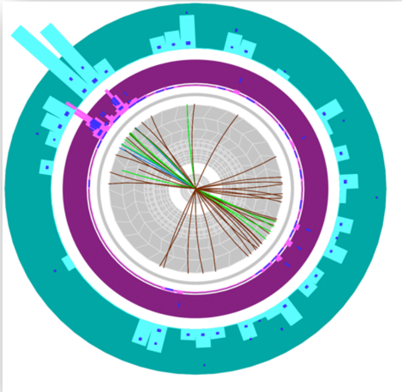
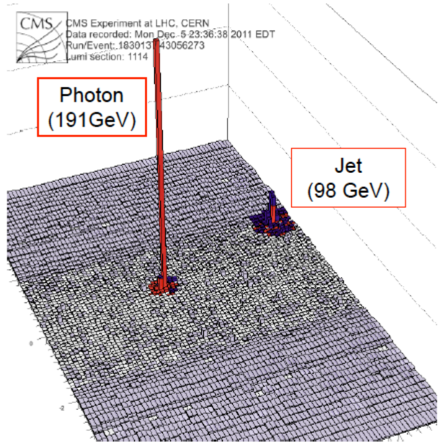
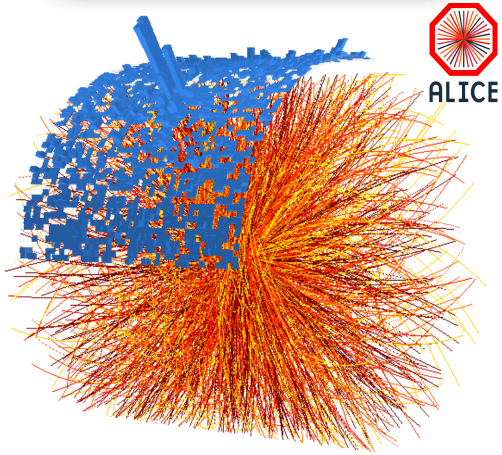


Jet Physics (Experiments)



Tatsuya Chujo
Univ. of Tsukuba



チュートリアル研究会
「重イオン衝突の物理：基礎から最先端まで」

Mar 26, 2015
理化学研究所（和光市）

筑波大学
University of Tsukuba

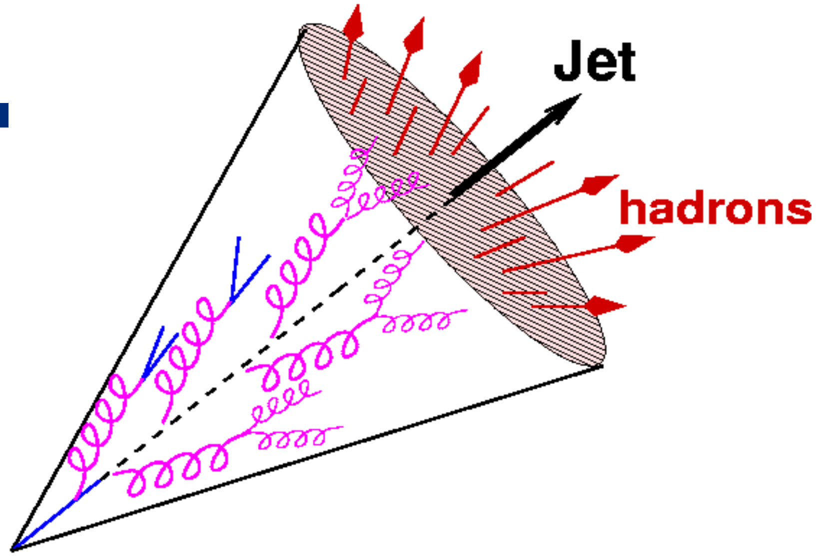
Outline

1. Introduction
2. Experimental techniques to find jets
3. Experimental retests
    - p+p
    - Pb+Pb
    - p+Pb
4. Future directions
5. Summary

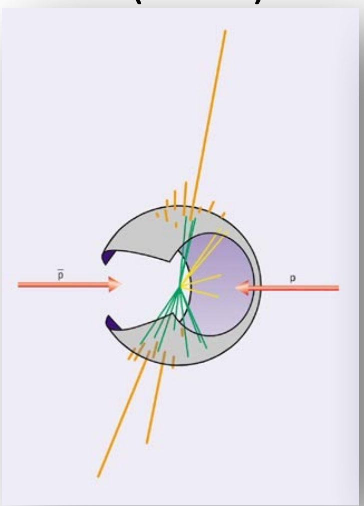
1. Introduction

Jets

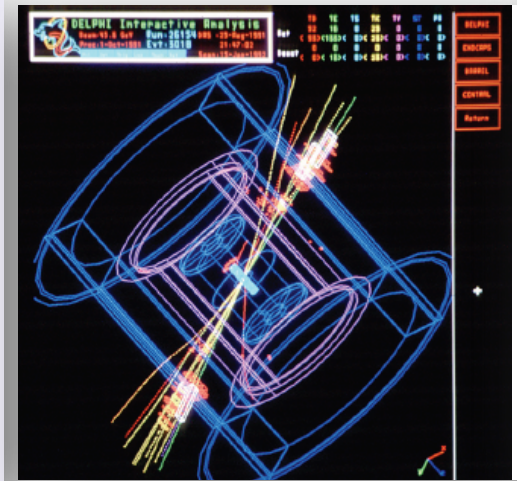
- Jets: a well defined object, and produced by the hard scatting of partons at the initial stage of the collision.
- A powerful probe to study the hot and dense QCD matter created in high energy heavy ion collisions, as a “self produced probe”.
- **LHC: dominantly produced compared to that in RHIC.**



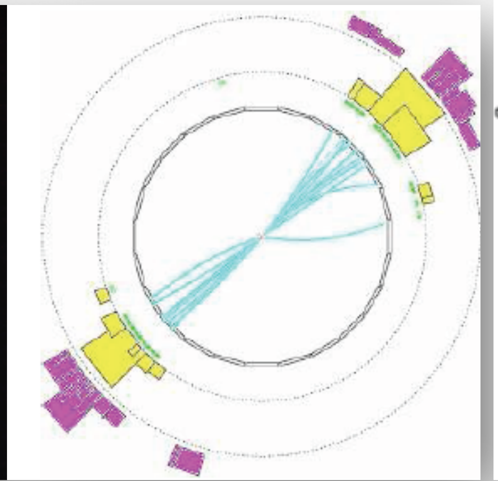
UA2 (1982)

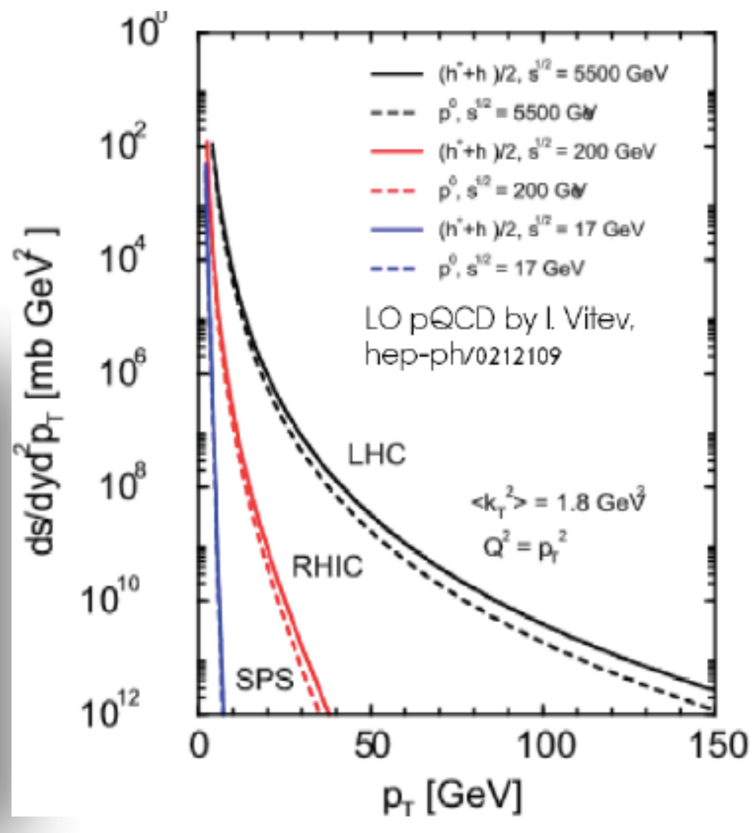


Delphi (1992)



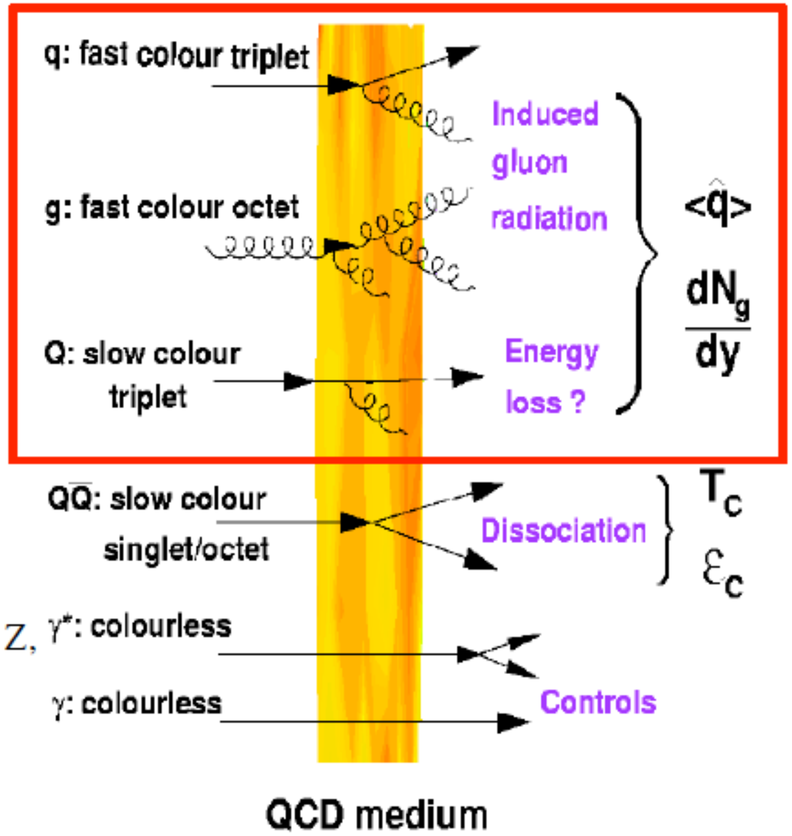
CDF





Jet and matter properties

from D. d'Enterria (QGPWS, 2008)



"Jet quenching"

J/Ψ & Υ suppression

direct γ, γ*, Z
(control)

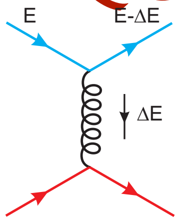
- **Jet quenching:**
  - Attenuation or disappearance of the spray of hadrons (jet) due to energy loss in the dense plasma produced by the reaction.
  - ΔE : energy loss by a particle in the medium

    ⇒ **provides fundamental information on its properties.**

Energy loss in QGP

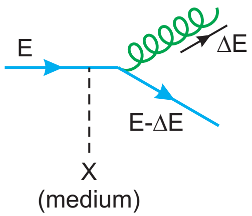
- **Jets and EM probes (photons):**

➡ **Powerful tools for the study of QGP's properties**



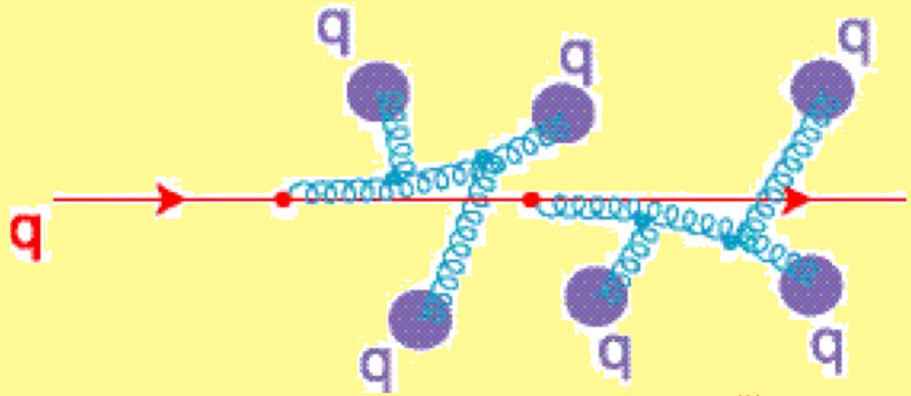
Collisional

$$\Delta E \propto \ell^1$$



Radiative

$$\Delta E \propto \ell^2$$



$$\Delta E \propto \alpha_S C_{\mathrm{R}} \langle \hat{q} \rangle L^2$$

pQCD

- Dominant energy loss is gluon radiation

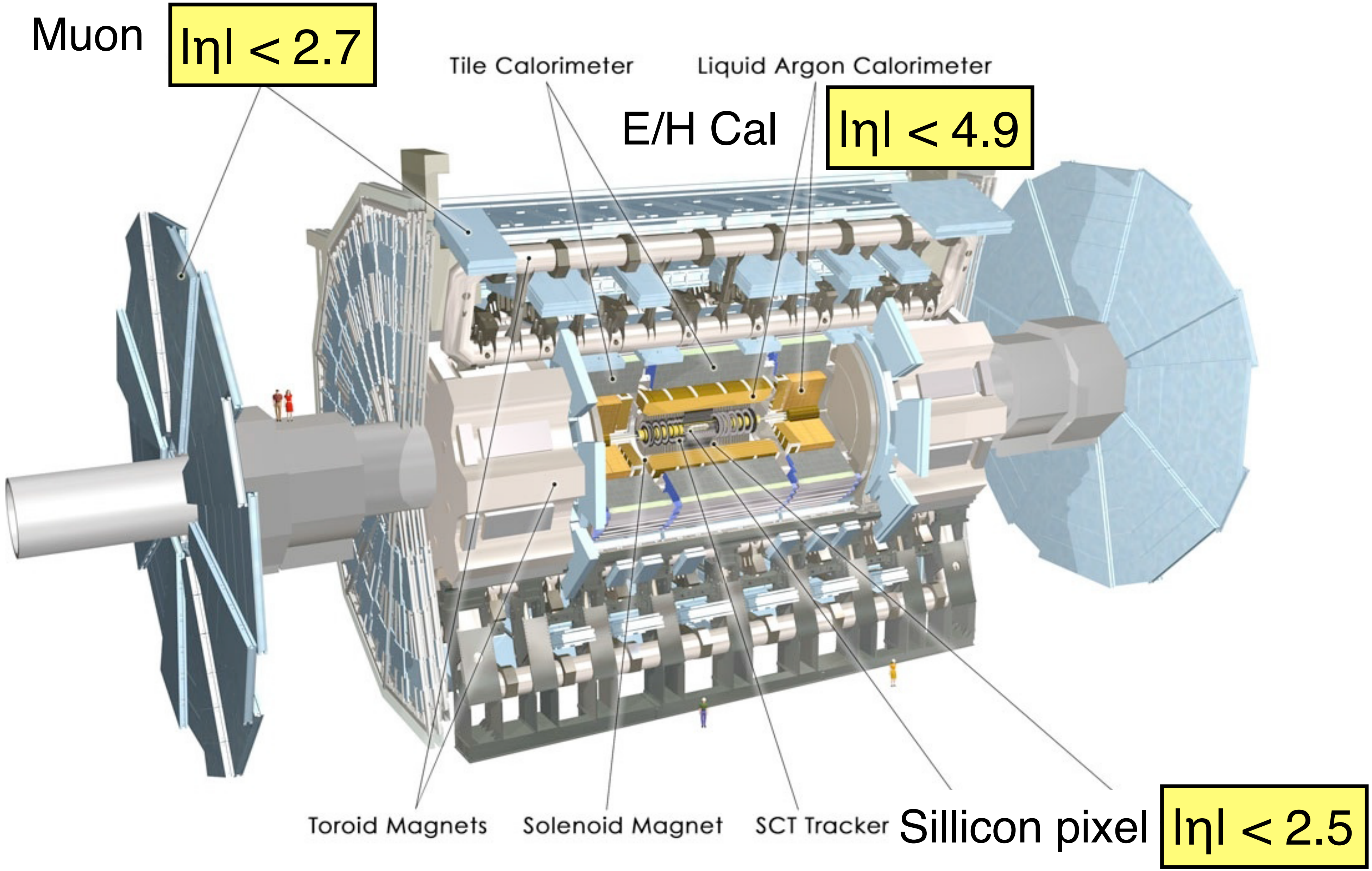
$$\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho\sigma$$

✓ **dE/dx meas. →Matter properties, jet tomography**

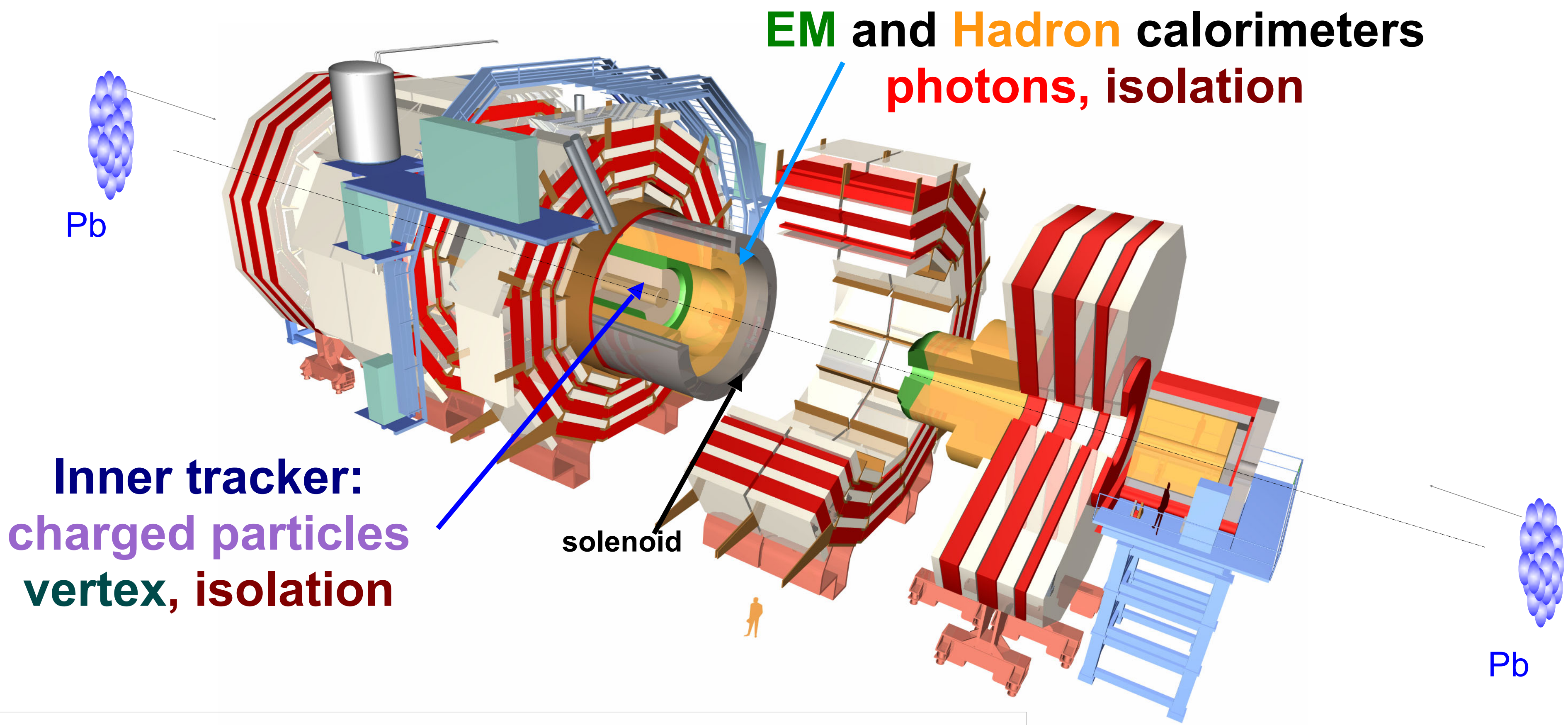
2. Jet measurements basics (experiment)

ATLAS jet measurement

ATLAS: Wide rapidity coverage by Calorimeters

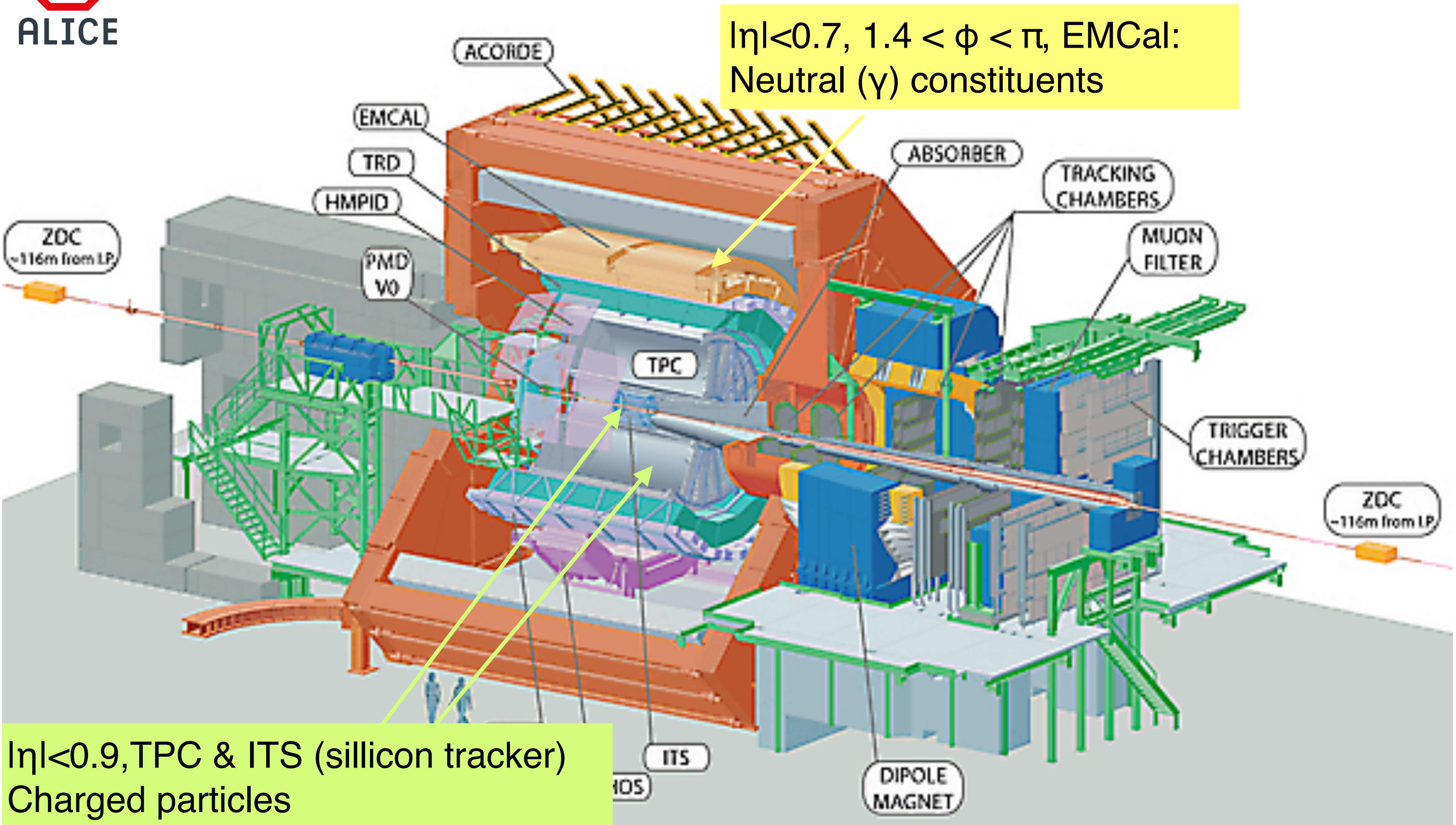


CMS jet measurement



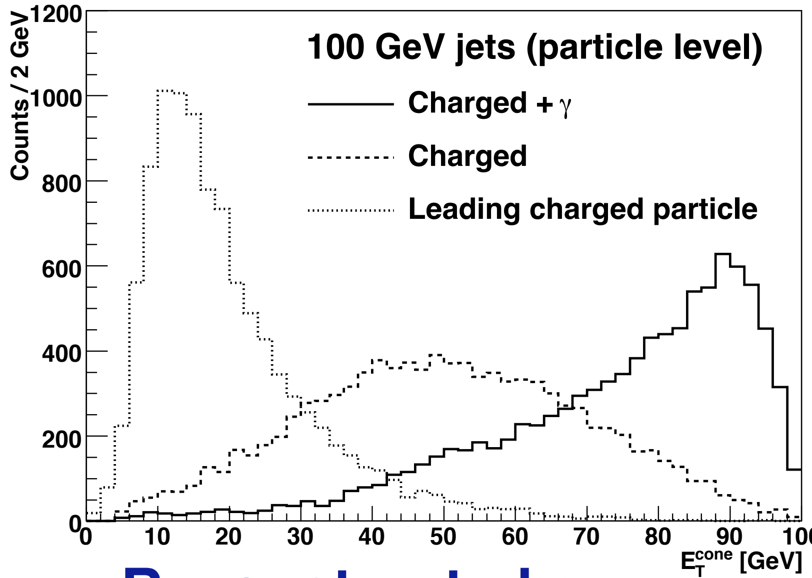
Detector	Acceptance	Jet type
Muon	$|\eta| < 2.4$	
HCAL	$|\eta| < 5.2$	Calojet
ECAL	$|\eta| < 3.0$	
Tracker	$|\eta| < 2.5$	Particle Flow Jet (track $p_T > 0.9$ GeV/c)

ALICE jet measurement



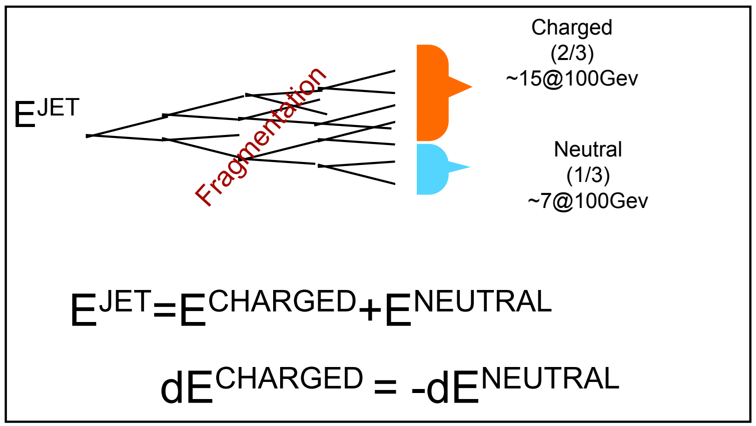
Full and charged jets

- **Full jets**: charged + neutral particles (except neutrinos)
  - Hadronic + Electromagnetic Calorimetry (ATLAS)
  - + tracking (particle flow; CMS)
  - Tracking + EMCal (ALICE) w/o neutrons, anti-neutrons
- **Charged jets**: only charged particles
  - Used by ALICE because of limited acceptance of EMCal



Reconstructed energy

Total jet energy is fixed.
fluctuation of neutral play significant role



M. van Leeuwen (Heavy Ion Cafe 2014), modified

Jet finding algorithms

1. Cone algorithm:

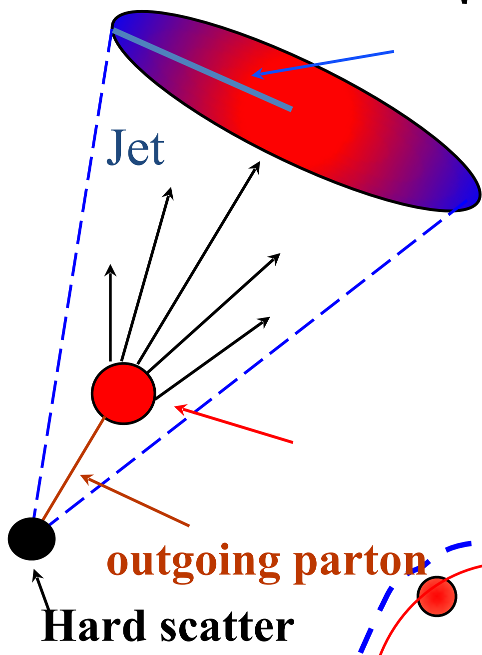
- Simple geometric motivation
- Split/merging procedure for overlapping cone
- ◆ UA1
- ◆ SIS cone
  - Seedless Infrared Safe Cone algorithm
  - insensitive to soft radiation

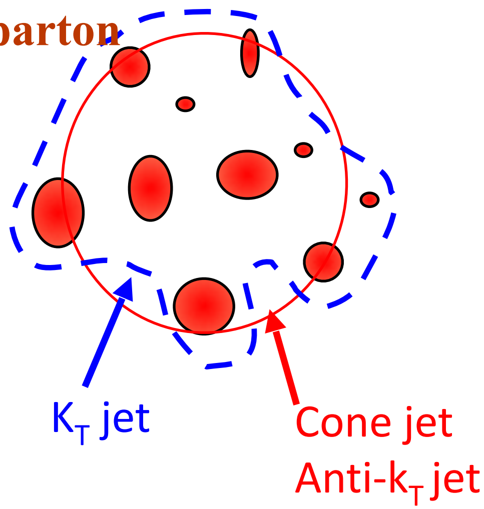
2. Sequential recombination algorithm:

- Cluster pairs of objects close in relative p_T
- Define "distance" between pairs
- ◆ k_T algorithm
  - Starting from low p_T particle
  - Standard algorithm for BG estimation
- ◆ anti-k_T algorithm
  - Starting from high p_T particle
  - Standard algorithm in HIC

Resolution parameter R

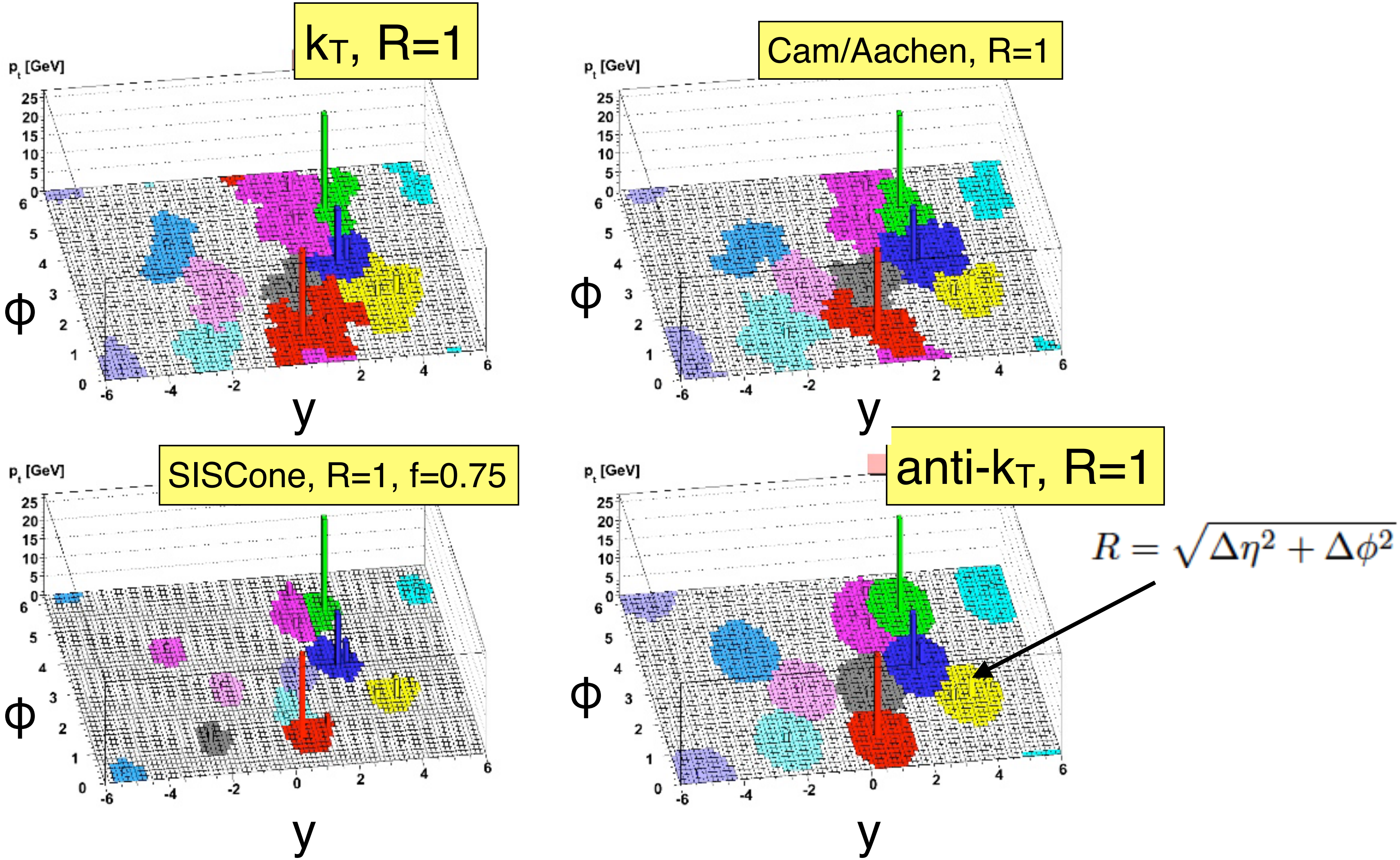
$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$





Jet reconstruction algorithms

Cacciari, Soyez, Salam (2008)



Detector corrections

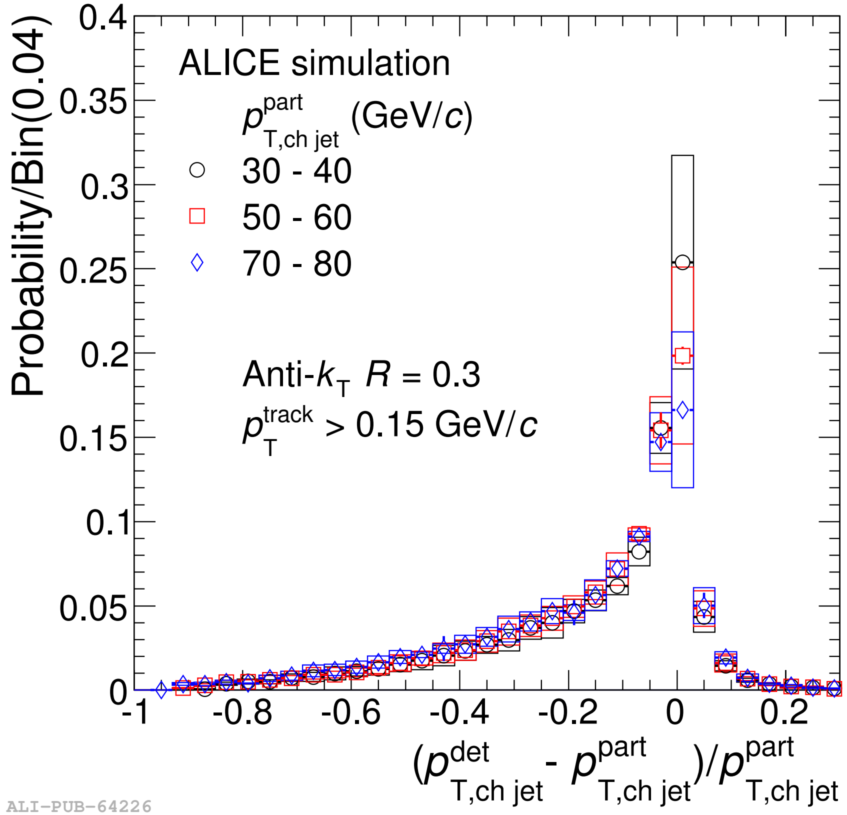
Definitions:

Particle level: as generated by event generator, e.g. PYTHIA.

Detector level: as reconstructed (PYTHIA+detector simulation)

Standard practice:

- Charged jets are corrected to charged jets at the particle level
  - main effect: tracking efficiency
- Full jets are corrected to full jets at the particle level
  - Calorimetric jets: HCal response
  - Tracking+EMCal: Unmeasured hadrons (neutrons, K^0_L, tracking efficiency)



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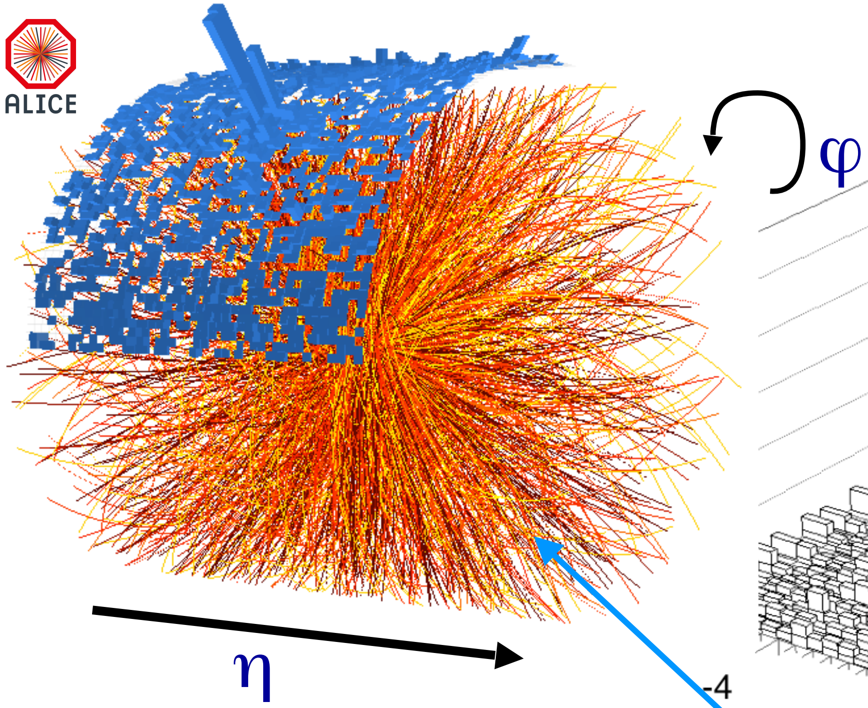
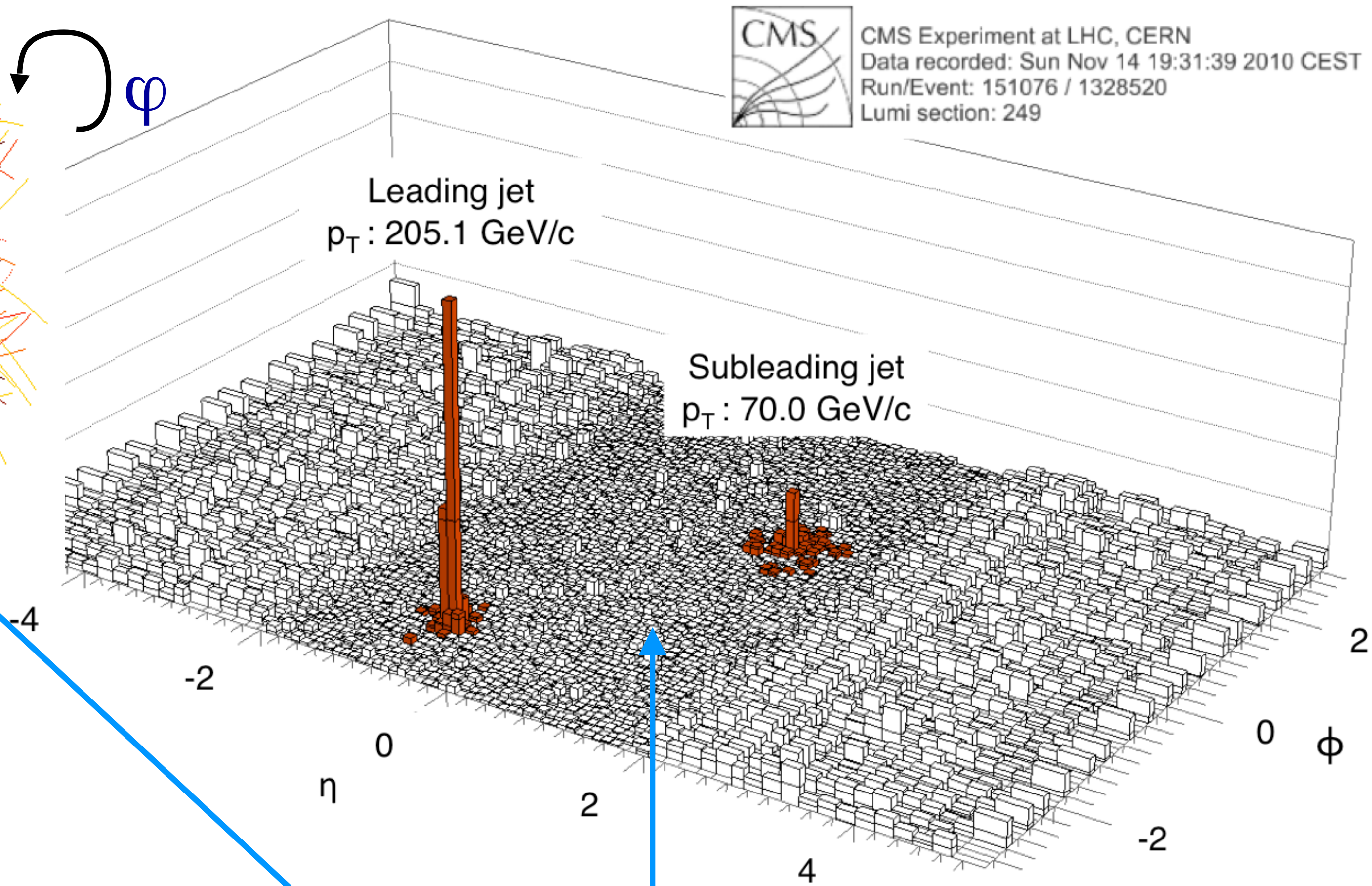
Jets at LHC, large soft background



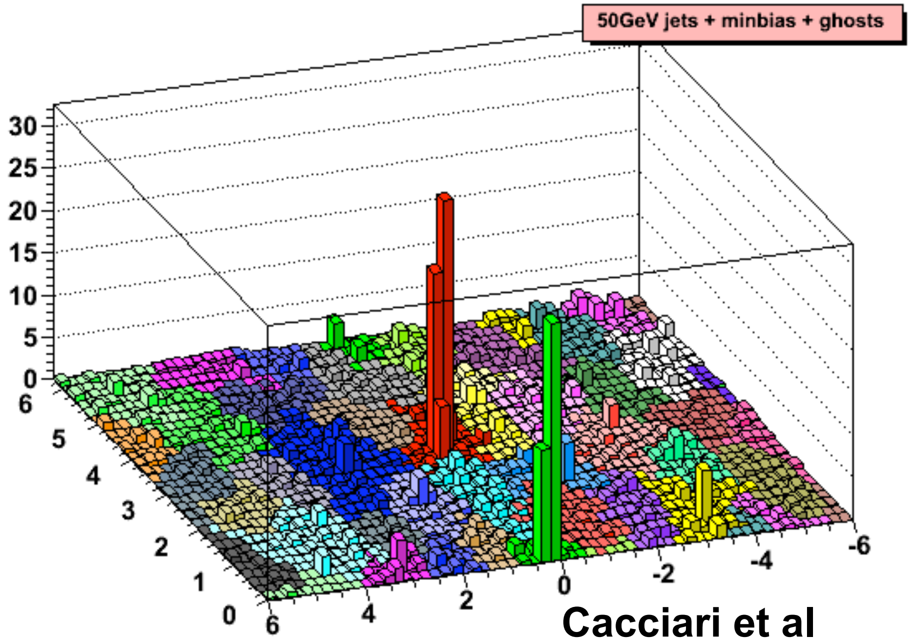


Clear jet peaks, but a lot of <u>uncorrelated "soft" background</u>

PbPb jet background

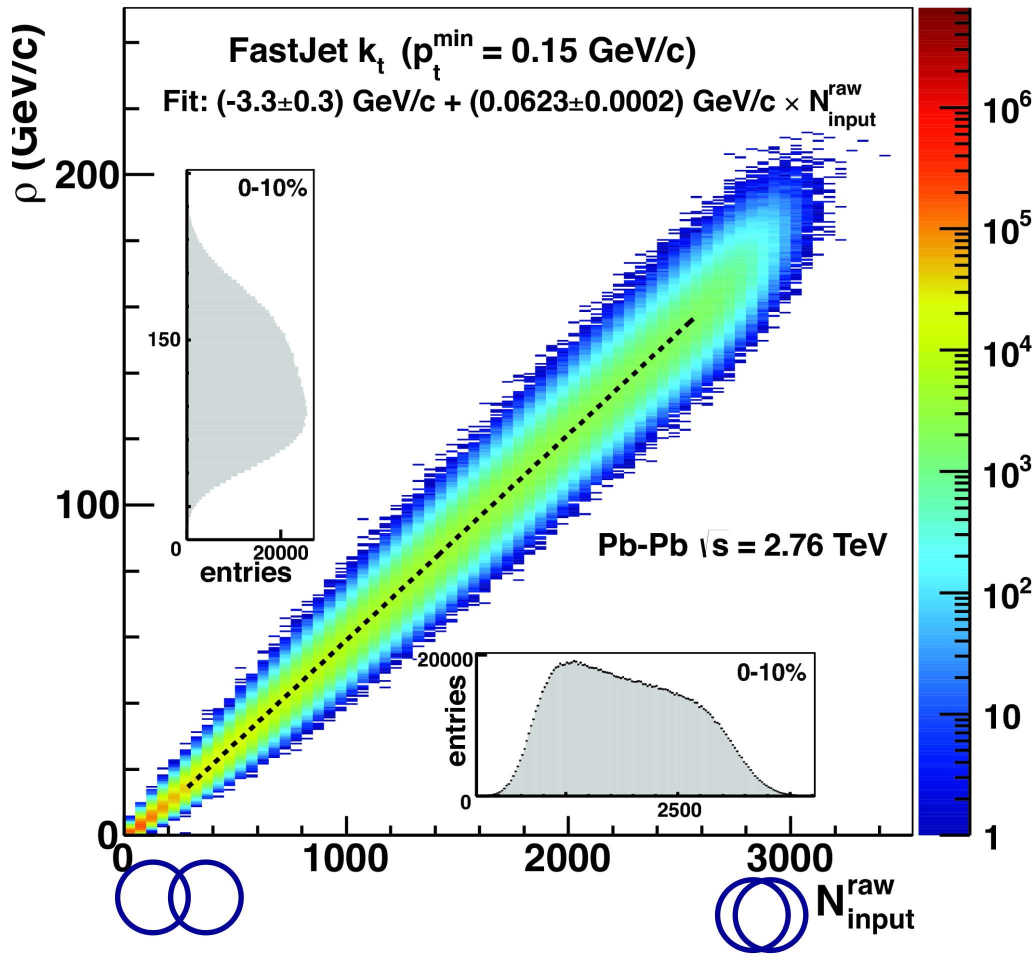
M. van Leeuwen (Heavy Ion Cafe 2014), modified

Jet finding illustration



η-φ space filled with jets
Many 'background jets'

Background density vs multiplicity



Background contributes up to ~180 GeV per unit area

Subtract background: $$p_{T,jet}^{sub} = p_{T,jet}^{raw} - \rho\ A$$

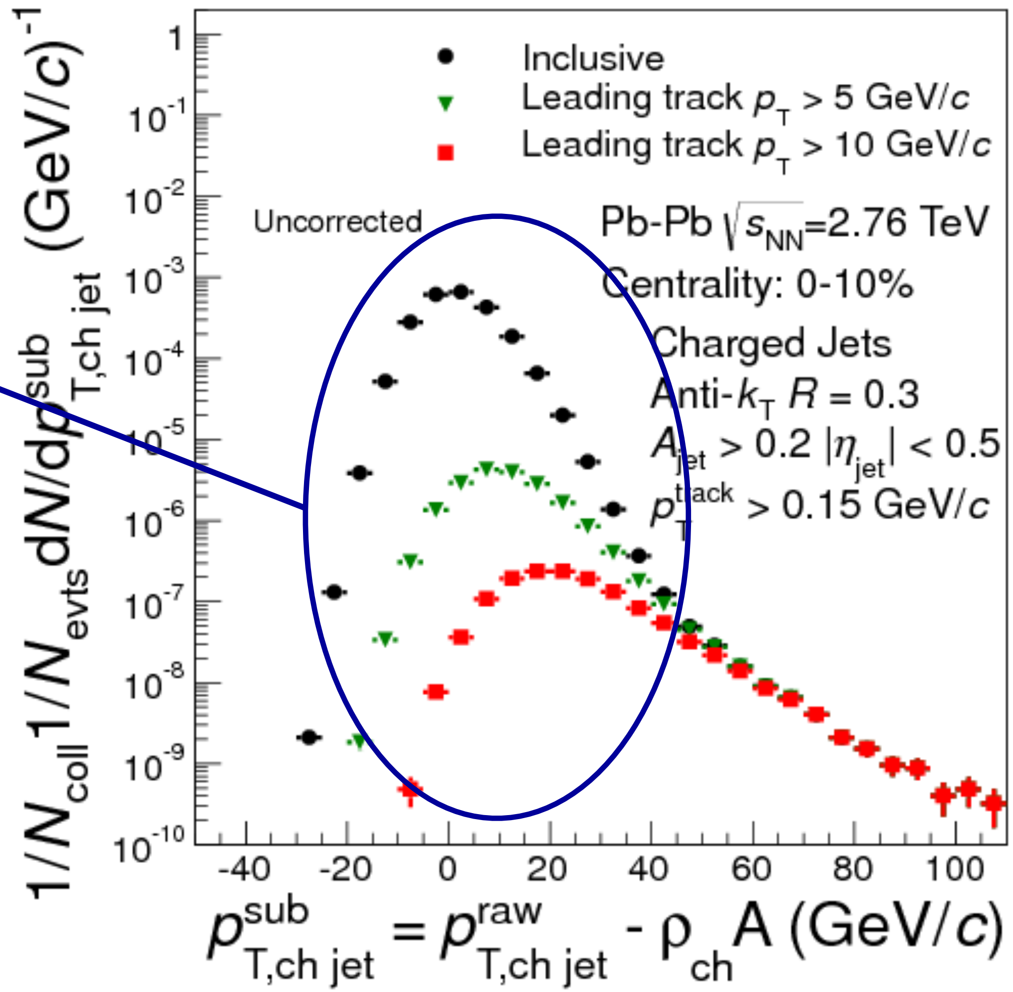
$$\rho = \mathrm{median}\left\{\frac{p_{\mathrm{T,jet}}^{\mathrm{reco,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}}\right\}$$

Statistical fluctuations remain after subtraction

Background jets

Raw jet spectrum

Event-by-event background subtracted



Low p_T: 'combinatorial jets'

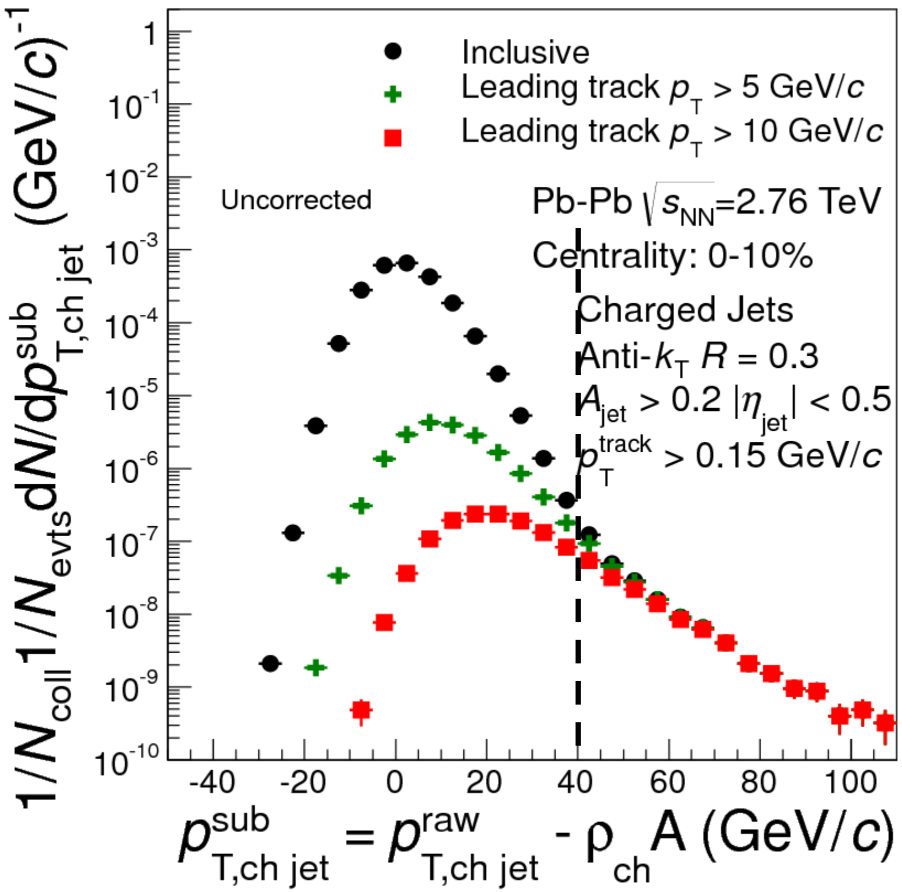
- Can be suppressed by requiring leading track
- However: no strict distinction at low p_T possible

Next step: Correct for background fluctuations and detector effects by unfolding/deconvolution

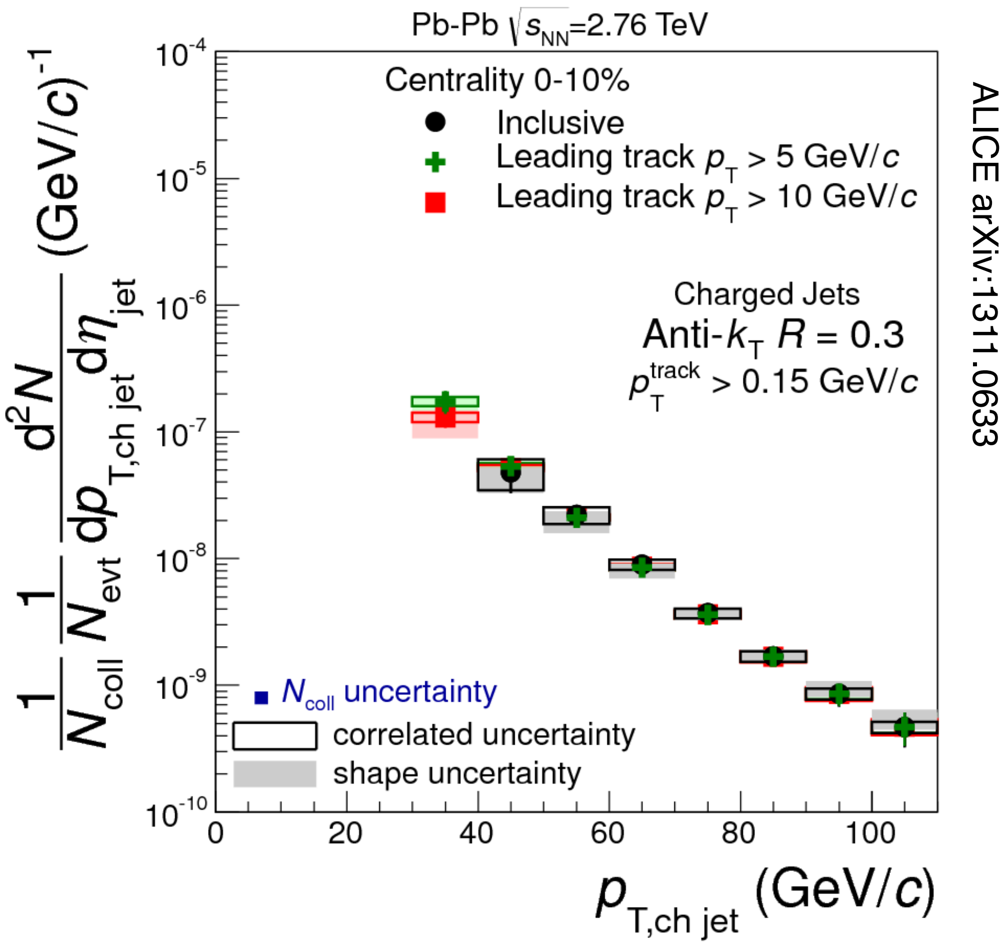
M. van Leeuwen (Heavy Ion Cafe 2014), modified

Removing the combinatorial jets

Raw jet spectrum



Fully corrected jet spectrum

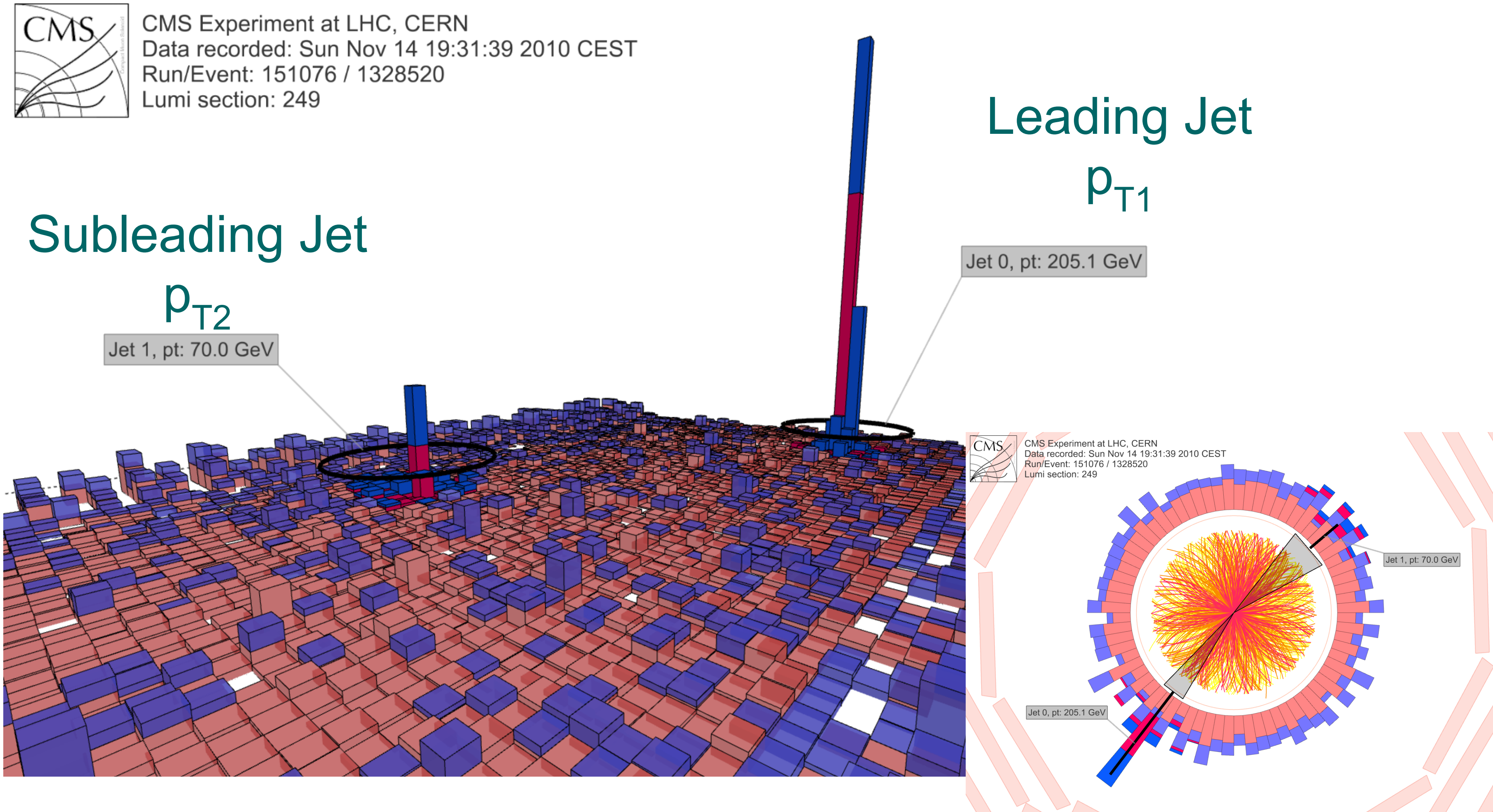


Correct spectrum and remove combinatorial jets by unfolding

Results agree with biased jets: reliably recovers all jets and removed bkg

M. van Leeuwen (Heavy Ion Cafe 2014), modified

leading and sub-leading jet



3. Experimental results

Experimental jet observables

- Single jet p_T spectrum
- Fragmentation function (FF)
- Jet R_{AA} or R_{CP} (central-to-peripheral ratio)
- di-jet energy imbalance A_J
- γ-jet correlations
- b-tag jet
- …

$$D_{h/k}(z),\ z = p_h/p_k:$$

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{dN_{AA}/dp_{\mathrm{T}}}{d\sigma_{pp}/dp_{\mathrm{T}}}$$

$$R_{\mathrm{CP}} = \frac{\left.\frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2N_{\mathrm{ch\,jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta}\right|_{\mathrm{central}}}{\left.\frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2N_{\mathrm{ch\,jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta}\right|_{\mathrm{peripheral}}}$$

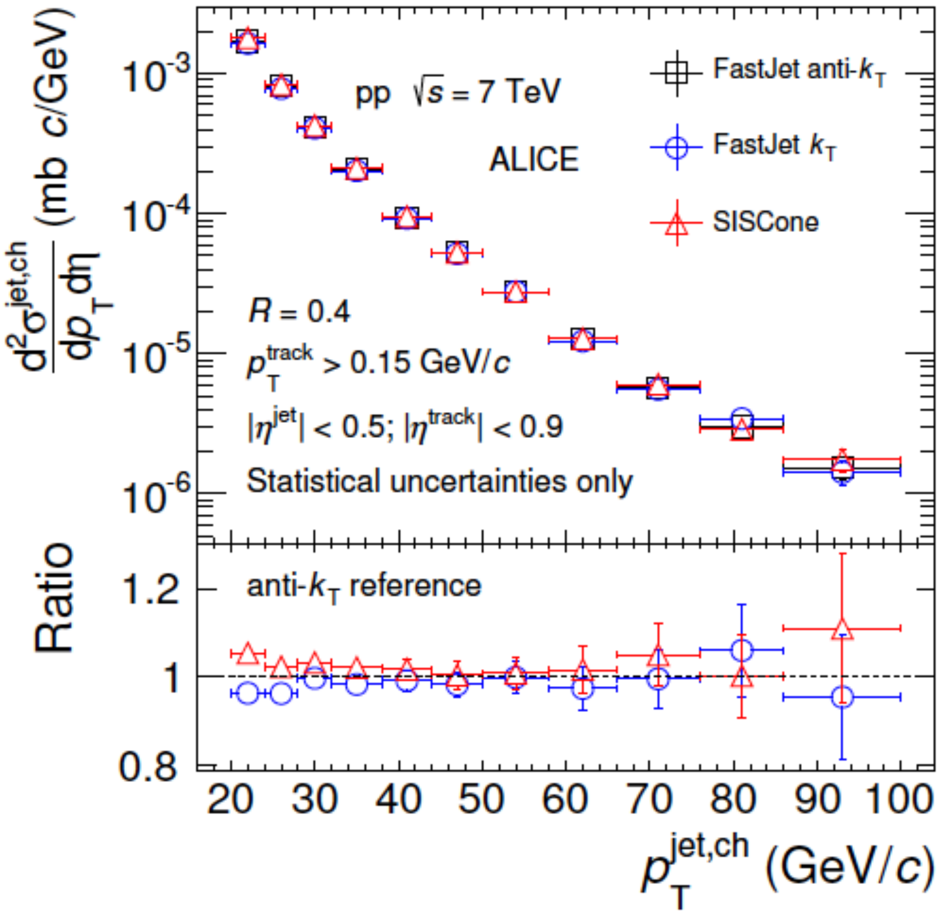
$$< x_{J\gamma} >= p_T^{jet}/p_T^{\gamma}$$

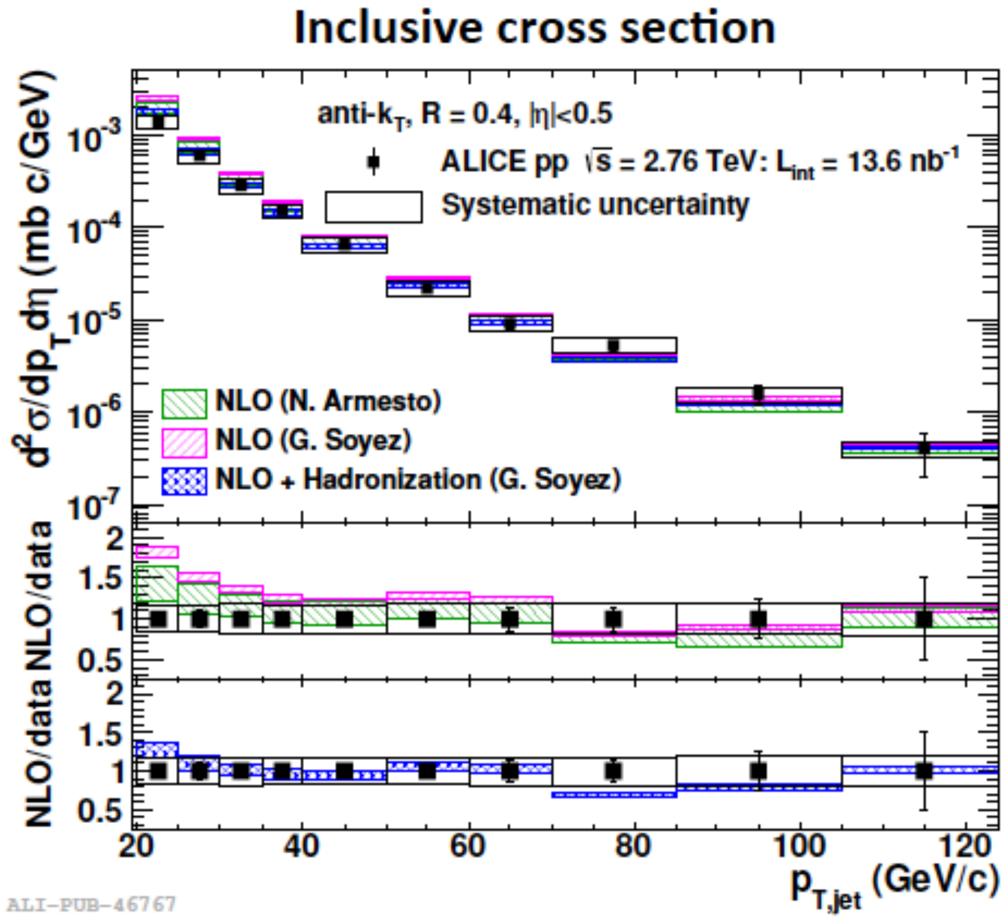
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

as a function of collision system (pp, PbPb, pPb, centrality, rapidity, …) for full / charged jets.

p+p

Jet in pp (full jet)

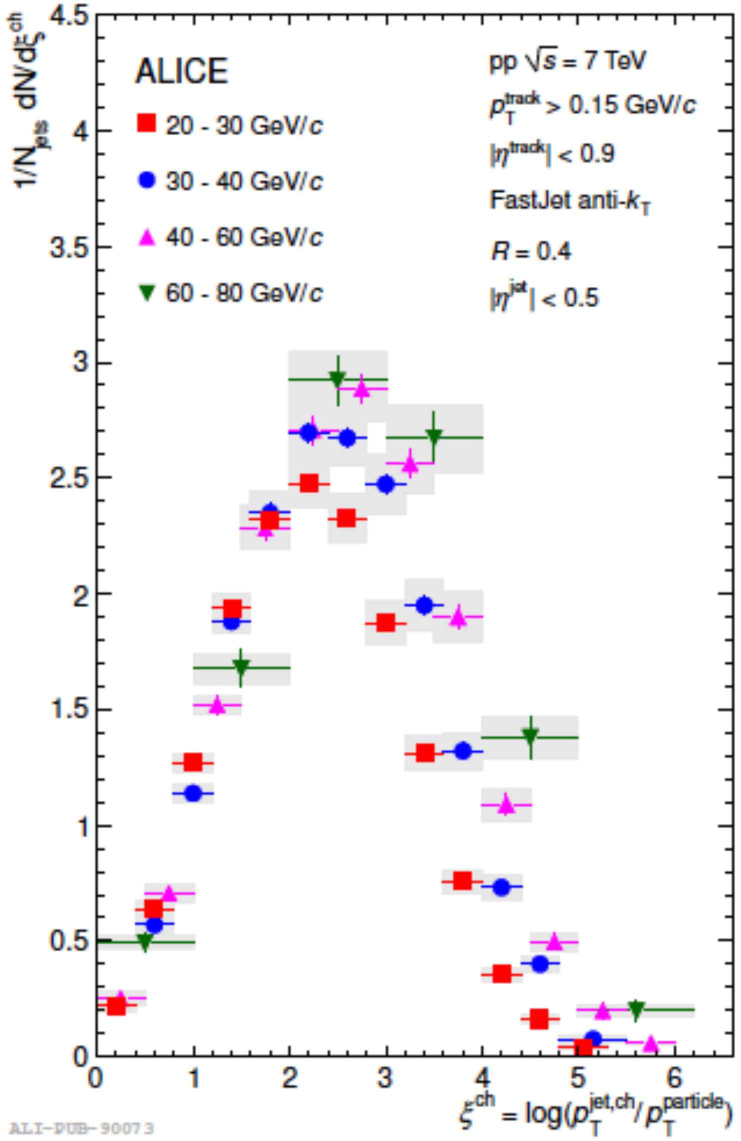


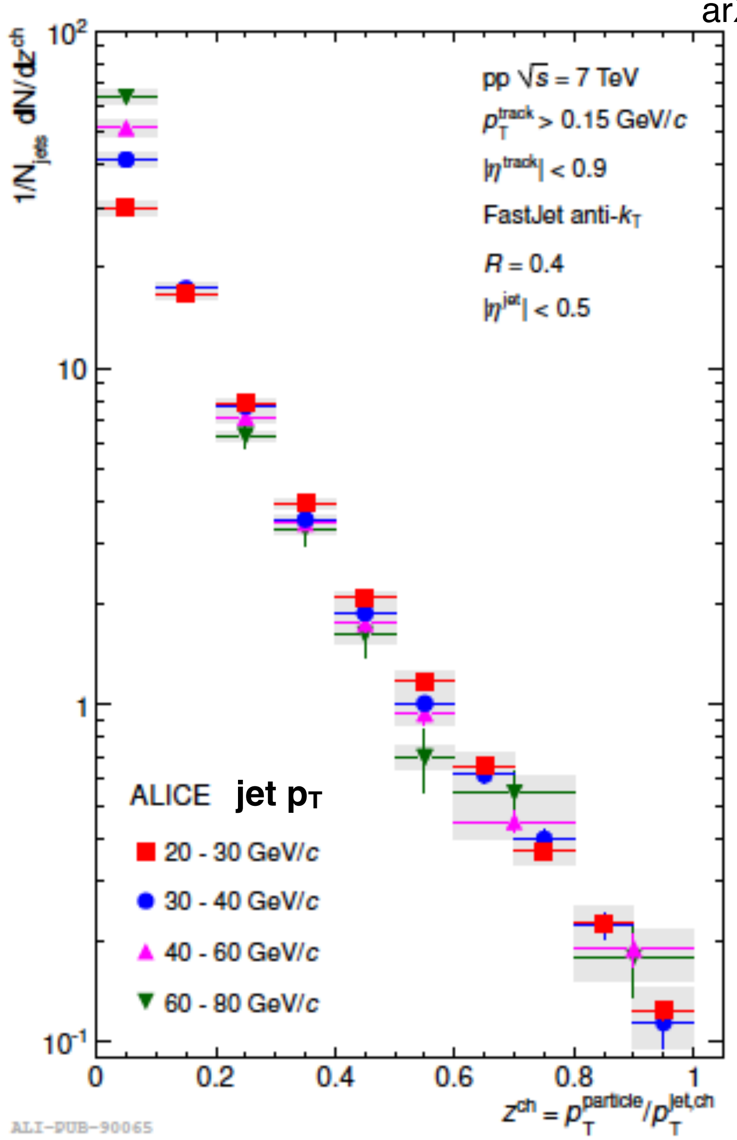


- Good agreement with NLO calculations
- Jet transverse energy profile: also agree with NLO calc.

Fragmentation Function (charged jet, pp)

arXiv:1411.4969

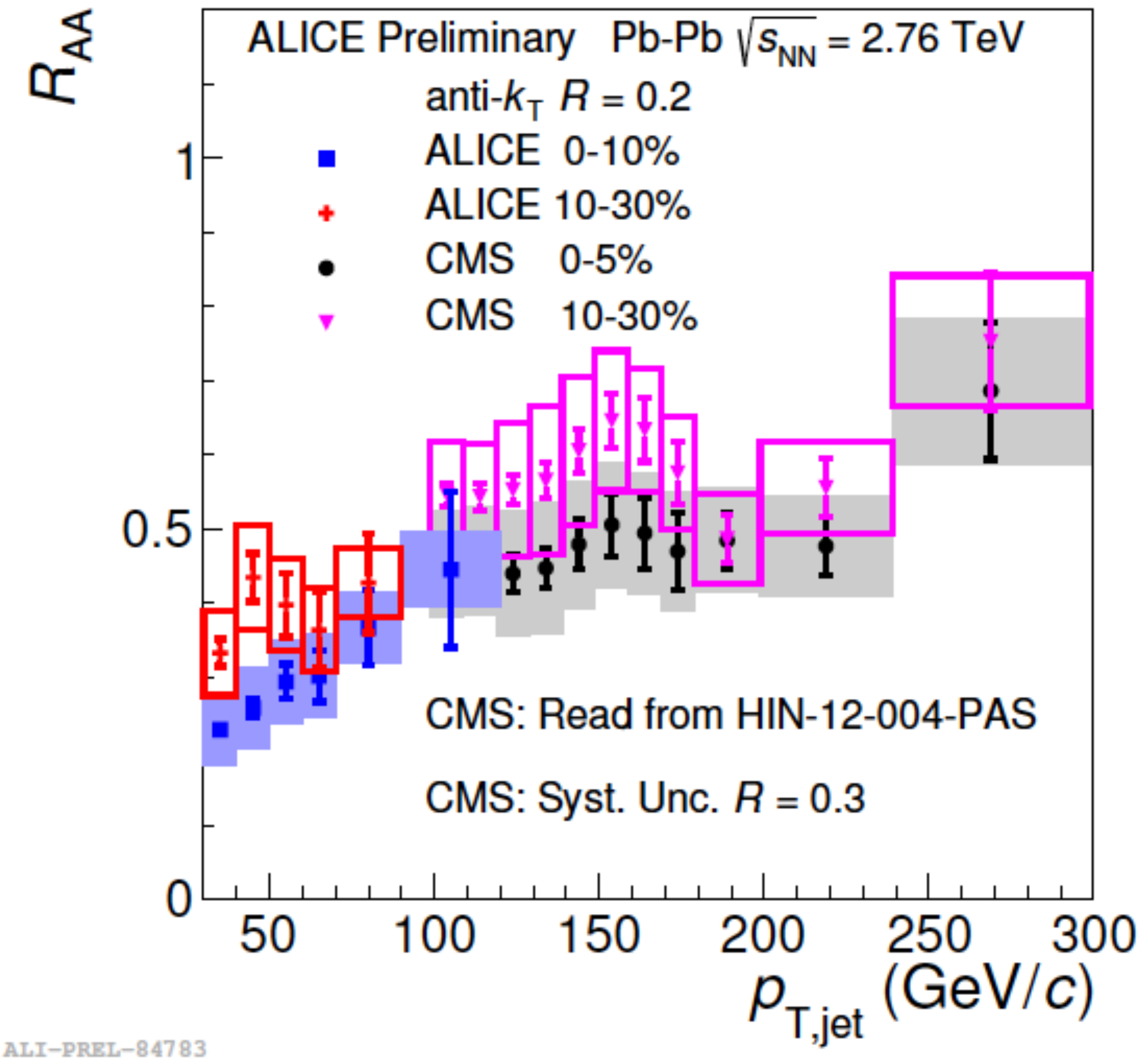




Hump-back plateau, approximate scaling at high z

Pb+Pb

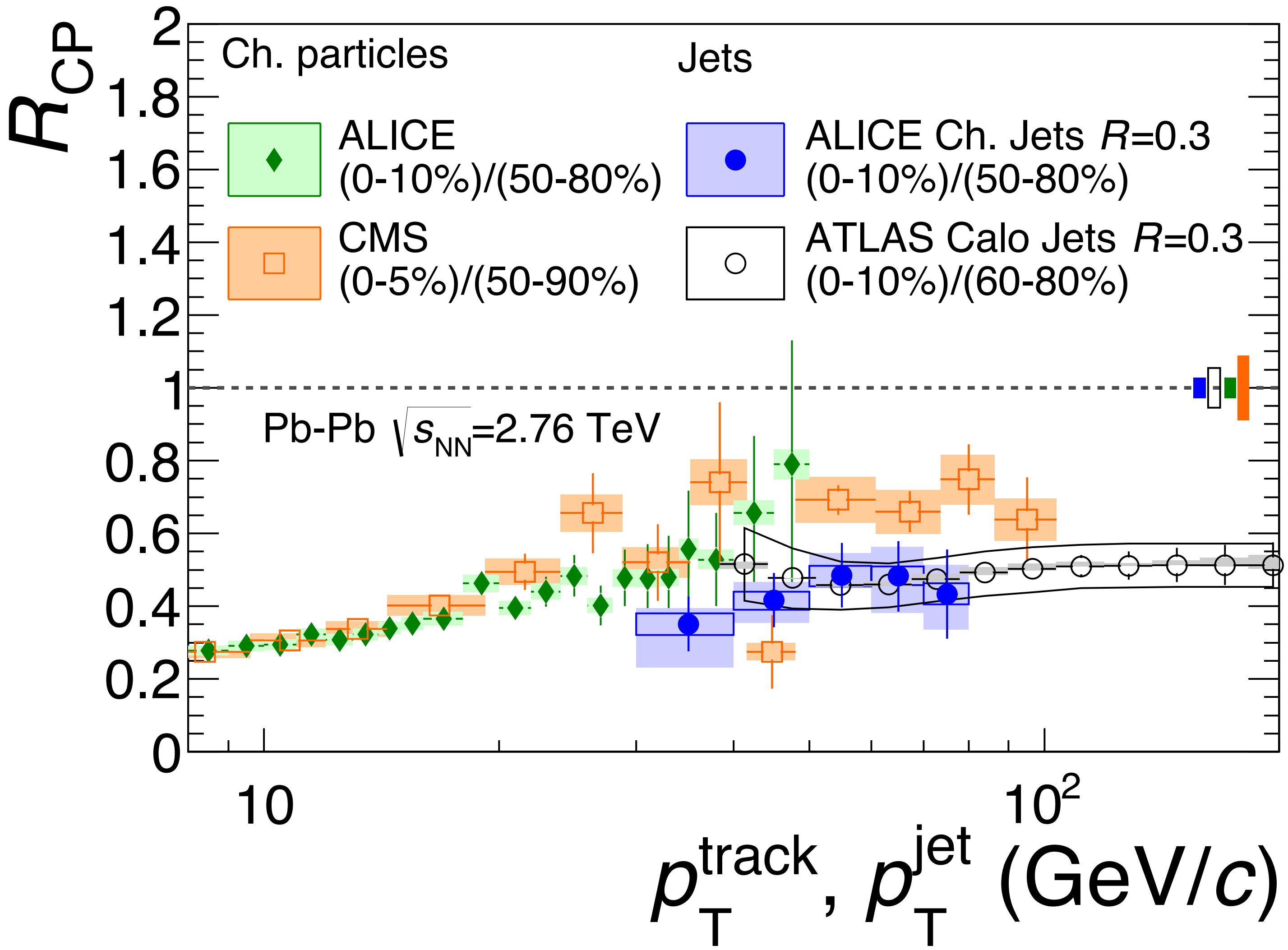
Full jet comparison: R_{AA}



ALICE: Allow complementary measurement at low p_T jet

Medium is opaque for jets up to jet p_T ~ 3000 GeV/c

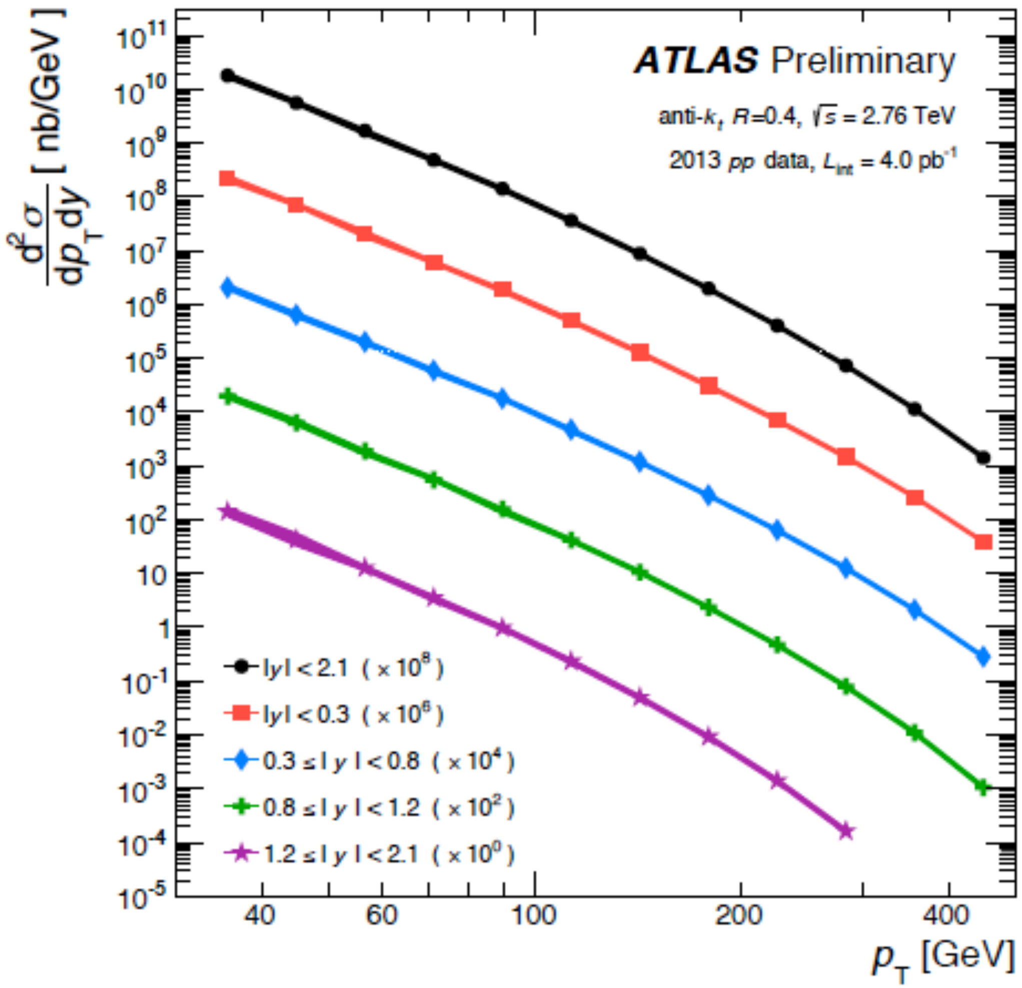
Comparing hadrons and jets



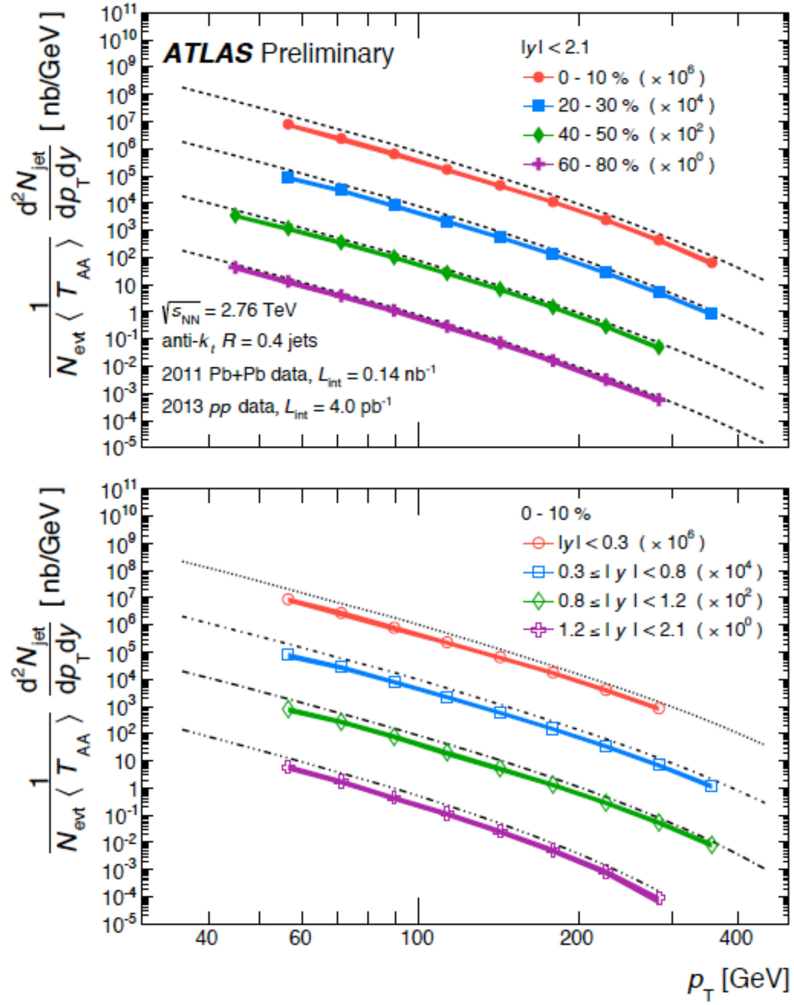
Suppression of hadron (leading fragment) and jet yield similar

Jet spectra in p-p, Pb+Pb (ATLAS)

pp 2.76 TeV



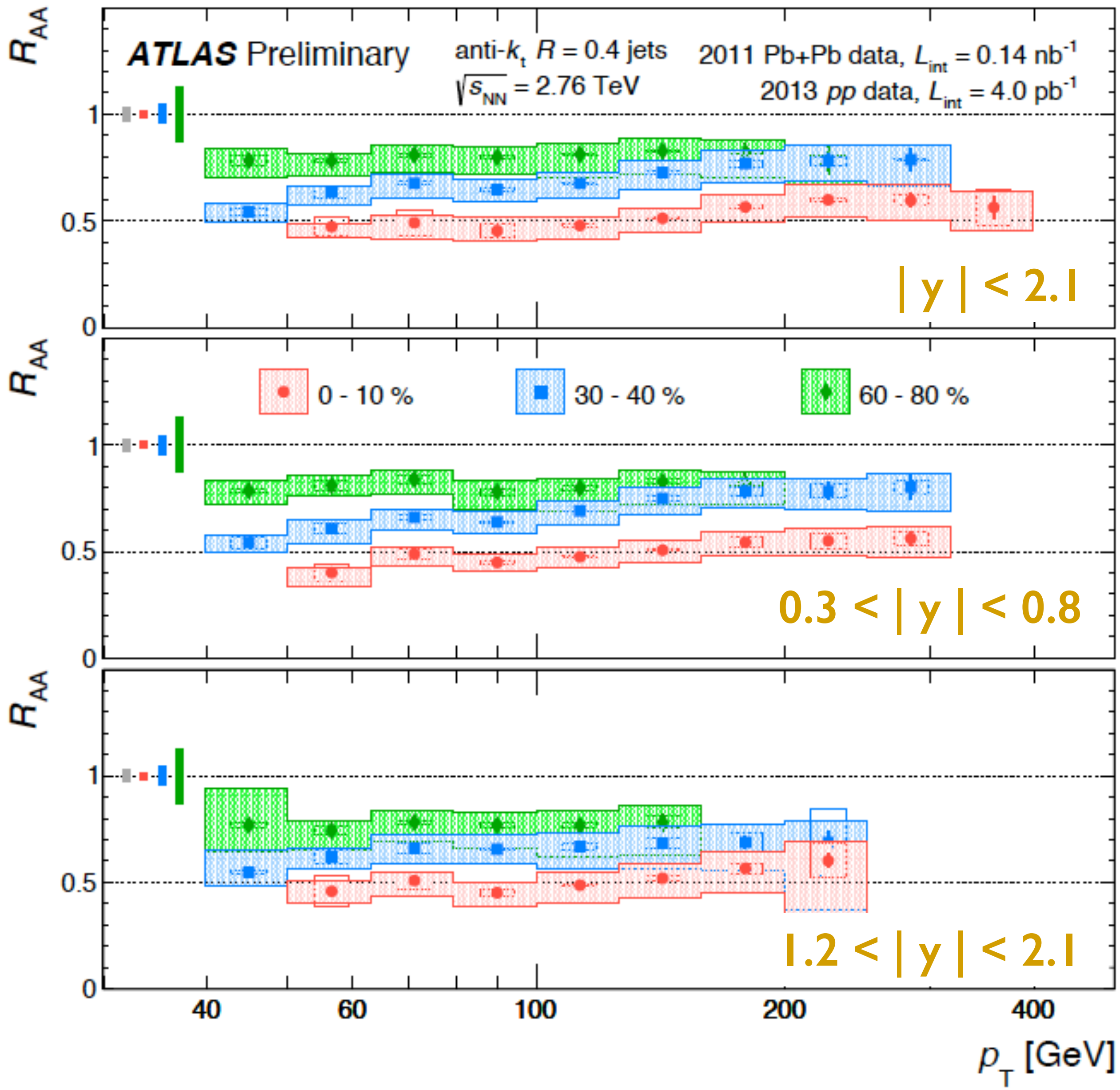
Pb-Pb 2.76 TeV



- ATLAS: in different y and centrality, up to p_T < 400 GeV

Jet R_{AA}: centrality and y dep.

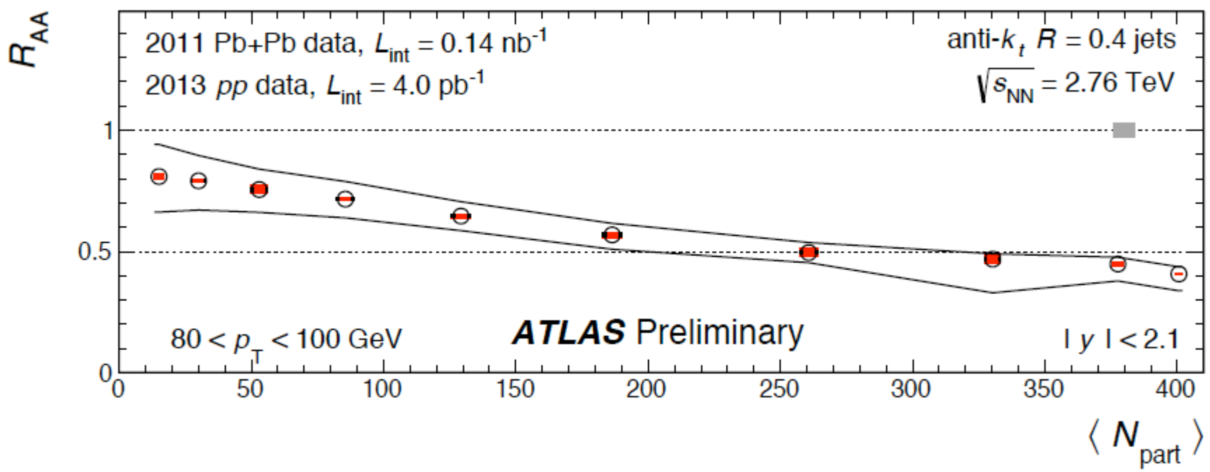
- Jet R_{AA} vs p_T and y.
- Factor of ~2 suppression **up to jet p_T of 400 GeV**
- Slow increase with increasing jet p_T, may vary with centrality



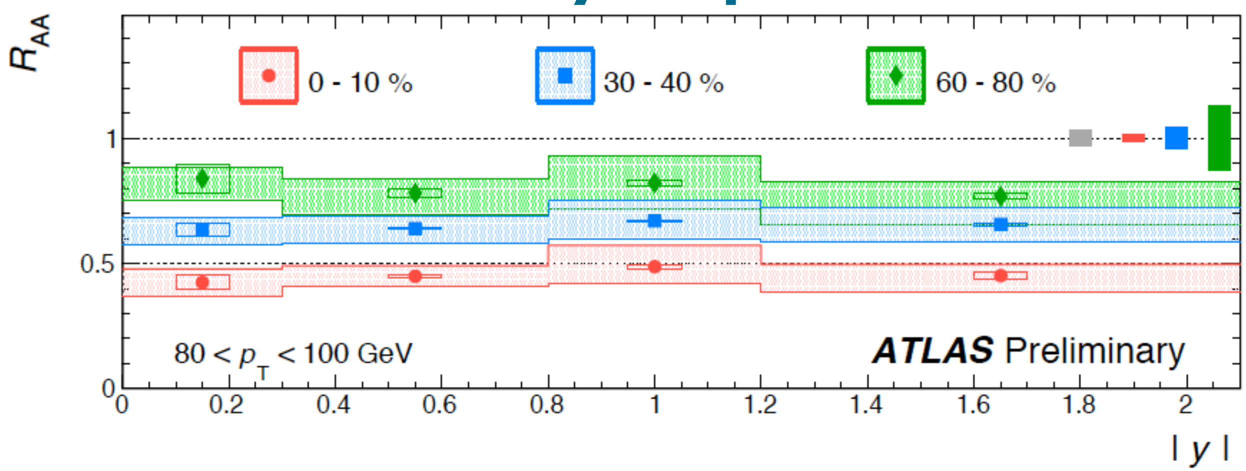
Jet R_{AA}: centrality and y dep.

- R_{AA} **monotonically decreases** vs N_{part}
  - R_{AA} ~0.8 in 60-80%,
  - R_{AA} ~0.4 in 0-1% at lower jet p_T
- No significant dependence on rapidity observed
  - Even though both spectrum shape and q/g fractions vary with y

Centrality dep.



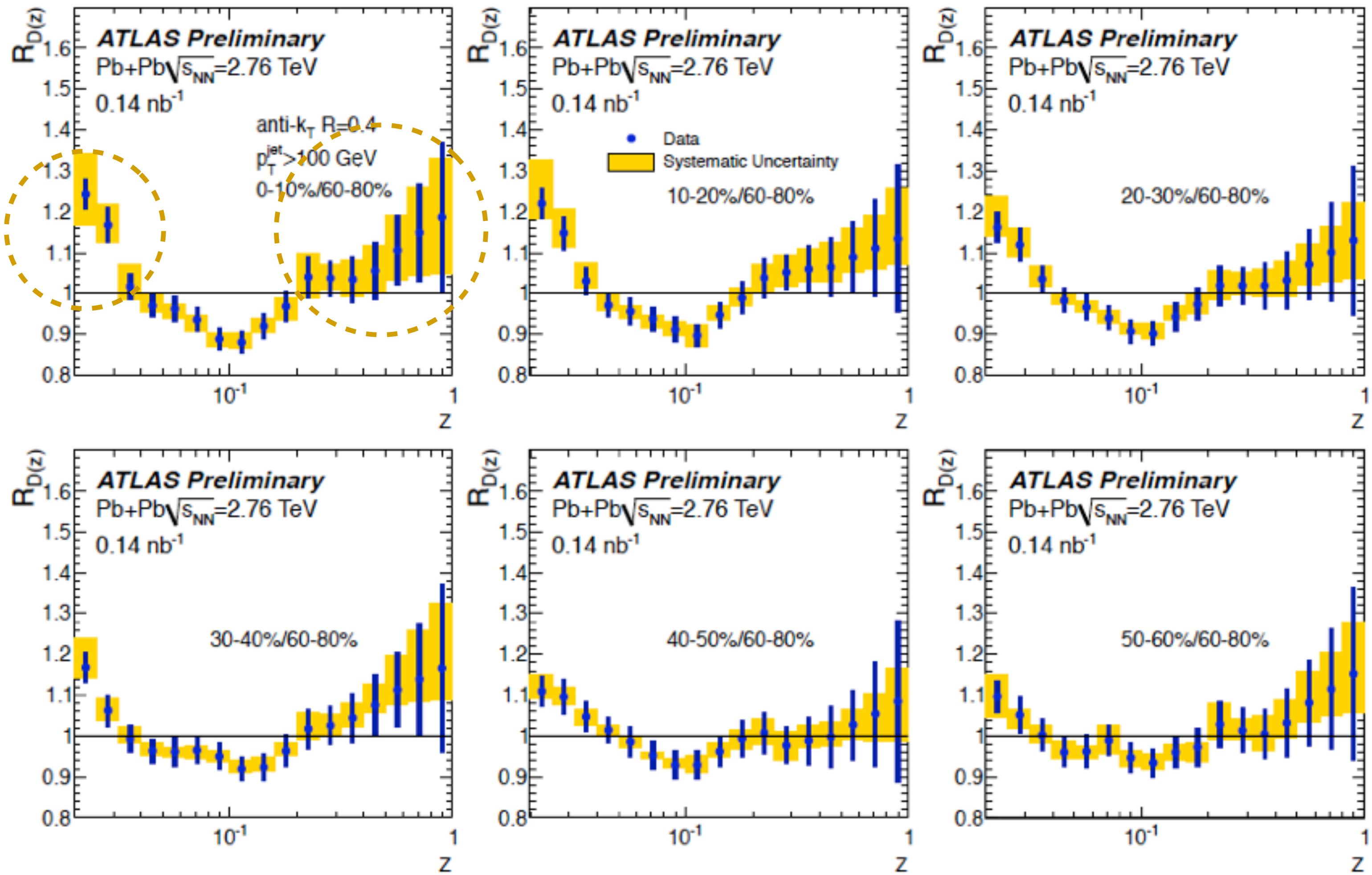
y dep.



Jet Fragmentation in PbPb

central

R= 0.4



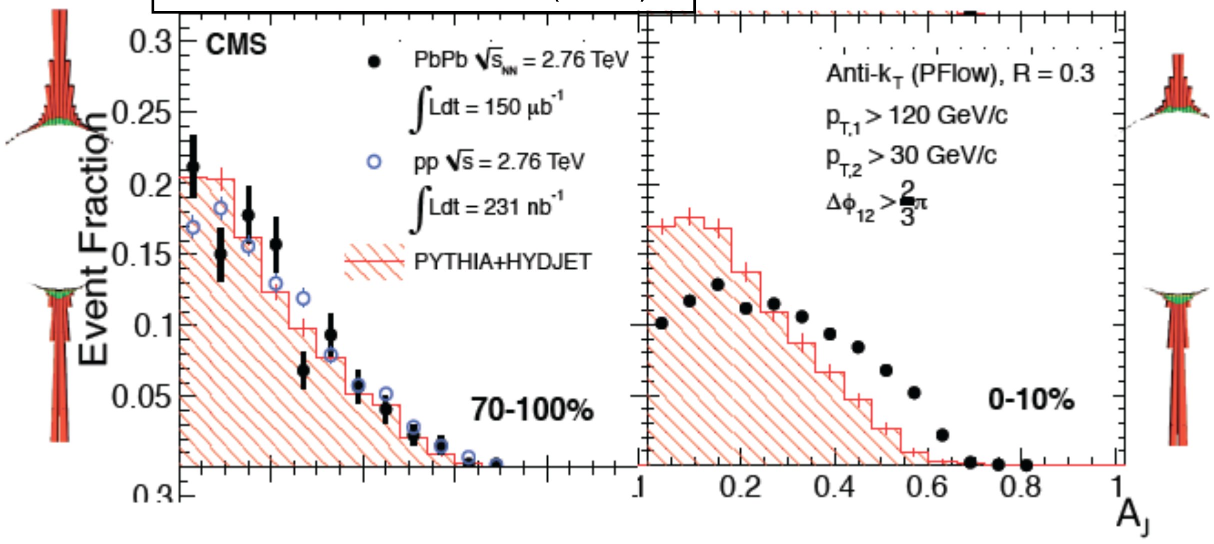
$z = p_h/p_{parton}$

peripheral

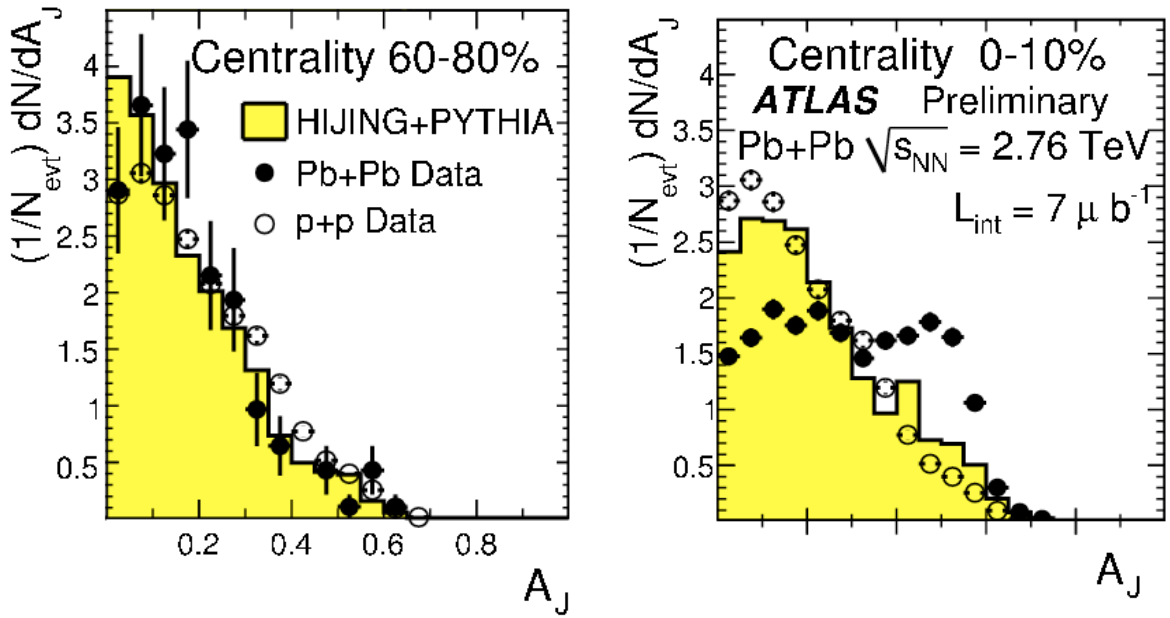
- **Ratios of D(z)** vs centrality, using baseline peripheral (60-80%)
- In addition to features previously seen (modification of small z (low pT)), **indication of an enhancement at large z**

Di-jet energy imbalance

CMS, PRC 84, 024906 (2011)



ATLAS, PRL, 105 (2010) 252303



1) Large energy imbalance is observed in central Pb-Pb.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$: leading jet
$p_{T,2}$: sub-leading jet

2) Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

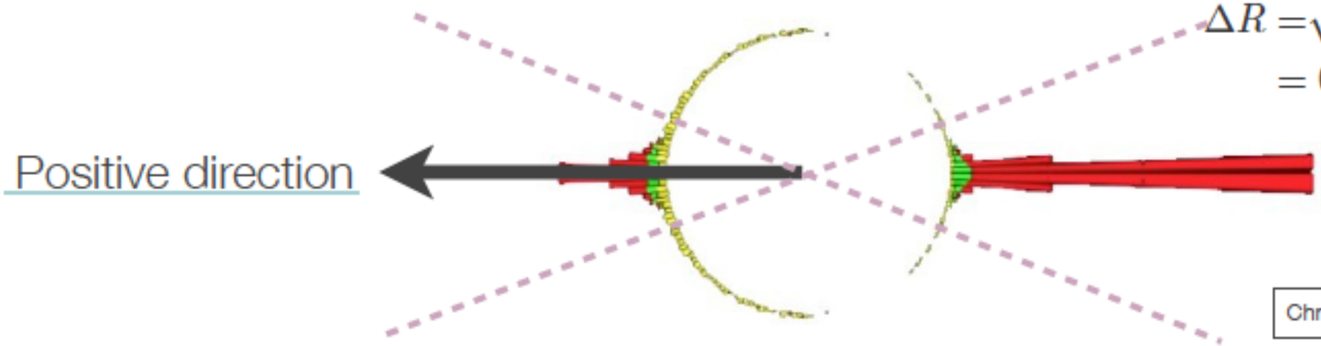
Energy balance by low p_T particle at large angle

Net-p_T along the sub-leading jet

CMS (2011)

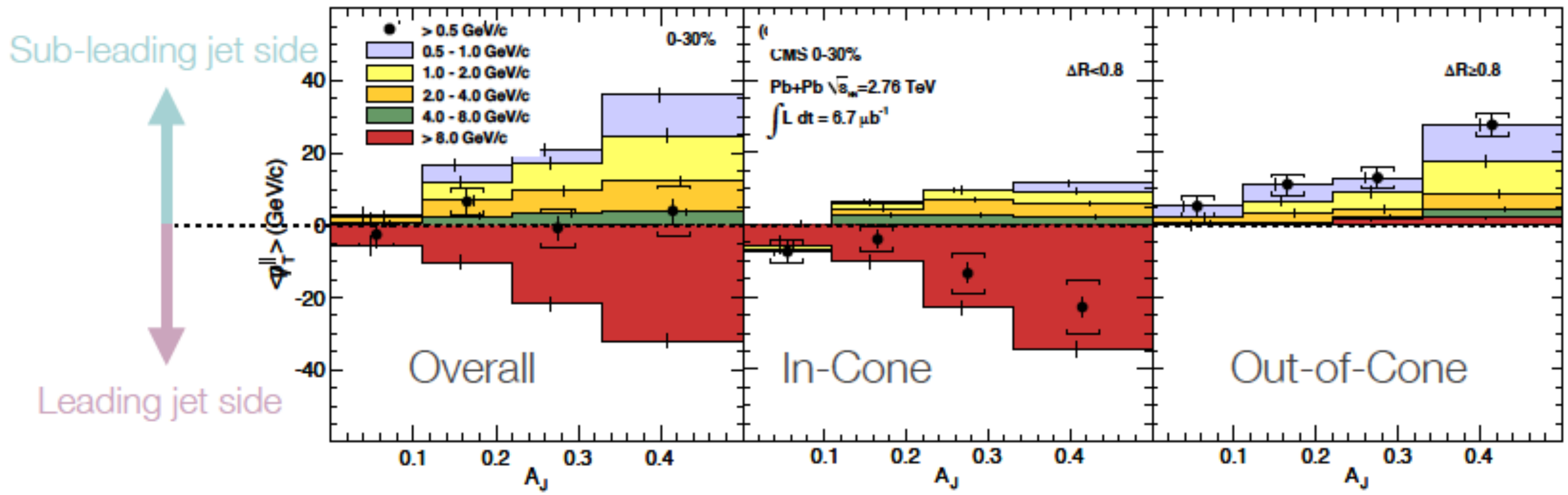
$$\not{p}_{\mathrm{T}}^{||} = \sum_i -p_{\mathrm{T}}^i \cos(\phi_i - \phi_{\text{Leading Jet}})$$

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.8$$



Leading Jet

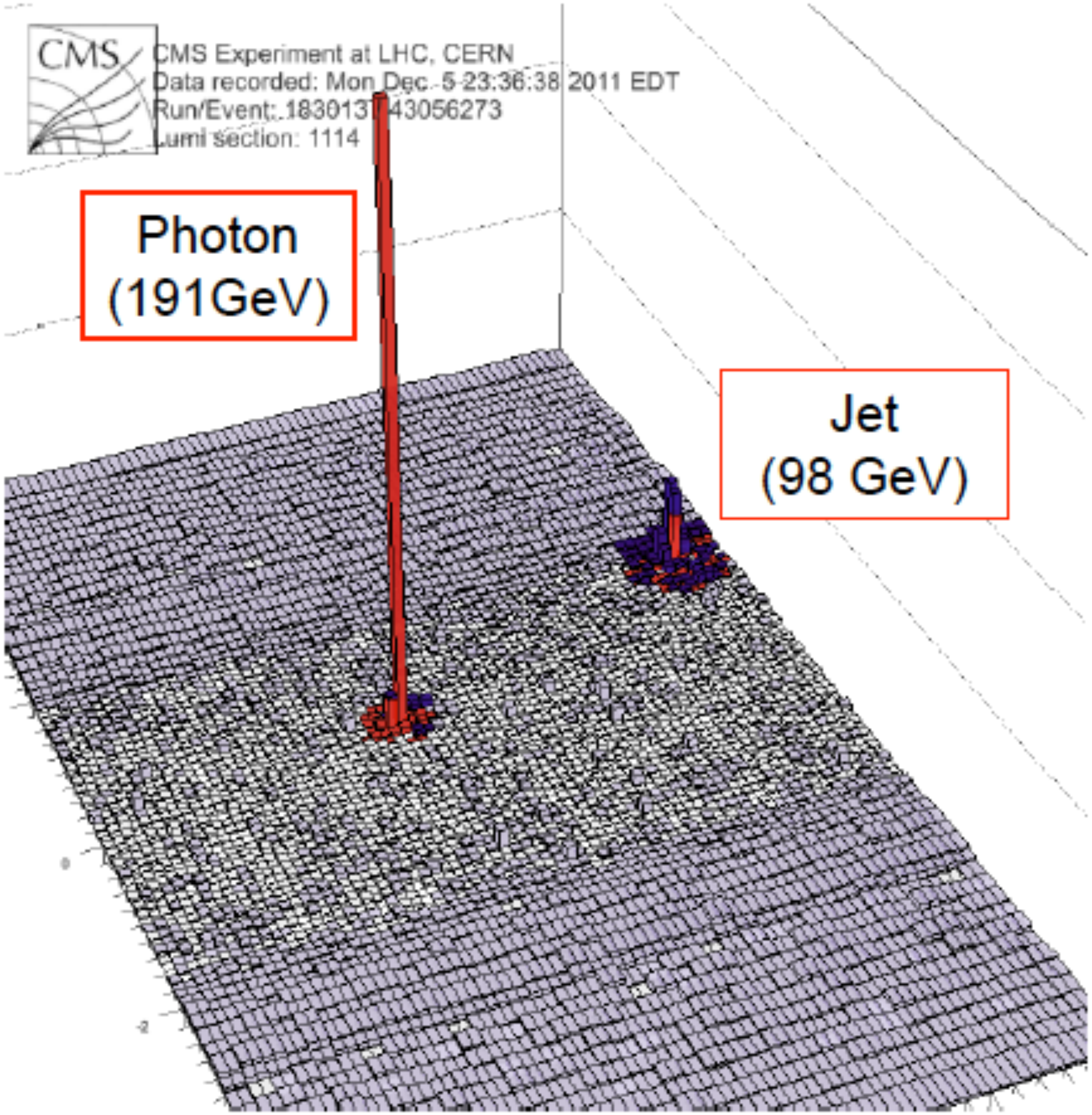
Christof Roland (talk at QM2011), modified

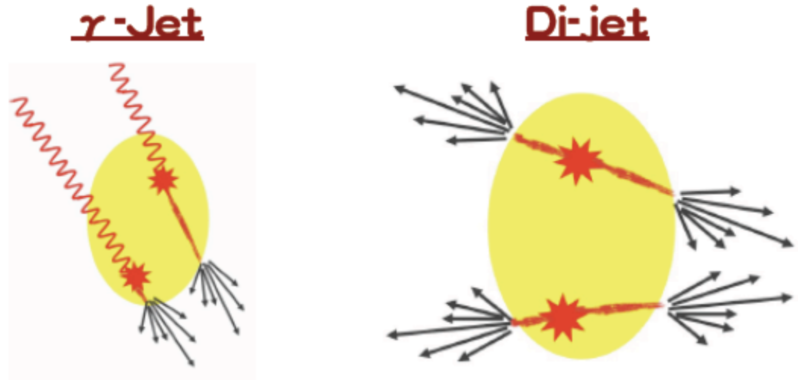


S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. C 84, 024906, modified

Slide from Y. Tachibana (ATHIC 2014)

γ-jet: E_γ as a calibrated jet energy





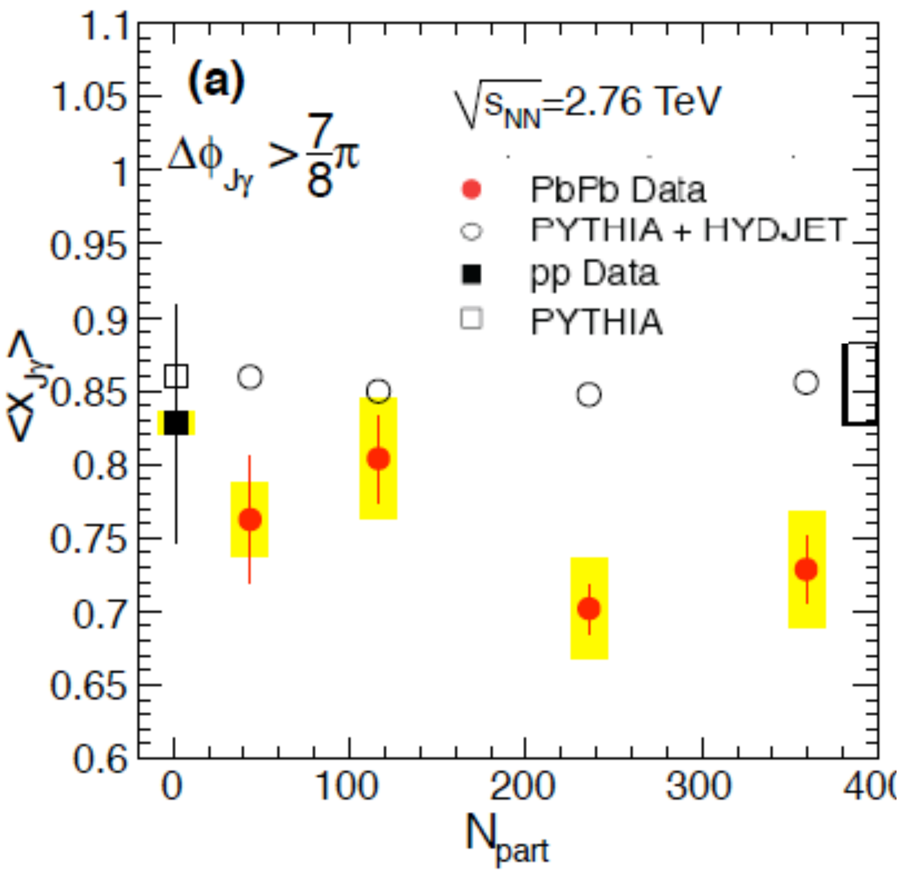
$$< x_{J\gamma} >= p_T^{jet} / p_T^{\gamma}$$

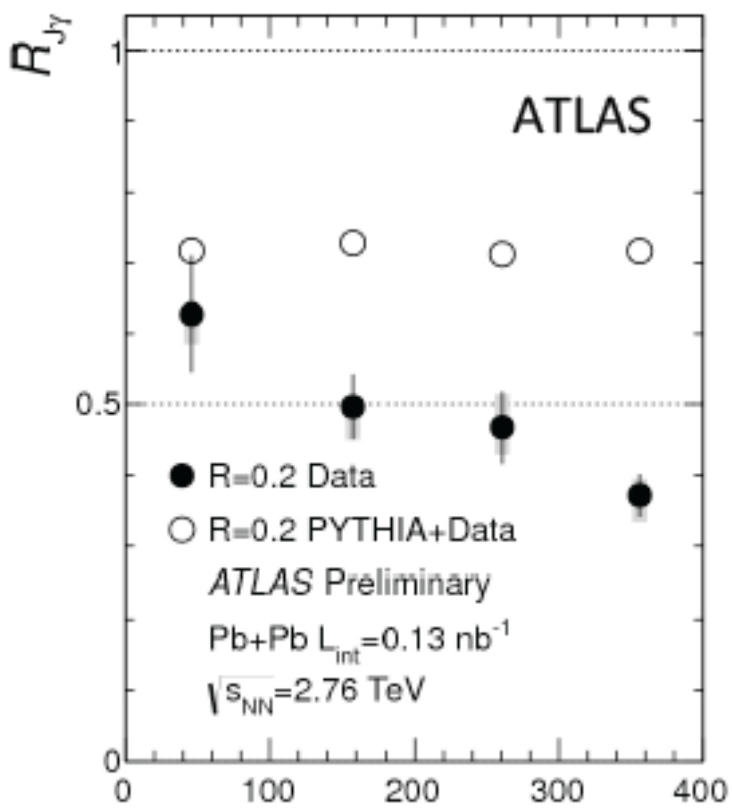
$R_{J\gamma}$: fraction of photons with jet partner (jet quenching)

γ-jet in Pb-Pb

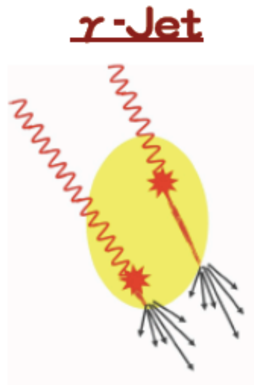
CMS, Phys. Lett. B 718 (2013) 773 $<x_{J\gamma}> = p_T^{jet}/p_T^{\gamma}$

$R_{J\gamma}$: fraction of photons with jet partner





N_{part}

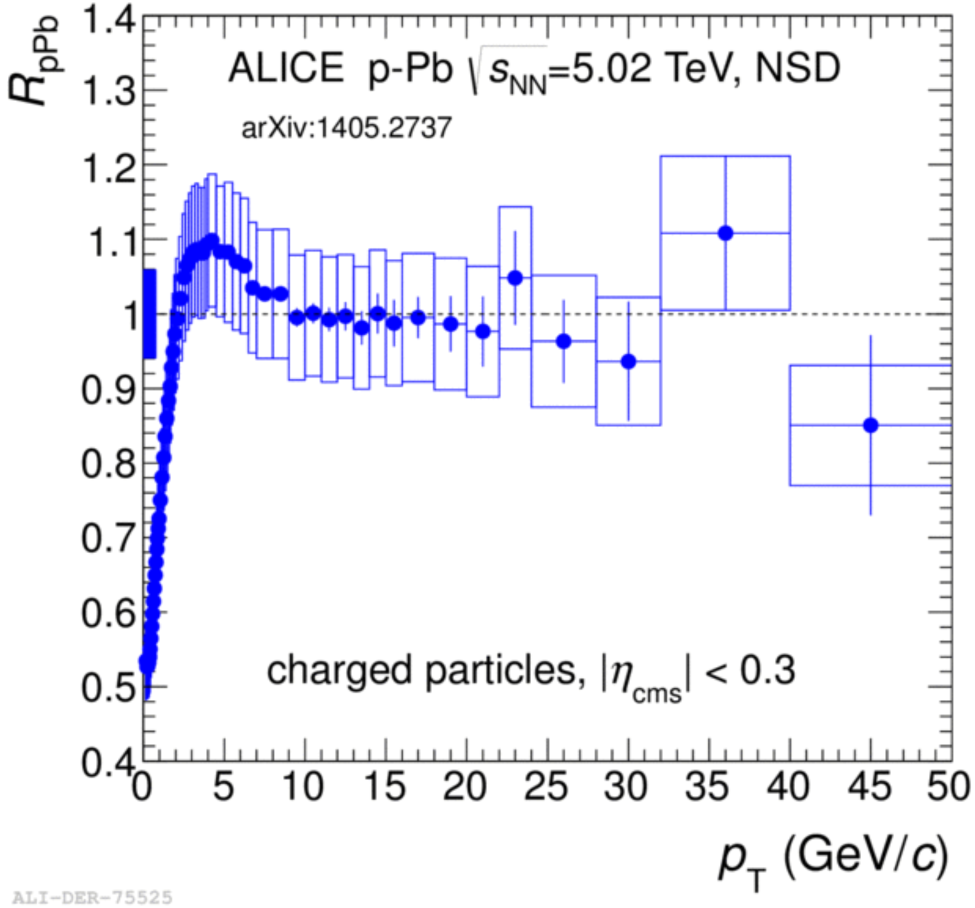


- γ as a calibrated probe of jet energy.
- significant change in $R_{J\gamma}$, $<x_{J\gamma}>$ compared to PYTHIA and pp.

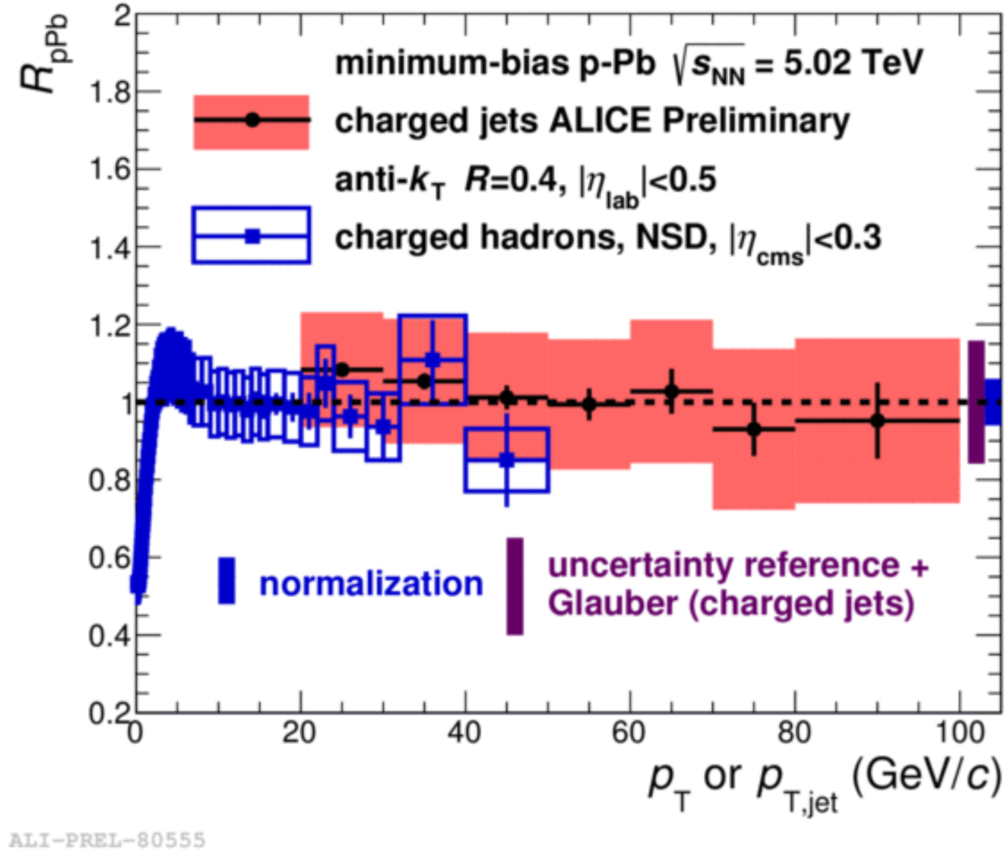
p+Pb

R_{AA} for $h^{\pm}$ and jet in p-Pb

Charged hadron

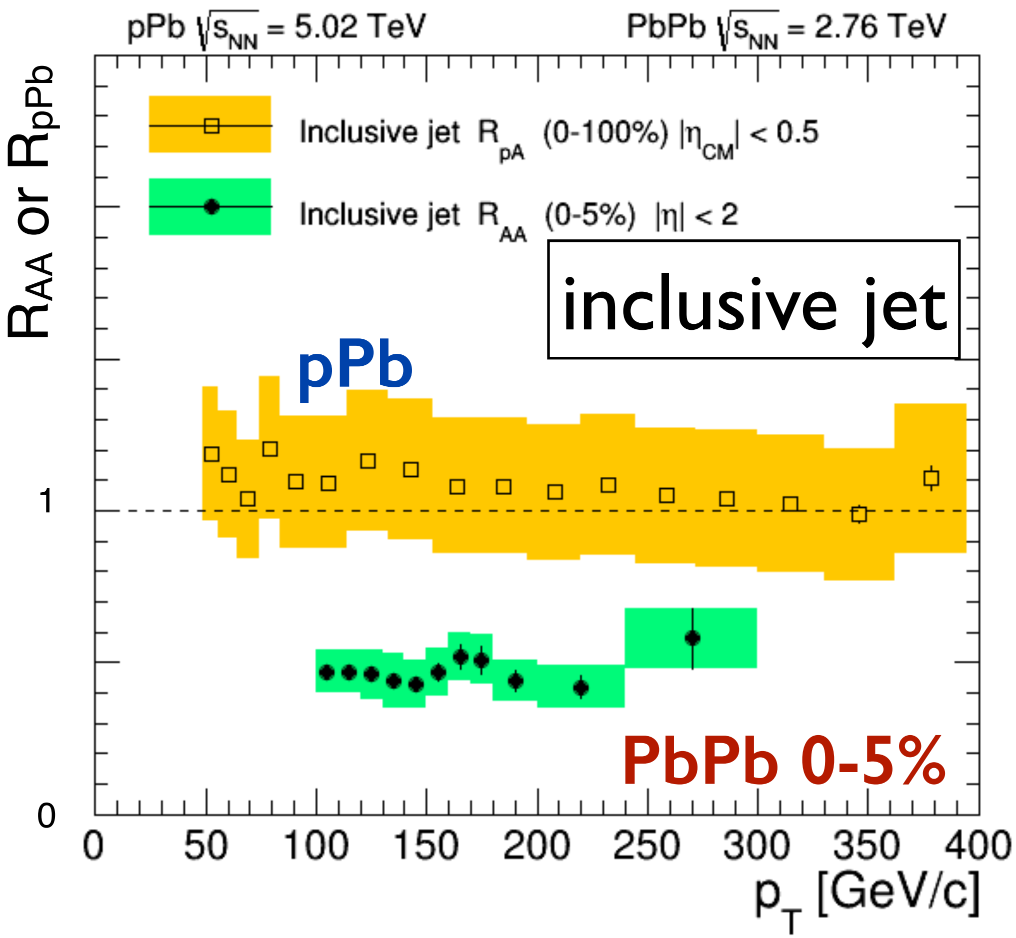


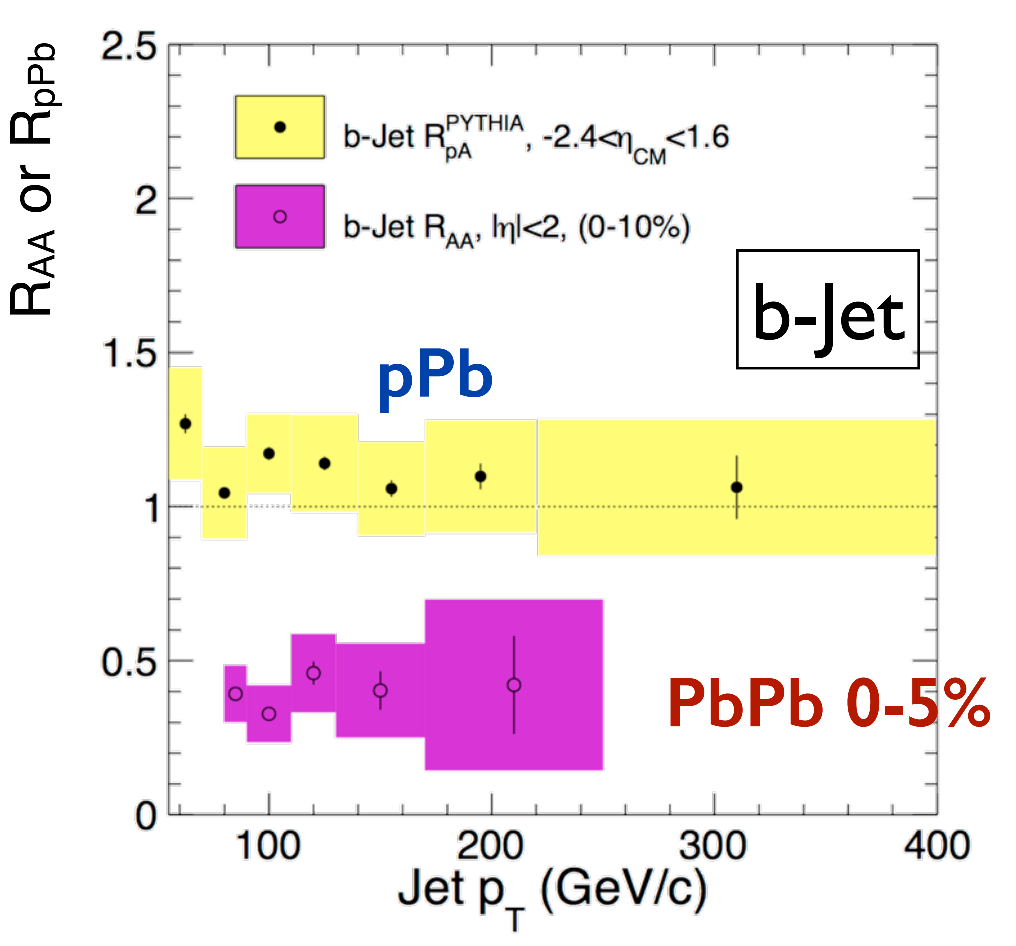
Jet (charged)



- Unmodified for charged hadron and jet in pPb.

R_{pA} & R_{AA} for b jets





- First measurement of b-jet suppression
- Observe b jet (~quark jet) R_{AA} consistent with inclusive jet (~gluon jet) R_{AA}
- **Where is the quark/gluon difference?**

4. Future directions

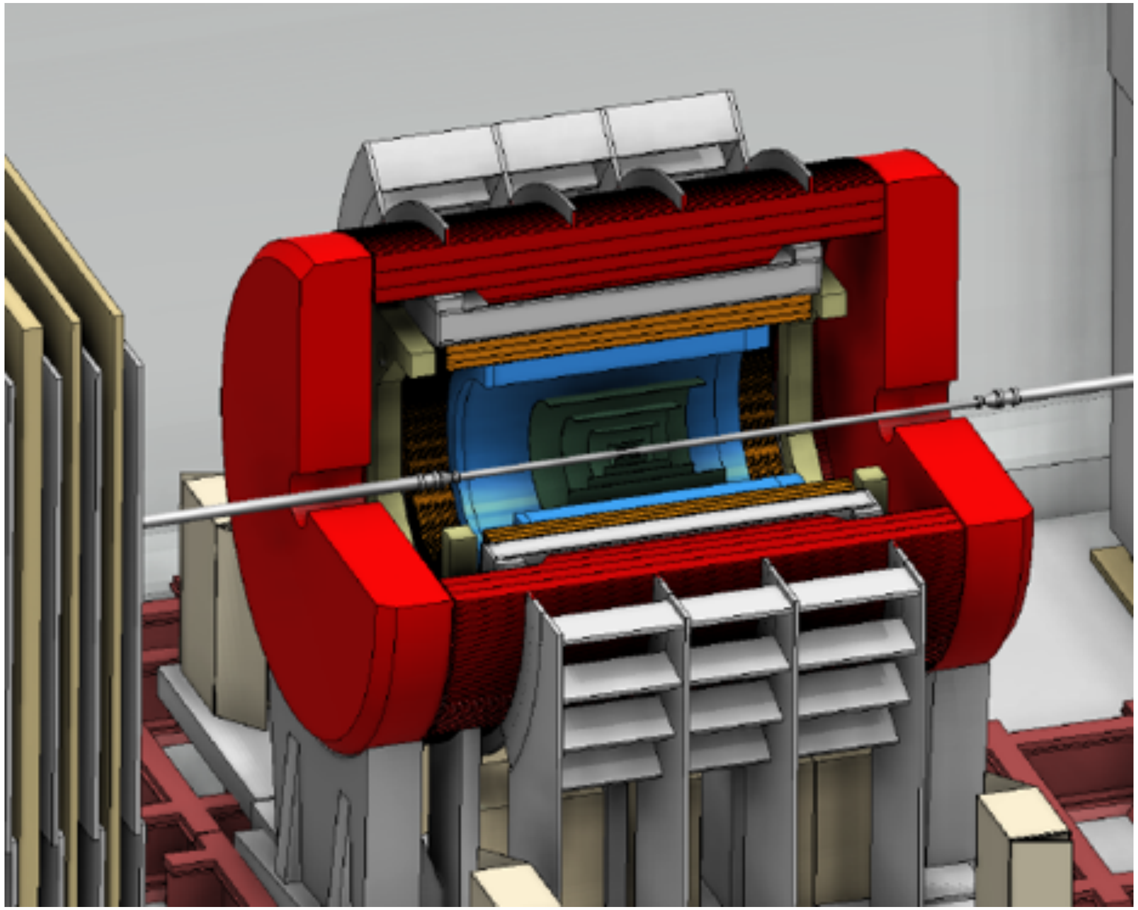
PHENIX実験 High-p_T 化

High-p_T 化
ジェット測定強化
重クォーク測定強化

- 測定器の新規建設

  PHENIX → **sPHENIX**

- 日本が建設を主導する検出器：
  - ✓ シリコン飛跡検出器
  - ✓ プレシャワー検出器



ジェット、重クォーク測定から、RHICエネルギーでのQGP中でのエネルギー損失(輸送係数)の温度依存性を決定

sPHENIX実験: 総額$20M-30M
arXiv:1207.6378

ジェット・フォトンで探るQGP物性 (LHC-Run-2)

1.jet-jet (di-jet), γ-jet, h-jet 測定

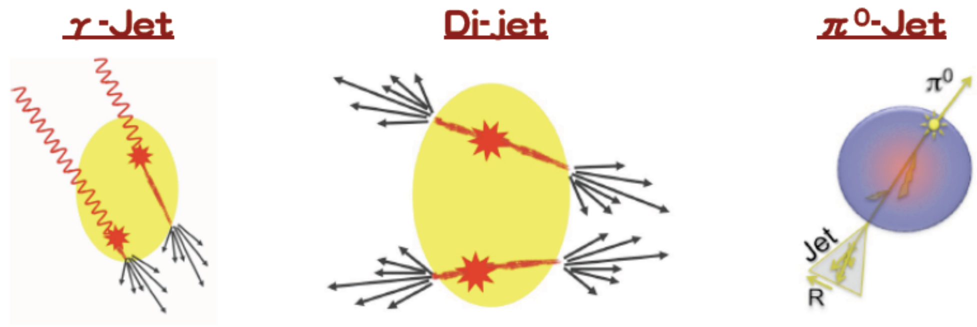
- パートン衝突位置の決定、エネルギー損失の通過距離依存性
- パートンエネルギー損失機構の解明

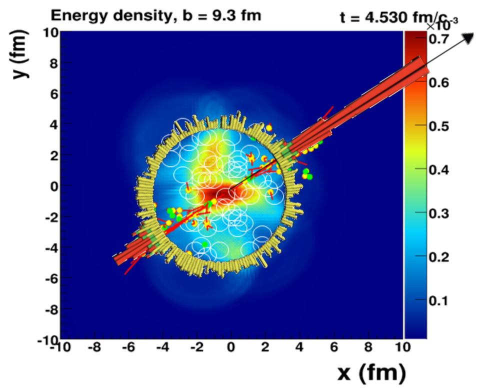
2.jet エネルギ損失とソフトハドロン生成

- QGPの媒質応答
- グルーオン衝撃波→EOS 決定の可能性

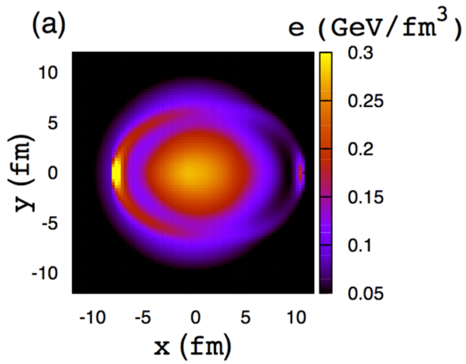
ALICE Run-2:

- 高統計（ダイ）ジェットサンプルが不可欠に
- DCal(Run-2 に新規導入) + PHOS:ジェット Level-1 トリガー導入（筑波大）

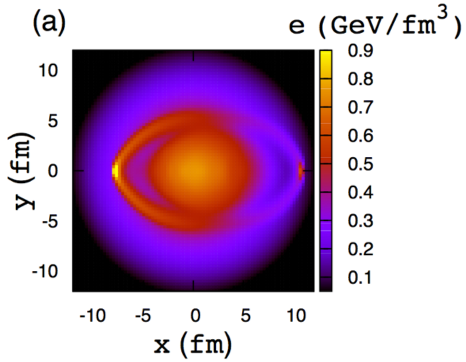




ジェットのエネルギー損失とソフトハドロン生成の様子

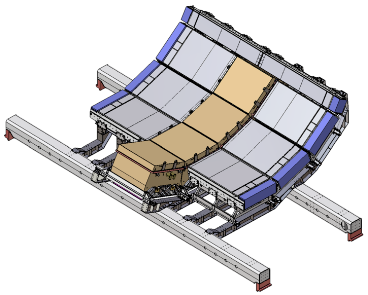


Ideal gas



Lattice

ジェットが落としたエネルギーによるソフトハドロン生成.
状態方程式により、放出角度が変化. Y. Tachibana, T. Hirano (2014)



質問群（1）

- QGP中でのパートンエネルギー損失の質量依存性について、特にグルーオン制動放射(dead cone effectなど)について
- ジェットとQGP媒質応答、EOS, 音速との関係
- jetで測ることのできることについて 詳しく教えてもらいたいです。
- di-jet aymmetryを理解する試みはどういうのがあるのか。
- 高エネルギー領域でのジェットイベント測定に期待される成果

質問群（2）

- ハードプローブとQGP中でのエネルギー損失機構について
- ハードな散乱とはどういうものなのでしょうか
- jetがQGP中でどのようにエネルギーを失うのか

質問群（３）「実験に関する質問」

- LHC、RHICではそれぞれ何が測定可能な量なのか。 各実験グループがそれぞれ何を測るのに向いているのか
- 実験や理論の進展を踏まえ、次に何を測定すれば、何が分かるのか？何を測ることが最重要なのか?
- ２０年後の展望
- 重イオン衝突で用いられるのはなぜ金原子なのでしょうか

Summary

- Jet: a powerful tool to study QGP.
  - well known self generated calibrated probe
  - LHC: full jet reconstruction, quenched jet in Pb+Pb, FF modified, large angle low p_T emission.
- Future directions:
  - Jet - QGP medium response
  - “T” dep. of QGP properties, probed by jet
    - sPHENIX vs. LHC experiments