Dijet Azimuthal Decorrelations in *pp* Collisions at 7 TeV

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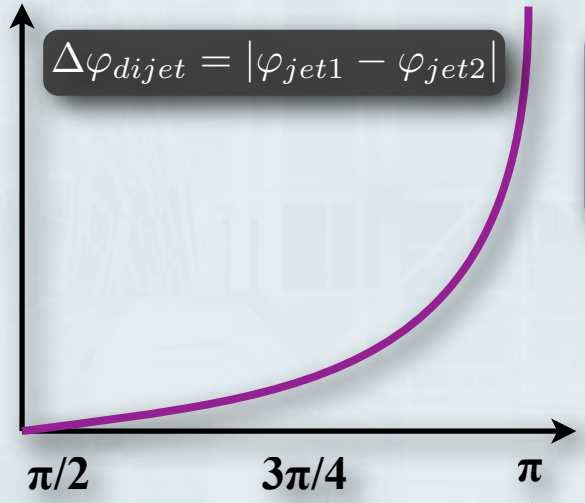
Outline

- Motivation
- Theoretical Framework
- Monte Carlo Simulations
- CMS Detector
- Jets at CMS
- Dijet Azimuthal Decorrelations
  - Event Selection
  - Corrections
  - Systematic Uncertainties
  - Results
- Summary

Motivation

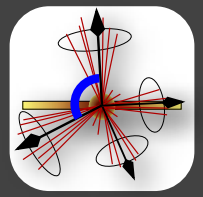
Measurement is sensitive to quark and gluon radiation effects



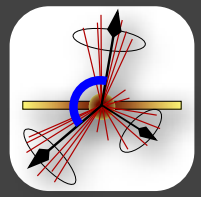
Test pQCD and Monte Carlo generators over a wide range of jet multiplicity

No need to reconstruct additional jets

Hard Radiation
$\Delta\varphi << \pi$



Soft Radiation
$\Delta\varphi < \pi$



No Radiation
$p_{T,jet1} = p_{T,jet2}$
$\Delta\varphi = \pi$

Useful to tune initial state radiation parameter in Monte Carlo generators

Previously measured at DØ

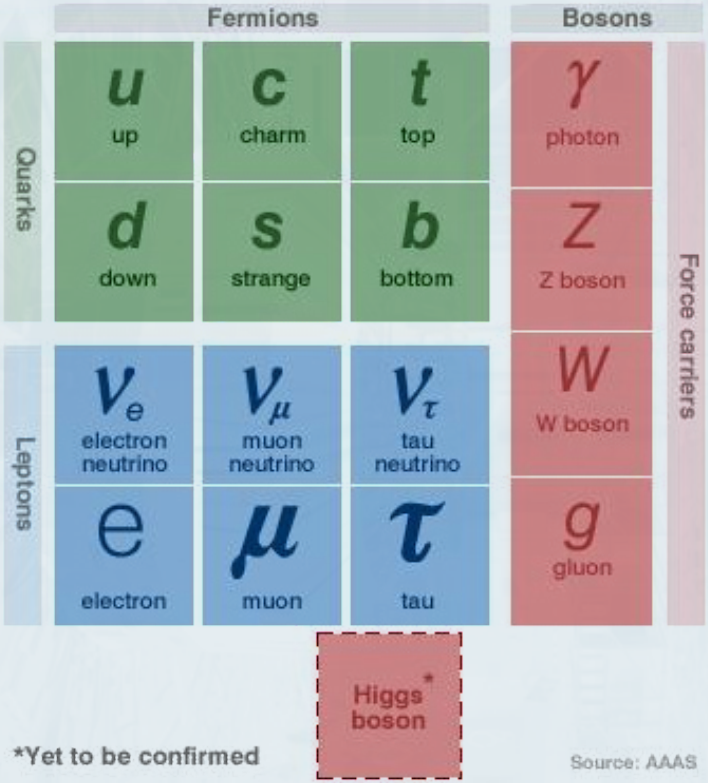
First measured at LHC by CMS

THEORETICAL FRAMEWORK

Standard Model

SM incorporates:

- Strong interaction (eight gluons)
- Electromagnetic interaction (photon)
- Weak interaction ($W^{\pm}$, Z^0)



Three generations of:

- Leptons (EM and/or Weak)
- Quarks (Strong, EM, Weak)

Not observed yet

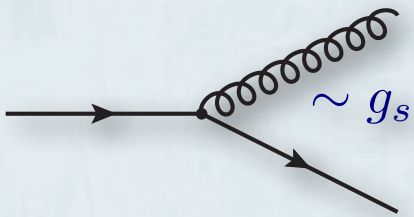
Higgs boson

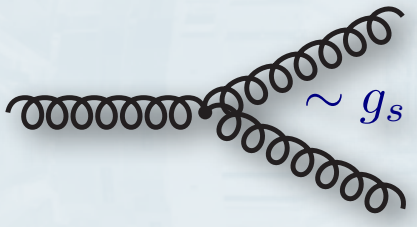
- give mass to particles

Quantum Chromodynamics I

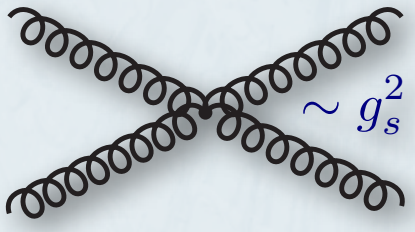
Describes the interactions between colored particles

- **Quarks (R,B,G)**
- **Gluons (color+anticolor)**



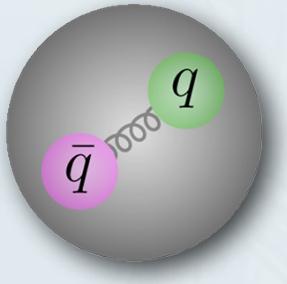


$$g_s = \sqrt{4\pi\alpha_s}$$

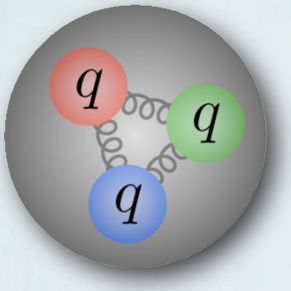


Quarks are observed as bound states

- **Mesons (quark-antiquark)**



- **Baryons (three quarks)**

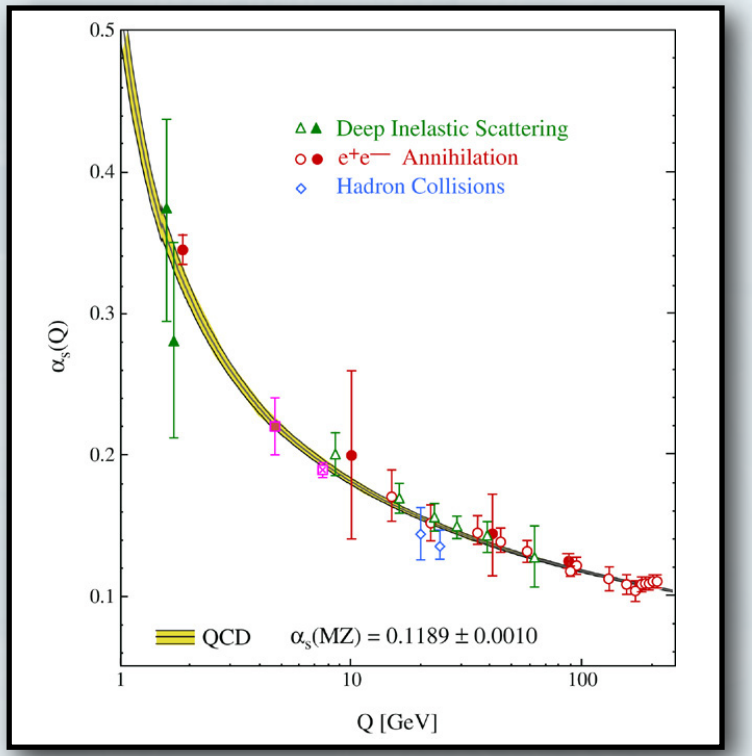


Quantum Chromodynamics II

The strength of the chromodynamic force is given by the strong coupling constant (α_s)

$$\alpha_s(Q^2) = \frac{12\pi}{(11n_c - 2n_f)\ln\frac{Q^2}{\Lambda^2}}$$

$$\Lambda \approx 200 \text{ MeV}$$

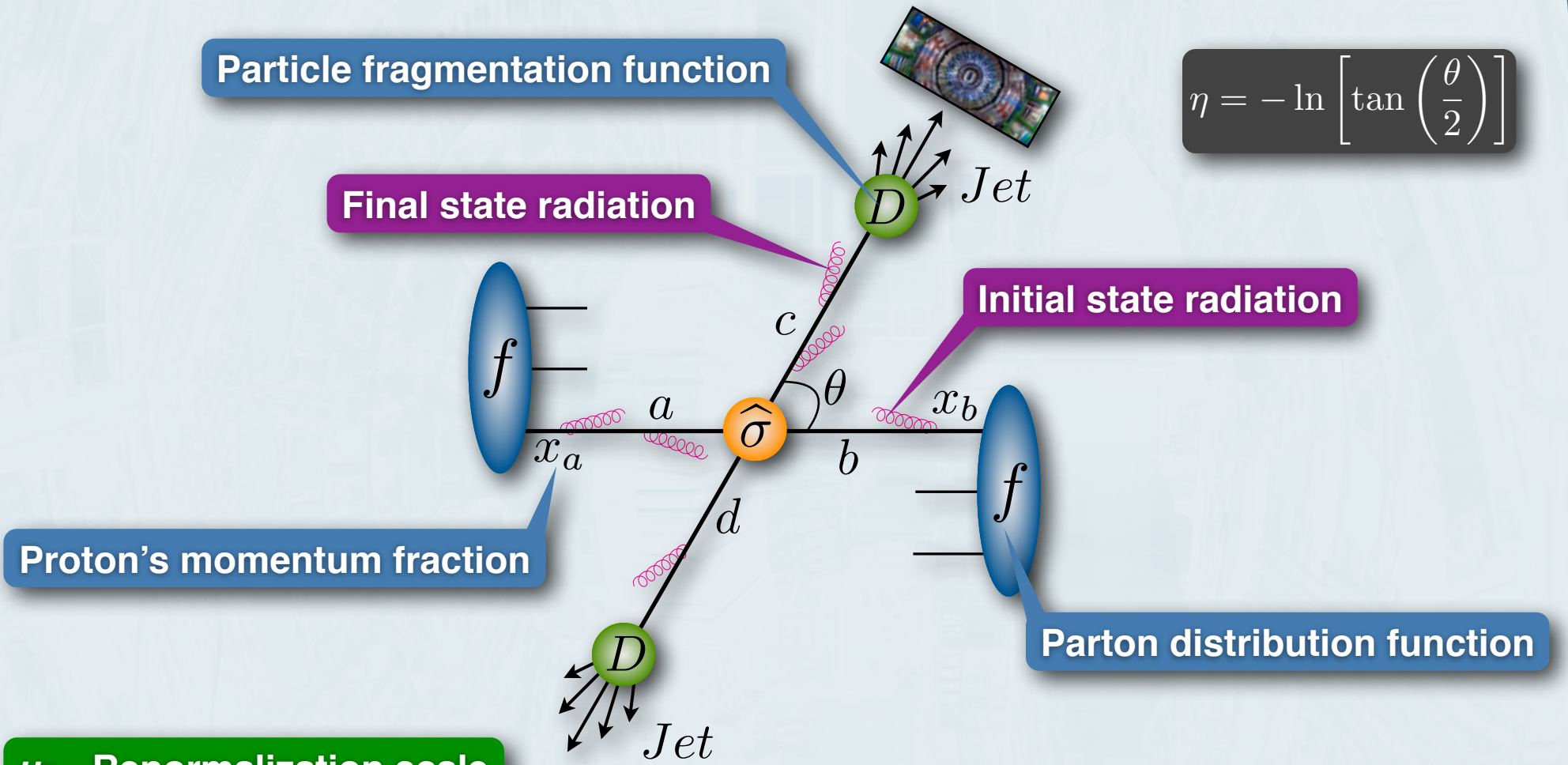


α_s decreases as Q^2 increases

Confinement

Asymptotic freedom (we can use pQCD)

Proton-Proton Interaction



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

μ_R - Renormalization scale

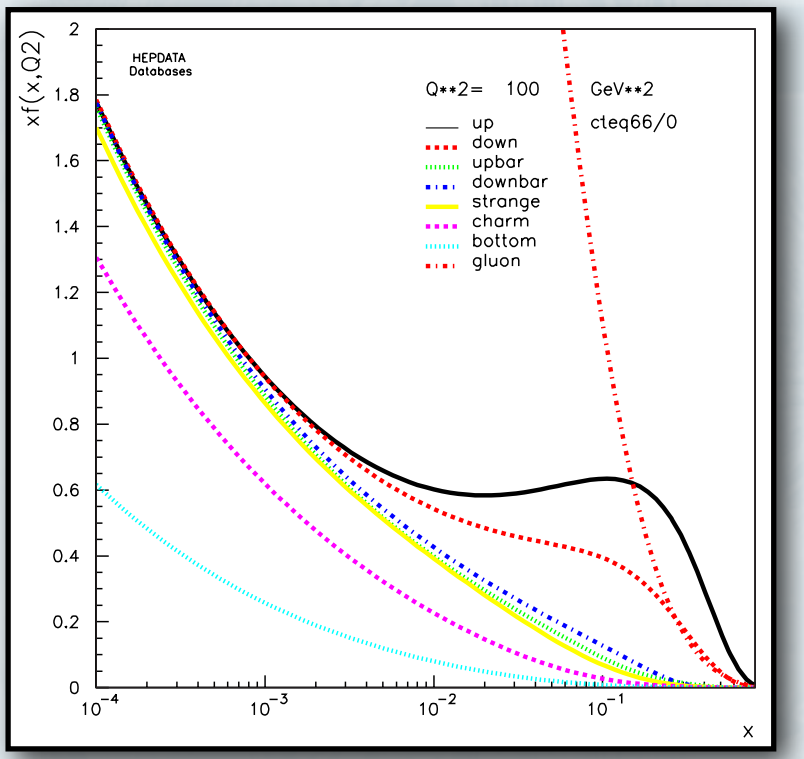
μ_F - Factorization scale

$\mu_F = \mu_R = Q = p_T$

$$\sigma_{ab} = \sum_{i,j} \int dx_a dx_b f_i\left(x_a, \mu_F^2\right) f_j\left(x_b, \mu_F^2\right) \widehat{\sigma}_{ij}\left(p_a, p_b, \alpha_s\left(\mu_R^2\right), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Parton Distribution Functions

Measured from data at a specific Q^2 and then evolved to the interaction scale of interest

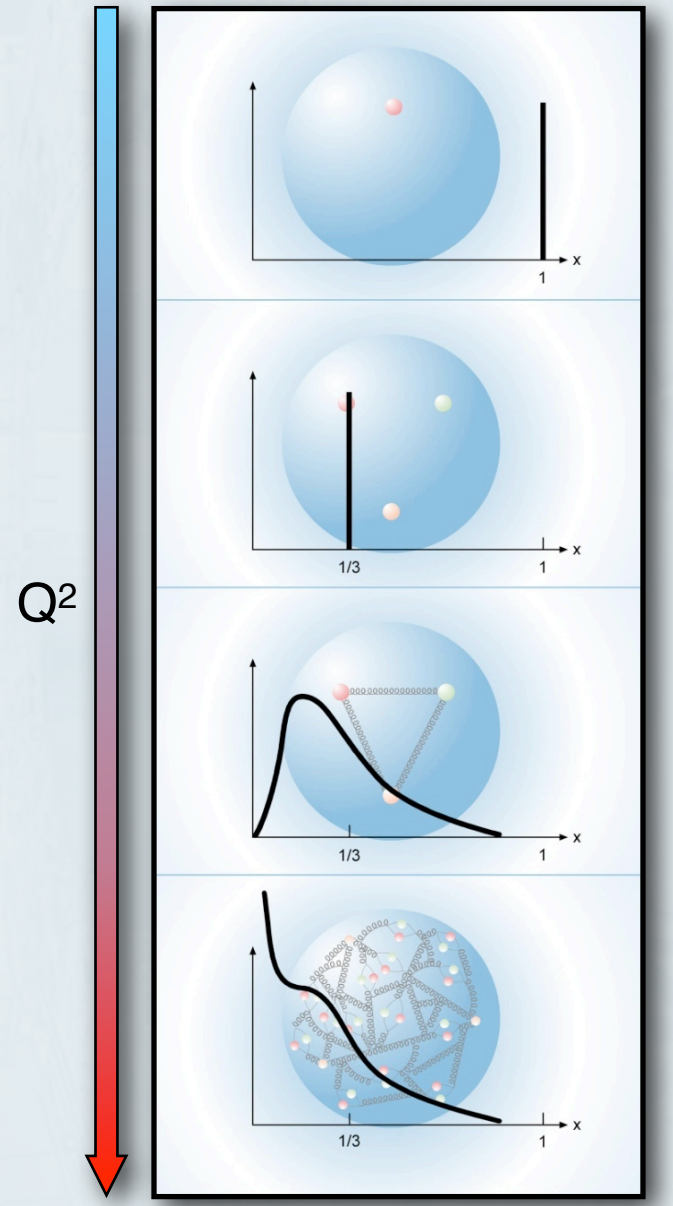


$$x f(x) = p_0 x^{p_1} (1-x)^{p_2} P(x)$$

Small x

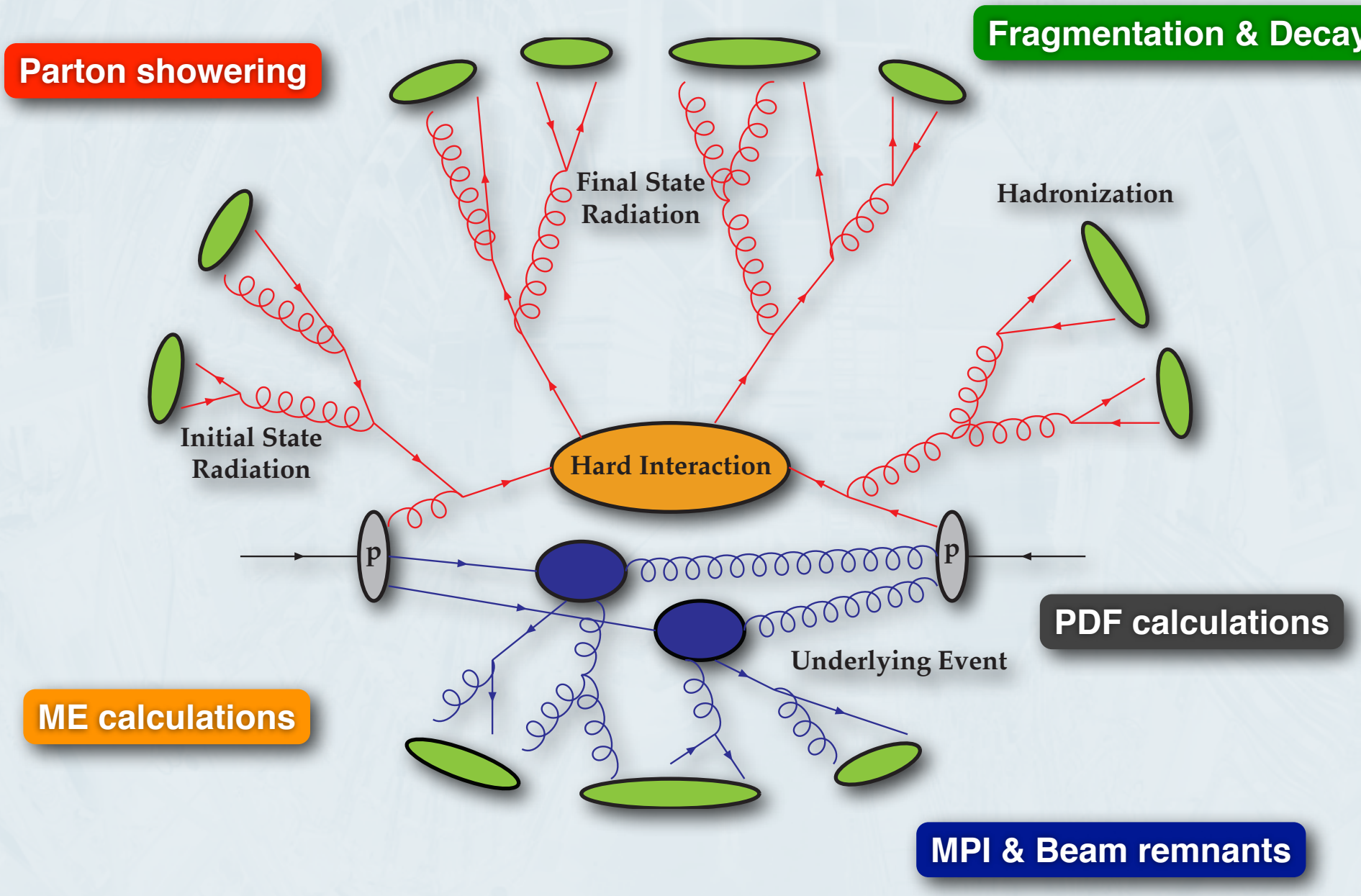
Large x

In between



MONTE CARLO SIMULATIONS

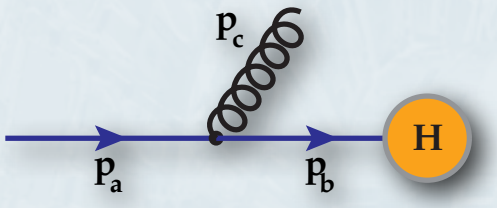
Event Description



Monte Carlo Models

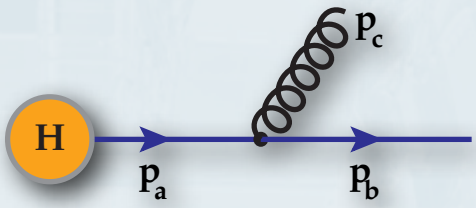
Parton showering models

Space-like branching (ISR)



$$|p_b^2| \gg |p_a^2|, |p_c^2| \ \& \ p_b^2 < 0$$

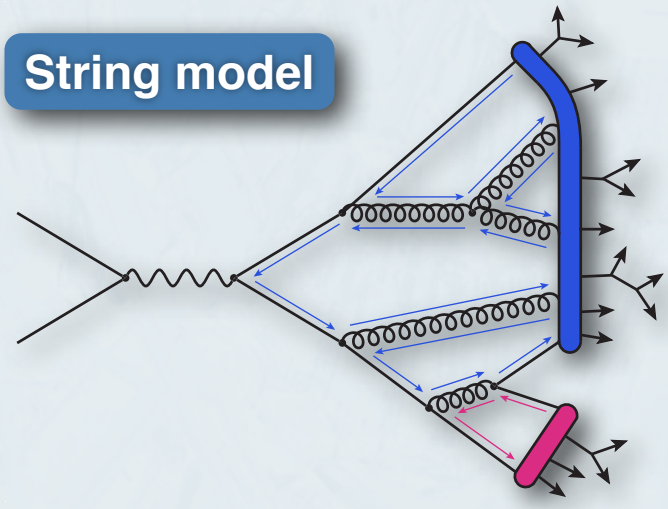
Time-like branching (FSR)



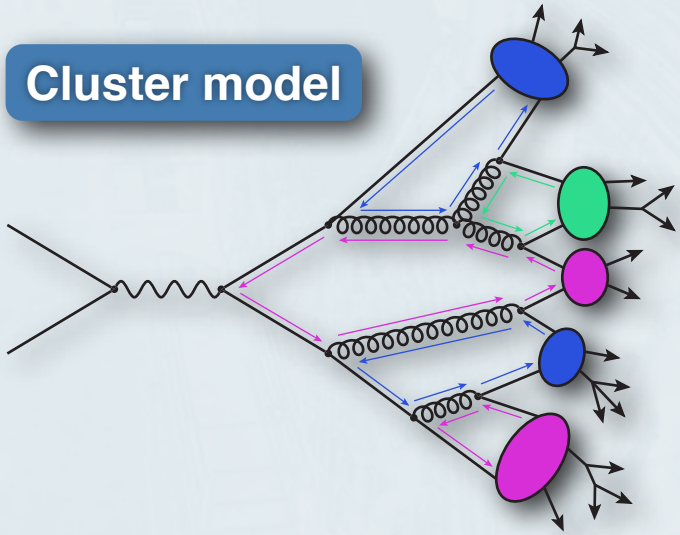
$$p_a^2 \gg p_b^2, p_c^2 \ \& \ p_a^2 > 0$$

Hadronization models

String model



Cluster model



Monte Carlo Generators

PYTHIA 6/8

- ME calculations for 2 → 2 LO tree-diagrams
- Higher multiplicities through parton showering (different ordering)
- String hadronization model
- various data tunes

HERWIG++

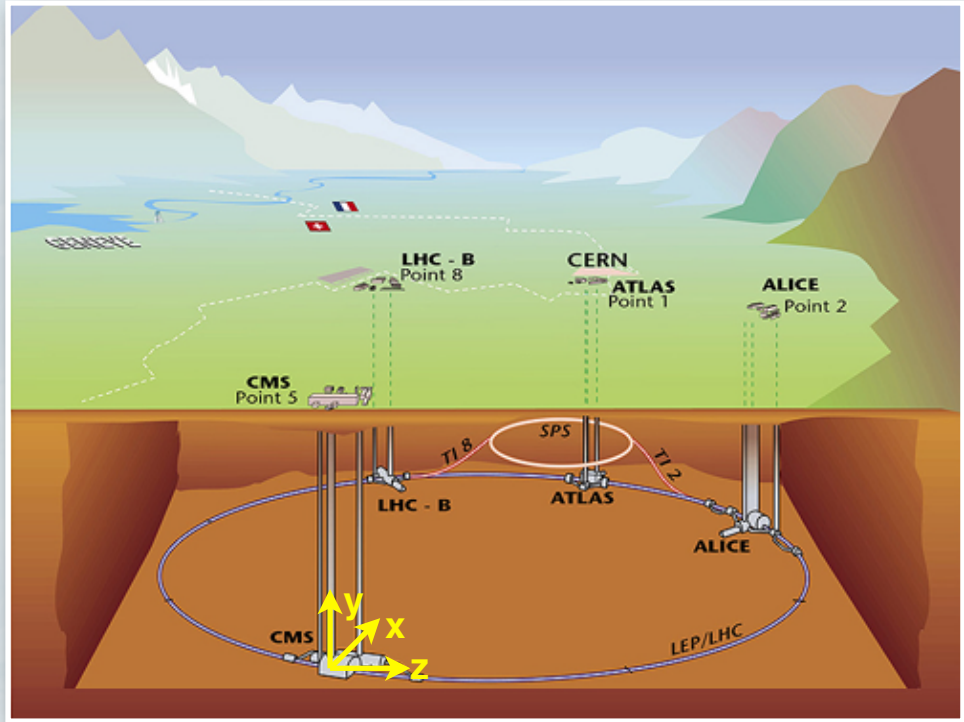
- ME calculations for 2 → 2 LO tree-diagrams
- Higher multiplicities through parton showering
- Cluster hadronization model

MADGRAPH

- ME calculations up to 2 → 7 LO tree-diagrams
- For showering and hadronization, events are passed through PYTHIA

CMS DETECTOR

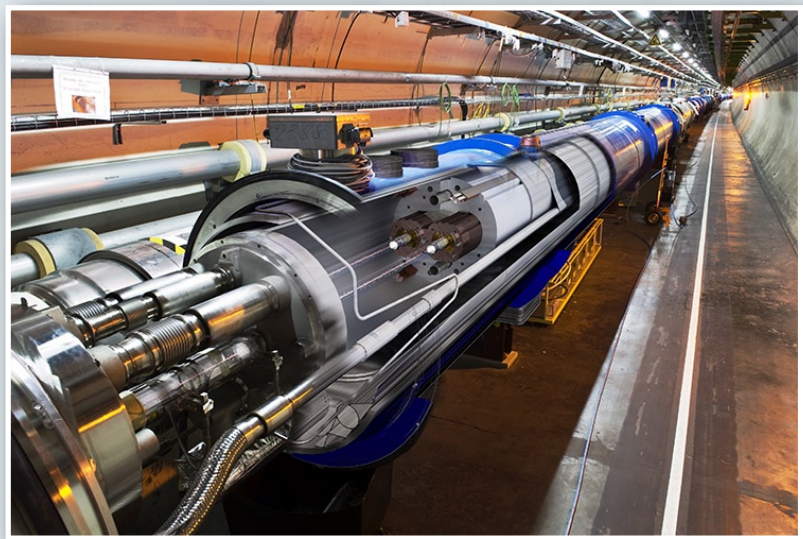
Large Hadron Collider



LHC is designed to collide

- protons at E_{CM} = 14 TeV (7 TeV)
- lead ions at 2.76 TeV per nucleon

Aug 2010 (10^{30} $cm^{-2}s^{-1}$)
Oct 2011 (10^{33} $cm^{-2}s^{-1}$)
Design (10^{34} $cm^{-2}s^{-1}$)



26.7 km (16.6 mi)

Houses four big experiments

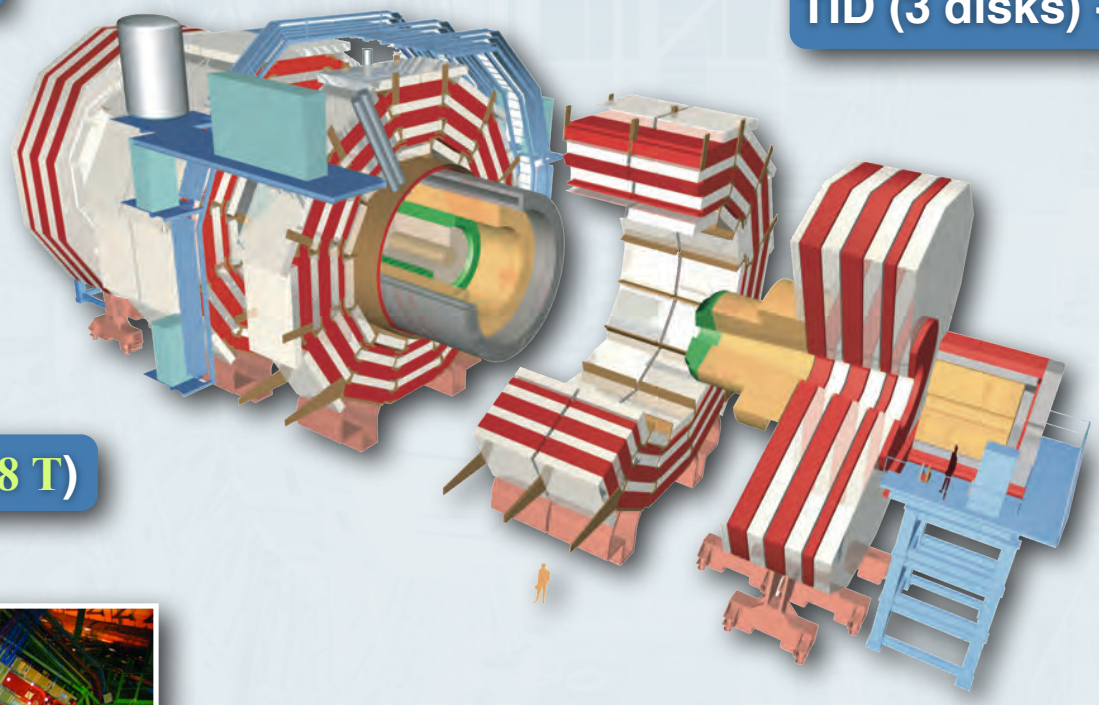
- CMS (multipurpose)
- ATLAS (multipurpose)
- ALICE (heavy ions)
- LHCb (b-physics)

CMS Tracking Systems

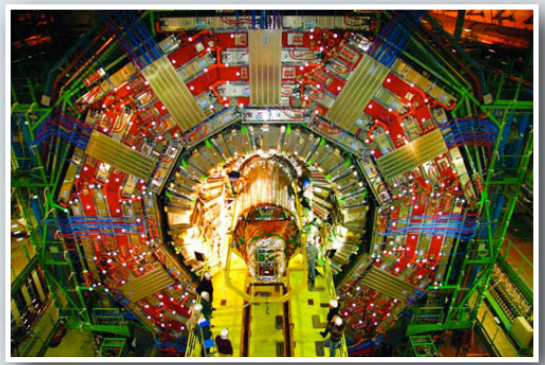
PIXEL ($|\eta| < 2.5$)
BPIX (3 layers)
FPIX (2 disks)

TRACKER ($|\eta| < 2.5$)
TIB (4 layers) + TOB (6 layers)
TID (3 disks) + TEC (9 disks)

Return Yoke



MAGNET (3.8 T)

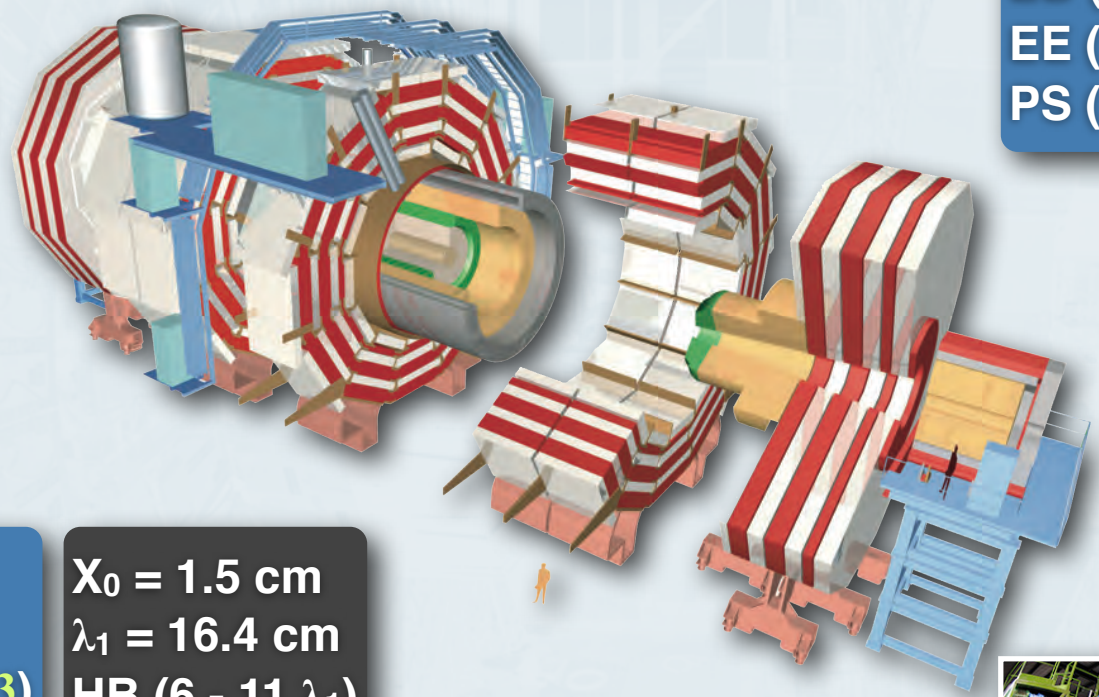


MUON SYSTEM ($|\eta| < 2.4$)
MB (4 DT stations + 6 RPC layers)
ME (4 CSC stations + 3 RPC layers)

CMS Calorimeters

CASTOR ($5.2 < |\eta| < 6.6$)

ZDC ($|\eta| > 8.3$)

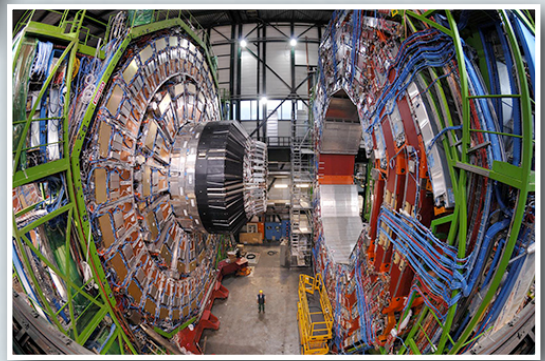


ELECTROMAGNETIC CALORIMETER
EB ($|\eta| < 1.5$)
EE ($1.5 < |\eta| < 3.0$)
PS ($1.6 < |\eta| < 2.6$)

X_0 = 0.9 cm
R_m = 2.2 cm
EB (26 X_0)
EE (25 X_0)
PS (3 X_0)

HADRONIC CALORIMETER
HB + HO ($|\eta| < 1.3$)
HE ($1.3 < |\eta| < 3.0$)
HF ($3.0 < |\eta| < 5.0$)

X_0 = 1.5 cm
λ_1 = 16.4 cm
HB (6 - 11 λ_1)
HO (1.5 λ_1)
HE (10 λ_1)
HF (10 λ_1)

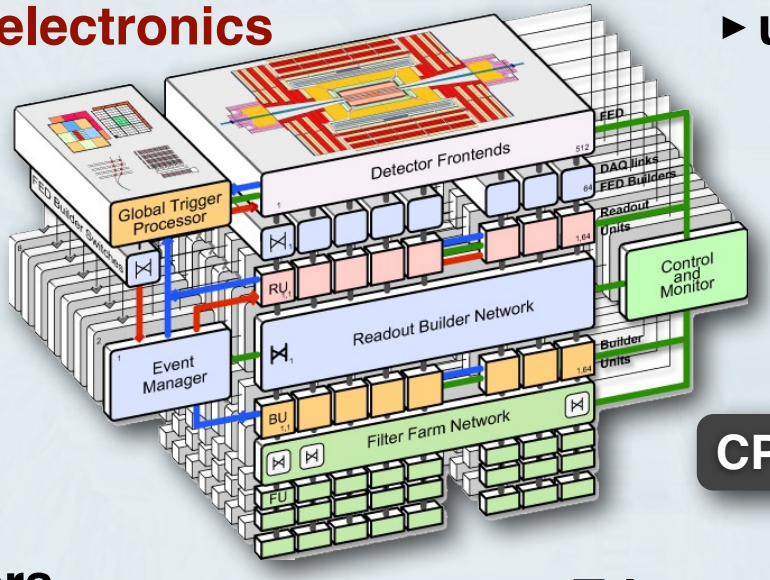


CMS Trigger System

Level-1 Trigger System

- Event rate reduced from > 40 MHz to ~100 kHz
  - using high-speed electronics
- Uses calorimeter and muon detectors
  - jet, e, γ, μ
- Can accommodate
  - 128 physics triggers (p_T, E_T, multiplicity, topology)
  - 64 technical triggers (on/off)

Latency: 3.2 μs



High-Level Trigger System

- Event rate reduced from ~ 100 kHz to ~200 Hz
  - using ~ 700 PC (8 cores)
- Uses the full detector readout

CPU time: 40 ms / event

- Trigger paths (reconstruction modules + selection filters)
  - seeded by Level-1 objects
  - jet, total & missing E_T & H_T, e, γ, μ, τ, b-jet, mixed, technical

Jet Triggers (2010)

Single Jet Triggers | Dijet Triggers | Multijet Triggers

Jets at HLT

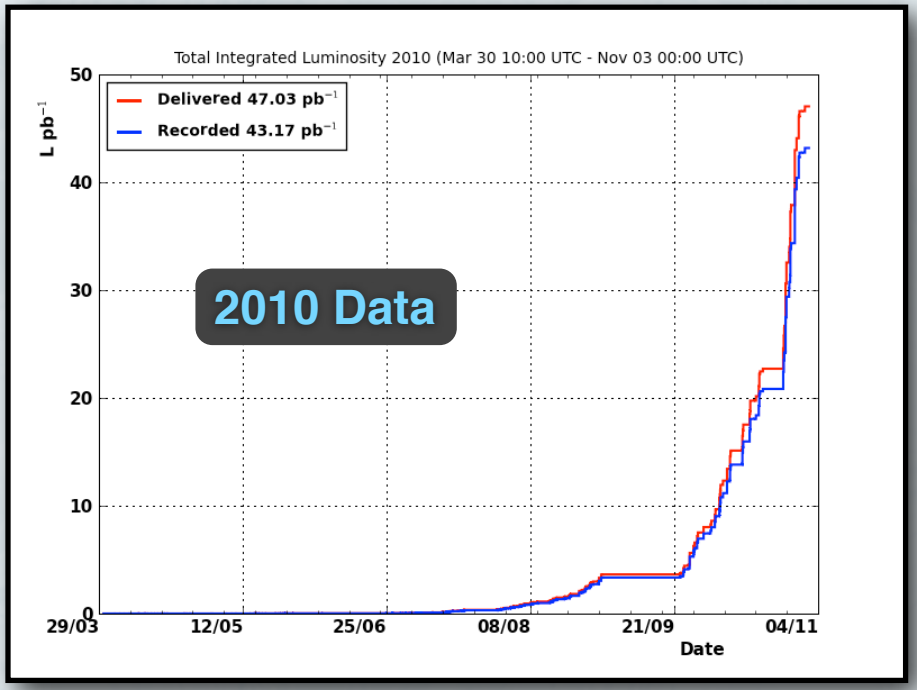
- reconstructed using Iterative Cone R = 0.5
- calorimeter towers with $p_T > 0.5$ GeV
- jet seed with $p_T > 1$ GeV
- no jet energy corrections applied (0.7 HF)

$L = 9 \times 10^{30}\ cm^{-2}s^{-1}$

Path Name	Level-1 Seed	Level-1 Prescale	HLT Prescale	Rate (Hz)
HLT_L1Jet6U	L1_SingleJet6	2	10000	1.47±0.03
HLT_L1Jet10U	L1_SingleJet10	1	4000	1.32±0.03
HLT_Jet15U	L1_SingleJet6	2	400	2.04±0.04
HLT_Jet30U	L1_SingleJet20	1	40	3.50±0.05
HLT_Jet50U	L1_SingleJet30	1	1	23.37±0.12
HLT_Jet70U	L1_SingleJet40	1	1	6.80±0.07
HLT_Jet100U	L1_SingleJet60	1	1	1.71±0.03

CMS Data

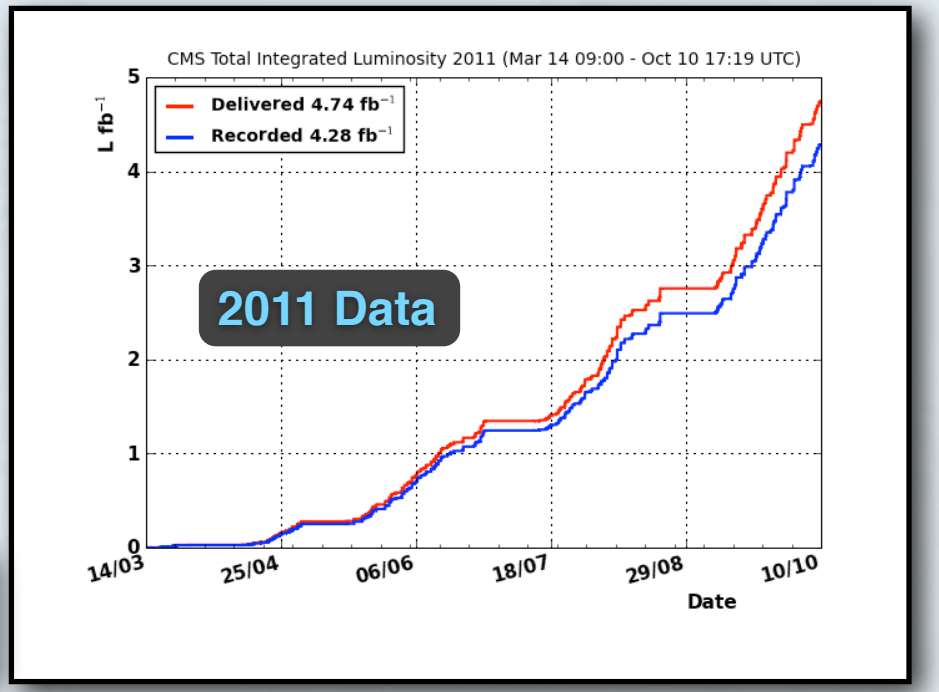
Data taking efficiency: > 90%



Delivered by LHC: 47 pb^{-1}
Recorded by CMS: 43 pb^{-1}

L_{2011} = 100 x L_{2010}

Delivered by LHC: 4.7 fb^{-1}
Recorded by CMS: 4.3 fb^{-1}

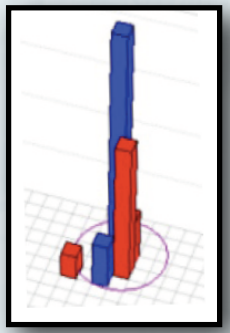


JETS AT CMS

Jet Types

Experimental signature of quarks and gluons

Observed as collimated sprays of particles

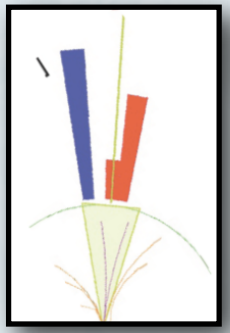


Calorimeter Jets

- using **ECAL** and **HCAL** information

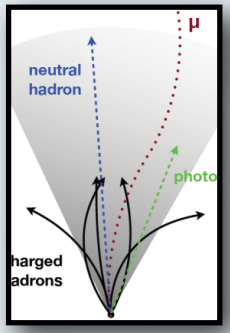
Track Jets

- using **TRACKER** information



Jet plus Track

- using **ECAL**, **HCAL**, and **TRACKER** information



Particle Flow Jets

- from identified **charged** and **neutral hadrons**, **γ**, **e**, **μ** using all detector components

Generated Jets

- using all stable particles from **MC** simulated events

Reconstruction Algorithms

$$d_{ij} = min\left(k_{t,i}^{2p}, k_{t,j}^{2p}\right)\frac{\Delta r_{ij}^2}{R^2}$$

$$\Delta r_{ij}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$$

$$y = \frac{1}{2} ln\left(\frac{E + p_z}{E - p_z}\right)$$

Seedless and computational efficient

k_t Algorithm (p = 1)

- **irregular** shape in y-φ space

R = 0.5 (0.7)

Anti-k_t Algorithm (p = -1)

- **cone-like** shape in y-φ space for isolated jets
- **CMS default**

Cambridge/Aachen Algorithm (p = 0)

- **clusters objects based on their position only**

Iterative Cone R = 0.5 (0.7)

SISCone R = 0.5 (0.7)

Jet Energy Calibration

Reconstructed Jet

↓

Offset Correction

- removes pile-up and noise contributions

↓

MC Truth Calibration

- flattens the jet response in η and corrects the jet p_T to generated level

↓

Relative Residual Correction

- accounts for differences between data and MC vs jet η (dijet p_T balance)

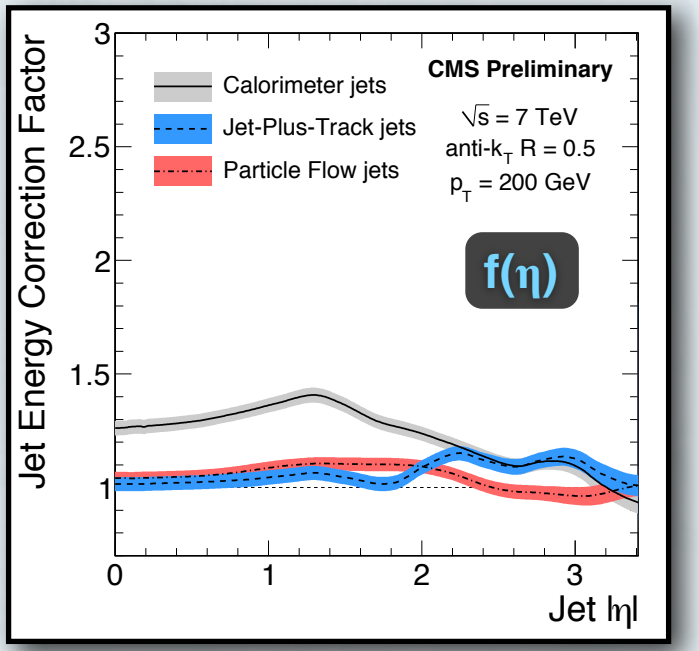
↓

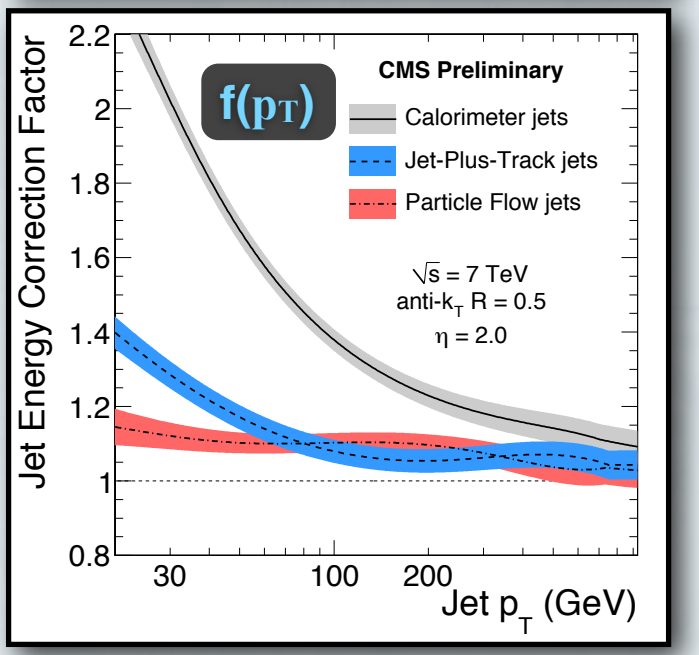
Absolute Residual Correction

- accounts for differences between data and MC vs jet p_T (dijet p_T balance, MPF)

↓

Calibrated Jet





Jet p_T Resolution

Asymmetry

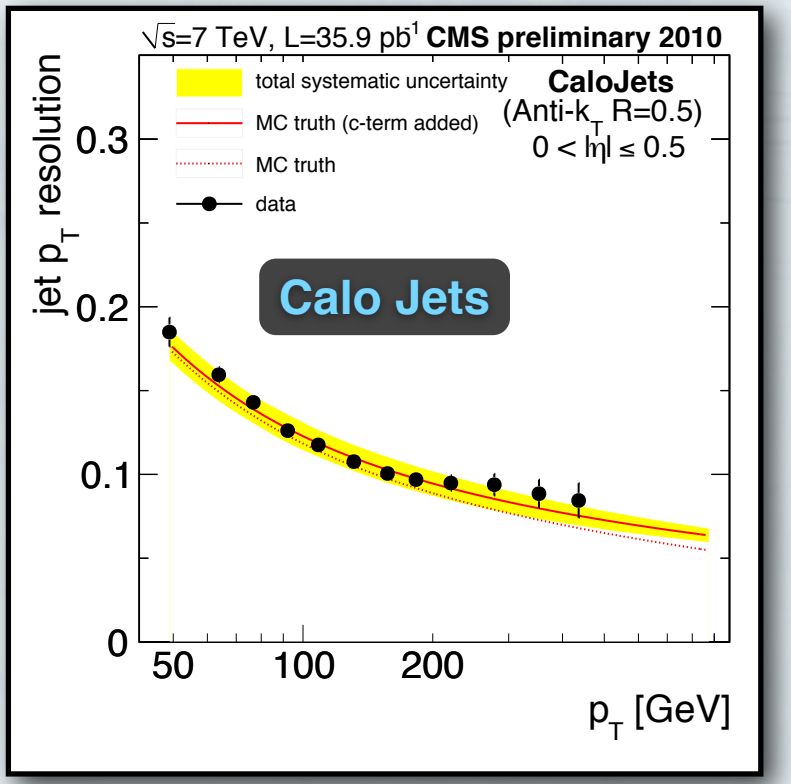
$$\mathcal{A} = \frac{p_{T,jet1} - p_{T,jet2}}{p_{T,jet1} + p_{T,jet2}}$$

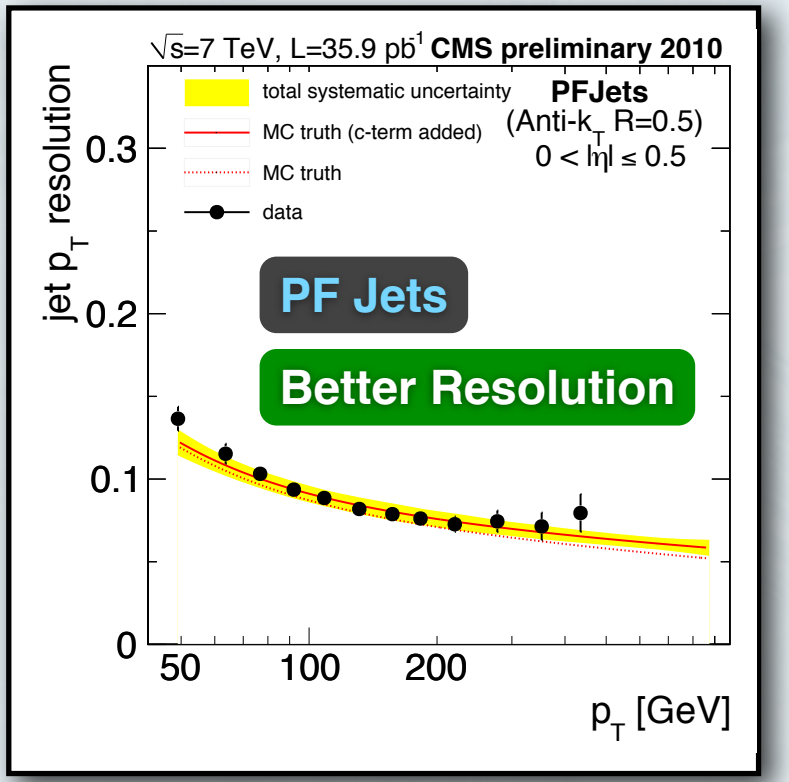
Dijet Asymmetry Method

Quark and gluon radiation effects reduced by 3rd jet $p_T \rightarrow 0$

Fractional p_T resolution

$$\frac{\sigma(p_T)}{p_T} = \sigma(\mathcal{A})\sqrt{2}$$



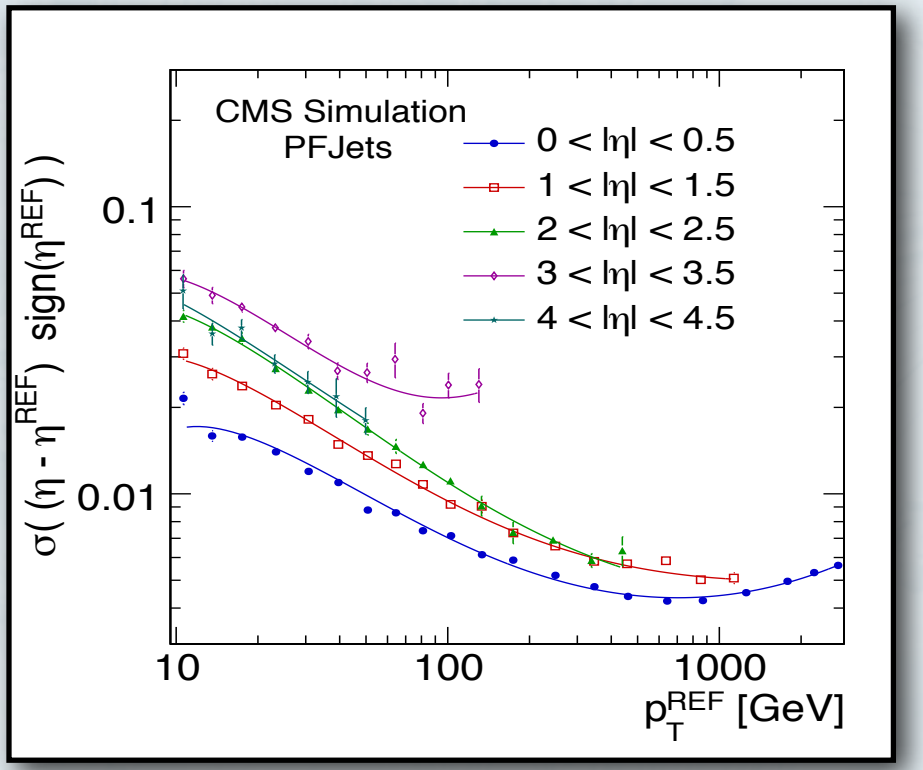


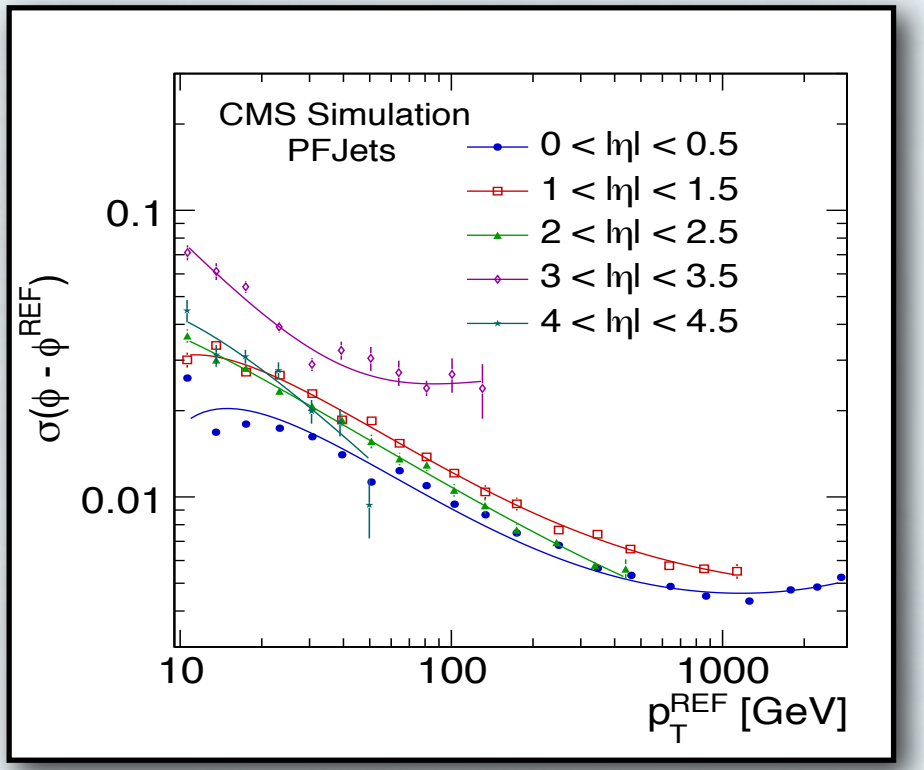
Jet Position Resolutions

Jet η resolution | **PF Jets** | **Jet φ resolution**

$$\Delta\eta = sign\left(\eta_{gen}\right) \cdot \left(\eta - \eta_{gen}\right)$$

$$\Delta\varphi = \varphi - \varphi_{gen}$$





DIJET AZIMUTHAL DECORRELATIONS

EVENT SELECTION

Event Selection

2010 Data (2.9 pb^{-1})
PYTHIA6 D6T(ISR/FSR) & Z2, PYTHIA8, HERWIG++, MADGRAPH

Online: HLT_Jet30U, HLT_Jet50U

Primary Vertex: $|z_{PV}| < 24$ cm & $n_{dof} > 4$

Particle Flow Jets with Anti-k_t R = 0.5
$|y_1| < 1.1$ & $|y_2| < 1.1$
$p_{T,min} < p_{T,1} < p_{T,max}$ & $p_{T,2} > 30$ GeV

Fake jets are eliminated by applying the jet ID

$N_{cand} > 1$
$N_{ch} > 0$
$f_{nh} < 0.9$
$f_{ch} > 0.0$
$f_\gamma < 0.9$
$f_e < 1.0$

$p_{T,max}$ [GeV/c]	80 - 110	110 - 140	140 - 200	200 - 300	300 - ∞
Number of Events	60837	160388	69009	14383	2284

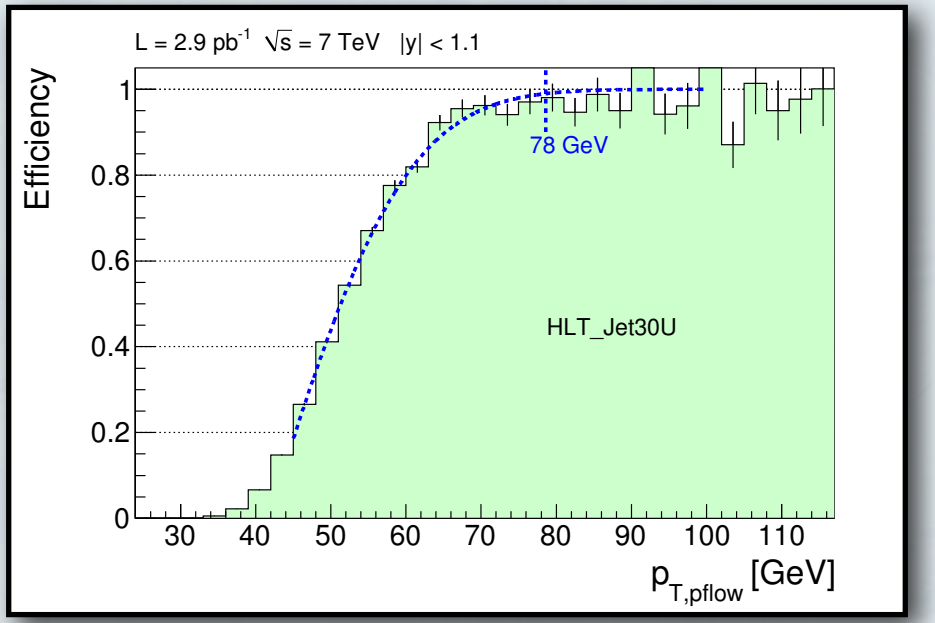
$p_{T,max}$ [GeV/c]	80 - 110	110 - 140	140 - 200	200 - 300	300 - ∞
Primary Vertex Cut	9	18	11	1	0
1st Jet ID	36	118	82	13	13
2nd Jet ID	31	119	44	6	3

Negligible rejection for all p_T regions

Trigger Efficiencies

HLT_Jet30U

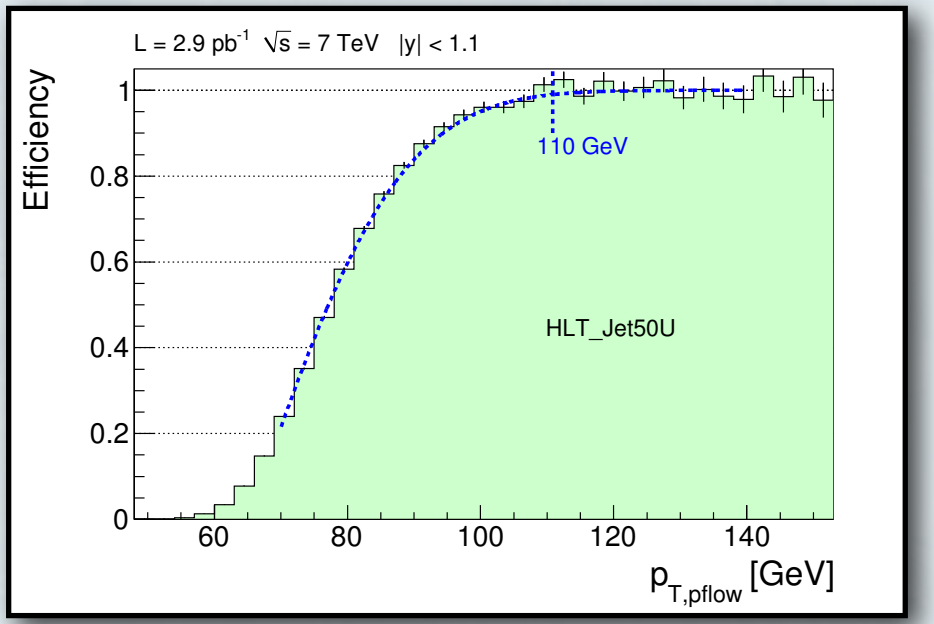
$$\epsilon = \frac{\mathrm{HLT_Jet30U}}{\mathrm{HLT_Jet15U}}$$



99% → 78 GeV

HLT_Jet50U

$$\epsilon = \frac{\mathrm{HLT_Jet50U}}{\mathrm{HLT_Jet30U}}$$

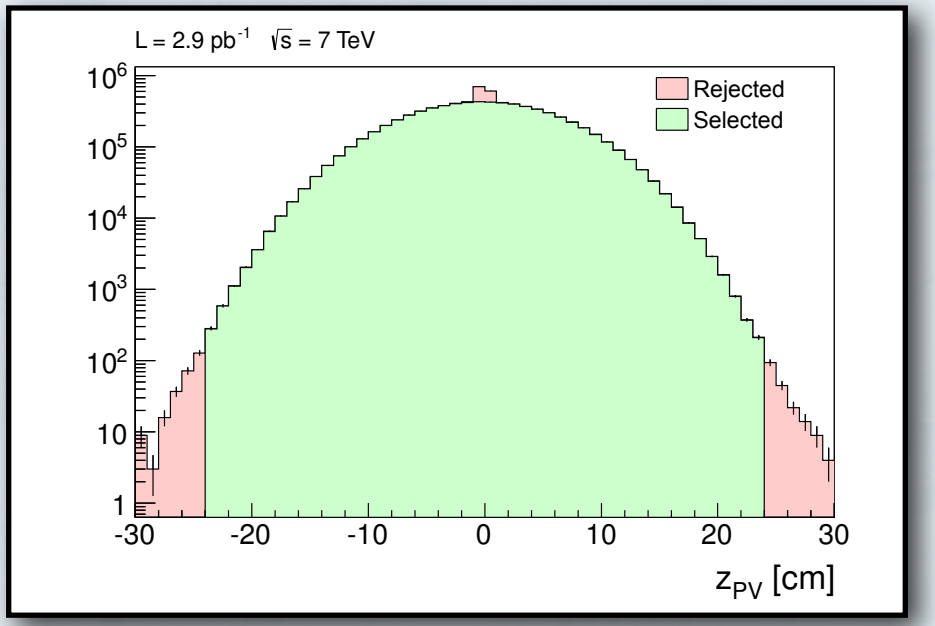


99% → 110 GeV

Primary Vertex Selection

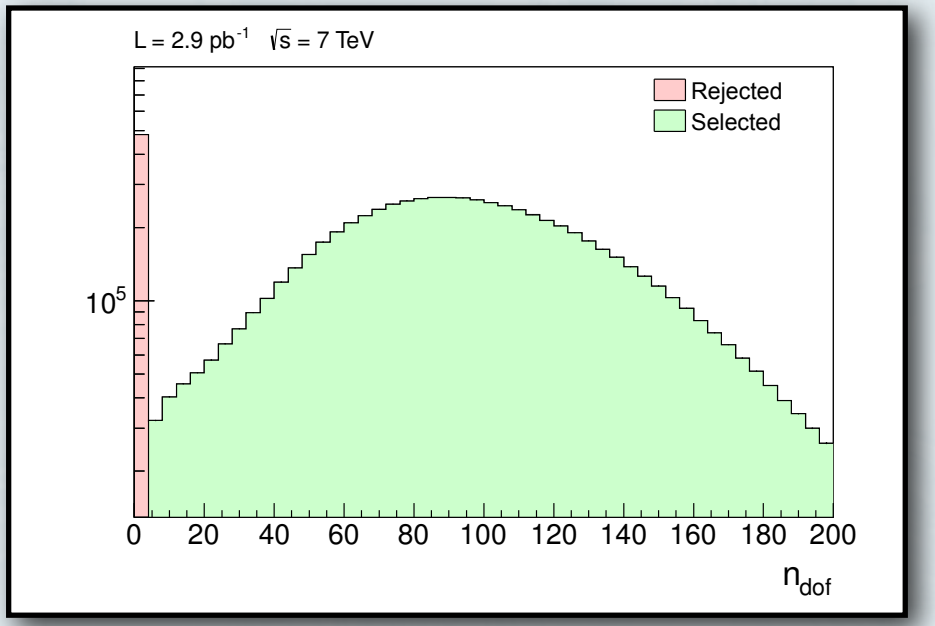
Position along the z-axis

$|z_{PV}| < 24$ cm



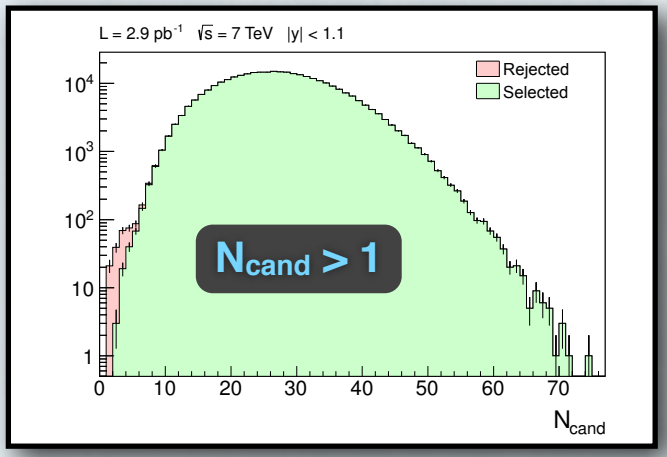
Number of degrees of freedom

$n_{dof} > 4$

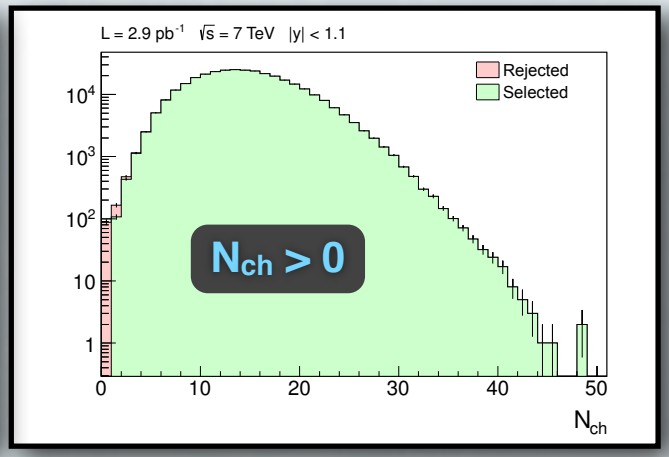


Jet Identification

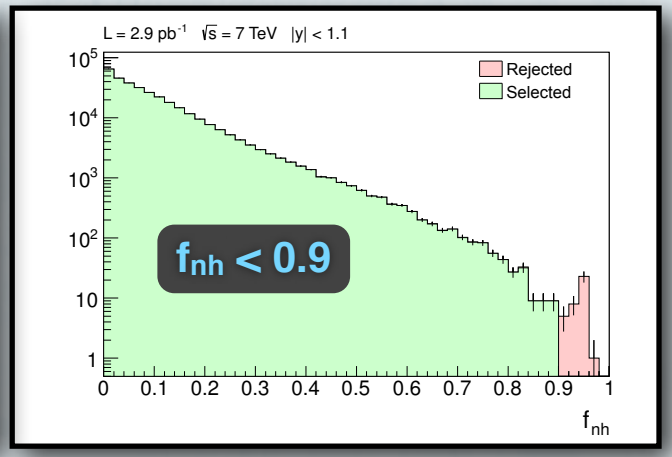
Number of candidates



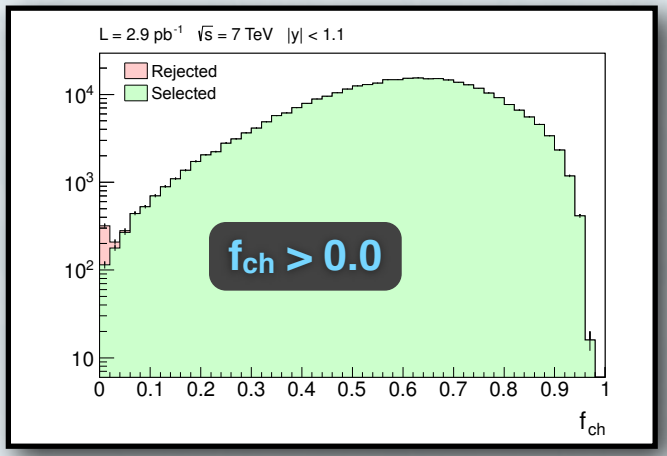
Number of charged hadrons



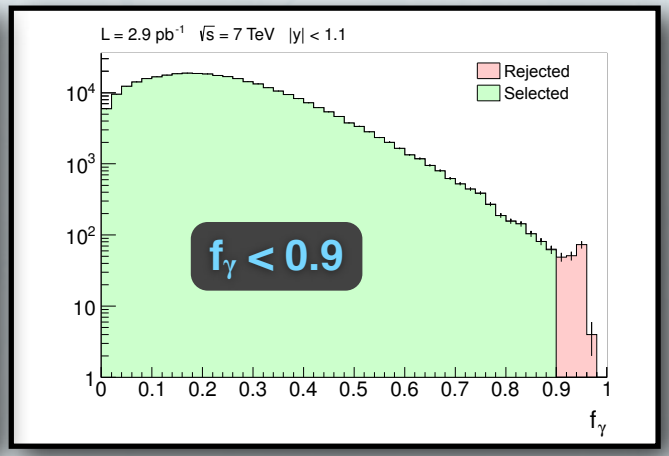
Neutral hadronic fraction



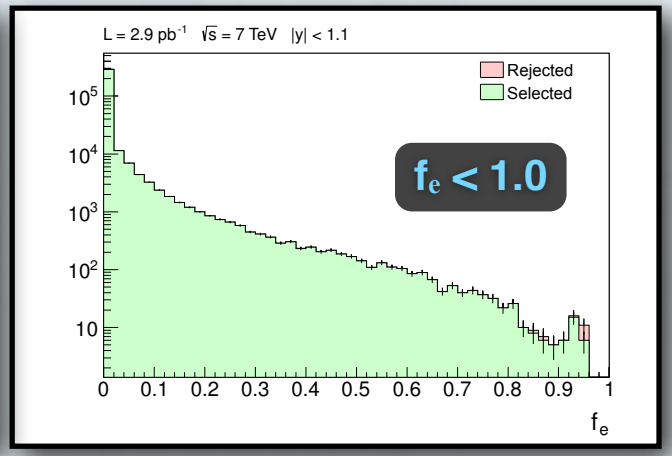
Charged hadronic fraction



Neutral EM fraction



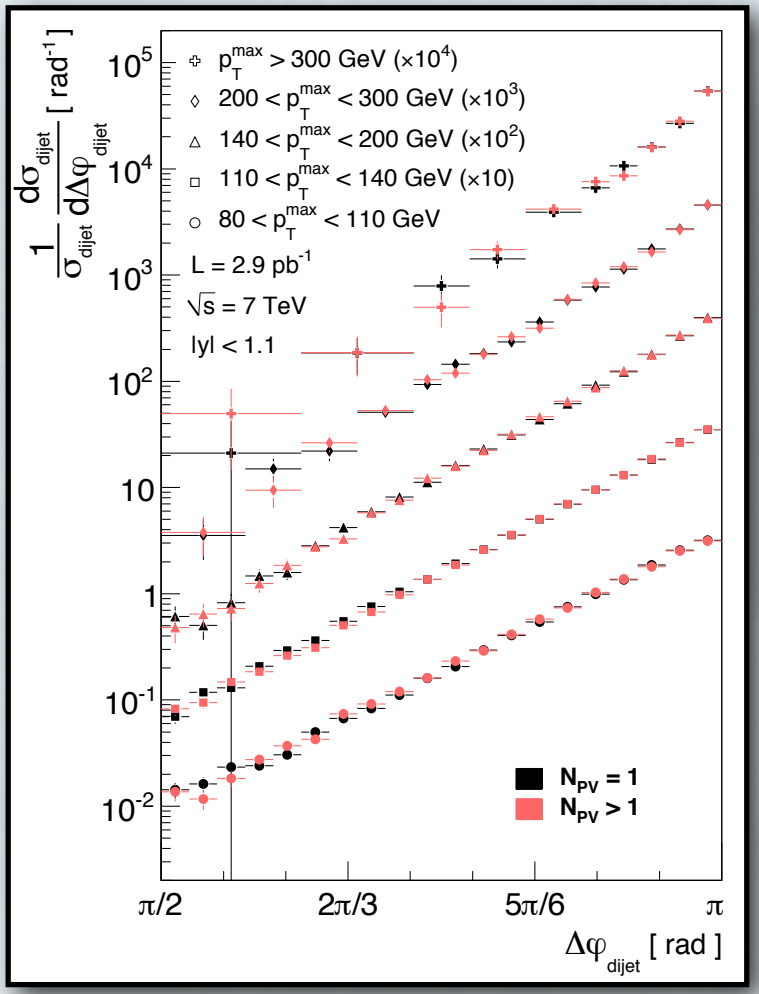
Charged EM fraction

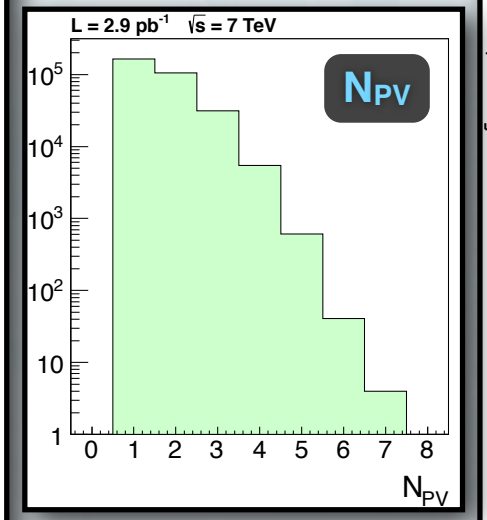


Pile-up Effects

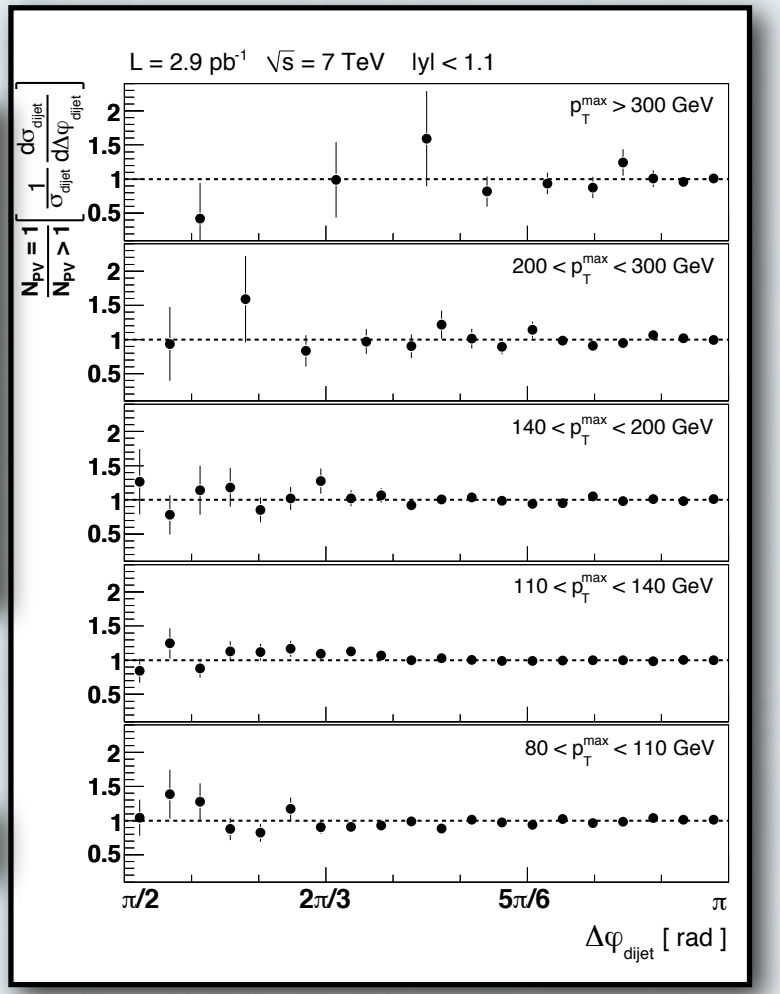
The number of *pp* interactions overlapping in the CMS detector increases with luminosity

This is estimated by counting the number of primary vertices





Negligible effects



UNFOLDING CORRECTIONS

Methodology

For data to MC or pQCD comparisons, the $\Delta\varphi$ distributions have to be corrected back to particle level

Lack of statistics in MC samples with a full simulation of the CMS detector requires a different approach

Detector effects are approximated by resolution effects

Jet p_T resolution

- event migration between p_T regions and jet order flipping

Jet η-position resolution

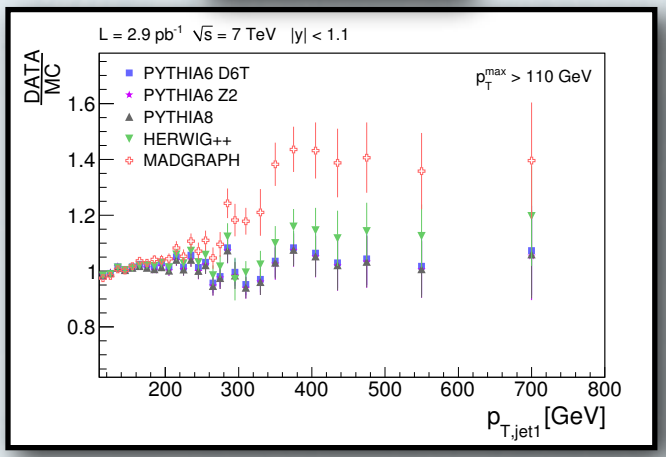
- jet migration across the boundaries of the central rapidity region

Jet φ-position resolution

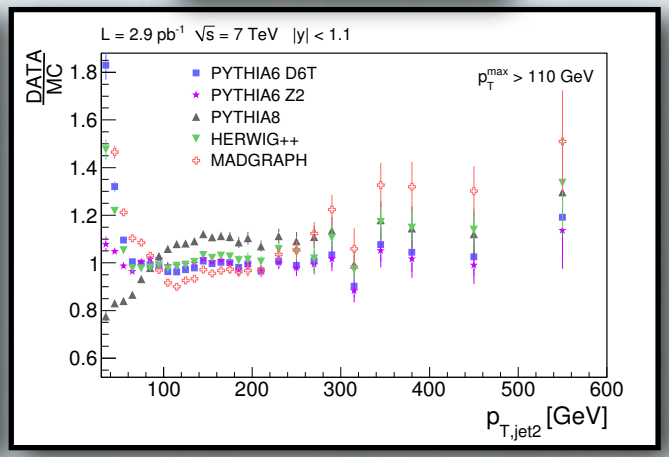
- event migration between the $\Delta\varphi$ bins

Data to MC Comparisons

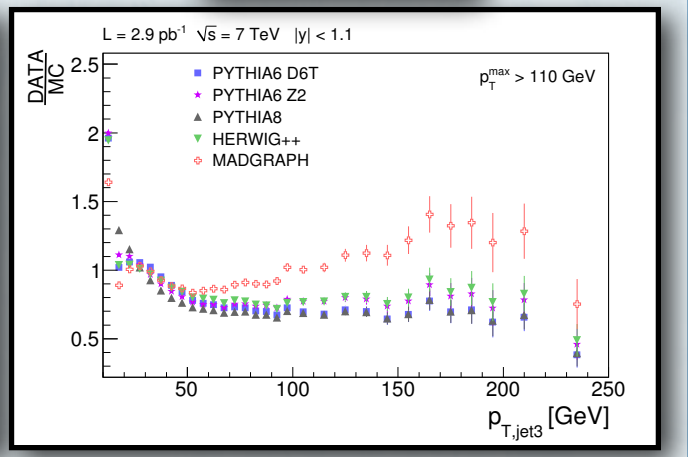
First jet p_T



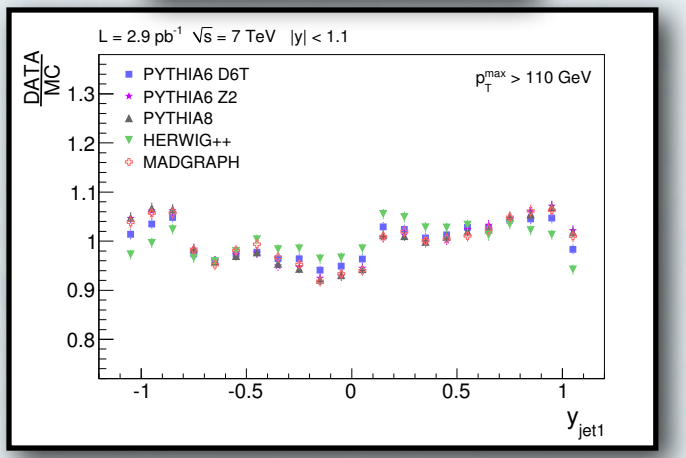
Second jet p_T



Third jet p_T

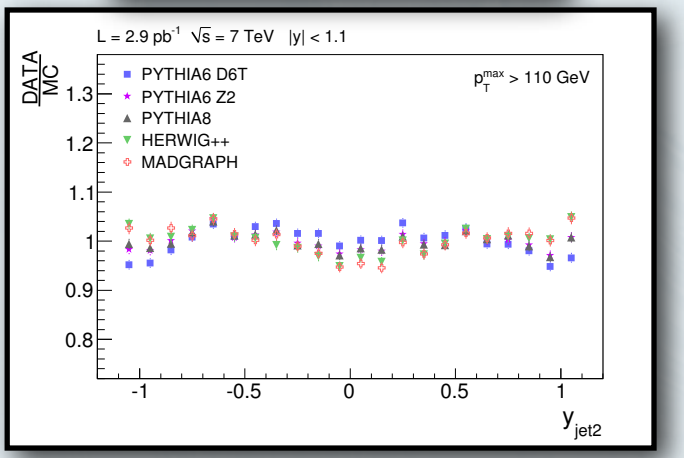


First jet rapidity



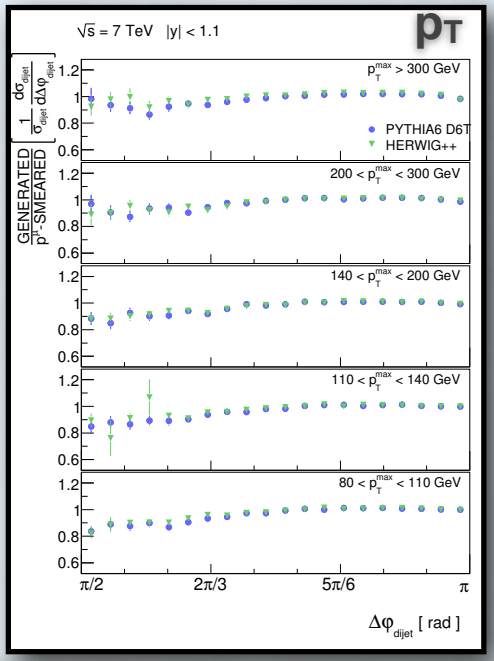
PYTHIA6 and HERWIG++ agree better

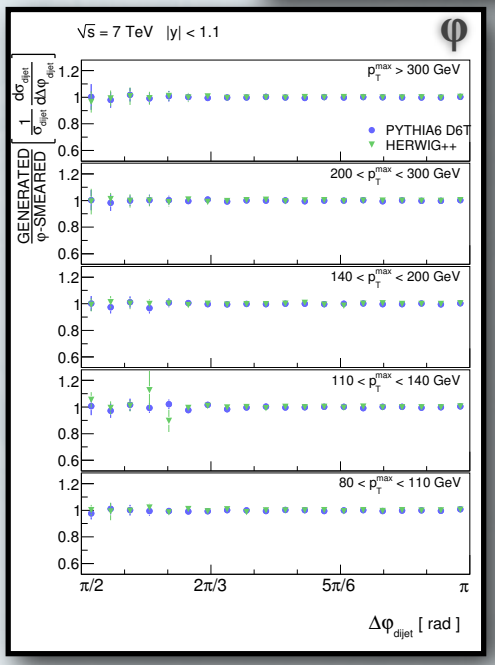
Second jet rapidity

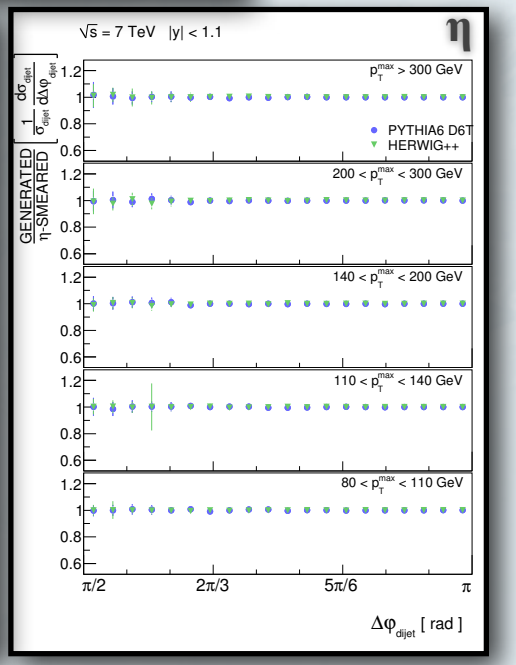


MC distributions obtained using generated jets smeared in p_T and position

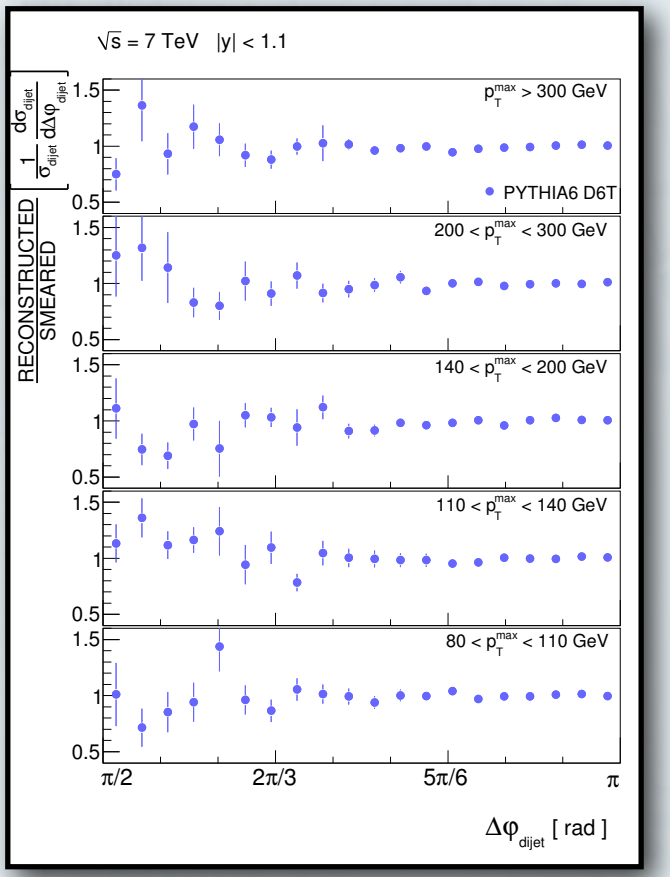
Resolution Effects







Generated jets are smeared in p_T and position



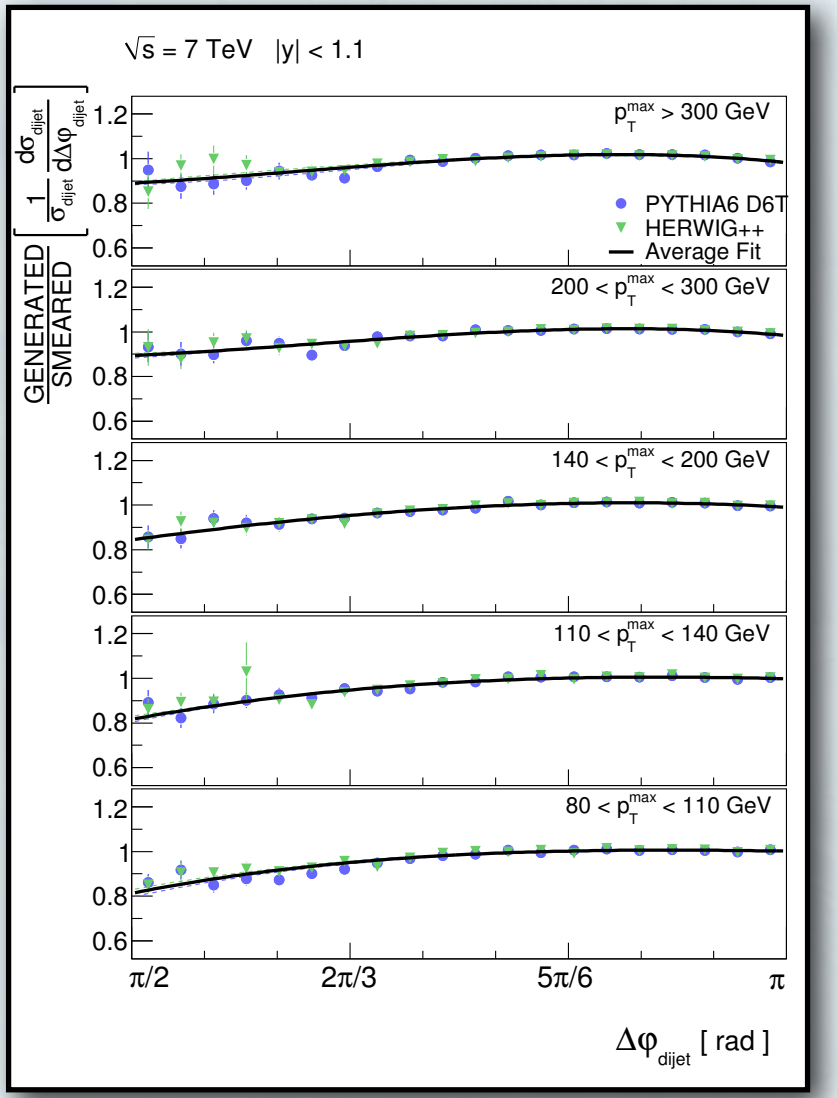
Detector effects are mainly resolution effects

Unfolding Corrections

Determined from PYTHIA6 D6T & HERWIG++

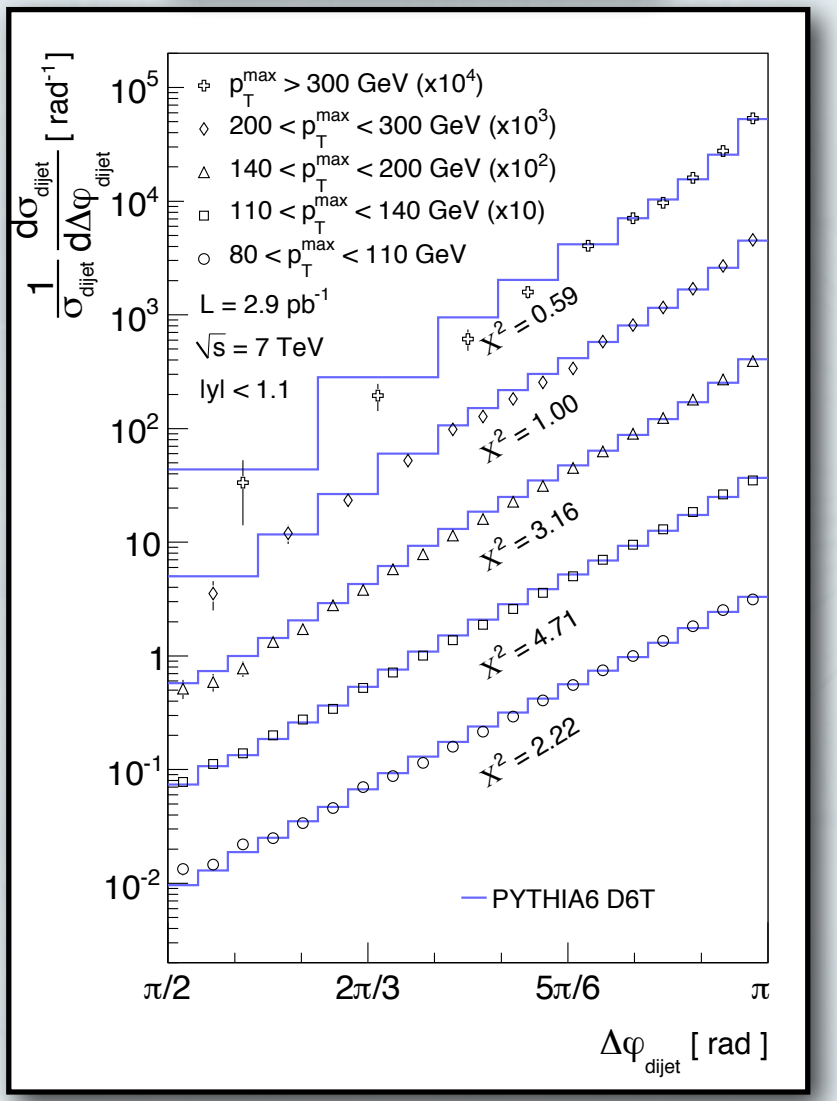
Calculated as the average of the two MC samples

Less than 2% for $\Delta\varphi > 5\pi/6$ and up to 19% (11%) at $\Delta\varphi \approx \pi/2$ for the lowest (highest) p_T region

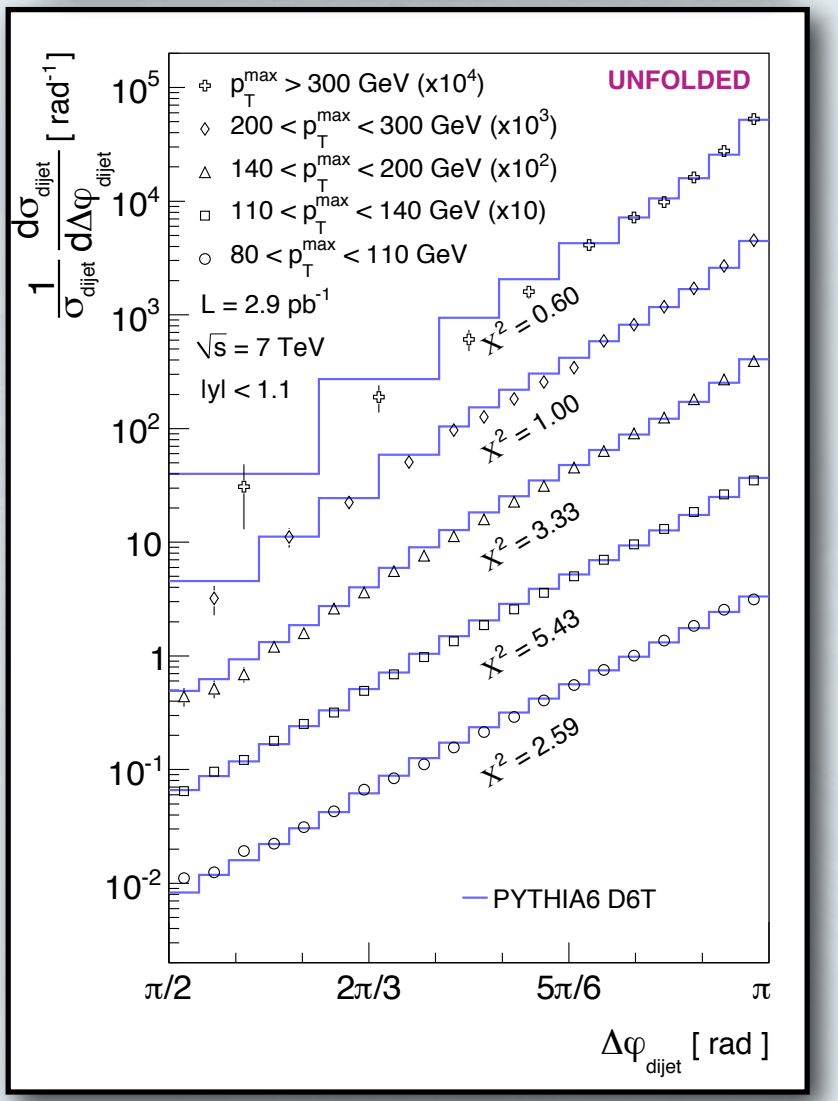


Chi2 Test on Corrections

Data vs smeared MC



Unfolded data vs generated MC



Similar X^2 values

SYSTEMATIC UNCERTAINTIES

Main Sources

Jet energy calibration

- estimated between 2.5% - 3.5% as a function of jet p_T and η
- propagated as variations in the jet p_T

Jet p_T resolution

- estimated to be 10%
- propagated through the smearing process of generated jets

Unfolding correction

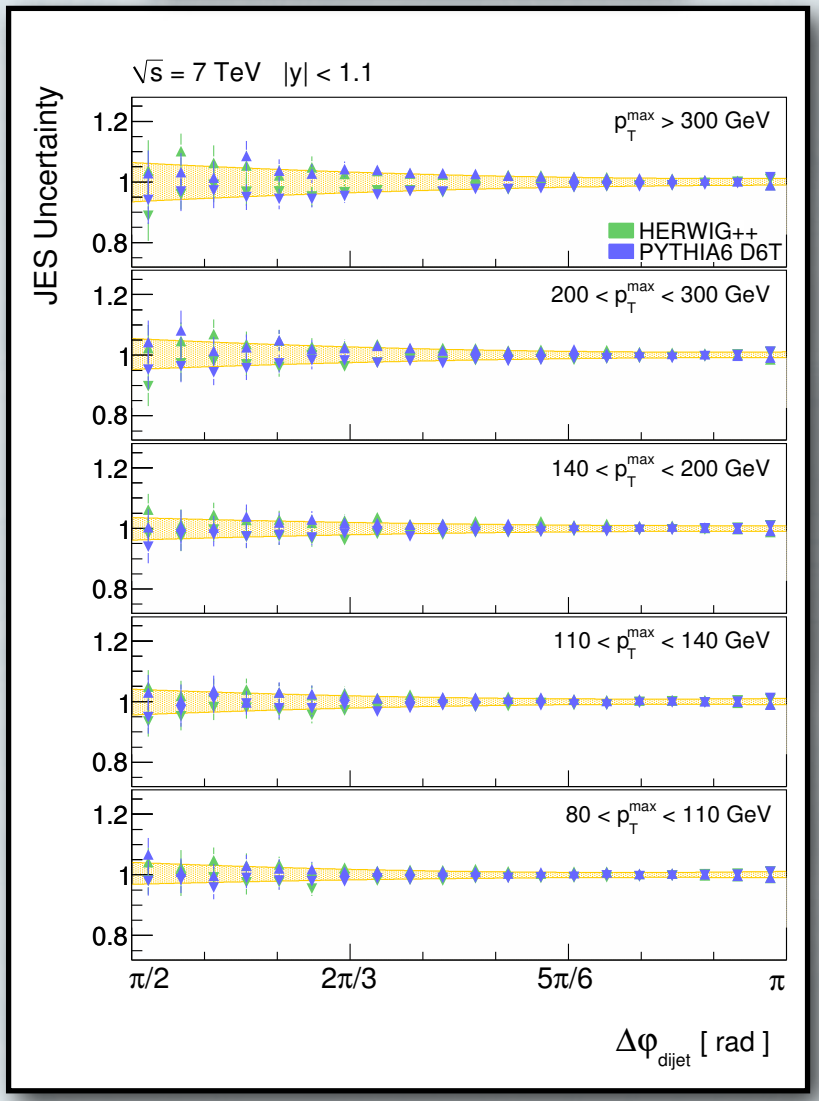
- quantified by looking at different MC samples

Smearing procedure

- determined by comparing the fully simulated distributions with the smeared ones

JEC & JPTR Uncertainties

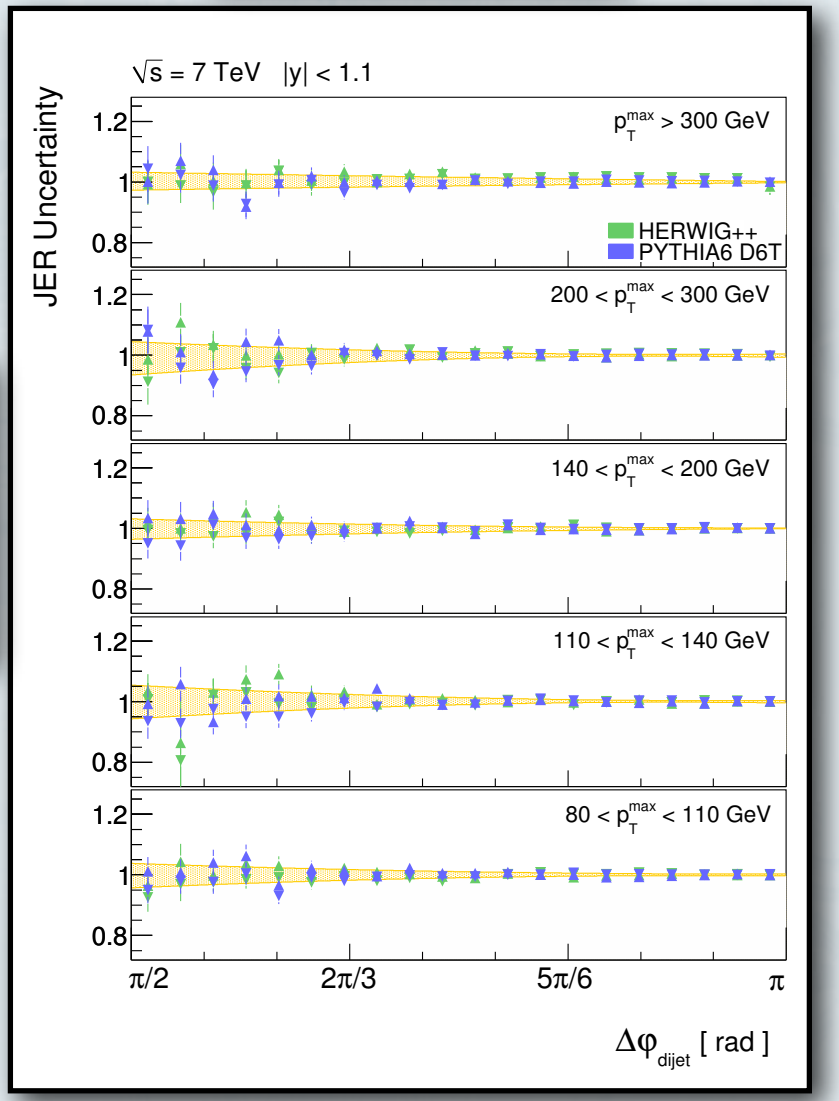
Jet Energy Calibration



1 - 5% from π to π/2

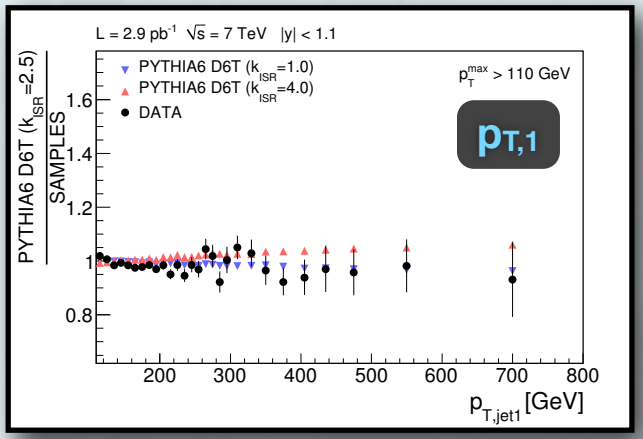
Calculated as the average of the two MC samples

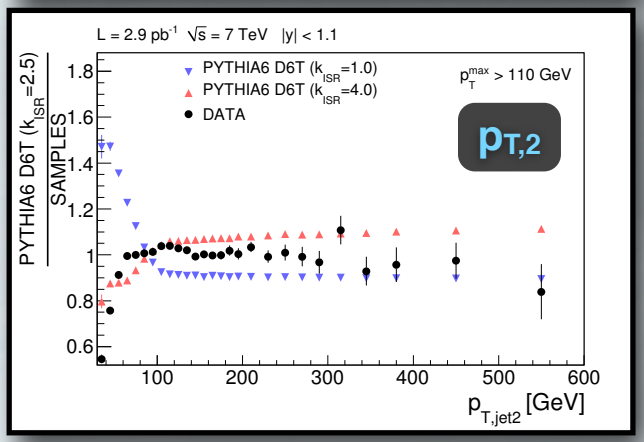
Jet p_T Resolution

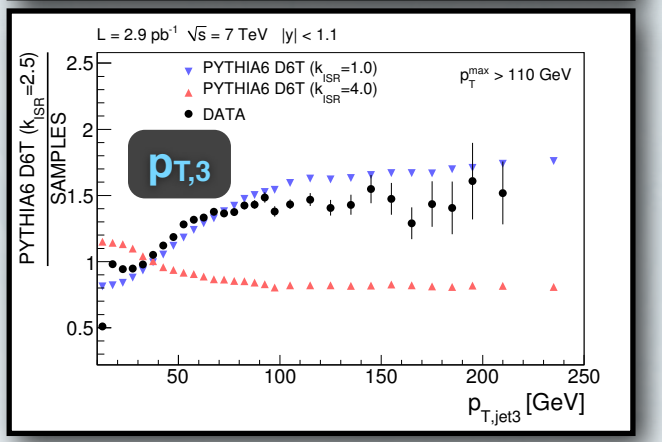


1 - 5% from π to π/2

Unfolding Uncertainties

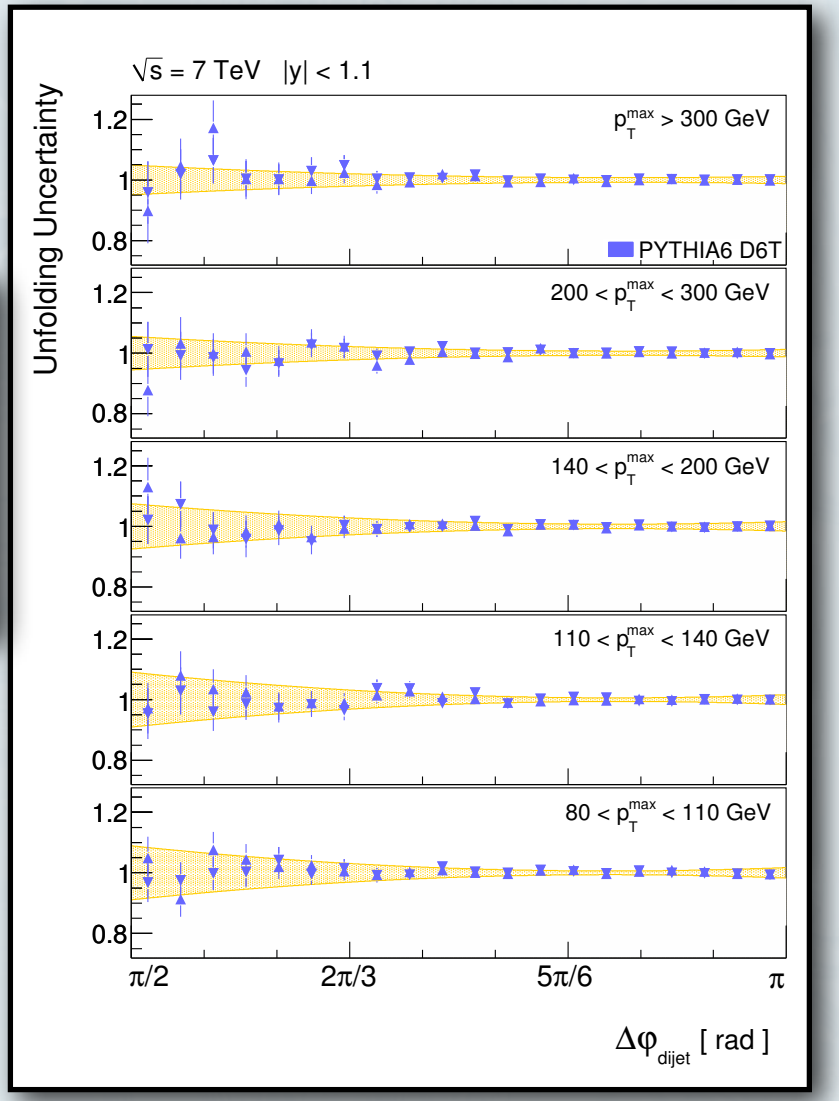






Using two PYTHIA6 samples with different ISR values which manifest extreme deviations from data

Data lay between the two limits



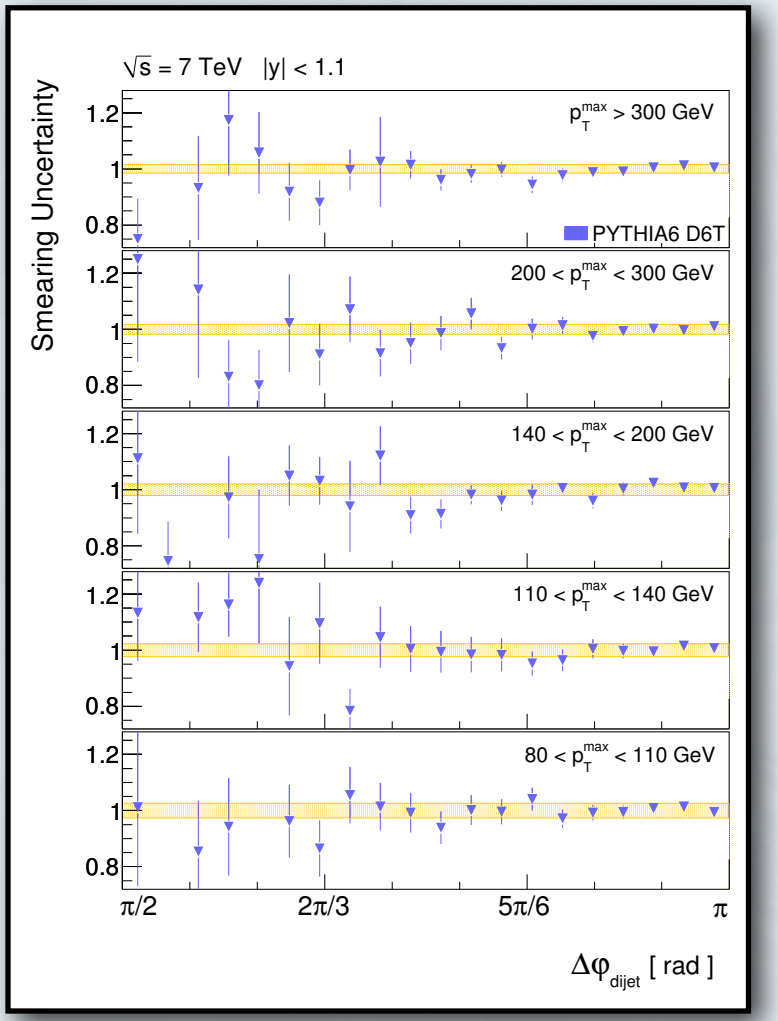
Difference in corrections from these limiting cases → 1.5 - 8% from π to $\pi/2$

Smearing Uncertainties

Detector effects are parametrized by simple gaussian distributions

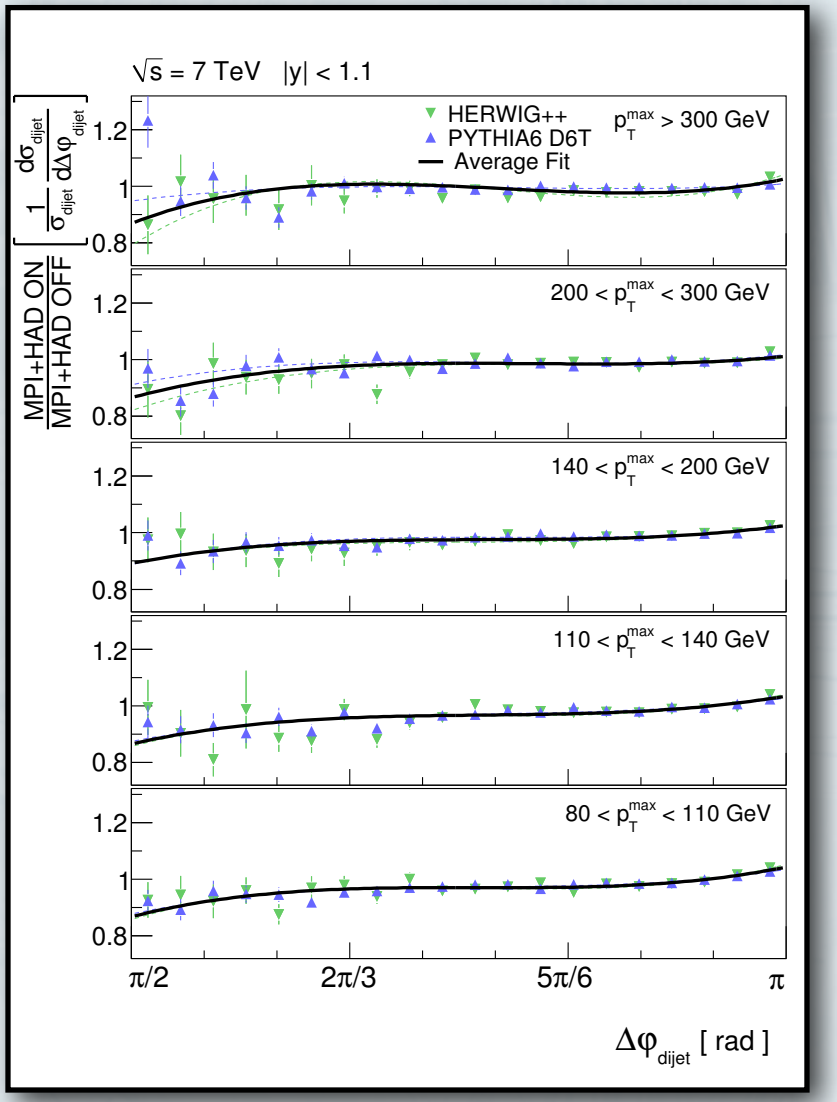
Estimated from PYTHIA 6 D6T

RMS of deviations from one
→ 2.5% flat



NON-PERTURBATIVE EFFECTS

Non-Perturbative Corrections



Determined from MC samples with MPI/UE and hadronization ON/OFF

PYTHIA6 D6T

- **MPI/UE (MSTP(81) = 0)**
- **Hadronization (MSTJ(1) = 0)**

HERWIG++

- **MPI/UE (ShowerHandler:MPIHandler NULL)**
- **Hadronization (LHCHandler:HadronizationHandler NULL)**

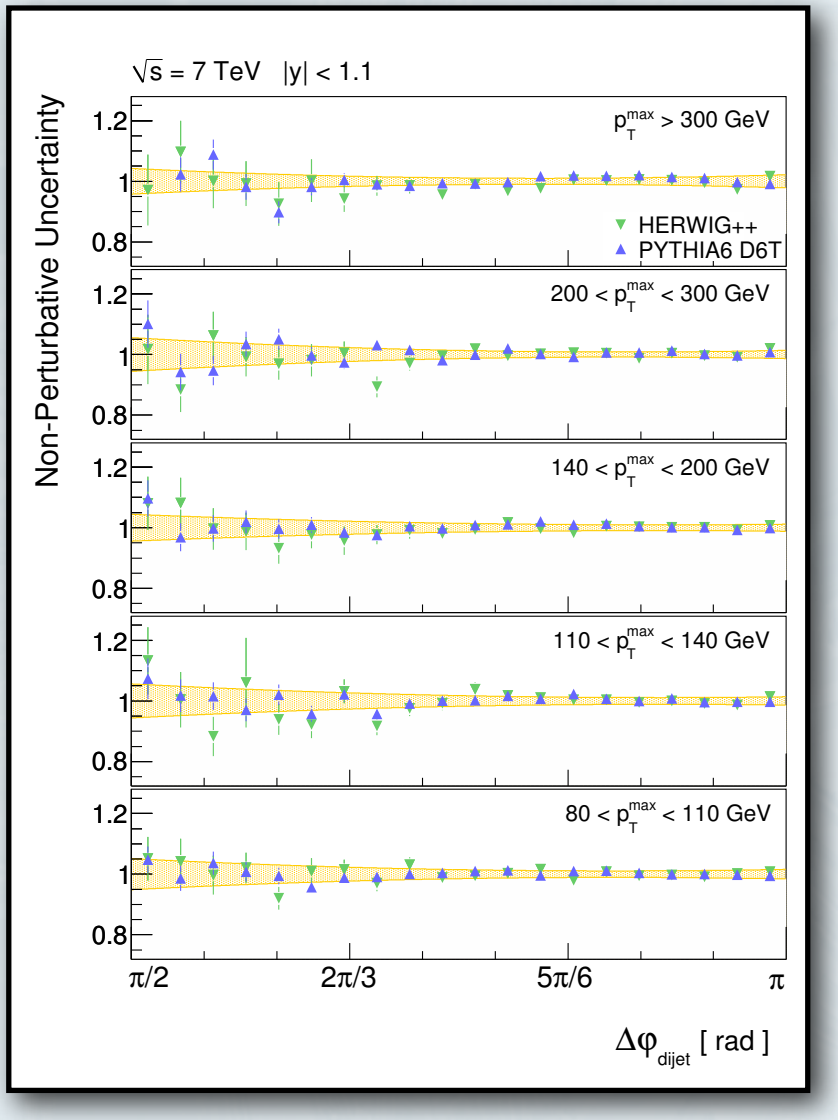
Calculated as the average of the two MC samples

Corrections between 4 - 13% from π to π/2

Non-Perturbative Uncertainties

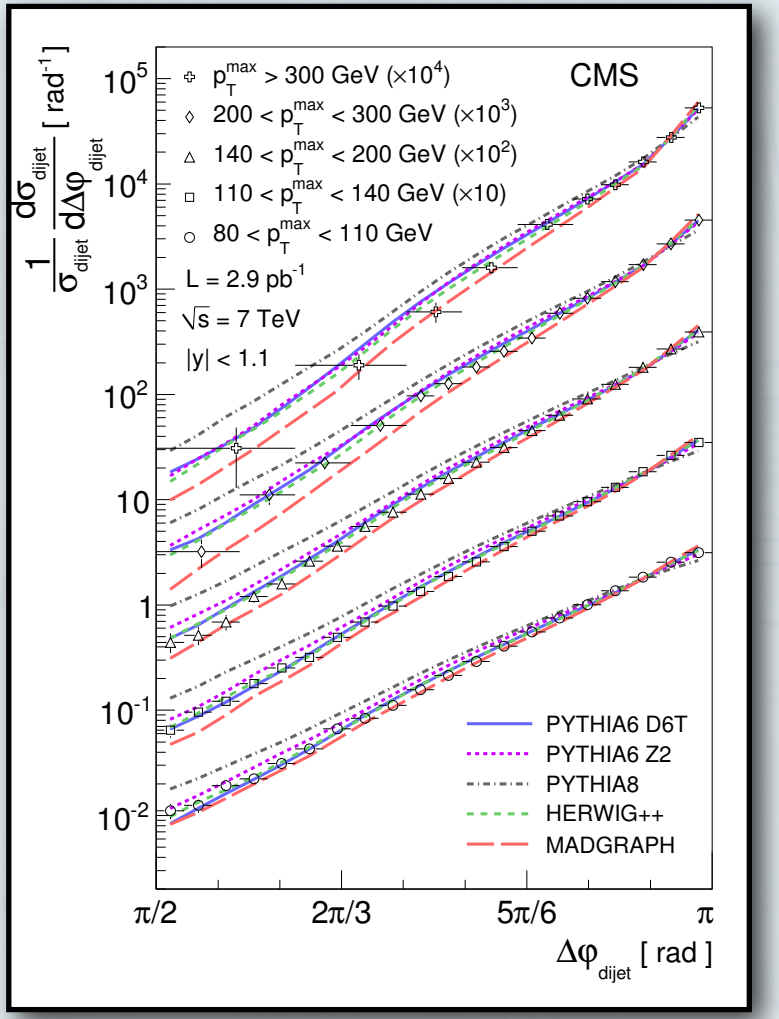
Calculated as the deviations of the two MC samples from the average

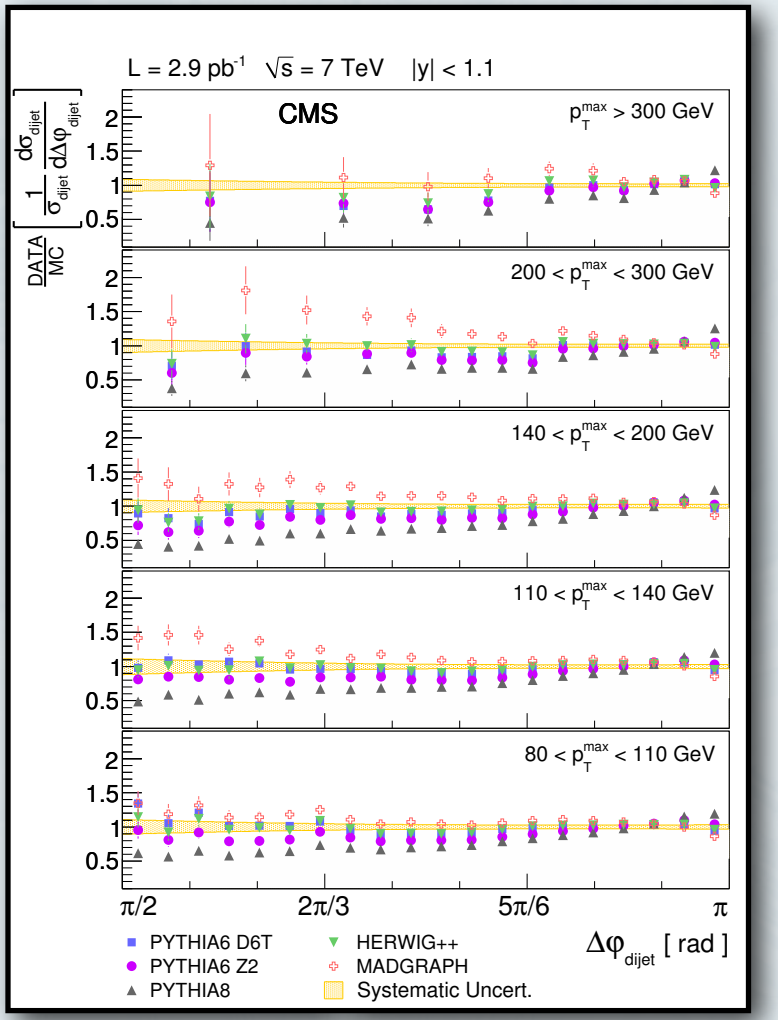
Uncertainties vary between 2 - 6% from π to $\pi/2$



RESULTS

Data vs MC



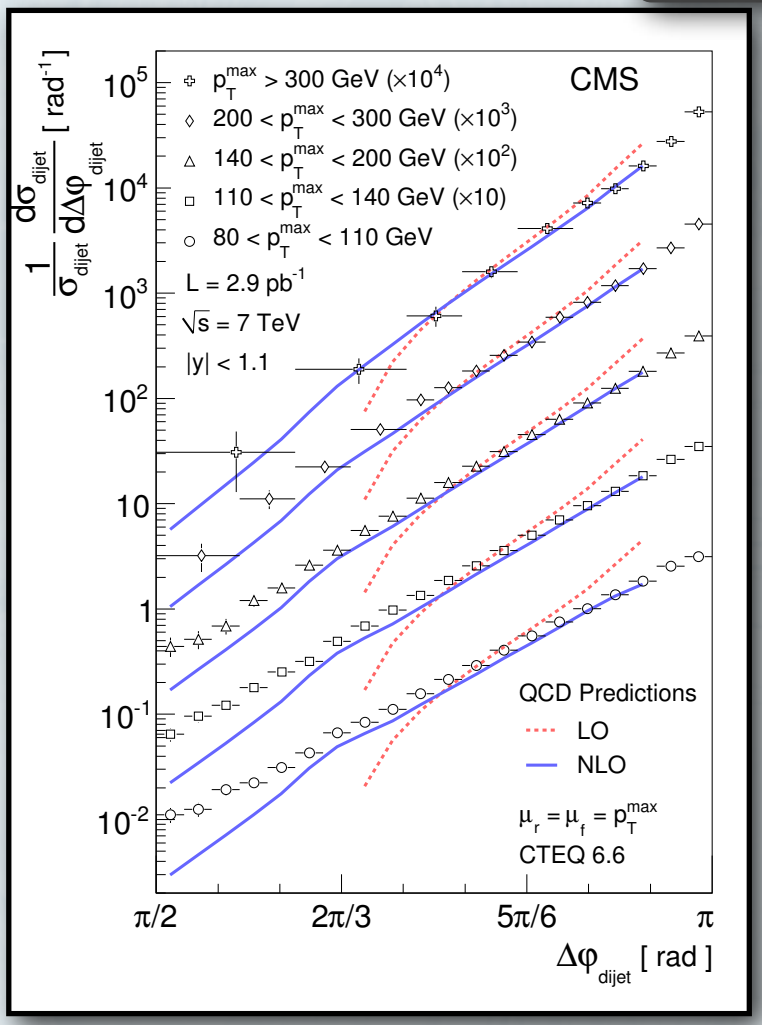


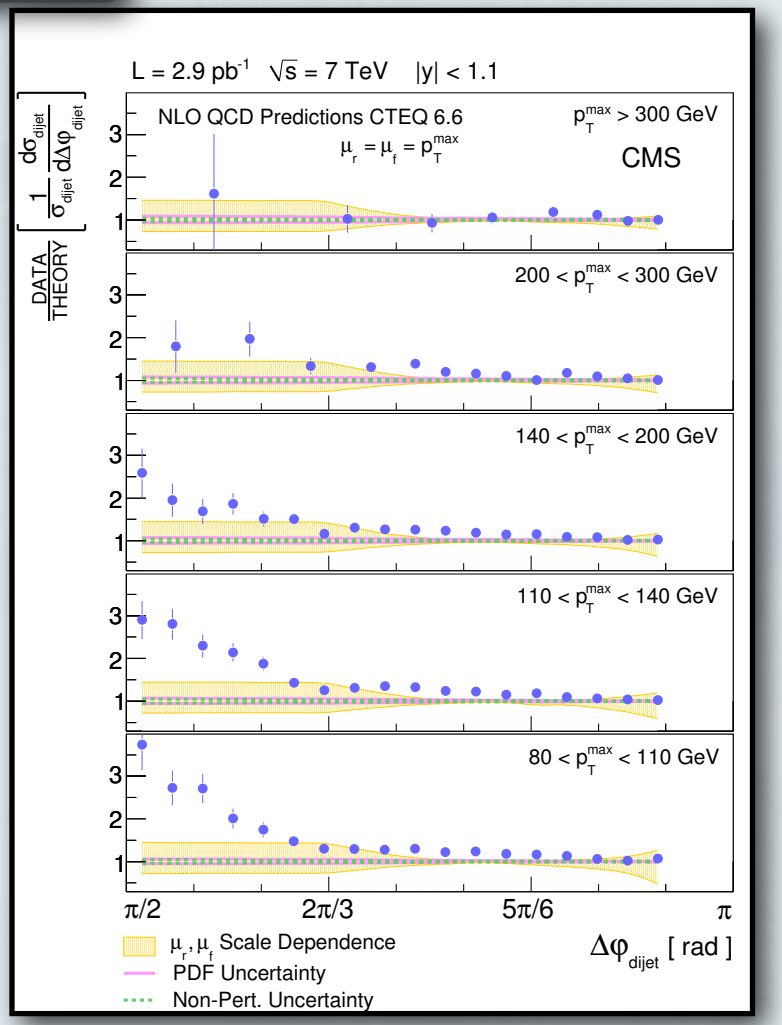
Error bars = STAT + SYS (3 - 12% from π to $\pi/2$)

PYTHIA6 & HERWIG++ reasonable agreement
MADGRAPH (PYTHIA8) predicts less (more)

Data vs pQCD

$$\frac{1}{\sigma_{\rm dijet}}\bigg|_{\rm (N)LO} \cdot \frac{d\sigma_{\rm dijet}}{d\Delta\varphi_{\rm dijet}}\bigg|_{\rm (N)LO}$$



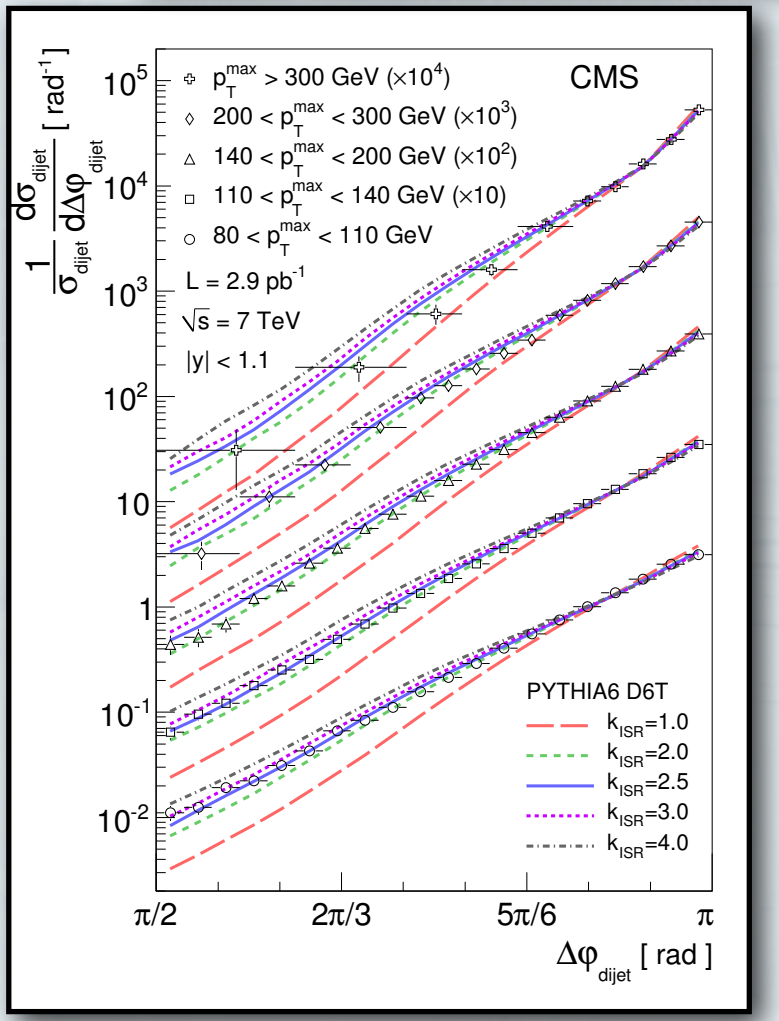


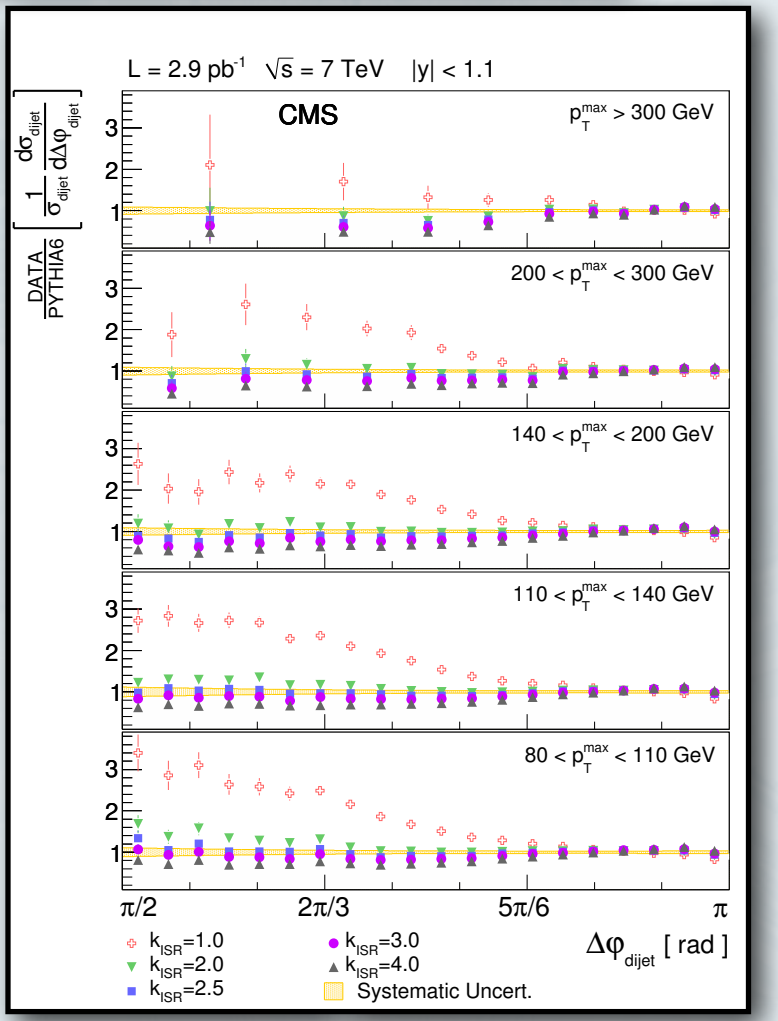
NLO better than LO but undershoot the data for $\Delta\varphi < 2\pi/3$ (2 → 4 LO)

Scale uncertainty (< 50%)
PDF uncertainty (2 - 9%)

Sensitivity to ISR

DØ measurements used to tune PYTHIA6 (PRL 94, 221801 (2005))





Virtuality = $k_{ISR} \cdot Q^2$

k_{ISR} = PARP(67)

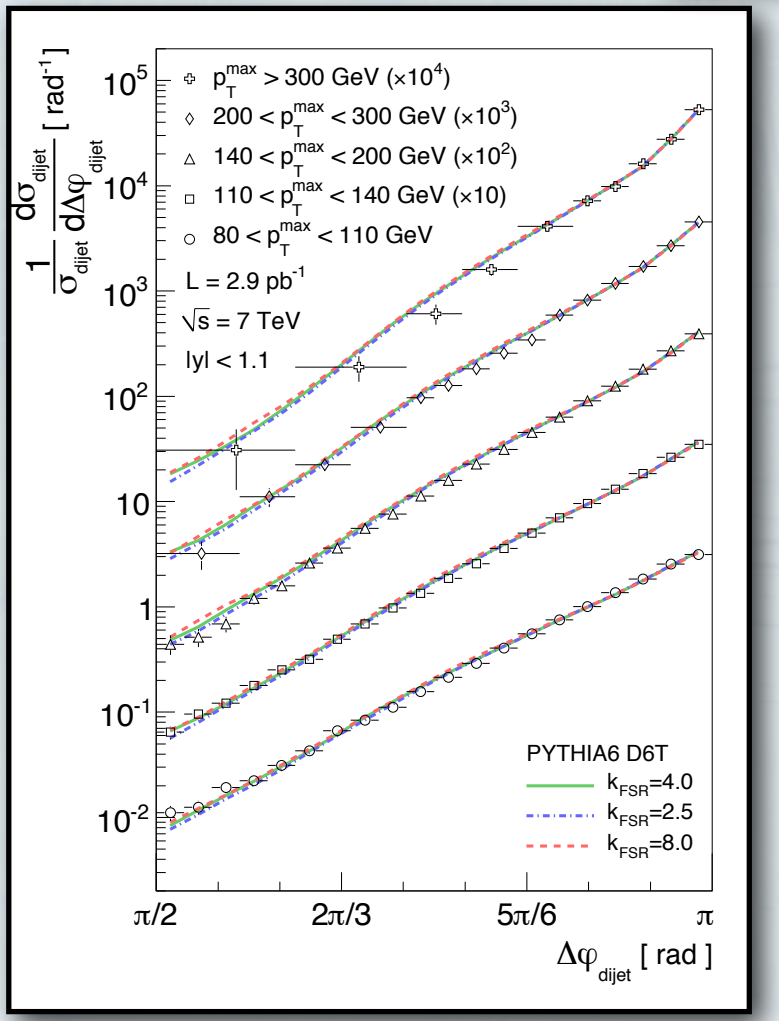
More virtuality → more radiation

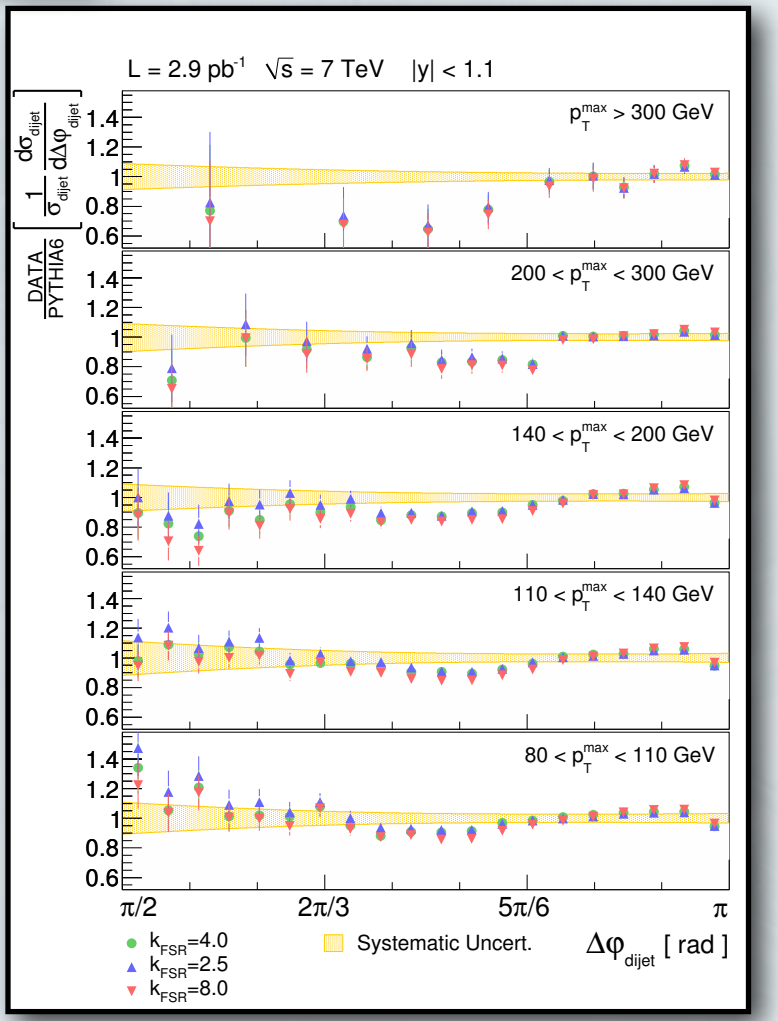
PYTHIA6 D6T default k_{ISR} = 2.5

k_{ISR} variations between 1.0 & 4.0

Sensitivity to FSR

Insensitive to FSR





Virtuality = $k_{FSR} \cdot Q^2$

k_{FSR} = PARP(71)

PYTHIA6 D6T default k_{FSR} = 4.0
k_{FSR} variations between 2.5 & 8.0

Summary

- The dijet azimuthal decorrelations are important for understanding QCD at LHC
- The measurements are performed at central rapidities ($|y| < 1.1$) and in five p_T regions. The total systematic uncertainty varies between 3% - 12%.
- PYTHIA6 and HERWIG++ are in reasonable agreement with data
- MADGRAPH (PYTHIA8) predicts less (more) decorrelation than what is observed in data. Both could be tuned to agree with data by changing the ISR parameters.
- NLO predictions give a better agreement than LO, but they undershoot the data for $\Delta\varphi < 2\pi/3$ (in this region 2→4 LO)
- The dijet azimuthal decorrelation is very sensitive to initial-state radiation and can be used to further tune PYTHIA

Dijet Azimuthal Decorrelations in pp Collisions at $\sqrt{s} = 7$ TeV

V. Khachatryan *et al.**
(CMS Collaboration)

(Received 26 January 2011; published 22 March 2011)

Measurements of dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV using the CMS detector at the CERN LHC are presented. The analysis is based on an inclusive dijet event sample corresponding to an integrated luminosity of 2.9 pb^{-1}. The results are compared to predictions from perturbative QCD calculations and various Monte Carlo event generators. The dijet azimuthal distributions are found to be sensitive to initial-state gluon radiation.

DOI: 10.1103/PhysRevLett.106.122003 PACS numbers: 13.85.Ni, 12.38.Bx, 12.38.Qk, 13.87.Ce

High-energy proton-proton collisions with high momentum transfer are described within the framework of quantum chromodynamics (QCD) as pointlike scatterings between the proton constituents, collectively referred to as partons. The outgoing partons manifest themselves, through quark and gluon soft radiation and hadronization processes, as localized streams of particles, identified as jets. At Born level, dijets are produced with equal transverse momenta p_T with respect to the beam axis and back to back in the azimuthal angle ($\Delta\varphi_{\mathrm{dijet}} = |\varphi_{\mathrm{jet1}} - \varphi_{\mathrm{jet2}}| = \pi$). Soft-gluon emission will decorrelate the two highest p_T (leading) jets and cause small deviations from π. Larger decorrelations from π occur in the case of hard multijet production. Three-jet topologies dominate the region of $2\pi/3 < \Delta\varphi_{\mathrm{dijet}} < \pi$, whereas angles smaller than $2\pi/3$ are populated by four-jet events.

Dijet azimuthal decorrelations, i.e., the deviation of $\Delta\varphi_{\mathrm{dijet}}$ from π for the two leading jets in hard-scattering events, can be used to study QCD radiation effects over a

Collaboration [1]. In this Letter, we present the first measurements of dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV at the CERN Large Hadron Collider (LHC).

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$, where pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise proton beam direction with respect to the center of the detector. A lead-tungstate crystal electromagnetic calorimeter and a brass-scintillator hadronic calorimeter surround the tracking volume. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ at central pseudorapidities. The granularity becomes coarser at forward pseudorapidities. A preshower detector made of silicon sensor planes and lead absorbers is installed in front of the electromagnetic calorimeter at $1.653 < |\eta| < 2.6$