Jetting through the Quark Soup

Yen-Jie Lee

Massachusetts Institute of Technology

The 7th Huada School on QCD
CCNU, Wuhan, China

Outline

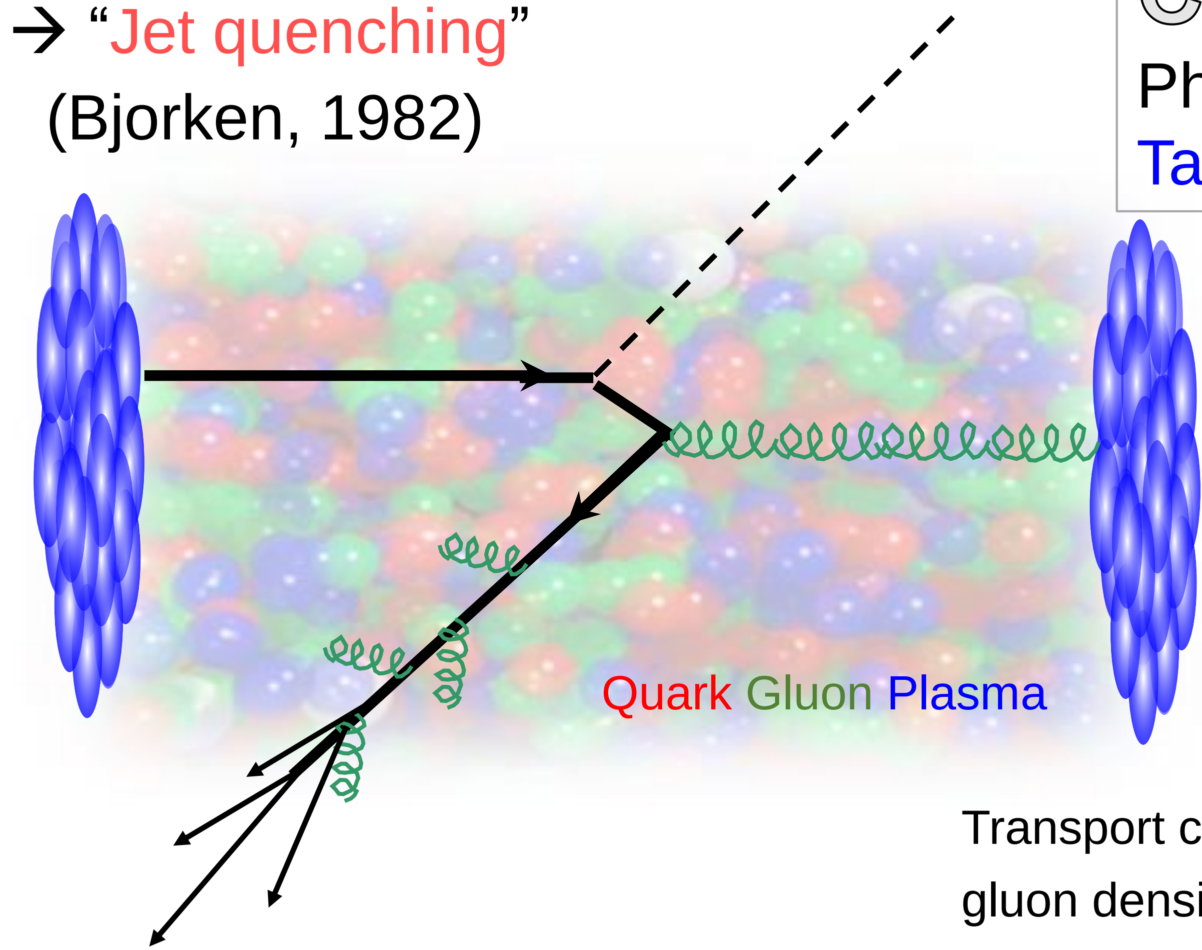
- Lecture 1
  Why do we study relativistic heavy ion collisions?
- Lecture 2
  How do we measure jets in heavy ion collisions?
- Lecture 3
  Parton energy loss and its parton flavor dependence
- Lecture 4
  Modification of jet substructure and medium response
- Lecture 5
  Open questions and future direction

Lecture 2

How do we measure jet quenching in relativistic heavy ion collisions?

Jetting through the Quark Soup

In medium parton energy loss
→ "Jet quenching"
(Bjorken, 1982)



Colorless Probes

Photons, electroweak bosons
Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

Colored Probes:

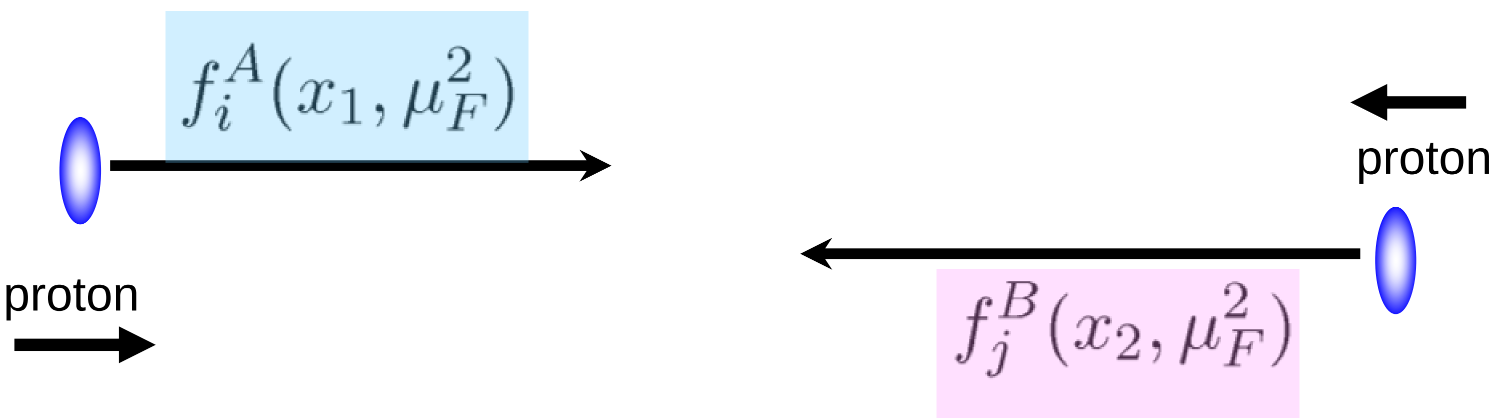
high energy quarks and gluons, heavy quarks
Studies of the medium properties

Factorization

Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

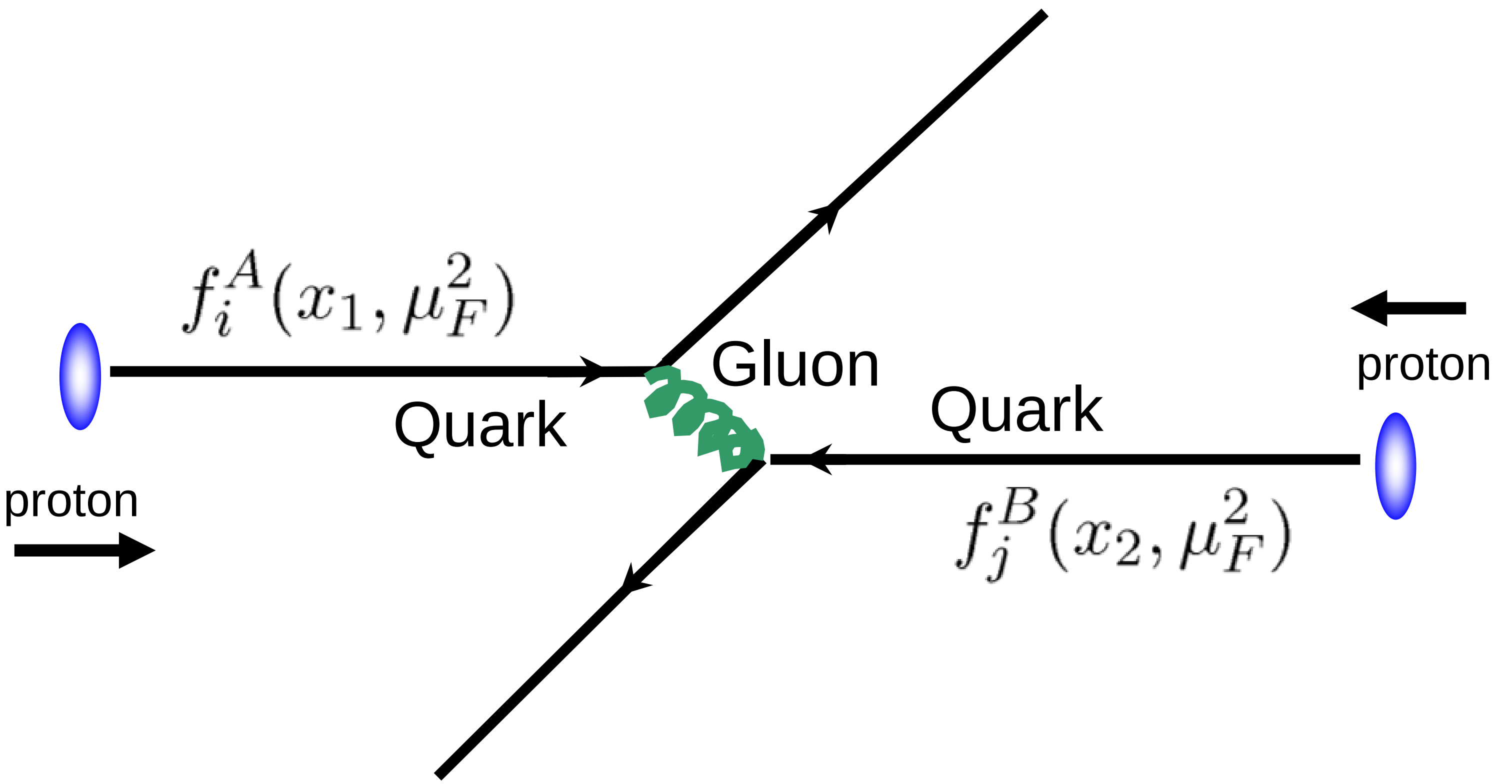
Parton Distribution Function (PDF)



Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

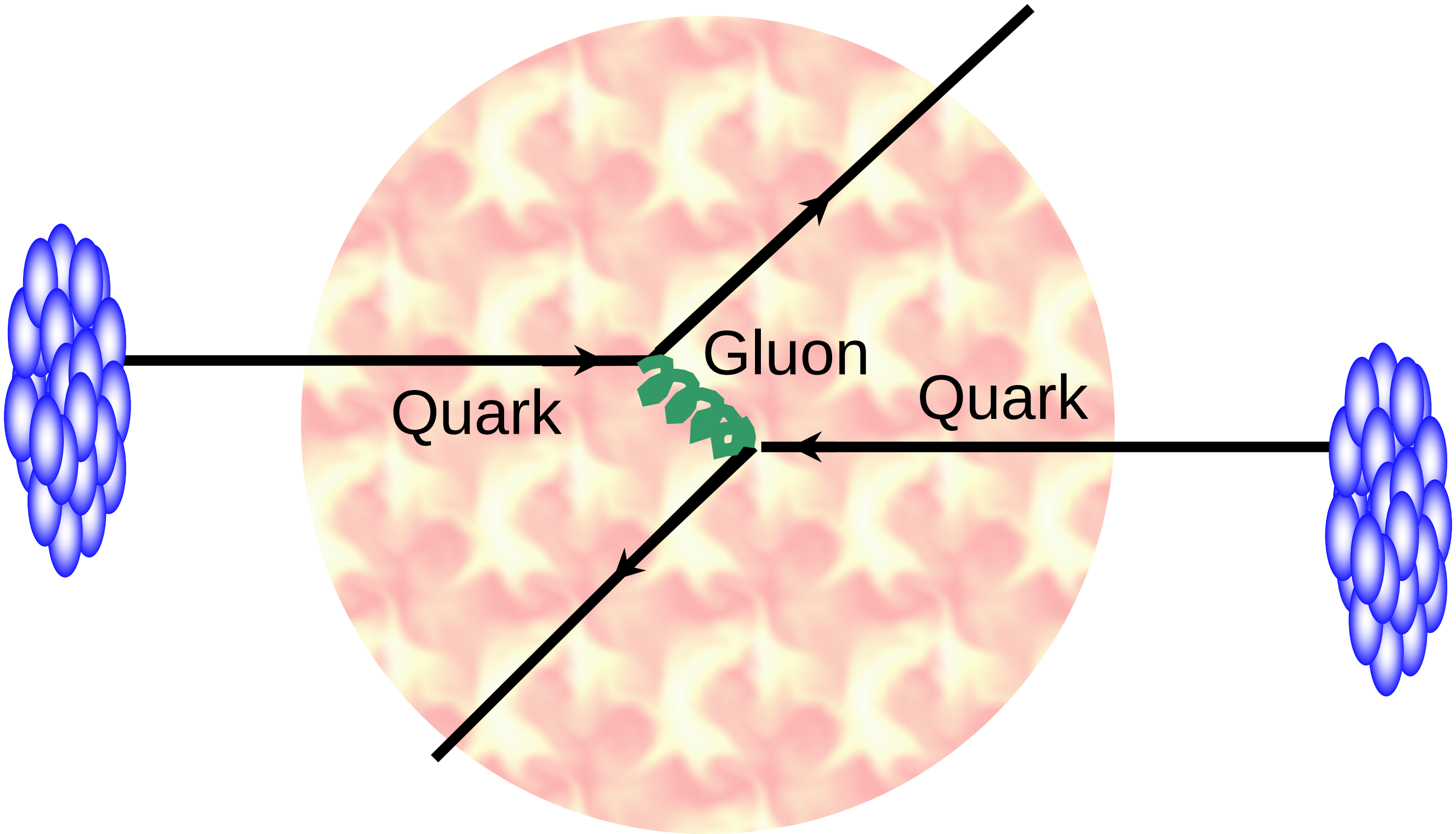
Parton Distribution Function (PDF) Cross-section of 2→2 process



Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1, \mu_F^2) \otimes f_j^B(x_2, \mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Nuclear Parton Distribution Function (nPDF) Cross-section of 2→2 process



Parton Energy Loss

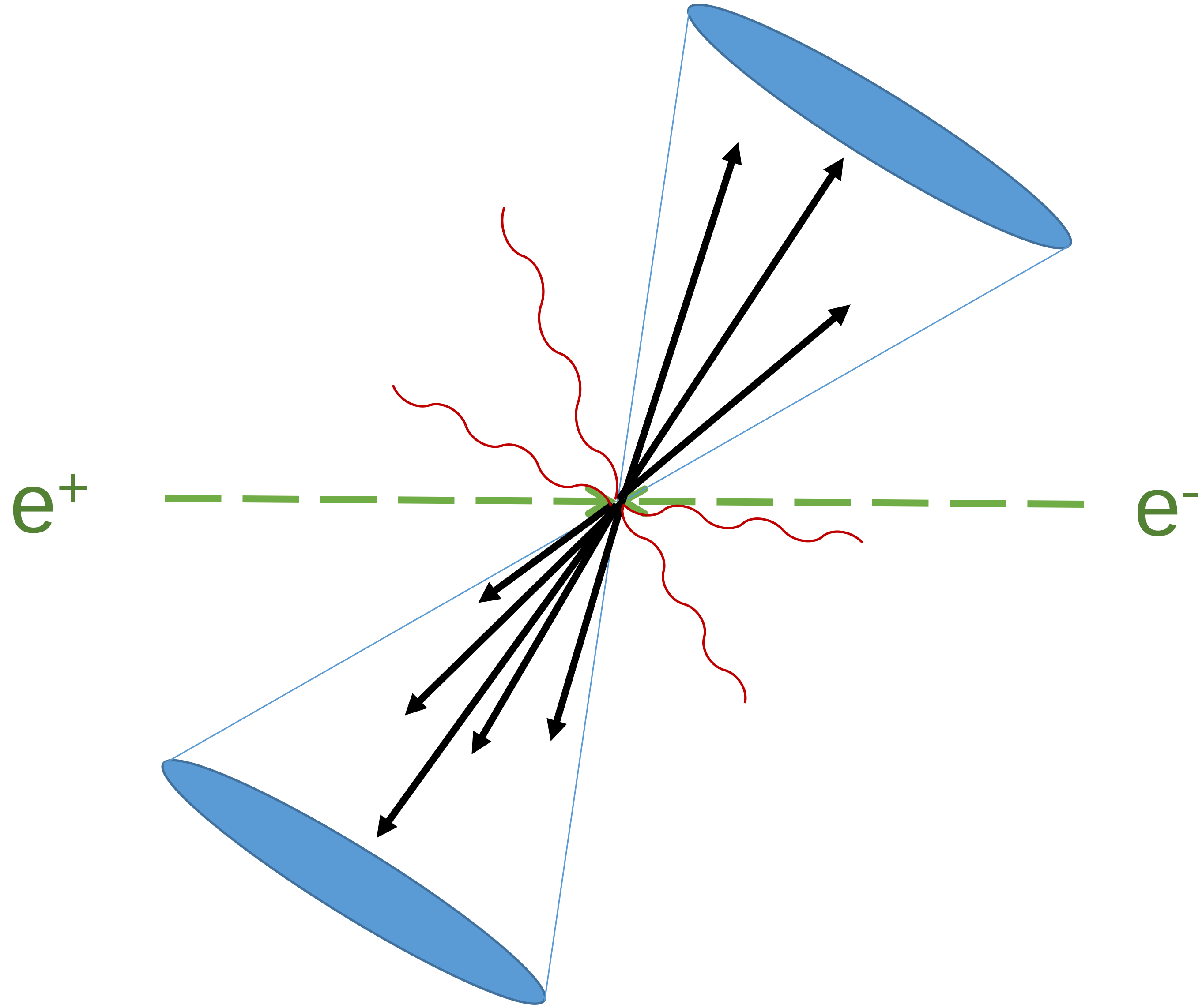
- Ideally, we would like to measure partons directly
- In reality, we could only measure final state particles which are coming from hard scattered partons

QCD branching:

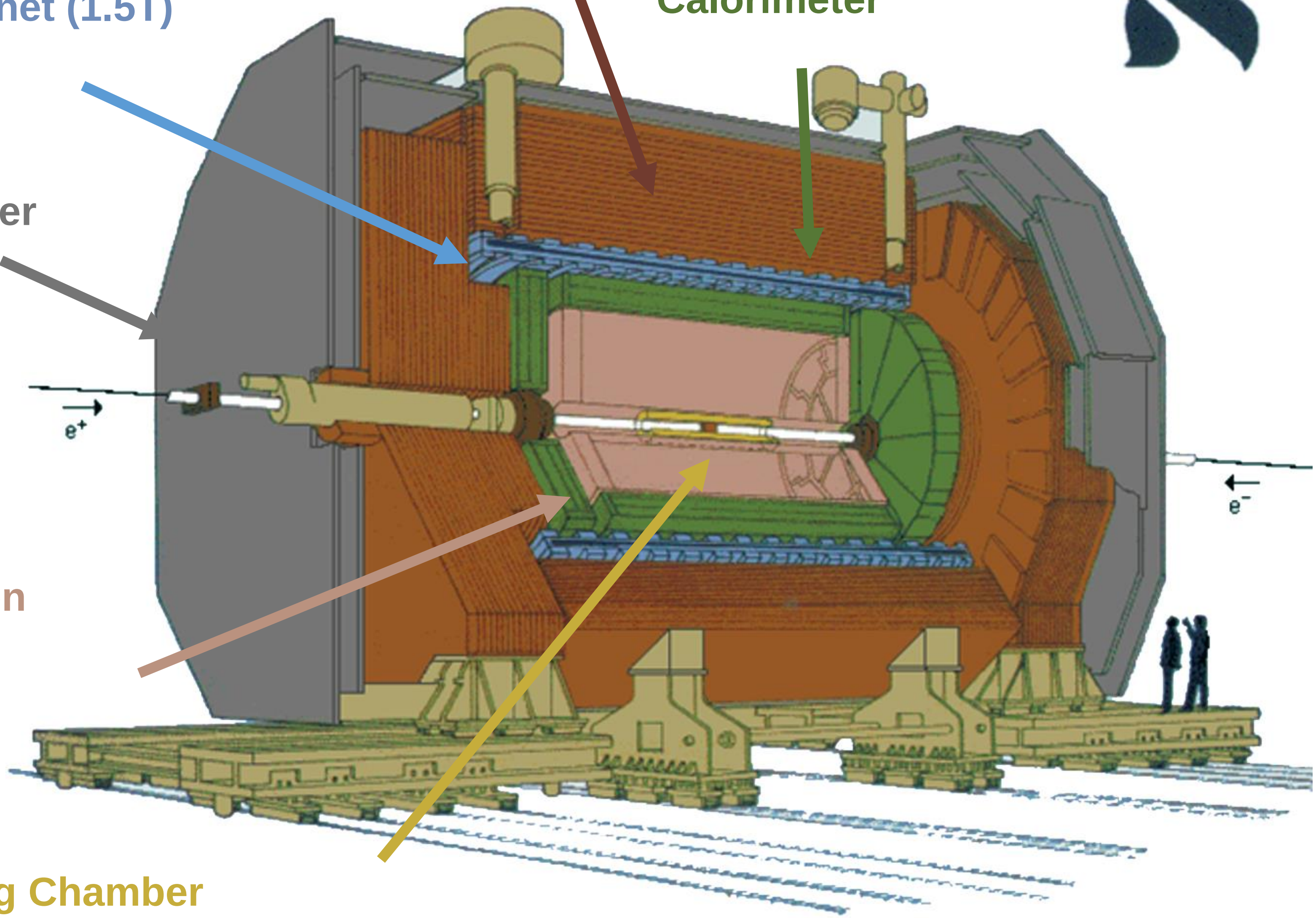
$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i, E_j)}\frac{d\theta_{ij}}{\theta_{ij}}$$

- The attempt to invert this process is called jet reconstruction, defined by jet algorithms

Electron-Position Annihilation

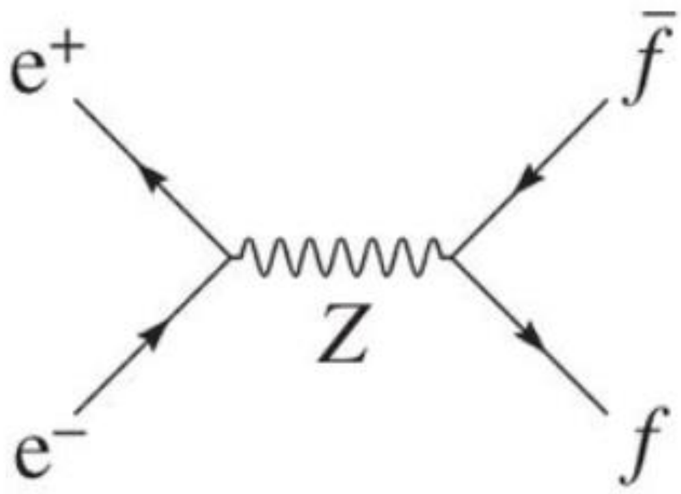


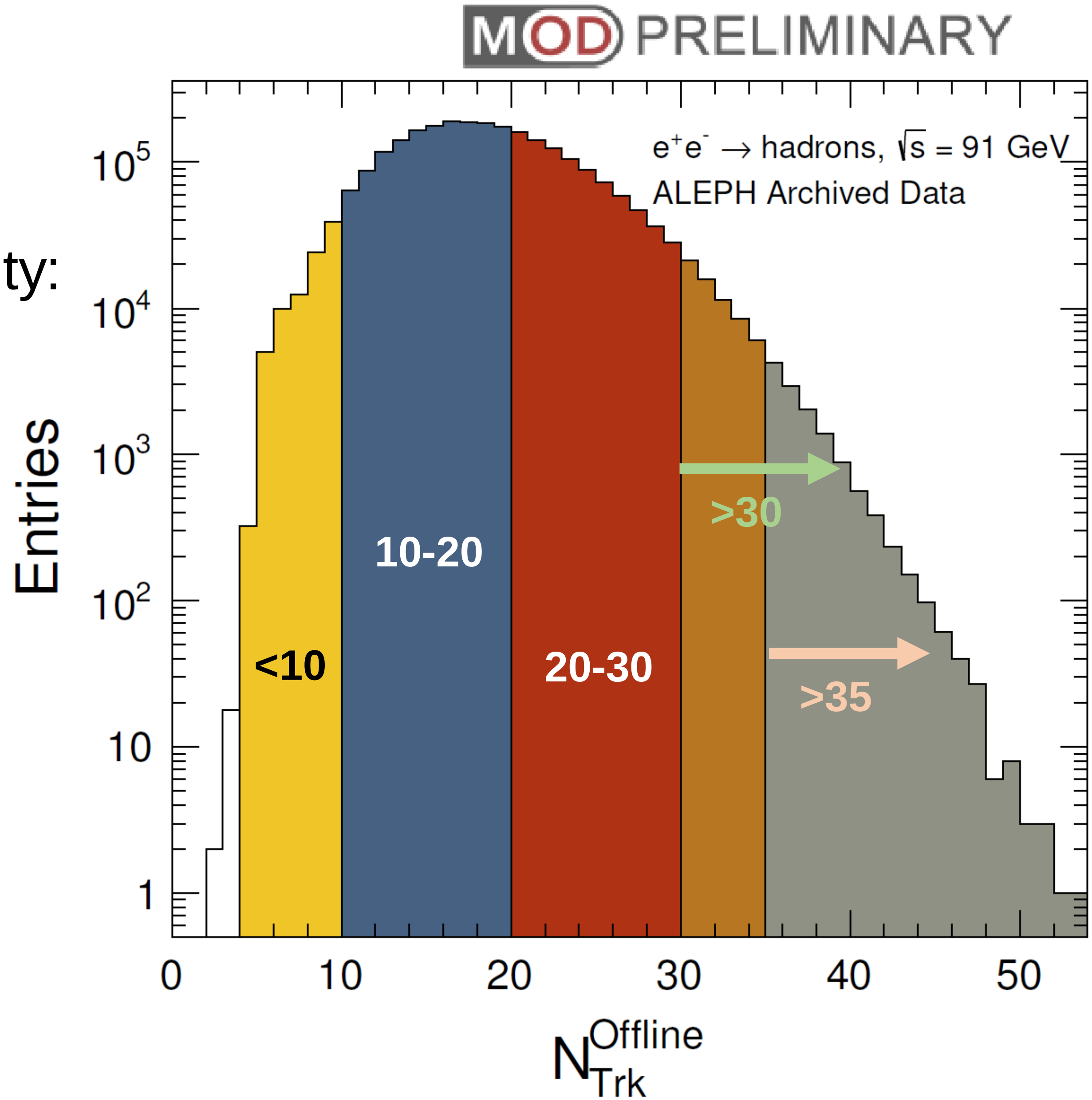
ALEPH detector



Charged Particle Multiplicity (LEP1)

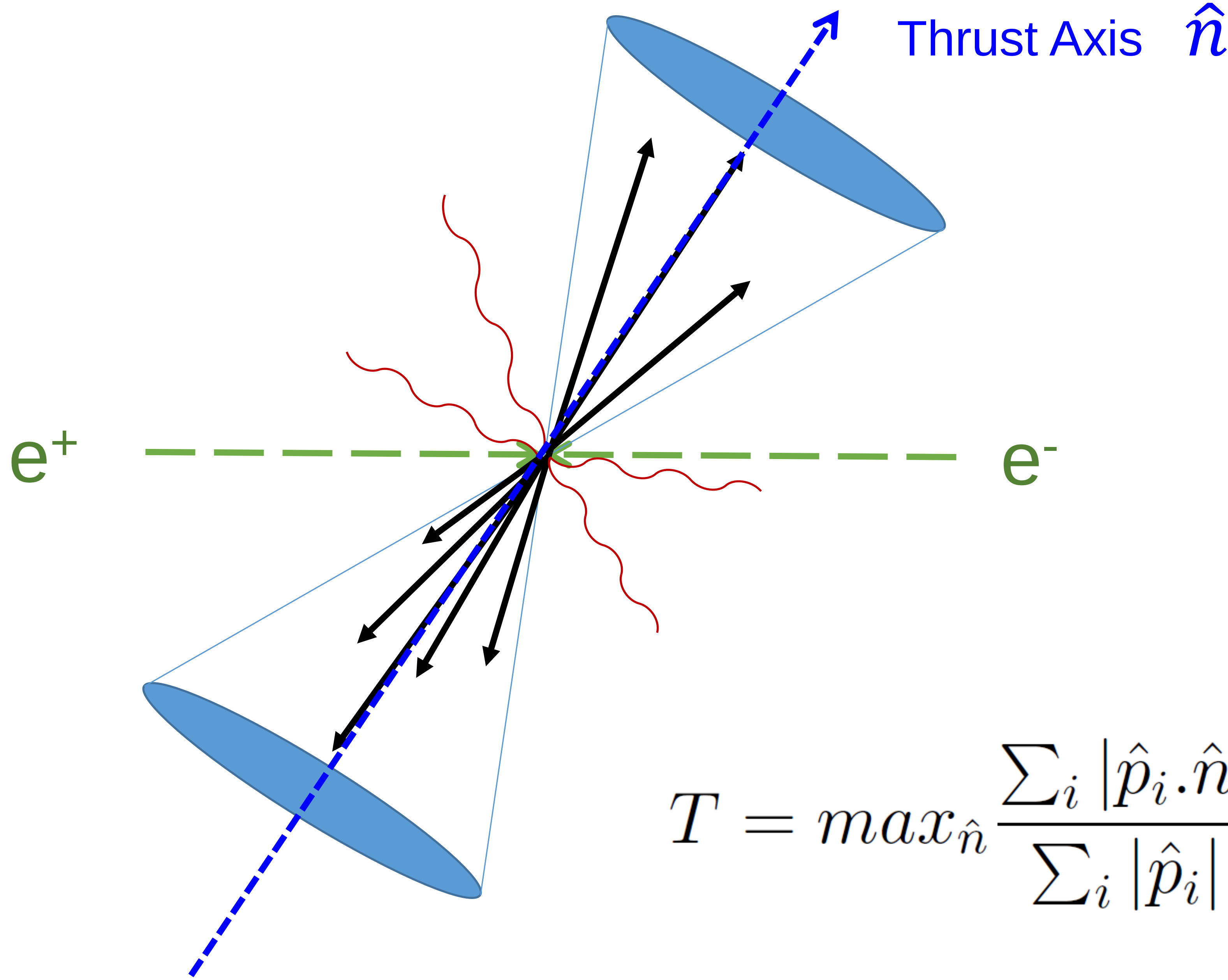
- LEP1 e^+e^- data at Z pole (91 GeV)
- Charged particles multiplicity:
  - $N_{Trk}^{Offline}$
  - p_T>0.2 GeV
  - $|\eta|$<1.74





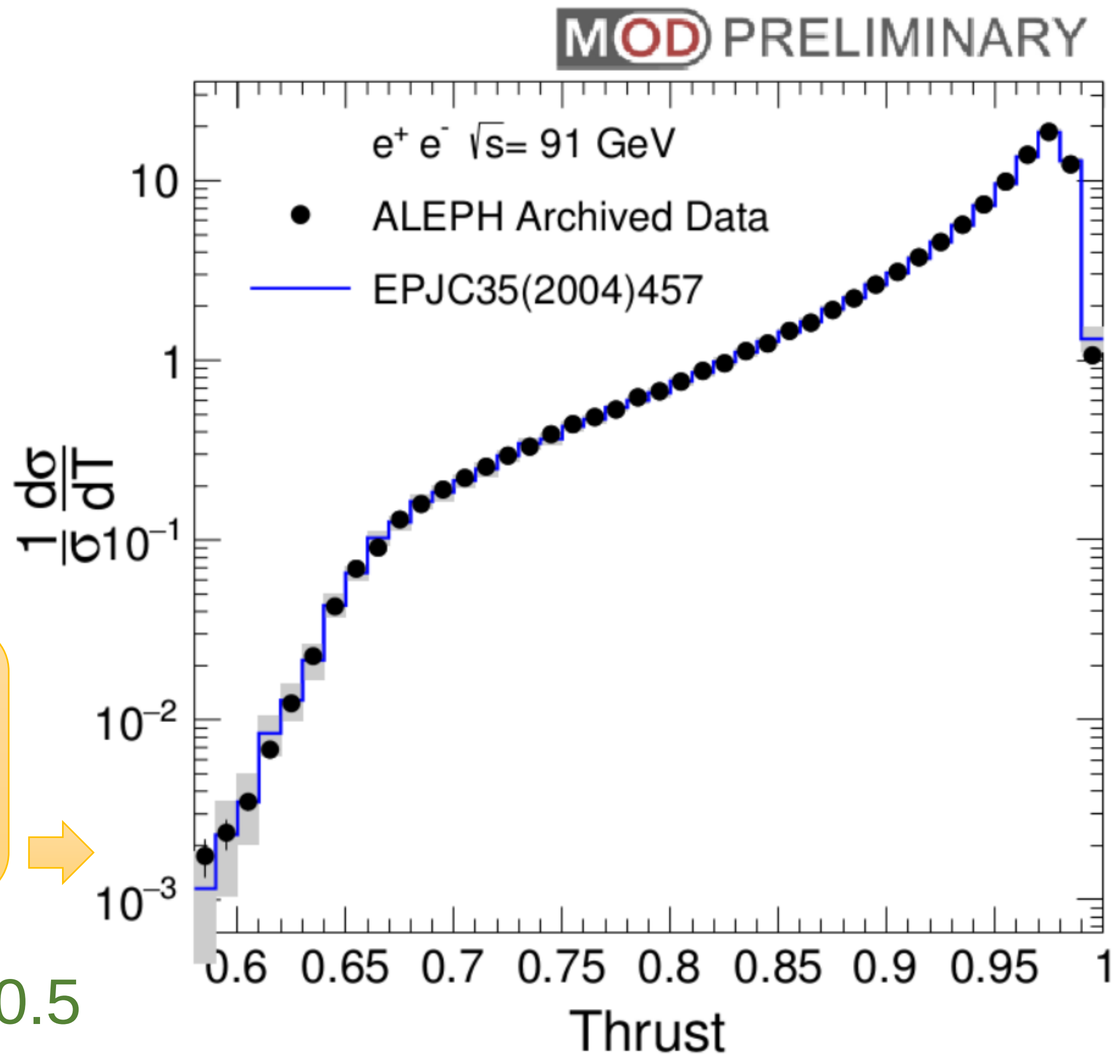
Large fluctuation in the produced number of final state particles

Event Shape: Thrust

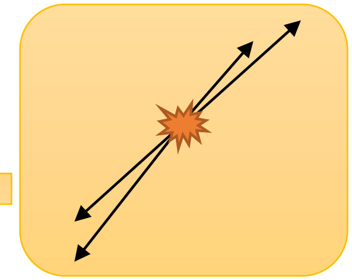


$$T = max_{\hat{n}} \frac{\sum_i |\hat{p}_i . \hat{n}|}{\sum_i |\hat{p}_i|}$$

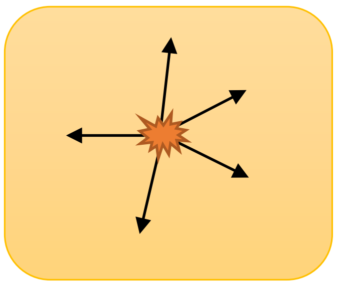
Unfolded Thrust Distribution



Pencil-like: T~1



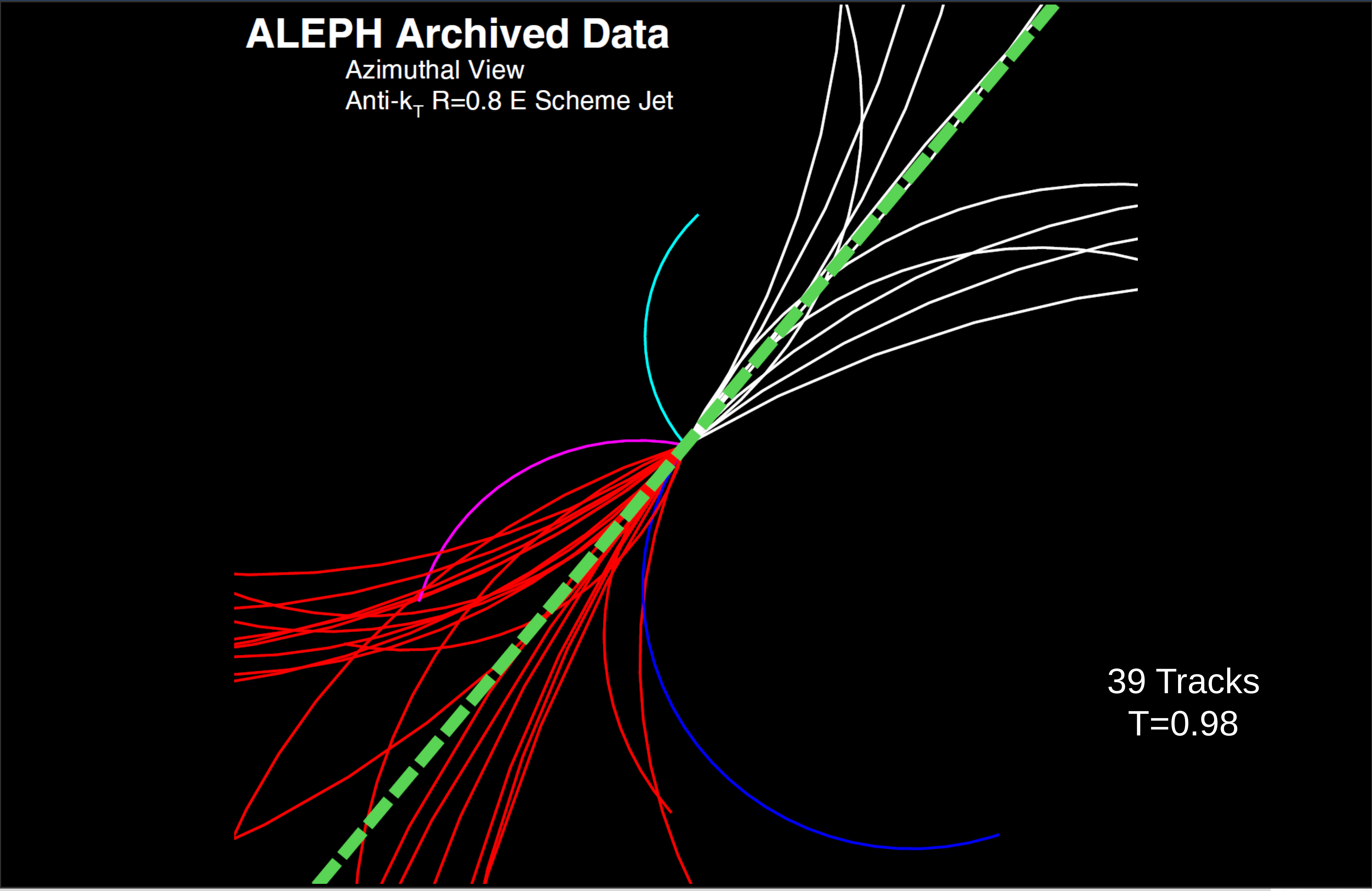
$$T = max_{\hat{n}} \frac{\sum_i |\hat{p}_i.\hat{n}|}{\sum_i |\hat{p}_i|}$$



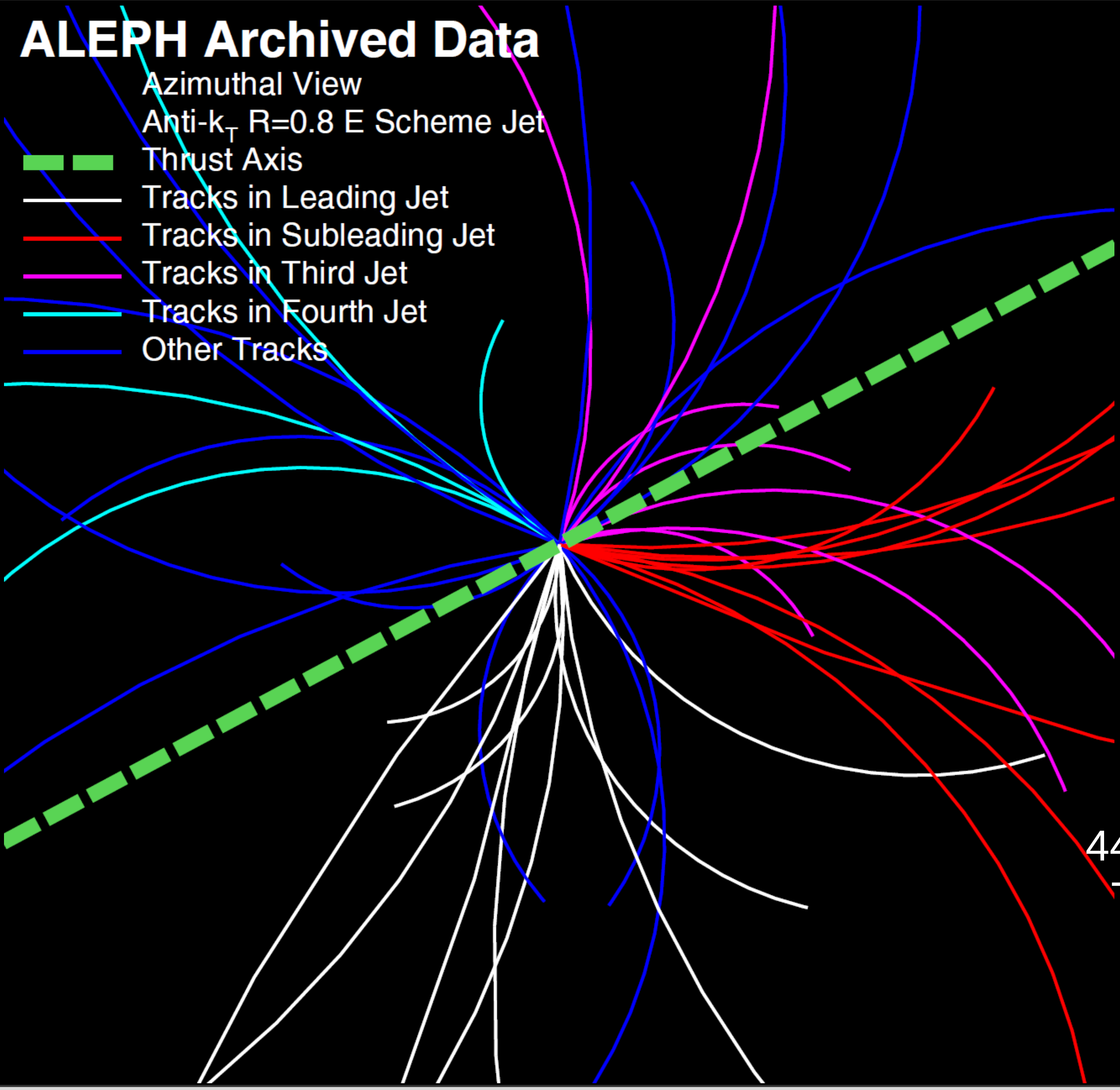
Spherical: T~0.5

Typical e^+e^- annihilation events are more **pencil-like**

A Jet Event in e^+e^- Collisions



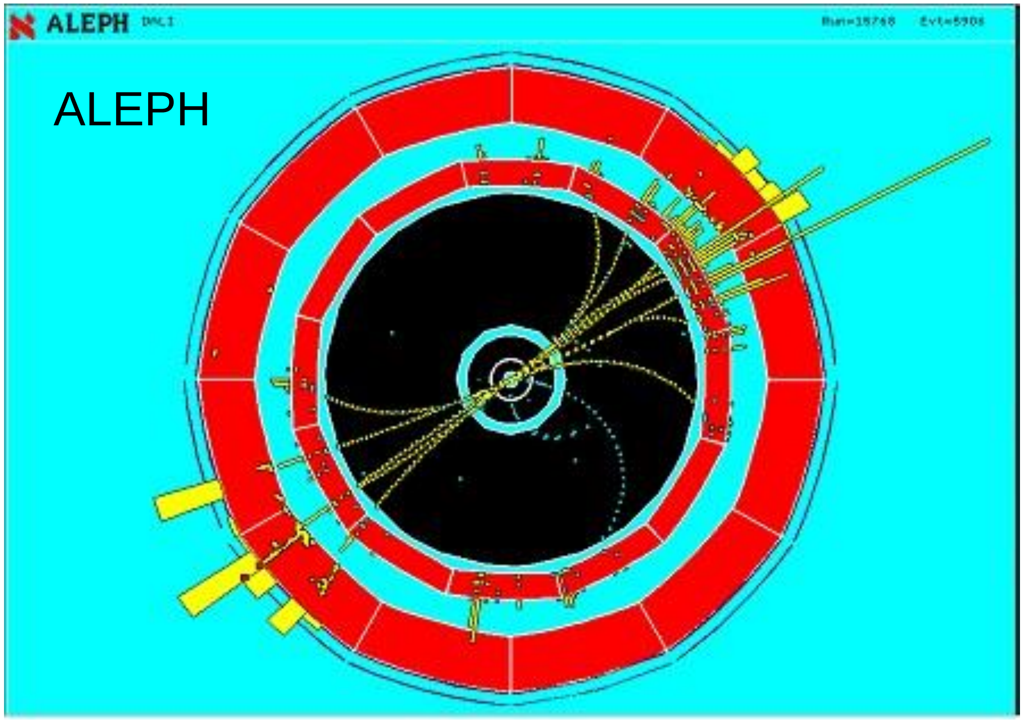
A Jet Event in e^+e^- Collisions



44 Tracks
T=0.57

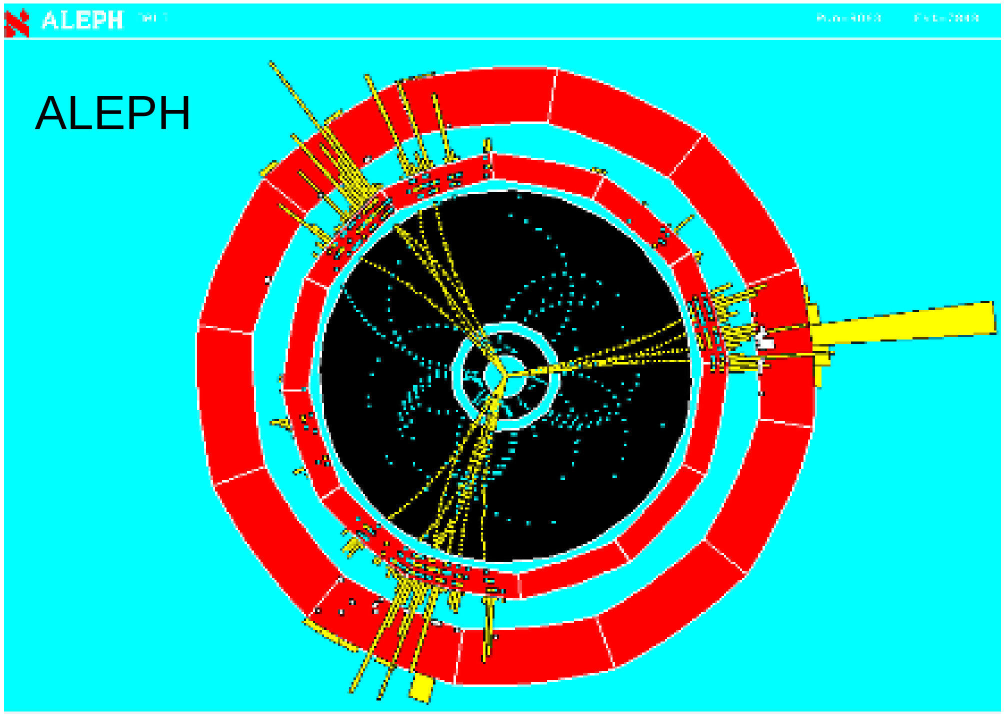
Detecting Quarks and Gluons

Dijet event



$$e^+ + e^- \rightarrow q + \bar{q}$$

Trijet event

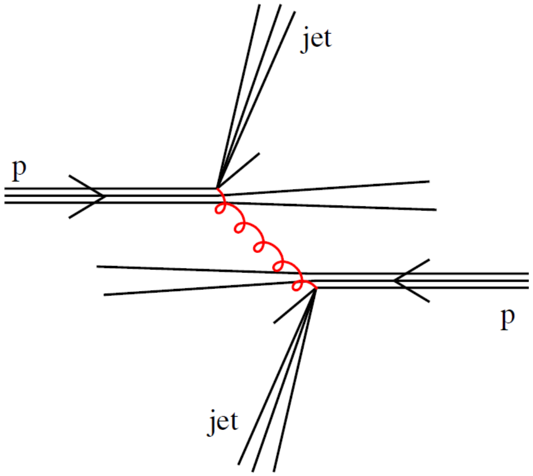


$$e^+ + e^- \rightarrow q + \bar{q} + g$$

Jets (defined by jet clustering algorithm) are used as a proxy of quarks and gluons

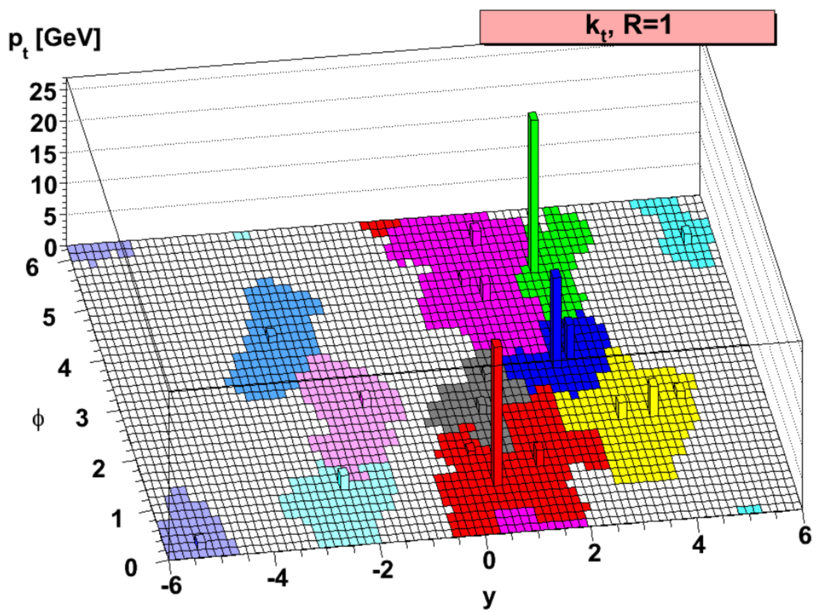
k_T algorithm

From Gavin Salam



$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = p_{ti}^2$$

PP event



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

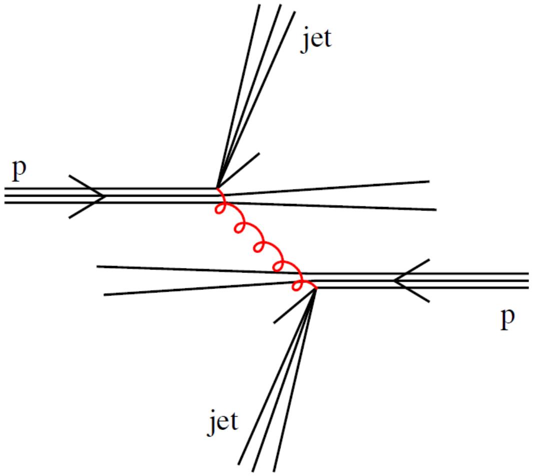
1. Find smallest of d_{ij}, d_{iB}
2. if ij, recombine them
3. if iB, call i a jet and remove from list of particles
4. repeat from step 1 until no particles left.

S.D. Ellis & Soper, '93

Clustering start from low p_T particles. Clustered shape has irregular shape.
In heavy ion collisions, the large background fluctuation could affect the clustering more

Anti-k_T algorithm

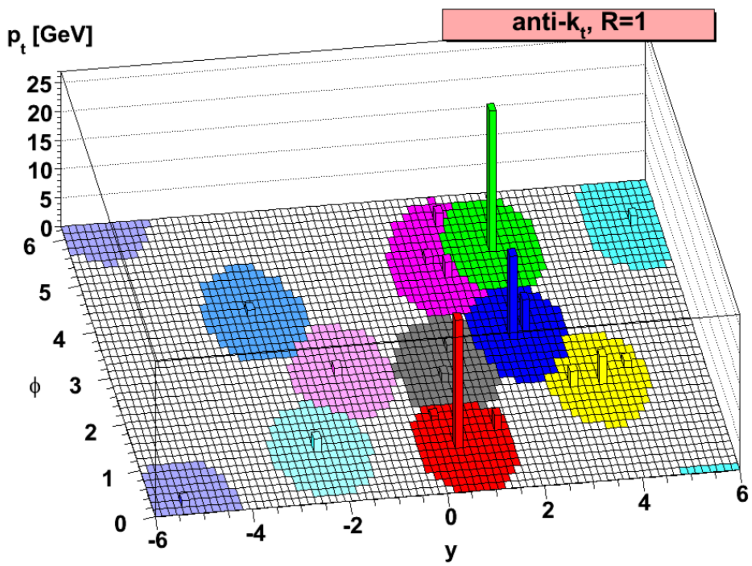
From Gavin Salam



$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{k_{ti}^2}$$

PP event

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



- 1. Find smallest of d_{ij}, d_{iB}
  2. if ij, recombine them
  3. if iB, call i a jet and remove from list of particles
  4. repeat from step 1 until no particles left.

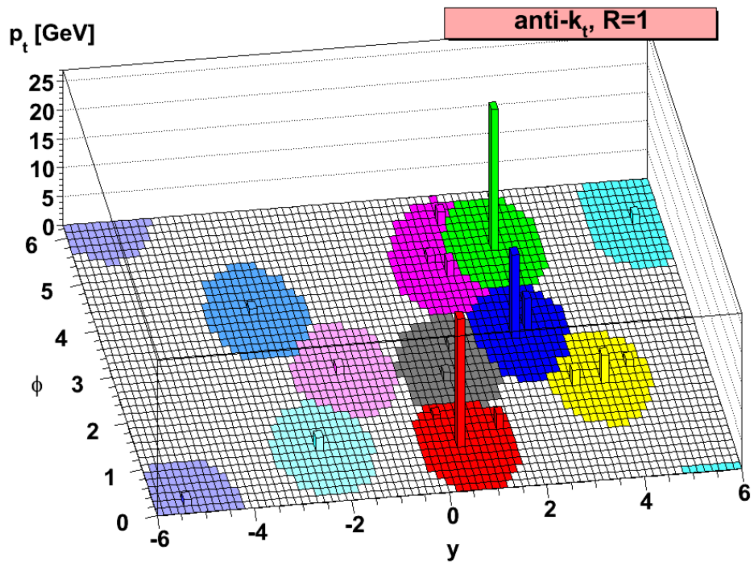
Cacciari, GPS & Soyez, '08

Clustering start from high p_T particles. Clustered shape has circular shape.
Now commonly used in the analysis of heavy ion collision

Jet Reconstruction

Need rules to group the hadrons

A popular algorithm is anti-k_T algorithm
Used in ALICE, ATLAS and CMS analyses for jets in pp and heavy ion collisions

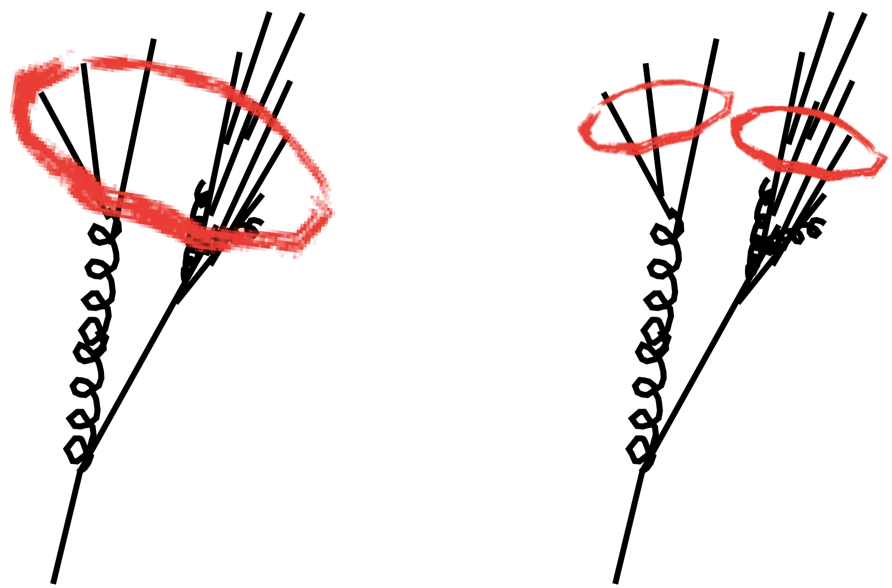


Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

Radius parameter: decide the resolution scale

Large radius parameter

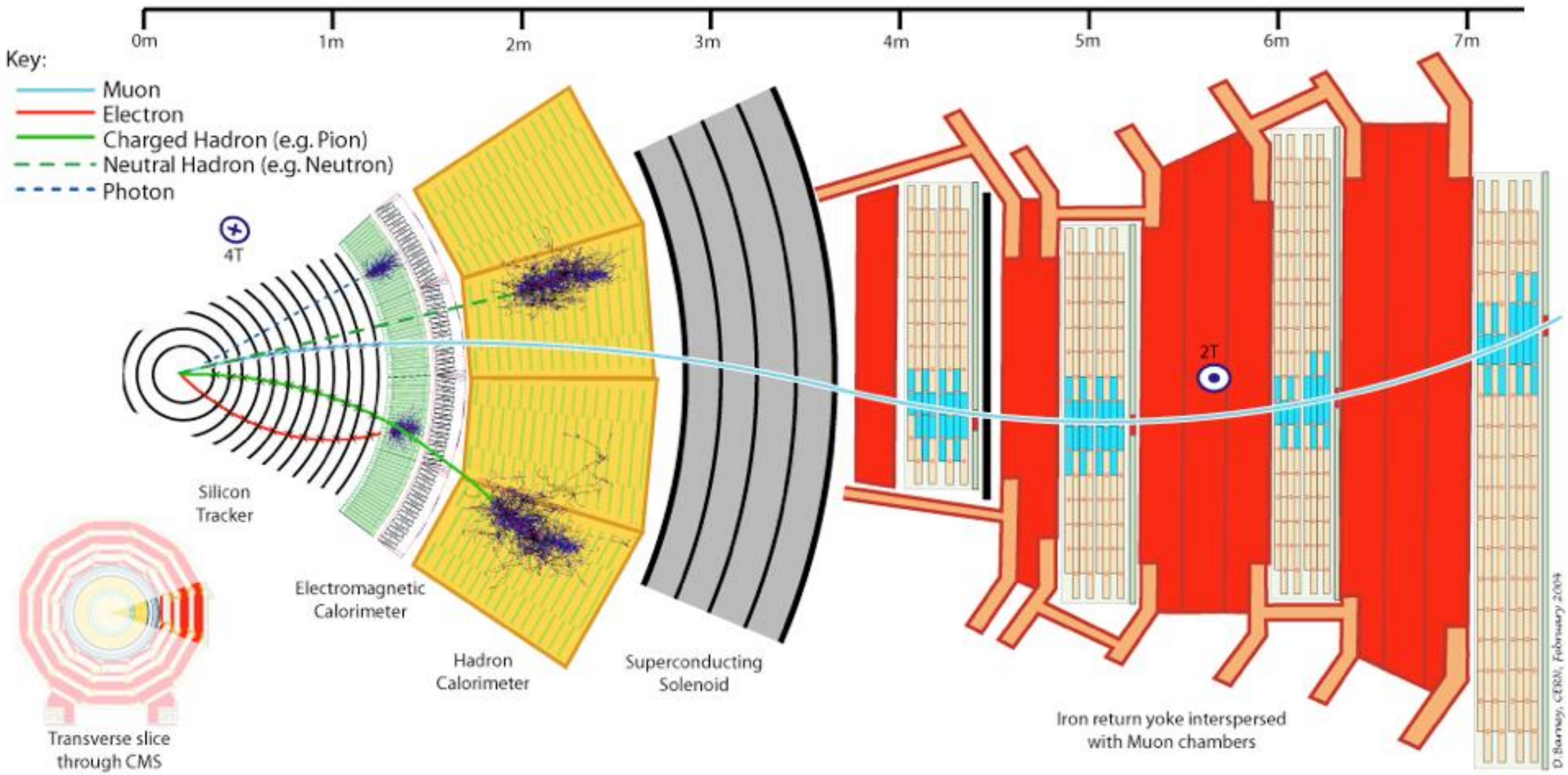
Small radius parameter
→ jet spliting



ΔR = 0.2, 0.3, 0.4, 0.5 are used in LHC analyses

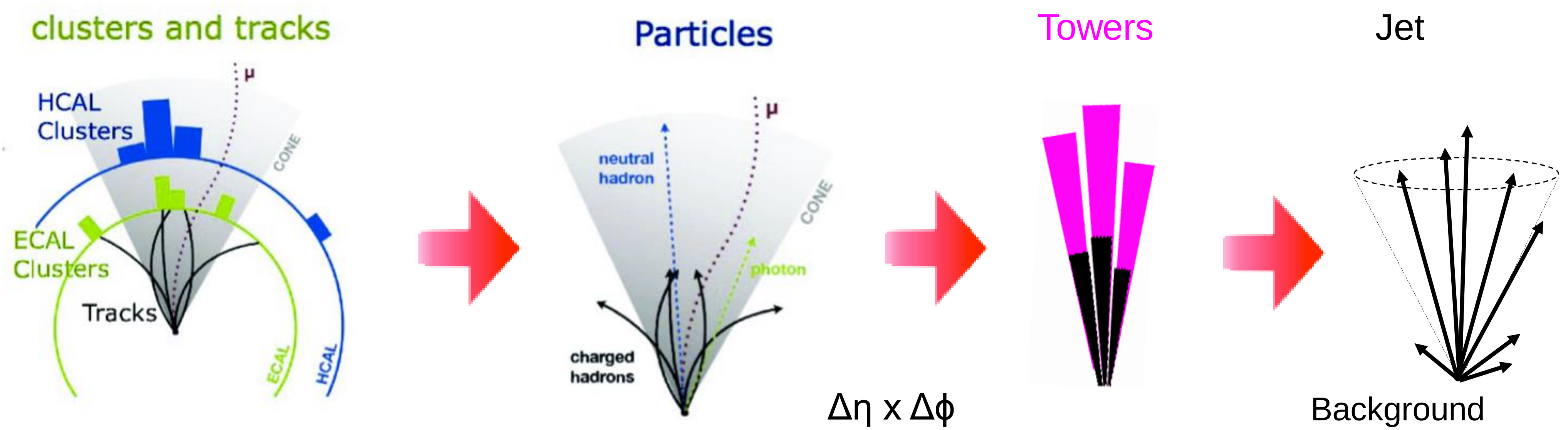
The CMS Detector

Primary sub-detectors: Silicon tracker, ECAL, HCAL, muon chambers



CMS can distinguish stable particles as: $h^{+/-}$, γ, h^0, μ, e

Jet composition



$\Delta\eta$ x $\Delta\phi$
0.076 x 0.076 in barrel

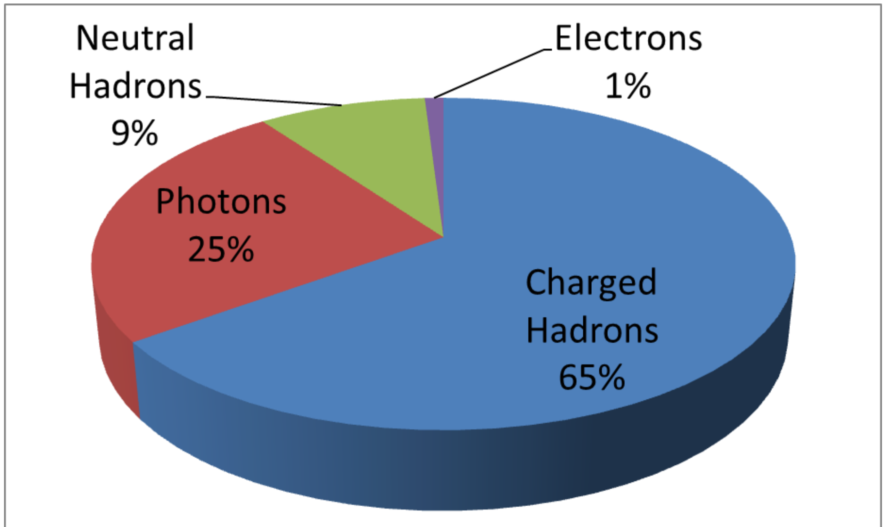
Background subtraction and jet clustering

Anti-k_T algorithm is used in most CMS publication

On average, charged hadrons carry 65% of the jet momentum

Measure the known part
Correct the rest by MC simulation

Optimize the use of calorimeter and tracker
Example: “Particle Flow” in CMS

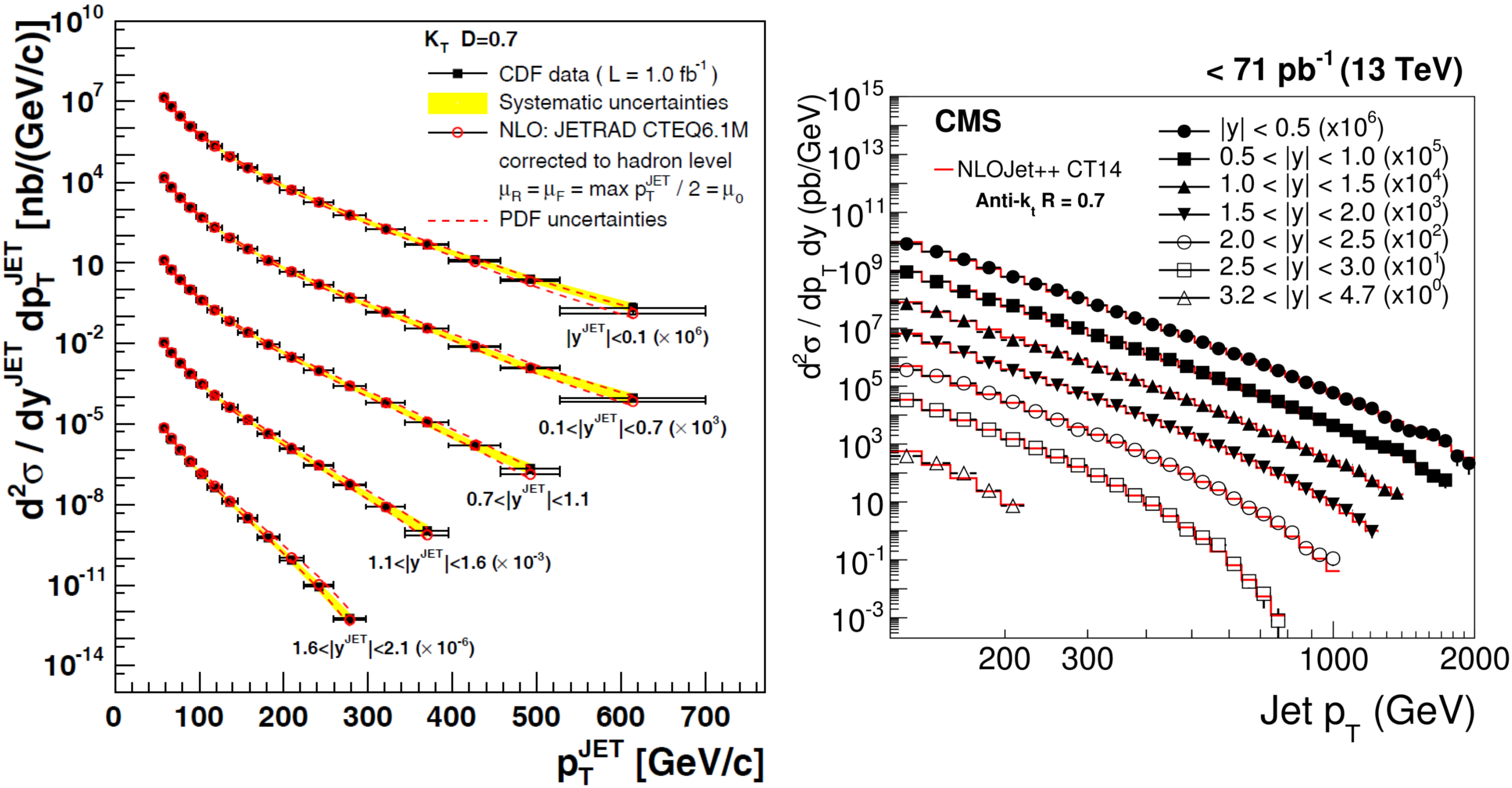


A typical high p_T jet

Jet Spectra in pp(bar) collisions

ppbar 1.96 TeV

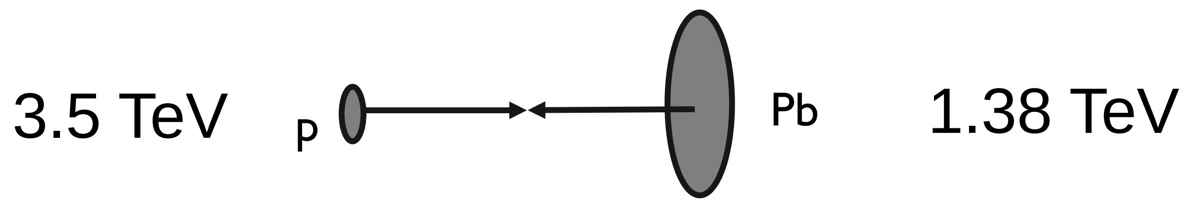
pp 13TeV



Jet spectra with large R parameter from proton-(anti-)proton collisions are well understood. Consistent with NLO calculations.

Nuclear Parton Distribution Function

Jet for constraining the nuclear parton distribution function



Parton Distribution Function

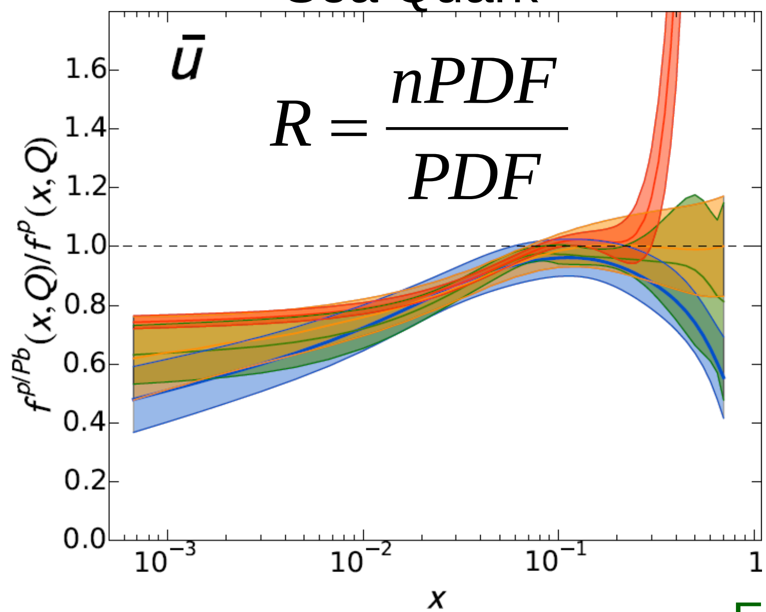
Nuclear Parton Distribution Functions (nPDF)

Deep Inelastic Scattering Data

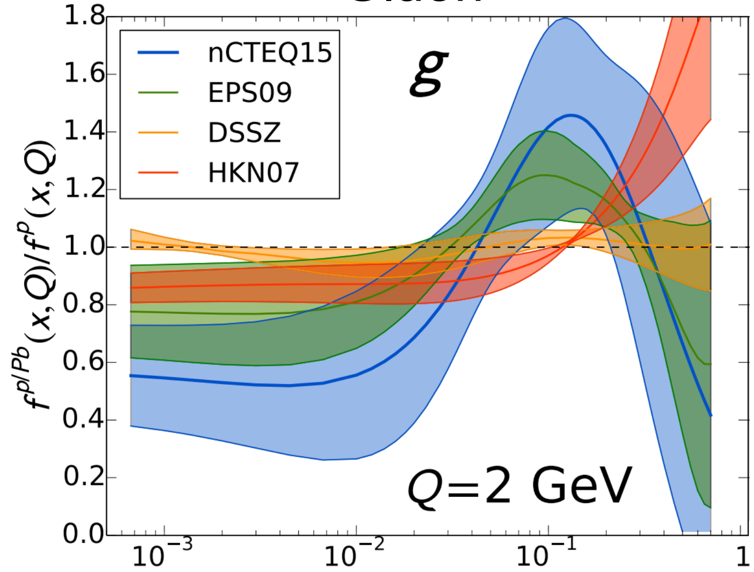
Drell-Yan Data

RHIC Pion Data

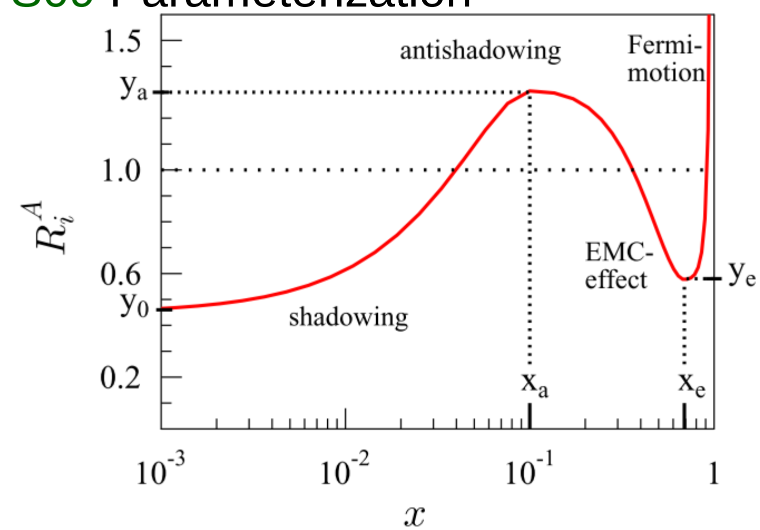
Sea Quark



Gluon



EPS09 Parameterization



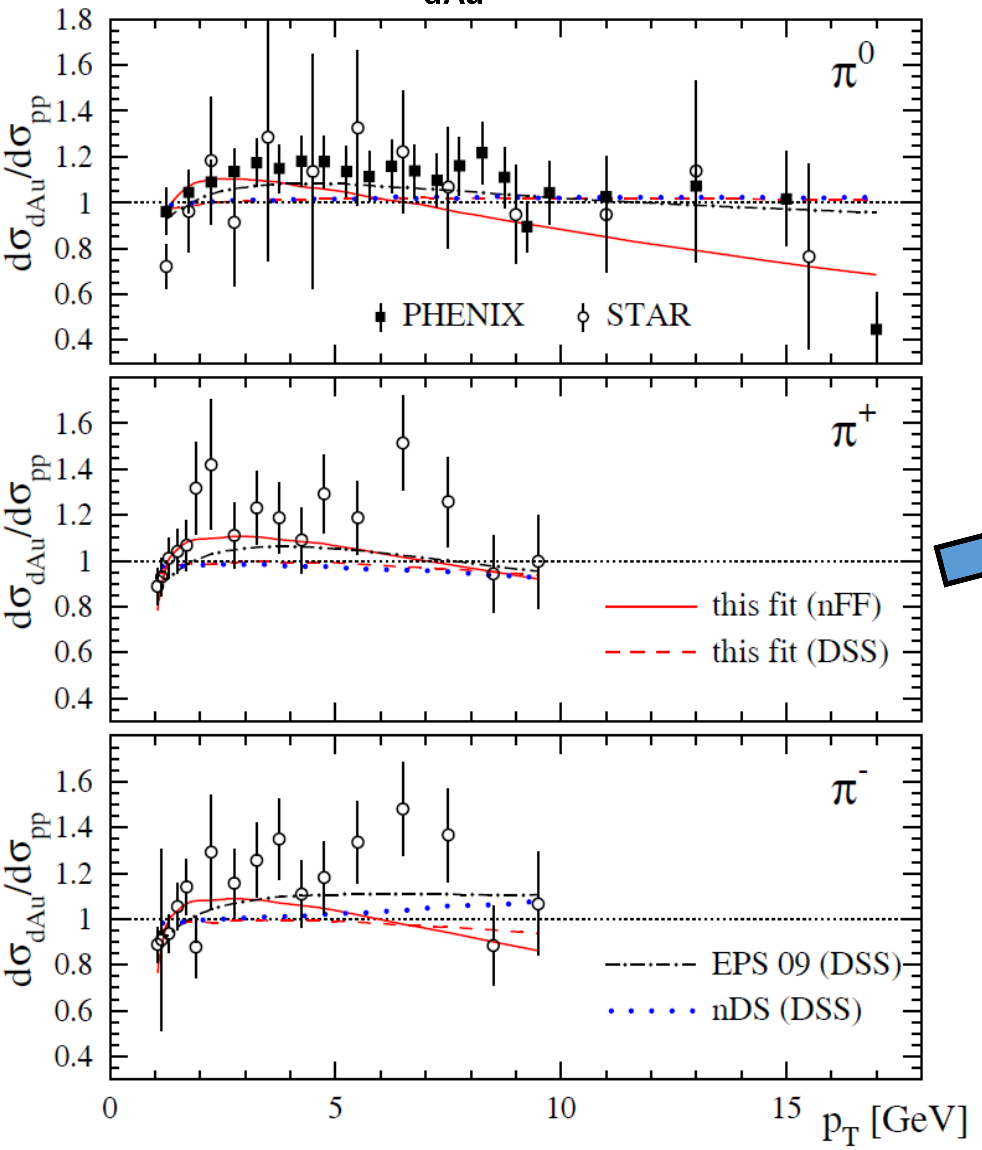
	Q^2 cutoff	DIS	DY	PHENIX Pion	STAR Pion
HKN07	1	V	V		
EPS09	1.69	V	V	V	
DSSZ	1	V	V	V	V
nCTEQ15	4	V	V	V	V

EPPS16: with LHC pPb data (W,Z, jets)

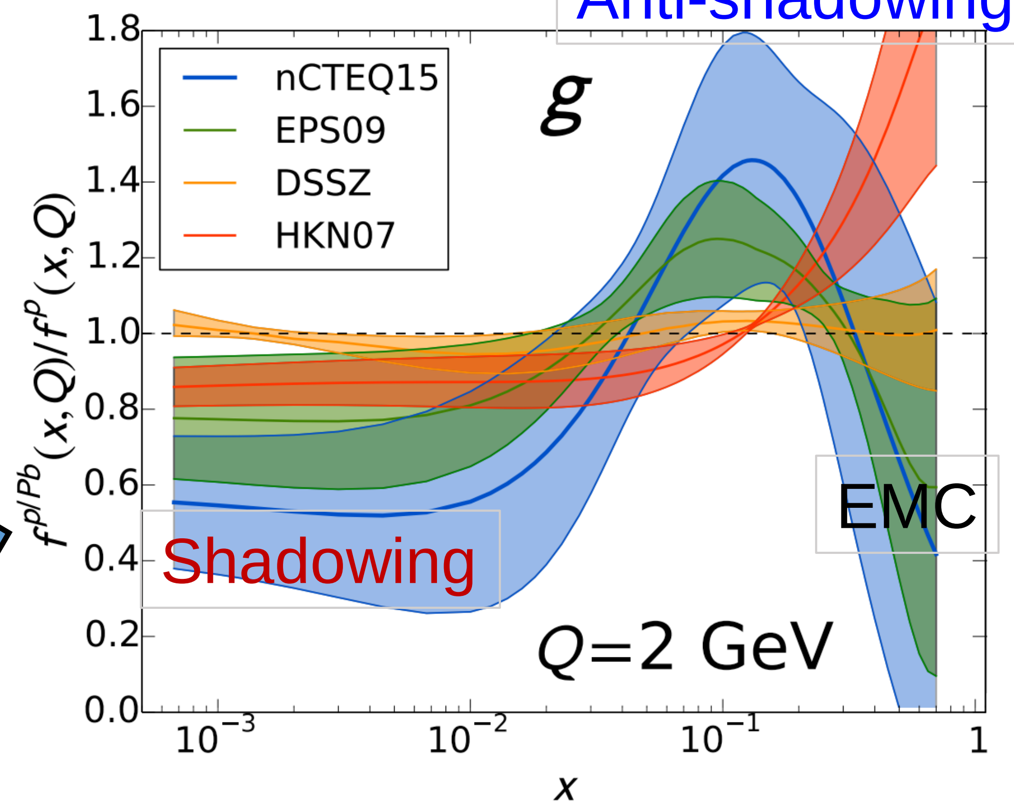
Different interpretation of the pion data

Hadron observables: sensitive to possible modifications of **fragmentation function** and **hadronization** → Different interpretation of the data!

RHIC Pion $\mathbf{R_{dAu}}$ dAu 200 GeV/c



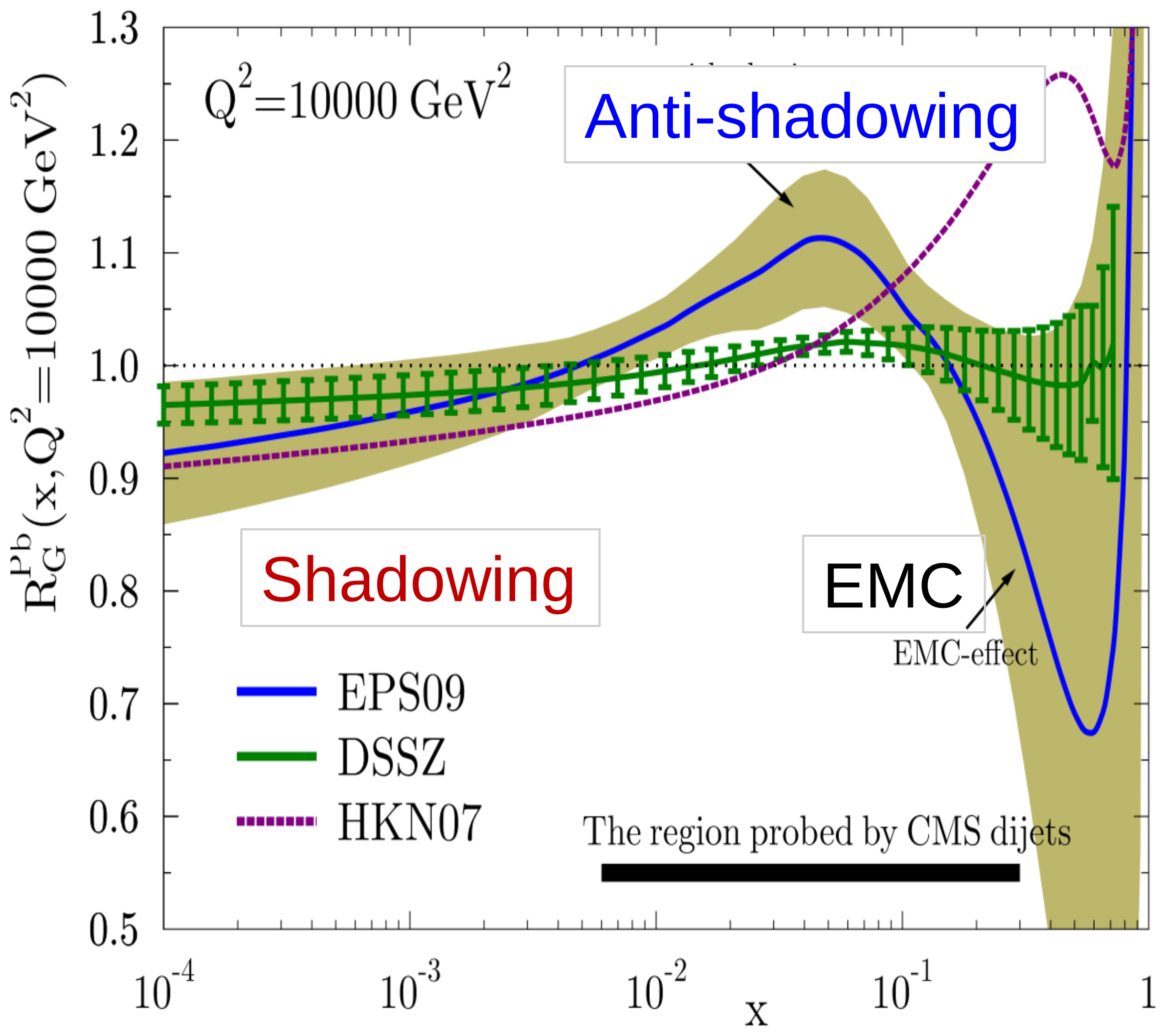
Gluon **R=nPDF/PDF**



- **EPS09** & **nCTEQ15**: hint of **anti-shadowing** and **EMC effect** of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing

nPDF modification at large Q^2

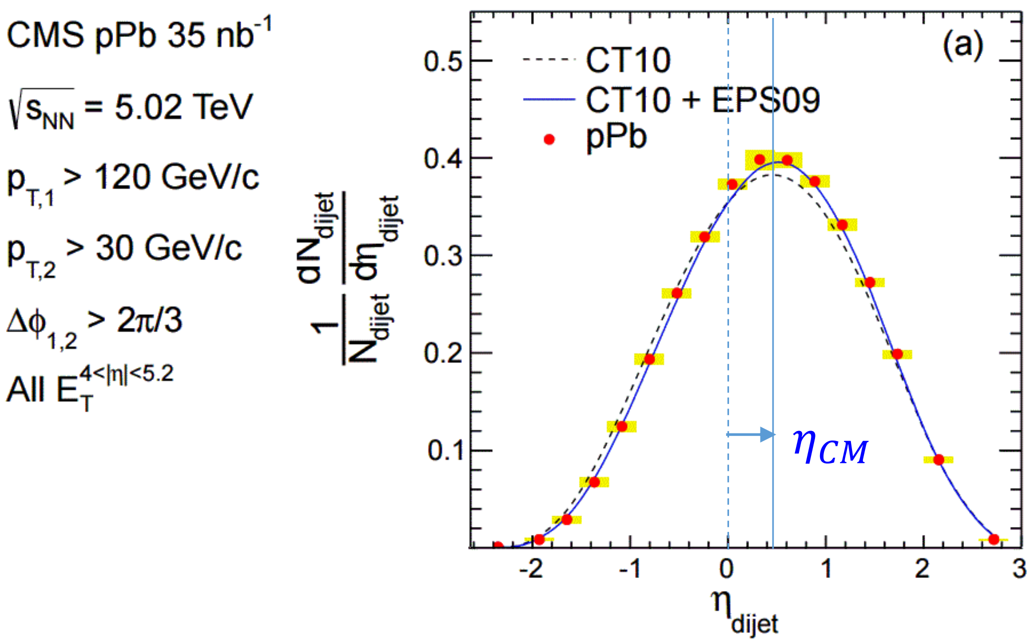
$$R = \frac{nPDF}{PDF}$$



Nuclear modification of hard scattering involving large momentum transfer due to PDF is small (at the order of 10%)

Dijet pseudorapidity in the LAB Frame

Idea: Angular distributions of high p_T dijets

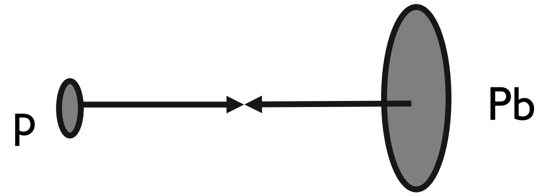


$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

$$\propto 0.5 \log\left(\frac{x_p}{x_{Pb}}\right) + \eta_{CM}$$

- Jets: Less sensitive to fragmentation functions and hadronization effects
- Can be calculated with pQCD with small theoretical uncertainties
- Normalized distribution: lead to smaller theoretical and experimental uncertainties

3.5 TeV



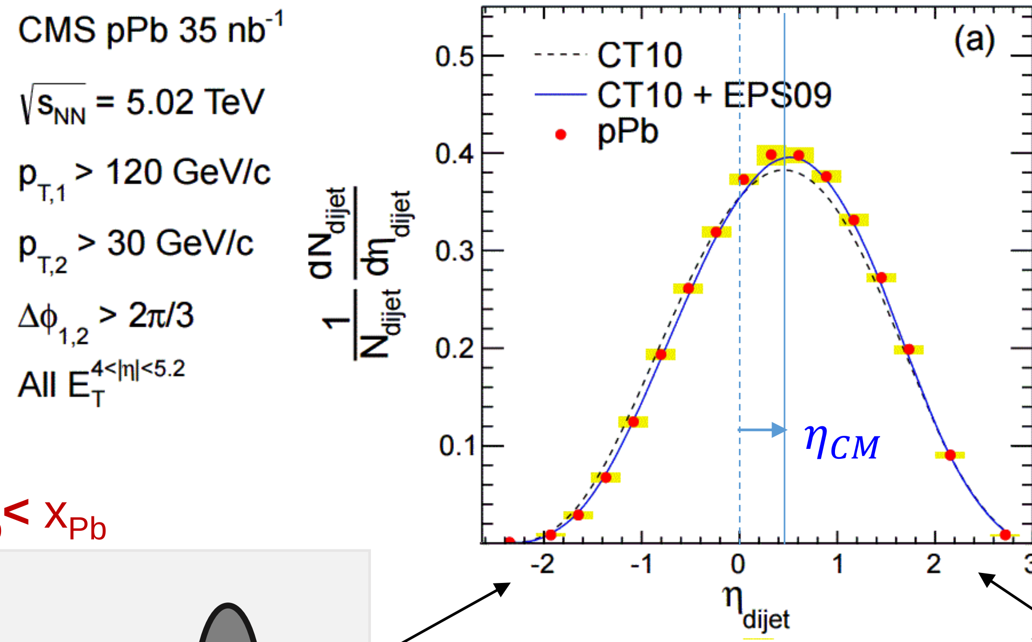
1.38 TeV

Distribution shift to positive value due to asymmetric proton and lead ion beam energy

EPJC 74 (2014) 2951

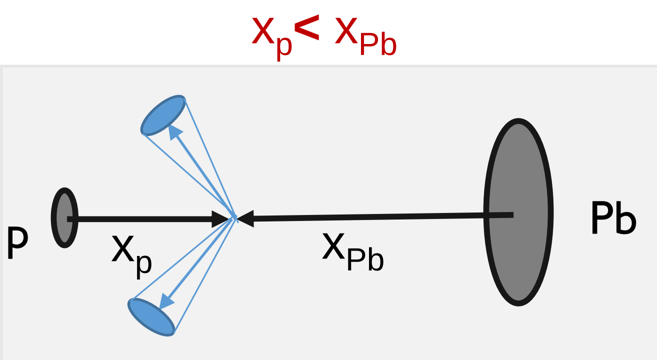
Dijet pseudorapidity in the LAB Frame

Idea: Angular distributions of high p_T dijets

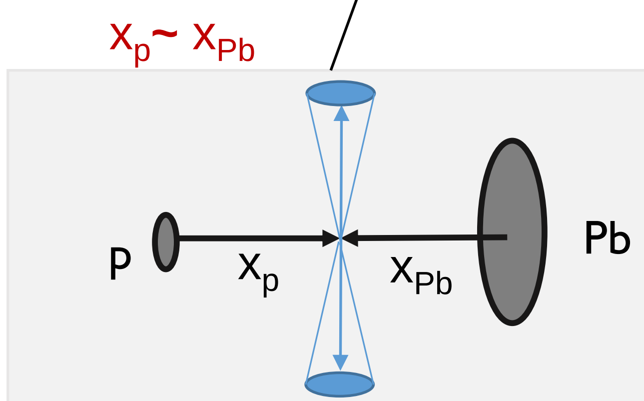


$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

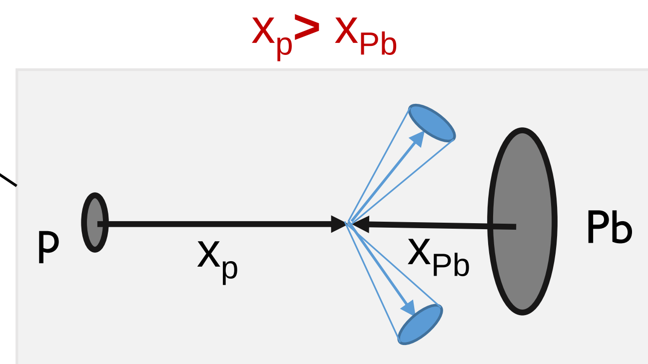
$$\propto 0.5 \log\left(\frac{x_p}{x_{Pb}}\right) + \eta_{CM}$$



Sensitive to EMC effect



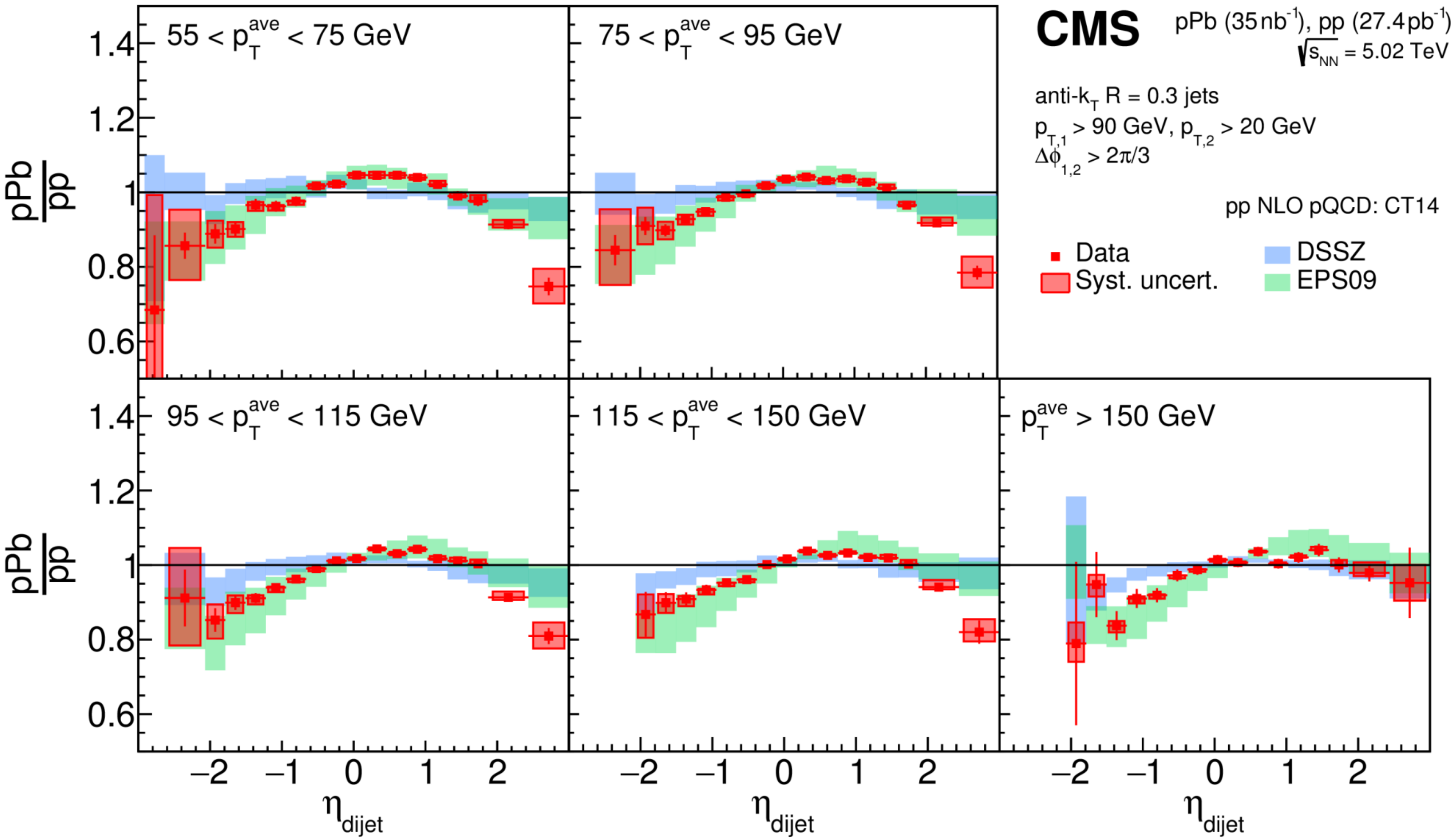
Sensitive to anti-shadowing



Sensitive to shadowing

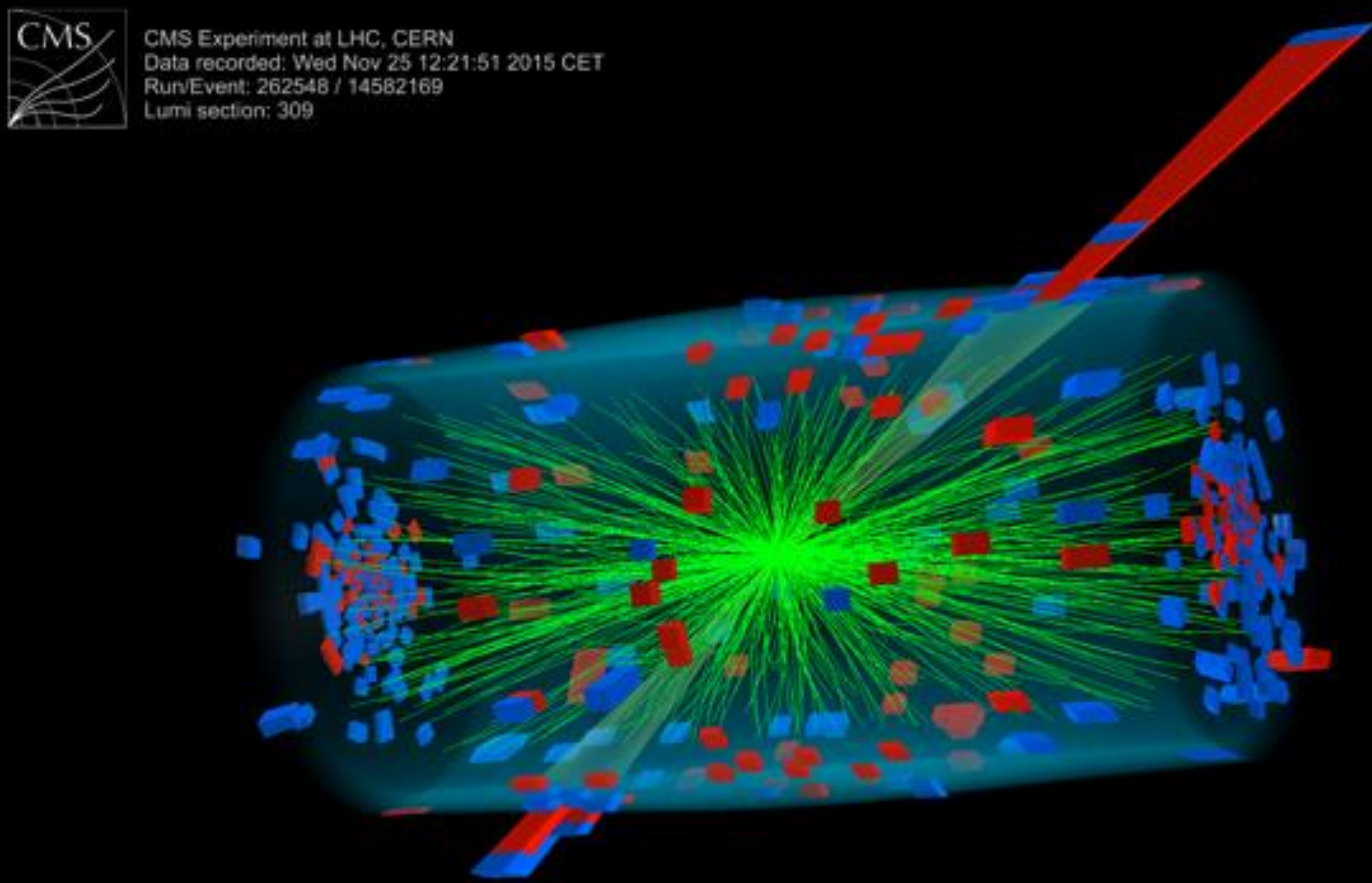
EPJC 74 (2014) 2951

Observation of gluon EMC effect



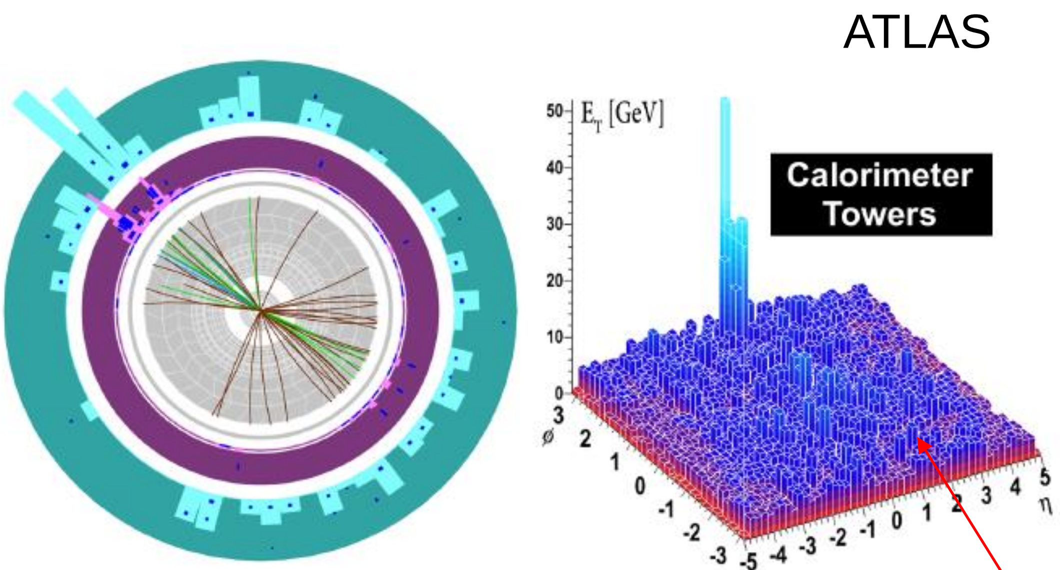
- **EPS09**: hint of **anti-shadowing** and **EMC effect** of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing

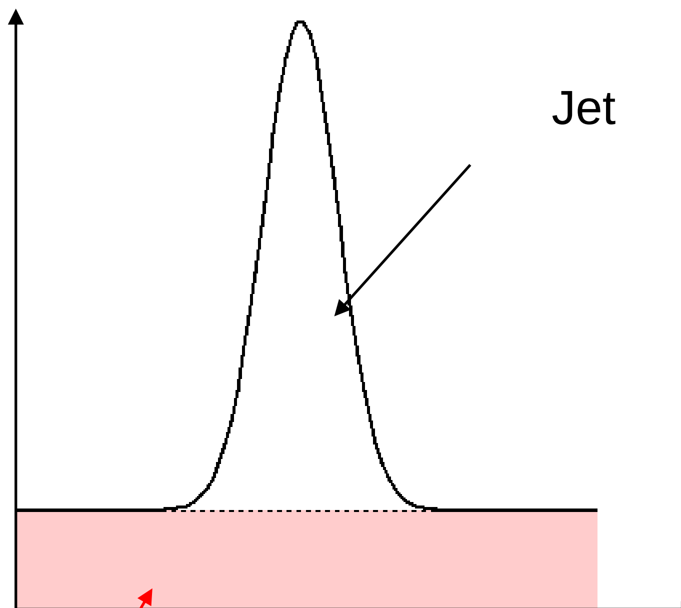
Jet Reconstruction in PbPb collisions



PbPb @ 5 TeV (2015)

Underlying event background



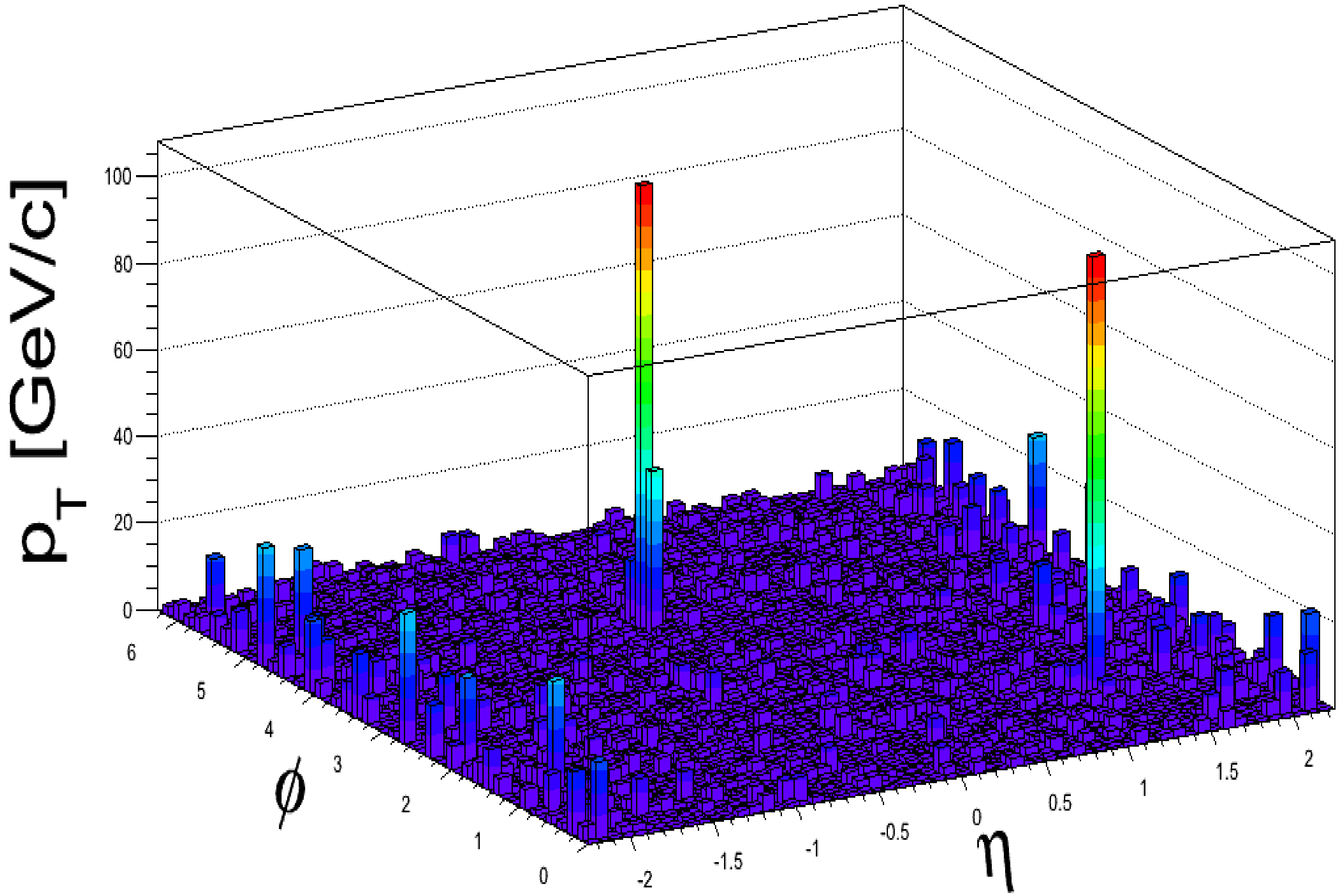


Multiple parton interaction

Large underlying event from soft scattering

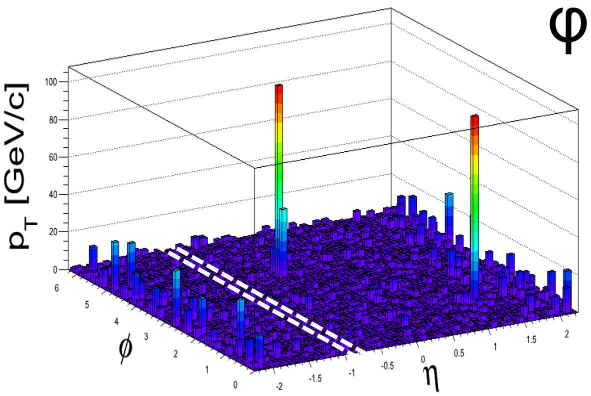
Need background subtraction

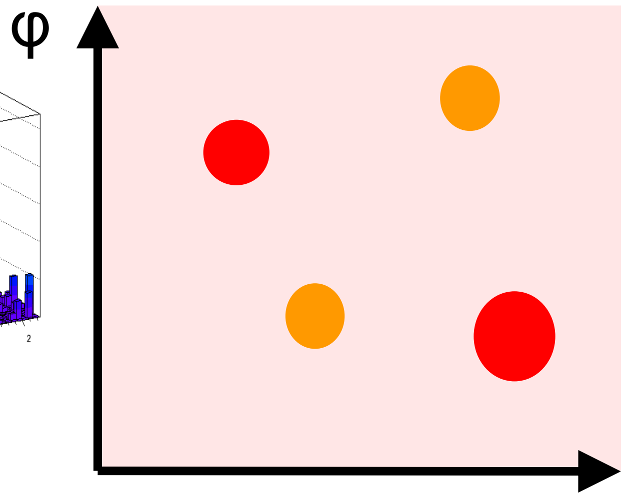
A jet event in CMS

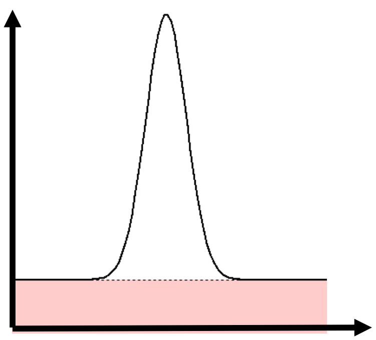


Background changes with η due to particle density and detector geometry

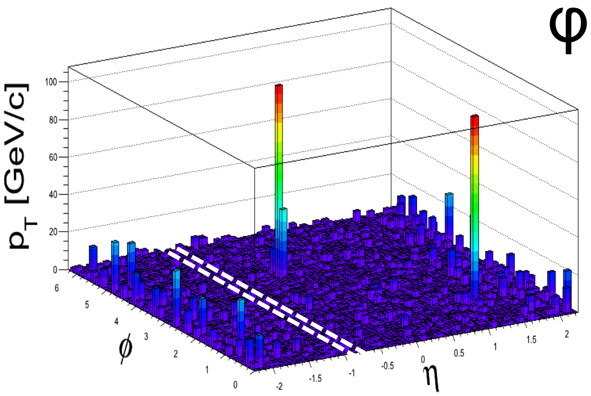
Iterative Background Subtraction

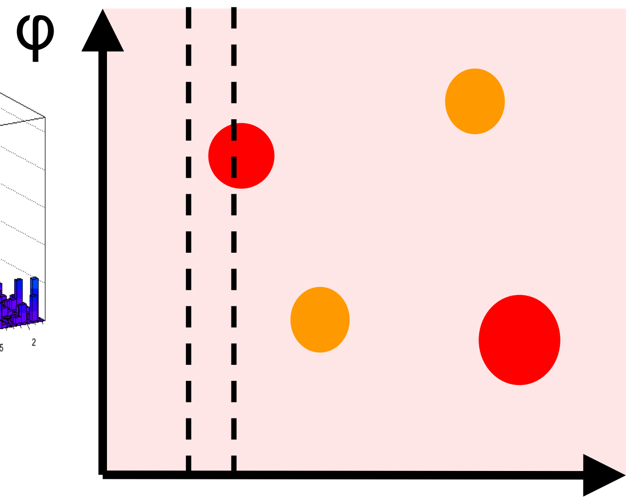




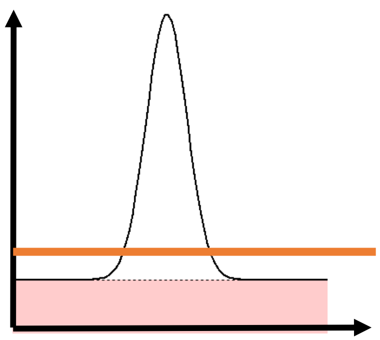


Iterative Background Subtraction





1. Background energy per tower calculated in strips of η. Pedestal subtraction

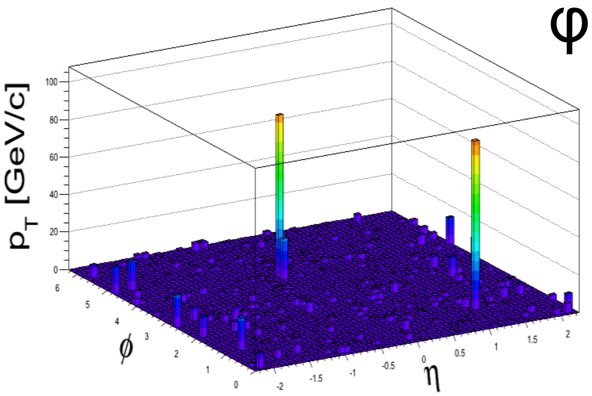


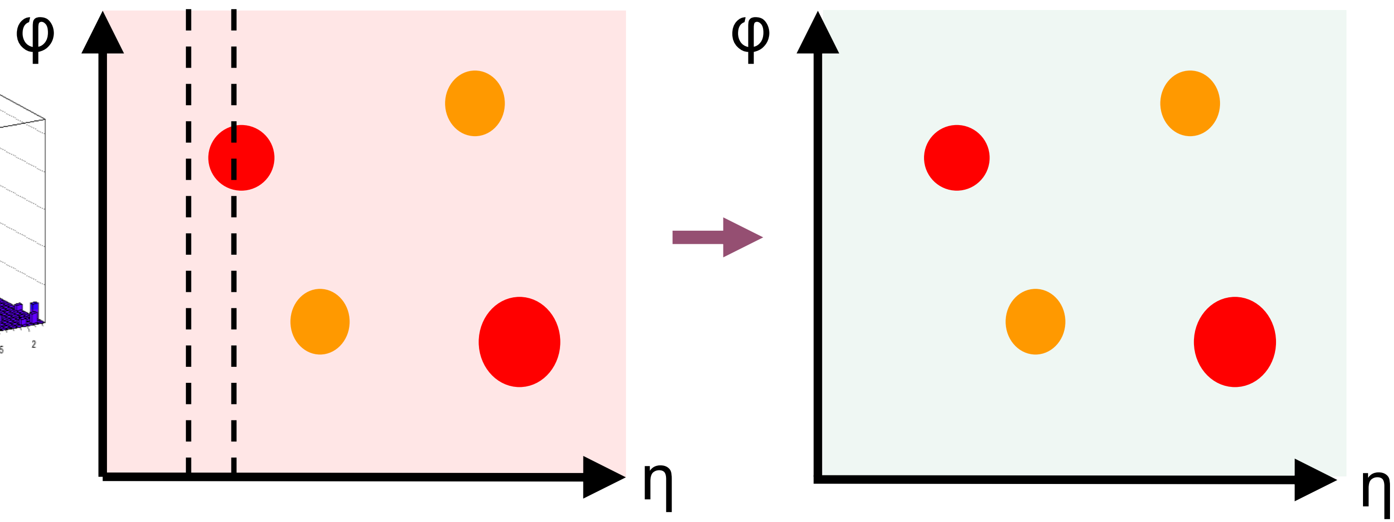
Background level

Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle$ + n $\sigma(p_T)$

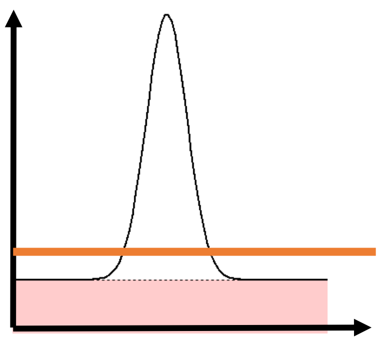
- Captures dN/dη of background
- n $\sigma(p_T)$: noise suppression. n is a real number
- Misses ϕ modulation – to be improved

Iterative Background Subtraction



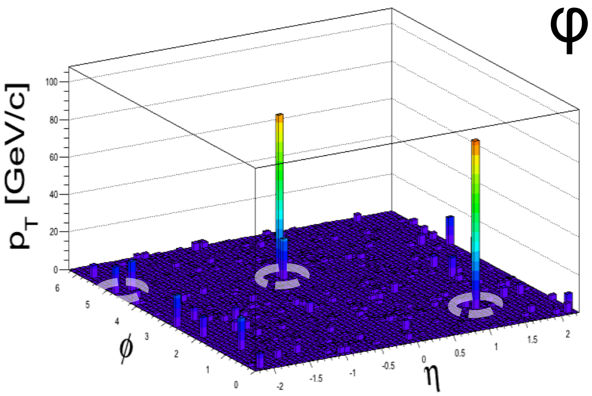


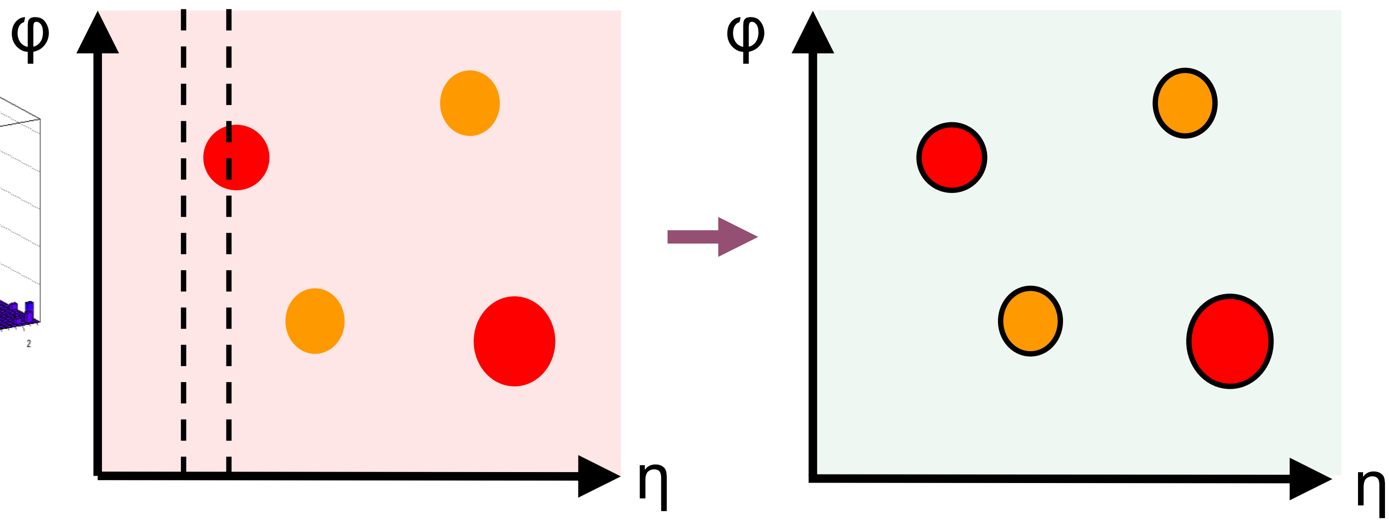
1. Background energy per tower calculated in strips of η. Pedestal subtraction



Background level

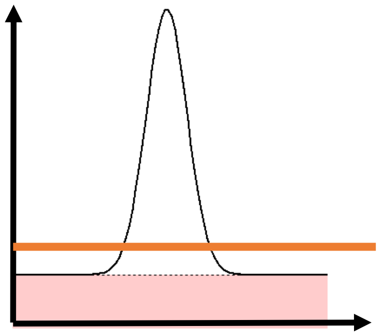
Iterative Background Subtraction





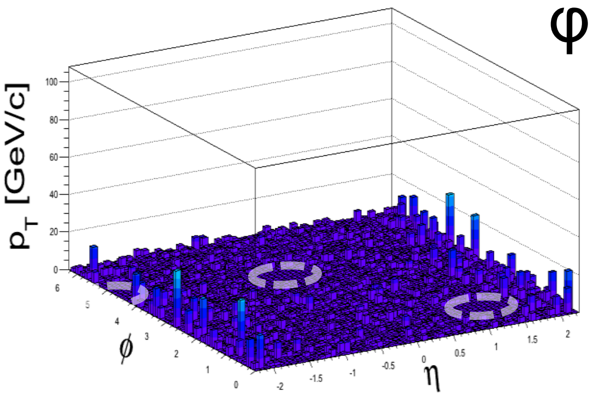
1. Background energy per tower calculated in strips of η. Pedestal subtraction

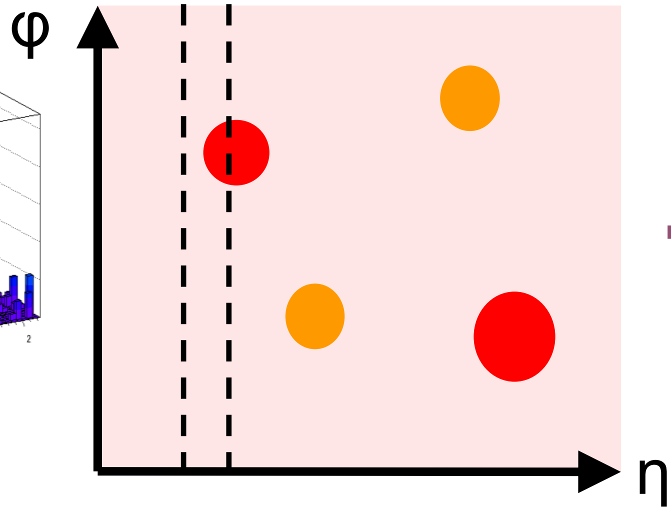
2. Run anti k_T algorithm on background subtracted towers



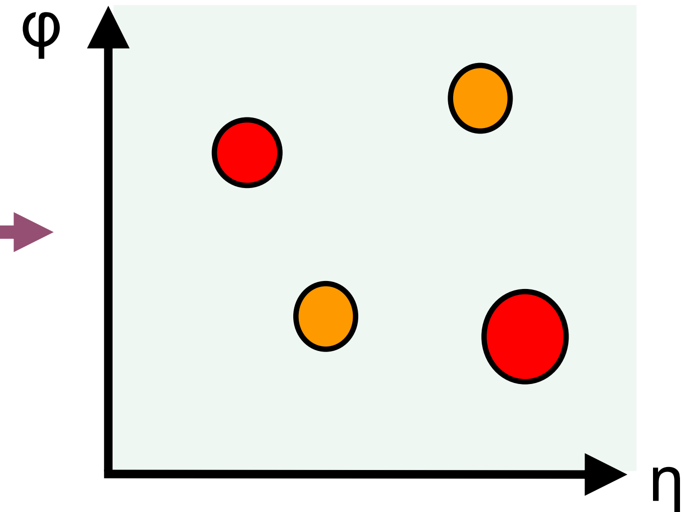
Background level

Iterative Background Subtraction

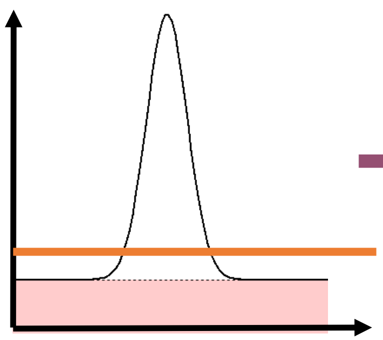




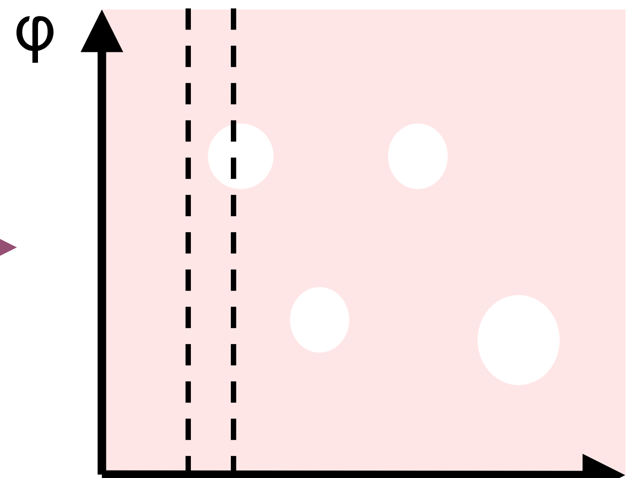
1. Background energy per tower calculated in strips of η. Pedestal subtraction



2. Run anti k_T algorithm on background subtracted towers

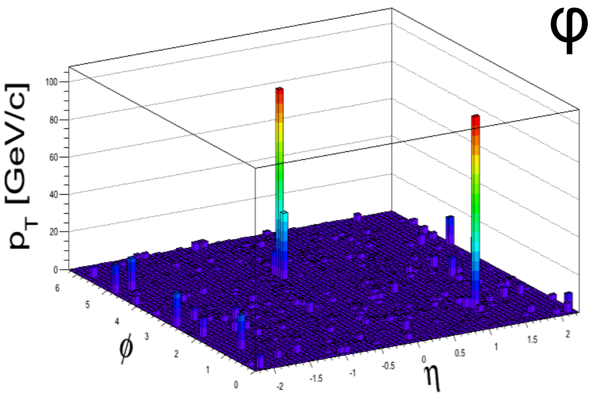


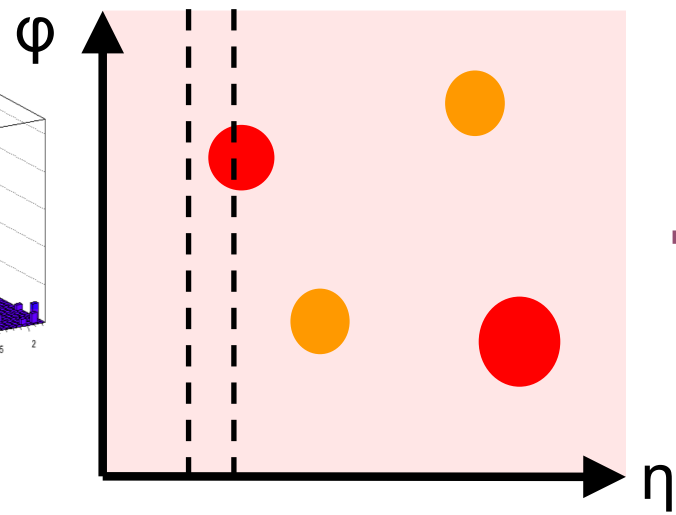
Background level



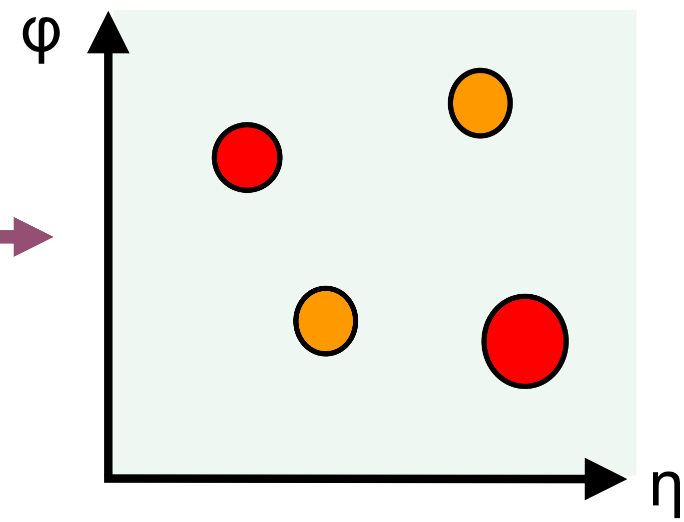
3. Exclude reconstructed jets > p_T^{cut}

Iterative Background Subtraction

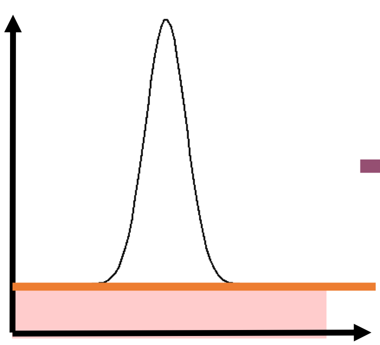




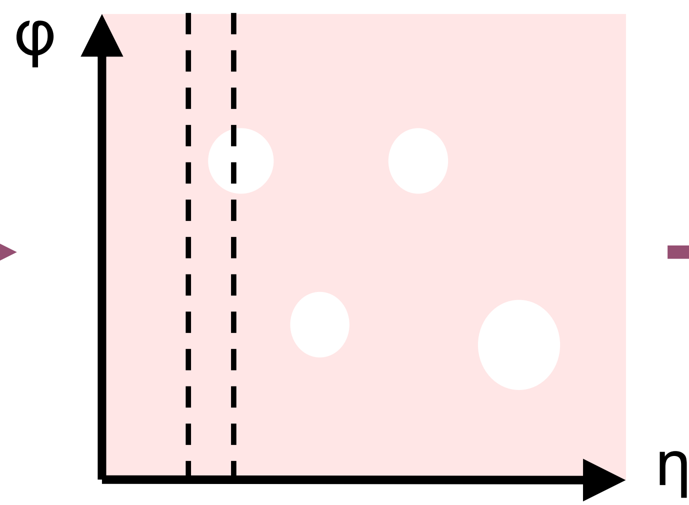
1. Background energy per tower calculated in strips of η. Pedestal subtraction



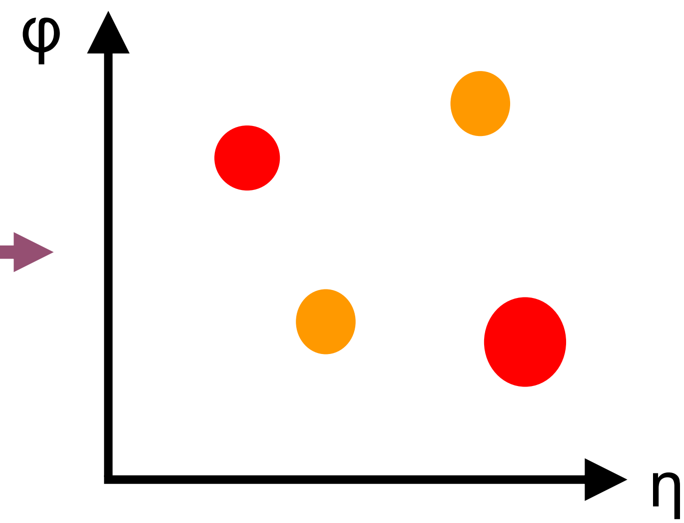
2. Run anti k_T algorithm on background subtracted towers



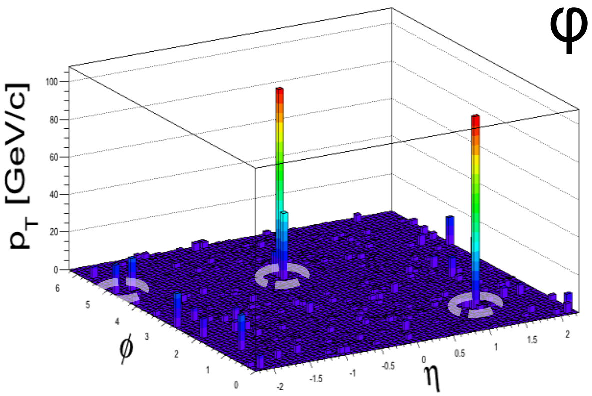
Background level

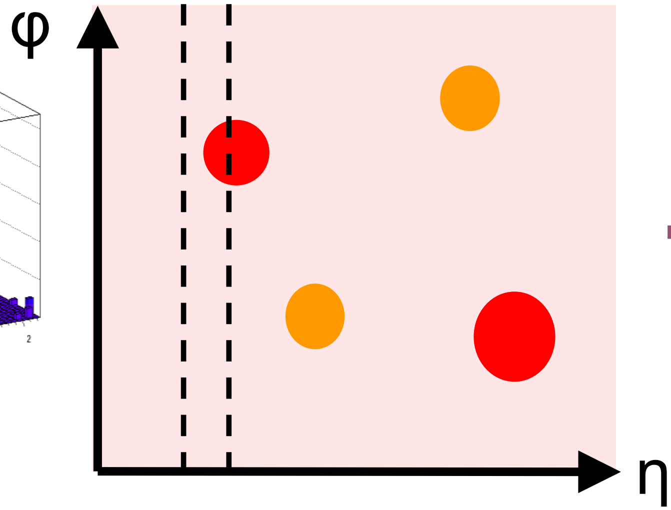


3. Exclude reconstructed jets > p_T^{cut}
Recalculate the background energy

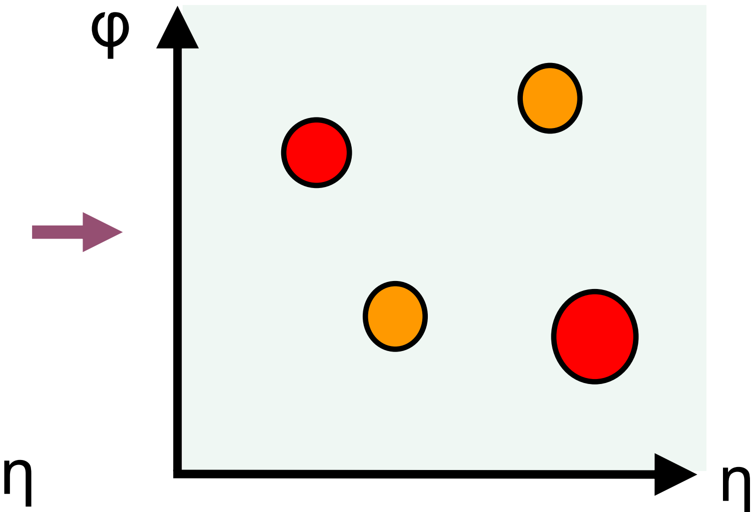


Iterative Background Subtraction

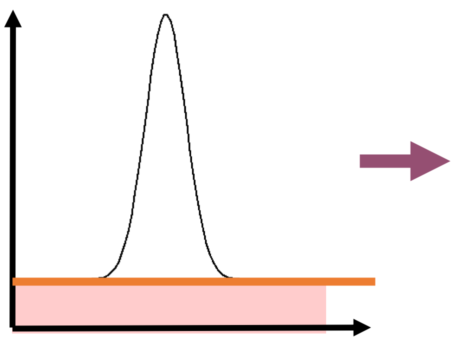




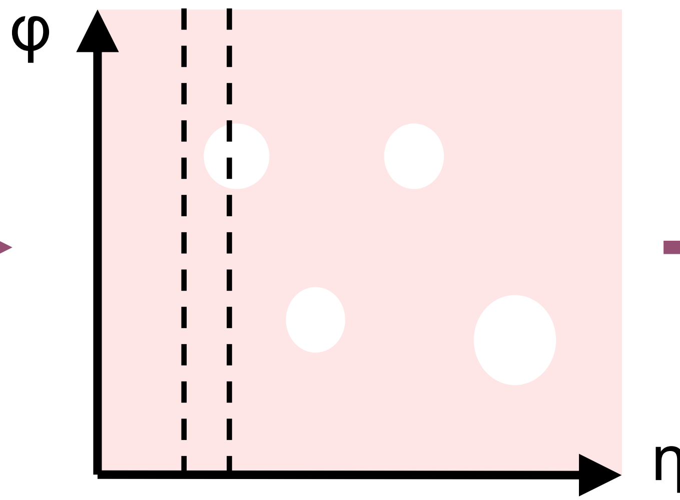
1. Background energy per tower calculated in strips of η. Pedestal subtraction



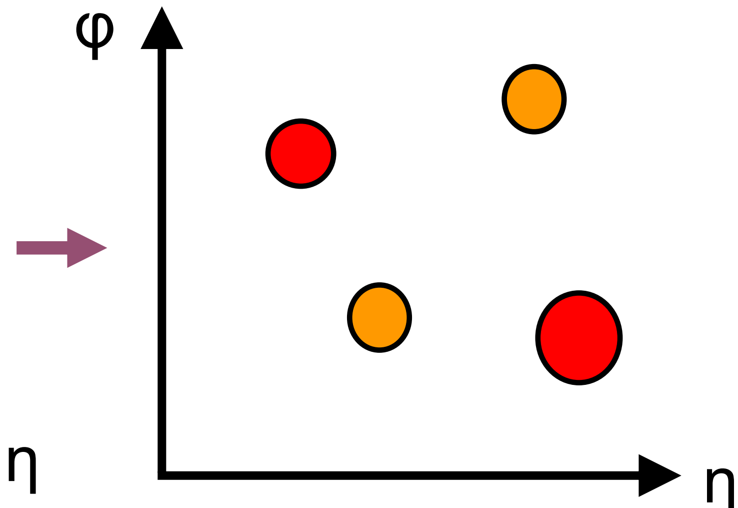
2. Run anti k_T algorithm on background subtracted towers



Background level



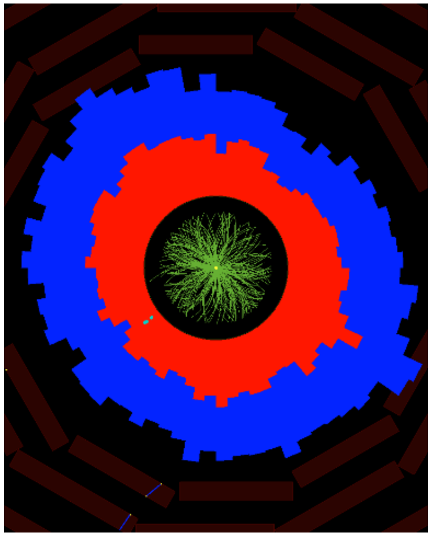
3. Exclude reconstructed jets > p_T^{cut}
Recalculate the background energy



4. Run anti k_T algorithm on background subtracted towers to get final jets

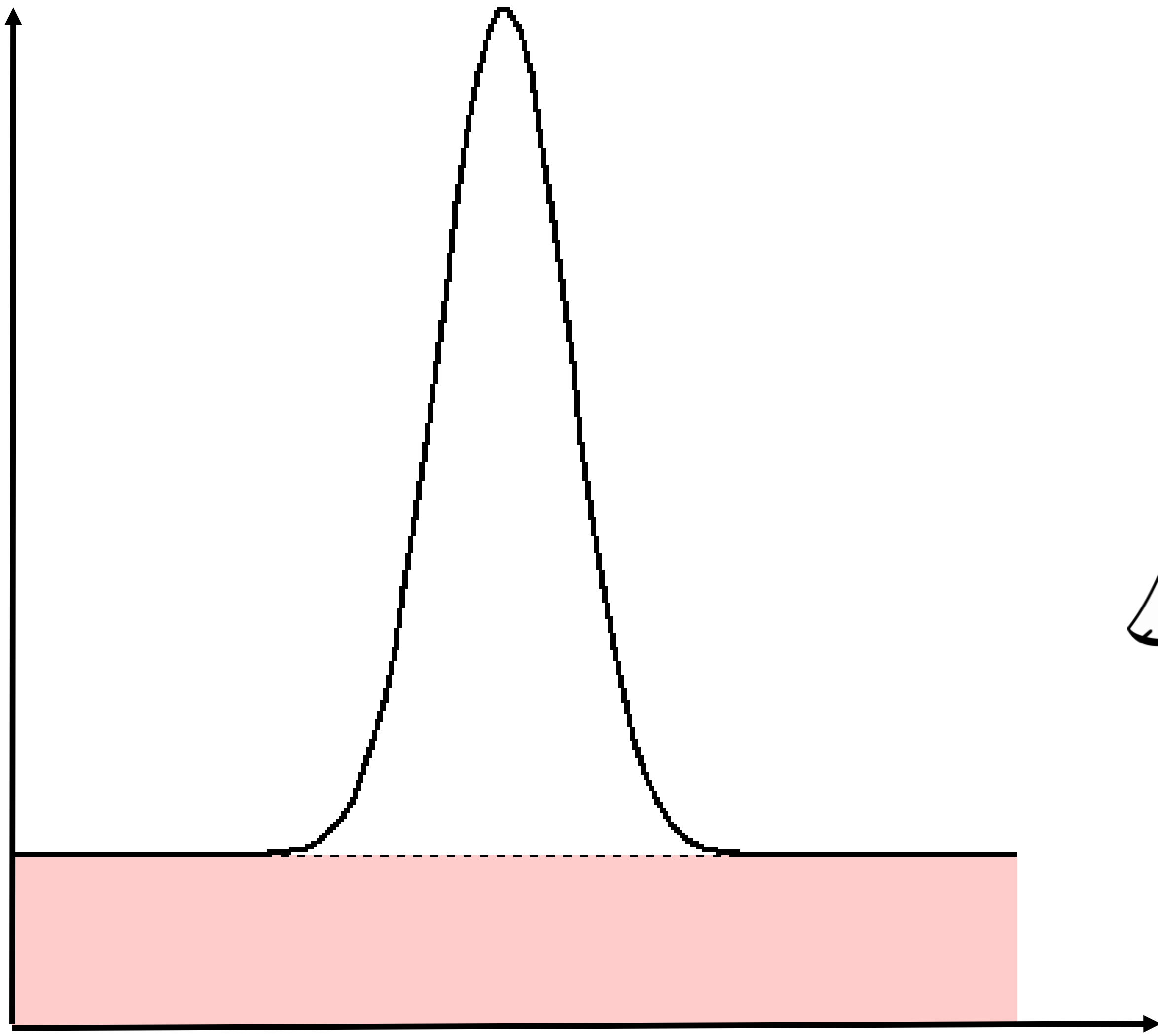
Iterative Background Subtraction

- A lot of CMS publications are performed with the iterative background subtraction algorithm
  - PRO:
    - Good jet resolution due to noise suppression
    - Stable performance, easy to commission
  - CON:
    - Bias at the low jet transverse momentum near the jet exclusion threshold p_T^{cut}
    - Did not correct for the flow modulation of the heavy ion underlying event
    - Noise suppression and pseudotower could distort the tail part of the jet substructure and reduce the jet substructure resolution



Particle level subtraction with flow modulation

Constituent Subtraction

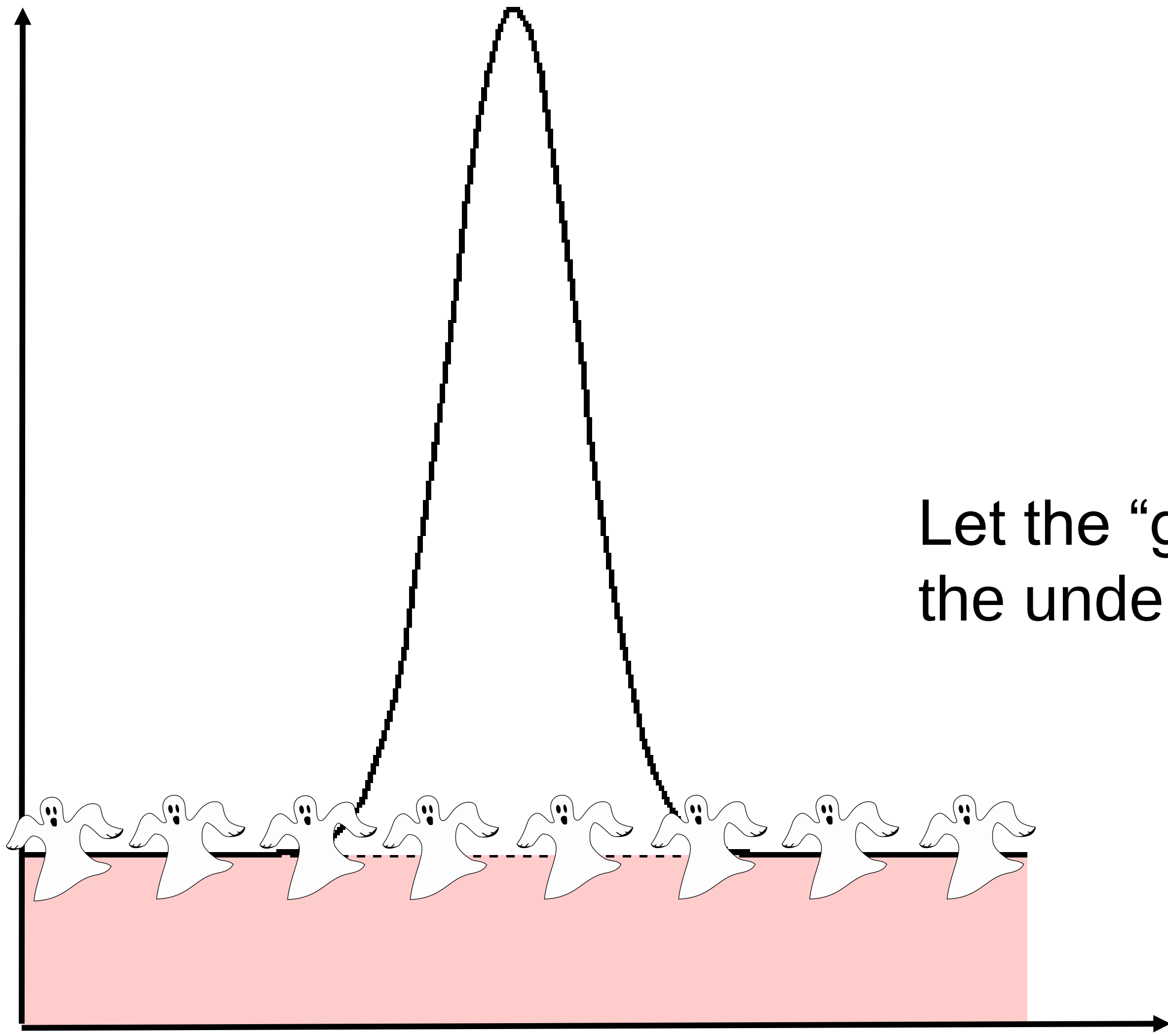


JHEP06 (2014) 092

Constituent subtraction

Constituent Subtraction

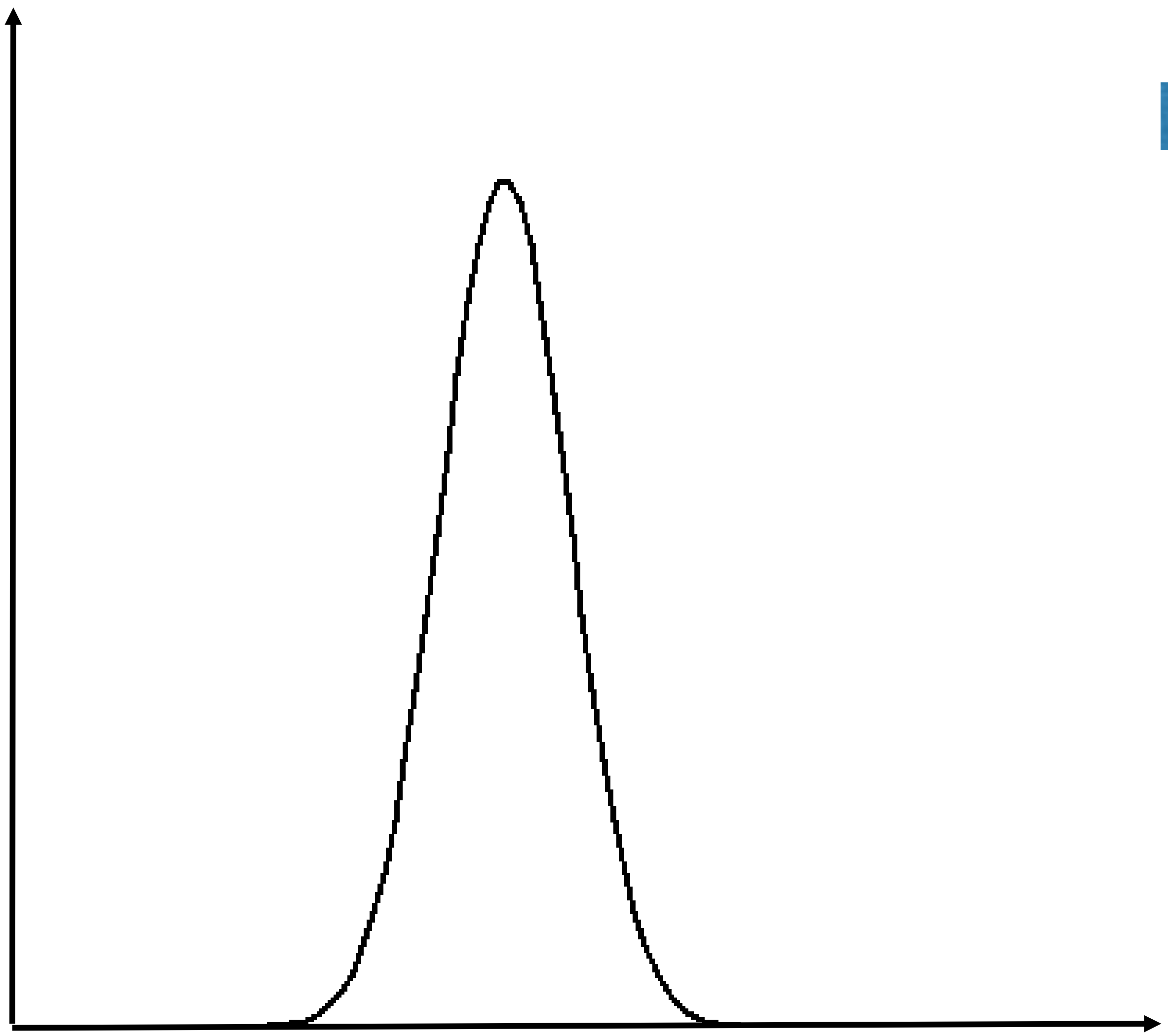
JHEP06 (2014) 092



Let the "ghost" remove the underlying event

Constituent subtraction

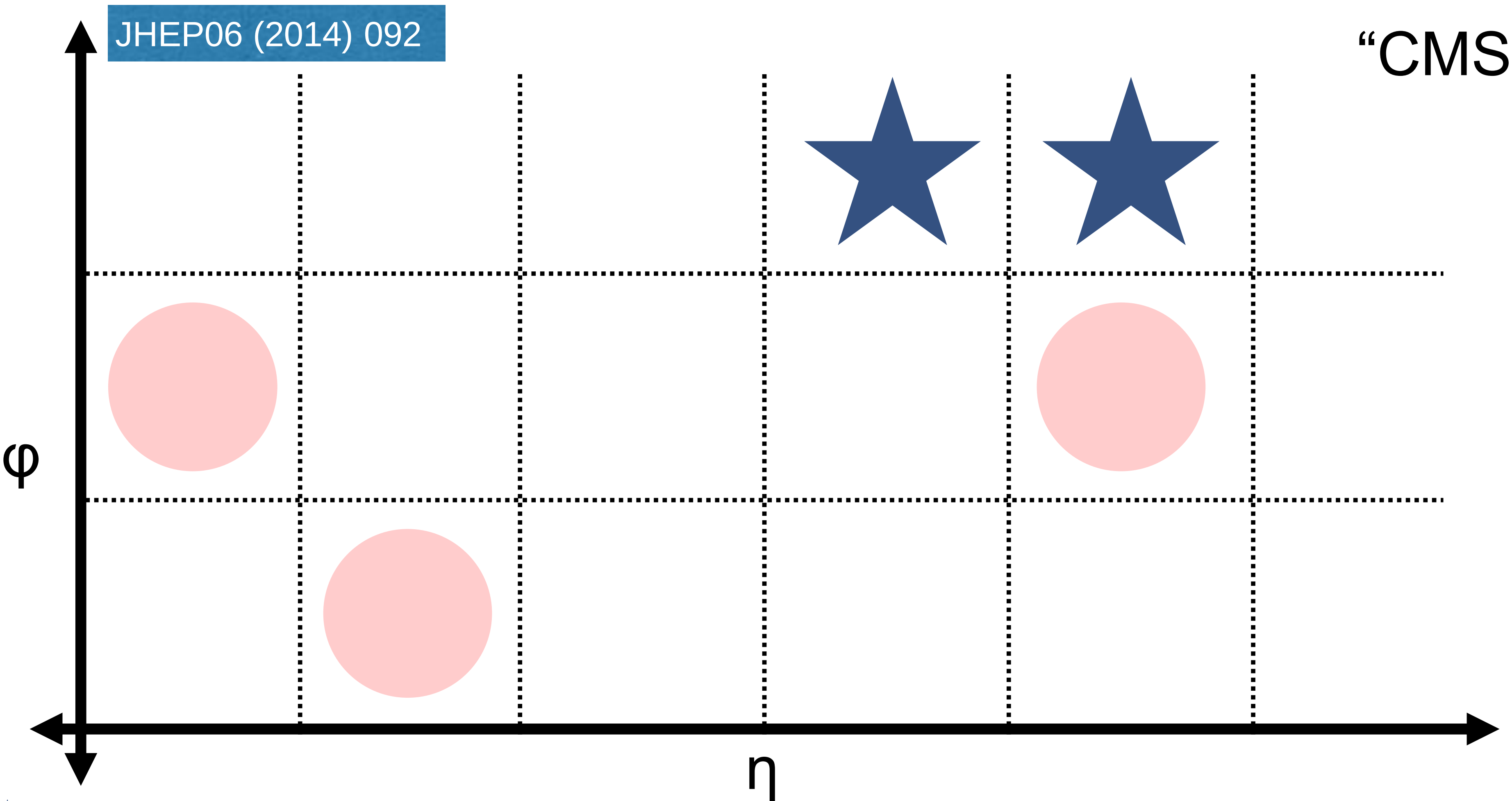
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction

Constituent Subtraction

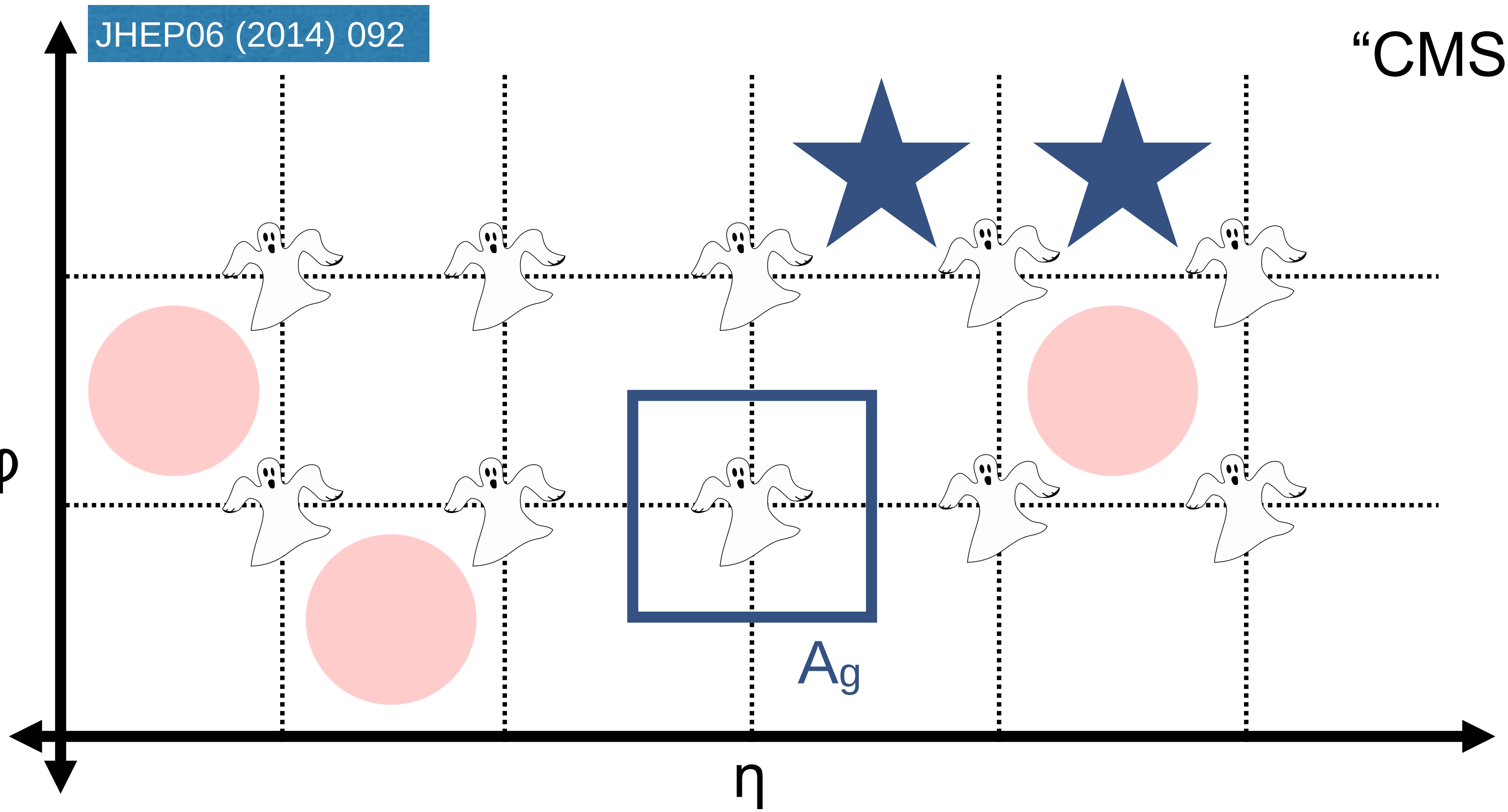


SIGNAL: Hard-scattering in PbPb collision producing jets

UNDERLYING EVENT: Uncorrelated particles from other parton-parton interactions

From Chris McGinn (MIT)

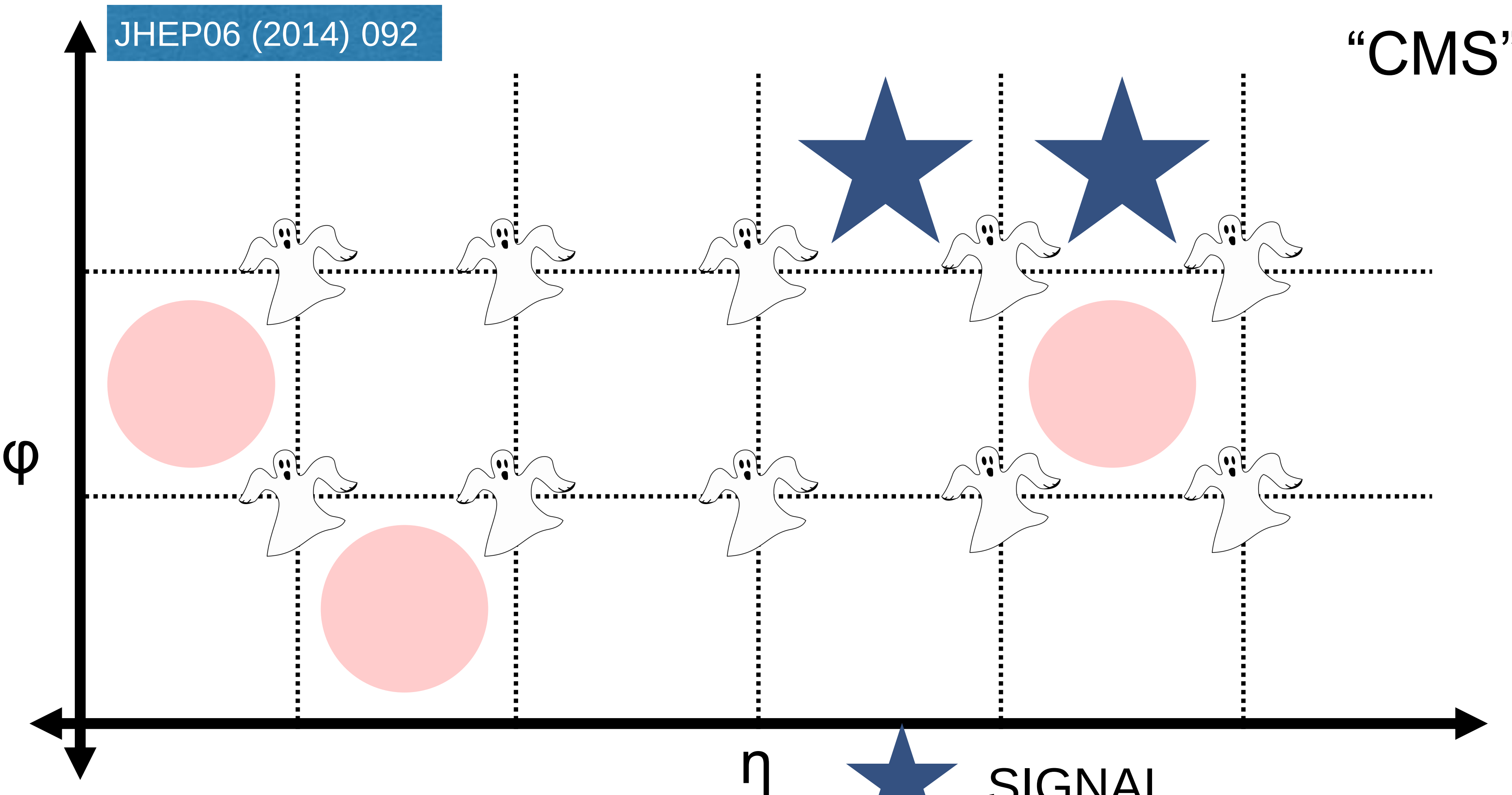
Constituent Subtraction

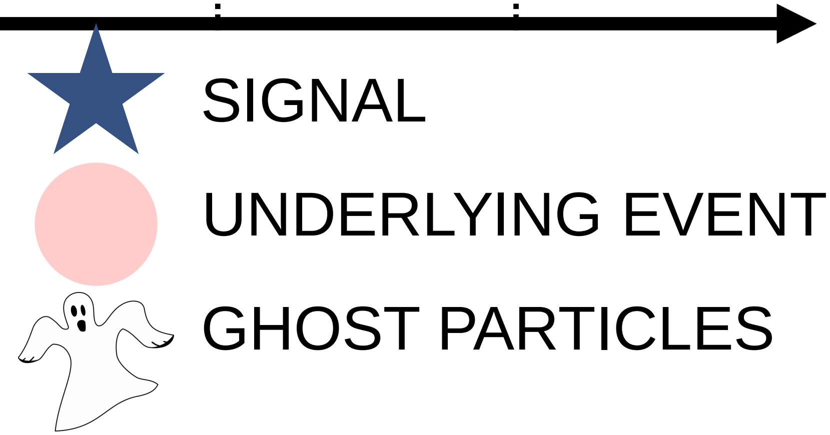


GHOST PARTICLES: Artificial particles added to the event on an η-φ grid. Ghosts are given a p_T according to ρ times the area the inhabit, A_g

From Chris McGinn (MIT)

Constituent Subtraction



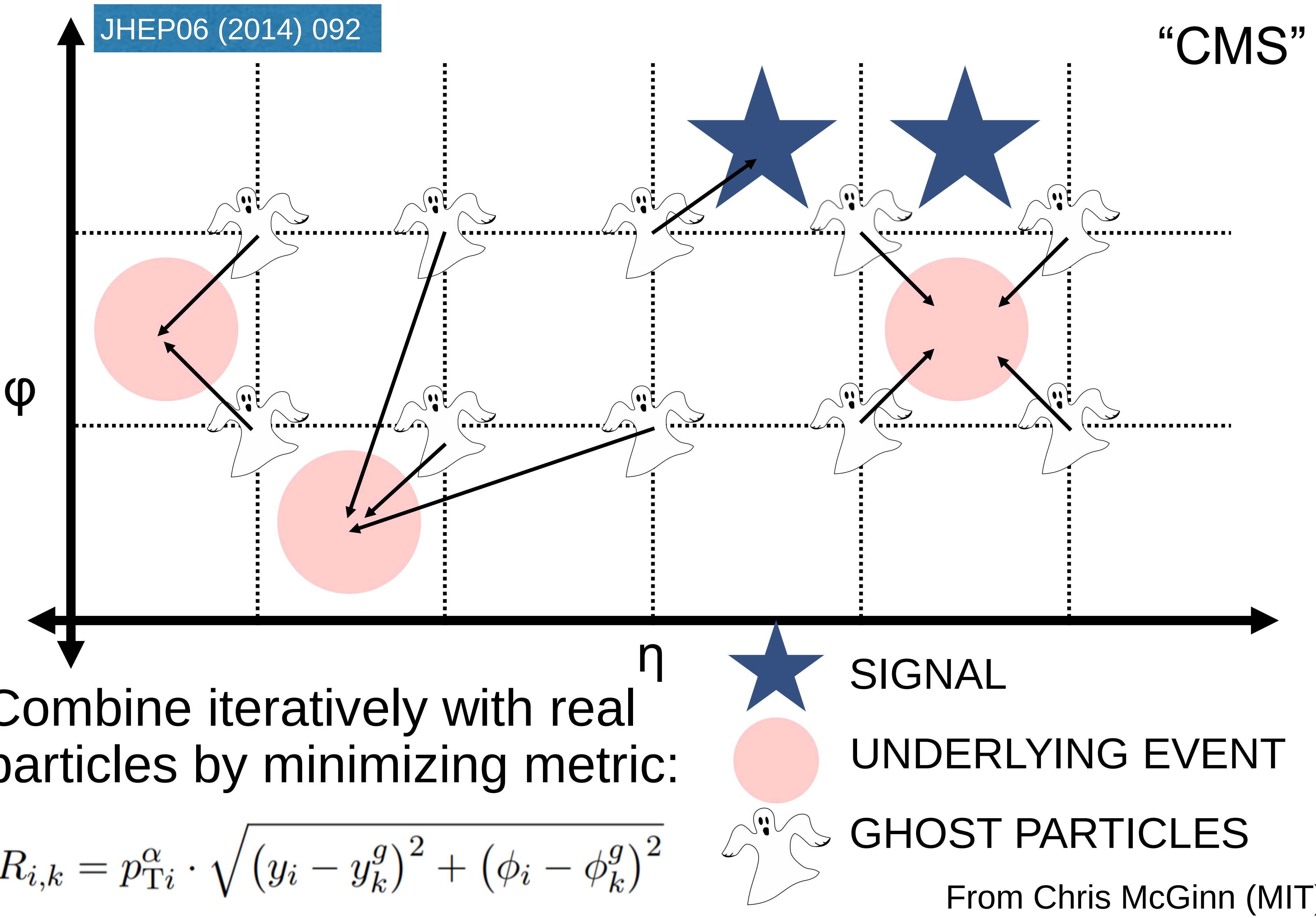


- Add "ghost" particles on η-φ grid according to:

$$p_{\mathrm{T}}^{g} = A_g \cdot \rho,$$

$$m_{\delta}^{g} = A_g \cdot \rho_m$$

Constituent Subtraction

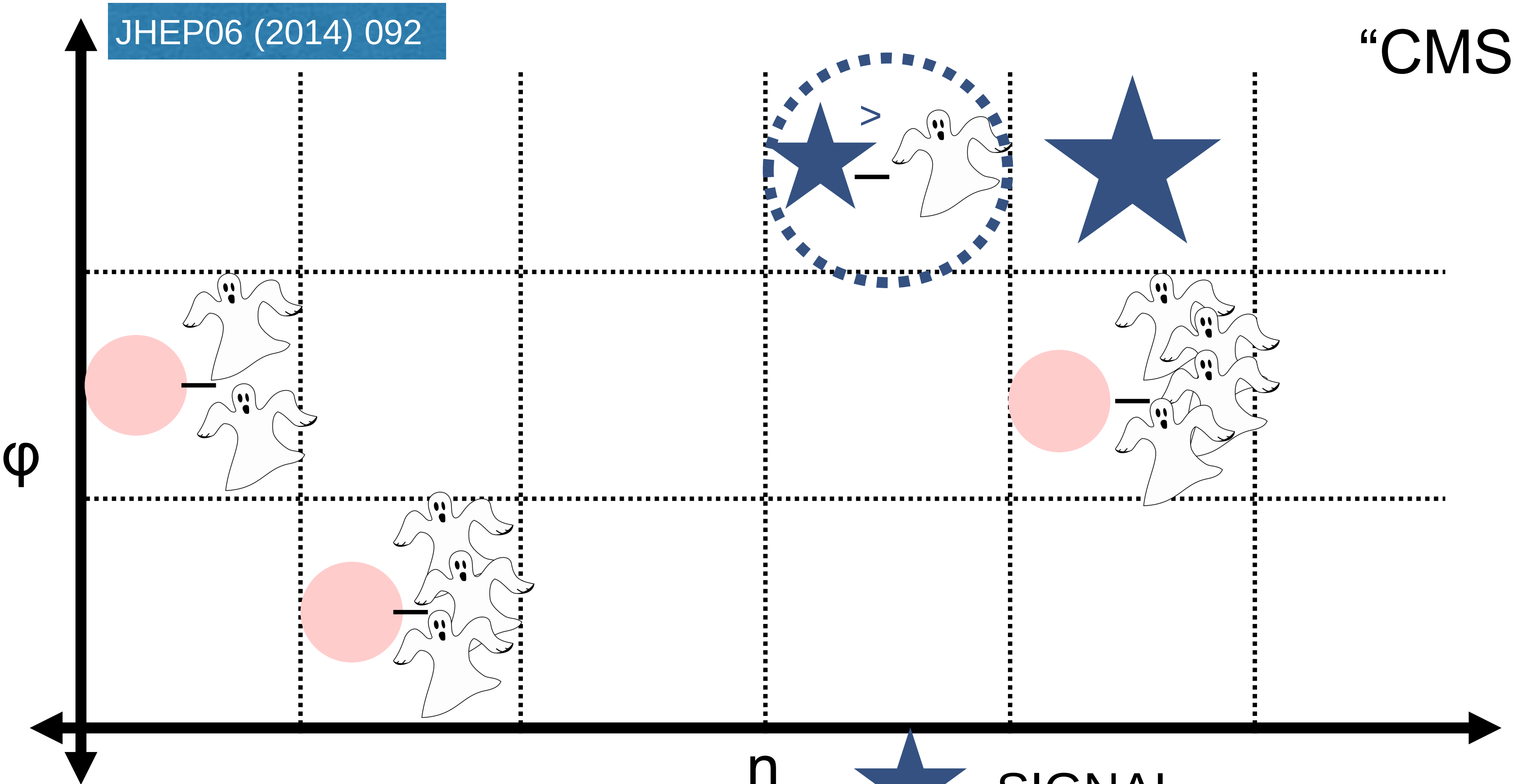


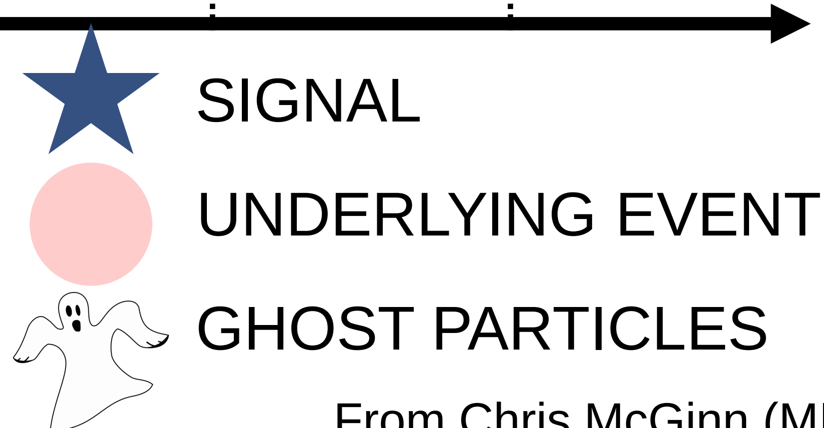
- Combine iteratively with real particles by minimizing metric:

$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{\left(y_i - y_k^g\right)^2 + \left(\phi_i - \phi_k^g\right)^2}$$

From Chris McGinn (MIT)

Constituent Subtraction

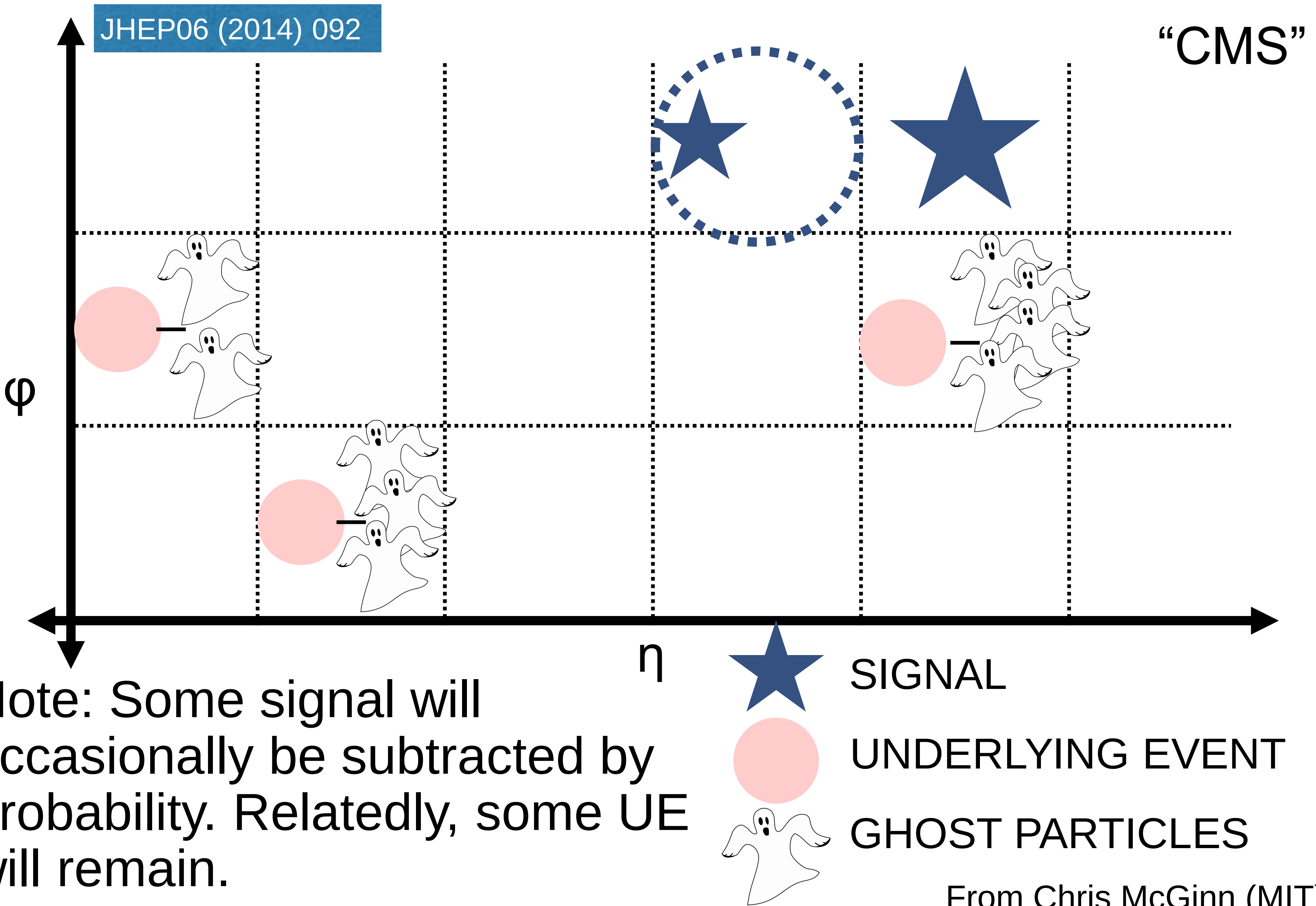




- Particle p_T **>** Ghost p_T
  - Ghost $p_T = 0$
  - Particle p_T -= Ghost p_T

From Chris McGinn (MIT)

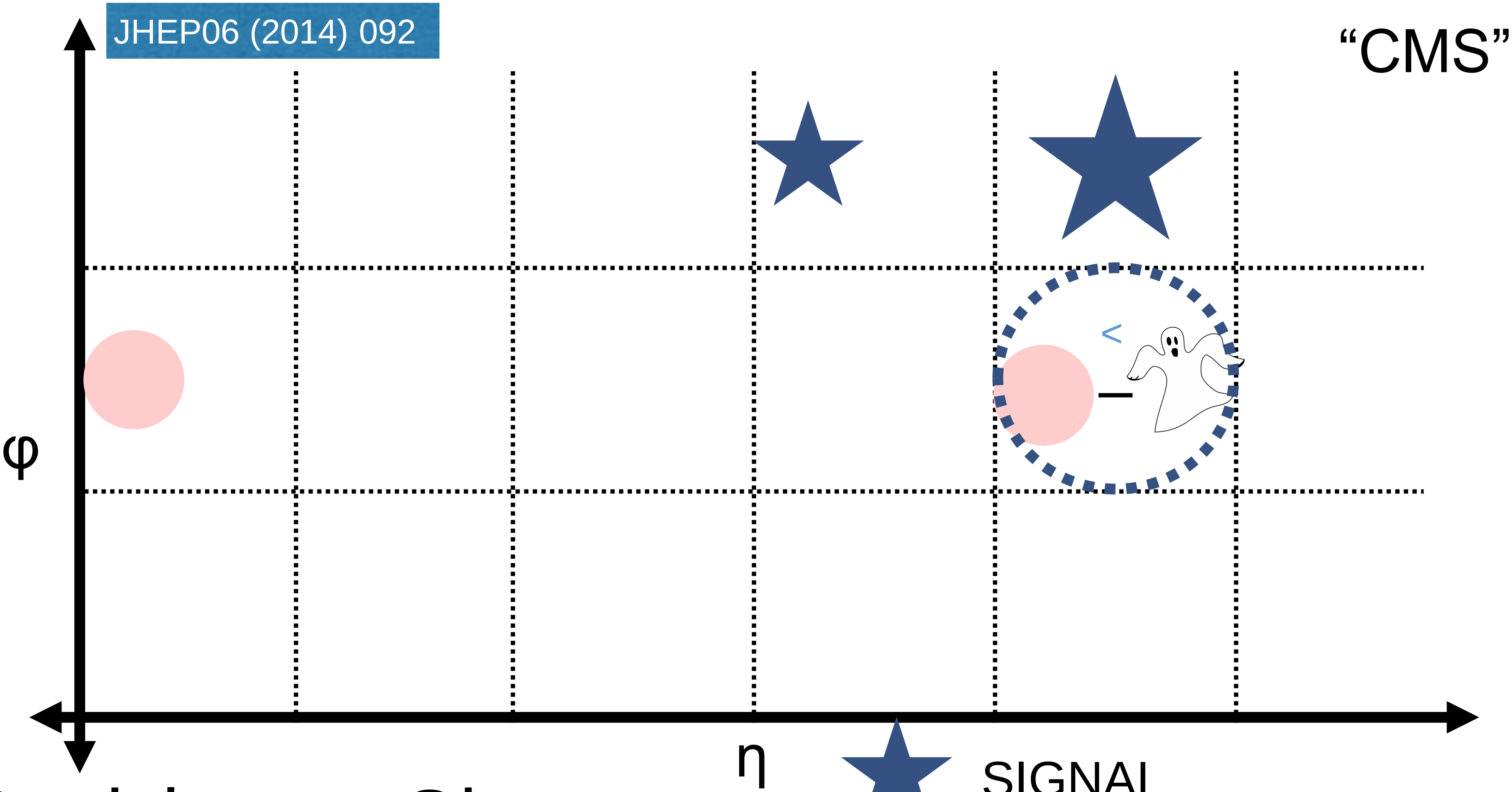
Constituent Subtraction



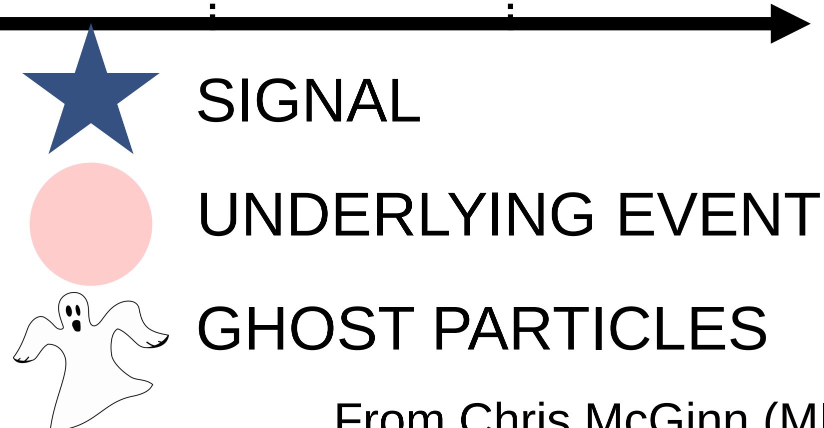
- Note: Some signal will occasionally be subtracted by probability. Relatedly, some UE will remain.

From Chris McGinn (MIT)

Constituent Subtraction

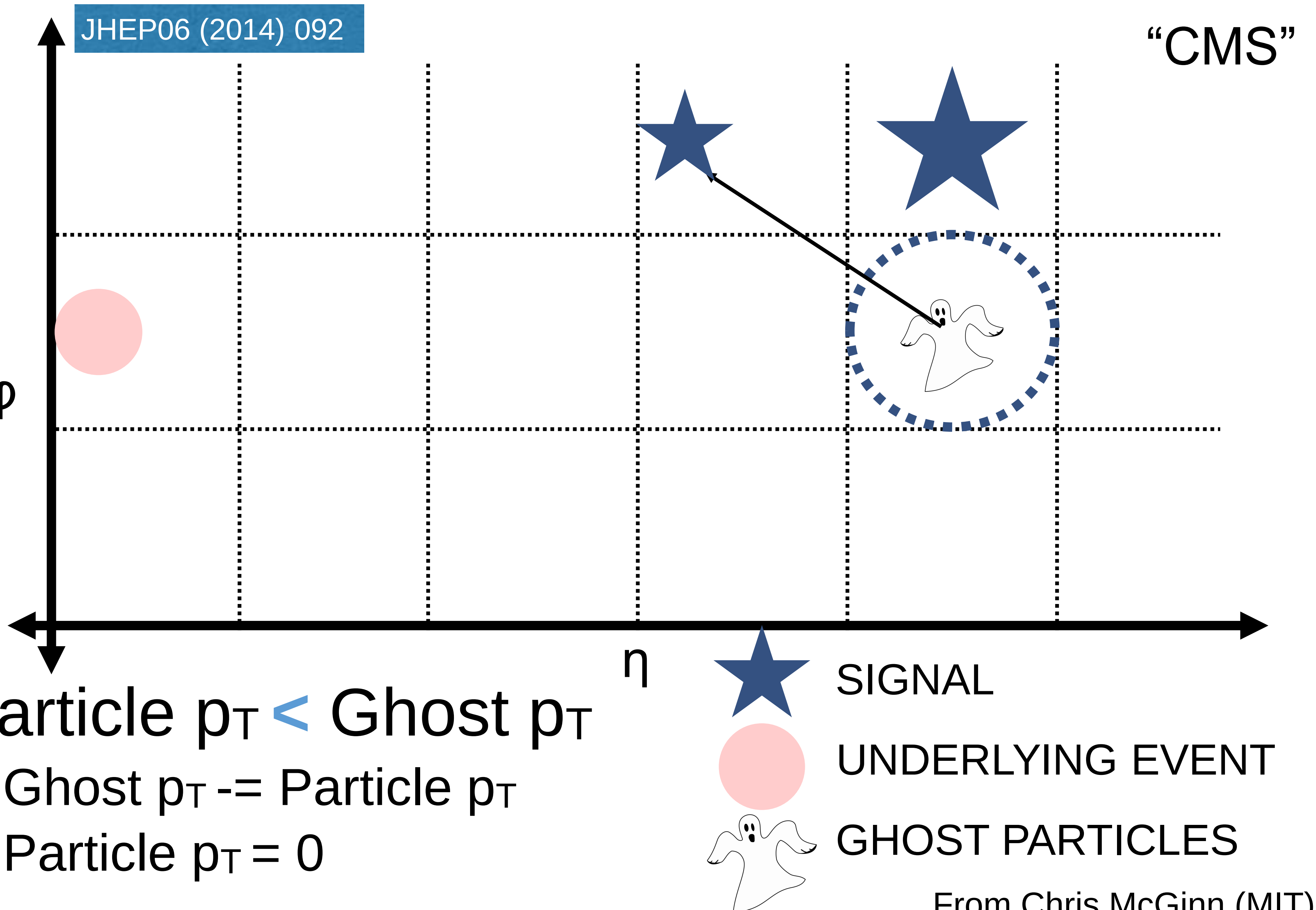


- Particle p_T < Ghost p_T
  - Ghost p_T -= Particle p_T
  - Particle $p_T = 0$



From Chris McGinn (MIT)

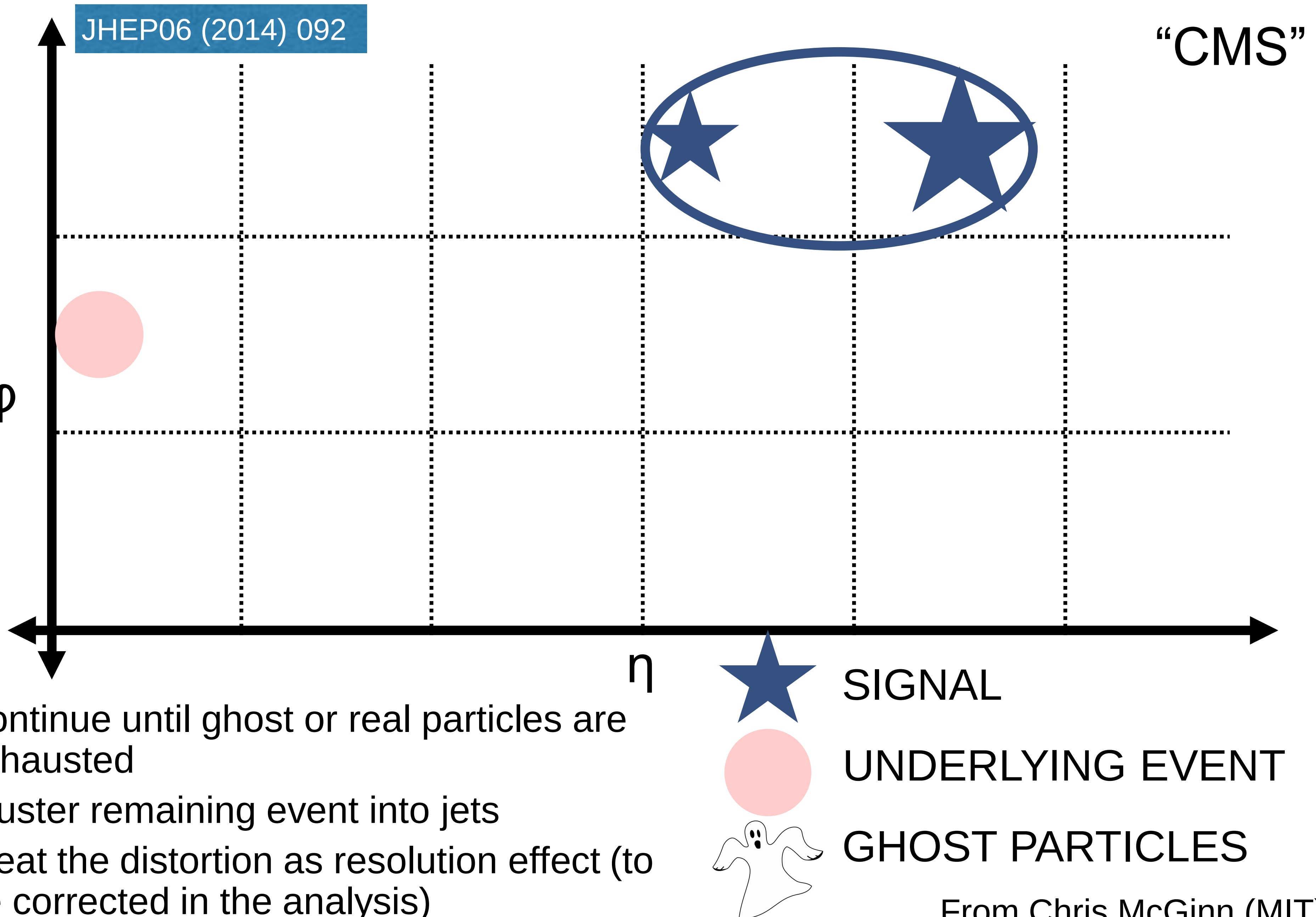
Constituent Subtraction



- Particle p_T < Ghost p_T
  - Ghost p_T -= Particle p_T
  - Particle $p_T = 0$

From Chris McGinn (MIT)

Constituent Subtraction



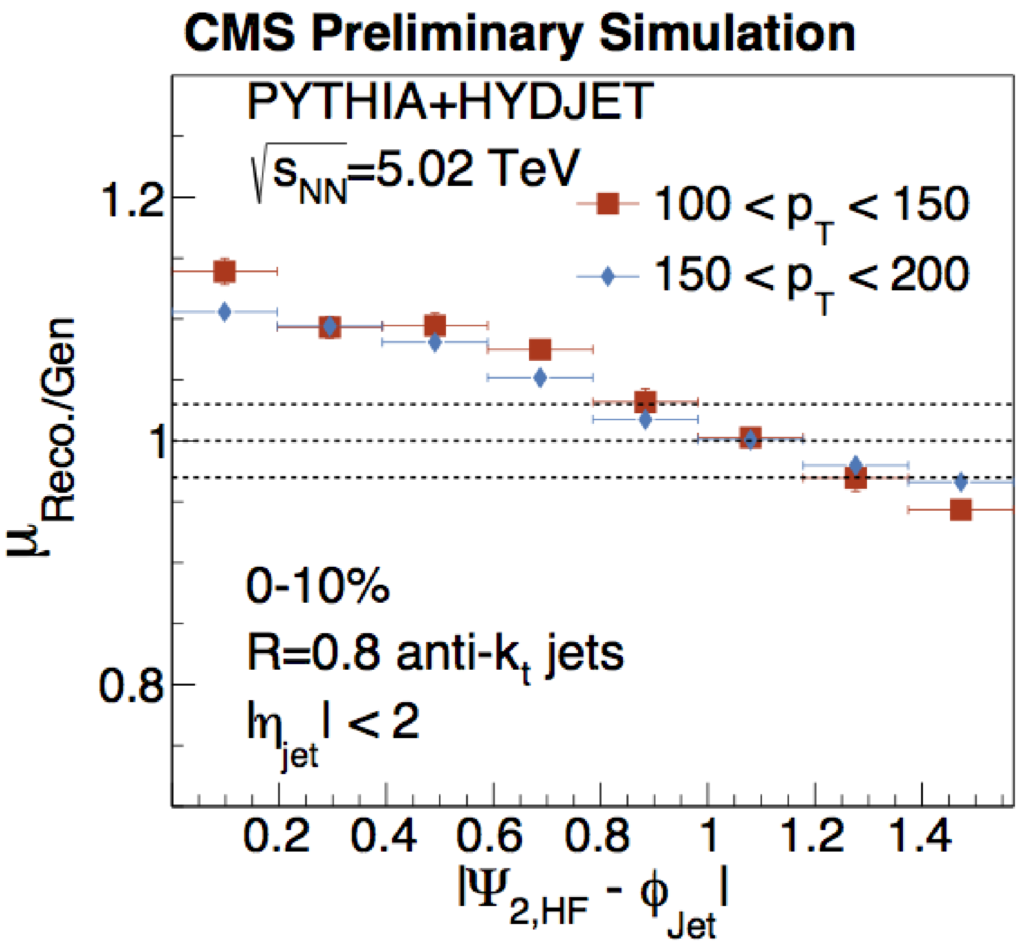
- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets
- Treat the distortion as resolution effect (to be corrected in the analysis)

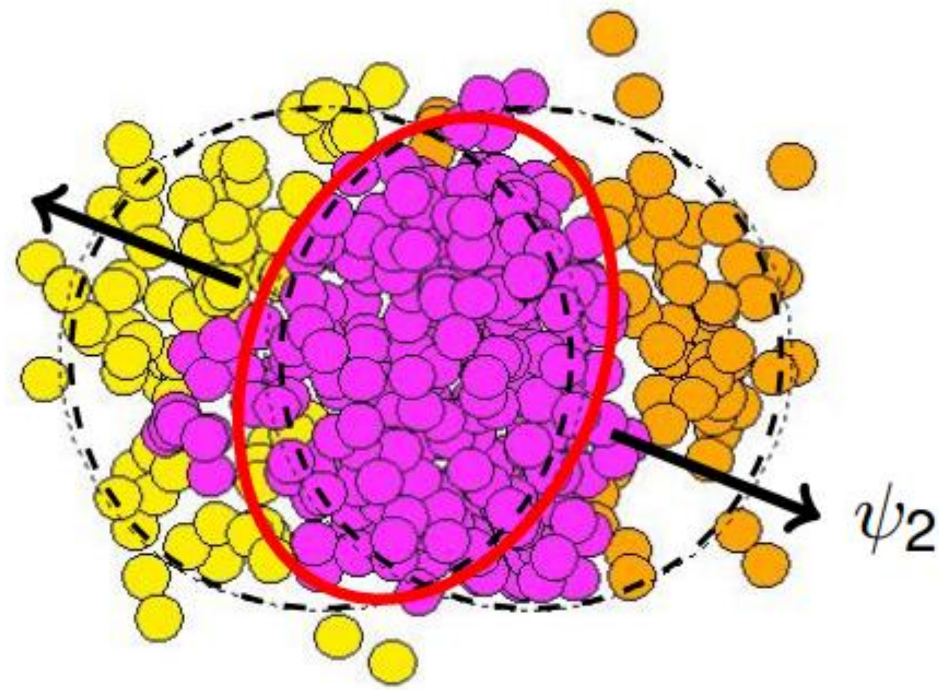
From Chris McGinn (MIT)

Dependence on the Azimuthal Angle

"Jet response" vs. azimuthal angle

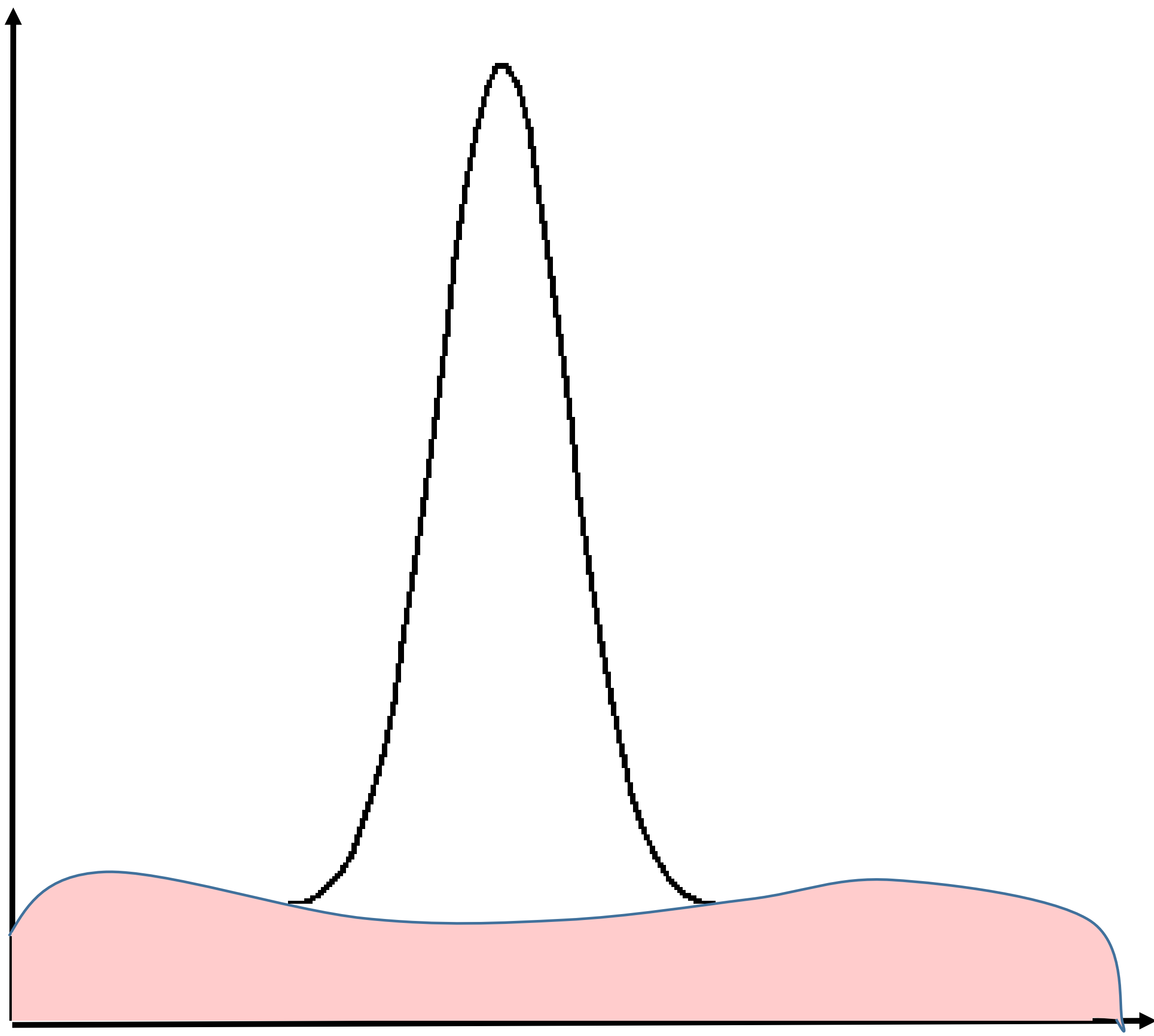
μ=1: perfectly subtracted





Large dependence on the azimuthal angle with respect to the event plane

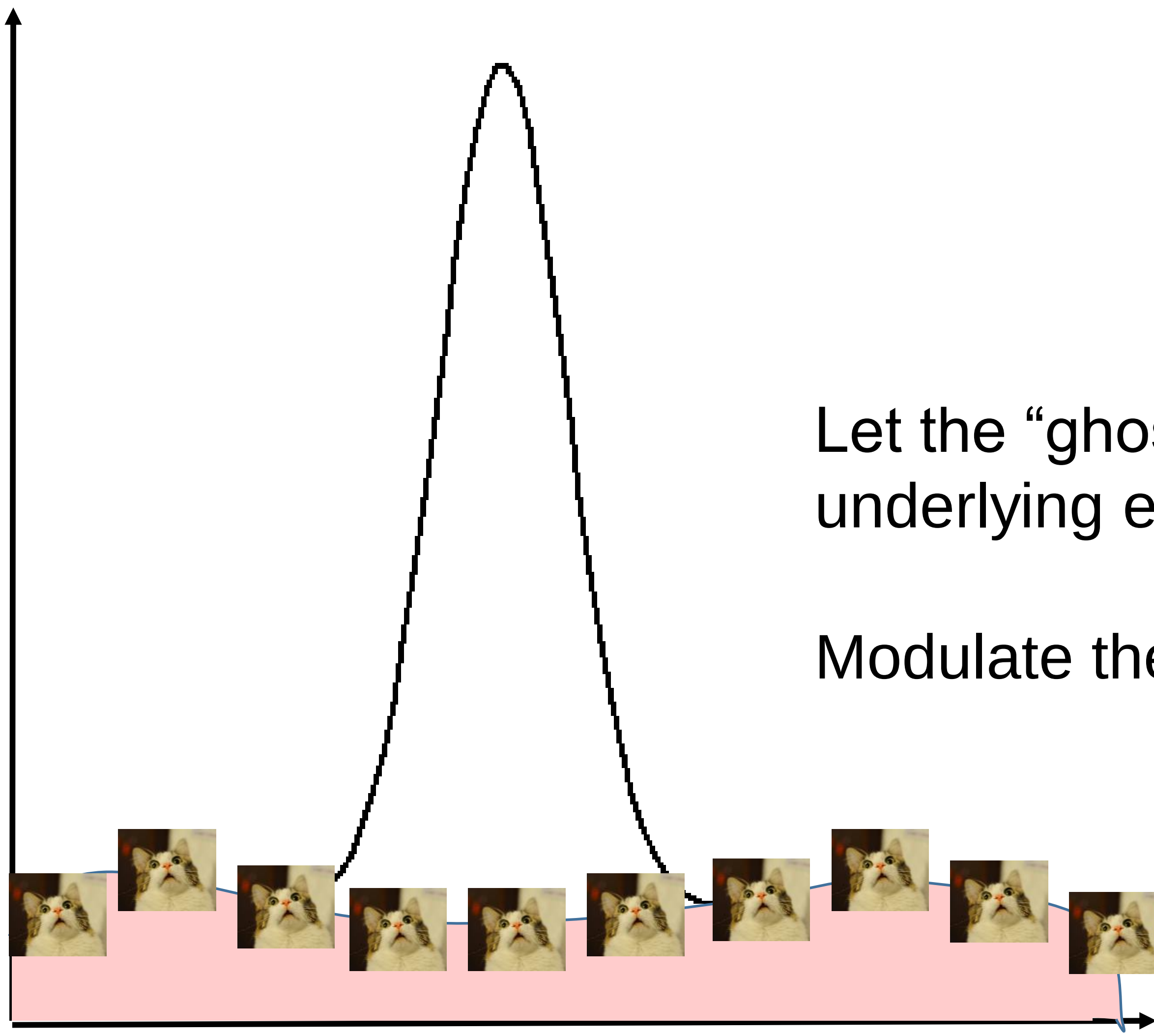
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction **with flow modulation**

Constituent Subtraction



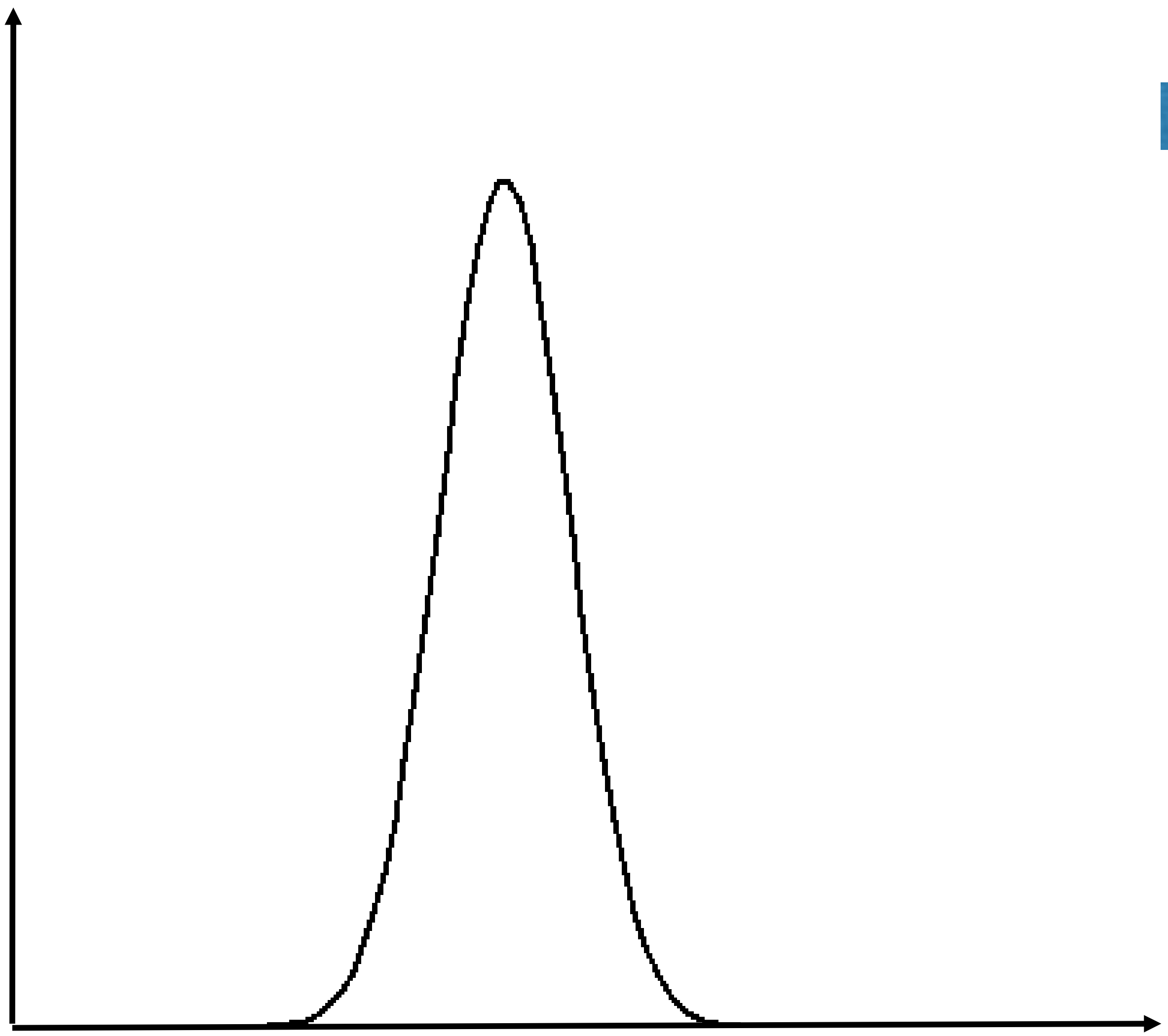
JHEP06 (2014) 092

Let the “ghost” remove the underlying event

Modulate the number of ghost!

Constituent subtraction **with flow modulation**

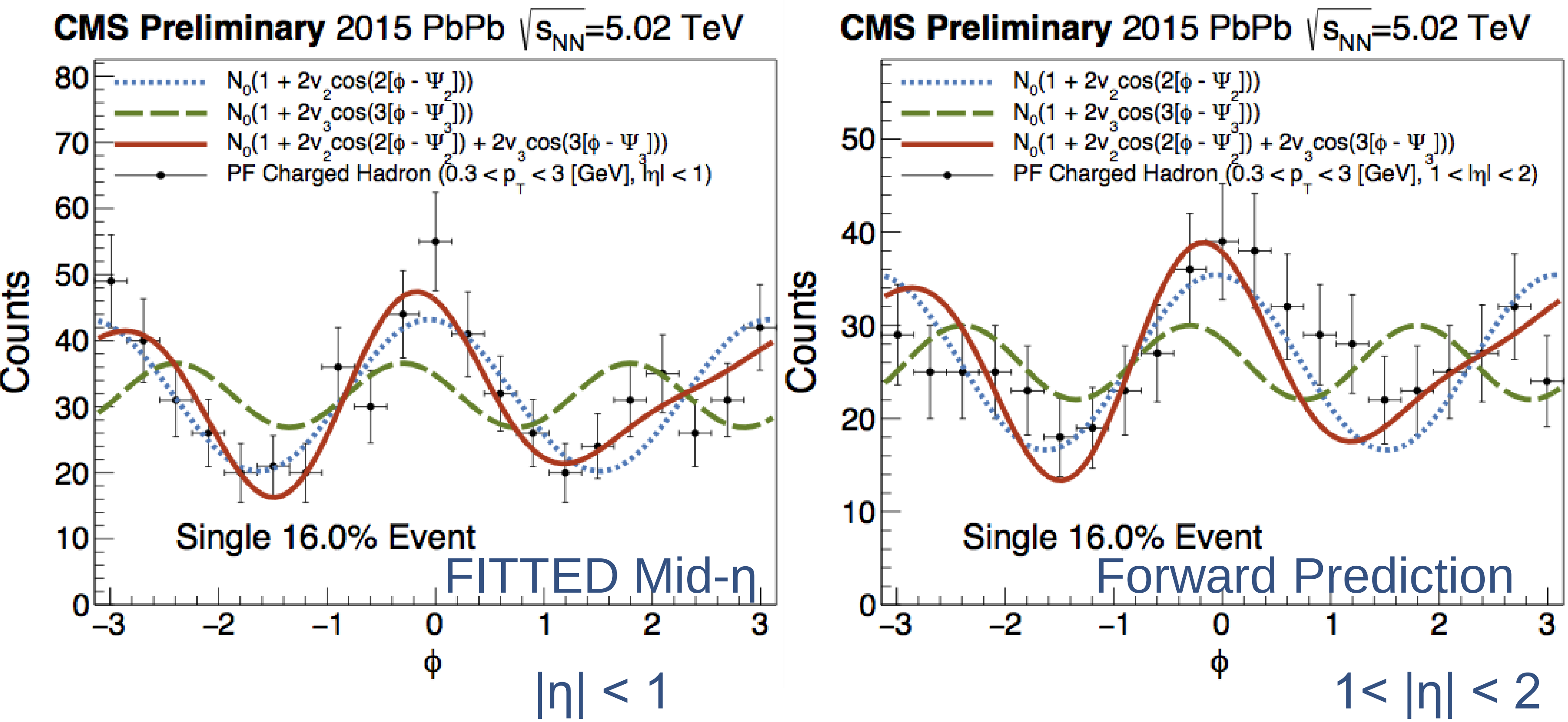
Constituent Subtraction



JHEP06 (2014) 092

Constituent subtraction **with flow modulation**

Estimating Flow Event-by-Event



Following Example Of:

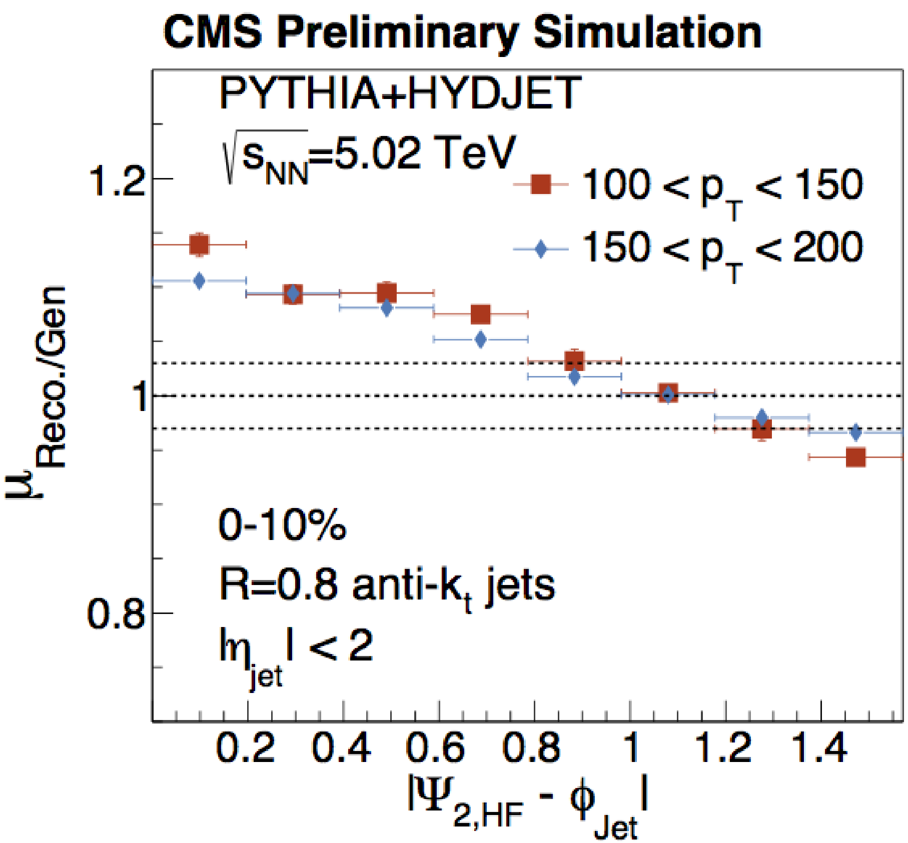
Phys.Lett. B 753 (2016) 511-525

- Extract an event-by-event v_2 and v_3 by fitting particle flow candidates
  - Charged Hadron candidates, $0.3 < p_T < 3$ and $|\eta| < 1$
  - Fit is employed over all η to model flow
- Extracted $v_2(v_3)$ are used to modulate CS ρ to add ghost particles

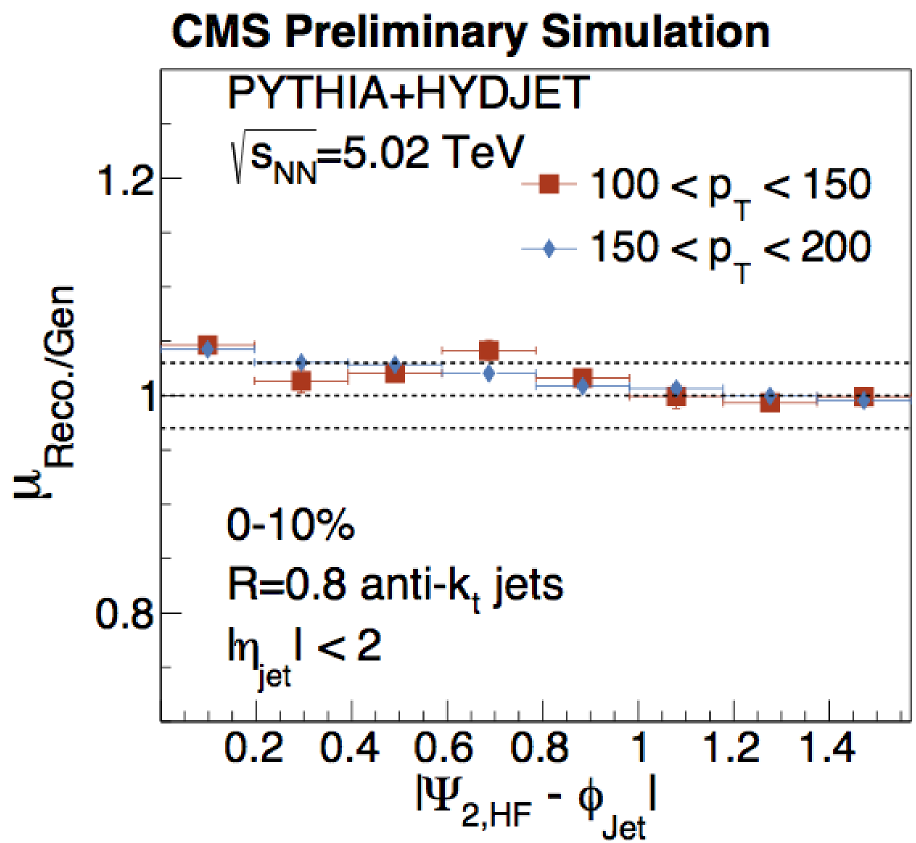
From Chris McGinn (MIT)

Fig. From: CMS-DP-2018

Scale Closure vs. Event Plane (R=0.8)



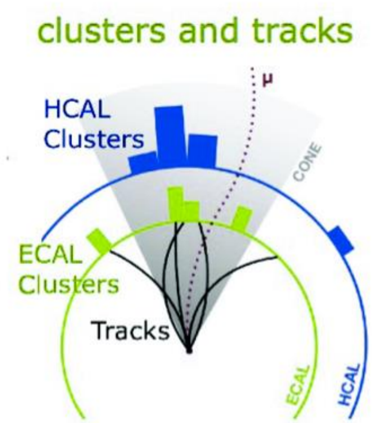
Add
Flow
Correction

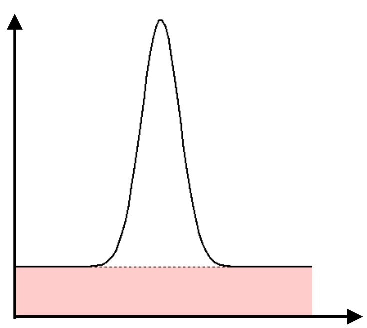


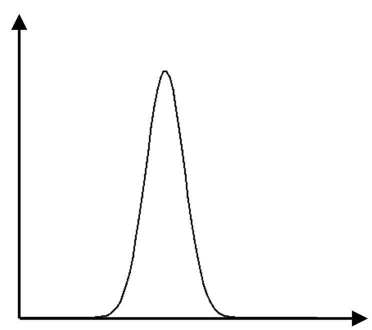
- Jet energy scale closure as function of event plane for R=0.8 w/o flow correction (**Left**) and with flow correction (**Right**)
- Significant flattening of scale translates directly to resolution reduction

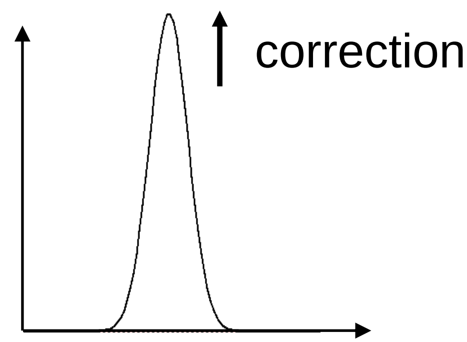
From Chris McGinn (MIT)

Summary of jet reconstruction









Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation PYTHIA