

# Jets – principle vs practice

# Jet formation in a vacuum

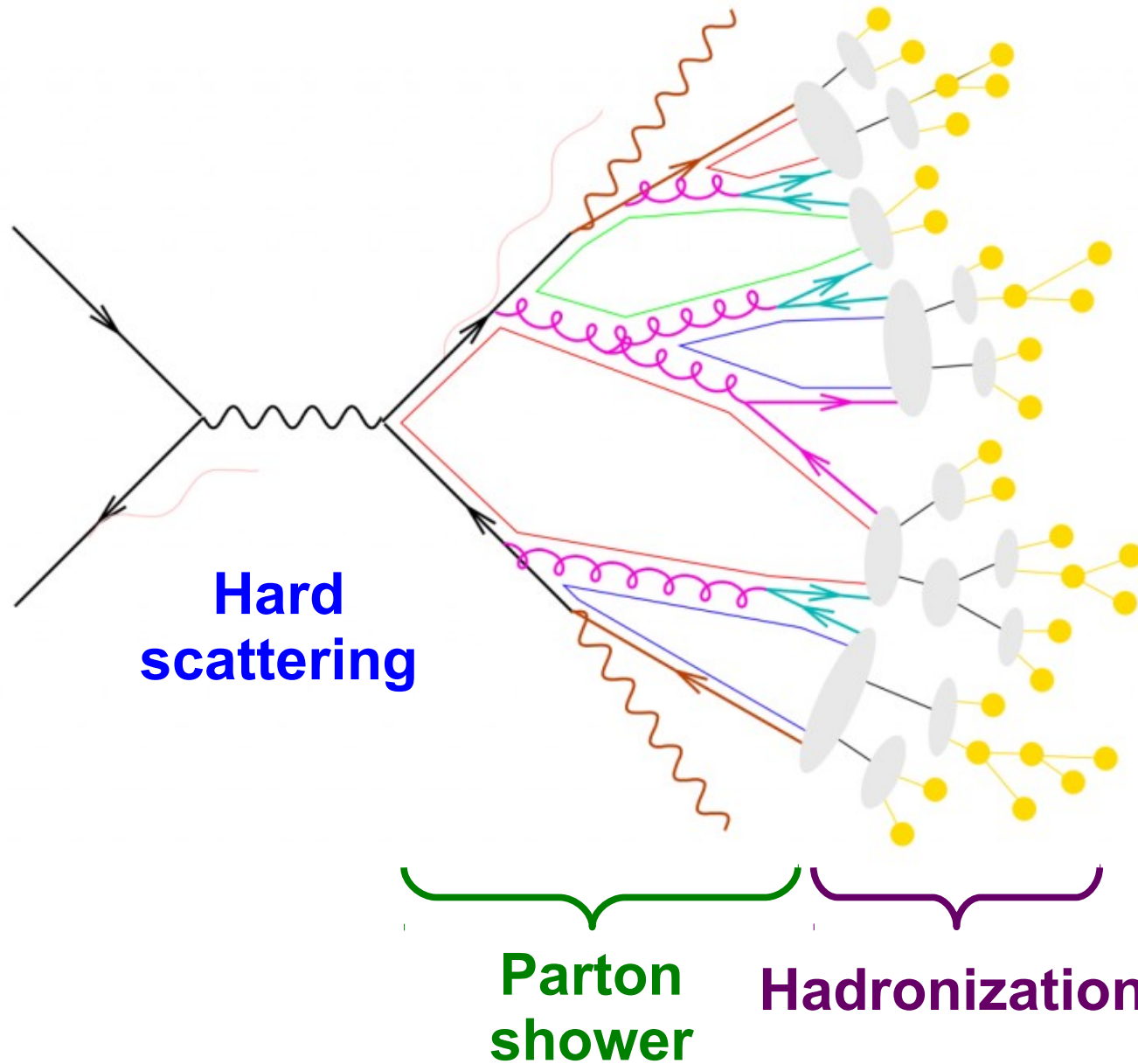


Image from <http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf>

# Jet formation in a vacuum

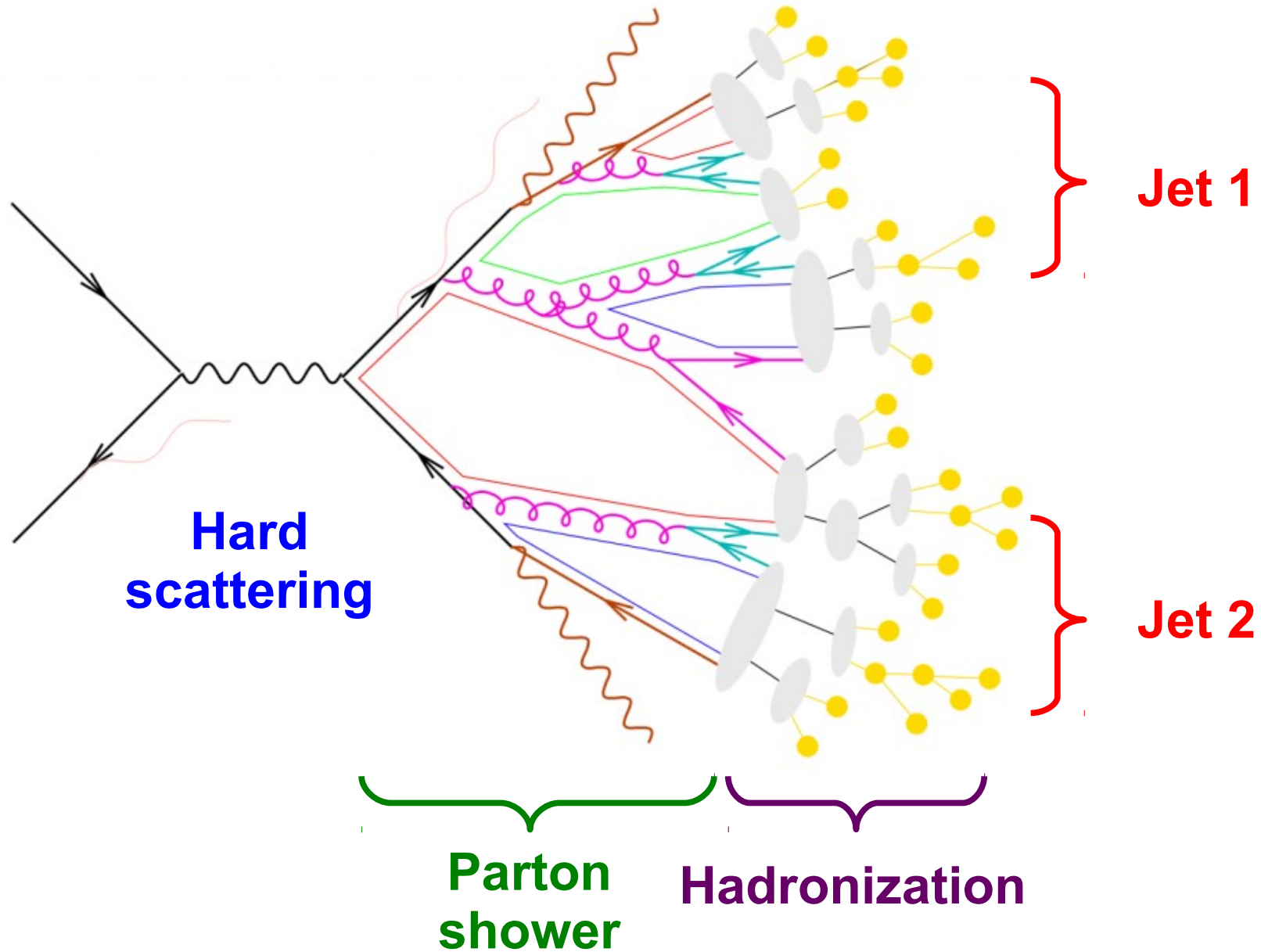


Image from <http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf>

# Jets in principle

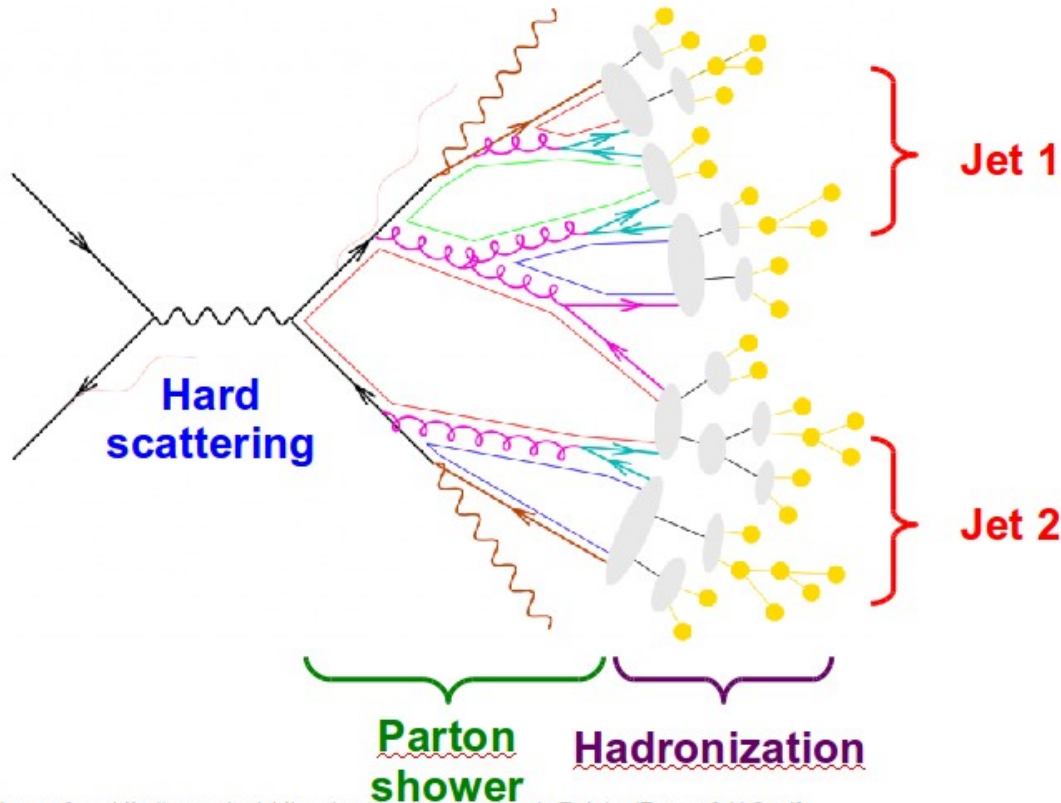
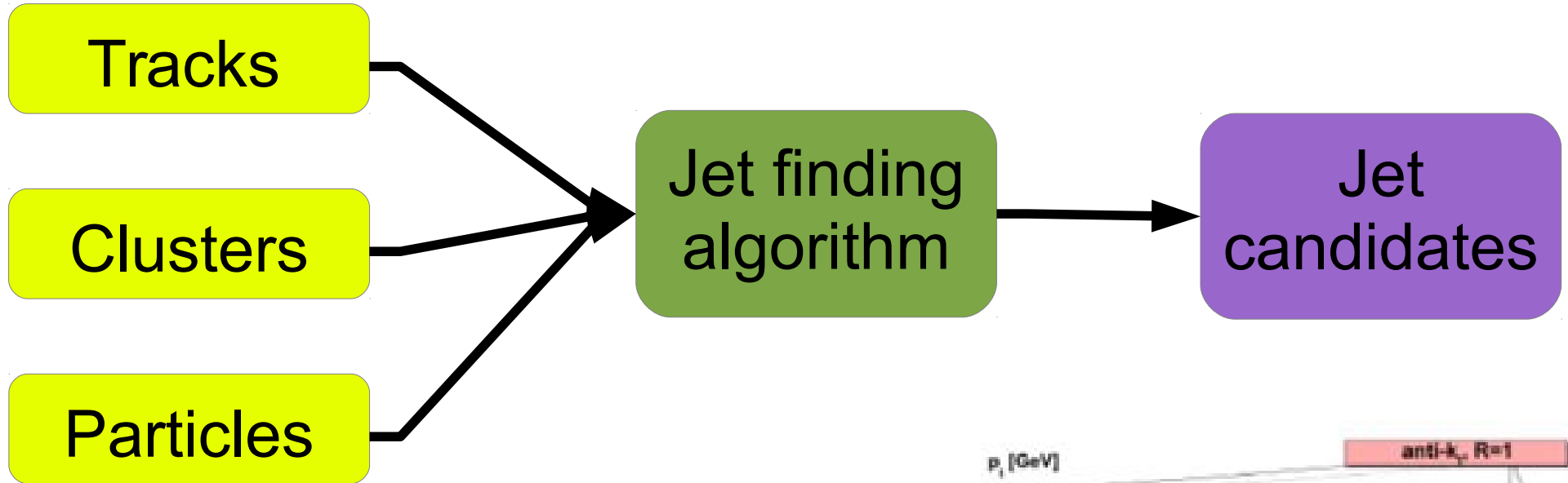


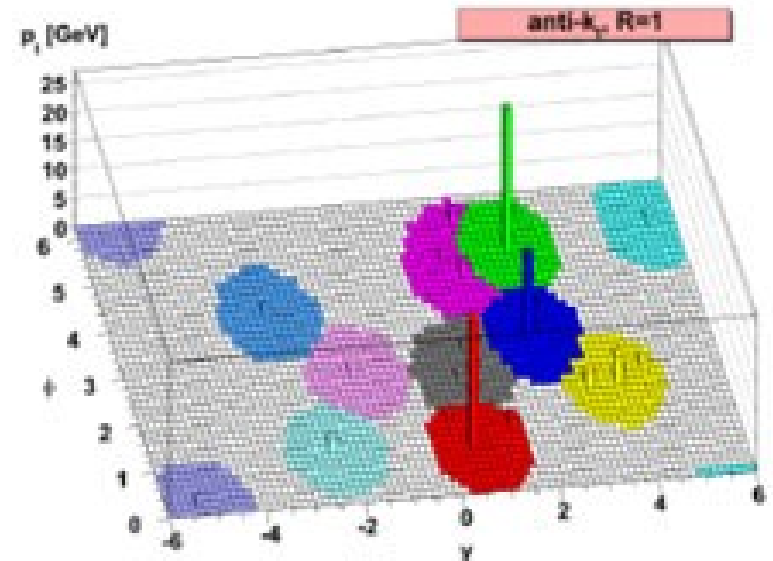
Image from <http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf>

- Jet measures partons
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and collinear safe

# Jet finding algorithms



- Any list of objects works as input
- Output only as good as input

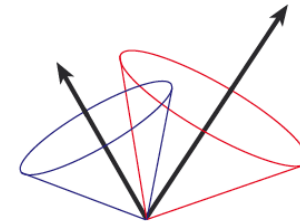


M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008

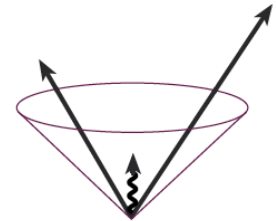
# Jet finding algorithms

- Required THEORETICAL features in a jet finding algorithm:

- *Infrared safety*: the algorithm should not be sensitive to soft radiation



OK

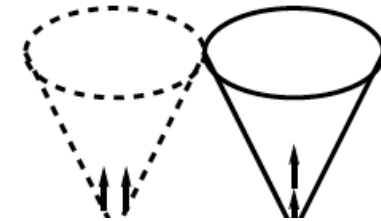


**BAD:** 2 jets are merged in one

- *Collinear safety*: the algorithm should be insensitive to any collinear radiation.

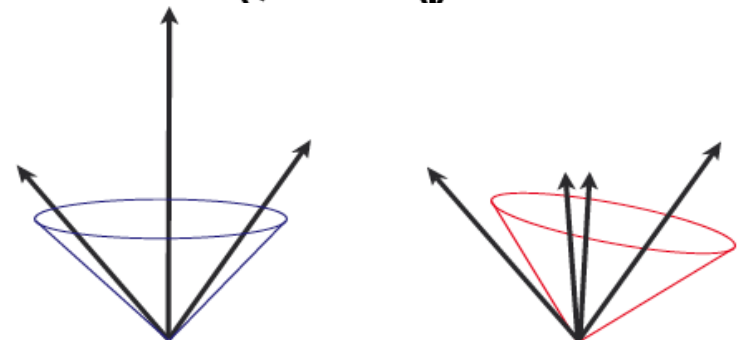
- Example A: if the energy is split among soft particles, and each tower is under a threshold, the jet is lost

- Example B: if the energy of a parton is split in two towers, and the algorithm starts with the particles with highest  $E$ , a different jet may be found



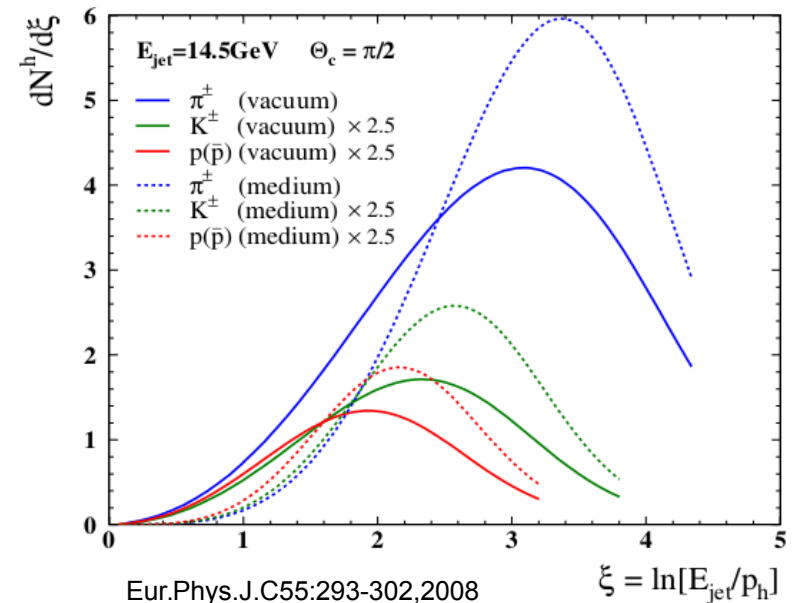
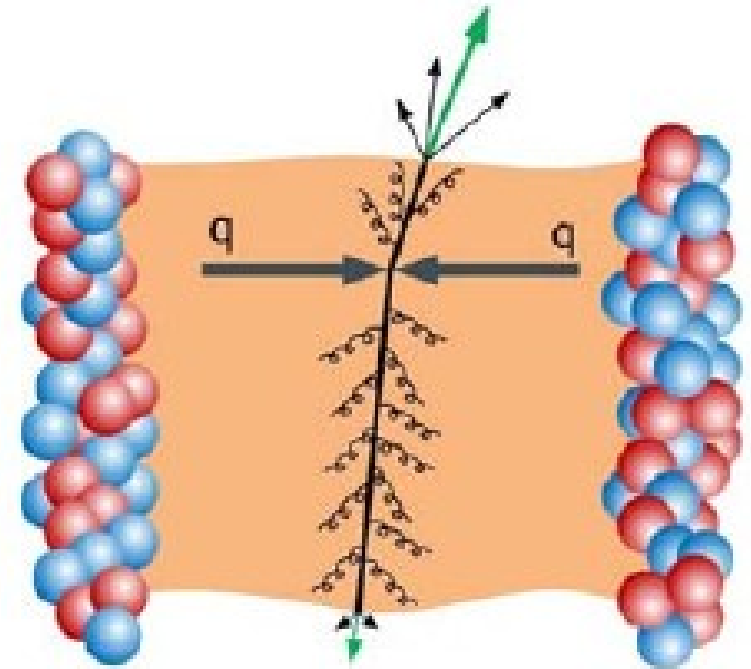
Recommended resource on jet finding algorithms: [Eur.Phys.J.C67:637-686,2010](#)

Experimental measurement and theoretical calculation should use same algorithm



# Jet modifications

- Jet quenching mechanisms
  - Gluon Bremsstrahlung
  - Collisional energy loss
- Broadens jets
- Softens fragmentation function
- Modified hadronization in-medium?
  - Quenching and modified hadronization might look the same experimentally



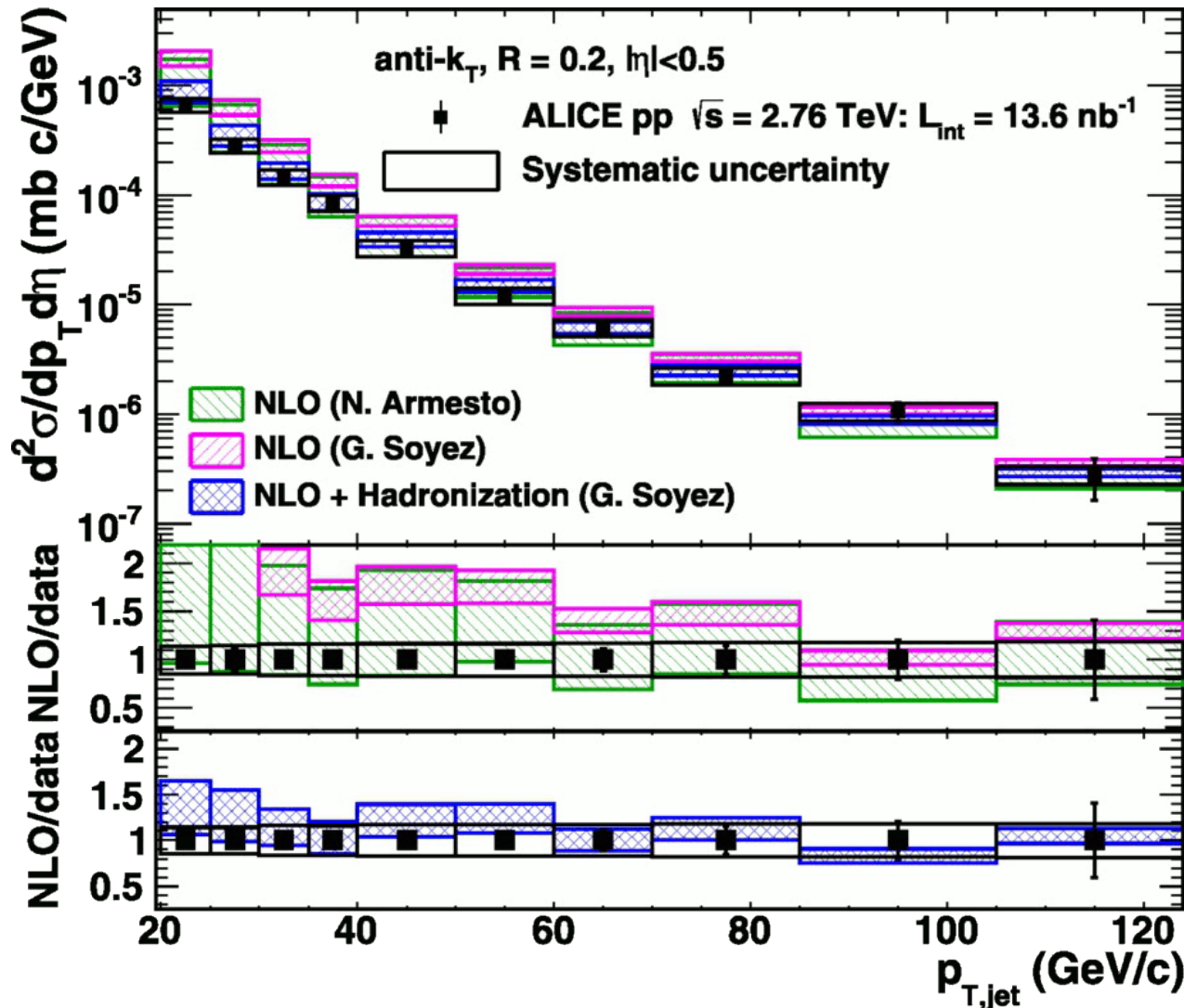
Hadronization is important.

# Full jet cross-section in pp

$\sqrt{s} = 2.76$  TeV,  $R = 0.2$  Inclusive

arXiv:1301.3475

PLB: 10.1016/j.physletb.2013.04.026



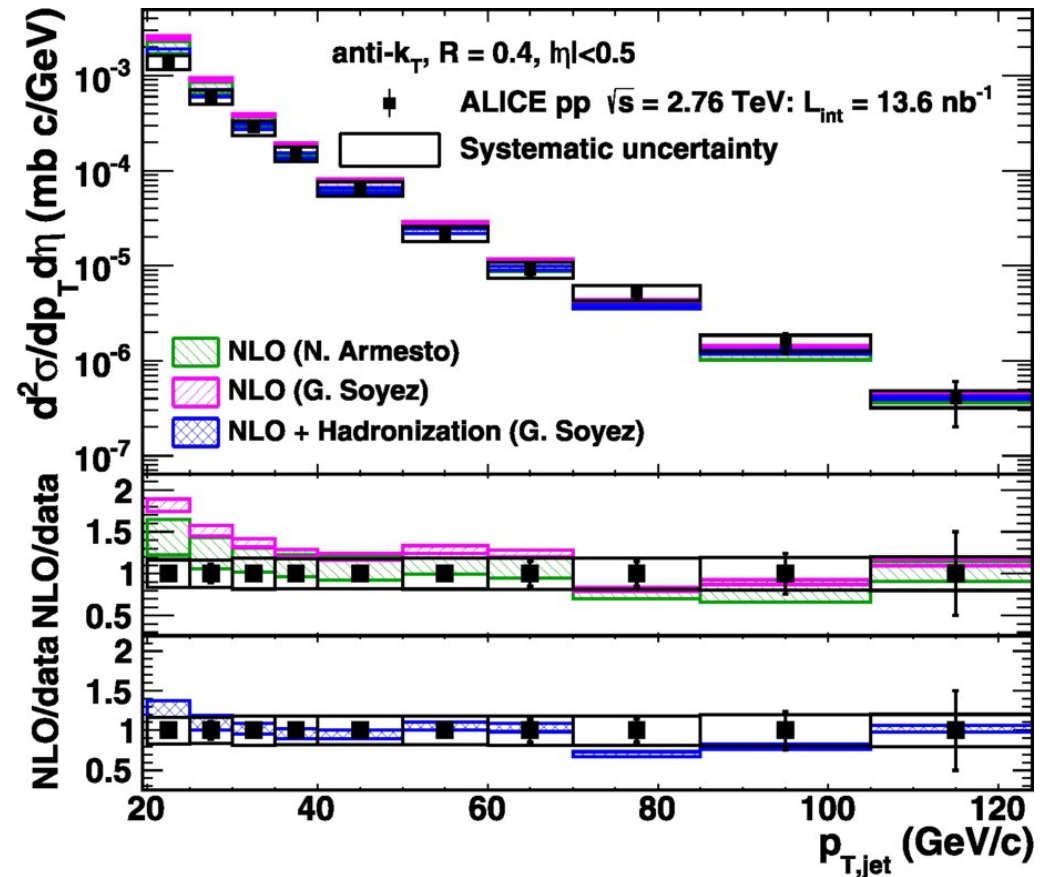
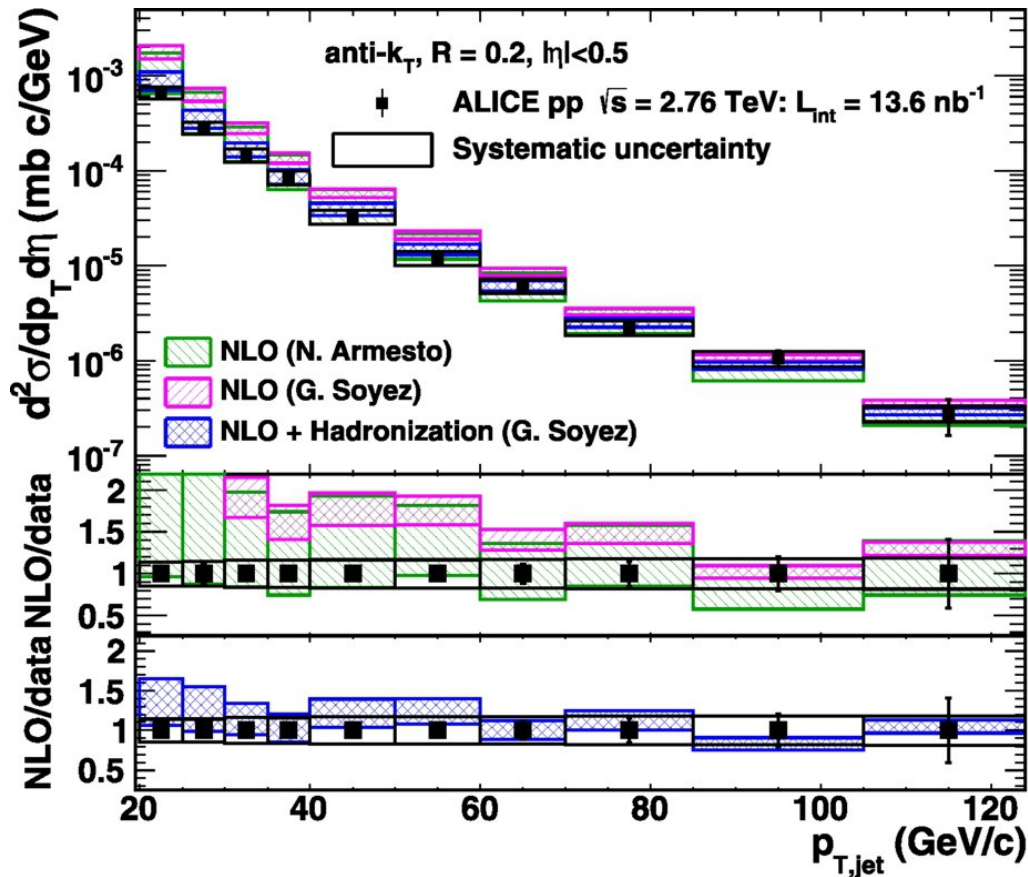
- $f_{\text{hadcor}} = 100\%$ ,
- $p_T > 150$  MeV/c
- $E_T > 300$  MeV
- **Green** and **magenta** bands: NLO on Parton level
- **Blue** band: NLO + hadronization
- Hadronization calculations necessary to describe data

# Full jet cross-section in pp

$\sqrt{s} = 2.76$  TeV,  $R = 0.2, 0.4$  Inclusive

arXiv:1301.3475

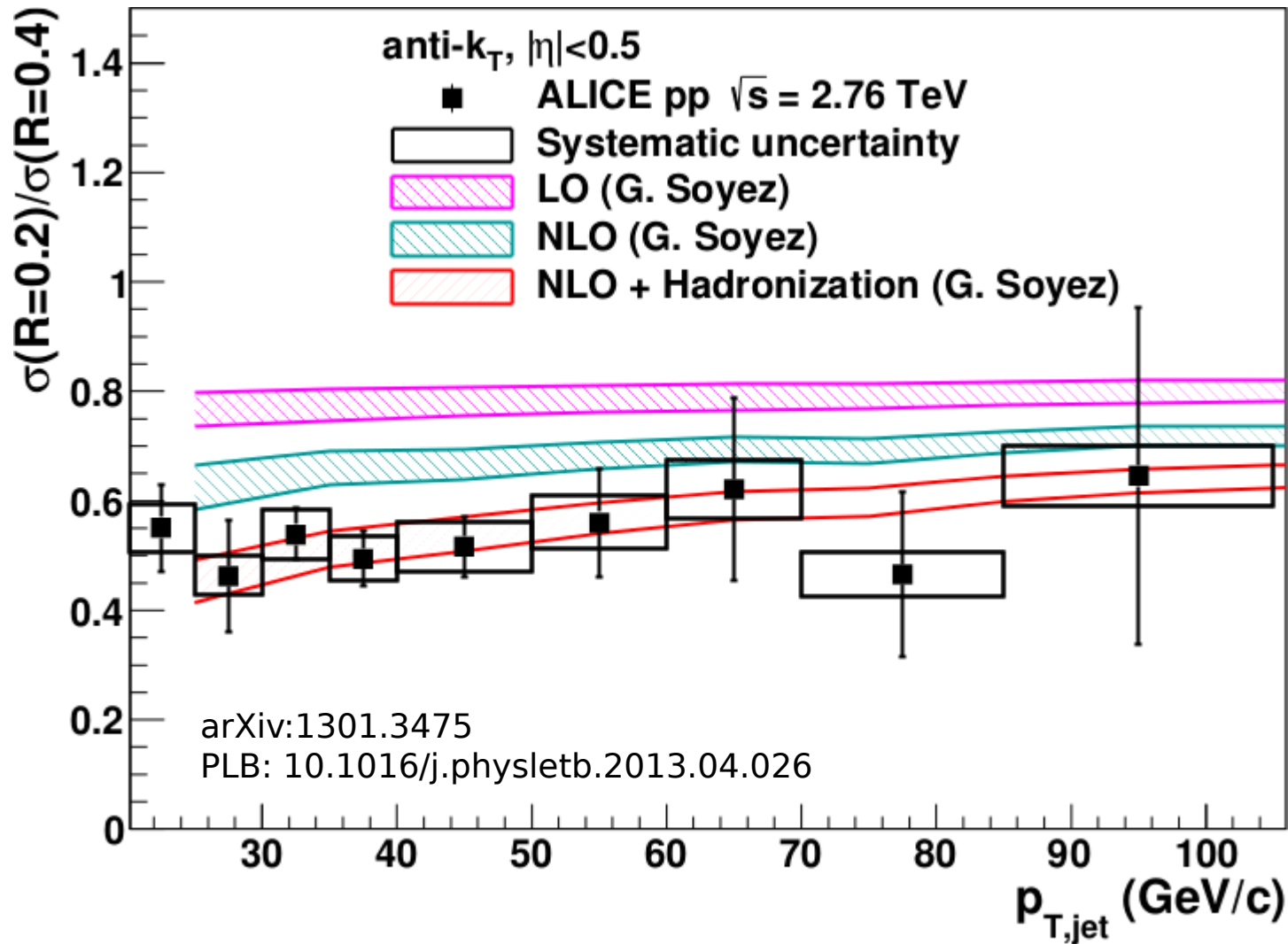
PLB: 10.1016/j.physletb.2013.04.026



**Data and NLO+ hadronization calculations agree well  
for both  $R = 0.2$  and  $0.4$**

# Full jet ratios in pp

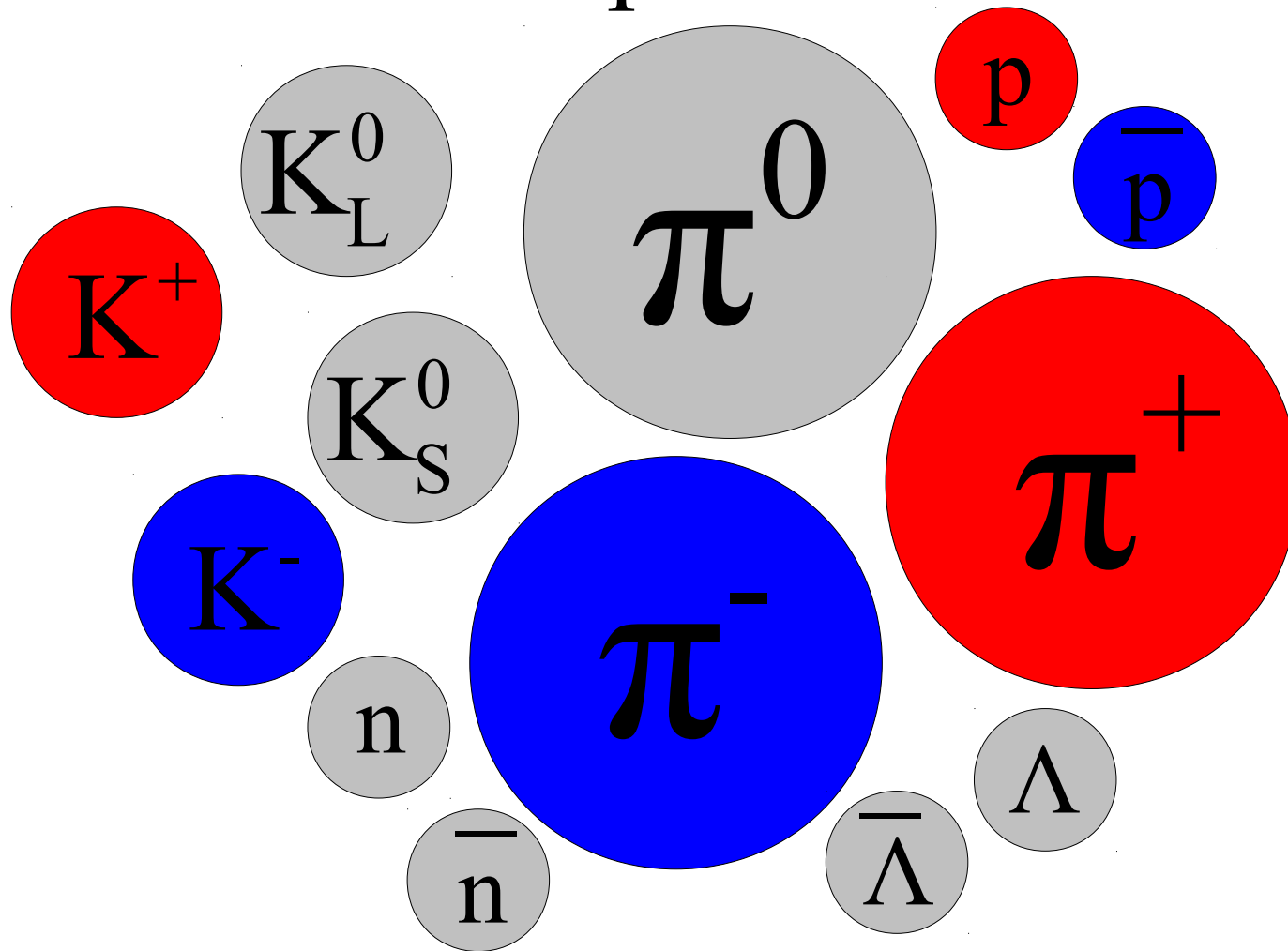
$\sqrt{s} = 2.76$  TeV,  $R = 0.2, 0.4$  Inclusive



**Data and NLO+ hadronization calculations agree well**

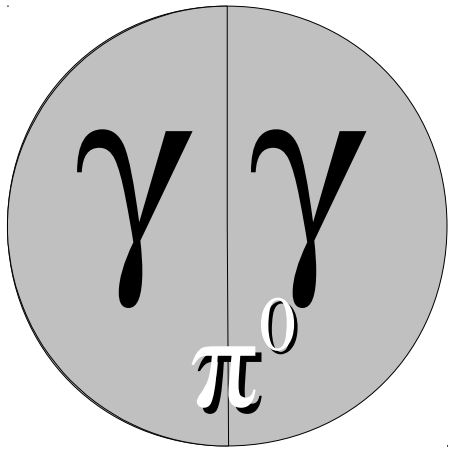
Experiments can't measure all particles

# How is energy distributed among final state particles?

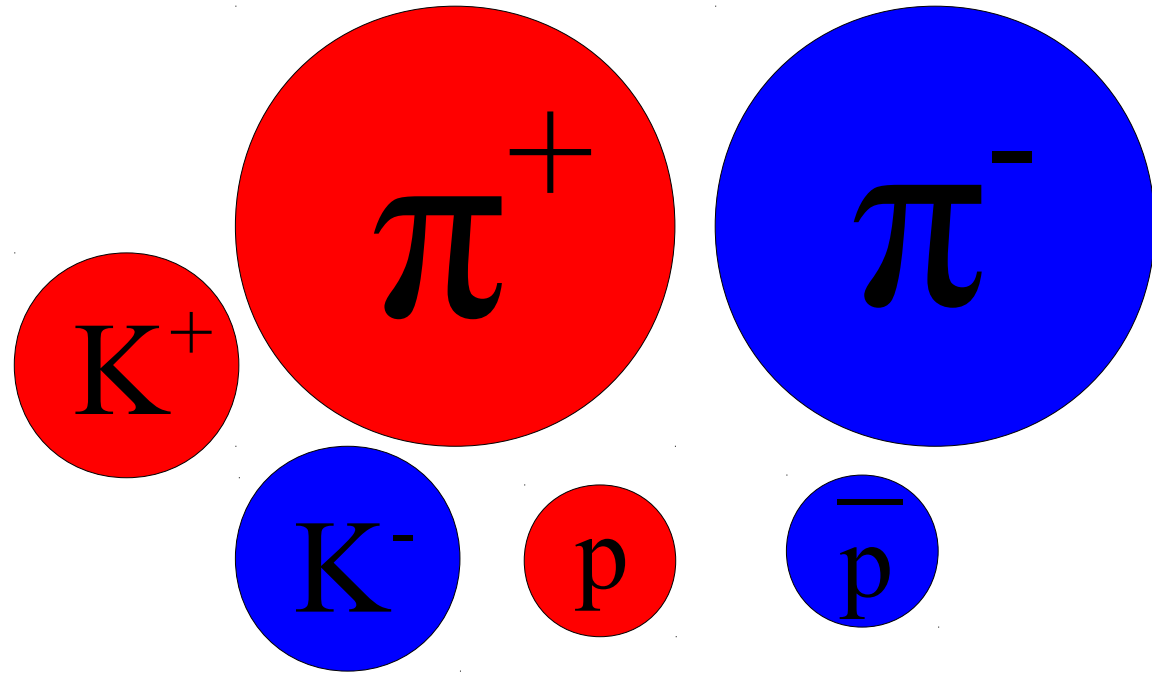
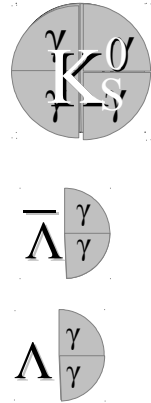


Size of circles proportional to the fraction of energy in that particle  
Scale: diameter in inches =  $\sqrt{\text{fraction}} * 5$

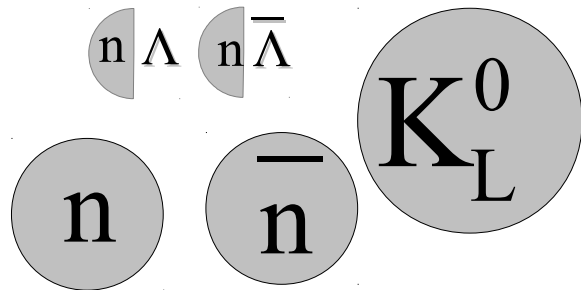
# How does it hit a detector?



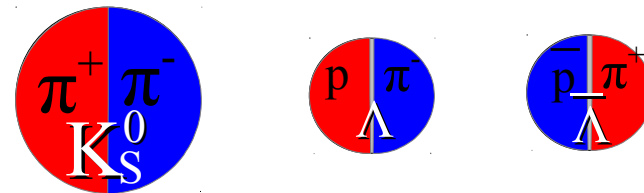
**24% as a  $\gamma$**



**58% in primary hadrons**



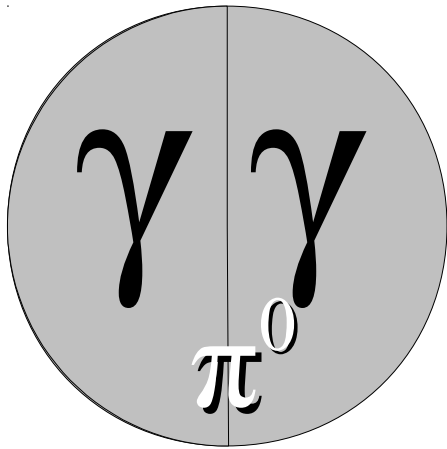
**11% as a neutral hadron**



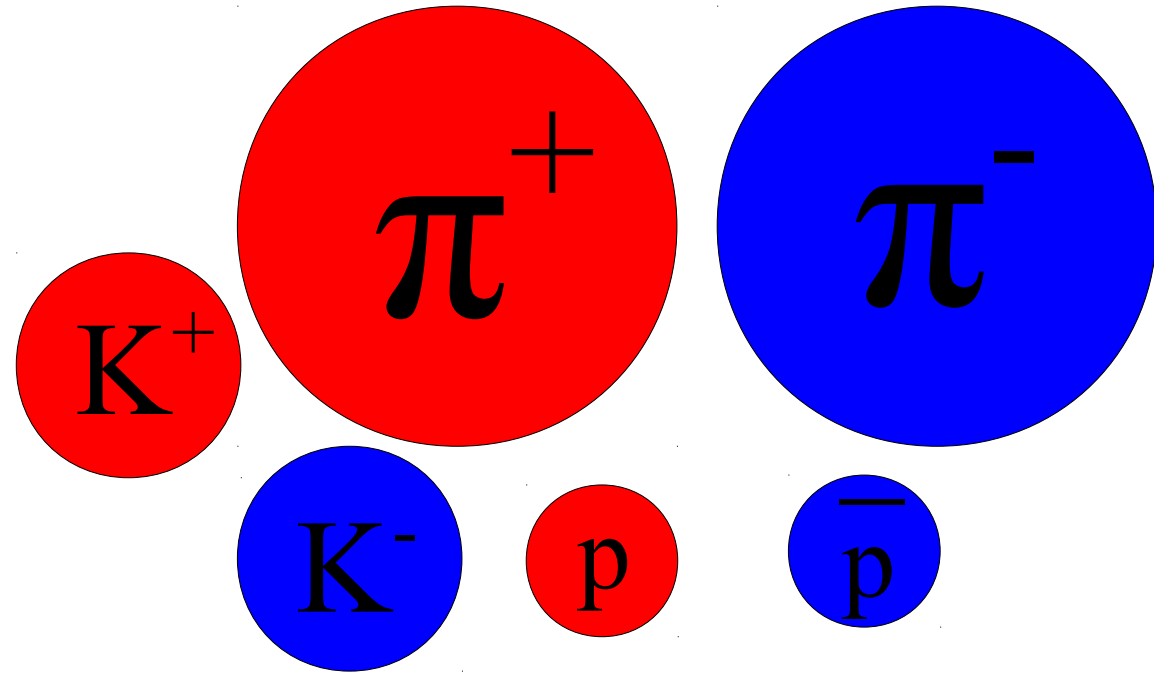
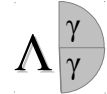
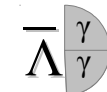
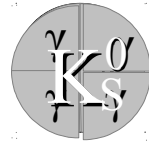
**7% in secondary hadrons**

Scale: diameter in inches =  $\sqrt{\text{fraction}} * 5$

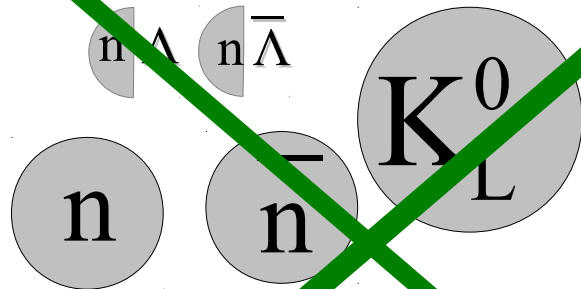
# What can ALICE see?



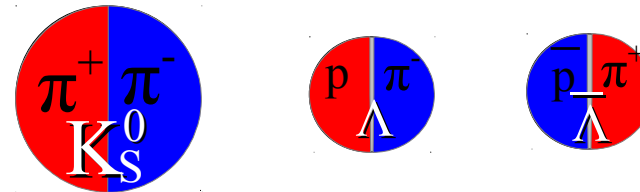
24% as a  $\gamma$



58% in primary hadrons  
<90% efficiency



11% as a  
neutral hadron



7% in secondary hadrons

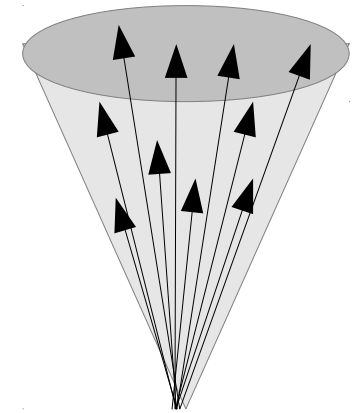
Low efficiency

Scale: diameter in inches =  $\sqrt{\text{fraction}} * 5$

# Hadronic calorimeters (ATLAS, CMS)

What a calorimeter measures:

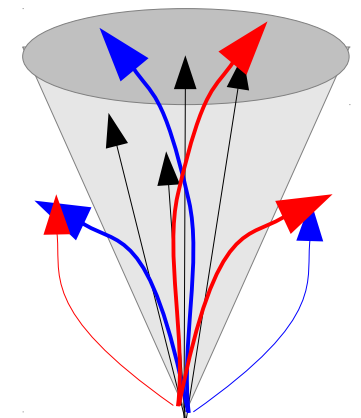
$$E = \begin{cases} \sqrt{p^2 + m^2} - m & \text{Nucleons} \\ \sqrt{p^2 + m^2} + m & \text{Anti-nucleons} \\ \sqrt{p^2 + m^2} & \text{Everything else} \end{cases}$$



Theoretical jet

Corrections are determined by Monte Carlo

- Some corrections are MC dependent
- Hadronic calorimeter deposits impacted by magnetic field
- 3.8T magnetic field in CMS, 2T in ATLAS and limits what particles can even reach these detectors
  - 0.1-0.2 GeV for ATLAS



Particles in magnetic field

# Lower momentum thresholds

## Example: CMS

Tracks:  $p_T > 900 \text{ MeV}/c$

Clusters: limited by B, usually

$E > 500 \text{ MeV}$

→ ~62% of inclusive  $E_T$  measured

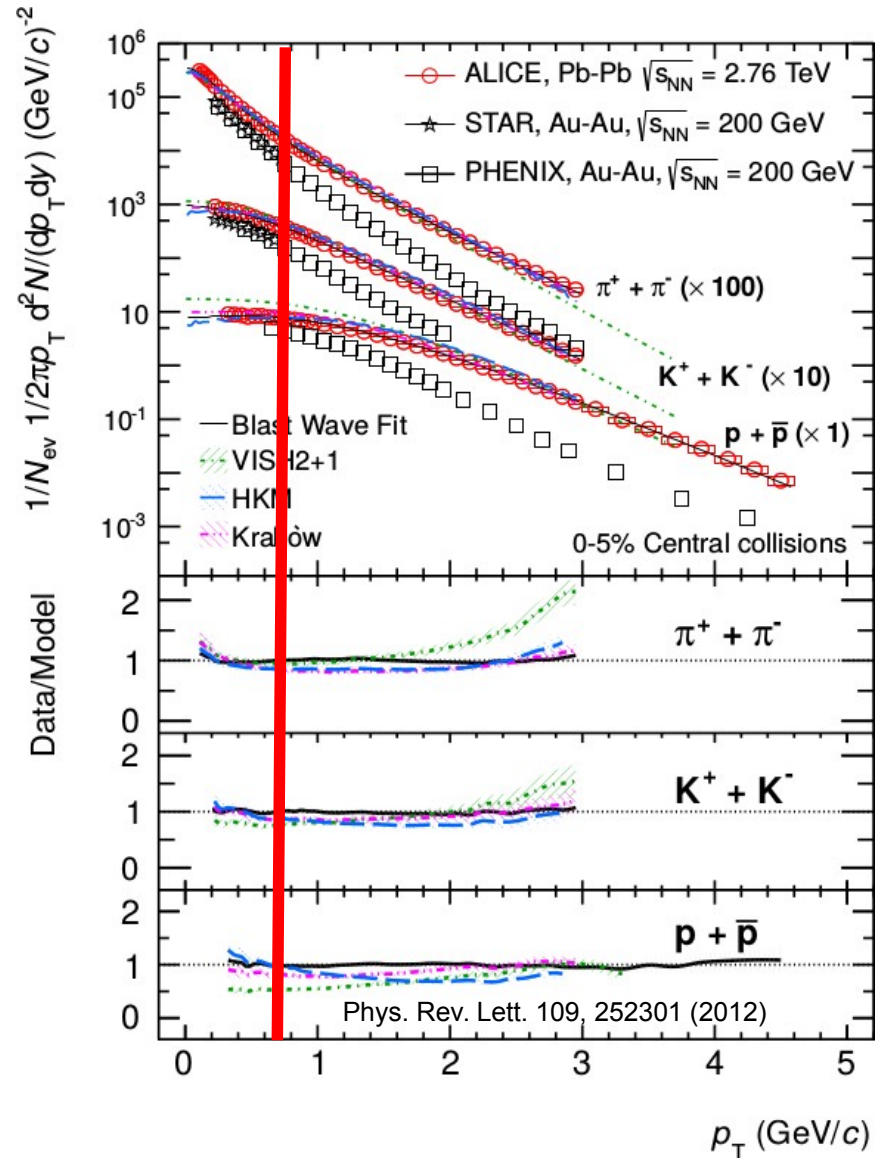
## Example: ALICE

Tracks:  $p_T > 150 \text{ MeV}/c$

EMCal Clusters:  $E > 300 \text{ MeV}$

→ ~50% of inclusive  $E_T$  measured

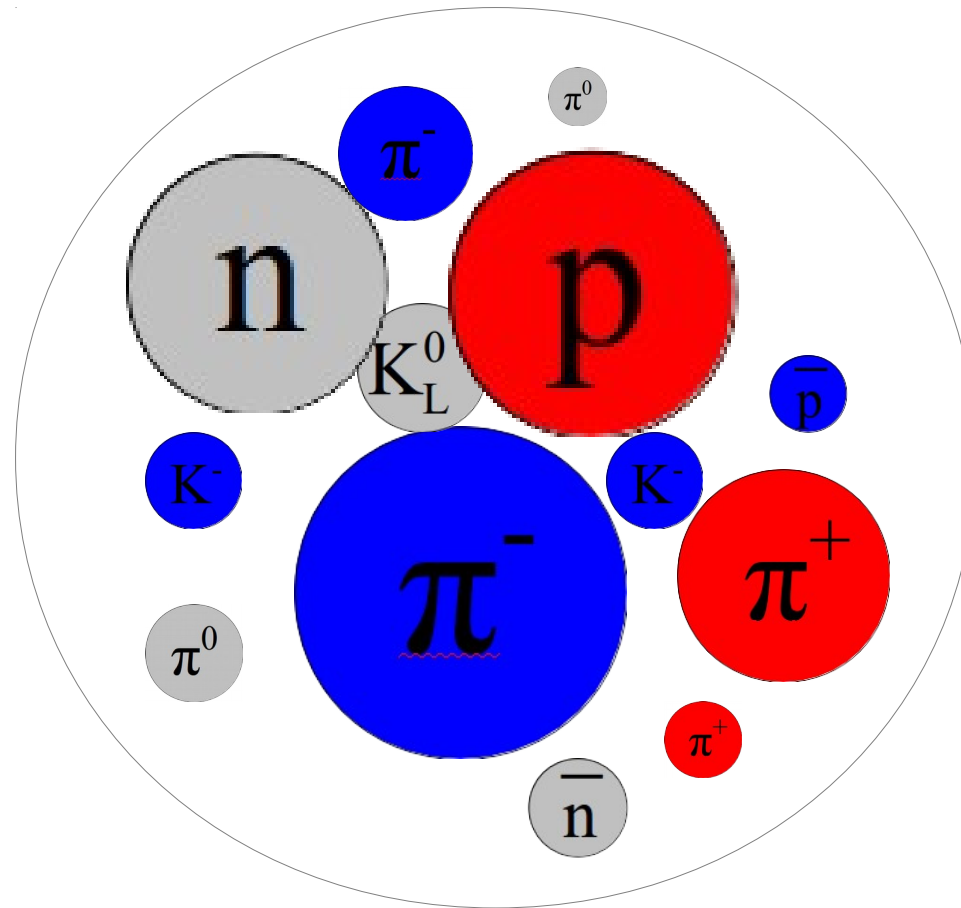
Fraction of energy measured in jets is higher, but...



$\langle p_T \rangle \sim 700 \text{ MeV}/c$

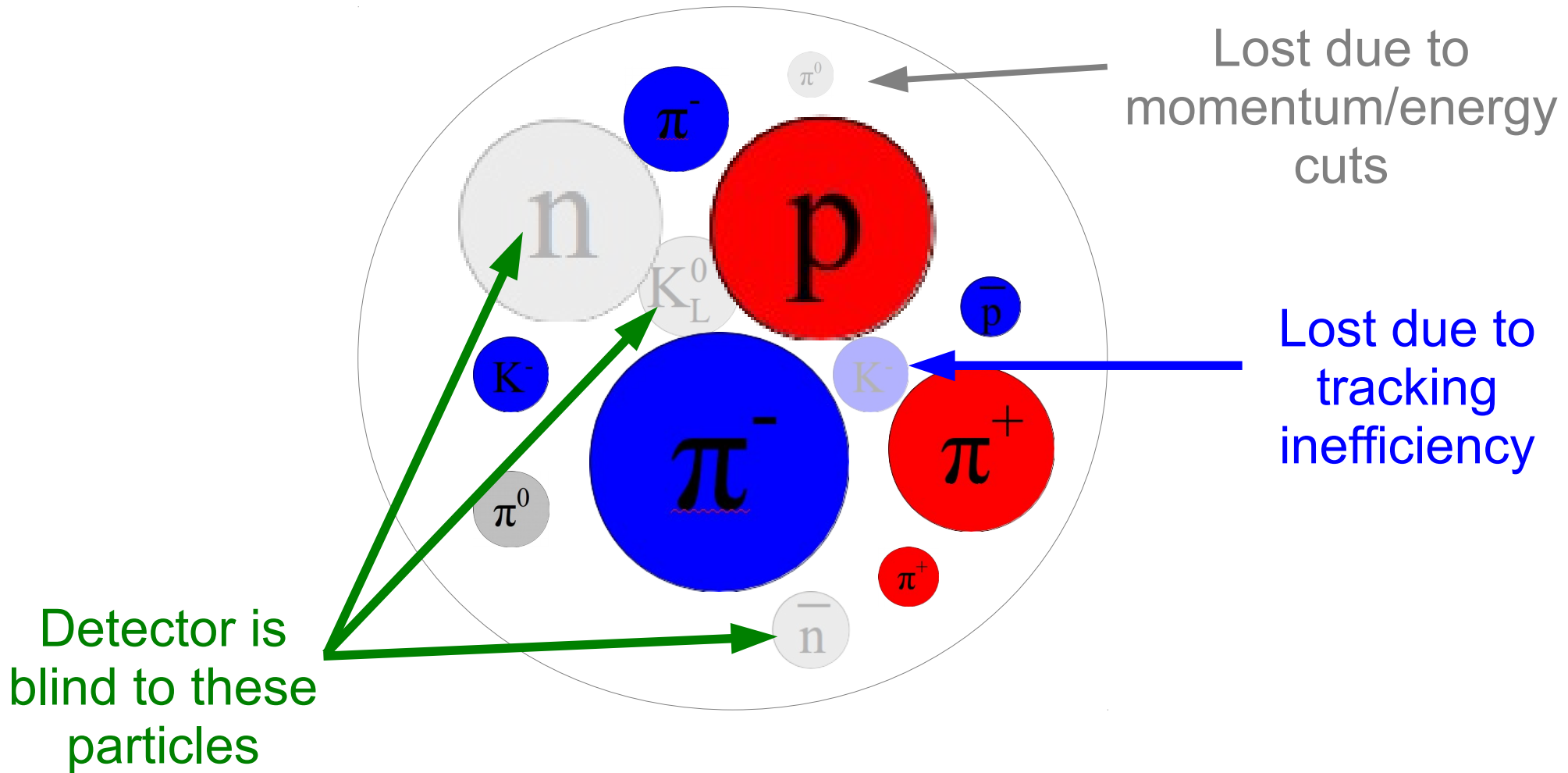
Phys. Lett. B 727 (2013) 371-380

# Theoretical jet



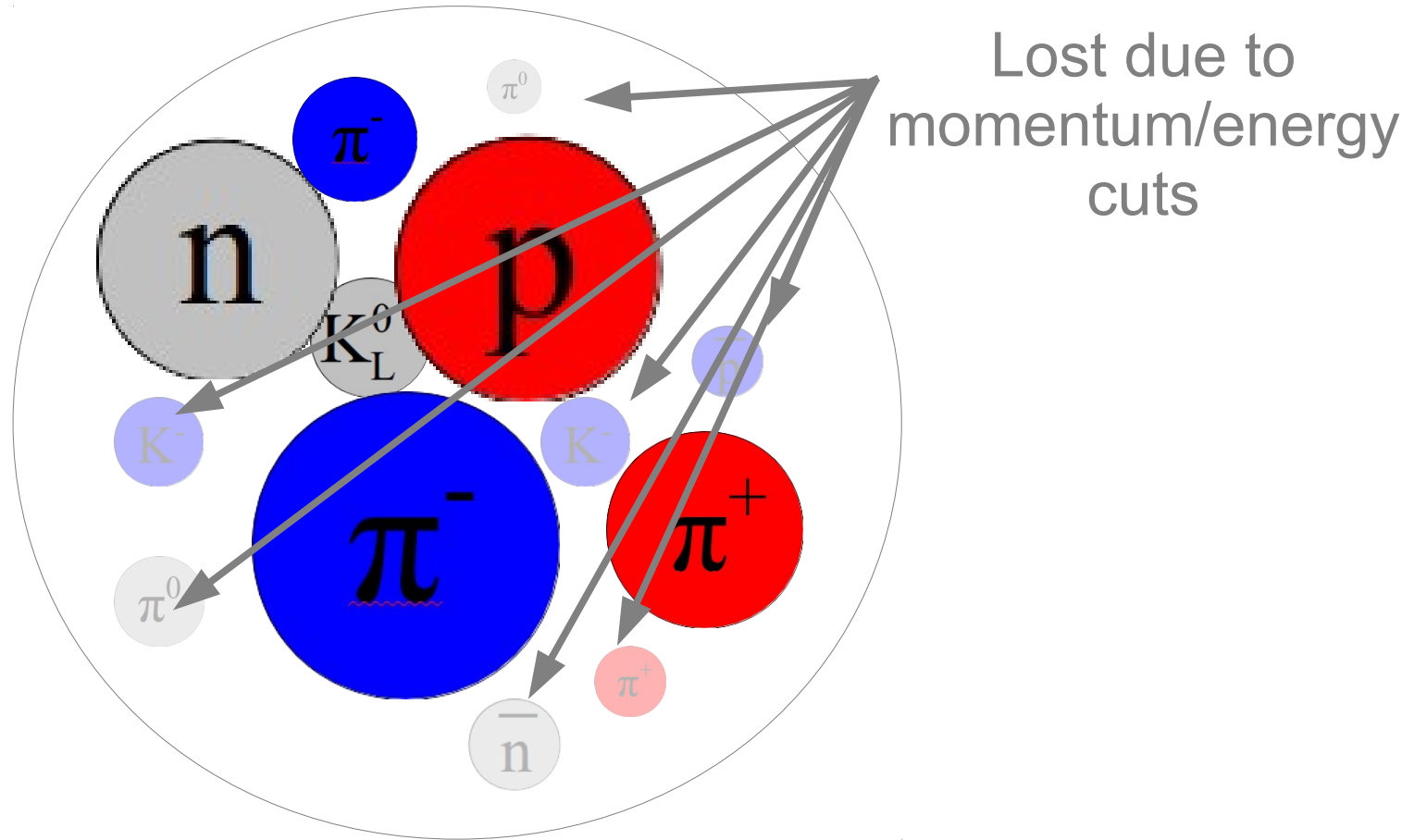
Schematic only  
Diameter of circle proportional to energy carried by particle

# What ALICE sees

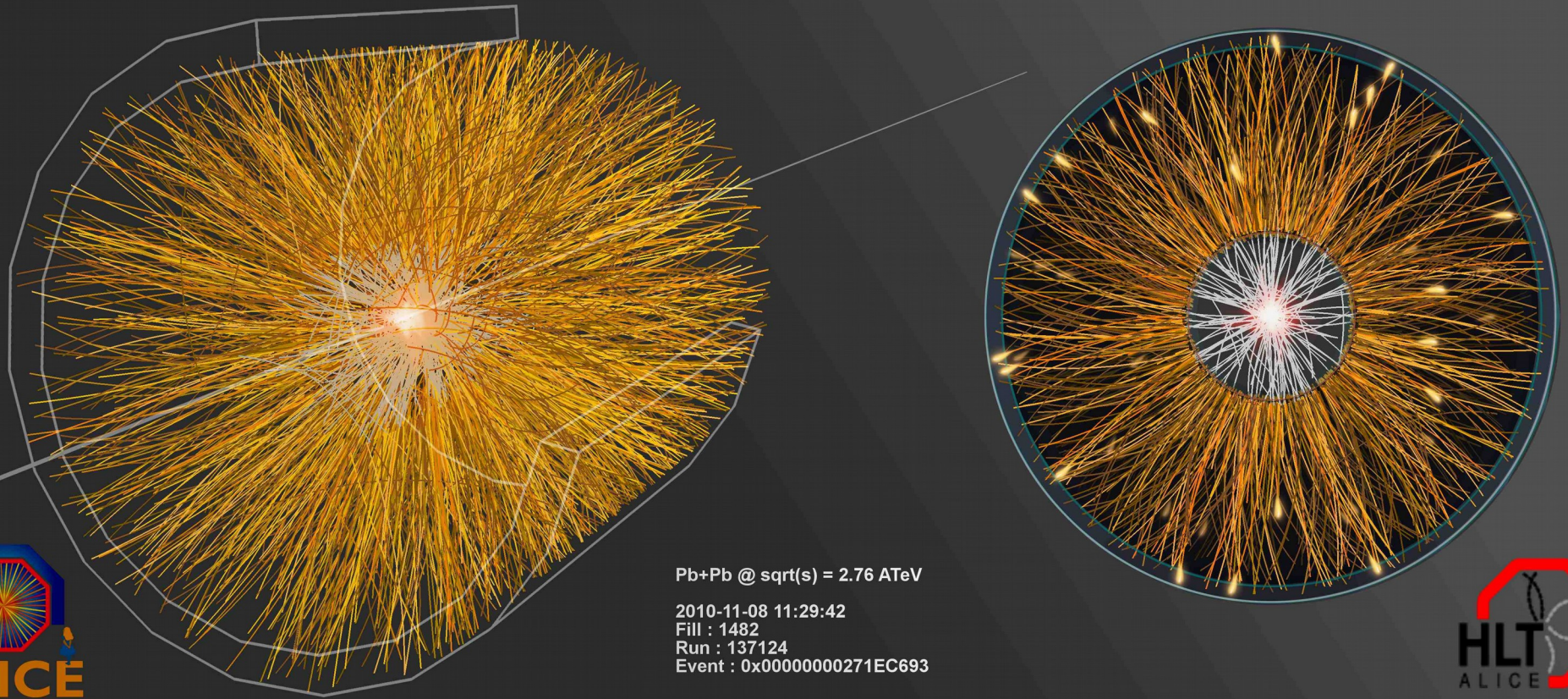


Schematic only  
Diameter of circle proportional to energy carried by particle

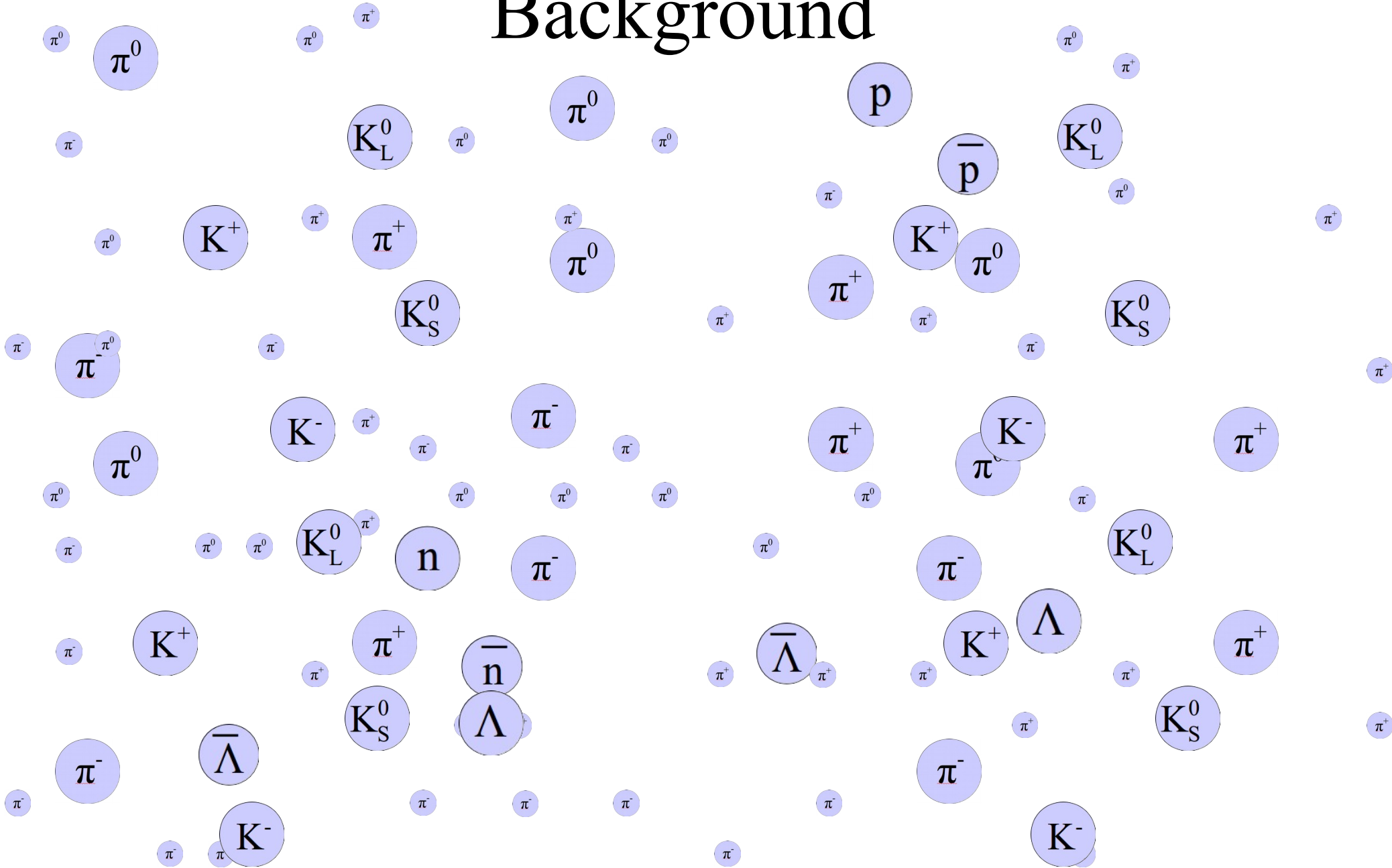
# What ALTA/CMS sees



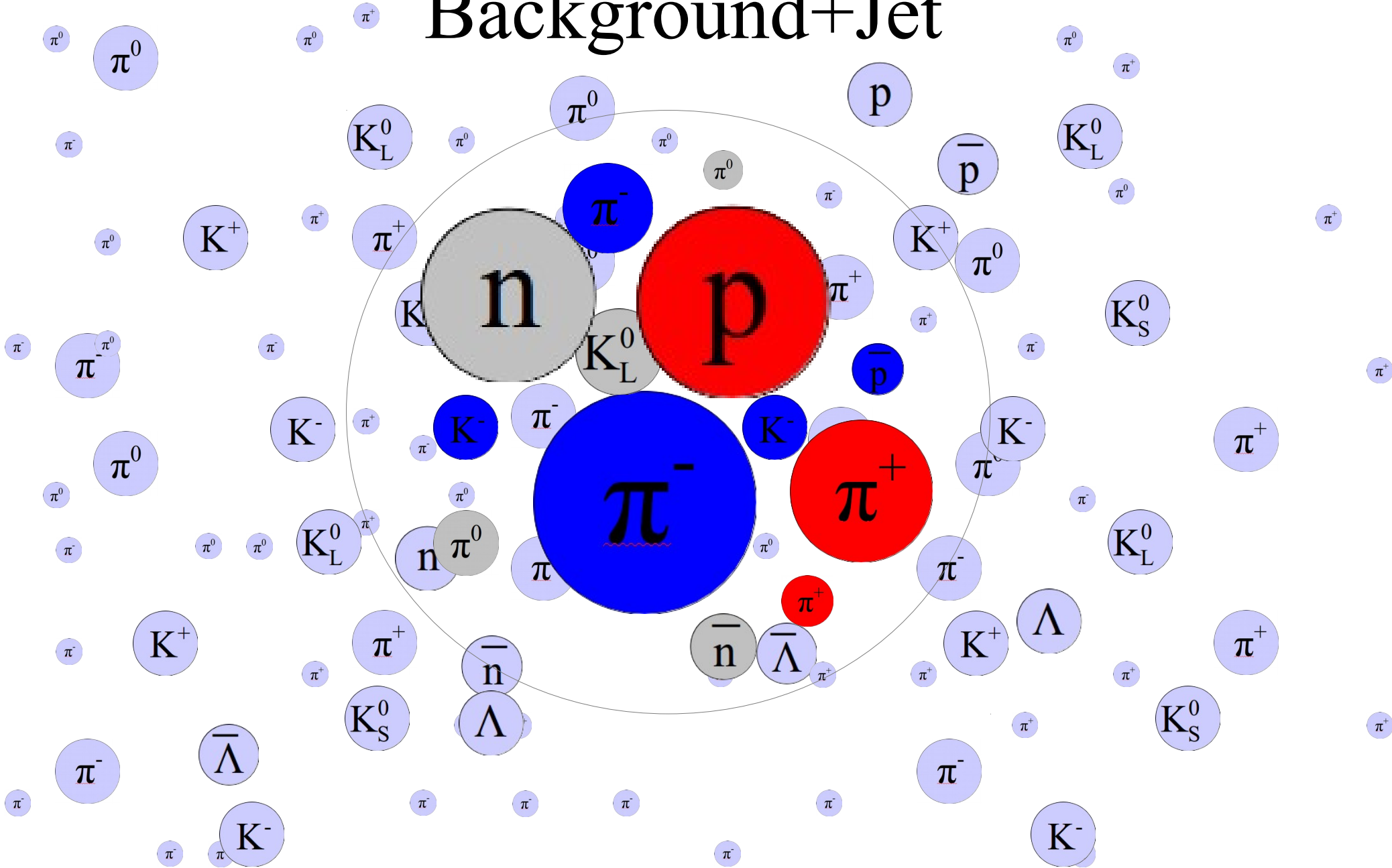
# About that pesky background...



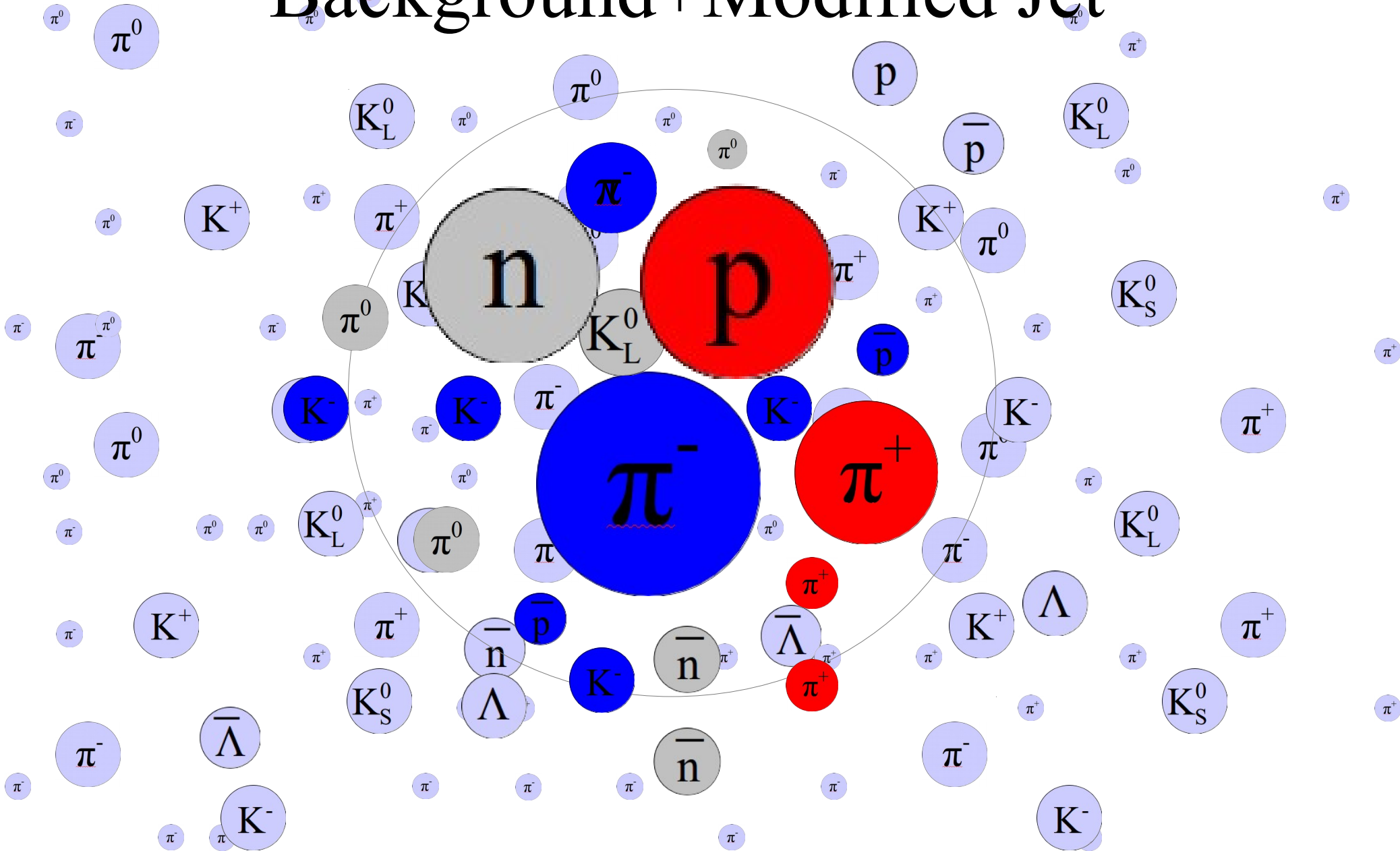
# Background



# Background+Jet

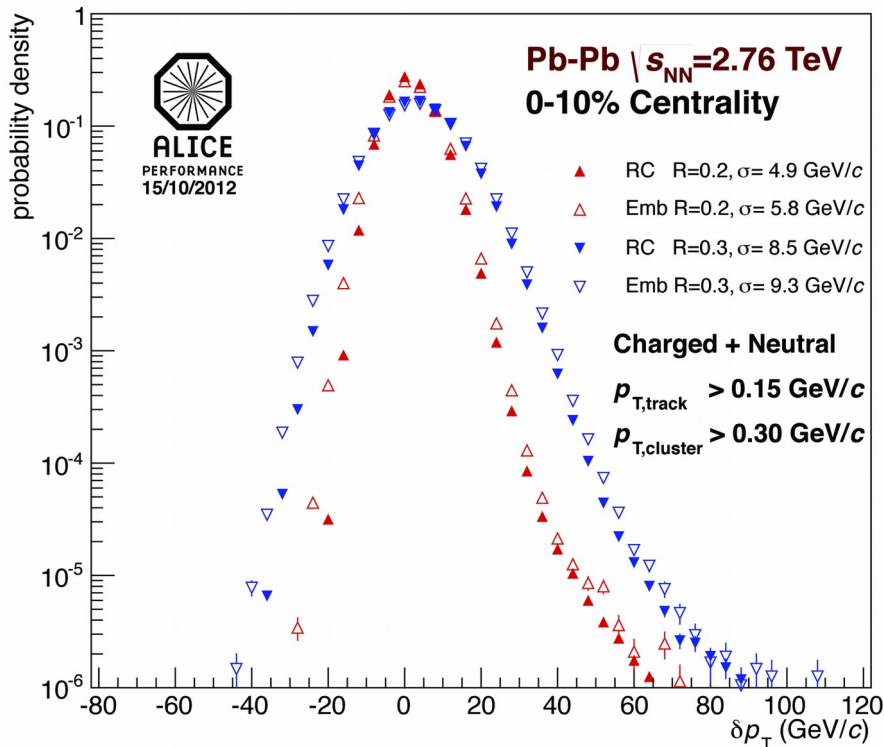


# Background+Modified Jet



# Combinatorial jets

Full Jets in Pb-Pb  $\sqrt{s_{NN}} = 2.76$  TeV



• Fluctuations in the background determined via  $\delta p_T$

• Random cones (RC)

• Depends on

• Constituent cut R

• Centrality

• Event plane

• Detector

$$\delta p_T = p_T^{rec} - \rho \pi R^2$$

$\delta p_T$  is not corrected for detector effects – Experiment specific

$\delta p_T$  is used to construct unfolding response matrix

# Leading track jet bias

$$\sqrt{s_{NN}} = 2.76 \text{ TeV Pb-Pb, } R=0.2$$

## Combinatorial “jets”

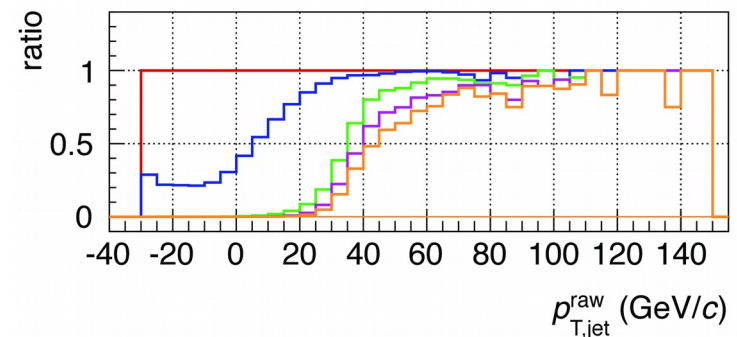
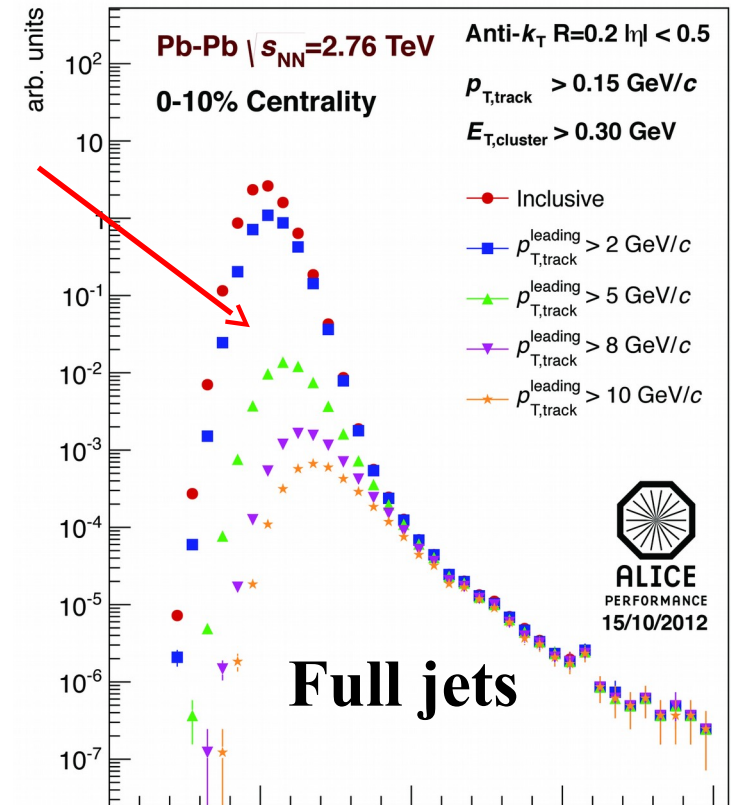
Combinatorial jets a challenge in HI collisions

- Require leading track  $p_T > 5 \text{ GeV}/c$
- Suppresses combinatorial “jets”
- Biases fragmentation

Measured spectra:

$$p_{T,jet}^{unc} = p_{T,jet}^{rec} - \rho A$$

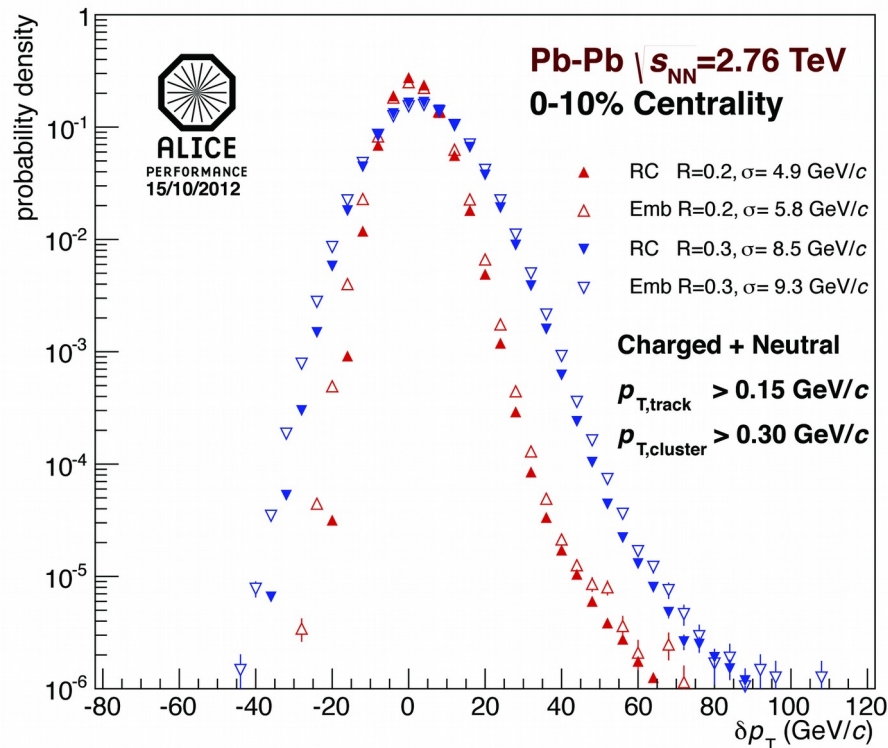
Where  $p_{T,jet}^{rec}, A$   
comes from FastJet anti- $k_T$  algorithm



ERF-44496

# Combinatorial jets

Full Jets in Pb-Pb  $\sqrt{s_{NN}} = 2.76$  TeV



• How to suppress:

- Reduce R
- Increase constituent cut
  - No longer colinear safe
- Require high  $p_T$  track
  - No longer colinear safe
- Focus on higher  $p_T$  jets

# Questions you should ask

- **How do the analysis cuts impact the jets used in the analysis?**
  - Small  $R \rightarrow$  eliminates out of cone radiation
  - High jet  $p_T/E$  biases towards unmodified jets
  - Requirement of high  $p_T$  track/cluster biases towards unmodified jets
  - High minimum constituent cut could make the analysis blind to medium modifications
- **Is this analysis sensitive to medium modifications?**

“Different jets are different.”  
-- Rosi Reed

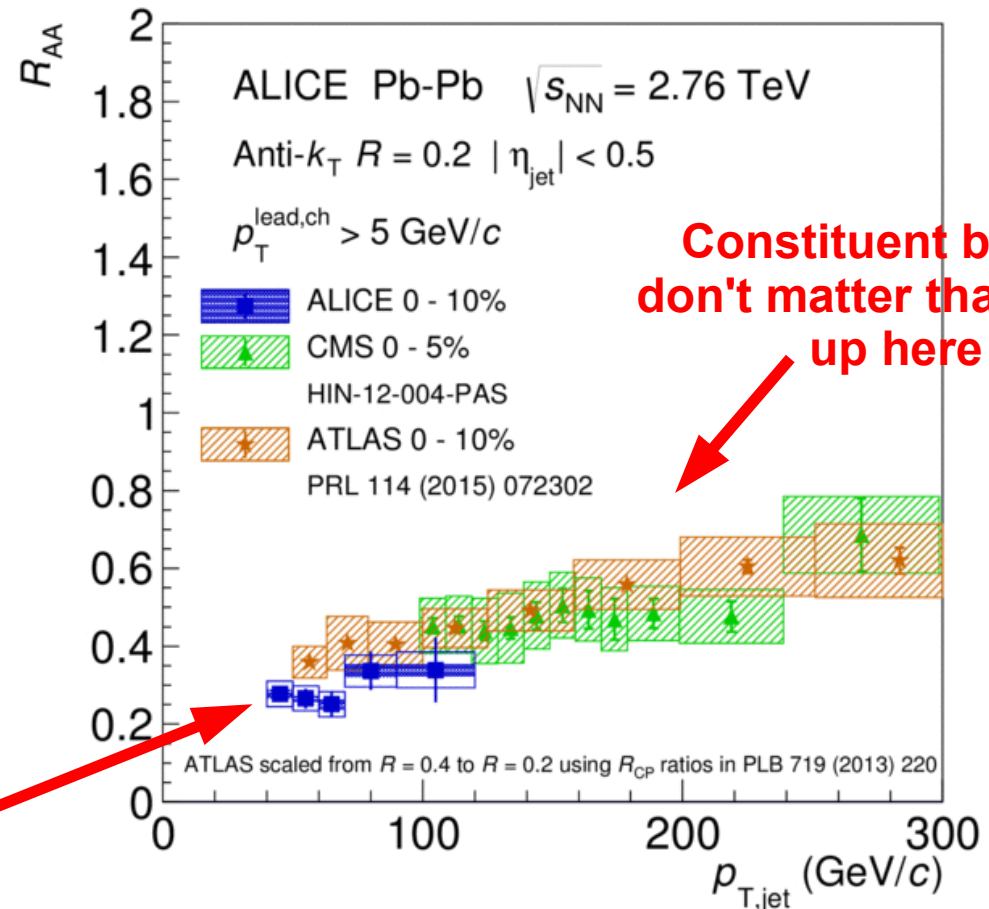
# Jet $R_{AA}$

$$\sqrt{s_{NN}} = 2.76 \text{ TeV}, R = 0.2 \text{ Inclusive}$$

ALICE: tracks  $> 150 \text{ MeV}/c$ , clusters  $> 300 \text{ MeV}$ ,  $5 \text{ GeV}/c$  track bias

CMS: tracks  $> 500 \text{ MeV}/c$ , hadronic calorimeter clusters

ATLAS: Calorimeter jets (primary)  
Track jets with tracks  $> 4 \text{ GeV}/c$  &  $7$  or  $8 \text{ GeV}/c$  constituent bias  
Scaled down from  $R=0.4$  to  $R=0.2$



But they do matter down here!

Constituent biases don't matter that much up here

ALI-DER-92552

**The fact that these results are consistent is telling us something about the medium!**

# CMS fragmentation functions

R = 0.3  
 Tracks + calorimeter  
 towers  
 Tracks > 0.9 GeV/c

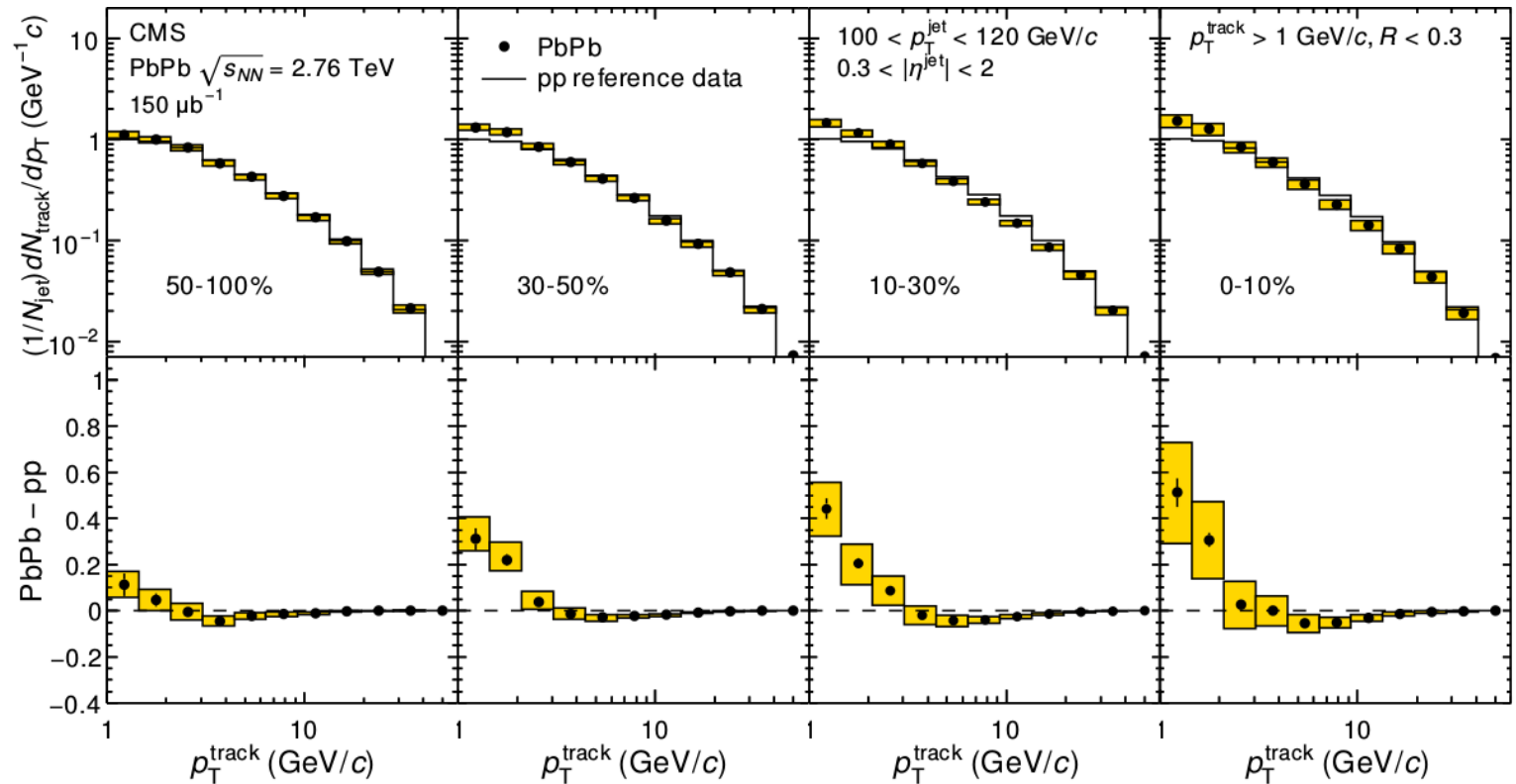


Figure 6: (Color online) The spectrum of tracks inside the cone of jets with  $100 < p_T^{\text{jet}} < 120 \text{ GeV}/c$ , as a function of track  $p_T$ , for PbPb (with increasing centrality from left to right) and pp. Both the PbPb and pp results are background subtracted, in the same manner as for the fragmentation function. The bottom panels show the difference of PbPb and pp spectra, demonstrating an excess of low- $p_T$  tracks in the PbPb events.

**How biased is this measurement towards unmodified jets?**

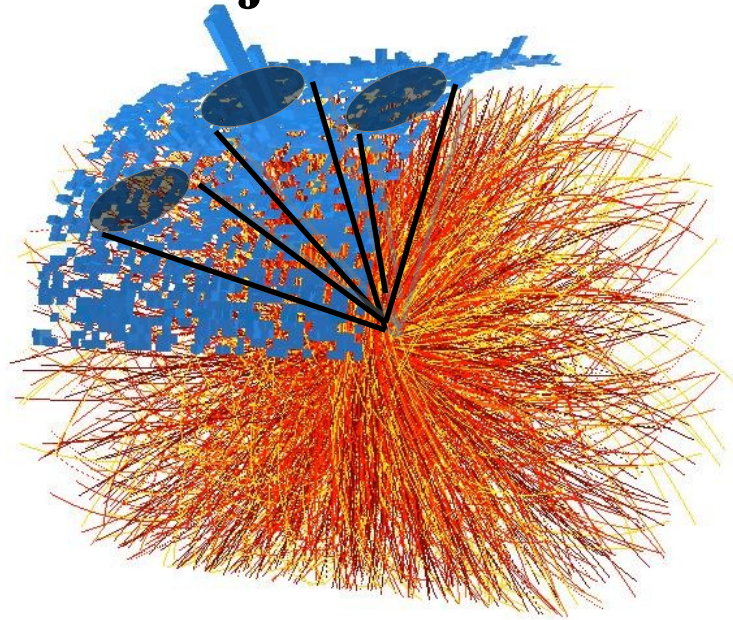
# Conclusions

- ~~Jet measures partons~~ jets measure some fraction of partonic energy, but this fraction depends on the measurement techniques
- ~~Hadronic degrees of freedom are integrated out~~ hadronization is really important!
- ~~Algorithms are infrared and colinear safe~~ measurements are not colinear safe!
- **Analysis cuts lead to biases in jet selection**
  - The bias can be a tool but it should influence interpretation of results

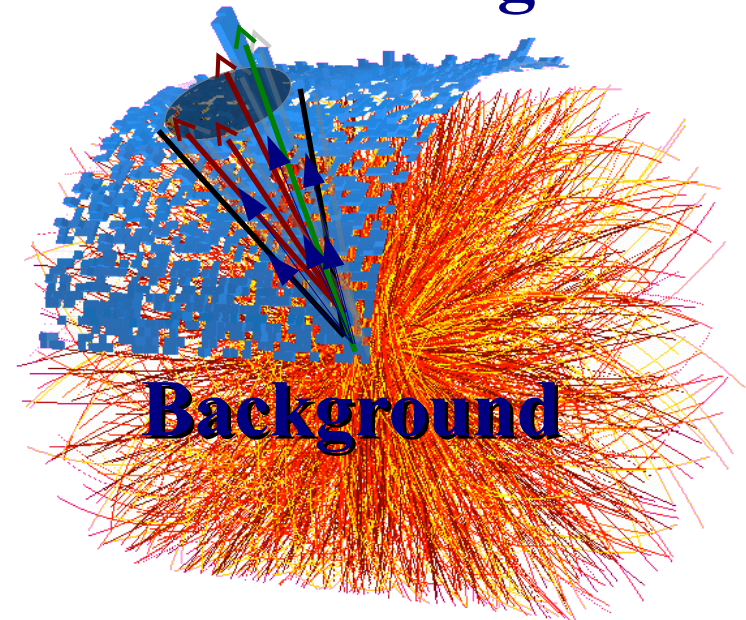
# Backup

# Method

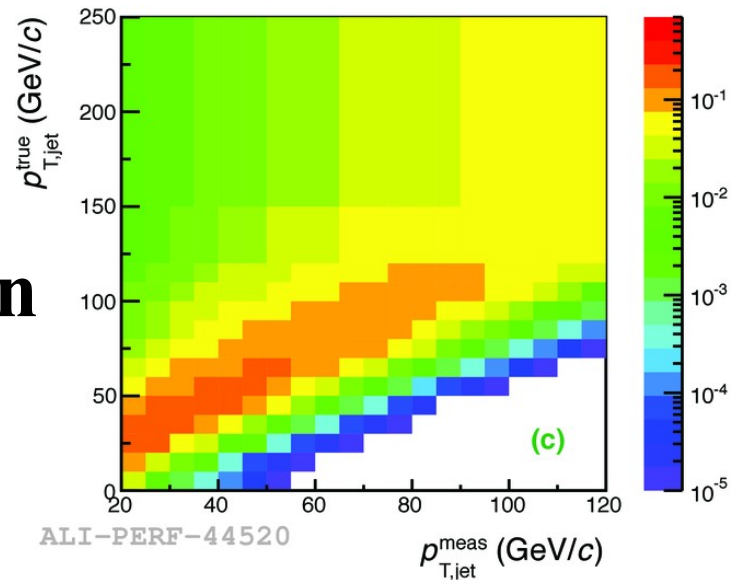
## 1. Find jet candidates



## 2. Subtract background

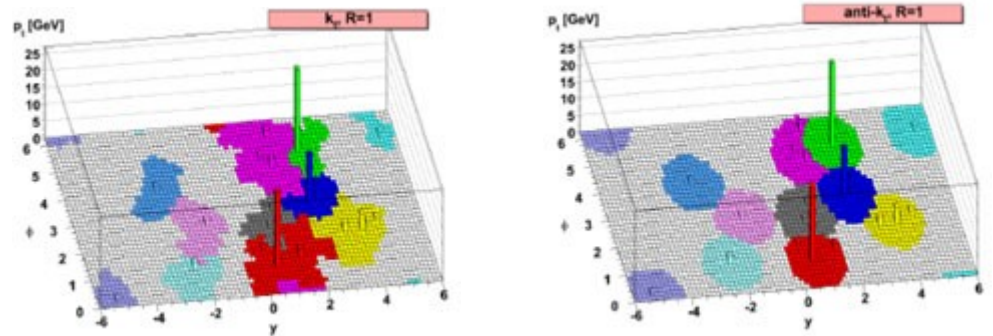
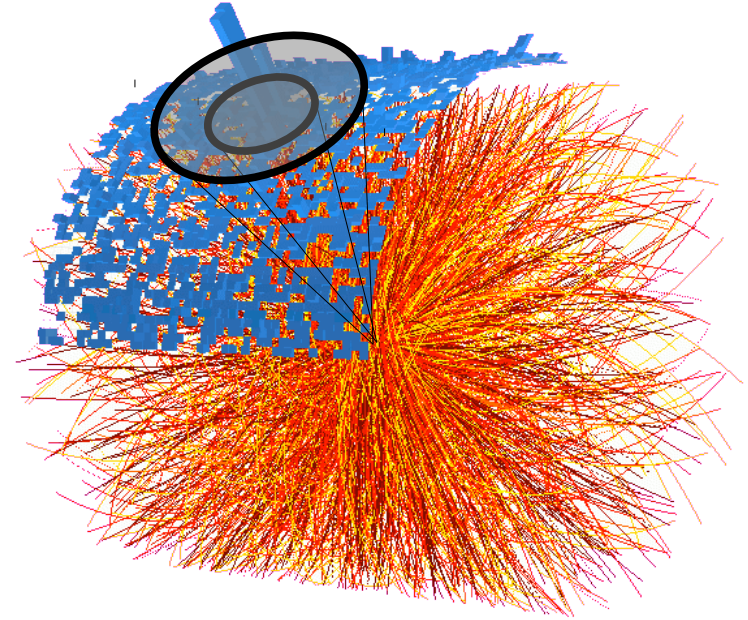


## 3. Correct for resolution



# Jet Reconstruction

- Jets reconstructed using FastJet package
  - $R = 0.2 - 0.4$
  - Anti- $k_T$  – Used for signal determination
  - $k_T$  – Used for background determination
- Correct for detector effects using unfolding
  - Momentum resolution
  - Energy resolution
  - Track Matching

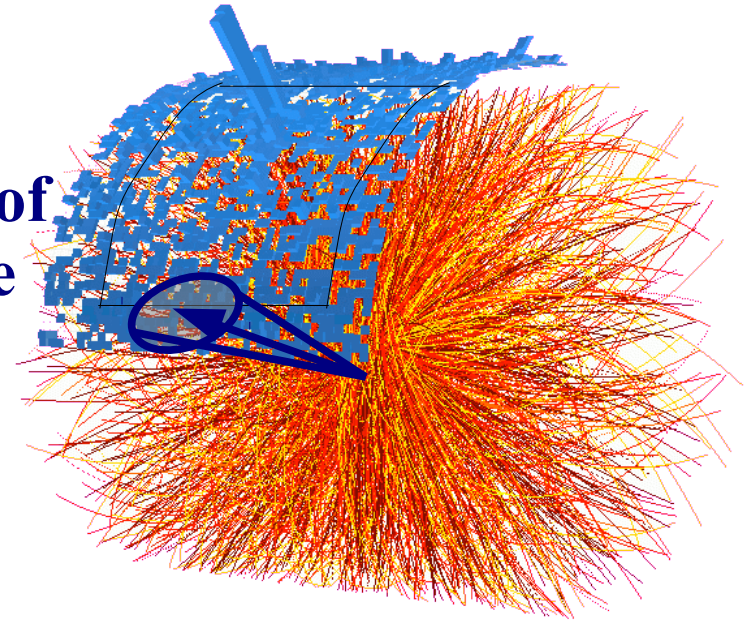


M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008

# Full Jet Selection Requirements

- EMCal fiducial acceptance cut
  - $R$  away from EMCal boundaries
  - $R=0.2$ :
    - $|\eta_{\text{jet}}| < 0.5$
    - $1.60 < \phi_{\text{jet}} < 2.94$
- Jets with leading track  $p_{\text{T}} > 100 \text{ GeV}/c$  are rejected due to limitations of tracking beyond  $100 \text{ GeV}/c$

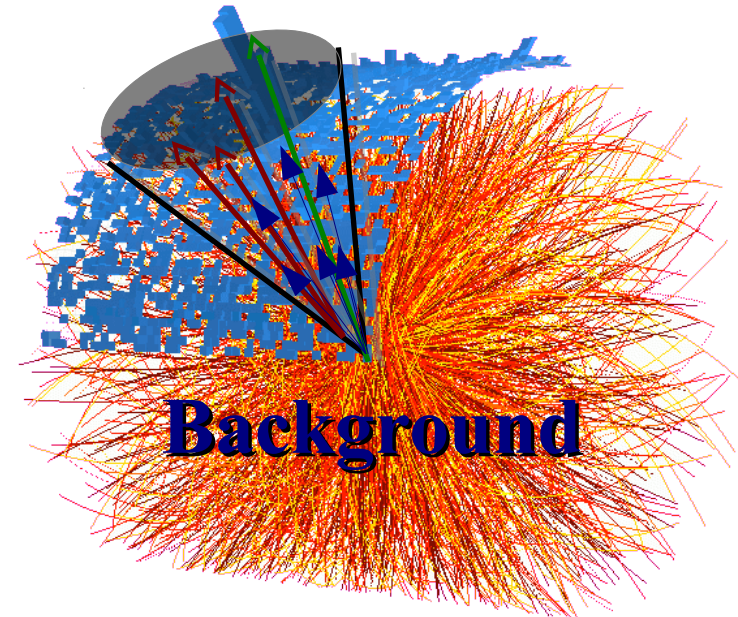
**Jet at edge of acceptance**



# Jets in Heavy Ion Collisions

## Experimental Challenges

- Need to remove underlying event (UE) contribution
  - $p_{T,Jet} = p_{T,Jet}^{rec} - \rho A + B_{\sigma}$
  - $A$  = Jet area,  $\rho$  = median UE momentum density
  - $p_{T,Jet}$  = Jet  $p_T$  from jet finder
  - We can only remove the average background contribution
- $B_{\sigma}$  from UE fluctuations
- Combinatorial (fake) jets can be reconstructed from UE
- Detector effect corrections depend on fragmentation
- Both background and detector effects are corrected in unfolding
  - Corrects spectra for the  $B_{\sigma}$  term
  - Quantified in Response Matrix (RM)

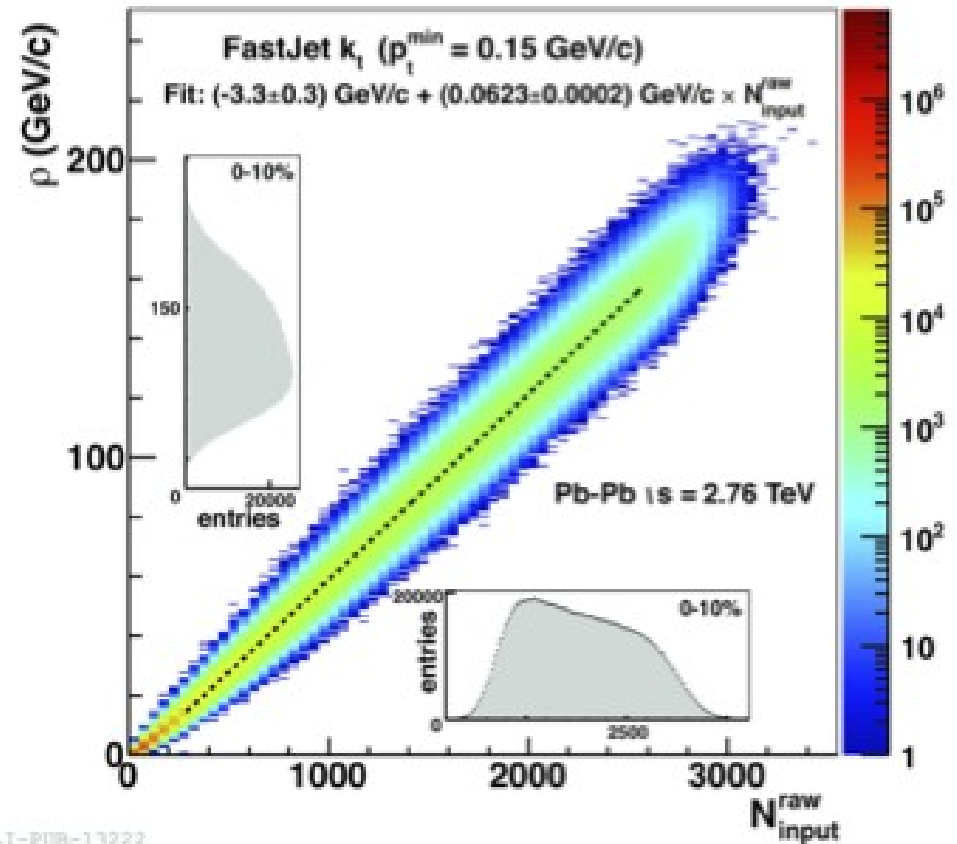


# HI Background Determination

Charged Jets  $\sqrt{s}_{NN} = 2.76$  TeV

- $\rho_{ch}$  : **median** of  $p_{T,kTjet}^{ch} / A_{kTjet}$ 
  - 2 leading jets removed
  - May be sensitive to jet fragments outside  $k_T$  jet cone
  - Determined event-by-event
- $\rho_{ch}$  is not corrected for detector effects or missing energy
- Subtracted from signal jets on a jet-by-jet basis

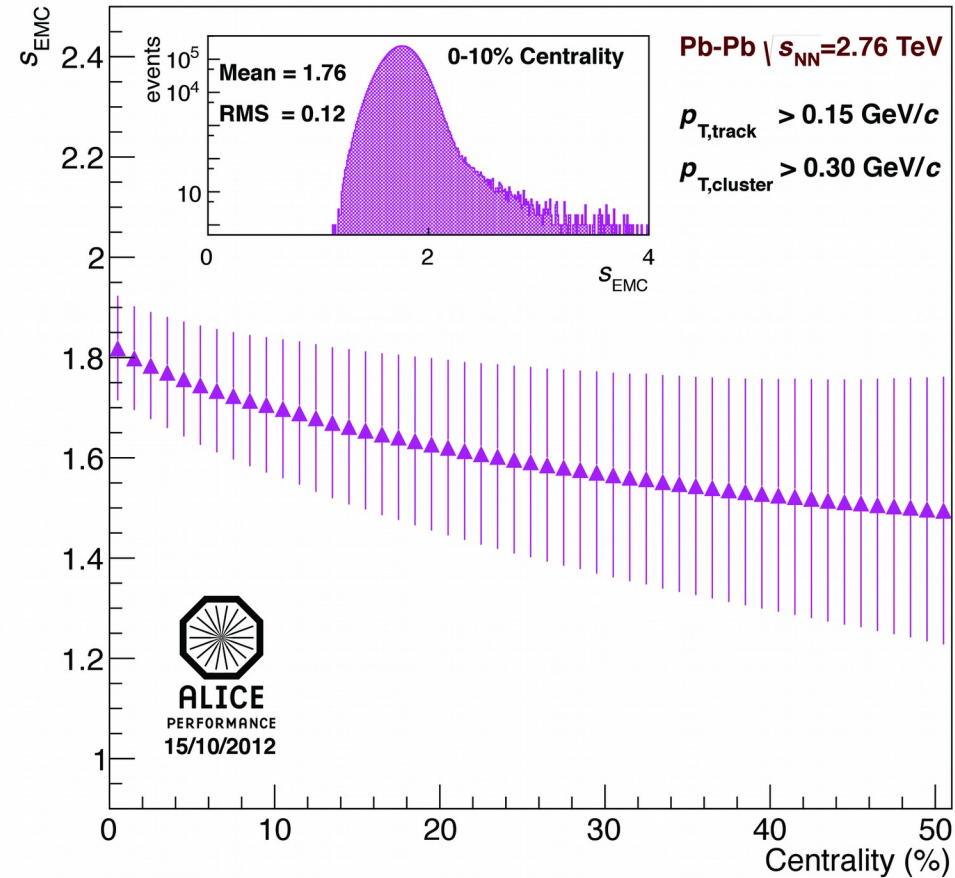
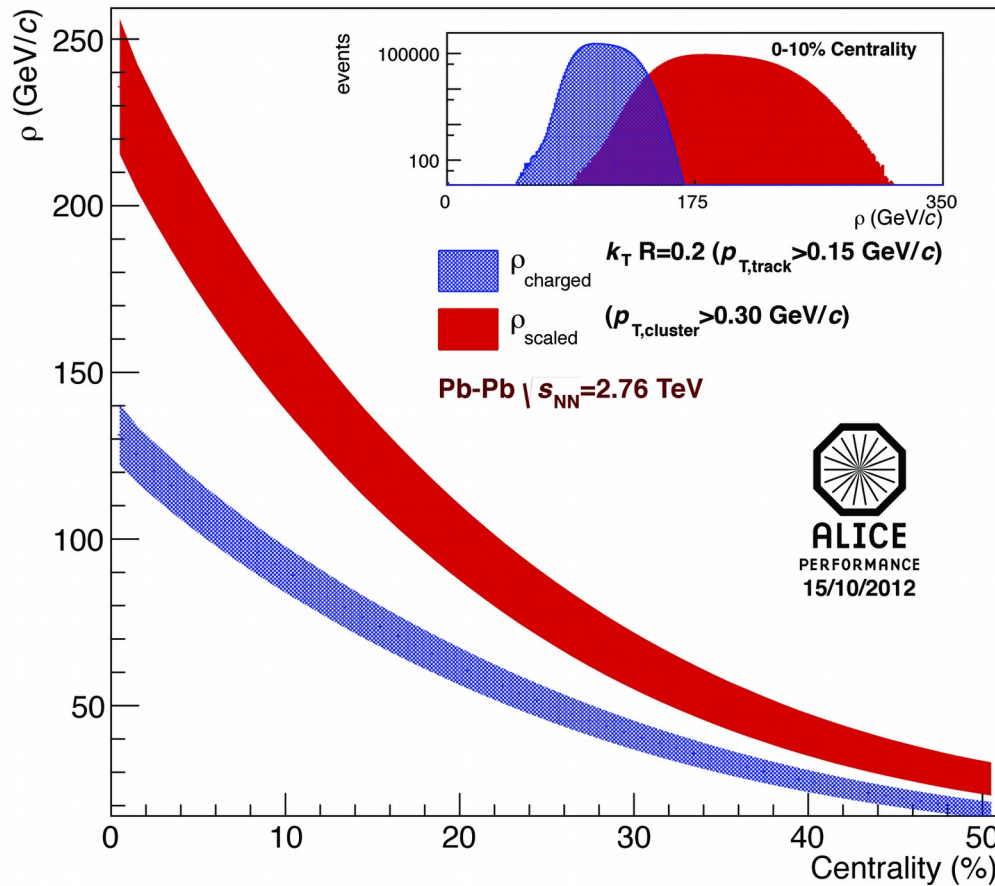
JHEP 1203:053, 2012  
(arxiv:1201.2423)



$$p_{T,jet}^{ch,unc} = p_{T,jet}^{rec} - \rho_{ch} A$$

# HI Background Determination

Full Jets  $\sqrt{s_{NN}} = 2.76$  TeV



ALI-PERF-44505

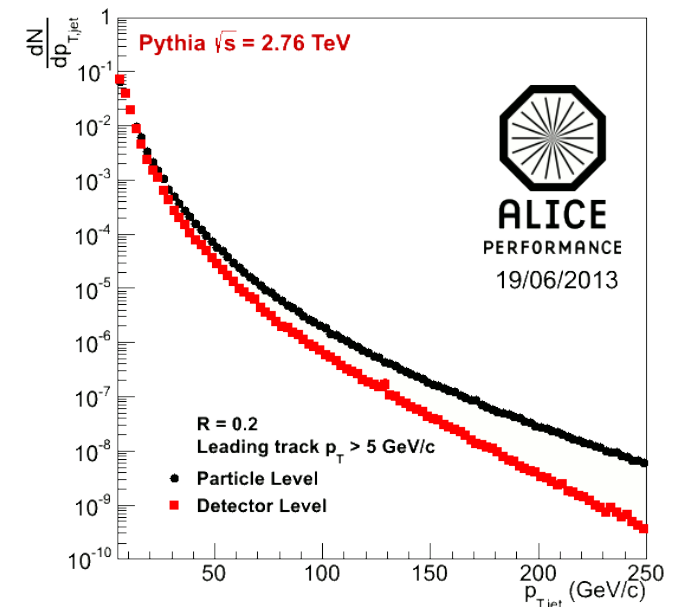
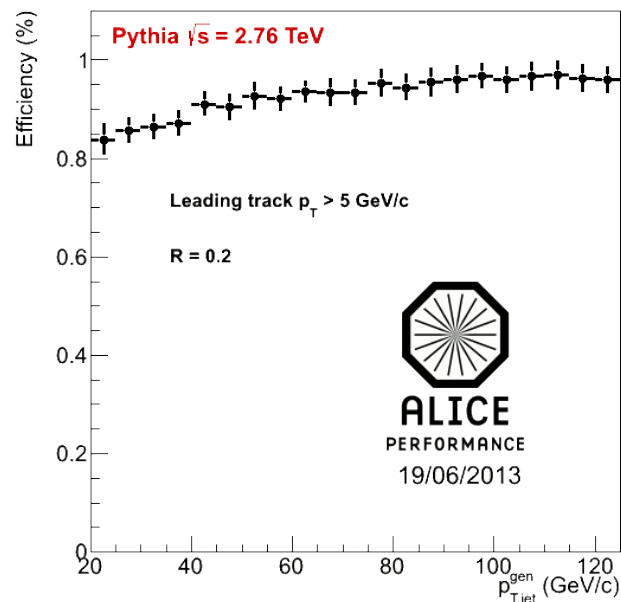
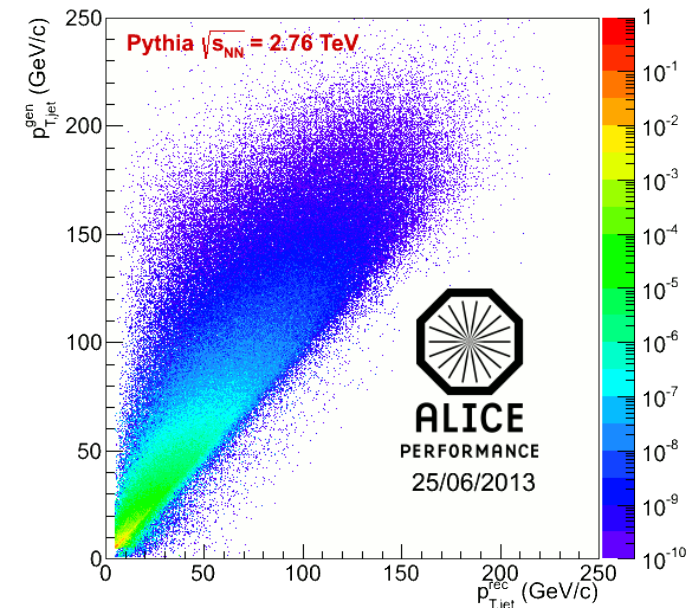
ALI-PERF-44509

Centrality dependent scale factor accounts for neutral energy

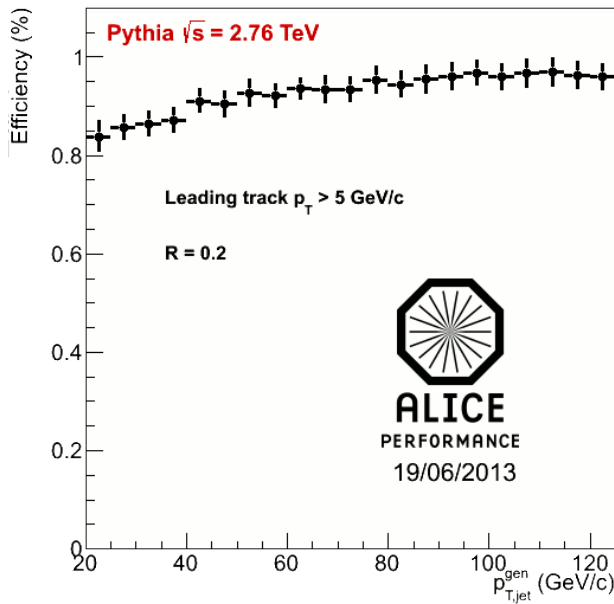
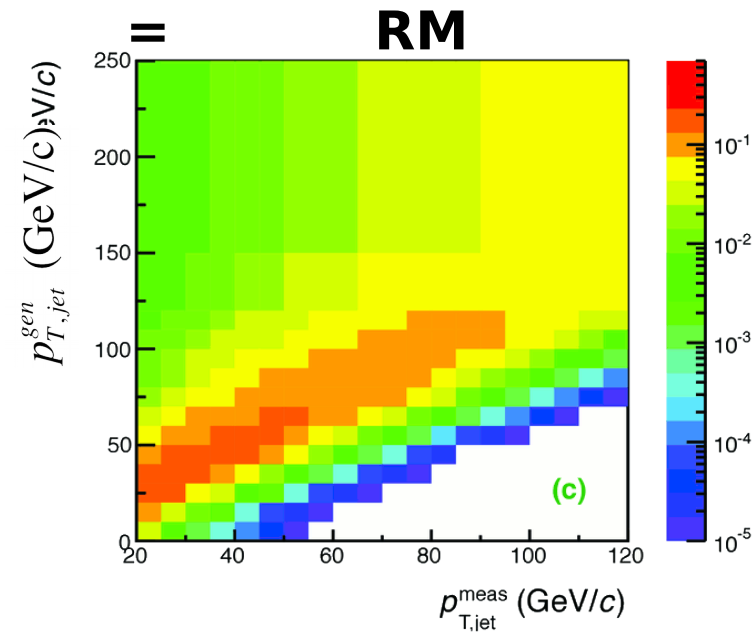
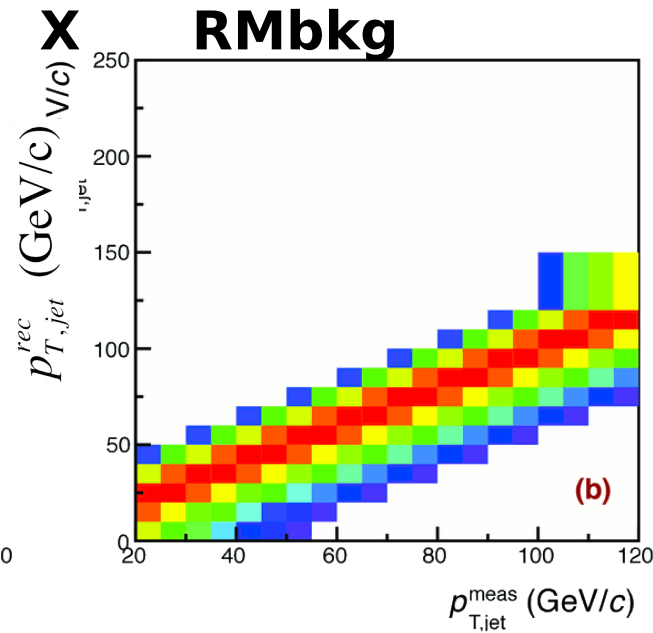
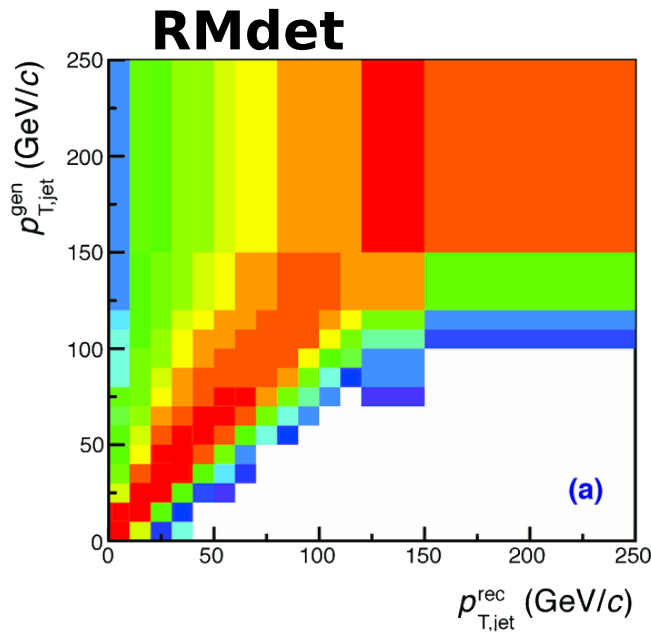
$$\rho_{\text{scaled}} = \rho_{\text{ch}} \times \rho_{\text{EMC}}$$

# Response matrix $RM_{\text{det}}$

- $RM_{\text{det}}$  quantifies detector response to jets
  - “Particle” level jets – defined by jet finder on MC particles
  - Pythia with Pb-Pb tracking efficiency
  - “Detector” level jets – defined by jet finder after event reconstruction through GEANT
  - Particle level jets are geometrically matched to detector level jets
  - Matrix has a dependence on spectral shape and fragmentation
- Jet-finding efficiency is probability of a matched particle level jet



# Response Matrix Construction



Anti- $k_T$   $R=0.2$

$p_{T,track} > 0.15$  GeV/c

$E_{T,cluster} > 0.30$  GeV

$p_{T,track}^{leading} > 5$  GeV/c

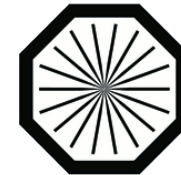
(a)  $RM_{det}$  Detector response matrix

(b)  $RM_{bkg}$  Background fluctuation matrix

(c)  $RM_{tot} = RM_{bkg} \times RM_{det}$

Pb-Pb  $\sqrt{s_{NN}} = 2.76$  TeV

0-10% Centrality

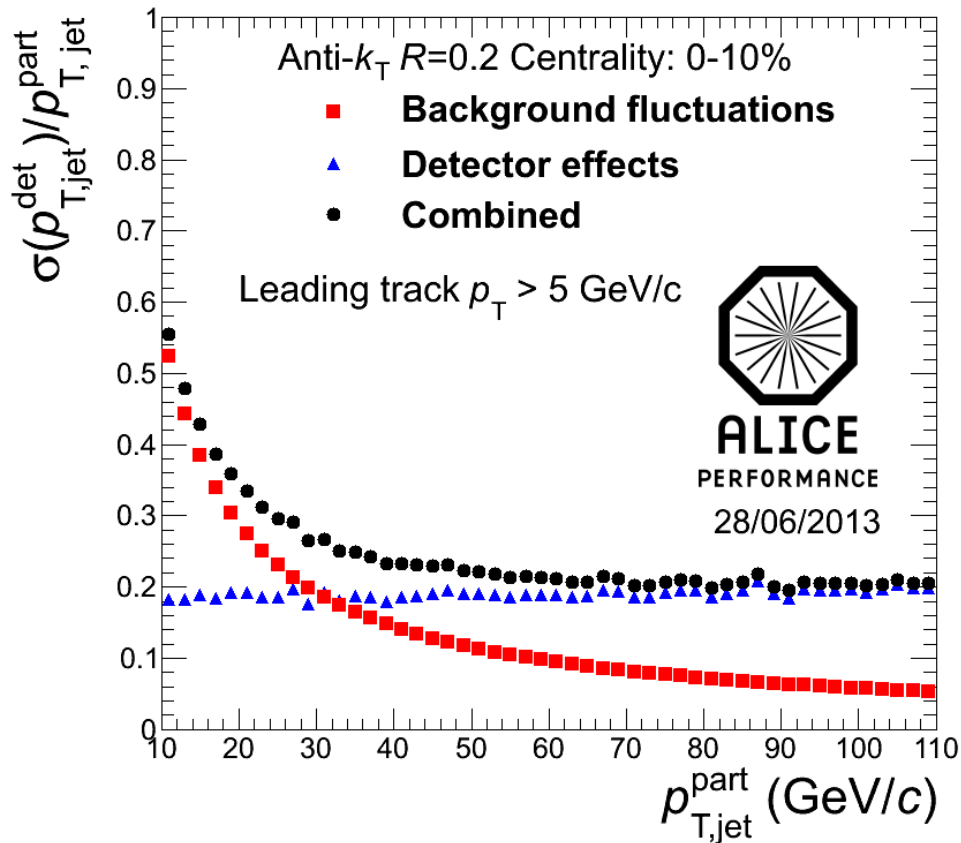


ALICE  
PERFORMANCE  
15/10/2012

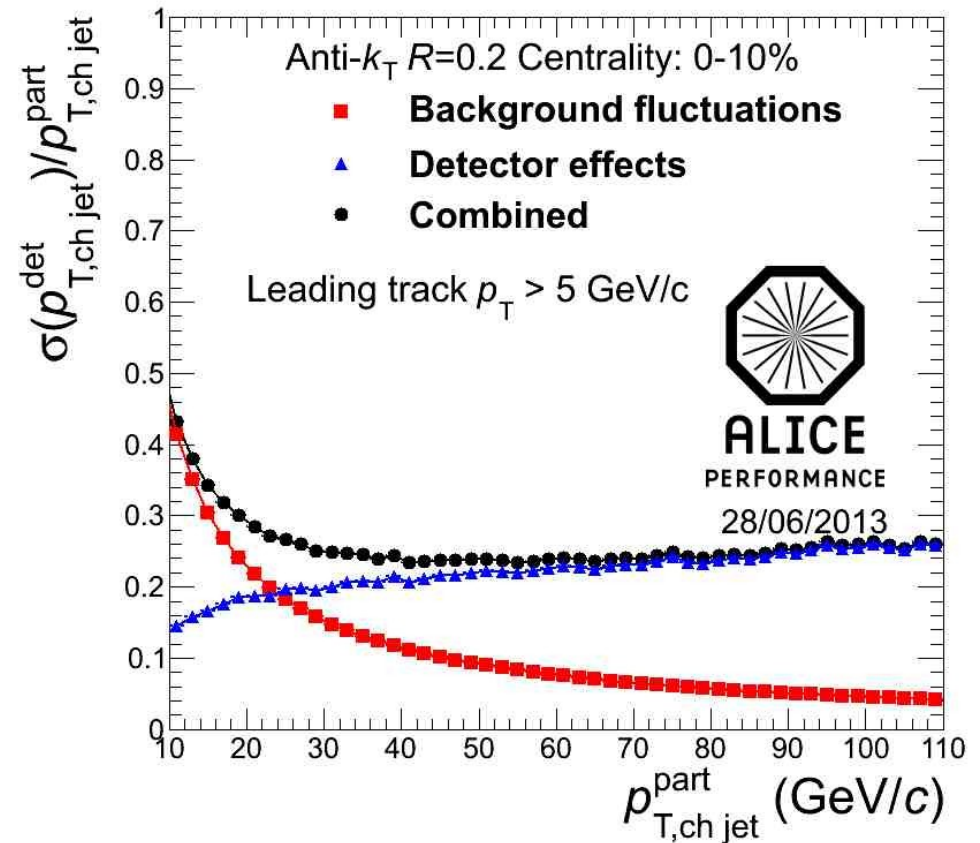
$RM_{bkg}$  and  $RM_{det}$  are approximately factorizable

# Jet Resolution

Full



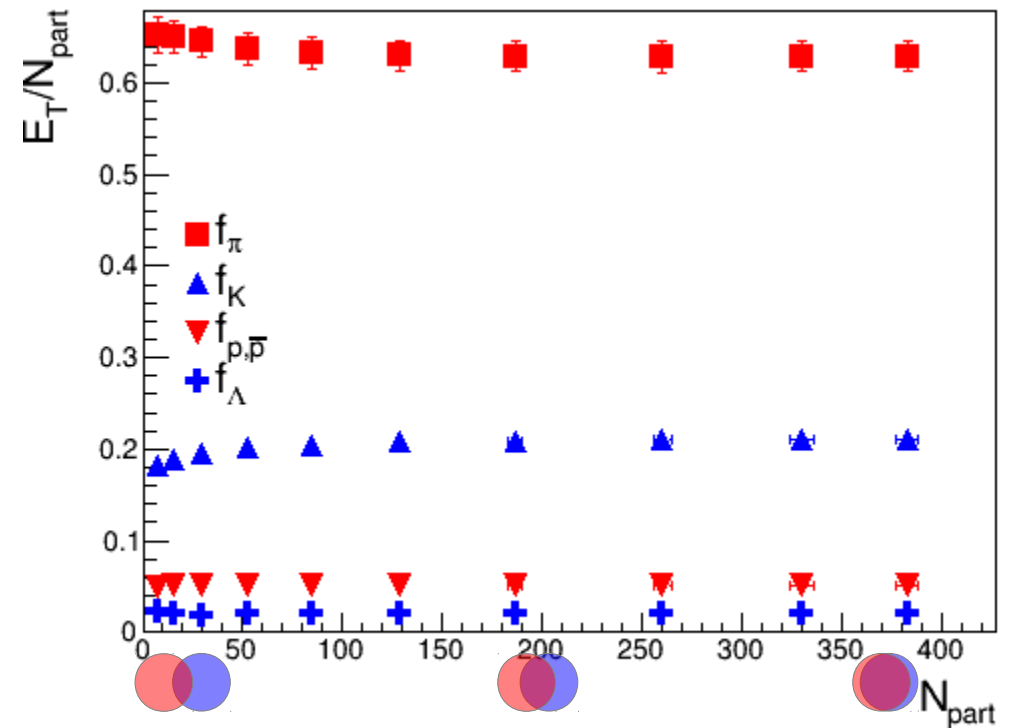
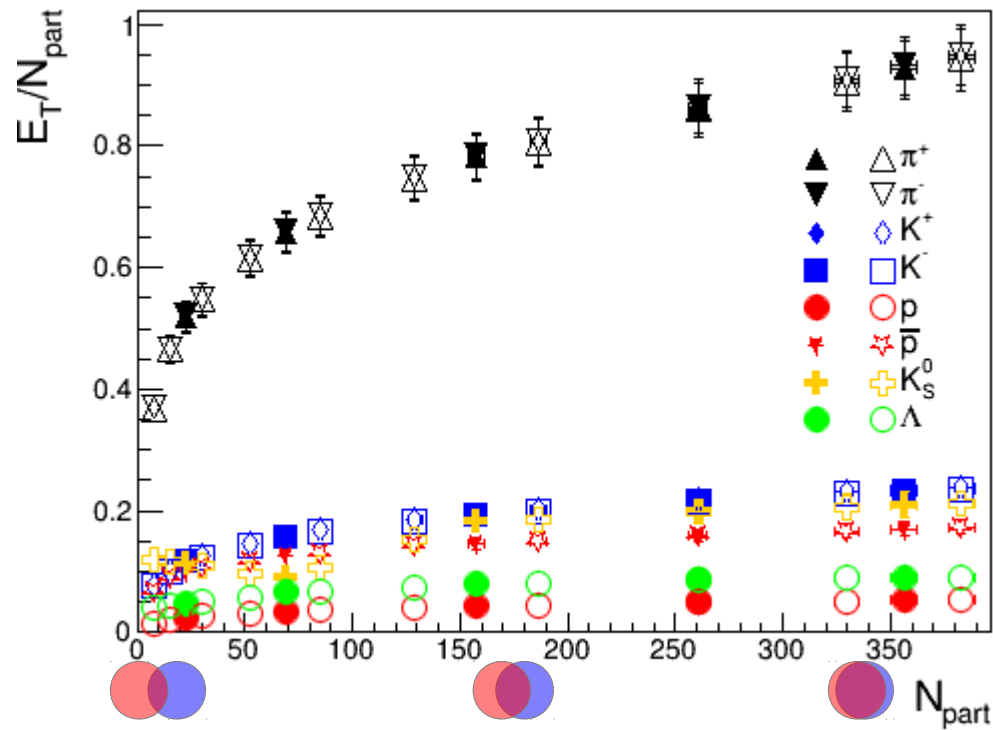
Charged



## • Jet resolution

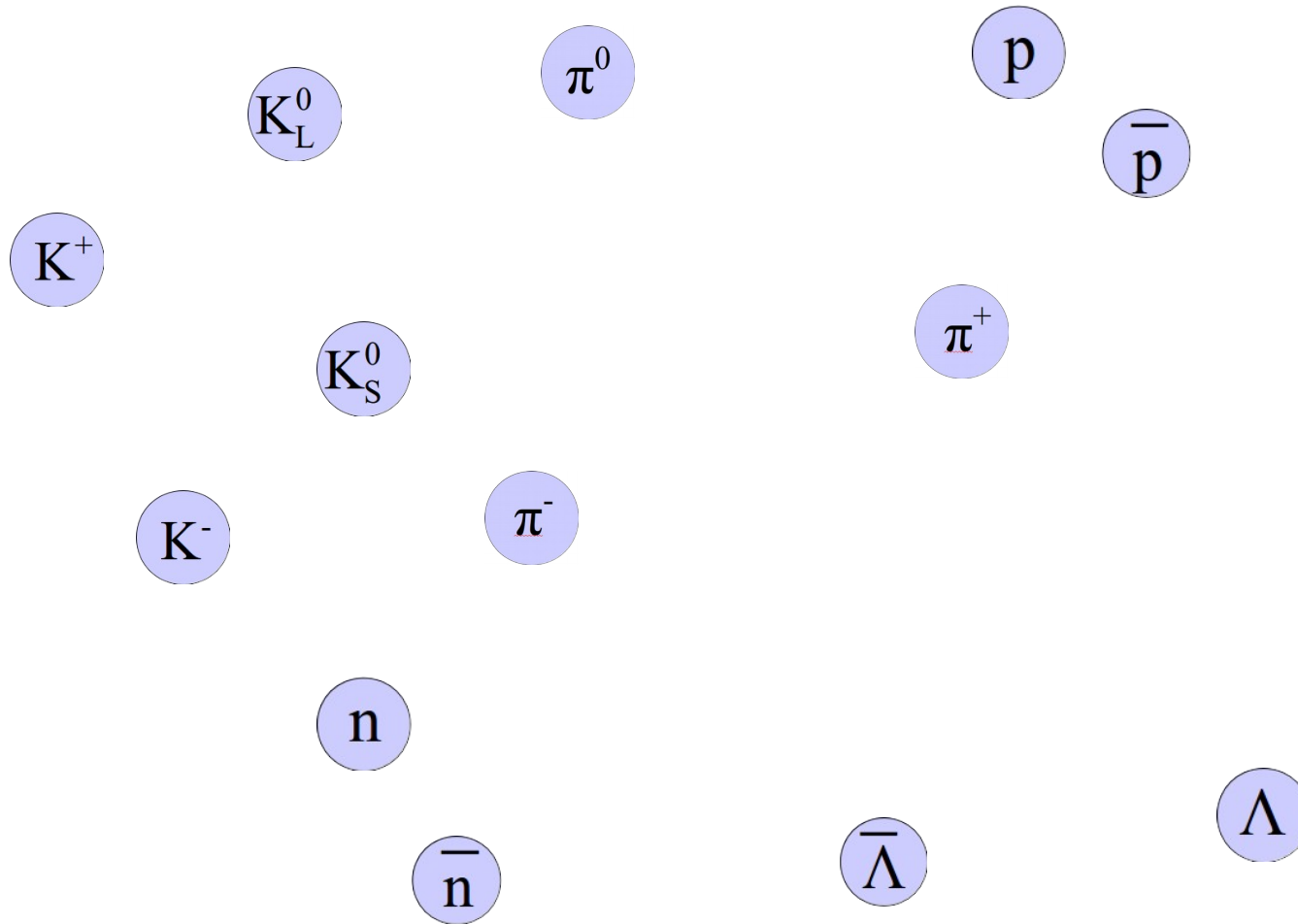
- Dominated by background fluctuations at low momentum
- Dominated by detector effects at high momentum

# Calculations from spectra



The distribution of energy is surprisingly centrality independent.

# Building blocks



Size of circles proportional to the fraction of energy in that particle  
Scale: diameter in inches =  $\sqrt{\text{fraction}} * 5$