Multi-jet correlations and colour coherence phenomena.

Jason Sang Hun Lee, University of Seoul
on behalf of the CMS collaboration
XLVI International Symposium on Multiparticle Dynamics
Jeju, South Korea

Outline

Introduction to Colour Coherence

Jets in CMS

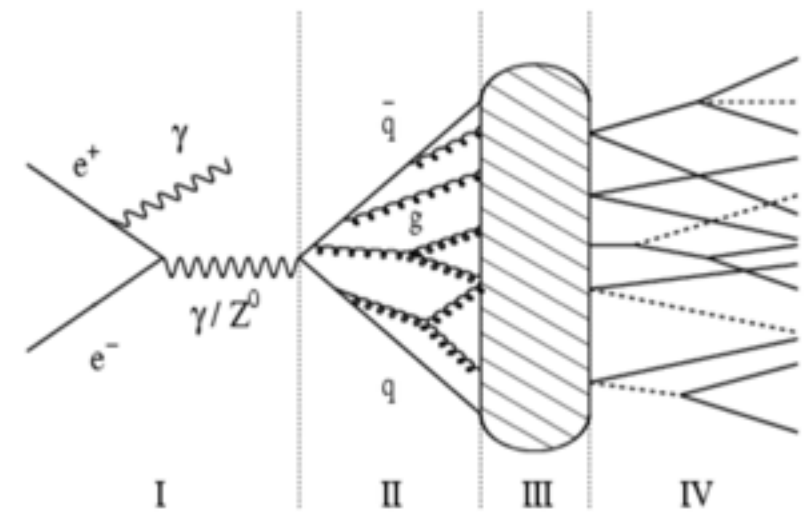
CMS 7 TeV results

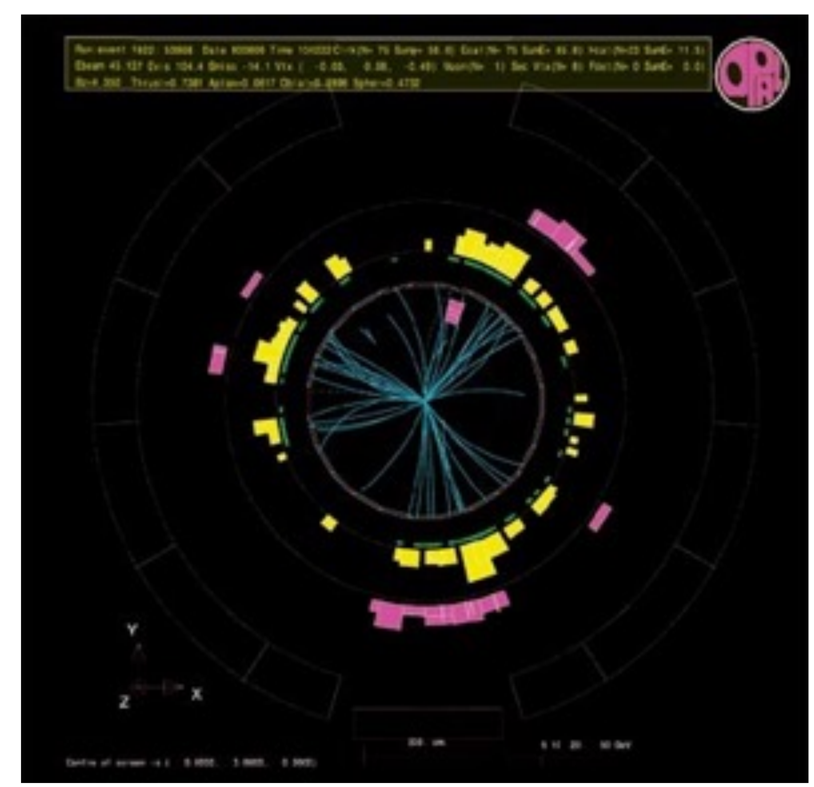
Parton Shower vs Matrix Element MC study

Introduction to Colour Coherence

What is Colour Coherence?

- ➡ In quantum chromodynamics (QCD) hard interactions outgoing partons produced continue to interfere with each other during their fragmentation phase
- ➡ initially observed in e^+e^- collisions by several experiments (PETRA, PEP and LEP)
- ➡ in $e^+e^- \rightarrow q\bar{q}g$ three-jet events there was a suppression of particle production in the region between the quark and antiquark jets

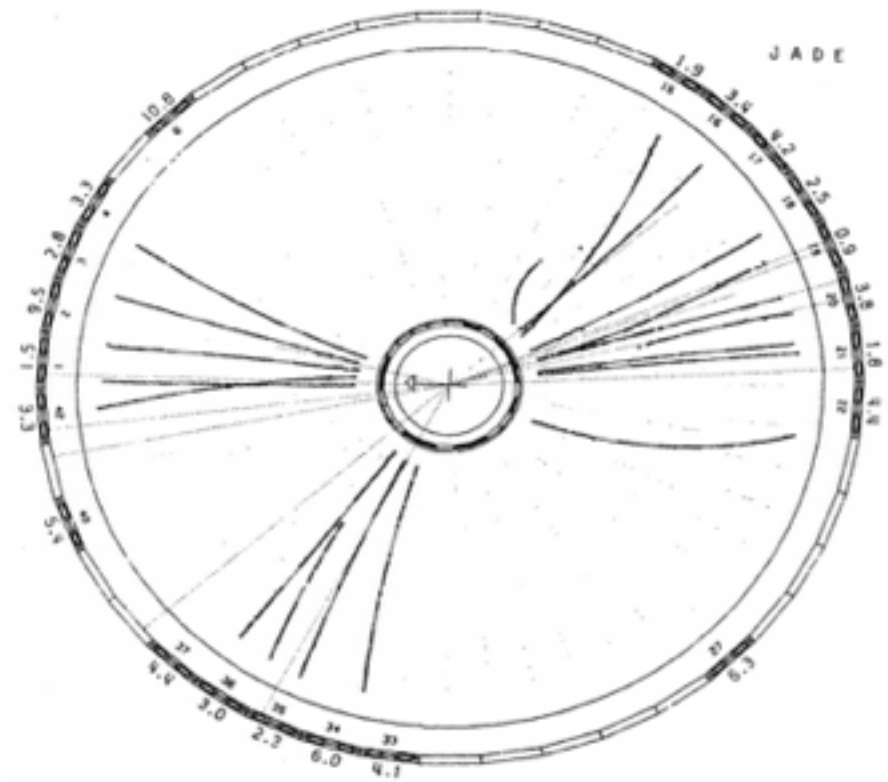


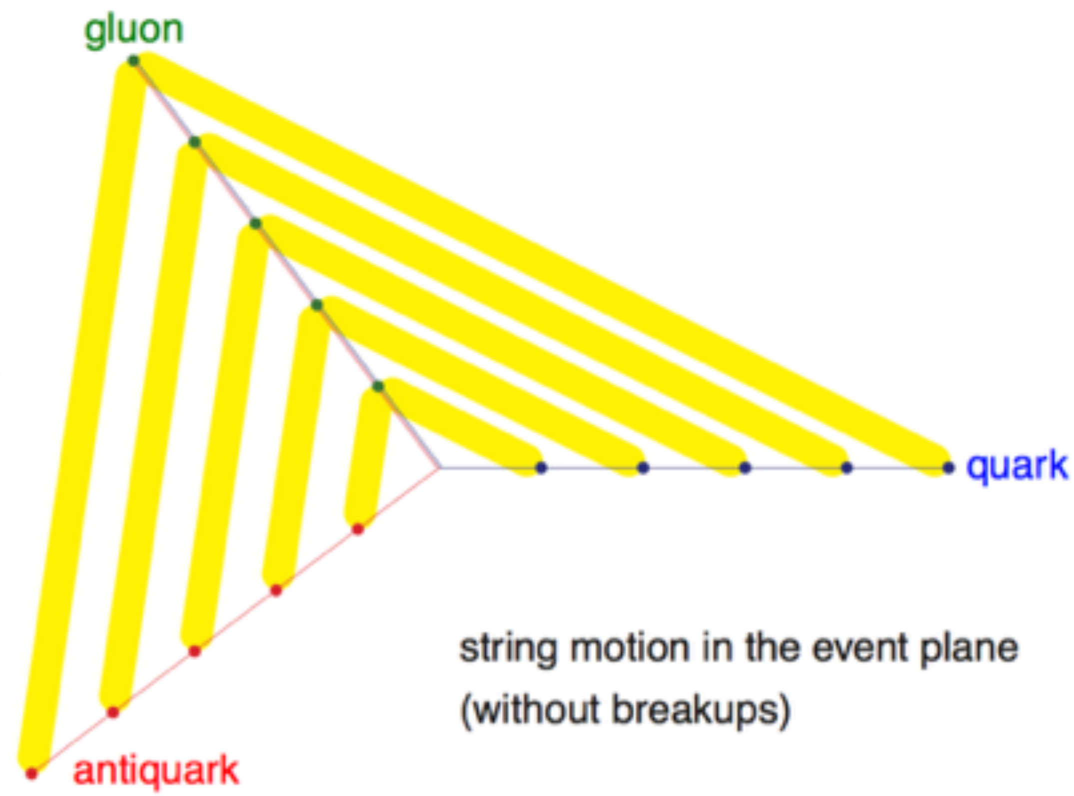


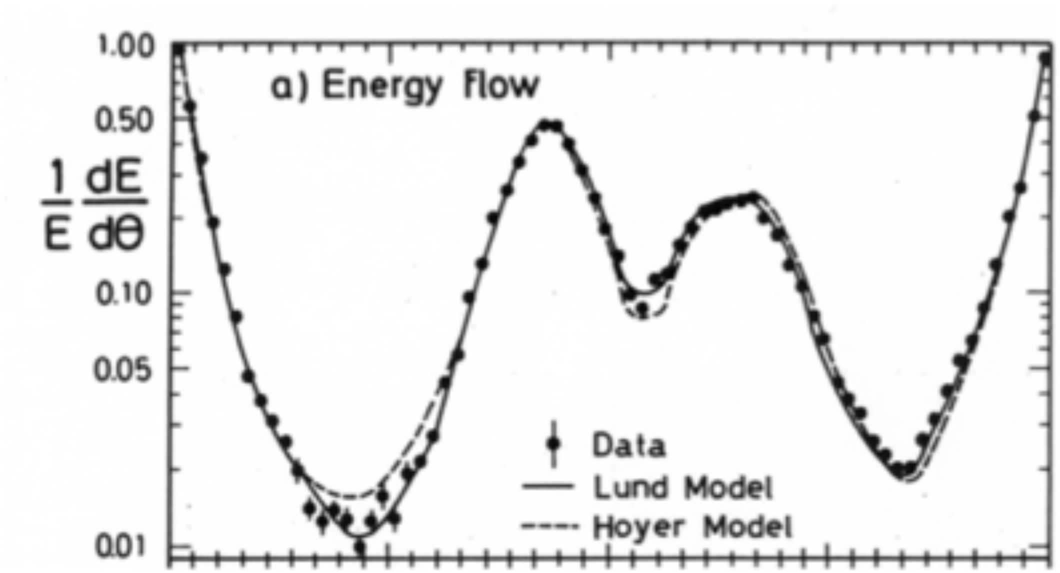
Introduction to Colour Coherence

1980: string (colour coherence) effect

LHCP 2016, Lund, 13 June 2016







Predicted unique event structure; inside & between jets.

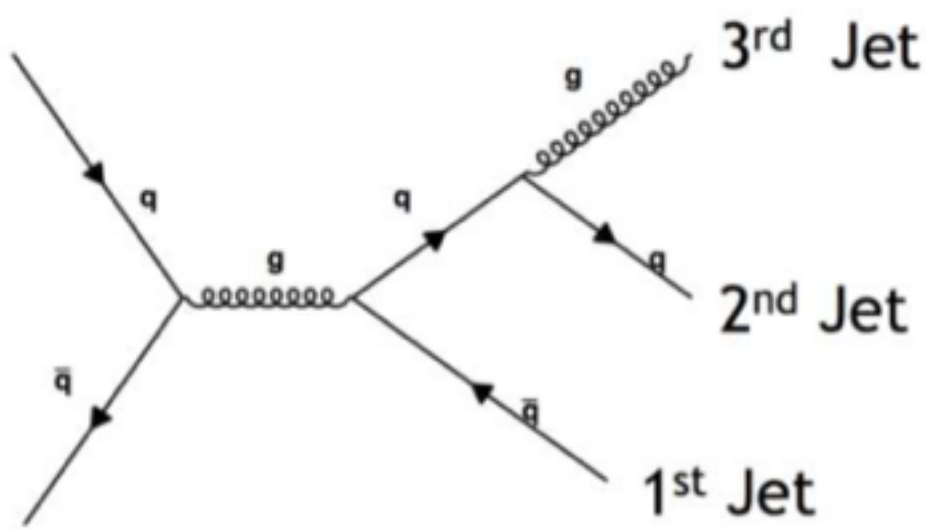
Confirmed first by JADE 1980.

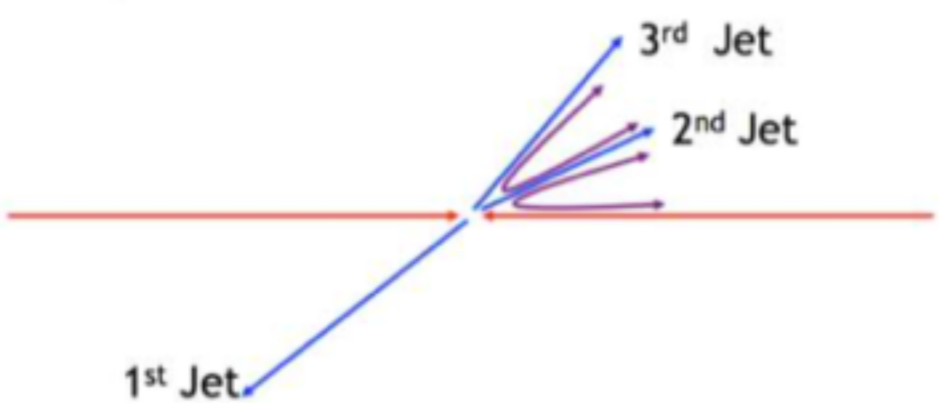
Generator crucial to sell physics!

(today: PS, M&M, MPI, . . .)

Colour Coherence in pp collisions

- In hadron collisions, constituents are also coloured
    - The final qqg or ggg are also colour connected to the proton constituents
- The Tevatron experiments showed that the variable 'β' is sensitive to colour coherence

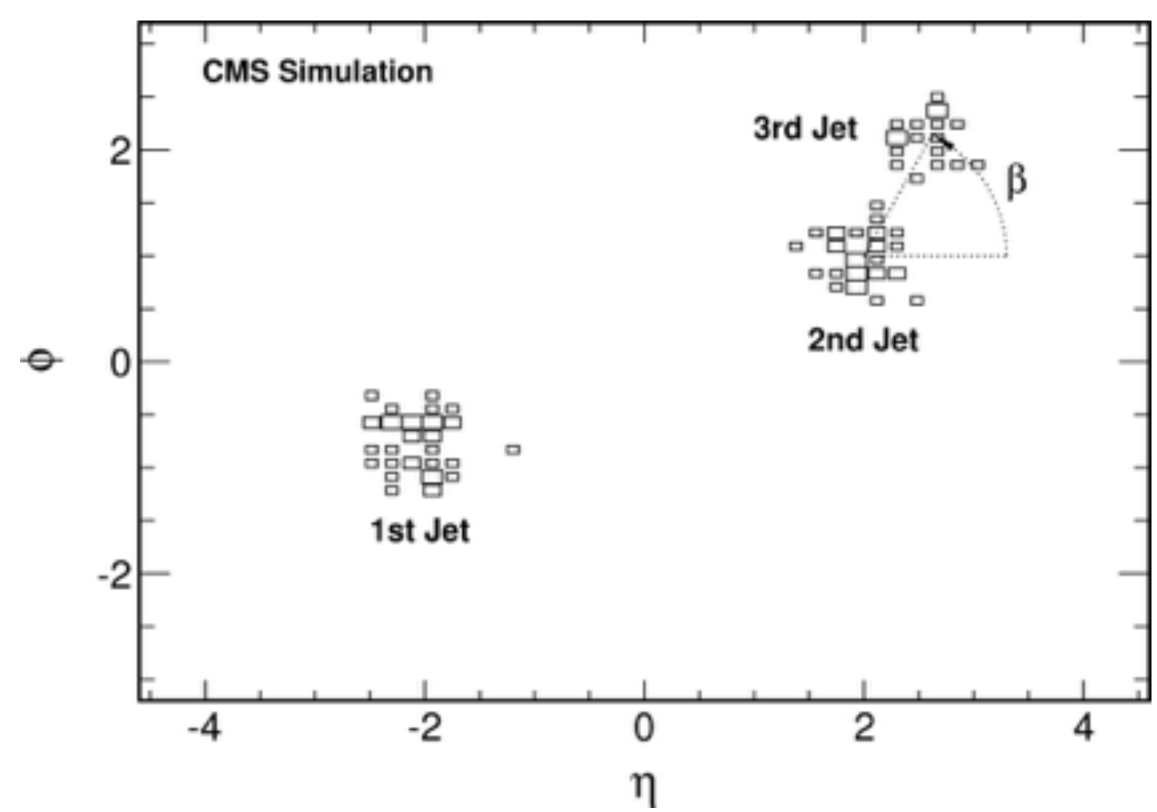




$$\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}, \ (0 \leq \beta \leq \pi)$$

$$\Delta\phi_{23} = \phi_3 - \phi_2, \ (0 \leq \Delta\phi_{23} \leq \pi)$$

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

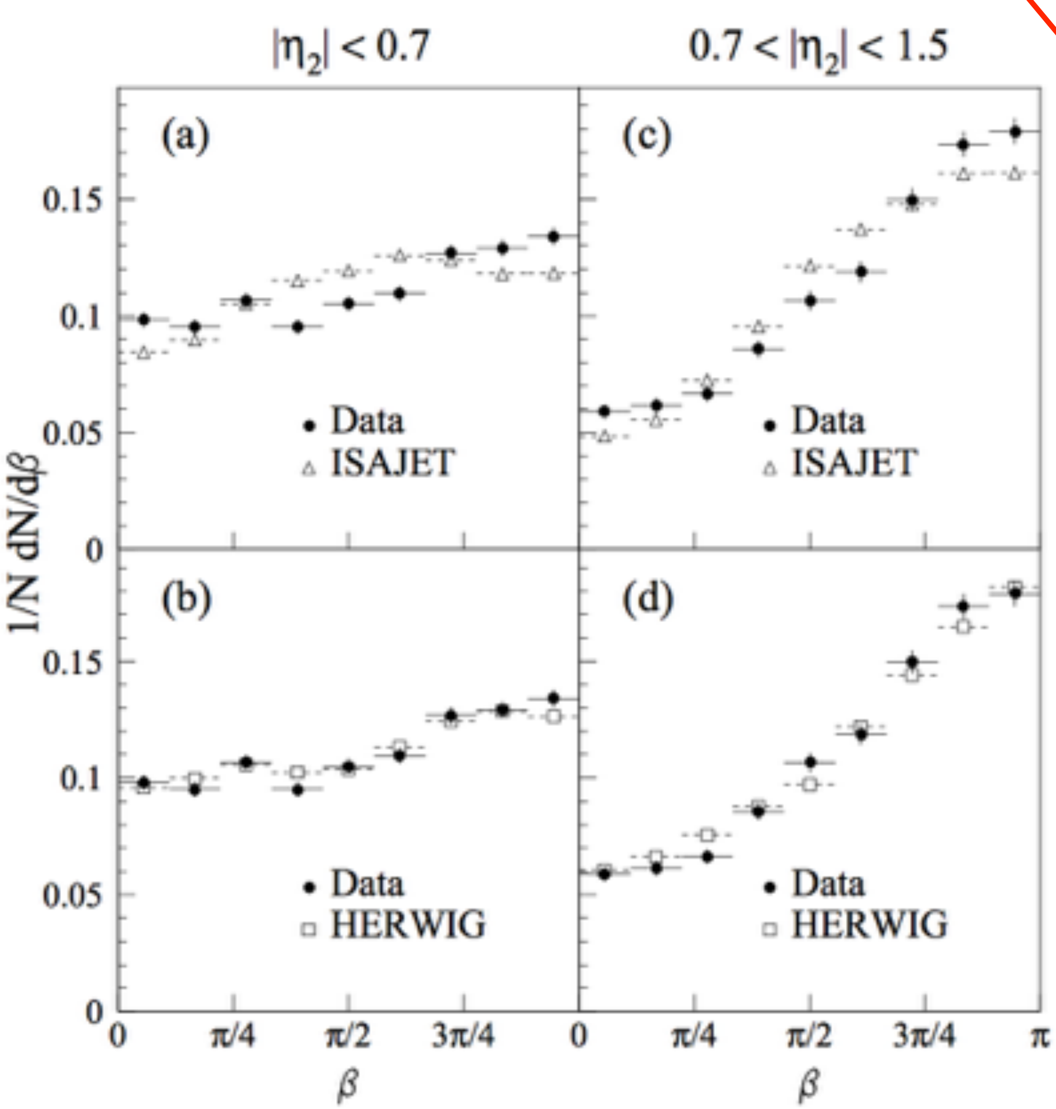


Colour Coherence in pp collisions

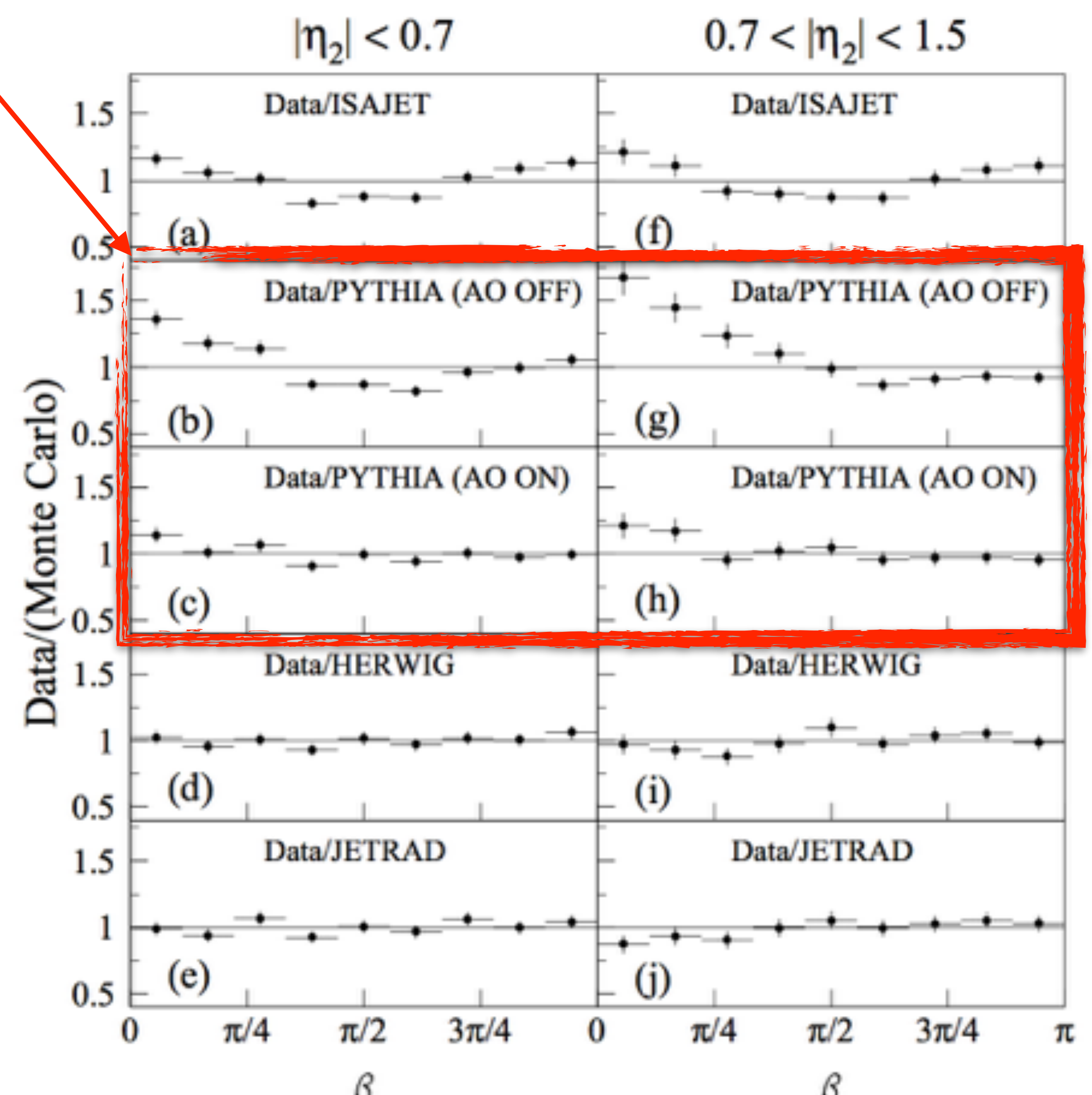
➡ The Tevatron experiments showed that the variable ’β’ is sensitive to colour coherence (D0 results shown in plots)

➡ Parton shower MC simulations with colour interference implemented with angular ordering (AO) showed good agreement

➡ Pythia with AO on and off highlighted this effect



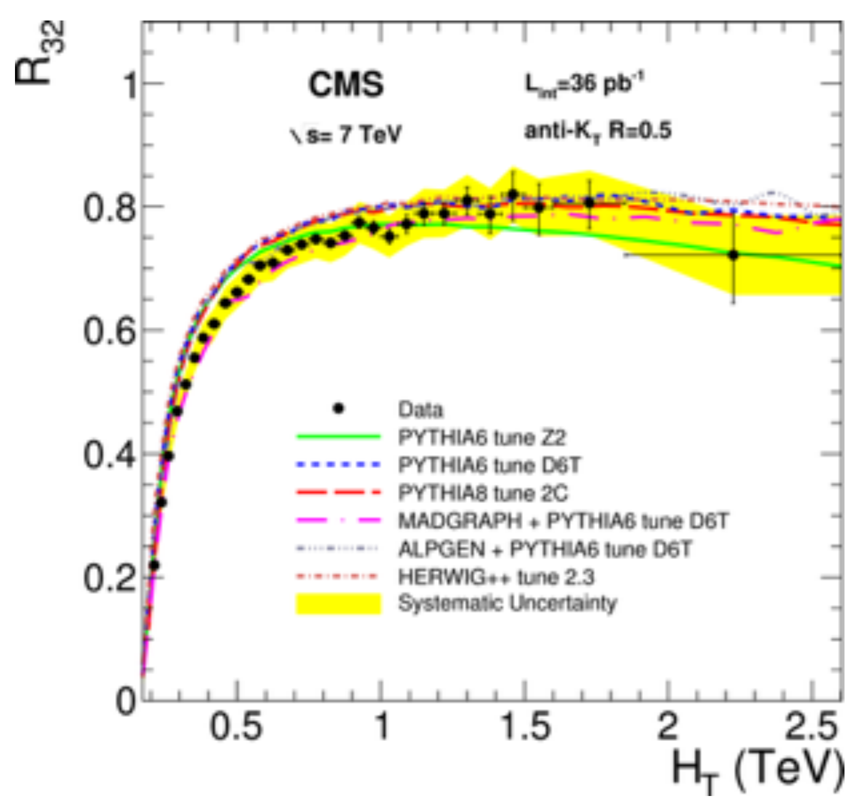
Phys.Lett. B414 (1997) 419-427



Jets in CMS

CMS uses particle flow objects as inputs for Anti-kt jet clustering, R=0.5 in Run1, R=0.4 for Run2

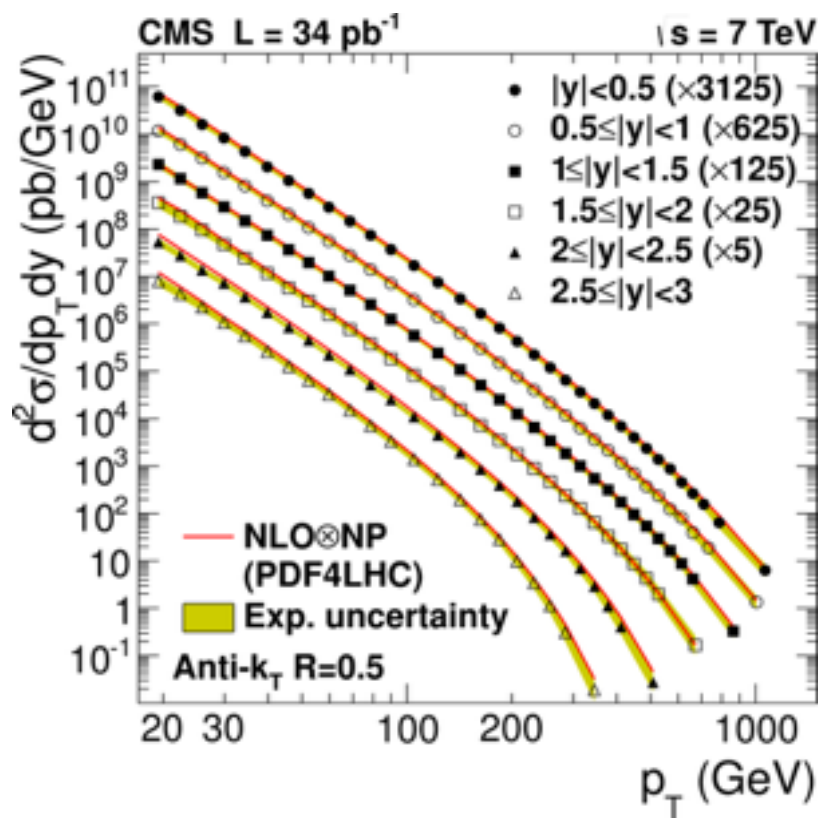
Cross Section



ratio of the inclusive 3-jet to 2-jet cross sections as a function of the total jet transverse momentum

Phys.Lett. B702 (2011) 336-354

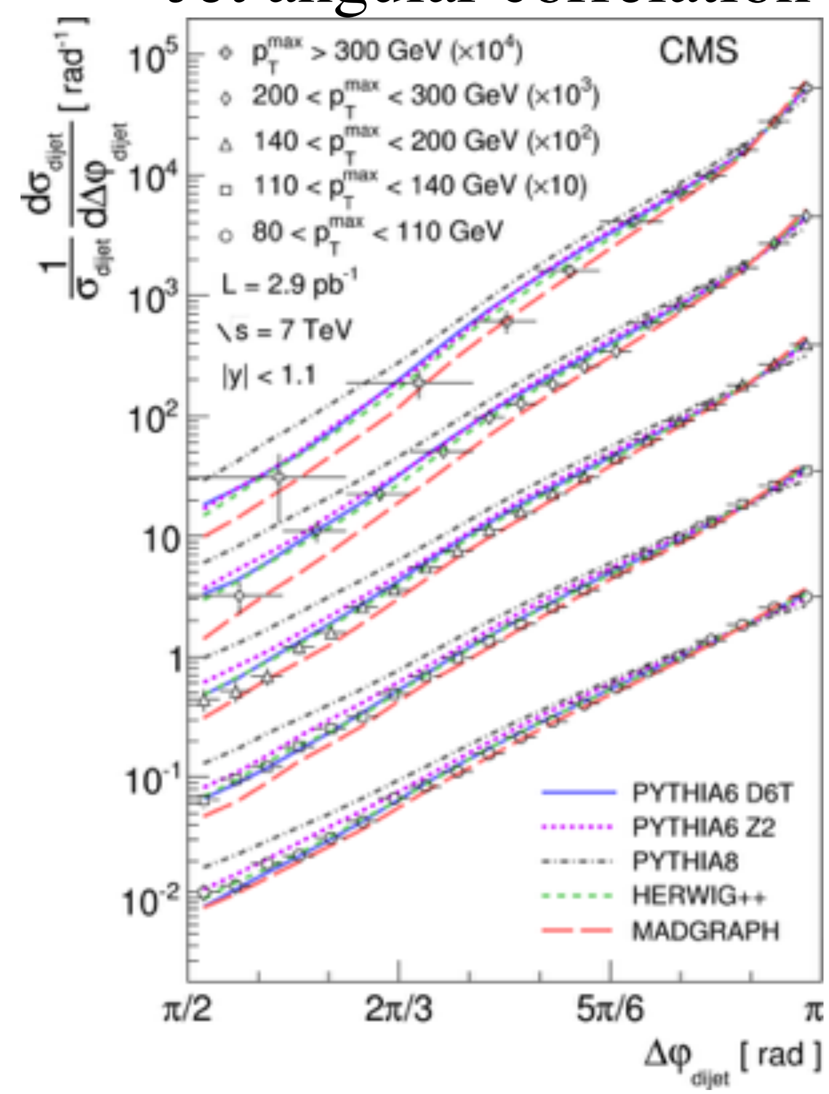
Jet p_T spectrum



inclusive jet differential cross sections

Phys.Rev.Lett. 107 (2011) 132001

Jet angular correlation

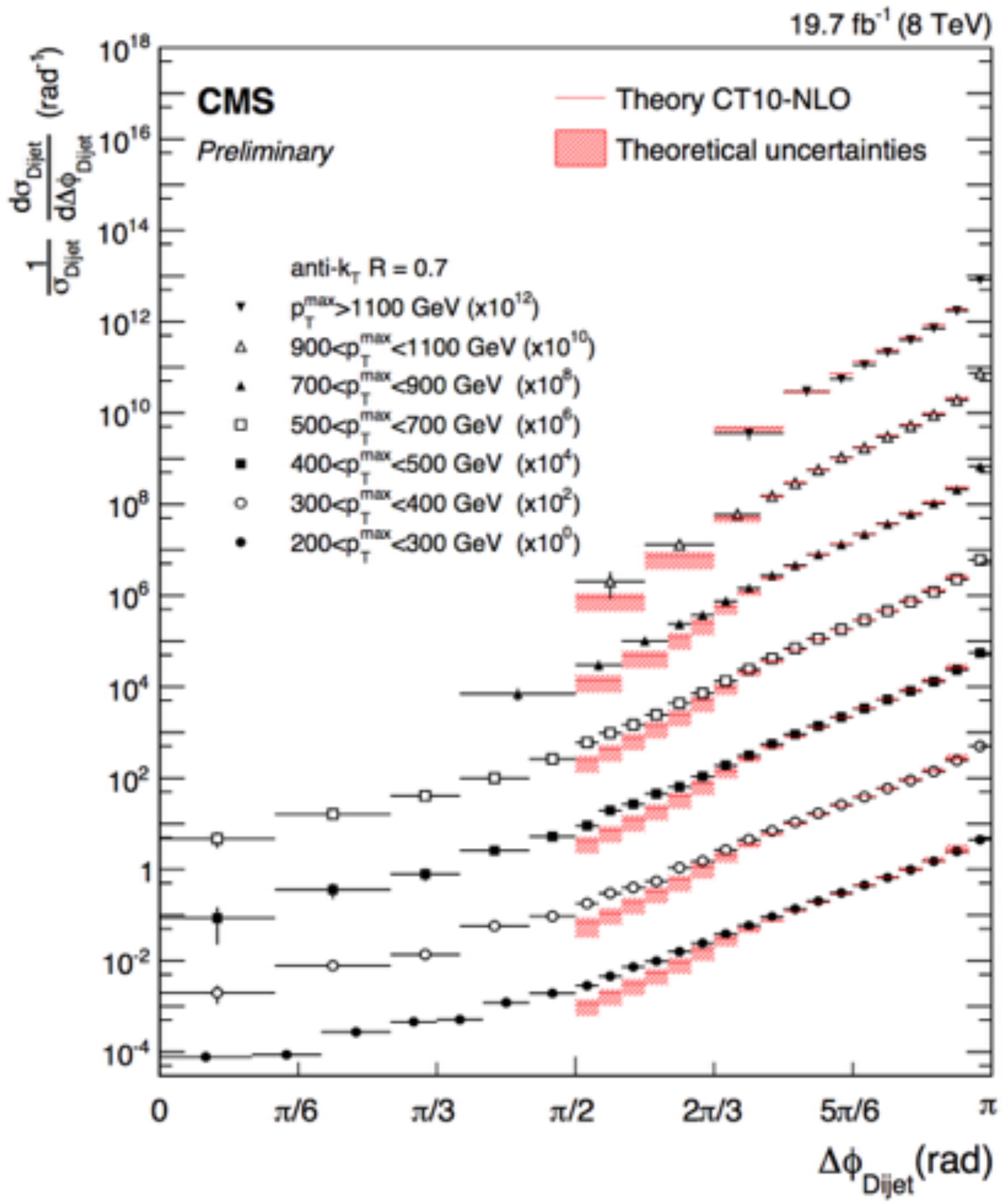


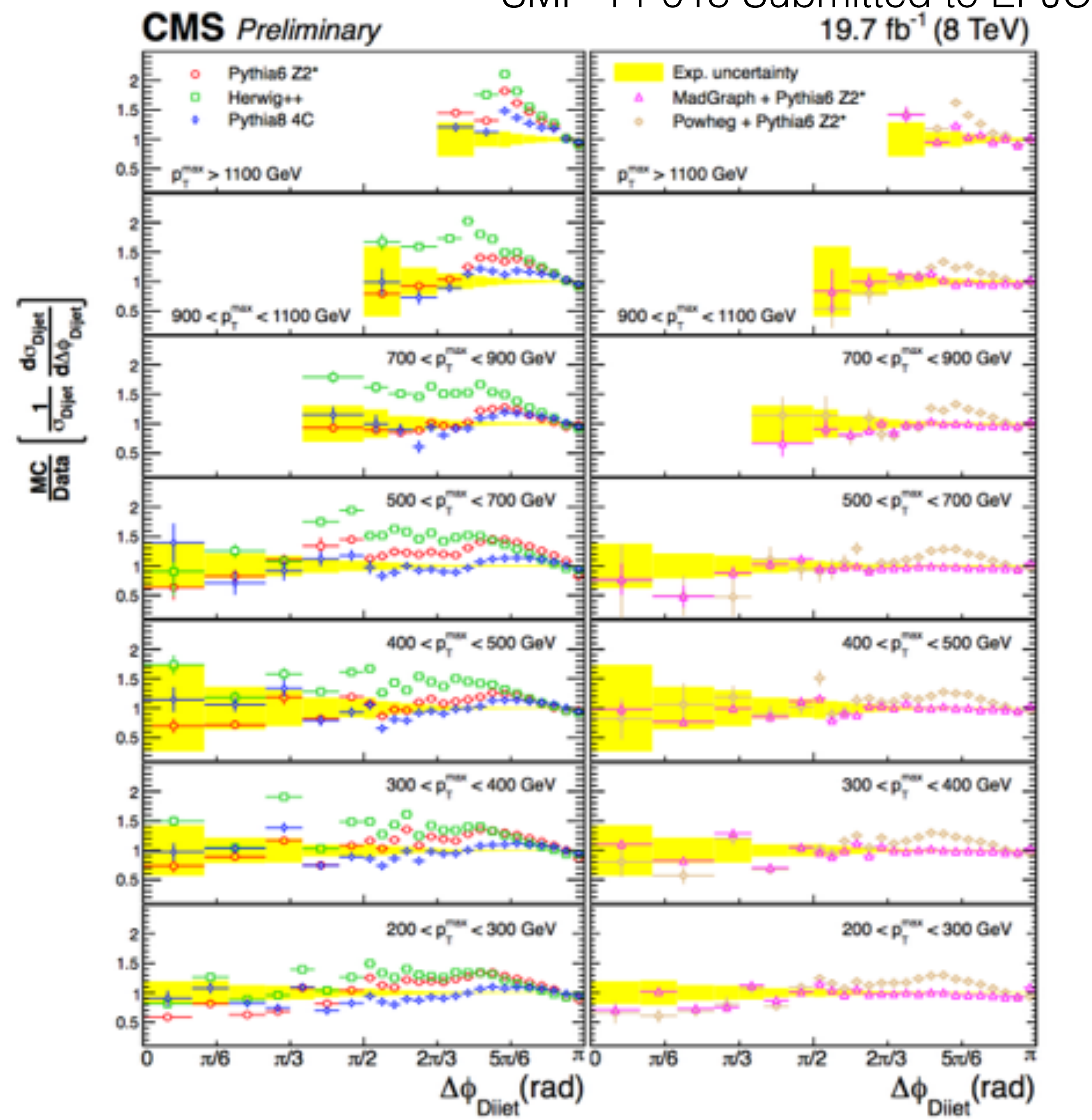
Normalised $\Delta\phi_{dijet}$ distributions

Phys.Rev.Lett. 106 (2011) 122003

Dijets in 8 TeV

SMP-14-015 Submitted to EPJC



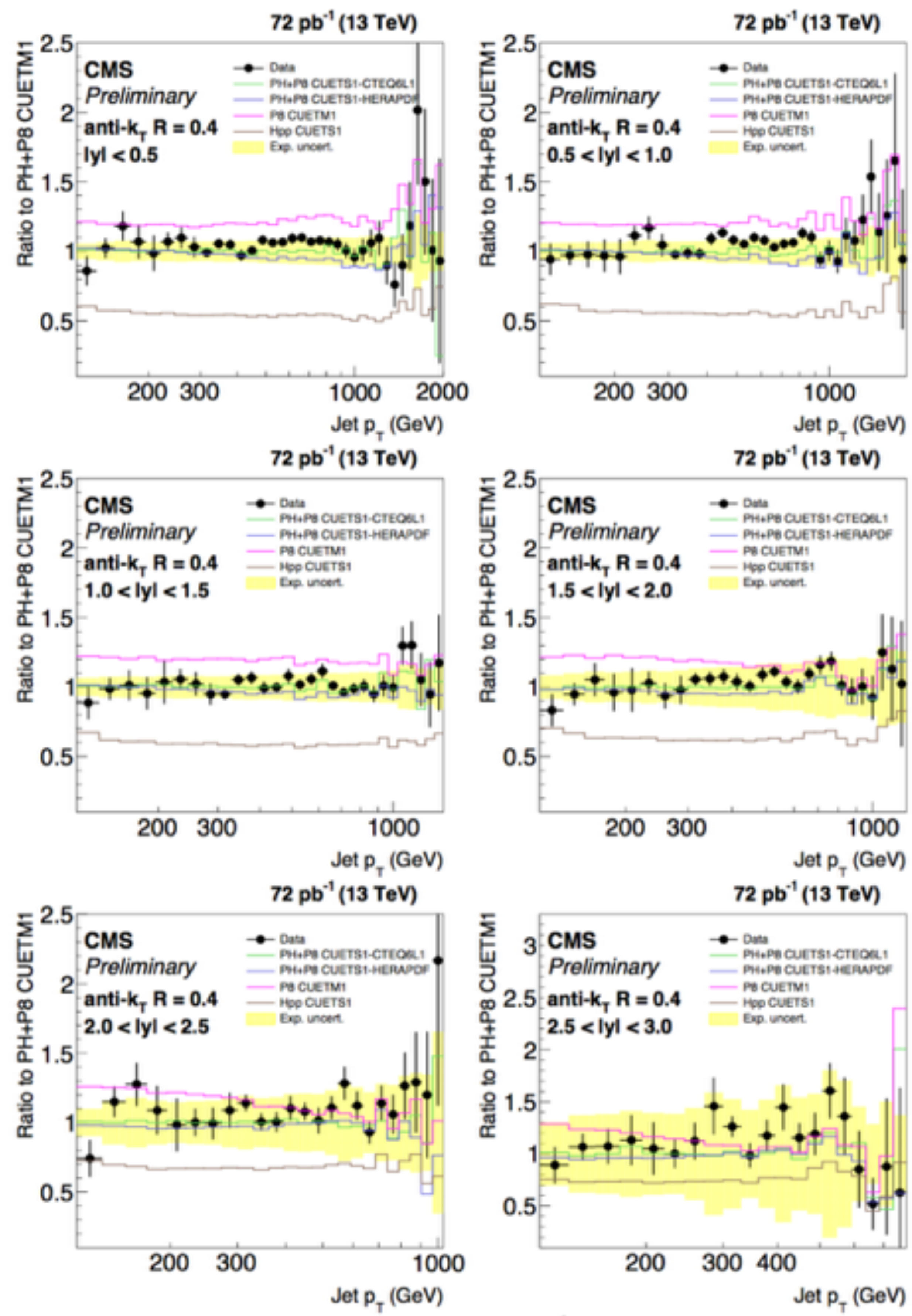


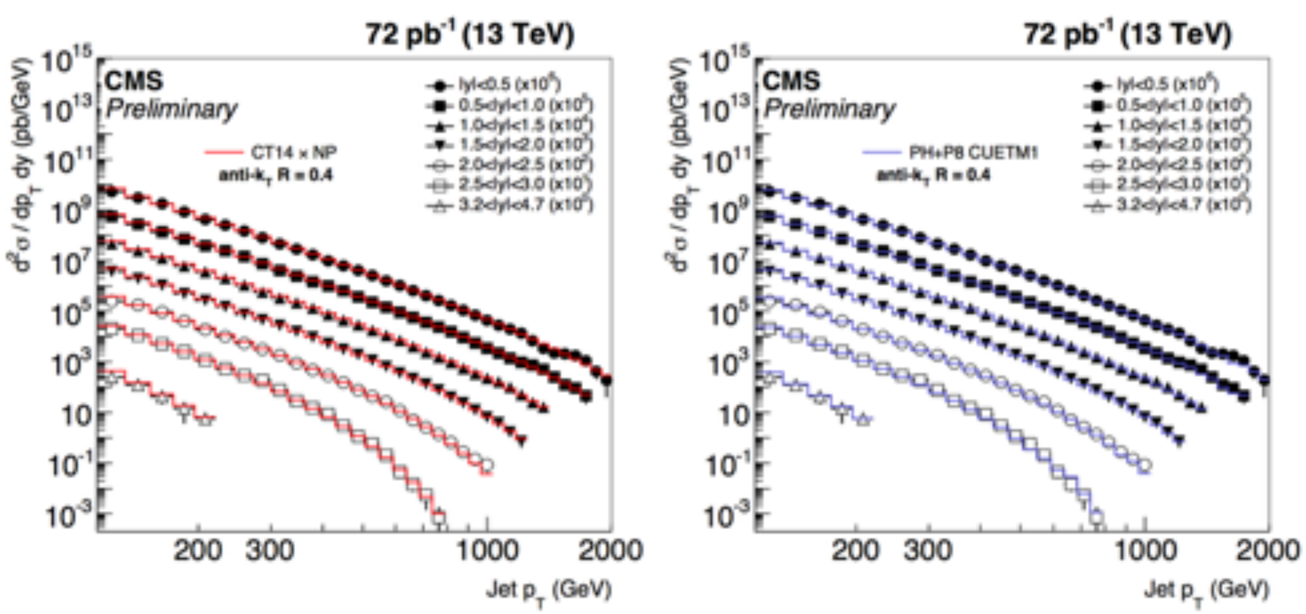
- ➡ dijet azimuthal decorrelation is sensitive to the radiation of additional jets and probes the dynamics of multijet production
- ➡ $\Delta\phi_{Dijet} > 2\pi/3$, well modelled by theory
- ➡ $\Delta\phi_{Dijet} \approx \pi/2$, due to additional jets, fixed-order calculation is LO only, see large discrepancies

Dijet double differential

function of jet p_T for different y bins

- ➡ POWHEG (NLO+PS) describes the data very well, even better than NLO parton level, especially for small jet radii
- ➡ LO MC generators PYTHIA8 and HERWIG++ exhibit significant discrepancies



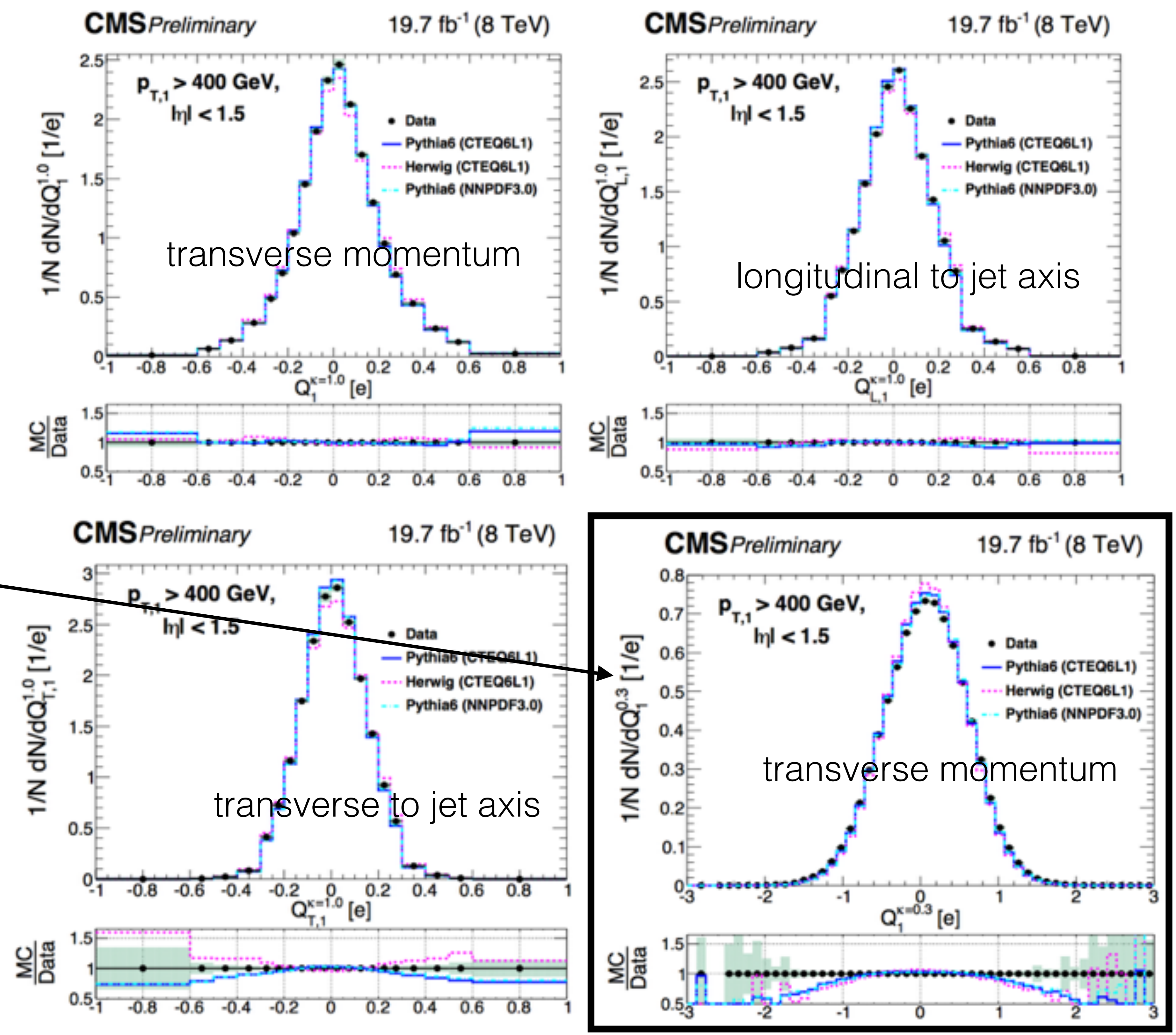


Eur. Phys. J. C 76 (2016) 451

Jet Charge

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

- Jet charge is measured in 3 directions
  - ➡ transverse momentum
  - ➡ longitudinal to jet axis
  - ➡ transverse to jet axis
- κ small, more weight to low momentum tracks
- transverse jet charge has biggest difference.



SMP-15-003

CMS 7 TeV results

Analysis with 7 TeV, 2010 data, integrated luminosity of 36 pb^{-1}

Events with least three jets, where the two jets with the largest transverse momentum exhibit a back-to-back topology

Selection criteria

- ➡ leading jet p_{T1} > 100 GeV, all other jets > 30 GeV
- ➡ pseudo rapidity of leading 2 jets, $|\eta_1|$, $|\eta_2| \leq 2.5$
- ➡ invariant mass of leading 2 jets, M_{12} > 220 GeV
- ➡ angular displacement of second and third jet, $0.5 < \Delta R_{23} < 1.5$

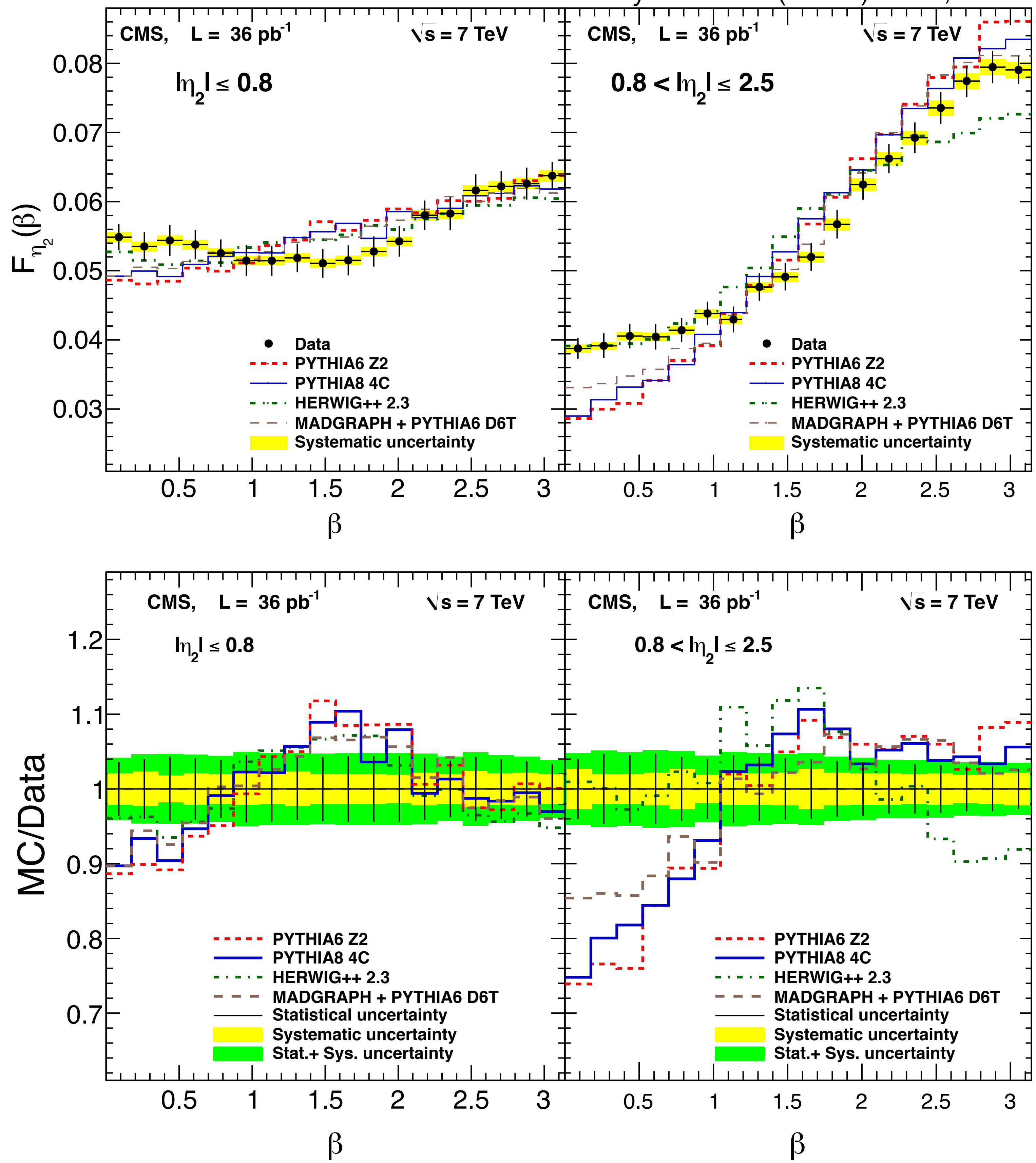
Different Monte Carlo generators were used to compare with data

- ➡ PYTHIA 6 Tune Z2
  - ➡ ME: 2 → 2 LO, Parton Shower: pT ordered.
  - ➡ Colour Coherence for first branching in ISR and FSR using Angular Ordering (LUND string model)
- ➡ PYTHIA 8 Tune 4C
  - ➡ ME: 2 → 2 LO
- ➡ HERWIG++ Tune 23
  - ➡ ME: 2 → 2 LO, Parton Shower: angular ordered showers
  - ➡ Colour Coherence through Angular Ordering – coherent branching algorithm.
- ➡ MADGRAPH
  - ➡ ME: 2 → 2 and 2 → 3 LO
  - ➡ Matched to PYTHIA 6 for PS.

CMS 7 TeV results

- Similar to the Tevatron experiments
- Pythia, Herwig and Madgraph have poor description in forward region

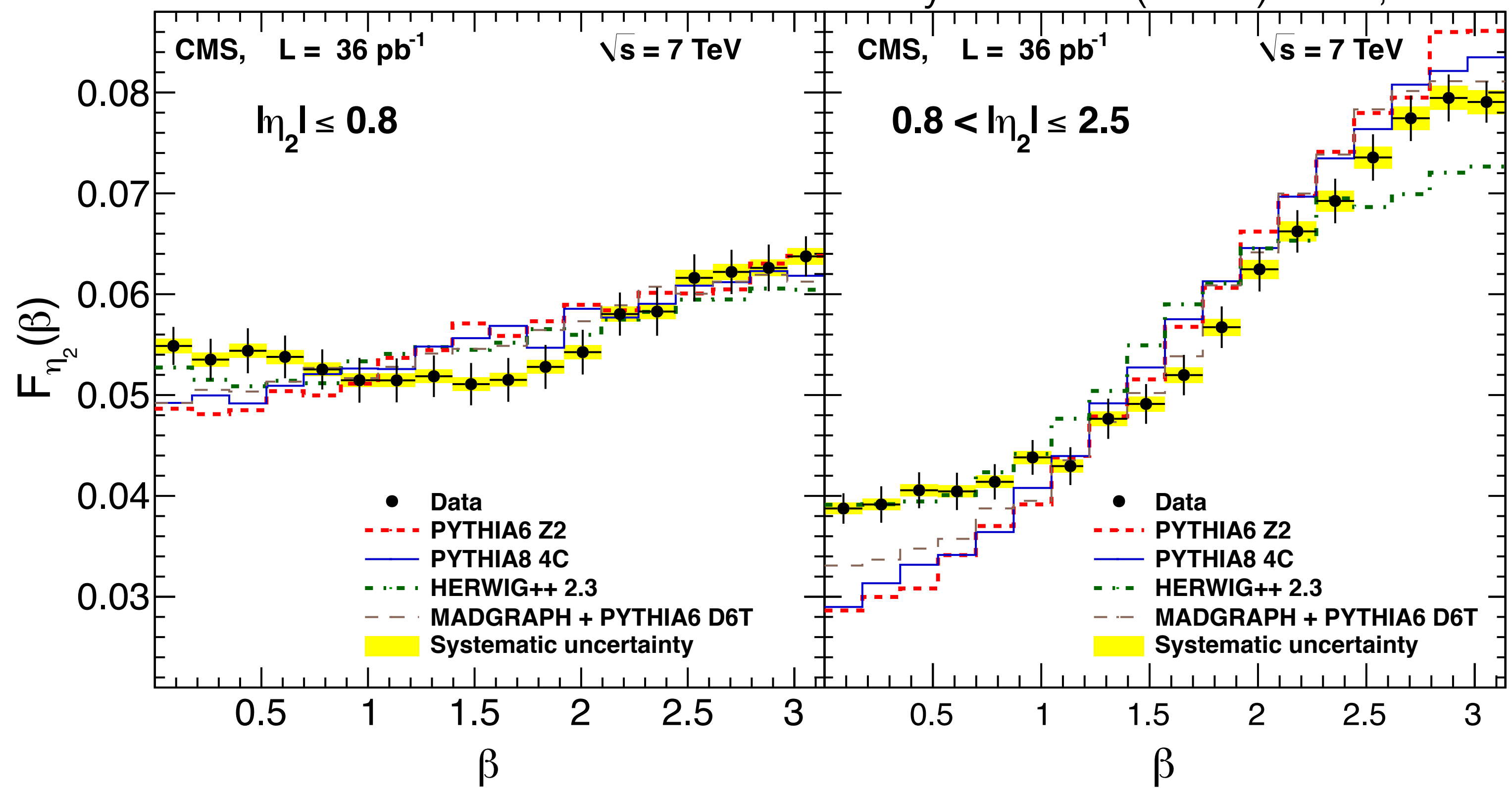
Eur.Phys.J. C74 (2014) no.6, 2901

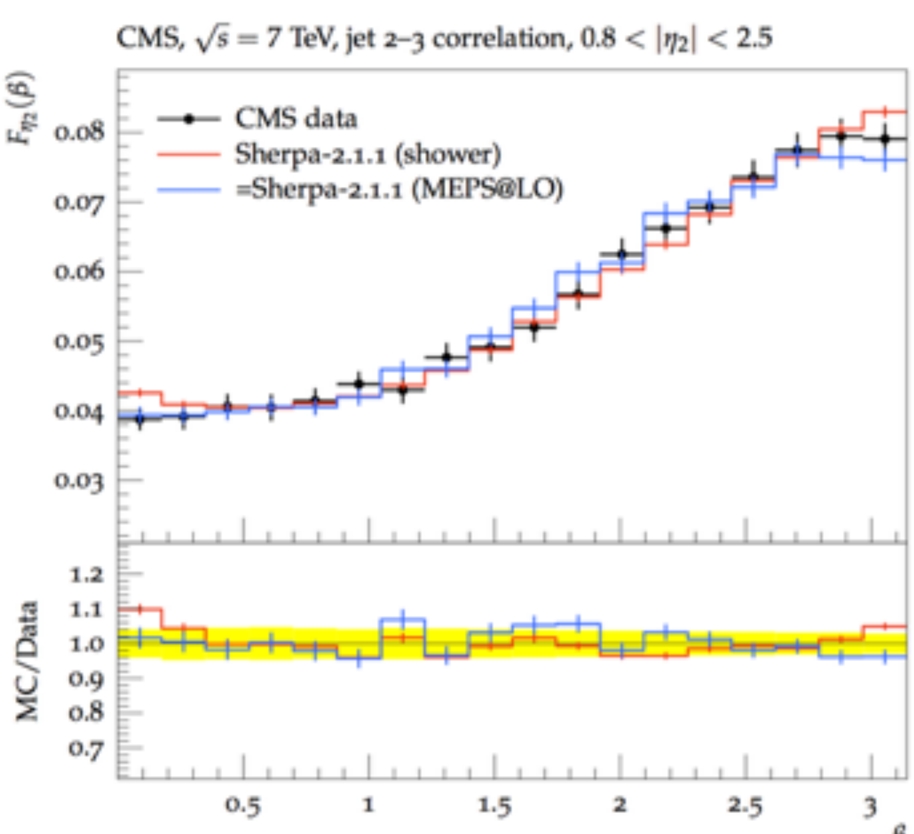


CMS 7 TeV results

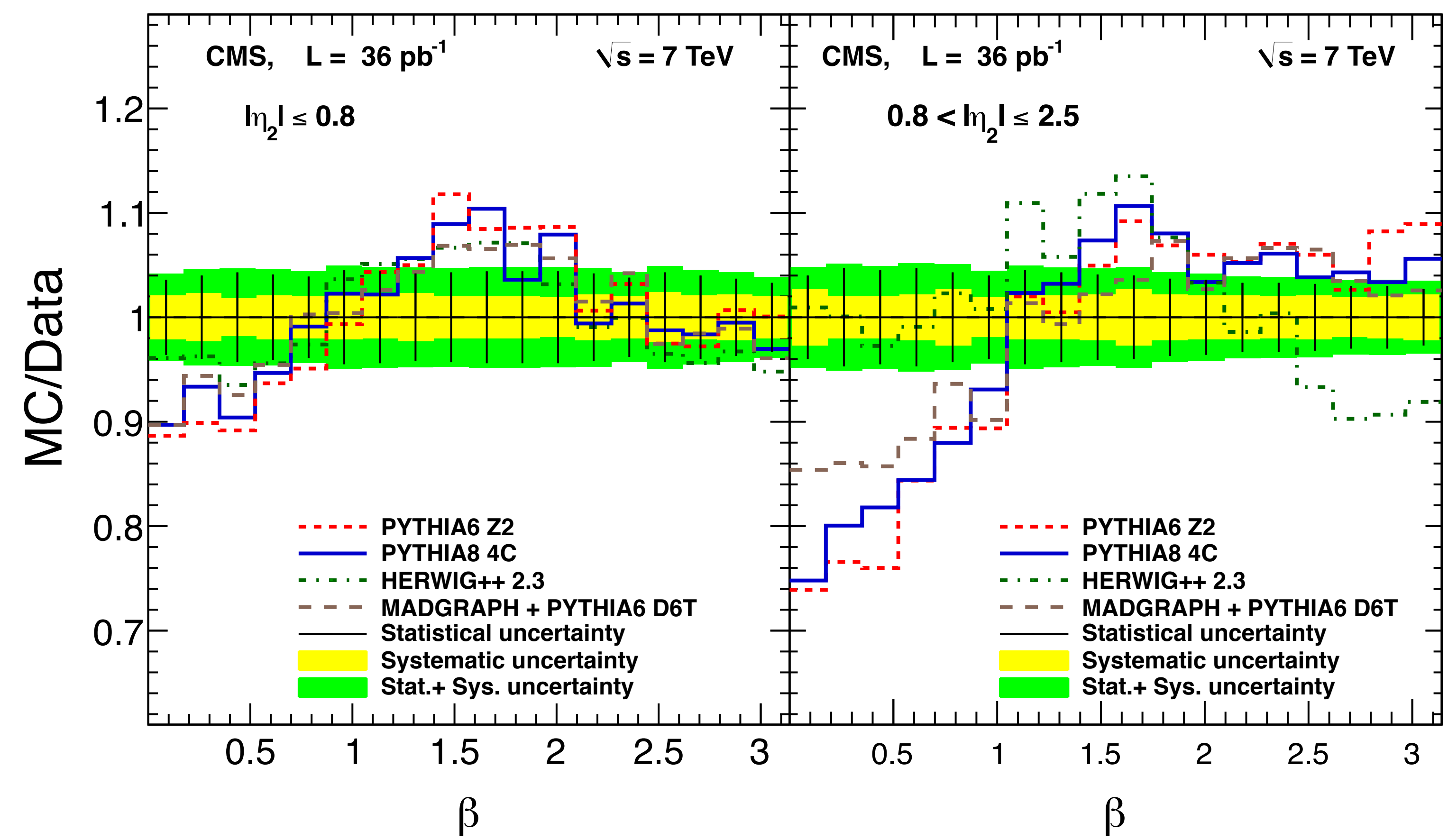
- Similar to the Tevatron experiments
- Sherpa description quite good

Eur.Phys.J. C74 (2014) no.6, 2901





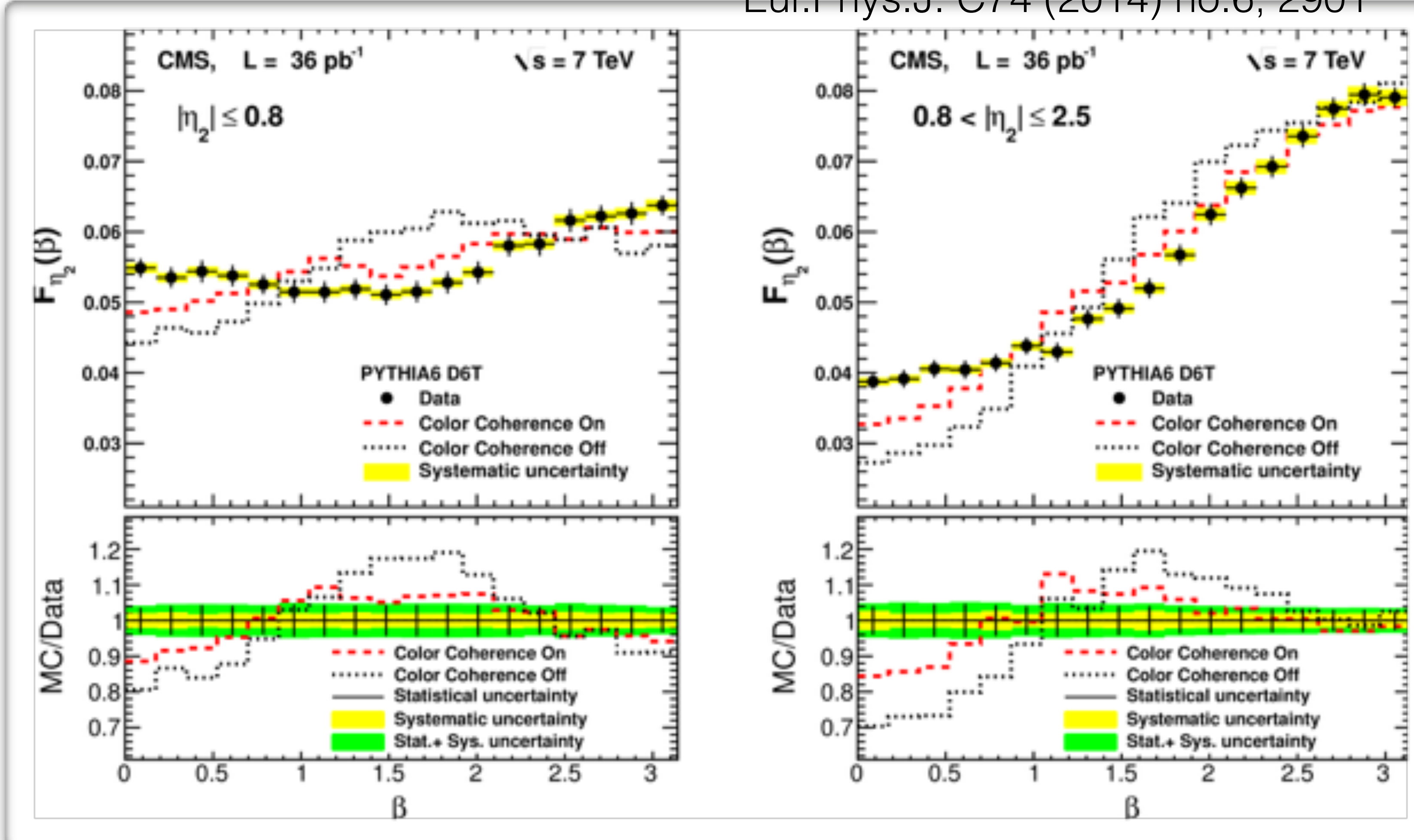
arXiv:1608.06425v1

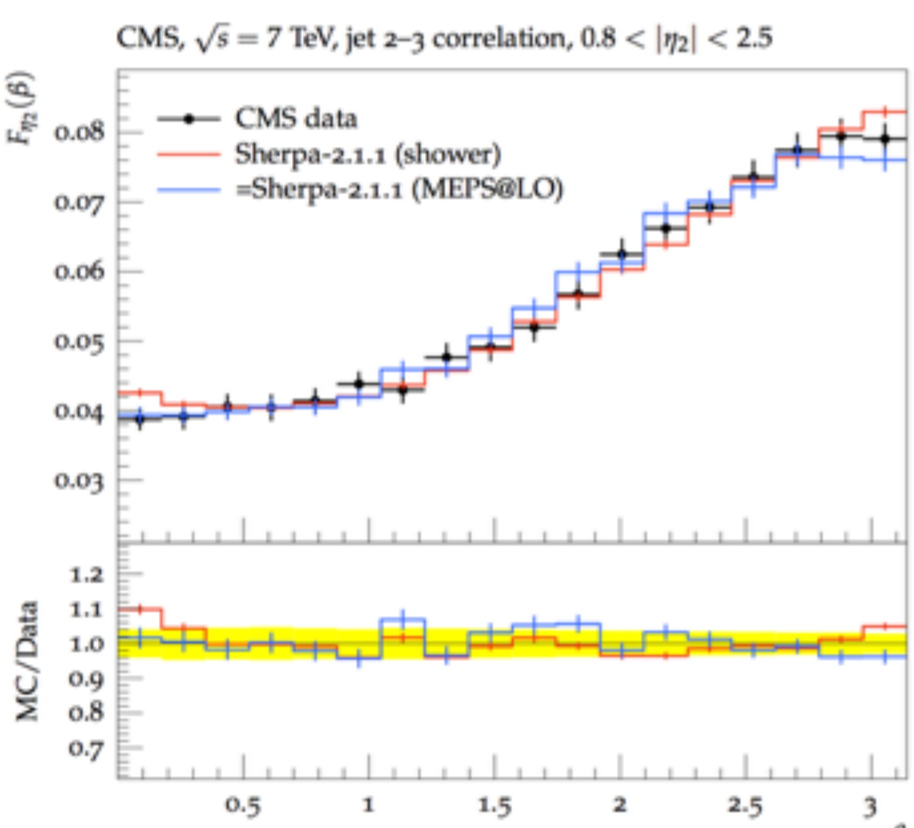


CMS 7 TeV results

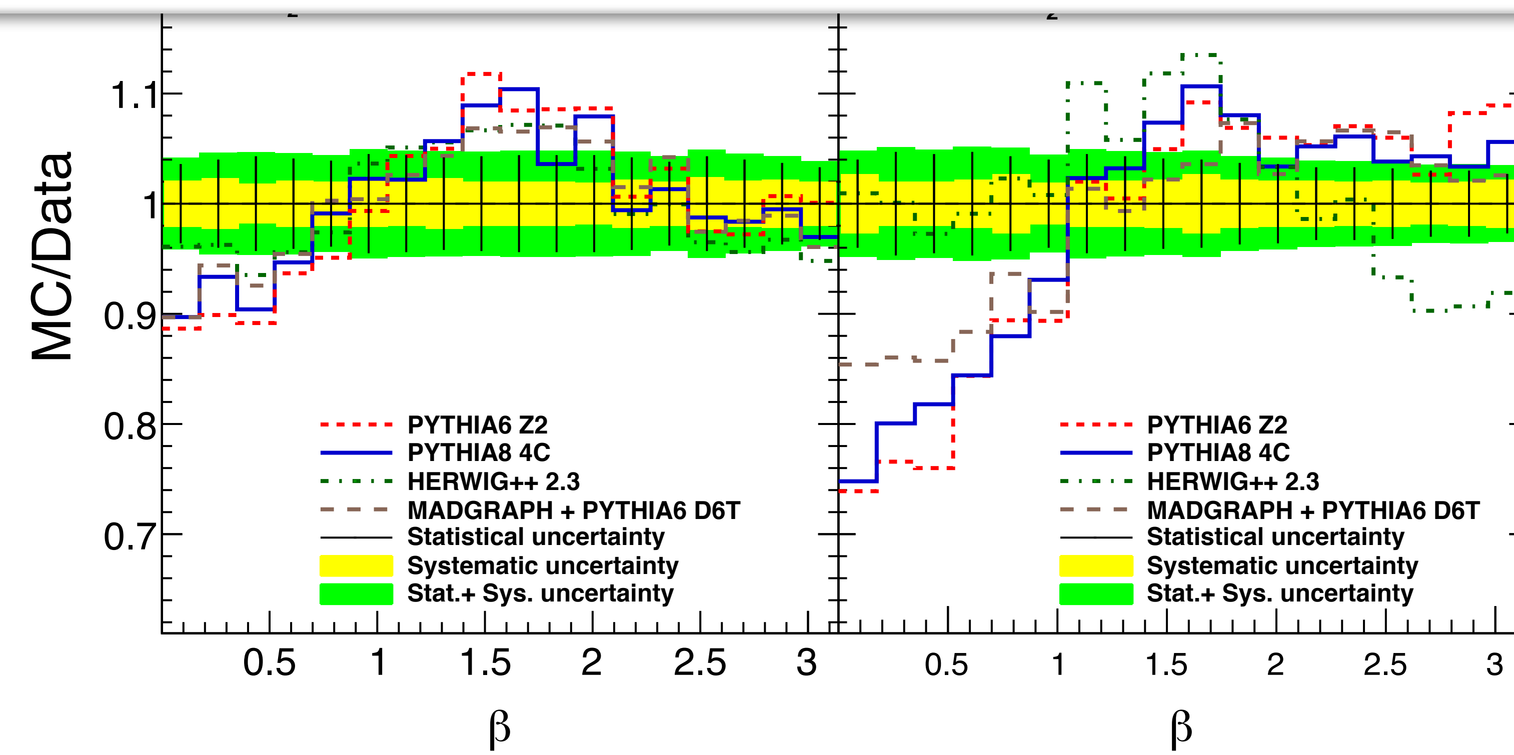
- Similar to the Tevatron experiments
- Sherpa description quite good
- Turning on colour coherence effects with Pythia shows better agreement with data

Eur.Phys.J. C74 (2014) no.6, 2901





arXiv:1608.06425v1



Parton Shower vs Matrix Element

Identifying Parton Shower (PS) dominant and Matrix Element (ME) dominant regions

Jet$_1$ p_T cut : 510 GeV < jet$_1$ p_T

MC generators

- ➡ PYTHIA8 (PS only)
- ➡ POWHEG + PYTHIA8 without PS (ME only)
- ➡ POWHEG + PYTHIA8 with PS (ME + PS)
- ➡ MADGRAPH + PYTHIA8 (ME + PS)

ΔR_{23} ($p_{T3}/p_{T2} < 0.9$)

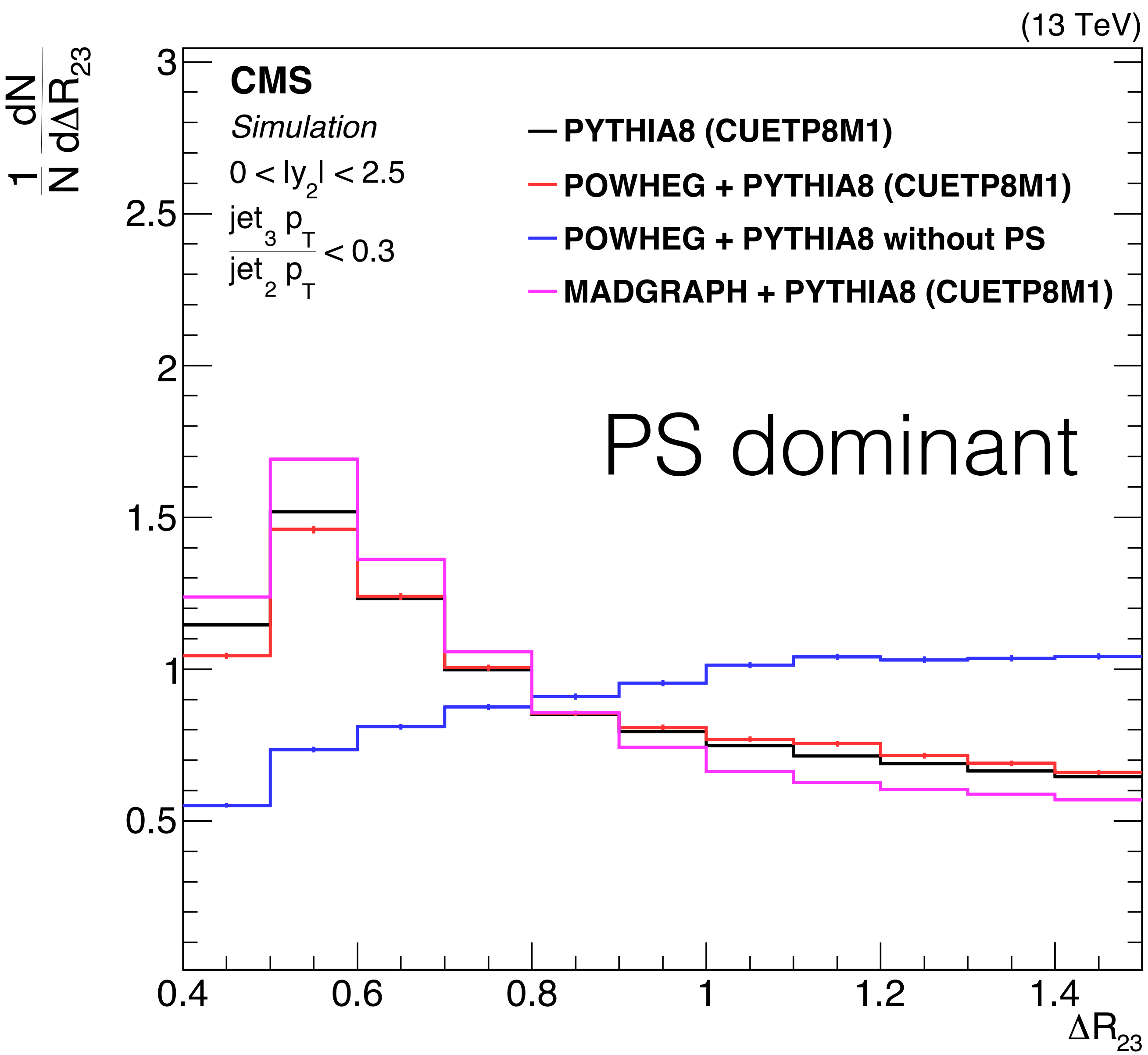
- ➡ $0.4 < \Delta R_{23} < 1.0$ (PS dominant)
- ➡ $1.0 < \Delta R_{23} < 1.5$ (ME dominant)

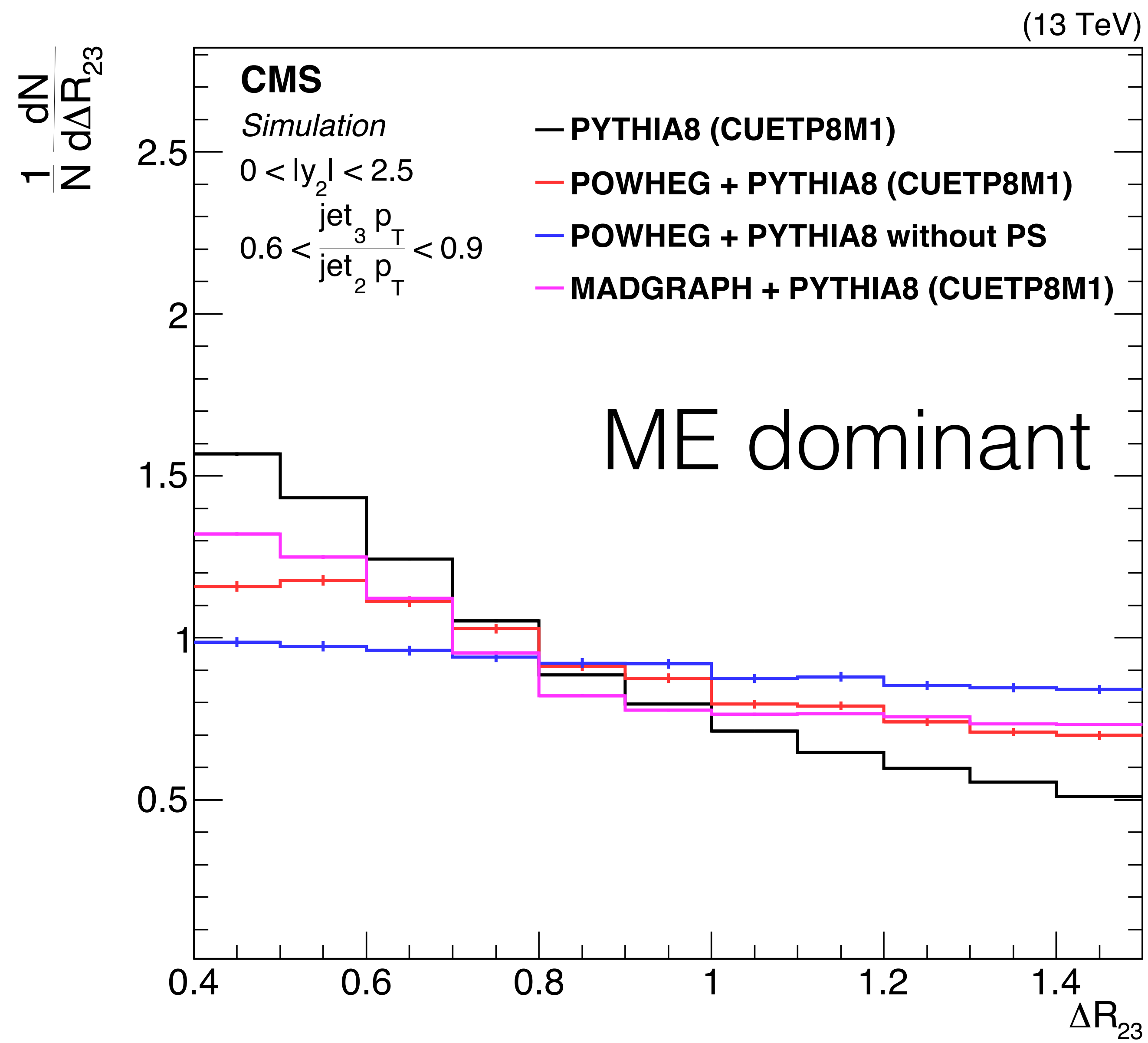
p_{T3}/p_{T2} ($0.4 < \Delta R_{23} < 1.5$)

- ➡ $p_{T3}/p_{T2} < 0.3$ (PS dominant)
- ➡ $0.6 < p_{T3}/p_{T2} < 0.9$ (ME dominant)

Delta R

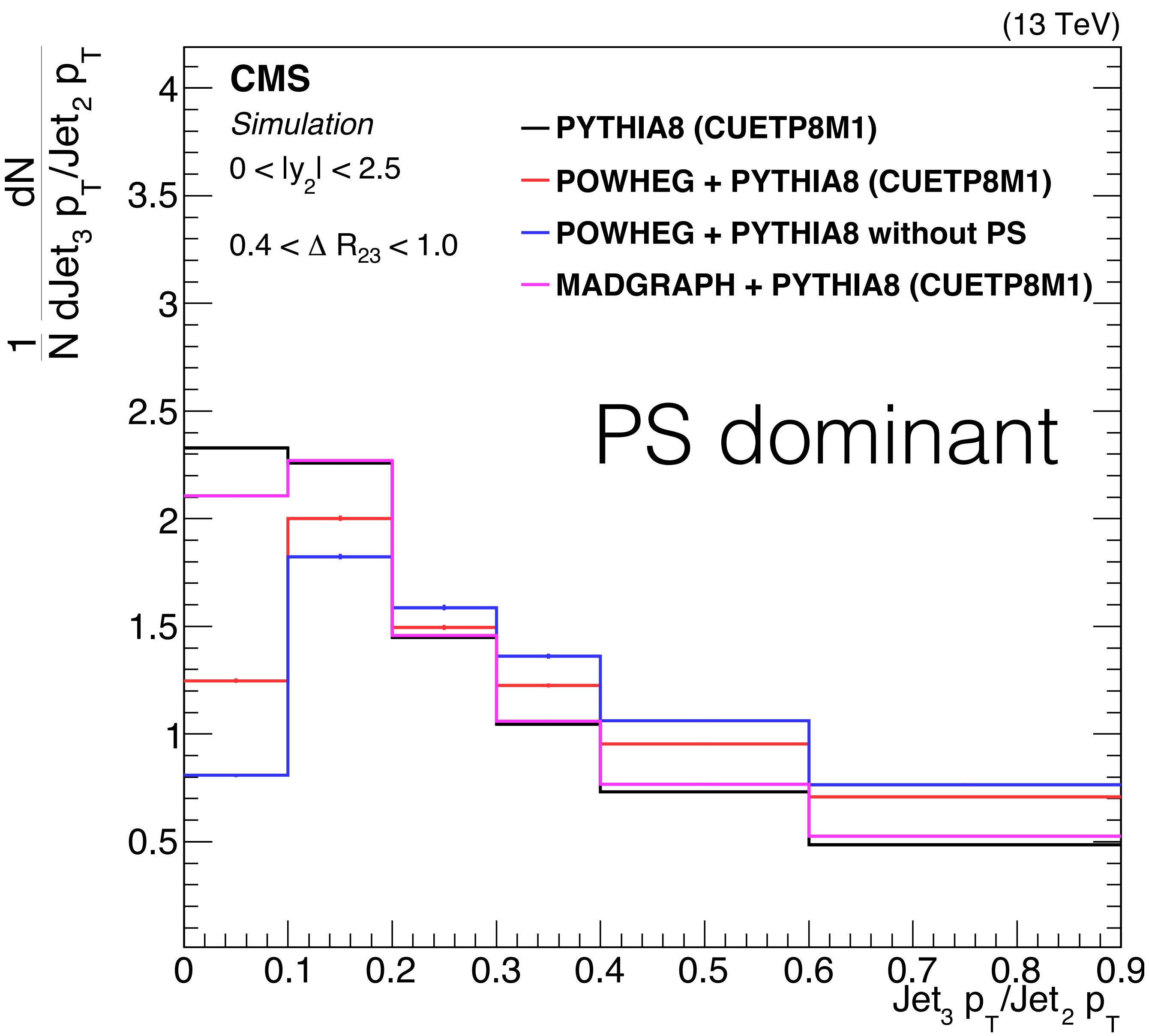
- ➡ soft jet 3 - PS dominant - PYTHIA8 agrees well with Powheg and MadGraph
- ➡ hard jet 3 - ME dominant - Powheg and MadGraph is closer to Powheg without PS

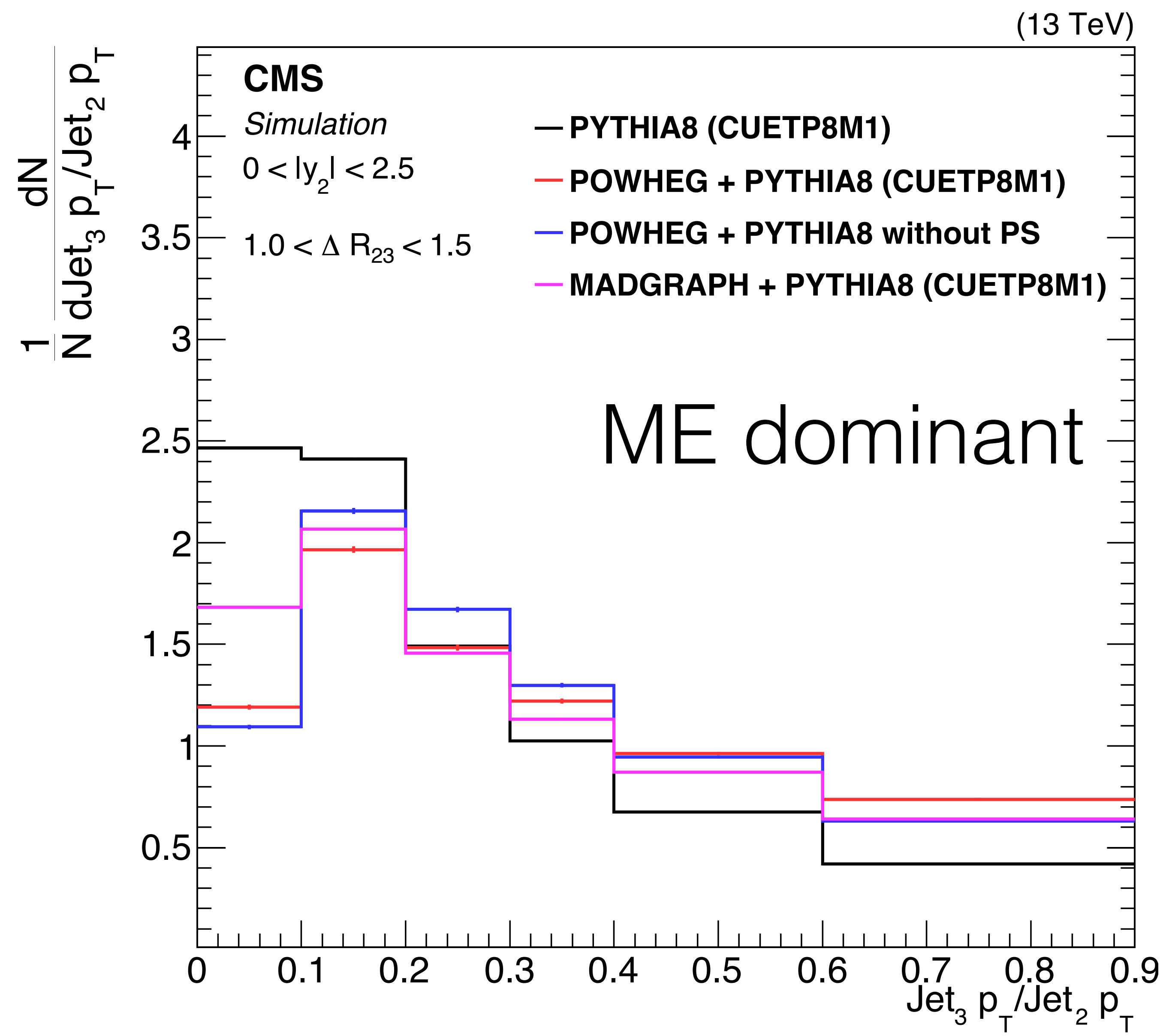




p_T ratio

- small angular displacement of jet 3 - PS dominant - PYTHIA8 agrees well MadGraph
- large angular displacement of jet 3 - ME dominant - Powheg and MadGraph is closer to Powheg without PS



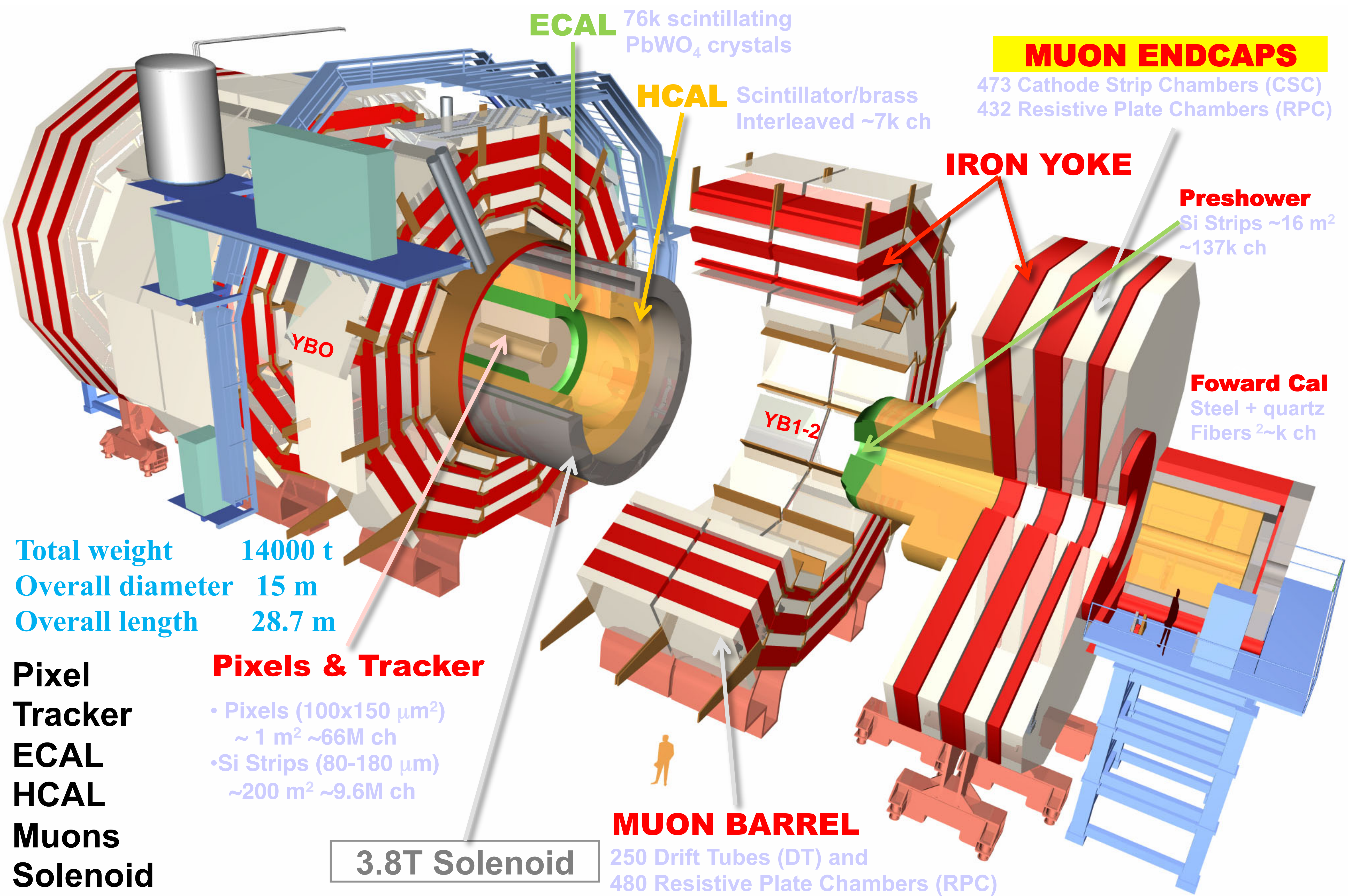


Summary

- ➡ The sensitive colour coherence region was studied
  - ➡ Currently, only a very old version of PYTHIA can turn off colour coherence effects
- ➡ In newer mc generators, cannot disentangle the colour coherence effects
- ➡ Looked into PS and ME dominant regions
  - ➡ easier to understand where the generators are poor
- ➡ New studies with CMS data are on-going, soon to conclude and get published

Backups

the CMS detector



Colour Coherence Tune

PYTHIA6 with D6T tune has some control over colour coherence

Colour coherence effect on/off

- ➡ MSTP(67) : Initial-state radiation (ISR)
- ➡ MSTJ(50) : Final-state radiation (FSR)

Card for cc on/off

- ➡ — Default: MSTJ(50) on, MSTP(67) on
- ➡ — ISR Off : MSTJ(50) on, MSTP(67) off (FSR only)
- ➡ — FSR Off : MSTJ(50) off, MSTP(67) on (ISR only)
- ➡ — CC Off : MSTJ(50) off, MSTP(67) off

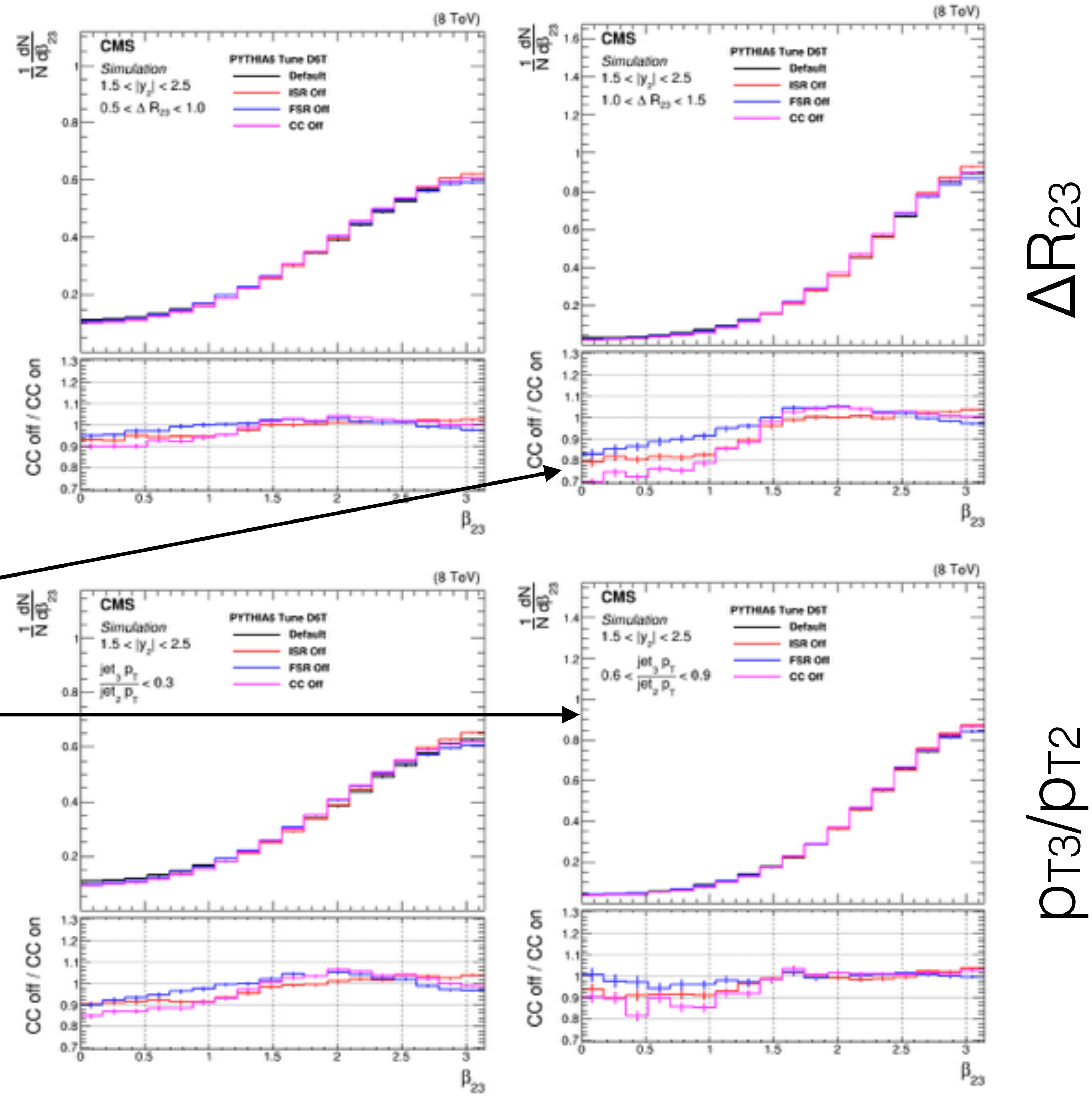
MSTP(67) : possibility to introduce colour coherence effects in the first branching of the backwards evolution of an initial-state shower in PYSSPA mainly of relevance for QCD parton-parton scattering processes.

MSTJ(50) : possibility to introduce colour coherence effects in the first branching of a PYSHOW final-state shower. Only relevant when colour flows through from the initial to the final state, i.e. mainly for QCD parton-parton scattering processes.

Colour Coherence MC study

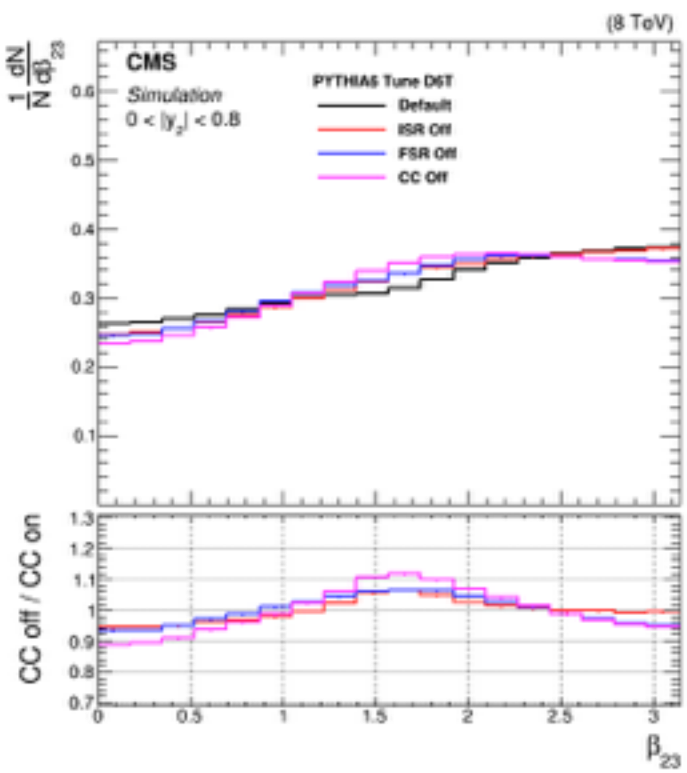
The sensitive colour coherence region was studied

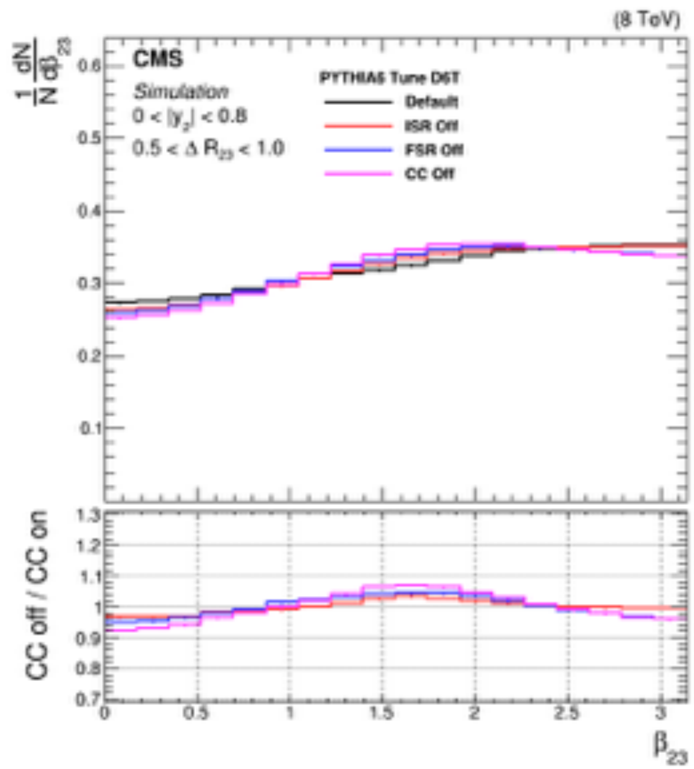
- Jet1 p_T > 510 GeV
- High y bin, 1.5 < $|jet_2\ y|$ < 2.5
- looking at pT3/pT2 and ΔR_{23}
- The 1.0 < ΔR_{23} < 1.5 region is sensitive on cc on/off
- At the 0.6 < p_{T3}/p_{T2} < 0.9 region, only ISR was effective on cc
- At the high y bin, near beta 0 was enhanced by cc effect

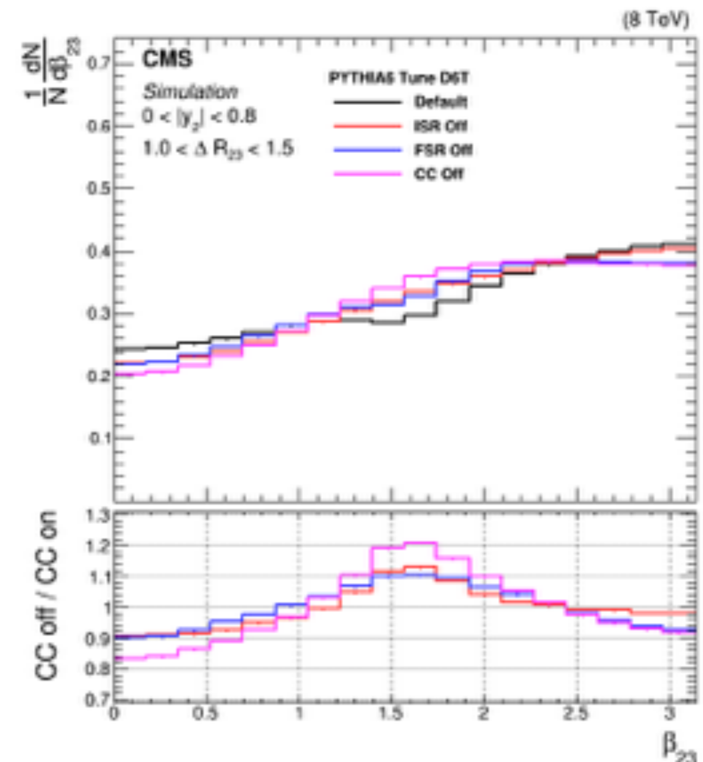


Low y bin

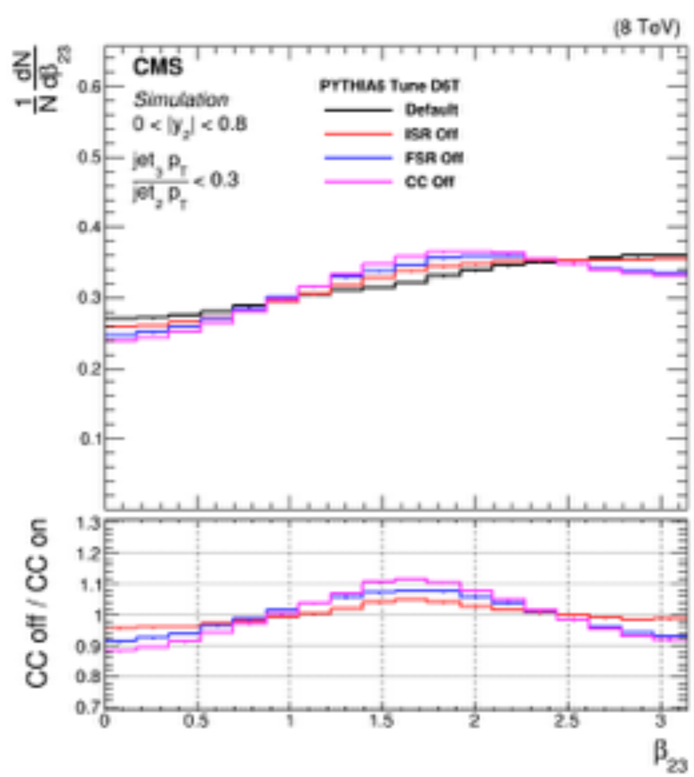
combined

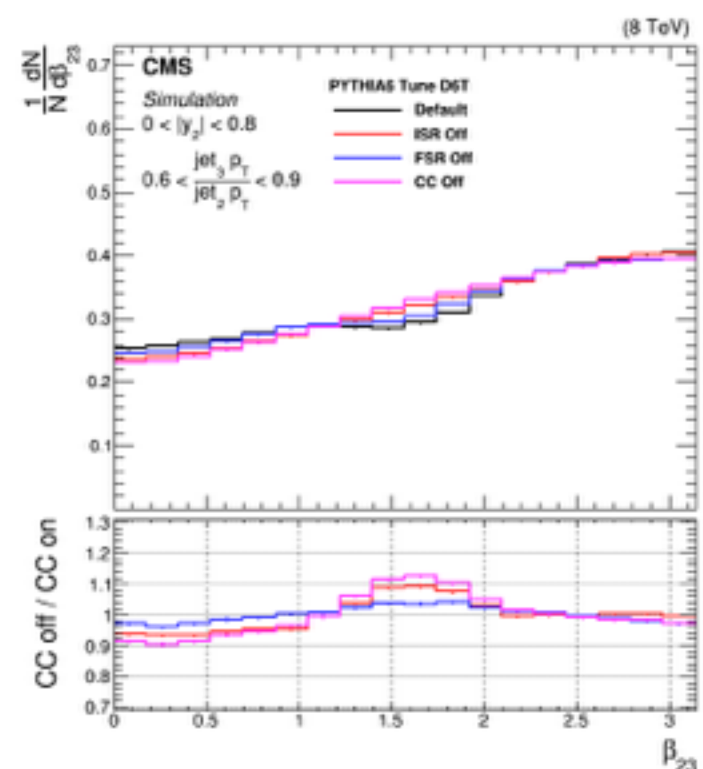






ΔR_{23}

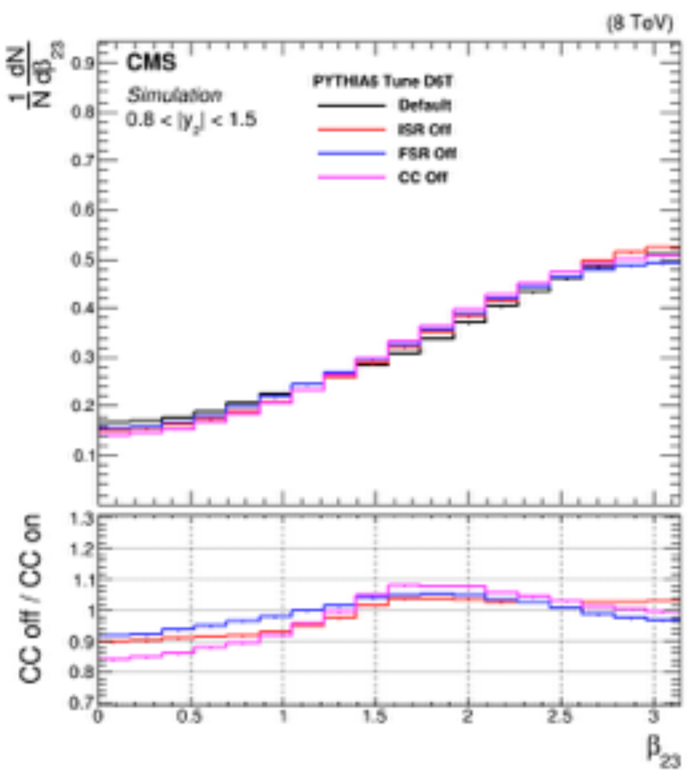


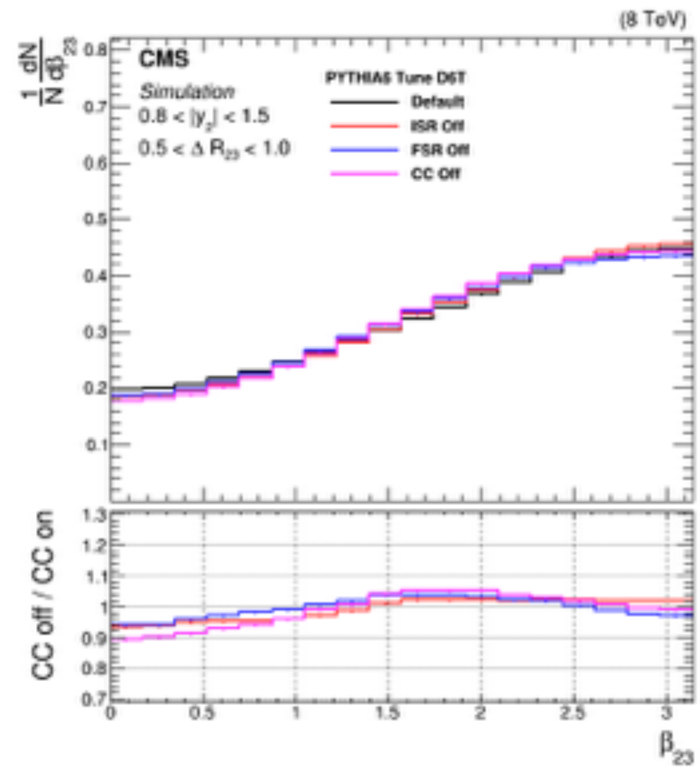


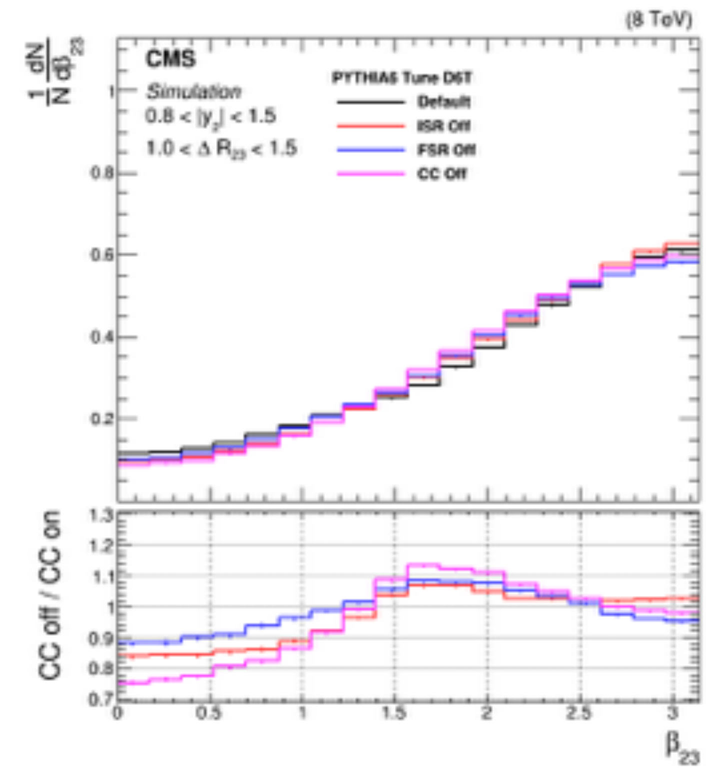
p_{T3}/p_{T2}

Medium y bin

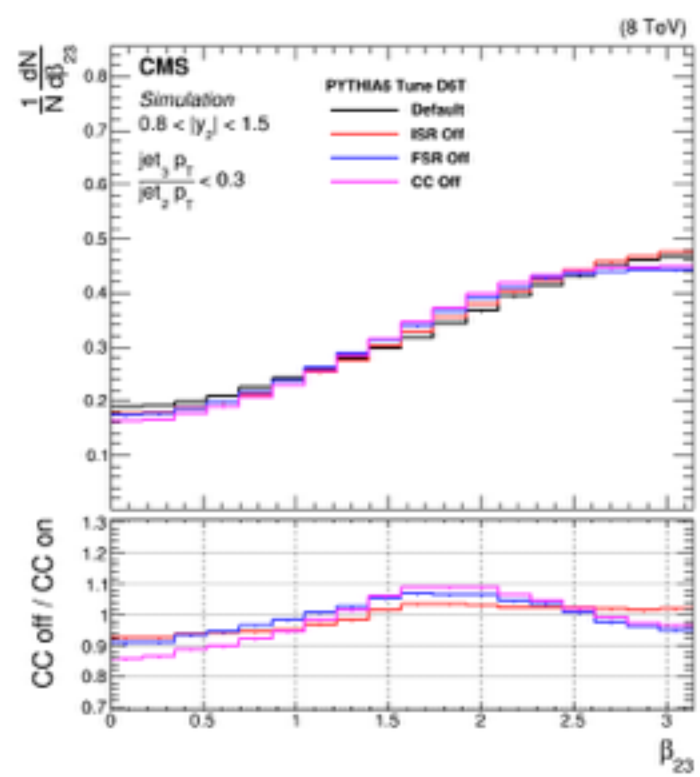
combined

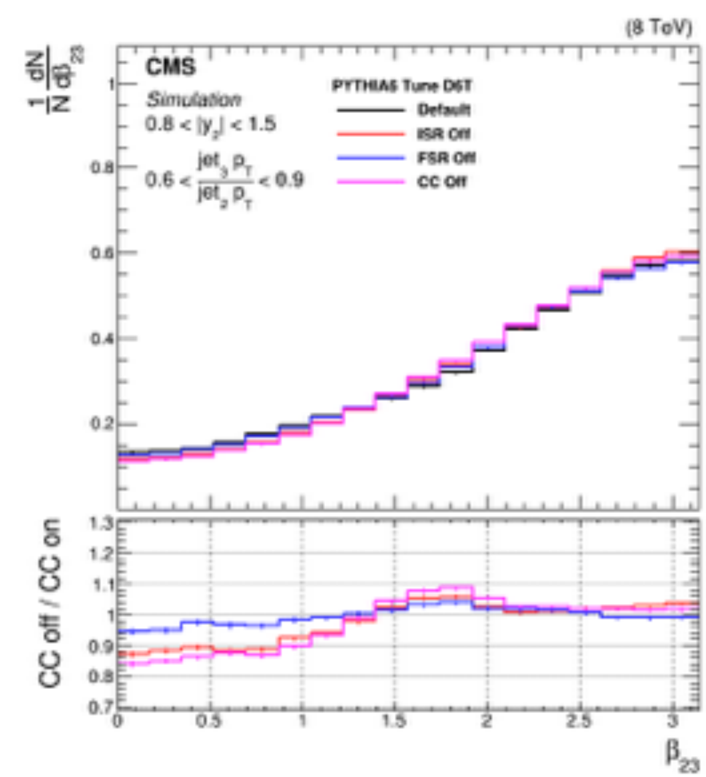






ΔR_{23}





p_{T3}/p_{T2}