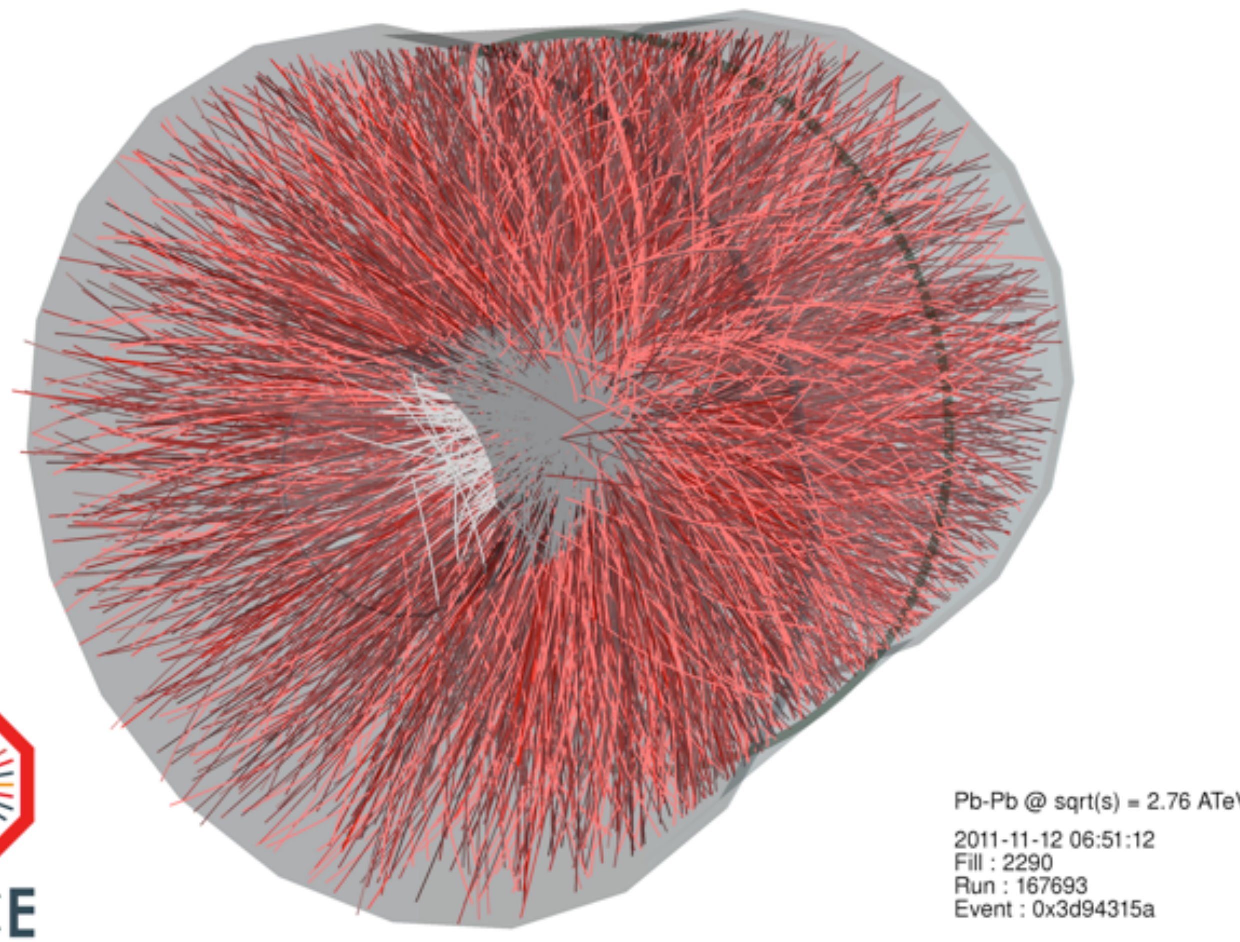
Measurement of event-by-event fluctuations and chemical freeze-out conditions at LHC energies with ALICE

A. Kalweit, *CERN*
on behalf of the ALICE collaboration

Many-body QCD and light flavor hadron production



ALICE
A JOURNEY OF DISCOVERY

central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$

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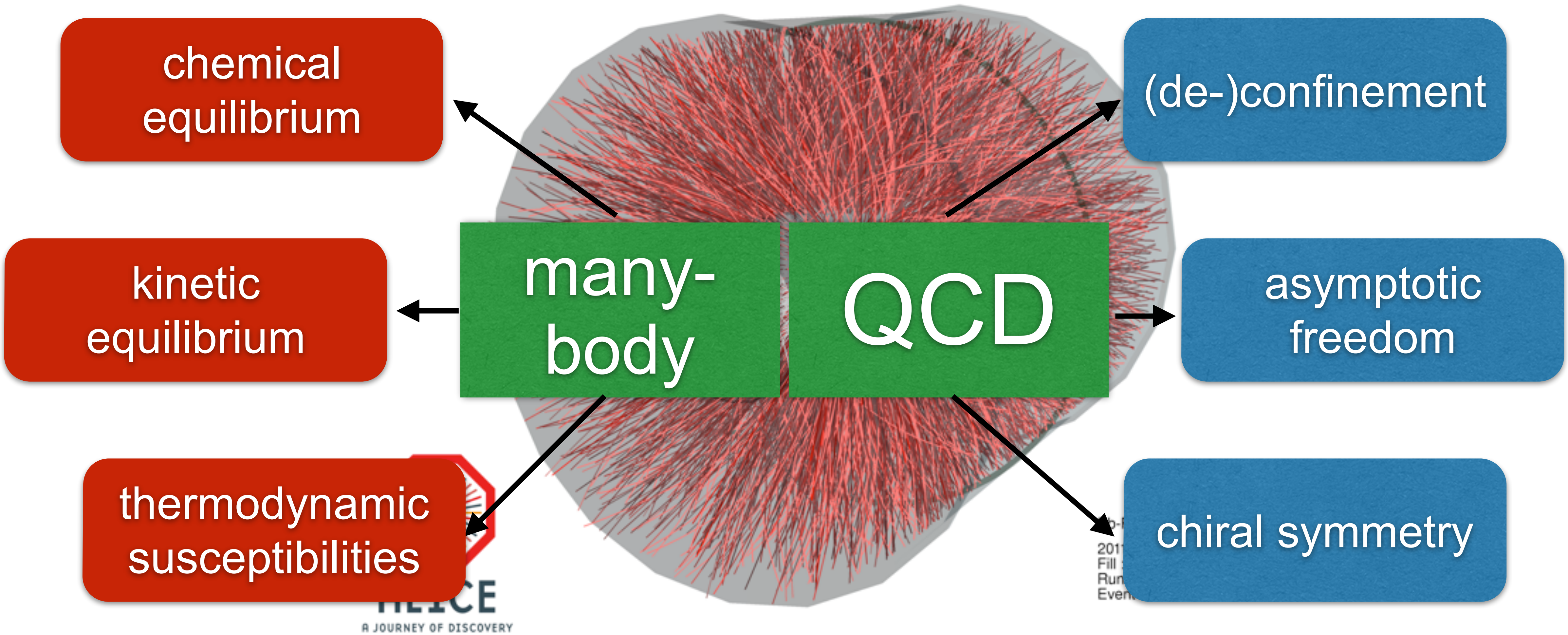

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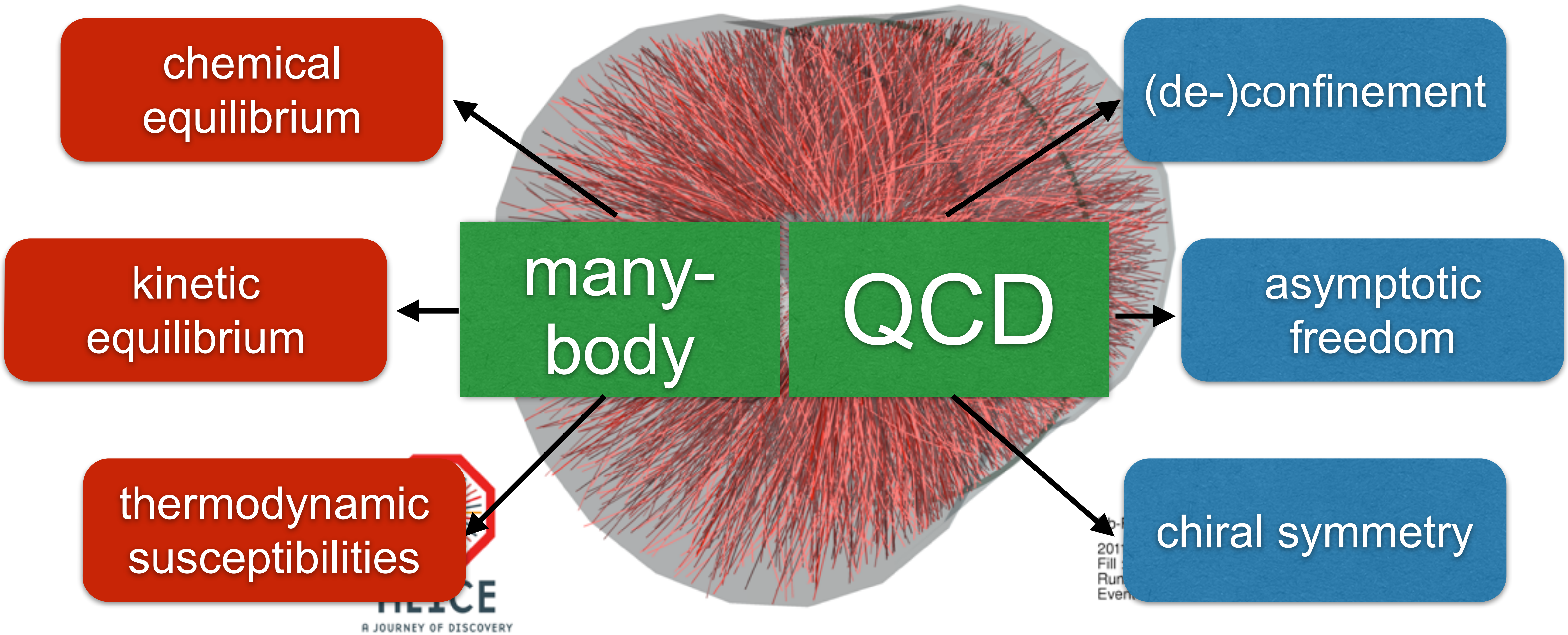

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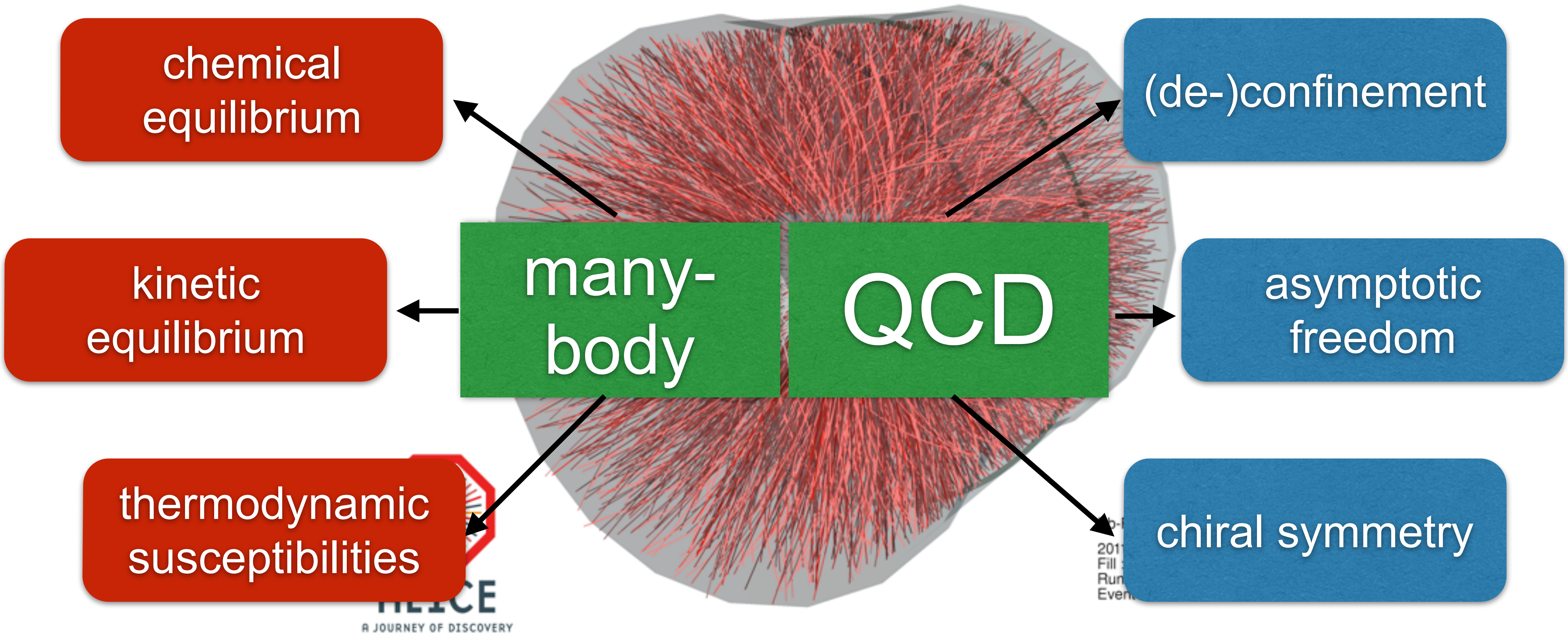

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98% of all particles are produced with $p_T < 2$ GeV/c → thermal particle production in a non-perturbative regime
=> **thermodynamics**
=> **LATTICE QCD** calculations

Introduction (1)

- Measurement of the production *yields* of identified particles and chemical freeze-out conditions:
  - Hadron resonance gas approach in thermal-statistical *models*

- Measurement of event-by-event *fluctuations* of conserved quantities:
  - net-charge fluctuations
  - plans for future measurements
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Very sensitive to critical behavior.

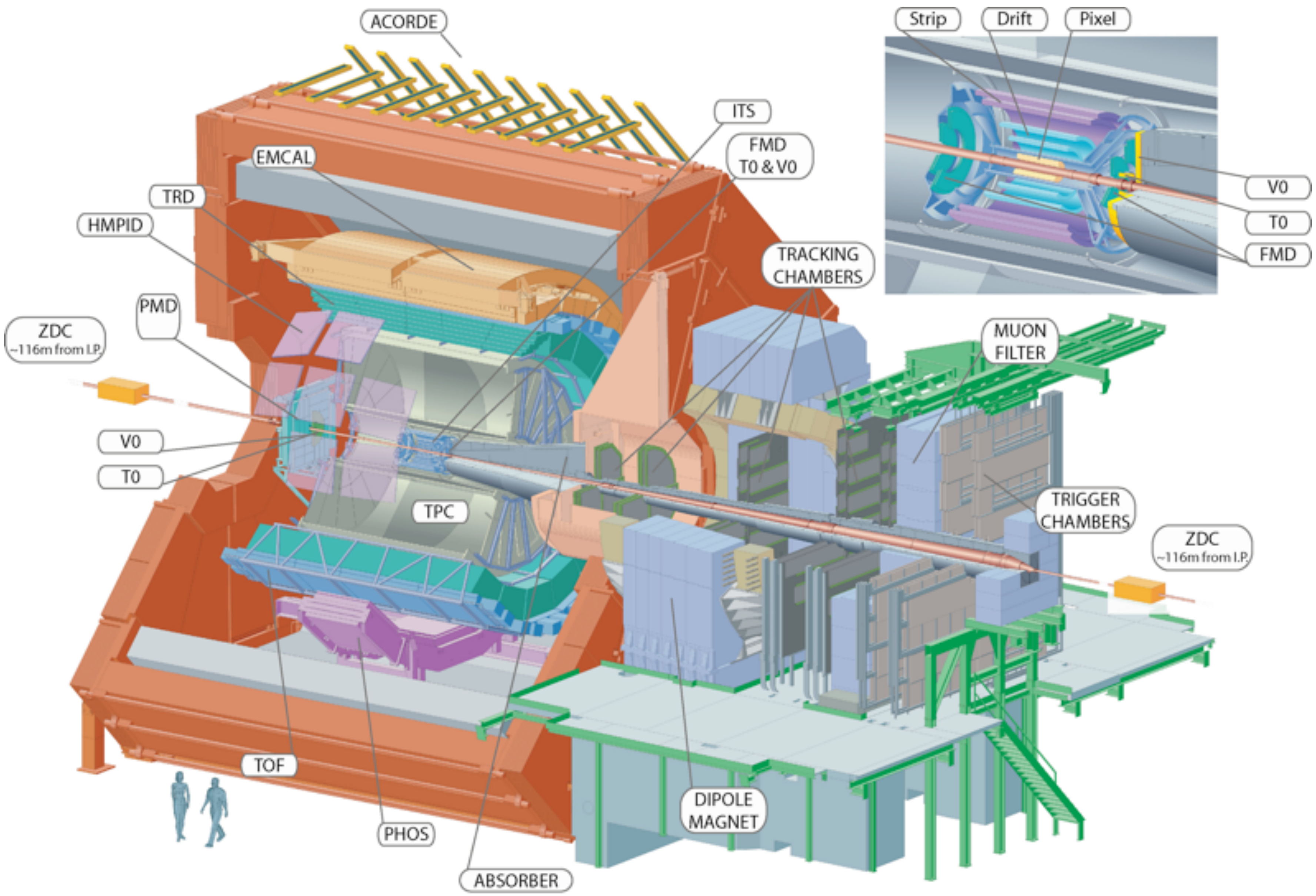
Still a lot of work to do at LHC energies.. Many questions are still open.

Introduction (2)

- Fluctuations can be of **statistical** or **dynamical** origin and we must carefully distinguish them. Dynamical fluctuations arise from physical phenomena.

- Ongoing and completed fluctuation analyses in ALICE:
  - **net-charge fluctuations**
  - **net-strangeness**
  - **balance functions**
  - **mean p_T fluctuations ➔** see next talk by Stefan Heckel
  - multiplicity fluctuations
  - higher moments of net-charge and net-baryon fluctuations
  - temperature fluctuations

The ALICE detector



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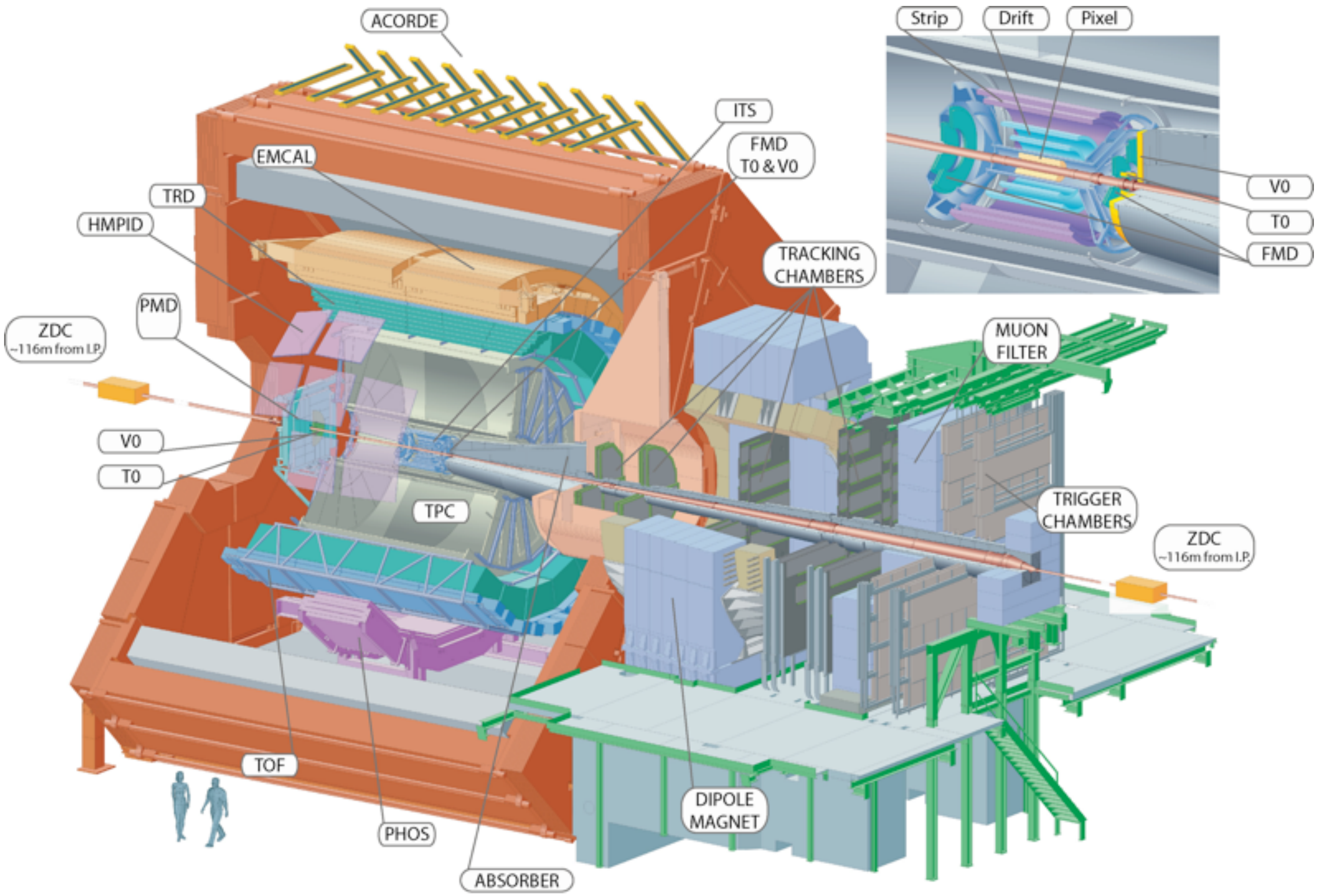
ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment.



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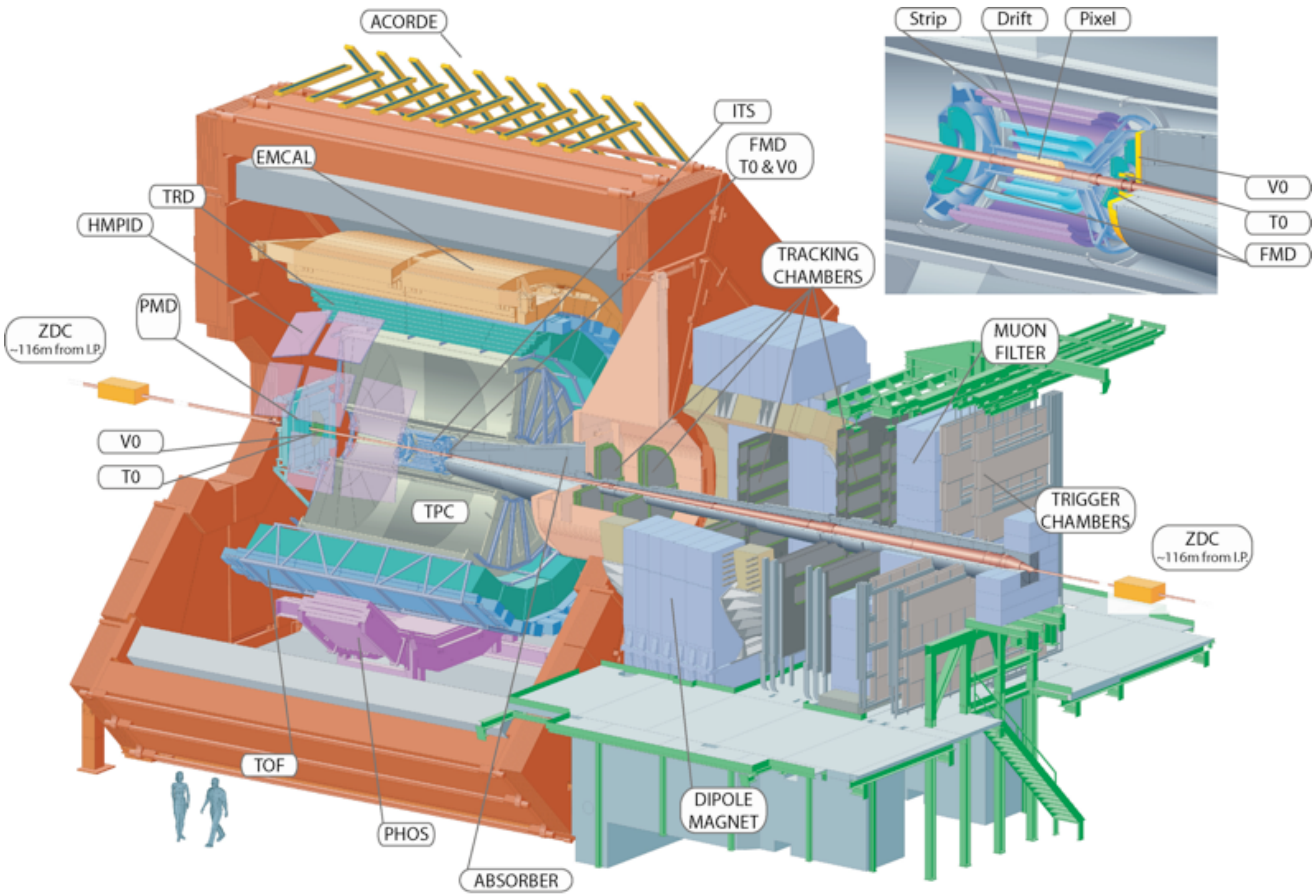

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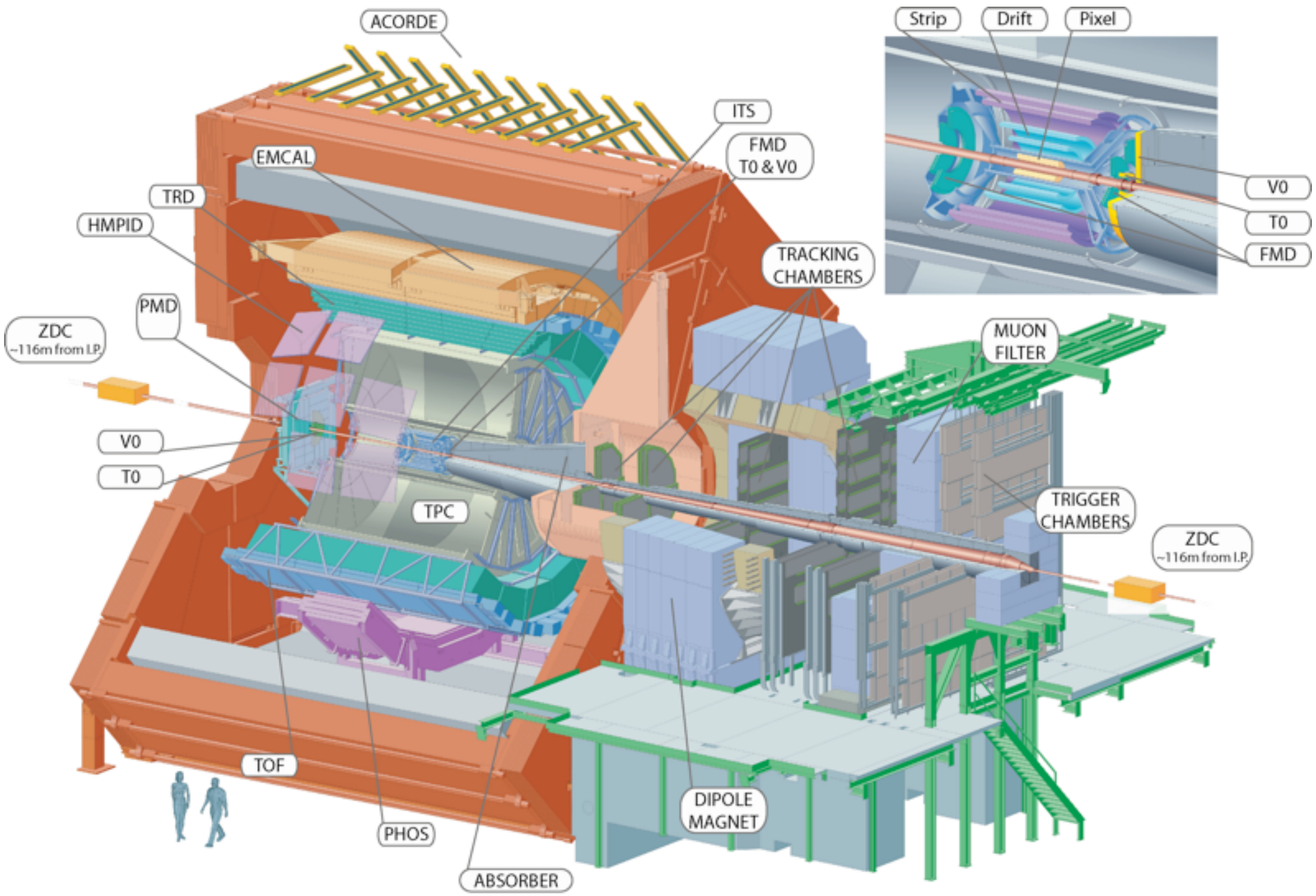

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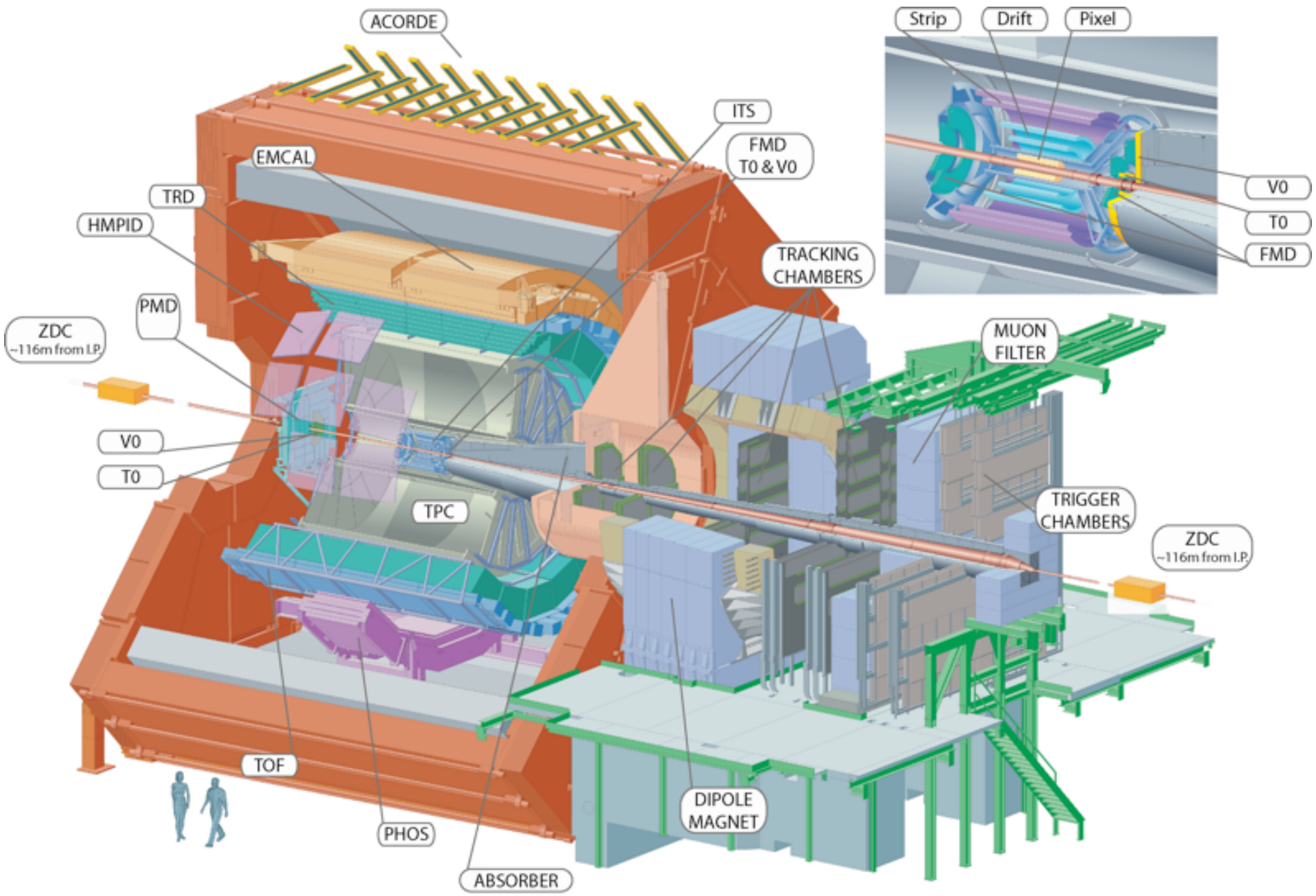

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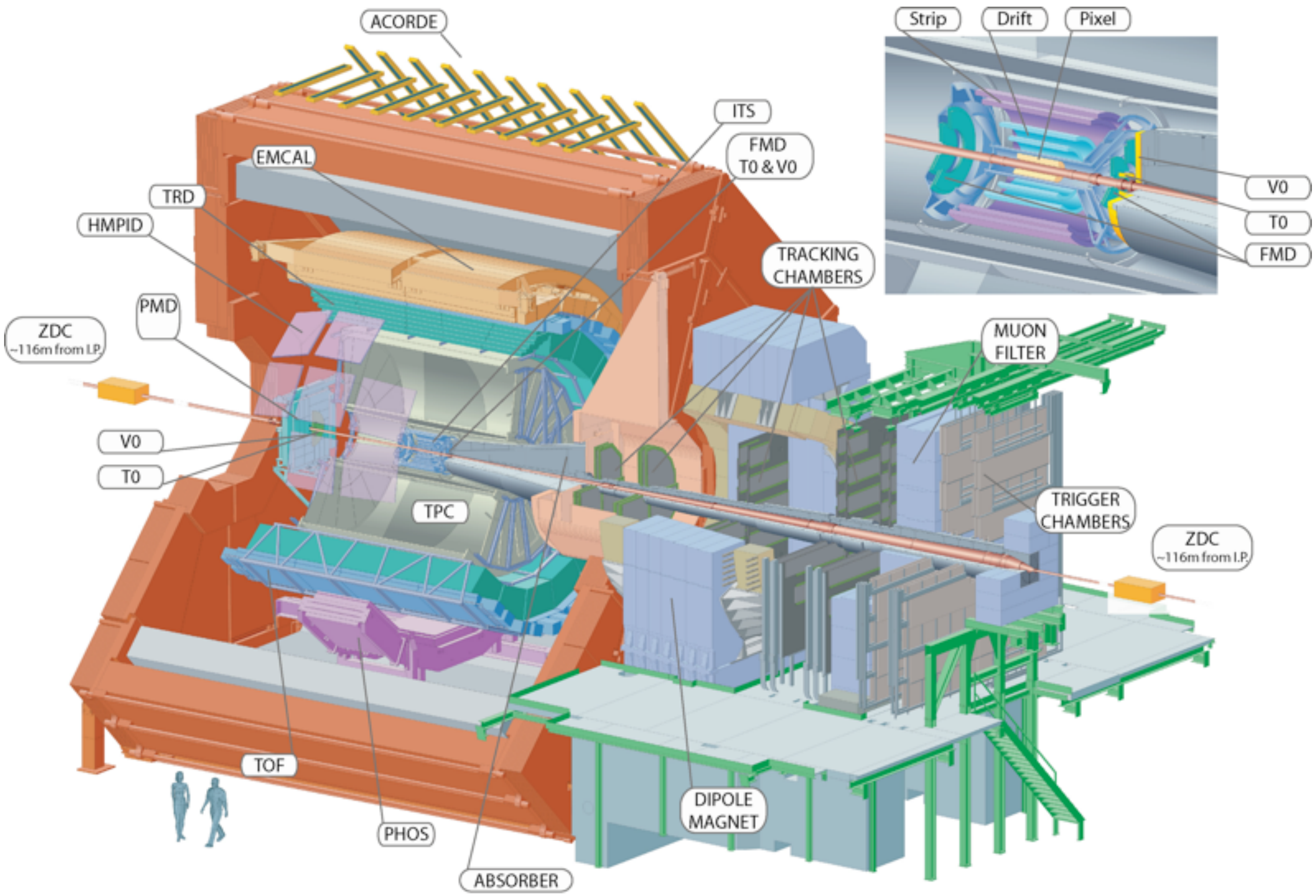

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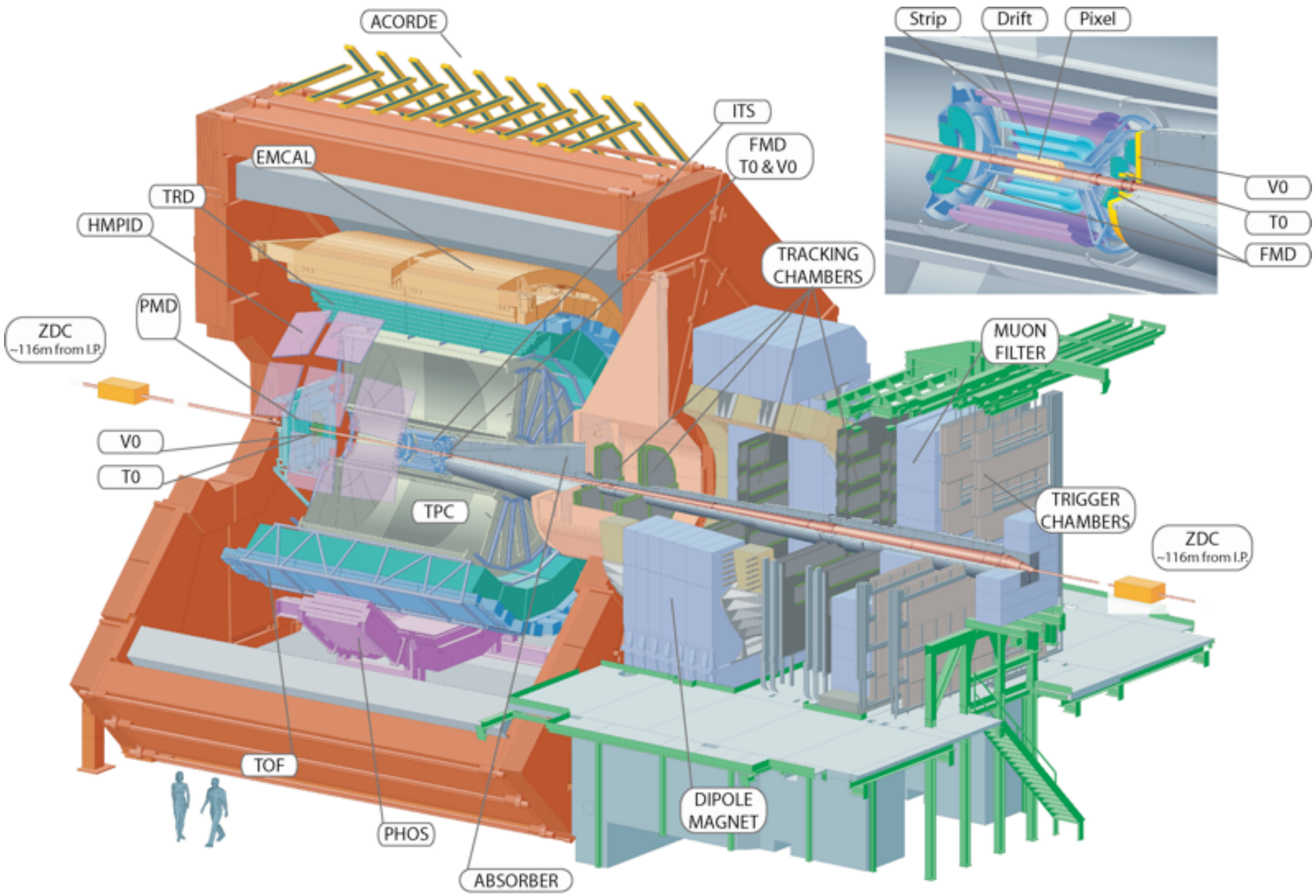

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ALICE is ideally suited for the measurement of light flavor hadrons on an event-by-event basis.

Bulk particle production

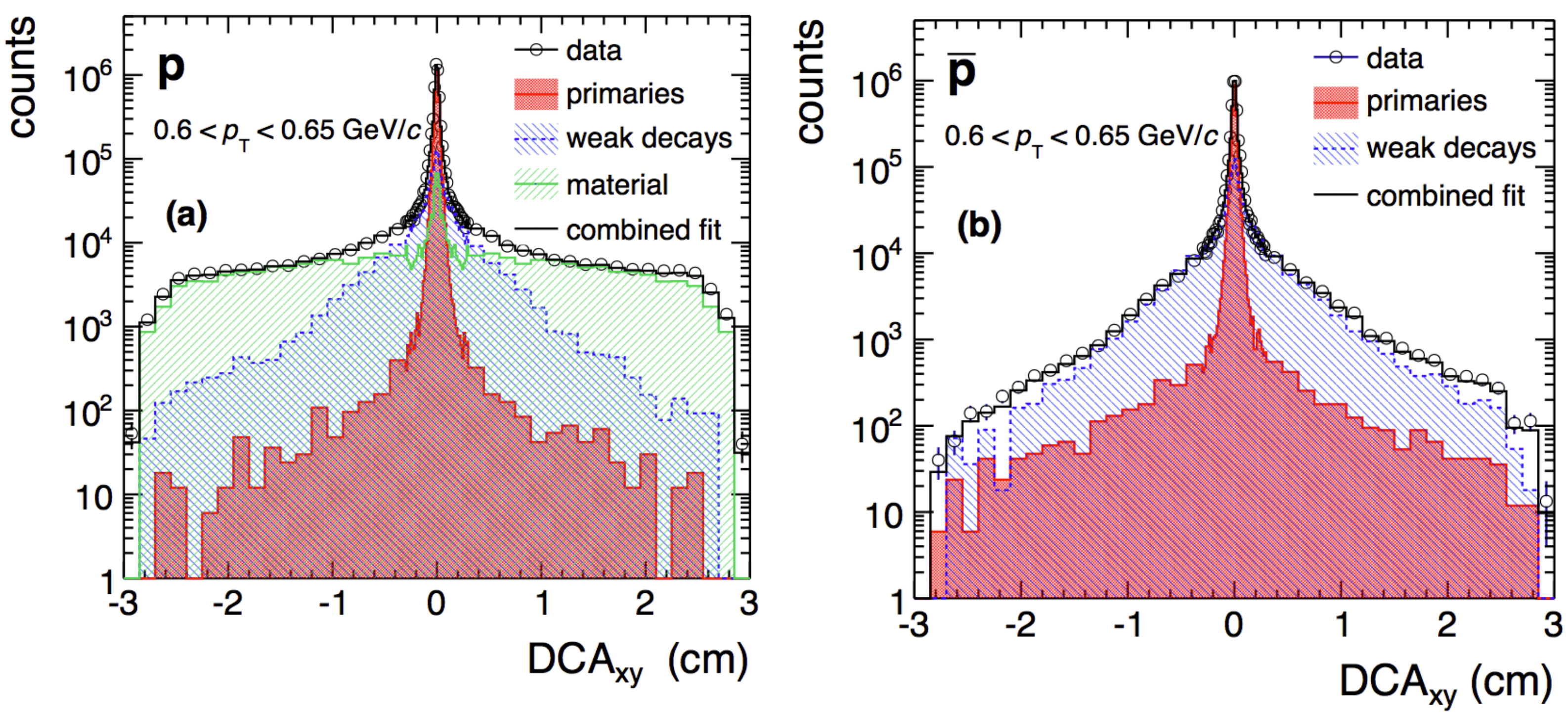
- Investigate matter in local thermal equilibrium => Look at the hadrons made up of the most abundantly produced quarks: u,d,s.

  π, K, p, Λ, Ξ, Ω, Φ, K^{*0}, d, ^{3}He, $^{3}_{\Lambda}H$, ^{4}He

- Decays of strange particles feed into the states with lower mass and need to be carefully subtracted for consistent data ↔ model comparisons:

  Λ → p π (63.9 %)

  Ξ → Λ π (99.87 %)



[Phys. Rev. C 88, 044910 (2013)]

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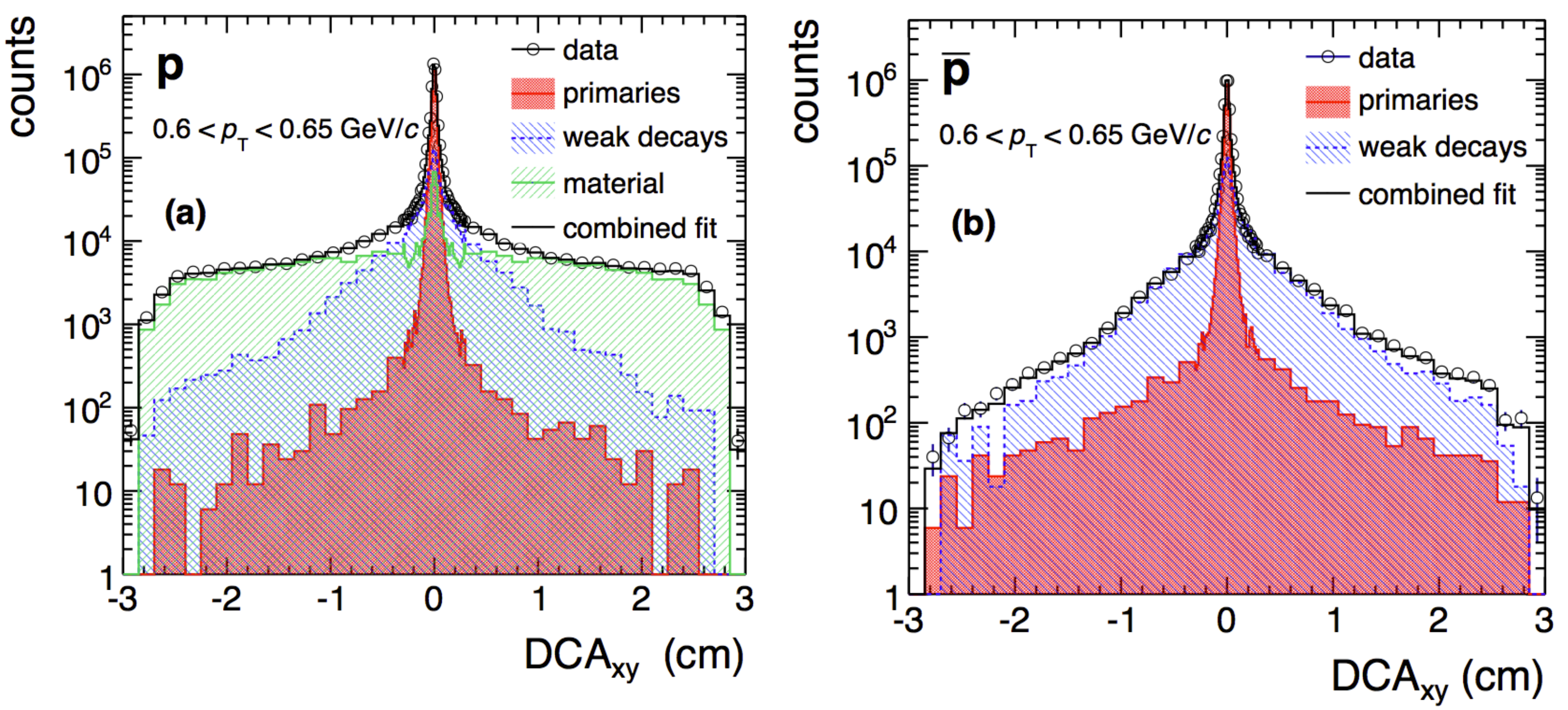
  $\Lambda \rightarrow p\,\pi$ (63.9 %)
  $\Xi \rightarrow \Lambda\,\pi$ (99.87 %)

(ALICE Definition) *Primary particles* are defined as prompt particles produced in the collision including all decay products, except products from weak decays of light flavor hadrons and of muons.



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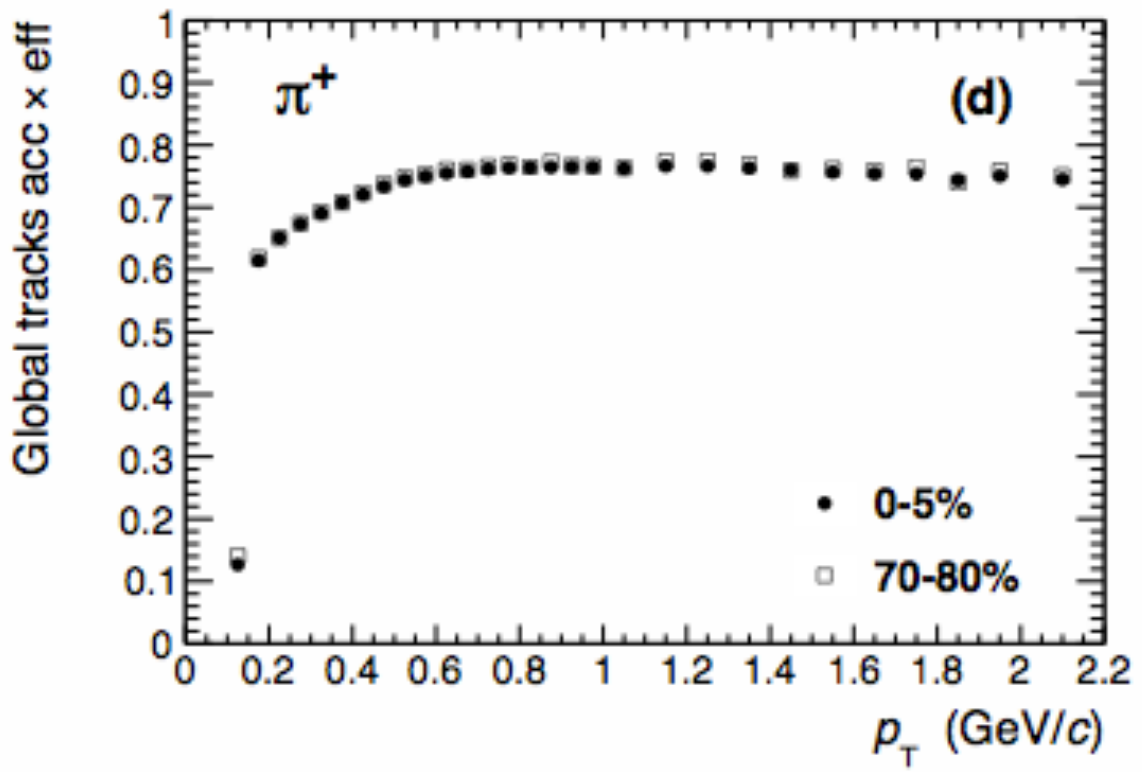
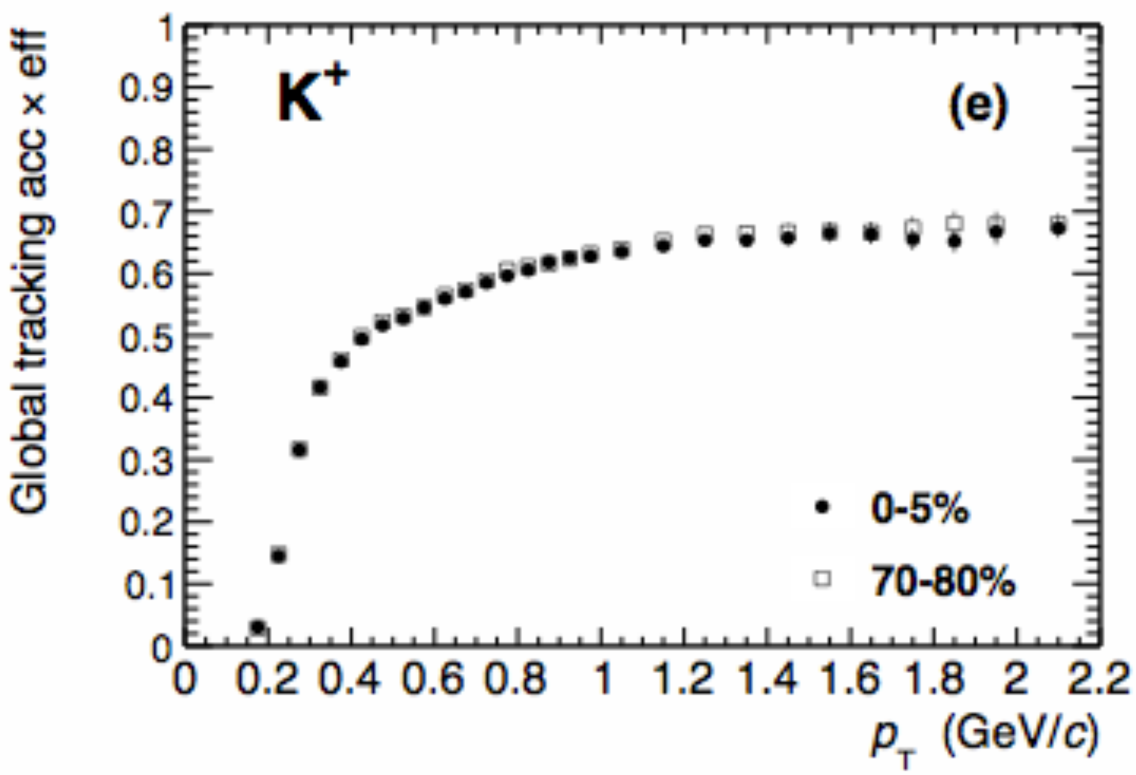
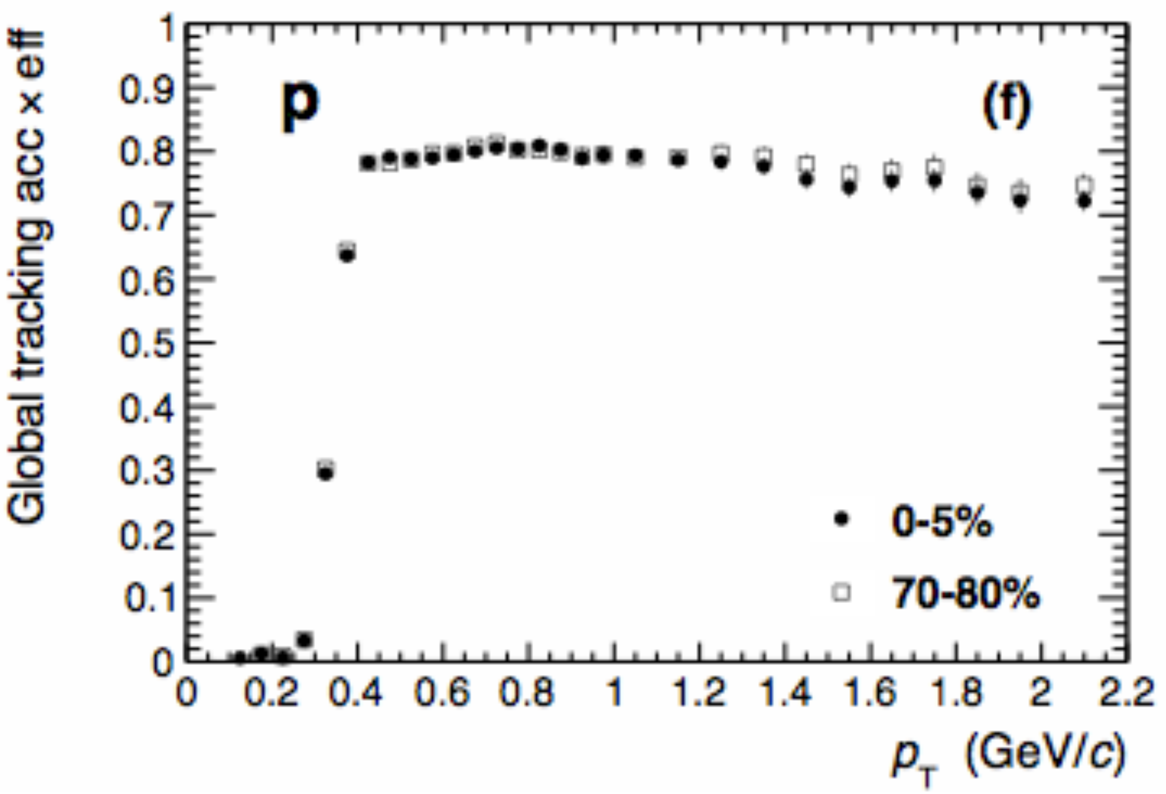
Detector efficiencies







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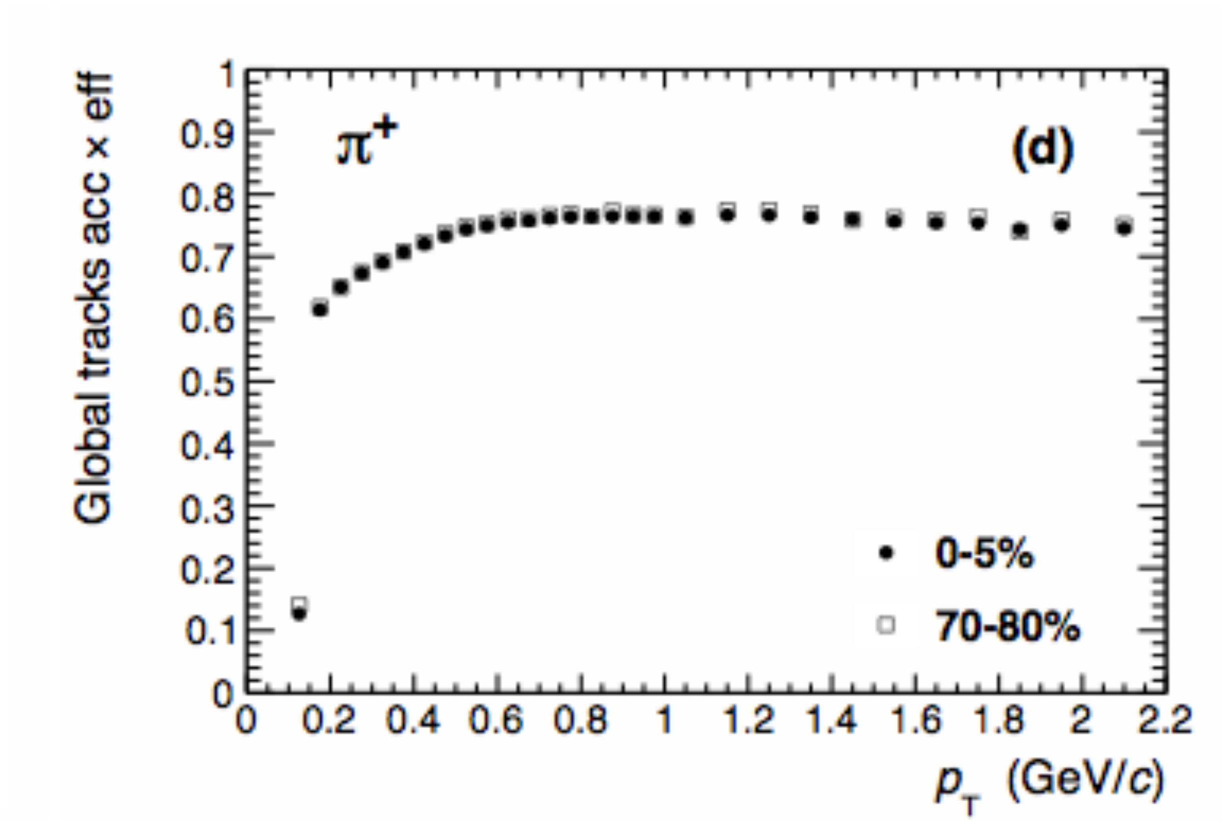
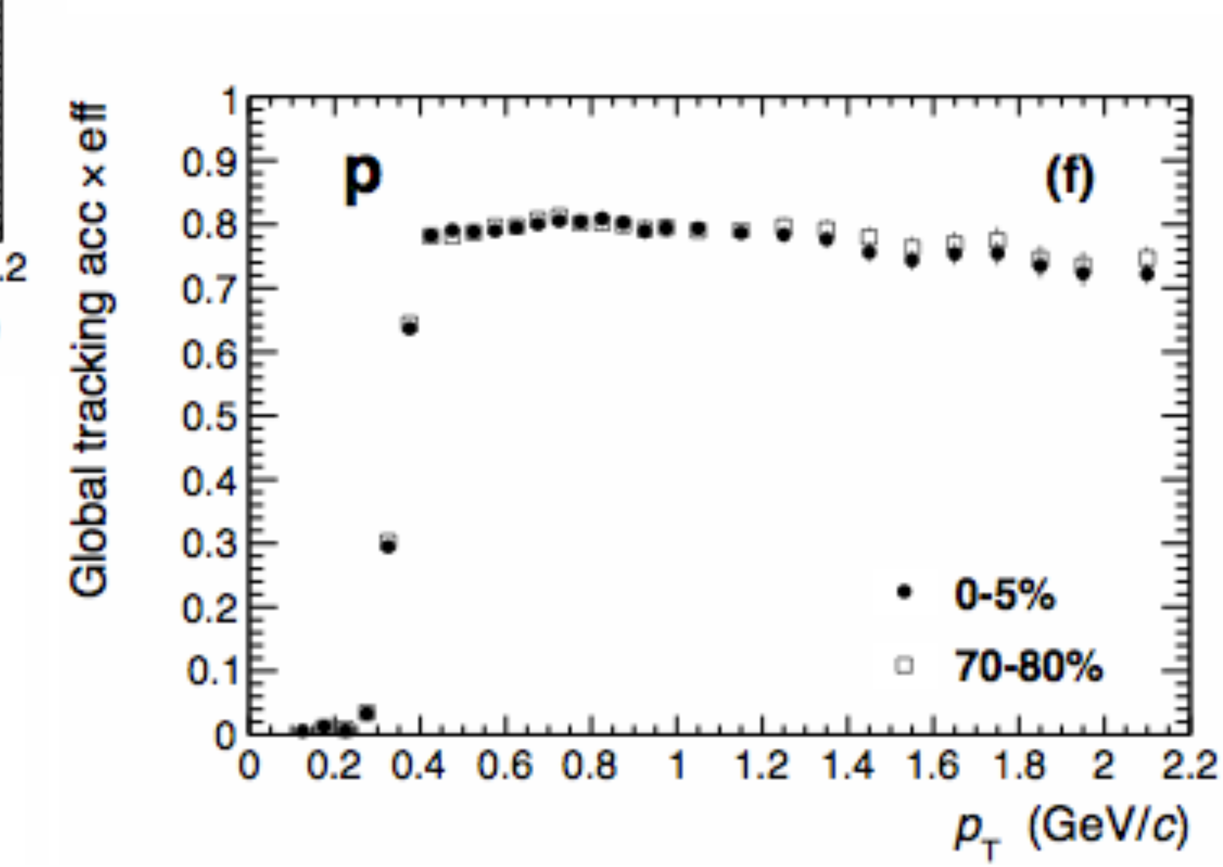
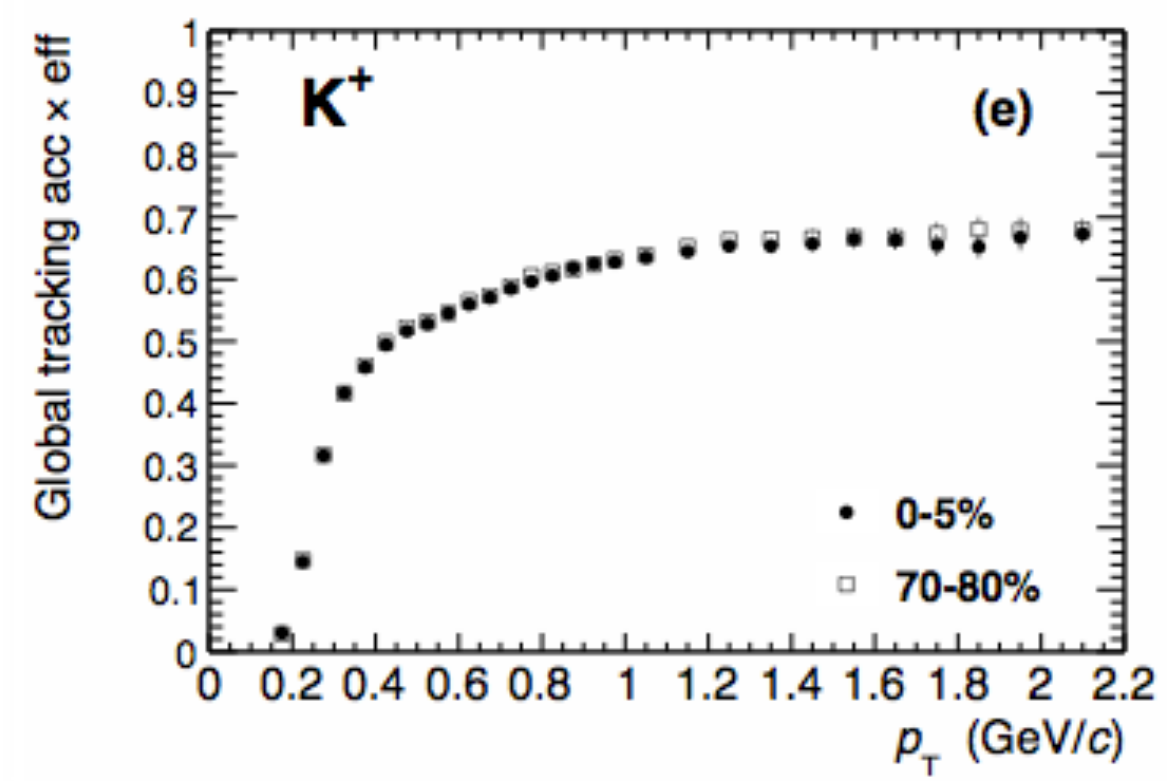


Detector originally optimised for d*N*/d*y* = 8000
=> negligible dependence of detector efficiencies on centrality.





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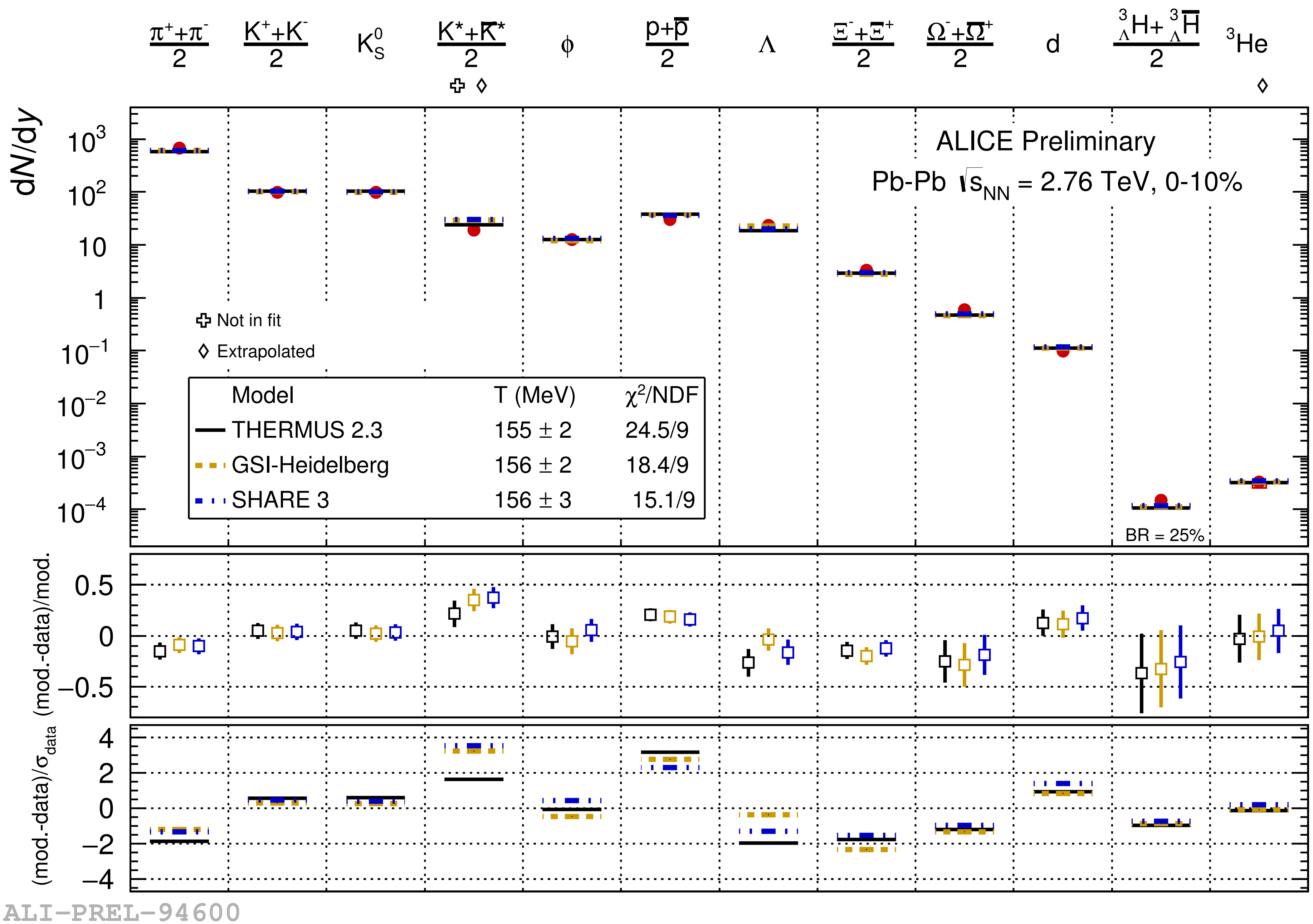
Chemical freeze-out and thermal model calculations

Pb-Pb: Thermal fits to ALICE data



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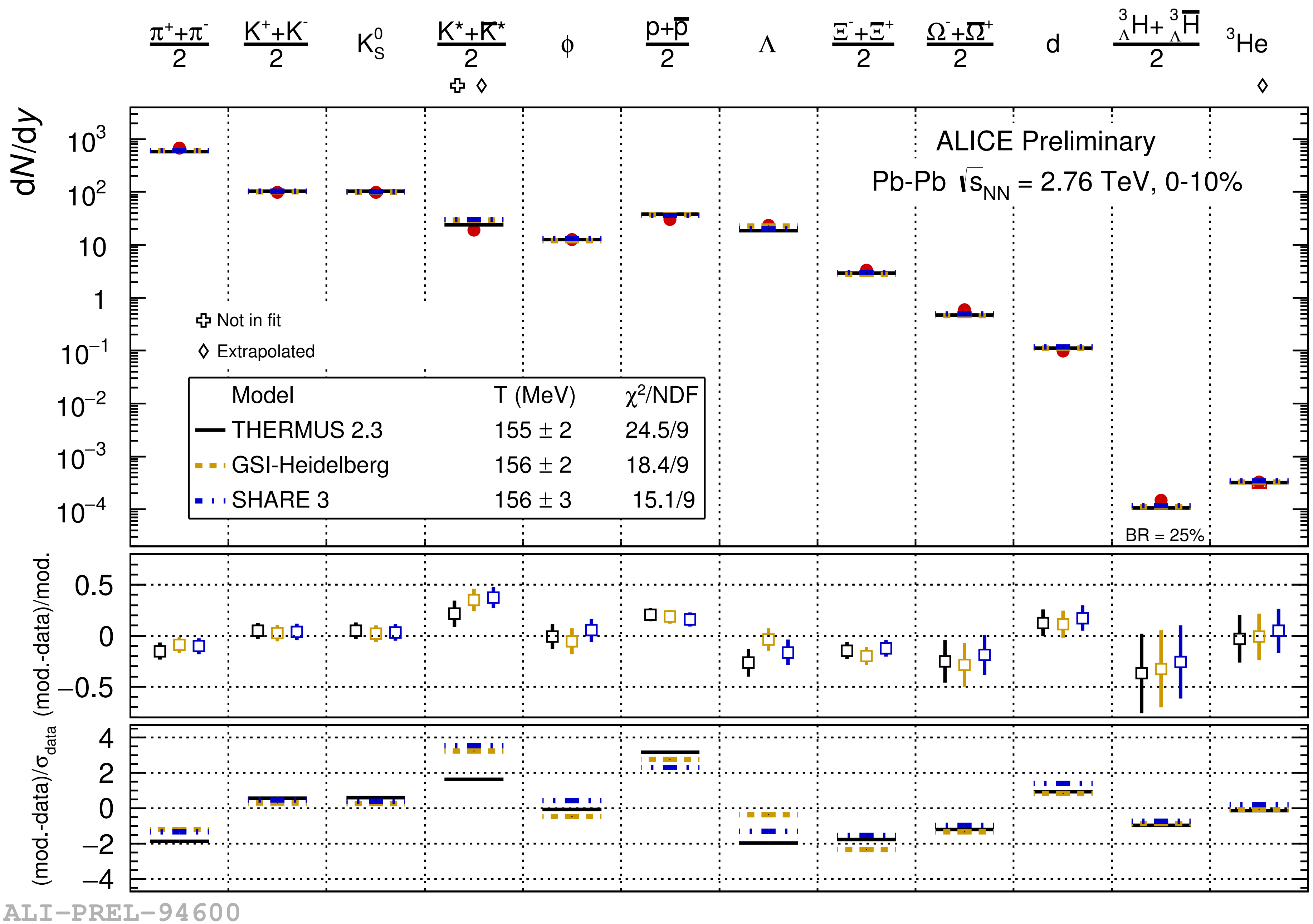

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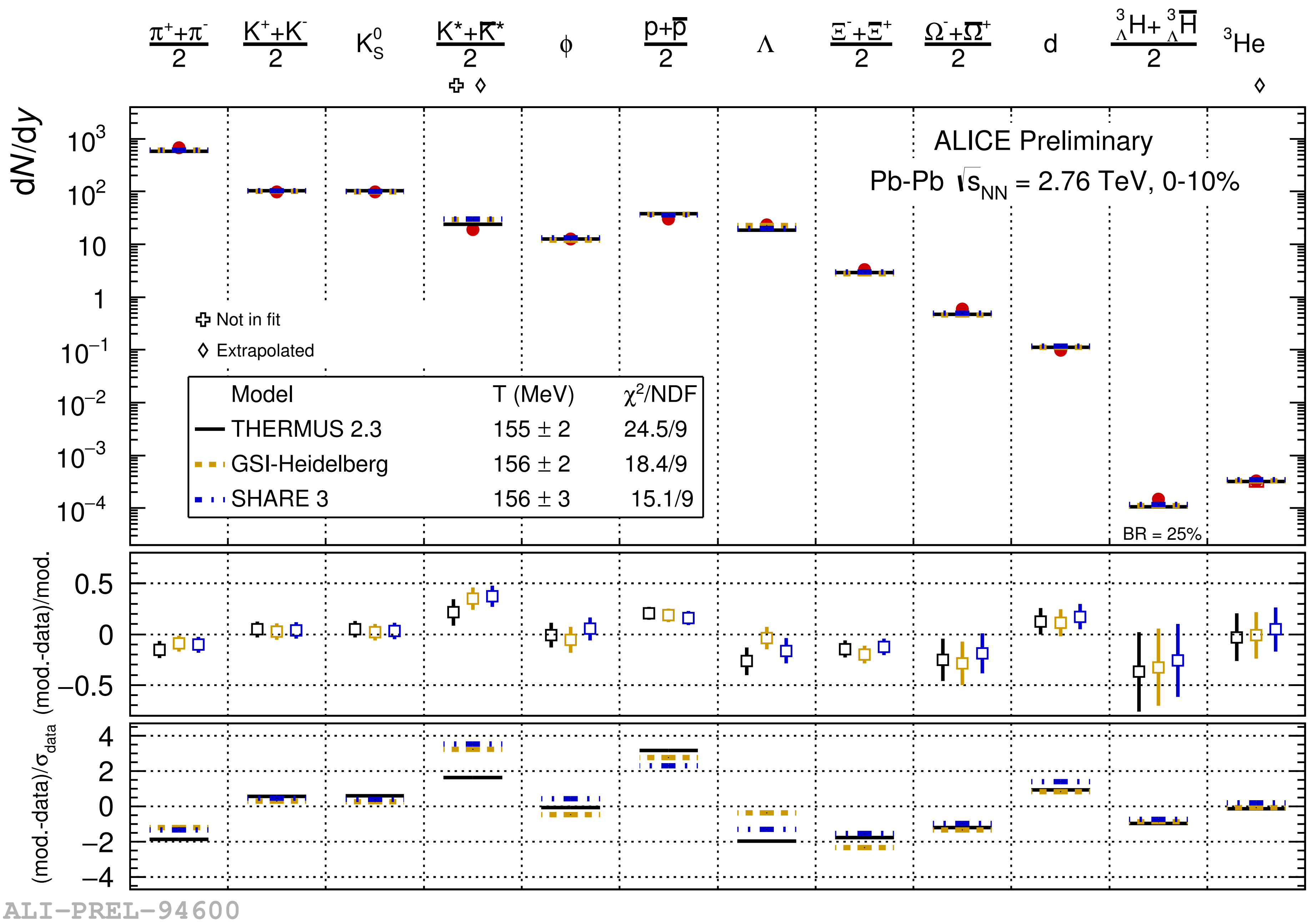

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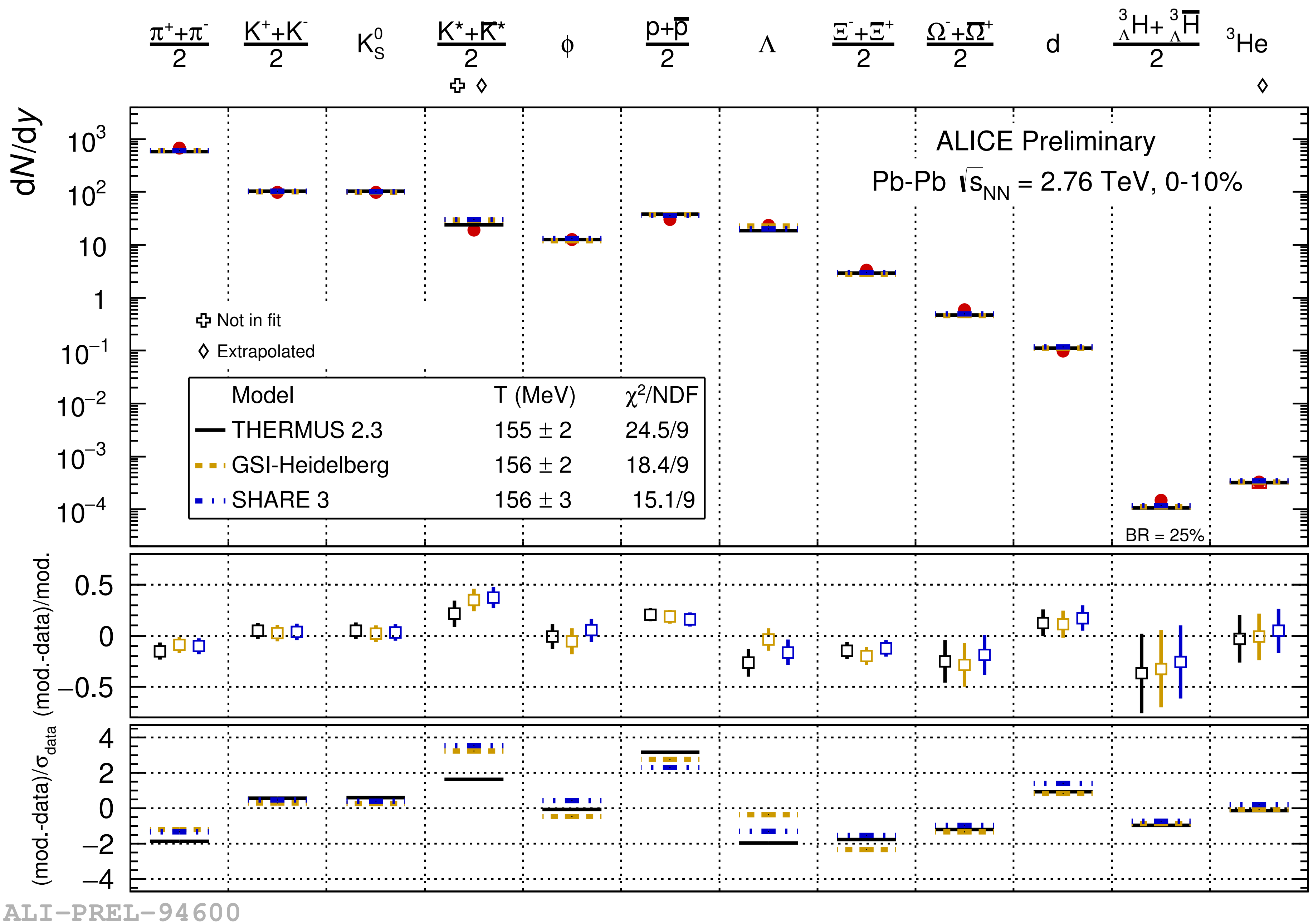

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Largest deviations observed for **protons** (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for $\mathbf{K^{*0}}$.

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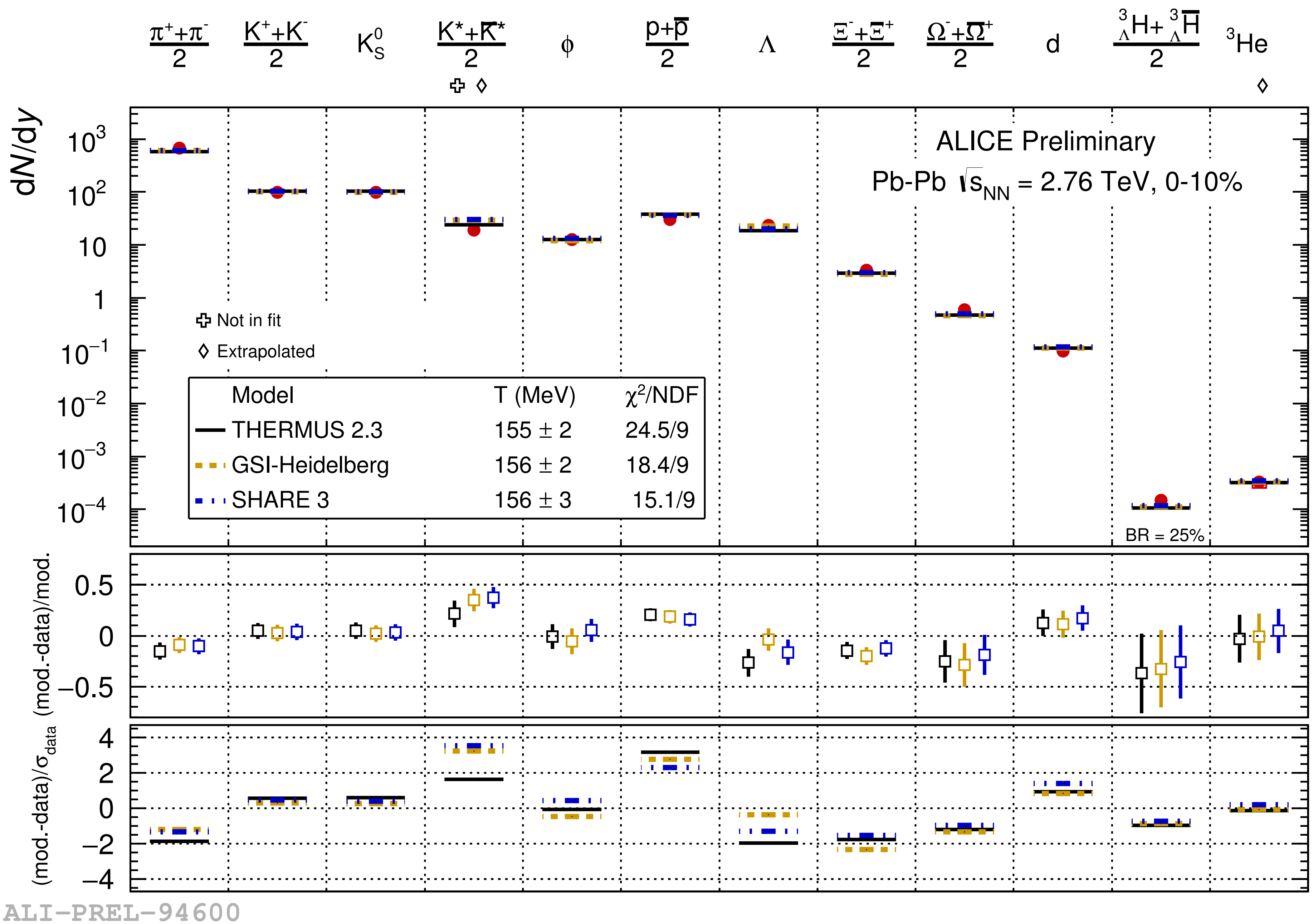

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Three different versions of thermal model implementations give similar results.

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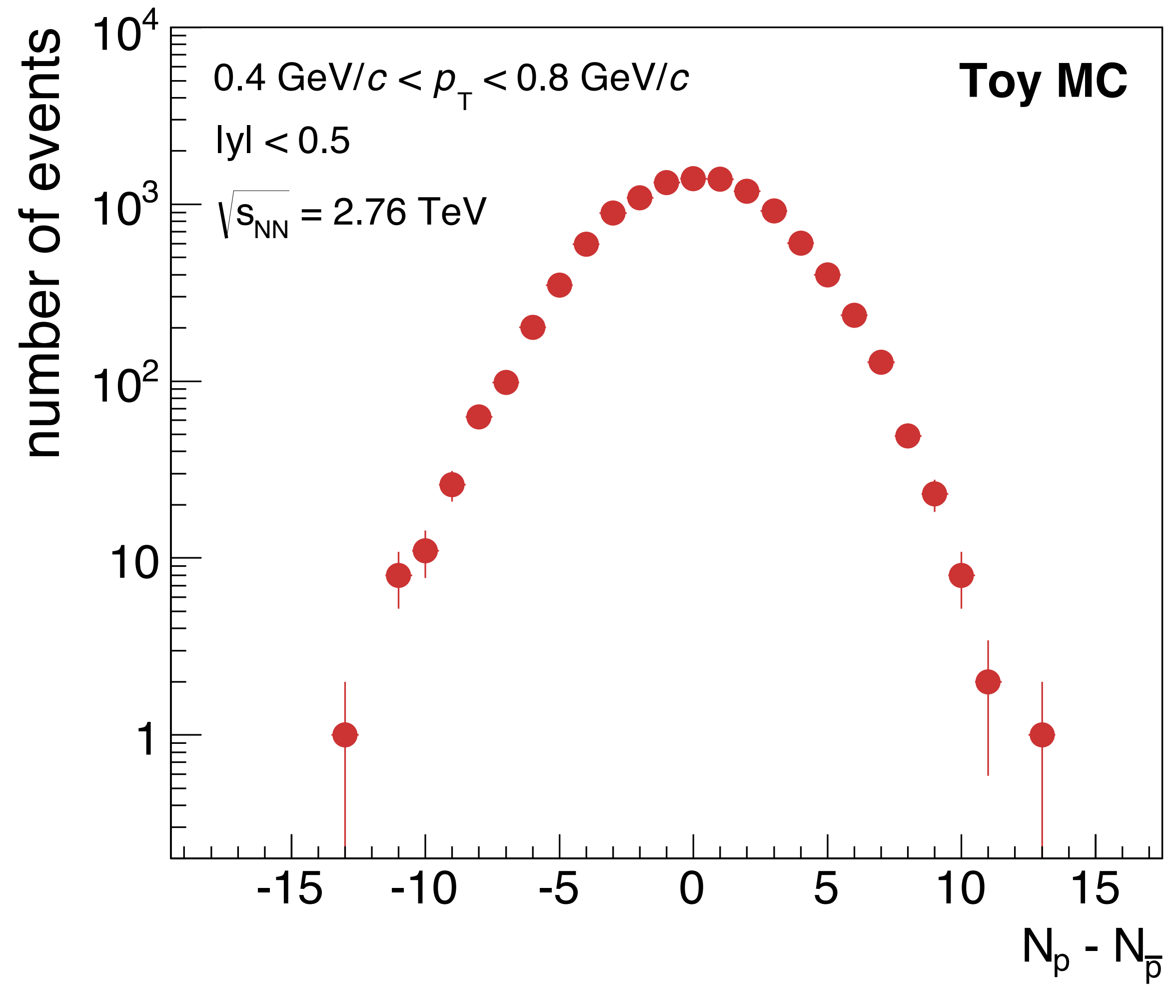
Event-by-event fluctuations of conserved quantities

Thermodynamic susceptibilities

- Event-by-event fluctuations of the conserved quantities in QCD (*charge Q*, *baryon number B*, *strangeness S*) correspond to thermodynamic susceptibilities χ of the system which can be directly calculated in Lattice QCD or in the Hadron Resonance Gas (HRG) model:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_S/T)^n}$$

- Statistical distribution of conserved quantities are quantified by their (central) moments or cumulants.



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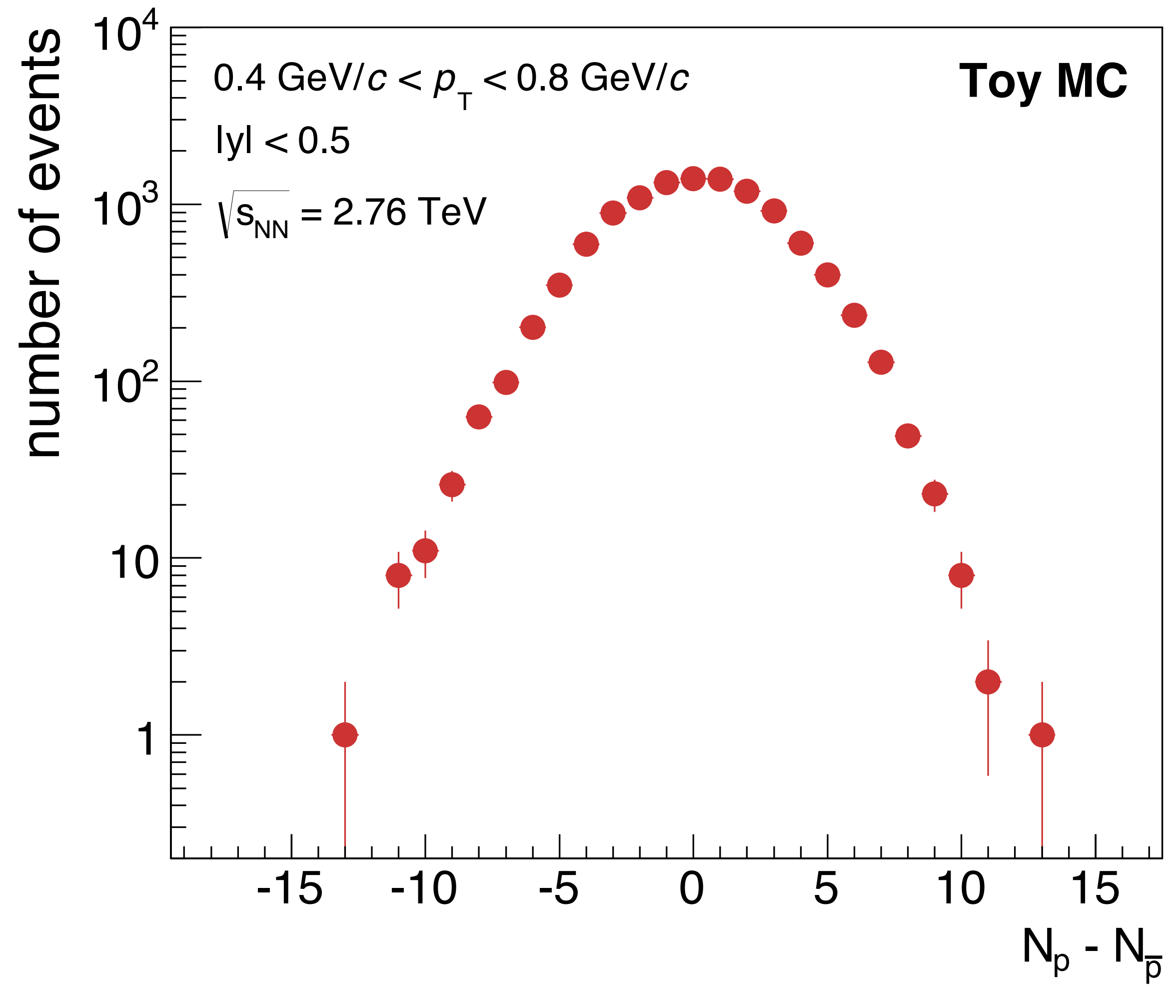

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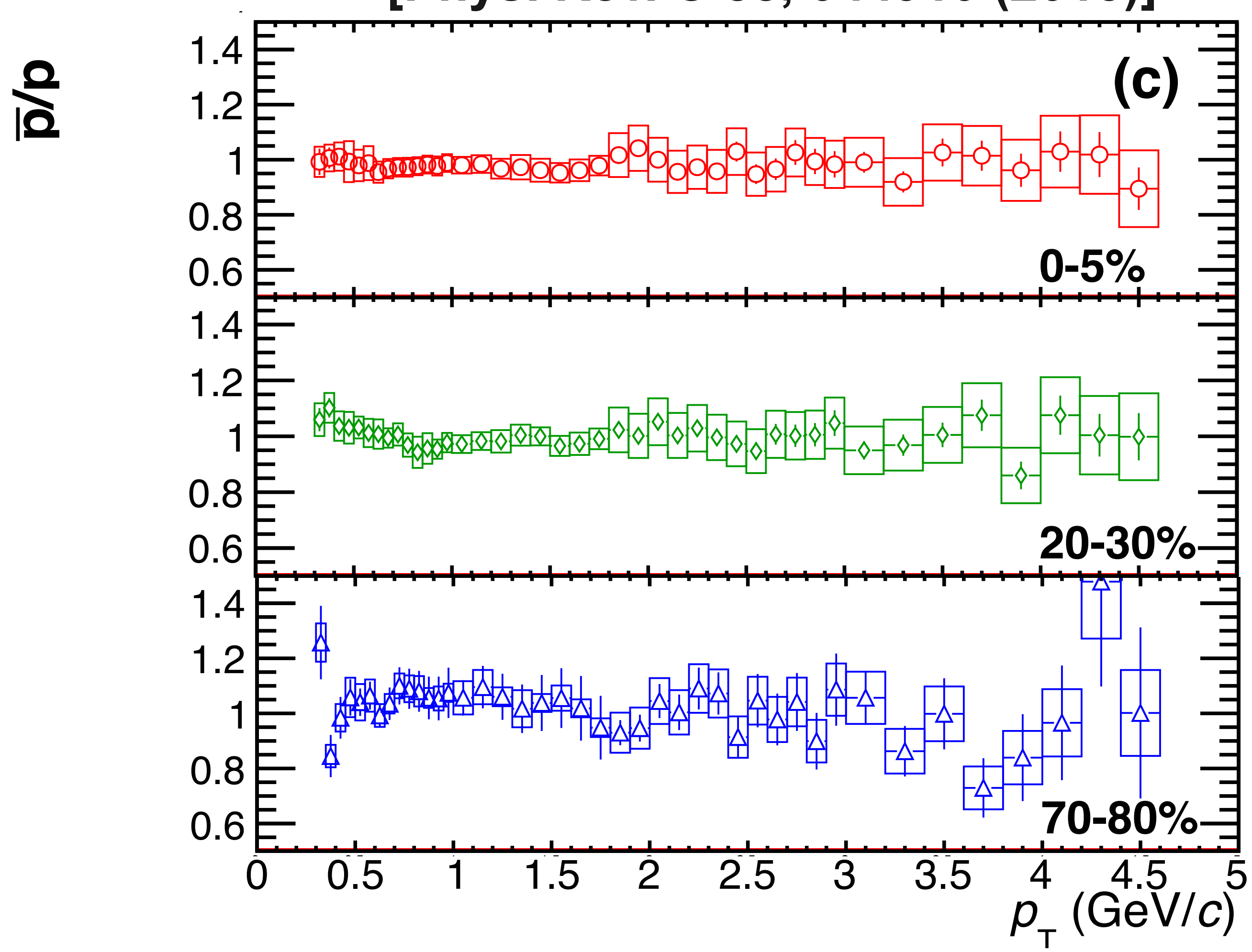
[Phys. Rev. C 88, 044910 (2013)]



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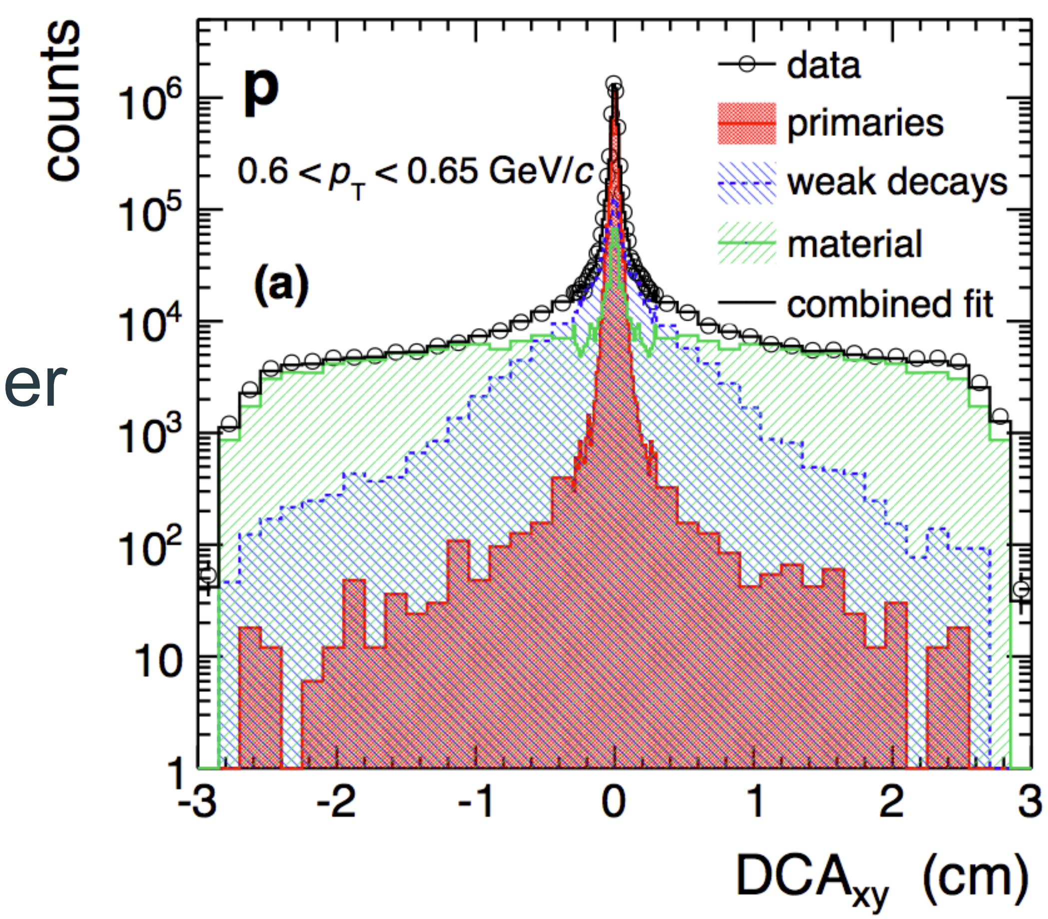
Towards a measurement of net-baryon number at LHC…

- The measurement is experimentally very challenging:
  - Correction for detector efficiency (N.B.: efficiencies differ for protons and anti-protons due to absorption).
  - Auto-correlations with centrality estimator. -> use forward detectors to avoid them.
  - Contamination from protons from material.
  - Contamination from weak decays:
    - Does the inclusion of them bring us closer to the total baryon number *B*?
    - Can one separate cleanly χ_B and χ_S?
  - Misidentified particles.



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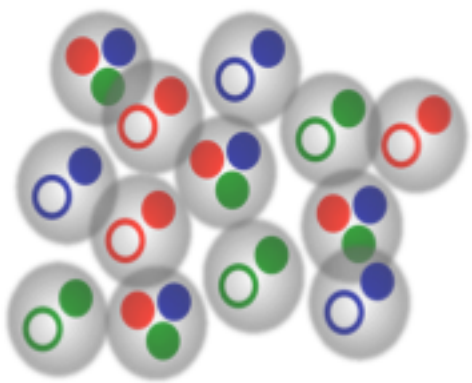
- However, we already know how to correct for these effects on average for particle spectra..

Net charge fluctuations

Net charge fluctuations — introduction

- So far, only a net-charge measurement corresponding to the second order moment has been finalised at LHC energies: **[Phys. Rev. Lett. 110, 152301]**.
- Simplified picture:



Hadronic phase:
q =±1
=> q^2 =±1

Partonic phase:
q =±(2/3),±(1/3)
=> q^2 =±(4/9),±(1/9)

- ν_{dyn} as robust variable to quantify dynamical fluctuations and to identify relevant charge carriers:

$$\nu_{(+-,dyn.)} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

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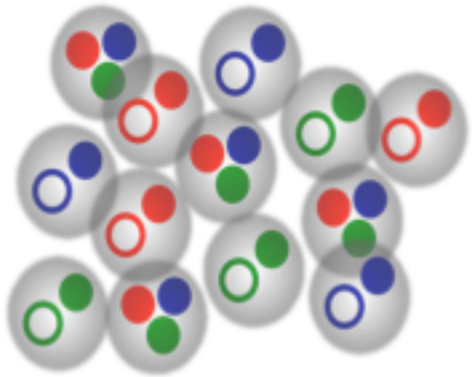

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Substantially smaller value of the correlation function is expected in the QGP phase than in the hadronic phase.

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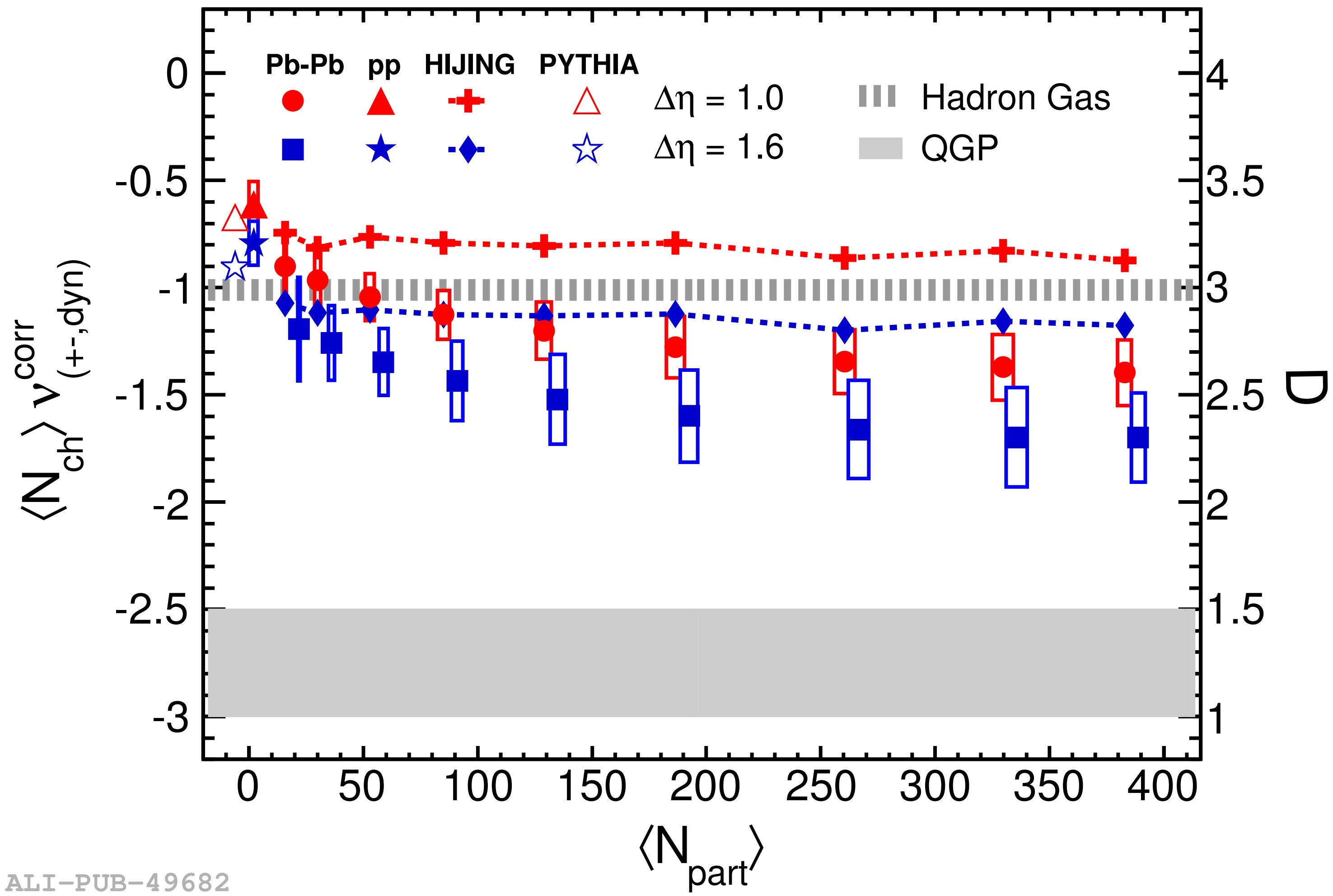
D-measure of net-charge fluctuations

- ν_{dyn} can be connected to the entropy of the system via the D-measure in order to relate it to theoretical expectations (corrected for acceptance and global charge conservation):

$$D = \langle N_{ch} \rangle \langle \delta R^2 \rangle$$

$$D \approx 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle} \approx \begin{cases} 3 & \text{HRG} \\ 1-1.5 & \text{QGP} \end{cases}$$

$$D - 4 \approx \langle N_{ch} \rangle \nu^{corr}_{(+-,dyn)}$$



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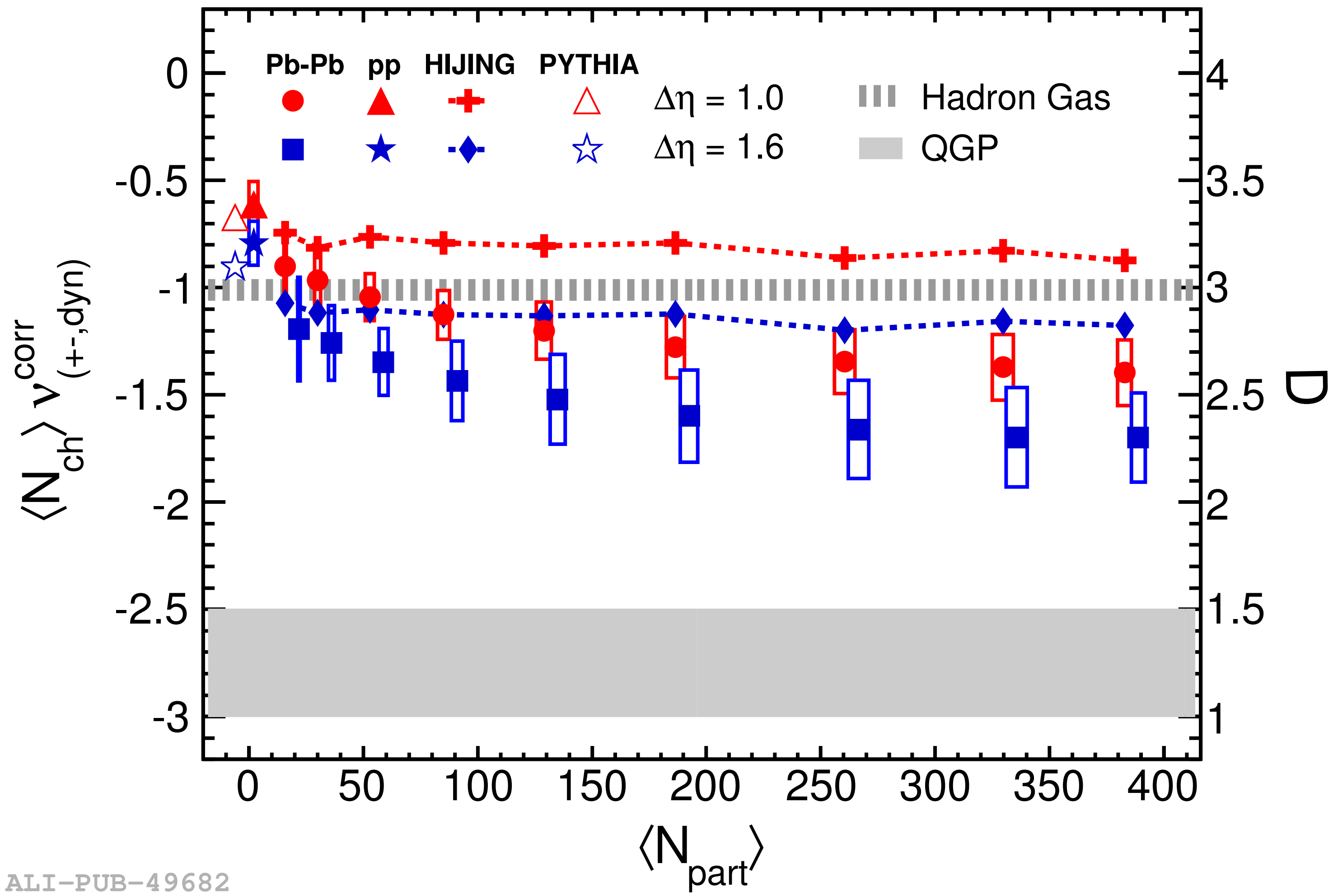

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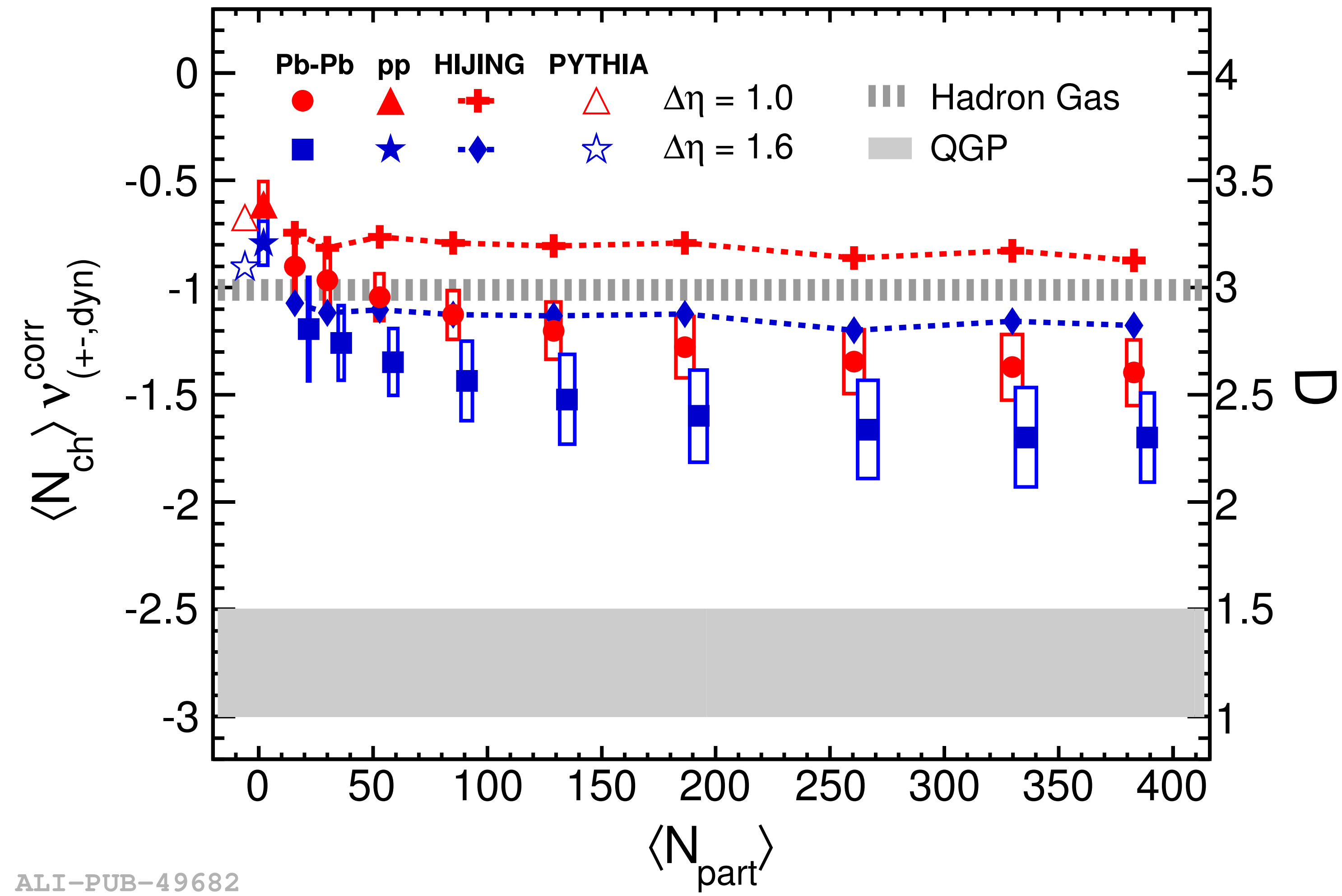

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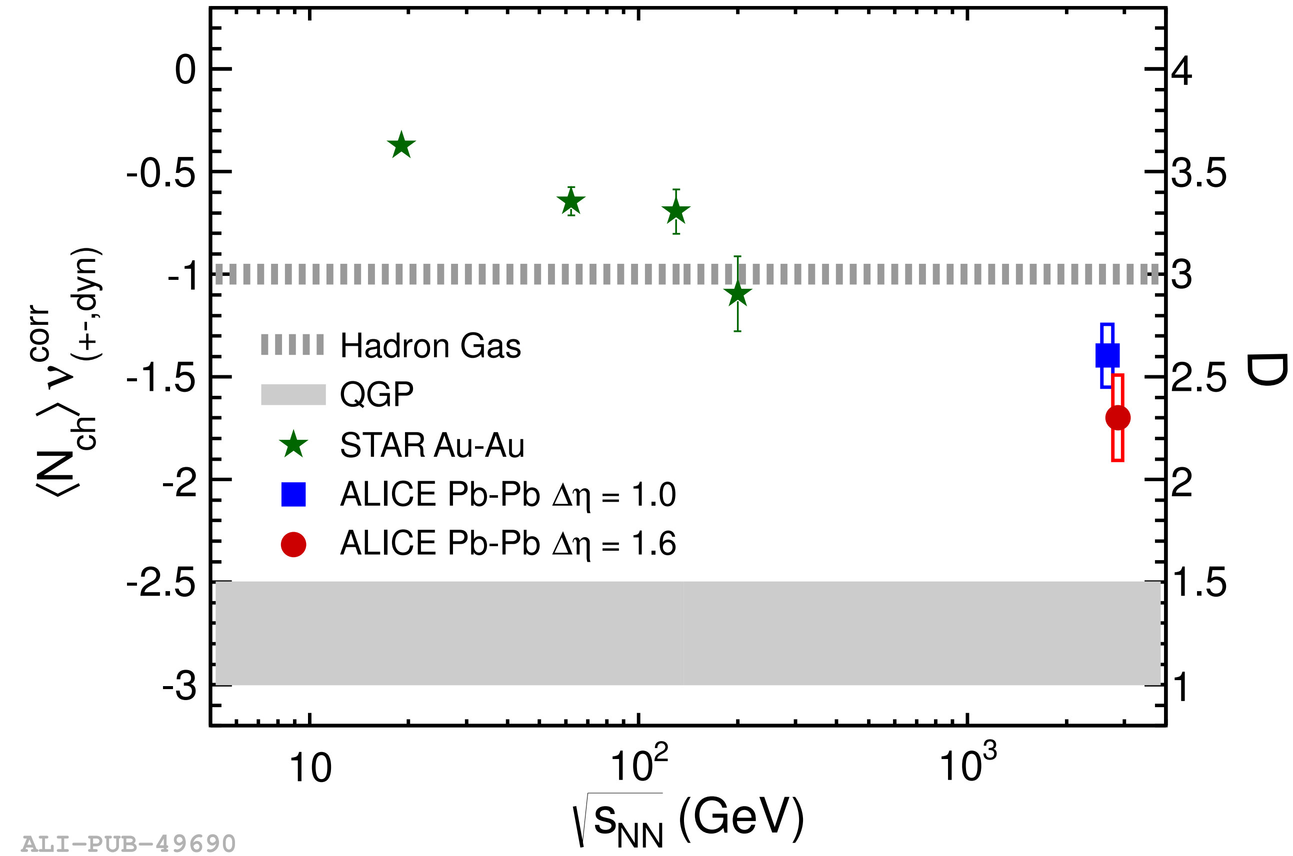
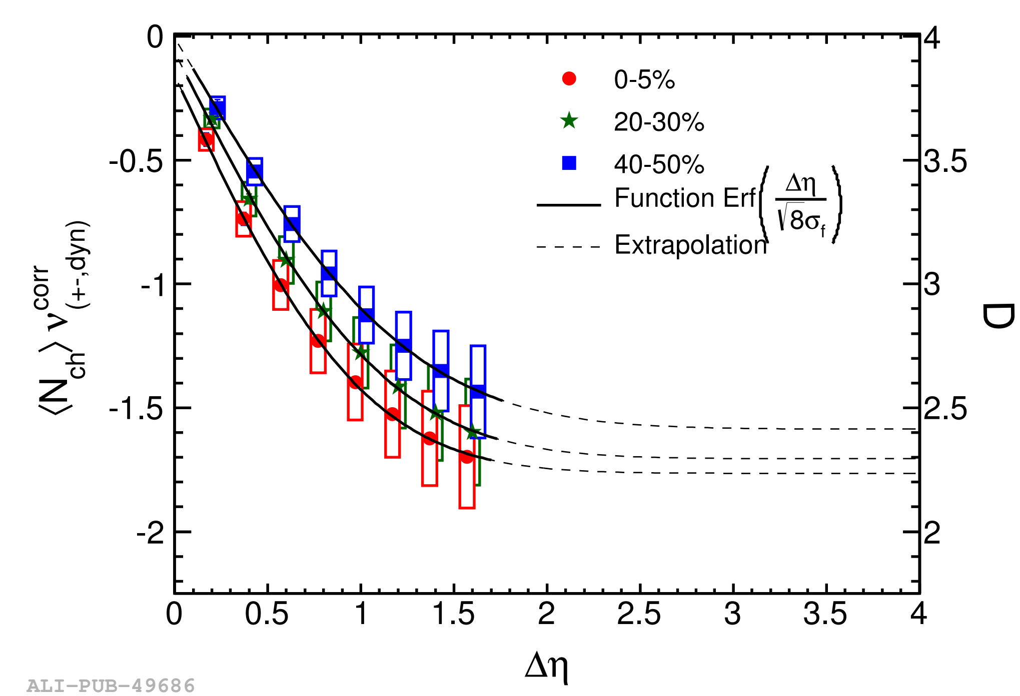
HIJING shows no centrality dependence and larger values than the data.

Energy and rapidity window dependence

- Results are shown for 0-5% most central collisions.
- Decreasing trend with increasing center-of-mass energy is observed.
- ALICE values significantly lower than the hadron gas expectation while RHIC measurements are still compatible.
- Strong dependence on rapidity window observed which seems to saturate above Δη ≈ 2.3 assuming diffusion functions. Initial fluctuations are diluted by final state interactions and limited experimental acceptance. Extending it further in η would be nice.





Balance function

Balance function

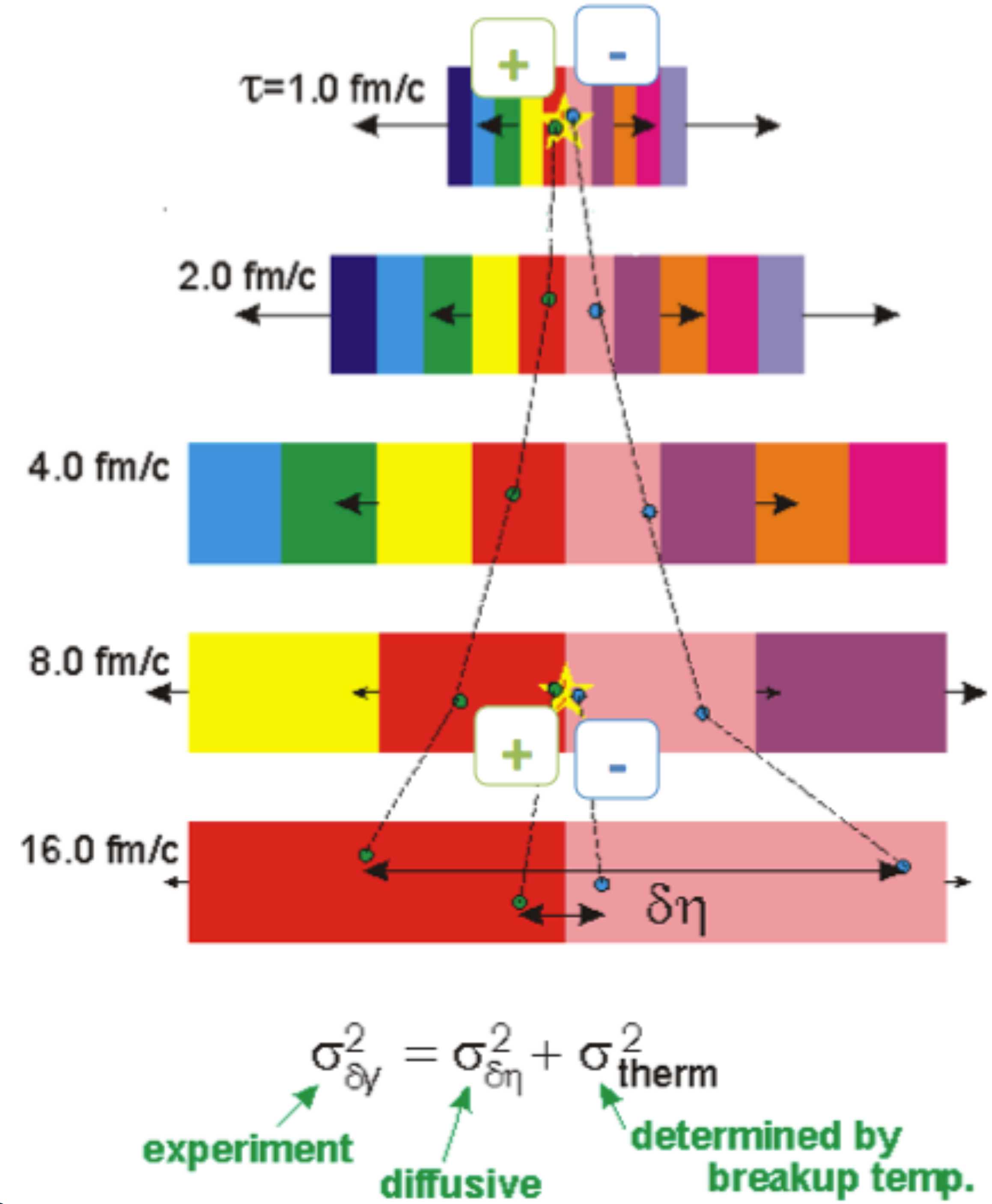
- Definition:

$$B(\Delta\eta,\Delta\varphi) = \frac{S(\Delta\eta,\Delta\varphi)_{US}}{B(\Delta\eta,\Delta\varphi)_{US}} - \frac{S(\Delta\eta,\Delta\varphi)_{LS}}{B(\Delta\eta,\Delta\varphi)_{LS}}$$

$$US = +-/-+$$

$$LS = ++/--$$

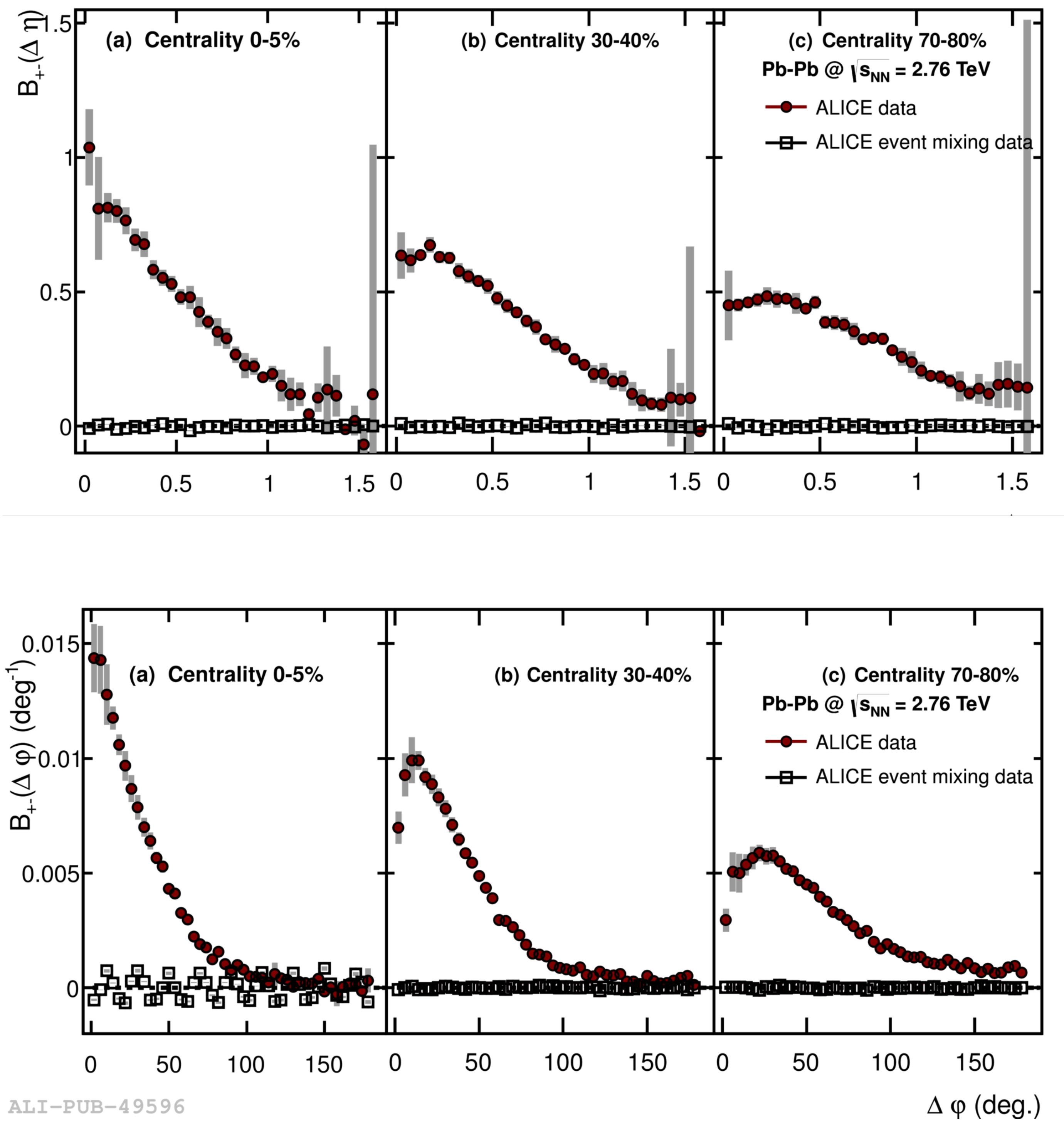
- Motivation:
  - Creation of balancing charges in rapidly expanding medium
  - What is the time ordering of the collision?
  - Can we detect different stages where charges are created?



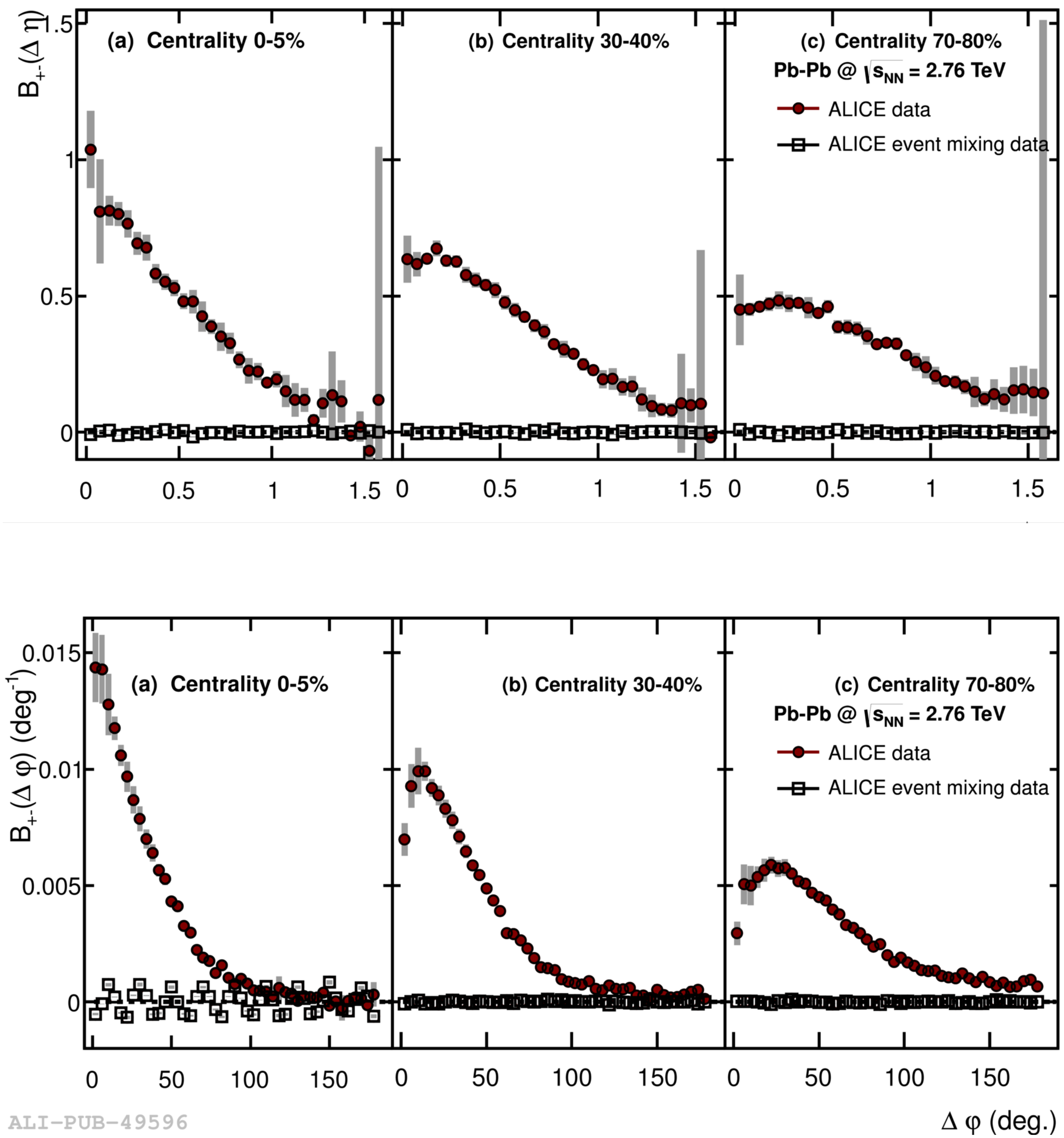
- Early stage creation: large final separation, **wider balance function**
- Late stage creation: pairs more correlated, **narrower balance functions**
- **BUT:** stronger flow can also lead to a stronger correlation of pairs and a narrow balance function.

Balance function in Pb-Pb collisions

[PLB, 723 (2013), 267]



Balance function in Pb-Pb collisions

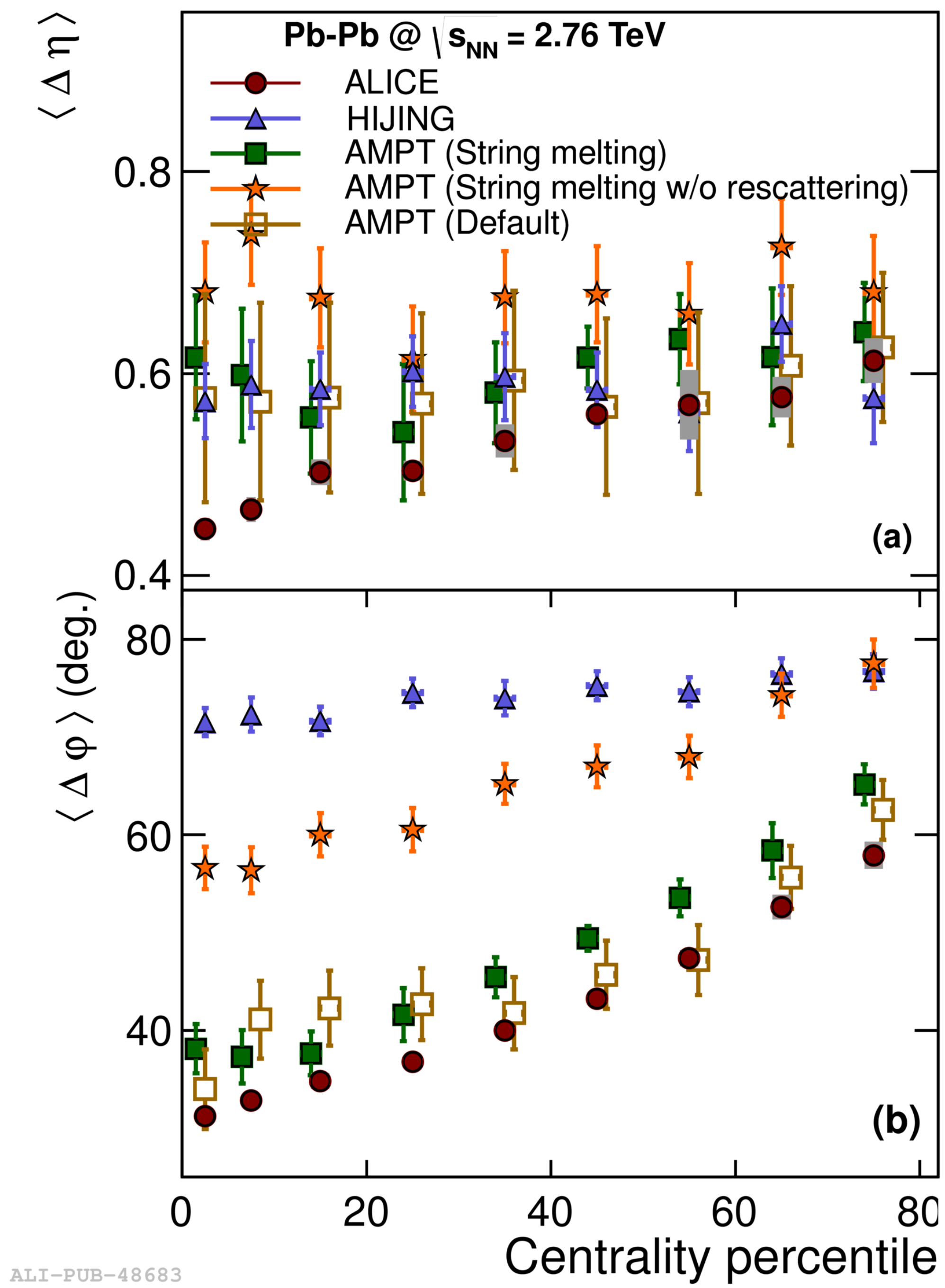


[PLB, 723 (2013), 267]

A narrowing is indeed observed in Δη and Δφ going from peripheral to central collisions.

Balance function in Pb-Pb collisions

[PLB, 723 (2013), 267]



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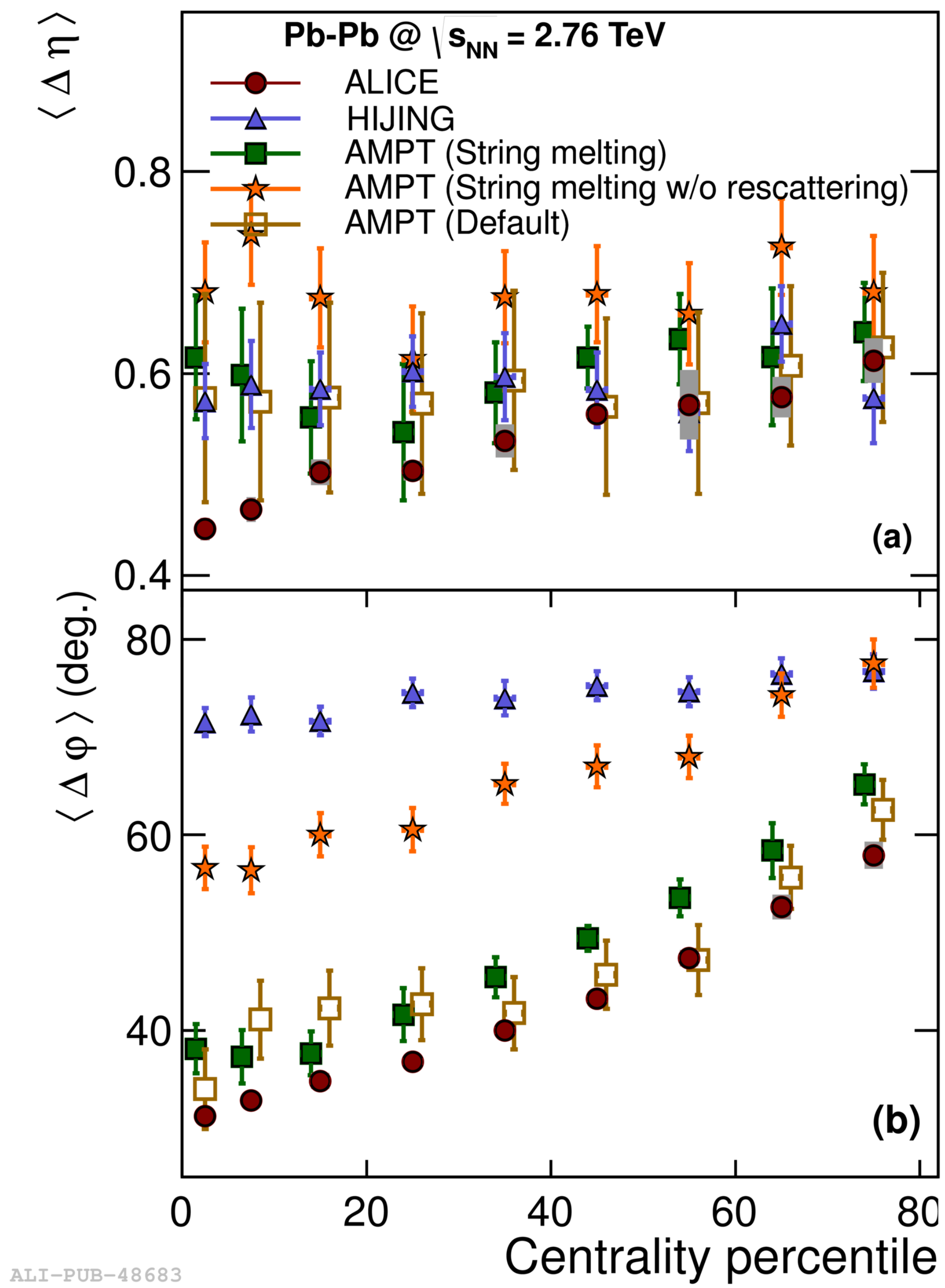
Balance function in Pb-Pb collisions

[PLB, 723 (2013), 267]



A narrowing is indeed observed in Δη and Δφ going from peripheral to central collisions.

The observed centrality dependence is stronger than predicted by models even if they are tuned to reproduce the ALICE v_2 data (AMPT).

Summary & conclusion

Summary and conclusions

- Light flavor hadron yields at LHC energies can be described in a thermal fit based on the hadron resonance gas model with a chemical freeze-out temperature of T_{chem} = 156 MeV.

- In order to find deviations from HRG, the measurements of event-by-event fluctuations of conserved quantities (charge, baryon number, strangeness) are on their way…

- Measurements of net-charge fluctuations indicate a reduction of fluctuations from RHIC to LHC (as expected), but also emphasise the importance of systematic studies w.r.t. to the acceptance window etc.

SUPPORTING SLIDES

Thermodynamic susceptibilities (2)

- Moments μ and cumulants K:

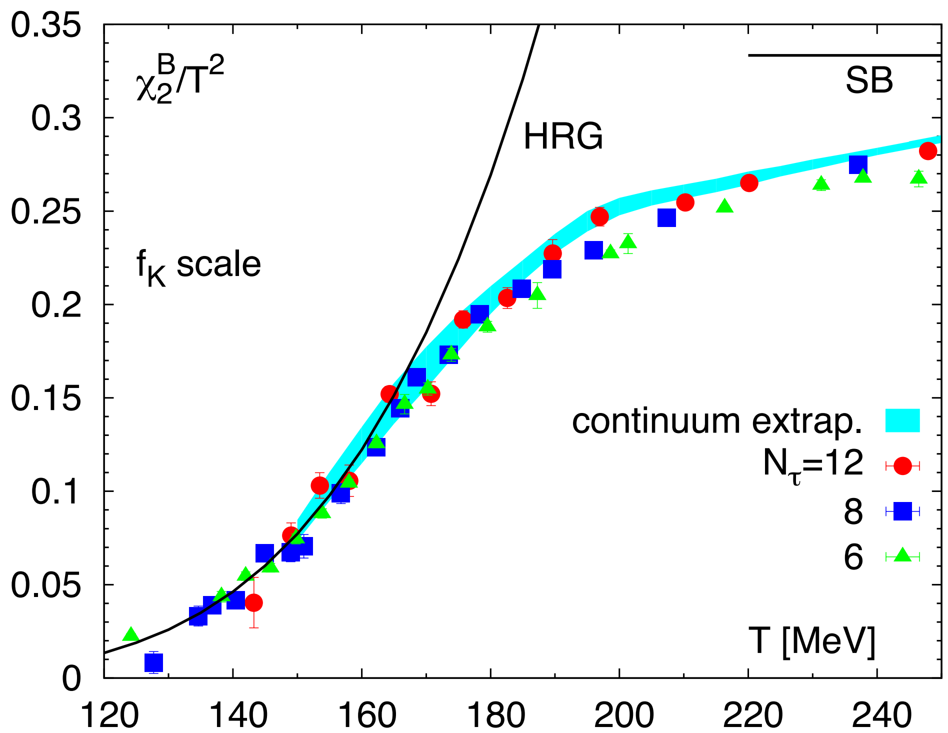
$$
\begin{array}{ccccccccc}
M & = & K_1 & = & \mu & = & \langle N \rangle & = & VT^3 \cdot \chi_1 \\
\sigma^2 & = & K_2 & = & \mu_2 & = & \langle (\delta N)^2 \rangle & = & VT^3 \cdot \chi_2 \\
S & = & K_3/\sigma^3 & = & \mu_3/\sigma^3 & = & \langle (\delta N)^3 \rangle/\sigma^3 & = & VT^3 \cdot \chi_3/(VT^3 \cdot \chi_2)^{3/2} \\
\kappa & = & K_4/\sigma^4 & = & (\mu_4 - 3\mu_2^2)/\mu_2^2 & = & \langle (\delta N)^4 \rangle/\sigma^4 - 3 & = & (VT^3 \cdot \chi_4)/(VT^3 \cdot \chi_2)^2
\end{array}
$$

- In ratios of cumulants, the volume dependence cancels:

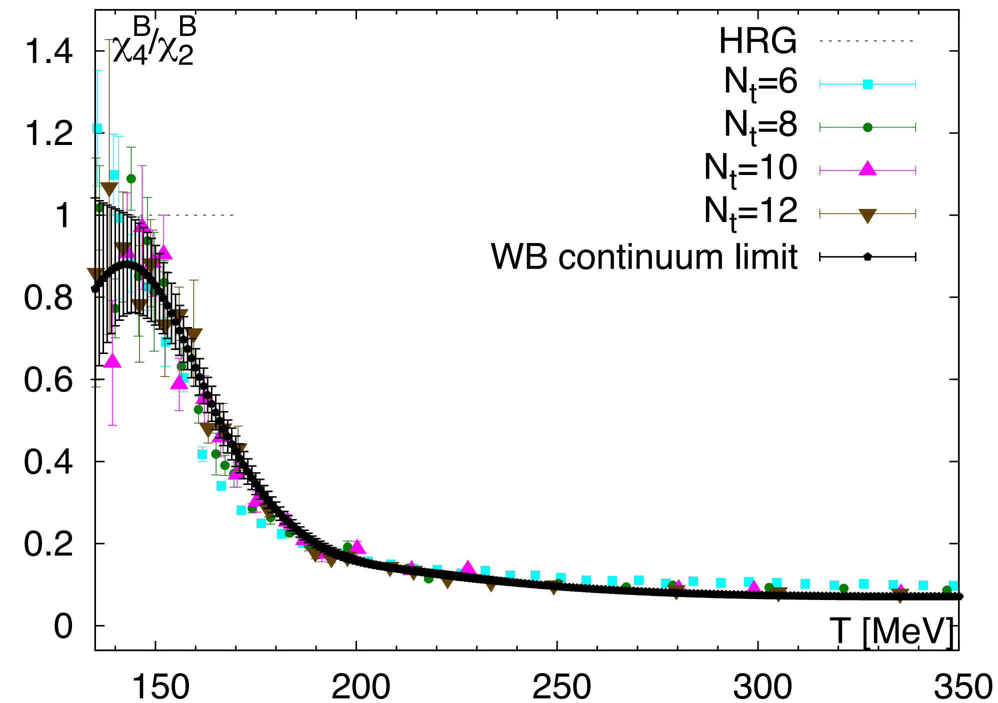
$$
\begin{array}{ccccccc}
\chi_2/\chi_1 & = & K_2/K_1 & = & \mu_2/\mu & = & \sigma^2/M \\
\chi_3/\chi_1 & = & K_3/K_1 & = & \mu_3/\mu & = & S \cdot \sigma^2/M \\
\chi_3/\chi_2 & = & K_3/K_2 & = & \mu_3/\mu_2 & = & S \cdot \sigma \\
\chi_4/\chi_2 & = & K_4/K_2 & = & (\mu_4 - 3\mu_2^2)/\mu_2 & = & \kappa \cdot \sigma^2 \\
\chi_6/\chi_2 & = & K_6/K_2 & = & (\mu_6 - 15\mu_4\mu_2 - 10\mu_3^2 + 30\mu_2^3)/\mu_2 & & .
\end{array}
$$

Fluctuations and lattice QCD

- Thermodynamic susceptibilities at $\mu_B = 0$ can be directly calculated in lattice QCD.



[1203.0784]

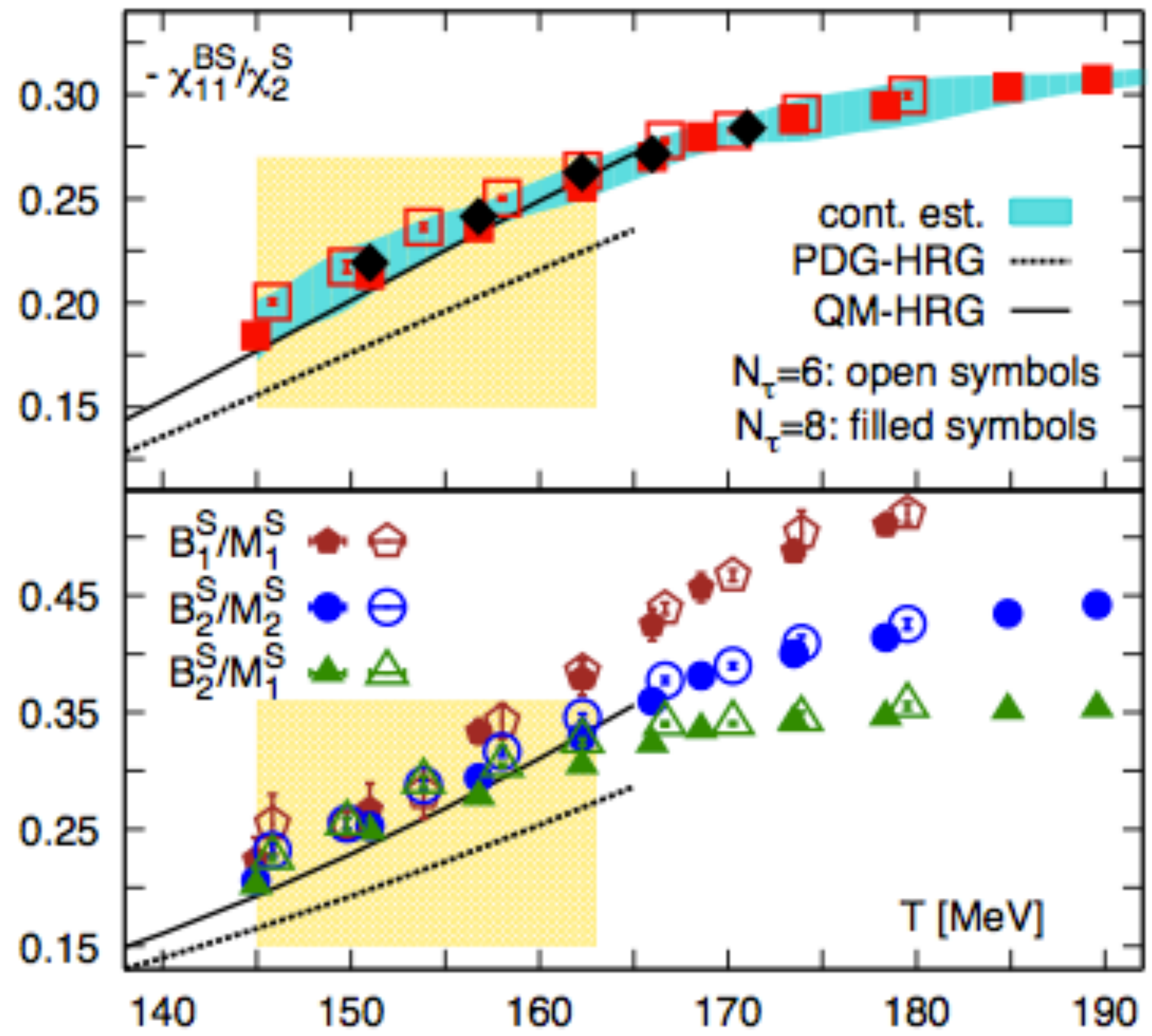


[1305.5161]

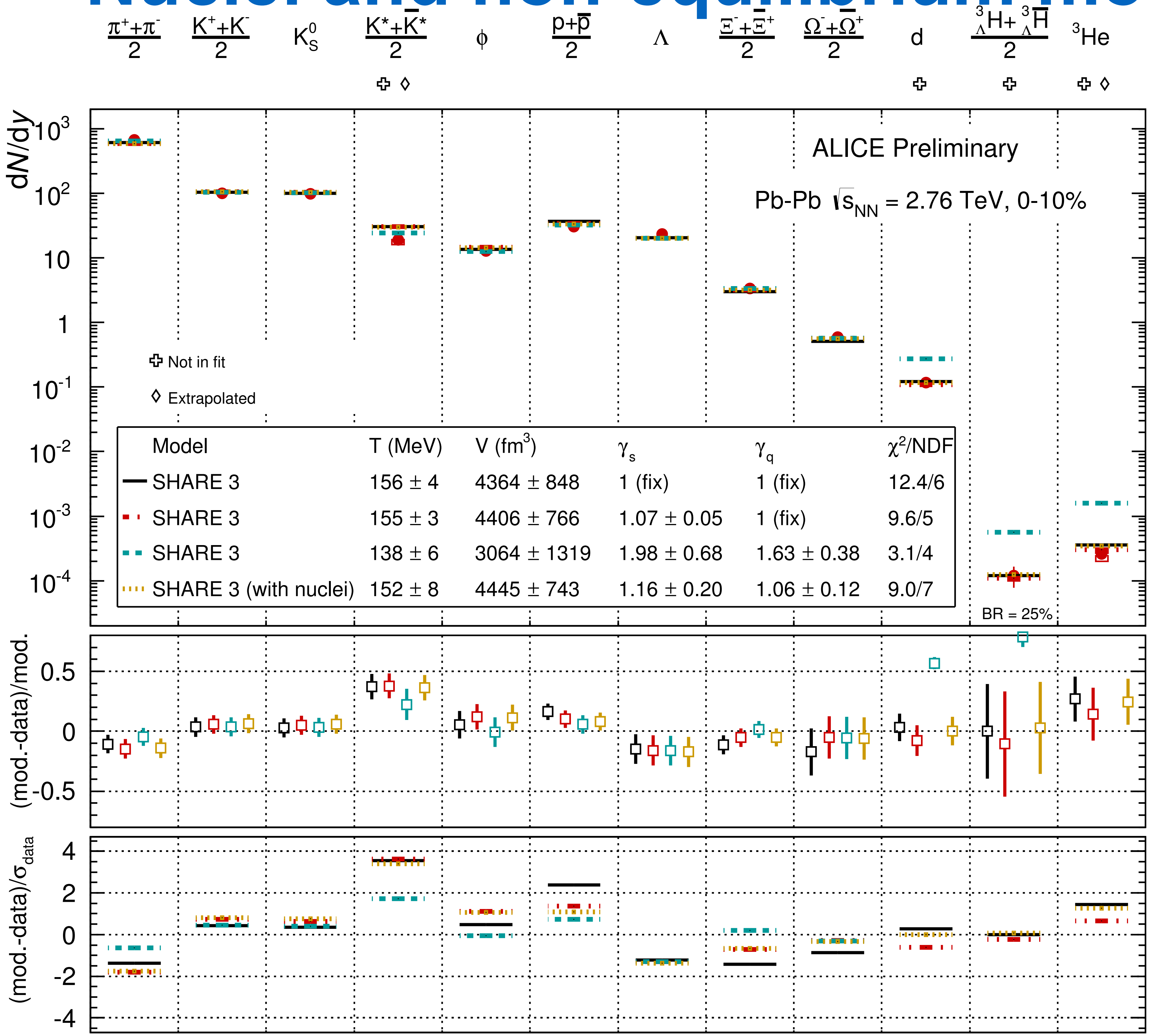
- The HRG is a very good approximation below T_c, but significant deviations at T_c are expected with increasing order of the moments due to remnants of the critical chiral behavior:
  $\chi_6/\chi_2 < 0$ at T_c in Lattice QCD and $\chi_6/\chi_2 = 1$ in HRG

Missing strange resonances (Lattice QCD)

[1404.6511]



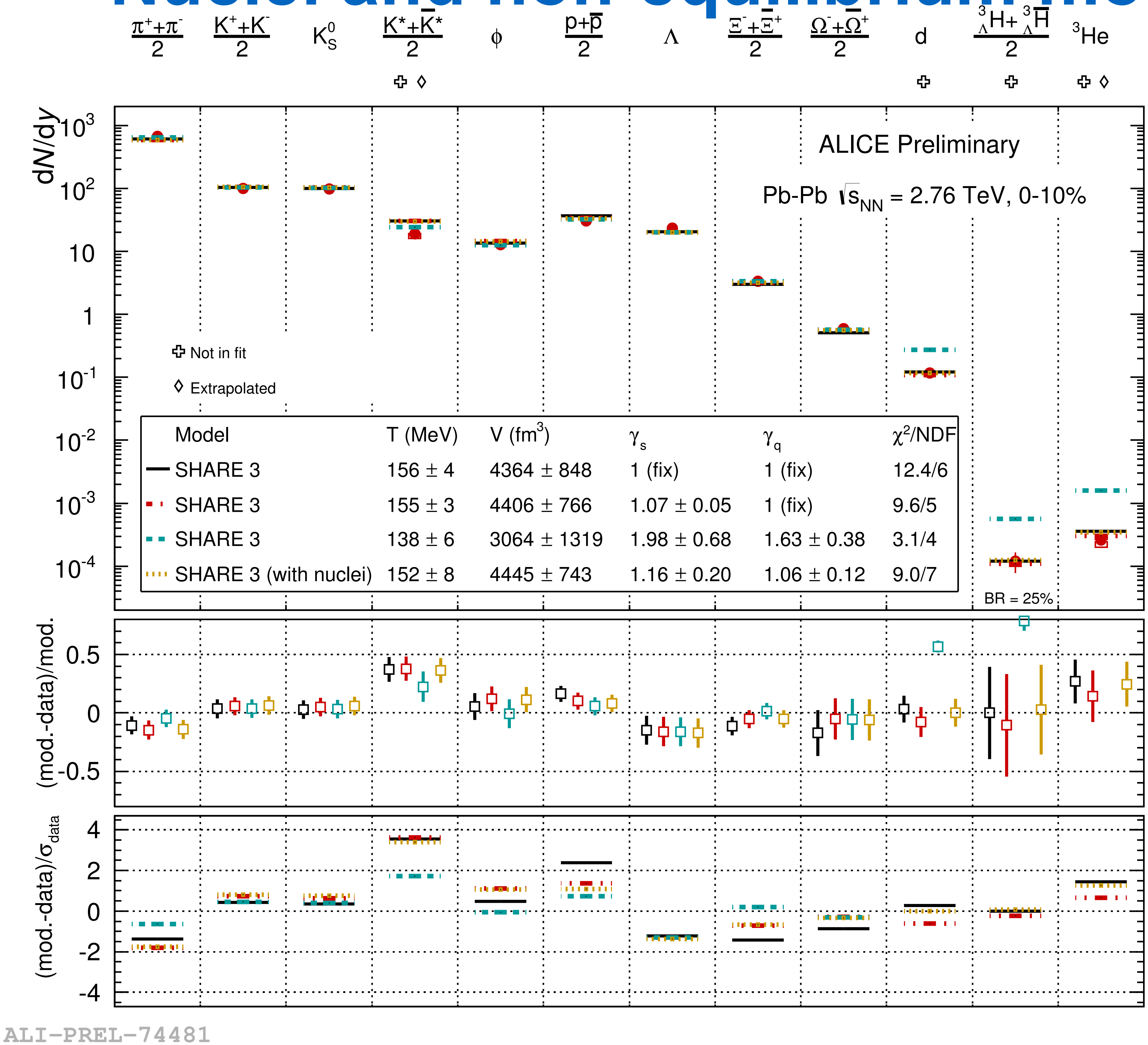
Nuclei and non-equilibrium models



Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
SHARE 3	156 ± 4	4364 ± 848	1 (fix)	1 (fix)	12.4/6
SHARE 3	155 ± 3	4406 ± 766	1.07 ± 0.05	1 (fix)	9.6/5
SHARE 3	138 ± 6	3064 ± 1319	1.98 ± 0.68	1.63 ± 0.38	3.1/4
SHARE 3 (with nuclei)	152 ± 8	4445 ± 743	1.16 ± 0.20	1.06 ± 0.12	9.0/7

ALI-PREL-74481

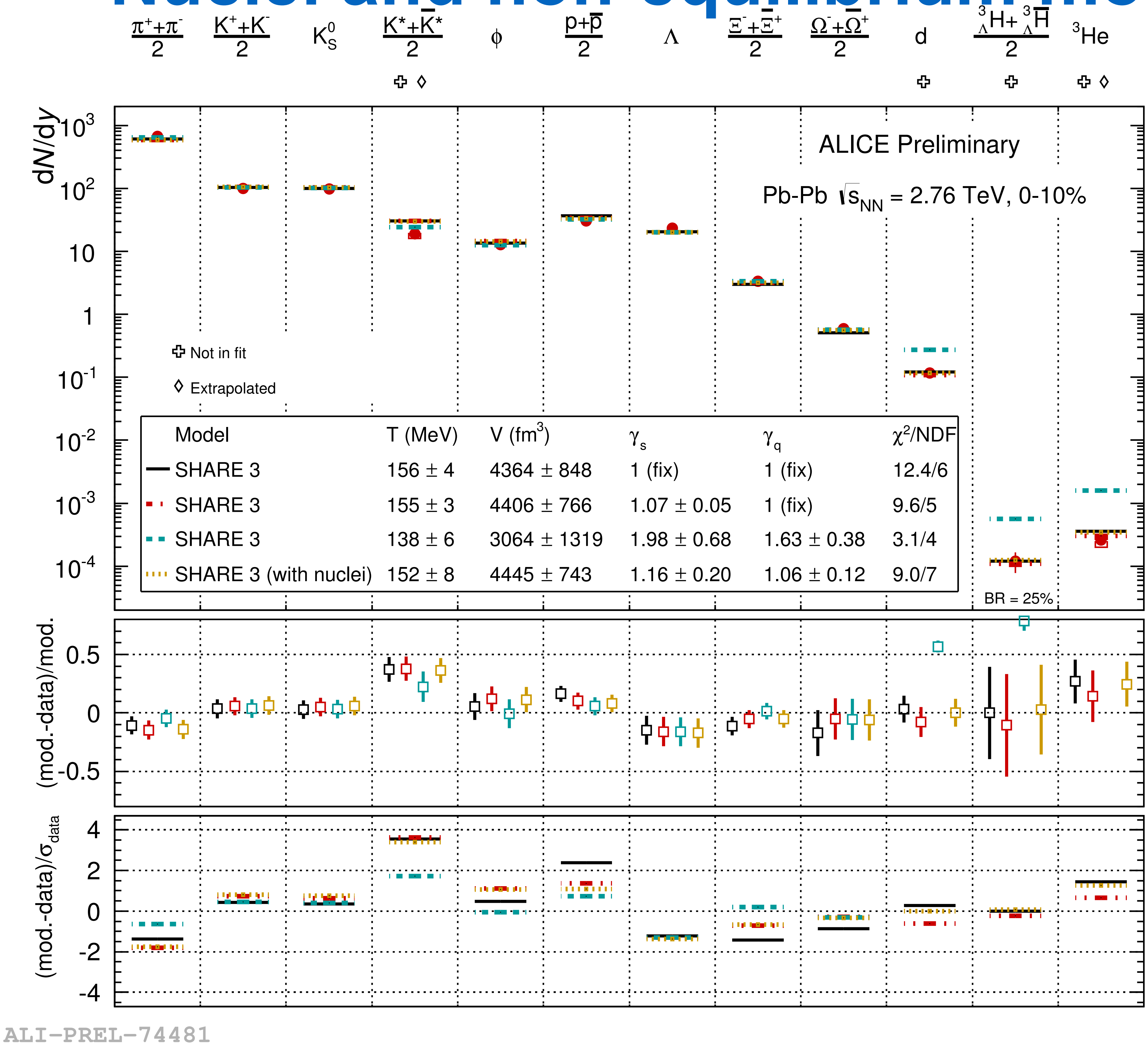
Nuclei and non-equilibrium models



SHARE performs a thermal fit in an equilibrium mode (γ_q=γ_s=1) or in a non-equilibrium mode (γ_q and γ_s free).

lexander.Philipp.Kalweit@cern.ch

Nuclei and non-equilibrium models



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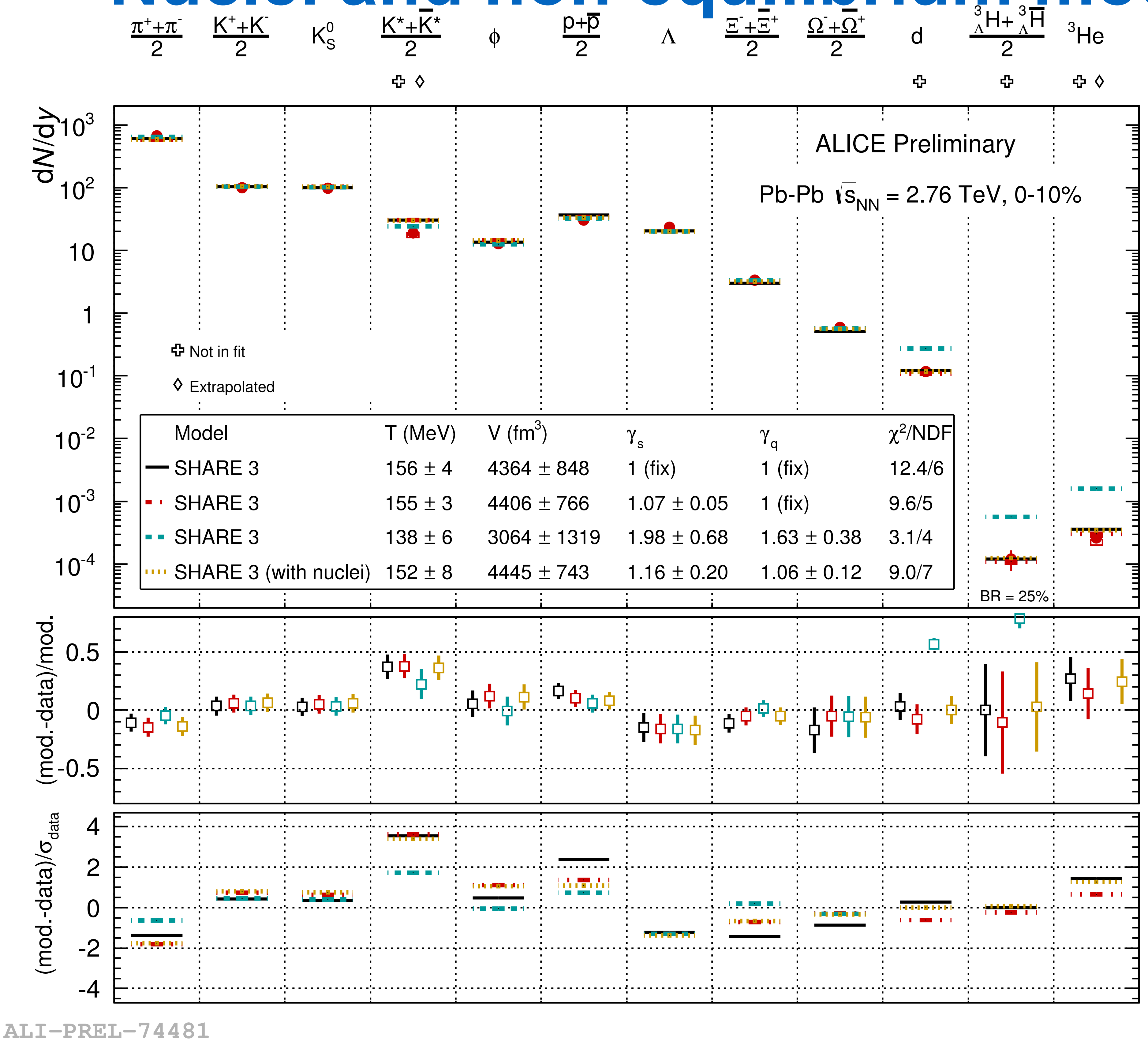
In equilibrium mode, the model describes the nuclei yields.

Nuclei and non-equilibrium models



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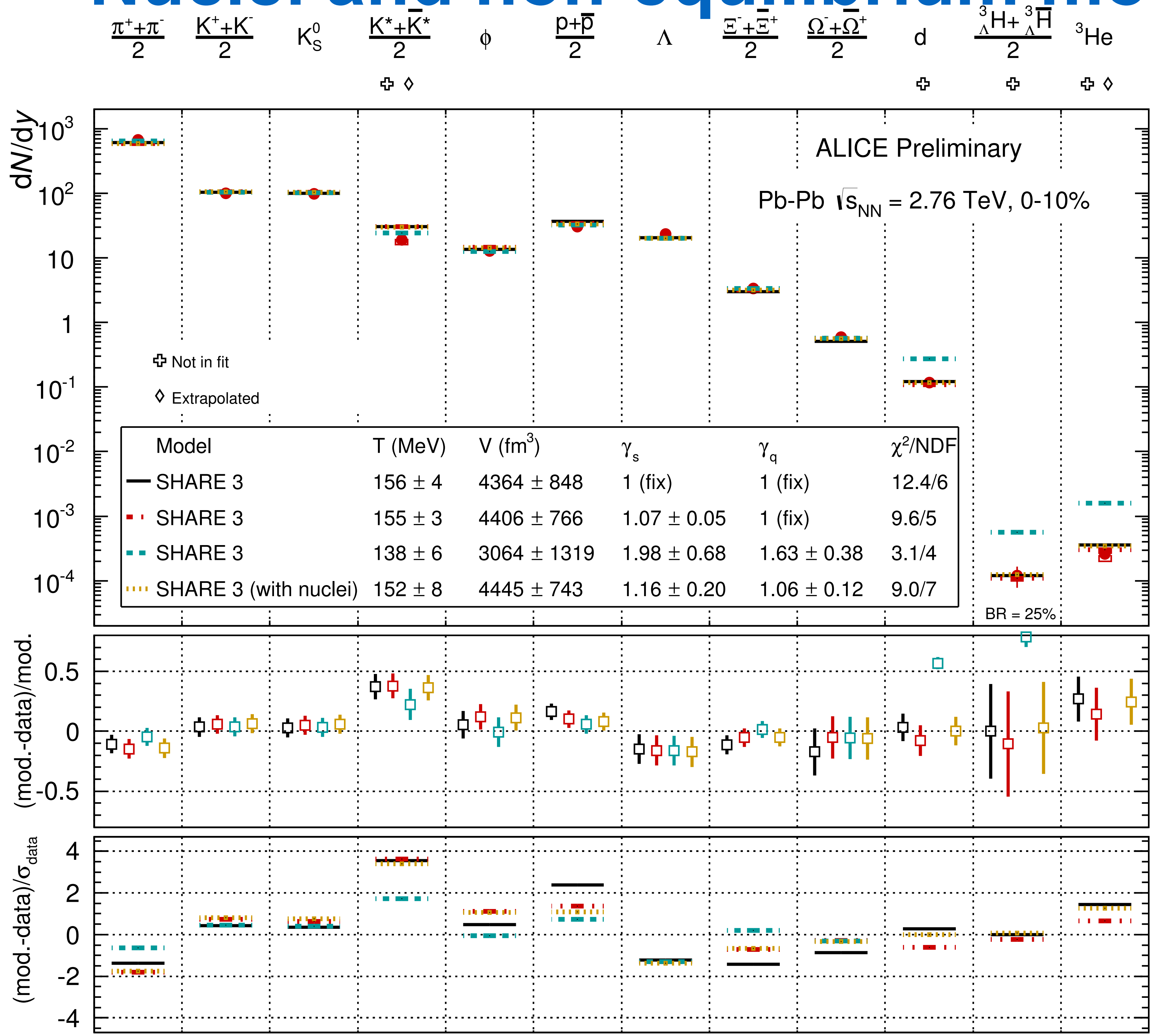
In non-equilibrium mode and *if nuclei are not included*, the model converges to values of γ_q and γ_s which are significantly different from 1 and yields a slightly better description for protons and Ξs.

Nuclei and non-equilibrium models



ALI-PREL-74481

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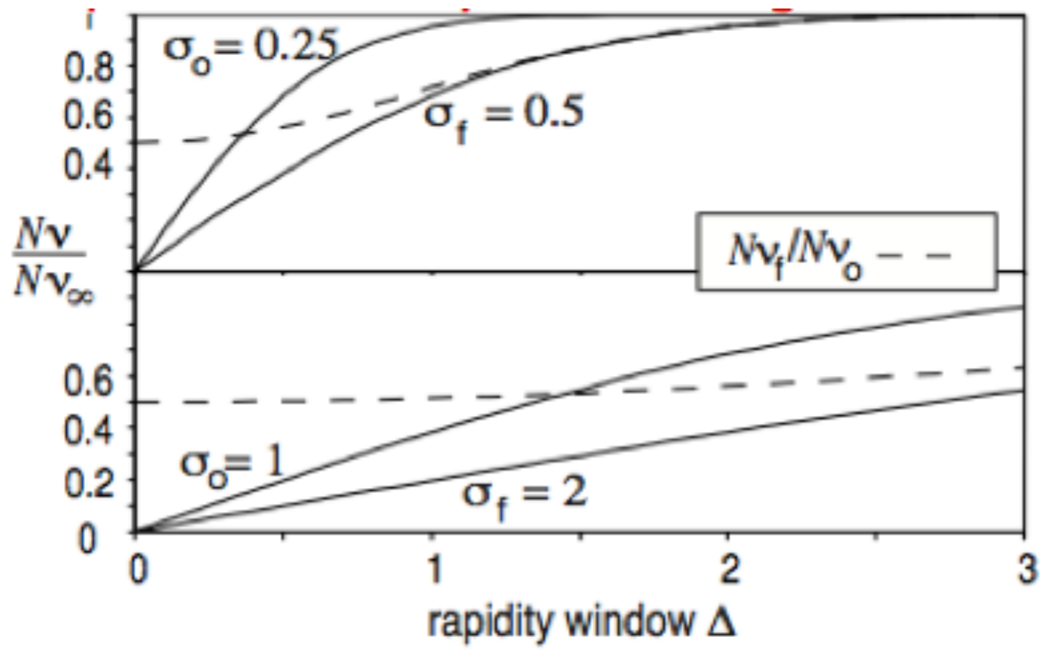
In non-equilibrium mode and *if nuclei are included*, the model converges to values of γ_q and γ_s which are in agreement with 1.



Ratio indicates the decrease of fluctuations with increase of the width.
Diffusion has increased the width from σ_0 = 1 to σ_f = 2 (bottom) and σ_0 = 0.25 to σ_f = 0.5 (top).
σ = width of fluctuations

$$\langle N_{ch}\rangle \nu = \langle N_{ch}\rangle \nu_{\infty} erf\left(\frac{\Delta\eta}{\sigma\sqrt{8}}\right)$$

[M Aziz and S. Gavin, PRC 70, 034905 (2004)]