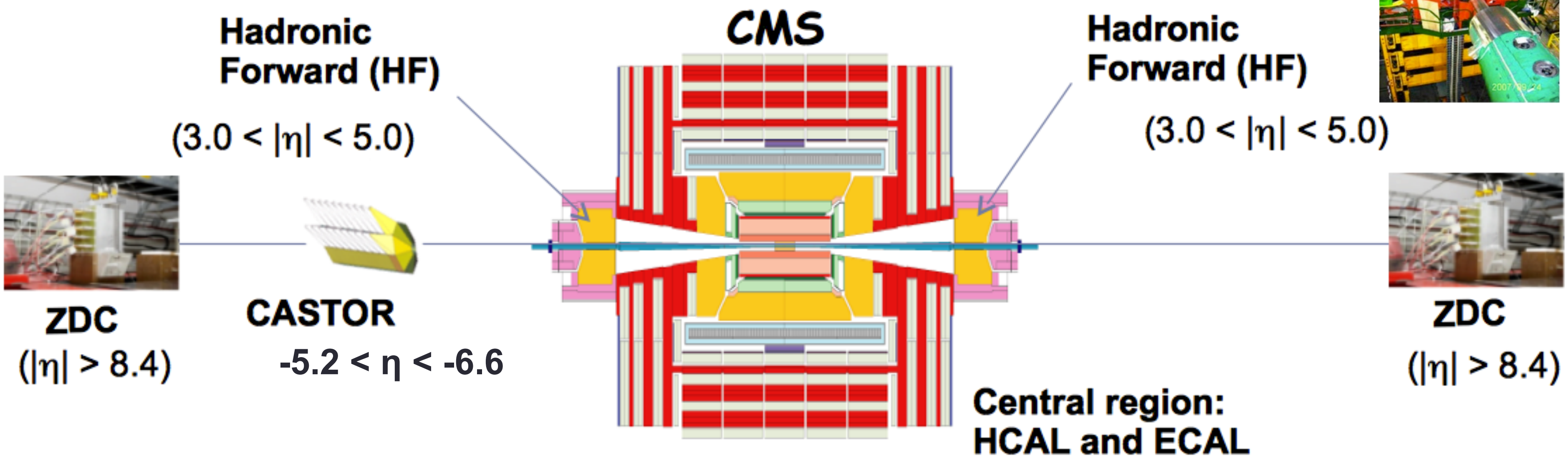
$$x_2 = \frac{k_{1\perp}}{\sqrt{s}} e^{-\eta_1} + \frac{k_{2\perp}}{\sqrt{s}} e^{-\eta_2}$$

- Forward jets with p_T>35 GeV in forward calorimeter (HF) reach $x_1 \sim 10^{-4}$, $x_2 \sim 0.2$.



Apparatus

- CMS has calorimeter coverage up to $|\eta|<5.0$.

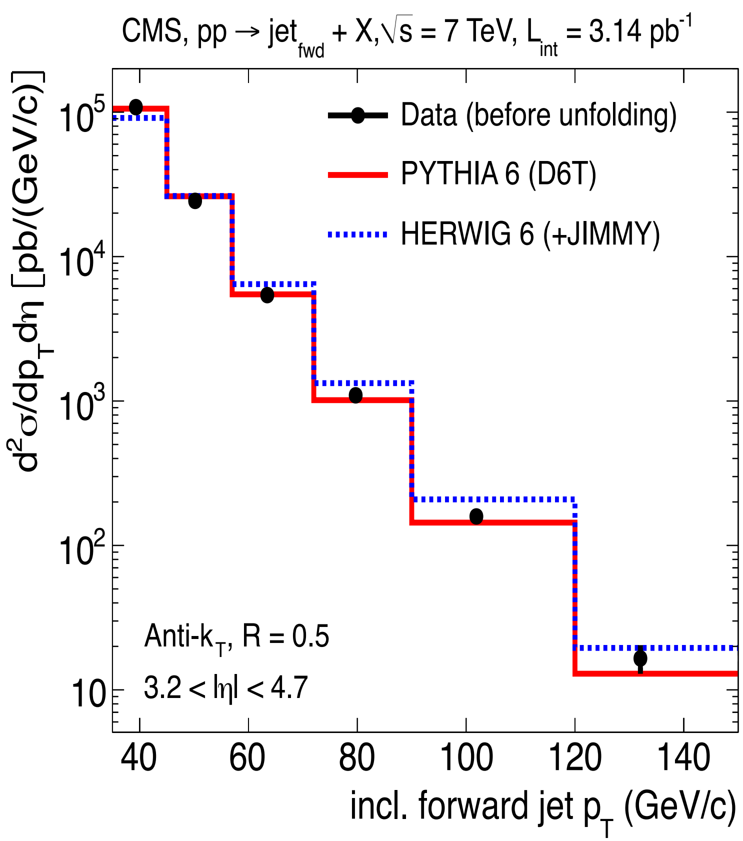


- For analyses presented here crucial are:
  - Brass/scintillator hadron calorimeter (HCAL) and crystal electromagnetic calorimeter (ECAL) for central rapidities.
  - Cherenkov-light Hadronic Forward (HF) calorimeter at $3<|\eta|<5$ rapidity.
- Some detectors may extend measured η range up to 6.6 or even further.

Inclusive cross-sections (1)

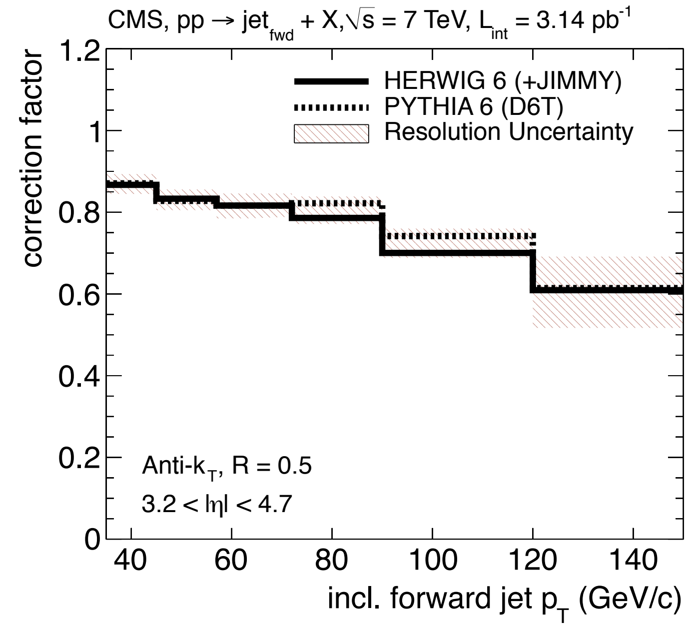
- Inclusive measurement of two topologies:
  - Forward jet present (3.2<|η|<4.7).
  - Forward jet and central jet (|η|<2.8) present.
- 2010 data analyzed, 7 TeV.
- p_T in the range 35-150 GeV.
- Jet reconstruction with anti-k_t algorithm, R=0.5.
- Raw jet energy corrected for the calorimeter response (jet energy scale).
- Right – forward jet spectrum after jet energy correction, before unfolding.

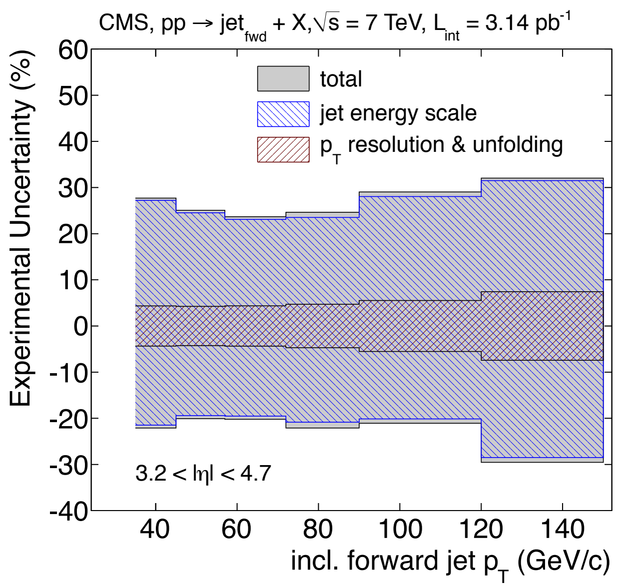
JHEP 1206 (2012) 036



Inclusive cross-sections (2)

- The problem is not only JES, but also Jet Energy Resolution. Migrations between bins at steeply falling spectrum cause large uncertainty.
- Results unfolded to the stable particle level with Pythia&Herwig.





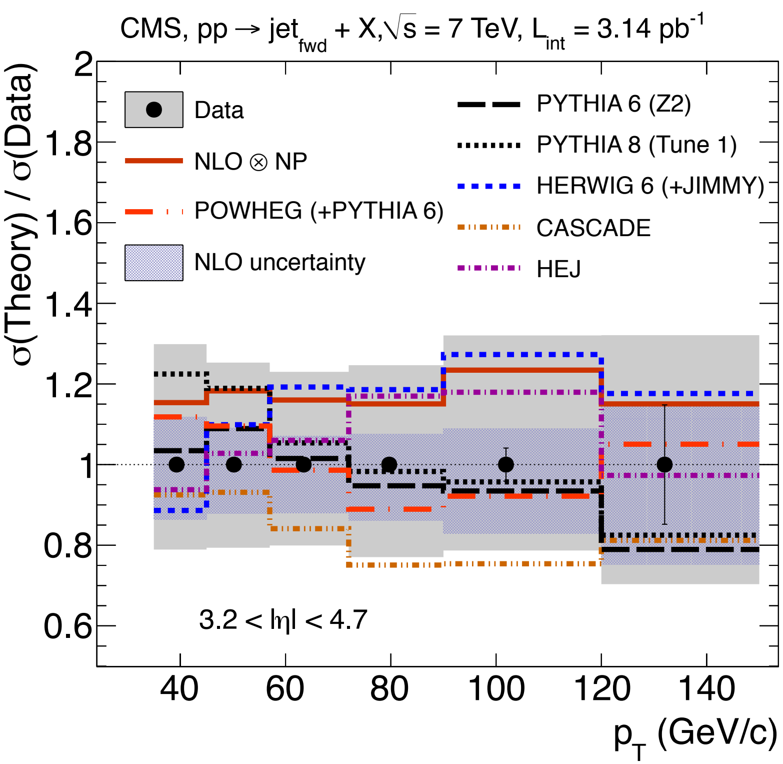
- Systematical uncertainty is estimated: ~30%.
- Largest input from JES

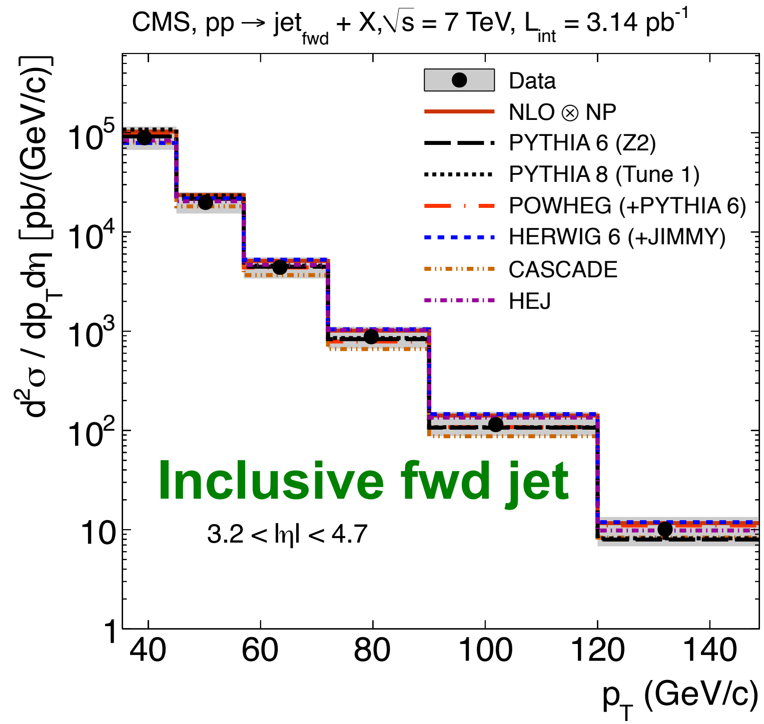
$$\frac{d^2\sigma}{dp_T\,d\eta} = \frac{C_{had}}{\mathcal{L}\cdot\varepsilon_t}\cdot\frac{N_{evts}}{\Delta p_T\cdot\Delta\eta}$$

- Final observable: $d\sigma/dp_T d\eta$ compared to different MC models: Pythia (DGLAP), Herwig (DGLAP), Cascade & Hej (CCFM/BFKL) and also NLO calculations (POWHEG and NLOJET++).

Inclusive cross-sections (3)

- First topology: presence of a jet in HF rapidity region (3.2<|η|<4.7).
- Results corrected for detector effects, syst. uncertainty as a gray band.

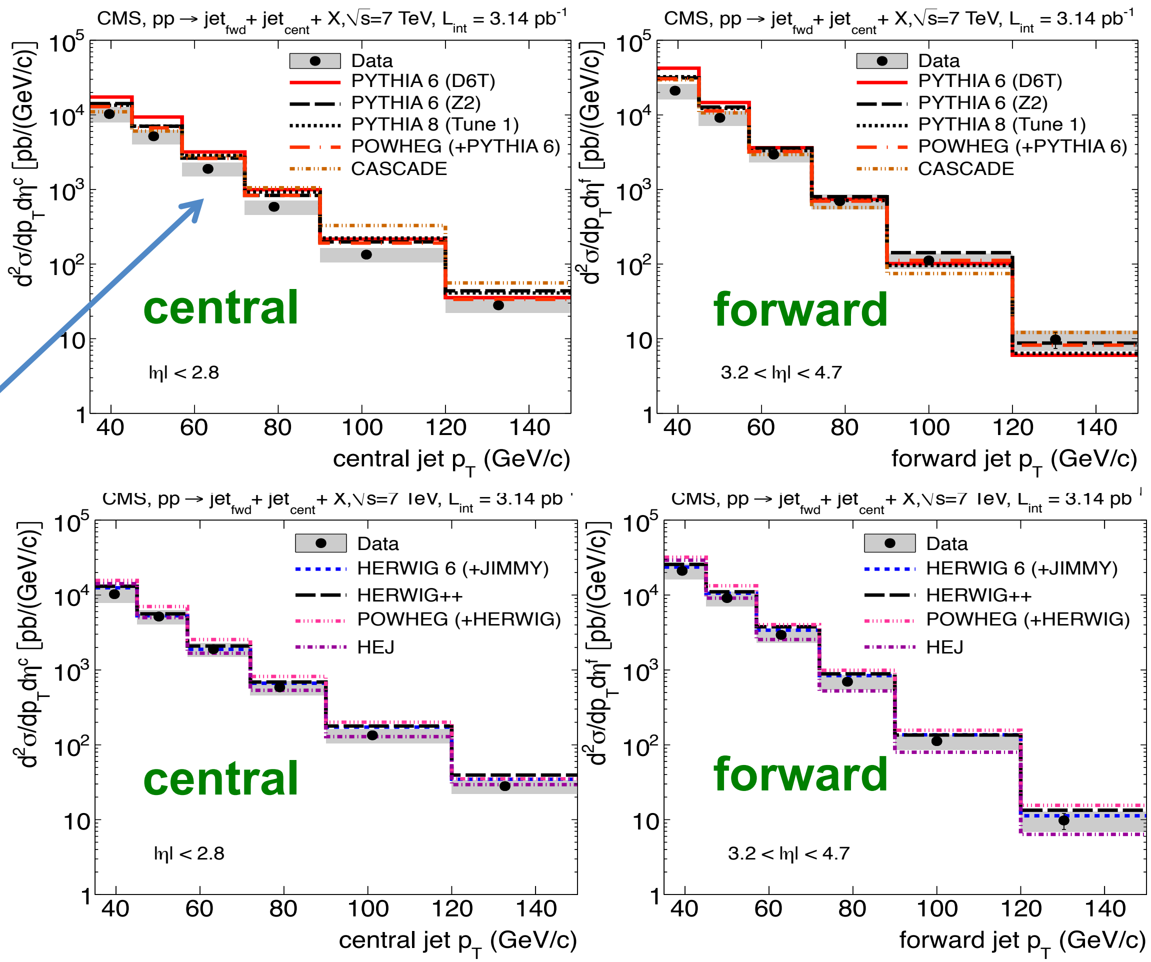




- Inclusive forward jets described properly by different MC models within uncertainties (experimental and theoretical).

Inclusive cross-sections (4)

- Second topology: Forward-central jets; same selection as for forward jet topology, additionally requiring at least one jet in the central region.

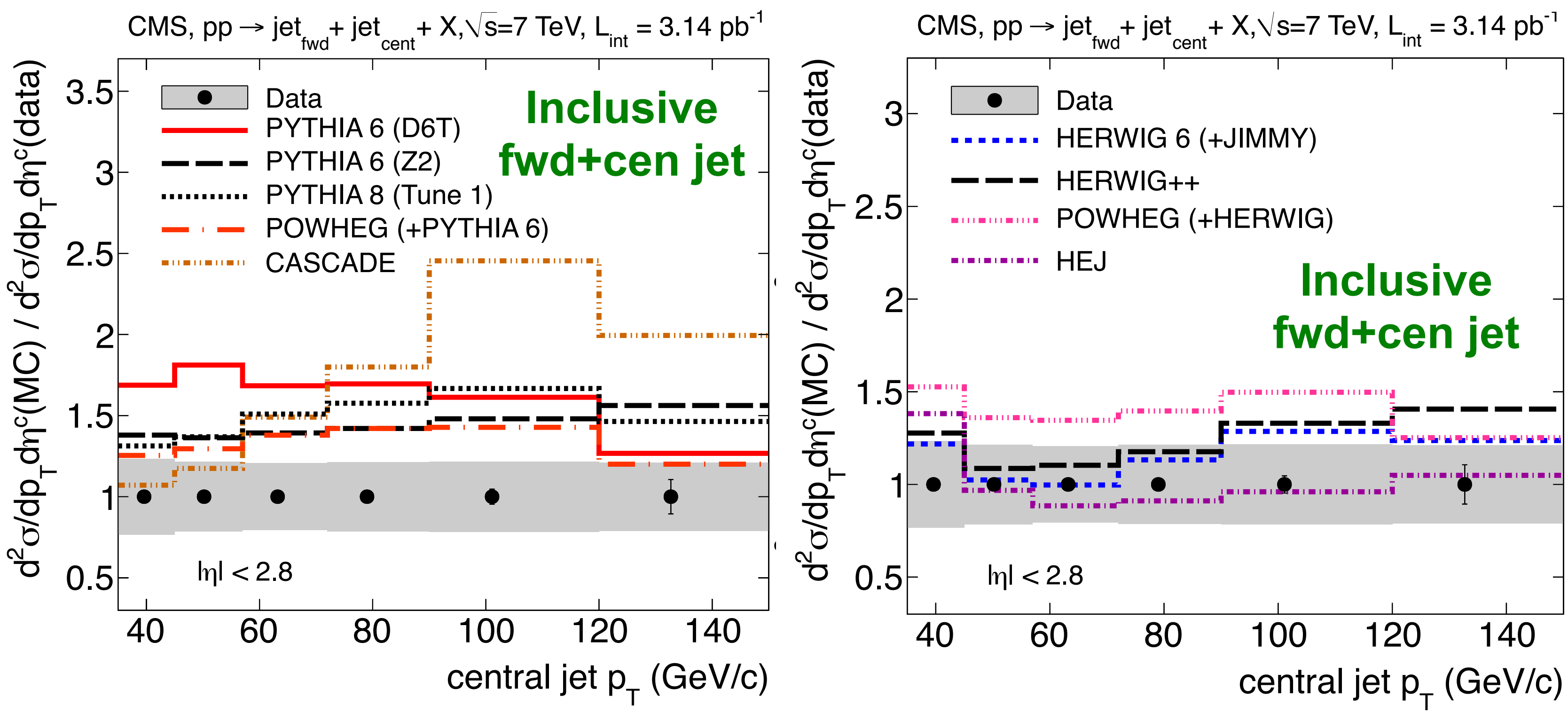


predictions are too large

Pythia 6, 8
Powheg
Cascade

Herwig6
Herwig++
Powheg
Hej

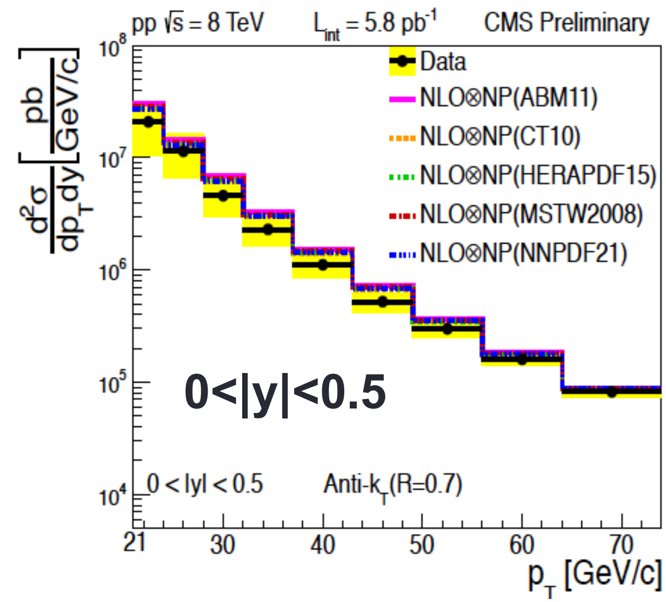
Inclusive cross-sections (5)

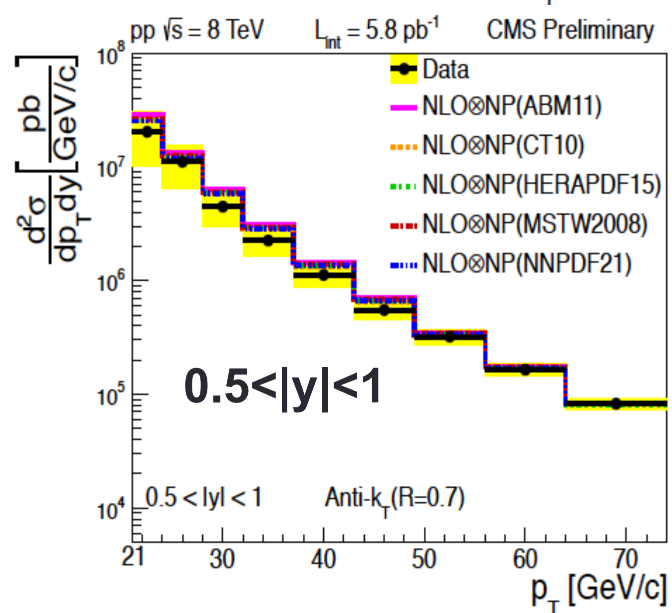


- Discrepancies for central jets observed, predicted values larger than measured.
- Herwig provides the best agreement (angular ordering for parton showering).
- Cascade predicts different behavior than observed in data.

Low p_t jets at 8 TeV (1)

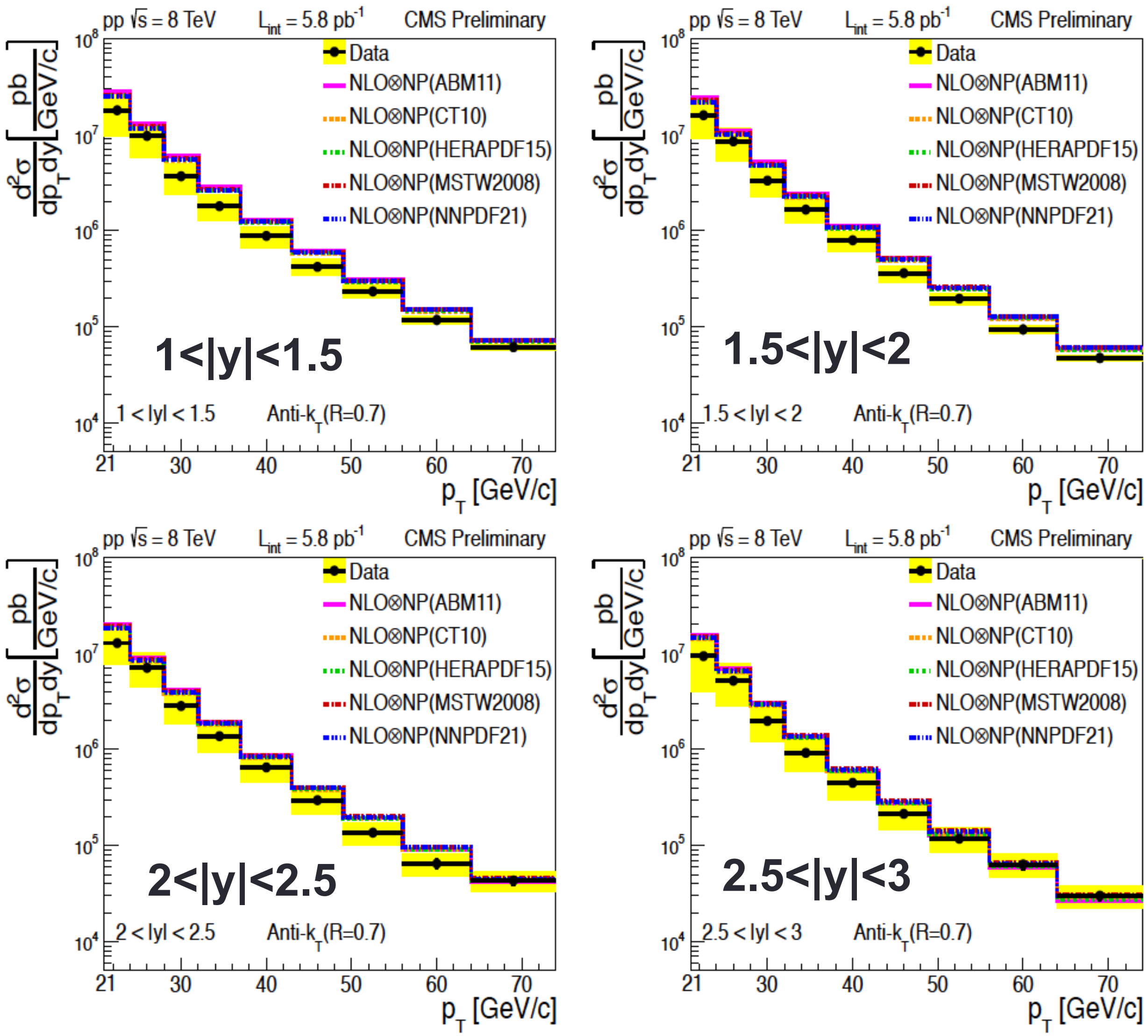
- Forward jets measured at the collision energy of 8 TeV (even smaller *x*).
- New measurement (8/2013): CMS-PAS-FSQ-12-031 based on 2012 data, 5.8 pb^{-1}
- Dedicated low pile-up run (4 interactions / bunch crossing), requirement on one "good" primary vertex in the event.
- Inclusive jet spectrum up to forward rapidities $|\eta|<4.7$.
- Low p_t: 21 GeV < p_t < 75 GeV (even smaller *x*) in bins of *y*.
- Zero bias trigger (> 2 tracks in Pixels).
- PF jets reconstructed with anti-k_t algorithm, R=0.7





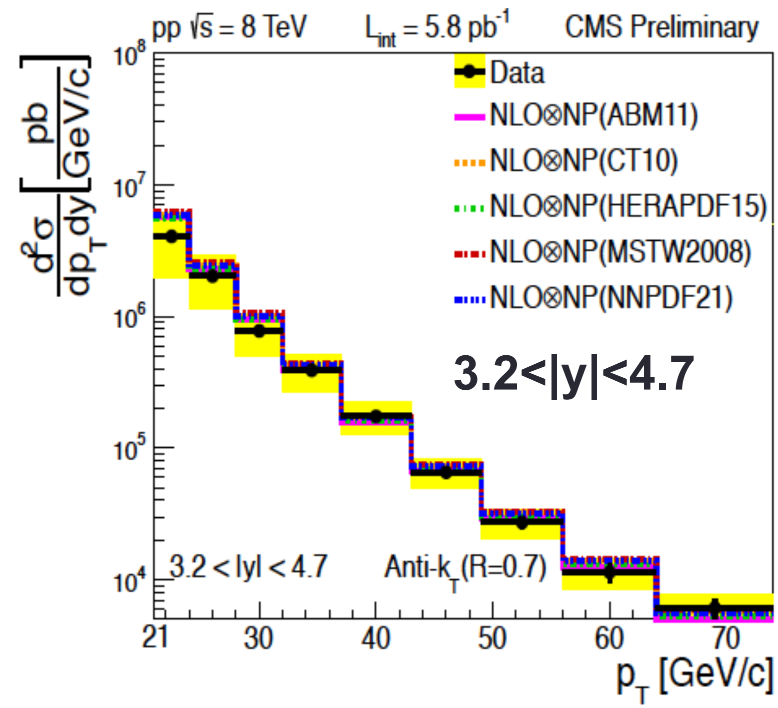
Low p_t jets at 8 TeV (2)

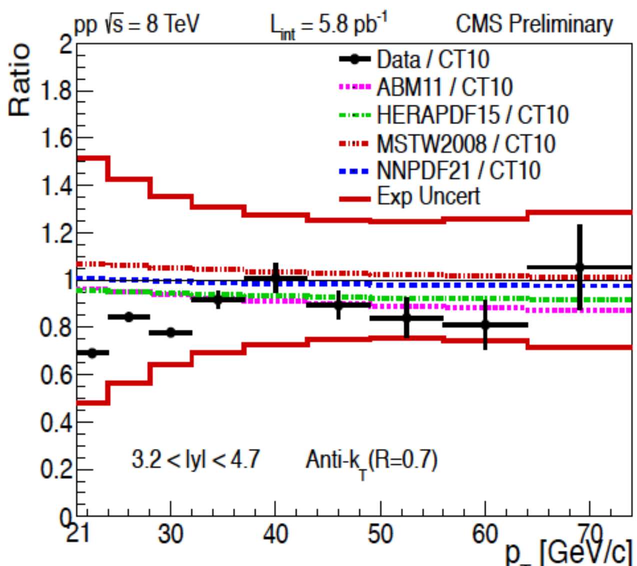
- Jet energy scale is estimated, results were unfolded to the stable particle-level.
- Systematic uncertainty is estimated to 60% (largest input from JES).
- Theoretical predictions seem to overestimate measured cross-sections.



Low p_t jets at 8 TeV (3)

- At forward rapidities -> similar conclusions as for the central rapidities:
- Theoretical predictions systematically overestimate x-section for both central and forward rapidity, but within experimental and theoretical uncertainties.

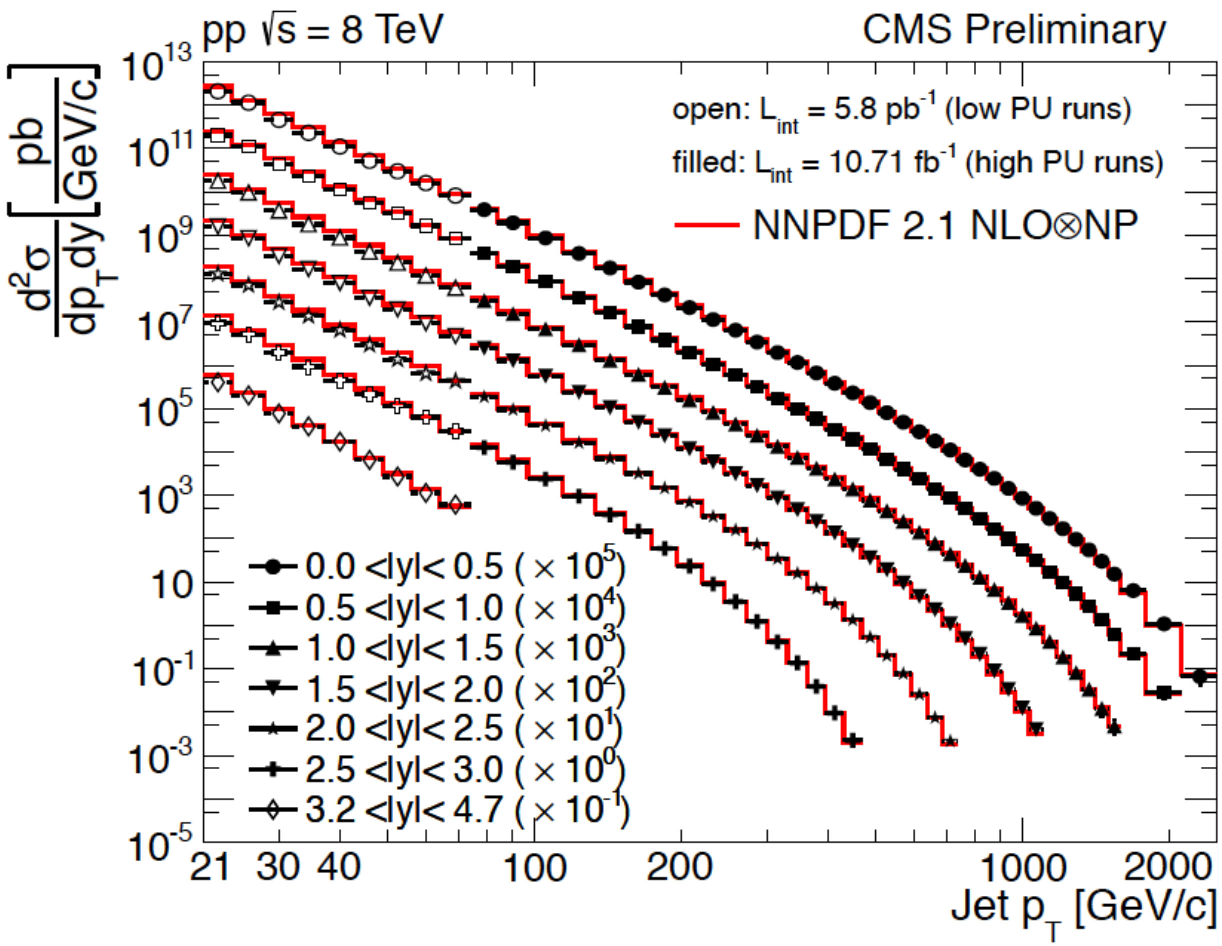




- Results for different PDF sets are consistent within systematical uncertainities.

Low p_t jets at 8 TeV (4)

- Combined jet spectrum (with CMS-PAS-SMP-12-012) with NLO predictions at 8 TeV.
- Cross-section: 15 orders of magnitude!



Cross-sections ratios (1)

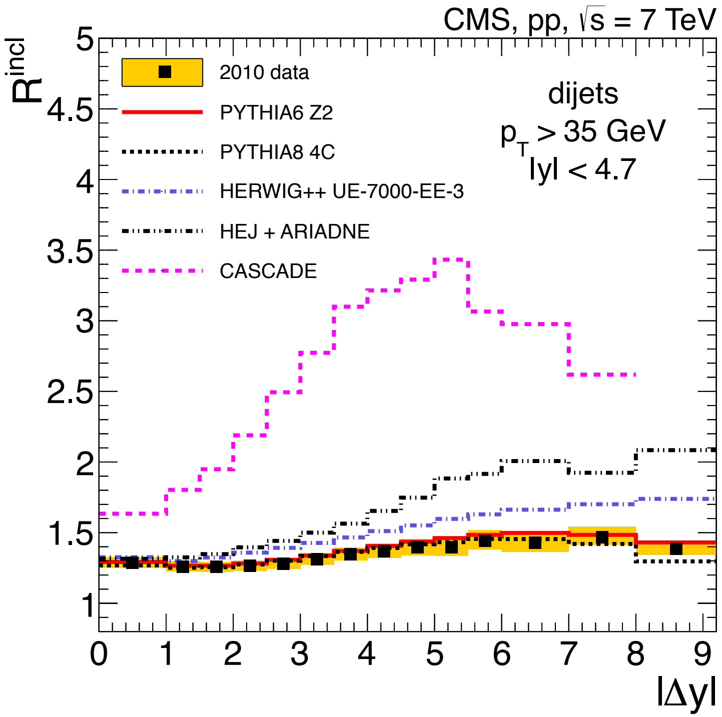
- 2010 data, 7 TeV, merging different triggers to collect data with large rapidity separation.
- All events: two jets with p_T>35 GeV in $|\eta|$<4.7 range.
- Three samples:
  - Inclusive (incl.) – all pairwise combinations of jets,
  - "Exclusive" (excl.) – exactly one pair of jets in each event,
  - Mueller-Navelet pair (MN) – from inclusive sample pair with the largest separation in η is selected.
- Observables we consider are ratios of inclusive/MN to exclusive cross-section:

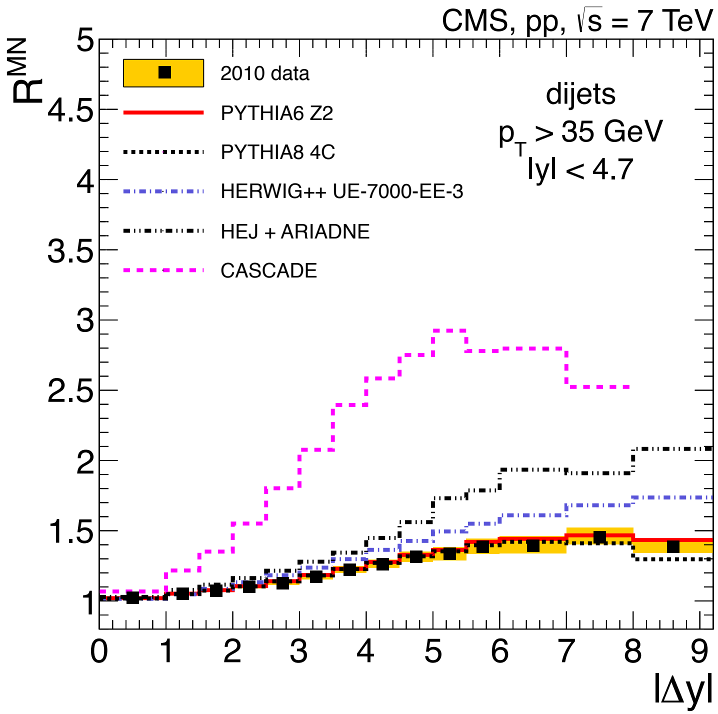
Eur. Phys. J. C (2012) 72:2216

$$R_{incl} = \frac{\sigma_{incl}(\text{dijet})}{\sigma_{excl}(\text{dijet})}, \quad R_{MN} = \frac{\sigma_{MN}(\text{dijet})}{\sigma_{excl}(\text{dijet})}$$

- Some systematical (luminosity, …) and theoretical (PDF, …) uncertainties cancel.
- Results corrected to the stable-particle level.
- Such observables, as a function of $\Delta\eta$ (up to 9.2), should be sensitive to BFKL effects.

Cross-sections ratios (2)





- σ(inclusive) is of the order of (1.2-1.4)*σ(exclusive), ratios rise and for large |Δη| and then drop due to kinematic limits.
- Both the Pythia 6 and Pythia 8 describe data properly.
- Herwig++ predicts too large R at large and medium separations.
- BFKL/CCFM-based MC generators, Hej and Cascade predict too large R.

Angular correlations of jets (1)

- Recently approved results (CMS-FSQ-12-002); more exclusive measurement of Mueller-Navelet dijets: its angular decorrelation.
- Measurement as a function of $\Delta\eta$ (<9.4), sensitive to BFKL effects.
- 2010 data, 7 TeV, requirement of one primary vertex.

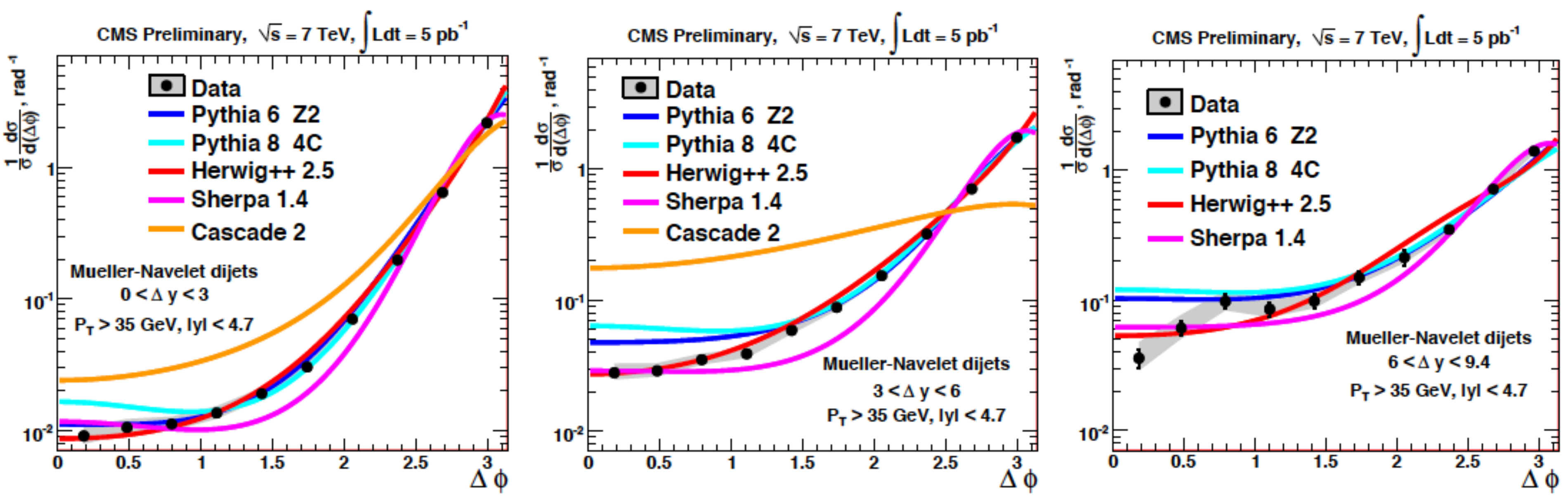
- Events with at least two jets passing cuts: p_T>35 GeV in $|\eta|$<4.7.
- For a pair of jets with the largest $\Delta\eta$ (MN dijet) the angular distance is calculated: $\Delta\phi = \phi_1 - \phi_2$
- We study $\Delta\phi$ distributions for different $\Delta\eta$, and correlation factors C_1, C_2, C_3 and its ratios C_2/C_1, C_3/C_2

$$C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle cos(n(\pi - \Delta\phi))\rangle$$

- For high correlation between jets ($\Delta\phi$=π) correlation coefficients are equal to 1.
- C_n may be considered as Fourier coefficients in Fourier expansion of a cross-section.

Angular correlations of jets (2)

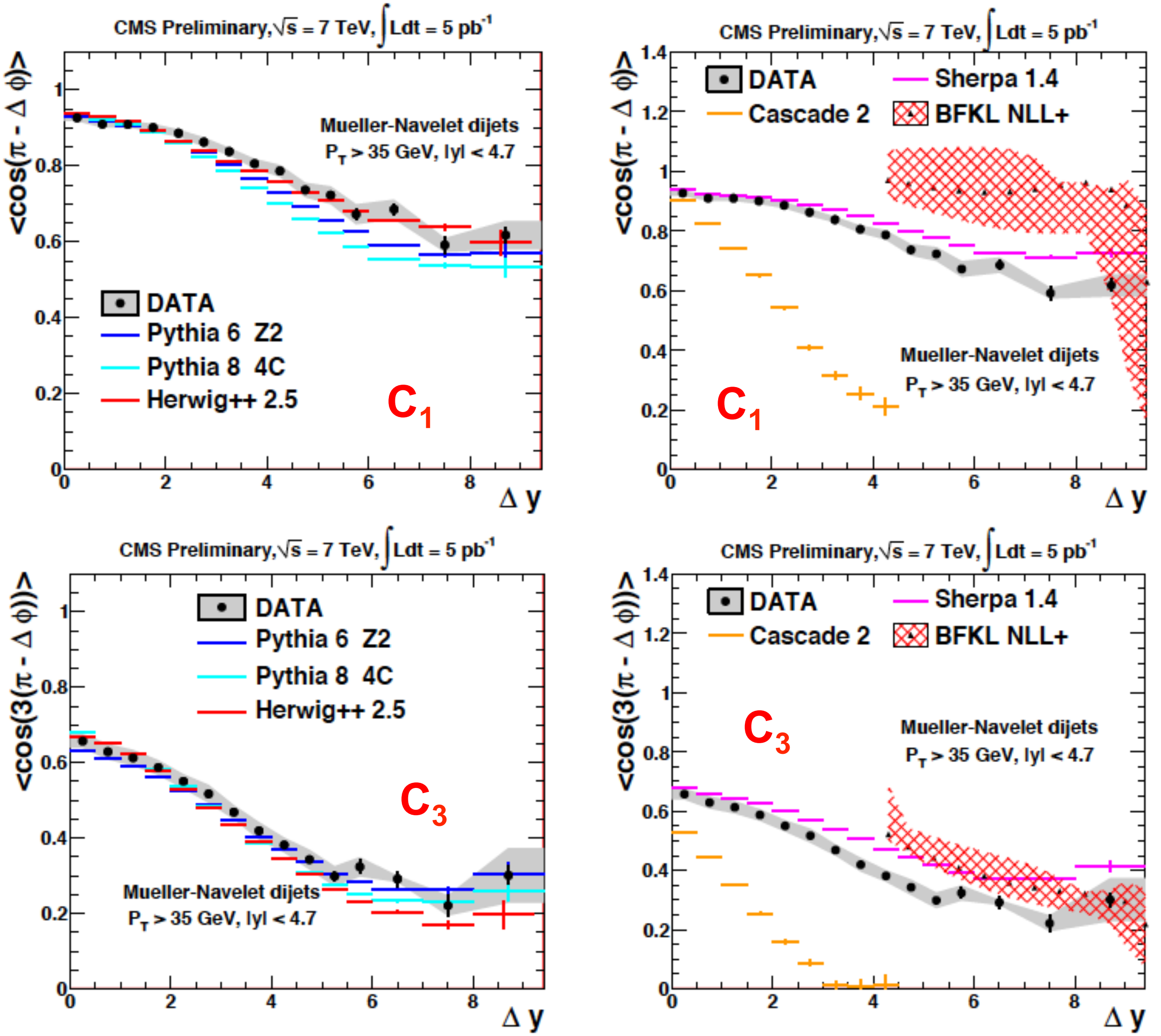
- Results are corrected to the stable particle level and compared to predictions of different MC generators and NLL calculations.
- Largest input to the systematic uncertainty comes from JES.
- We observe decreasing correlation between jets with $\Delta\eta$ growth due to increase of parton activity.
- For large and mid separation DGLAP-based MCs show deviation from the data.
- CCFM Cascade predicts large too strong decorrelation.



Angular correlations of jets (3)

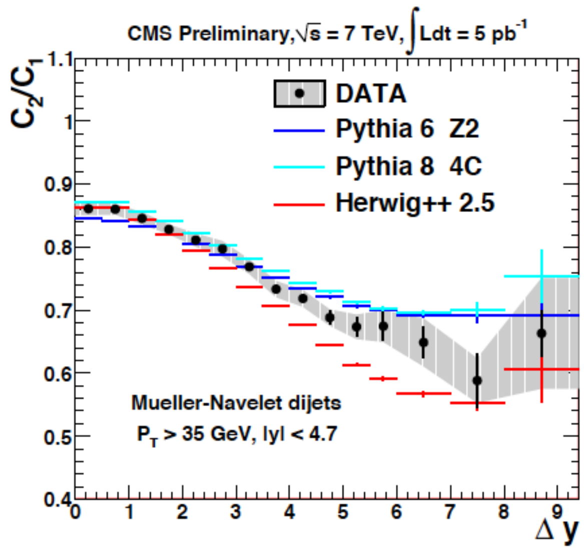
- Average cosines decrease with $\Delta\eta$ increase.
- Pythia 6/8 show stronger decorrelation than observed in data.
- Herwig++ provides the best description of the data.
- Sherpa and analytical BFKL calculations underestimate decorrelation.
- Cascade strongly overestimates decorrelation.

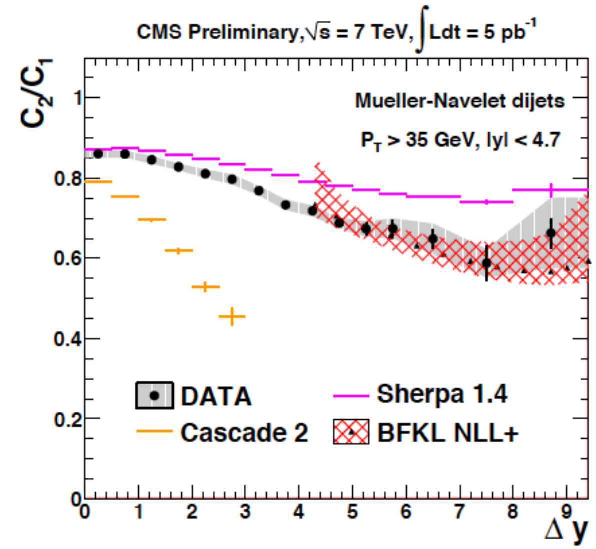
BFKL NLL: B. Duclou´e, L. Szymanowski, S.Wallon, arXiv:hep-ph/1302.7012

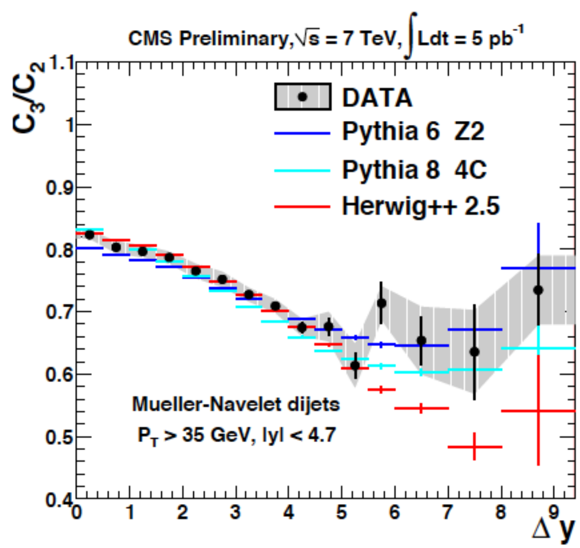


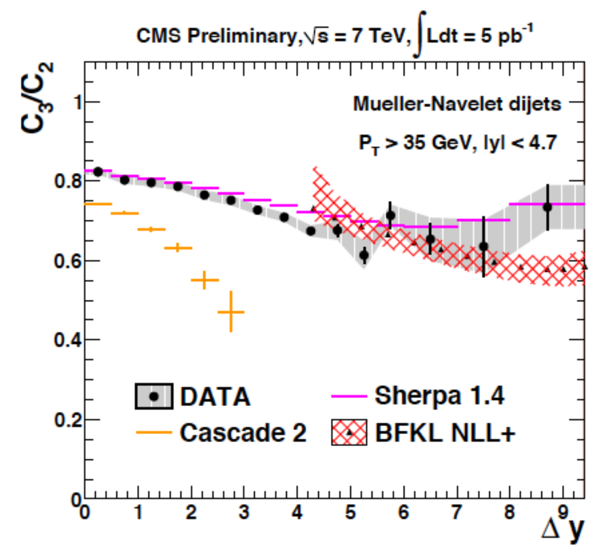
Angular correlations of jets (4)

- Ratios of cosines are expected to be more sensitive to BFKL effects.
- At low $\Delta\eta$ agreement between data and Pythia/Herwig.
- At high $\Delta\eta$ differences between Pythia and Herwig.
- NLL BFKL calculations are consistent with data within uncertainties.









Conclusions:

- At mid and high y description of data by DGLAP predictions is worse for both $\Delta\phi$ and C_n.
- On the other hand BFKL/CCFM generators do not provide good description of data in full $\Delta\eta$ range.
- Large unc. of NLL BFKL calculations.

Conclusions

- I have presented selected results for low-*x* QCD.
- Such kind of studies are important for understanding of QCD (tuning parameterization of models to data) and in searches for BFKL effects.
- No clear indication of BFKL effects in the data was found.

- Outlook: working on M-N decorrelation paper, combined high-pT/low-pT spectrum at 8 TeV; Stay tuned!

Thank you for your attention!