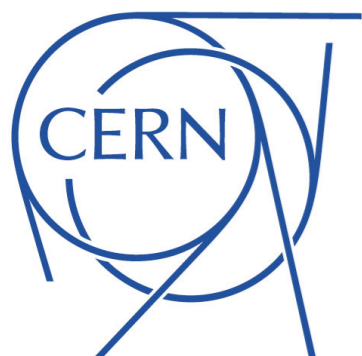


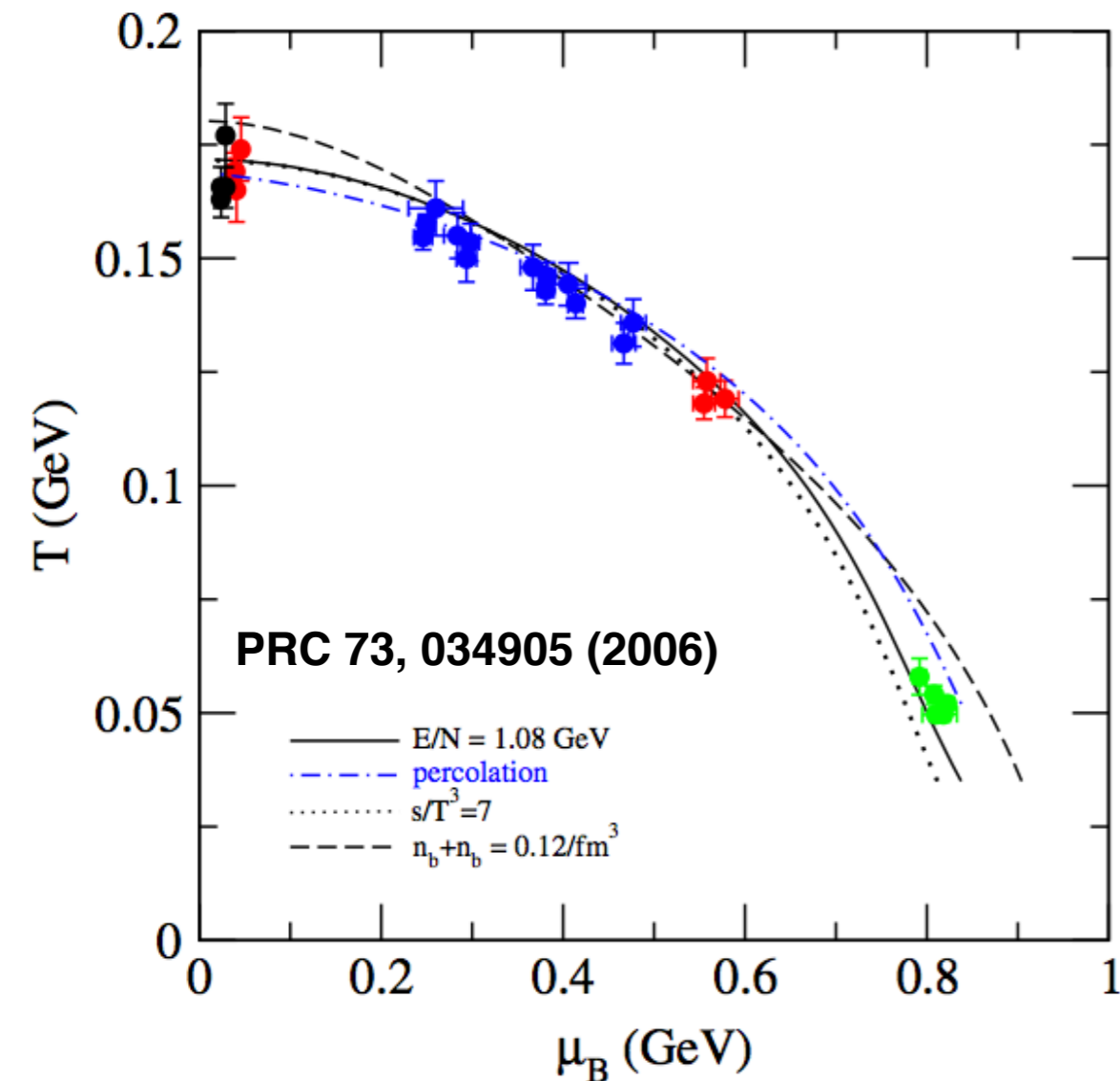
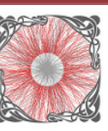
# XXIV QUARK MATTER DARMSTADT 2014



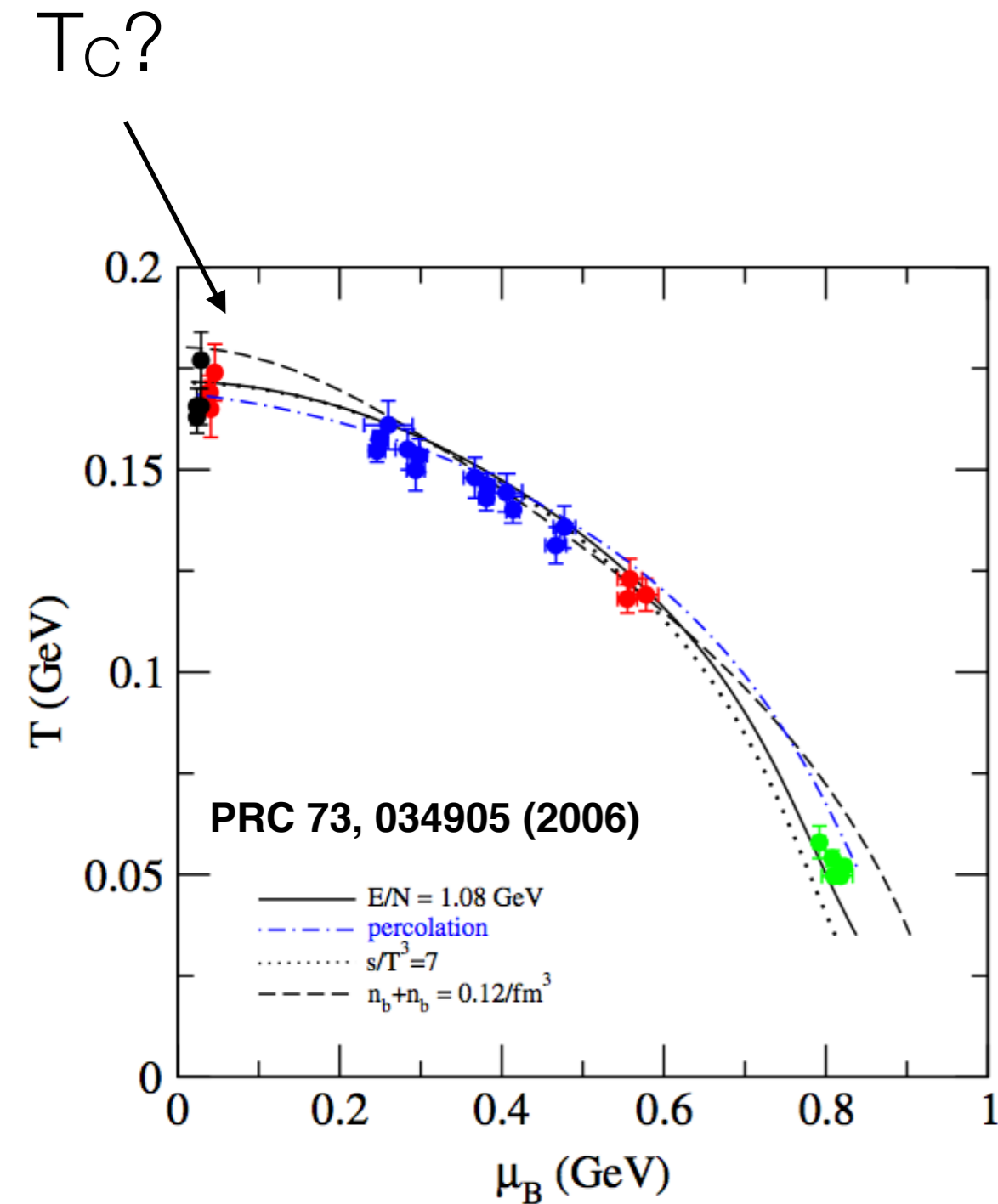
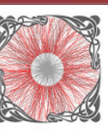
## Hadron yields and the phase diagram of strongly interacting matter

(a biased review)

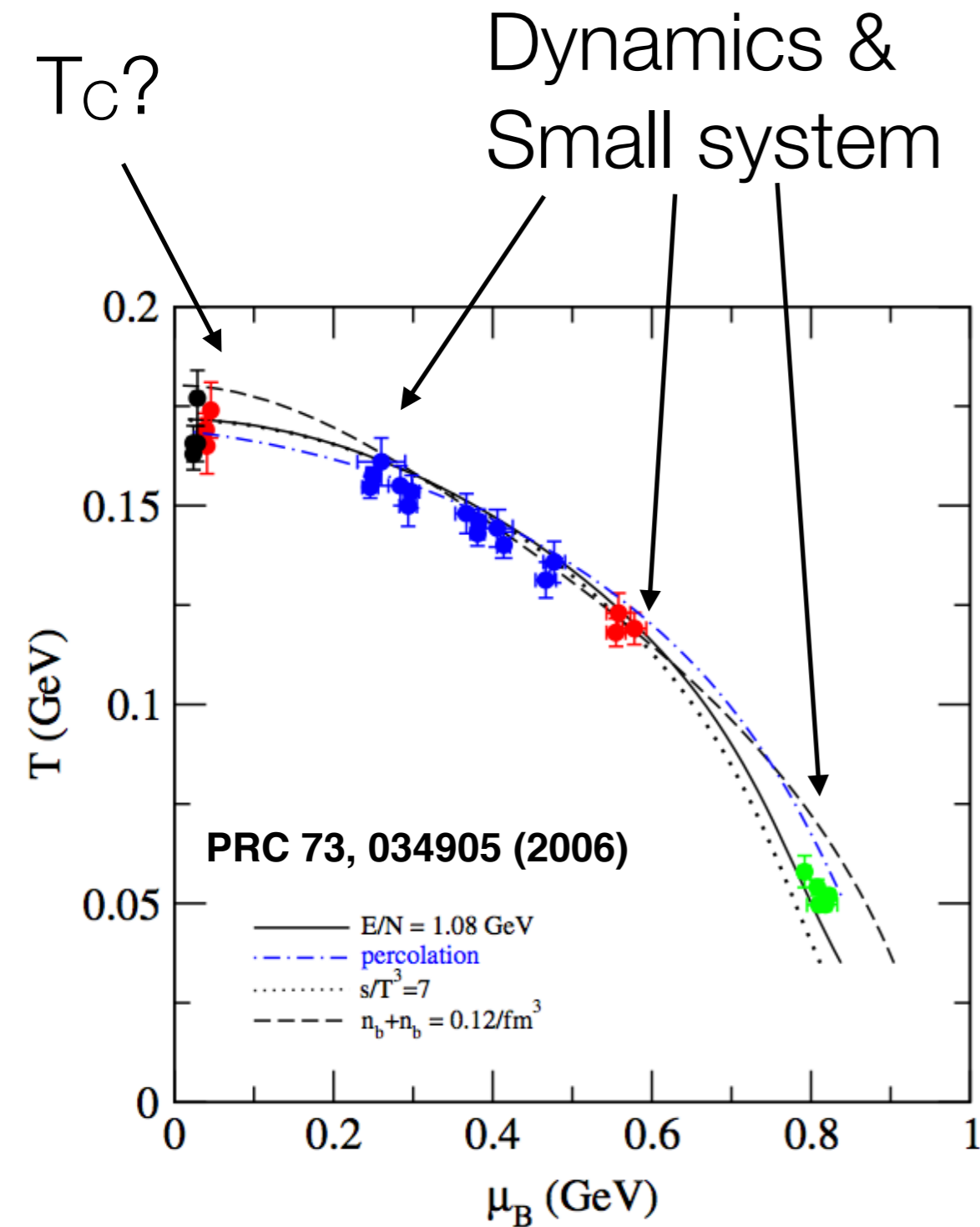
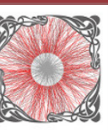
Michele Floris  
CERN  
May 22, 2014



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- Measurements at different  $\sqrt{s}$  line up in a **hadron freeze-out curve**
- Key Questions:
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  - **How** is this apparent equilibrium reached?
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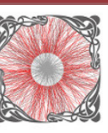


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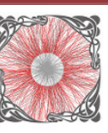


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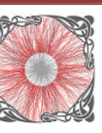


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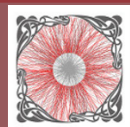
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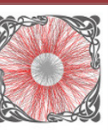
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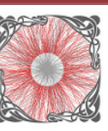


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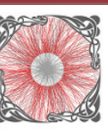
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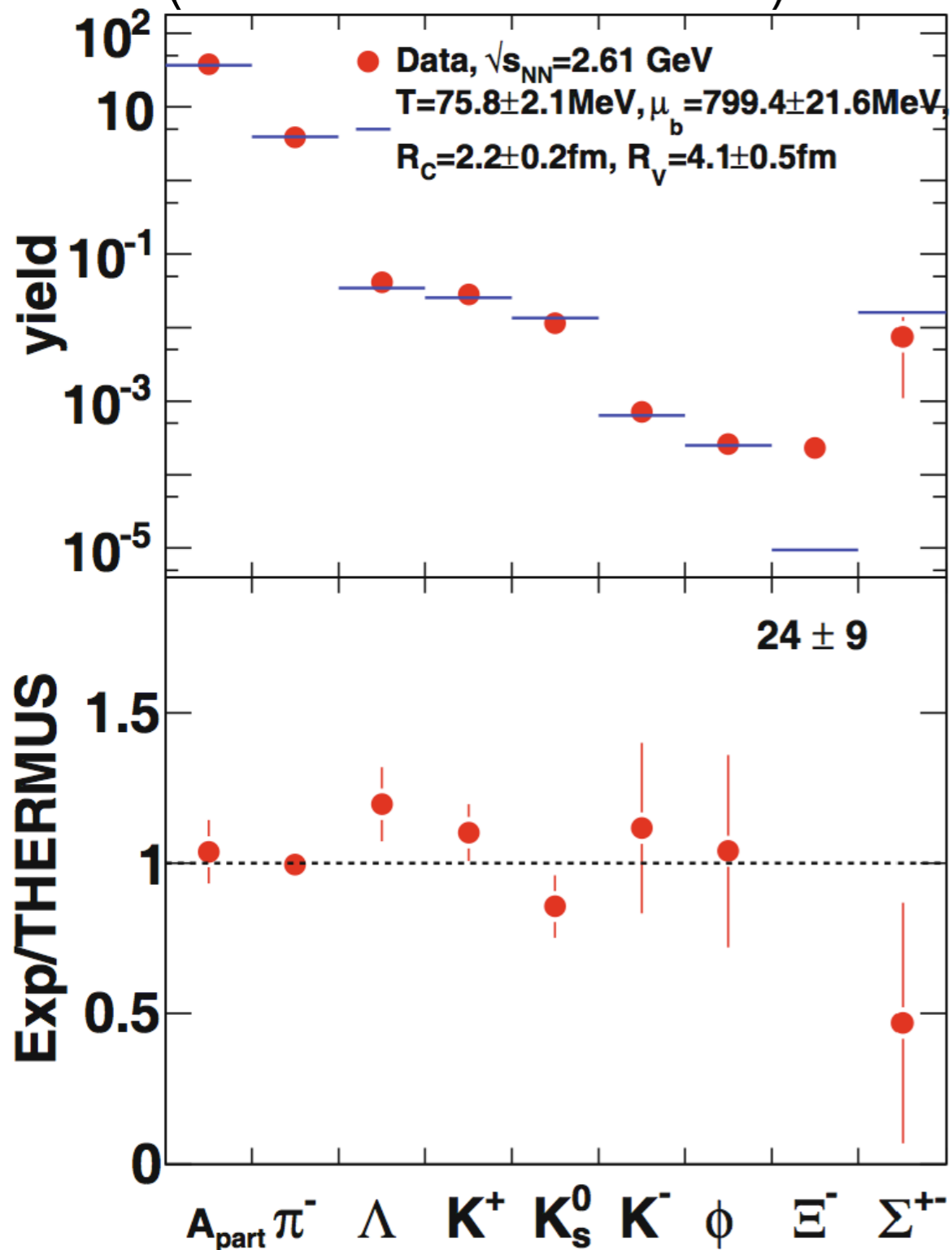
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- Physical picture of non-equilibrium models: **supercooled quark-gluon plasma** undergoes **sudden hadronization**  $\rightarrow$  no further re-interaction

Low Energy

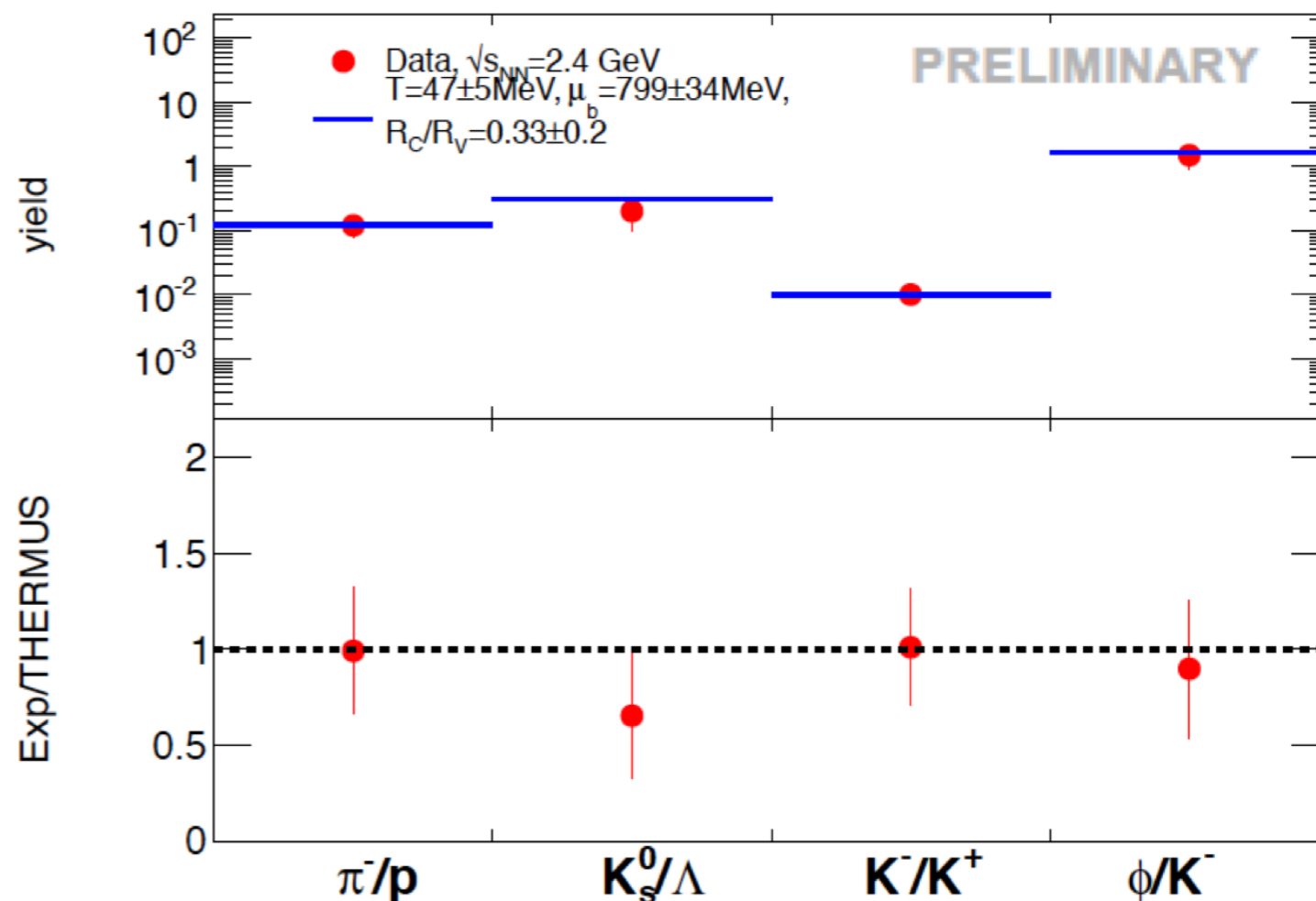
# Hades results, $\sqrt{s} \sim 2.5$ GeV



Ar-KCl,  $\sqrt{s} = 2.61$  GeV  
( $\sim 40+40$  nucleons)



Au-Au,  $\sqrt{s} = 2.4$  GeV

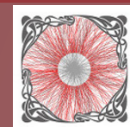


Why does the statistical model work at these low energies?  
Strangeness production mechanism?

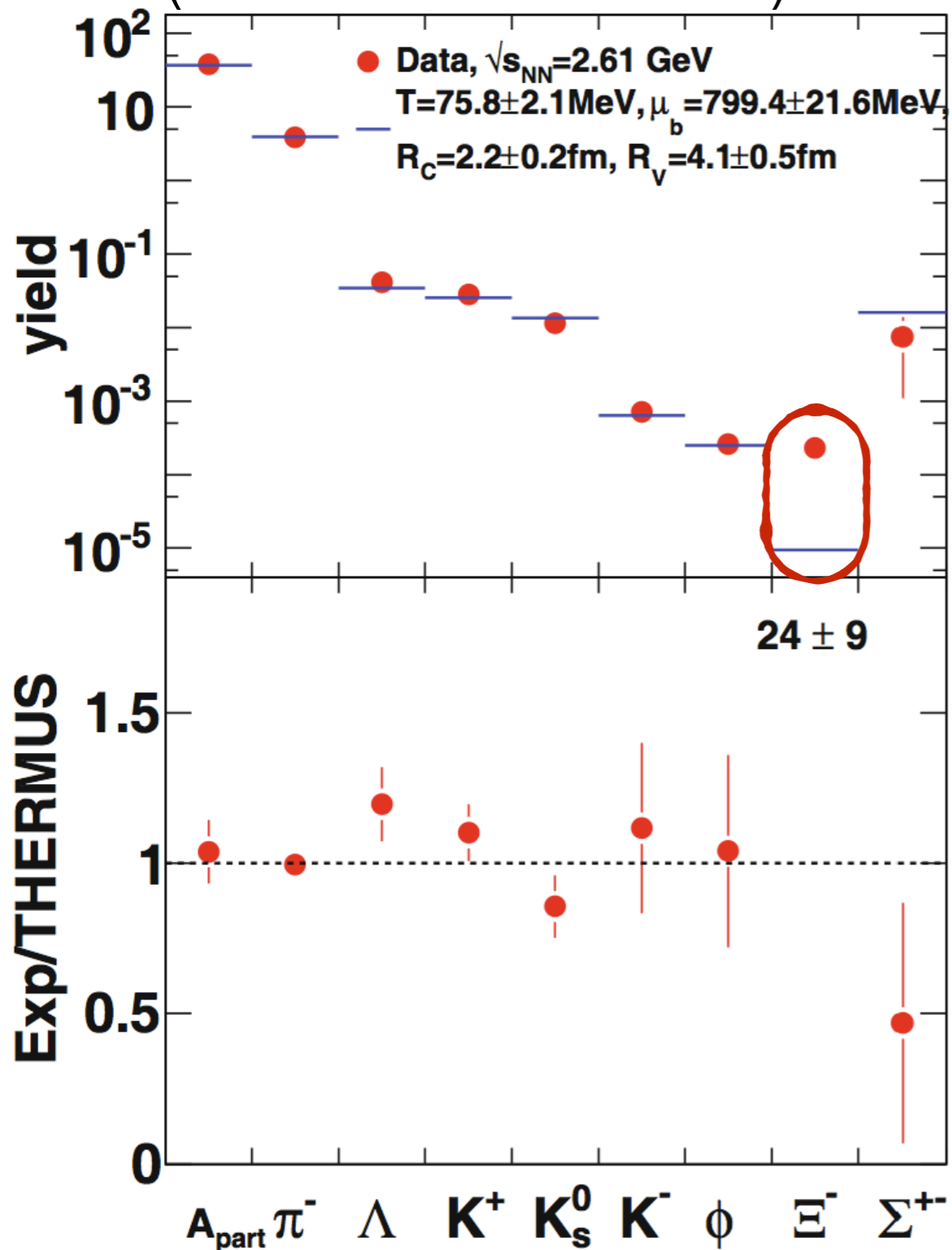
$$R_C/R_V \approx 0.5$$

M. Lorenz, HADES, Tue 20

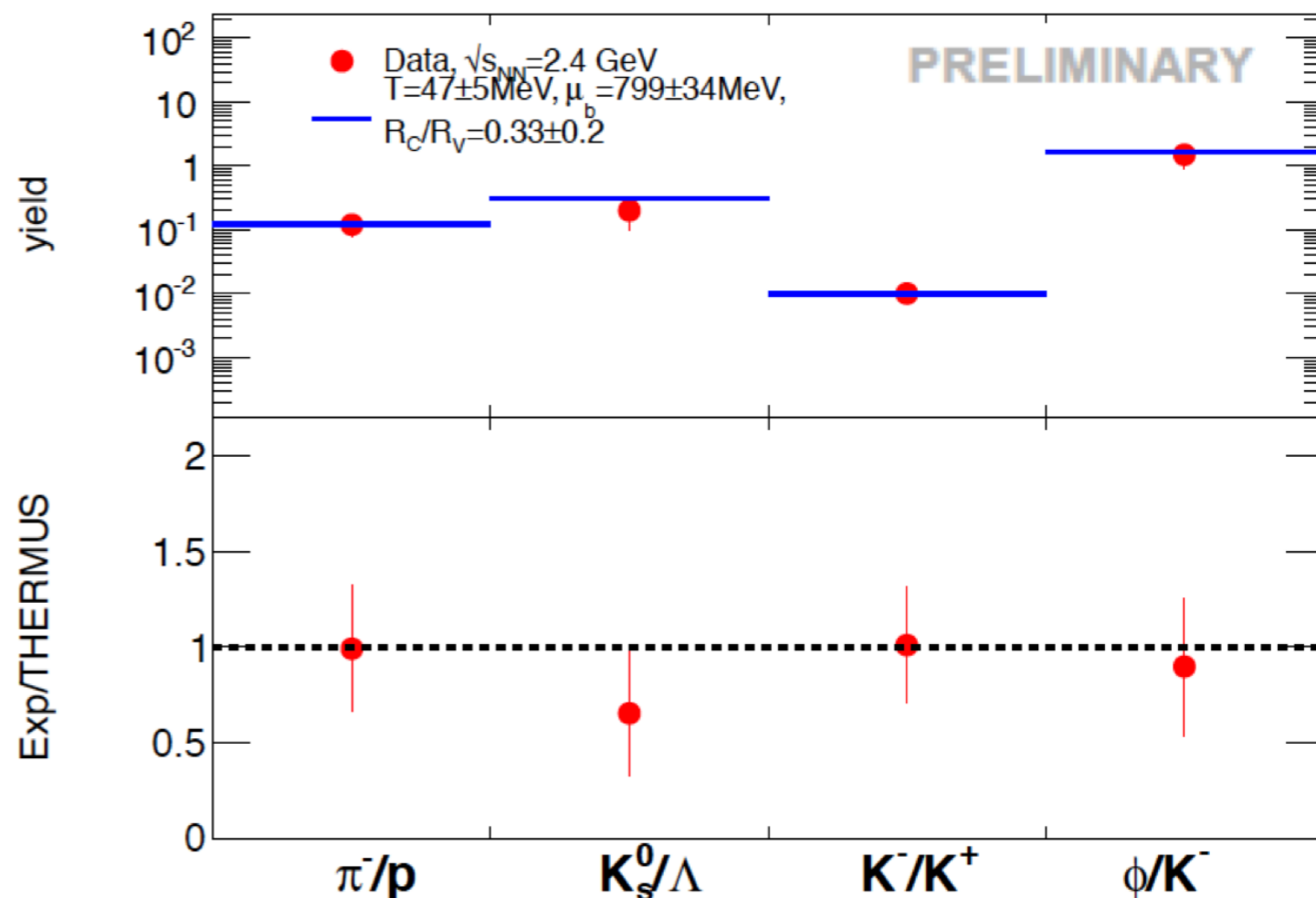
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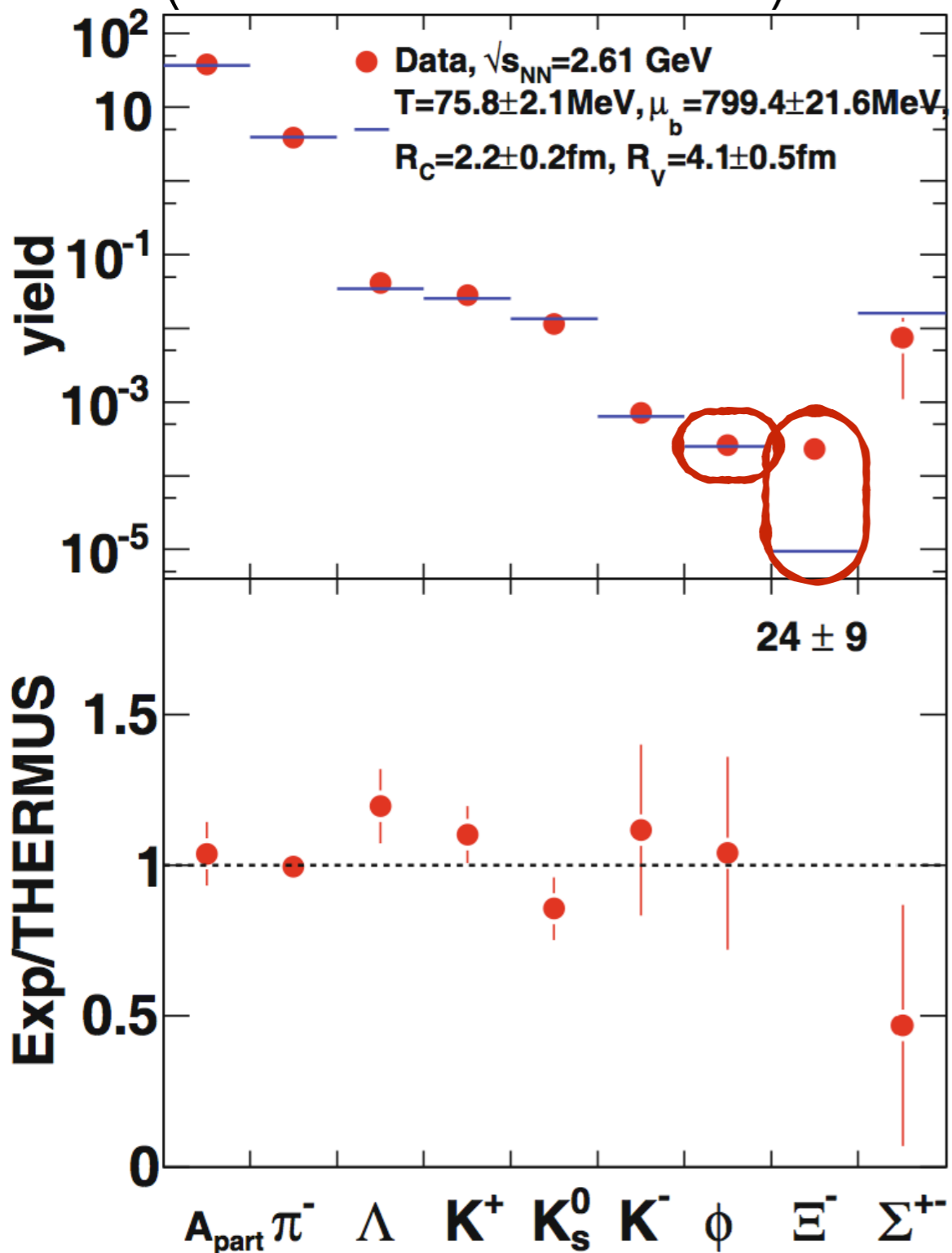
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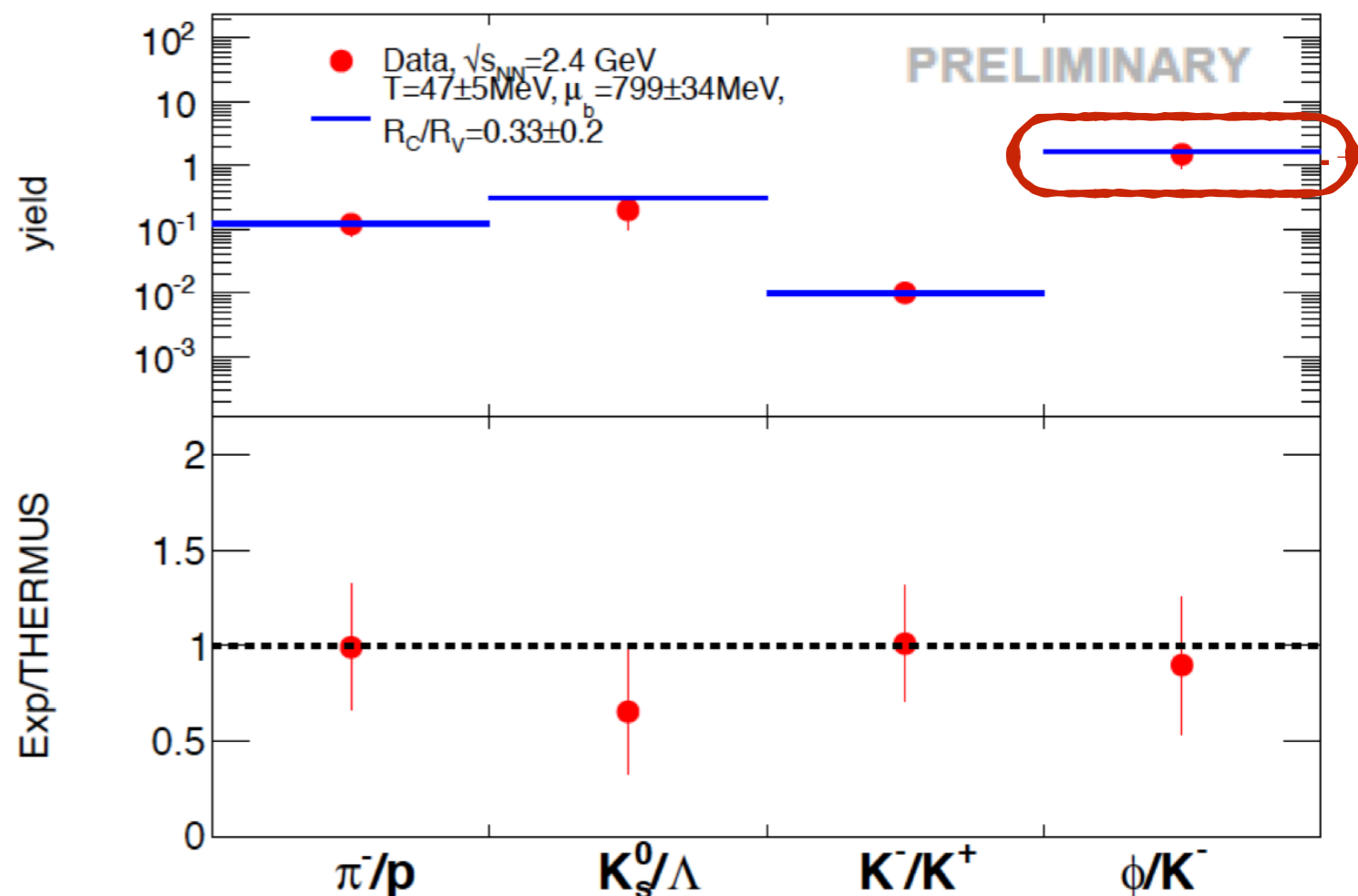
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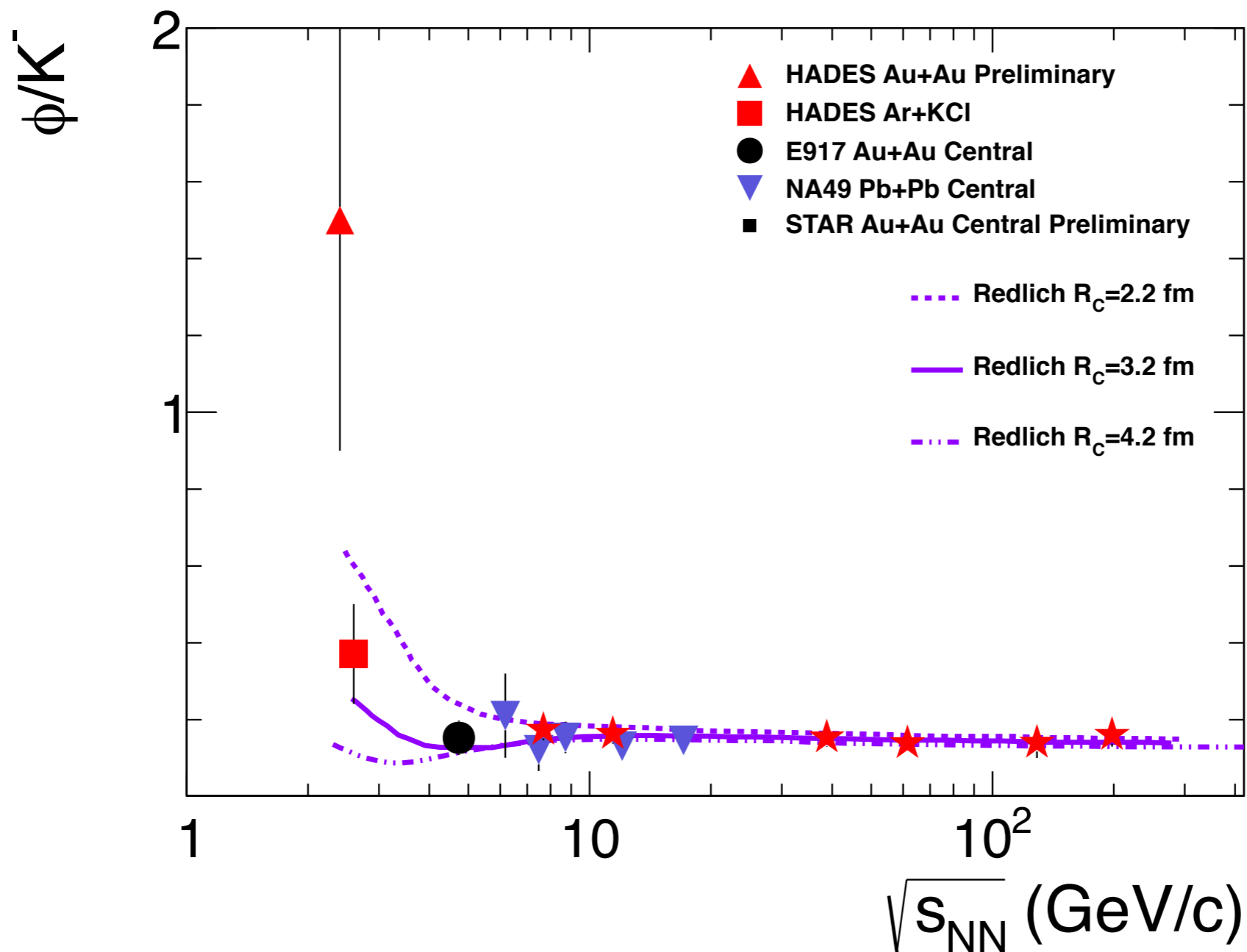
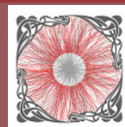
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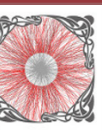
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M. Lorenz, HADES, Tue 20



Rise of  $\Phi/K^-$  ratio with decreasing beam energy predicted by statistical model using  $R_c$





Kraus et al, PRC 79 014901

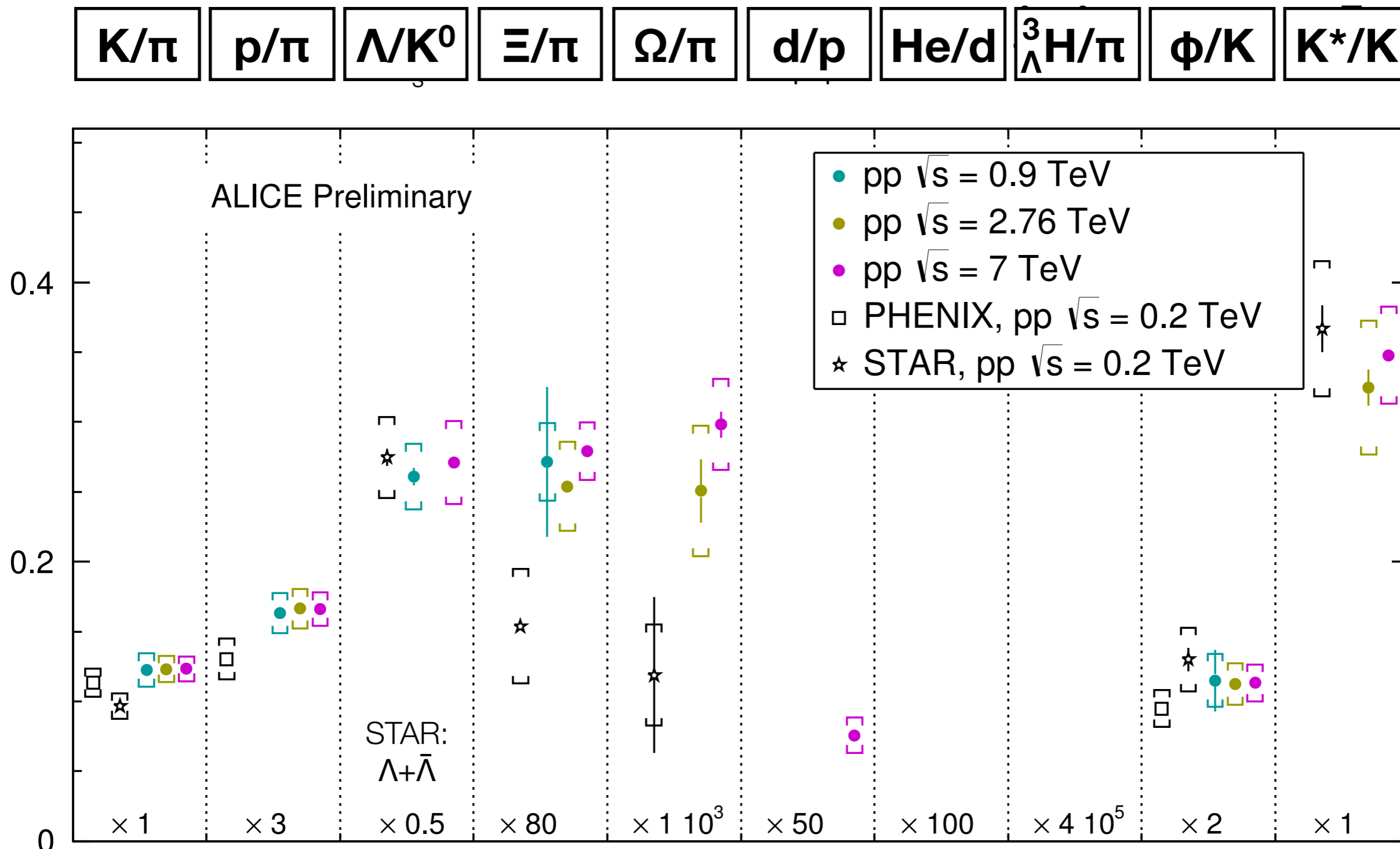
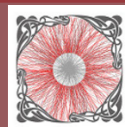
SPS pp, $\sqrt{s} = 17.3$ GeV		$\gamma_s$	$R_c$
Particle	Data	Fit (b)	Fit (c)
$\pi^-$	$3.02 \pm 0.15$	3.01	3.01
$\pi^+$	$2.36 \pm 0.11$	2.32	2.32
$K^-$	$0.258 \pm 0.055$	0.268	0.270
$K^+$	$0.160 \pm 0.050$	0.162	0.166
$\Lambda$	$0.116 \pm 0.011$	0.119	0.120
$\bar{\Lambda}$	$0.0137 \pm 0.0007$	0.0135	0.0134
$K_S^0$	$0.18 \pm 0.04$	0.21	0.20
$\bar{p}$	$0.0400 \pm 0.0068$	0.0464	0.0469
$\phi$	$0.0120 \pm 0.0015$	0.0271	0.0598

Rise of  $\Phi/K^-$  ratio with decreasing beam energy  
predicted by statistical model using  $R_c$   
How does this reconcile with SPS data?

M. Lorenz, HADES, Tue 20

# pp Collisions at the LHC

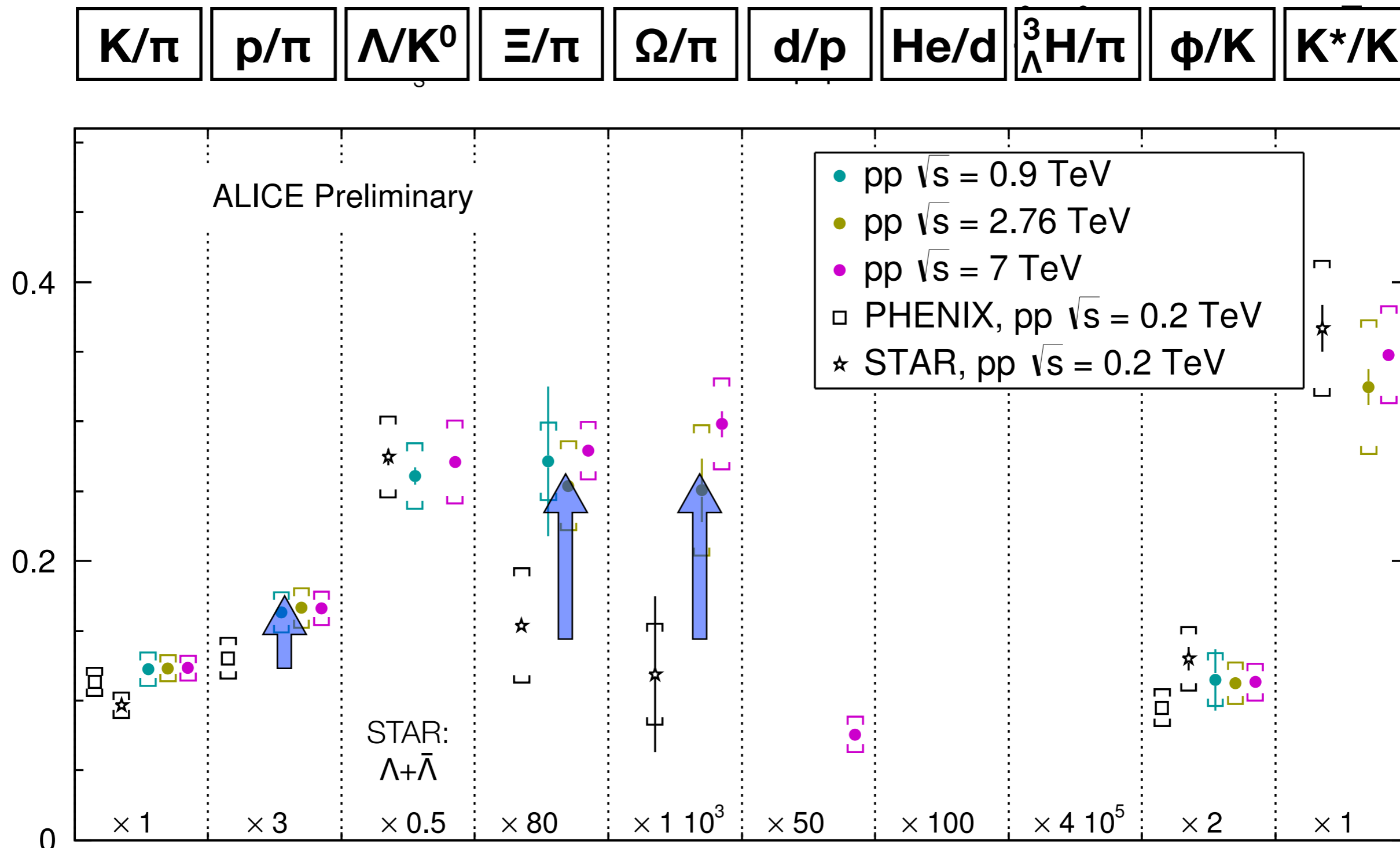
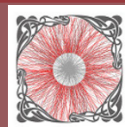
# pp ratios, from RHIC to LHC



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)

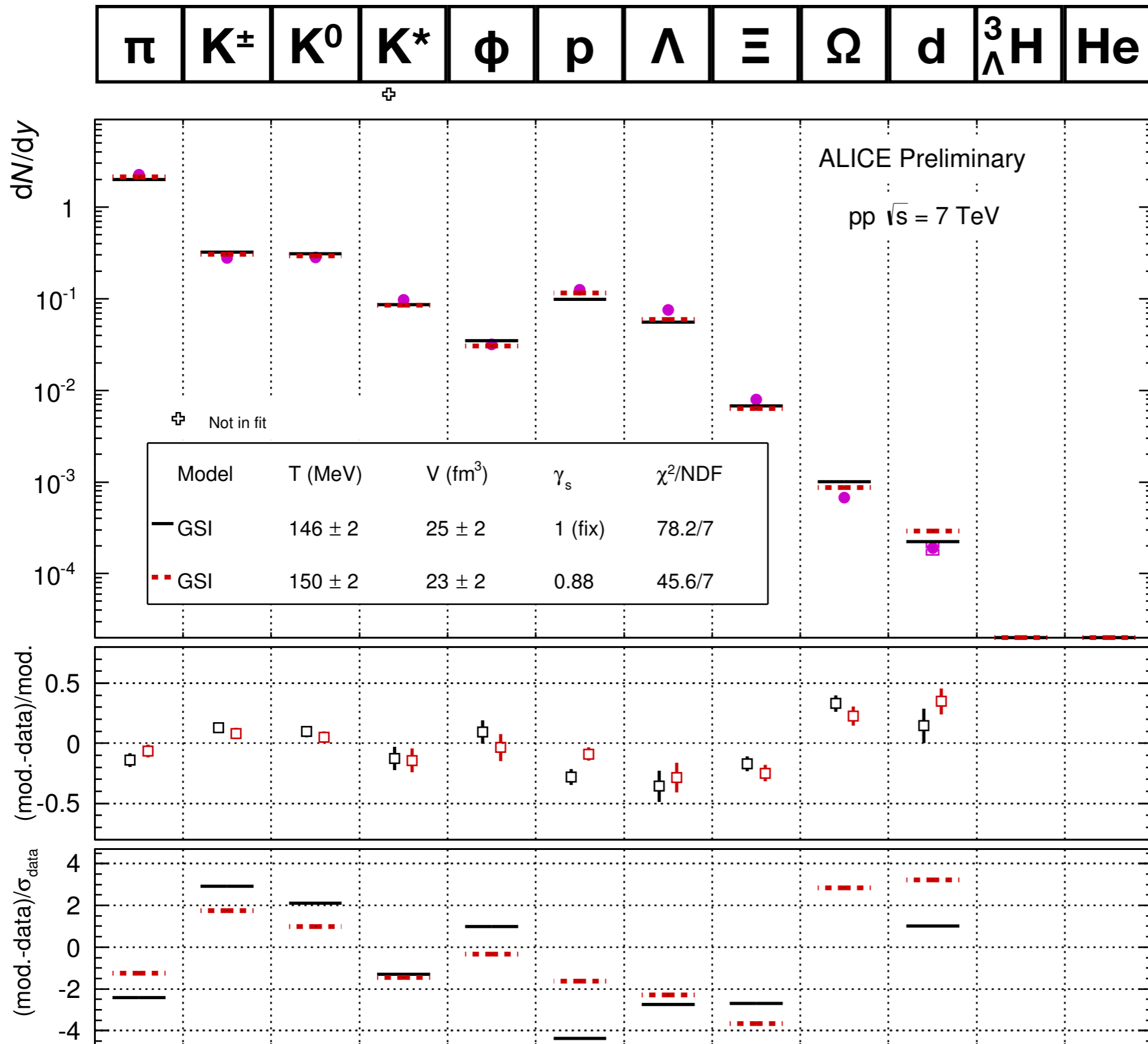
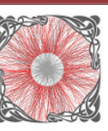
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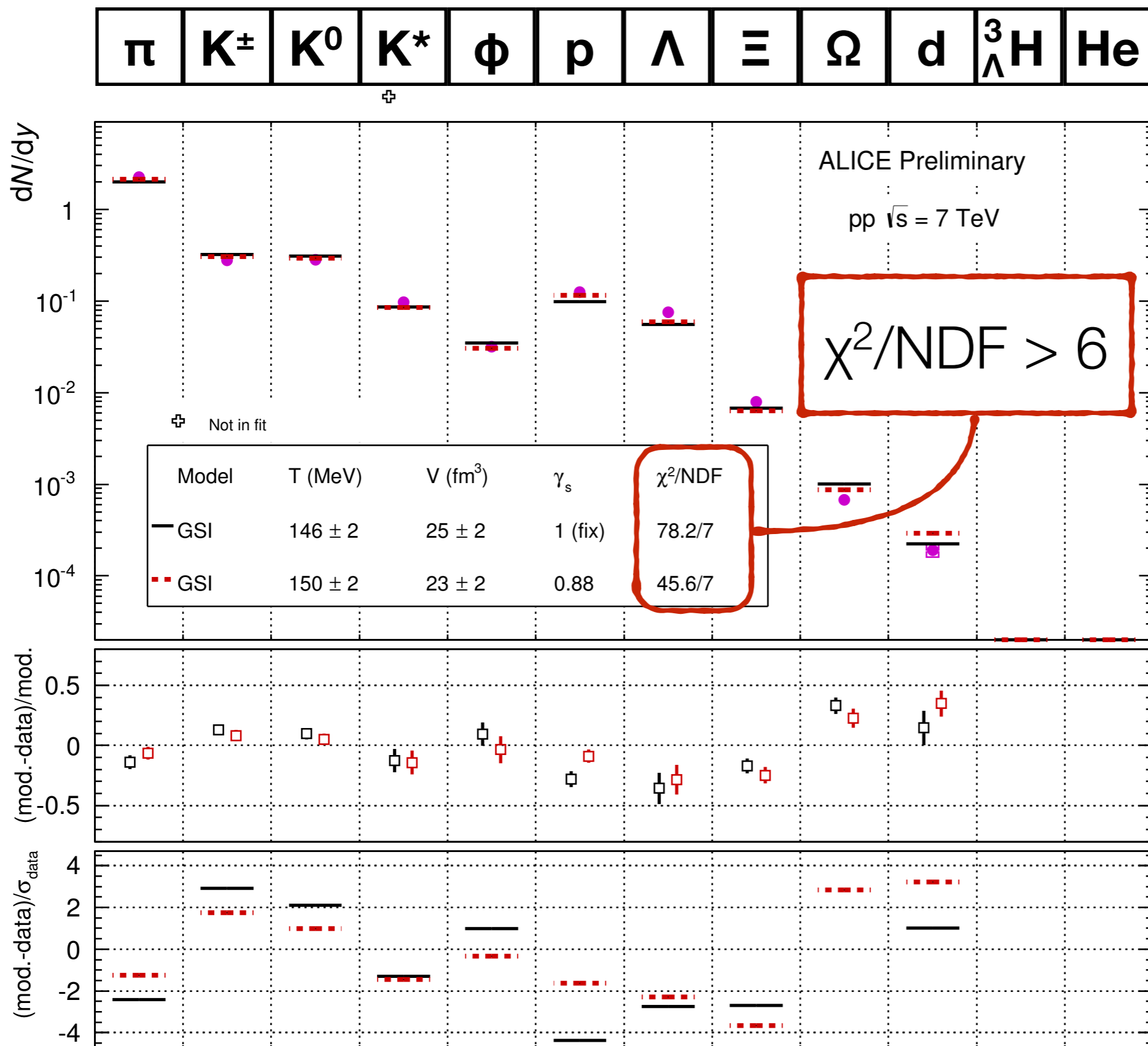
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# GC fits at the LHC (pp collisions)



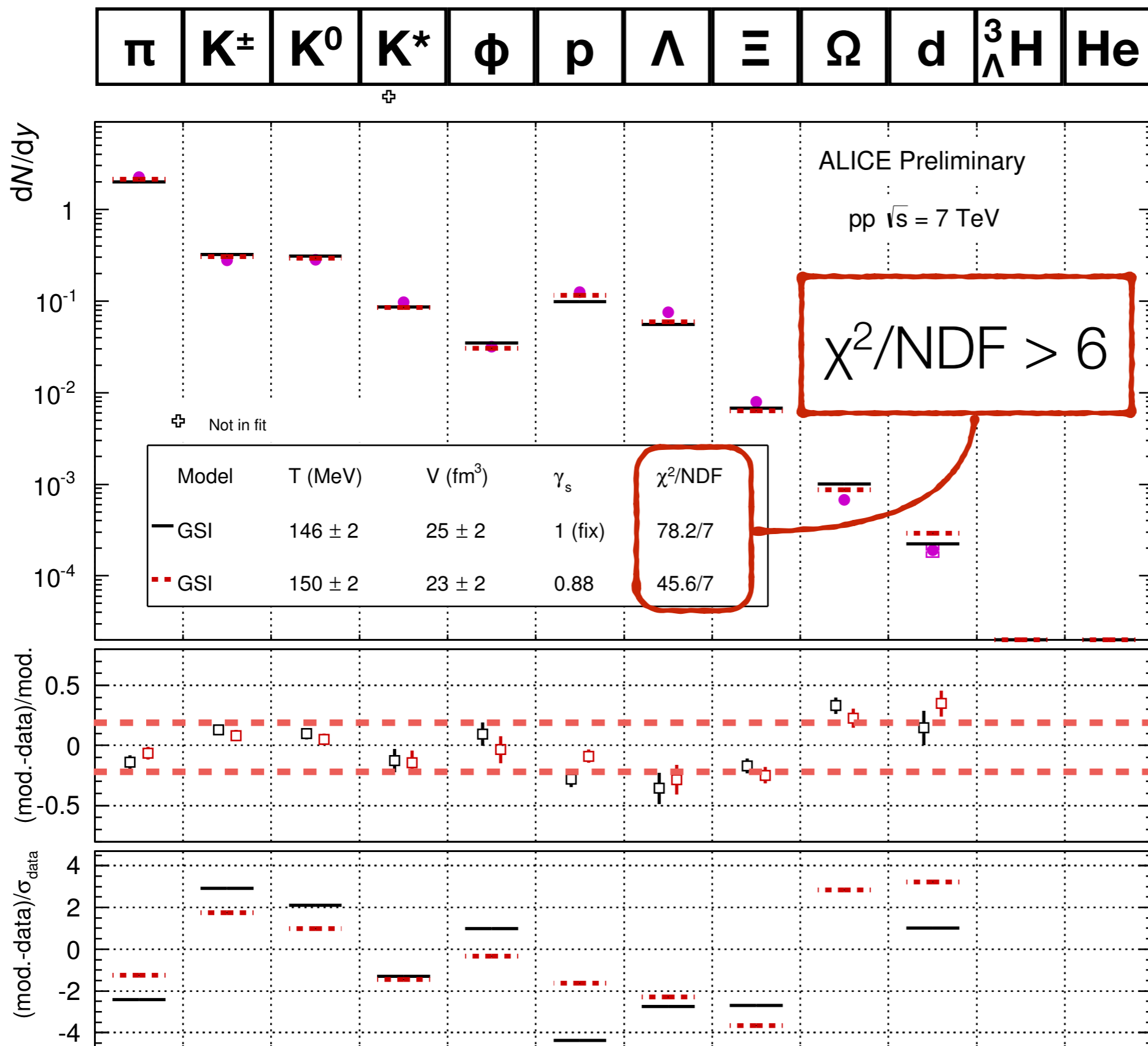
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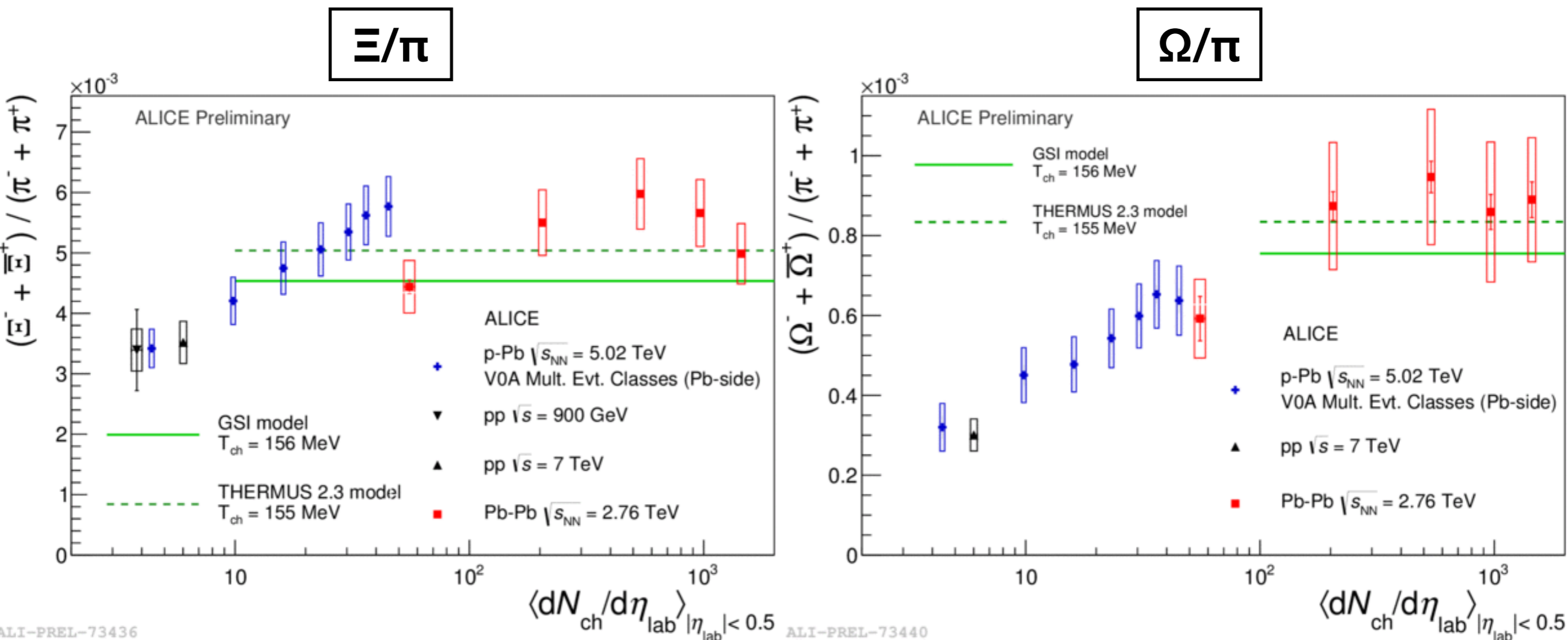
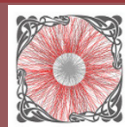


Poor fit with Grand Canonical ensemble in pp collisions

Small  $\rightarrow$  Large at LHC



# Strangeness production in p-Pb collisions



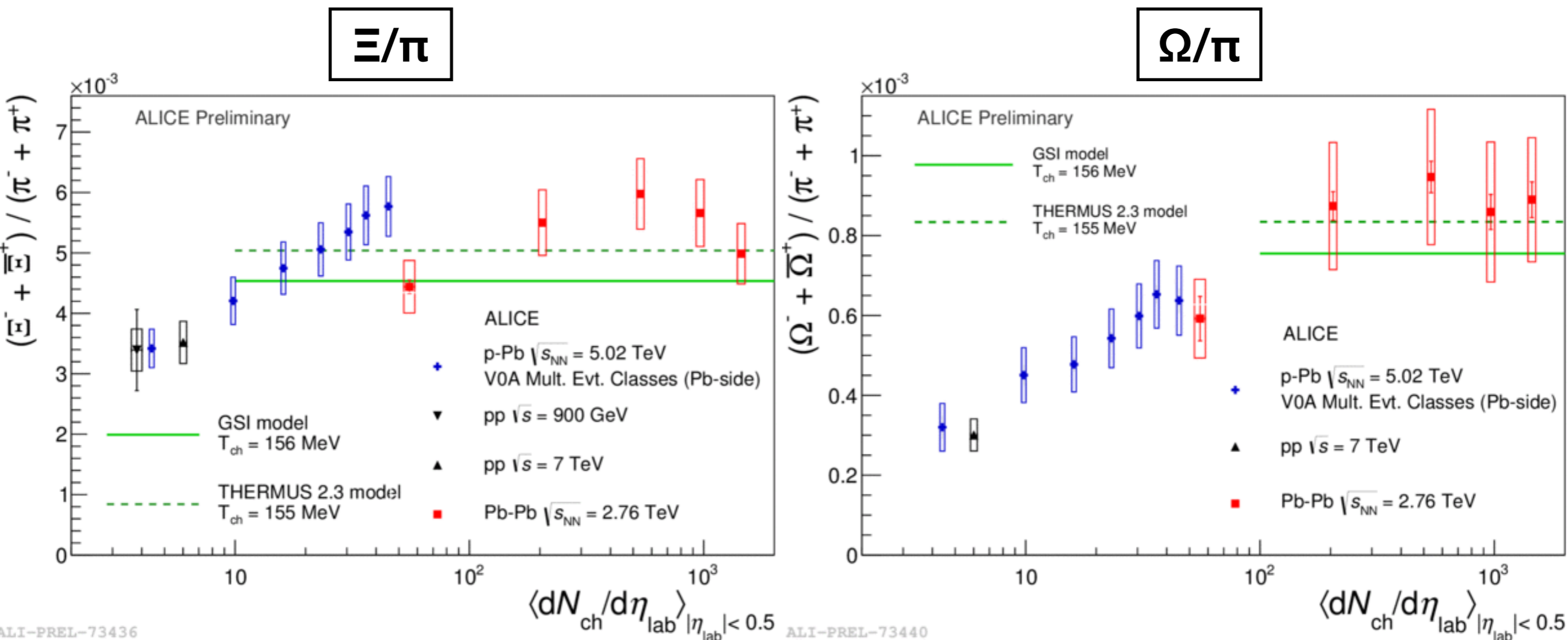
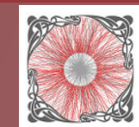
Strangeness enhancement in p-Pb collisions!

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Origin of the tension?

D. Alexandre, ALICE, Wed 21

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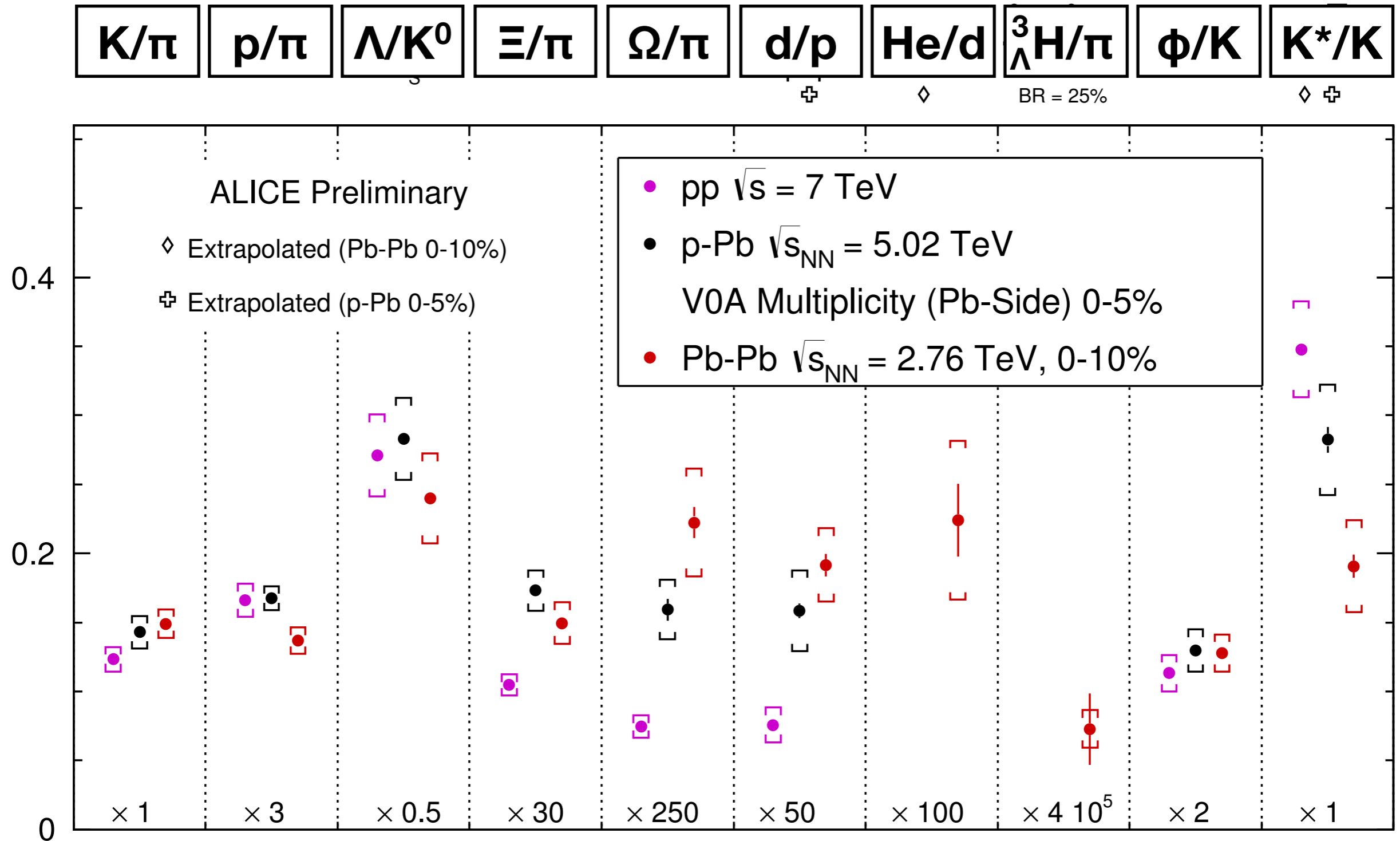
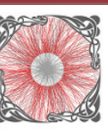
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F. Bellini, ALICE, Tue 20

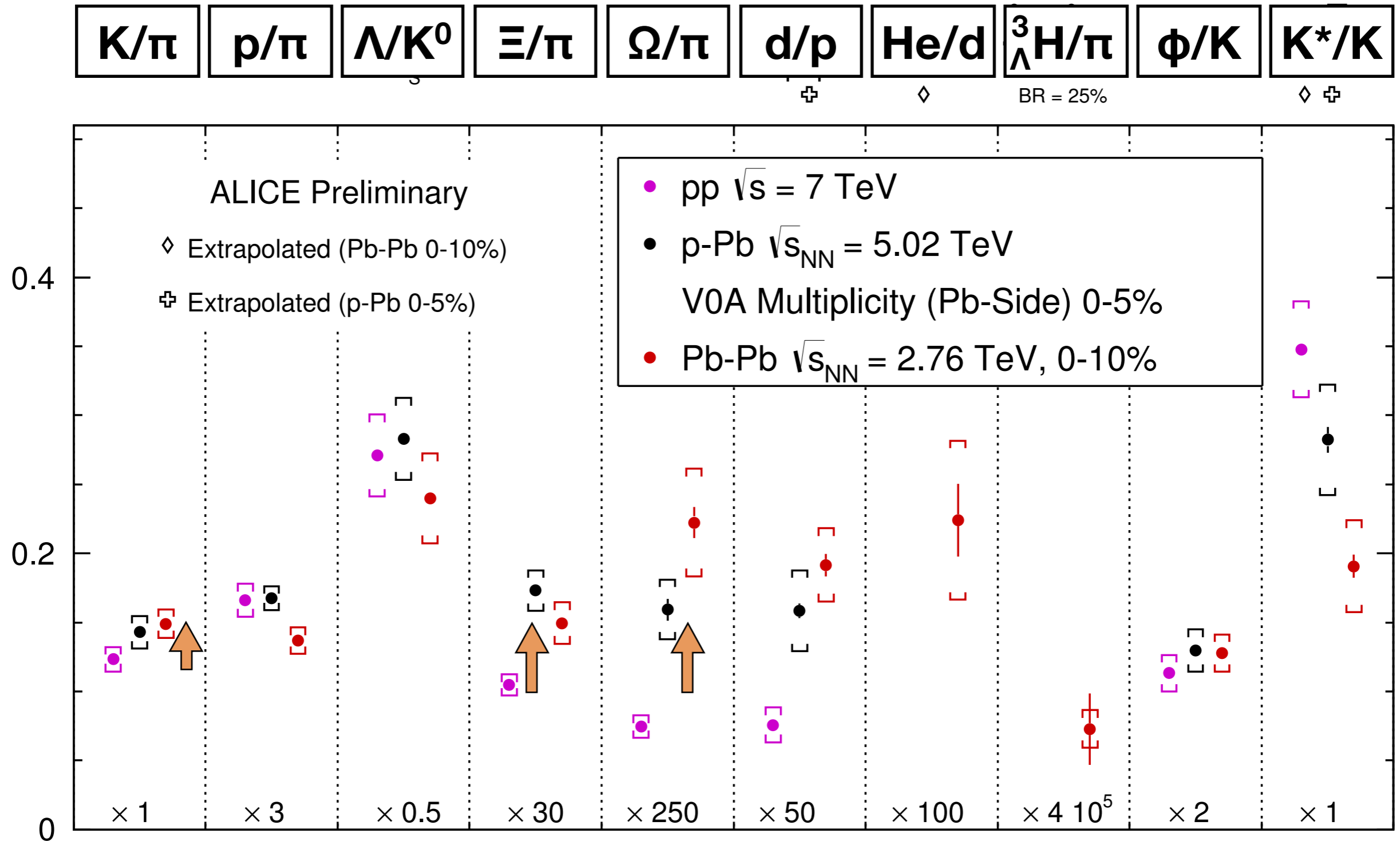
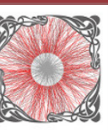
N. Martin, ALICE, Wed 21

D. Alexandre, ALICE, Wed 21

# Ratios, system size dependence at the LHC

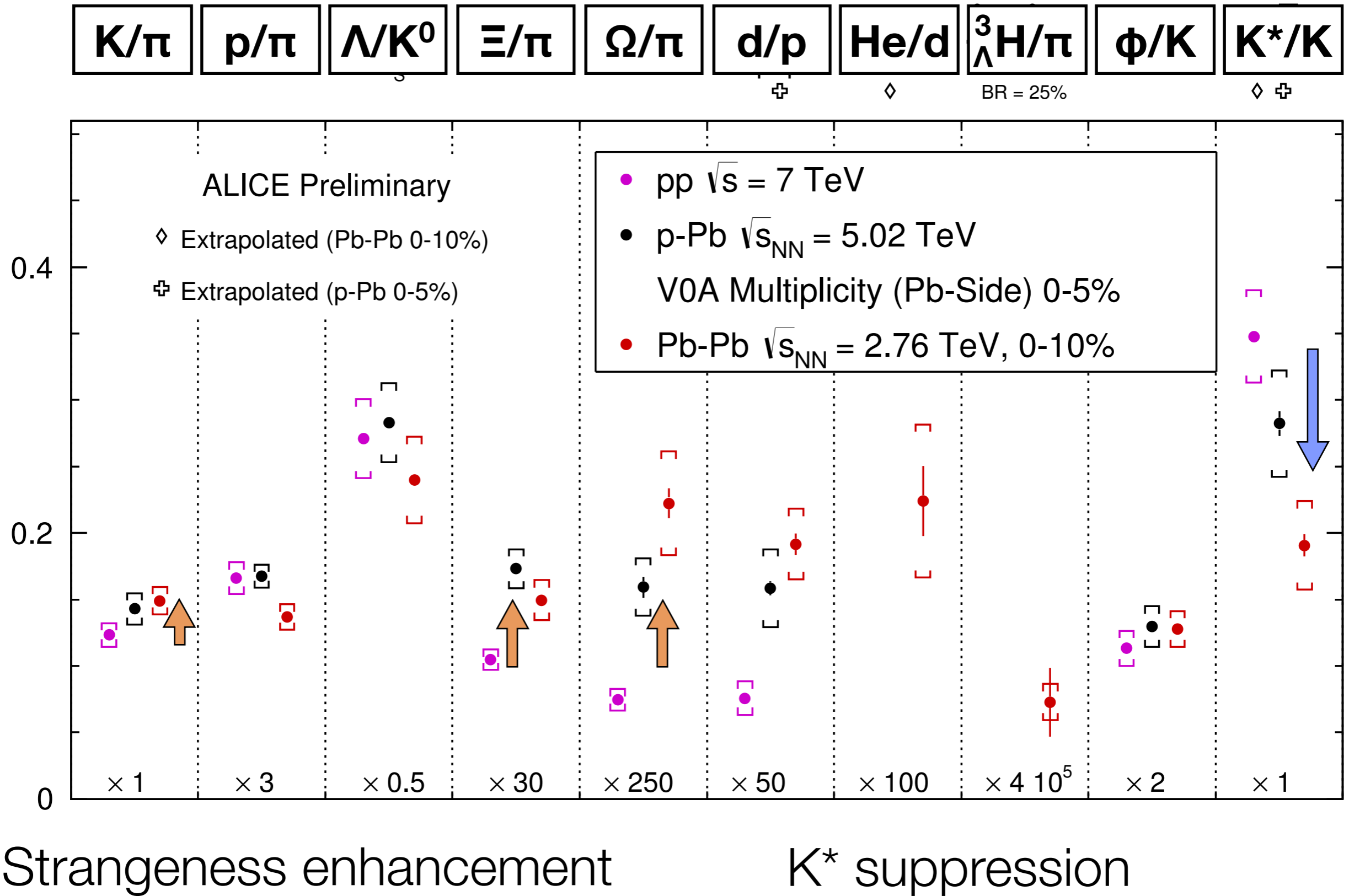
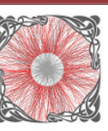


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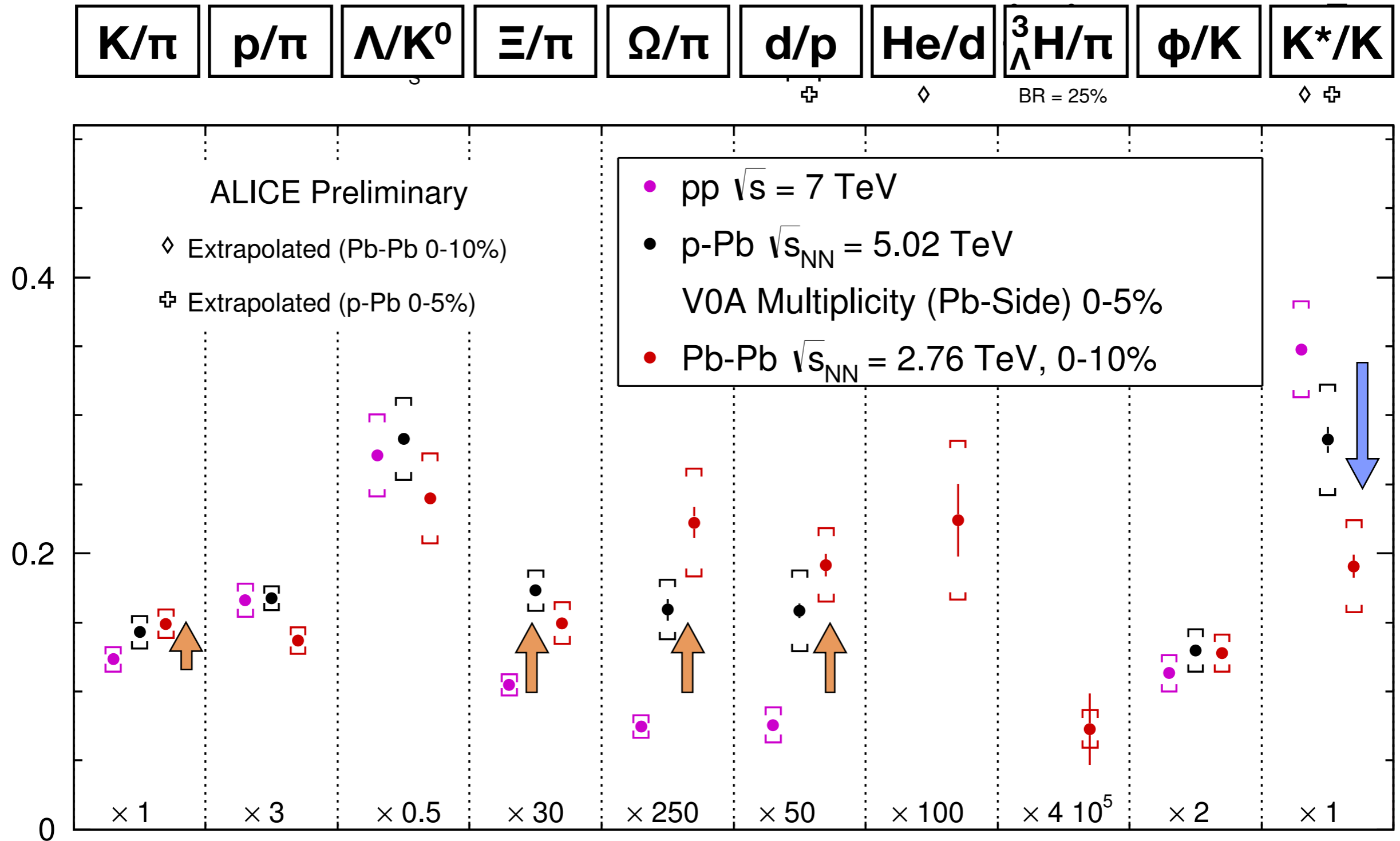
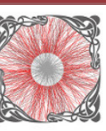


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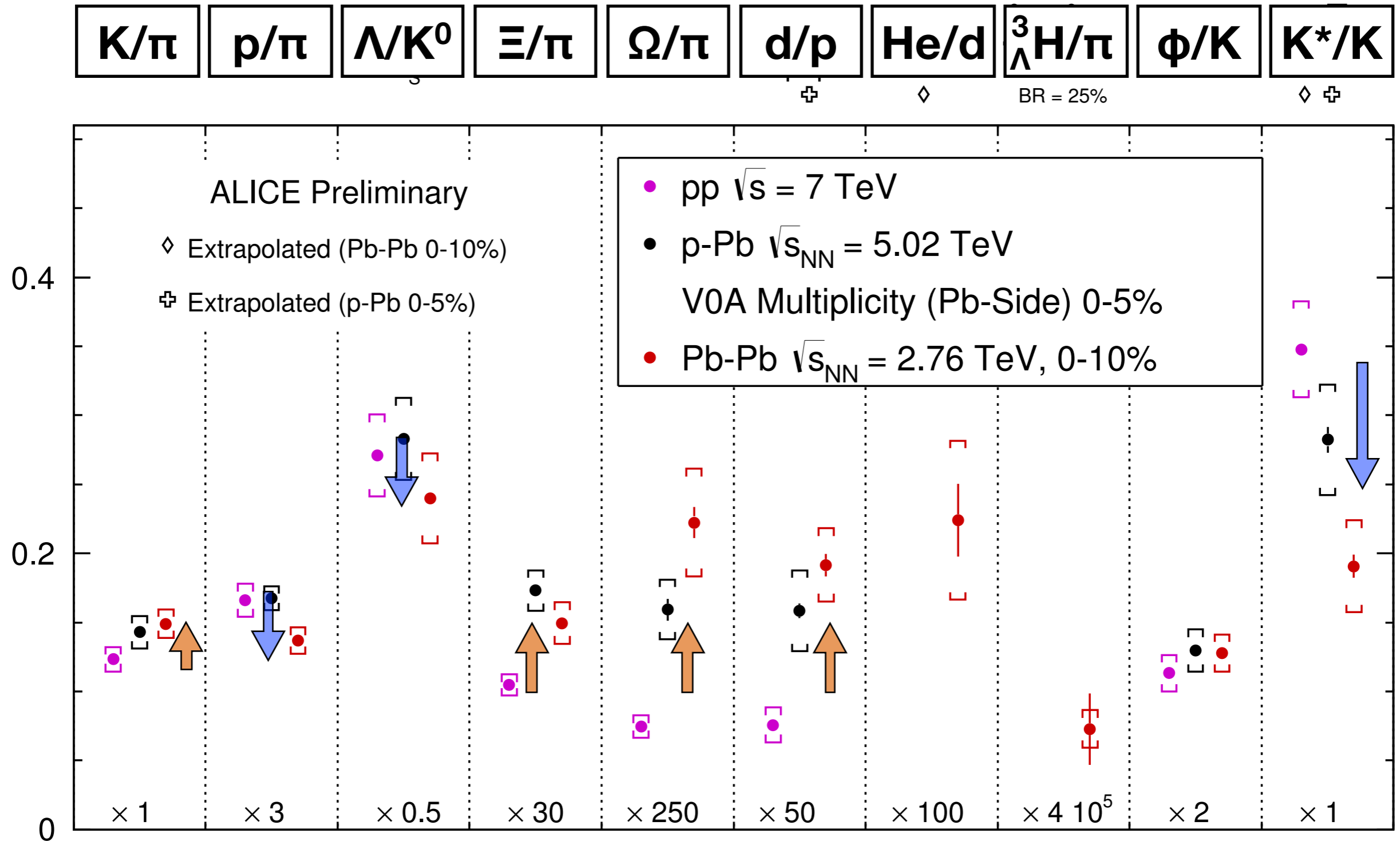
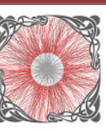


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$K^*$  suppression

Deuteron enhancement

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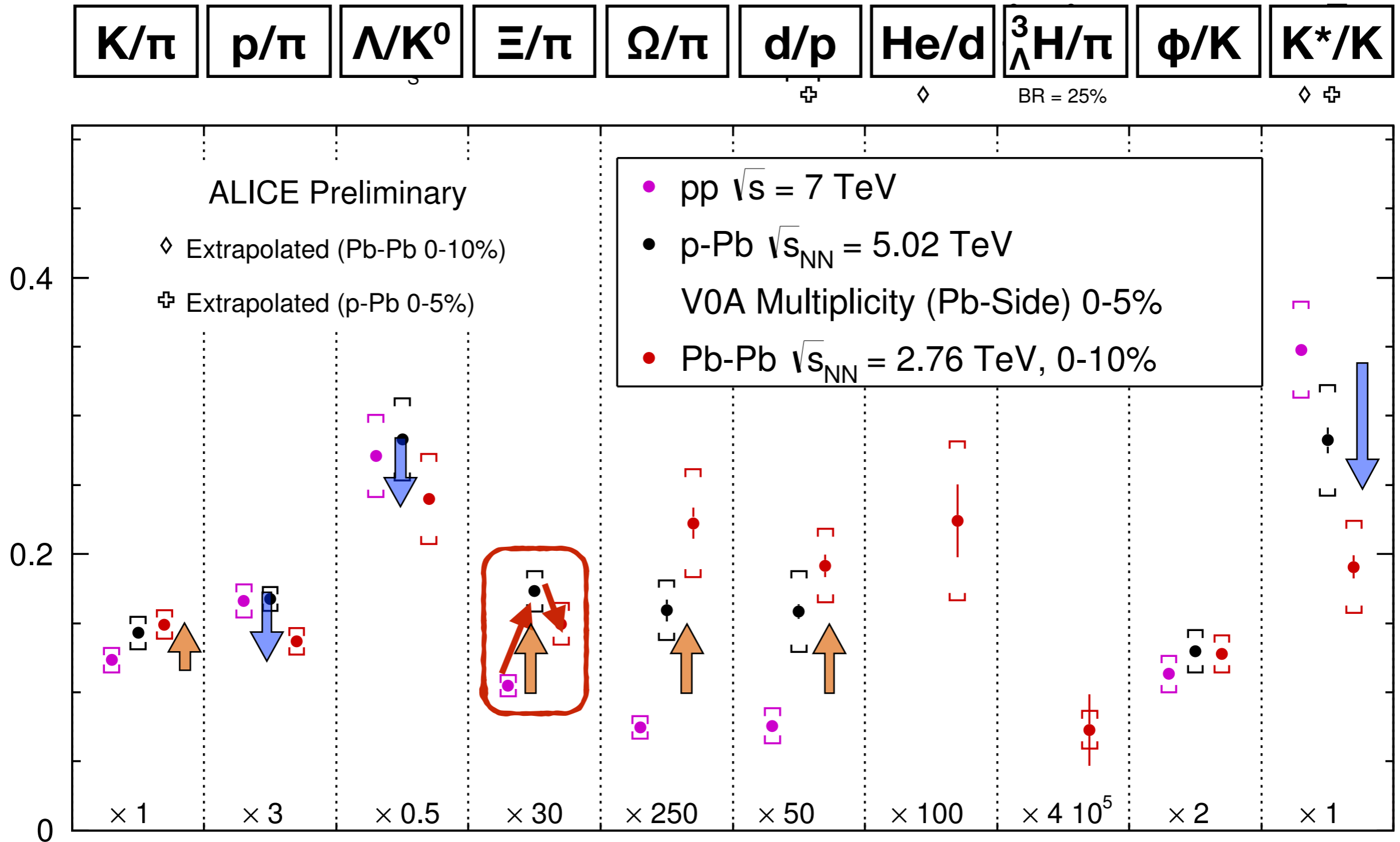
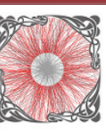
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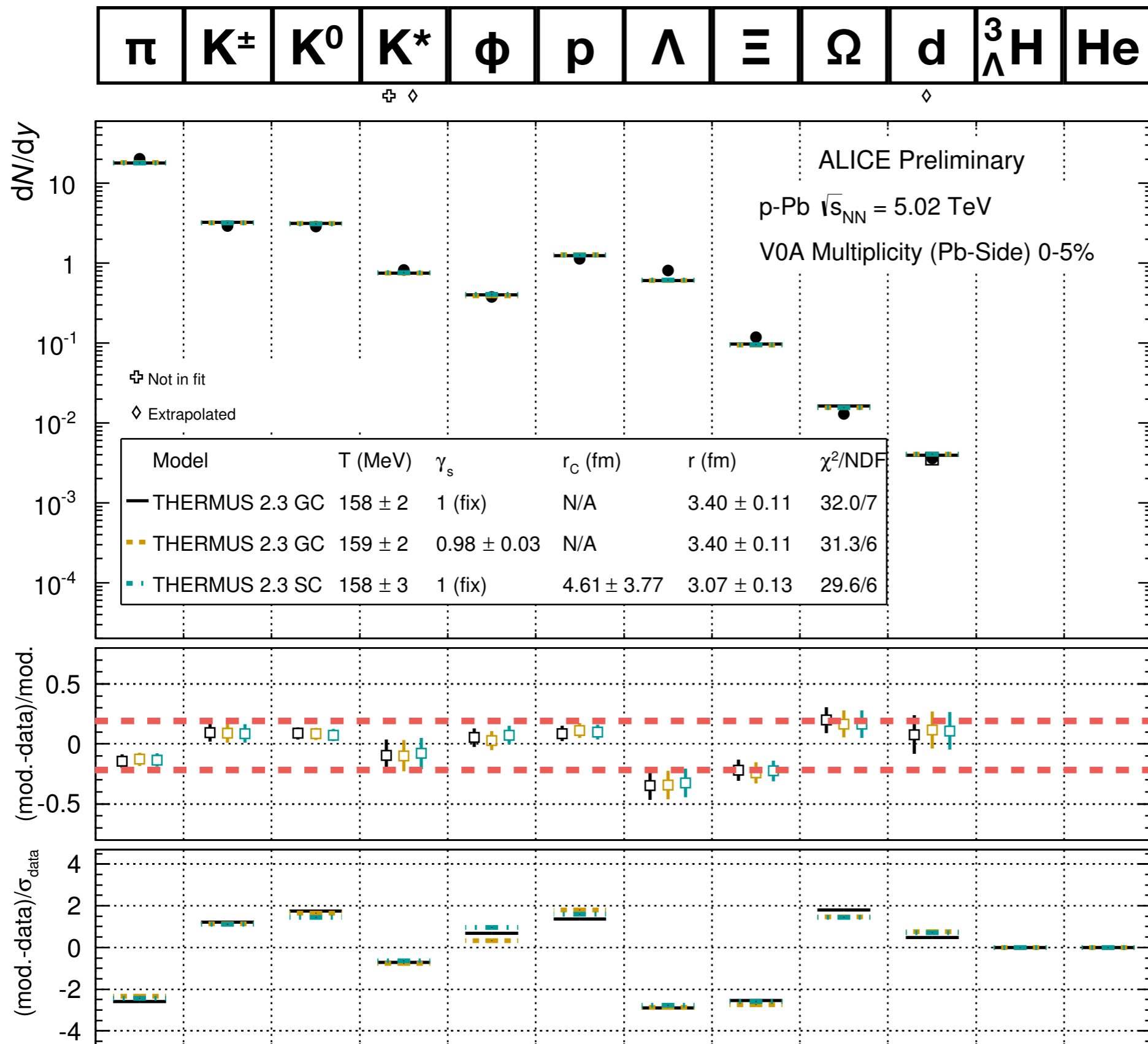
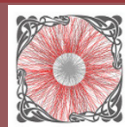
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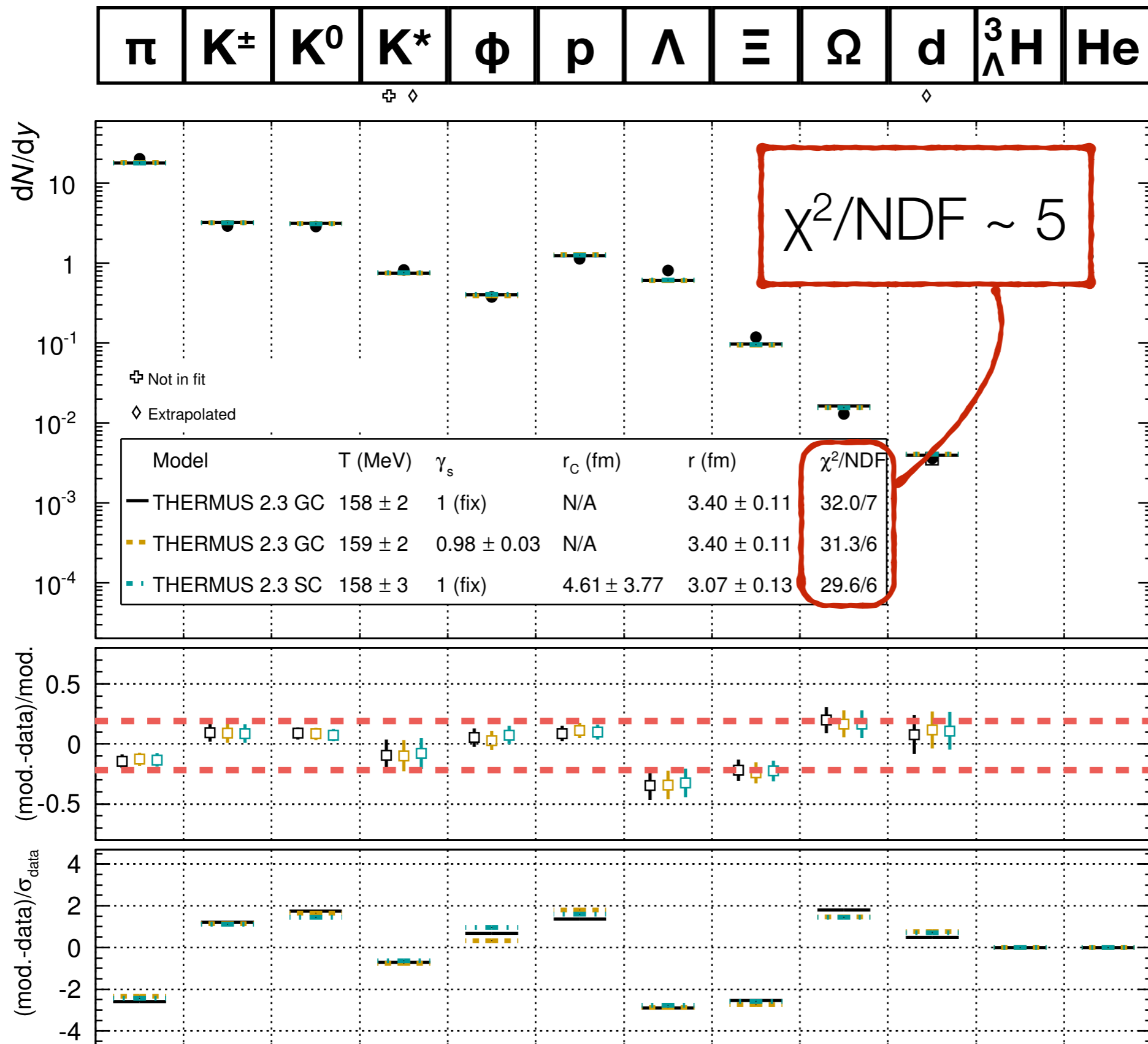
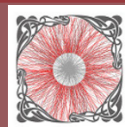
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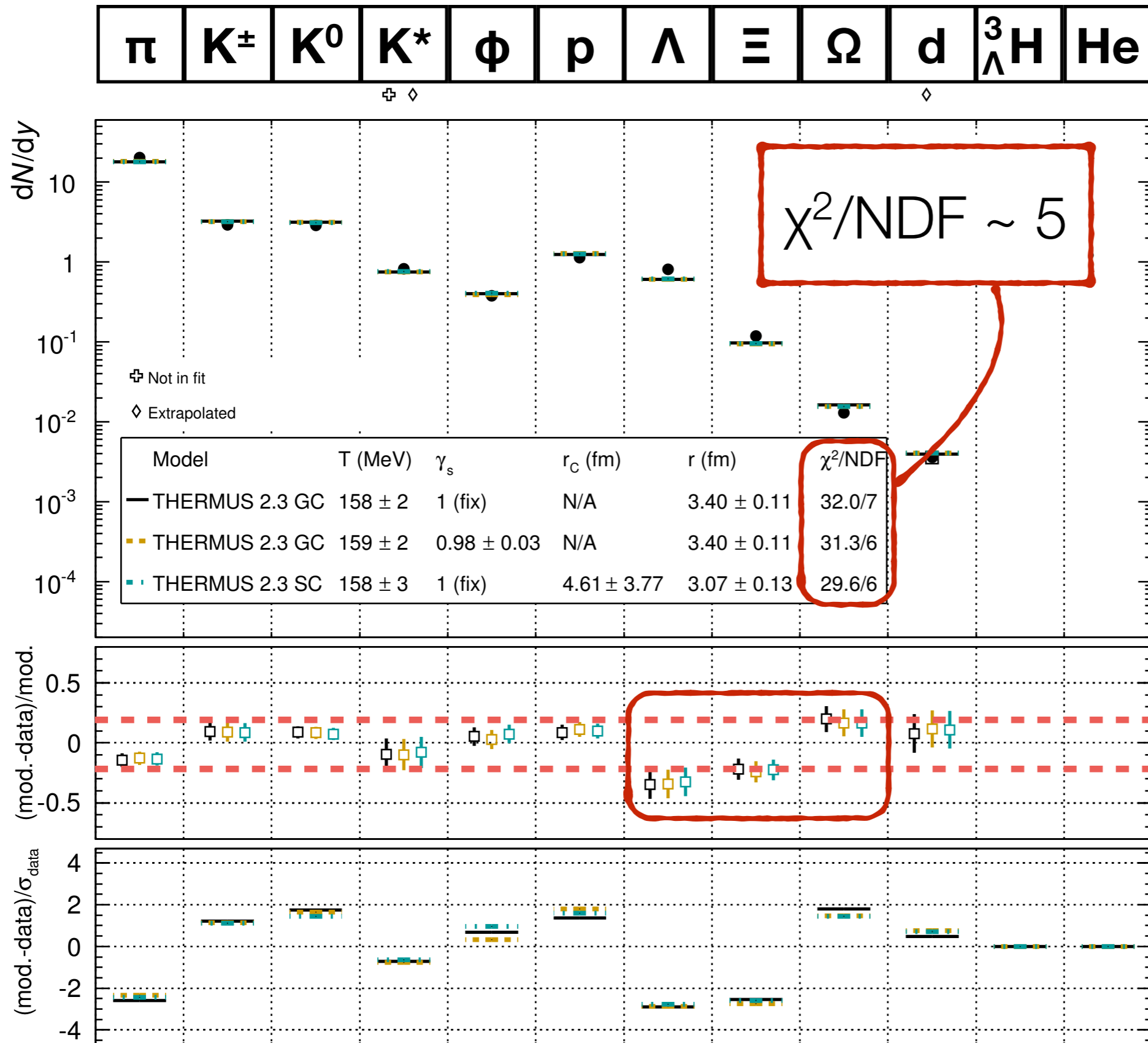
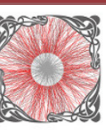
Fit quality not good  
Note:

- $\Omega$  and  $\Xi$  pull in opposite directions
- $\gamma_s$  compatible with 1 if free
- Low mult:  $\gamma_s < 1$  (not shown)



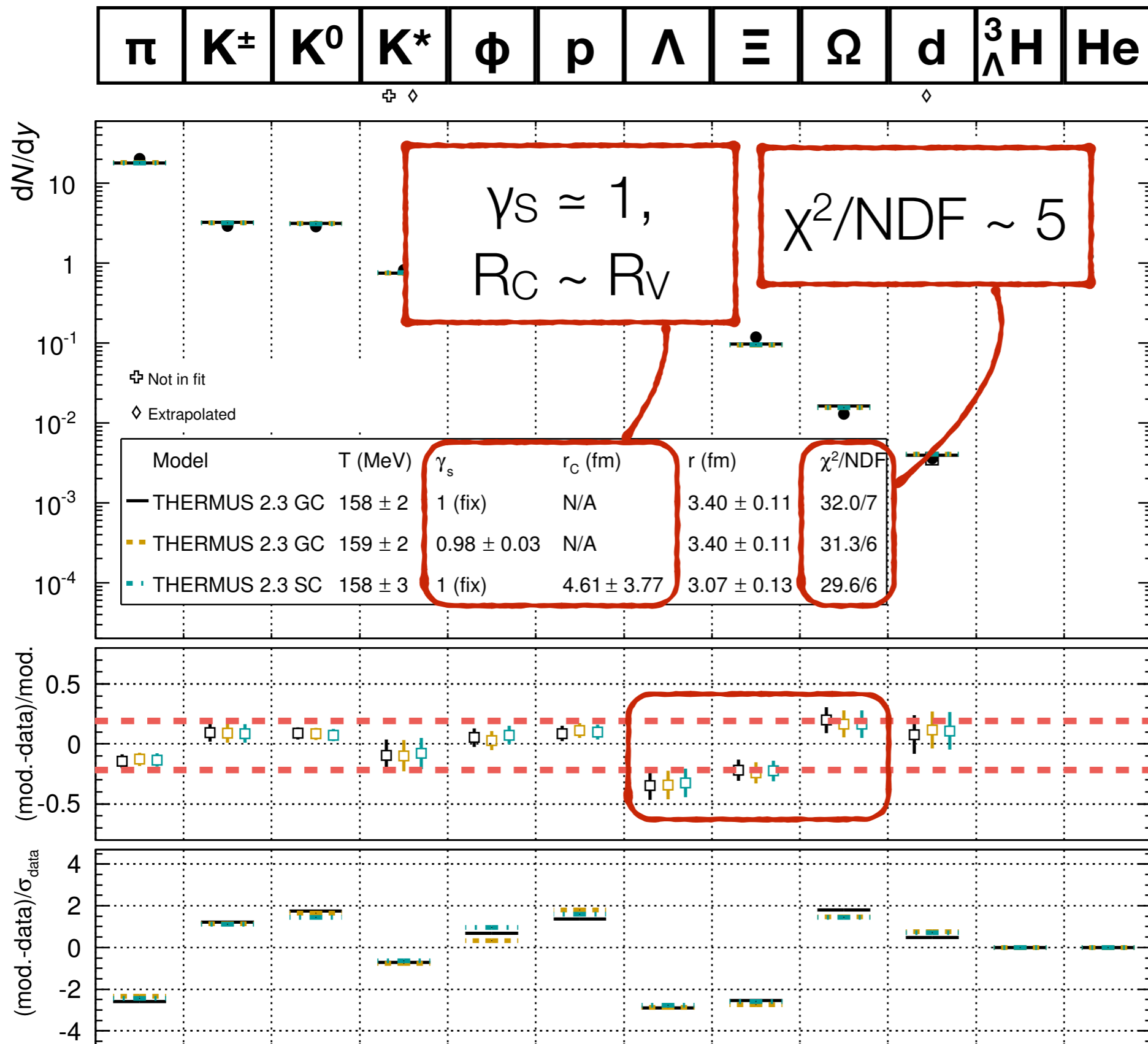
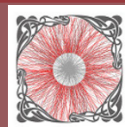
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$\gamma_s \approx 1,$   
 $R_C \sim R_V$

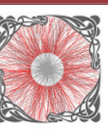
$\chi^2/\text{NDF} \sim 5$

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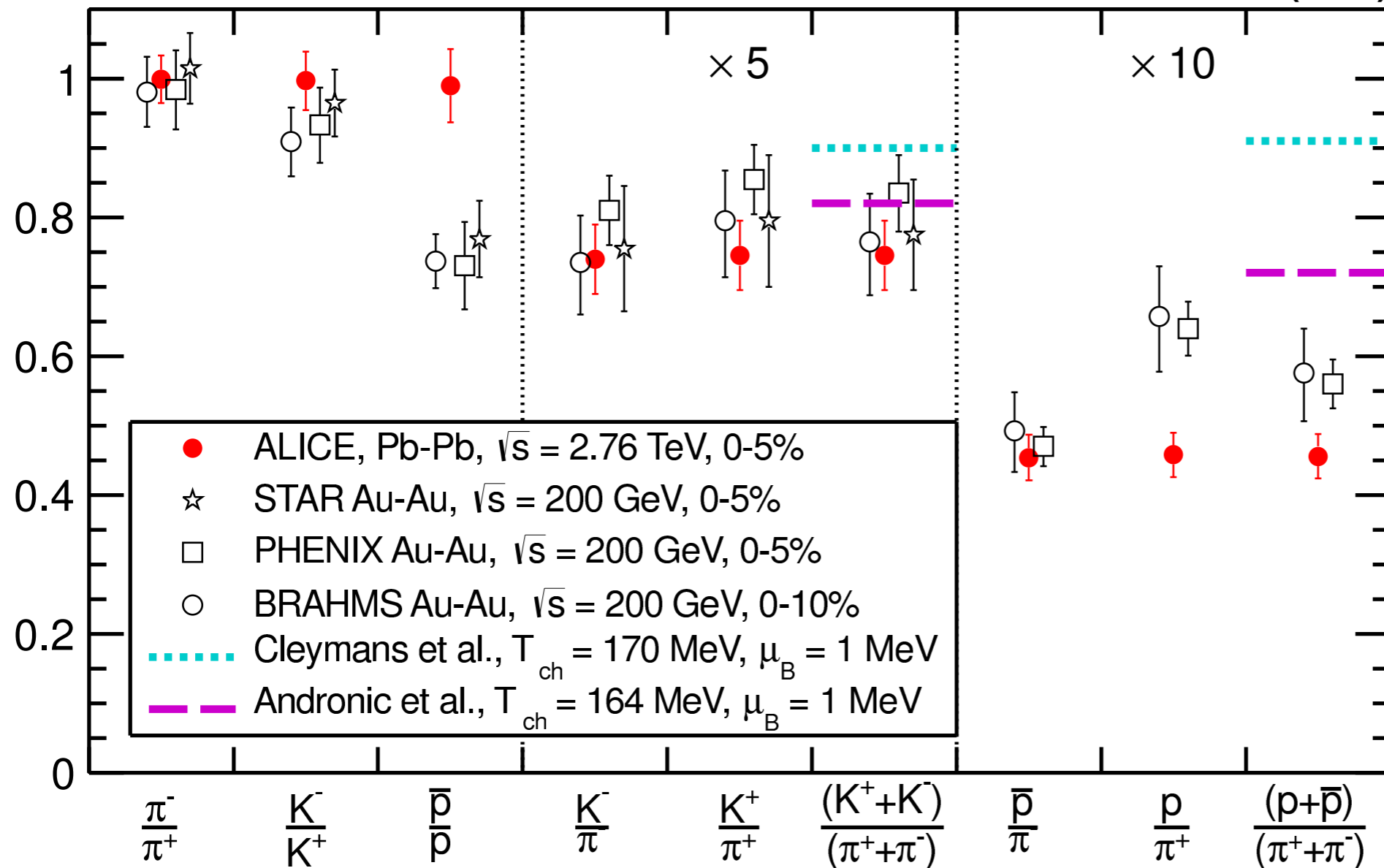
# Heavy ions at High Energy

# Anomalous $p/\pi$ ratio at the LHC



PRL 109 252301 (2012)

ALICE, QM11



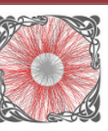
$p/\pi$ : 1.5  
smaller than  
expectations

Is it only protons or all baryons?

Why?!

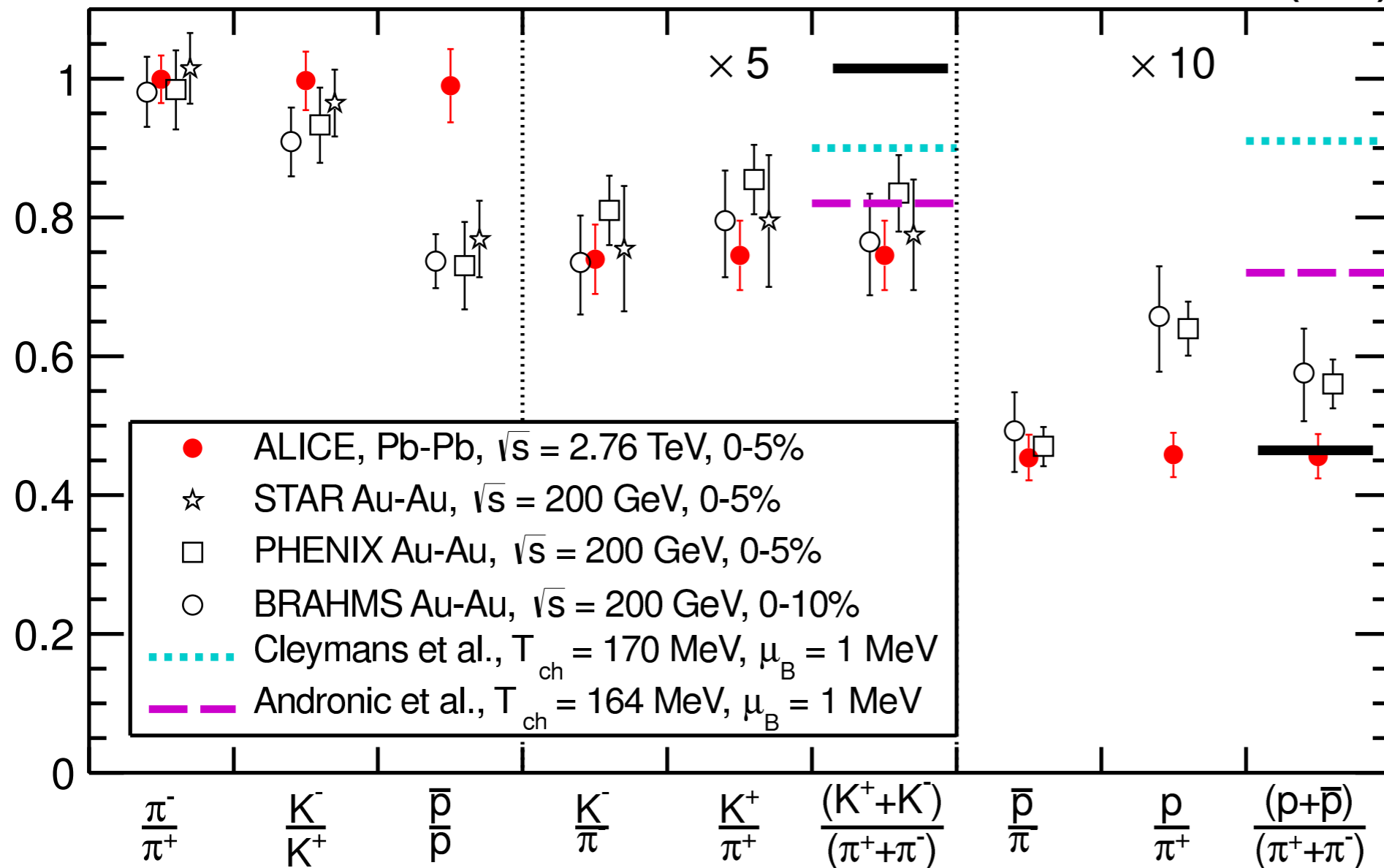
(NB with these 3 particles, it would be enough to lower  $T \sim 140$  MeV)

# Anomalous $\rho/\pi$ ratio at the LHC



PRL 109 252301 (2012)

ALICE, QM11

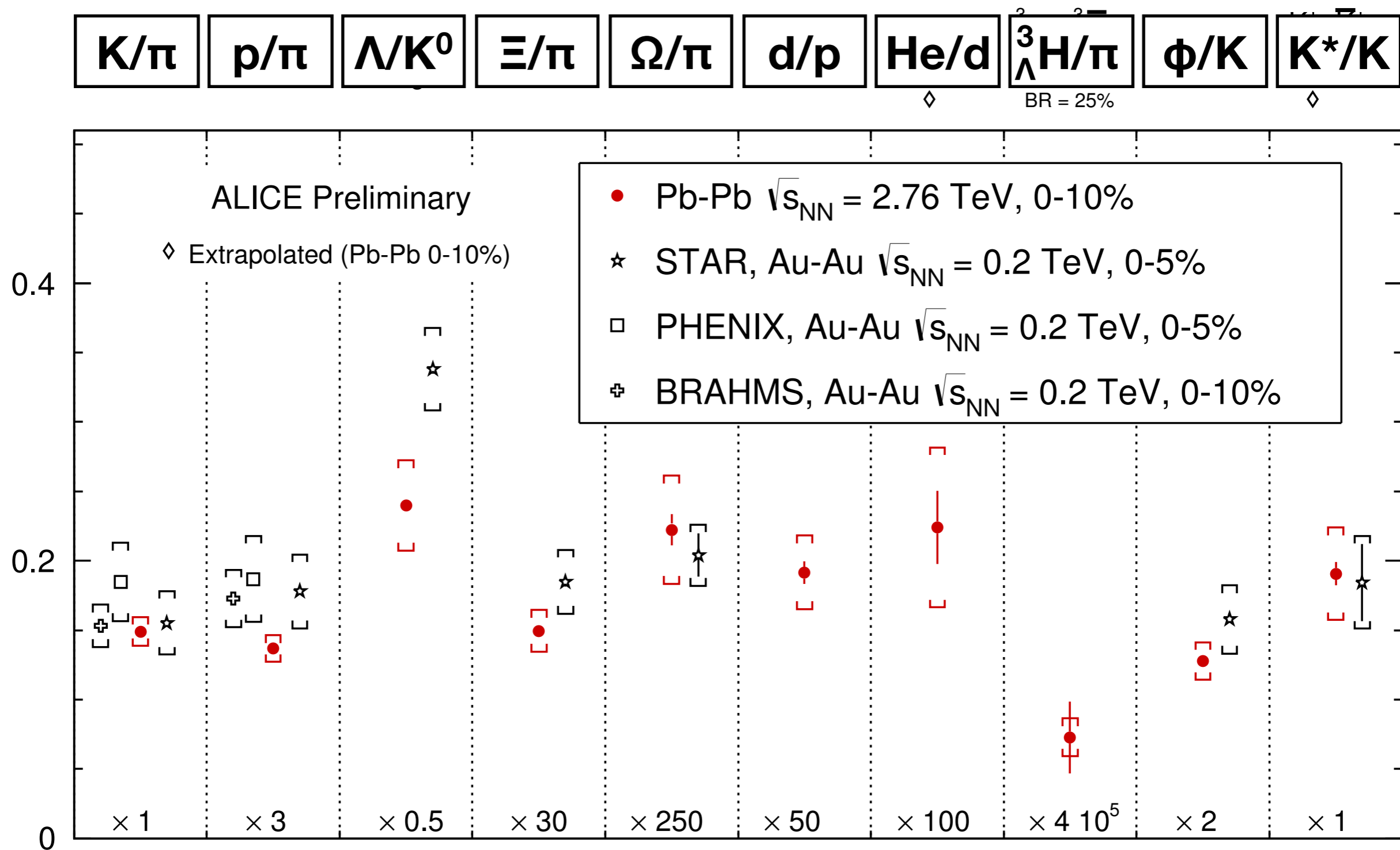
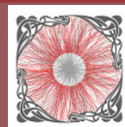


$\rho/\pi$ : 1.5  
smaller than  
expectations

$T = 137.7 \text{ MeV}$ ,  $\gamma_q \sim 1.6$ ,  $\gamma_s \sim 2.75$   
 Hadronization pressure  $P = 82 \text{ MeV/fm}^3$   
**Rafelski, Letessier, PRC 83, 054909 (2011)**

Non equilibrium model prediction

# Ratios, Comparison to RHIC (AA)

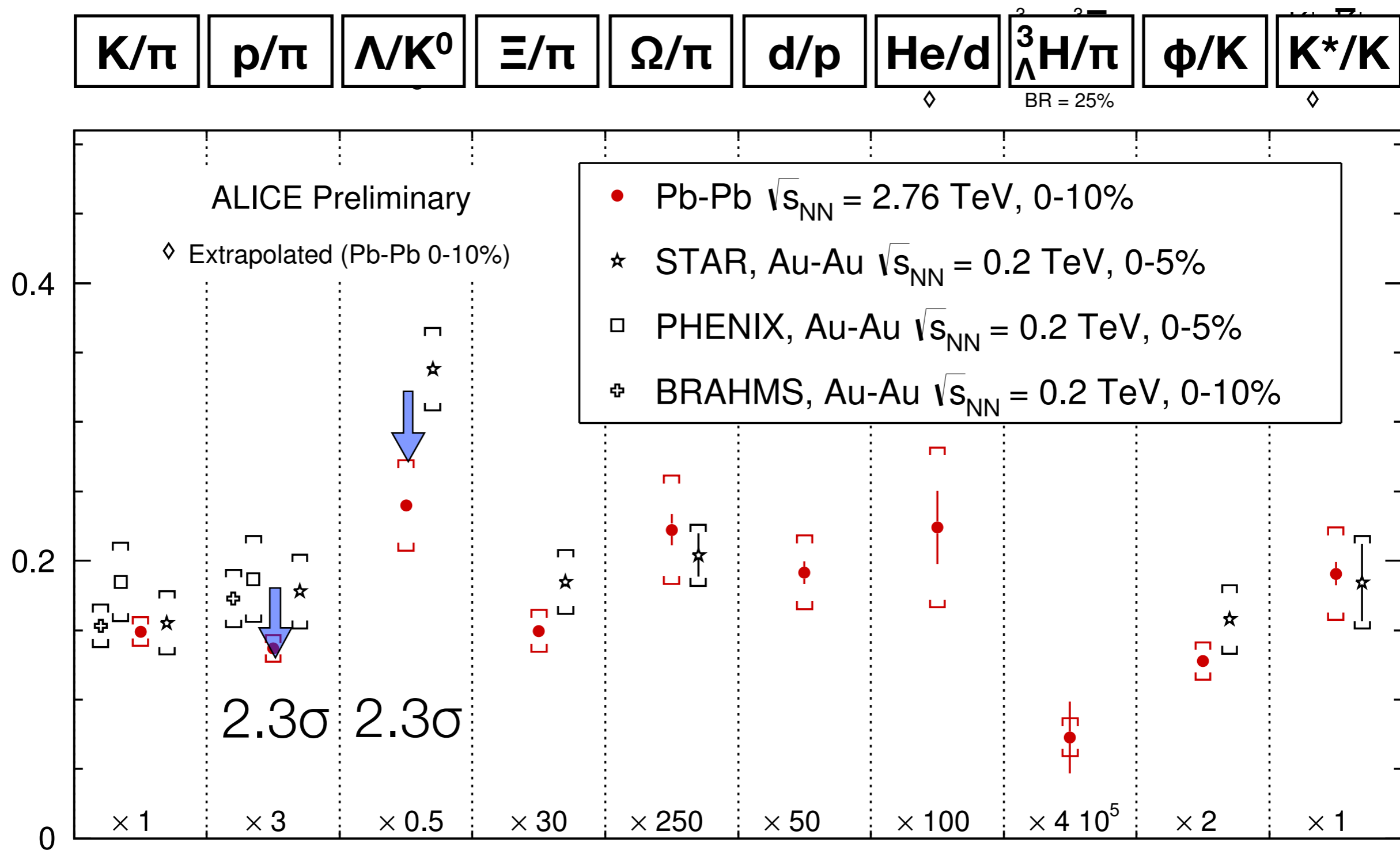
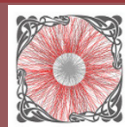


(In this plot: STAR p feed-down corrected with thermal model)

ALI-PREL-74452

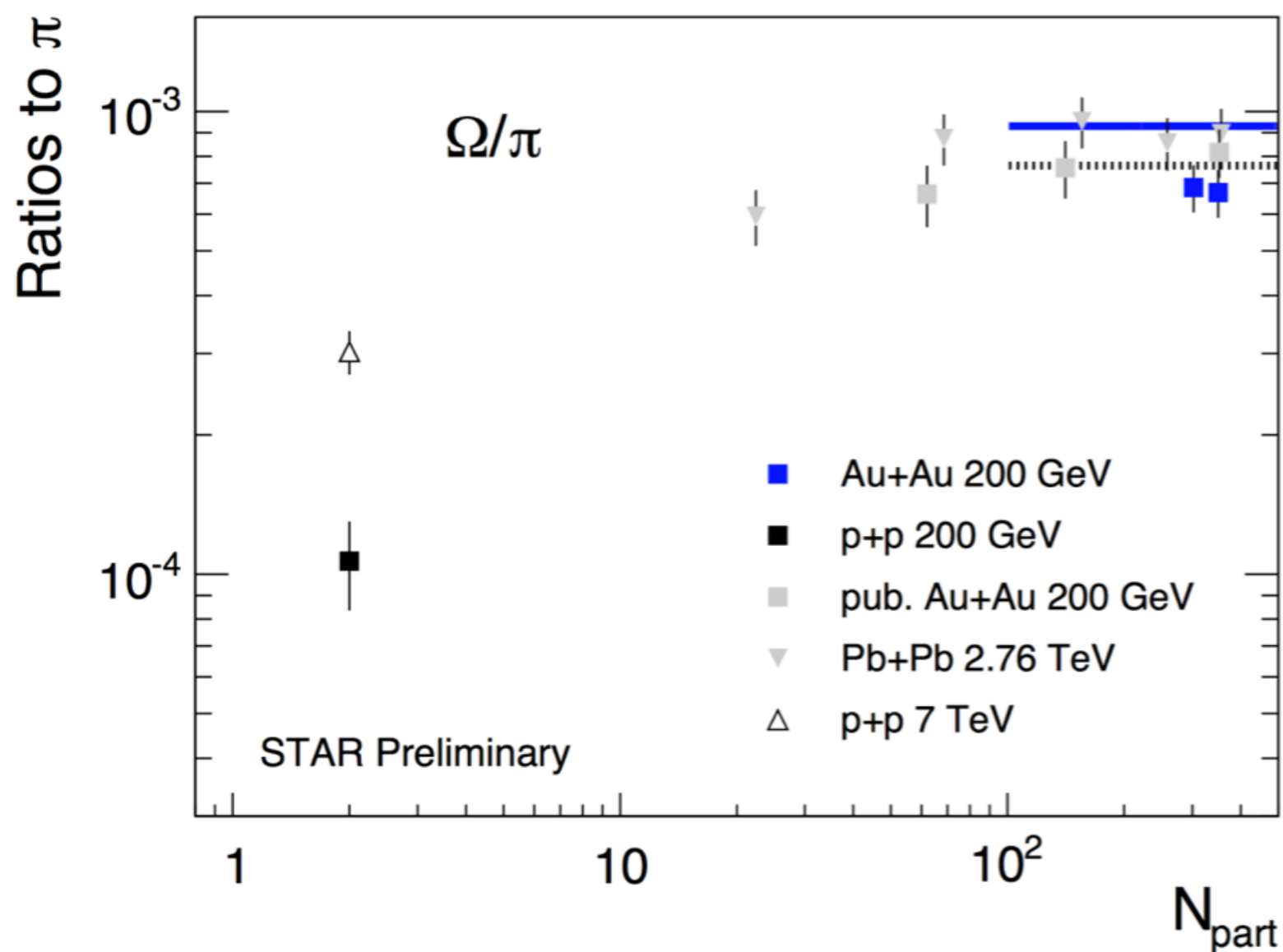
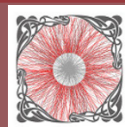


# Ratios, Comparison to RHIC (AA)



(In this plot: STAR p feed-down corrected with thermal model)

ALI-PREL-74452



Thermal models:

**Fitting to RHIC,  $T = 164$  MeV**

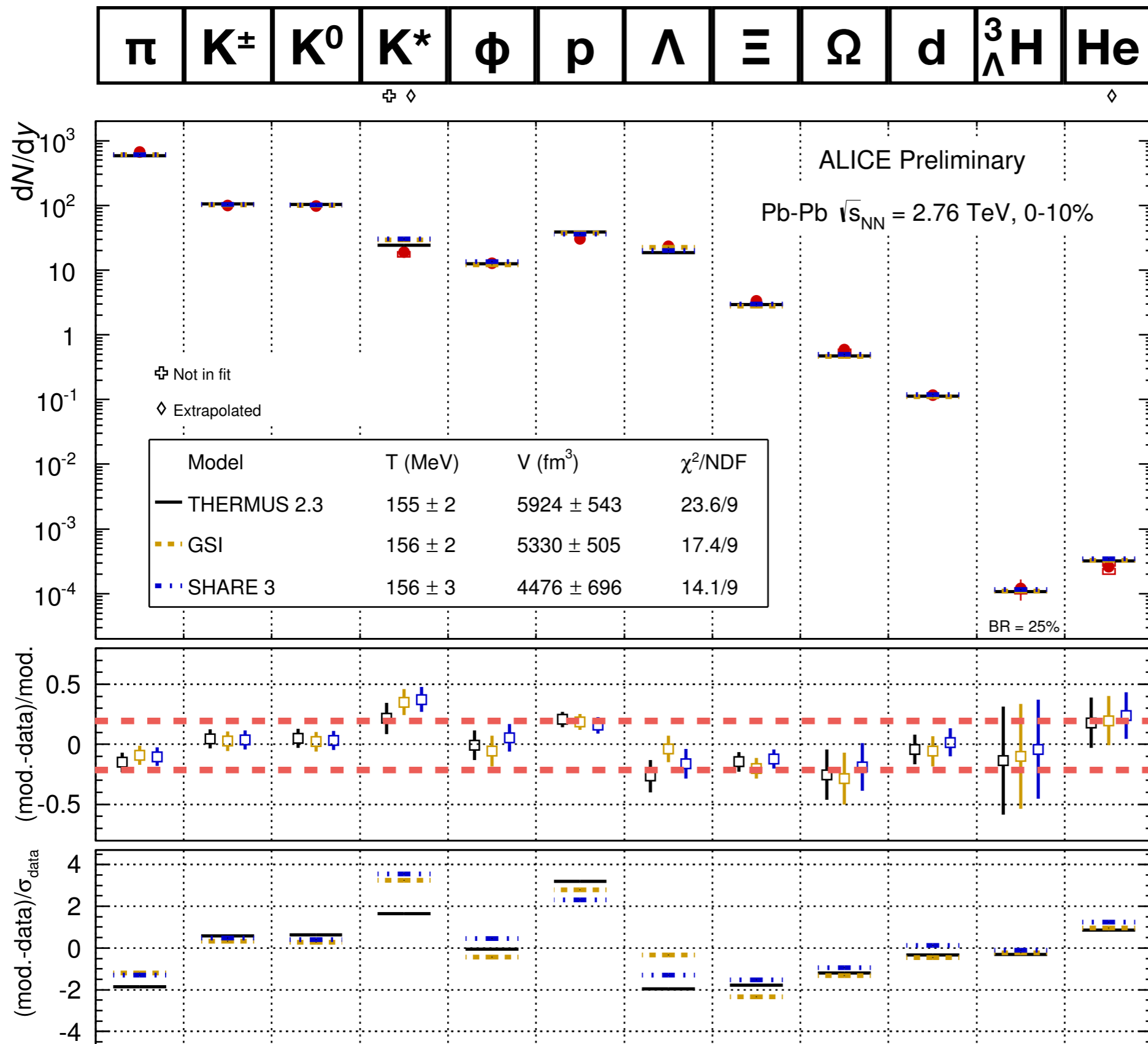
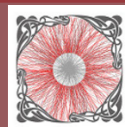
*Andronic, et al., Phys. Lett. B 673 (2009) 142; Phys. Lett. B 678 (2009) 516*

*Fitting to LHC,*

*Stachel, et al., arXiv: 1311.4662*

**$T = 156$  MeV**

# Equilibrium SHM Fits

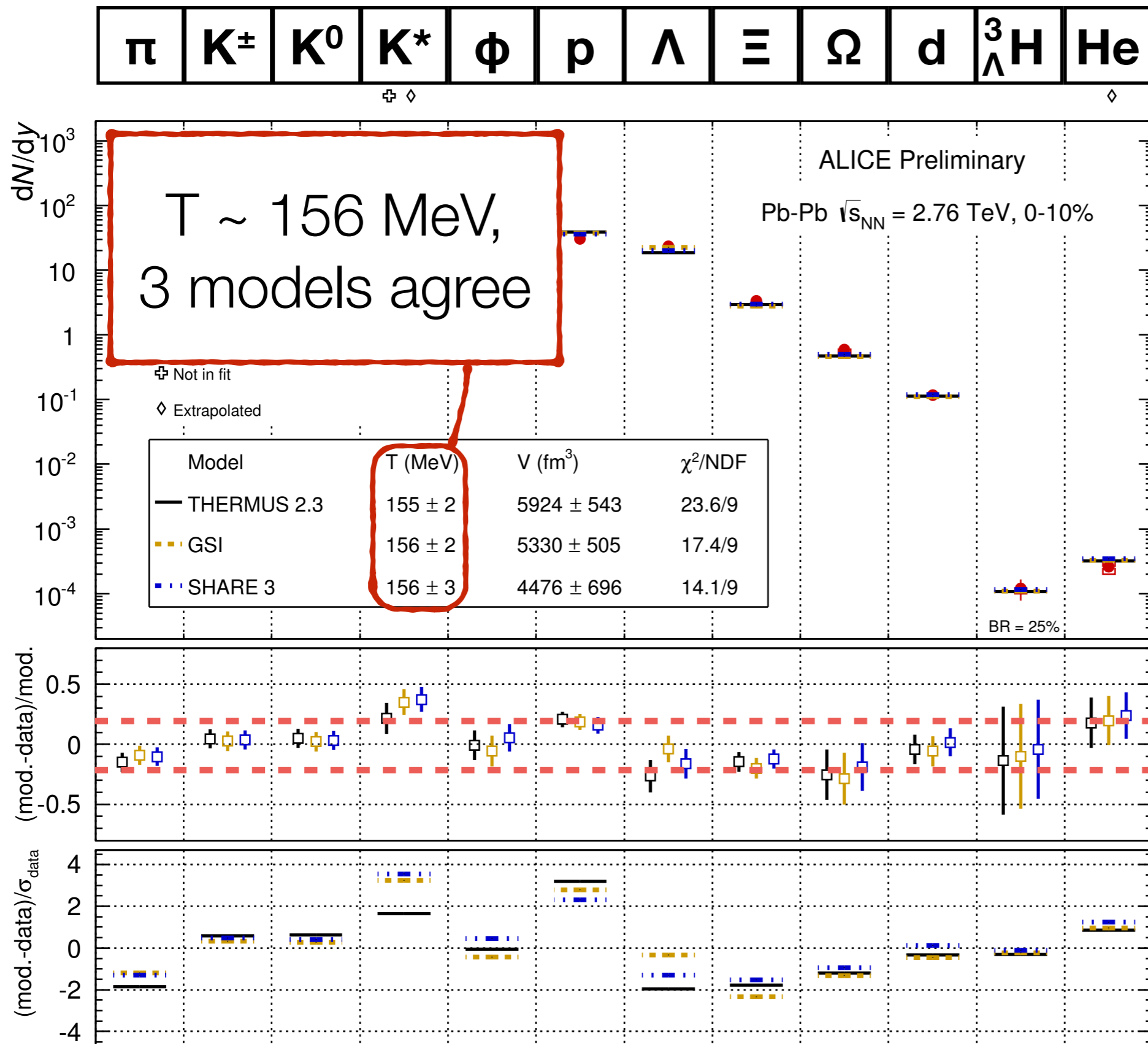
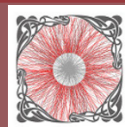


N.B.  
RHIC  
 $\sqrt{s} = 200$  STAR  
 $\chi^2$ /NDF  $\sim 1$

Better fit in  
60-80%,  
(feel free to ask about it)

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

# Equilibrium SHM Fits

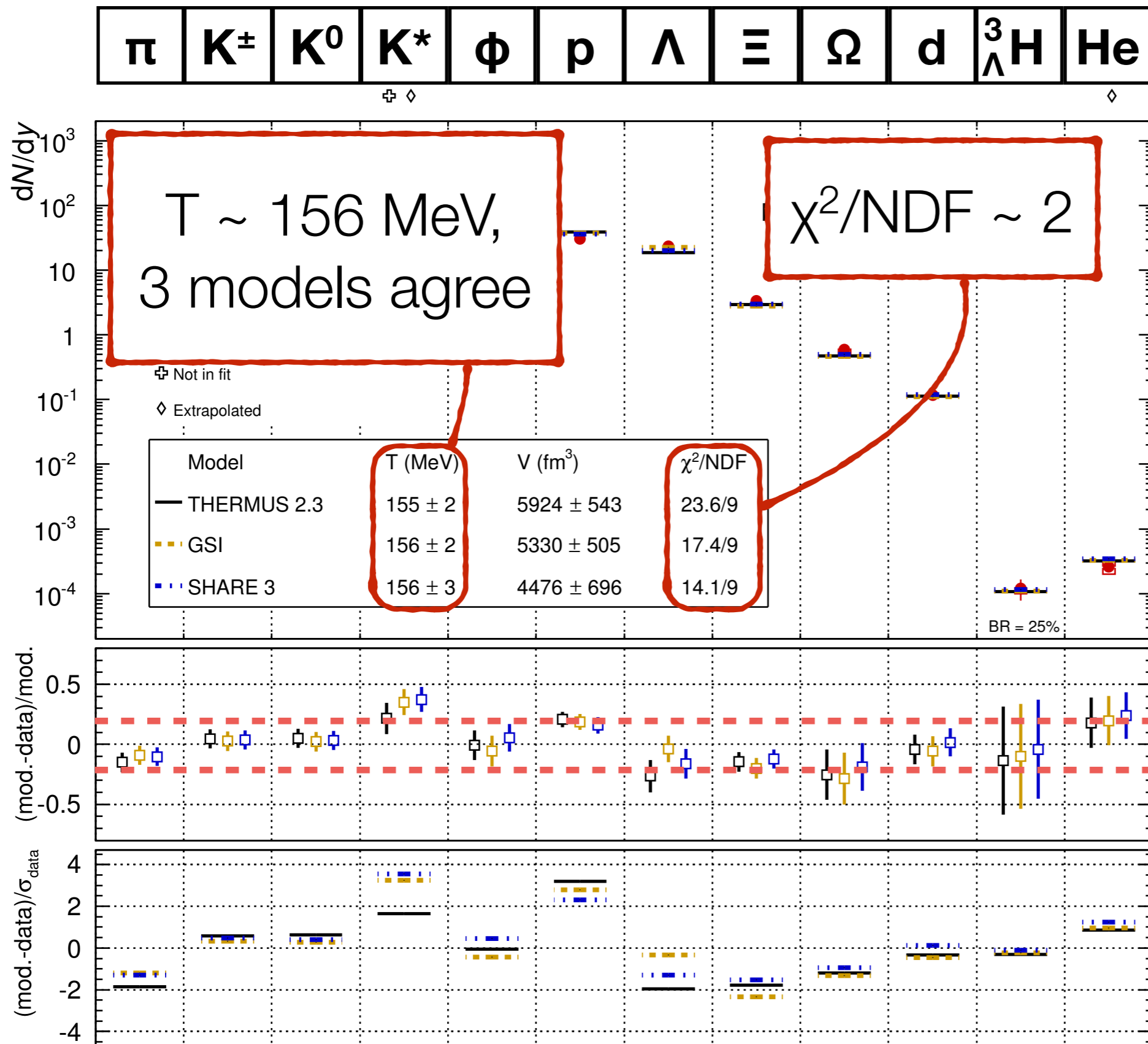
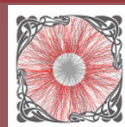


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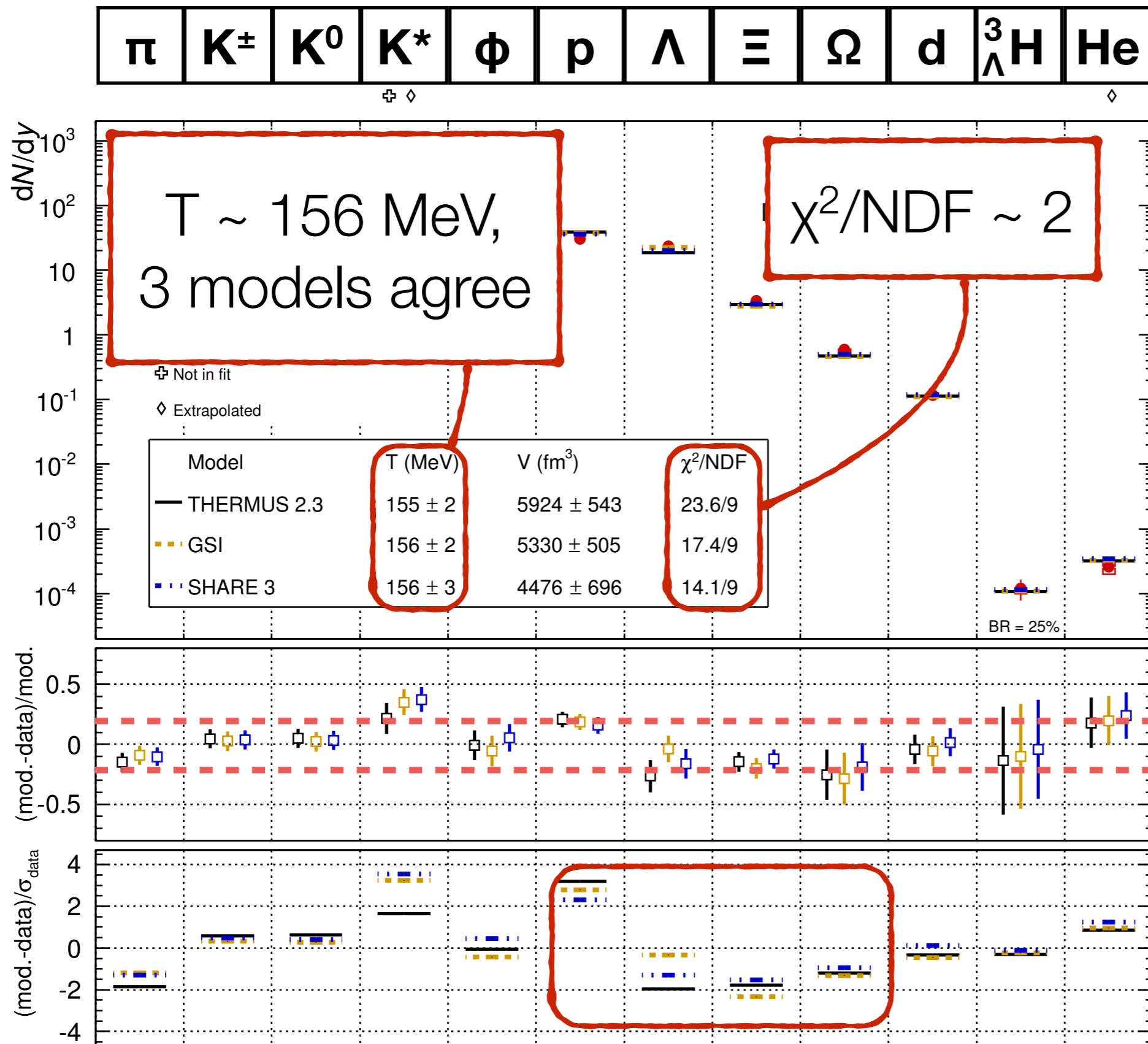
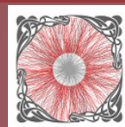


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# Equilibrium SHM Fits

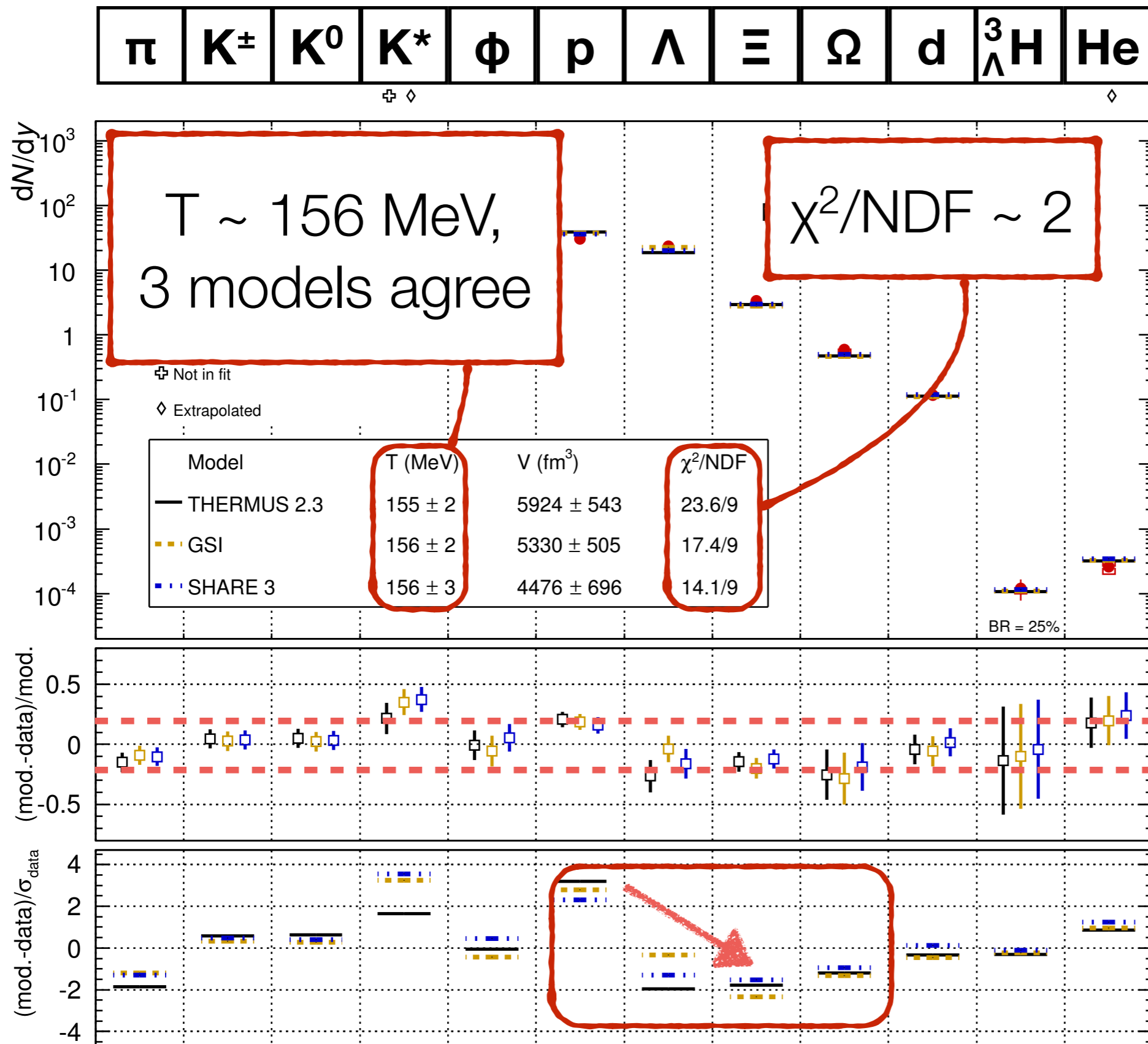
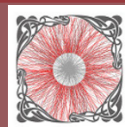


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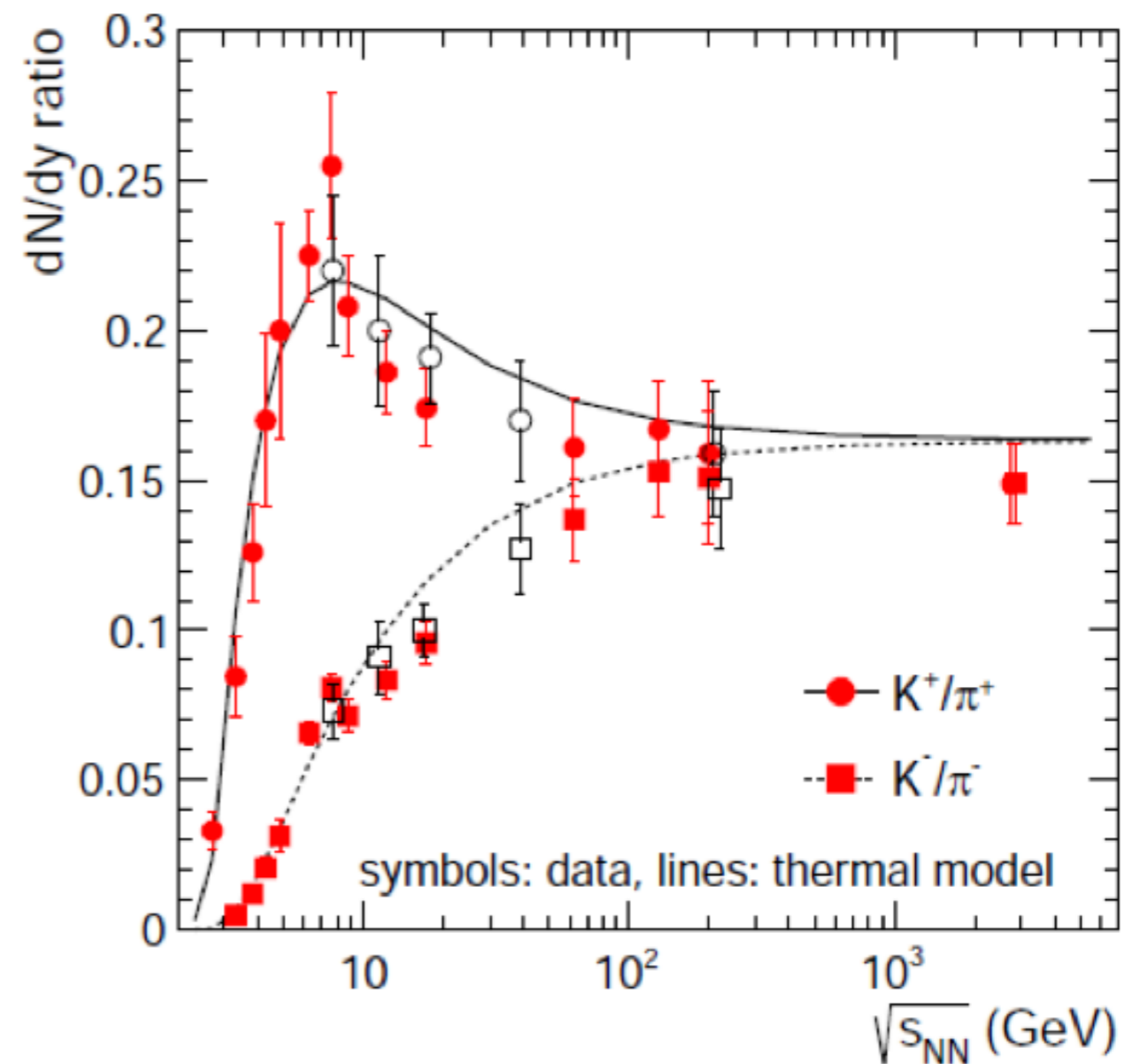
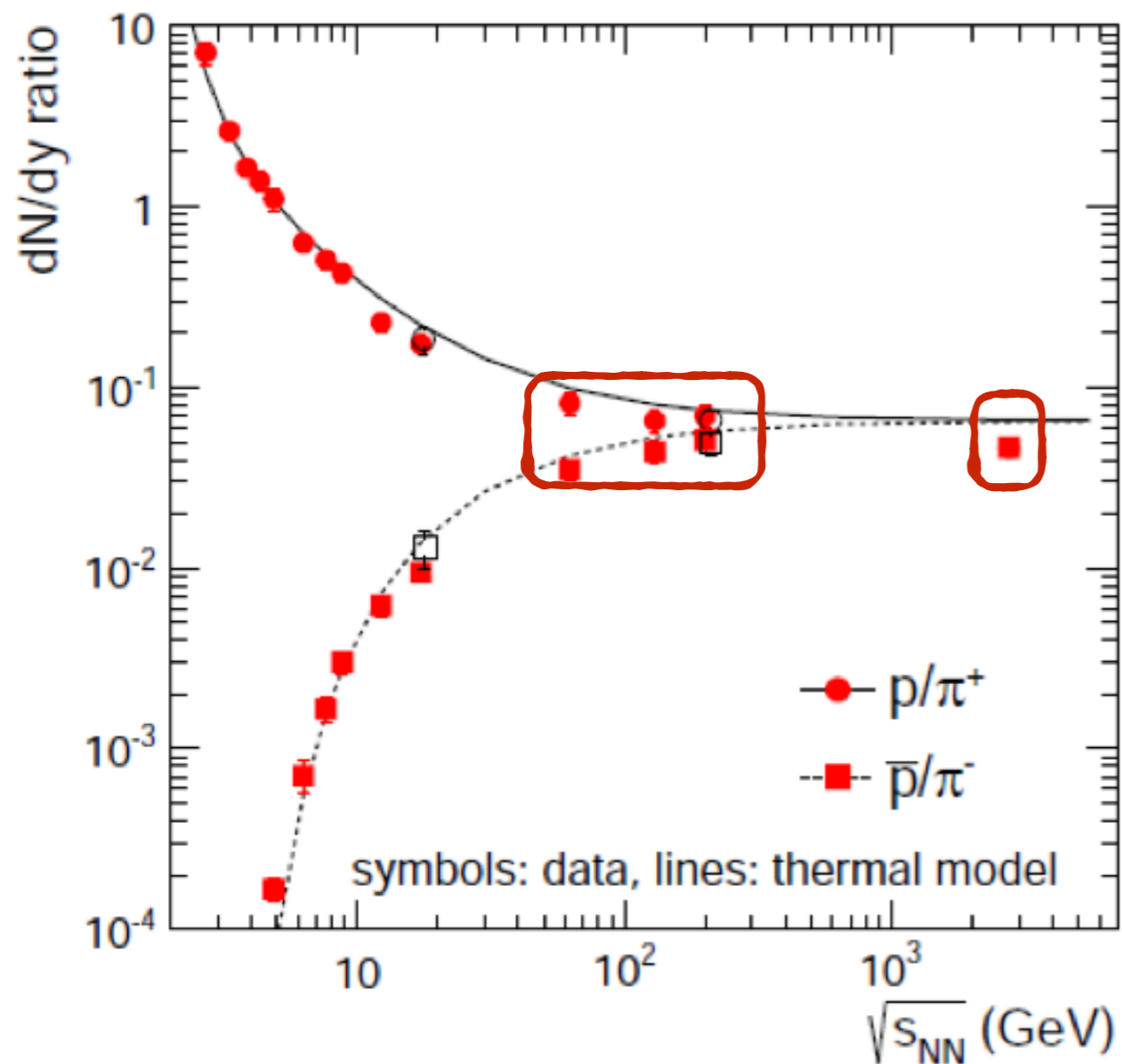
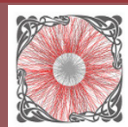


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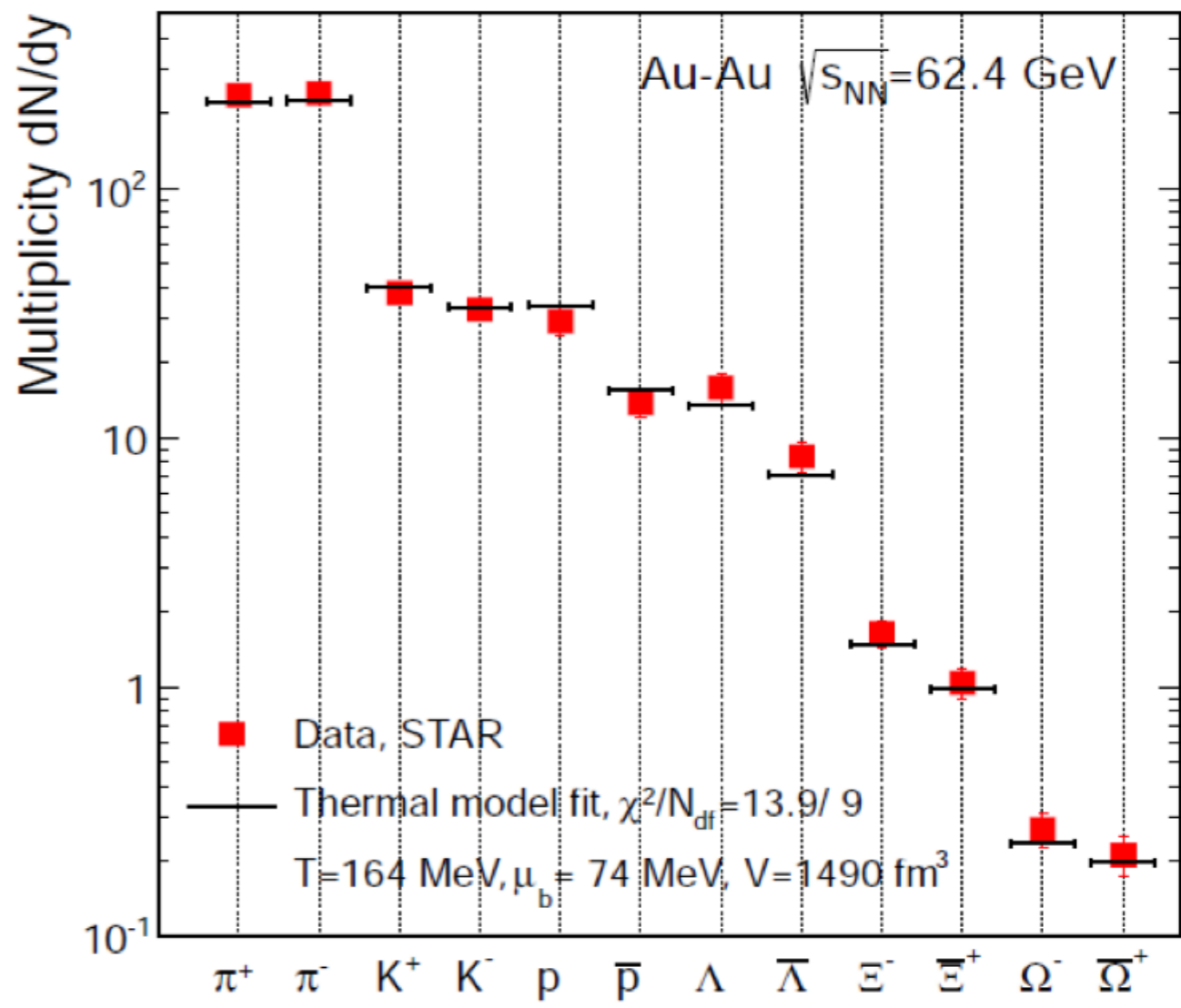
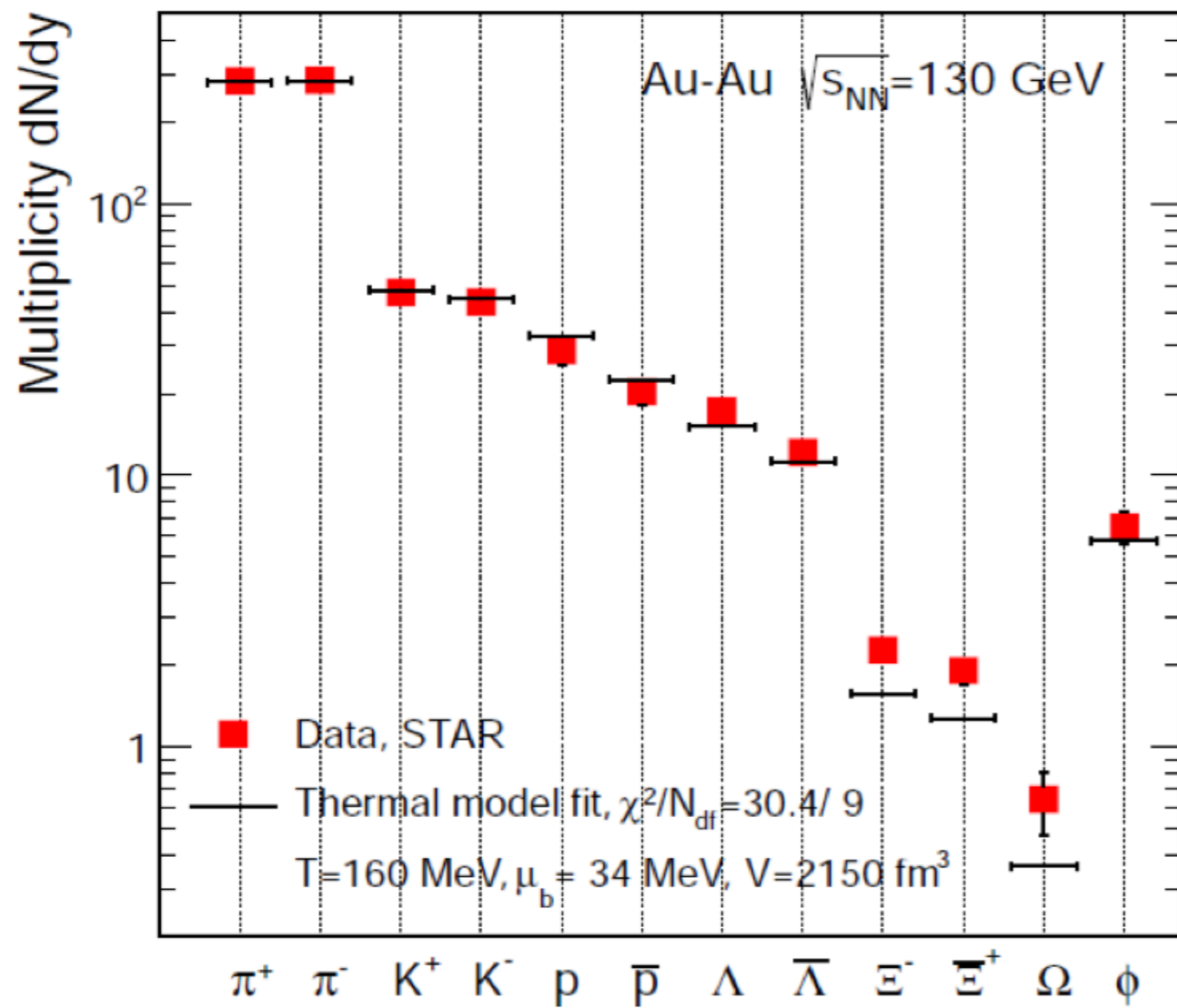
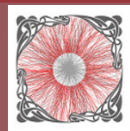
Petran et al, arXiv:1310.5108  
 Wheaton et al,  
 Comput.Phys.Commun, 180 84  
 Andronic et al, PLB 673 142

# Re-establishing the baseline: RHIC and SPS

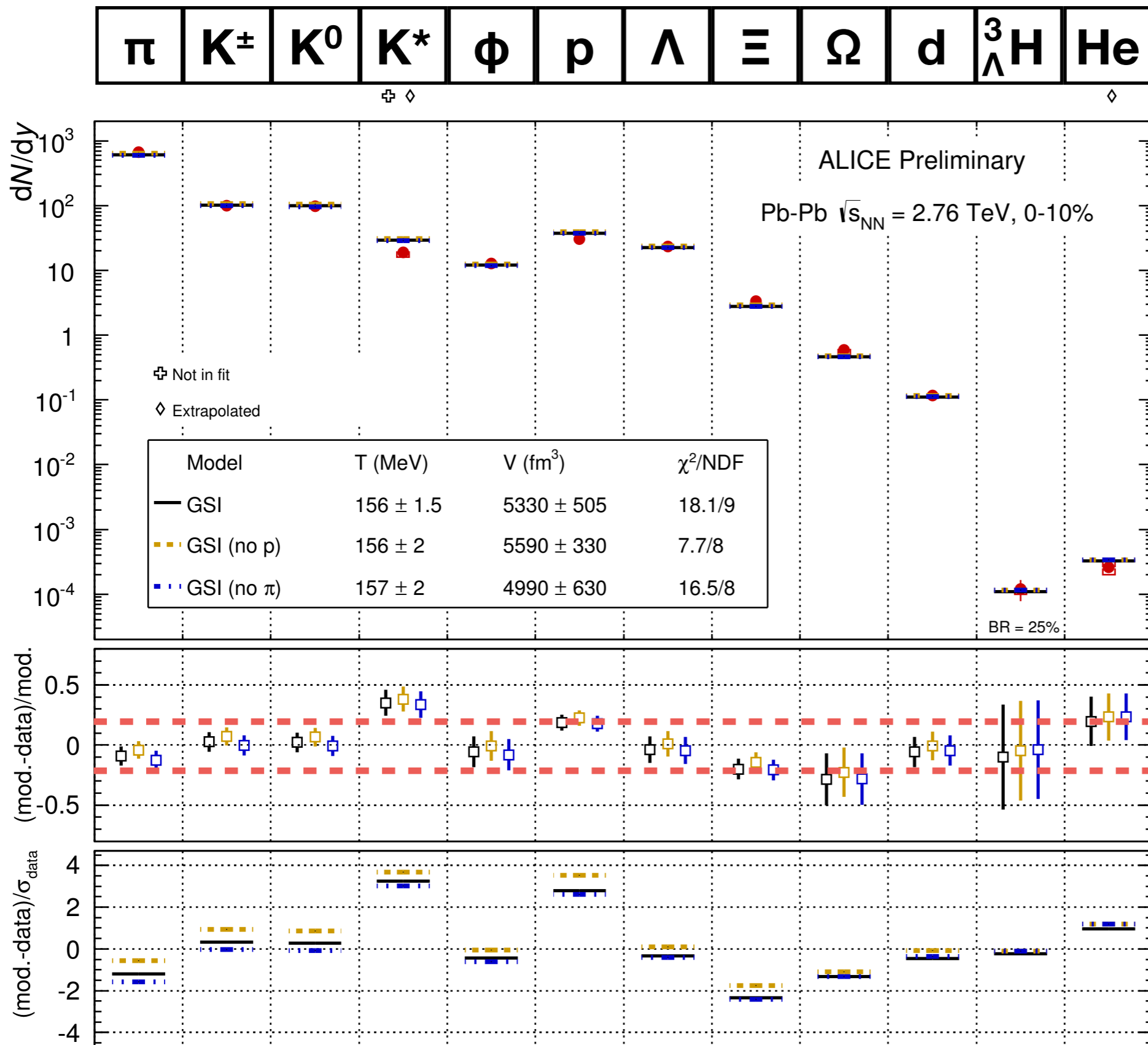
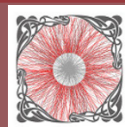




# Re-establishing the baseline: RHIC and SPS



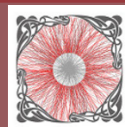
# Excluding protons or pions (GSI)



**No  $\pi$**   
Fit quality does not improve  
(no evidence for pion condensate, as opposed to n.eq. model)

**No p**  
Better fit, proton anomaly?

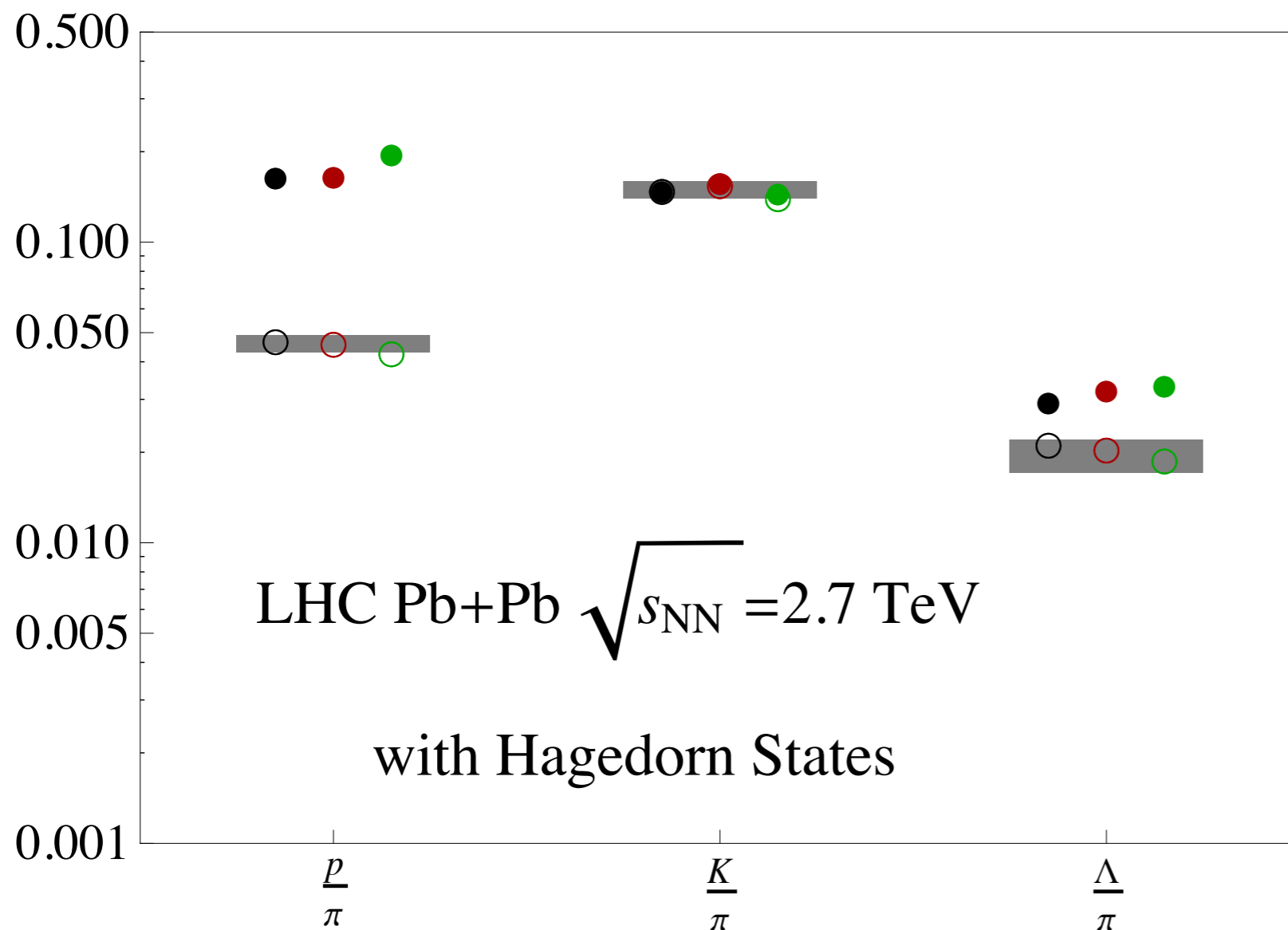
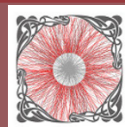
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**No  $\pi$**   
 Fit quality does not improve  
 (no evidence for pion condensate, as opposed to n.eq. model)

**No p**  
 Better fit, proton anomaly?

# Incomplete hadron spectrum



**Lines:** ALICE data  
**Points:** Model based on Hagedorn states

HS descriptions

$$N_x^{\tau=0} = E q. \quad \rho_1 \quad \rho_2 \quad \rho_3$$

$$N_x^{\tau=0} = 0 \quad \circ \quad \circ \quad \circ$$

Using assumptions on Hagedorn states,  $p/\pi$  reproduced

See also:

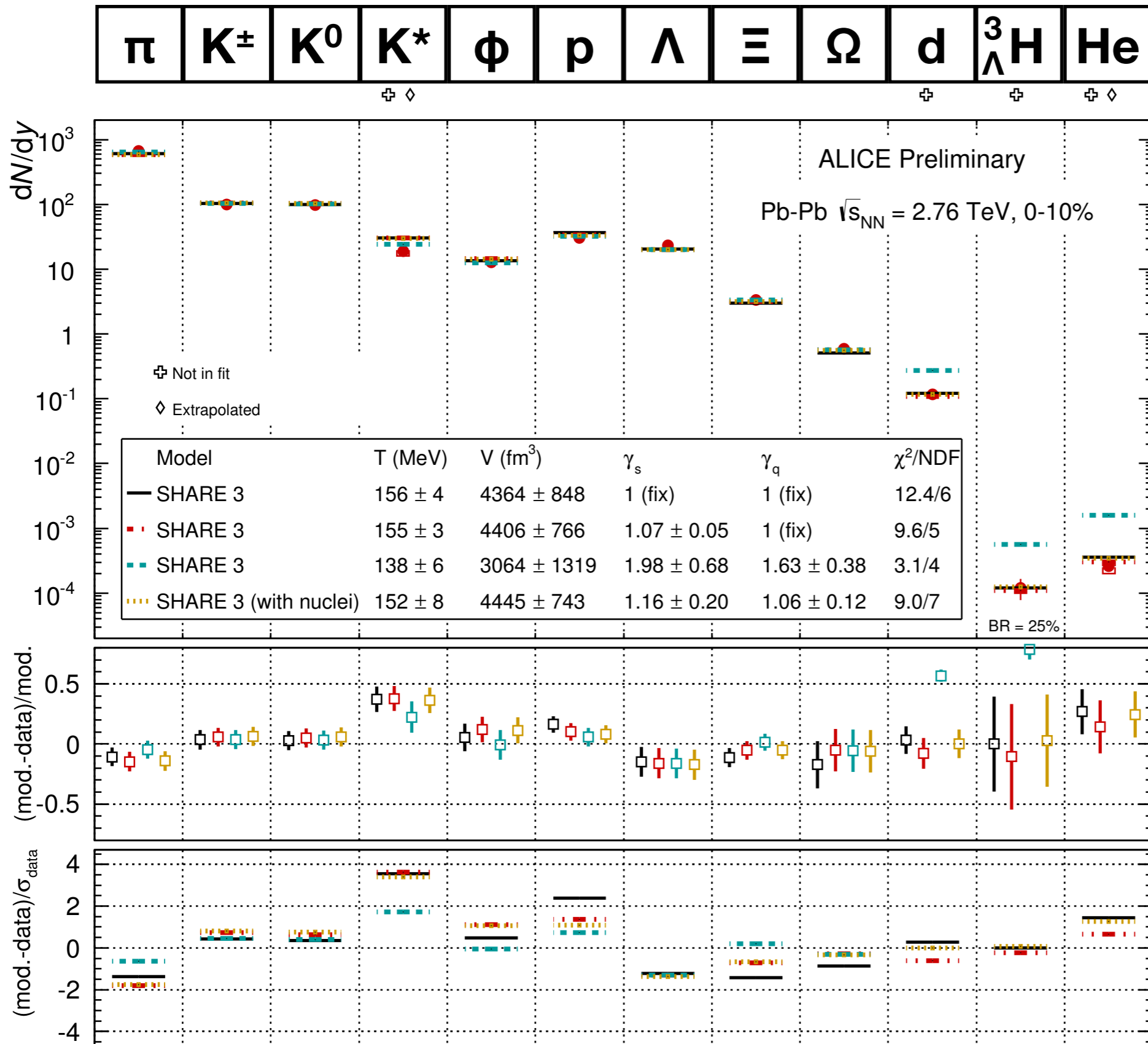
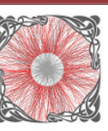
**C. Schmidt, Wed 21** (Baryonic strange states)

**J. Noronha-Hostler, Wed 21**

J. Stachel et al, SQM13

J. Noronha-Hostler, arXiv:0906.3960 (RHIC)

# Non equilibrium SHM: Fits

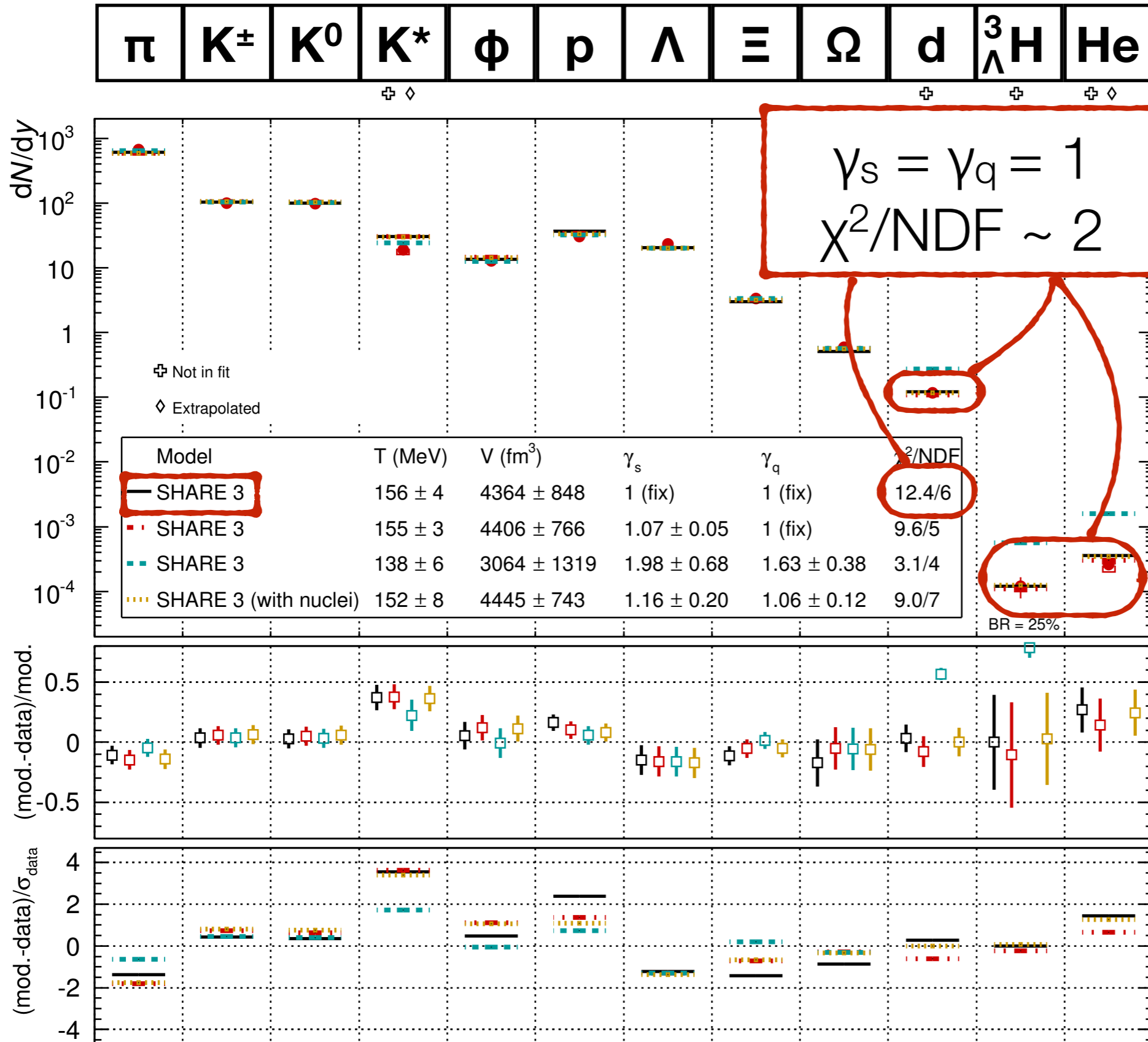
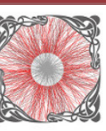


Very good if not including nuclei (similar to Refs)

Nuclei prediction off by factor  $\sim 5$   
Try to include nuclei in fit  $\gamma_q \rightarrow 1$

Petran et al PRC 88 021901  
Petran et al, arXiv:1303.2098  
Petran et al, arXiv:1310.2551  
Petran et al, J. Phys. G 509 012018

# Non equilibrium SHM: Fits



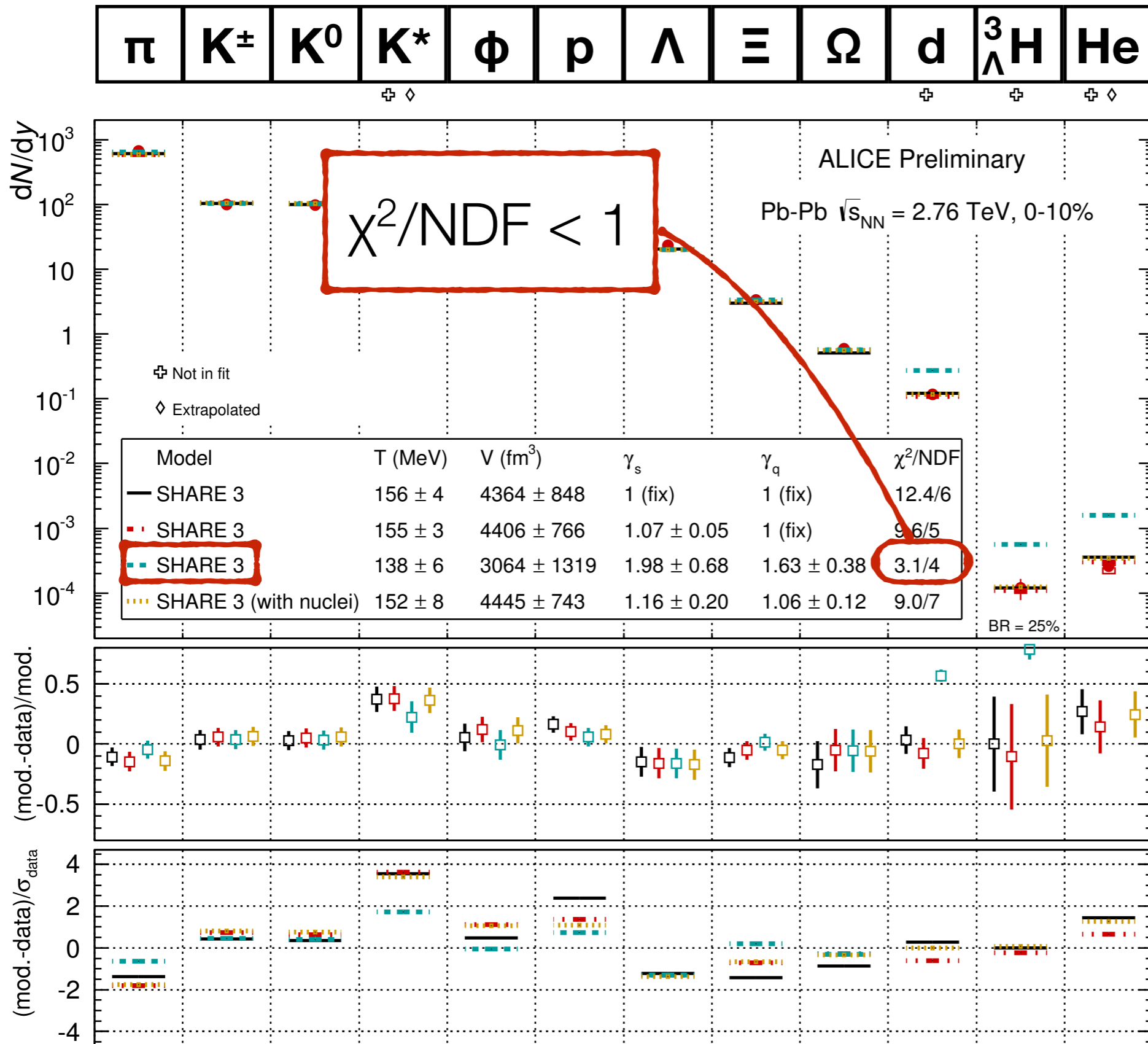
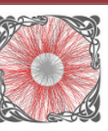
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Nuclei prediction off by factor ~ 5  
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Petran et al PRC 88 021901  
 Petran et al, arXiv:1303.2098  
 Petran et al, arXiv:1310.2551

Petran et al, J. Phys. G 509 012018

# Non equilibrium SHM: Fits

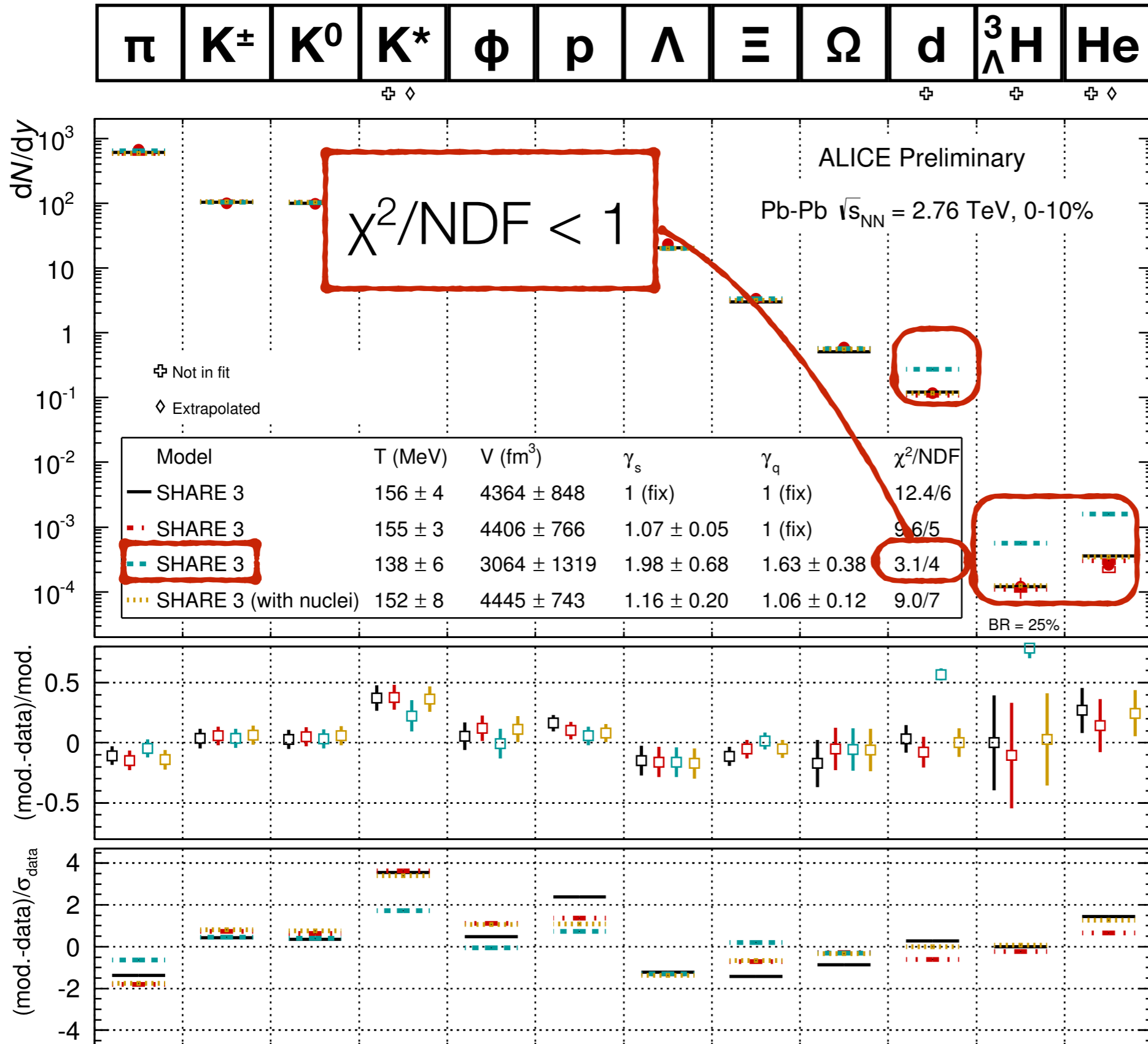
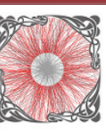


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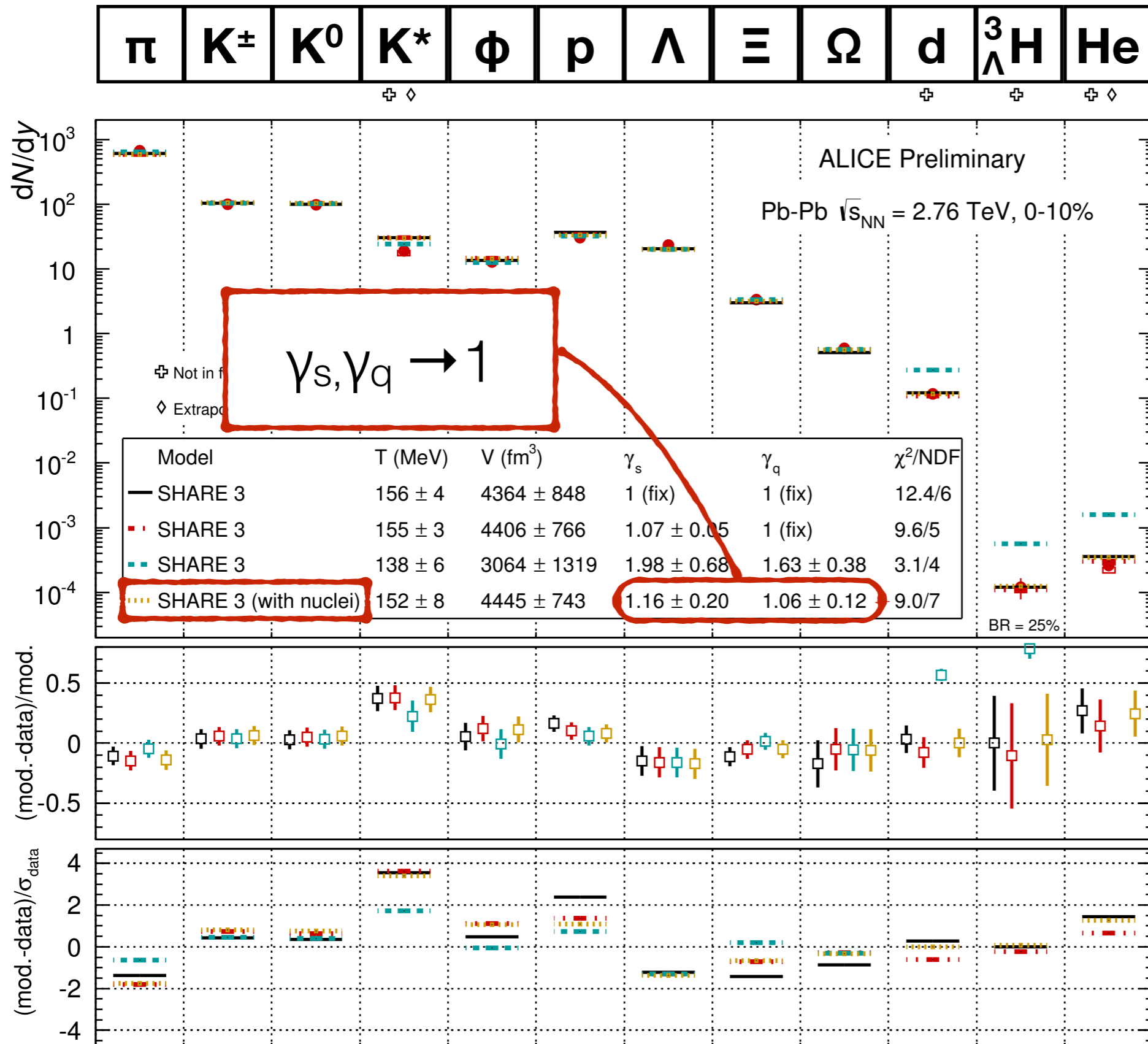
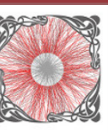
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Petran et al, J. Phys. G 509 012018



# Non equilibrium SHM: Fits

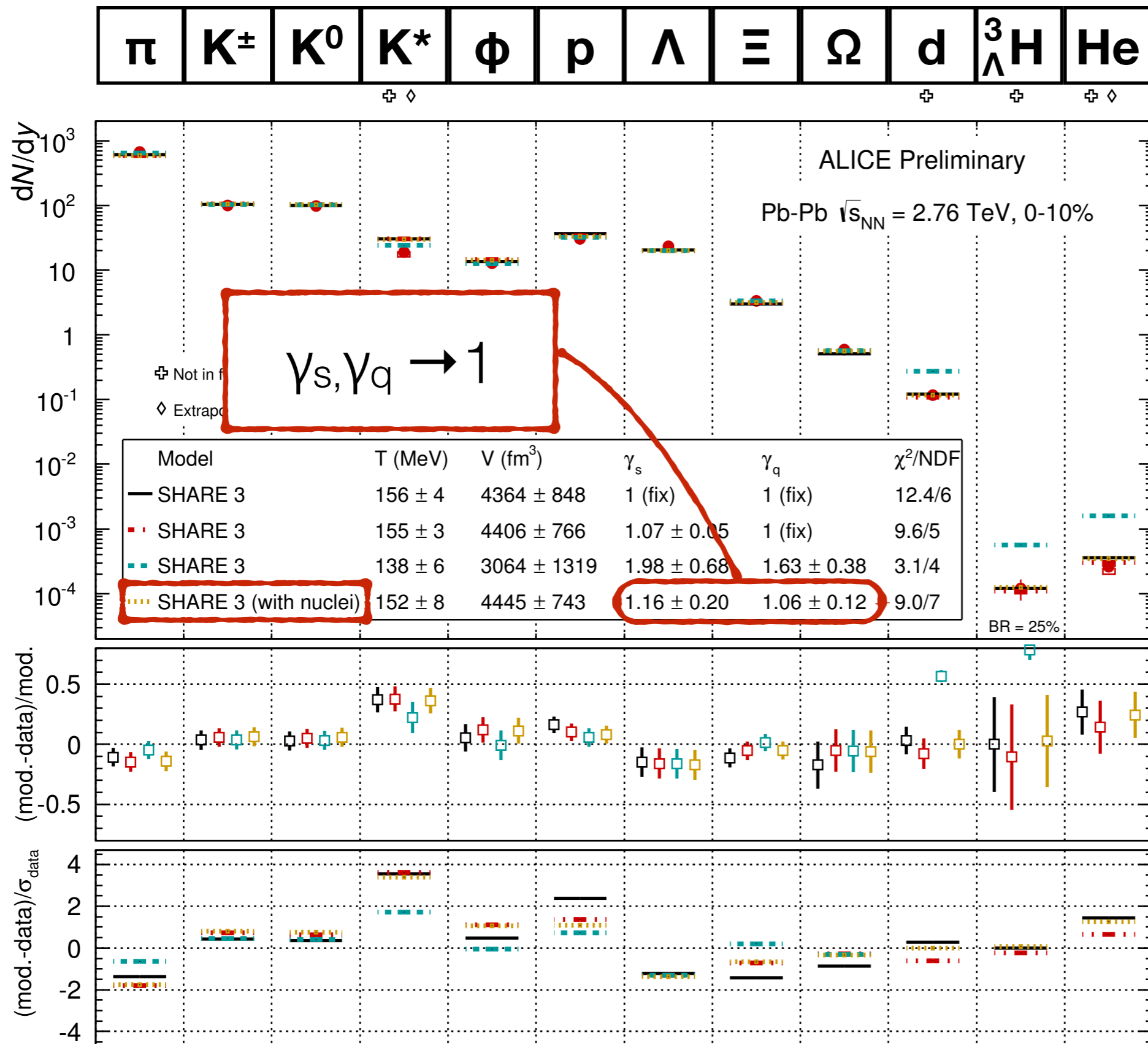
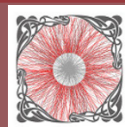


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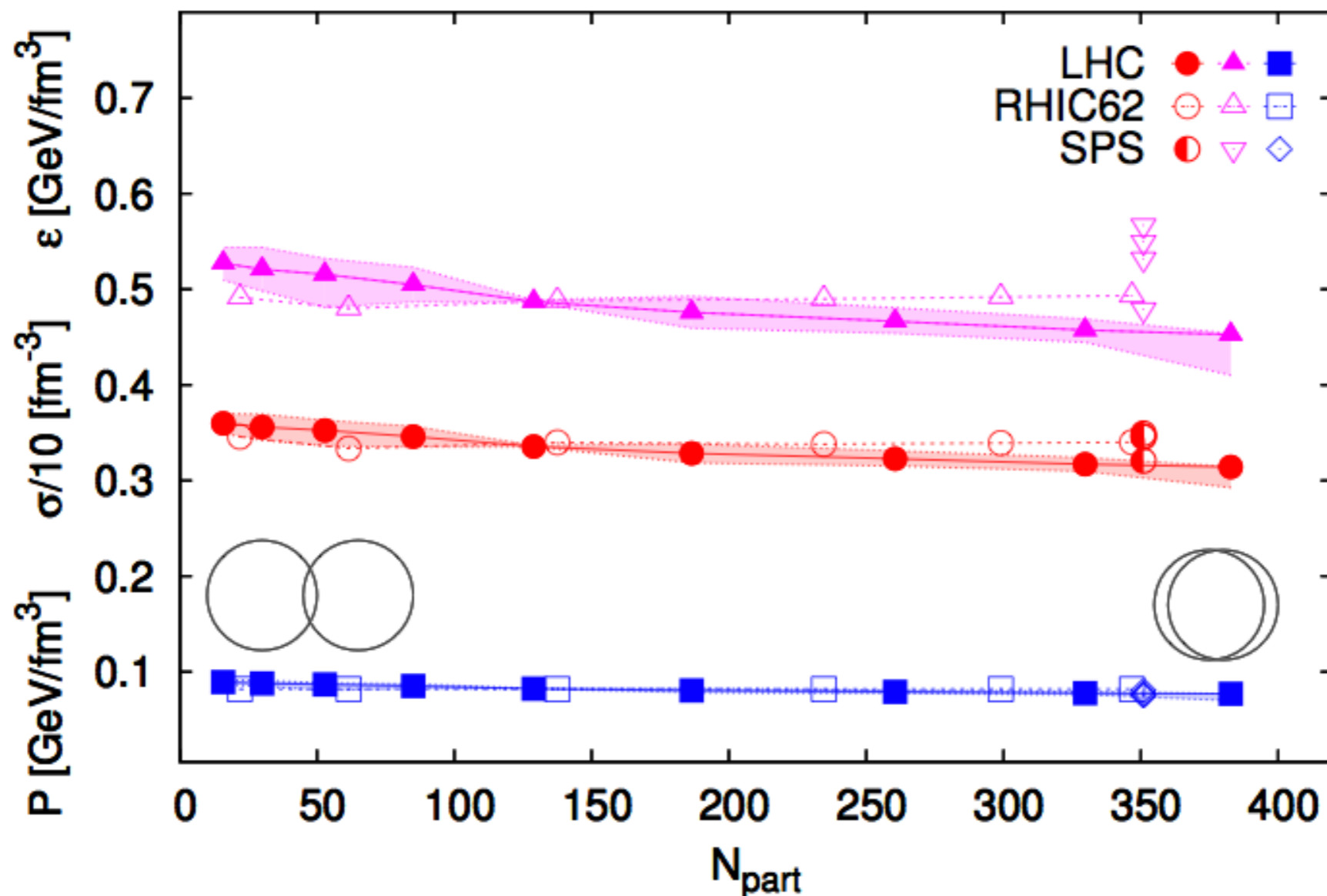
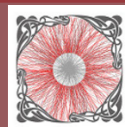
Nuclei prediction off by factor ~ 5  
 Try to include nuclei in fit  $\gamma_q \rightarrow 1$

Nuclei  $v_2$  in AuAu:

**R. Haque, STAR, Mon 19**

Petran et al PRC 88 021901  
 Petran et al, arXiv:1303.2098  
 Petran et al, arXiv:1310.2551  
 Petran et al, J. Phys. G 509 012018

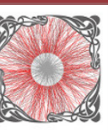
# Non equilibrium fits vs $\sqrt{s}$ and system size



**Uniformity** of fireball freeze-out parameters across energy and centrality

Strangeness/entropy smaller than at RHIC?

Rafelski, HIF CERN, March 20, 2014  
Rafelski et al, A. Phys.Pol. B. Supp 7 35



## Late freeze-out for protons?

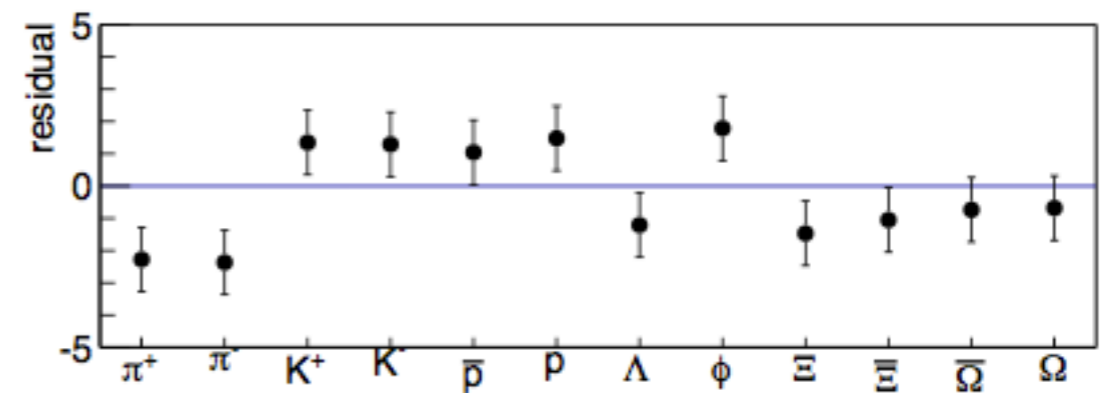
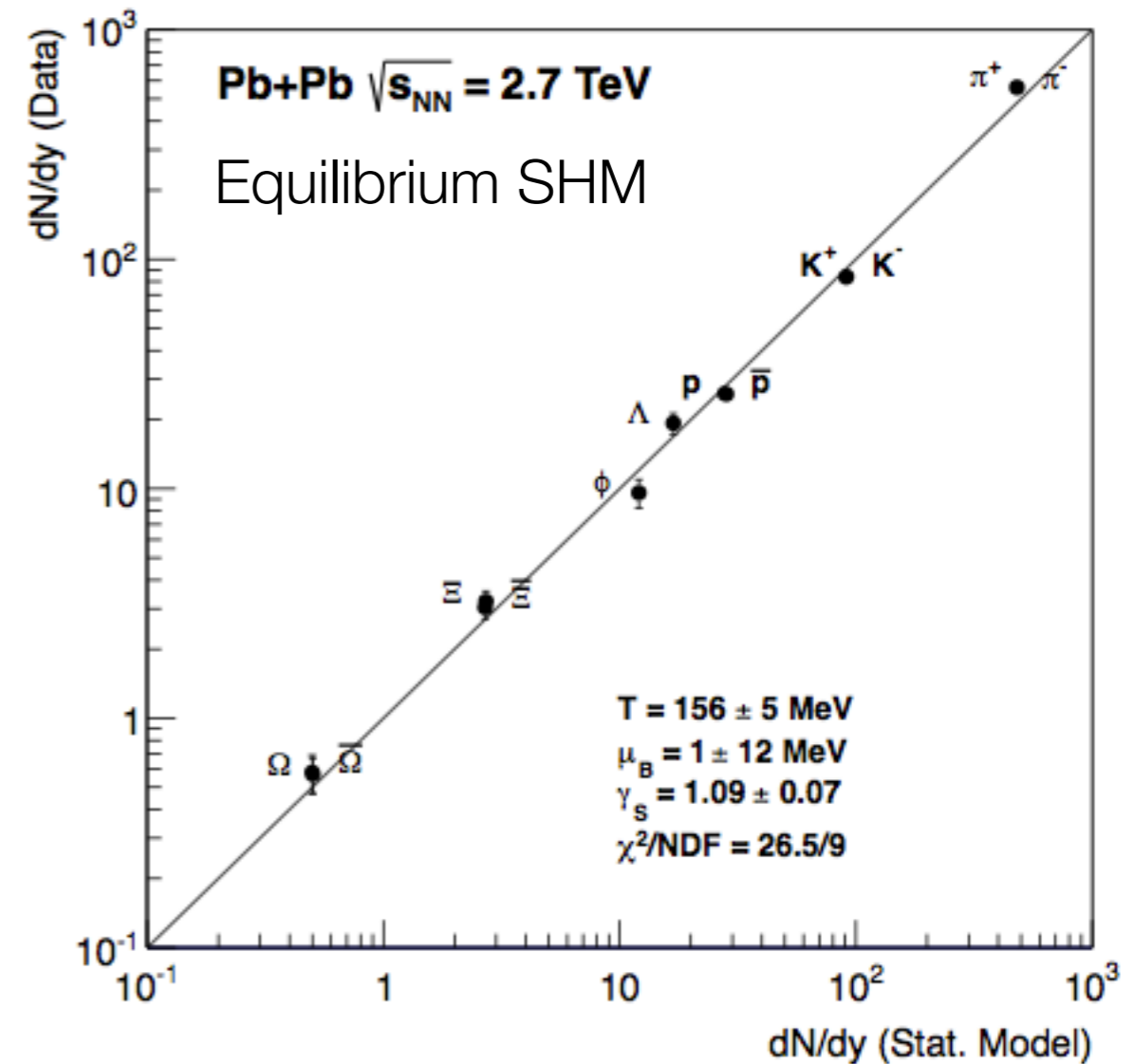
Baryon annihilation  $\searrow$  p yield

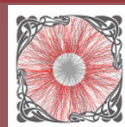
Unmeasured cross sections?

Inverse reactions

$(n\pi \rightarrow p\bar{p}, \text{ heavy meson} \rightarrow p\bar{p})?$

Centrality dependence?





## Late freeze-out for protons?

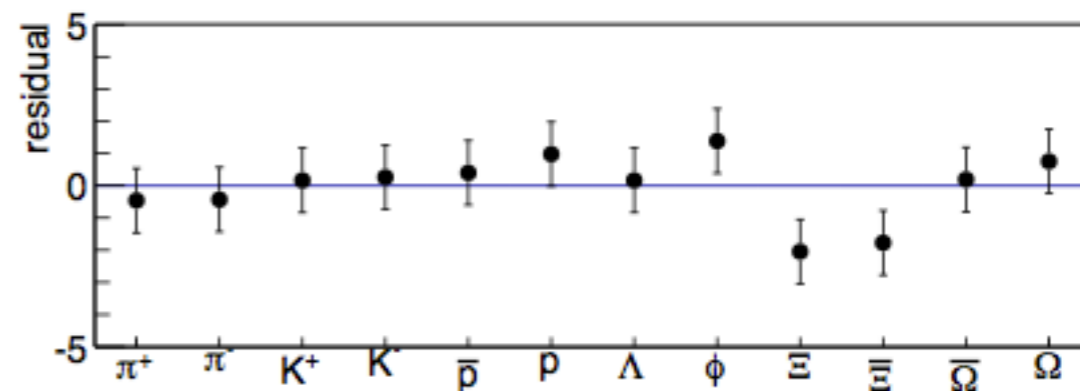
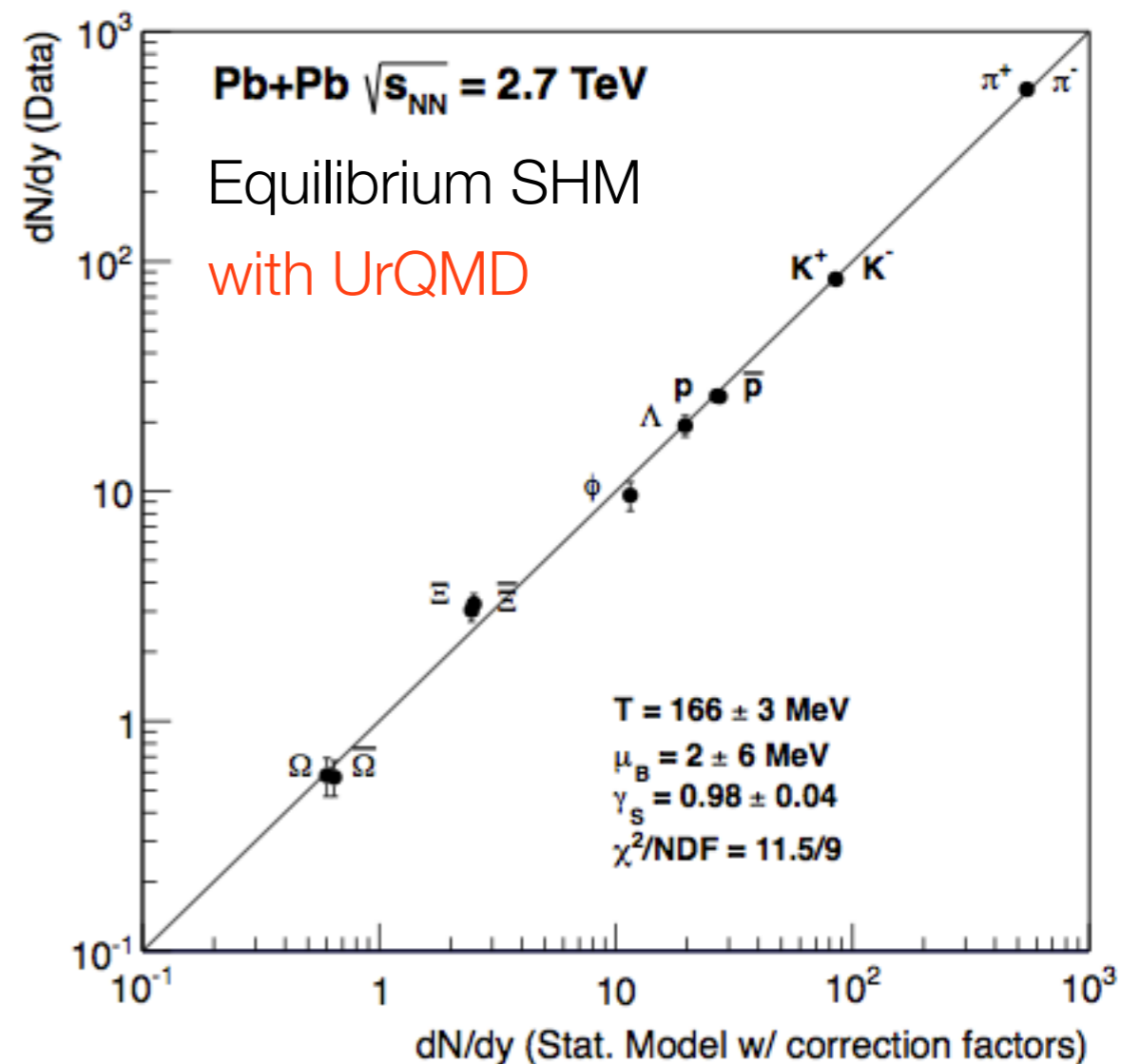
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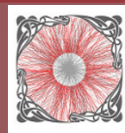
Inverse reactions

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Centrality dependence?



# Hadronic phase



## Late freeze-out for protons?

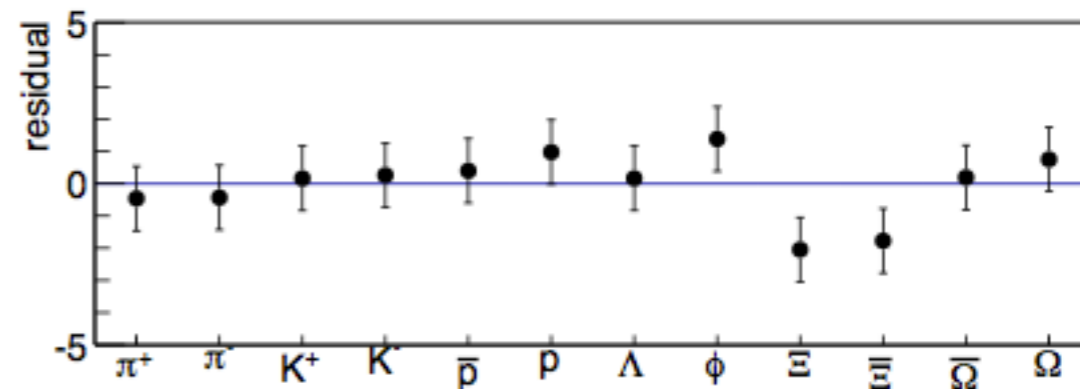
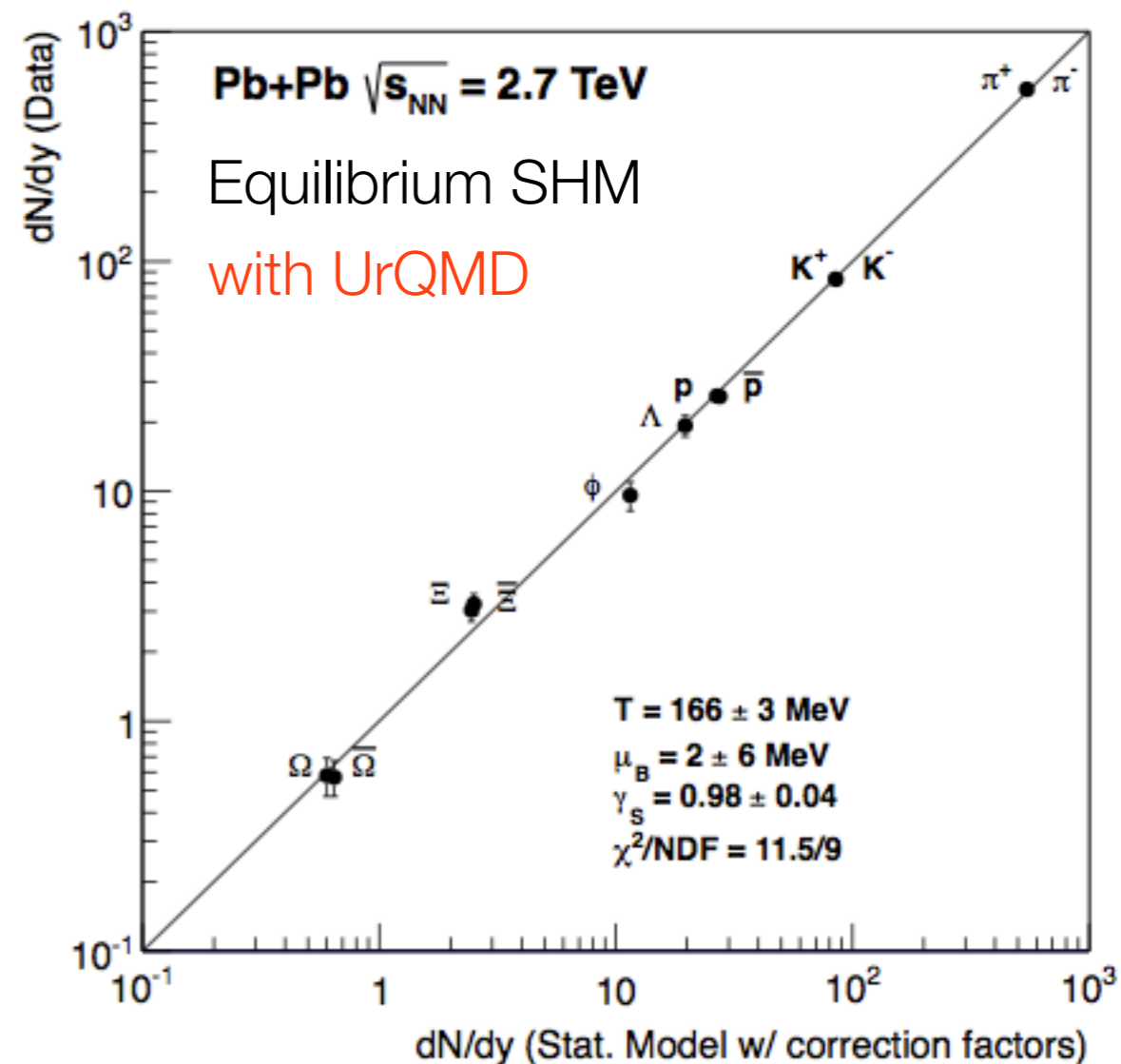
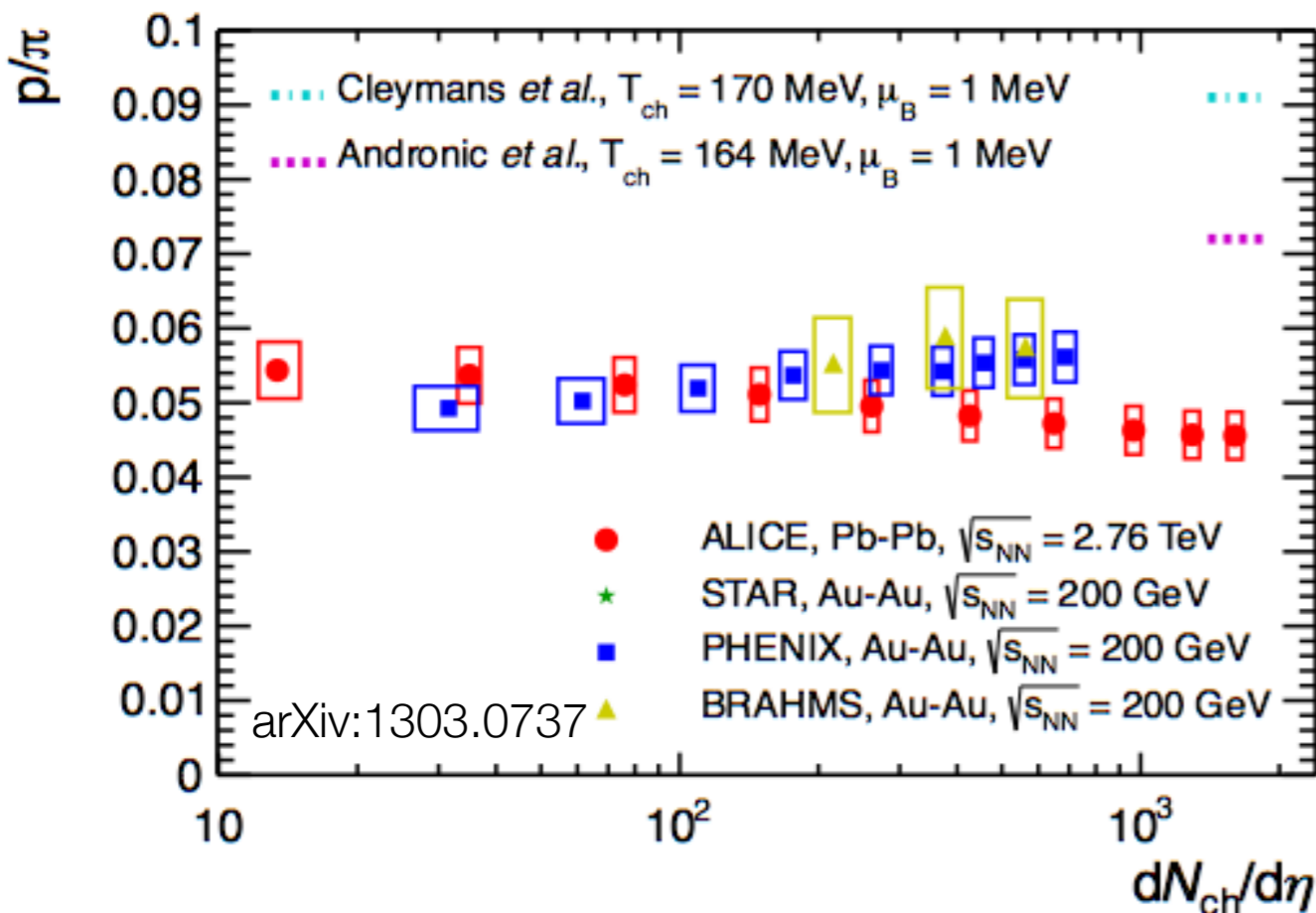
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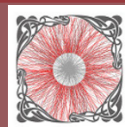
Inverse reactions

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Centrality dependence?



# Hadronic phase



## Late freeze-out for protons?

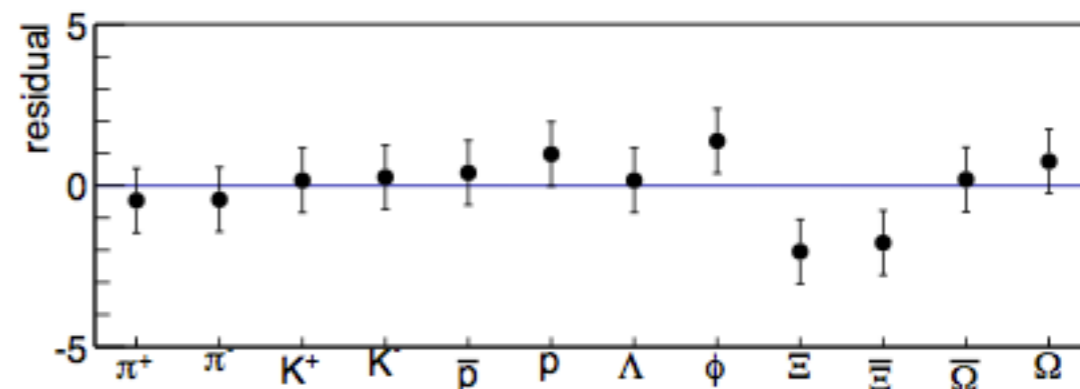
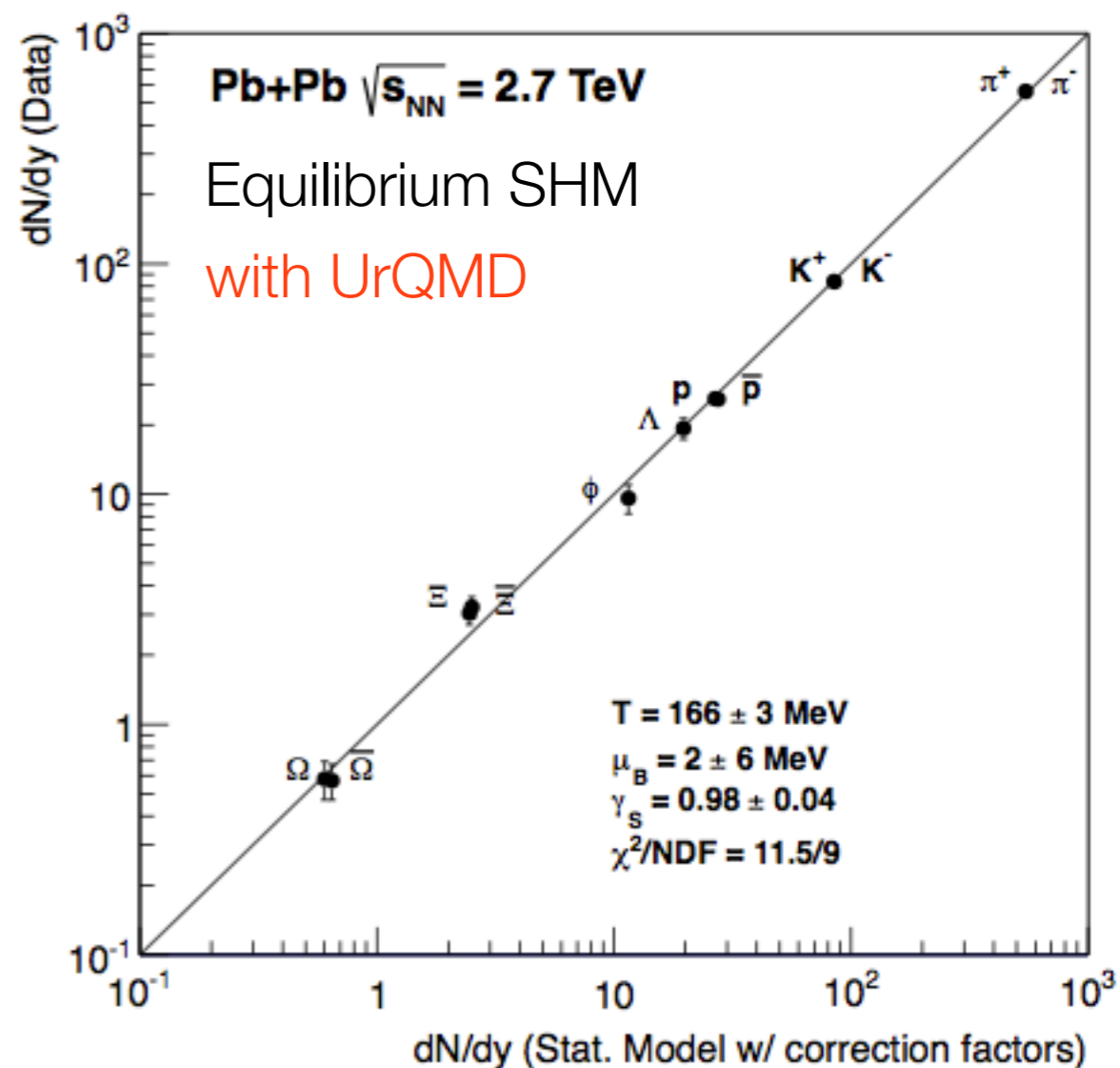
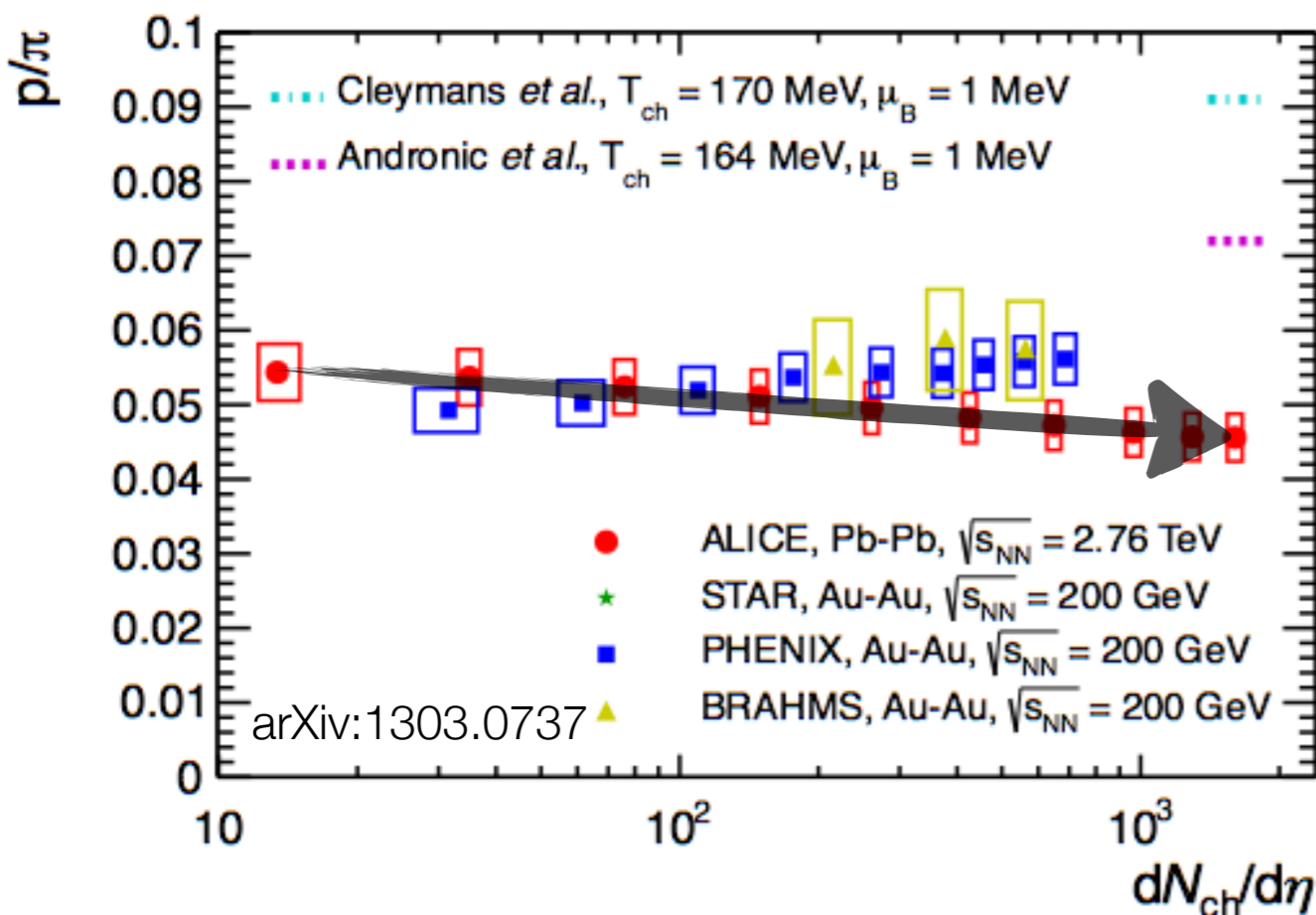
Baryon annihilation  $\searrow$  p yield

Unmeasured cross sections?

Inverse reactions

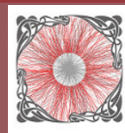
( $n\pi \rightarrow p\bar{p}$ , heavy meson  $\rightarrow p\bar{p}$ )?

Centrality dependence?



Becattini et al, arXiv:1212.2431

# Hadronic phase



## Late freeze-out for protons?

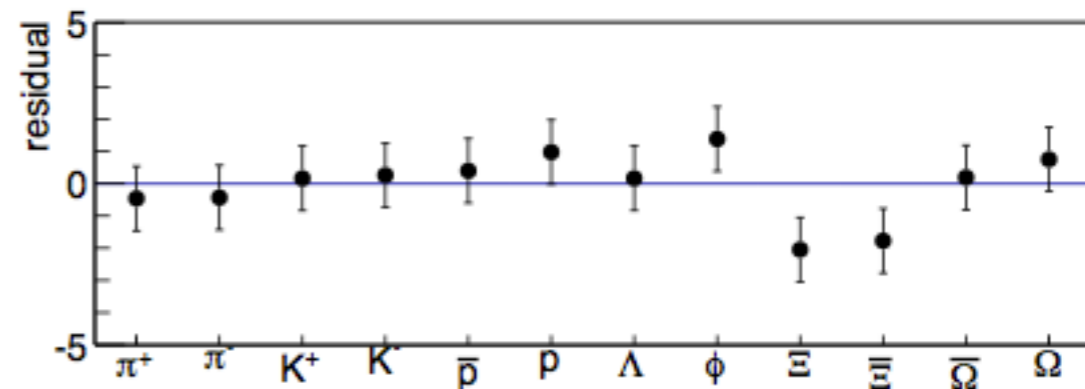
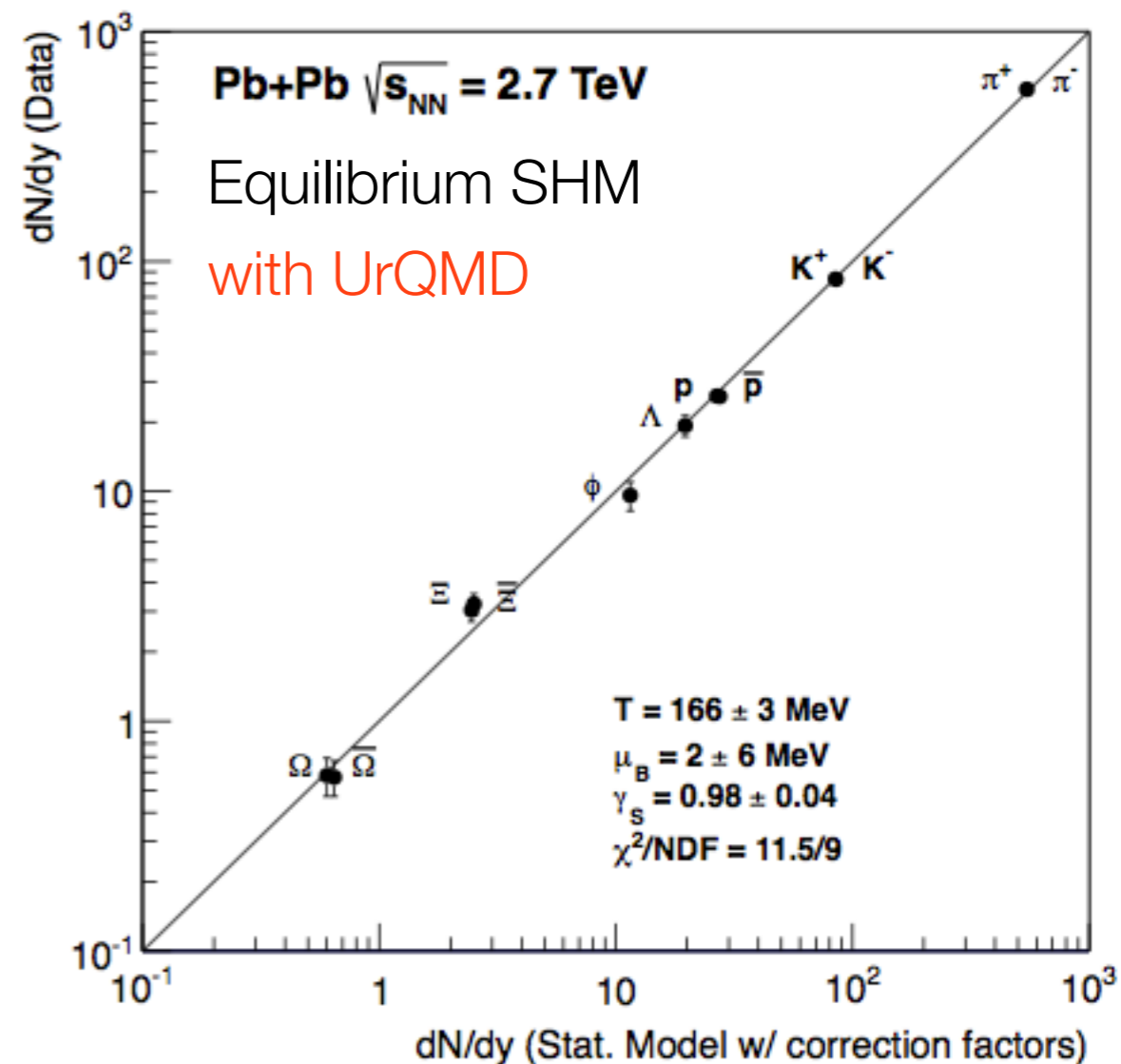
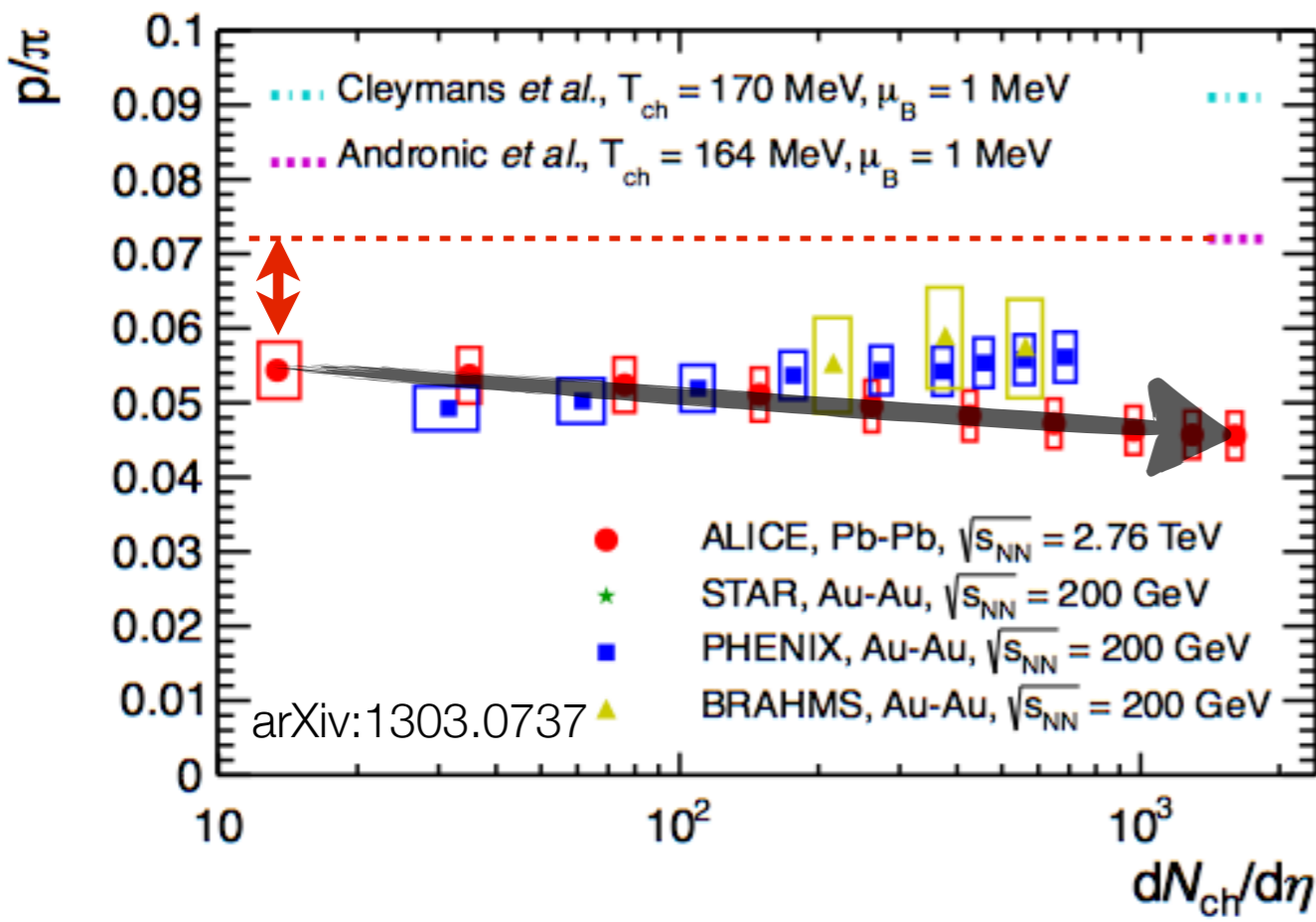
Baryon annihilation  $\searrow$  p yield

Unmeasured cross sections?

Inverse reactions

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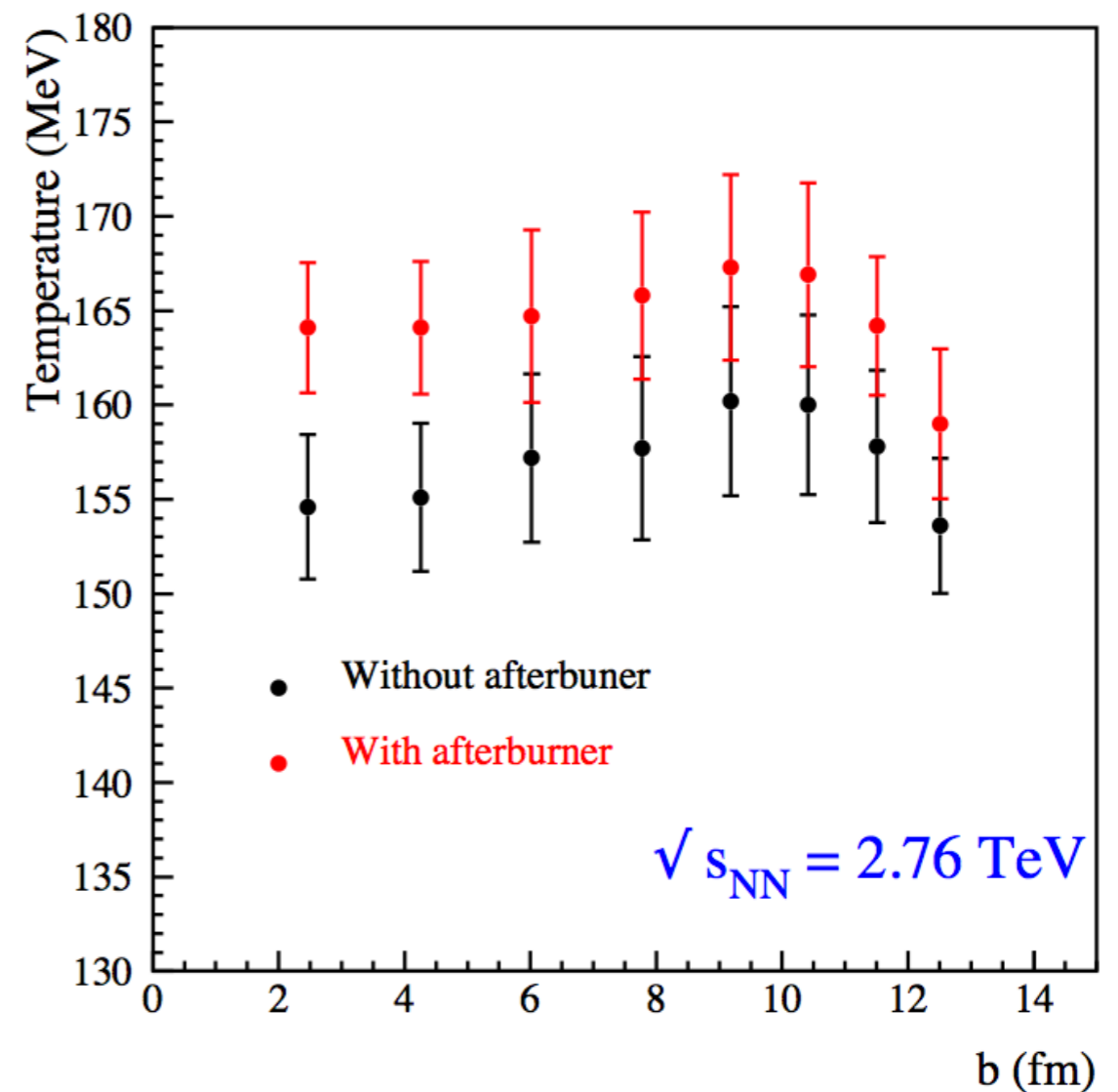
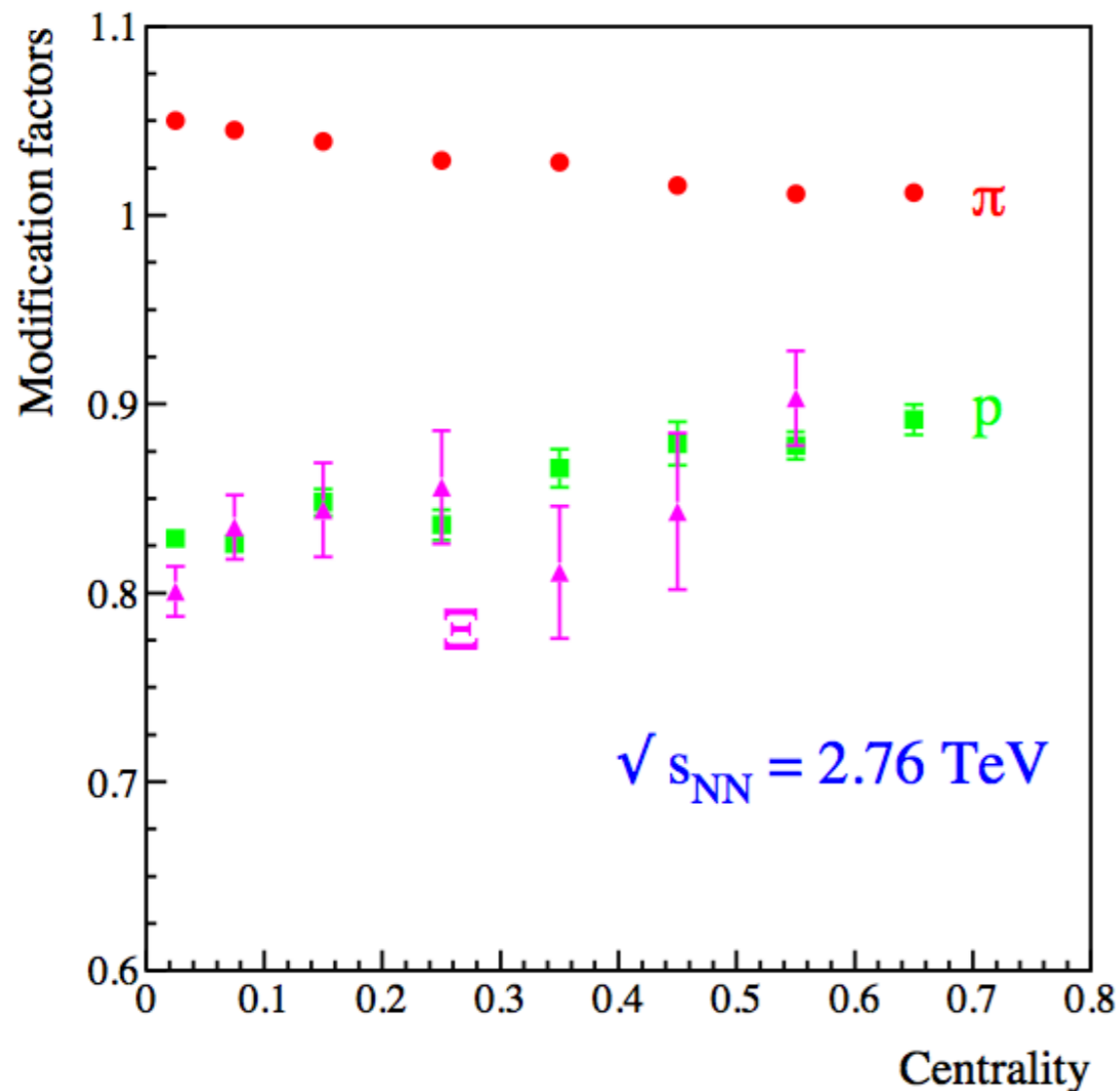
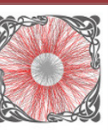
Centrality dependence?



Becattini et al, arXiv:1212.2431

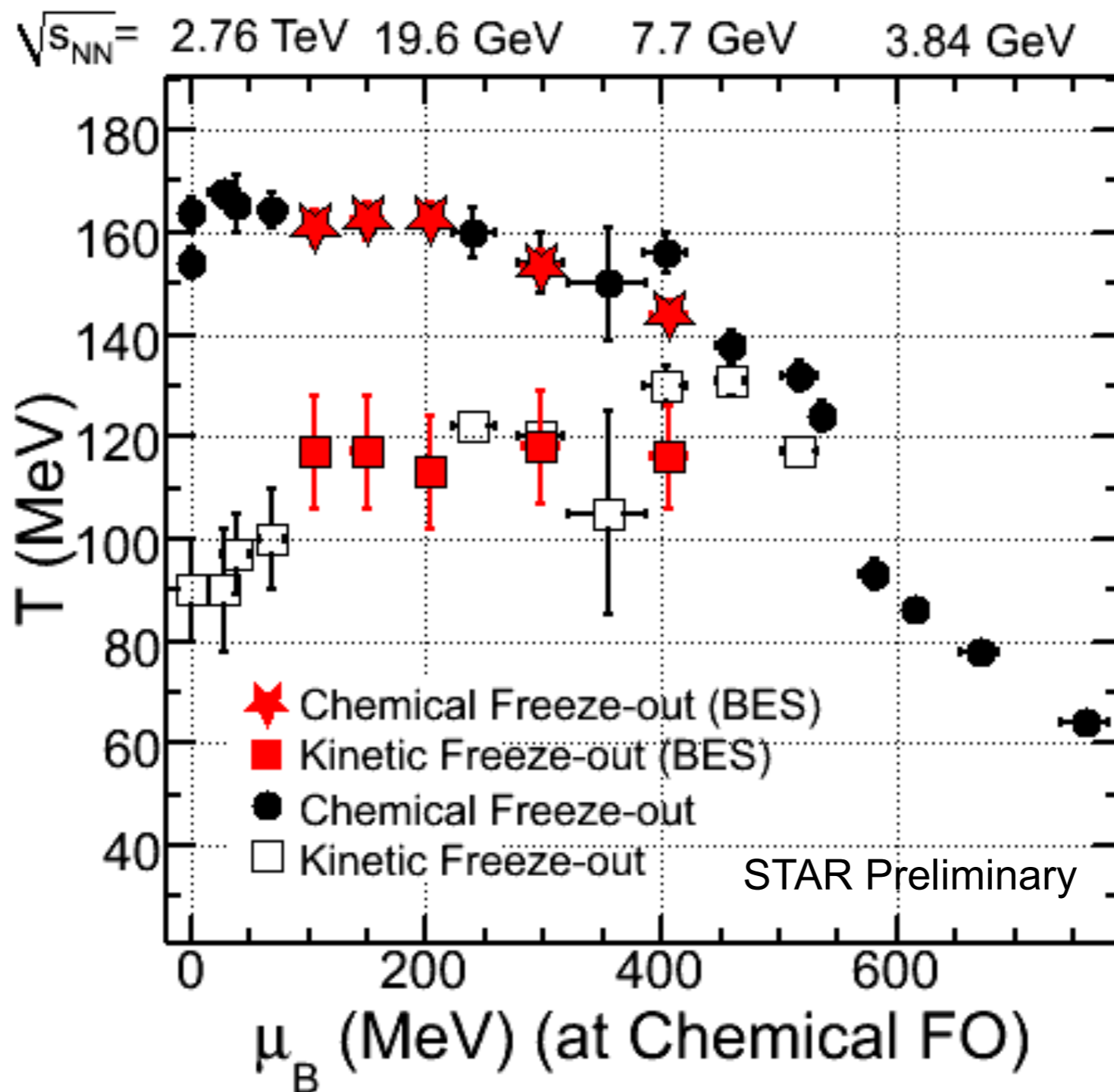
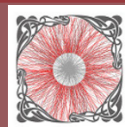


# Centrality dependence calculation



Correction factors now computed for **all centrality bins**  
**Back-reaction neglected**, effect estimated to be small  
(but no rigorous estimate yet)

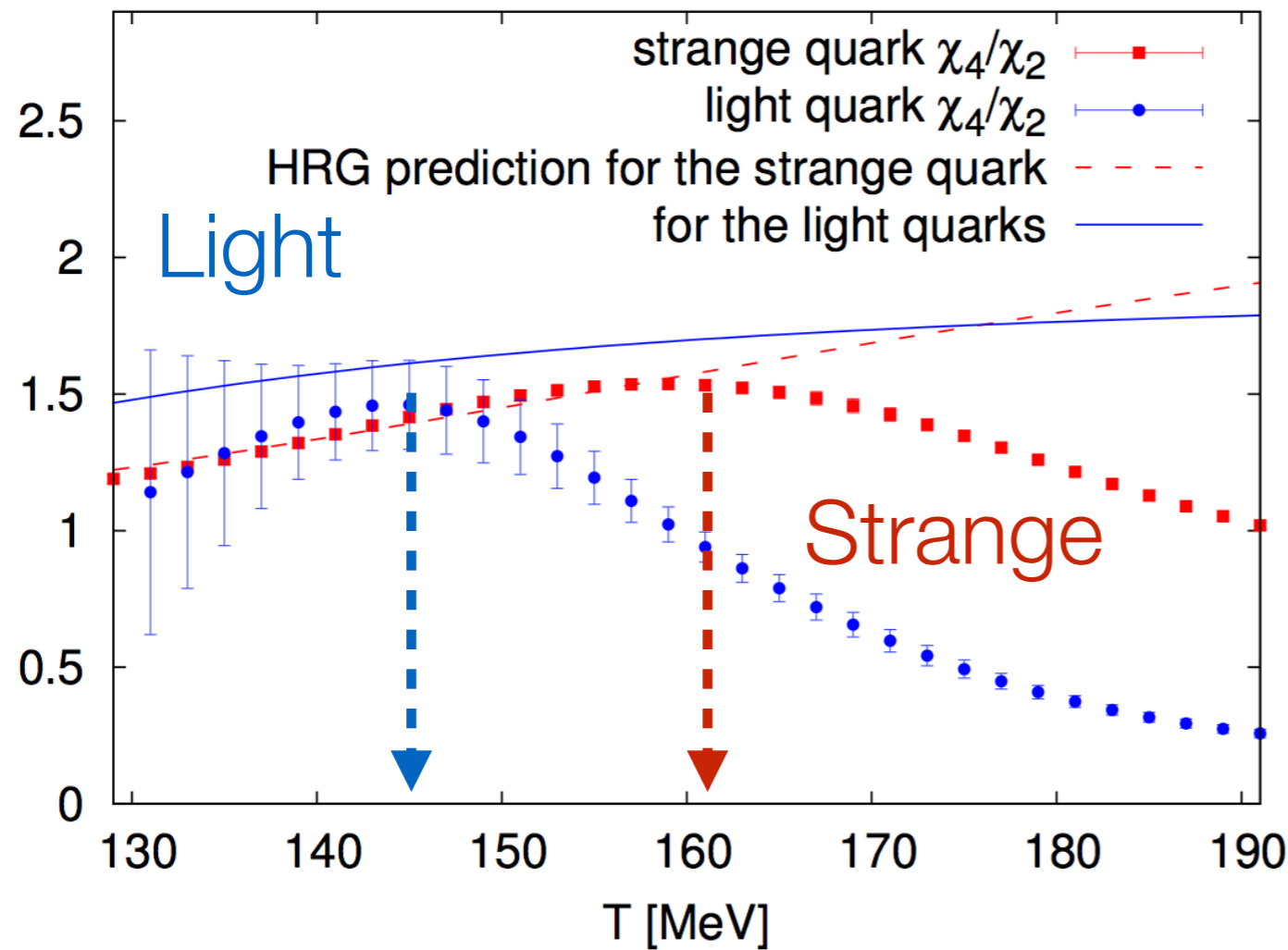
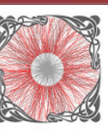
# $T_{\text{kin}}$ VS $T_{\text{ch}}$ VS $\sqrt{s}$ (STAR BES)



$T_{\text{kin}} - T_{\text{ch}}$  grows for  $\mu_B \rightarrow 0$

Importance of hadronic phase?

L. Kumar, STAR, Wed 21



Lattice: indication of a **flavor hierarchy** at freeze-out?

Pre-hadronic bound states: strangeness above  $T_c$ ?

## Connection to experiment:

higher order moments of net charges?

(related to susceptibilities ratios of conserved charges)

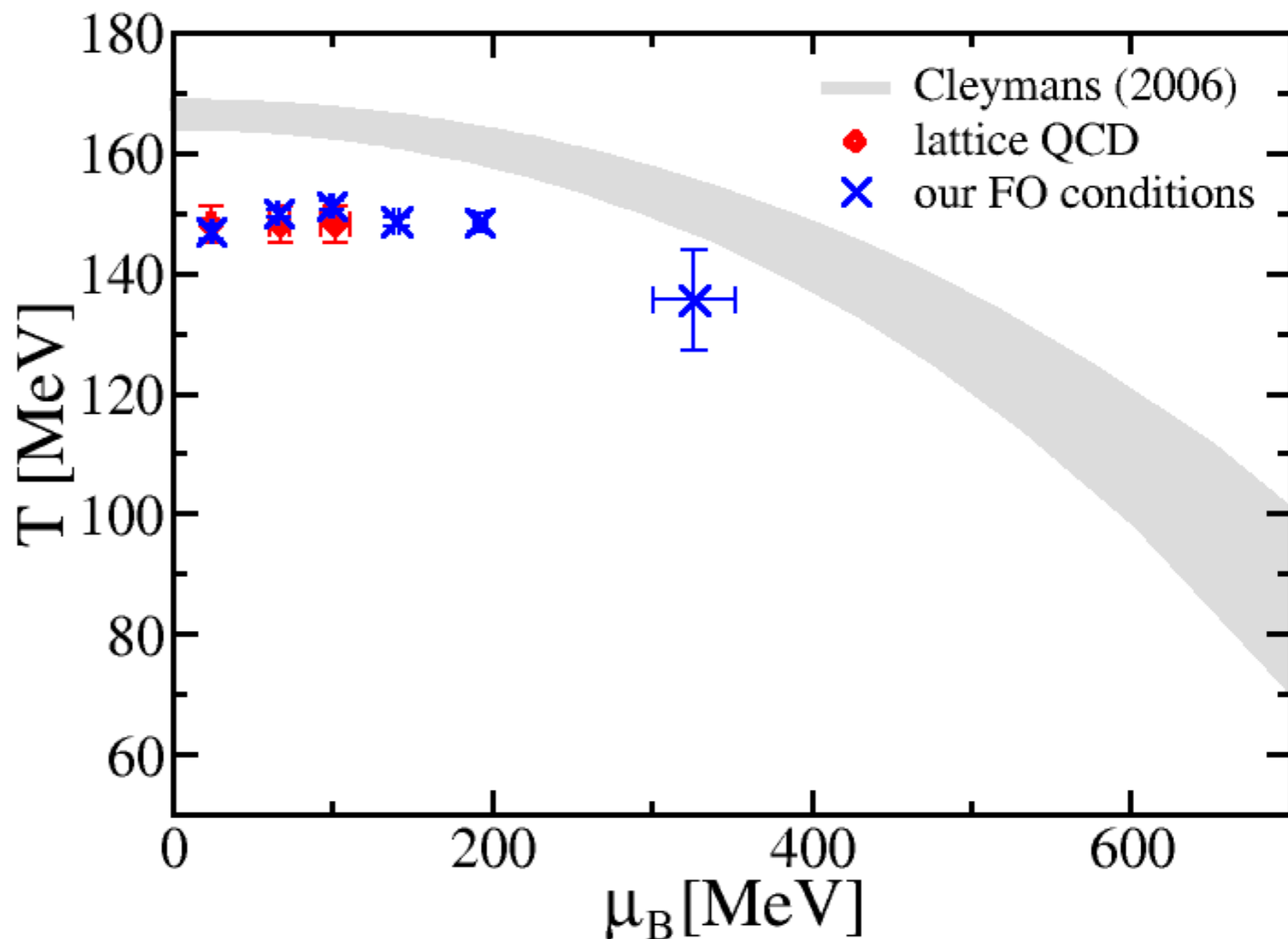
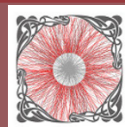
**Caveats:** needs strange baryons, limited phase space, baryons vs protons ...

Bellwied et al, PRL 111 202302

Ratti et al PRD85 014004

F. Karsh, Cent. Eur. J. Phys., 10 1234

# Higher moments: HRG and STAR



**M. Bluhm, Wed 21**

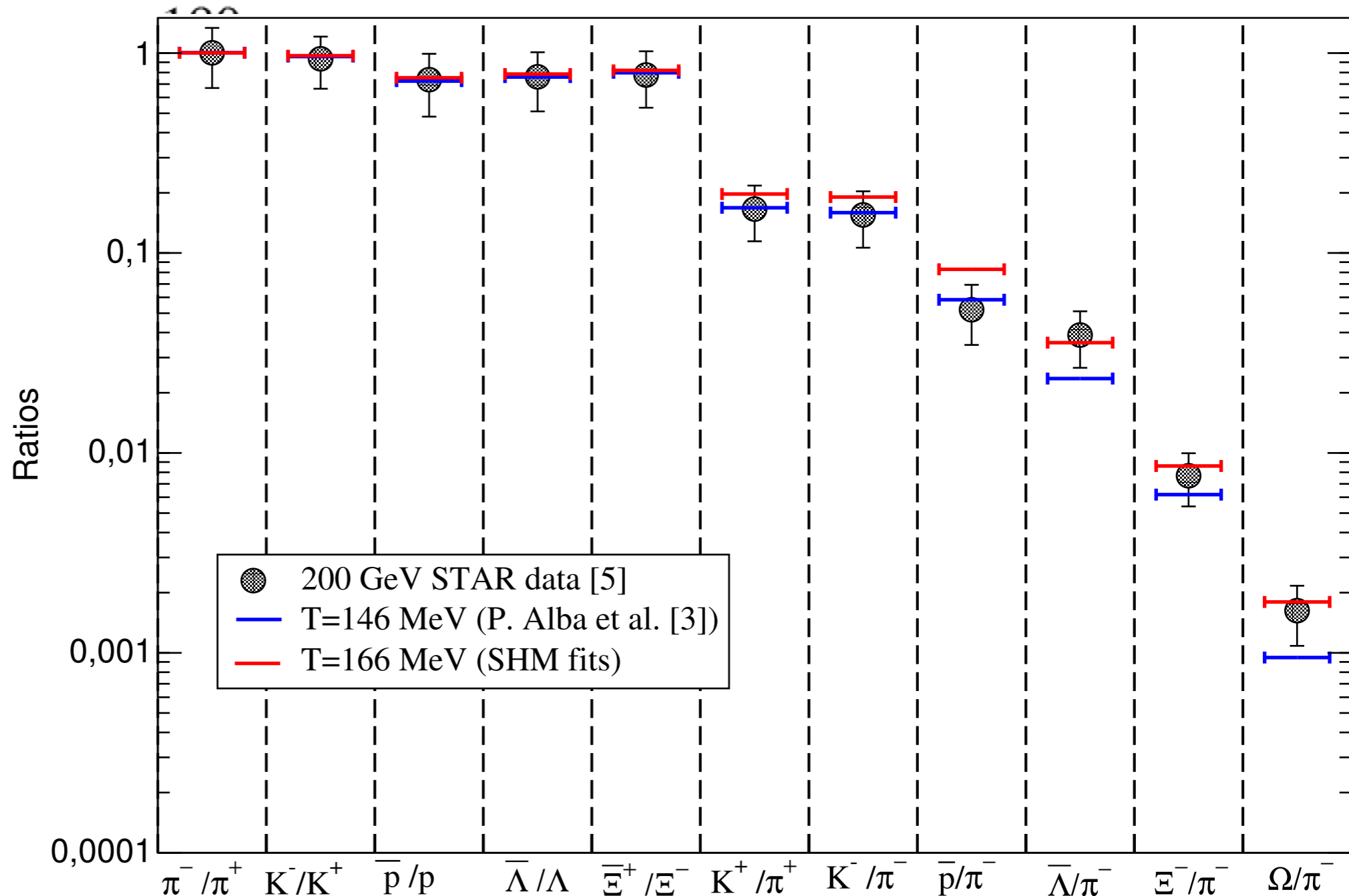
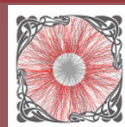
**P. Alba, poster B-01**

**C. Ratti, Wed 21** (Comparison to Lattice)

**A. Sarkar, STAR, Wed 21**

P. Alba et al, arXiv:1403.4903  
S. Borsanyi et al, arxiv.org:1403.4576  
STAR arXiv:1402.1558  
STAR, PRL, 112 (2014) 032302

# Higher moments: HRG and STAR



**M. Bluhm, Wed 21**

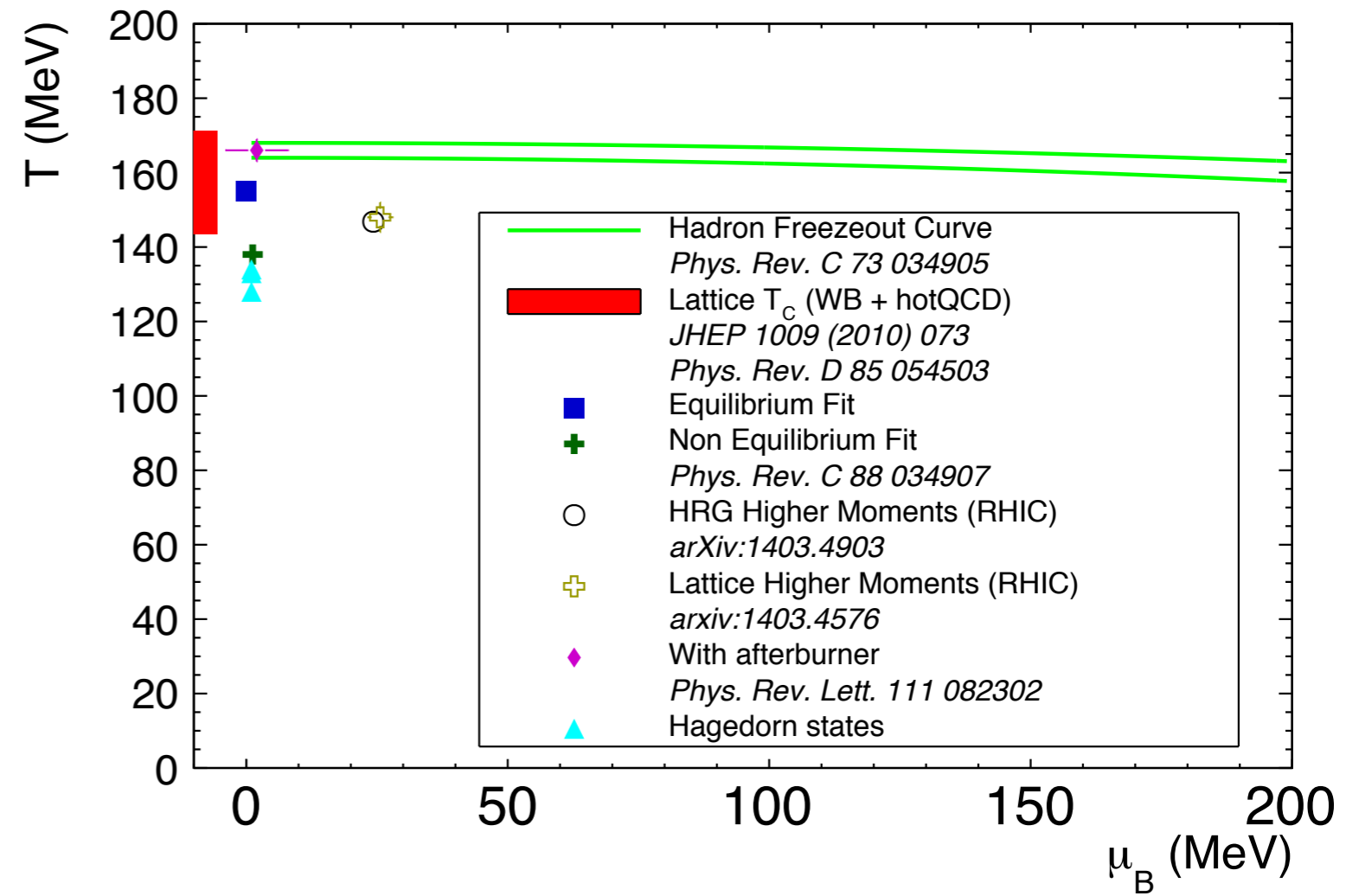
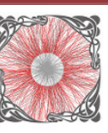
**P. Alba, poster B-01**

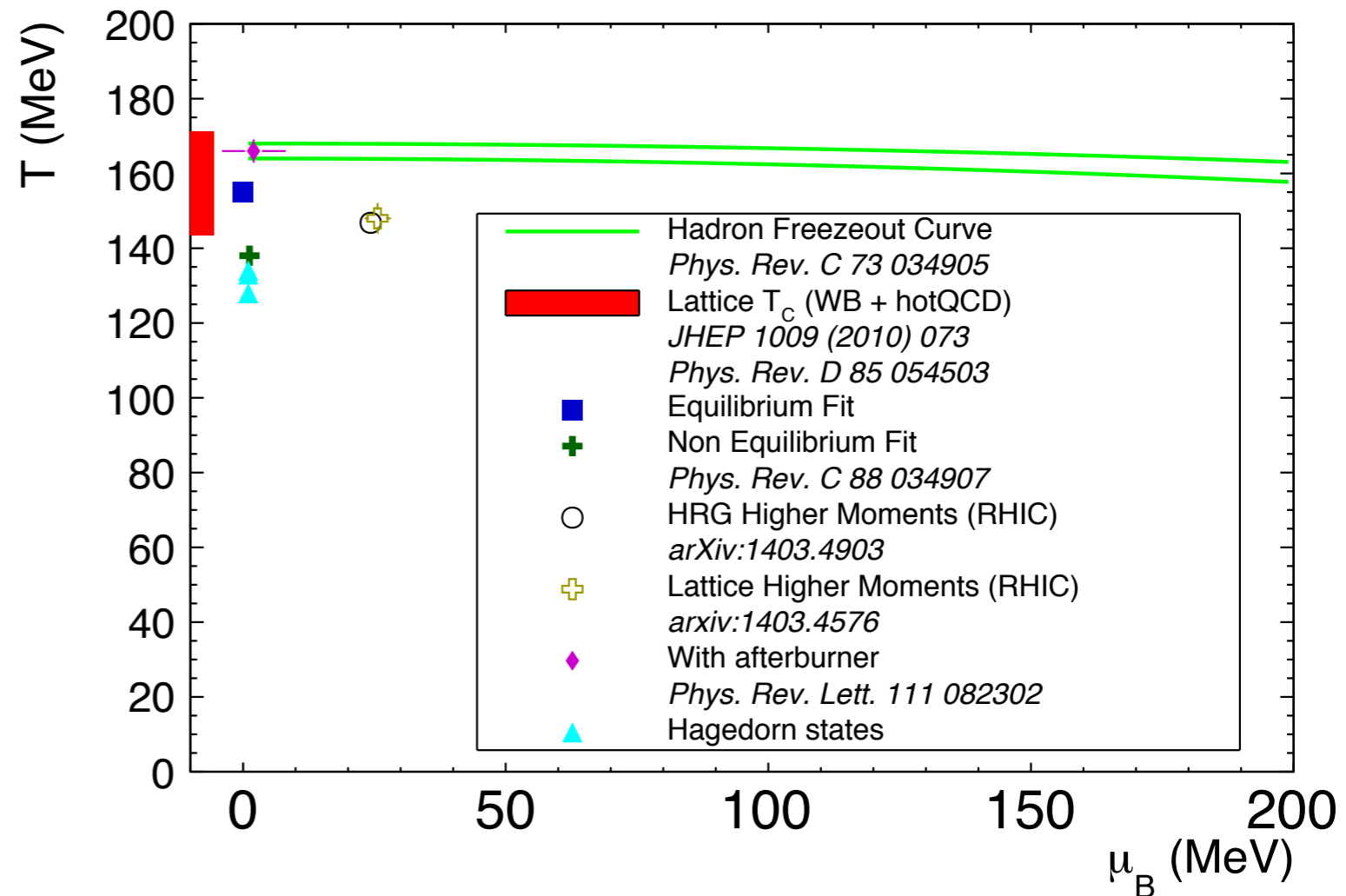
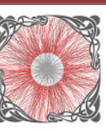
**C. Ratti, Wed 21** (Comparison to Lattice)

**A. Sarkar, STAR, Wed 21**

P. Alba et al, arXiv:1403.4903  
 S. Borsanyi et al, arxiv.org:1403.4576  
 STAR arXiv:1402.1558  
 STAR, PRL, 112 (2014) 032302

# High energy and thermal fits: wrap-up

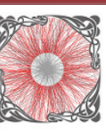




The Jury is still out!

Needs additional evidence:

- Separate errors vs centrality
- Measure heavy light-flavor mesons (e.g.  $\omega_{\text{neq}} / \omega_{\text{eq}} \approx 1.40$ )
- Repeat measurements at lower energy with improved detectors (vertex)
- Higher moments at LHC and RHIC (net strangeness?)

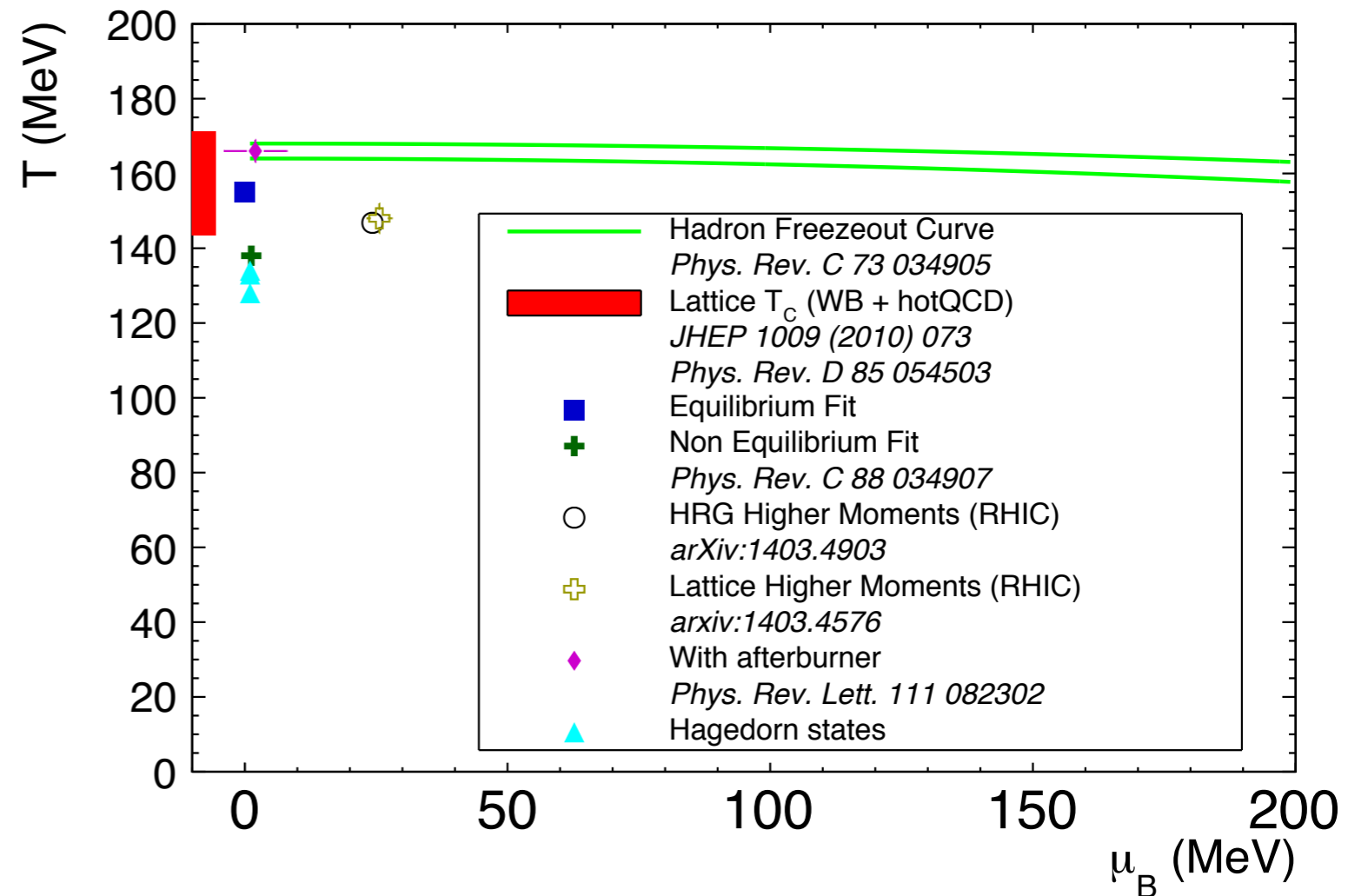


## Thanks!

**ALICE Colleagues:** A Andronic, B Hippolyte, B Doenigus, H Oeschler, R Bellwied, J Schukraft, F Antinori, K Safarik, A Kalweit, M Ploskon...

**Other Exps:** M Lorenz, N Xu, L Kumar, X. Zhu

**Theory:** J Rafelski, F Becattini, J Noronha-Hostler, C Ratti, K Redlich, P Alba, M Petran



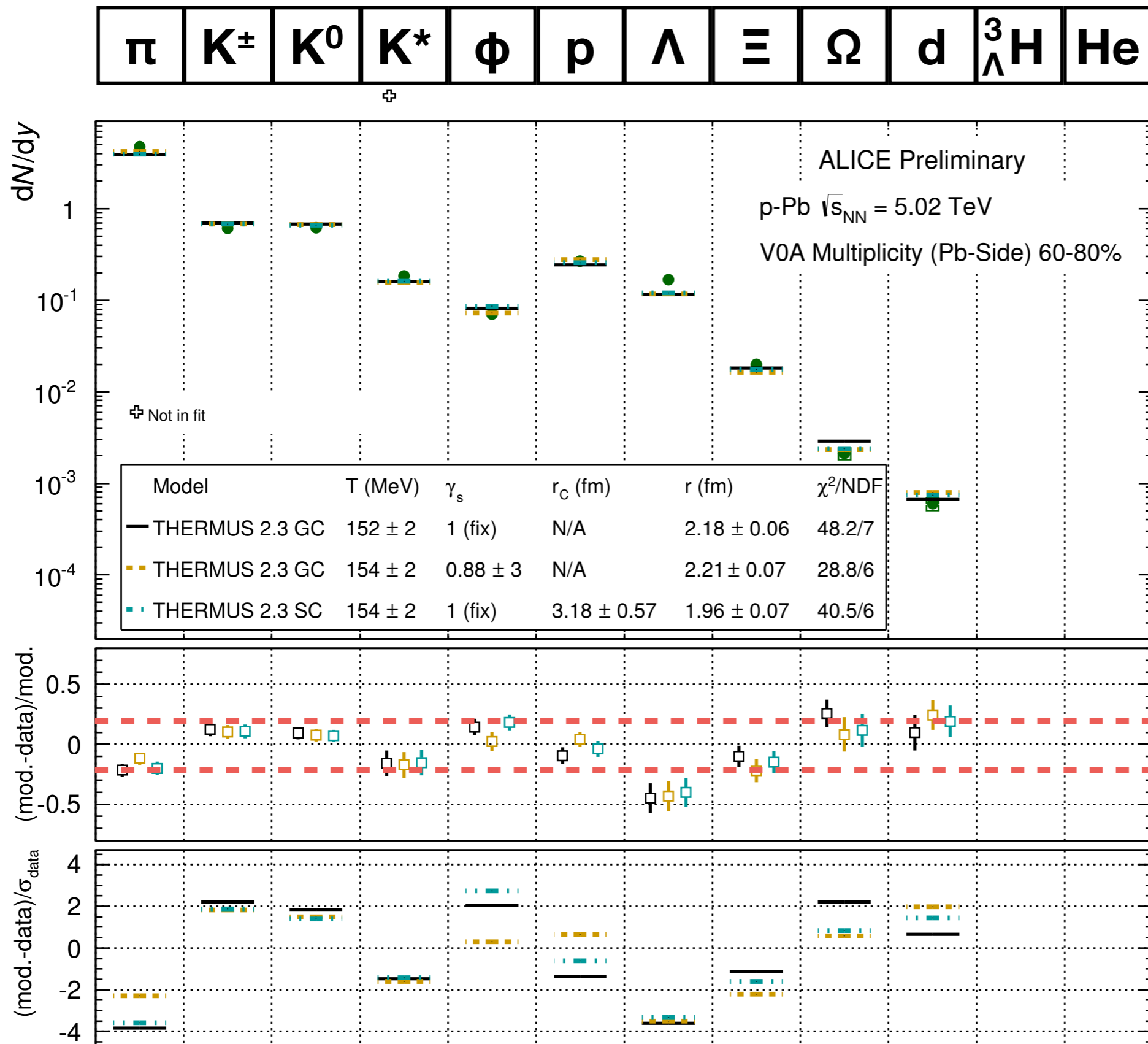
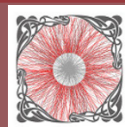
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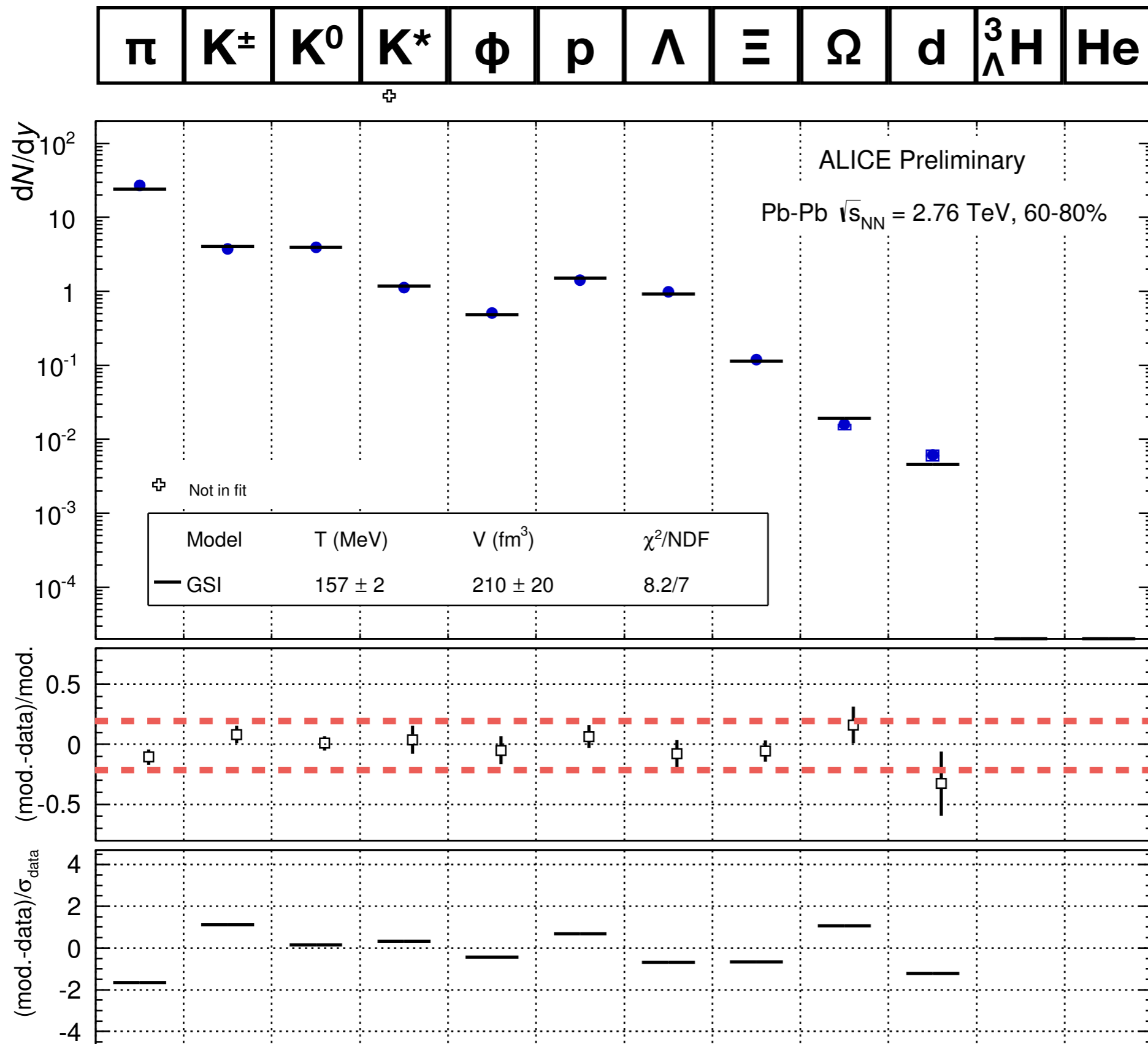
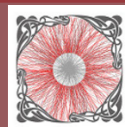
- Separate errors vs centrality
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Backup

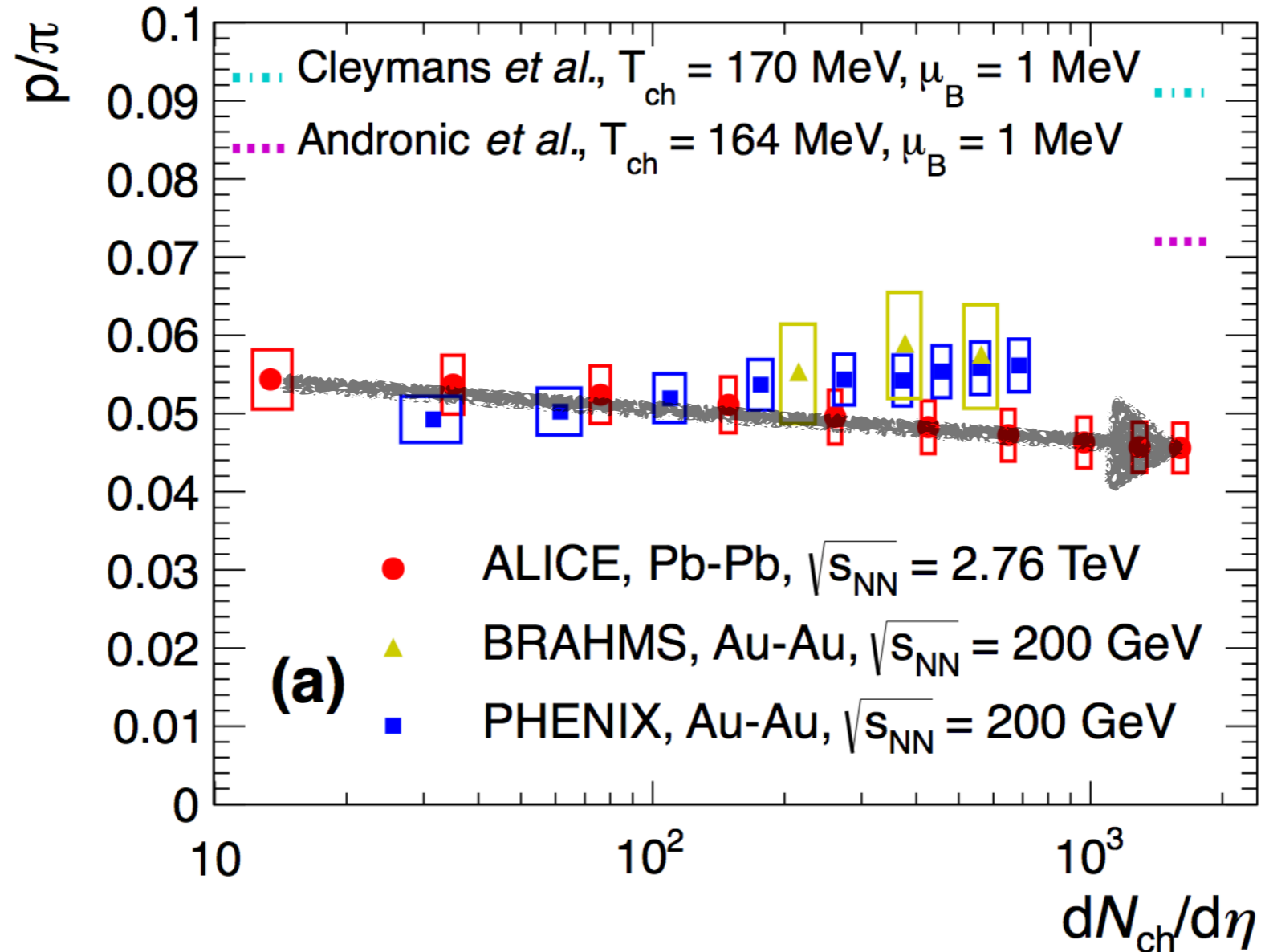
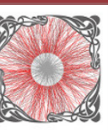


$\gamma_s < 1$   
 $R_C > R$ ?

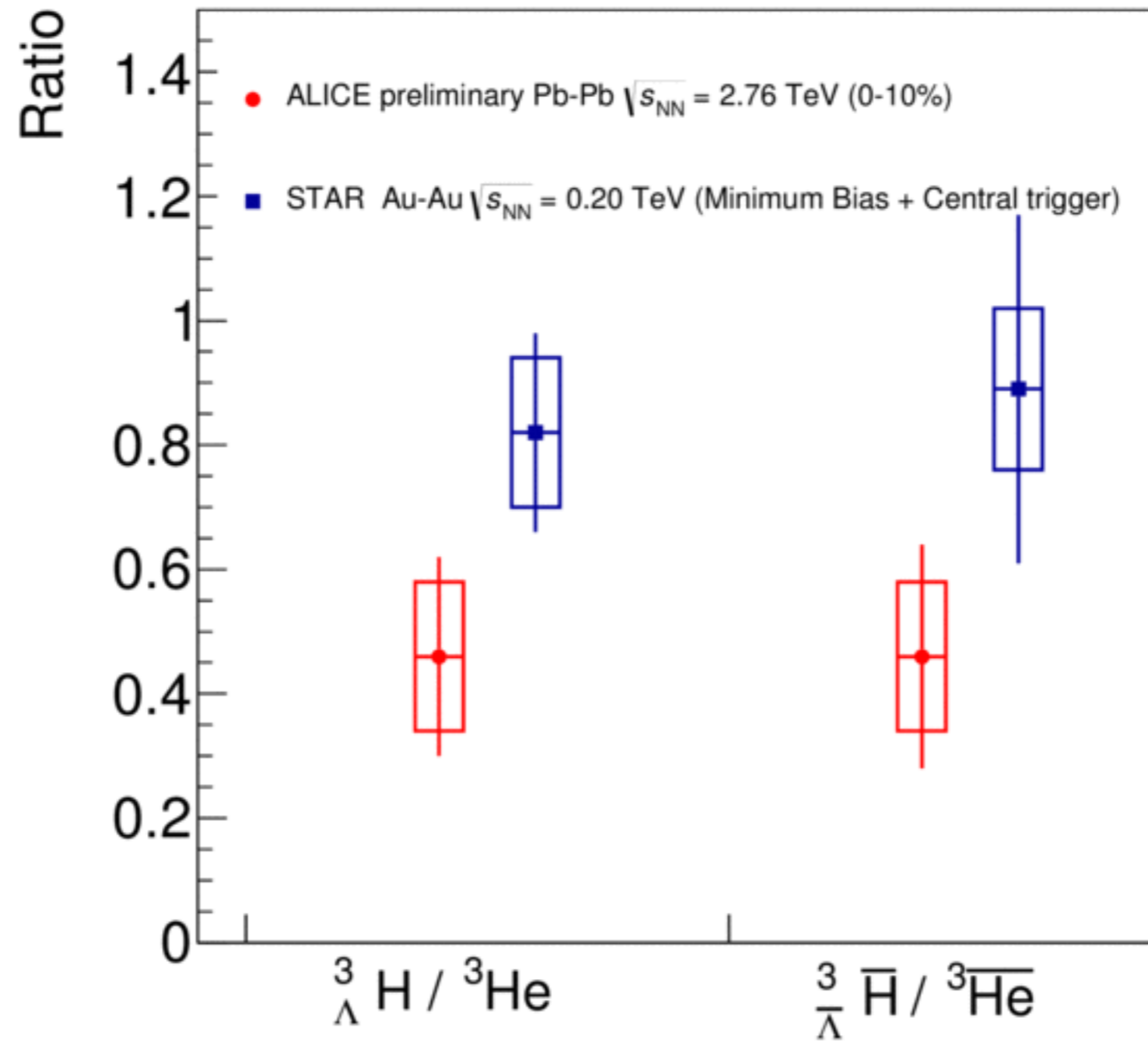
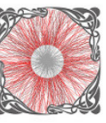


Similar thermal parameters to 0-10%  
Fit quality better

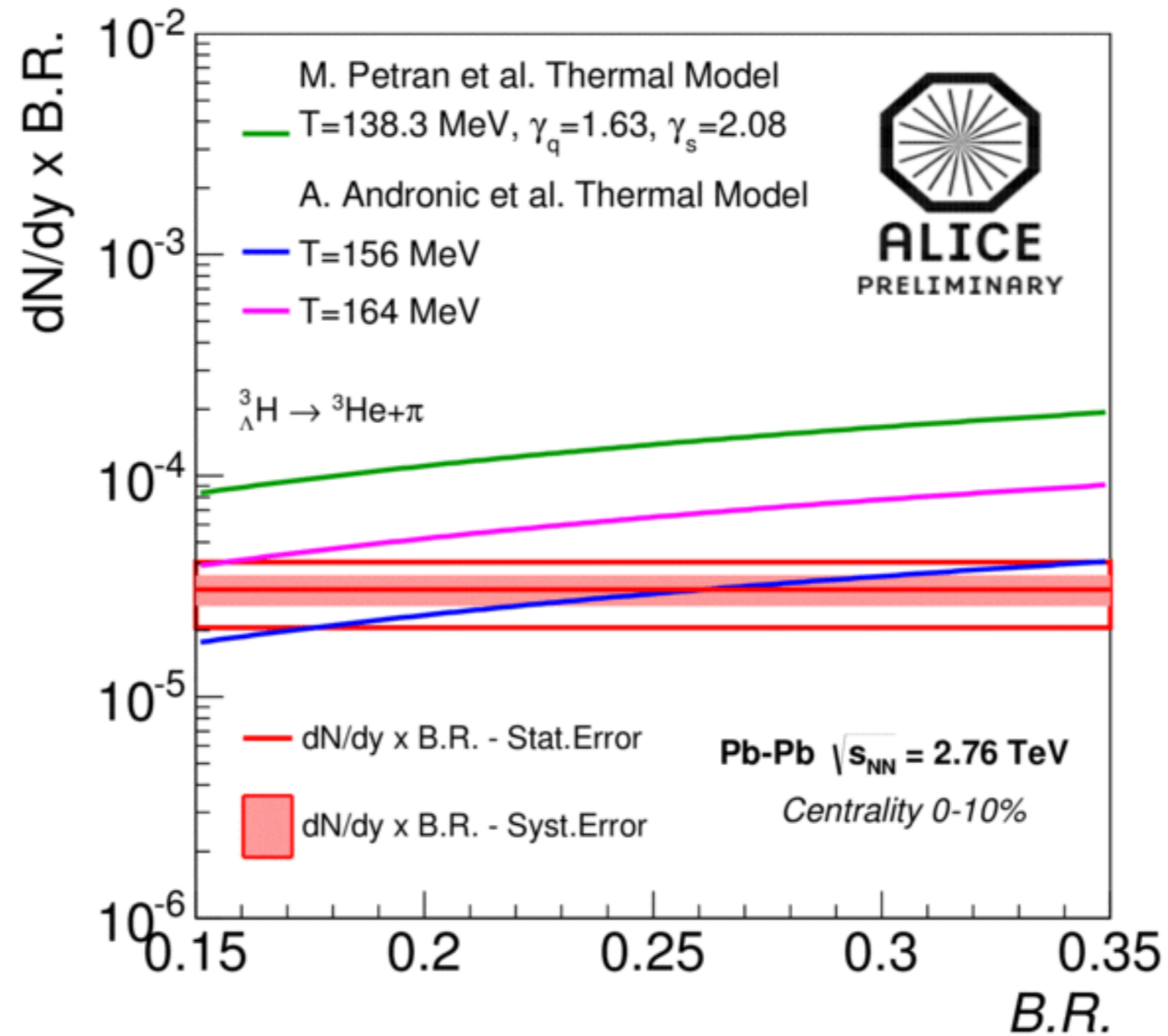
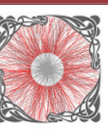
# Why is fit quality better in 60-80%?



Hint for a decreasing  $p/\pi$  vs mult.  
Physics or systematics? Needs new analysis.

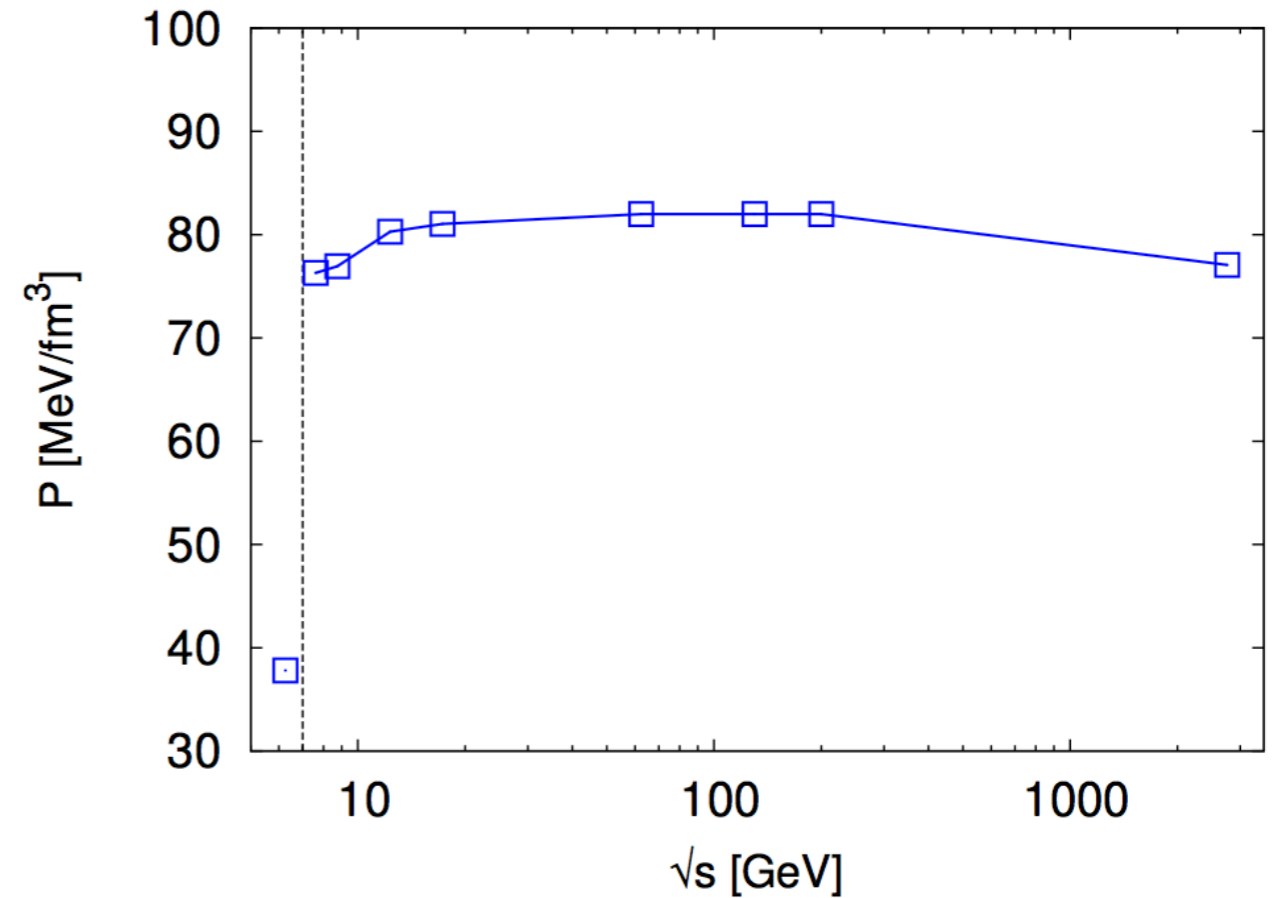
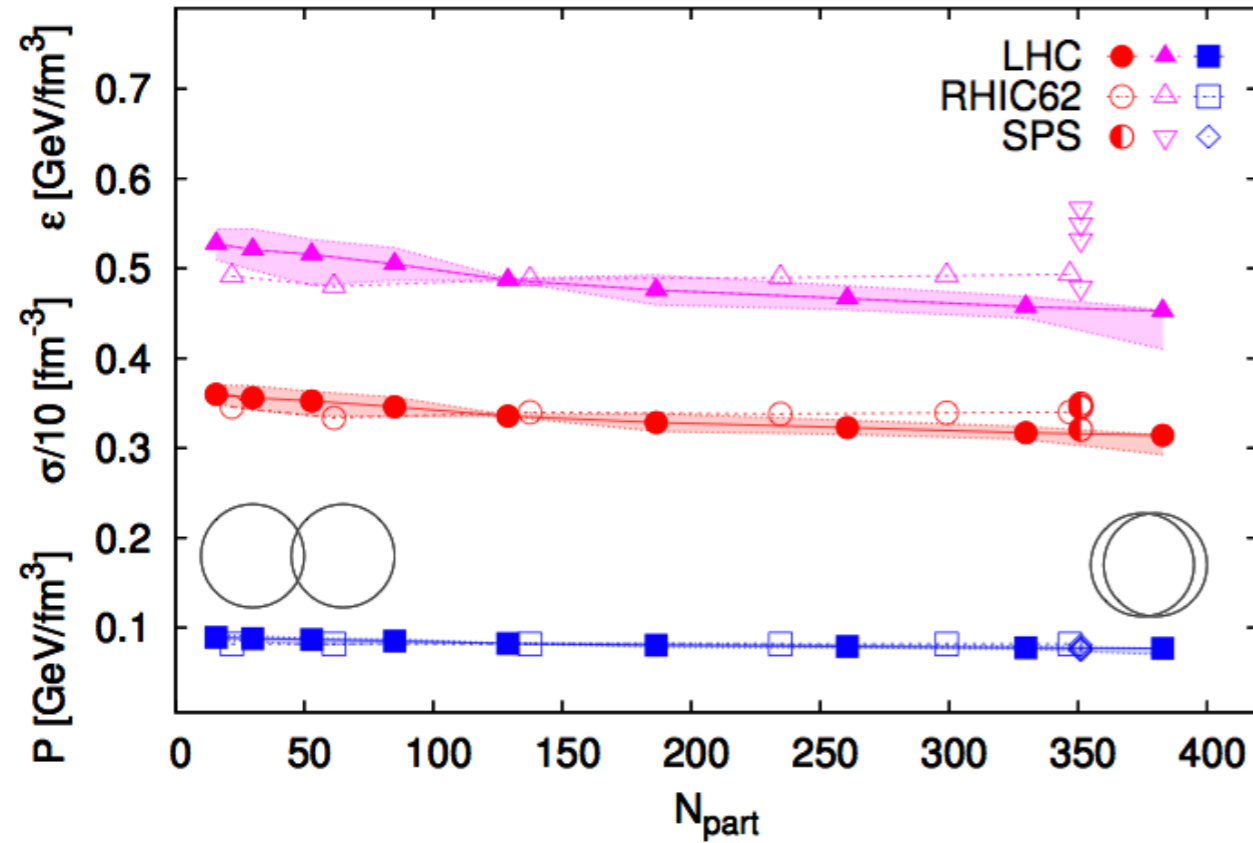
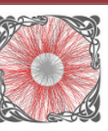


ALI-PREL-81005



ALI-PREL-54321

# Non equilibrium fits vs $\sqrt{s}$ and system size

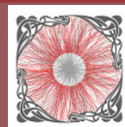


**Uniformity** of fireball freeze-out parameters across energy and centrality

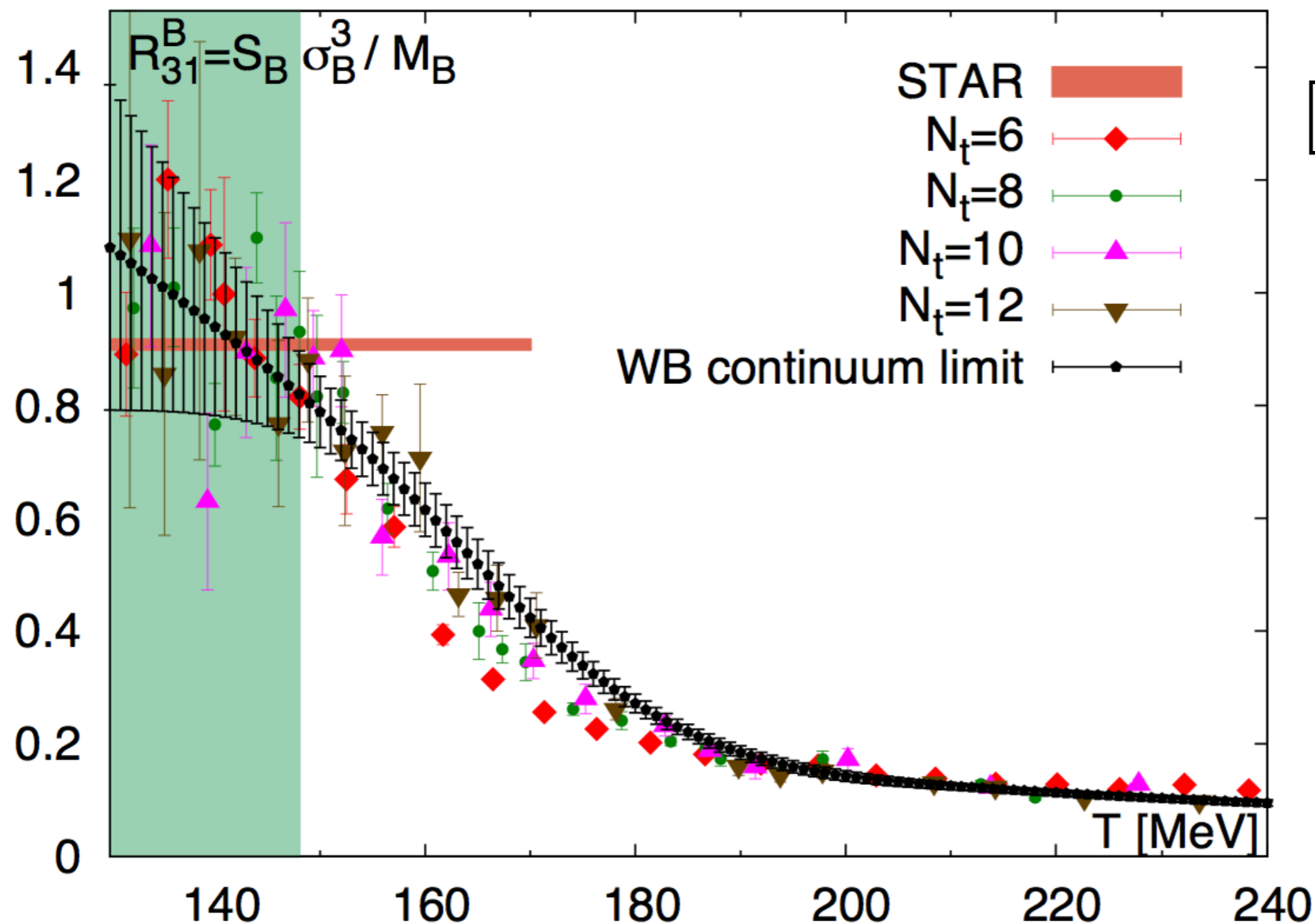
Strangeness/entropy smaller than at RHIC?

Rafelski, HIF  
Rafelski et al, 1403.4036

# Comparing lattice and experiment



S. Borsanyi et al, arXiv:1403.4576



C. Ratti, Wed 21

A. Sarkar, STAR, Wed 21

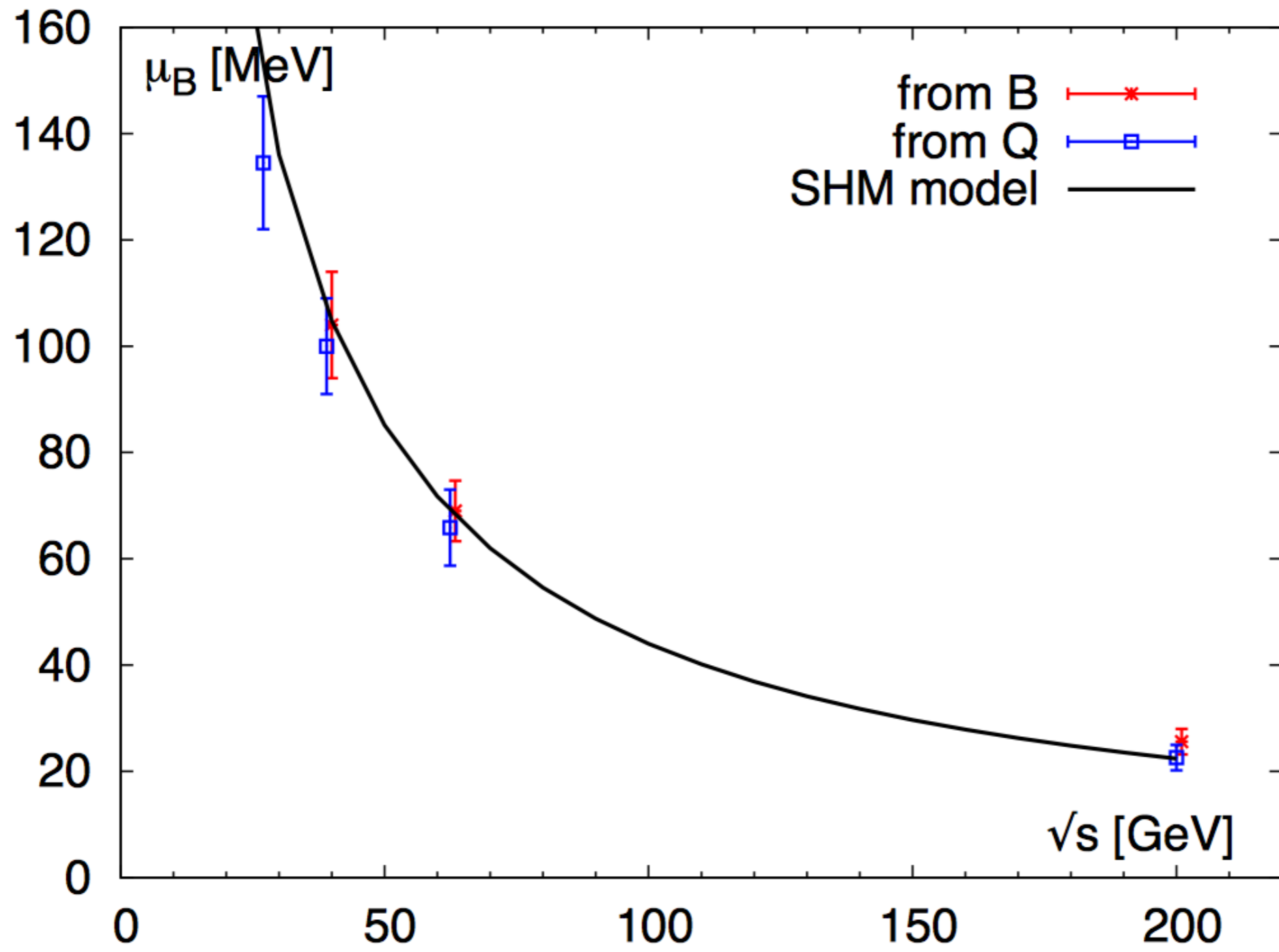
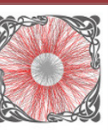
STAR, PRL, 112 (2014) 032302

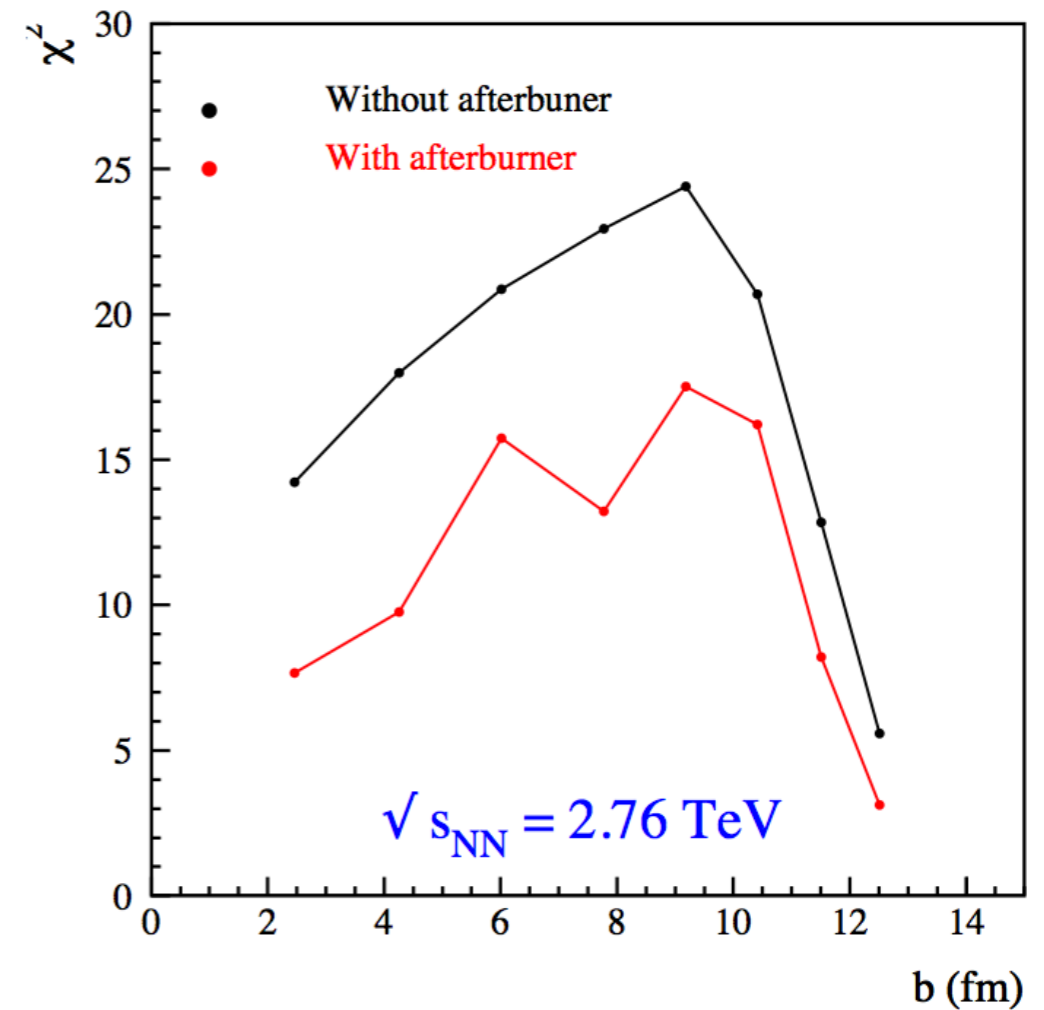
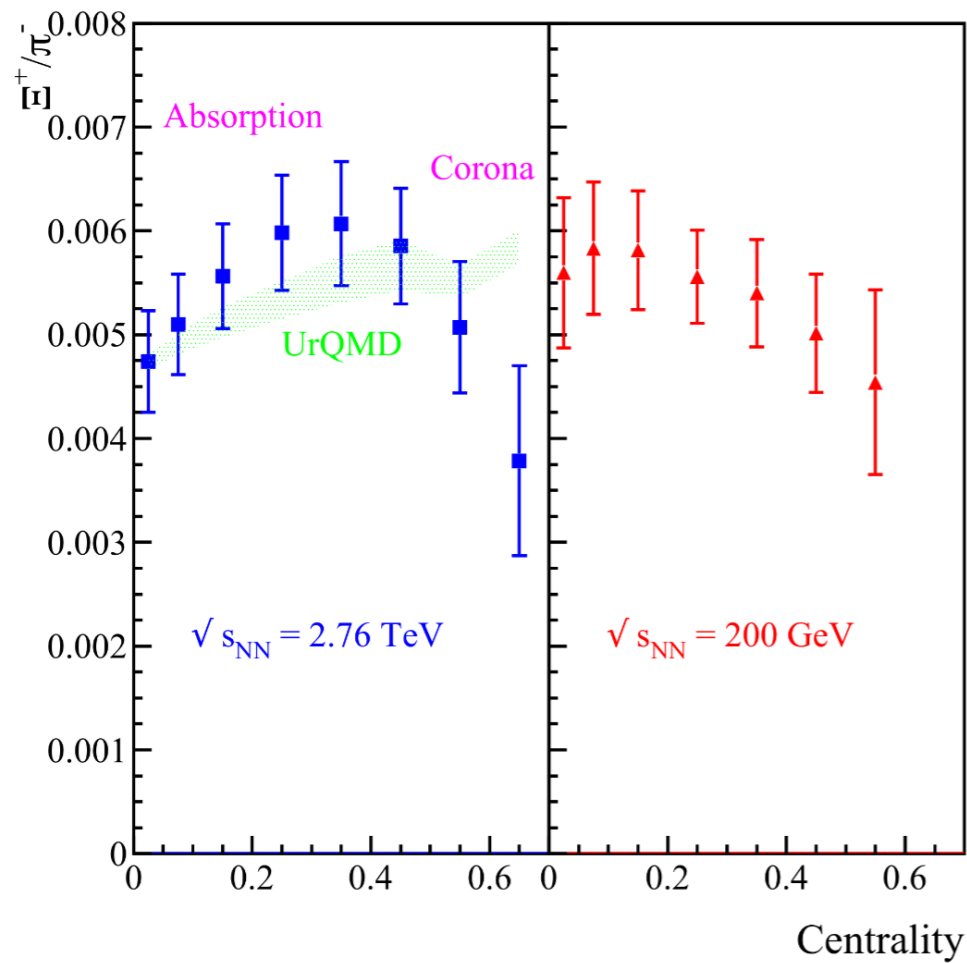
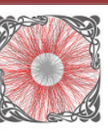
Comparison of higher moments in lattice and experiments suggests  $T \lesssim 148$  MeV

(Caveat: Baryons vs Protons)

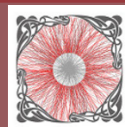
NB  $\mu_B$  agrees with SHM







"Consequently we can assume that neglecting the back reaction implies a small quantitative uncertainty in the modifications factors and does not basically alter our findings"



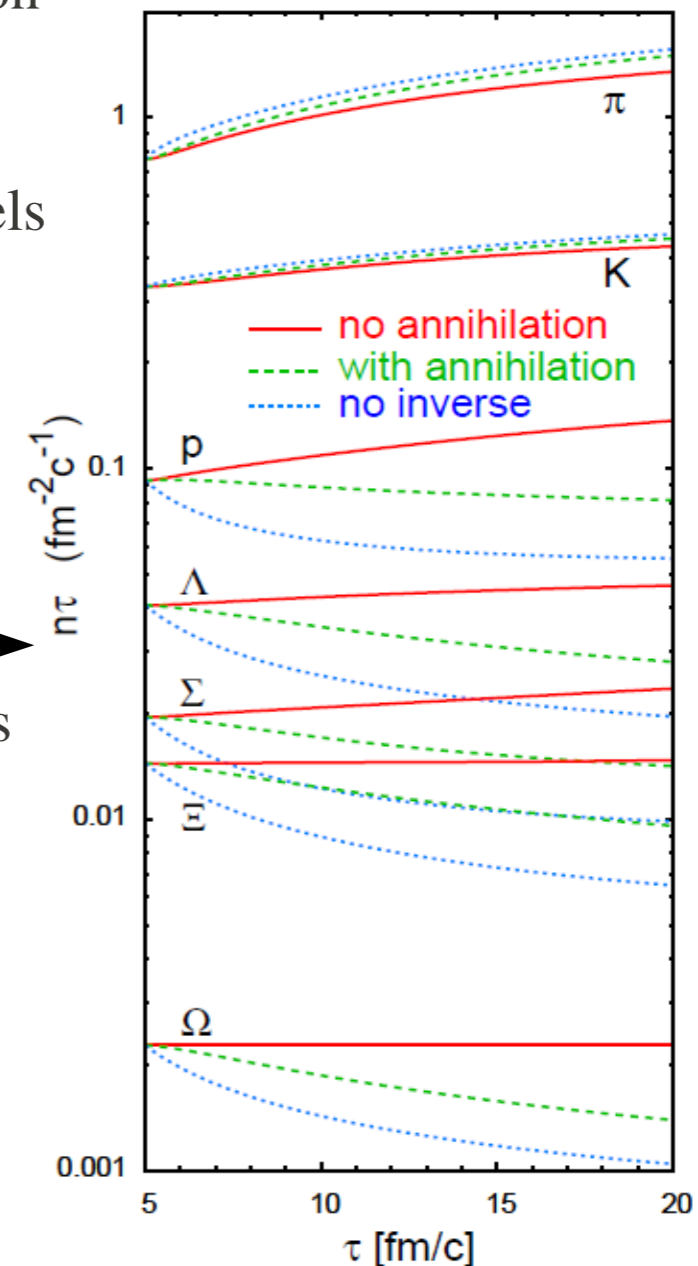
## Annihilation in the hadronic phase?

- but need to take into account full detailed balance, backreaction like  $5\pi \rightarrow p\bar{p}$  (not in RQMD)

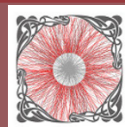
analysis by Rapp and Shuryak 2008 for SPS energies: this cancels the annihilation effect, equilibrium value at  $T_{\text{chem}}$  is recovered

recent analysis by Pan and Pratt, PRL 110 (2013) 042501: taking account backreaction cancels half of the effect of annihilation

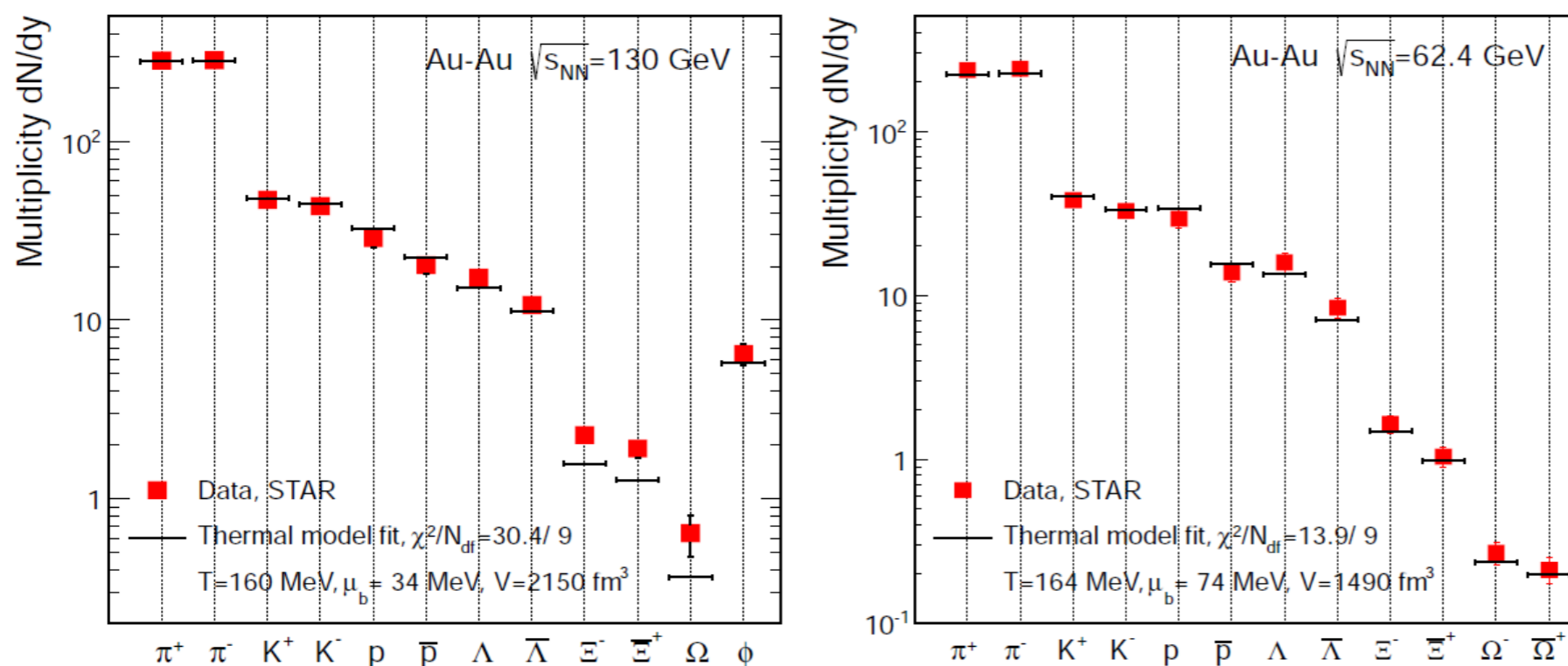
- Why should only proton be affected? and not hyperons? Cross sections should be very similar, e.g.  $\Omega + N\bar{b} \rightarrow 2\pi + 3K$  evaluate 10 mb at threshold Braun-Munzinger, JS, Wetterich, Phys. Lett. B596 (2004) 61
  - they show if anything opposite effect
- what about nuclei?? they fit perfectly and their cross sections are larger



# Parameters and fit quality vs RHIC

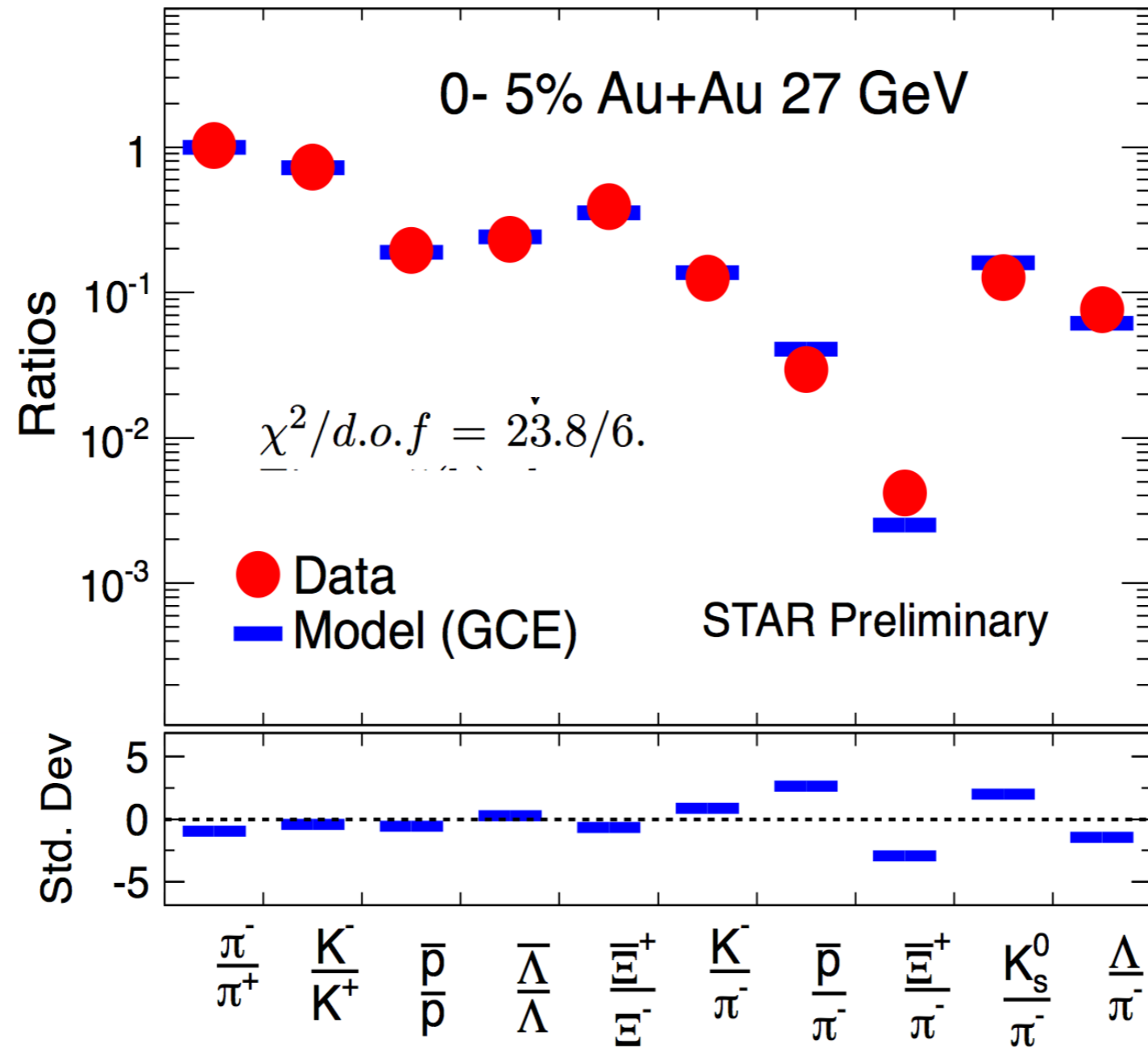
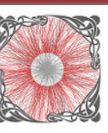


PBM at QM12

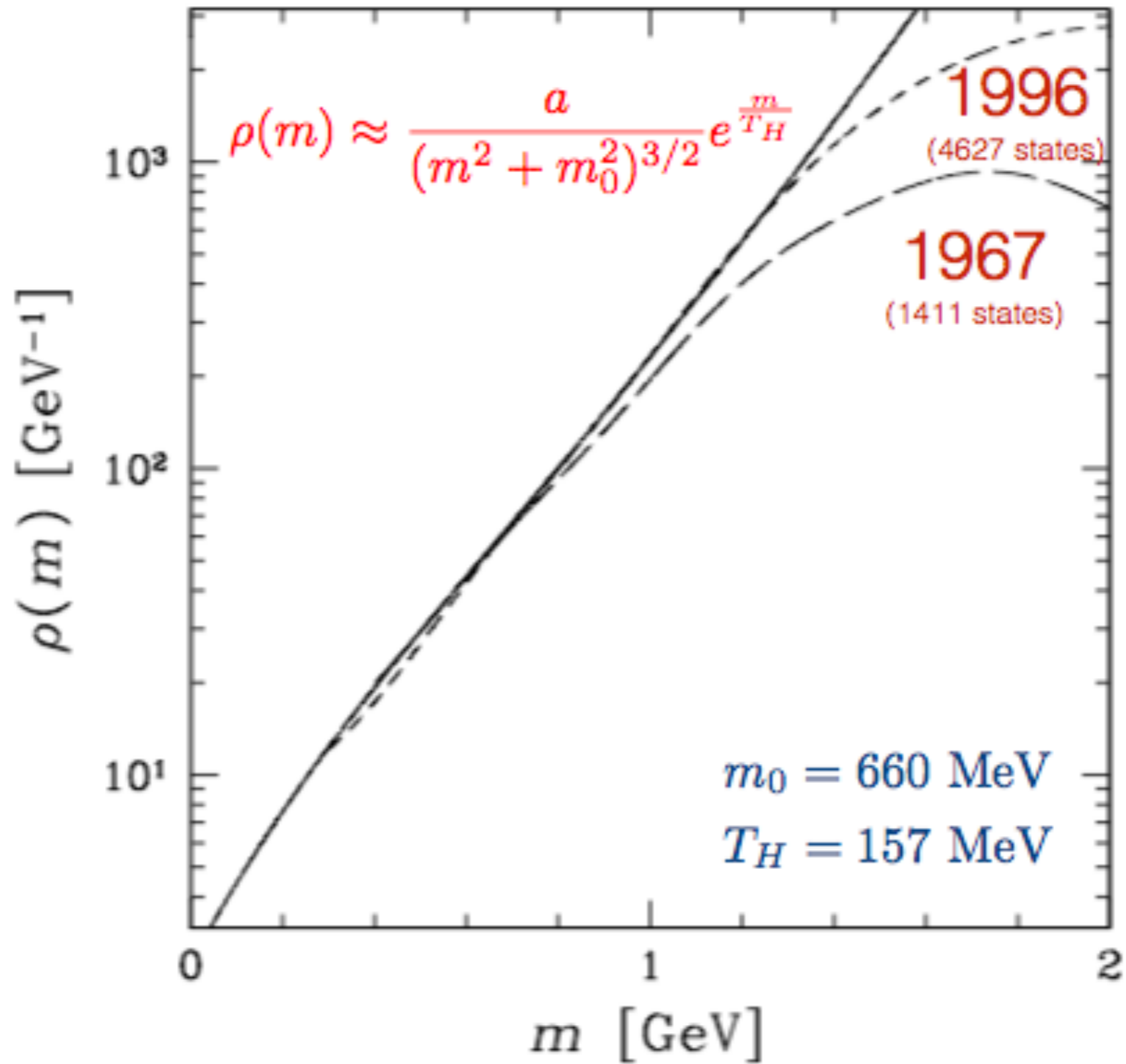
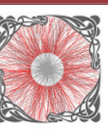


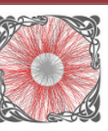
- Pre-LHC prediction  $T = 164 \pm 4$ ,<sup>[1]</sup> post LHC calculations confirm 160–164 MeV at RHIC
- $T$  slightly lower at LHC? (156 MeV,  $\sim 2 \sigma$  effect)
- Quality slightly worse than  $\sqrt{s} = 200$  GeV, however
  - RHIC quality in 130 and 62 GeV also worse than 200 GeV
  - Quality at LHC driven by protons, better accuracy at LHC, tension also at RHIC
- $p/\pi$  drives  $T$  at LHC (remember, difference to RHIC in central collisions is  $\sim 2.3$  sigma)

[1] Andronic et al, Nucl. Phys. A772 (2006) 167



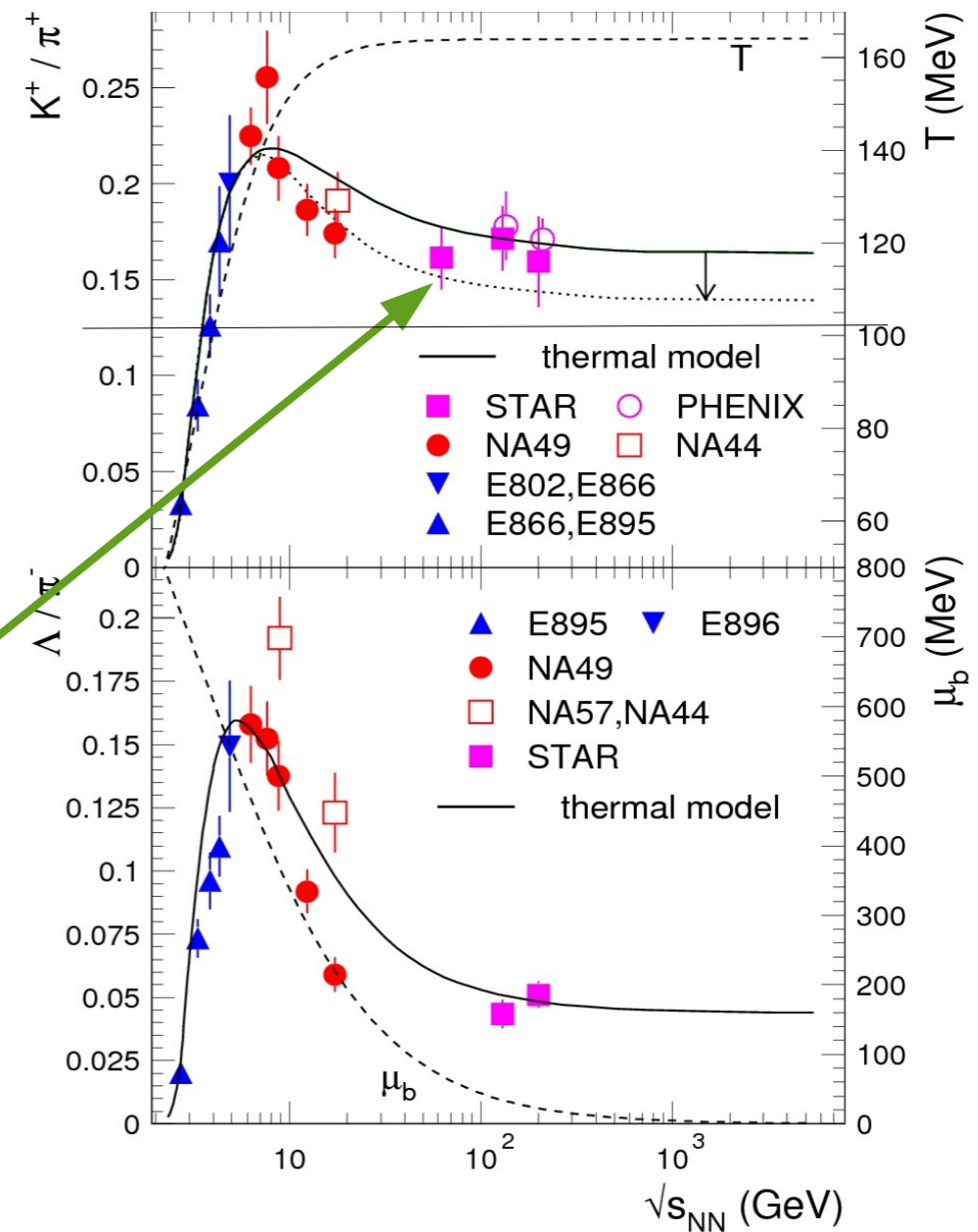
# Hagedorn spectrum

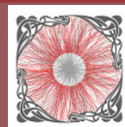




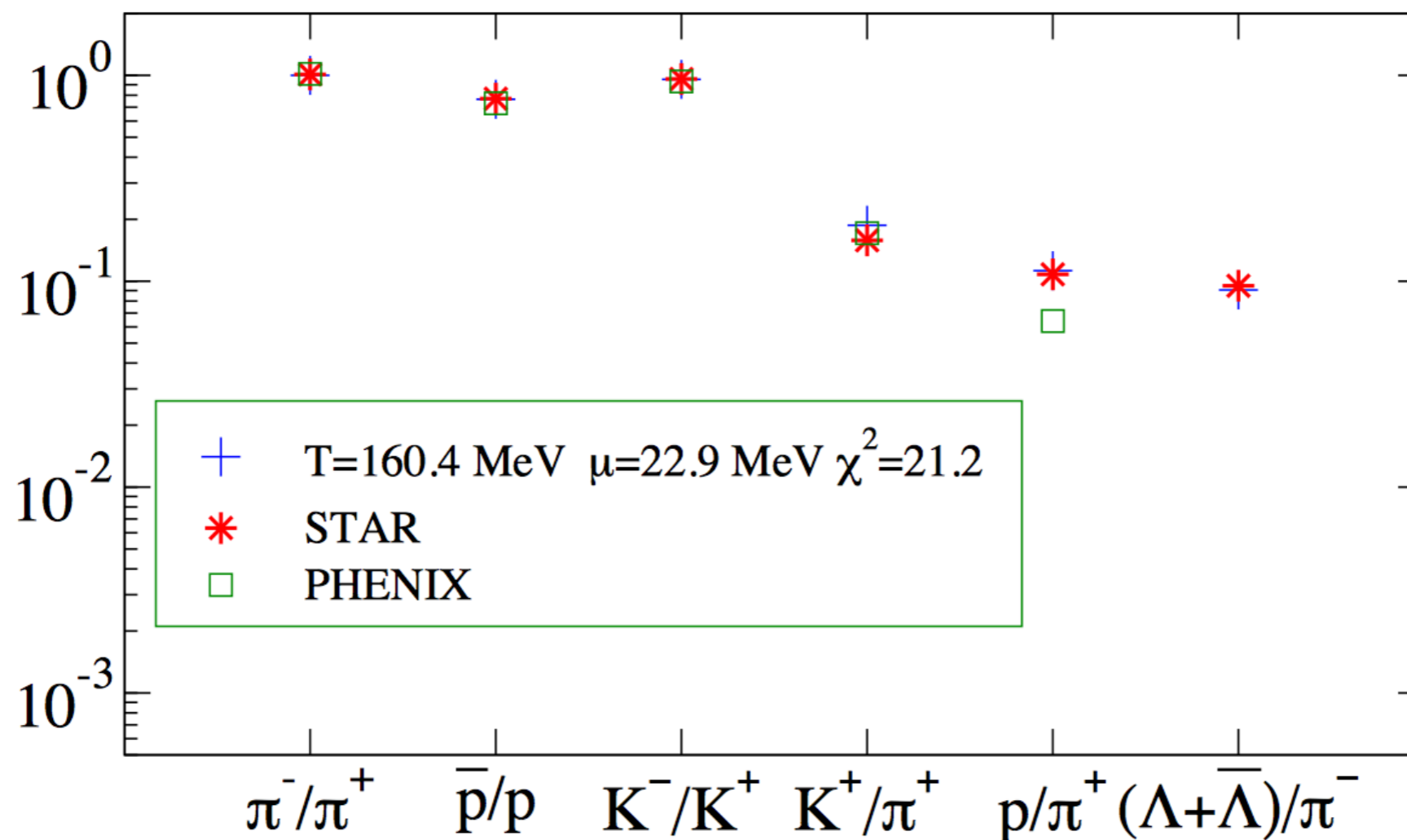
## Effect of incomplete hadron spectrum

we studied this for  $K/\pi$  ratio:  
 (Andronic, Braun-Munzinger, JS Phys. Lett. B673 (2009) 142)  
 estimate effect by extending mass spectrum beyond 3 GeV based on  $T_H = 200$  MeV and assumption how states decay  
 strongest contribution to kaon from  $K^*$  producing one K  
 all high mass resonances produce multiple pions  
 -> further reduction of  $K^+/\pi^+$





## RHIC 200 GeV Au+Au

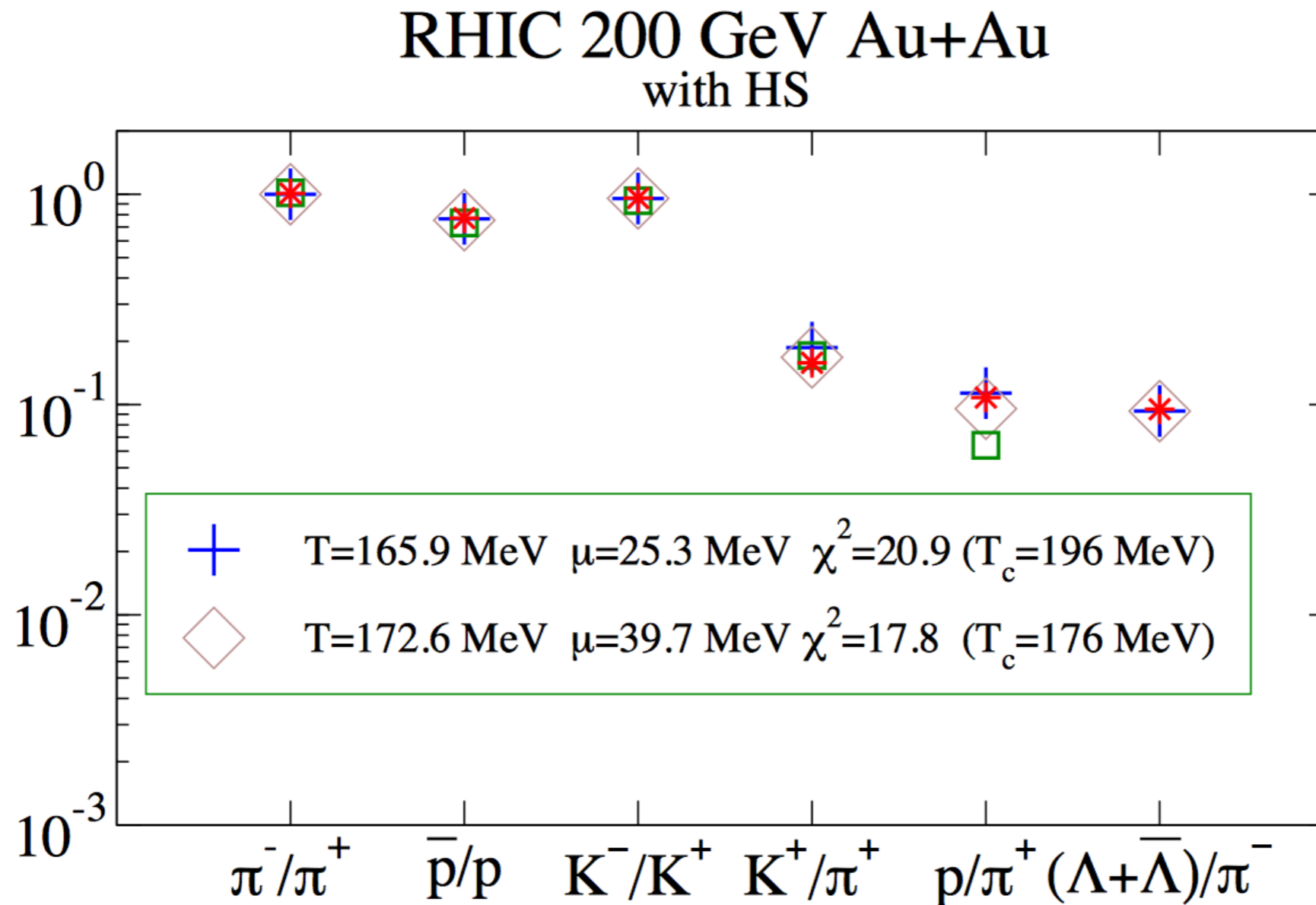
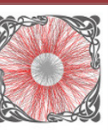


Using assumptions on hadron gas, they reproduce  $p/\pi$

**J. Noronha-Hostler, Wed 21**

arXiv:0906.3960 (RHIC)

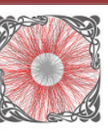




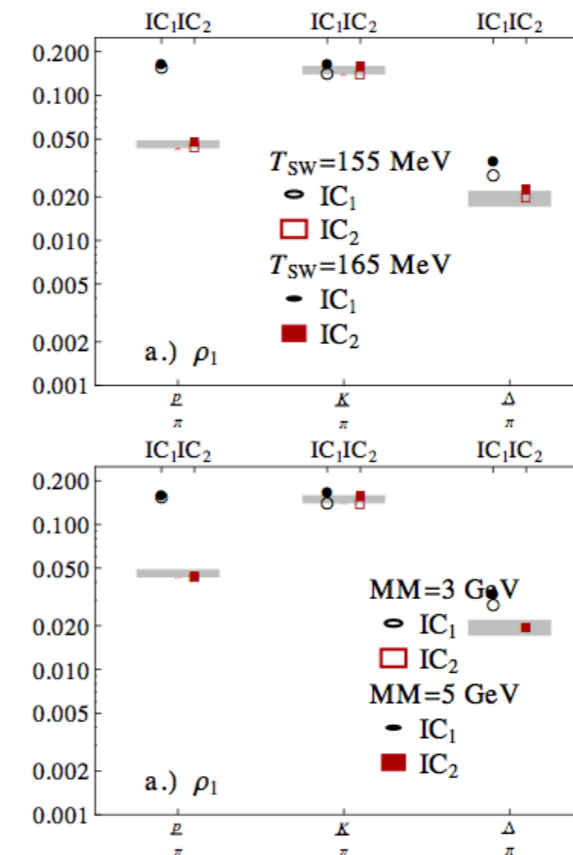
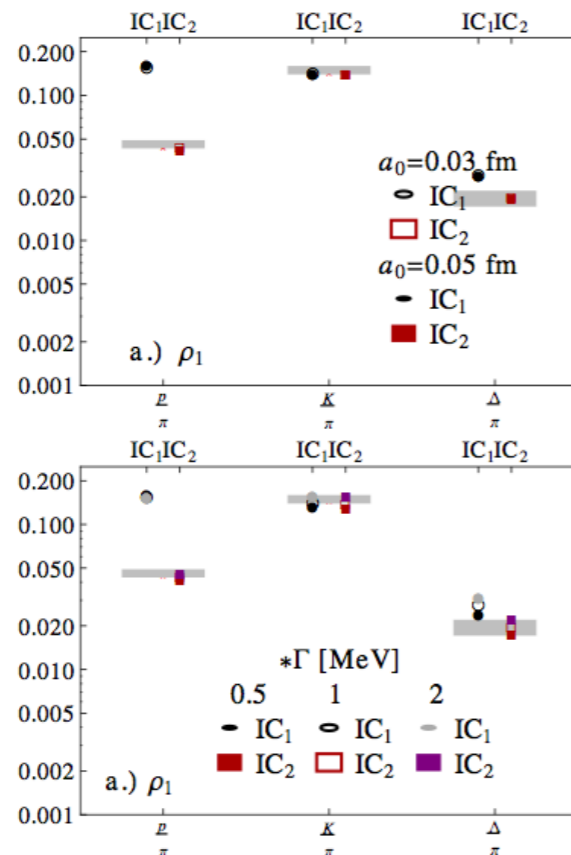
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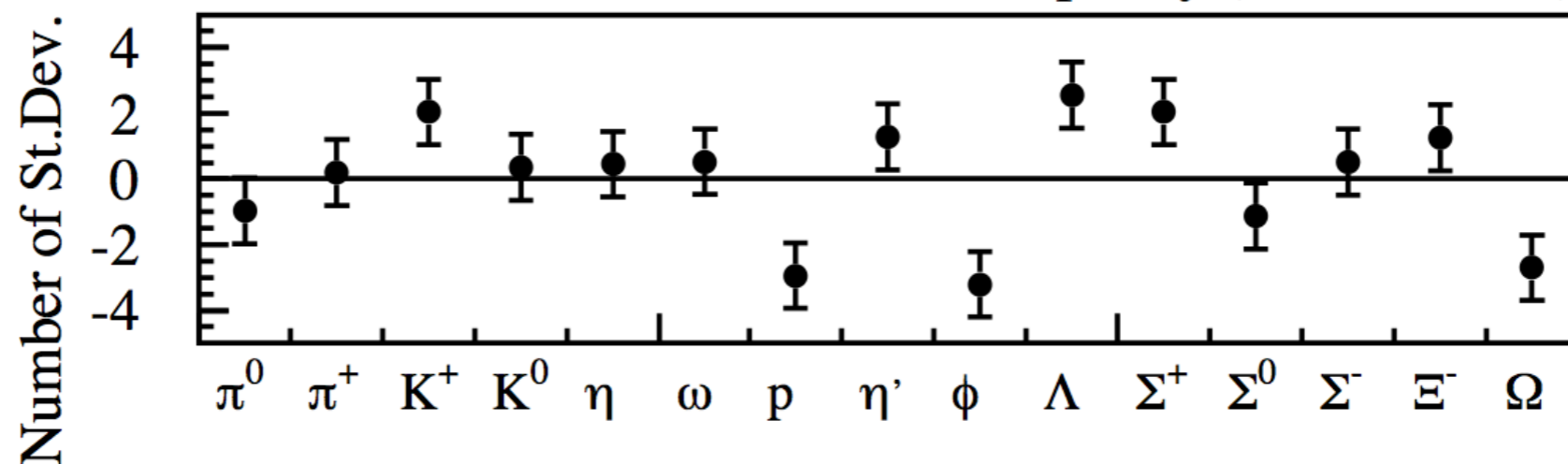
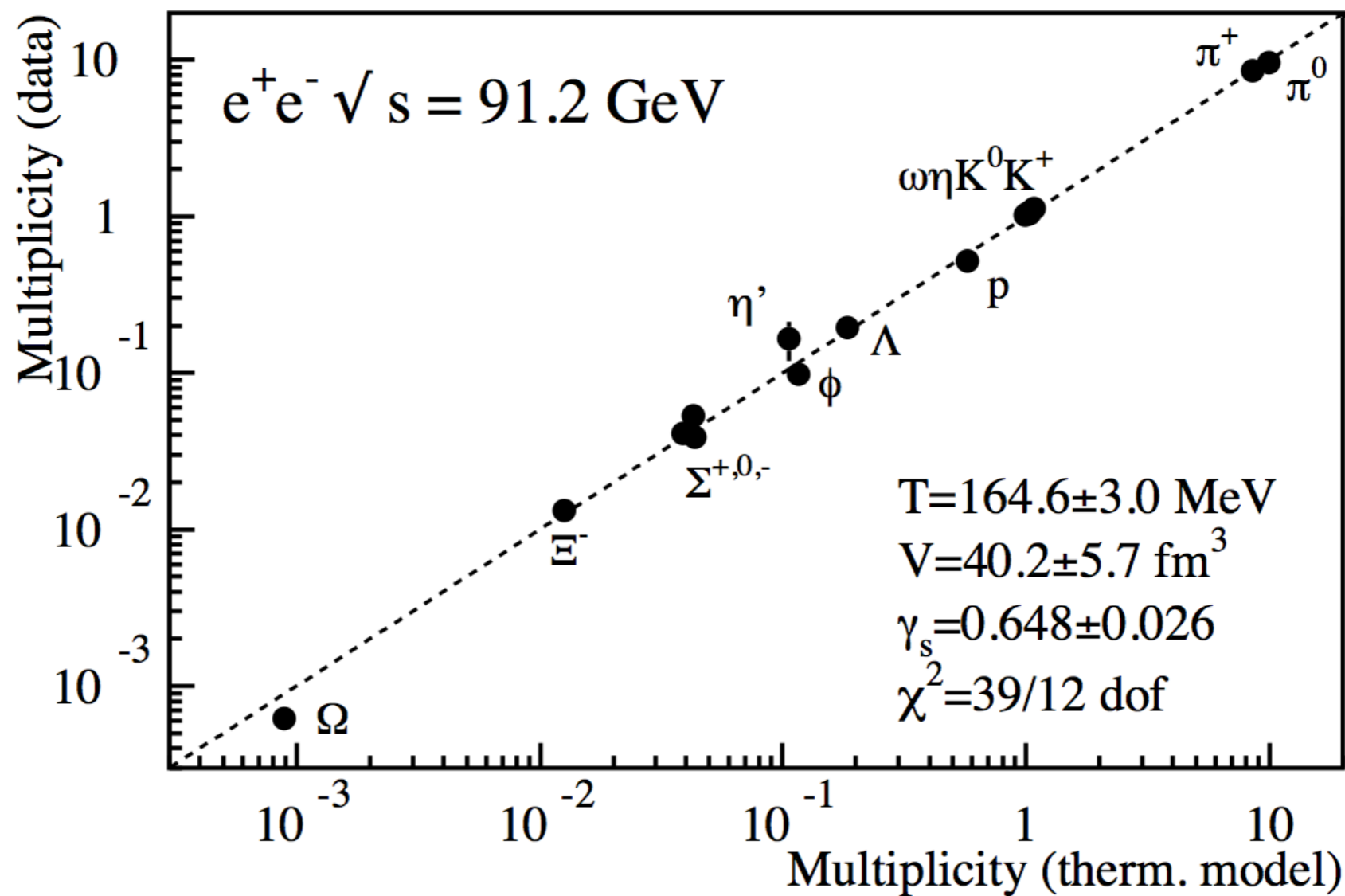
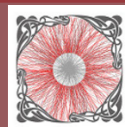


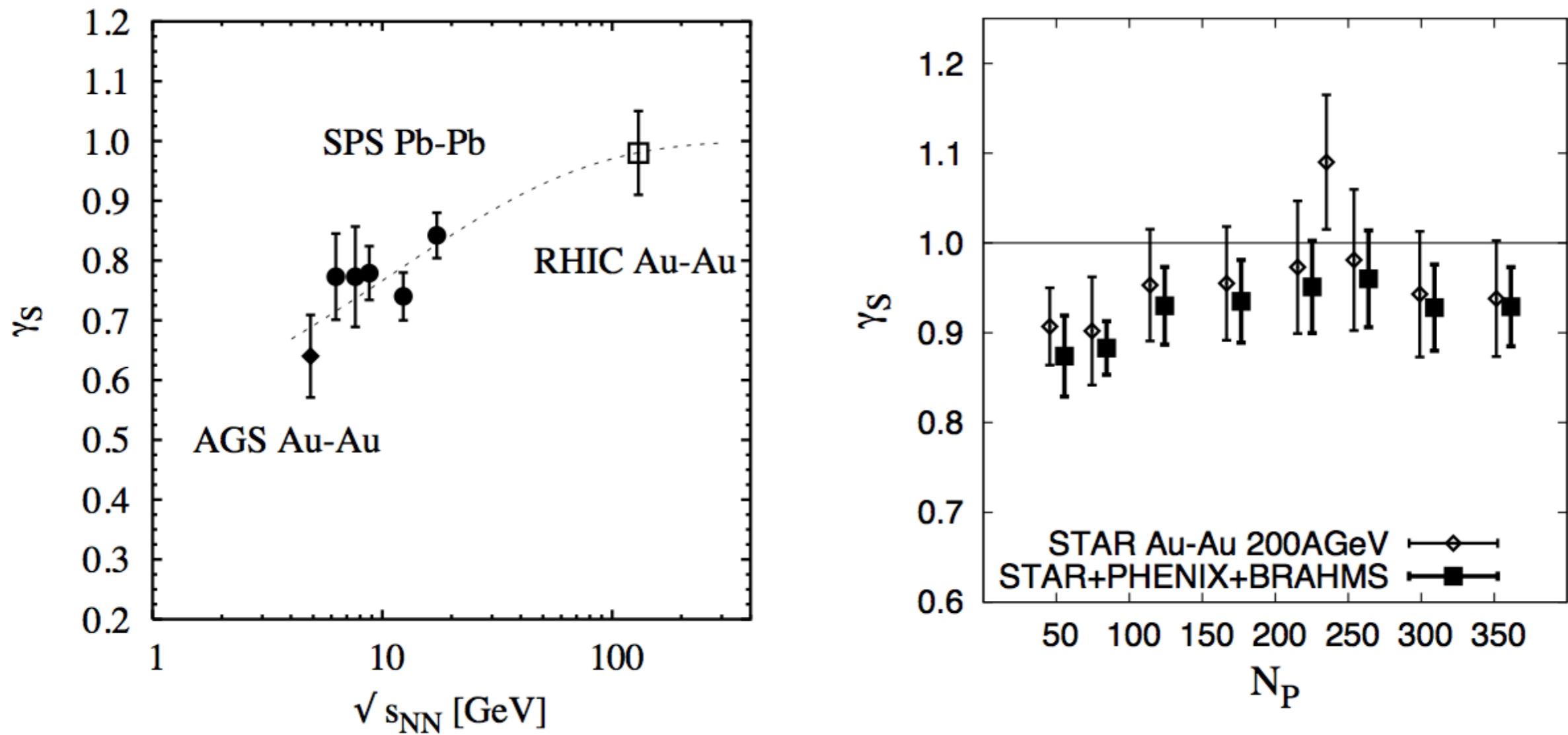
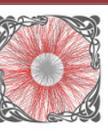
# Results: Hagedorn States fits are robust



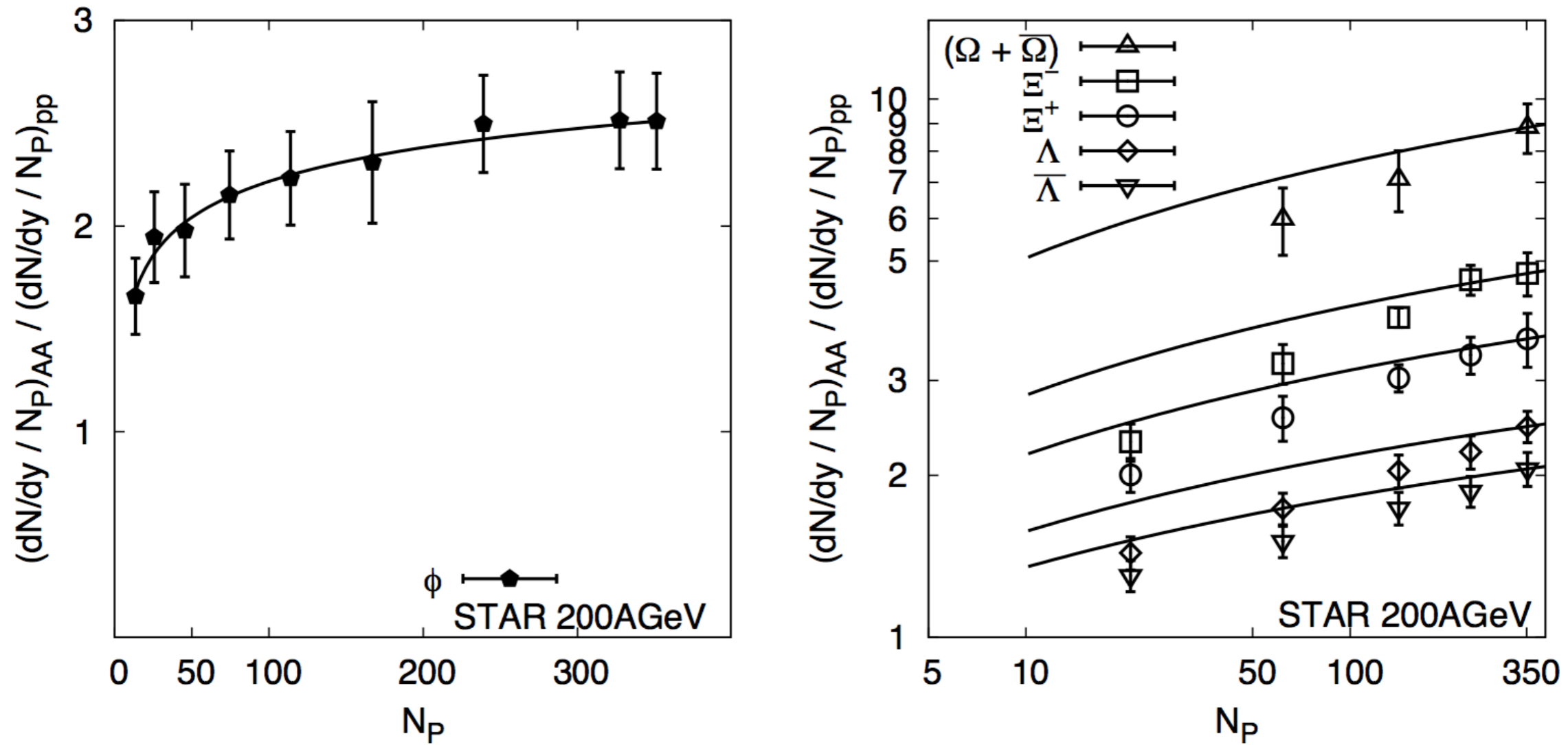
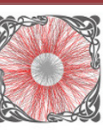
JNH and C. Greiner- to appear shortly

- Changing the expansion has almost no effects.
- Increasing the decay width still fits, decreasing is below data (slightly)
- Too high switching temperature=overpopulation
- Increased maximum mass of HS still fits data
- Similar results obtained for other HS descriptions (see upcoming paper)

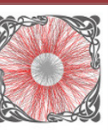




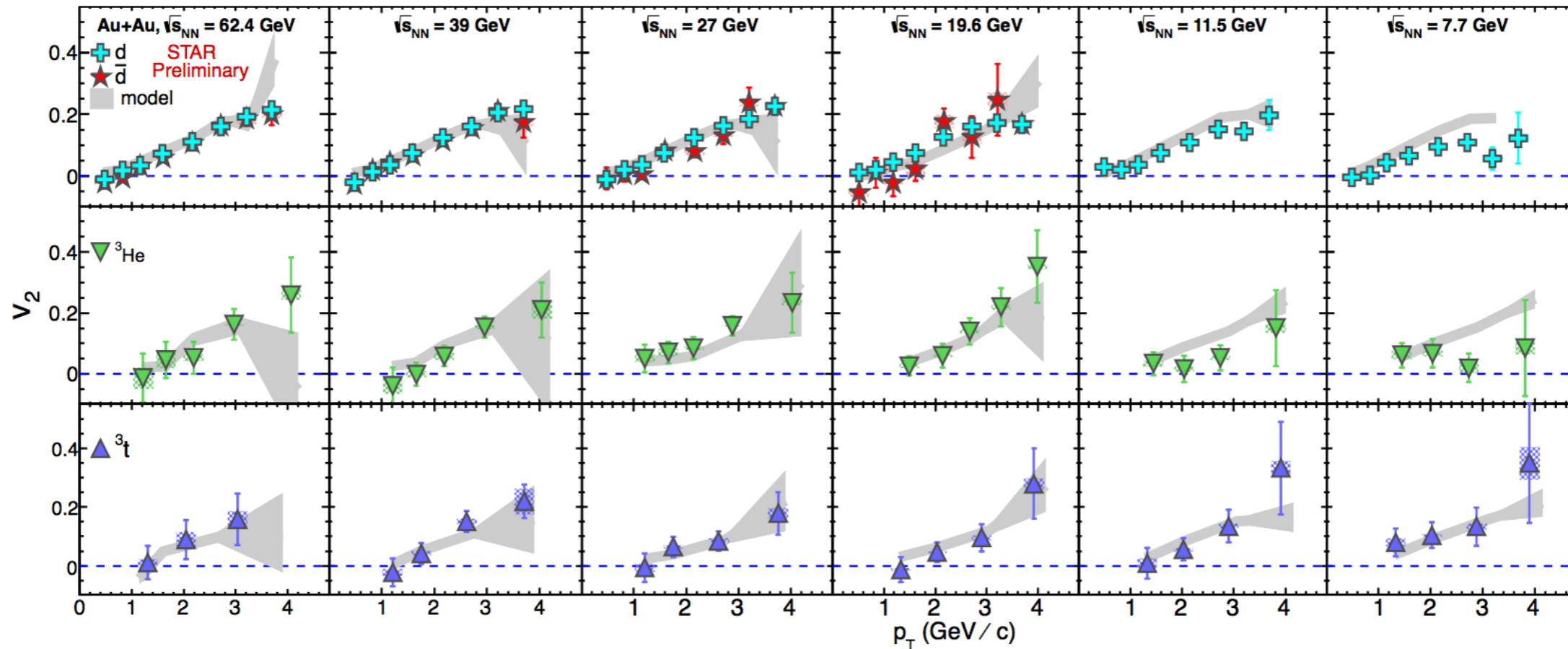
**Figure 2.** Left panel:  $\gamma_S$  as a function of centre-of-mass energy in central heavy ion collisions (from ref. [6]). Right panel:  $\gamma_S$  as a function of centrality in Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV in central heavy ion collisions [7].



**Figure 5.**  $\phi$  (left panel) and hyperons (right panel) rapidity density per wounded nucleon as a function of participants normalized to pp collisions. Data points from STAR [17]; solid lines are the predictions from core-corona superposition (see text).



# Coalescence model results

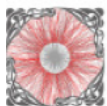


*Coalescence model agrees with data*

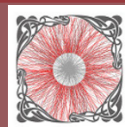
*→ Another indication of coalescence of nucleons to form nuclei*

- ✓ Probability for producing a nucleus is given by the overlap of nucleon phase-space distribution with the Wigner phase-space function of nucleons inside the nuclei.
- ✓ Nucleon phase space information used from a transport (AMPT) model.

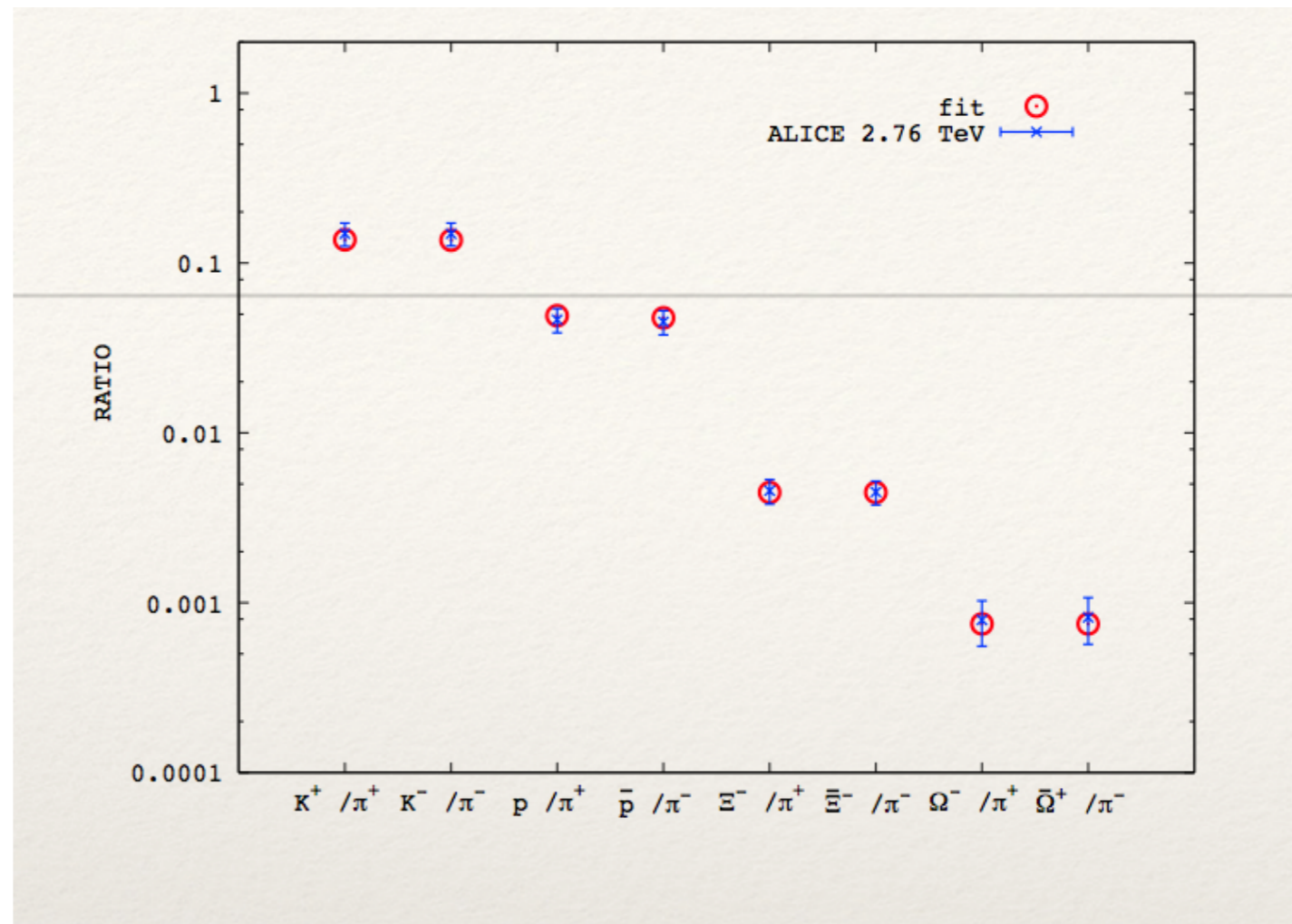
*R. Mattiello et al. Phys. Rev. Lett. 74, 2180 (1995), L. W. Chen et al. Phys. Rev. C 68, 017601 (2003)*  
*AMPT model: Zi-Wei Lin et al. Phys. Rev. C 72, 064901 (2005)*



# Chemical and Thermal analysis



Idea: take into account effect of resonances in a limited acceptance with a 2-freezeout blast wave model, using an iterative procedure



	$T$	$\mu_B$	$\mu_S$	$\rho_0$	$\eta_{max}$	$\chi^2/N$
C.F.	150.7	0.37	0.15			0.9
T. F.	112.9			1.28	6.05	3.4

**K. Seog Lee et al, Poster G-10**