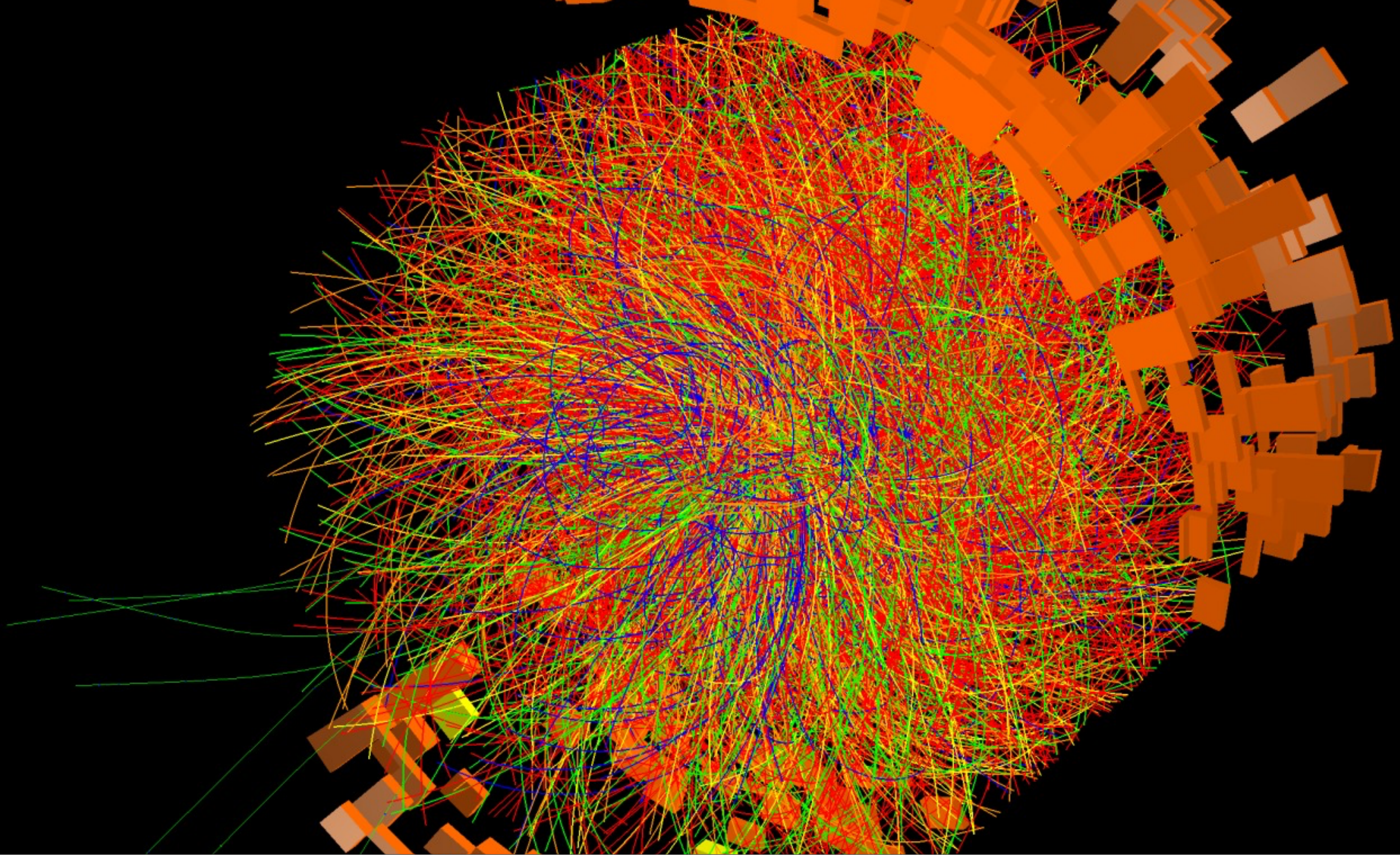


Highlights from the ALICE experiment

and why this is not (only) a heavy-ion talk

Michele Floris (CERN)

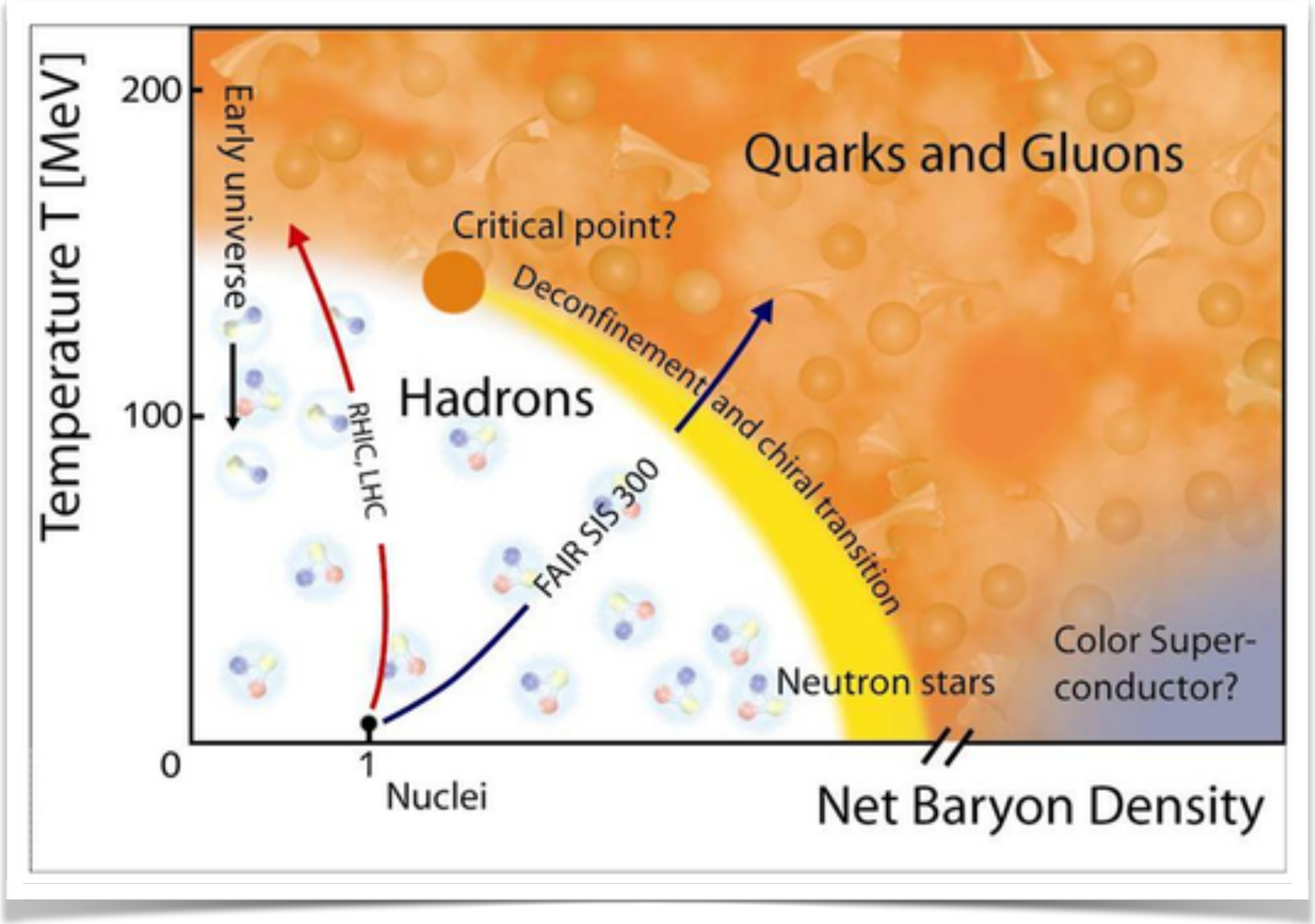
EPS-HEP, Venice

July 12, 2017

Heavy-Ion Physics "Standard Model"

QCD predicts **deconfined medium** at high temperature, the **Quark-Gluon Plasma** ($T_c \simeq 155$ MeV)

Heavy Ions: study the **QCD phase diagram** in the laboratory, create and **characterize the QGP**



Basic idea:

- Collision of Pb-Pb nuclei creates the conditions for the phase transition
- The system gets close to thermal equilibrium and expands collectively
- Expansion ⇒ cool-down: transition to hadrons

Current research

- Precise measurement of macroscopic properties
- Understanding microscopic fabric of QGP

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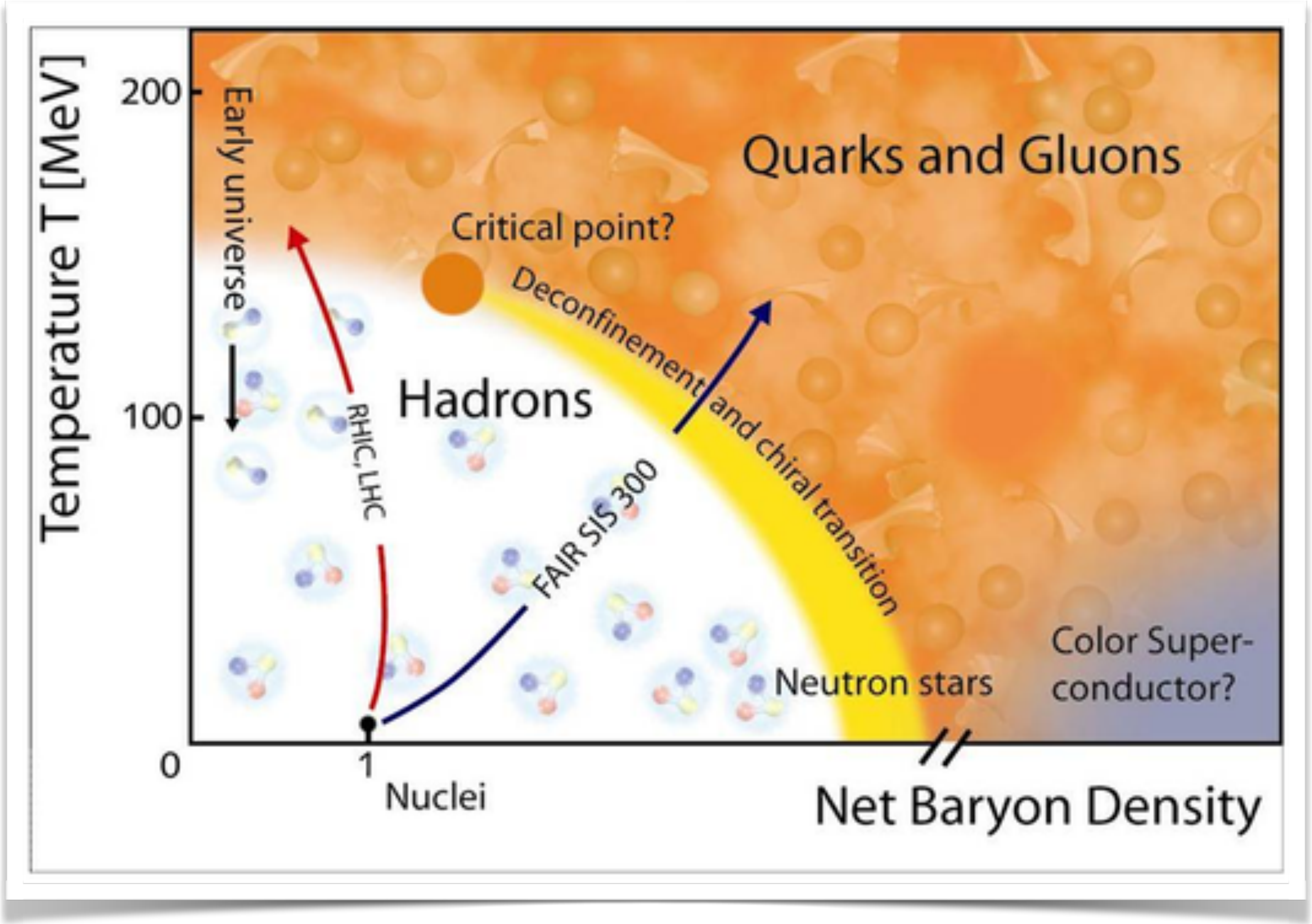

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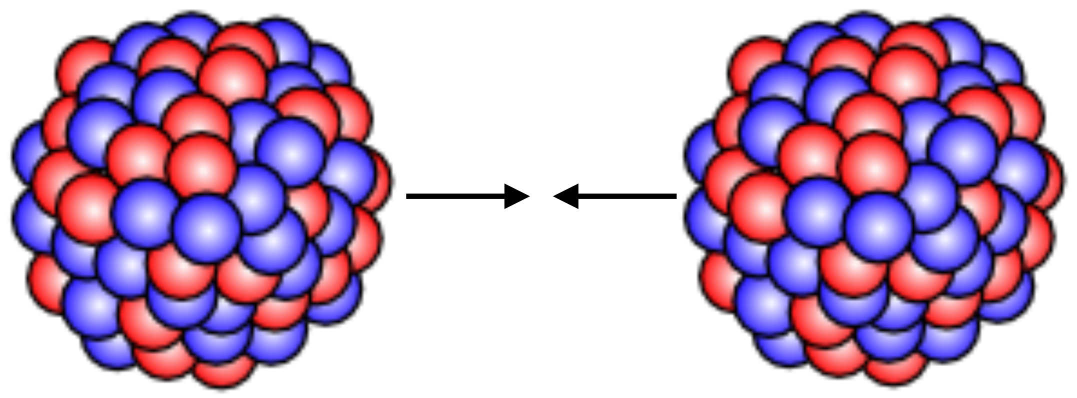
Supported by 3 decades of measurements and theoretical research! *[J. Stachel, today]*

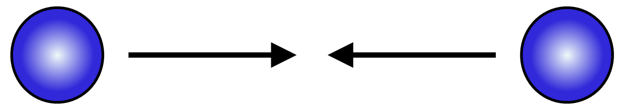
New challenges and **opportunities** from recent results in pp and p–Pb

The Paradigm



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

- Core business: create and characterize the QGP



pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

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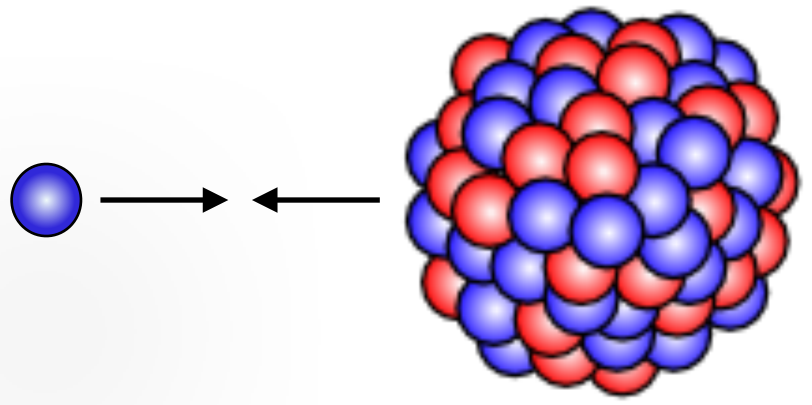
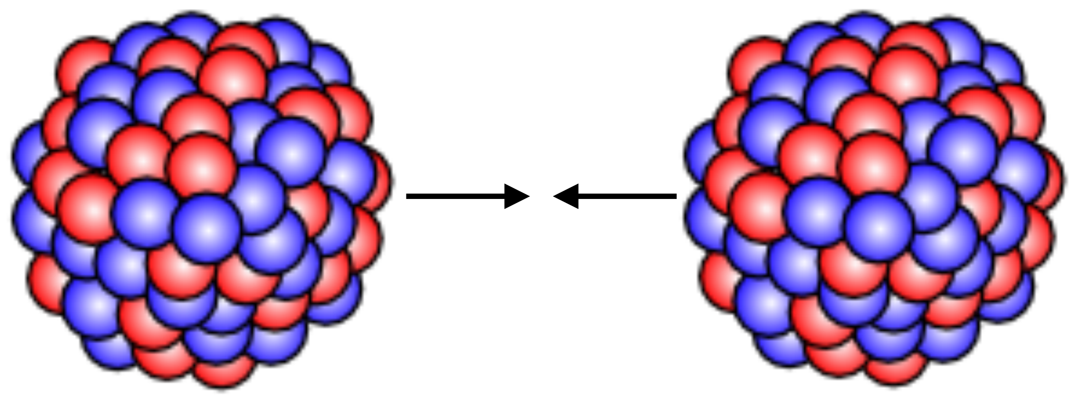


p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

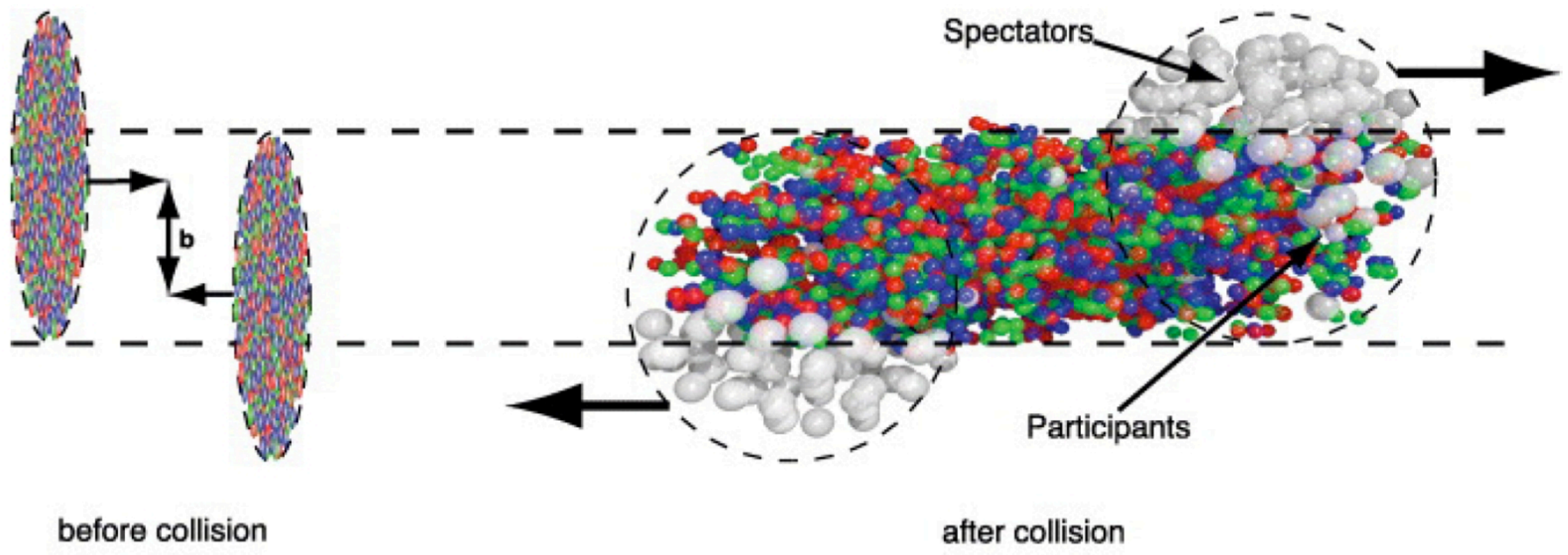
- Control experiment
- “Cold nuclear matter” effects (e.g. modifications to PDF)

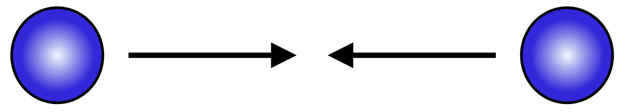
The Paradigm



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

- Core business: create and characterize the QGP
- Centrality





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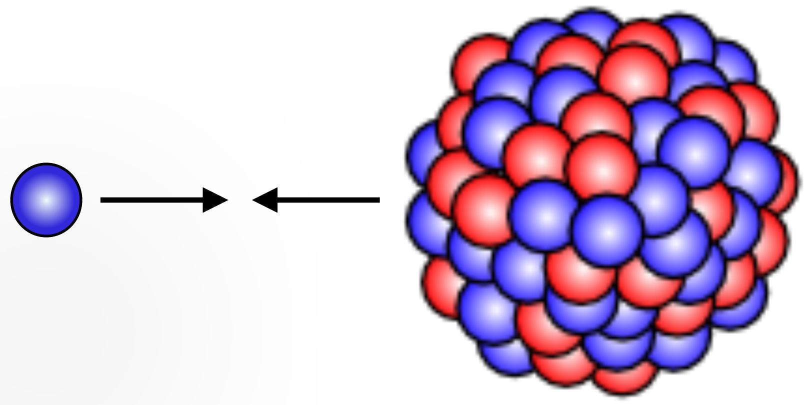

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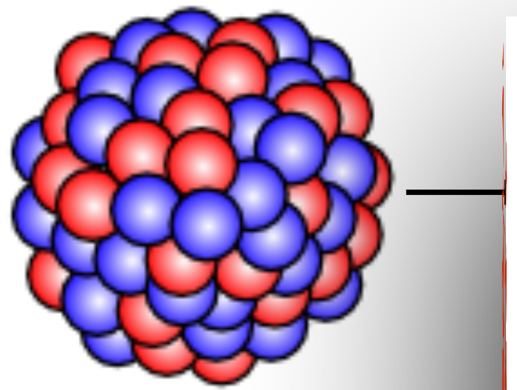
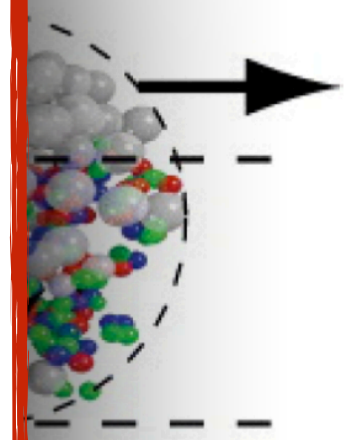
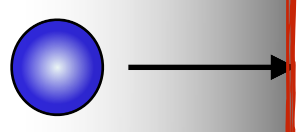


e QGP

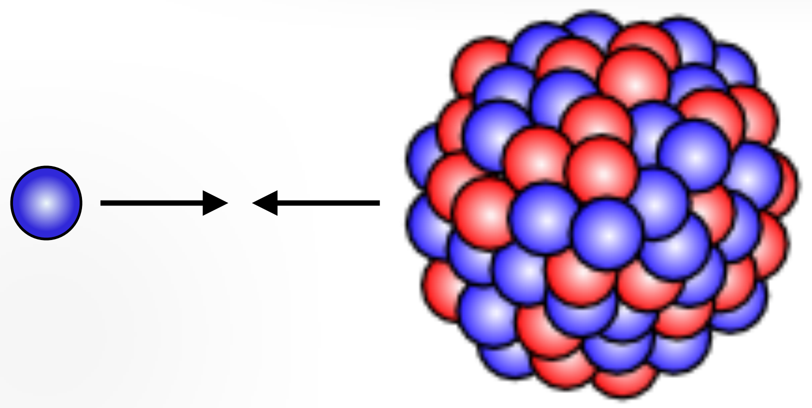




Towards a paradigm shift!

Striking **similarities** between pp/p–Pb/Pb–Pb
Phenomena considered **hallmarks of heavy-ions** seen **in smaller systems**
(discovered in high multiplicity events, seem to be relevant also for minimum-bias events)

⇒ Important consequences for the **interpretation of all hadronic collisions**!



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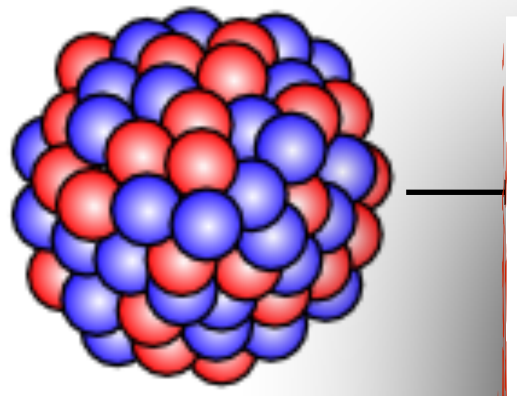

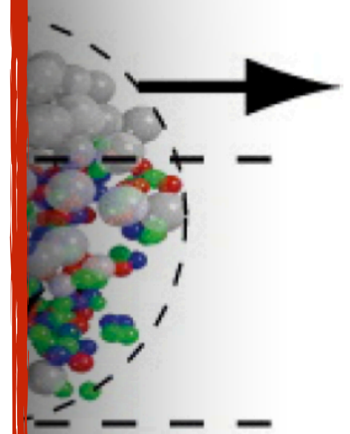

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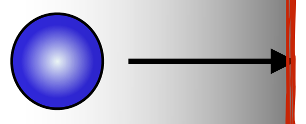
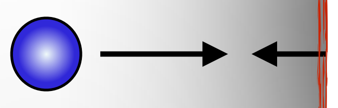


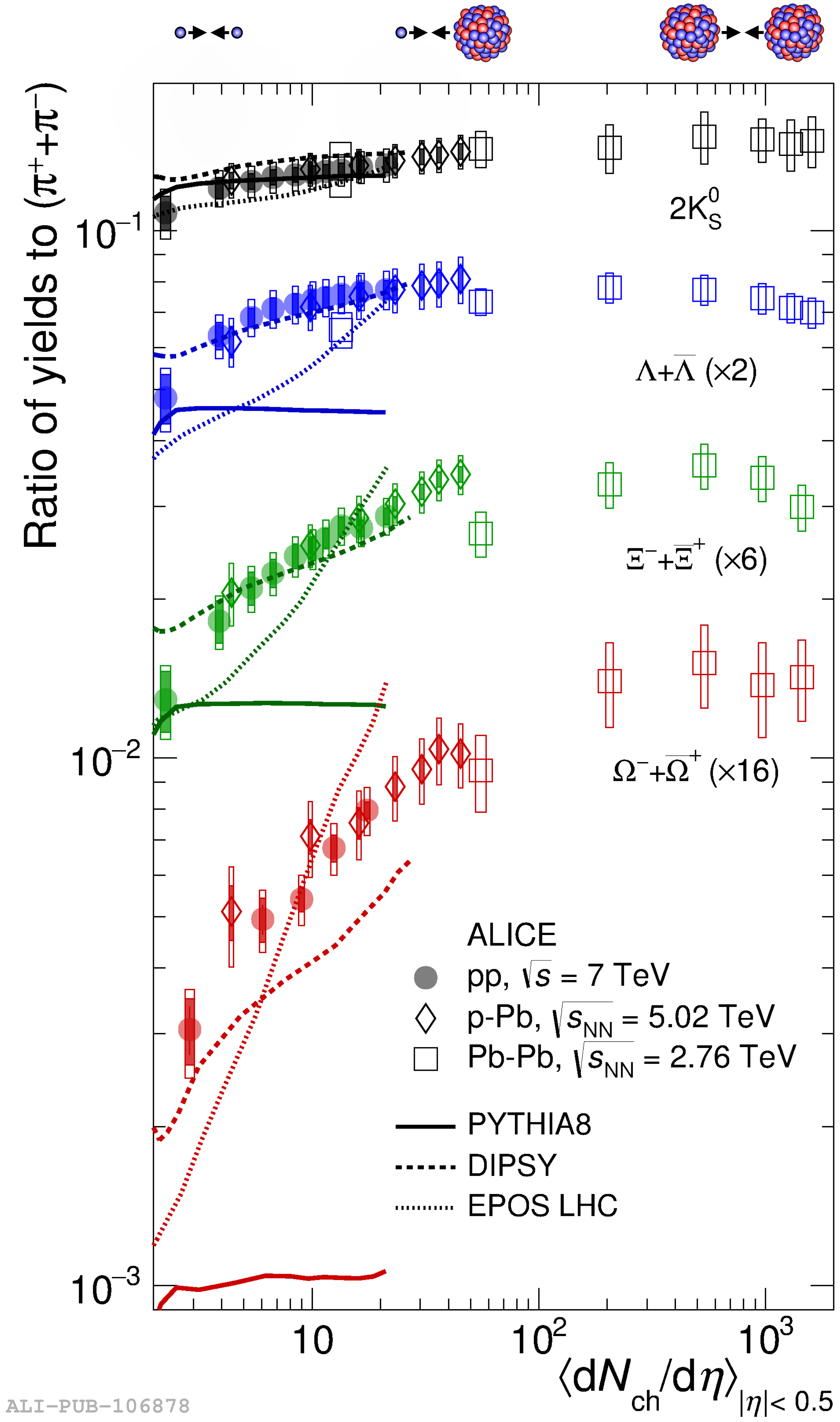
This is a talk about **multiparticle production** in
hadronic collisions
and **emergent properties of QCD**



(e.g. modifications to PDF)

Hadronization, particle spectra and abundances

Strangeness Enhancement



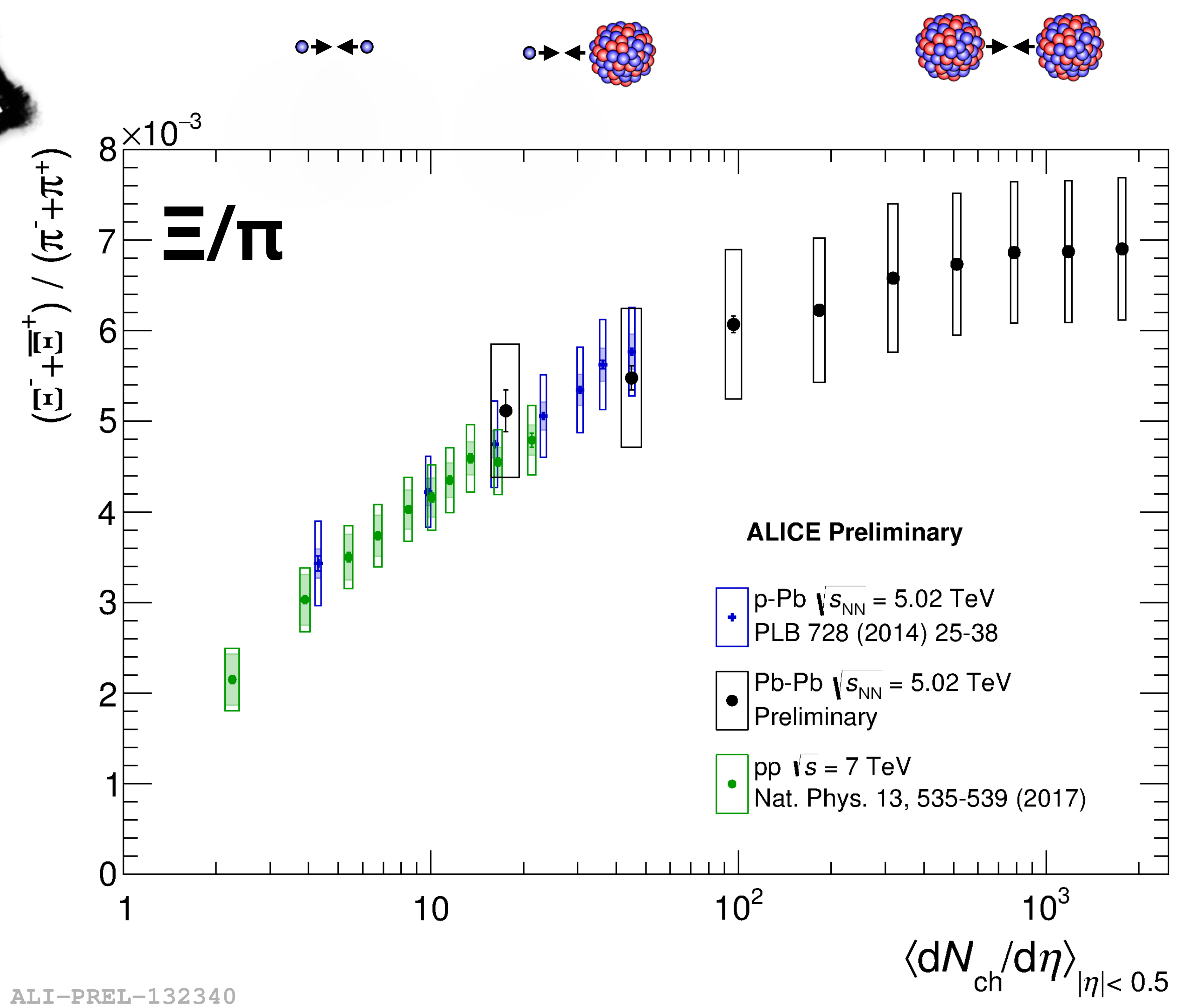
Nature Phys. 13 (2017) 535-539

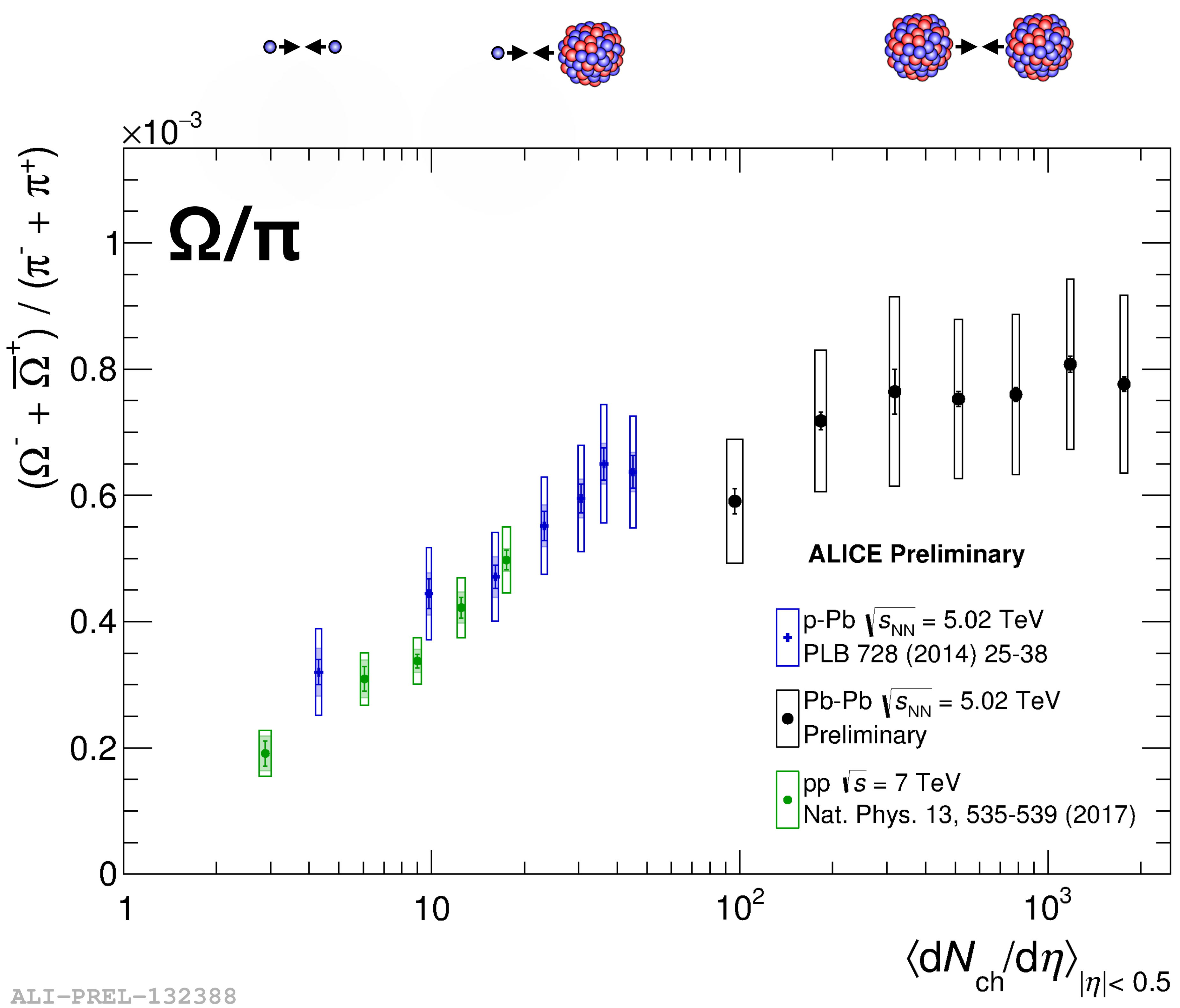
- **Smooth evolution** of particle ratios with multiplicity
- **Strangeness enhancement** considered defining feature of heavy-ions
  - Now also seen in high-multiplicity pp / p–Pb!
- Not reproduced by traditional **soft QCD models** (e.g. Pythia)
  - Challenges **universality** and **factorization** of fragmentation Fischer, Sjostrand, JHEP01(2017)140
  - Study of **hadronization mechanisms**
- **Multiple Parton Interactions** lead to densely packed strings in the transverse plane (e.g. EPOS and DIPSY)

[G. Bencedi, 6/7 9:00]

Strange particles in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

NEW!





New results on strange particle production in **Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV**

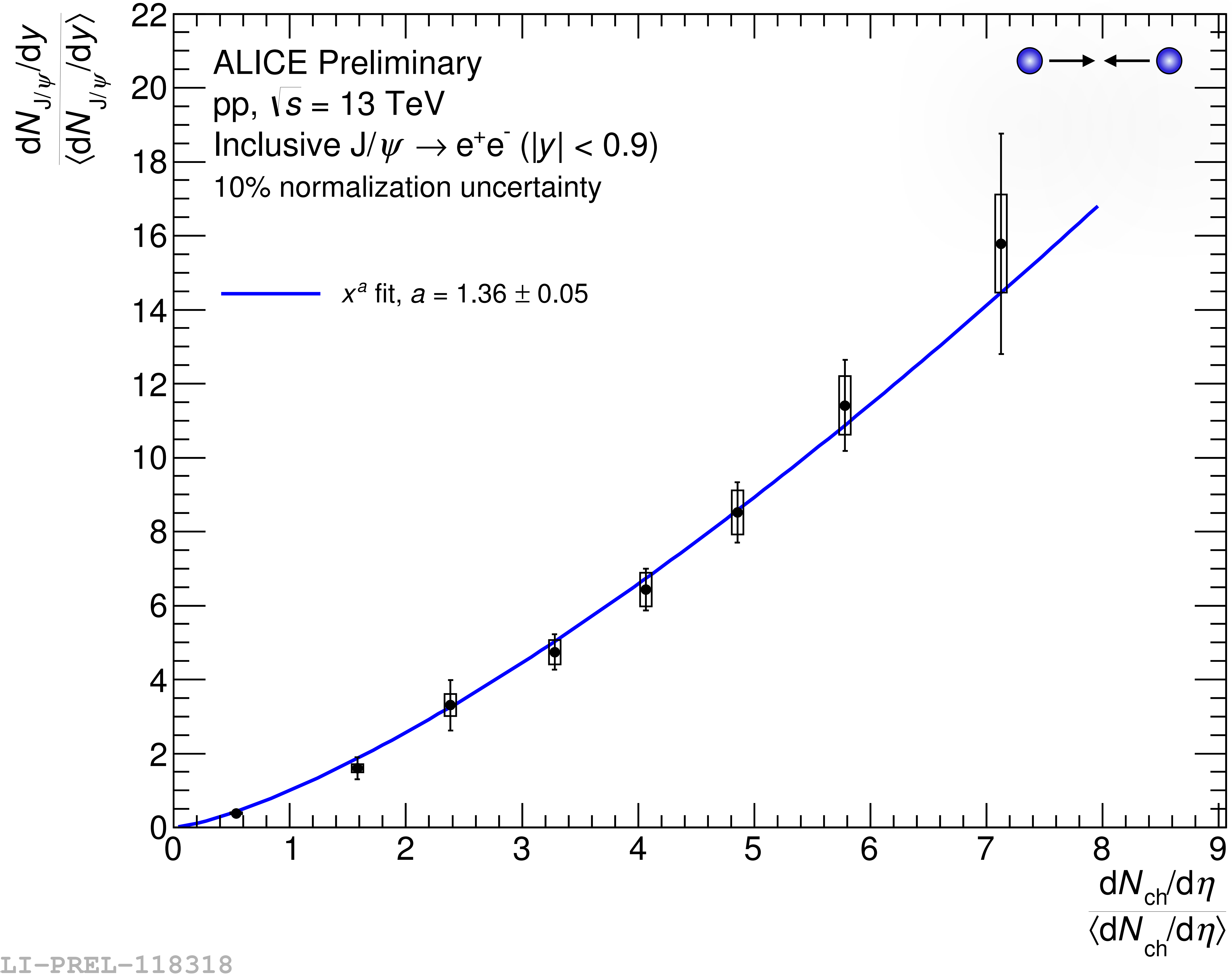
In Pb–Pb, hadrons produced in apparent (near) **thermal and chemical equilibrium**:

d*N*/dy(m) ≃ $e^{-m/T}$ (+ conservation laws, feed down, degeneracy)

Same language used successfully in some **pp models** (e.g. EPOS)

Shed light on **dynamic origin** of **equilibrium**? Will **pp ratios** converge to **Pb-Pb values**?

[P. Kalinak, 6/7 16:45]

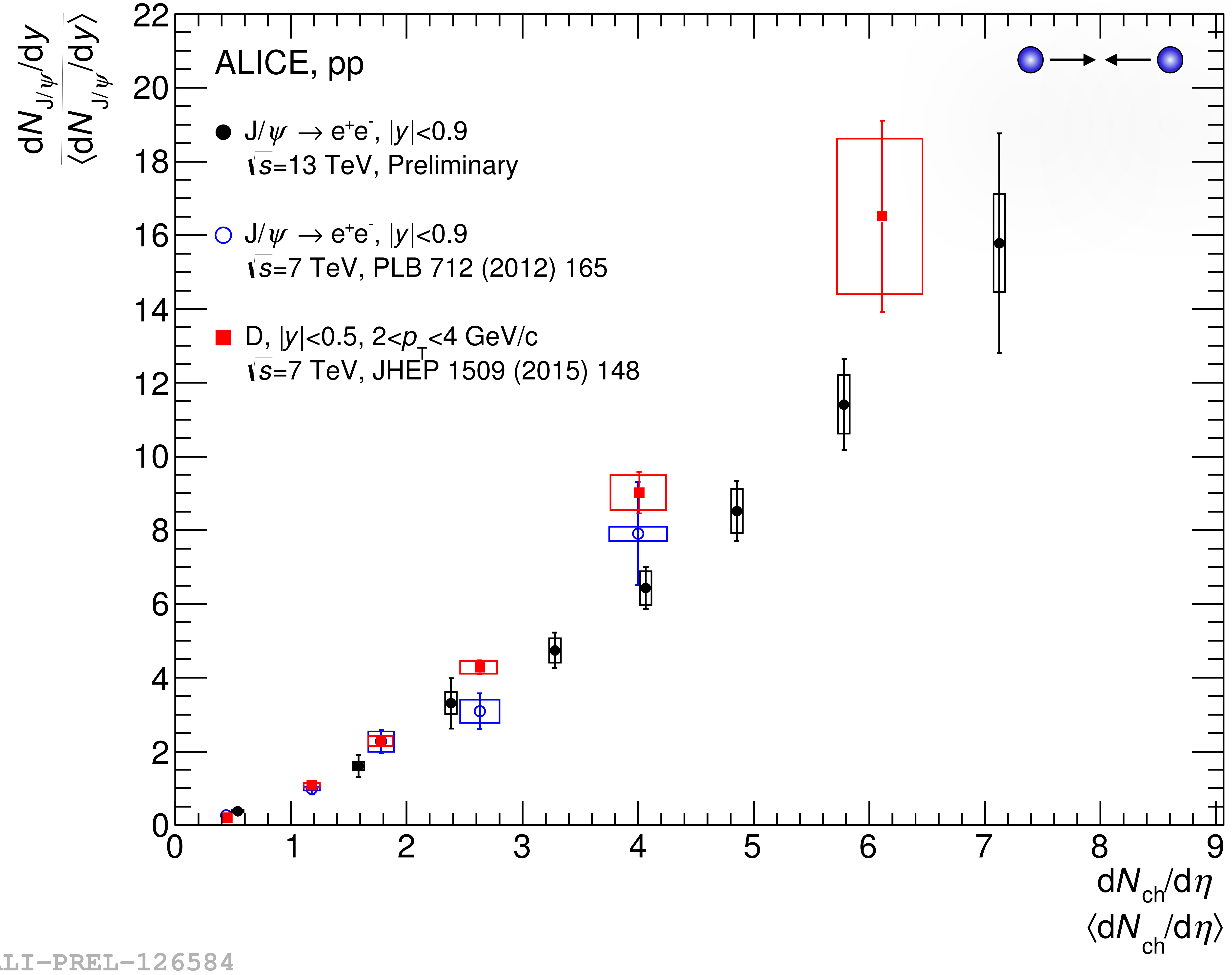


J/ψ increase with multiplicity:
multiple (semi-hard) **parton interaction (MPI)!**

Similar for *D* / J/ψ:
not affected by hadronization?

Soft/Hard interplay: evolution of the
“dense” string core vs multiplicity / MPIs

[J. Crkovska, 6/7 10:30]



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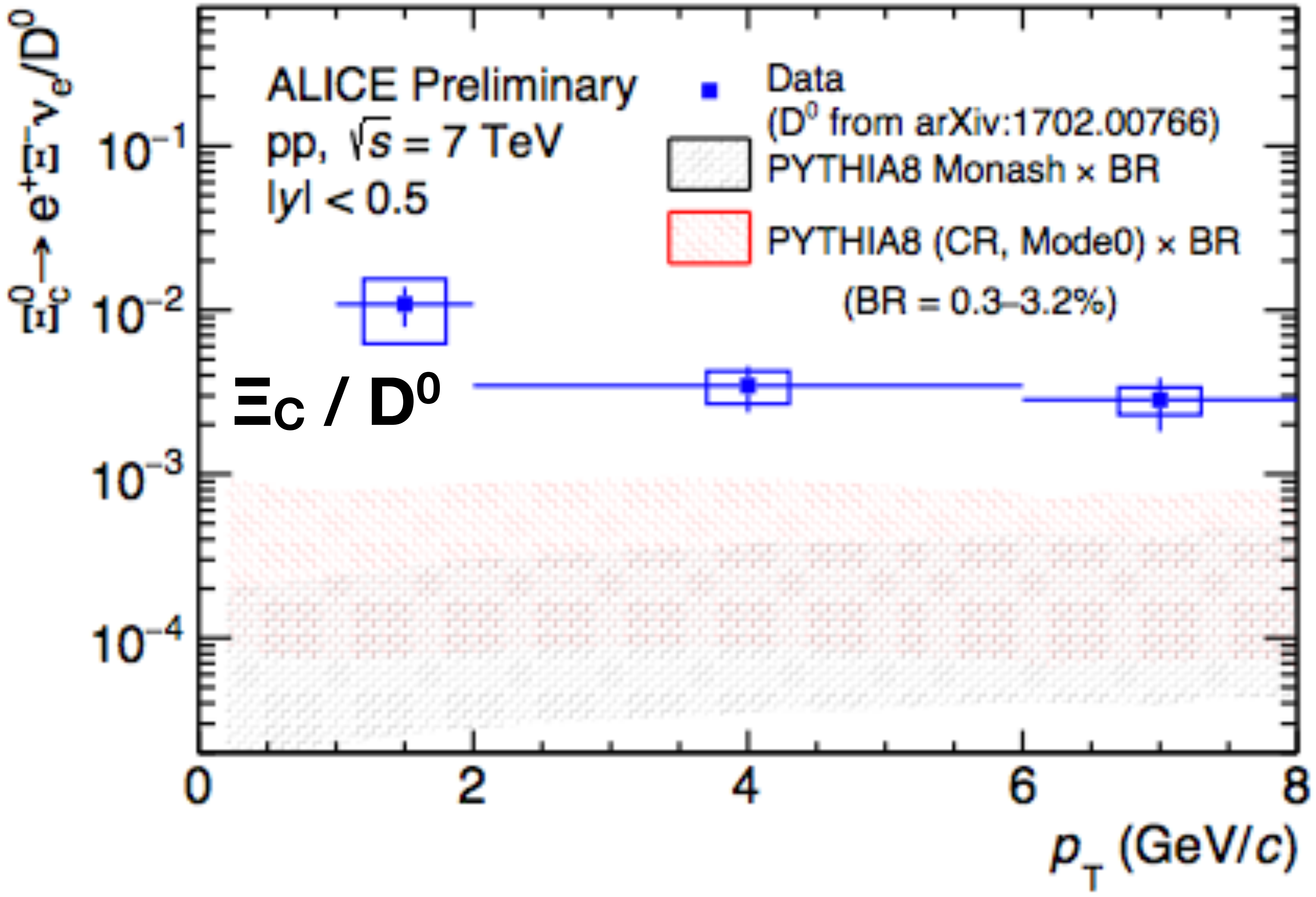
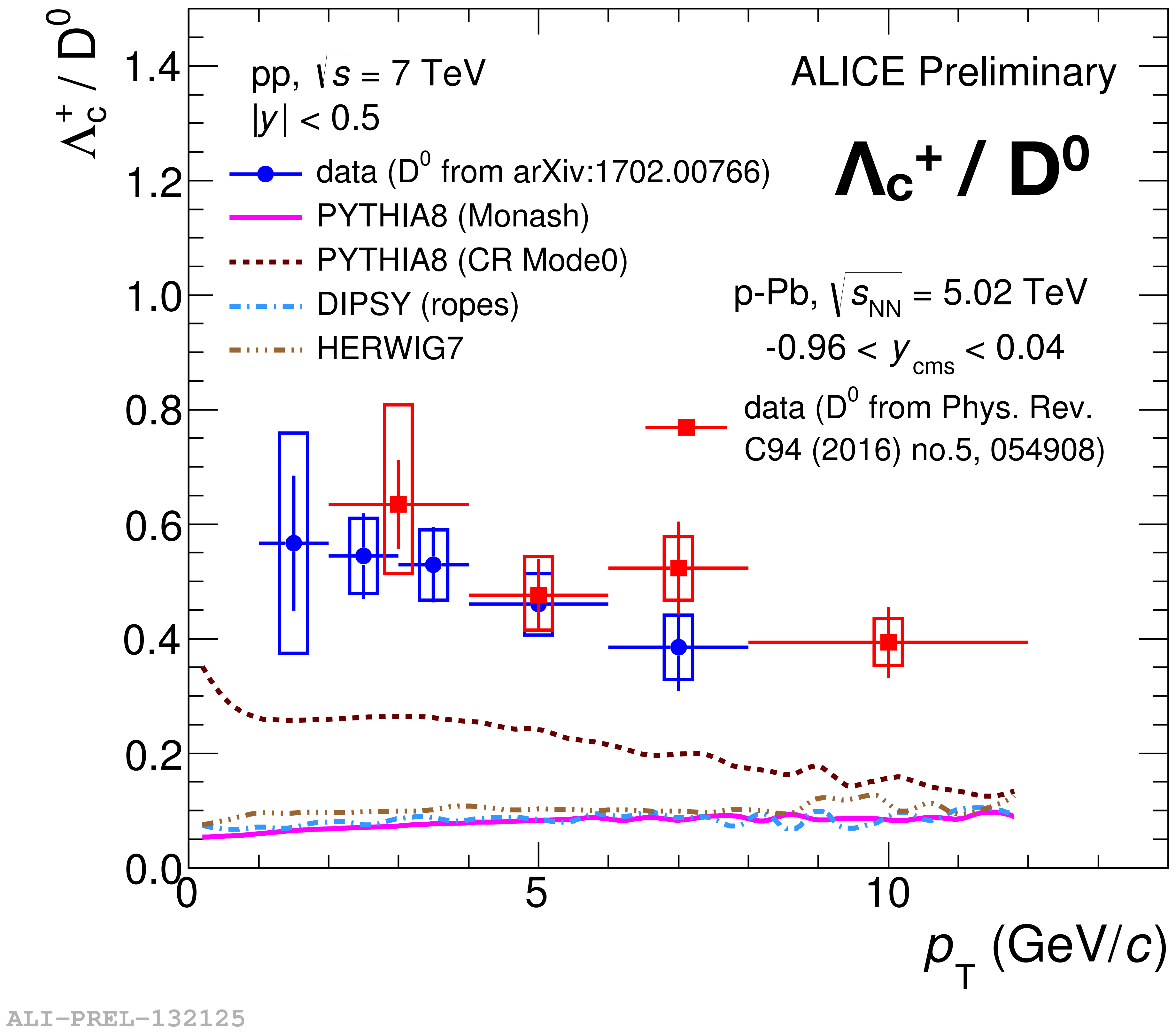
[J. Crkovska, 6/7 10:30]

First cross section **measurement** of Ξ_c^0 in **pp** and Λ_c^+ in **p-Pb** (and mid-y pp) at LHC

NEW!

Ratio of charm baryons to *D* mesons not reproduced in event generators
Important constraints on charm hadronization and nuclear effects!





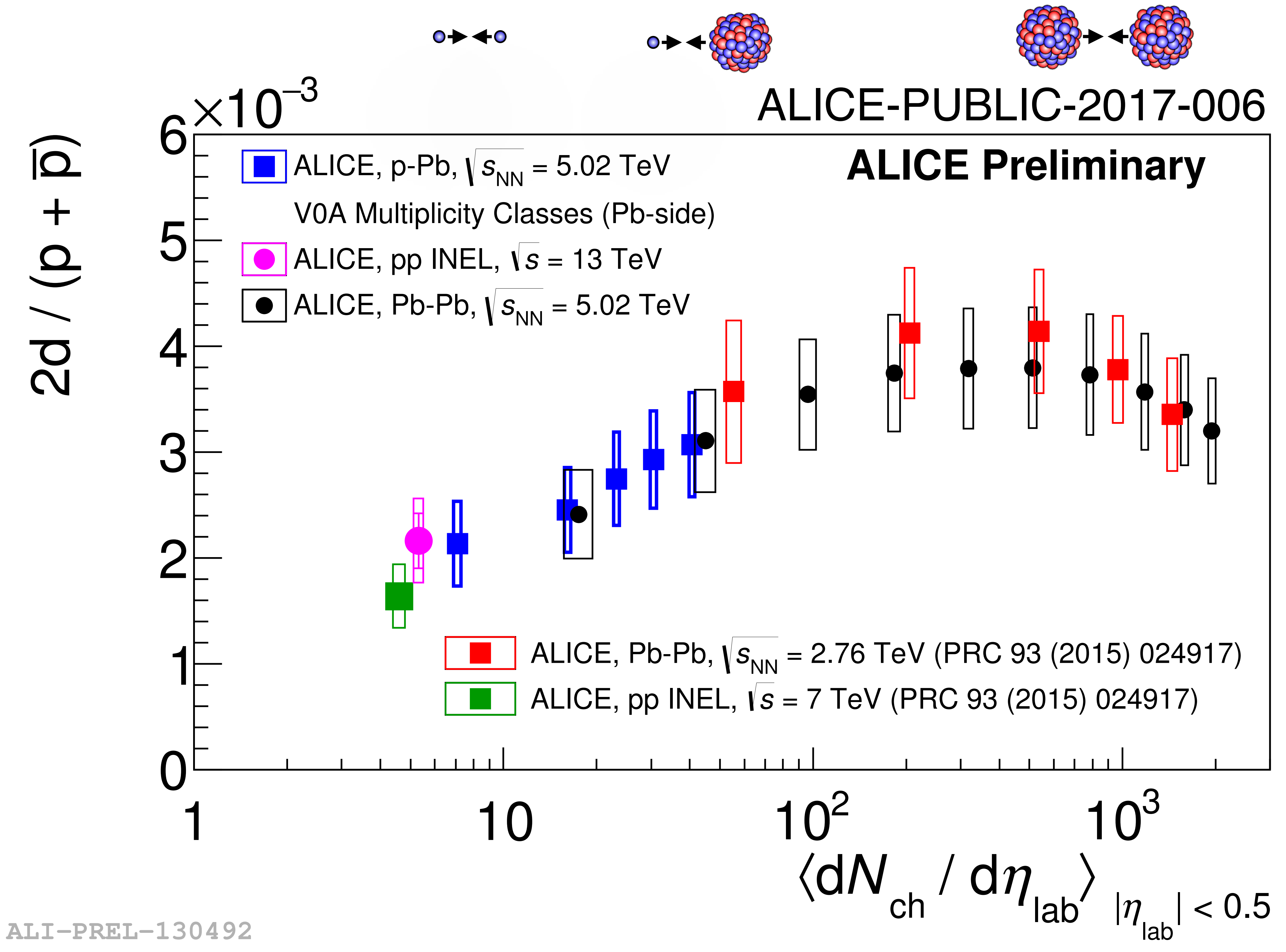
[A. De Caro, 6/7 11:45]
[C. Terrevoli, 6/7 15:45]

Nuclei Measurements

Heavy Ion collisions are also an excellent **(hyper-)nuclei factory**

Production mechanism of compound objects: coalescence vs thermal production

NEW!



Increase of **d/p vs dN/dη**

(**weakly bound** object)

Hint of non-monotonic trend

[S. Trogolo, 6/7 17:30]

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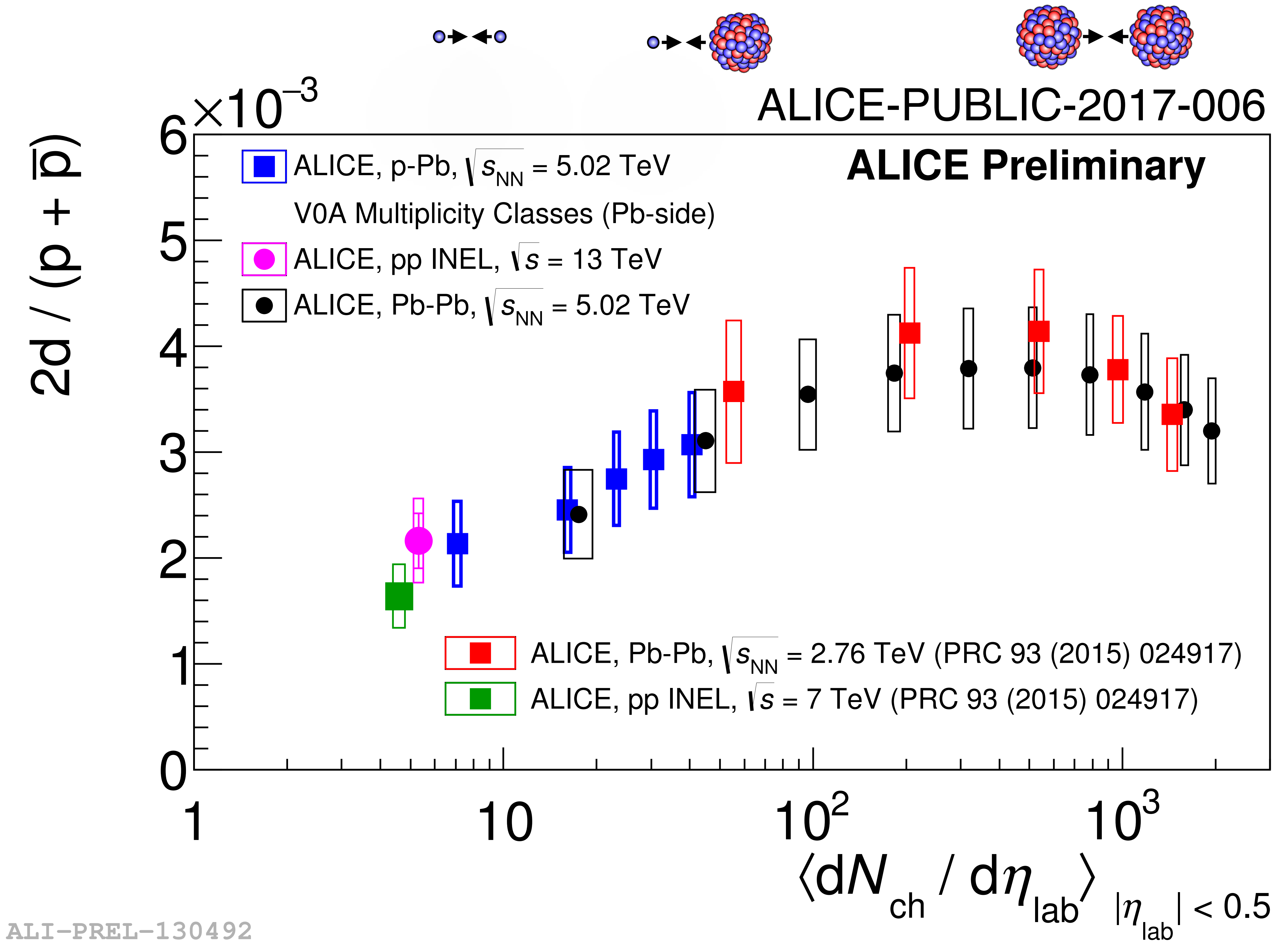

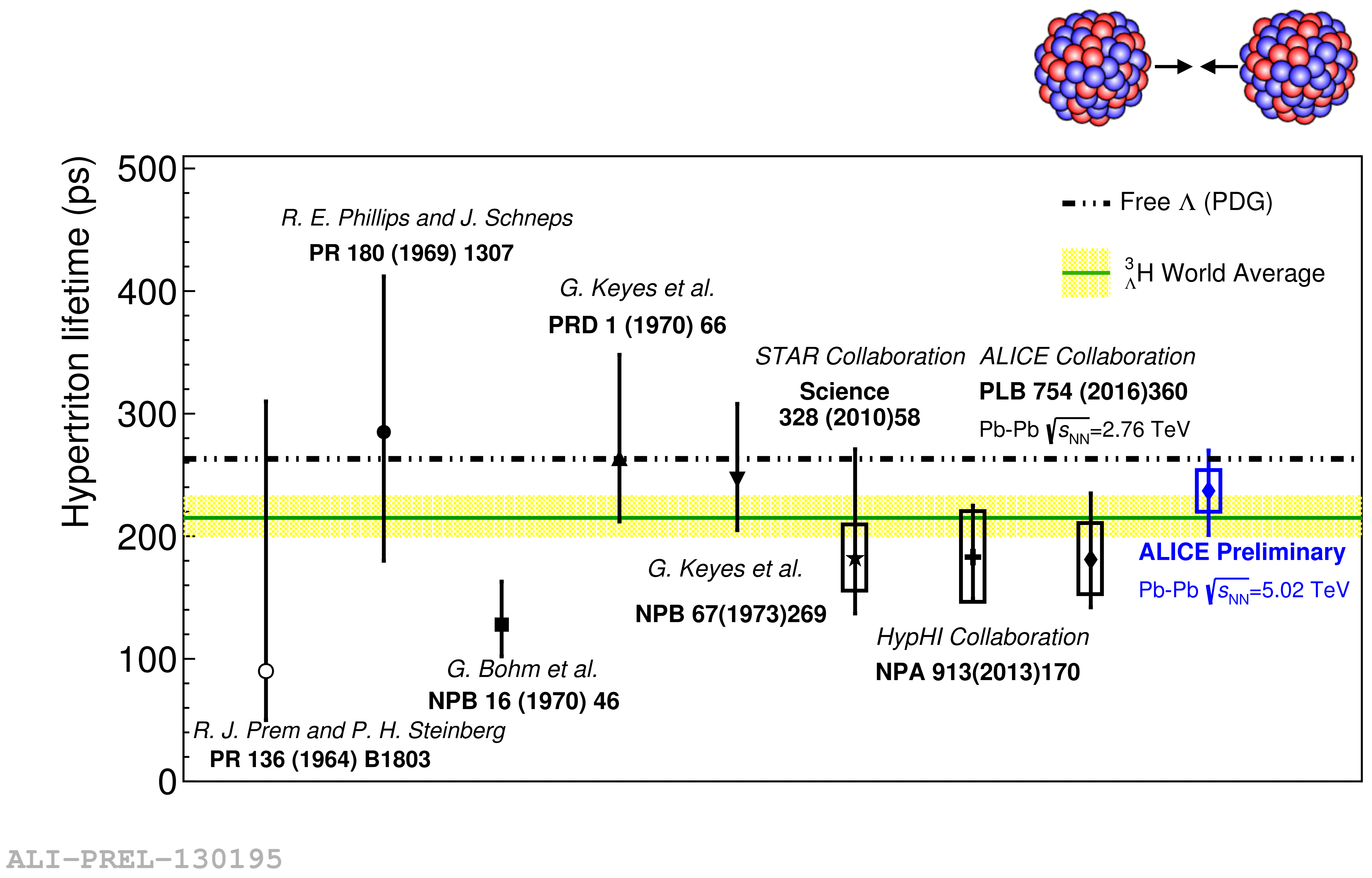

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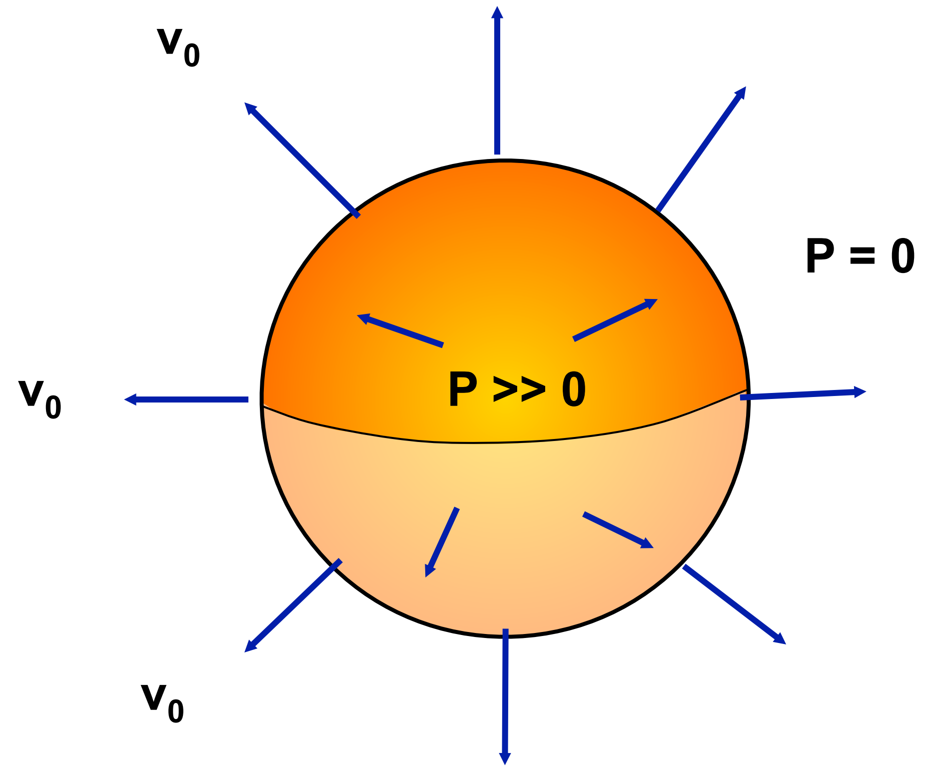
One of the most precise measurement of **$^{3}_{\Lambda}$H lifetime**!

[S. Trogolo, 6/7 17:30]

Collective Expansion



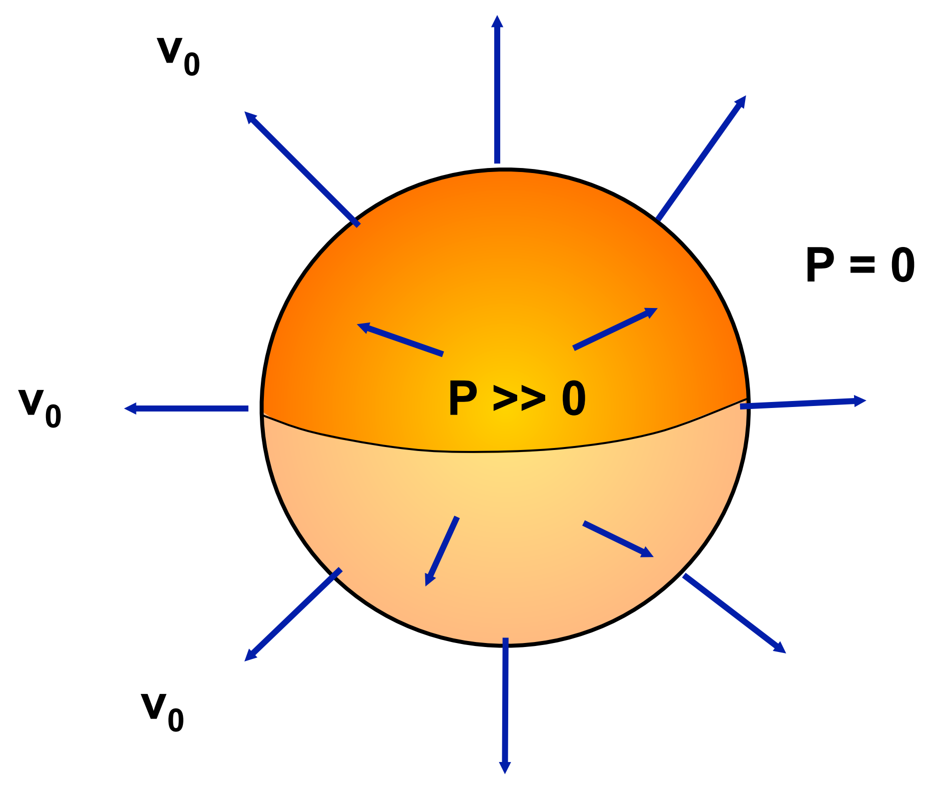
Thermalization ⇒ **pressure** drives the expansion

Cornerstone in the interpretation of Heavy–Ion data

Particles move in a **common velocity field**

Momentum distribution “**blue-shifted**” + **mass ordering**

[J. Otwinowski, 6/7, 17:00]



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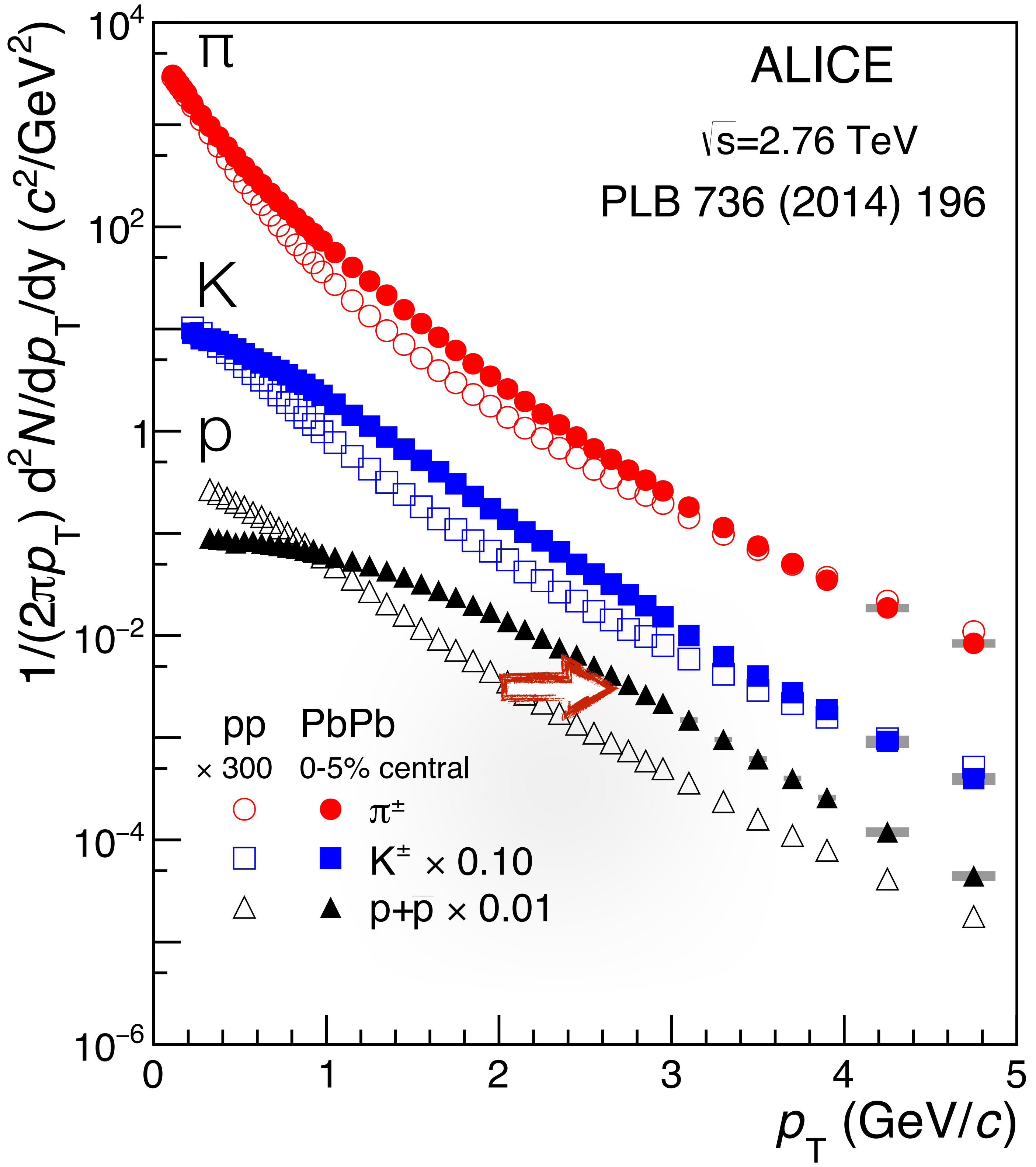
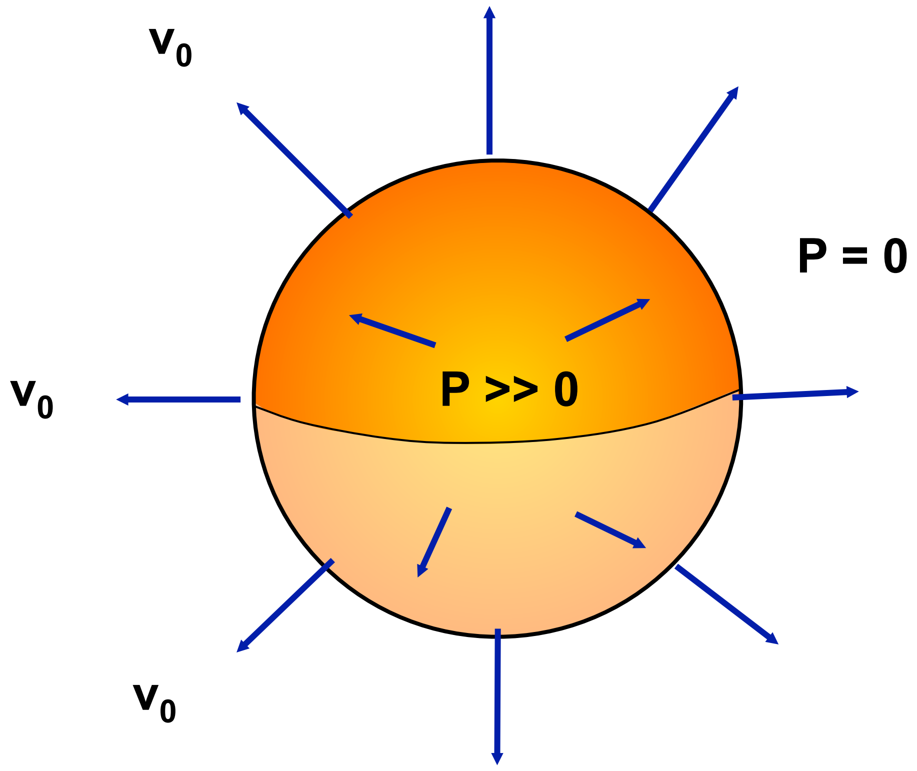


[J. Otwinowski, 6/7, 17:00]



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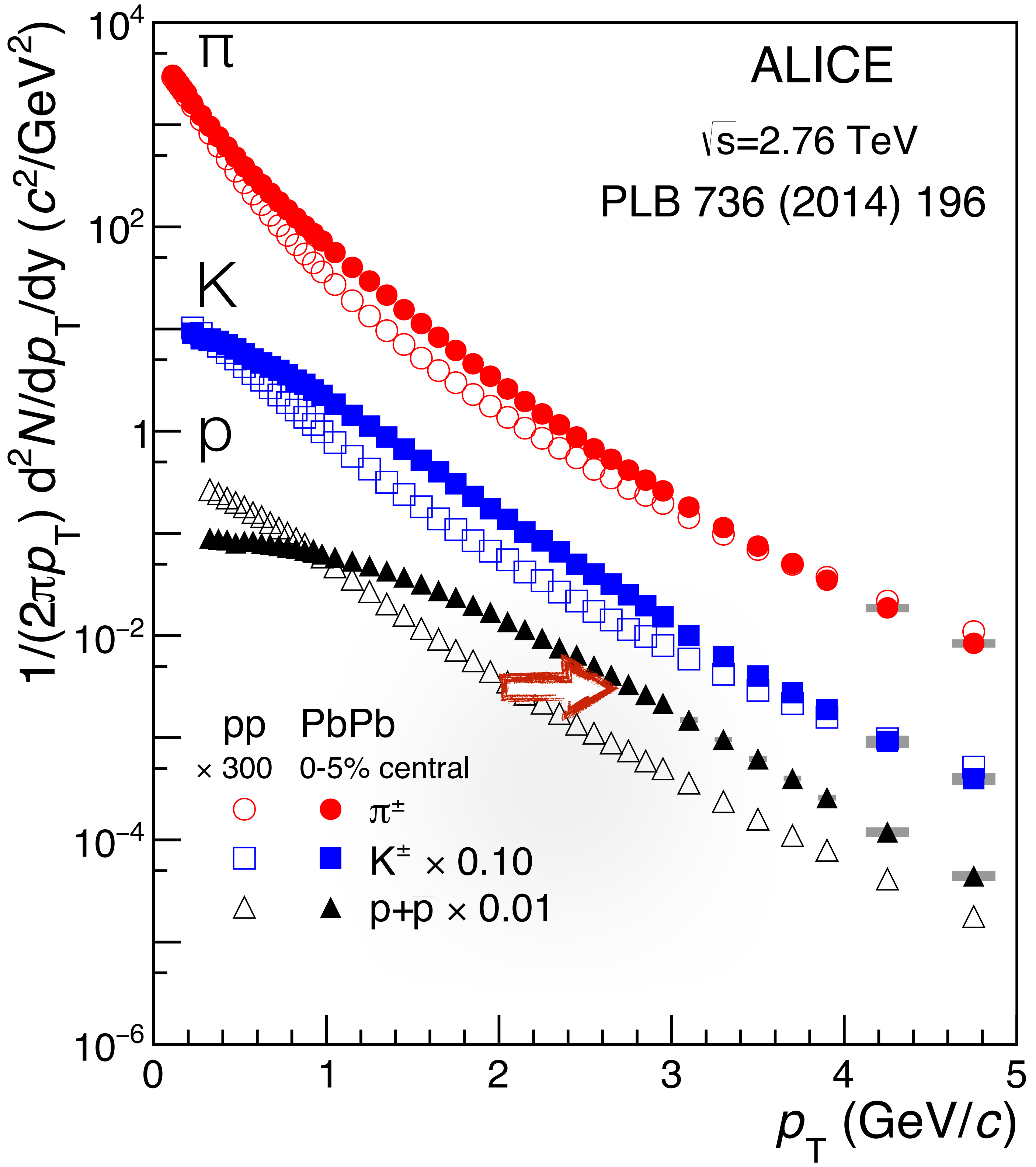
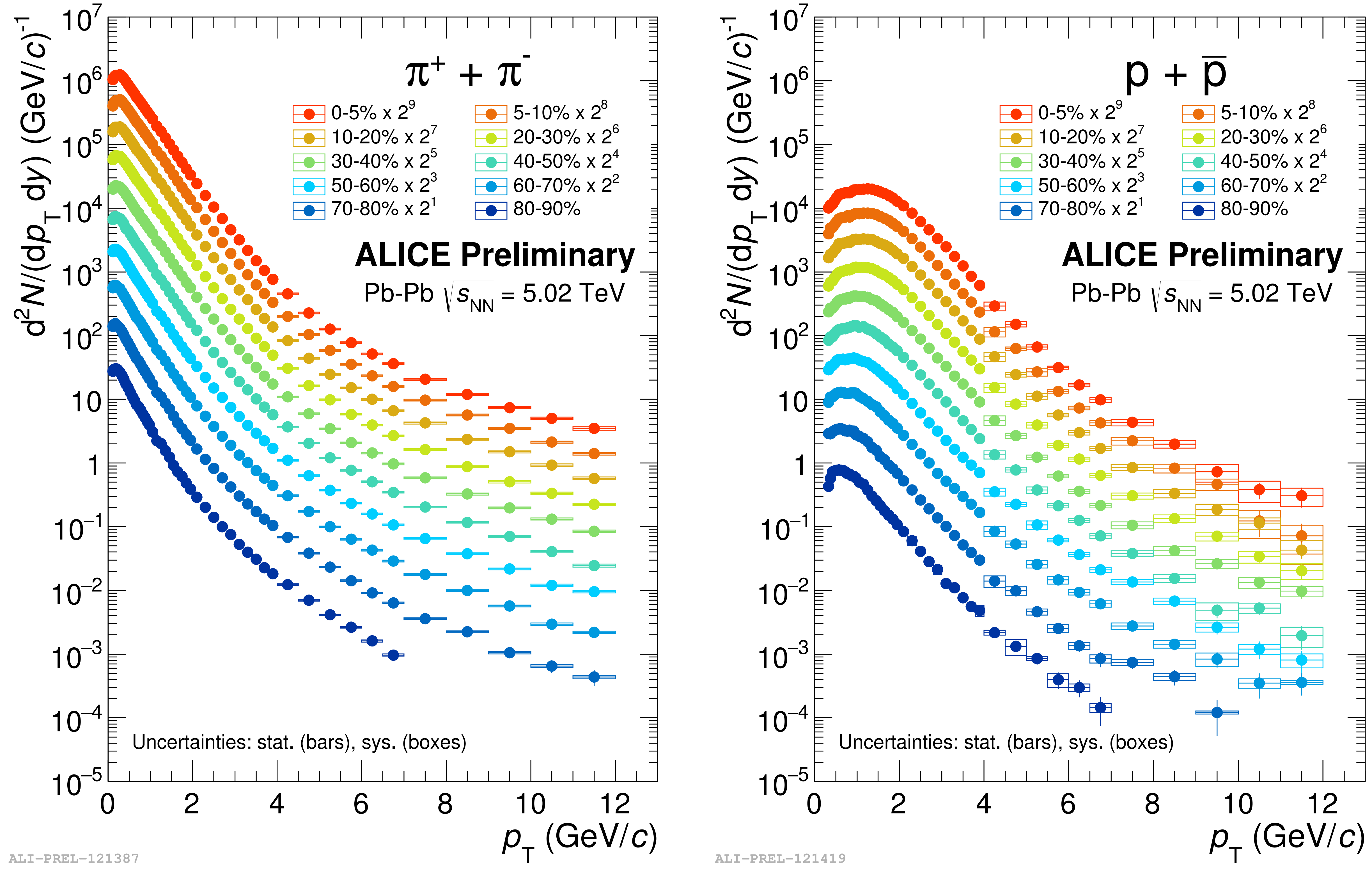
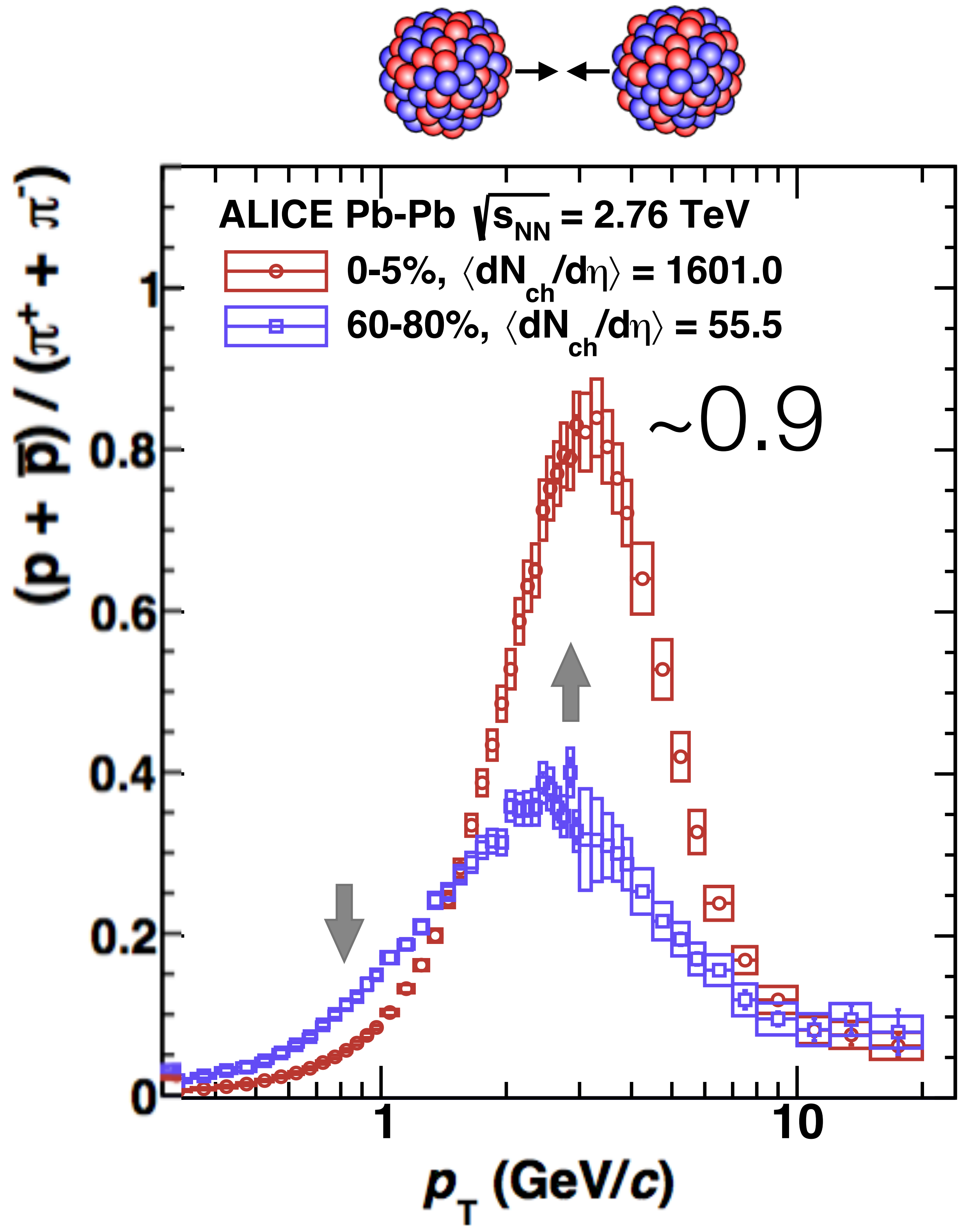


High precision results from Run 2



[J. Otwinowski, 6/7, 17:00]

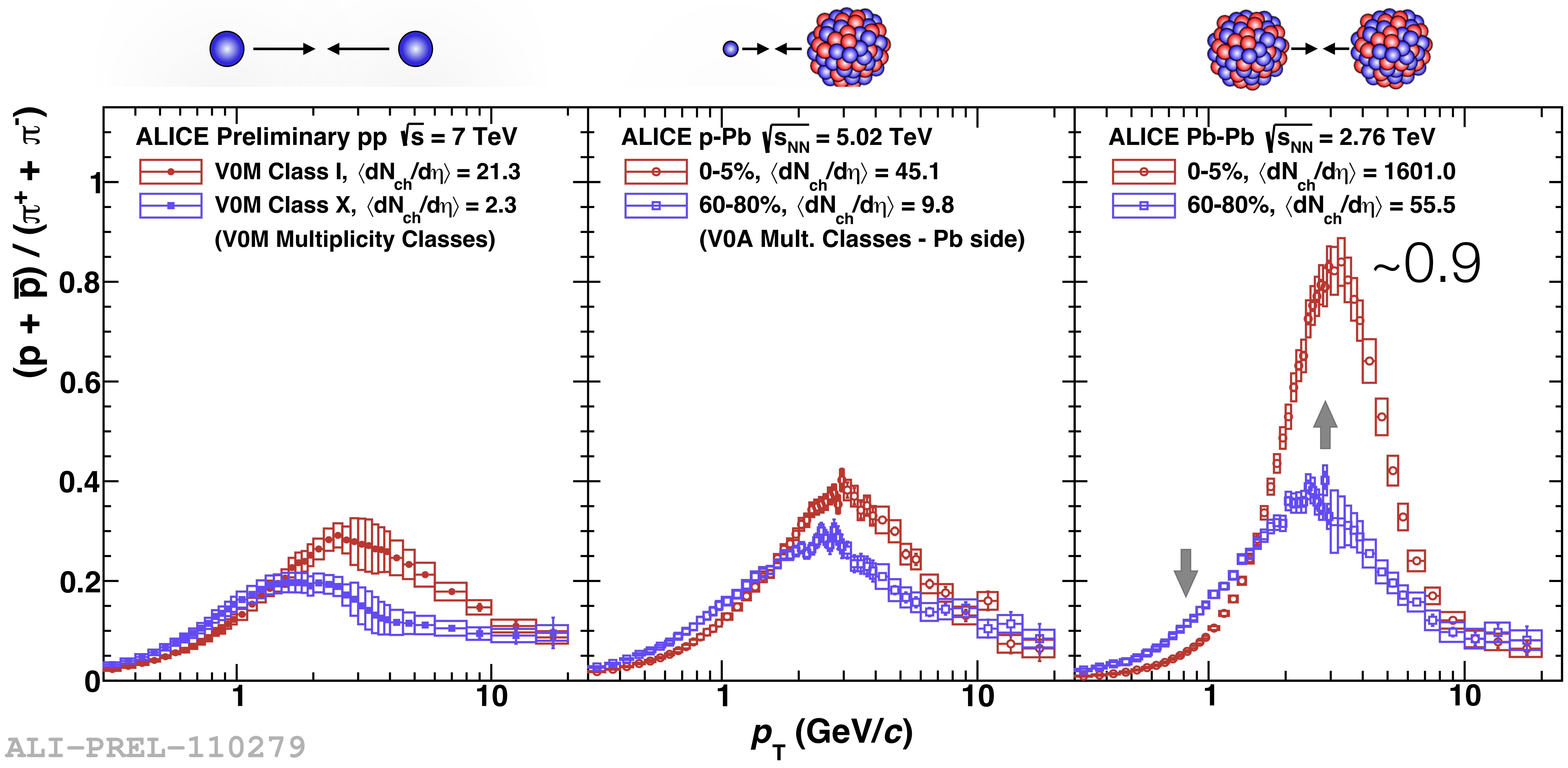
Baryon/Meson Ratios



Depletion at low p_T increase at intermediate p_T
Similar evolution seen in pp and p-Pb collisions

Low to mid-p_T described by **hydrodynamic models**,
freezeout from expanding fluid with a common velocity
Idea implemented (successfully!) also for pp and p–Pb

[J. Otwinowski, 6/7, 17:00]



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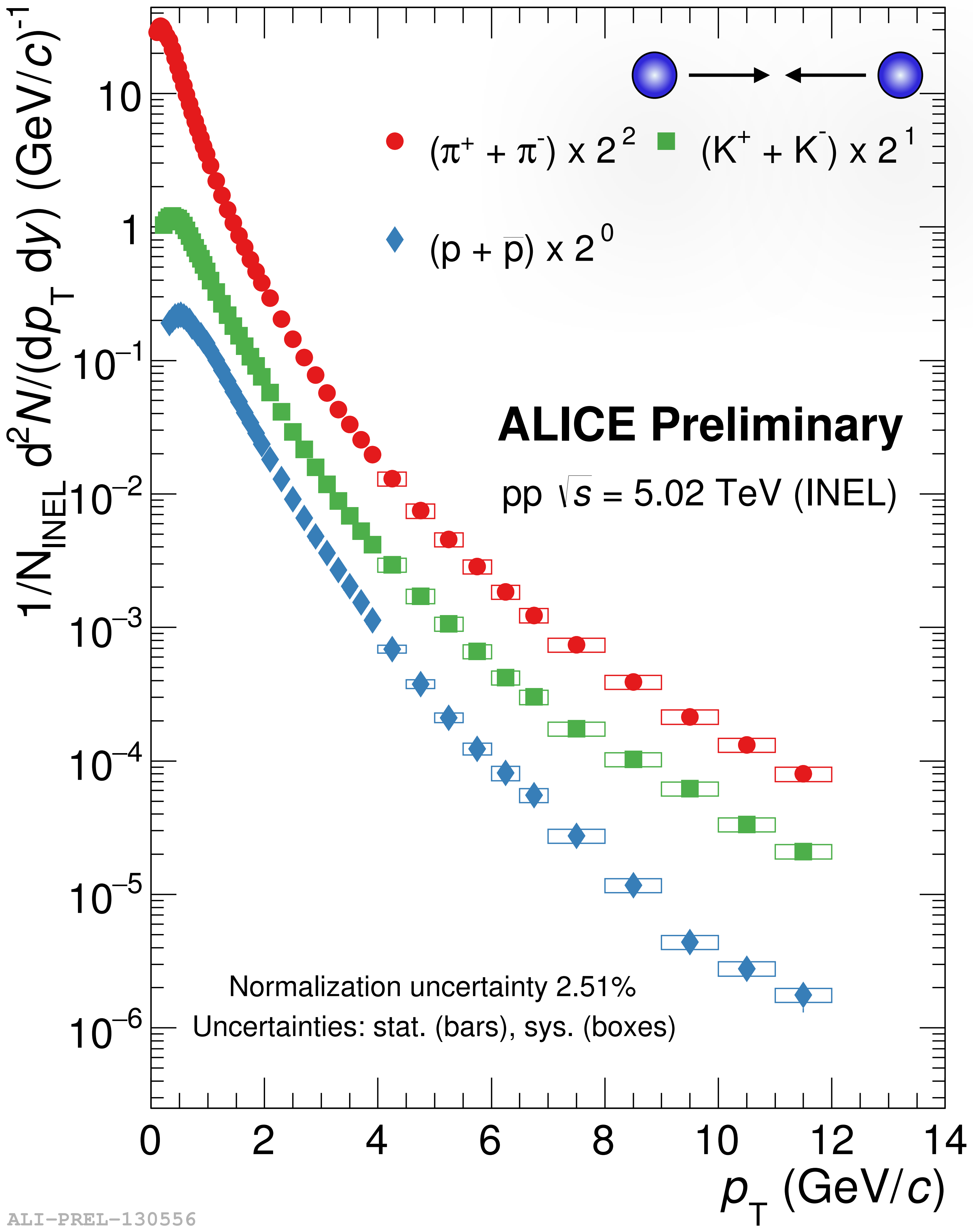
[J. Otwinowski, 6/7, 17:00]

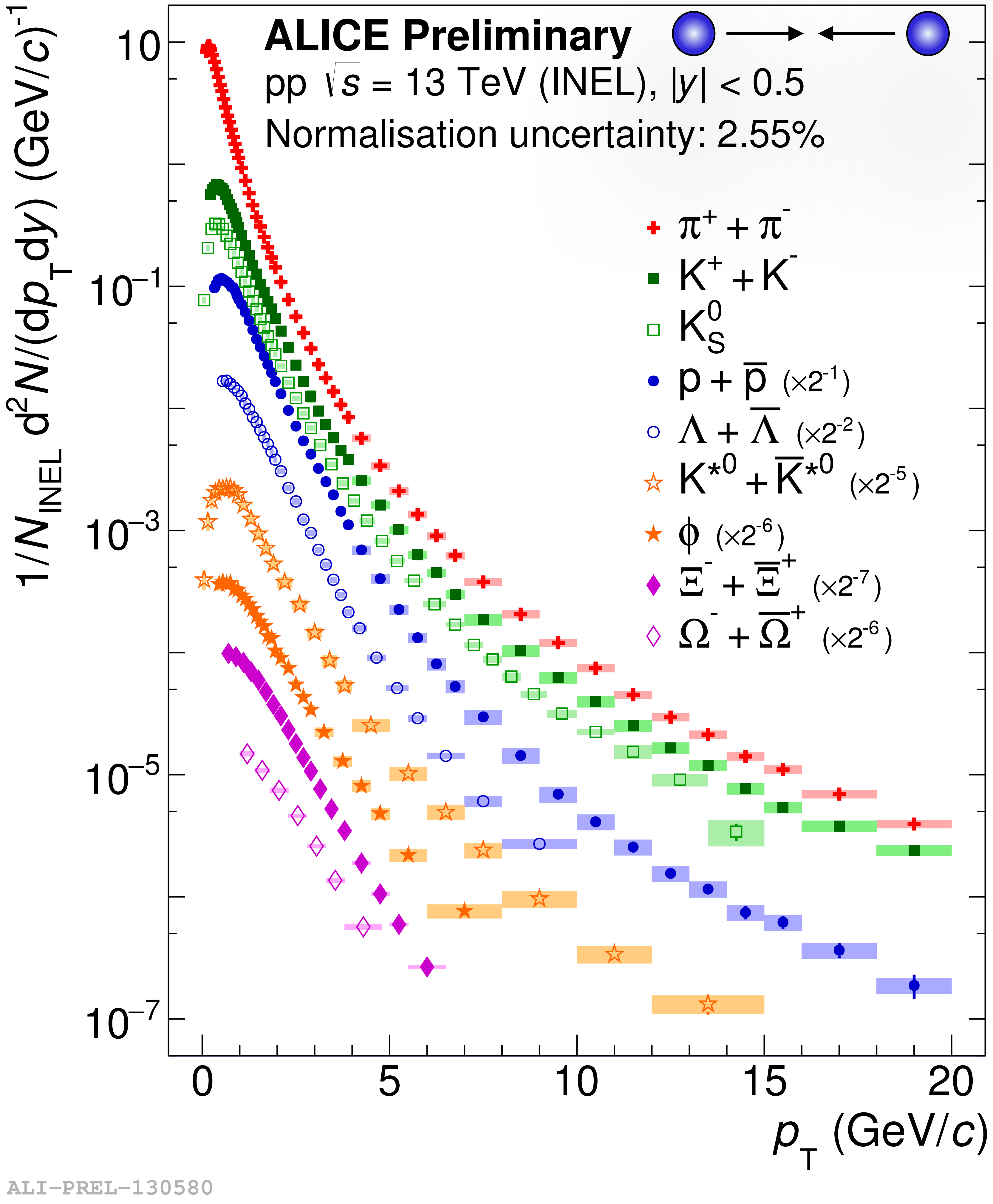
Run 2: identified particles in pp

NEW!

$\sqrt{s}$ = 5 TeV



$\sqrt{s}$ = 13 TeV



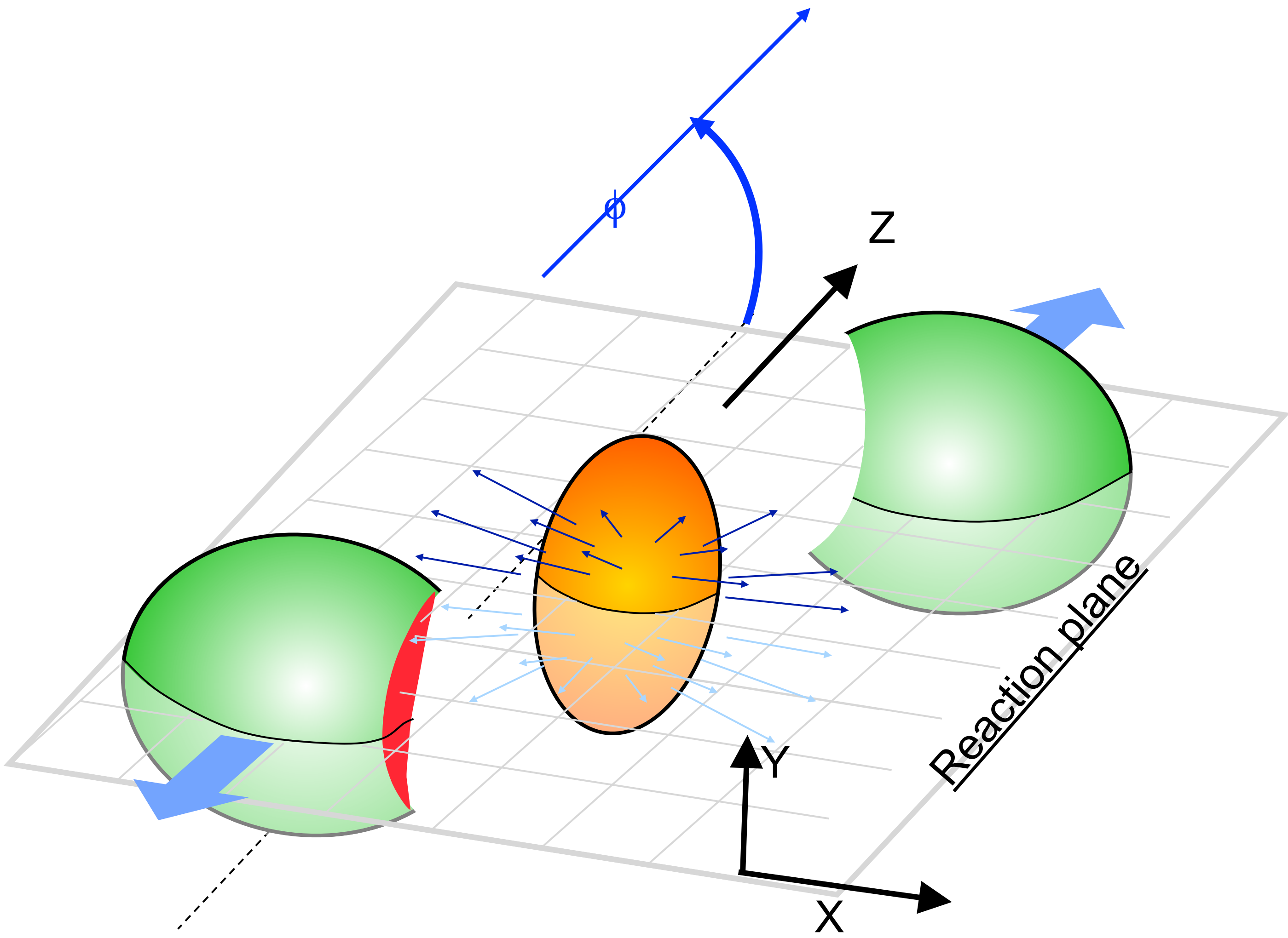
Measurements of common light-flavor species in **minimum bias** collisions well advanced

Studies as a **function of multiplicity** (MB & HM triggers) in progress

Reach to Pb–Pb—like multiplicity

[G. Bencedi, 6/7 9:00]

Spatial deformation



[M. Nguyen, today]

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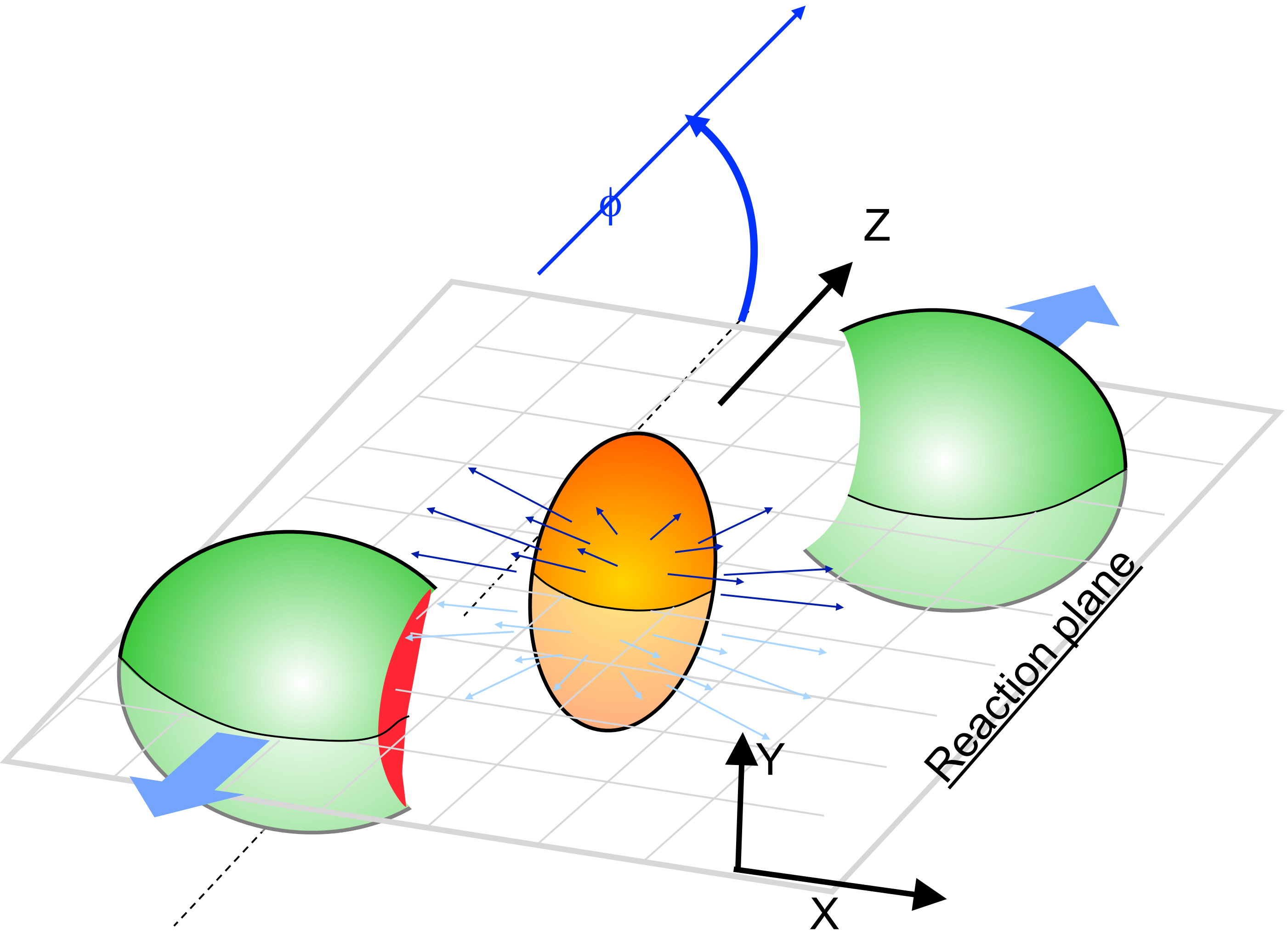
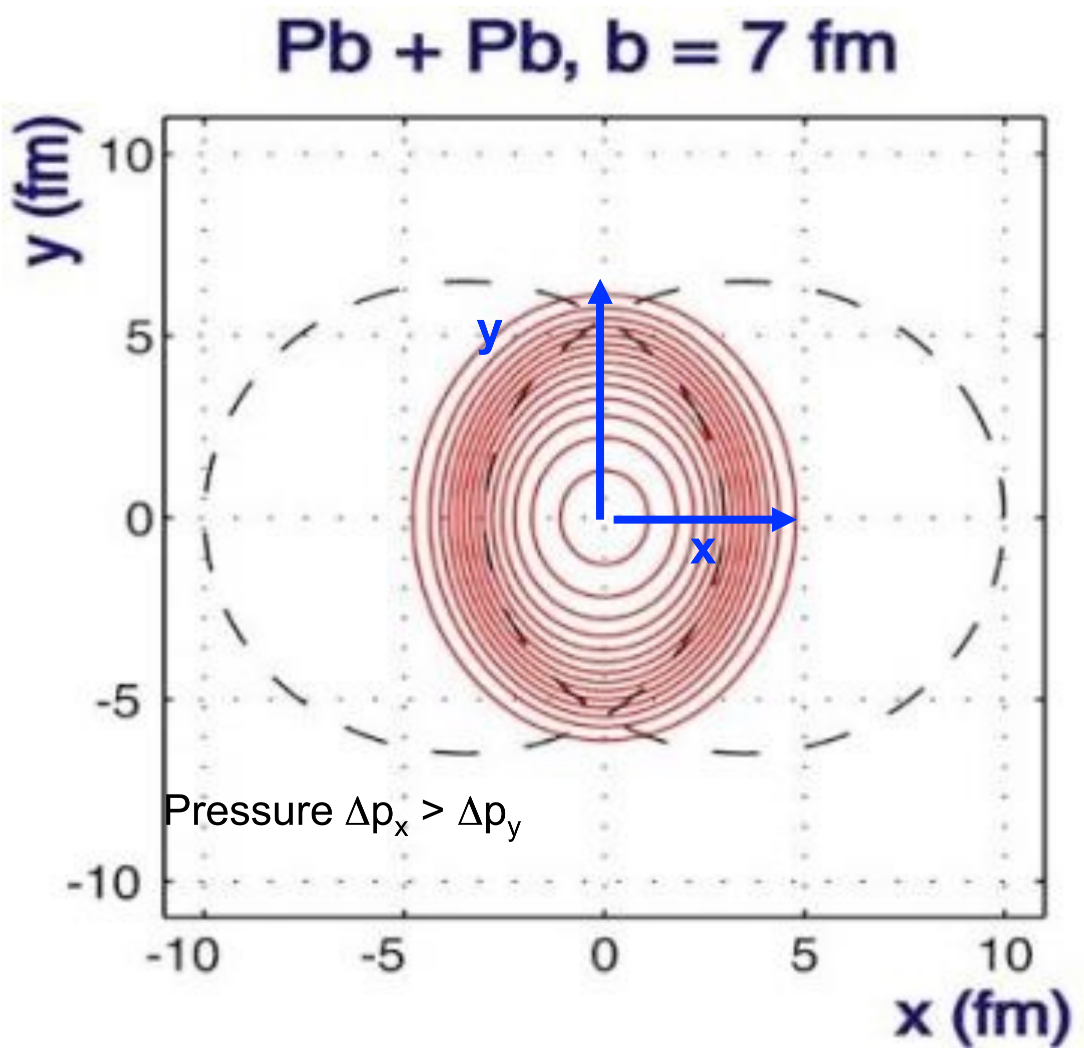


Azimuthal (φ)
pressure gradients



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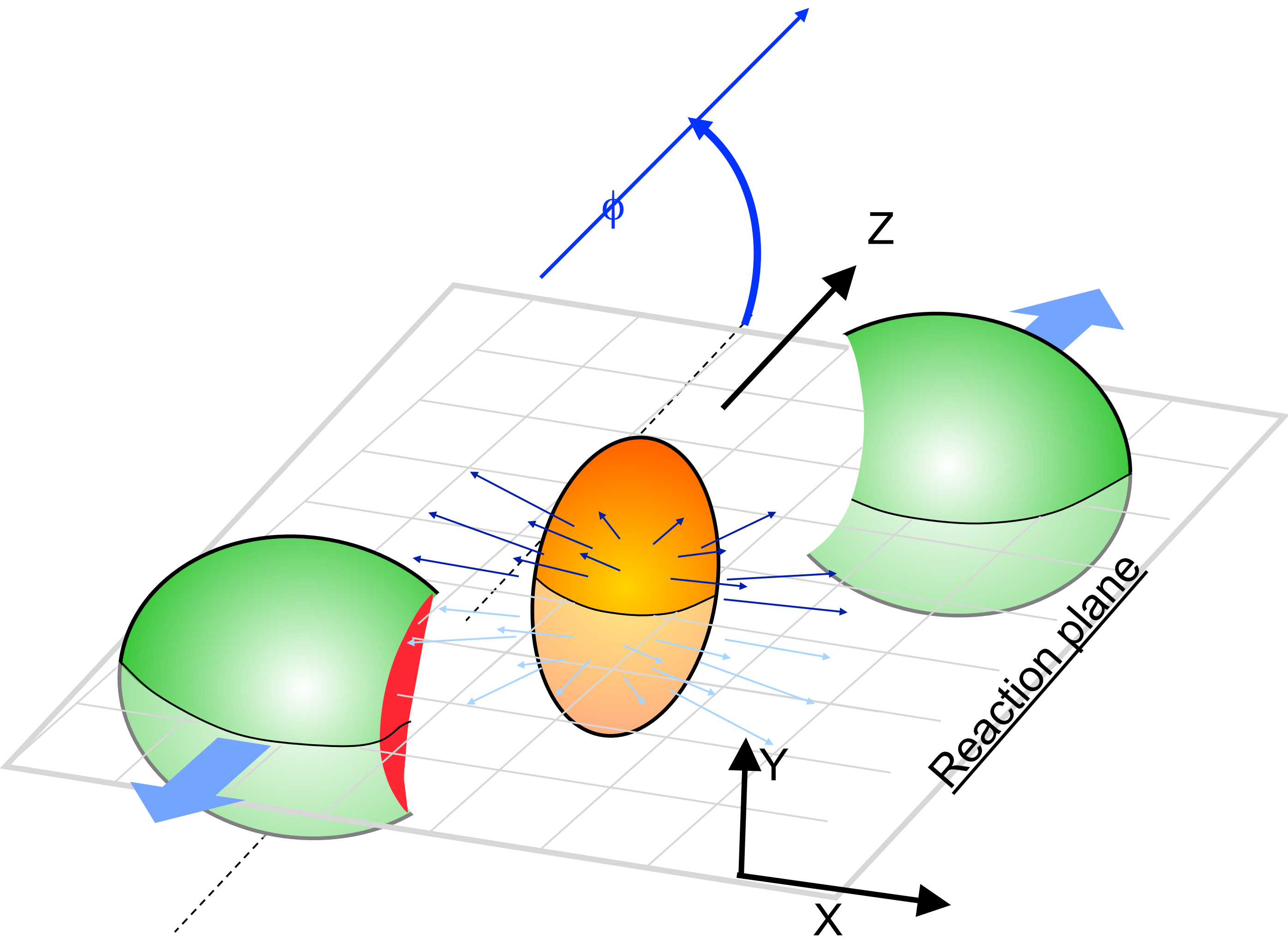

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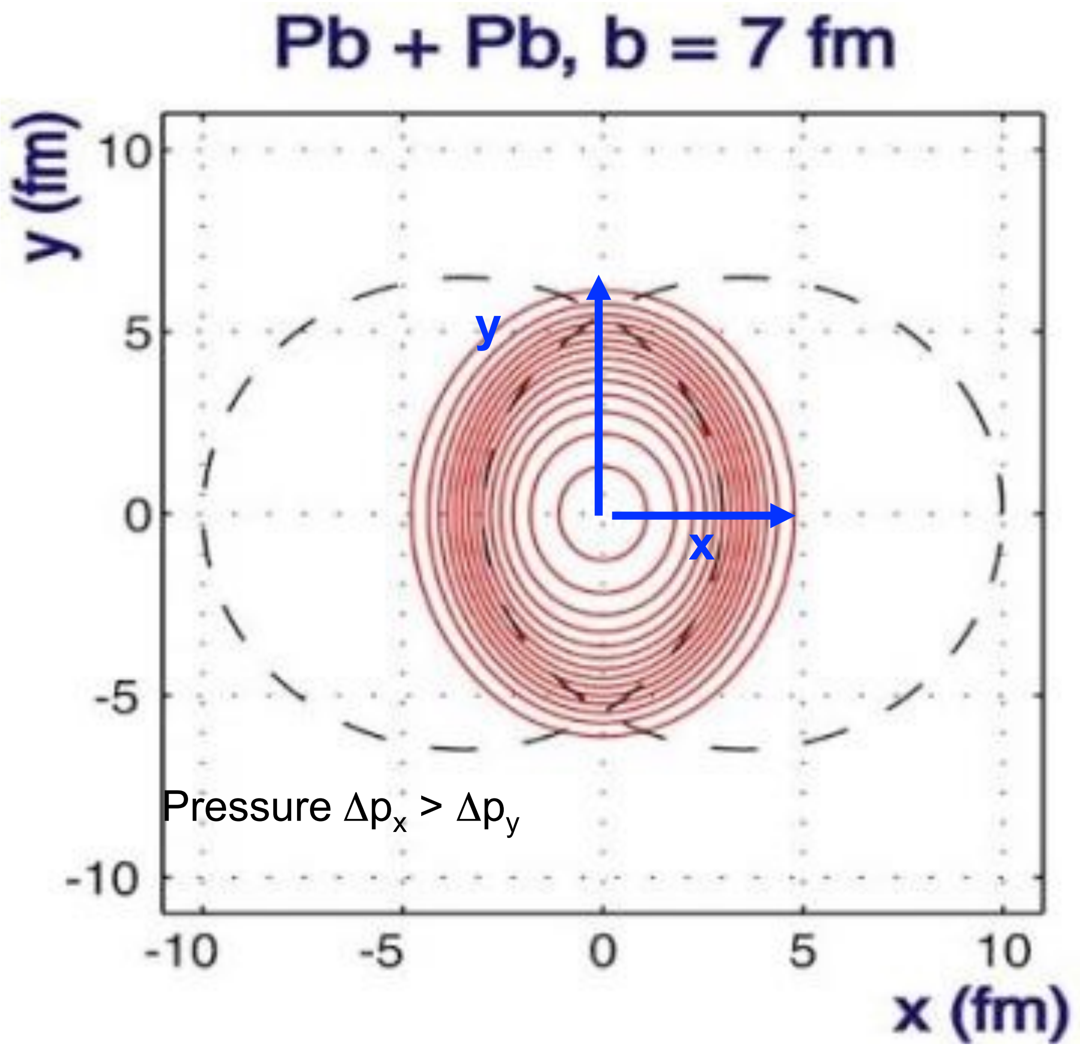
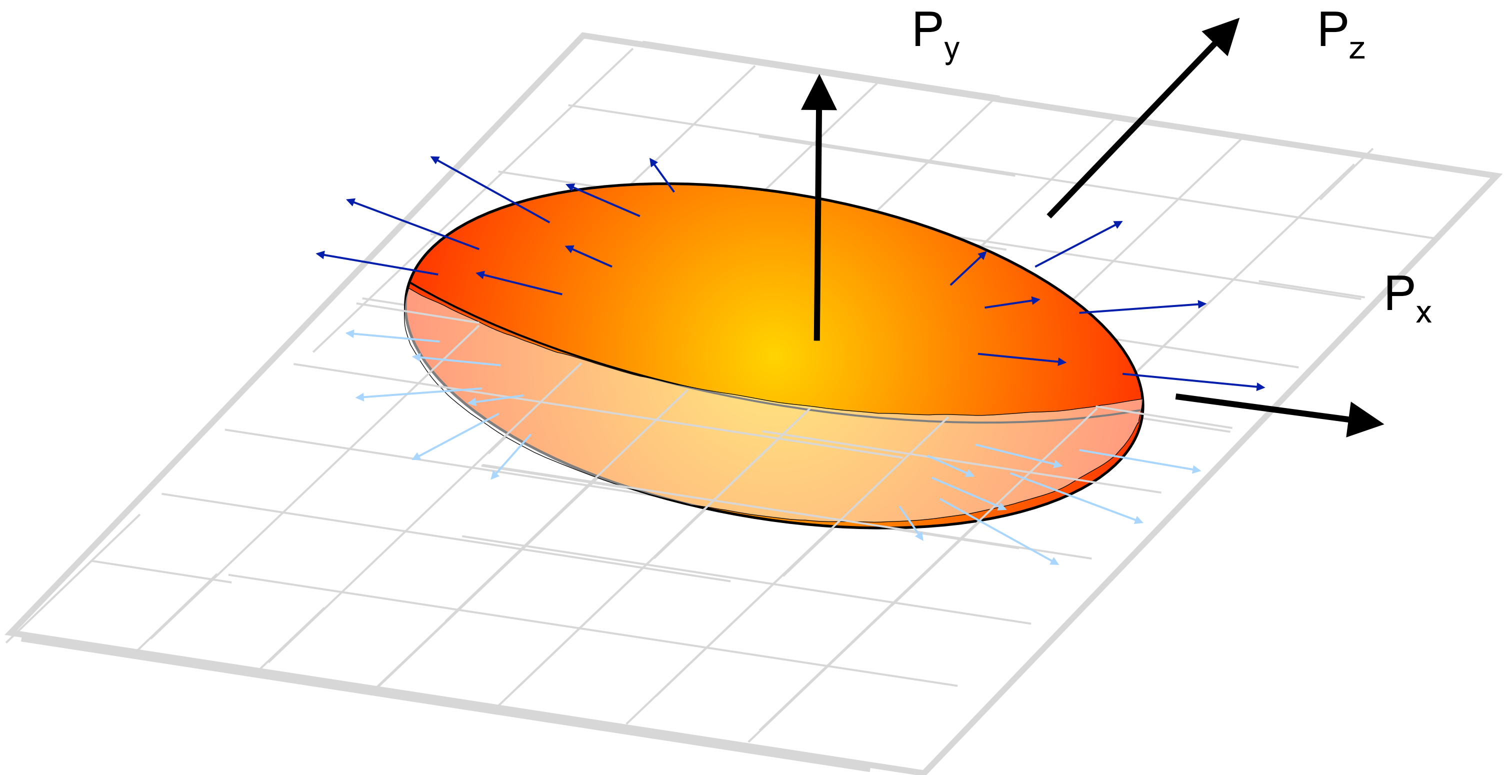


Anisotropic particle density



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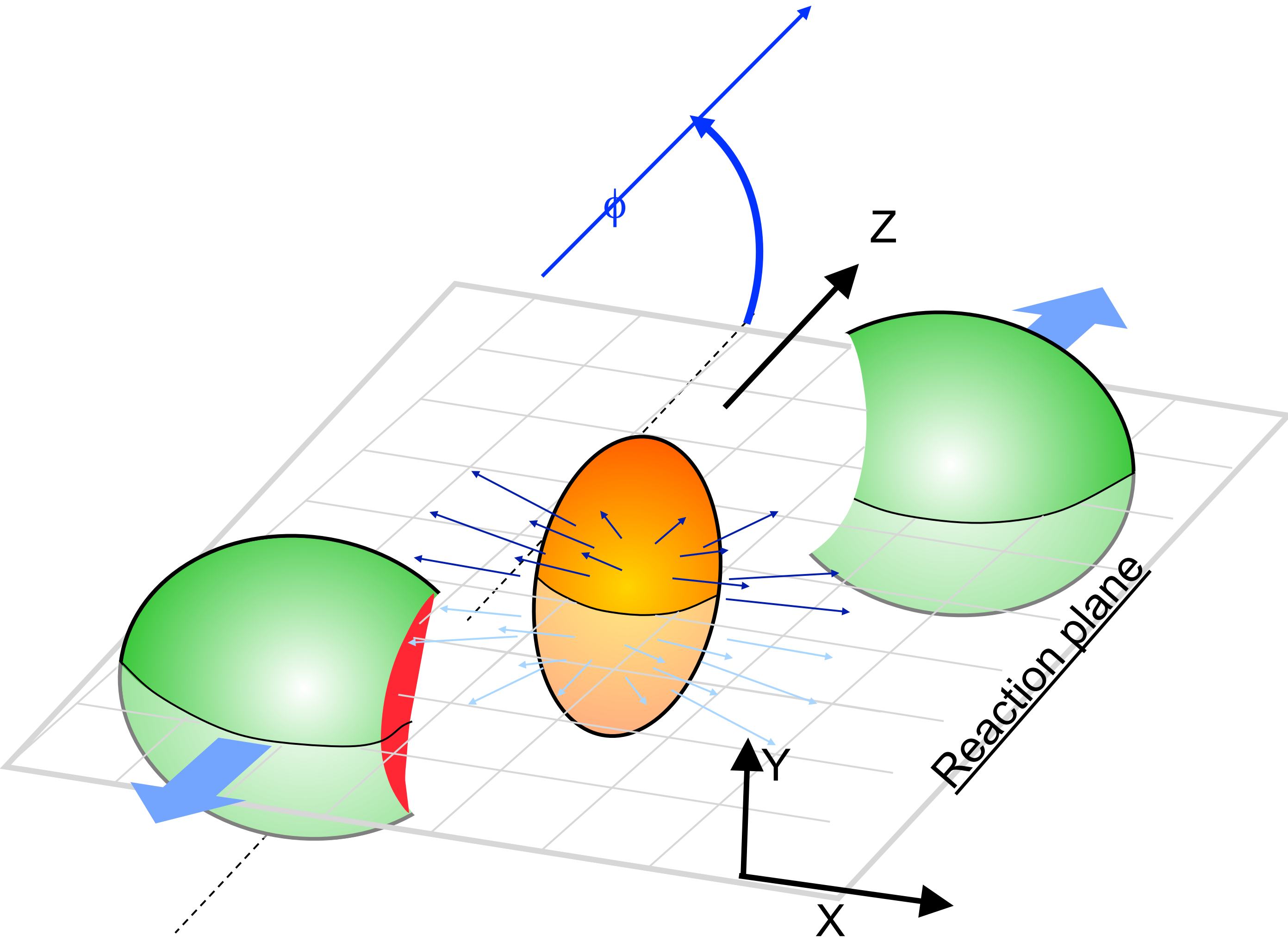

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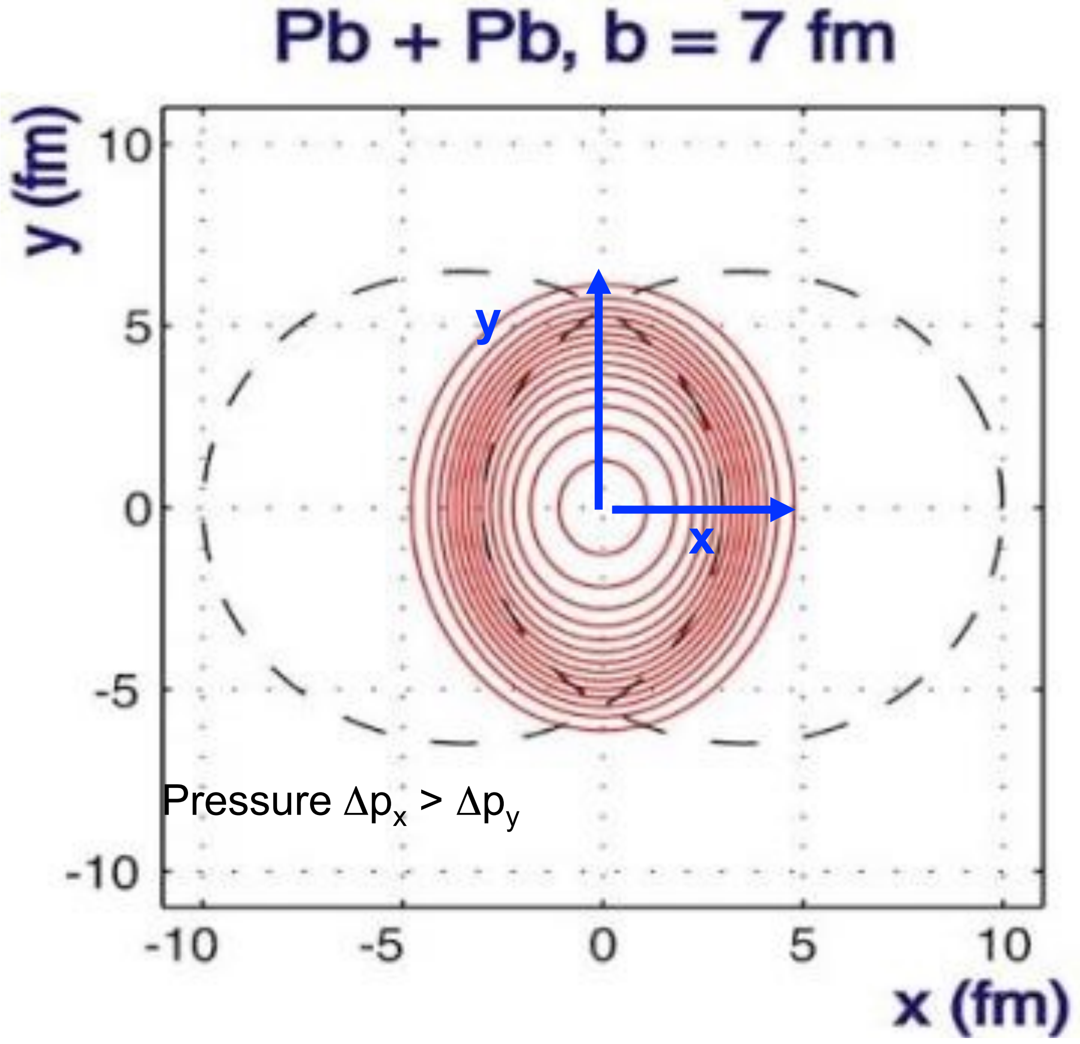

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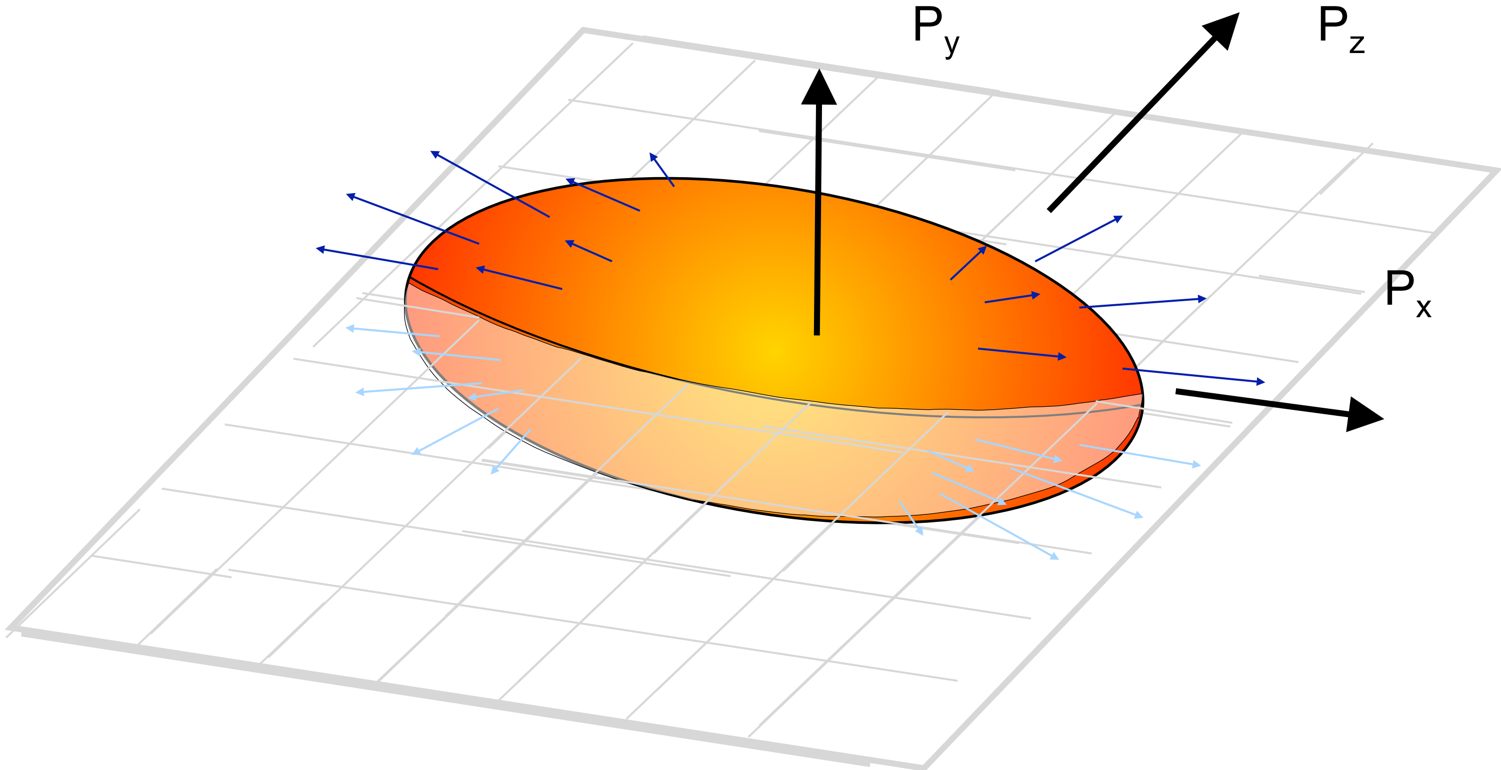
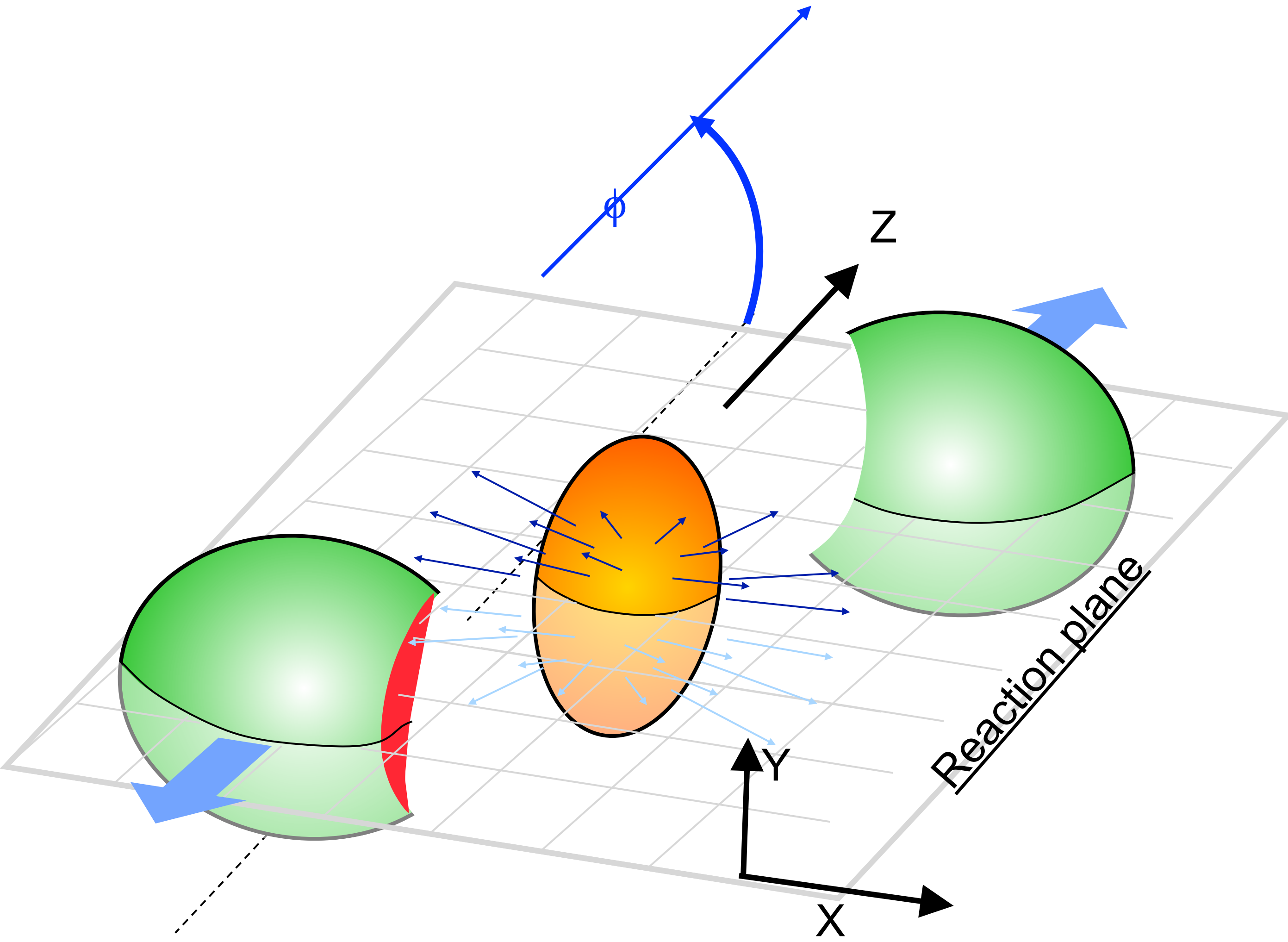


$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

[M. Nguyen, today]

Anisotropic Flow

Spatial deformation



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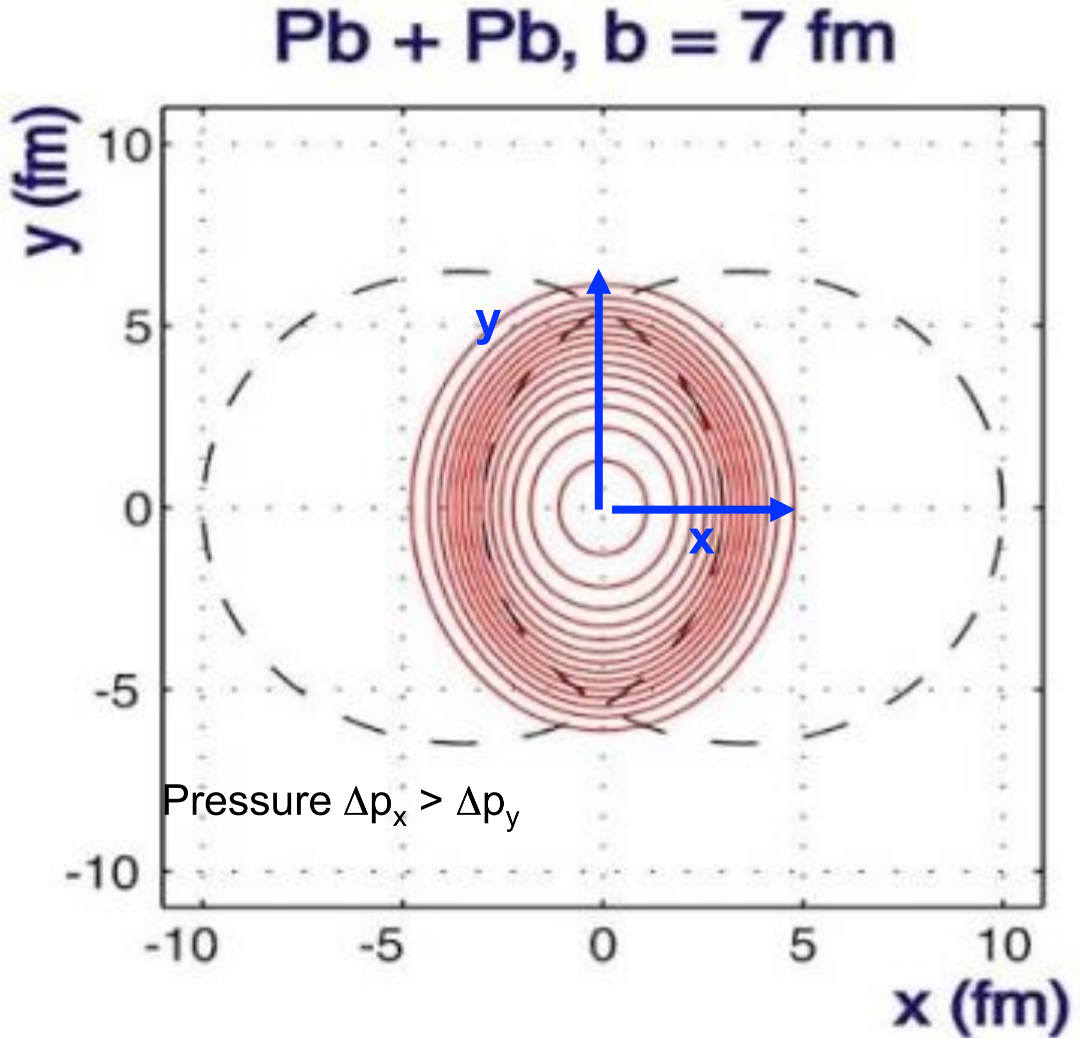

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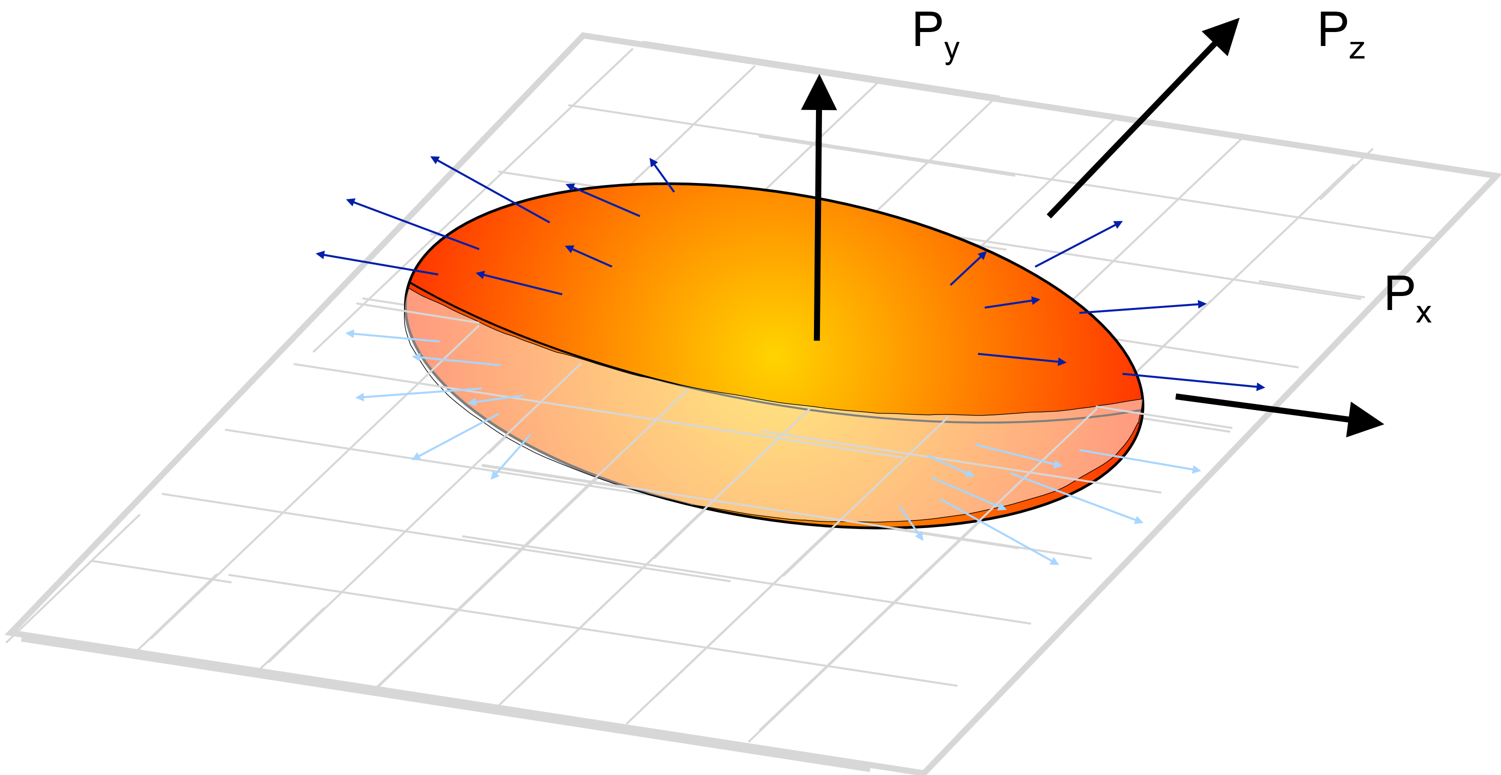

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***v*$_n$** are sensitive to the **full evolution** of the collision system

Initial conditions → QGP phase → Hadronization

Full industry of methods / measurements, only the basic examples here

Sensitive to **sub-nucleonic fluctuations (of gluon densities)**

(important for precision studies and small systems)

[M. Nguyen, today]

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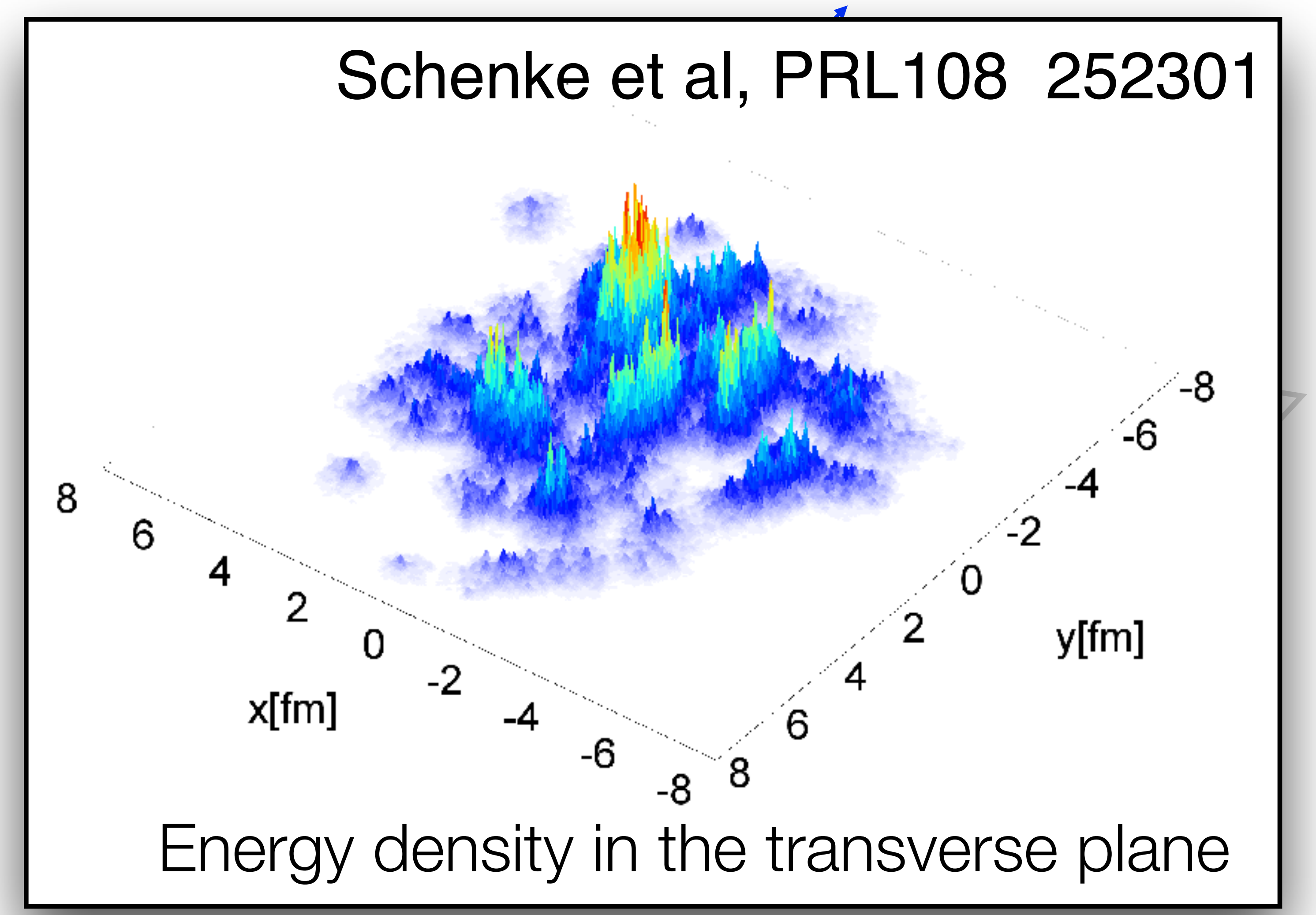

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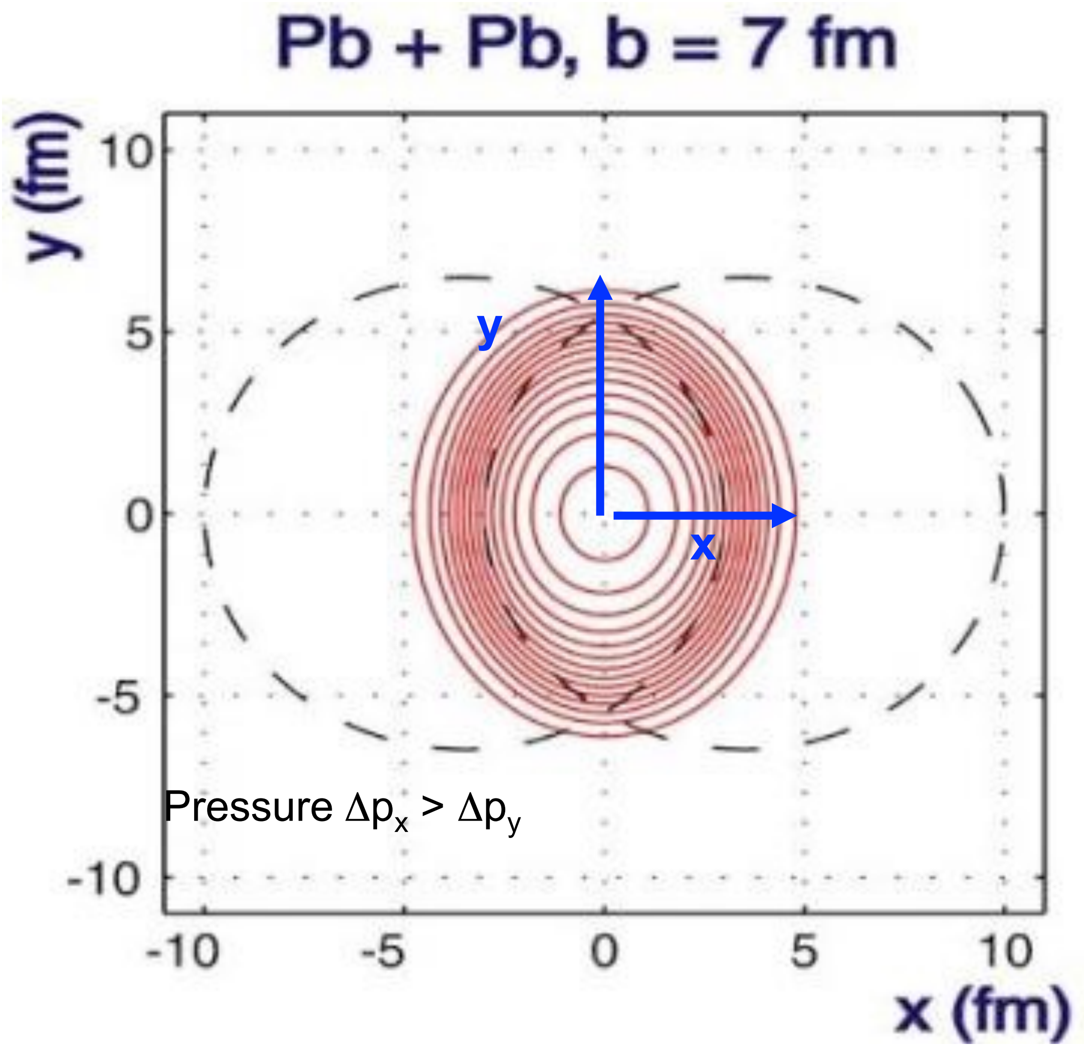
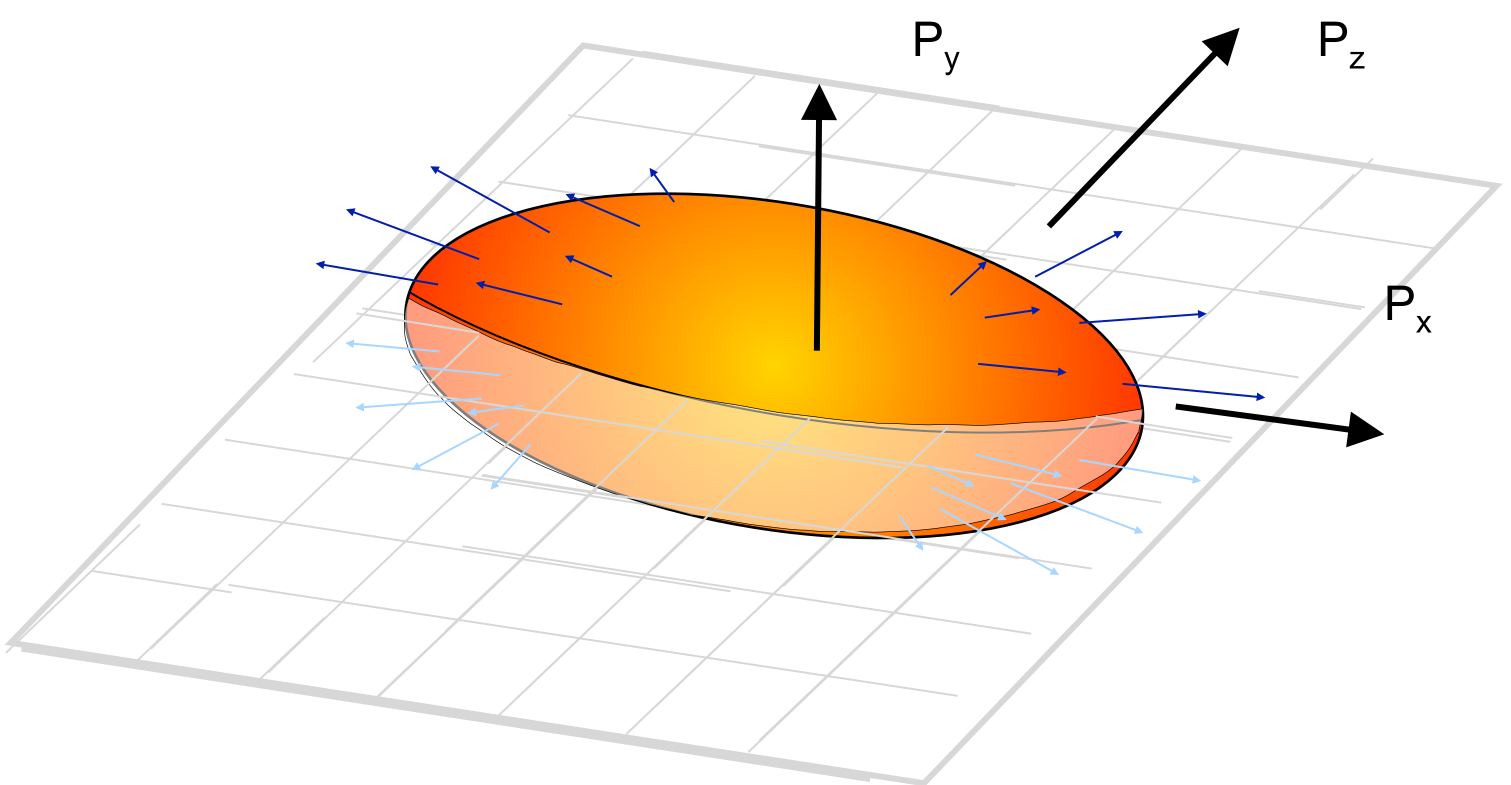


Anisotropic particle density



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

v_n are sensitive to the **full evolution** of the collision system

Initial conditions → QGP phase → Hadronization

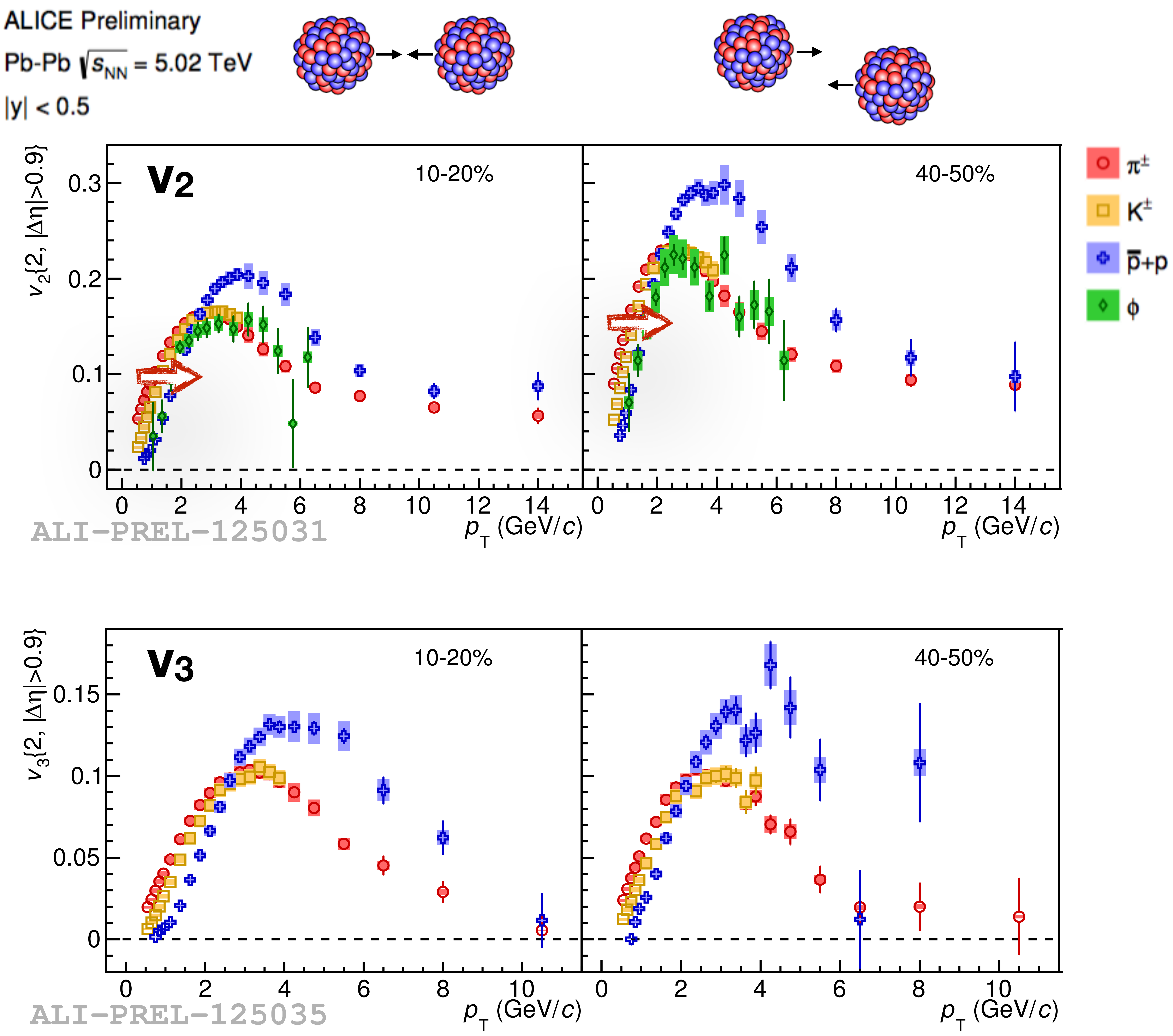
Full industry of methods / measurements, only the basic examples here

Sensitive to **sub-nucleonic fluctuations (of gluon densities)**

(important for precision studies and small systems)

[M. Nguyen, today]

v_n of identified particles



Mass ordering expected in **collective expansion** scenario

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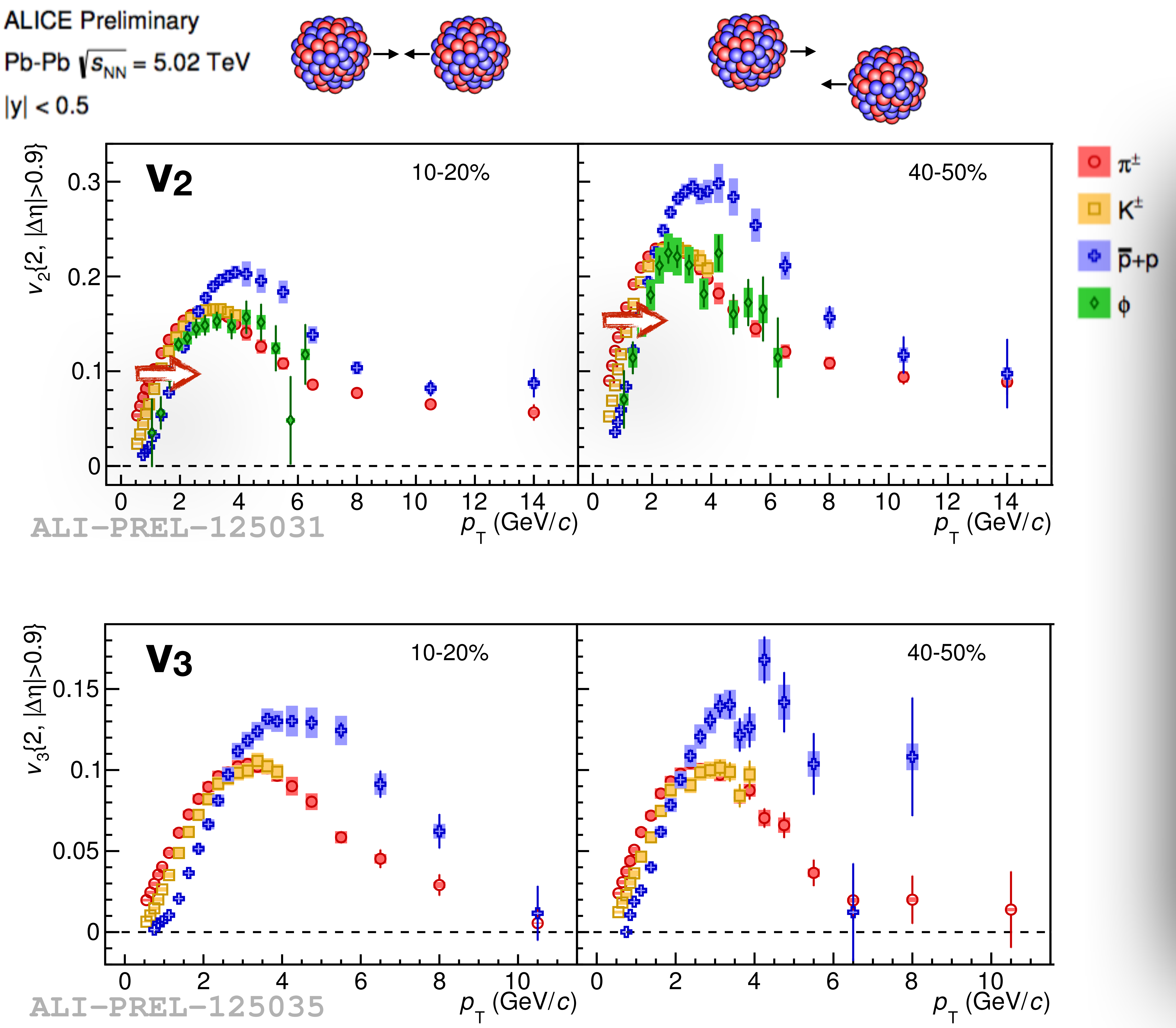

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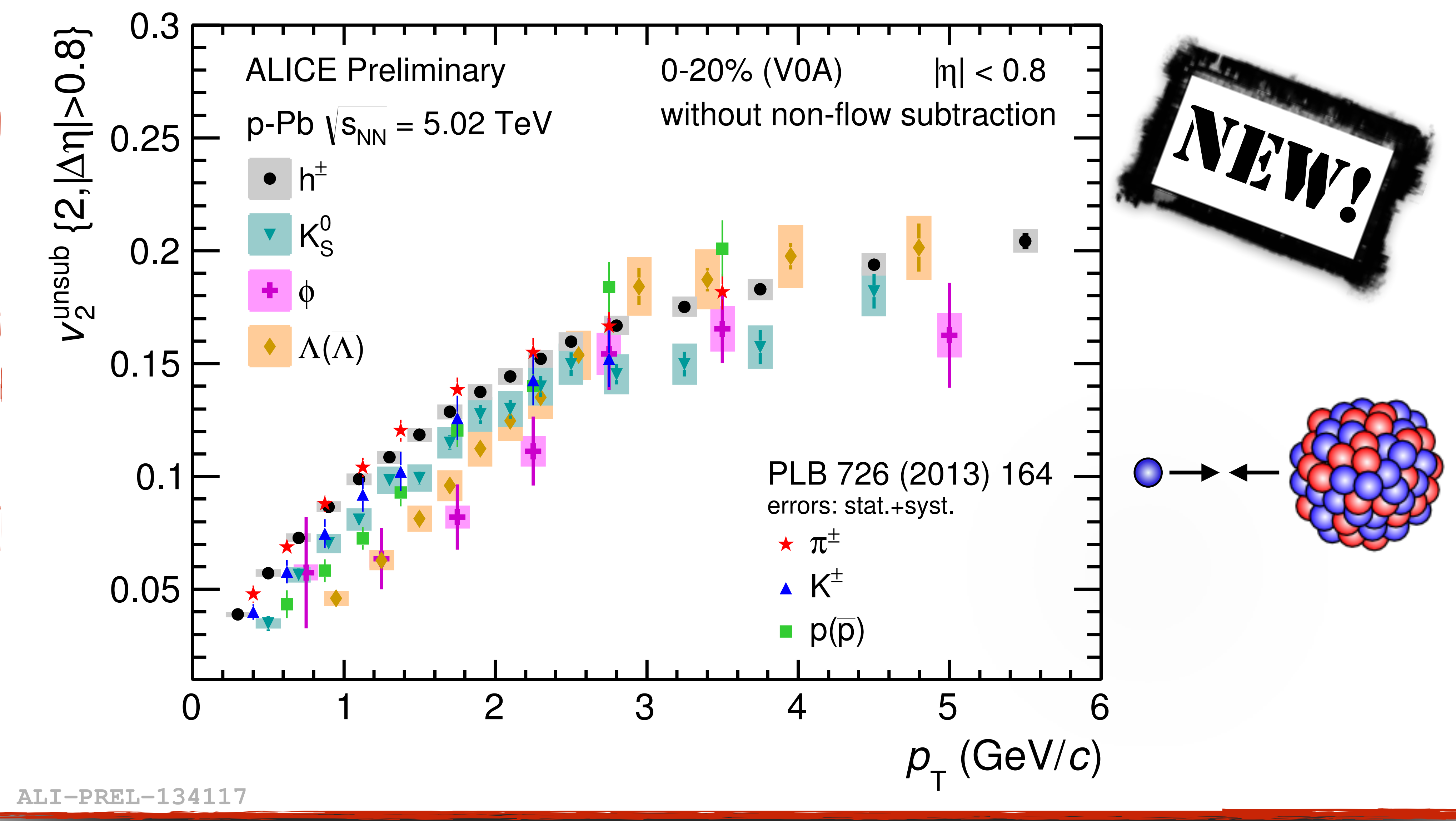
Similar results seen in **high mult p-Pb!**
Final (**expansion**) or
Initial (**saturation**) state effect?
Thermal equilibrium in
pp/p–Pb/Pb–Pb?



[See also P. Romatschke, 7/7 9:00]

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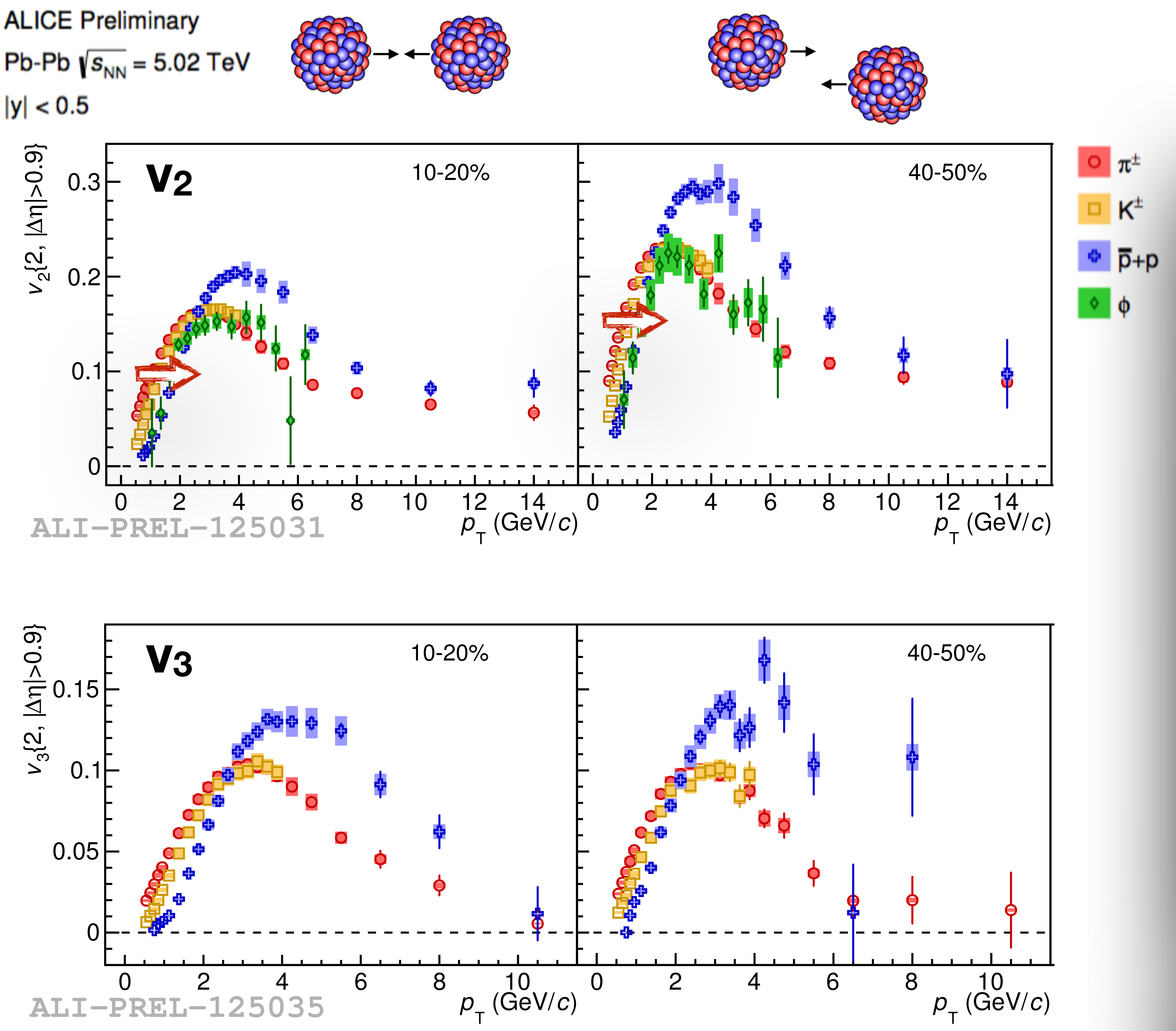

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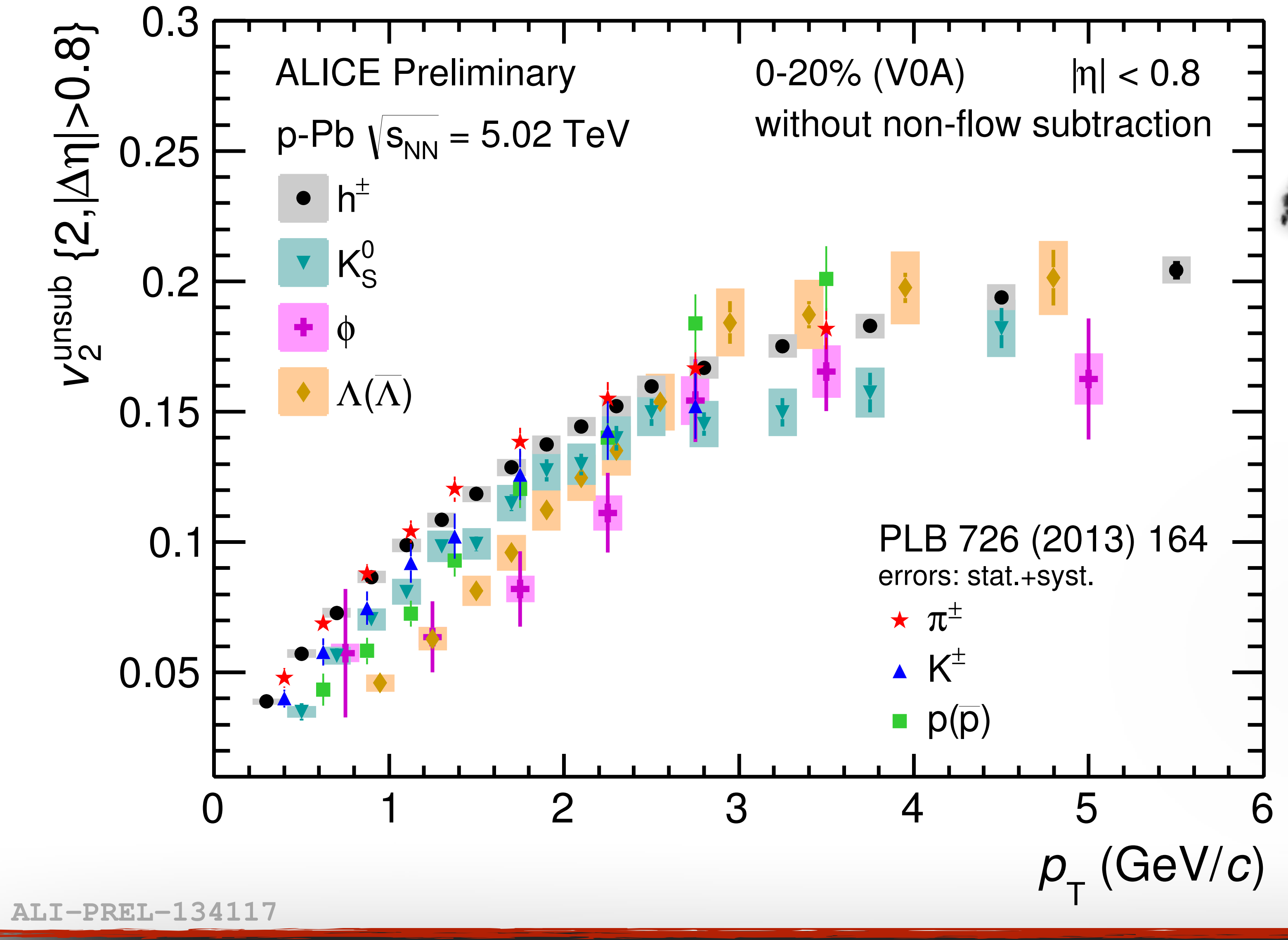
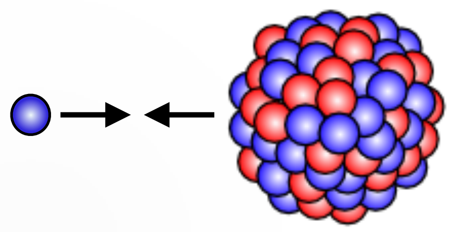
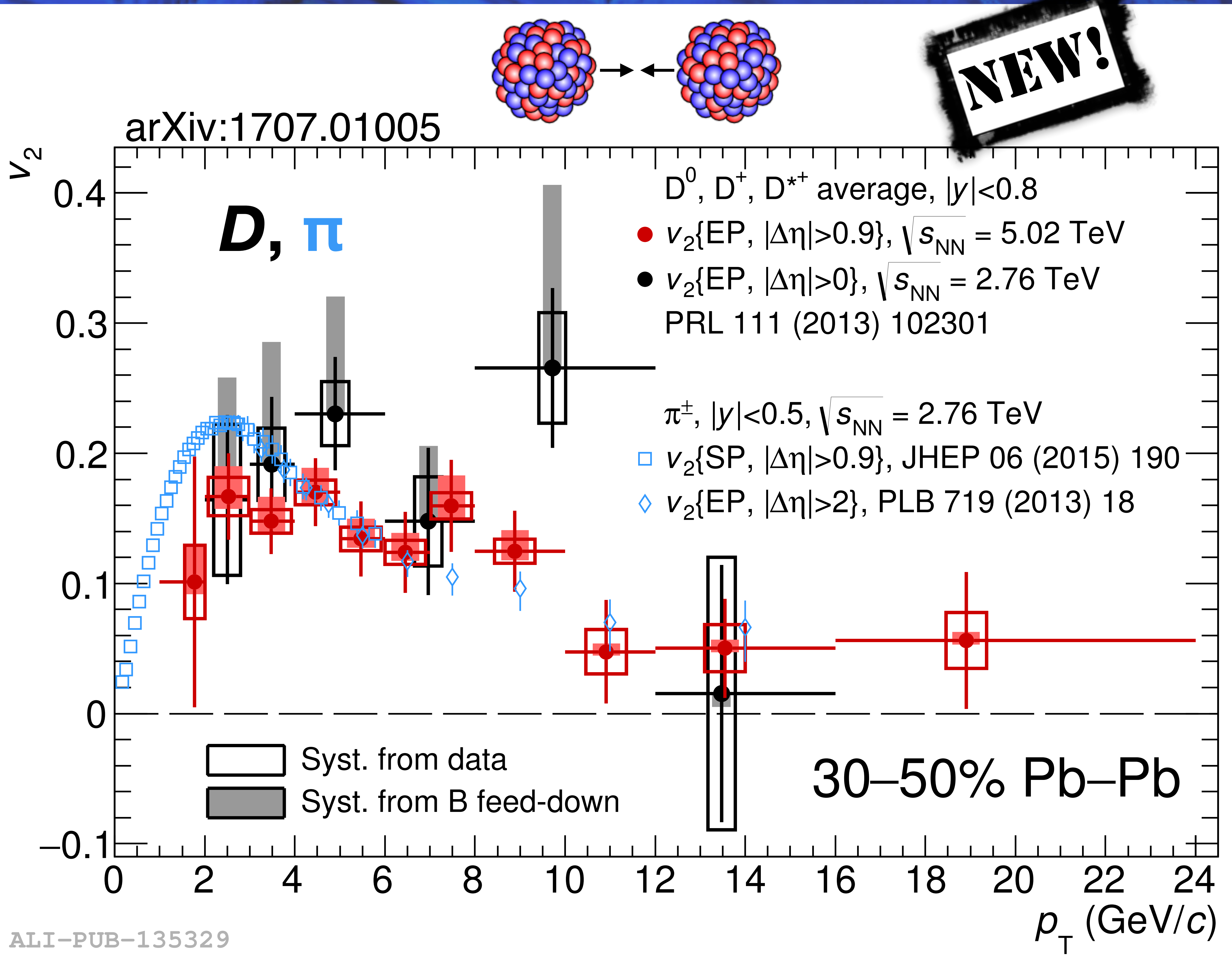


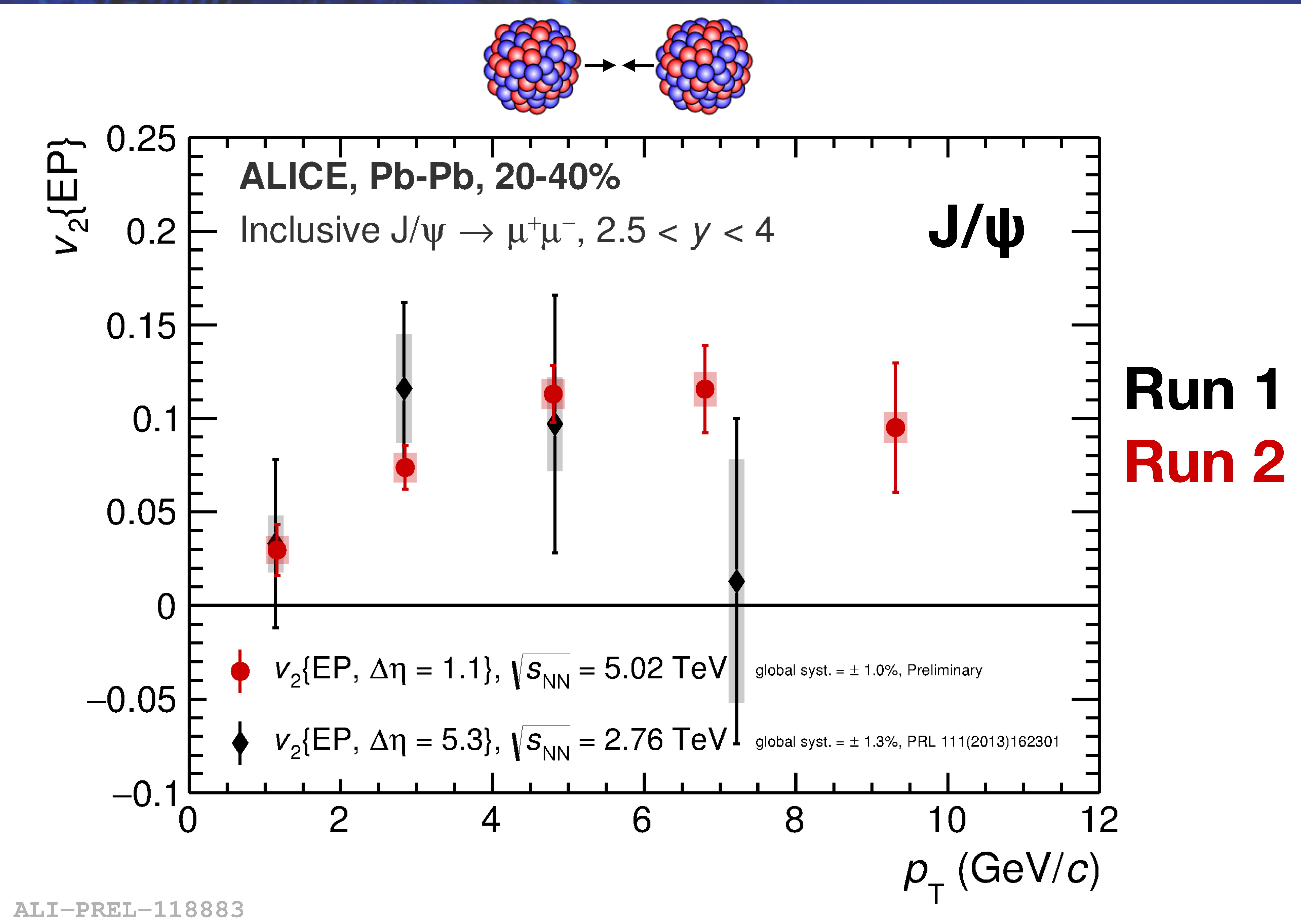
NEW!



What's **v_2 for charm?**
Insight in thermalization process!

Charm Flow





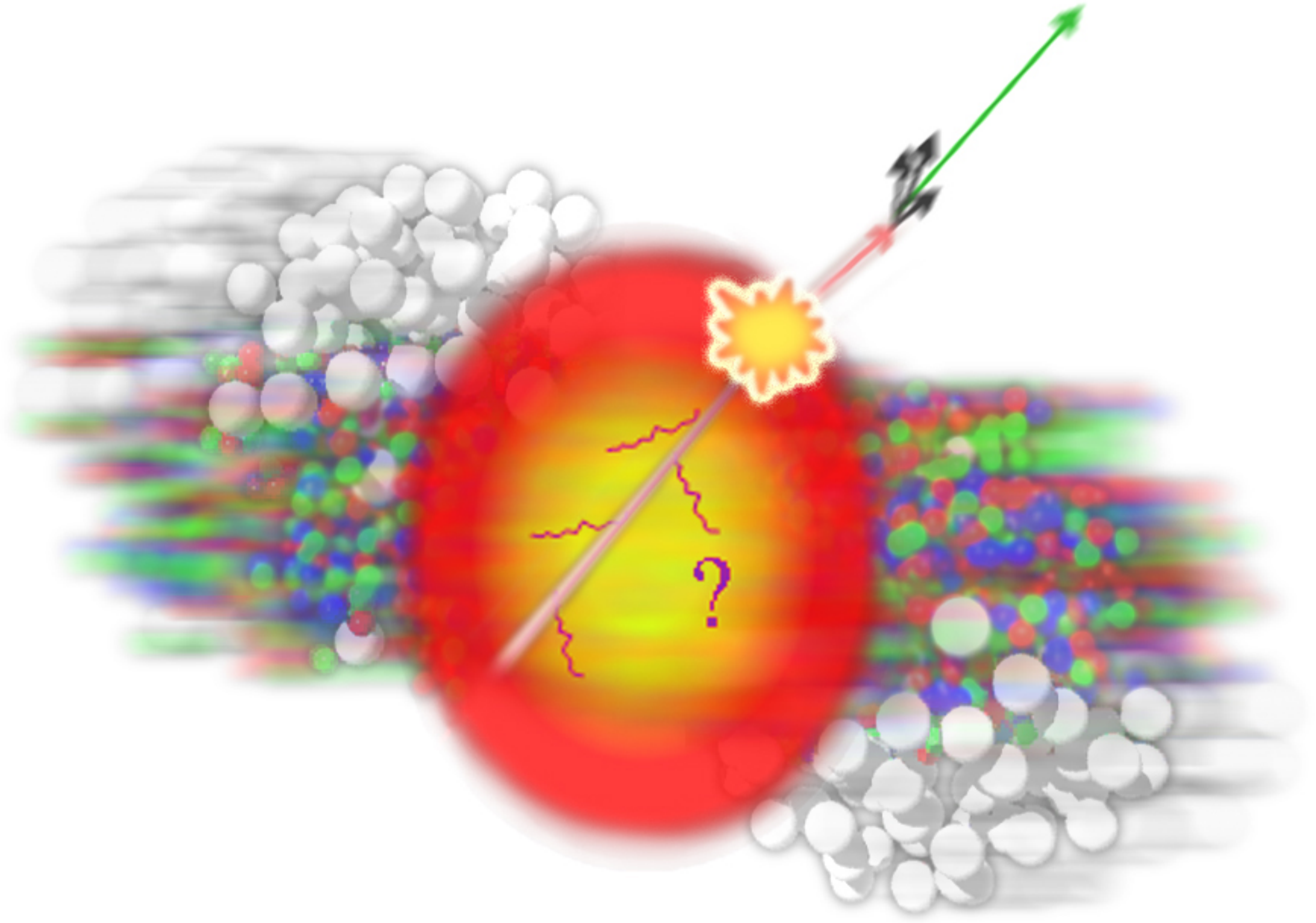
Significant **v_2 of D mesons** and **J/ψ** measured with Run 2 Pb-Pb data!

Indicates participation of low p_T charm to **collective motion** in the QGP

New results also on D_S (R. Arnaldi, next talk)

[X. Zhang, 6/7 15:00] *[R. Arnaldi, today]* *[I. Das, 6/7 9:30]*

Hard Processes



High momentum partons lose energy while propagating through the QGP ⇒ Jets "**quenched**" in Pb-Pb collisions

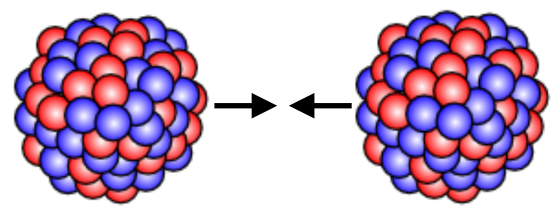
Simplest measurements: $\mathbf{R_{AA}/R_{pPb}}$

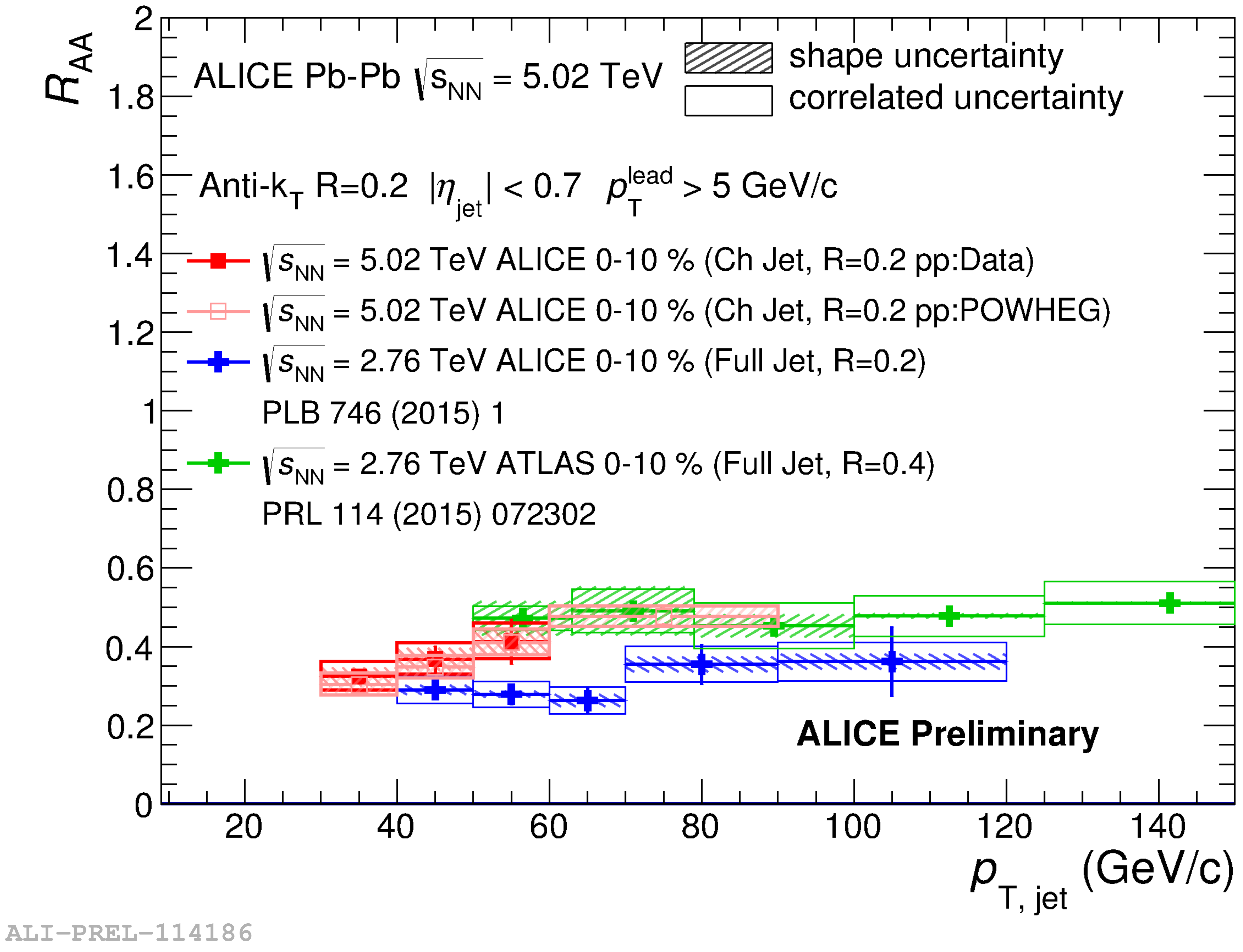
$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\text{scaled pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

Energy loss depends on **parton type** properties of the medium and can modify **color flow**

[R. Arnaldi, today]
[M. Nguyen, today]

[C. Nattrass, 7/7, 15:00]
[A. Shabetai, 6/7 11:30]
[X. Zhang, 6/7 15:00]





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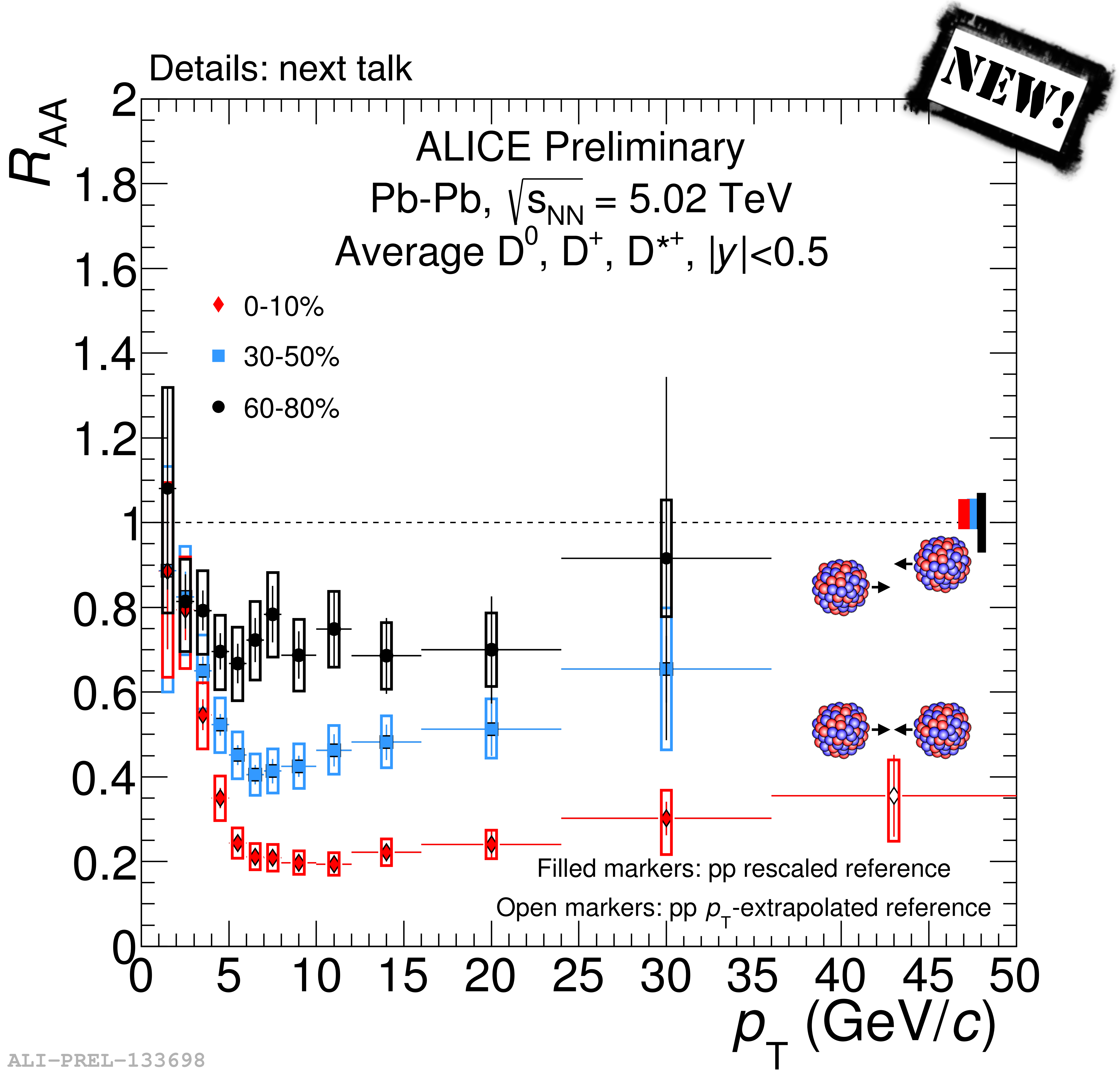
Jet quenching in Heavy-Ion



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[C. Nattrass, 7/7, 15:00]
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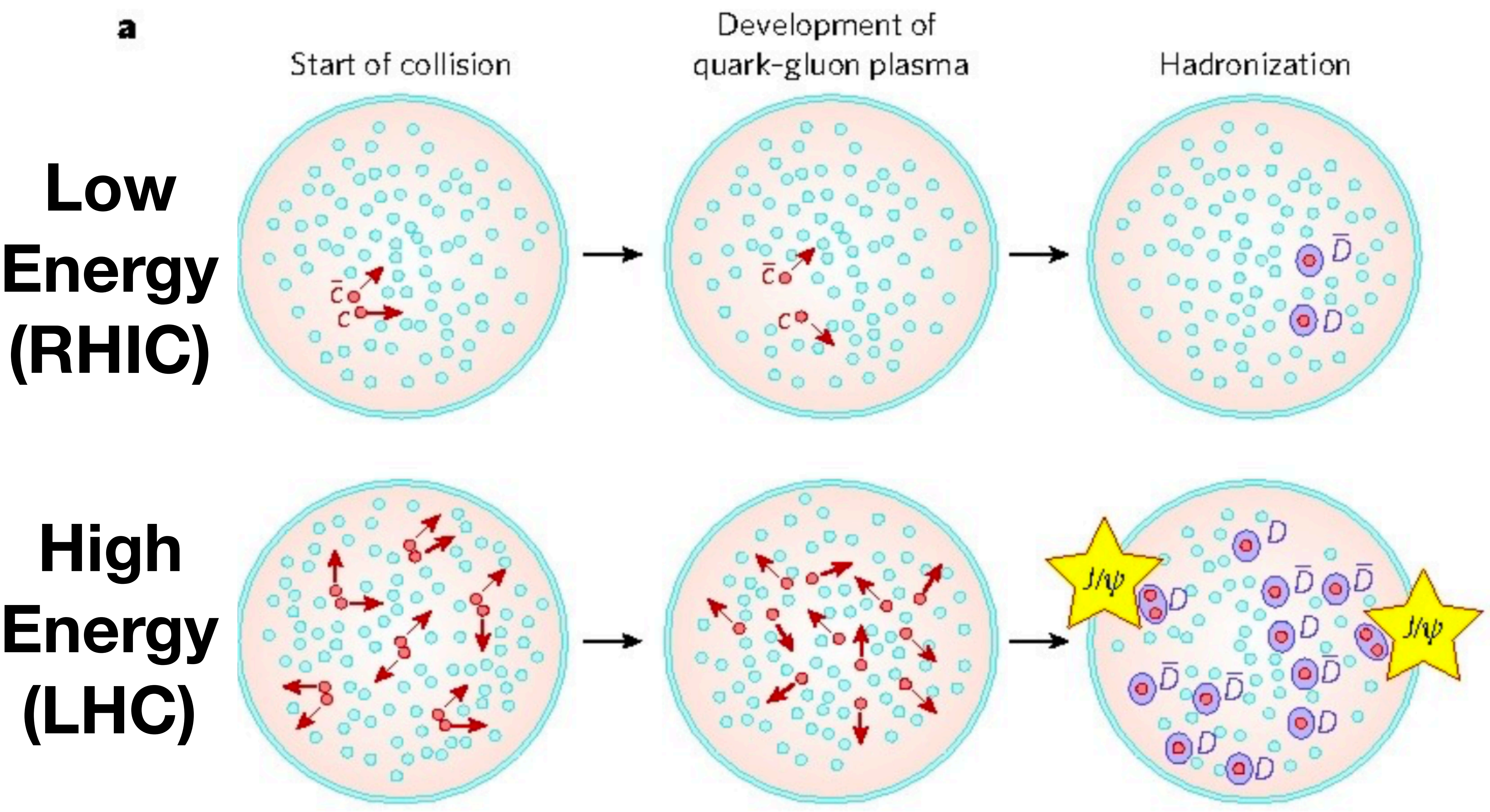
J/ψ R_{AA} in Pb-Pb



Time →

QGP **screens the $c\bar{c}$ interaction** ⇒ J/ψ **suppressed**

If many $c\bar{c}$ are created in the collision J/ψ can form via **quark (re)combination**

New results at $\sqrt{s_{NN}}$ = 5.02 TeV

[B. Paul, 6/7 10:30]

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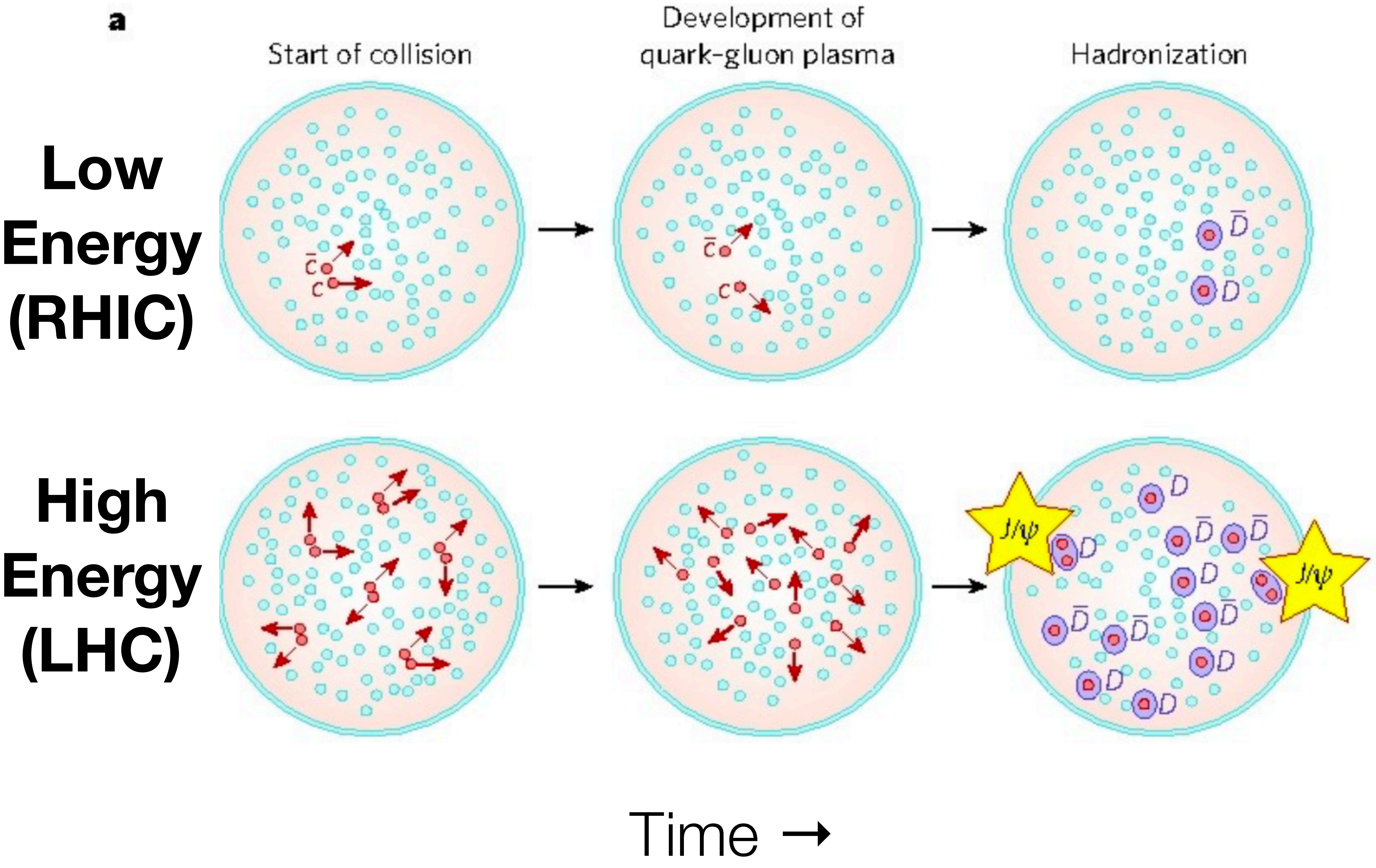

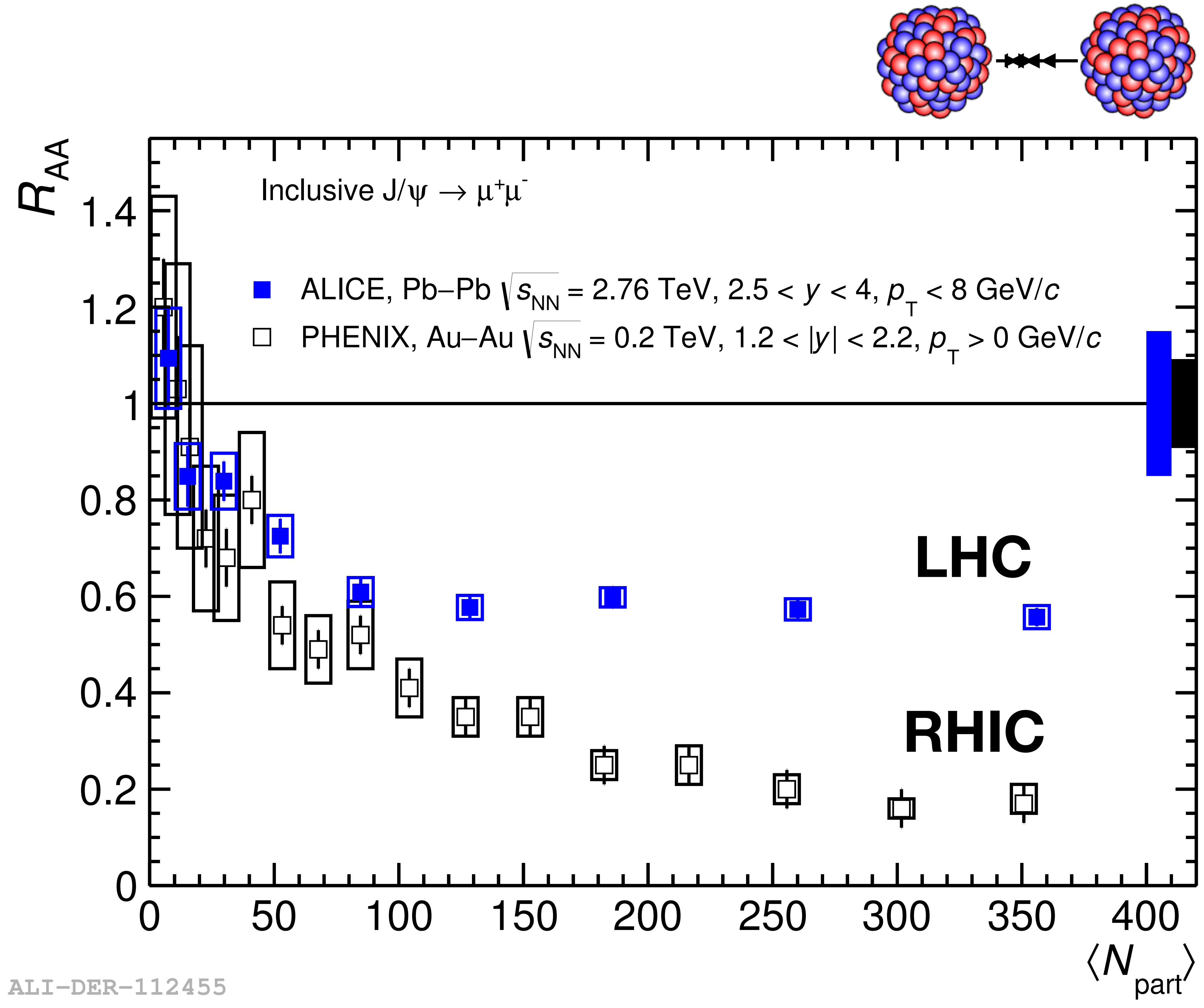

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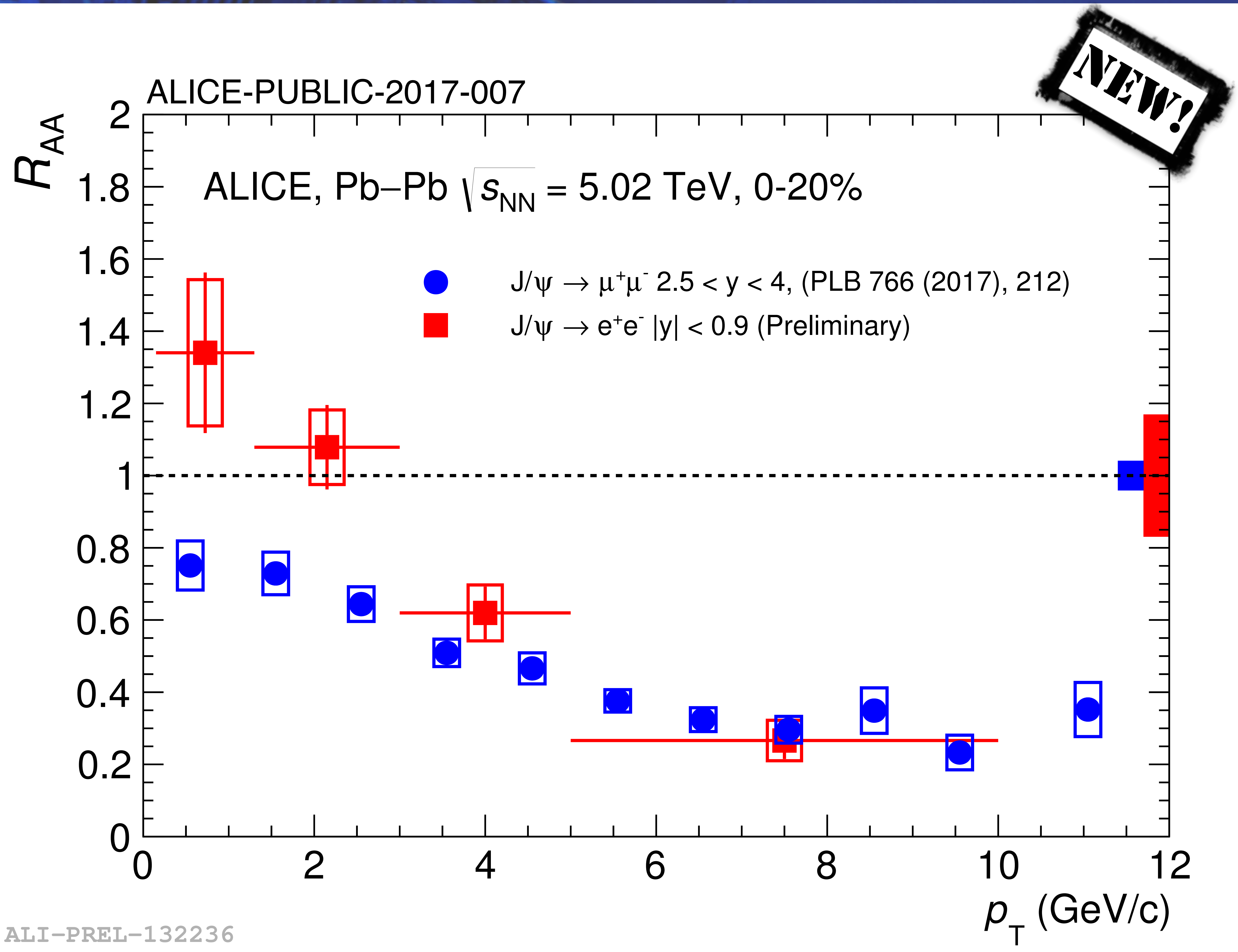
[B. Paul, 6/7 10:30]

Mid-y less suppressed than **forward-y**

Low p_T: Smaller suppression
(and weak centrality dependence, not shown)

More charm quarks at low p_T
and mid-rapidity



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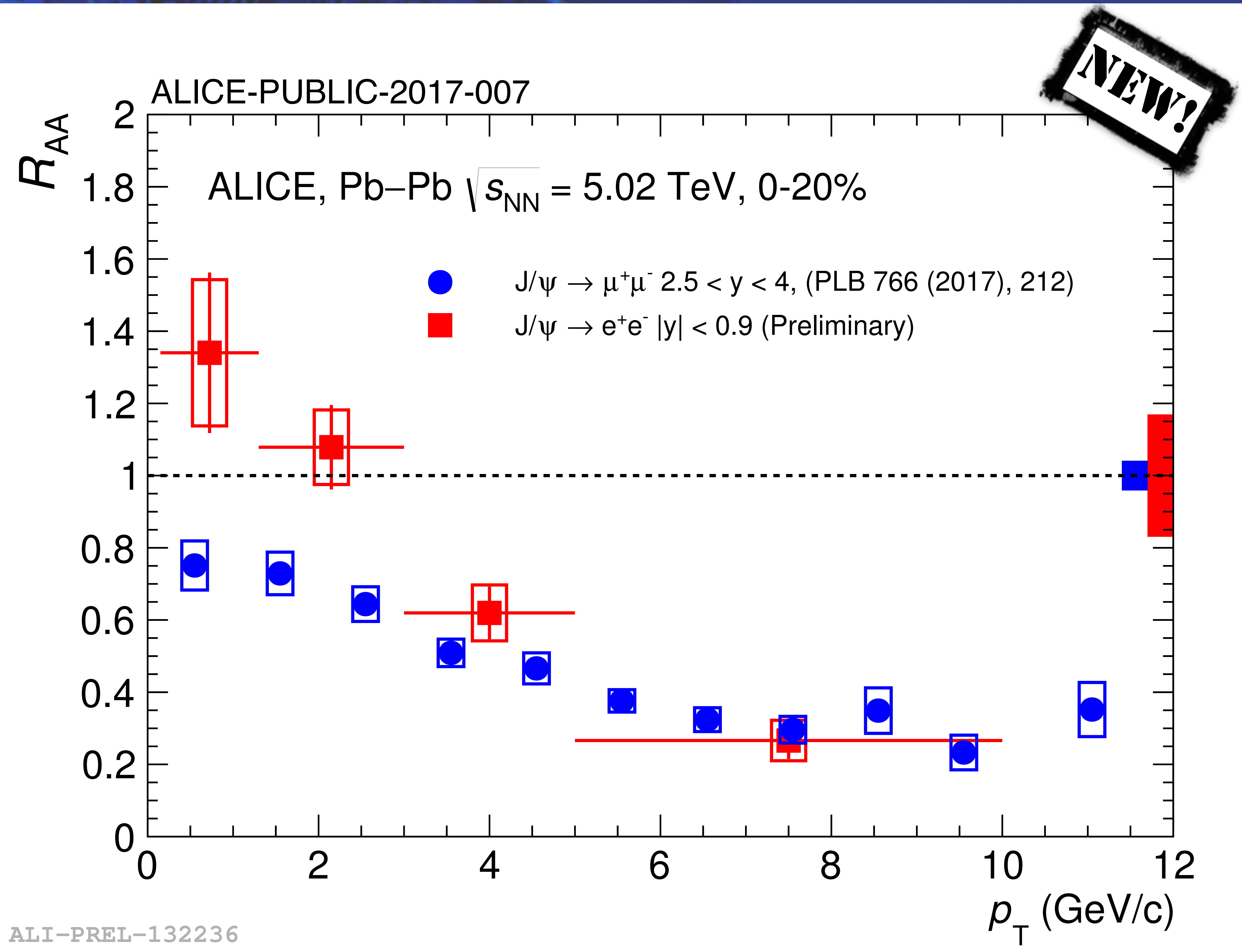
Consistent with (re)combination scenarios



[B. Paul, 6/7 10:30]

Jets Shapes and Jet Substructure

Jet shapes are constructed taking a weighted sum over the 4-momenta of all jet constituents

Information on:

- parton-to-jet **fragmentation**
- intra-jet distributions (**broadening, collimation**)
- **quark/gluon** differences

[C. Nattrass, 7/7, 15:00]
[G. Milhano, 7/7 14:30]
[M. Nguyen, today]

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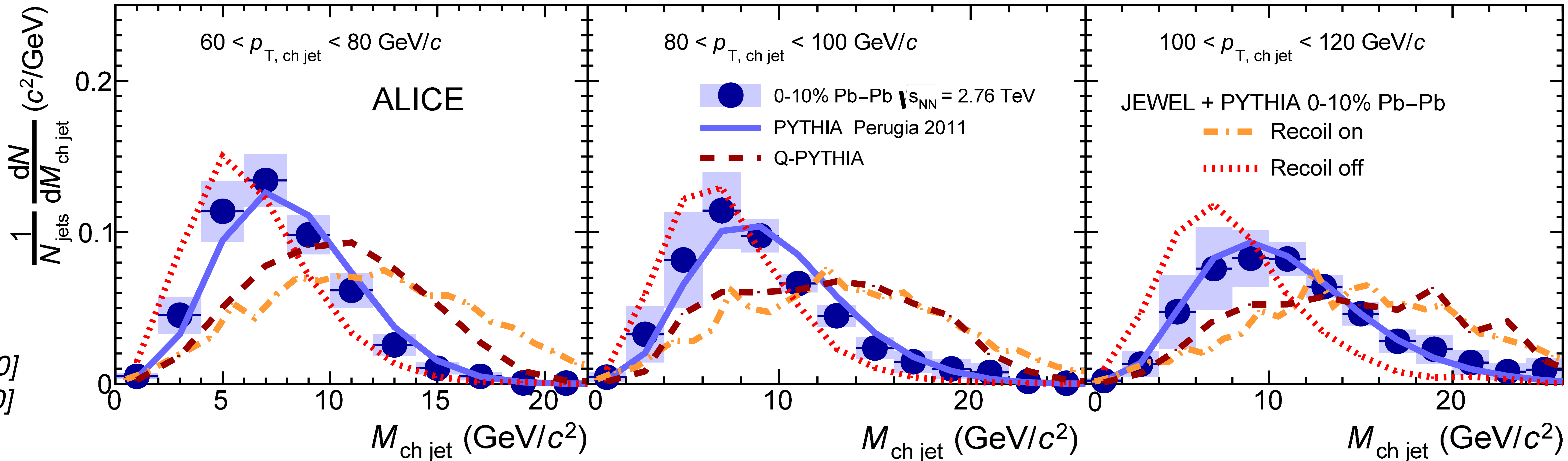
Agreement PYTHIA / Pb-Pb data: no mass modifications, lack of intrajet broadening

Hint for slightly more collimated jets (see also other jet shapes)



arXiv:1702.00804

[C. Nattrass, 7/7, 15:00]
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[M. Nguyen, today]

Energy loss in p-Pb?

Many **similarities** between pp/p-Pb/Pb-Pb: **is there also jet quenching in small systems?**

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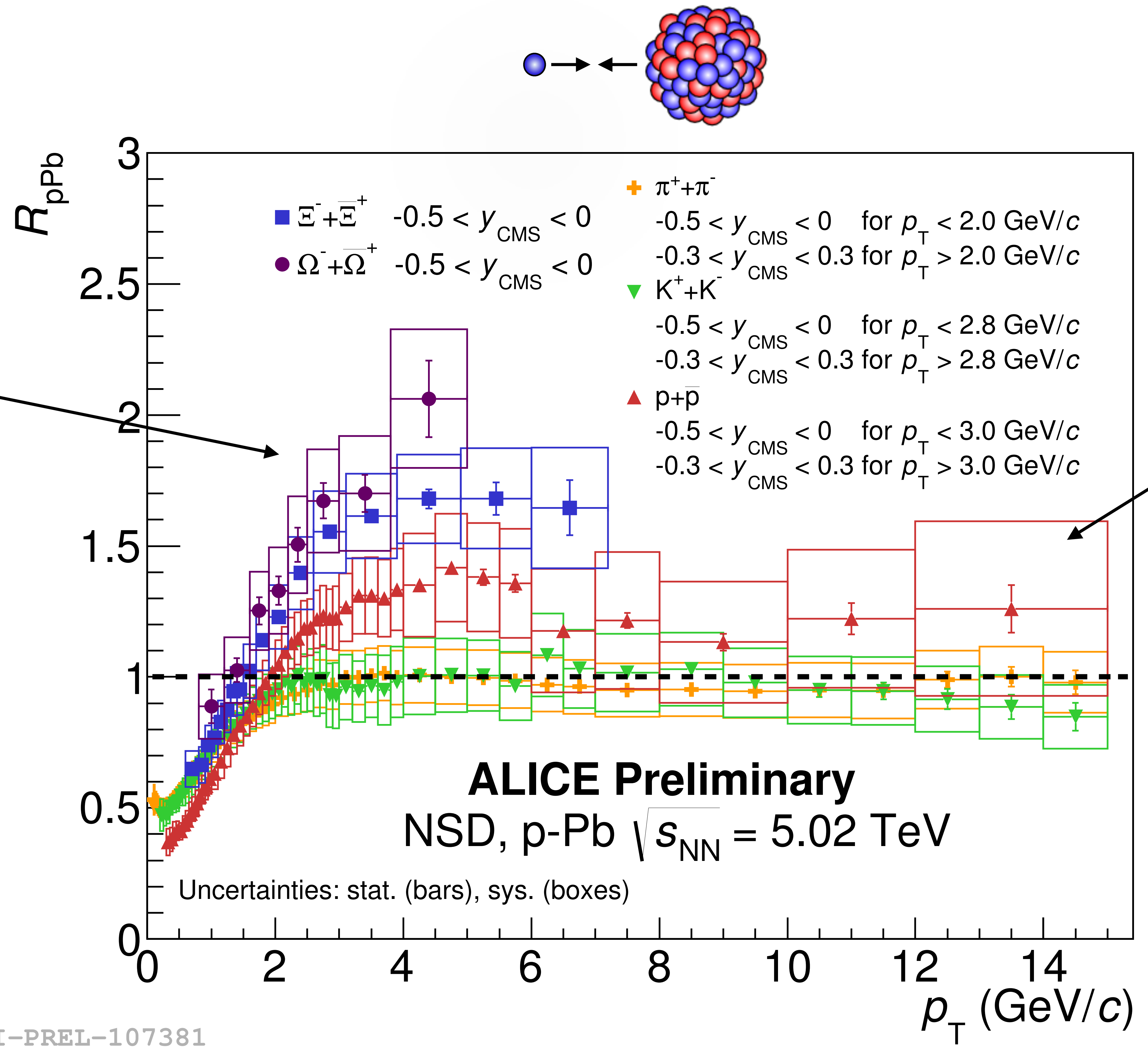
modification expected in case of flow



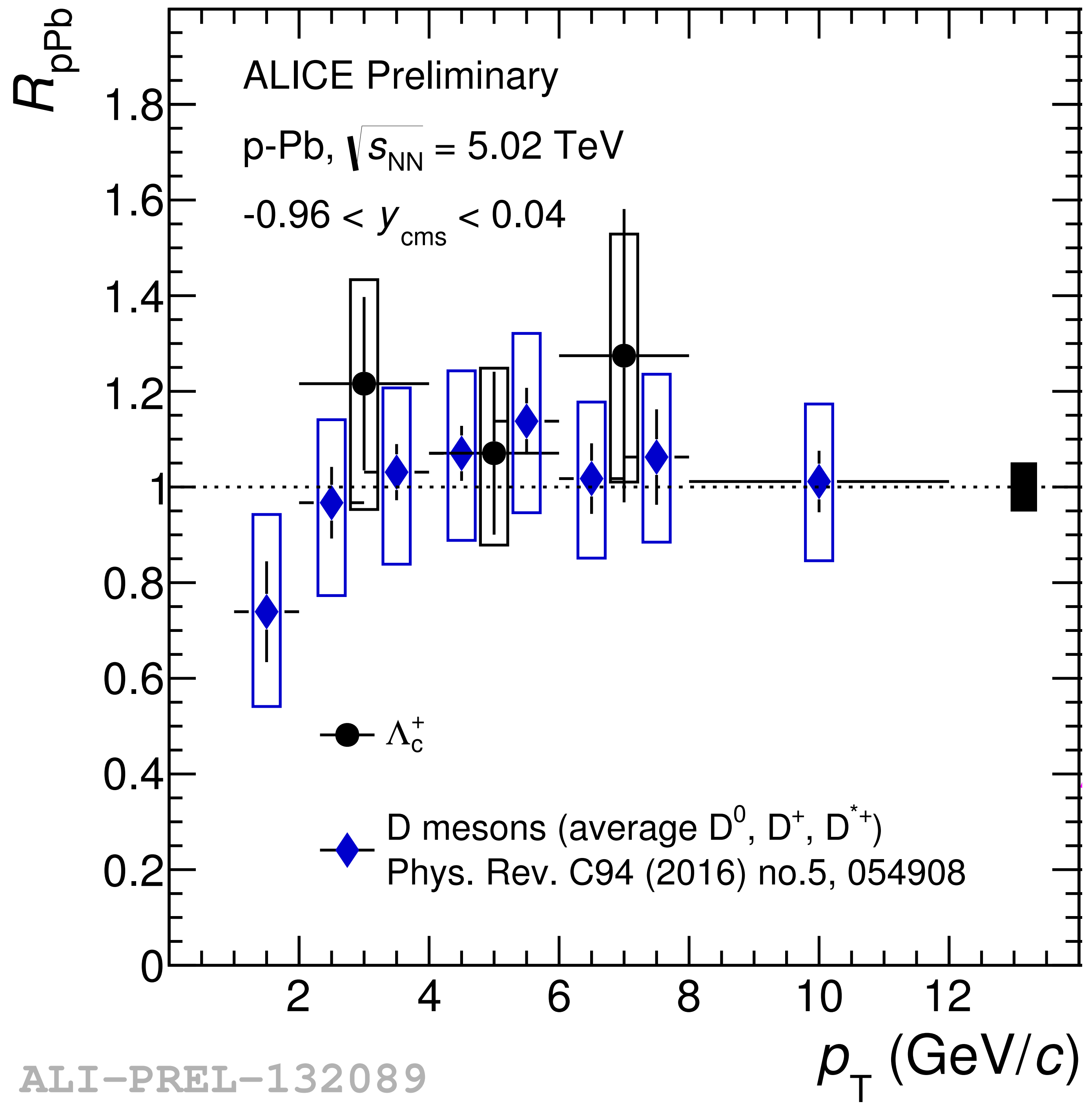
modification expected in case of jet quenching

No evidence for suppression in p-Pb (so far)

New measurement of ***D*** *R_{pPb}* and **first measurement** of the **Λc** *R_{pPb}*

NEW!

Λc and ***D*** R_{pPb} compatible



ALICE-PUBLIC-2017-008
[C.Terrevoli, 6/7 15:45]

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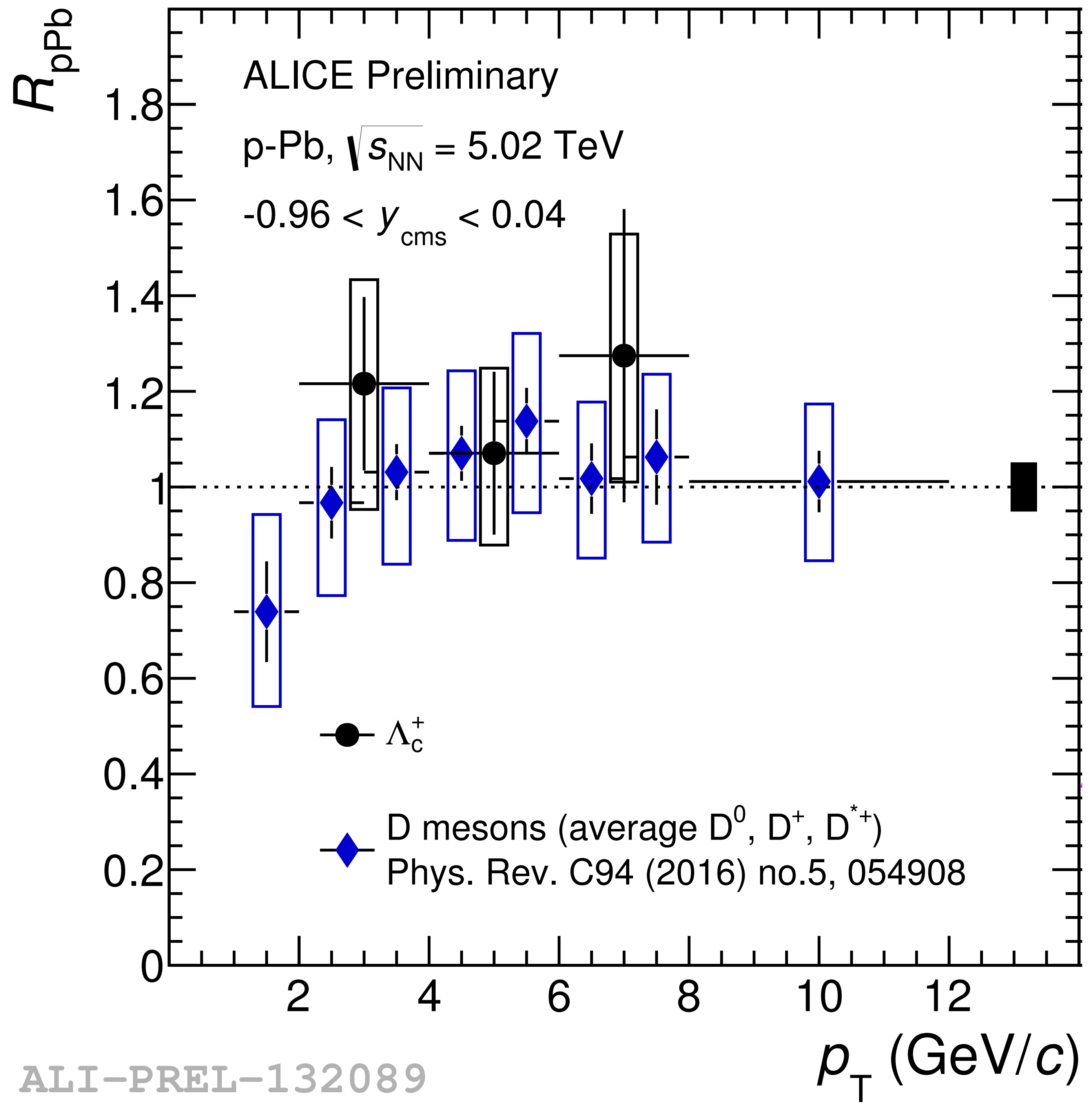
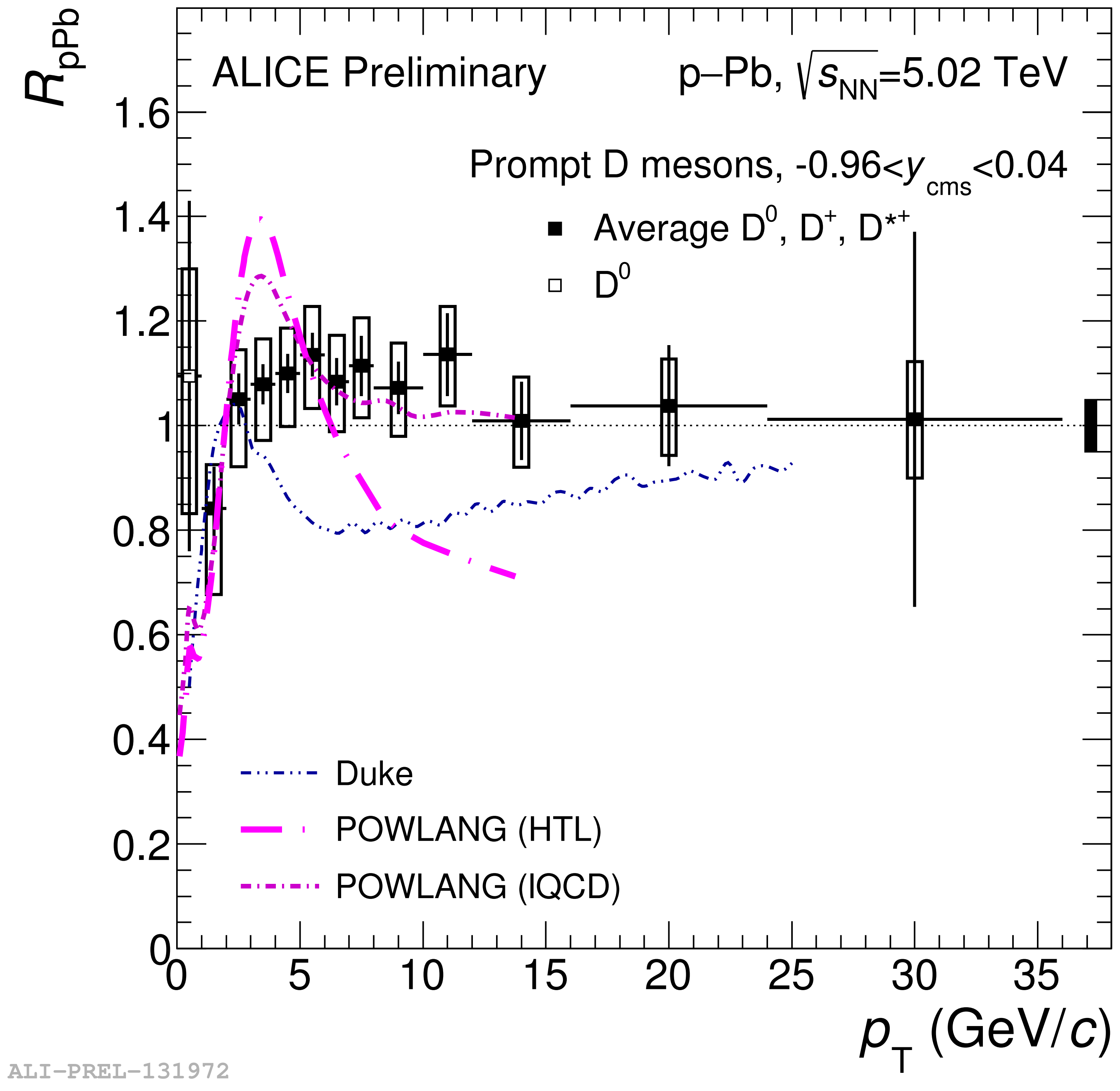


D meson R_{pPb} vs models

Medium effects



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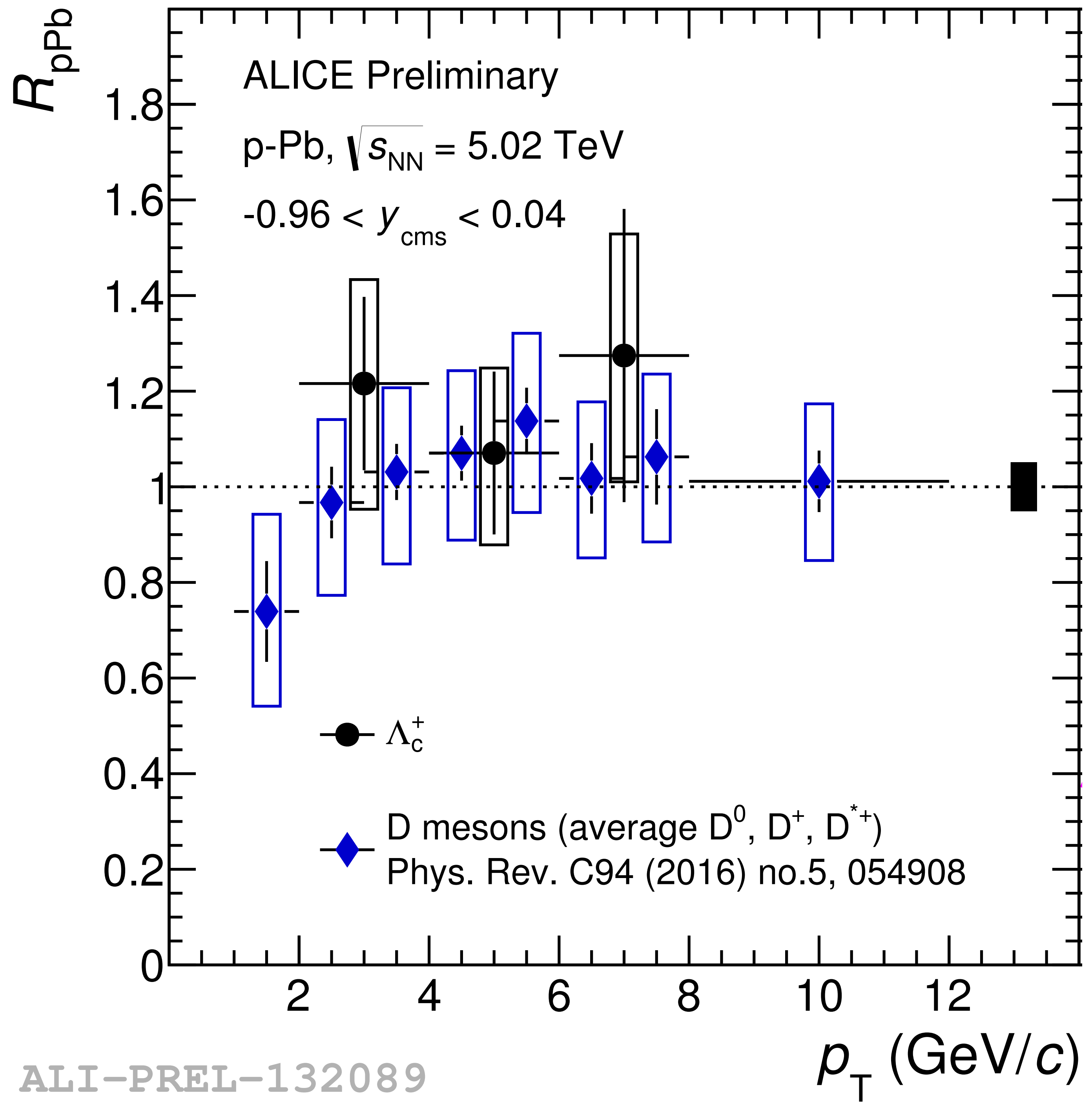

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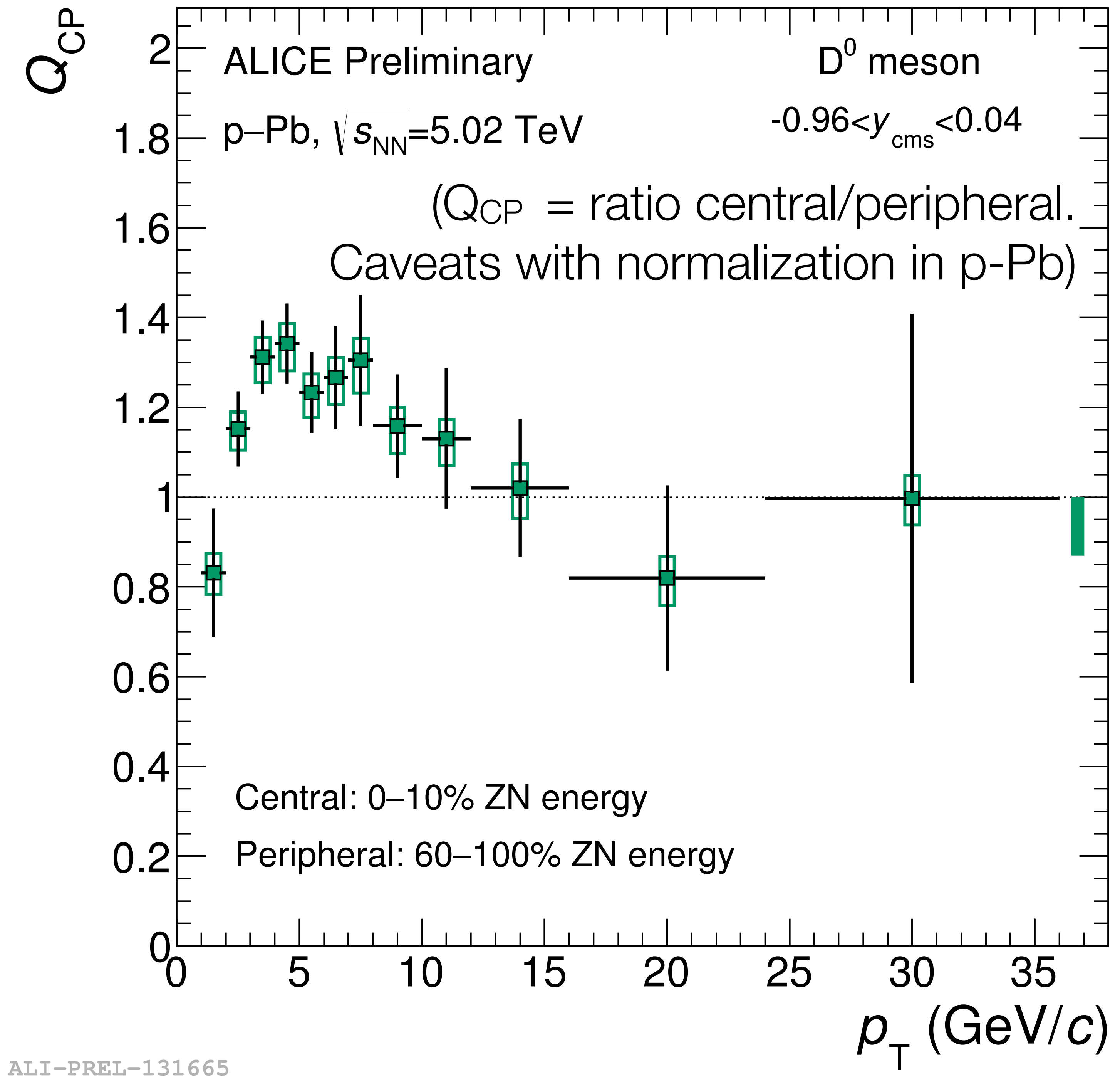

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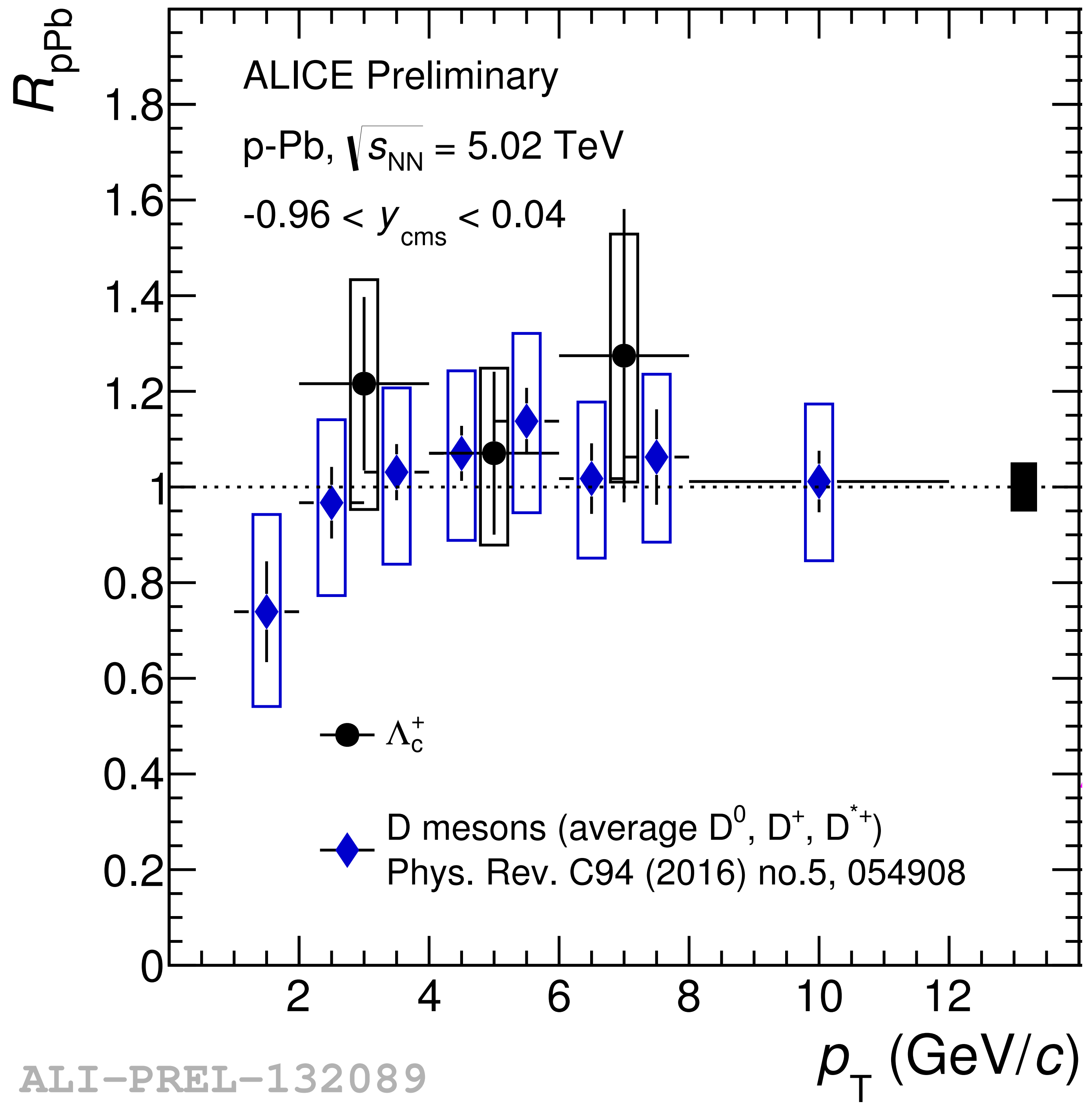

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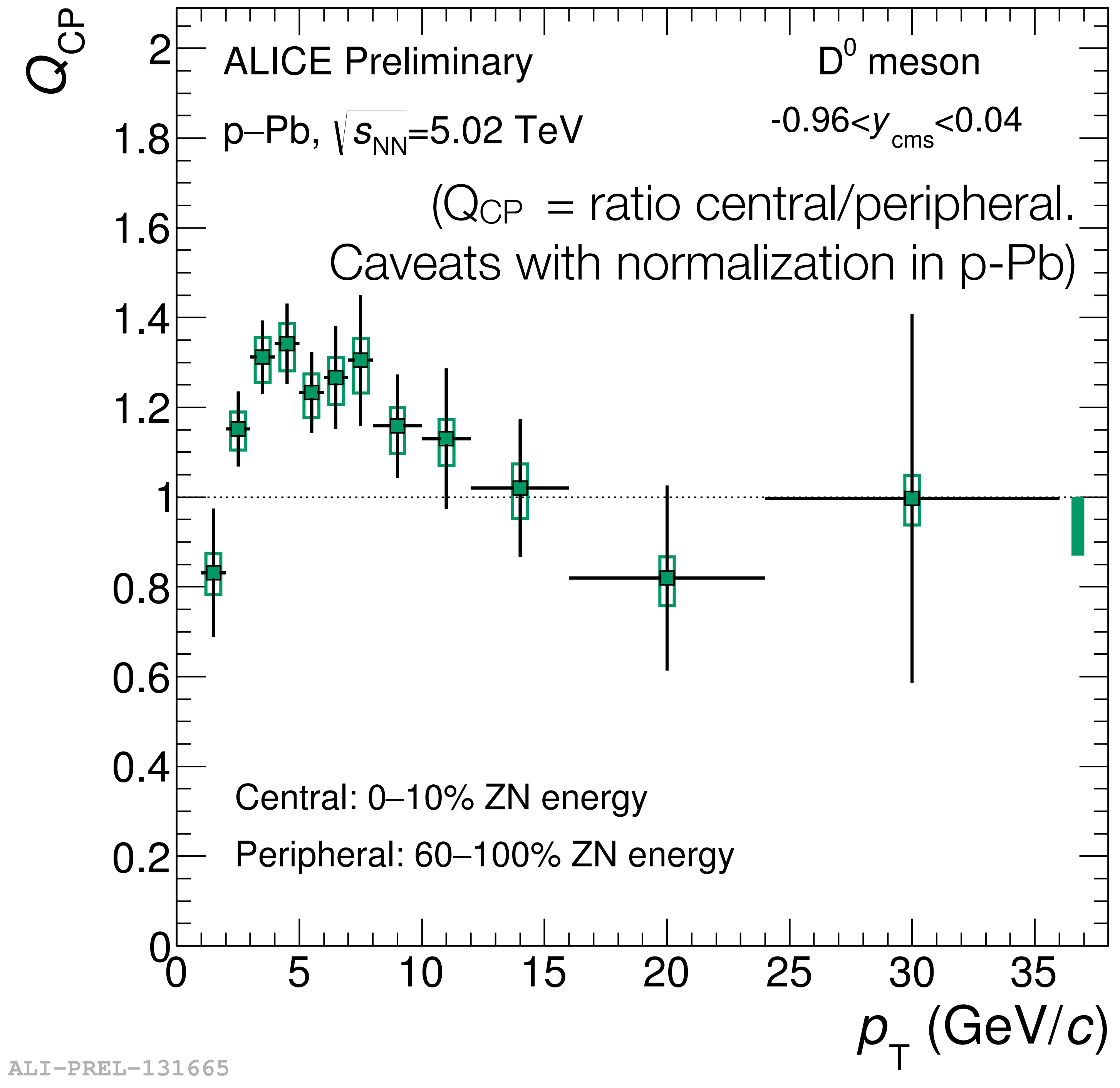
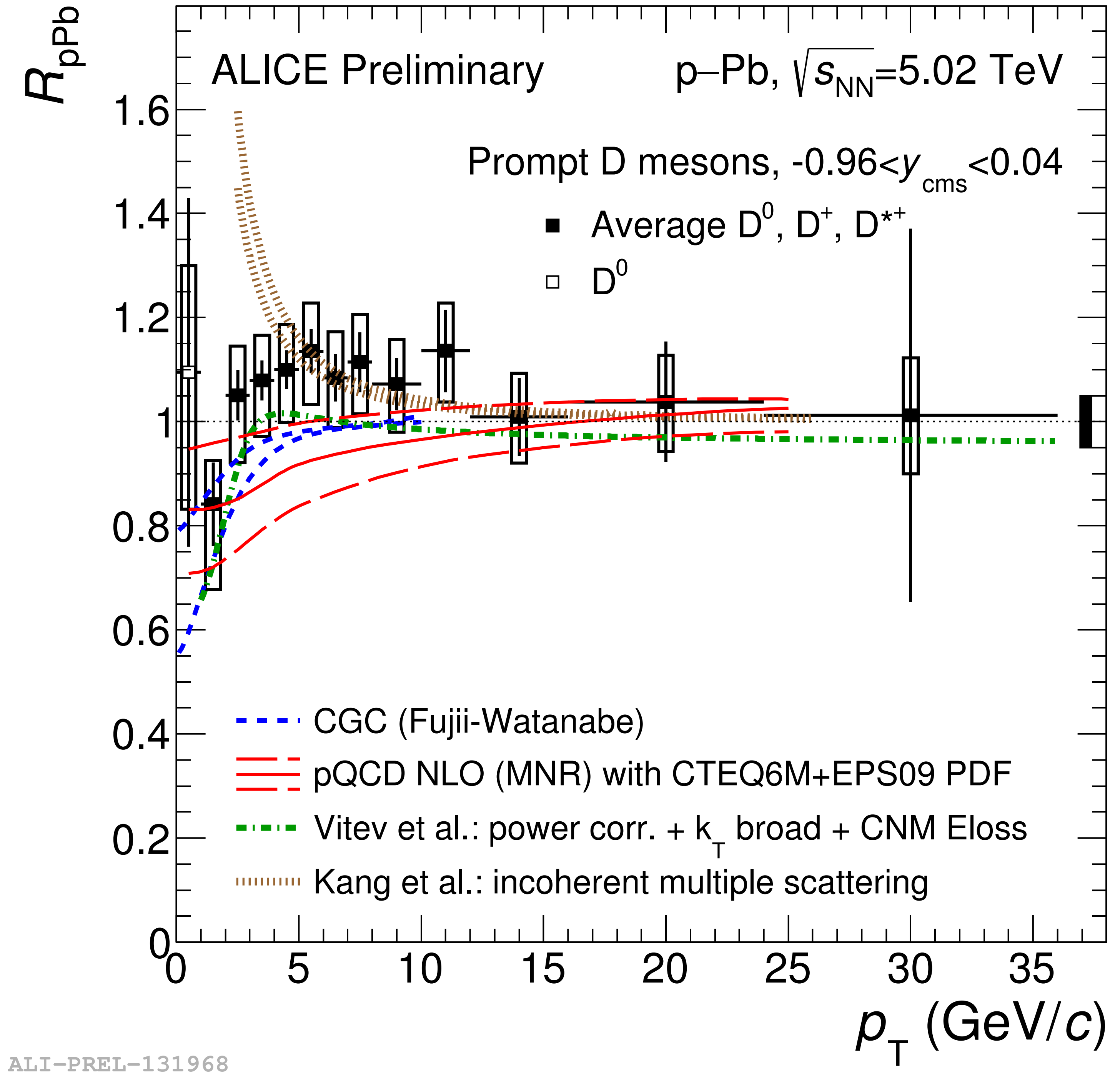
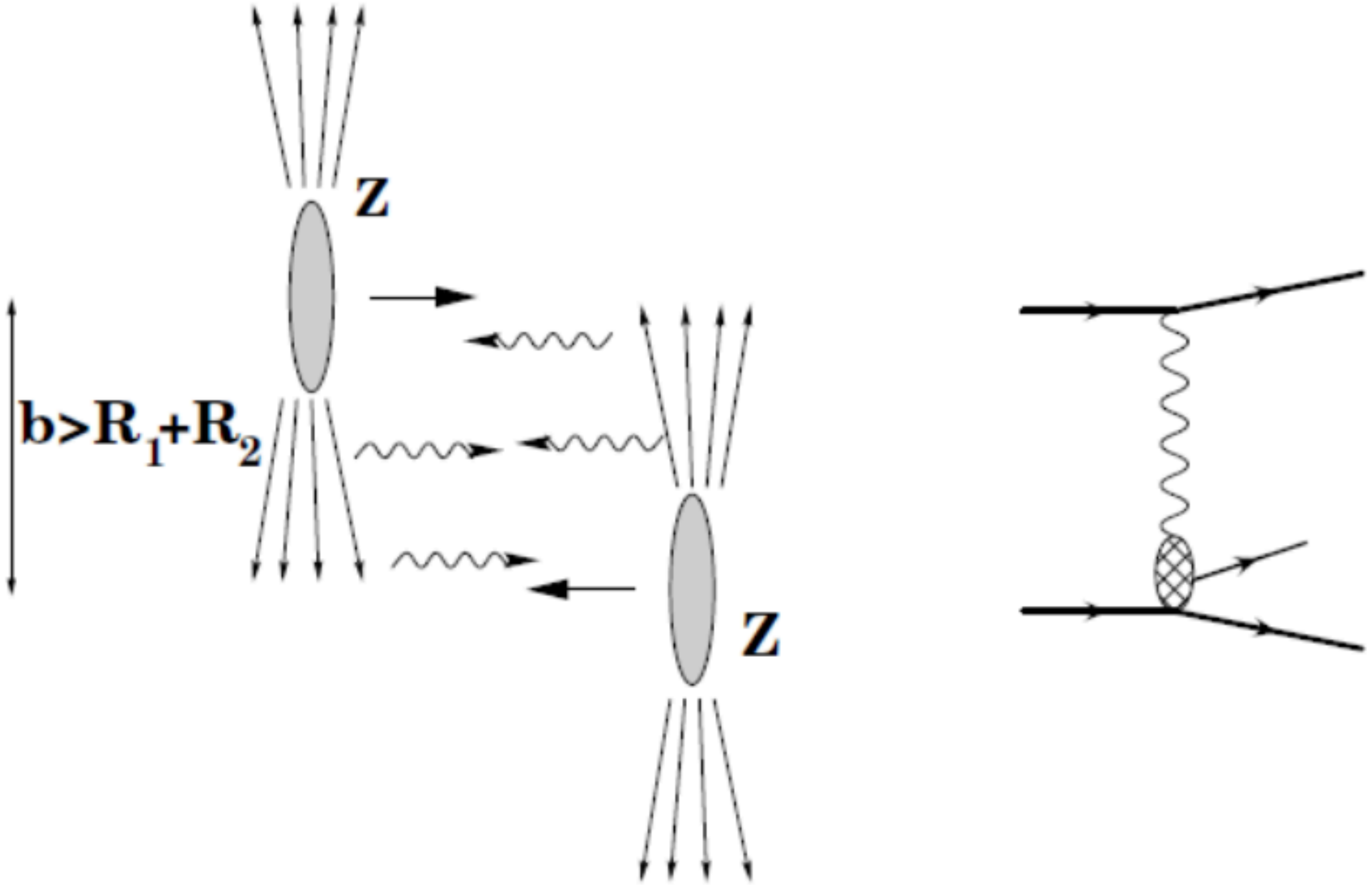


“Cold Nuclear Matter” effects (e.g. shadowing)



ALICE-PUBLIC-2017-008

[C.Terrevoli, 6/7 15:45]



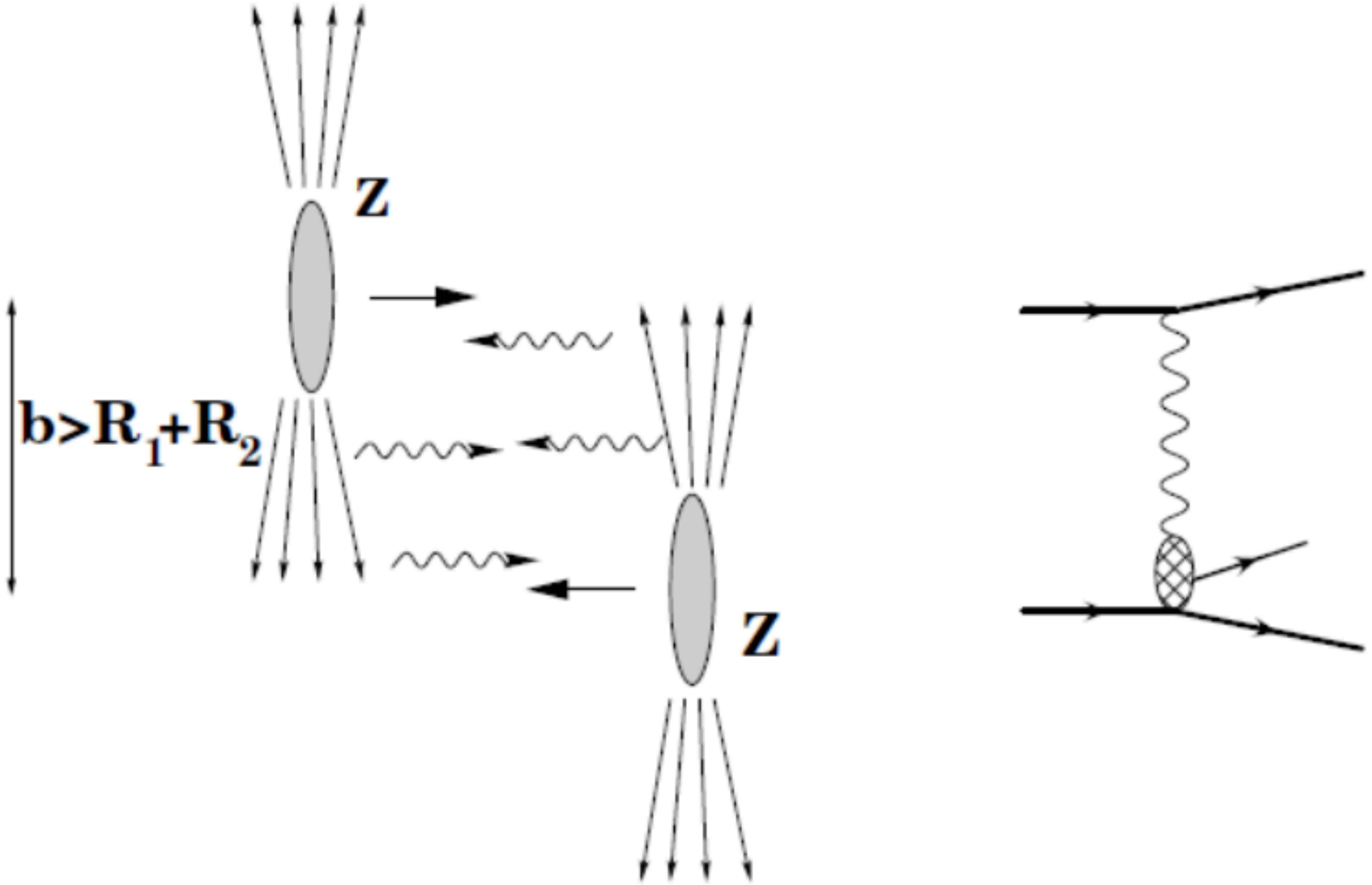
Ultra Peripheral Collisions (UPC): collisions with b > 2 × Lead Radius

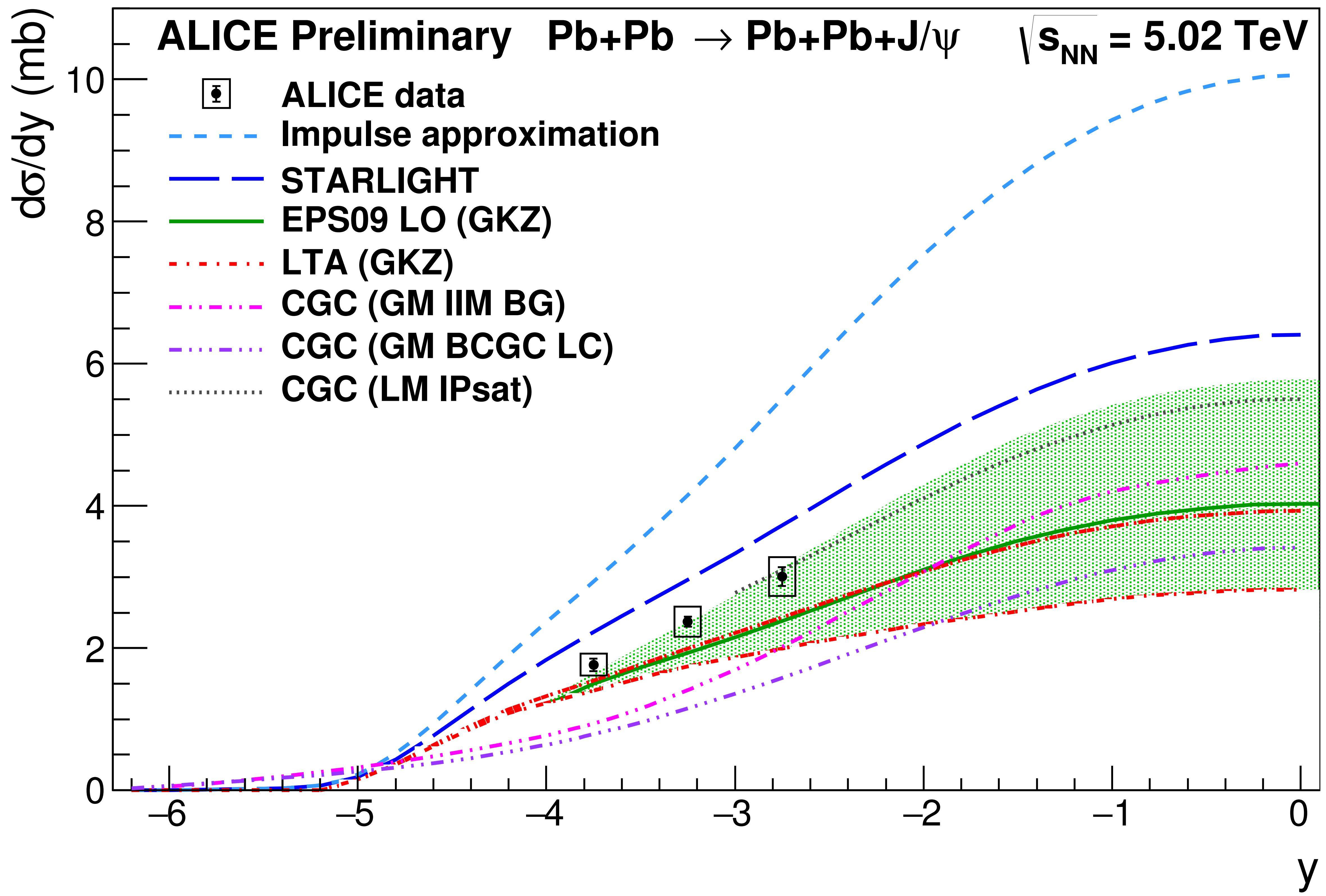
γ – Nucleus interaction: clean probe and information on nuclear effects (e.g. shadowing)

Indicate moderate shadowing

[V. Pozdniakov, 6/7 18:15]

Ultra Peripheral Collisions





ALI-DER-117542

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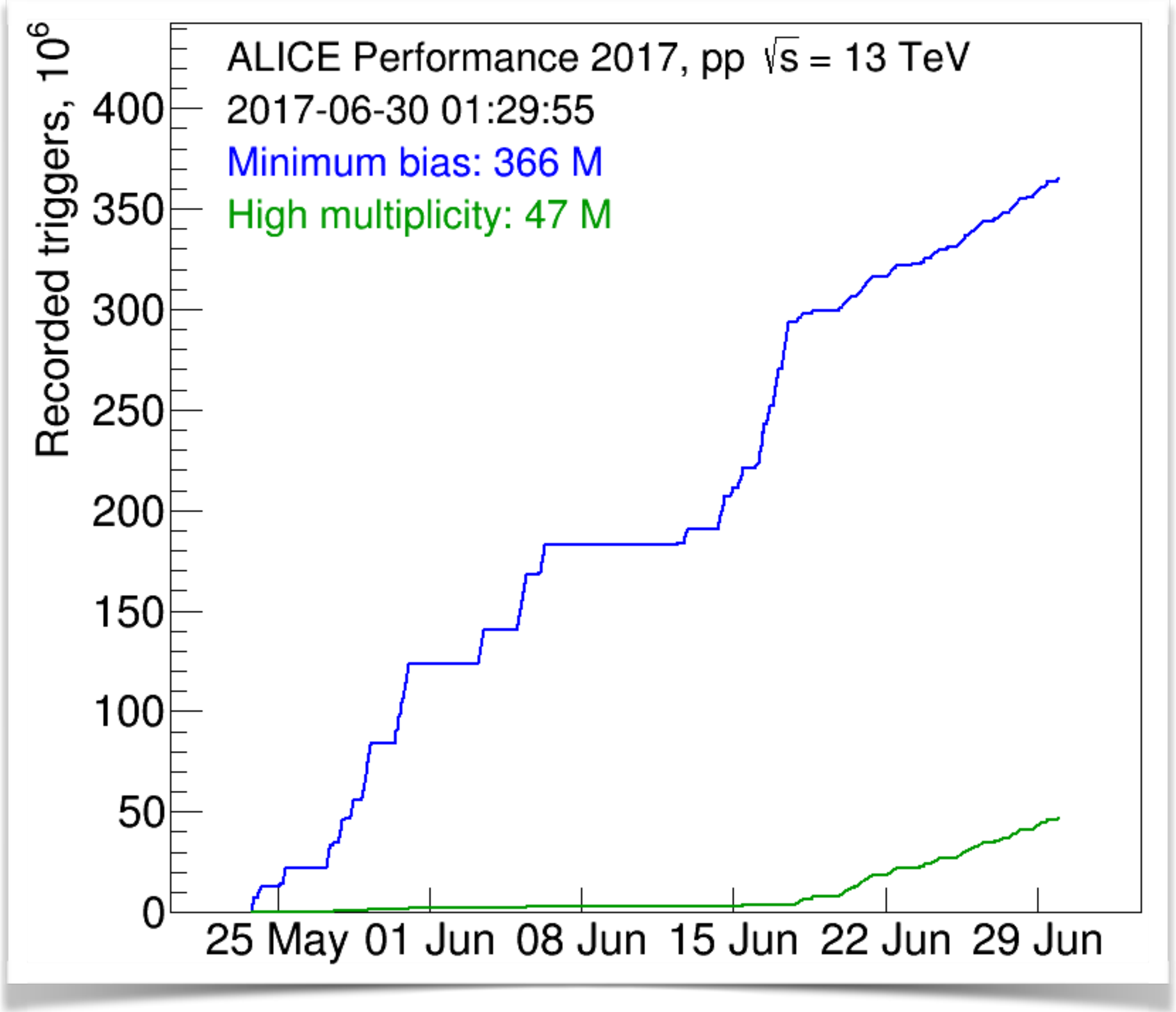
[V. Pozdniakov, 6/7 18:15]

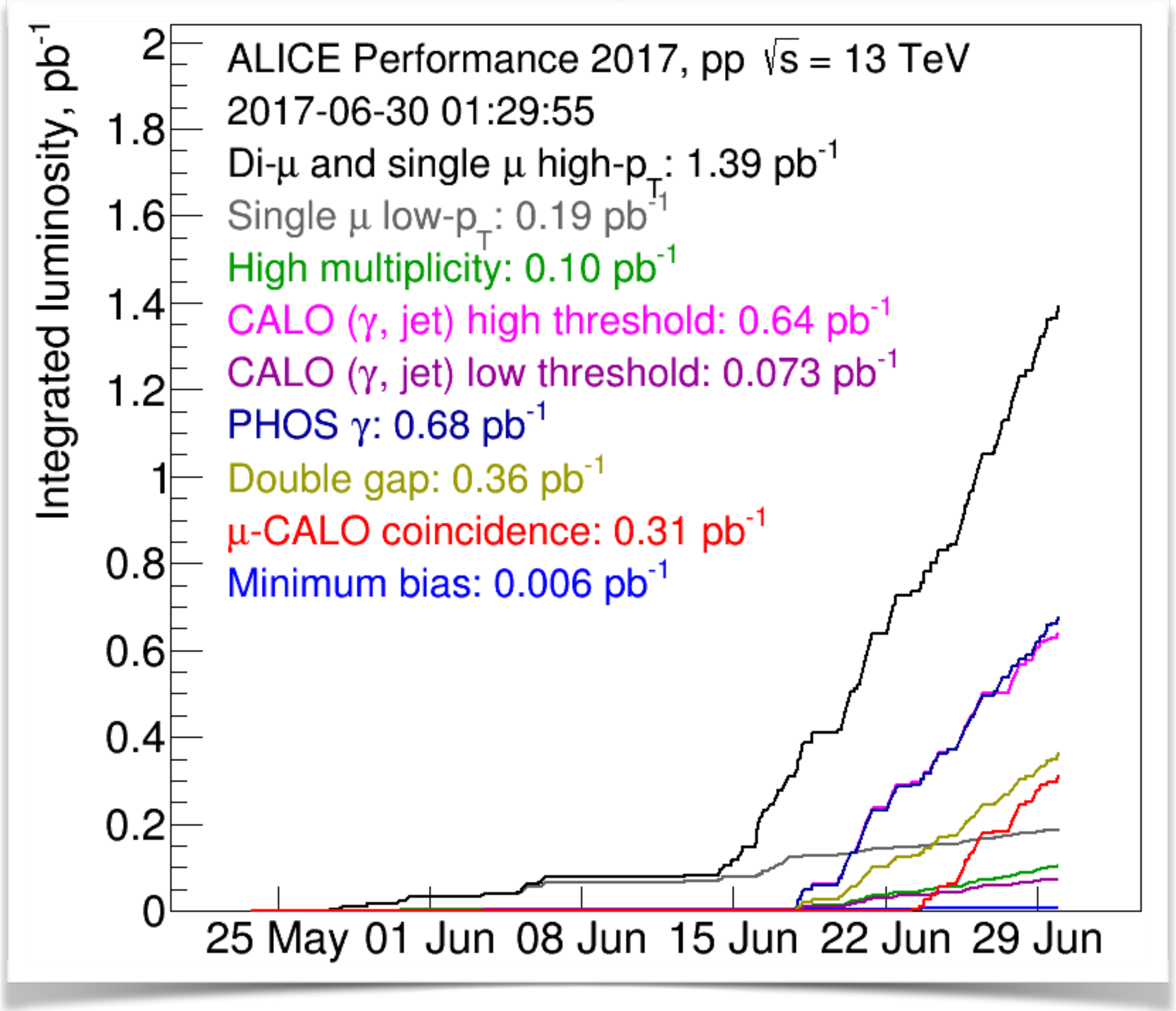
Data taking and upgrade

Run 2: Collected (Goal)

	pp, 5 TeV	pp, 13 TeV	p-Pb, 5 TeV	p-Pb, 8 TeV	Pb-Pb 5 TeV
L_{int}	112 nb^{-1} (1 pb^{-1})	14 (50) pb^{-1}	3.4 nb^{-1}	21 nb^{-1}	250 μb^{-1} (1 nb-1)
N_{MB}	128 (1000) M	1.5 G (3.7 G)	764 M	70 M	157M (250M)
N_{HM}	N/A	814 M (2.5 G)	N/A	47 M	(200 M)

Data Taking in 2017





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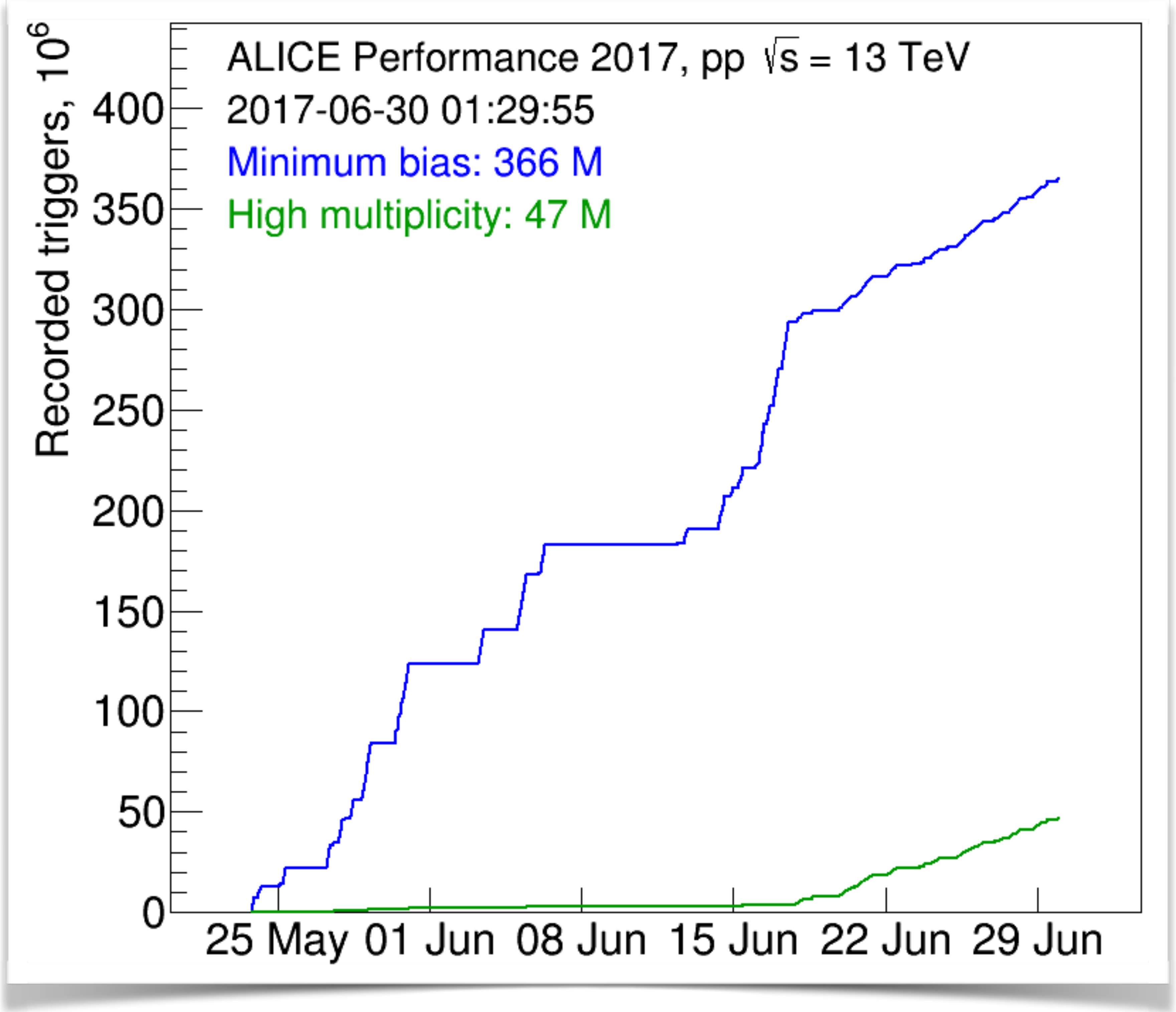
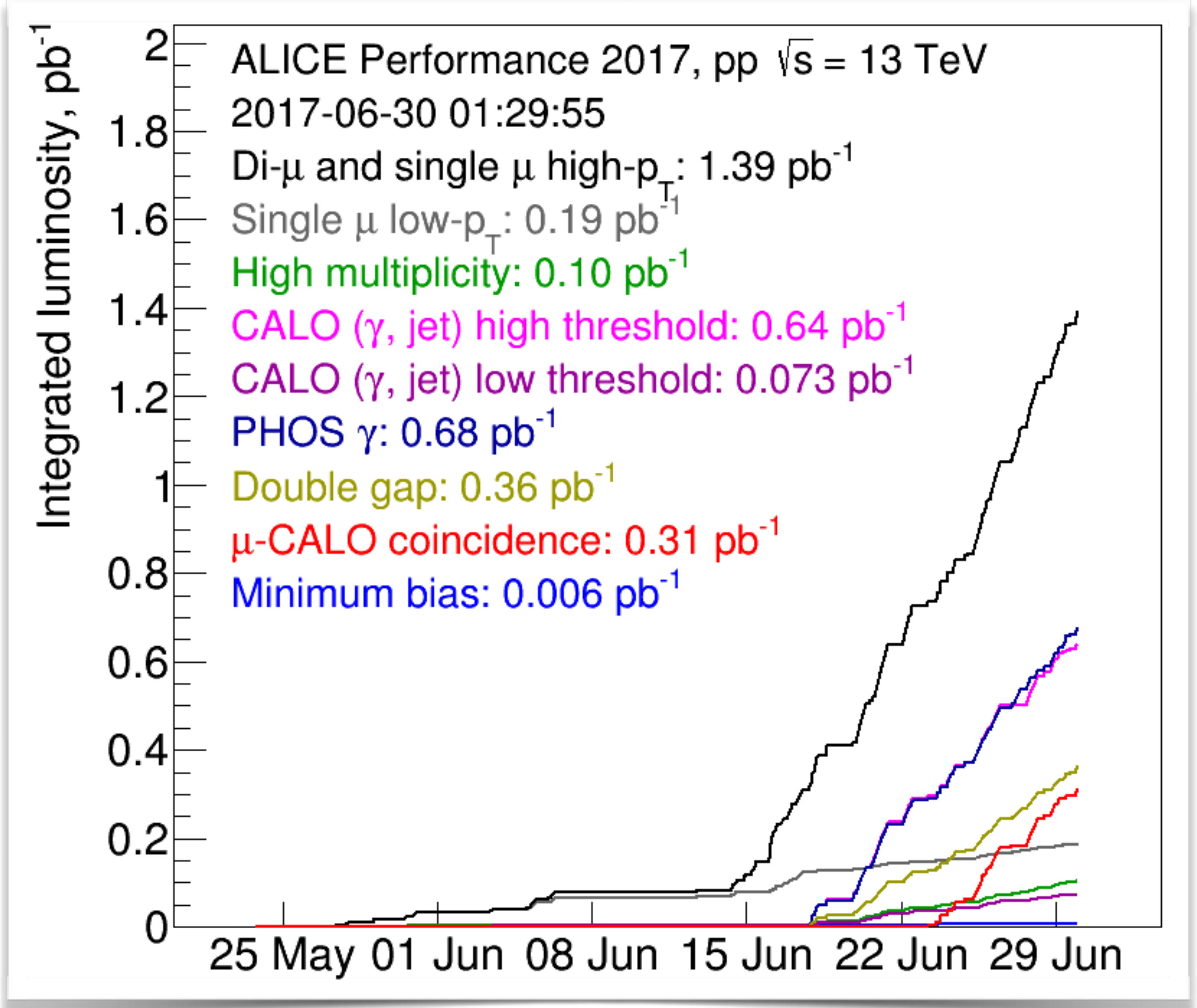




Goals: study **rare low p_T** probes (heavy flavor, low mass dielectrons, nuclei): **Cannot be triggered!**

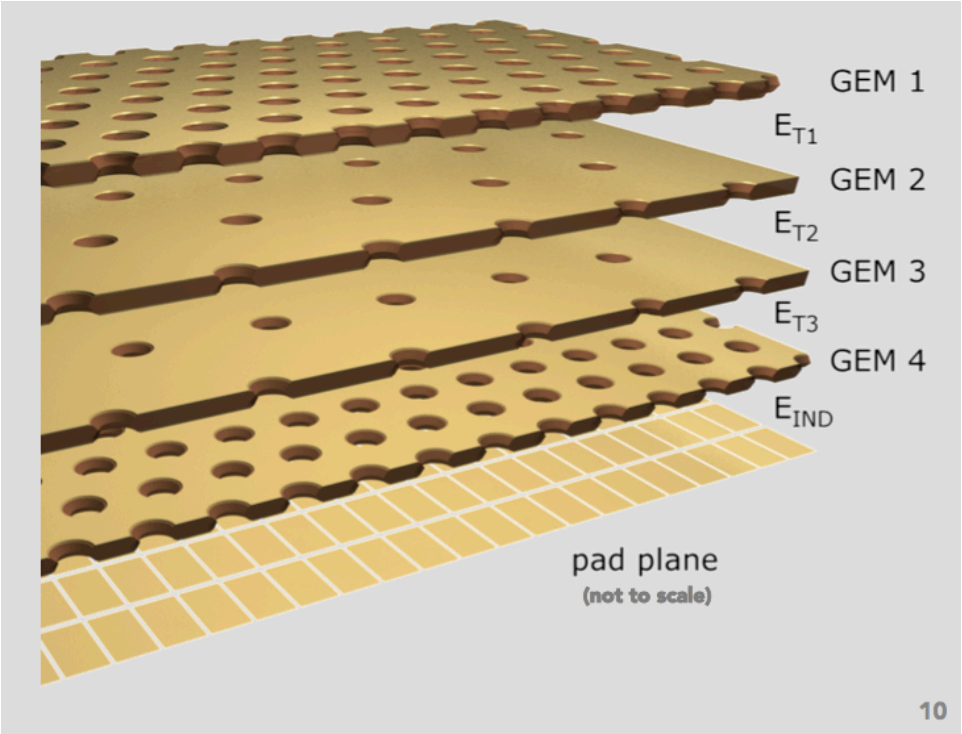
⇒ **Continuous readout** and data reduction via (semi)**online reconstruction**

Several detector, electronics and computing **upgrades**

Deployment: LS2 (2019-2020), **Data taking: Run 3-4** (2021-2029)

TPC:

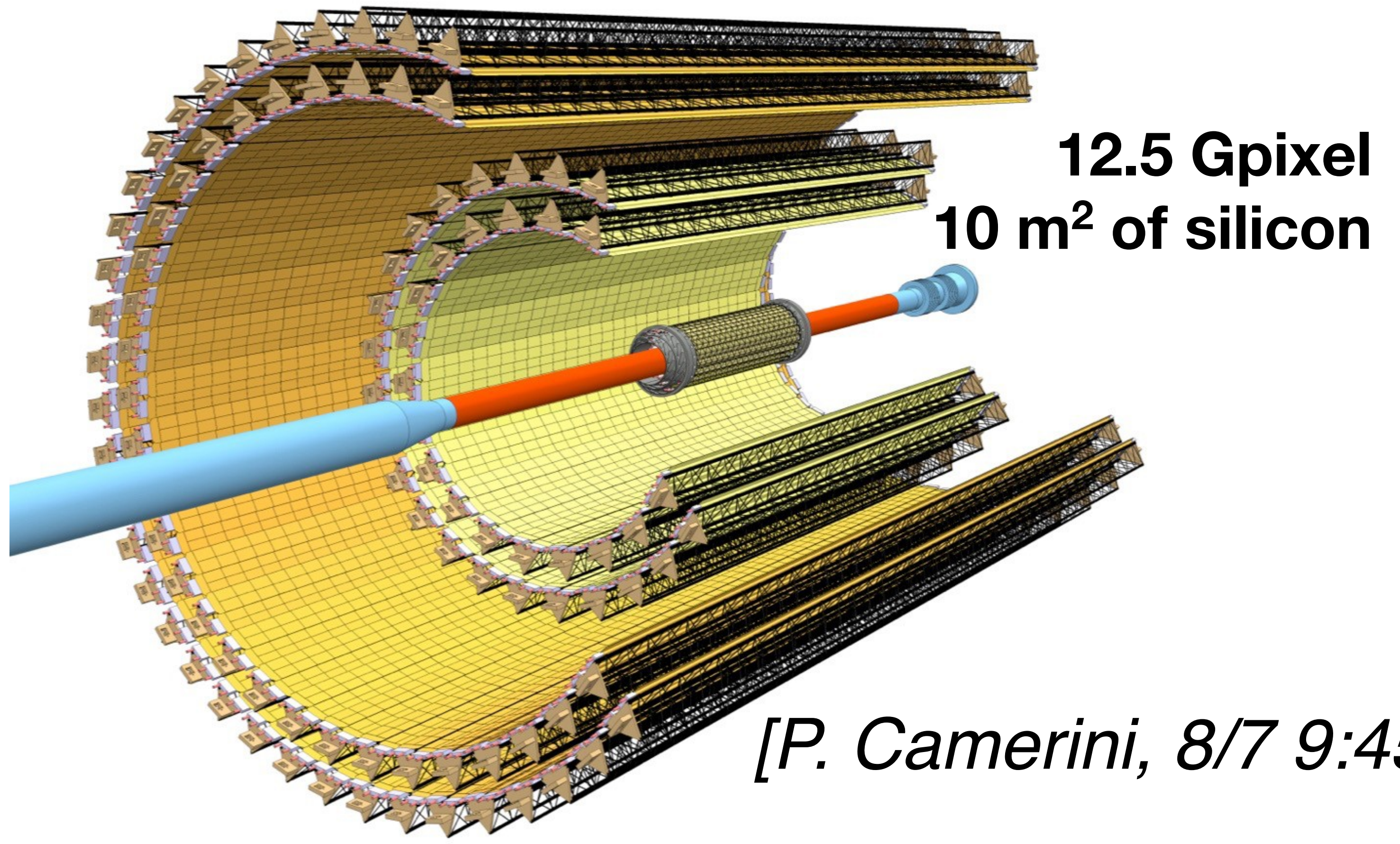
Main ALICE Tracker
4-GEM stack for endcaps
(suppress ion back flow with continuous operations)



[C. Lippmann, 8/7 10:00]

Inner Tracker:

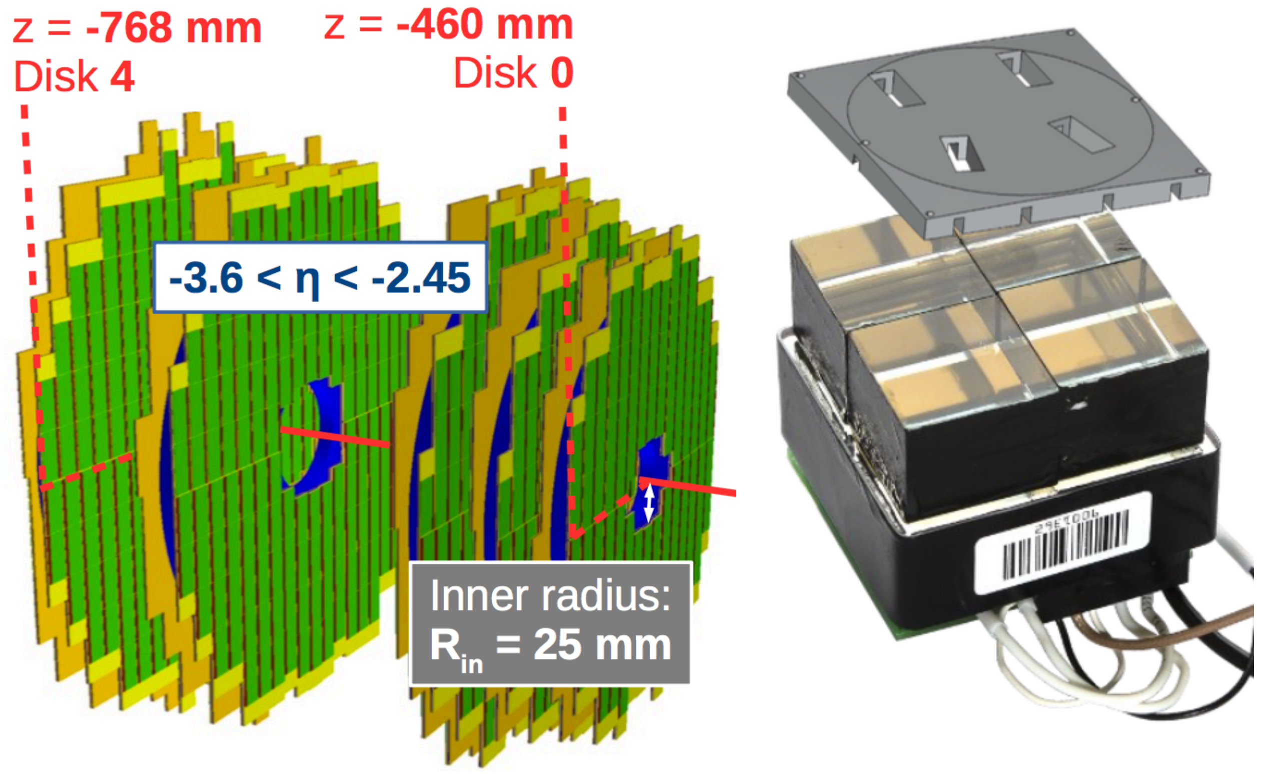
Low p_T tracking
Monolithic Active Pixel Sensors,
very low material budget
(0.3%-1%) X_0



[P. Camerini, 8/7 9:45]

Forward detectors:

FIT for trigger and centrality,
Silicon in the forward region to add vertexing to the muon arm



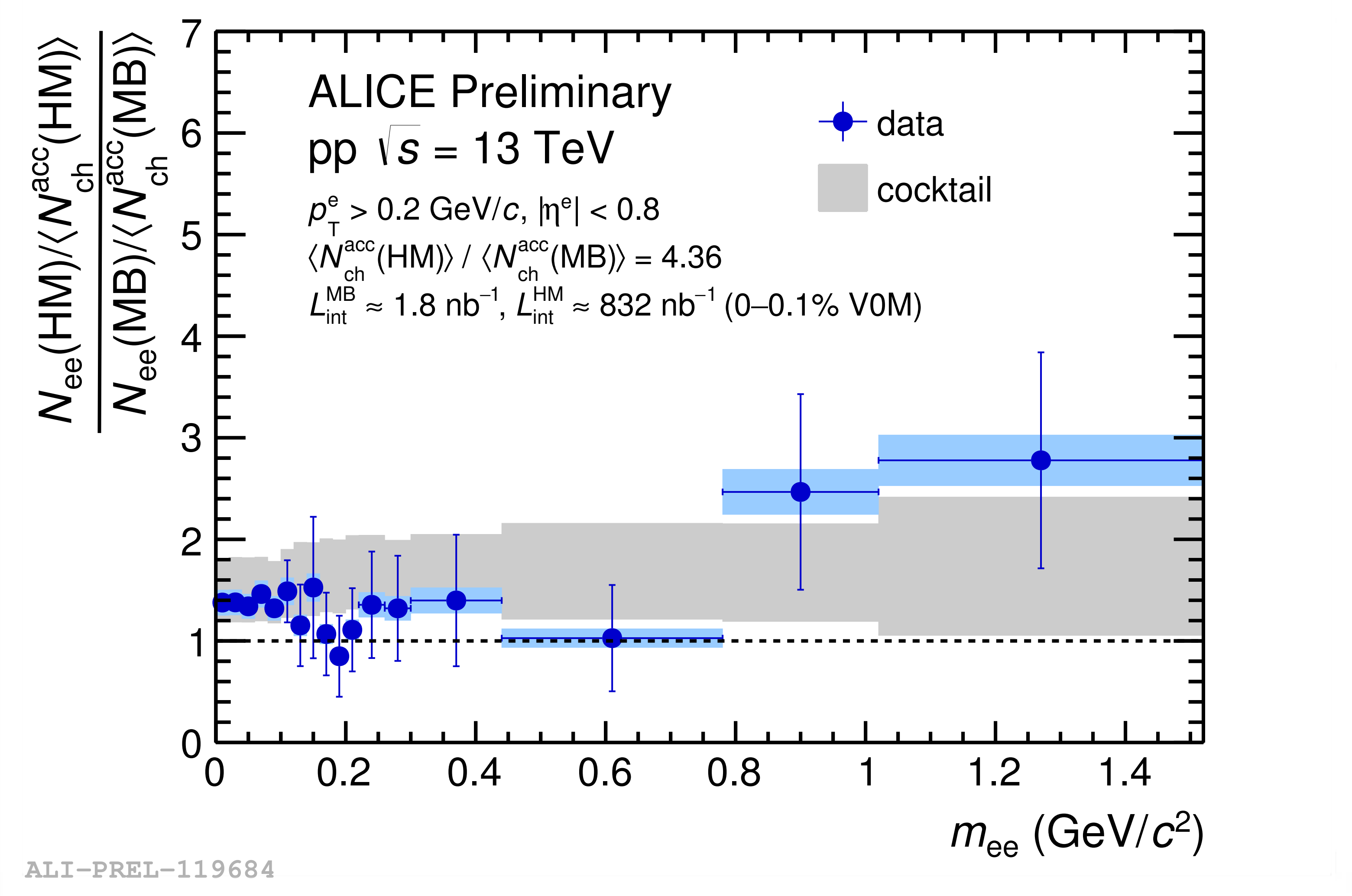
[M. Slupecki, 6/7 15:15]

+ online/offline system, trigger and readout upgrades

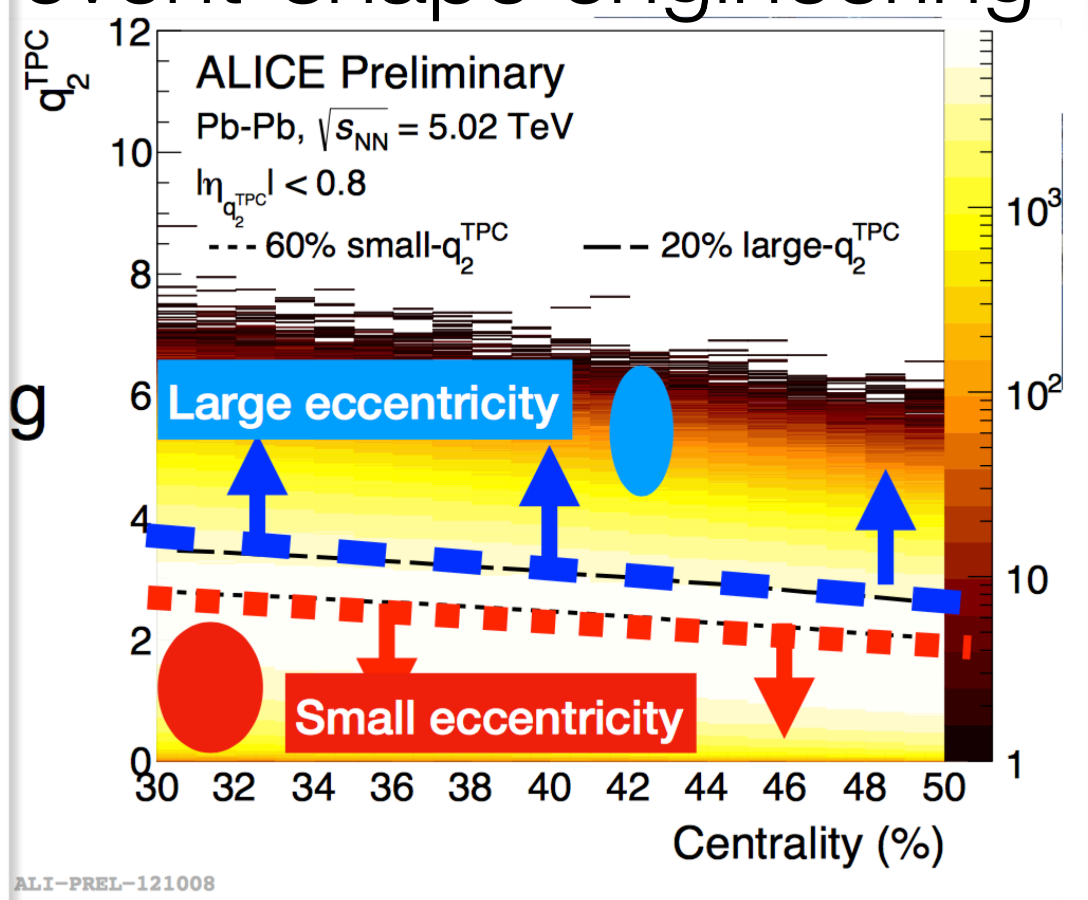
CERN-LHCC-2013-019 ; CERN-LHCC-2013-020 CERN-LHCC-2013-024 CERN-LHCC-2015-001 CERN-LHCC-2015-002 CERN-LHCC-2015-006

Other Results

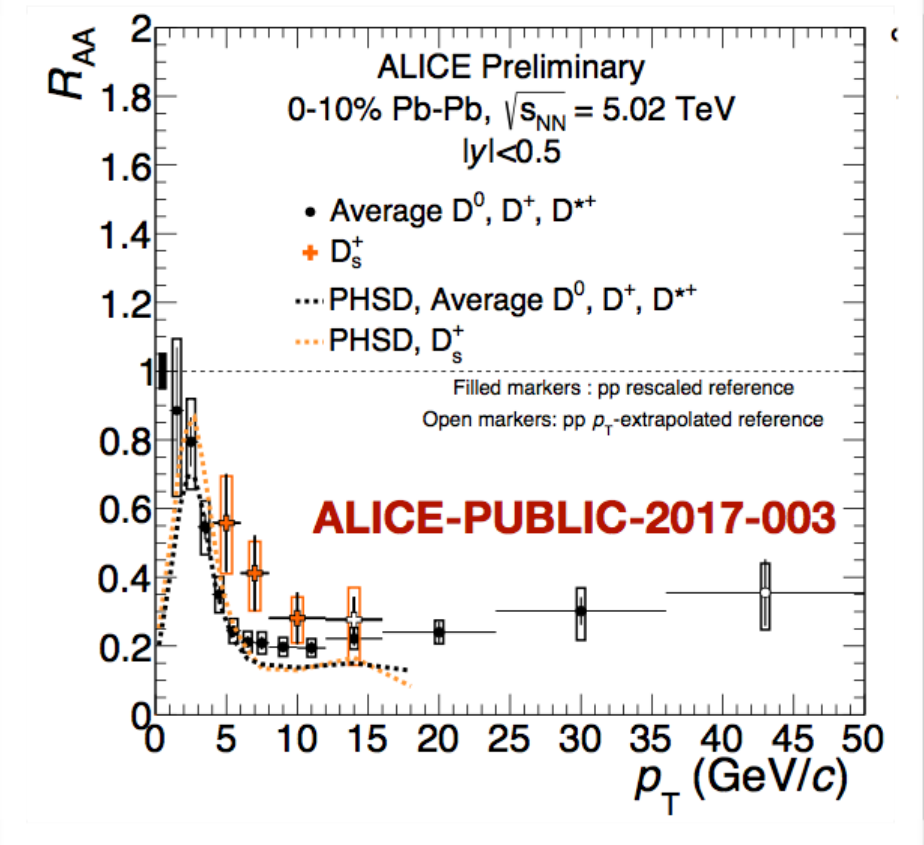
Low Mass Dielectrons



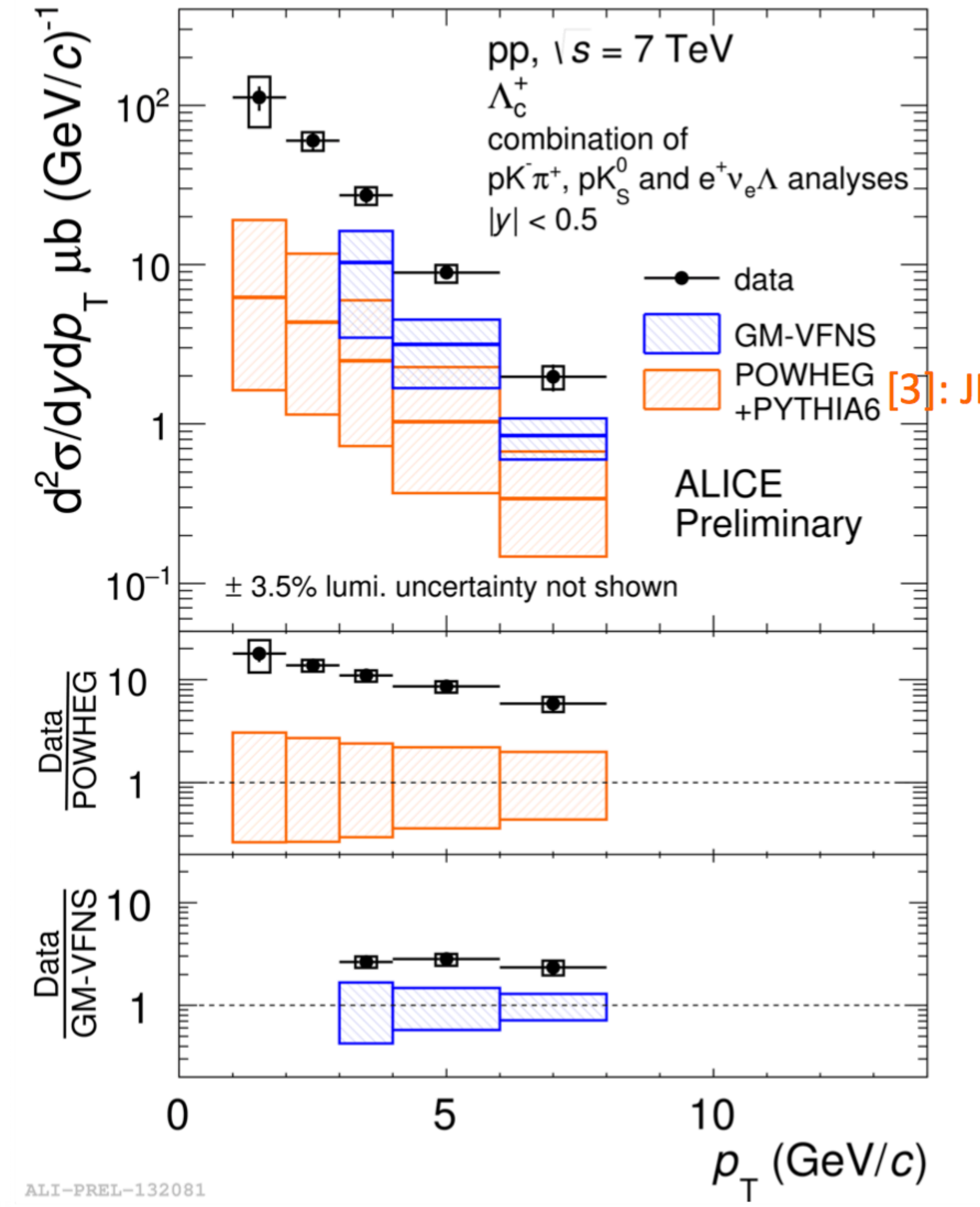
D mesons event-shape engineering



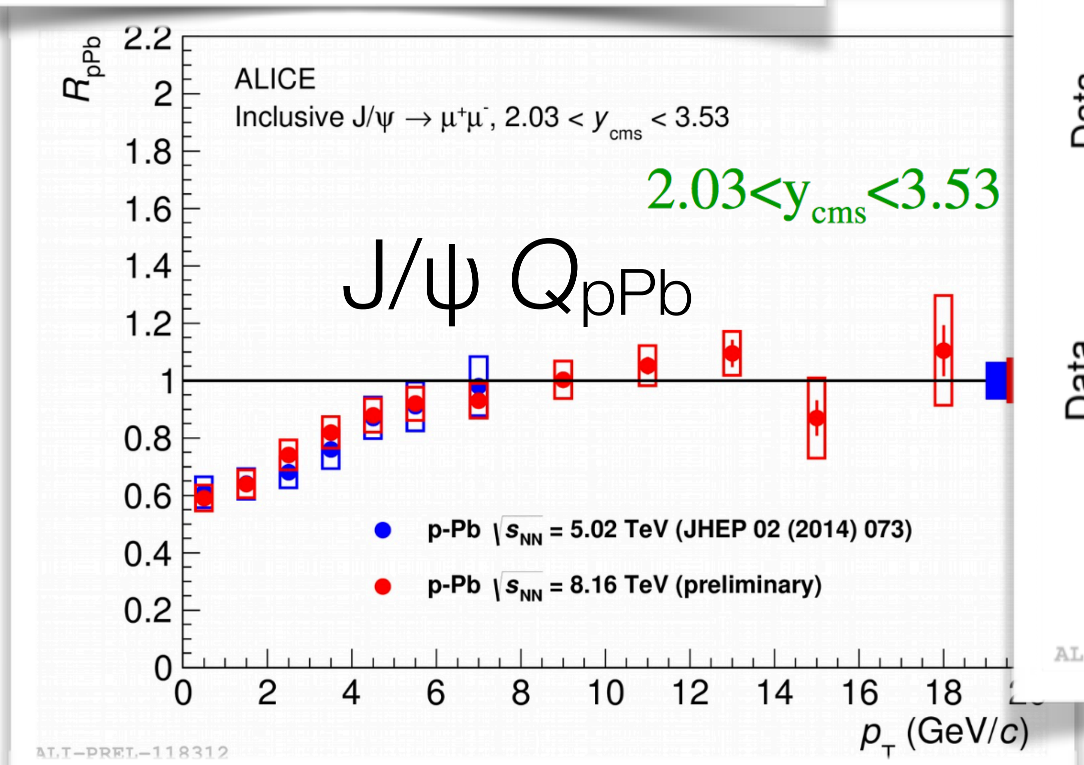
Ds meson



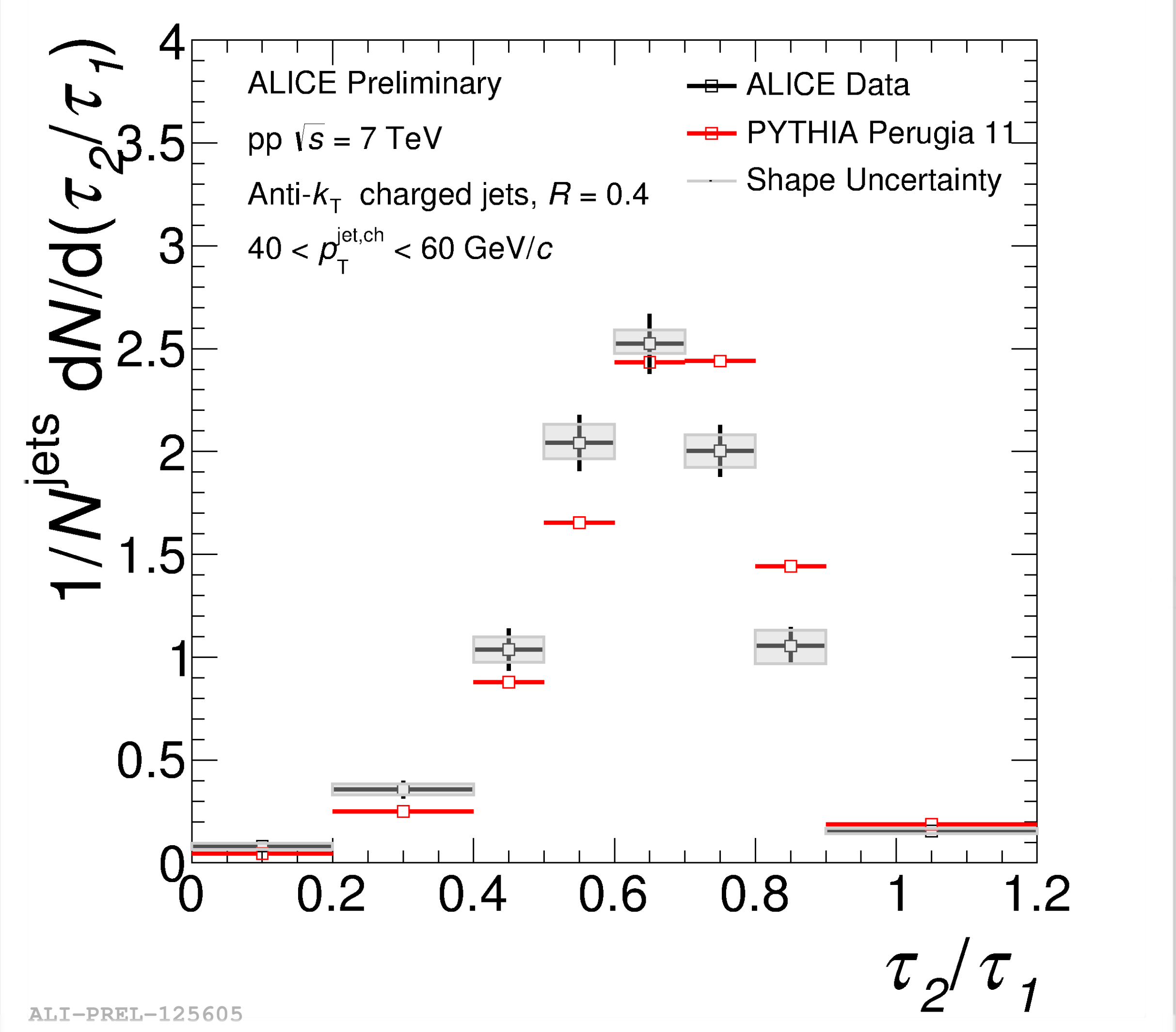
Λc, pp



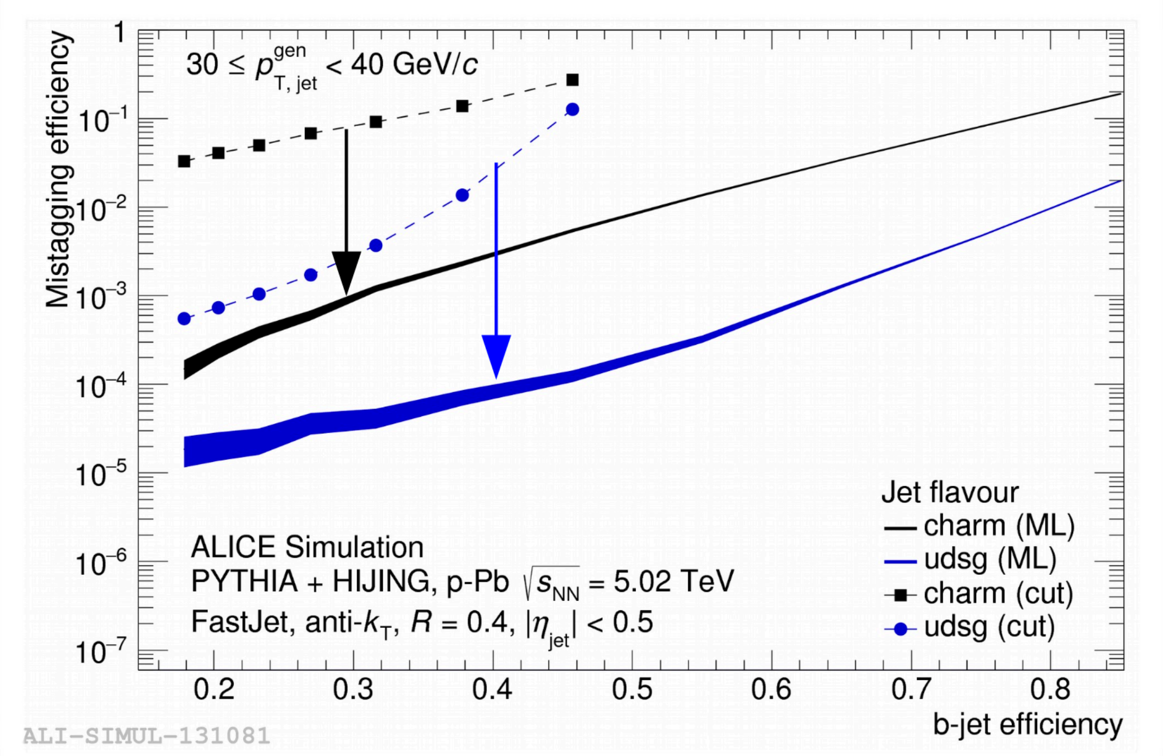
J/ψ QpPb



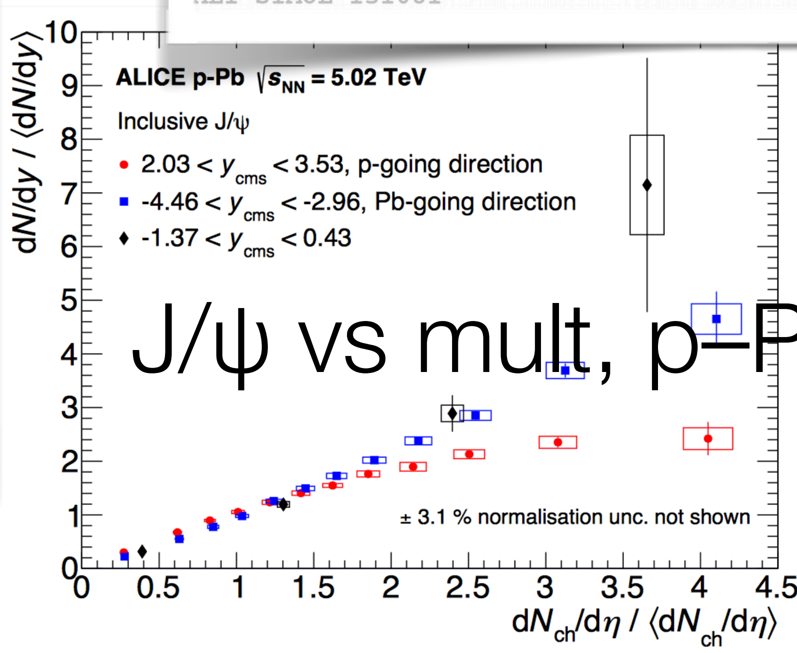
sub-jettiness



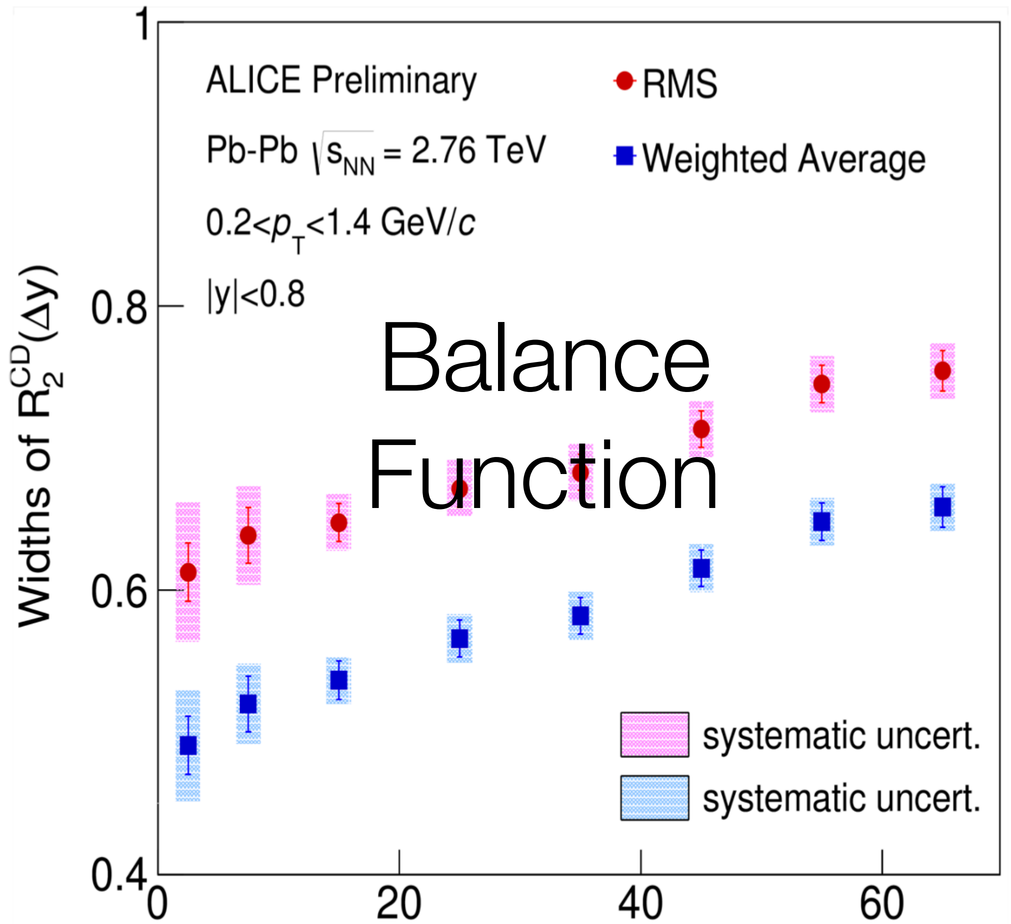
Deep learning b tagger



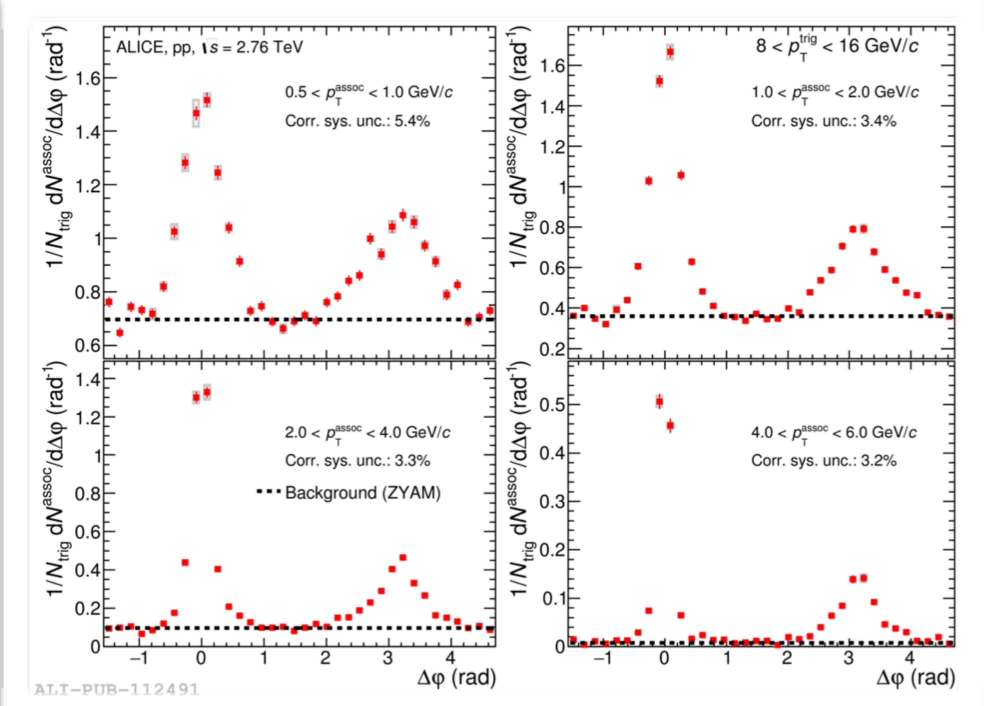
J/ψ vs mult, p–Pb



Balance Function



π⁰ - hadron



Conclusions

Tremendous activity to understand **similarities between pp/p-Pb/Pb-Pb**:

- **Paradigm shift** in the description of **hadronic collisions**
- Challenges to the accepted soft QCD (**universality of fragmentation**) and QGP (**thermalization**) models?
- **Precursor phenomena? QGP** created in **pp** collisions??

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Progress in the **characterization of the QGP** created in **heavy-ion collisions**

- Run 2 (Pb–Pb at 5 TeV): similar trends, more data ⇒ **precise** characterization

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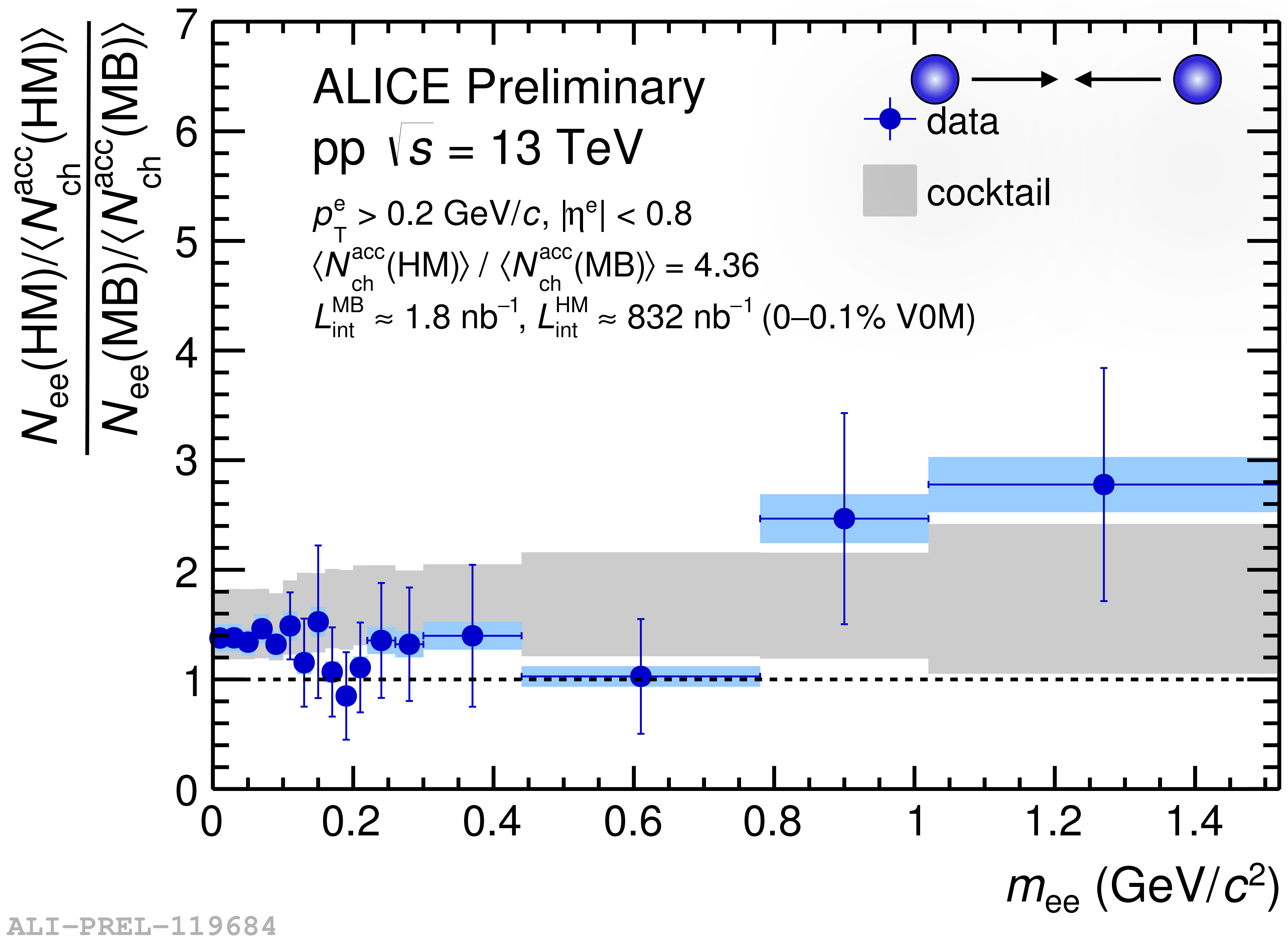
---

These programs require good **low and high p_T** tracking and **particle identification**:

- **ALICE specialities**!
- More to come with the **upgrade**: high Pb-Pb luminosity and improved tracking

Backup

A long-lived, interacting, (thermalized) system emits **thermal radiation**
Seen as **virtual photons** producing (excess) **dilepton** pairs
Relevant $\mathbf{p_T}$ **~ mass ~** $\mathbf{T}$ **= O(100 MeV)**

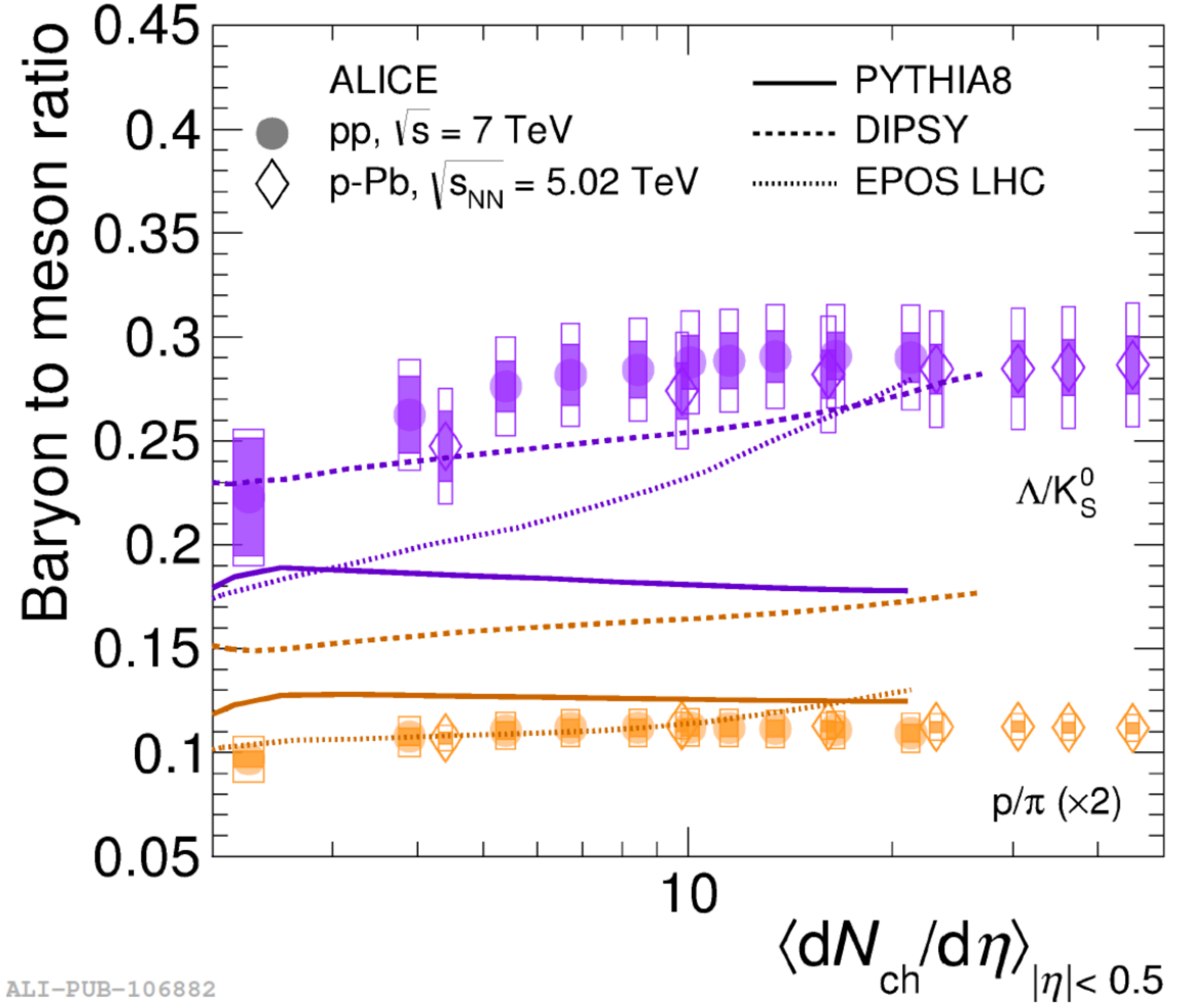


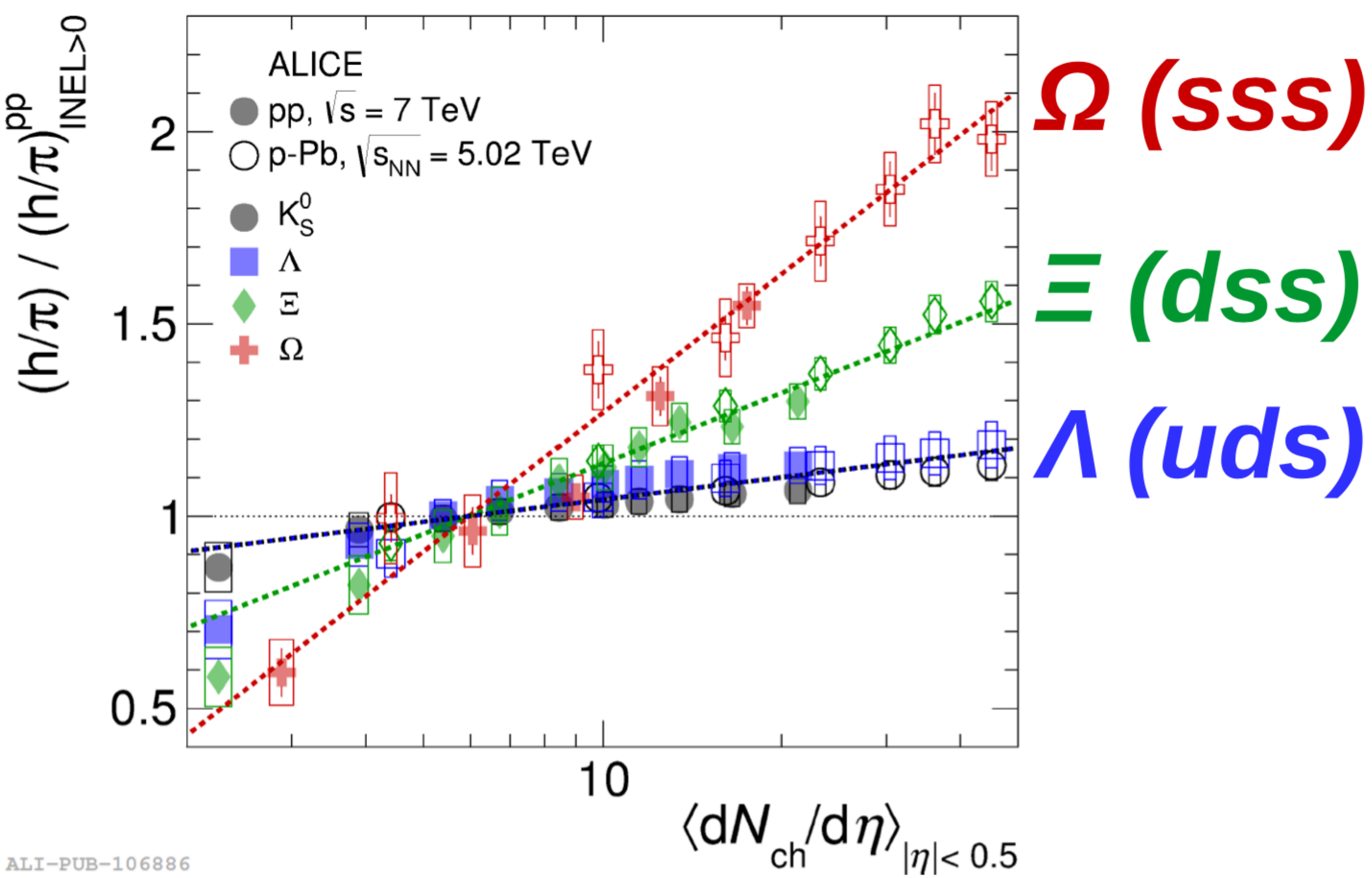
Low-mass dileptons in HM events consistent with expectations from hadronic sources

5x more data available in the 2016 data sample + Machine-Learning based analysis

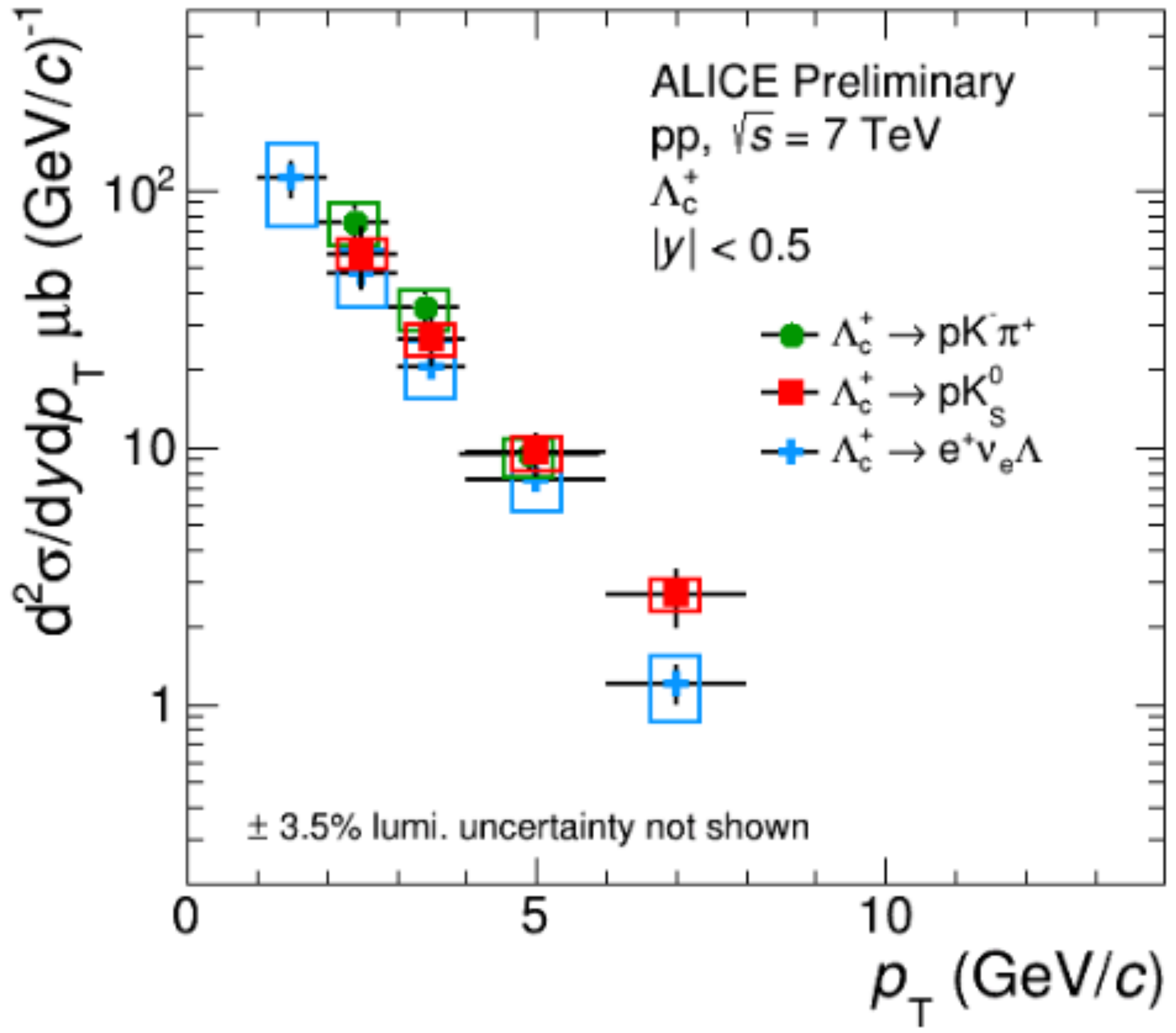
Very **challenging measurement**, see ALICE upgrade
(also in Pb–Pb, also addresses chiral symmetry restoration at high temperature)

R. Bailhache, R. Haake


Baryon to meson ratio
ALICE
pp, √s = 7 TeV
p-Pb, √sNN = 5.02 TeV
PYTHIA8
DIPSY
EPOS LHC
Λ/K0S
p/π (×2)
⟨dNch/dη⟩|η|< 0.5
ALI-PUB-106882

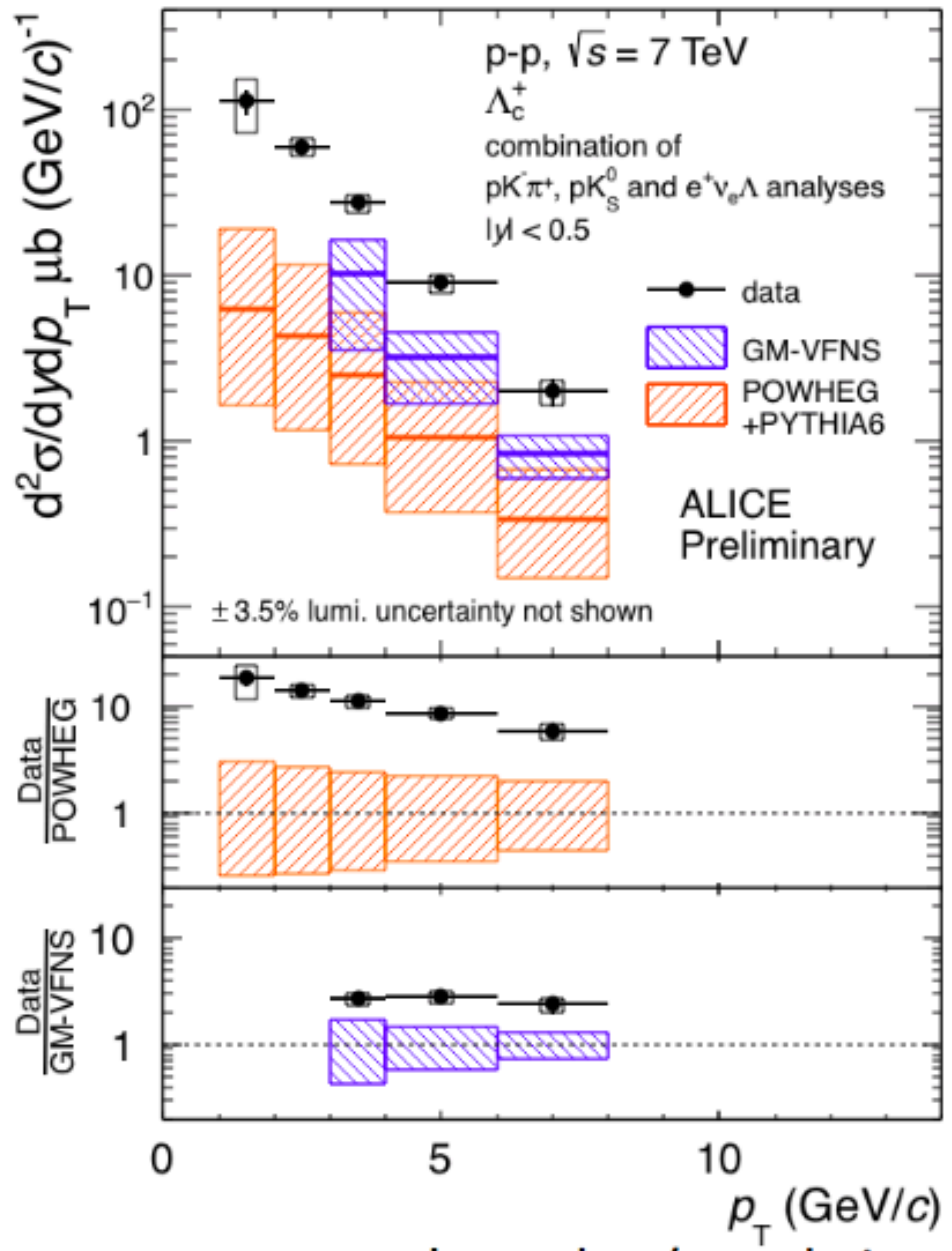

(h/π) / (h/π)ppINEL>0
ALICE
pp, √s = 7 TeV
p-Pb, √sNN = 5.02 TeV
K0S
Λ
Ξ
Ω
⟨dNch/dη⟩|η|< 0.5
ALI-PUB-106886
Ω (sss)
Ξ (dss)
Λ (uds)

First Λ_c^+ measurements @ mid-rapidity



All the measured cross sections compatible within statistical and systematic uncertainties (BR uncertainties included)

NEW



All measurements averaged together (correlation in the uncertainties taken into account)

GM-VFNS underestimates by a factor 2.5 the measurements

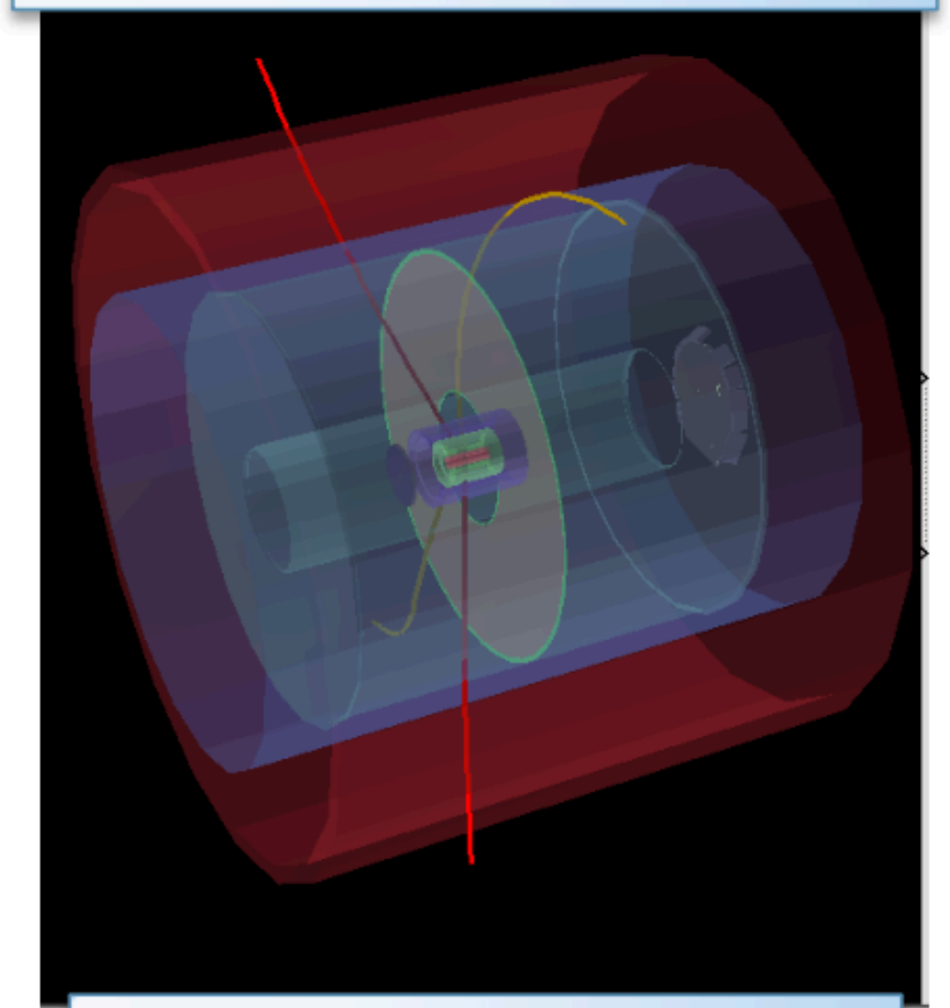
POWHEG significantly underpredicts the measured cross section

7/6/17 EPS Conference on High Energy Physics - Venice, Italy A. De Caro 10

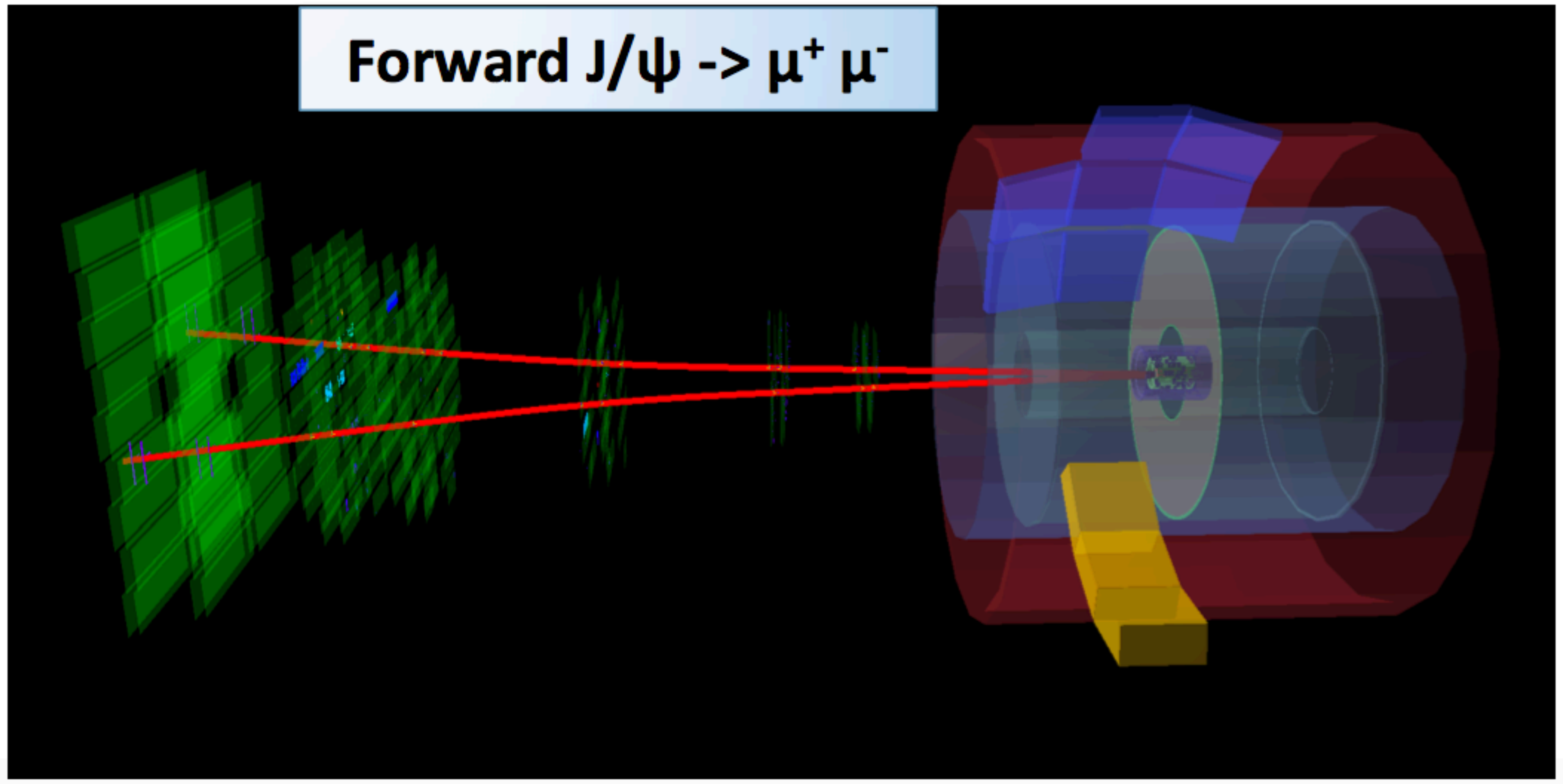
Ultra-peripheral collisions

- Very clean signature - two or four tracks in an otherwise empty detector
- Decay channels:
  - $\rho^0 \to \pi^+ \pi^-$
  - $J/\psi \to l^+ l^-$
  - $\psi(2S) \to l^+ l^-$
  - $\psi(2S) \to J/\psi\, \pi^+ \pi^-$

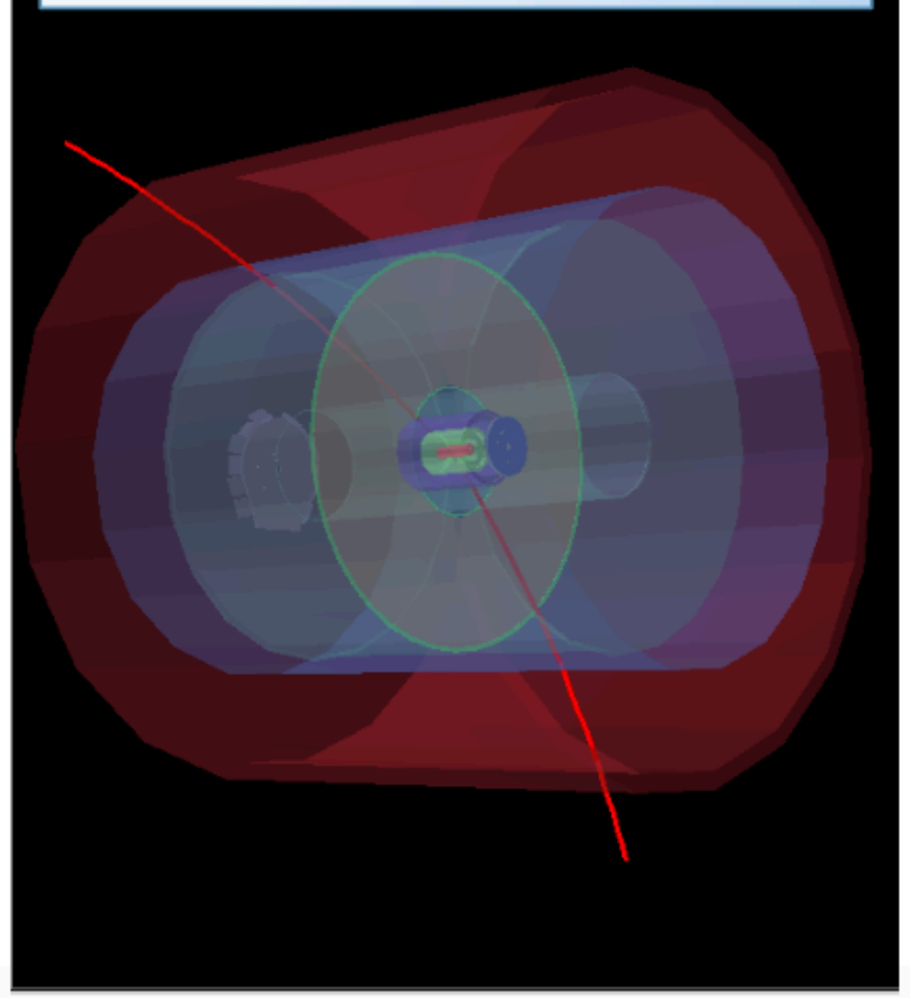
$\psi(2s) \to e^+ e^- + \pi^+ \pi^-$



Forward $J/\psi \to \mu^+ \mu^-$



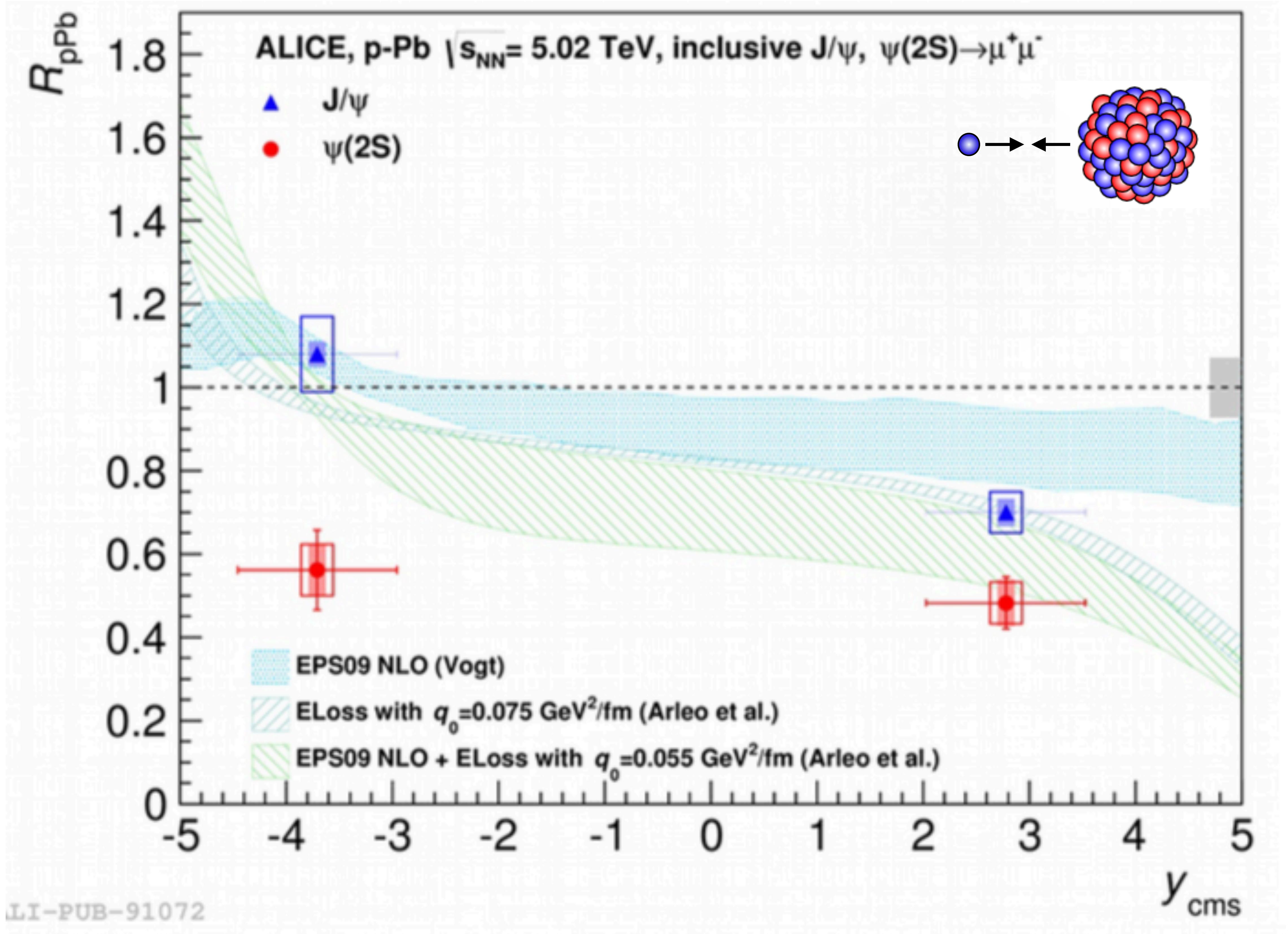
Central $J/\psi \to \mu^+ \mu^-$



R_{pPb} also affected by initial-state **nuclear effects** (e.g. nPDF)

Difference in **R_{pPb} of J/psi and ψ(2s)**

Not expected from initial production ⇒ Indication of **final state effects?**



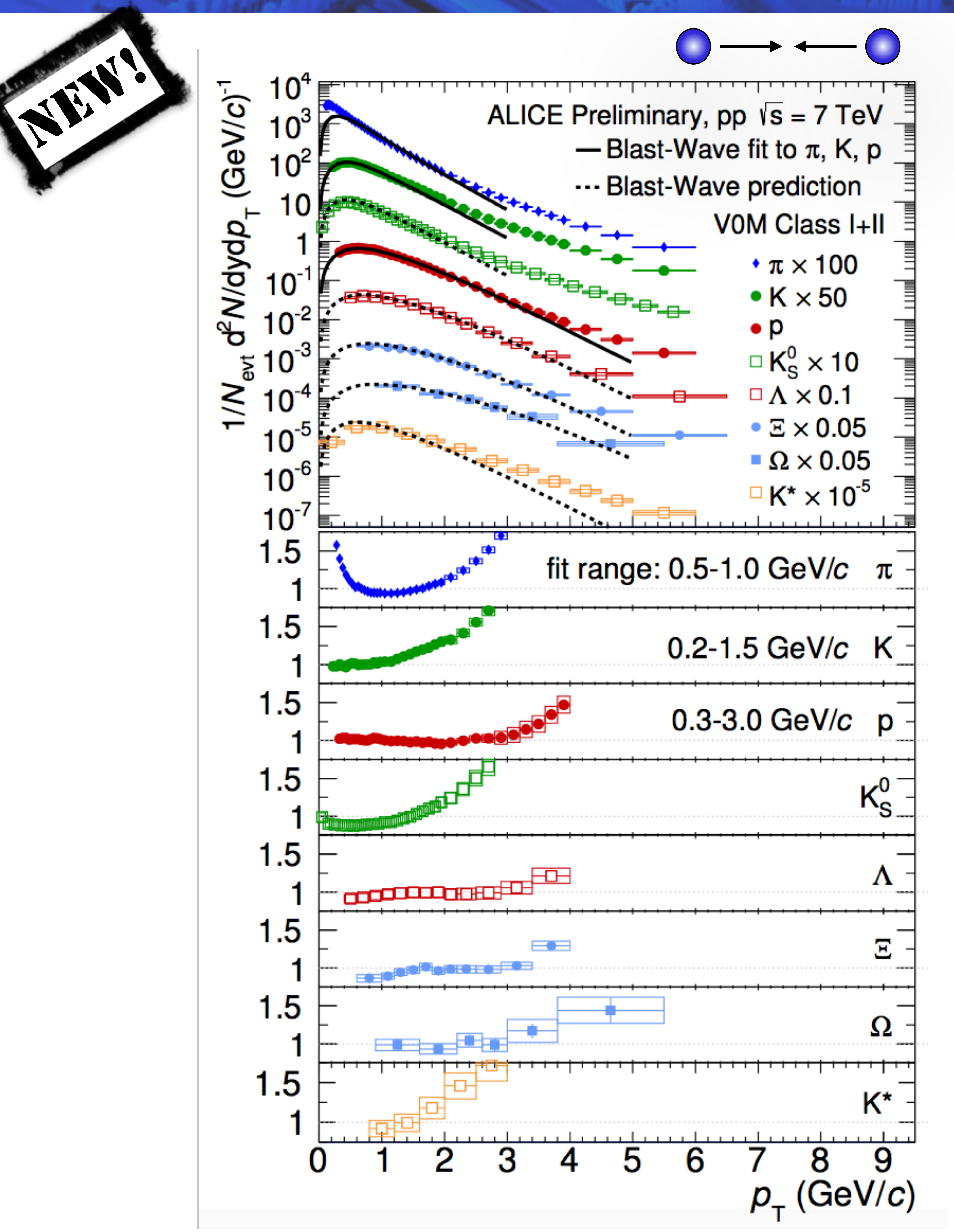
New 8 TeV results allow more detailed studies!

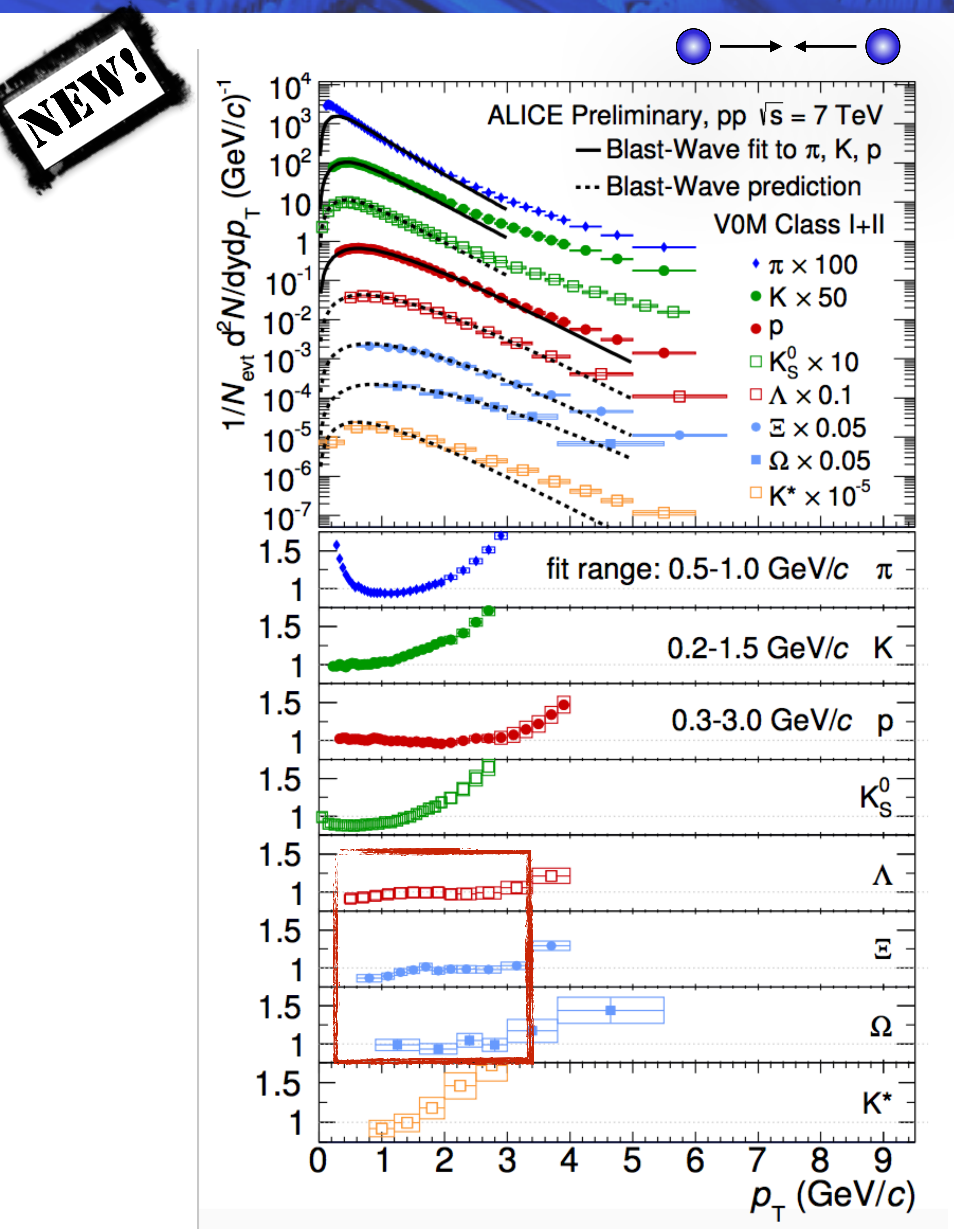
R Arnaldi

Biswarup Paul

Blast Wave Fits

Blast Wave is a hydro-inspired parameterization
Fit to PID spectra and extract **freeze-out parameters**





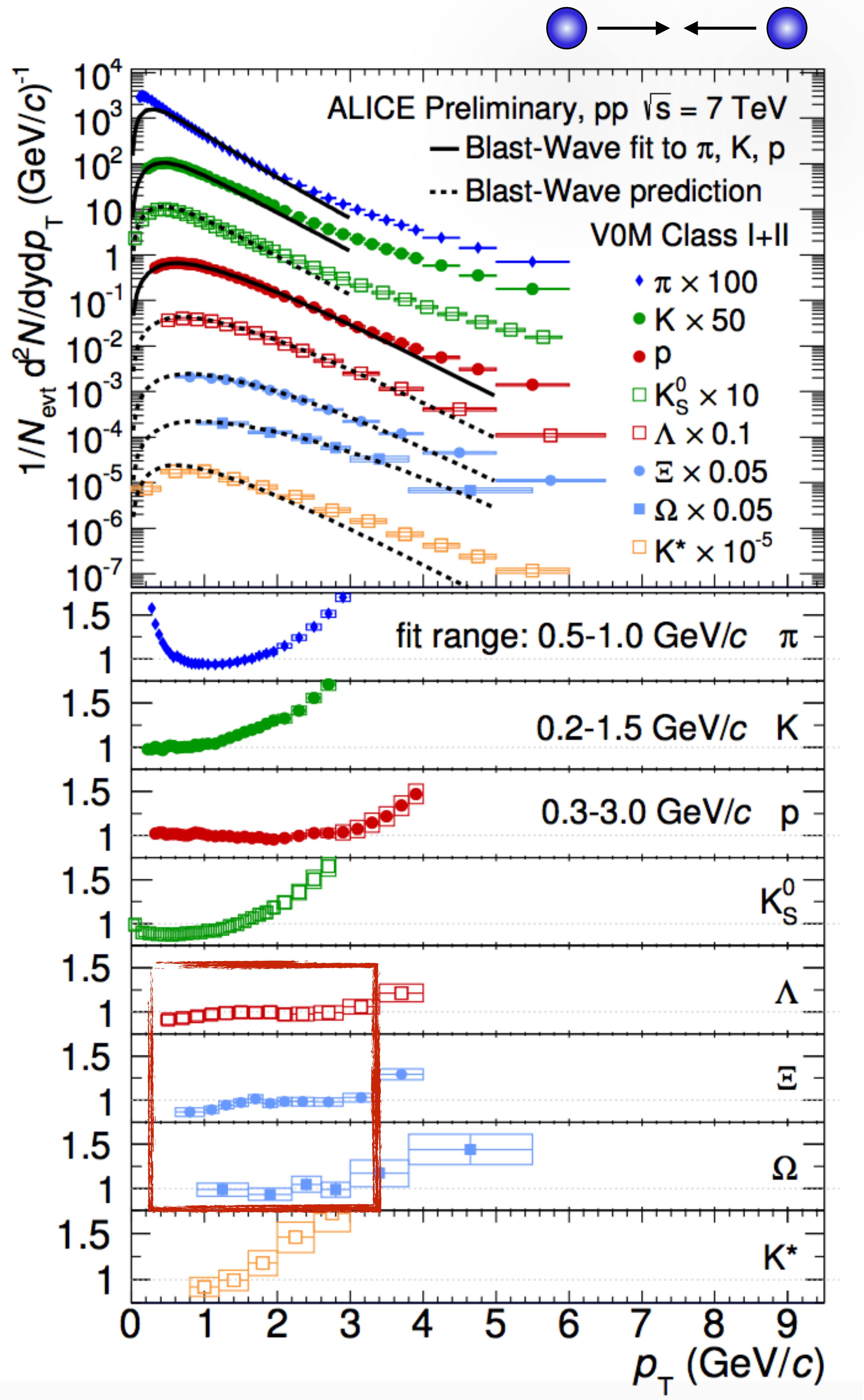
Blast Wave is a hydro-inspired parameterization

Fit to PID spectra and extract **freeze-out parameters**

Fit to π, K, p predicts Λ, Ξ, Ω shape at low p_T

Blast Wave Fits

NEW!



Blast Wave is a hydro-inspired parameterization

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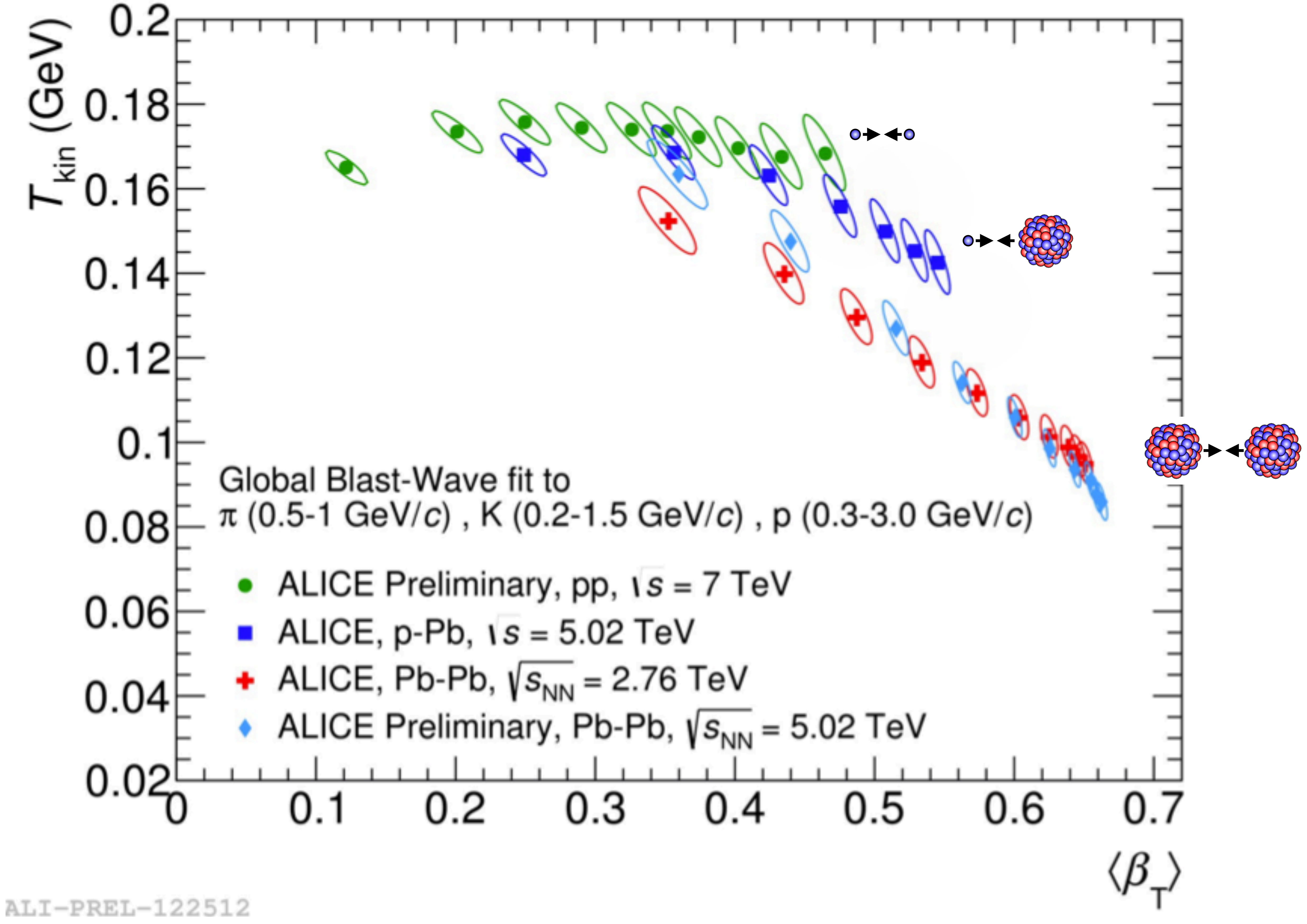
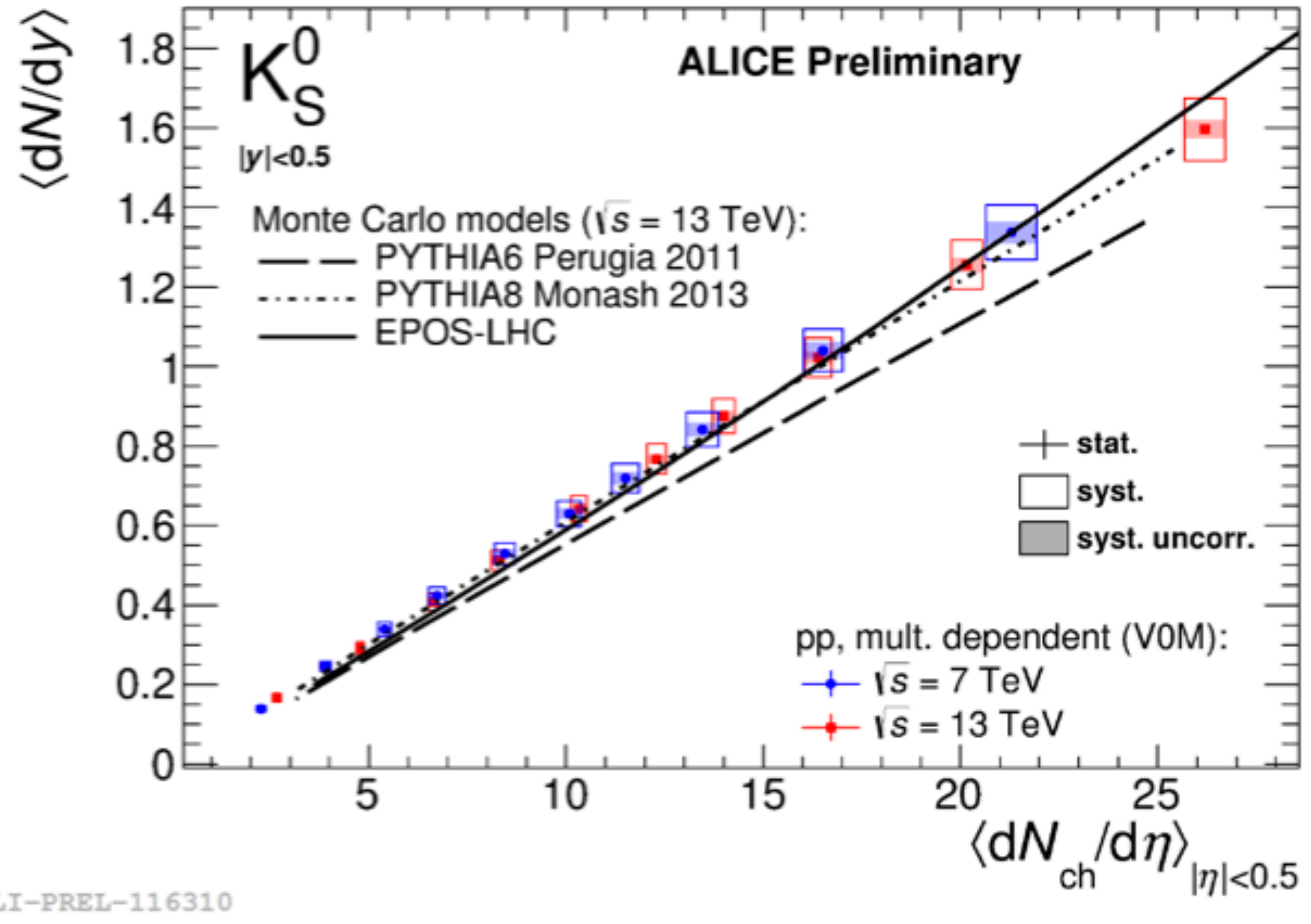
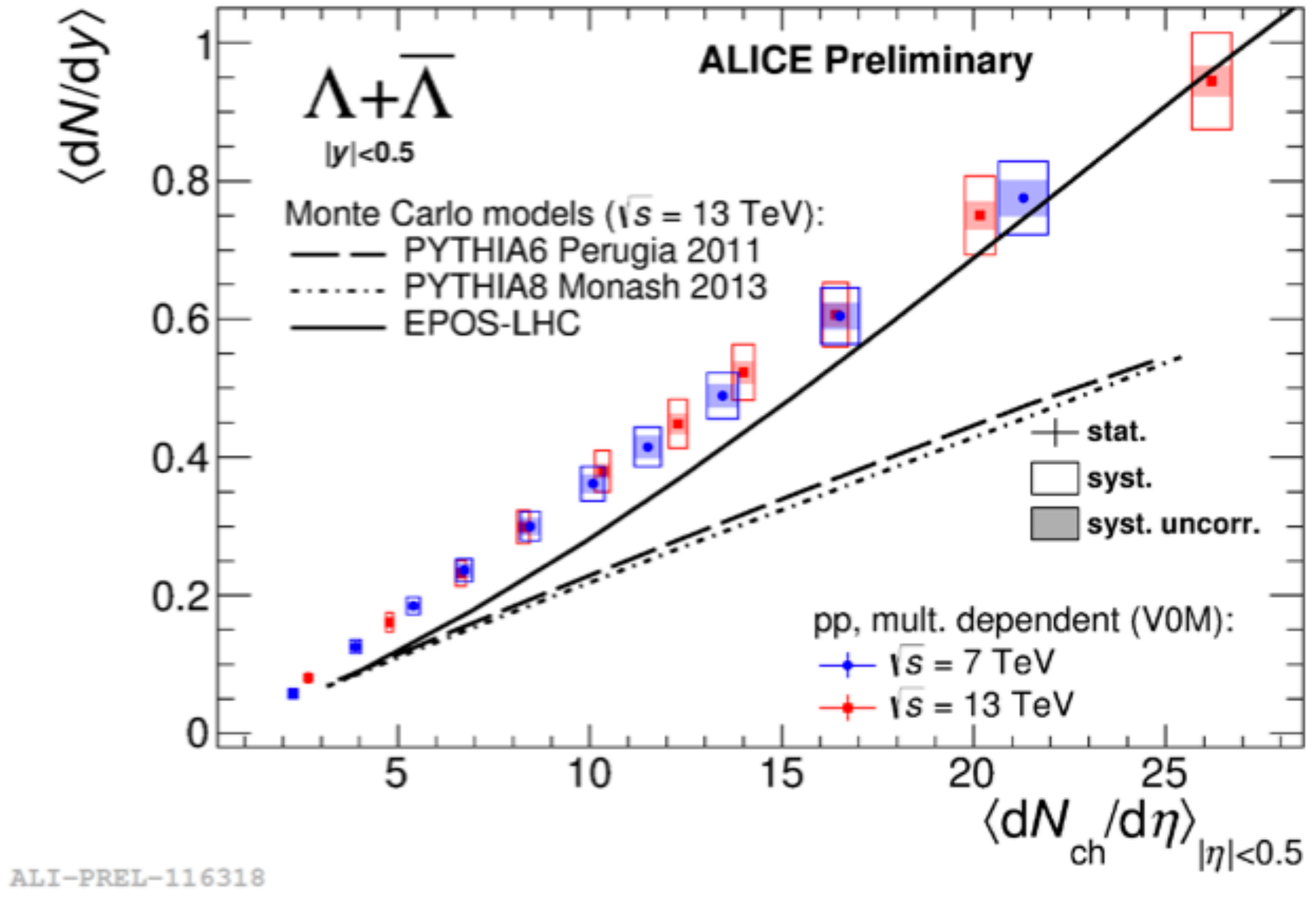
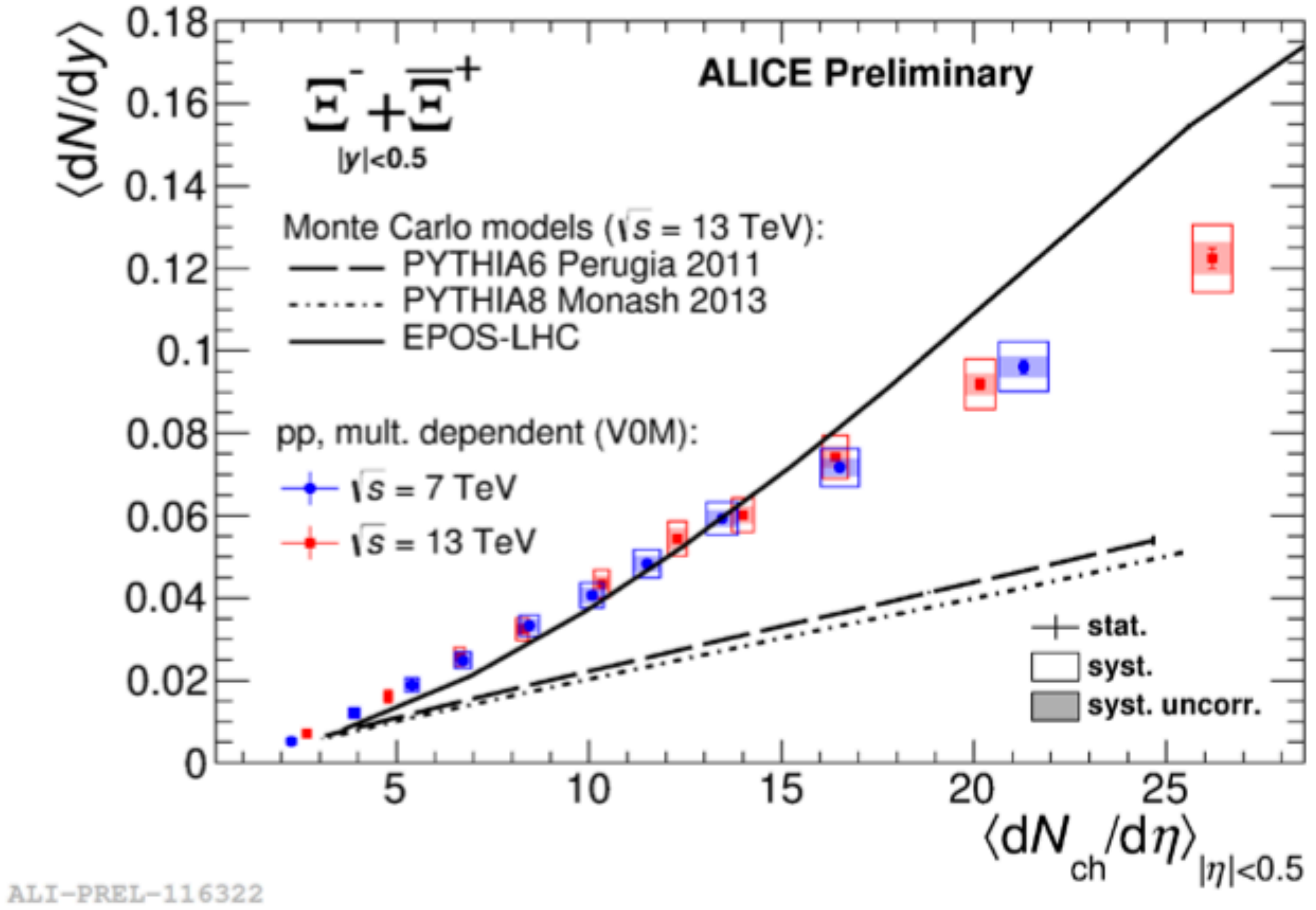


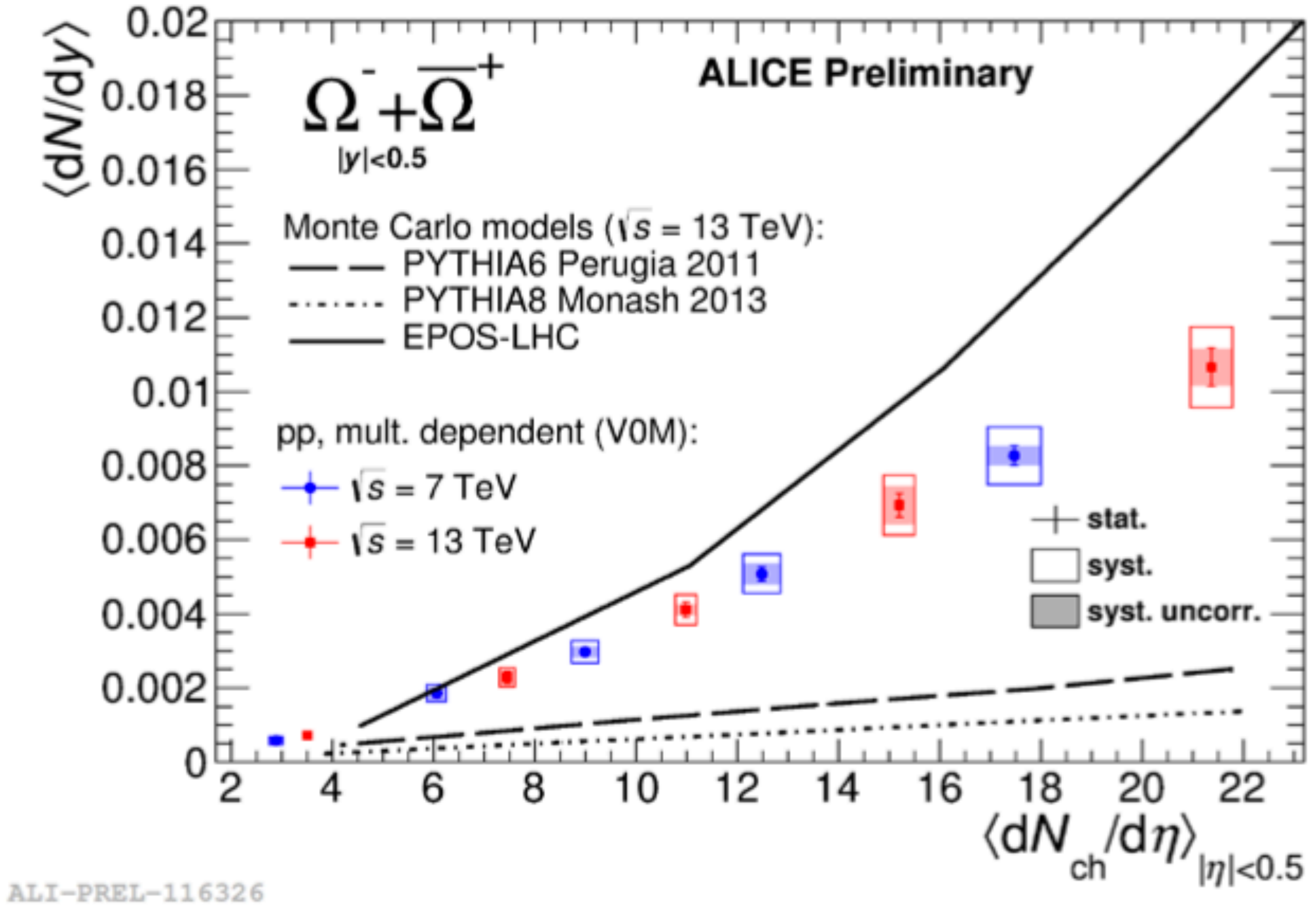
Multiplicity dependence: strange hadron production at different √s



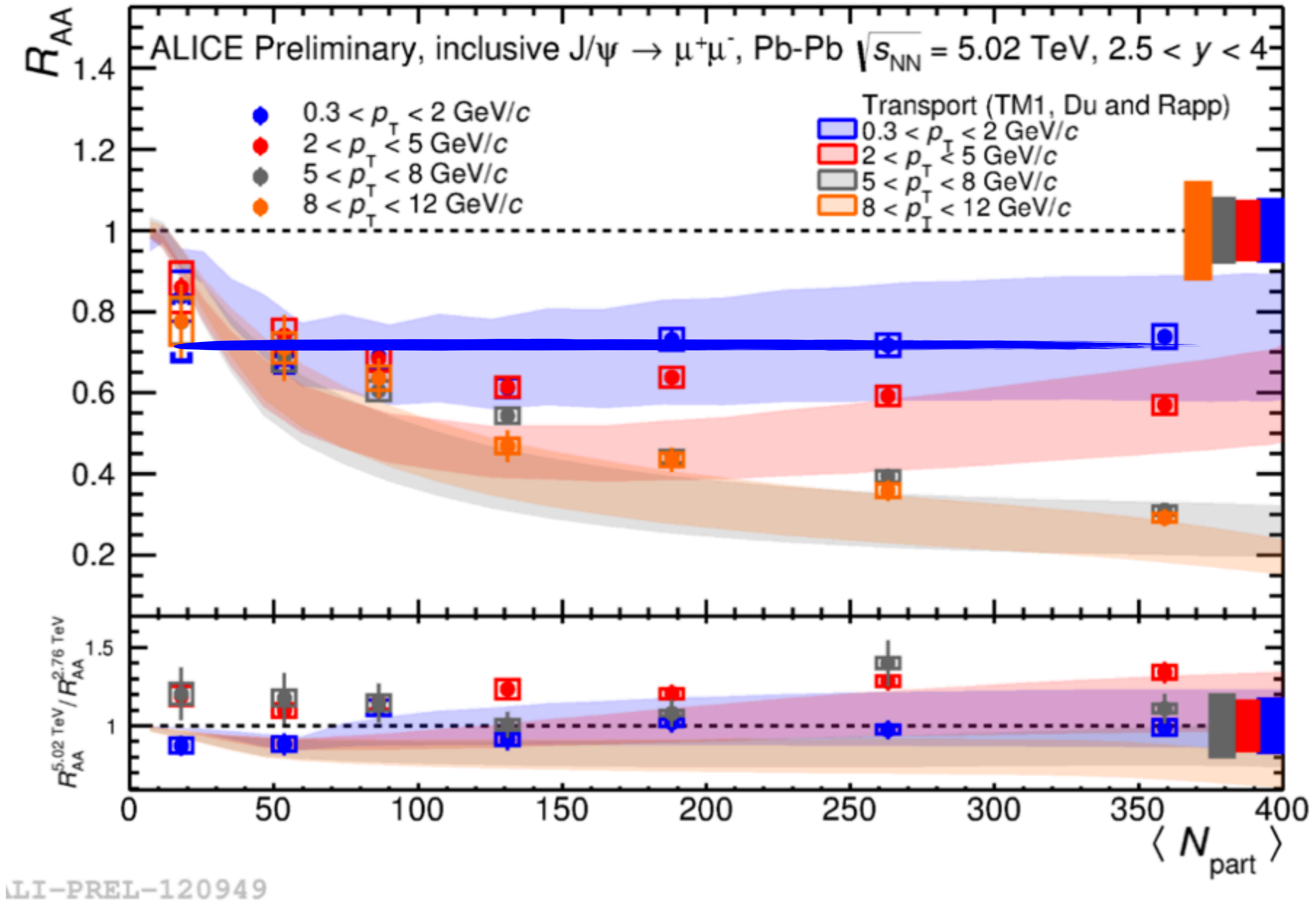


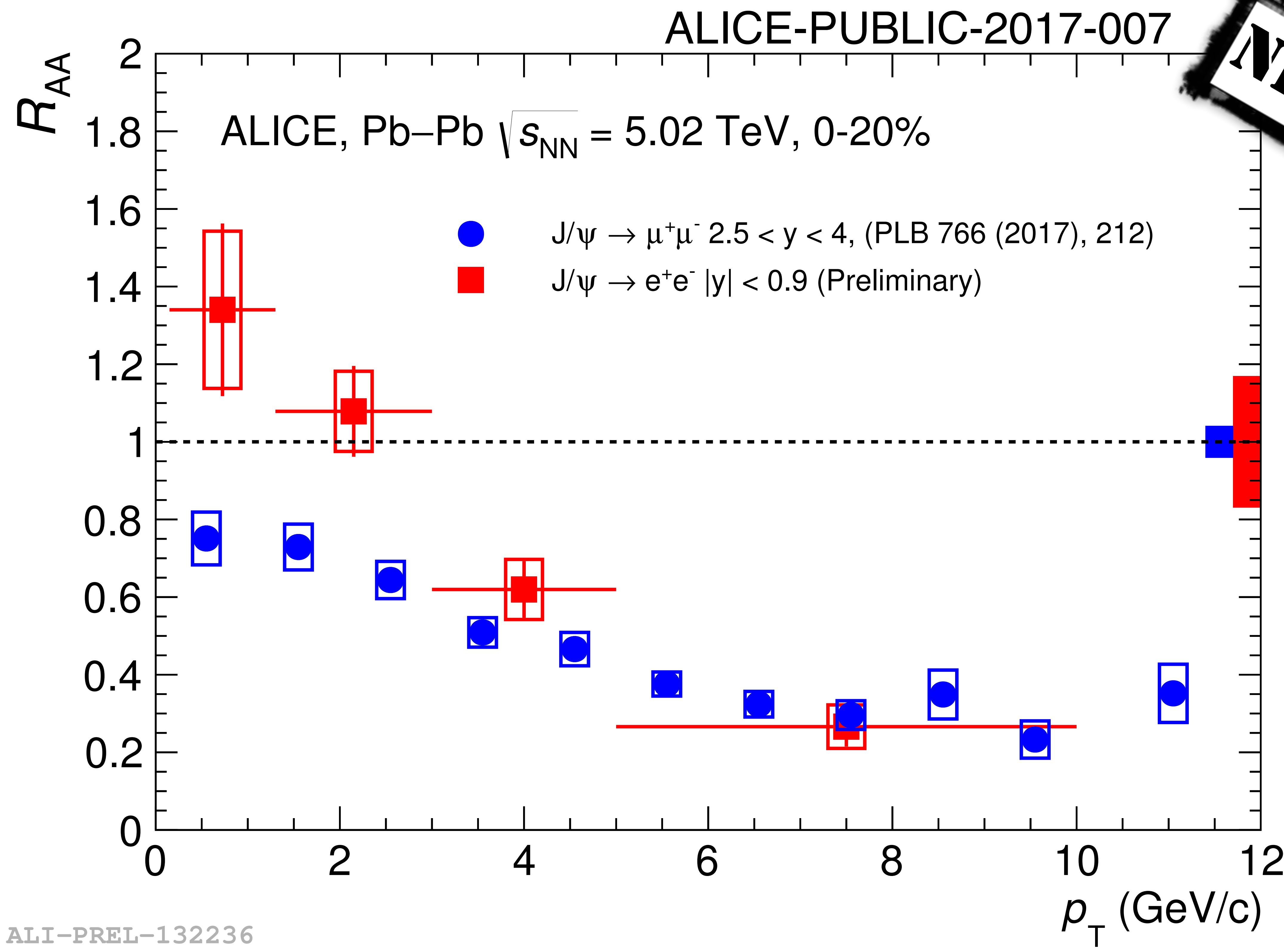
Hadrochemistry is driven by multiplicity rather than √s





J/ψ R_{AA} in Pb-Pb



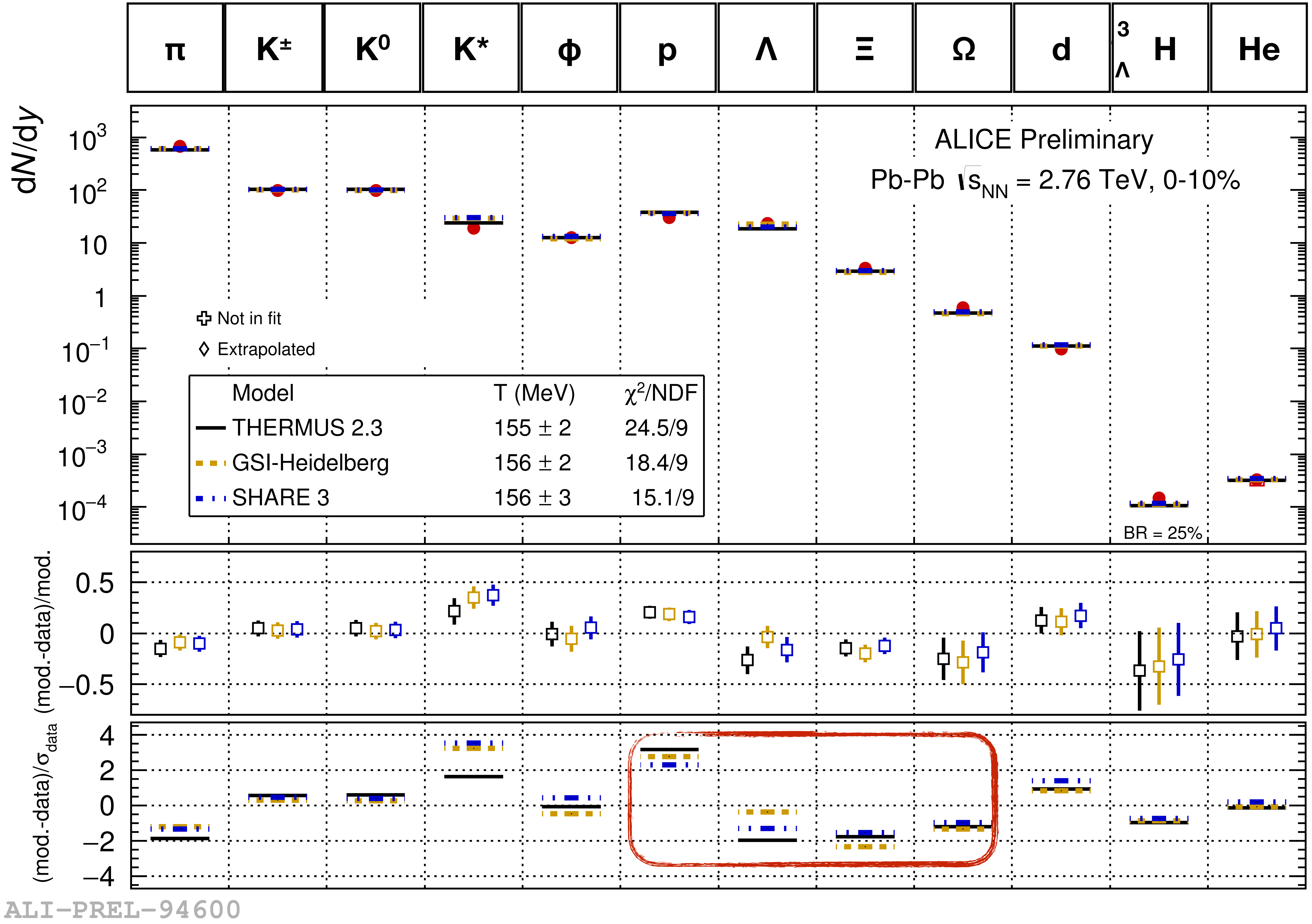


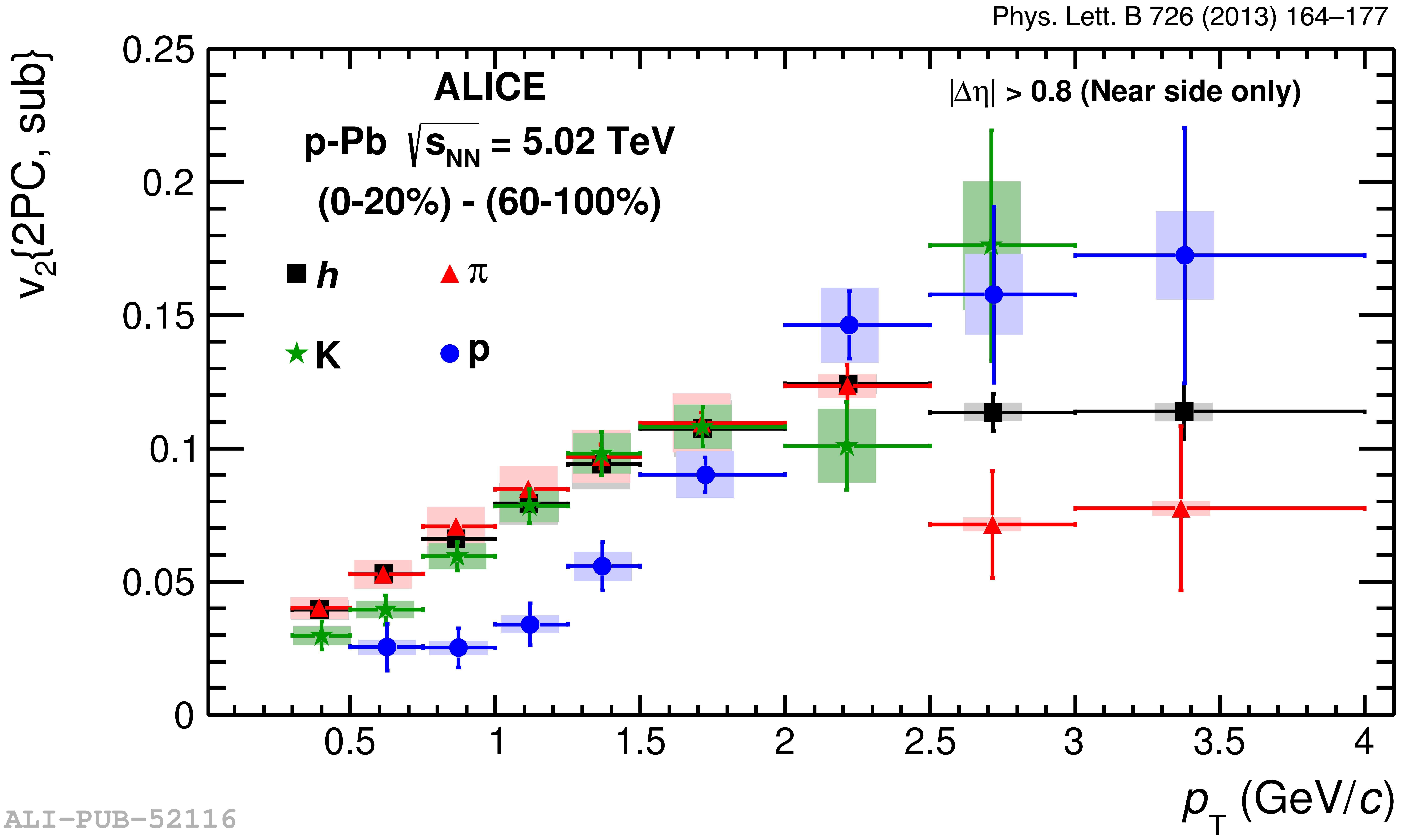
Low p_T: Smaller suppression and weak (no?) centrality dependence

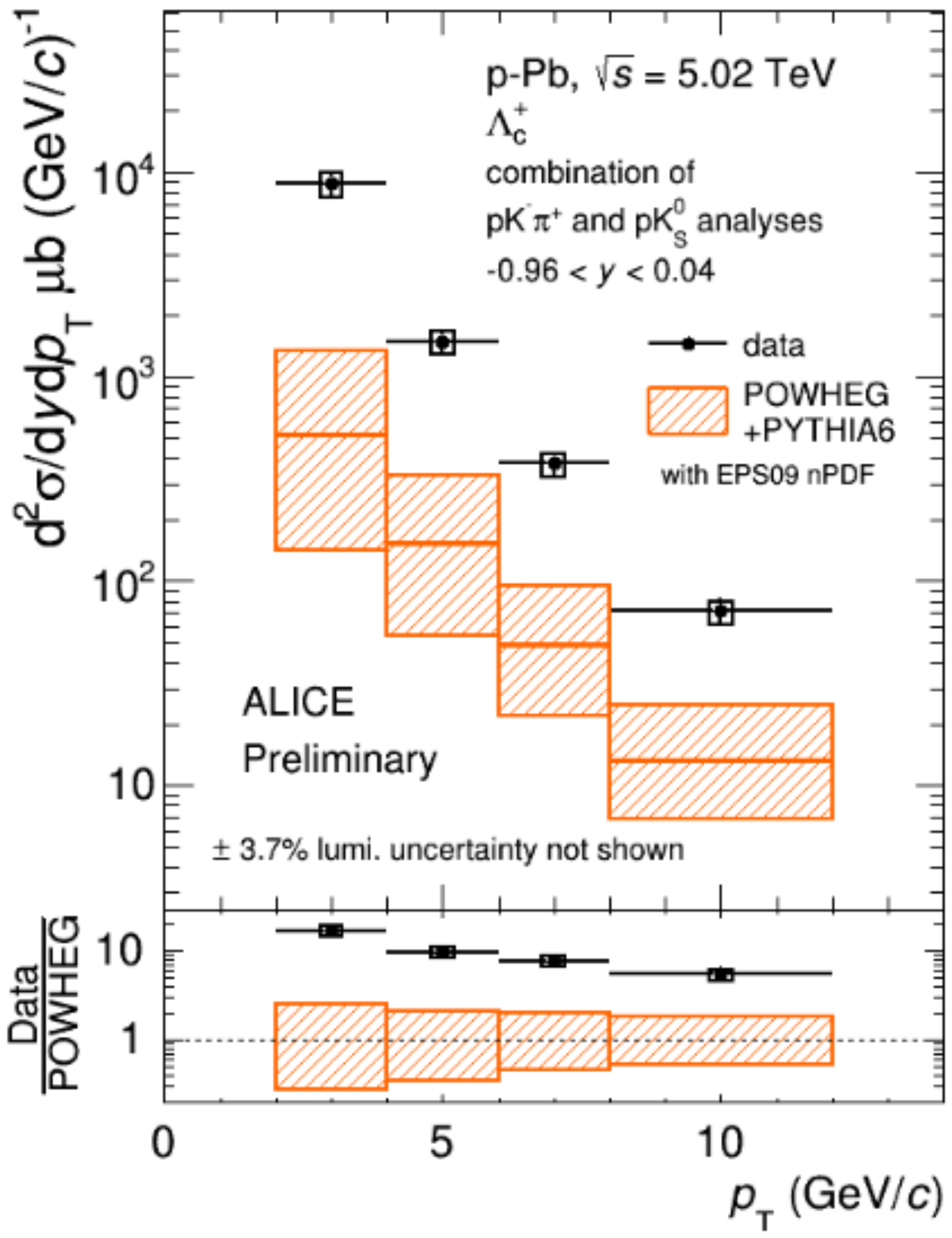
Mid-y less suppressed than **forward-y** (more charm at mid-y), smaller suppression

Consistent with (re)combination scenarios

[B. Paul, 6/7 10:30]


π
K±
K0
K*
φ
p
Λ
Ξ
Ω
d
3 Λ H
He
ALICE Preliminary
Pb-Pb √sNN = 2.76 TeV, 0-10%
dN/dy
Not in fit
Extrapolated
Model T (MeV) χ2/NDF
THERMUS 2.3 155 ± 2 24.5/9
GSI-Heidelberg 156 ± 2 18.4/9
SHARE 3 156 ± 3 15.1/9
BR = 25%
(mod.-data)/mod.
(mod.-data)/σdata
ALI-PREL-94600

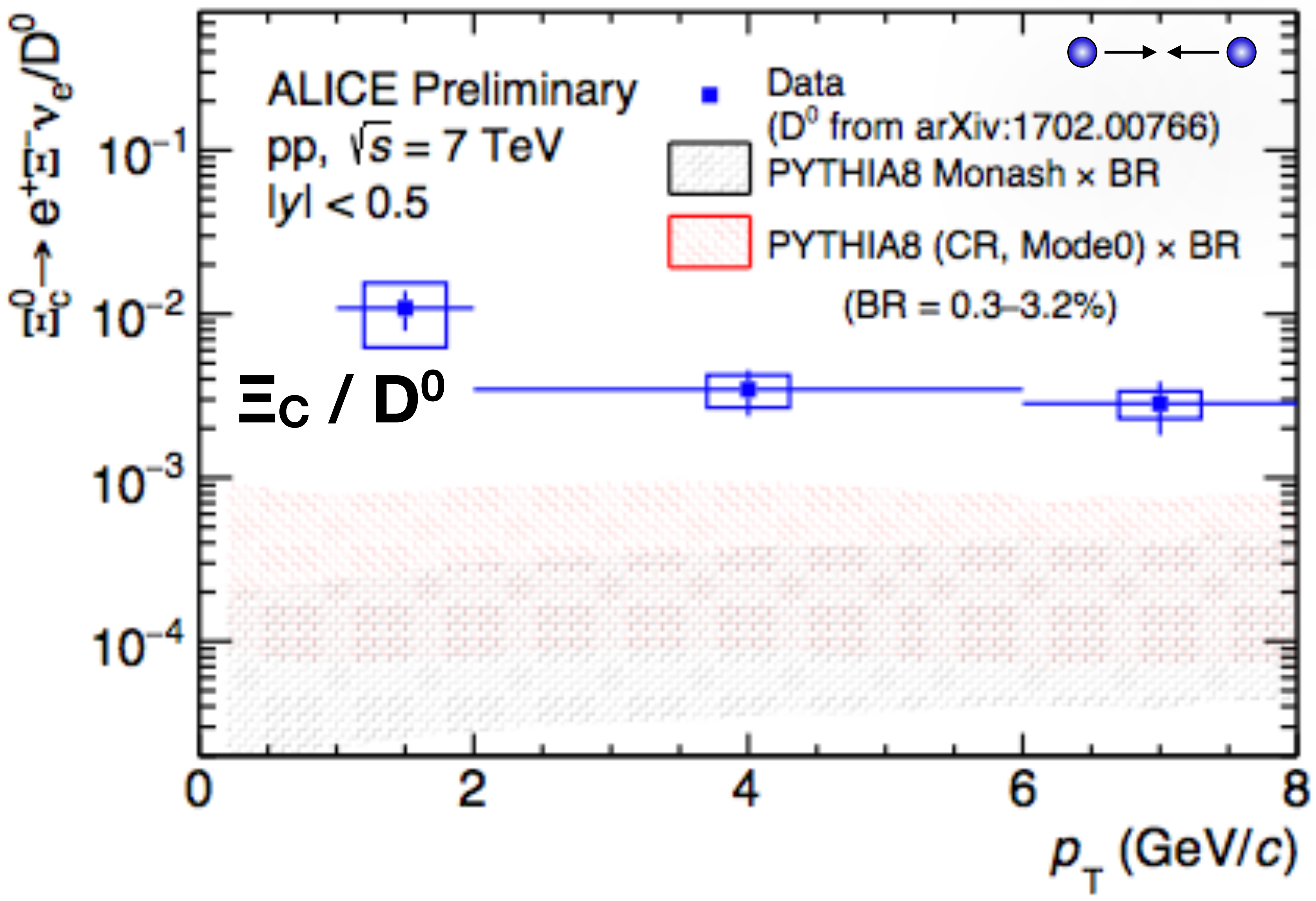

Phys. Lett. B 726 (2013) 164–177
ALICE
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
(0-20%) - (60-100%)
|Δη| > 0.8 (Near side only)
h
π
K
p
$v_2\{2PC, sub\}$
p_T (GeV/c)
0
0.05
0.1
0.15
0.2
0.25
0.5
1
1.5
2
2.5
3
3.5
4
ALI-PUB-52116

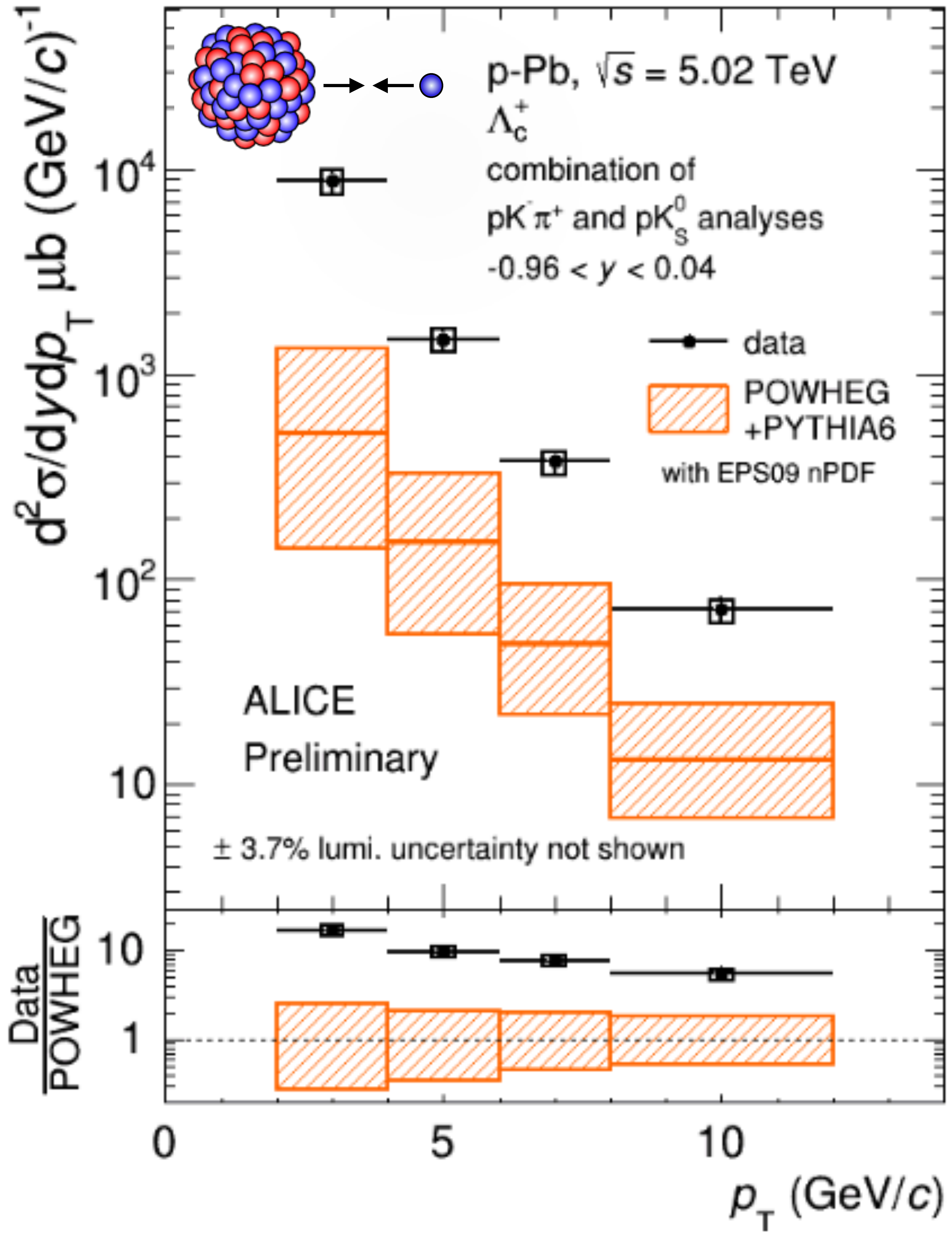

p-Pb, √s = 5.02 TeV
Λc+
combination of
pK-π+ and pK0S analyses
-0.96 < y < 0.04
data
POWHEG
+PYTHIA6
with EPS09 nPDF
ALICE
Preliminary
± 3.7% lumi. uncertainty not shown
d2σ/dydpT μb (GeV/c)-1
Data/POWHEG
pT (GeV/c)
0
5
10
10
1
10
10^2
10^3
10^4

First cross section **measurement** of Ξ_c^0 in pp and Λ_c^+ in p-Pb (and mid-y pp) at LHC

NEW!

Not reproduced by pQCD+fragmentation models
Important constraints on charm hadronization and nuclear effects!





Λ_c^+

[A. De Caro, 6/7 11:45]
[C. Terrevoli, 6/7 15:45]