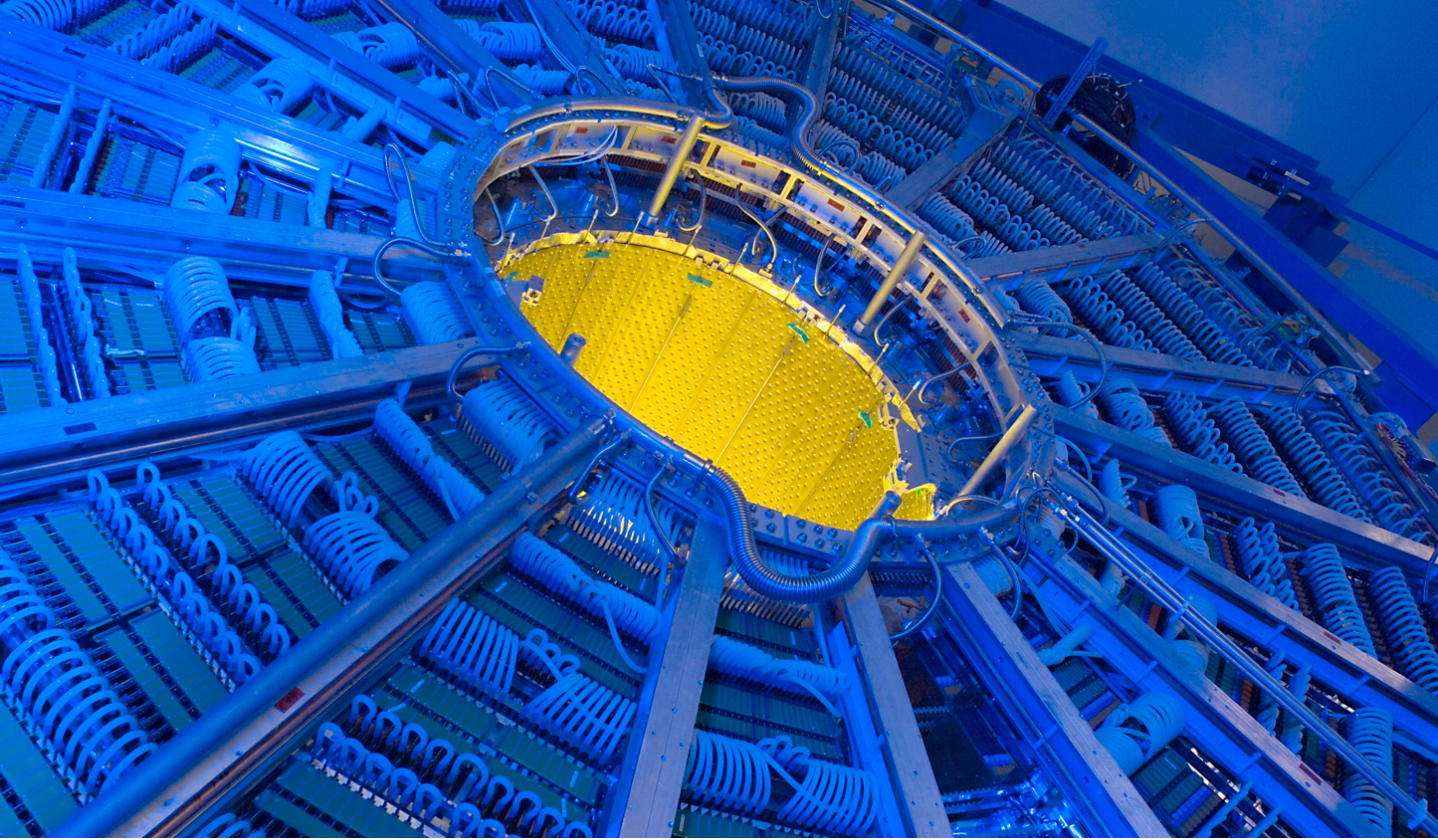


System Size Evolution of Flow and Yields

Michele Floris (CERN)
Incontro sulla Fisica con Ioni Pesanti a LHC, May 2015

Executive Summary

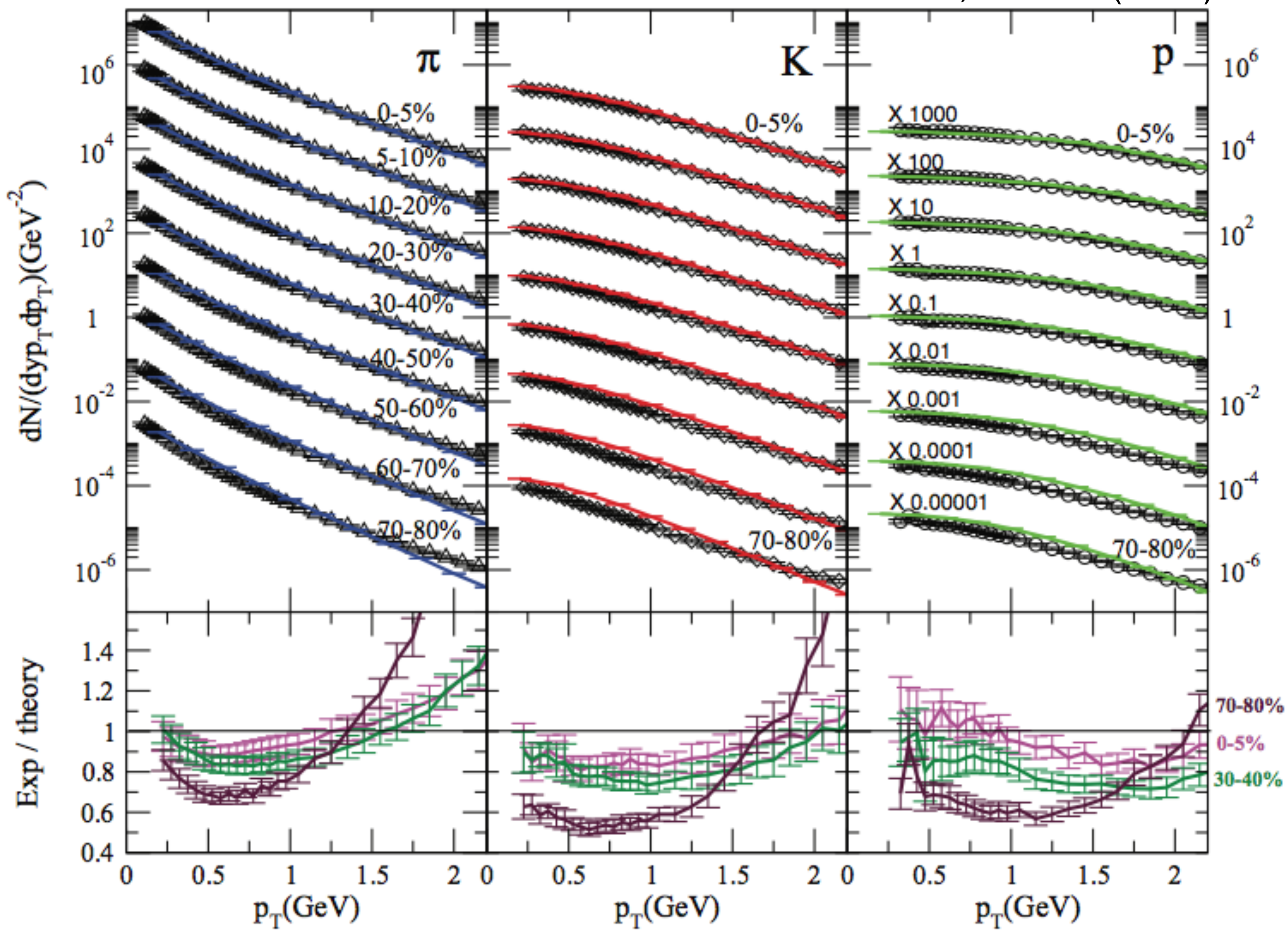
- Heavy ion "standard model": works at LHC, but **late and early stage**?
- **Similarities** between pp/p-Pb/Pb-Pb
- Traditional **flow observables** also seen in **p-Pb (& pp?)**
  - Spectra "flattening" w/ mass ordering ⇔ radial flow
  - Correlations & ridges ⇔ anisotropic flow

- **Particle ratios** change little from small to large systems (caveat: strangeness), small systems towards gran canonical equilibrium?
  - Tension of Pb-Pb ratios with SHM
- … but the devil is in the details

Pb-Pb results: state of the art

Radial flow: Comparison to Hydro Models

PRC 89, 034919 (2014)

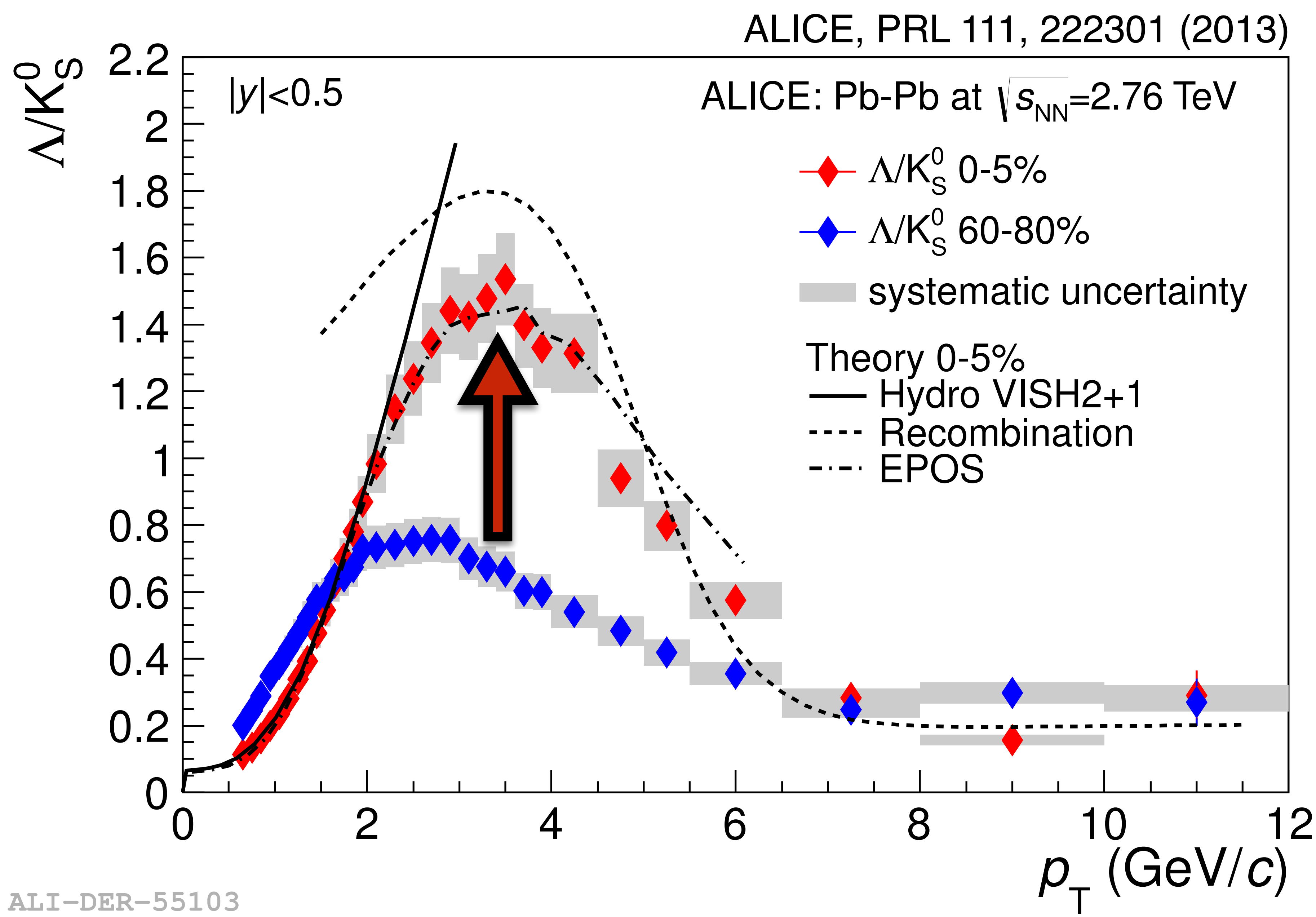


Hydro models give a satisfactory description

Pure hydro: not enough flow

Hadronic interactions: too much flattening?

B/M ratios: the rise and the fall

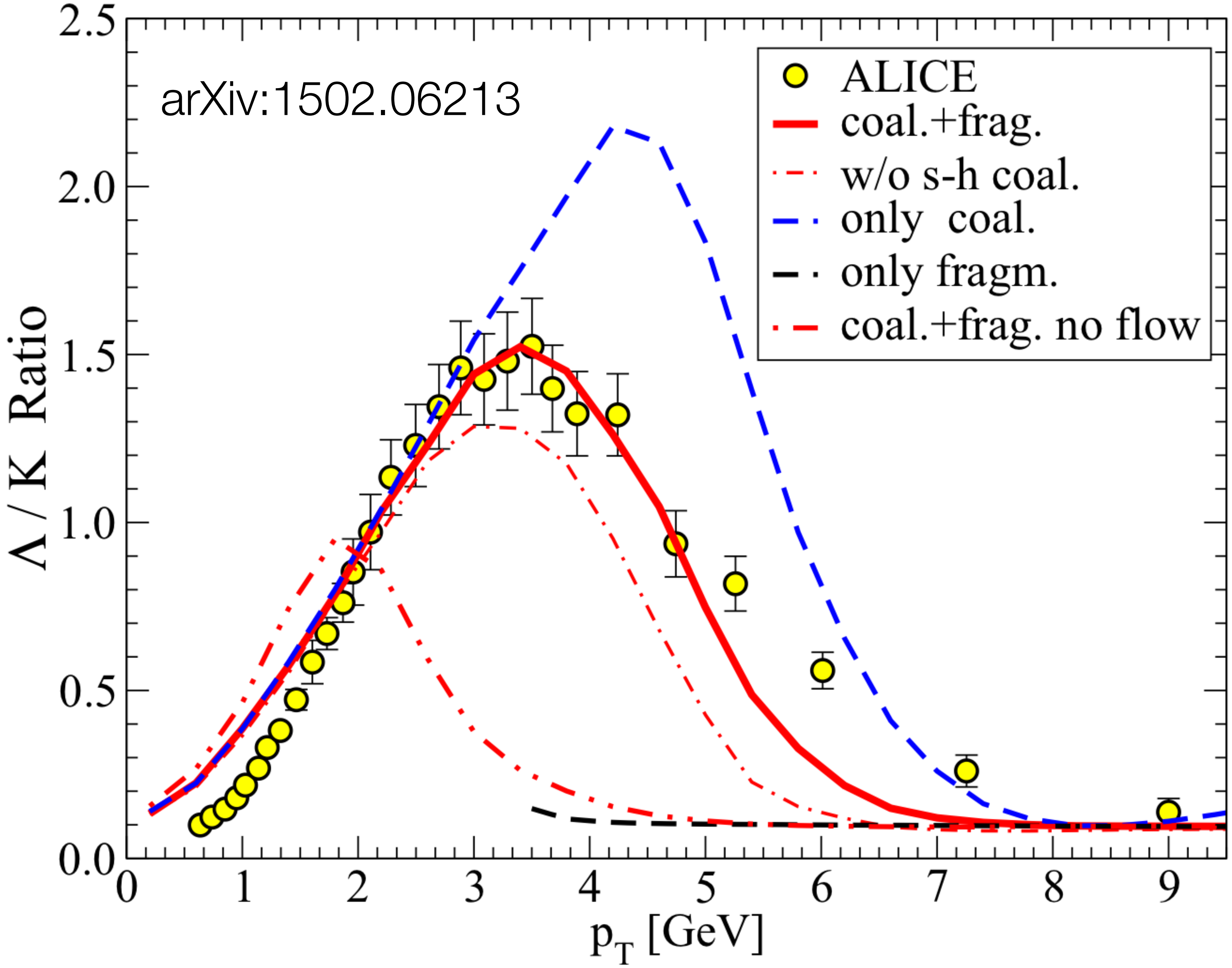


Radial Flow explains rise

Recombination describes some features of the data

Realistic models: “bulk" **flow** and hard **fragmentation**

B/M ratios: the rise and the fall



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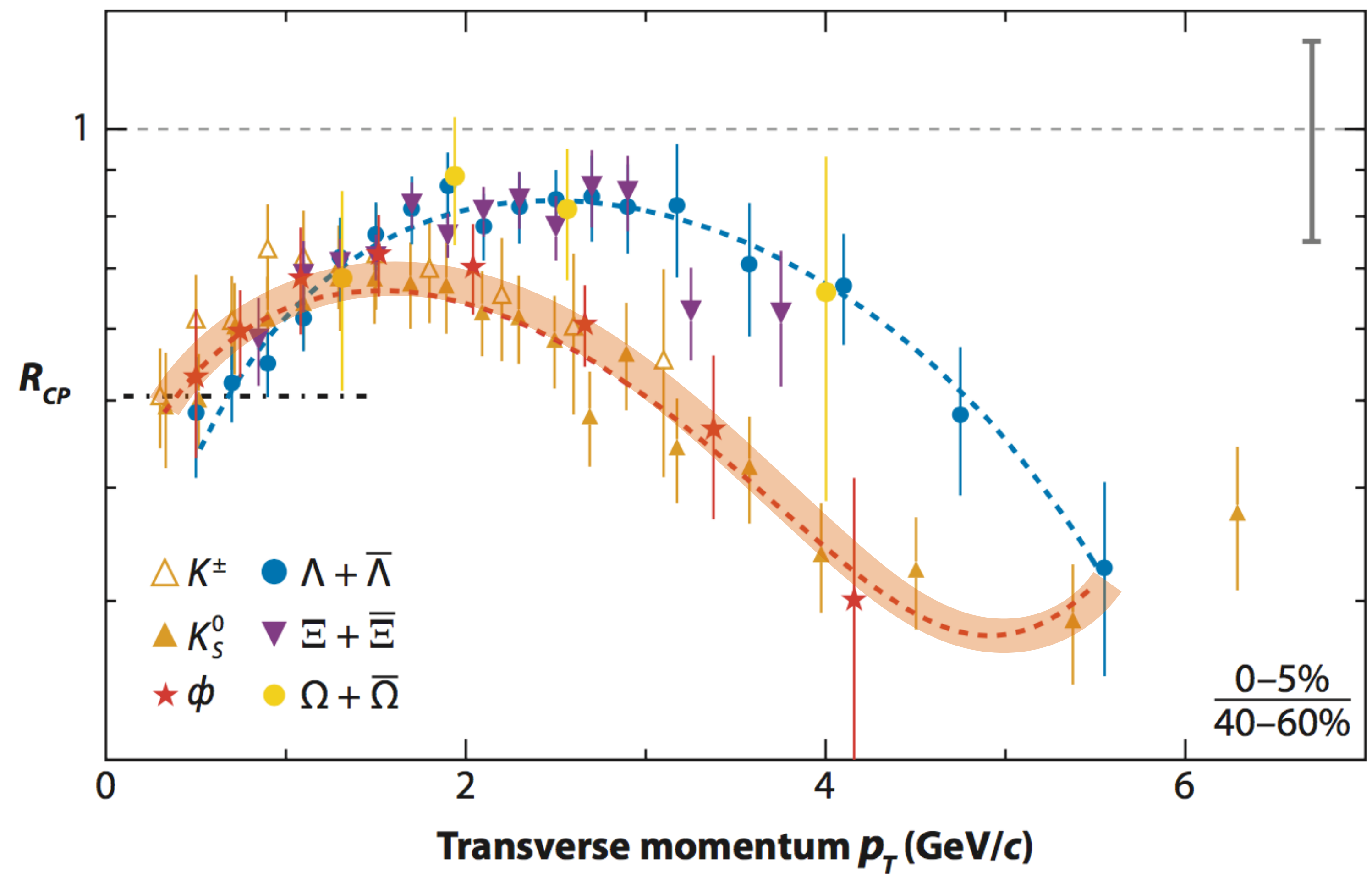
B/M ratios: p/ϕ

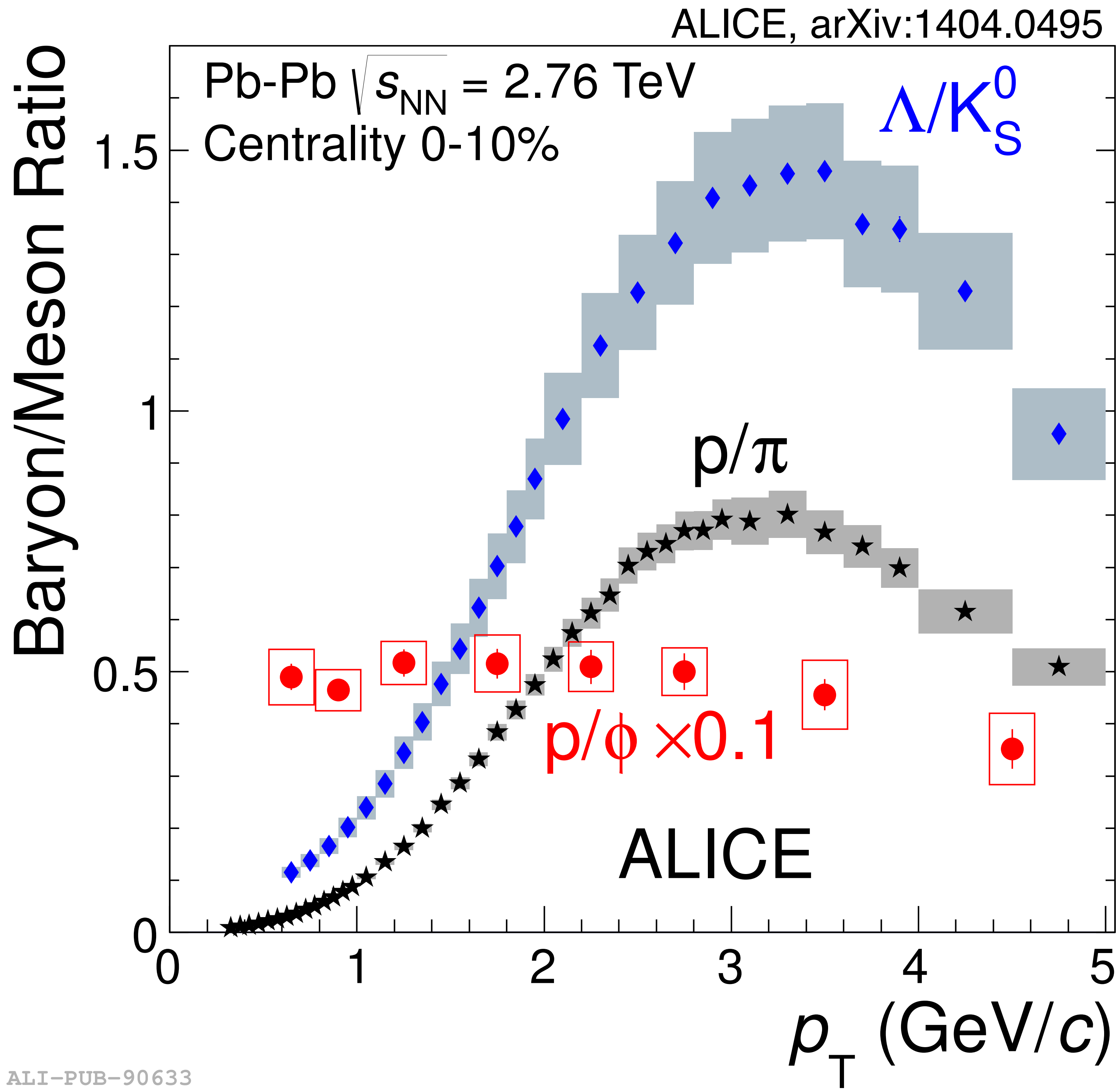
- Splitting of R_{CP} at RHIC of **baryons and mesons** was used as argument in favor of reco
  - but R_{CP} is influenced by reference

Annu. Rev. Nucl. Part. Sci. 2008. 58:177–205

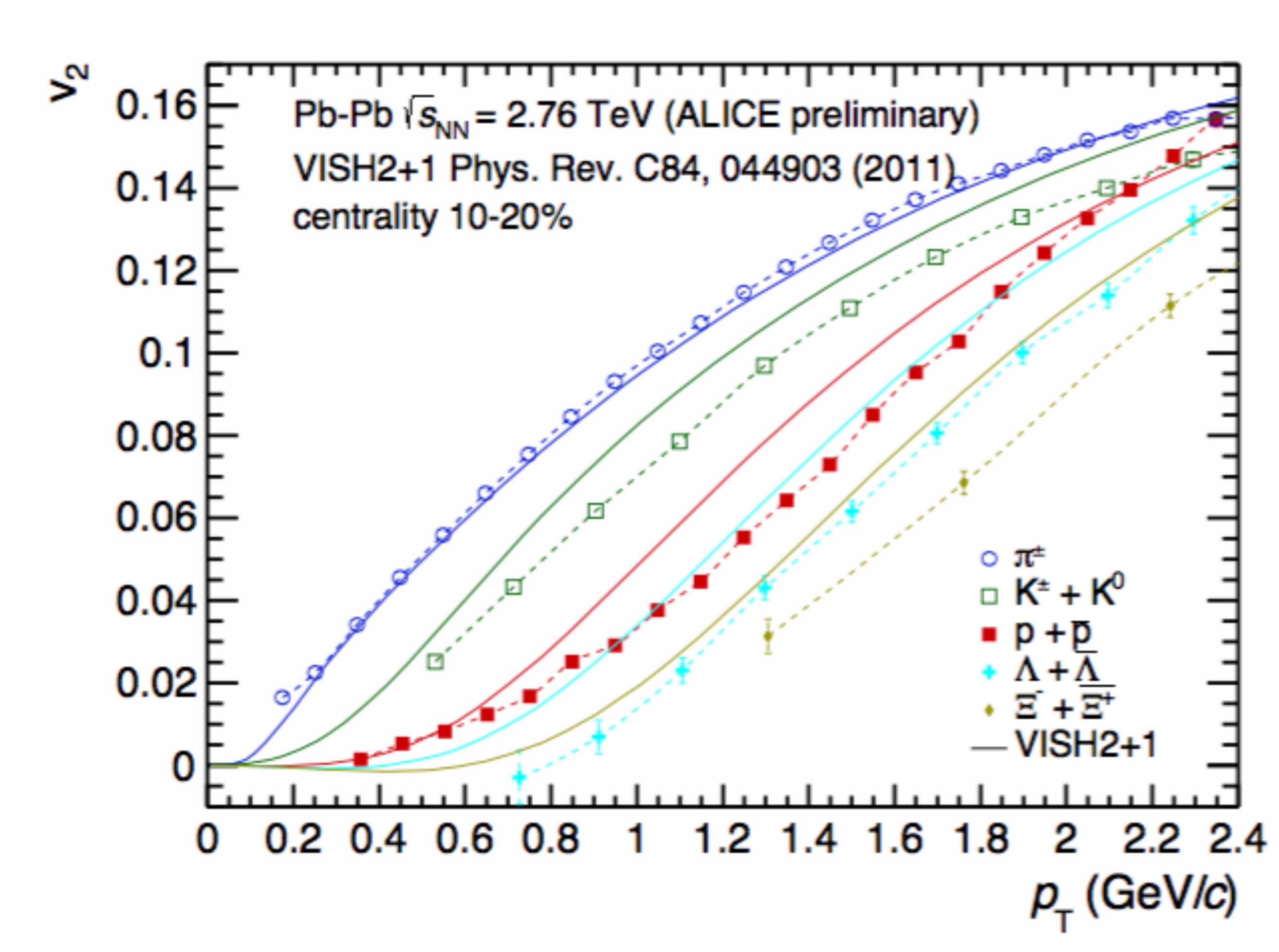


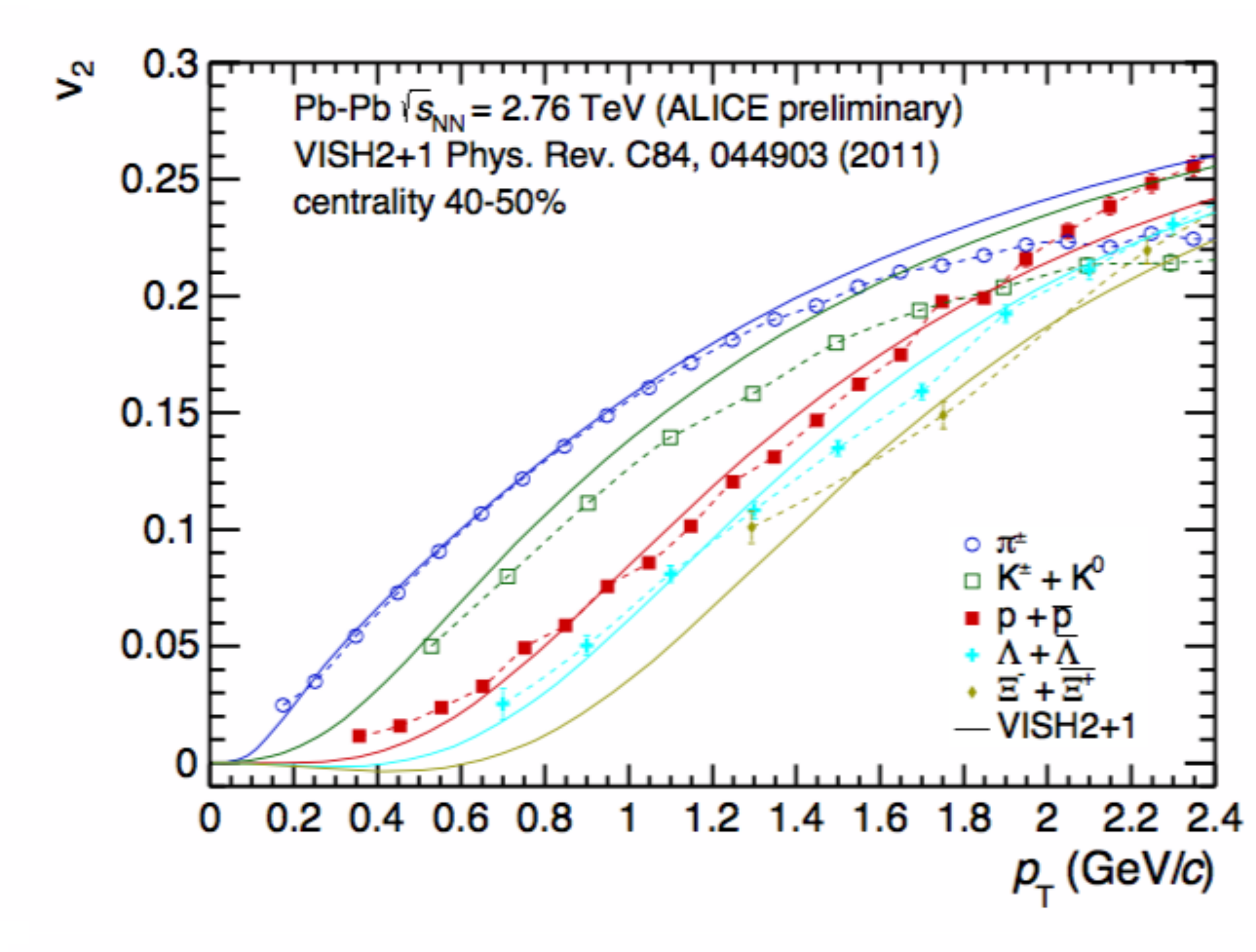
B/M ratios: p/ϕ

- Splitting of R_{CP} at RHIC of **baryons and mesons** was used as argument in favor of reco
  - but R_{CP} is influenced by reference
- The ϕ meson has the same shape as p: **mass ordering** (radial flow)?
  - (in a more realistic reco model p ~ ϕ, but fragmentation?)
- Do we need recombination?
- Is there a unique signature of recombination?



Elliptic flow at the LHC





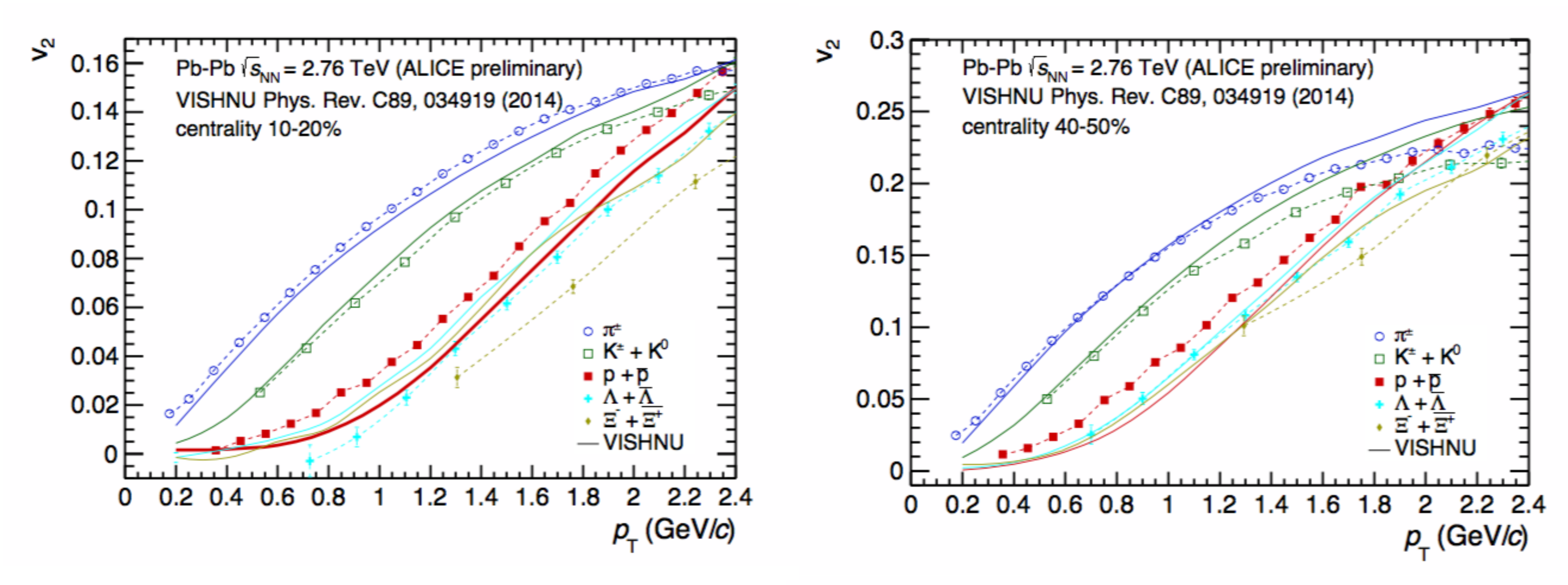
Mass dependence of v_2 ~ in line with hydro

Not enough flow with **pure hydro**

Too much flow with **hadronic phase** for p wrt hyperons

inverted mass-ordering (Λ-Ξ-p, instead of p-Λ-Ξ)

Unknown cross sections in UrQMD?



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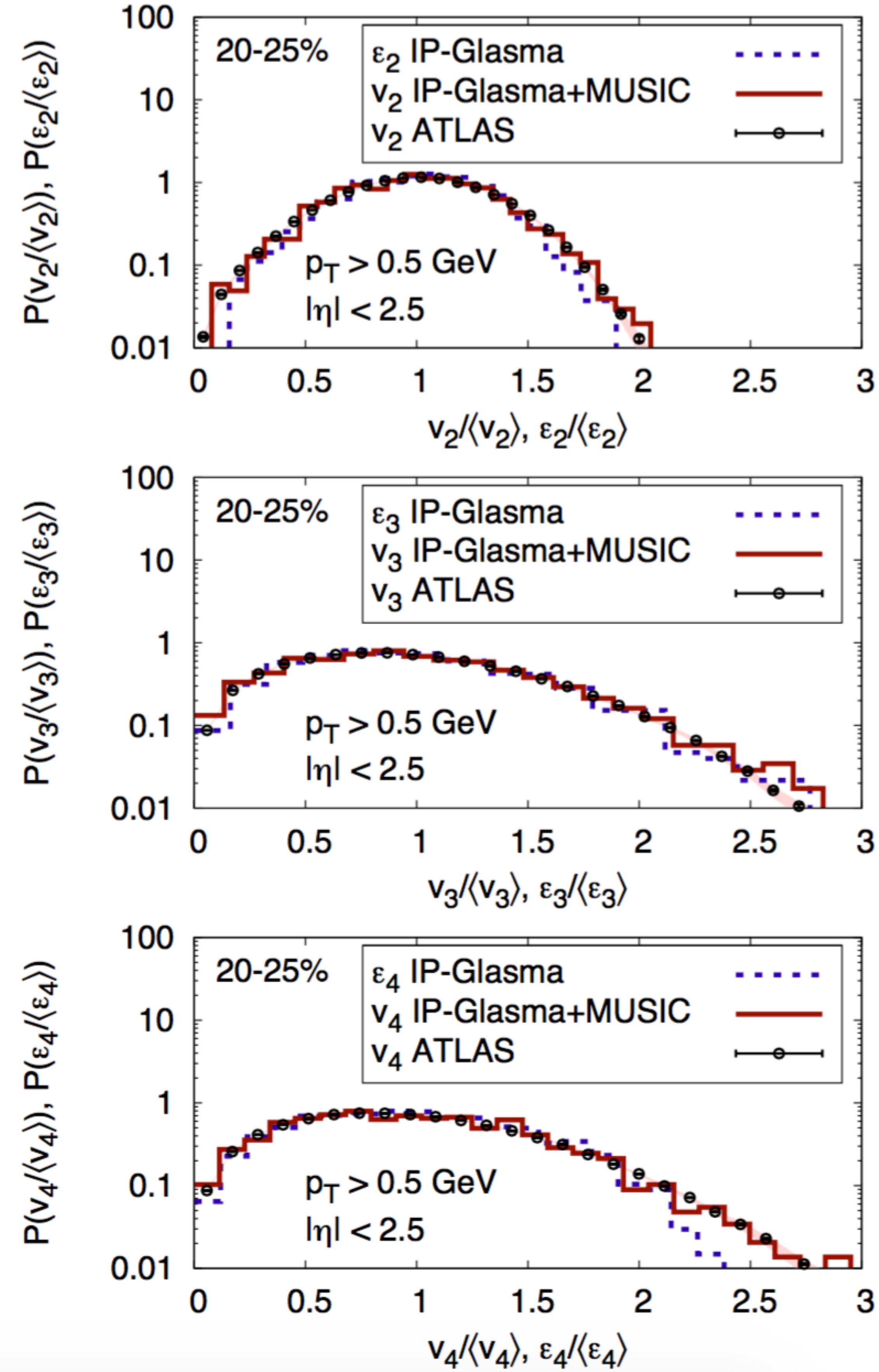
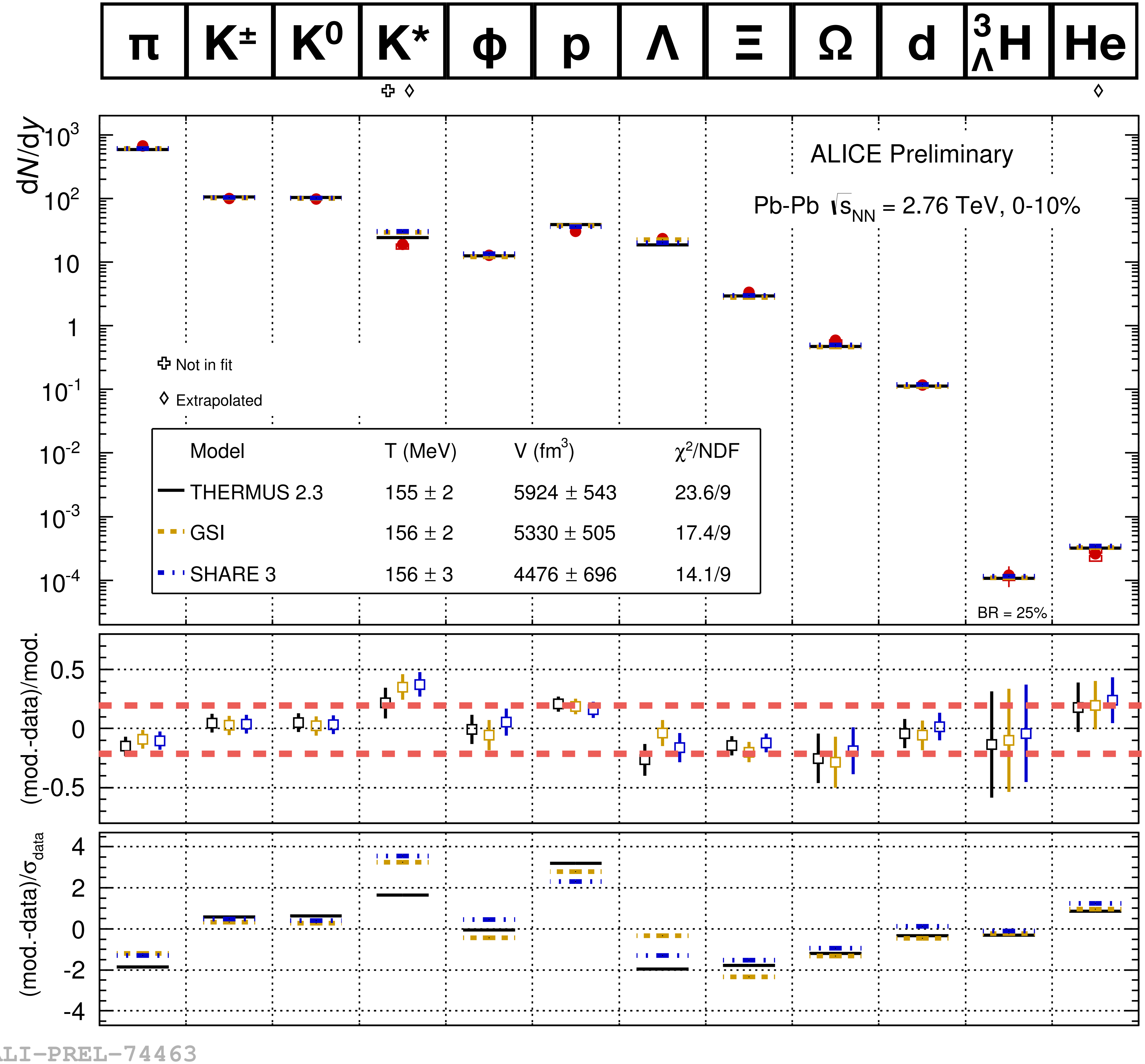
Pre-equilibrium dynamics and sub-nucleonic fluctuations crucial to reproduce E-by-E results



Equilibrium SHM Fits



N.B.
RHIC
$\sqrt{s}$ = 200 STAR
χ^2/NDF~1

Too few protons relative to pions

Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

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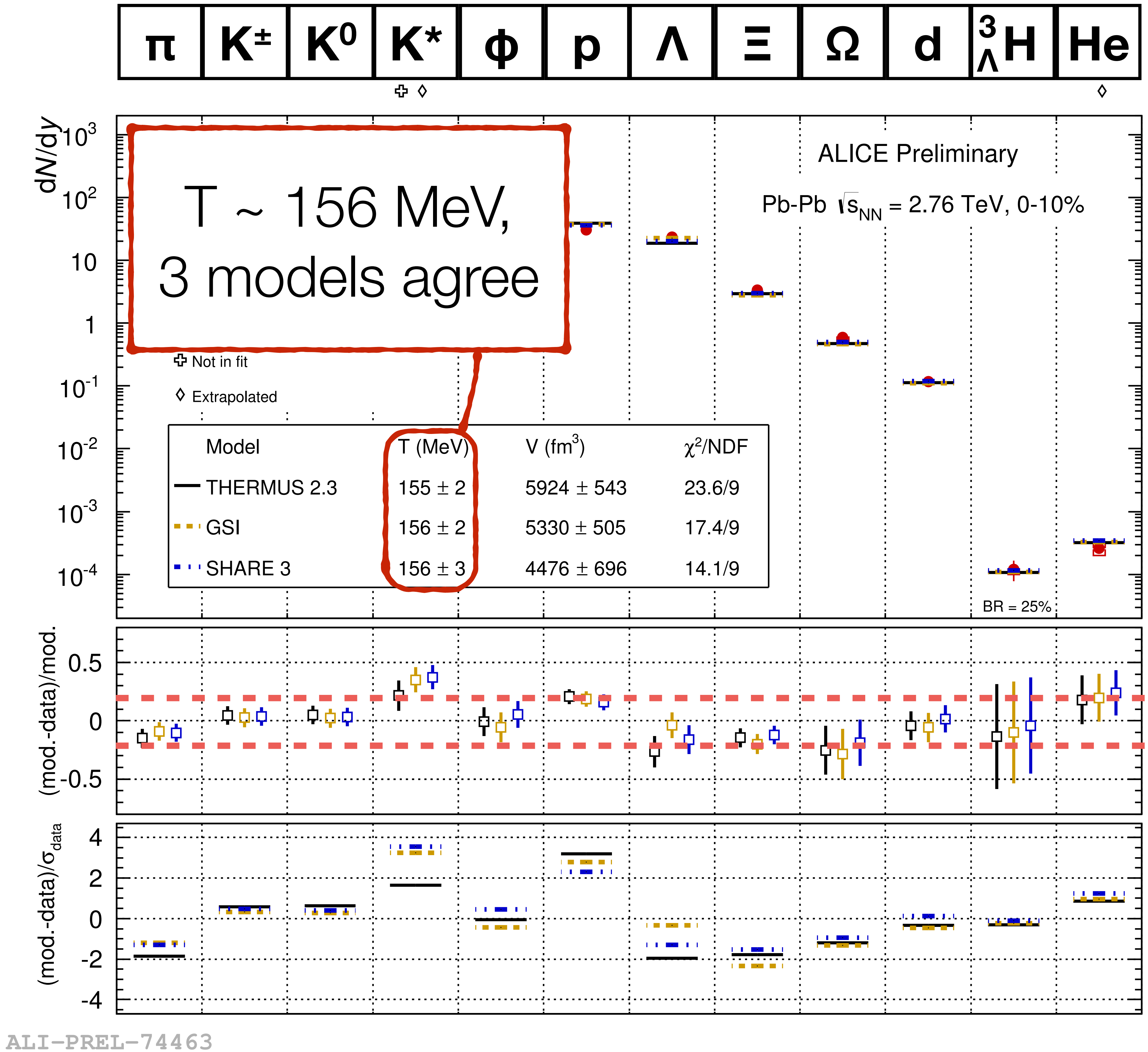

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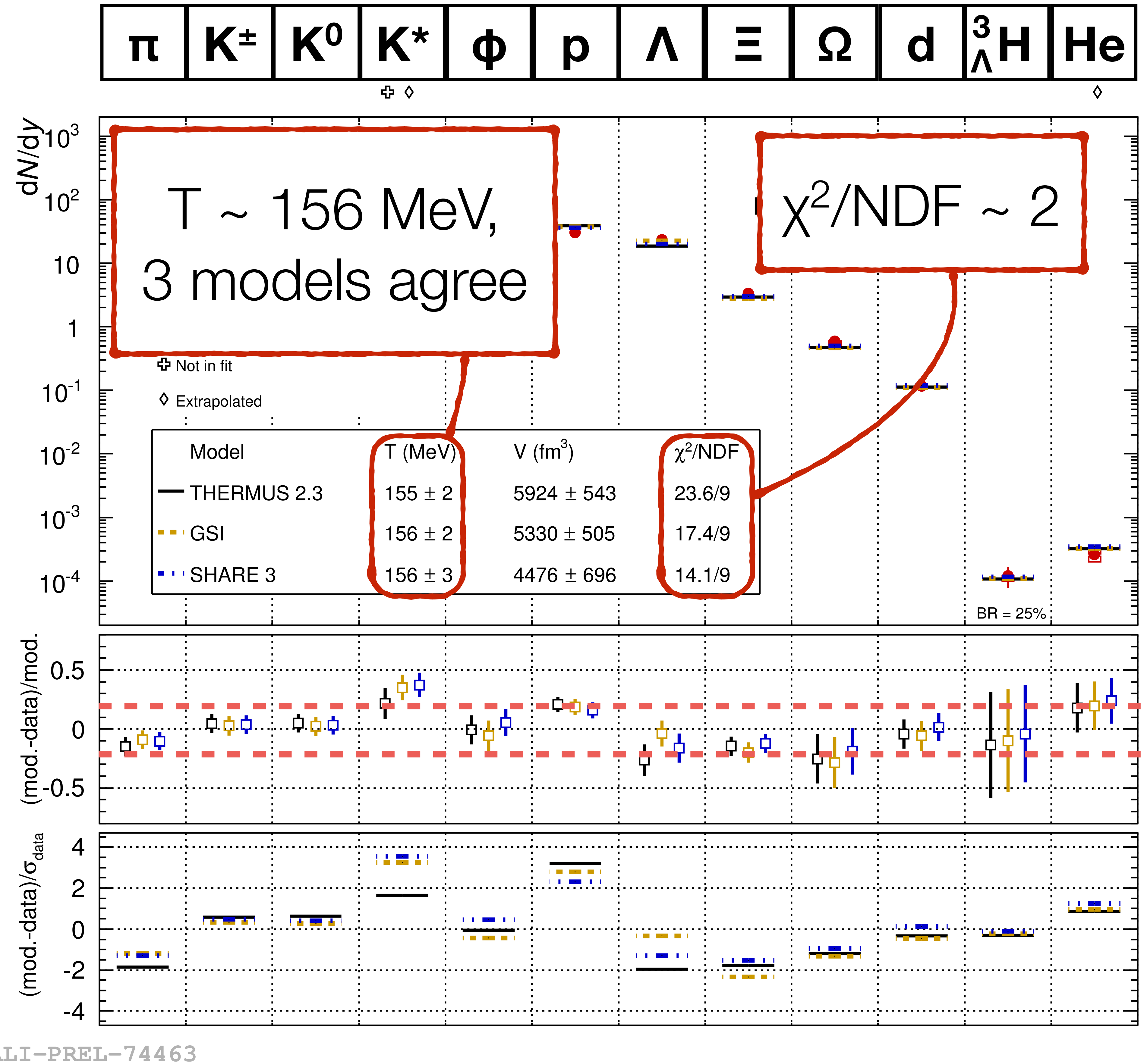

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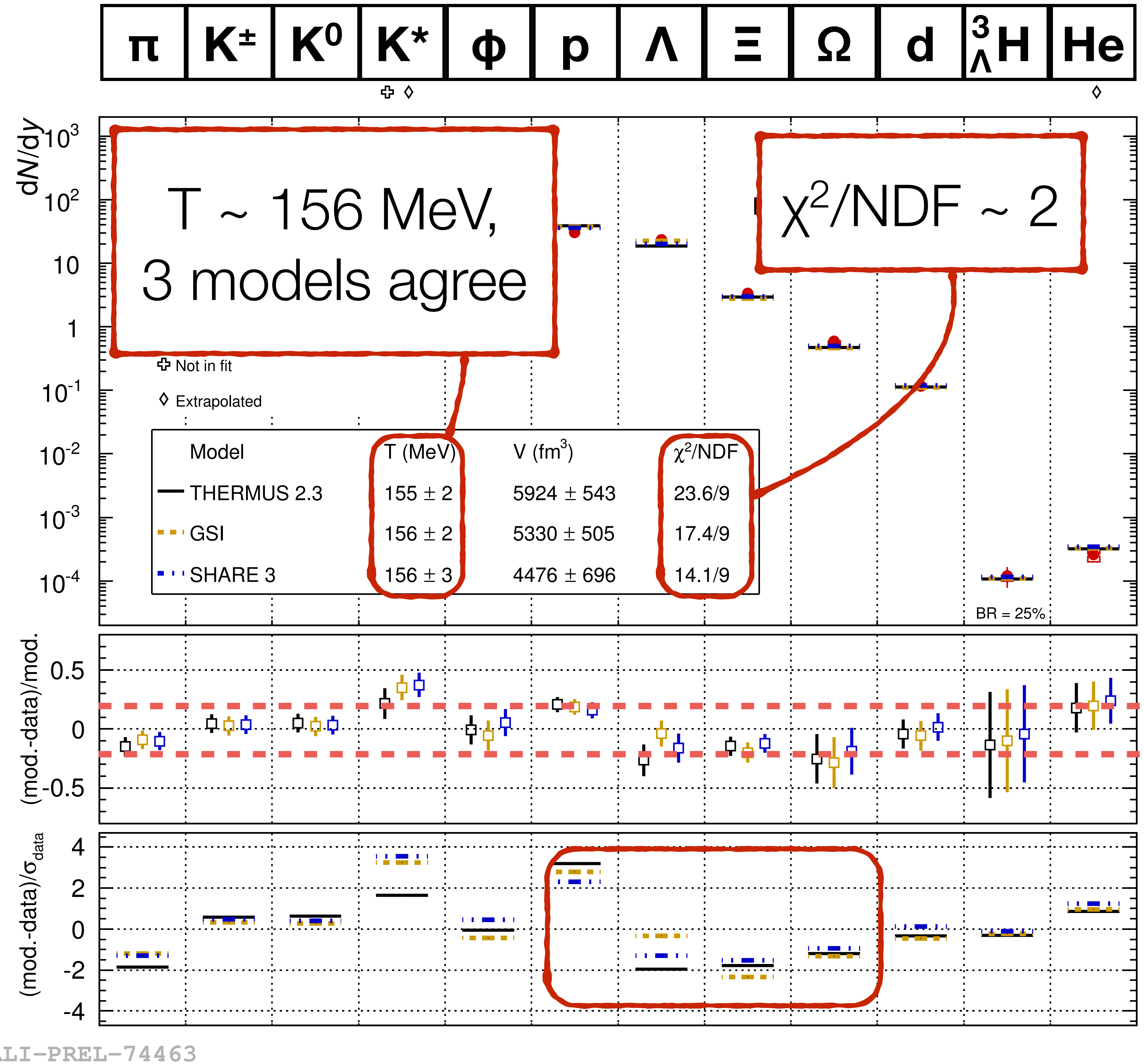

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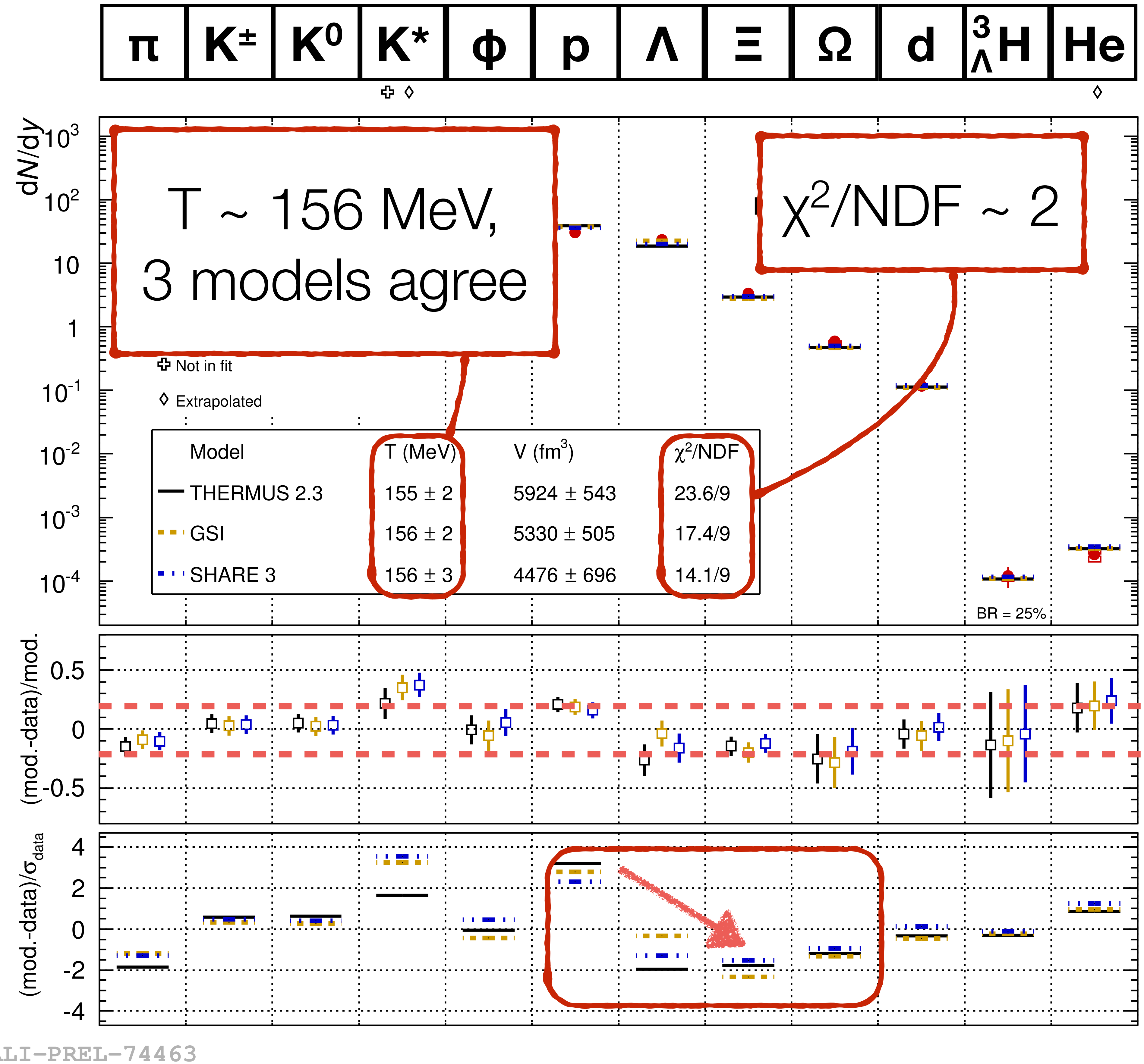

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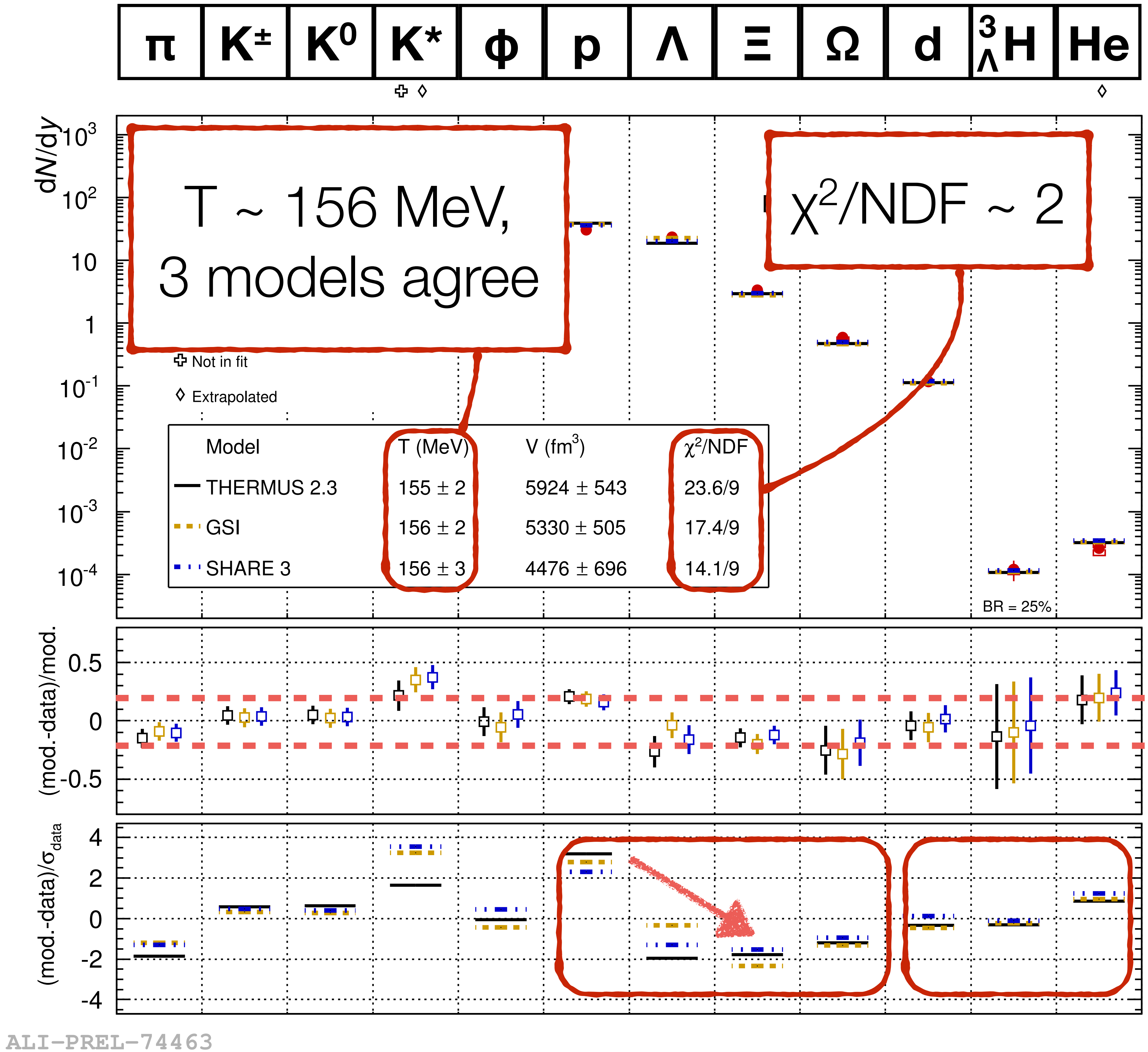

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Origin of the “Proton anomaly”

- Too few protons relative to pions: **hadronic phase**?
  - Supported by centrality dependence (uncertainties?)
  - Problem with nuclei?
  - Unknown cross sections?
  - How can we validate (or falsify) this hypothesis?
- Alternative scenarios
  - **Non-equilibrium** models → Additional measurements, nuclei?
  - **Flavor hierarchy** at freeze out → Fluctuations and lattice
  - **Missing hadronic states** → Lattice and Quark Model
- How can we get to “precision” physics?

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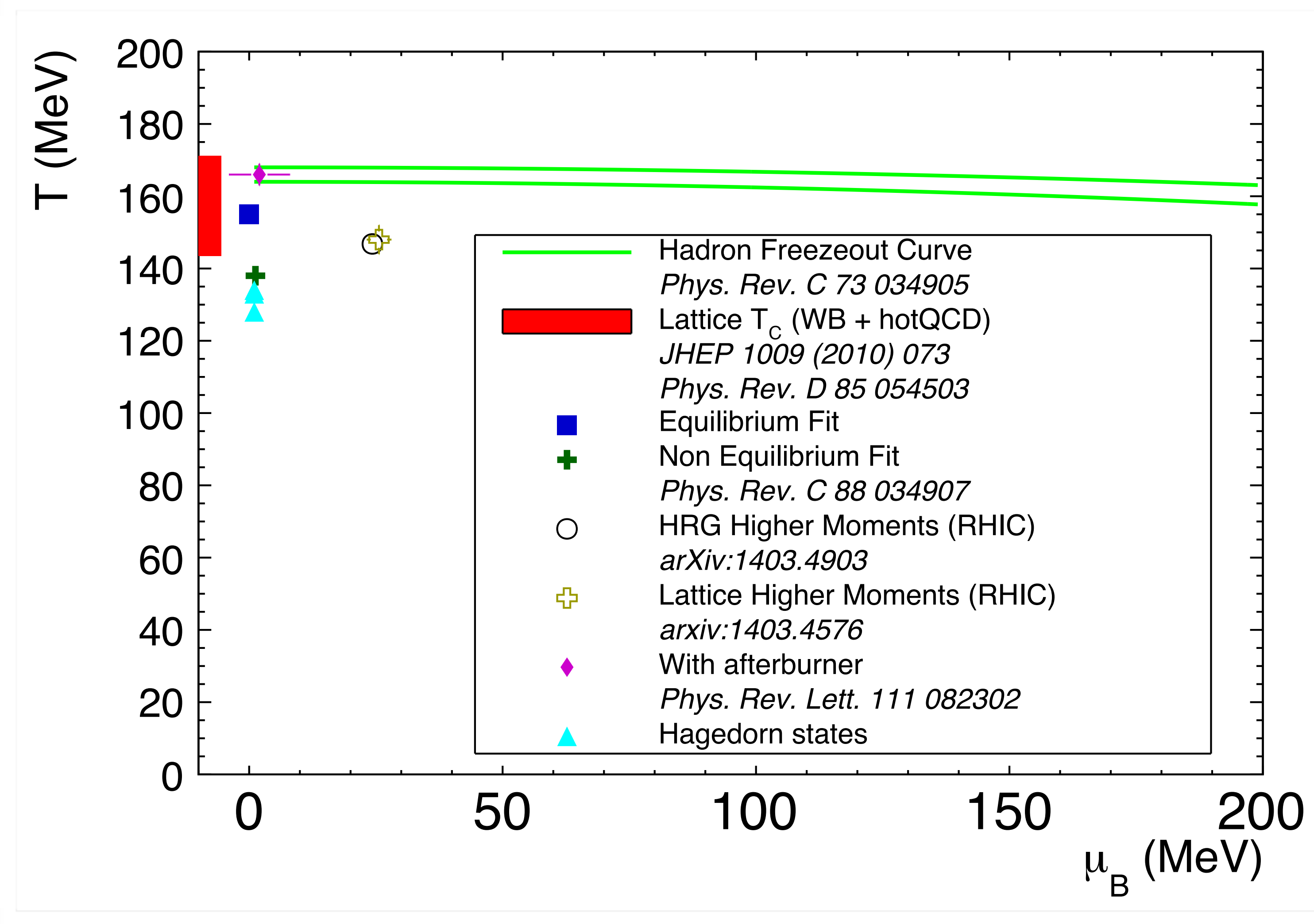

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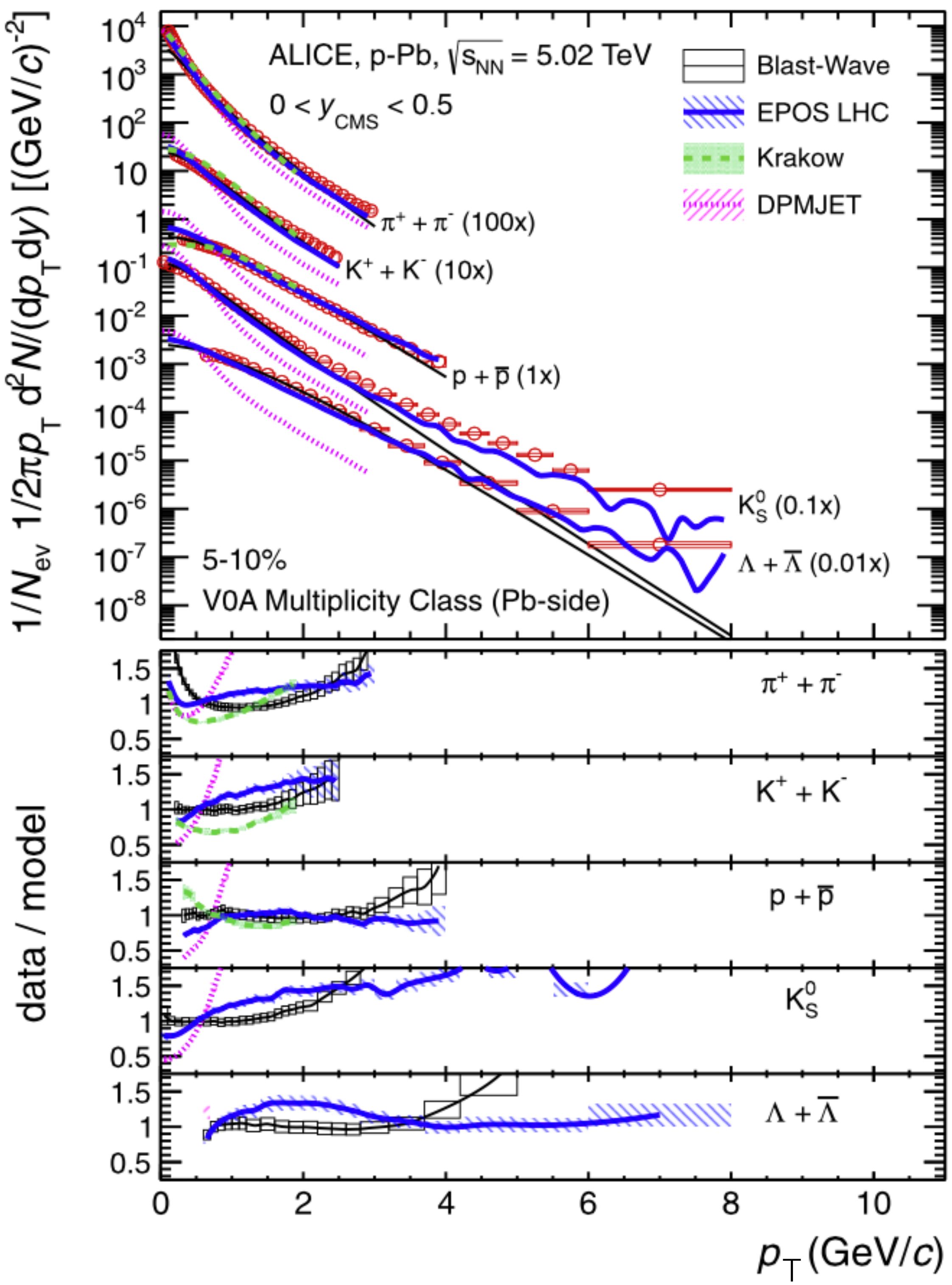
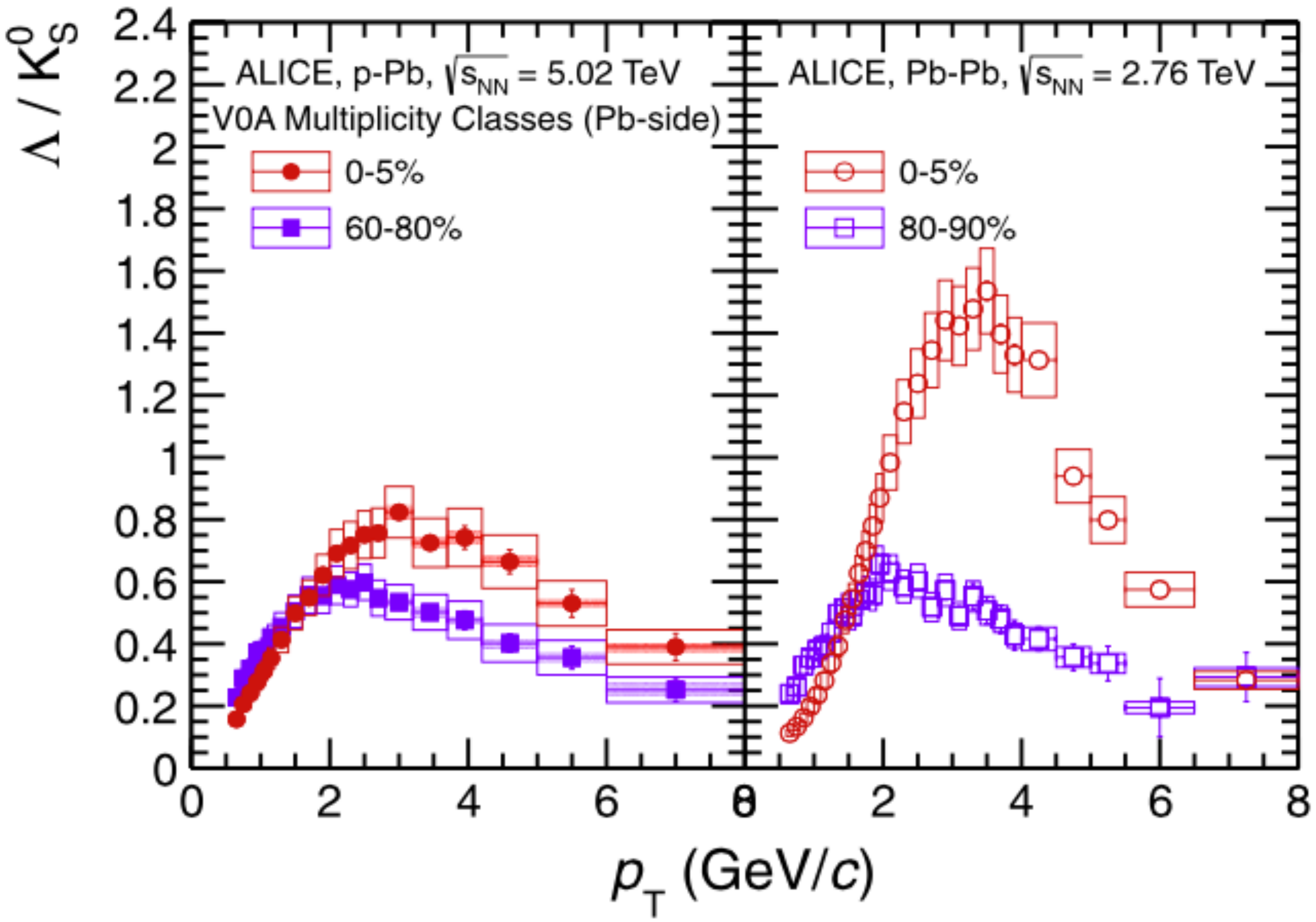
pp and p-Pb

Hints for radial flow in p-Pb

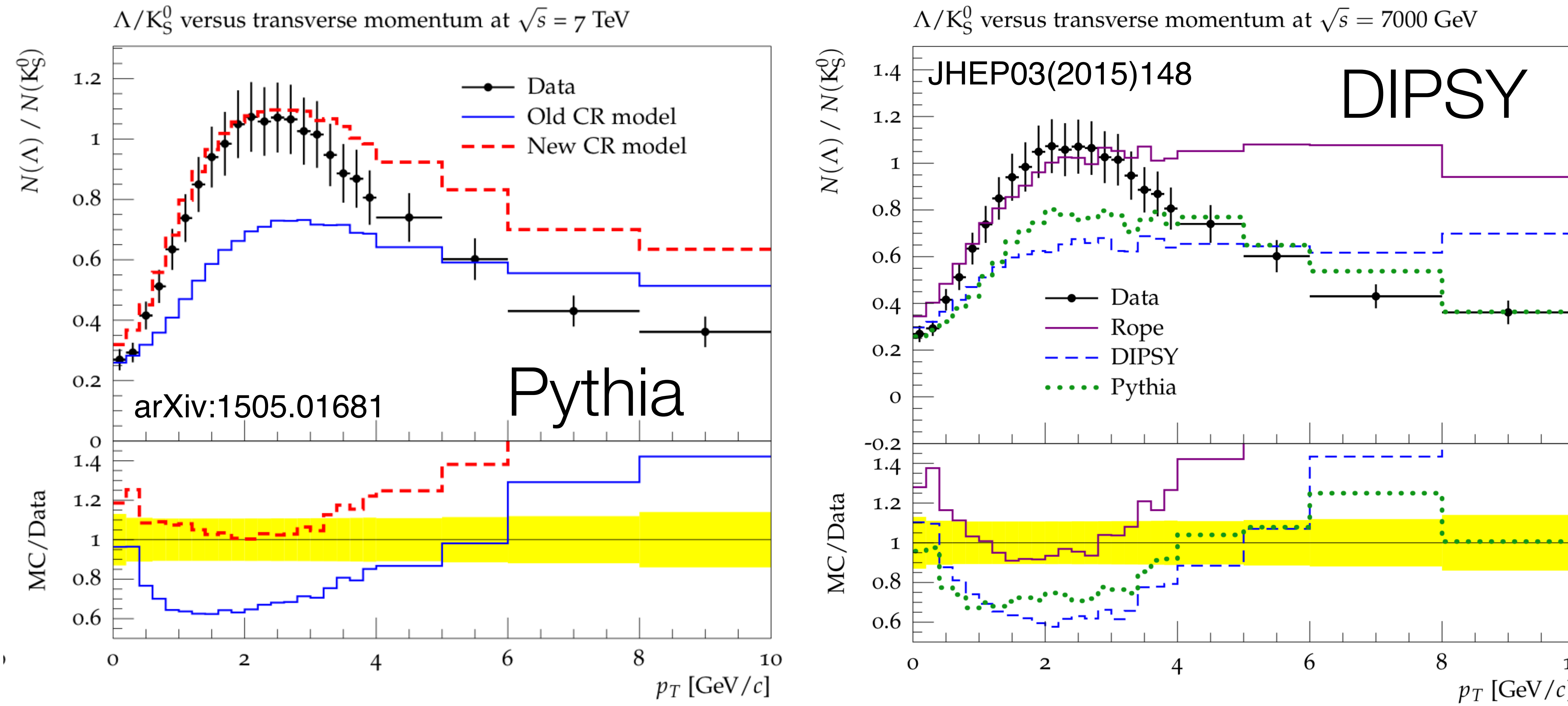


ALICE, PLB 728 (2014) 25–38



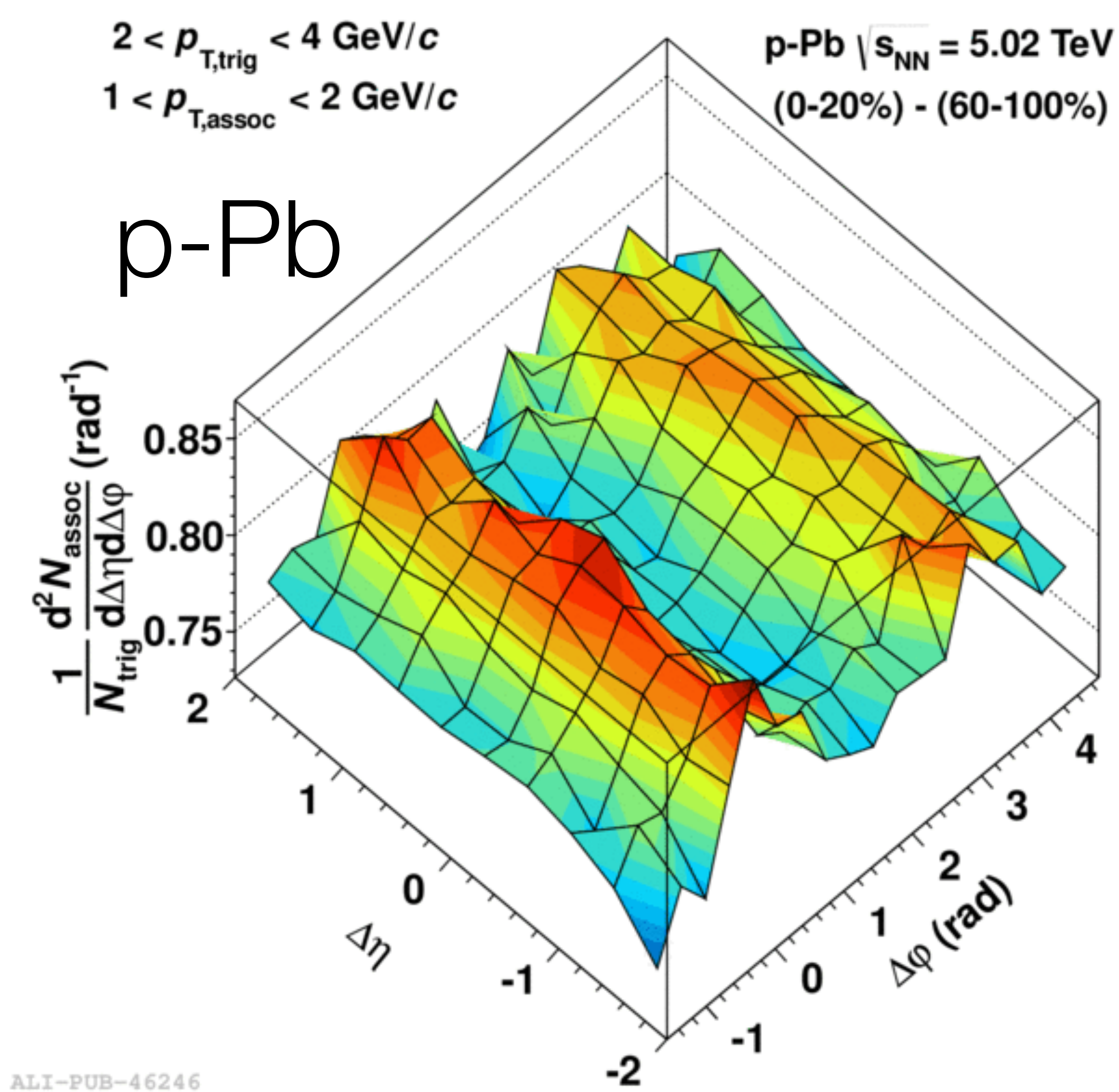
Hardening of spectra (reproduced by Hydro) and mass ordering (B/M enhancement)

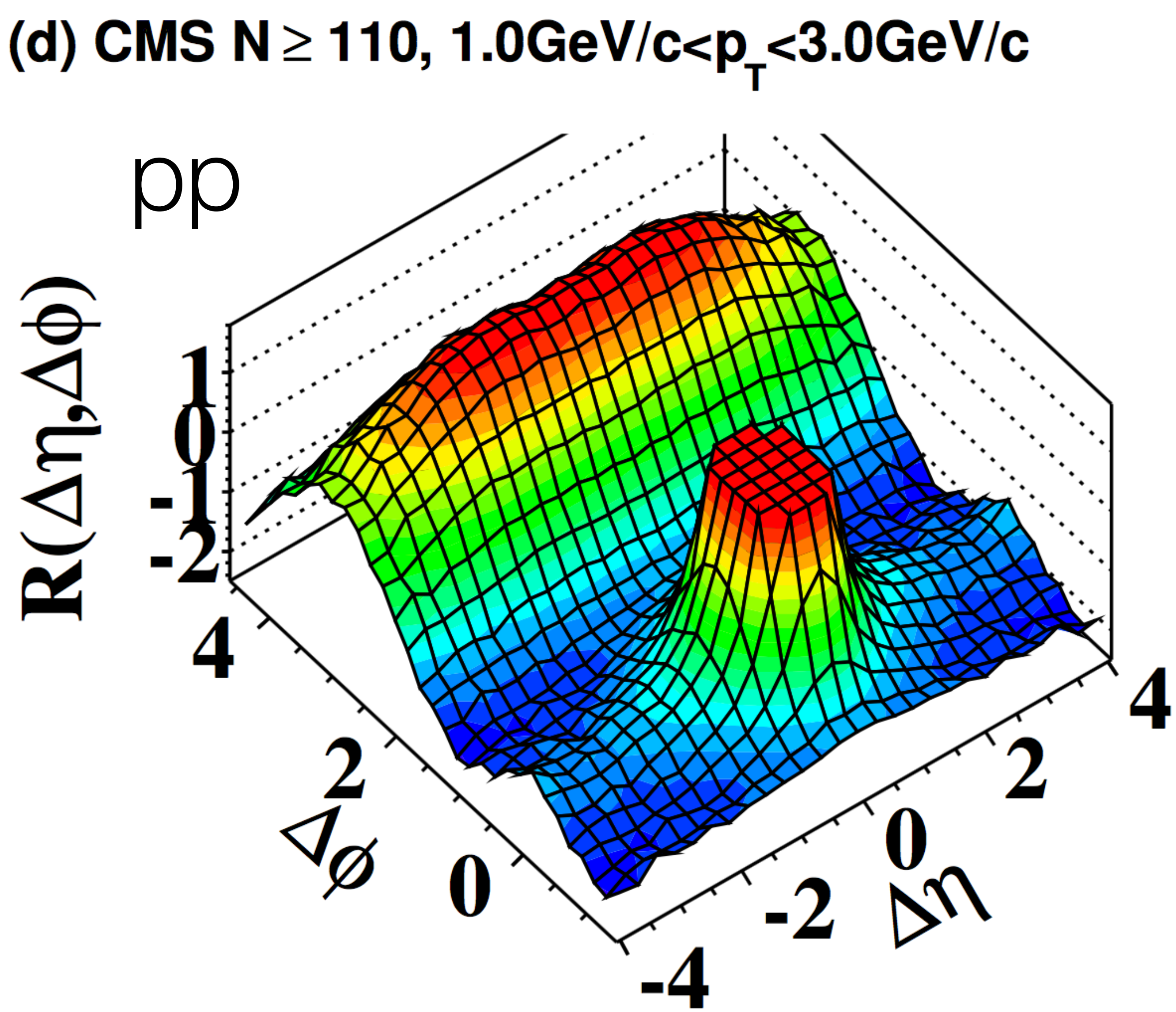
QCD Inspired models



Flow like effects in QCD inspired models
Recent developments: MPIs + improved color reconnection and color ropes

Anisotropic flow in p-Pb



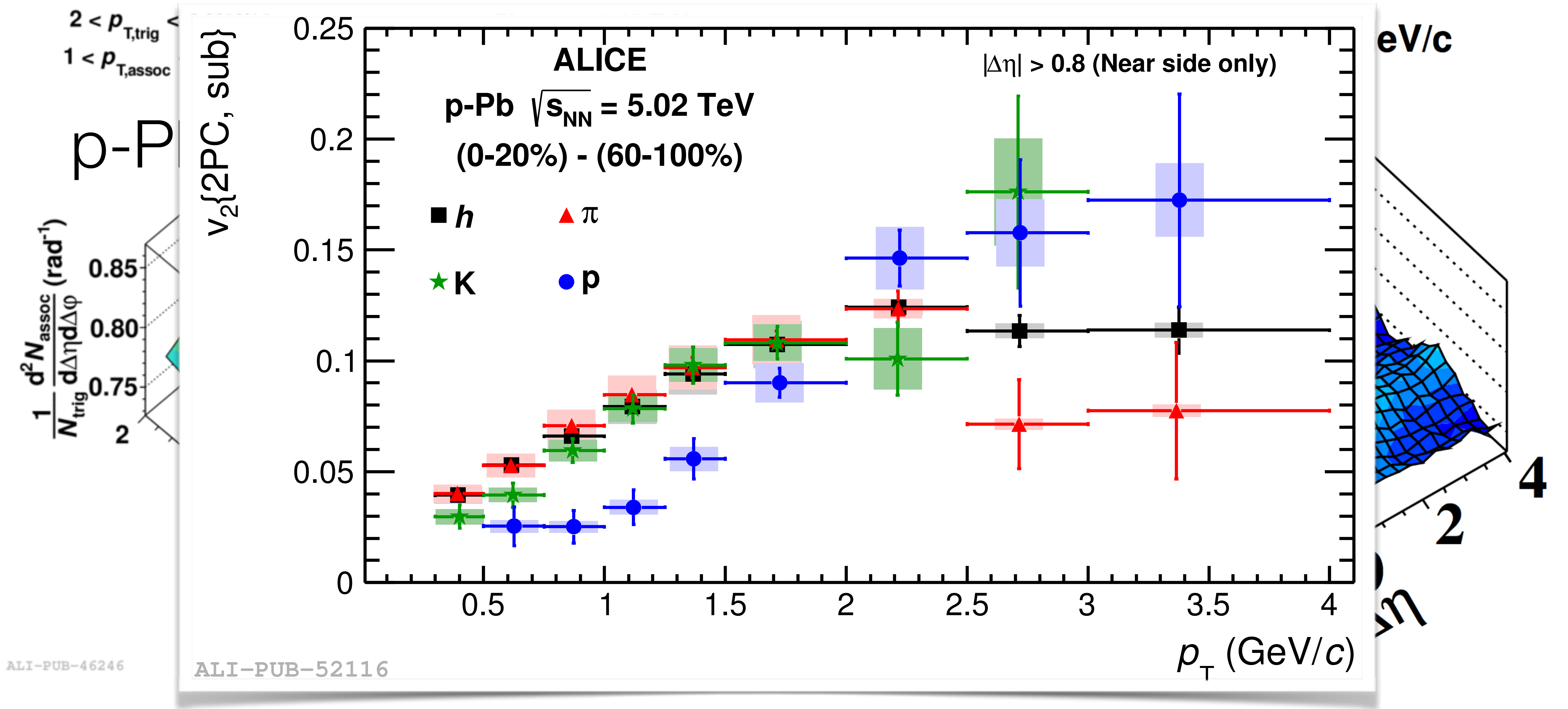


Mass ordering and magnitude similar to Pb-Pb

Hydro models explain this naturally

CGC models provide an alternative?

Anisotropic flow in p-Pb

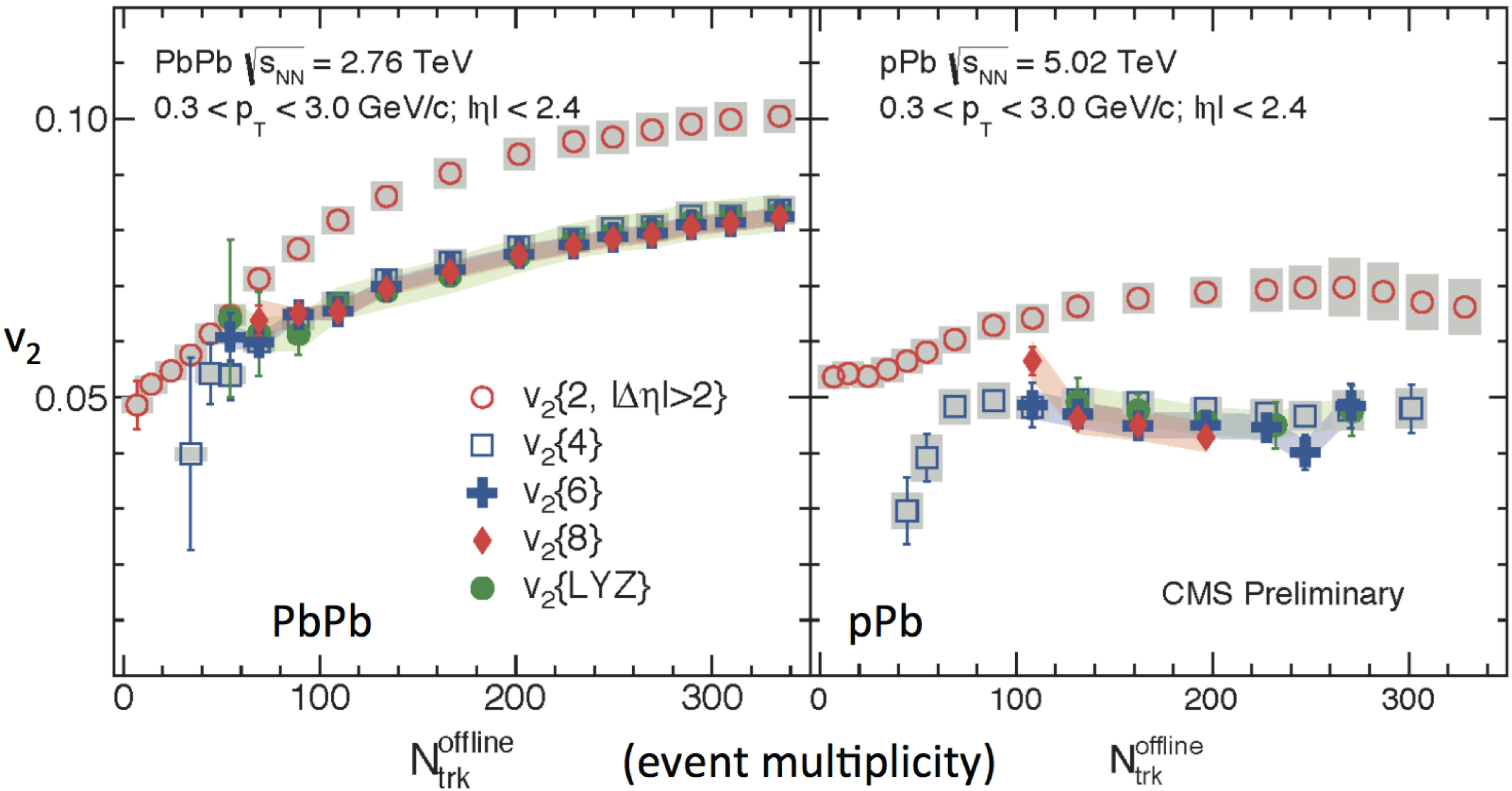


Mass ordering and magnitude similar to Pb-Pb

Hydro models explain this naturally

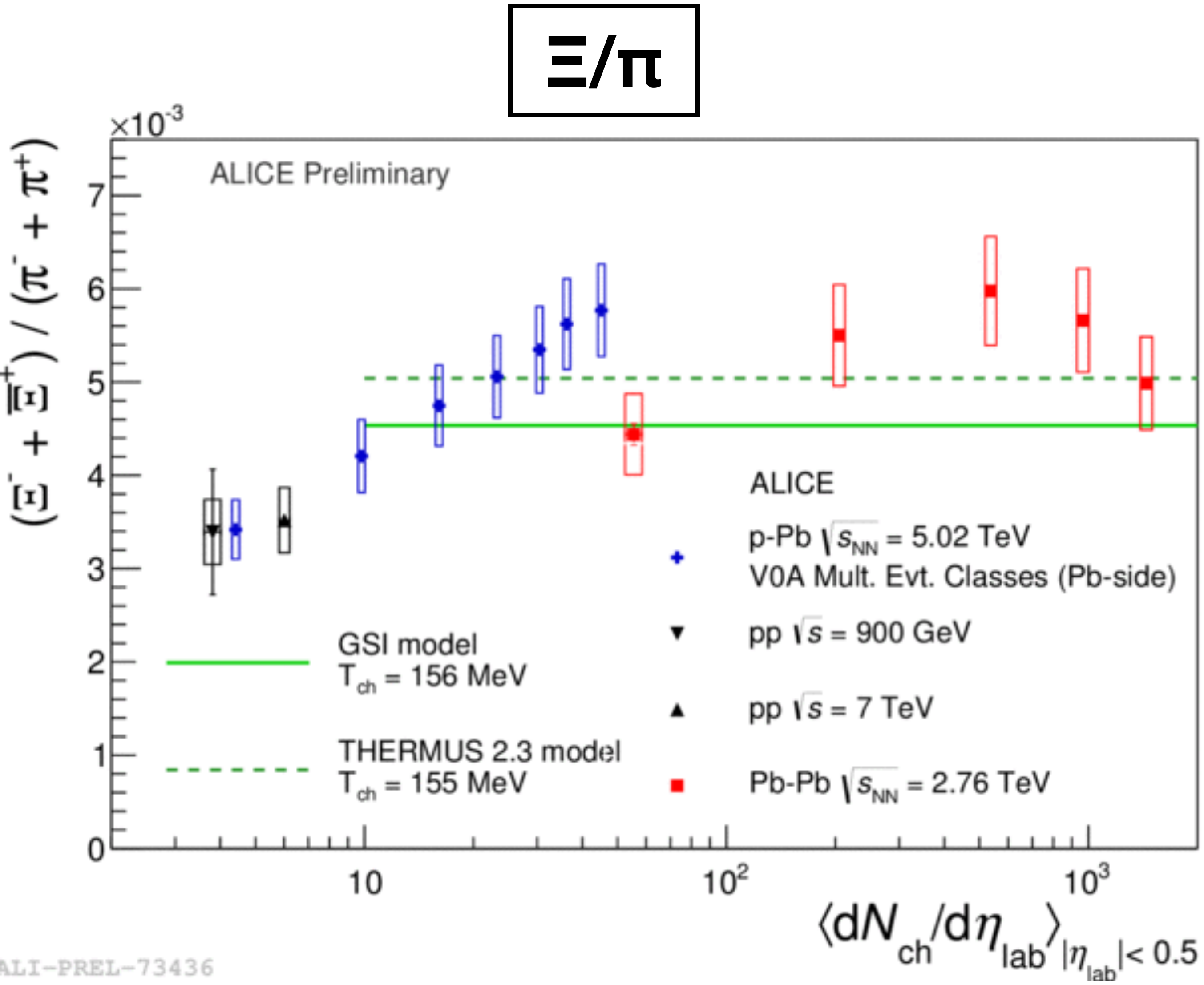
CGC models provide an alternative?

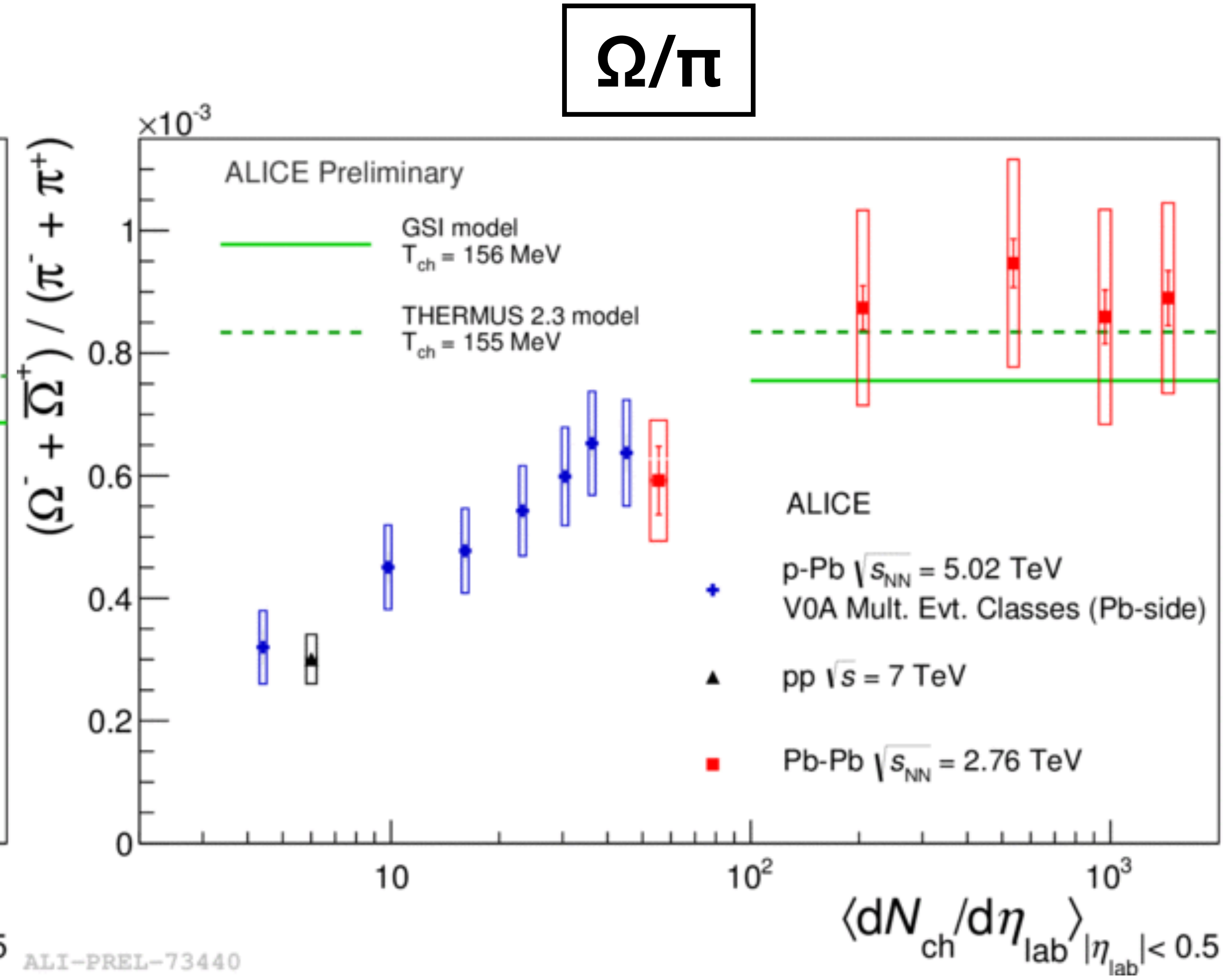
Elliptic flow in pA is a collective effect



Higher order Cumulants consistent:
it is a collective effect

Strangeness production in p-Pb collisions



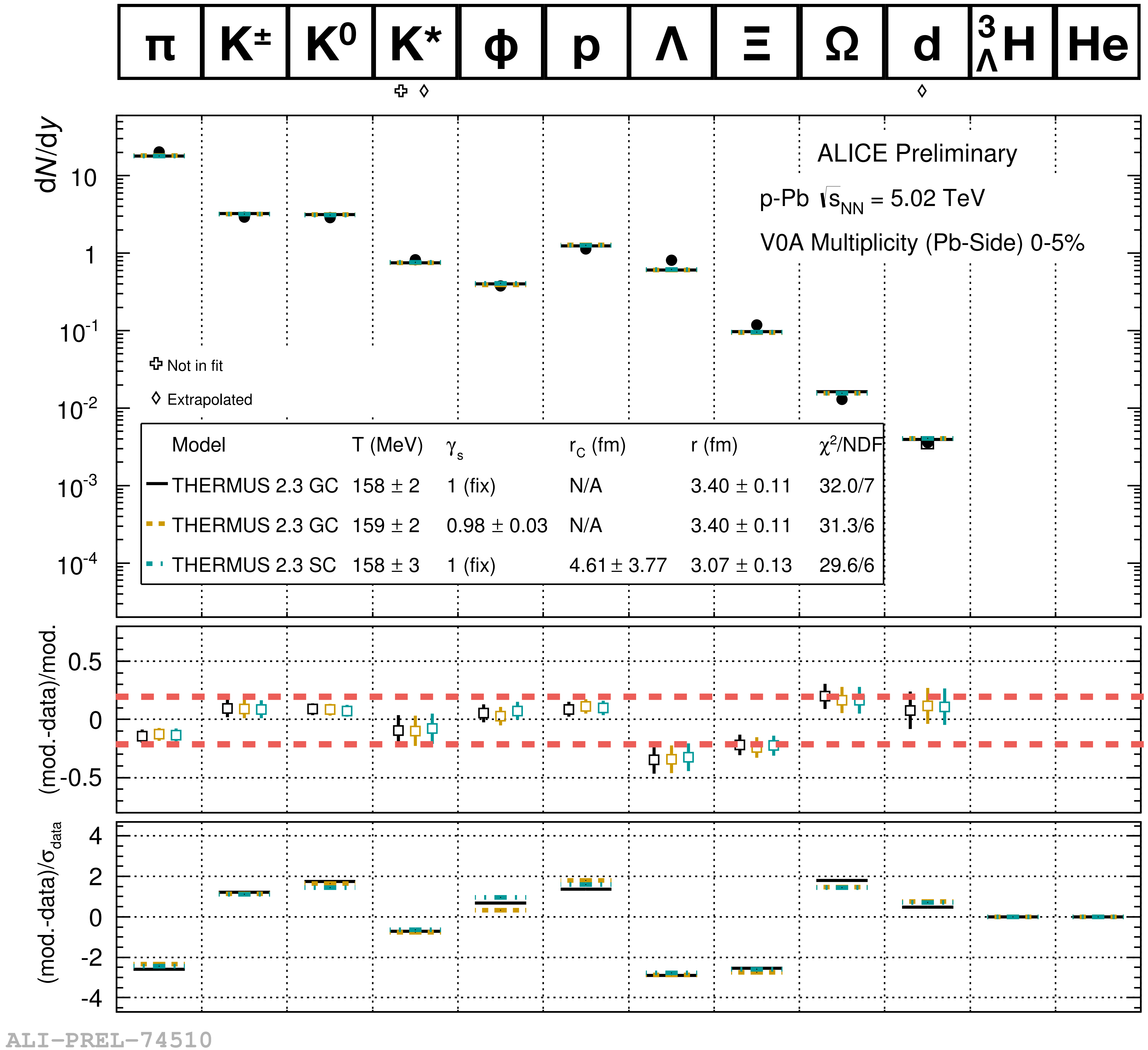


Strangeness enhancement in p-Pb collisions!

- Ξ reaches the Pb-Pb (GC?) value
- Ω not yet

Recent developments in QCD inspired models provide also some strangeness enhancement

p-Pb, 0-5%

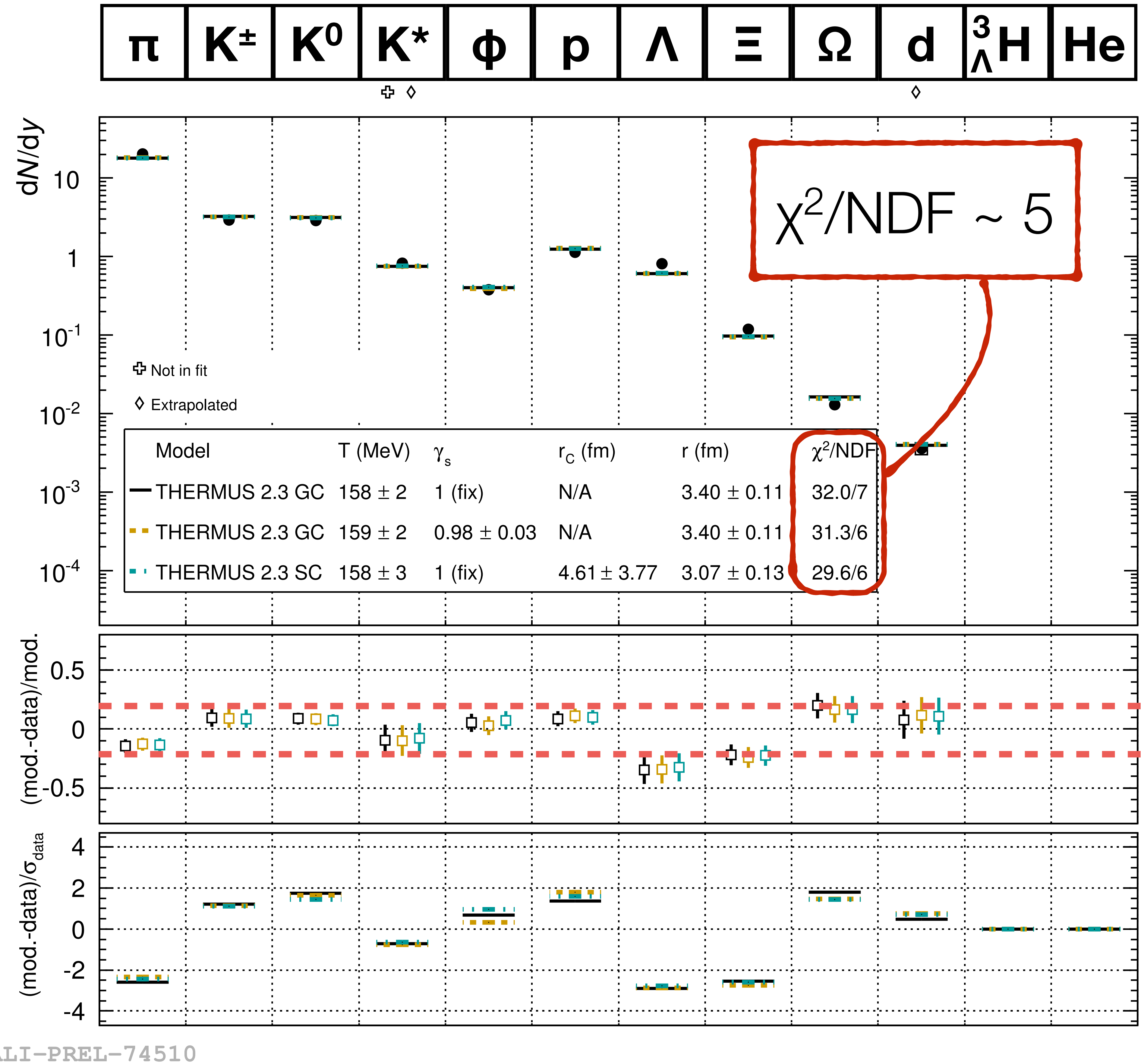


Fit quality not good

Note:

- Ω and Ξ pull in opposite directions
- γ_s compatible with 1 if free
- Low mult: $\gamma_S < 1$ (not shown)

p-Pb, 0-5%



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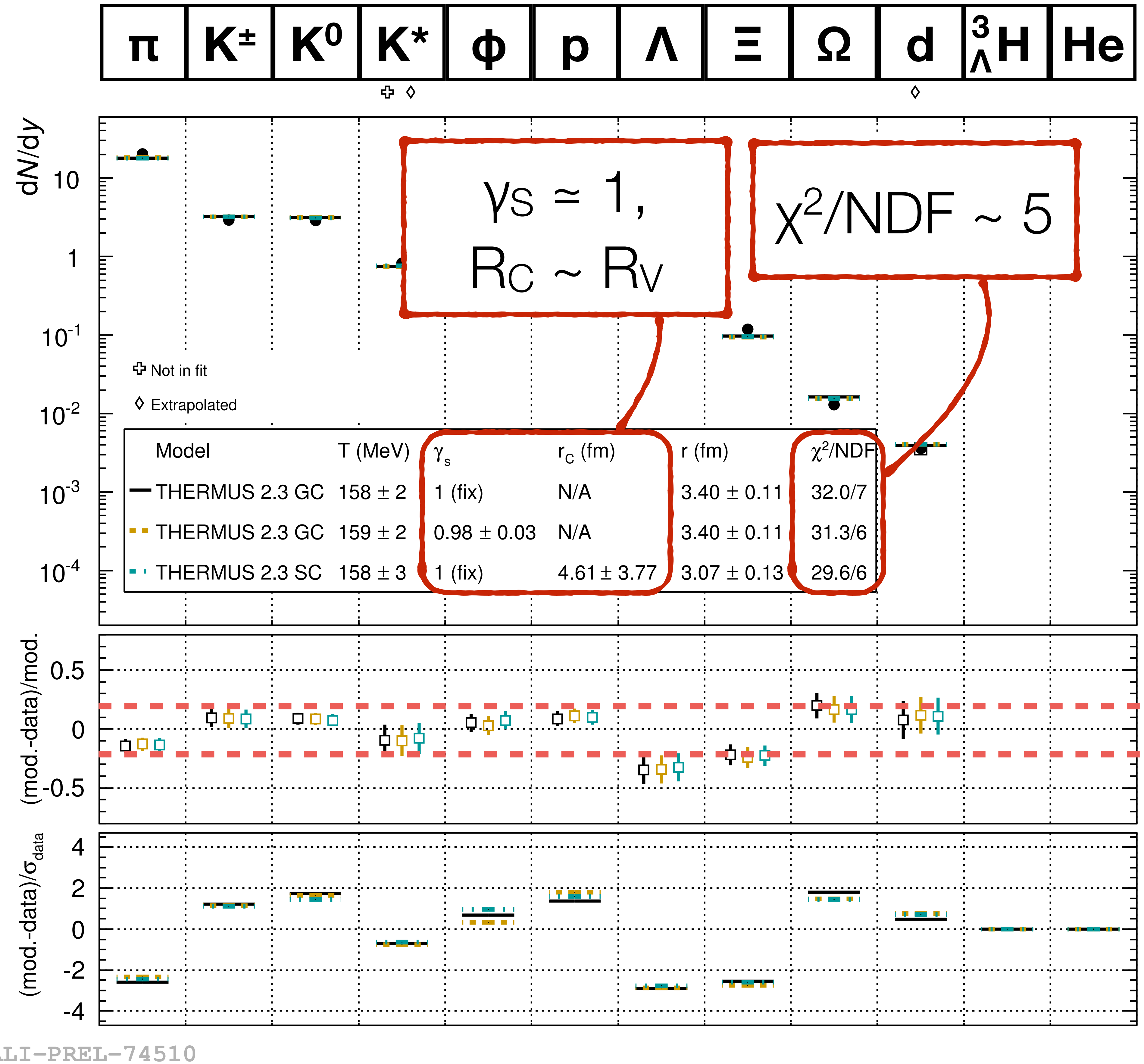

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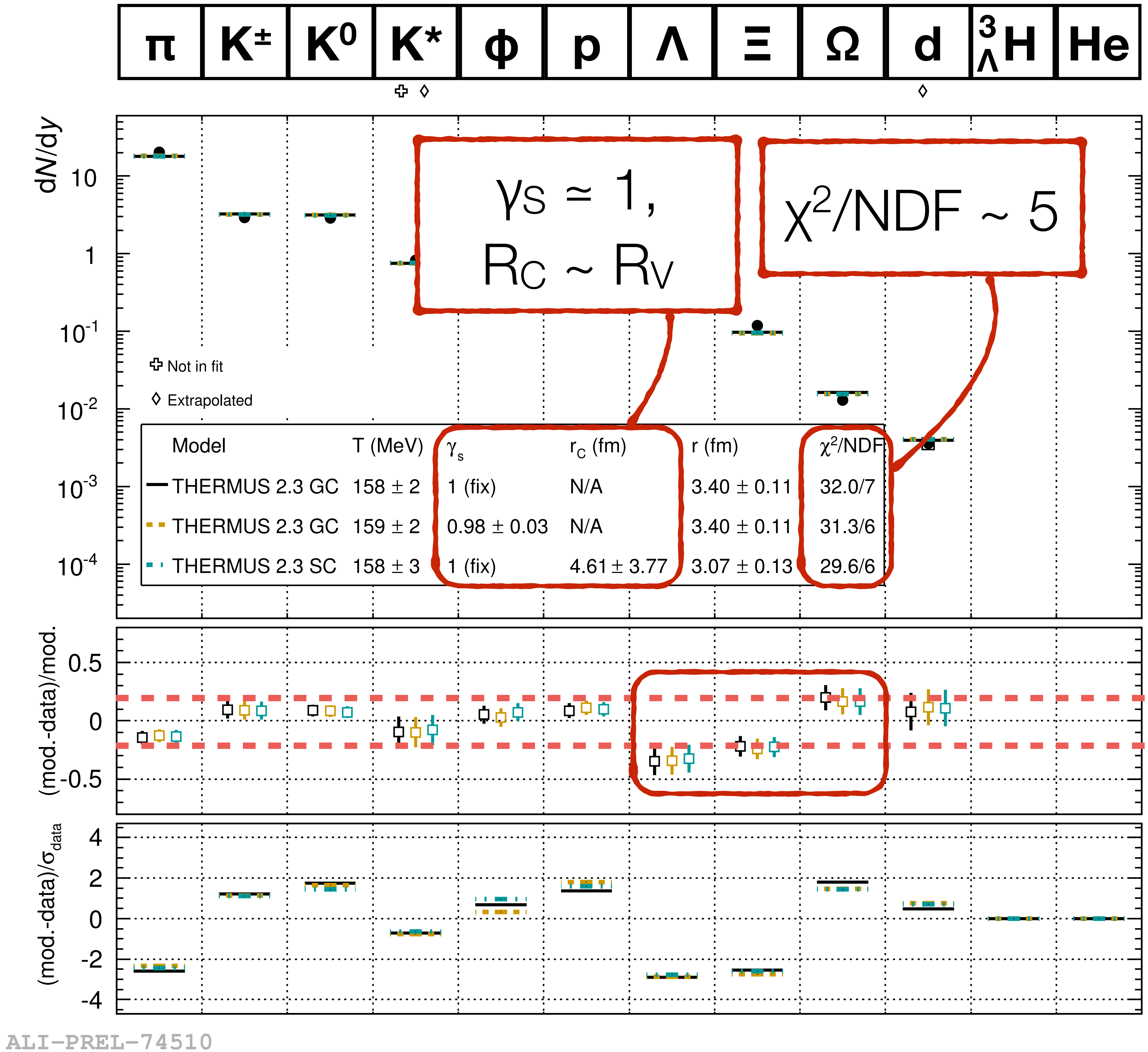

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Pb-Pb wrap up

Hydro + chemical equilibrium describes data at first order, but indications of additional effects

Initial conditions & late stages to be further constrained/understood

p-Pb (& pp?) wrap up

Hydro does a good job, but QCD-inspired models and CGC provide plausible alternatives

What is the mechanism at the origin of the results seen in pp, pA?

Questions

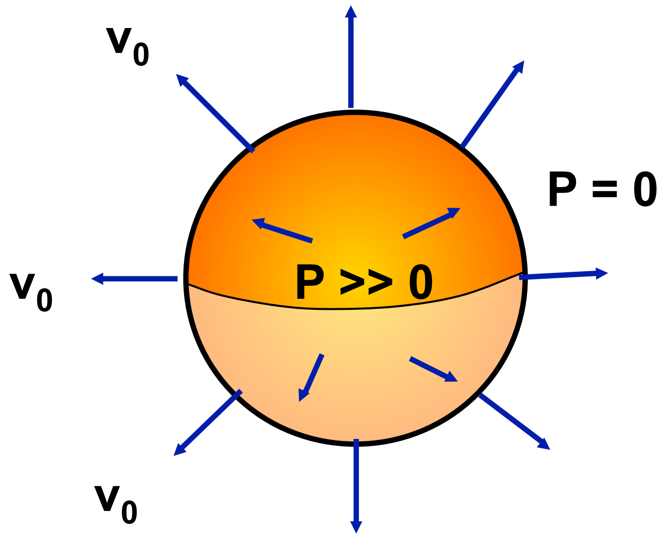
- How does the system evolve from string fragmentation to hydro?
- Is there life after "freeze out" (dynamics in the hadronic phase)?
- Do we need recombination? How it evolves from pp to PbPb? Relation with string melting/color ropes?

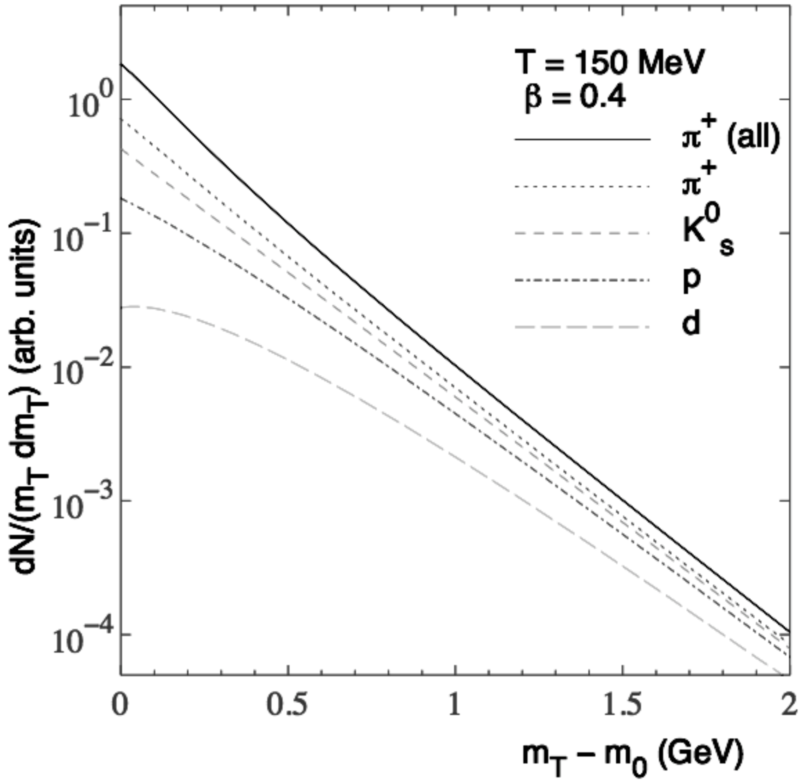
Backup

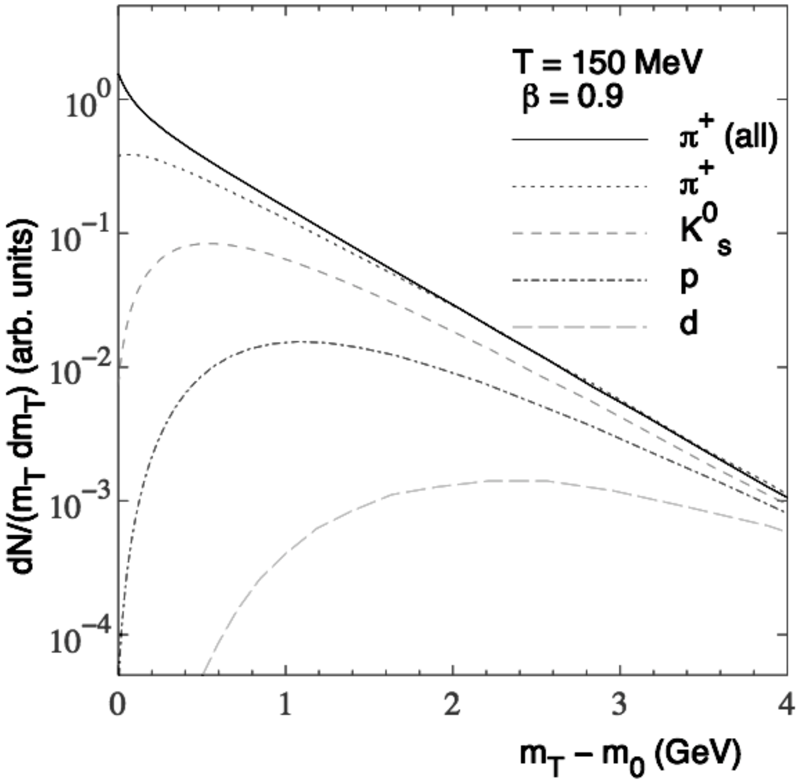
HBT and Hydro in pPb

Isotropic (radial) flow

hep-ph/0407360







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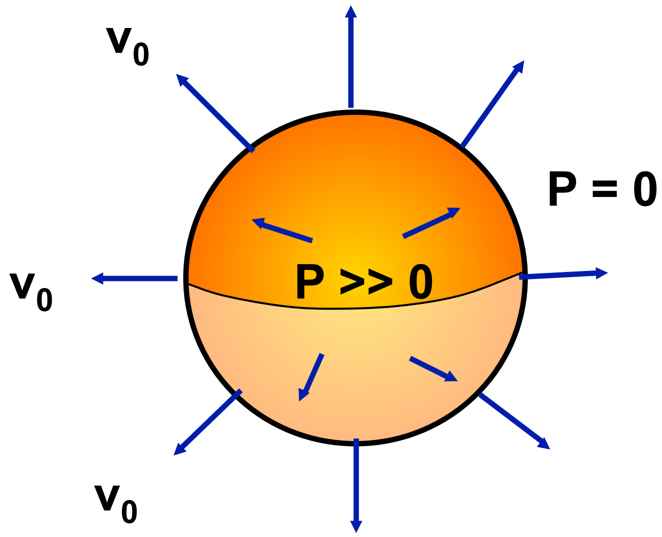

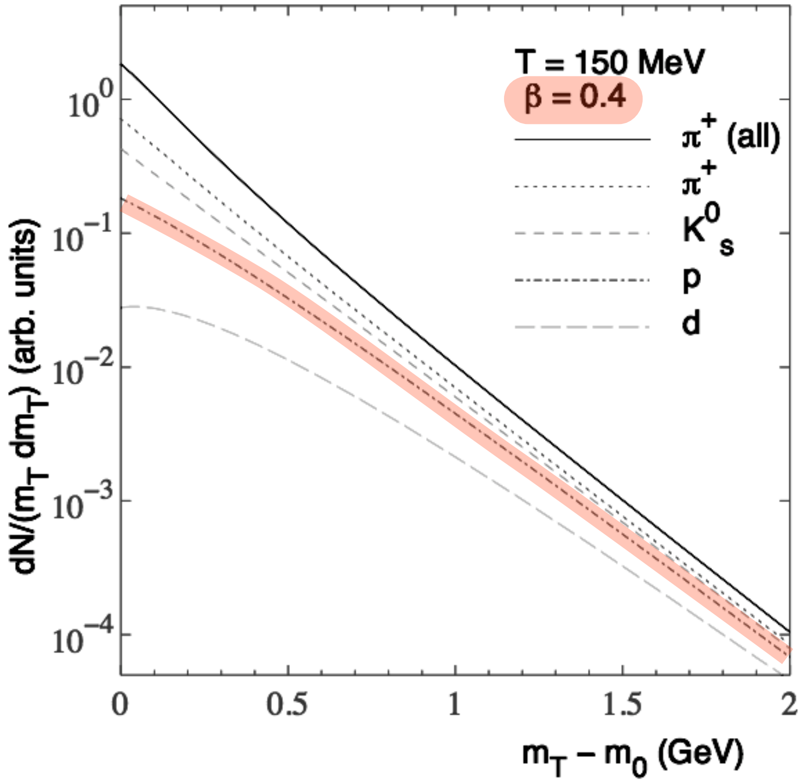

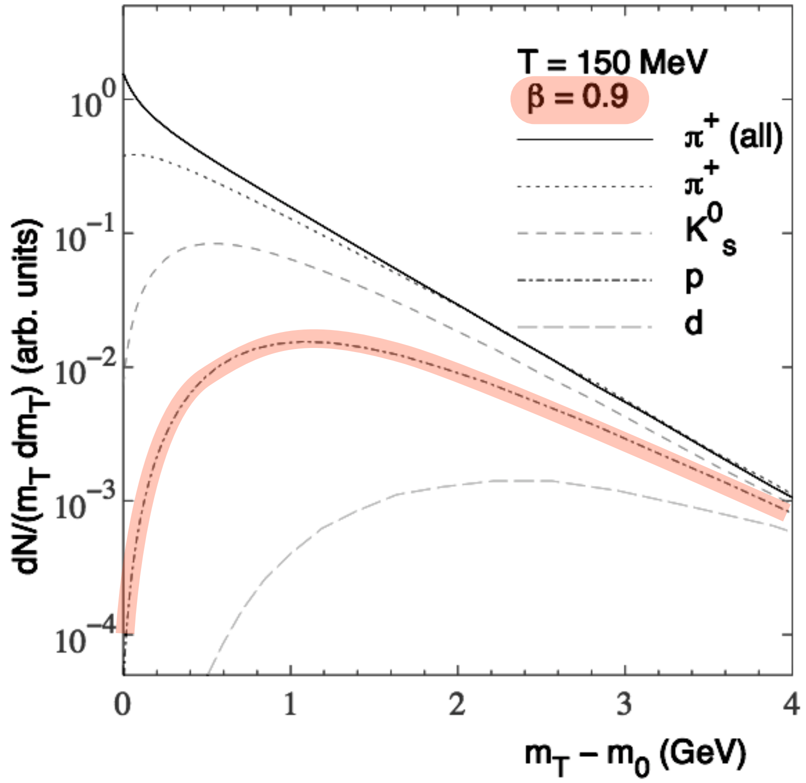

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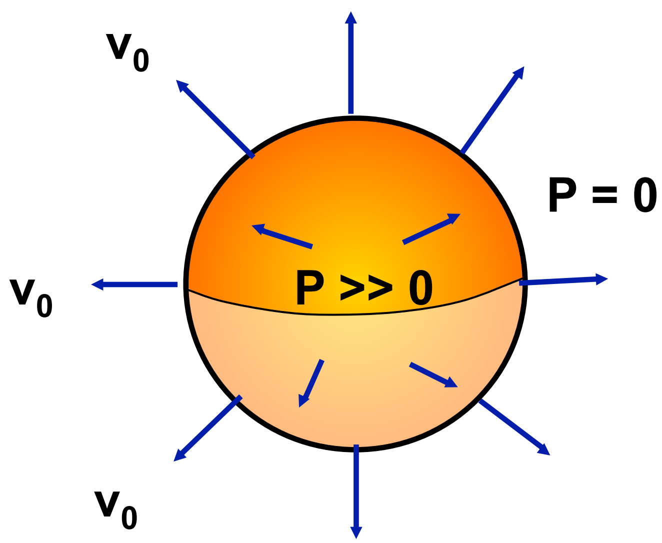
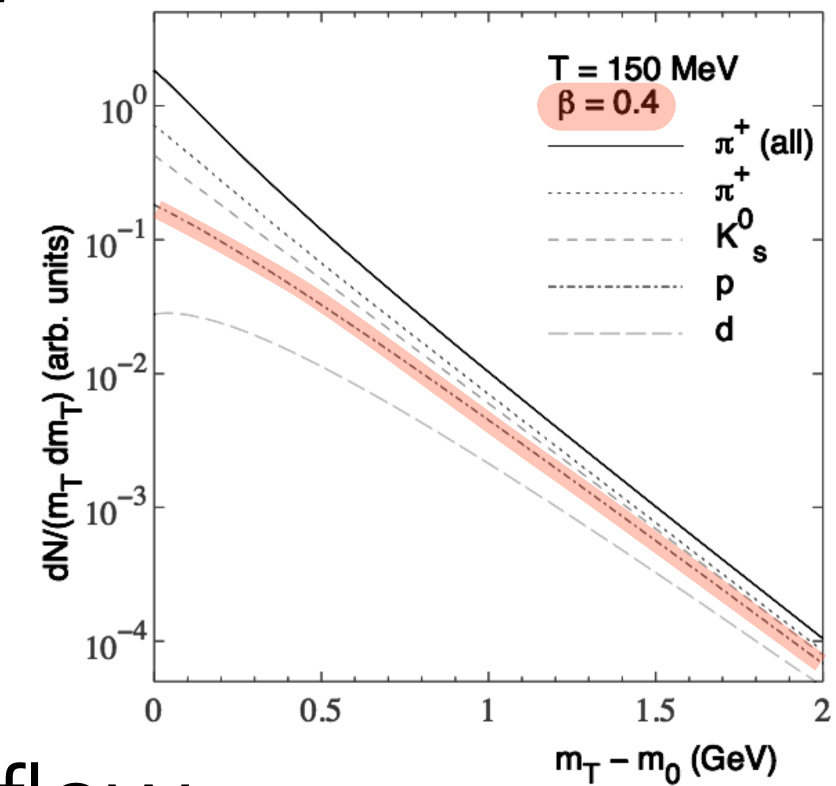
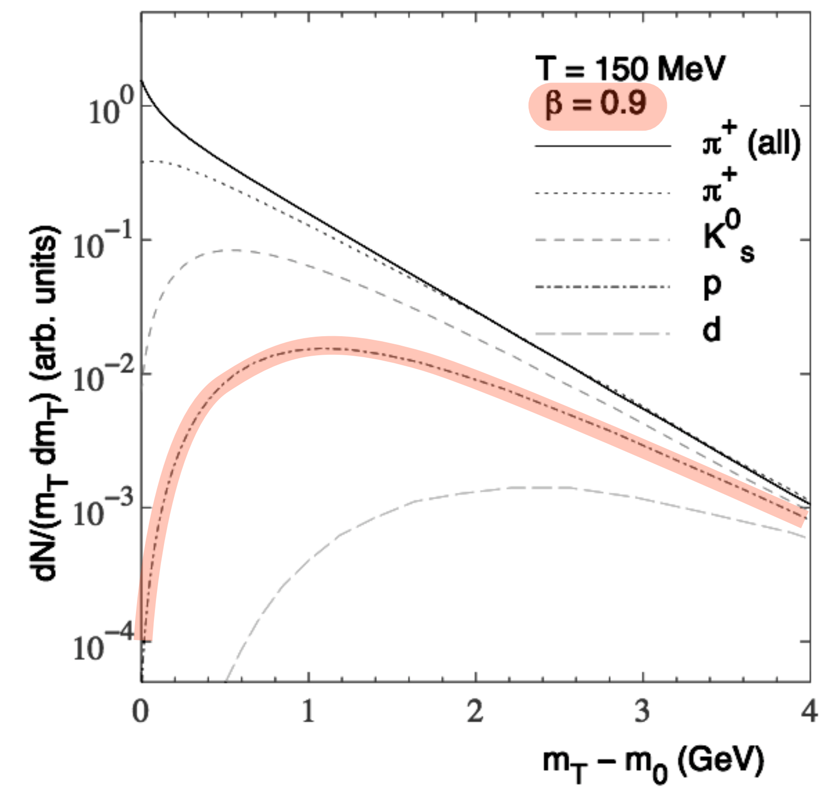
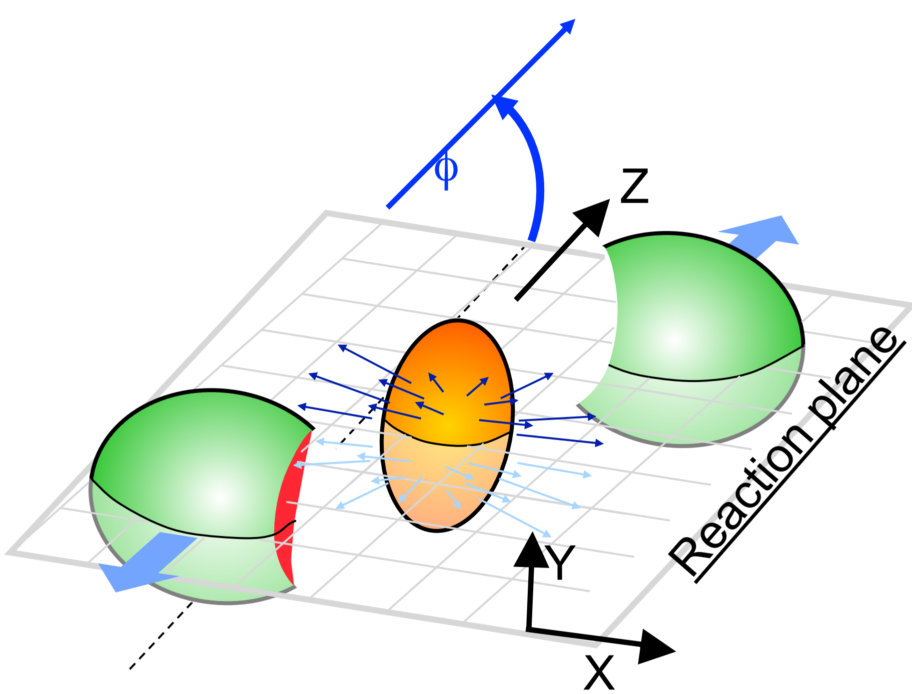




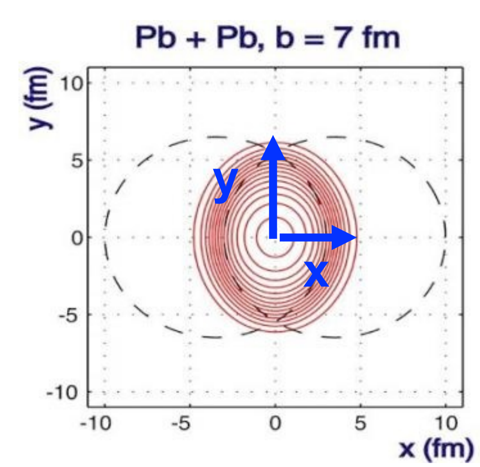


Anisotropic (elliptic) flow

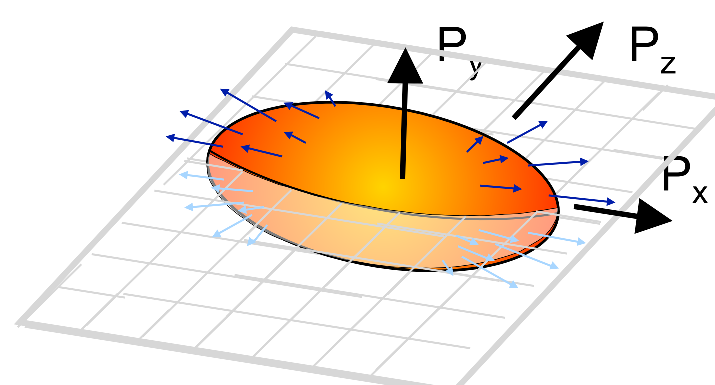
Spatial deformation



Azimuthal (ϕ) pressure gradients



Anisotropic particle density

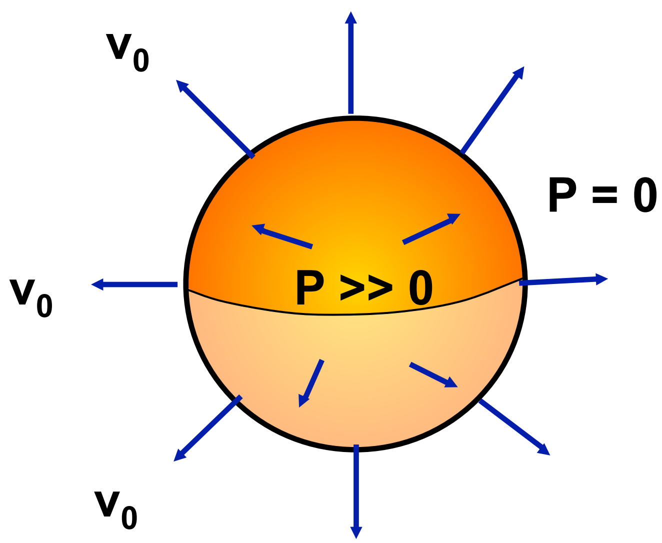


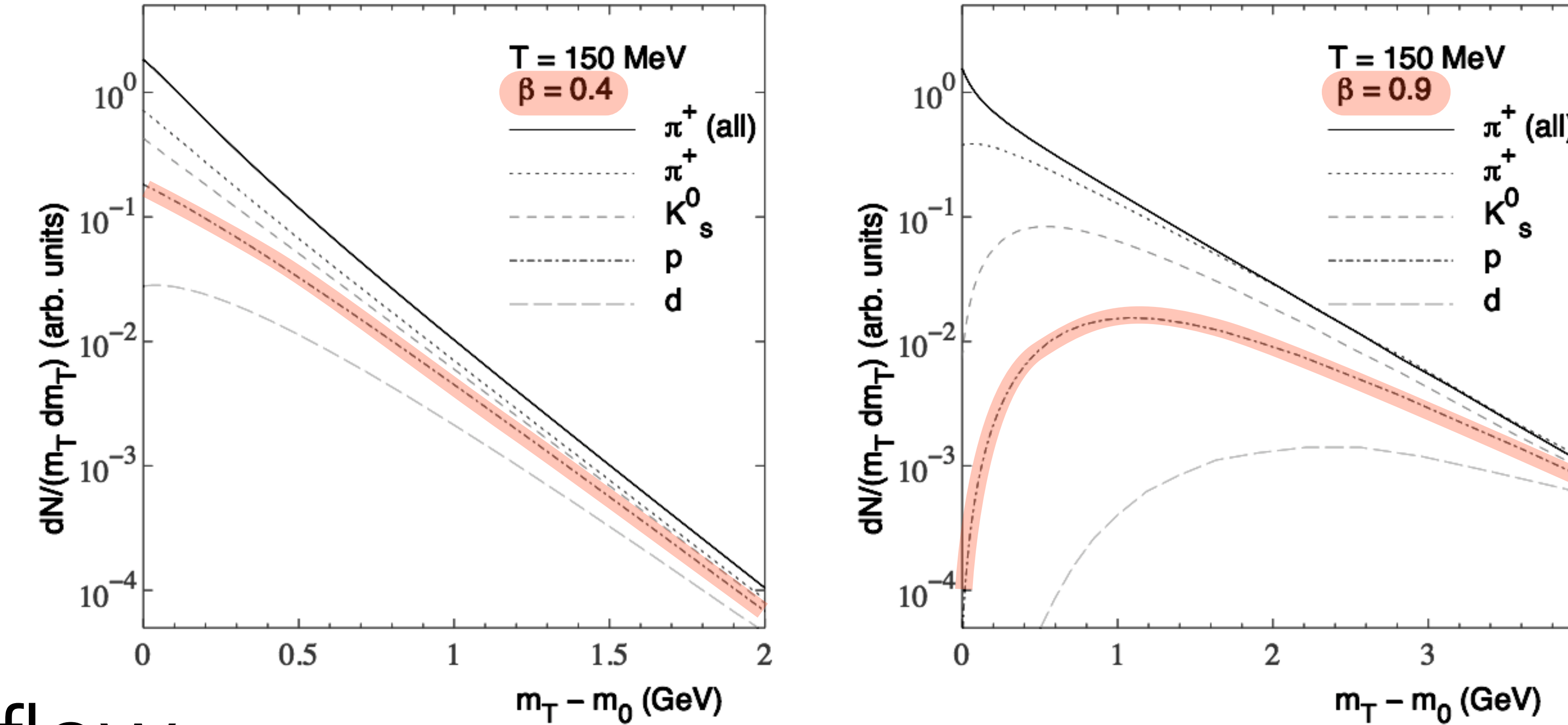
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + \ldots$$

Observable Consequences: Flow

Isotropic (radial) flow

hep-ph/0407360





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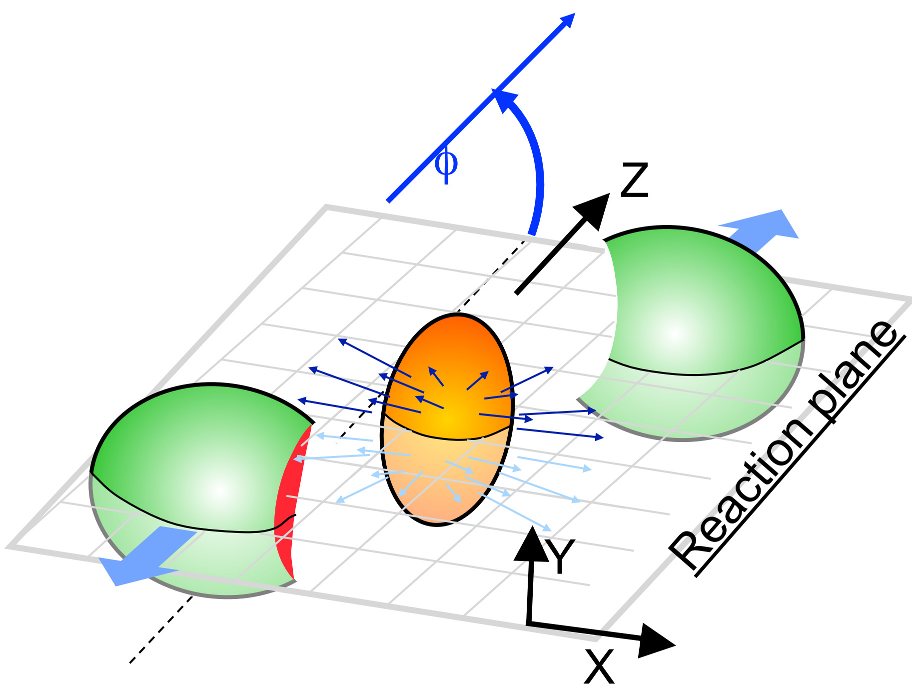

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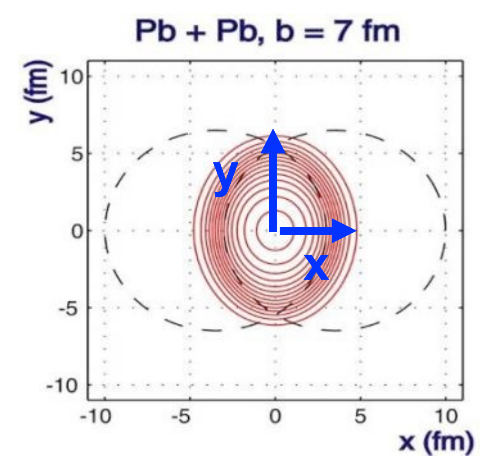

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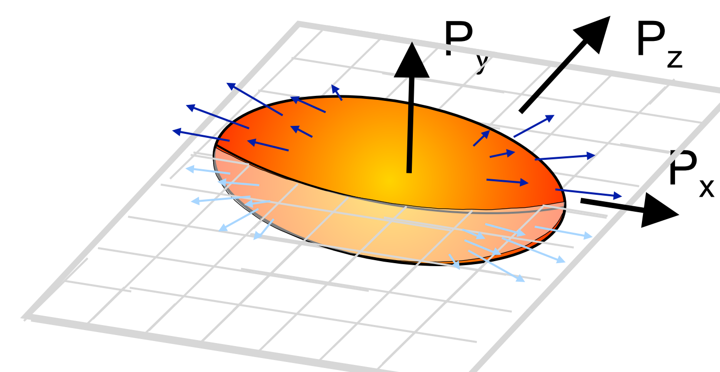

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What about the p/d?

Does the p/d constrain annihilation? The idea:

$d/p \propto S/p \rightarrow$ once the proton number and entropy is fixed so is the d/p
Of course we can have annihilation before 'chemical freeze out'!

Scenario 1

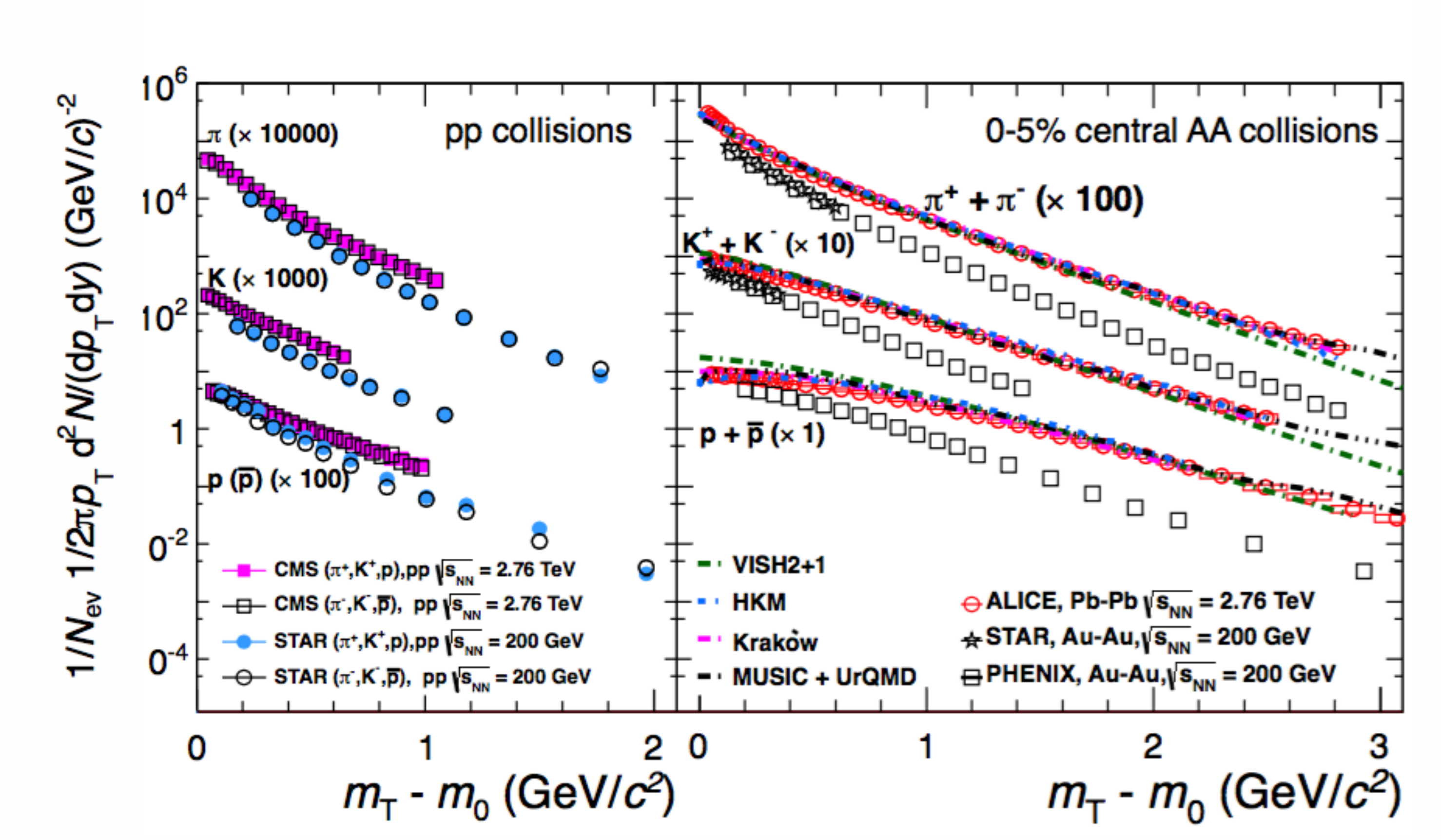
- Both are fixed at a specific T_{CH}, then also d/p is fixed at that T_{CH}
- Consistency! Therefore: No annihilation
- But that of course has to be the case since we have defined T_{CH} that way: A tautology

Scenario 2

- There is no single T_{CH}
- Then d/p should be fixed whenever the proton number and entropy are fixed.
- d/p is consistent with the 'effective' T_{CH} of protons.

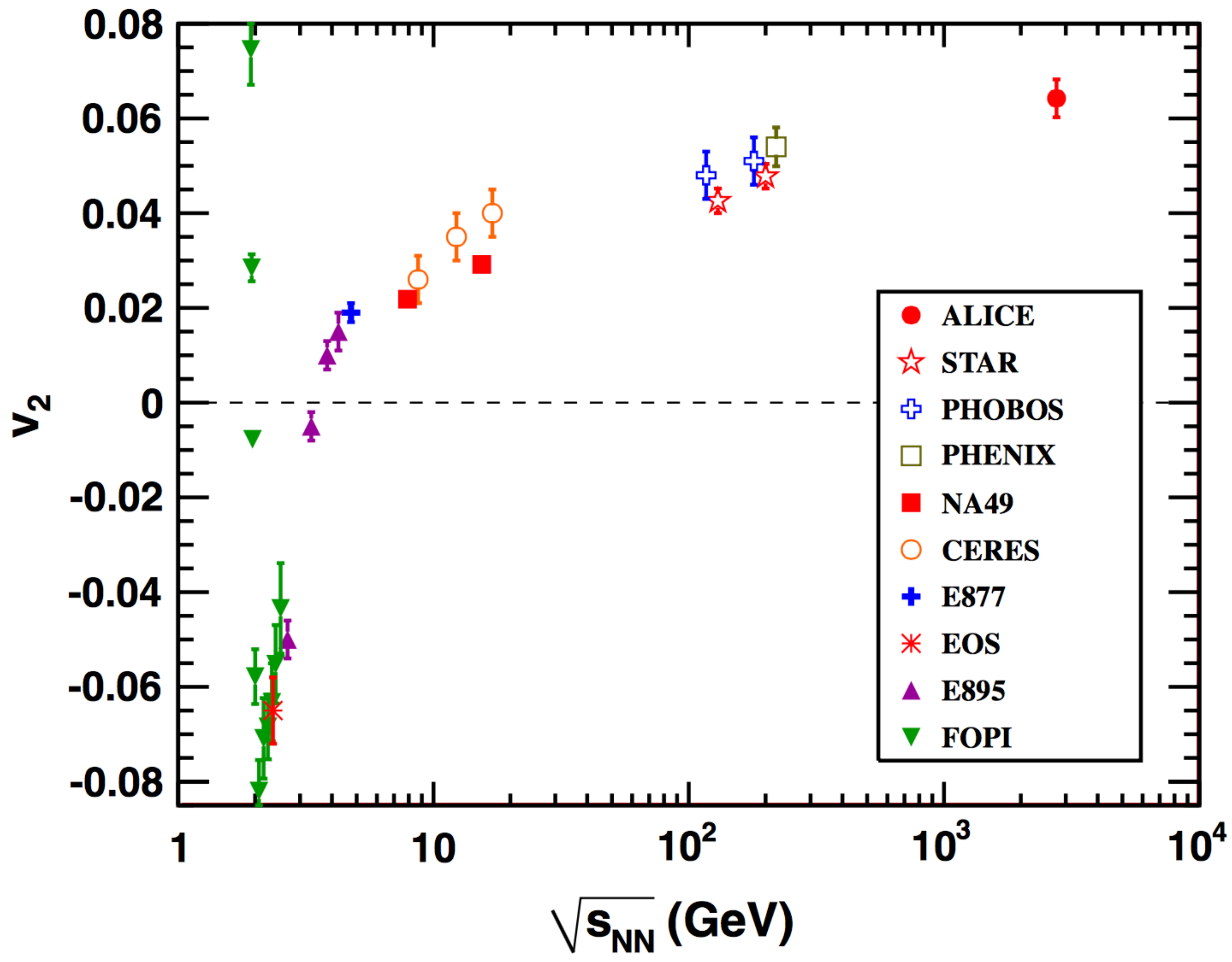
identified hadron p_T-spectra

Data: ALICE. VISH2+1 pre-diction: PRC 84 (2011) 044903)



A purely hydrodynamic description does not produce quite enough radial flow in central collisions (although it qualitatively reproduces the much larger mass splitting of $v_2(p_T)$ due to stronger radial flow at LHC compared to RHIC)

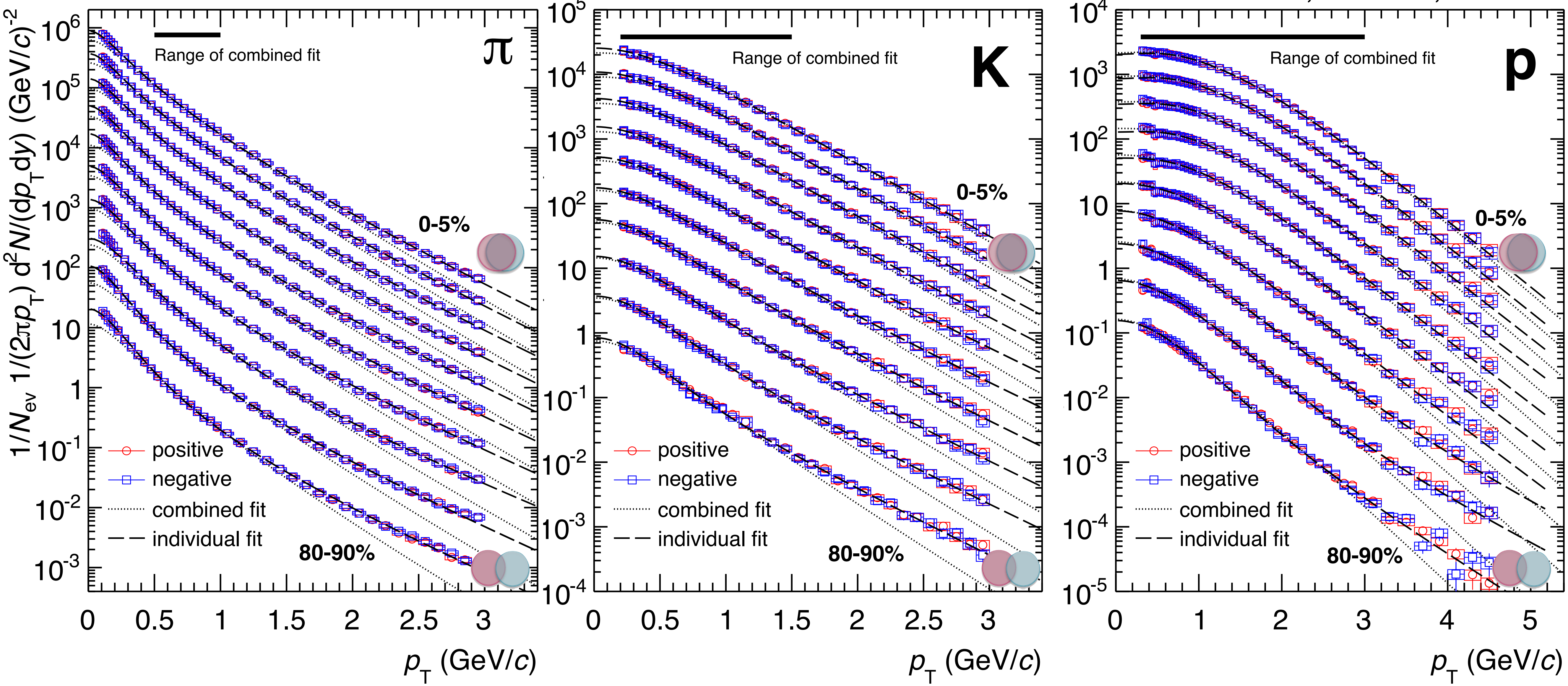
PRL 105, 252302 (2010)



Average in line with expectations

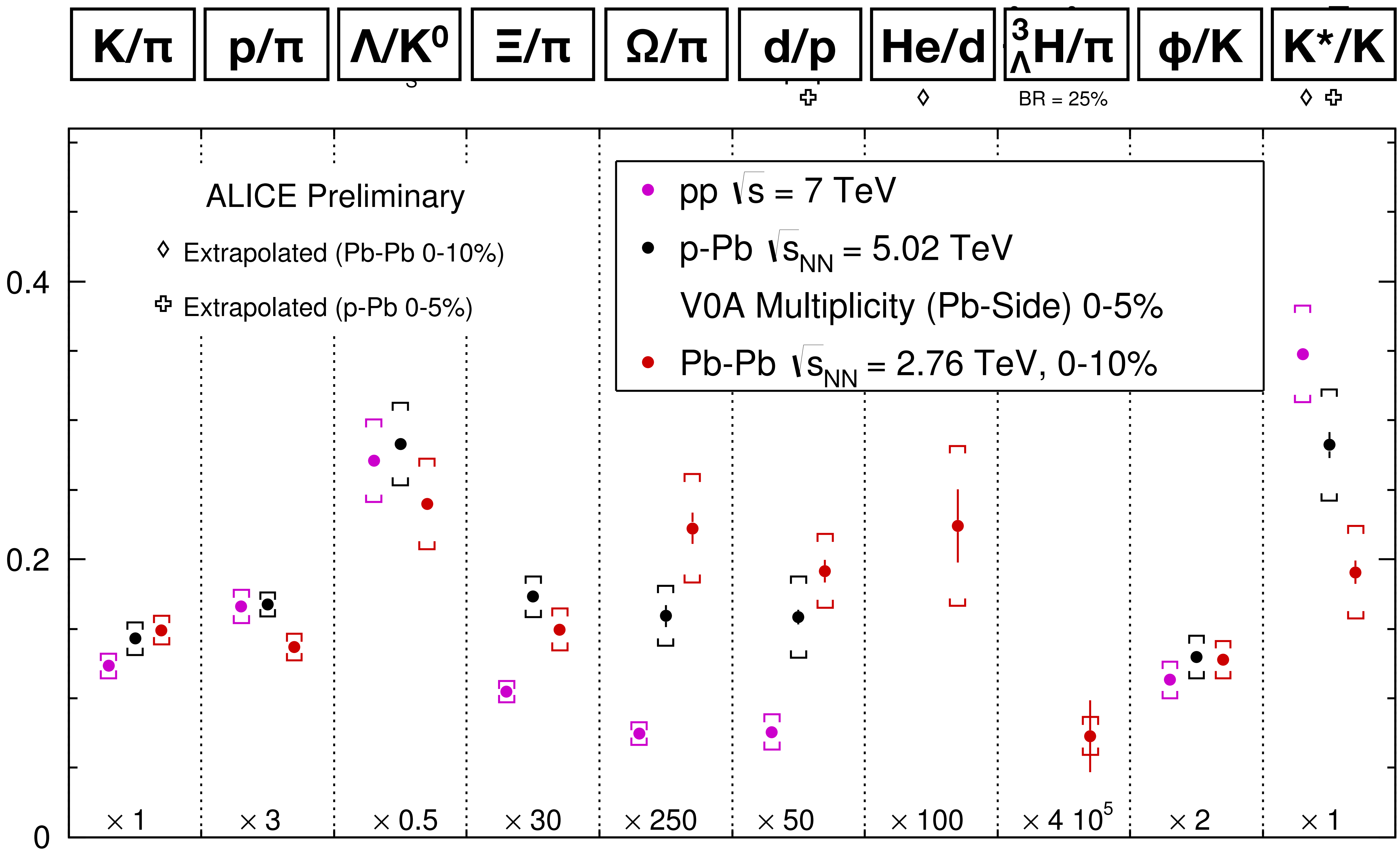
Transverse momentum distributions

ALICE, PRC 88, 044910

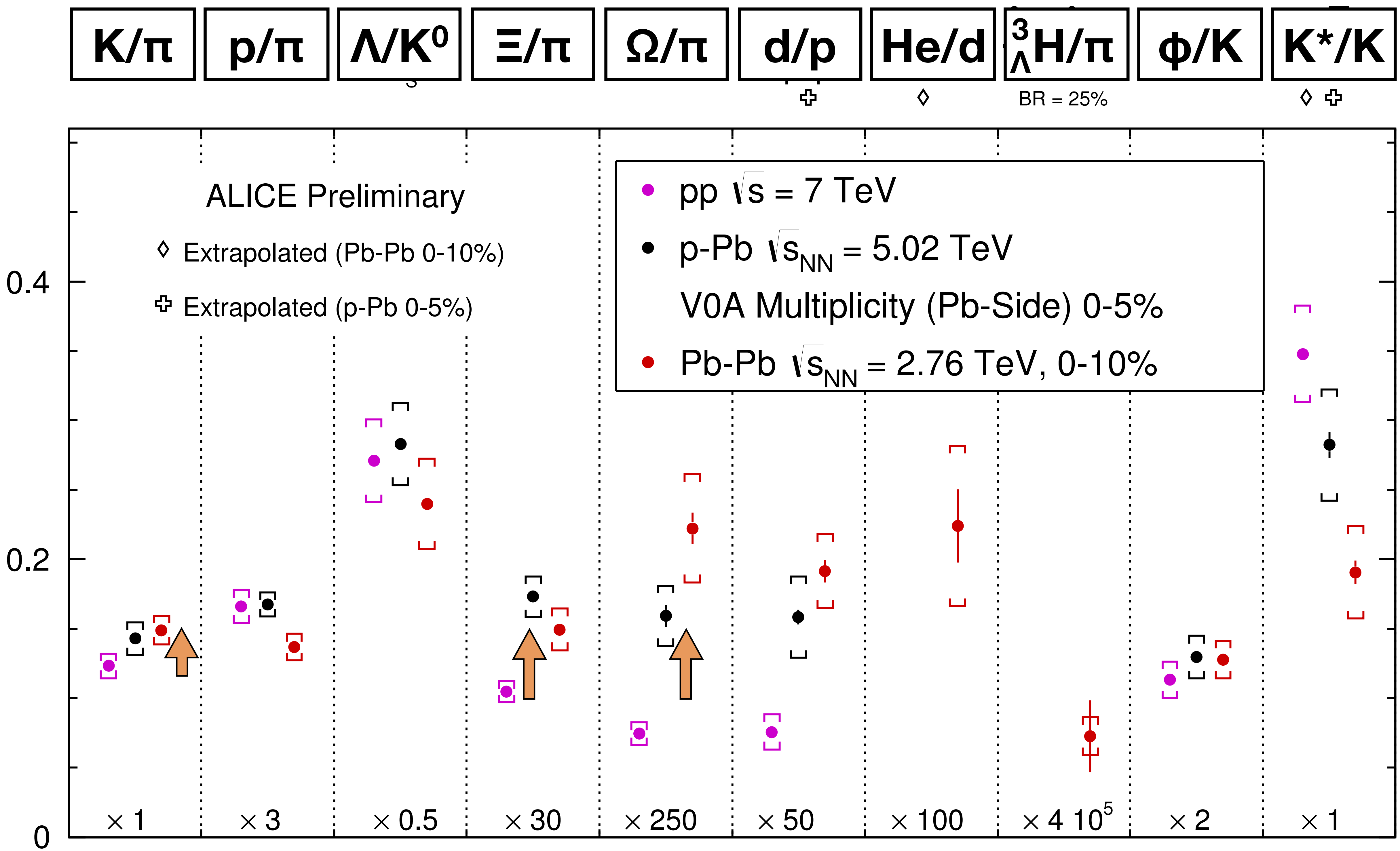


- Clear evolution of spectra with centrality.
- Central collisions: flat at low p_T, nearly exponential at high p_T
  - Indication for collective radial expansion

Ratios, system size dependence at the LHC

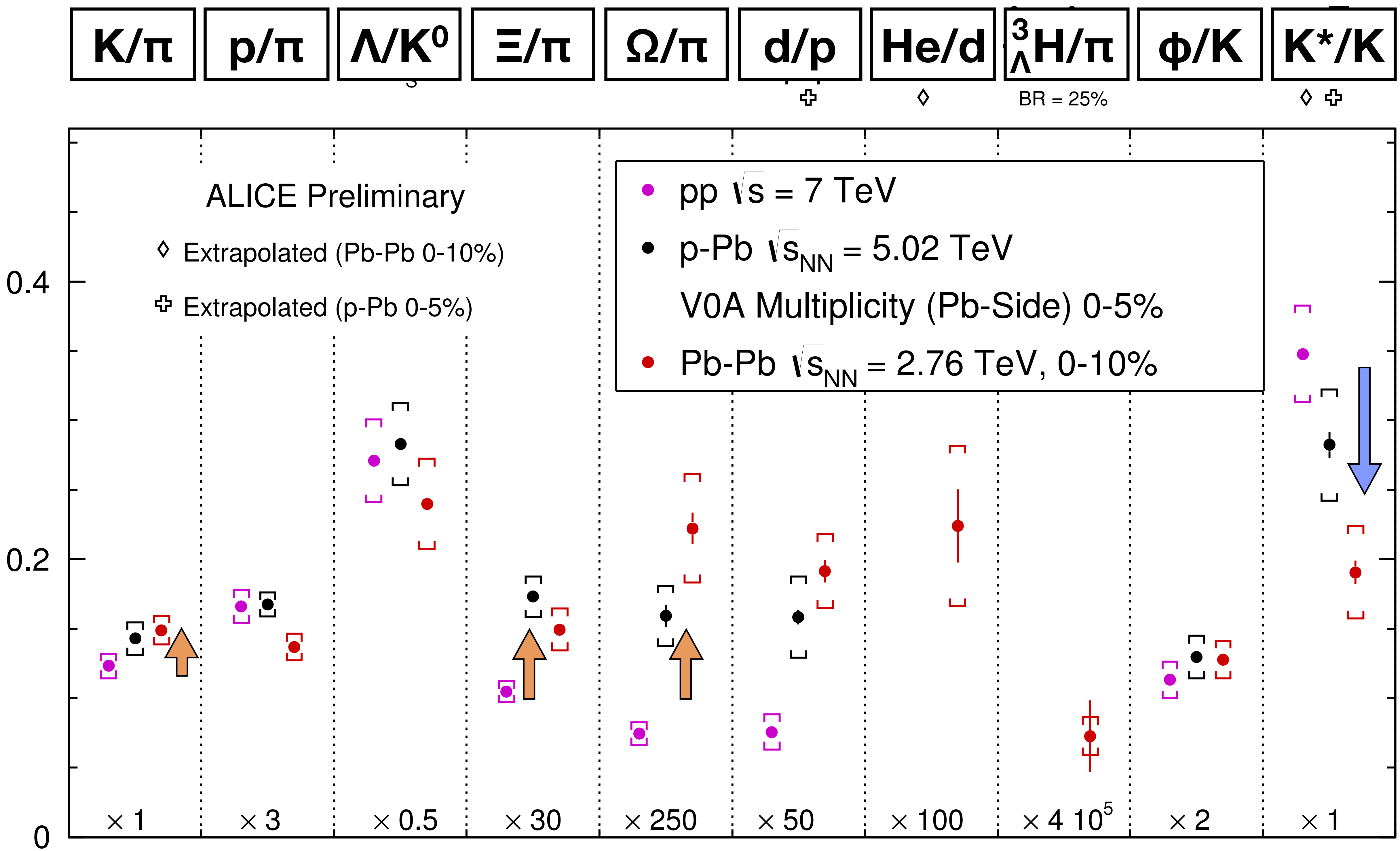


Ratios, system size dependence at the LHC



Strangeness enhancement

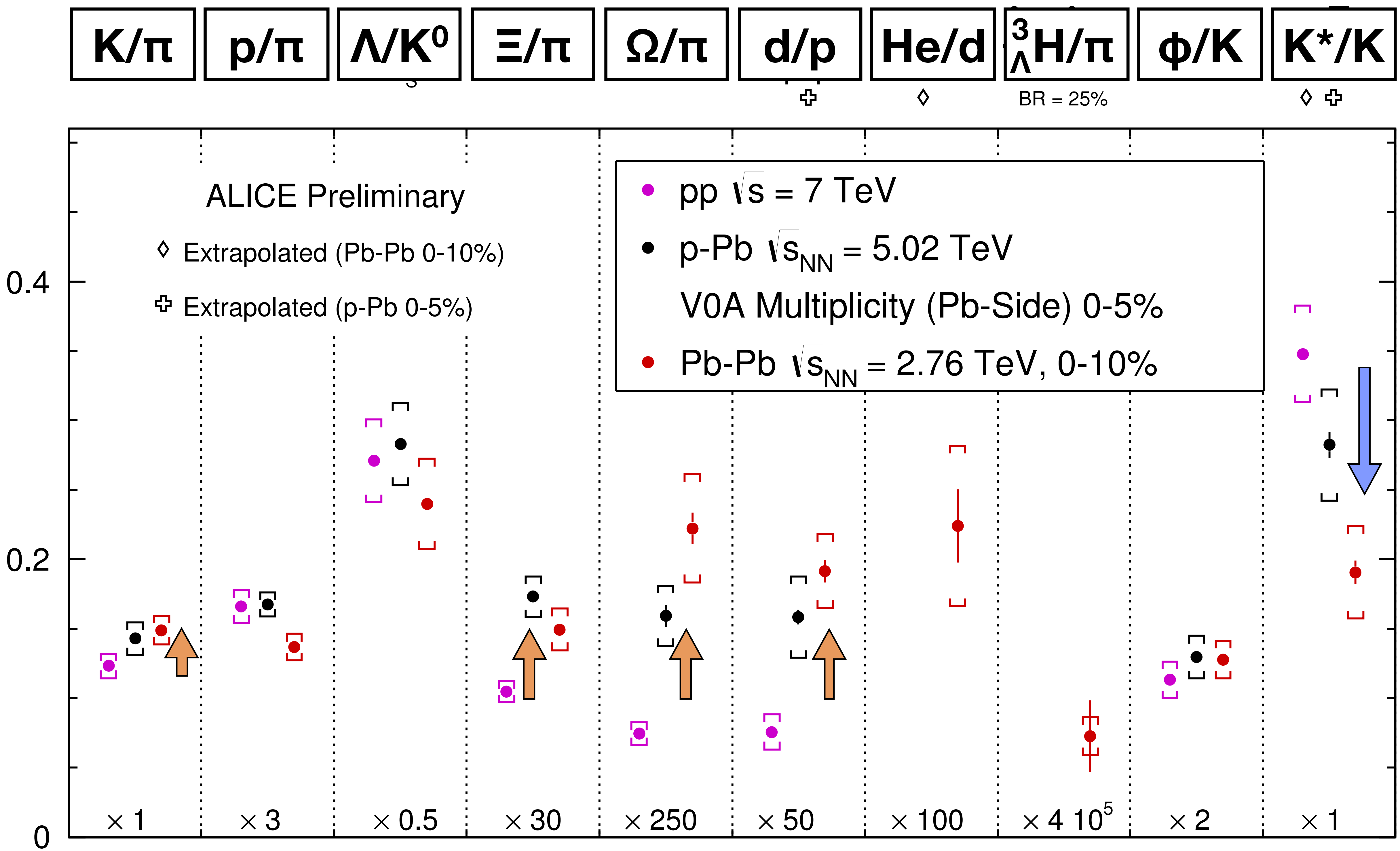
Ratios, system size dependence at the LHC



Strangeness enhancement

K* suppression

Ratios, system size dependence at the LHC

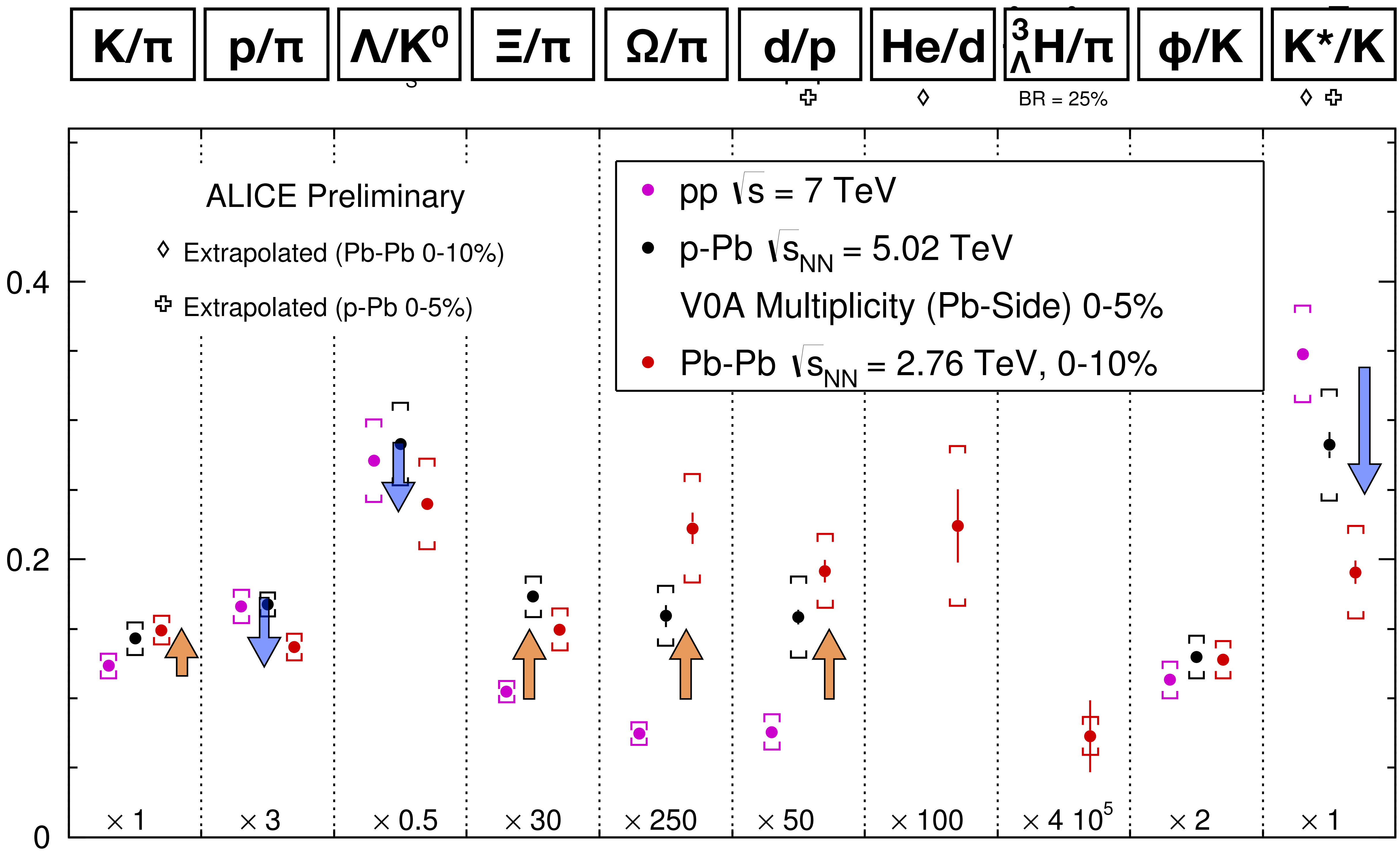


Strangeness enhancement

K* suppression

Deuteron enhancement

Ratios, system size dependence at the LHC



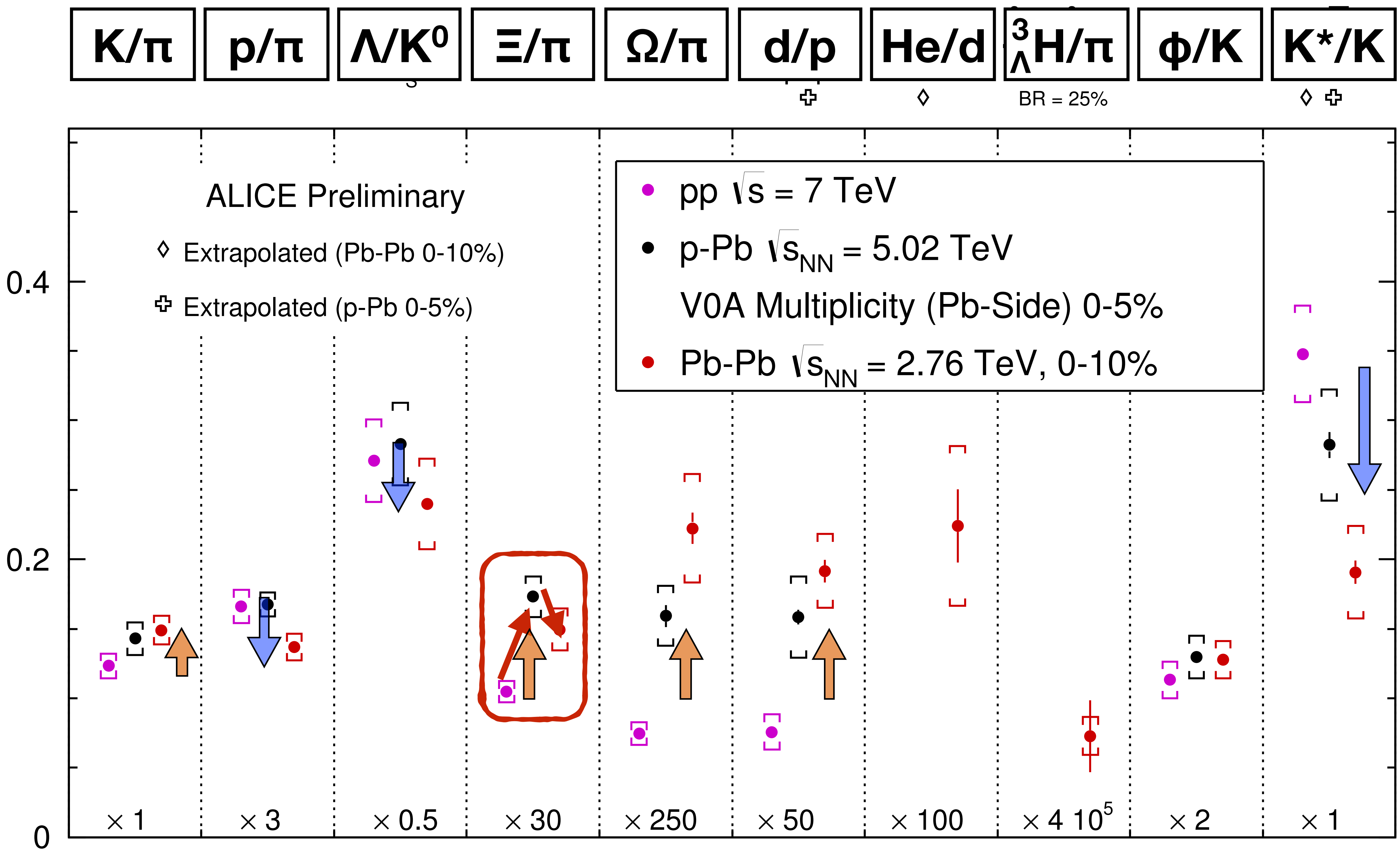
Strangeness enhancement

Deuteron enhancement

K* suppression

Baryon suppression?

Ratios, system size dependence at the LHC



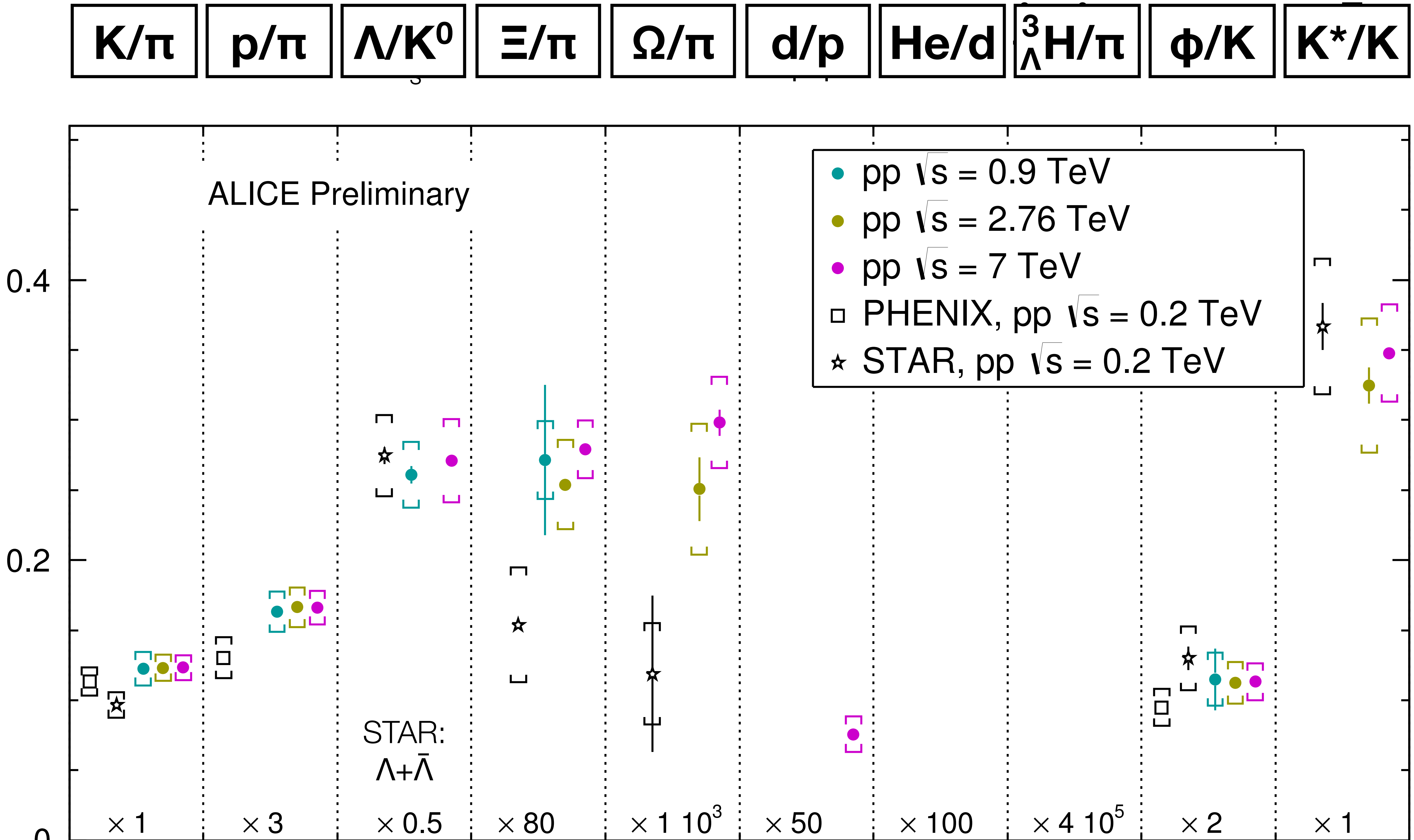
Strangeness enhancement

Deuteron enhancement

K* suppression

Baryon suppression?

pp ratios, from RHIC to LHC



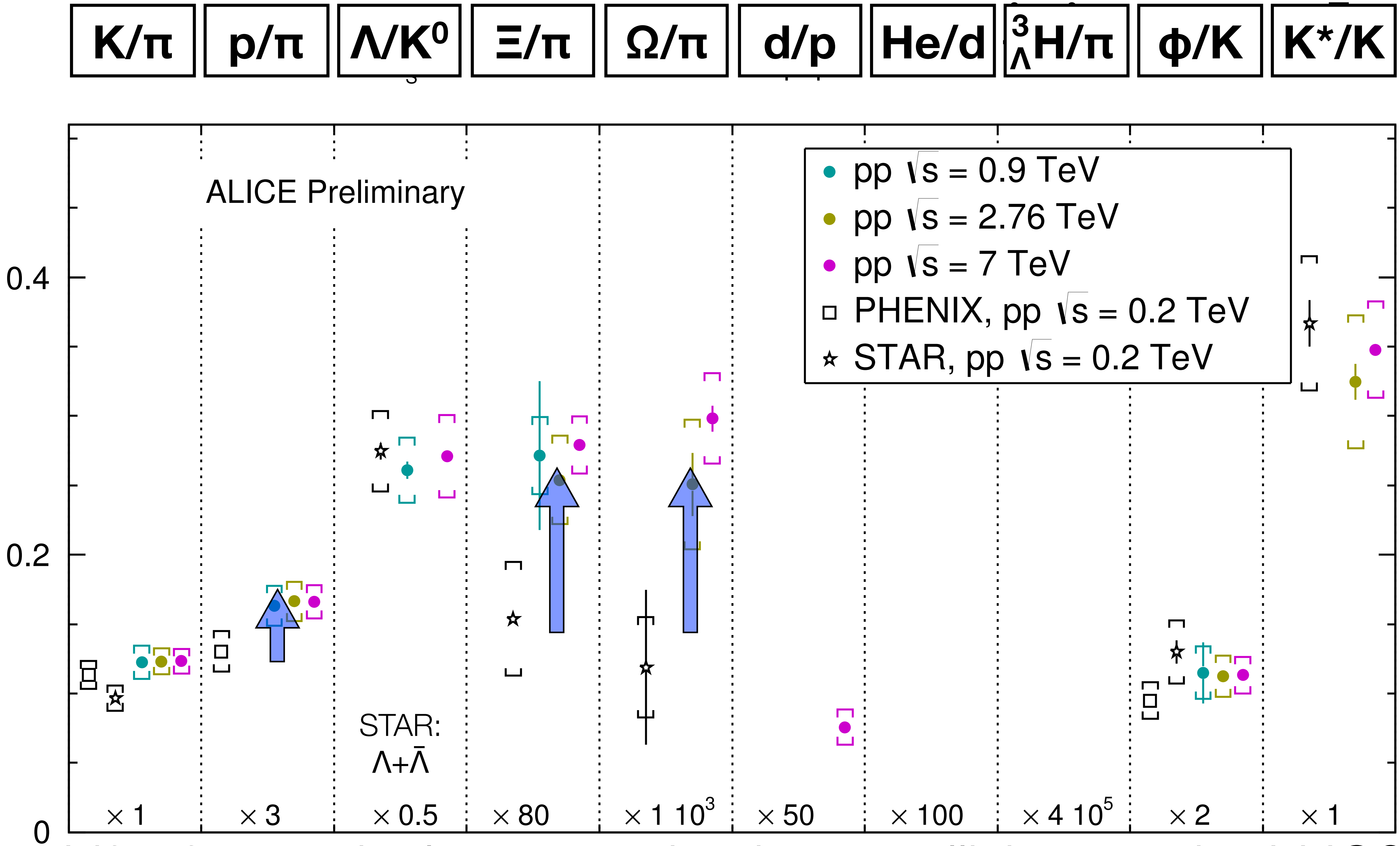
Lift of canonical suppression in pp collisions at the LHC?

GC ensemble applicable in pp at the LHC?

See, e.g. Becattini SQM13

Becattini et al, JPG 025002 (2011)

pp ratios, from RHIC to LHC



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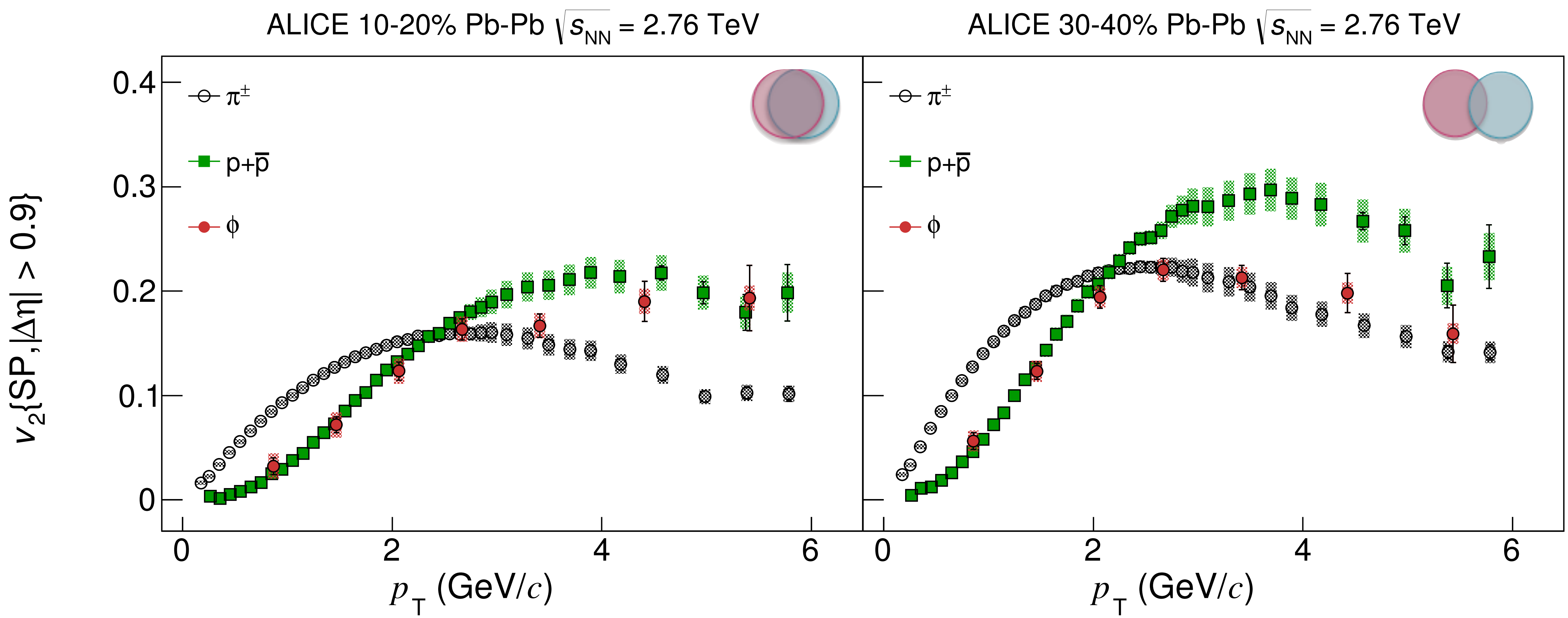
Recombination and anisotropic flow

ALICE, arXiv:1405.4632

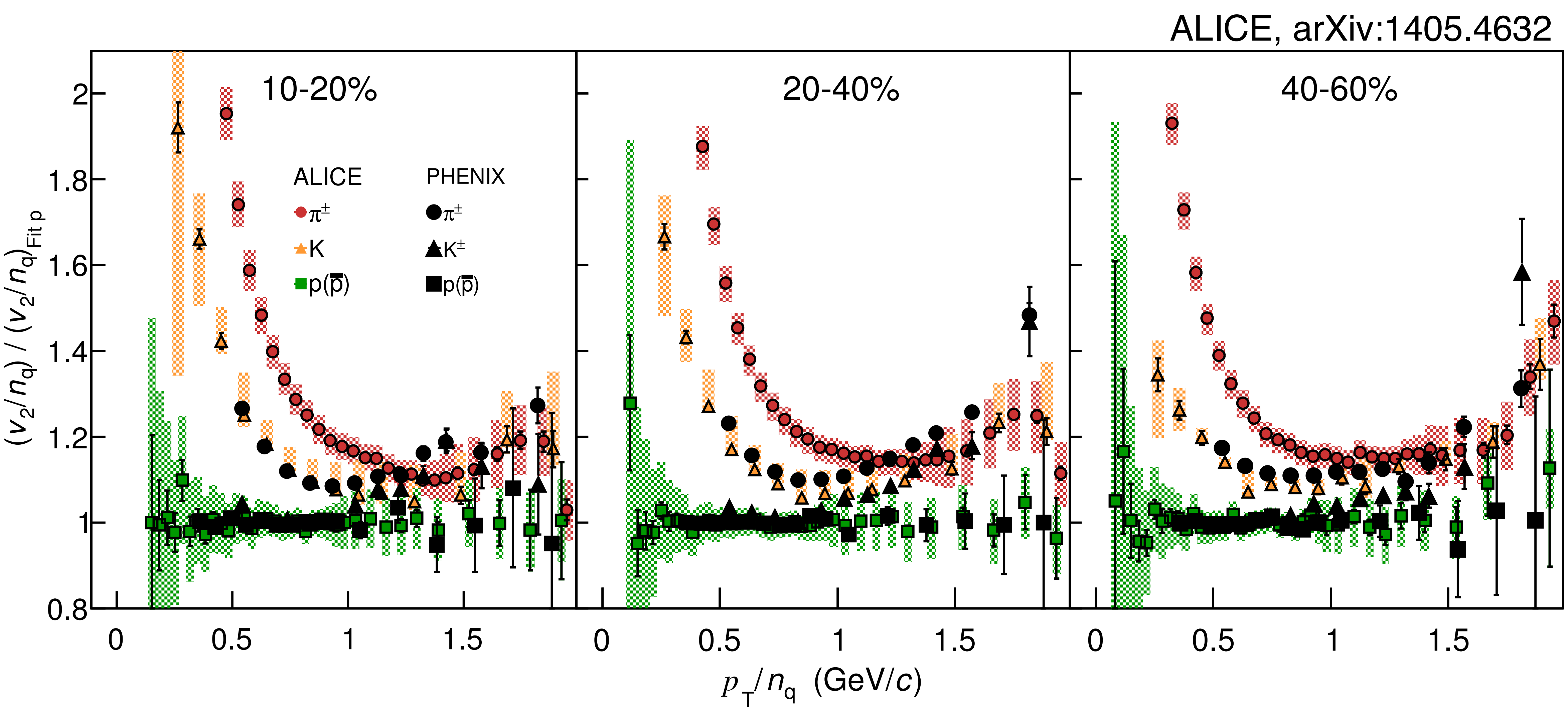


Recombination and v_2 ⇒ B/M ordering + NCQ scaling

ϕ central: mass ordering at all p_T (close to p)

ϕ semi-central: mass ord. low p_T, follows π high p_T

Recombination and anisotropic flow



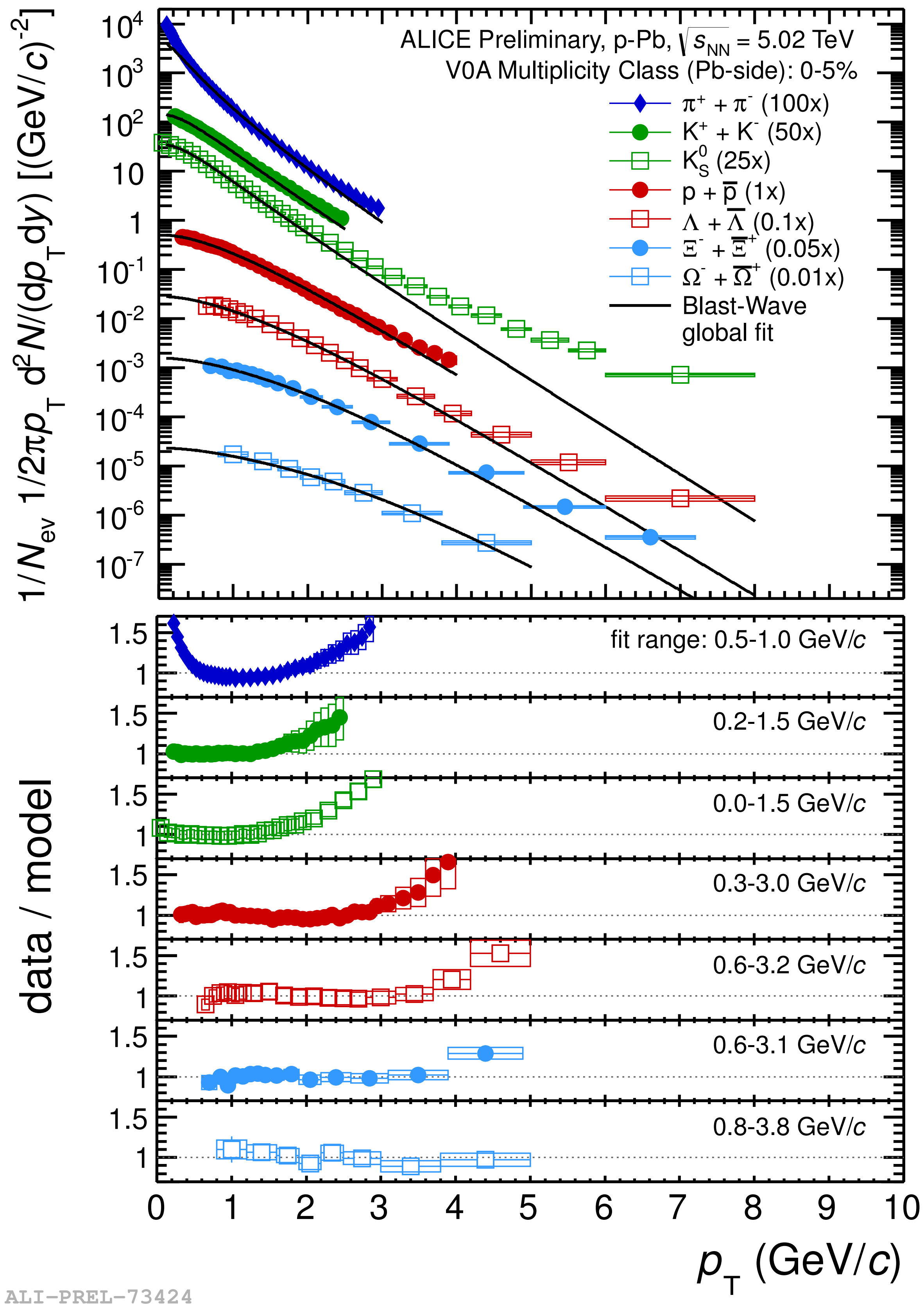
ALI-PUB-82622

Recombination and v_2 ⇒ B/M ordering + NCQ scaling

ϕ central: mass ordering at all p_T (close to p)

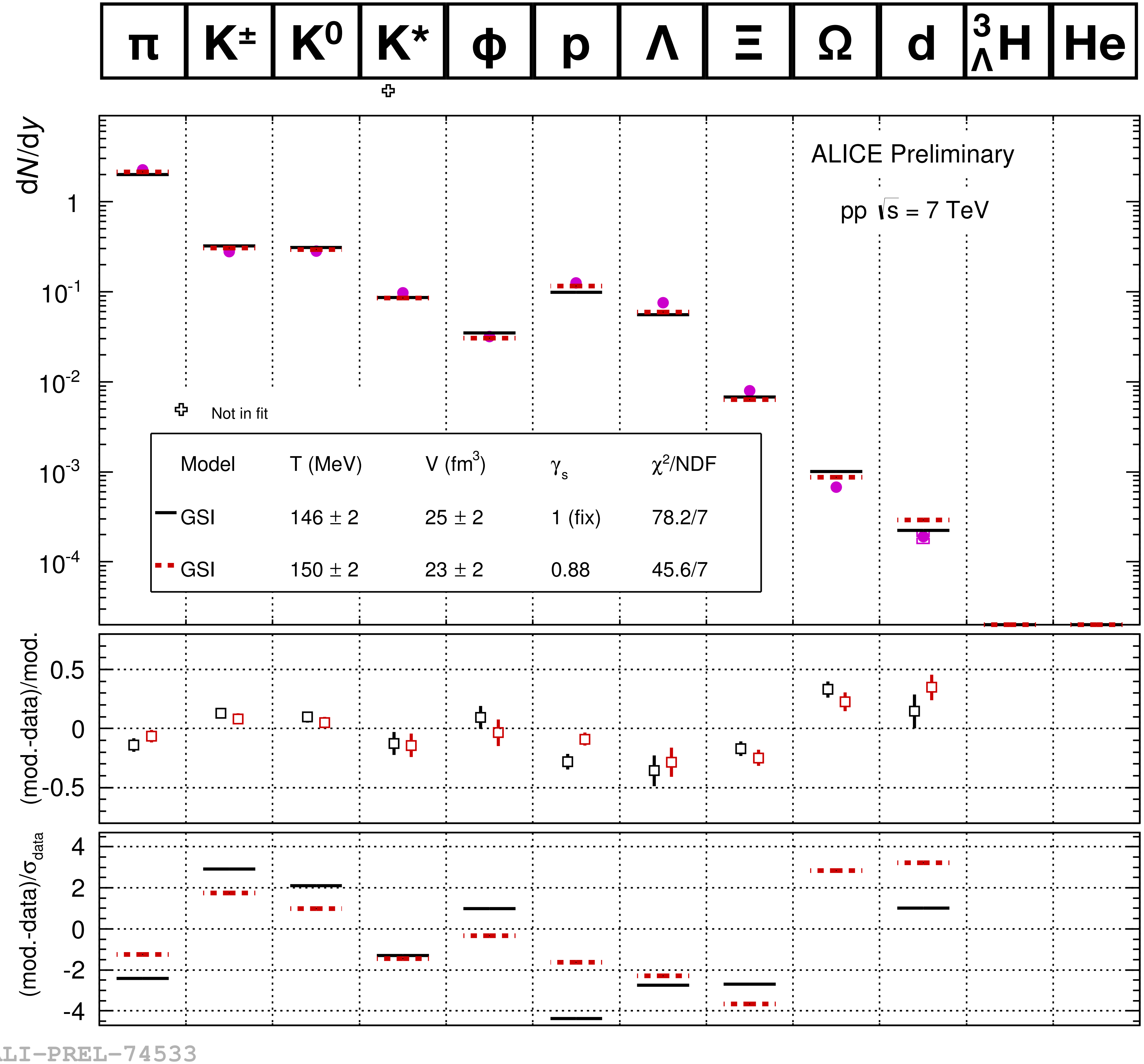
ϕ semi-central: mass ord. low p_T, follows π high p_T

Violation of constituent quark scaling ~ ±20%



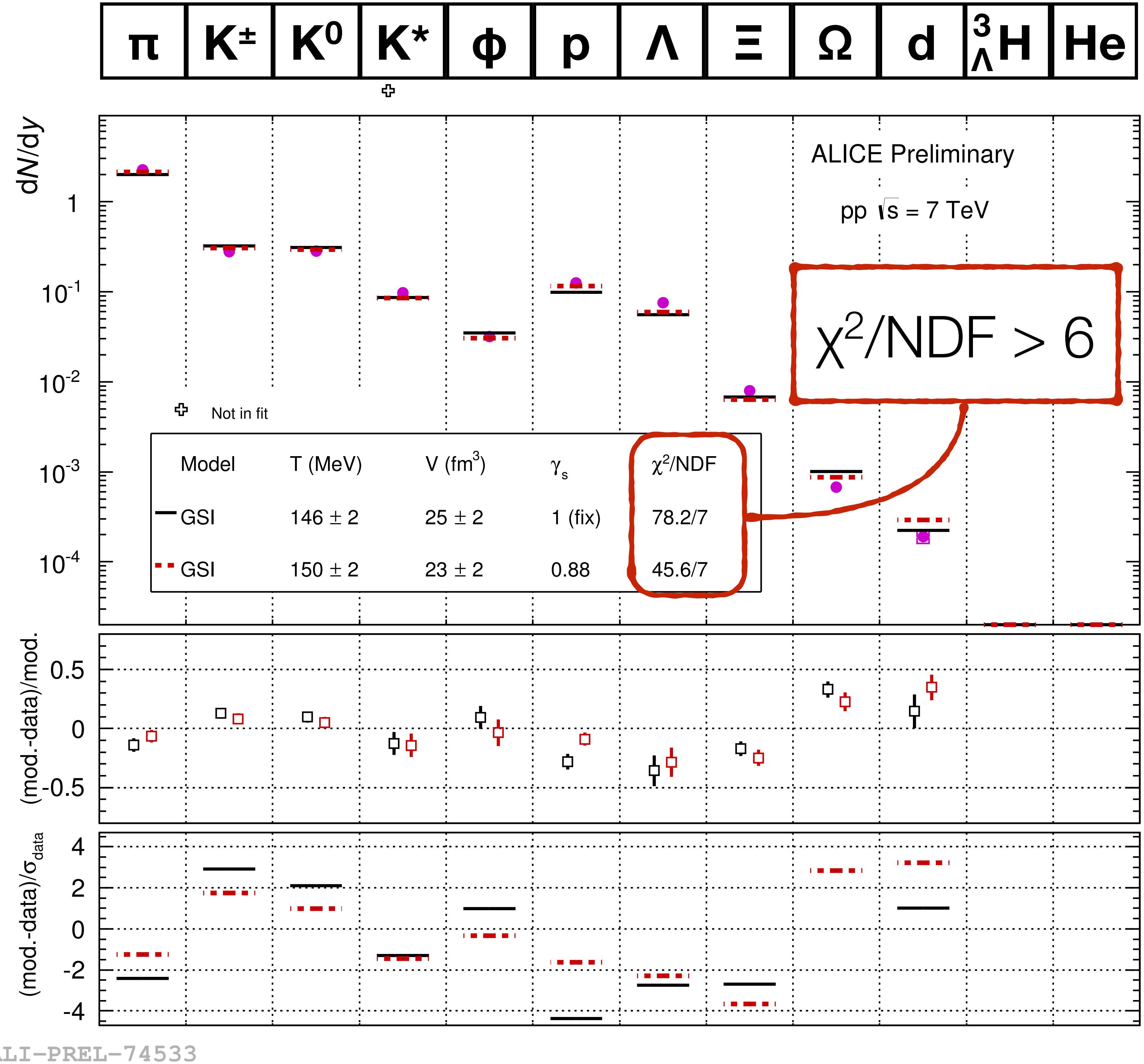
ALICE Preliminary, p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
V0A Multiplicity Class (Pb-side): 0-5%
$\pi^+ + \pi^-$ (100x)
$K^+ + K^-$ (50x)
K^0_S (25x)
$p + \bar{p}$ (1x)
$\Lambda + \bar{\Lambda}$ (0.1x)
$\Xi^- + \bar{\Xi}^+$ (0.05x)
$\Omega^- + \bar{\Omega}^+$ (0.01x)
Blast-Wave global fit
$1/N_{ev}\ 1/2\pi p_T\ d^2N/(dp_T dy)\ [(GeV/c)^{-2}]$
data / model
fit range: 0.5-1.0 GeV/c
0.2-1.5 GeV/c
0.0-1.5 GeV/c
0.3-3.0 GeV/c
0.6-3.2 GeV/c
0.6-3.1 GeV/c
0.8-3.8 GeV/c
p_T (GeV/c)
ALI-PREL-73424

GC fits at the LHC (pp collisions)



Poor fit with Grand Canonical ensemble in pp collisions

GC fits at the LHC (pp collisions)



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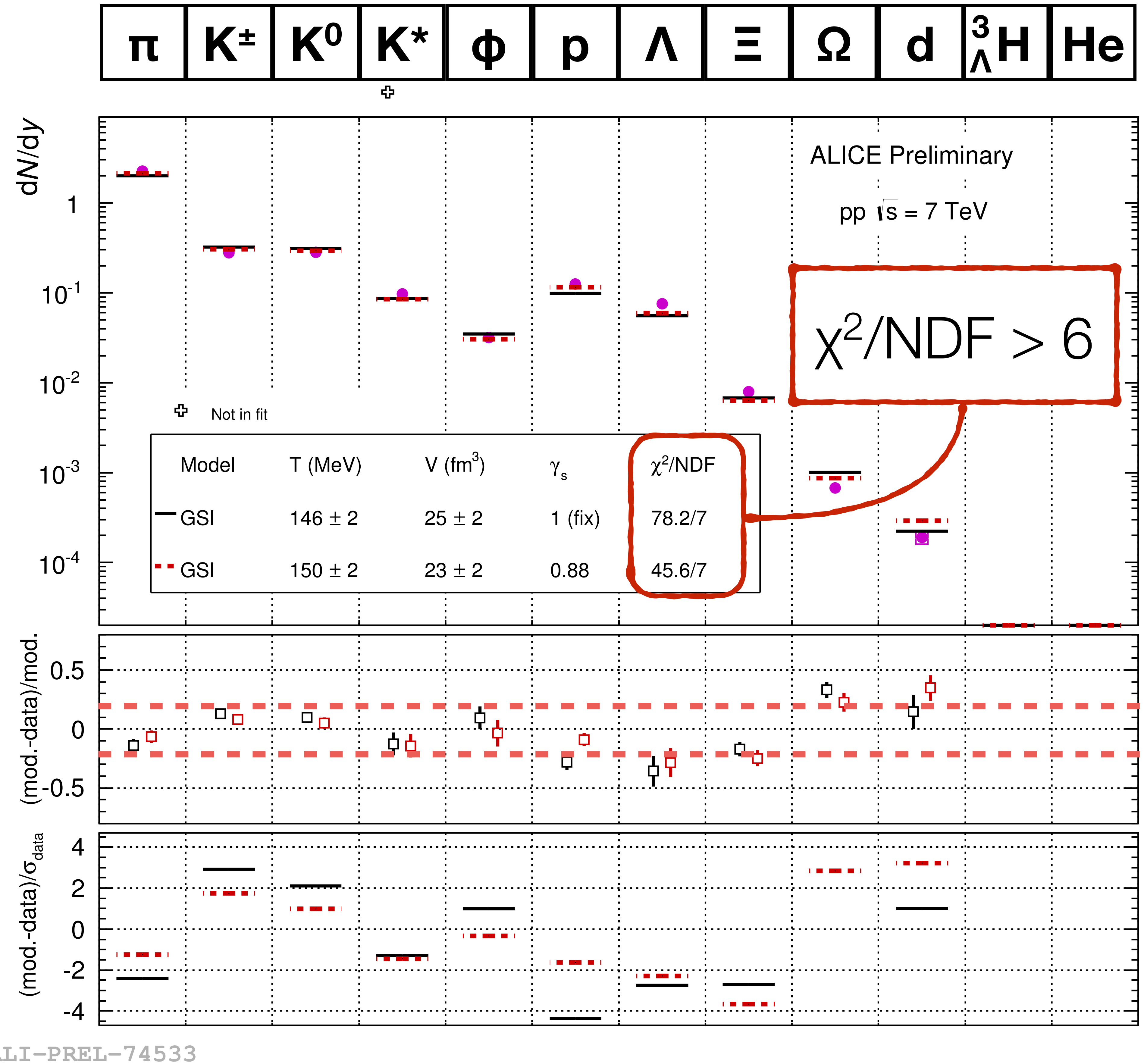
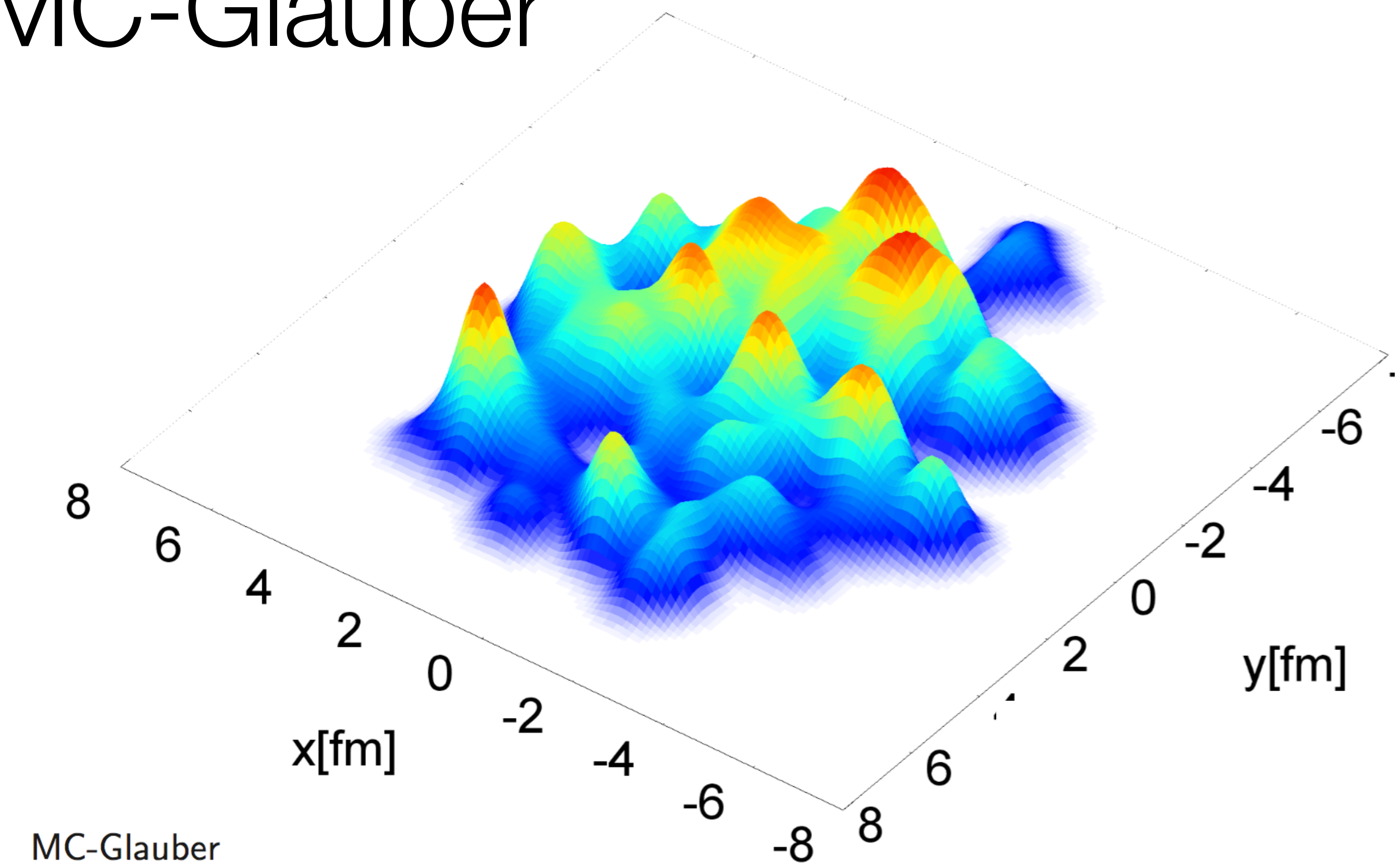
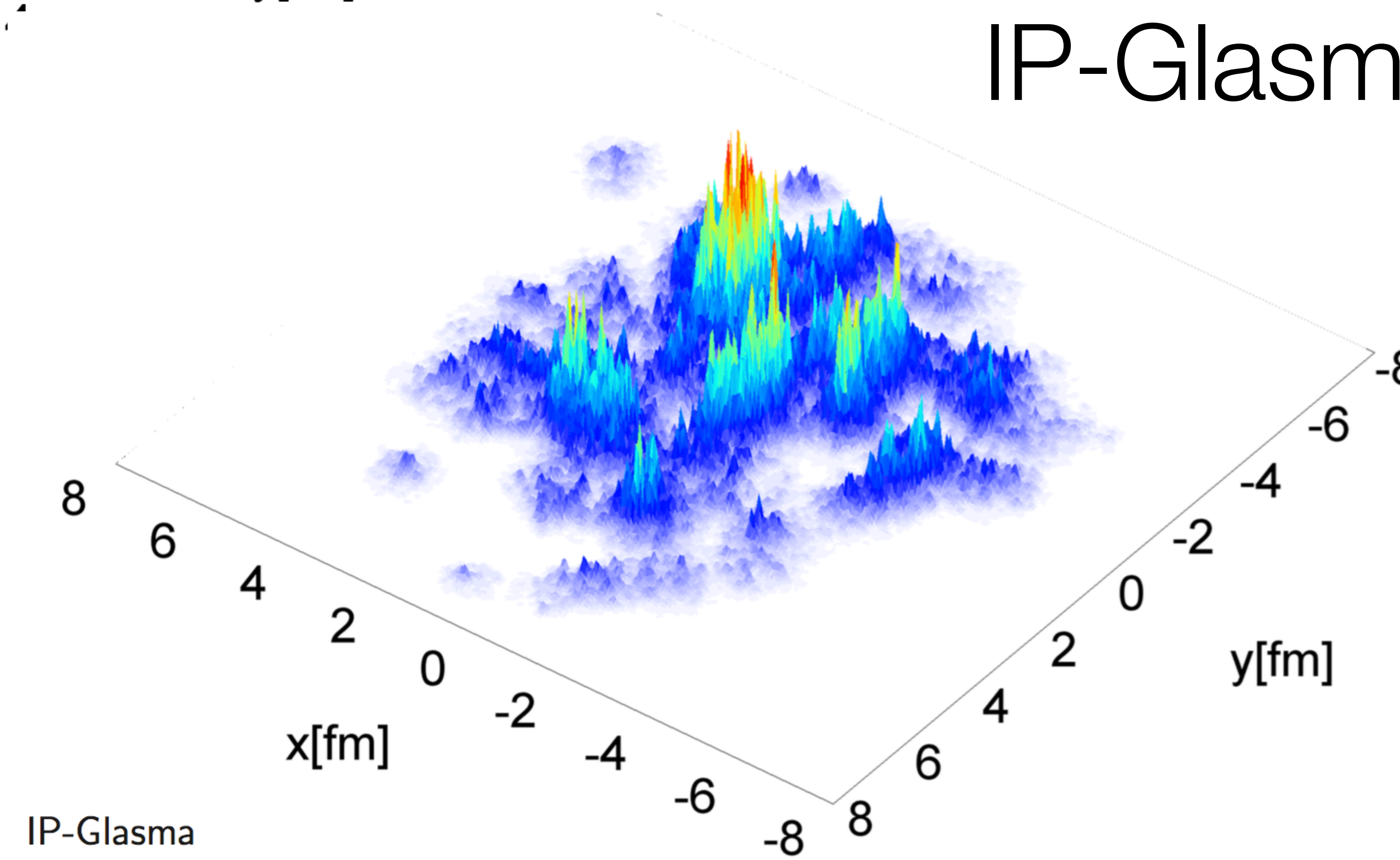


Poor fit with Grand Canonical ensemble in pp collisions

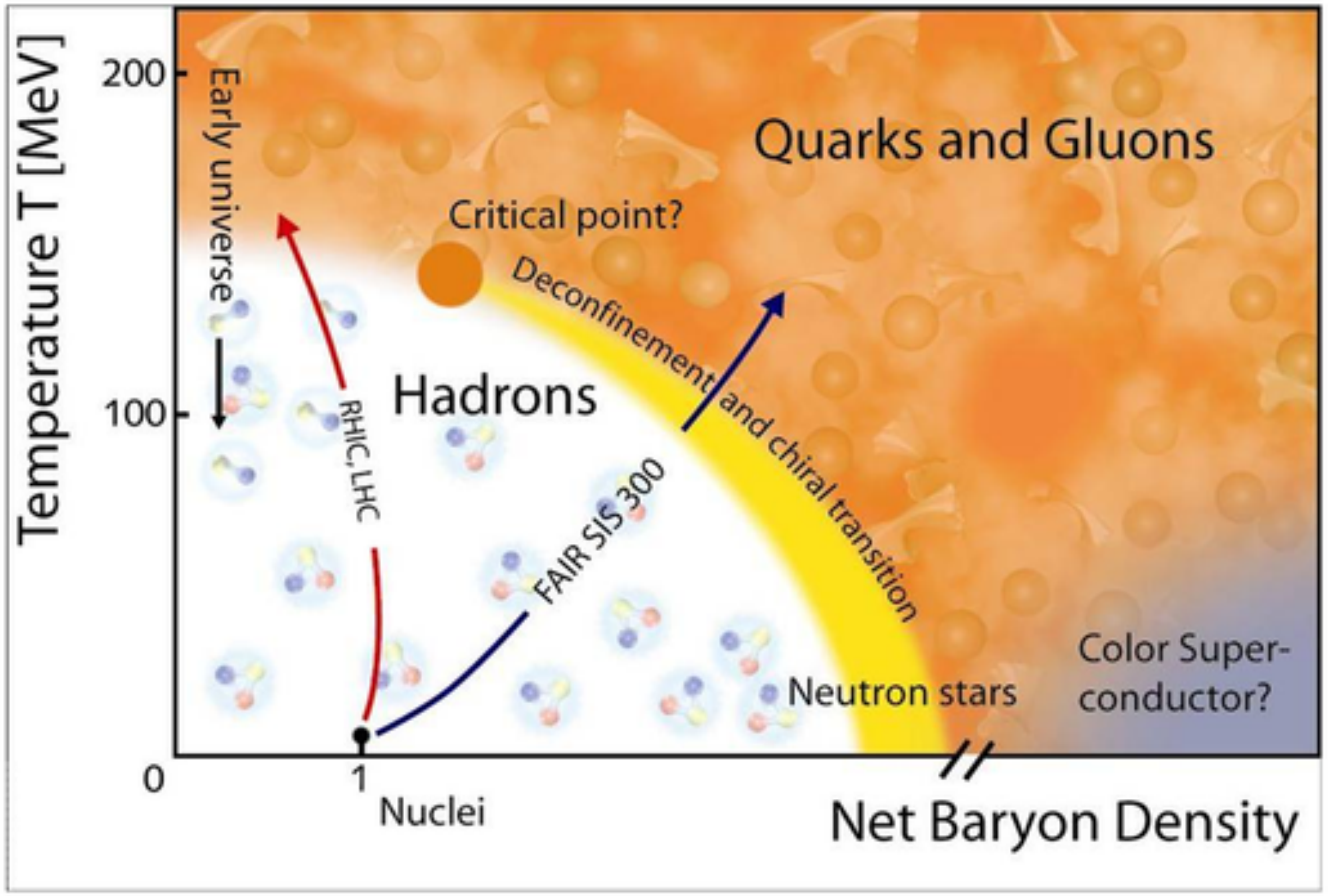
MC-Glauber



IP-Glasma



Fireball expansion: the “standard model”



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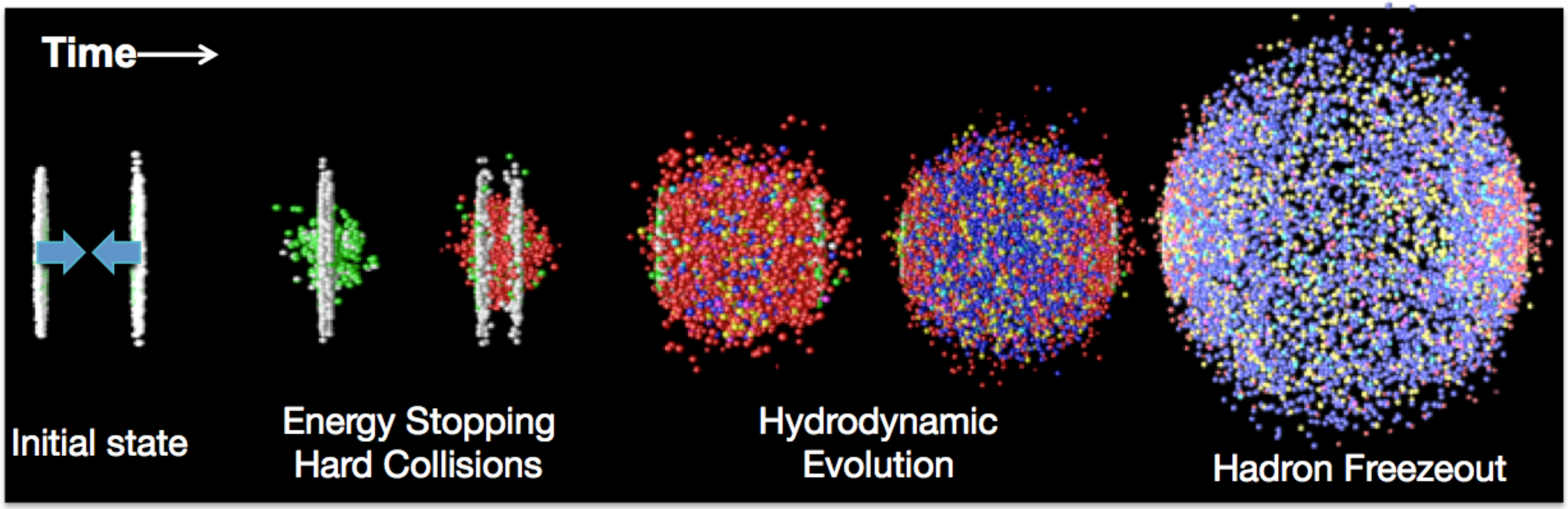

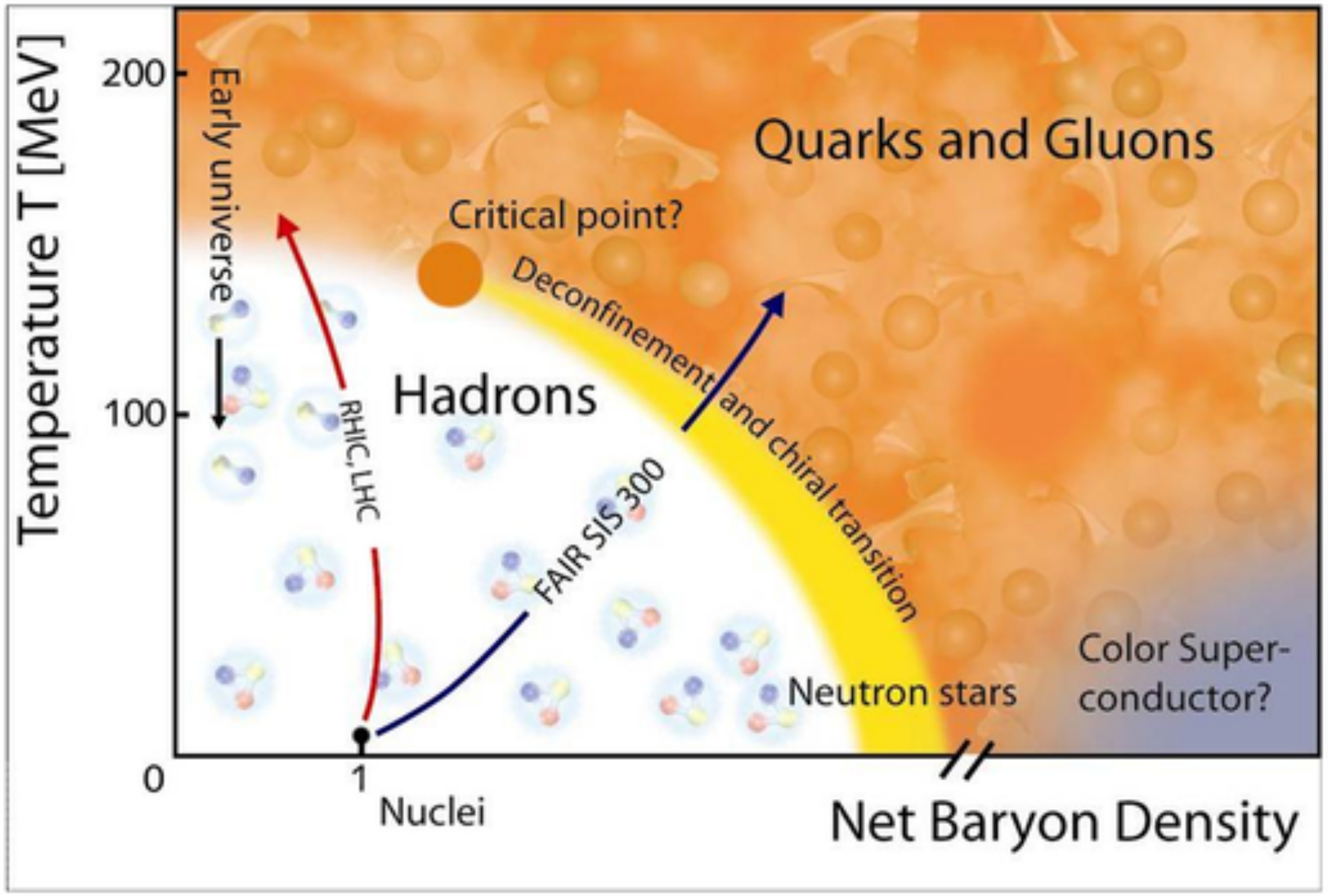

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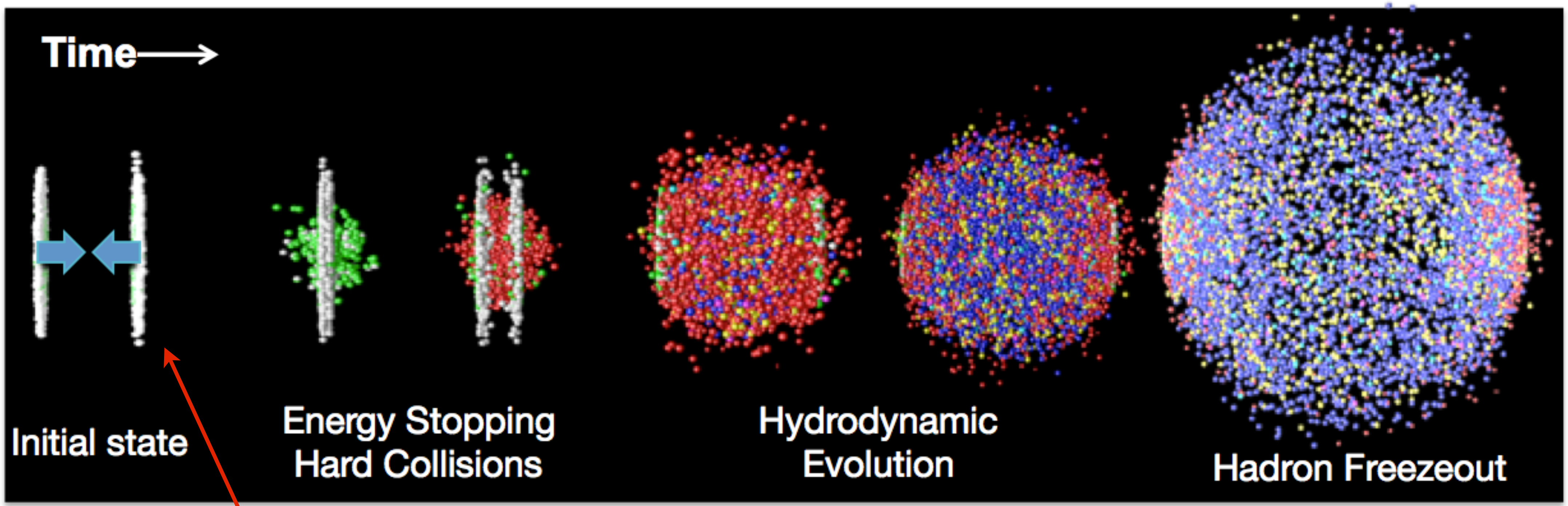

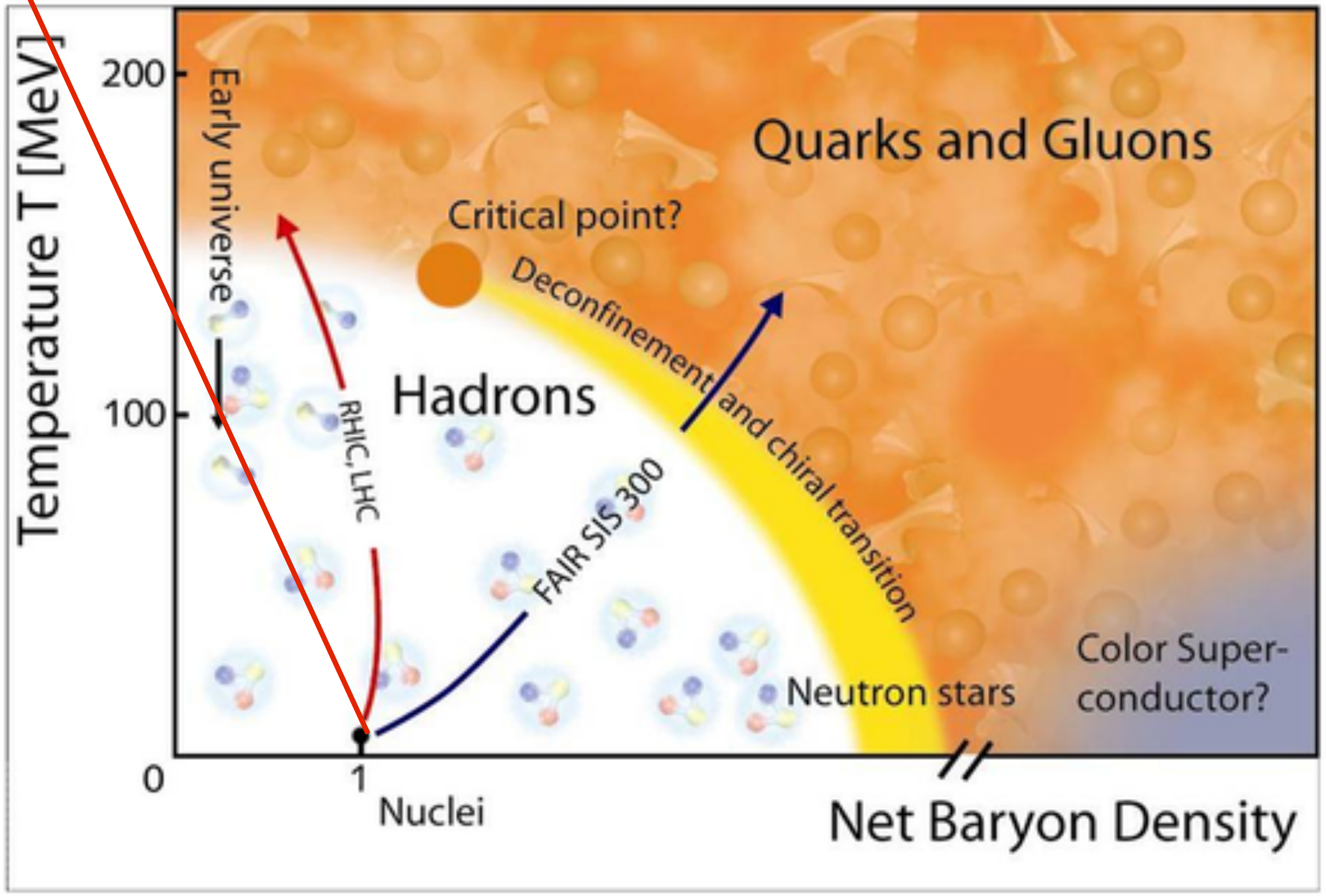

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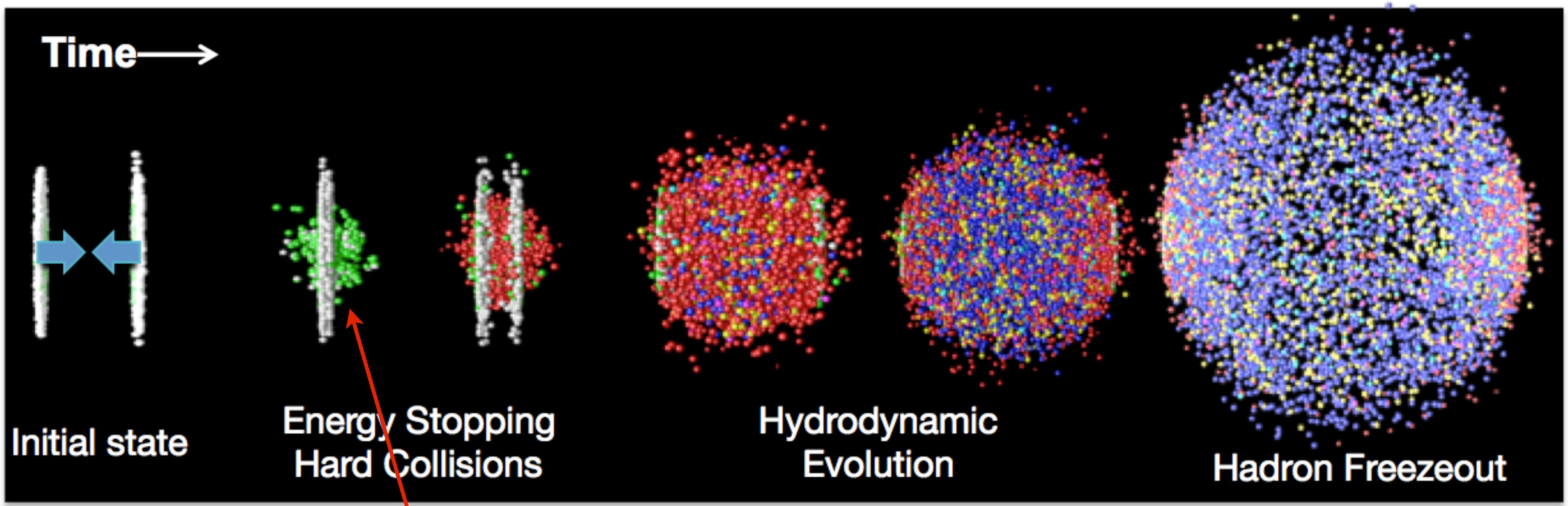
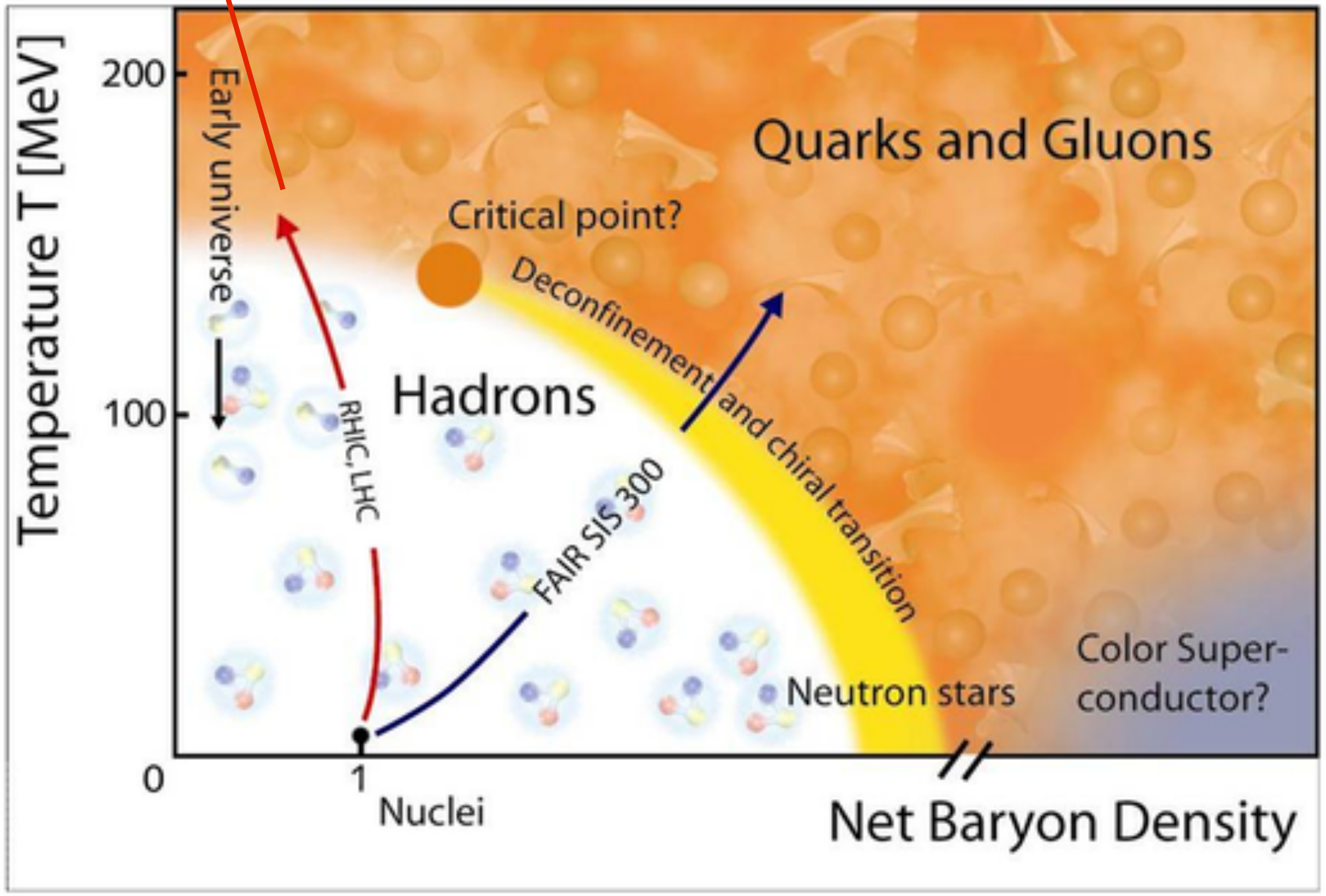


hard scattering



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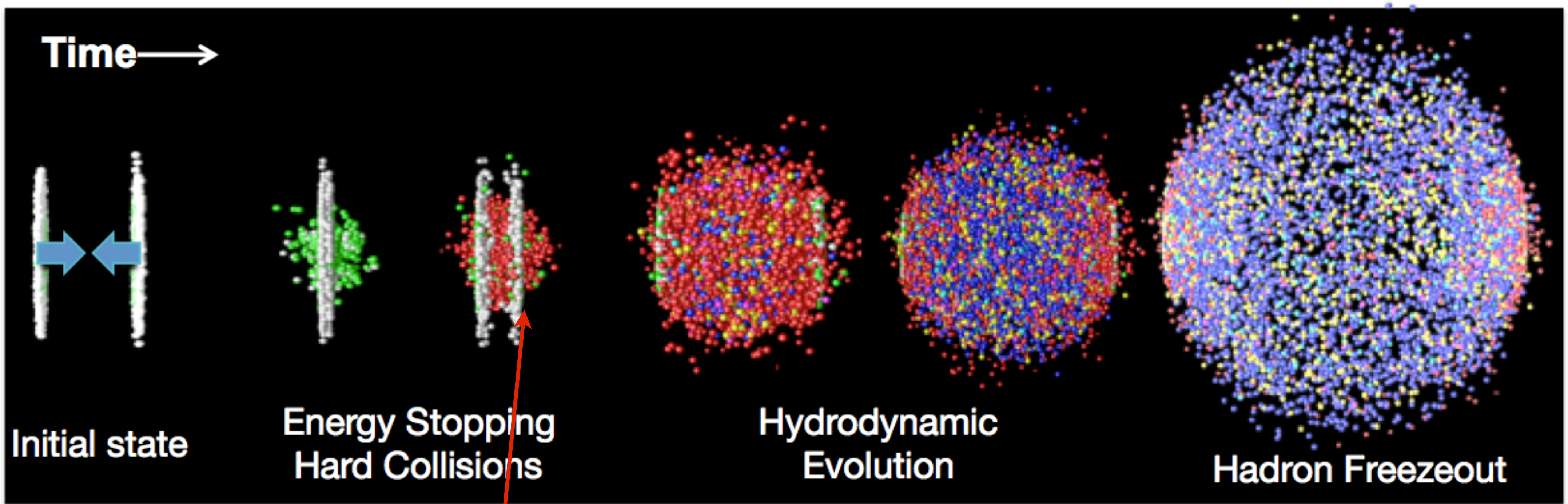
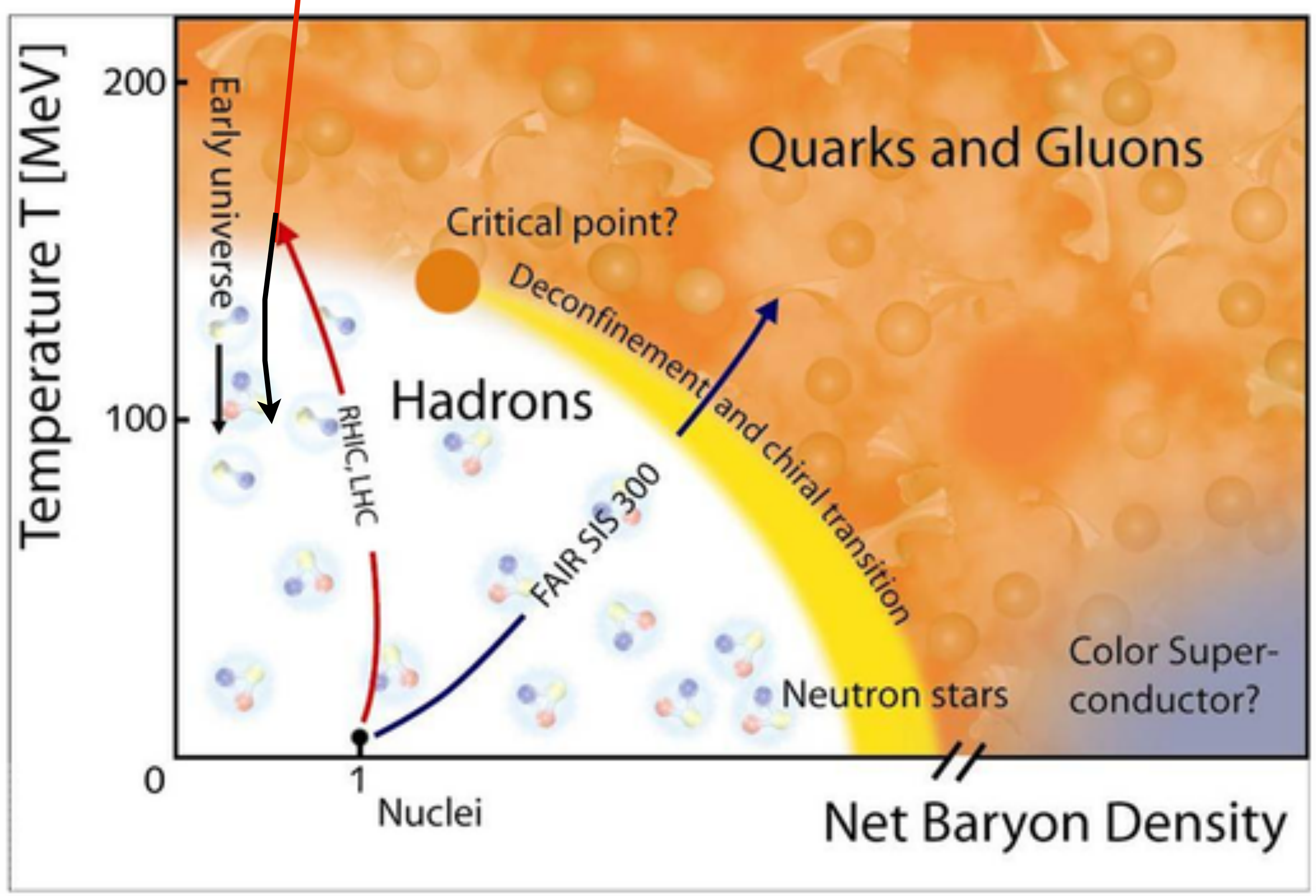


hard scattering

thermalization



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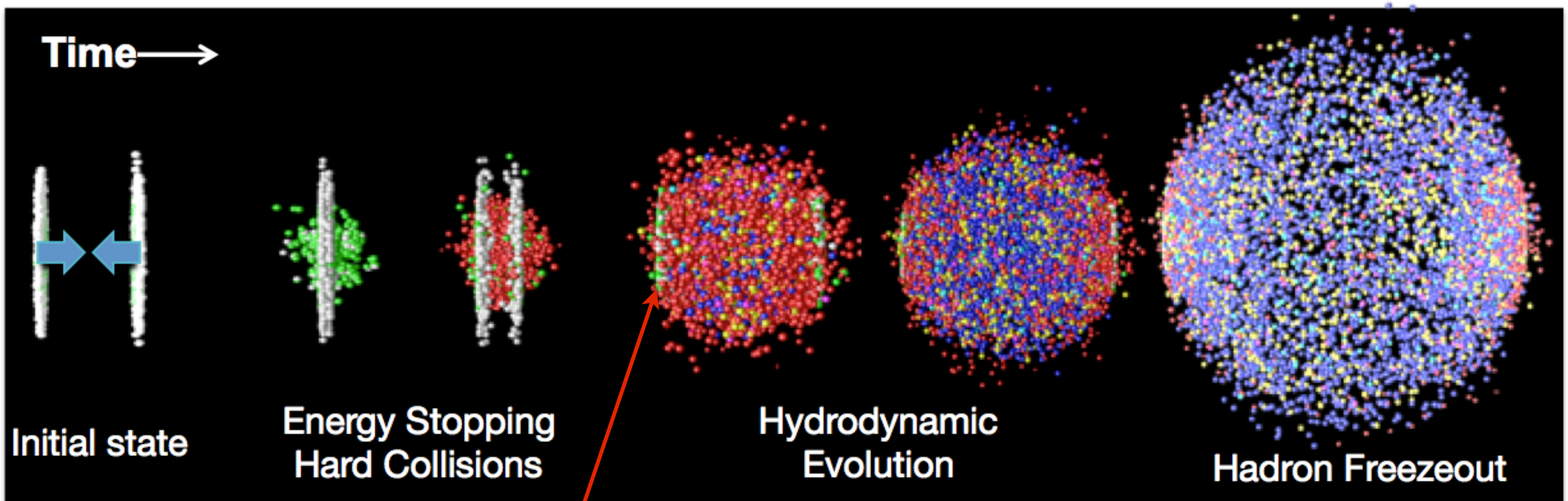

hard scattering

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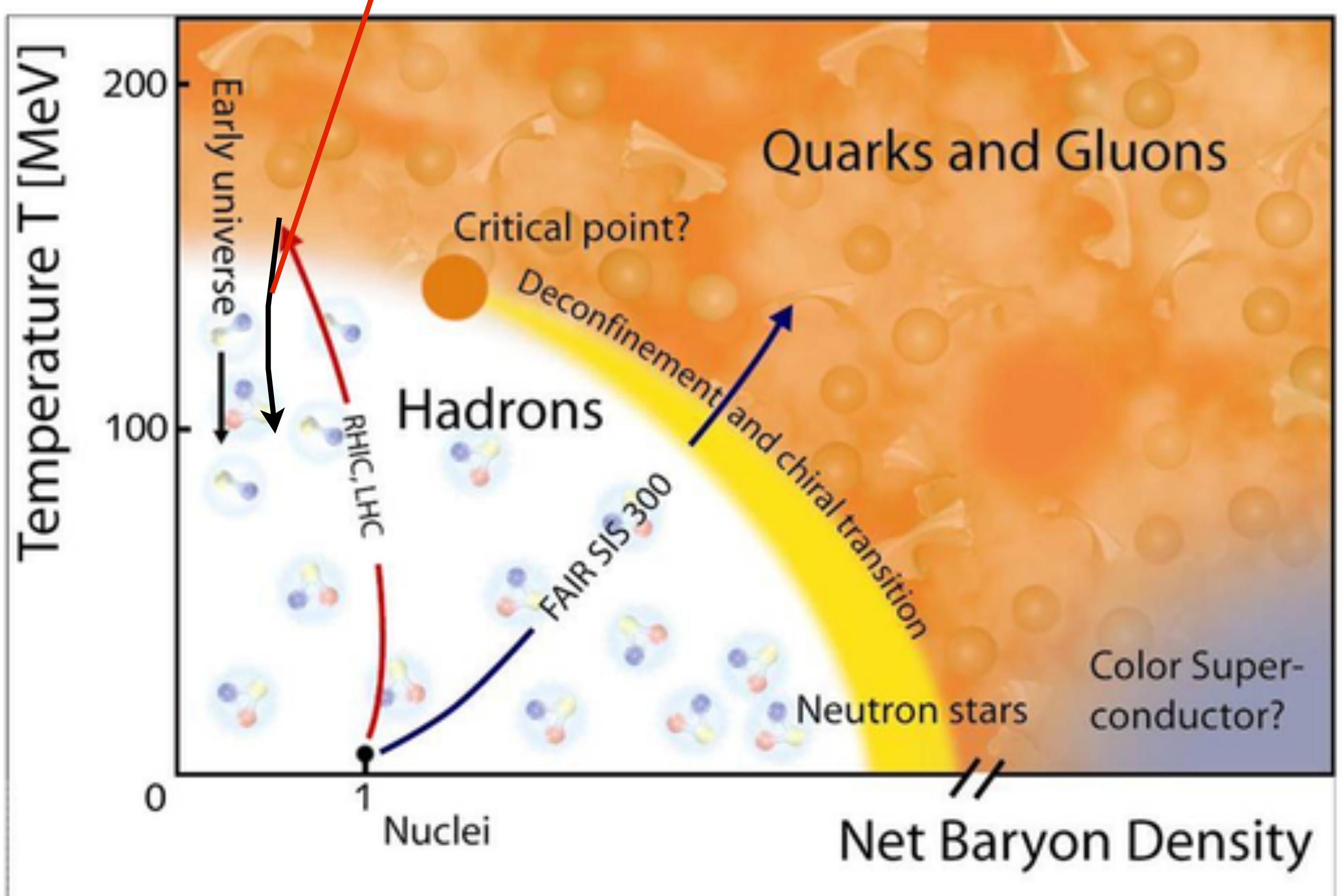
hydrodynamic flow



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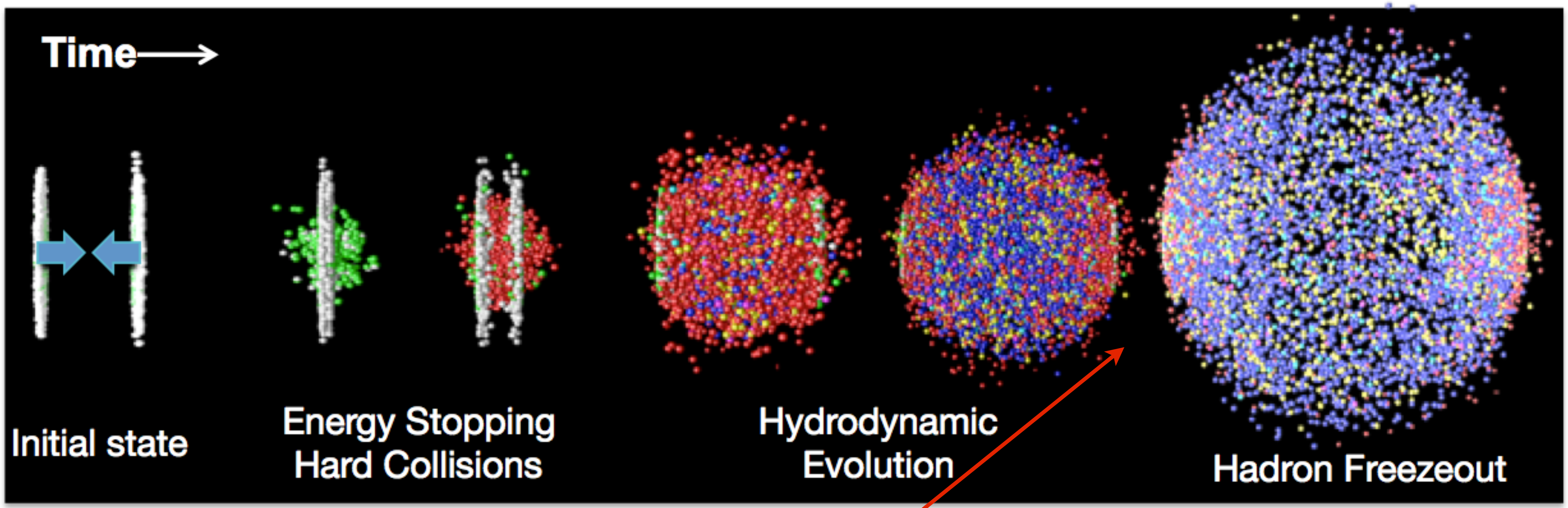

hard scattering

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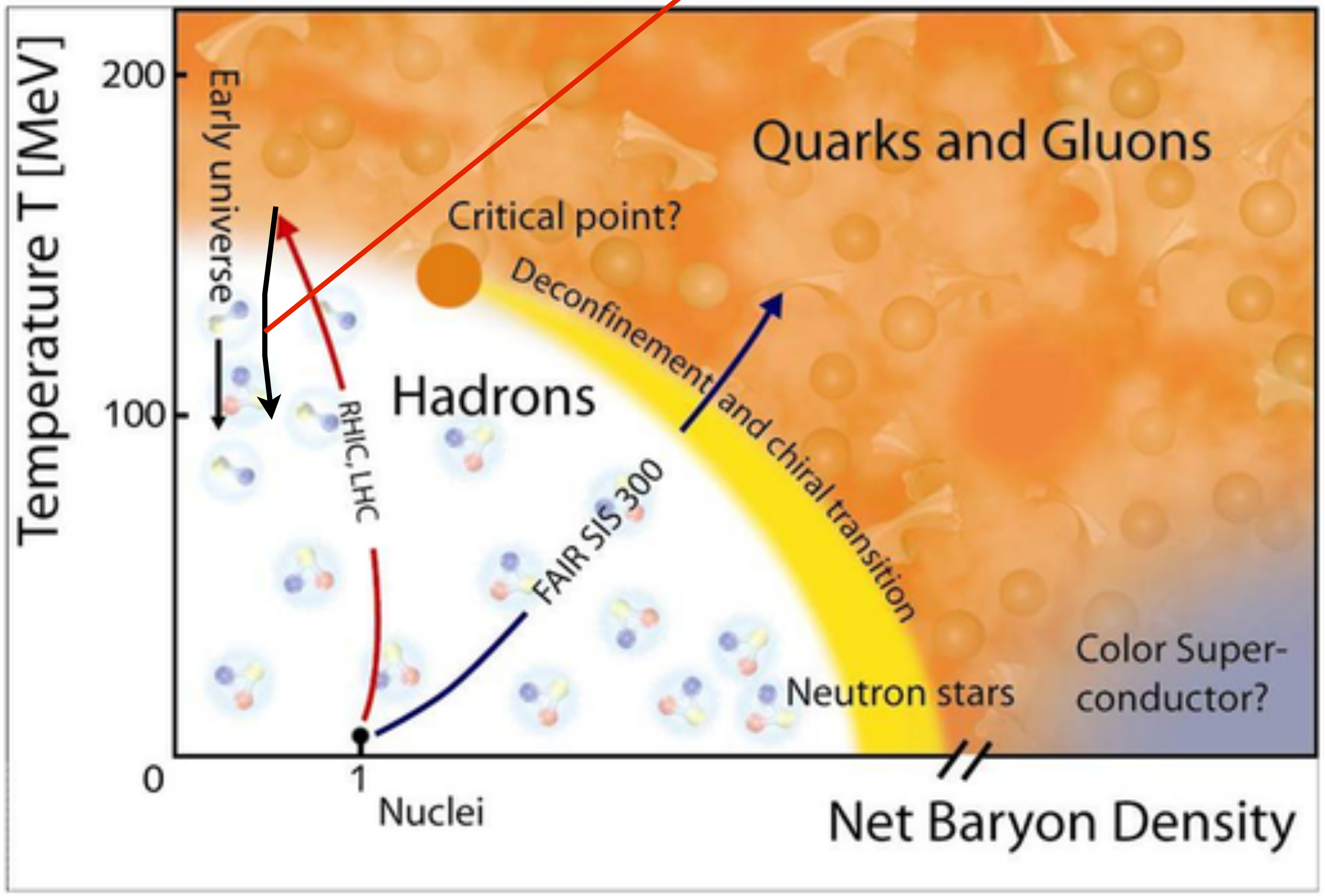

chemical
freezeout
(particle ratios)

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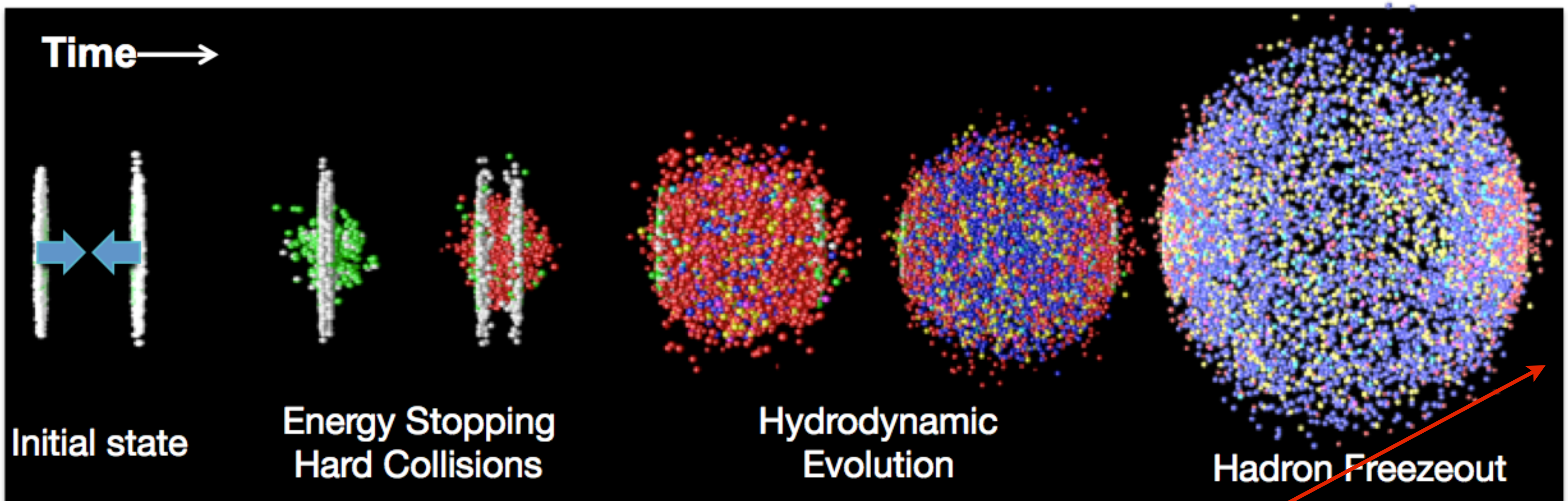

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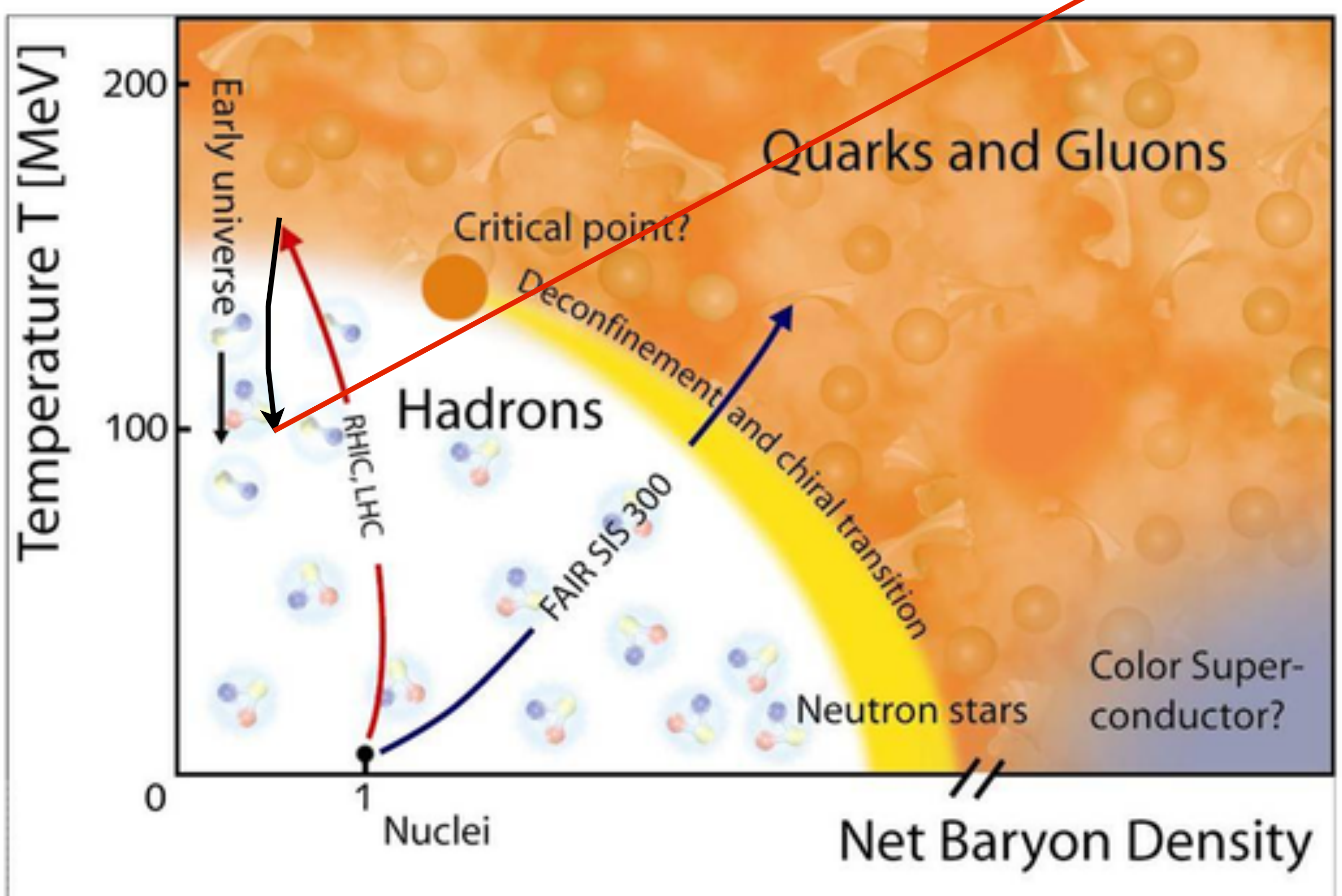
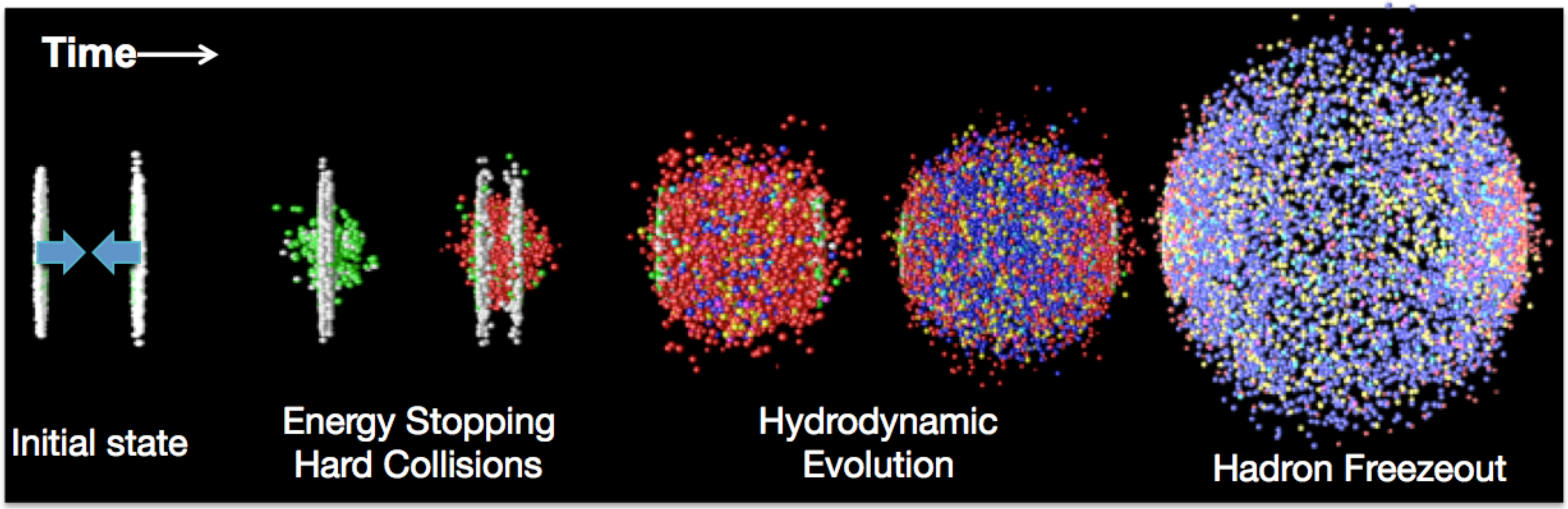


chemical freezeout
(particle ratios)

kinetic freezeout
(momentum distribution)

Fireball expansion: the "standard model"



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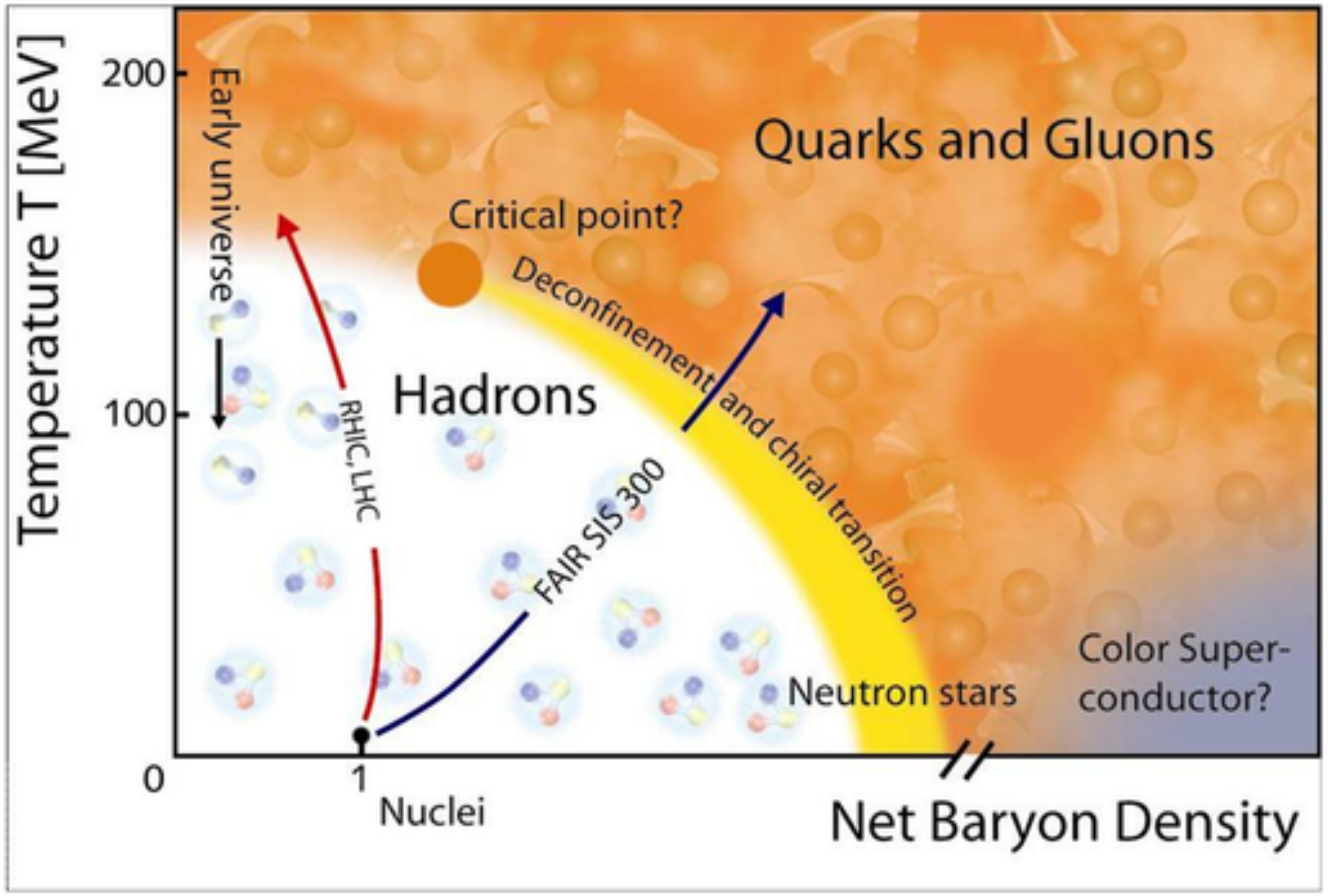

chemical freezeout
(particle ratios)

kinetic freezeout
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Fireball expansion: the “standard model”

Observable consequences:

Radial flow (p_T distributions)

Elliptic flow (azimuthal asymmetry)

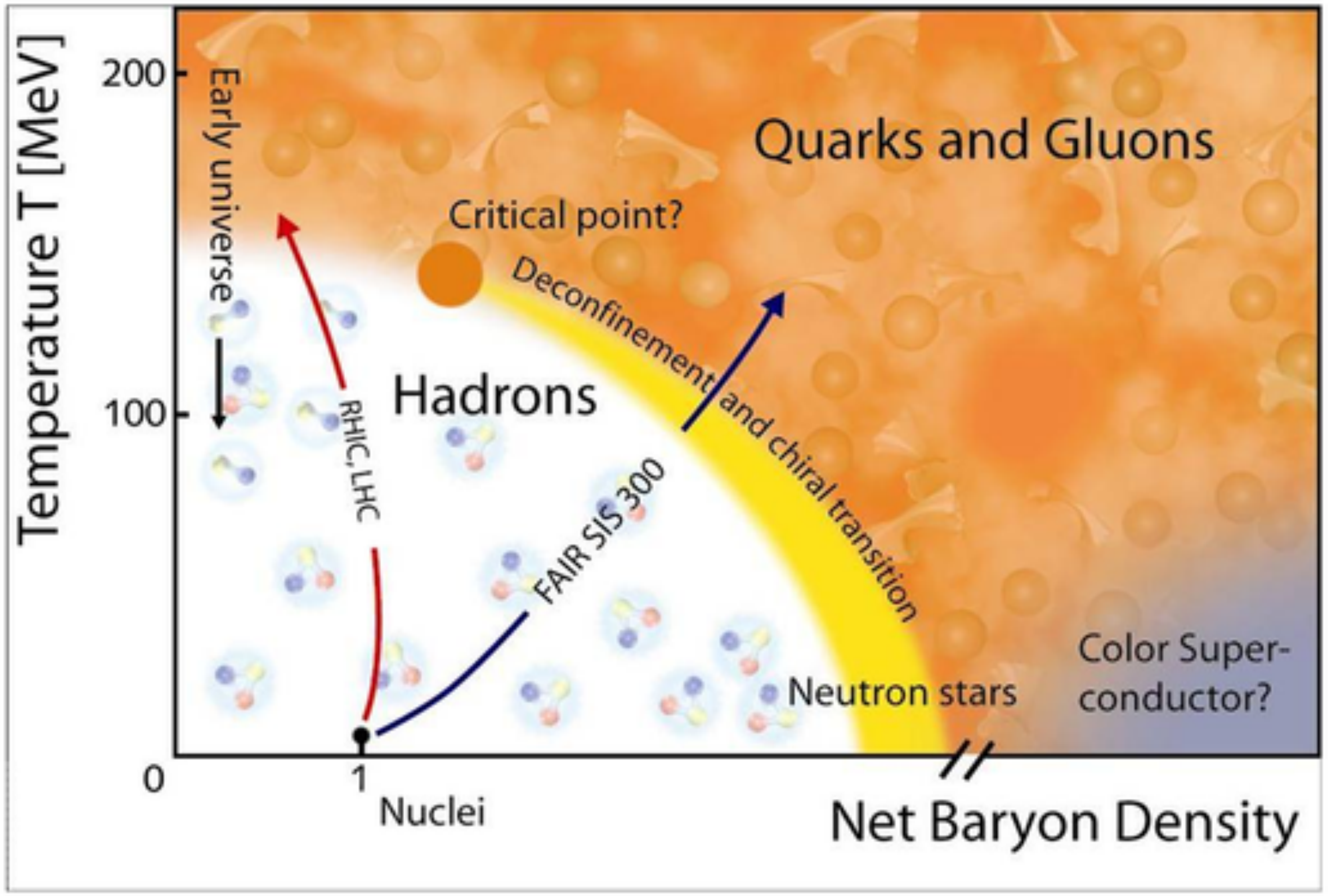
Chemical equilibrium (particle abundances)

Hadronization mechanism / recombination

hard scattering

thermalization

hydrodynamic flow



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