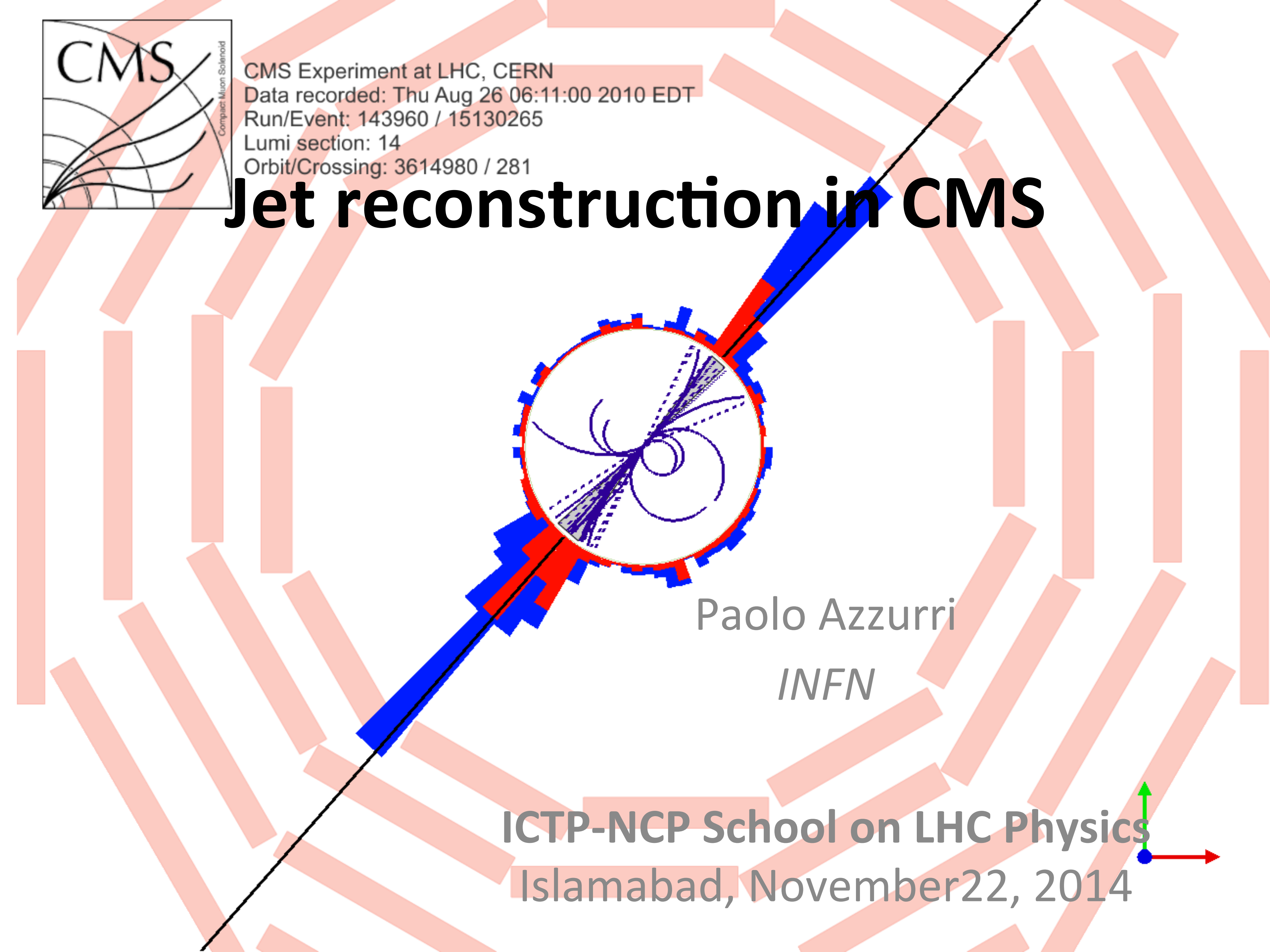


Jet reconstruction in CMS

Paolo Azzurri

INFN

ICTP-NCP School on LHC Physics

Islamabad, November22, 2014

Overview

- What are hadronic Jets ?
- Jet clustering algorithms
- Reconstruction of Jets in CMS
- Energy calibration of CMS Jets
- A few CMS results with jets
- Jets in a specific CMS analysis (EWK Z+2jets)
- Quark/Gluon jet tagging

What are hadronic Jets ?

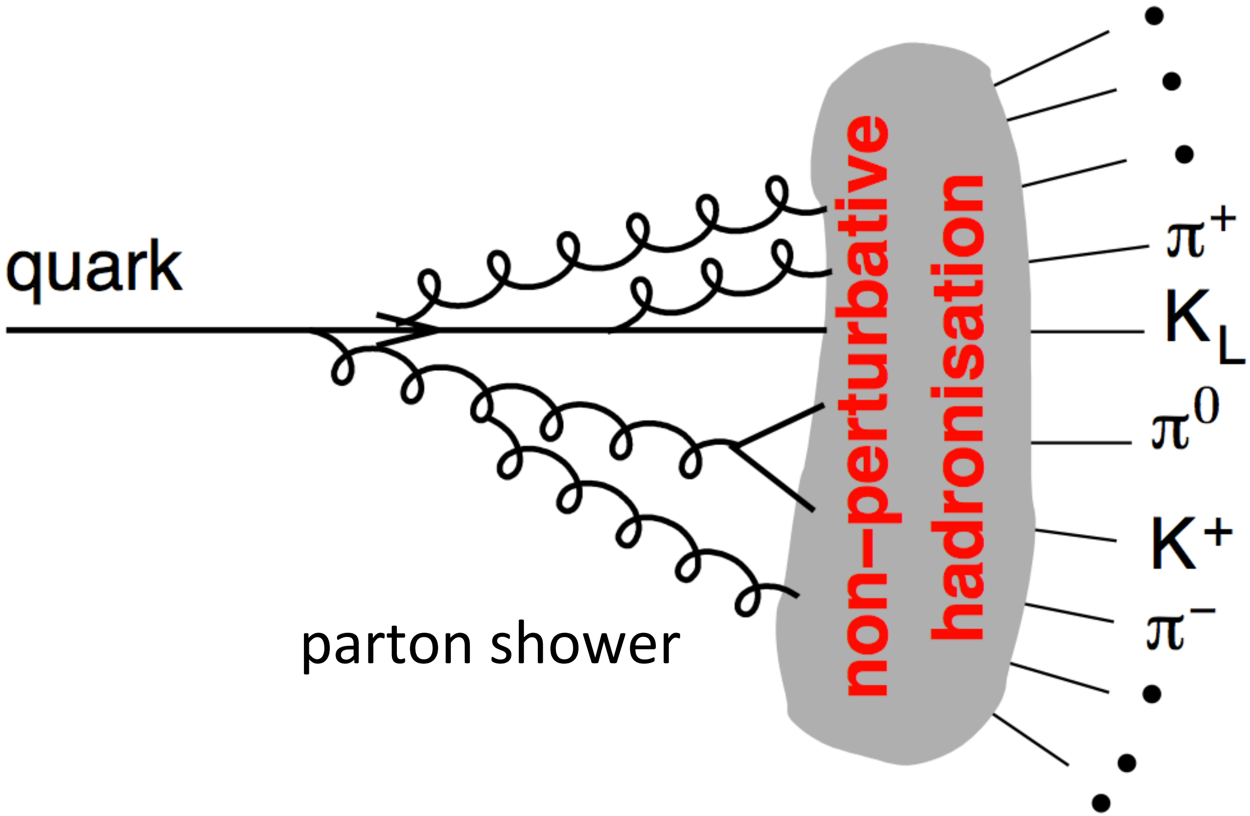
Jets are experimental manifestations of partons
quarks and **gluons**

Predicted by QCD: quarks and gluons carry color

- at small distances interactions are small (asymptotic freedom)
- at large distances interactions are large (color confinement)

Because of confinement free particles can't carry color
and quarks and gluons can only be seen as jets of hadrons

Hadronization



produced hadrons need to color connect to another initial parton in the event to close the global color neutrality

Partons of high energy ($E >> m_\pi$) lead to collimated bursts of hadrons

Discovery of jets (quarks)

Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation*

G. Hanson, G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, D. L. Hartill,† B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 8 October 1975)

We have found evidence for jet structure in $e^+e^- \to$ hadrons at center-of-mass energies of 6.2 and 7.4 GeV. At 7.4 GeV the jet-axis angular distribution integrated over azimuthal angle was determined to be proportional to $1+(0.78\pm0.12)\cos^2\theta$.

Mark I Collaboration

$$e^+e^- \to qq$$

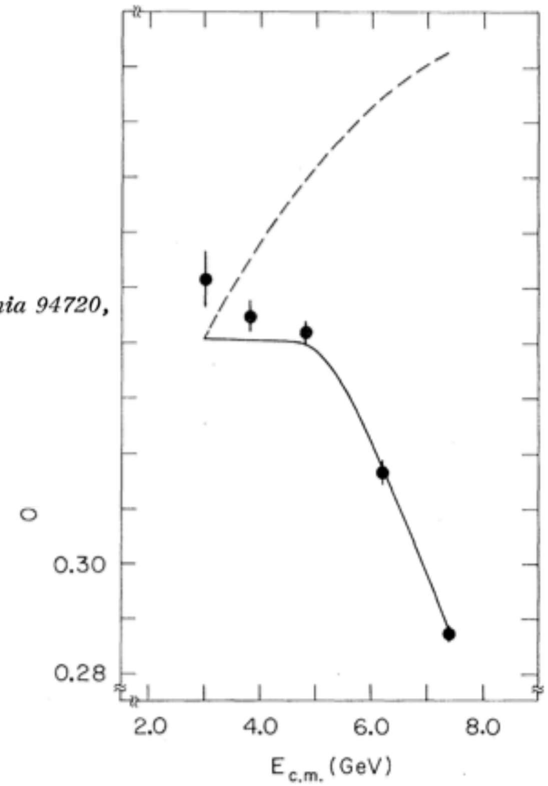


FIG. 1. Observed mean sphericity versus center-of-mass energy $E_{\text{c.m.}}$ for data, jet model with $\langle p_\perp \rangle = 315$ MeV/c (solid curve), and phase-space model (dashed curve).

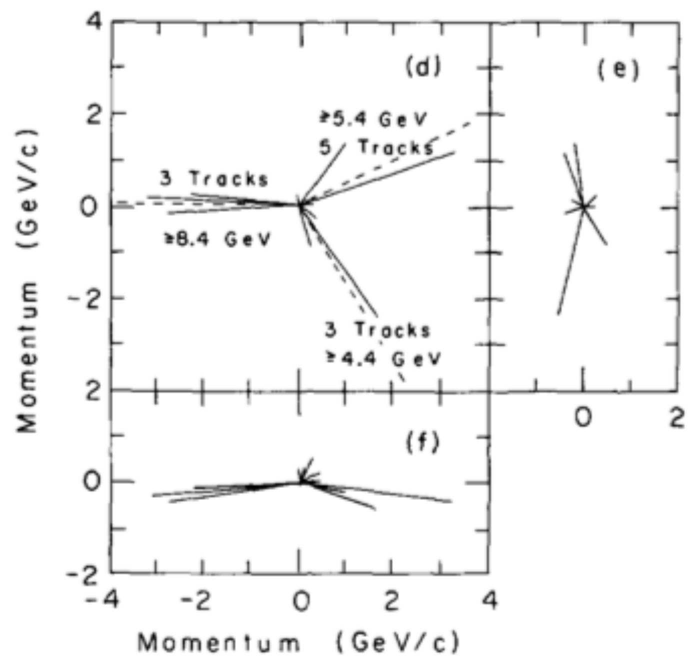
Discovery of gluon jets

Volume 86B, number 2 PHYSICS LETTERS 24 September 1979

EVIDENCE FOR PLANAR EVENTS IN e^+e^- ANNIHILATION AT HIGH ENERGIES

TASSO Collaboration

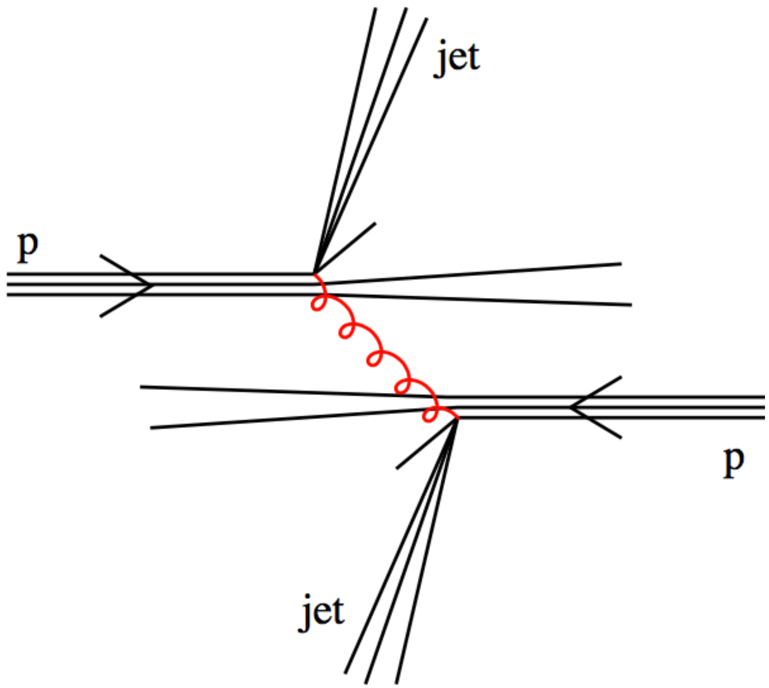
$$e^+e^- \rightarrow qqg$$

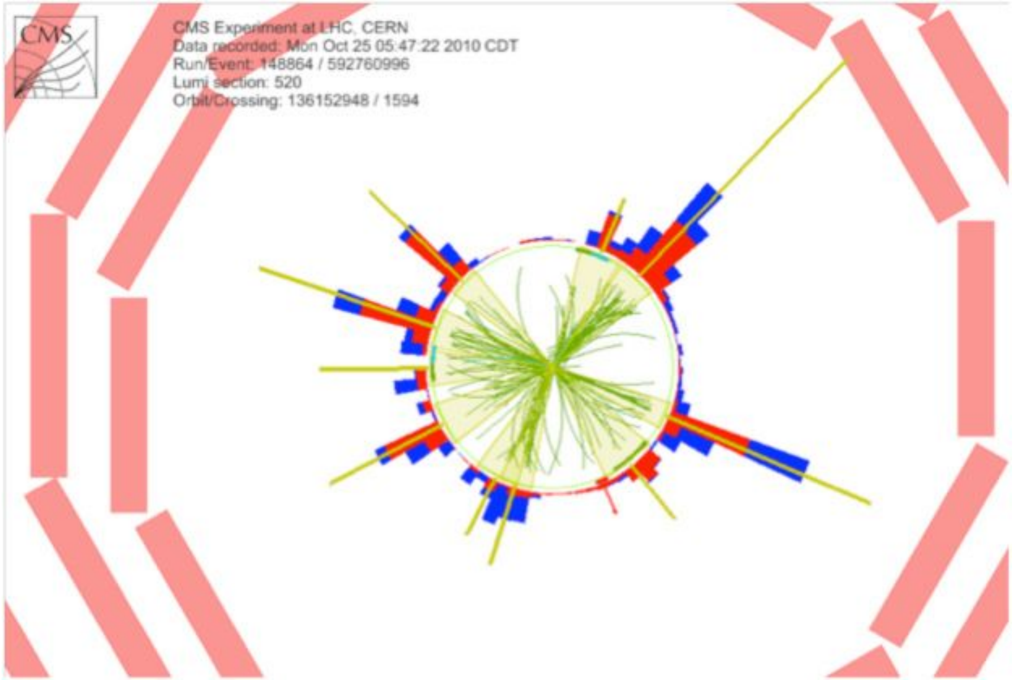


Hadron jets produced in e^+e^- annihilation between 13 GeV and 31.6 GeV in c.m. at PETRA are analyzed. The trans verse momentum of the jets is found to increase strongly with c.m. energy. The broadening of the jets is not uniform in azimuthal angle around the quark direction but tends to yield planar events with large and growing transverse momenta the plane and smaller transverse momenta normal to the plane. The simple $q\bar{q}$ collinear jet picture is ruled out. The obse vation of planar events shows that there are three basic particles in the final state. Indeed, several events with three well separated jets of hadrons are observed at the highest energies. This occurs naturally when the outgoing quark radiates a hard noncollinear gluon, i.e., $e^+e^- \rightarrow q\bar{q}g$ with the quarks and the gluons fragmenting into hadrons with limited transver momenta.

Hadronic Jets in CMS

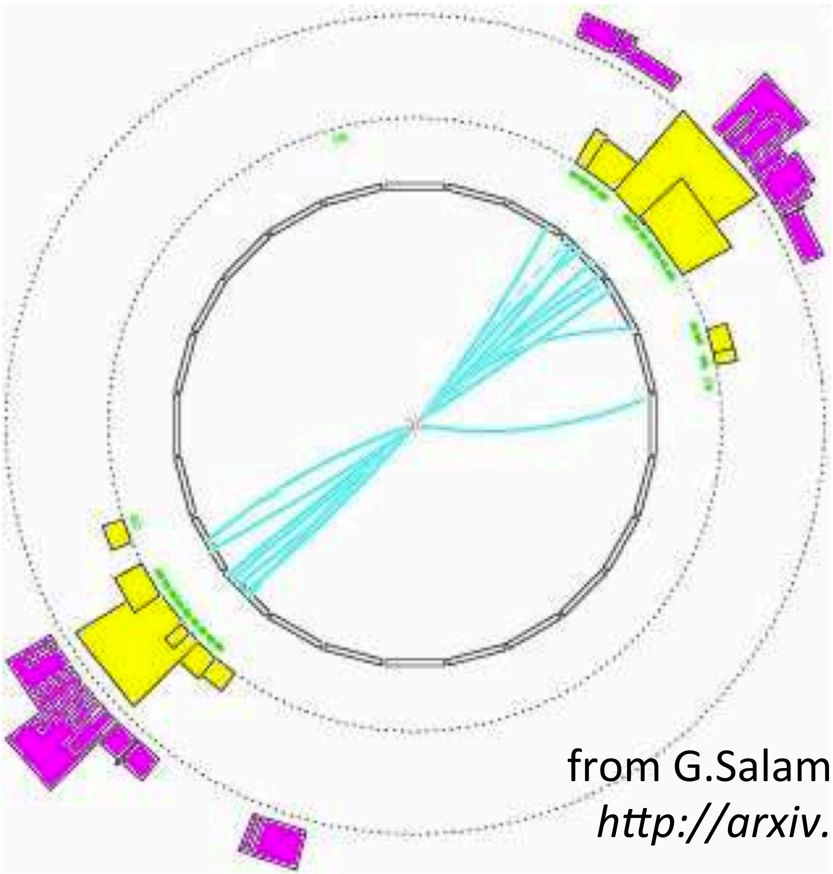
Jets are unavoidable in high energy hadron collision (parton scattering)

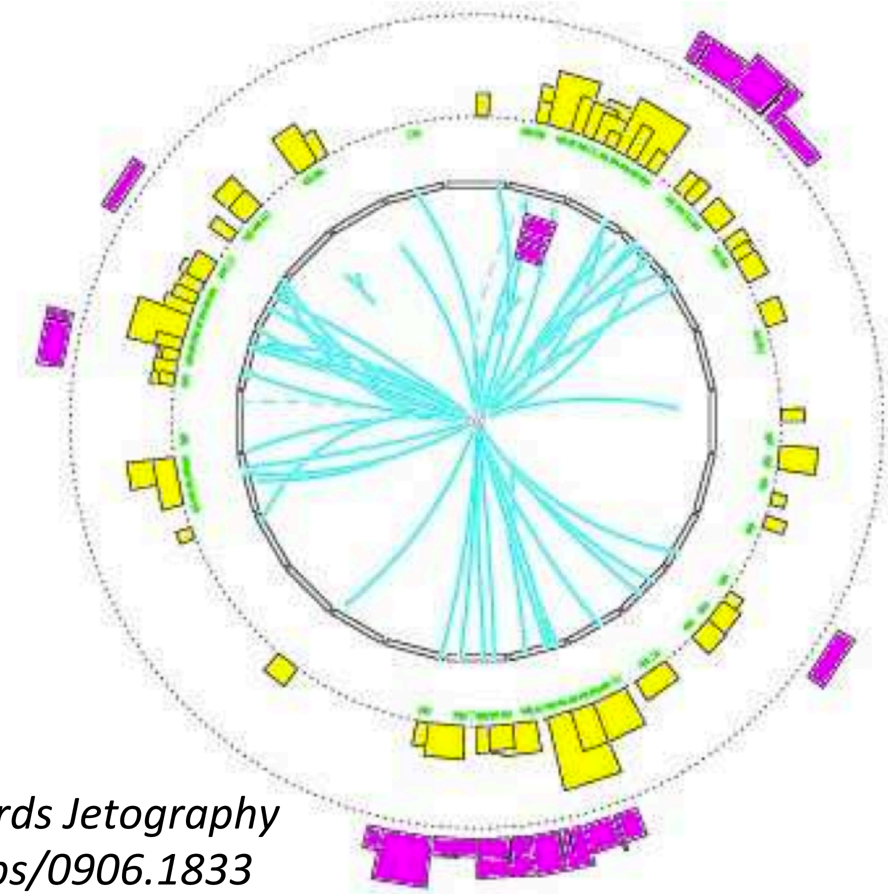




Any analysis of CMS data deals with the presence of hadronic jets

How do we define a hadronic Jet ?



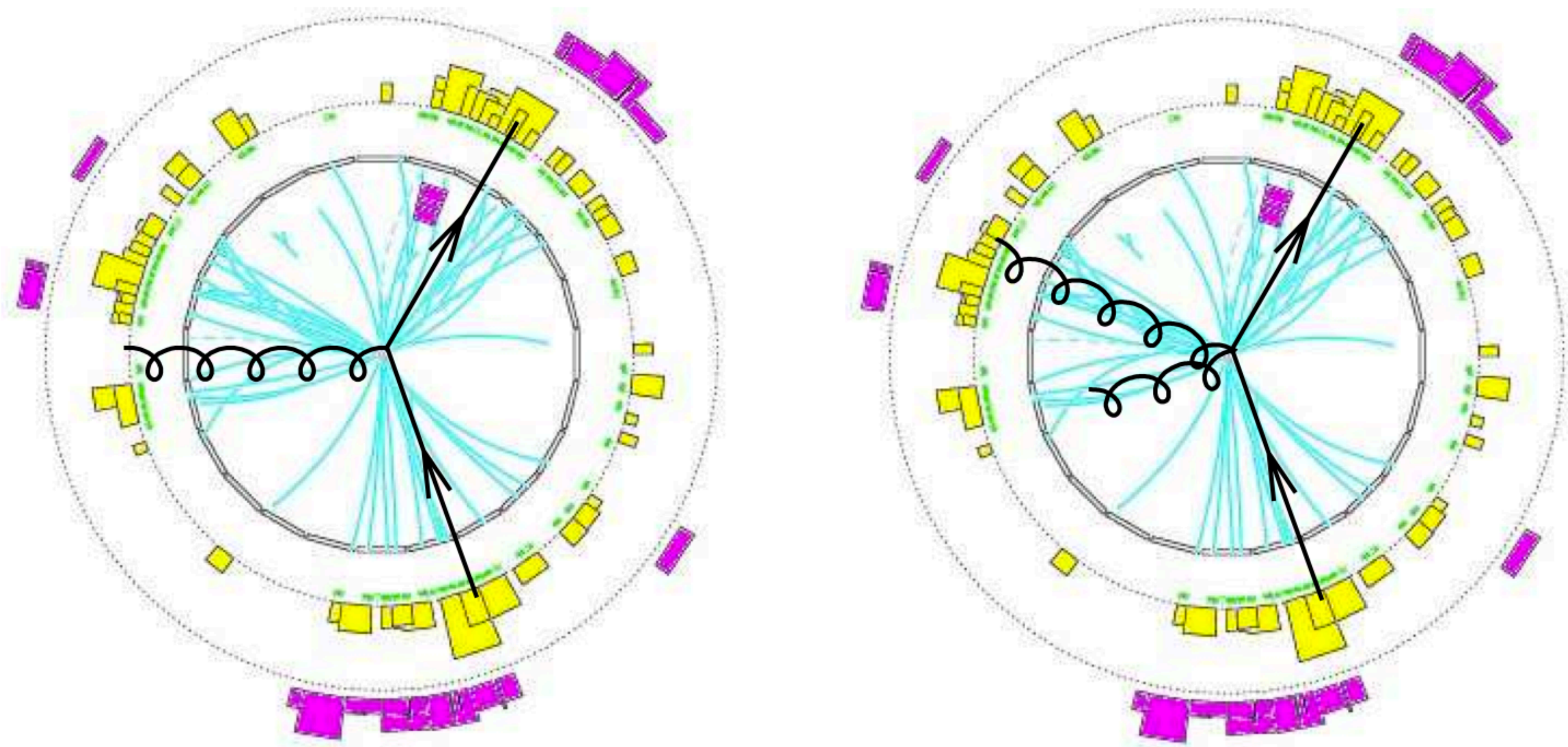


from G.Salam *Towards Jetography*
http://arxiv.org/abs/0906.1833

Two jets here

How many jets here ?

How do we define a hadronic Jet ?



Need a recipe to group final state hadrons into “Jets”

Jet definitions

Jet definitions provide a link between the theory and the experimental results

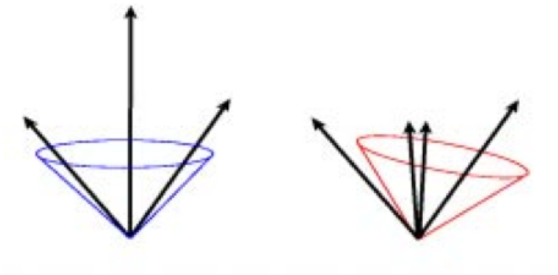
Two main questions

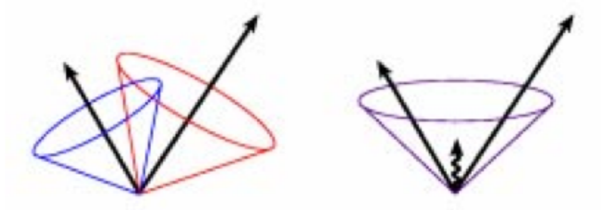
1. which particles go together ? **jet algorithm**
2. how are they combined ? **recombination scheme** (normally with the 4-momentum sum)

Jet definitions

Theorist like jets to be invariant for

collinear splitting & infrared emission





Infrared and Collinear Safety (IRC)

to avoid

- non-perturbative effects inherent to the definition
- divergent NLO QCD calculations
- dealing with effects that are not resolvable at detector level

Jet algorithms

- **Sequential recombinations** (*bottom-up*)

repeatedly combining pairs of particles in a single one

need to define when do you stop combining them

most widely used at LEP, HERA, and now LHC

- **Stable Cones** (*top–down*)

find cones that have the same direction as the contained particles (usually needs seeded directions)

most widely used at the Tevatron

Sequential recombinations

$$m^2 = 2E_1E_2\left(1-\cos\theta_{12}\right) \sim E_1E_2\theta_{12}^2$$

Inclusive kT algorithm:

$$\Delta R_{ij}^2 = \left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

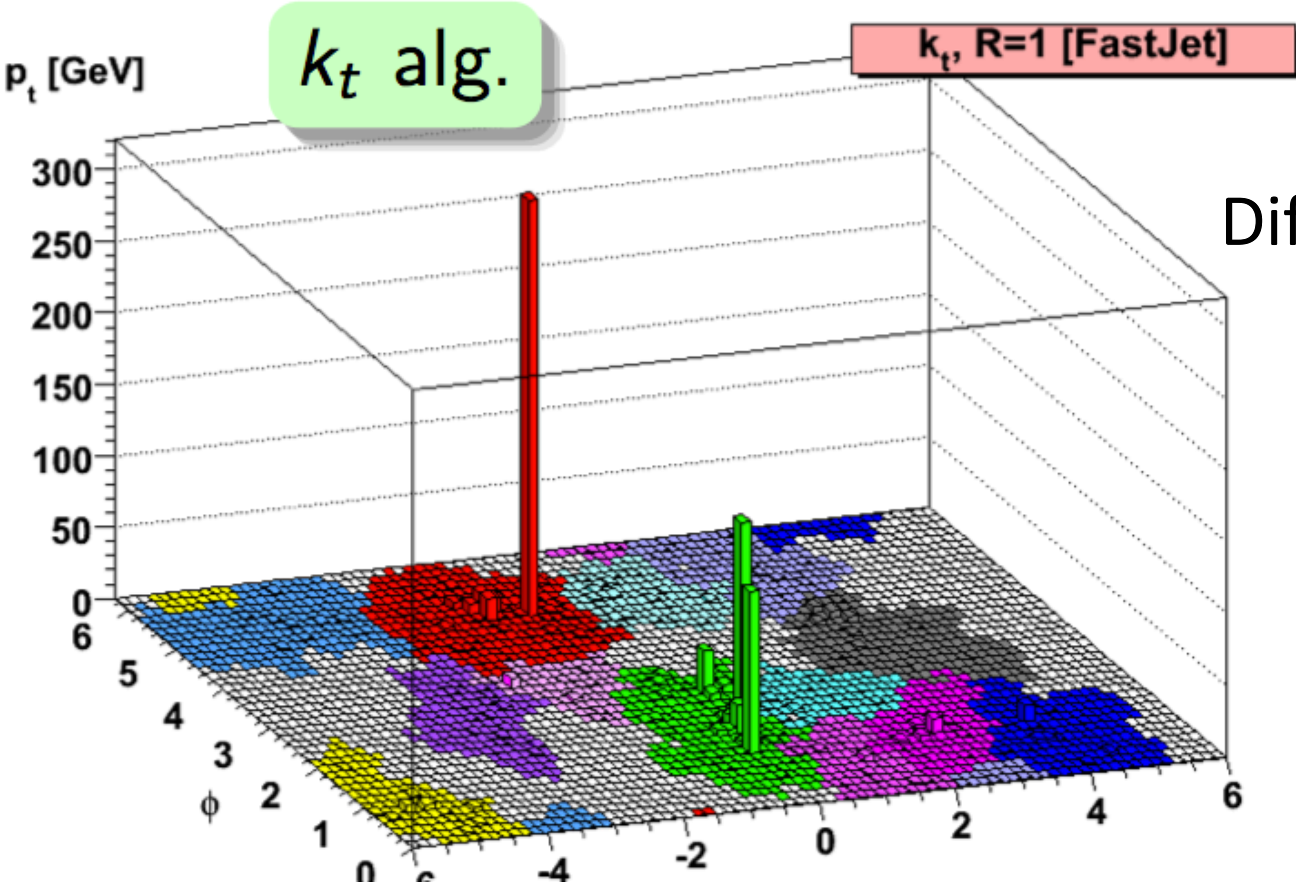
$$d_{ij} = \min\left(p_{Ti}^2, p_{Tj}^2\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^2$$

- Find smallest of dij , diB
- if ij, recombine them
- if iB, call i a jet and remove from list of particles
- repeat from step 1 until no particles left.

kT jets

kT Jets are irregular : soft particles are clustered together first



Difficult acceptance corrections

The anti-kT algorithm

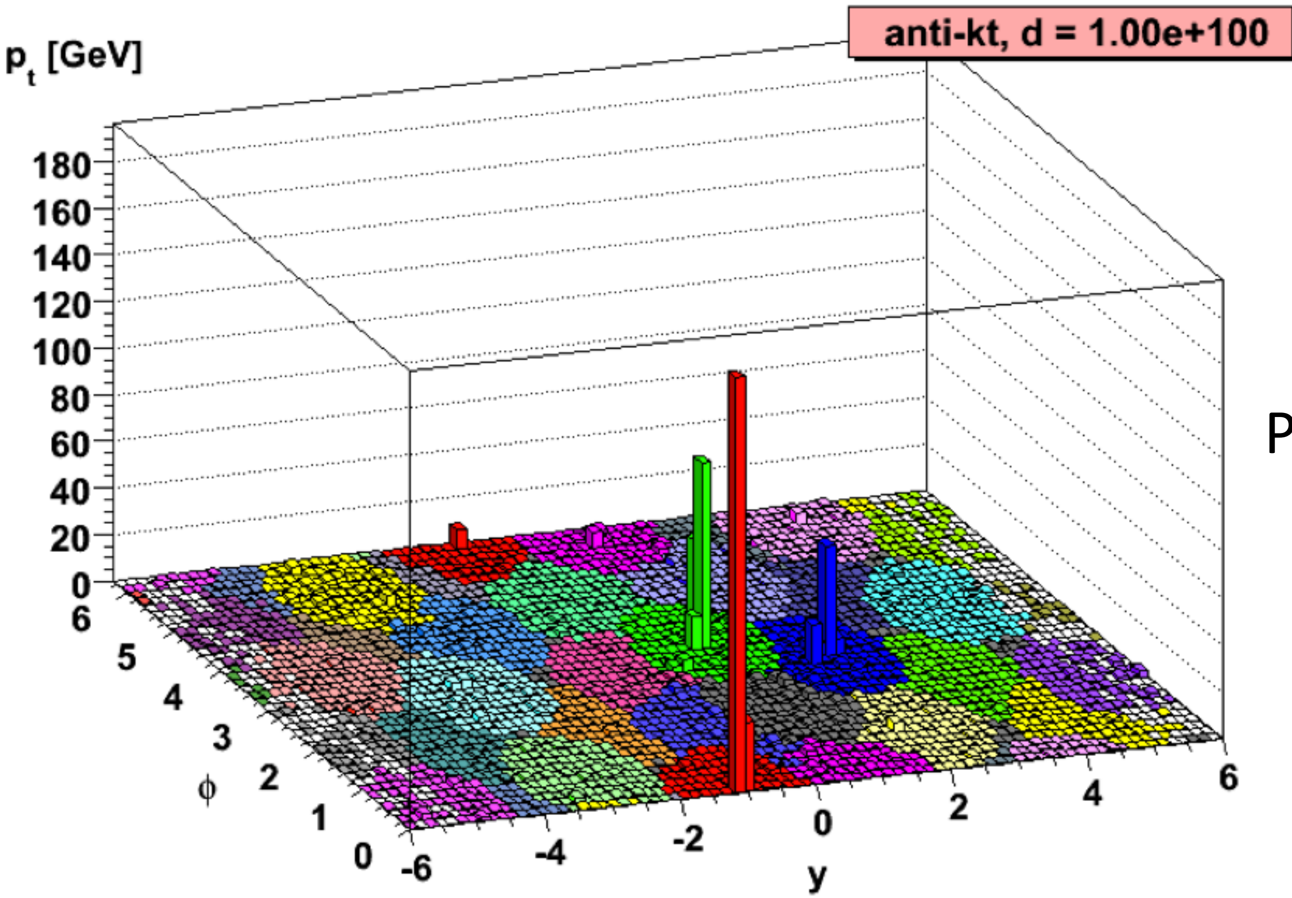
$$\Delta R_{ij}^2 = \left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

$$d_{ij} = \frac{1}{\max\left(p_{Ti}^2, p_{Tj}^2\right)} \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{Ti}^2}$$

Hard particles cluster first with neighbors !

anti-kT jets



Produces circular cone shaped jets with effective radius R without using stable cone algorithms

SIS cone Jets

Seedless Infrared Safe cones : find all stable cones

- Find all distinct ways of enclosing a subset of particles in a $y - \phi$ circle
- Check, for each enclosure, if it corresponds to a stable cone
- still need to run a split–merge procedure if the stable cones overlap

Runs in $N^2 \ln N$ time

Type inputs for CMS Jets

- **PF Jets** based on the "Particle Flow" algorithm which attempts to reconstruct each individual particle in the event, prior to the jet clustering, based on information from all relevant sub-detectors. -> new **PF** Jets with **Charged Hadron Subtraction**
  JPT Jets based on the "Jet-Plus- Track" algorithm which improves the measurement of calorimeter jets by exploiting the associated tracks
- **Calo Jets** based on calorimeter energy deposits only
- **Track Jets** based on reconstructed charged tracks only, clustered per Primary Vertex (pile-up transparent)

see e.g. http://cdsweb.cern.ch/record/1279362/files/JME-10-003-pas.pdf

Type of algorithms in CMS Jets

Main used type in Run 1 was **Anti-kT R=0.5**

- **Anti-kT R=0.5** R=0.7
- SISCone R=0.5 R=0.7
- kT R=0.5 R=0.7

Run2 main type will be **Anti-kT R=0.4**

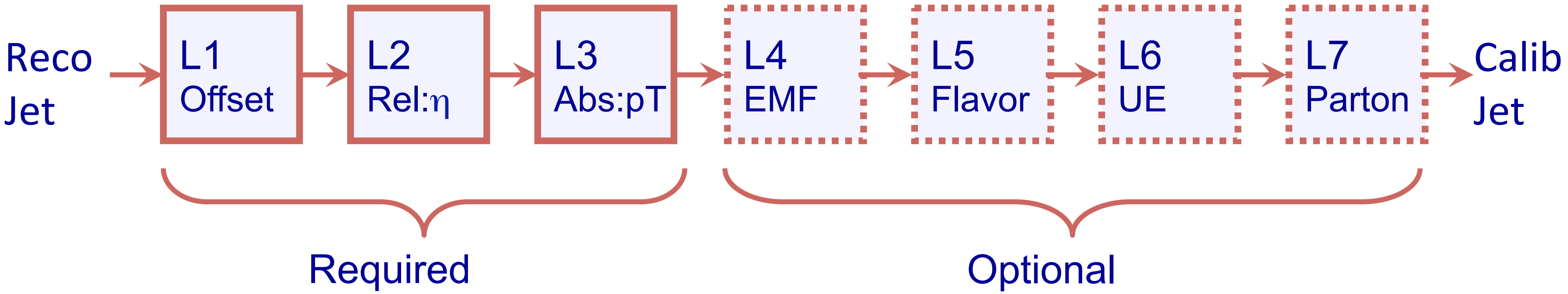
Jet Energy Calibration

Jet Energy Corrections in CMS

- CMS has adopted a **factorized** solution to the problem of jet energy corrections, where each level of correction takes care of a different effect.
- The corrections are derived both from *MC truth* and *data driven* methods.
- each correction is a **scaling** of the jet four momentum with a scale factor (correction) which depends on jet related quantities
- the levels of correction are applied **sequentially** (the output of each step is the input to the next) and with **fixed order**.

Jet Energy Corrections Levels

1. **Pile-up**: remove the energy coming from pile-up events
2. **Relative (η):** variations in jet response with η relative to central region.
3. **Absolute (p_T):** correction to particle level (GenJet) versus jet p_T.
4. EM fraction: correct for energy deposit fraction in em calorimeter
5. Flavor: correction to particle level for different types of jet (b, τ, etc.)
6. Underlying Event: remove the UE contribution
7. Parton: correction to parton level



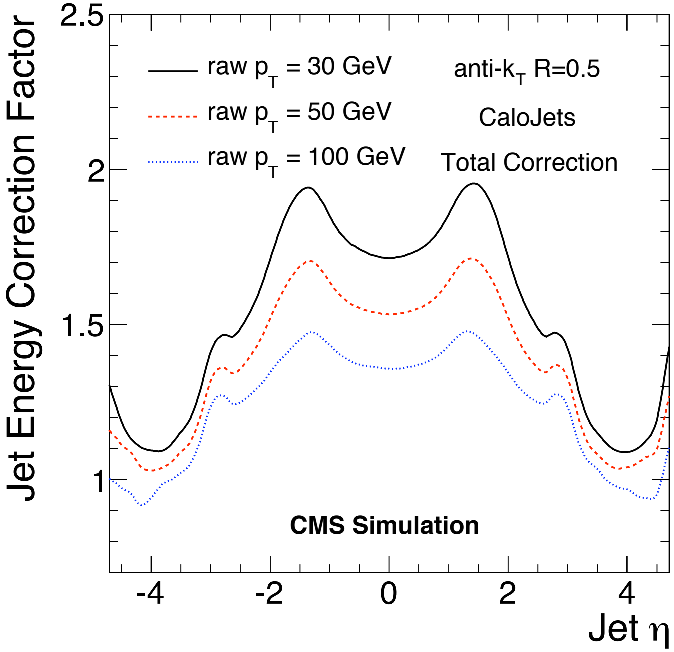
Jet Energy Corrections in CMS

Residual Calibration of Data jets (L2L3residuals) : small residual calibration (eta and pt dependent) is applied which fixes the differences between data and MC. The residual calibration is applied to **data only.**

The minimum correction levels to be applied on any CMS analysis using jets are
Monte Carlo L1(Pile Up)+L2(Relative)+L3(Absolute)
Data L1(Pile Up)+L2(Relative)+L3(Absolute)+L2L3Residuals

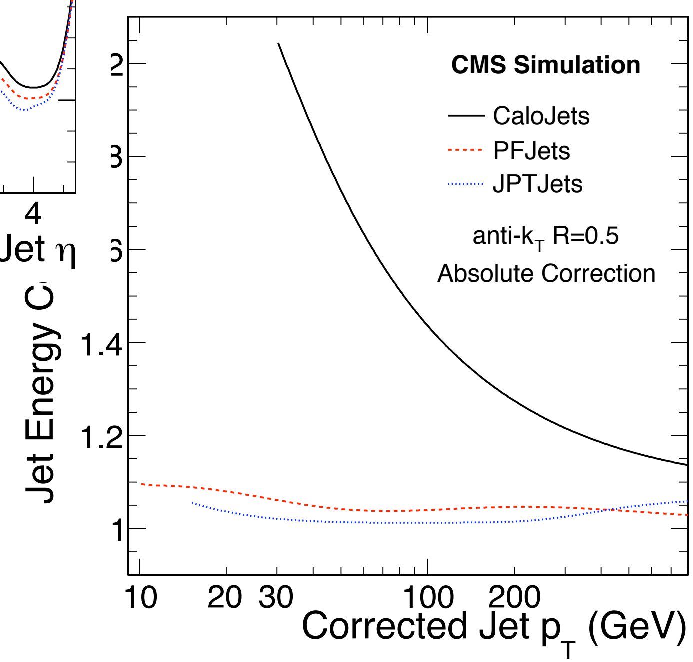
$$E_{Corr} = (\mathrm{E}_{\mathrm{Uncorr}} - E_{PU}) \times C_{Rel}(\eta, p_T'') \times C_{Abs}(\mathrm{p}_T')$$

Correction Factors



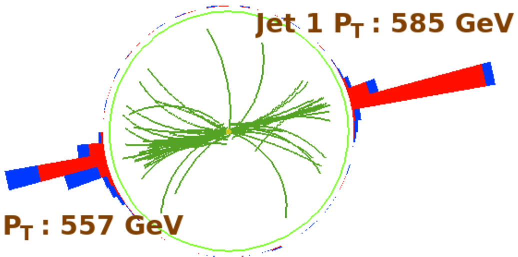
Relative η corrections

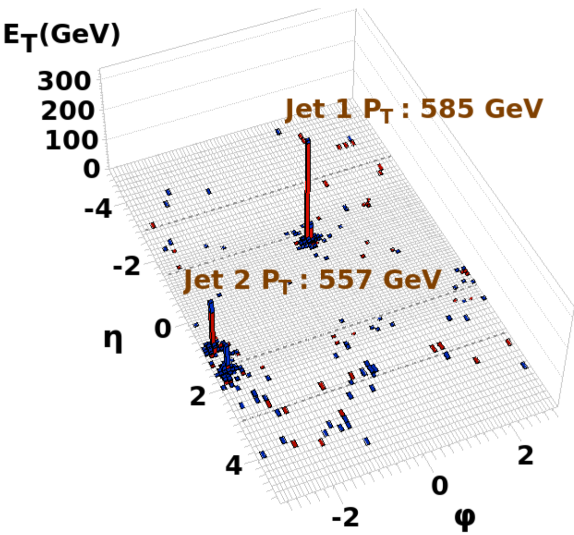
Absolute Energy corrections



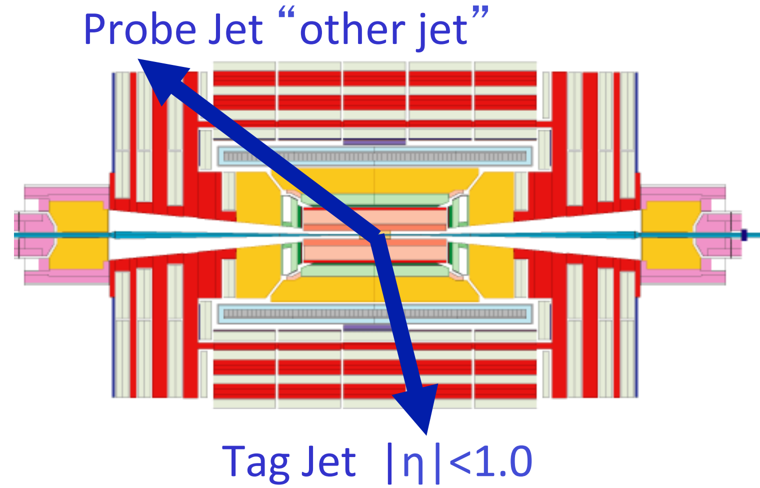
Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV

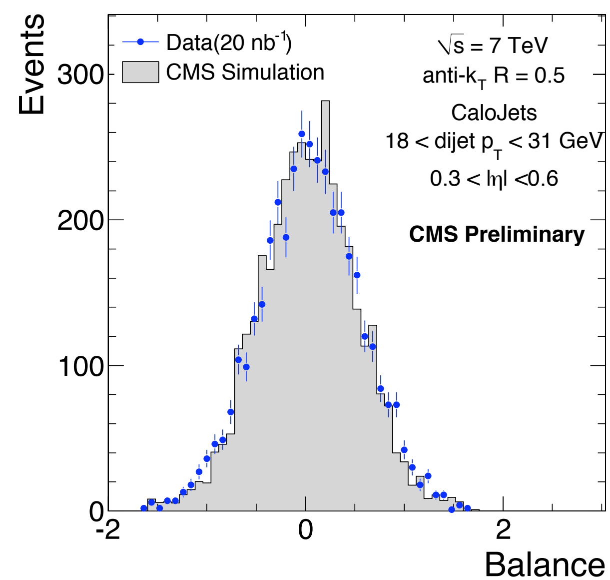
Di-jet balance



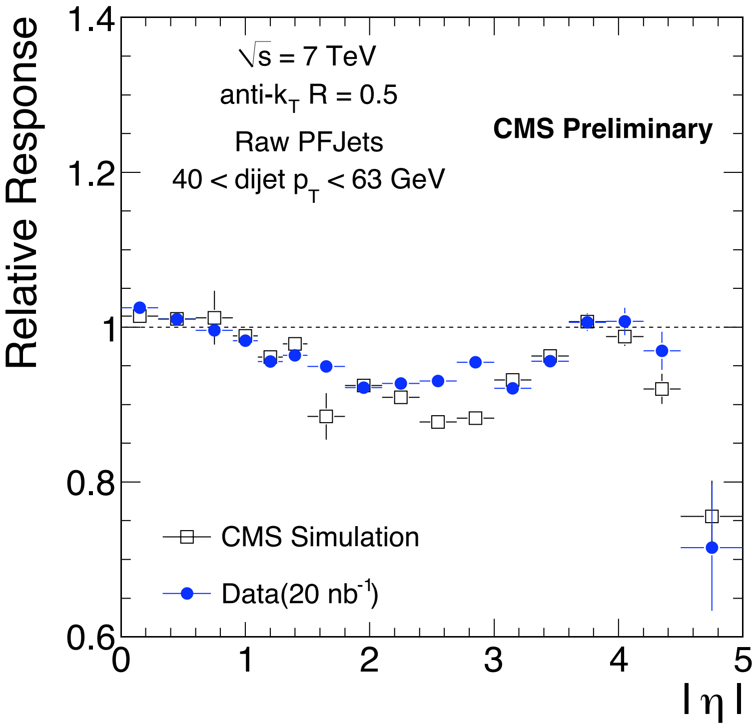


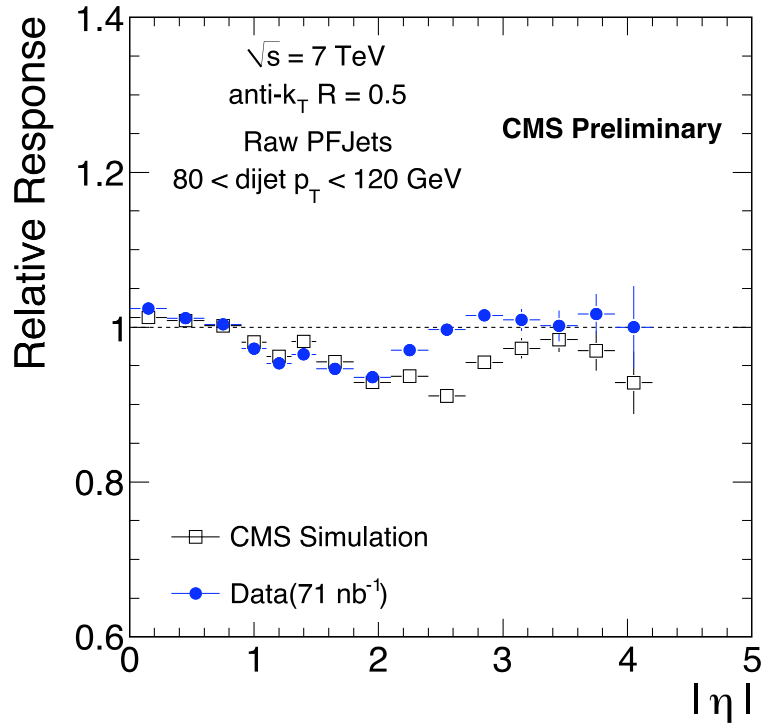
$$B = 2\,\frac{p_T^{probe} - p_T^{barrel}}{p_T^{probe} + p_T^{barrel}}$$





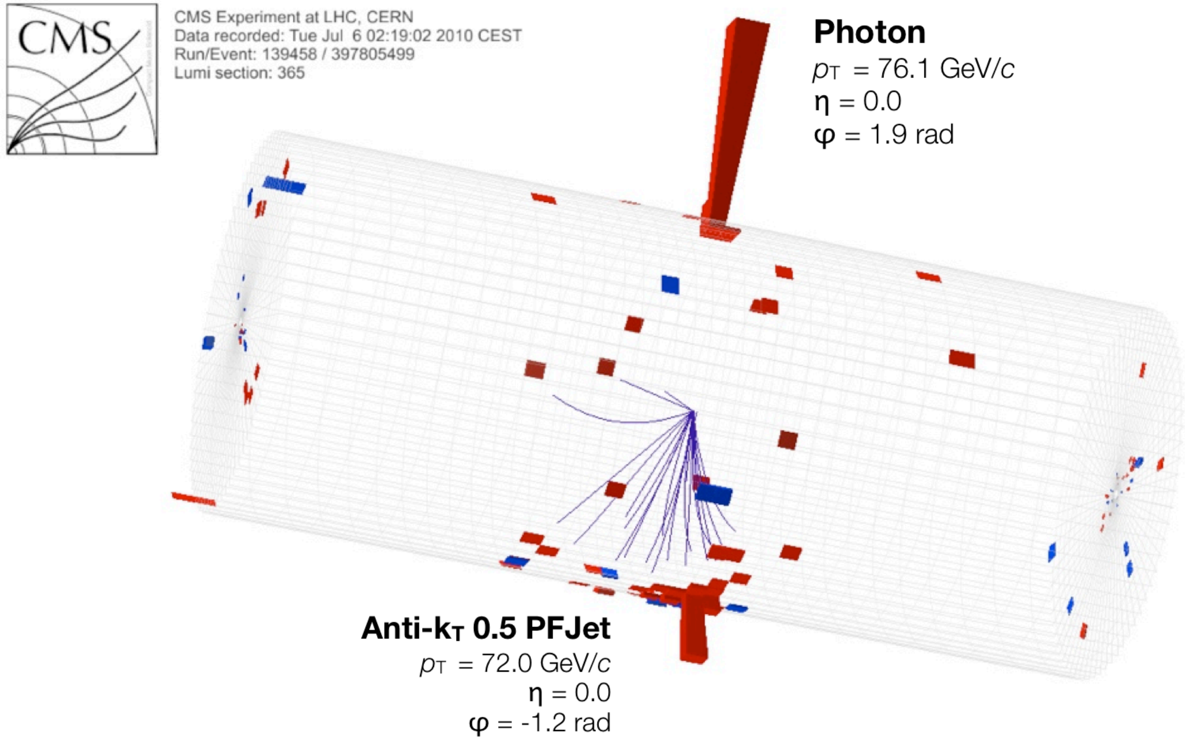
Relative response with di-jets

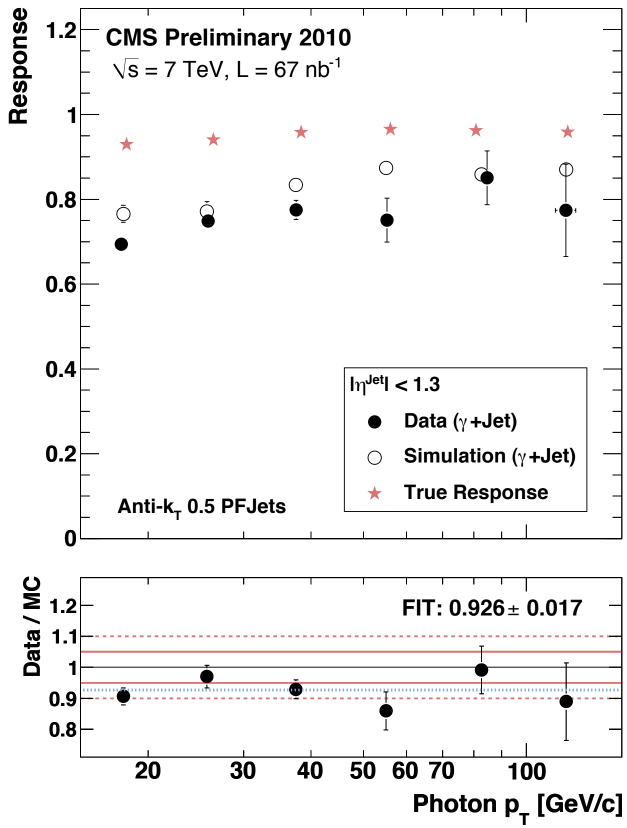




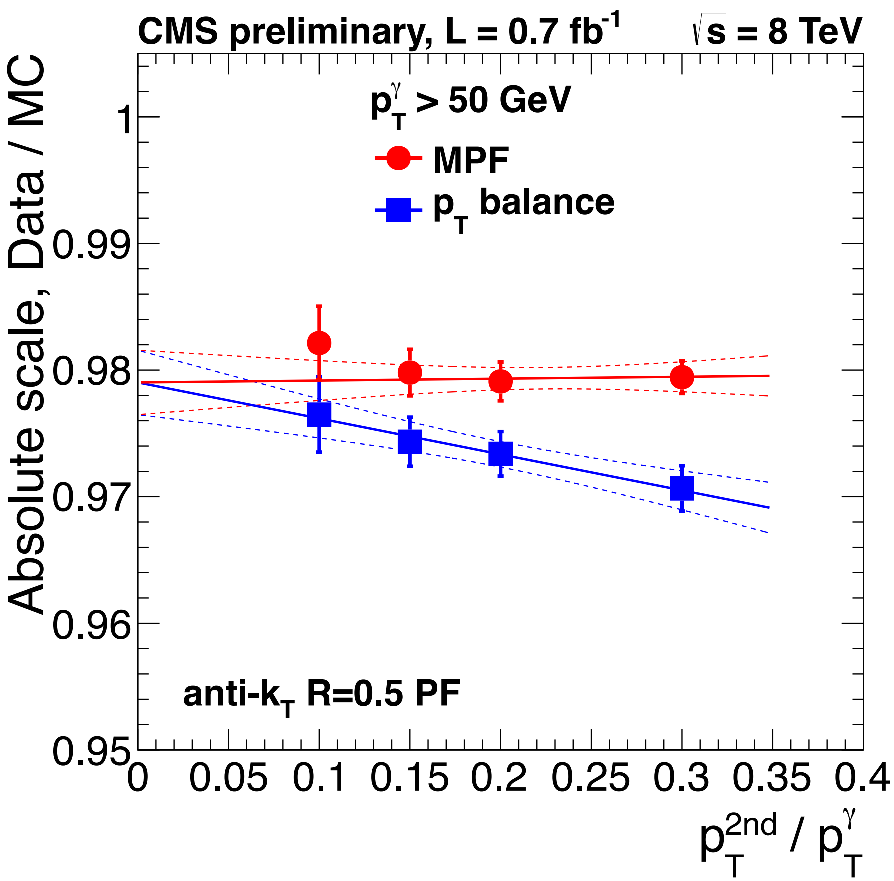
-> L2 residual corrections

photon + jet balance



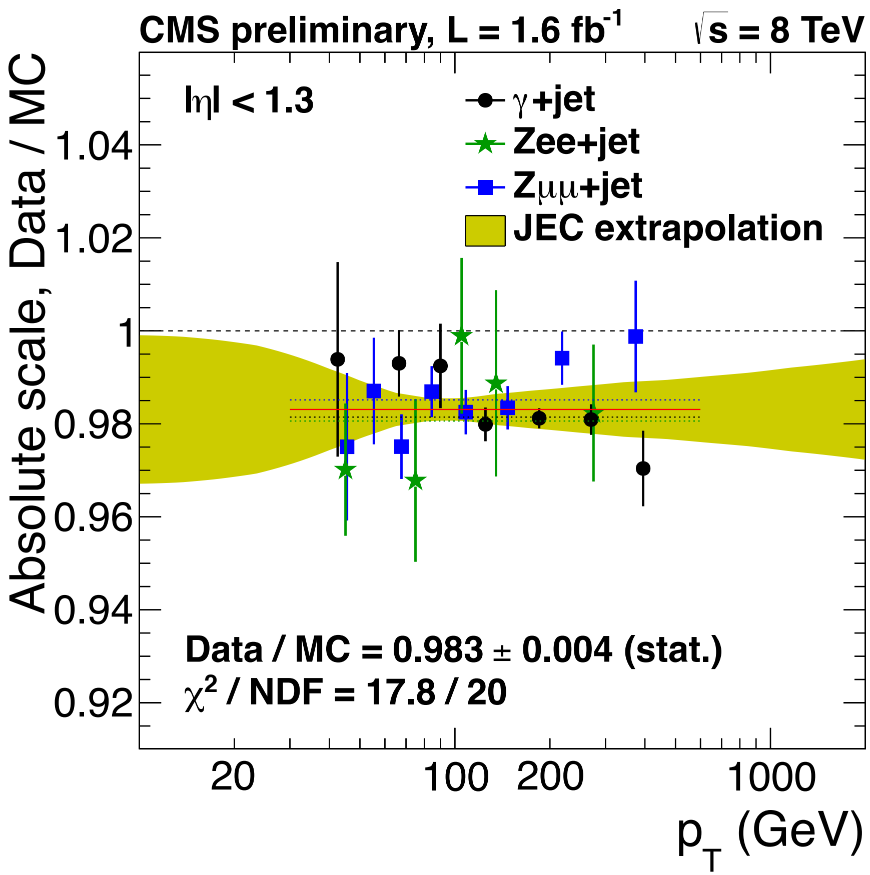


photon/Z + jet balance



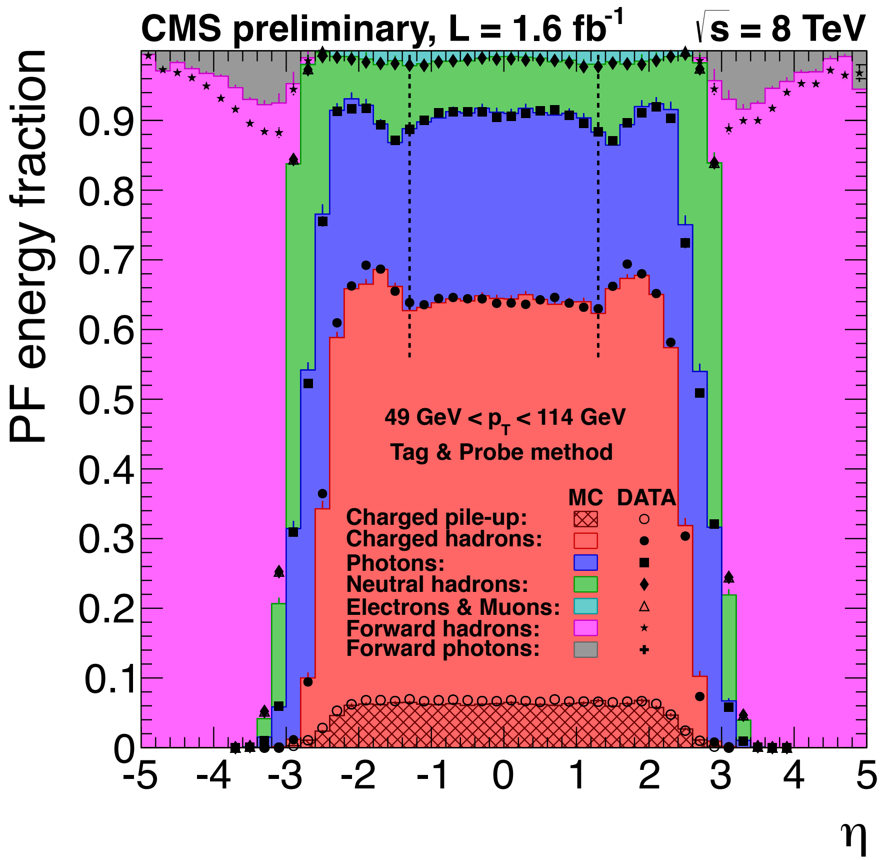
The 'pT balance' method used for determining absolute JEC with photon+jet (shown) and Z+jet samples is biased by additional jet activity, but agrees well with the Missing-ET projection fraction (MPF) method after extrapolating additional jet activity to zero.

photon/Z + jet balance

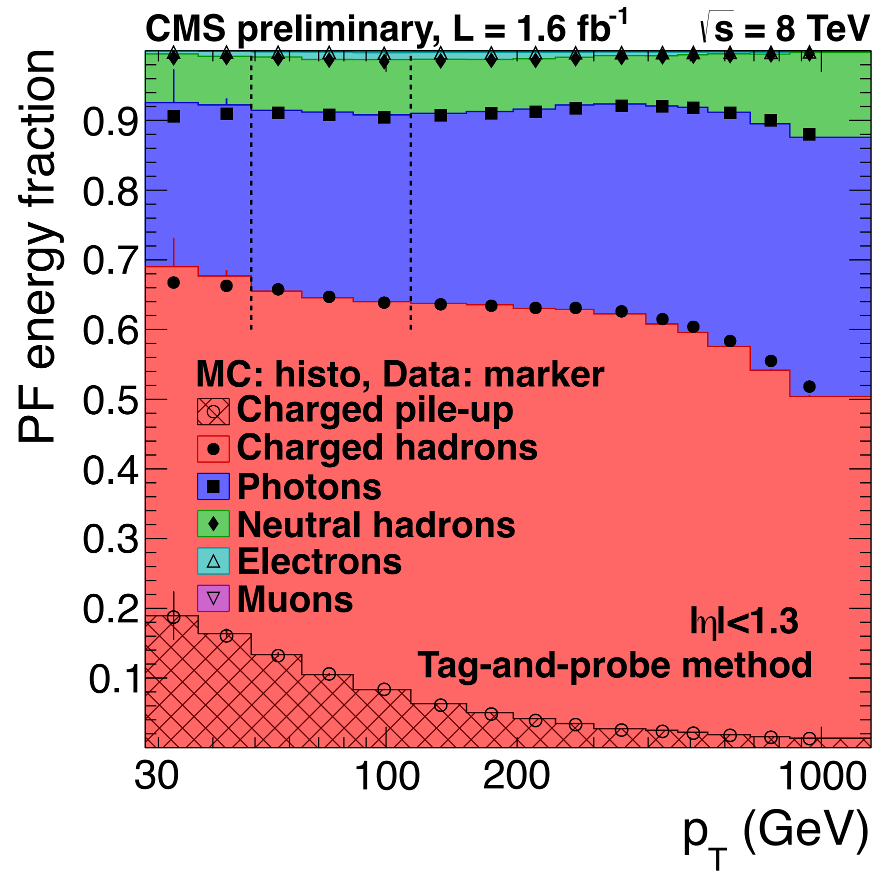


Data/MC ratio for the absolute scale after combining the photon+jet sample with two Z+jet decay modes. The residual correction required for absolute scale is of the order of 1.5% for all subchannels, and shows no significant pT dependence. Possible pT dependence is covered by extrapolation systematics based on a comparison of Pythia and Herwig fragmentation models and on the uncertainty in single particle response propagated to jets.

PF Jet composition

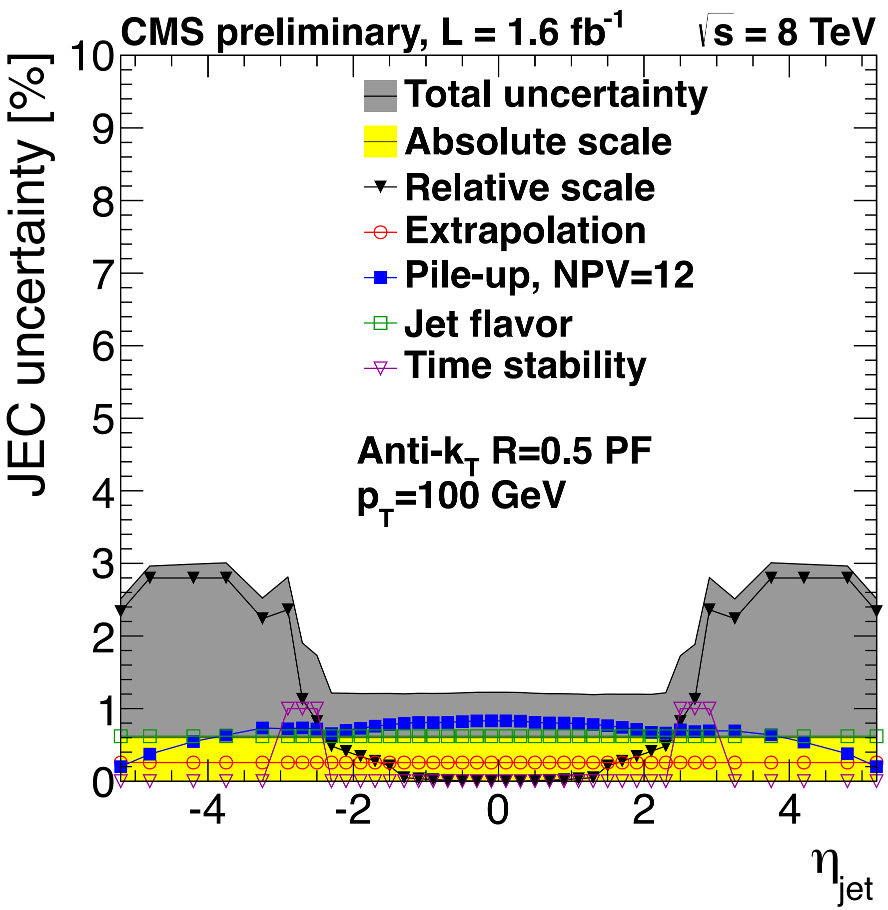


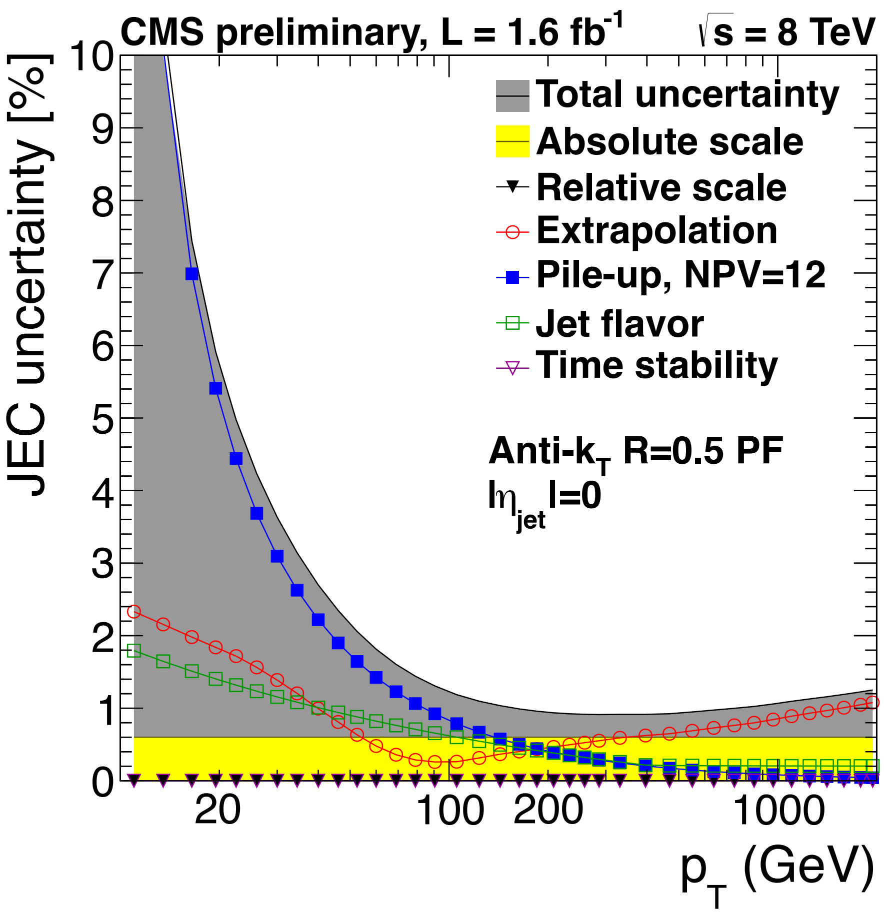
Jet composition versus jet η. The composition shows good agreement in the barrel region, but small differences in the more forward regions.



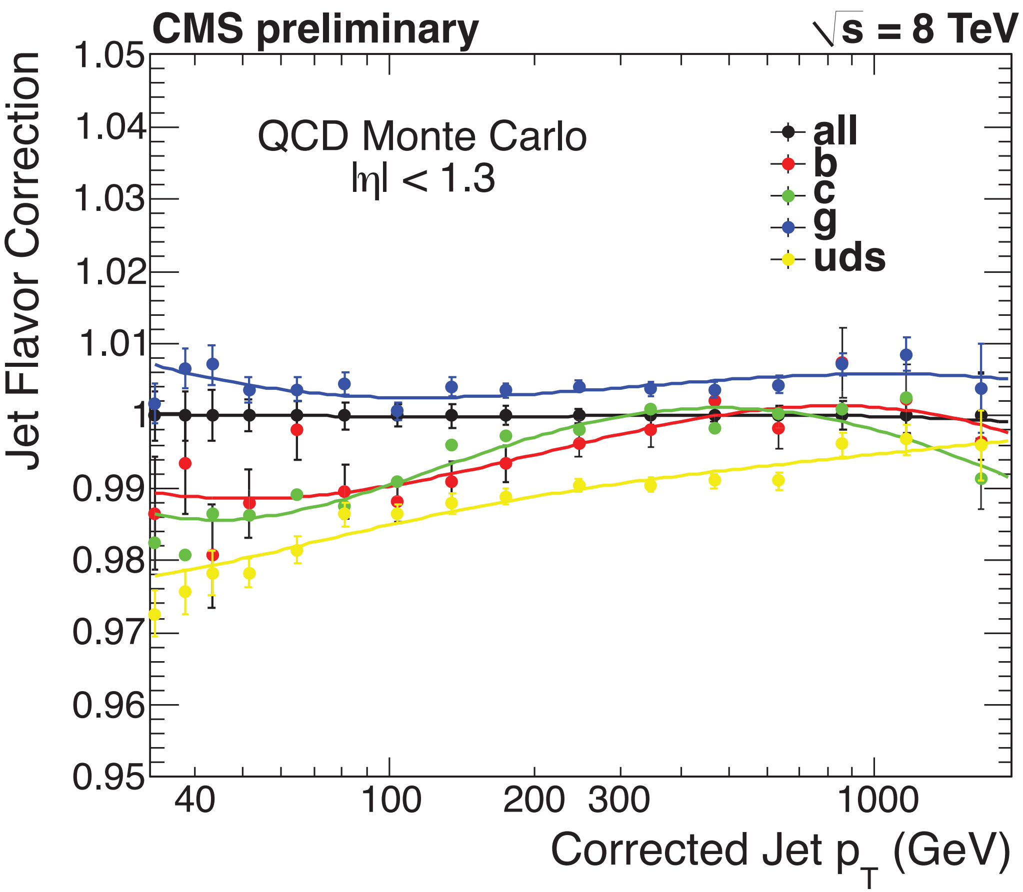
Jet composition versus jet pT in the barrel region |η|<1.3.

CMS Jet Energy Uncertainty





Jet Energy Flavor

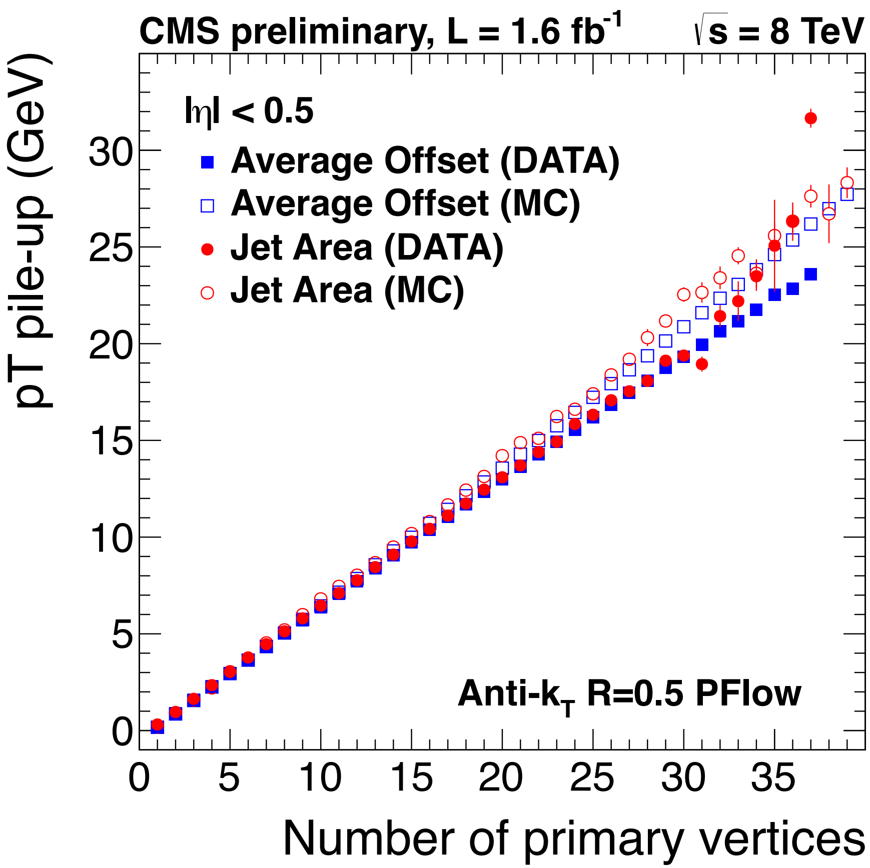


Jet energy corrections shown separately for different jet flavors. Gluons (g) have a high color charge compared to quarks, which causes them to fragment to more particles than quarks and results in larger JEC.

The high mass of heavy quarks (c, b) also results in fragmentation to more particles than for light quarks (uds).

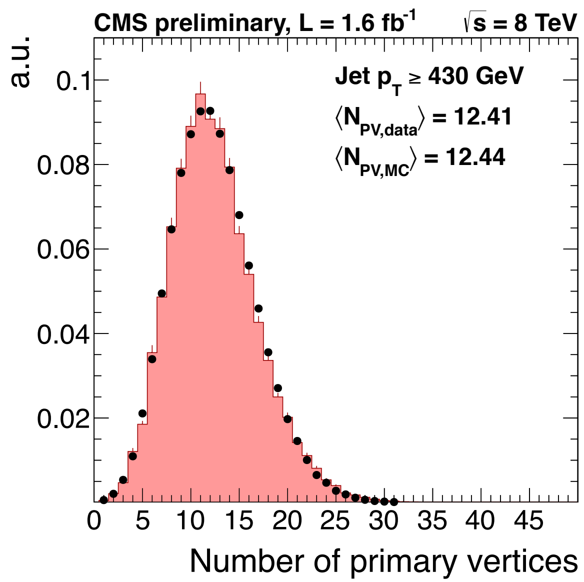
The neutrinos produced in semi-leptonic decays of heavy quarks are not included in the generator-level particle jets when computing the corrections.

Pile-up contributions

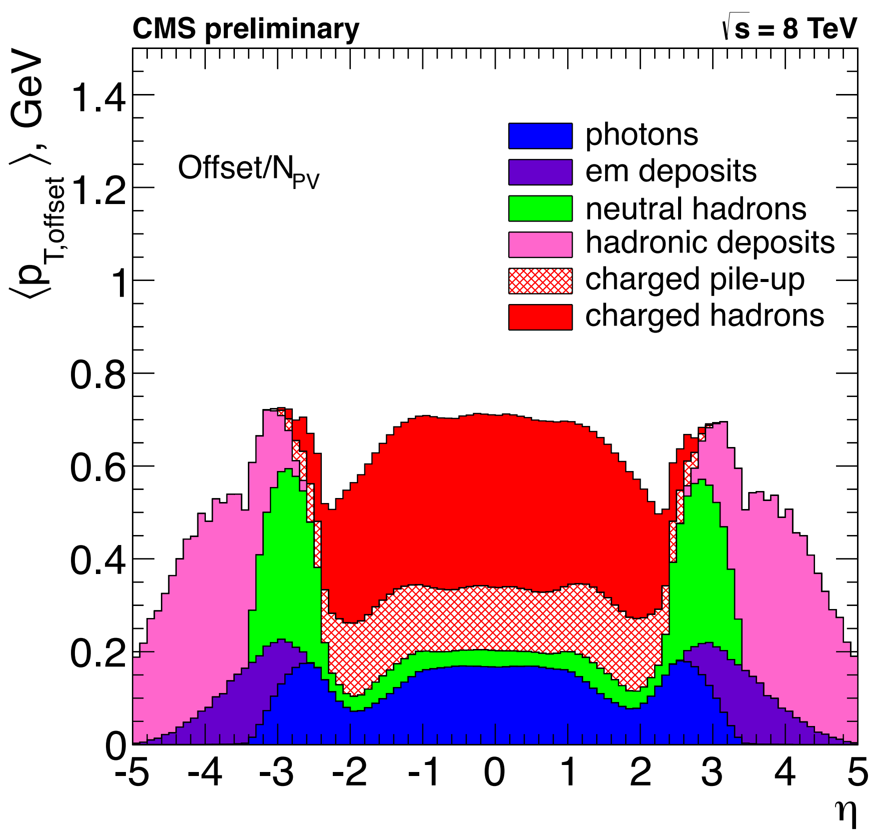


~600 MeV / nPV

800-900MeV / nPU



Pile-up composition

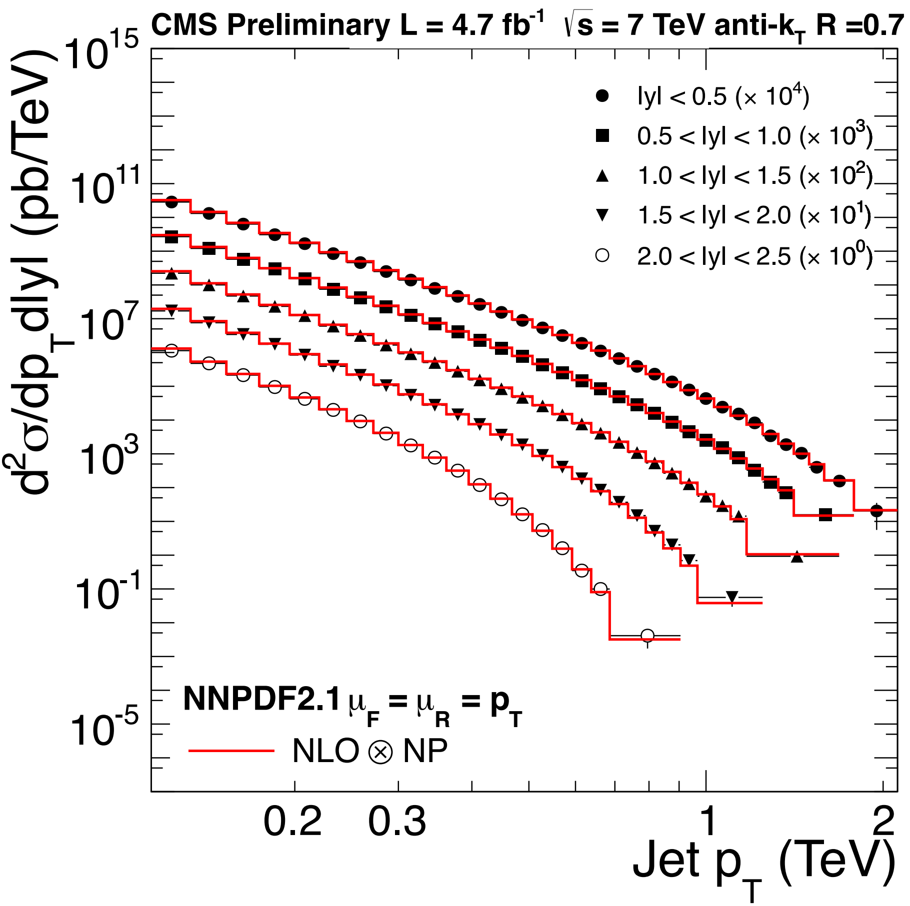


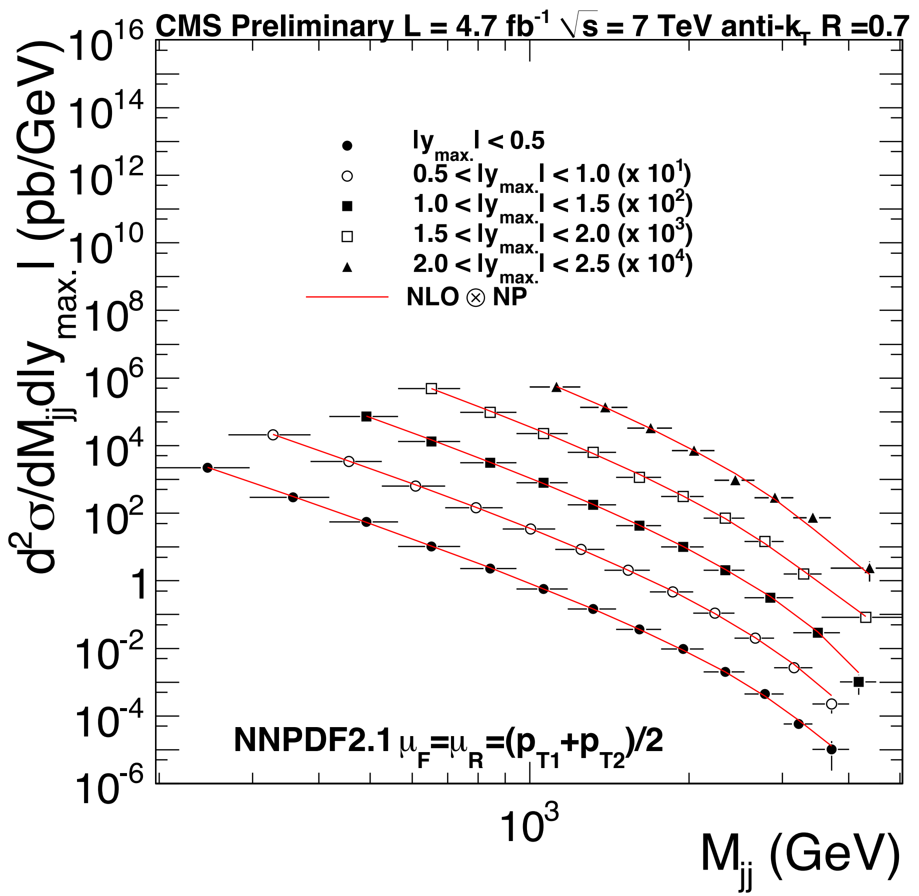
Pile-up composition in data. The 'charged pile-up' is PF charged hadrons that are not associated to a primary vertex, and therefore are not removed by the charged hadron subtraction (CHS). Instead, they are handled by pile-up corrections together with neutral contributions.

This plot is produced with the 'Random Cone' method by taking pile-up at NPV=20 and subtracting pile-up at NPV=10 to estimate the average pile-up per vertex.

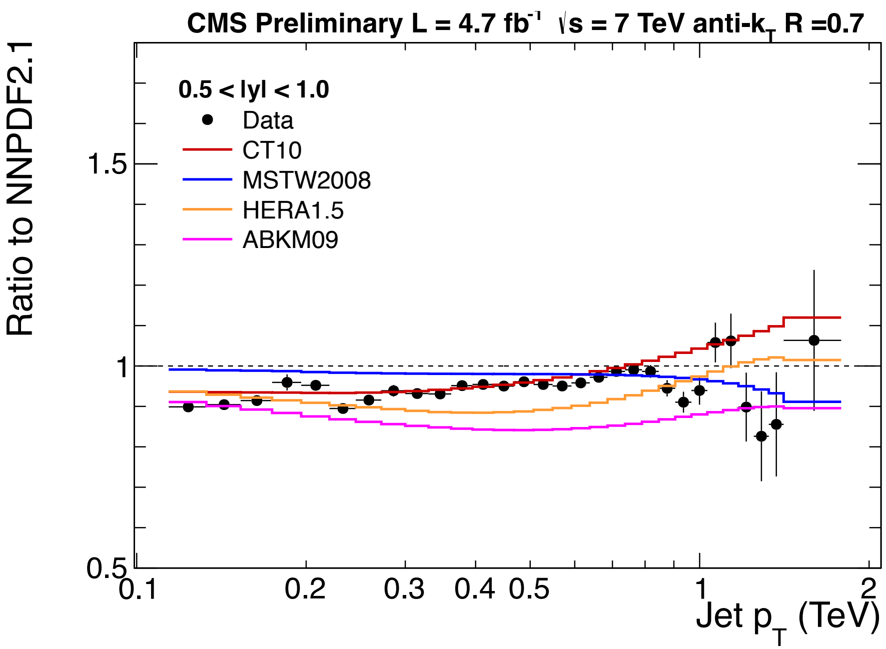
Some CMS results with Jets

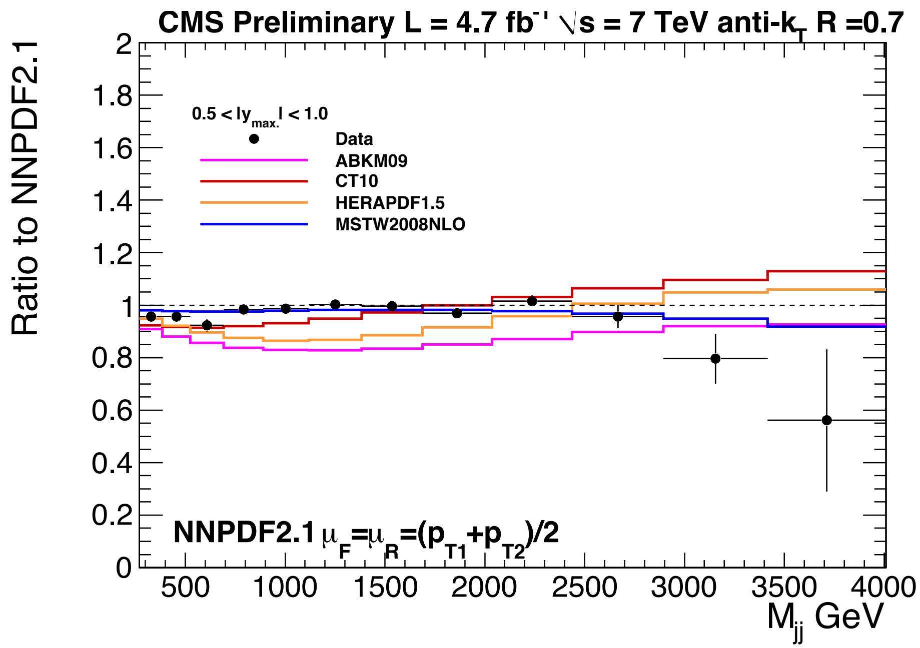
Inclusive & di-Jet cross sections





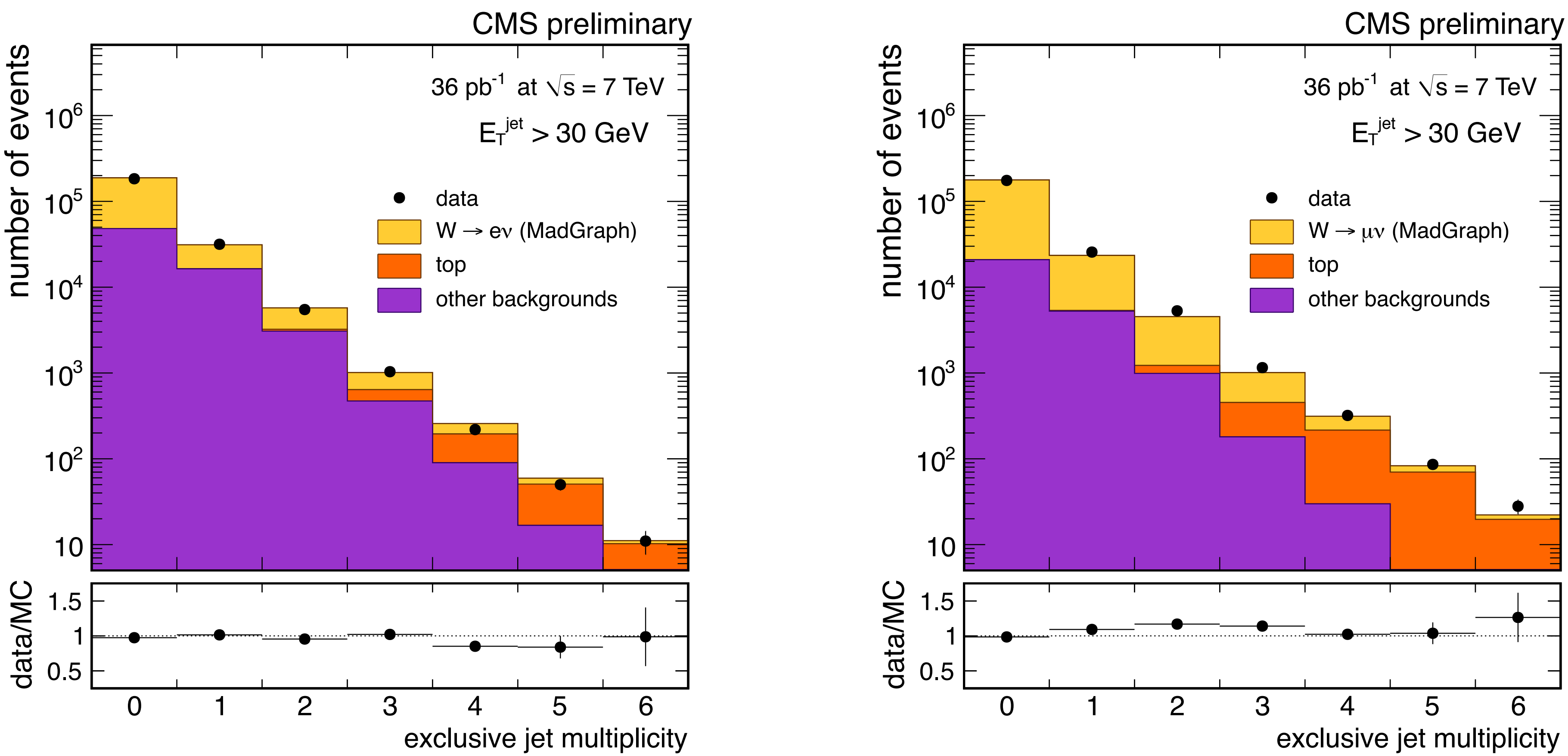
Inclusive & di-Jet cross section





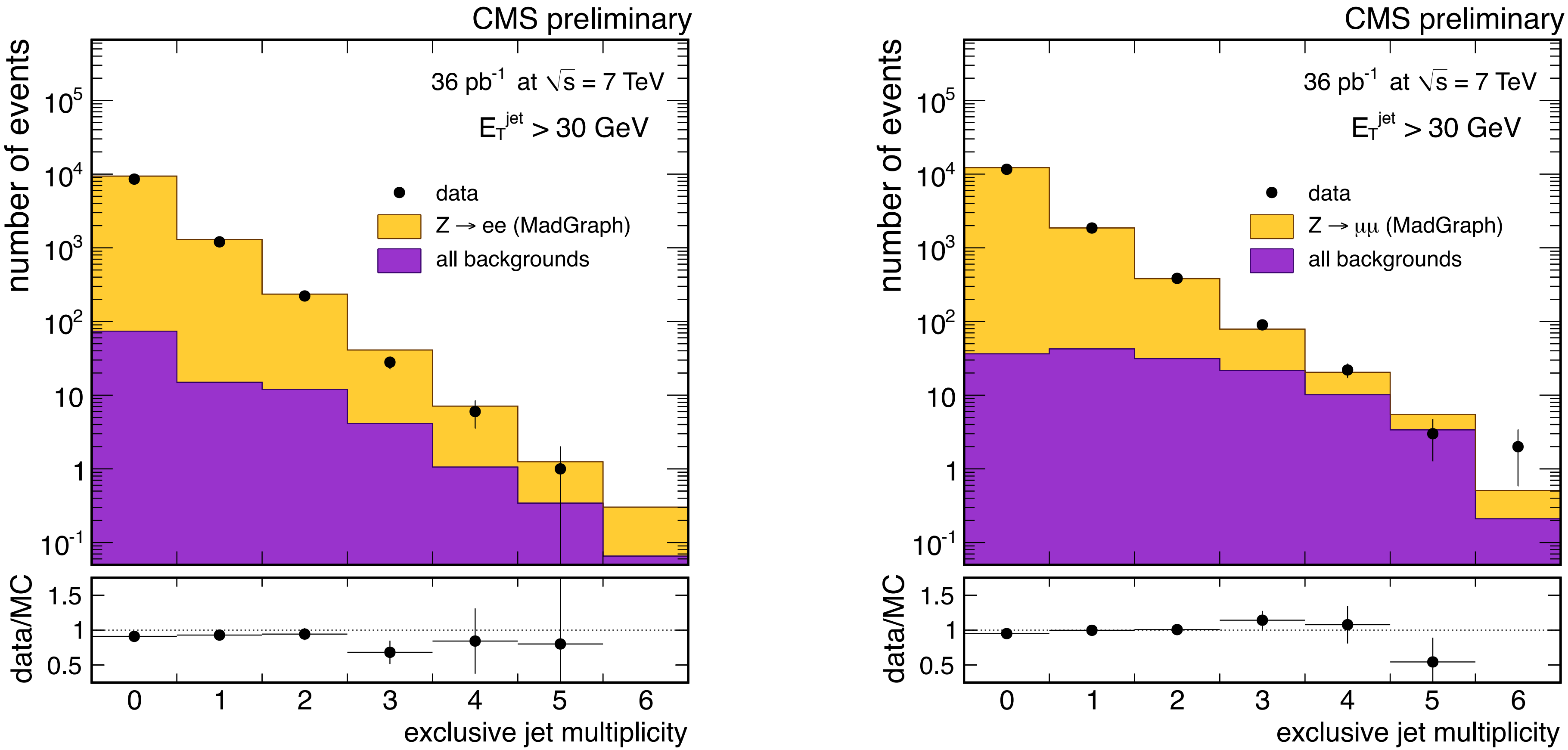
Data results are used in the global Parton Density Function (PDF) fits

W + jets



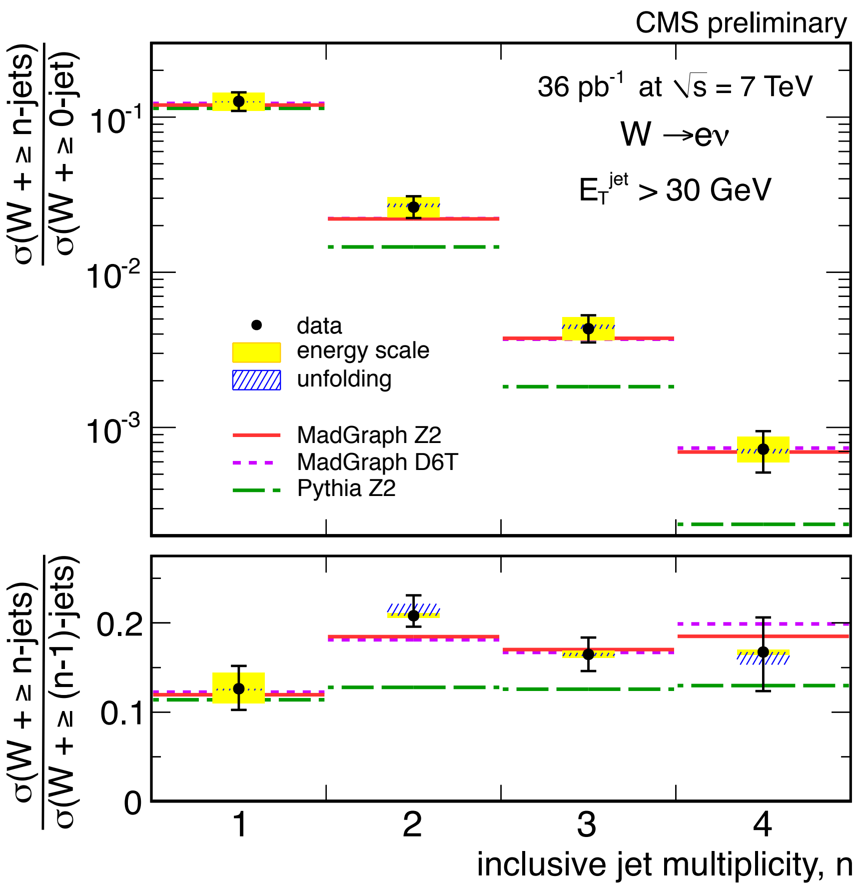
Exclusive number of reconstructed jets with ET(jet)> 30 GeV in events with $W \rightarrow e\nu$, and $W \rightarrow \mu\nu$

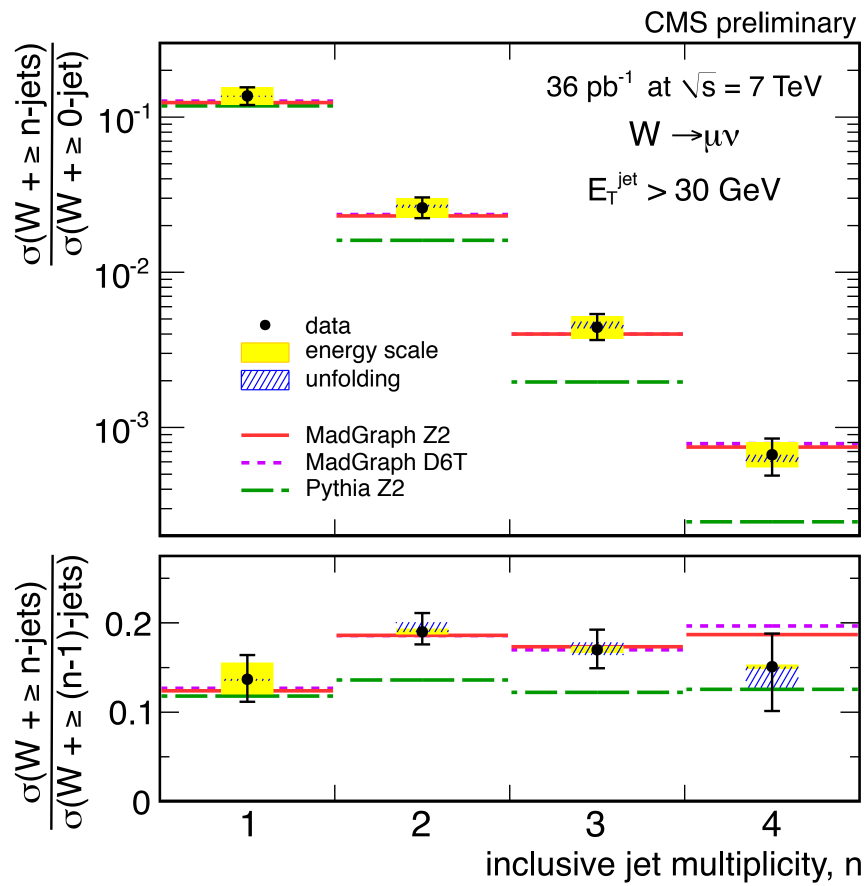
Z + jets



Exclusive number of reconstructed jets with ET(jet)> 30 GeV in events with $Z \rightarrow ee$, and $Z \rightarrow \mu\mu$

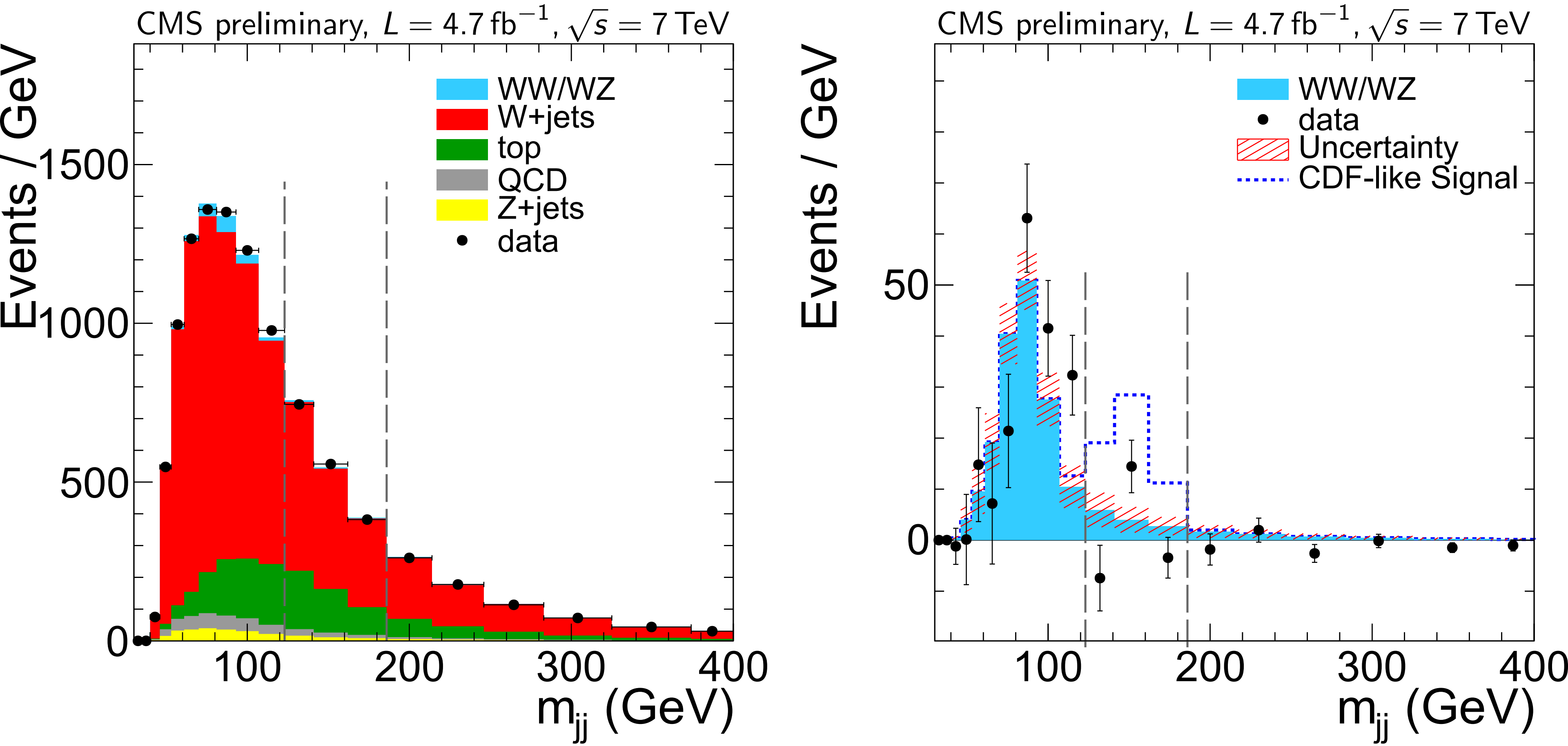
W+ jets ratios





Unfolded jet multiplicity ratios : test of Berends-Giele scaling (QCD couplings)

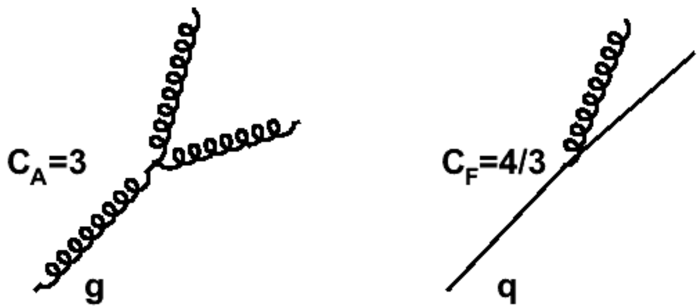
dijet invariant mass distribution in W→ lν plus jets events



no evidence for a resonant enhancement near a dijet mass of 150 GeV

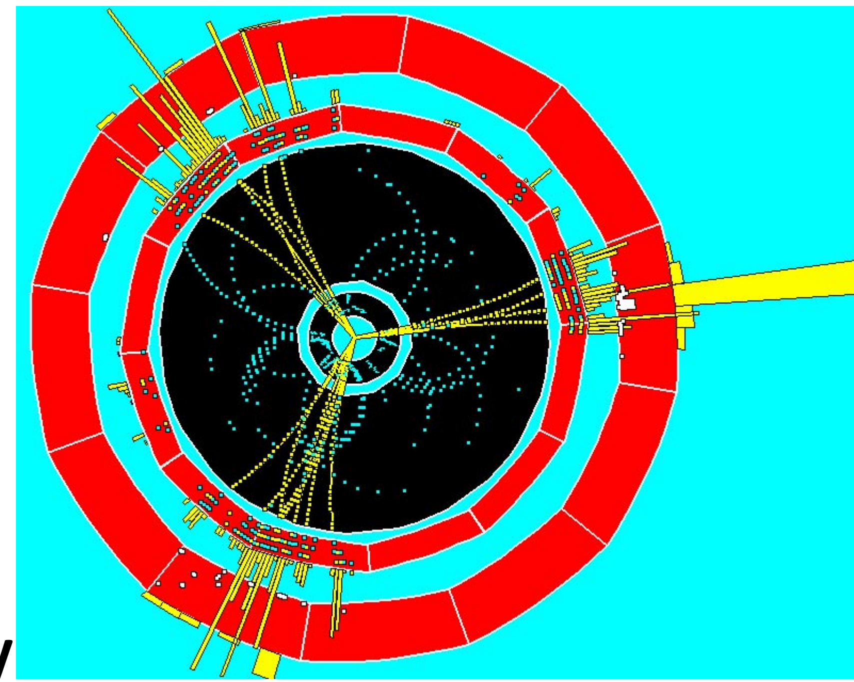
Quarks & Gluons

Differences in the fragmentation of quark and gluon jets have been well established at LEP and TeVatron.



Gluons split & radiate more than Quarks

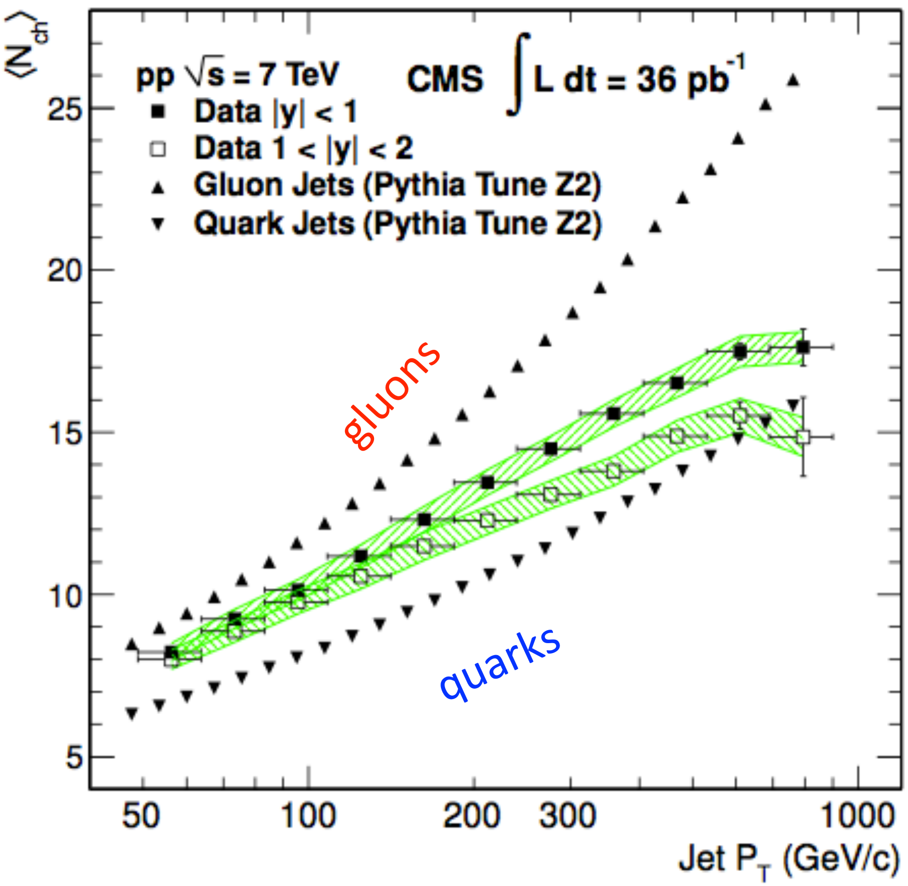
At a given energy a resulting **gluon** jet will, <u>on average</u> :

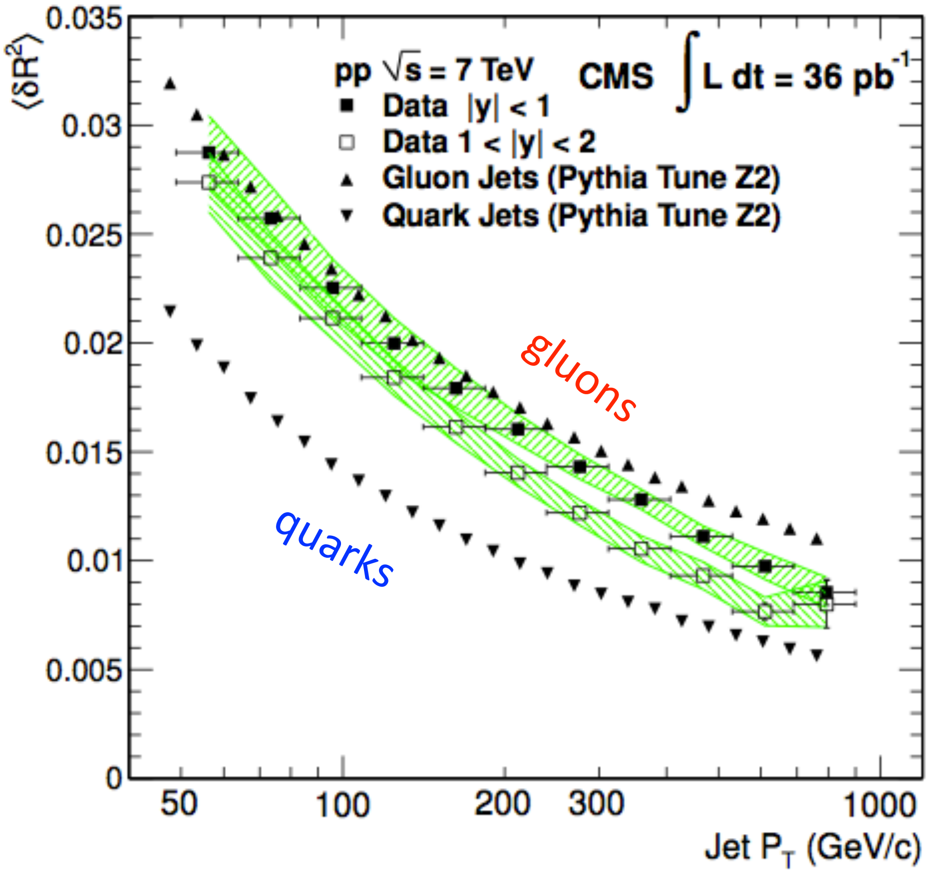


1. have a **larger** particle **multiplicity**
2. be angularly **wider**
3. be more **uniformly** distributed

$$e^+e^- \rightarrow qqg$$

Jet multiplicity and opening





Quark/Gluon jet tagging

approximately half or more of QCD jets are gluon originated
can make use of jet composition / shape variables to separate them
from signal quark-induced jets in EW processes

For **Central** (|eta|<2) jets

1. Axis1 (major ηϕ RMS)
2. Axis2 (minor ηϕ RMS)
3. Pull (asymmetry)
4. N_Chg
5. R_ch = max(pTi_ch)/sum(pTi)

All variables with charged-PU subtraction

For **Transition**(2<|eta|<3) jet and
Forward (3<|eta|<4.7) jets

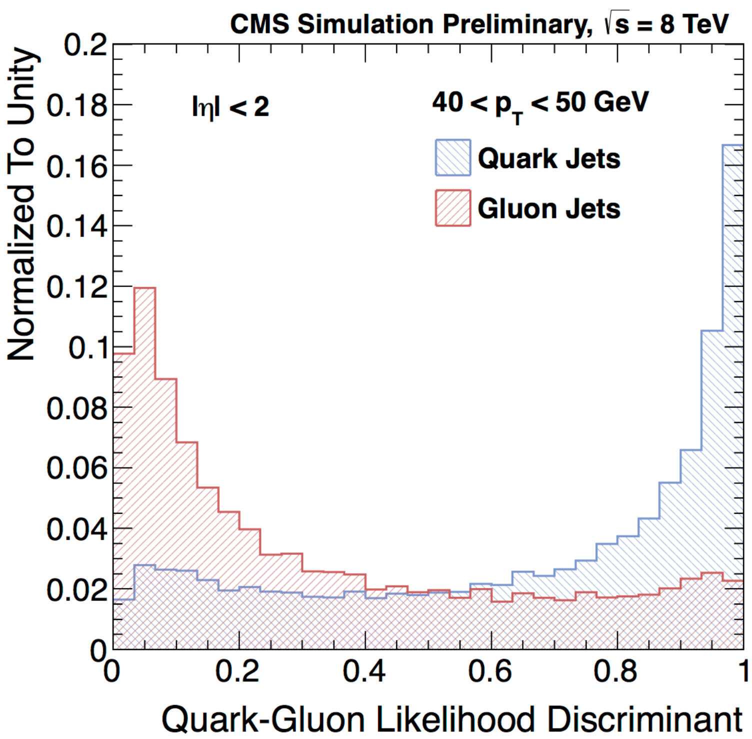
1. Axis1
2. Axis2
3. Pull
4. N_Chg + N_Neu
5. R = max(pTi)/sum(pTi)

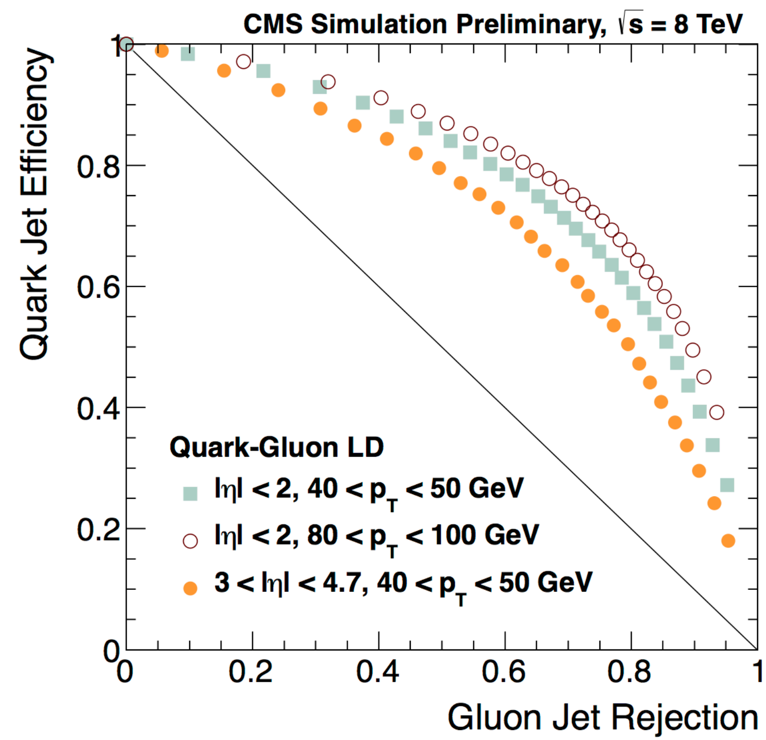
All variables without charged-PU subtraction

combined with a simple MVA likelihood

Used in H>ZZ>qqll, VBF Hbb, VBF Z CMS physics analysis

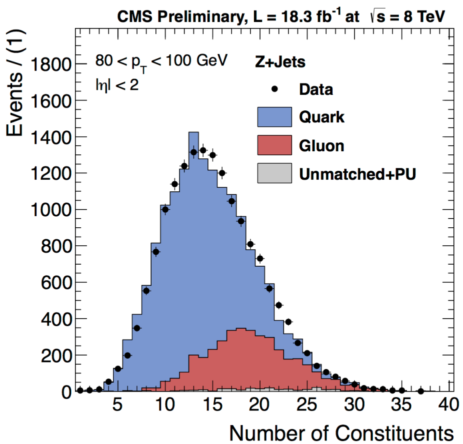
Quark/Gluon separation

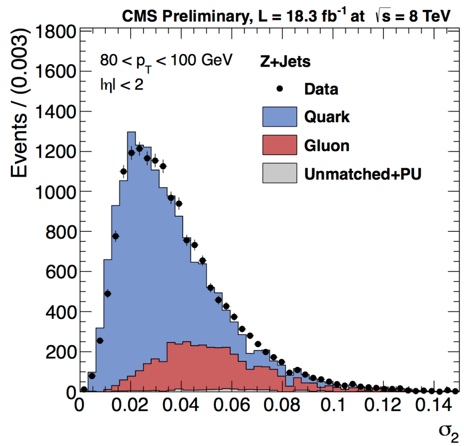


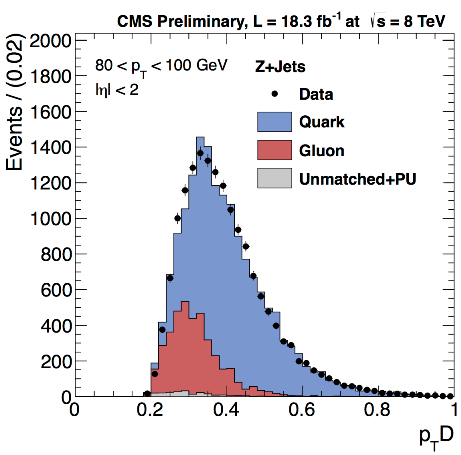


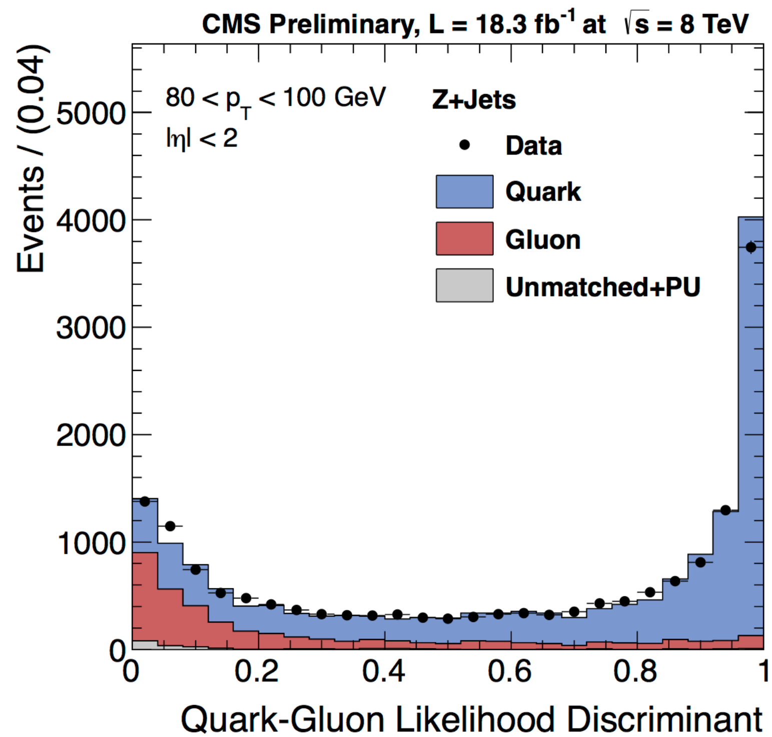
CMS PAS JME-13-002

Quark/Gluon data validation



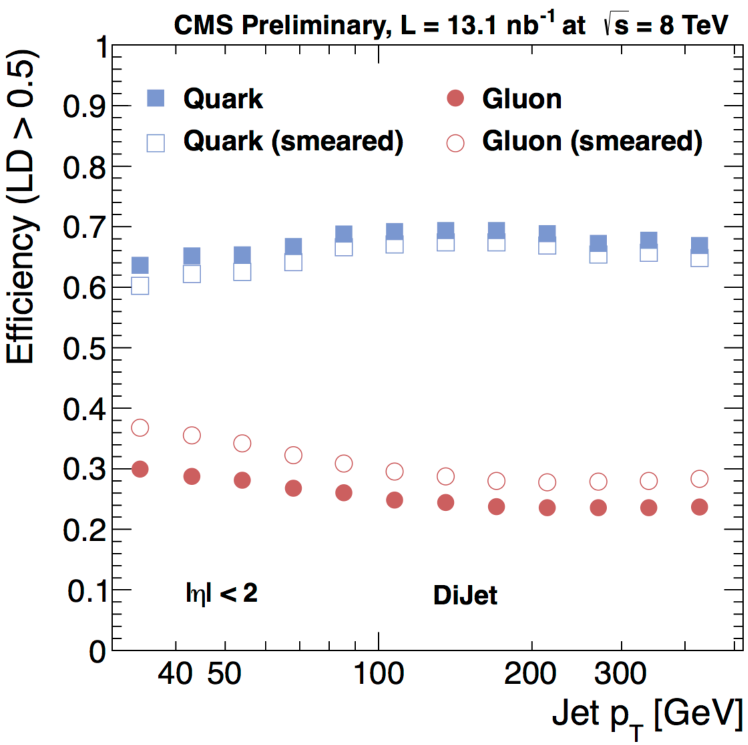


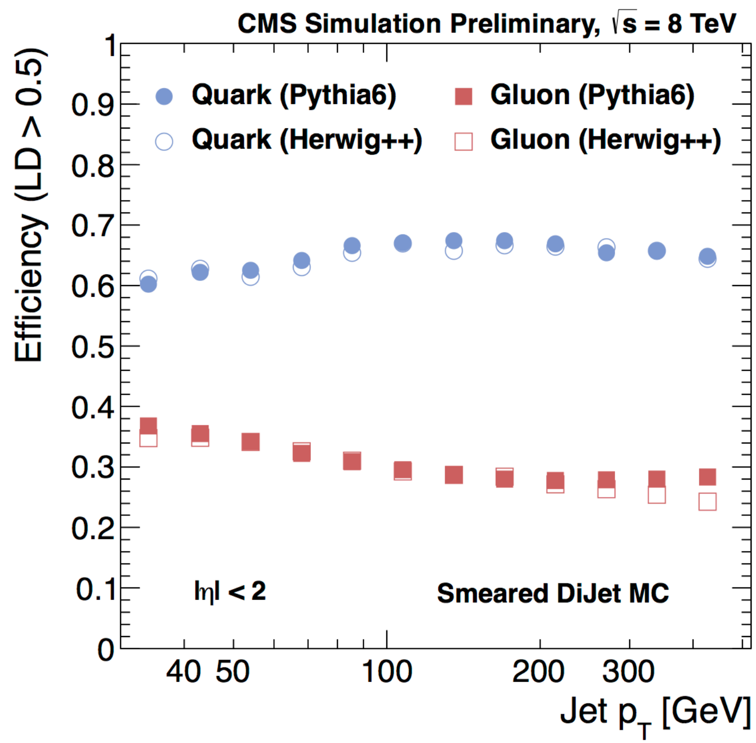




CMS PAS JME-13-002

Quark/Gluon data driven corrections





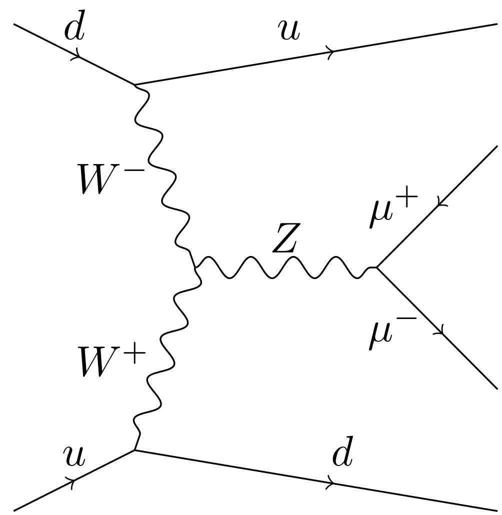
Herwig++ ←→ Pythia closure

CMS PAS JME-13-002

Jets in a CMS analysis:

Study of the pure electroweak (VBF) production of Z + 2 jets

Vector boson fusion: WW → Z

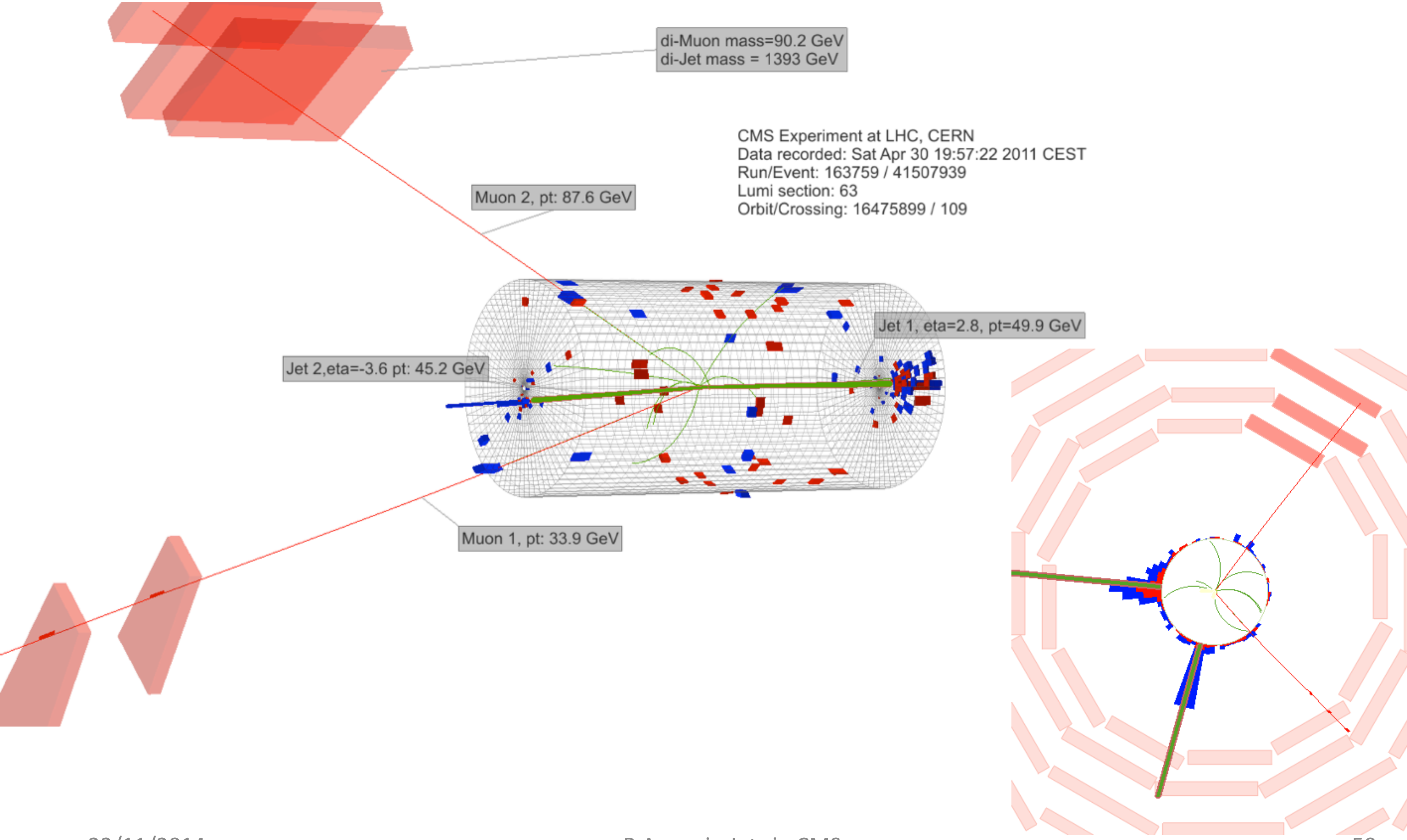


features of a VBF Z are:

- Central Z decay associated with energetic forward-backward jets
- A large η separation between the jets
- A large invariant dijet mass
- Pure EWK process: no color exchange between the tagging quarks

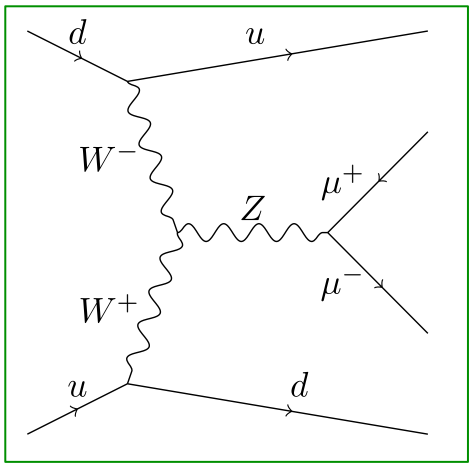
→ low hadronic activity in the central part of the detector

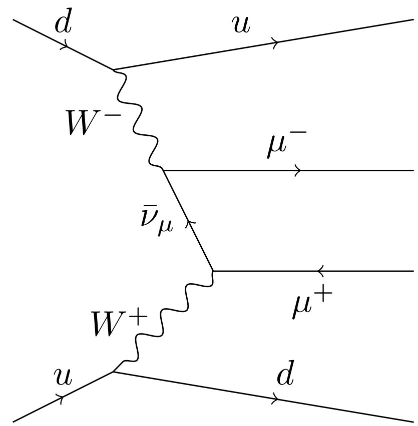
VBF Z candidate

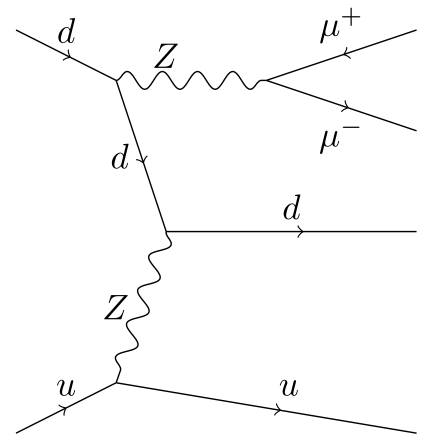


VBF & EWK Z/γ*>ll + 2jets

many other pure EWK processes lead to the lljj final state







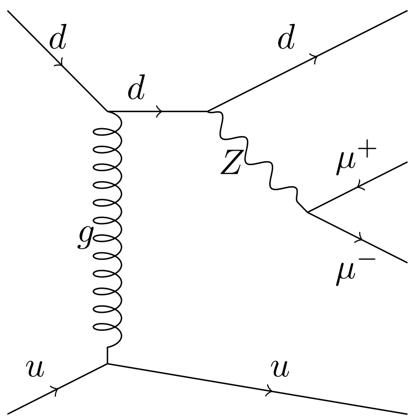
strong negative interference effects (EW gauge cancellations)

σ(7TeV) = 0.7 pb (with mjj>120, excludes WZ,ZZ) 173K events

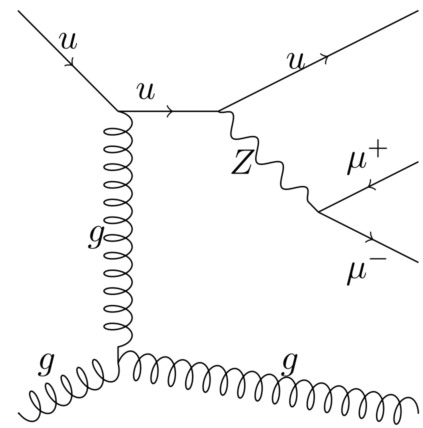
/DYToLL_Mll-50_Mjj-120_7TeV_madgraph-pythia6/Fall11-PU_S6_START42_V14B-v1

Standard Drell-Yan Z/γ*>ll+jets

mixed QCD+EWK processes



Z + 2 jets

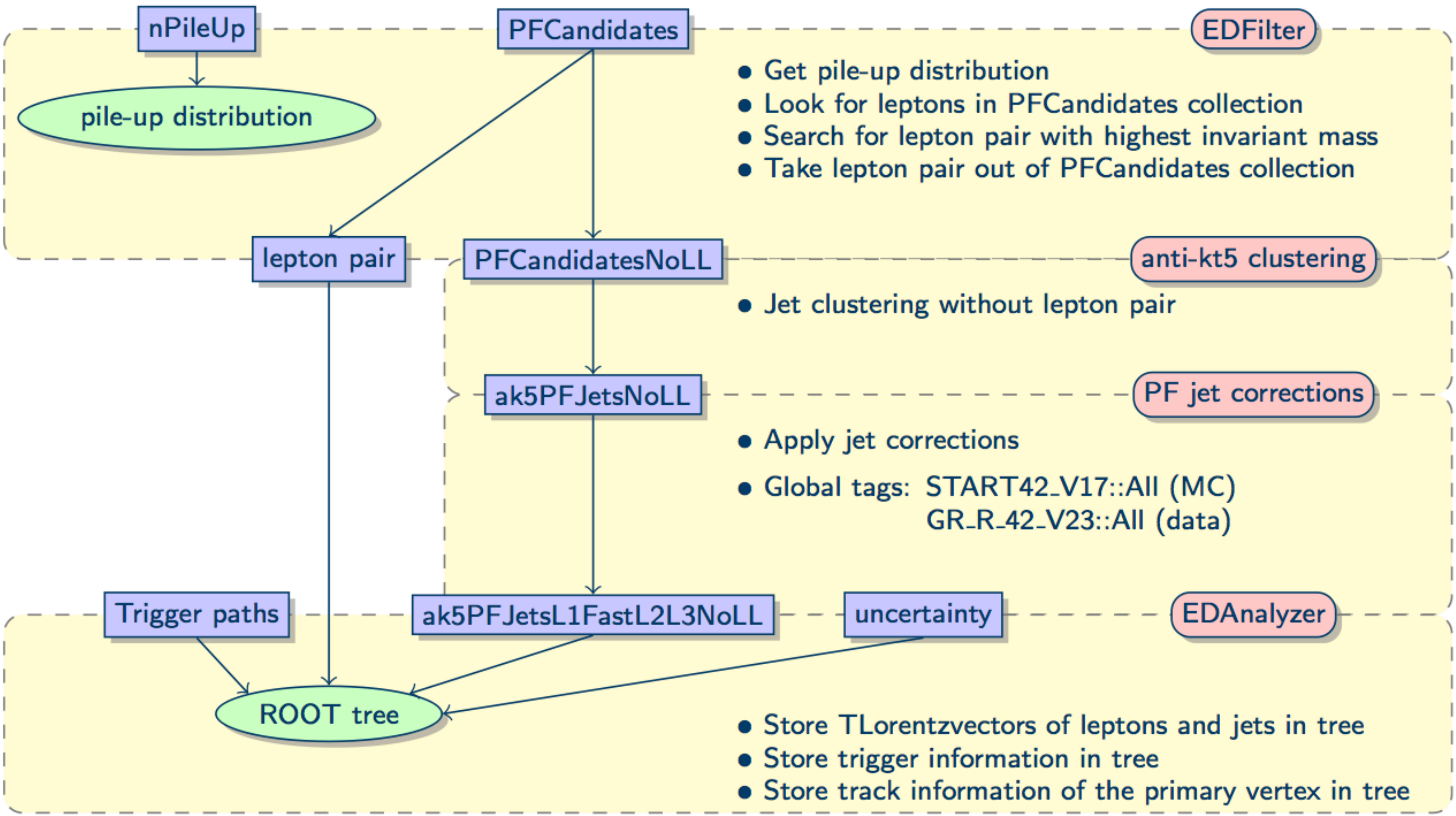


/DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola

σ(7TeV) = 3 nb (for all ll+jets with m(ll)>50)

negligible (≤0.1%) interference effects with the pure EWK productions
(careful study done with help from Fabio Maltoni, Marco Zaro and Johan Alwall)

Particle Flow Analysis



PF Lepton Selection

- pT > 20 GeV |η |<2.4

PF muons with reference to reco muons:

- **Tight** muon selection as recommended by the muon POG

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideMuonId#Tight_Muon_selection_aka_VBTF_li

- Relative Tracker only based isolation < 0.1 (no PU effects)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideMuonId#Muon_Isolation

PF electrons with reference to GSF electrons:

- Basic cuts at **working point 90%**

https://twiki.cern.ch/twiki/bin/viewauth/CMS/VbtfEleID2011

- Relative Tracker only based isolation < 0.1 (no PU effects)

- M_{ll} > 50 GeV

Jets clustered without the leptons

in the **python config file**

```
if MC: process.GlobalTag.globaltag = 'START53_V27::All'        # for MC
else : process.GlobalTag.globaltag = 'FT53_V21A_AN6::All'     # for DATA
# filter/producer
PFCandidatesNoV = cms.EDFilter("PFCandidatesNoV",
            pfCandidatesInputTag    = cms.InputTag("particleFlow"),
)
# jet producer
process.ak5PFJetsNoV = process.ak5PFJets.clone(
            src = cms.InputTag('PFCandidatesNoV','pfCandidatesNoV')
)
# jet energy corrections
process.load('JetMETCorrections.Configuration.DefaultJEC_cff')
if MC: jetcorrection = 'ak5PFL1FastL2L3'                          # for MC
else : jetcorrection = 'ak5PFL1FastL2L3Residual'            # for DATA
process.ak5PFJetsL1FastL2L3NoV = cms.EDProducer('PFJetCorrectionProducer',
          src        = cms.InputTag('ak5PFJetsNoV'),
           correctors  = cms.vstring(jetcorrection)
)
```

Central Hadronic Activity

build the collection of “Extra Tracks” with

- highPurity tracks, pT>300 MeV
- not associated to the leptons nor to the two leading jets
- make minimum |dz(PV)| when associated to the hardest PV
- |dz(PV)|<2mm |dz(PV)|<3σz(PV) to the hardest PV

cluster “soft” TrackJets with the “Extra Tracks” collection with

- anti-kt 0.5
- pT>1 GeV

Central Region defined as η(jet-bkw)+0.5 < η < η(jet_fwd)-0.5

Extra Tracks & TrackJets

in the **python config file**

```
# extra tracks producer (out of 2-lepton + 2-jets system)
process.extraTracks = cms.EDProducer('ExtraTracks')

# Soft Track Jet producer (anti-kt 0.5)
process.ak5SoftTrackJets = process.ak5TrackJets.clone()
process.ak5SoftTrackJets.src  = ('extraTracks')
process.ak5SoftTrackJets.jetPtMin = cms.double(1.0)

#full analysis path
process.p = cms.Path(process.kt6PFJets * process.PFCandidatesNoLL
* process.ak5PFJetsNoLL * process.ak5PFJetsL1FastL2L3NoLL
* process.GluonTagProducer * process.extraTracks *process.ak5SoftTrackJets * ....)
```

CMSSW Code for this example

in https://github.com/UAEDF/EWKV
mostly written by Tom Cornelis (University of Antwerp)

PFCandidatesNoV edm::EDFilter & Producer :
https://github.com/UAEDF/EWKV/blob/master/PFCandidatesNoV/src/PFCandidatesNoV.cc

ExtraTracks edm::EDProducer
https://github.com/UAEDF/EWKV/blob/master/ExtraTracks/src/ExtraTracks.cc

edm::EDAnalyzer
https://github.com/UAEDF/EWKV/blob/master/Analyzer/src/Analyzer.cc

THE END

Thank You for your attention