Jets & high-p_T Hadron Production in p-p collisions at CMS

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for the
CMS Collaboration

Winter Workshop on Recent QCD Advances at the LHC, Les Houches

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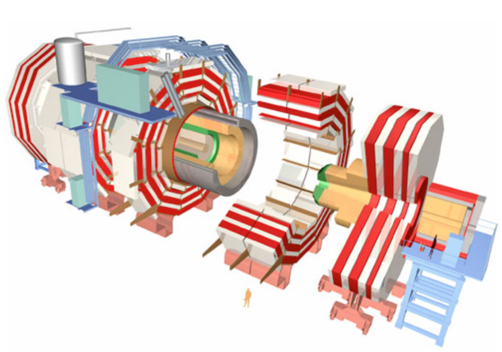
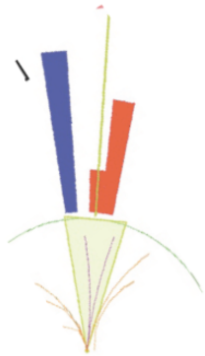
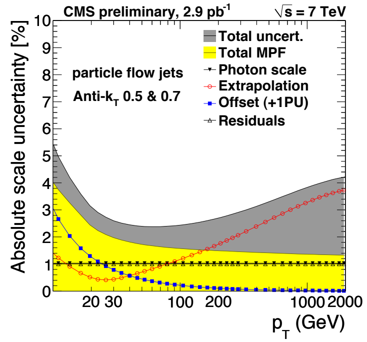
Outline

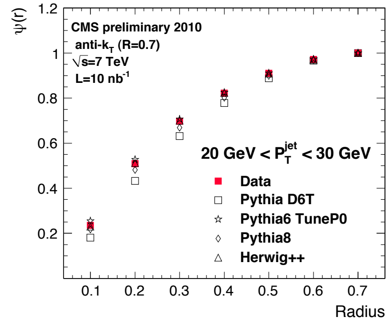
1. Jet reconstruction and performance in CMS



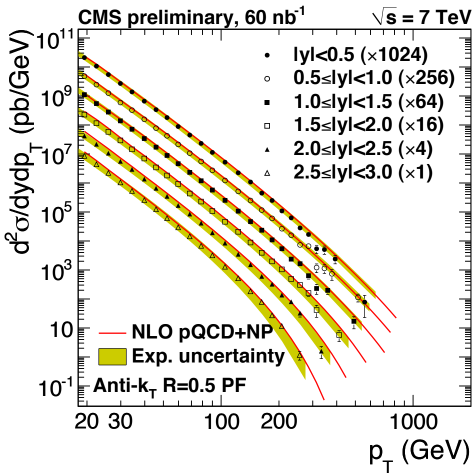




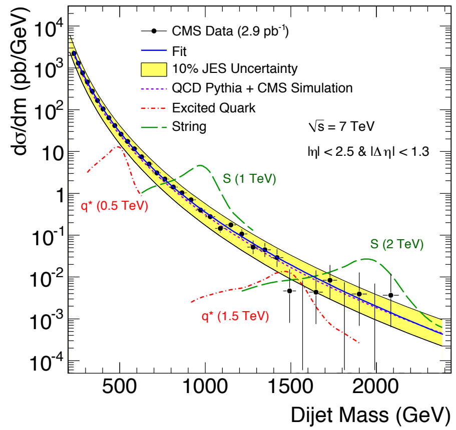
2. Jet properties



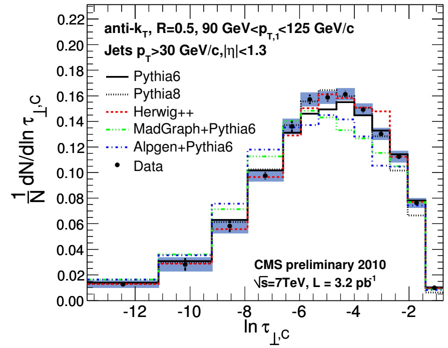
3. Inclusive jets



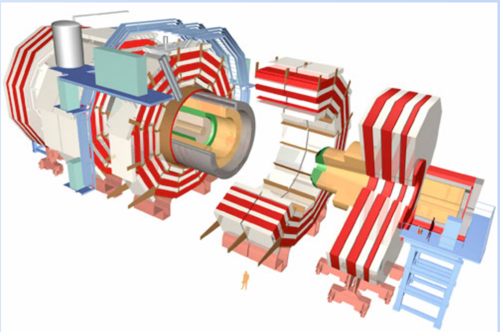
4. Di-jets and searches for new Physics

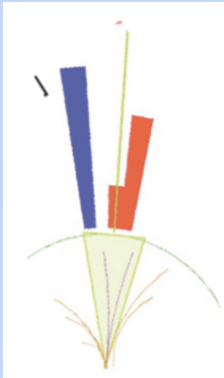


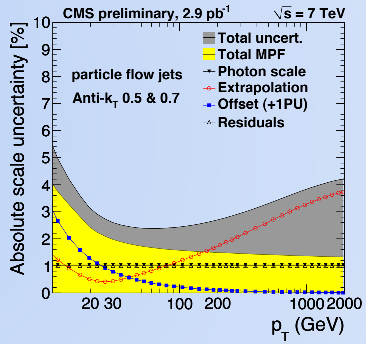
5. Multi-jet final states



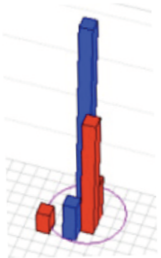
1. Jet reconstruction and performance





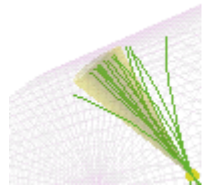


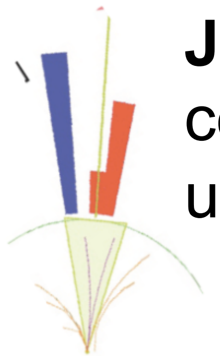
Jet reconstruction in CMS



Calorimeter Jets
clustered from
calorimeter towers

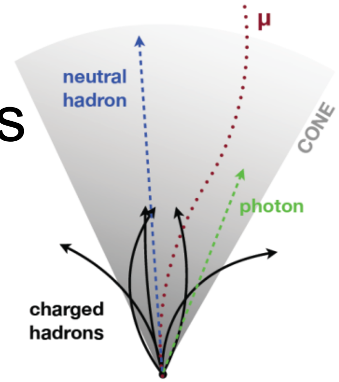
Track Jets
clustered from
tracks





Jet plus Tracks
correct Calorimeter Jets
using momentum of tracks

Particle Flow Jets
clustered from
identified particles
reconstructed
using all detector
components

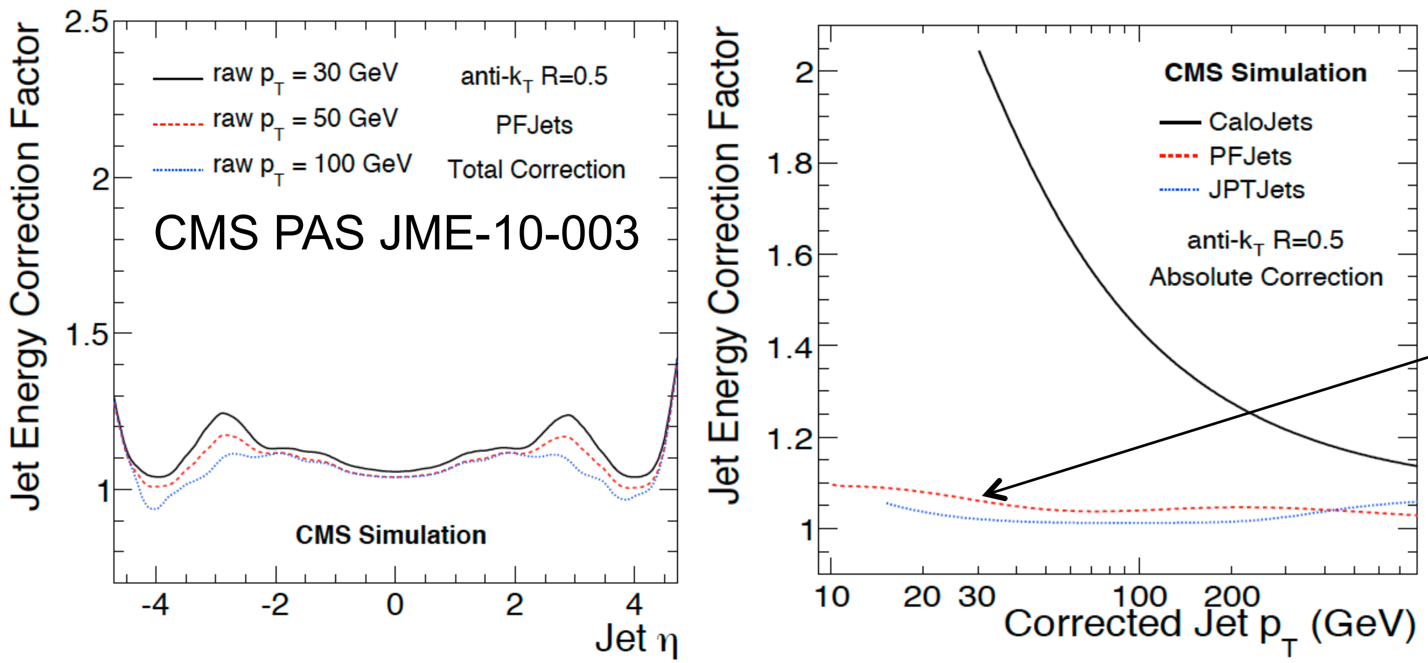


- Default jet clustering algorithms for p+p collisions:
  - Anti-K_T with R=0.5 (and 0.7)

Jet energy calibration in CMS

CMS uses factorized approach

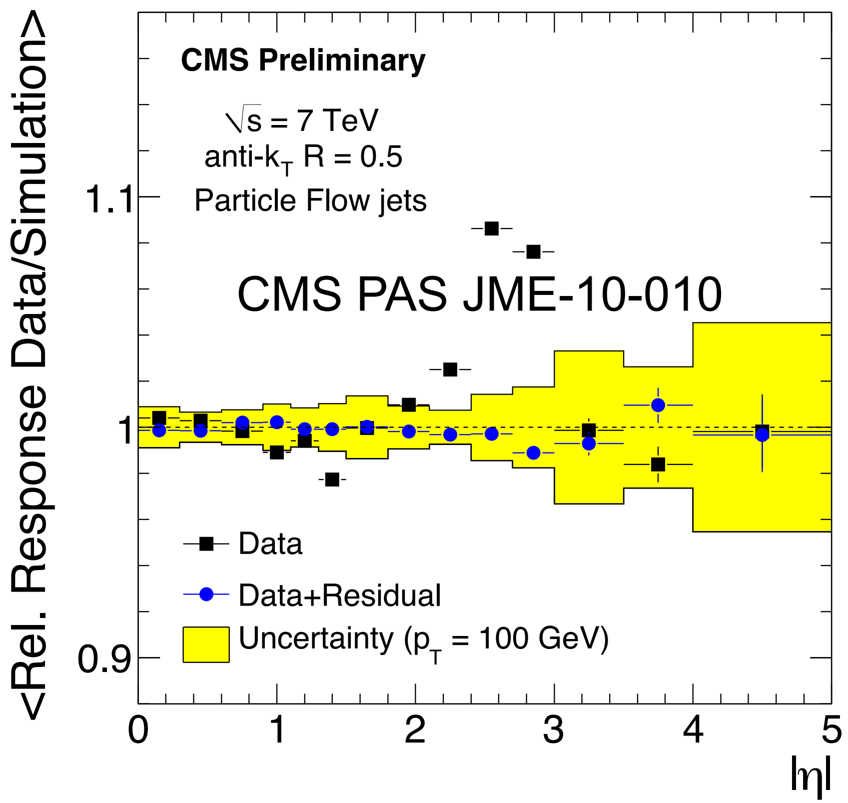
1. **Offset correction**: remove pile-up and noise contribution (treated as uncertainty in presented results)
2. **MC-truth correction**:
   - based on test-beam calibration and simulation
   - flaten jet response in p_T and η

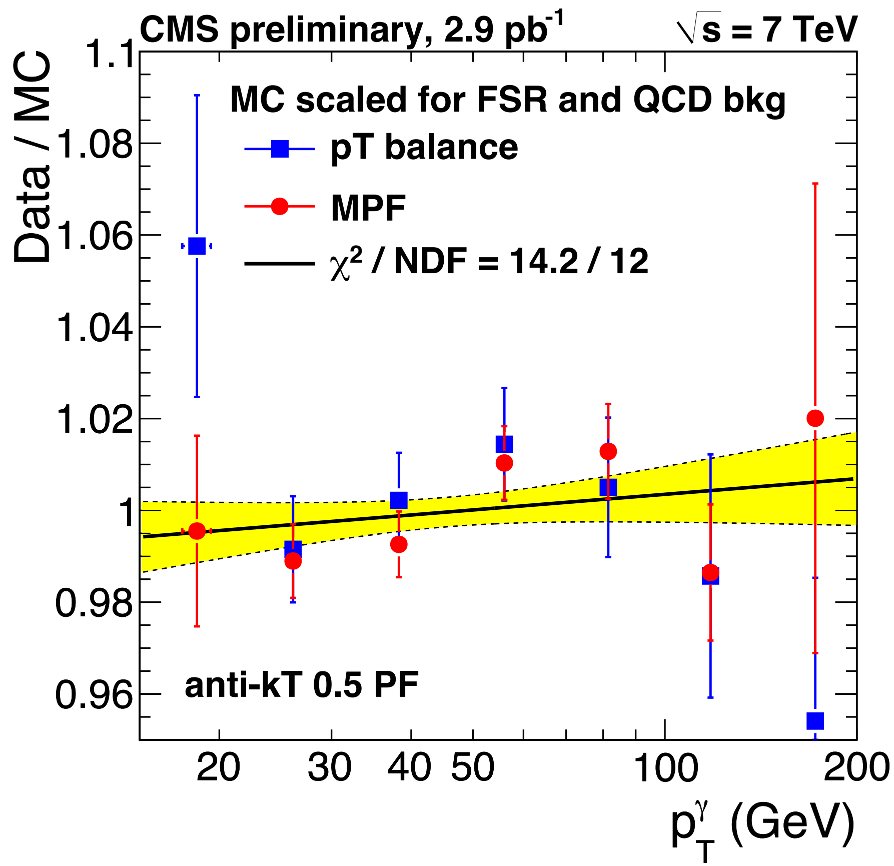


ParticleFlow and JPT make use of tracks

Jet energy calibration in CMS – cont'd

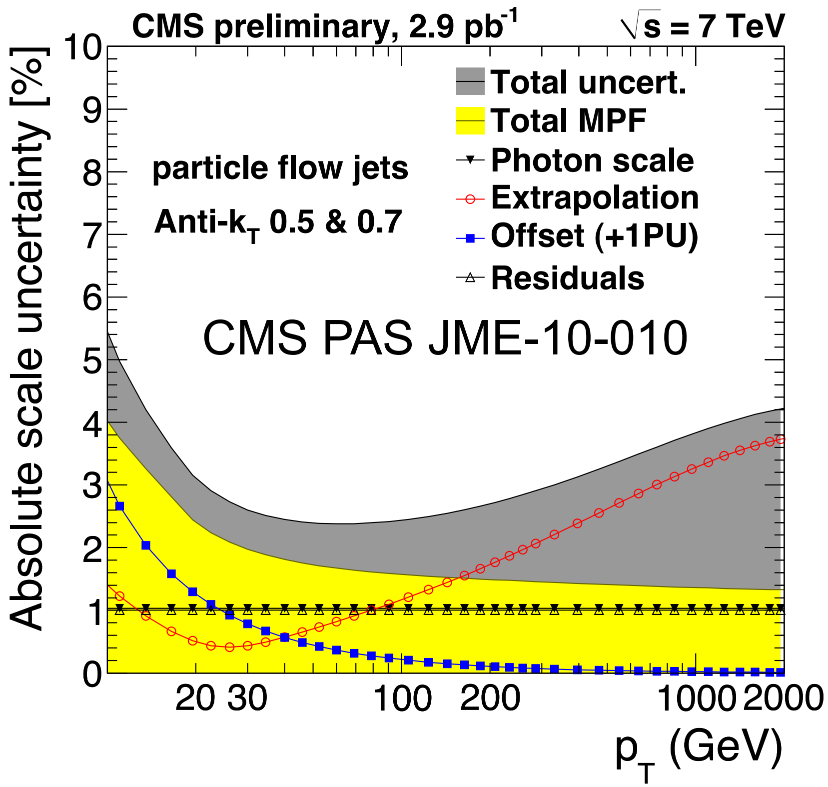
3. **In-situ residual correction**:
   - flaten jet response in η using di-jet p_T balance method
   - flaten jet response in p_T using photon+jet Missing-E_T Projection Fraction method (MPF from D0)

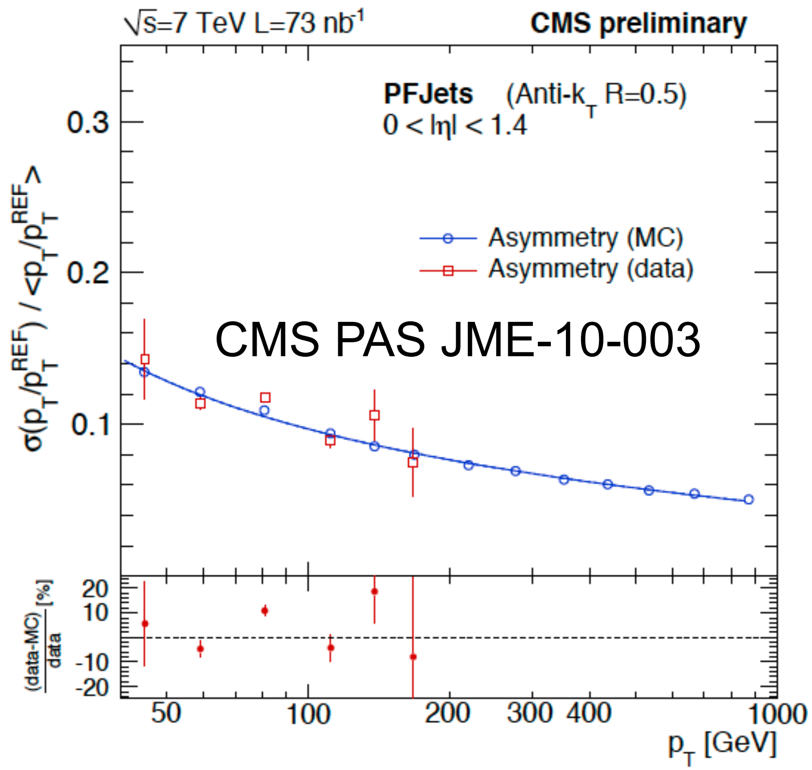




Jet performance in CMS

- Jet calibration vs. η better than 1% per unit of pseudorapidity
- Jet energy scale uncertainty: 3-5% over whole p_T range
- Jet energy resolution from dijet p_T asymmetry method: 10% @ p_T = 100 GeV
- Jet position resolution in Φ and η: ~0.01 @ p_T = 100 GeV





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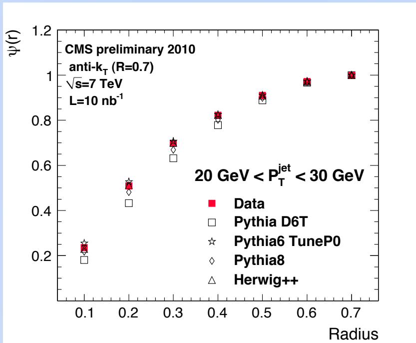
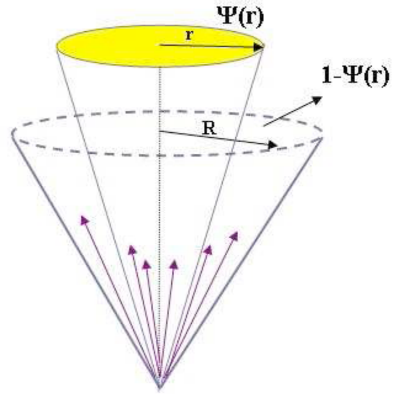


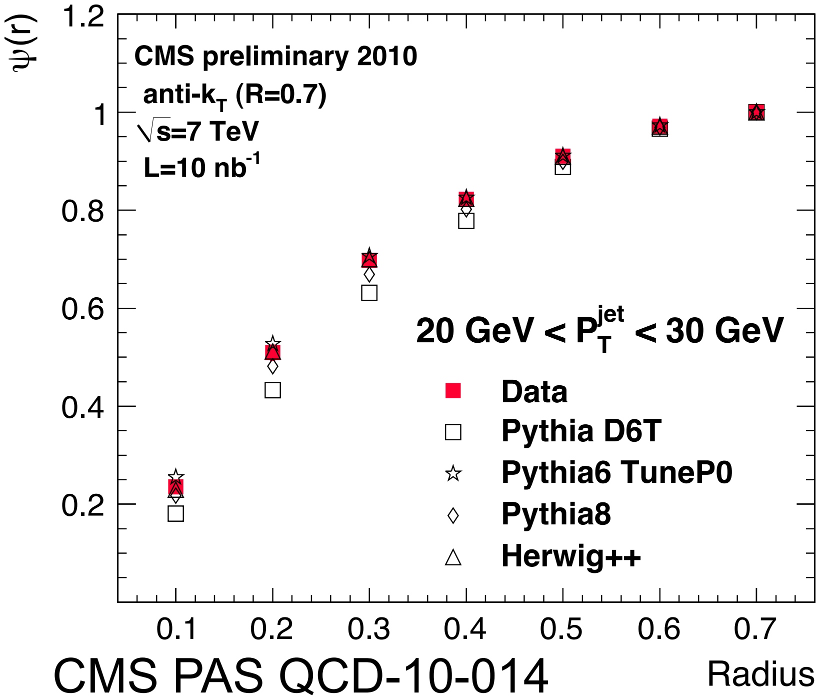
Jet shapes

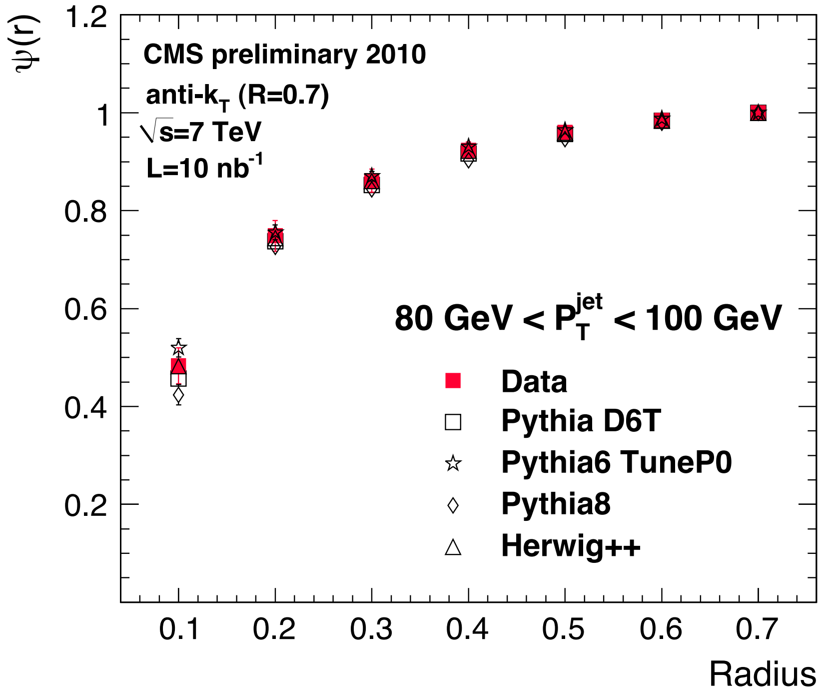
- **Integrated jet transverse shape**:

$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$



- Probe transition between pQCD and soft gluon radiation
- Sensitive to the quark/gluon jet mixture
- Test parton shower event generators at non-perturbative levels

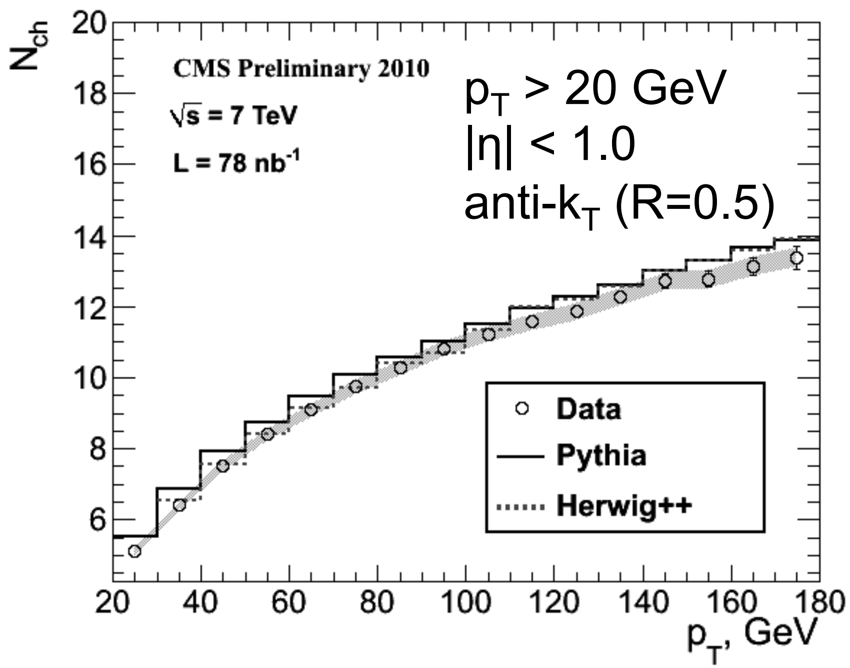


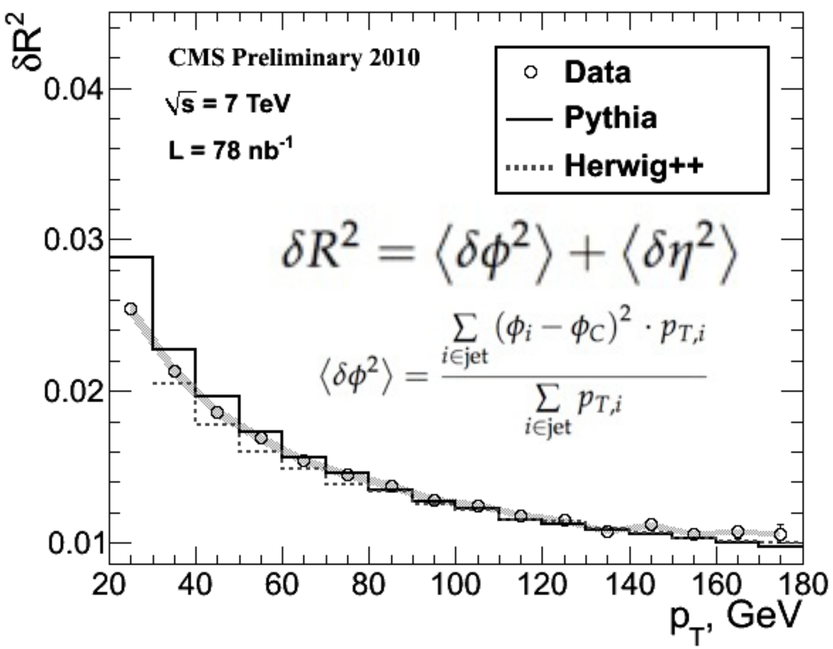


CMS PAS QCD-10-014

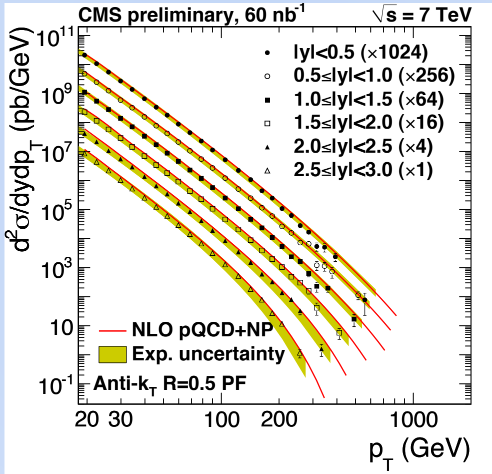
Jet shapes – cont‘d

- Good agreement between data and theoretical models observed
- At 20 < p_T[GeV] < 50 Pythia tune D6T predicts slightly too broad jets while Herwig++ predicts slightly too narrow jets



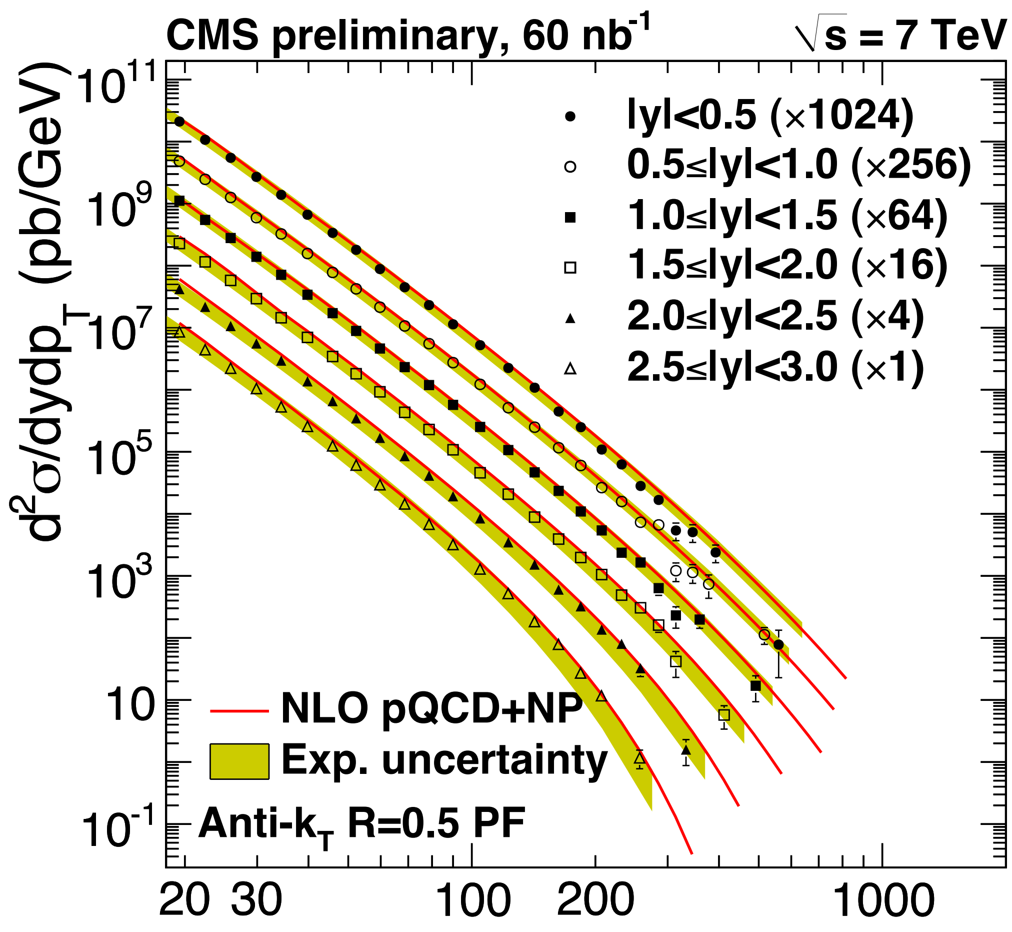


3. Inclusive jets



Inclusive jets

- Extending the high p_T limit beyond Tevatron reach
- Accessing the low p_T part using ParticleFlow jet reconstruction
- Rapidity coverage |y|<3
- Derived using three jet types (Calo, JPT, PF) yielding compatible results
- **Good agreement between data and NLO QCD**



CMS PAS QCD-10-011

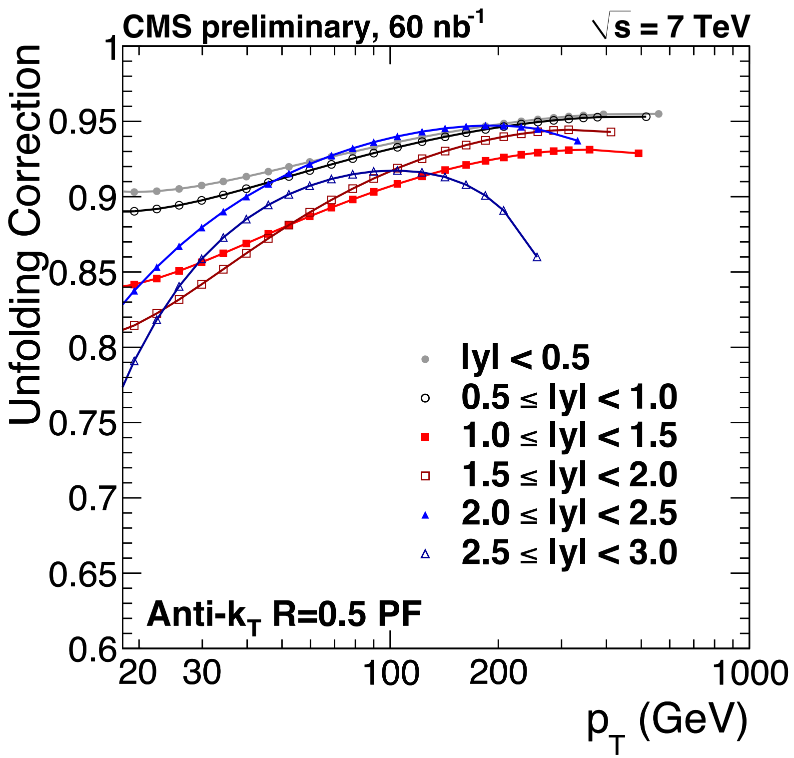
- Update with increased luminosity in preparation

Inclusive jets – cont'd

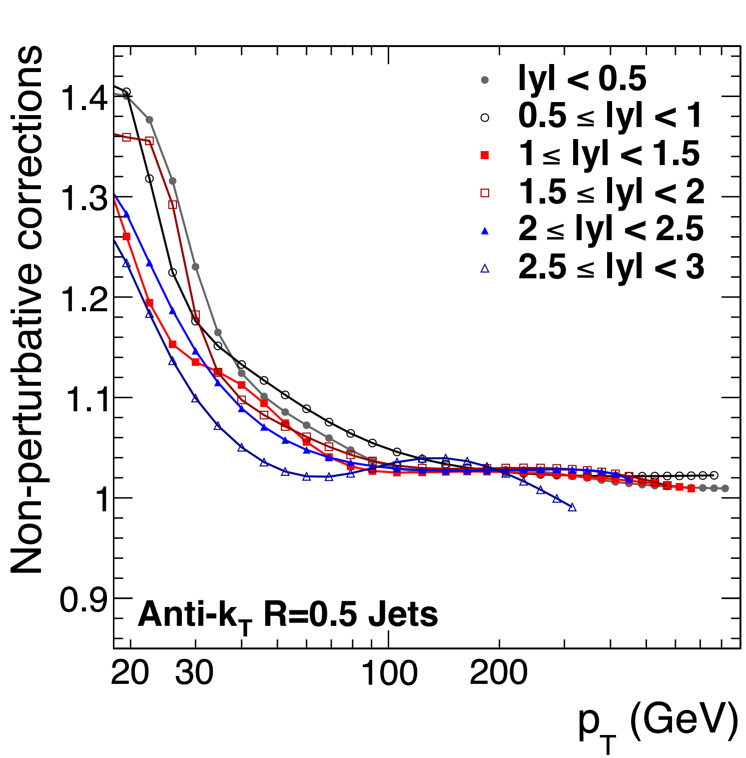
- Data:
  - Ansatz resolution unfolding to particle level

$$f(p_T) = N_0 p_T^{-\alpha} \underbrace{\left(1 - \frac{2p_T \cosh(y_{\min})}{\sqrt{s}}\right)^{\beta}}_{\text{high } p_T} \underbrace{\exp(-\gamma/p_T)}_{\text{low } p_T \text{ and b-jets}}$$

new

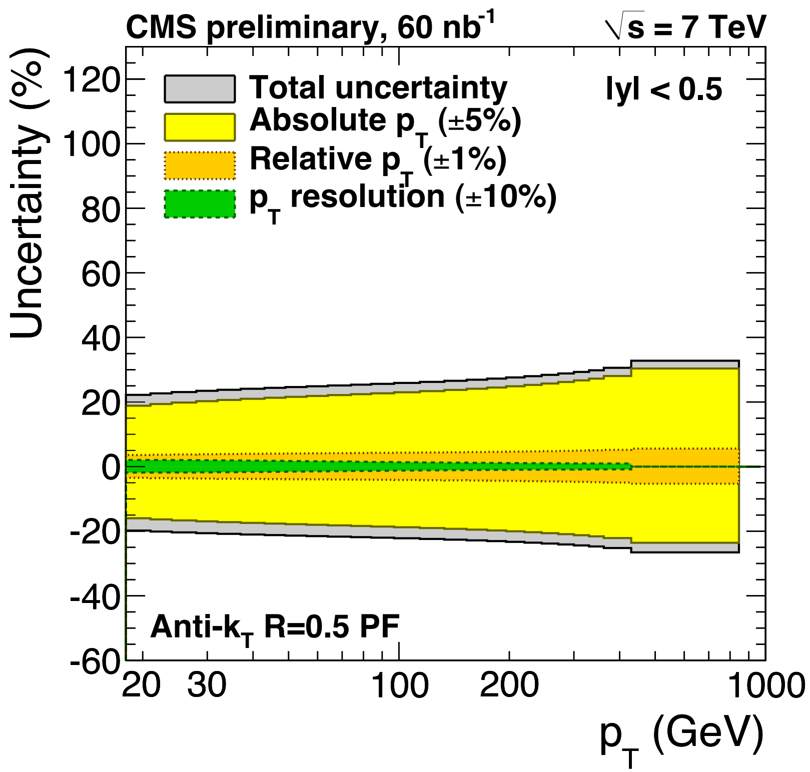


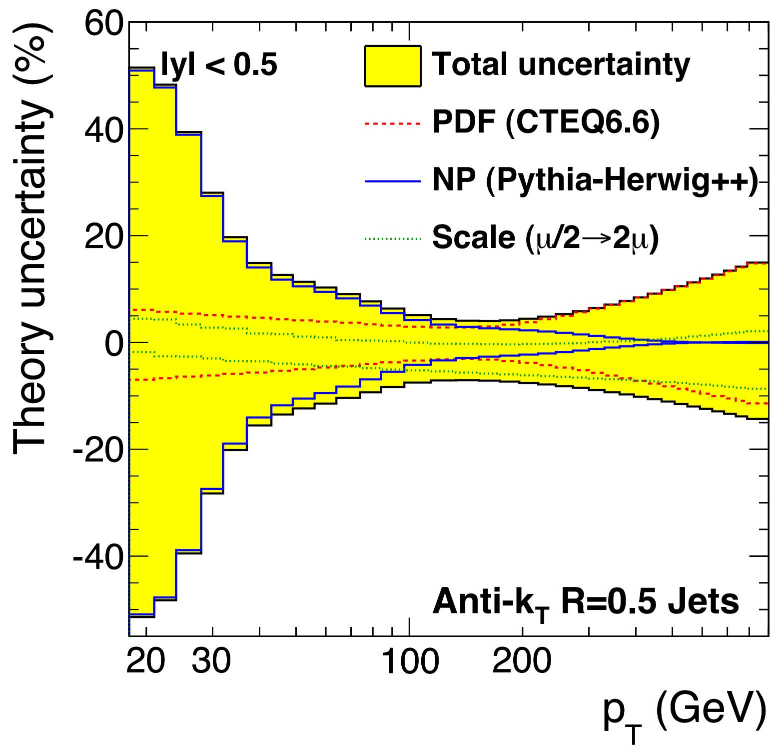
- Theory:
  - NLO pQCD using NLOJet++ with CTEQ6.6 PDFs
  - Non-perturbative corrections from Pythia6-Herwig++ average



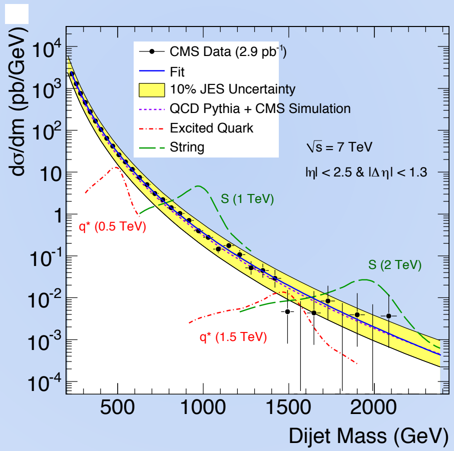
Inclusive jets – cont'd

- Systematic uncertainties:
  - Data:
    - Jet energy scale (5%)
    - Jet p_T resolution (10%)
    - Luminosity (11%)
  - Theory:
    - PDF uncertainty from CTEQ6.6
    - μ_R, μ_F uncertainty: $p_T/2 \rightarrow 2\ p_T$
    - Non-perturbative corrections: 50% × (Pythia6 - Herwig++)

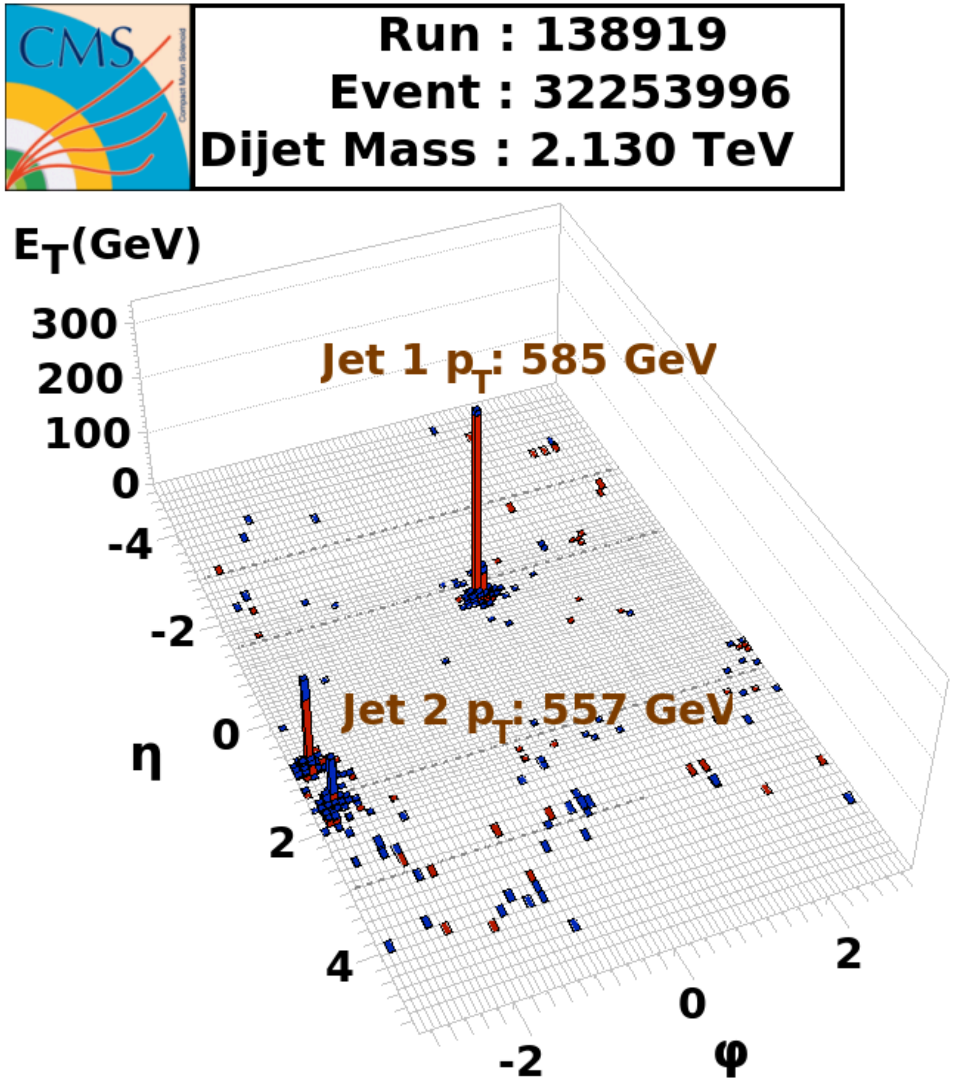


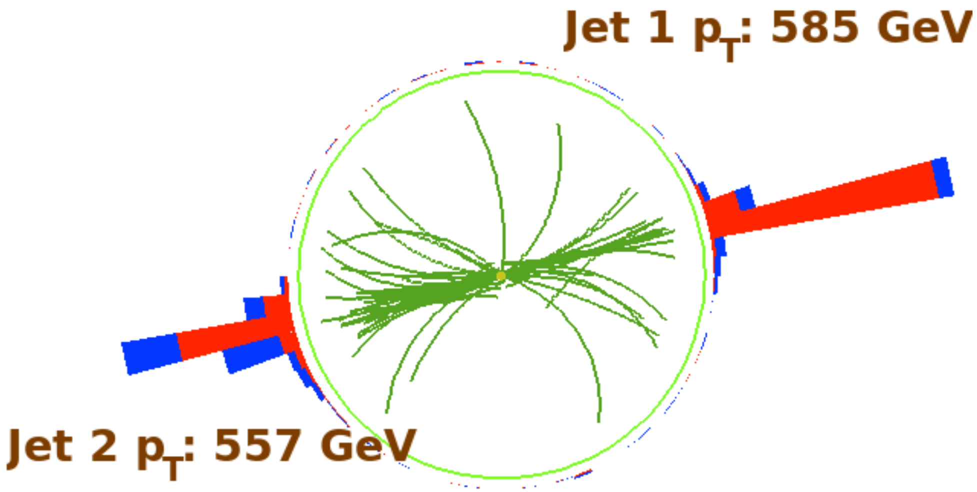


4. Di-jets and searches for new physics



Di-jet event from 7 TeV collision





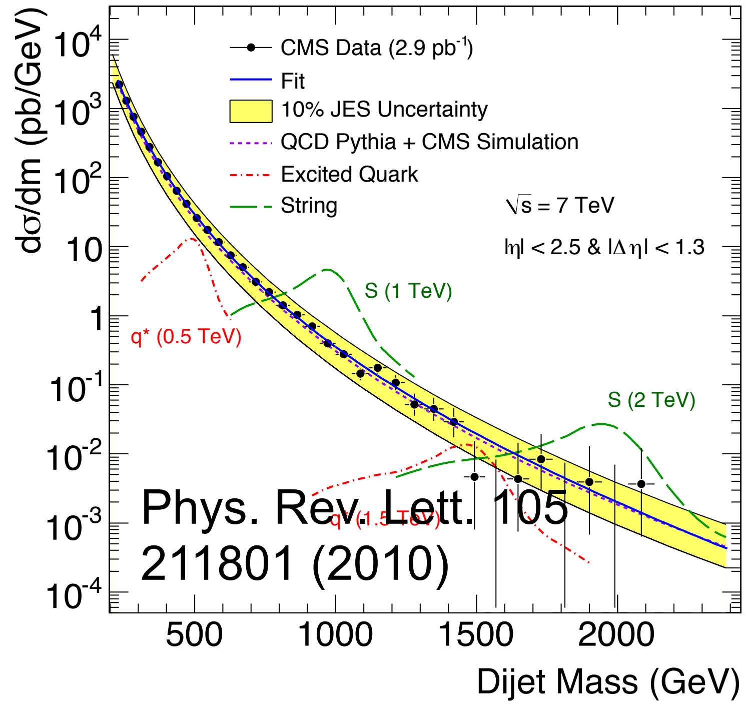
Two jets clustered using anti-k_T algorithm with R=0.7

Di-jet mass distribution

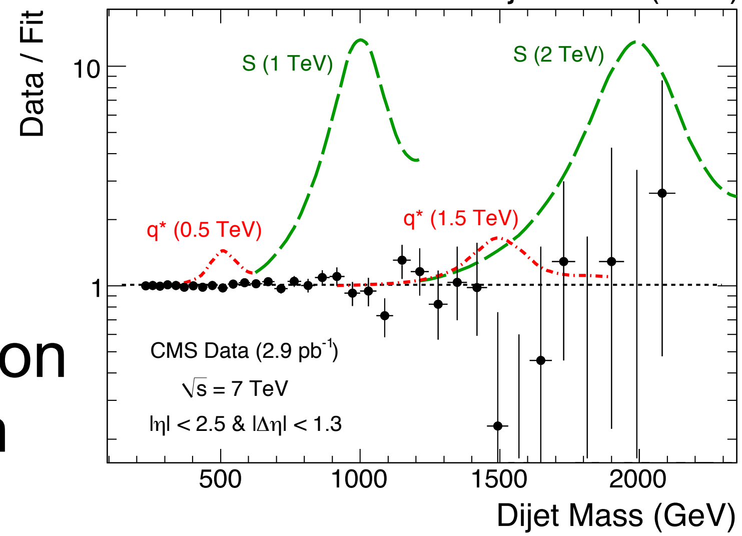
- **Data in good agreement with Pythia6 + CMS simulation**
- Search for narrow resonances decaying to di-jets with natural width less than experimental resolution
- Use model-independent resonance search to obtain mass exclusion limits at 95% CL for a variety of resonance models

	Excluded Regions (TeV)
String Resonance	0.50–2.50
Excited Quark	0.50–1.58
Axigluon/Coloron	0.50–1.17, 1.47–1.52
E6 Diquark	0.50–0.58, 0.97–1.08, 1.45–1.60

- Extended measurement with comparison to pQCD at particle level in preparation



Phys. Rev. Lett. 105 211801 (2010)



Di-jet centrality ratio

- Di-jet centrality ratio:

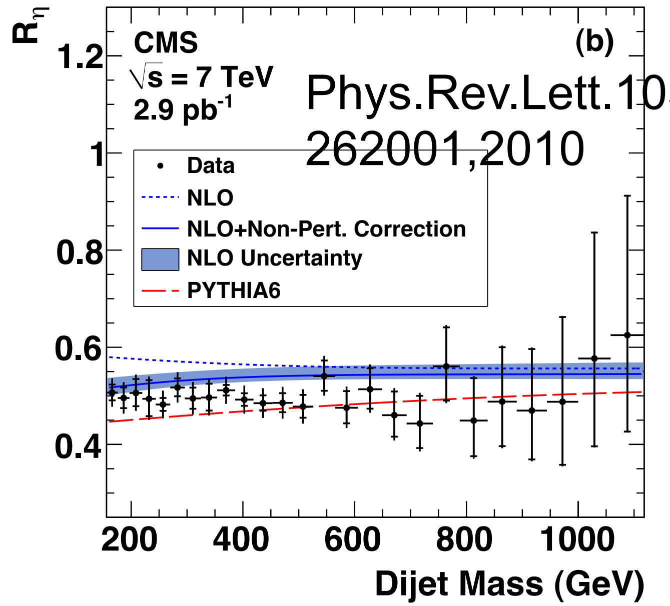
  N(|η|<0.7) / N(0.7<|η|<1.3)

- **Precison test of pQCD with low systematic uncertainties due to ratio**

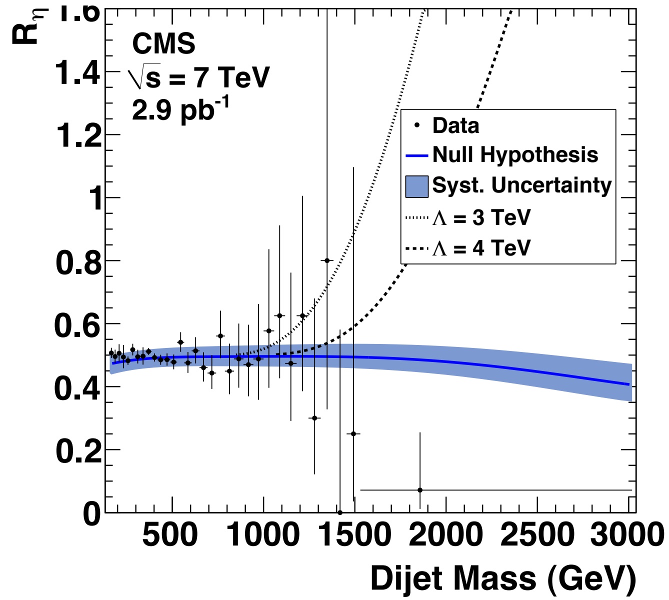
- Sensitive to contact interactions (CI) and dijet resonances

$$\mathcal{L}_{qq} = +\frac{2\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$$

- Limit on CI scale Λ using frequentist inspired CL_S:
  - Exclude Λ < 4.0 TeV at 95% CL
  - Expected limit: Λ < 2.9 TeV



Phys.Rev.Lett.105 262001,2010

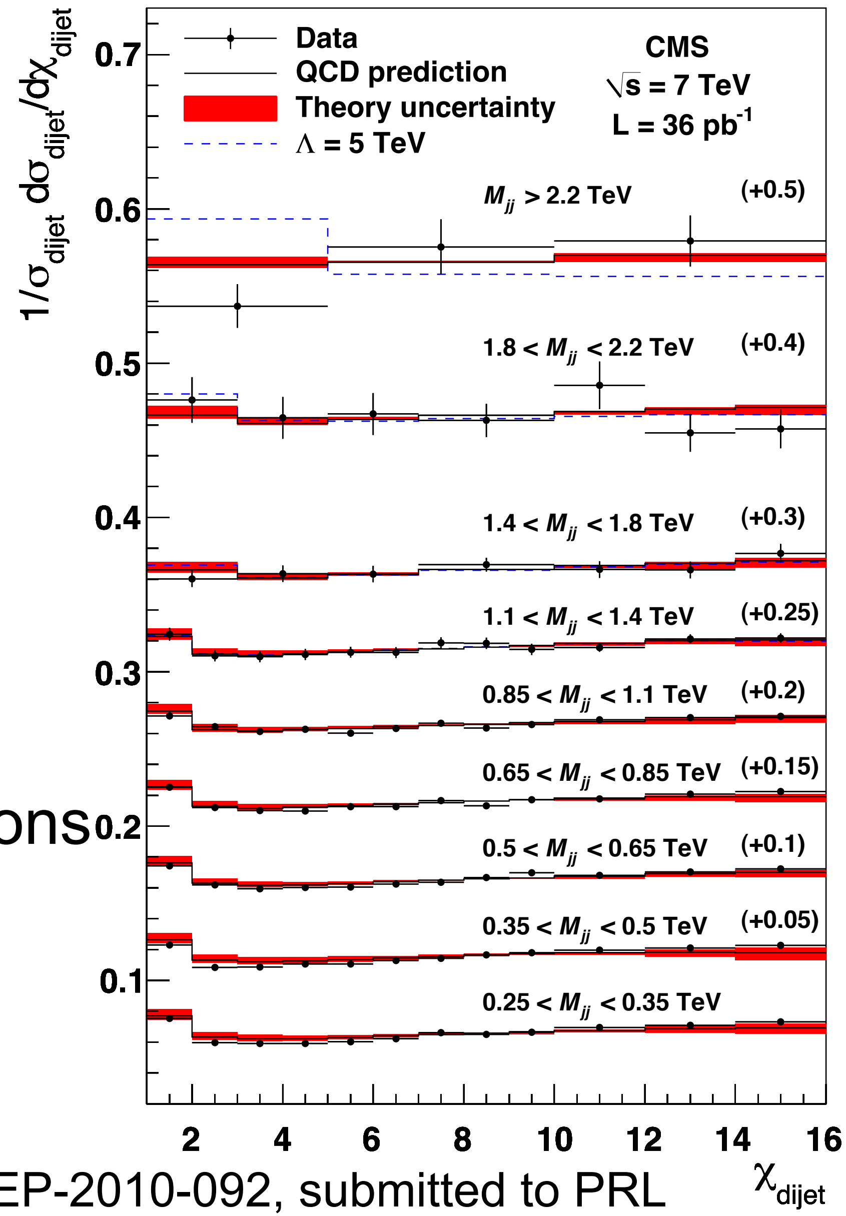


Di-jet angular distributions

- Probe parton-parton scattering angle

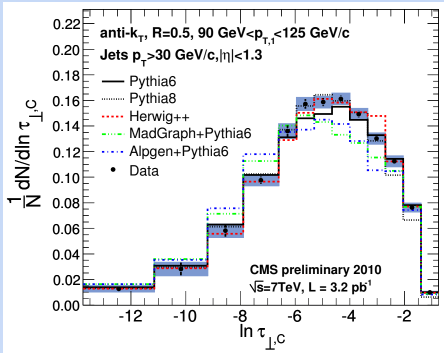
$$\chi_{dijet} = e^{|y_1 - y_2|} \sim \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

- QCD like t-channel → flat in χ
- Isotropic new physics peaks at low χ (e.g. contact interactions (CI))
- Low systematic uncertainties due to normalization in each mass bin
- Good agreement with pQCD predictions
- Exclude $\Lambda < 5.6$ TeV at 95% CL
- Expected limit: $\Lambda < 5.0$ TeV
- **Most stringent limit to date**



CERN-PH-EP-2010-092, submitted to PRL

5. Multi-jet final states



Di-jet azimuthal decorrelation

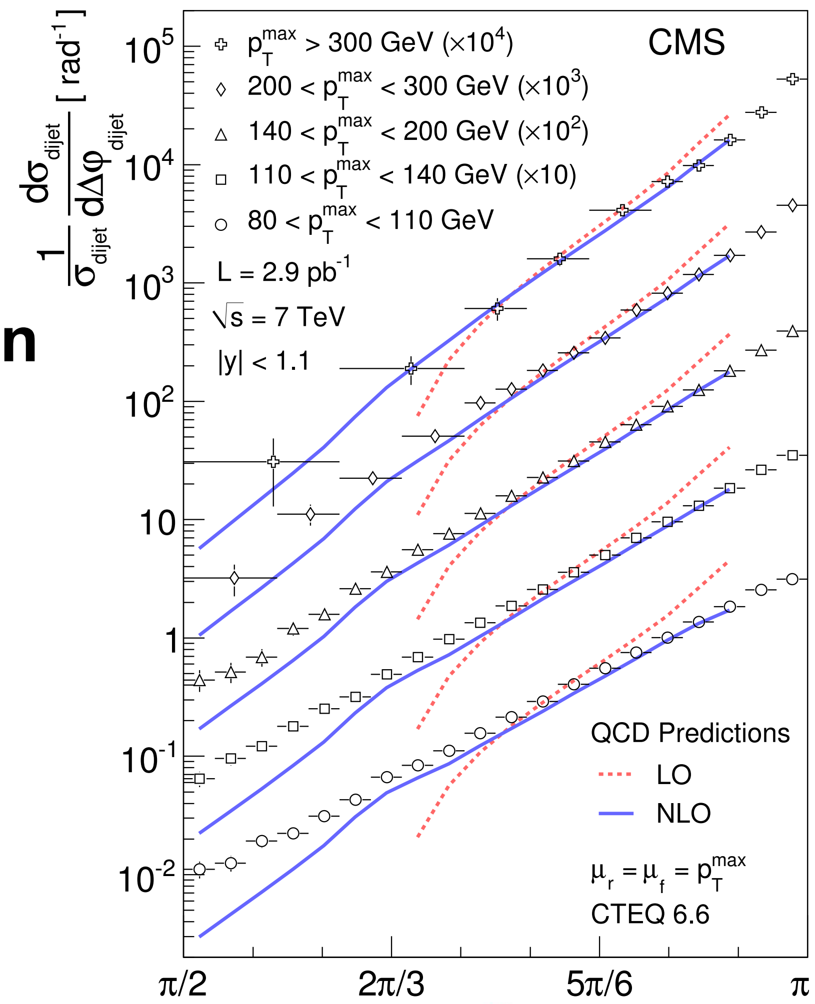
- Measurement of azimuthal angle between two leading jets:

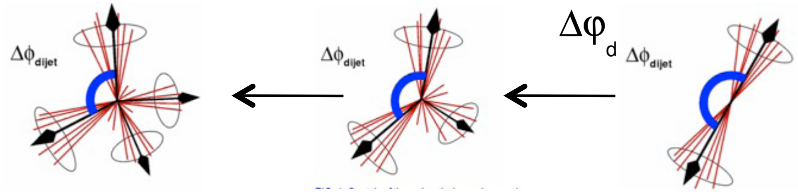
  $\Delta\varphi_{dijet} = |\varphi_1 - \varphi_2|$

- **Sensitive to higher order radiation w/o explicitly measuring the radiated jets**

- Low systematic uncertainties due to normalization in each p_T bin

- Useful for tuning phenomenological parameters (ISR) in MC event generators

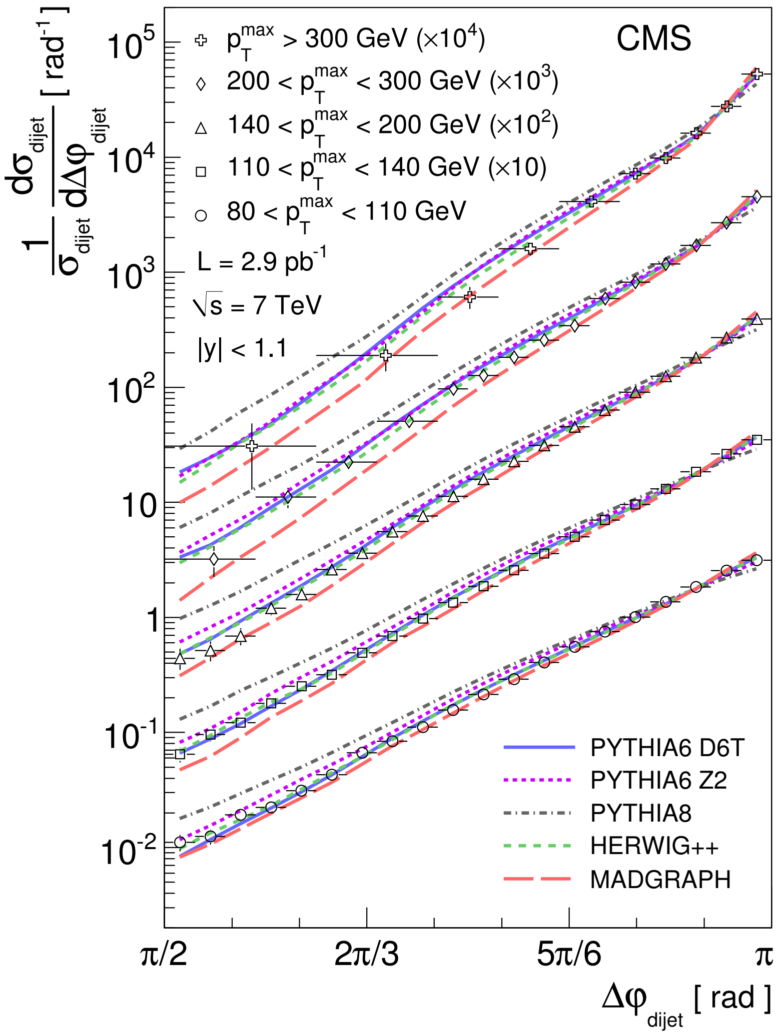


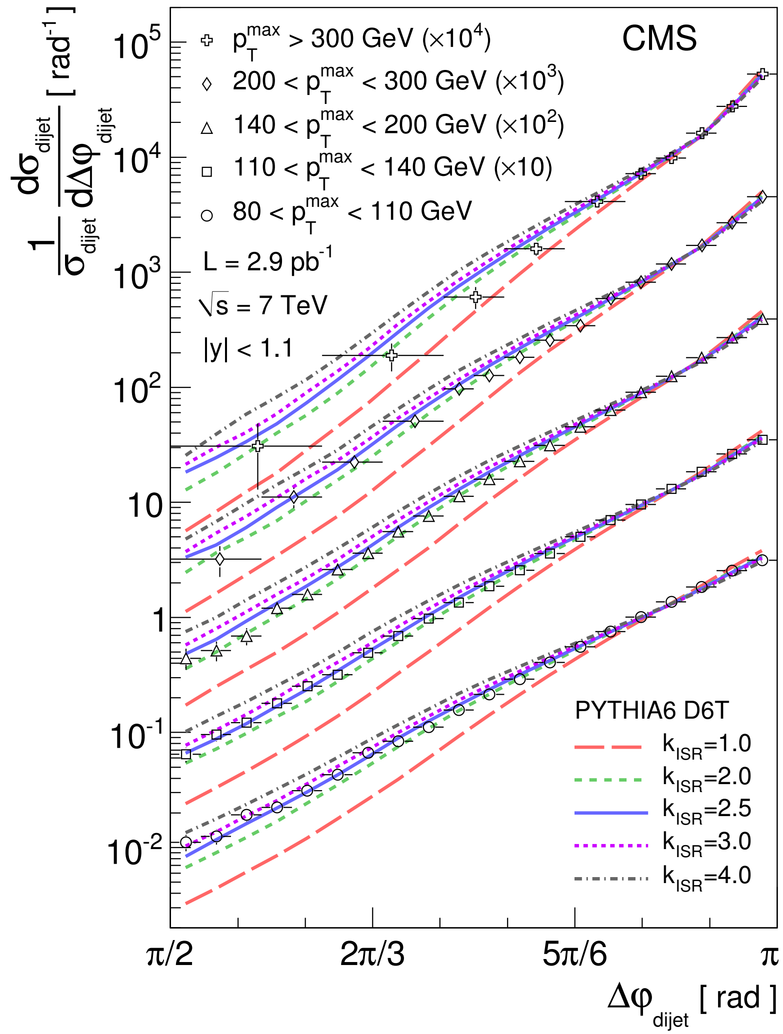


CERN-PH-EP-2010-086, submitted to PRL

Di-jet azimuthal decorrelation – cont'd

- Pythia6 and Herwig++ in reasonable agreement with data
- PYTHIA8.135 used in this analysis. In PYTHIA8.145 comparison improve due to a bug fix

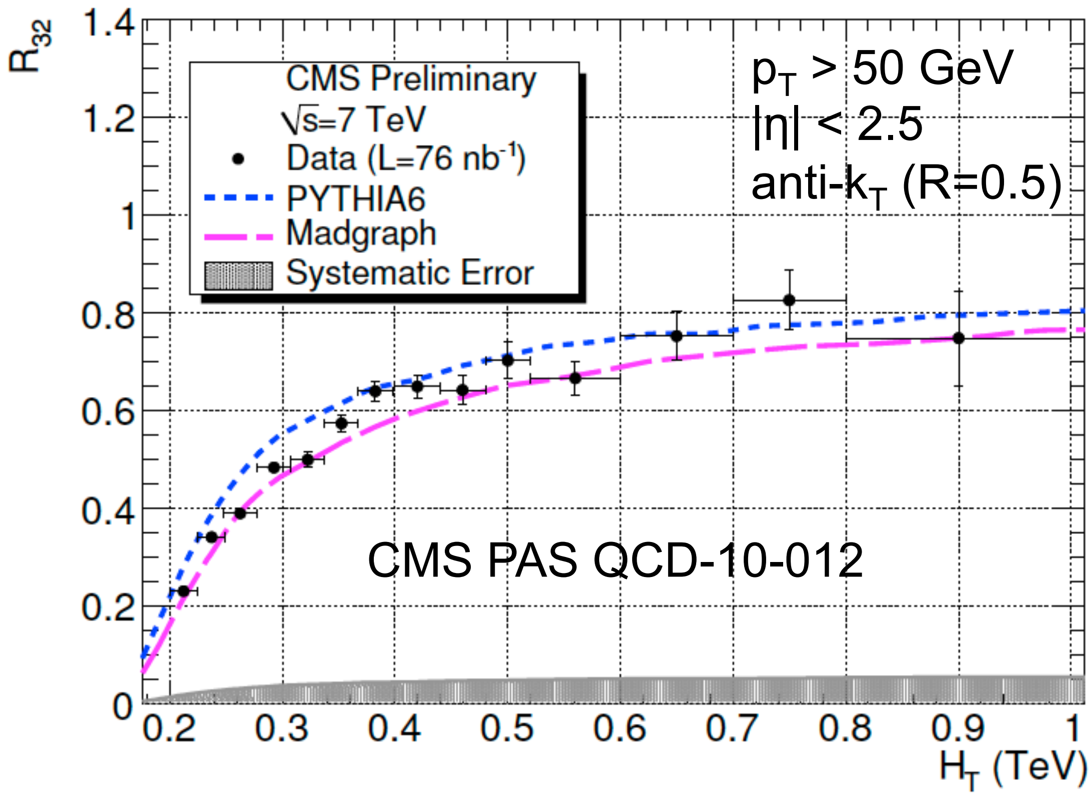




3-jet to 2-jet ratio

- Ratio of inclusive 3-jet to 2-jet cross section:

$$R_{32} = \frac{d\sigma_3 / dH_T}{d\sigma_2 / dH_T}$$



- Plateau sensitive to strong coupling

- **Good agreement with Pythia6 and Madgraph within uncertainties**

- Update with increased luminosity in preparation

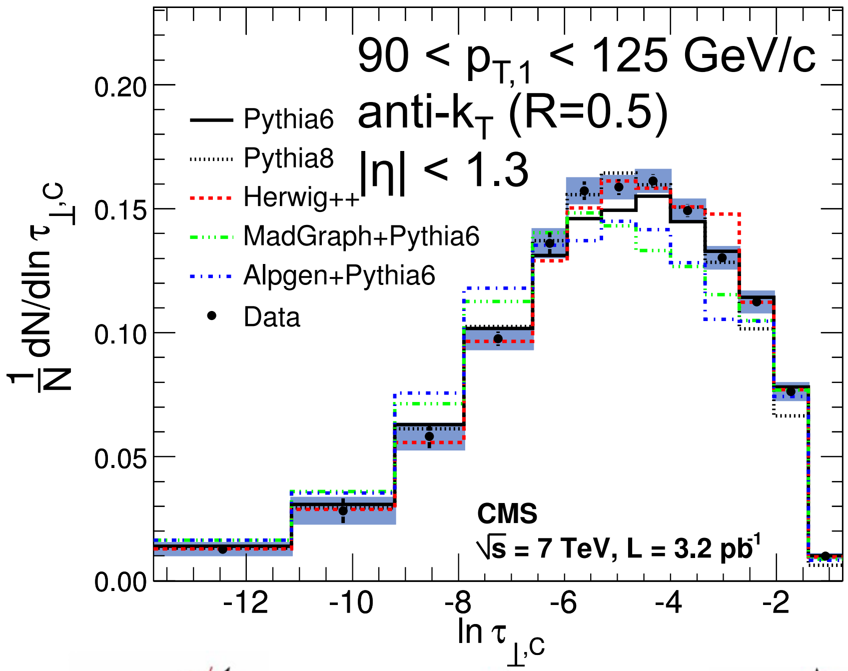
Hadronic event shapes

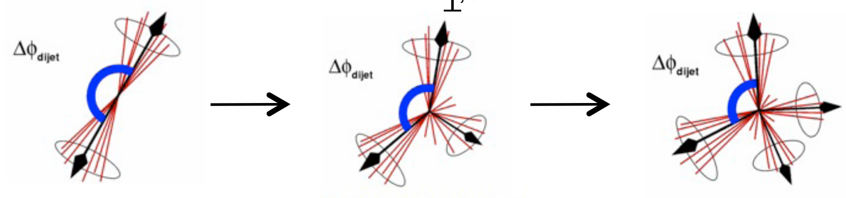
- Event shapes provide geometric information about energy flow in hadronic events
- Central transverse thrust: maximum of projection on a transverse axis

$$\ln \tau_{\perp,\mathcal{C}} = \ln(1 - T_{\perp,\mathcal{C}})$$

$$T_{\perp,\mathcal{C}} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

CERN-PH-EP-2010-072
submitted to PLB





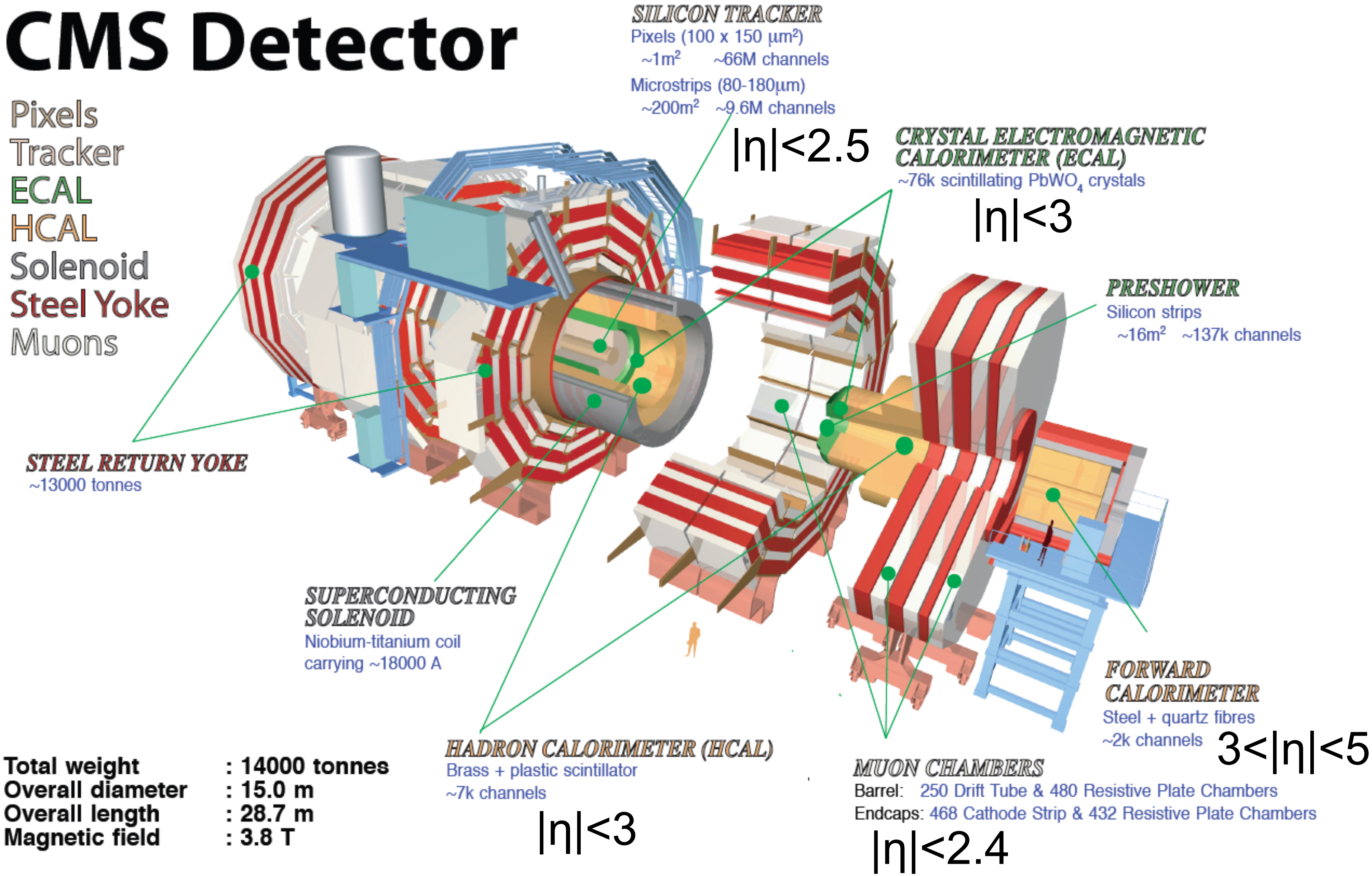
- Measured in exclusive p_T bins: 90, 125, 200 GeV
- Essential for tuning non-perturbative effects in MC event generators
- Low systematic uncertainties due to normalization in p_T bins
- **Dedicated talk by Matthias Weber (ETH Zürich)**

Conclusions

- Excellent performance of LHC in 2010
- Rich variety of results from high-p_T QCD program at CMS
  - Rather precise jet measurements with first CMS data
  - Many analysis already exceed Tevatron reach
  - Global data characteristics correctly described by QCD
  - Detailed measurements of jets and their characteristics constrain model building
  - Instruments for search for new physics evaluated on the data
- All CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

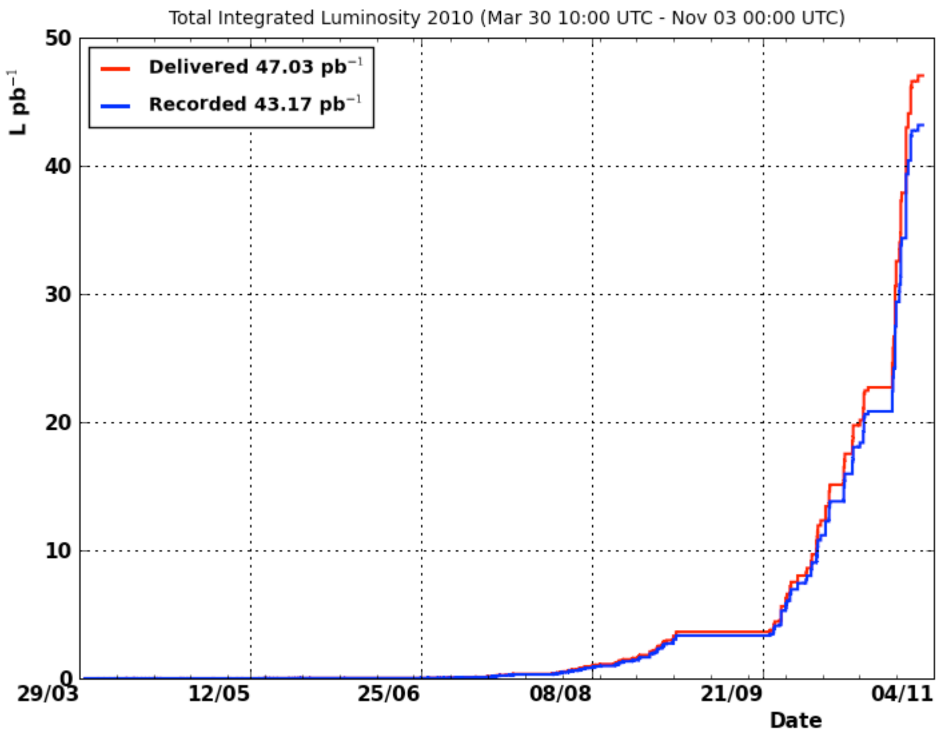
Backup

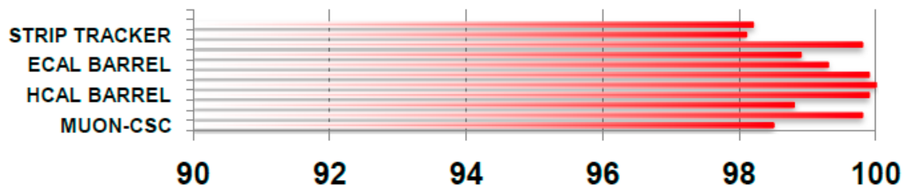
The CMS detector



Collected data in 2010

- 47 pb^{-1} pp data at $\sqrt{s}$ = 7 TeV delivered by the LHC
- 43 pb^{-1} recorded by CMS
  - Overall data taking efficiency greater than 90%
  - ~85% recorded with all subdetectors in perfect condition
- All subdetectors have at least 98% of all channels operational
- Luminosity uncertainty is currently 11%





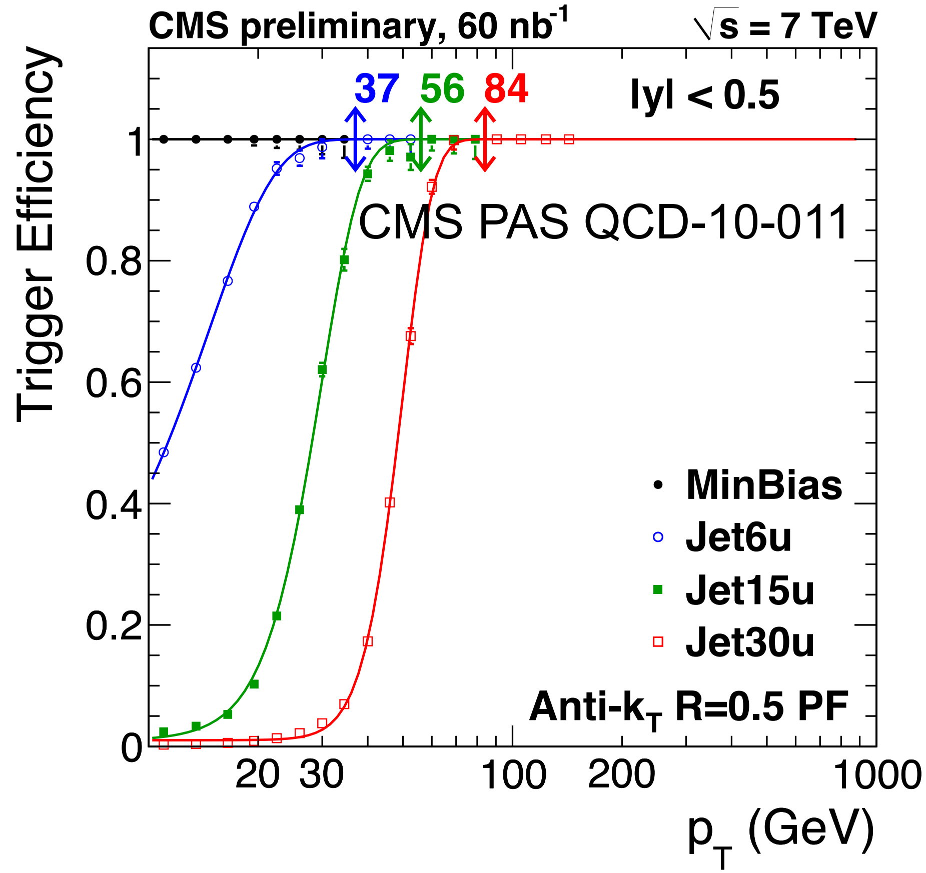
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

CMS trigger system

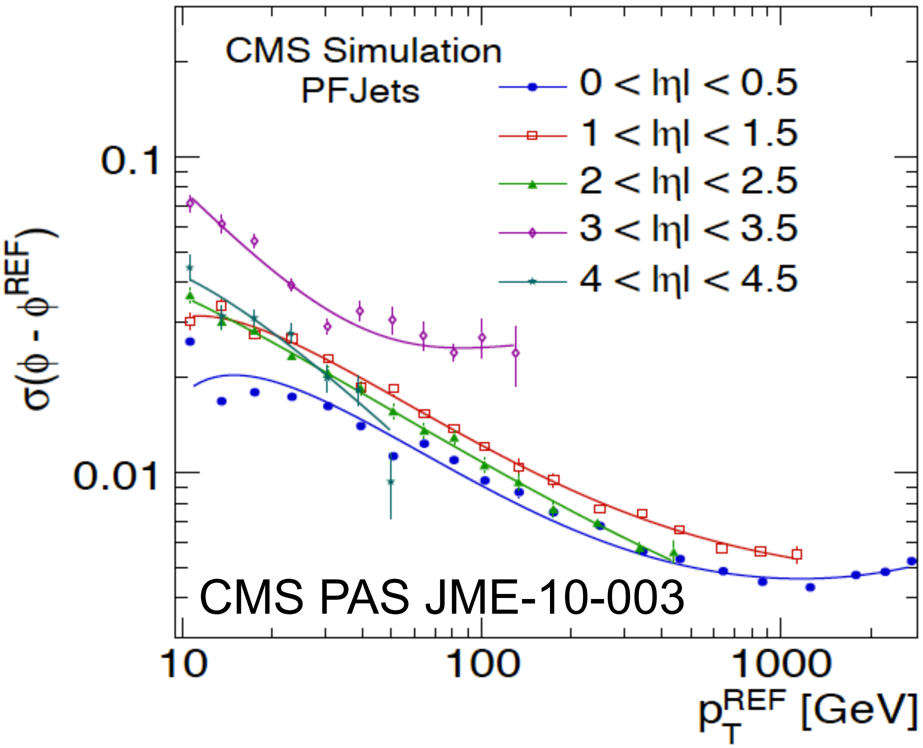
- Two-tiered system:
  - L1: hardware, firmware (40 MHz → 100 kHz)
  - HLT: high-level software (100 kHz → ~100-200 Hz)

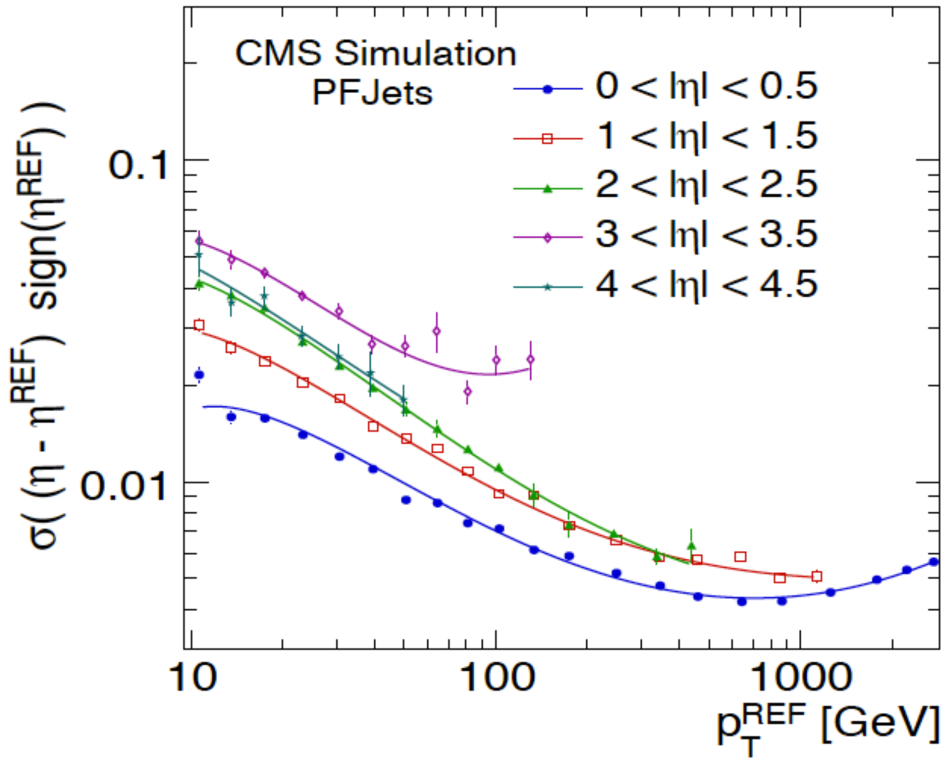
- Minimum Bias Trigger
  - Coincidence of Beam Scintillator Counters

- Jet Triggers
  - Using uncalibrated Calorimeter Jets
  - >99% efficient above turn-on
  - Lowest threshold trigger unprescaled over 2010 run: Jet140u

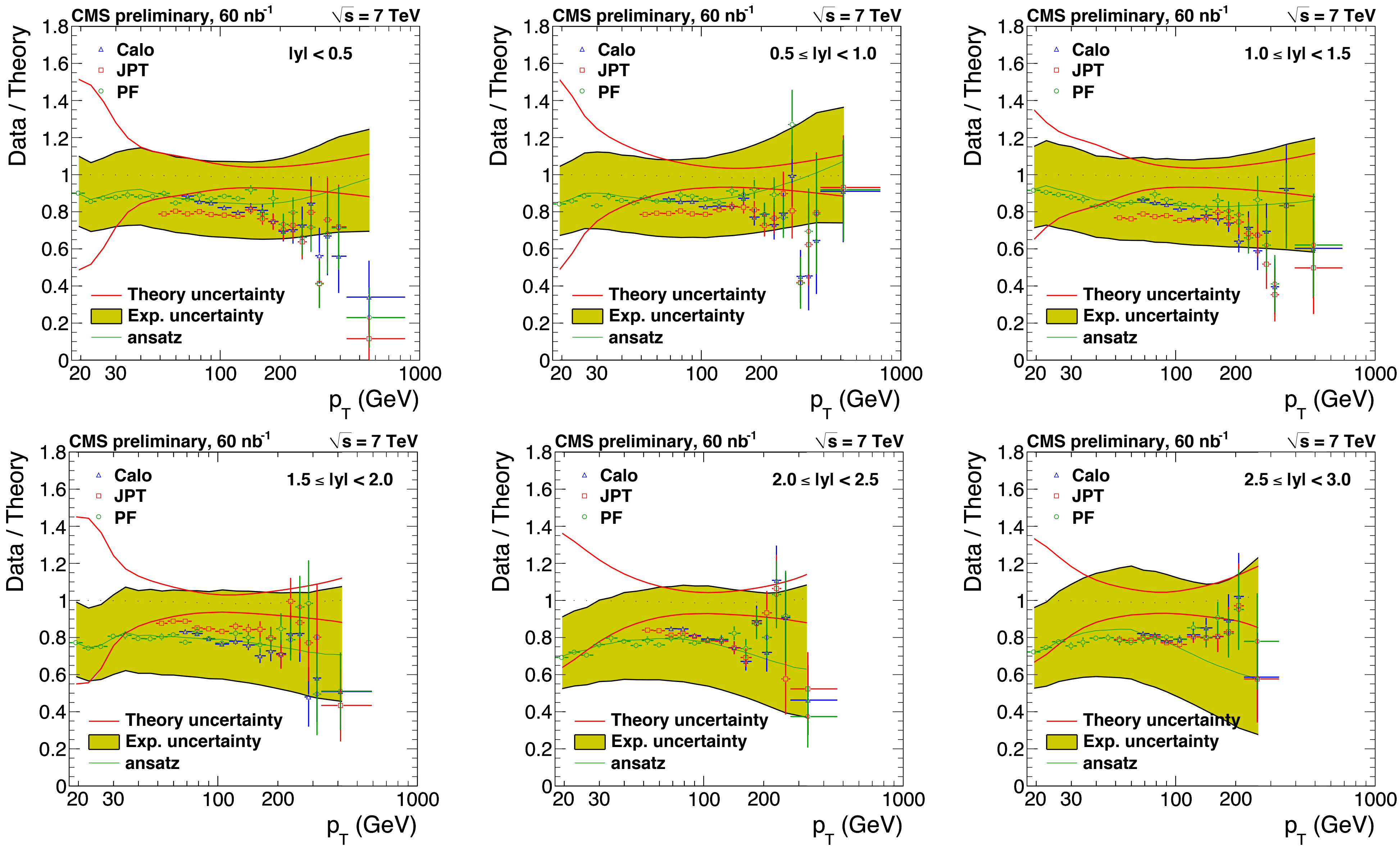


Jet performance in CMS – cont'd

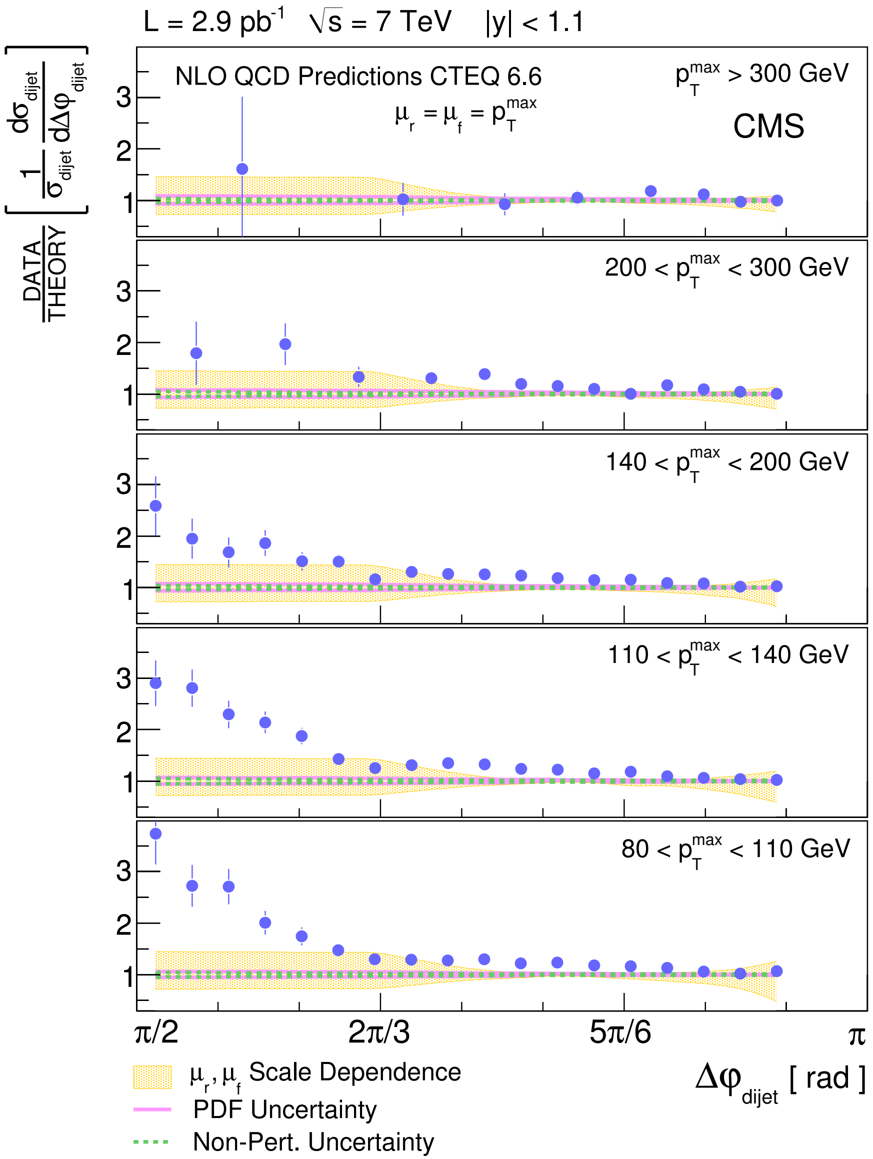


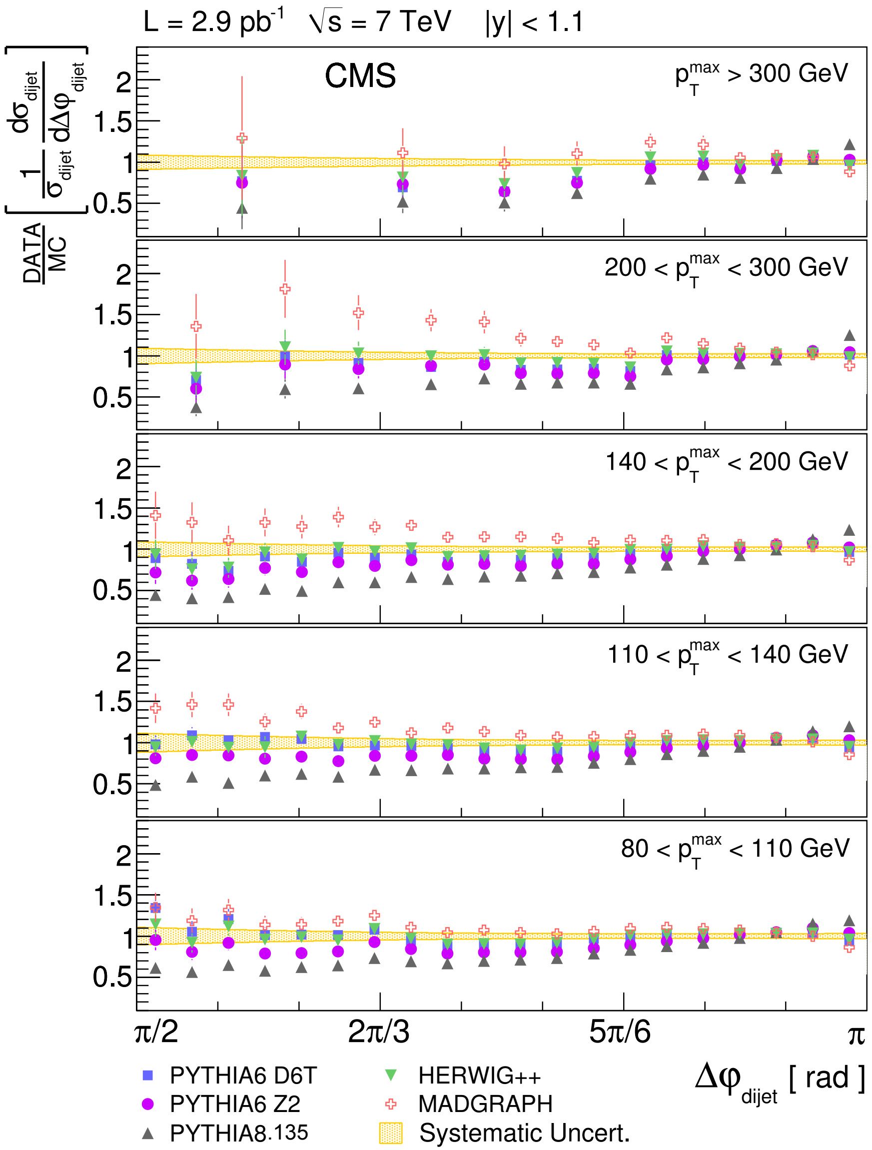


Inclusive jets – cont'd



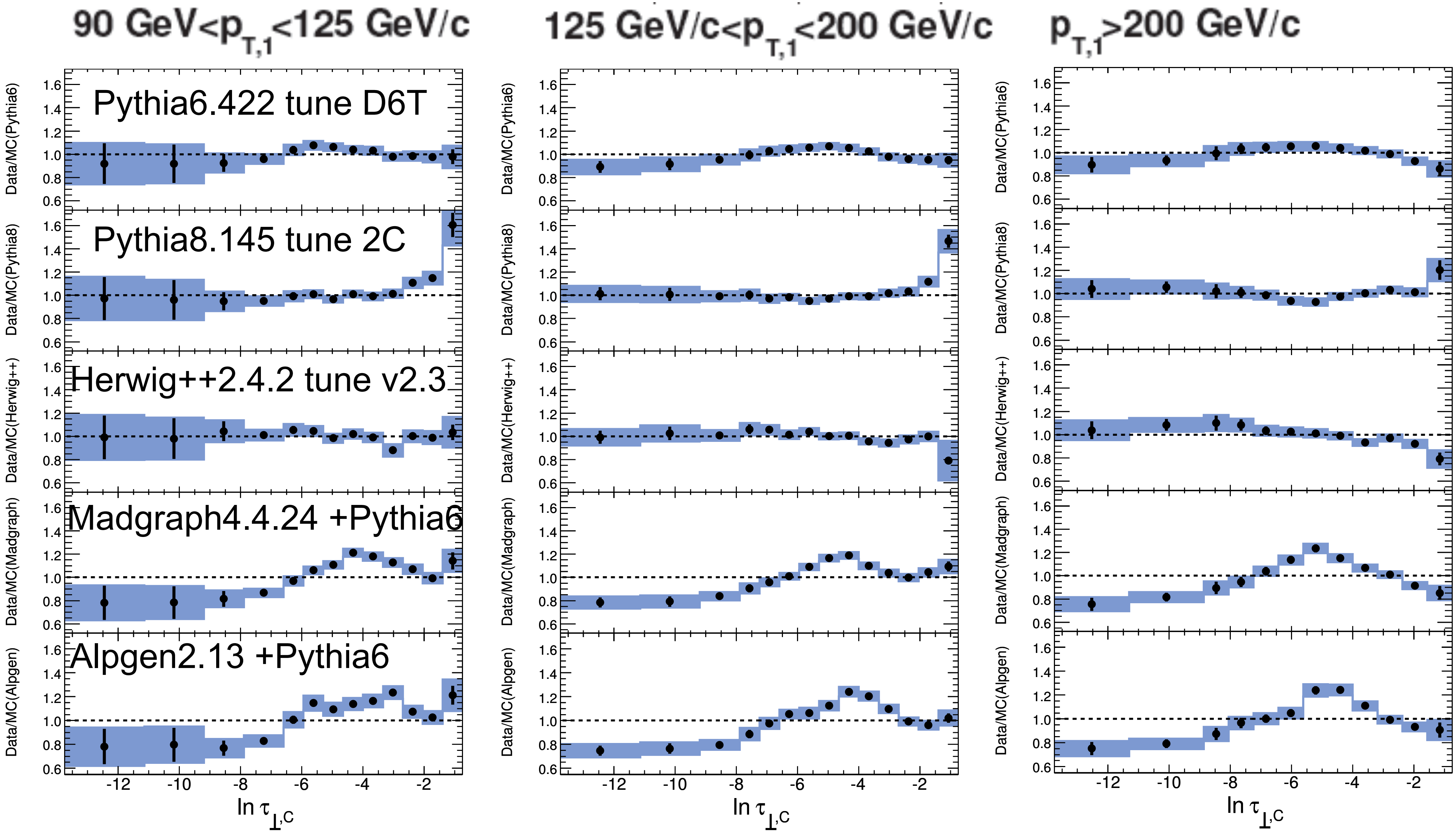
Di-jet azimuthal decorrelation – cont'd





Hadronic event shapes – cont'd

Central transverse thrust



Hadronic event shapes – cont'd