Multijet Correlations in CMS

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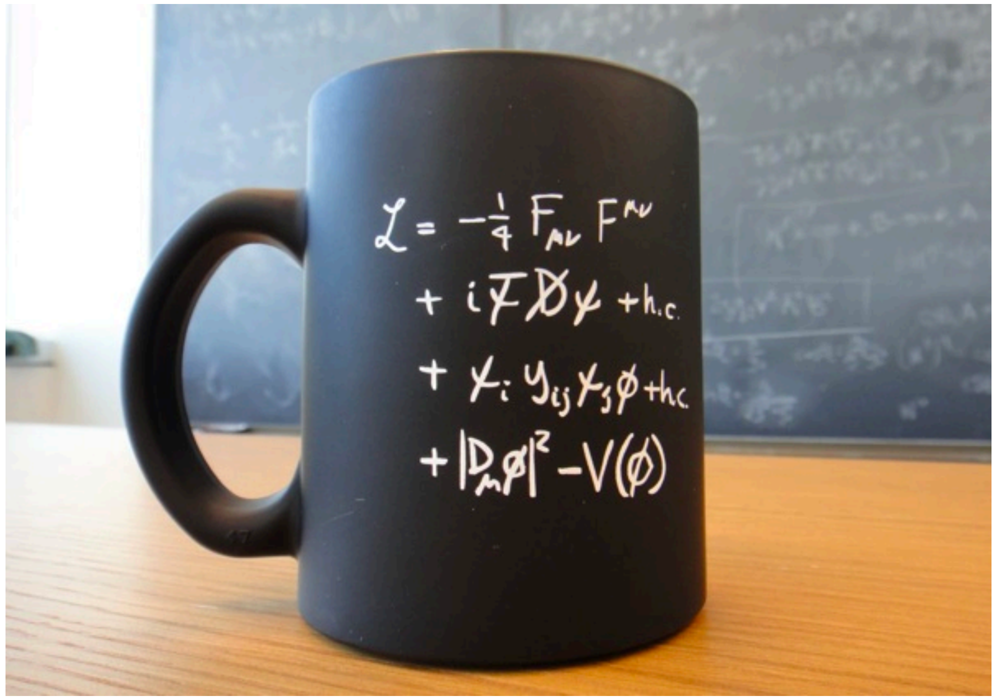
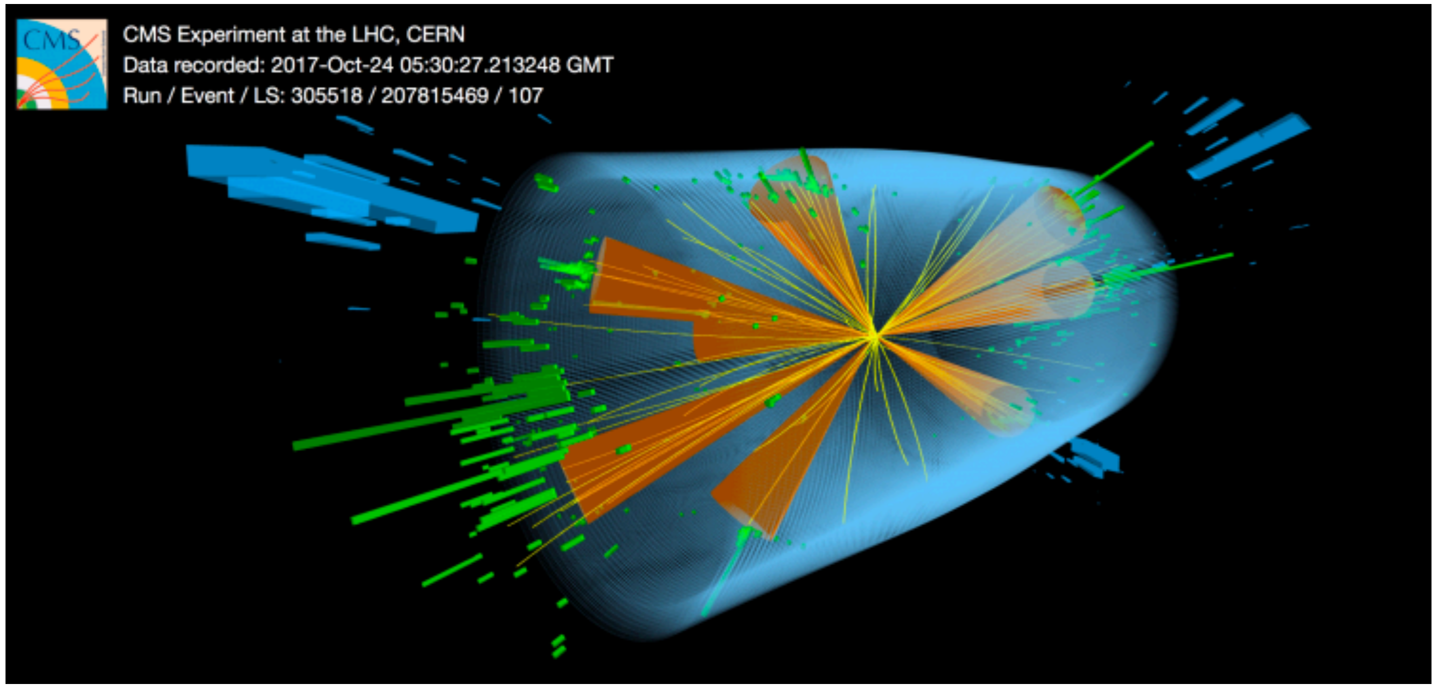
Introduction

A single-line formula of a fundamental theory



And experimental realities



Event Generator

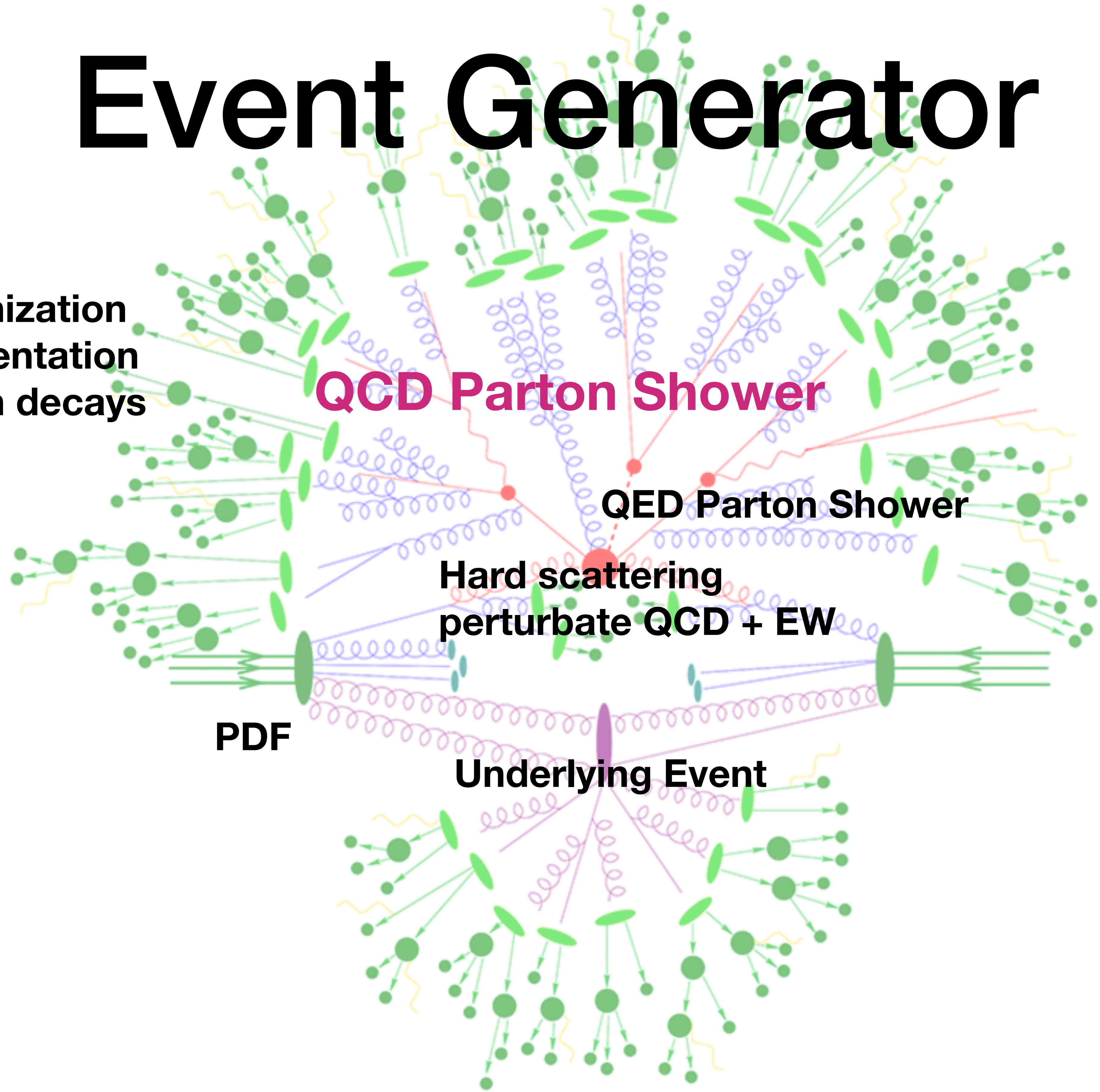


Image: https://sherpa-team.gitlab.io/monte-carlo.html#monte-carlo-event-generators

String Fragmentation

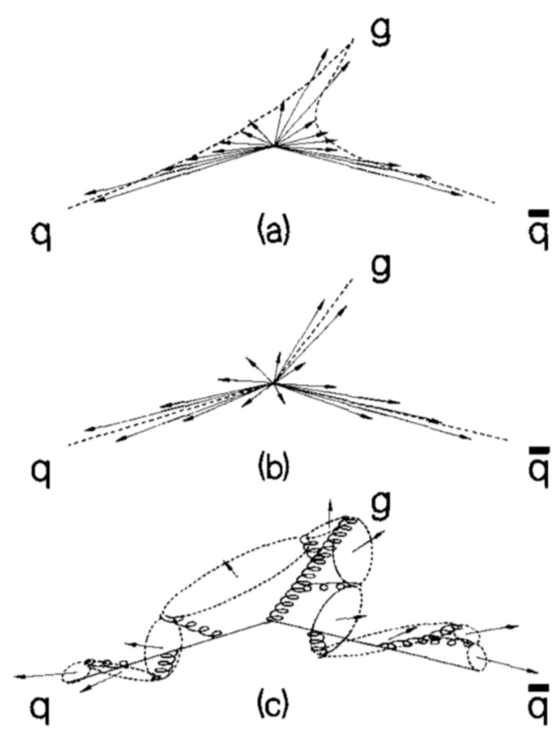


Figure 2.6: 3-jet event structure for (a) SF, (b) IF, and (c) CF models. In (a) and (b), the arrow indicate the momentum space distribution of particles. The dashed curve in (a) represent strings stretched between the partons, in (b) they represent the parton directions. (c) shows the CF model quark-gluon shower (solid and curly lines) and clusters (dashed ellipses). The motion of the clusters is indicated by arrows; the resulting momentum space distribution of particles is similar to that in (a) for CF models exhibiting a depletion effect [5].

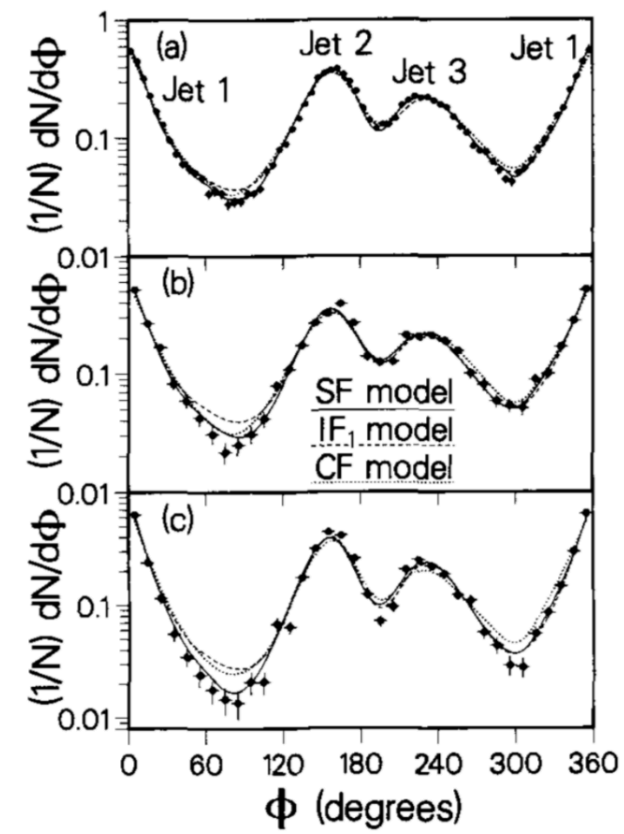
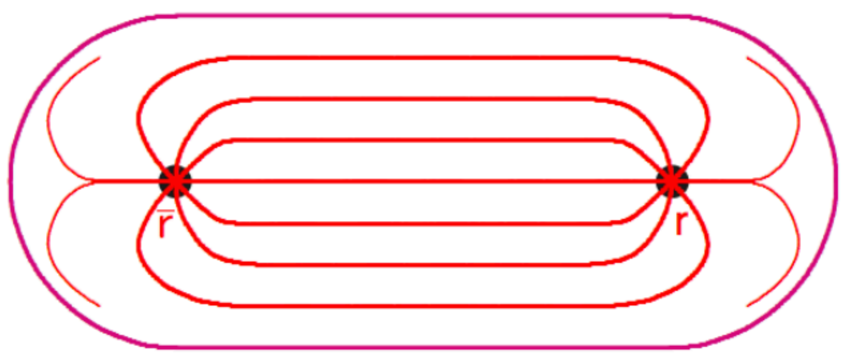


Figure 2.7: Particle density distribution $(1/N)dN/d\phi$ in 3-jet events for (a) all charged particles and photons, for (b) those charged particles and photons satisfying $0.3 < p_{out} < 0.5$ GeV/c and for (c) a heavy particle sample of charged and neutral kaons, protons, and lambdas. Also shown are the predictions of SF, IF_1, and CF models with full detector simulation [5].

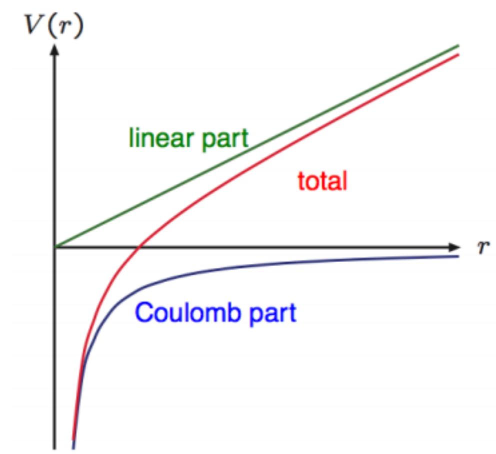
H. Aihara *et al.*, "Tests of models for quark and gluon fragmentation in e^+e^- annihilation $\sqrt{s} = 29$ GeV," *Z. Phys.*, vol. C28, p. 31, 1985.

QCD Potential

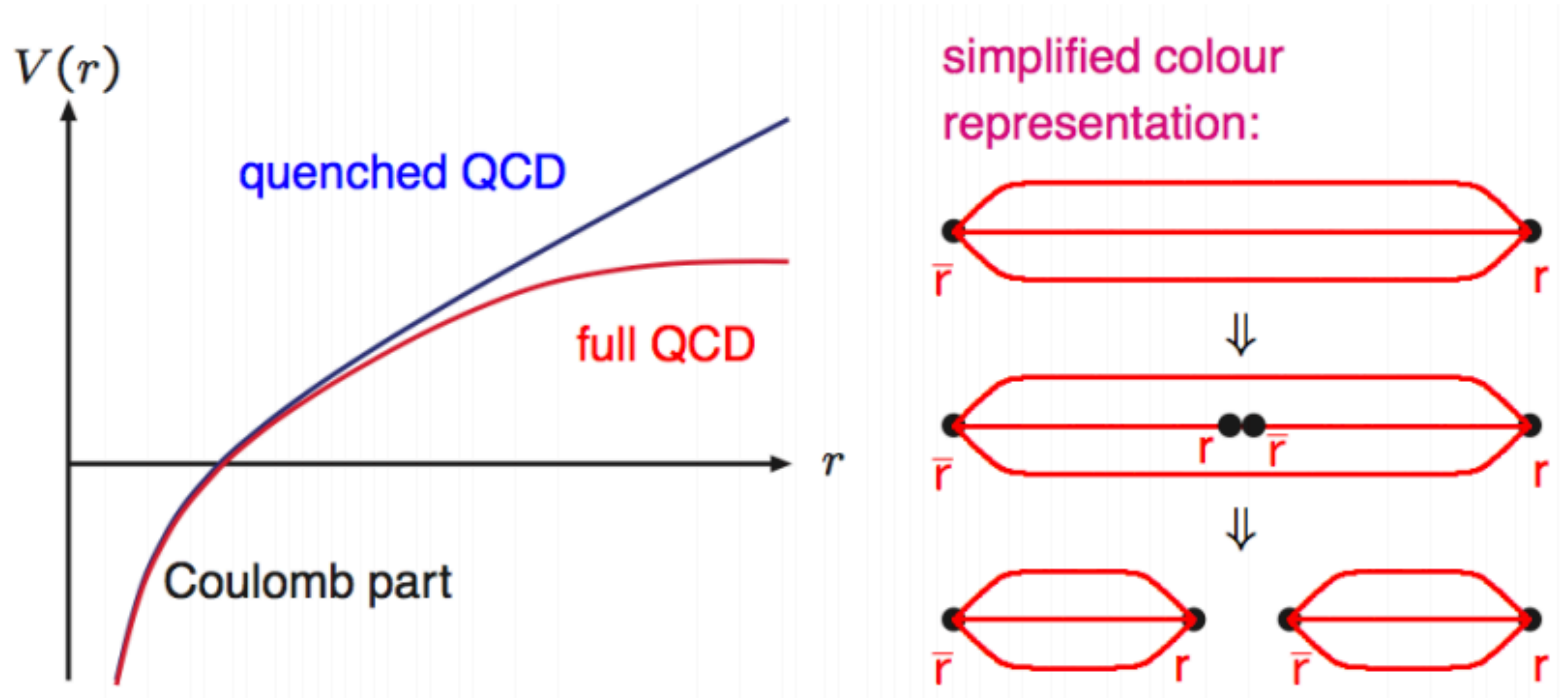


Gives force/potential between a q and a $\bar{q}$:

$F(r) \approx \text{const} = \kappa \iff V(r) \approx \kappa r$



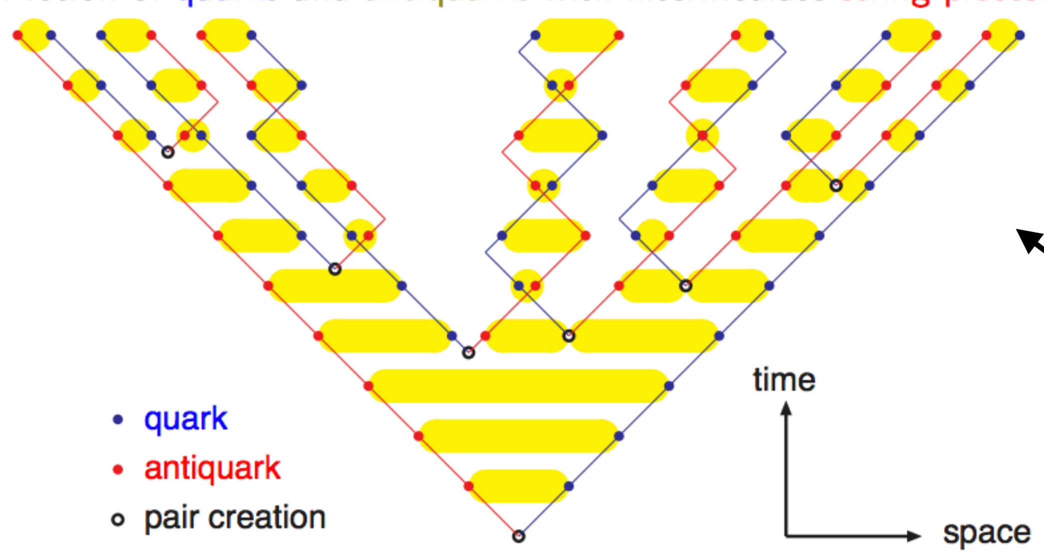
- The color charged dipole are compressed to a tubelike region
- The potential can be linear: quenched QCD
- Full QCD: virtual fluctuation gluon and string break



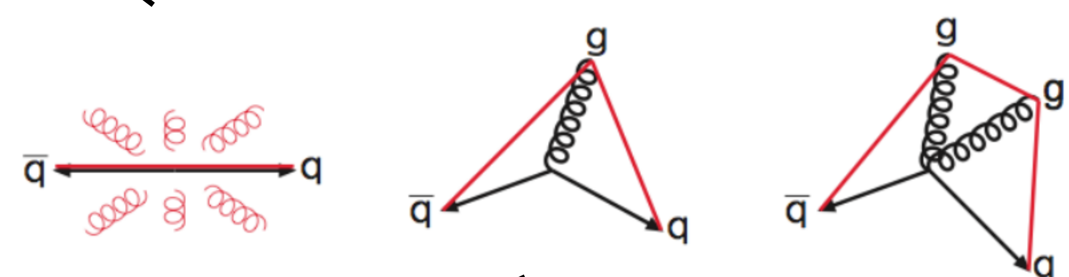
T. Sjöstrand, "Introduction to event generators," July 2016.

Lund Model (String Model)

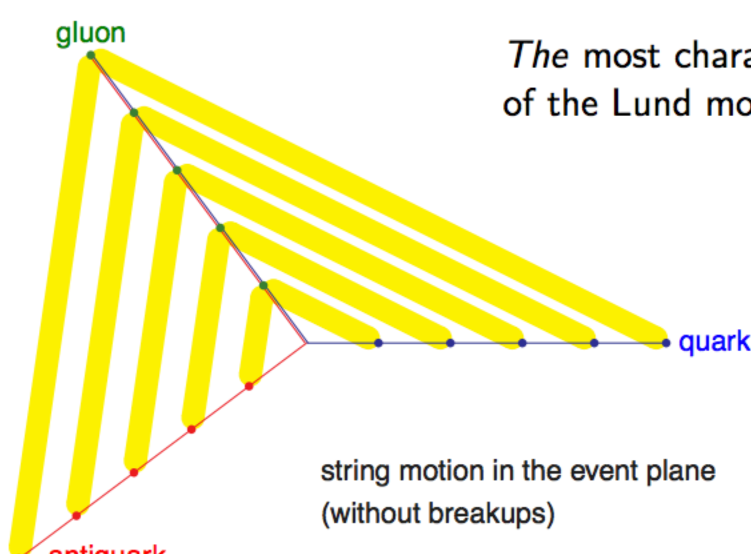
Motion of quarks and antiquarks with intermediate string pieces:



A q from one string break combines with a $\bar{q}$ from an adjacent one.



The most characteristic feature of the Lund model:



T. Sjöstrand, "Introduction to event generators," July 2016.

Parton Shower with AO

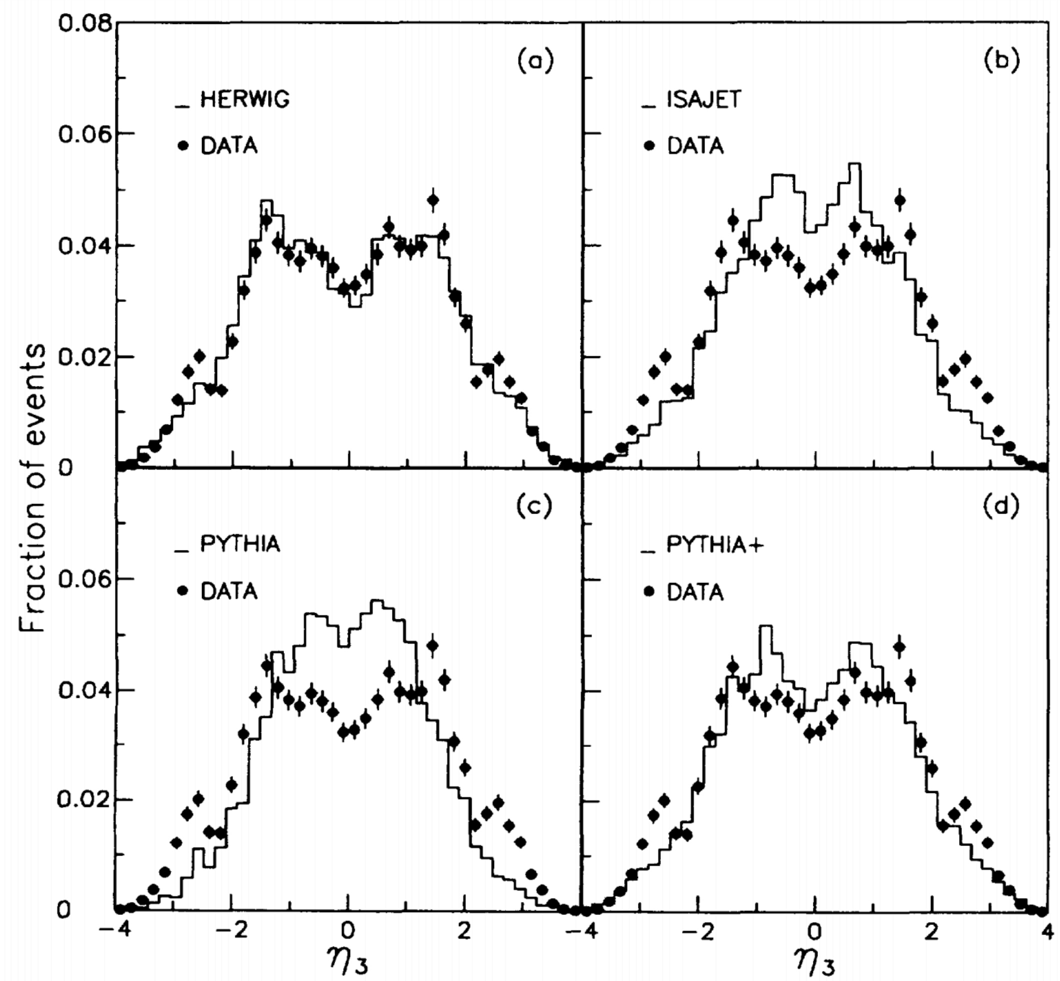
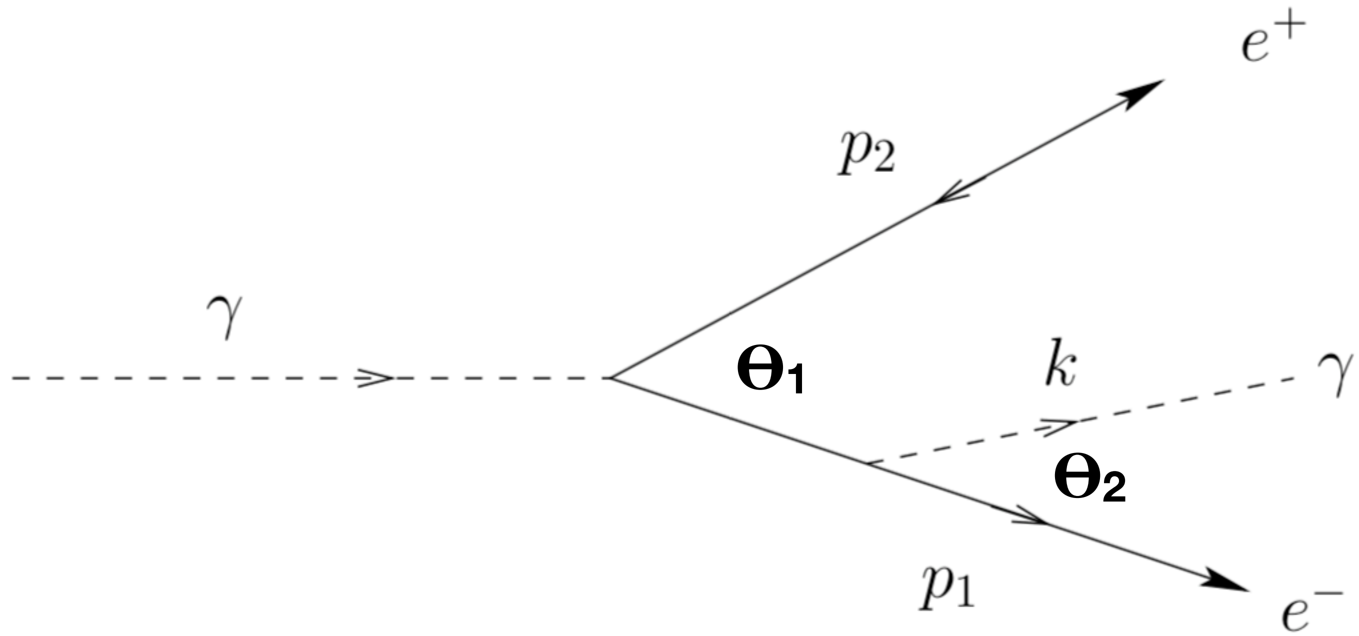


FIG. 13. Observed η_3 distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

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.

CDF color coherence study shows that only the MC with angular ordering (AO) described third jet pseudorapidity distribution.

Chudakov Effect

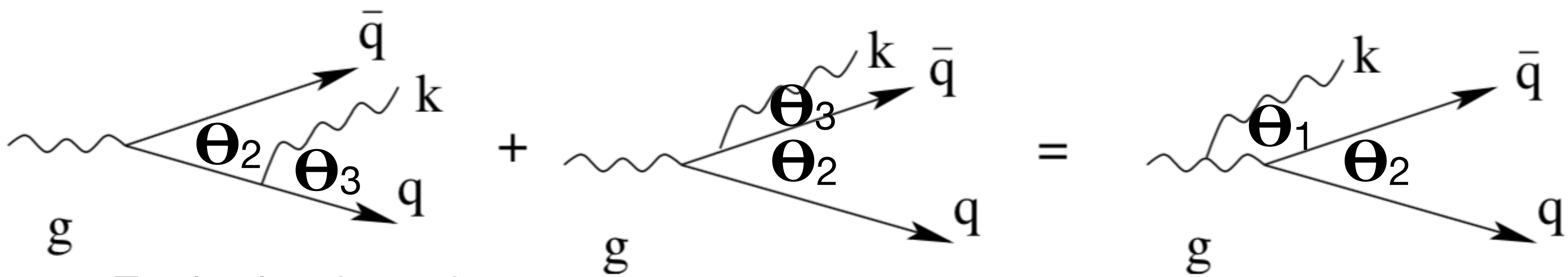


$\Theta_1 << \Theta_2$: γ to be strongly suppressed

So, coherent Bremsstrahlung radiation is $\Theta_1 > \Theta_2$

Y. Dokshitzer, *Basics of perturbative QCD*. Atlantica Séguier Frontières, 1991.

QCD (Color) Coherence

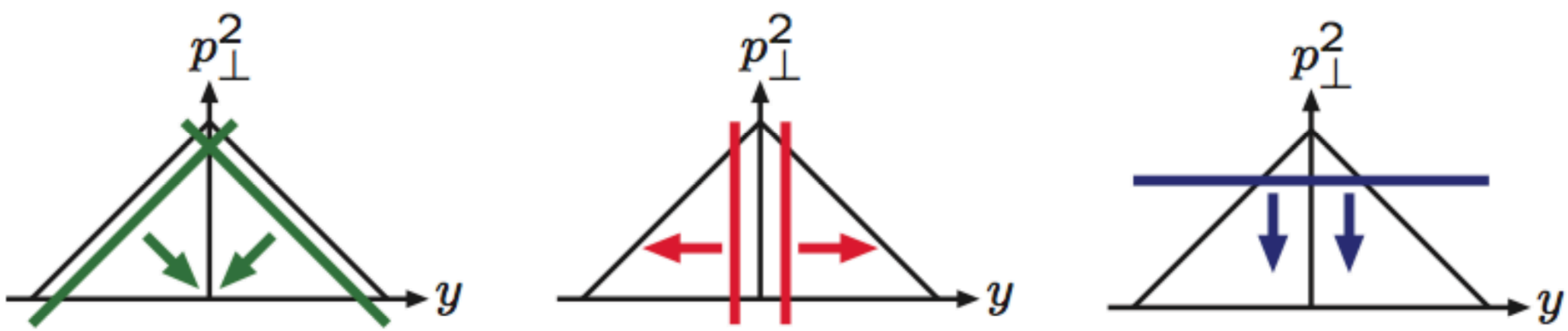


Total color charge is not 0,
soft gluon radiation from the parent gluon imagined to be on shell

$\theta_3 < \theta_2 < \theta_1$

Y. Dokshitzer, *Basics of perturbative QCD*. Atlantica Séguier Frontières, 1991.

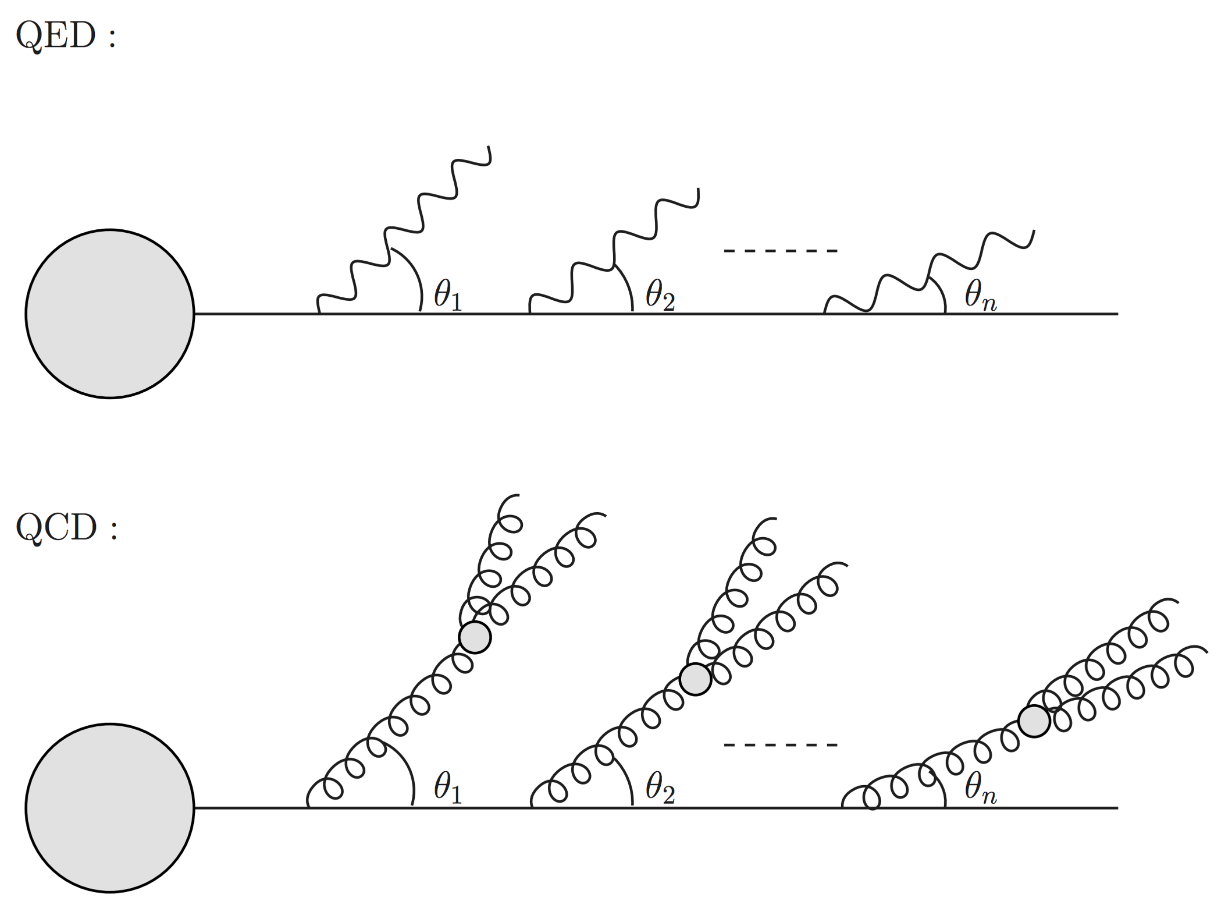
PYTHIA: $Q^2 = m^2$ HERWIG: $Q^2 \sim E^2\theta^2$ ARIADNE: $Q^2 = p_\perp^2$



large mass first large angle first large $p_\perp$ first

T. Sjöstrand, "Introduction to event generators," July 2016.

Angular Ordering (AO)



QED and QCD angular ordering radiation can be considered in the same way

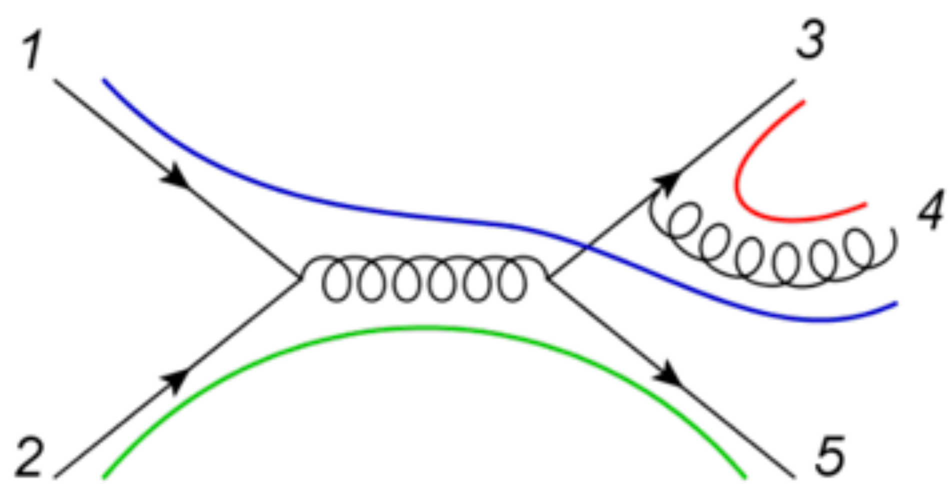
G. Luisoni and S. Marzani, "QCD resummation for hadronic final states," *J. Phys.*, vol. G42, no. 10, p. 103101, 2015.

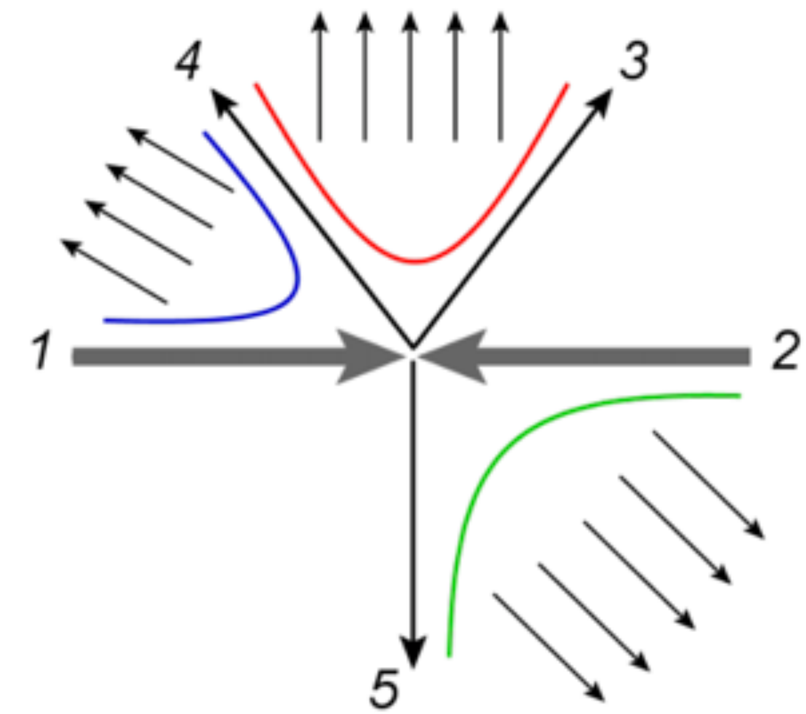
Color Coherence @ CMS

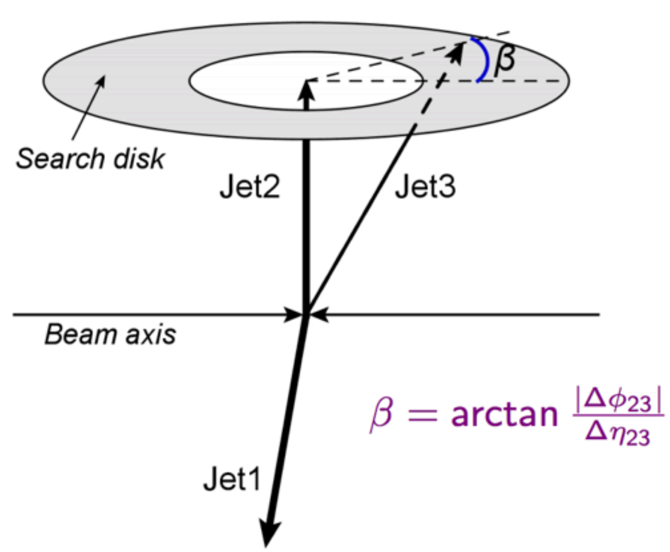
Color coherence phenomena: interference of soft gluon radiation emitted along color connected object

Experimental signature:
- **At least 3 jets event**
- **Di-jet topology (back to back)**
- **Relative abundance of soft radiation in the region between color connected final state partons**

Measure the angular correlation between 2nd and 3rd jet

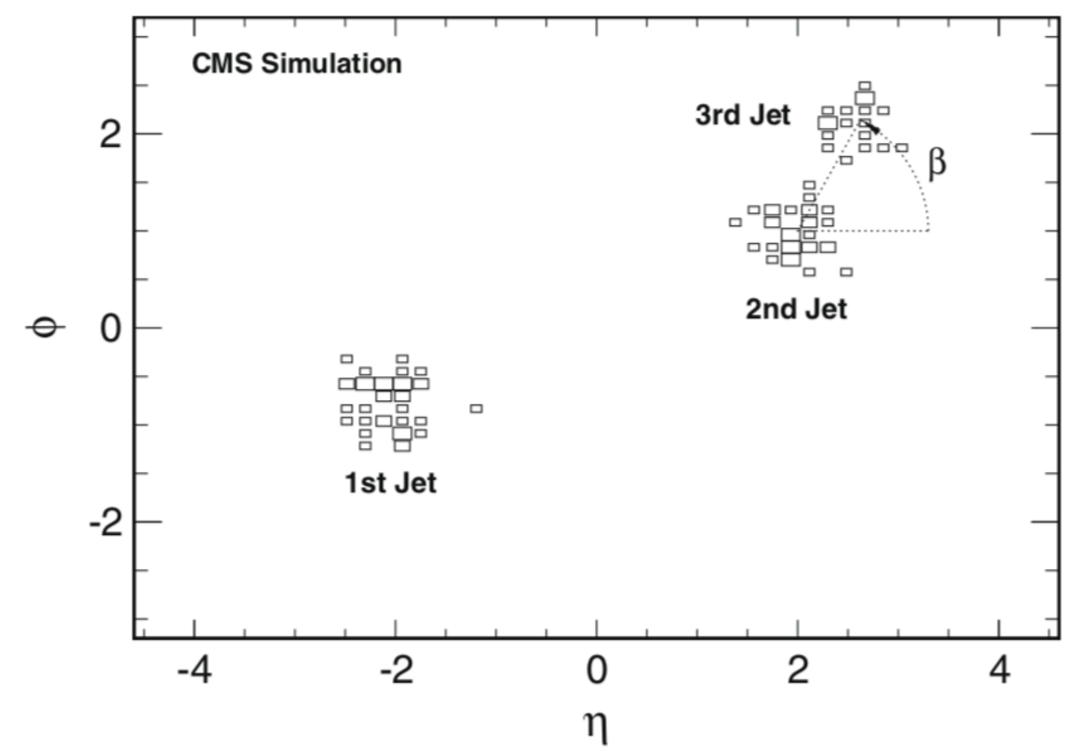






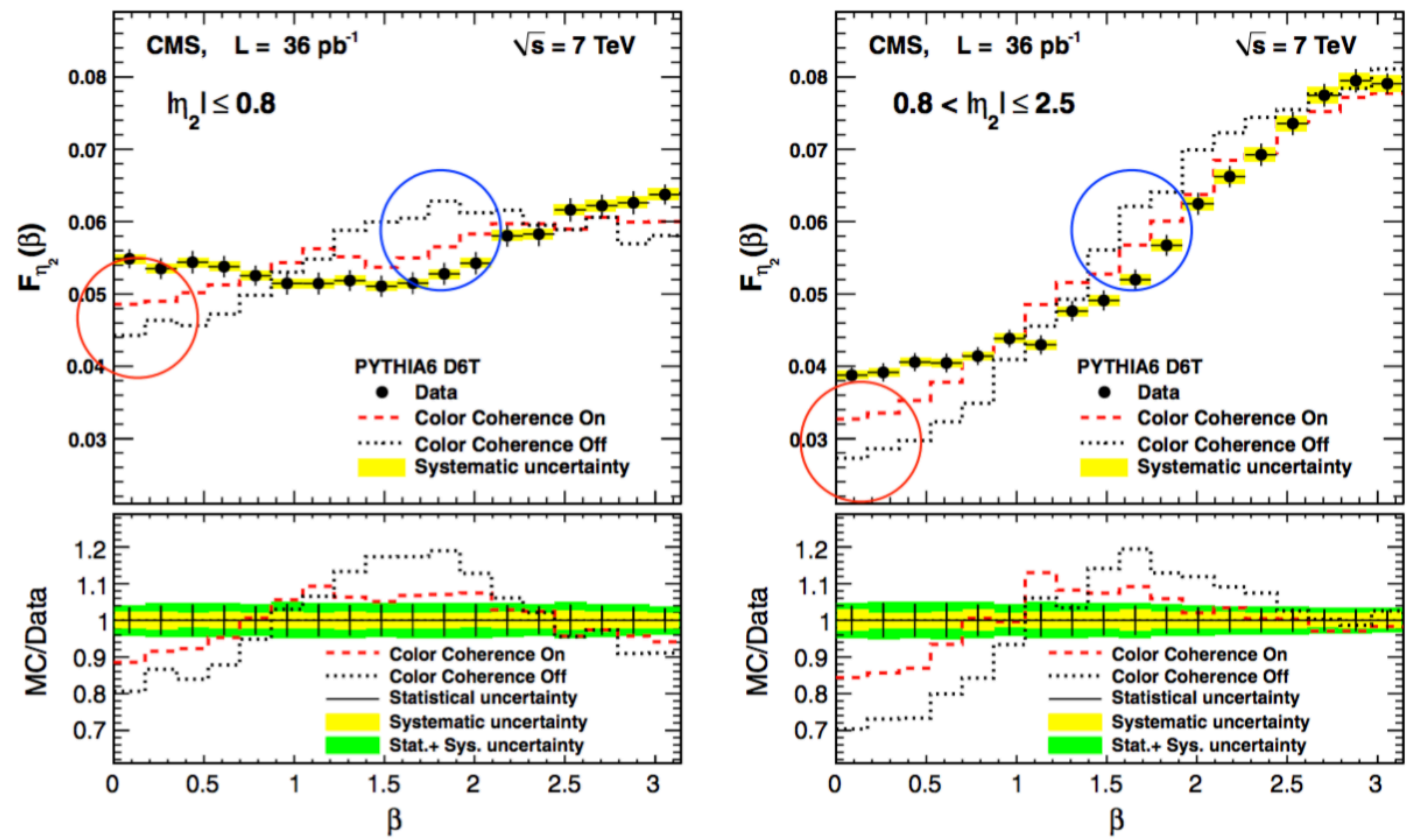
$\beta = \arctan \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$

$\phi_{23} = \phi_3 - \phi_2$
$\eta_{23} = \text{sign}(\eta_2)\cdot(\eta_3 - \eta_2)$



CMS 7 TeV Result

- PYTHIA6 D6T
- Color Coherence effect on/off
  - ISR
  - FSR
- Color coherence on
  - Enhanced β ~0
  - 3rd jet prefer lay on event plane
- Color coherence off
  - Enhanced β ~ π/2
  - 3rd jet prefer lay on out of event plane
- **This 7 TeV analysis had other kinematic effects and complicated variable**



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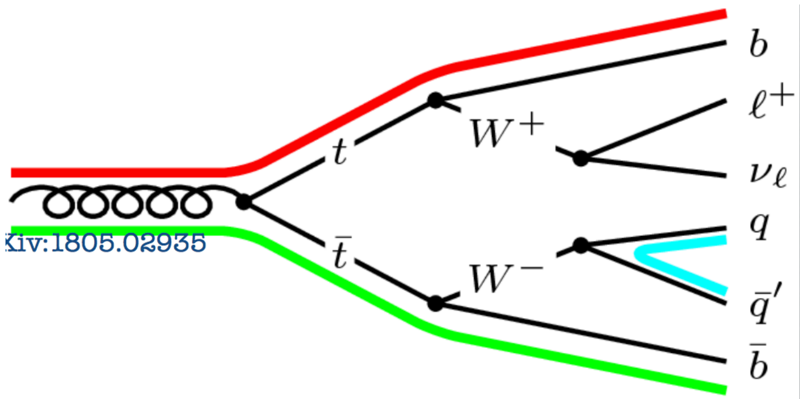
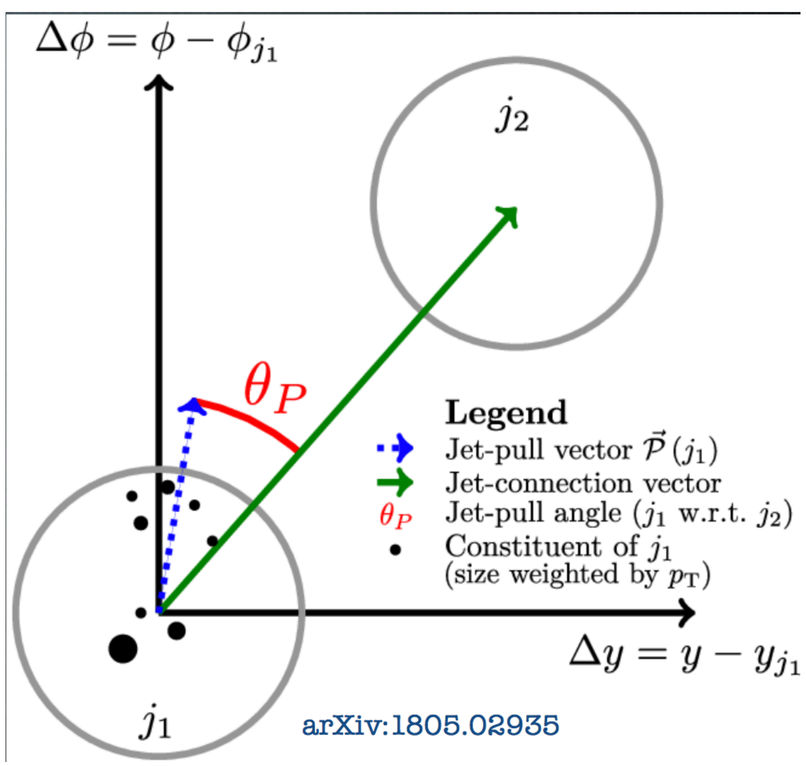
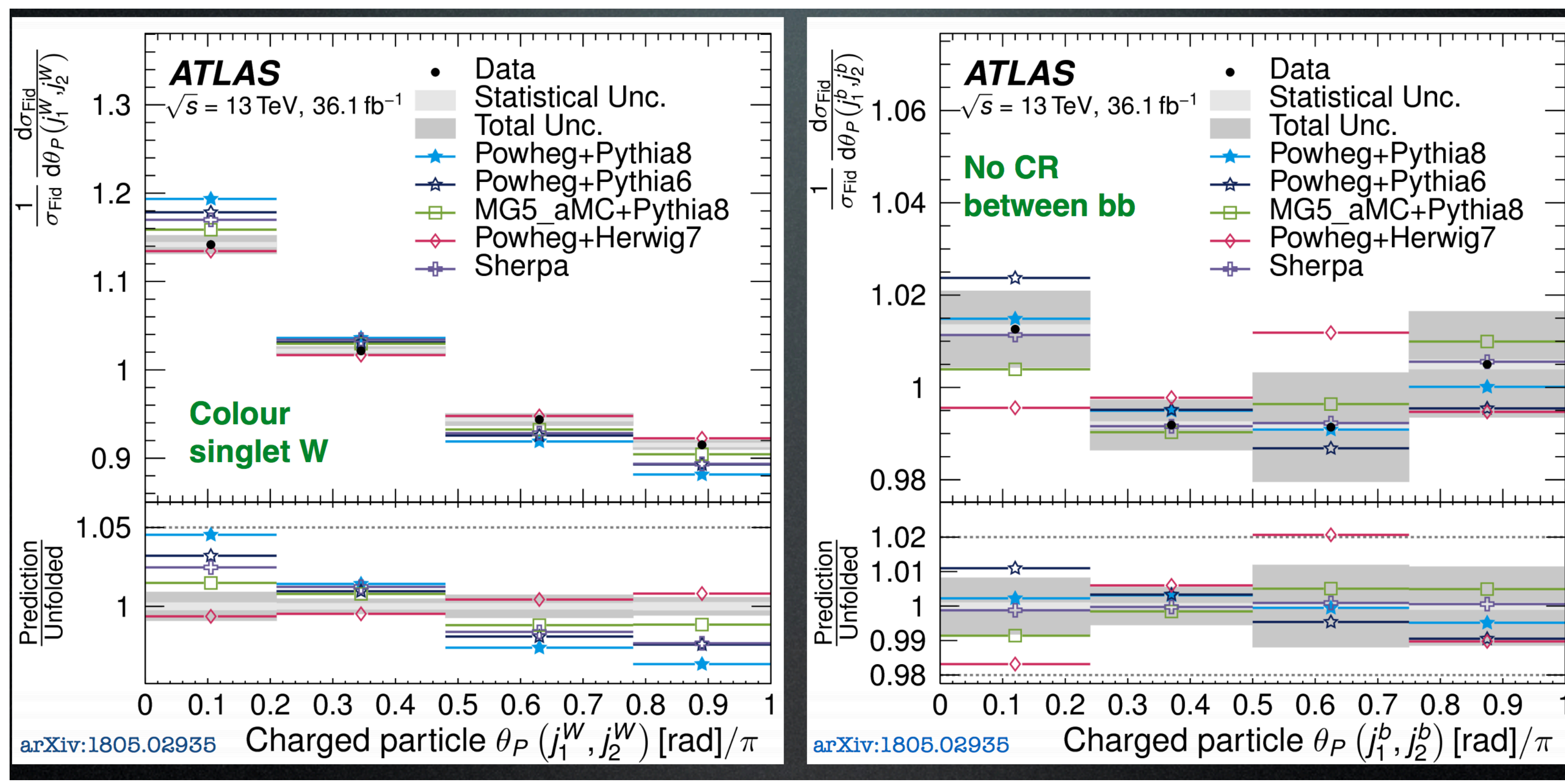
CMS-SMP-12-010, CERN-PH-EP-2013-200
DOI: 10.1140/epjc/s10052-014-2901-8

Color flow in TTbar events







Close to zero for color connected jets, uniform if no color connection

MCs predict stronger color connection than data

Powheg+Herwig7 describes the data the best

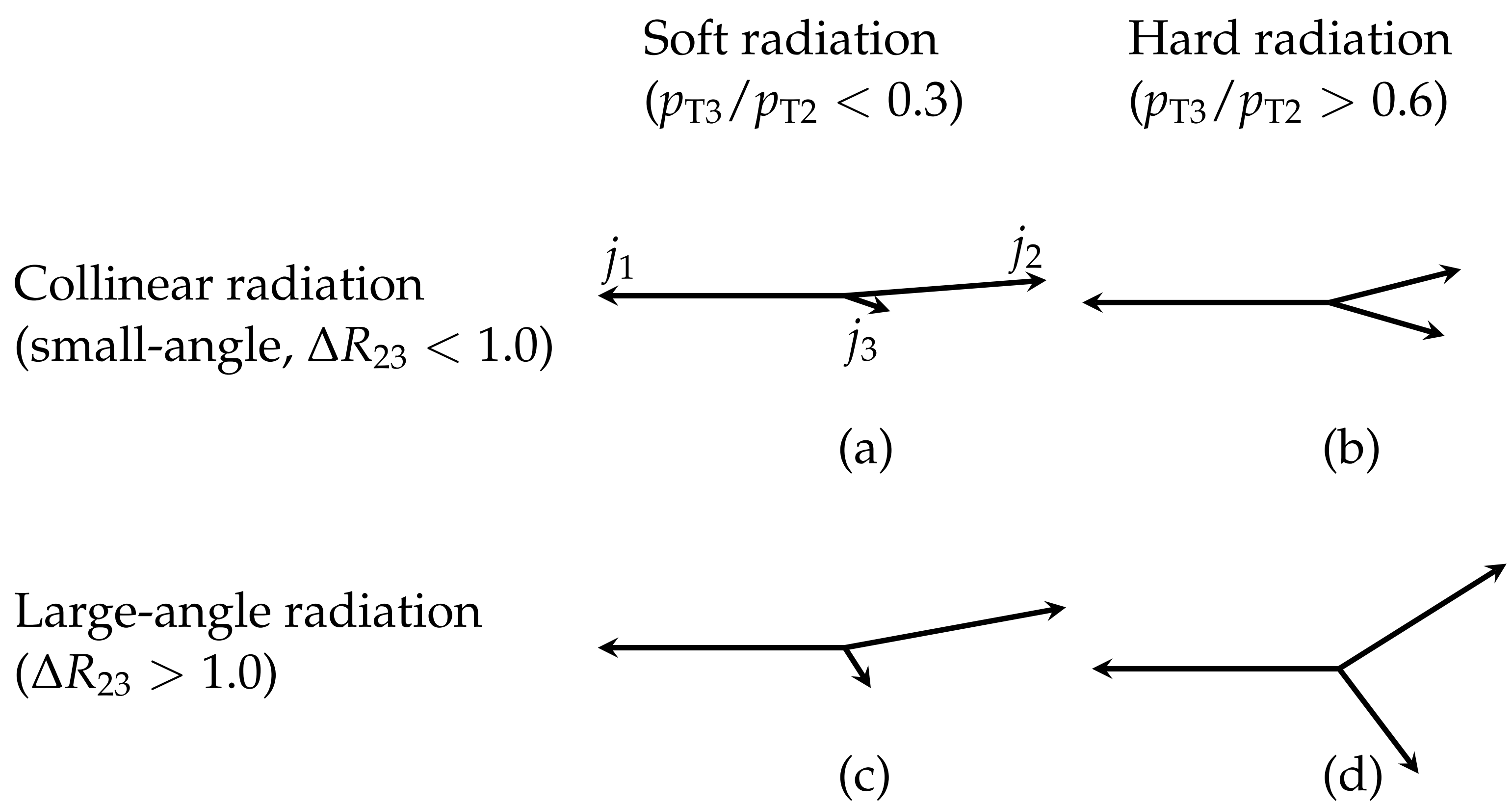
Complexity

- The $\boldsymbol{\beta}$ variable is sensitive to color coherence effect but…
  - It is not only color coherence effect but also several kinetic effects
  - Difficult to show clear color coherence effect
  - Event selections are not always $q\bar{q}g$
- New variables need to test QCD (color) coherence

New Motivation

- Untangle the different features of the radiation in the collinear and large-angle events
- Investigate how well the PS approach describes the hard and large-angle radiation patterns
- Illustrate how ME calculations can attempt to describe the soft and collinear regions
- Soft/hard radiation → p_{T3}/p_{T2}
- Collinear or large-angle → ΔR_{23}
- Two physics channel
  - Three-jet: Jets are fully color connected
  - Z + two-jet: Z boson (j_1) is color neutral, so color coherence effects should not appear so strongly
  - Different kinematic regions and initial-state flavor compositions are being probed

Event Criteria

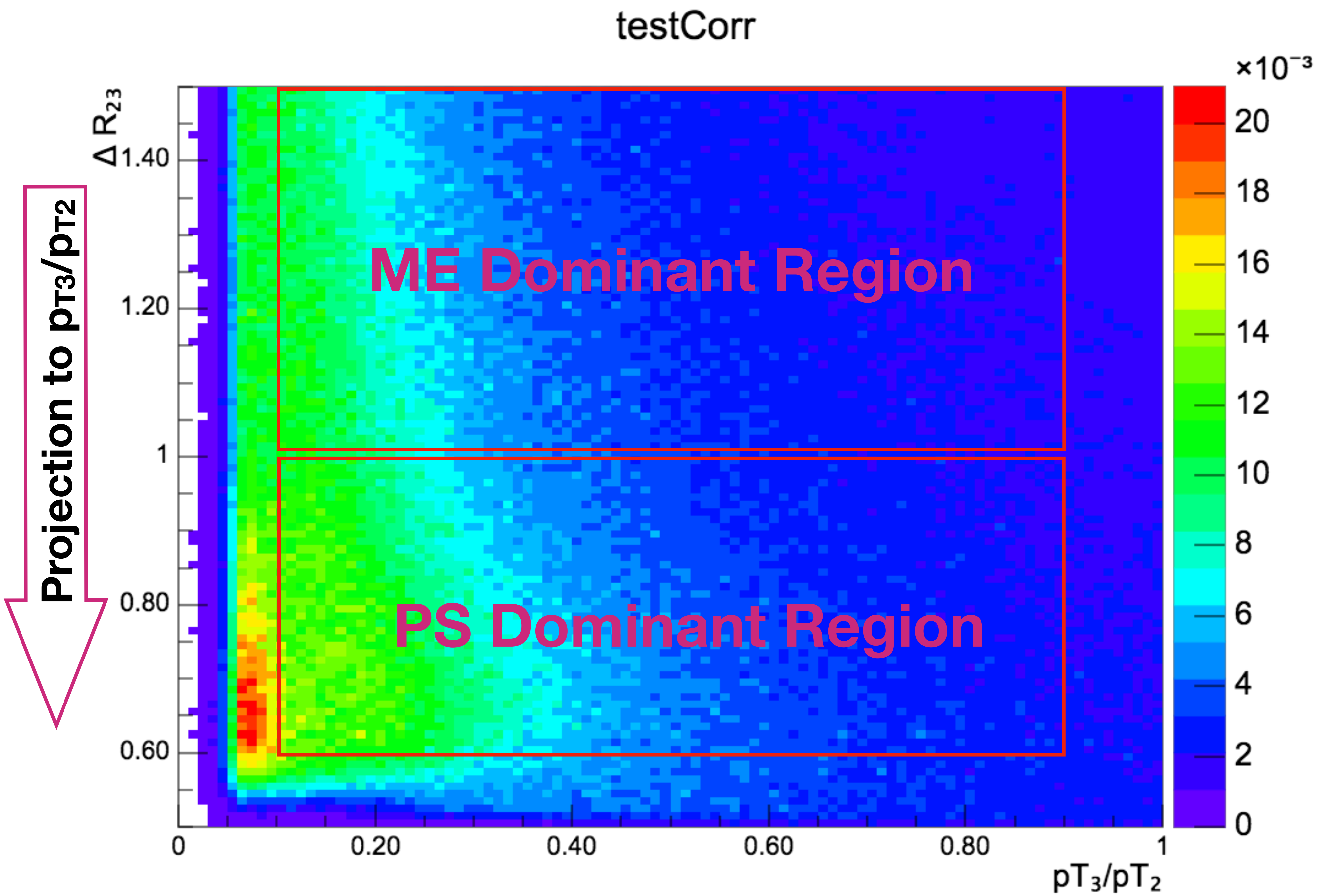


Criteria	Radiation type	Observable
$p_{T3}/p_{T2} < 0.3$ $p_{T3}/p_{T2} > 0.6$	soft p_T radiation hard p_T radiation	ΔR_{23}
$\Delta R_{23} < 1.0$ $\Delta R_{23} > 1.0$	small angle radiation large angle radiation	p_{T3}/p_{T2}

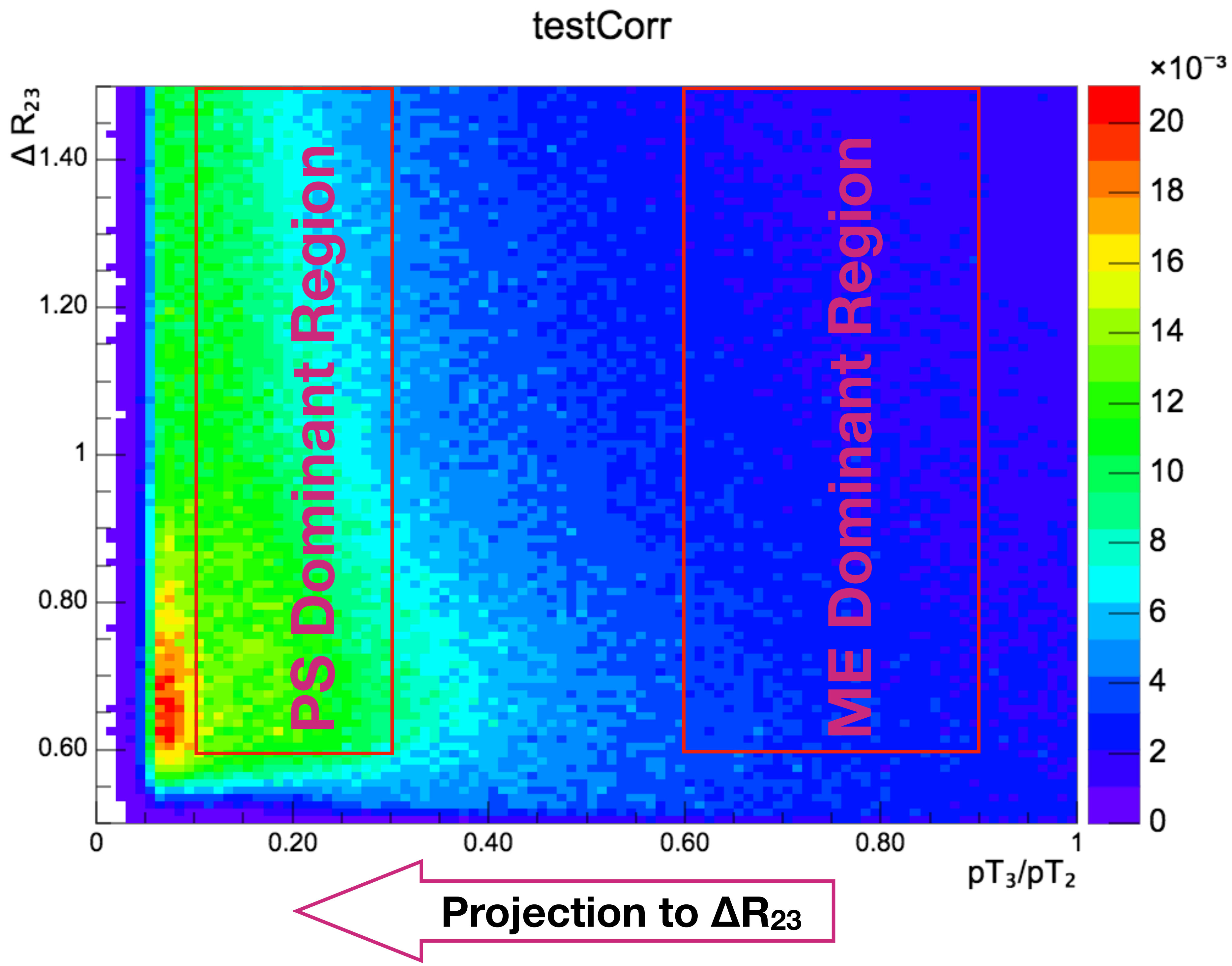
Observables

- pT ratio of 2nd jet and 3rd jet shows if parton radiation is soft or hard
  - PS describes soft radiation ($p_{T3}/p_{T2} < 0.3$)
  - ME describes hard radiation ($p_{T3}/p_{T2} > 0.6$)
- ΔR_{23} is representation of parton radiation opening angle
  - $\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\phi_3 - \phi 2)^2}$
  - PS describes small-angle radiation ($\Delta R_{23} < 1.0$)
  - ME describes large-angle radiation ($\Delta R_{23} > 1.0$)

For p_{T3}/p_{T2} Distribution



For ΔR23 Distribution



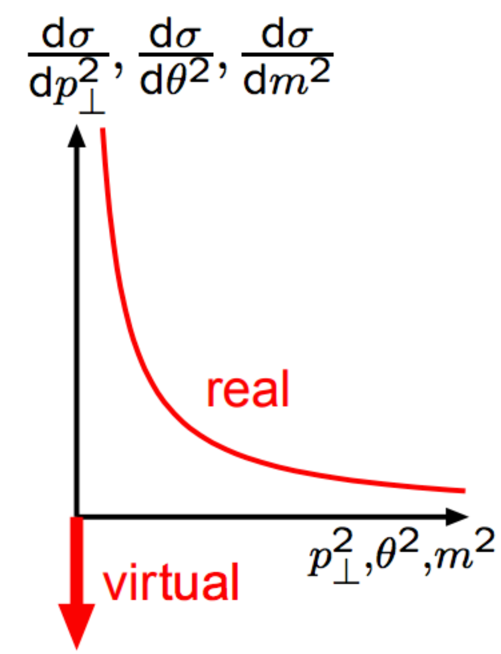
ME and PS Domain

- 3 jet event
  - Di-jet topology
  - 3rd jet from 2nd jet (parton shower)
  - In 3 jet events, looking correlation between 2nd and 3rd jet
- Parton Shower (PS) vs Matrix Element (ME)
  - PS: soft and collinear approximation
  - ME: fixed order, good for hard radiation
- PS method dominant regions
  - Soft radiation ($p_{T2} >> p_{T3}$)
  - Small-angle radiation (small ΔR_{23})
- ME method dominant regions
  - Hard radiation ($p_{T2} \sim p_{T3}$)
  - Large-angle radiation (large ΔR_{23})

ME vs PS

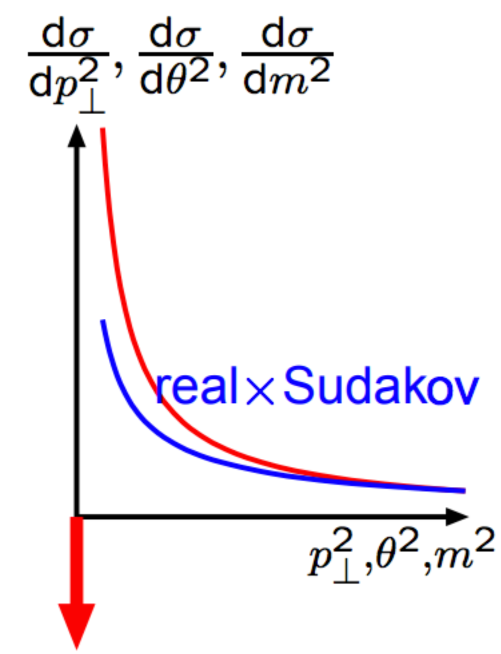
Matrix Elements (ME)

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



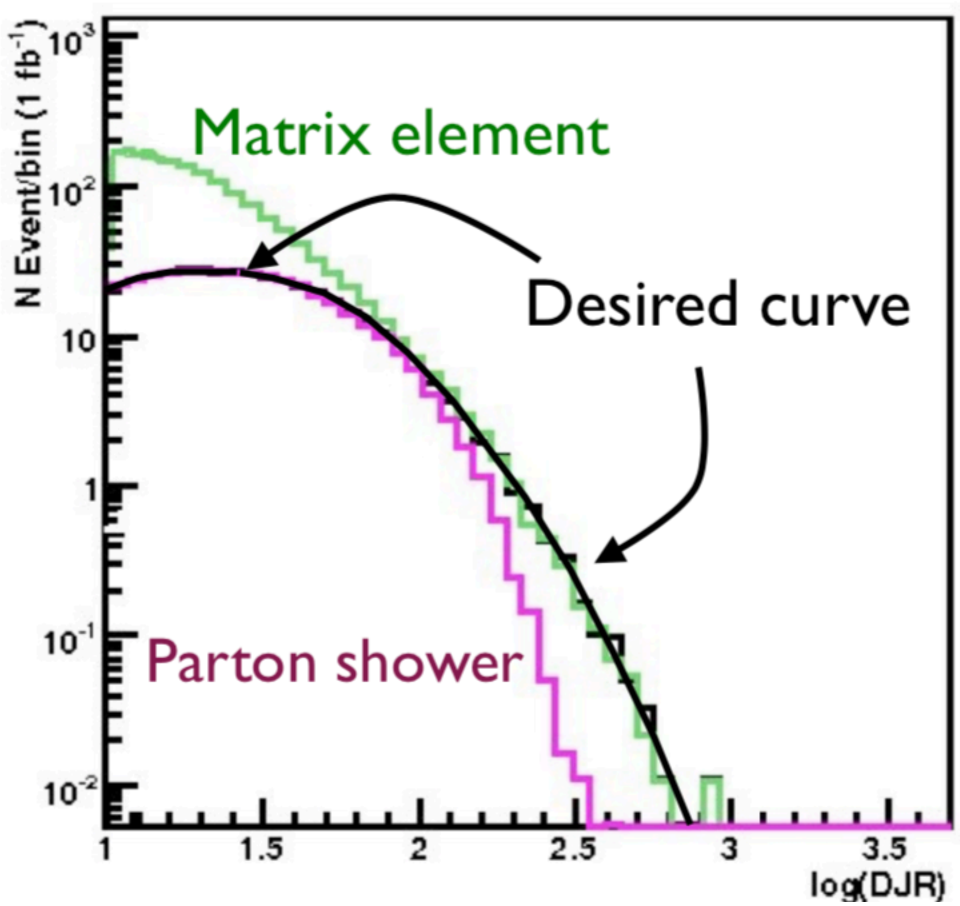
Parton Showers (PS)

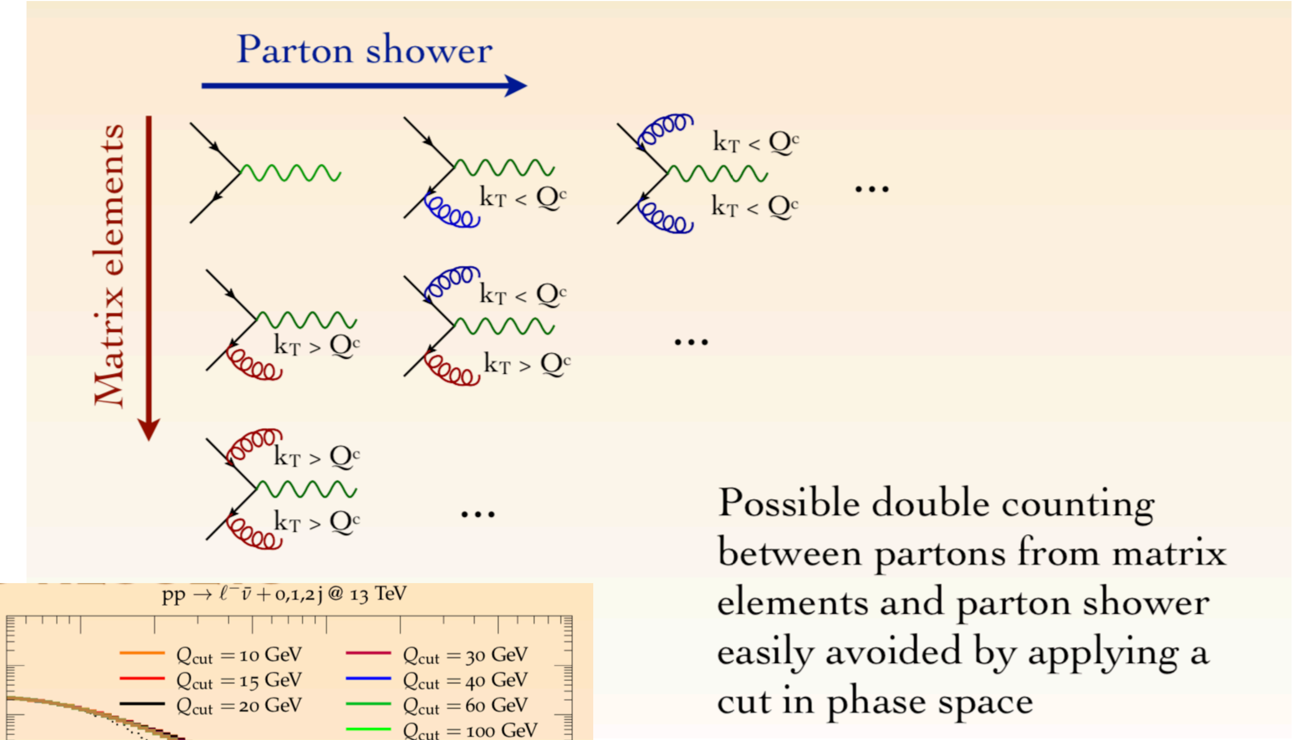
- Approximate, resums logs to all orders (LL or NLL)
- Main topology not predetermined: inefficient for exclusive states
- Computationally cheep
- Simple multi parton
- Valild when parsons are **soft and/or collinear**
- Sudakov form factors/resummation: sensible jet/event structure
- Easy to match to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

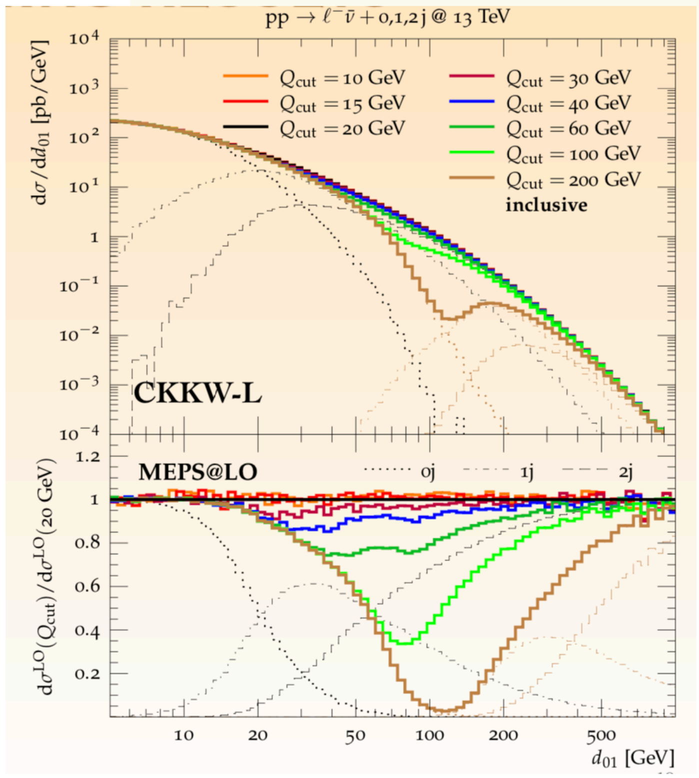


ME and PS Matching

- The best way to describe data with MC is matching ME and PS method
  - **Avoid double counting**
  - **Ensure smooth distributions**







LO ME and PS jet merging:

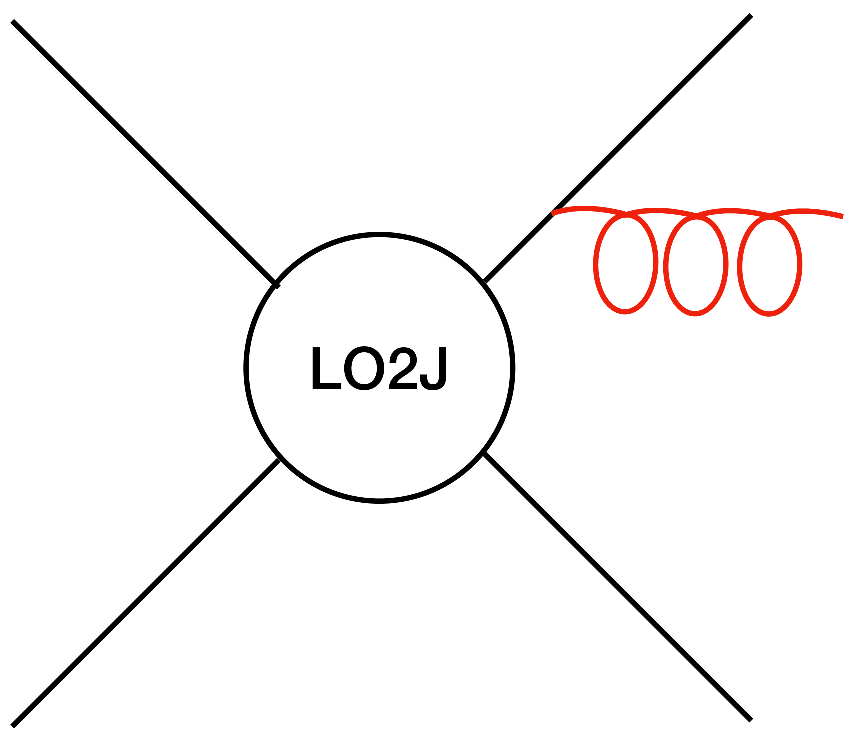
- **Merging scale with t_{cut}**
- **Use ME where all partons are harder than t_{cut}** and add Sudakov dampening to the ME

Event Generators

Event generator	Parton-level process	PDF set	Tune
Three-jet events			
PYTHIA 8.219	LO 2j+PS	NNPDF2.3LO	CUETP8M1
MADGRAPH 5.2.3.3 + PYTHIA 8.219	LO 4j+PS	NNPDF2.3LO	CUETP8M1
POWHEG 2 + PYTHIA 8.219	NLO 2j+PS	CT10 NLO	CUETP8M1
Z + two-jet events			
PYTHIA 8.219	LO Z+1j+PS	NNPDF2.3LO	CUETP8M1
MADGRAPH 5.1.3.30 + PYTHIA 6.425	LO Z+4j+PS	CTEQ6L1	Z2Star
SHERPA 1.4.0 + CSSHOWER++	LO Z+4j+PS	CT10	AMISIC++
aMC@NLO + PYTHIA 8.223	NLO Z+1j+PS	NNPDF30_nlo_nf_5_pdfas	CUETP8M1

To facilitate the comparison of data with theory, the **data are unfolded** from reconstruction to stable-particle level, defined by a mean decay length larger than 1 cm, so that measurement effects are removed and that the true distributions in the observables are determined

LO + PS

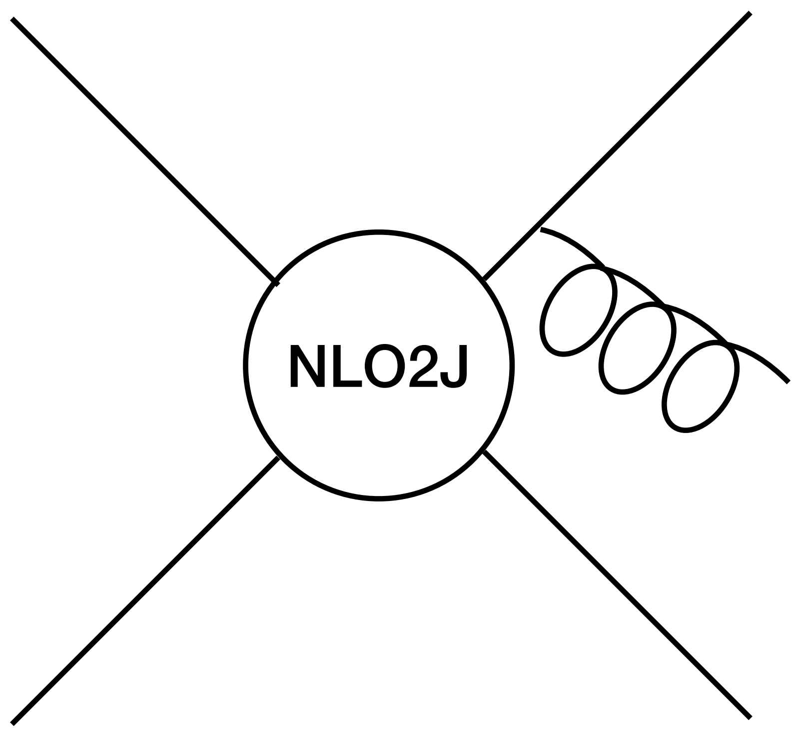


L02J + PS:
3rd jet is from PS calculation

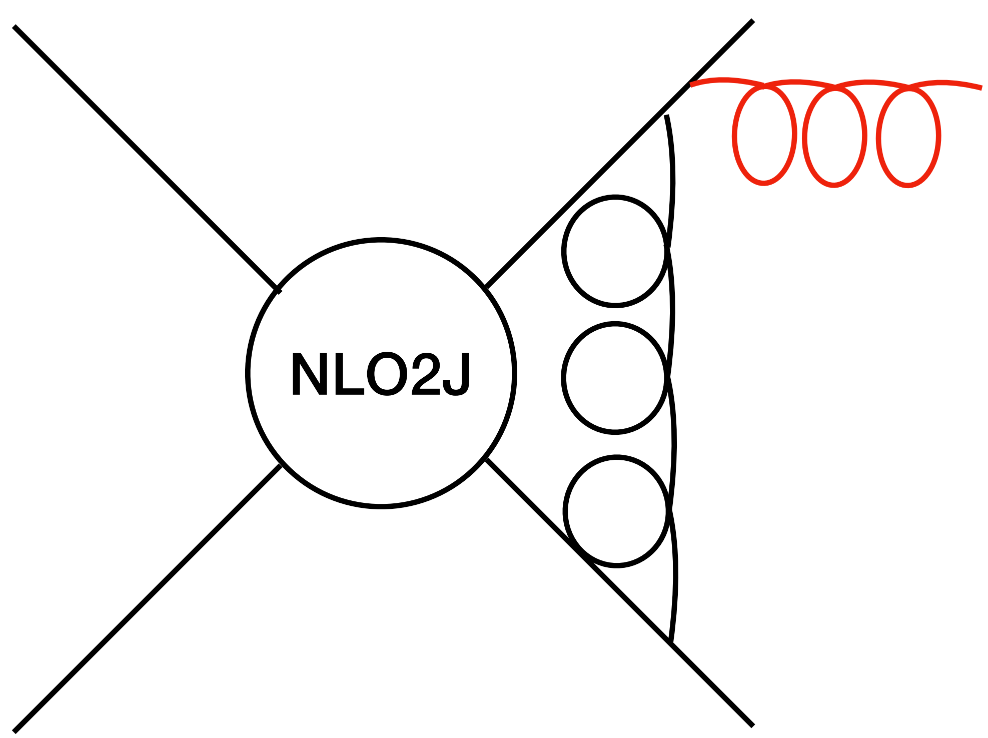
Hard scattering
- **pQCD + EW**
- **ME correction (default)**

+ PS
- **ISR, FSR**
- **Underlying Event**
  - **MPI**
  - **Beam remnants (color reconnection)**
- **Hadronization**
- **Ordinary decay**

NLO + PS

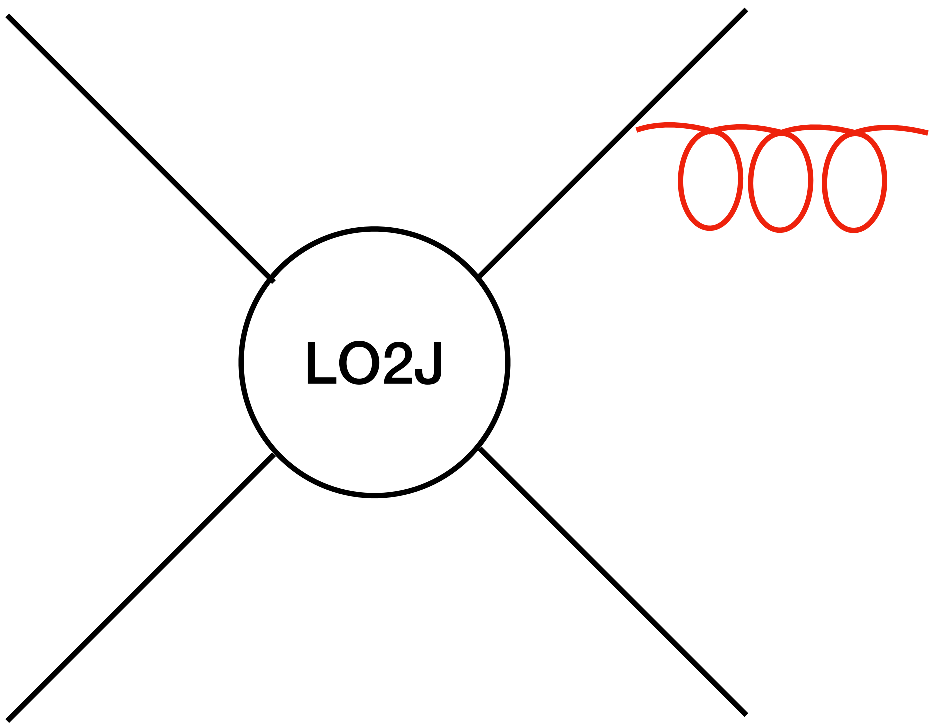


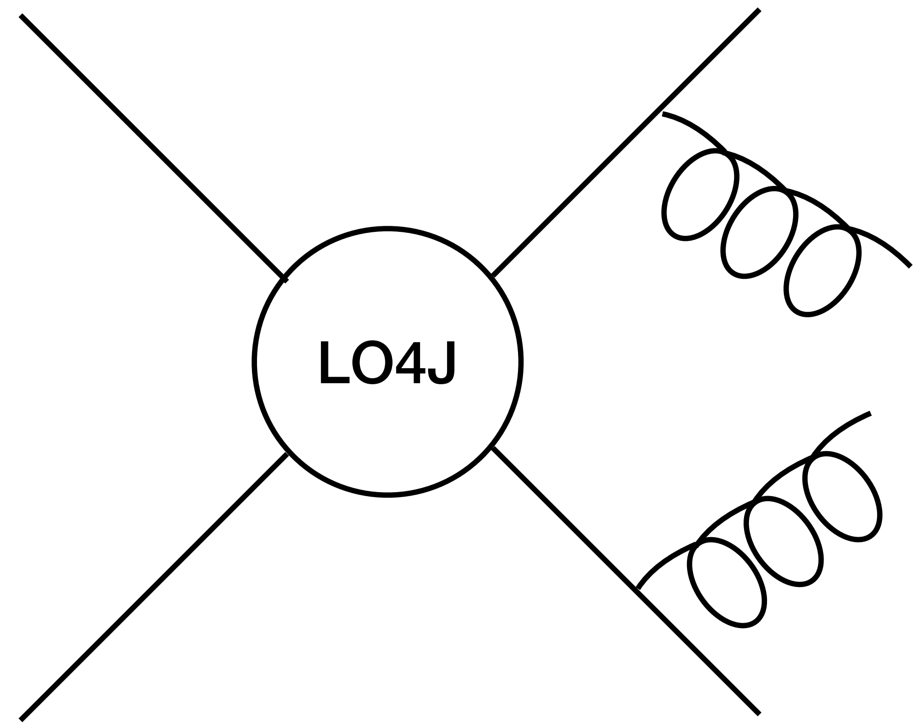
- **NLO ME calculation**



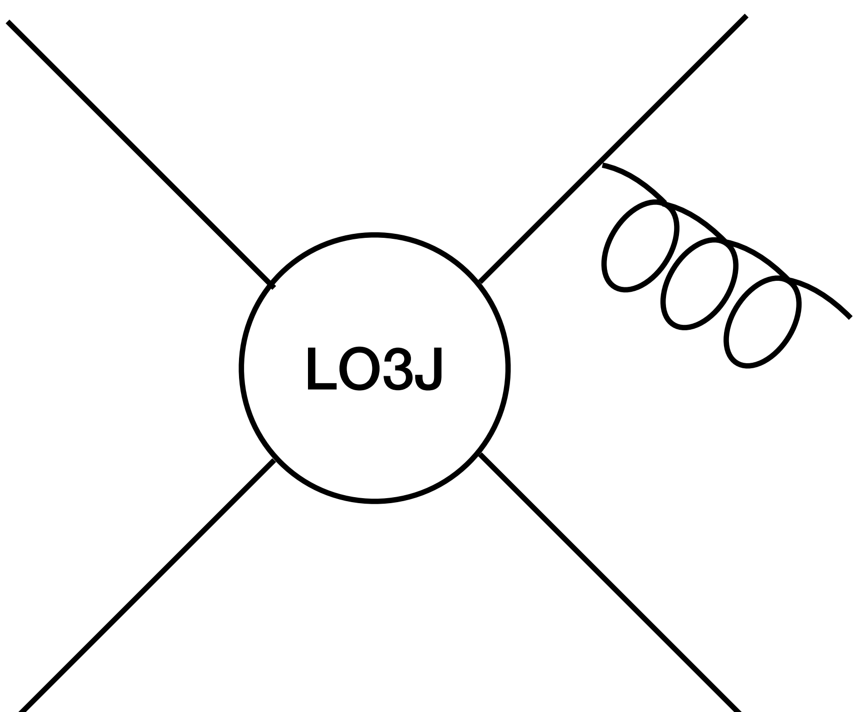
NL02J + PS:
3rd jet is from ME (NLO) calculation
Or ME (virtual) + PS

LO (High-multiplicity) + PS



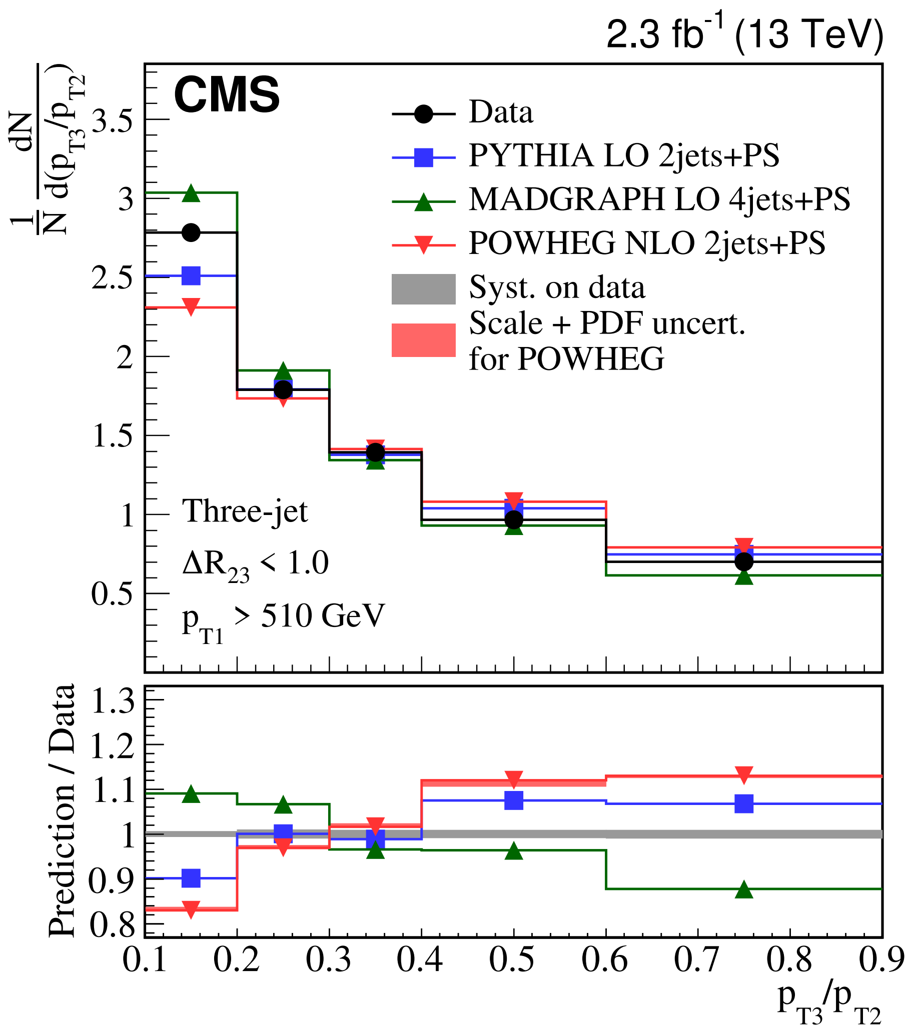


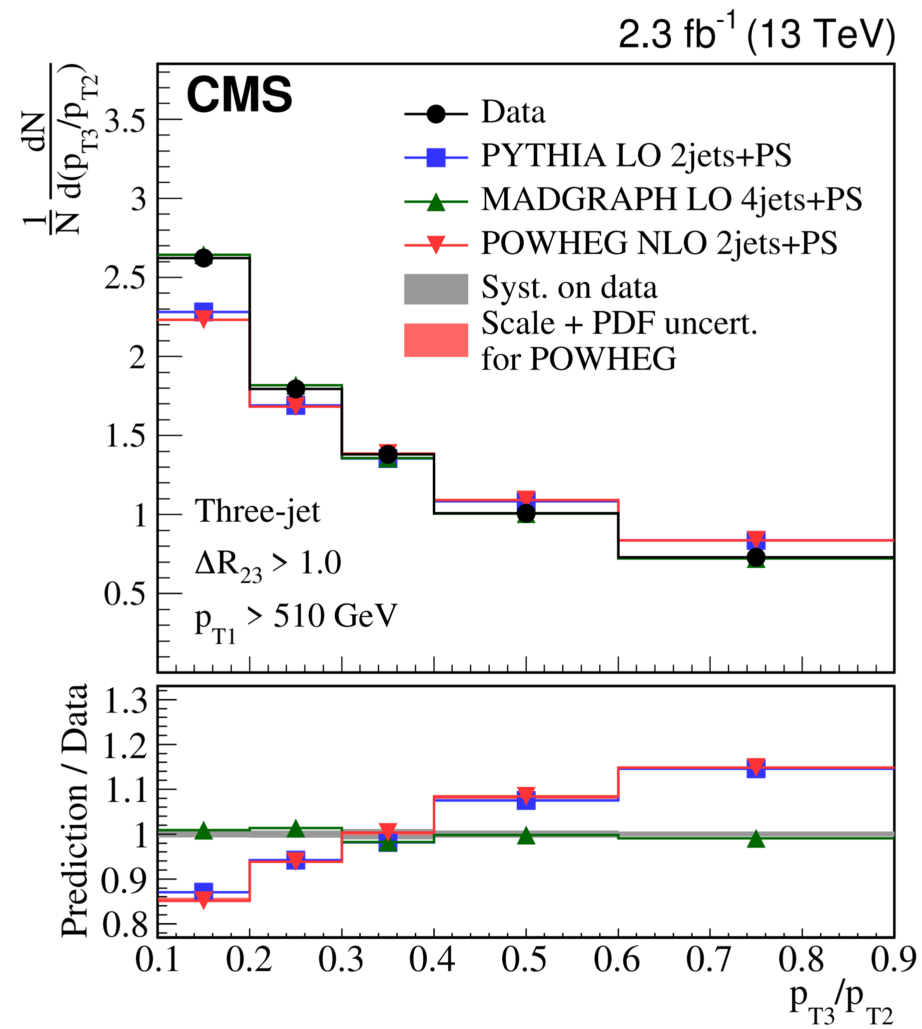
- **LO ME calculation**
- **PS jet merging**
  - **2 → 2 + 3 + 4 with Q_{cut} = 10 GeV**



L04J + PS:
3rd jet is from PS calculation
Or ME

Three-jet p_{T3}/p_{T2}

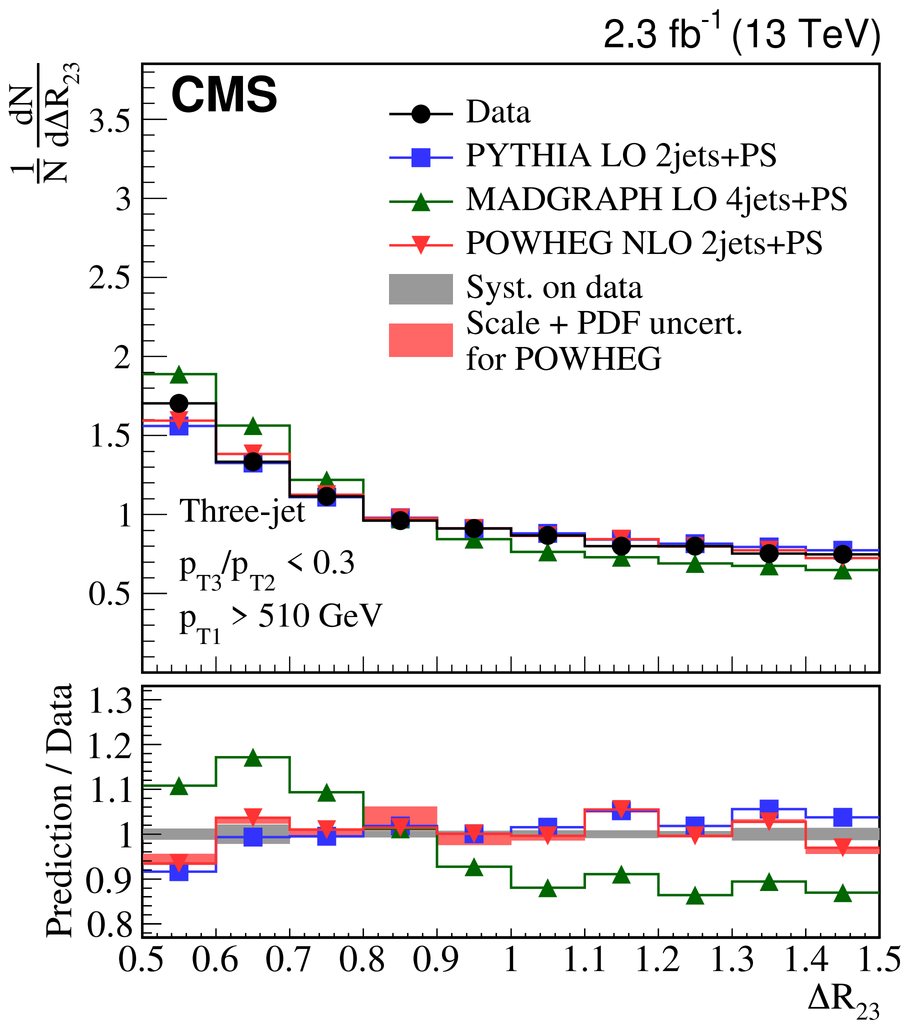


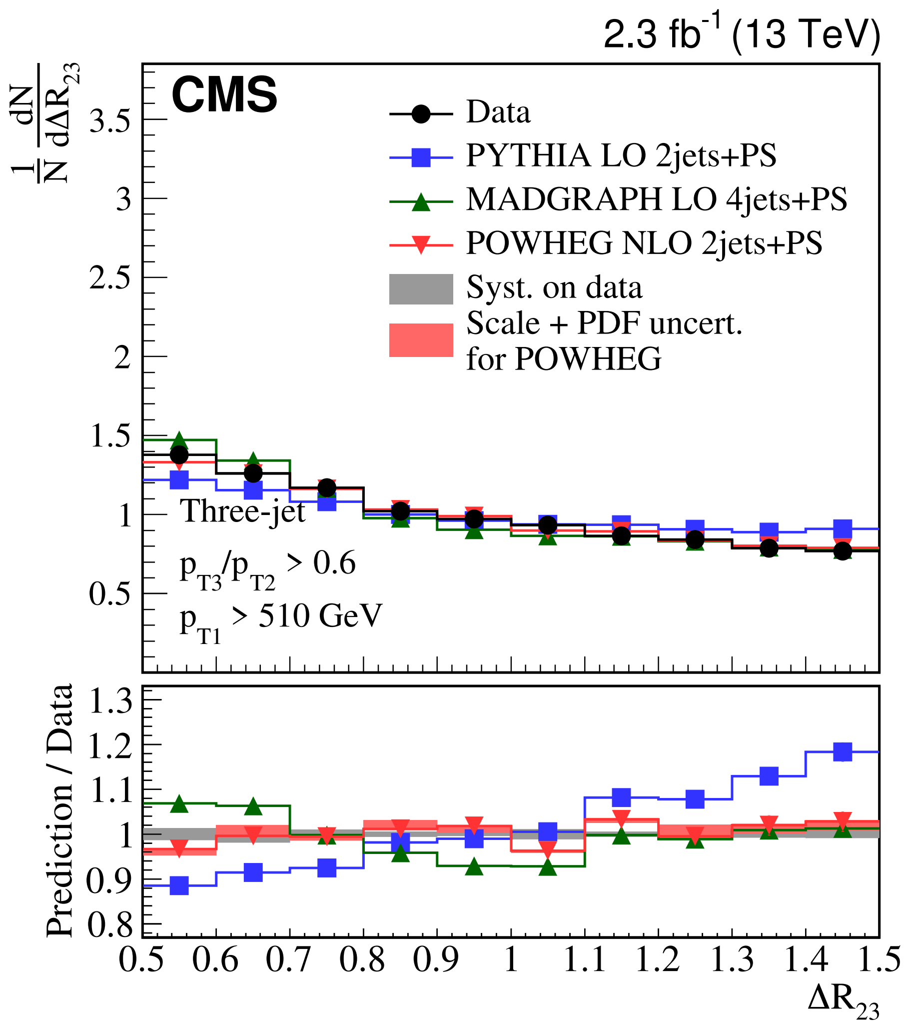


Eur. Phys. J. C **81,** 852 (2021). https://doi.org/10.1140/epjc/s10052-021-09570-2

- Small-angle radiation region (left)
  - All predictions show significant deviations from the measurements.
  - LO 4j+PS prediction shows different behavior compared with LO 2j+PS and NLO 2j+PS
  - The number of partons in the ME calculation and the merging method with the PS in the present simulations lead to different predictions
- Large-angle radiation region (right)
  - The LO 4j+PS calculations well described
  - The LO 2j+PS and NLO 2j+PS predictions show large deviations from the measurements

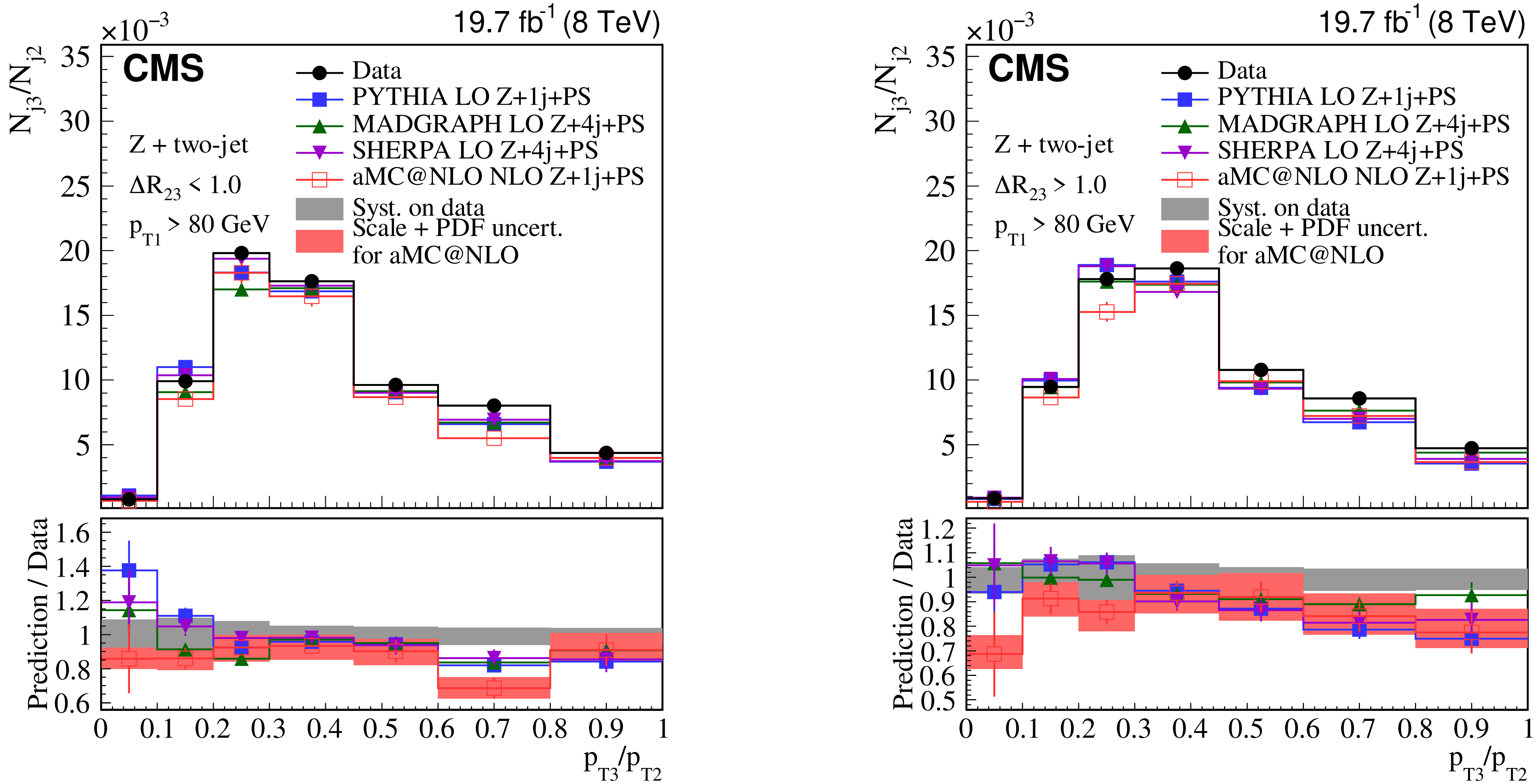
Three-jet ΔR_{23}





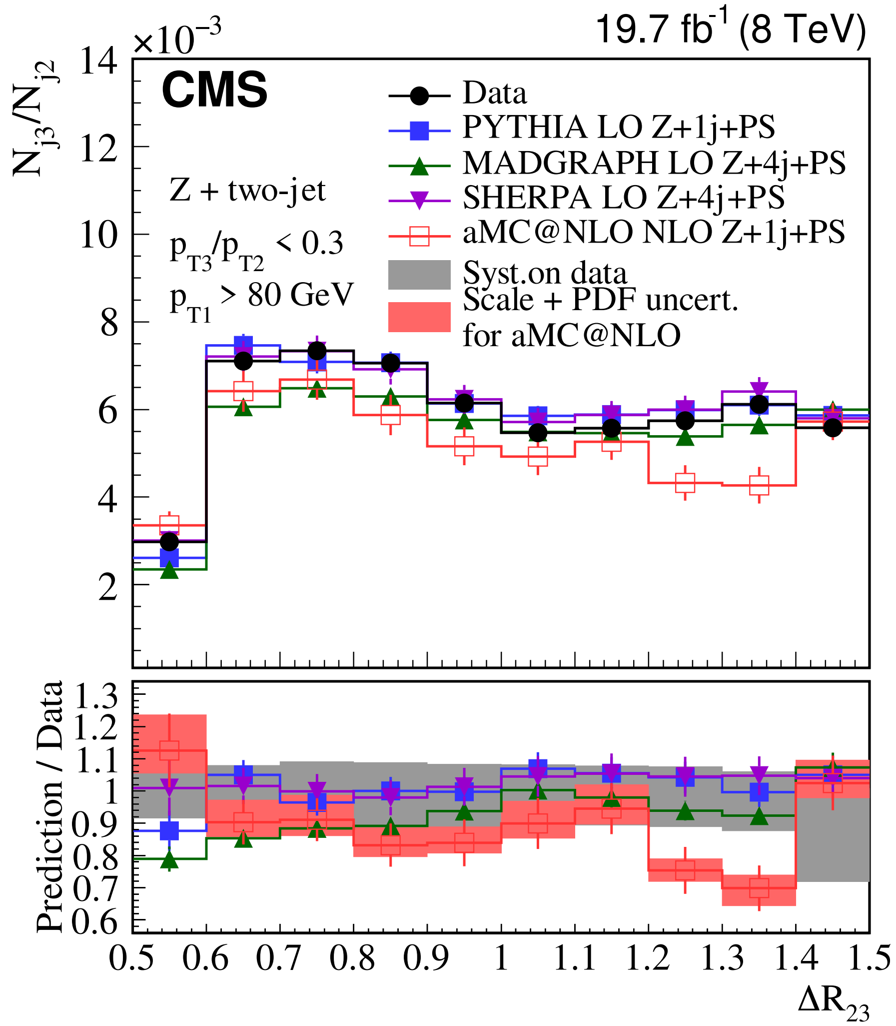
- Soft radiation region (left)
  - The predictions from LO 2j+PS and NLO 2j+PS describe the measurement well
  - The prediction from LO 4j+PS shows a larger deviation from the data
- Hard radiation region (right)
  - The predictions for distributions from LO 2j+PS differ from the measurement
  - The predictions from NLO 2j+PS and LO 4j+PS agree well
  - Higher-multiplicity ME calculations are needed to describe well

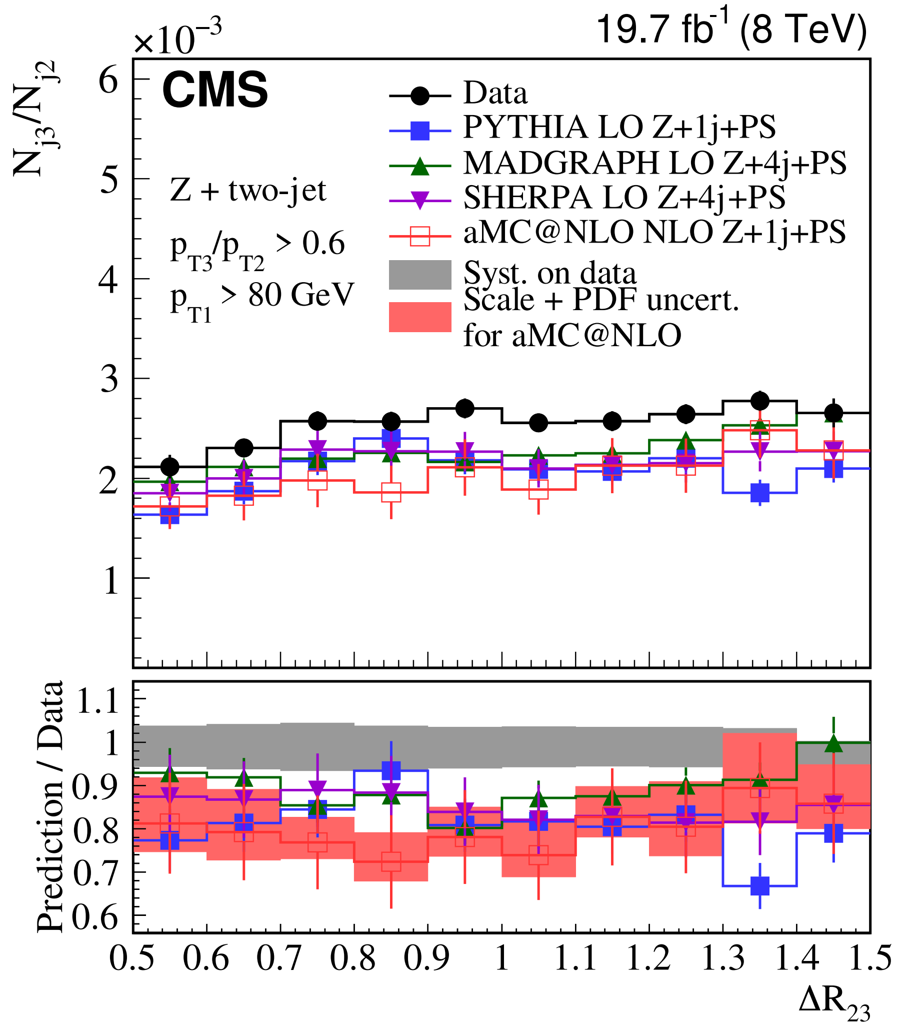
Z + two-jet p_{T3}/p_{T2}



- All distributions are normalized to the selected number of Z + one-jet events
- In general, the measurements with Z + two-jet events are well described by all theoretical predictions, except for the underestimation of the j_3 emission
- The contribution of the background (ttbar production with full leptonic decay and dibosons) increases the probability of j_3 emission from 2% (soft radiation) to 10% (hard radiation) depending on the phase space region

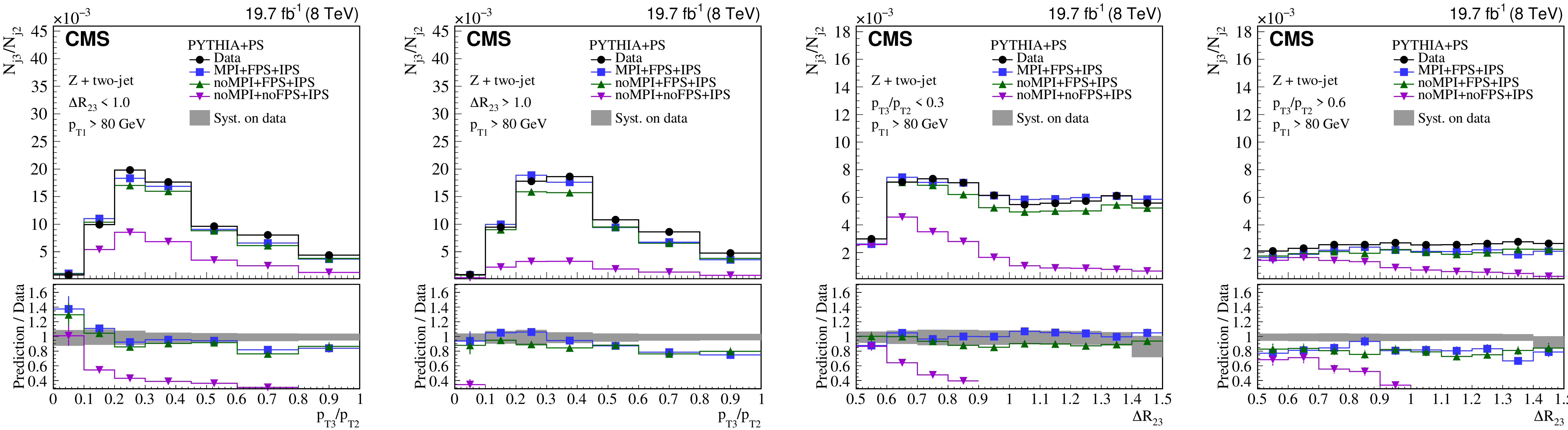
Z + two-jet ΔR_{23}





- In comparison with the three-jet measurements, Z + two-jet measurements show significant differences
- The different kinematic selection criteria relative to three-jet events, thus reducing the sensitivity in the soft and collinear region
- Within the available phase space, the measurements are in reasonable agreement with both PS and ME calculations

Z + two-jet



- Compare the event distributions with predictions from PYTHIA 8 with the final-state PS and MPI switched off
- The initial-state PS was kept because one of the jets must originate from PS when Z + two-jet events are selected
- Multiple parton interactions play a very minor role, while the final-state PS in PYTHIA 8 is very important
- When the final-state PS is switched off, events where both jets come from the initial-state PS
- The initial-state PS are kept with a tendency to be close to each other in ΔR_{23}

Summary

- Two kinematic variables are introduced to quantify the radiation pattern in multijet events
- Transverse momentum ratio (pT3/pT2) is measured
  - Small-angle radiation: $\Delta R_{23} < 1.0$
  - Large-angle radiation: $\Delta R_{23} > 1.0$
- Angular separation (ΔR_{23}) is measured
  - Soft radiation: $p_{T3}/p_{T2} < 0.3$
  - Hard radiation: $p_{T3}/p_{T2} > 0.6$
- Three-jet
  - **The collinear region is not well described by all predictions**
  - The PS approach fails to describe the regions of large-angle and hard radiation region but well describes the measurement in the soft radiation region
  - Higher-multiplicity ME calculations are needed to describe well in the hard radiation region
  - The methods of merging ME with PS calculations are not yet optimal for describing the full region of phase space
- Z + two-jet
  - **The distributions in Z + two-jet events are reasonably described by all tested generators**
  - An underestimation of third-jet emission at large pT3/pT2 both in the collinear and large-angle regions, for all of the tested models
  - The background contribution may partially cover the difference
  - The different kinematic regions and initial-state flavor composition may be the reason why the three-jet measurements are less consistent with the theoretical predictions relative to the Z + two-jet final states

Backup

Event Selection

Table 1: Phase space selection for the three-jet and Z + two-jet analyses.

Three-jet events	
Transverse momentum of the leading jet (j_1)	$p_{T1} > 510\,\text{GeV}$
Transverse momentum of each jet and rapidity of $j_{1,2}$	$p_T > 30\,\text{GeV}$, $\lvert y_{1,2}\rvert < 2.5$
Azimuthal angle difference between j_1 and j_2	$\pi - 1 < \Delta\phi_{12} < \pi$
Transverse momentum ratio between j_2 and j_3	$0.1 < p_{T3}/p_{T2} < 0.9$
Angular distance between j_2 and j_3	$R_{jet} + 0.1 < \Delta R_{23} < 1.5$
Number of selected events at $\sqrt{s} = 8\,(13)$ TeV	777,618 (613,254)

Z + two-jet events	
Transverse momentum of the Z boson (j_1)	$p_{T1} > 80\,\text{GeV}$, $\lvert y_1\rvert < 2$
Transverse momentum and rapidity of j_2	$p_{T2} > 80\,\text{GeV}$, $\lvert y_2\rvert < 1$
Transverse momentum and rapidity of j_3	$p_{T3} > 20\,\text{GeV}$, $\lvert y_3\rvert < 2.4$
Azimuthal angle difference between Z and j_2	$2 < \lvert\Delta\phi_{12}\rvert < \pi$
Dimuon mass	$70 < m_{\mu^+\mu^-} < 110\,\text{GeV}$
Angular distance between j_3 and j_2	$0.5 < \Delta R_{23} < 1.5$
Number of selected events	15 466

Systematics

- Considered systematics
  - Jet Energy Scale (JES)
  - Jet Energy Resolution (JER)
  - Pileup weight (PU)
  - Physics Model (MOD)
  - Unfolding (UNFOLD)
- Systematics are compared in normalized yield
- Maximum values are used
- Unfolded (particle level) systematics
- 8 TeV MOD and UNFOLD uncertainties are grater that 13 TeV
  - 8 TeV MADGRAPH response matrix used PYTHIA 6 for PS