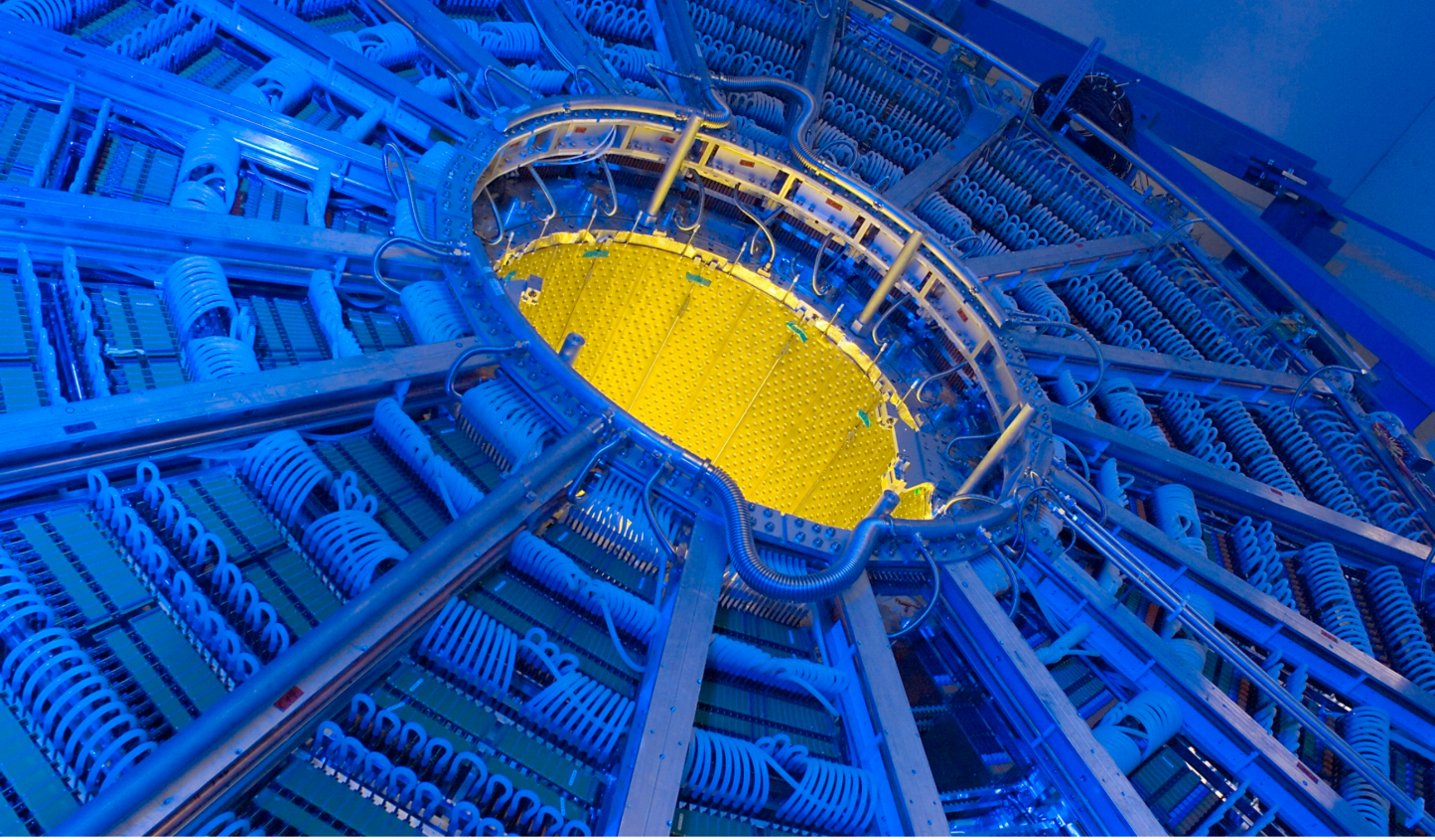
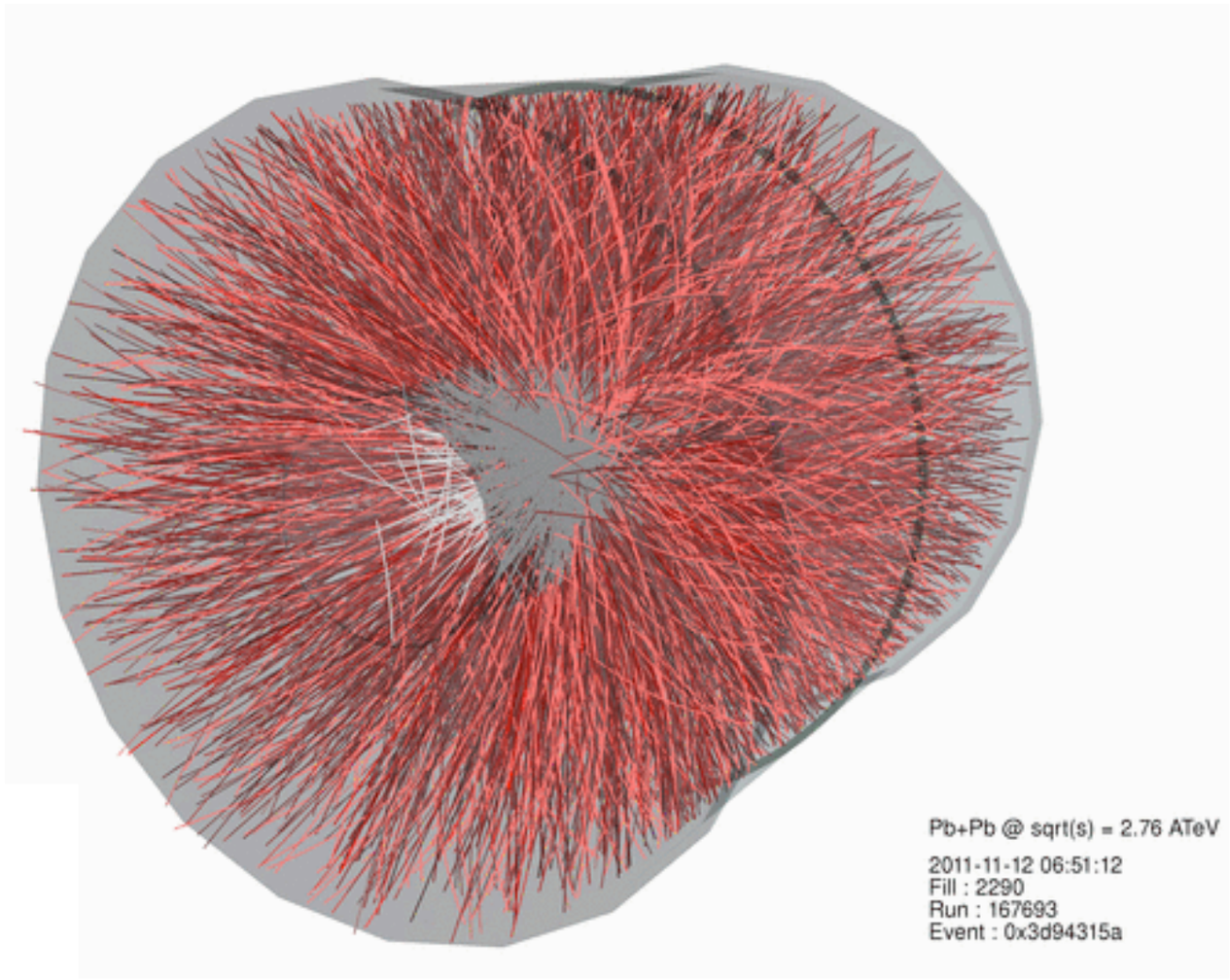


Light-flavor hadron production in Pb-Pb collisions at the LHC

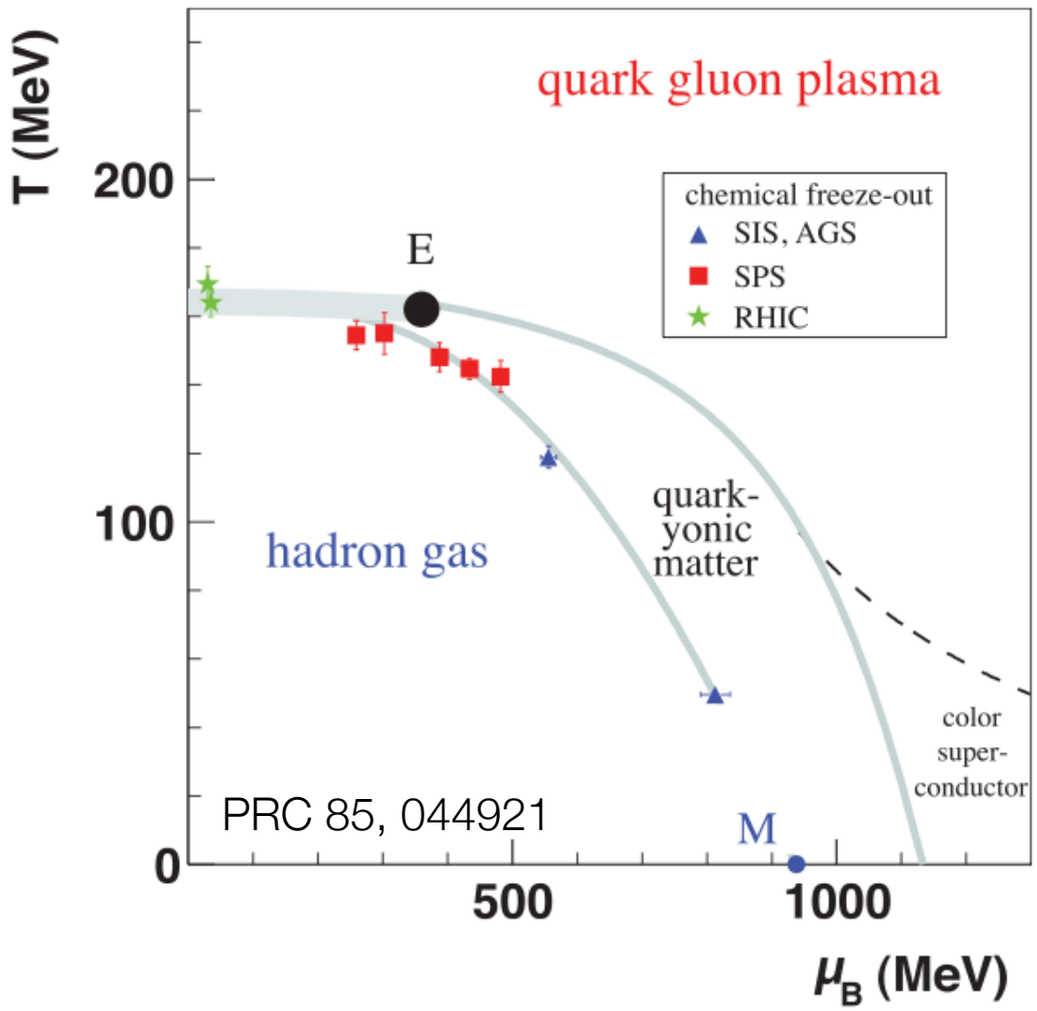
Michele Floris
for the ALICE Collaboration
PH Seminar, Mar 19, 2013

Outline

- Heavy ion collisions dynamical evolution
- Why identified, light flavor particles?
- Low p_T results: collective flow
- Intermediate p_T: recombination, soft vs hard
- High p_T: parton energy loss



Heavy ion collisions evolution



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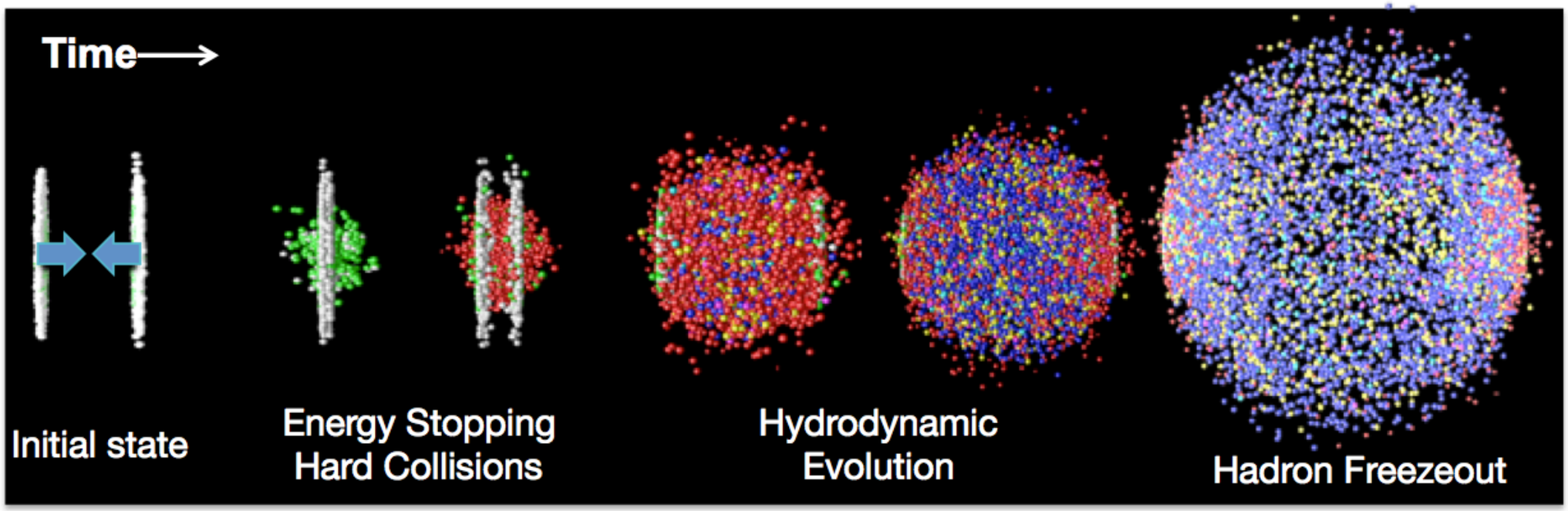

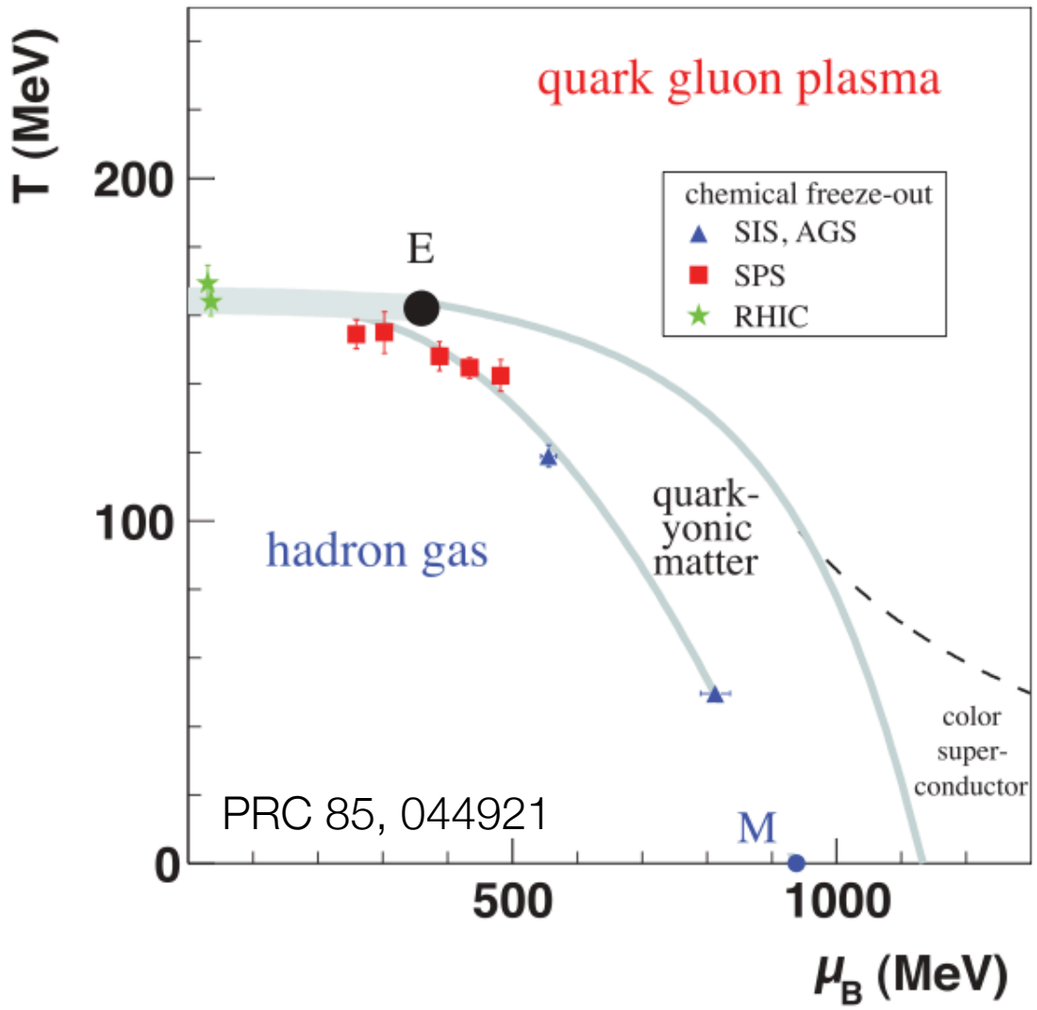

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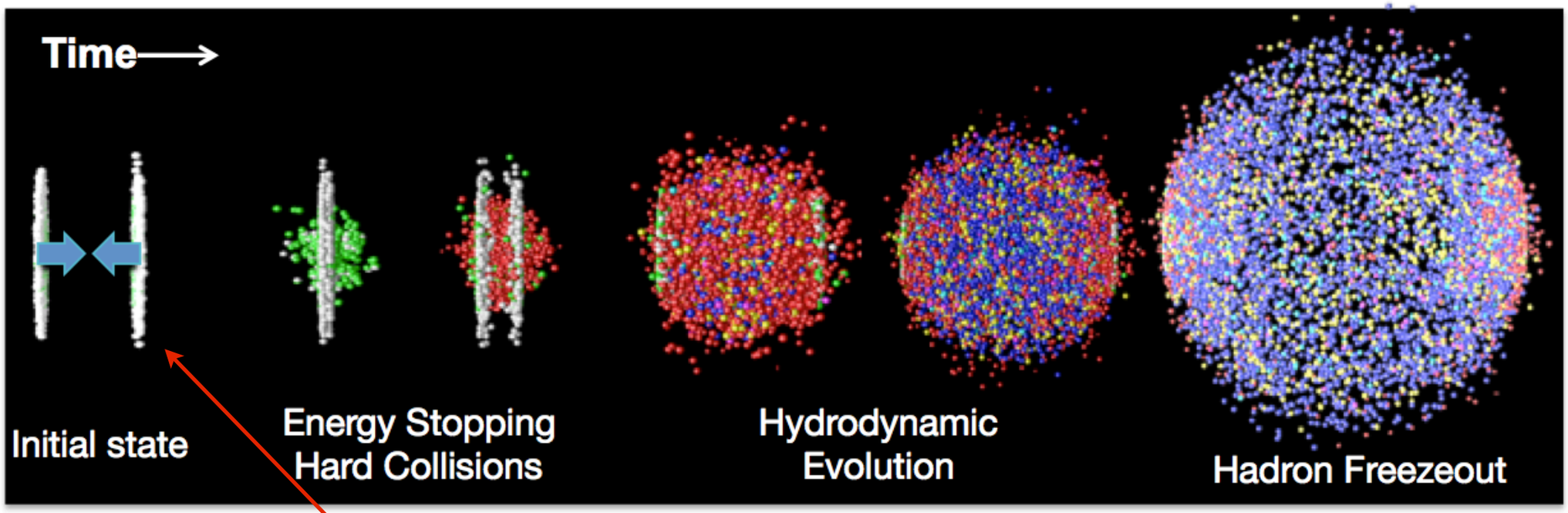

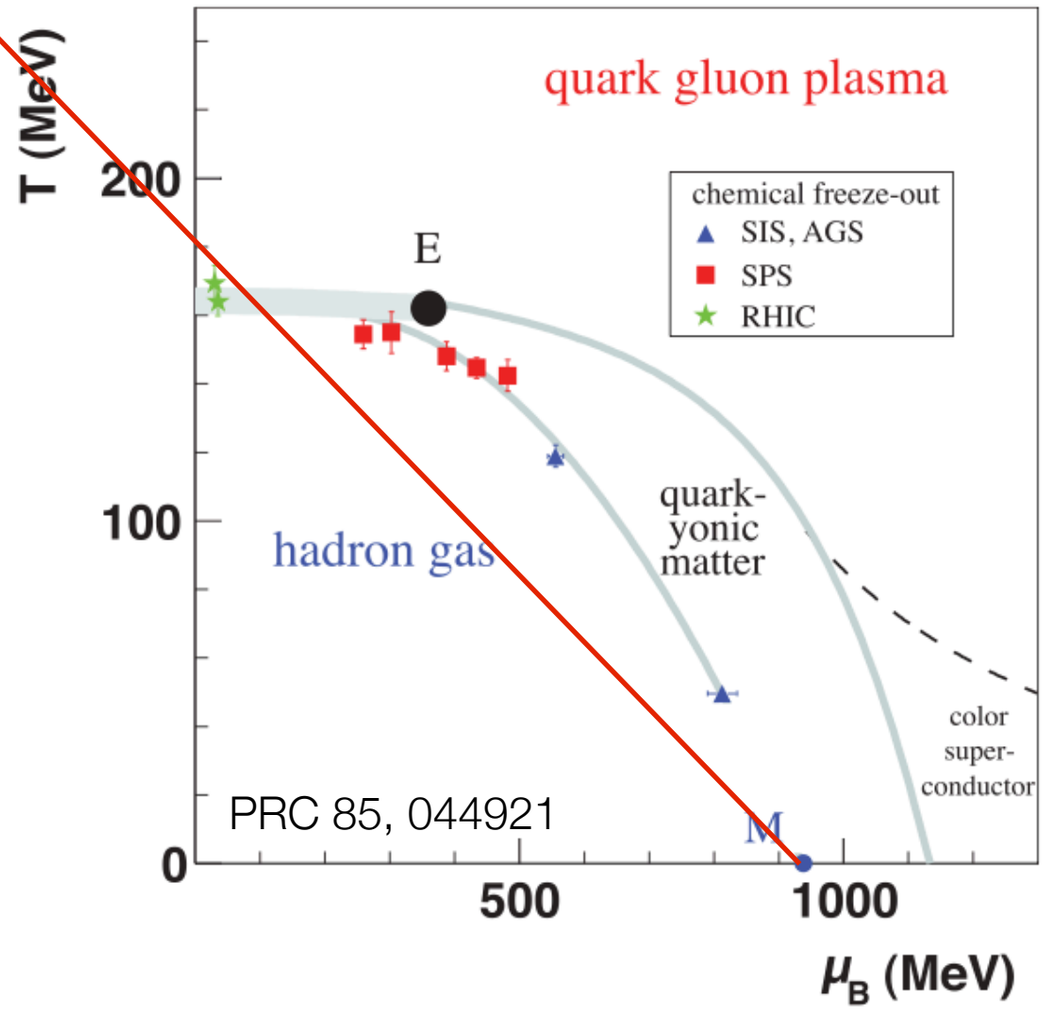

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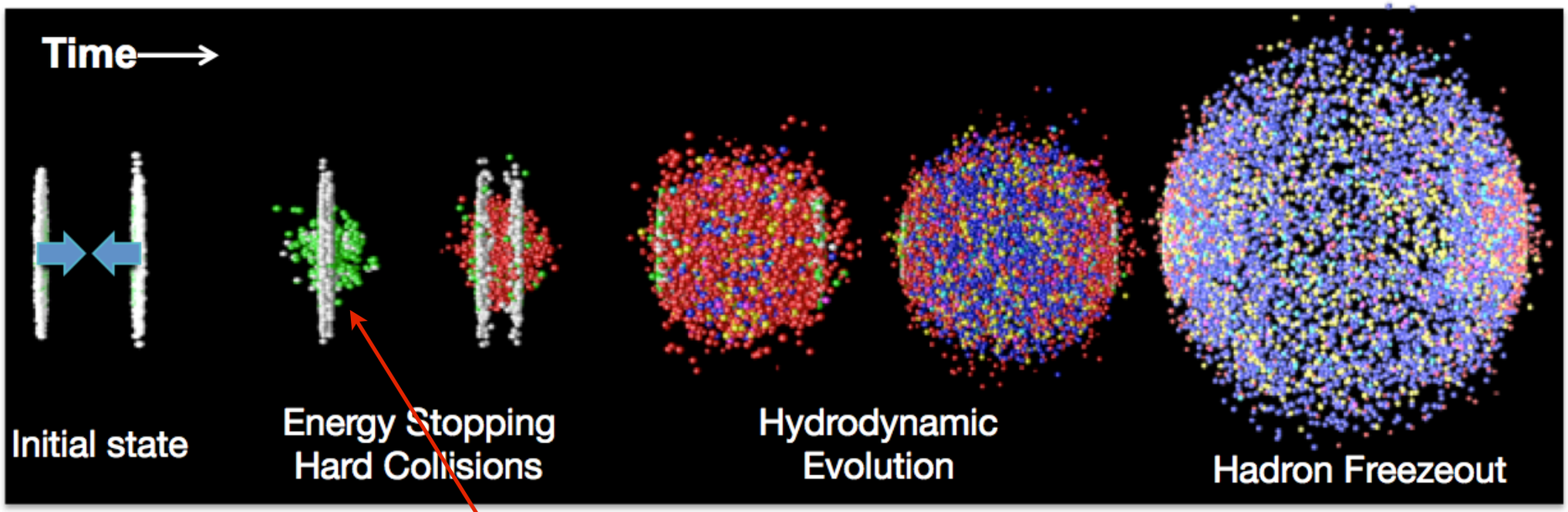
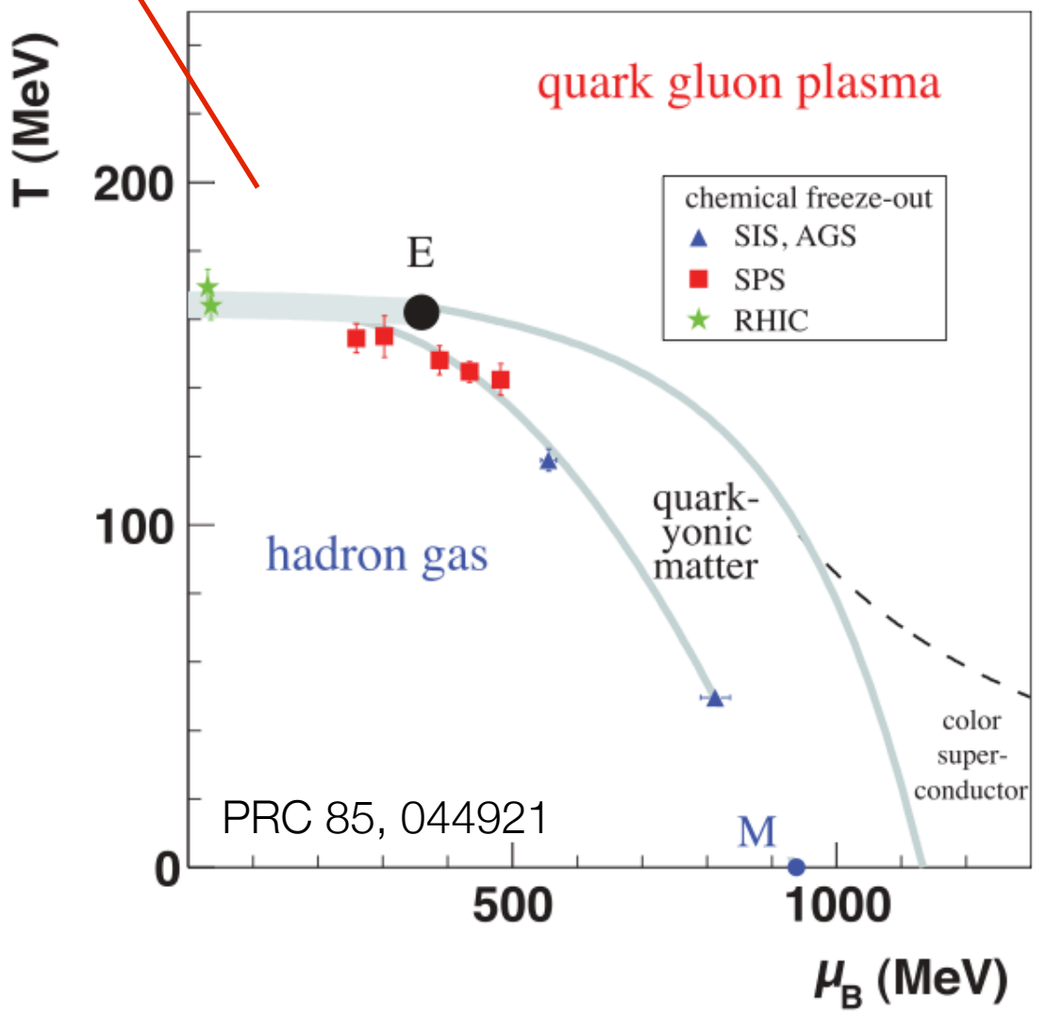


hard scattering



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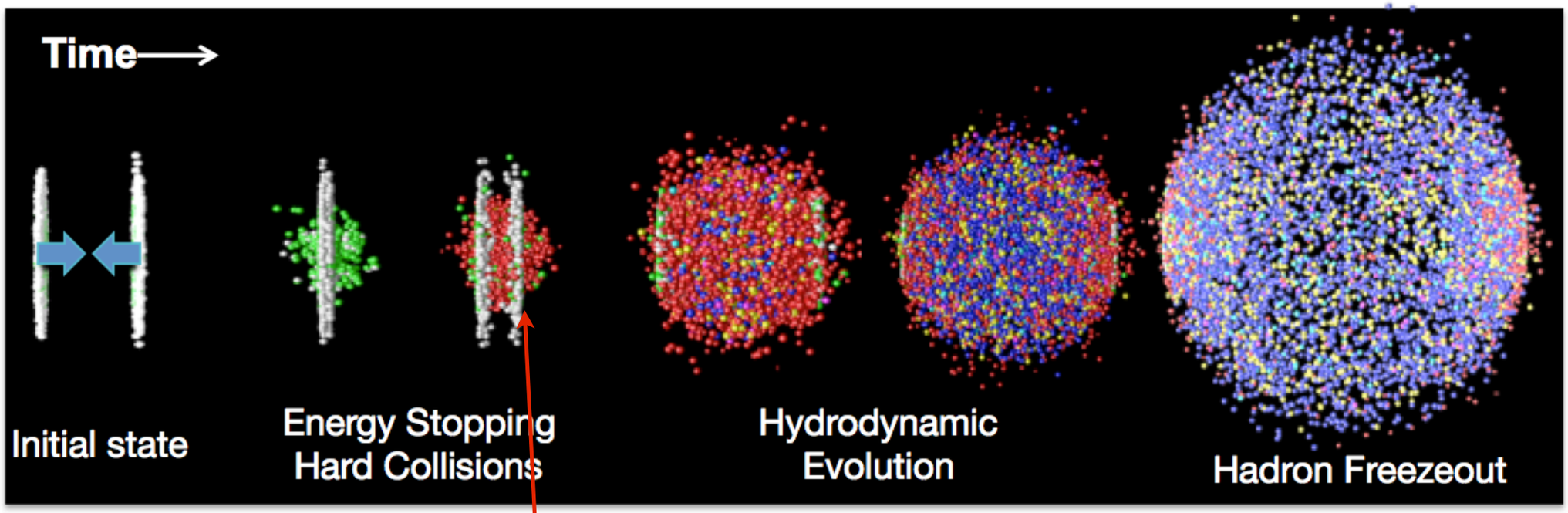

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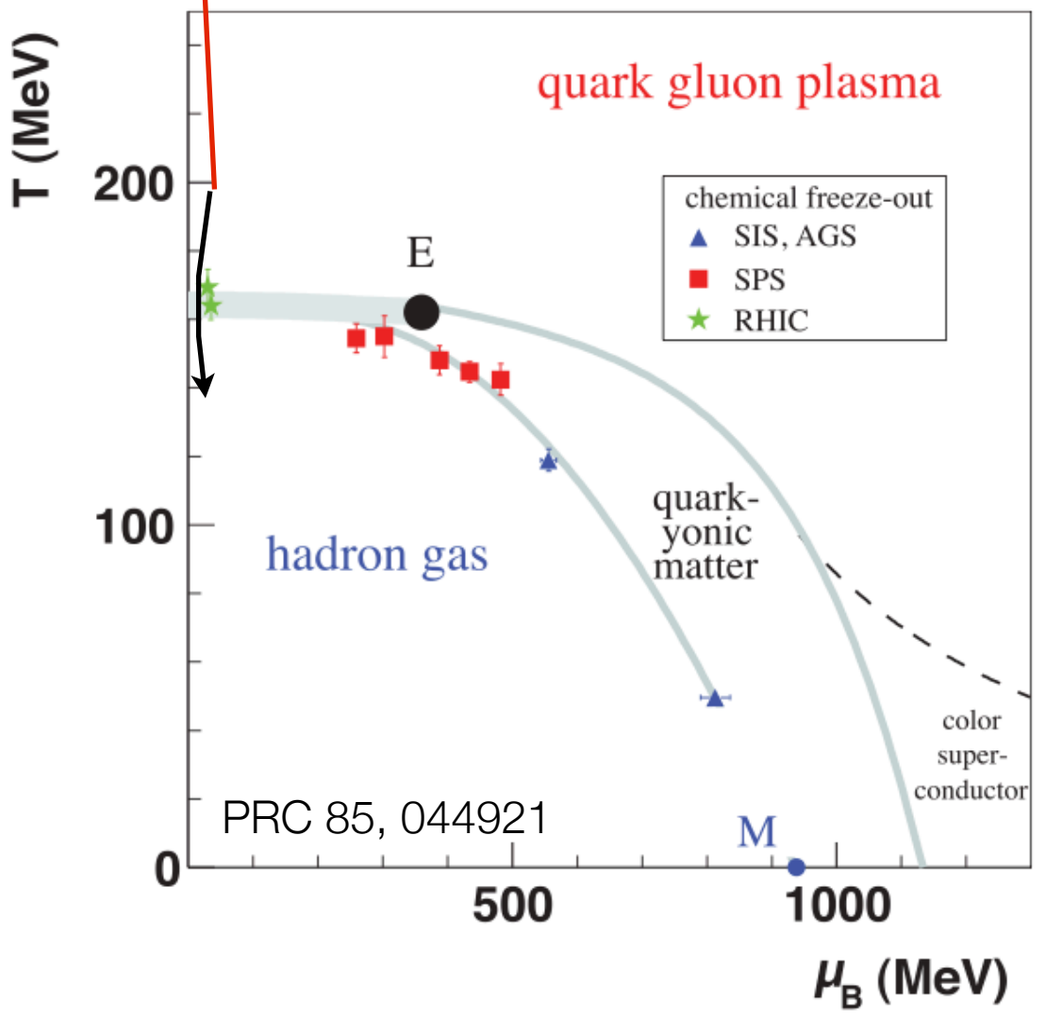
thermalization



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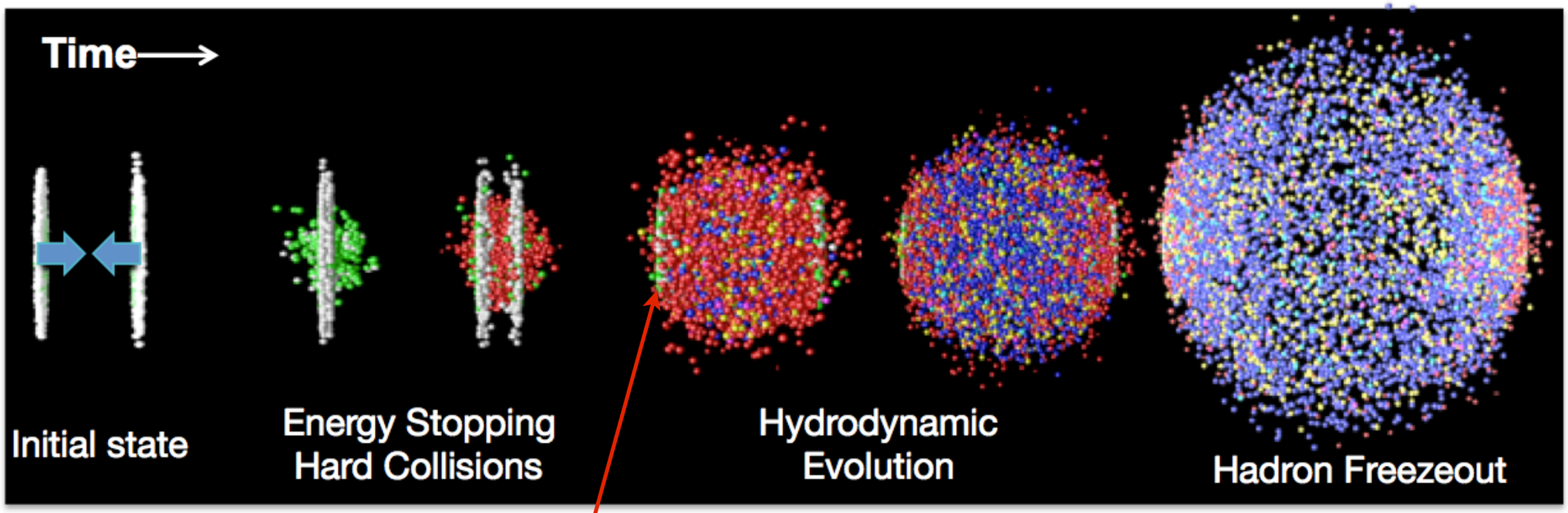

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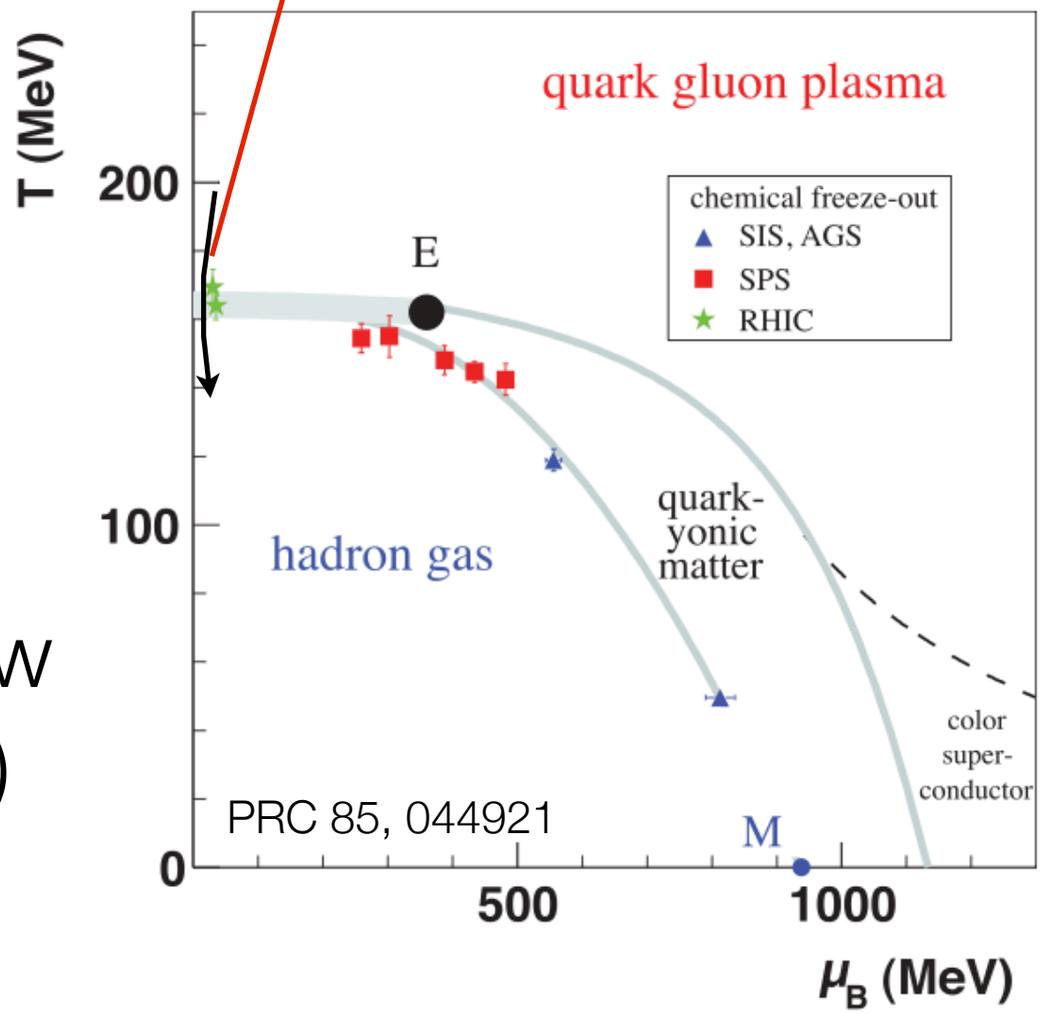
(radial and elliptic)



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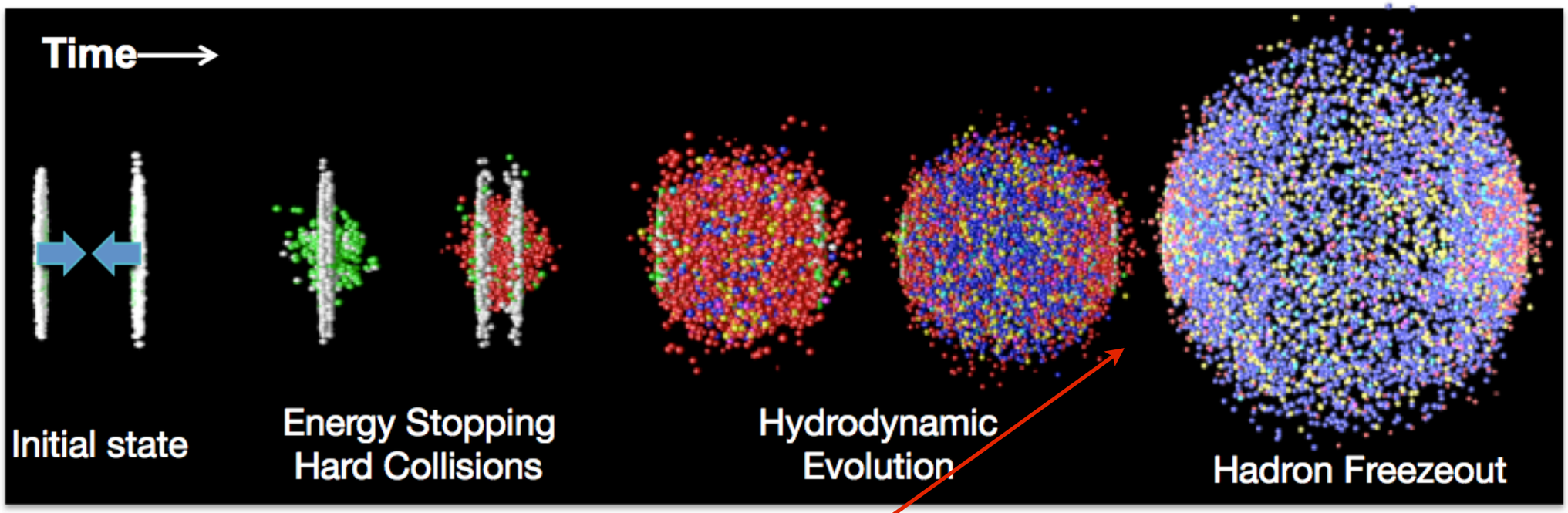

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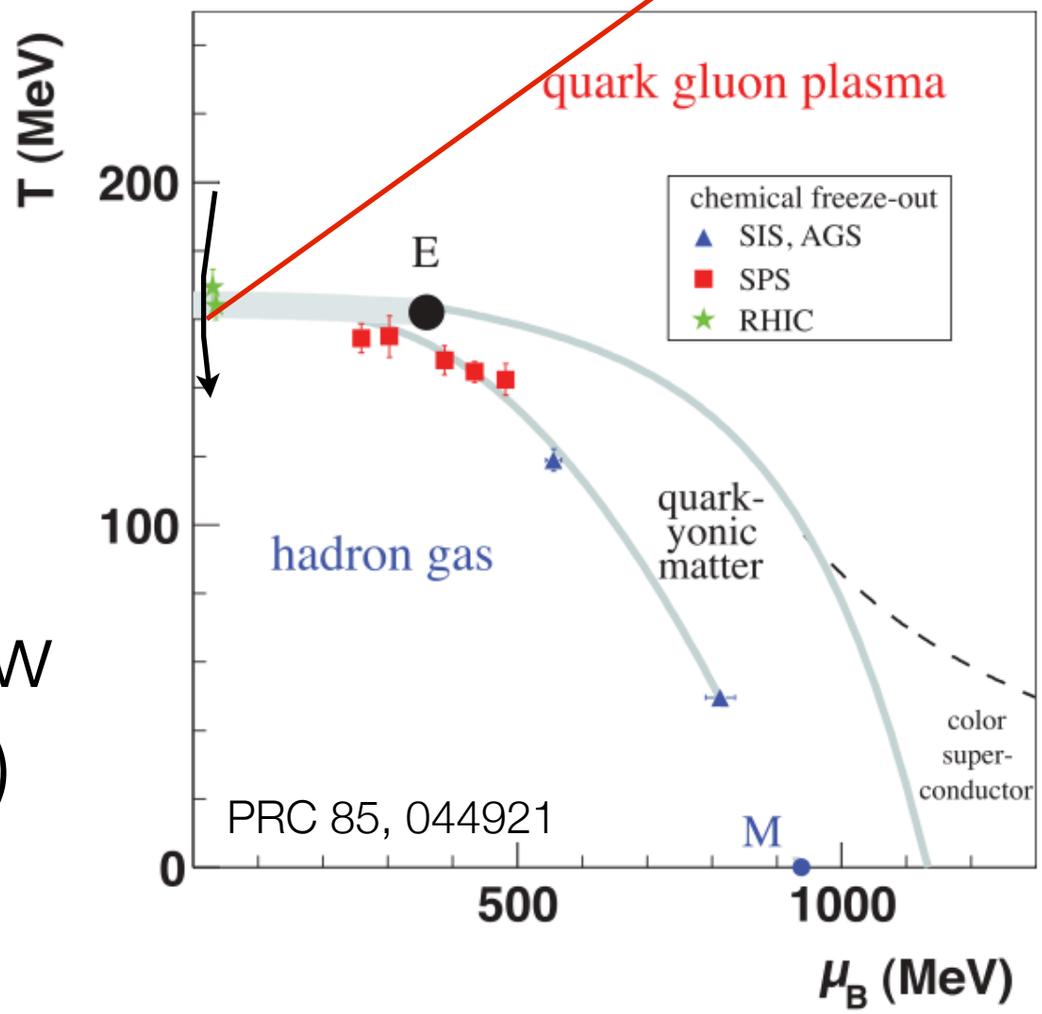

chemical freezeout
(particle ratios)

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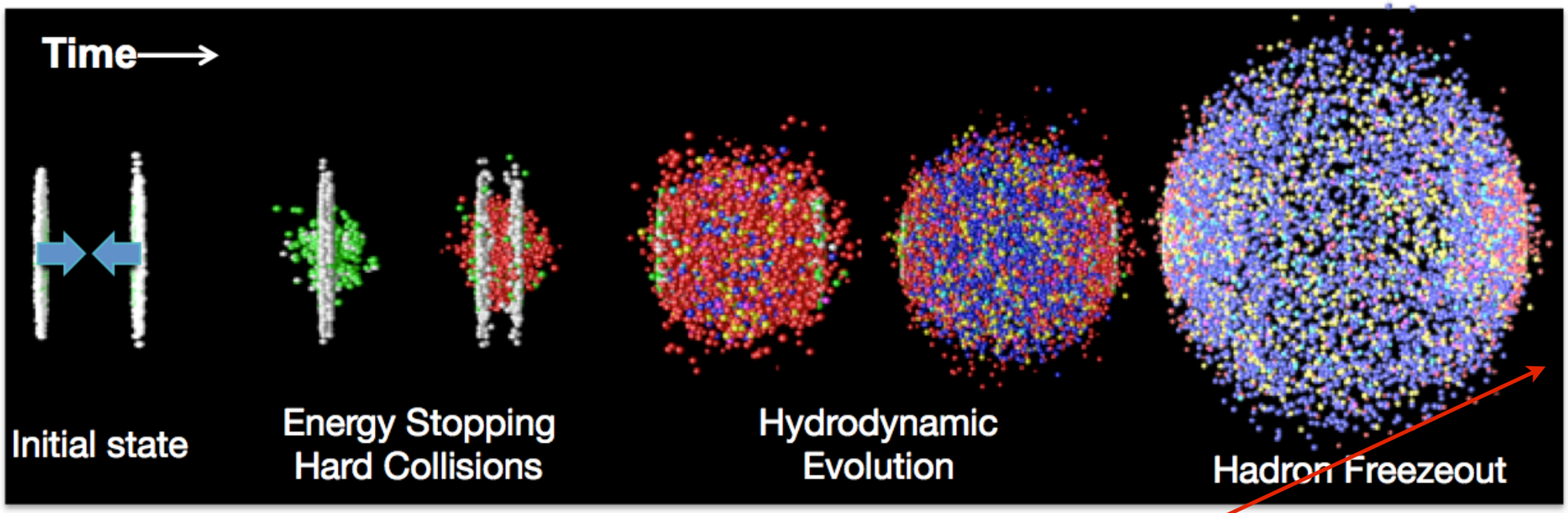

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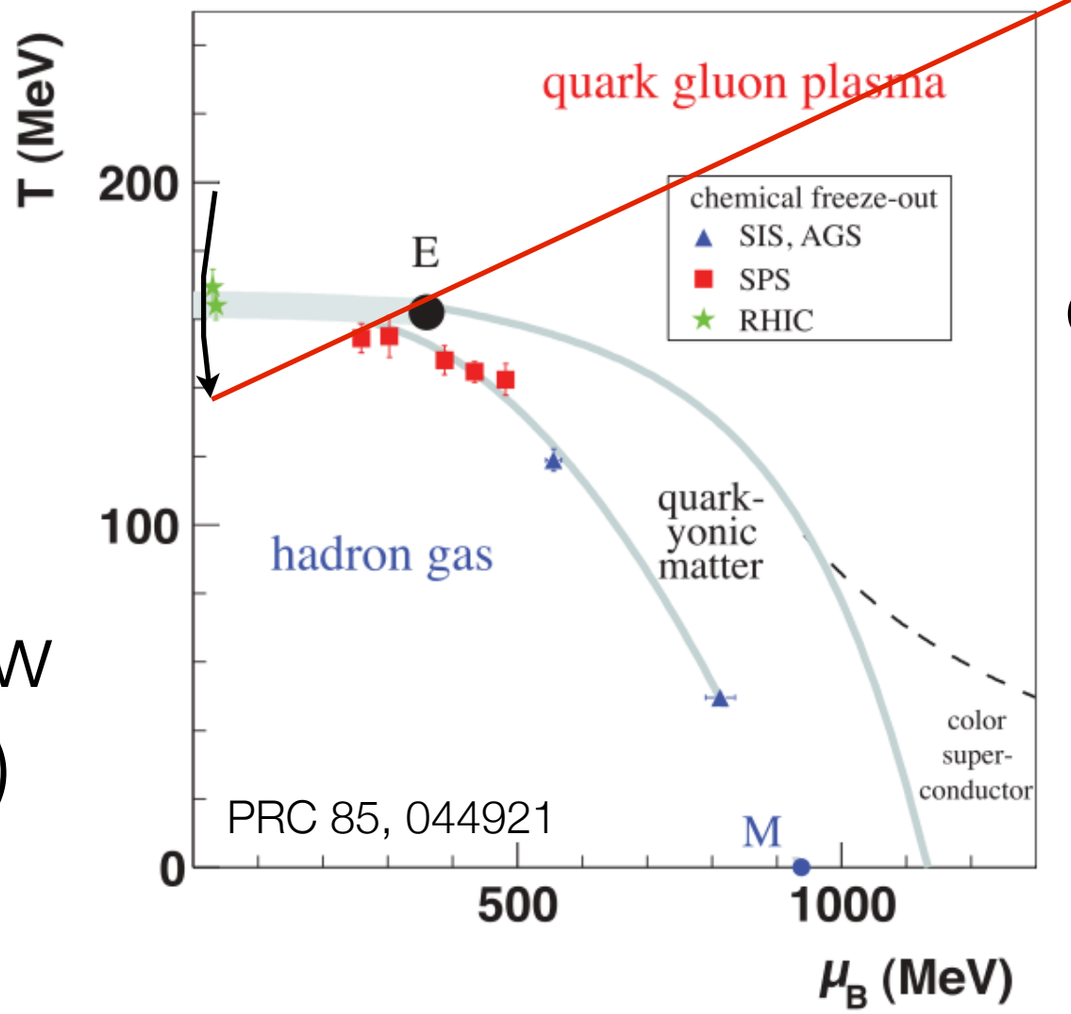

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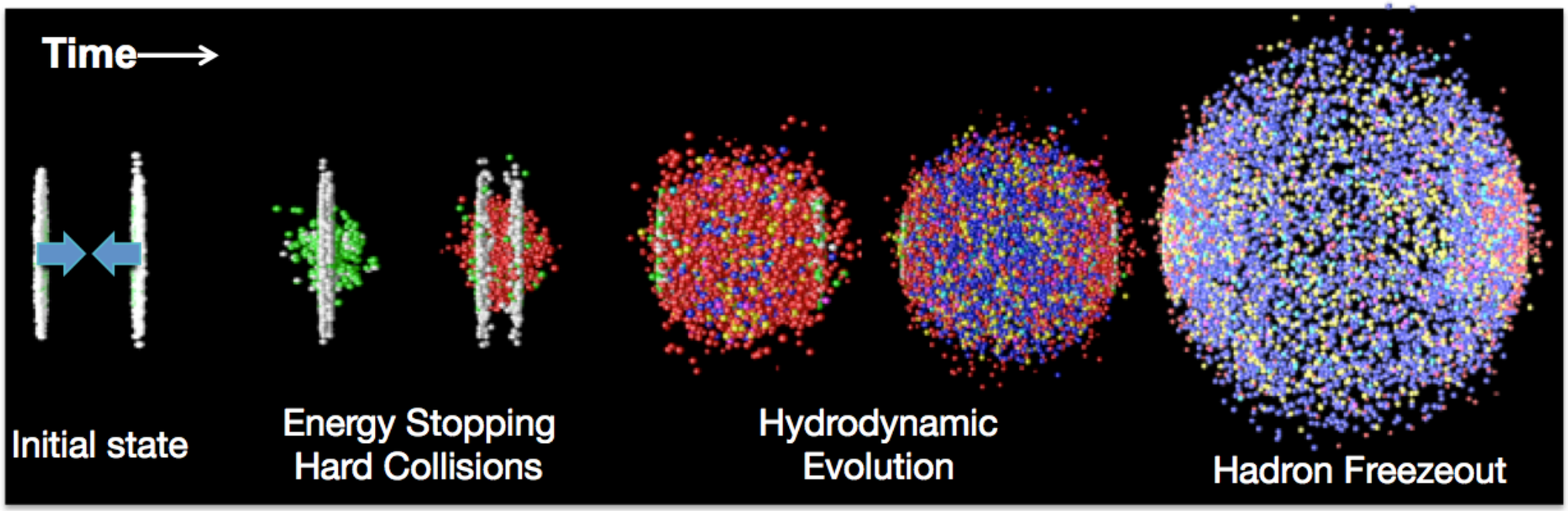

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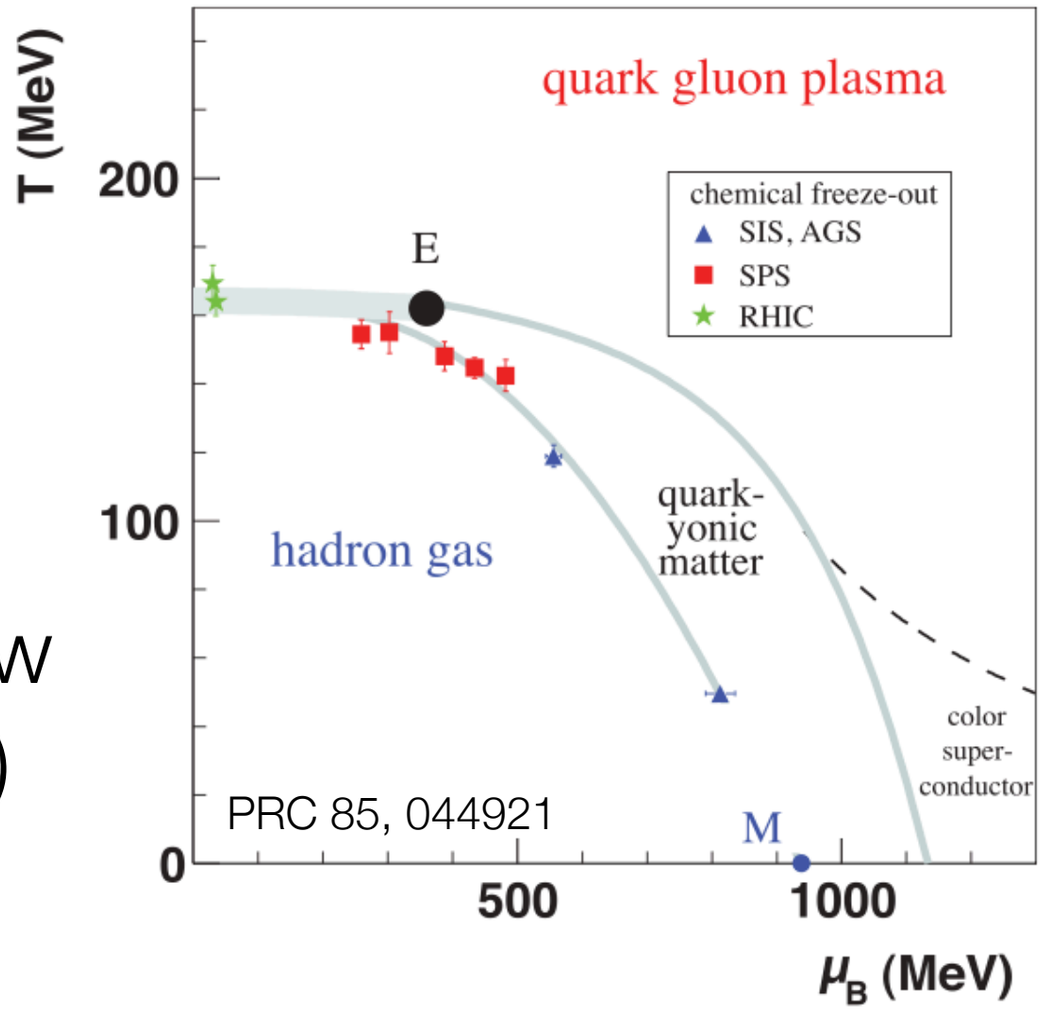

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kinetic freezeout
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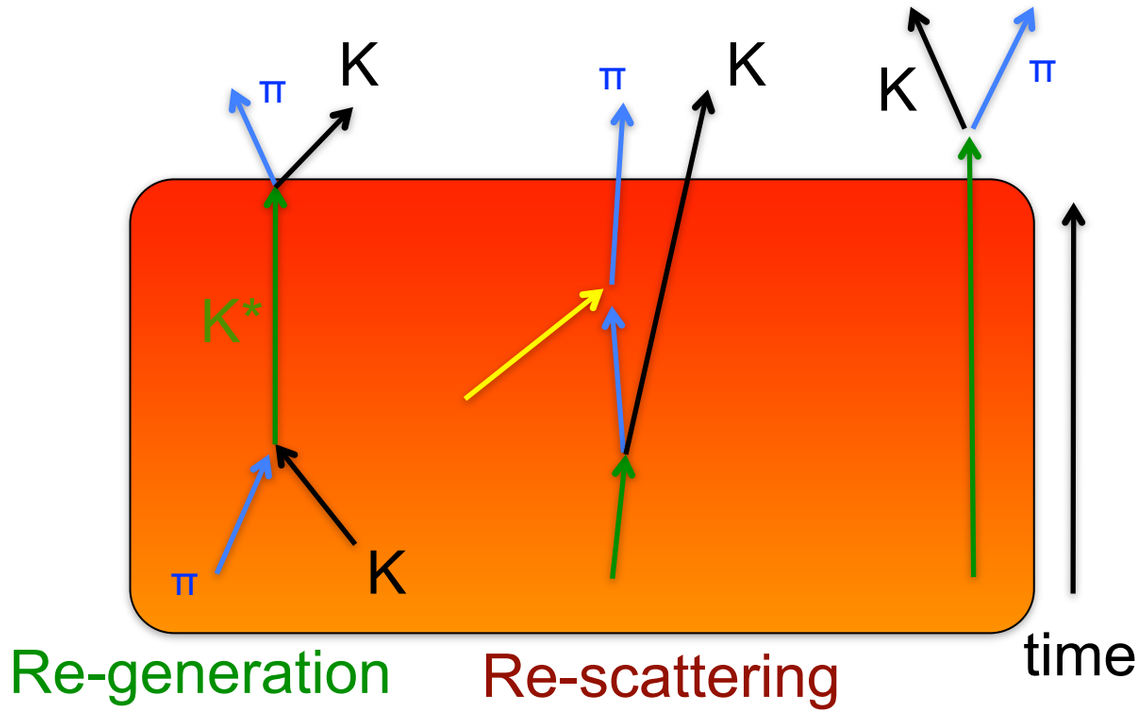
Sudden freezeout?

1. Resonances: lifetime ~ that of the medium
   Rescattering or regeneration?



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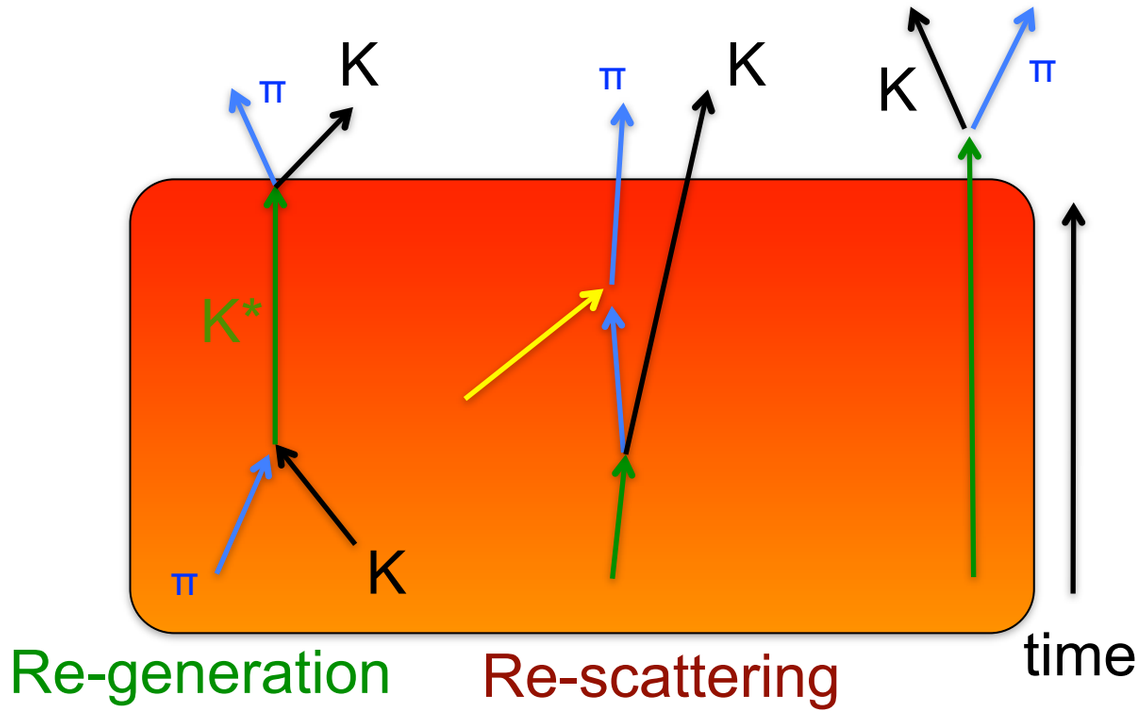

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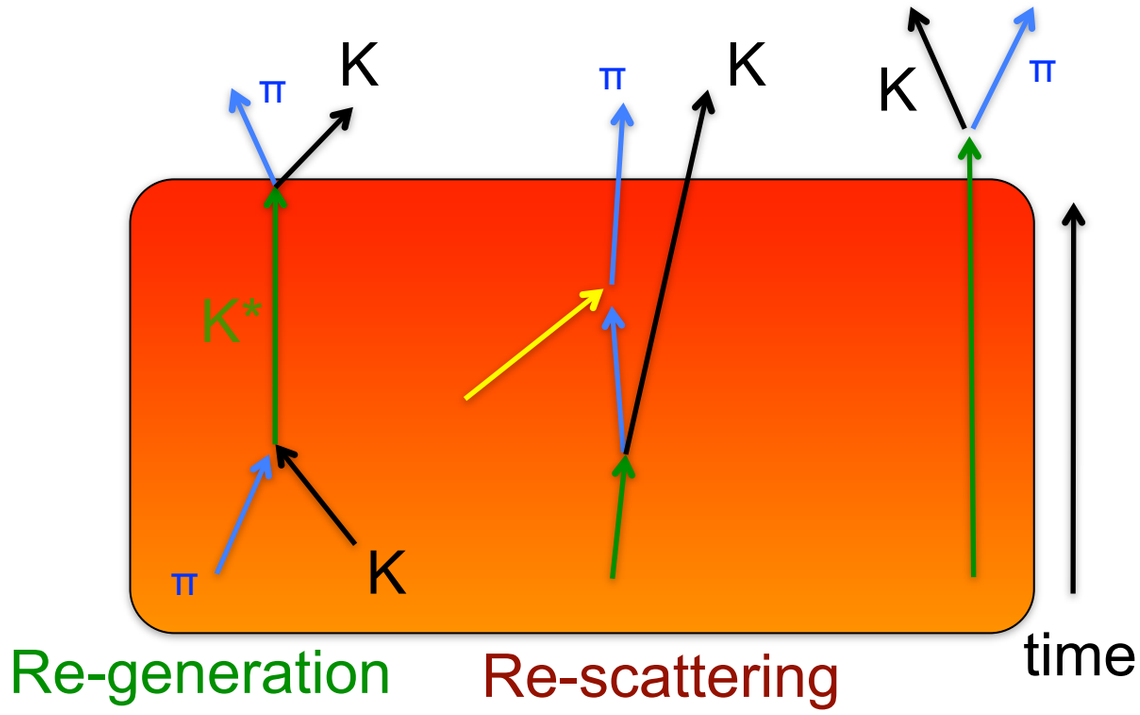
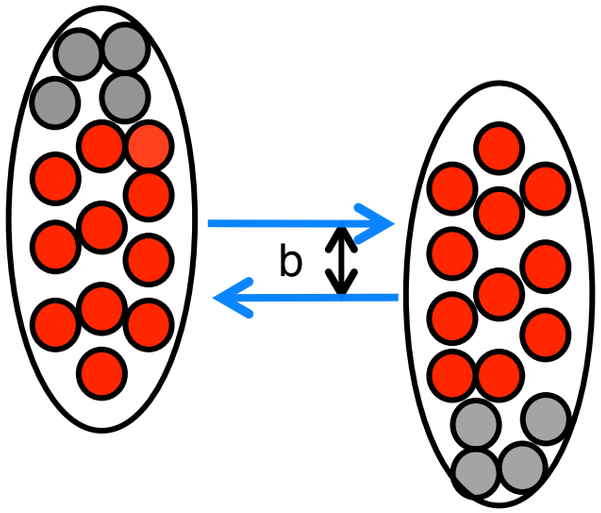


2. Baryon annihilation, inelastic interactions?

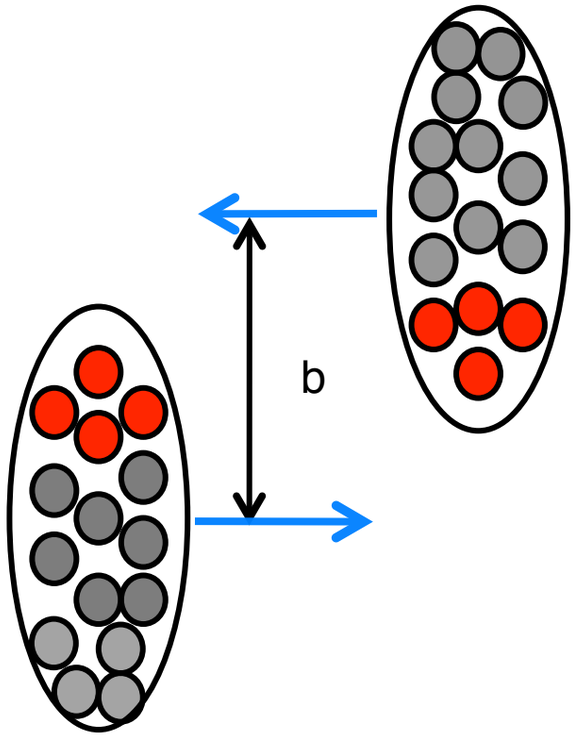
3. “Pion wind” increases radial push
   Early decoupling of (multi)strange particles?

Collision geometry: centrality

Central



Peripheral



Nuclei are extended objects
Geometry related to observables via Glauber Model

ALICE, arXiv:1301.4361

Collision geometry: centrality

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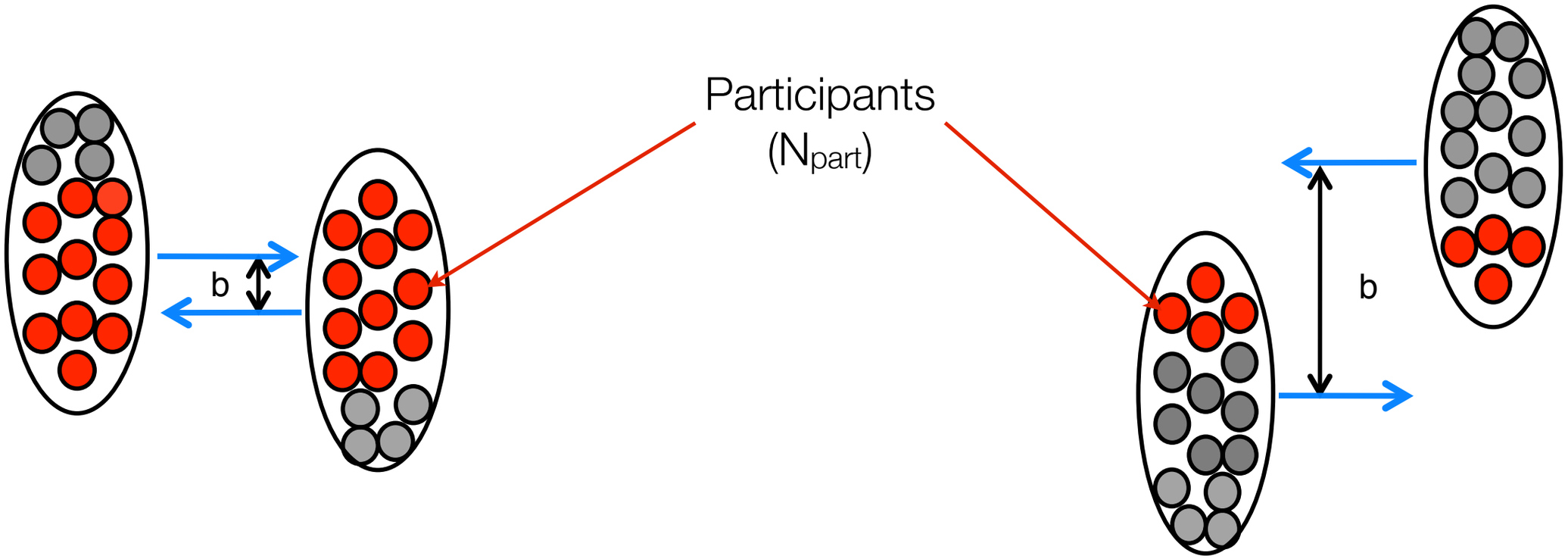

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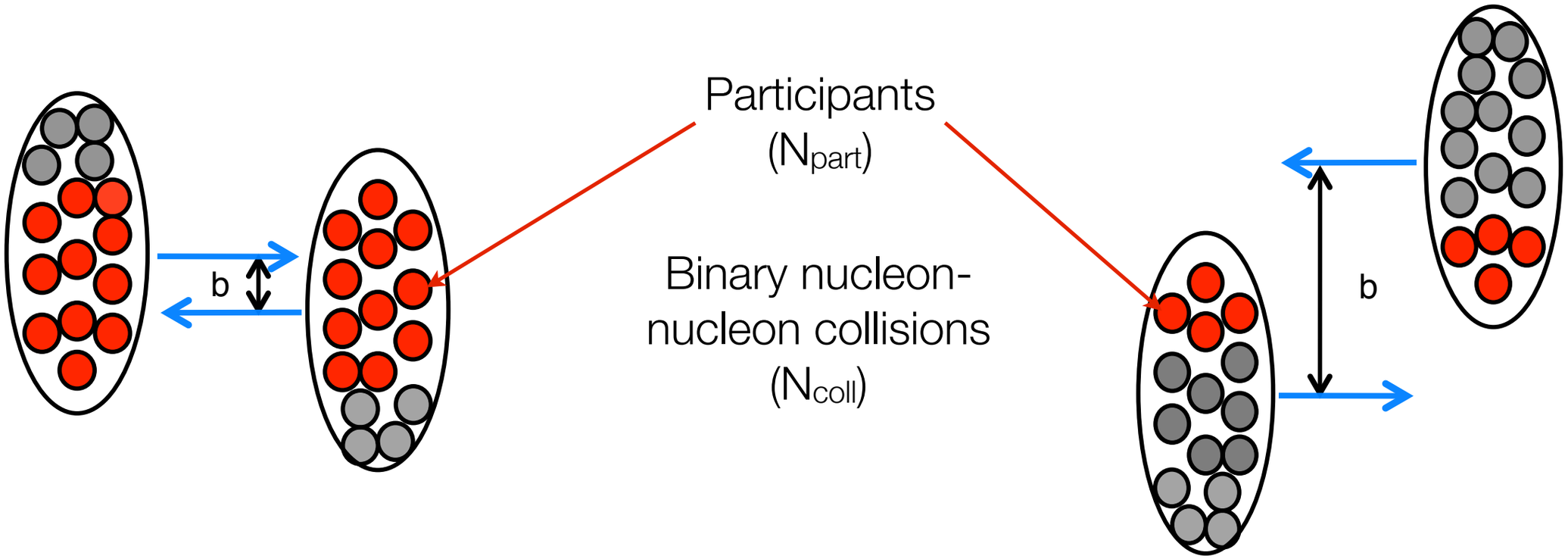

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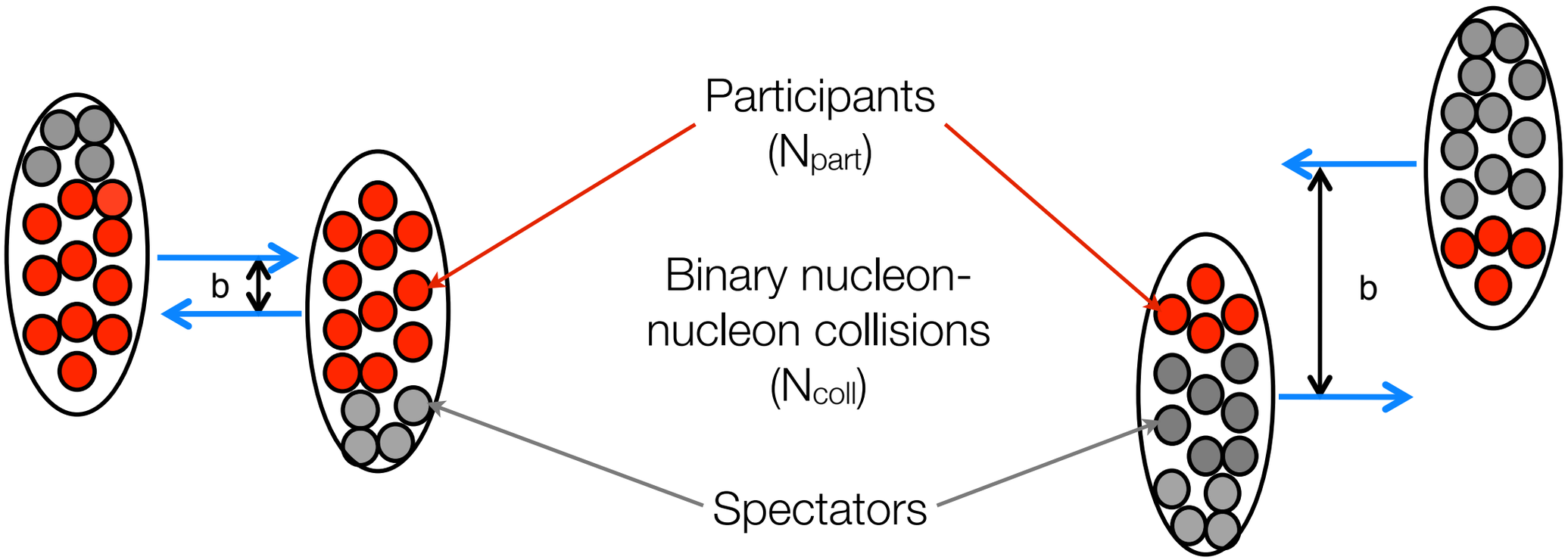

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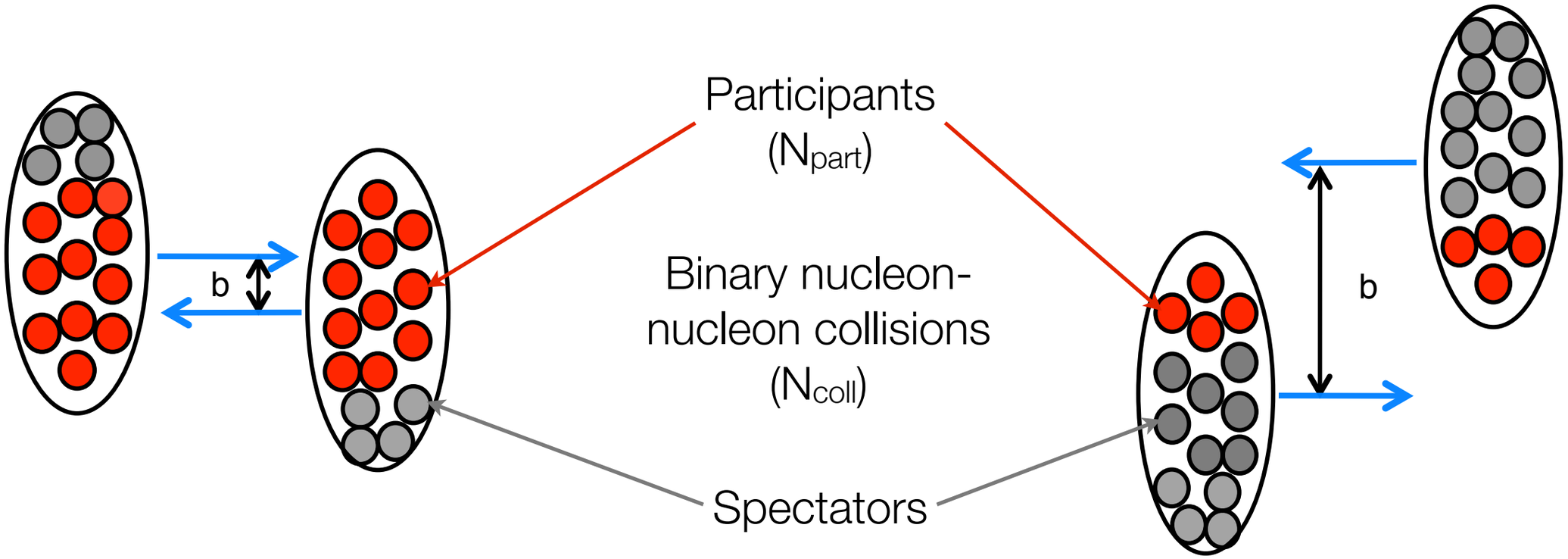

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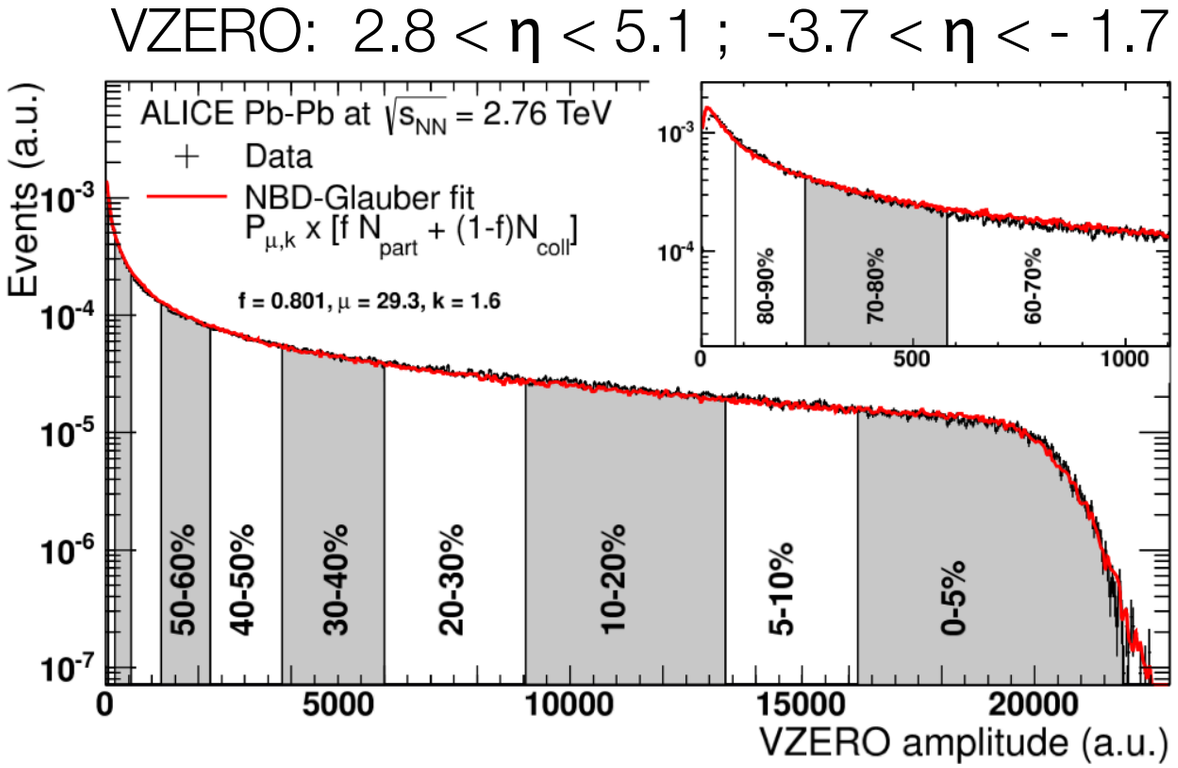

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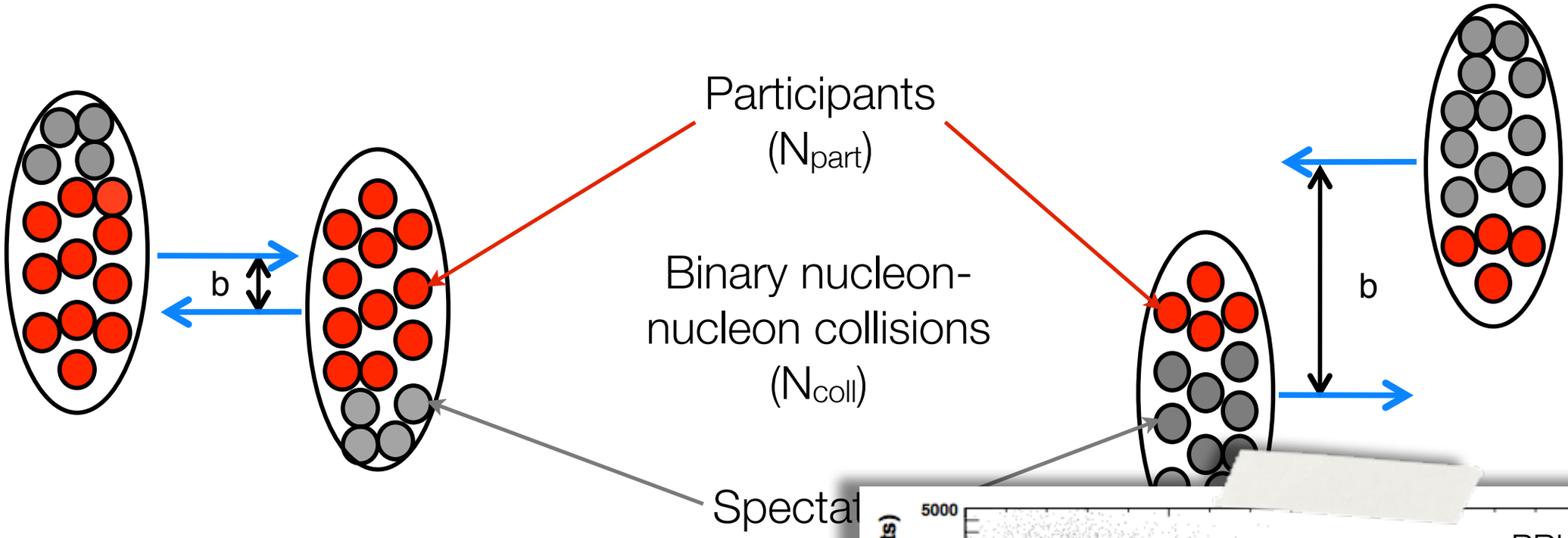

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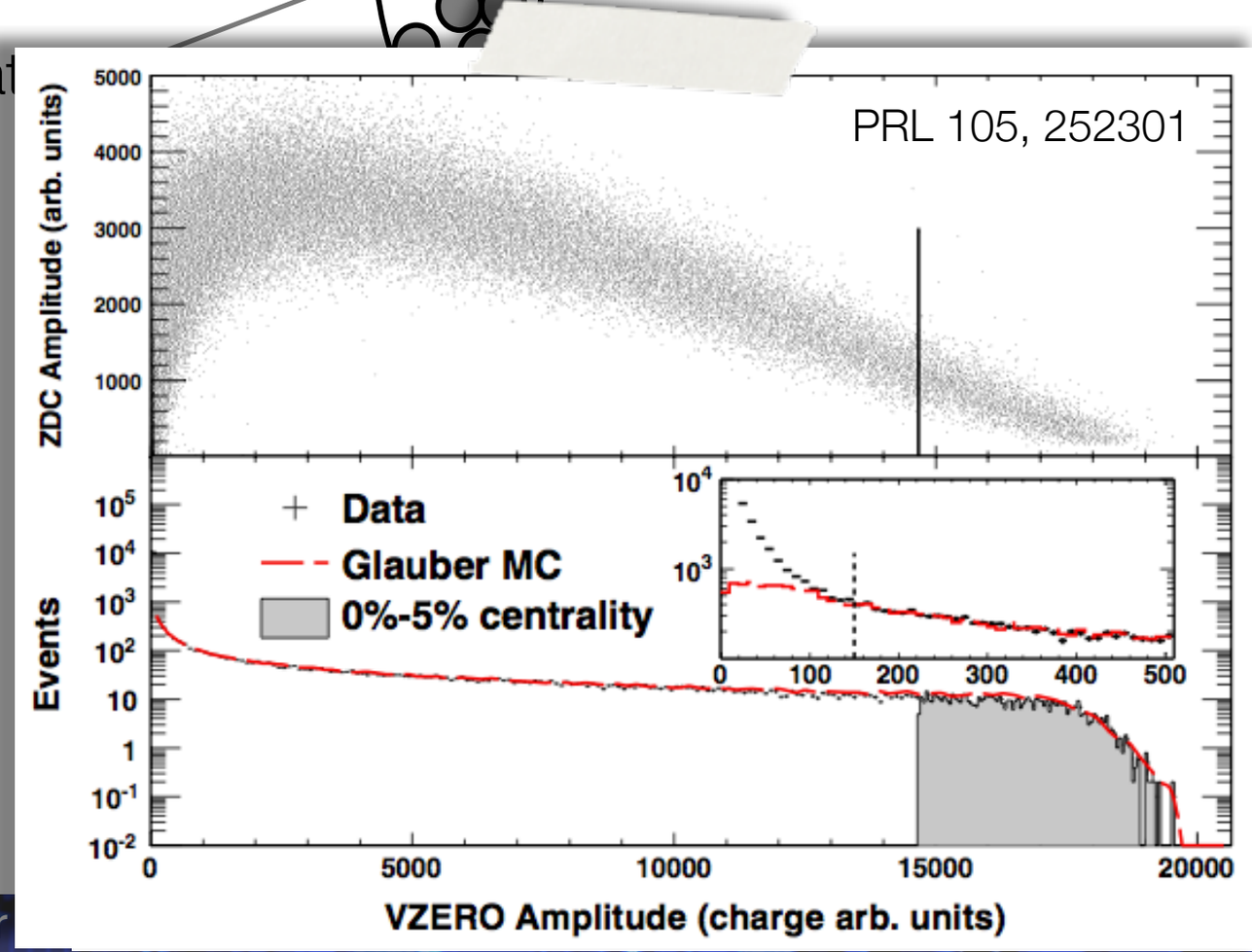

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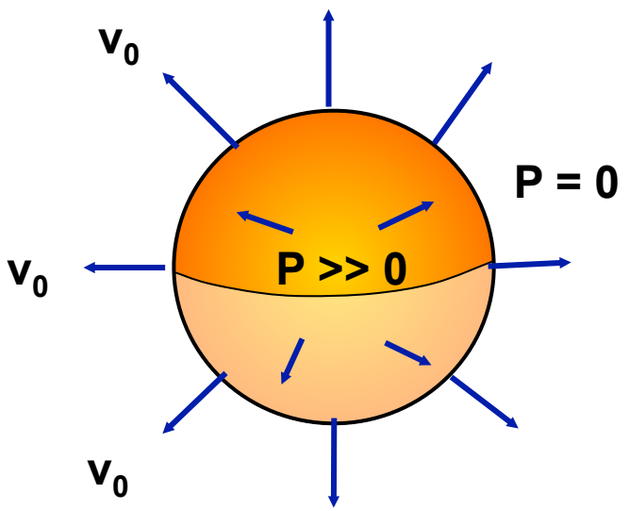
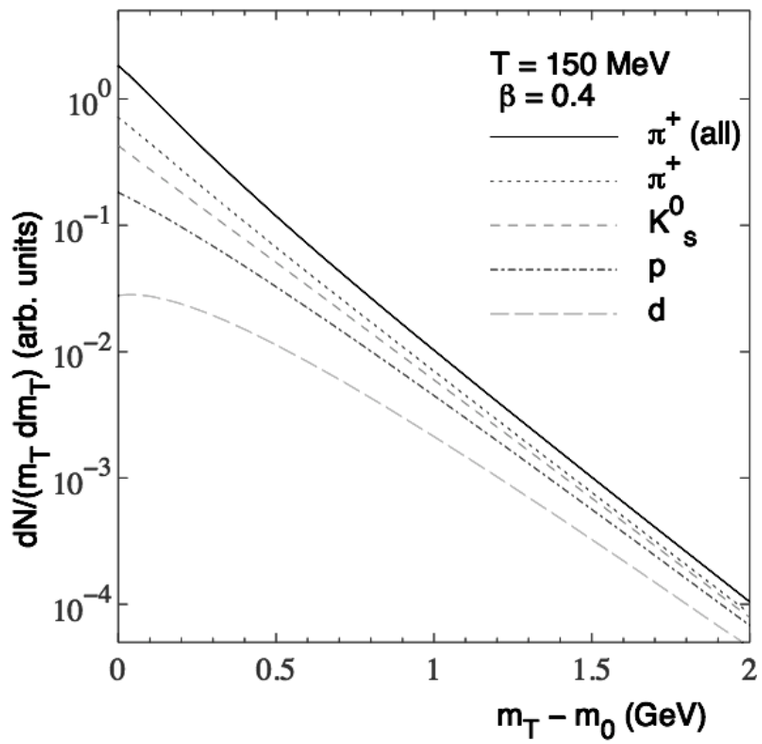
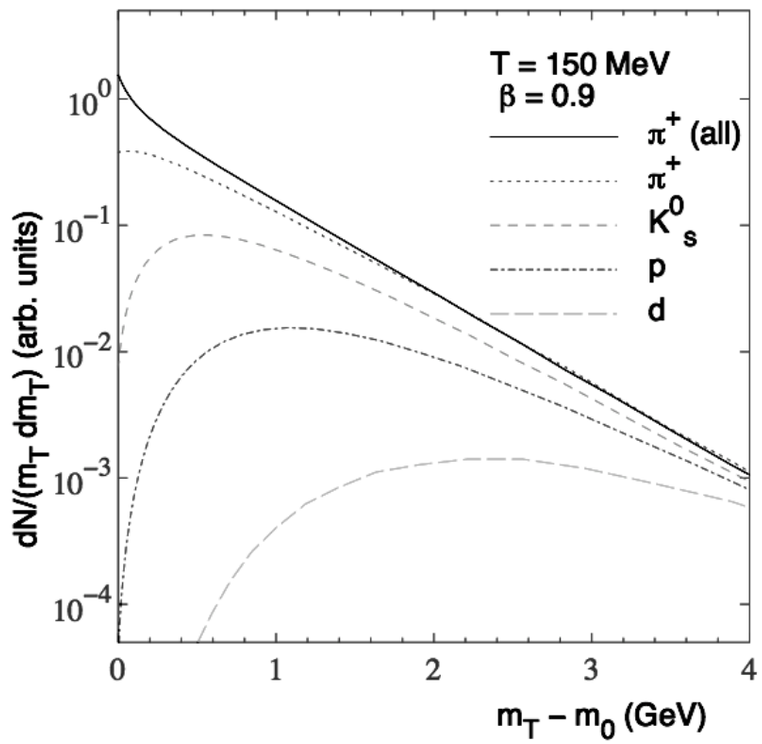
Radial and Elliptic Flow

Isotropic radial flow







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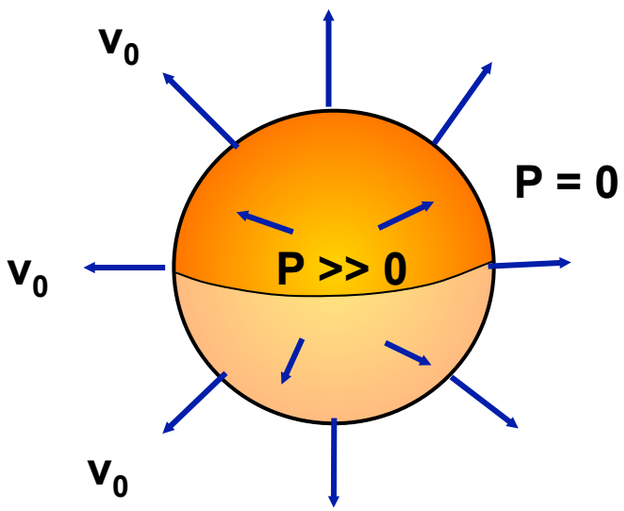

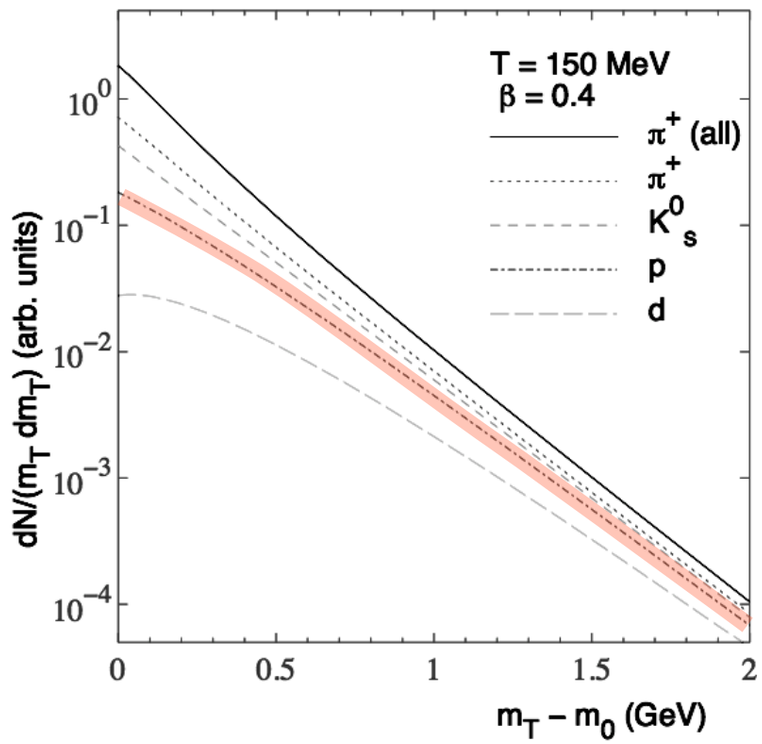

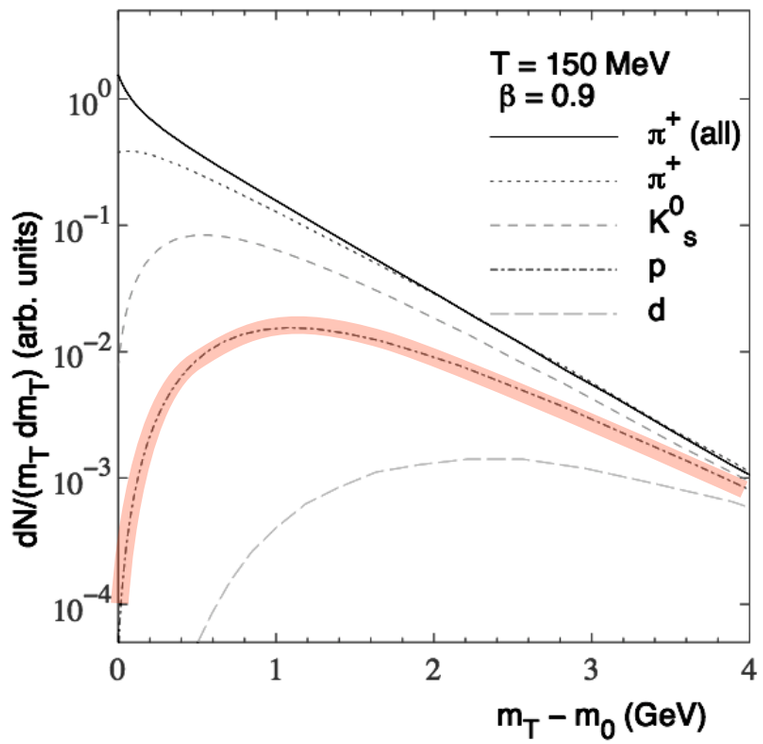

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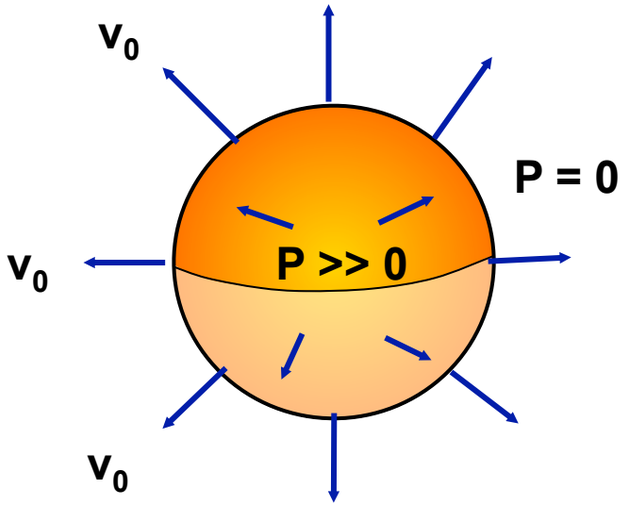
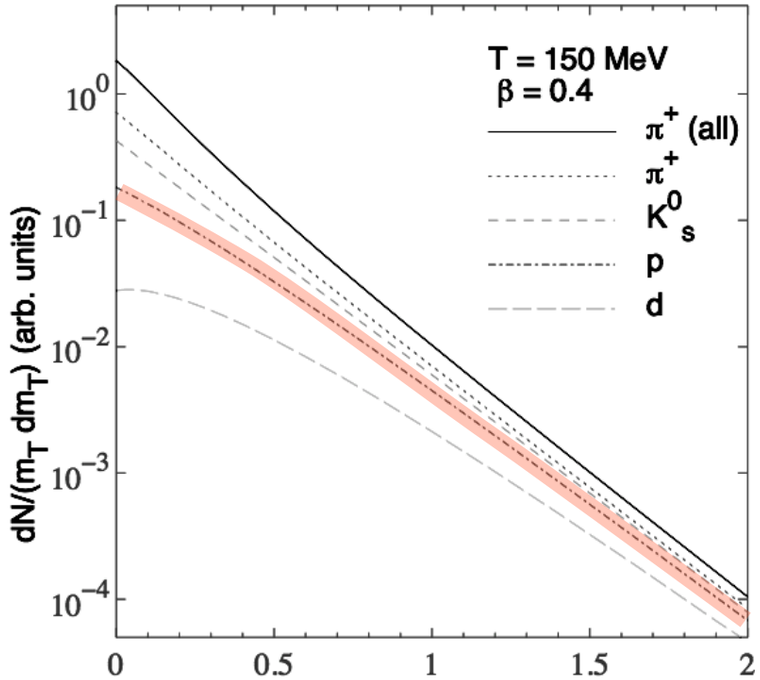
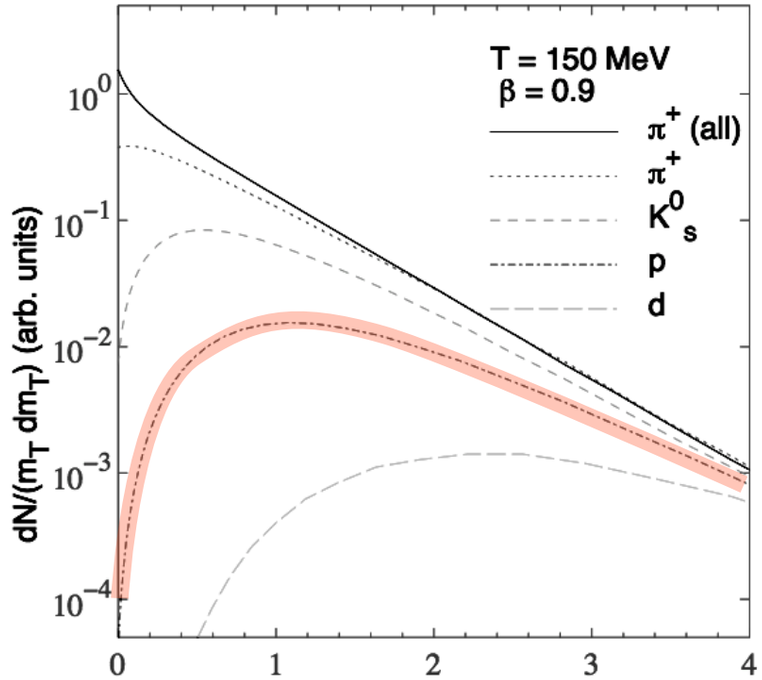
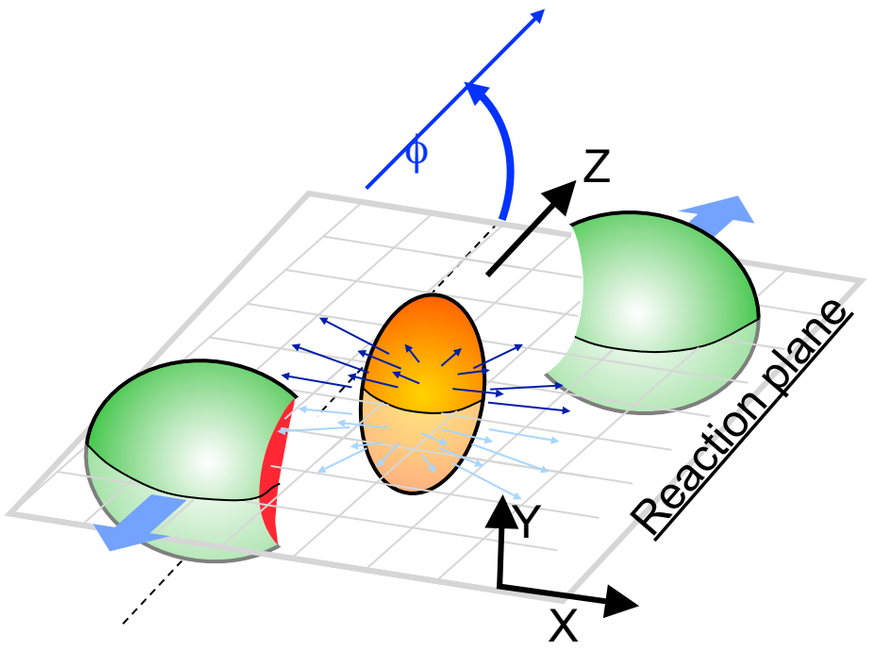




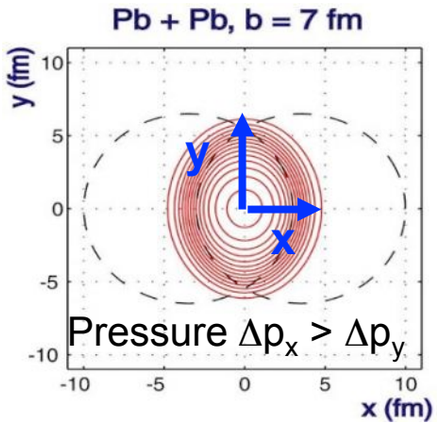


Anisotropic (elliptic) flow

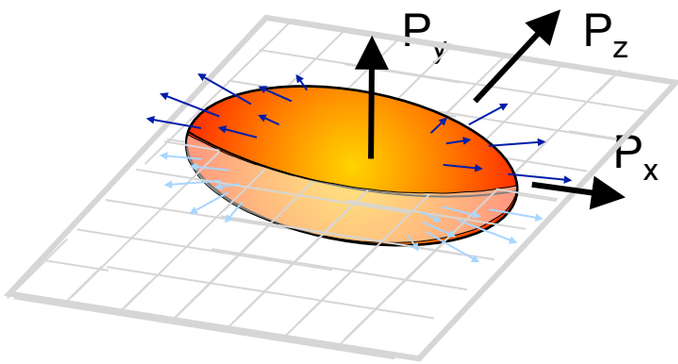
Spatial deformation



Azimuthal (φ) pressure gradients



Anisotropic particle density



$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + \ldots$$

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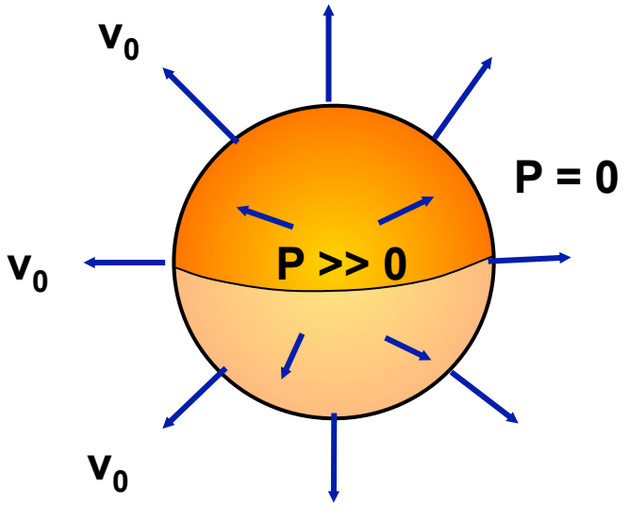

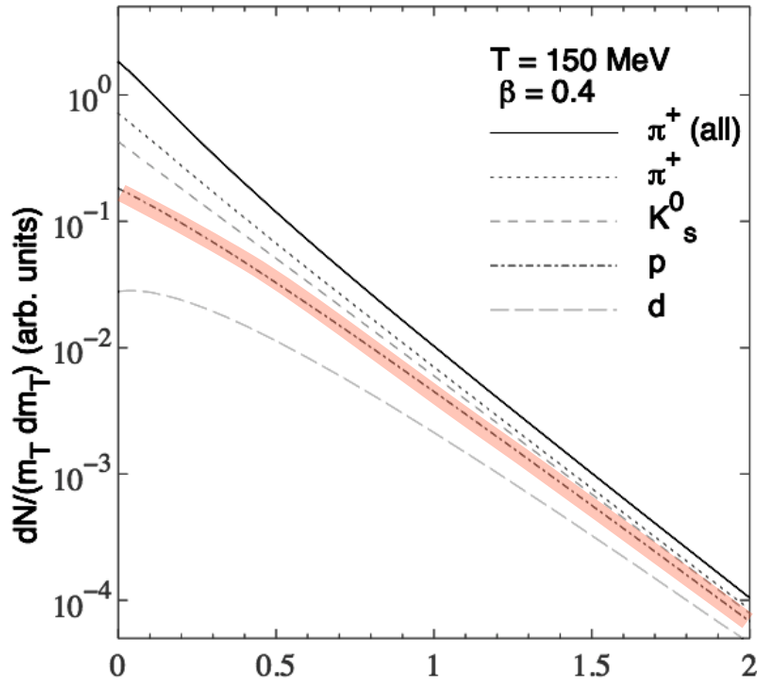

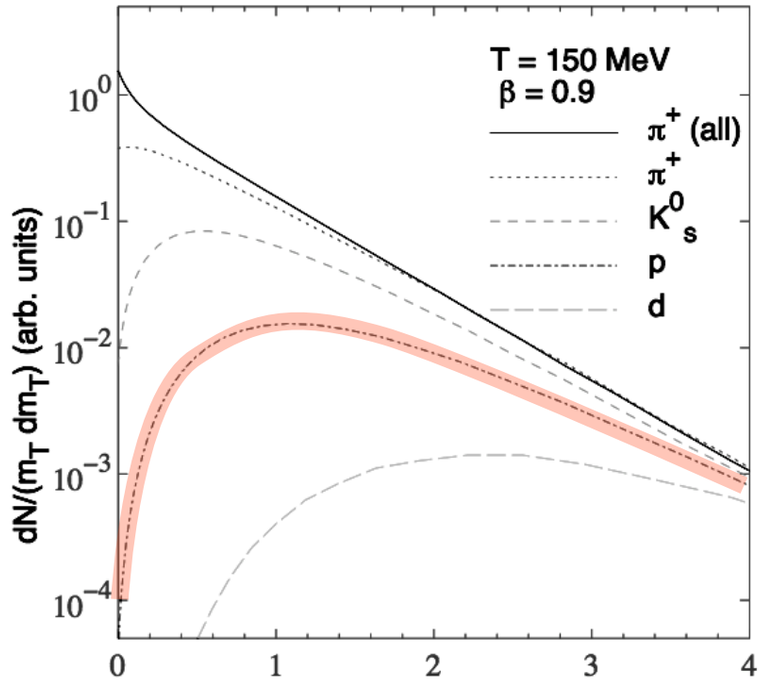

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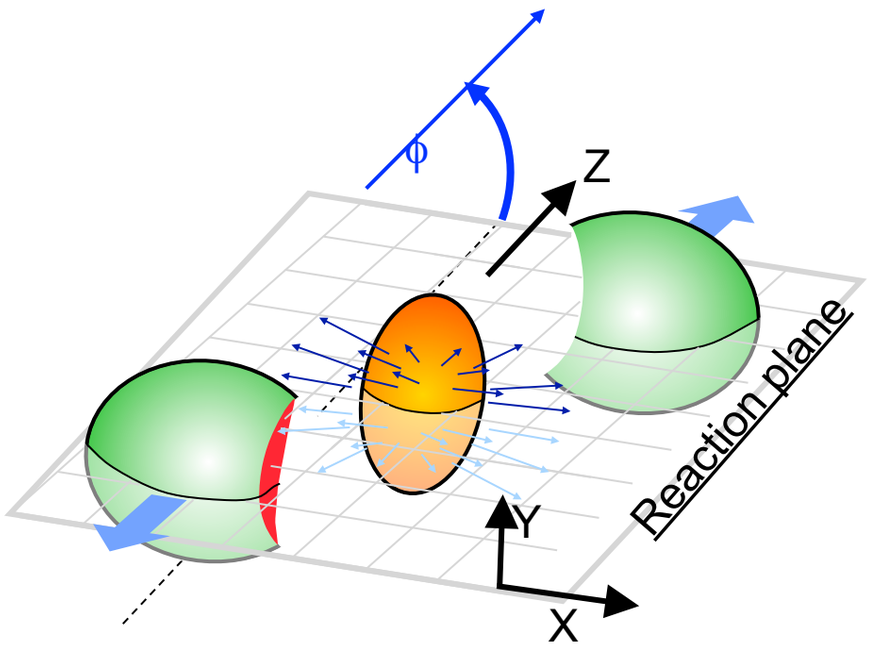

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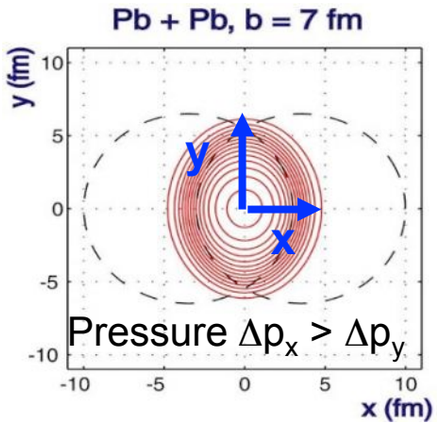

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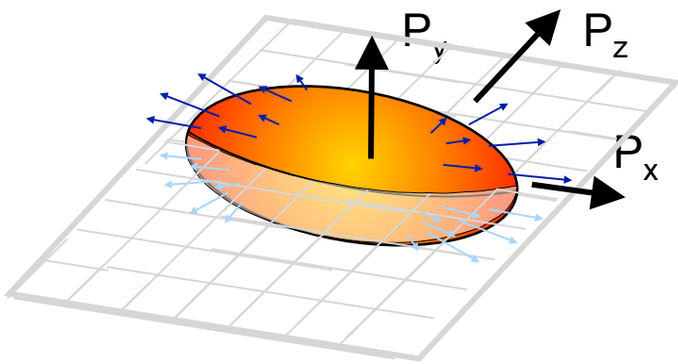

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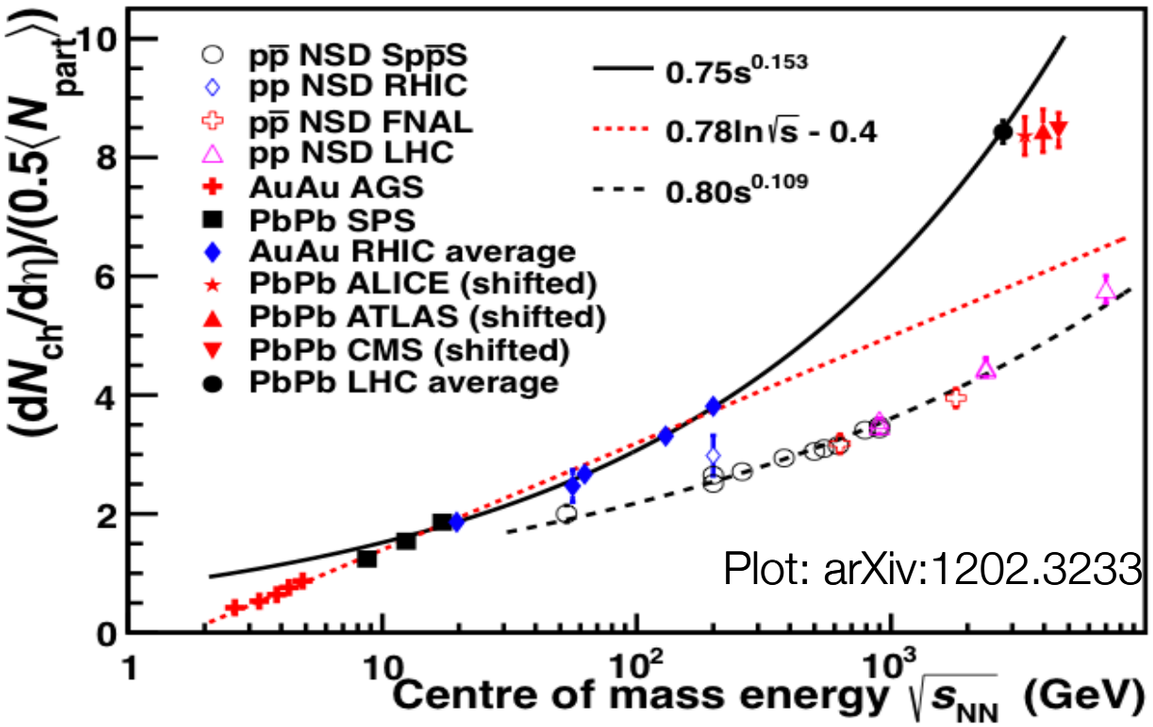
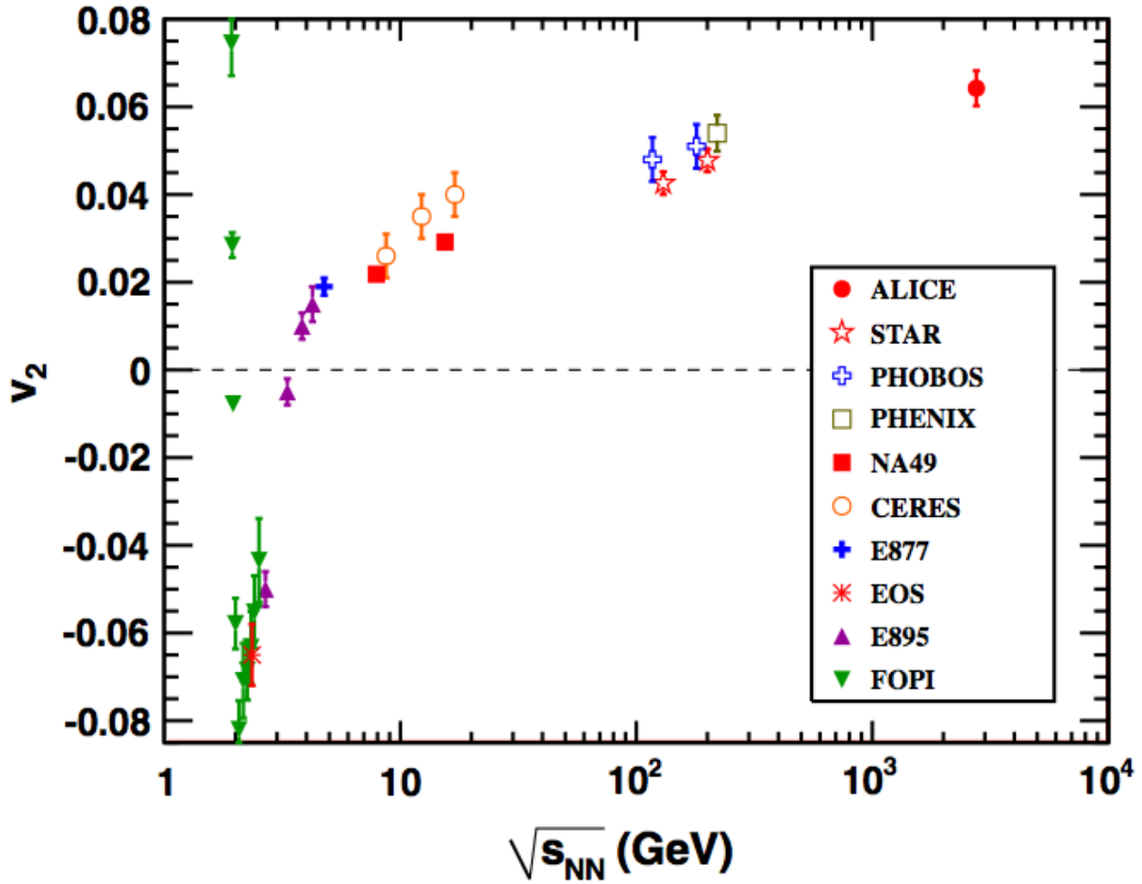
New energy regime: early evidence





- Early LHC results: qualitative features
  ~ lower √s, quantitative difference?
  - Fireball parameters?
  - Energy Loss?
  - Hadronization Mechanism?

ALICE, PRL 105, 252302
ALICE, PRL 105, 252301 ATLAS, PRL 105, 252303
ALICE, PRL 106, 032301 ALICE, PLB 693, 53

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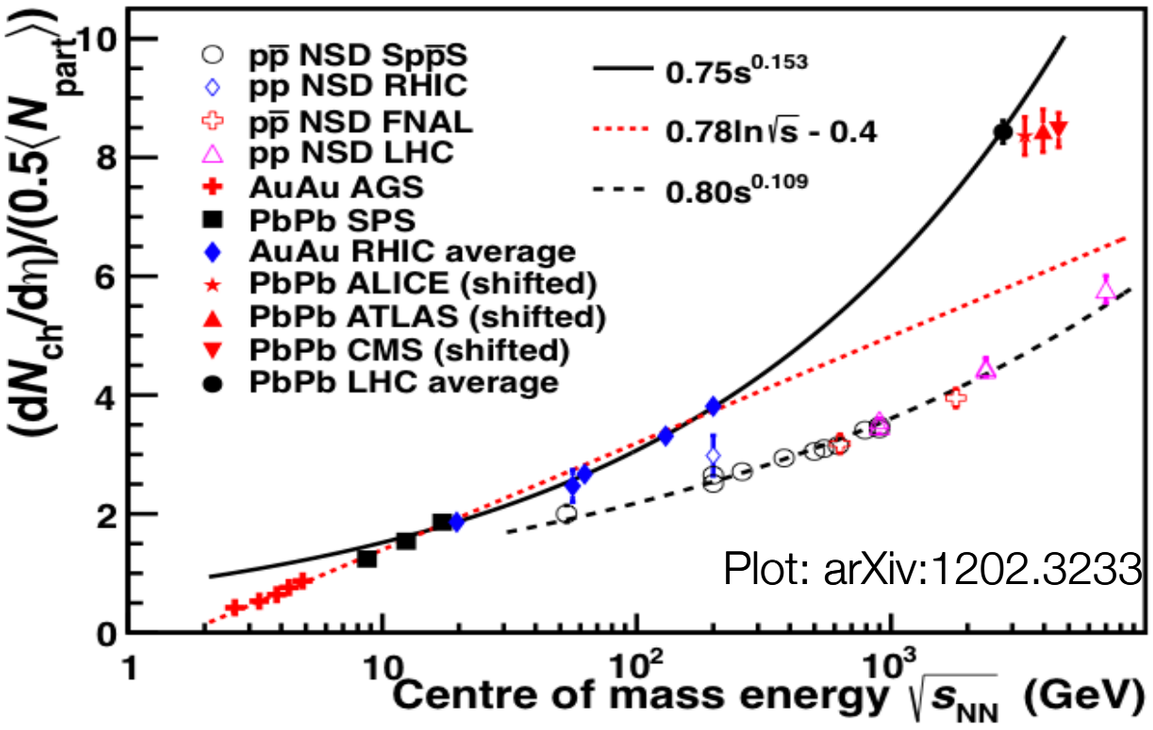

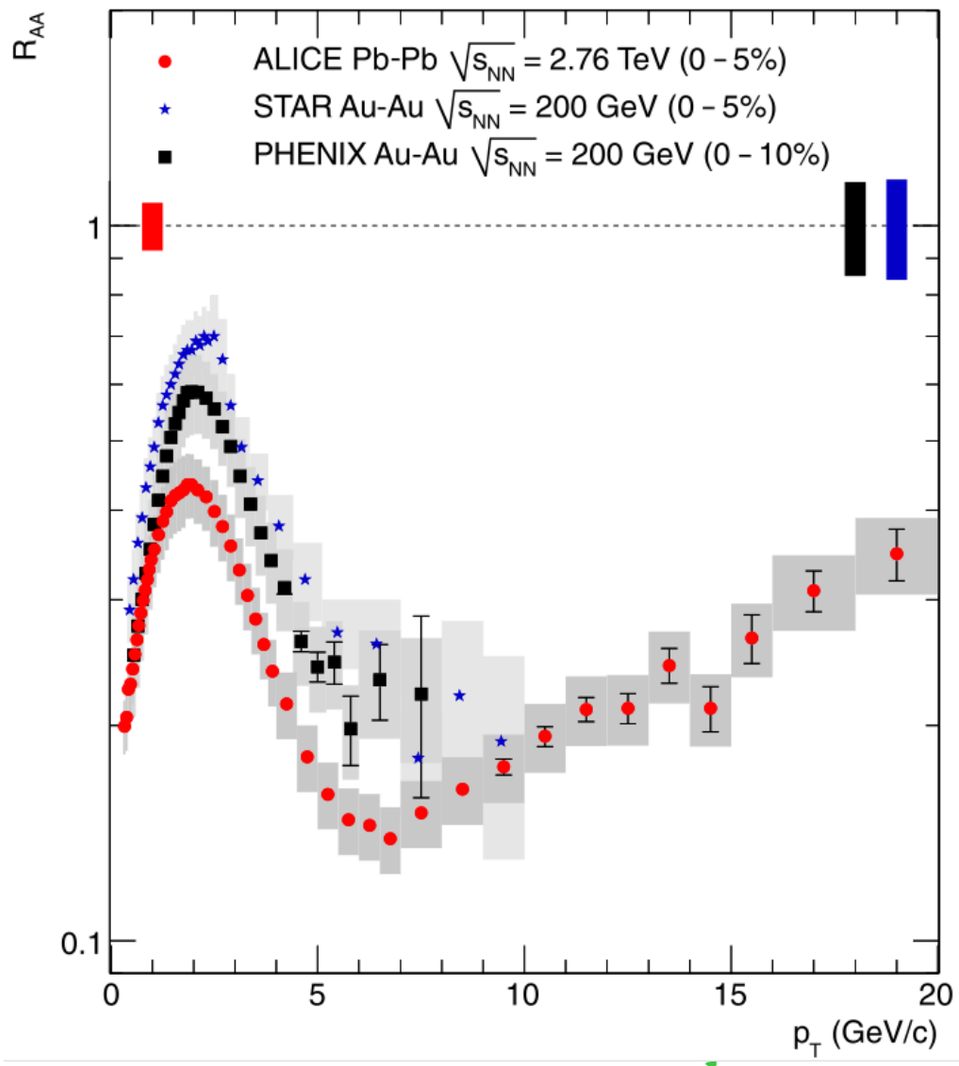

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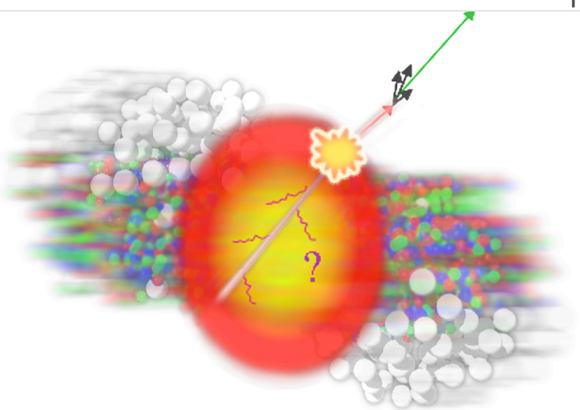

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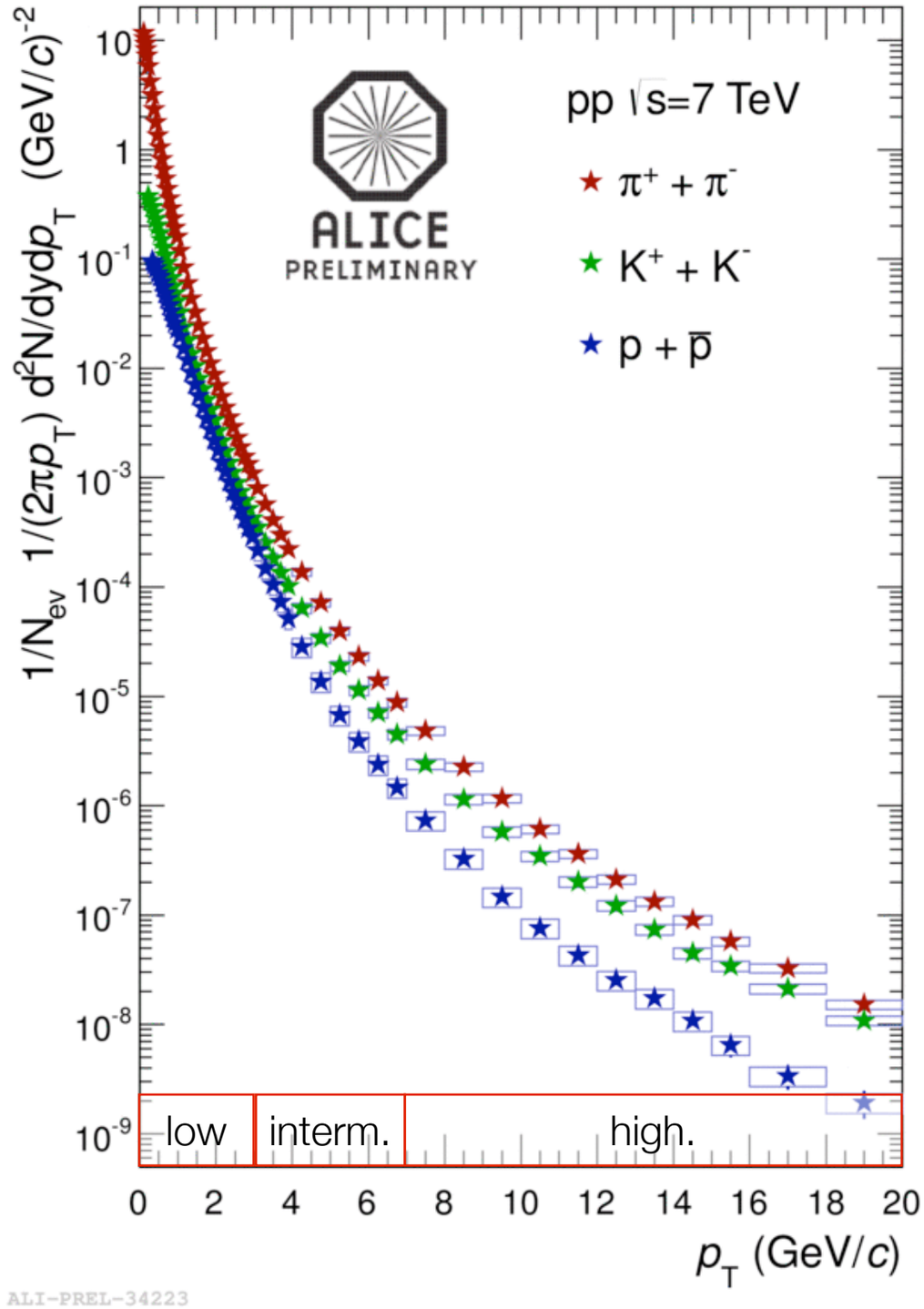
ALICE, PRL 105, 252301 ATLAS, PRL 105, 252303
ALICE, PRL 106, 032301 ALICE, PLB 693, 53

$$R_{AA} = \frac{AA}{\text{rescaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$

Transverse momentum regimes



Low: $p_T < 3$ GeV/c

Bulk properties and flow

Intermediate: $3 < p_T < 7$ GeV/c

Anomalous baryon enhancement and coalescence

High: $p_T > 7$ GeV/c

"Jet Quenching": Search for medium modification of fragmentation functions

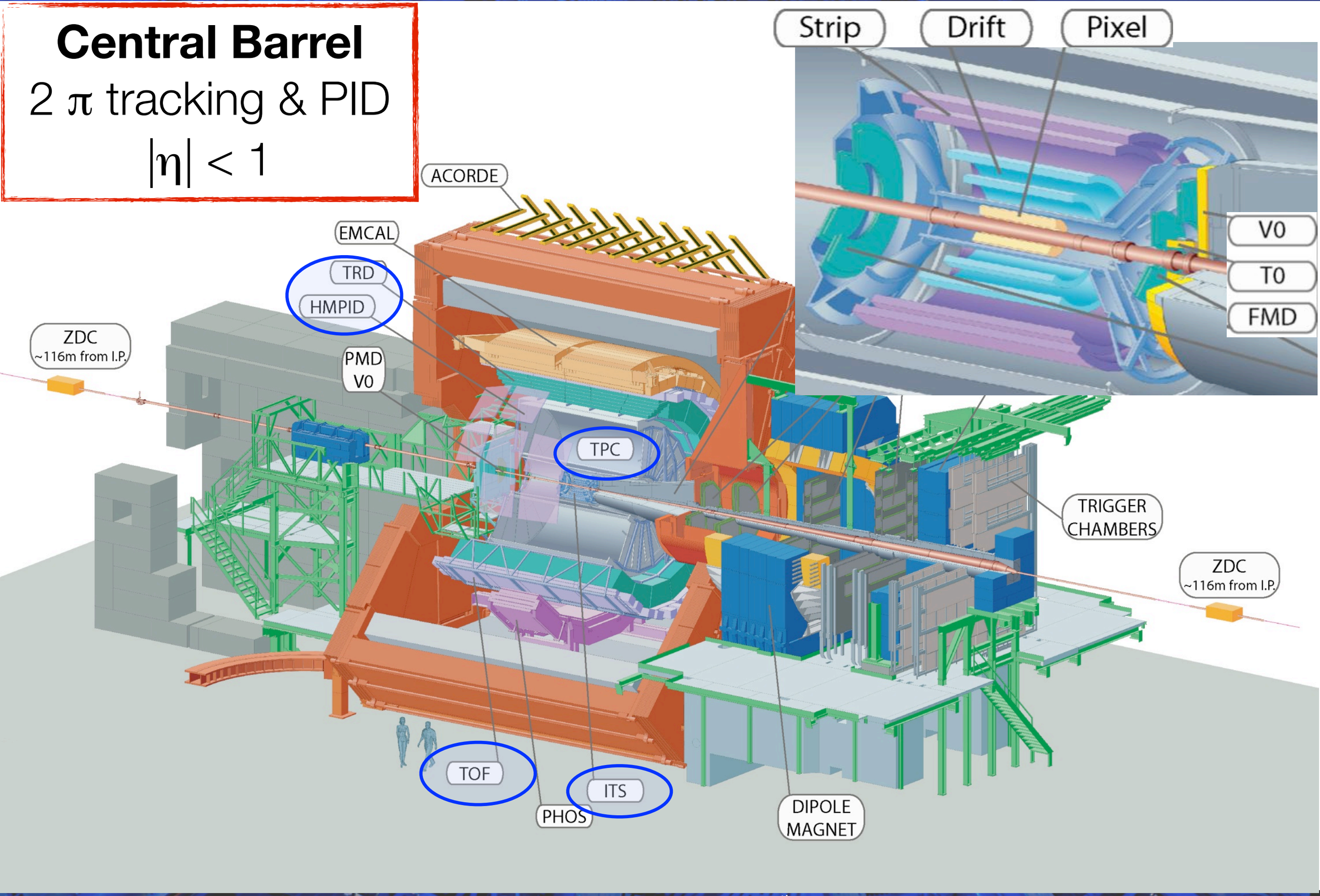
Precision tracking and PID over a broad momentum range from 100 MeV/c to 20 GeV/c

The ALICE detector

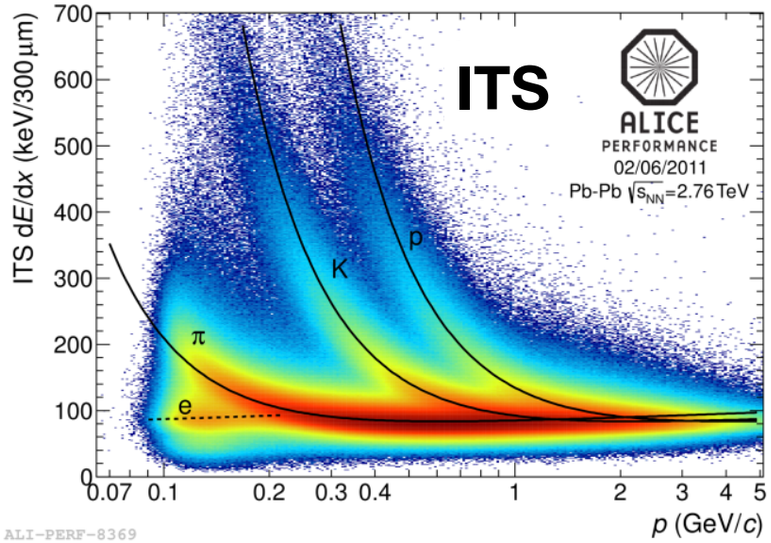
Central Barrel

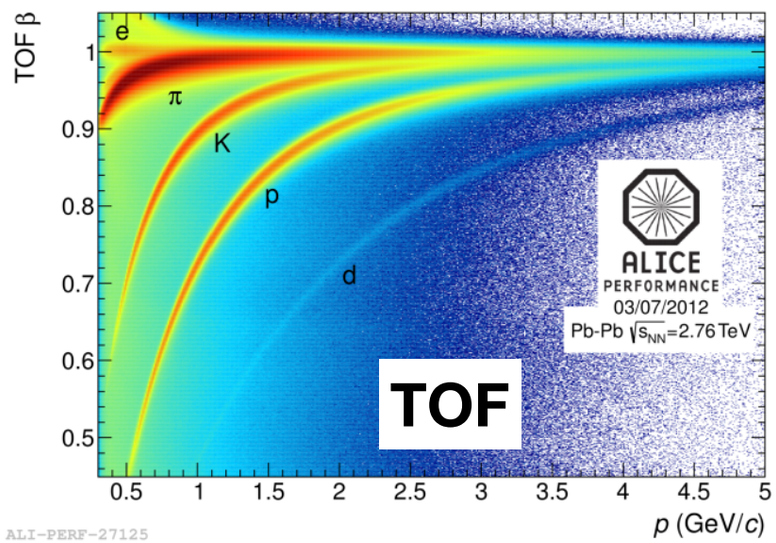
2 π tracking & PID

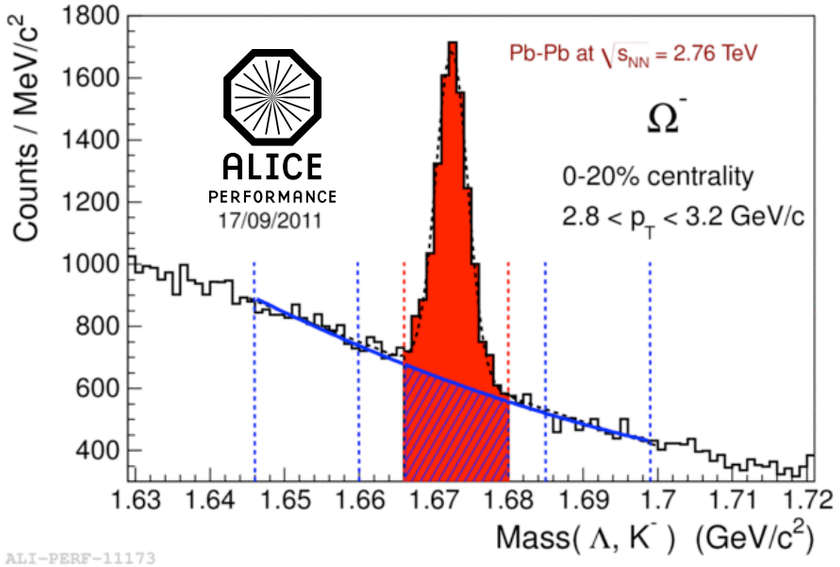
$|\eta| < 1$

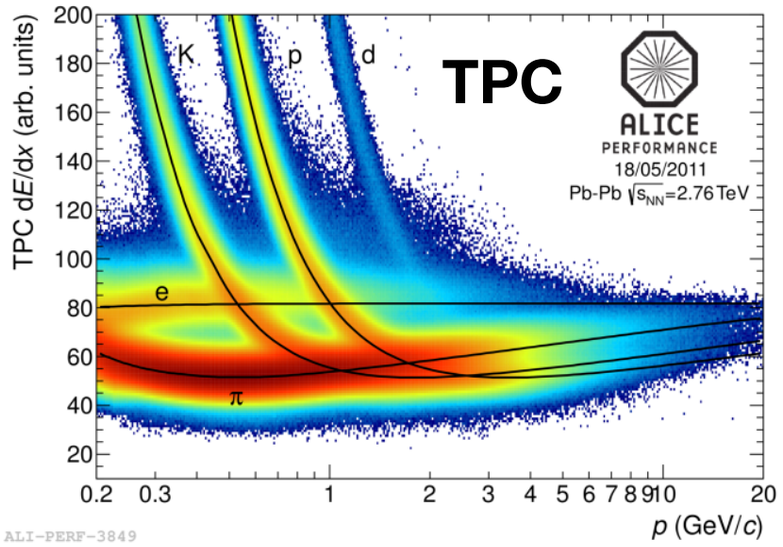


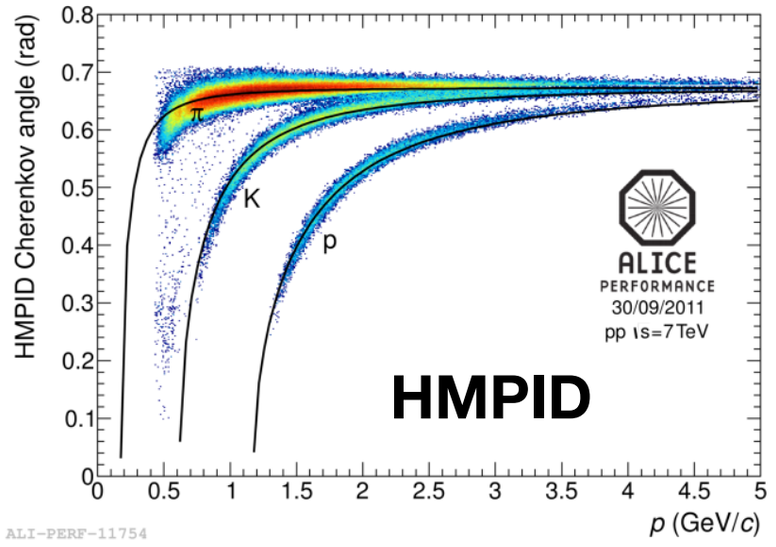
Tracking and Particle Identification

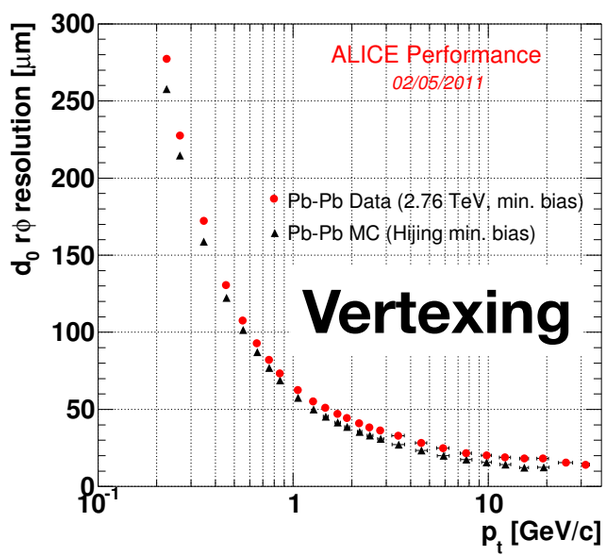












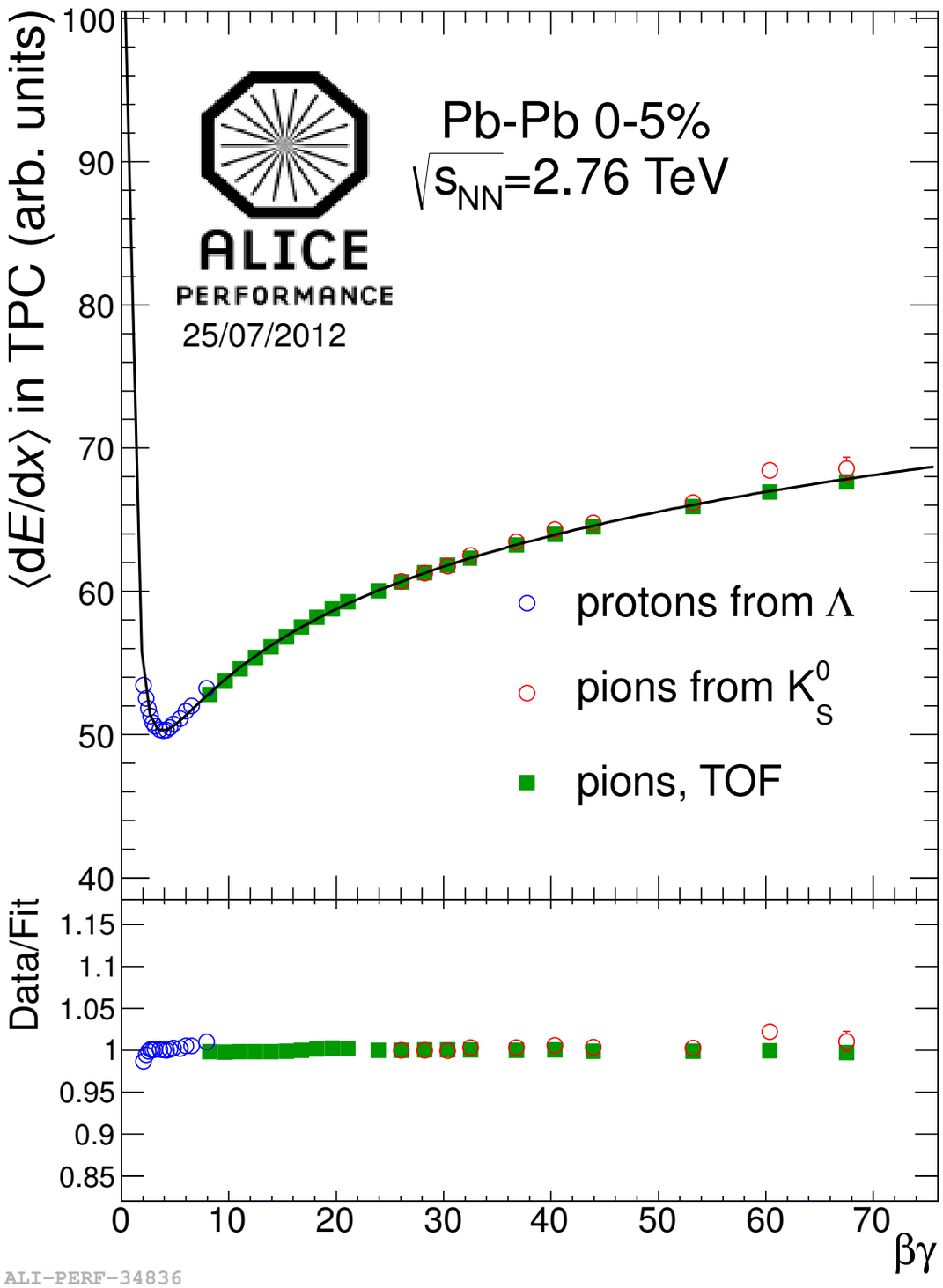
Particle identification (many different techniques)

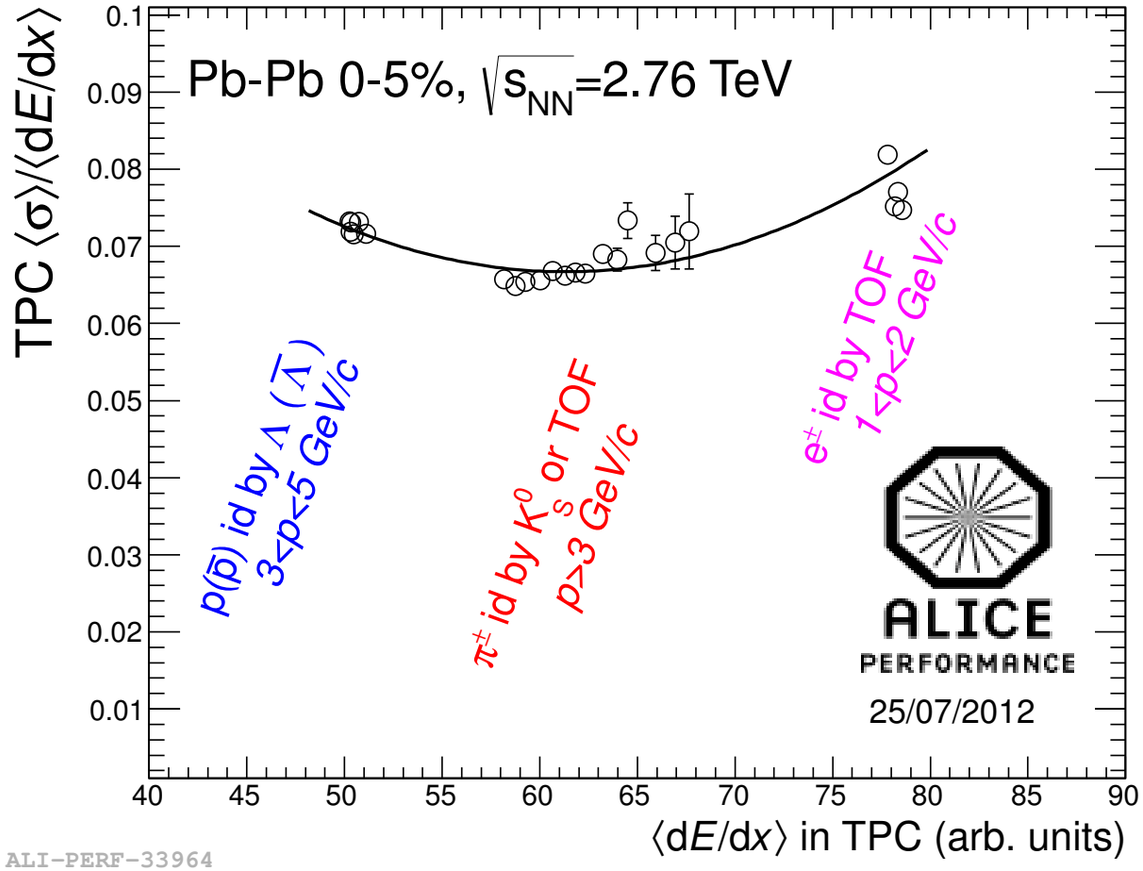
Extremely low-mass tracker ~ 10% of X_0

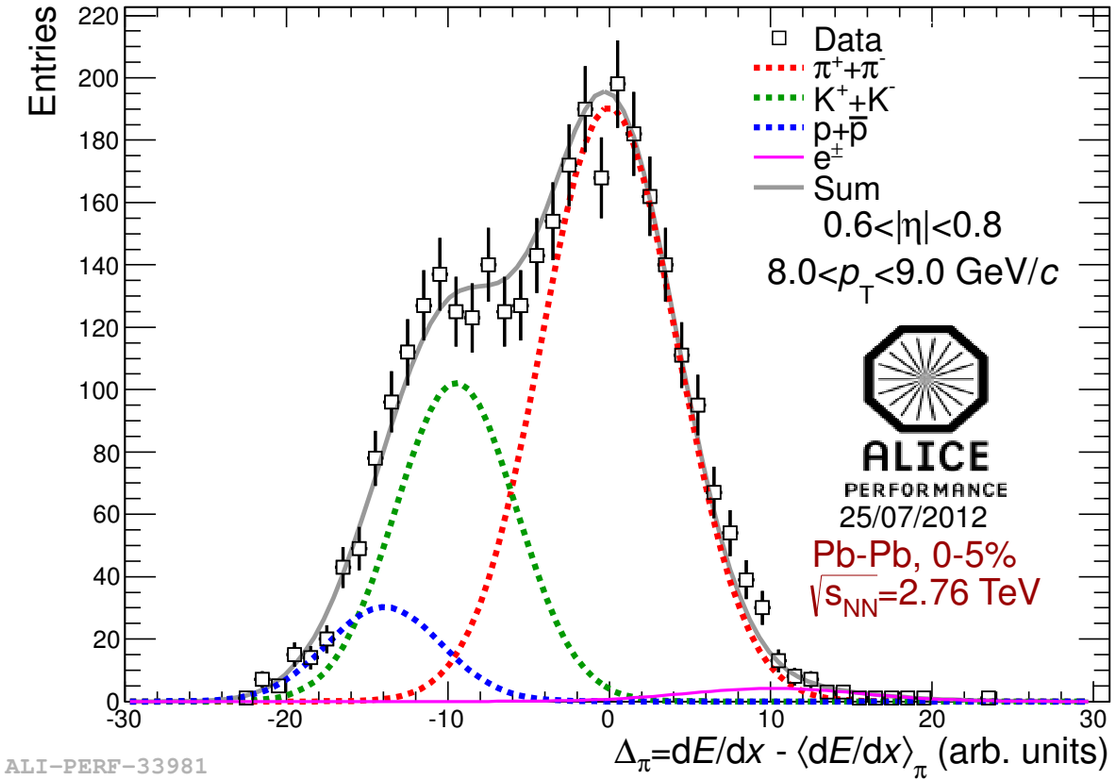
Excellent vertexing capability

Efficient low-momentum tracking – down to ~ 100 MeV/c

Analysis in the relativistic rise





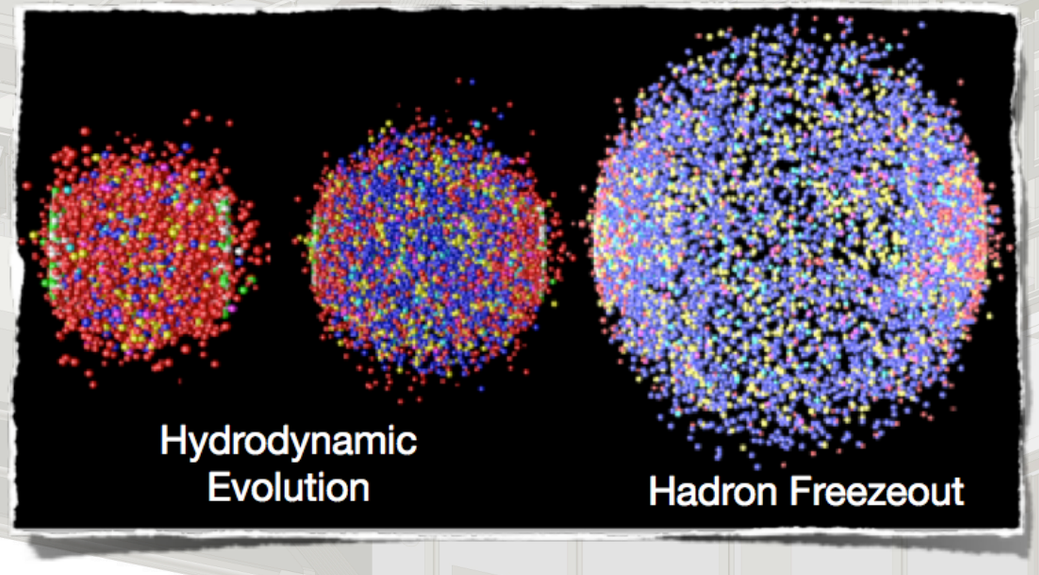


ALICE's particle zoo

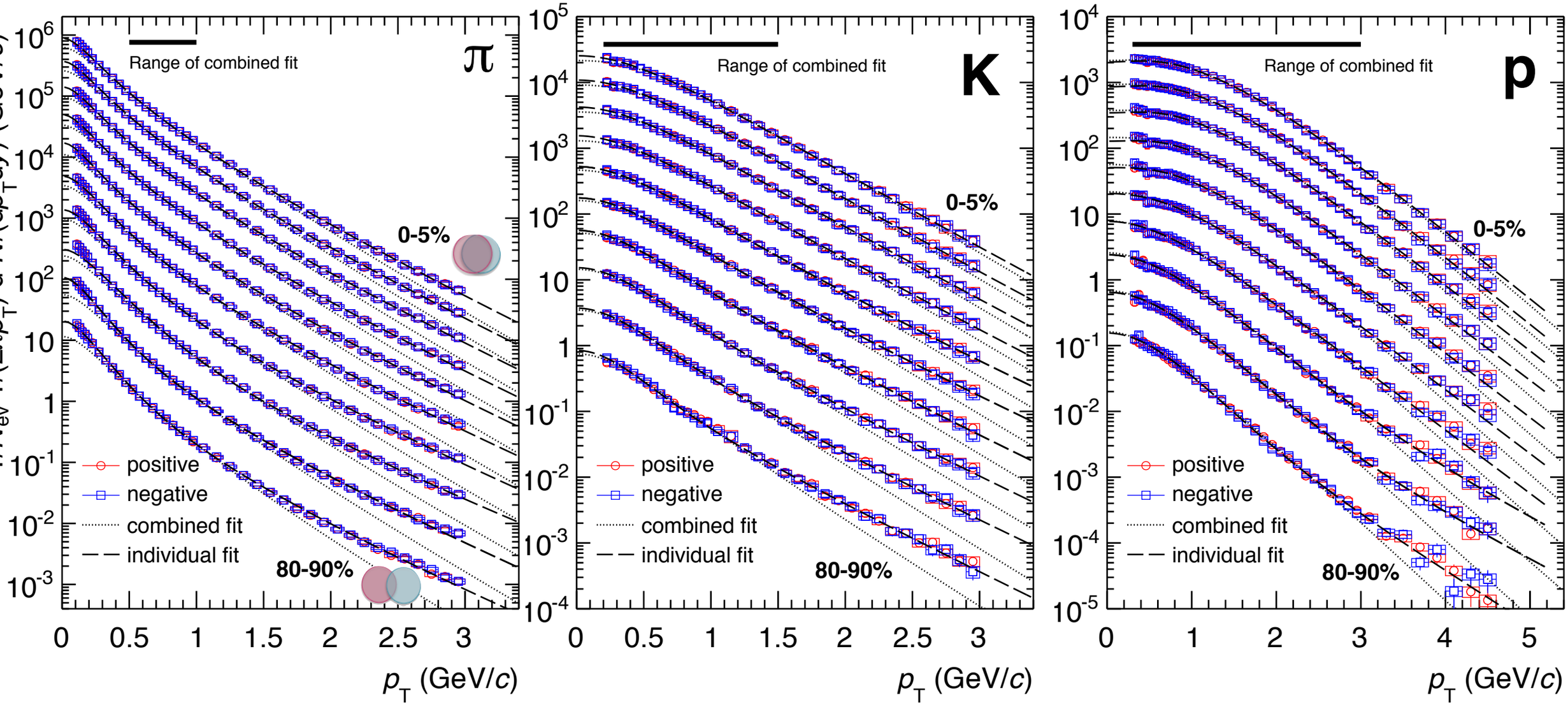
Results presented today:

- Bulk particles: π, K, p (p_T < 20 GeV/c)
- Low, intermediate and high p_T separately
- (Multi)strange: K^0_S ,Λ, Ξ, Ω,(p_T < 9 GeV/c)
- Resonances: ϕ, K^* (p_T < 5 GeV/c)

Low p_T



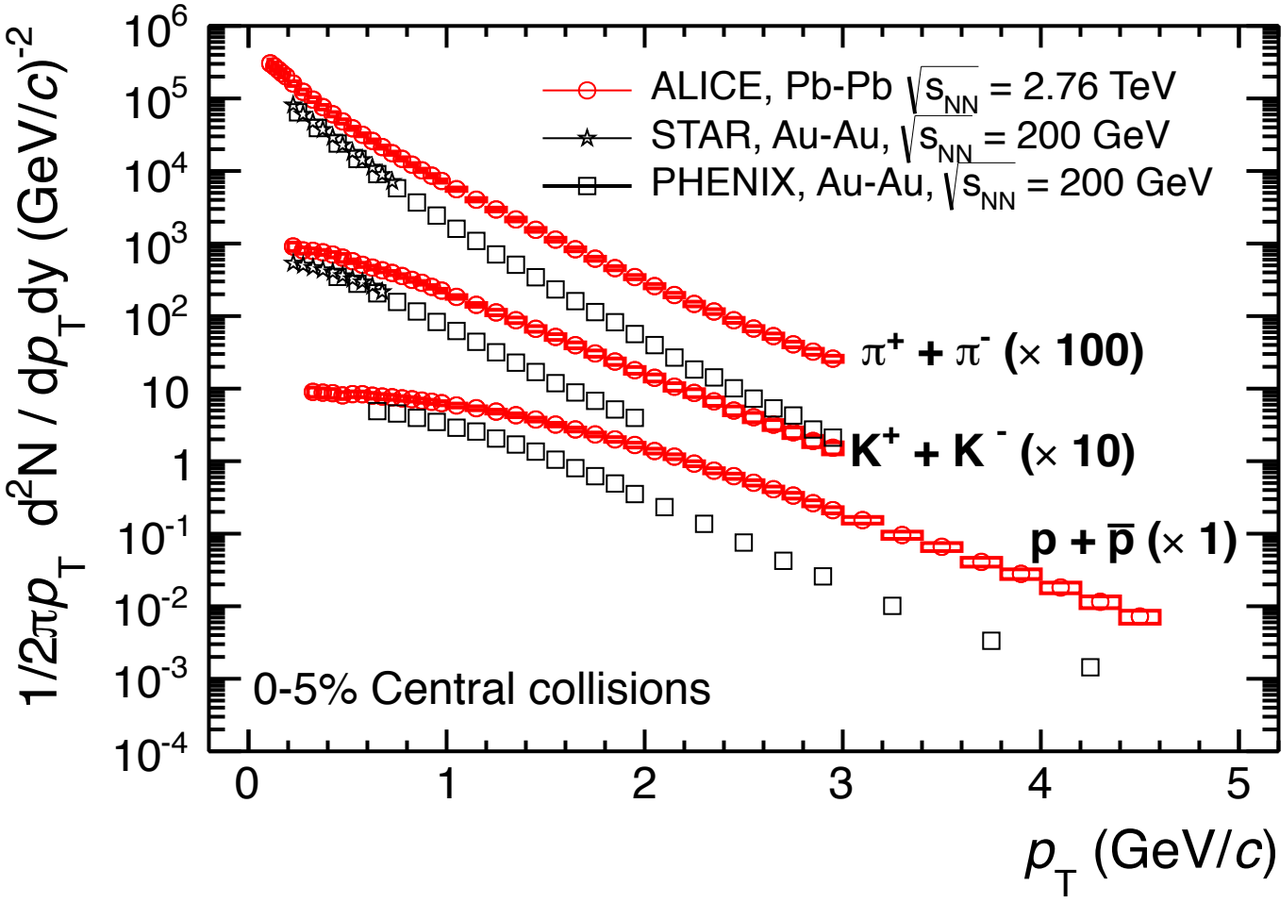
π, K, p spectra (low p_T)



- Identification based on ITS, TPC, TOF
- Clear evolution of spectra with centrality.
- Central collisions: flat at low p_T, nearly exponential at high p_T

ALICE, arXiv:1303.0737

Kinetic freezeout: Blast wave fits



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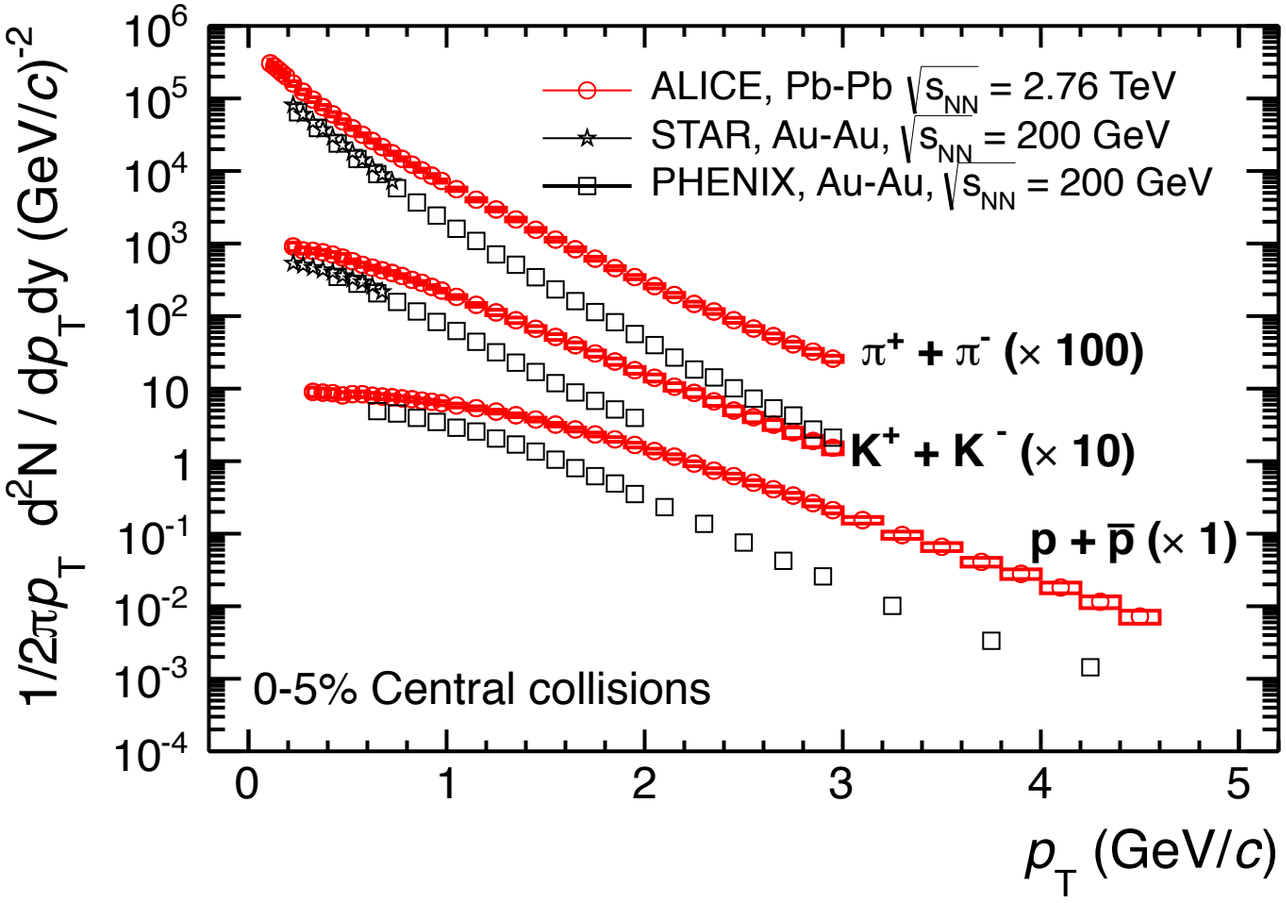
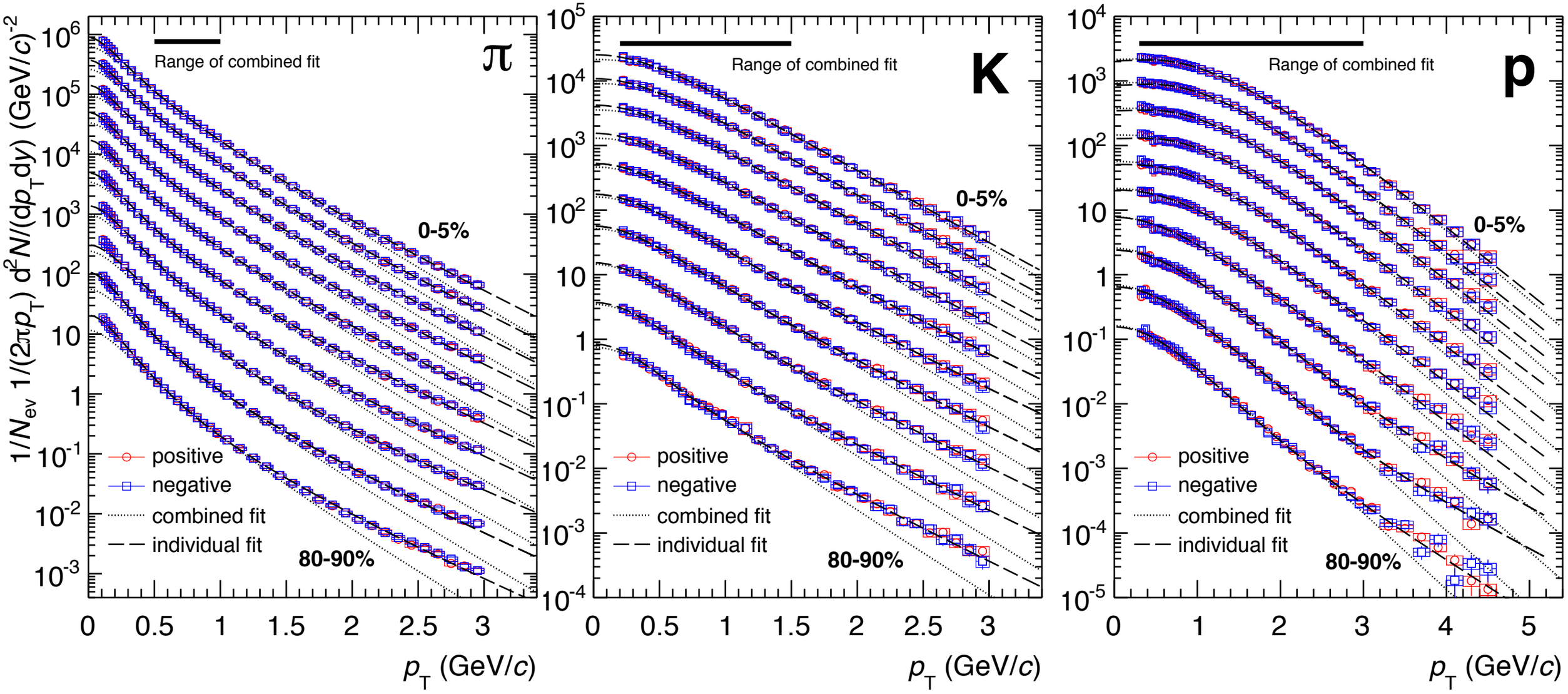


Blast wave model: thermalized volume elements, expanding in a common velocity field

Parameters: T_{kin}, $\beta_T = \beta_S \cdot (r/R)^n$

Kinetic freezeout: Blast wave fits



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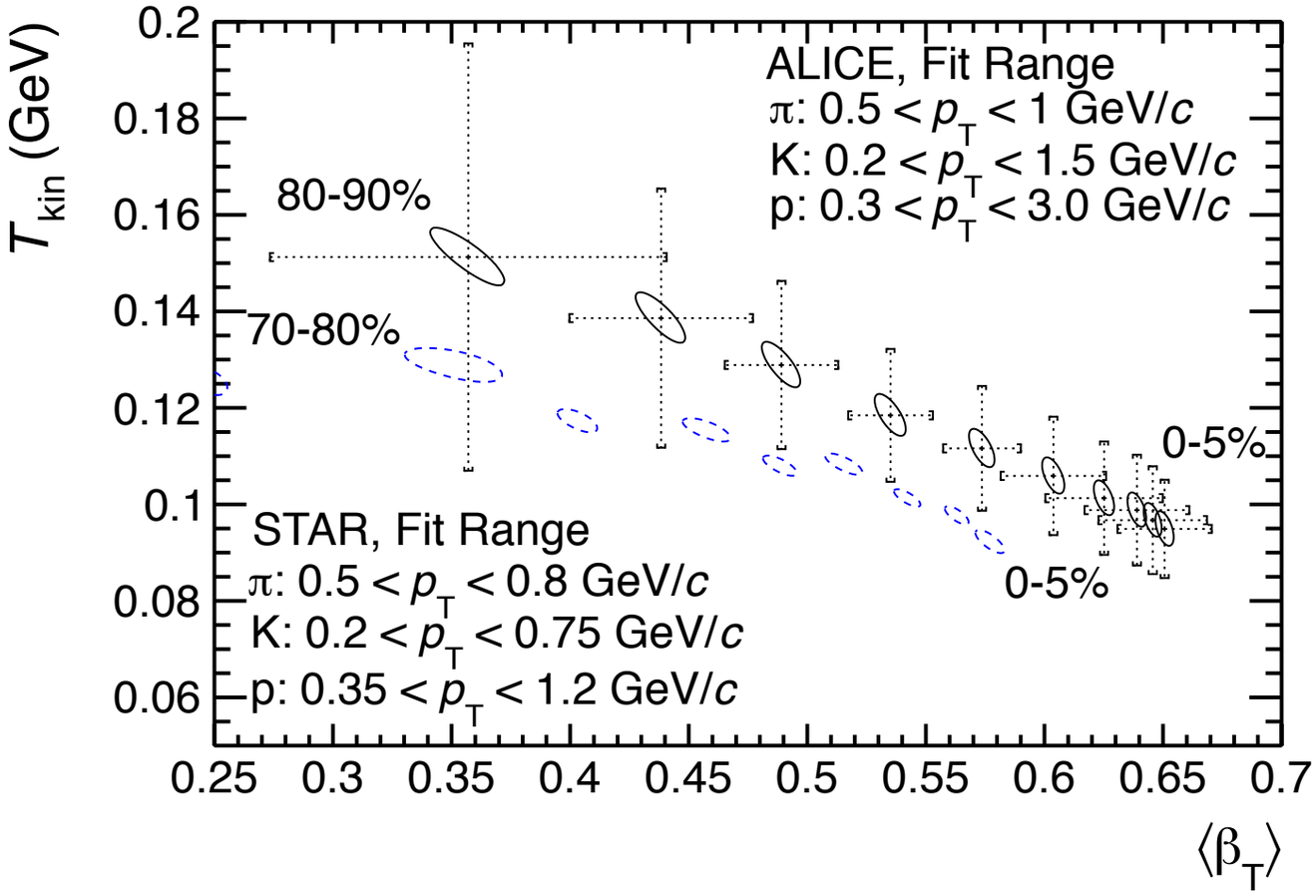

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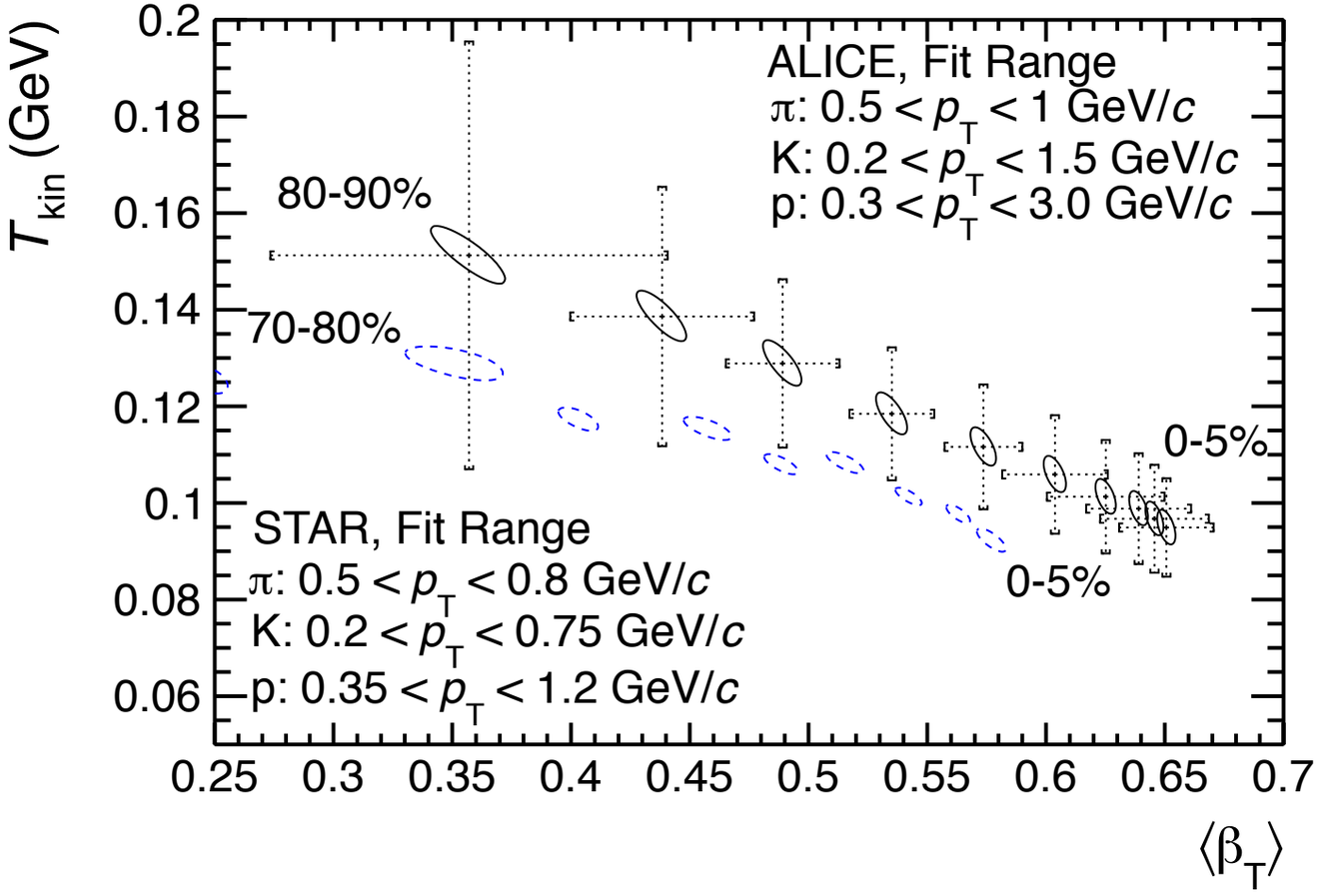

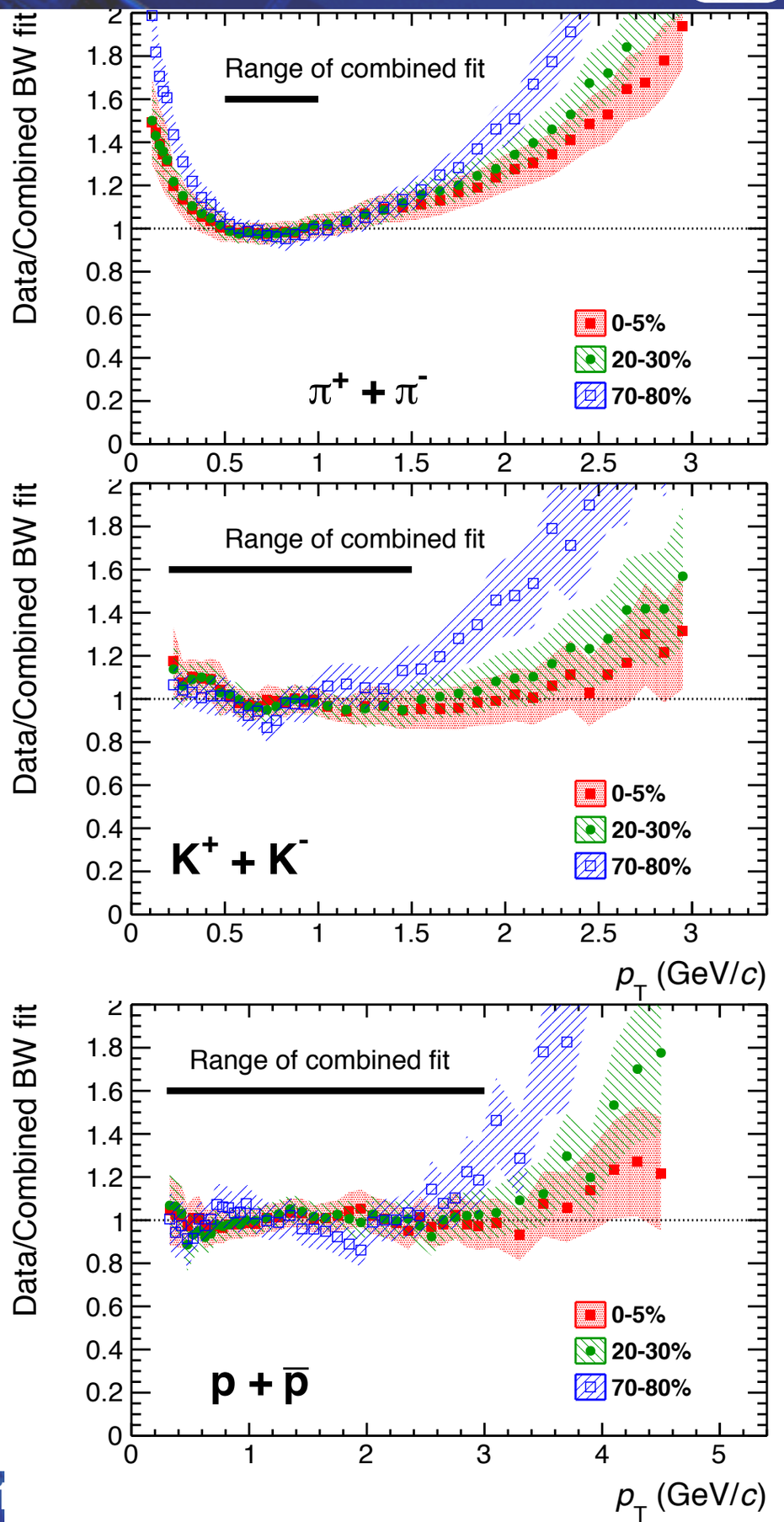

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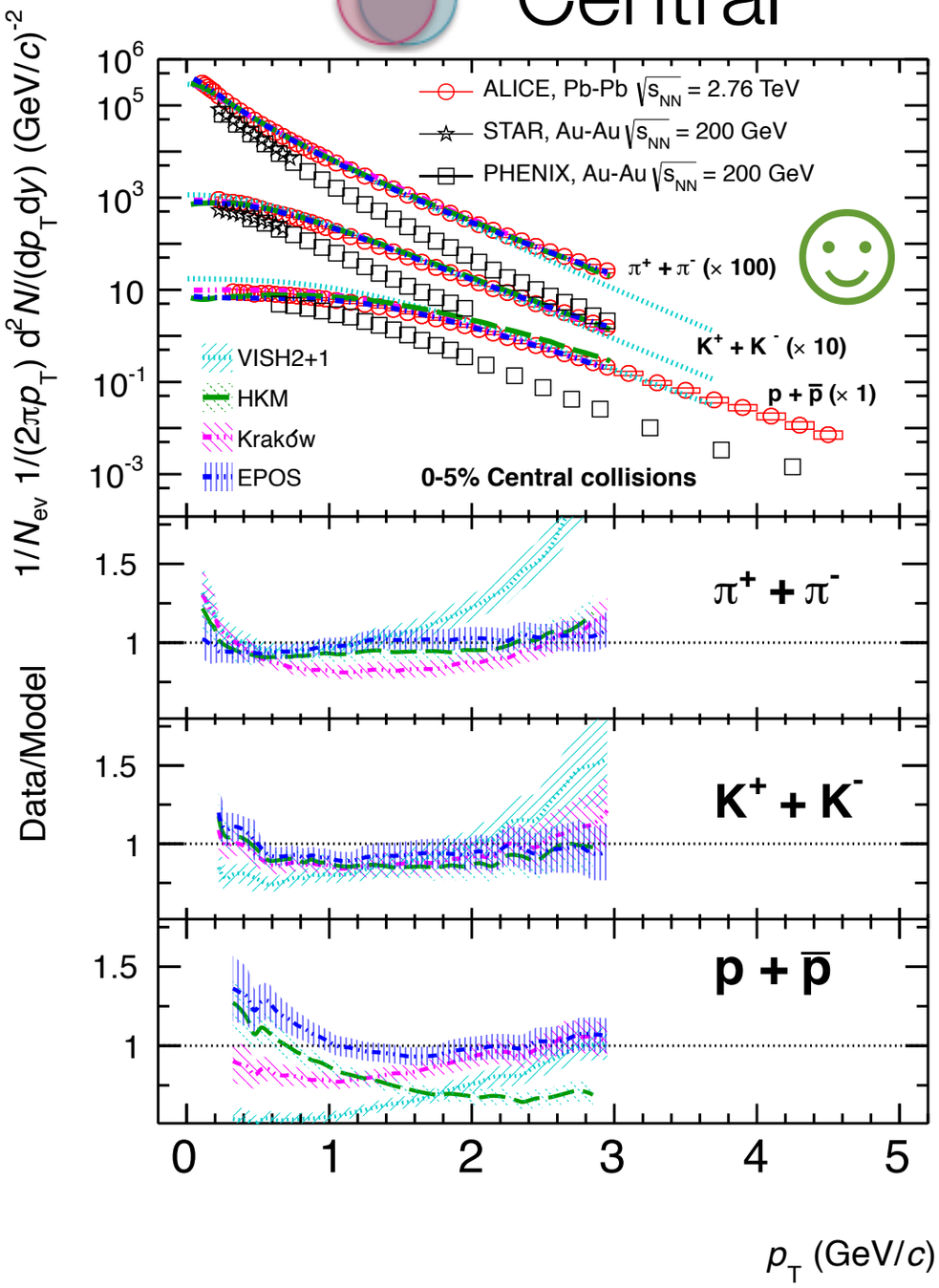
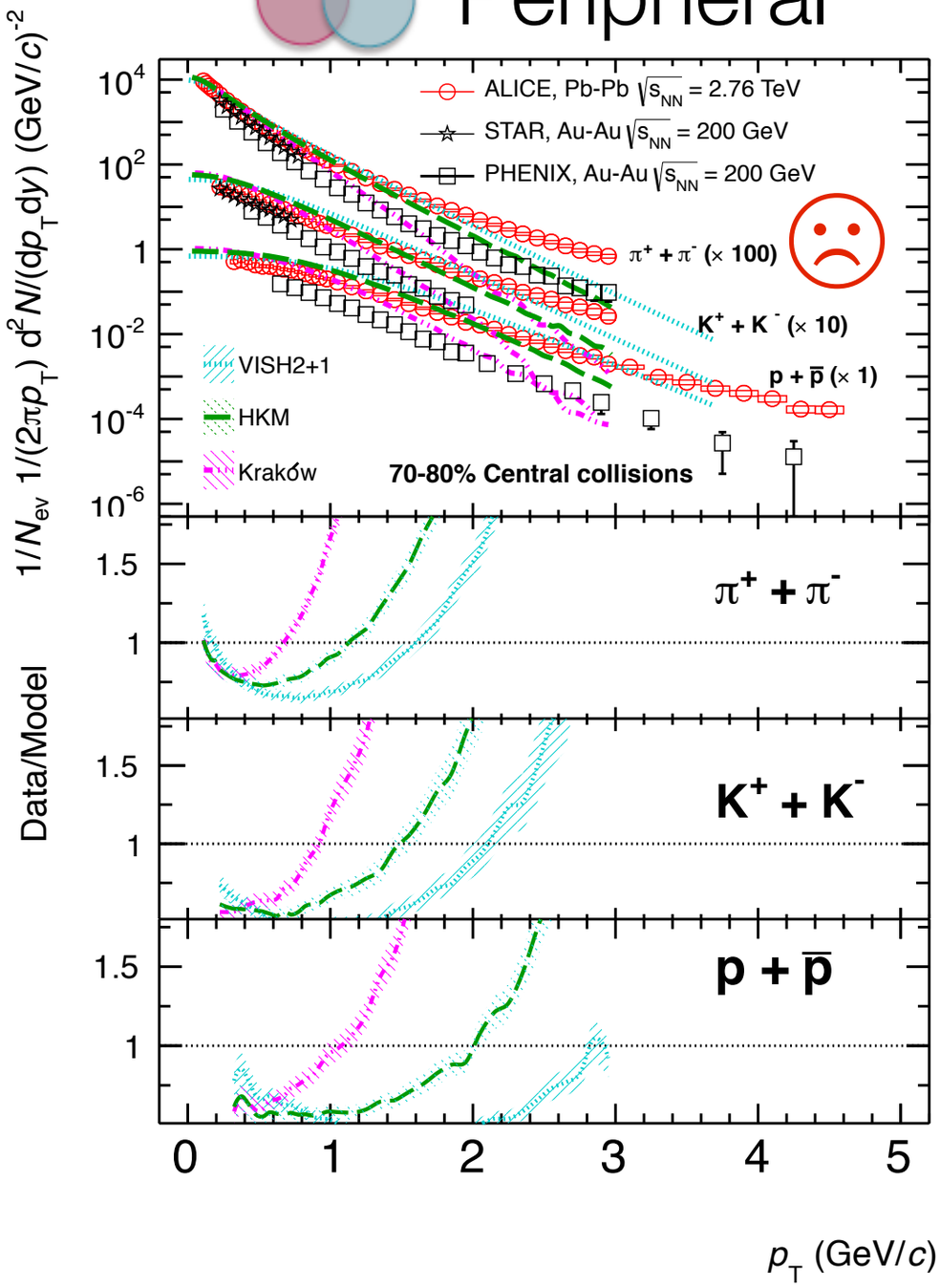
Comparison to hydro models

Central



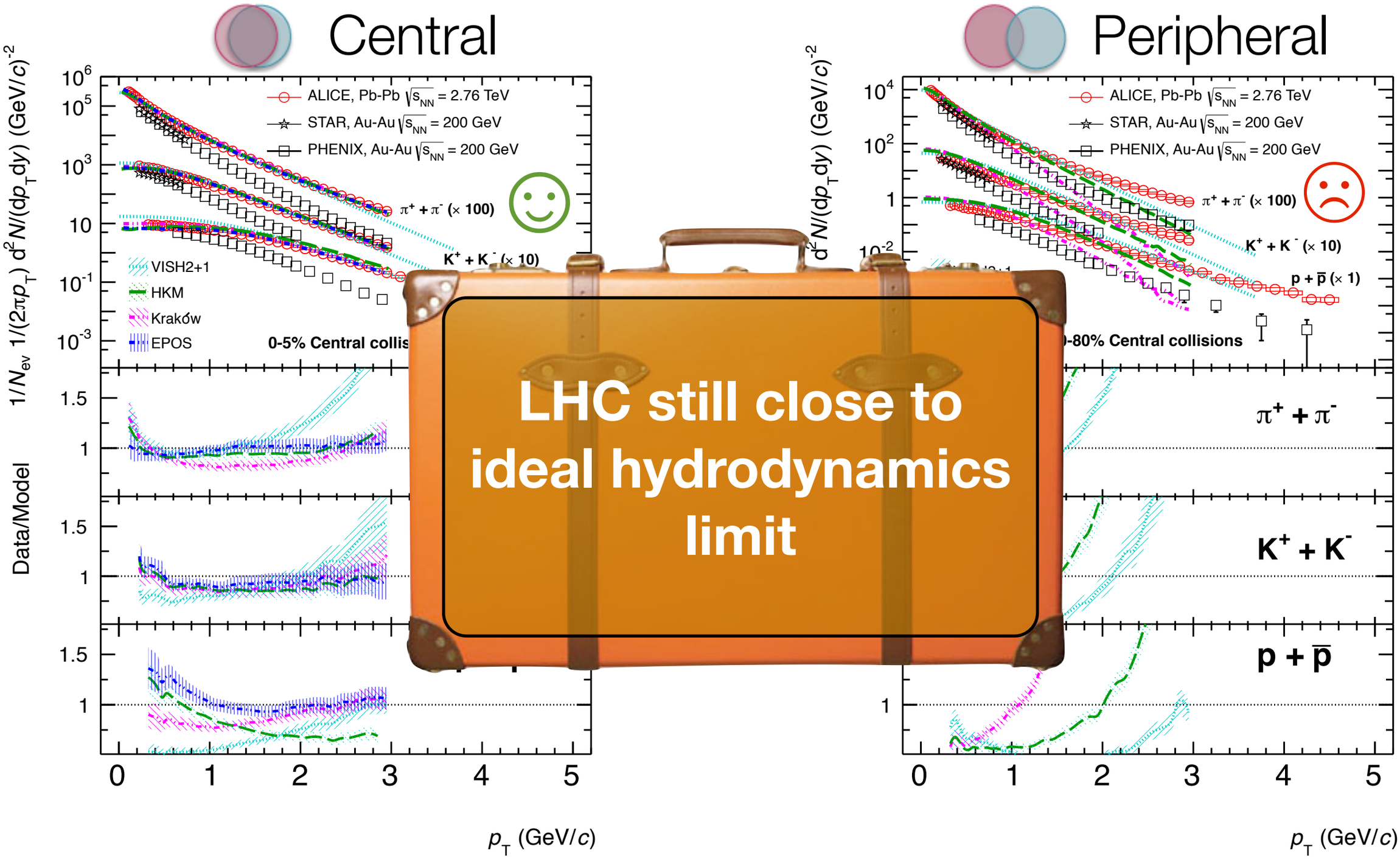
Peripheral



Description of the late stages of the fireball needed?

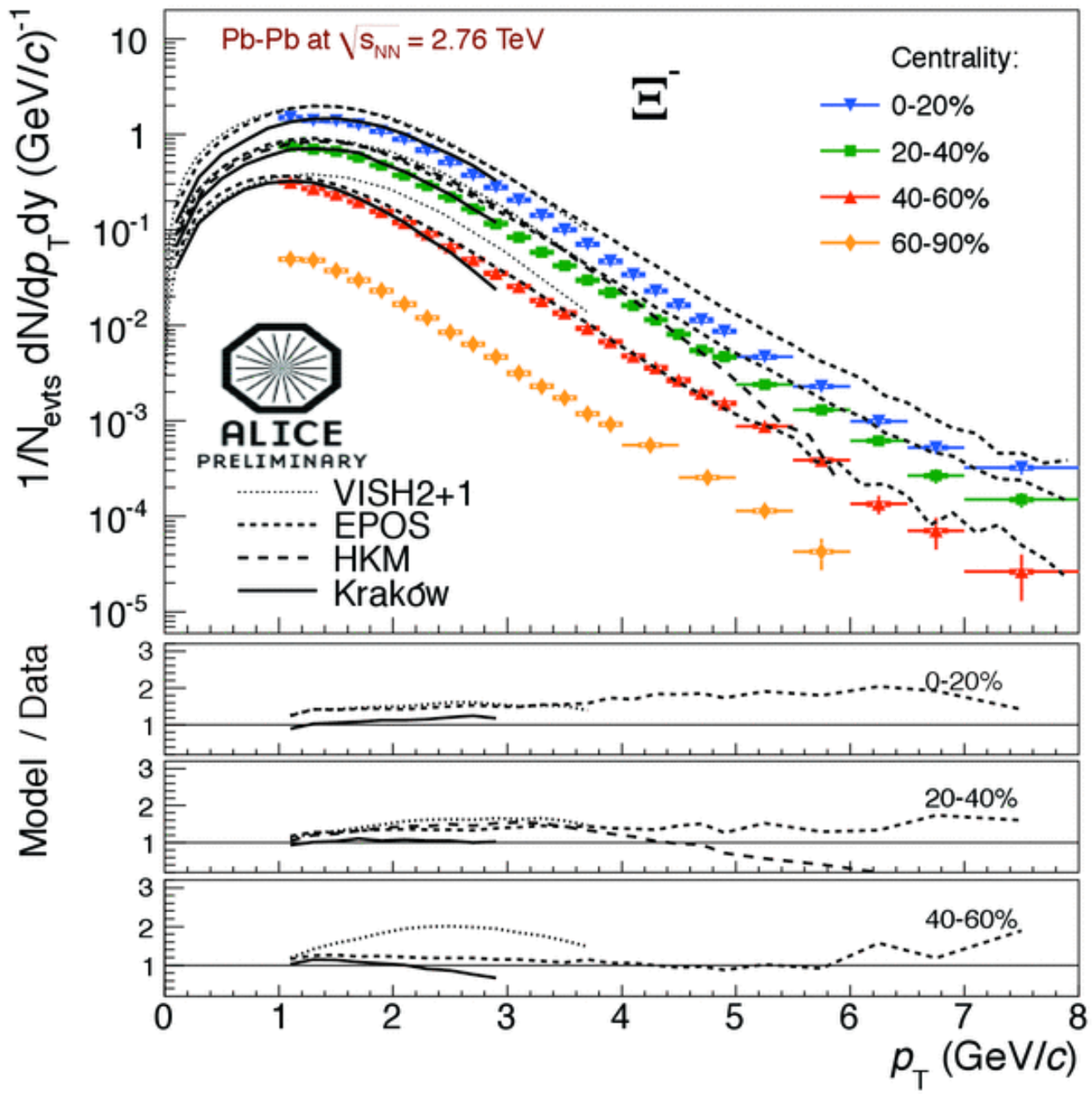
Not expected to work in peripheral collisions

Comparison to hydro models

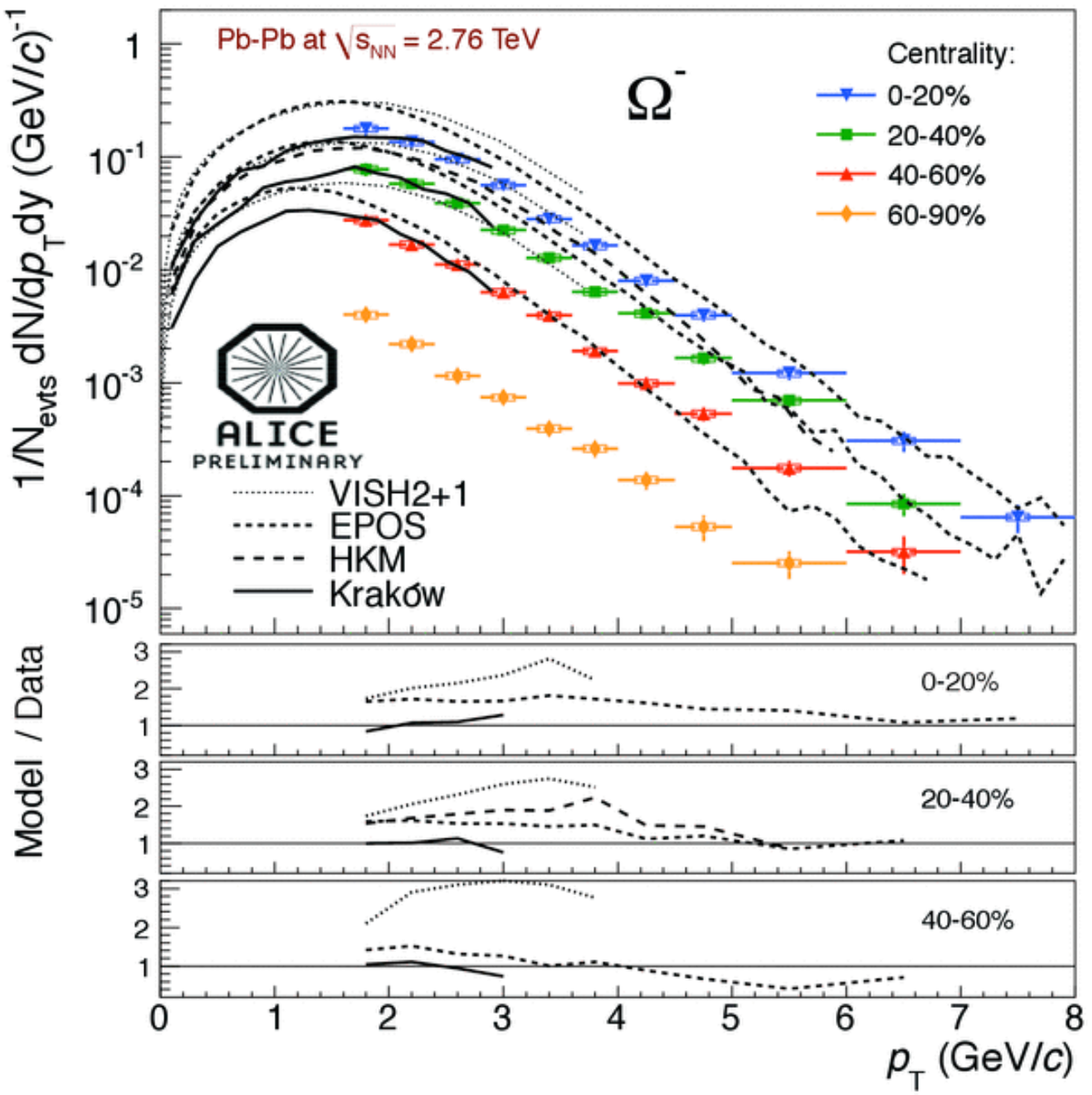


Description of the late stages of the fireball needed?
Not expected to work in peripheral collisions

Early kinetic freezeout of ϕ, Ξ, Ω?



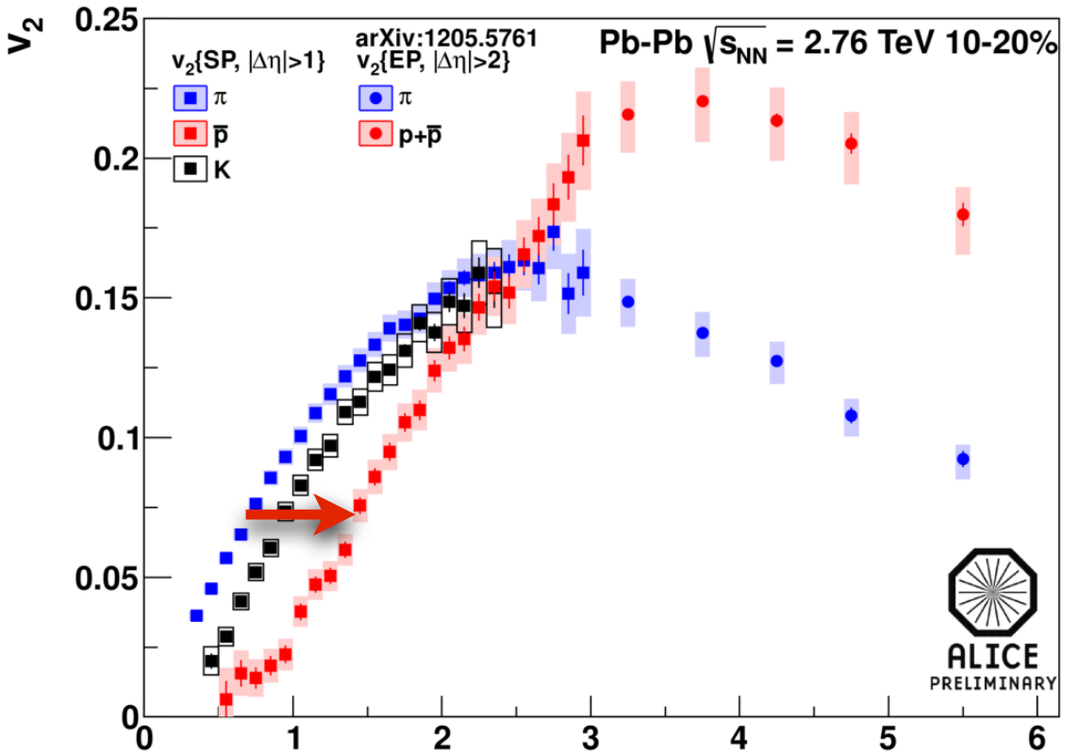
ALI-PREL-47058

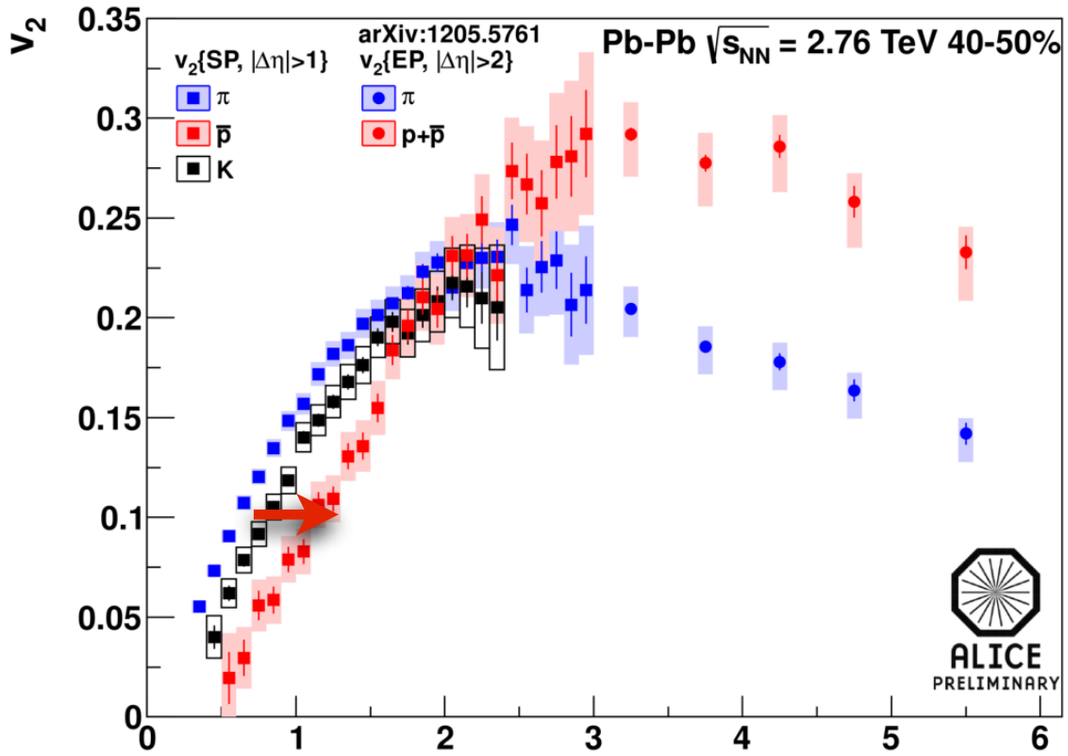


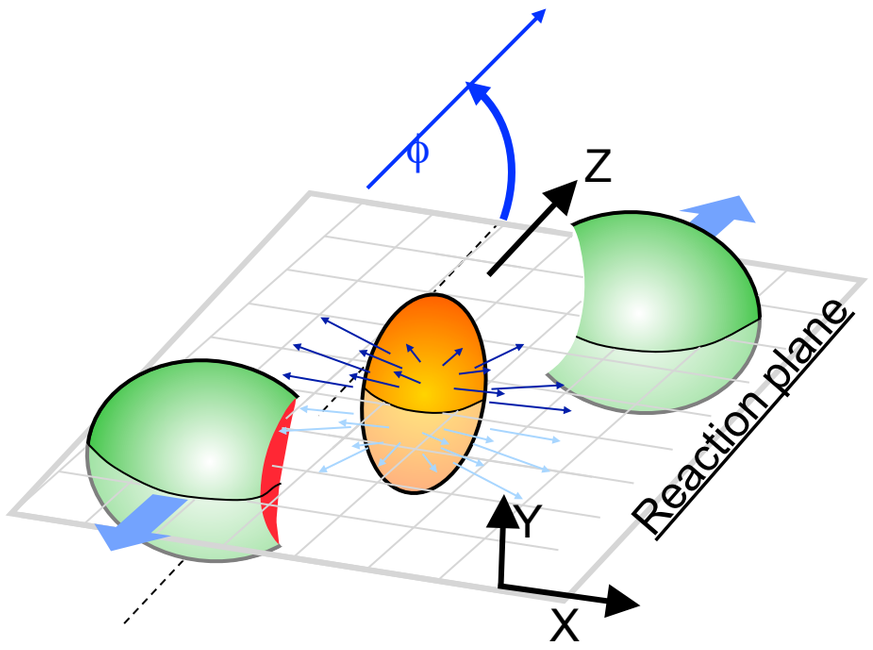
ALI-PREL-47062

Sequential freezeout (smaller hadronic cross-section)?

Elliptic flow

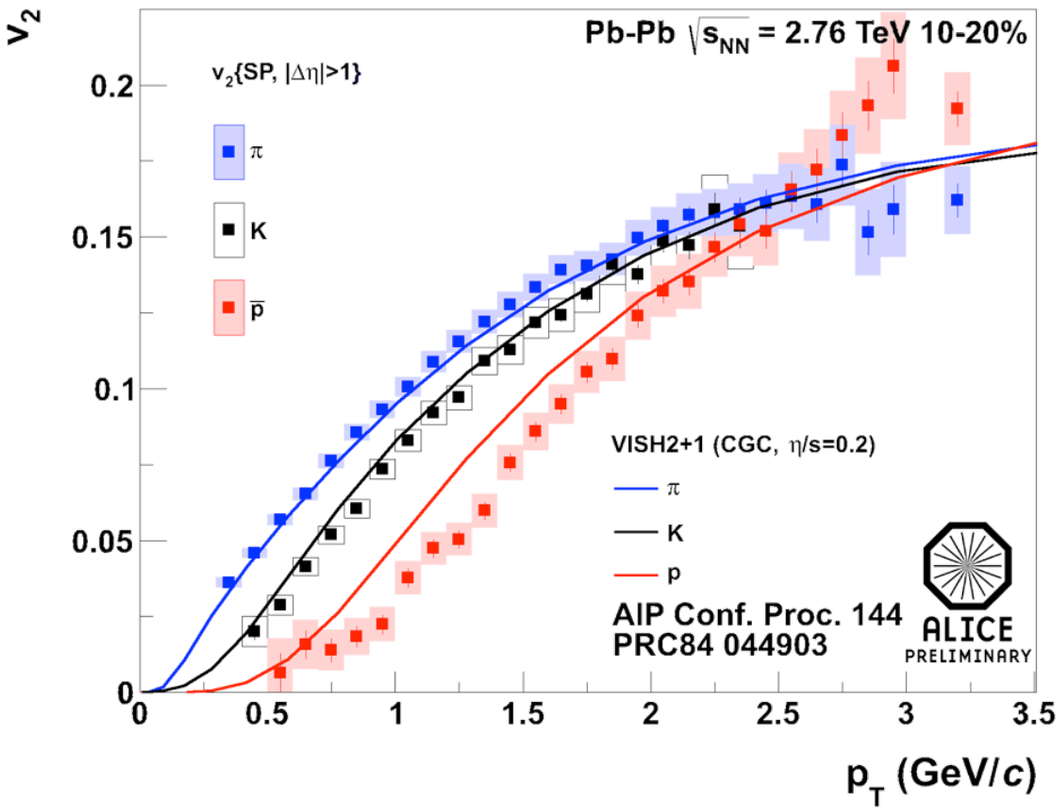


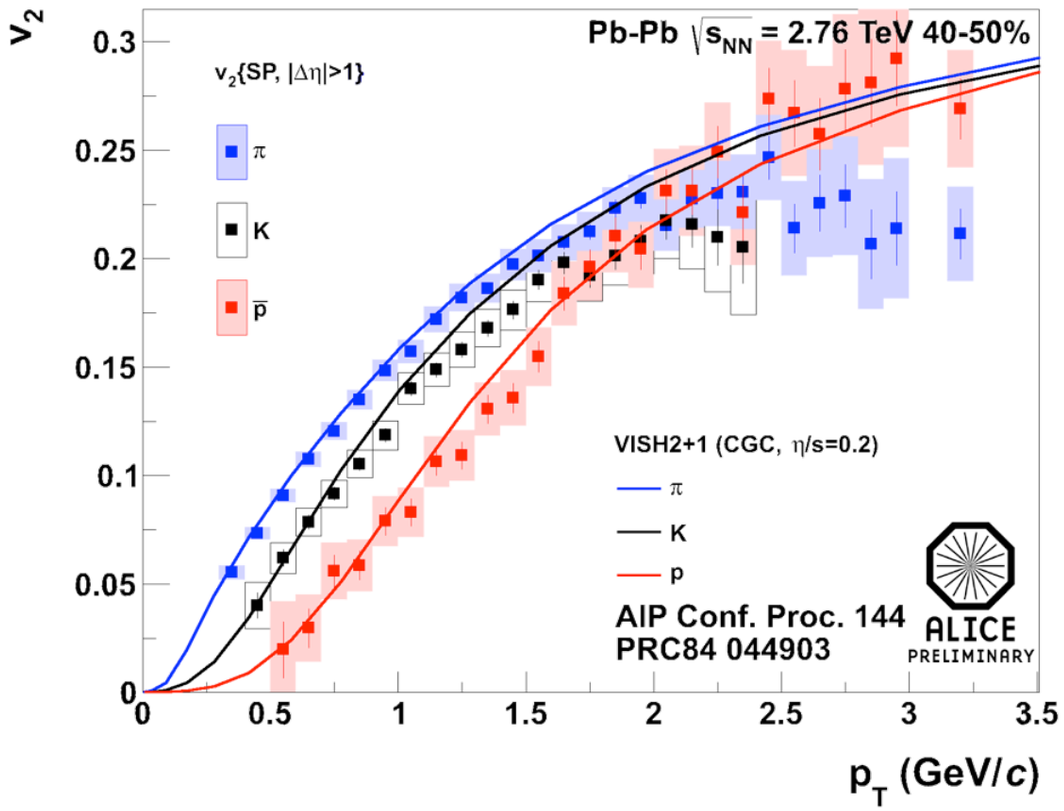


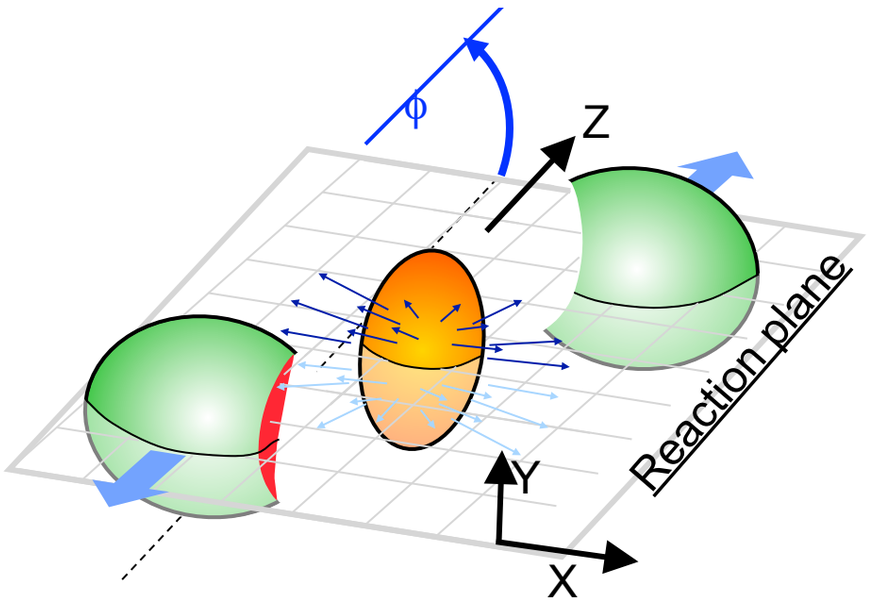


Hydro models qualitatively describe species dependence

Elliptic flow



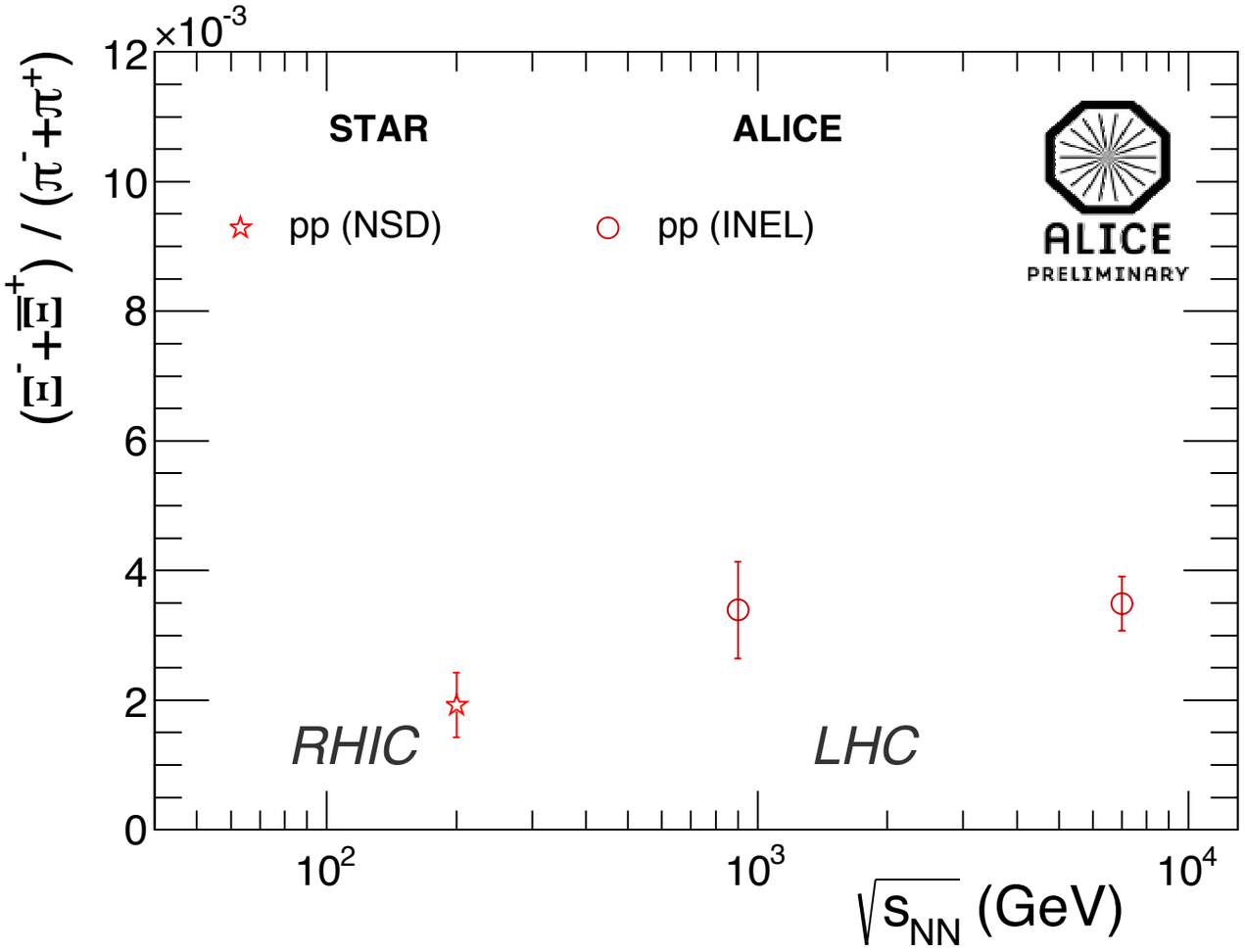




Hydro models qualitatively describe species dependence

Chemical Freezeout: strangeness enhancement

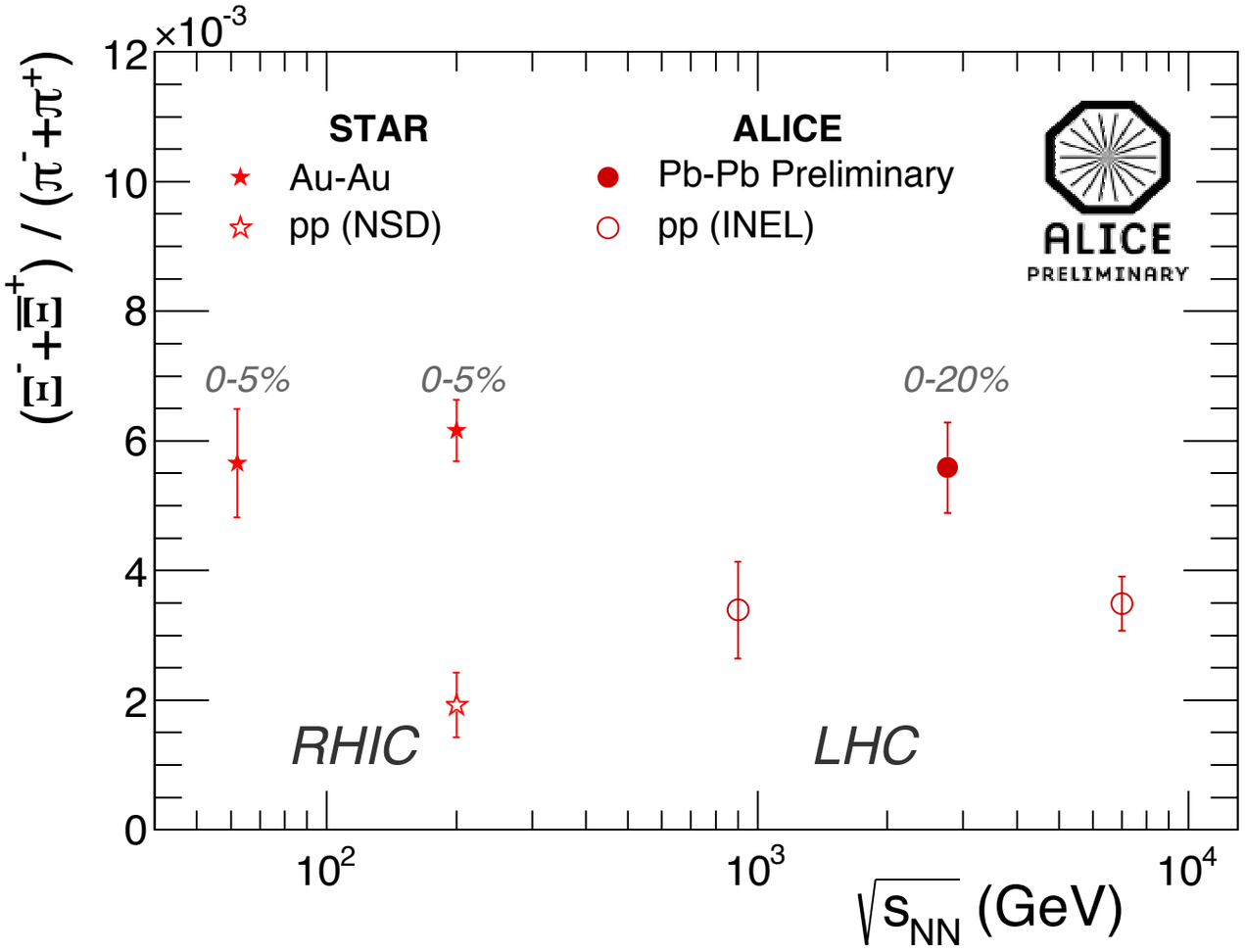
ALICE, PLB 712, 309



Strangeness enhancement still seen at the LHC

Chemical Freezeout: strangeness enhancement

ALICE, PLB 712, 309



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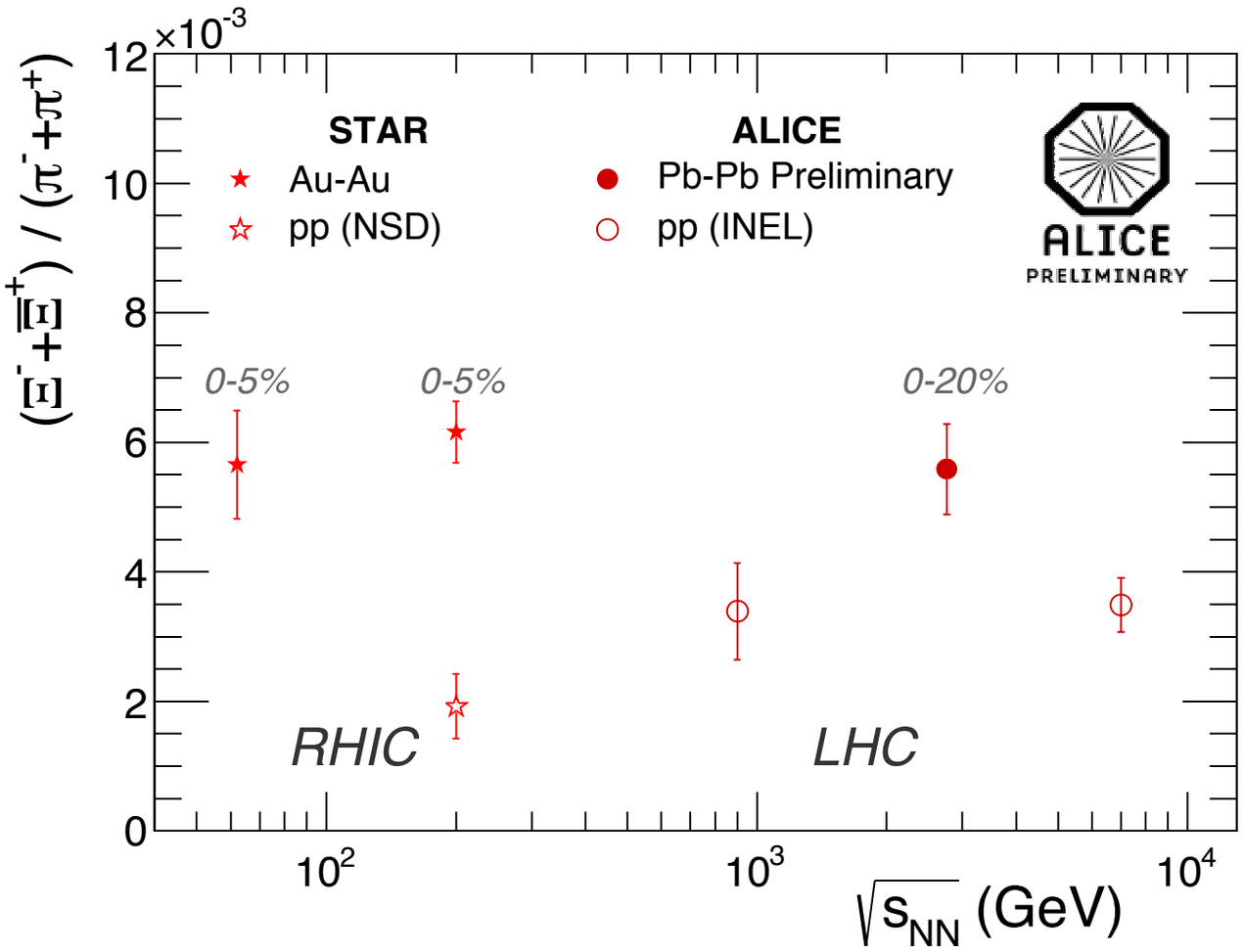
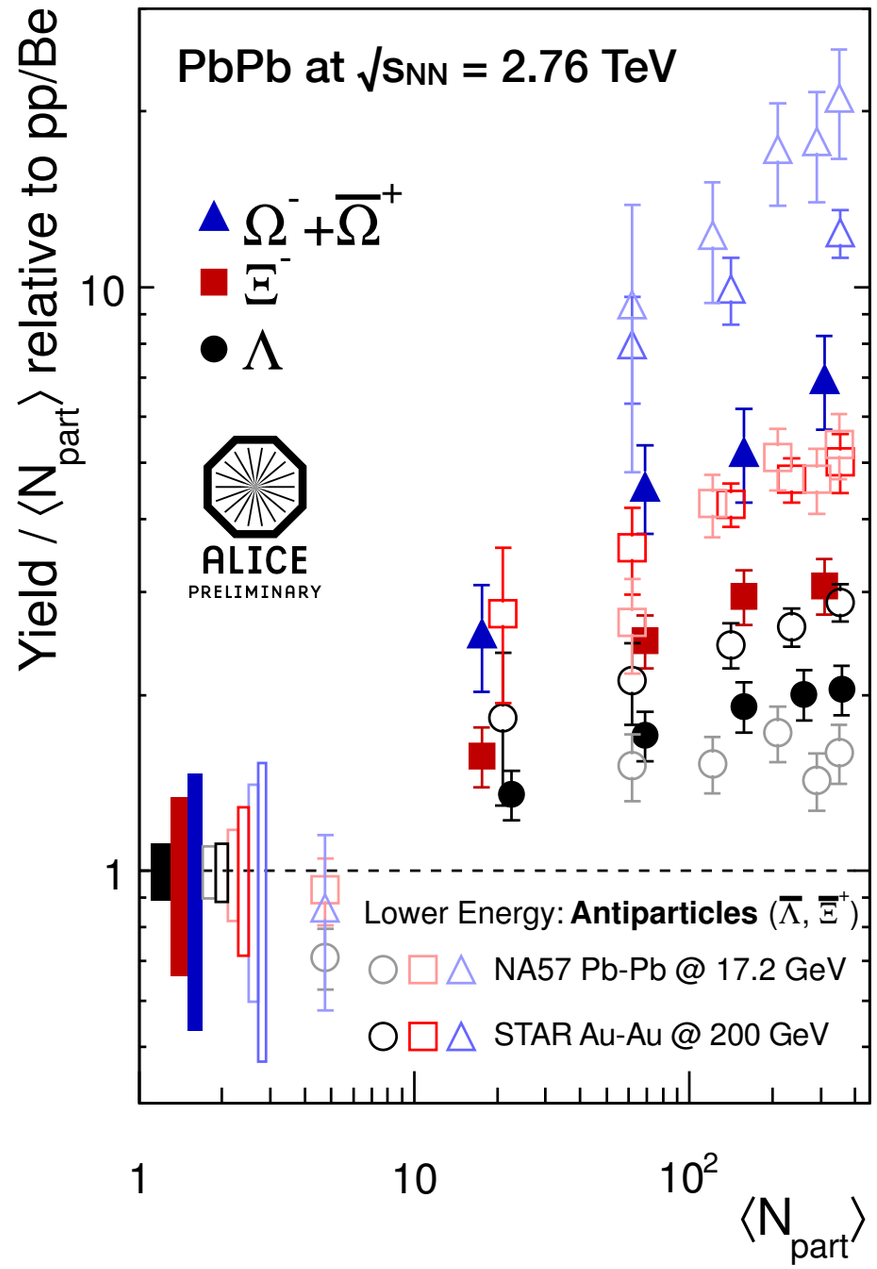
ALICE, PLB 712, 309

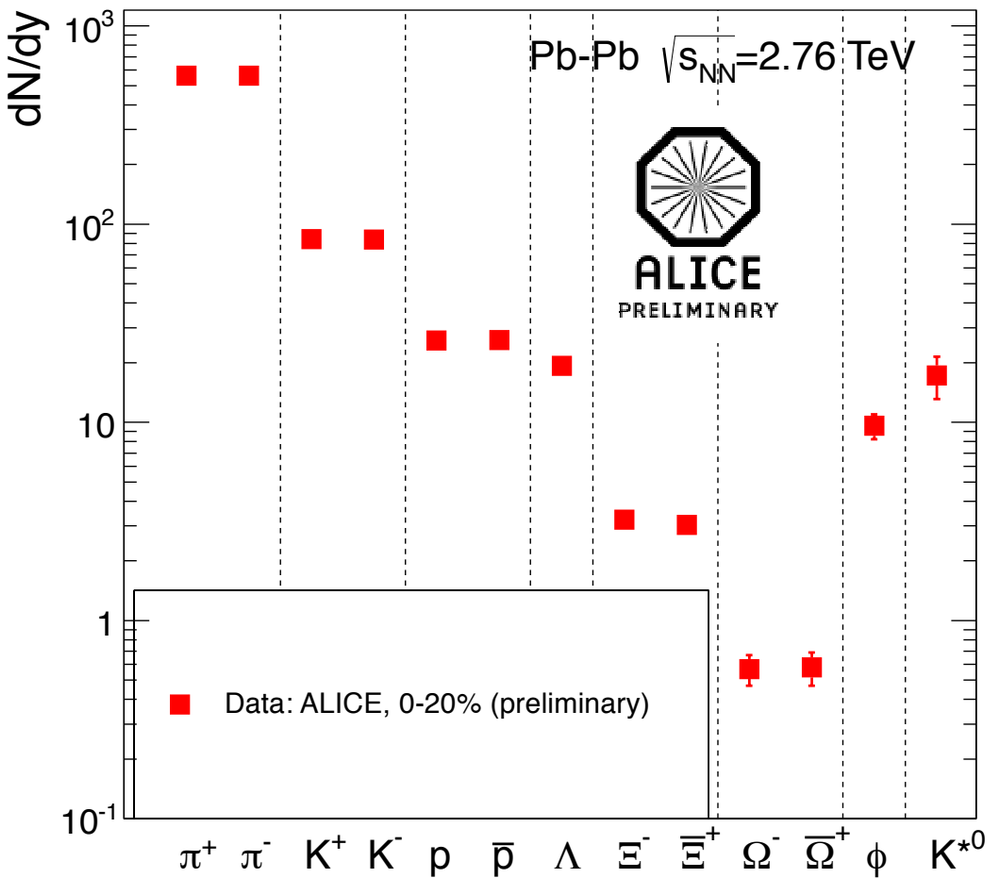




Strangeness enhancement still seen at the LHC

Smaller than at lower energies (pp reference raises)

Thermal production of hadrons

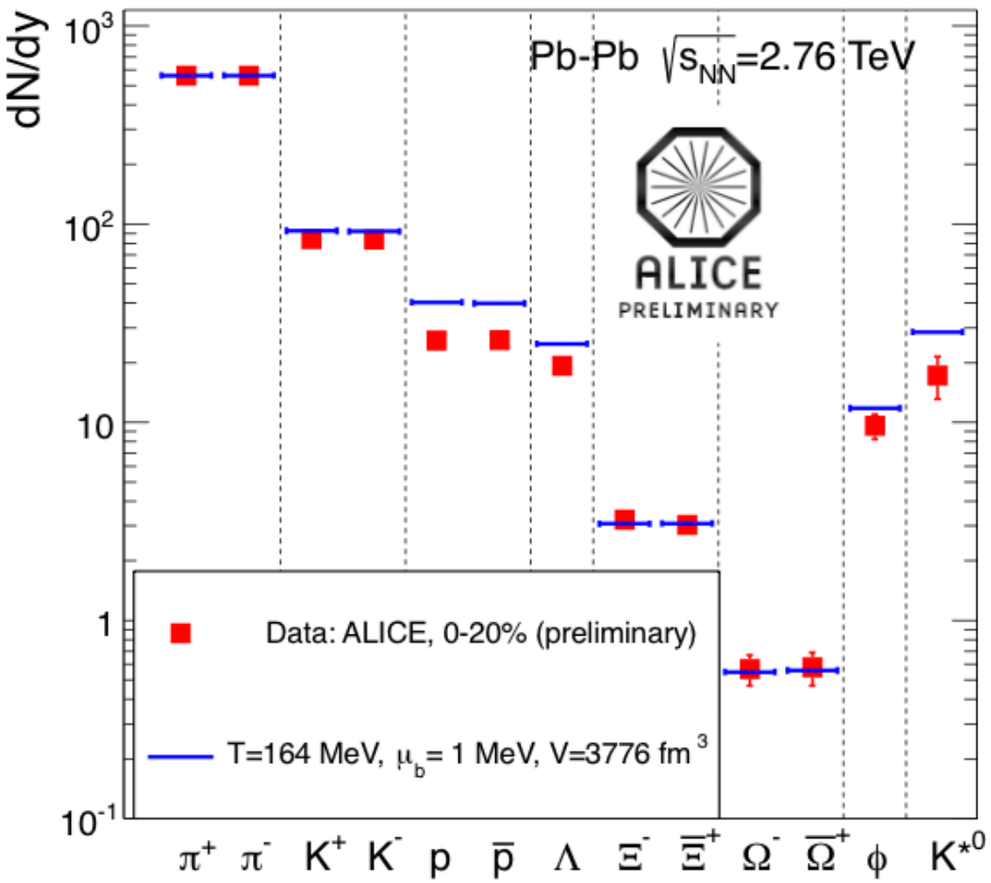


Integrated yields at midrapidity:

- Data are feed down corrected
- At lower $\sqrt{s}$ well described (~10%) by statistical (thermal) model

Thermal model: Andronic et al, PLB 673, 142

Thermal production of hadrons



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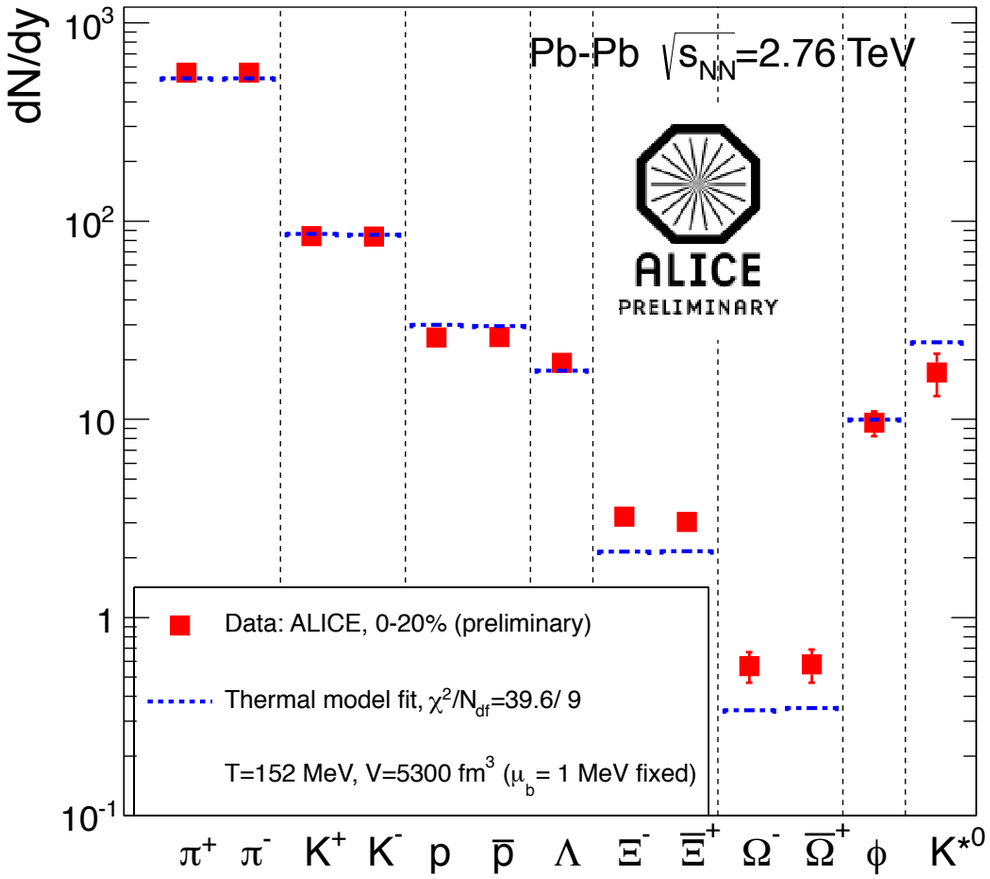

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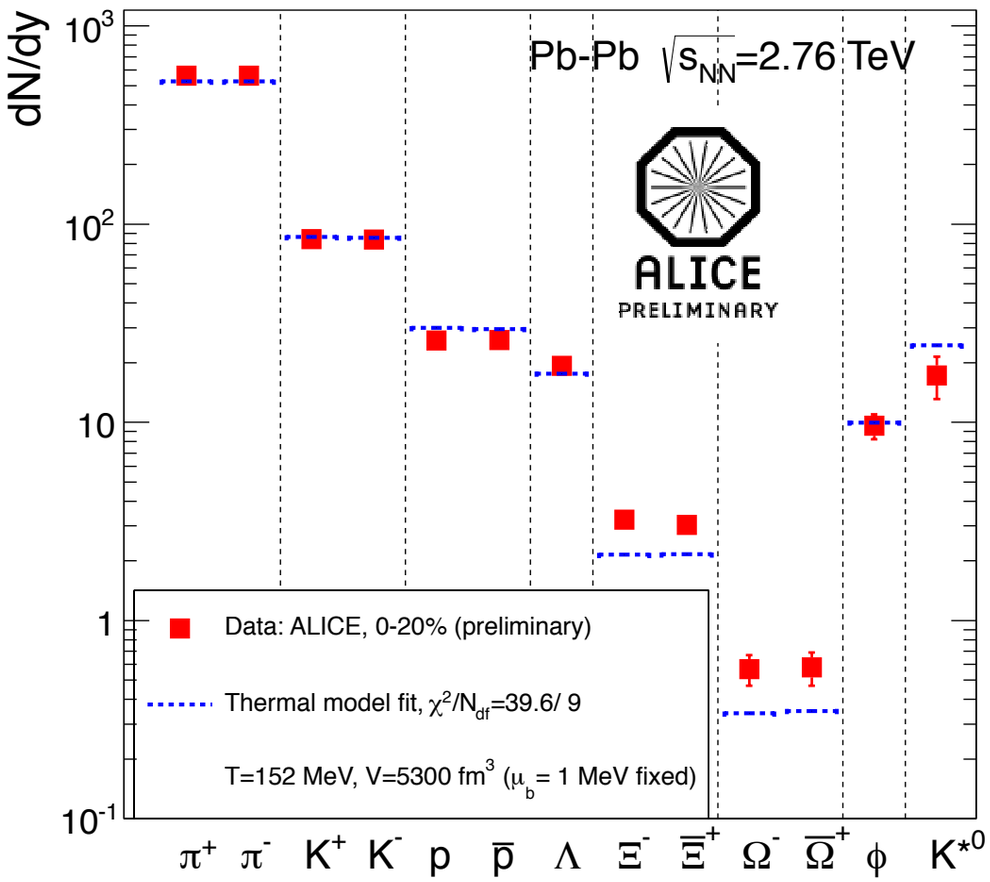

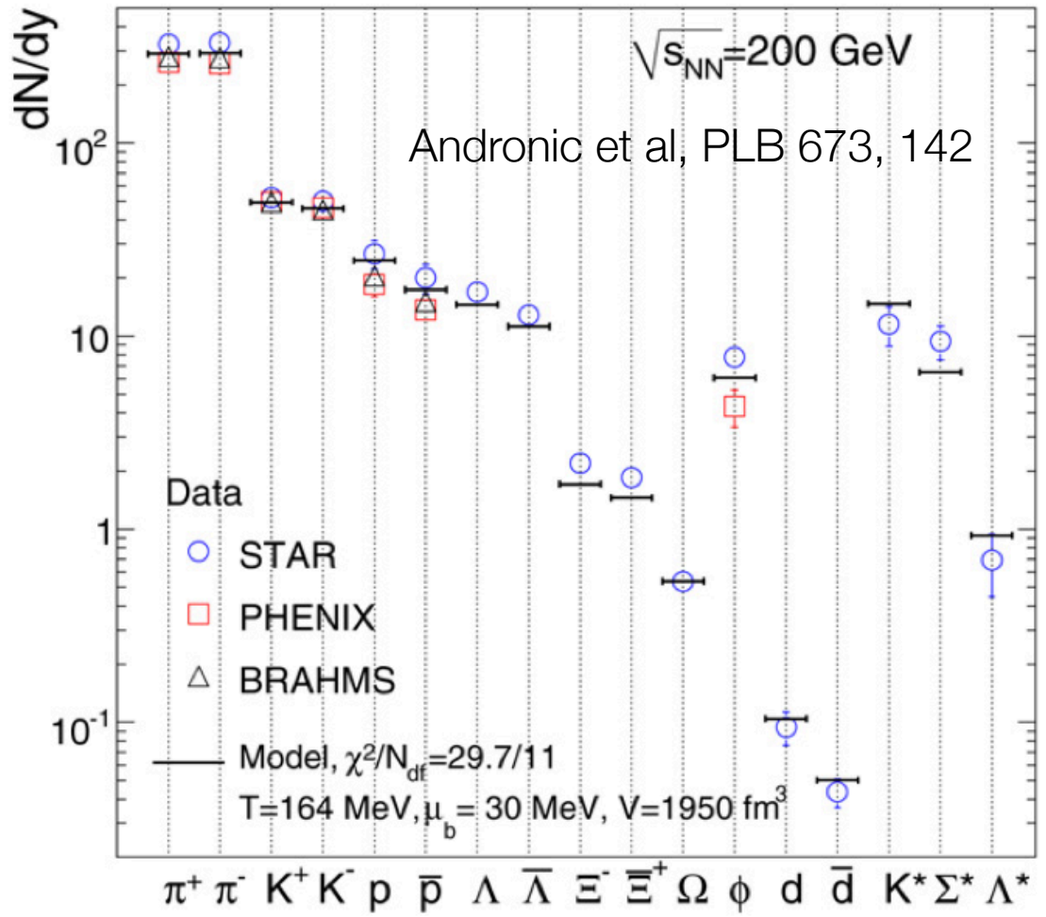

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Comparison to RHIC

- Feed down: p_{STAR} (-37%) π_{PHENIX} (-10%)
- Tensions already at RHIC?

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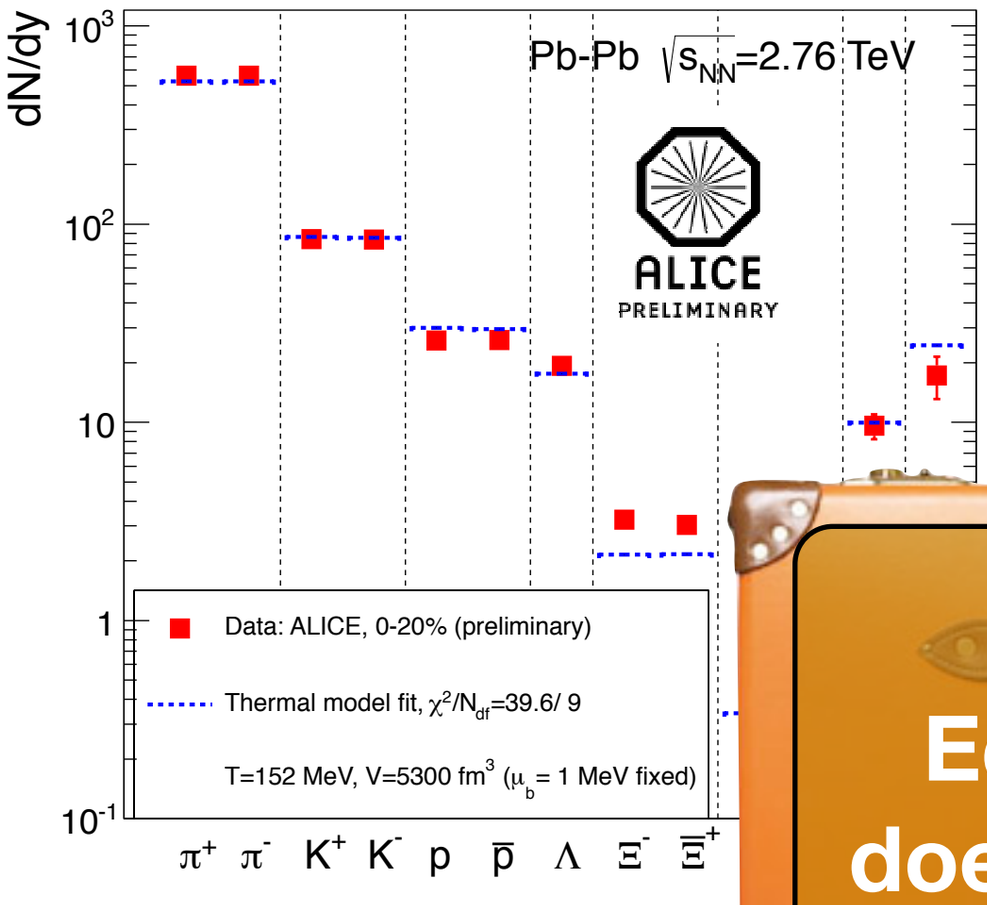
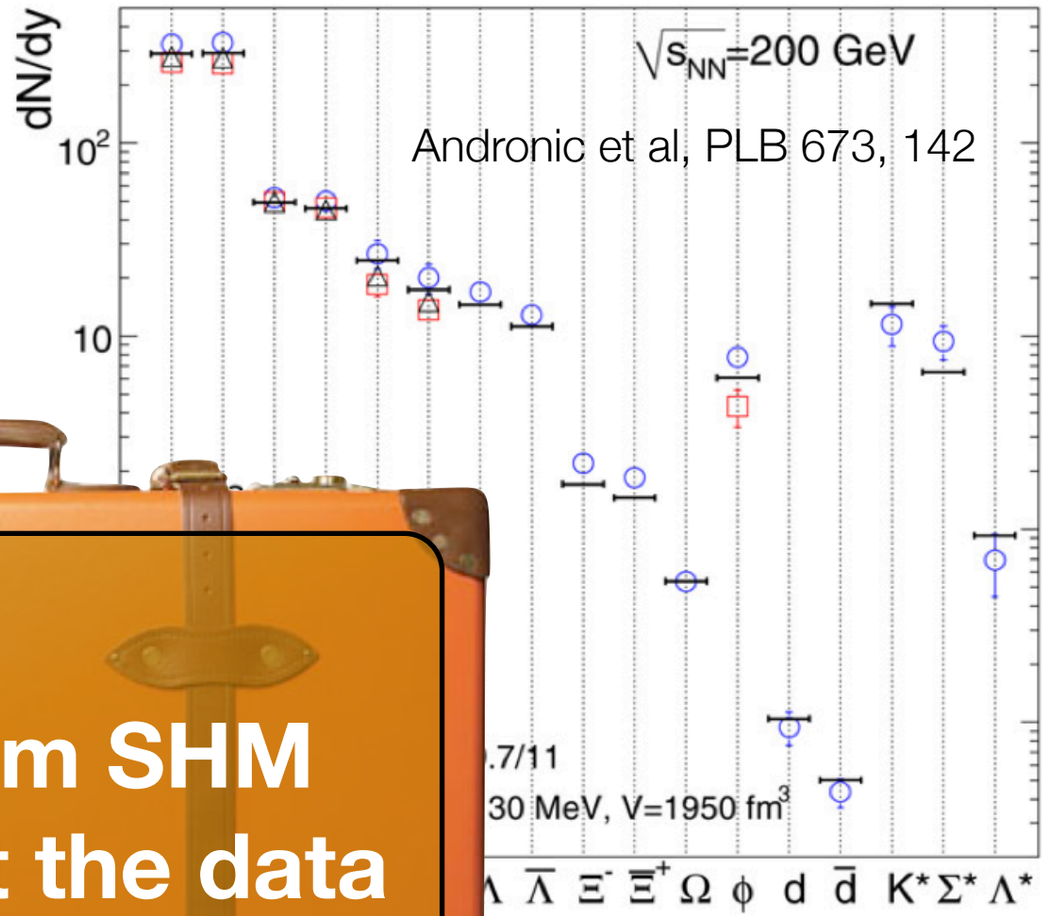
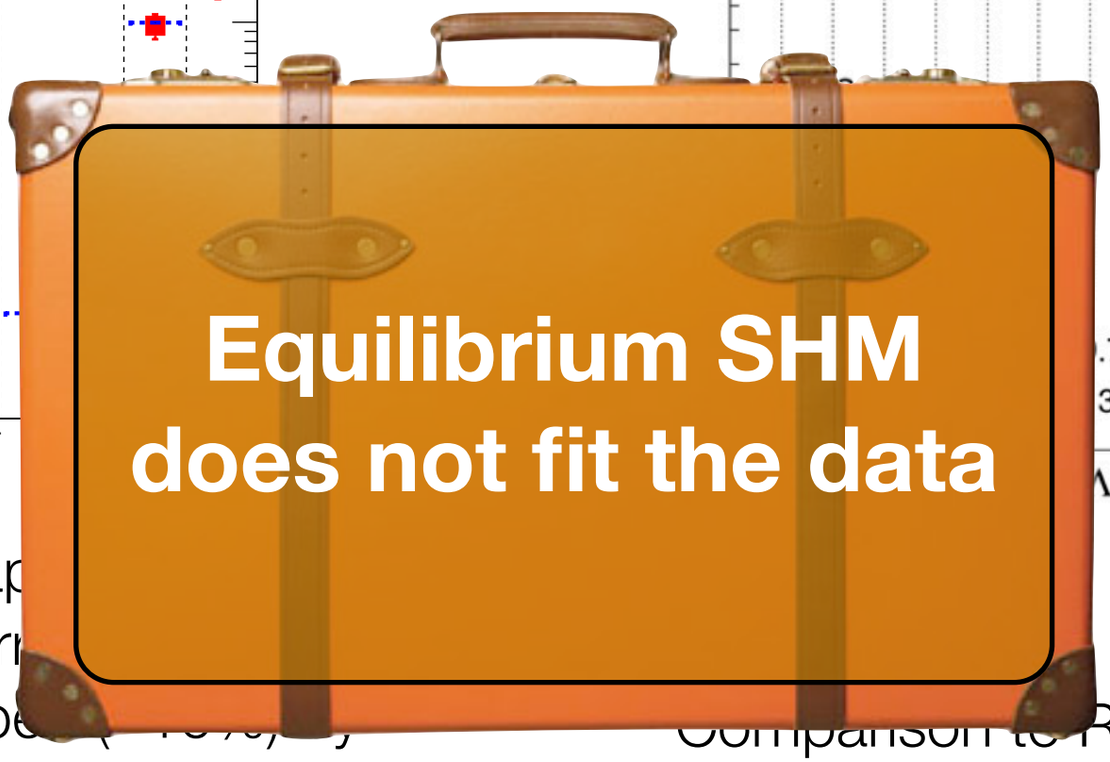
Thermal production of hadrons







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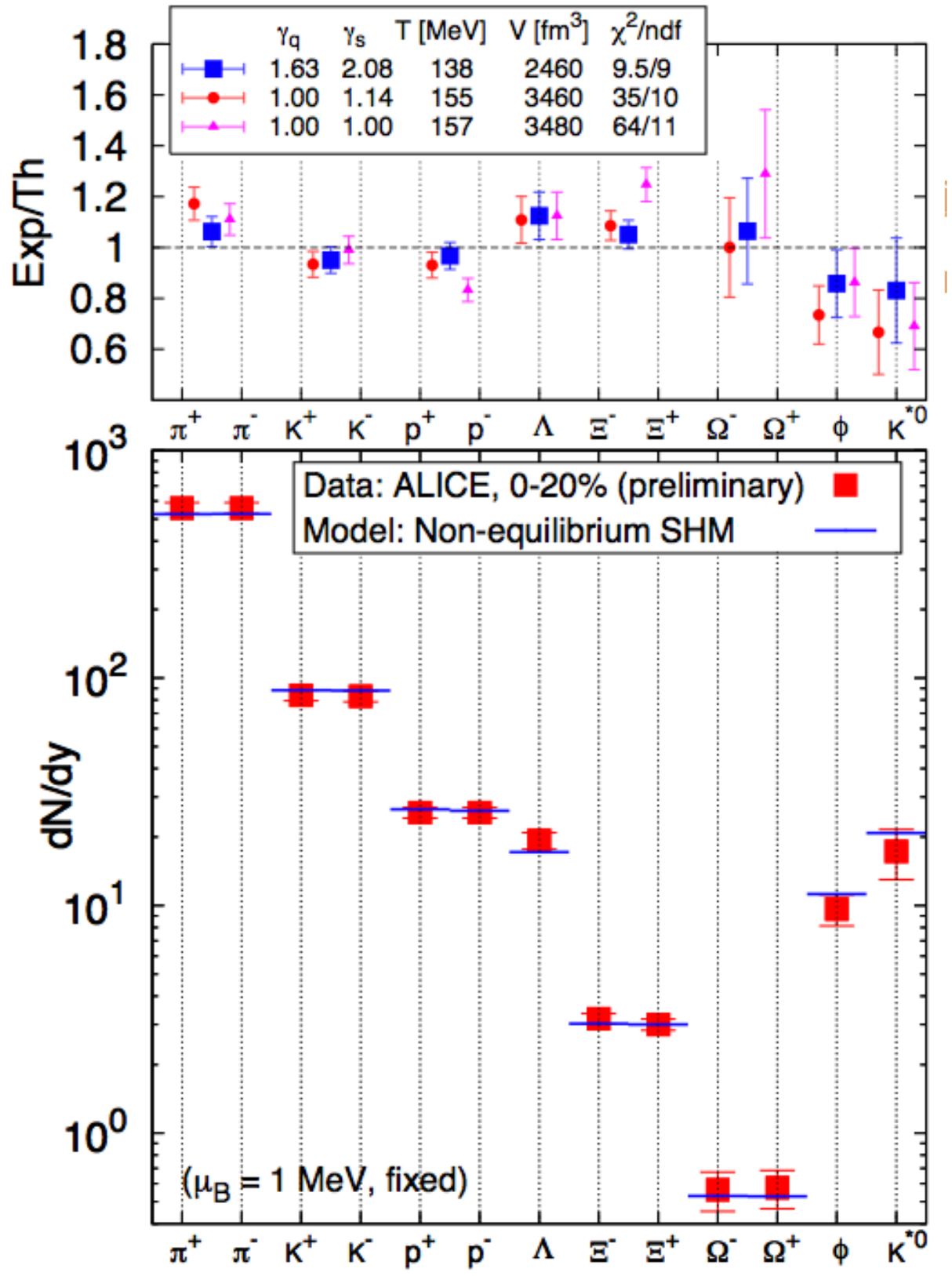
Non equilibrium SHM

QGP is in thermal equilibrium, not hadron gas

Fits the data

More free parameters?

strangeness/entropy in equilibrium, lower than at RHIC?



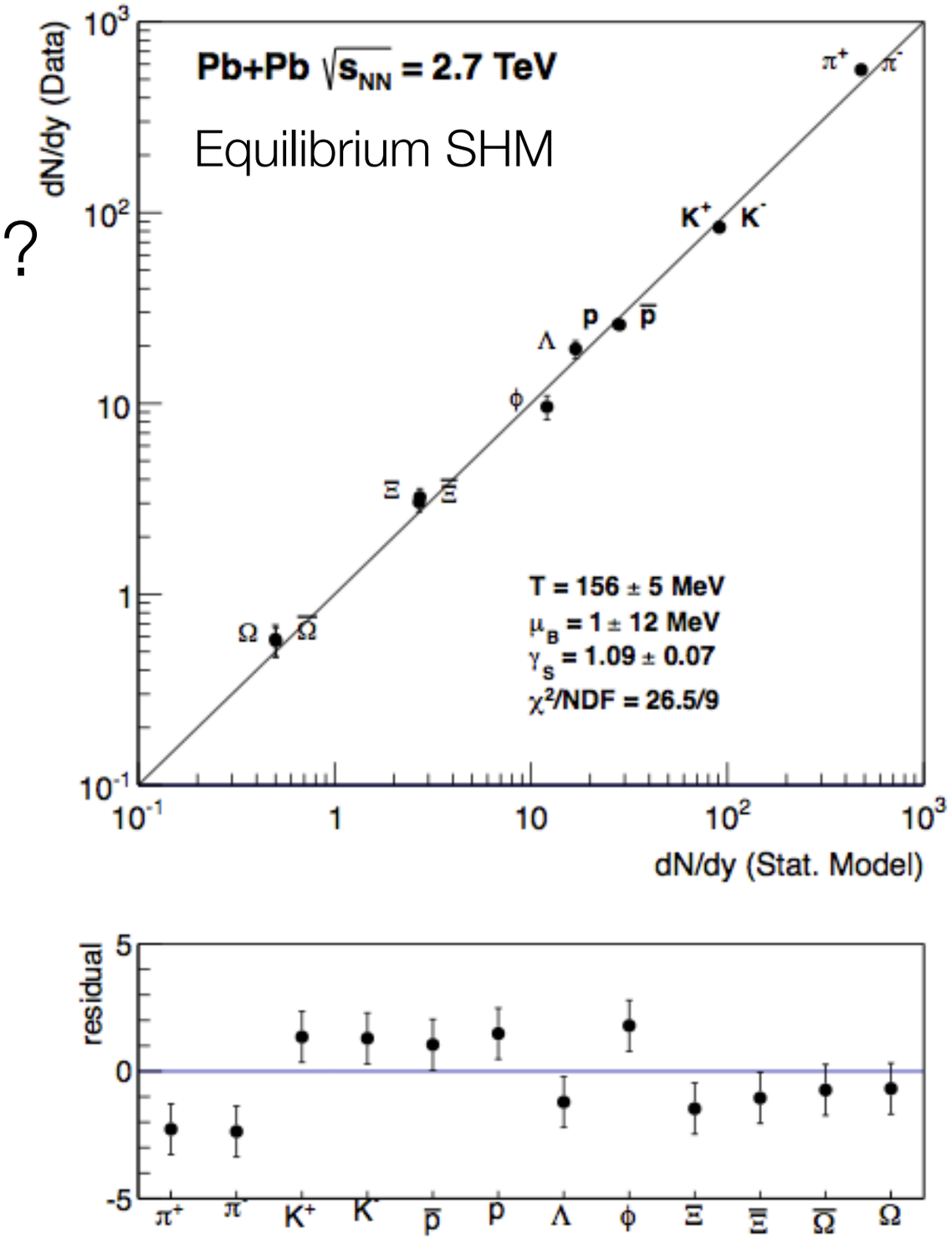
Petran, Rafelski et al arXiv:1303.0913
Petran, Rafelski et al arXiv:1303.2098

Hadronic phase

Sequential freezeout?
Baryon annihilation ↘ p yield

Supported by some hydro models?

Unmeasured cross sections?
Inverse reactions
($n\pi \rightarrow p\bar{p}$, heavy meson $\rightarrow p\bar{p}$)?
Centrality dependence?



Becattini et al, arXiv:1212.2431

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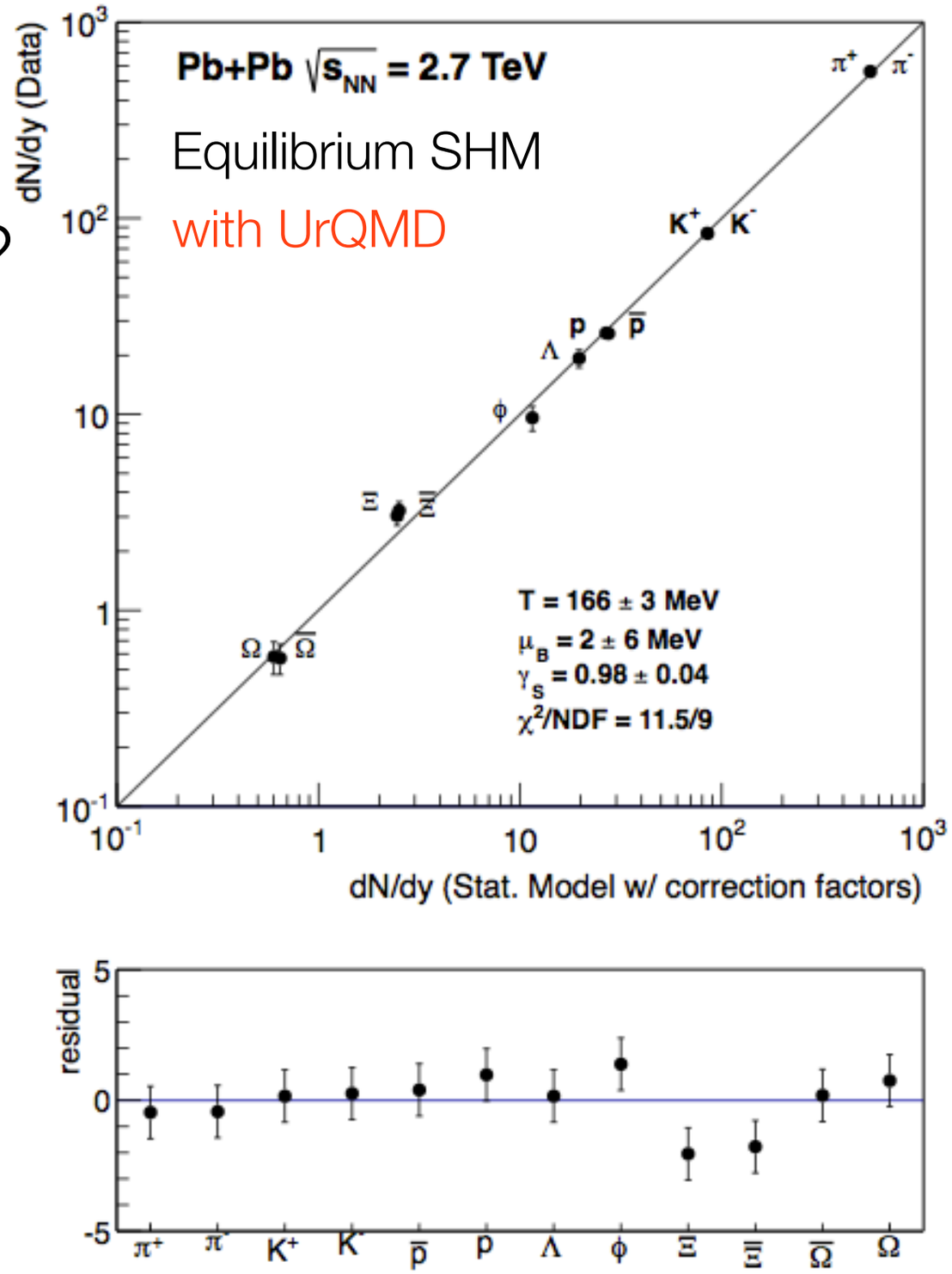

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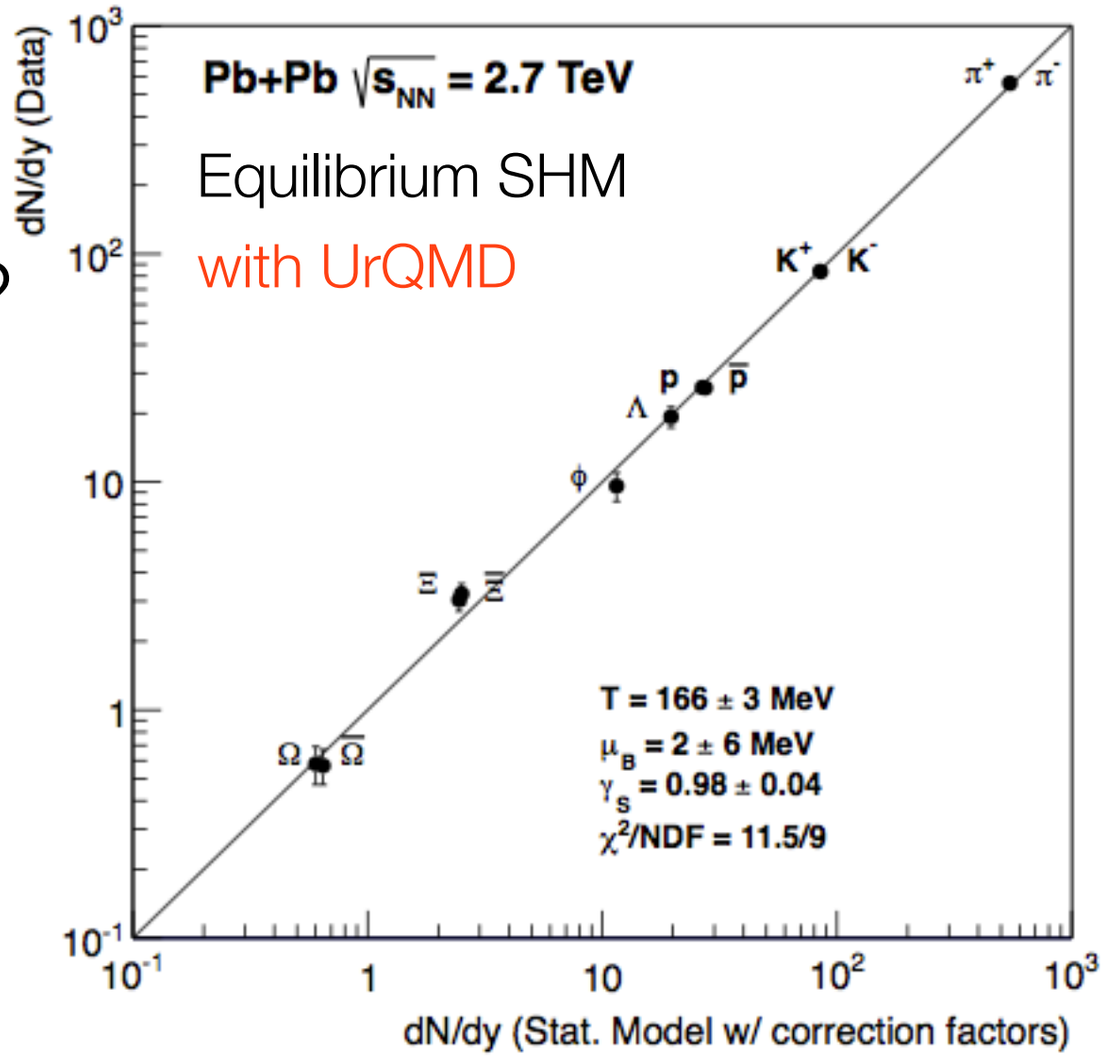

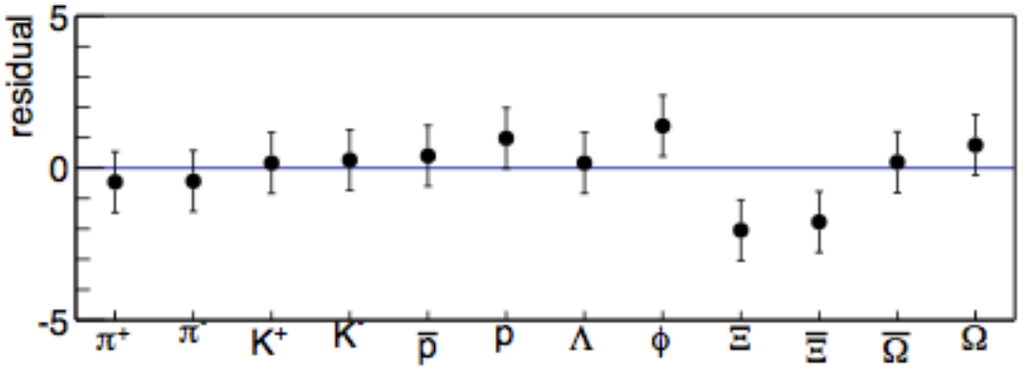

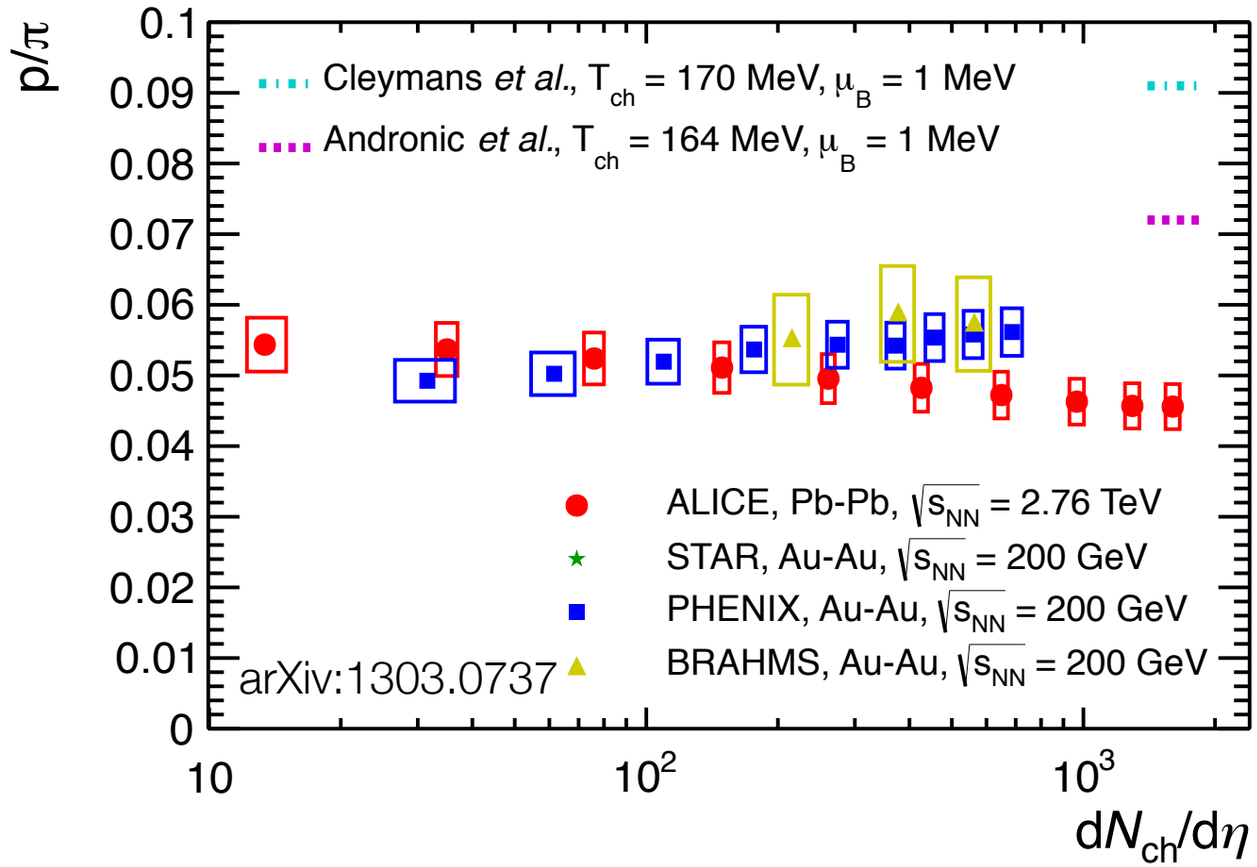

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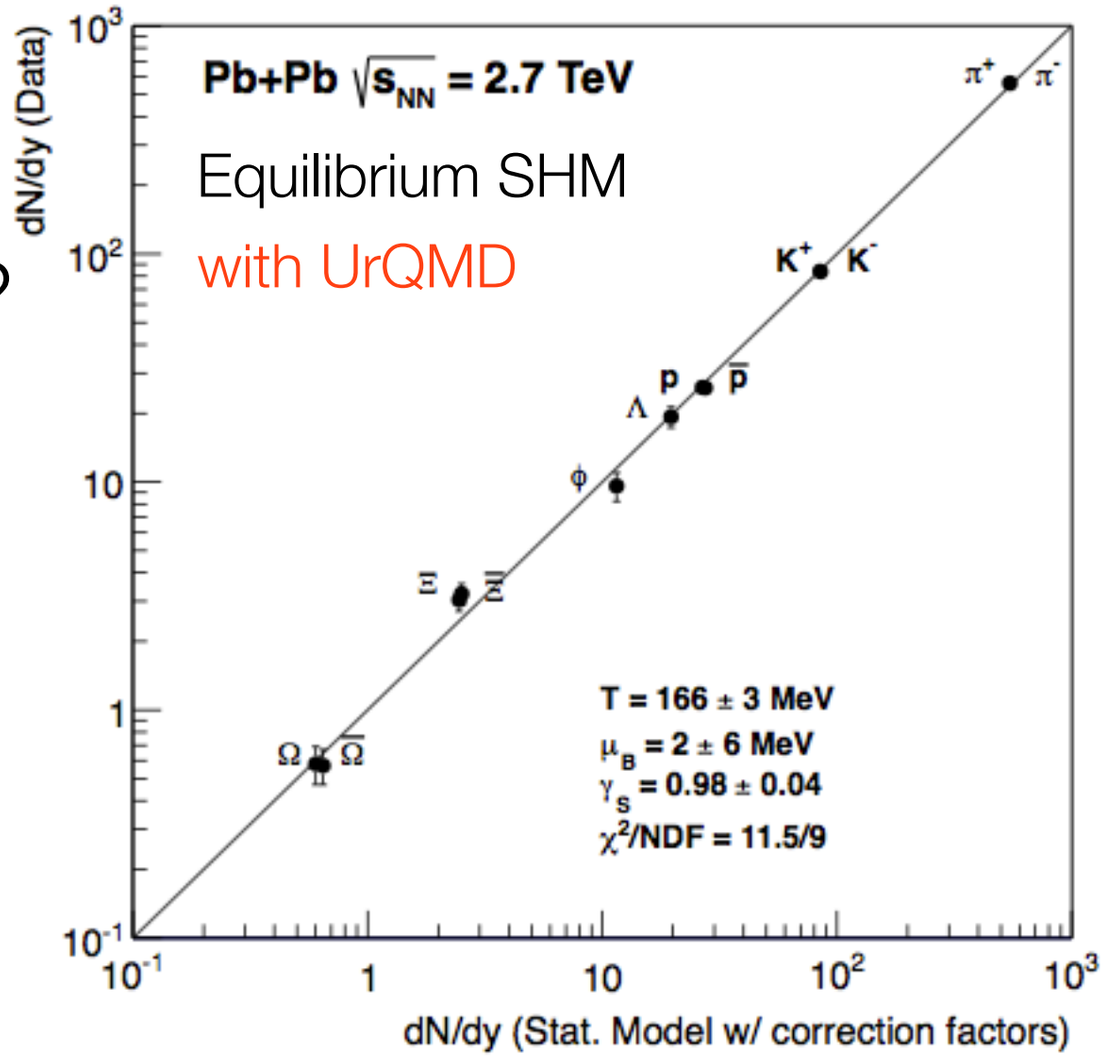
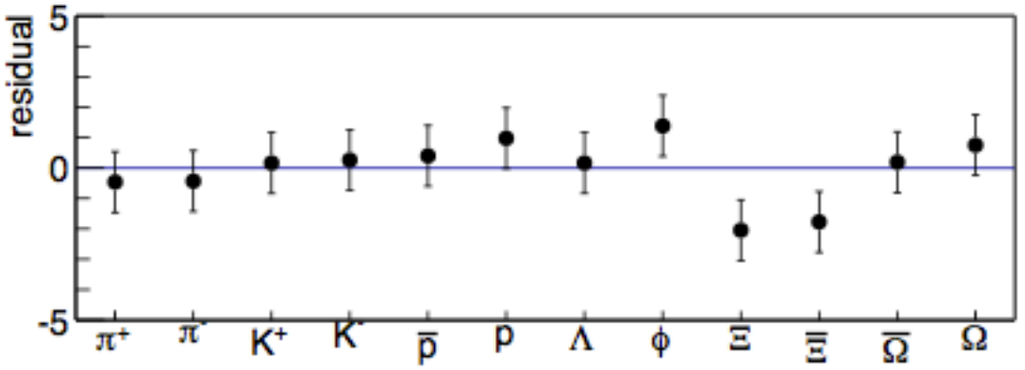
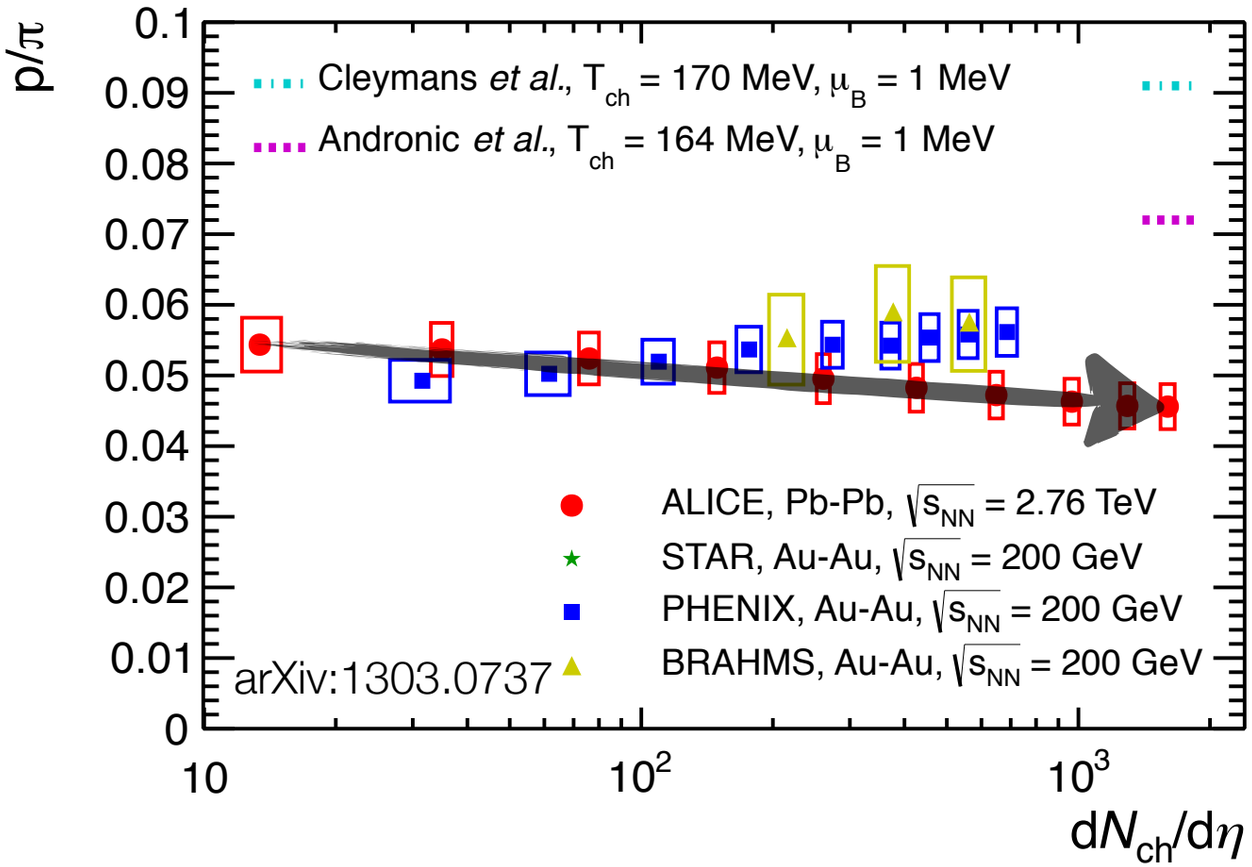






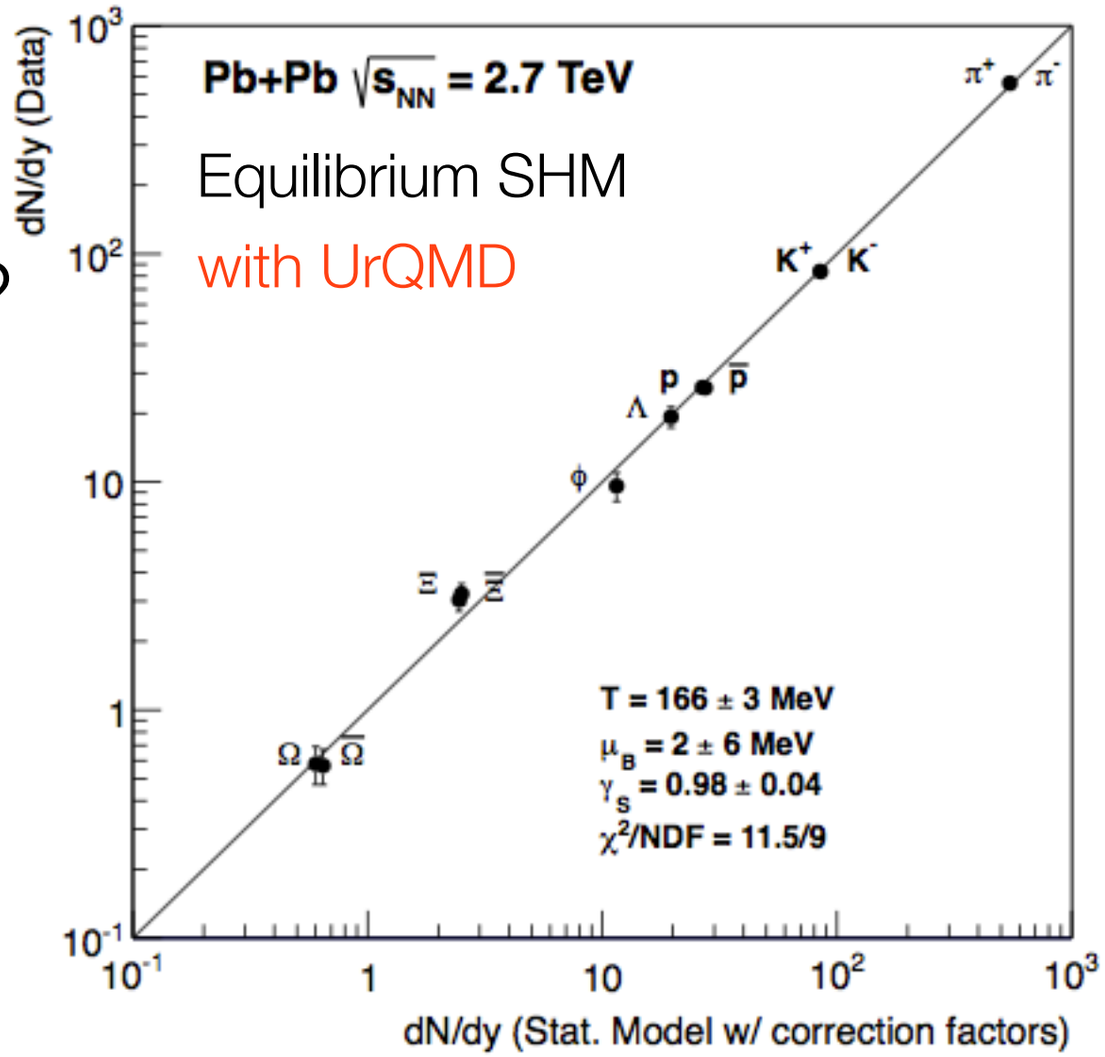
Becattini et al, arXiv:1212.2431

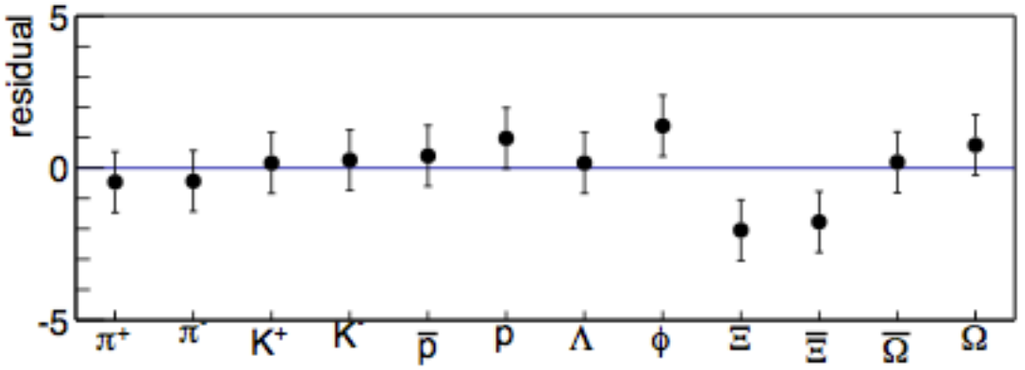
Hadronic phase

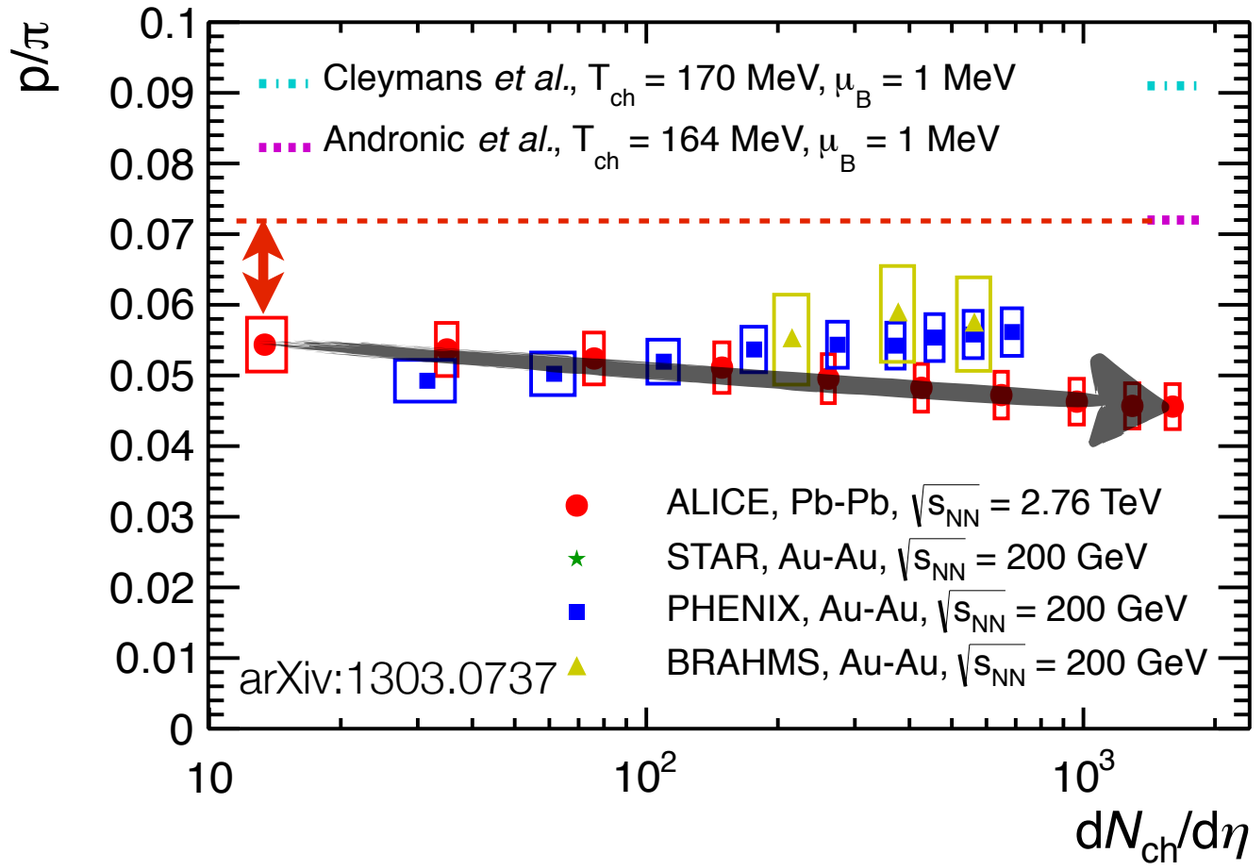
Sequential freezeout?
Baryon annihilation ↘ p yield

Supported by some hydro models?

Unmeasured cross sections?
Inverse reactions
($n\pi \rightarrow p\bar{p}$, heavy meson $\rightarrow p\bar{p}$)?
Centrality dependence?

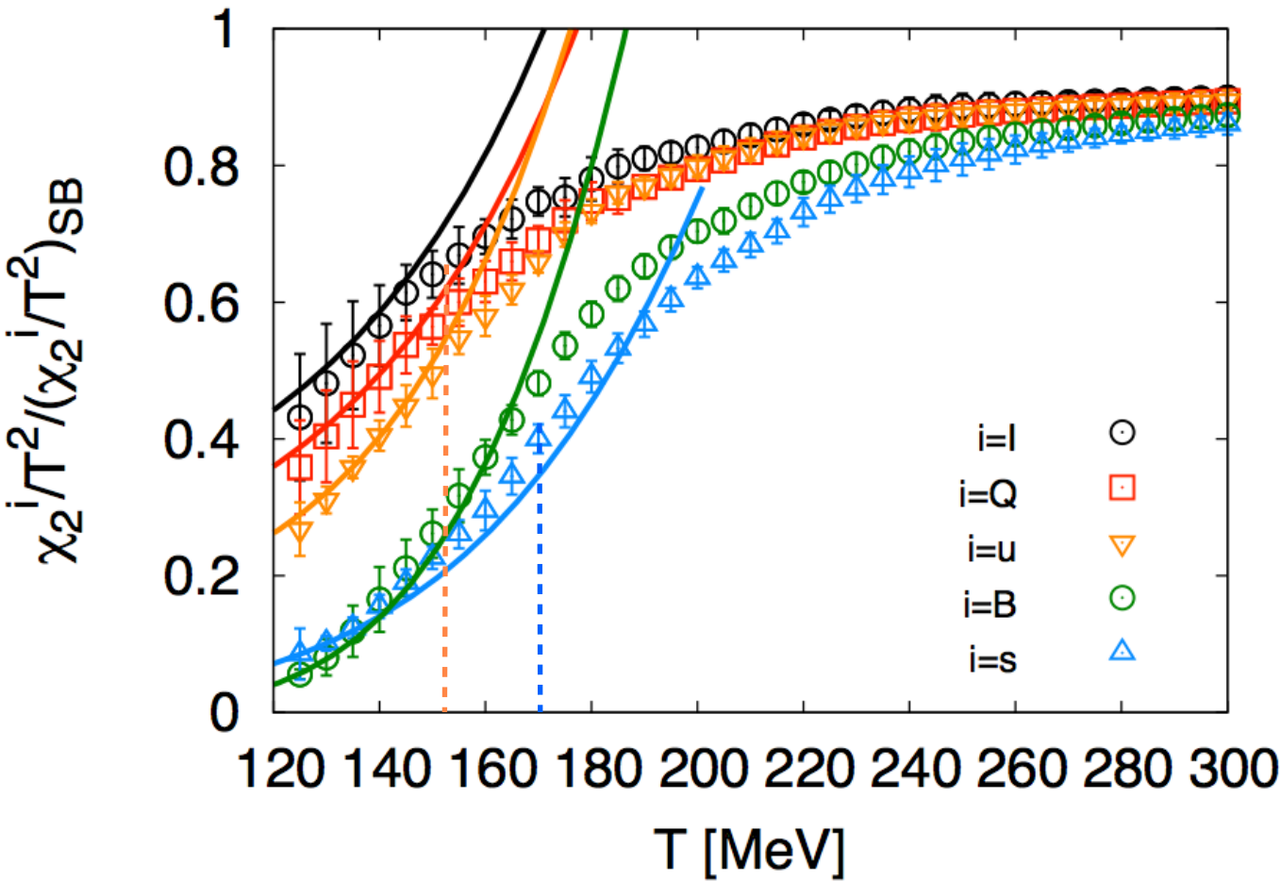






Becattini et al, arXiv:1212.2431

Flavor hierarchy in the QCD phase transition



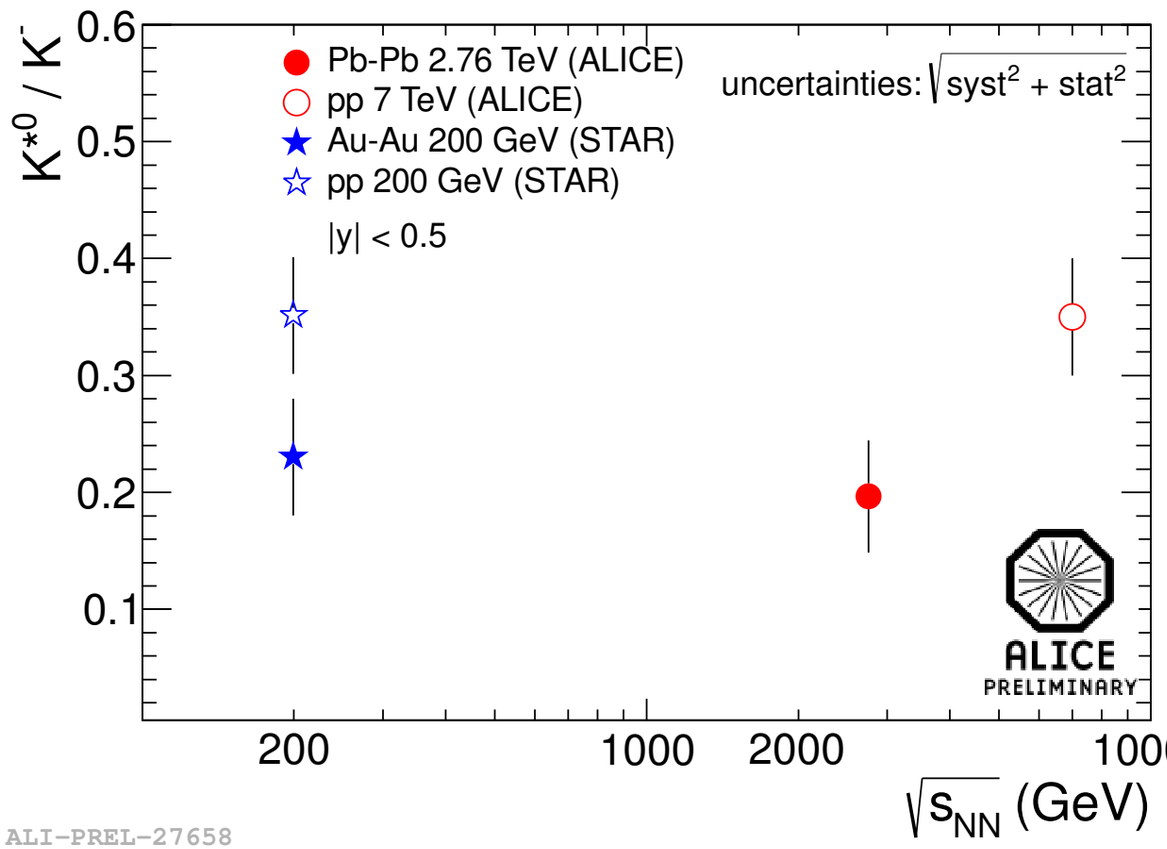
Lattice: Pre-hadronic bound states: strangeness above T_C?

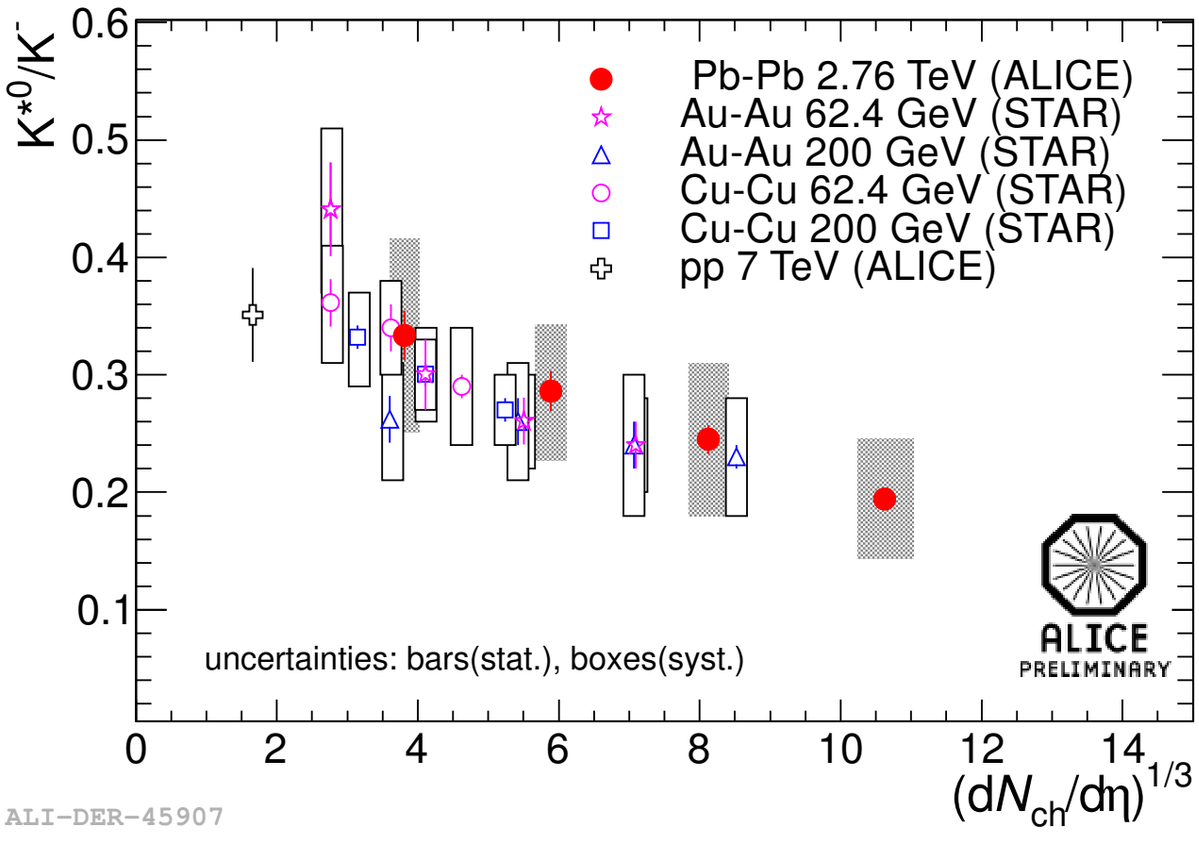
Flavor hierarchy?

Indication of light flavor fugacity?

Bellwied et al, arXiv:1205.3625,
Ratti et al PRD85 014004

Resonances: sequential freezeout?



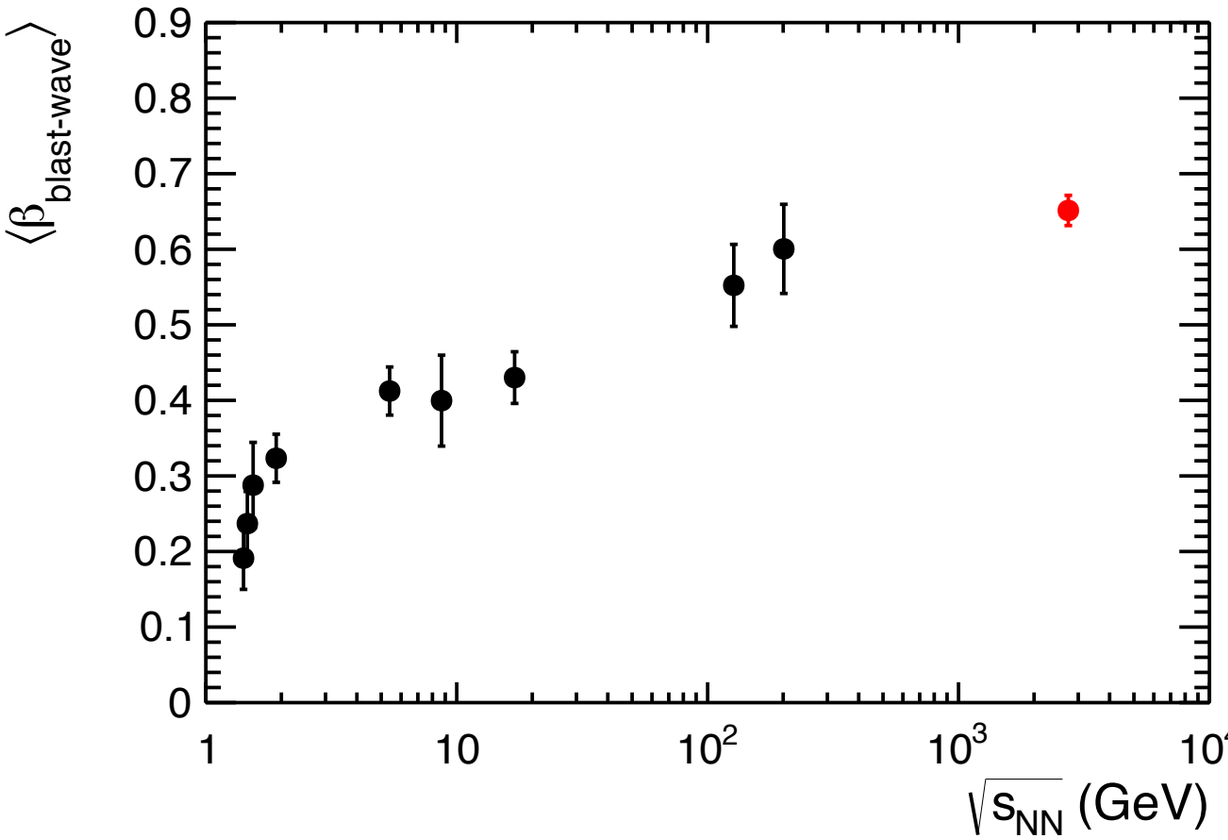


Hints for sequential kinetic freezeout:

- K^*/K^- lower in pp as compared to Pb-Pb?
- Decreasing trend with centrality?

Low p_T summary: $\sqrt{s}$ dependence

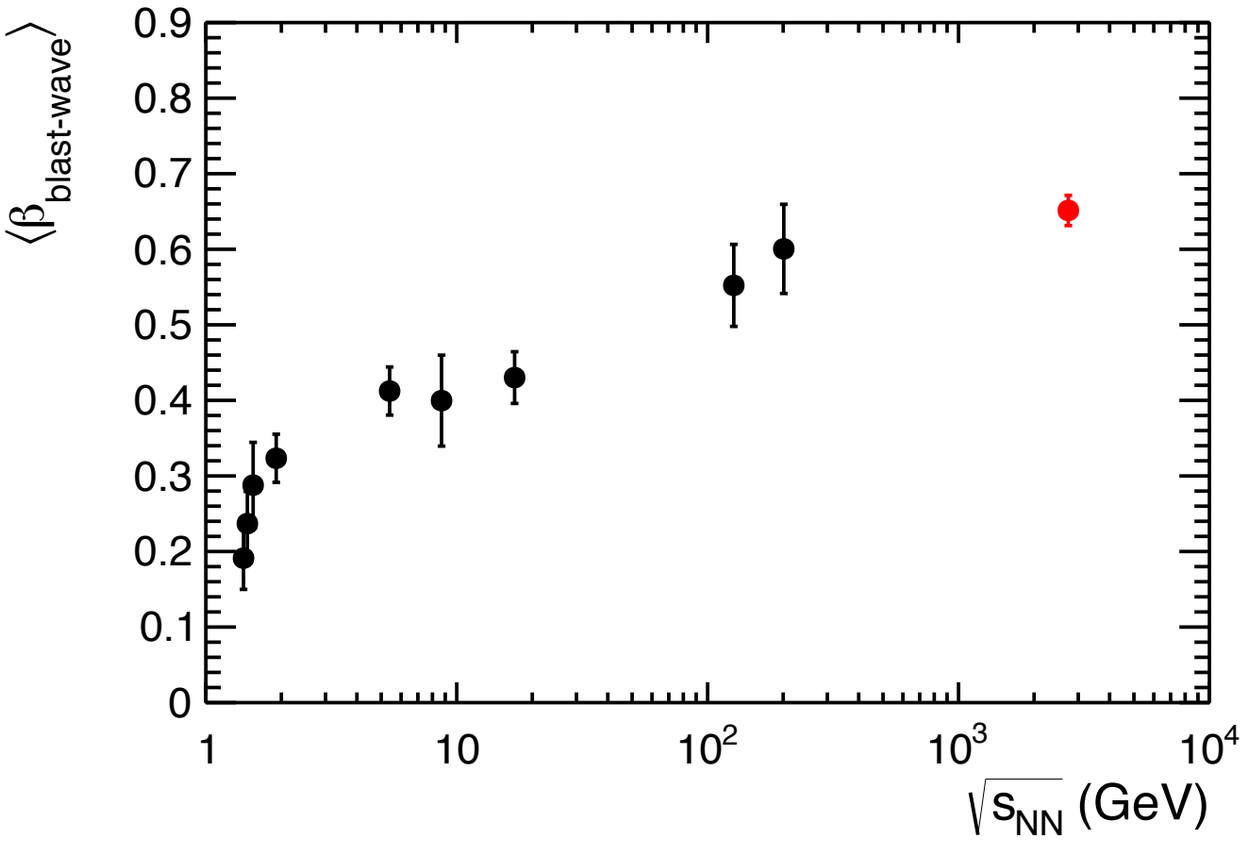
eq-SHM (+UrQMD): Becattini et al, arXiv:1212.2431
neq-SHM: Petran, Rafelski et al arXiv:1303.2098



Smooth trend from lower energy

T compilation, Mohanty et al, STAR collaboration
$\langle\ \beta\ \rangle$ compilation from Xu, Prog. in Part. Nucl. Phys. 53, 165

Low p_T summary: $\sqrt{s}$ dependence



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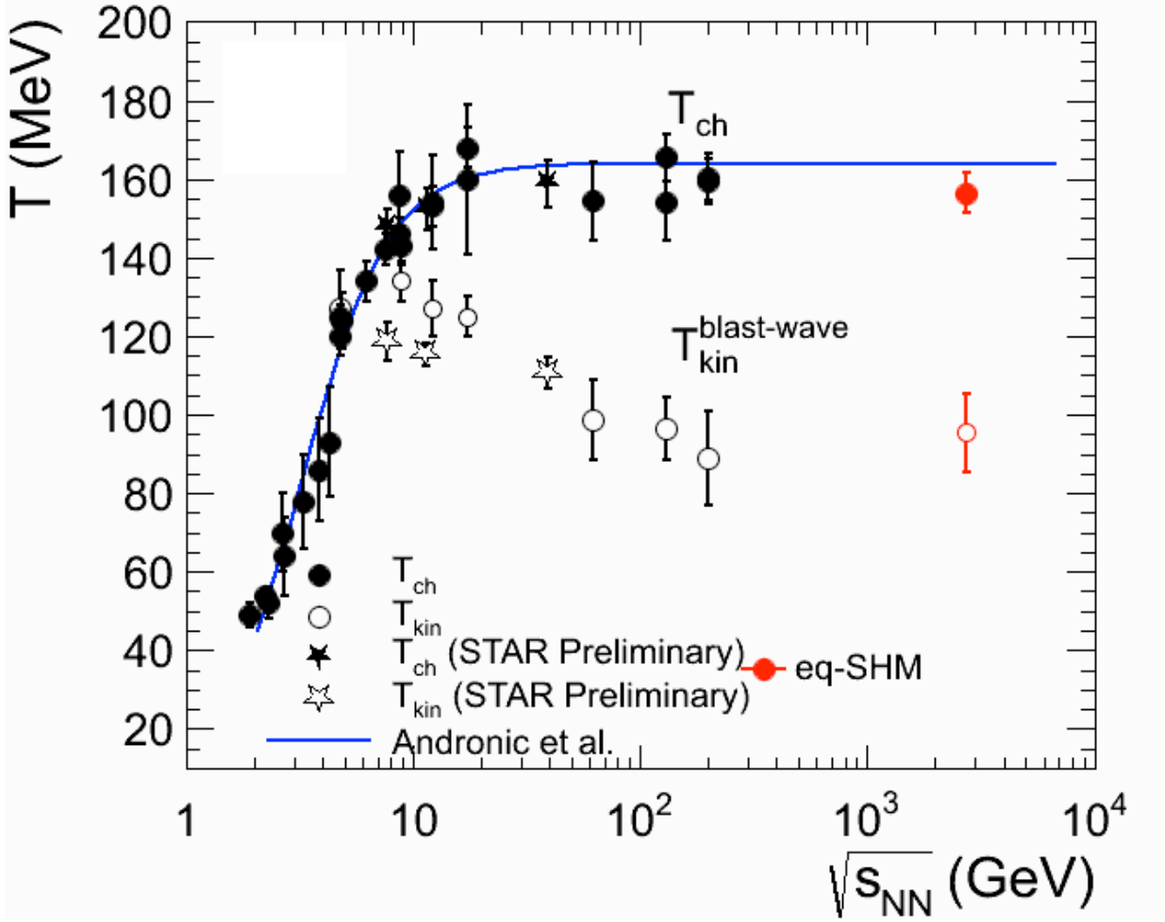

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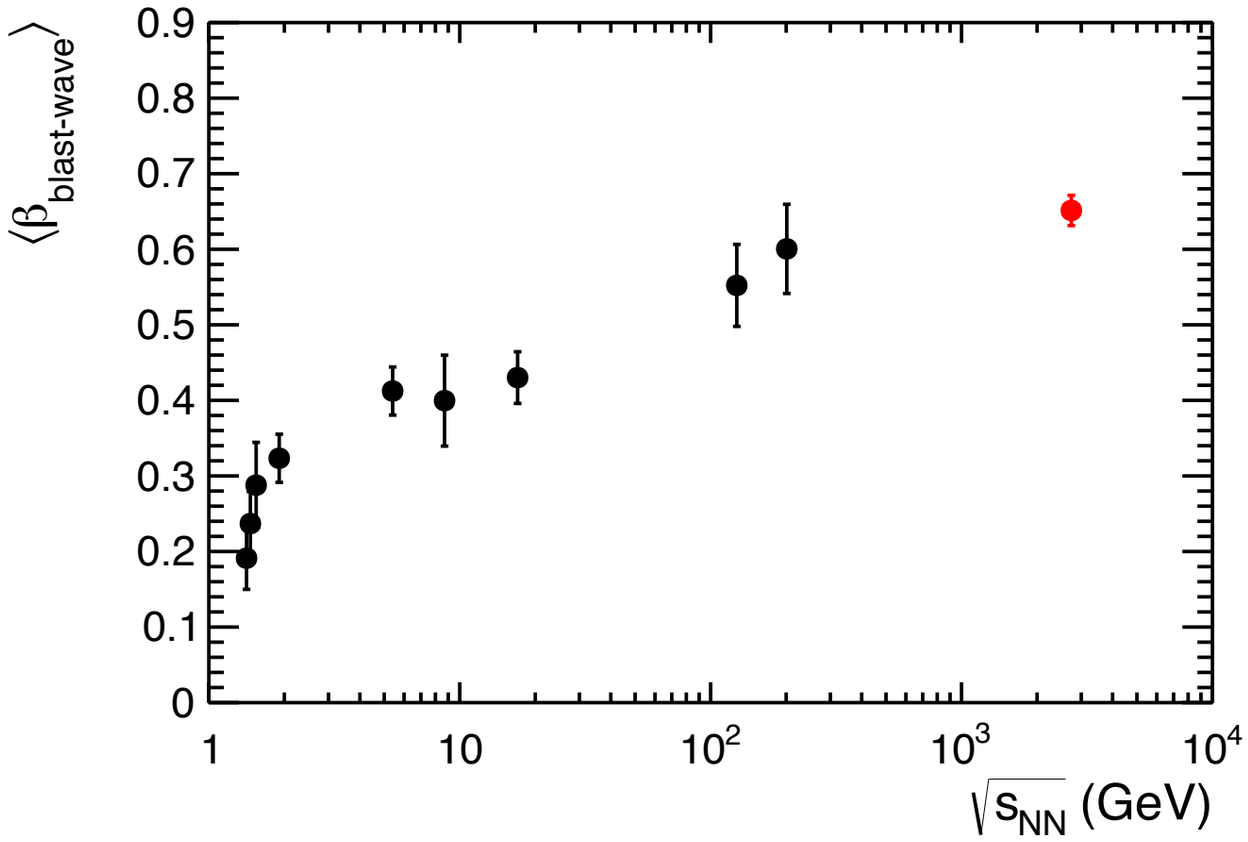

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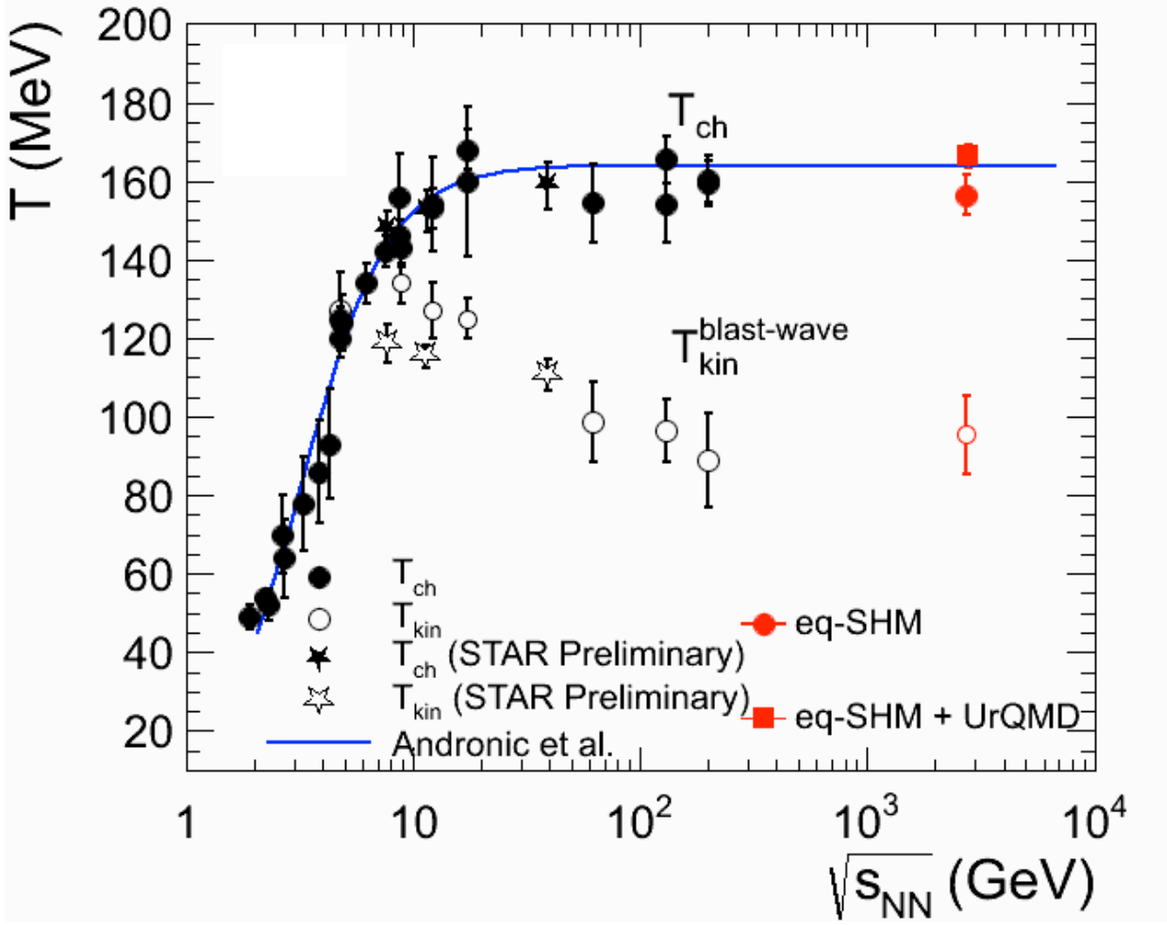

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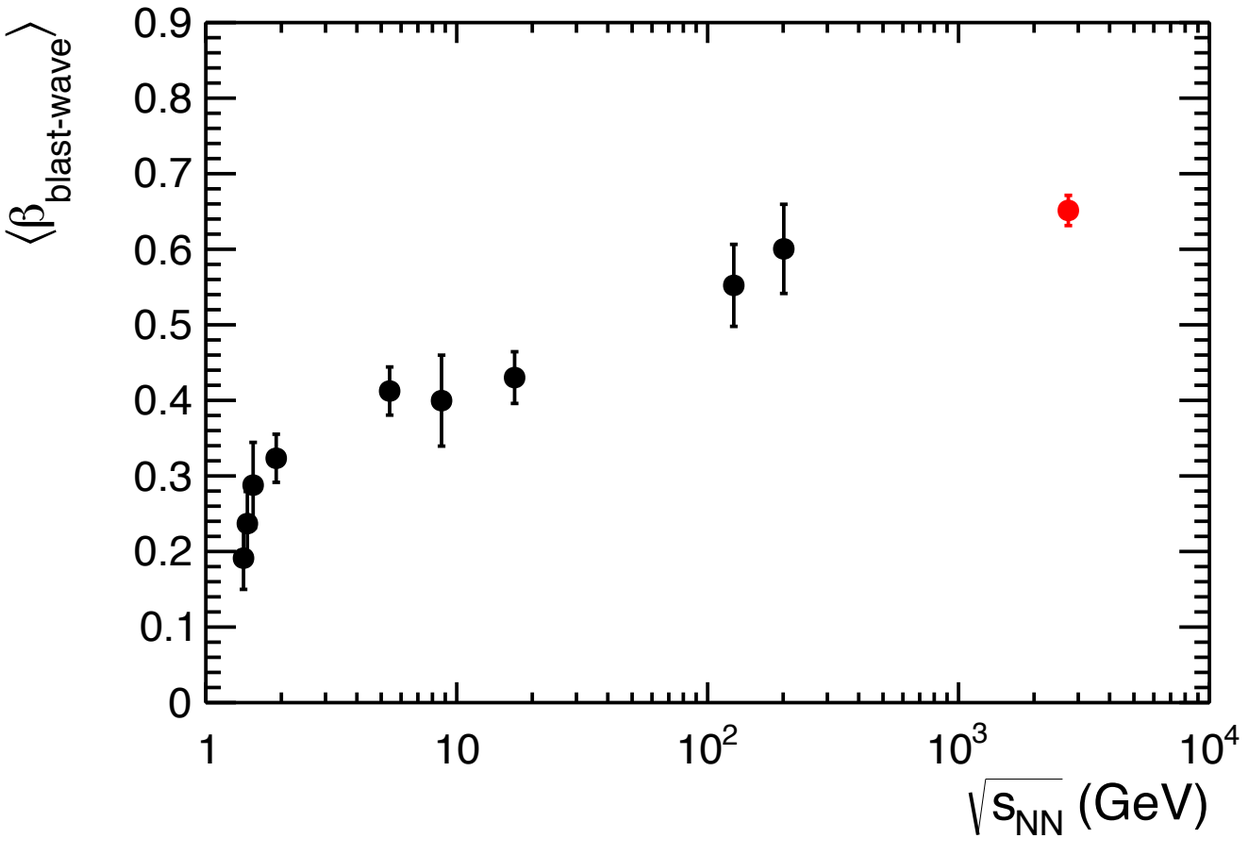

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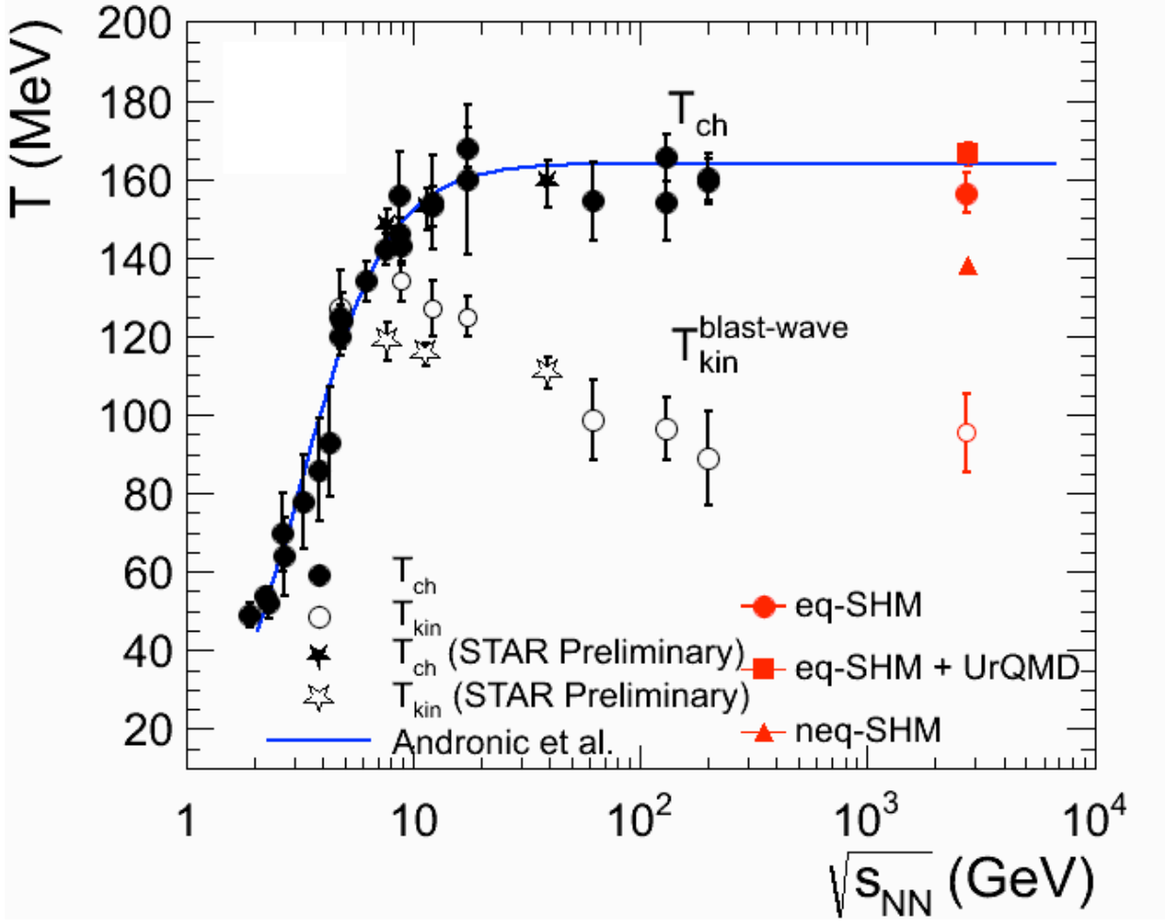
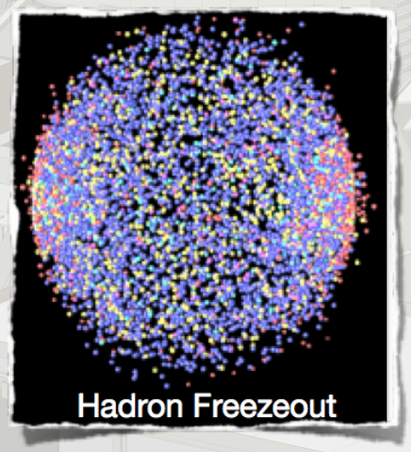


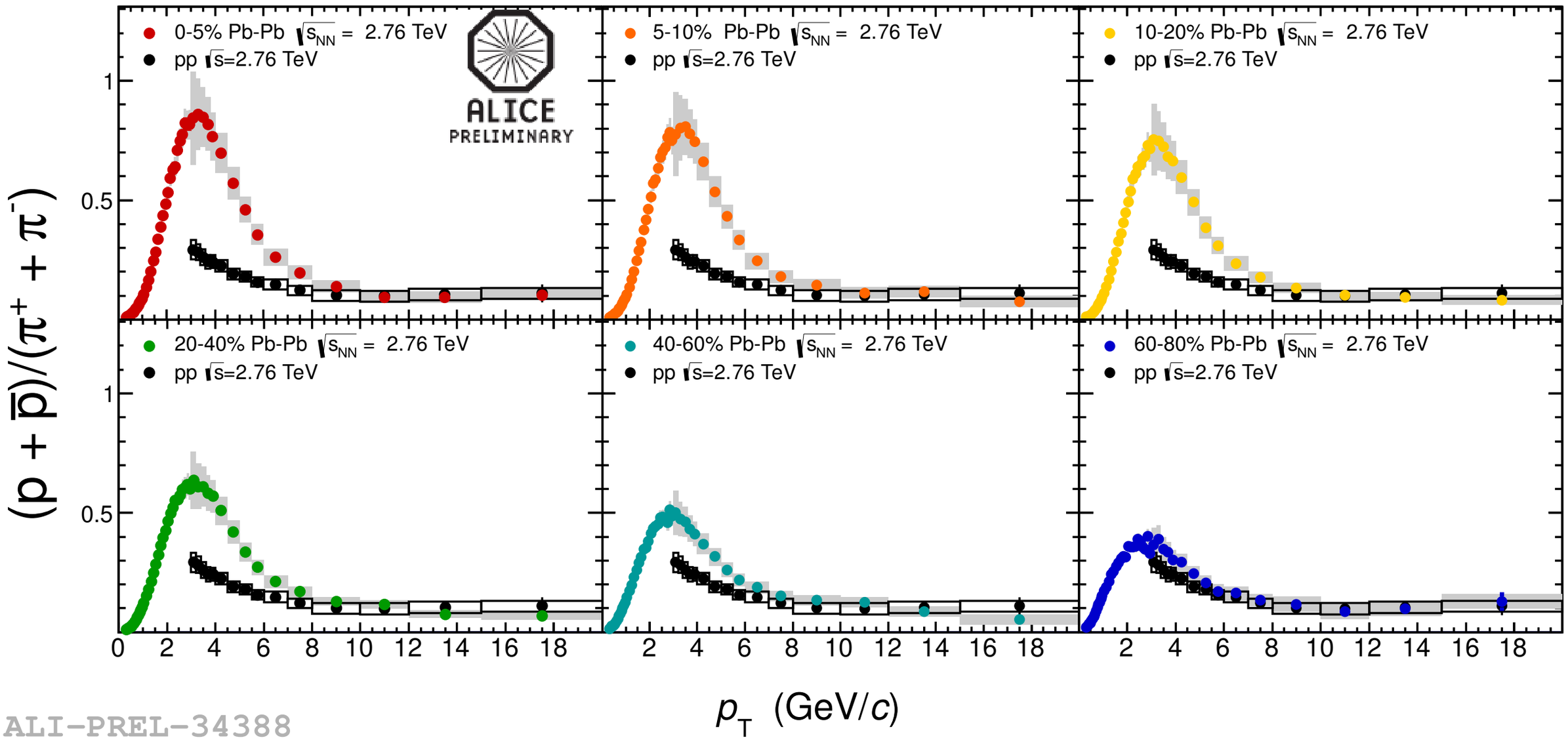
Smooth trend from lower energy
Chemical equilibrium?

T compilation, Mohanty et al, STAR collaboration
⟨ β ⟩ compilation from Xu, Prog. in Part. Nucl. Phys. 53, 165

Intermediate p_T



p/π ratio as a function of centrality



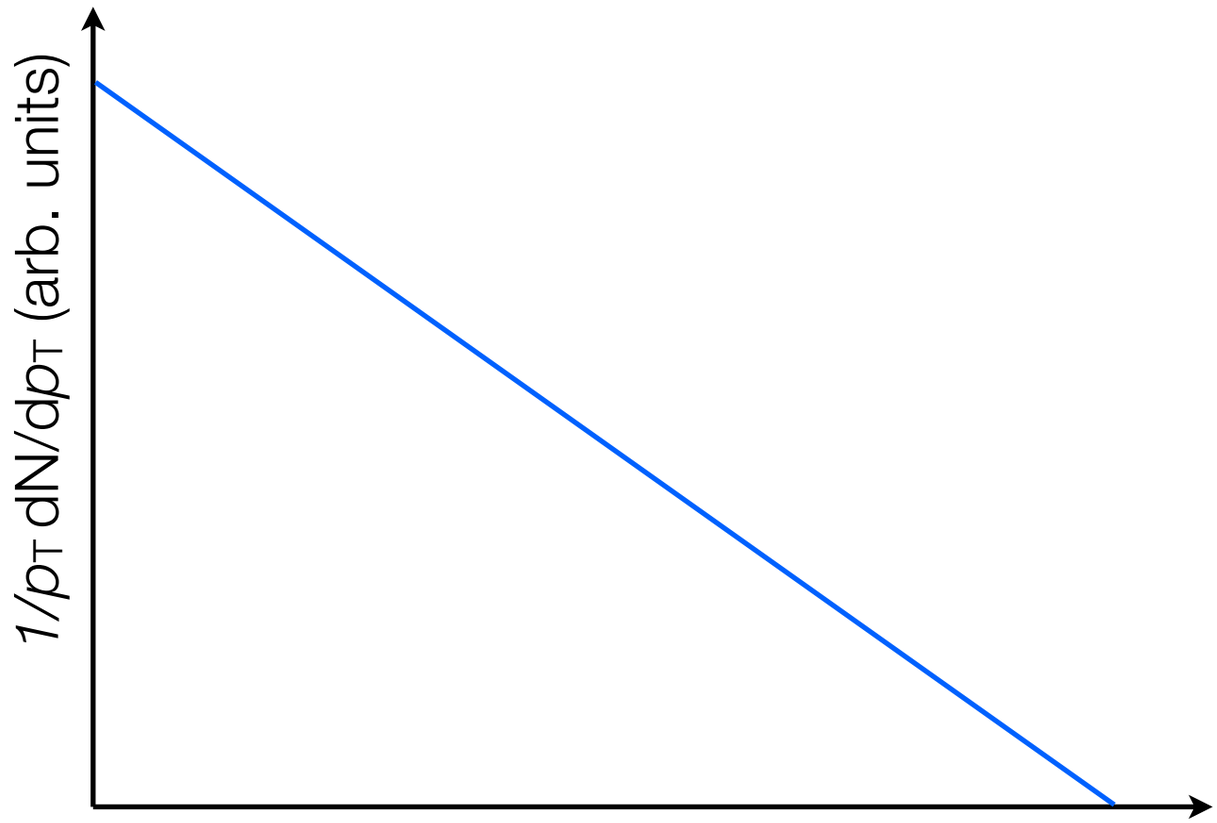
ALI-PREL-34388

Strong increase of the p/π ratio at intermediate p_T

Decrease at high p_T

Push from radial flow?

Quark coalescence



Fragmentation: single parton with $p_T > p_T^{[hadron]}$

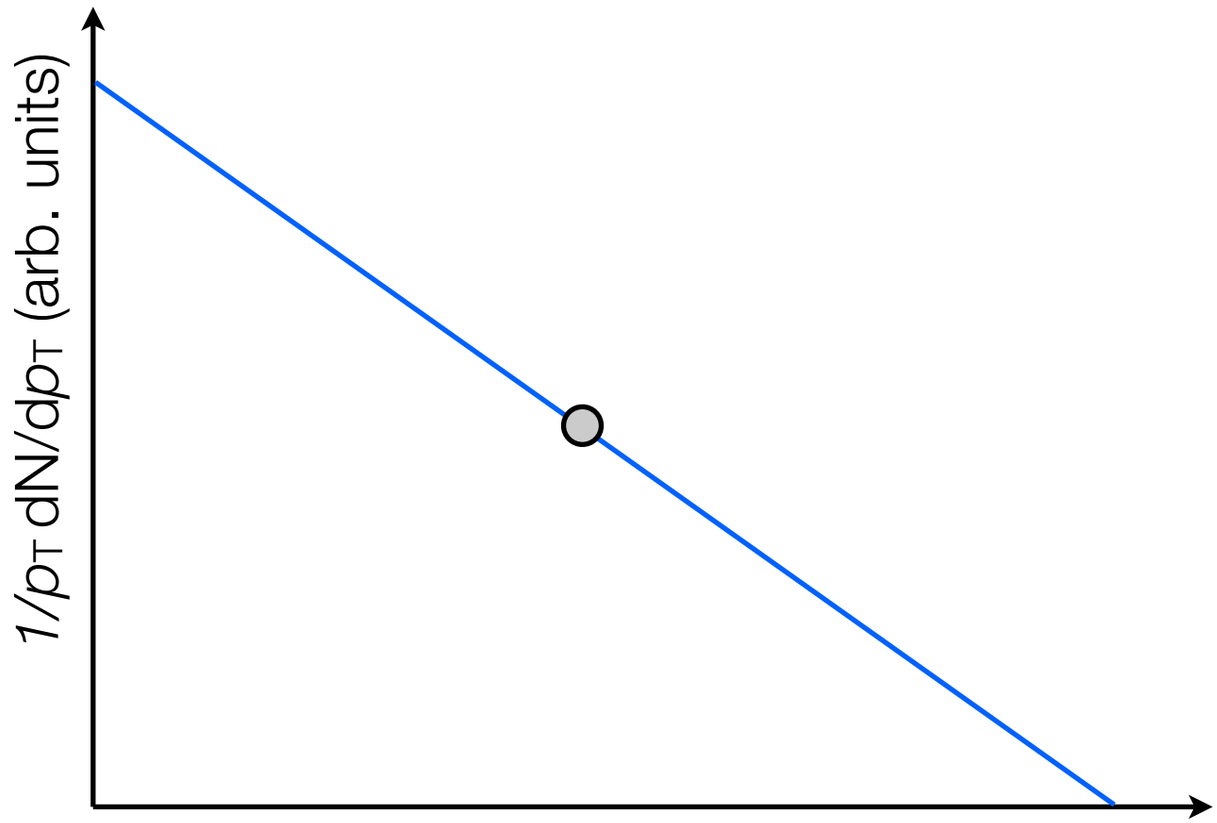
Recombination: 2(3) partons with $p_T \sim p_T^{[hadron]}/2(3)$

⇒ enhances B/M

In some models: thermal + minijet recombination

recent review: Greco, Fries, Sorensen, Annu. Rev. Nucl. Part. Sci. 2008.58:177-205.

Quark coalescence



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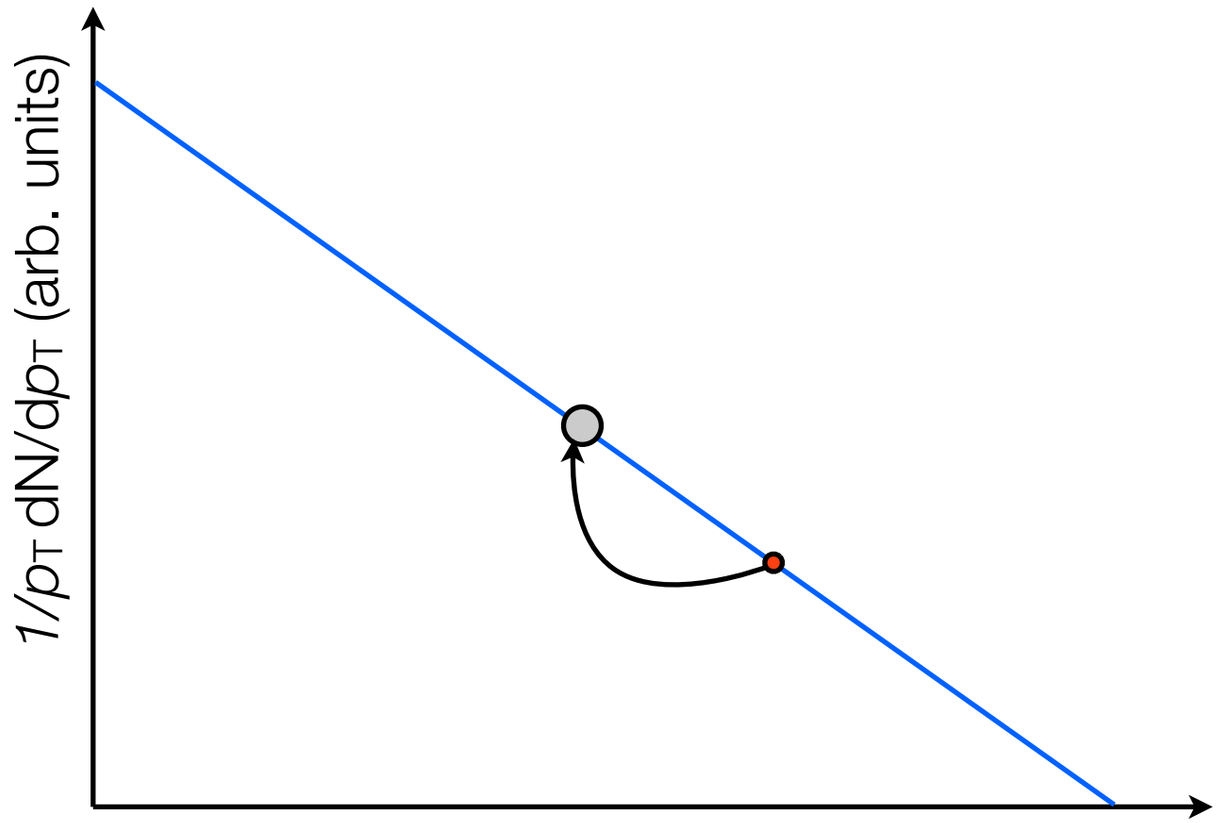

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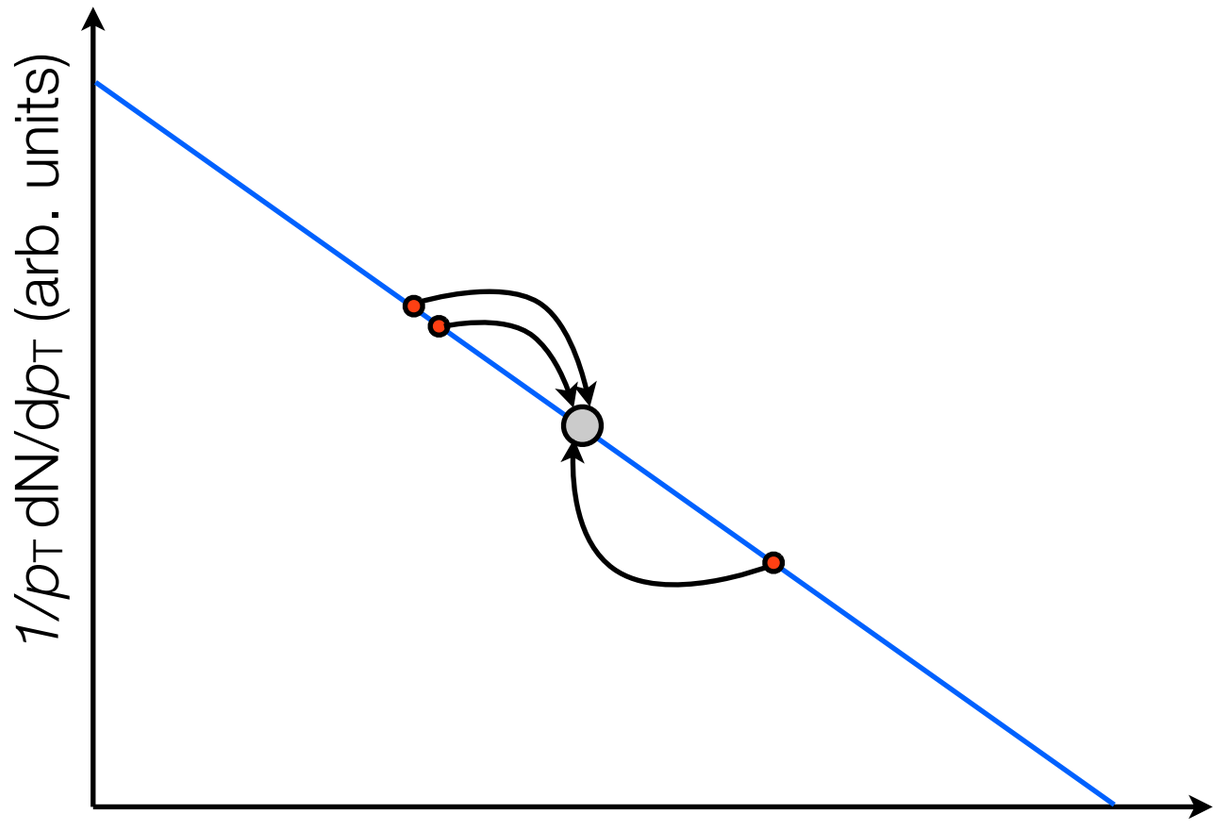

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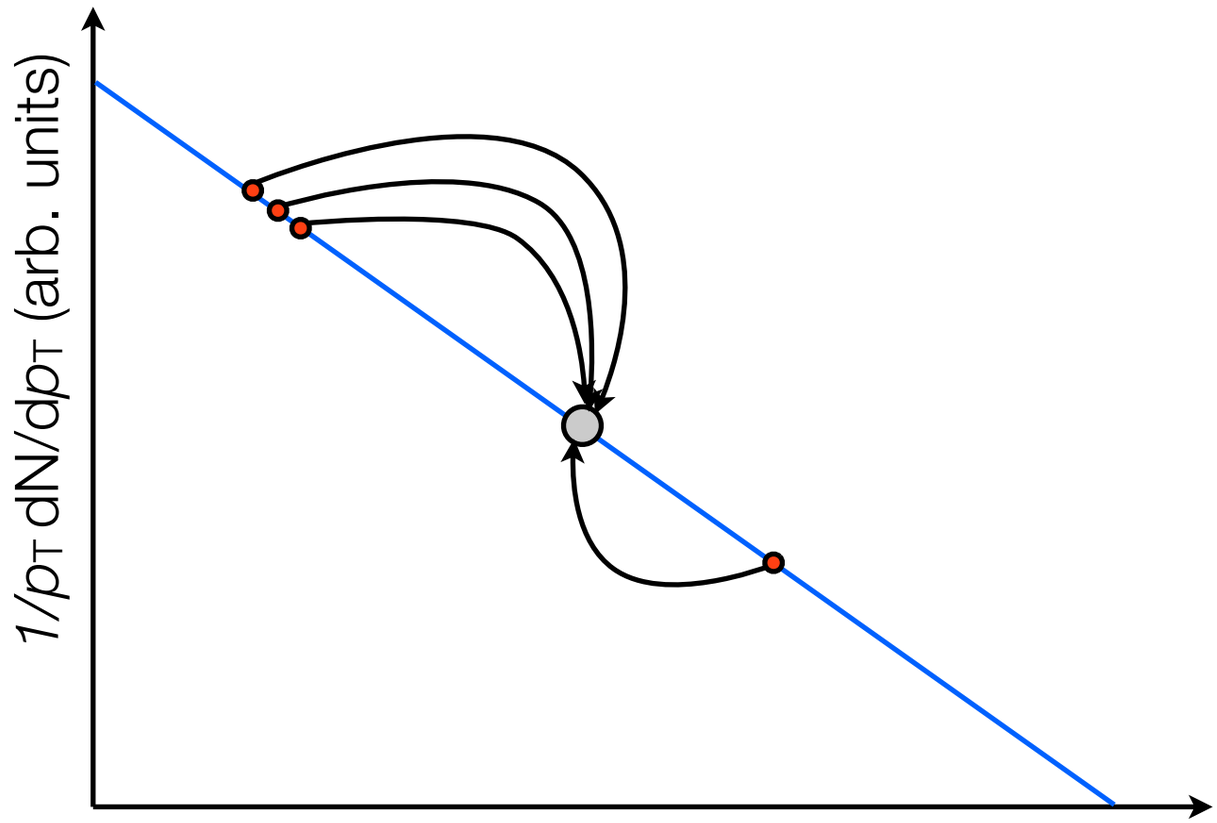

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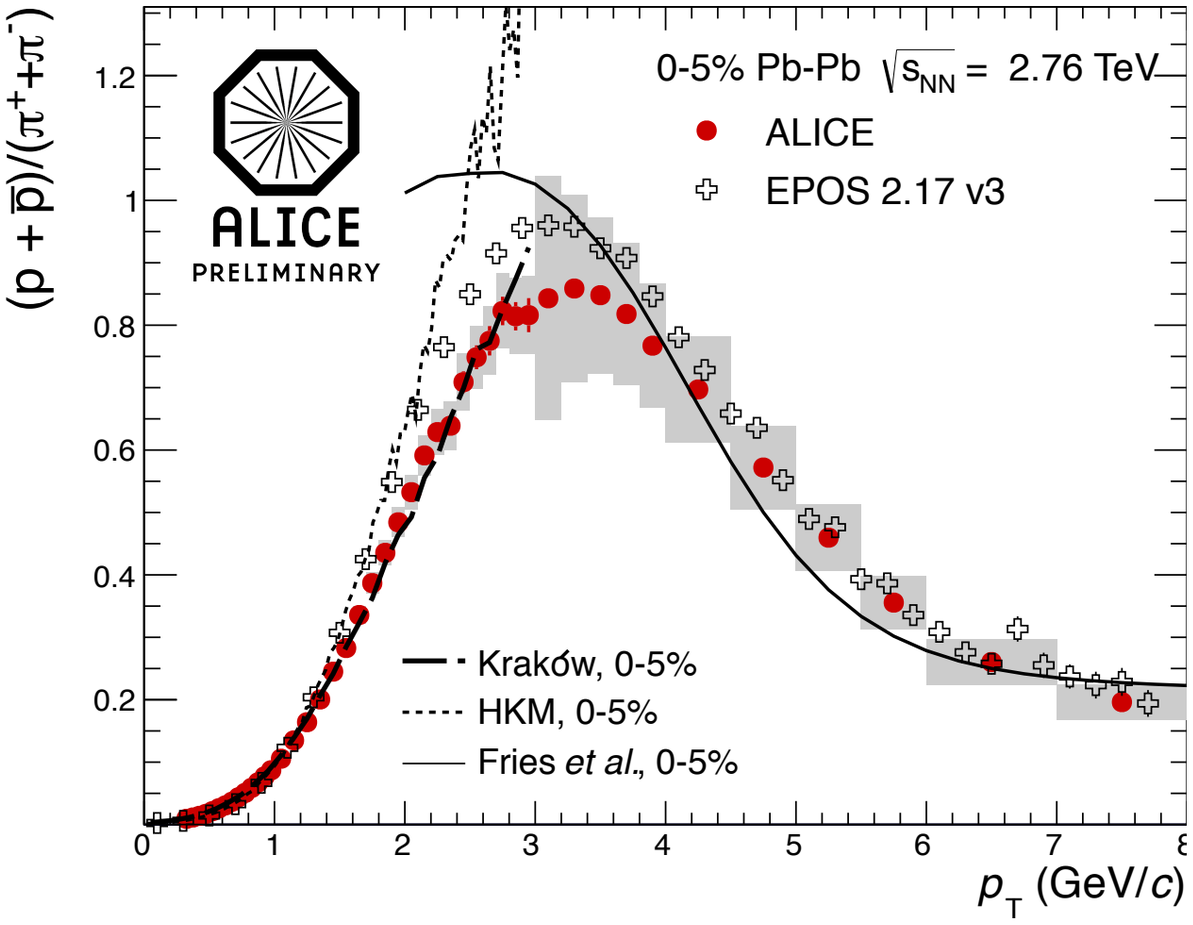
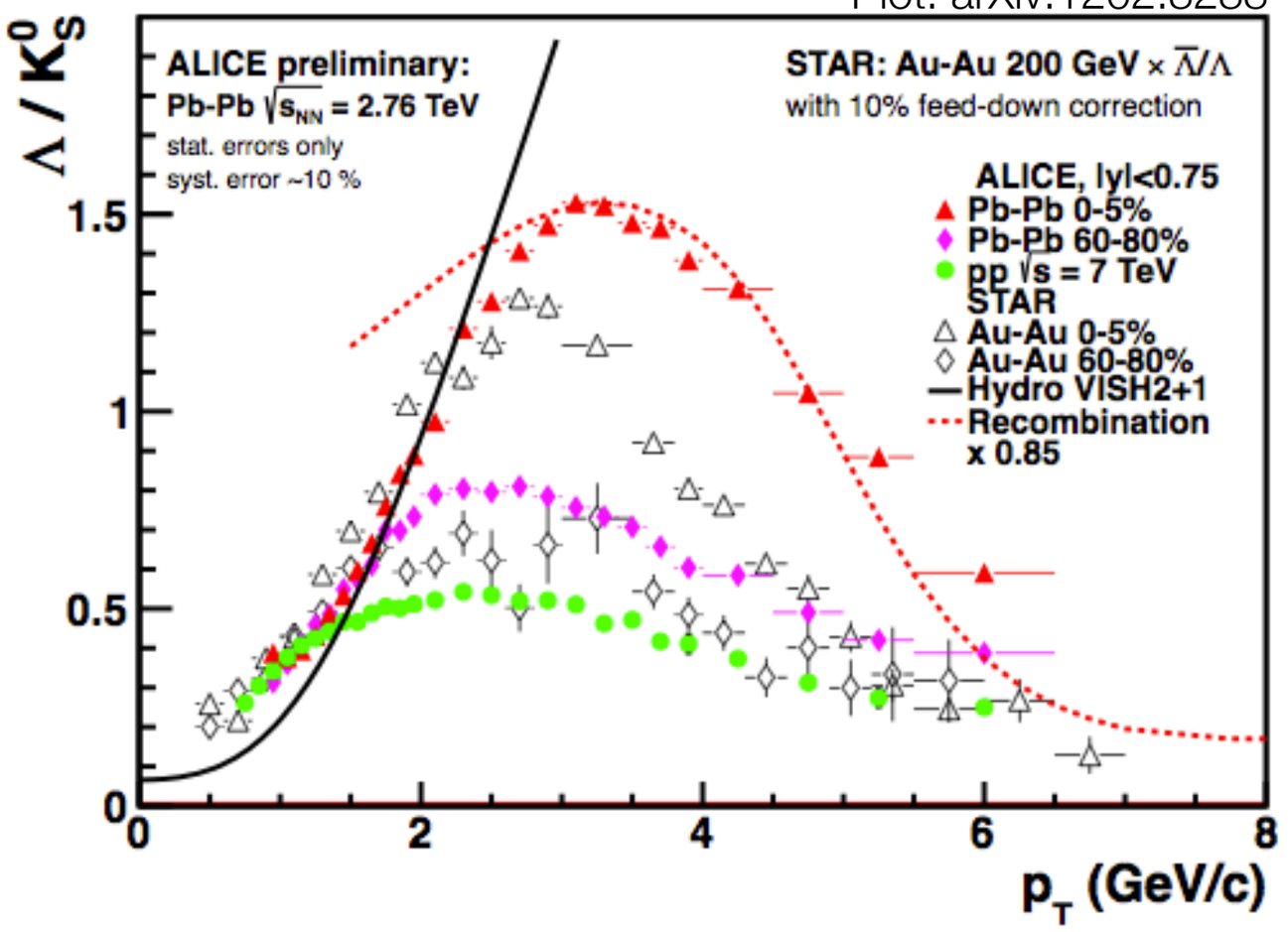
p/π and Λ/K^0_s



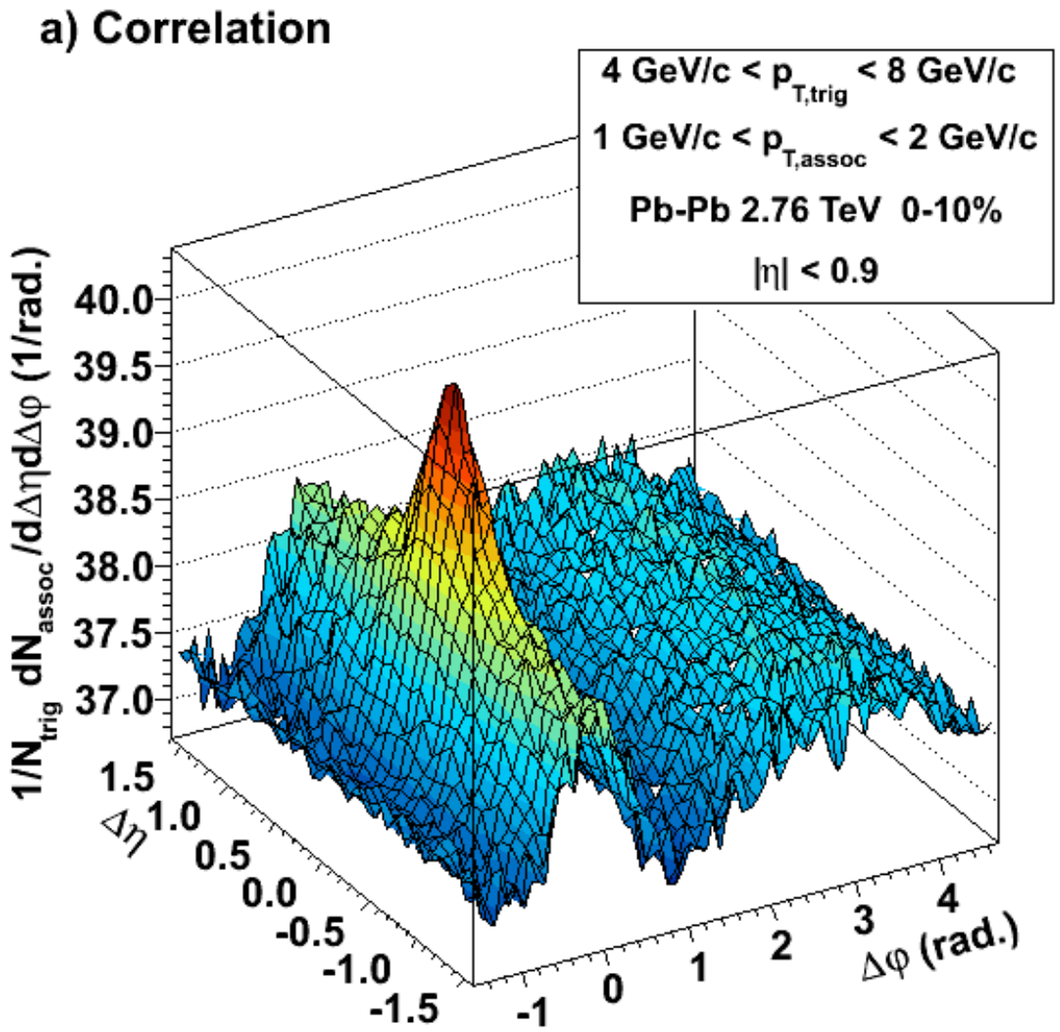
Plot: arXiv:1202.3233



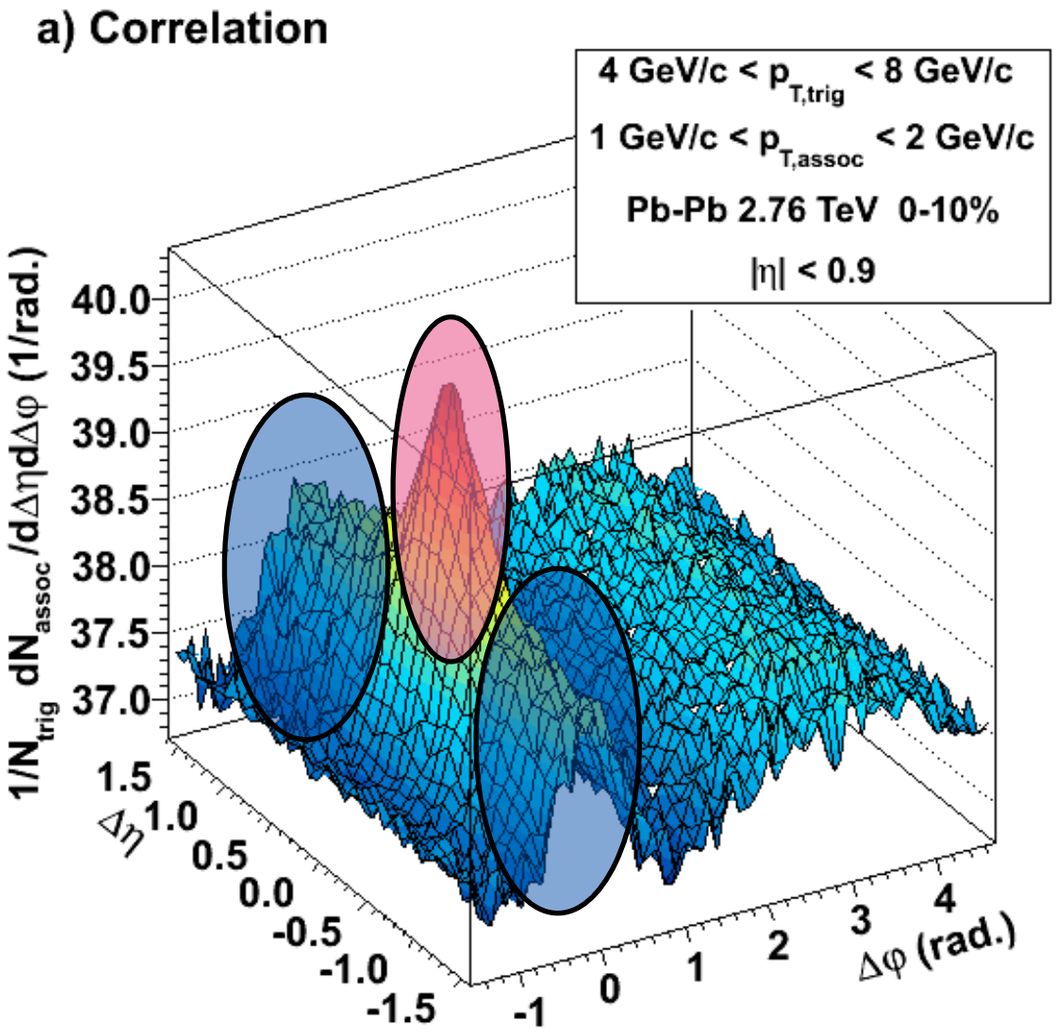
- Measurement of additional particles
- Consistent description of different ratios in the same models?

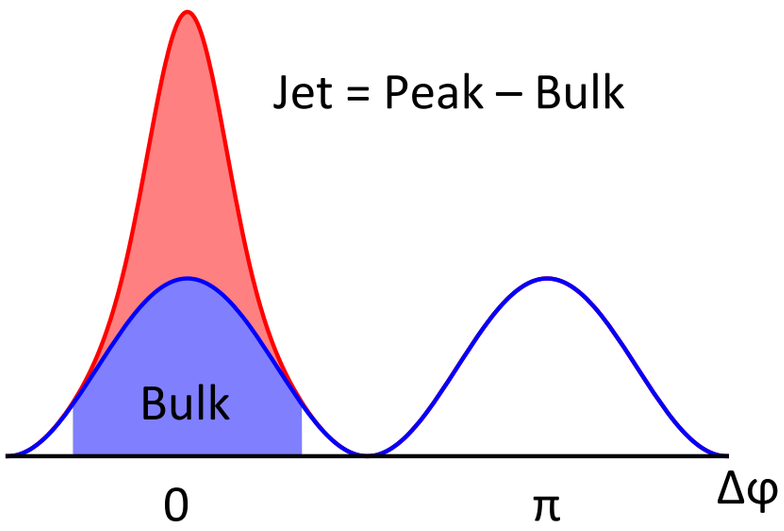
Recombination: Fries et al., Private communication; PRL. 90, 202303; PRC 68, 044902

Intermediate p_T in the bulk and in the jet



Intermediate p_T in the bulk and in the jet





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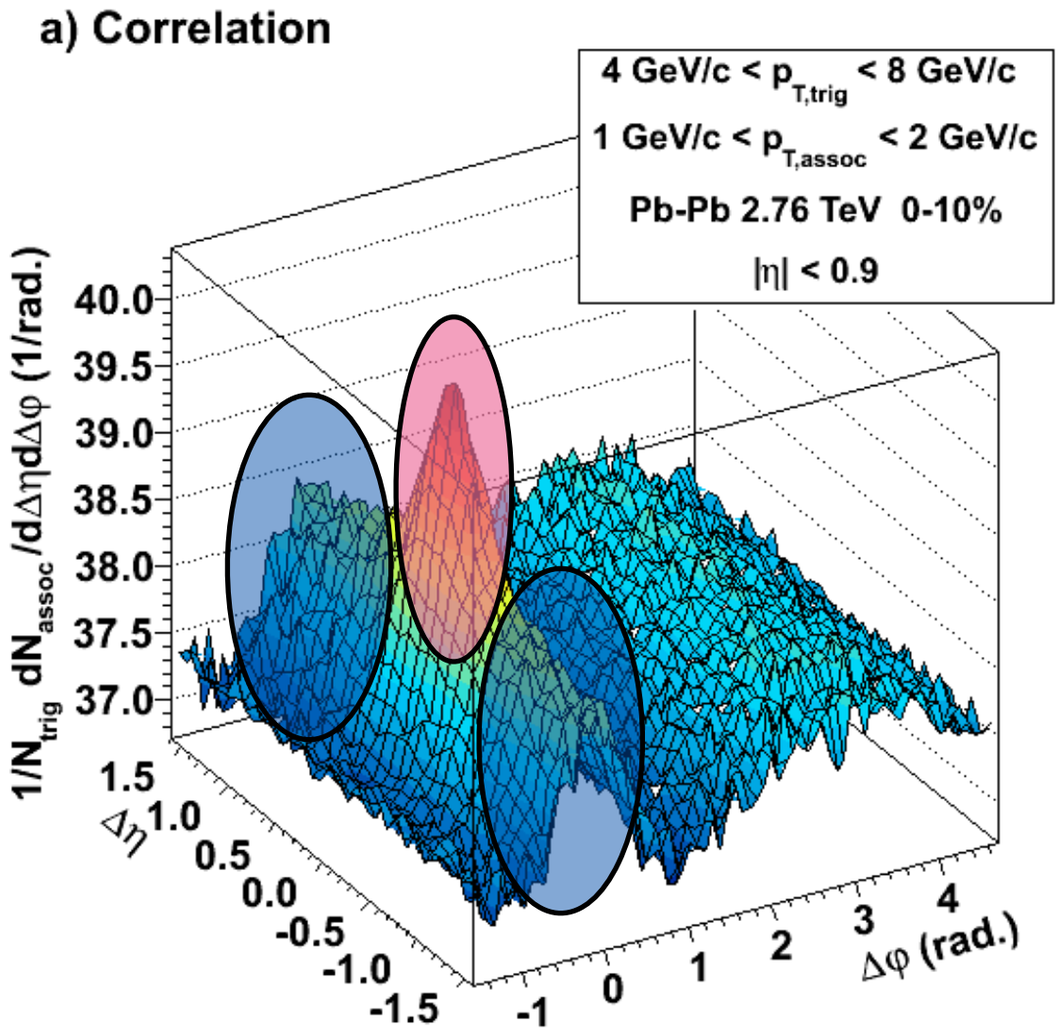

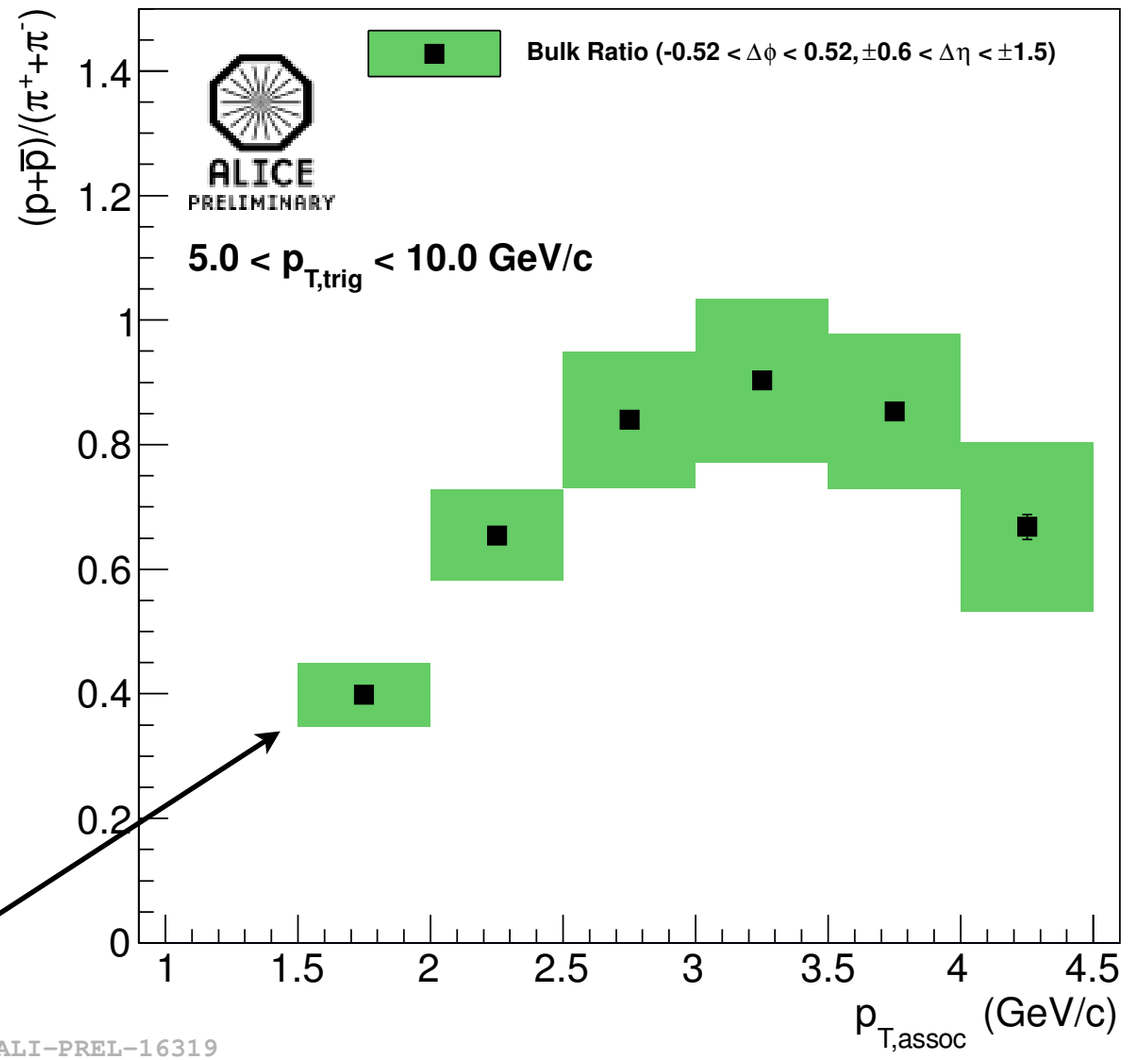

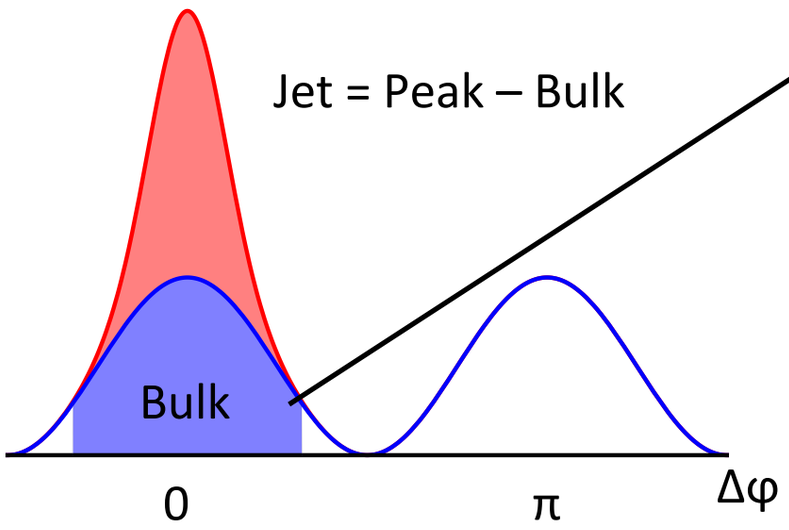

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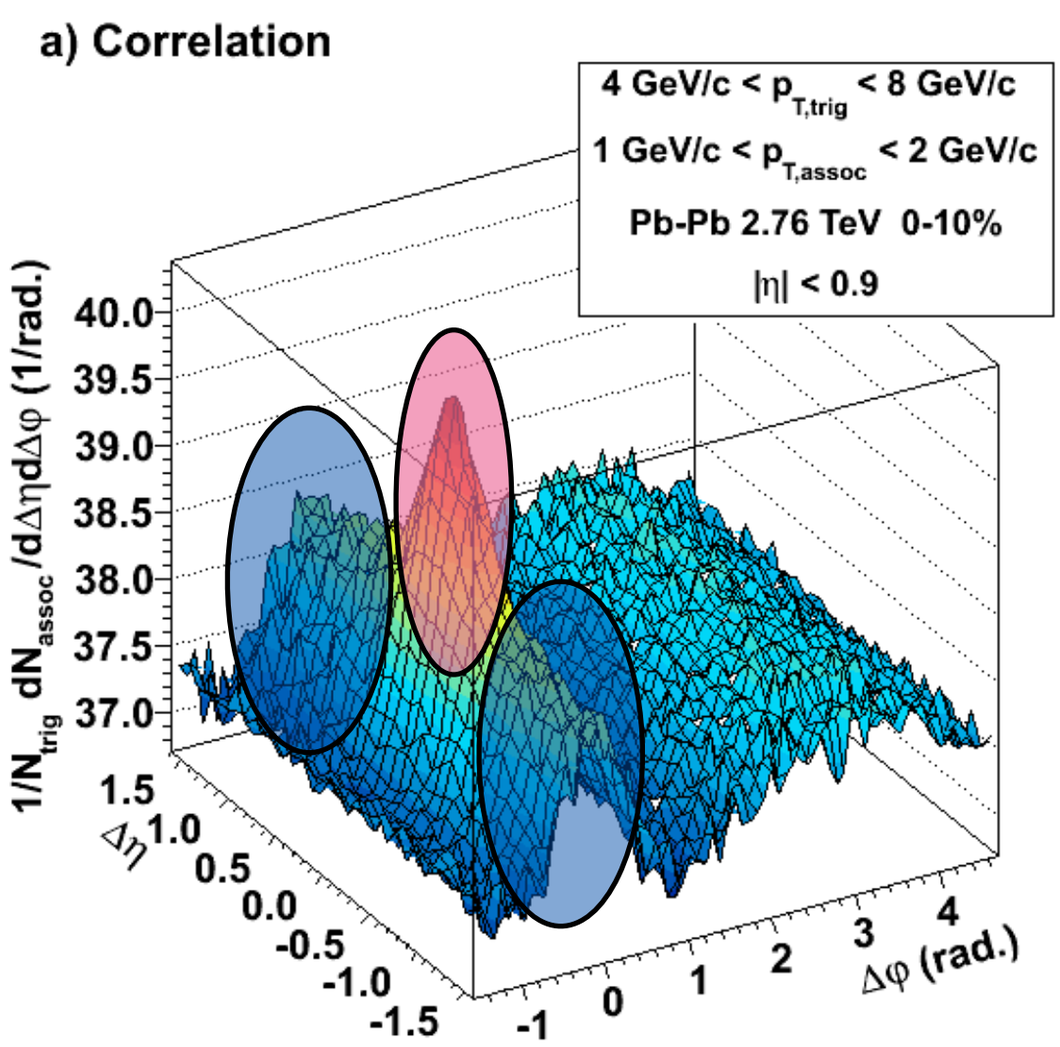

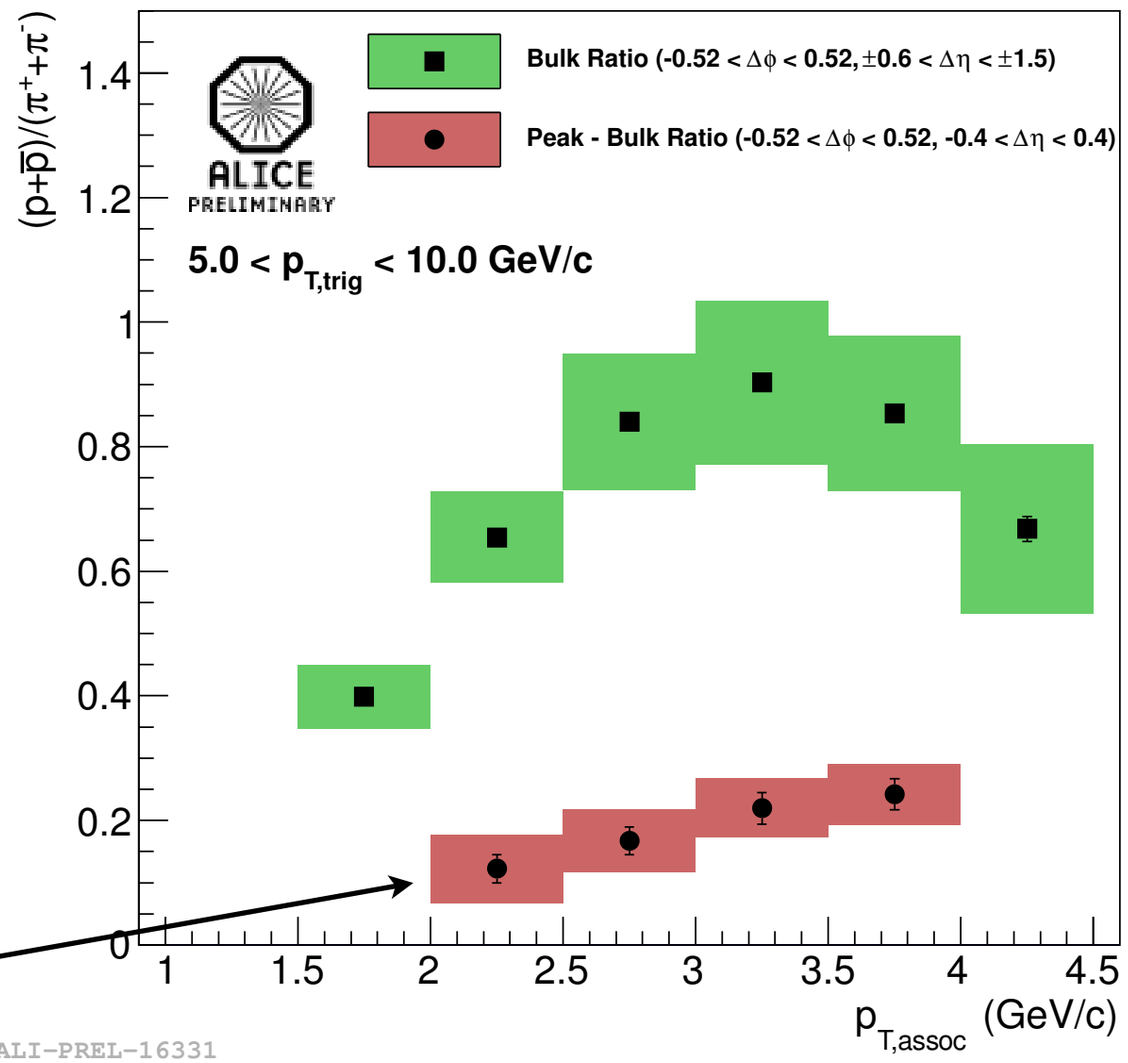

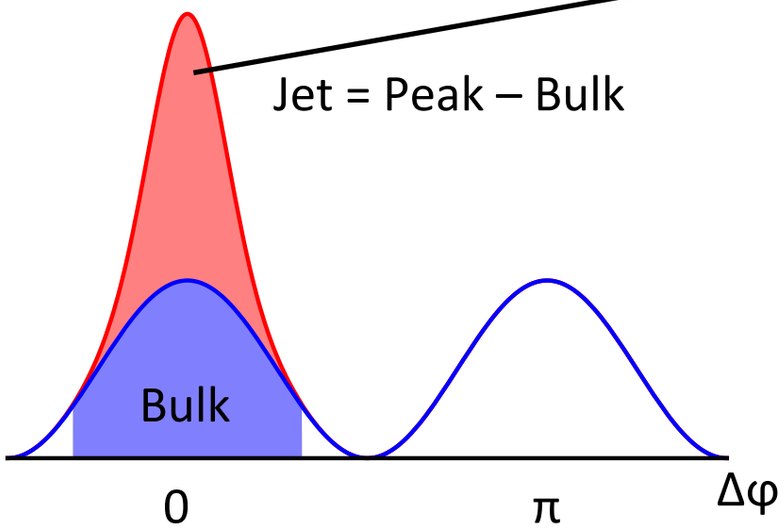

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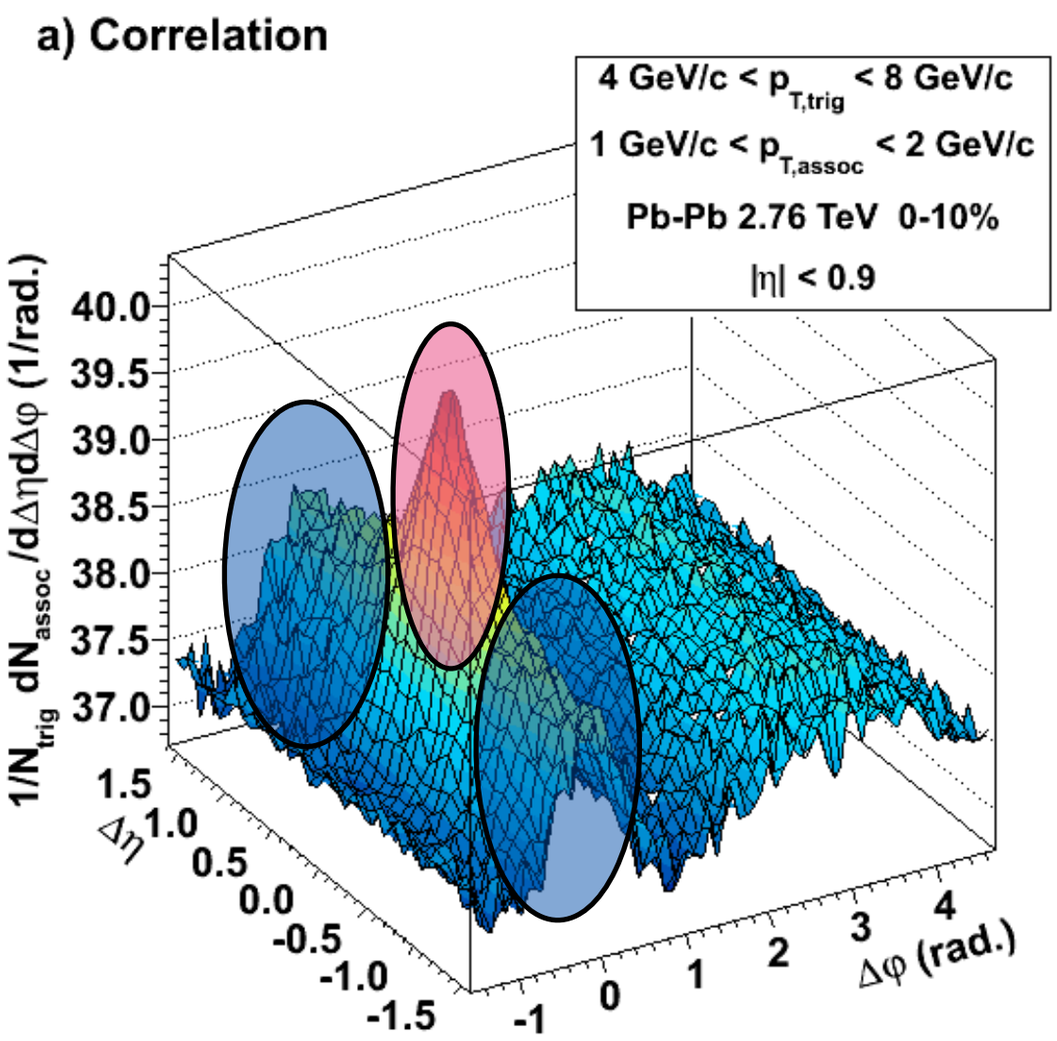

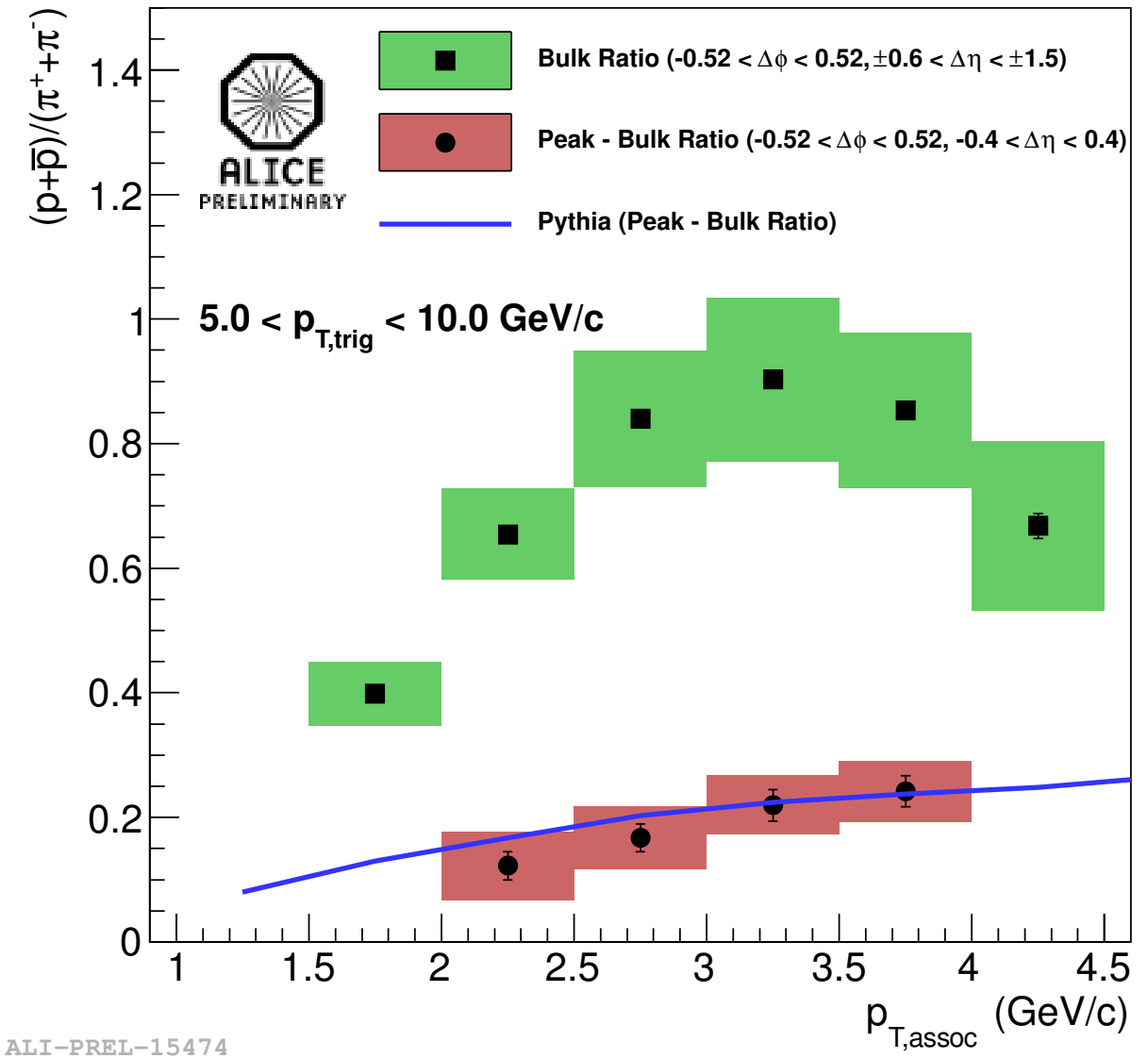

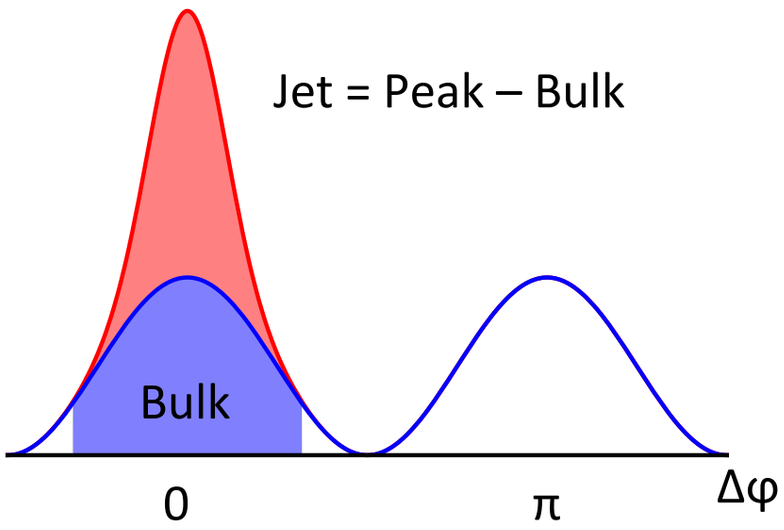

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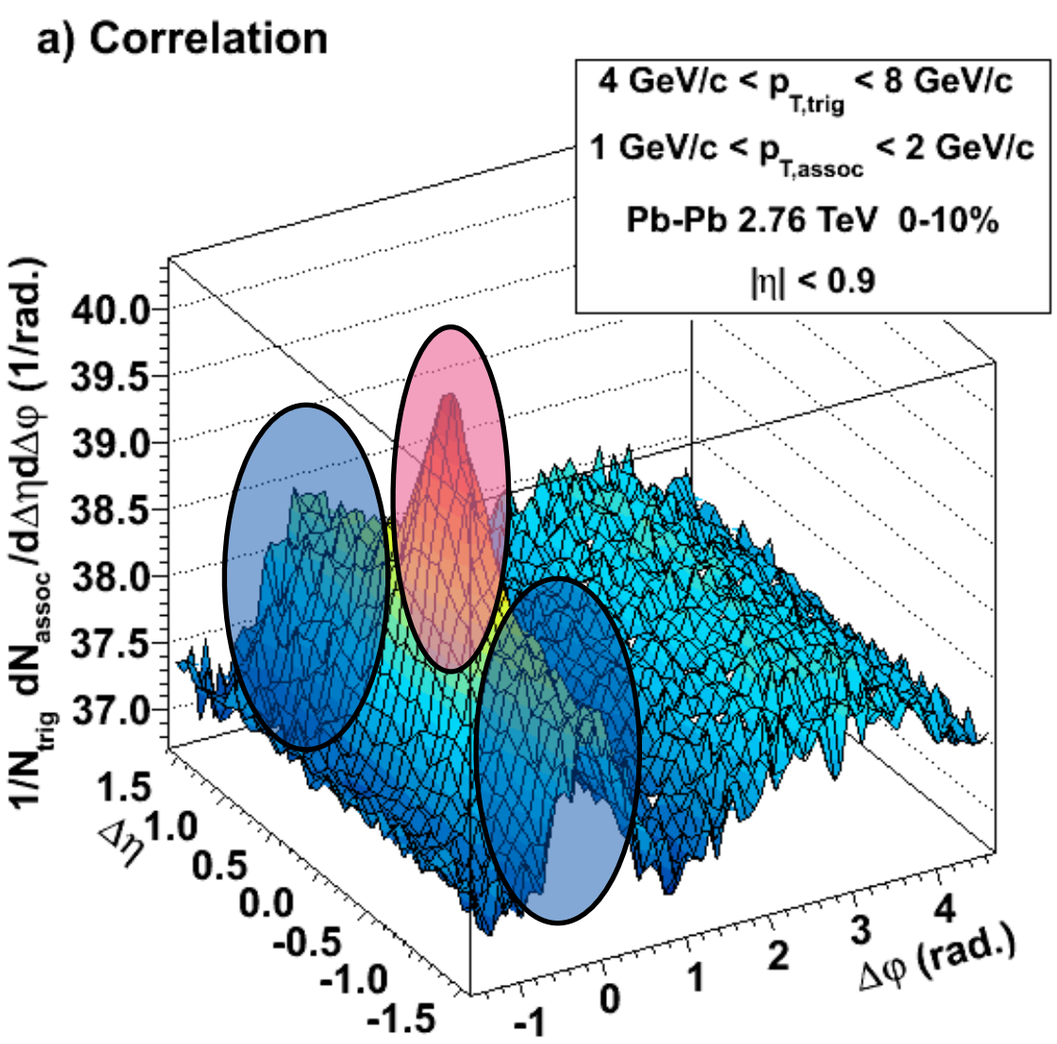
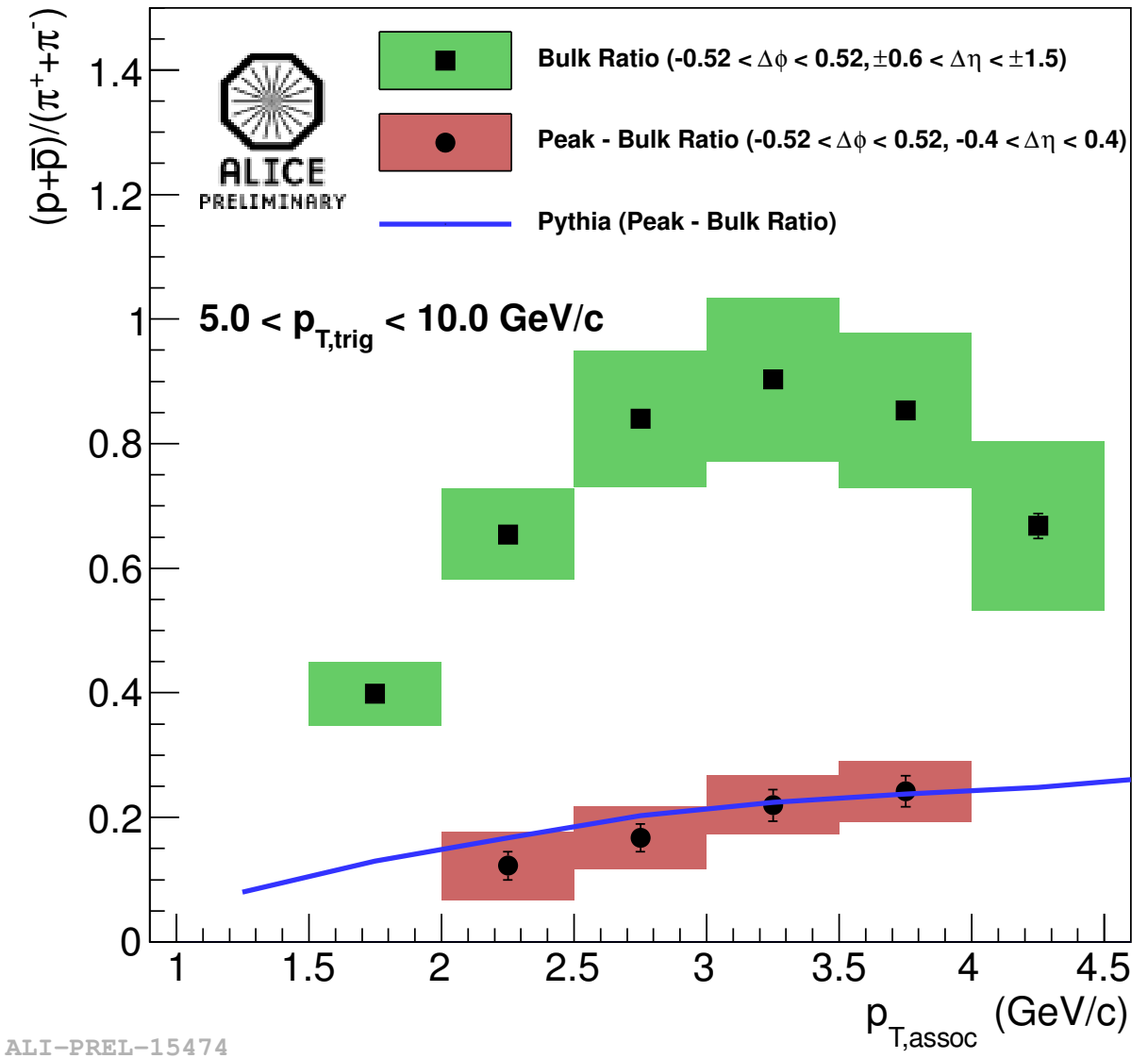
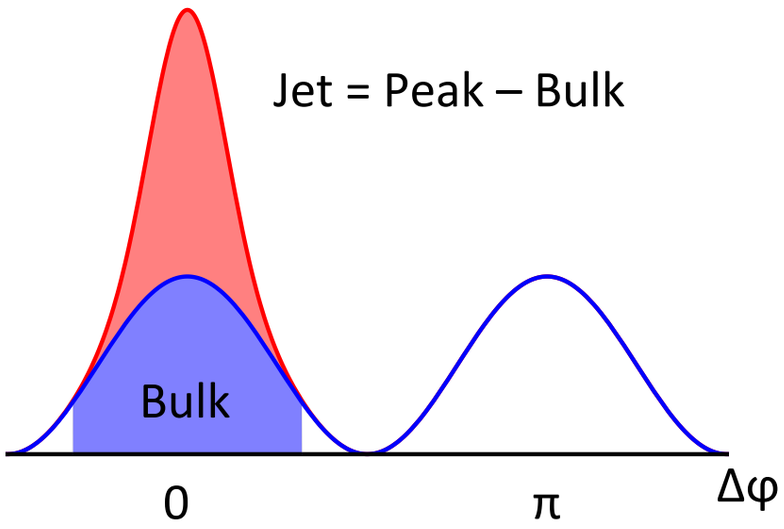


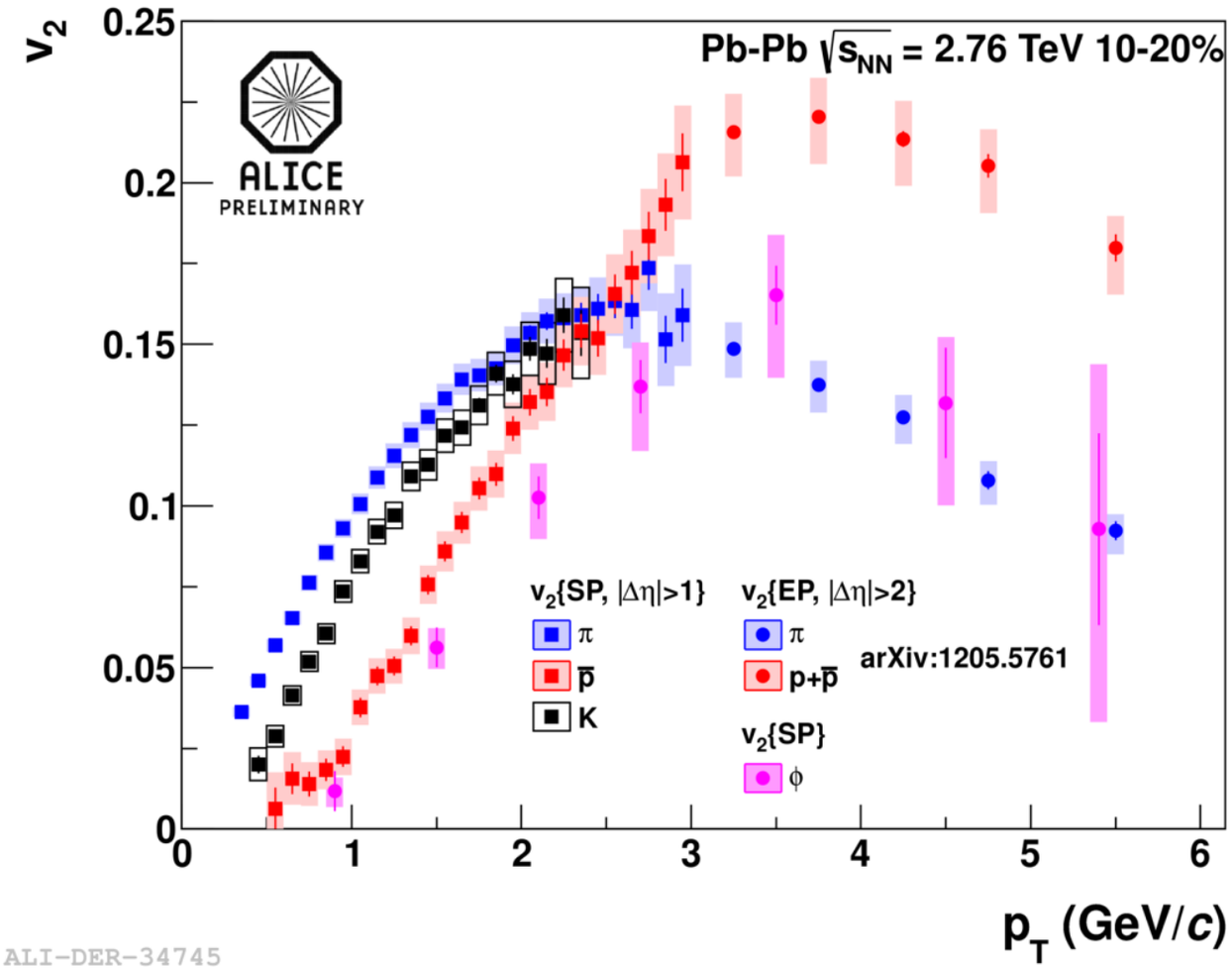


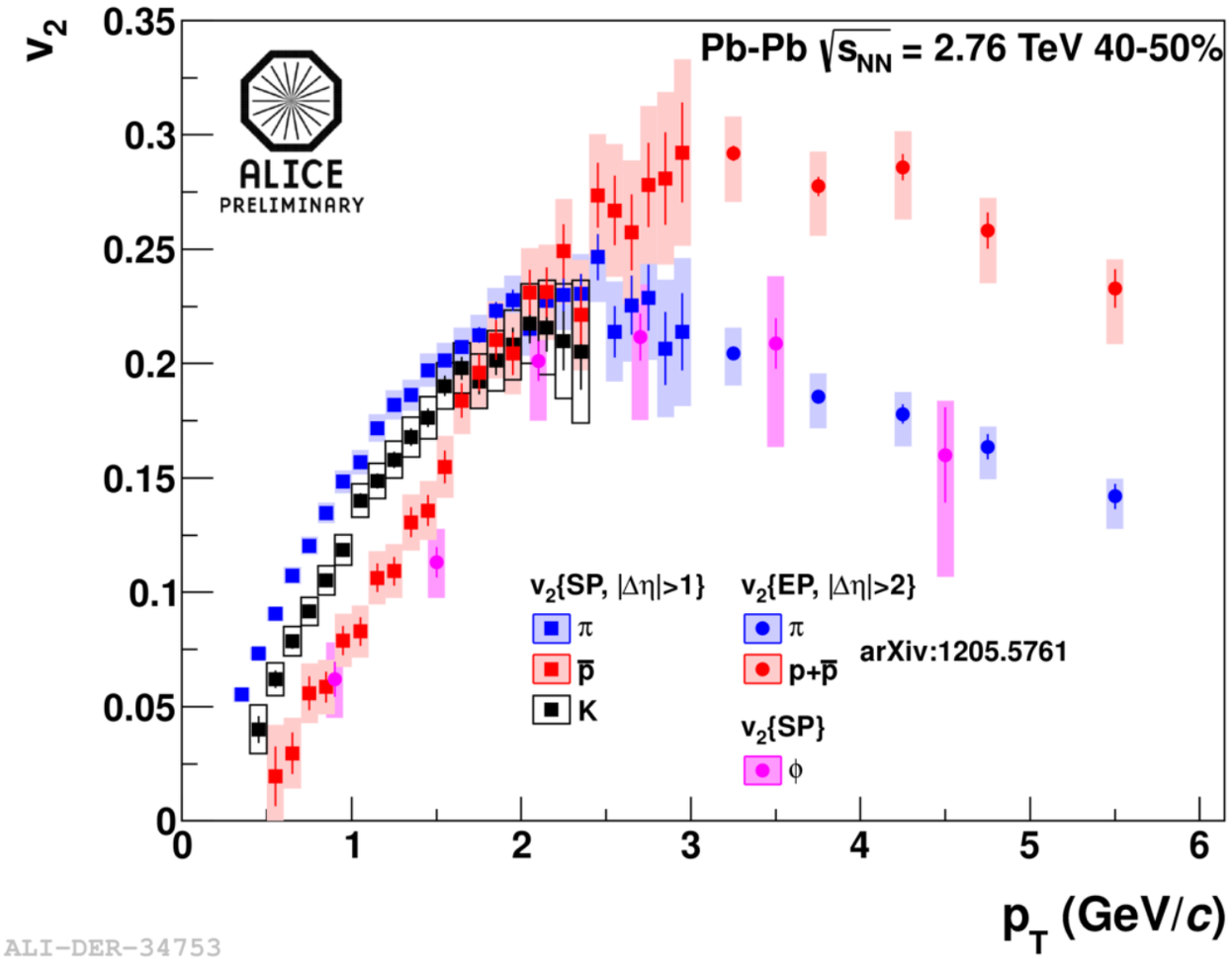


The "baryon anomaly" is a bulk effect!

Surface bias, effect on the away side?

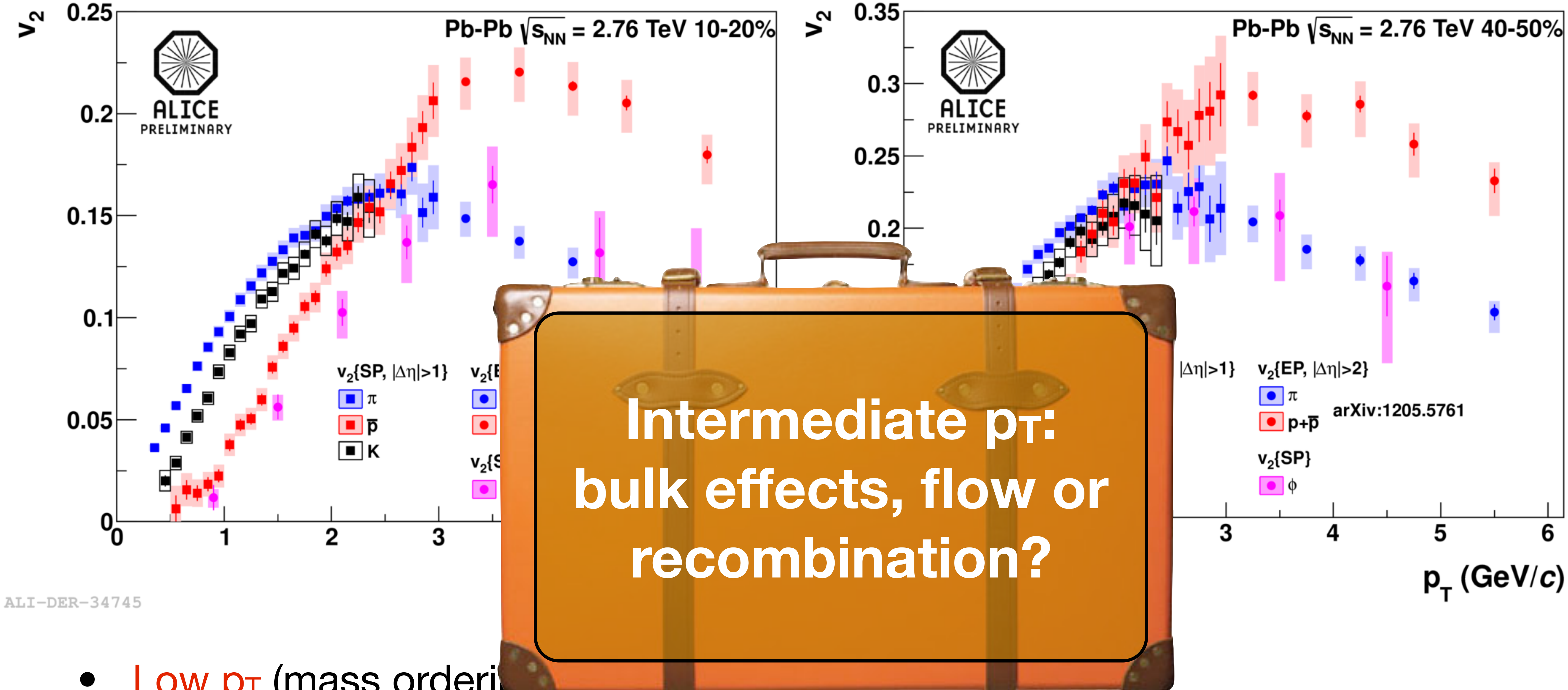
v_2 of ϕ meson





- Low p_T (mass ordering?): ϕ-meson v_2 ~ proton v_2
  - Anisotropic flow is affected by radial boost?
- High p_T (baryon/meson ordering?) ϕ-meson v_2 ~ pions v_2
  - coalescence?

v_2 of ϕ meson



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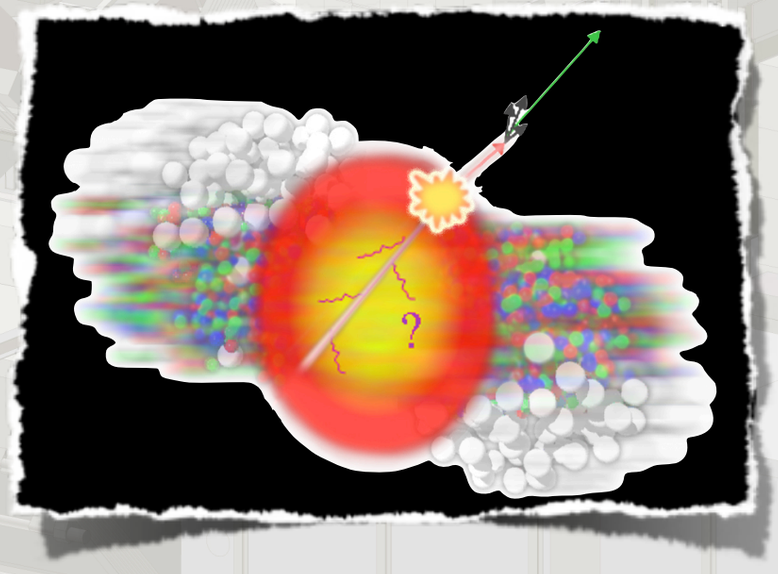
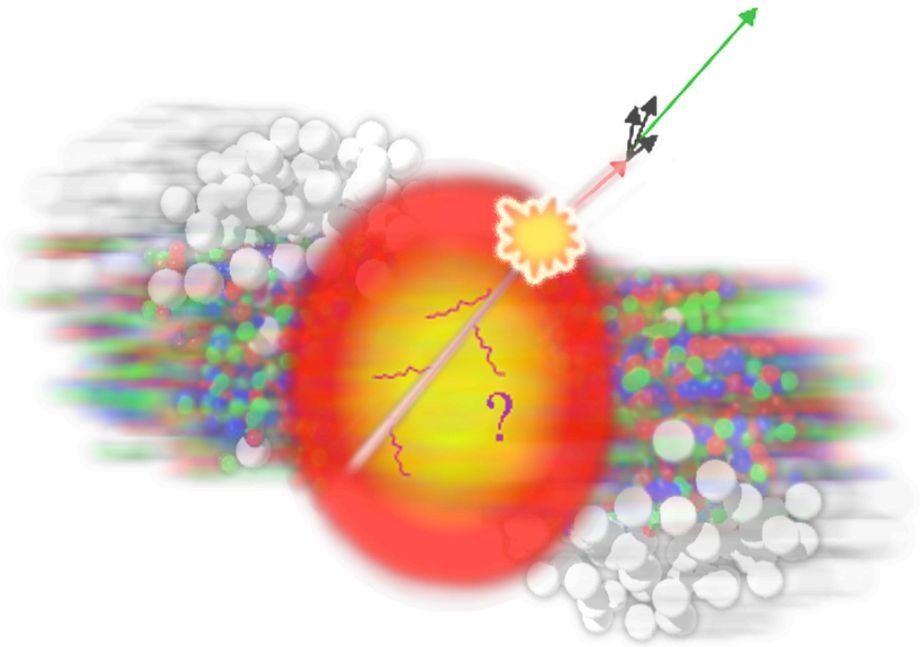
High p_T



High p_T suppression

Suppression of high p_T particles

Control experiment: p-Pb



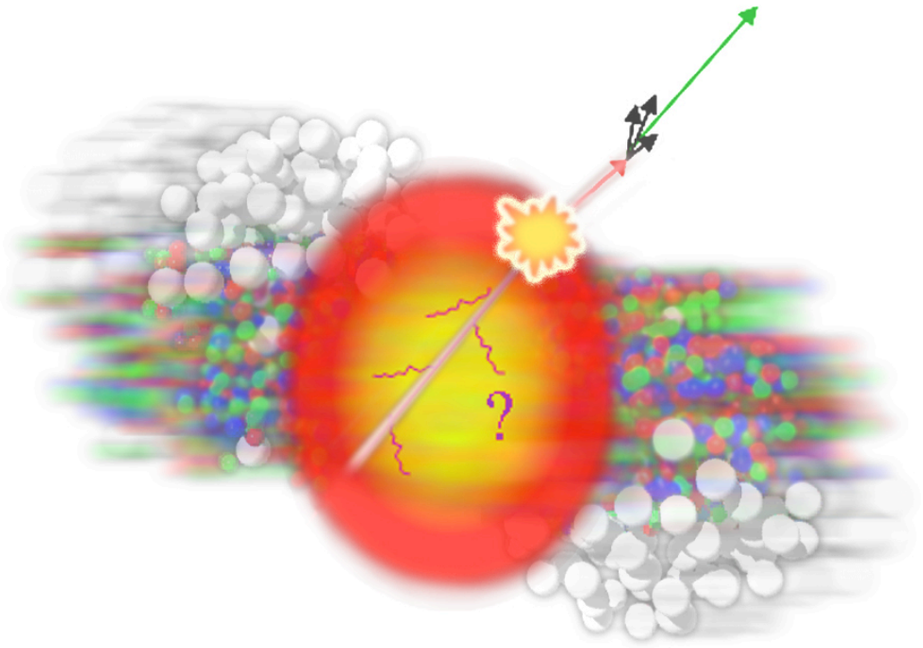
Studied through “nuclear modification factor” R_{AA}

$$R_{AA} = \frac{d^2N_{AA}/dp_{\mathrm{T}}dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_{\mathrm{T}}dy}$$

ALICE, PLB 720, 52
ALICE, PRL 110, 082302

High p_T suppression

Suppression of high p_T particles

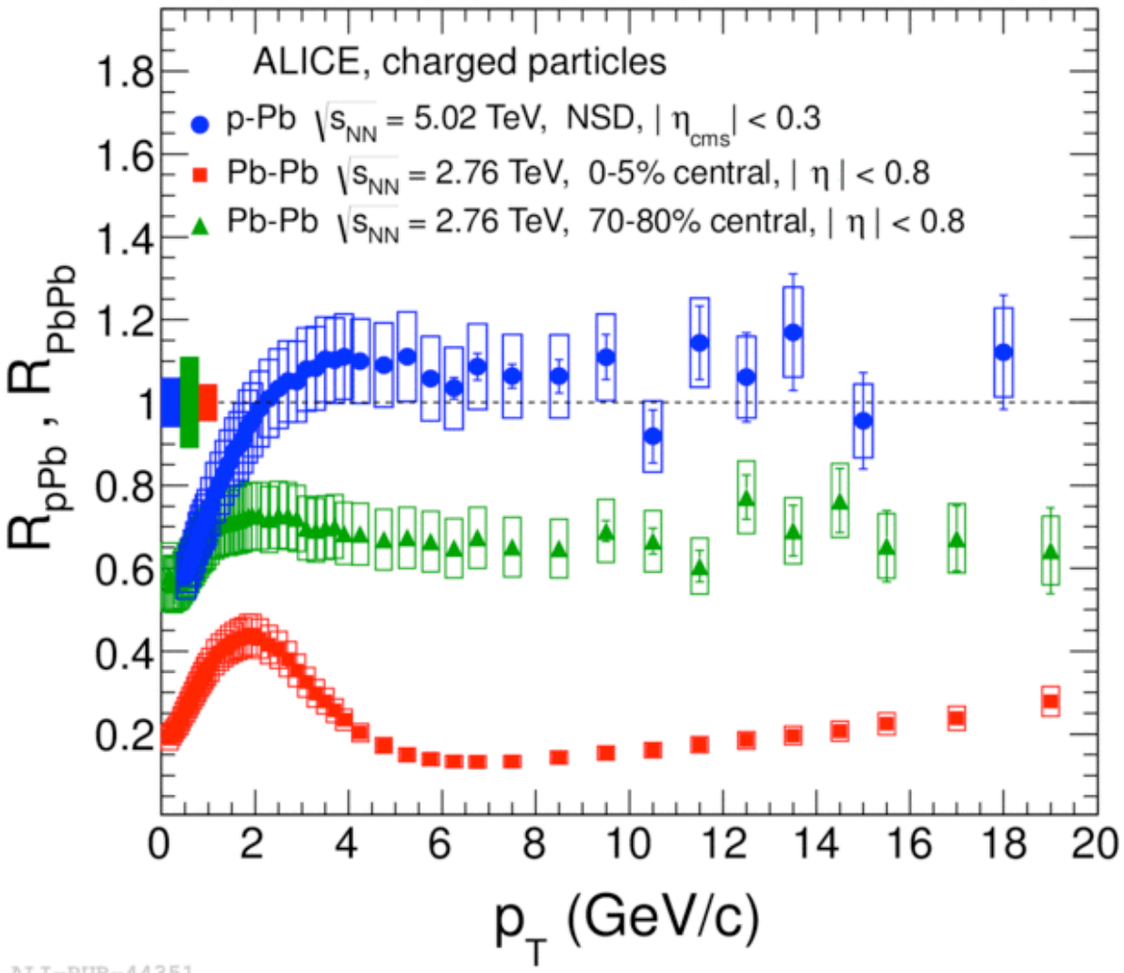


Studied through "nuclear modification factor" R_{AA}

$$R_{AA} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$

Control experiment: p-Pb

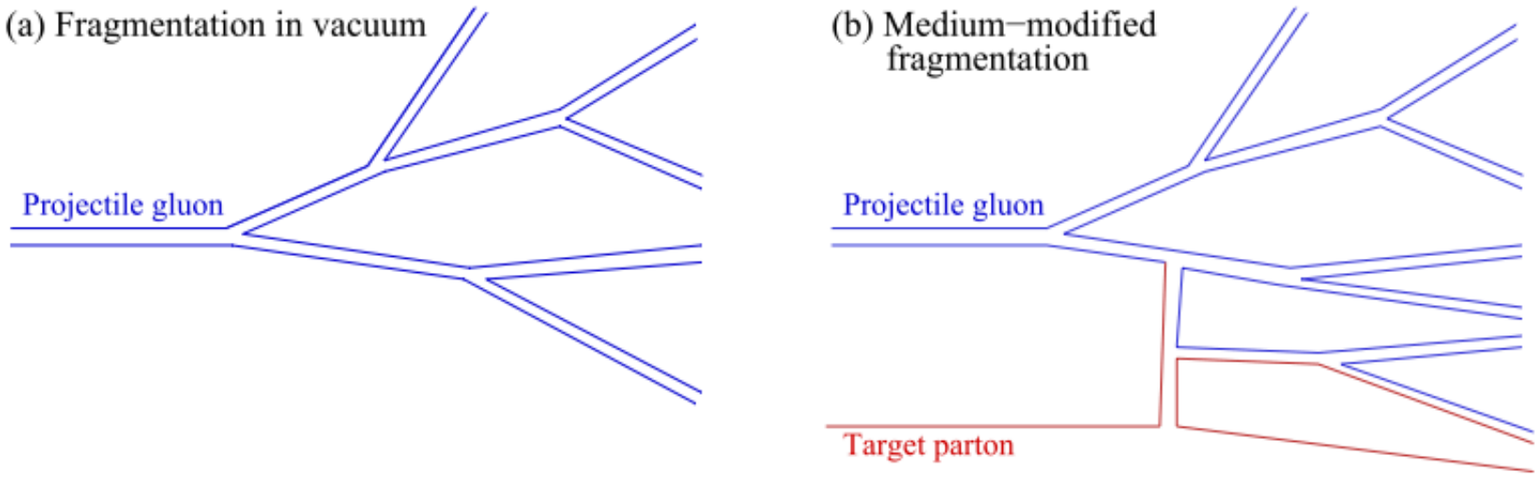
Not an initial state effect!



ALICE, PLB 720, 52
ALICE, PRL 110, 082302

Flavor dependence of R_{AA}?

- Quark jets vs gluon jets
- Color exchange with the medium



- Heavy flavor? (dead cone effect)

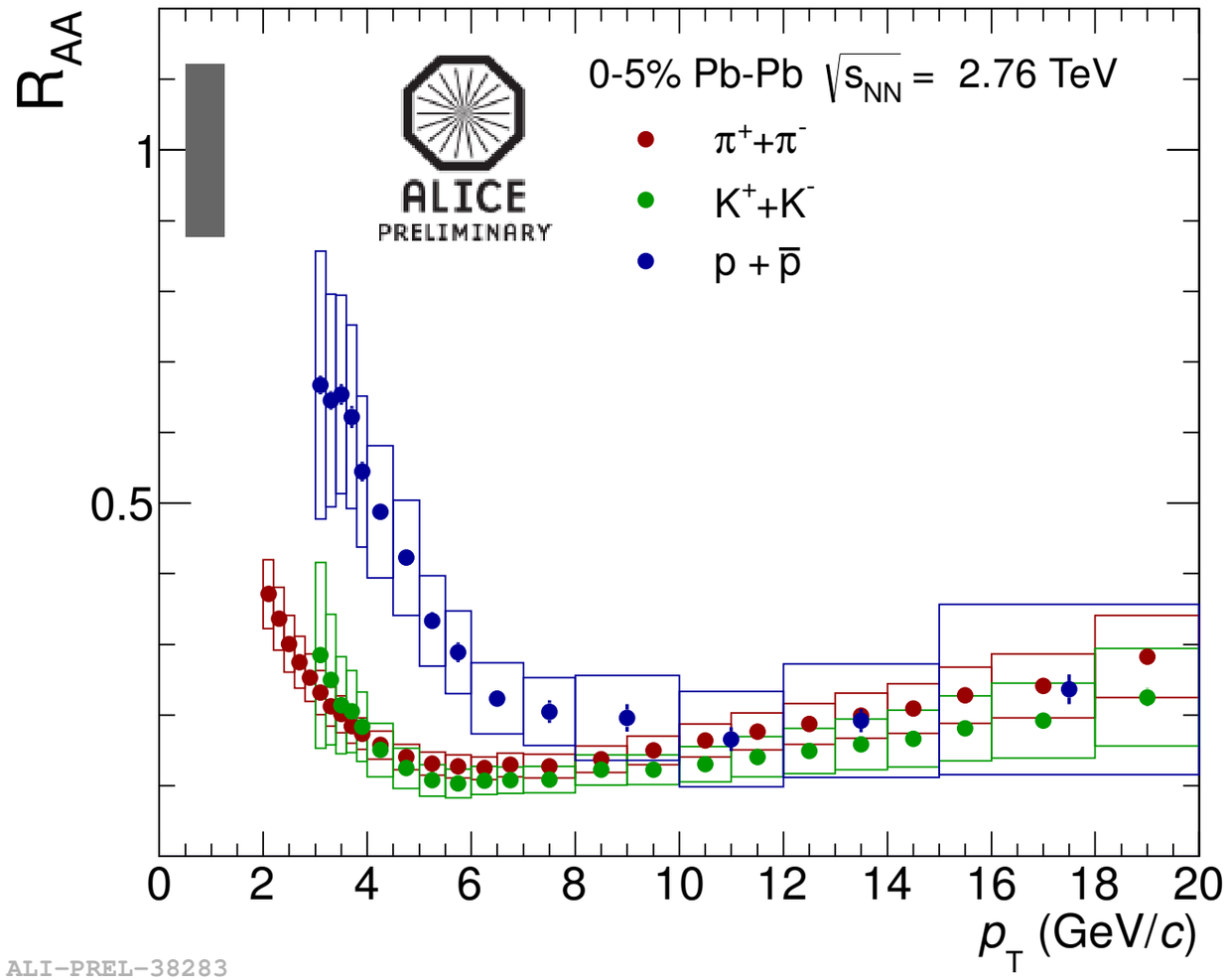
$$\Delta E_{quark} < \Delta E_{gluon} \quad , \quad \Delta E_{massive\ quark} < \Delta E_{light\ quark}$$

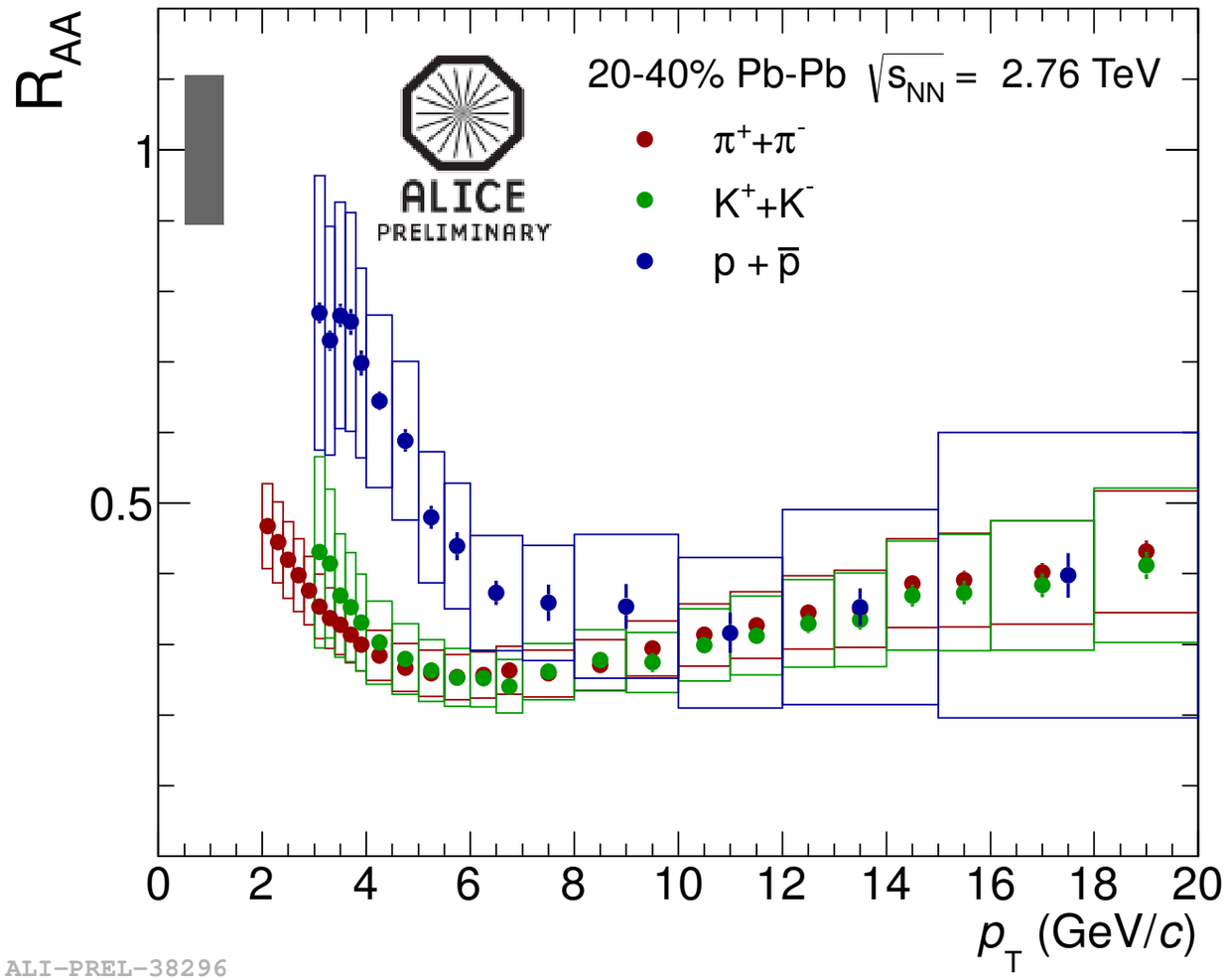
$$\Downarrow$$

$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

Wiedemann et al, EPJC 55, 293–302

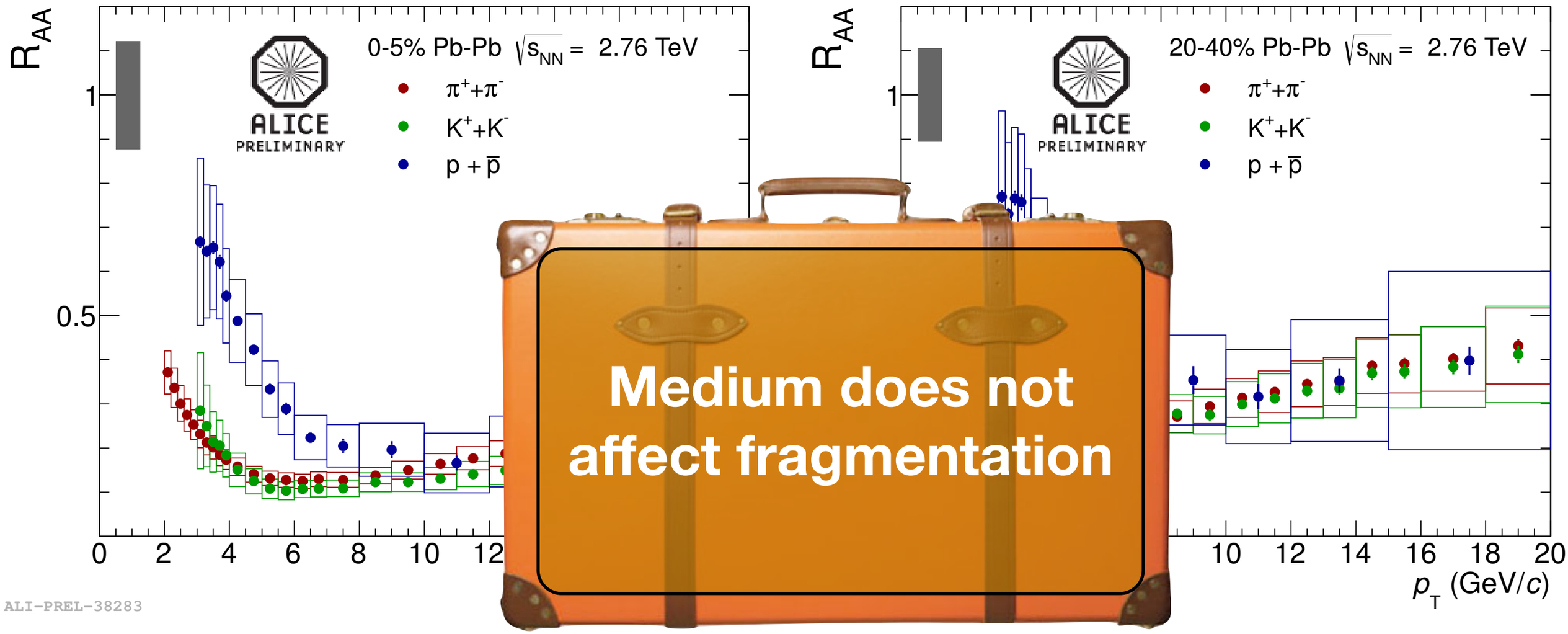
R_{AA} of identified particles





R_{AA} for π/K/p compatible
medium does not affect the fragmentation?

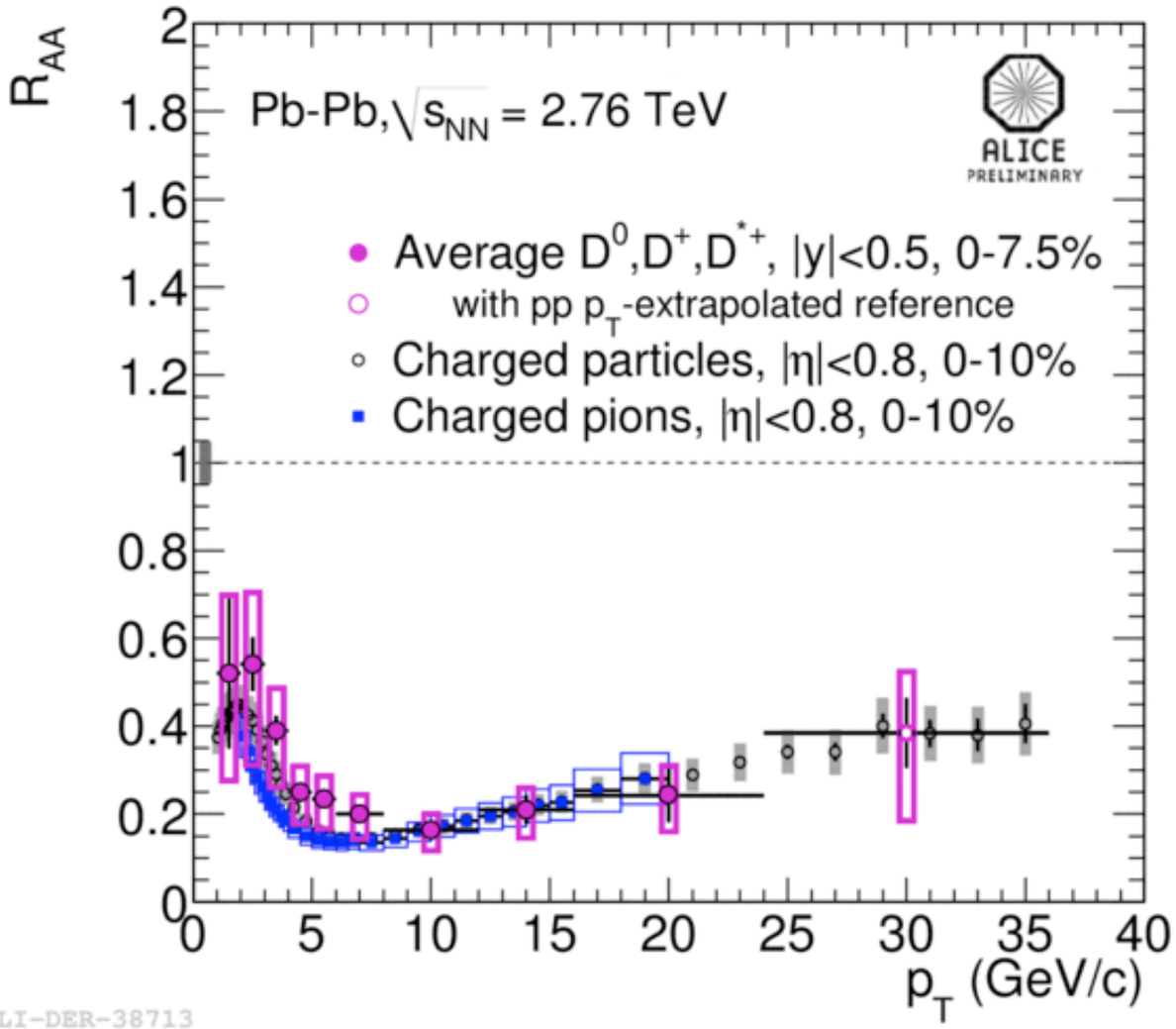
R_{AA} of identified particles

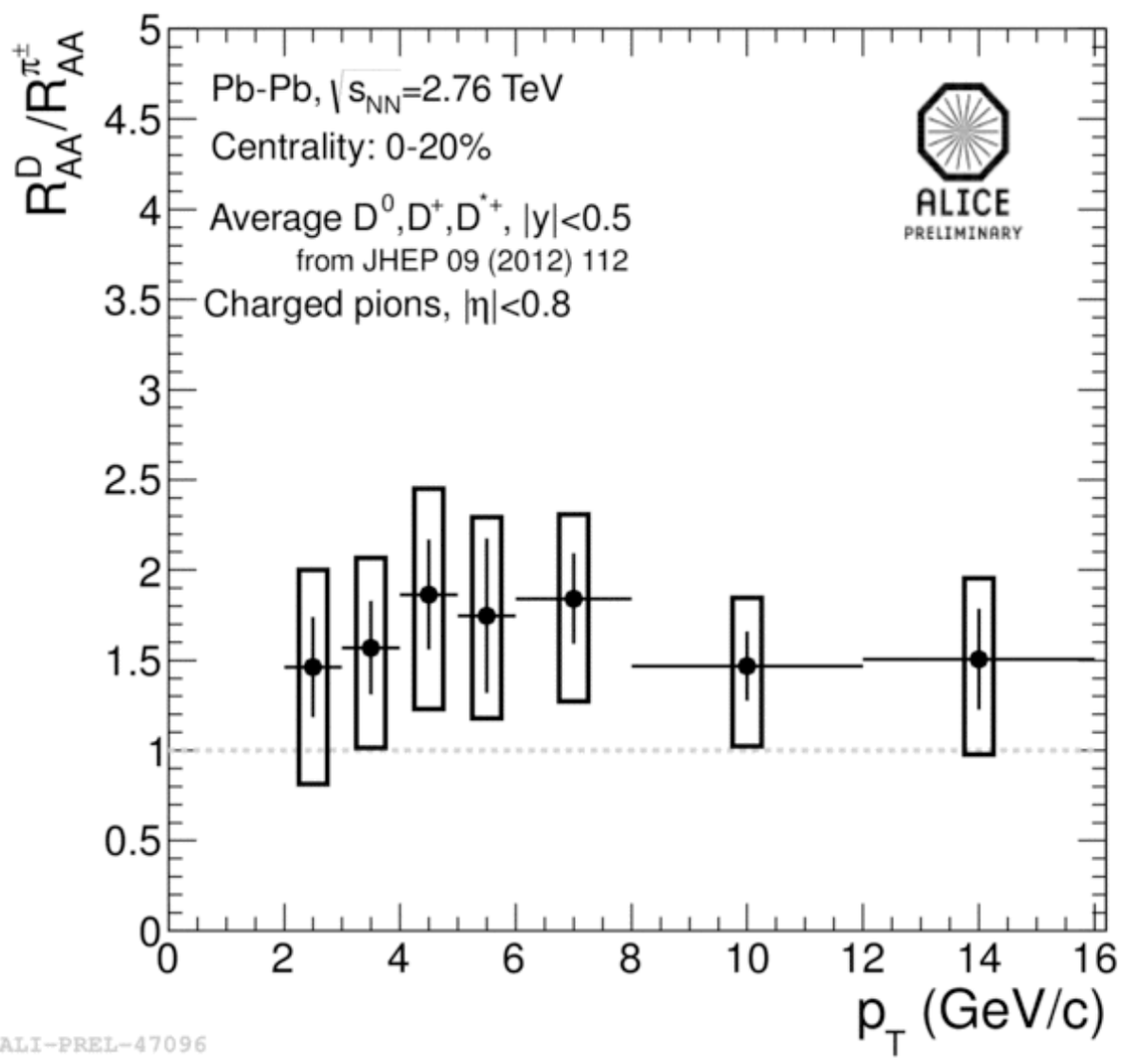


Medium does not affect fragmentation

R_{AA} for π/K/p compatible
medium does not affect the fragmentation?

R_{AA} of Open Charm





Similar trend vs. p_T for D, charged particles and $\pi^\pm$

Hint for $R_D > R_\pi$ at low p_T

http://indico.cern.ch/conferenceDisplay.py?confId=195394

Conclusions

Identified light-flavor measurements crucial to constrain bulk properties of the matter created in HI collisions

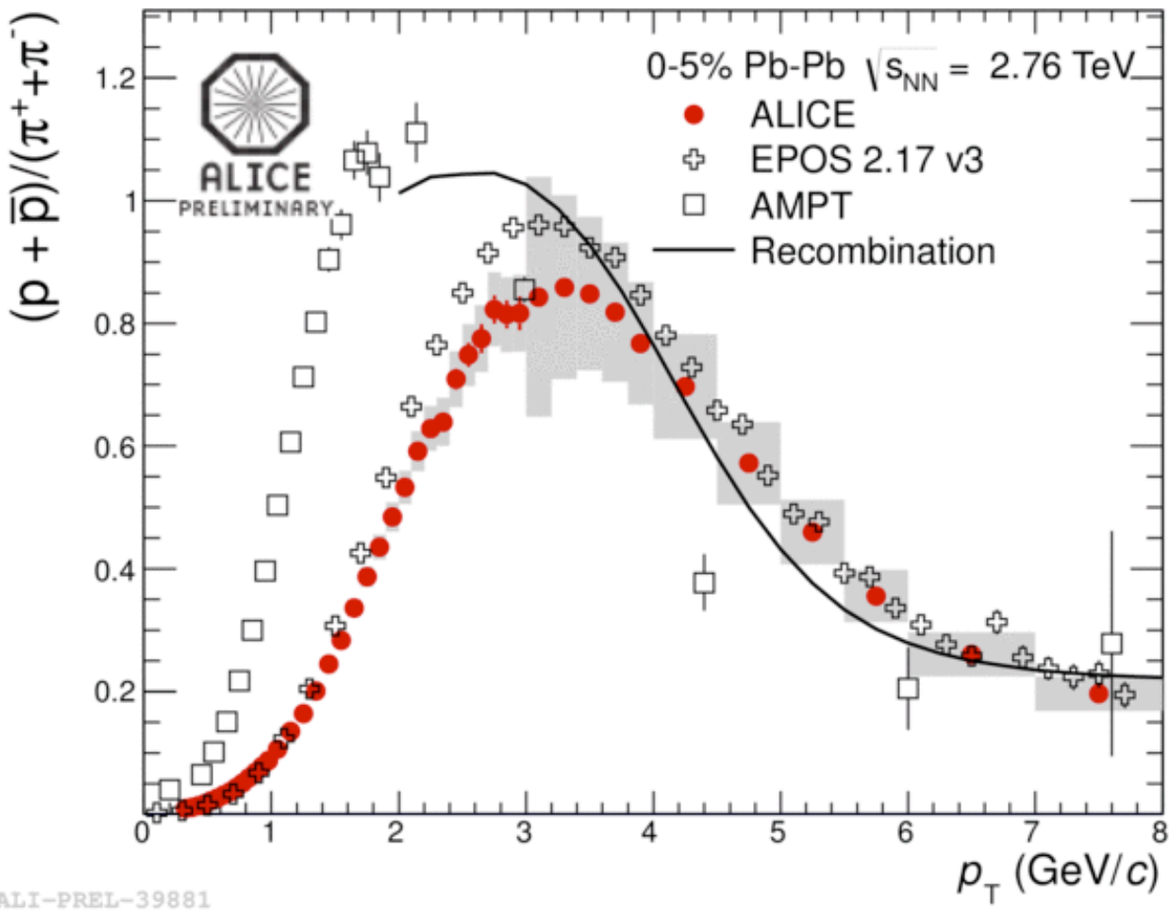
- LHC still close to hydrodynamic limit for (semi) central collisions
  - Very strong radial flow, $\beta_{\text{blast-wave}} \simeq 0.65$
  - Protons spectra thermal up $p_T > 3$ GeV/c
- Equilibrium thermal model cannot fit the data
  - Puzzle still open
- “Baryon anomaly” is a bulk effect, strong constraints for coalescence models
  - Additional data / comprehensive model description needed
- No (light) flavor dependence of the R_{AA} at high p_T

Alice Collaboration

ALICE

36 Countries, 132 Institutes, over 1300 members

Spare Slides

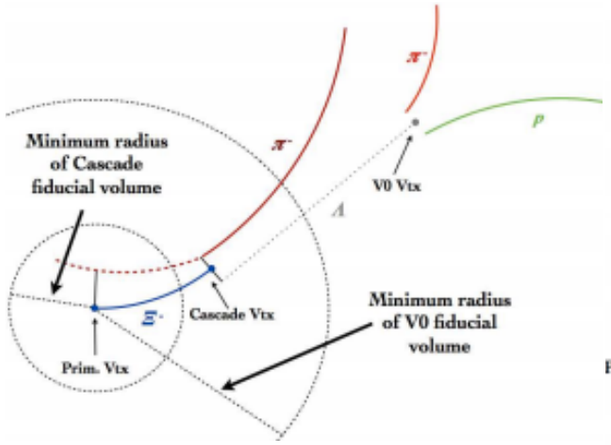

ALICE
PRELIMINARY
0-5% Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE
EPOS 2.17 v3
AMPT
Recombination
$(p+\bar{p})/(\pi^+ + \pi^-)$
p_T (GeV/c)
ALI-PREL-39881

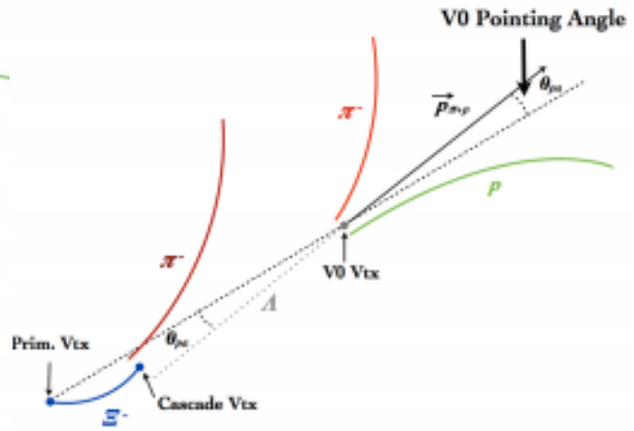
Signal extraction

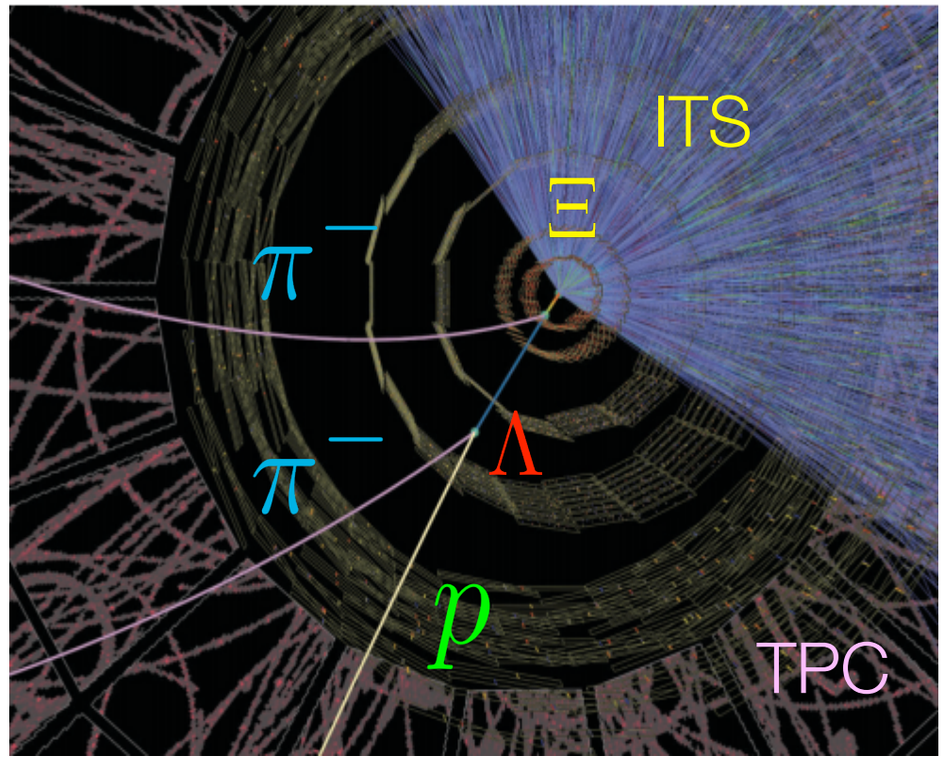
Multi-strange baryons reconstructed via decay topology:

$\Xi^- \rightarrow \Lambda\, \pi^- \rightarrow p\, \pi^-\, \pi^-$ BR: 43.3 %

$\Omega^- \rightarrow \Lambda\, K^- \rightarrow p\, K^-\, K^-$ BR: 63.9 %

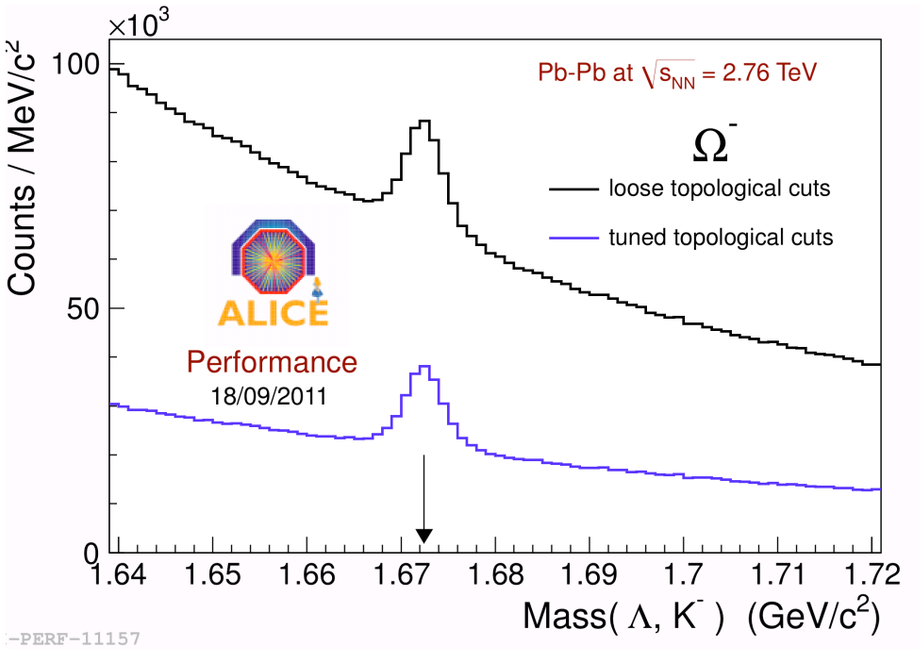


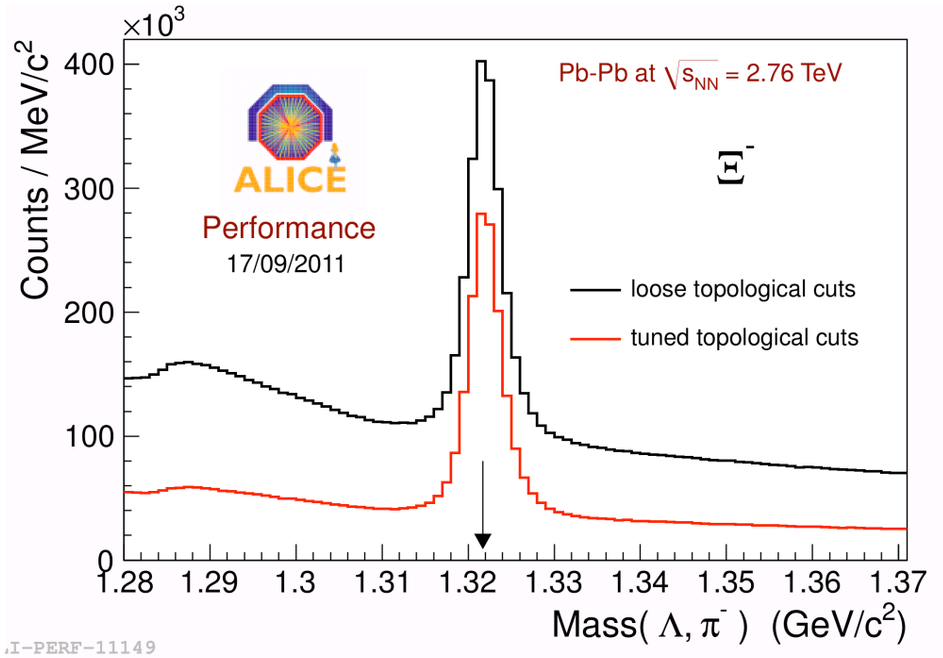




Topological cuts are tuned to reduce background

Ref: ALICE PPR v-II



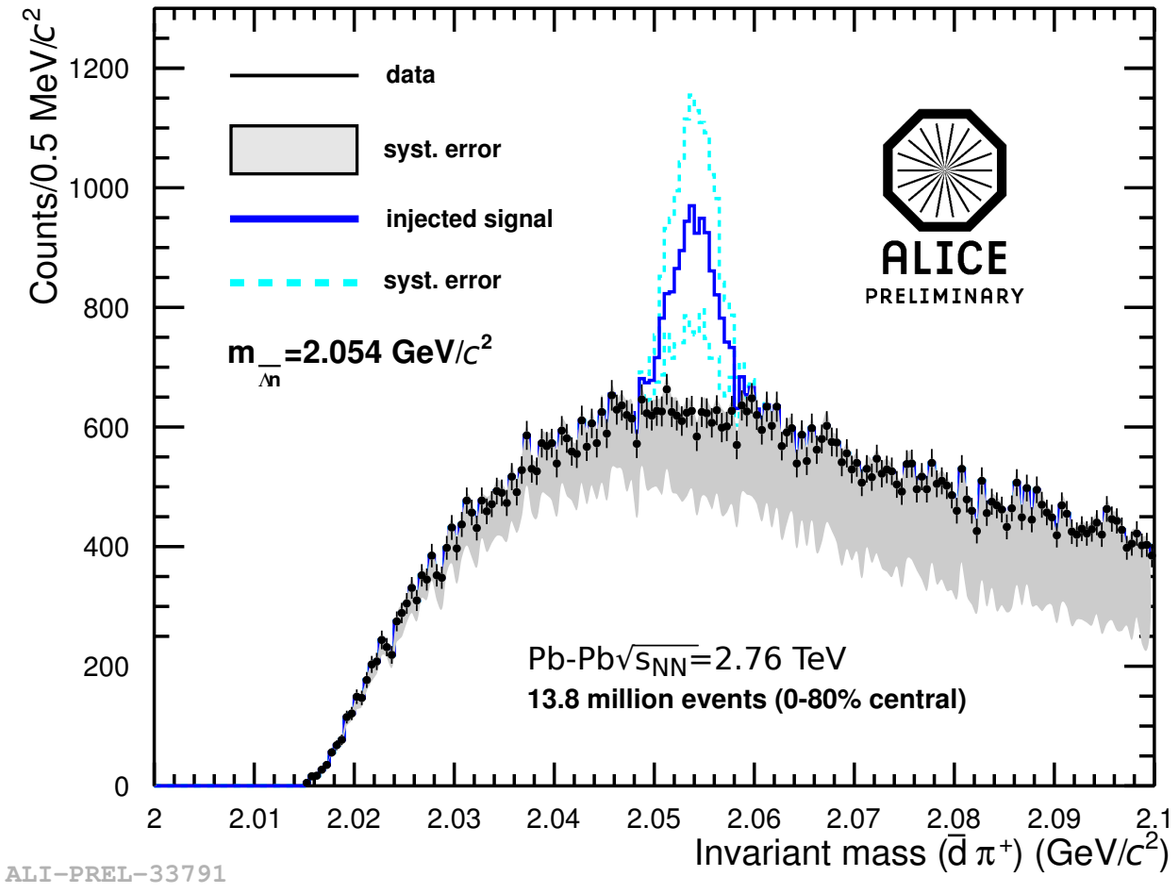


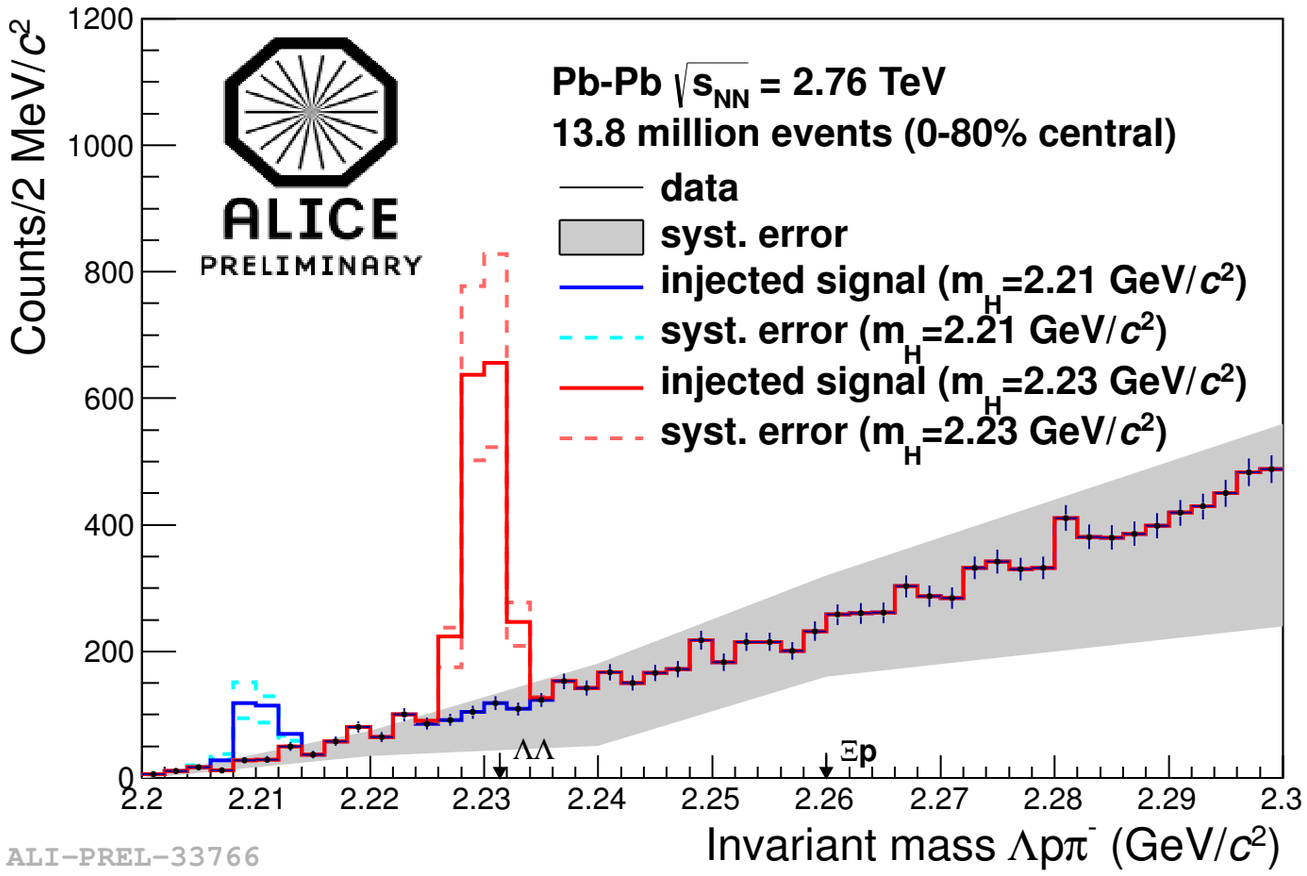
In addition, Λ and K_S^0 are reconstructed from the following decay channel:

$\Lambda \rightarrow p\, \pi^-$

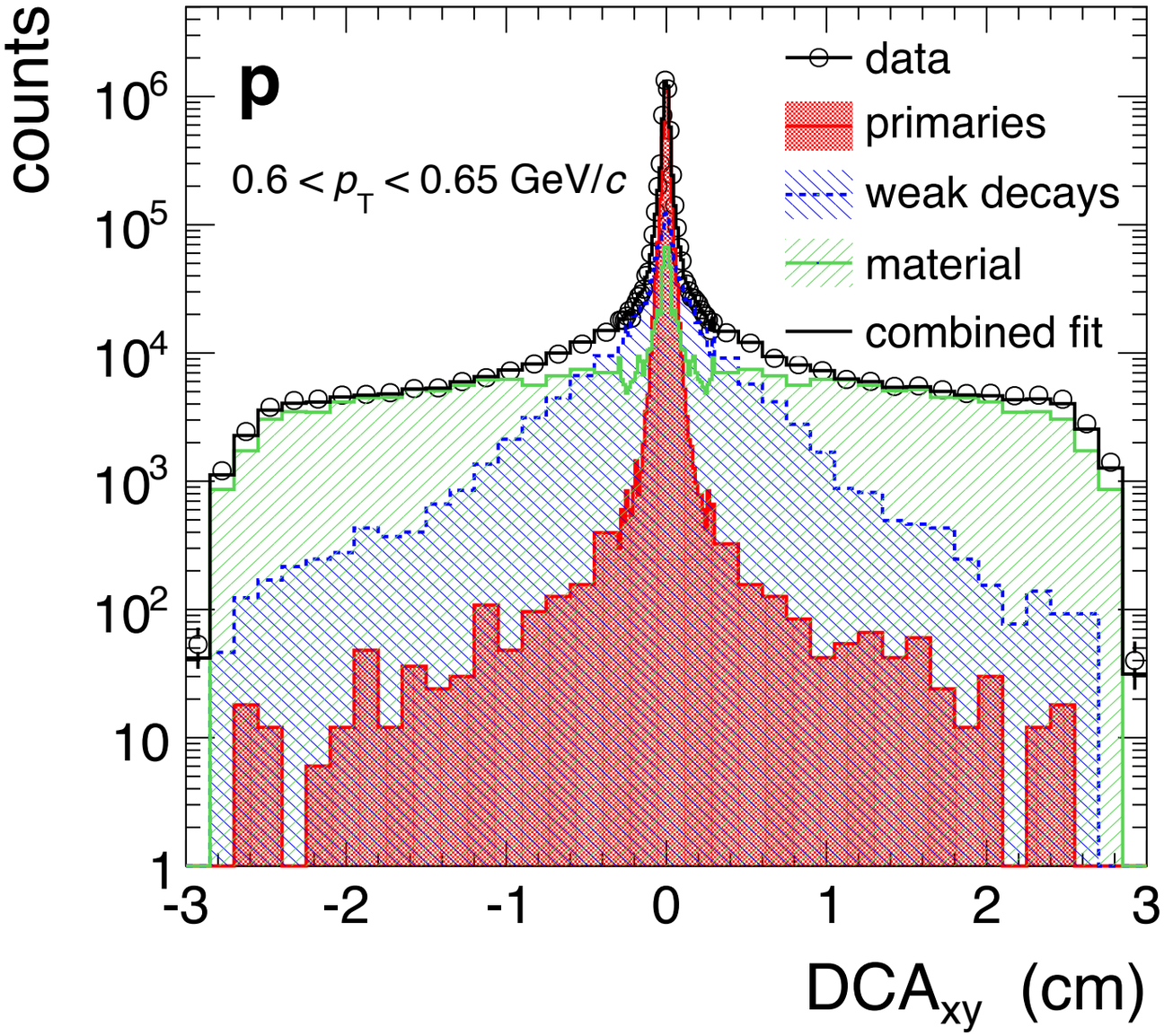
$K_S^0 \rightarrow \pi^+\, \pi^-$

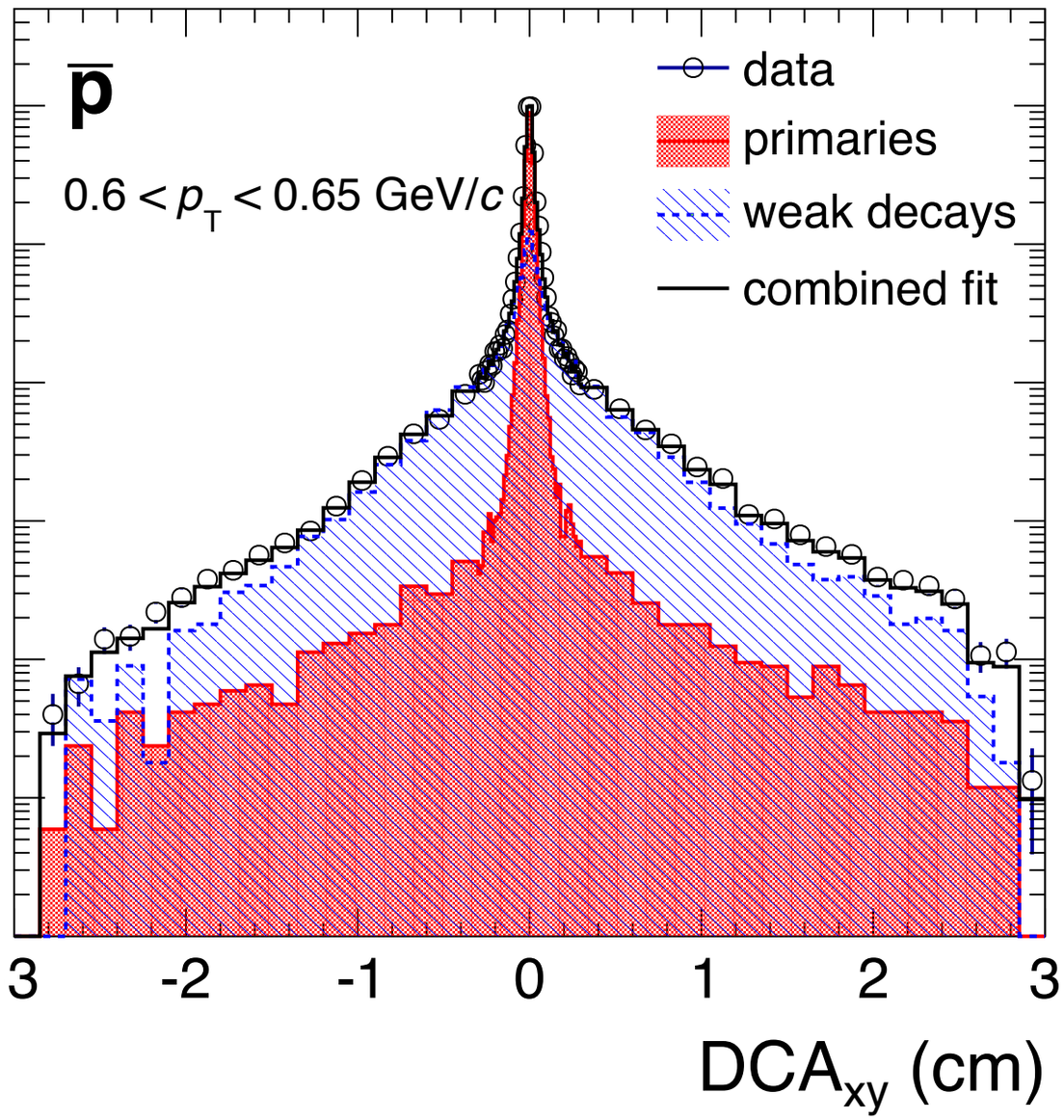
Exotica searches





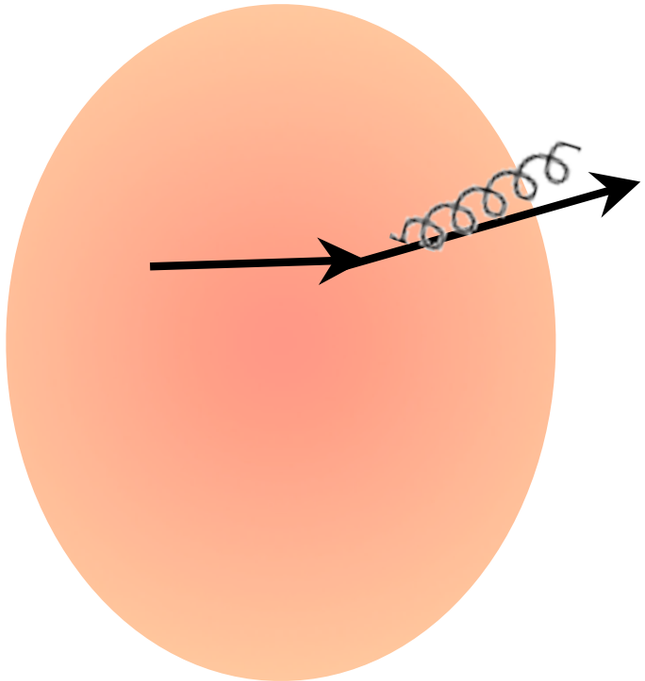
Secondary subtraction





Secondary correction based on data!
(possible thanks to the ITS)

Parton energy loss and the nuclear modification factor



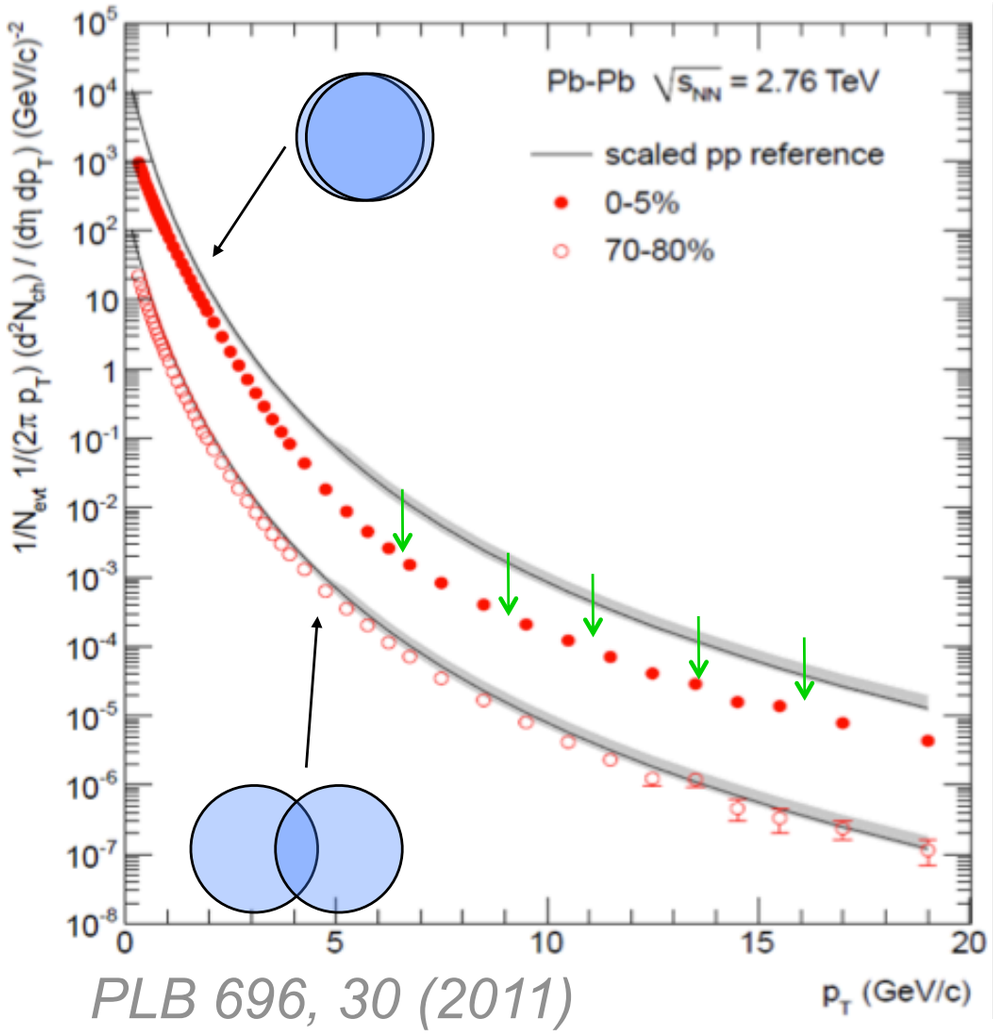
'QCD medium'

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

$$p' = p - \Delta E(\varepsilon_{medium})$$

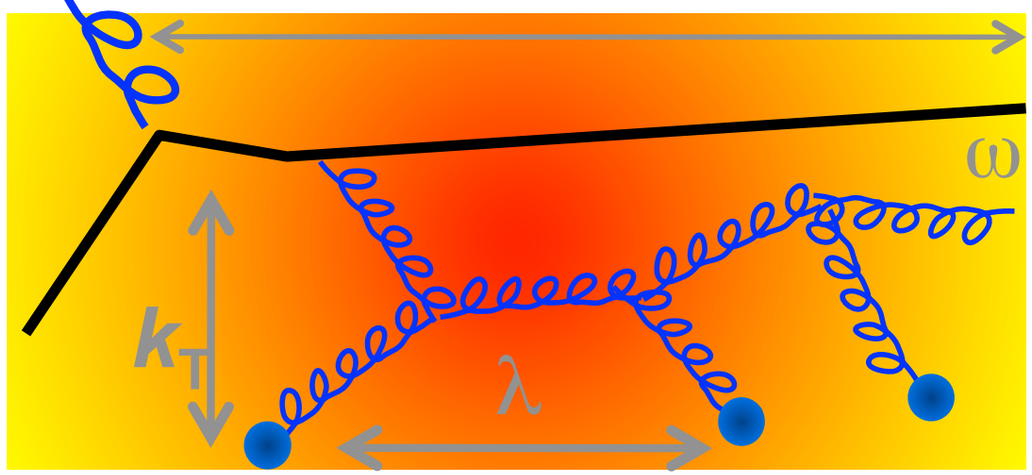
$$dN_{AA}/dp_t \quad < \quad \langle N_{coll} \rangle \, dN_{pp}/dp_t$$

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t} < 1$$



PLB 696, 30 (2011)

The parton and the medium



BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

(BDMPS case)

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q}L^2}{\omega}}$$

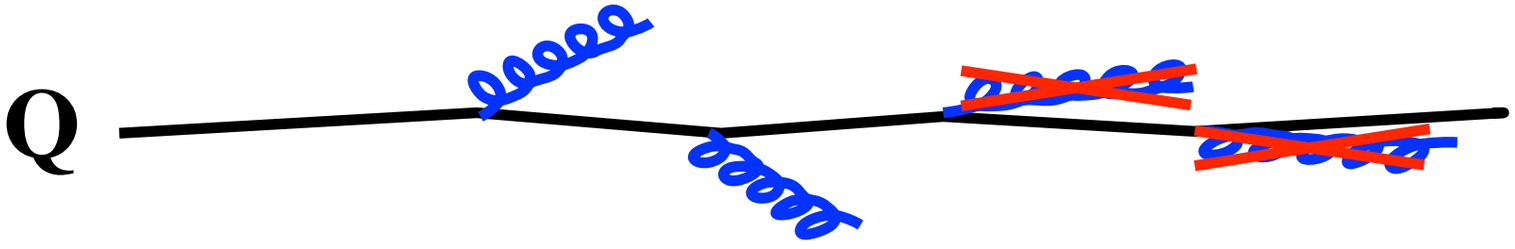
C_R = Casimir coupling factor: 4/3 for q, 3 for g

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

Less gluon radiation for heavy quarks?

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

→ "dead cone" effect

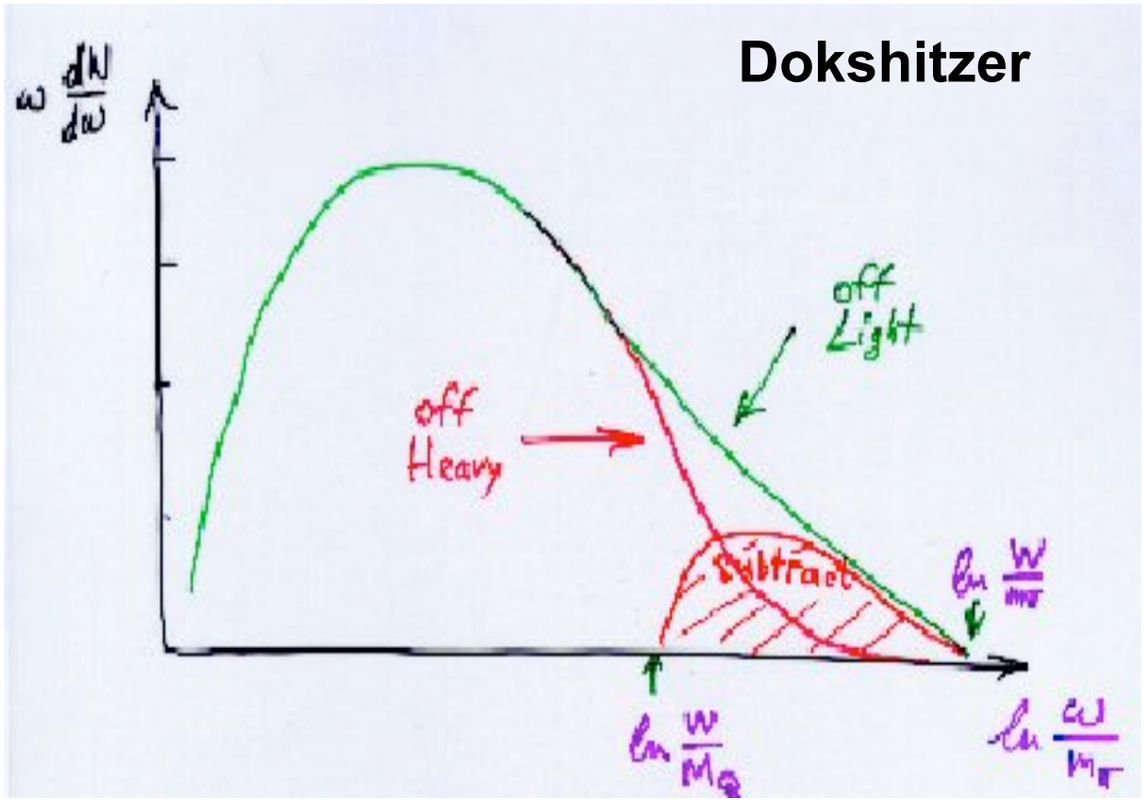


Gluonsstrahlung probability

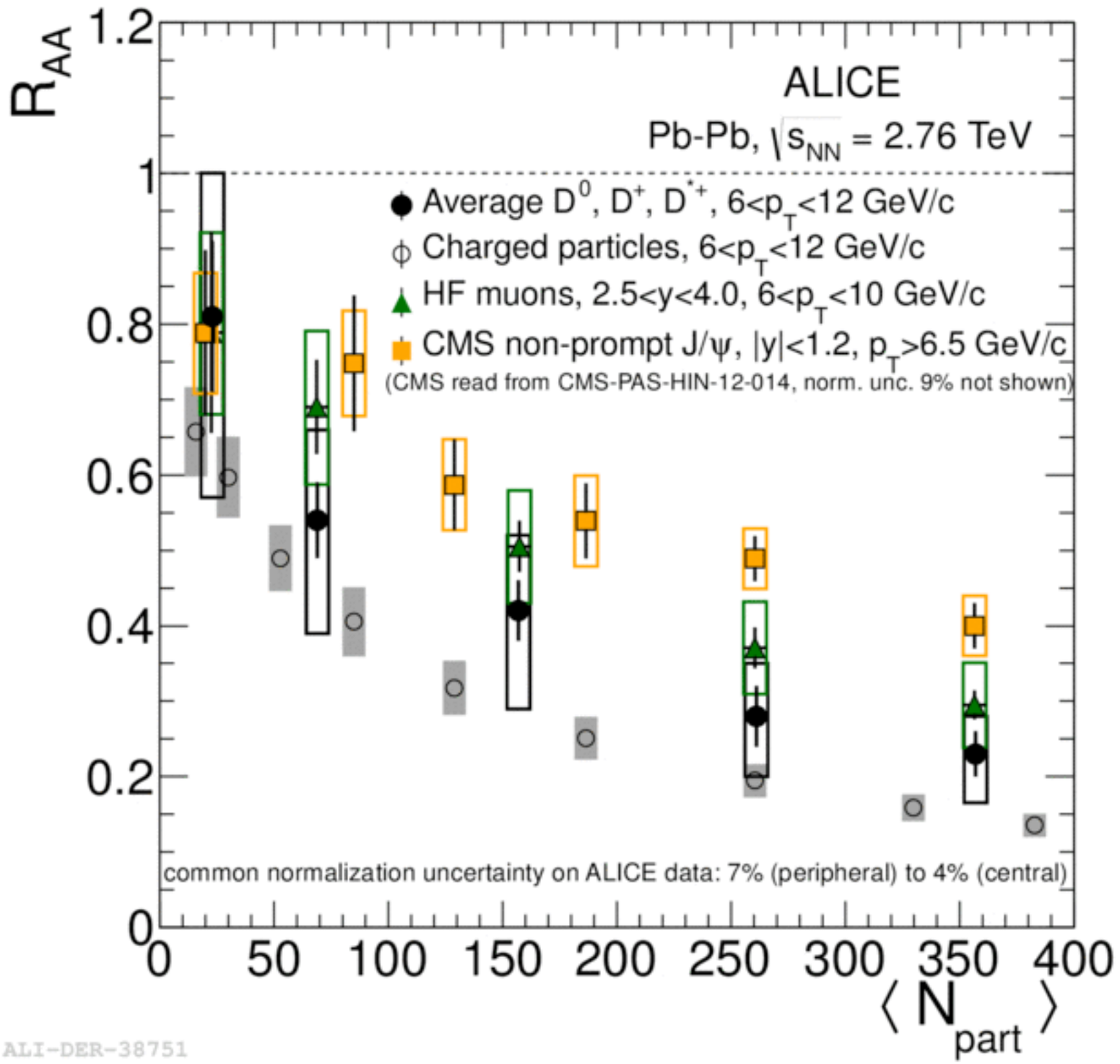
$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppress high-ω tail

$$\omega \left.\frac{dI}{d\omega}\right|_{HEAVY} = \omega \left.\frac{dI}{d\omega}\right|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

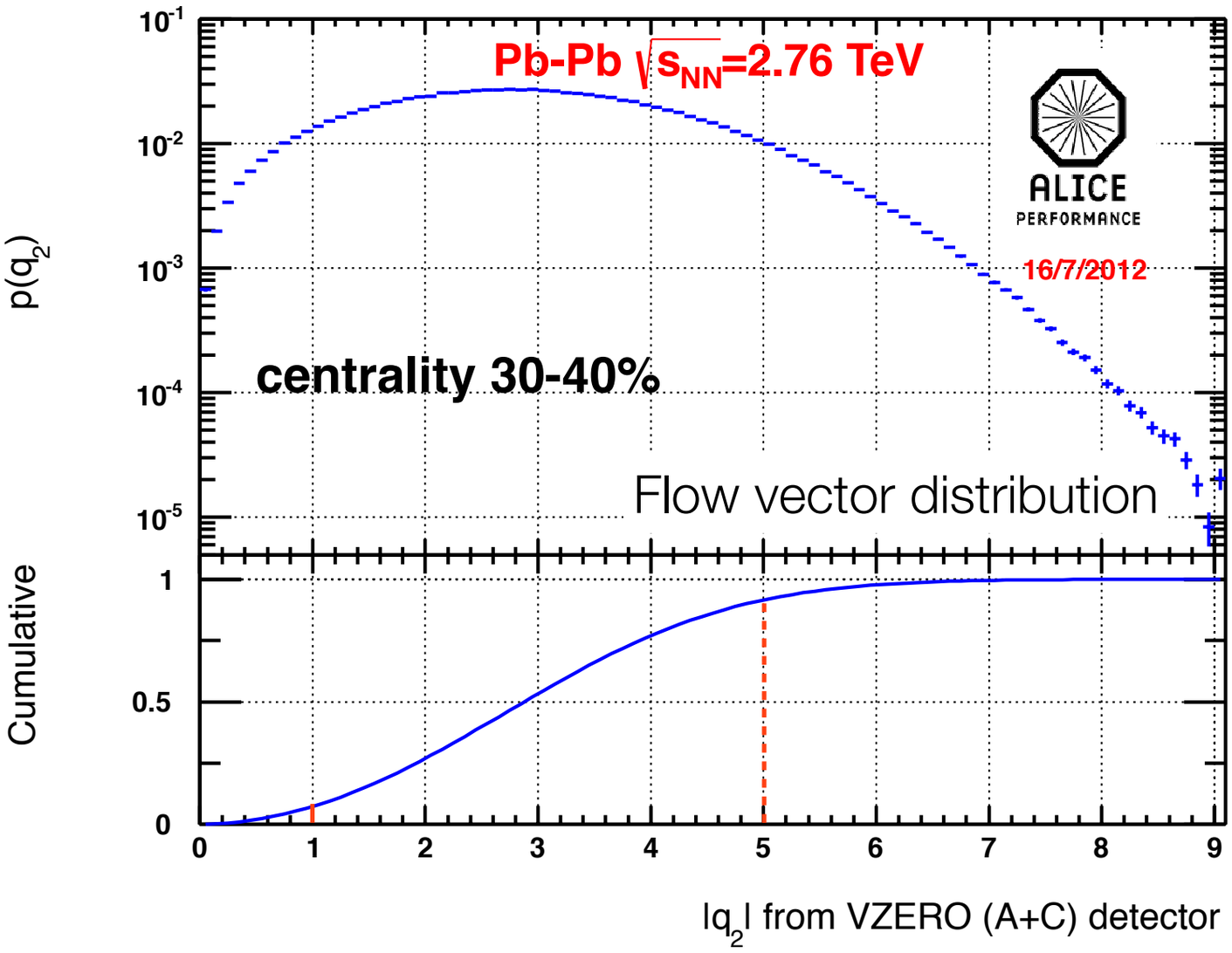


Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.


ALICE
Pb-Pb, √s_NN = 2.76 TeV
Average D⁰, D⁺, D*⁺, 6<p_T<12 GeV/c
Charged particles, 6<p_T<12 GeV/c
HF muons, 2.5<y<4.0, 6<p_T<10 GeV/c
CMS non-prompt J/ψ, |y|<1.2, p_T>6.5 GeV/c
(CMS read from CMS-PAS-HIN-12-014, norm. unc. 9% not shown)
common normalization uncertainty on ALICE data: 7% (peripheral) to 4% (central)
R_AA
⟨ N_part ⟩
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400
ALI-DER-38751

Combining v_2 and radial flow

Flow vector $q_2 = Q_2/\sqrt{\text{multiplicity}}$



Potential biases:

multiplicity bias

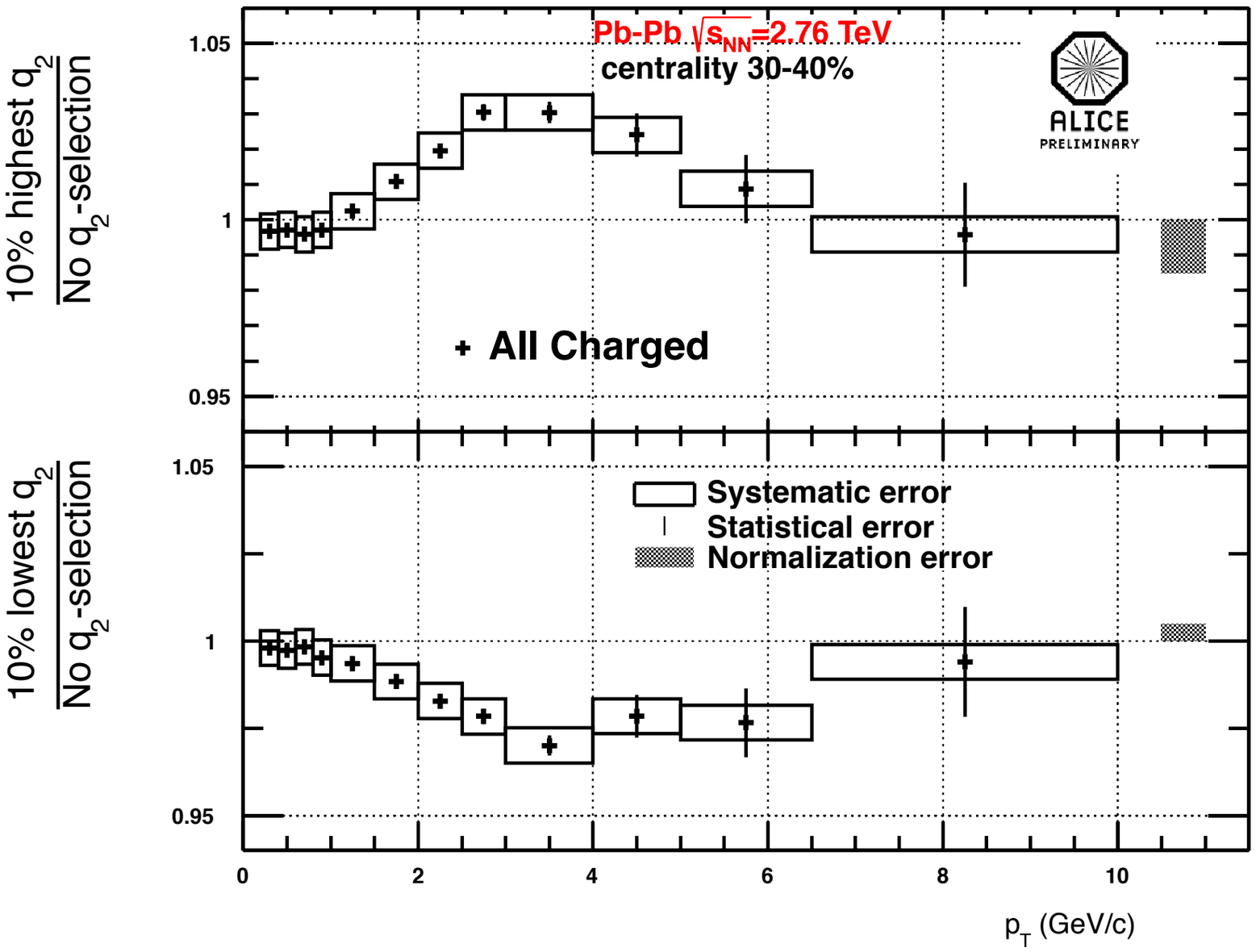
v_2 increases with decreasing centrality

jet contribution

is the large q_2 due to an increased jet contribution?

We want to select the 10% highest (lowest) elliptic flow events

p_T spectra vs E-by-E flow

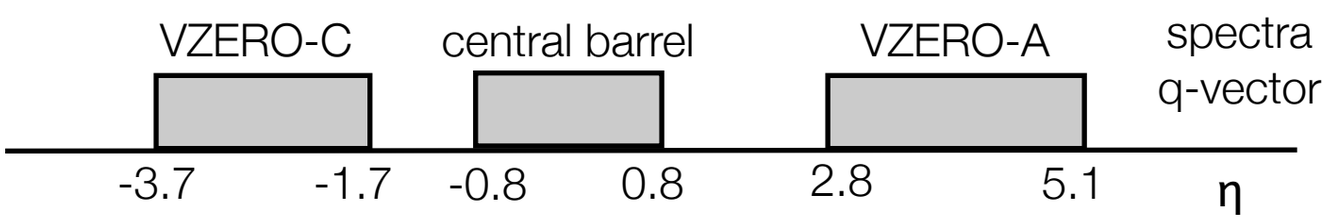


Ratio of raw spectra, efficiency does not depend on q2 selection

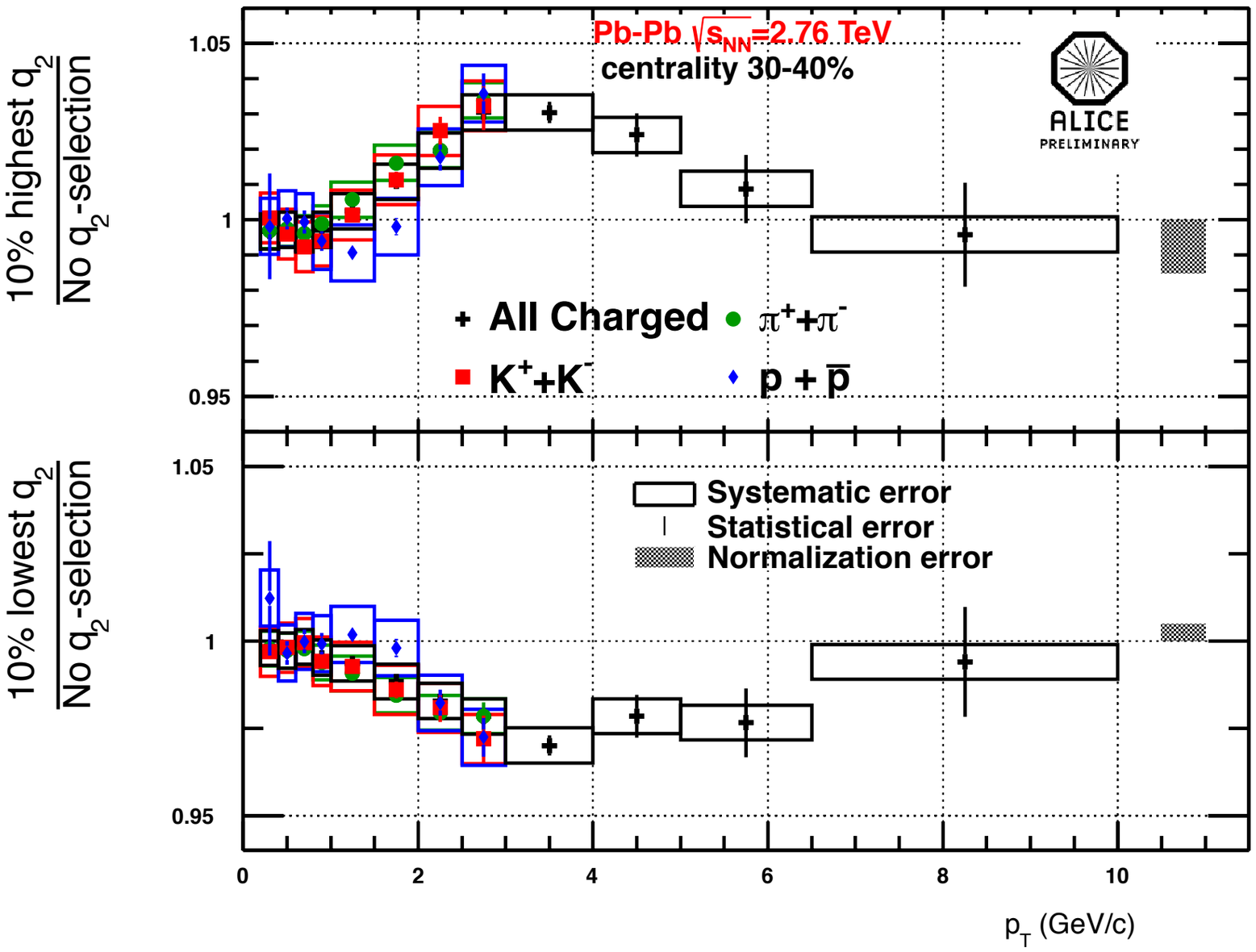
Modification of the p_T spectrum:
large q_2 ⇒ harder spectrum,

opposite for small q_2

Vanishing at high p_T:
not due to jet contribution



p_T spectra vs E-by-E flow



Ratio of raw spectra, efficiency does not depend on q2 selection

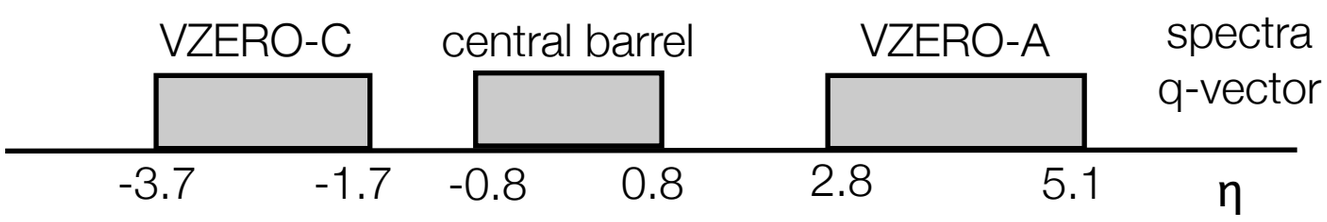
Modification of the p_T spectrum:
large q_2 ⇒ harder spectrum,

opposite for small q_2

Vanishing at high p_T:
not due to jet contribution

same effect for all the particles

hint of mass ordering?



Are v_2 and radial flow correlated?

Checks on potential biases

- *Multiplicity bias*
  - centrality from tracks in the central barrel instead of VZERO
  - bin 30-40% obtained as the sum of 10 bins 1% wide

shift negligible

Checks on potential biases

- *Multiplicity bias*
  - centrality from tracks in the central barrel instead of VZERO
  - bin 30-40% obtained as the sum of 10 bins 1% wide

shift negligible

- *Jet contribution:*

Background:

p_T_tot = total p_T in the event

density = p_T_tot/acceptance

Energy in a cone:

- seed particle: (p_T>5GeV/c)
- p_T_*sum* = sum of p_T in R<0.3
- *area*=π x R^2
- p_T_*jet*= p_T_*sum* - *density* x *area*

Checks on potential biases

- *Multiplicity bias*
  - centrality from tracks in the central barrel instead of VZERO
  - bin 30-40% obtained as the sum of 10 bins 1% wide

shift negligible

- *Jet contribution:*

Background:

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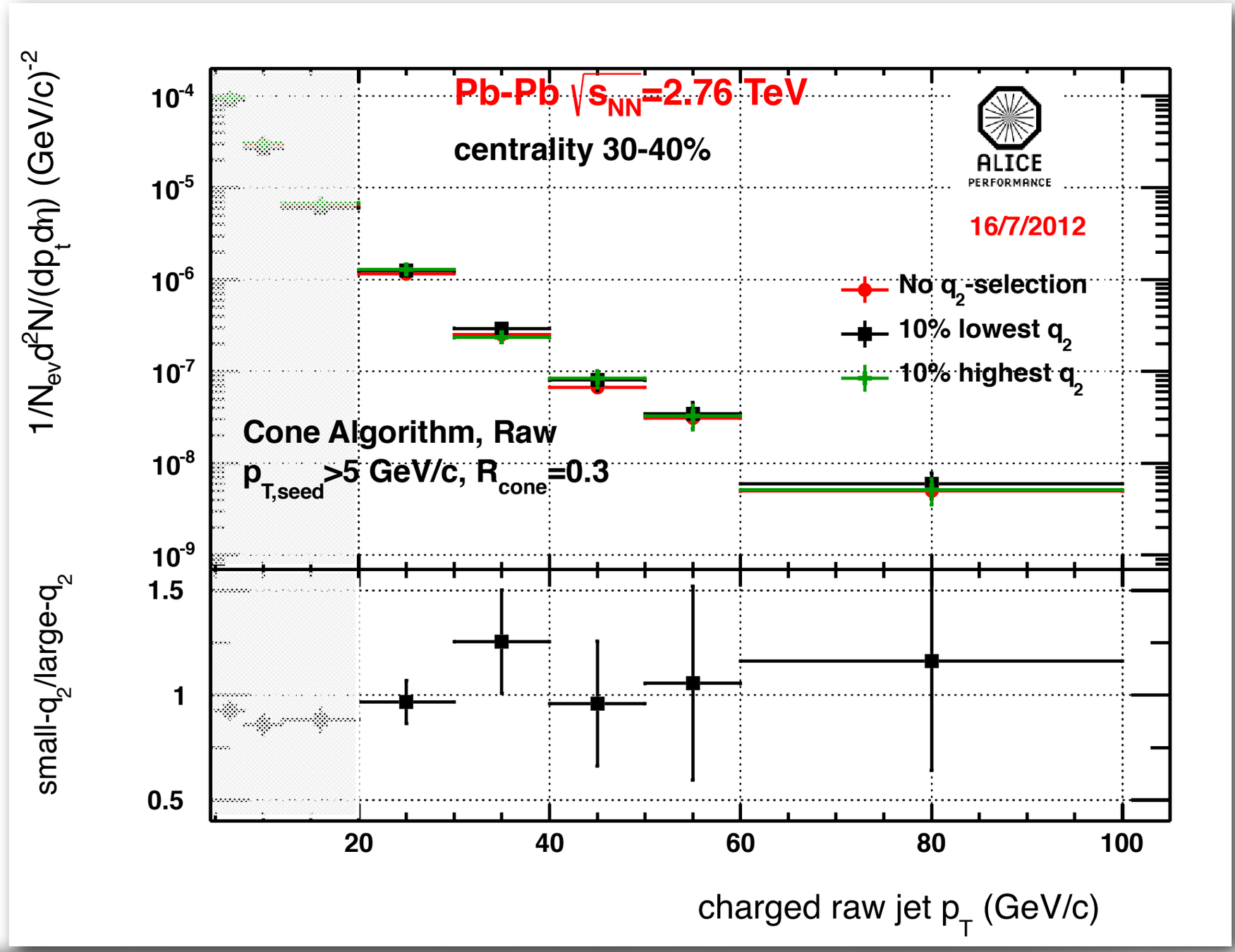
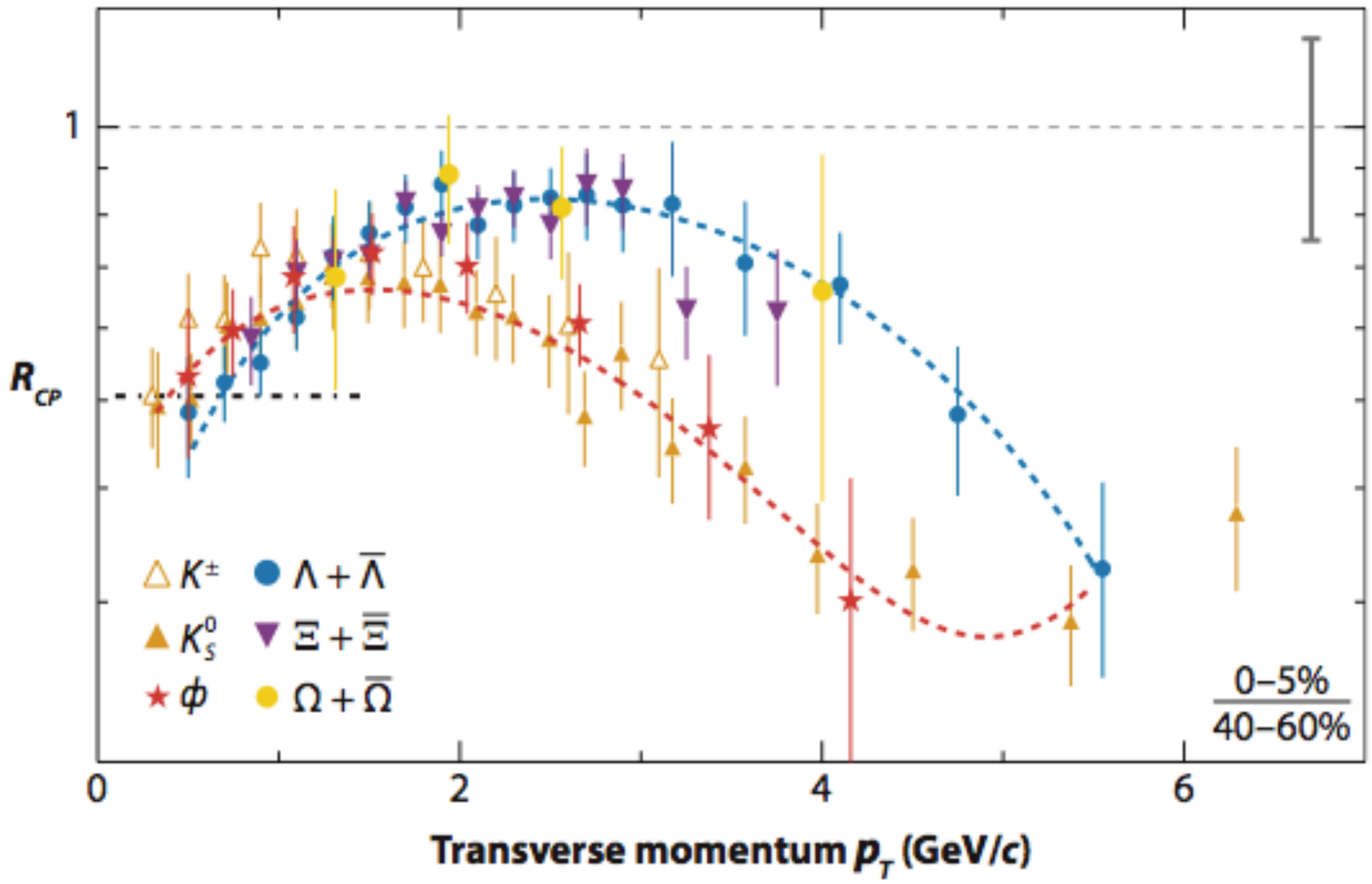
Energy in a cone:

- seed particle: (p_T>5GeV/c)
- p_T_sum = sum of p_T in R<0.3
- *area*=π x R^2
- p_T_jet= p_T_sum - *density* x *area*

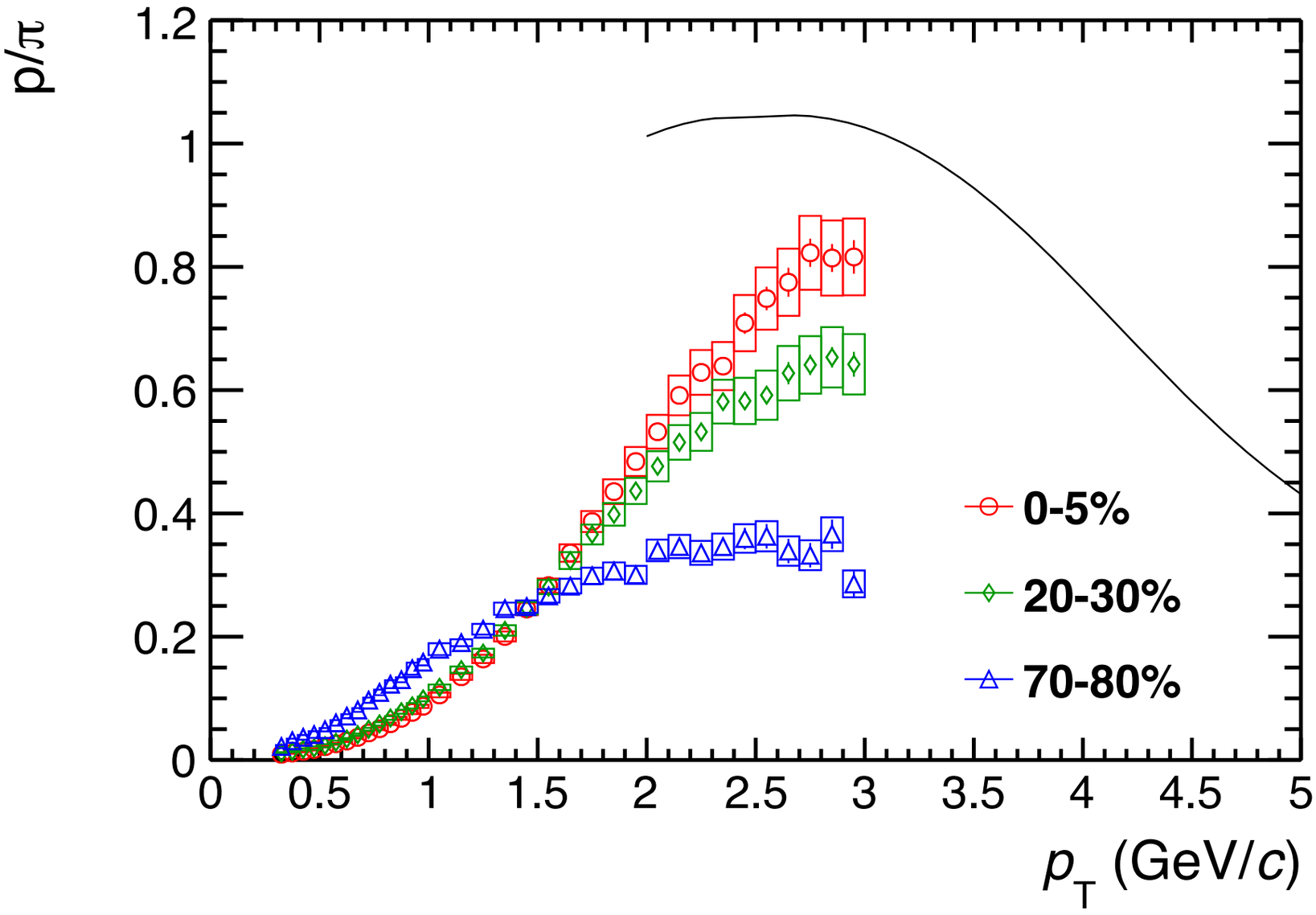
- method reliable only above ~20 GeV/*c*
- ratio is flat, "jet" contribution similar



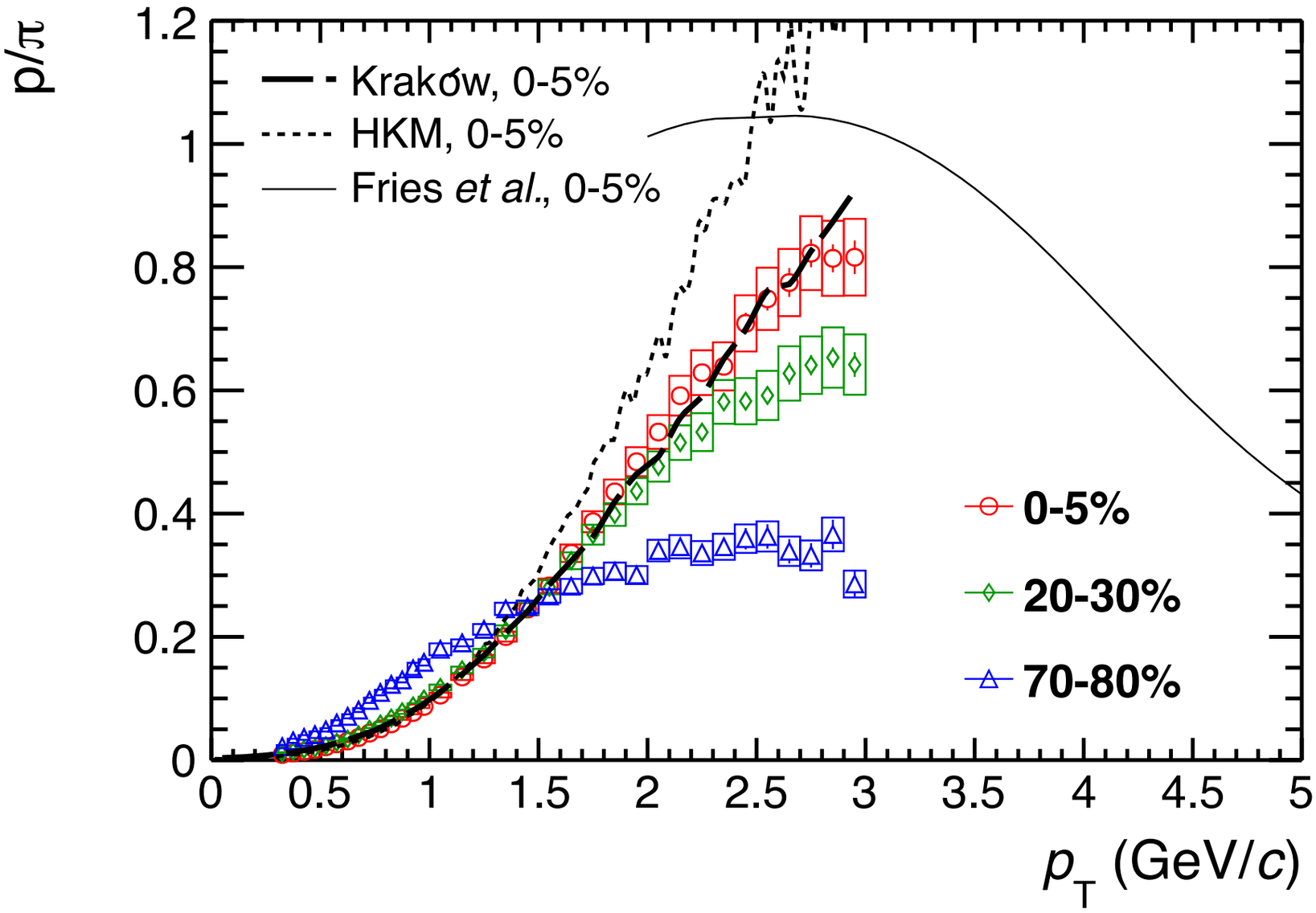


Plot from: Greco, Fries, Sorensen, Annu. Rev. Nucl. Part. Sci. 2008.58:177-205.

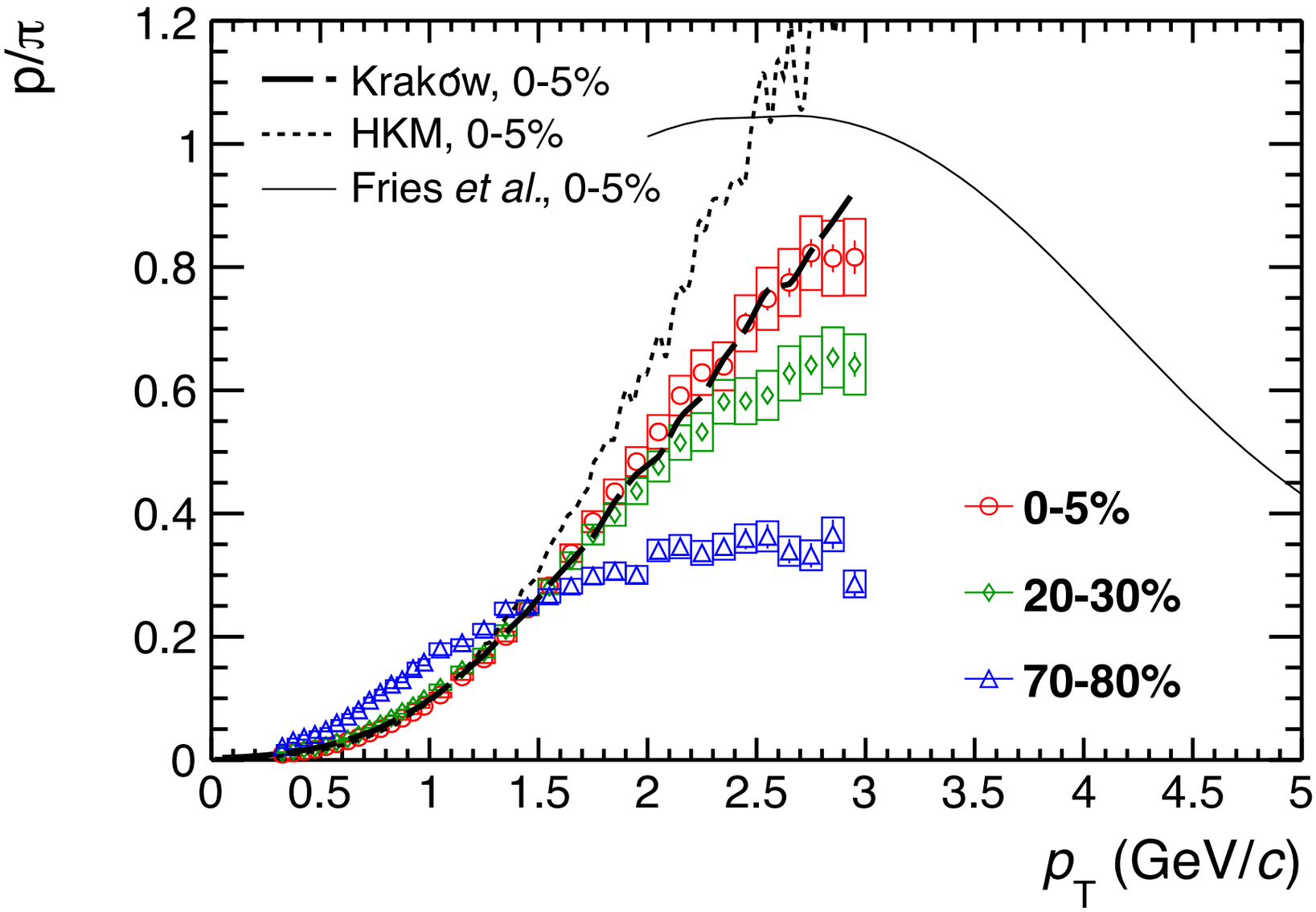
Recombination



Recombination



Recombination



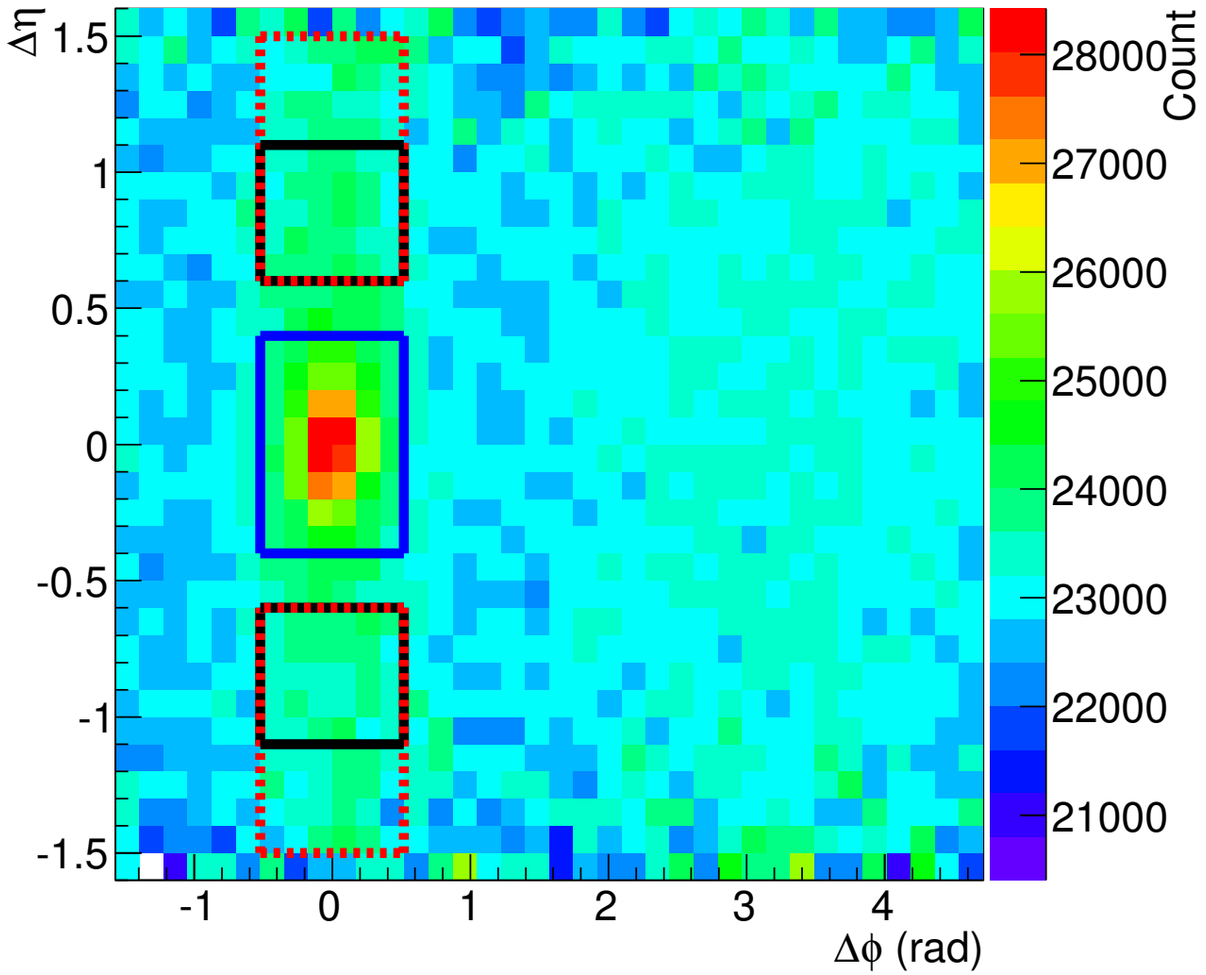
Extend measurement to higher p_T, other ratios

Intermediate p_T in the bulk and in the jet

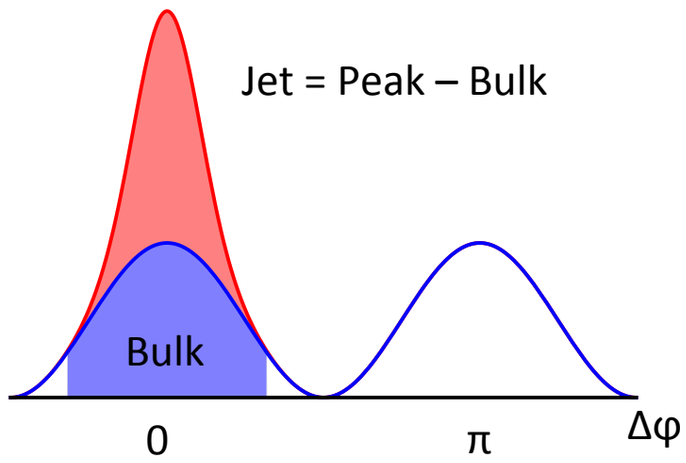
ALICE PERFORMANCE
May 21st, 2012

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV
0-10% central
$2.0 < p_T < 2.5$ GeV/c, $|\eta| < 0.8$

Peak
Bulk I
Bulk II



ALI-PERF-15359



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Peak
Bulk I
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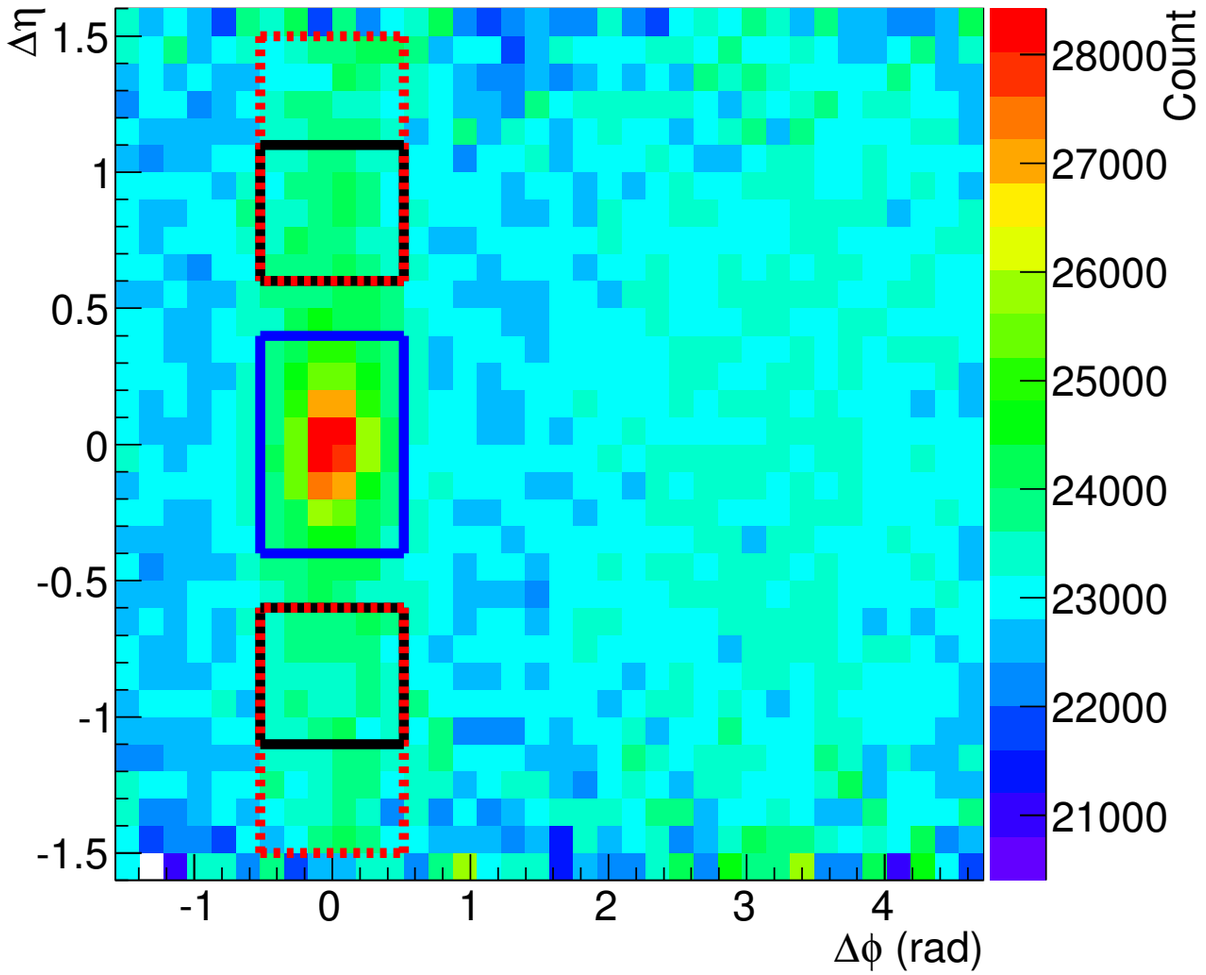
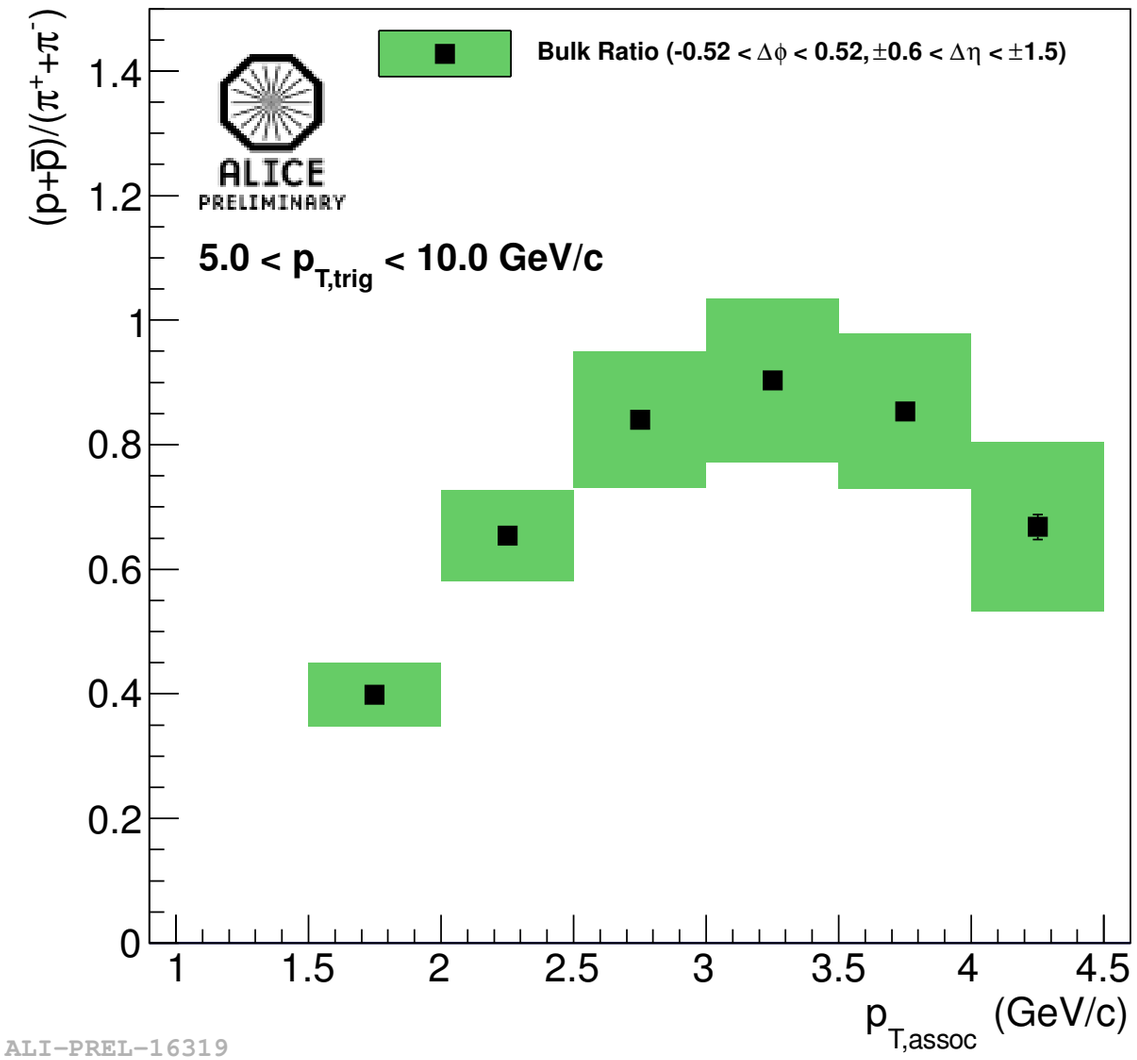
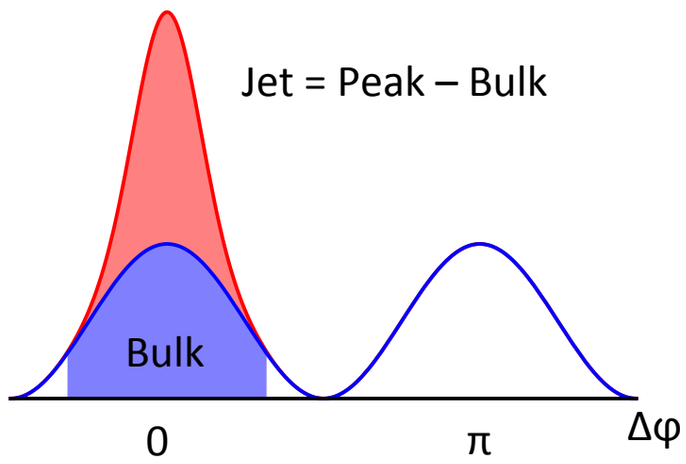


ALI-PERF-15359

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV, 0-10% central



ALI-PREL-16319

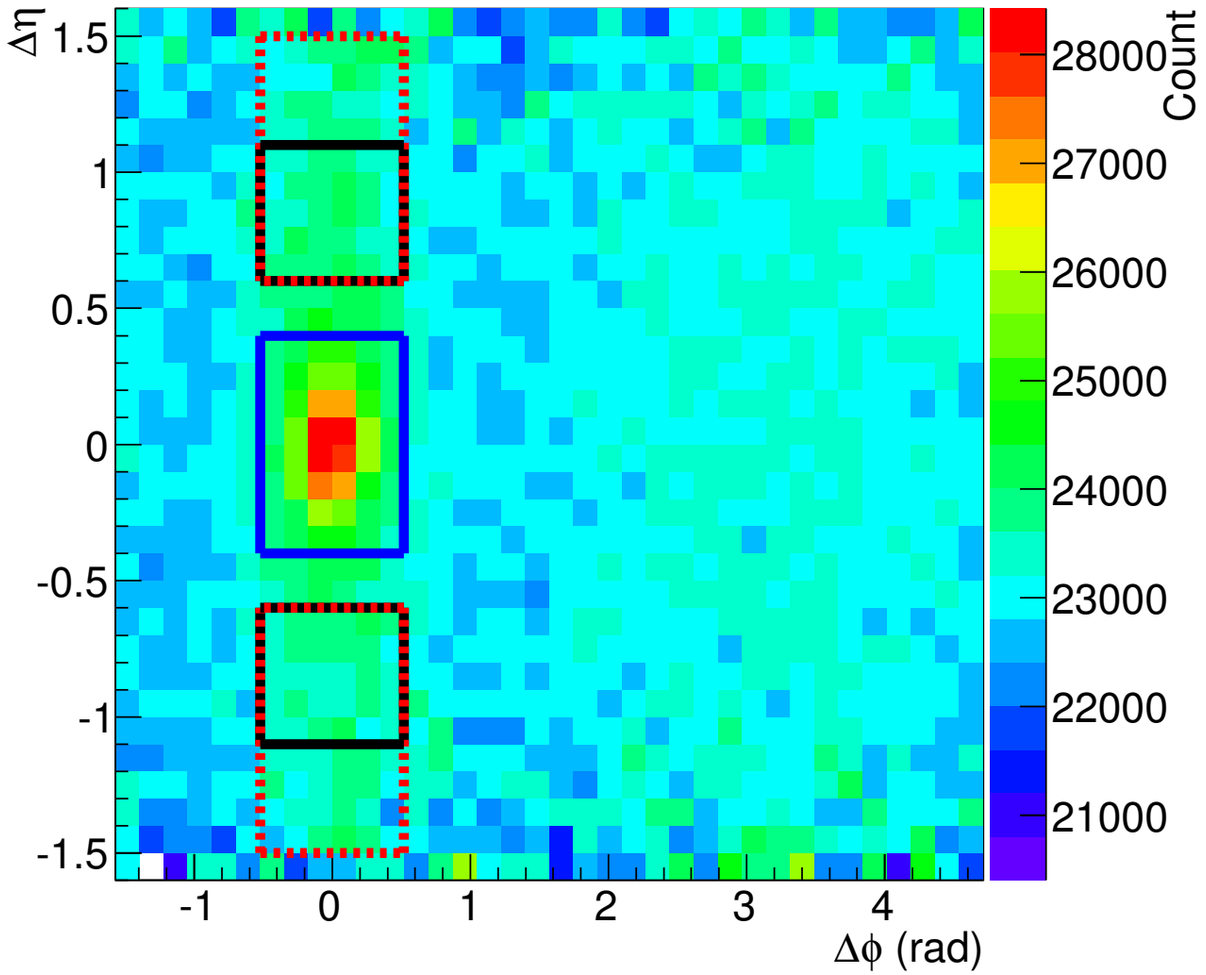


Intermediate p_T in the bulk and in the jet

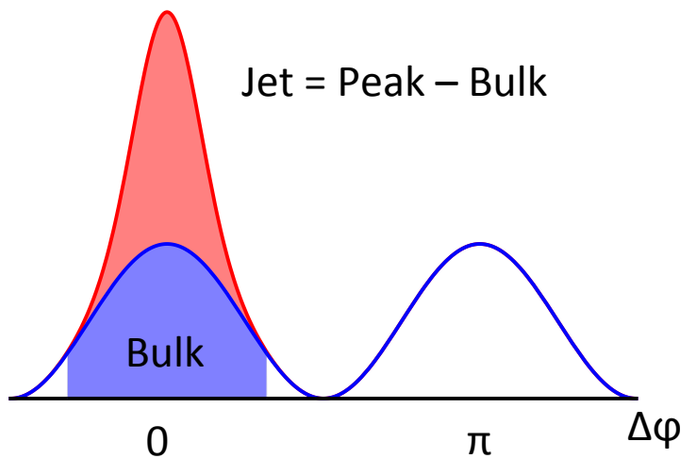
ALICE PERFORMANCE
May 21st, 2012

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV
0-10% central
$2.0 < p_T < 2.5$ GeV/c, $|\eta| < 0.8$

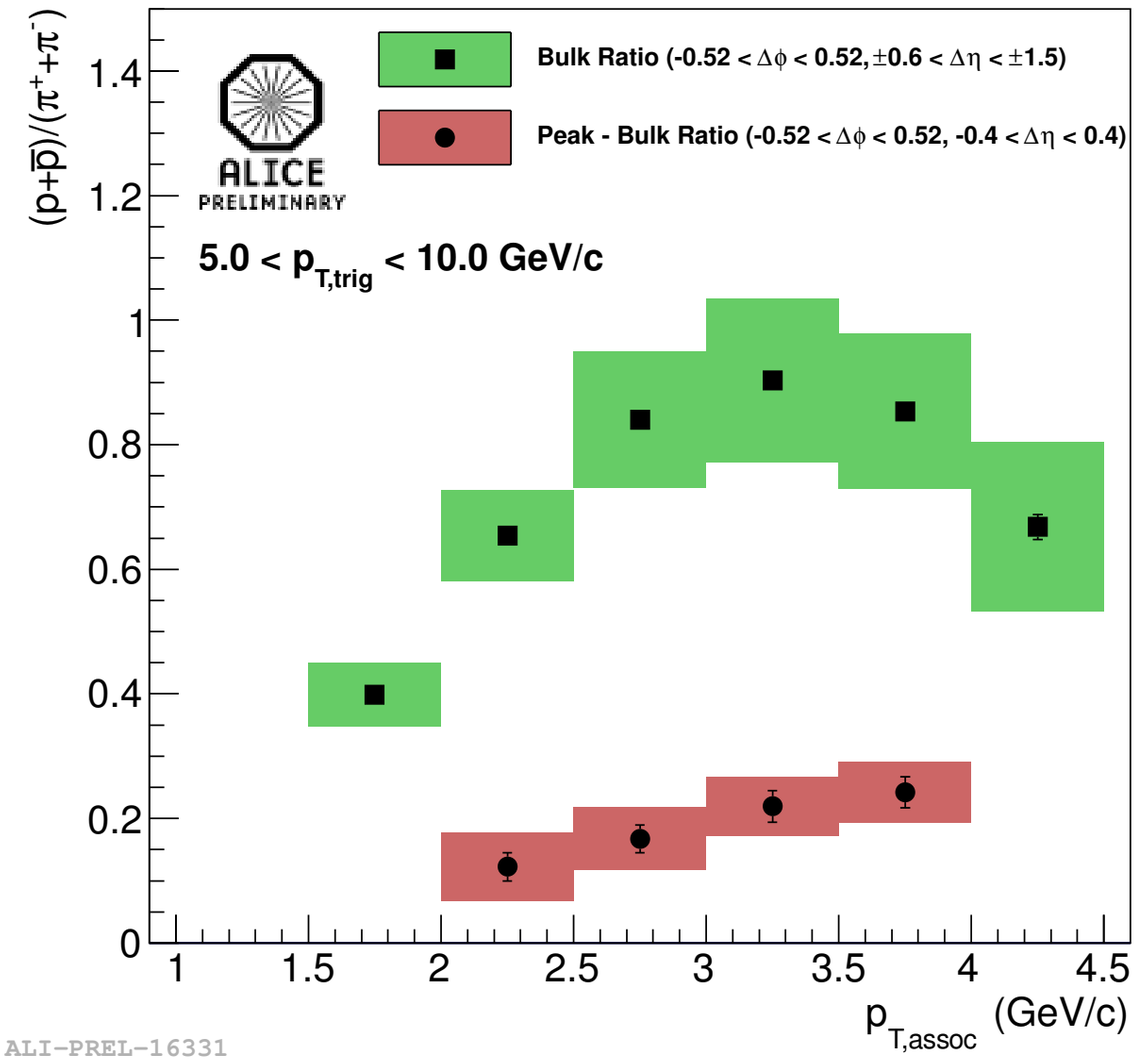
Peak
Bulk I
Bulk II



ALI-PERF-15359



Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV, 0-10% central



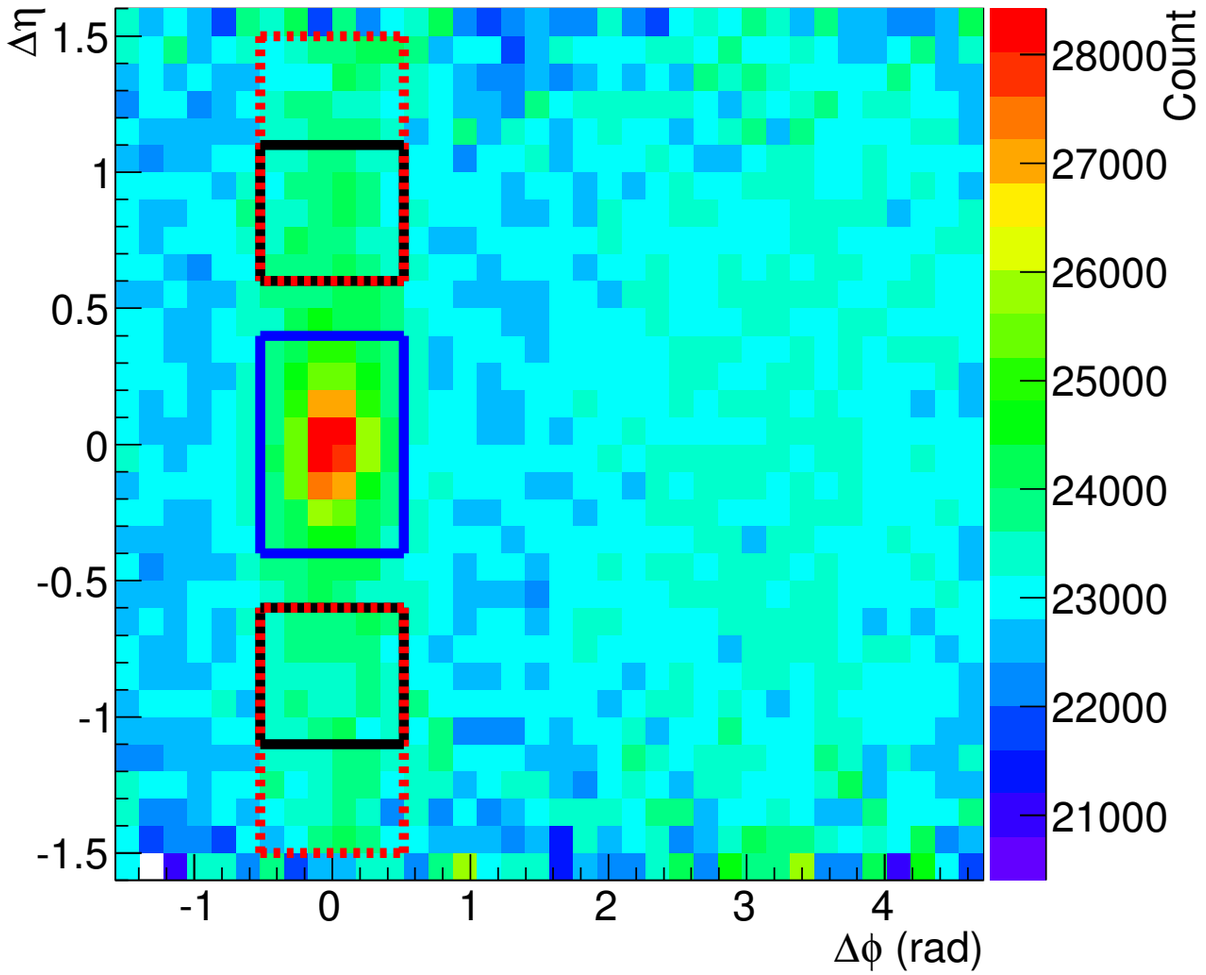
ALI-PREL-16331

Intermediate p_T in the bulk and in the jet

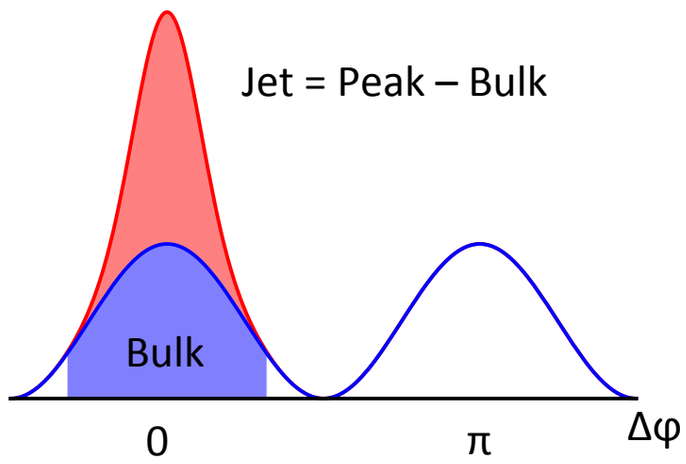
ALICE PERFORMANCE
May 21st, 2012

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV
0-10% central
$2.0 < p_T < 2.5$ GeV/c, $|\eta| < 0.8$

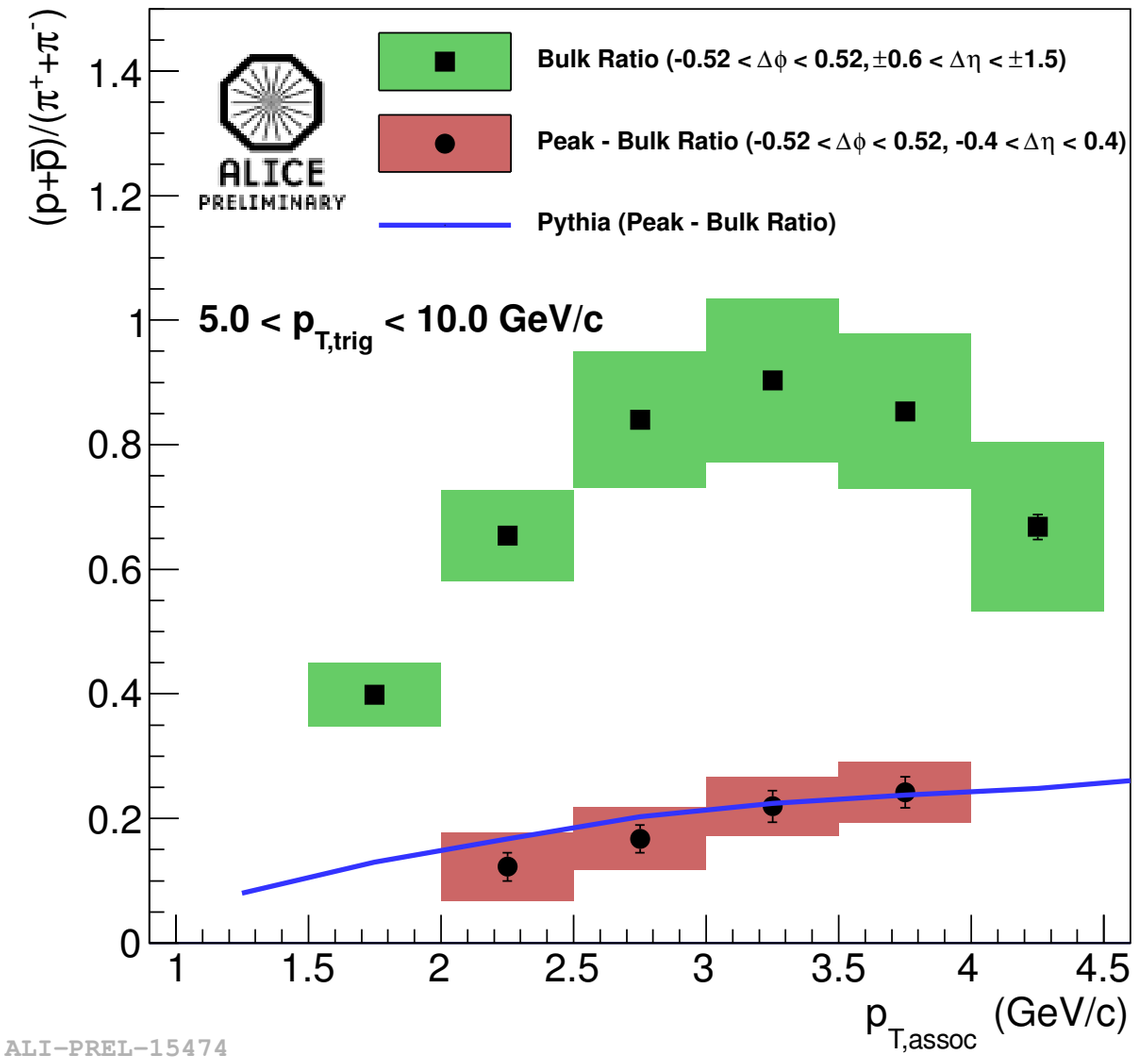
Peak
Bulk I
Bulk II



ALI-PERF-15359



Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV, 0-10% central



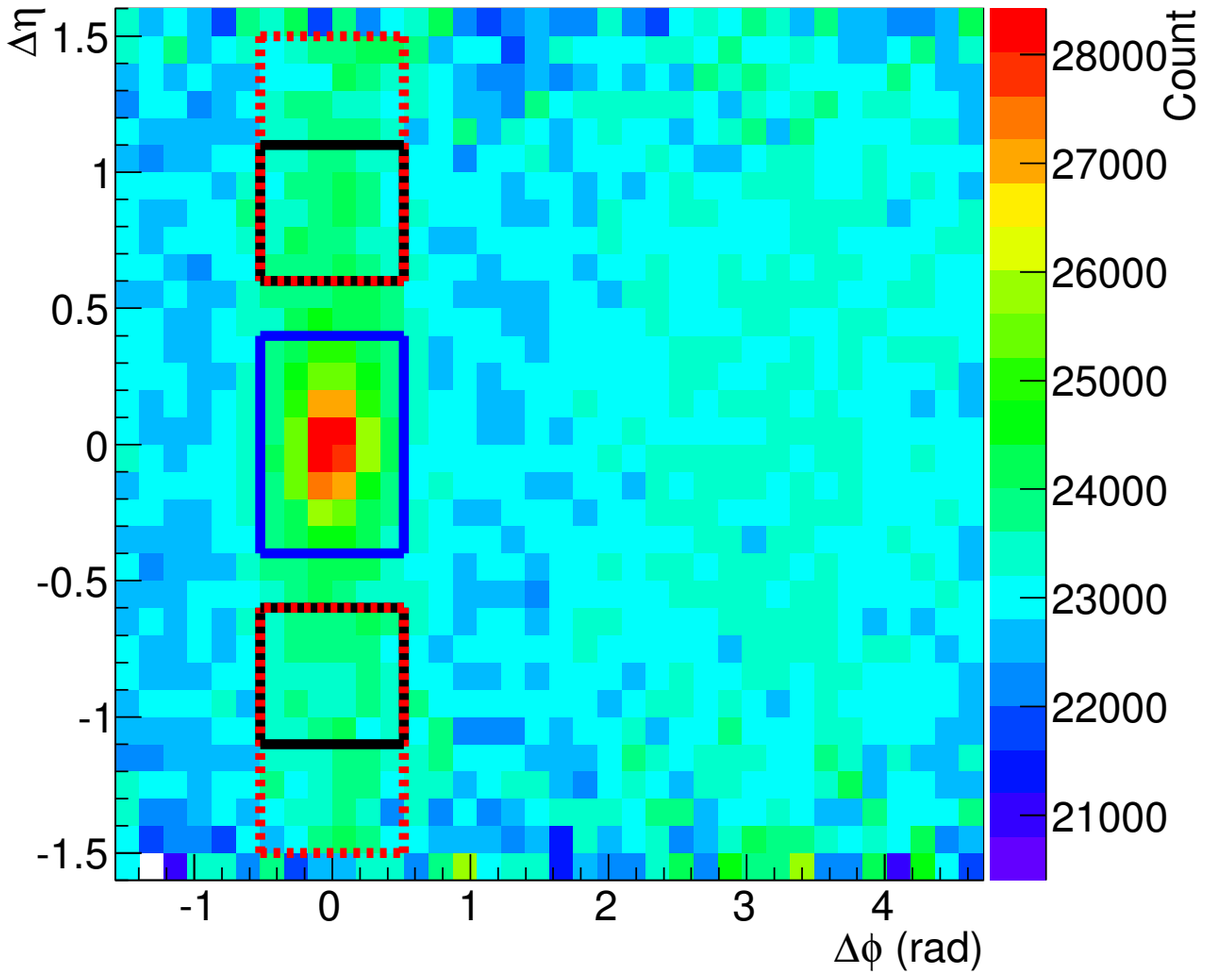
ALI-PREL-15474

Intermediate p_T in the bulk and in the jet

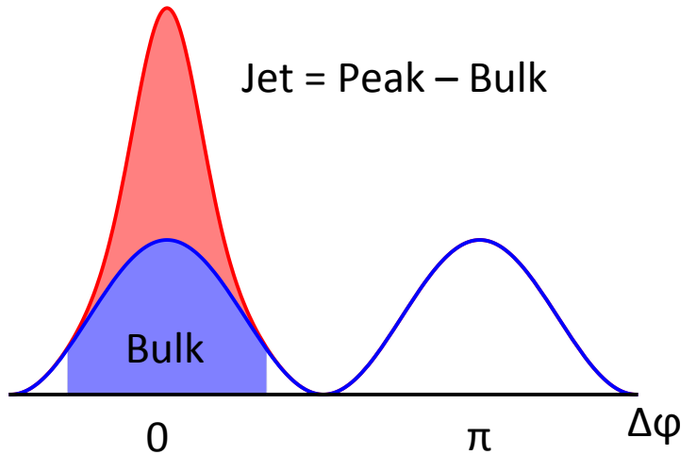
ALICE PERFORMANCE
May 21st, 2012

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV
0-10% central
$2.0 < p_T < 2.5$ GeV/c, $|\eta| < 0.8$

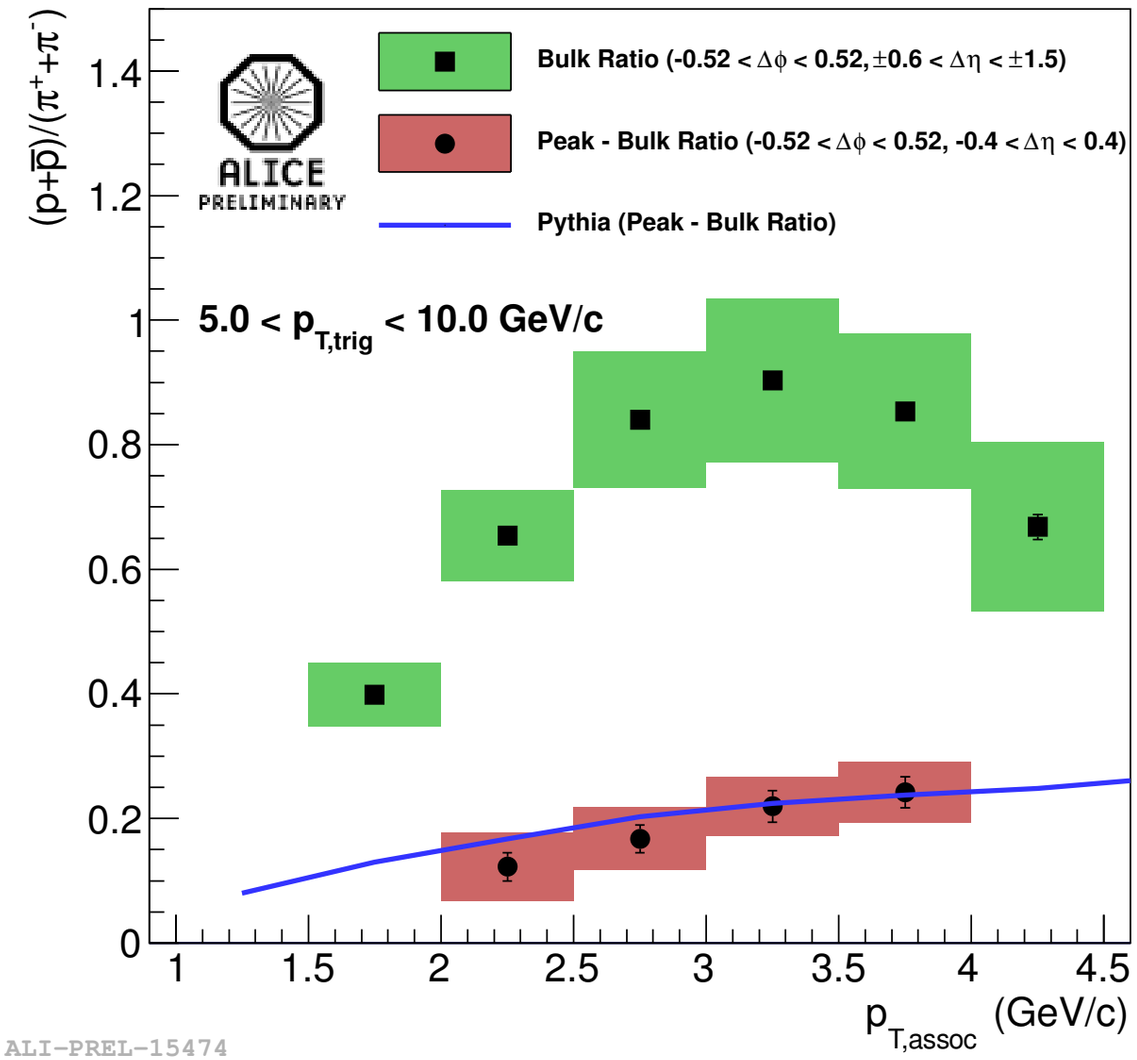
Peak
Bulk I
Bulk II



ALI-PERF-15359



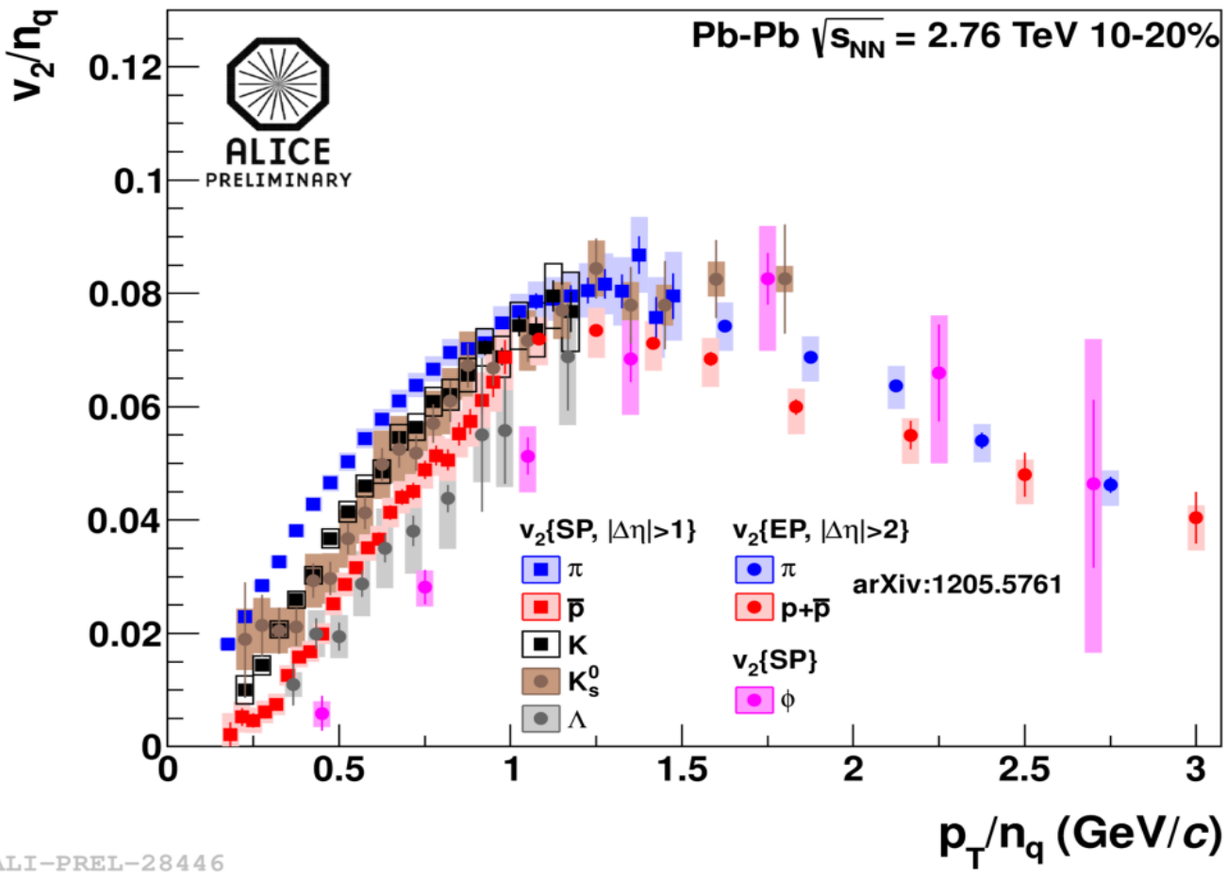
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV, 0-10% central

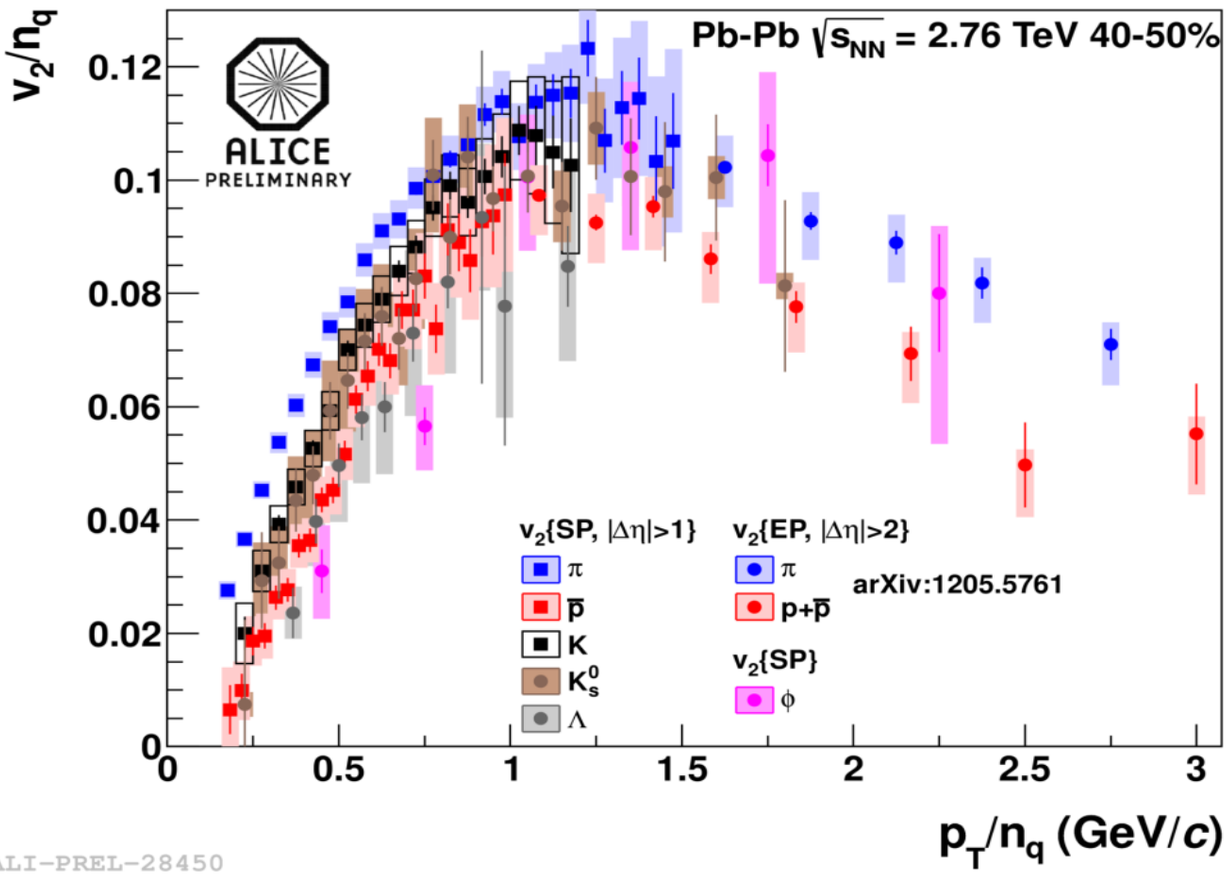


ALI-PREL-15474

The “baryon anomaly” is a bulk effect!

Number of Constituent Quarks scaling of v2

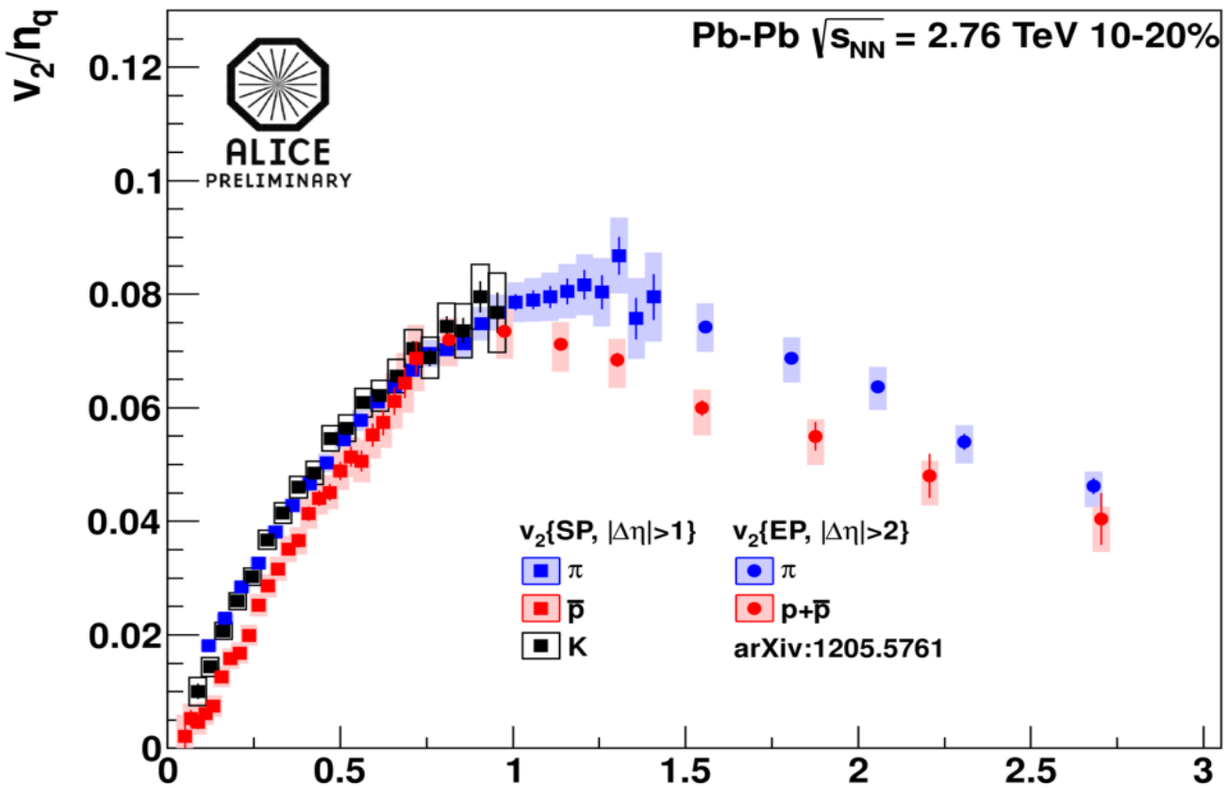


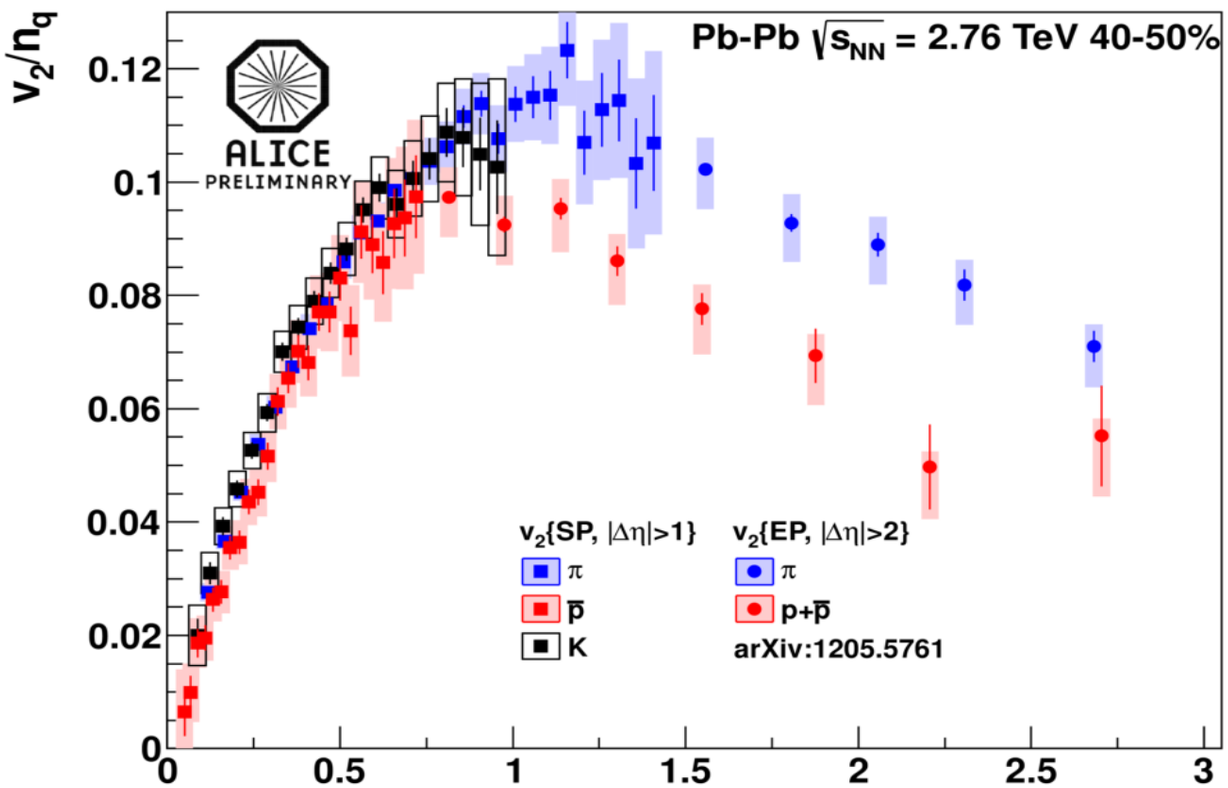


- v2 measured in the pT region of 3-6 GeV/c can be used to test the model of the hardon production via quark coalescence

- v2/nq vs. pT/nq (nq is the number of quarks per meson/baryon) shows that if such scaling exists it is only approximate (holds within 20%)

NCQ scaling of v2 vs. transverse kinetic energy



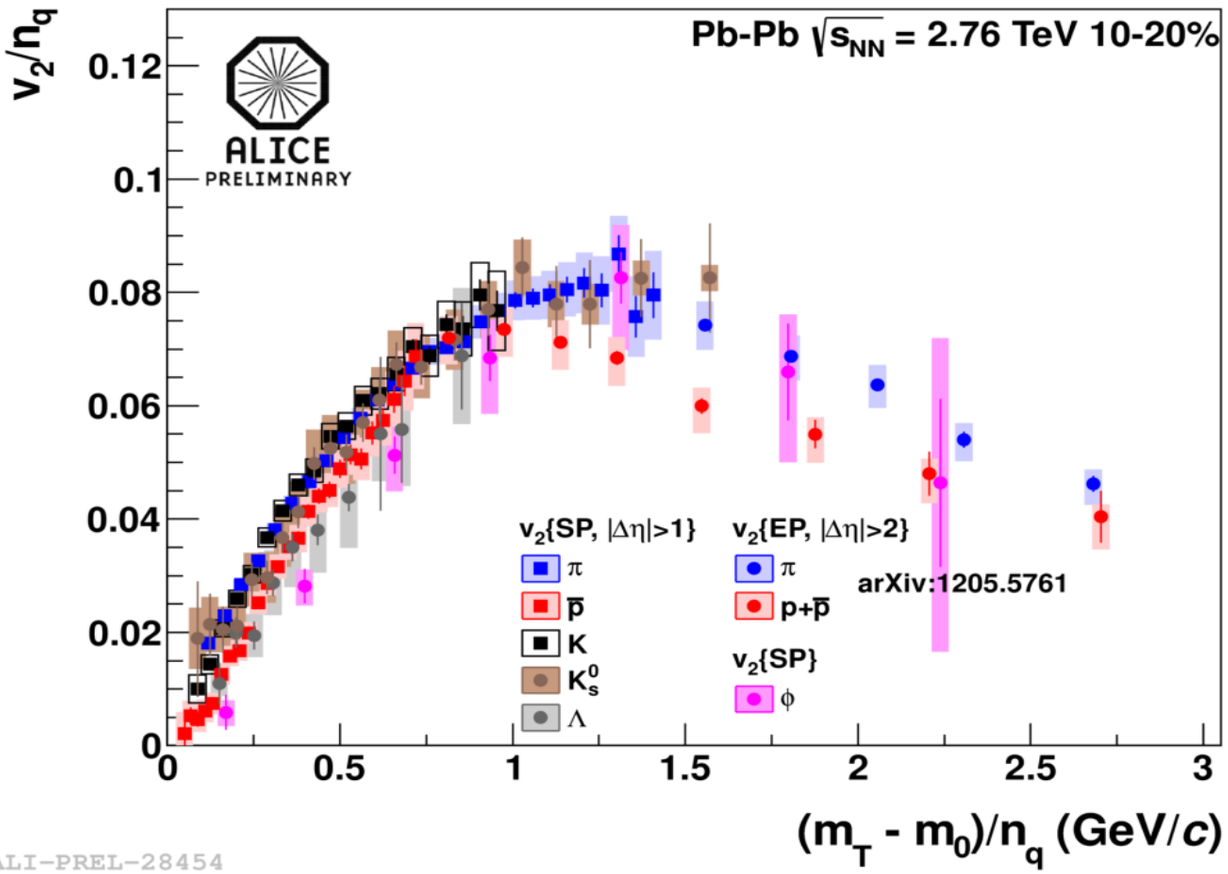


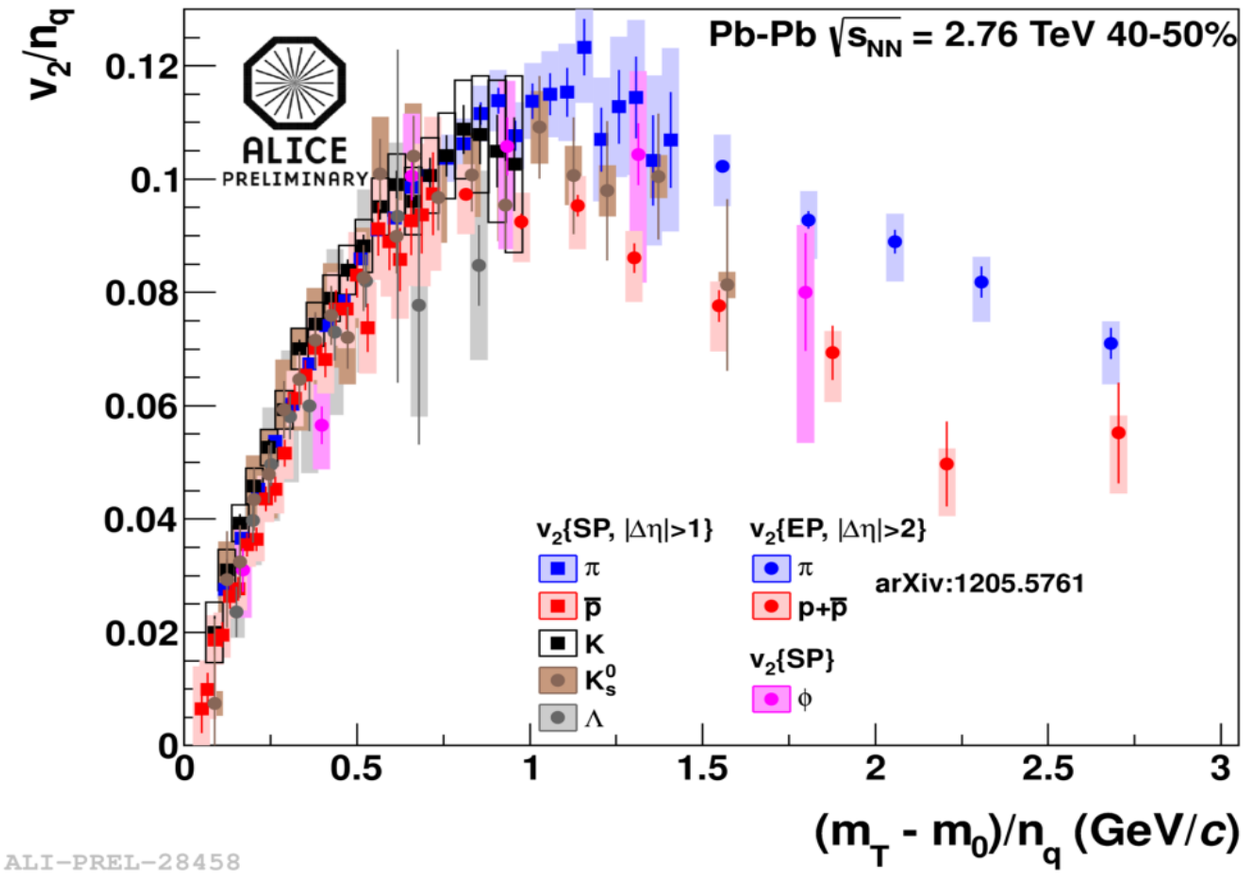
$$m_T = \sqrt{m^2 + p_T^2}$$

KET = Transverse Kinetic Energy = mT – m0

- For low pT: v2/nq together with KET scaling is violated at LHC
- For KET/nq > 1 GeV/c antiproton's v2 is lower than that of pions

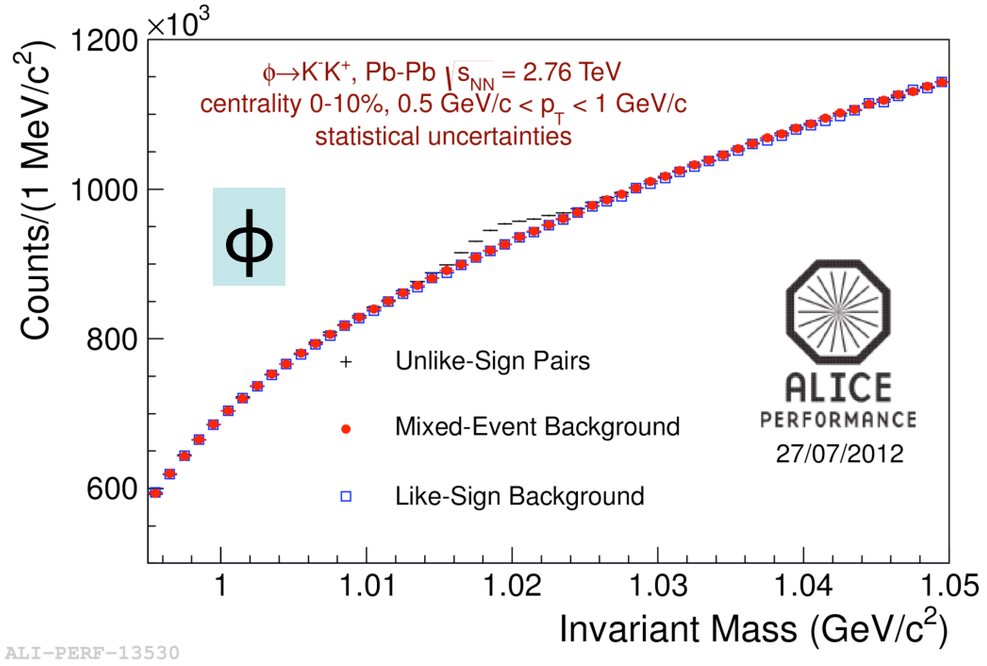
v2/nq and KET scaling for all species



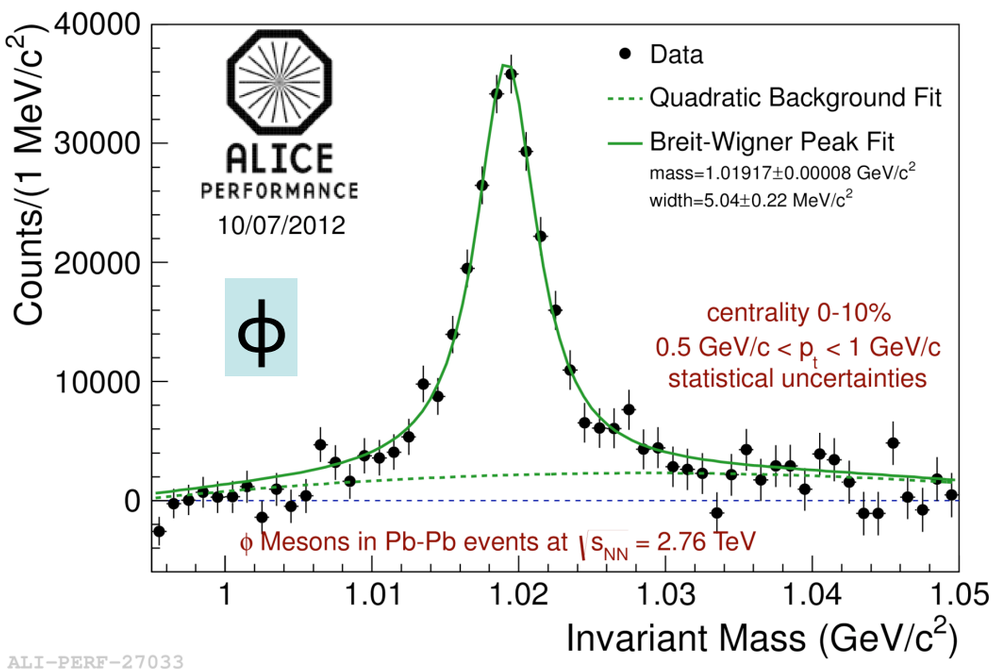


NCQ scaling maybe violated also for heavier particles, including the φ-meson

Signal extraction: Resonances



After combinatorial background subtraction



- Reconstructed via their hadronic decay channels:

$$\phi \rightarrow K^+K^- \quad \begin{cases} K^{*0} \rightarrow K^+ \pi^- \\ \overline{K^{*0}} \rightarrow K^- \pi^+ \end{cases}$$

- Construction of combinatorial background:
  - Mixed event technique.
  - Like Sign technique.

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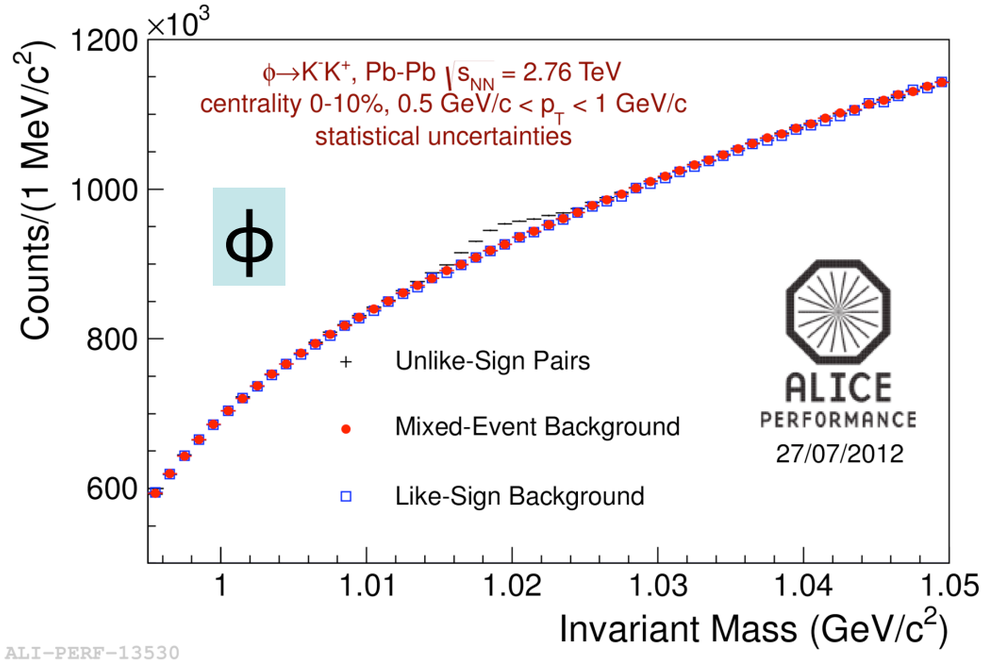

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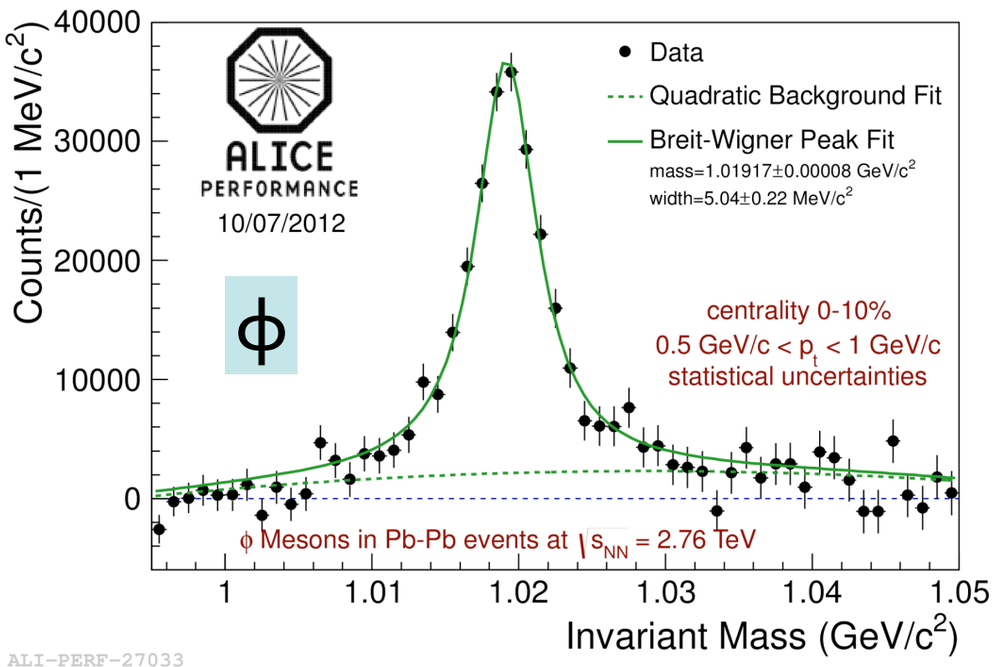

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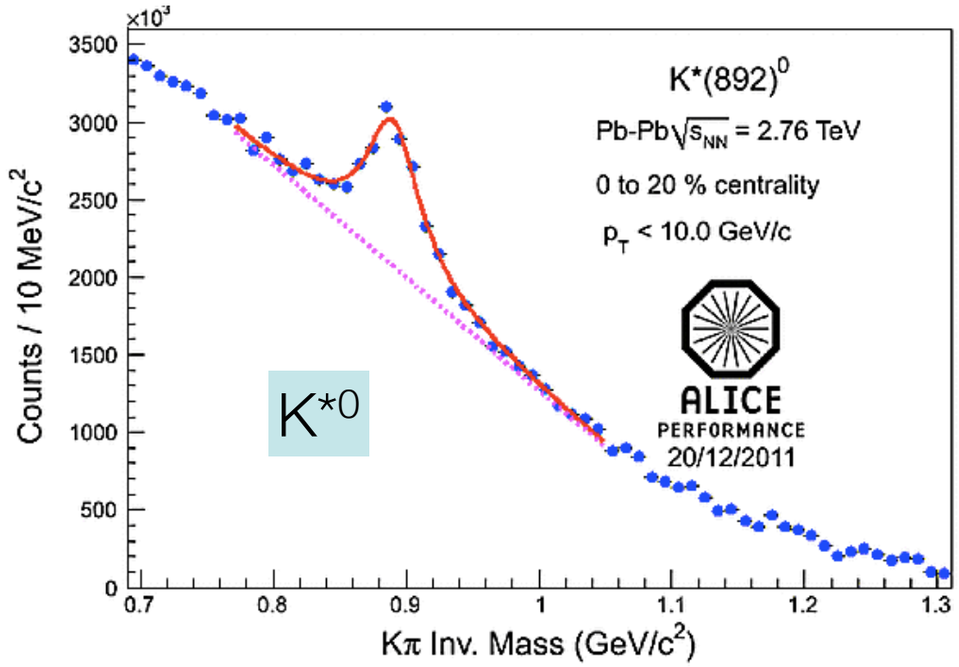
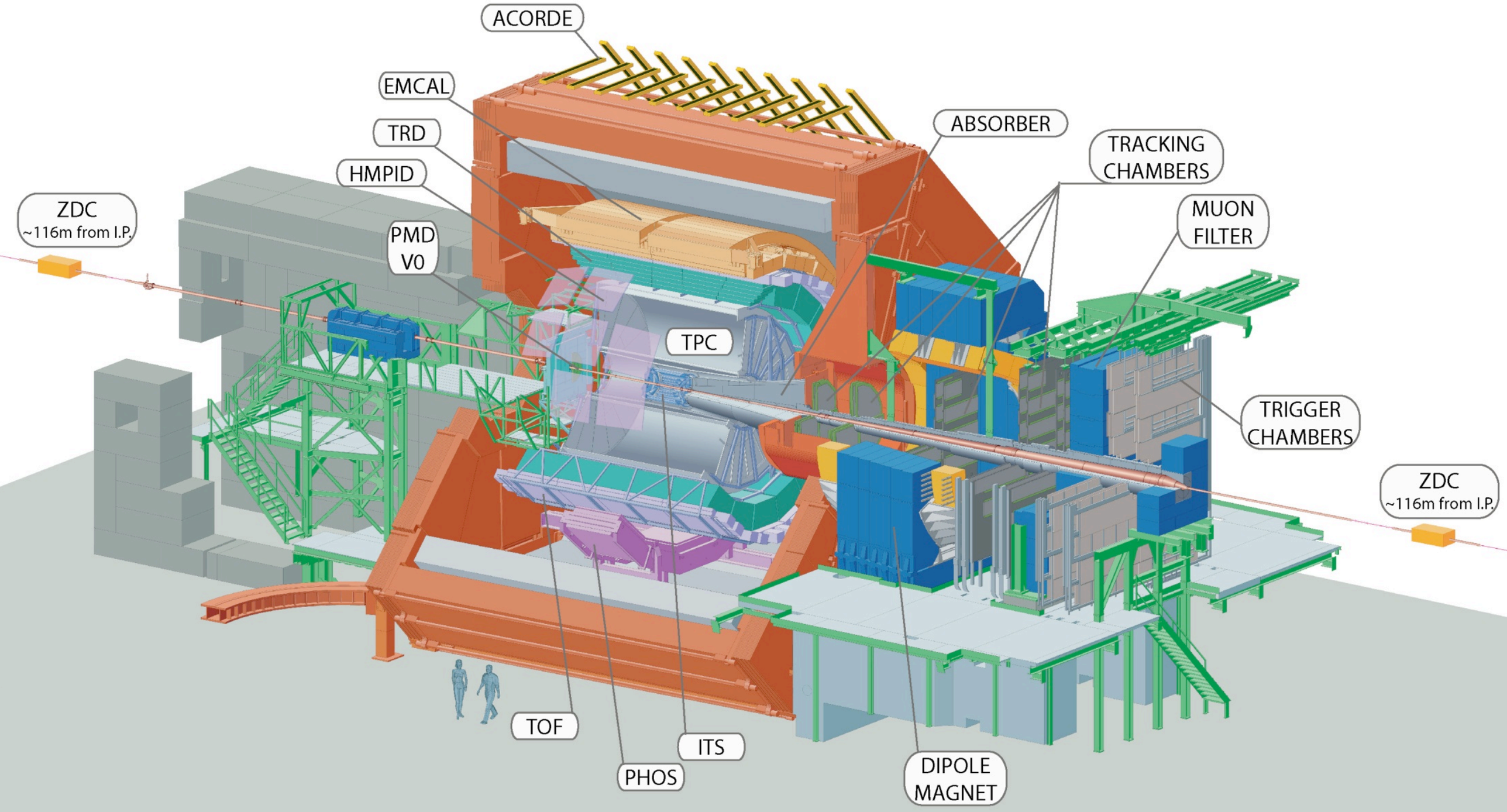


ALICE detector



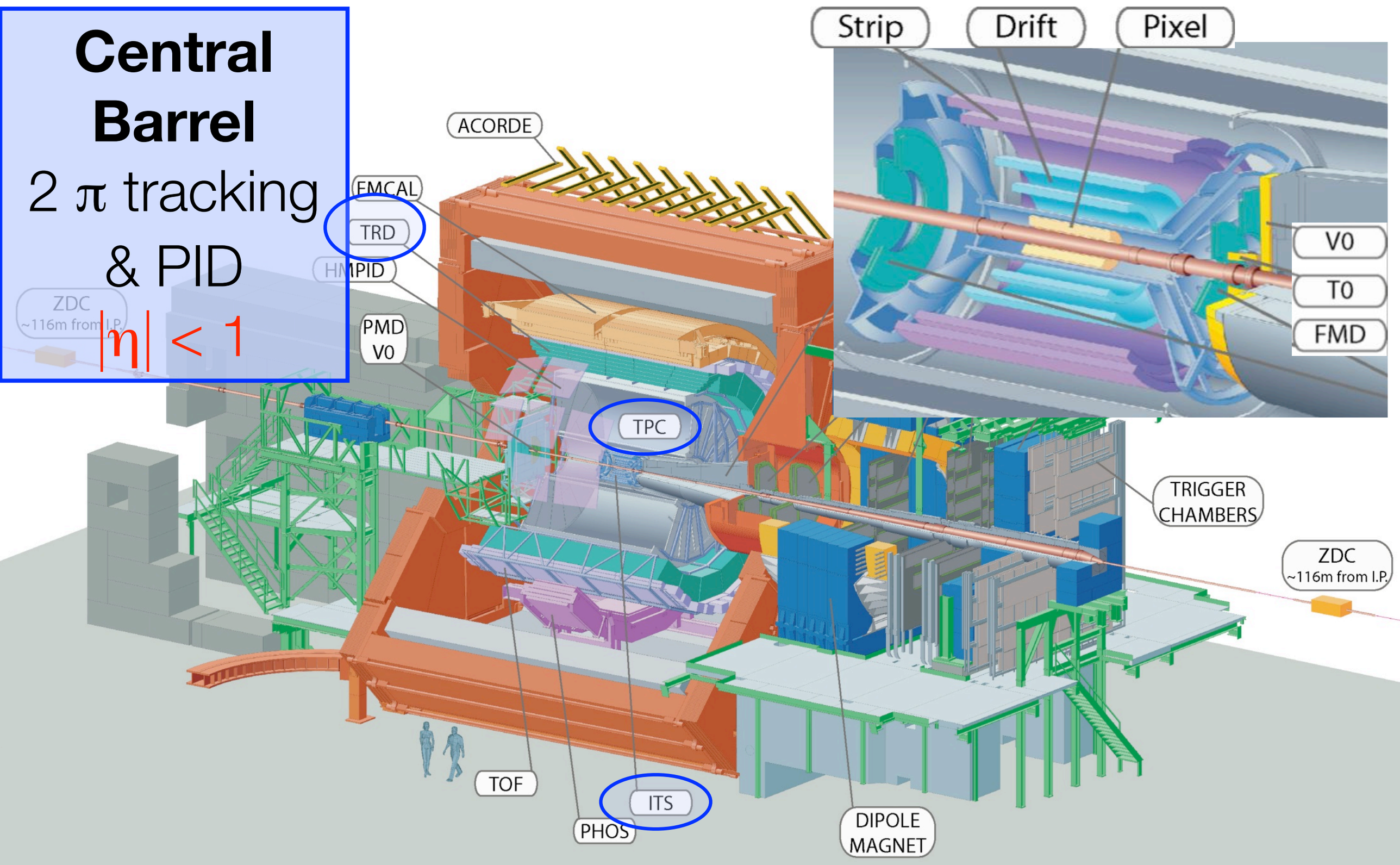
Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

Central Barrel

2 π tracking & PID

$|\eta| < 1$



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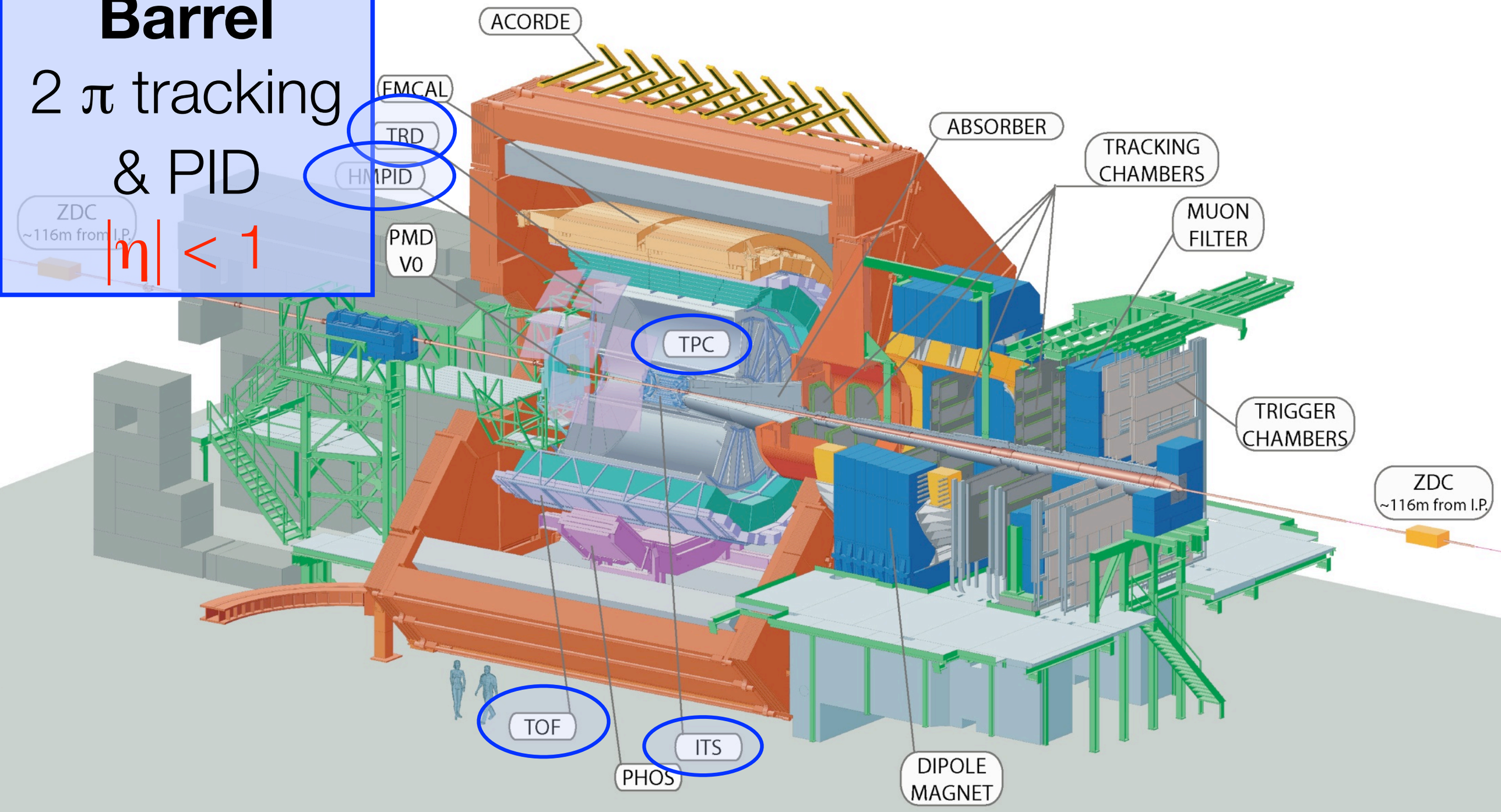

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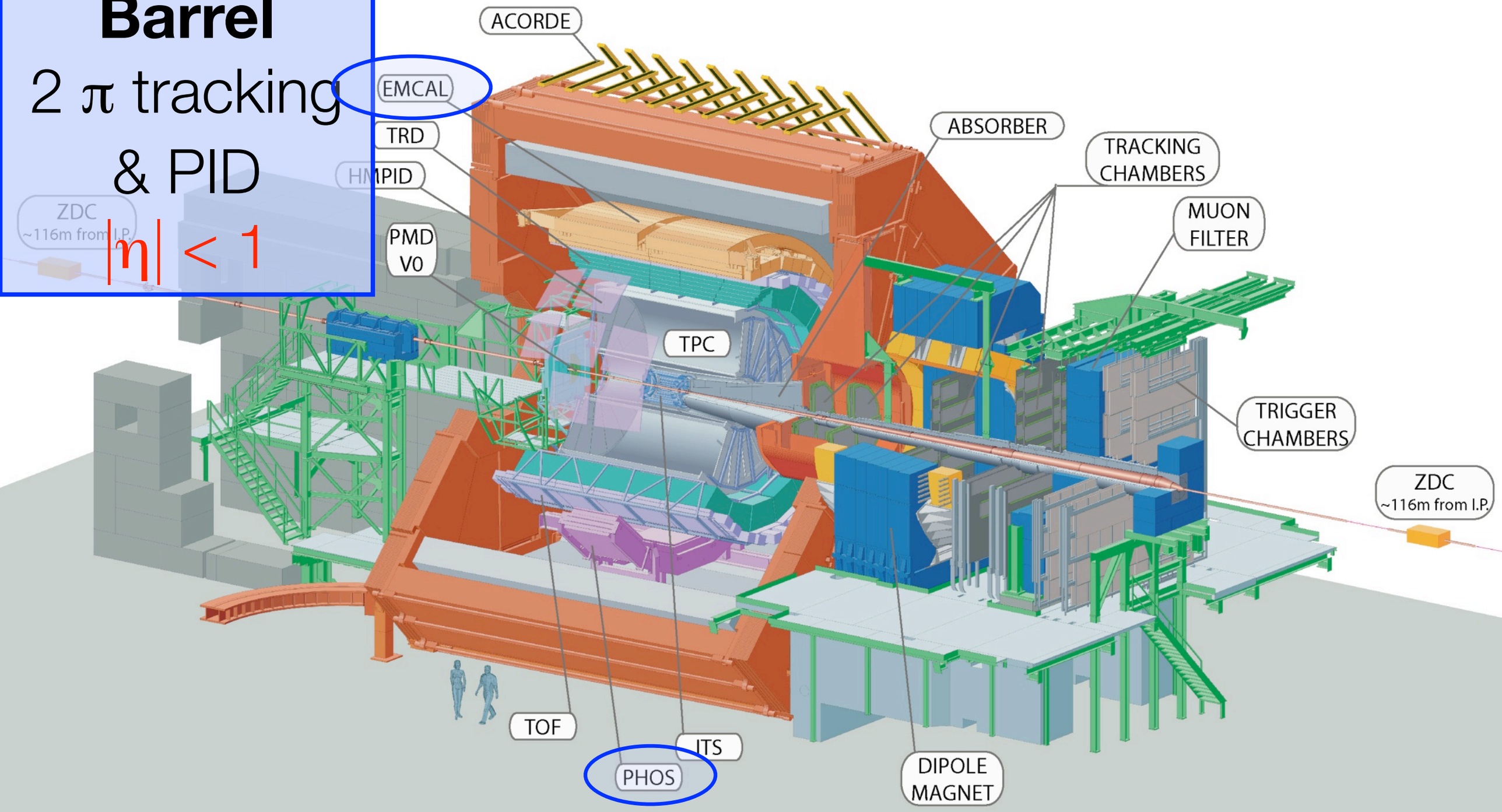

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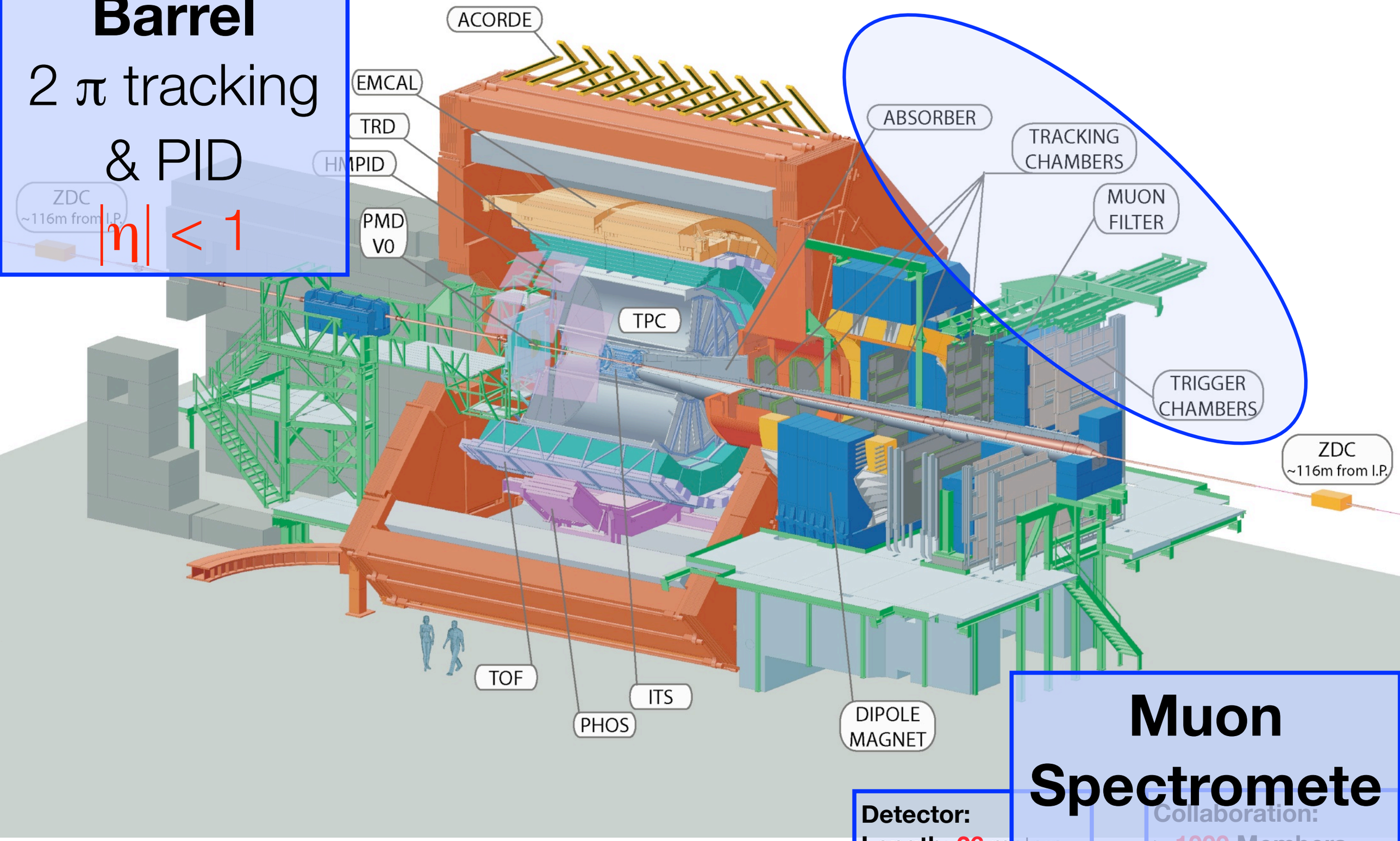

Muon Spectrometer

$-2.5 > \eta > -4$

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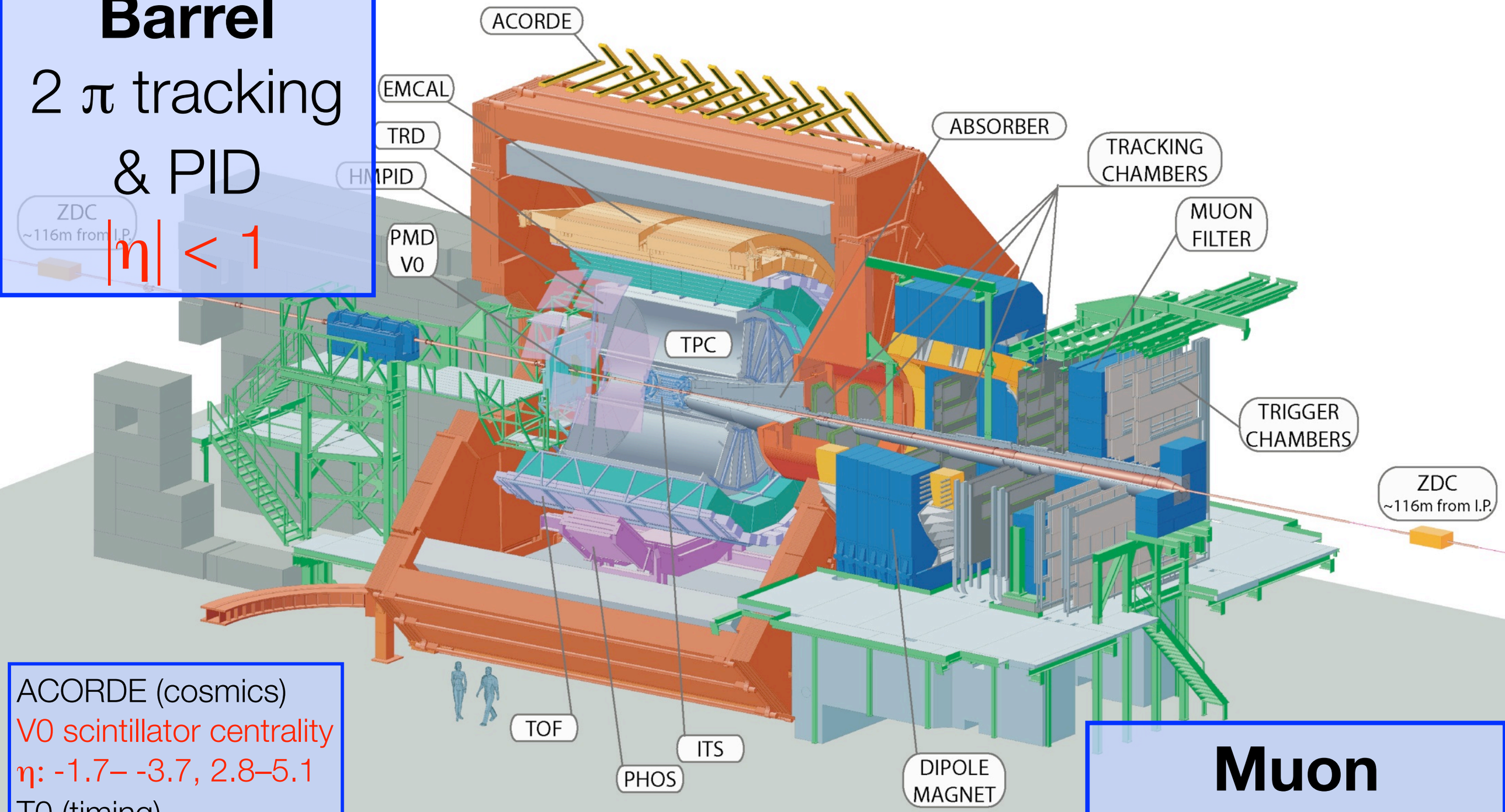

ACORDE (cosmics)
V0 scintillator centrality
η: -1.7– -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} -3.4<η<5)
PMD ($N\gamma$, N_{ch})

Detector:
Length: 26 meters
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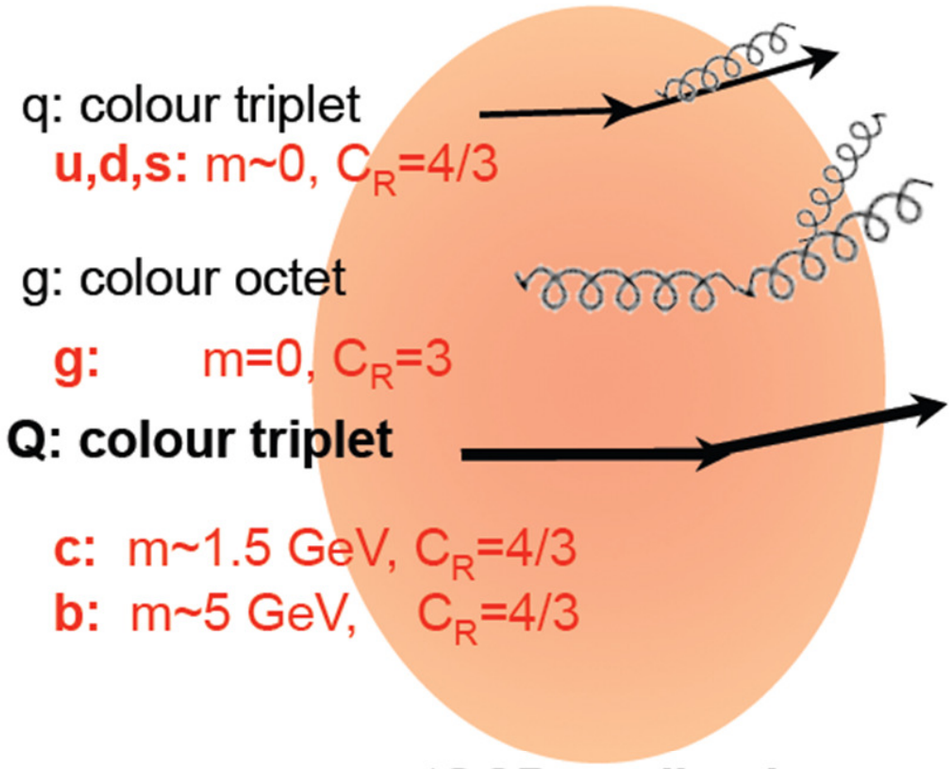
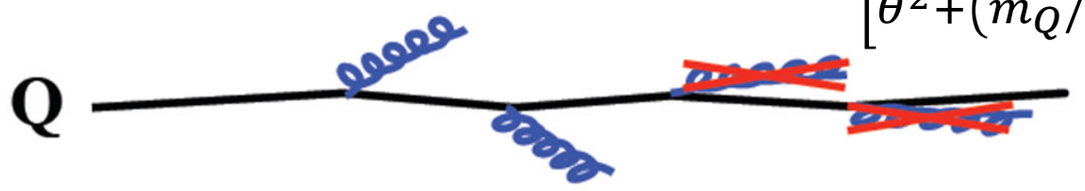
Heavy quark energy loss

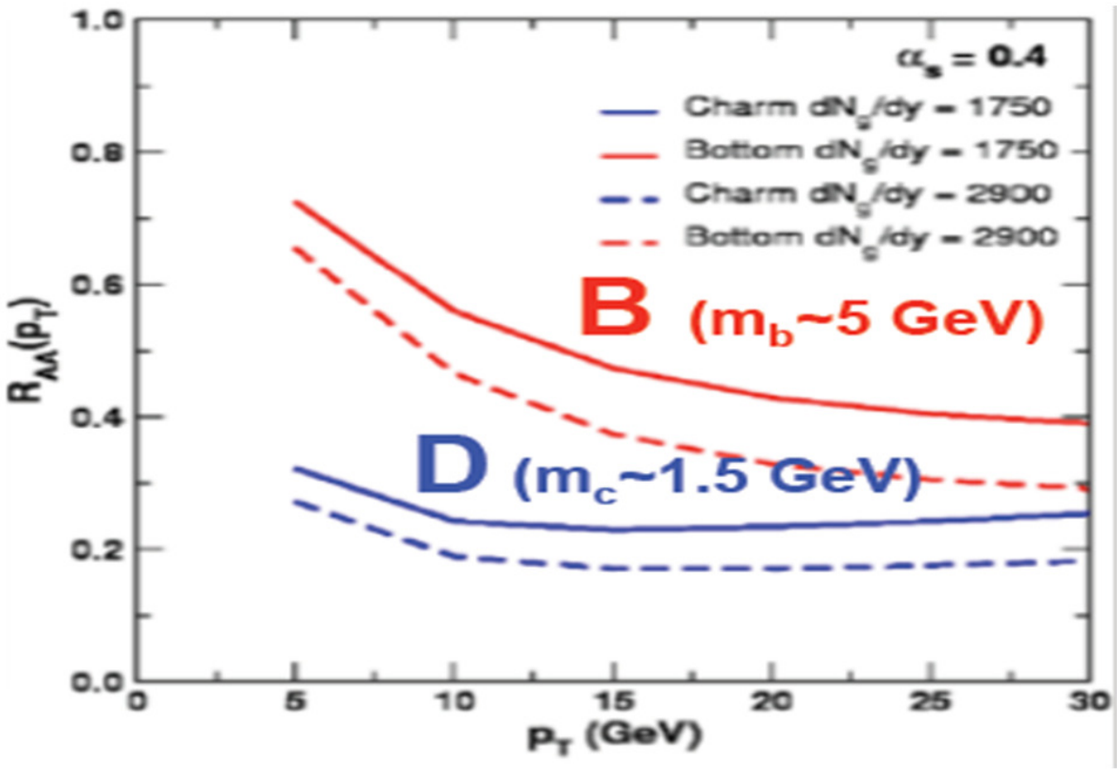


- Energy loss ΔE depends on
  - ⇨ Properties of the medium: density, temperature, mean free path
  - ⇨ Path length in the medium (L)
  - ⇨ Properties of the parton:
    - ✓ ***Casimir coupling factor*** (C_R)
    - ✓ ***Mass of the quark (dead cone effect)***

gluonstrahlung probability $\propto \frac{1}{\left[\theta^2+\left(m_Q/E_Q\right)^2\right]^2}$



📖 **Dokshitzer and Kharzeev, PLB 519 (2001) 199**



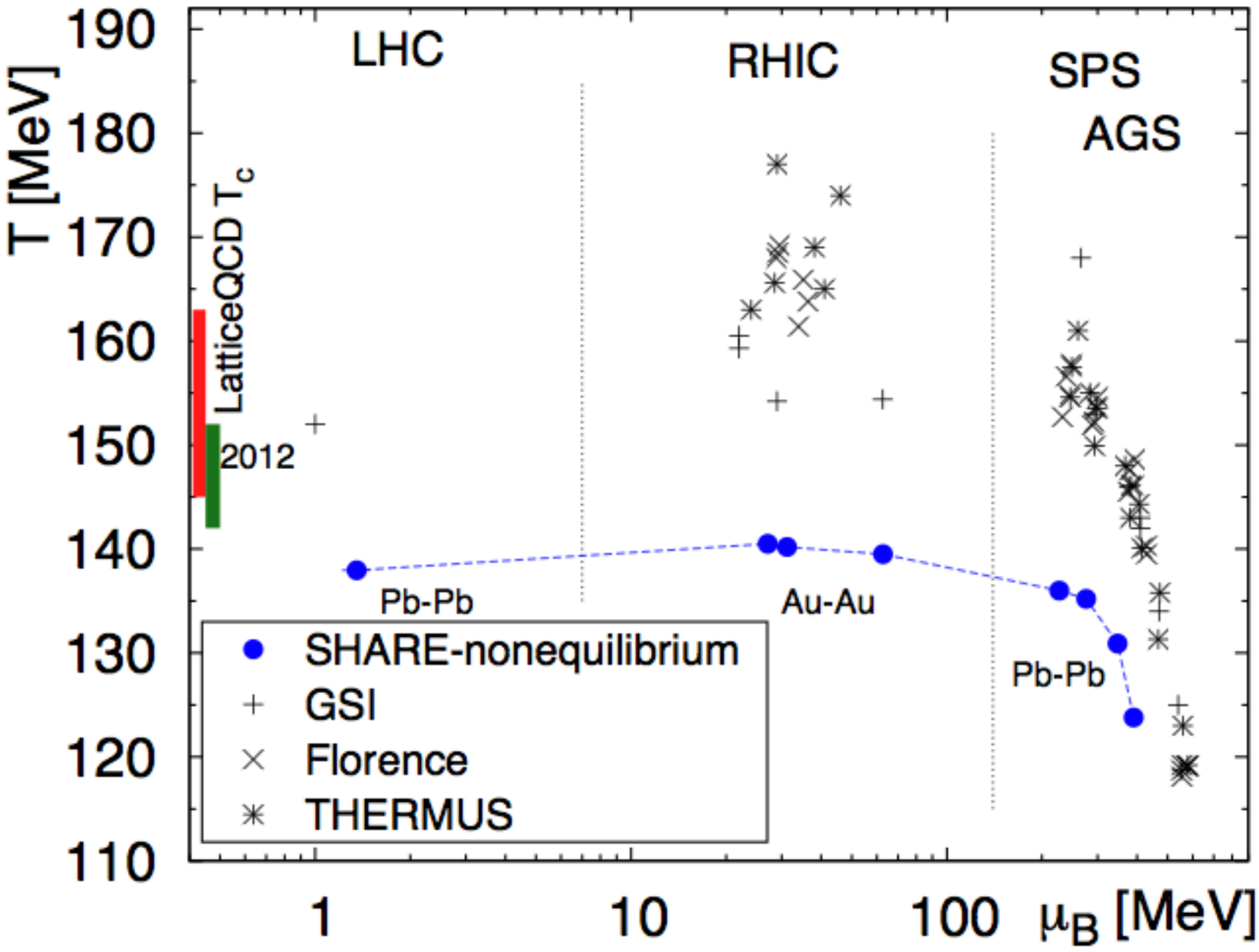
$$\Delta E_{quark} < \Delta E_{gluon} \quad , \quad \Delta E_{massive\ quark} < \Delta E_{light\ quark}$$

$$\Downarrow$$

$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

📖 **Wicks, Gyulassy, Last Call for LHC predictions, J.Phys. G35 (2008) 054001**

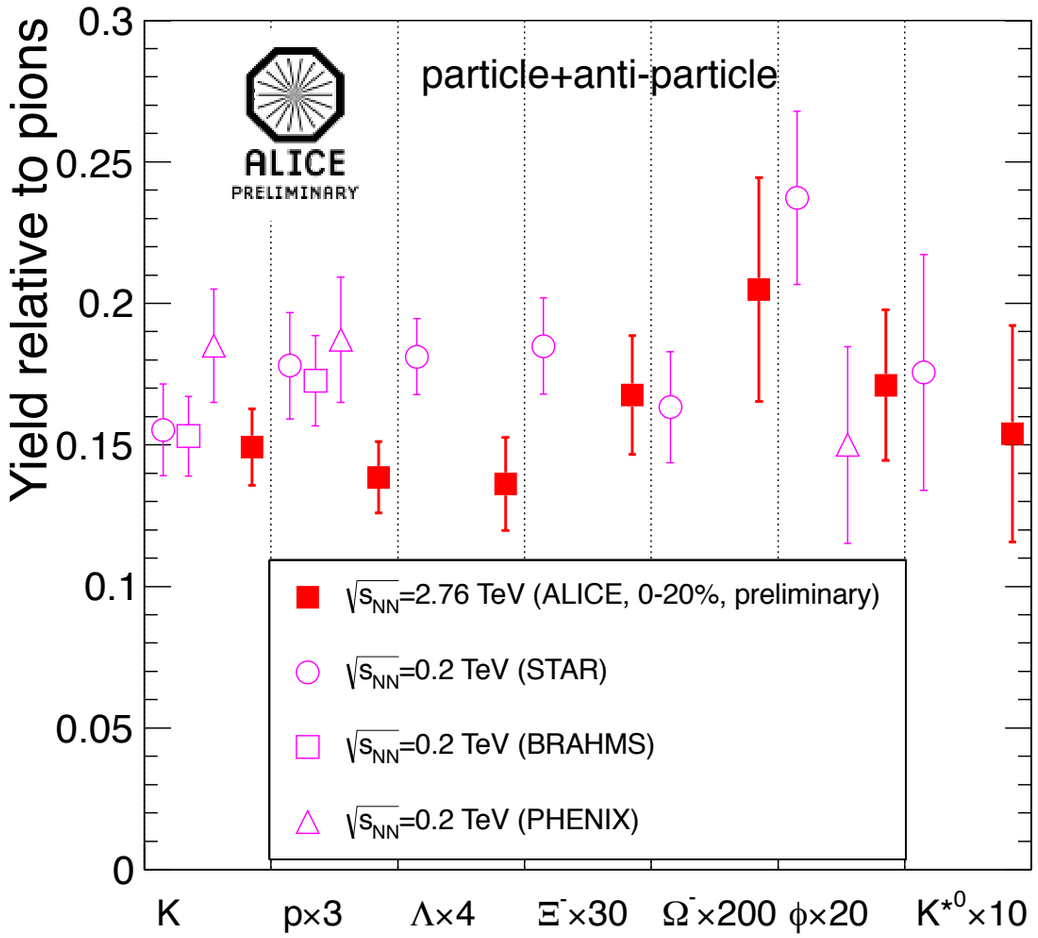
Hadron freeze-out curve



arXiv:1303.2098

Comparison to RHIC

- Feed down: p_{STAR} (-37%) π_{PHENIX} (-10%)
- Decreasing ratios at the LHC?
- p/π and Λ/π different at the LHC
- Tensions already at RHIC?



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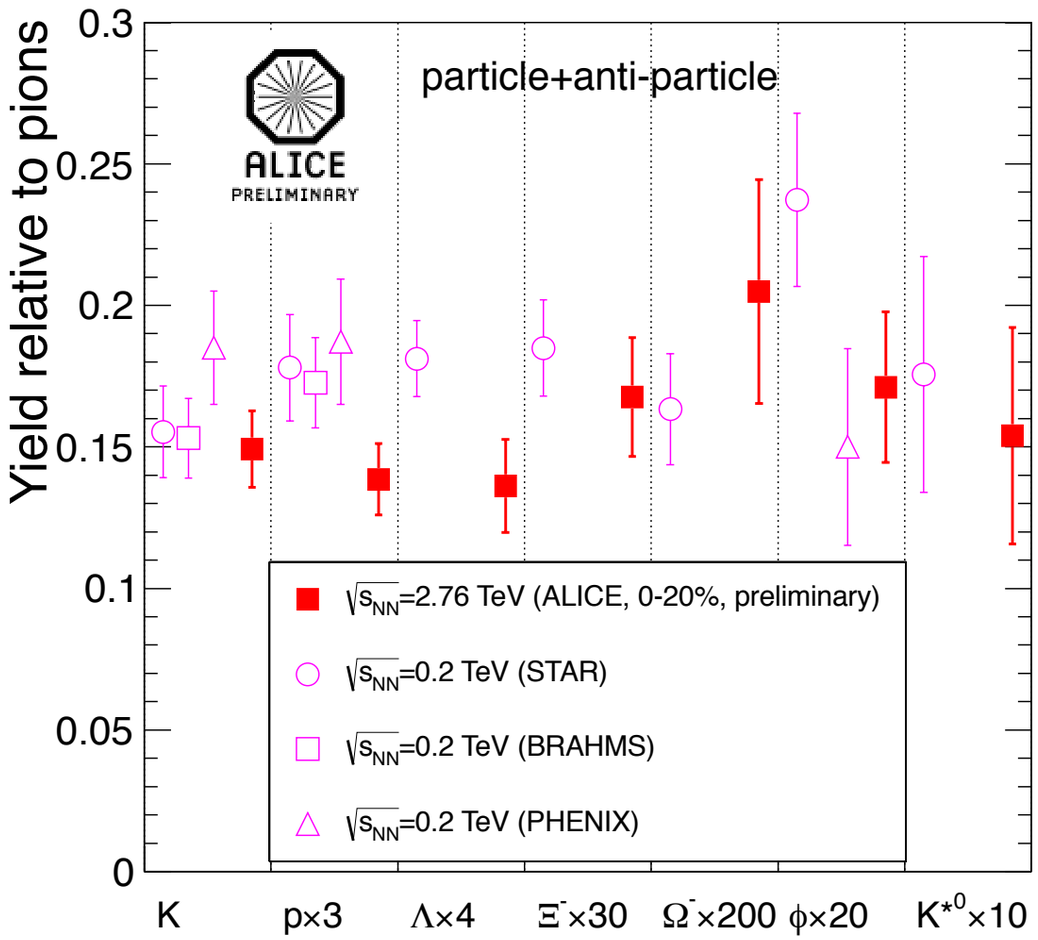

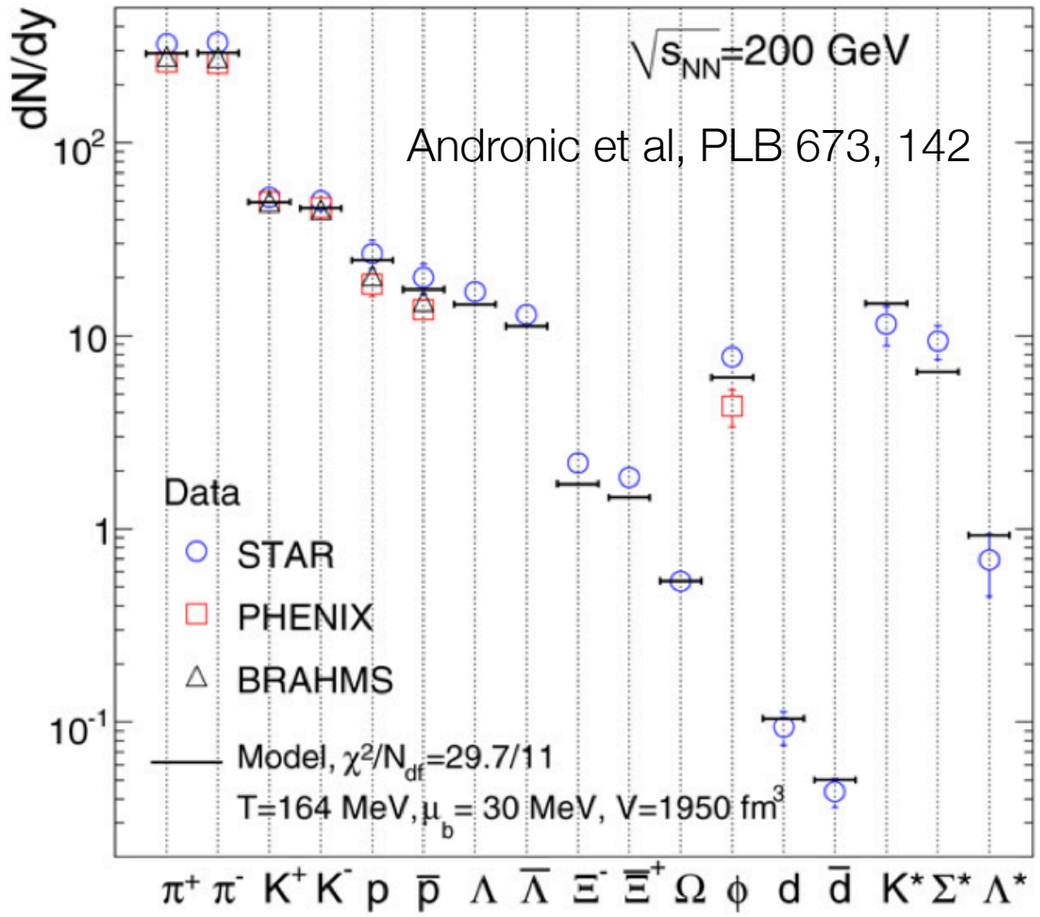

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