JET FRAGMENTATION

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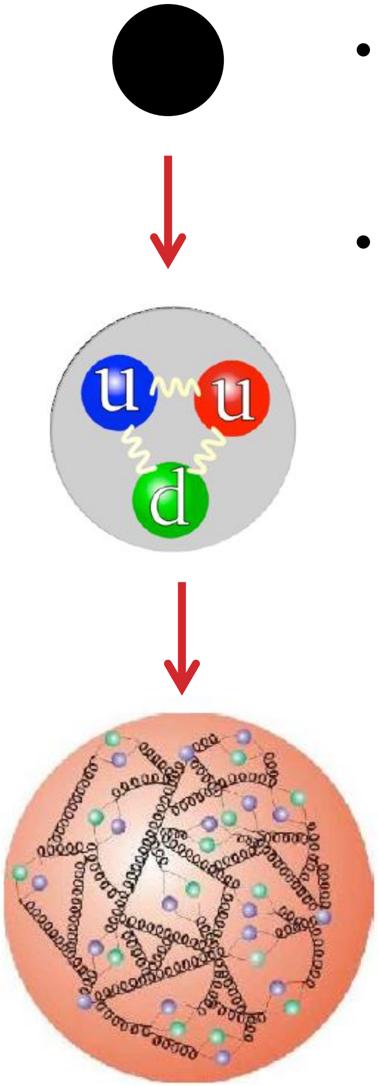
OUTLINE

- **Physics introduction**
  - Introduction to jet physics
  - Jets in heavy-ion-collisions
  - Jet reconstruction

- **Paper discussion**
  - The CMS experiment
  - Data selection and track/jet reconstruction
  - Analysis
  - Physics outcome

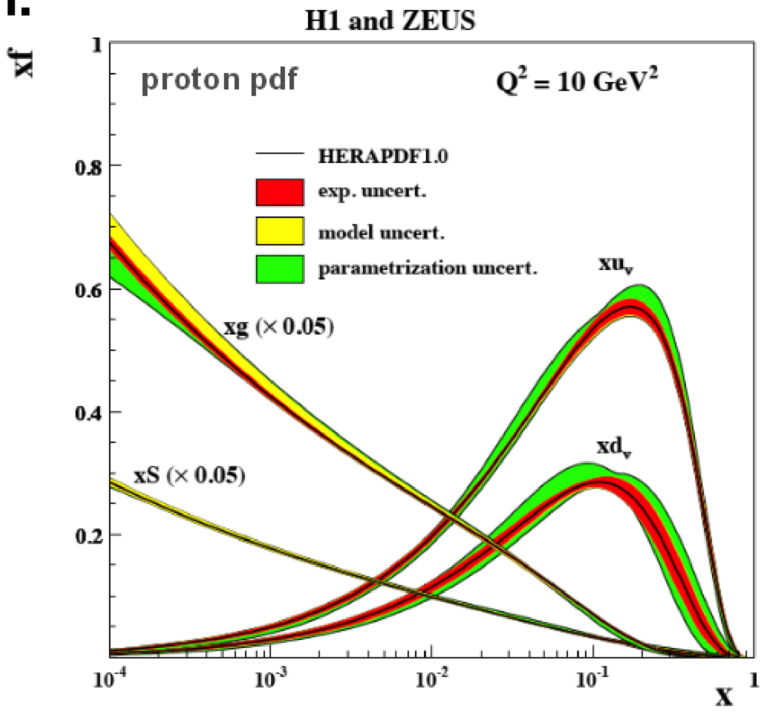
PROTON SUBSTRUCTURE



- **Proton substructure is described by Parton distribution functions**

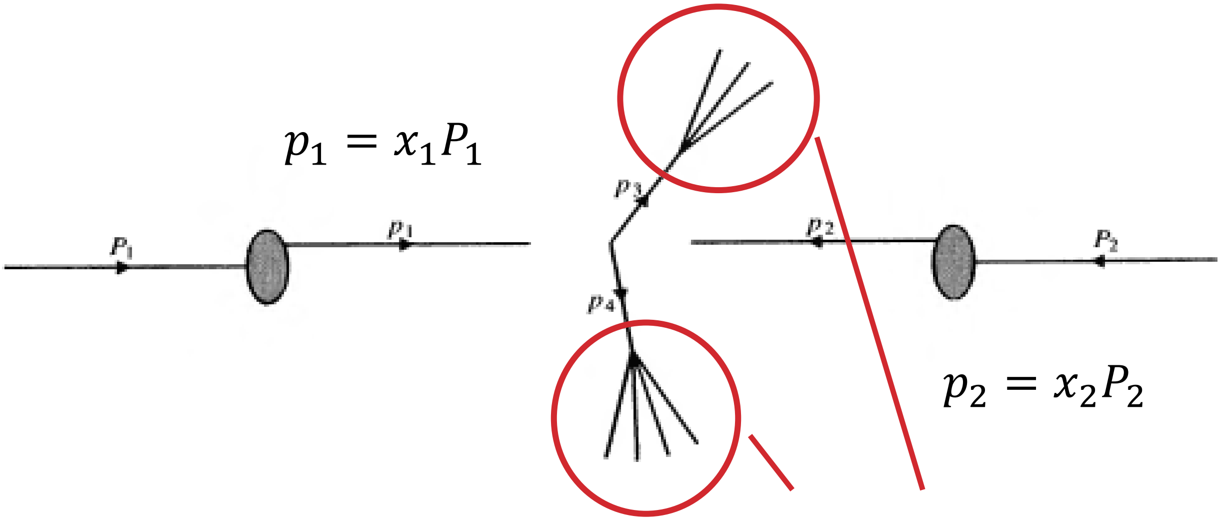
- **Parton distribution functions give the probability to find a parton with a given momentum fraction $x = \frac{p_{parton}}{p_{hadron}}$ in the proton.**

Deep inelastic scattering @ HERA (1992-2007)



JETS

Production of Jets in hadron collisions:

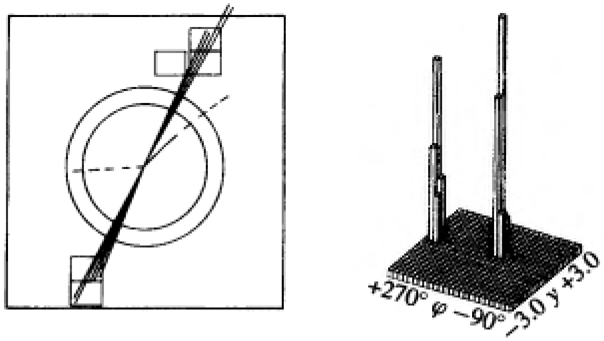


$p_1 = x_1 P_1$

$p_2 = x_2 P_2$

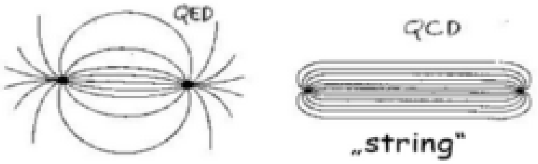
Hadronisation/Fragmentation

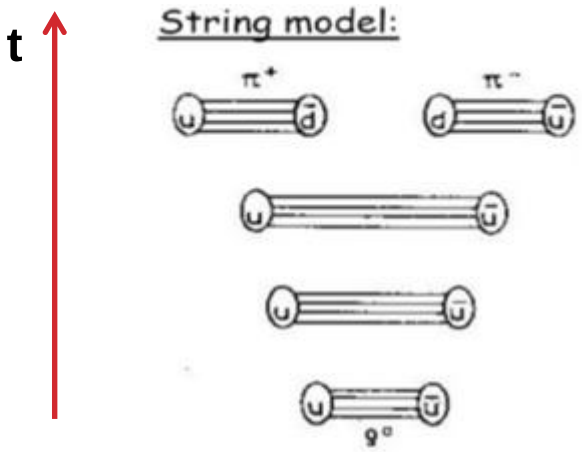
- **Scattering of partons inside the hadrons**
- **Subsequent fragmentation of the scattered partons will lead to hadron-spray: Jets**
- **Only back-to-back in φ due to different momenta of initial partons**



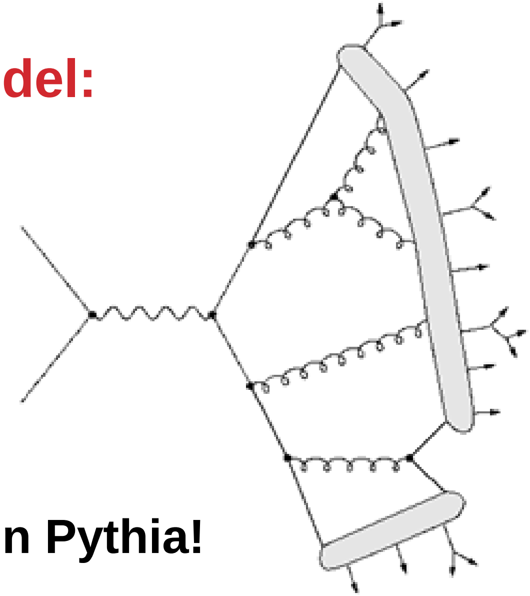
HADRONISATION MODELLING

- QCD potential: $V(r) \sim -\frac{1}{r} + \kappa r$ with $\kappa \sim 1 \frac{GeV}{fm}$
- $q\bar{q}$ connected via flux tube („string“)
- String can break into new $q\bar{q}$ pairs





Lund string model:
(1983)



→ **Default model in Pythia!**

HIGH p_T HADRON PRODUCTION

- **QCD asymptotic freedom: $\alpha_s(Q^2 \to \infty) \to 0$**
- **High energy parton-parton scattering → pQCD**
- **QCD factorization theorem: High-p_T hadron production cross-section in hadron hadron collisions can be writtten (to some order):**

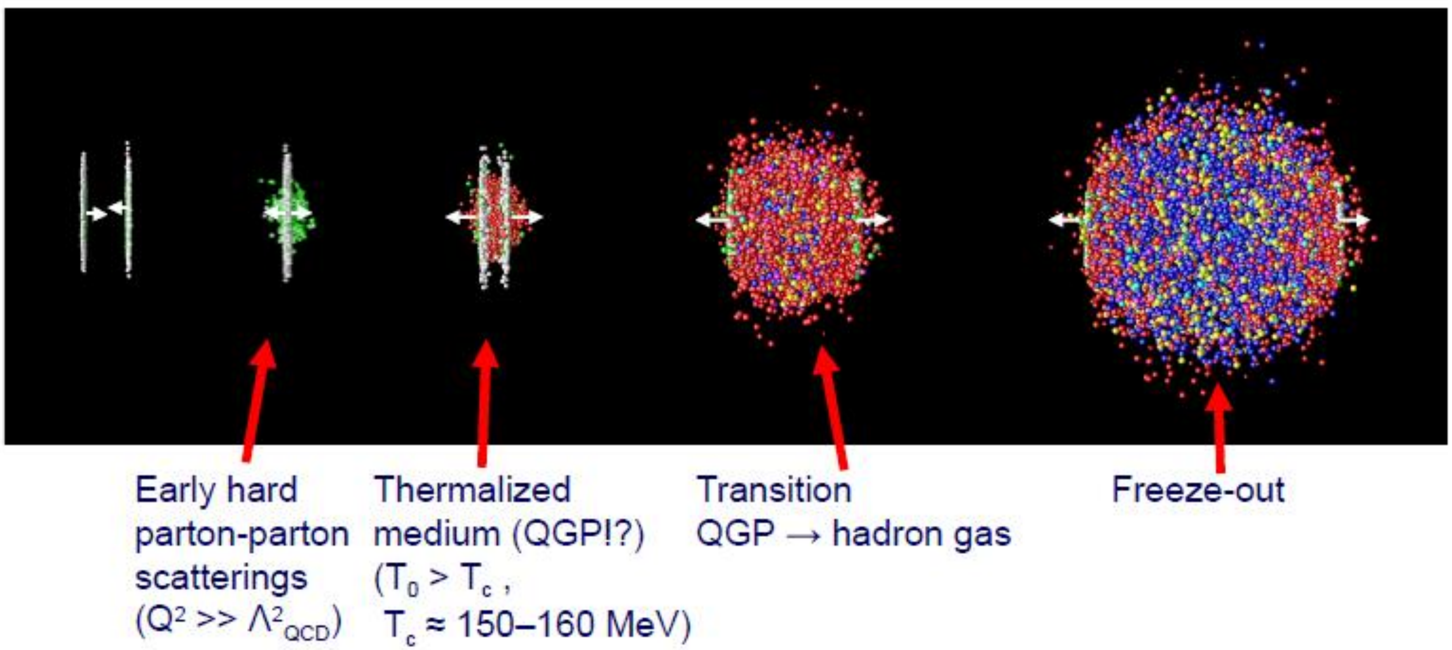
$$d\sigma^{\text{hard}}_{AB\to h} = \underbrace{f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_2, Q^2)}_{\text{PDF's}} \otimes \underset{\substack{\downarrow \\ \text{Parton-parton} \\ \text{crosssection}}}{d\sigma^{\text{hard}}_{ab\to c}(x_1, x_2, Q^2)} \otimes \underset{\substack{\downarrow \\ \text{Fragmentation} \\ \text{function}}}{D_{c\to h}(z, Q^2)}$$

- **Fragmentation functions encode the probability of a parton to fragment into a hadron with a momentum fraction**

$$z = \frac{p^{hadron}}{p^{parton}}$$

Also useful: $\xi = ln\frac{1}{z}$

JETS IN HEAVY-ION-COLLISIONS

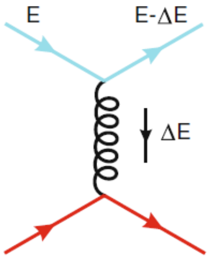


- **High-p_T partons are produced early in the collision**
- **They will propagate through the entire medium**
- **Jet quenching → „Smoking gun“ of QGP formation**

JET QUENCHING

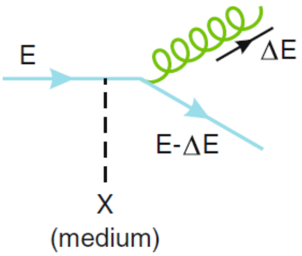
- A parton traversing the medium will lose energy by scattering or bremsstrahlung
- Energy loss will depend on particle and plasma properties

Scattering



Dominates at low momenta

Gluon radiation



Dominates at high momenta

- BDMPS approach: (Rad. E loss)

$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

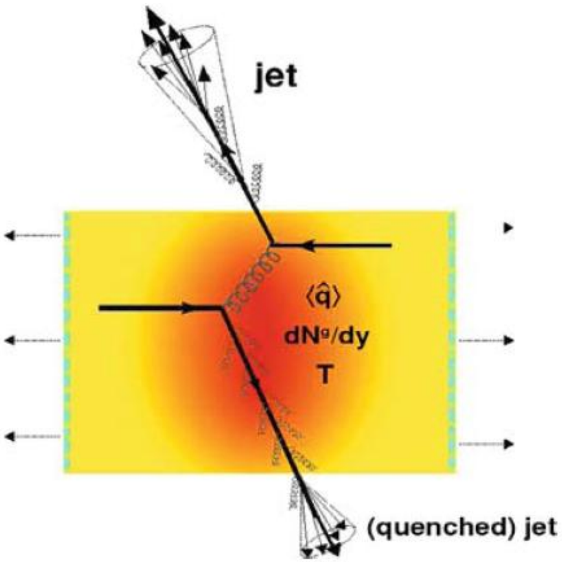
Energy loss ΔE in a static medium of length L for $E \to \infty$

$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

Medium parameter $\hat{q} = \frac{\mu^2}{\lambda}$

μ^2 : Typical momentum transfer from the medium to the parton

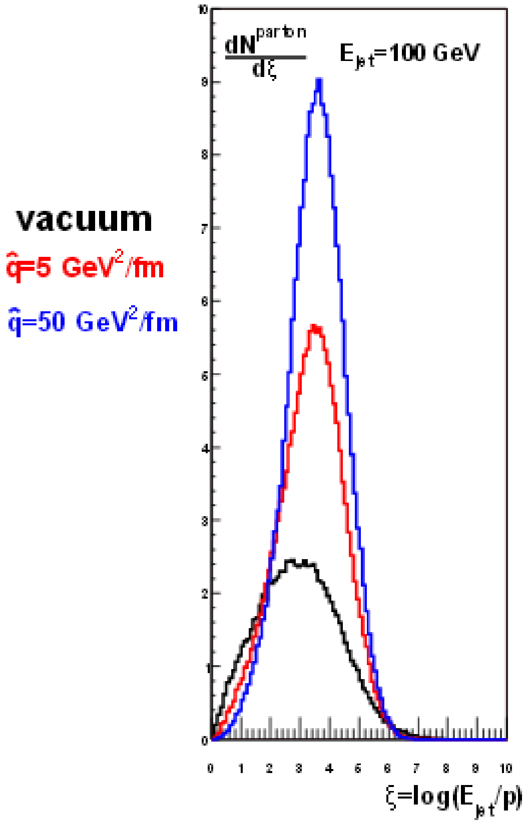
λ : Mean free path



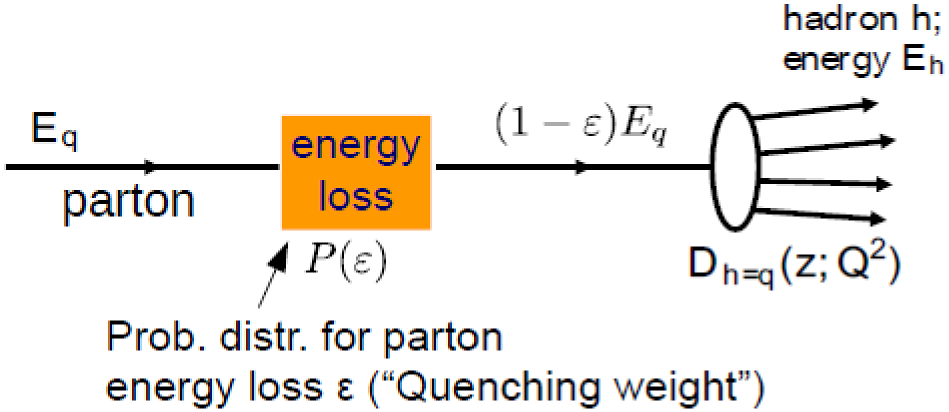
FRAGMENTATION FUNCTIONS IN THE MEDIUM

- **Some models of jet quenching predict an effective change of the shape of the fragmentation function**
- **Changes of the fragmentation function would give access to the properties of the medium**

„Q-Pythia“:



„Kinematic rescaling“: Fragmentation in the vacuum with rescaled energy



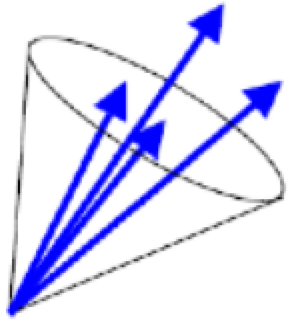
JET RECONSTRUCTION

- **Idea: Reconstruct energy and direction of initial parton**
- **Two main classes of jet finding algorithms:**

Cone algorithms:

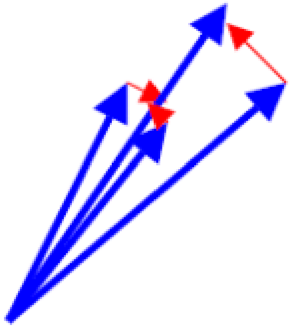
Sum up all momenta in cone with given radius around seed particle *i*

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 < R^2$$



Sequential recombination:

Merge hadrons wich have smallest difference in transverse momentum



SEQUENTIAL RECOMBINATION

- Introduce distances $d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$ $d_{iB} = k_{ti}^{2p}$

  p=1: k_T
  p=0: Cambridge/Aachen
  p=-1: Anti-k_T

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

- Find smallest of the distances and

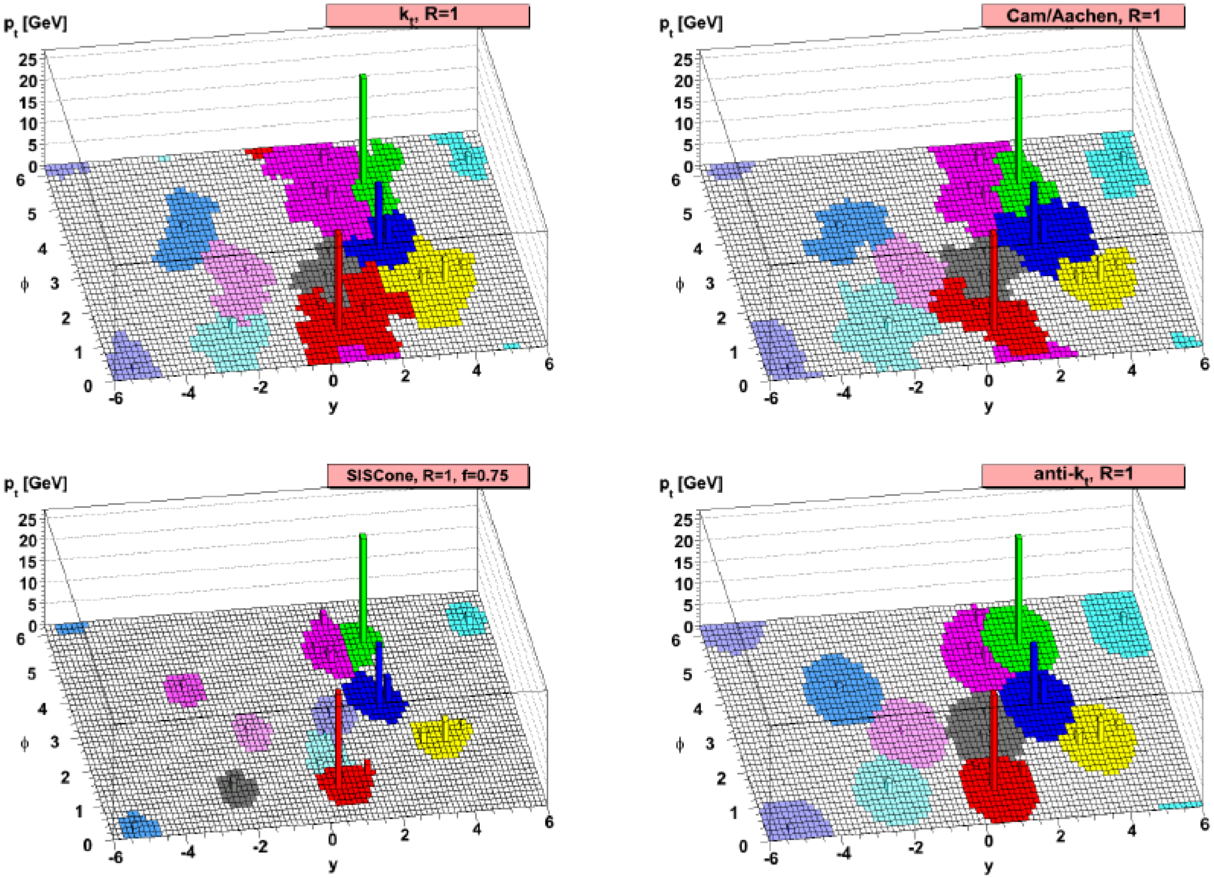
  if it is a d_{ij} → recombine entities (e.g. add 4-momenta)

  if it is a d_{iB} → move entities to list of jets

- Procedure is repeated until no entities are left

- Anti-k_T: Soft particles will tend to cluster with hard ones long before clustering among themselves

COMPARISON OF DIFFERENT ALGORITHMS:



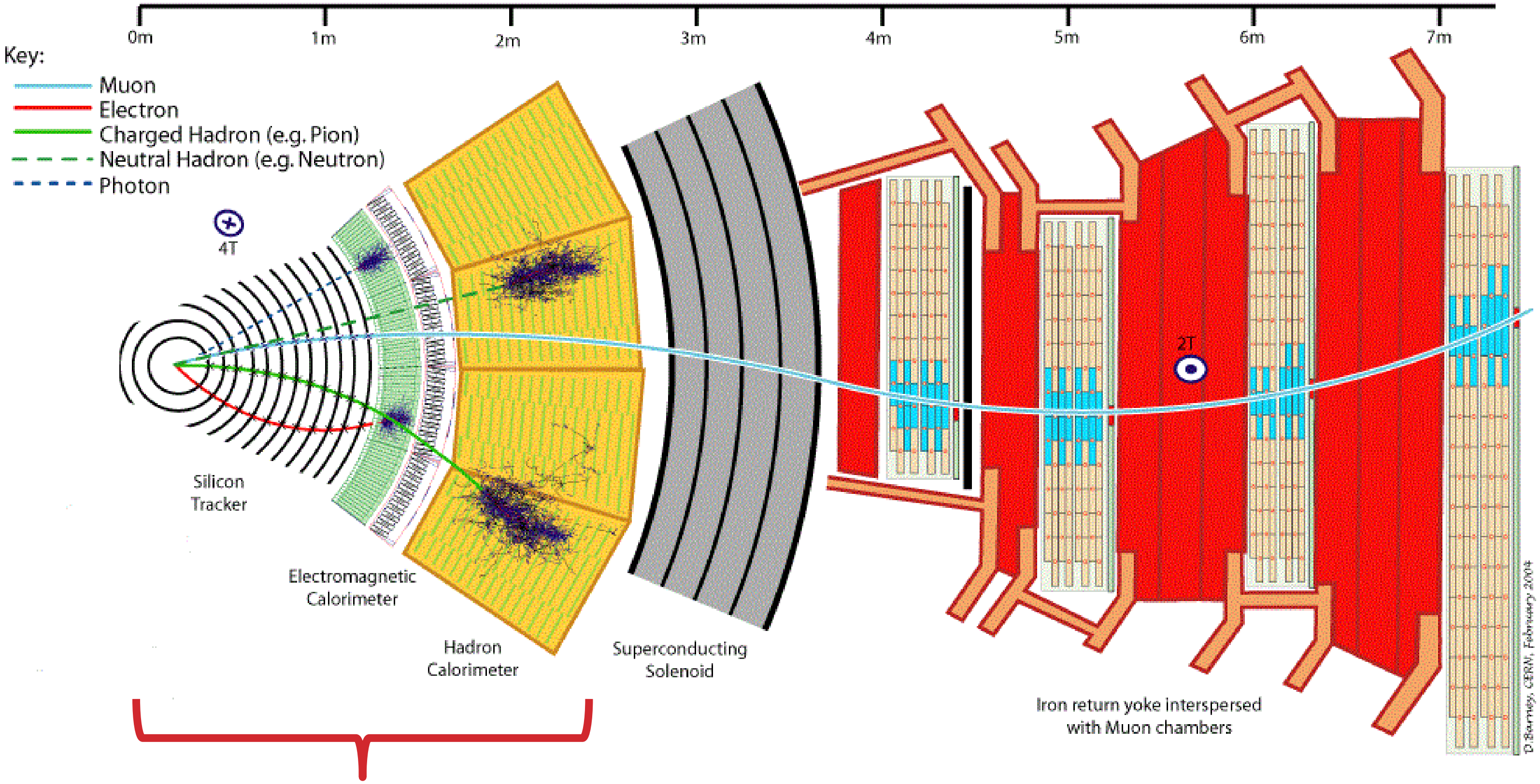
PAPER DISCUSSION

- **Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$**

The CMS Collaboration, 2013 [arXiv:1205.5872]

THE CMS EXPERIMENT

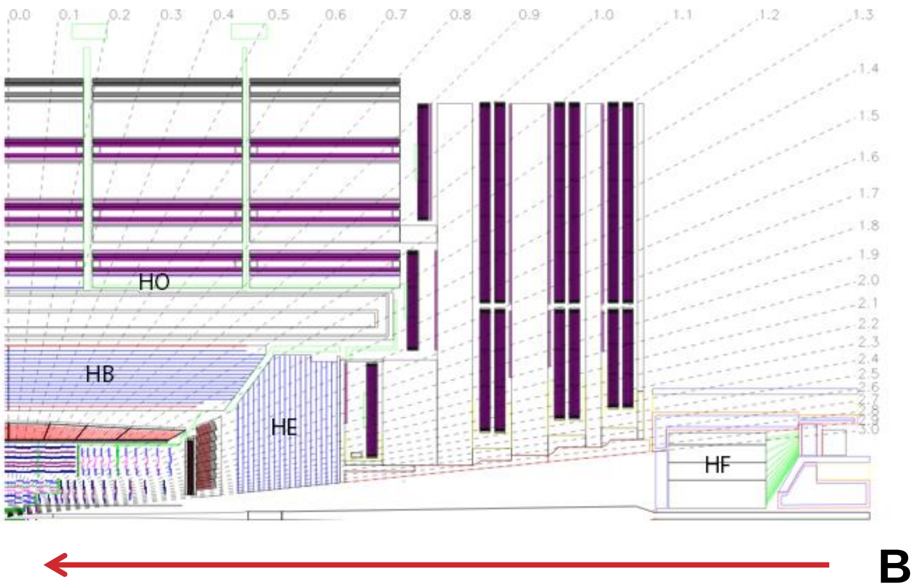
CMS: Compact Muon Solenoid



Used in this analysis

DATA SELECTION

- Use 2010/11 $E_{cmsNN} = 2.76\ TeV$ pp and PbPb Data
- Use HLT to select events containing high p_T jets in calorimeters (pp: $p_T > 40\ GeV/c$, PbPb: $p_T > 35\ GeV/c$)
- Standard event selection criteria
- Determine centrality from transverse energy in HF



Beam

HO: Hadron Outer calorimeter

HB: Hadron Barrel calorimeter

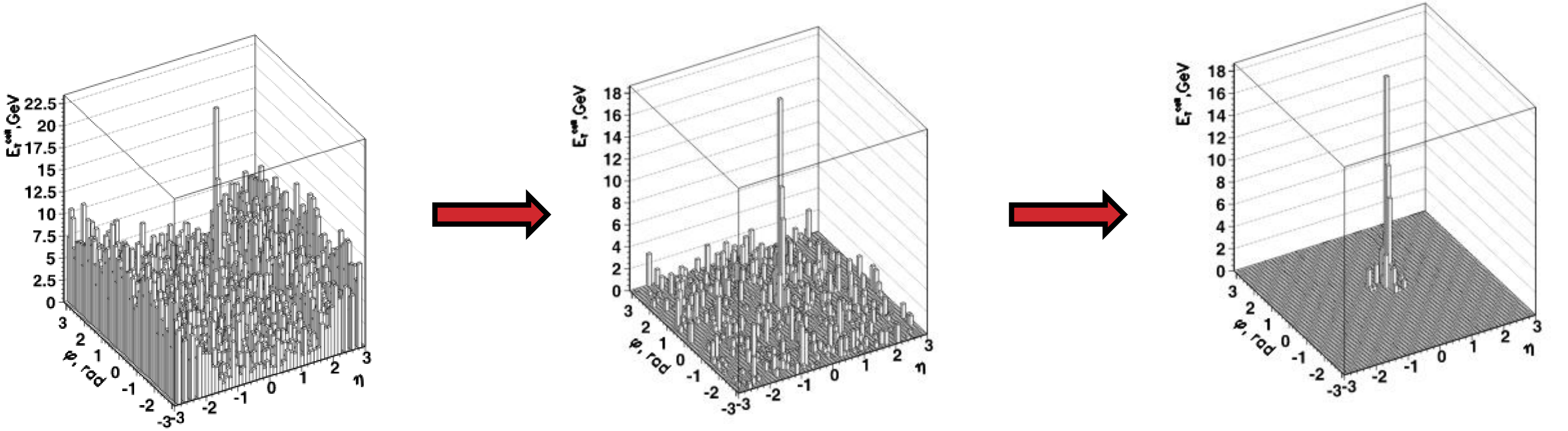
HE: Hadron Endcap calorimeter

HF: Hadron Forward calorimeter

$$3 \leq |\eta| \leq 5.2$$

TRACK AND JET RECONSTRUCTION

- **Particle-flow approach: Reconstruct all stable particles first using tracking and calorimetric information**
- **In PbPb: Substract underlying event with iterative pile-up method:**



Calculate average tower energies in rings of η and substract from event

Find jets and recalculate average energy using initial towers outside jet

Substract new average energy from initial event and find jets again

- **Reconstruct jets with Anti-k_T algorithm with R=0.3**

SYSTEMATIC UNCERTAINTIES

- **Jet finding efficiency:** >95% for jets with p_T>40 GeV/c

  >99% for jets with p_T>50 GeV/c
- **Jet momentum resolution:** pp: 19%(13%) at p_T = 40(100) GeV/c

  central PbPb: 24%(16%) at p_T = 40(100) GeV/c
- **Reconstructed jet momenta** are corrected to final state stable particle level using factors derived from PYTHIA
- **Jet energy scale uncertainty:**

  pp: 3% ⟶ per-bin-yield uncertainty: 15%

  peripheral PbPb: 4% ⟶ per-bin-yield uncertainty: 20%

  central PbPb: 5% ⟶ per-bin-yield uncertainty: 25%
- **Track finding efficiency:** 60-70% → reweighting of tracks
- **Track momentum reconstruction resolution:** ~1-3%

ANALYSIS

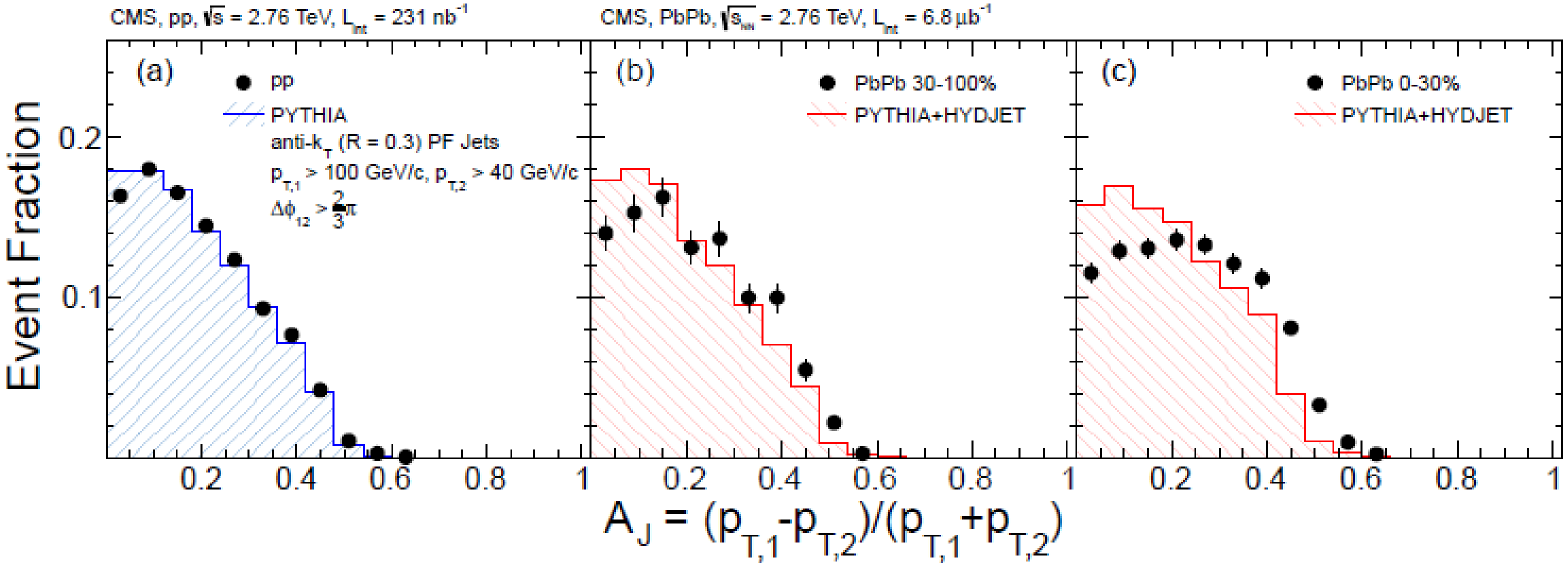
- **Leading jet:** $p_{T,1} > 100\ GeV/c$

$|\eta| < 2$

- **Subleading jet:** $p_{T,2} > 40\ GeV/c$

$\Delta\phi_{12} > \frac{2}{3}\pi$

- **Compare to Pythia (pp) and Pythia events embedded in Hydjet PbPb collision**

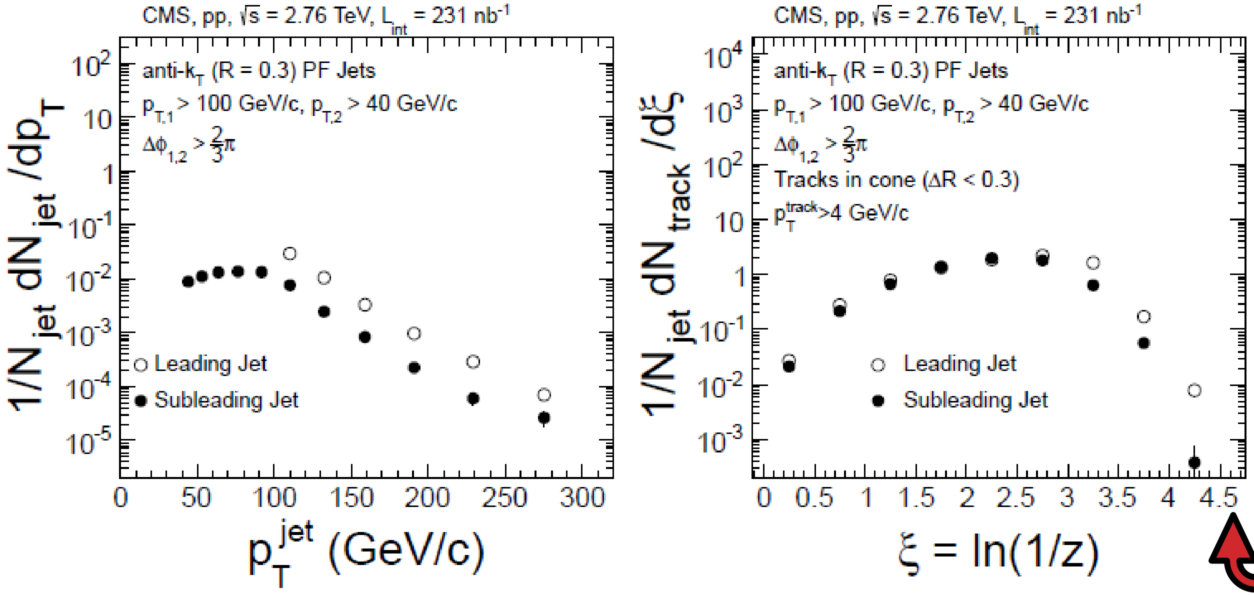


Observation of parton energy loss in central PbPb collisions

Fragmentation functions:

$$z = \frac{p_{||}^{track}}{p^{jet}} \qquad \xi = ln\frac{1}{z}$$

- **Momentum components and angles are calculated in dijet centre-of-mass frame**
- **Estimate remaining UE contribution by selecting tracks in background cone obtained by flipping the jetcone around $\eta = 0$**



Reduce UE contribution:

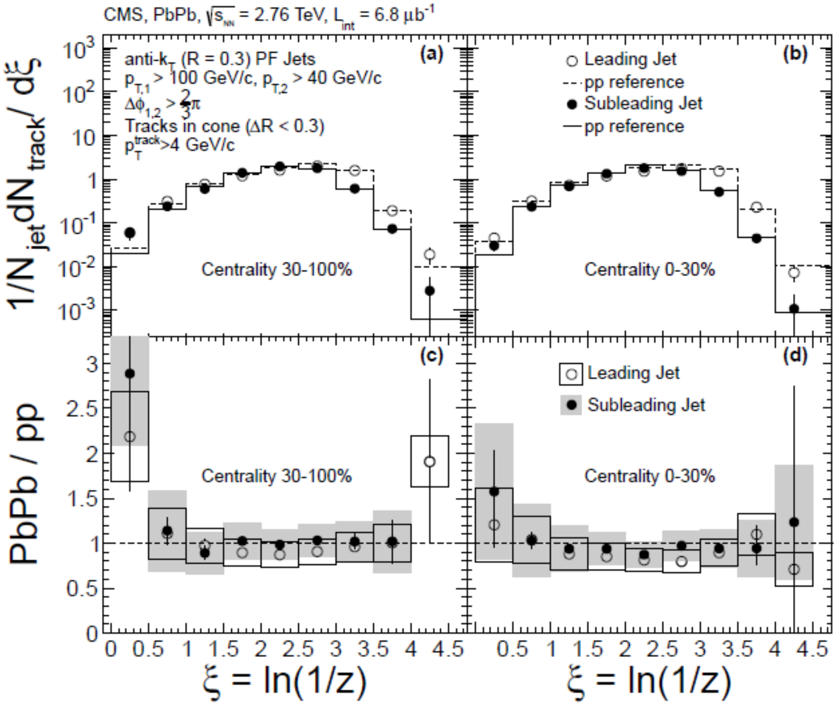
$$p_T^{track} > 4\ GeV/c$$

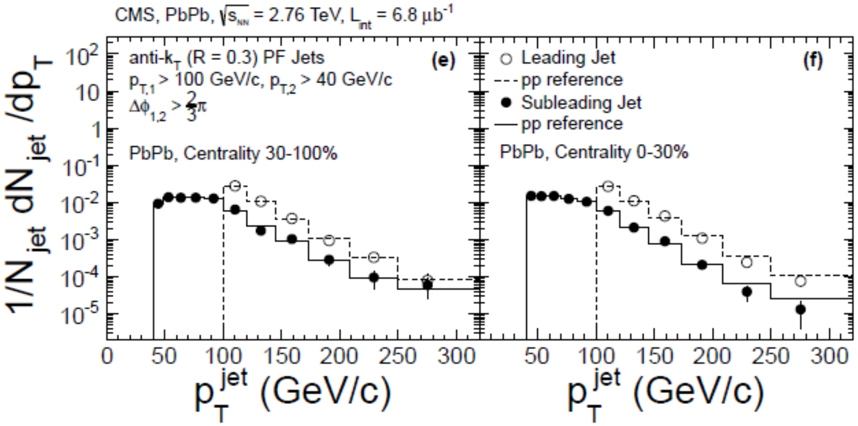
High track momenta → Low track momenta

Comparison of fragmentation functions in pp and PbPb

- **Take momentum resolution deterioration in PbPb into account**
  → Smear reconstructed p_T of jets in pp data by quadratic difference of UE contribution

- **Match p_T distributions → apply p_T dependent reweighting to pp data (Compare FF for matching p_T spectra)**





Shape of fragmentation functions in pp and PbPb agree within uncertainties

OTHER SOURCES OF SYSTEMATIC UNCERTAINTIES

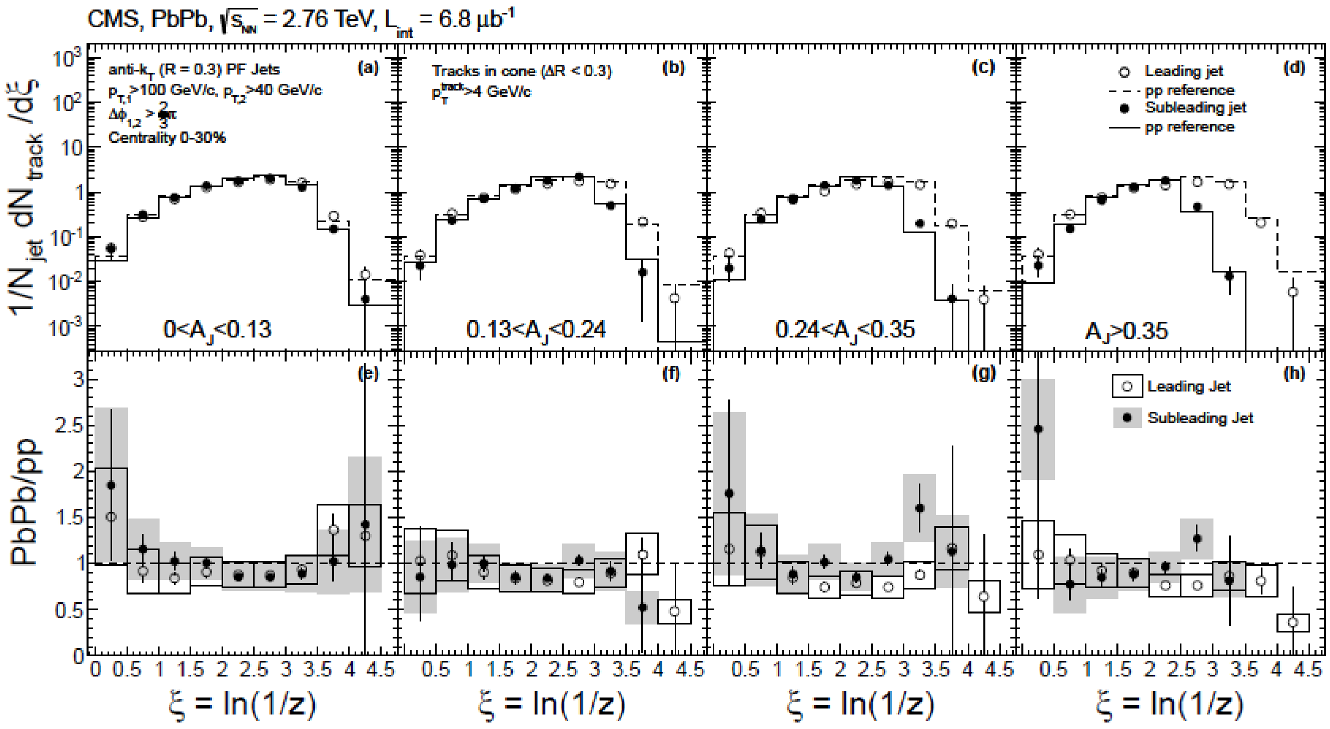
- **Uncertainties in jet response**
    - Smearing of jet energy due to fluctuations
    - Miscalibration of the overall energy scale
    - Residual offset in jet energy

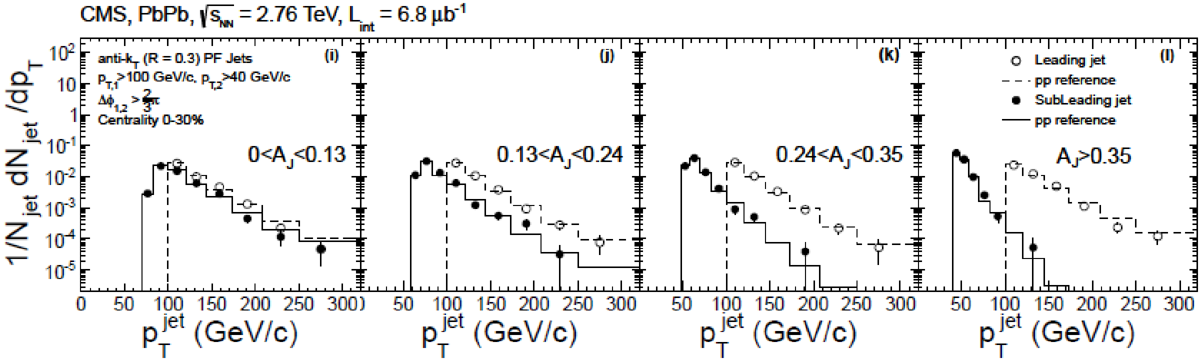
- **Uncertainties from track reconstruction**
    - Failure to reconstruct high- p_T charged particle
    - Momentum resolution of reconstructed charged particle tracks

→ **Study with Monte-Carlo**

→ **Combine all uncertainties in quadrature**

Fragmentation of the most central events in different dijet momentum asymmetry classes:





Also in agreement with 1

PHYSICS OUTCOME

- **Partons in PbPb collisions are reconstructed as jets with significantly reduced momentum**

- **The partition of the smaller momentum that remains within the jet cone into $p_T > 4\ GeV/c$ particles corresponds within the uncertainties to that observed for jets fragmenting in the vacuum (pp)**