Toward jet tomography of QGP with ALICE

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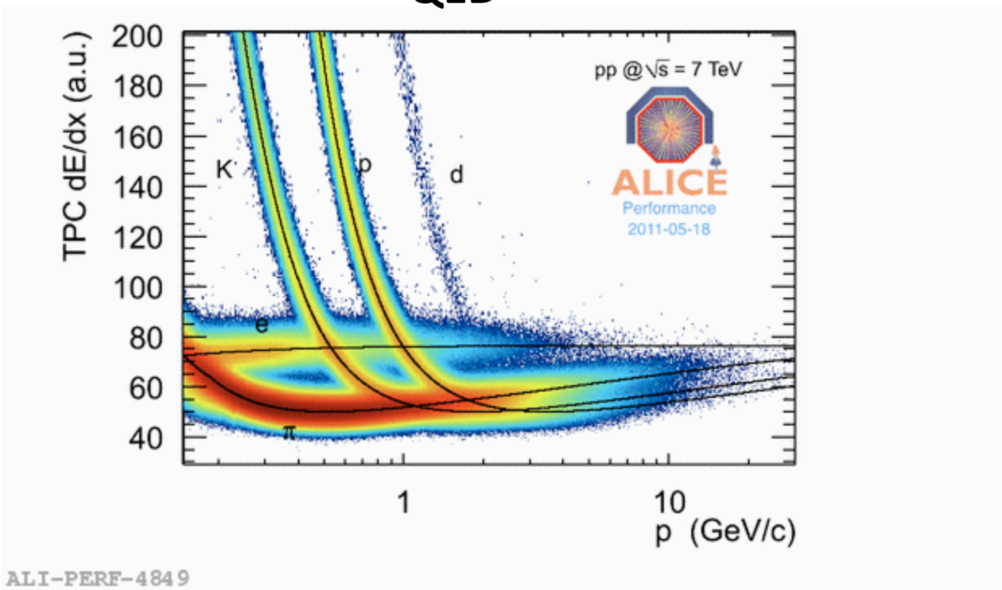
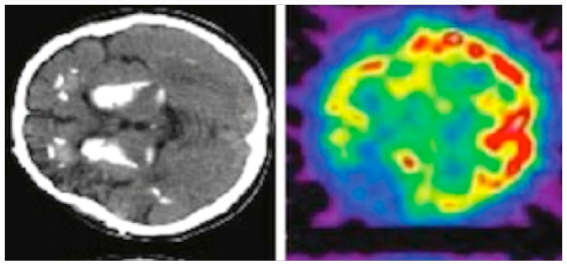
Motivations

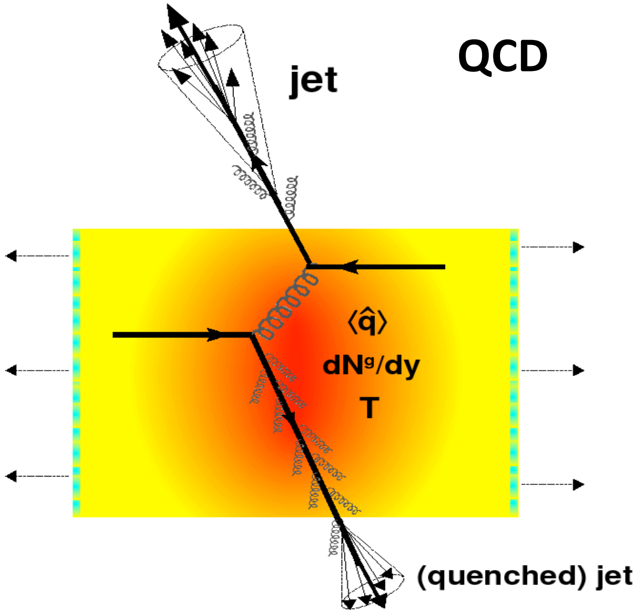
- Make a tomography of strongly interacting QCD matter produced in Pb-Pb collisions
- Achieve same level of understanding as QED « Bethe-Bloch » curve

QED





QCD



Medium features :

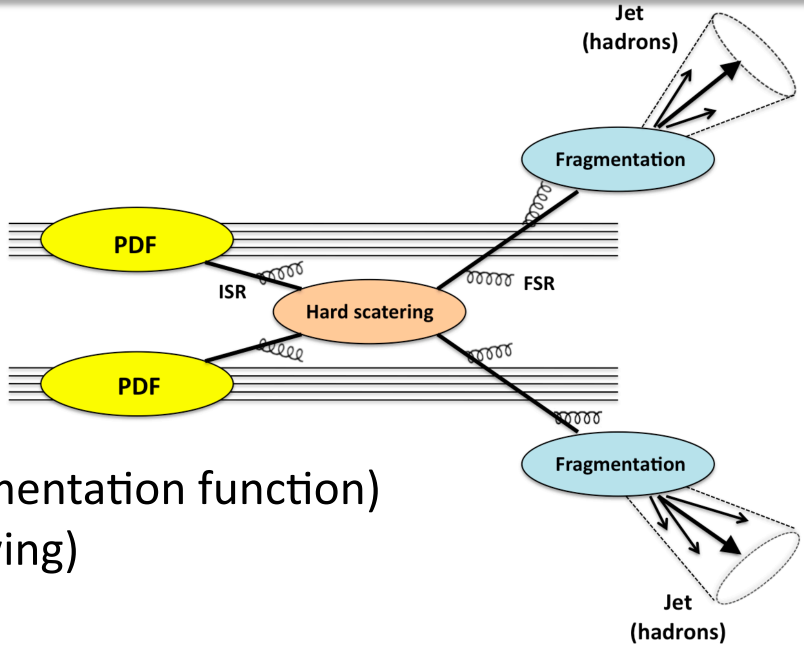
- mean free path λ
- gluon density dN^g/dy
- temperature T°C
- transverse size (L)

=> transport coefficient $<\hat{q}>$ (α ΔE)

Parton energy loss

1. QCD factorization ($\tau^{parton} << \tau^{QGP}$)

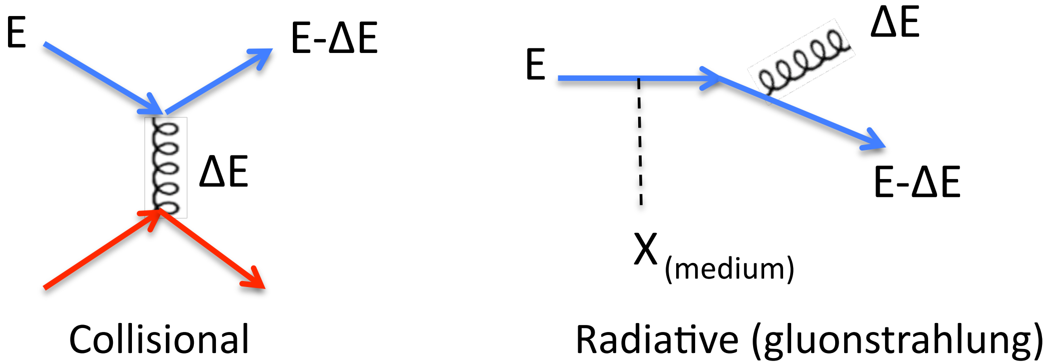
$$d\sigma_{hard}(A+B\rightarrow h+X)$$
$$=\sum_{a,b}\phi_{a/A}(x_1,Q^2)\otimes d\hat{\sigma}_{hard}^{ab\rightarrow c+X}\otimes D_{c\rightarrow h}(z,Q^2)$$



→ Final state : parton energy loss (modified fragmentation function)
→ Initial state : cold nuclear effect (nPDF, shadowing)

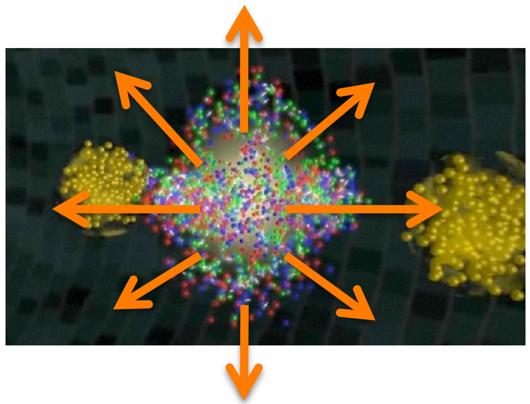
2. Models

energy loss



+

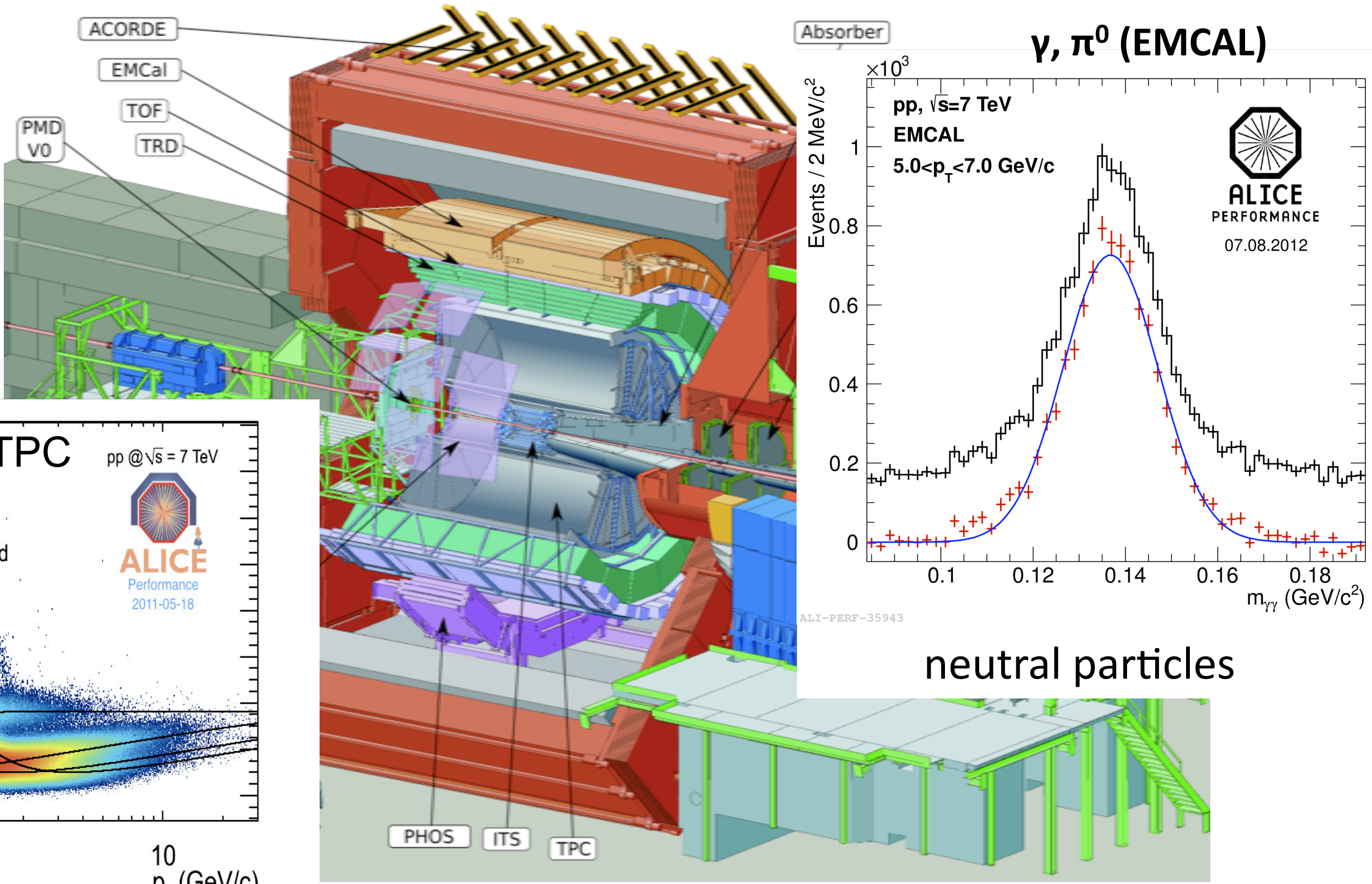
medium evolution



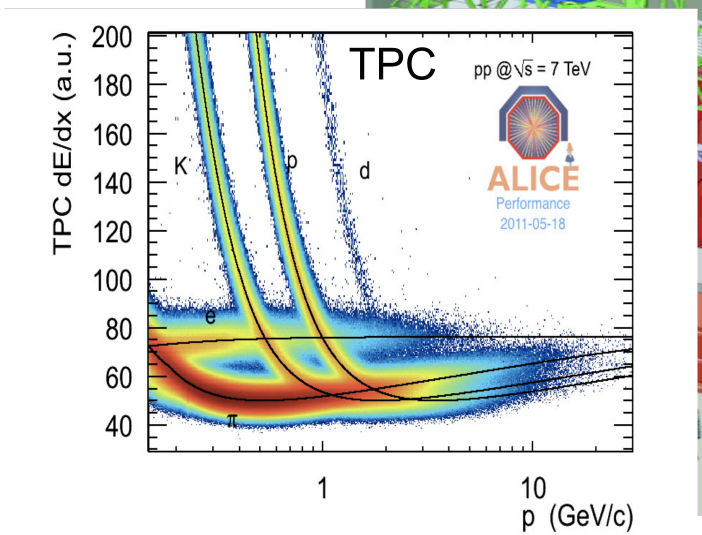
3. Reference : parton fragmentation in vacuum (pp, p-Pb collisions)

ALICE : particles PID

- Low-p_T hadron measurements ($\rightarrow \approx$ 100 MeV/c)
- PID and tracking capabilities in high multiplicity environment



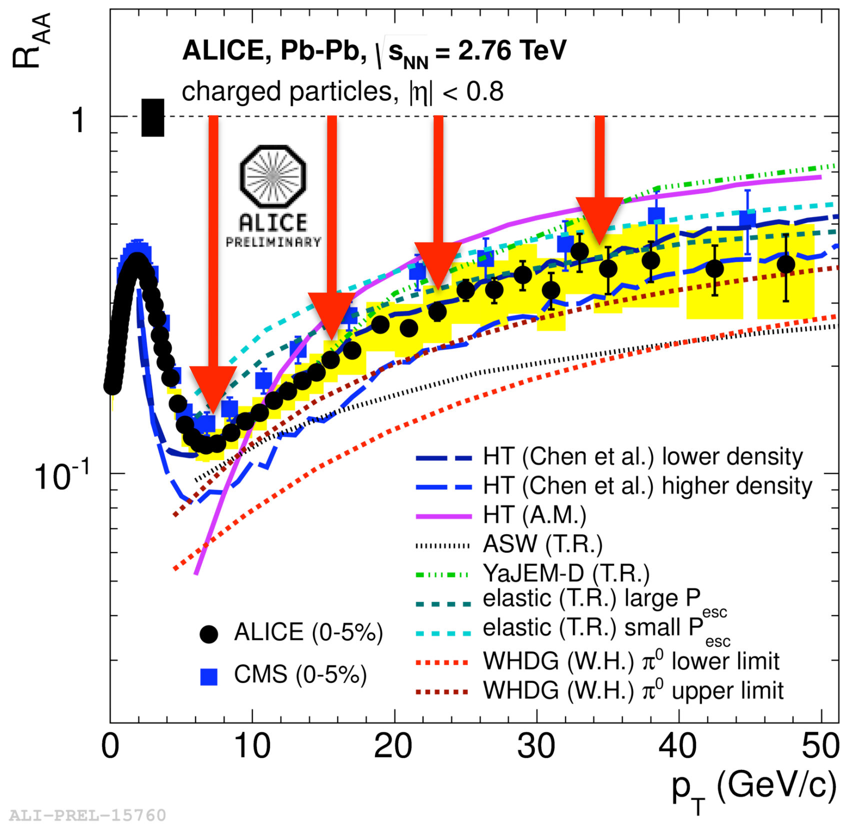
neutral particles



charged particles

Single hadron

- Naive picture : $d\sigma_{AB}^{hard} = A \cdot B \cdot d\sigma_{pp}^{hard} \Leftrightarrow dN_{AB}^{hard} = \langle N_{coll} \rangle \cdot dN_{pp}^{hard}$
- Nuclear suppression factor : $$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b) \rangle \times d^2\sigma_{pp}/dydp_T}$$



→ Clear suppression with p_T dependence
→ Collective medium effects at low-p_T (< 8 GeV/c)

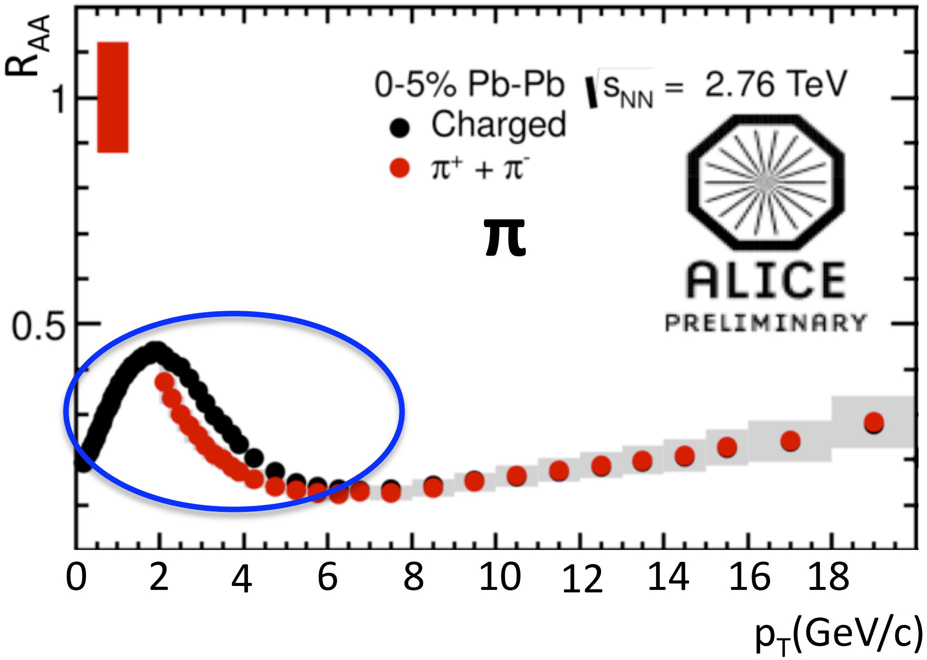
Energy loss dependences :

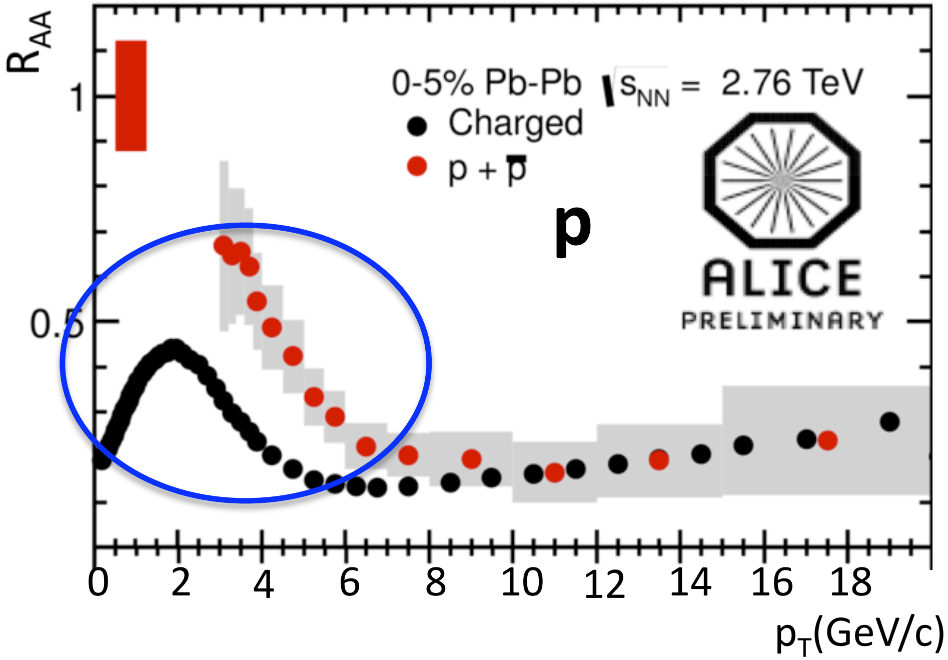
- initial parton energy → **$R_{AA}(p_T)$**
- path length (L) → **in plane / out of plane**
- color factor → **baryon / meson**
- mass dependence → **heavy / light quark**

→ **Particle identification**

Identified light hadrons

- Compare meson (pion) and baryon (proton) suppression in Pb-Pb collisions

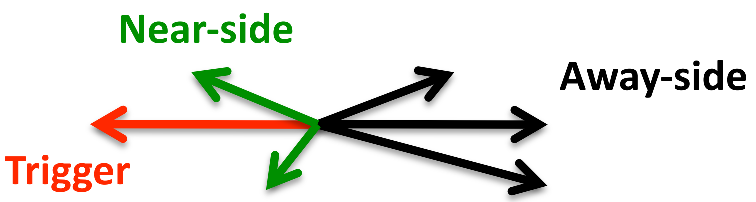


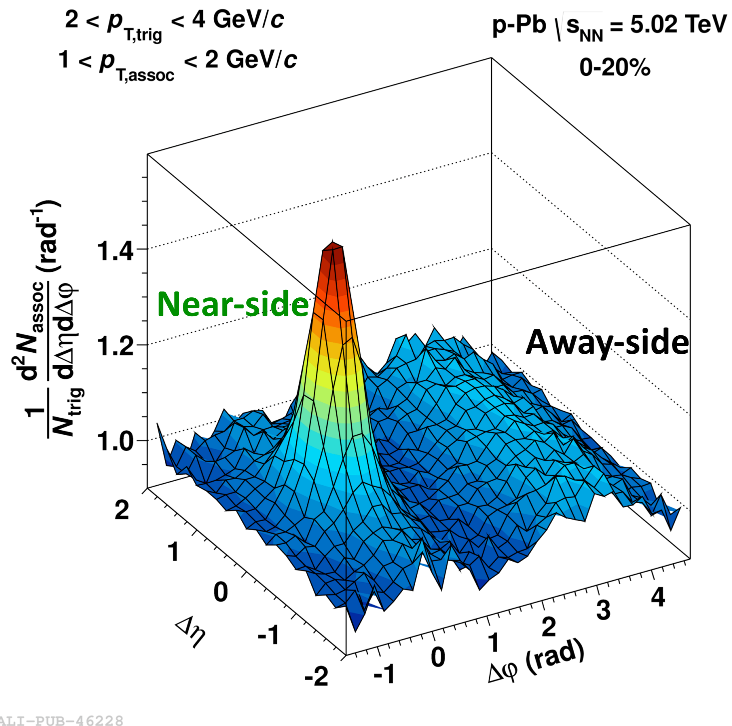


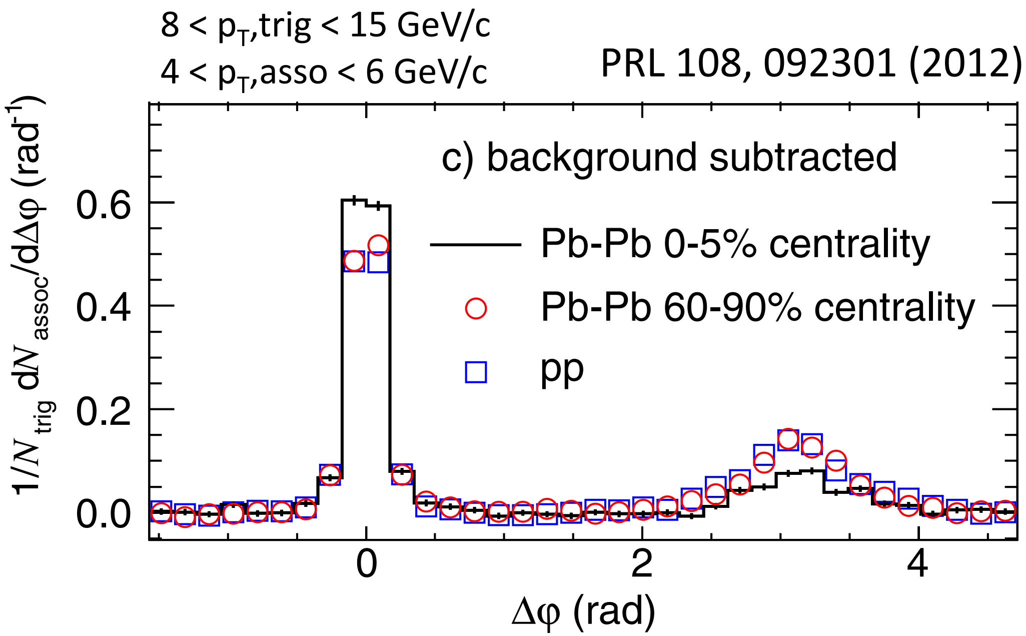
- $R_{AA}^{\pi} < R_{AA}^{charged} < R_{AA}^{p}$ for p_T < 6-8 GeV/c ⟷ collective effects (coalescence)
- $R_{AA}^{\pi} \approx R_{AA}^{charged} \approx R_{AA}^{p}$ for p_T > 8 GeV/c ⟷ fragmentation+hadronization in vacuum (?)

Hadron correlations

- High-p_T hadron (trigger particle) correlated with associated hadrons
- Study ($\Delta\eta$,$\Delta\phi$) in the near-side and away-side





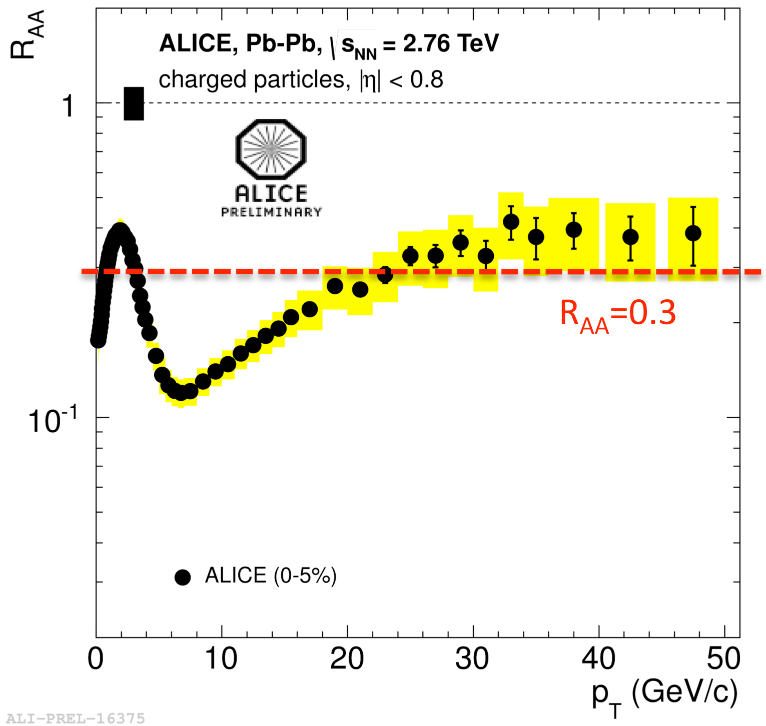


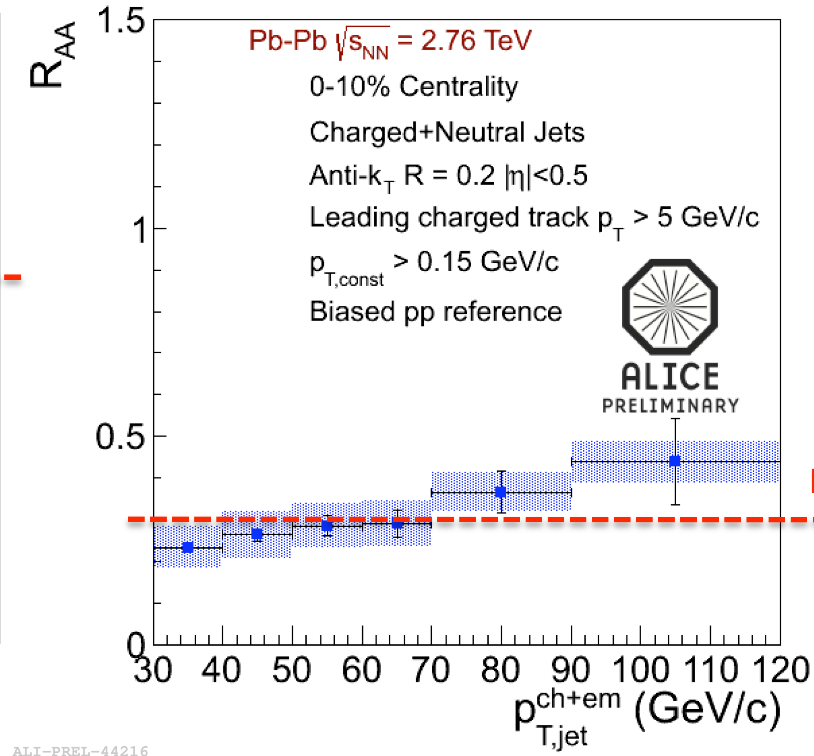
PbPb compare to pp :
- away-side peak → suppression
  → broadening
- near-side peak → enhancement

Jets shape

- Jet reconstruction gives detailed informations about energy loss :

⟶ shape : radiated gluons angle (R_{AA}^{jet} as a function of R_{cone})





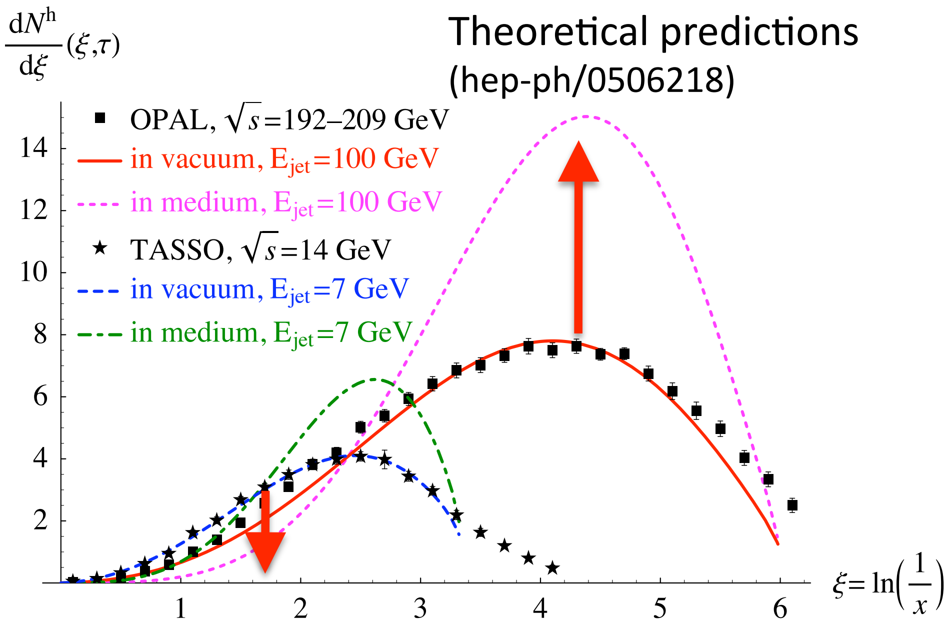
R_{AA}=0.3

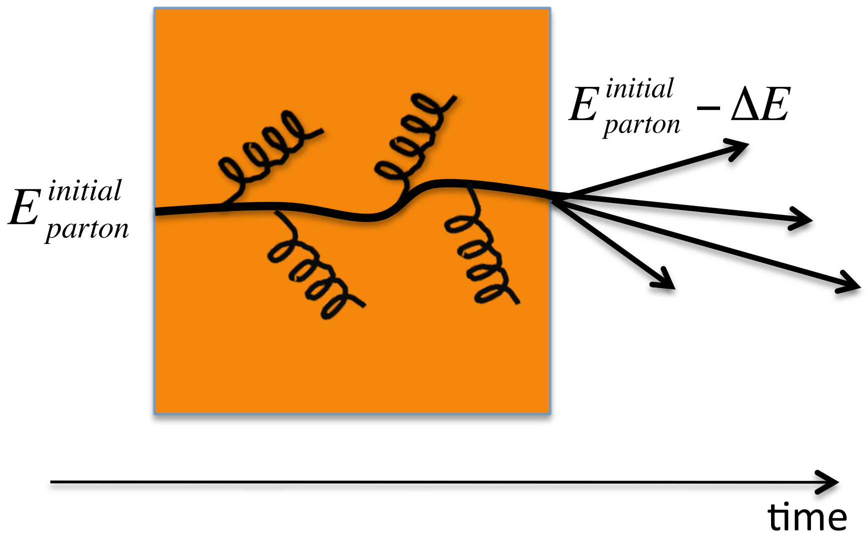
$p_T^h \approx 0.5 p_T^{jet}$

⟶ $R_{AA}^{jet} \approx 0.3 \approx$ leading hadron suppression
⟶ Energy loss not found in R = 0.2 (larger angle, R > 0.5 ?)
⟶ p_T^{hadron} cut is a fundamental parameter

Jet fragmentation

- Medium effects included in modified fragmentation function (theoretical models)
- Observables : $x = p_T^{hadron} / p_T^{jet}$, $\xi = \log(p_T^{jet} / p_T^{hadron}) = \log(1/x)$
- « Hump Back plateau » structure in pp ⬄ modified in AA collisions (↘ high-p_T, ↗ low-p_T)





Need to carrefully define what we call « fragmentation function » :

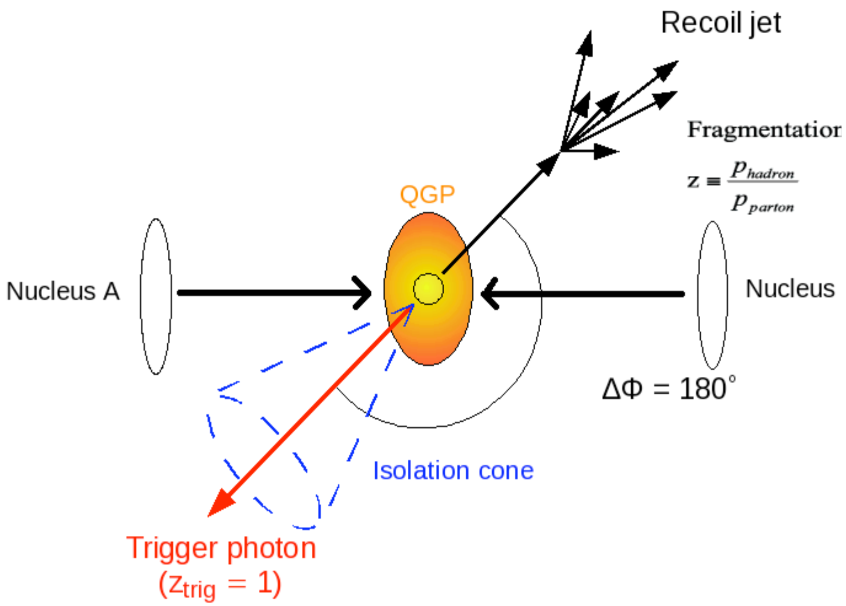
⟶ $FF_1 = E^{hadron} / (E^{initial}_{parton} - \Delta E)$ ⬄ bias FF with respect to E_{loss} (ΔE)

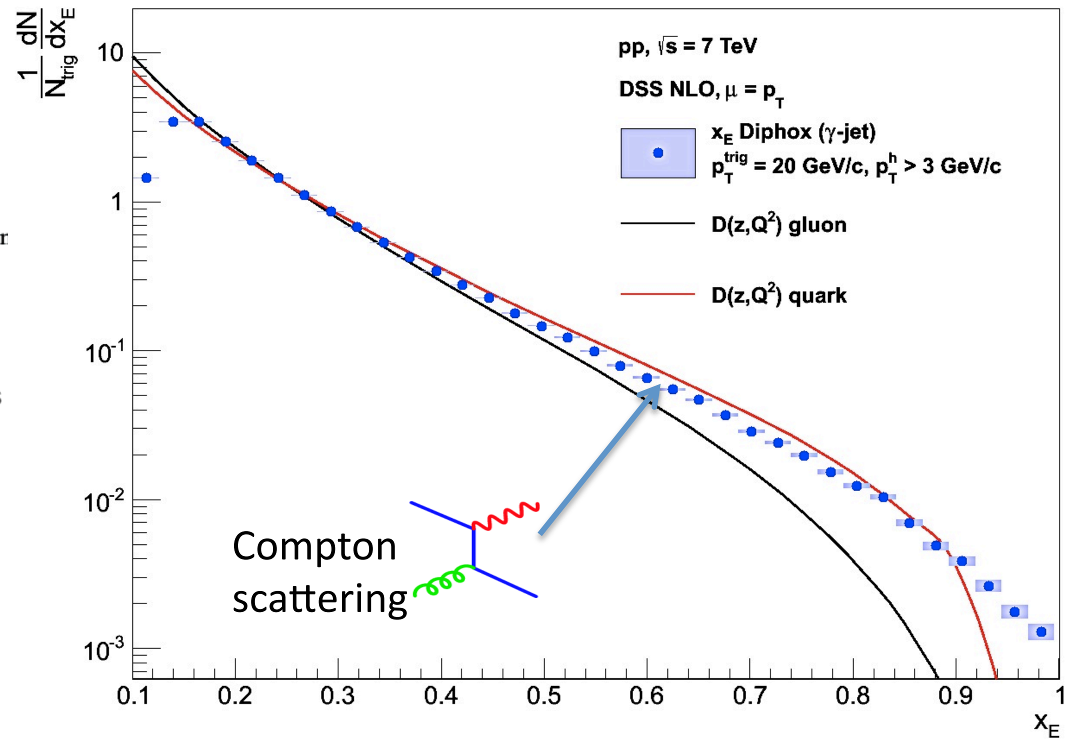
⟶ $FF_2 = E^{hadron} / E^{initial}_{parton}$ ⬄ theoretical FF definition

Isolated photon-hadron correlations

- Access parton energy via photon energy measurement
- Study parton fragmentation for p_T < 30 GeV/c (complementary to jet analysis)

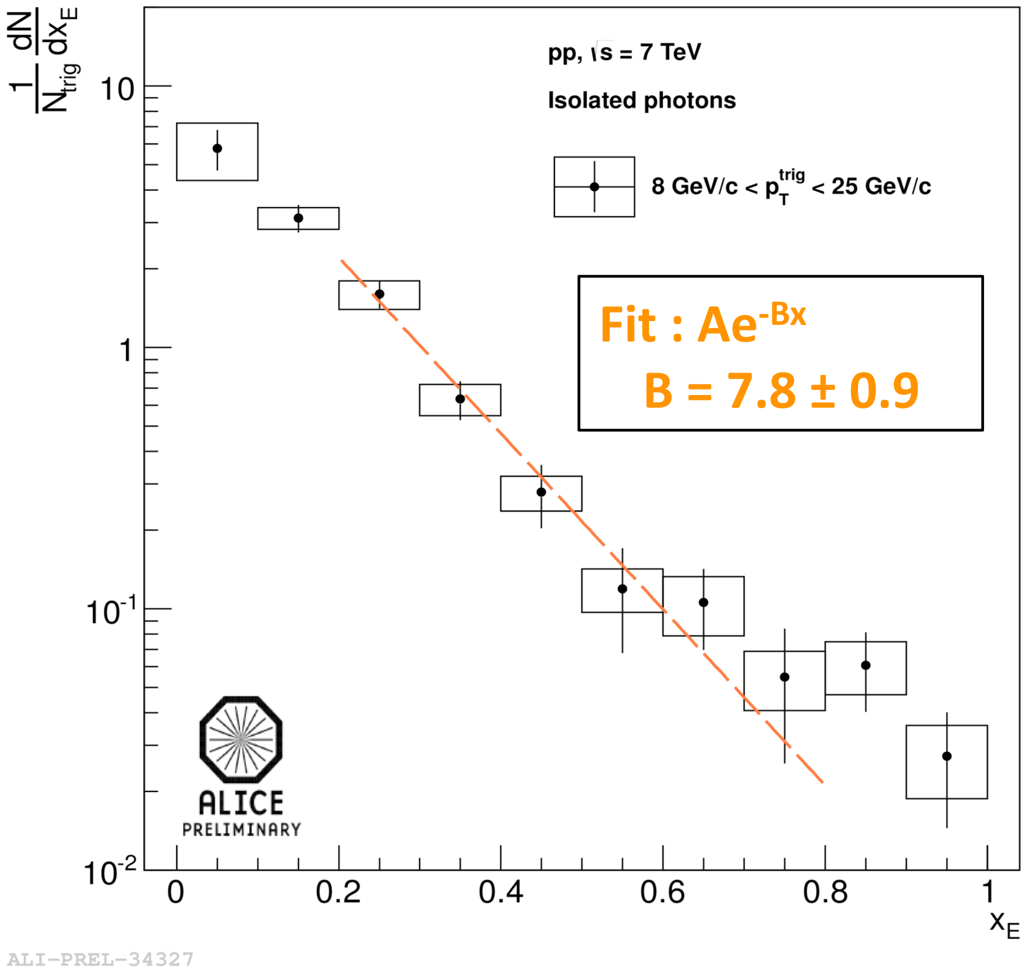
$$x_E = -\frac{p^h{}_T}{p^\gamma{}_T}\cos\Delta\Phi \quad \xrightarrow[p_T^\gamma \approx p_T^{parton}]{\text{Isolated photon}} \quad x_E \approx z = \frac{p^h}{p^{parton}}$$





x_E isolated photons (pp)

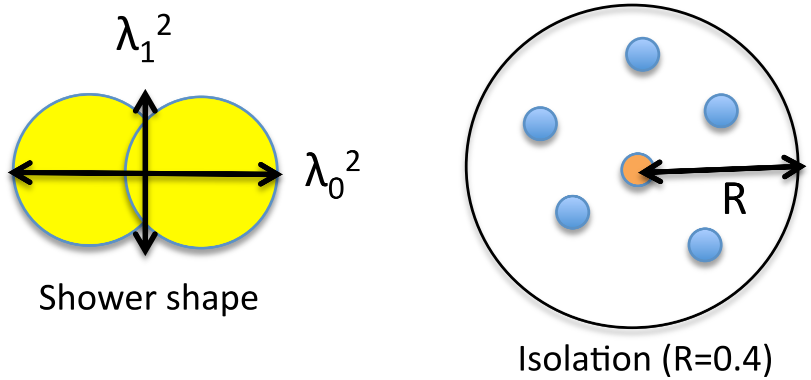
- Select direct photon with p_T > 8 GeV/c (EMCal)
- Select charged hadrons with p_T > 0.2 GeV/c (TPC+ITS)



Photon ID : background removal

→ cluster shape (decay γ)

→ Isolation (fragmentation/decay γ)



Baseline for the study of medium modified parton fragmentation in Pb-Pb

Summary / Outlook

- LHC provides a wide list of parton energy loss observables :

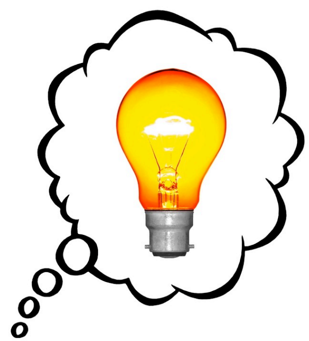
  ⟶ ALICE has excellent capabilities for PID and low-p_T measurements
  ⟶ key word is « complementarity »

- We can start to discriminate some energy loss mechanisms :

  ⟶ current picture : radiative + collisionnal energy loss, fragmentation (vacuum)
  ⟶ challenge : disentangle soft / hard components

- On-going work to study more observables :

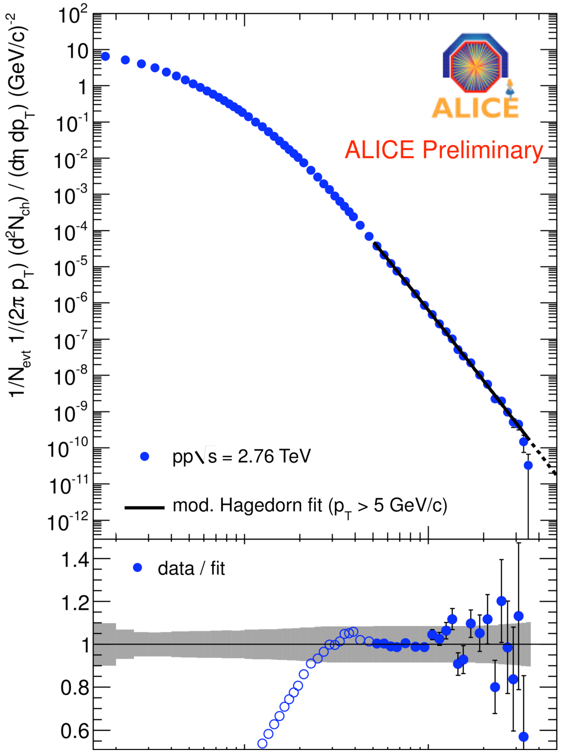
  ⟶ gamma-hadron correlations, gamma-jets
  ⟶ heavy-quark (see QGP session on Friday)
  ⟶ …



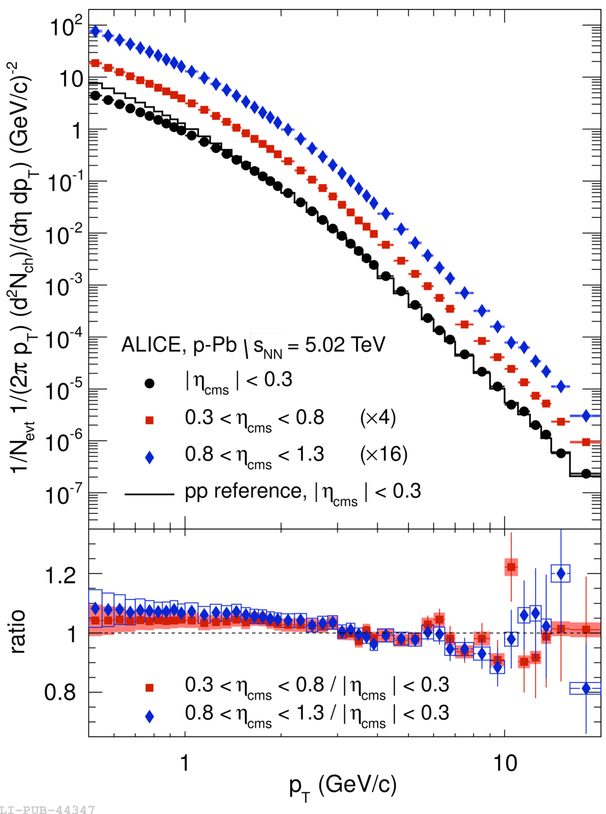
Back up

Single hadron : pp, p-Pb spectra

- Measure pp collisions spectra ⟶ NLO predictions
- Measure p-Pb collisions spectra ⟶ cold nuclear effects (nPDF, shadowing)



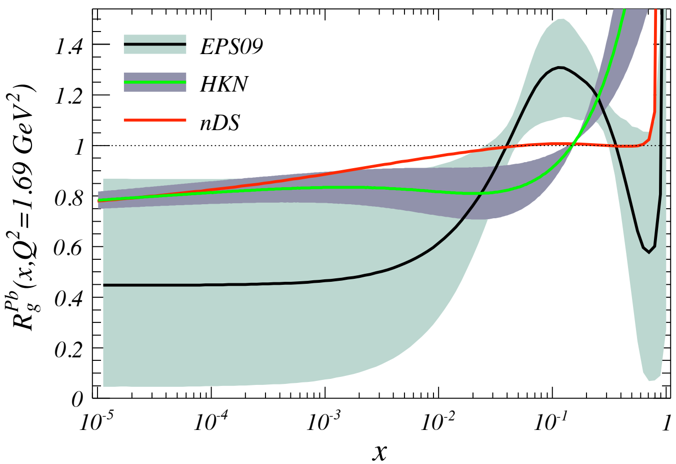
Inclusive charged hadrons (pp)



Inclusive charged hadrons (p-Pb)

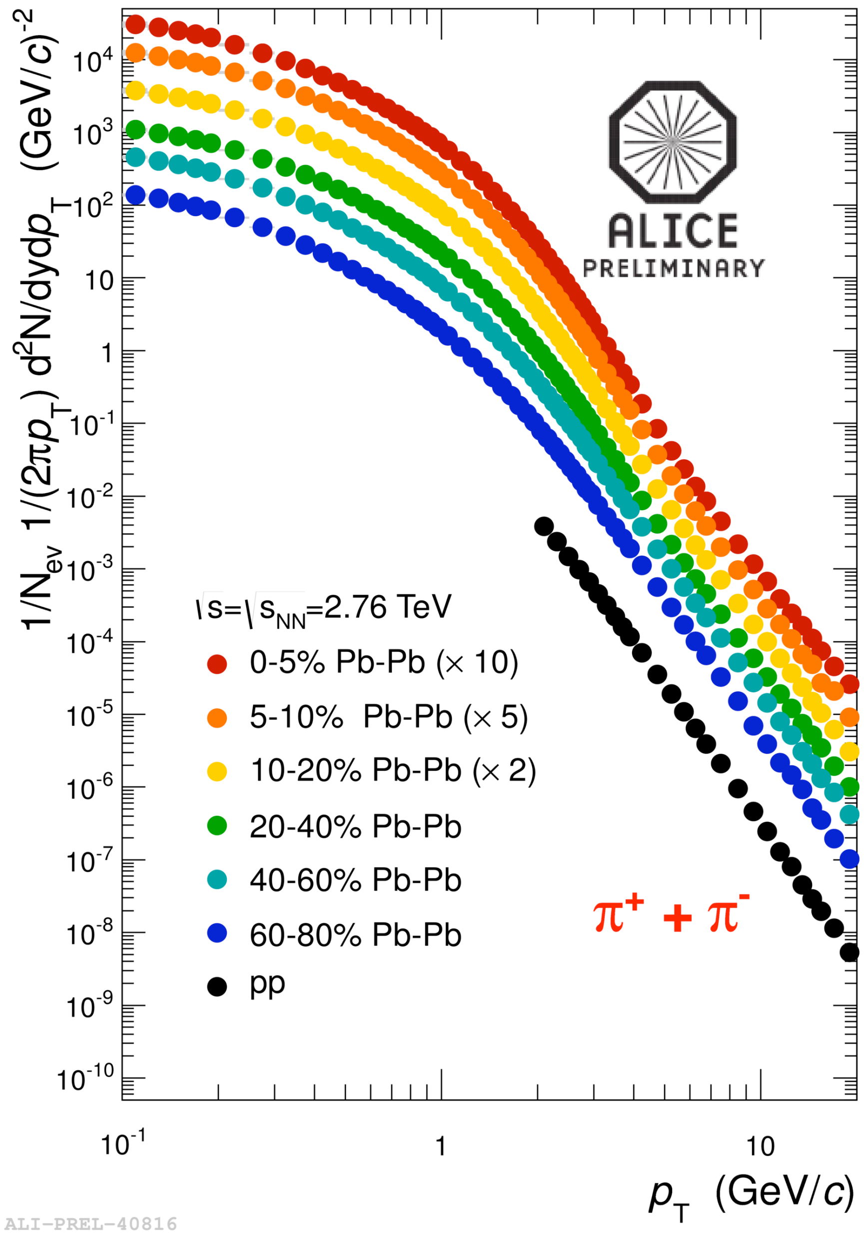
p-Pb spectra show :

- η dependence
- excess at $p_T < 3$ GeV/c



nPDF

Identified light hadrons



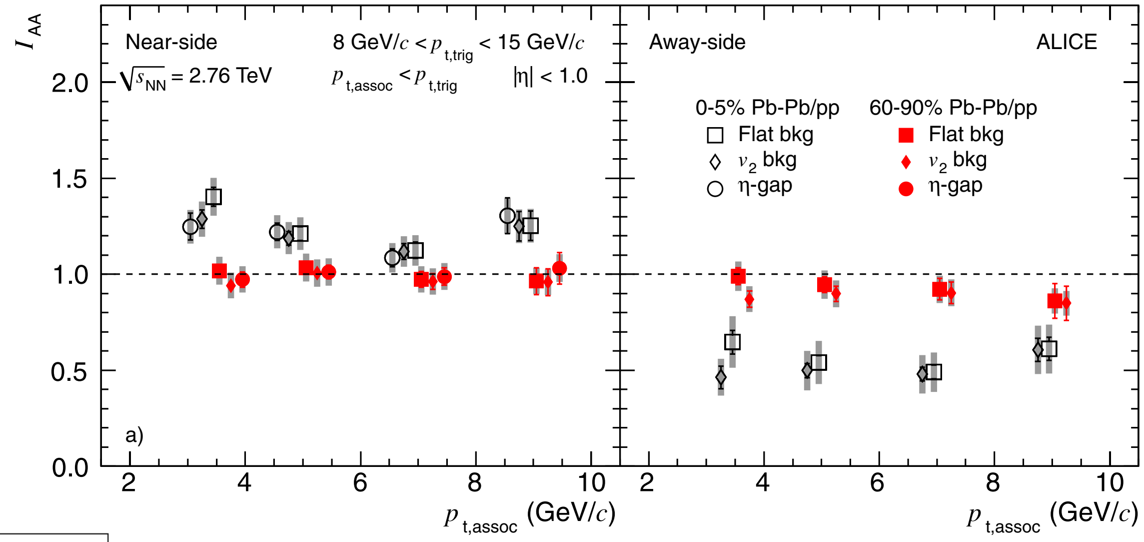
- Use ALICE PID capabilities to measure identified hadrons R_{AA}

- Hadrons production p_T regimes :
  1. **Low ($p_T \leq$ 2 GeV/c)**
     → radial flow (mass dependence)
     → energy loss (radiated gluons)
  2. **Intermediate (2 GeV/c ≤ $p_T \leq$ 8 GeV/c)**
     → radial flow (mass dependence)
     → jet-medium coalescence
     → energy loss (radiated gluons)
  3. **High ($p_T \geq$ 8 GeV/c)**
     → high-p_T parton fragmentation

Correlation in Pb-Pb collisions

- Azimuthal correlations in pp, Pb-Pb
  - → Suppresion Δϕ peak
  - → Enhancement Δη peak

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$



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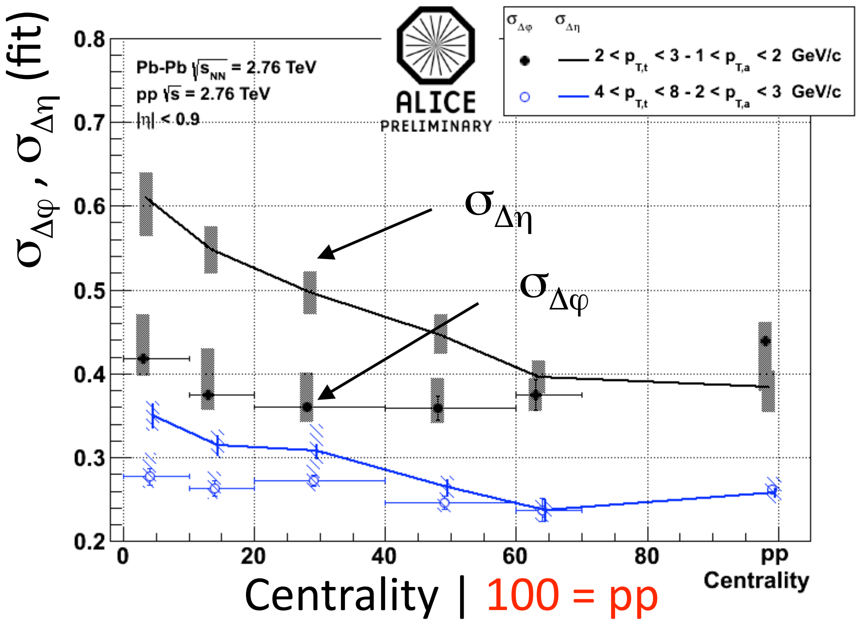
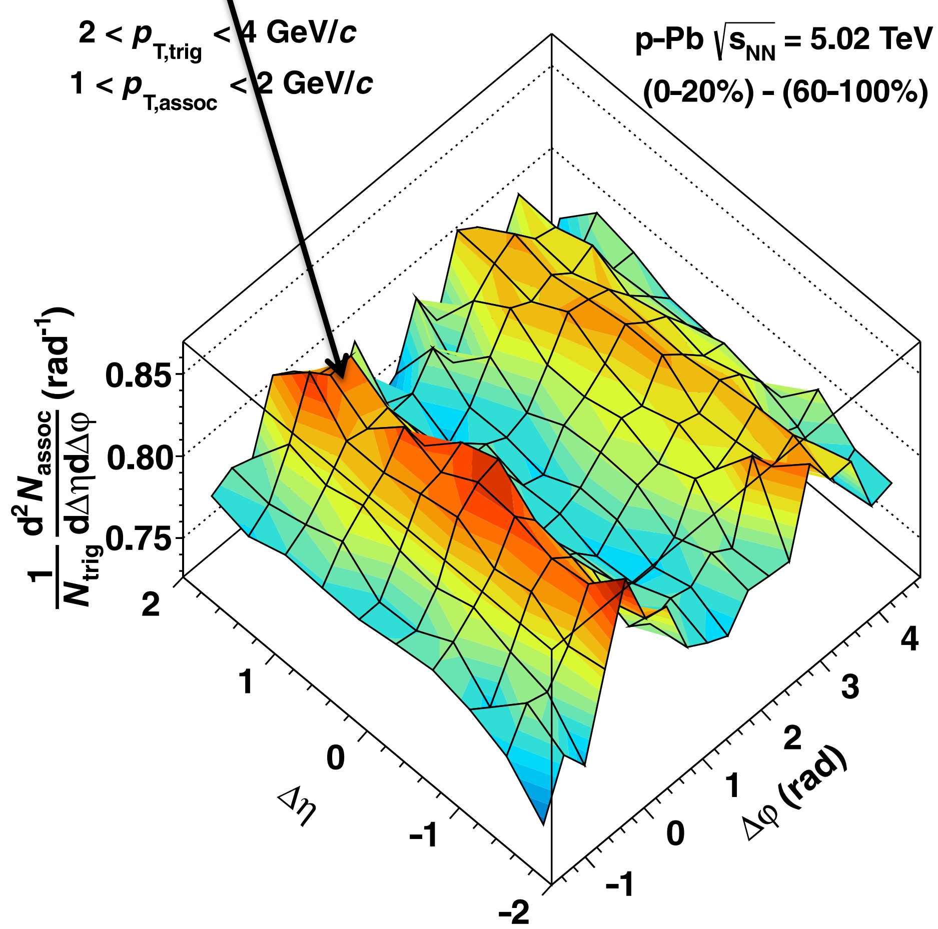


- $\sigma_{\Delta\eta}$, $\sigma_{\Delta\phi}$ increase with centrality
- Need to disentangle :
  - → collective effects (flow)
  - → parton energy loss

Correlation in p-Pb collisions

- Near-side « ridge » (!)



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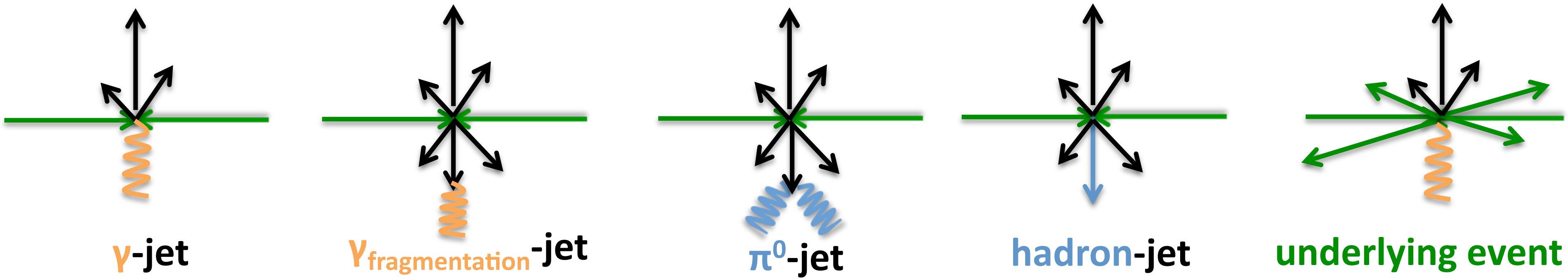
<u>Different explanations</u> :
- longitudinal flow
- large angle emissions
- Cerenkov-like radiation
- shock wave phenomena
- …

γ–hadron : analysis strategy

EMCal clusters : Isolation + Photon identification



Inclusive isolated clusters | **UE**

Purity : p = S/(S+B)

(Background (B) dominated by π^0)

Signal | **Background** | **UE**

$$x_E^{\gamma\ iso} = \frac{1}{p} x_E^{clusters\ iso} - \frac{(1-p)}{p} x_E^{\pi^0\ iso} - x_E^{UE}$$

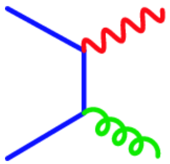
$(x_E^{\pi^0} \approx x_E^{hadron})$

Photon ID : isolation

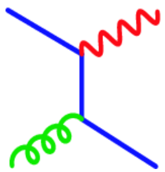
Select **direct photons :**

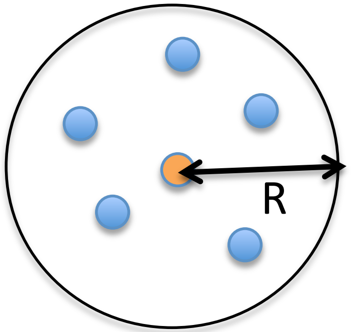
- most of direct photons are isolated, most of decay photons are not (jet)
- isolation parameters : cone radius $R=\sqrt{\Delta\eta^2+\Delta\phi^2}$, $p_T^{threshold}$

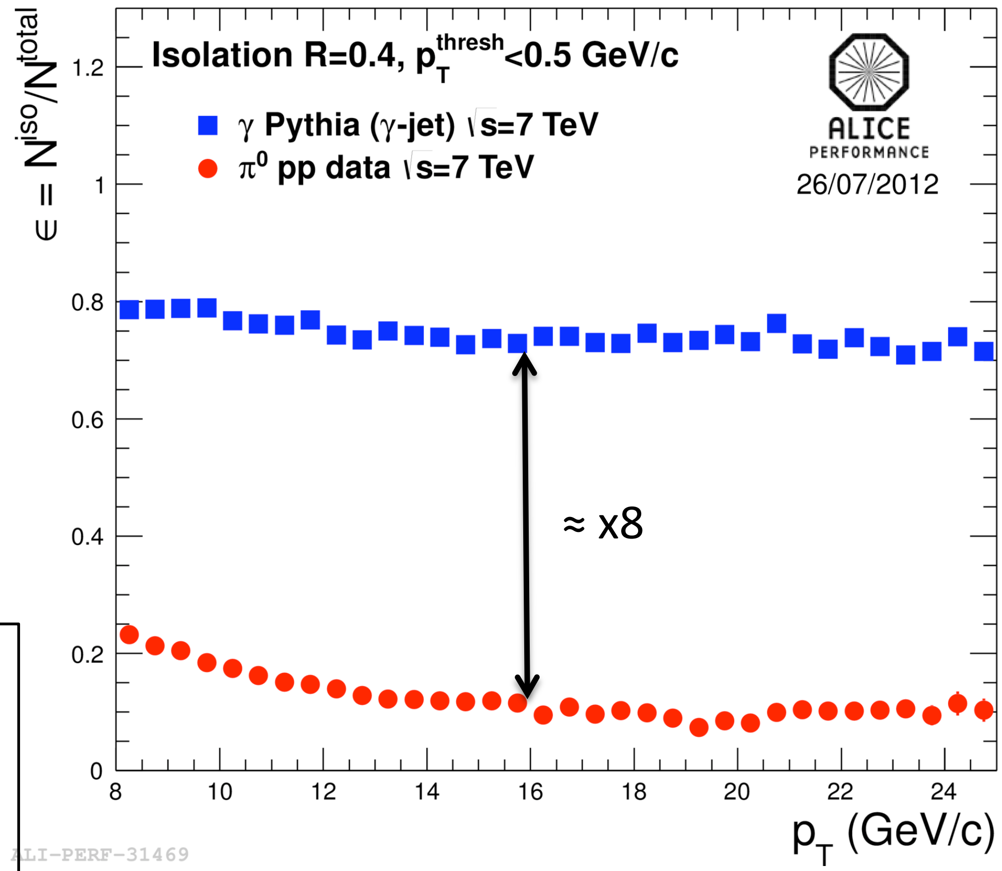
Annihilation



Compton







Isolated cluster

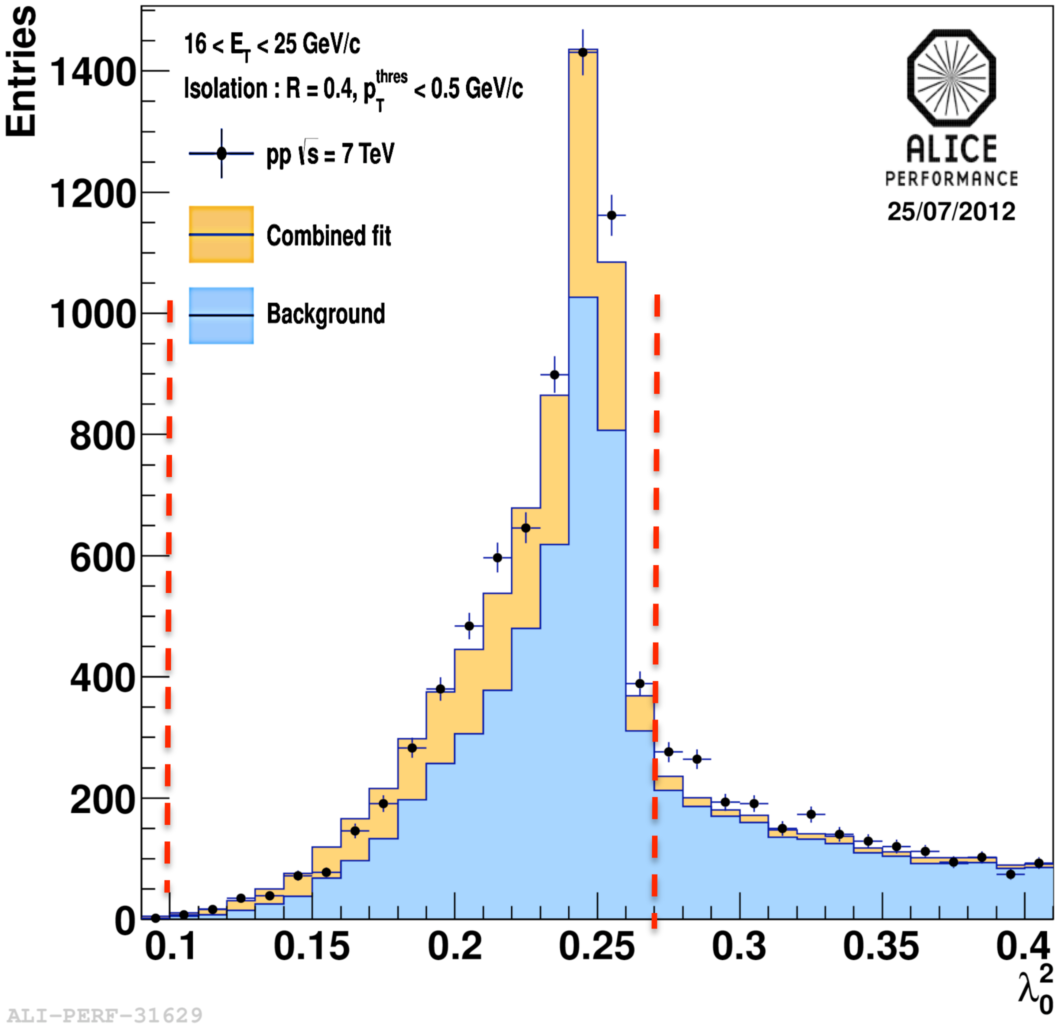
⇔

no particle with p_T above 0.5 GeV/c in cone R = 0.4

Shower shape : purity estimate

- Isolated clusters sample = isolated photons + background
- Binned likelihood **fit of the shower shape distribution** :

→ combined signal (MC) and background (data) shower shape to fit data

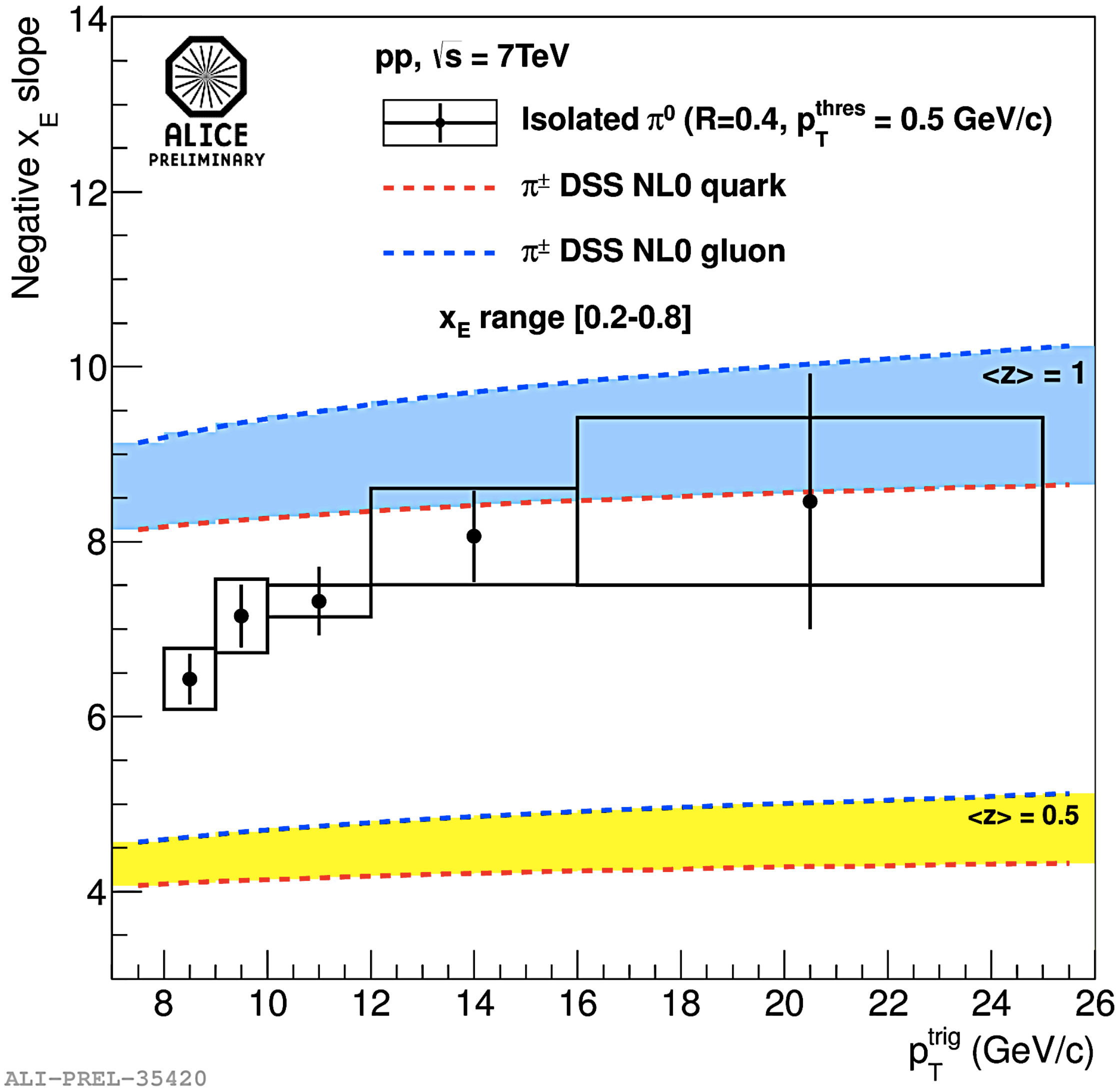


$$\text{Purity} = \frac{\int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} [\text{orange}]}{\int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} [\text{orange}] + \int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} [\text{blue}]}$$

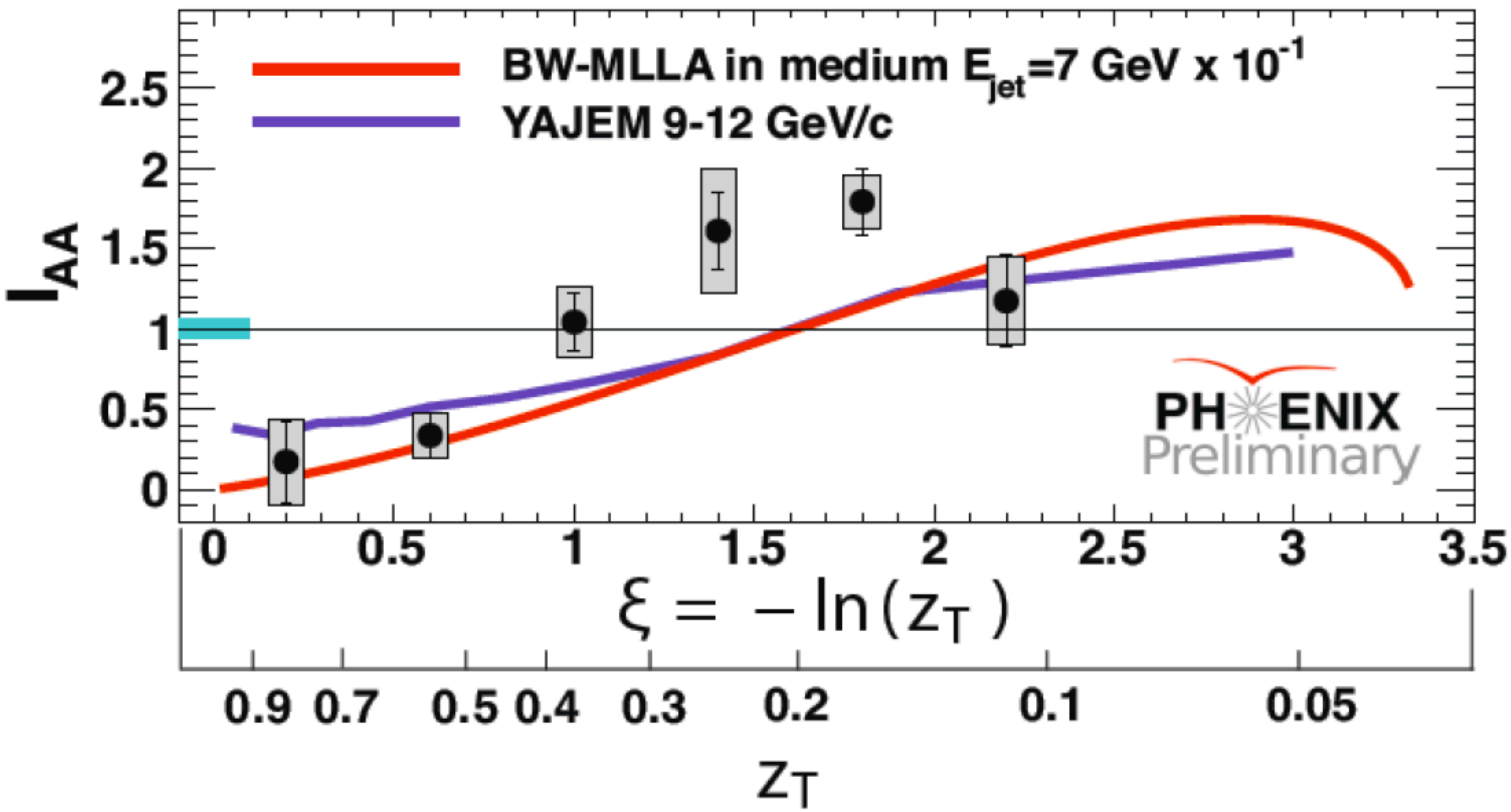
pT bins (GeV/c)	Purity
8-12	0.08 ± 0.01
12-16	0.31 ± 0.05
16-25	0.59 ± 0.04

x_E π^0 : slope parameter

- Compare slopes from isolated π^0 with fragmentation function
- Isolated π^0 slopes sample <z> ≈ 0.8



Quark Matter 2012 : PHENIX



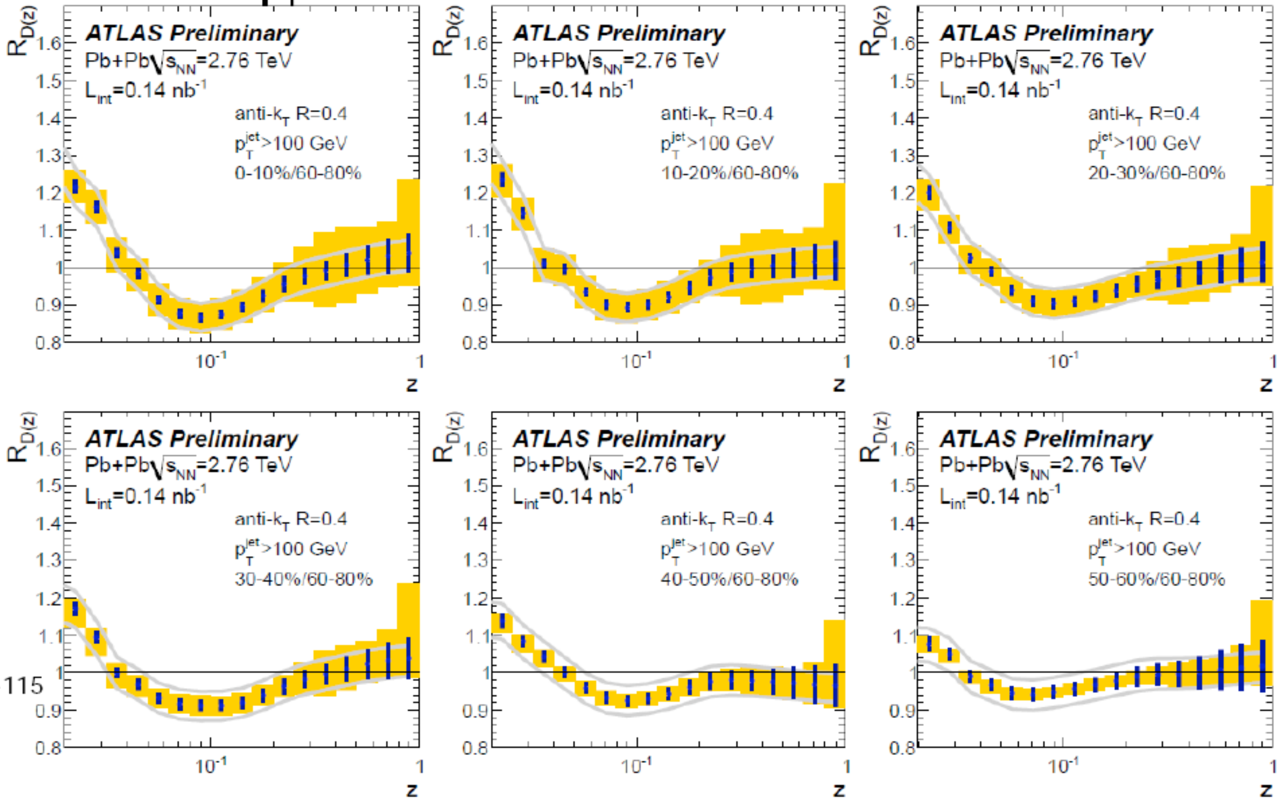
I_{AA} (ratio AA/pp) from γ-hadrons correlations shows :

- Suppression of high p_T particles (> $0.4xE_{jet}$)
- Increase of low p_T particles (< $0.4xE_{jet}$)

Quark Matter 2012 (2)

Jet fragmentation

$p_T^{had} > 2\text{GeV}$ $\quad z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos\Delta R$ $\quad R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$



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- Enhancement at low z, suppression at z≈0.1
- No modification at high z
- Similar results found for R=0.2 and 0.3 jets