Jet physics measurements at CMS

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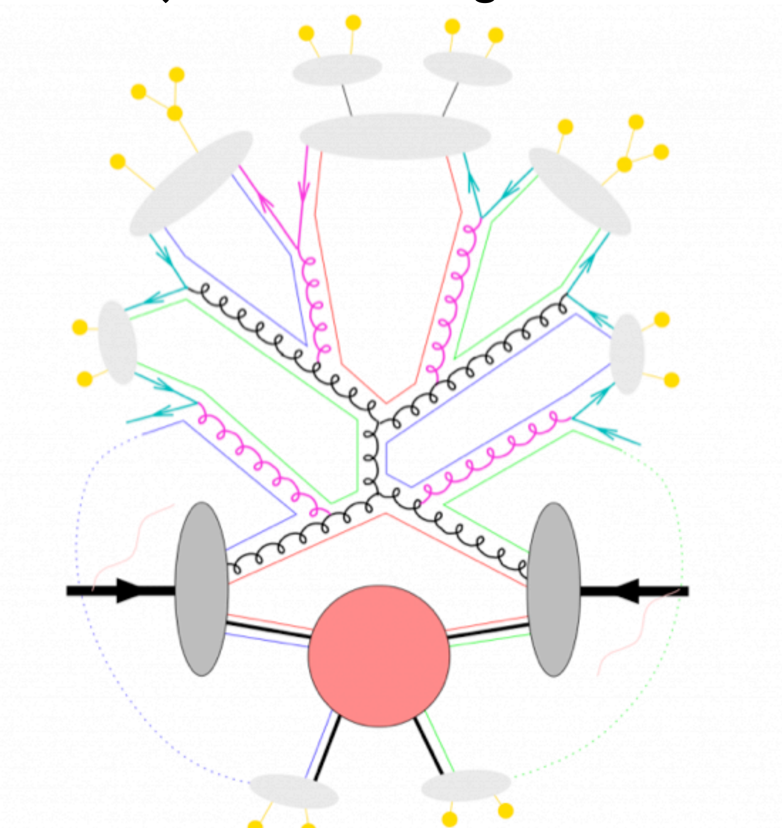
for the CMS collaboration

We present CMS results related to jet production cross sections, which pose a central test to perturbative QCD predictions and which place an important constraint on parton distribution functions and the strong coupling constant. Results include recent measurements performed with 2011 data taken at center-of-mass energy of 7 TeV and 2012 data taken at 8 TeV. We also review the early 2013 measurements on dijet production in p-Pb collisions taken at nucleon center-of-mass energy of 5.02 TeV.

Jet physics

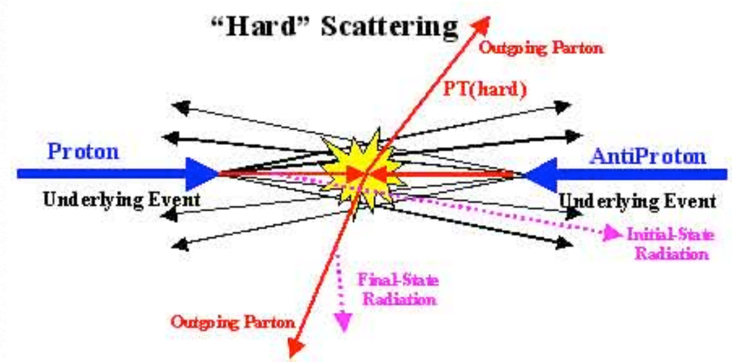
- Main goal is to improve our detailed description of **Quantum Chromodynamics**
  - "Hard": Parton distribution functions (**PDF**), strong coupling constant (**α_S**), perturbative QCD (**pQCD**), initial and final state radiation (ISR, **FSR**), parton shower (**PS**)
  - "Soft": multiparton scattering, fragmentation, underlying event
- Searches of New Physics in jets at high p_T with Exotica group
- Dijets as hard probes of Quark Gluon Plasma in heavy ion collisions
- QCD jets are also high statistics calibration source and background for searches

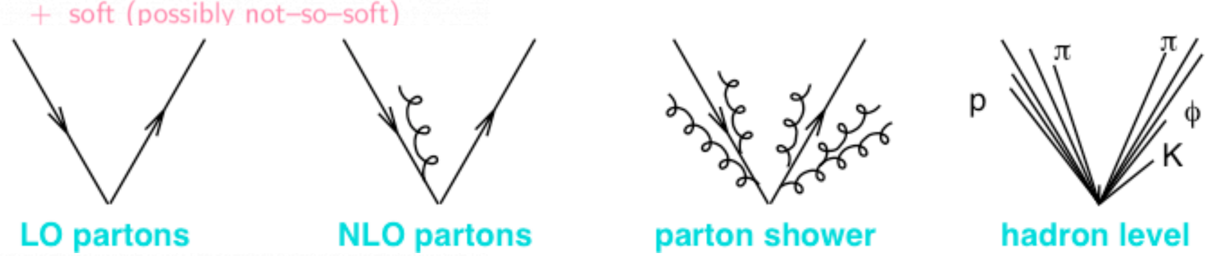


- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

and in addition

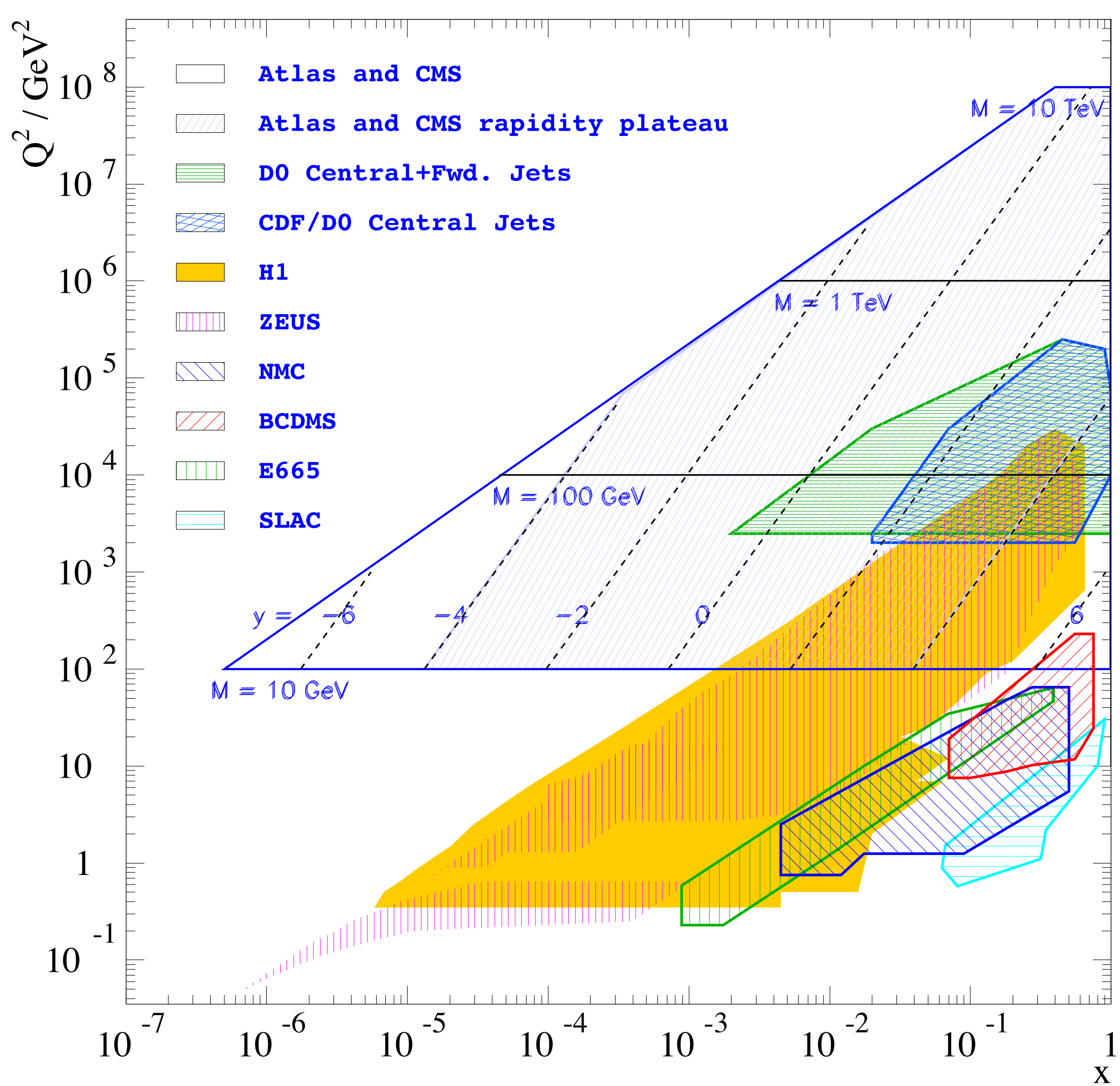
+ backward parton evolution
+ soft (possibly not–so–soft)



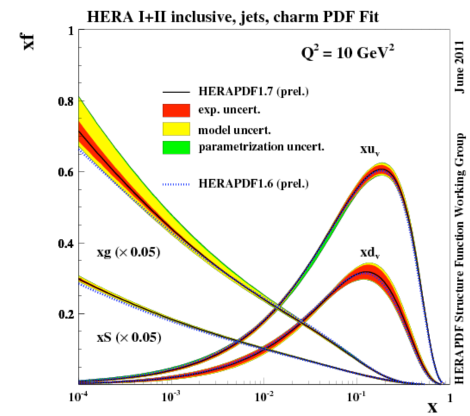


Jet physics landscape

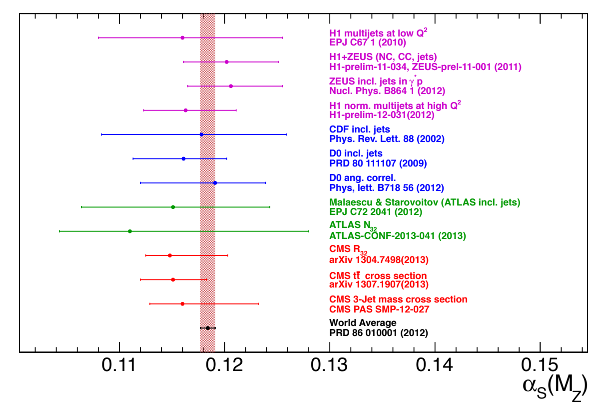
- Jet measurements are a foundation for LHC physics
- Plenty of phase space to cover

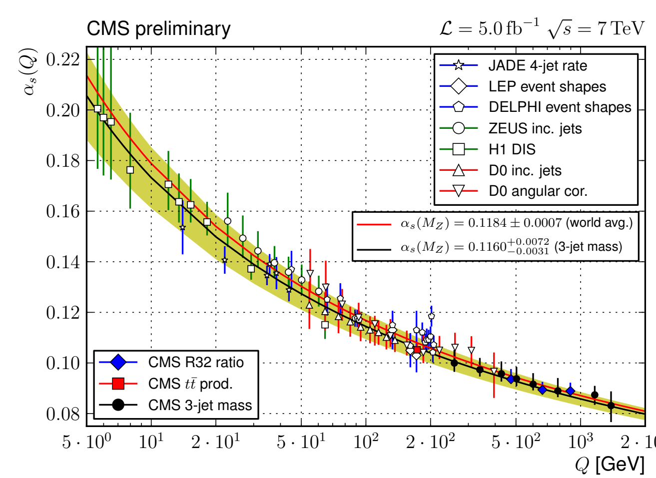


PDF

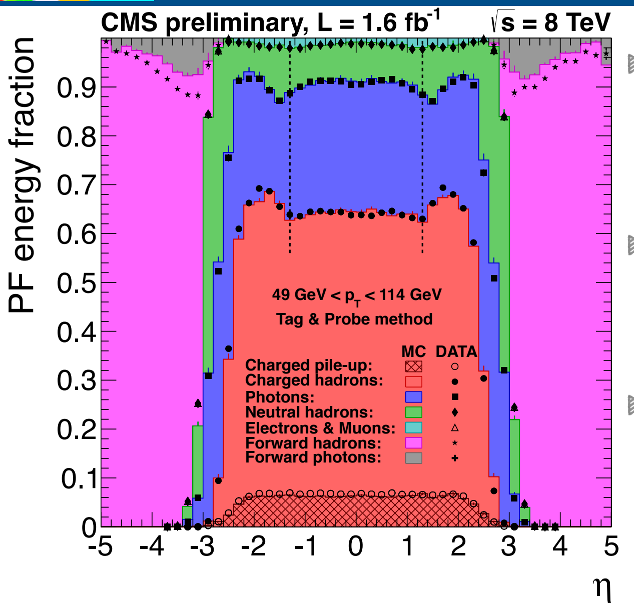


α_s

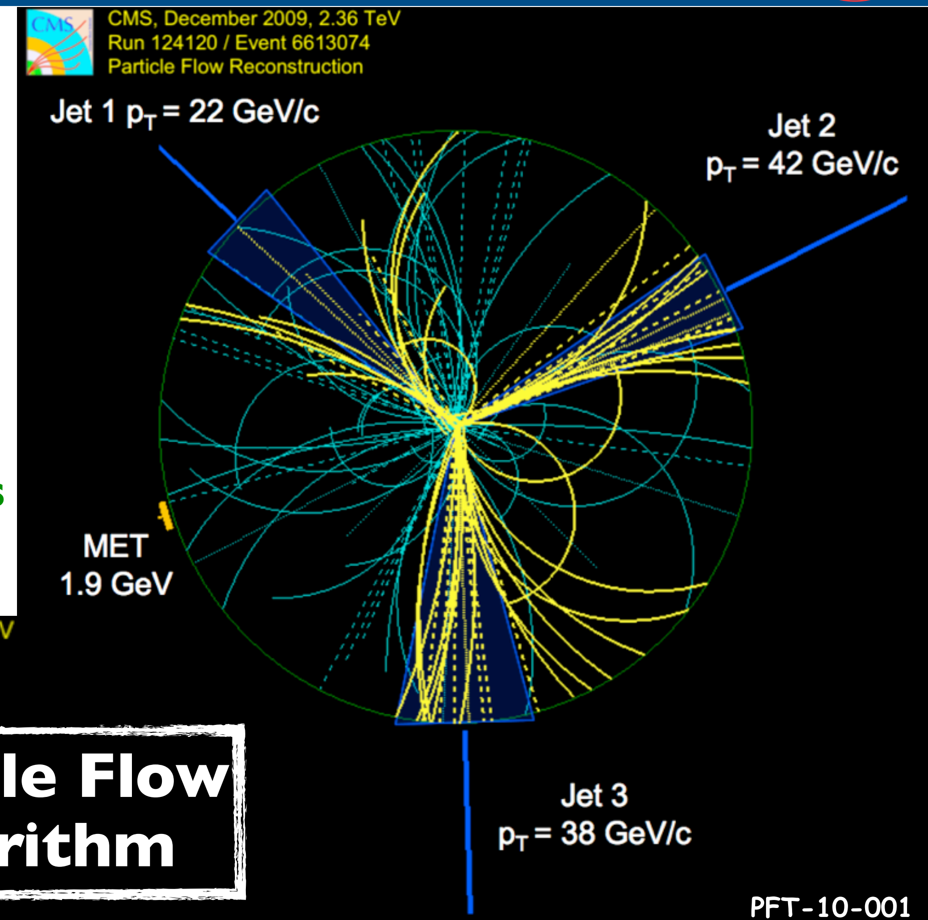


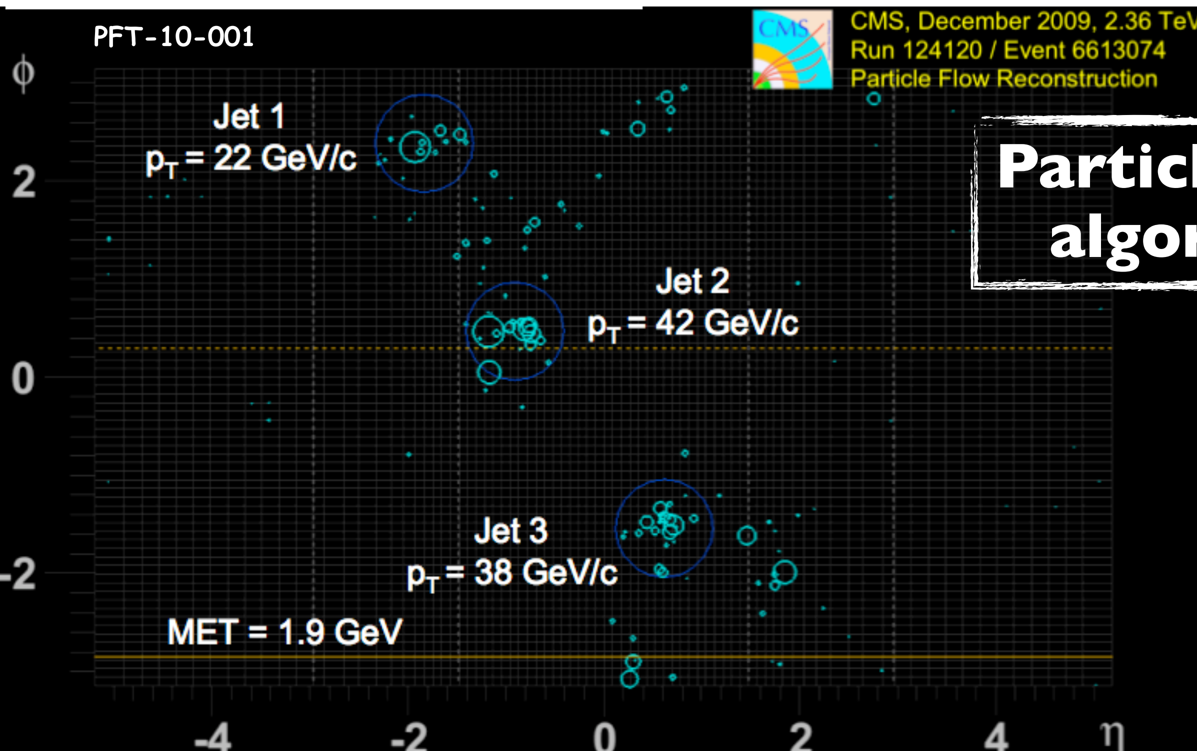


Jet reconstruction



- **65% charged hadrons ($\pi^\pm$, $K^\pm$): tracks**
  - some from pile-up
- **25% photons ($\pi^0 \to \gamma\gamma$, $\eta^0 \to \gamma\gamma$): isolated ECAL clusters**
- **10% neutral hadrons (K_L, Λ, n): isolated HCAL clusters**
  - (plot by M.Sc. J. Pekkanen)

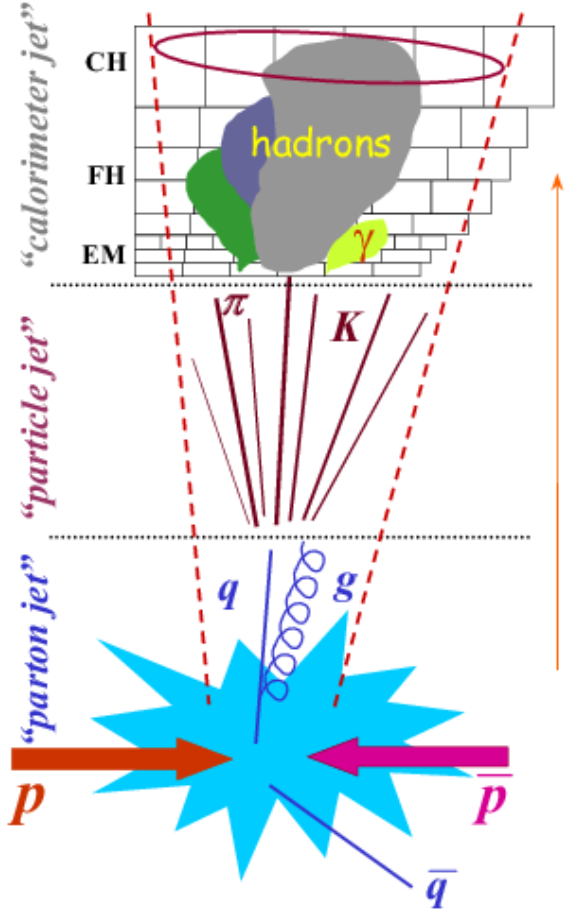




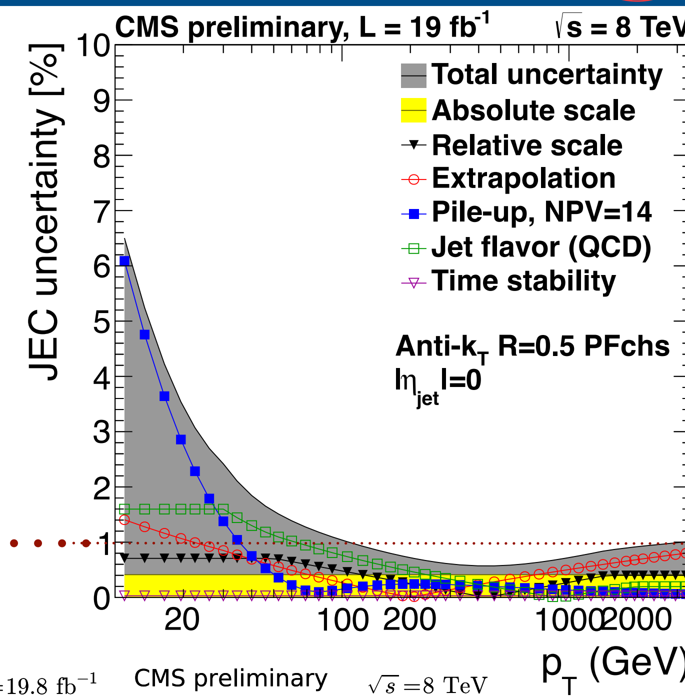
Particle Flow algorithm

Combining detector inputs optimally **before jet clustering** allows CMS to tackle bent tracks, non-linear calorimeter response and overlapping collisions in an **ideal way**

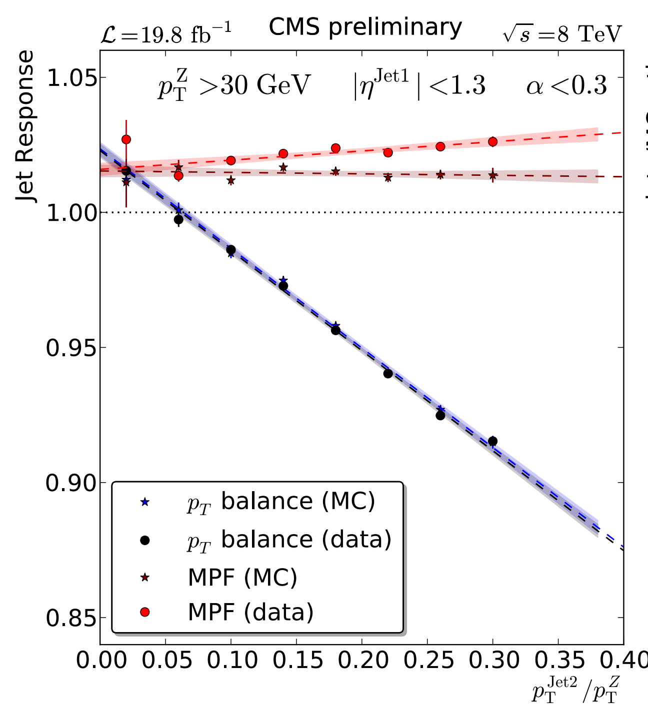
Jet energy correction

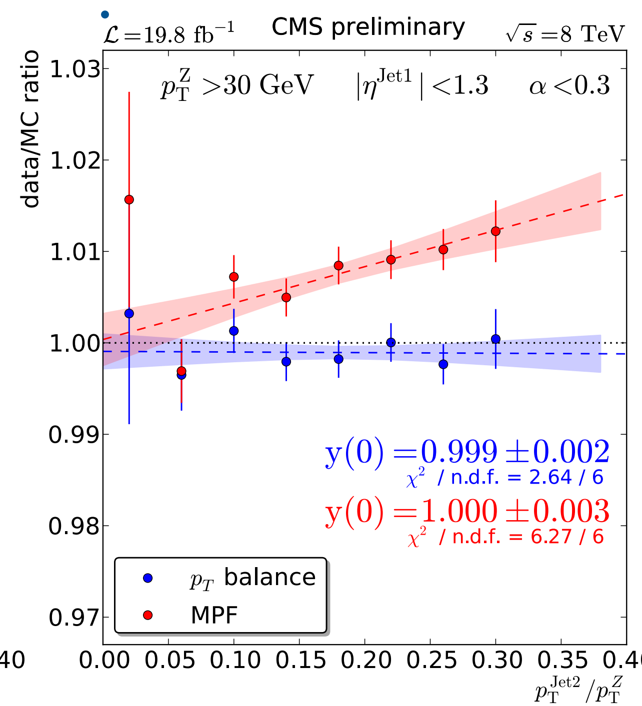


- JEC corrects jet p_T back to particle level on average
- η-dependent correction relative to |η|<1.3 with high statistics **dijet** events
- Absolute correction is fixed to precise ECAL and tracker scales with **γ+jet/Z+jet** events
- Uncertainty **below 1%** at best!



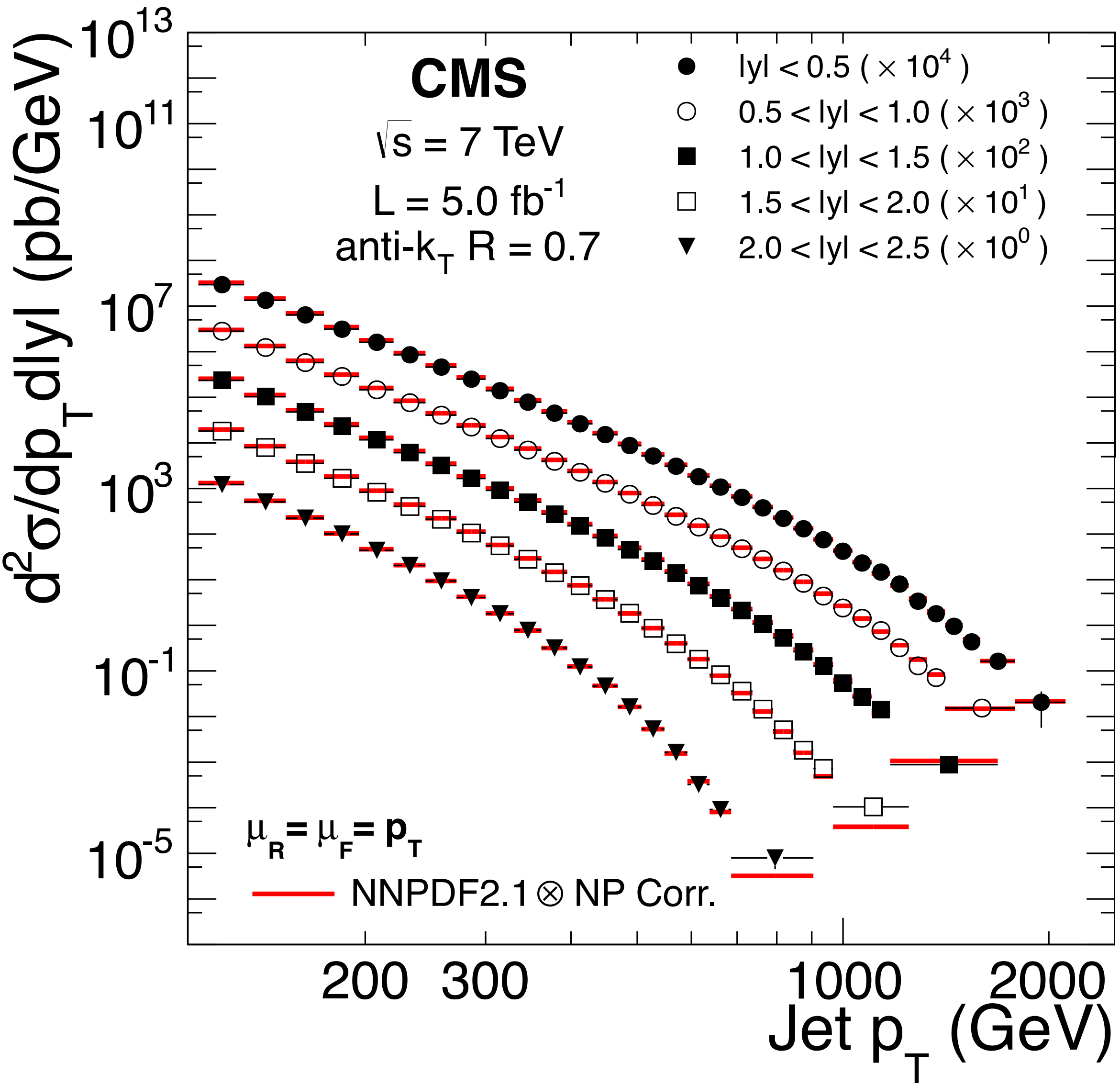
- Detector simulation has good (~1.5%) precision in barrel region, |η|<1.3
- Confirmed with two methods, four samples (γ/Zee/Zμμ+jet, Wqq')

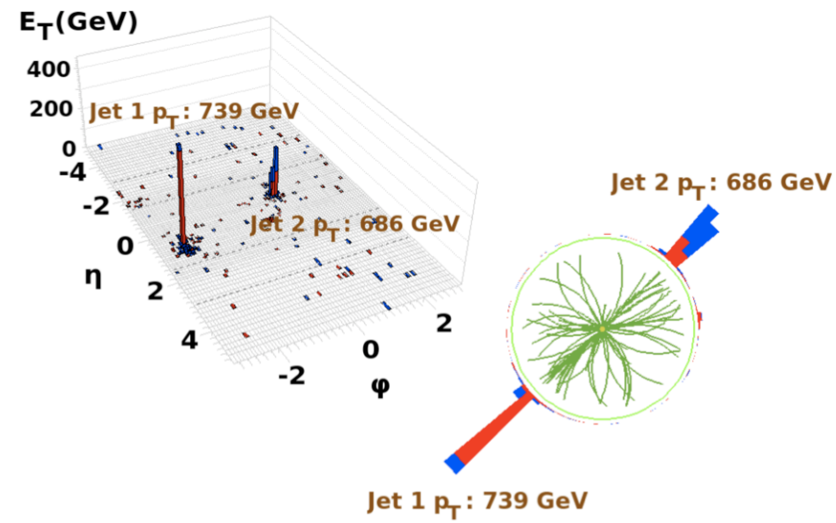


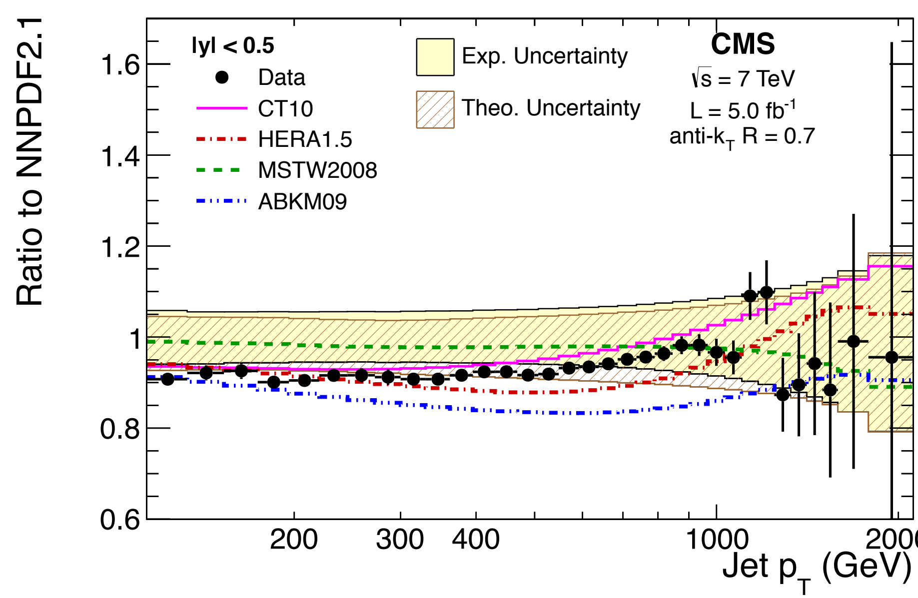


Inclusive jets, 7 TeV

- Inclusive jet cross section with full 5 fb^{-1} data set at 7 TeV published in PRD
- Precise results with full set of uncertainty correlations making an impact on **PDFS**, α_s

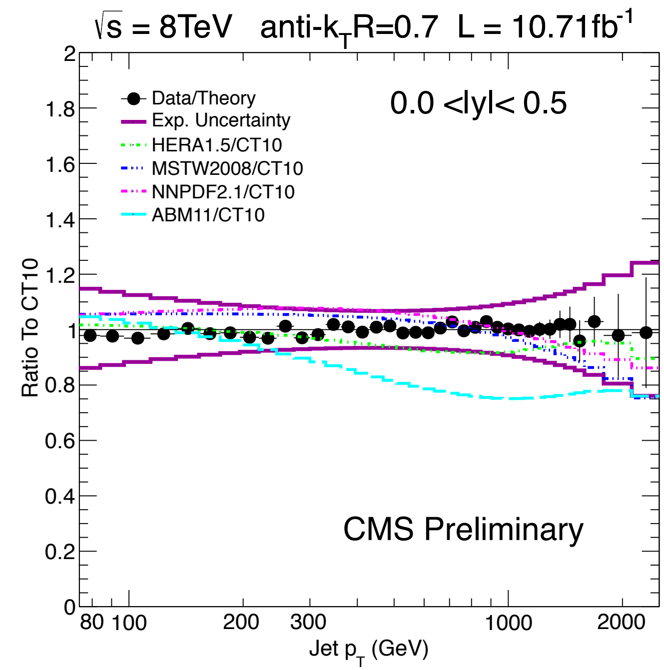


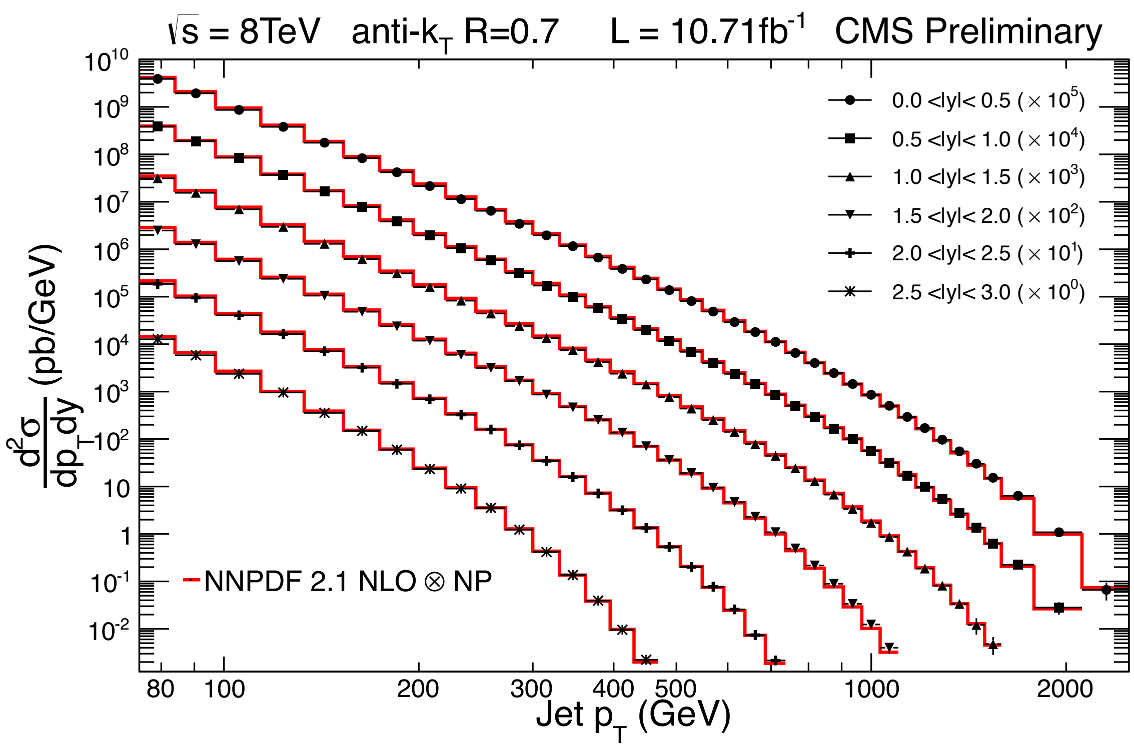


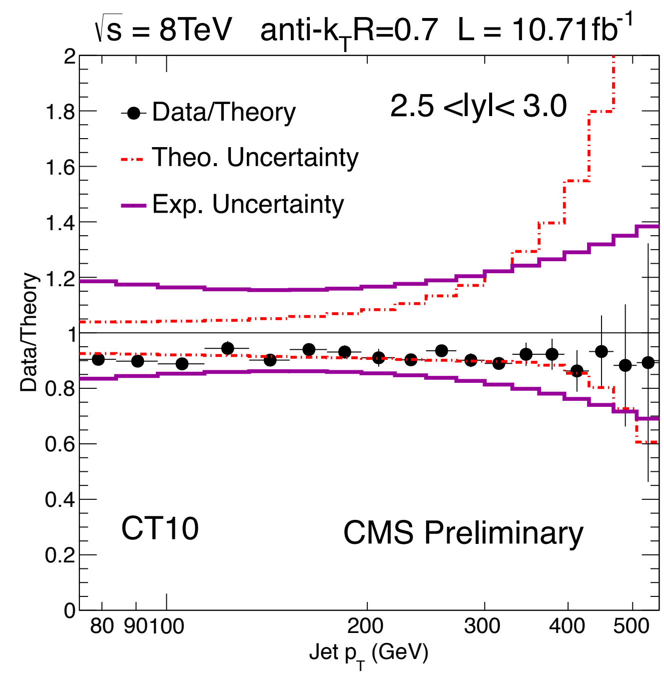


Inclusive jets, 8 TeV

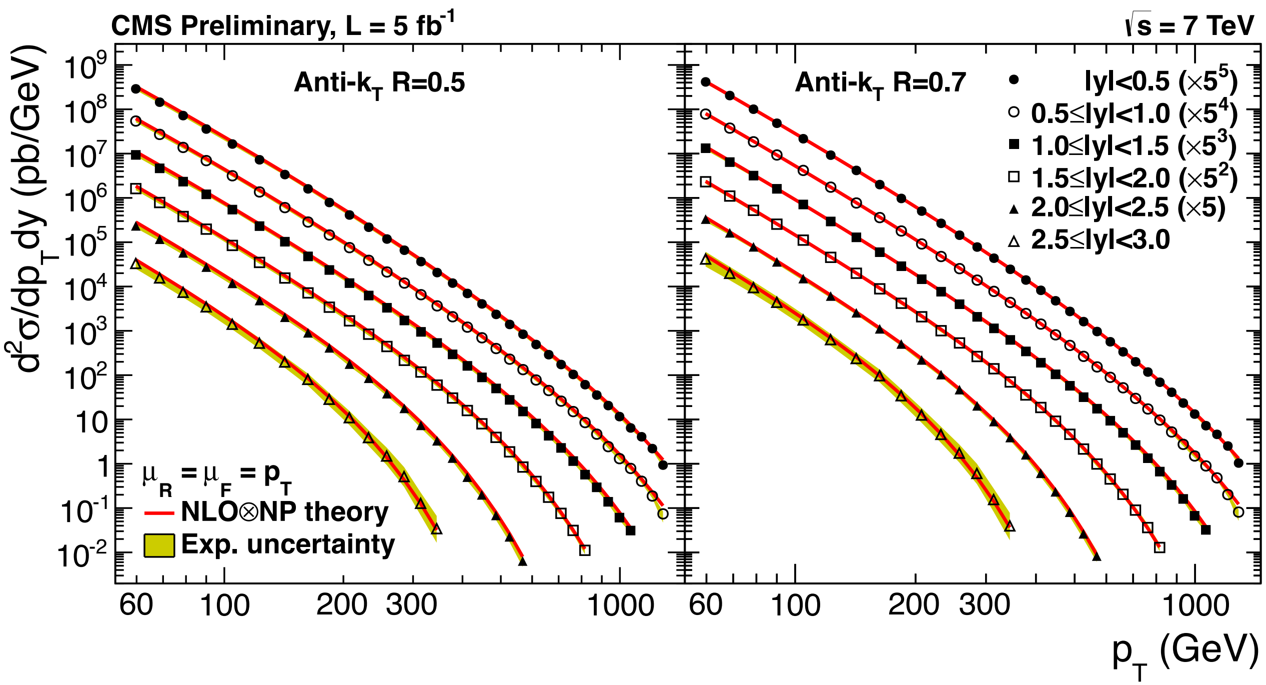
- Preliminary measurement of inclusive jet cross section at 8 TeV (11 fb^{-1}) looks promising
- JEC uncertainty at ~1% for 10 fb^{-1}, superb agreement between data and theory (with CT10 PDF)
  - Expect to further reduce PDF uncertainties with final 19 fb^{-1} data set and even more precise JEC
  - Also planned: 7/8 TeV ratio measurement with reduced experimental and theoretical systematics



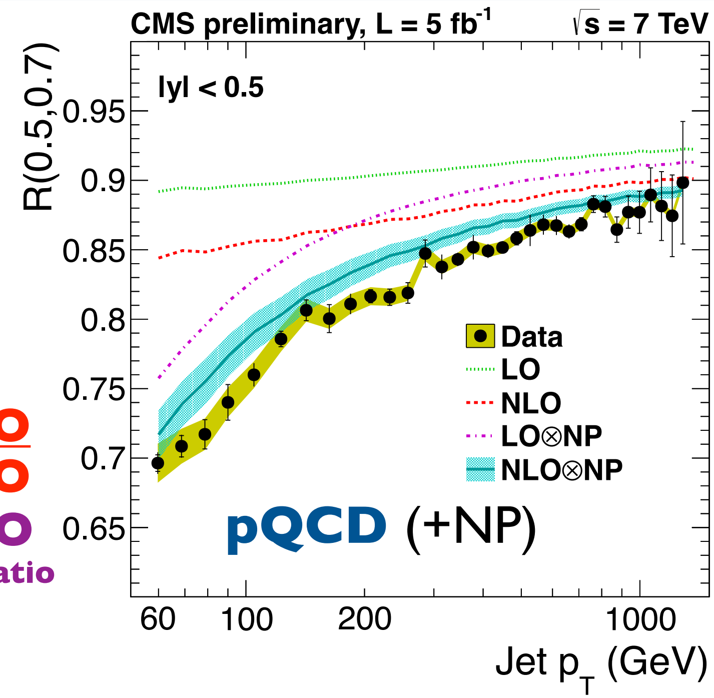




Jet radius ratio, R(0.5,0.7)

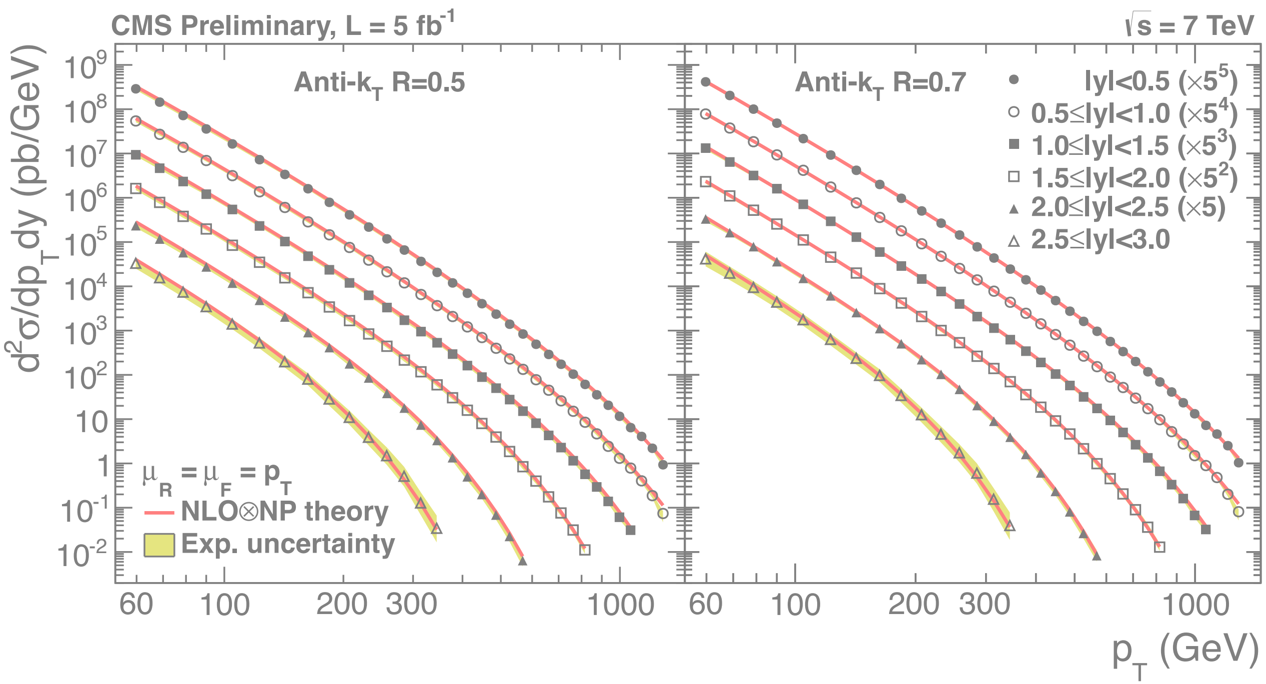


NLO
NLO
= LO
for ratio

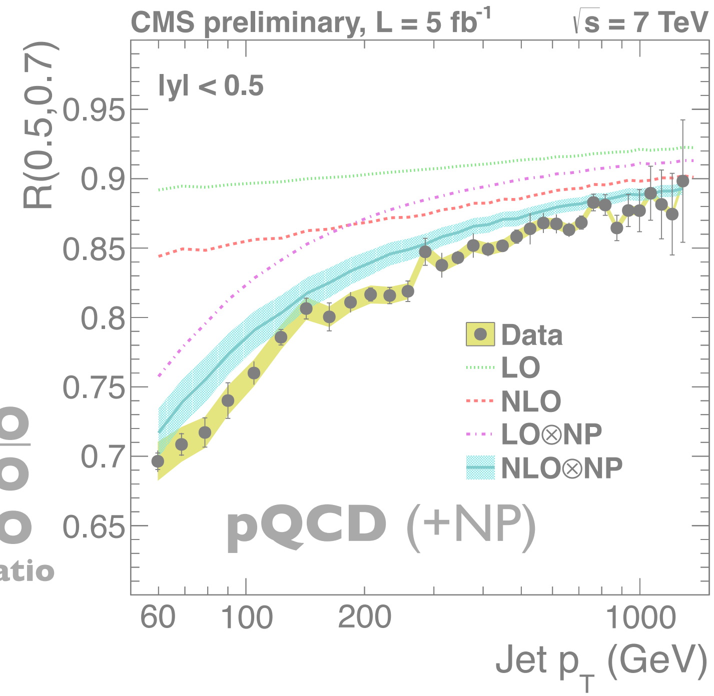


- Jet radius ratio (ratio of cross sections with R=0.5, R=0.7) sensitive to **FSR**, i.e. to high orders of **pQCD**
  - Also to non-perturbative (NP) corrections at low p_T
  - NLO for jet radius ratio tests NNLO for cross sections
- Interesting observable due to cancellation of experimental and theoretical uncertainties to a high degree

Jet radius ratio, R(0.5,0.7)



NLO / NLO = LO for ratio



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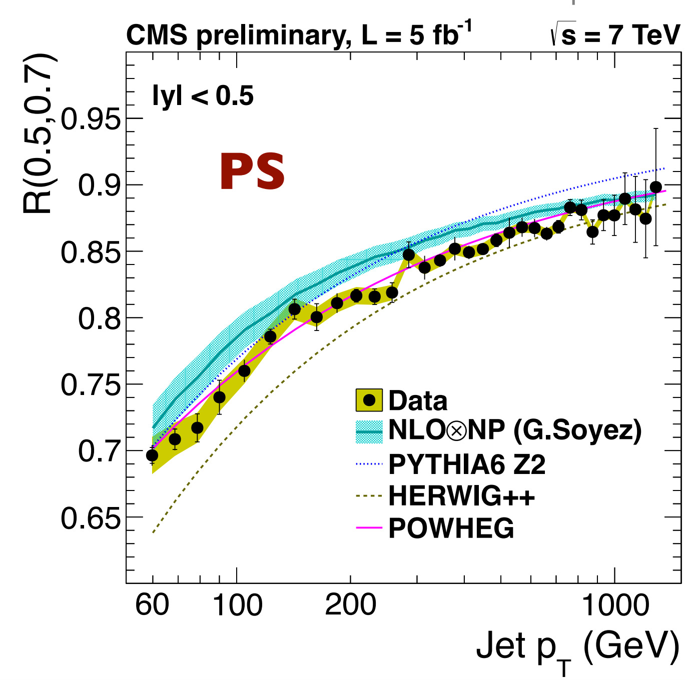
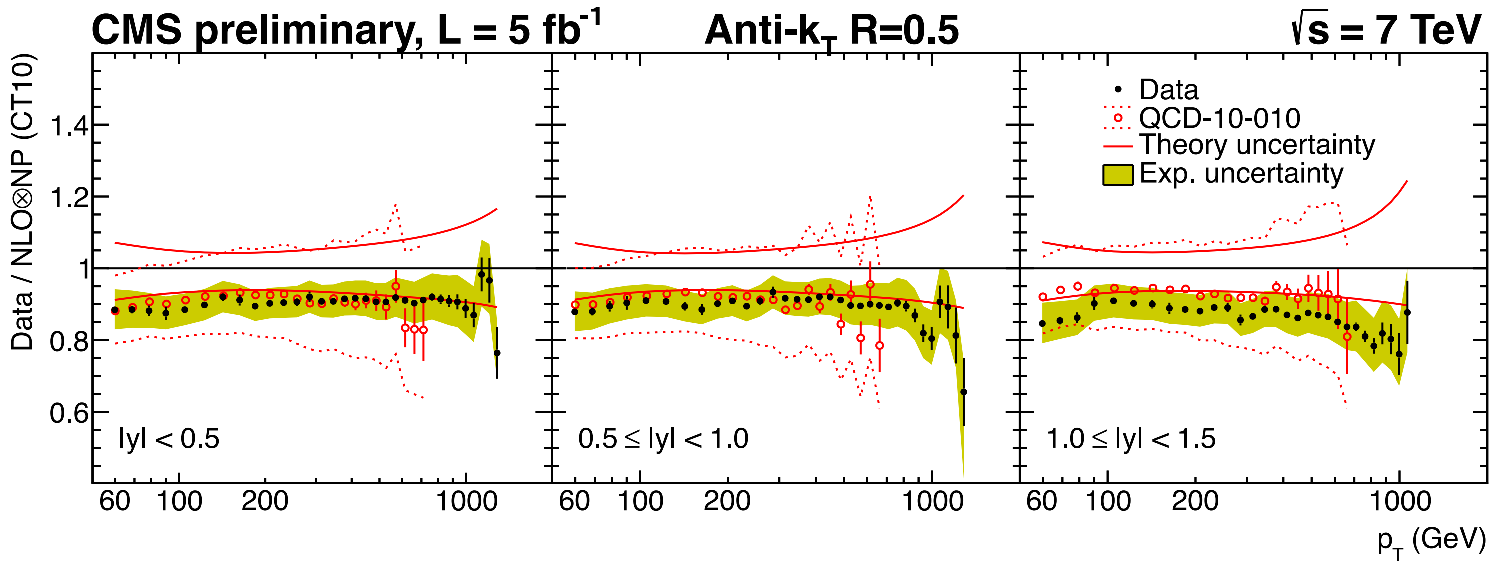
  - Also to non-perturbative (NP) corrections at low p_T
  - NLO for jet radius ratio tests NNLO for cross sections
- Interesting observable due to cancellation of experimental and theoretical uncertainties to a high degree
- Can be used as a test of parton shower (**PS**) models
  - Best data/theory with (N)LO+matched PS (e.g. Powheg)



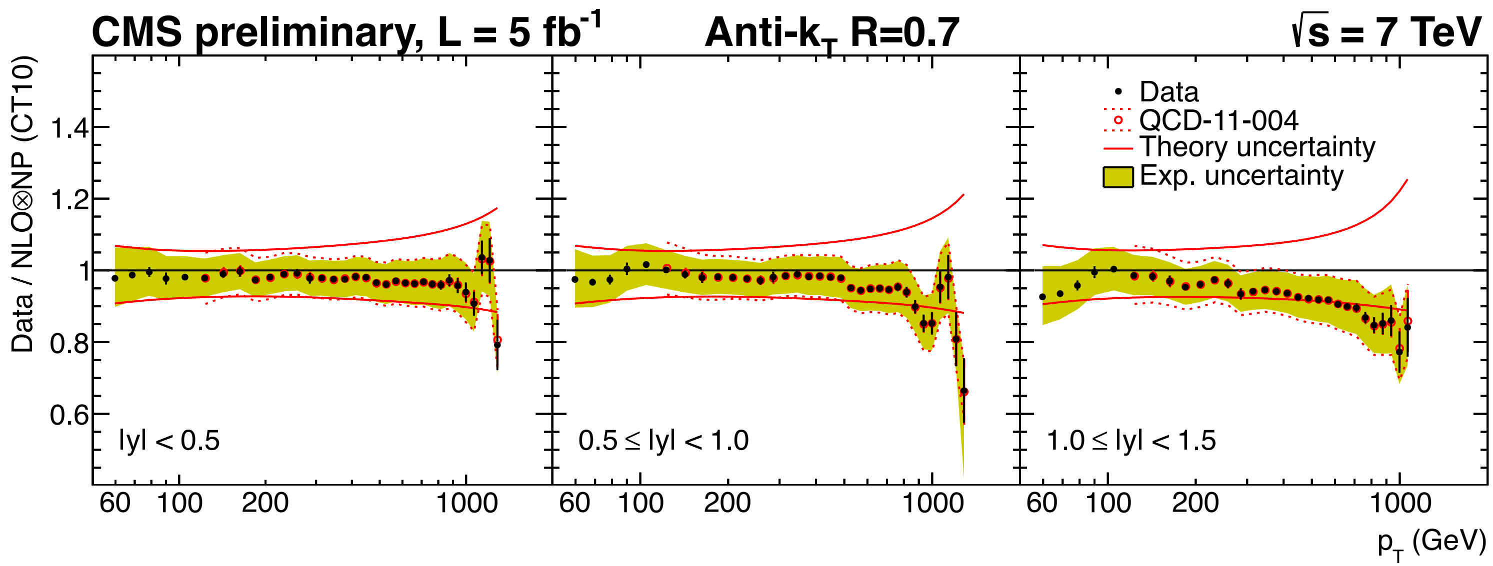
Jet radius ratio, R(0.5,0.7)

- Useful for understanding data/pQCD consistency with different jet radii R
  - Better agreement with R=0.7; smaller R=0.5 cone more sensitive to FSR



R=0.5

(2010, 36 pb^{-1})

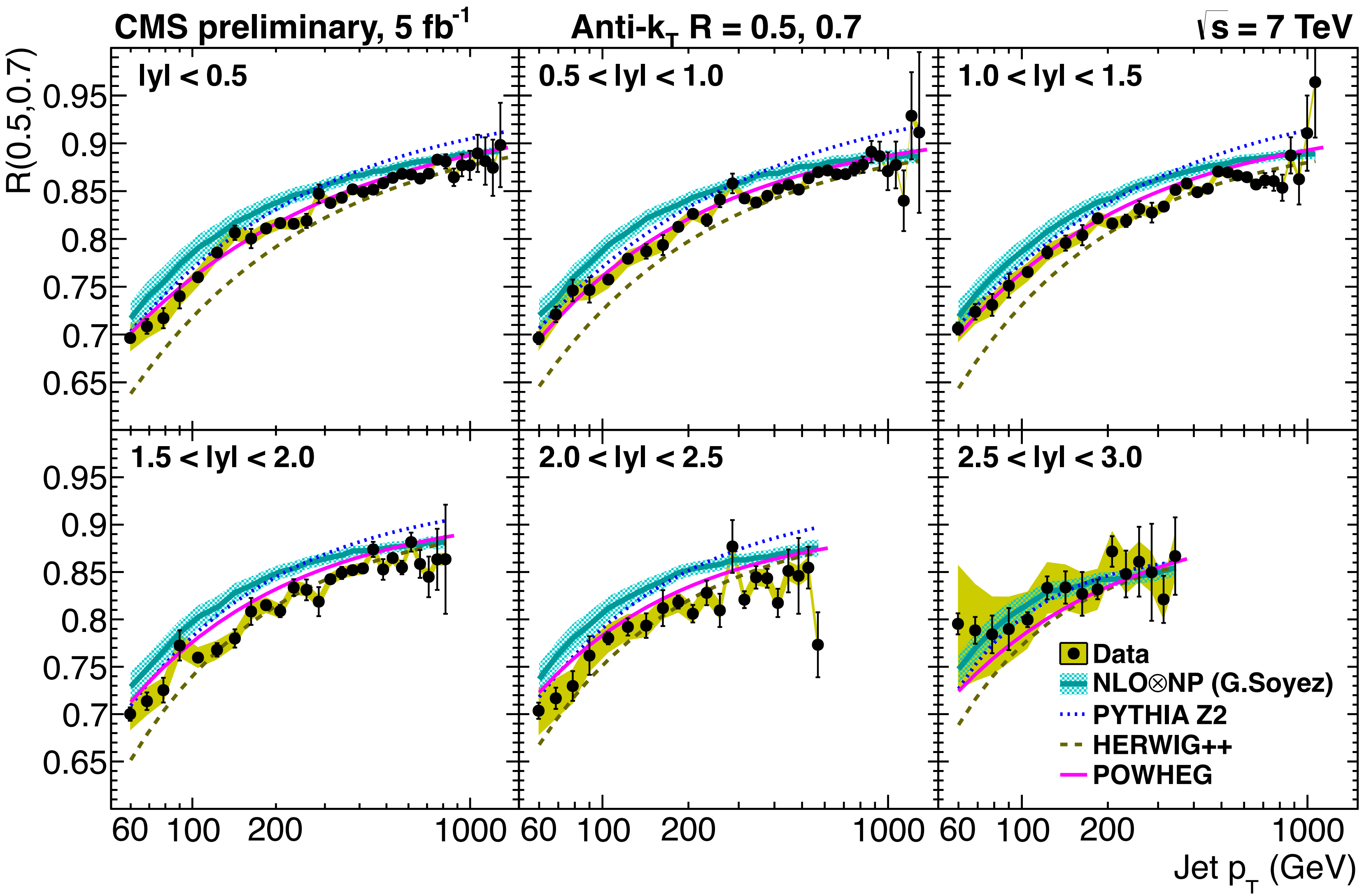


R=0.7

(2011, 5 fb^{-1})

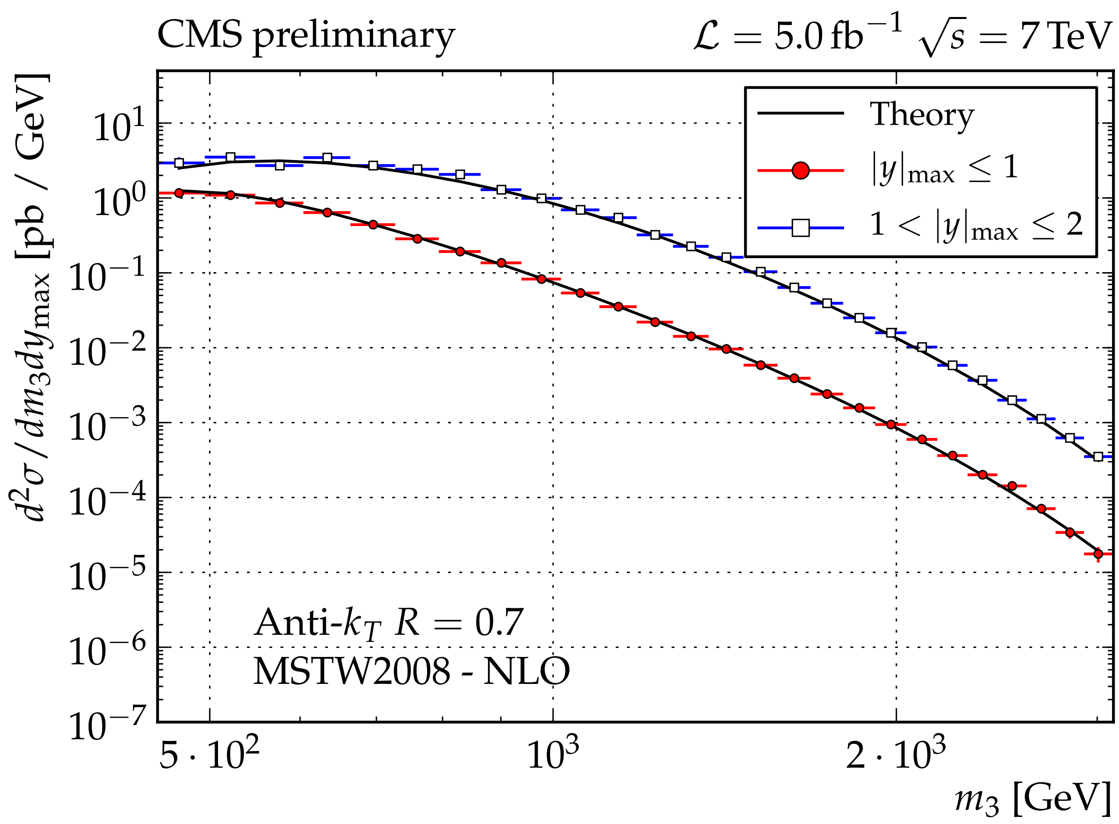
Jet radius ratio, R(0.5,0.7)

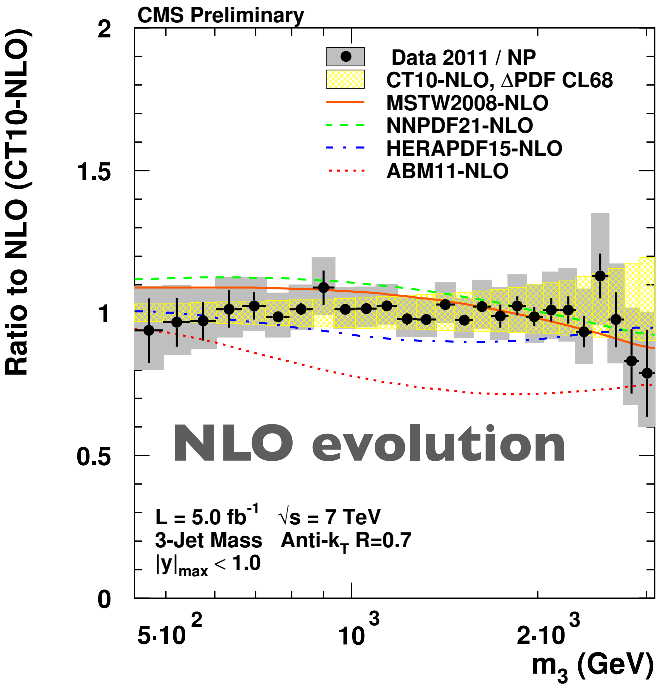
- Jet radius ratio largely independent of jet rapidity
  - good agreement with Powheg in all rapidity bins
  - experimental systematics limit conclusions in more forward regions

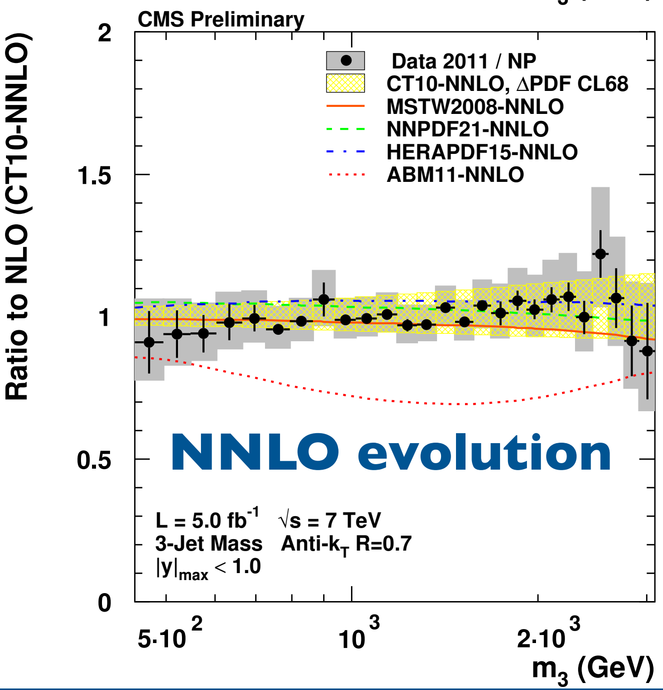


3-jet mass, m3

- 3-jet mass m3 particularly sensitive probe of α_s due to additional radiation of a gluon
- Well described by most PDFs and **NLO** pQCD
  - Cross-check with **NNLO** evolution of PDFs works well
    - However matrix element still only NLO: slight inconsistency
  - Good agreement of PDFs, and both NLO and NNLO evolution schemes means robust measurement of α_s

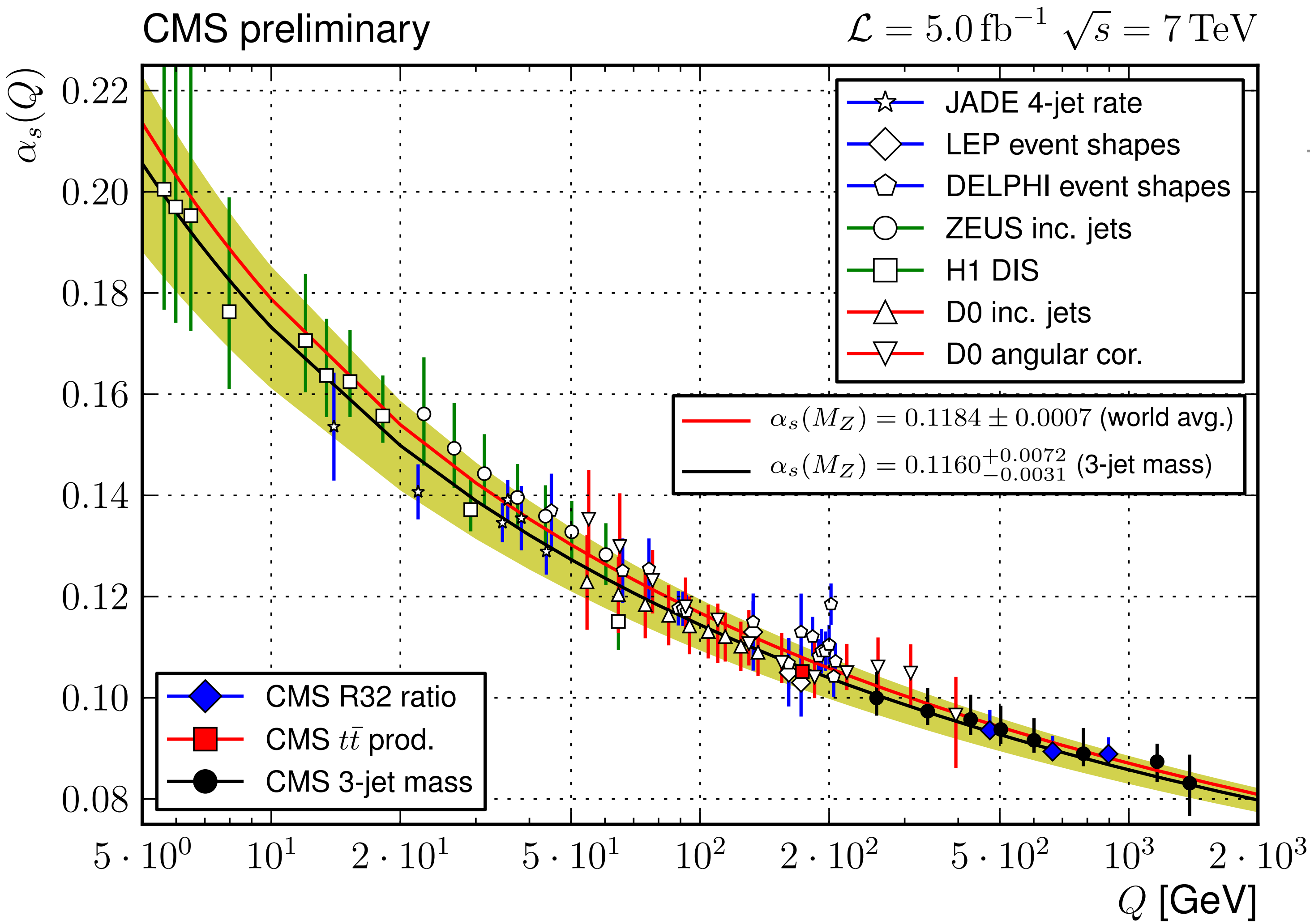






3-jet mass, m_3

- Constraints on **running of α_S** up to $Q \approx 1.4$ TeV
- MSTW2008-NLO consistent with CT10, HERAPDF1.5 and NNPDF2.1 with NLO & NNLO
  - variation with NNLO evolution less than with NLO, despite using NLO matrix element
- Compatible with CMS with 3-jet rate (R_{32}) at NLO and tt cross section at NNLO



PDF	$\alpha_S(M_Z)$
CT10-NLO	0.1169
CT10-NNLO	0.1164
HERAPDF15-NLO	0.1200
HERAPDF15-NNLO	0.1159
MSTW2008-NLO	0.1160
MSTW2008-NNLO	0.1167
NNPDF21-NLO	0.1140
NNPDF21-NNLO	0.1168

Δ_{max}(NLO) = 0.0060

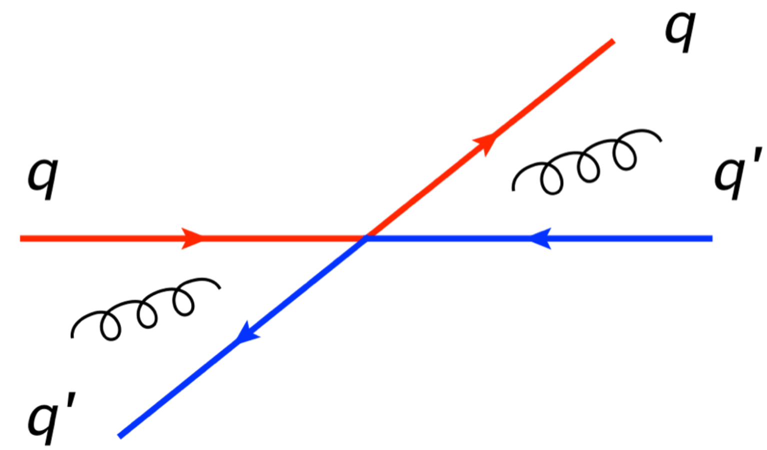
Δ_{max}(NNLO) = 0.0009

HERAPDF15-NNLO: +0.0030 / -0.0013

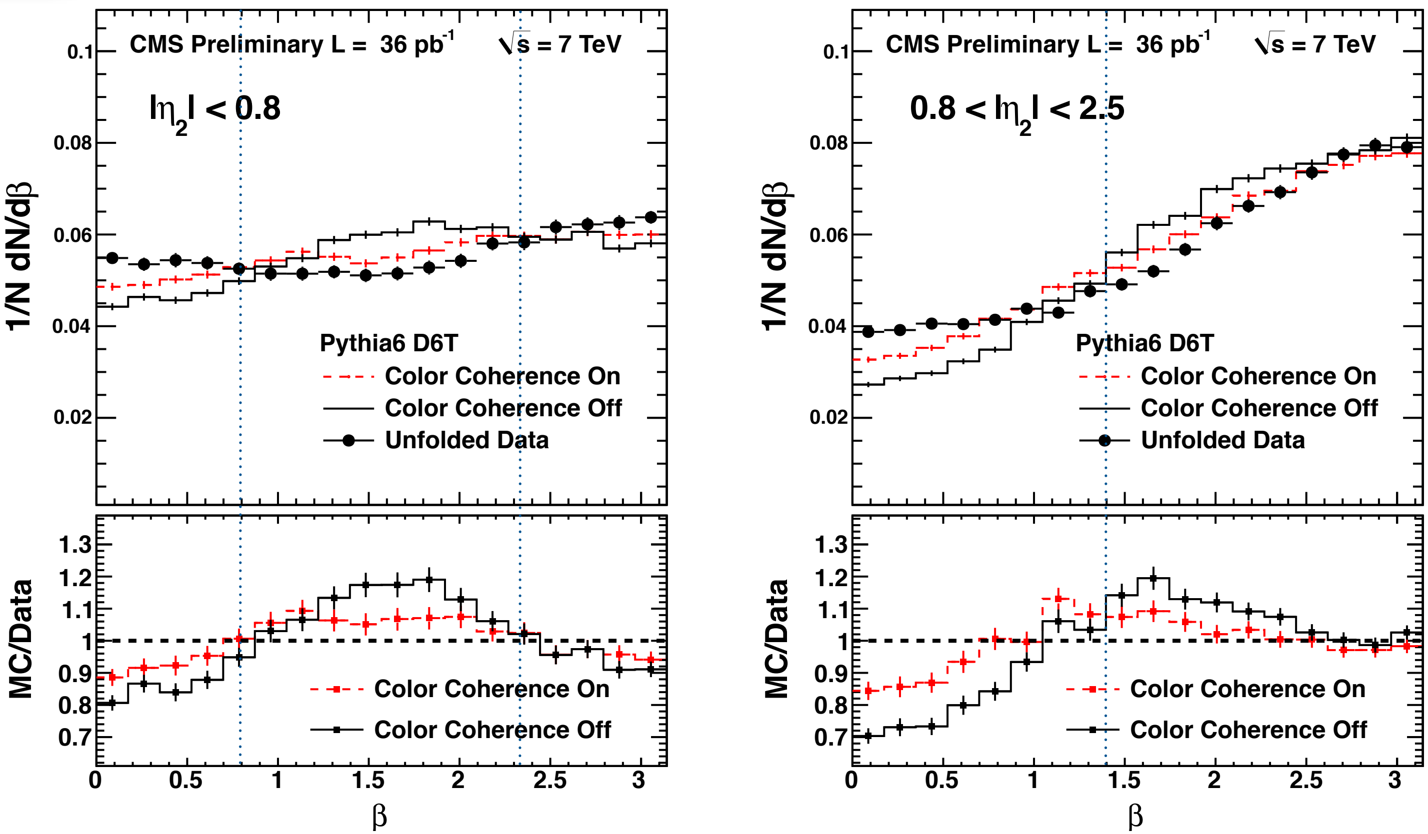
Color coherence

- In QCD, incoming and outgoing partons can interfere through color effects
- Main effect is enhancing radiation in plane of emitting parton and beam axis (β=0, π) and suppressing out of plane (β=π/2)

$$\beta = |\mathrm{atan2}(\Delta\phi_{23}, \Delta\eta_{23})|$$



- Effect clearly visible by switching color coherence on and off in Pythia6 **PS**
  - off switch only affects first shower branching
  - CC effect in Pythia6 was tuned to Tevatron data, not as strong at the LHC



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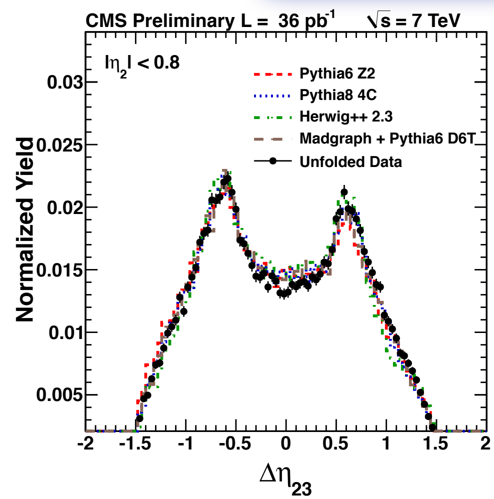
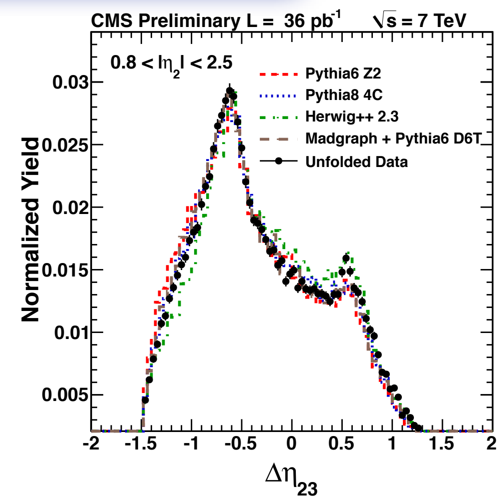
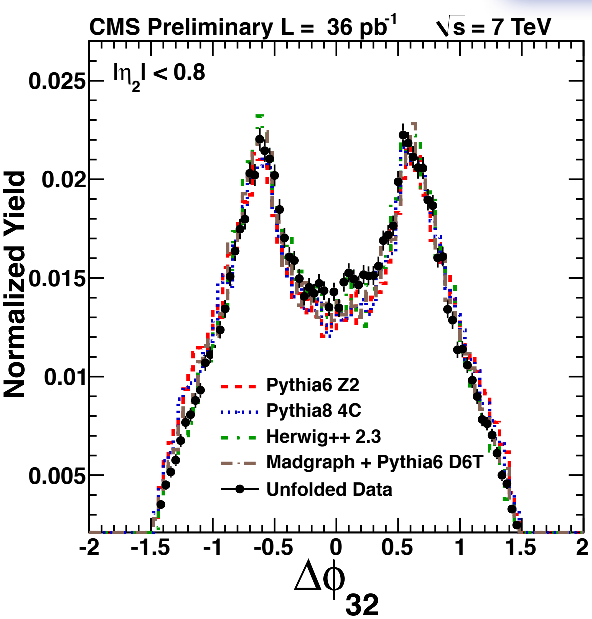
$$\beta = |\mathrm{atan2}(\Delta\phi_{23}, \Delta\eta_{23})|$$

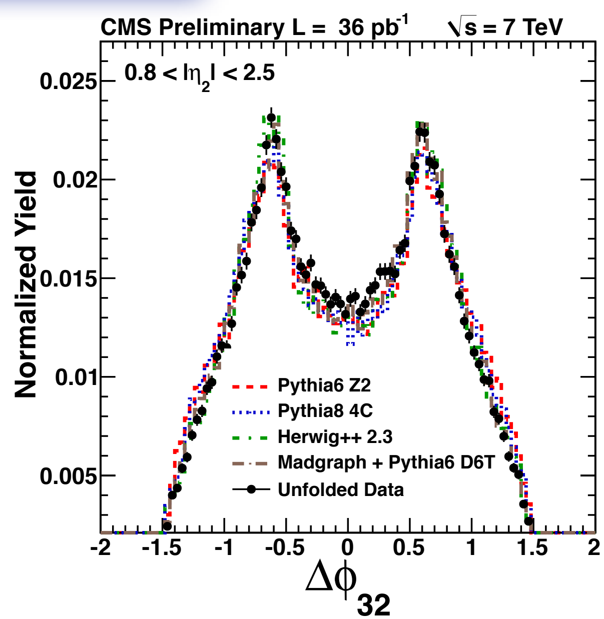
$$\Delta\eta_{23} = \mathrm{sign}(\eta_2) \cdot (\eta_3 - \eta_2)$$

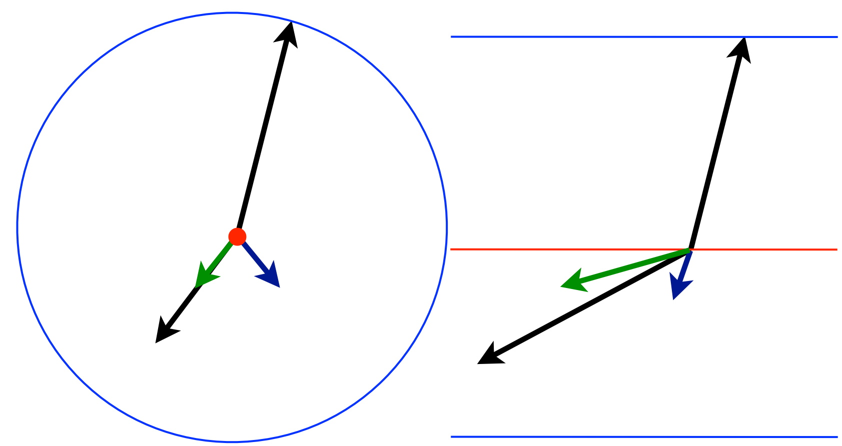




$$\Delta\phi_{23} = \phi_3 - \phi_2$$







$p_T > 30$ GeV
$|\eta_1|, |\eta_2| < 2.5$
$M_{12} > 220$ GeV
$0.5 < \sqrt{(\Delta\eta_{23}^2+\Delta\phi_{23}^2)} < 1.5$

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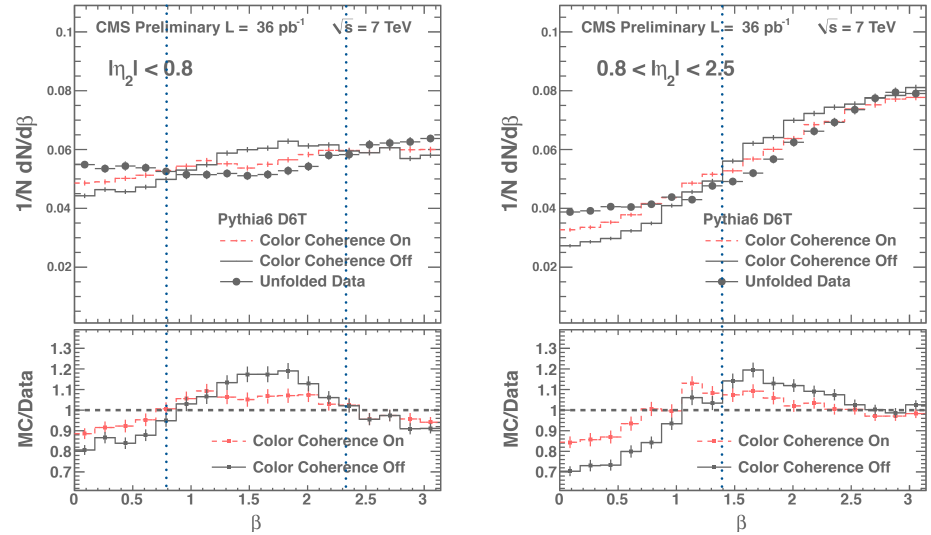
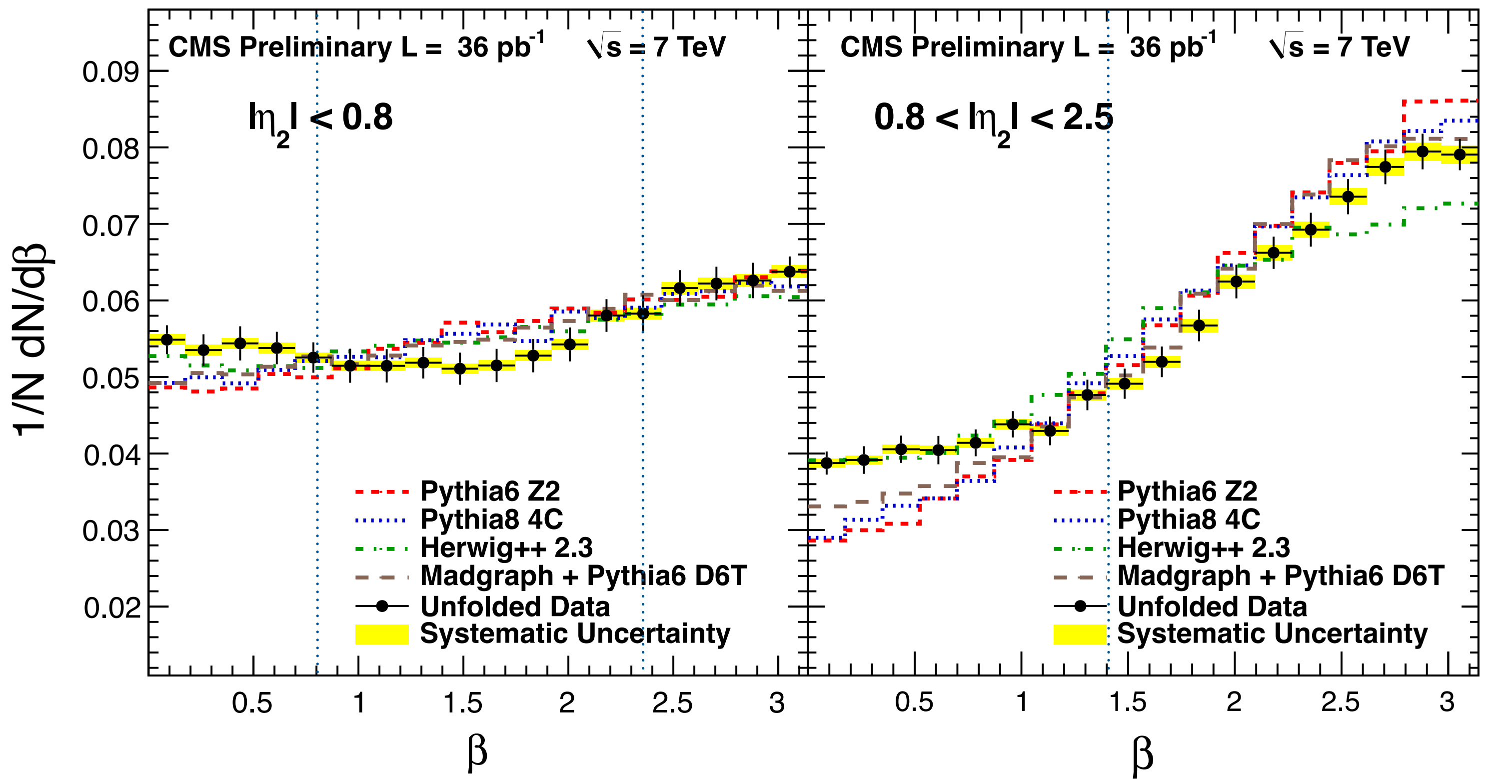


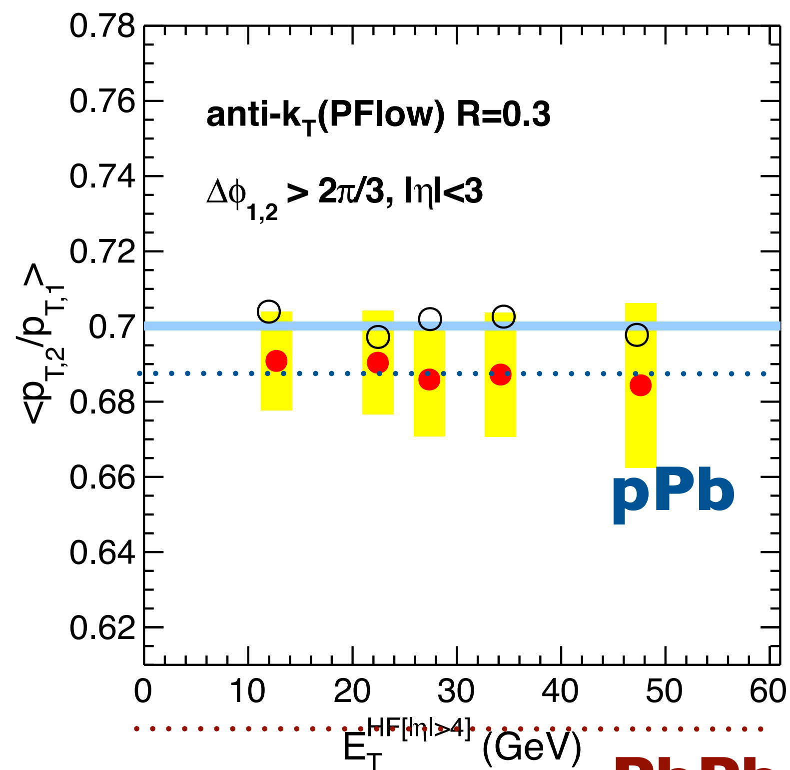
Color coherence in **PS**:

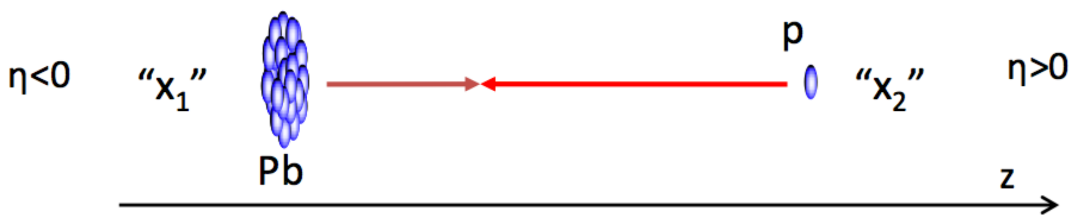
- Pythia: angular ordering algorithm
- Herwig++: coherent branching algorithm (also angular ordering)
- MadGraph: exact 2->3 matrix element
  - CC emerges naturally from color sums
  - clear improvement over plain Pythia



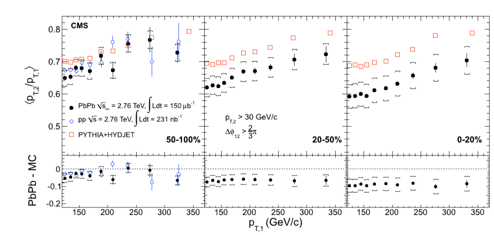
pPb collisions

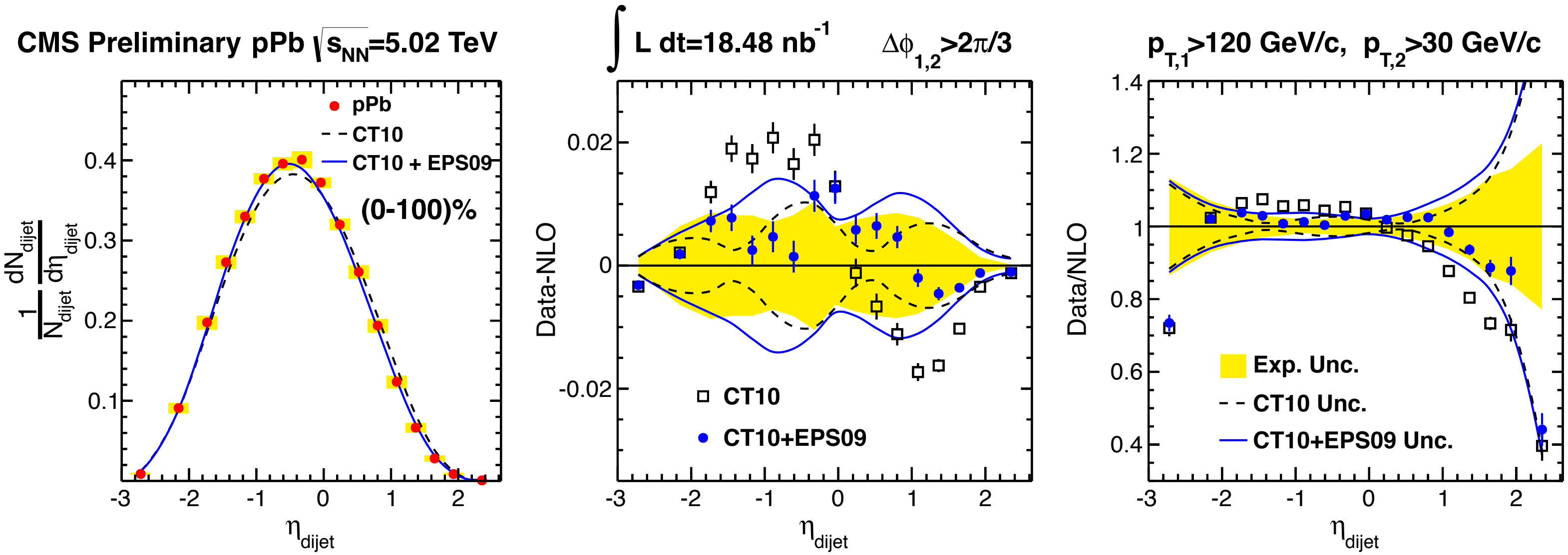
- proton-lead collisions are a useful reference for PbPb collisions, where QGP results in strong jet quenching
- Dijet balance $<p_{T,1}/p_{T,2}>$ shows no quenching in pPb
- The pPb probes cold nuclear matter effects in PDFs (gluon saturation, EMC effect, etc.) that are not present in reference pp collisions
  - well-modeled by CT10+EPS09 nuclear PDFs





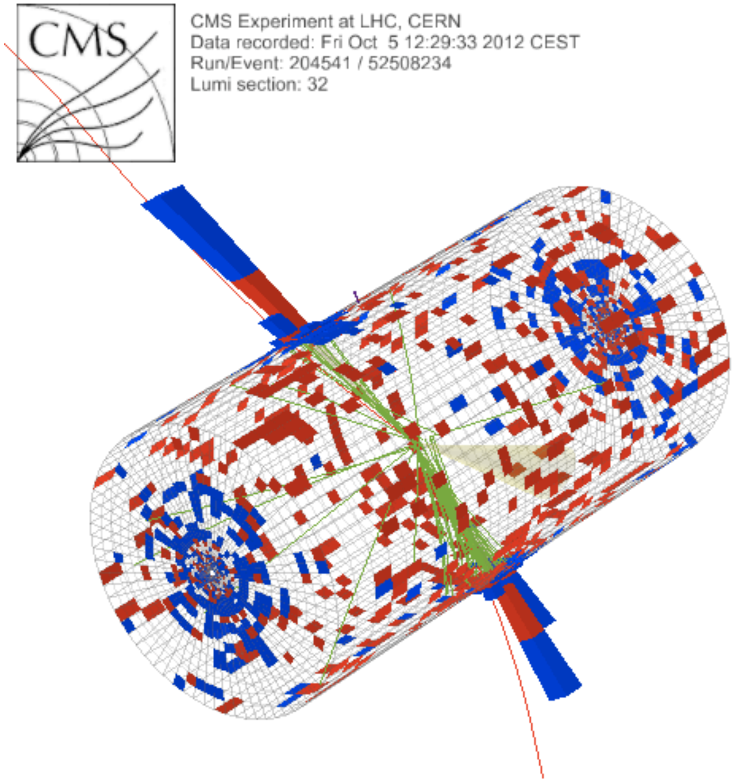
PbPb

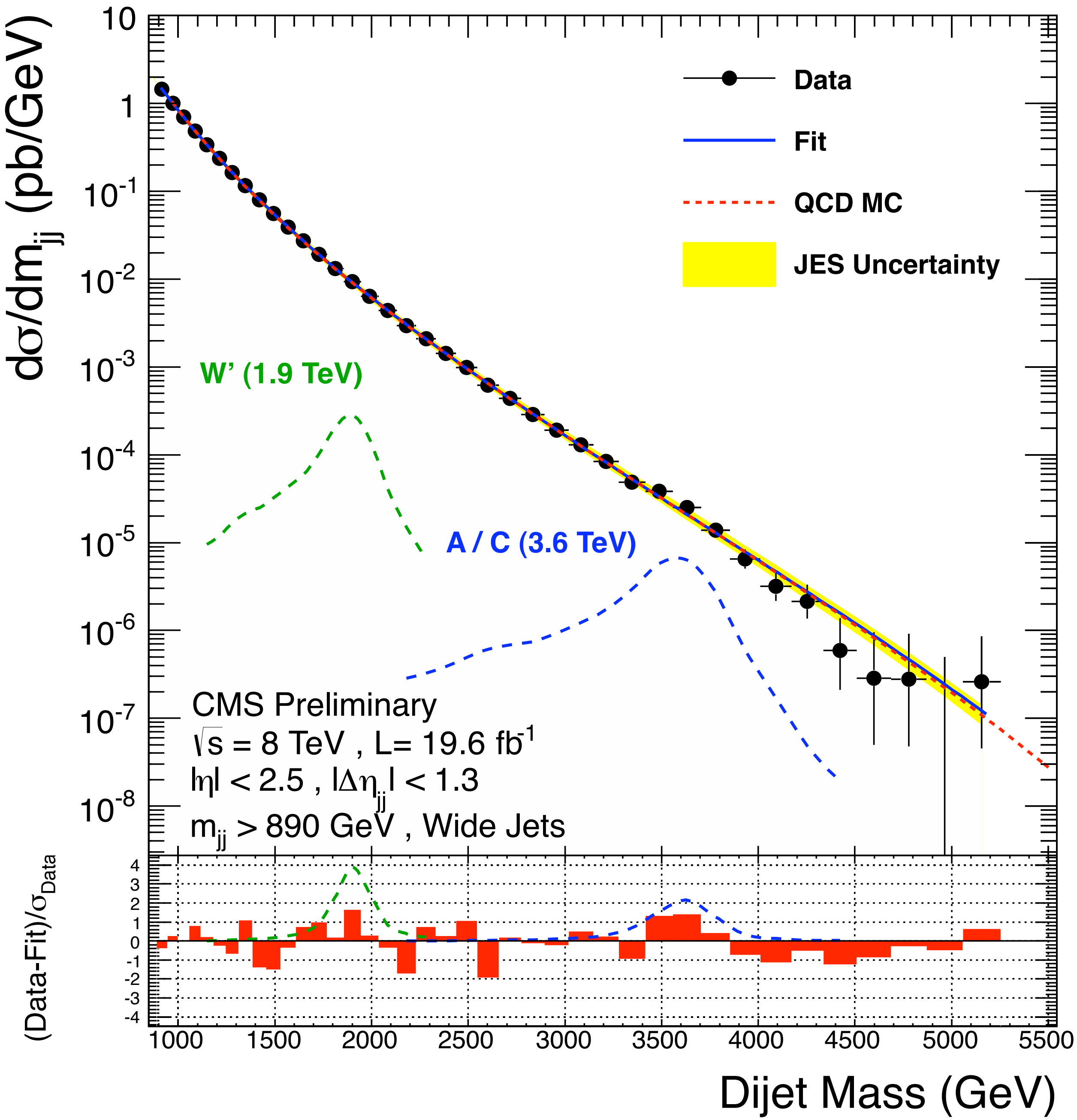




Dijet mass

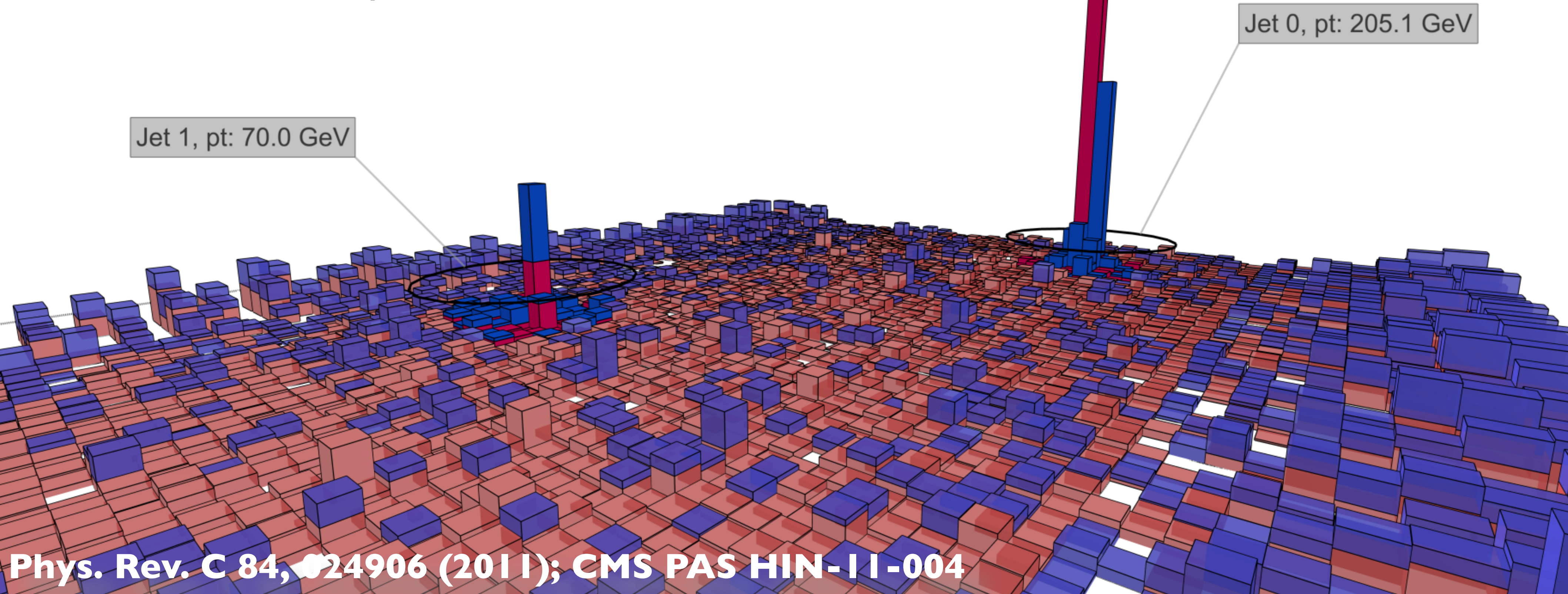
- Dijet mass is a standard model measurement, but also used for bump hunts
- Sensitive to exotic heavy particles decaying to pairs of quarks or gluons
- Already extending to M~5 TeV, interesting analysis in LHC Run 2





Conclusions and outlook

- Many precise jet measurements of standard model physics coming out
  - Sensitive enough to measure PDFs and running of α_S, discriminate fixed order pQCD vs PS models, test color coherence models
  - Still improving the already impressive precision
- These set the stage for many other physics analyses, e.g.
  - studies of quark gluon plasma
  - searches of heavy resonances



Phys. Rev. C 84, 024906 (2011); CMS PAS HIN-11-004

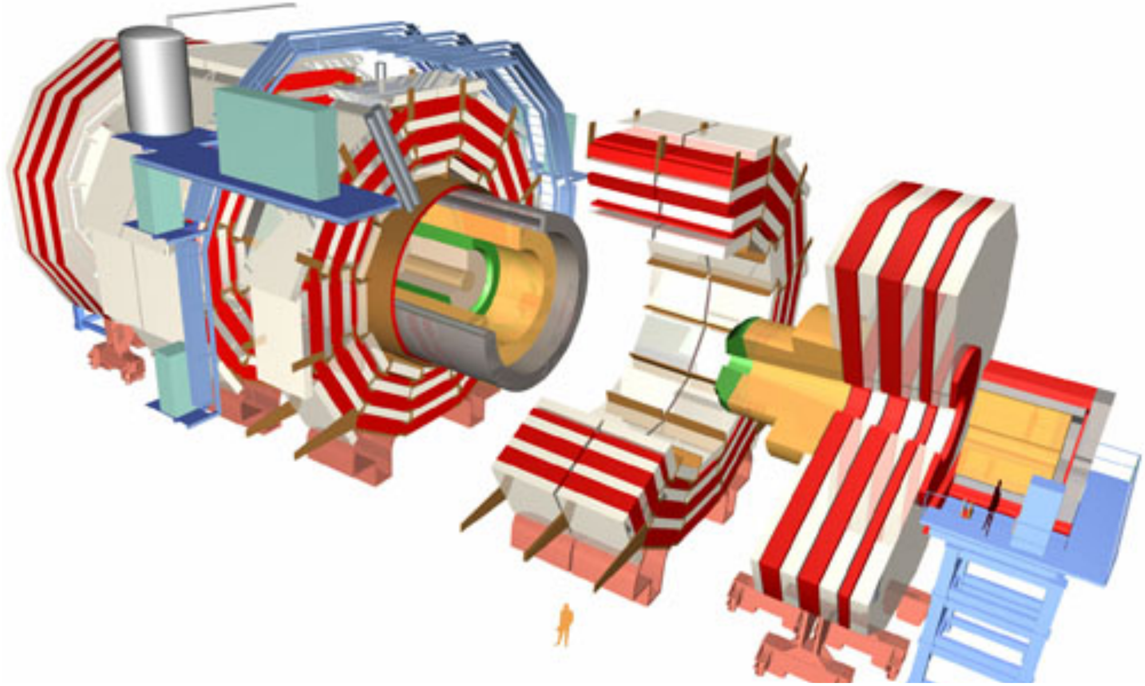
References to analyses

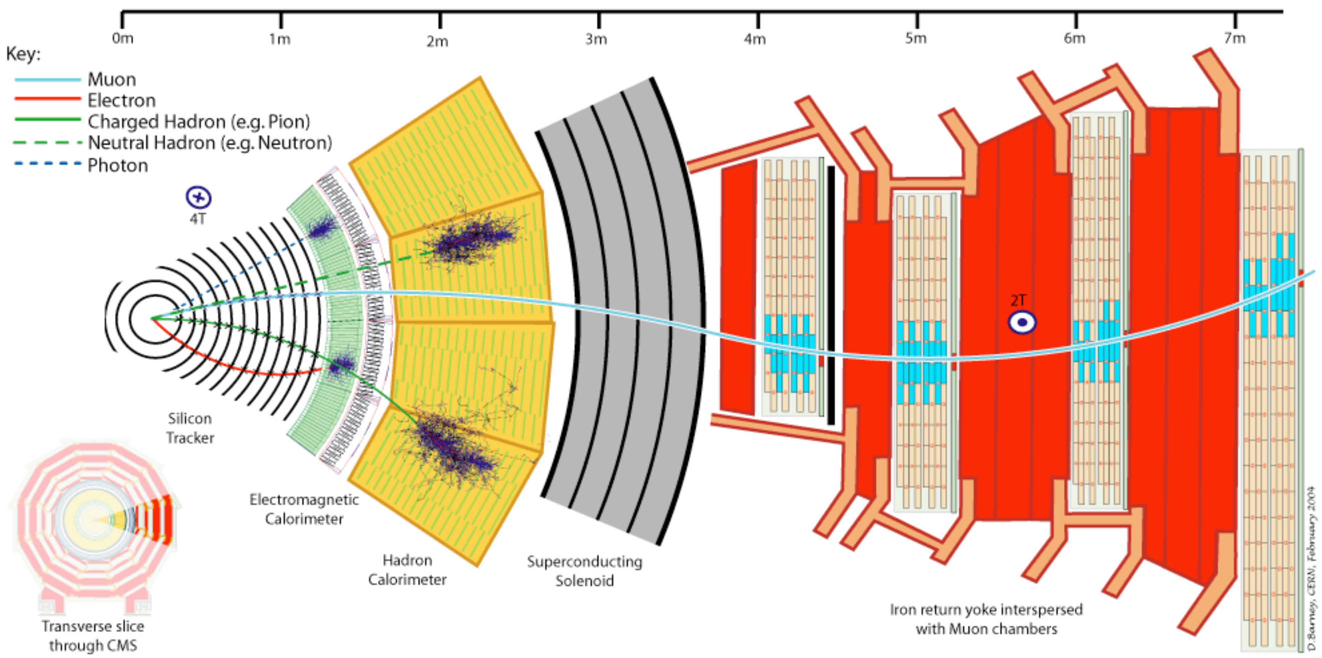
- **Inclusive jets, 7 TeV**
  - Phys. Rev. D 87 (2013) 112002 ; http://cds.cern.ch/record/1502672
    - Measurements of differential jet cross sections in proton-proton collisions at $\sqrt{s}=7$ TeV with the CMS detector
- **Inclusive jets, 8 TeV**
  - CMS-PAS-SMP-12-012 ; https://cds.cern.ch/record/1547589
    - Measurement of the double-differential inclusive jet cross section at sqrt(s) = 8 TeV with the CMS detector
- **Jet radius ratio at 7 TeV**
  - CMS-PAS-SMP-13-002 ; http://cds.cern.ch/record/1558088
    - Measurement of the ratio of inclusive jet cross sections with radius parameters R=0.5 and R=0.7 using the anti-kt algorithm
- **3-jet mass at 7 TeV**
  - CMS-PAS-SMP-12-027 ; http://cds.cern.ch/record/1562985
    - Measurement of the 3-jet mass cross section in pp collisions at 7 TeV and determination of the strong coupling constant from 3-jet masses in the TeV range
- **Color coherence at 7 TeV**
  - CMS-PAS-SMP-12-010 ; http://cds.cern.ch/record/1554549
    - Measurement of color coherence effects in pp collisions at root s = 7 TeV
- **Dijet mass resonance search at 8 TeV**
  - CMS-PAS-EXO-12-059 ; http://cds.cern.ch/record/1519066
    - Search for Narrow Resonances using the Dijet Mass Spectrum with 19.6fb-1 of pp Collisions at sqrts=8 TeV
- **Dijets in pPb collisions**
  - CMS-PAS-HIN-13-001 ; http://cds.cern.ch/record/1545781
    - Study of dijet momentum balance and pseudorapidity distributions in pPb collisions at $\sqrt{s_{NN}}=5.02$ TeV

Backup slides

Compact Muon Solenoid

- **Precise silicon pixel and silicon strip tracking at |η| < 2.4**
- **Fine-grained lead tungstate crystal ECAL at |η| < 3.0**
- **Brass+scintillator HCAL at |η| < 3.0**
- **Tracking, ECAL and HCAL embedded inside 3.8 T solenoid magnet**
- **Muon chambers outside magnet, interleaved with iron return yoke**





Calorimeter granularity:
ECAL 5×5 vs HCAL 1×1