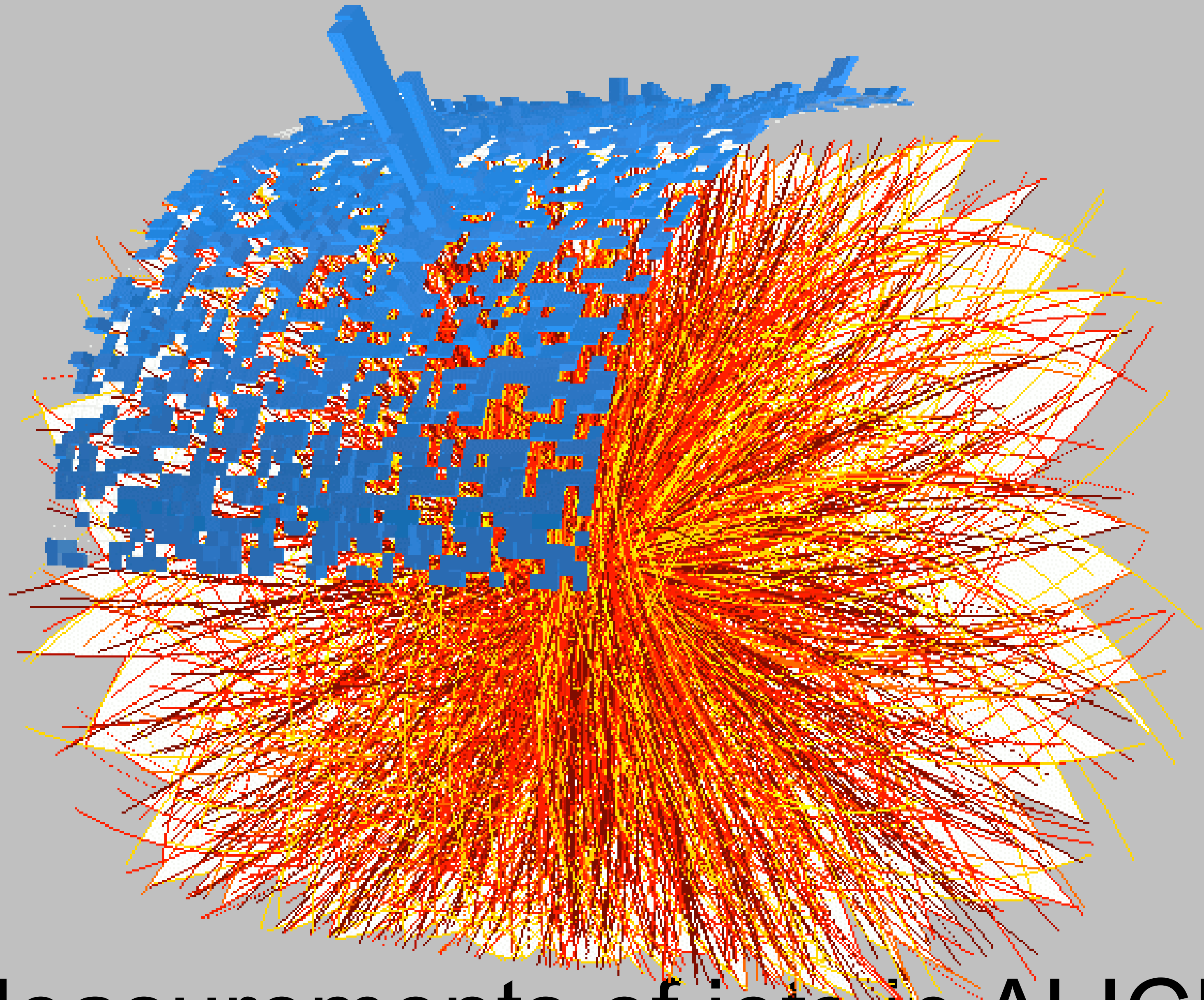
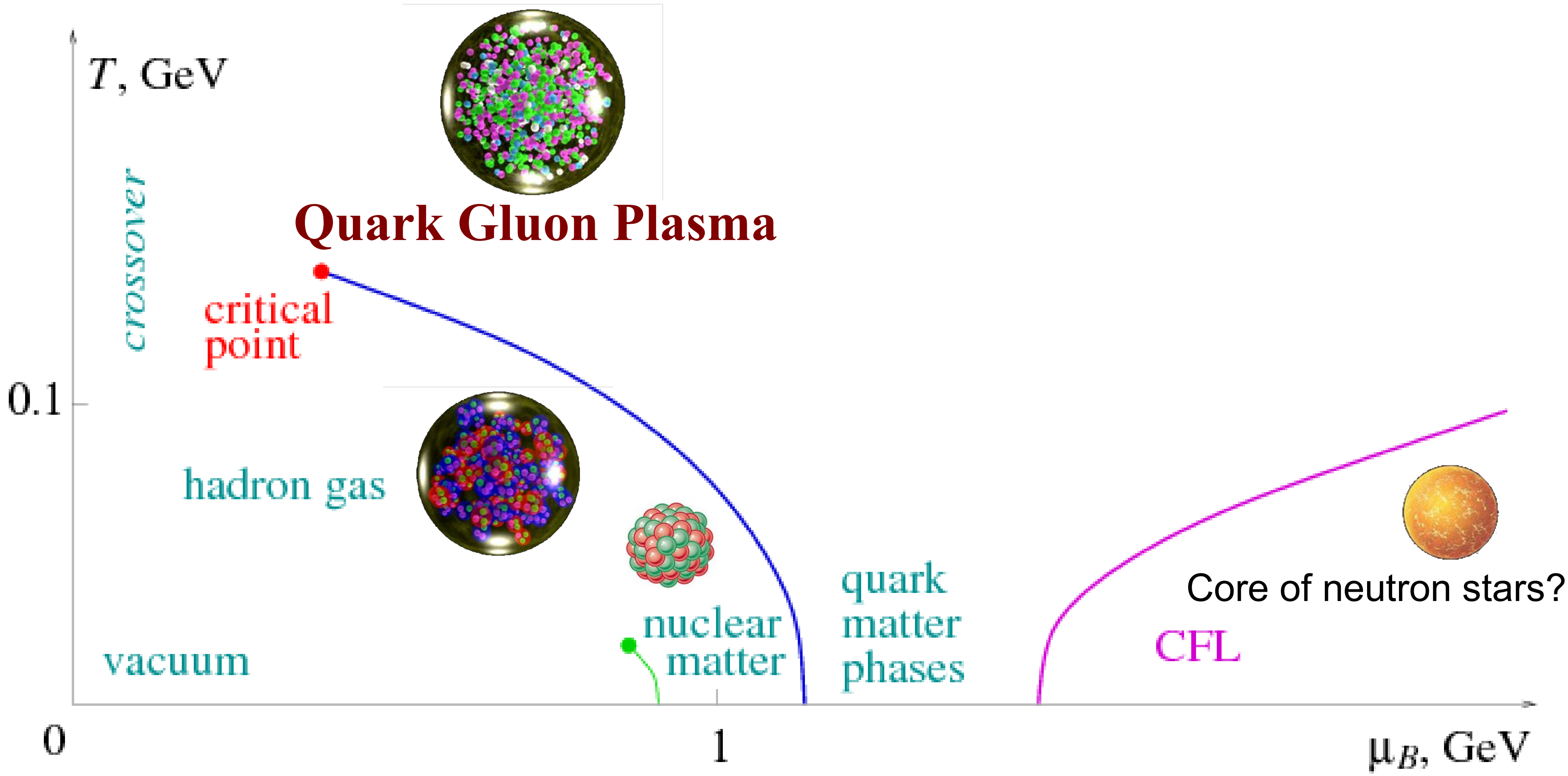


Measurements of jets in ALICE

Christine Nattrass
University of Tennessee, Knoxville

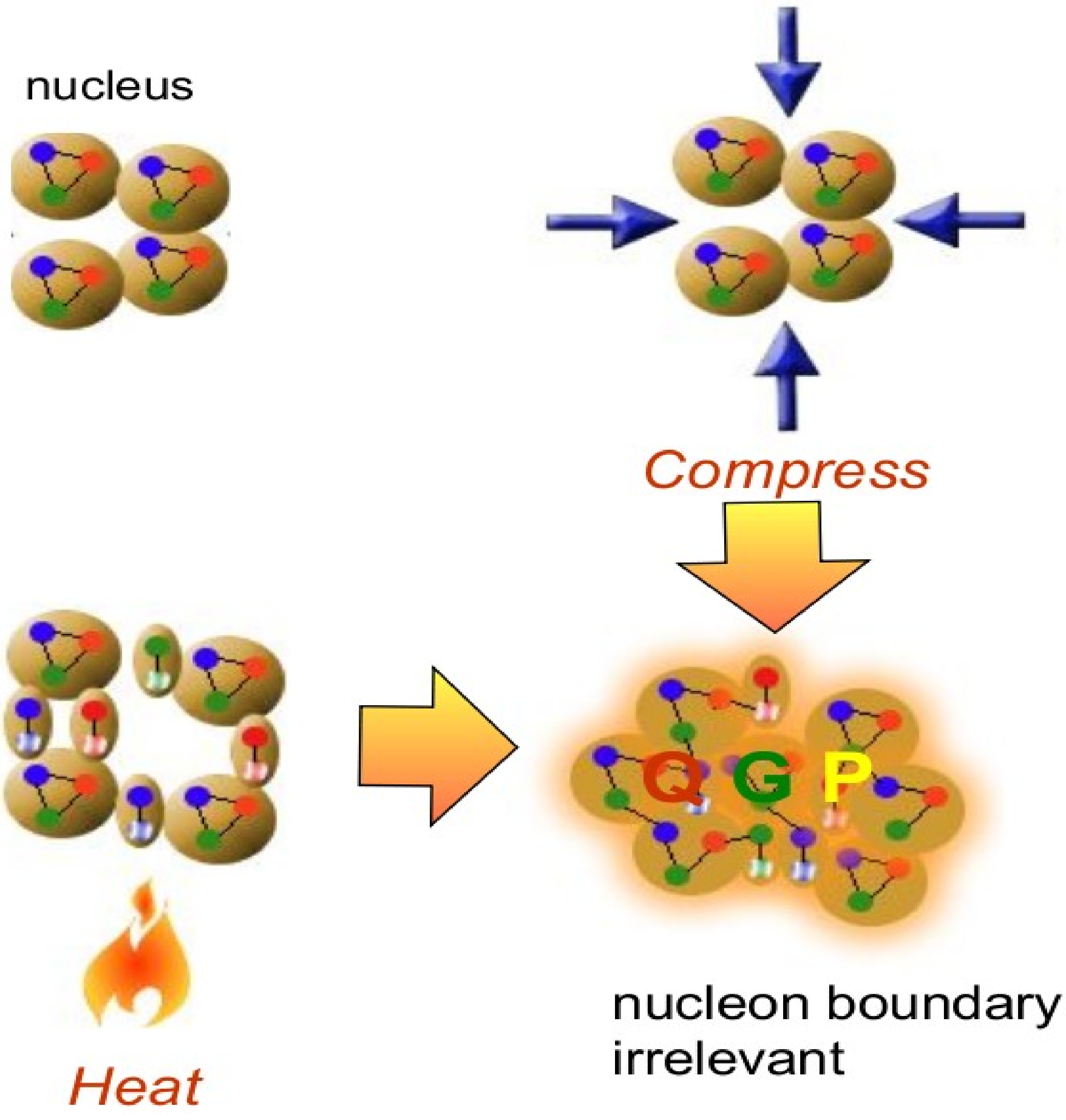
How I learned to stop worrying and love the Quark Gluon Plasma

Phase diagram of nuclear matter

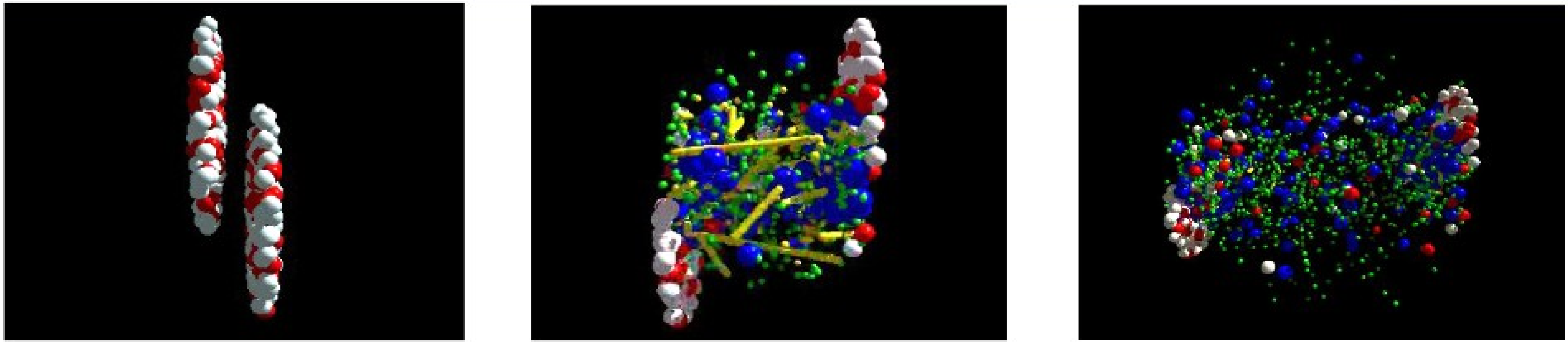


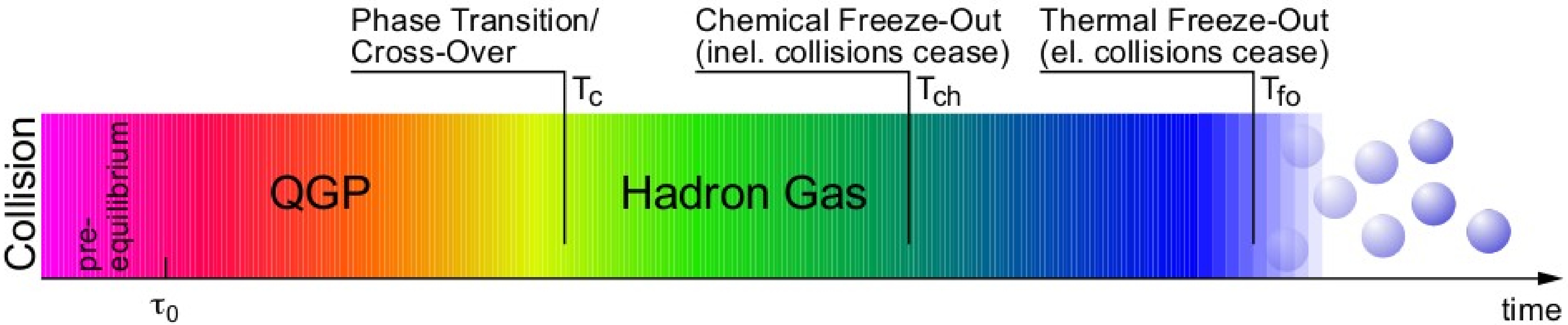
Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun

How to make a Quark Gluon Plasma

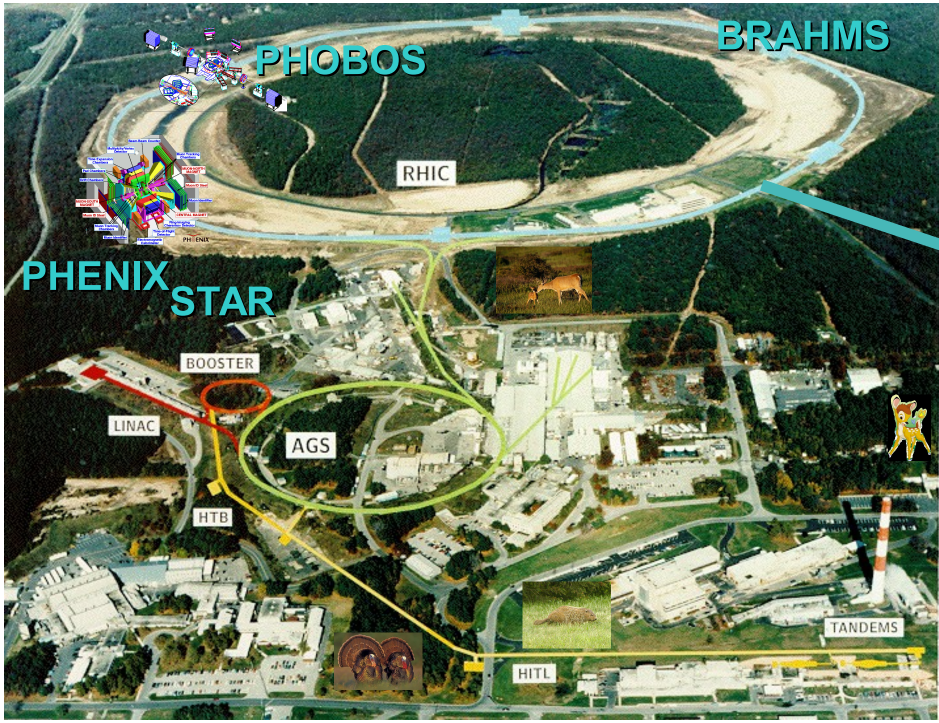


The phase transition in the laboratory



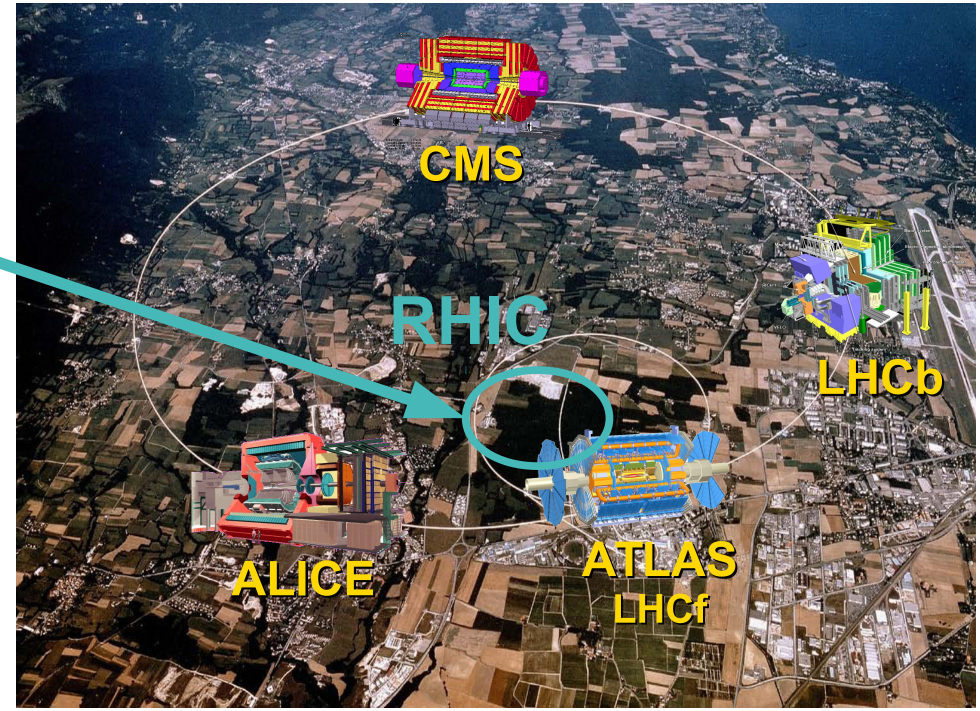


Relativistic Heavy Ion Collider

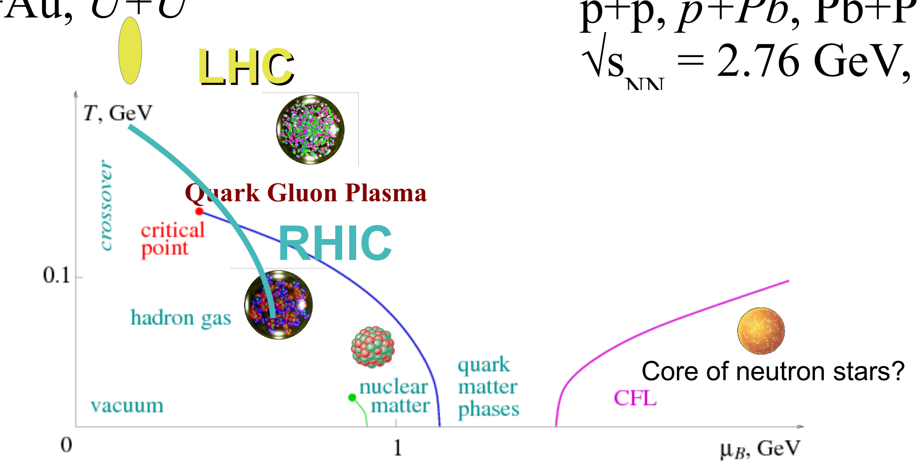


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*



Comparison of colliders

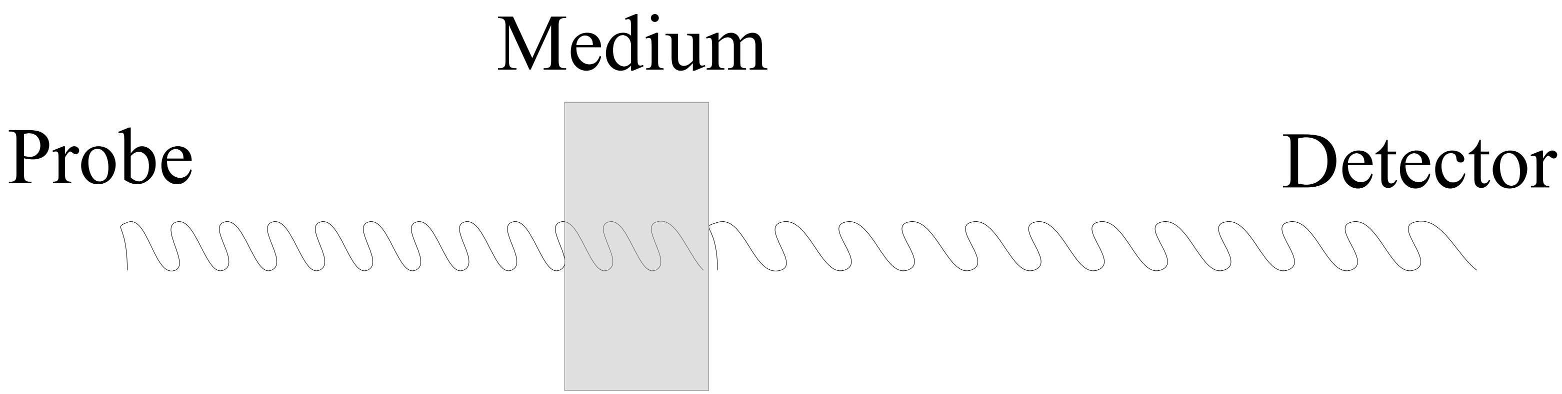
	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	~15	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

RHIC and LHC:

Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$= 9 GeV –5.5 TeV)

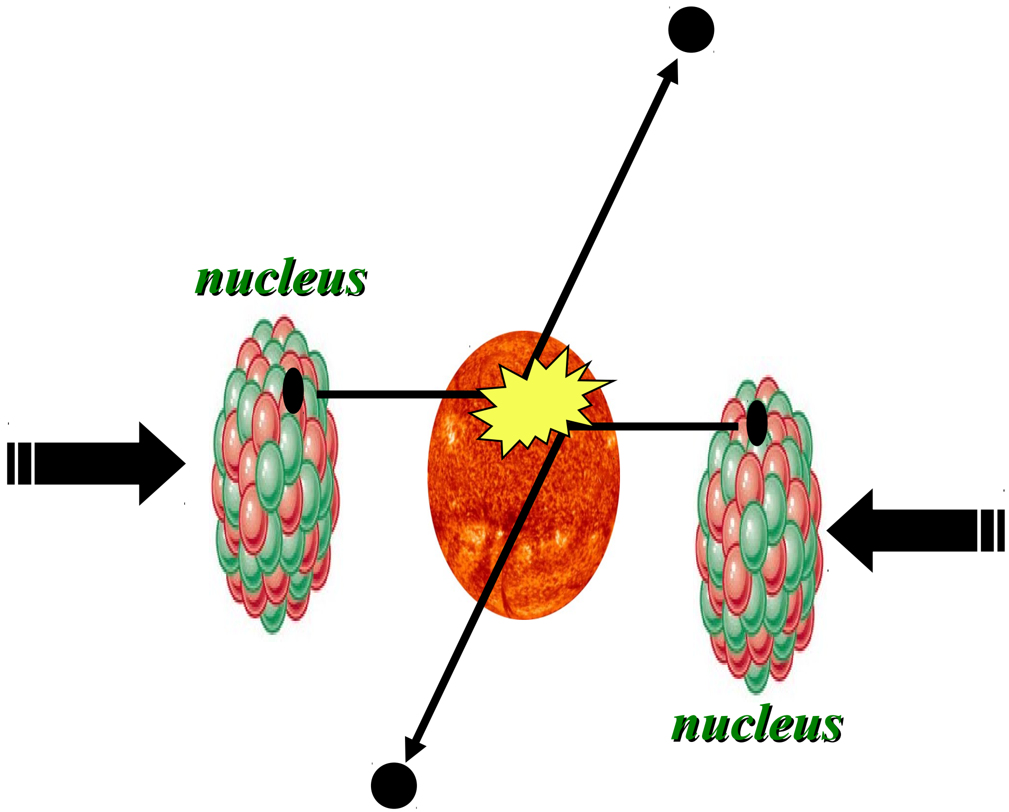
To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

Probing the Quark Gluon Plasma



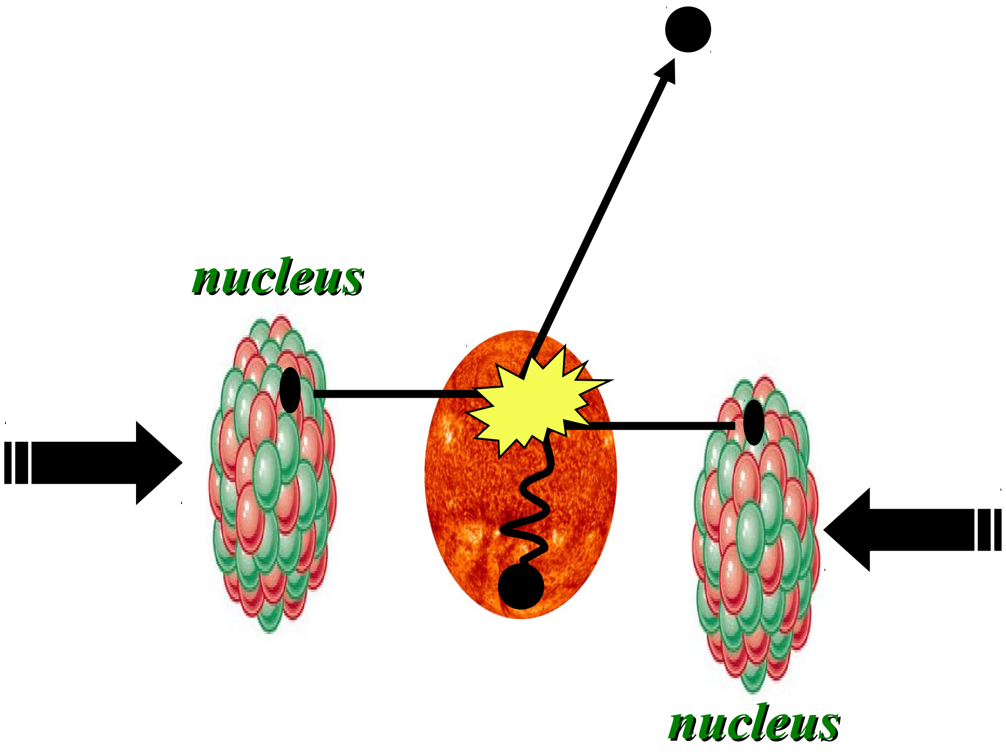
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



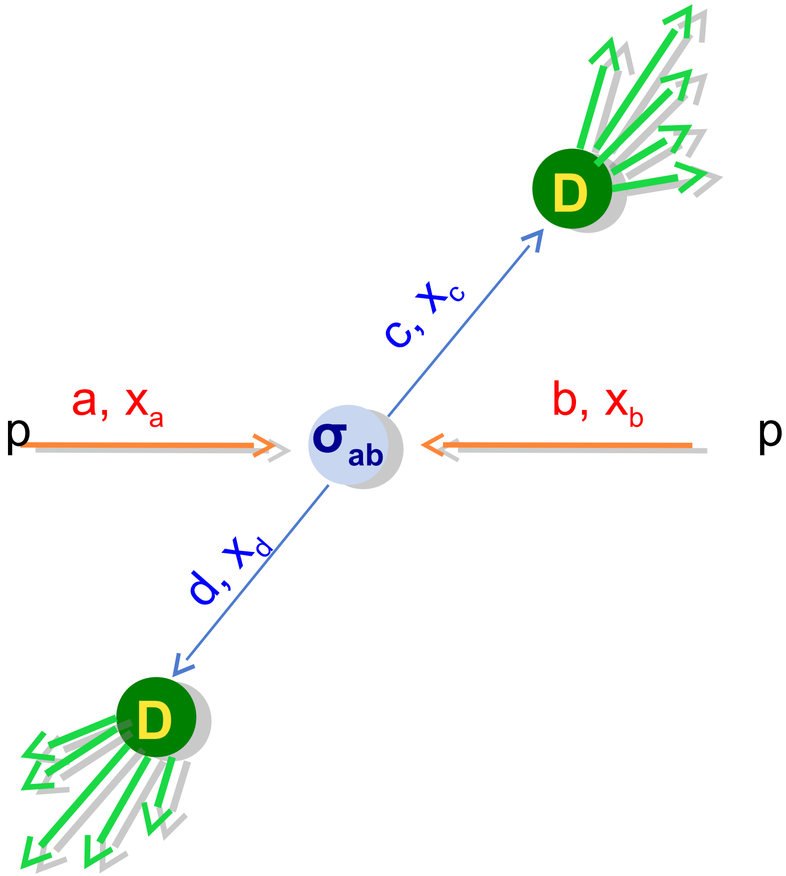
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

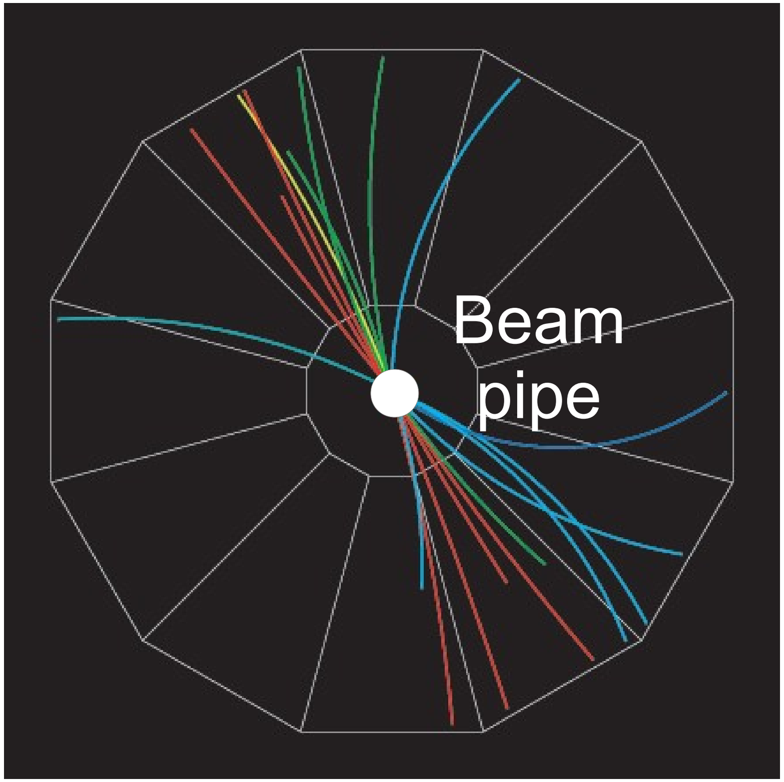


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

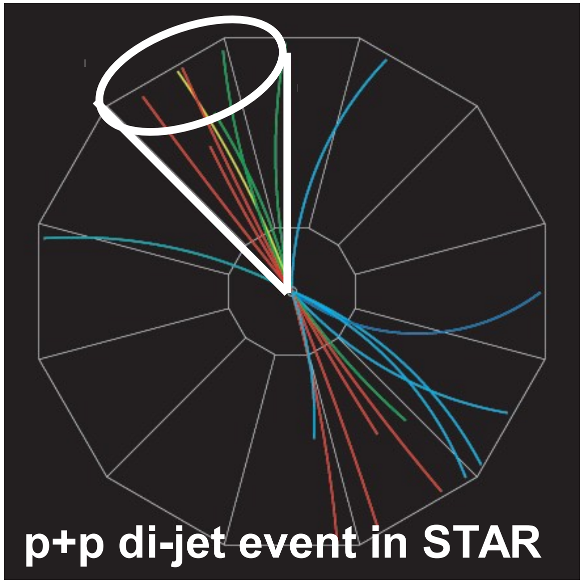


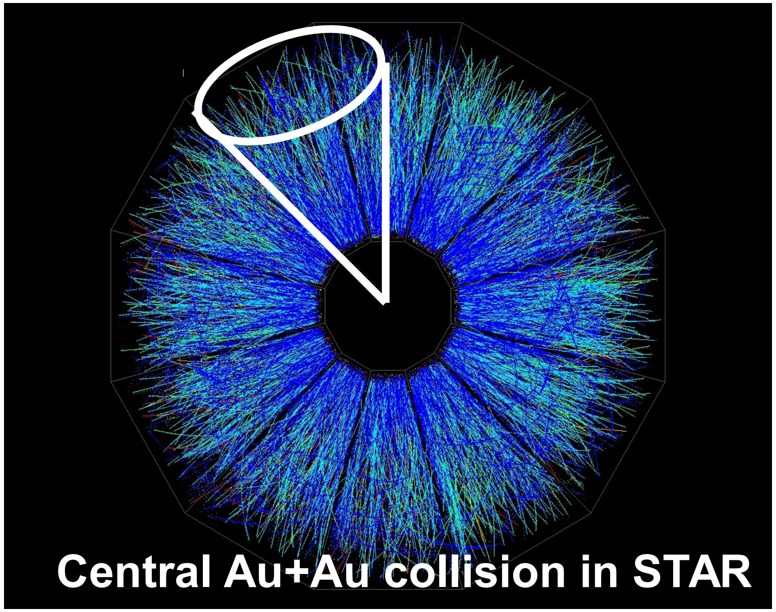
p+p → dijet



Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

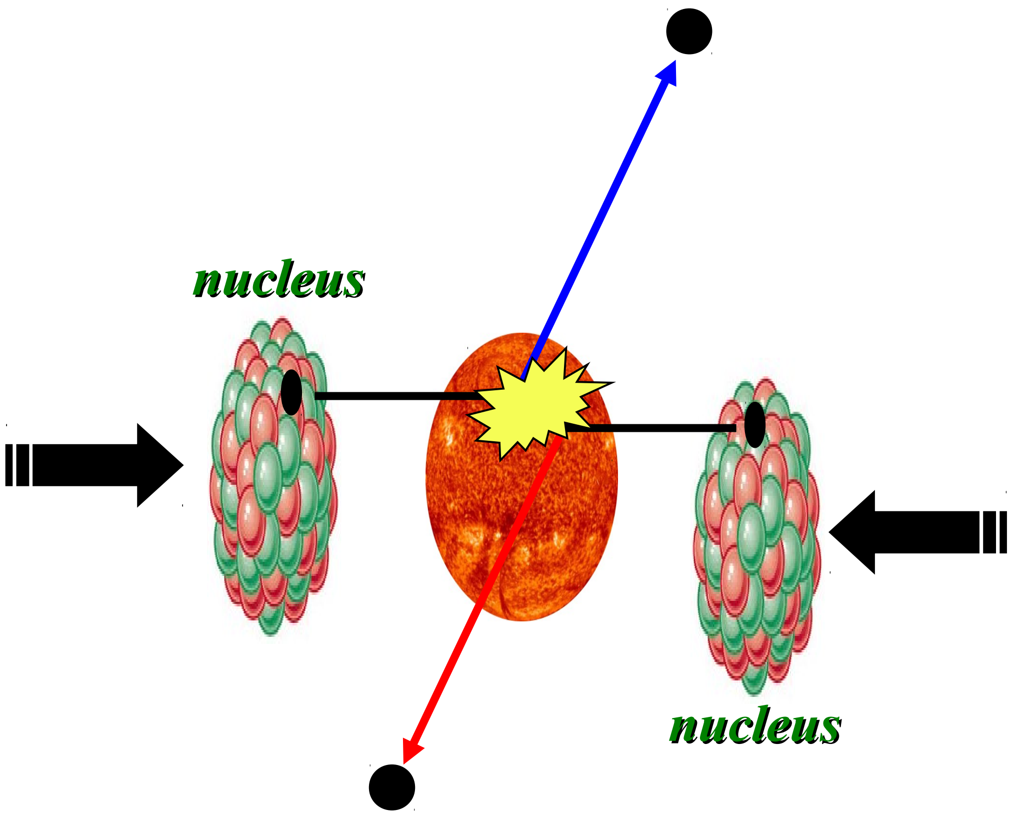
Jet reconstruction



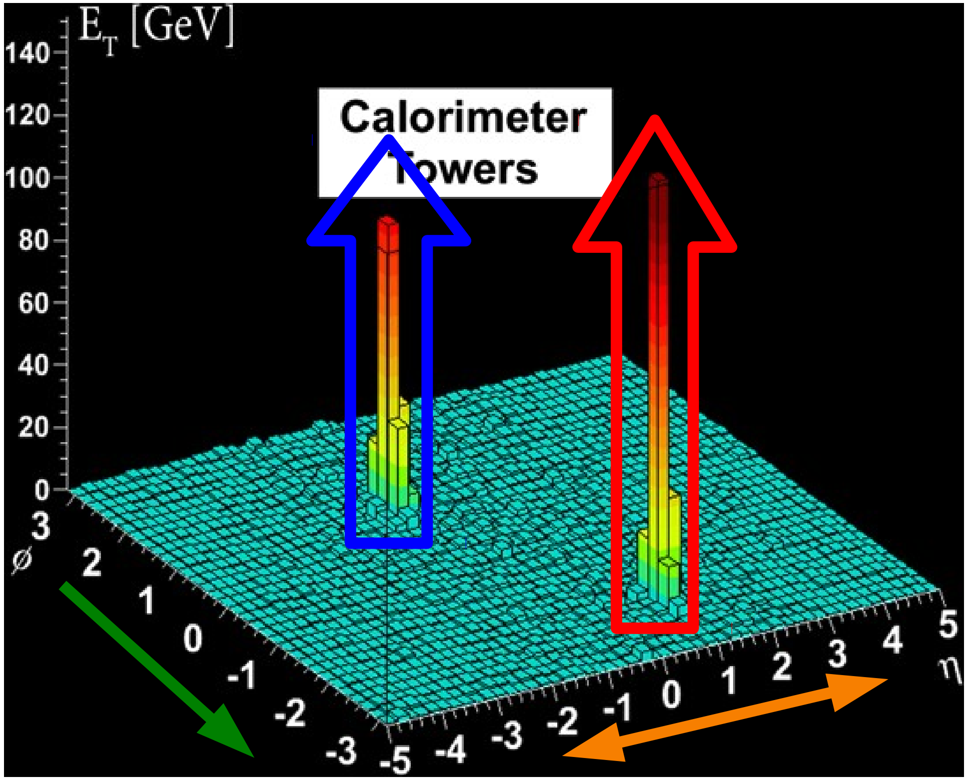


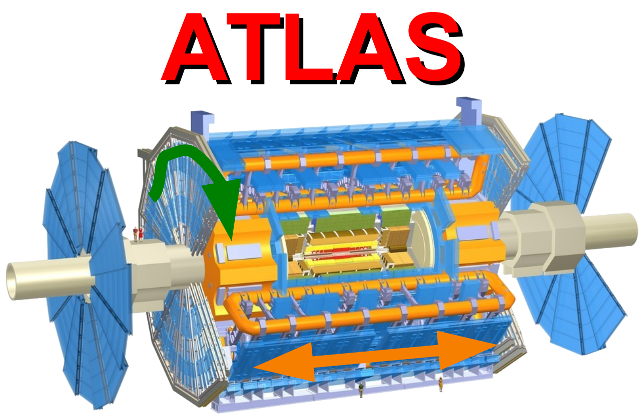
- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

Jets

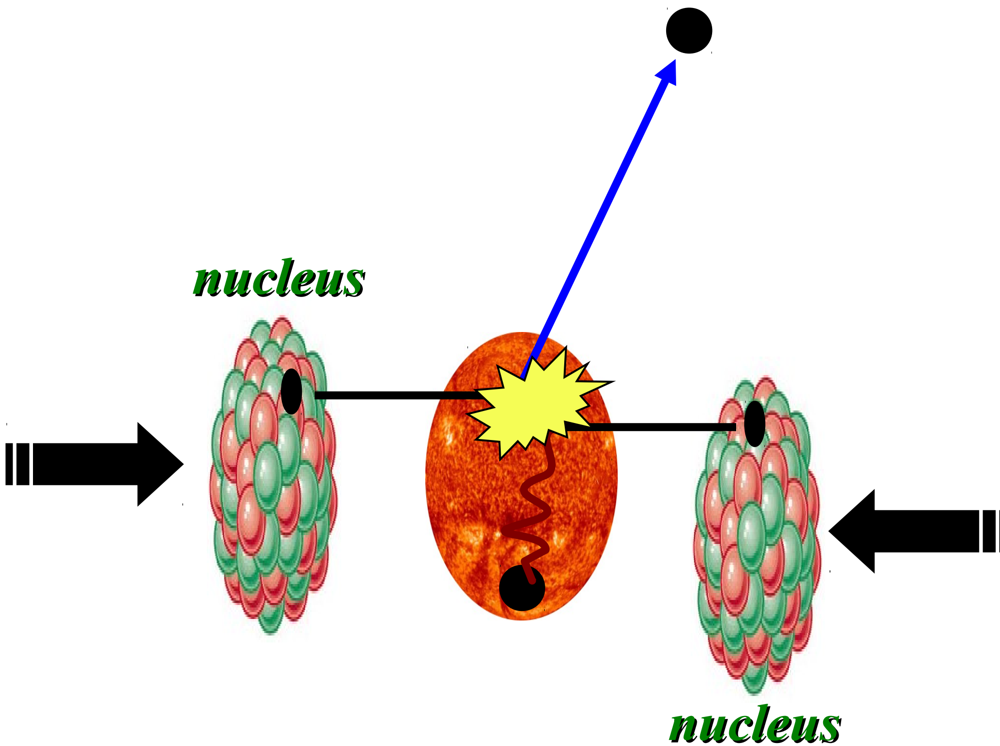


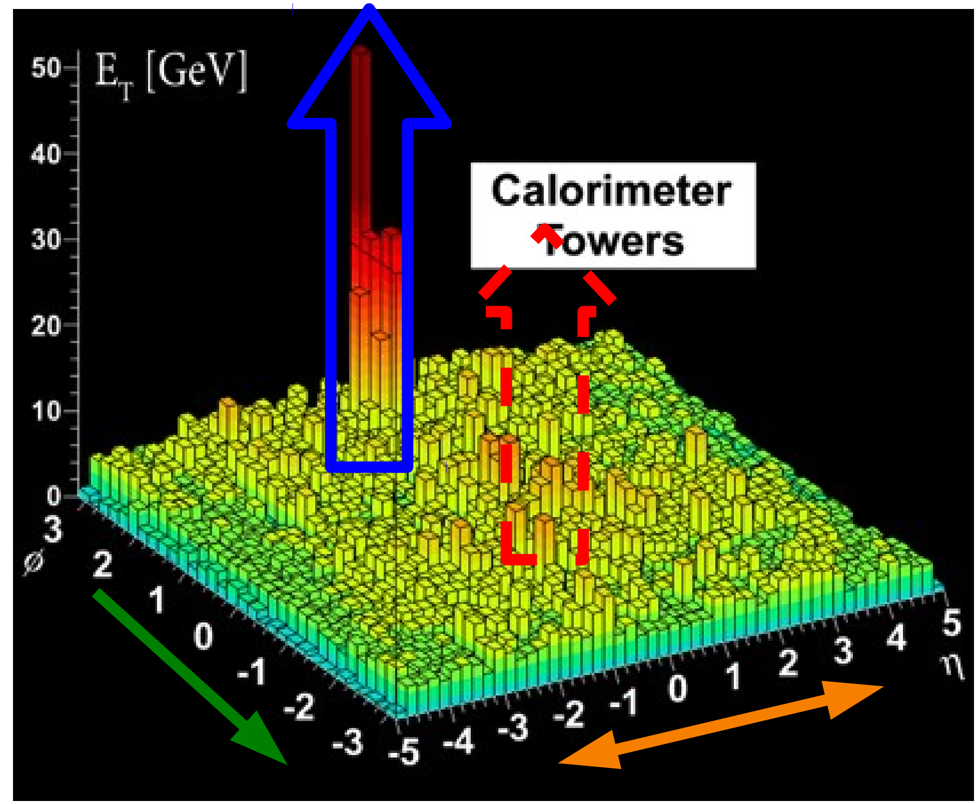
Phys.Rev.Lett. 105 (2010) 252303

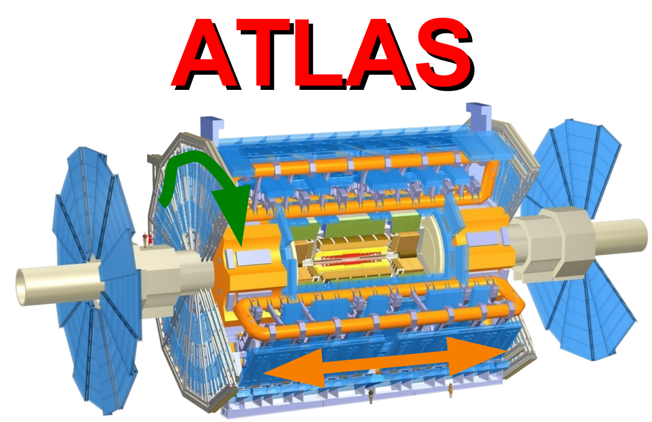




Quenched jets

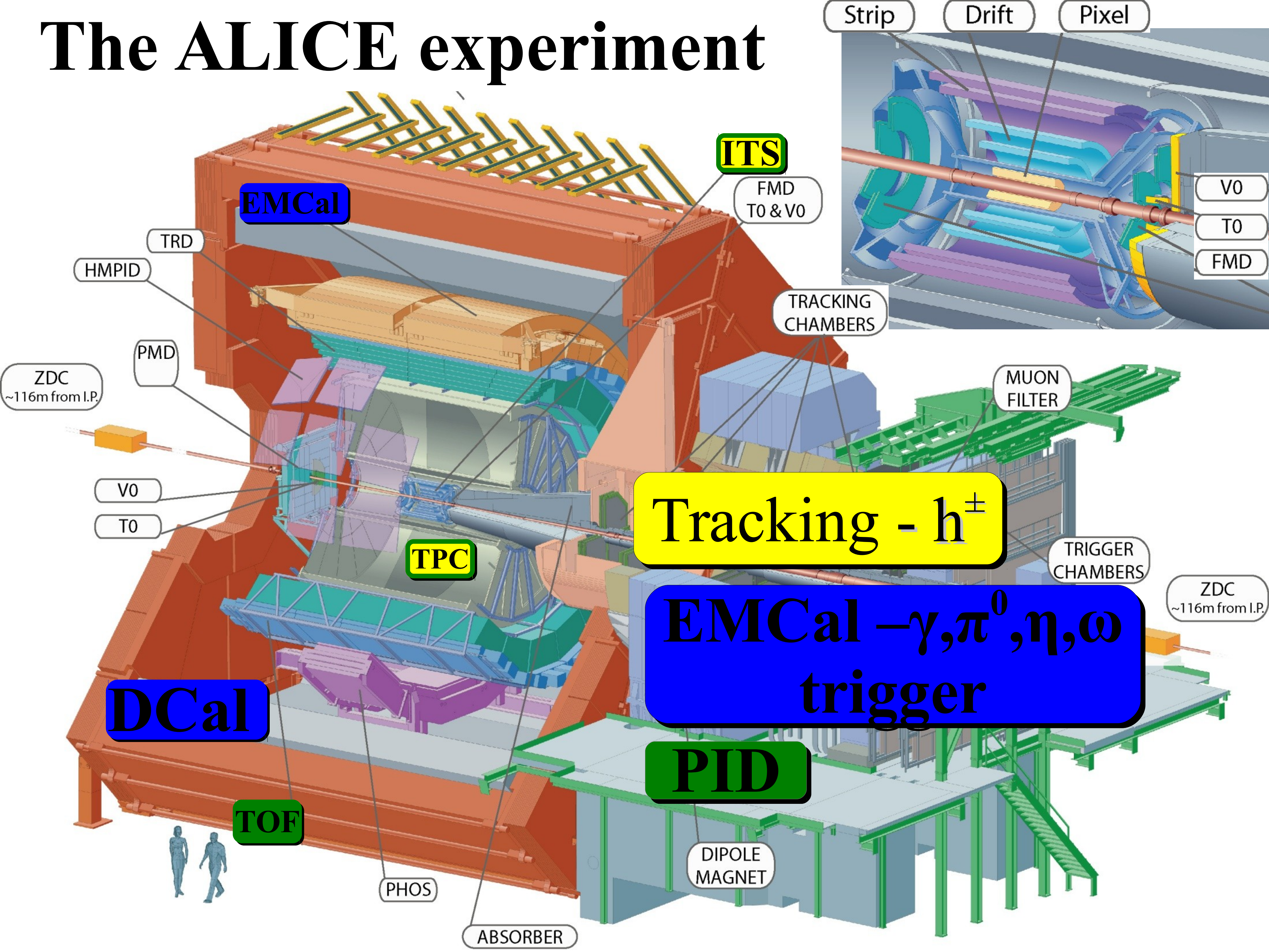




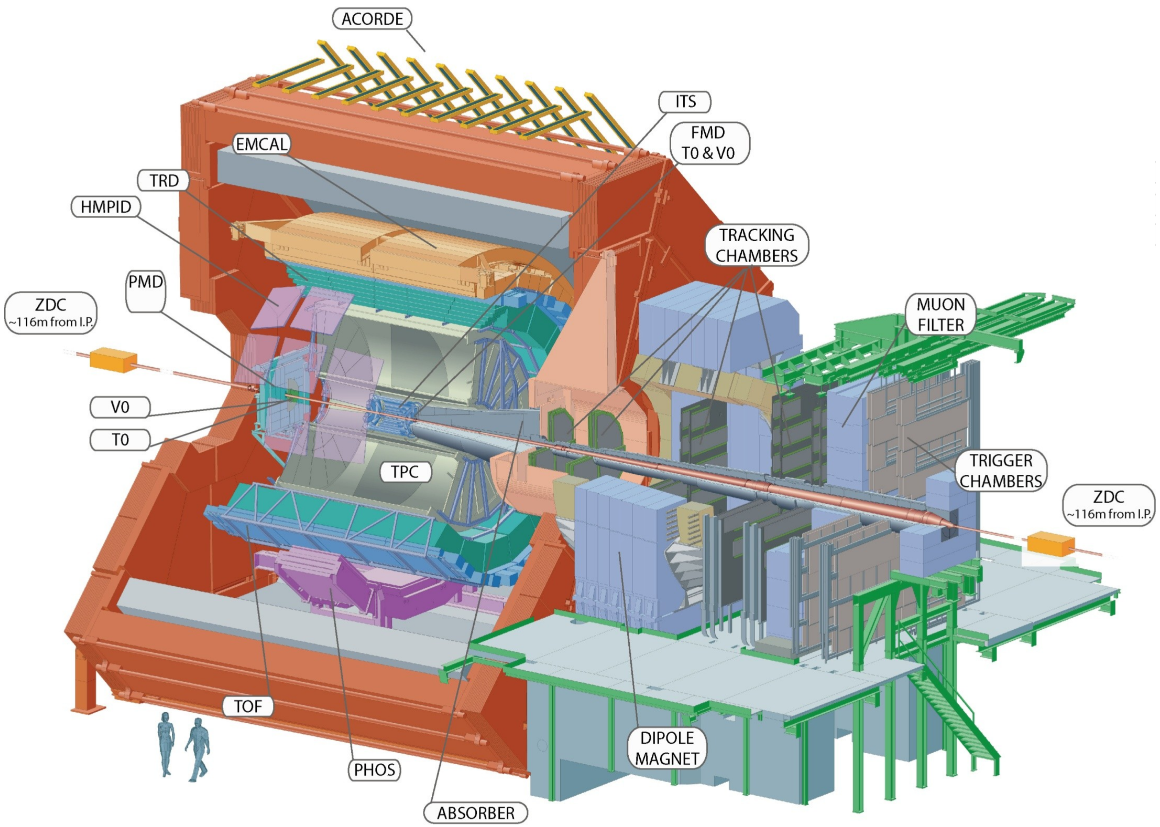


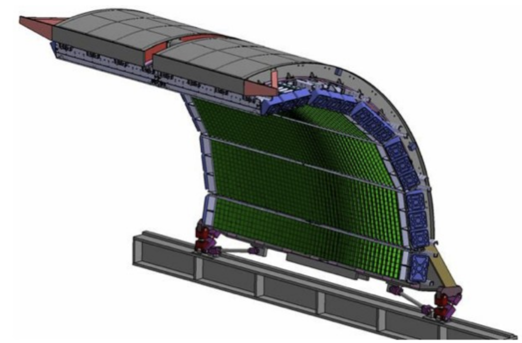
- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

The ALICE experiment



Jets in ALICE





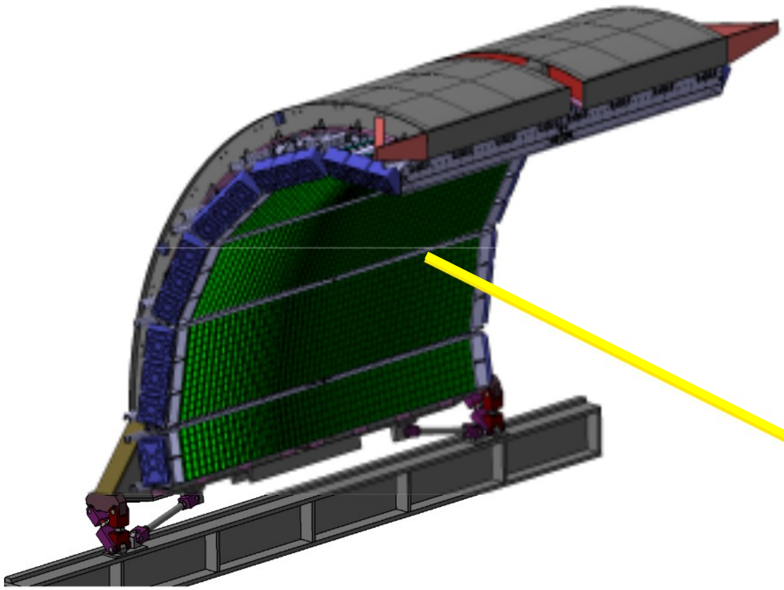
- EMCal is a Pb-scintillator sampling calorimeter which covers:
  - $|\eta| < 0.7,\ 1.4 < \phi < \pi$
  - tower $\Delta\eta \sim 0.014, \Delta\phi \sim 0.014$

Remove contamination from Charged particles

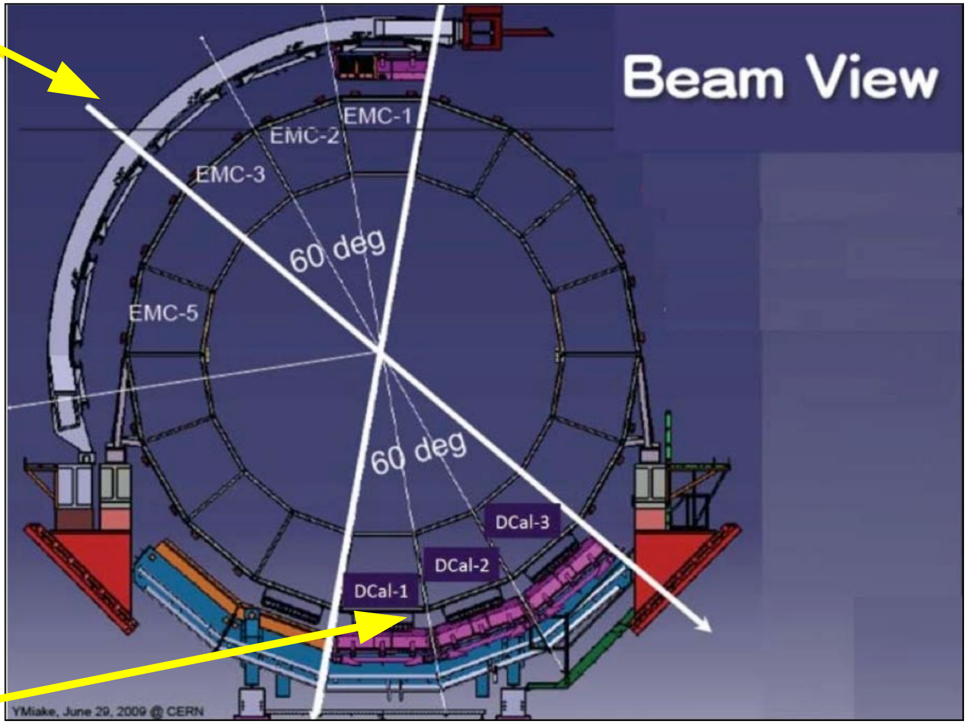
Neutral constituents

Tracking: $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
TPC, ITS → ***Charged constituents*** → **Jet**

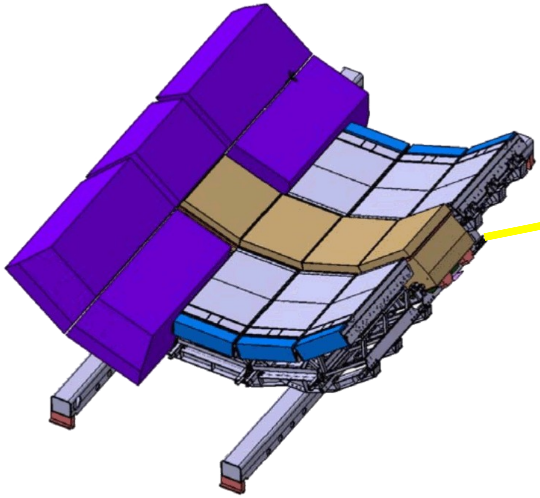
EMCal & DCal



$\Delta\eta=1.4, \Delta\varphi=107^o$



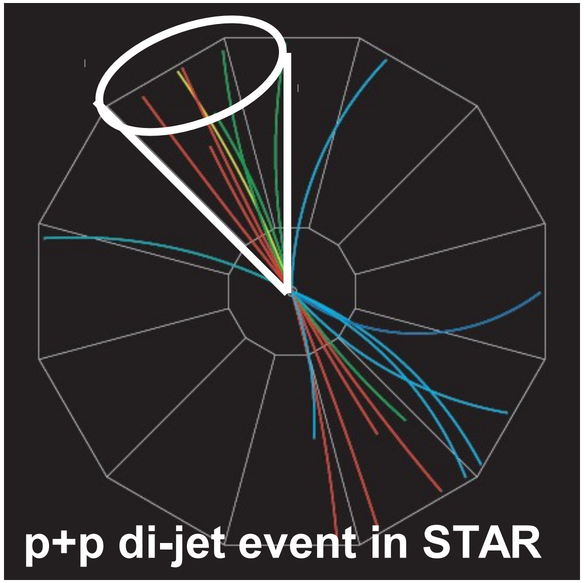
Installed by Fall 2014
$\Delta\eta=1.4, \Delta\varphi=60^o$



- Lead-scintillator sampling calorimeter
- 13 k towers
- Each tower $\Delta\eta$ X $\Delta\varphi$= 0.014 X 0.014
- $\sigma(E)/E=0.12/\sqrt{E} + 0.02$

Method

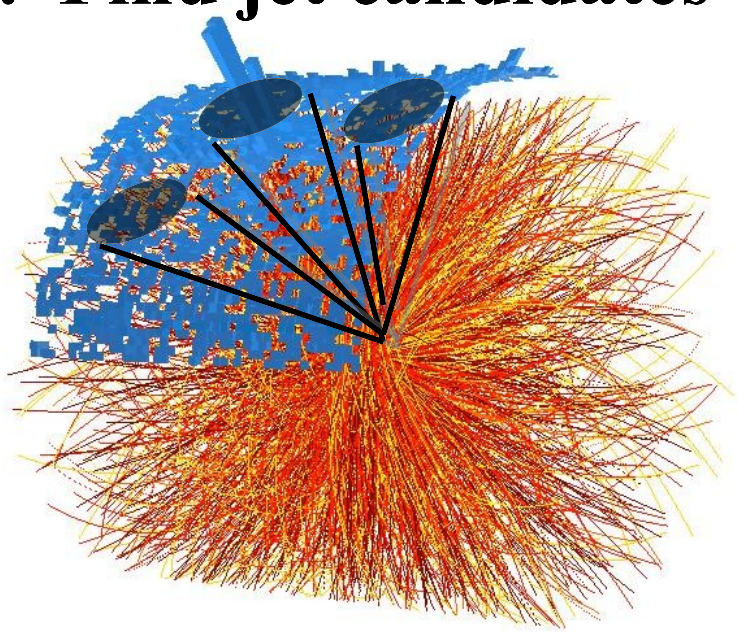
Jet reconstruction



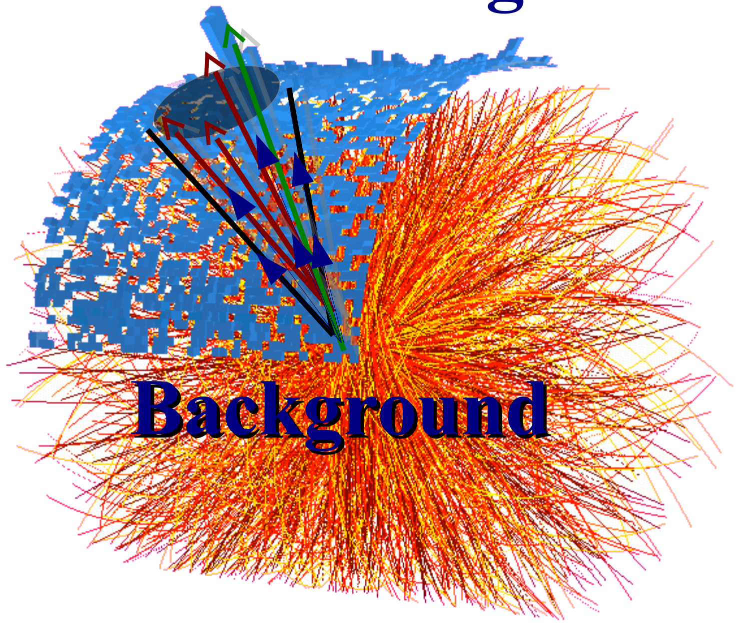
- **Jet finder:** algorithm for grouping particles (tracks and clusters) into jet candidates
- **Simple example:** cone algorithm – find a high p_T particle and draw a cone around it
- **Pretty picture:** A fully reconstructed jet tells you the original parton's momentum and energy
- **In practice:** A jet is what a jet finder finds.

Method

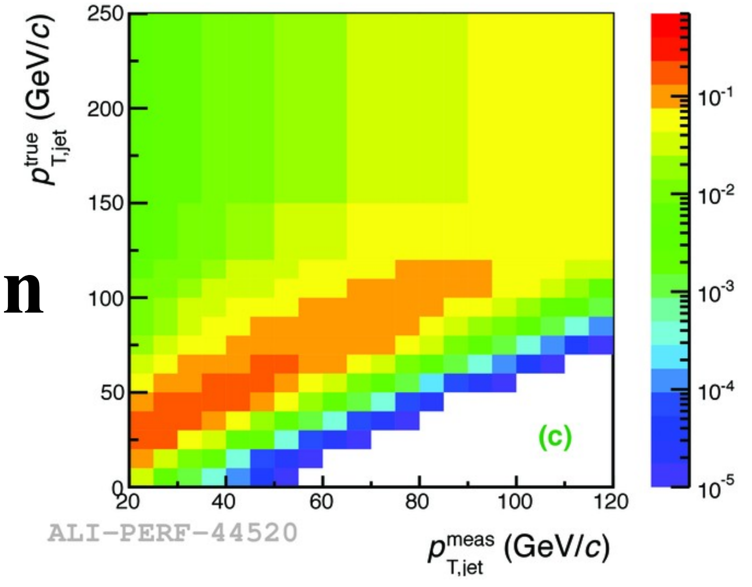
1. **Find jet candidates**



2. **Subtract background**



3. **Correct for resolution**

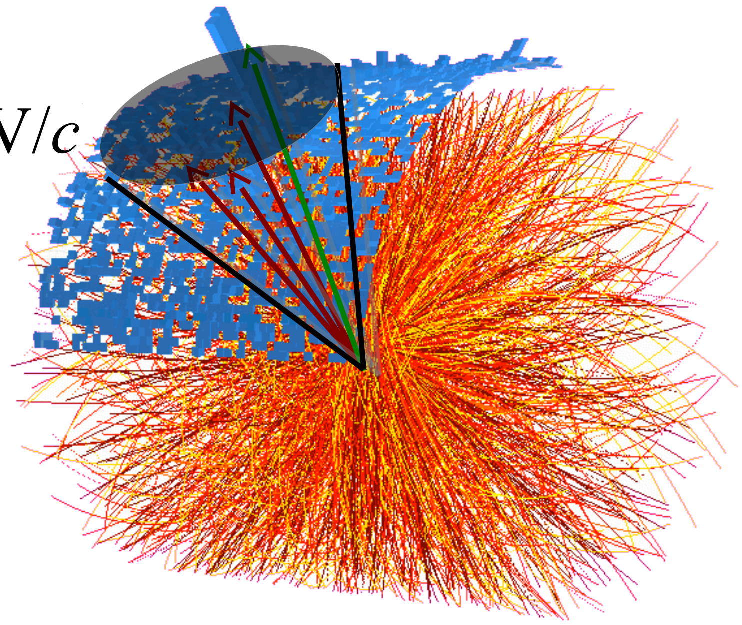


Jet Reconstruction

- Input to the jet finder
  - Assumed to be massless
  - Charged tracks (ITS+TPC) with $p_T > 150$ MeV/c
  - Cluster energies $E_{cluster} > 300$ MeV
  - EMCal cluster energies corrected for charged particle contamination with

$$E^{cor}_{cluster} = E^{orig}_{cluster} - f \Sigma p^{Matched},\ E^{cor}_{cluster} \geqslant 0$$

  f = 100%



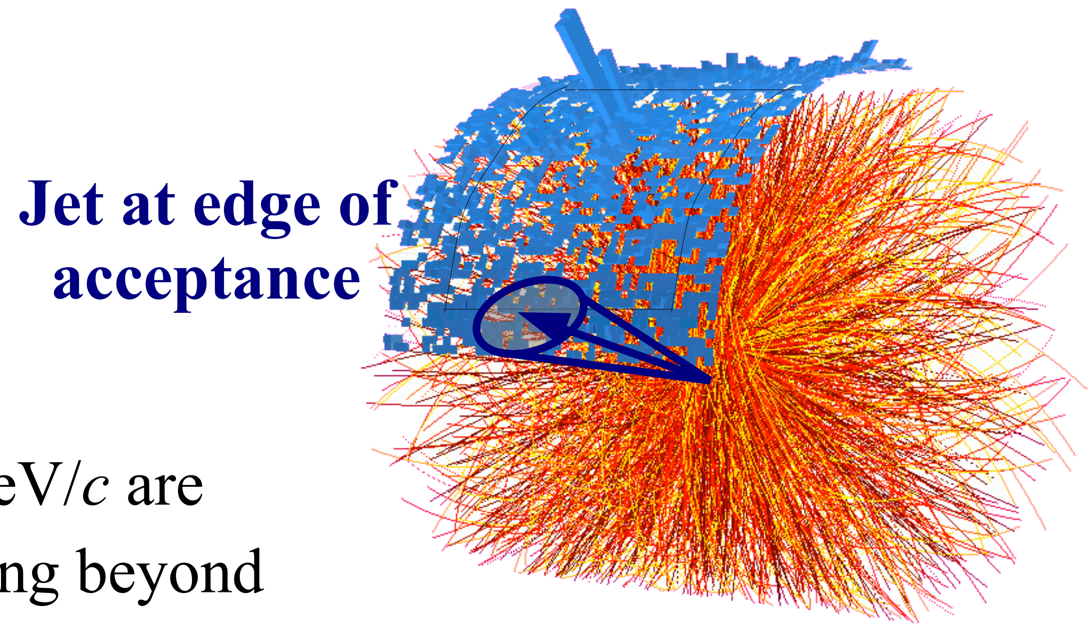
- ALICE measures both

Full Jets (tracks + clusters) – corrected to parton* energy and **charged jets** (tracks only) - corrected to energy measured in charged particles

*actually corrected to particle jet energy, with hadronization effects

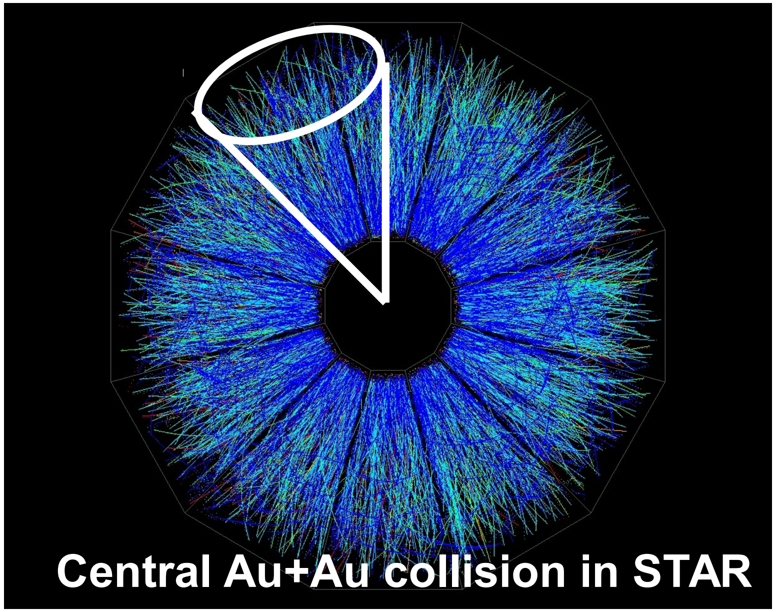
Full Jet Selection Requirements

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



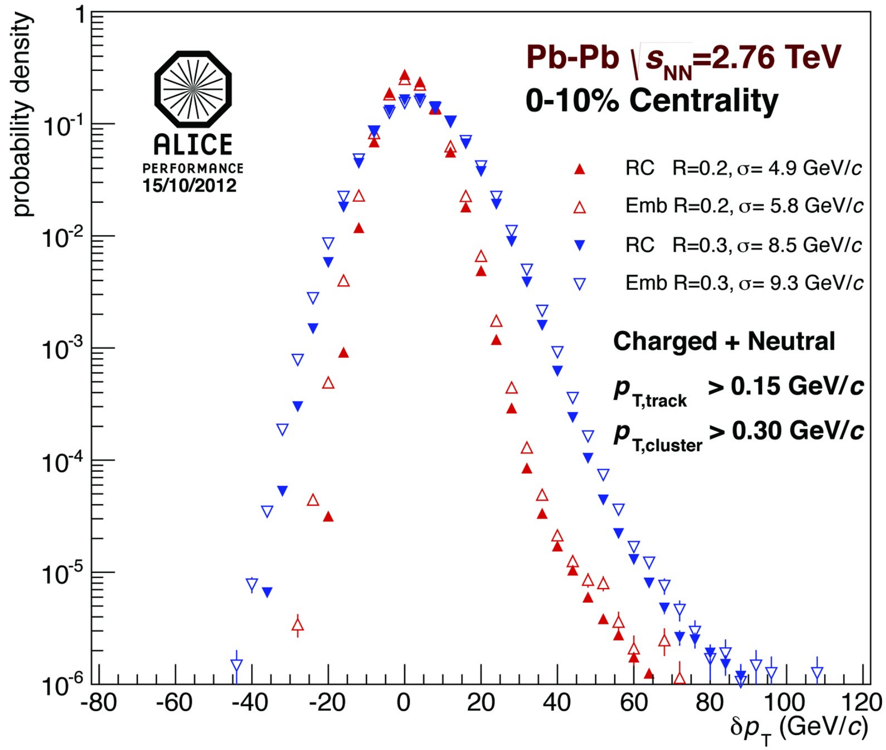
Background

- Ways to suppress background:
  - Increase the energy/momentum threshold on particles you use for jet finding
  - Look at very high energy jets
  - Look at smaller jets
- Ways to subtract background:
  - Look at “fake” jets to estimate the amount of energy from the underlying event (ALICE)
  - Use the symmetry of the collision (ATLAS, CMS)



Background Fluctuations

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



- Fluctuations in the background determined via δp_T
  - Random cones (RC)
  - Depends on
    - Constituent cut R
    - Centrality
    - Event plane
    - Detector

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

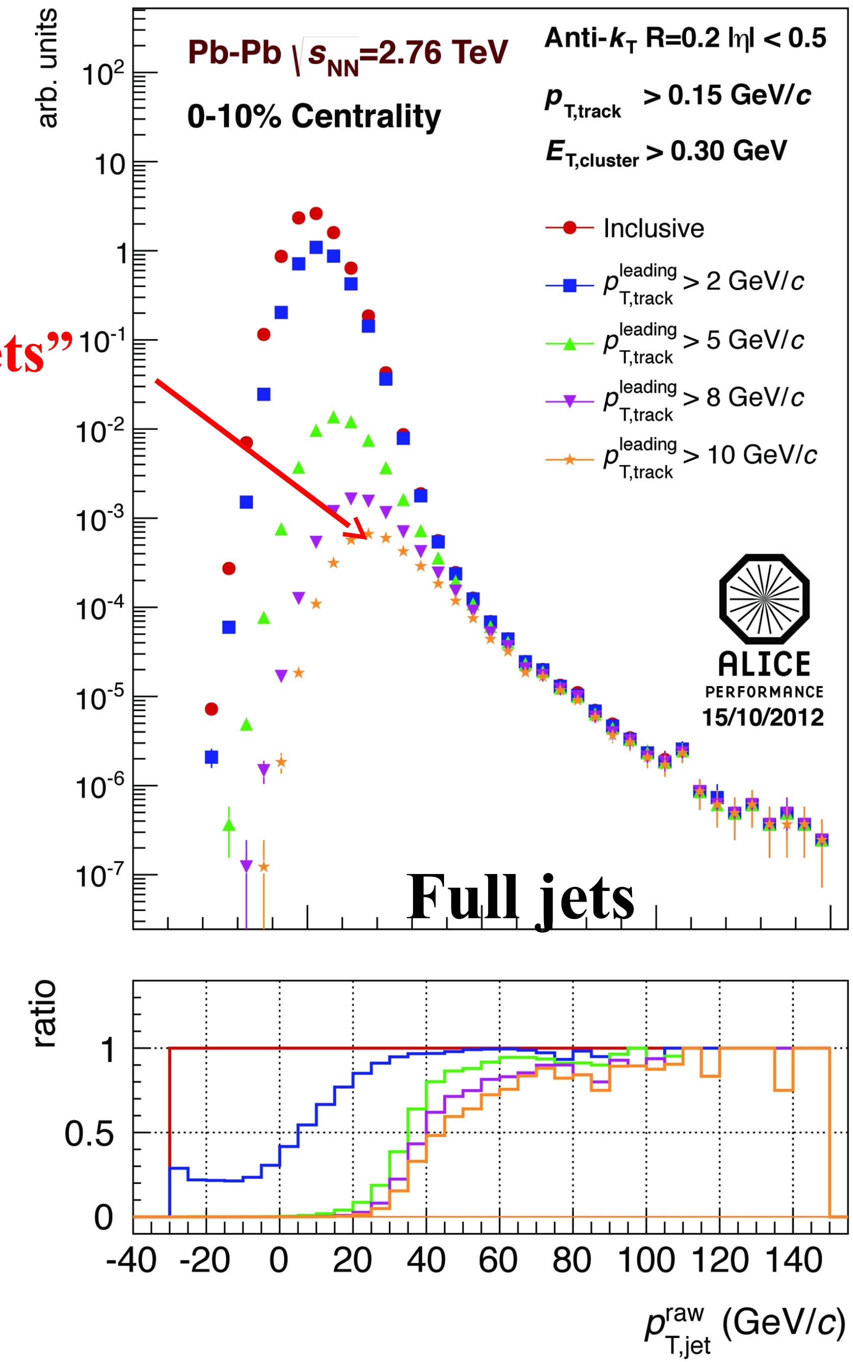
δp_T is not corrected for detector effects – Experiment specific

δp_T is used to construct unfolding response matrix

Leading Track Jet Bias

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

Combinatorial "jets"



- Combinatorial jets a challenge in HI collisions
  - Require leading track p_T > 5 GeV/c
  - Biases fragmentation
  - Suppresses combinatorial "jets"

Measured spectra:

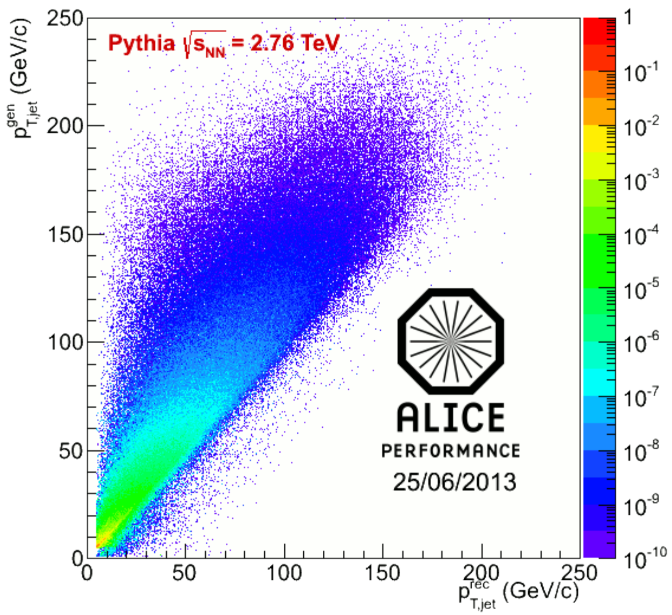
$$p_{T,jet}^{unc} = p_{T,jet}^{rec} - \rho A$$

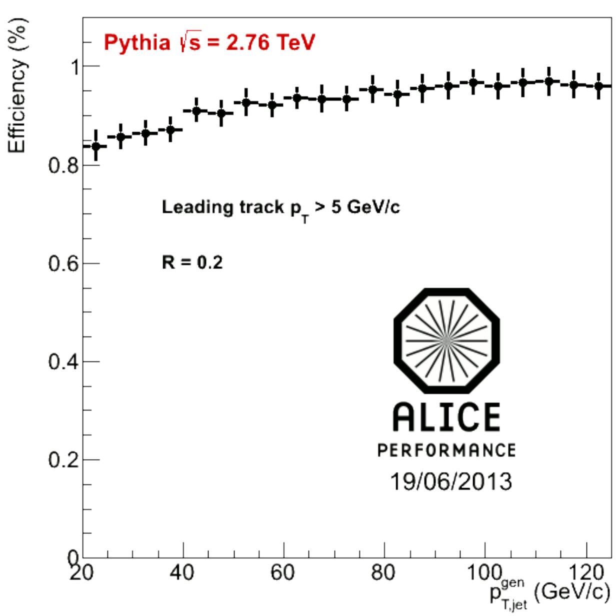
Where $p_{T,jet}^{rec}, A$ comes from FastJet anti-k_T algorithm

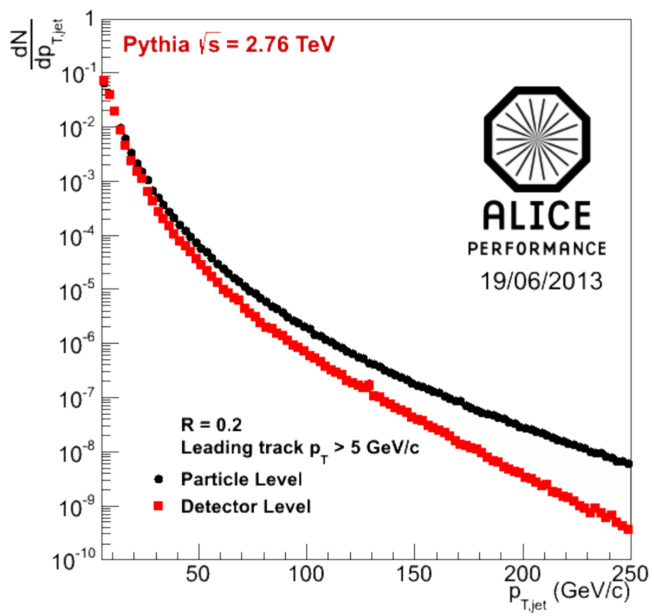
ERF-44496

Response matrix RM_{det}

- RM_{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

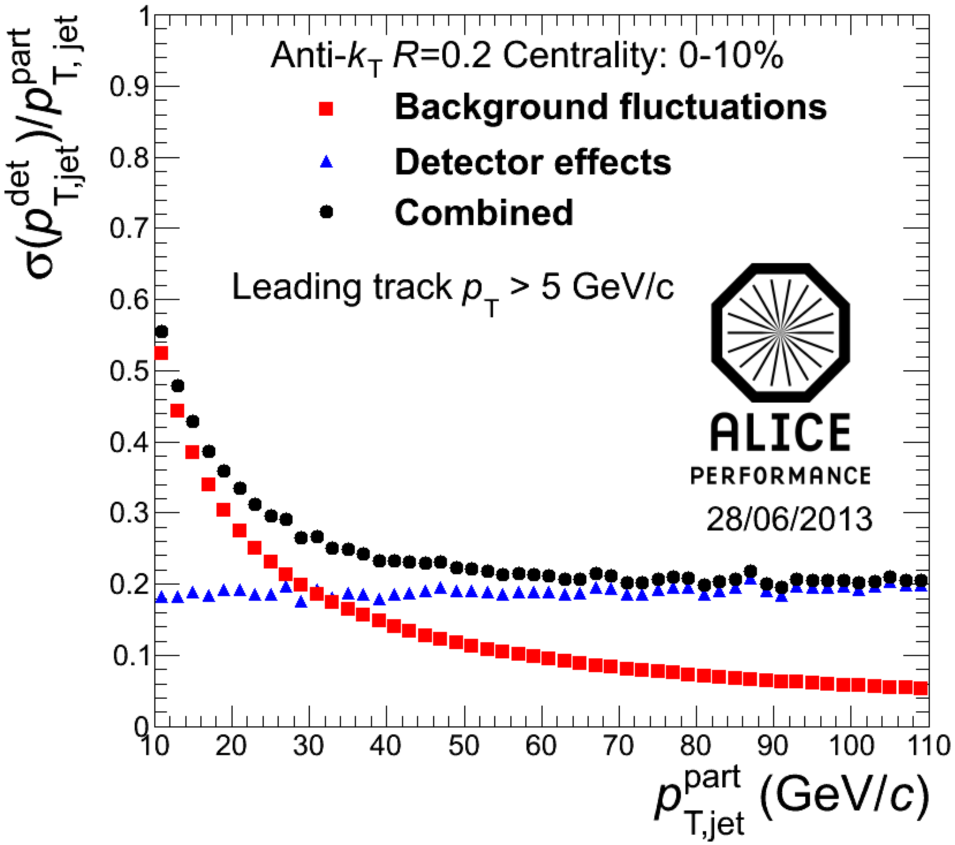




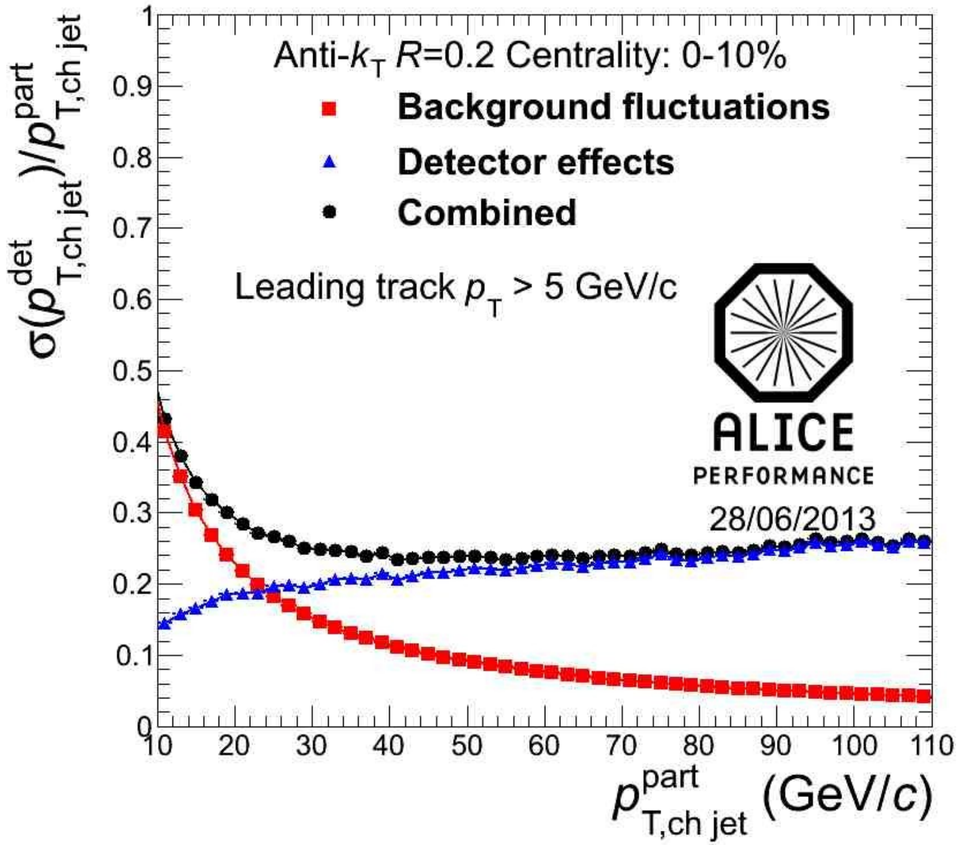


Jet Resolution

Full



Charged



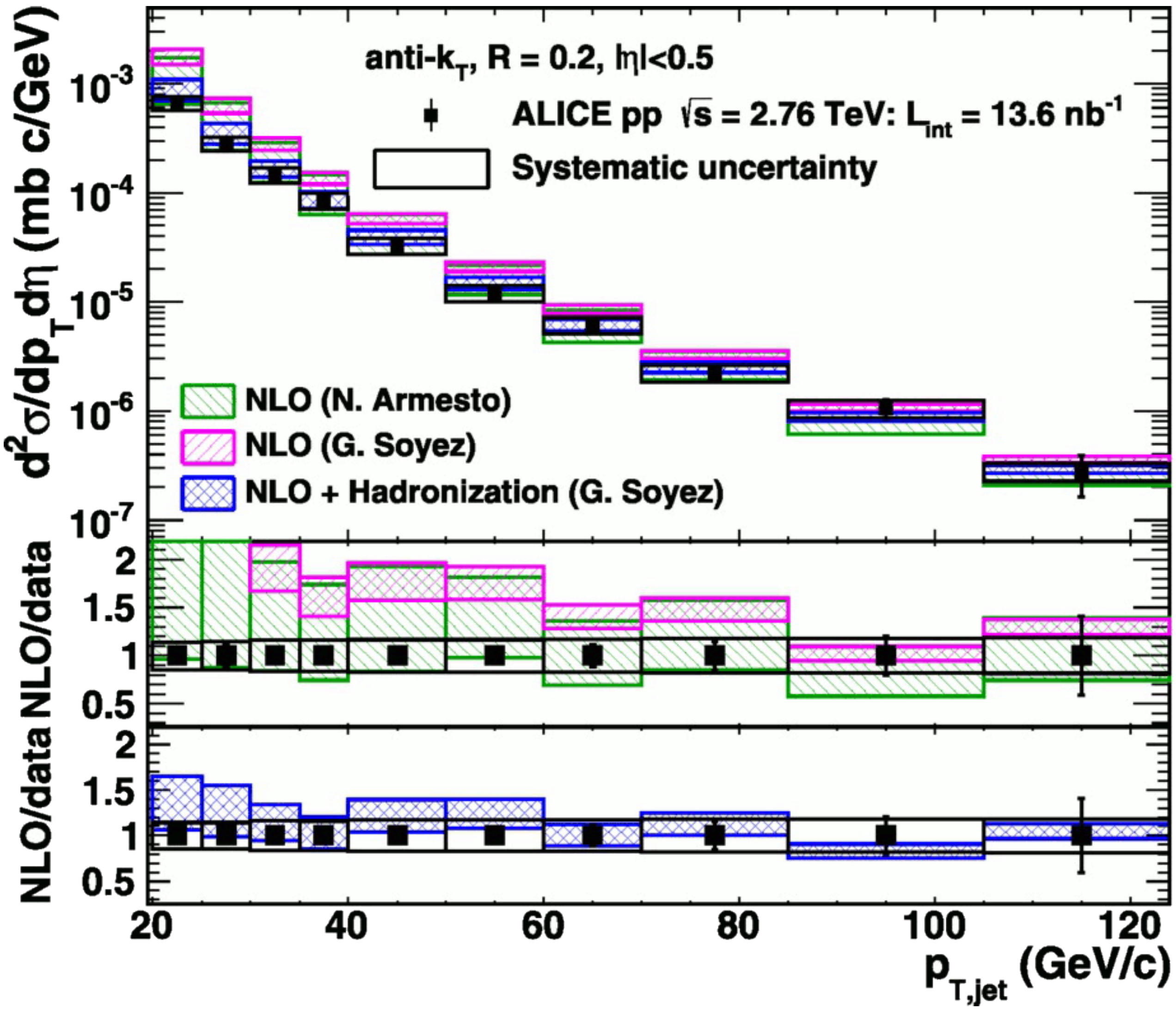
- Jet resolution
  - Dominated by background fluctuations at low momentum
  - Dominated by detector effects at high momentum

Results

Full Jet Cross-Section in pp

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

arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026



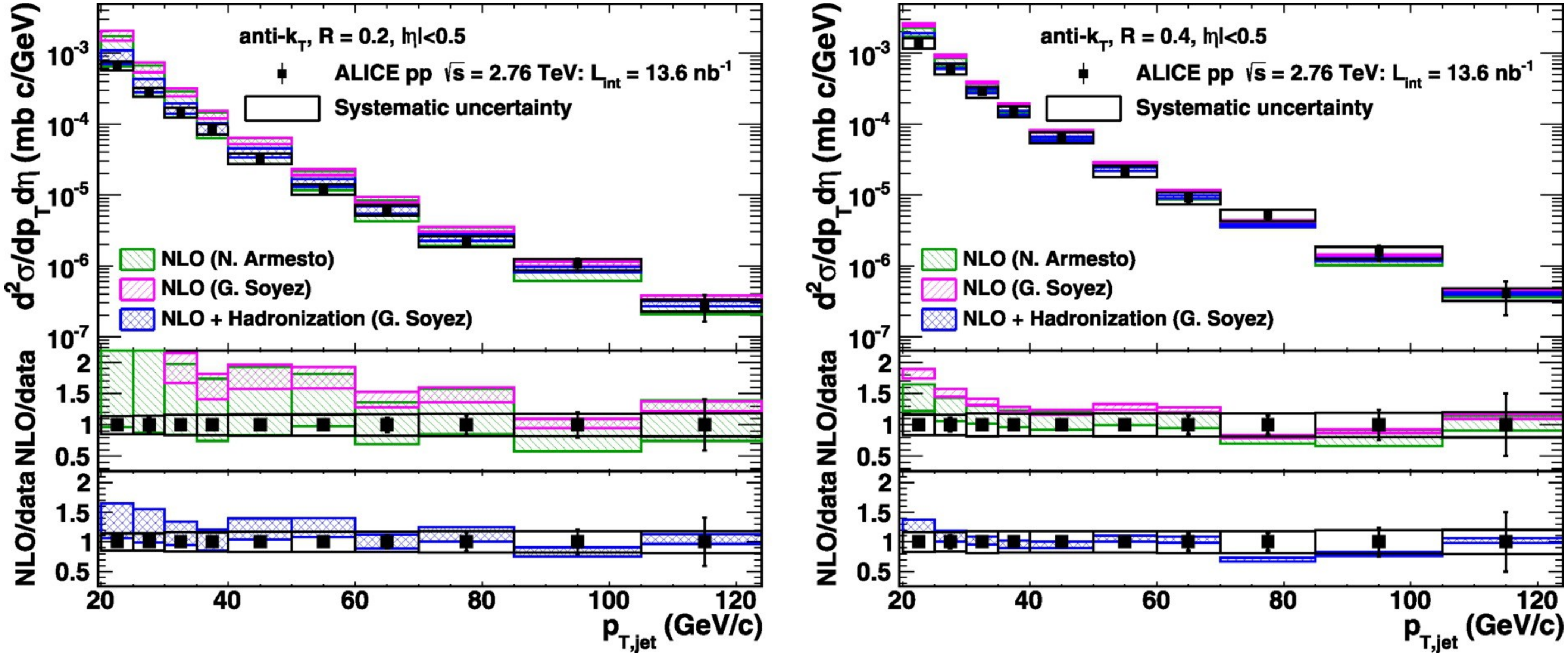
- f_{hadcor} = 100%,
- p_T > 150 MeV/c
- E_T > 300 MeV
- Green and magenta bands: NLO on Parton level
- Blue band: NLO + hadronization
- Hadronization necessary for better fit to data

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

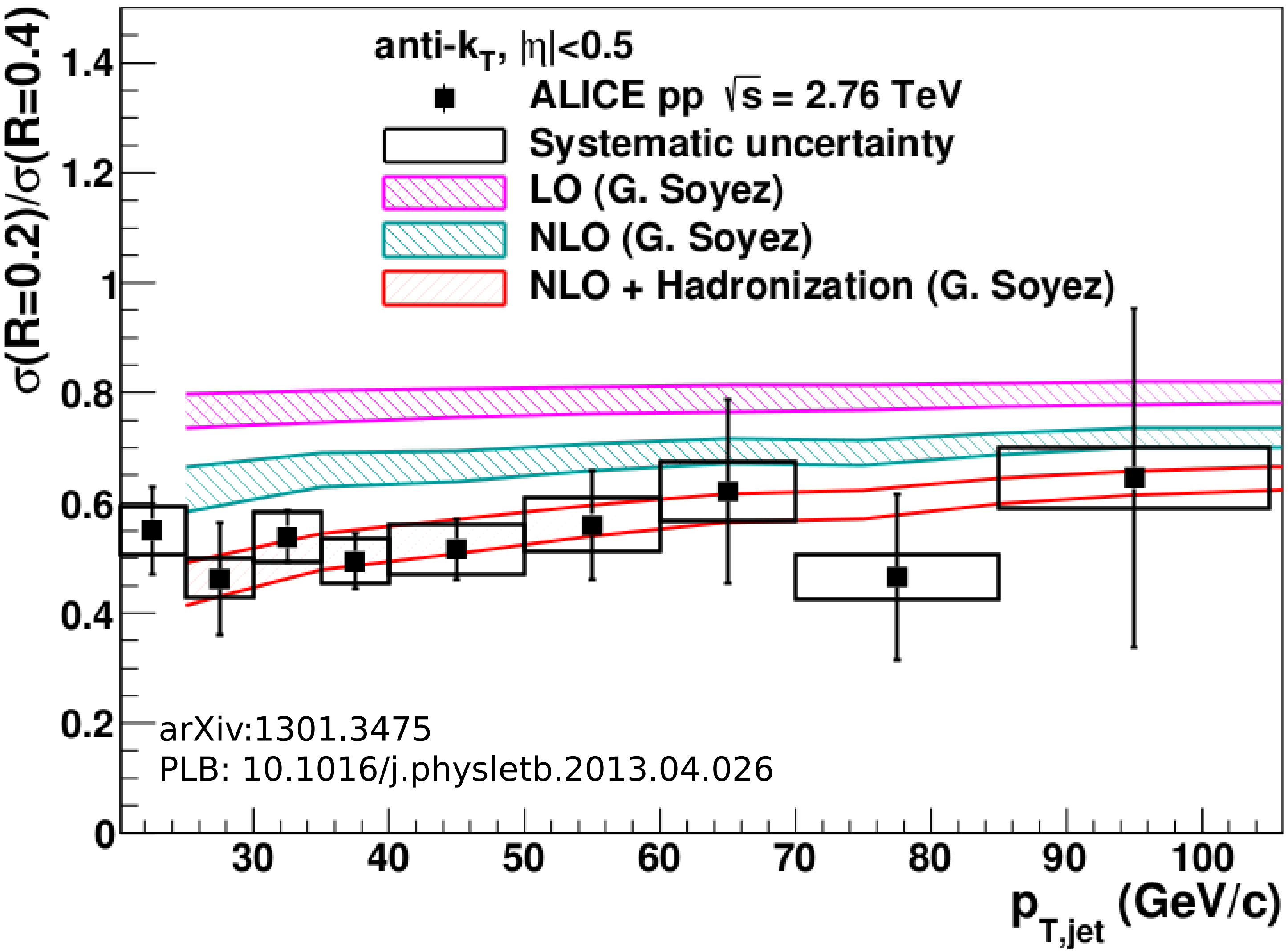


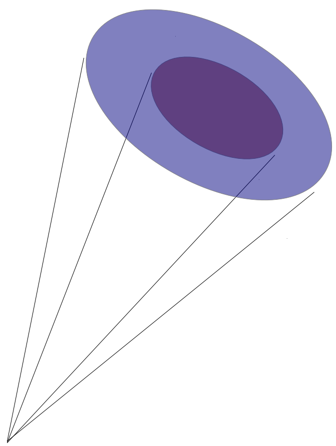
Agreement between data and NLO+ hadronization calculations

is good for both R = 0.2 and 0.4

Full Jet ratios in pp

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

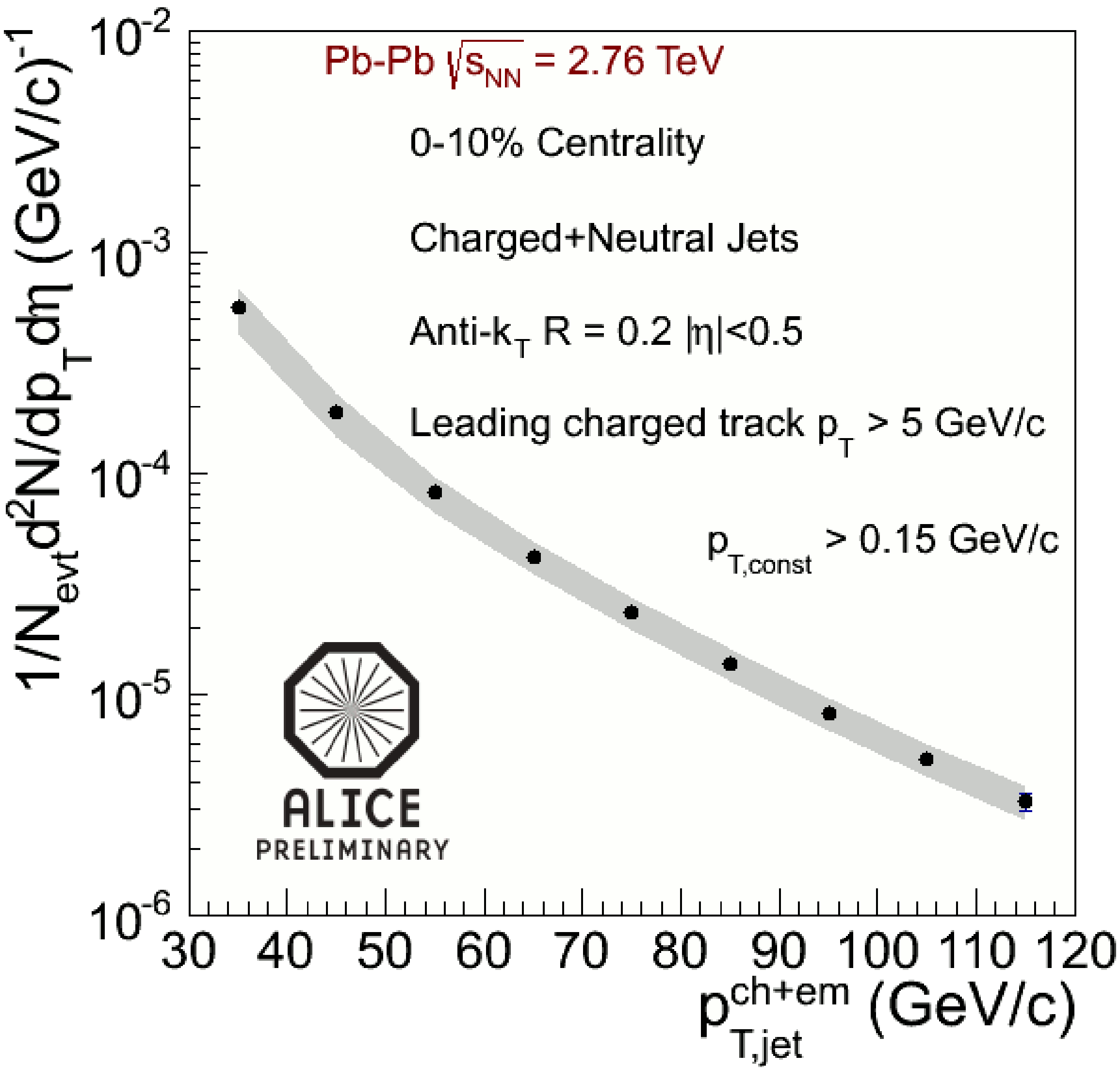




Good agreement between data and NLO+ hadronization calculations

Full Jet Spectrum in Pb-Pb

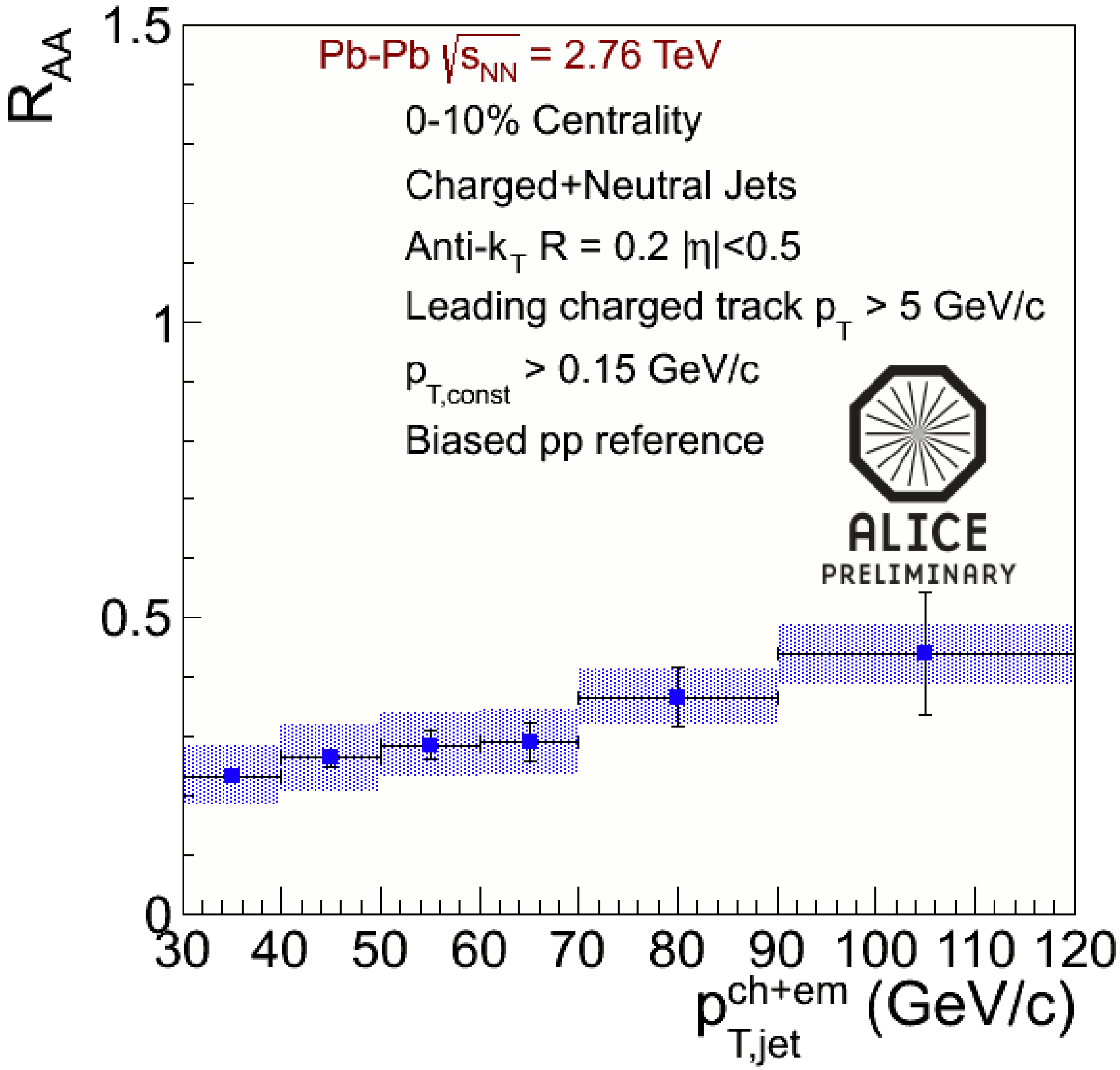
Charged+EMCal Jets $\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2 0-10%



- Jets are corrected for background fluctuations and detector effects in unfolding
  - Bayesian method
- Systematics:
  - ~19% (p_T dependent)
  - EMCal effects (Resolution, scale, clusterizer, non-linearity)
  - Unfolding
  - Tracking efficiency
  - Background

Full Jet R_{AA}

$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2 0-10%

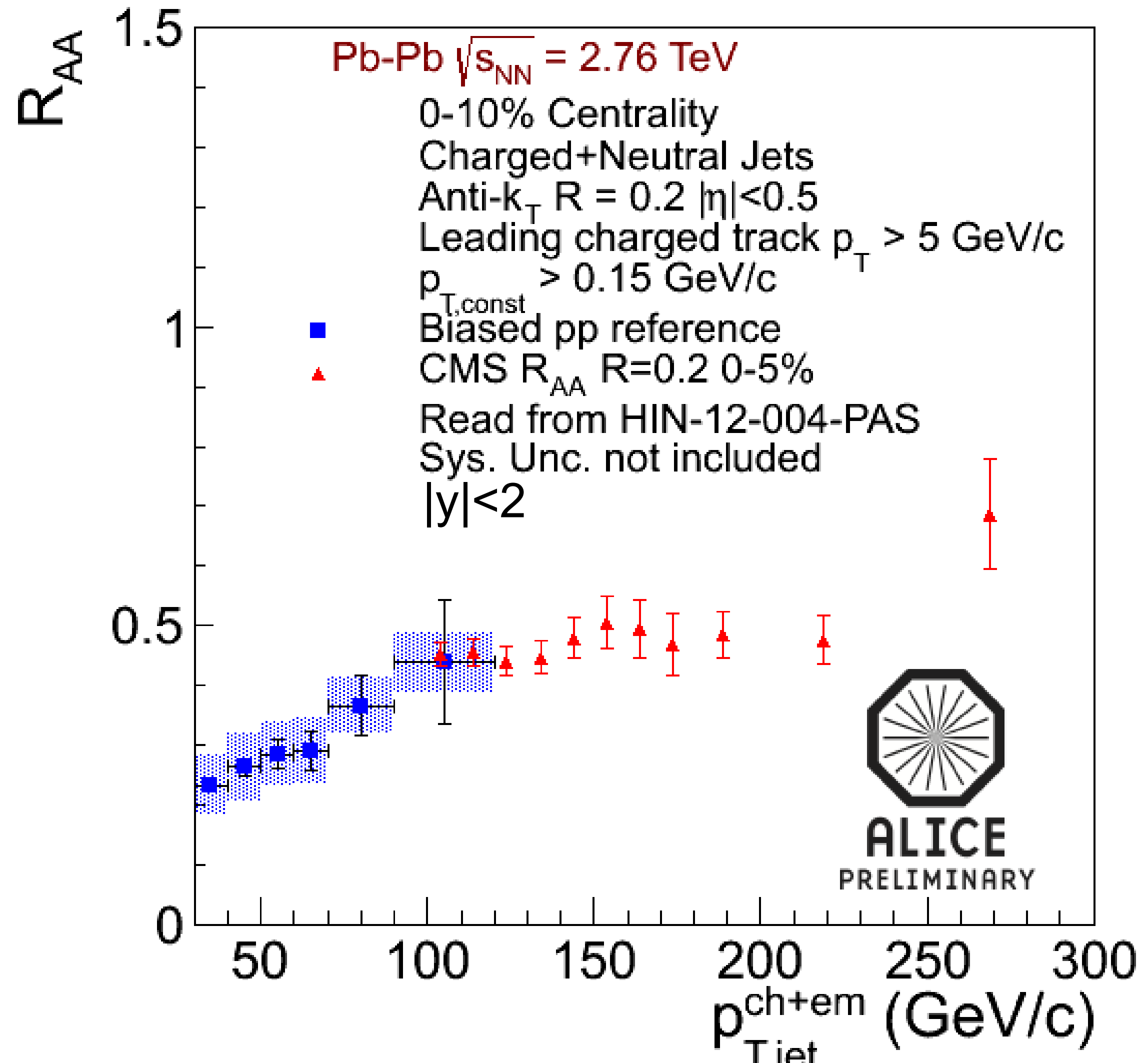


- Reference pp spectrum and Pb-Pb spectrum both have leading track p_T > 5 GeV/c
- R = 0.2 jets are suppressed in central collisions
- f_{hadcor} = 100%,

  p_T > 150 MeV/c

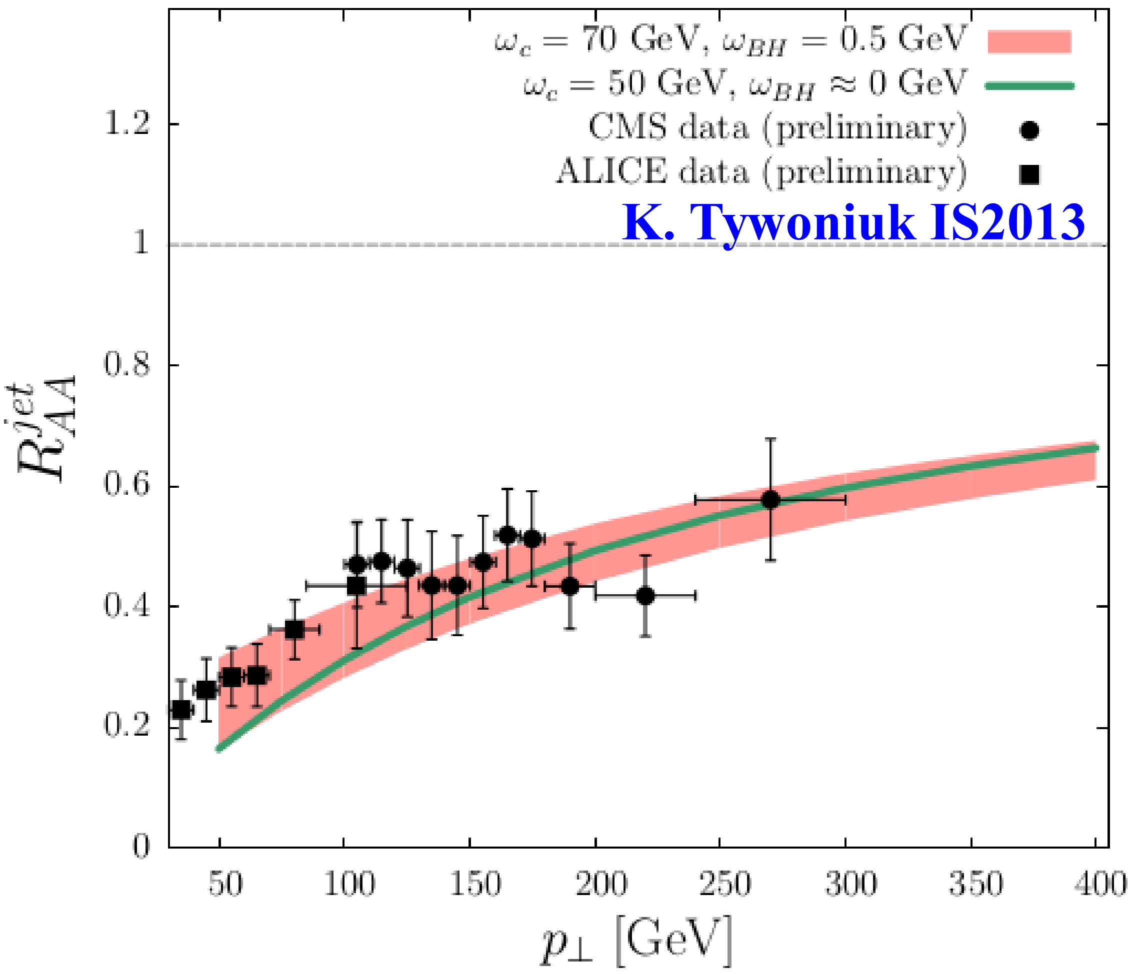
  E_T > 300 MeV

LHC Jet R_{AA} Comparisons



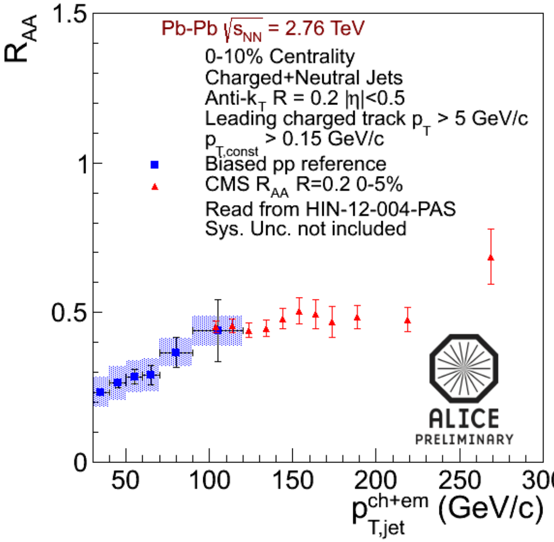
- ALICE and CMS are consistent within overlap region with the same R and different constituent cuts, background subtraction method and acceptance

LHC Jet R_{AA} Theory Comparisons



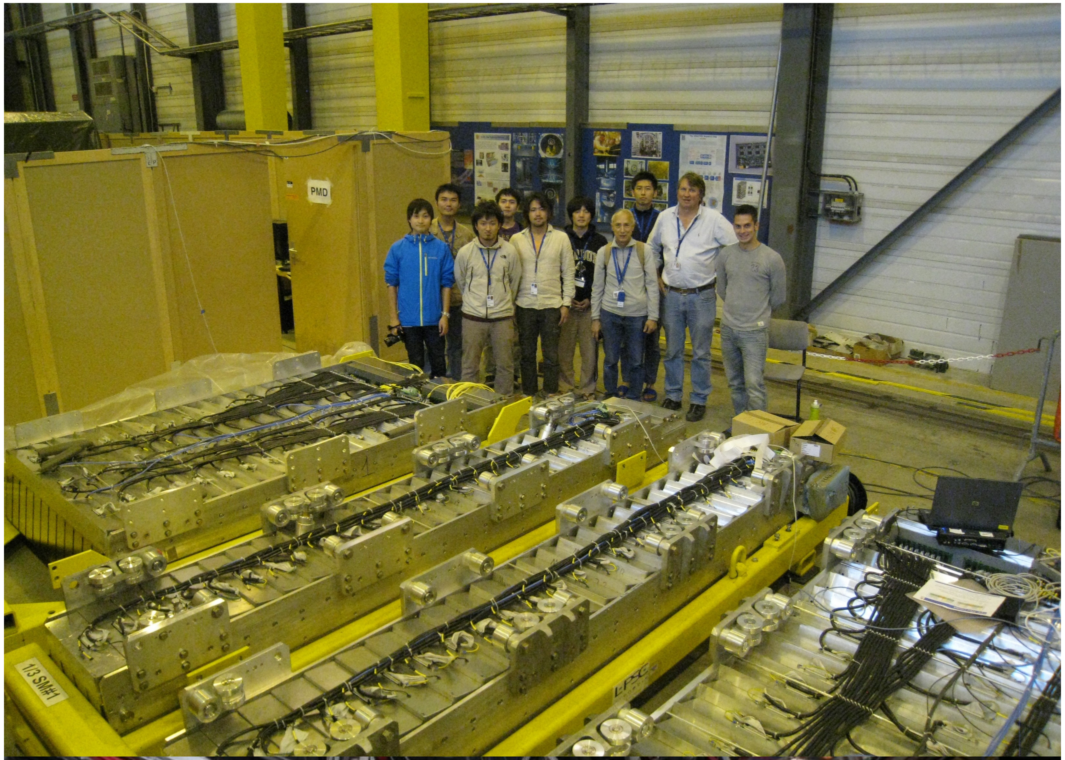
Summary

- Jets can be used to study heavy ion collisions
  - Background subtraction important
  - Background affected by what's in the measurements
- Jets are described well in pp
- Jets are suppressed in AA



Future

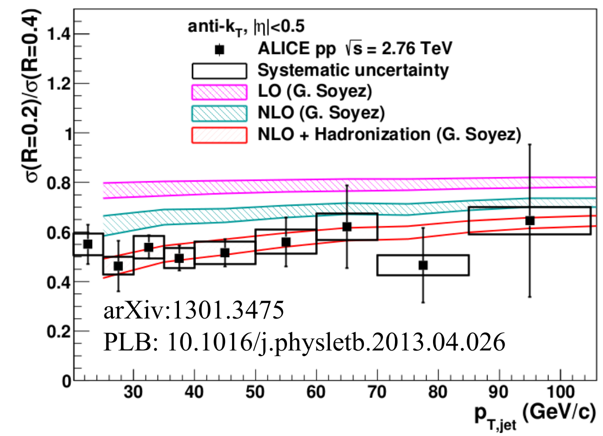
- Identified particles in full jets
- Calorimeter triggered jets
  - Reaction plane dependence
- DCal for back-to-back full di-jets



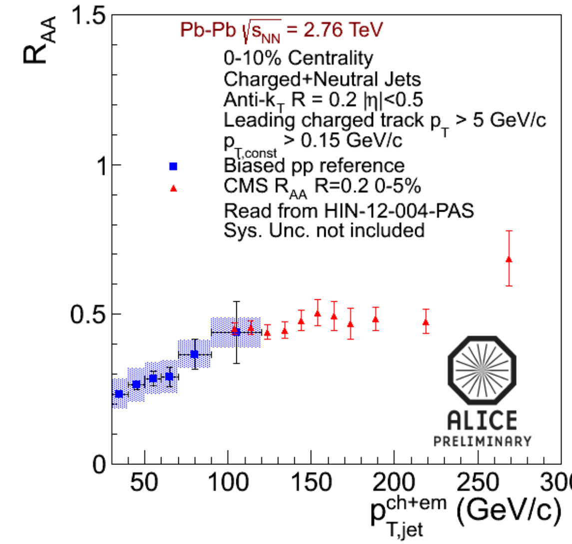
Backup

Conclusions

- Jet in pp consistent with NLO

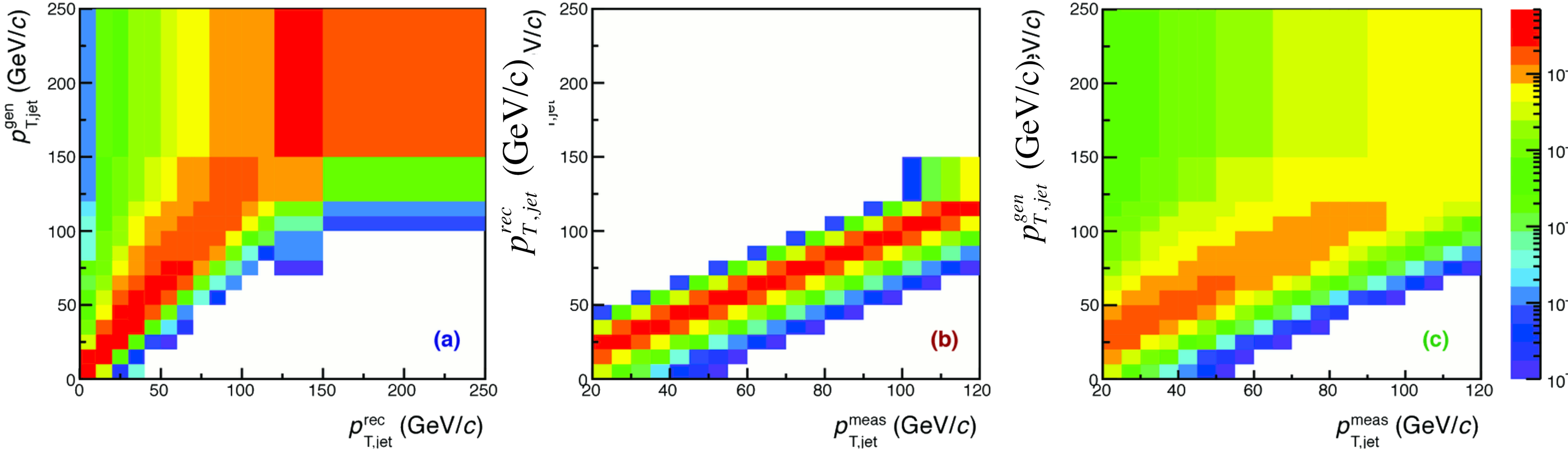


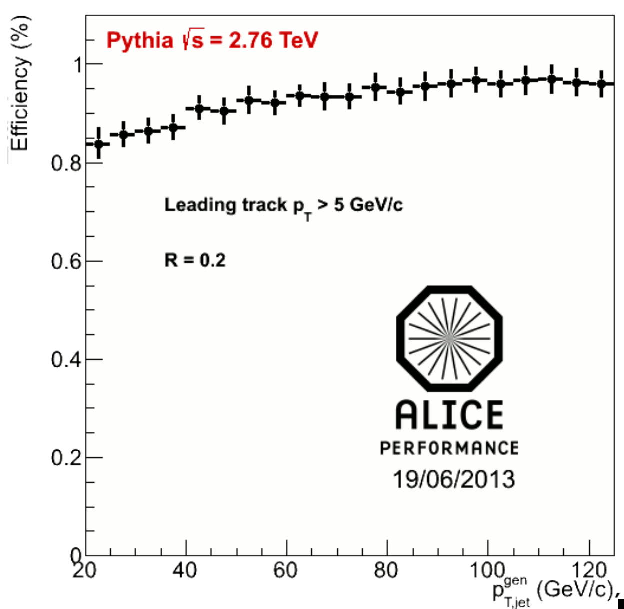
- Jet R_{AA}
  - Indicates strong suppression of jets
  - Consistent with CMS with same R



Response Matrix Construction

RM_{det} X RM_{bkg} = RM





Anti-k_T R=0.2

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

$E_{T,cluster}$ > 0.30 GeV

$p^{leading}_{T,track}$ > 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

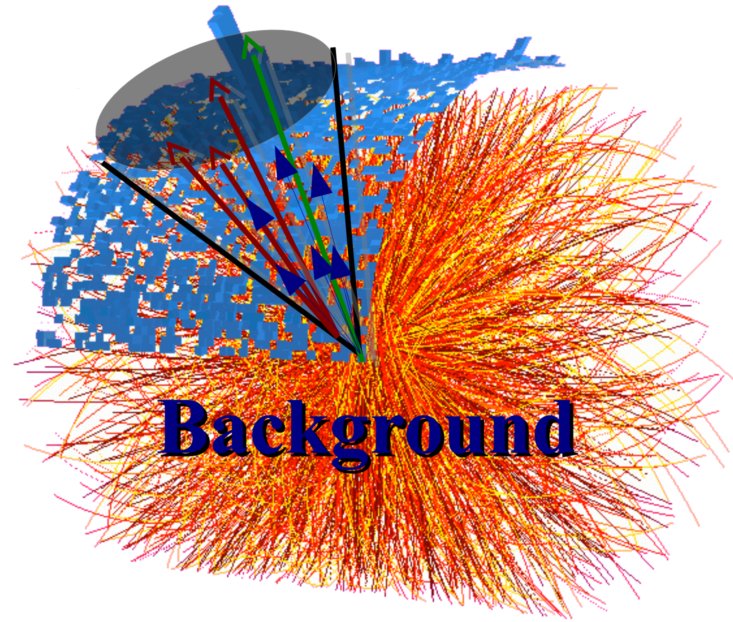
ALICE PERFORMANCE 15/10/2012

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

ALI-PERF-44520

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, ρ = median UE momentum density
  - $p_{T,Jet}^{rec}$ = Jet p_T from jet finder
  - We can only remove the average background contribution
- B_σ 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_σ term
  - Quantified in Response Matrix (RM)

HI Background Determination

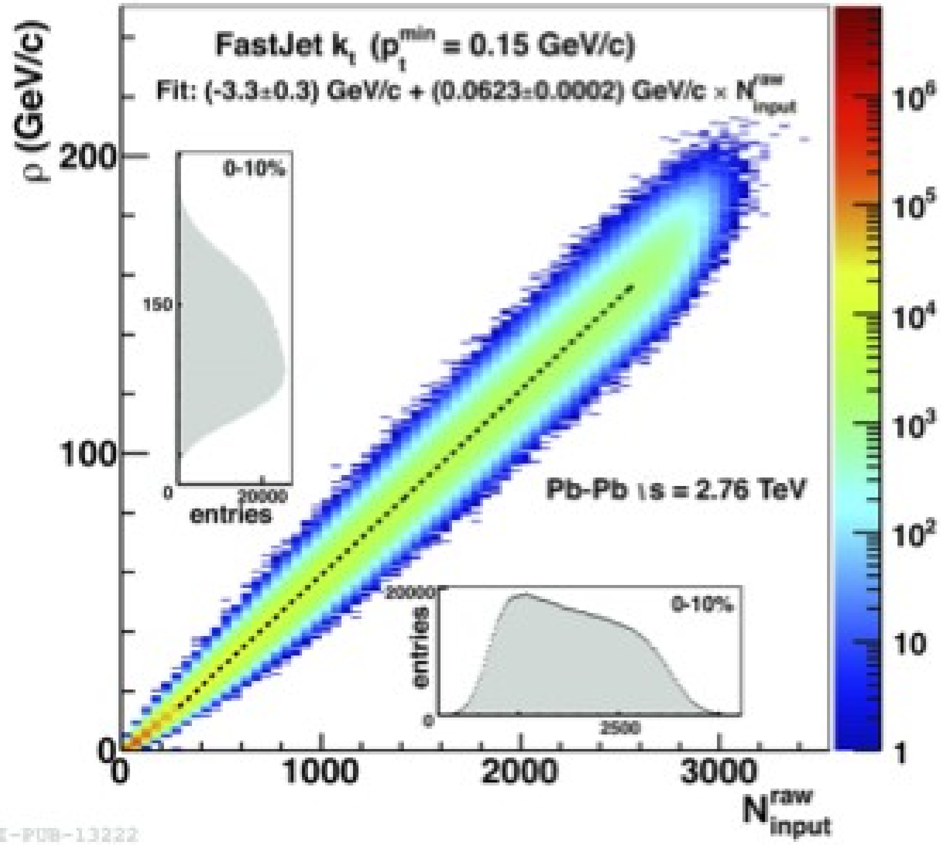
Charged Jets $\sqrt{s_{NN}}$ = 2.76 TeV in PbPb

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

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

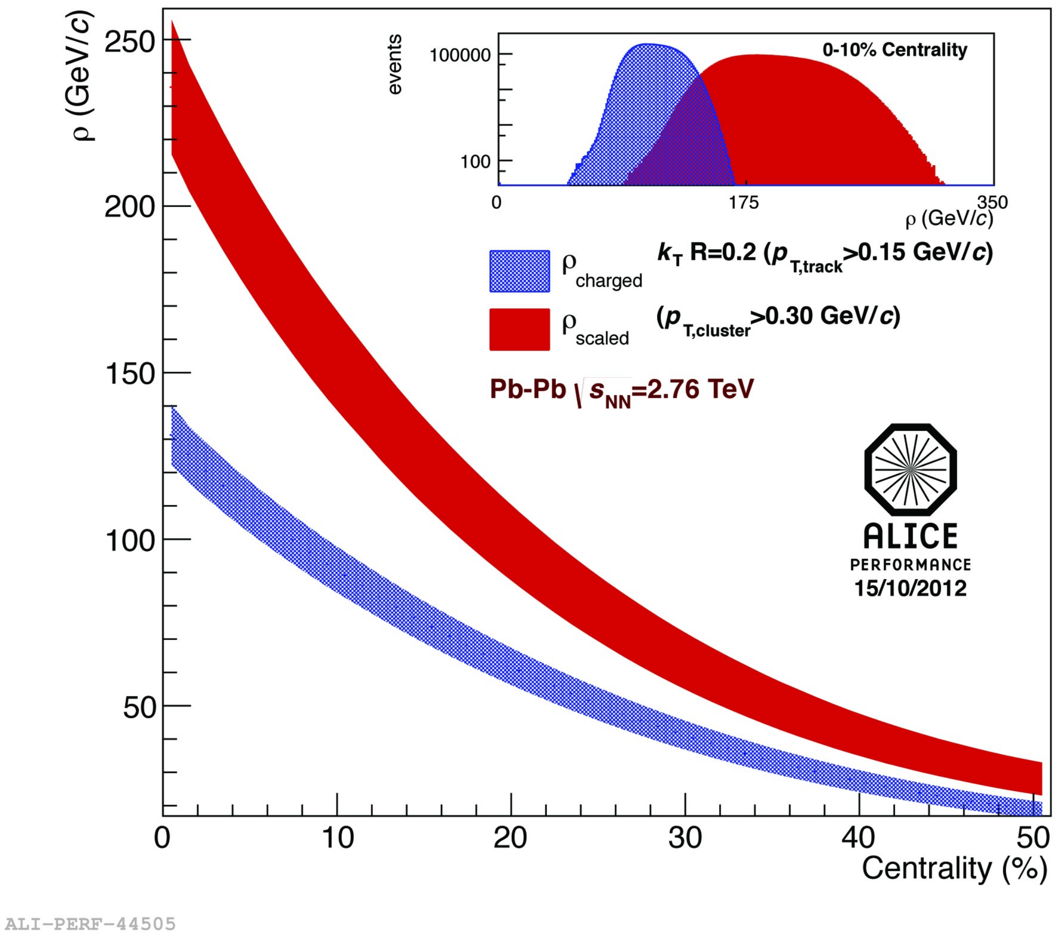
- Scaled up for full jets

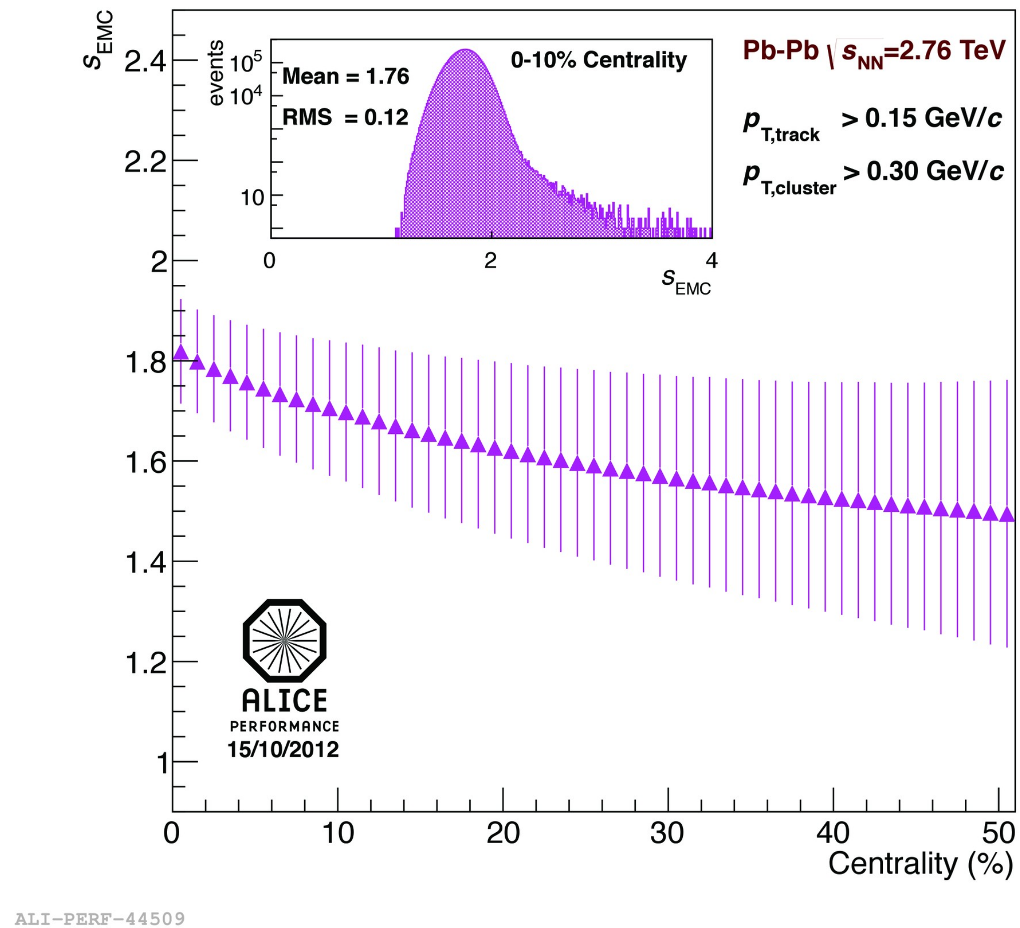
JHEP 1203:053, 2012 (arxiv:1201.2423)



HI Background Determination

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

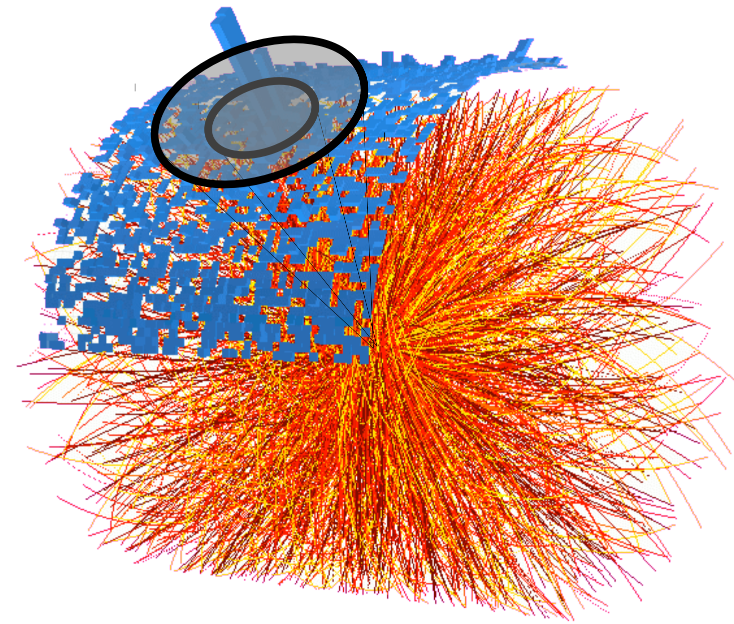




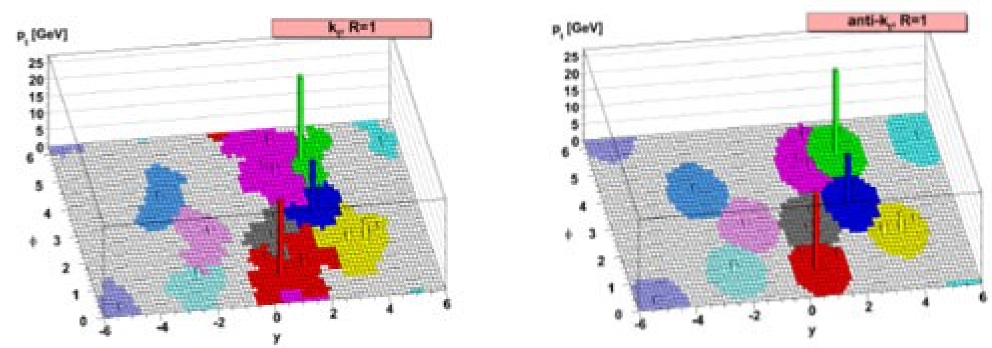
Centrality dependent scale factor accounts for neutral energy

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

Jet Reconstruction

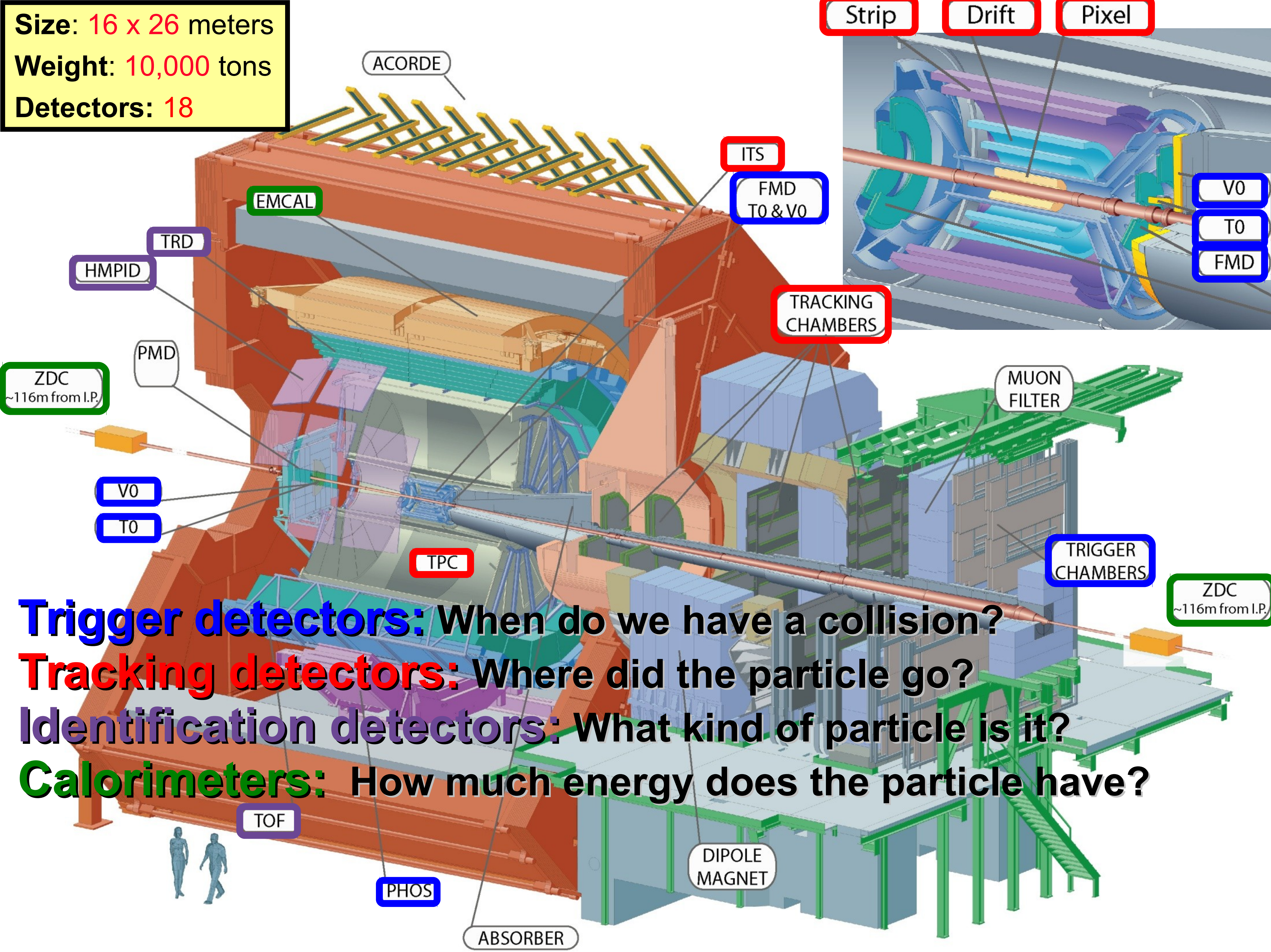


- Jets reconstructed using FastJet package
  - $R = 0.2$ - 0.4
  - Anti-k_T – Used for signal determination
  - k_T – Used for background determination
- Correct for detector effects using unfolding
  - Momentum resolution
  - Energy resolution
  - Track Matching



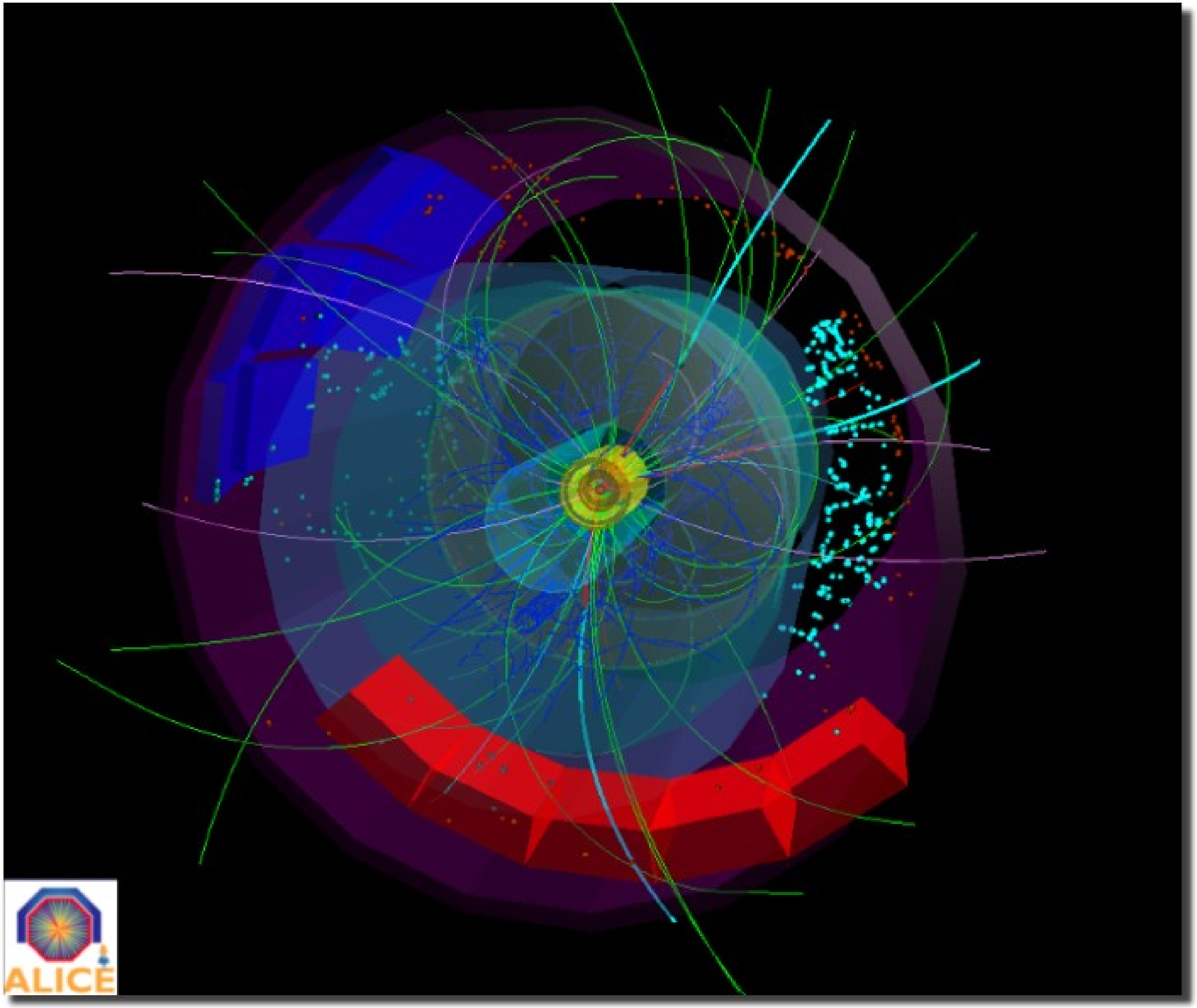
M. Cacciari, G. P. Salam, G.Soyez, JHEP 0804:063,2008

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



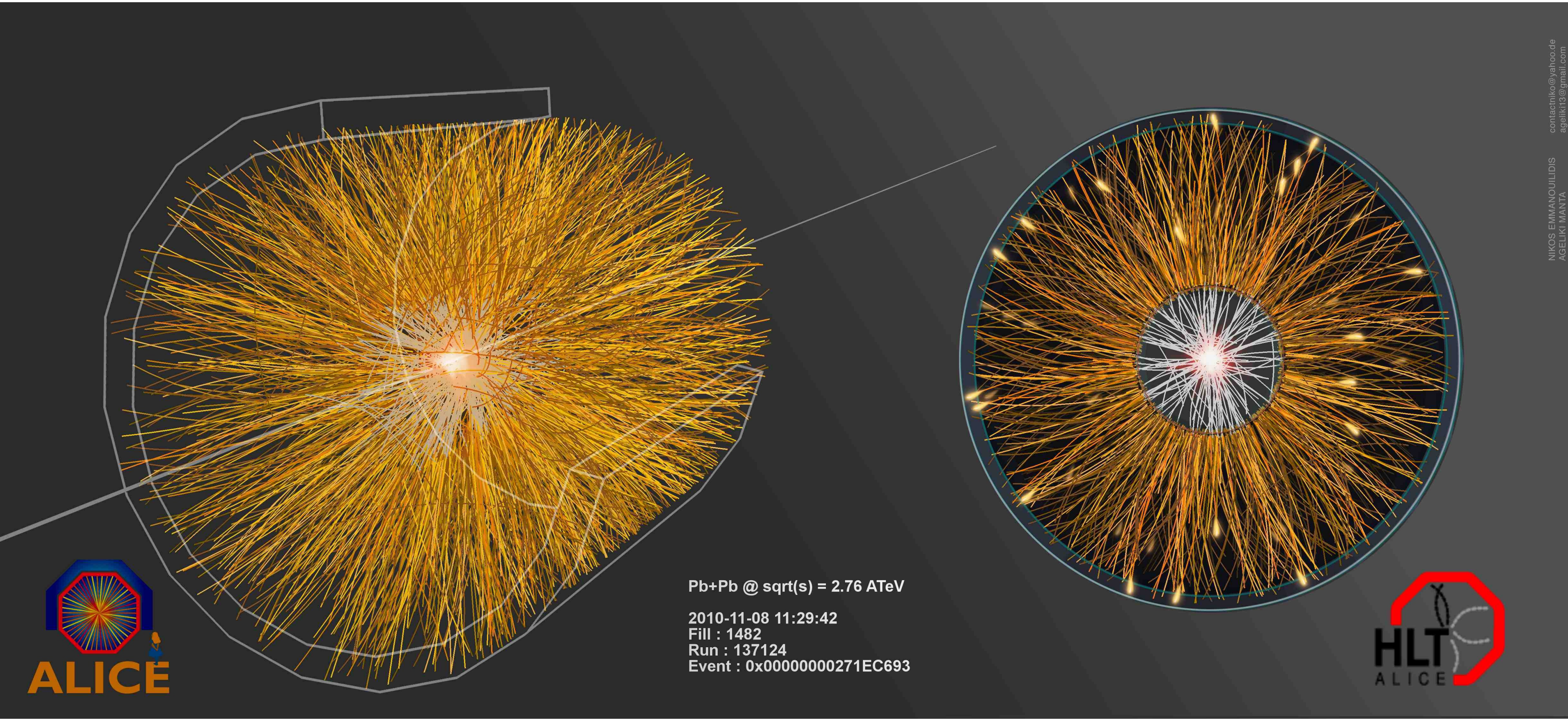
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?

p+p collisions



3D image of each collision

Pb+Pb collisions

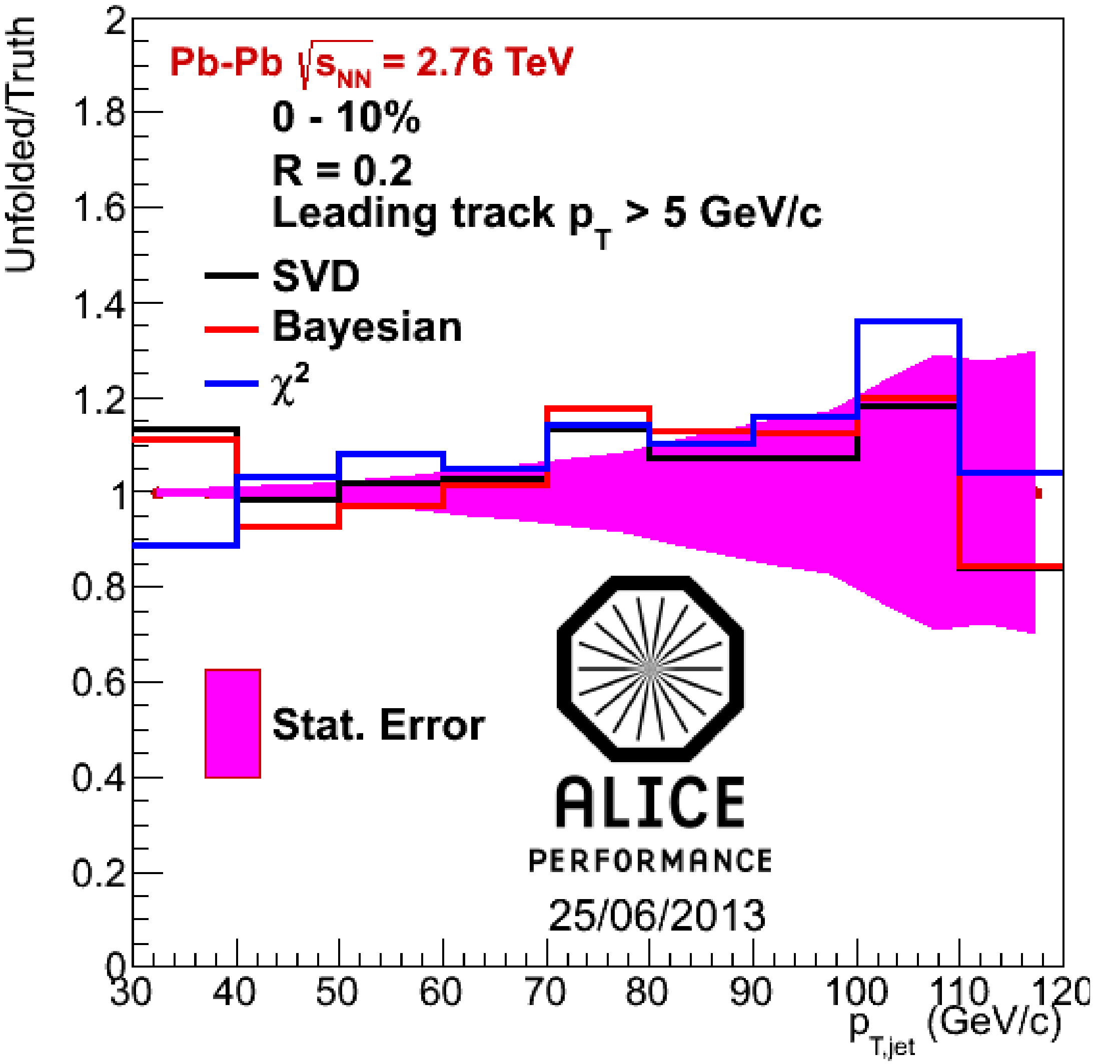


Unfolding Evaluation

Closure test

- To benchmark unfolding methods “truth” spectra are embedded into data
  - Do we recover this truth spectrum?
- Embed Pythia jets into Pb-Pb data, at particle level and at detector level
  - Select detector level jets with MC energy “measured jets”
  - Unfold the “measured” jets and compare to embedding particle level jets
  - Tests corrections for both detector effects and background fluctuations
  - Does not test the effect of fake jets

Closure test



- **Measured** jets are all **reconstructed** jets with MC energy > 1 GeV
  - Background subtracted
- **Unfolded** jets are corrected from measured jets
  - RMbkg constructed with RC
  - RMdet constructed with PYTHIA
- **Truth** is PYTHIA **particle level** jets

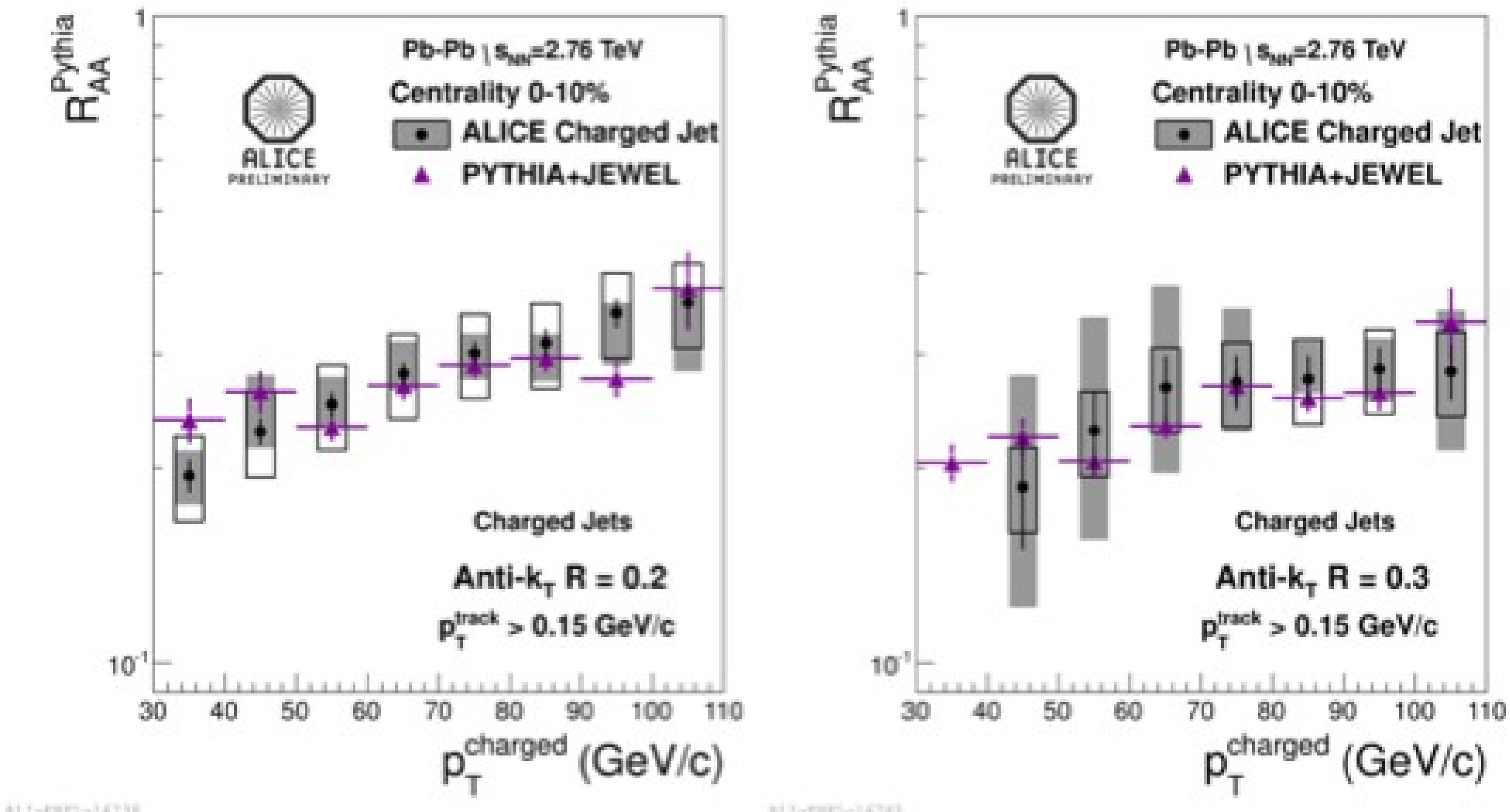
SVD, **Bayesian** and **χ2 minimization**

Unfolding Methods

- Bayesian
  - Toy model investigation indicates that this method is susceptible to fakes
  - Regularization is number of iterations
  - Requires a reasonable prior
  - Prior is the initial solution for the unfolding method
- SVD
  - Toy model investigation shows this method performs well
  - Tikhonov regularization method suppresses small singular values
  - Requires a reasonable prior
- $\chi 2$
  - Toy model studies show good agreement with SVD
  - Regularization is employed by assuming a local power law (for jet spectra)
  - Does not have a strong dependence on prior

Comparison to Models

√sNN = 2.76 TeV, R=0.2,0.3 0-10%

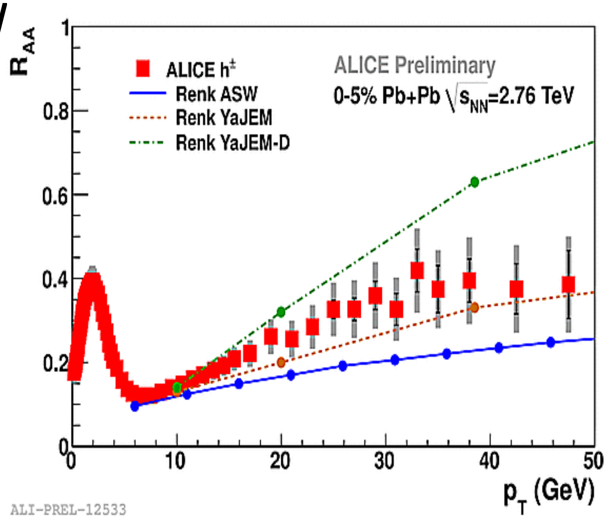


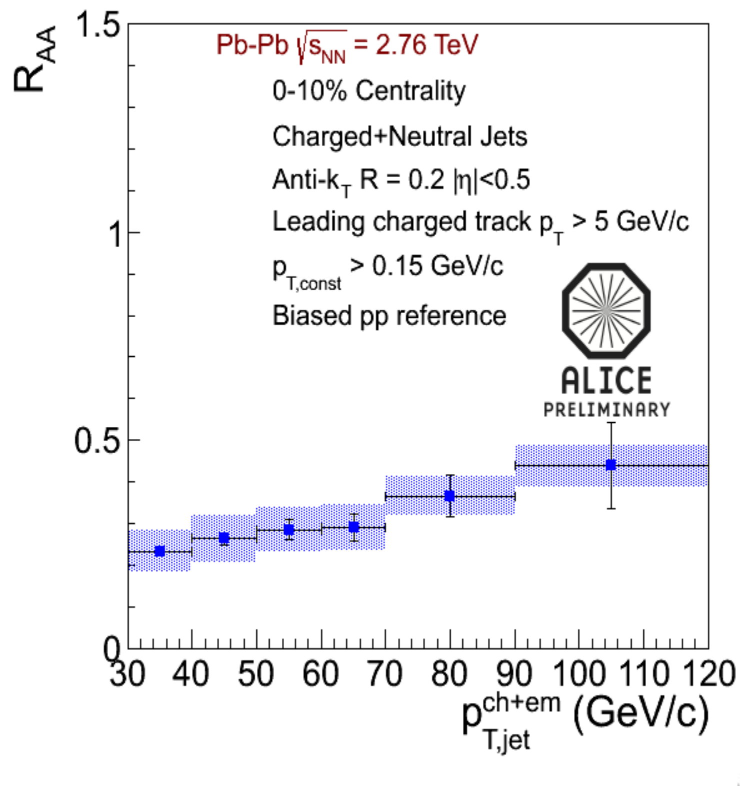
PYTHIA used for charged pp reference spectrum for RAA calculation R=0.2,0.3 jets are suppressed in central collisions

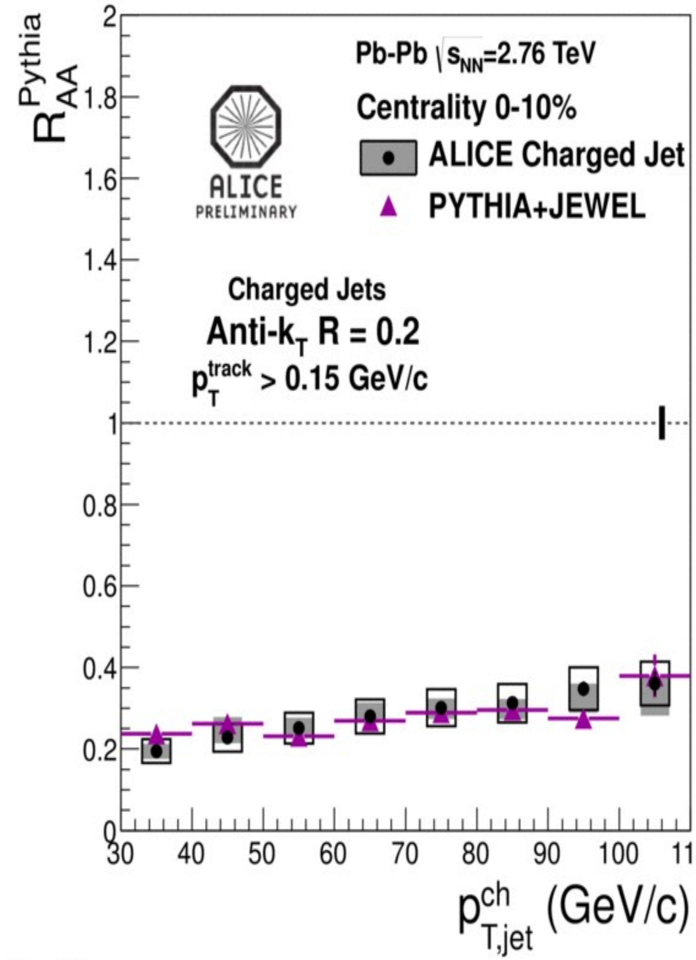
Good agreement between JEWEL and inclusive charged jet RAA

RAA Comparison

Jet RAA ~ Hadron RAA
Charged jet RAA ~ Full Jet RAA



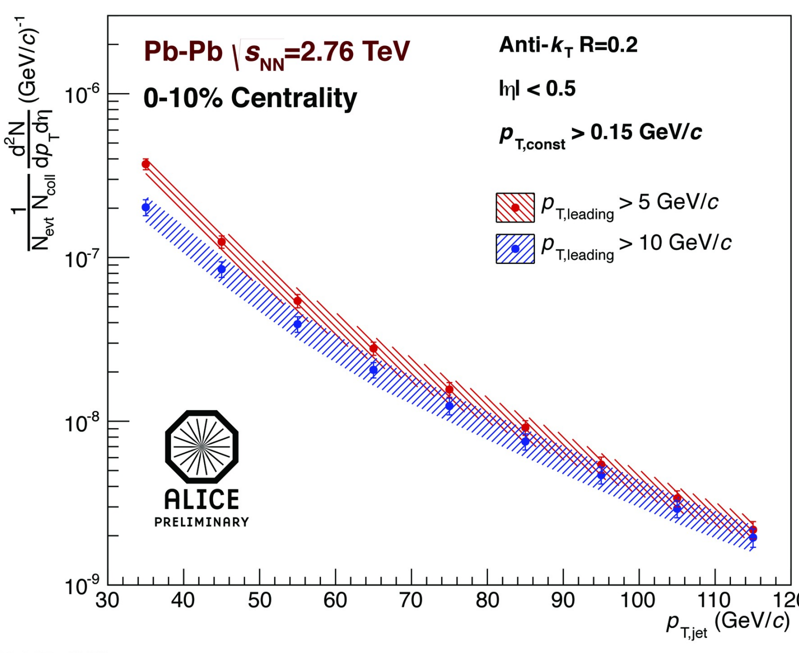




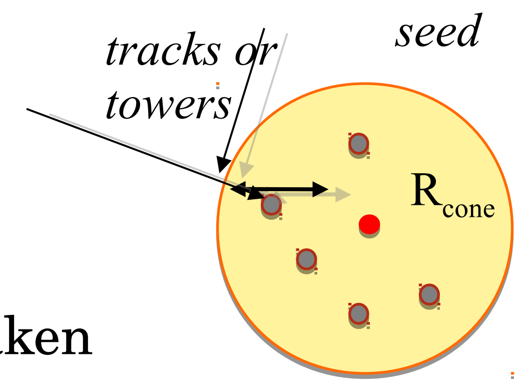
Jet RAA was surprisingly low, though this is reproduced by some models
Where is the missing energy? Large angles? Low pT?

Unfolded Biased Jet Spectra

- Leading track bias improves unfolding stability
  - Reduces combinatorial jets
    arXiv:1208.1518
  - Bias of 5 GeV/c does not significantly change pp, Pb-Pb spectra

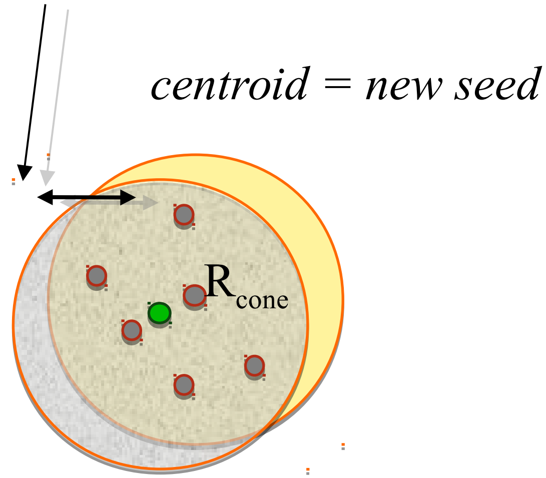


CONE ALGORITHM



- A '*seed*' defines the approximate jet direction
  - *seed* = track with $E>E_{threshold}$
- Tracks which are within a radius of $R<R_{cone}$ are taken ($R=\sqrt{(\Delta\Phi^2+\Delta\eta^2)}$)

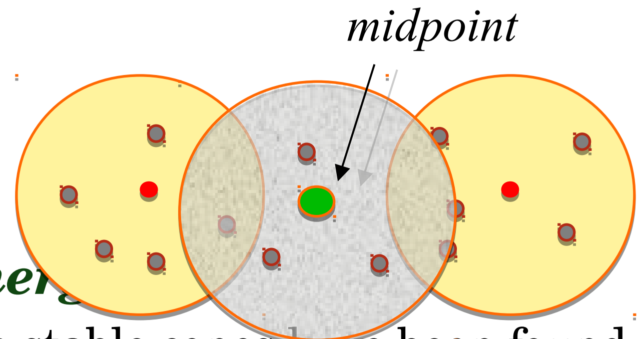
- The centroid of the cone is given by summing the momenta of the particles inside the cone
- The centroid becomes the new *seed* : procedure iterated until the seed position is stable



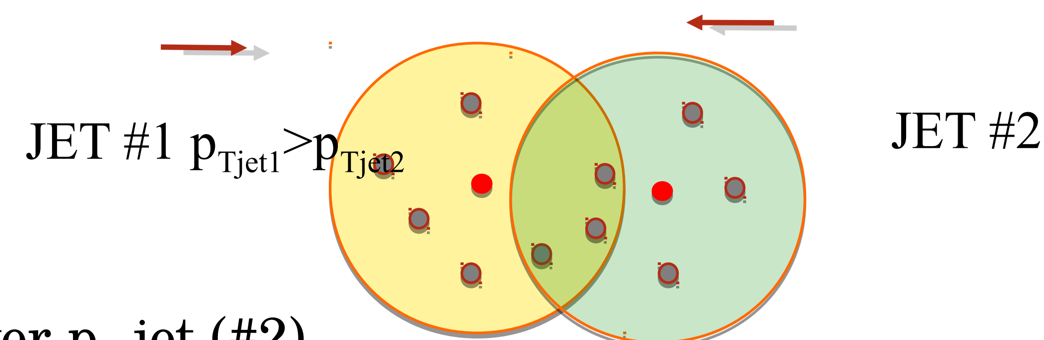
Elena Bruna, Yale University

MIDPOINT CONE ALGORITHM

- PART I: ***searching midpoint***
  - Search for missing jets using the midpoint of all the pairs of found jets as seed



- PART II: ***splitting/merging***
  - This stage starts once stable cones have been found (see previous slide)
  - IDEA: disentangle jets which share common towers in the calorimeter



1. Take the lower-p_T jet (#2)
2. **f**$=E_{shared}/E_{jet\#2}$
3. **if** f>50% then MERGE jet#1 and jet#2
   else SPLIT the jets

Elena Bruna, Yale University

K_T JET ALGORITHM

- Start with a list of *preclusters*, i.e. 4-vectors of tracks, and calorimeter towers. Each precluster is defined by: E, **p**, y.
- Calculate:
  - For each precluster i:
  - For each pair (i,j) of preclusters:

  (D is a parameter of the jet algorithm)
- Find the minimum of all the d_i and d_{ij} and label it d_{min}
- If d_{min} is a d_{ij}, remove preclusters i and j from the list and replace them with a new merged precluster
- If d_{min} is a d_i, the precluster i is not "mergeable" and it can be added to the list of jets.
- Repeat the procedure until the list of preclusters is empty, i.e. all the jets have been found

Elena Bruna, Yale University