Studies of QCD jet production with the CMS detector in pp Collisions at $\sqrt{s}$ = 7 TeV

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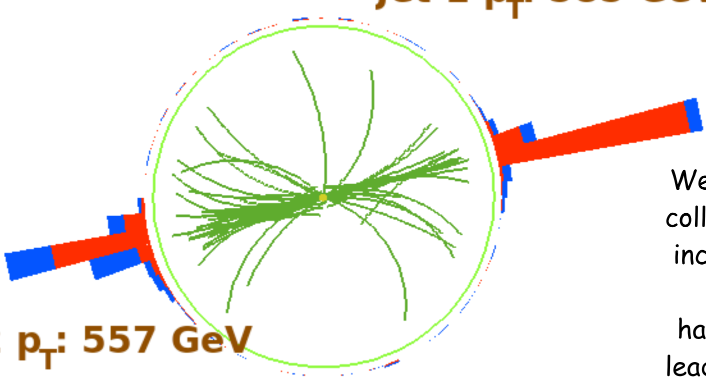
for the CMS collaboration

Outline

- Introduction
- Experimental techniques
- Inclusive jets
- Ratio measurements
- Conclusions

Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV



Analyses:

QCD-10-011 : inclusive jets
QCD-10-012 : 3/2-jet ratio
QCD-10-013 : event shapes
QCD-10-014: transerse structure
QCD-10-015: dijet Δφ and χ (chi)

Related analyses and talks:

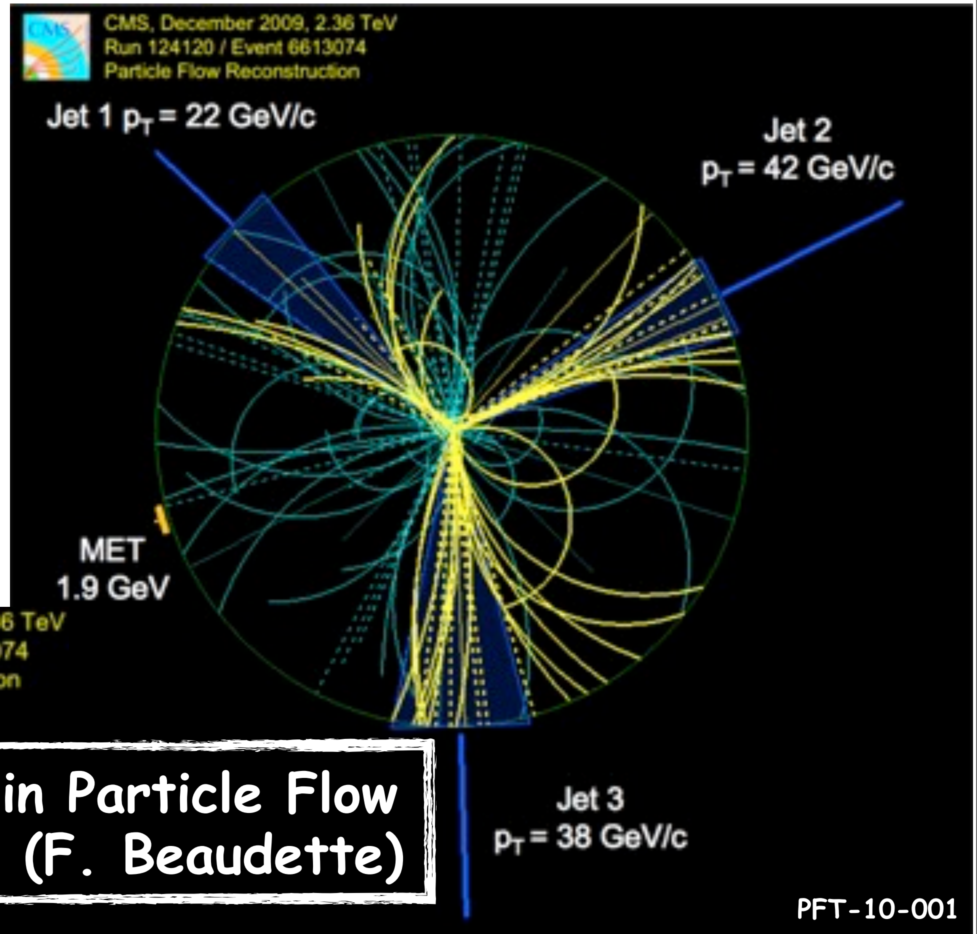
JME-10-003 - jet performance (J.Weng) 01/22.7. 16:55
PFT-10-002 - Particle Flow (F. Beaudette) 01/22.7. 17:15
BPH-10-009 - b-jets (L. Caminada) 05/22.7. 17:15
EXO-10-001 - dijet mass (K. Kousouris) 10/23.7. 14:40
QCD-10-00 - underlying event (P. Bartalini) 03/24.7. 11:40

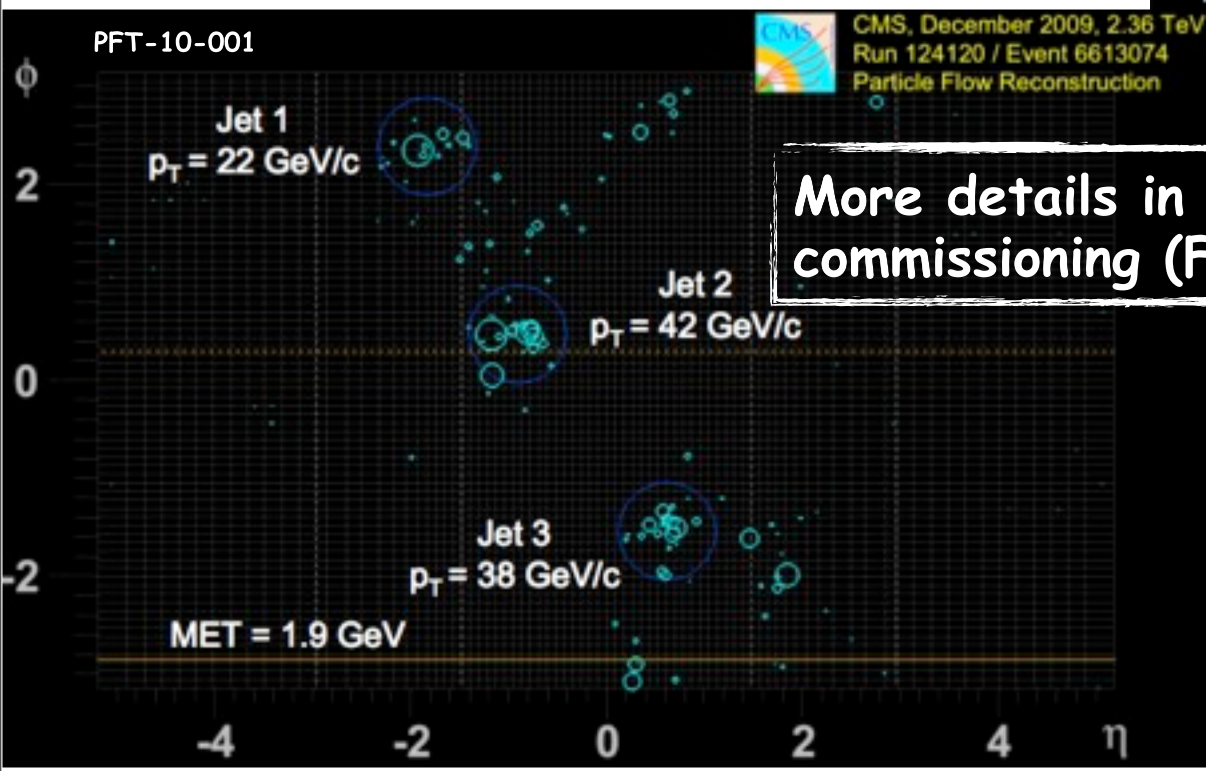
Abstract:

We report on an **extensive list** of analyses in order to test QCD predictions for jet production in pp collisions at sqrt(s)=7 TeV, recorded by the CMS experiment. The list includes a measurement of the inclusive jet spectra, obtained with different jet reconstruction methods, the ratio of the inclusive three-jet over two-jet cross sections as a function of the total jet transverse momentum HT, hadronic event shapes as determined from jet momenta, azimuthal decorrelations between the two leading jets, dijet invariant mass spectra and the production ratio for events with two leading jets in two regions of pseudorapidity. Finally, we also present a study of the jet transverse structure, the charged hadrons multiplicity in jets and the longitudinal and transverse momentum distribution of charged hadrons relative to the jet axis. Many of these analyses are based on ratio quantities, where important experimental systematic uncertainties and most notably the luminosity uncertainty cancel.

Jet reconstruction

- Four inputs to anti-k_T R=0.5 algorithm:
  - Calorimeter towers => CaloJets
  - Tracks => TrackJets
  - Calorimeter towers + track corrections => JetPlusTracks, JPT
  - Particle Flow objects reconstructed as a heuristic combination of HCAL cells, ECAL crystals and matched tracks => PFJets



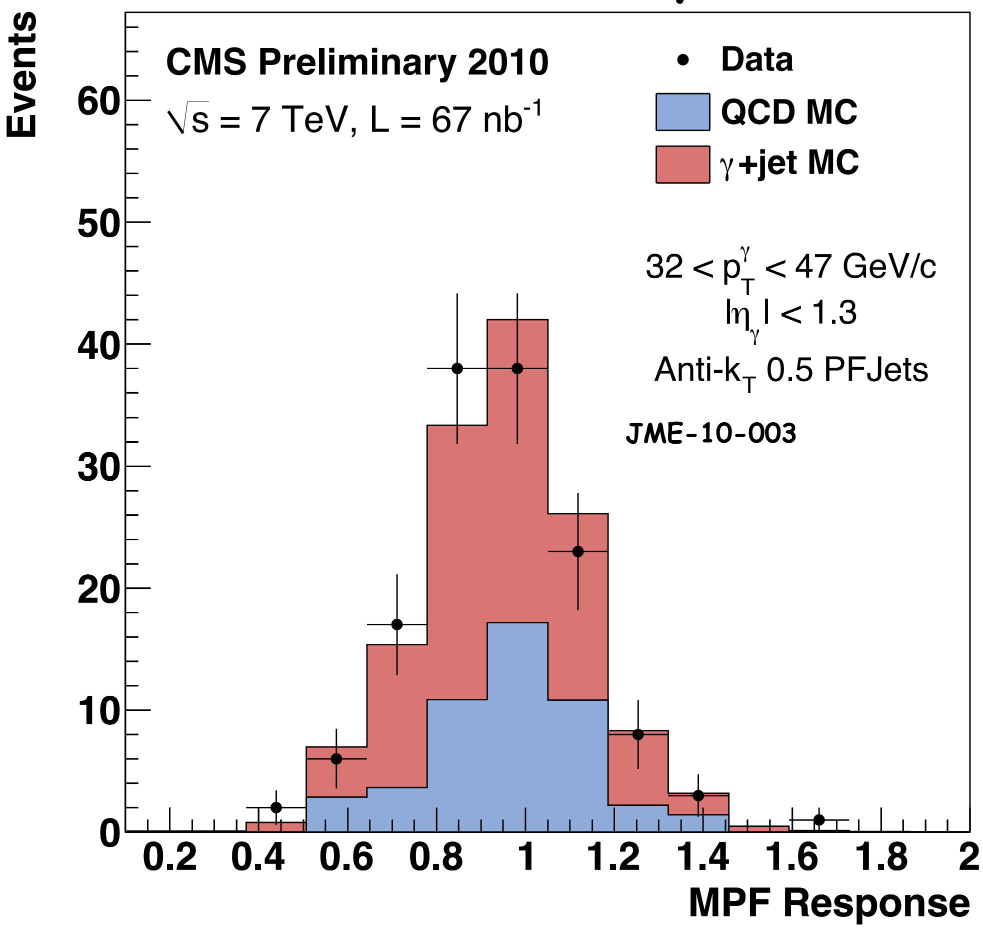


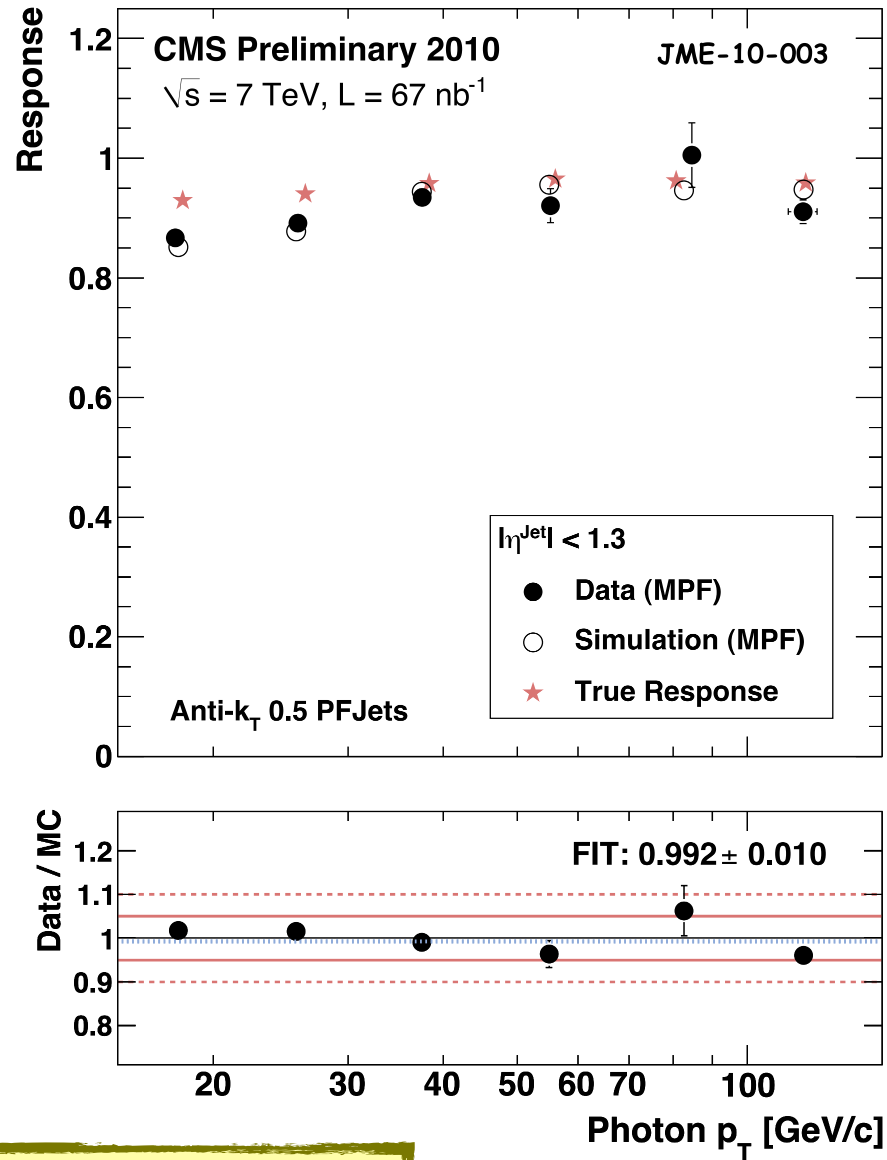
More details in Particle Flow commissioning (F. Beaudette)

Using different inputs allows CMS to study and constrain experimental systematics for good understanding of jet identification, resolutions and energy scale

Jet corrections: absolute p_T

- A-priori estimate of JEC uncertainty in barrel 5% for tracking-based jets (JPT, PFJets, track jets), 10% for CaloJets
- Direct evidence from Missing-E_T projection fraction method (MPF, from D0) supports **5%/10% JEC uncertainty** as conservative



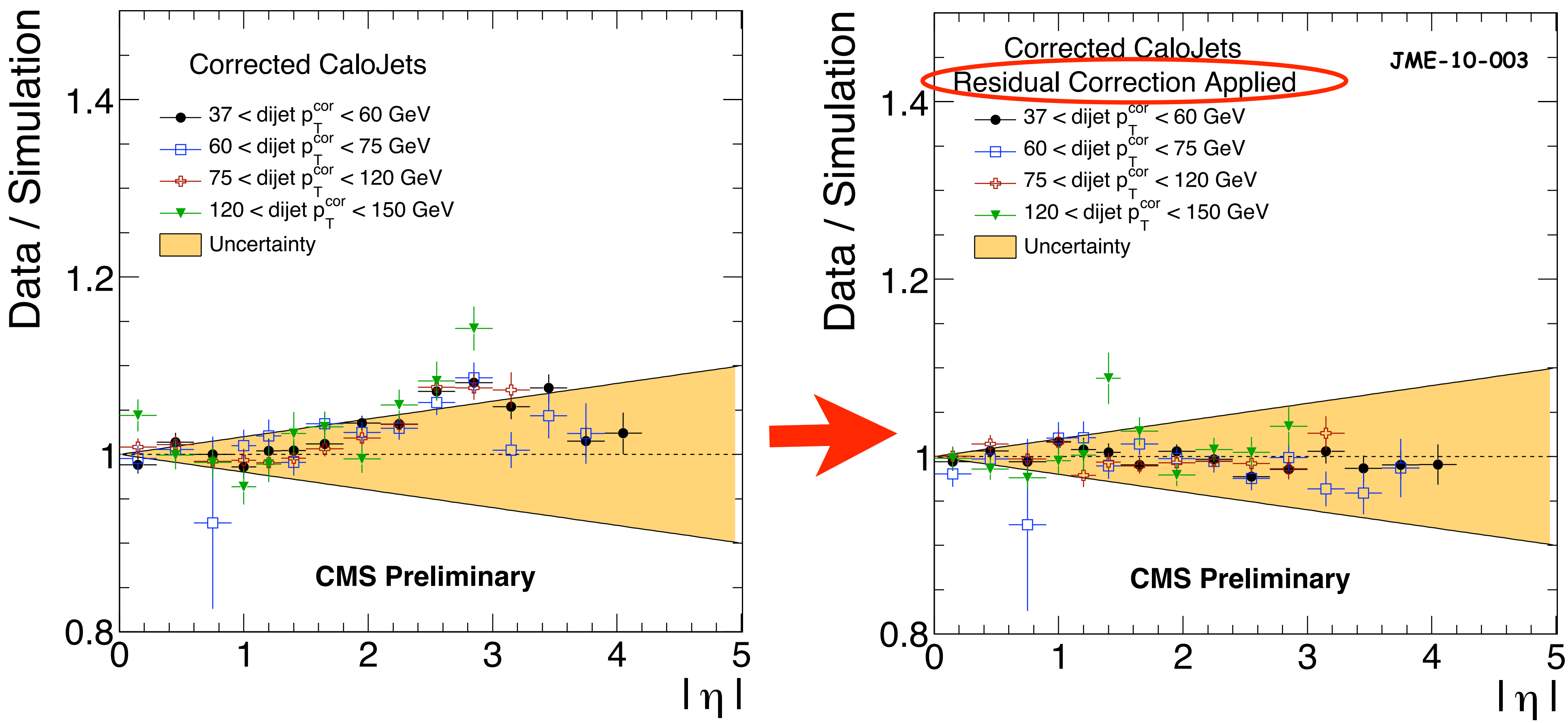


More details in CMS JetMET performance talk (J. Weng)

Jet corrections: relative η

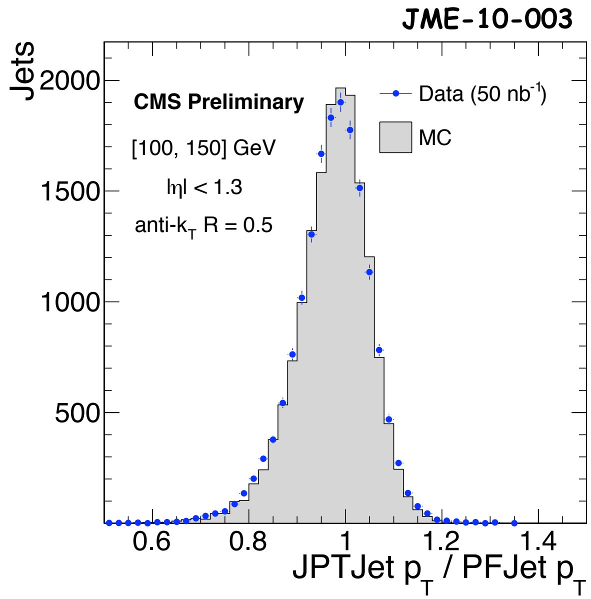
- Response rapidity dependence is extracted from dijet asymmetry
- Residual correction is applied for inclusive jets, other studies are covered by the systematic uncertainty band of **2% times unit of rapidity**

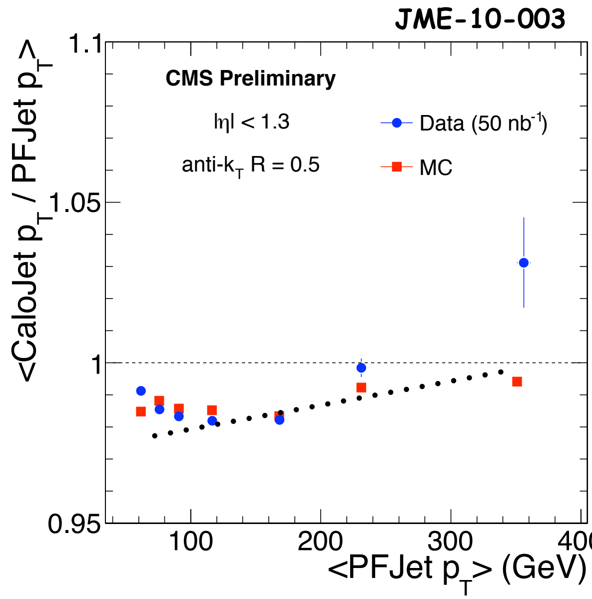
Jet correction = Absolute(p_T) [MC] × Relative(η) [MC+data]

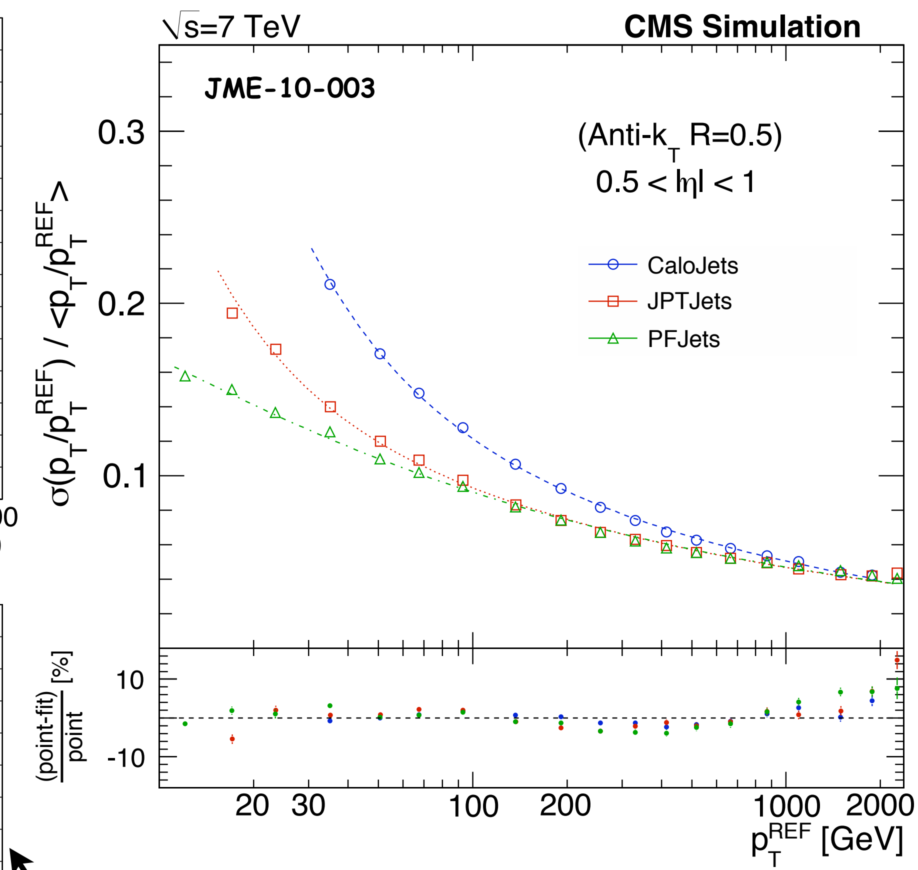


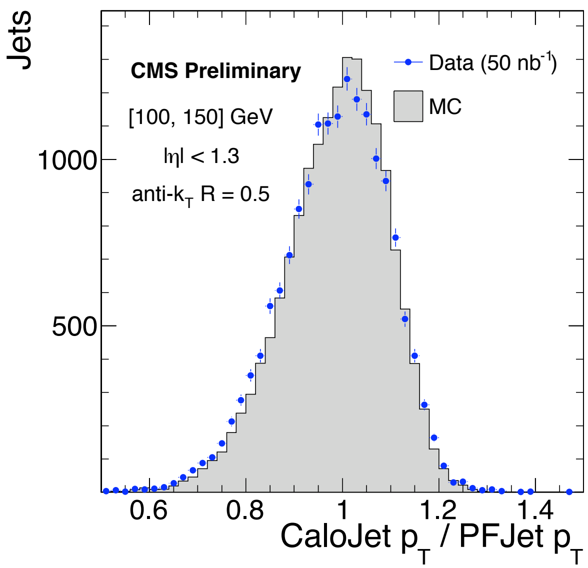
Jet correction: jet types

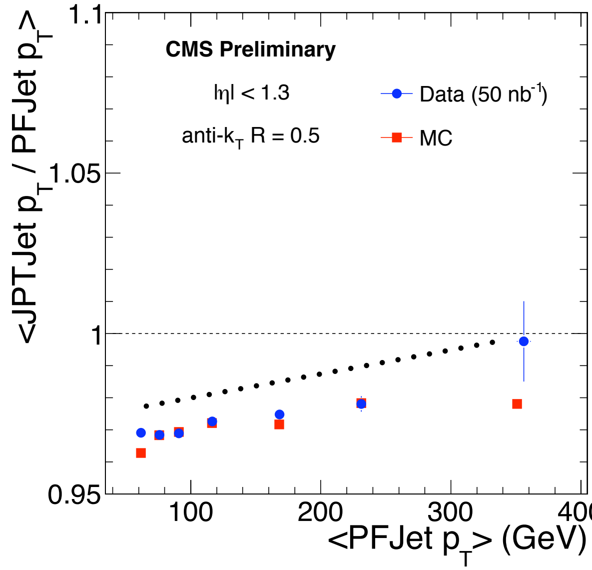
- Relative p_T of matched jets of different reconstruction types confirm good MC modeling and **10% resolution uncertainty** based on dijet asymmetry







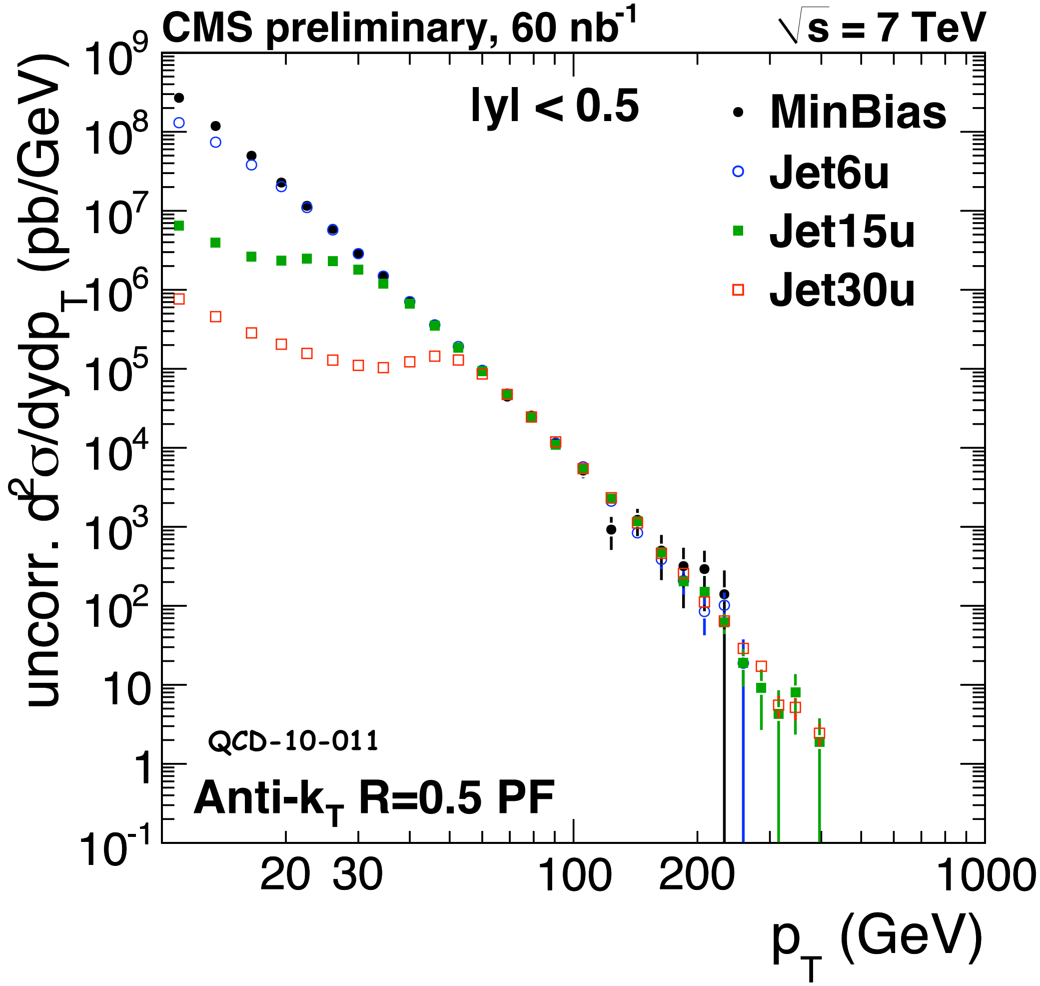


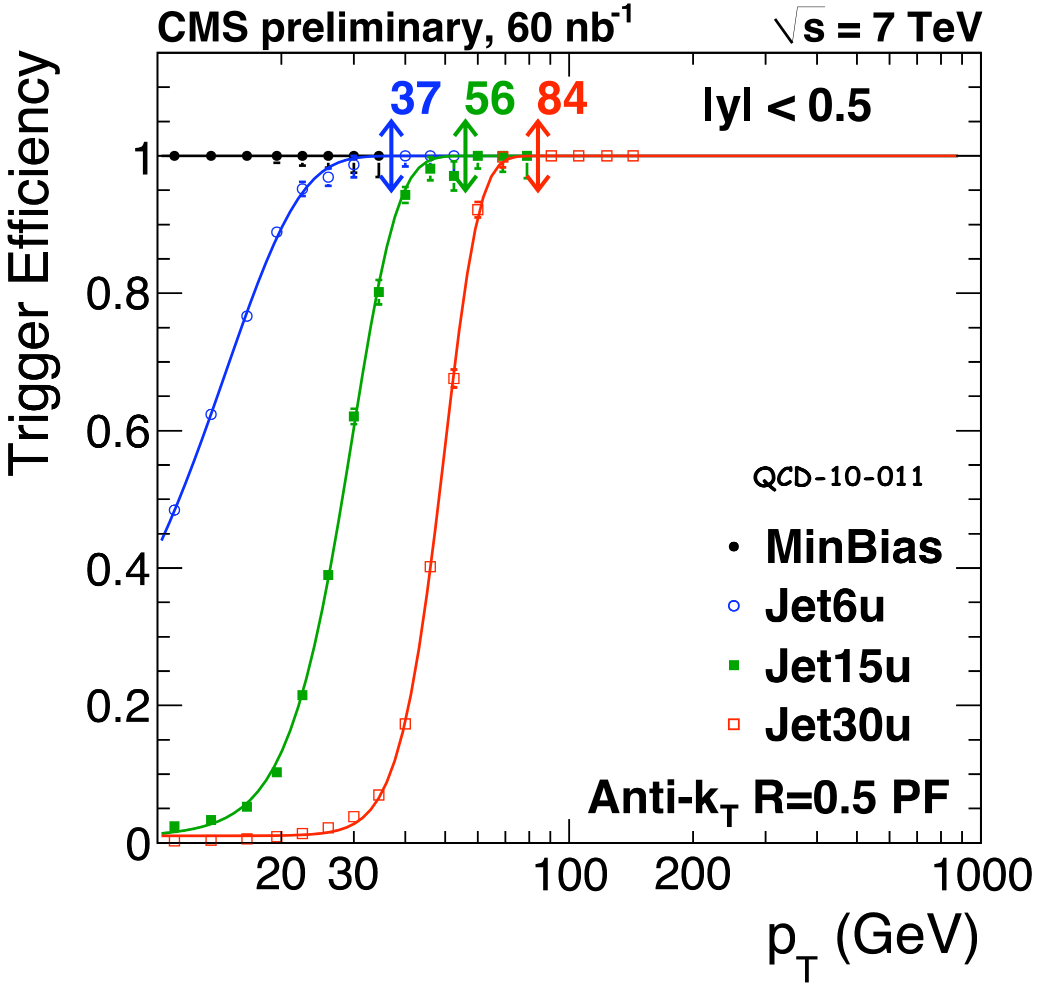


NB: small bias in comparisons comes from jet resolutions and steep spectrum (dotted)

Collecting events

- Events are collected from a combination of Minimum Bias and jet triggers
- Unprescaled triggers for p_T>32-56 GeV (~10 nb^{-1}) and p_T>64-84 GeV (~100nb^{-1})
- Low p_T results are limited to run periods with negligible pile-up (10 nb^{-1}), while high p_T results can use maximum luminosity with small offset systematics





Unfolding

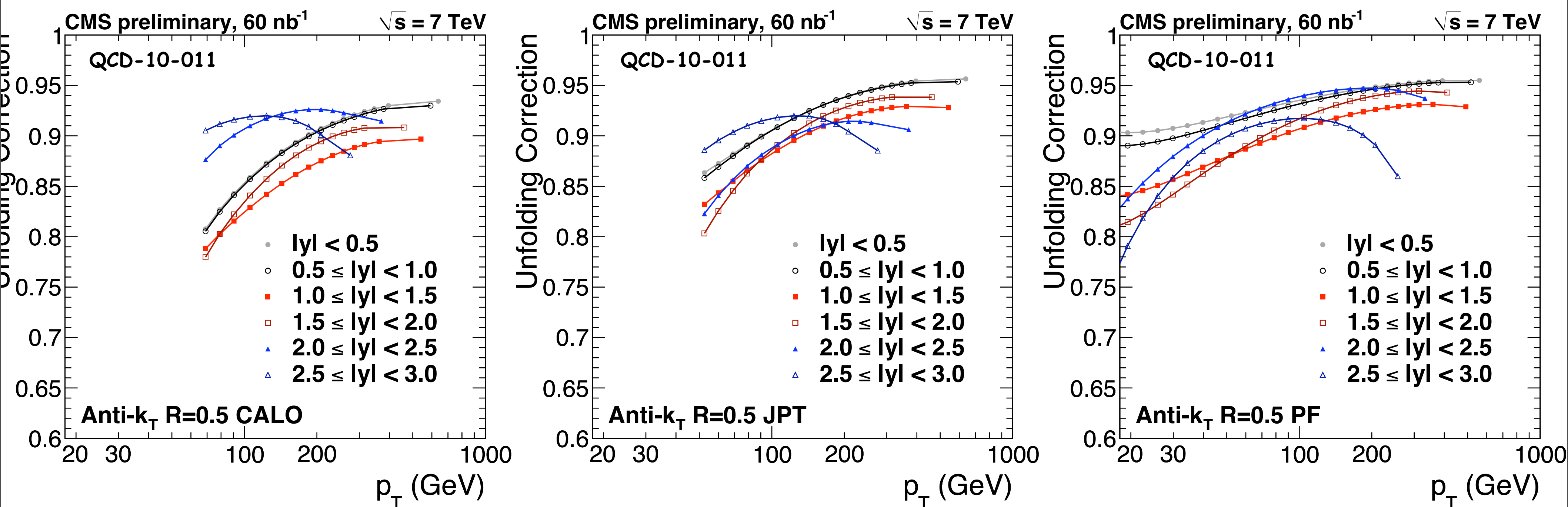
- Inclusive jet cross section uses **ansatz** unfolding to get to the particle level
- Phenomenological power law motivated by parton model (Feynman/Field/Fox), extended at the Tevatron, and updated at CMS for low p_T and b-jets

Inclusive b-jets (L. Caminada)

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

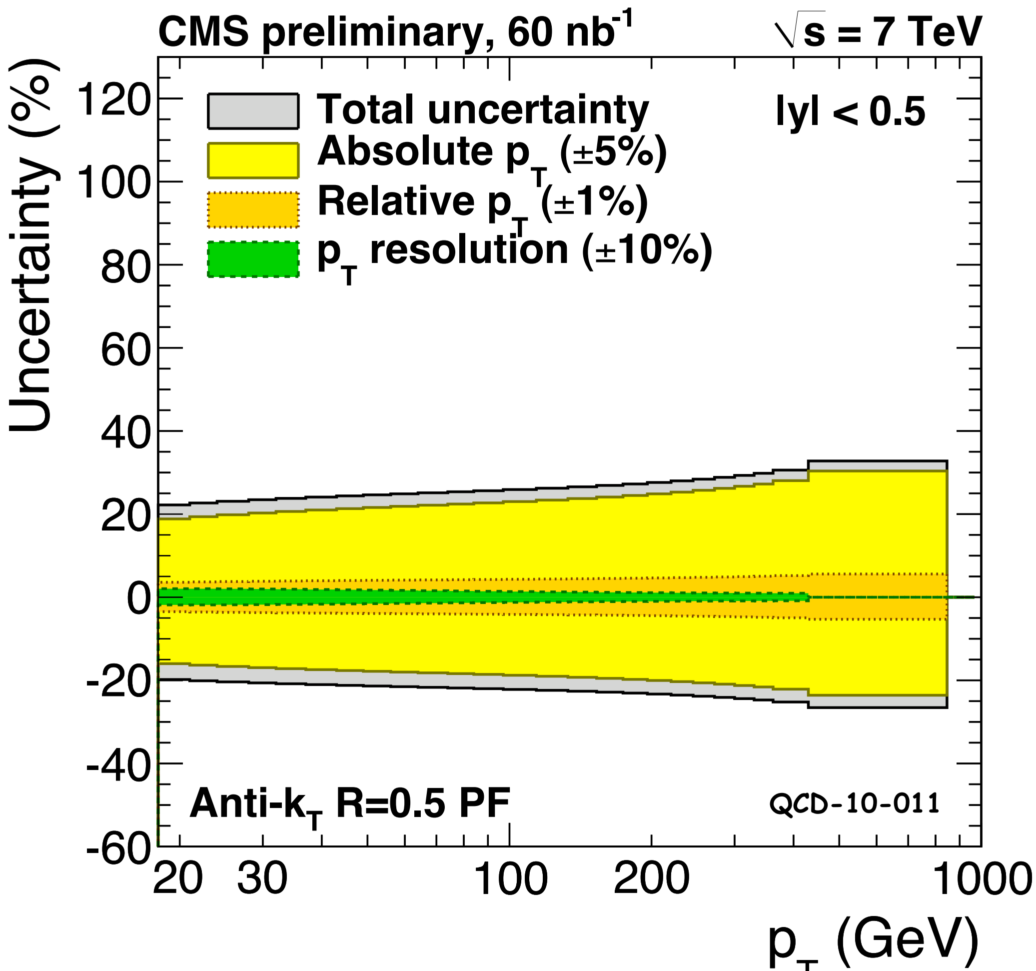
new

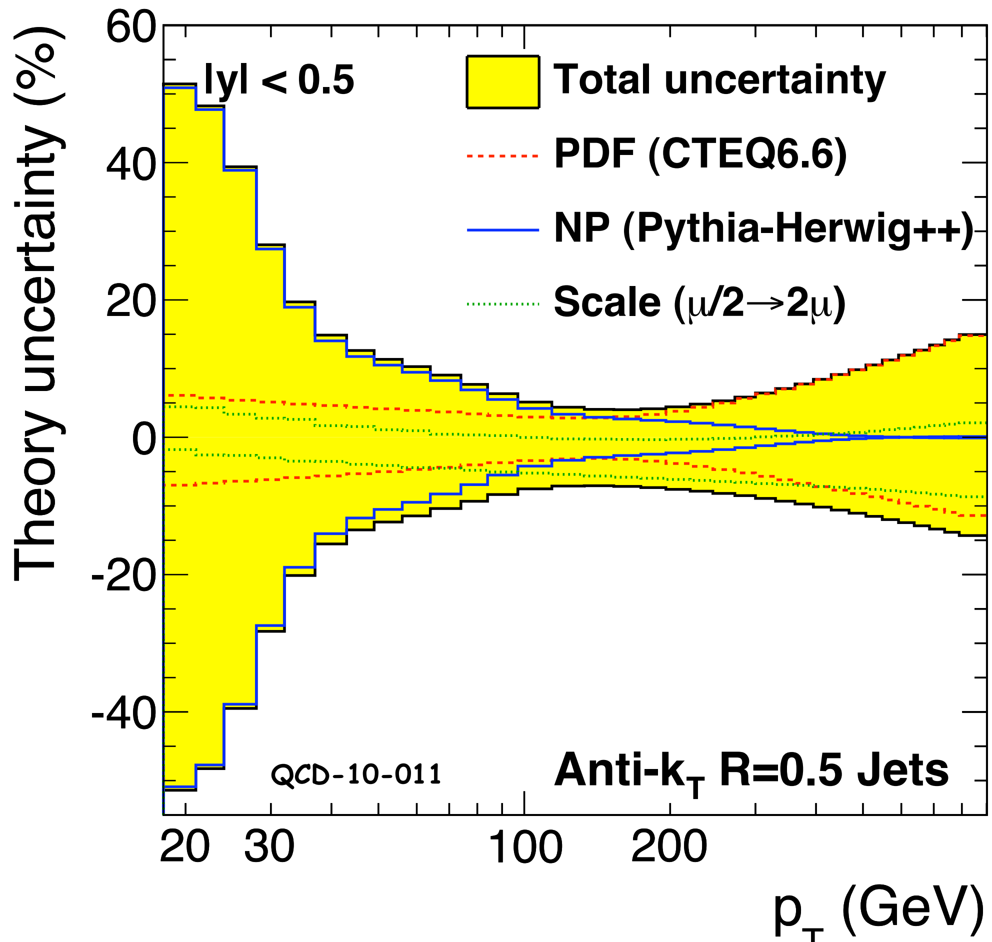
$$C_{\text{smear}}(p_T) = \frac{f(p_T)}{F(p_T)}, \qquad F(p_T) = \int_{x=0}^{x=\infty} f(x) g(p_T - x) dx,$$



Inclusive jet cross section

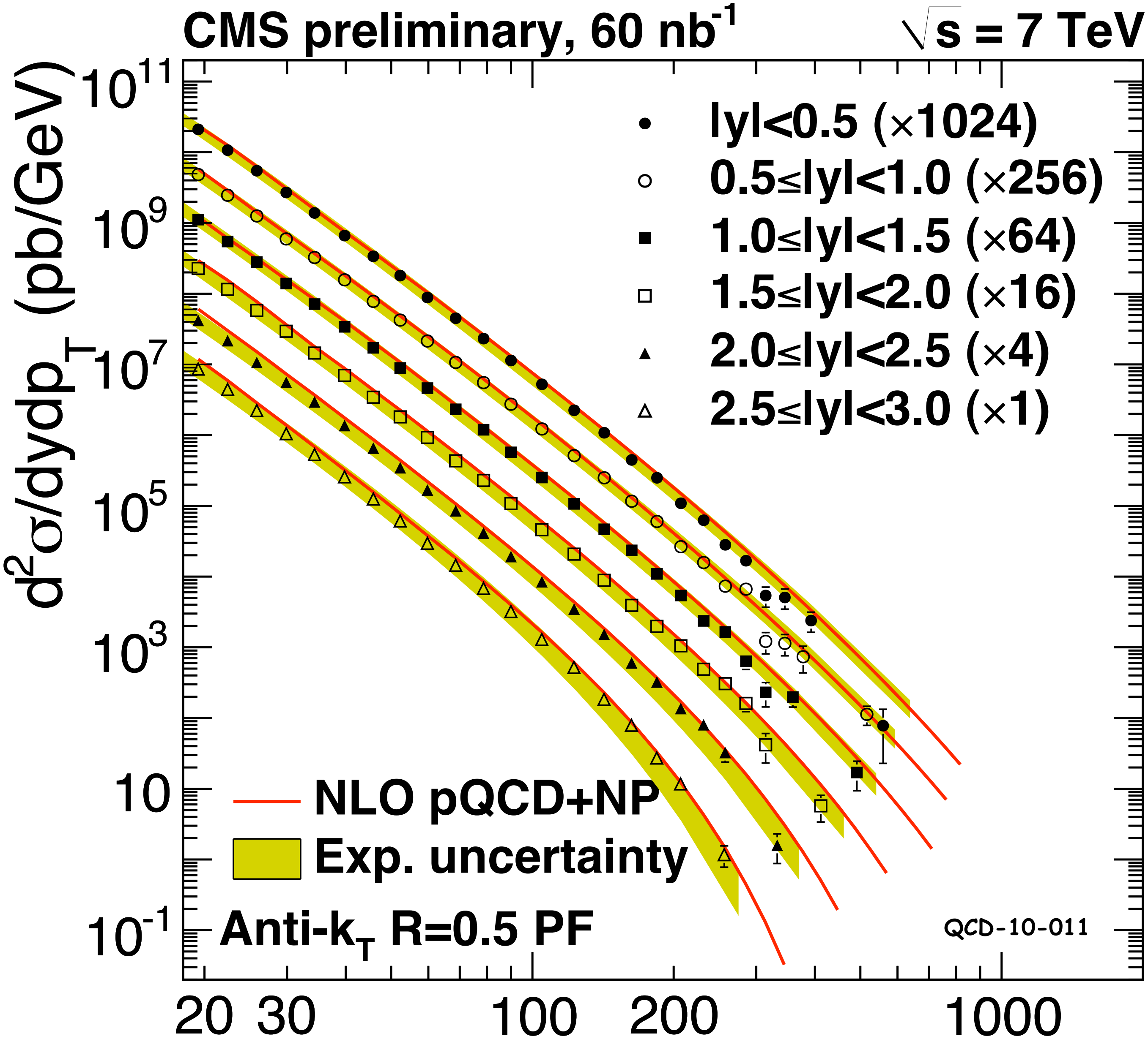
- Main systematics for inclusive jet cross section, as for most other jet analyses: jet energy scale (5-10%), jet resolutions (10%) and luminosity (11%)
- Many analyses use ratio measurements to normalize out JEC and/or luminosity
- From theory side dominant systematics are parton distributions (PDF), non-perturbative corrections (NP) and factorization/renormalization scales ($\mu_{R,F}$)





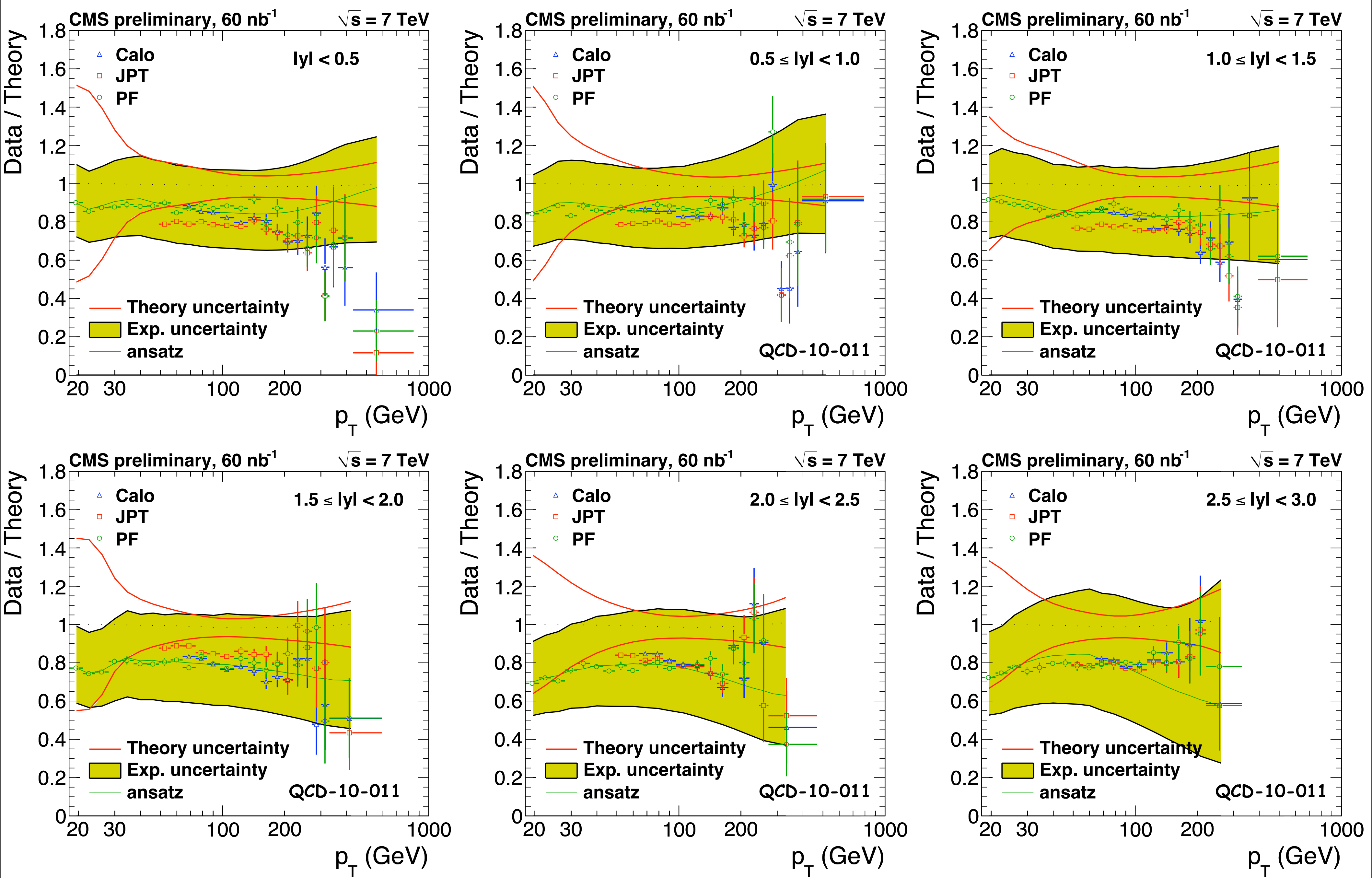
Inclusive jet cross section

- Inclusive jet p_T spectra are in good agreement with NLO theory for all reconstruction types
- Past Tevatron published (0.7 fb^{-1}) record of 624 GeV jet at high p_T
- Extending below TeV's 50 GeV at low p_T thanks to novel reconstruction methods (Particle Flow)
- Extending up to |y|<3.0 **(P. Bartalini: 3<|y|<4.7)**
- Low p_T reach limited from theory side by non-perturbative corrections
- Systematic uncertainty is centered around PF ansatz



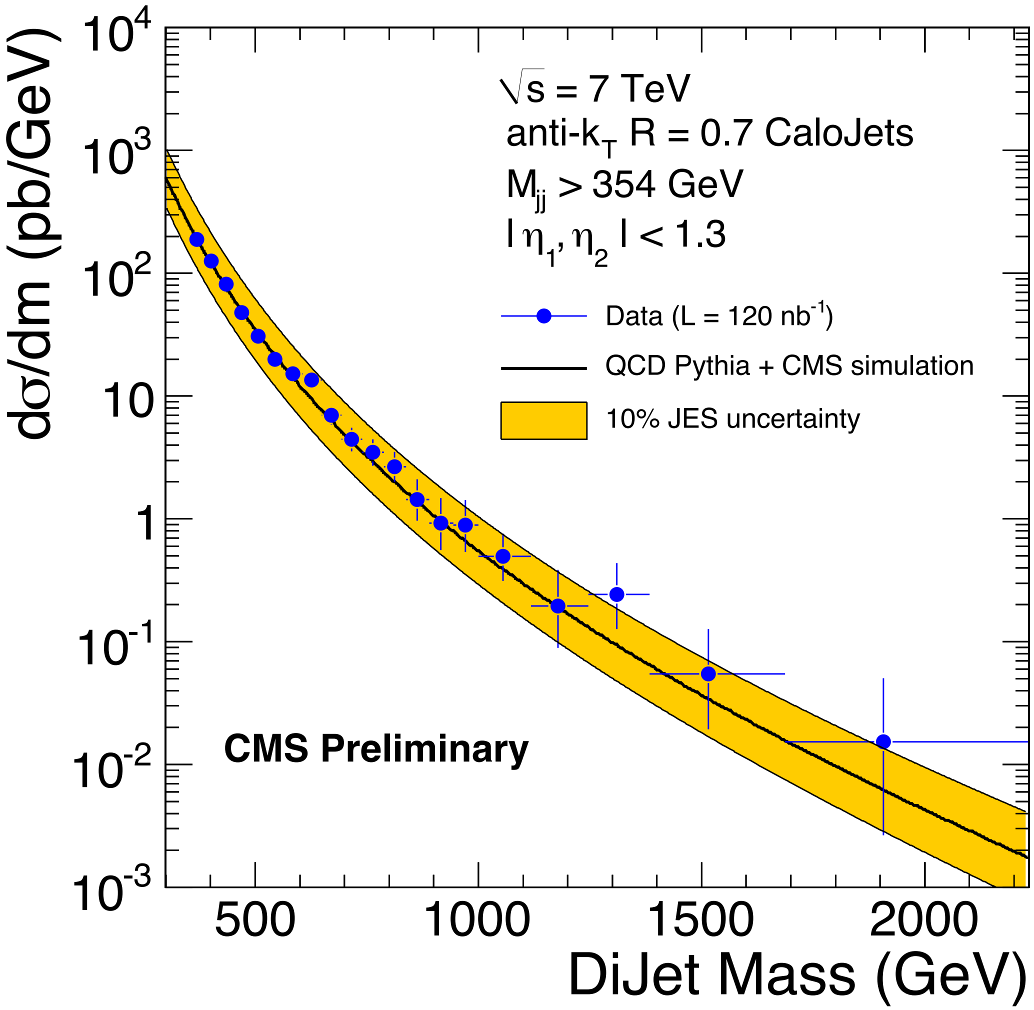
$x_T = p_T/\sqrt{s} = 0.005$

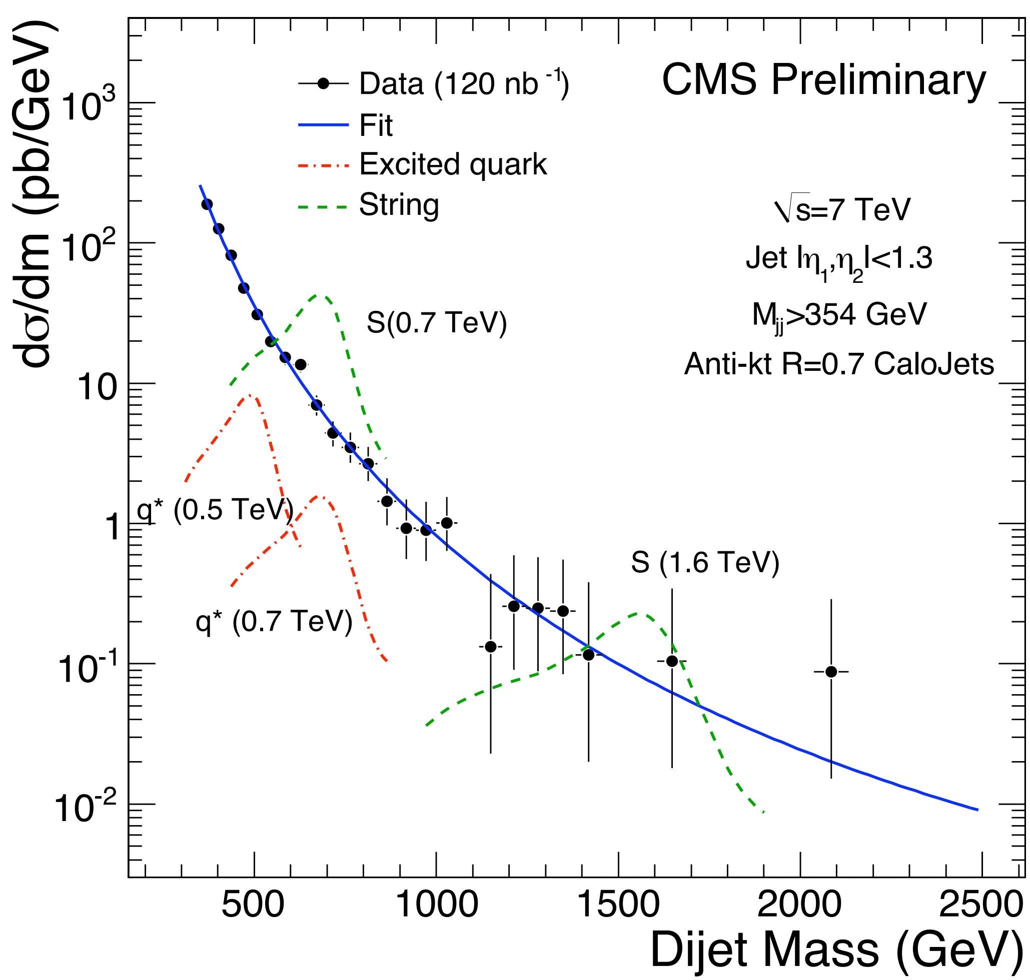
Inclusive jet cross section



Dijet mass

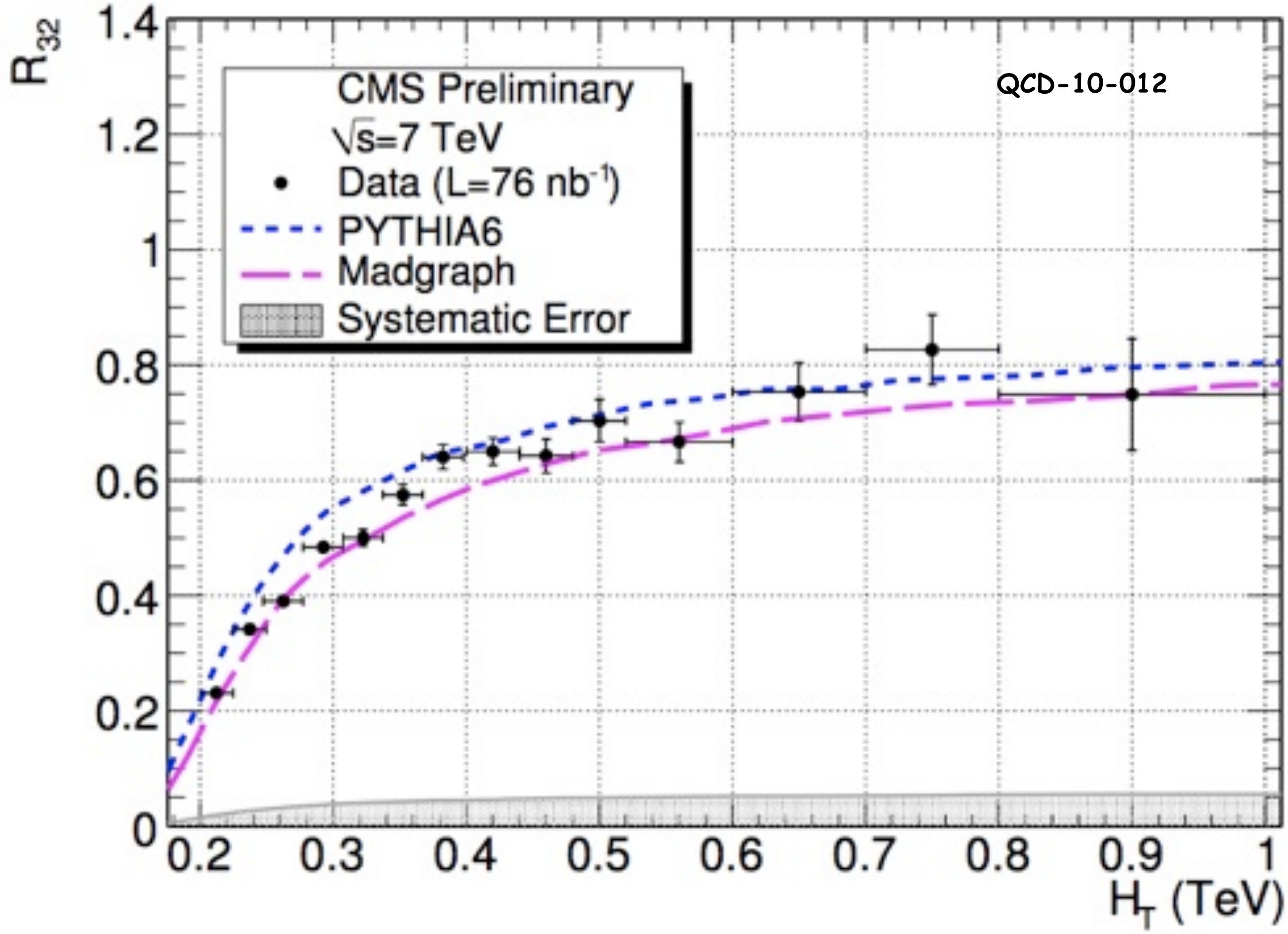
- Dijet mass measurement is sensitive to JEC and luminosity, but doubles as a bump-hunt for new physics **(talk by K. Kousouris)**
- Theory sensitivity to PDFs and scale similar to inclusive jets





3/2-jet ratio

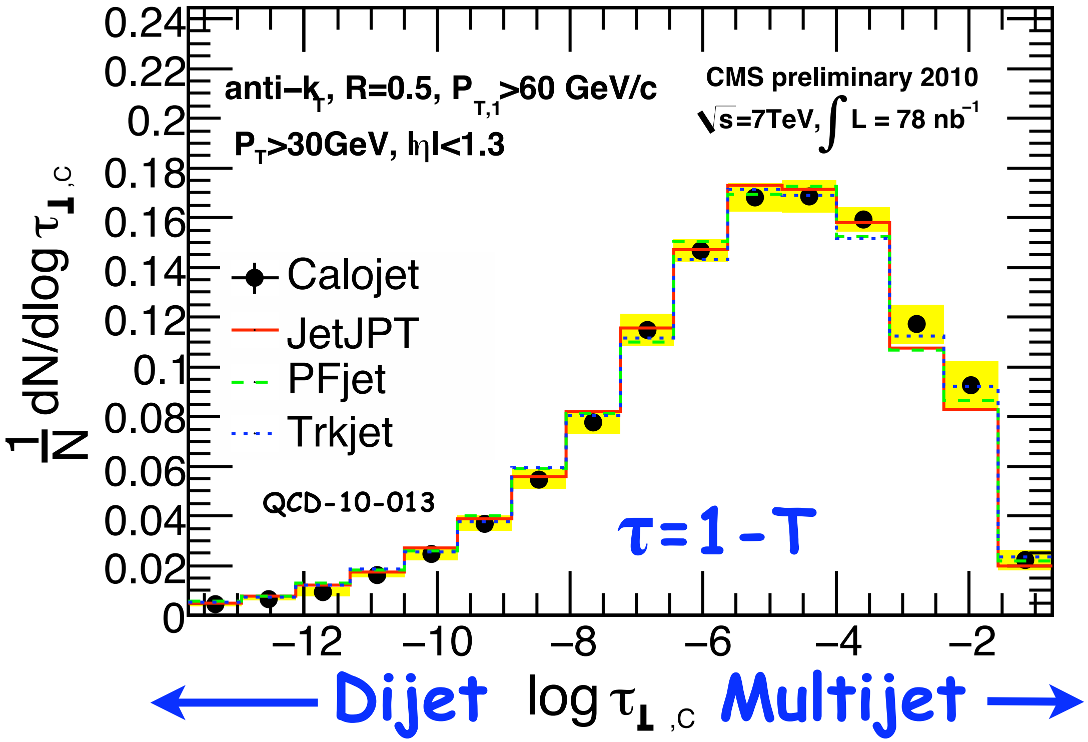
- Starting from inclusive jets, more specific topologies focus on different aspects of theory; ratio measurements also reduce JEC and lumi uncertainty
- Ratio of inclusive 3-jet and inclusive 2-jet cross sections is a good example; $p_{T,}$jet > 50 GeV, |y| < 2.5, $R_{32} = (d\sigma_3/dH_T) / (d\sigma_2/dH_T)$
- Good agreement found with Pythia and Madgraph within uncertainties



Plateau sensitive to α_S

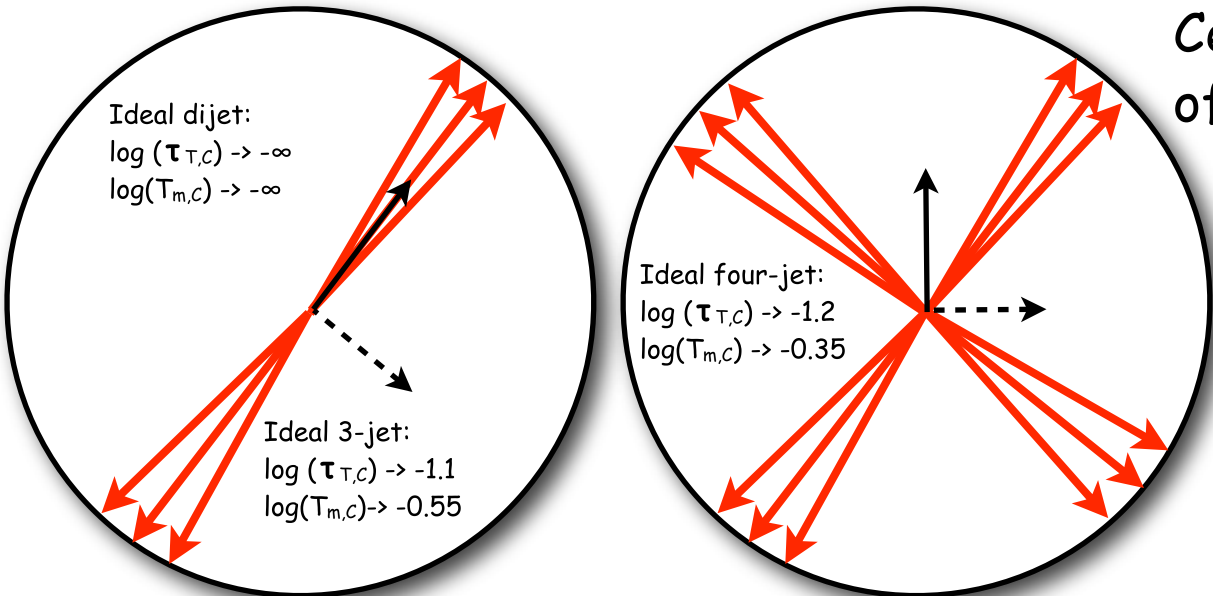
Hadronic event shapes

- Event shapes provide geometric information about energy flow in hadronic events
- Essential for tuning parton shower and non-perturbative components of Monte Carlo event generators
- Event shapes are robust against choice of jet reconstruction, as well as JEC and JER uncertainties



Central transverse thrust: maximum of projection on a transverse axis

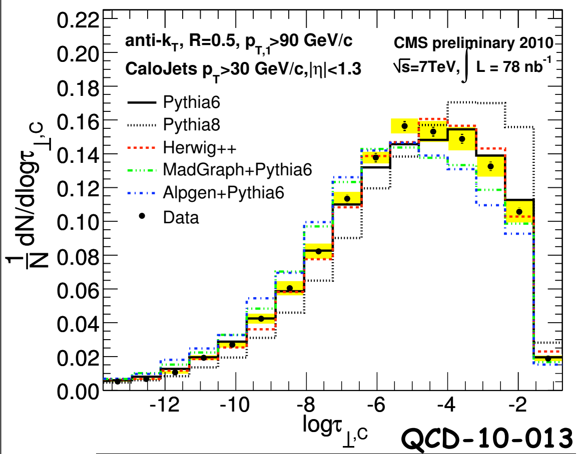
$$T_{\perp,\mathcal{C}} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

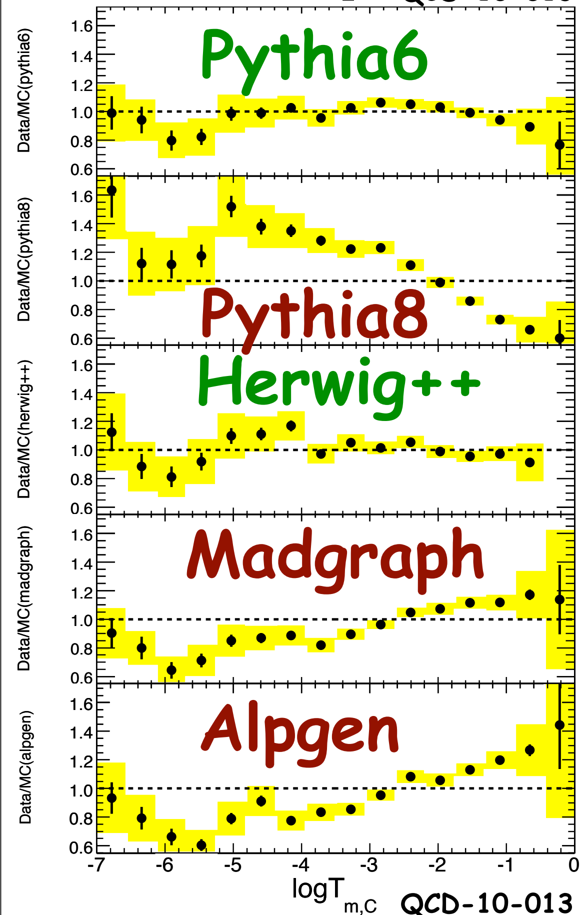


Central thrust minor: projection out of the plane of beam axis and transverse axis n_T

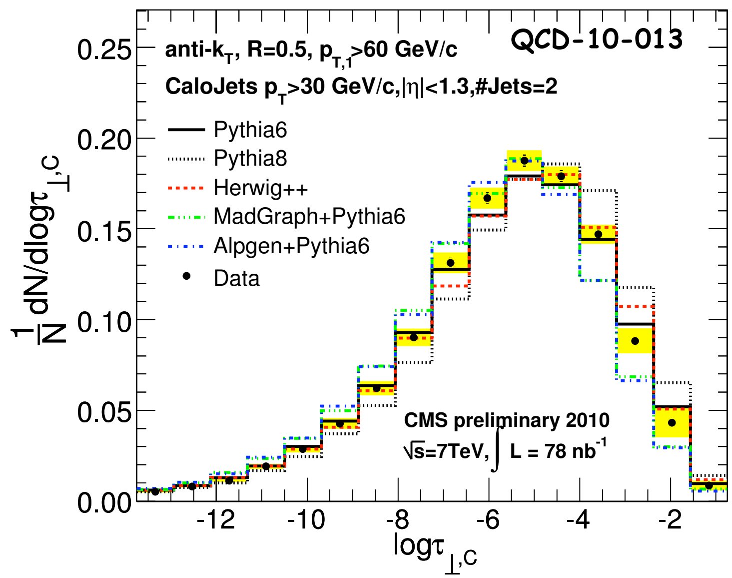
$$T_{m,\mathcal{C}} \equiv \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i} \times \vec{n}_{T,\mathcal{C}}|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

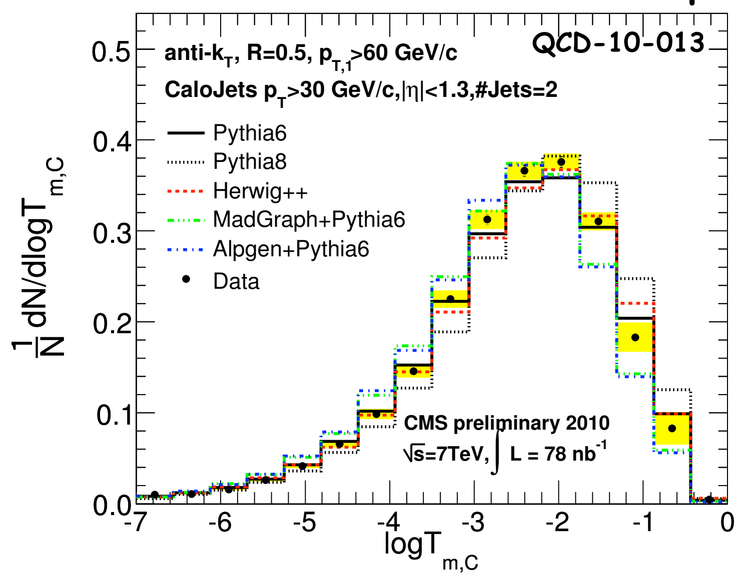
Hadronic event shapes

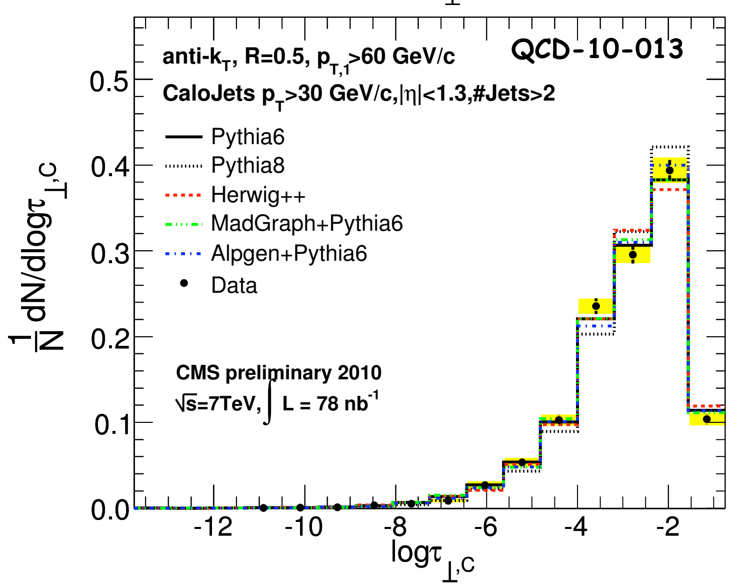


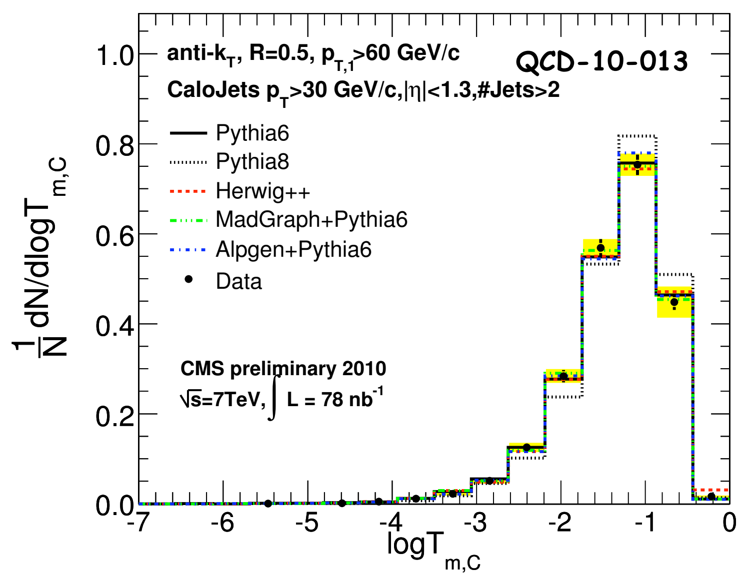


Pythia 6 and Herwig++ agree with data within uncertainties; Alpgen and Madgraph overestimate fraction of back-to-back dijets, and Pythia 8 underestimates it; similar at all p_T



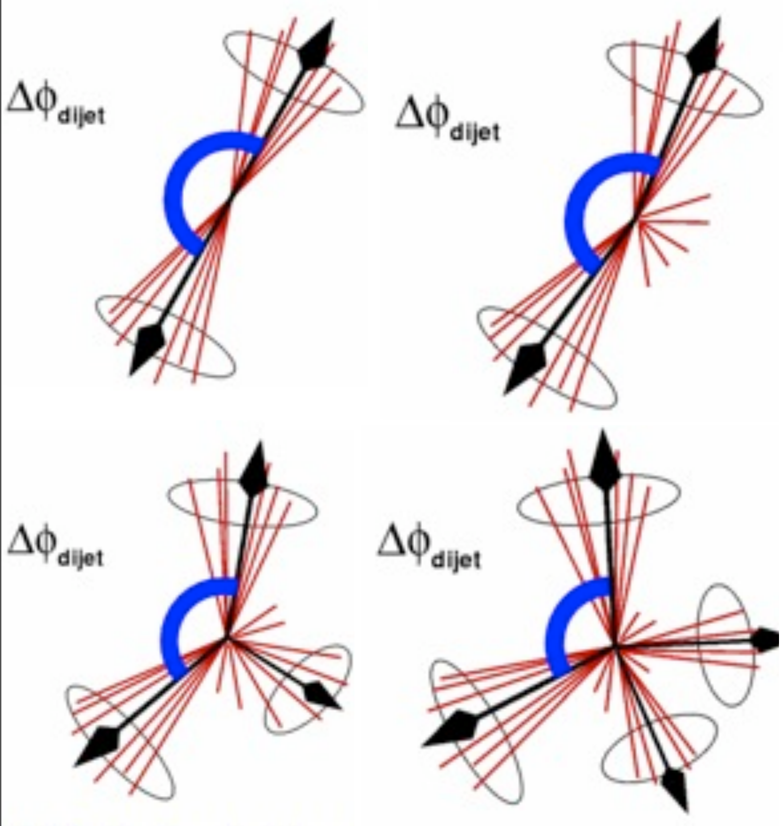




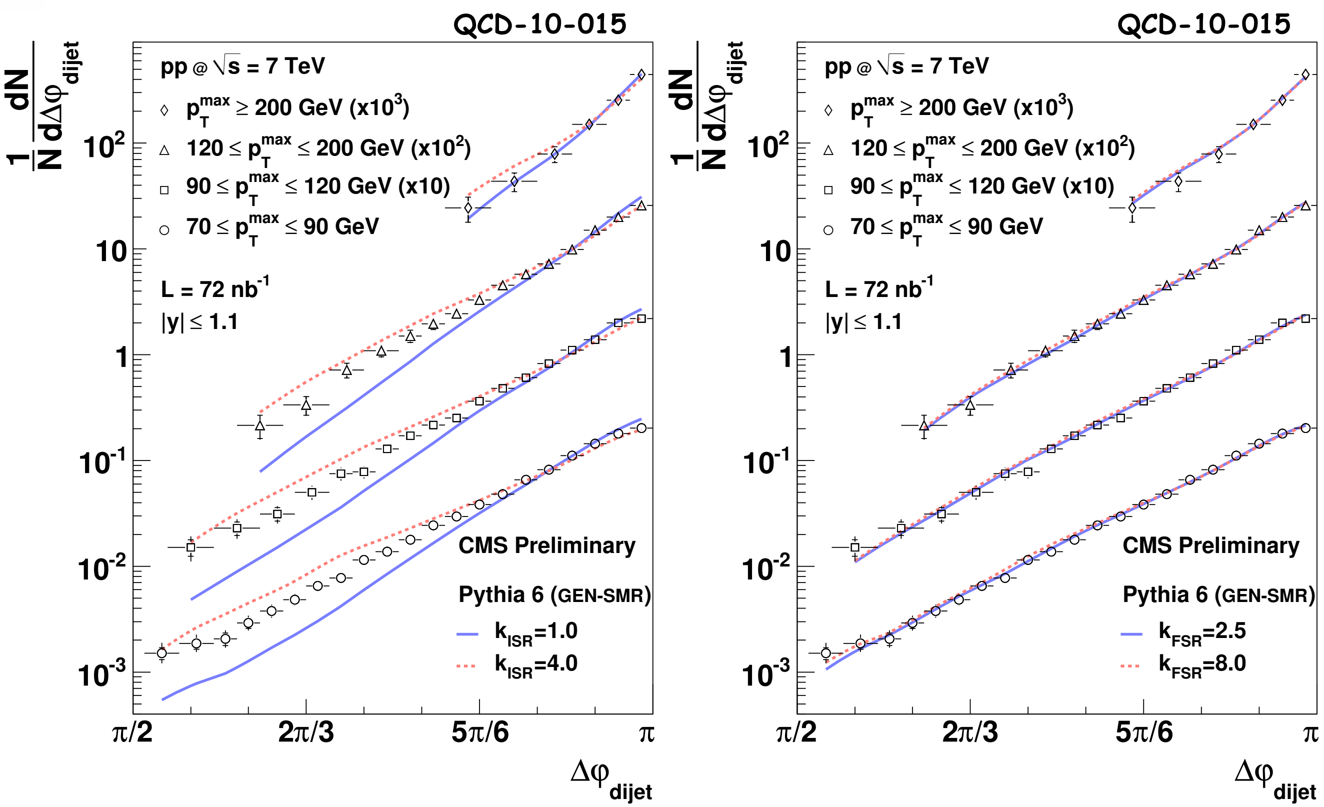


Azimuthal decorrelations

- Azimuthal decorrelations was the first QCD measurement from D0 Run II: little sensitivity to JEC and luminosity, but much to perturbative radiation
- Observable is very sensitive to initial state radiation (k_{ISR}=PARP(67)), but shows little sensitivity to final state radiation (k_{FSR}=PARP(71))
- Good agreement between data and Pythia default tune (k_{ISR}=2.5, k_{FSR}=4.0)

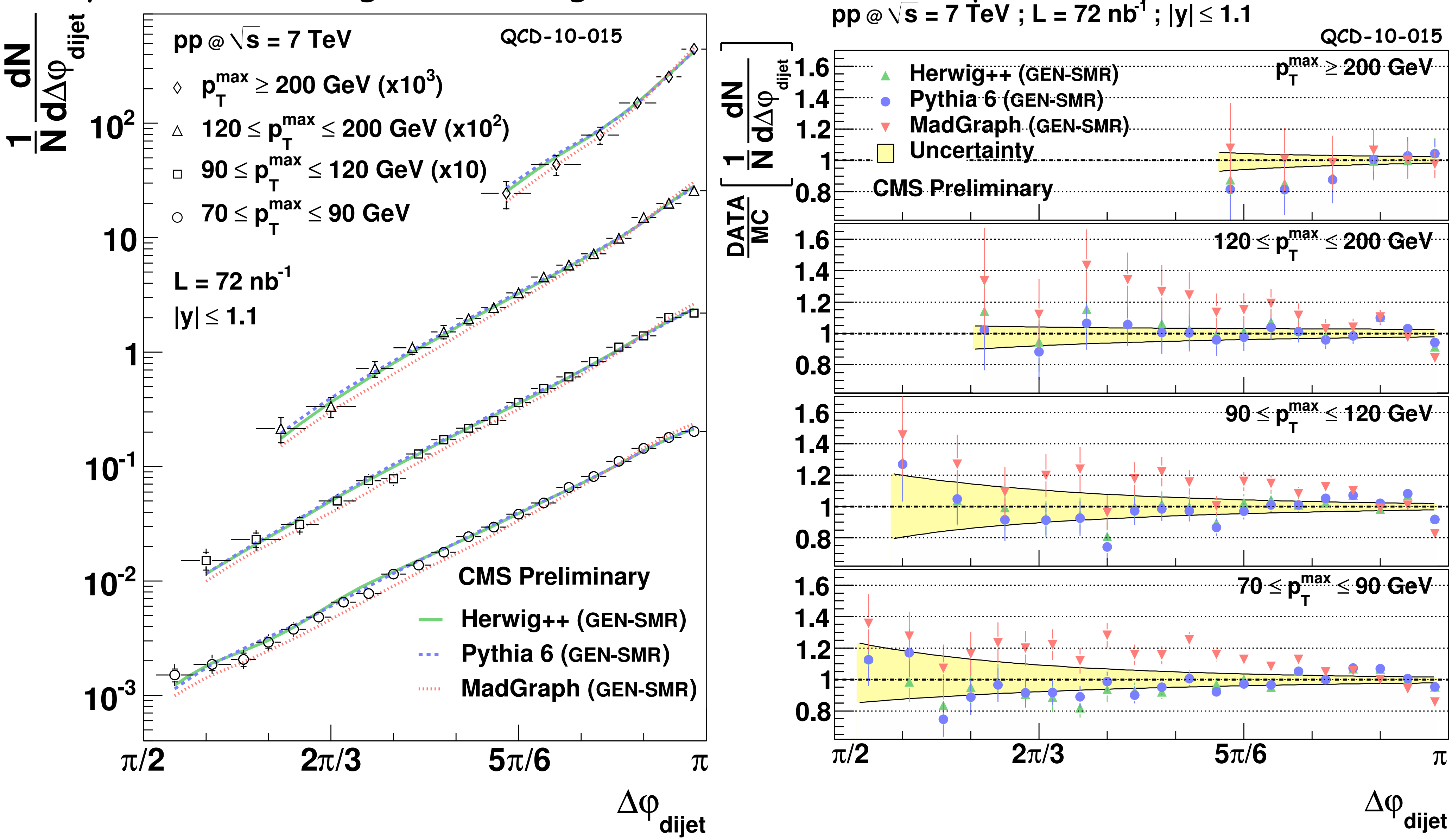


graphics: D0



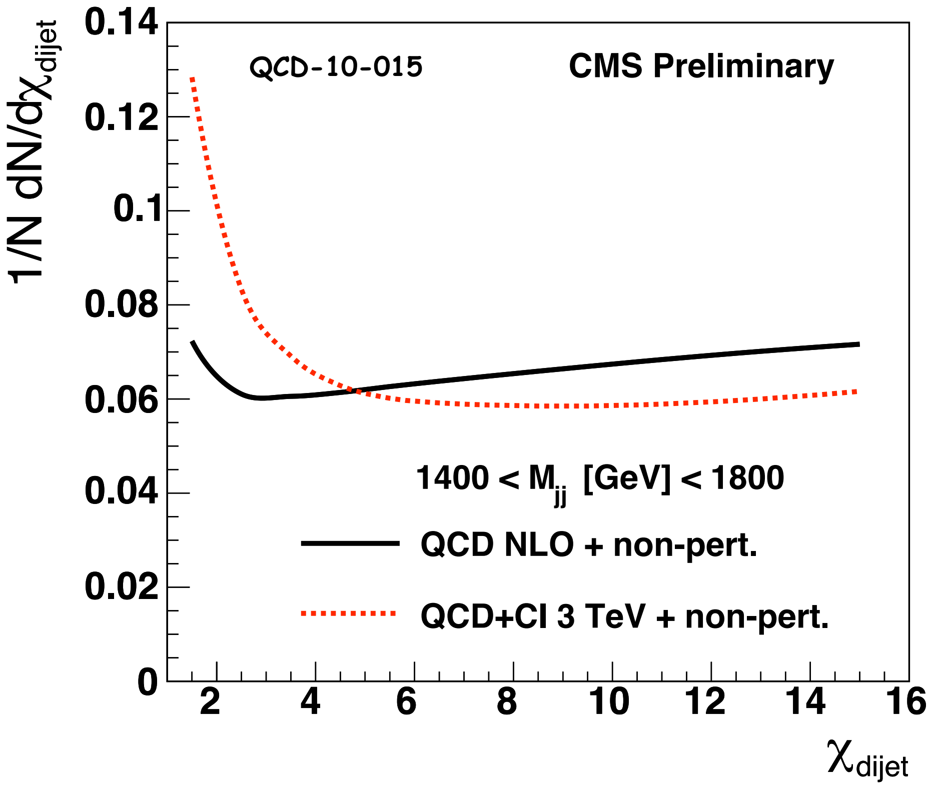
Azimuthal decorrelations

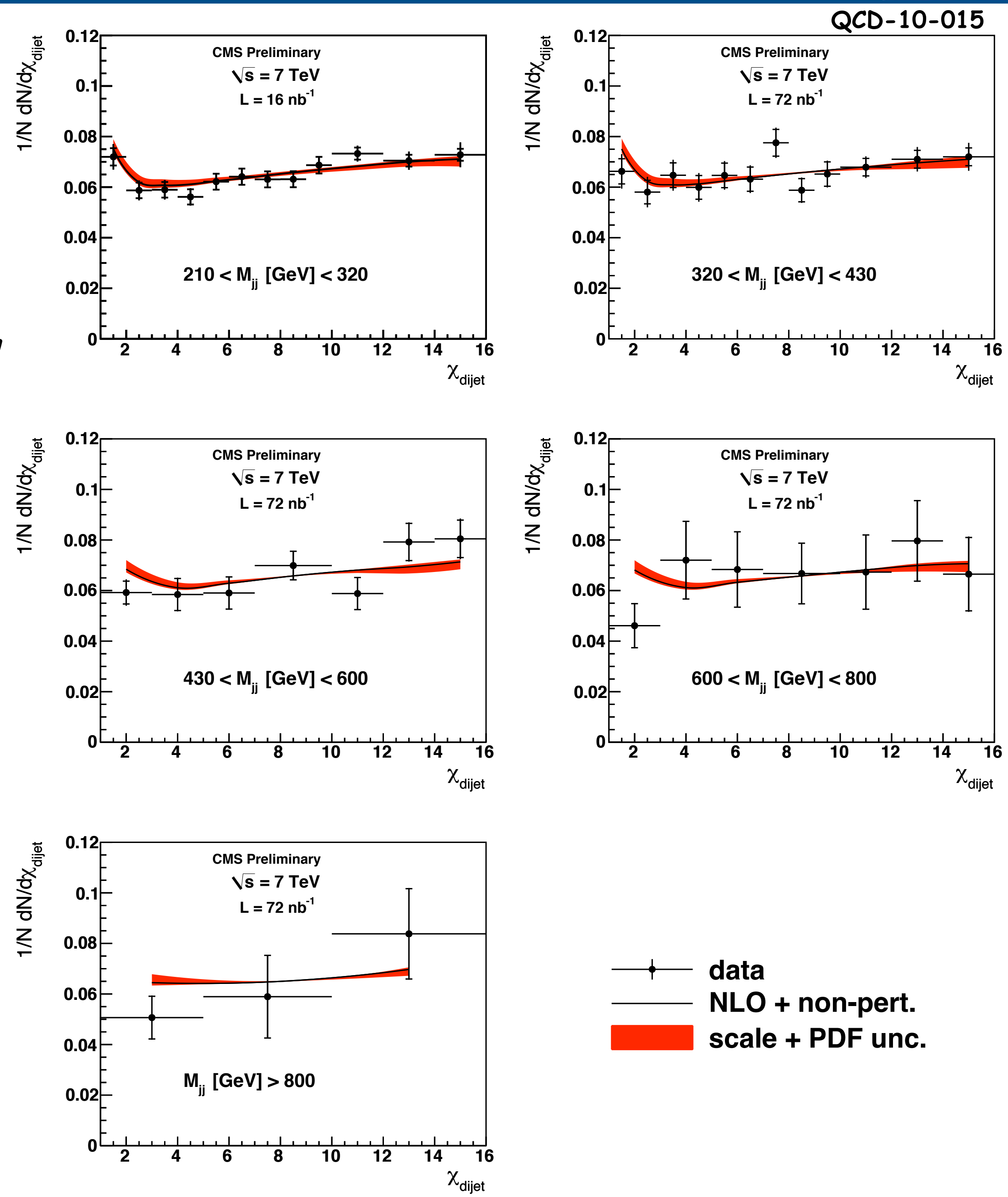
- Comparisons between data and different models show good agreement with Pythia and Herwig, but less agreement with MadGraph at low p_T



Dijet angular distributions

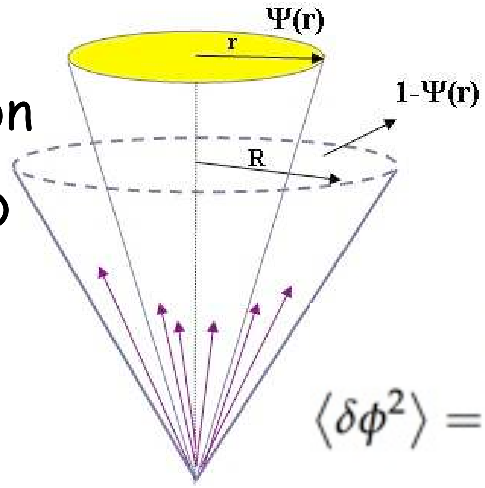
- Isotropic new physics peaks at low χ ($y_1 \sim y_2$), e.g. contact interactions
- QCD mostly t-channel =>flat in $\chi_{dijet} = \exp(|y_1 - y_2|)$
- Sensitivity up to Λ=3 TeV with few pb^{-1}; Tevatron limits Λ > 2.8-3 TeV





Jet transverse shapes

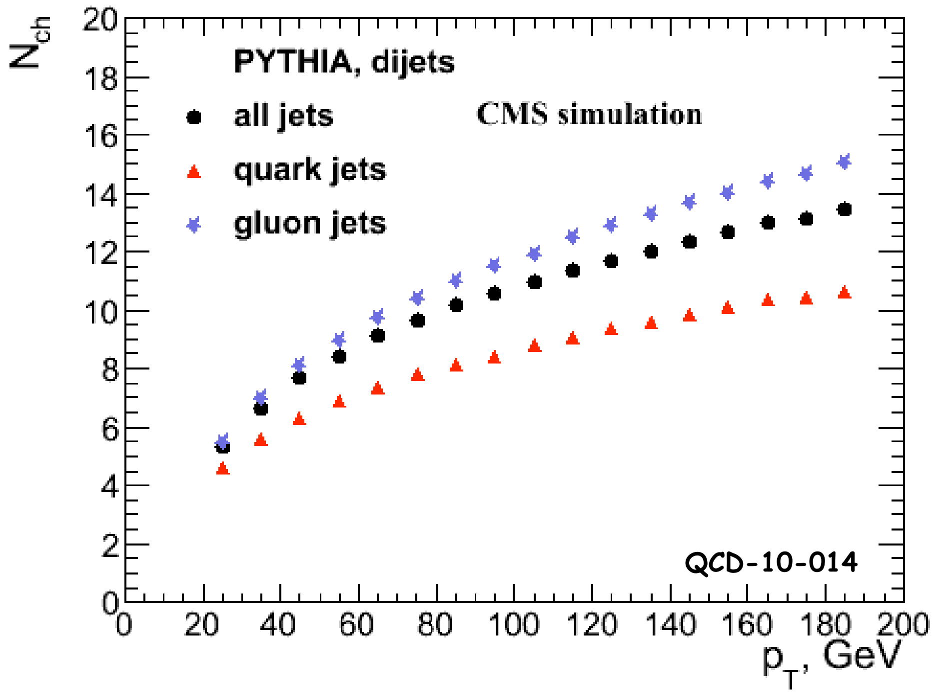
- Jet transverse shapes probe transition between hard pQCD and soft gluon radiation
- Phenomenological models motivated by QCD and tuned at e^+e^- colliders
- At hadron colliders underlying event is an important ingredient; models tuned at 2 TeV, but extrapolation to LHC uncertain
- Jet data dominated by gluon jets

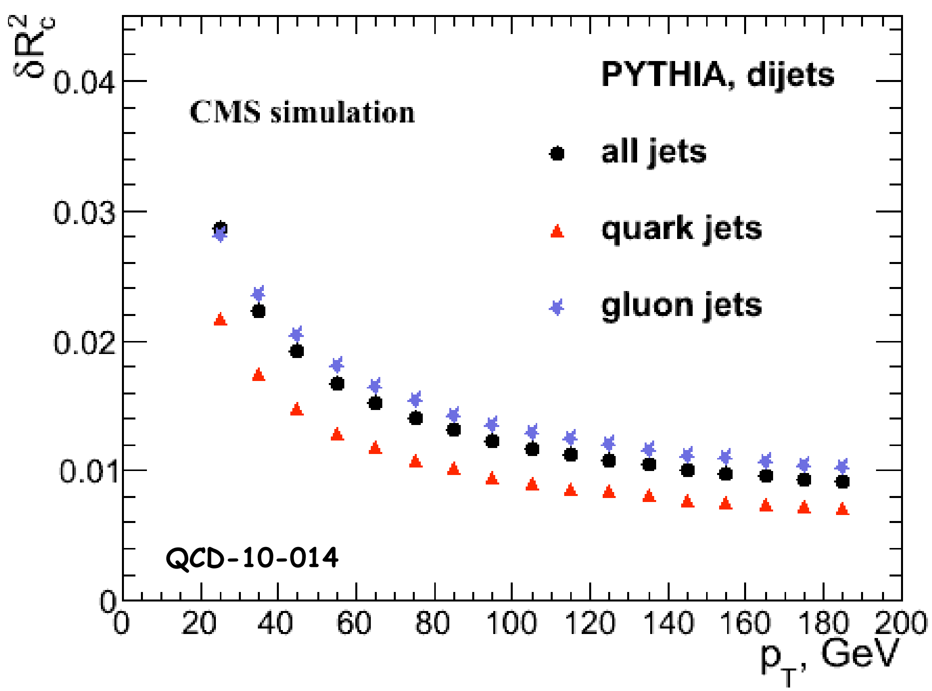


$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$

$$\langle \delta\phi^2 \rangle = \frac{\sum_{i \in \mathrm{jet}} (\phi_i - \phi_C)^2 \cdot p_{T,i}}{\sum_{i \in \mathrm{jet}} p_{T,i}}$$

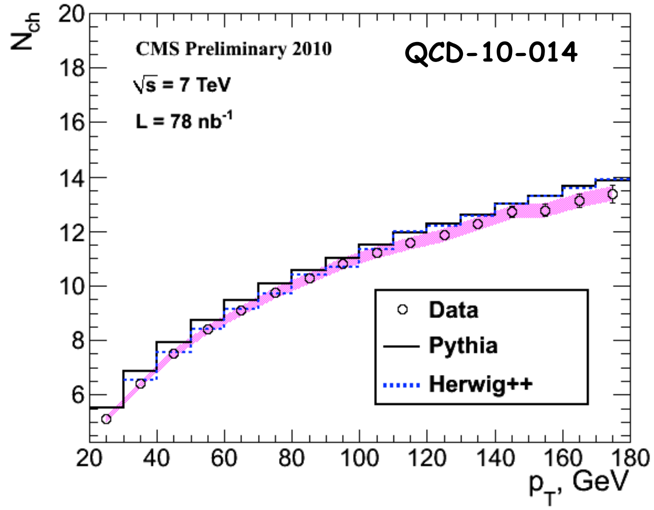
$$\delta R^2 = \langle \delta\phi^2 \rangle + \langle \delta\eta^2 \rangle$$

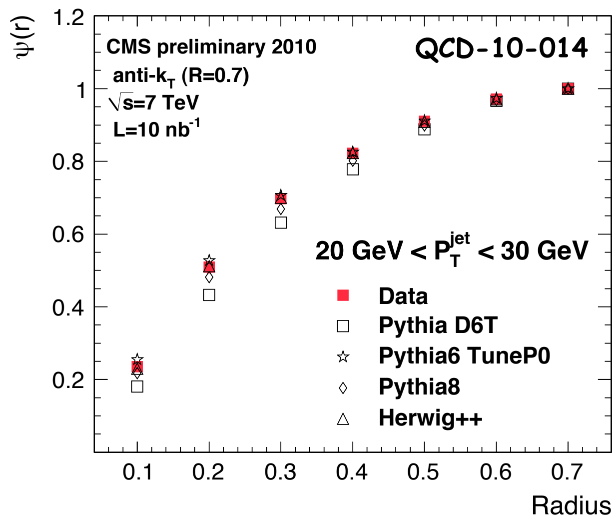


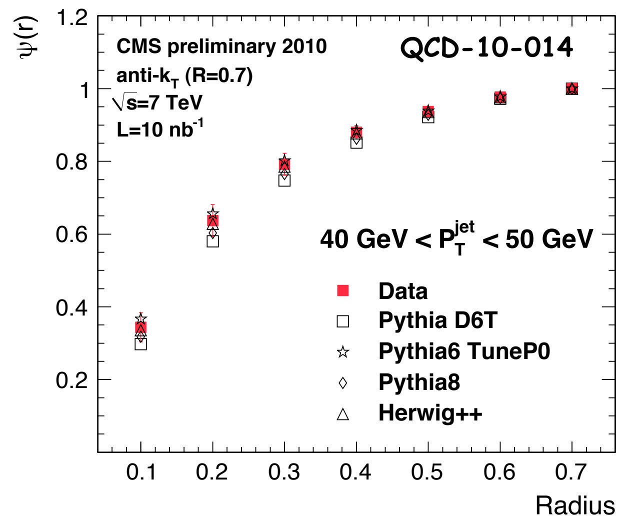


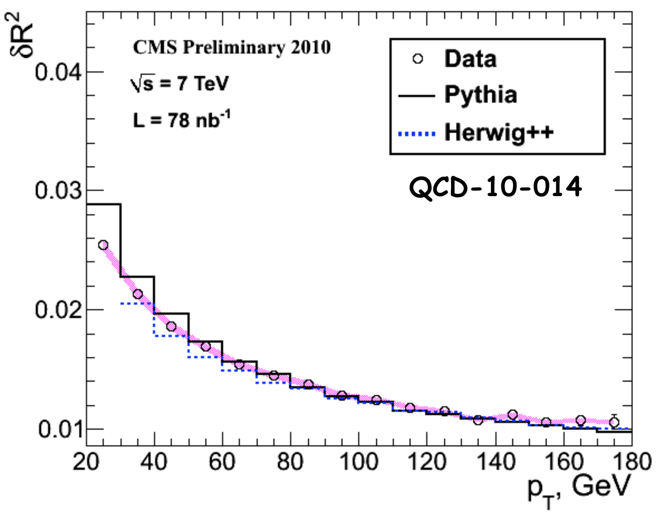
Jet transverse shapes

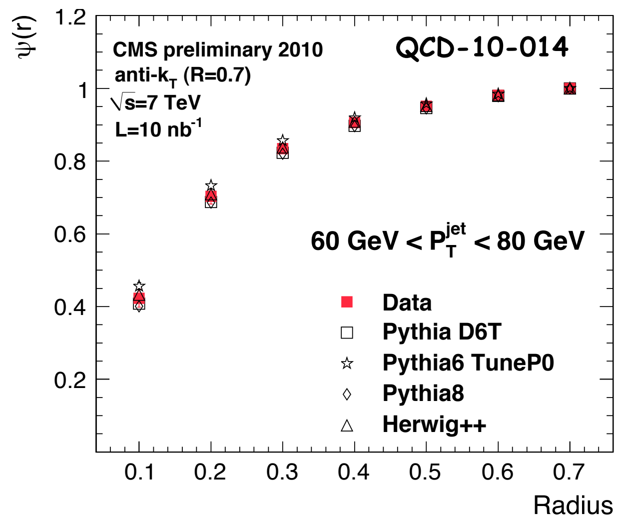
- Good agreement between data and theory at $p_T > 50$ GeV; at $p_T < 50$ GeV Pythia predicts slightly too broad, Herwig slightly too narrow jets
- Jet shapes are sensitive to underlying event (at R~0 due to $\psi(R_{cone})=1$), but not yet precise enough to differentiate between theoretical predictions

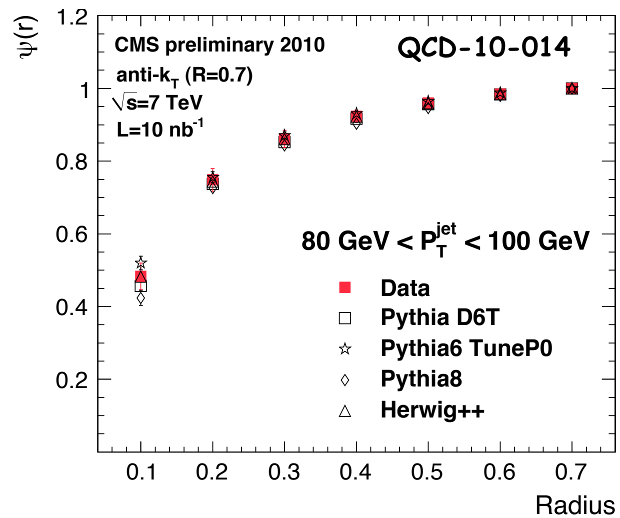












Conclusions

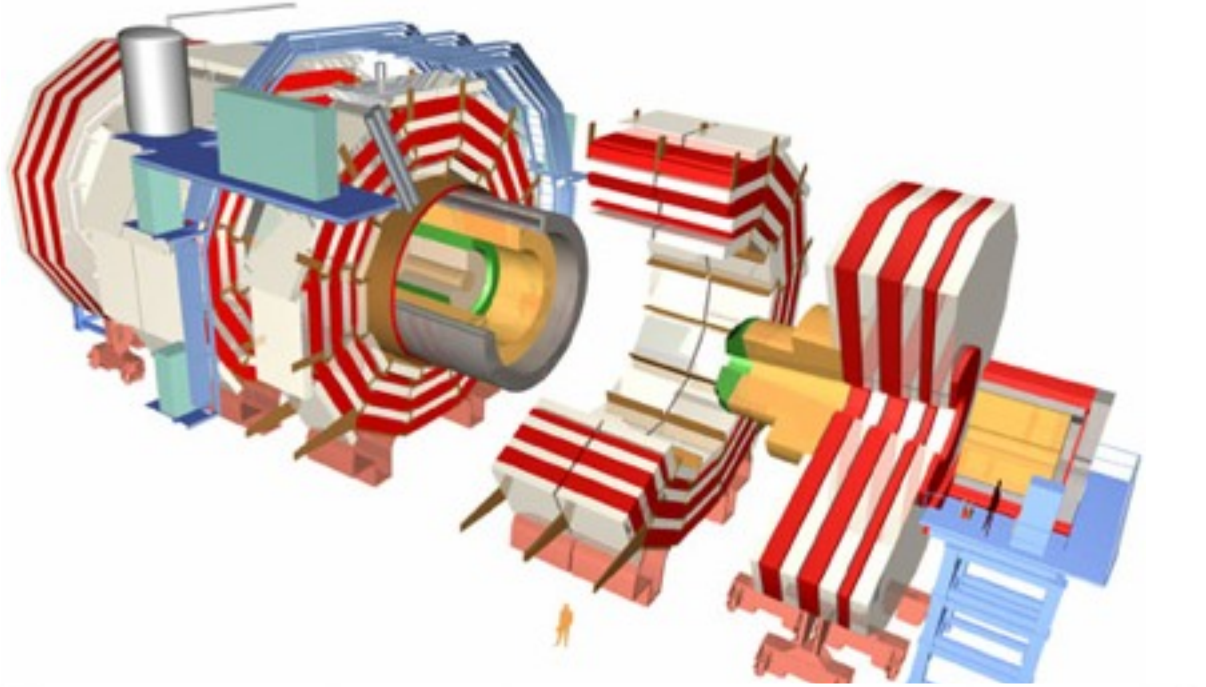
- CMS QCD program has started in full speed with the first 7 TeV data; at 3 months old, CMS is already starting to push at Tevatron boundaries
- Multiple jet reconstruction algorithms combining calorimetry and tracking offer many new handles on reducing experimental systematic uncertainties
- CMS detector simulation has shown remarkable agreement with data, and MC models tuned to LEP and Tevatron data (Pythia and Herwig++) already work reasonably at LHC
- First round of measurements use ratio quantities to reduce systematics from JEC, JER and overall normalization, but full cross section measurements also already possible; next round will reduce systematics
- MC is tuning well underway, and probes of new physics are soon to follow

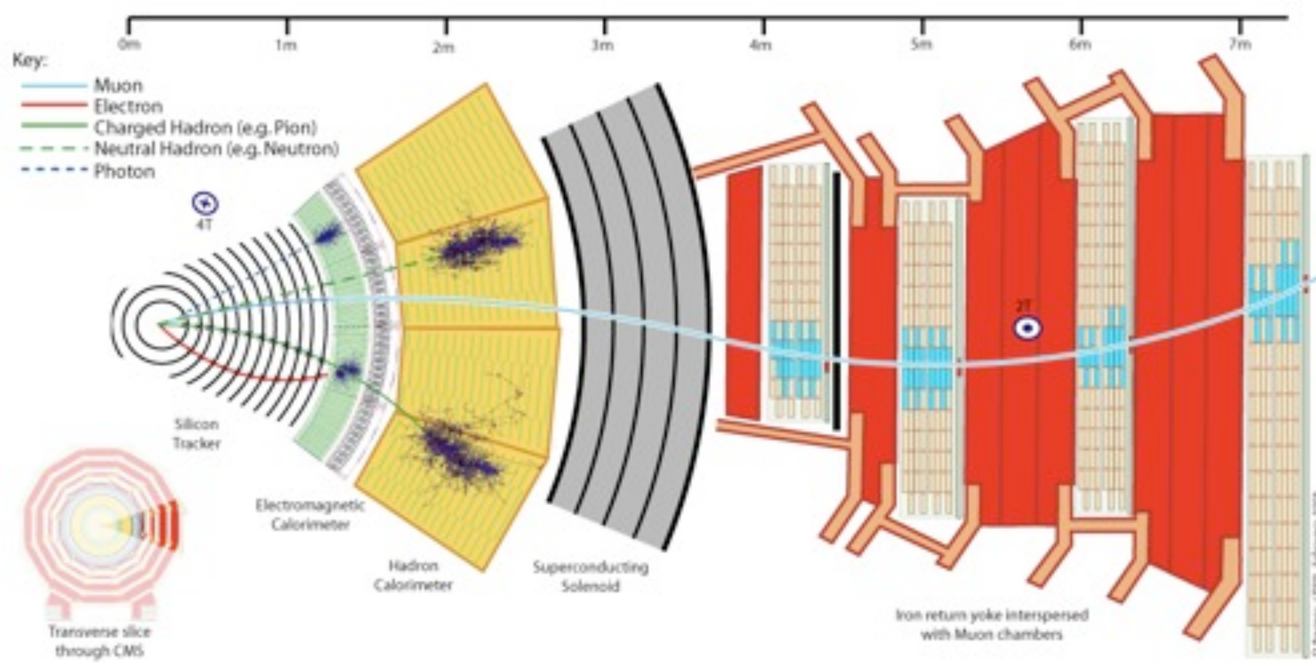
Backup slides

CMS detector

- Tracking, ECAL and HCAL all embedded inside 3.8 T solenoid magnet
- Muon chambers outside magnet, interleaved with iron return yoke
- Precise silicon pixel and silicon strip tracking system at $|\eta| < 2.4$
- Fine-grained (Moliere radius ~2 cm) lead tungstate crystal ECAL at $|\eta| < 3.0$
- Barrel+end cap HCAL up to $|\eta| < 3$, hadronic forward up to $|\eta| < 5$

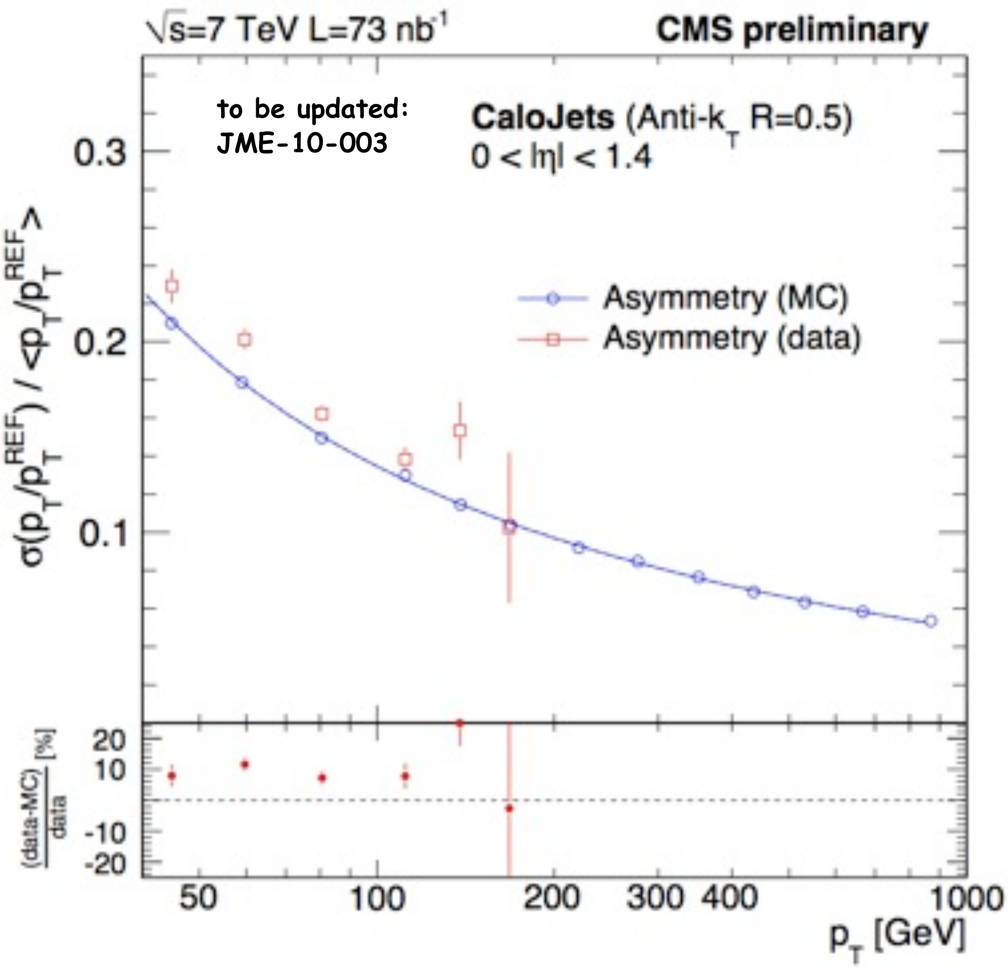
HCAL granularity
$\eta \times \varphi = 0.087 \times 0.087$
ECAL 5×5 vs HCAL 1×1

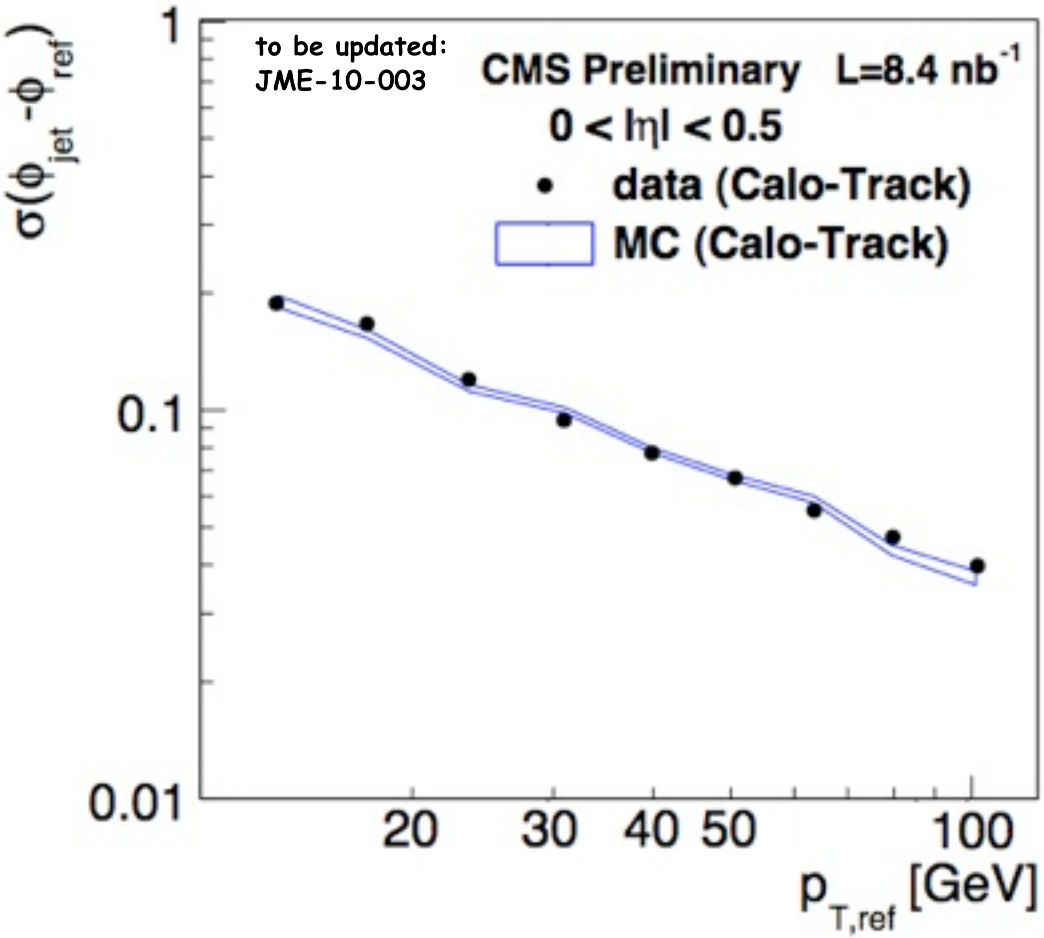




Jet resolutions: p_T, η, φ

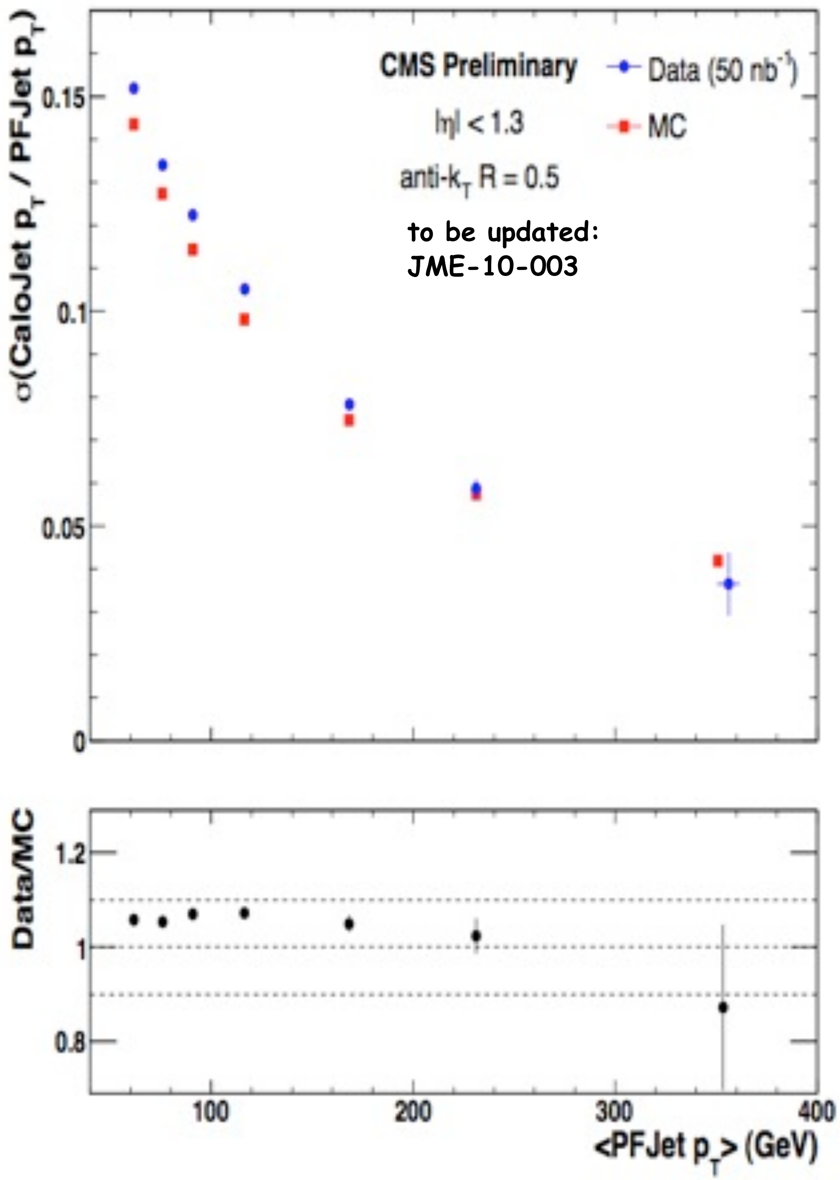
- Jet p_T resolutions for all reconstruction types within a-priori 10% uncertainty
- Positions resolutions (η, φ) between different algorithms well-modeled by MC; tested in many combinations

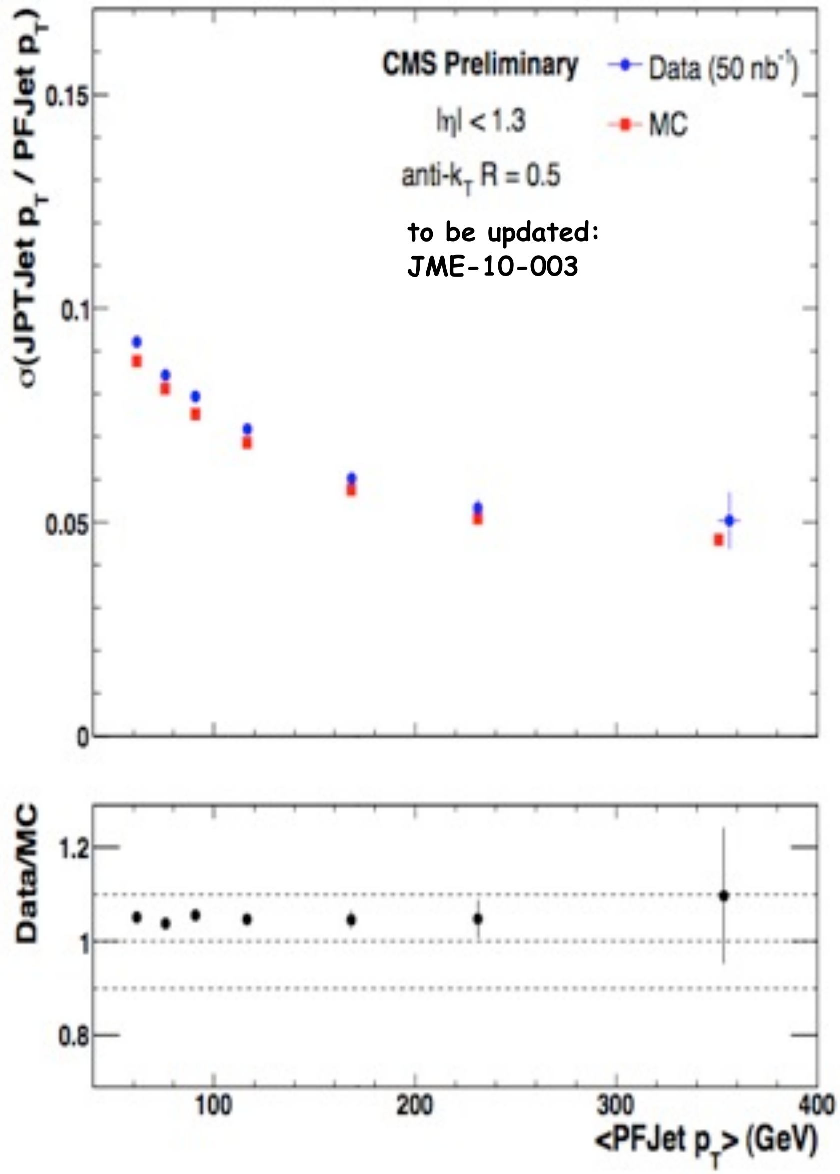




Relative resolution

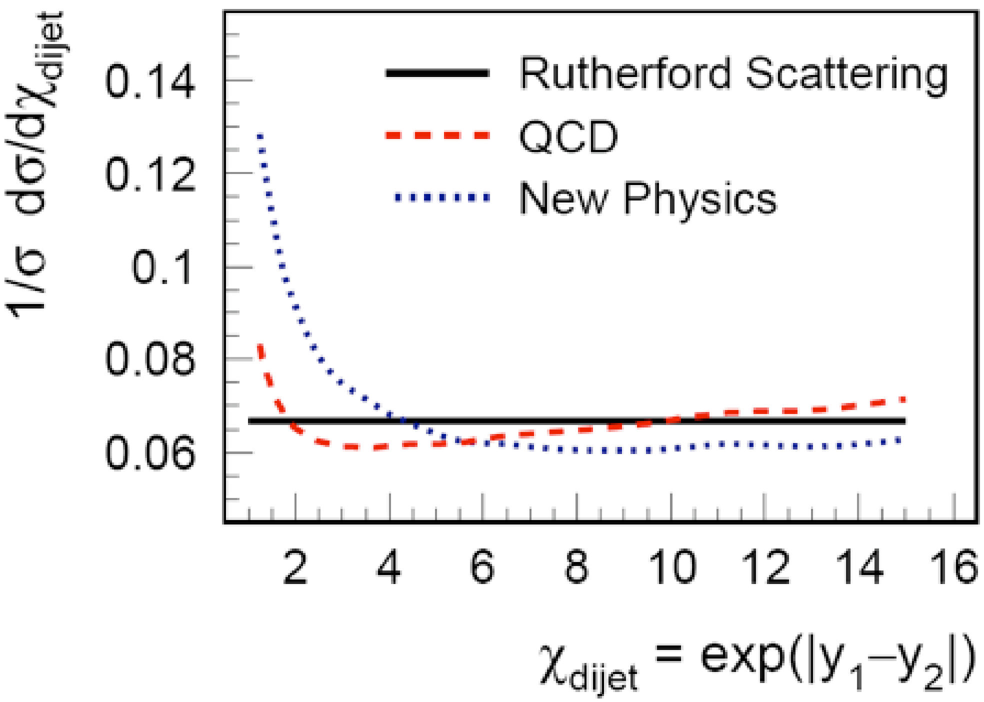
- Resolution measured by dijet asymmetry also confirmed by jet matching

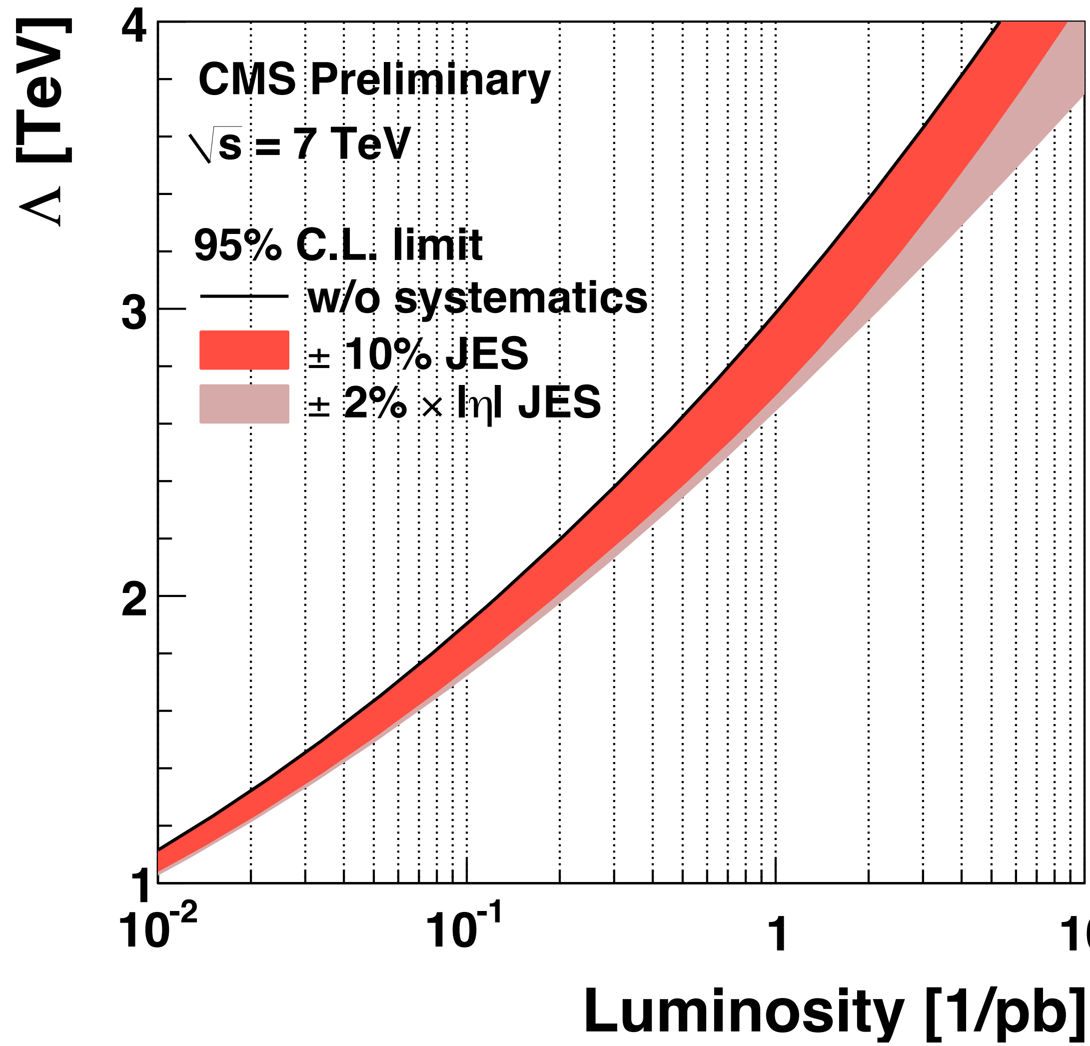




Dijet chi

- Measurement of polar angle distributions can show difference between Rutherford scattering, QCD and New Physics
- Sensitivity to contact interactions at $\Lambda > 3$ TeV with only few pb^{-1}





Jet shapes

- Jet shapes are sensitive to underlying event (at R~0 due to $\psi(R_{cone})=1$), but not yet precise enough to differentiate between theoretical predictions