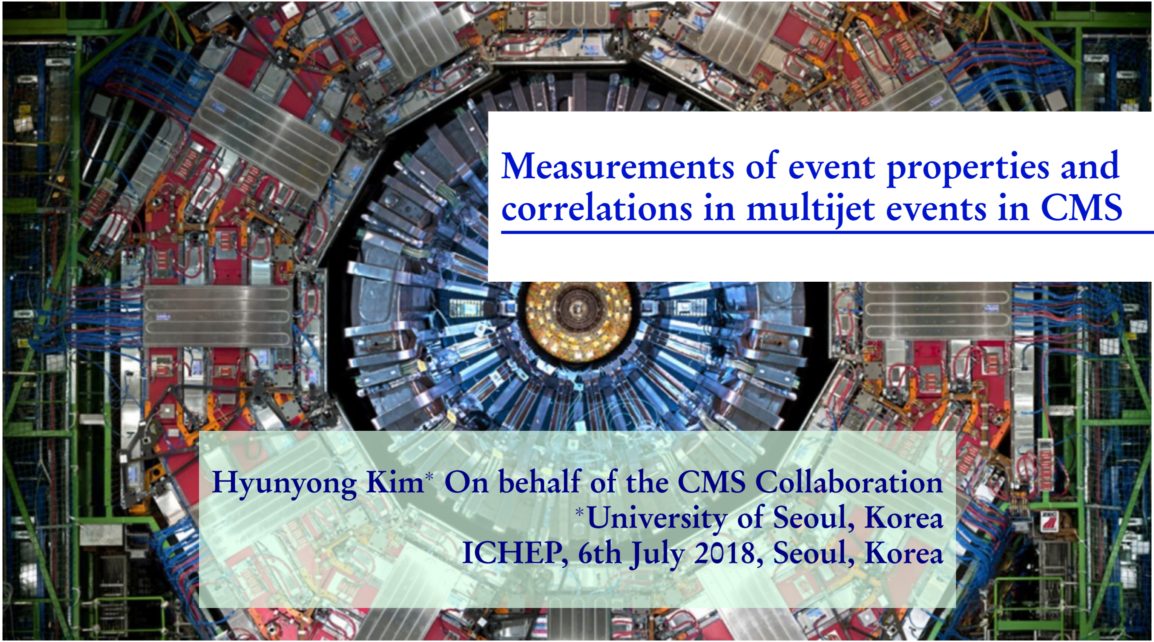


Measurements of event properties and correlations in multijet events in CMS

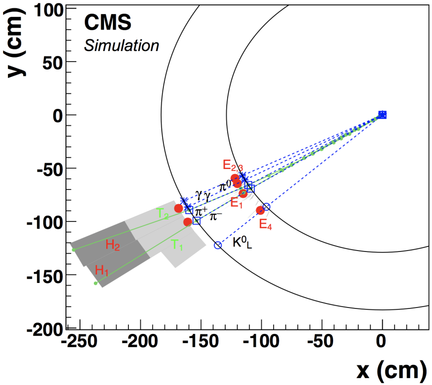
Hyunyong Kim* On behalf of the CMS Collaboration

*University of Seoul, Korea

ICHEP, 6th July 2018, Seoul, Korea

Introduction

- Jet
  - Particles in collimation
  - Dominant feature in high p_{T} hadron collision
- Jet production
  - QCD hard scattering processes
  - High p_{T} parton
  - Fragmentation and hadronization
- Particle flow (PF) jet in CMS
  - Optimal combination of all sub-detector
  - Identify individual particles
  - Big improvement in jet energy resolution
  - Reduce jet scale uncertainty

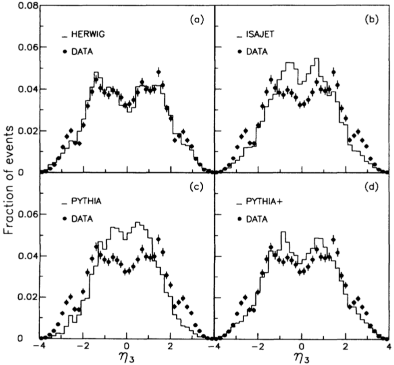


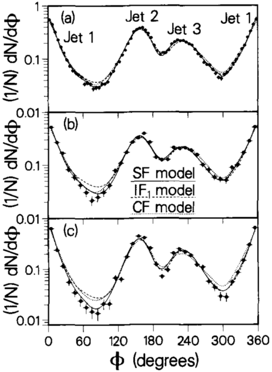
Probing color coherence effects in *pp* collisions at $\sqrt{s} = 7$ TeV

Eur. Phys. J. C (2014) 74:2901
DOI 10.1140/epjc/s10052-014-2901-8

Color Coherence

- Color coherence phenomena: interference of soft gluon radiation emitted along the color connected object
- Color coherence explanation has been improved with **angular ordering (AO)** and **Lund model (String model)**

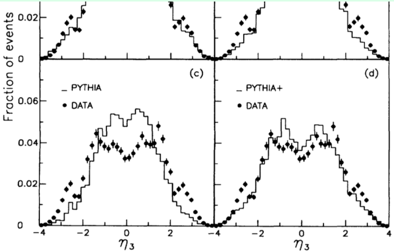


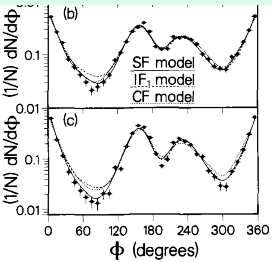


Color Coherence

- Color coherence phenomena: interference of soft gluon radiation emitted along the color

- Feynman diagrams at hadron collision
- Di-jet topology (back to back event)
- The 3rd jet is from final state radiation (FSR) of the 2nd jet
- The 2nd jet and 3rd jet have correlations
- Color coherence affects the 3rd jet





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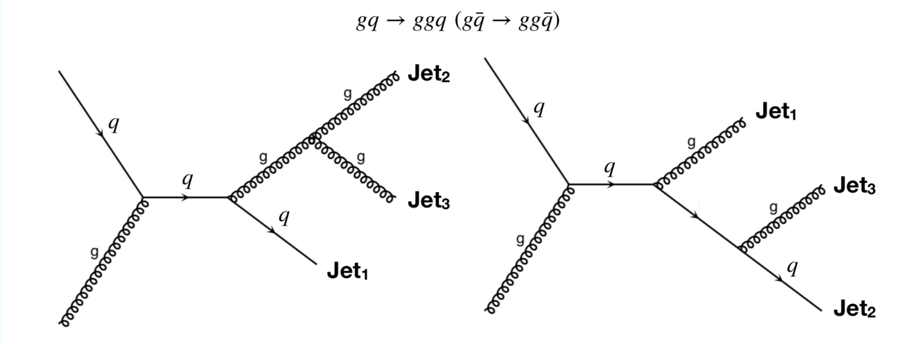

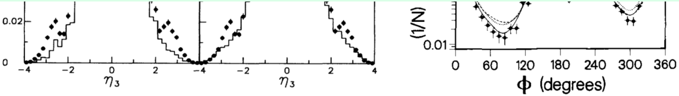

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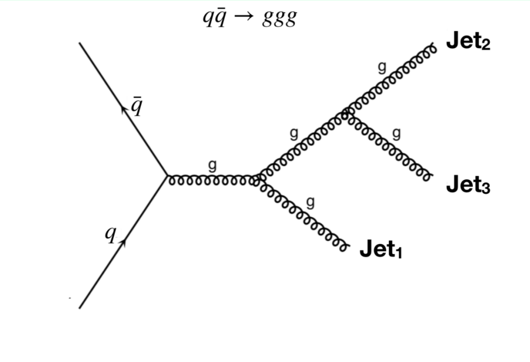

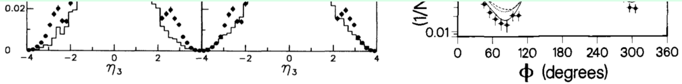

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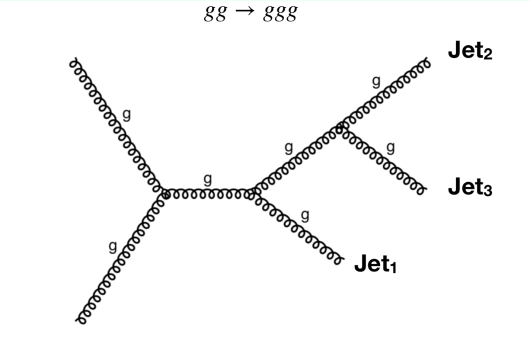

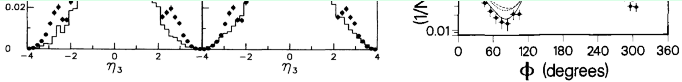

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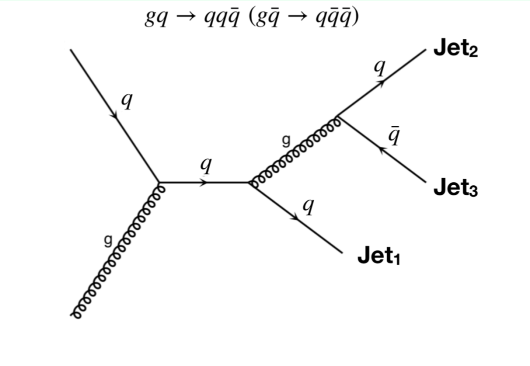

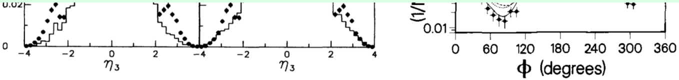

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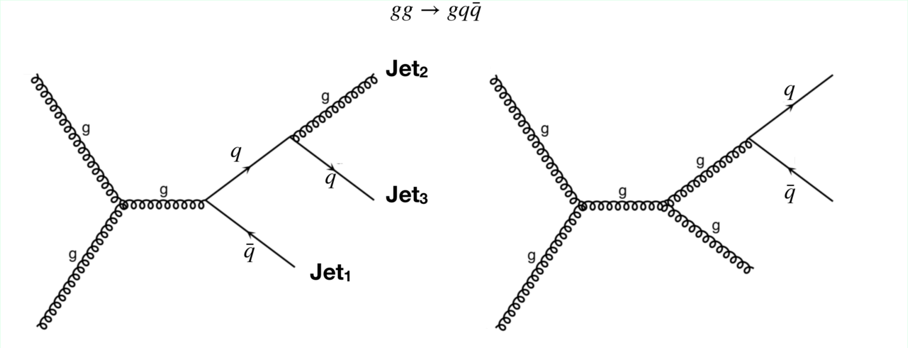

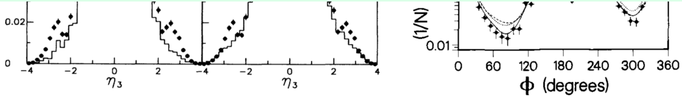

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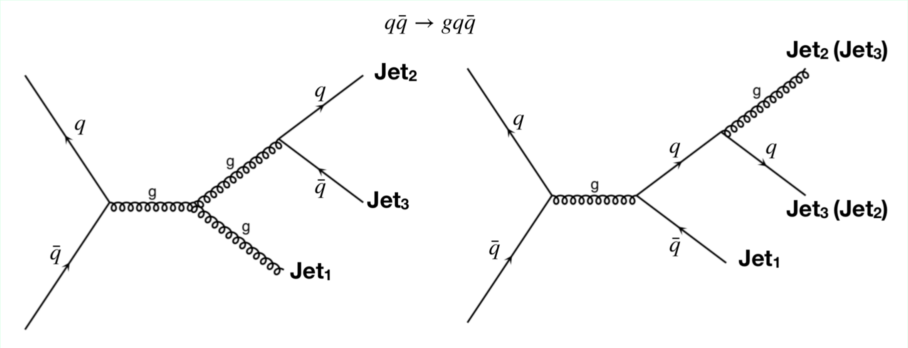

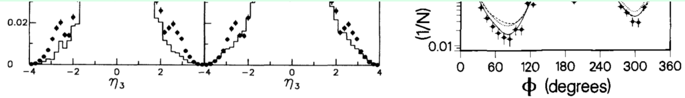

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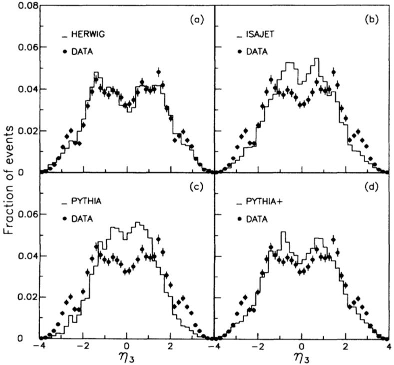

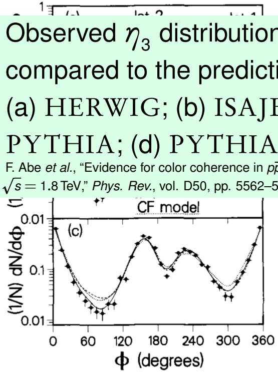

Observed η_3 distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA +.

F. Abe *et al.*, "Evidence for color coherence in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV," *Phys. Rev.*, vol. D50, pp. 5562–5579, 1994.

Color Coherence

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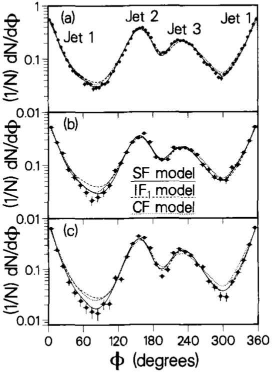
Particle density distribution $(1/N)dN/d\phi$ in 3-jet events for (a) all charged particles and photons, for (b) those charged particles and photons satisfying $0.3 < p_{out} < 0.5$ GeV/c and for (c) a heavy particle sample of charged and neutral kaons, protons, and lambdas. Also shown are the predictions of SF, IF_1, and CF models with full detector simulation.

H. Aihara *et al.*, "Tests of models for quark and gluon fragmentation in e^+e^- annihilation $\sqrt{s} = 29$ GeV," *Z. Phys.*, vol. C28, p. 31, 1985.



Introduction

Color Coherence

Results

Monte Carlo Update

At $\sqrt{s} = 7$ TeV MC Results

Updated Theoretical Prediction

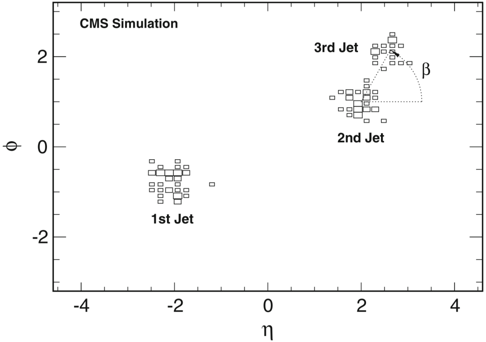
Azimuthal correlations

Jet Mass

Summary

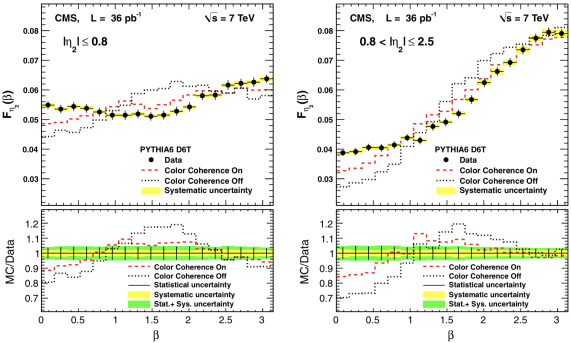
Observable β

- $\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$
  - $\Delta\phi_{23} = \phi_3 - \phi_2, \ (-\pi \leq \Delta\phi_{23} \leq \pi)$
  - $\Delta\eta_{23} = \mathrm{sign} \cdot (\eta_3 - \eta_2), \ (\eta = -\ln\tan\frac{\theta}{2})$



$\sqrt{s} = 7\,\text{TeV}$ Color Coherence Results

- Measure the angular correlation between 2nd and 3rd jet
- Color coherence effect on/off
- Color coherence effect on
  - Enhanced β near 0
  - 3rd jet prefer to lay on event plane
- Color coherence effect off
  - Enhanced β near $\pi/2$
  - 3rd jet prefer to lay on out of event plane
- β is sensitive at color coherence effect, but it has many other kinematic effects at the hadron collision



S. Chatrchyan *et al.*,"Probing color coherence effects in pp collisions at $\sqrt{s} = 7\,\text{TeV}$," *Eur. Phys. J.*, vol. C74, no. 6, p. 2901, 2014.

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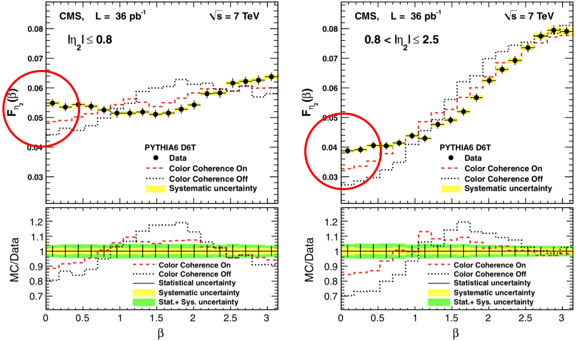

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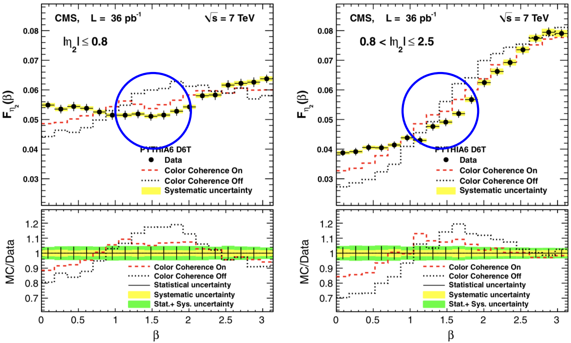

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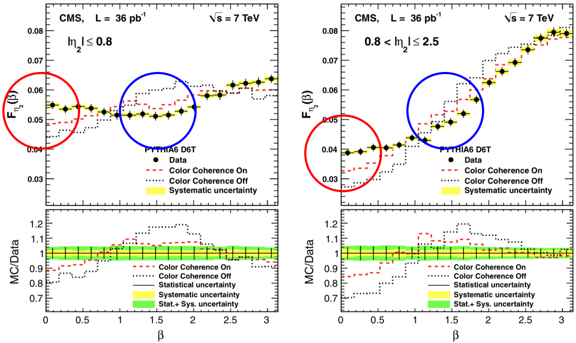

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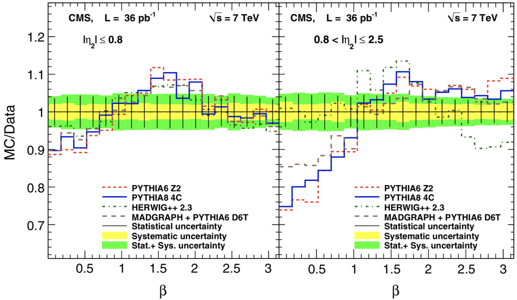
At $\sqrt{s} = 7$ TeV MC Results

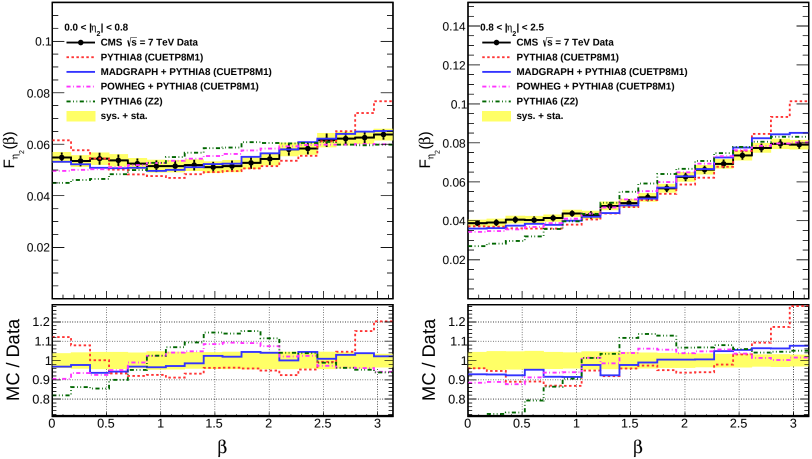


MC event generator	χ^2/NDF	
	$\|\eta_2\| \leq 0.8$	$0.8 < \|\eta_2\| \leq 2.5$
PYTHIA 6 Z2	2.5	8.1
PYTHIA 8 4C	1.7	6.4
HERWIG++ 2.3	1.2	3.5
MADGRAPH + PYTHIA 6	1.6	3.3

Updated Theoretical Prediction

- PYTHIA (LO2J + PS)
  - Version 8.2
  - CUETP8M1 tune
- MADGRAPH (LO4J + PS)
  - Version 5.2.5
  - $2 \rightarrow 2 + 3 + 4$ with jet matching scale $Q_{\mathrm{cut}} = 14\,\mathrm{GeV}$
  - PS with PYTHIA 8 CUETP8M1 tune
- POWHEG (NLO2J + PS)
  - Version 2
  - NLO calculation
  - CT10 pdf
  - PS with PYTHIA 8 CUETP8M1 tune

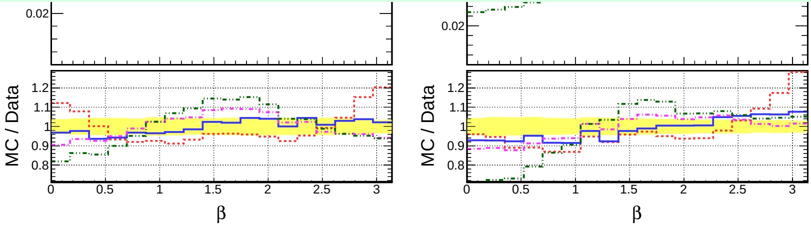
Updated MC Results



H. Kim *et al.*, "Monte Carlo Updates on Color Coherence at 7 TeV," *JKPS*, Vol. 70, No. 5, pp. 465-468, 2017

Updated MC Results

	$\|\eta_2\| < 0.8$	$0.8 < \|\eta_2\| < 2.5$
PYTHIA8 CUETP8M1	2.0	3.2
MADGRAPH + PYTHIA8	0.4	1.1
POWHEG + PYTTHIA8	1.1	1.5
PYTHIA6 Z2	3.5	10.9



H. Kim *et al.*, "Monte Carlo Updates on Color Coherence at 7 TeV," *JKPS*, Vol. 70, No. 5, pp. 465-468, 2017

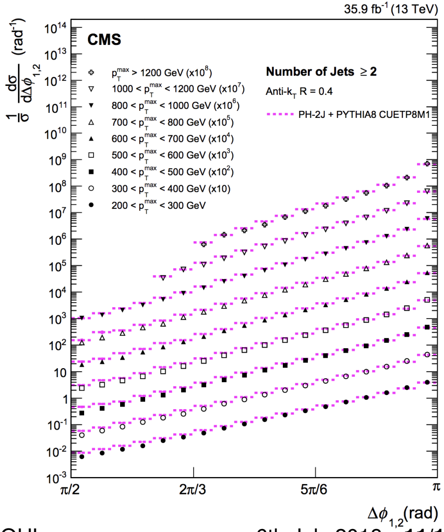
Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in *pp* collisions at 13 TeV

CMS-SMP-16-014, CERN-EP-2017-290

e-Print: arXiv:1712.05471 [hep-ex]

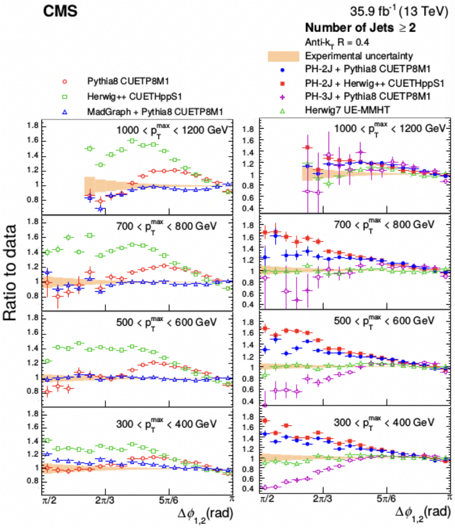
Azimuthal correlations in 2-jet events

- $\frac{1}{d\sigma_{1,2}} \frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}$
- Bin size: 5°
- Interesting tool to test theoretical predictions of multijet production processes
- Region away from π is sensitive to hard radiation from ME
- Region close to π is sensitive to resummed contributions from PS
- Overall description of the data is achieved and understood
- JES is the dominant systematic uncertainty (from 3 % at $\pi/2$ to 0.1 % at π)



Azimuthal correlations in 2-jet events

- MADGRAPH (up to 2⟶4 LO) describes well the data whereas P8 and HERWIG++ (2⟶2 LO) fail significantly
- POWHEG 2J and POWHEG 3J are not able to describe the data better than PYTHIA 8 and HERWIG++, even though they provide multi-leg ME
- HERWIG 7 (MC@NLO for matching to PS), formally NLO but effectively 2⟶3 LO, gives a good description of the data
- For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method



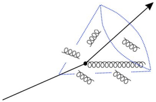
Measurement of the differential jet production cross section with respect to jet mass and transverse momentum in dijet events from *pp* collisions at $\sqrt{s} = 13$ TeV

CMS-PAS-SMP-16-010

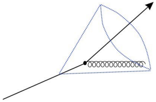
Jet Mass at $\sqrt{s} = 13$ TeV

- Sensitive to the internal structure of jets (PS in MC generators)
- Soft and collinear singularities
- Sudakov peak ($m/p_T \approx 0.1$), splitting threshold ($m/p_T \approx 0.3$)

Ungroomed



Groomed



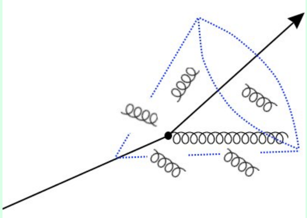
- Soft and hard parts of the jet

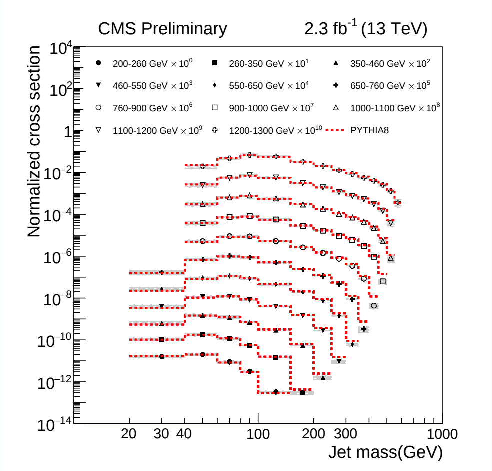
- “Soft drop” to remove the soft part of the jet
- Sensitive to the hard part of the jet
- Sensitive to physics modeling
- Possible use in global fits for parameter tuning

Jet Mass at $\sqrt{s} = 13\,\text{TeV}$

- Sensitive to the internal structure
- Soft and collinear singularities

Ungroomed





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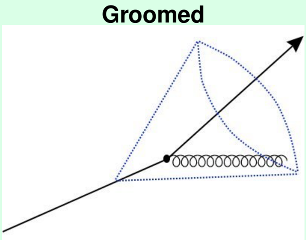

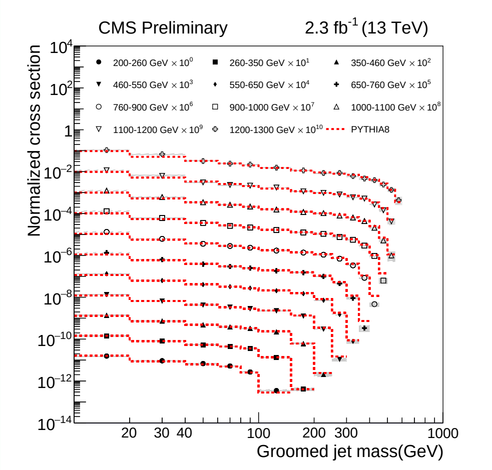

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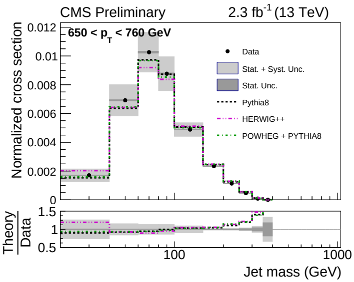
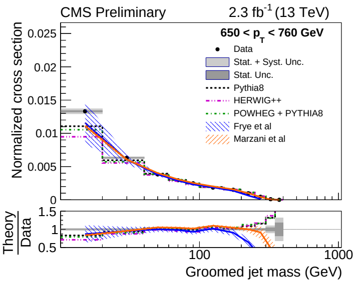




- For groomed jets, the Sudakov peak is suppressed and the precision in the intermediate mass region improves
- For m/p_T > 0.3, the fixed-order matrix element matching is insufficient to capture the true dynamics
- Semi-analytical calculations beyond NLL accuracy of the groomed jet mass agrees for masses lower than 30 % of the p_T
- PS has the largest effect on the jet mass (agreement between PH + P8 and P8)

Summary

- Color coherence at $\sqrt{s} = 7$ TeV
  - The 3rd jet has strong correlations with 2nd jet because the 3rd jet is from FSR of the 2nd jet at di-jet topology, and the 3rd jet is effected on color coherence
  - The β variable is sensitive at color coherence effect, but it is not only color coherence effect but also several kinetic effects at the hadron collision
  - The latest ME-method-based MC generators have improved and describe the data much more successfully
- Dijet azimuthal angular correlations at $\sqrt{s} = 13$ TeV
  - Overall description of the data is achieved and understood
  - For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method
- Jet mass at $\sqrt{s} = 13$ TeV
  - Sensitive to the internal structure of jets
  - PS has the largest effect on the jet mass
  - Semi-analytical calculations beyond NLL accuracy of the groomed jet mass agrees for masses lower than 30 % of the p_{T}

Backup

PS and ME

Parton Shower (PS)

- Approximate, resums logs to all orders (LL or NLL)
- Main topology not predetermined: inefficient for exclusive states
- Sudakov form factors/resummation: sensible jet/event structure
- Simple multi parton
- Easy to match to hadronizaion
- Computationally cheep
- **Valild when partons are soft and/or collinear**

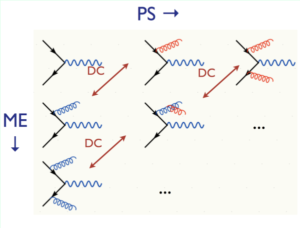
Matrix Element (ME)

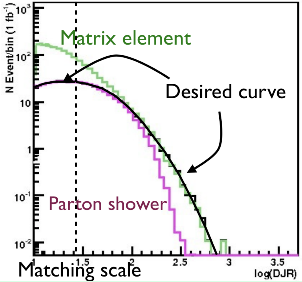
- Systematic expansion in α_S: exact calculation
- Powerful for multi parton Born level
- Flexible phase space cuts
- Quantum interference correct
- Loop calculations are computationally expensive
- Negative cross section in collinear regions: unpredictive jet/event structure
- Difficult to match to hadronization
- **Valid when partons are hard and well separated**

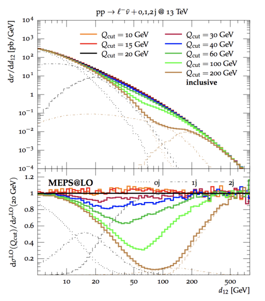
PS and ME

The best way to describe data with MC is matching ME and PS method

- Avoid double counting
- Ensure smooth distributions







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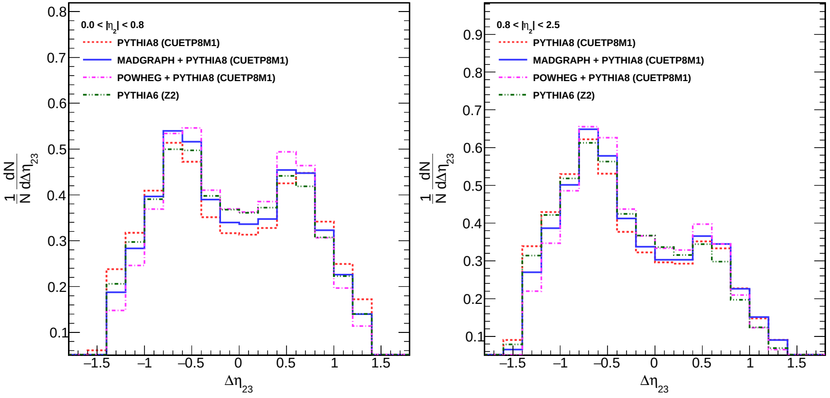
Johan Alwall, "Parton shower and MLM matching," KIAS MadGrace school, Oct 24-29 2011

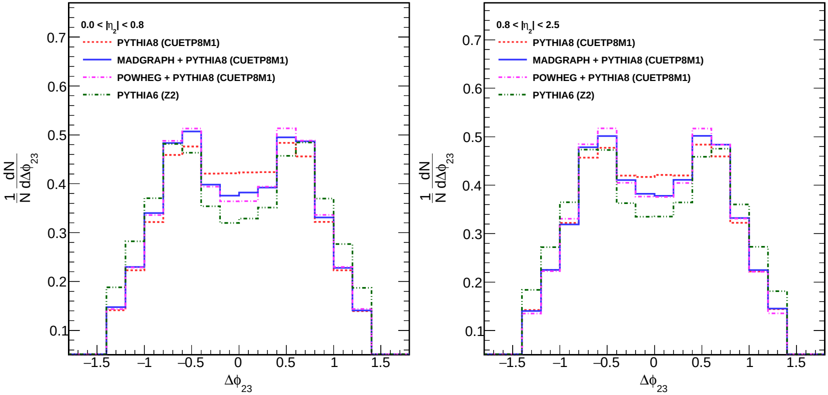
Kallweit *et al.*,"NLO QCD+EW predictions for V + jets including off-shell vector-boson decays and multijet merging," *JHEP*, vol. 04, p. 021, 2016

Updated MC Results for $\Delta\eta_{23}$



H. Kim *et al.*, "Monte Carlo Updates on Color Coherence at 7 TeV," *JKPS*, Vol. 70, No. 5, pp. 465-468, 2017

Updated MC Results for $\Delta\phi_{23}$



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Event Selection for Color Coherence

- CMS $\sqrt{s} = 7$ TeV Data
- Anti-k_{T} R = 0.5 particle flow (PF) jet (AK5 PF jet)

Selection criteria
$p_{\mathrm{T}1} > 100\,\mathrm{GeV} > p_{\mathrm{T}2} > p_{\mathrm{T}3} > 30\,\mathrm{GeV}$
$0.5 < \Delta R_{23} < 1.5$
$\lvert\eta_1\rvert, \lvert\eta_2\rvert \leq 2.5$
$M_{12} > 220\,\mathrm{GeV}$