What's hot – what's not at RHIC and LHC

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Topics I plan to address

- Collision energy dependent measurements in heavy ion collisions
  - Softest point
  - Critical point searches
  - Chemical freeze-out parameters
  - Low mass diletpons

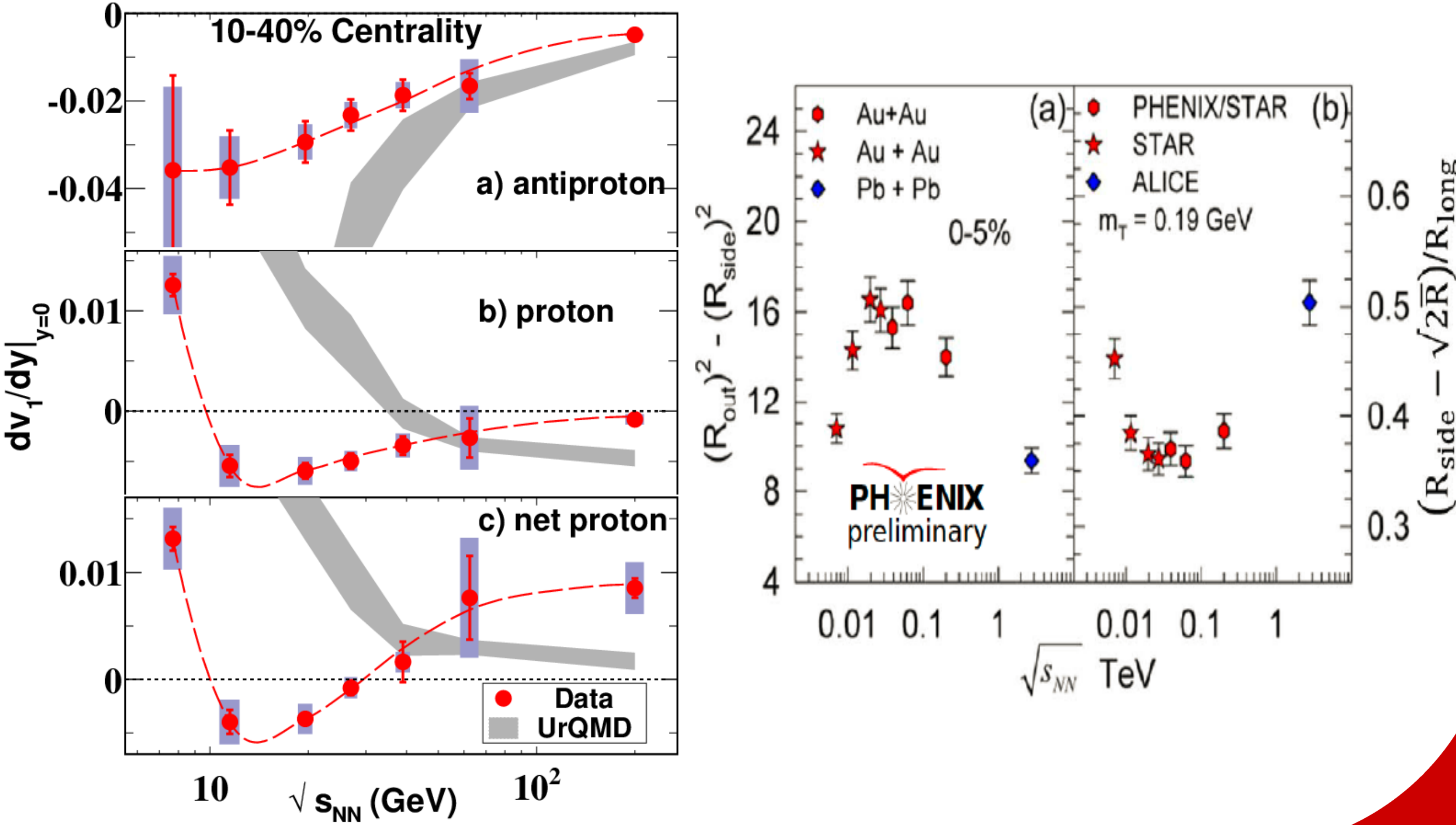
- Particle production and hadronization in heavy ion collisions
  - Strangeness and hypernuclei
  - Thermalization of charm
  - NCQ scaling and recombination

- Small systems – hot or not ?
  - Flow and particle production in pp and pPb
  - Color reconnection – is it interesting ?

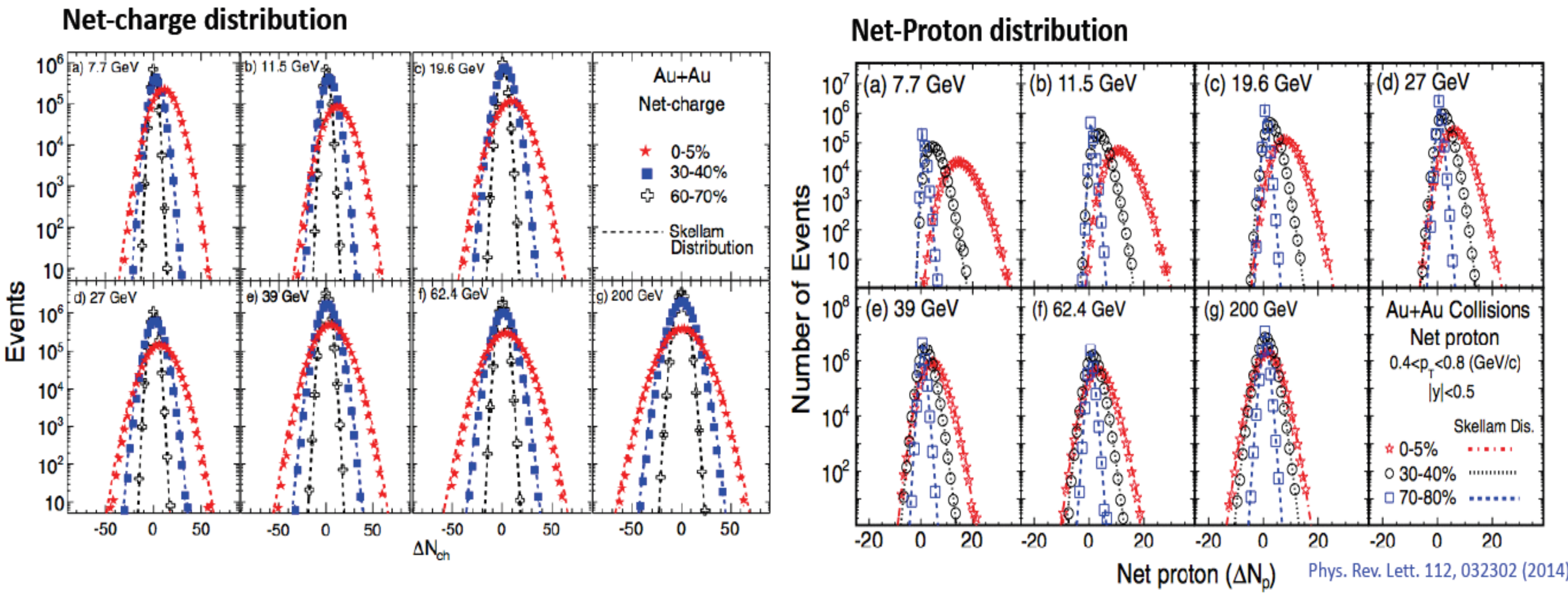
Beam Energy Scan results

The softest point (changing EOS)

Measuring directed flow (v_1) and HBT in BES (STAR, PHENIX)



The critical point (experimental approach): measure net-distributions and calculate moments



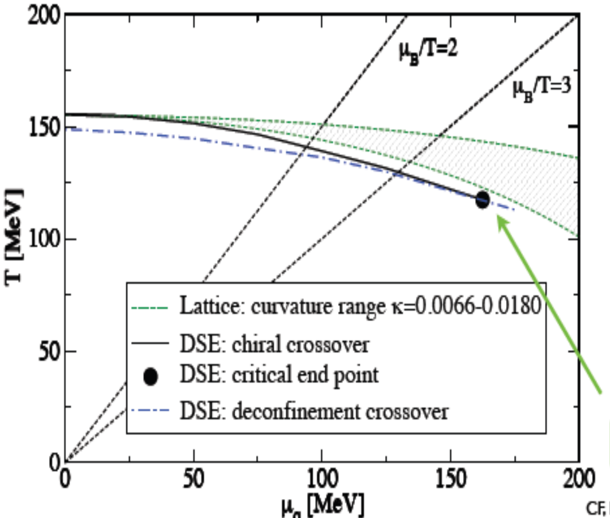
STAR distributions: the means shift towards zero from low to high energy

Then: calculate moments (c1-c4: mean, variance, skewness, kurtosis)

The critical point (theoretical approach)

- For a Gaussian distribution: skewness and kurtosis are zero.
- Look for non-Gaussian distribution near critical point
- Baseline for net-quantitites: Skellam (folded Poissonians)
- Fluctuations depend on correlation length

Theories / Models: PNJL, Dyson Schwinger, Lattice, NLSM

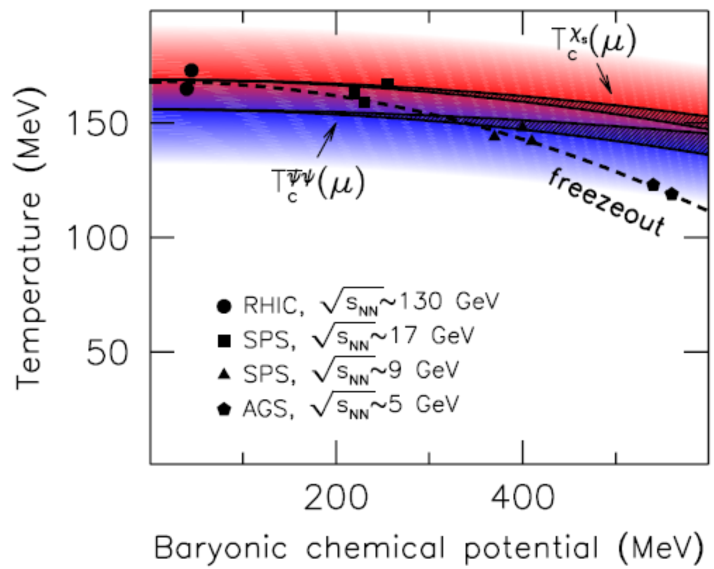


Extrapolated curvature from lattice

Kaczmarek at al. PRD 83 (2011) 014504,
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001
Cea, Cosmai, Papa, PRD 89 (2014) 074512

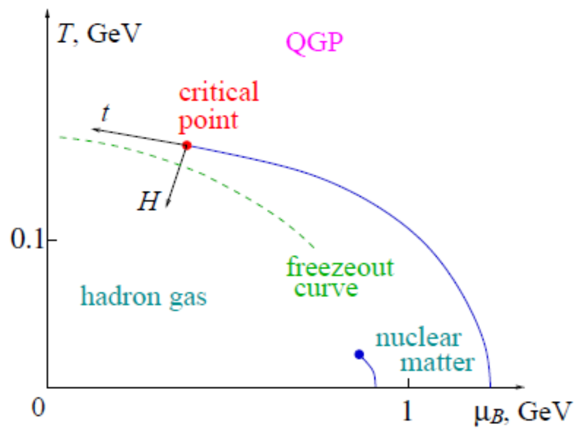
CEP at large μ

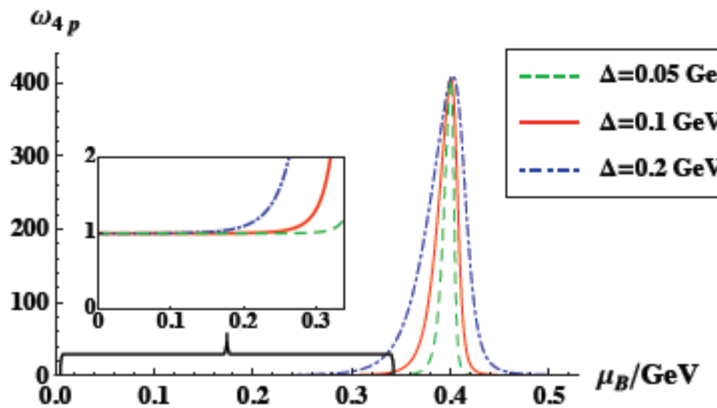
CF, Luecker, PLB 718 (2013) 1036,
CF, Fister, Luecker, Pawlowski, PLB in press, arXiv:1306.6022
CF, Luecker, Welzbacher, arXiv:1405.4762

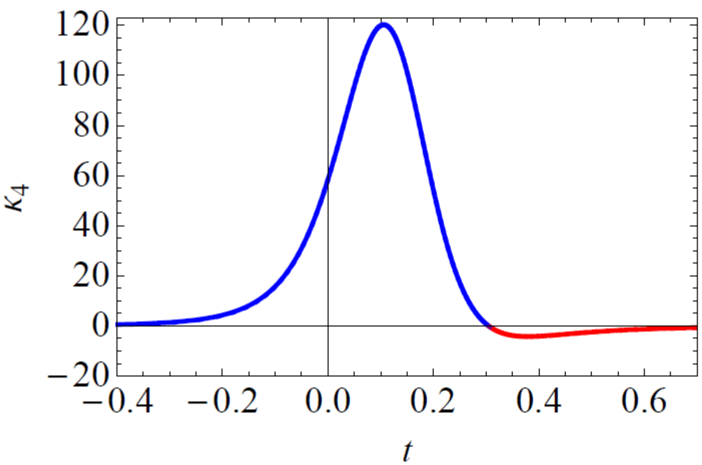


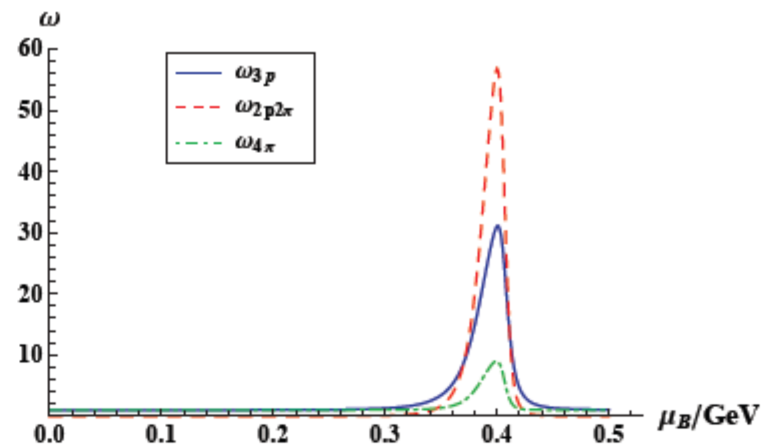
Theory: key predictions

- **The sigma field is isospin blind and its coupling can be applied to each particle species** (net-baryon = net-proton = proton distribution)
- **The coupling strength depends on the particle mass**, i.e. proton should show the strongest fluctuations, pions should not show much fluctuations (net-charge might be flat, net-protons need to show fluctuations)
- **Kurtosis should change its sign near critical point**





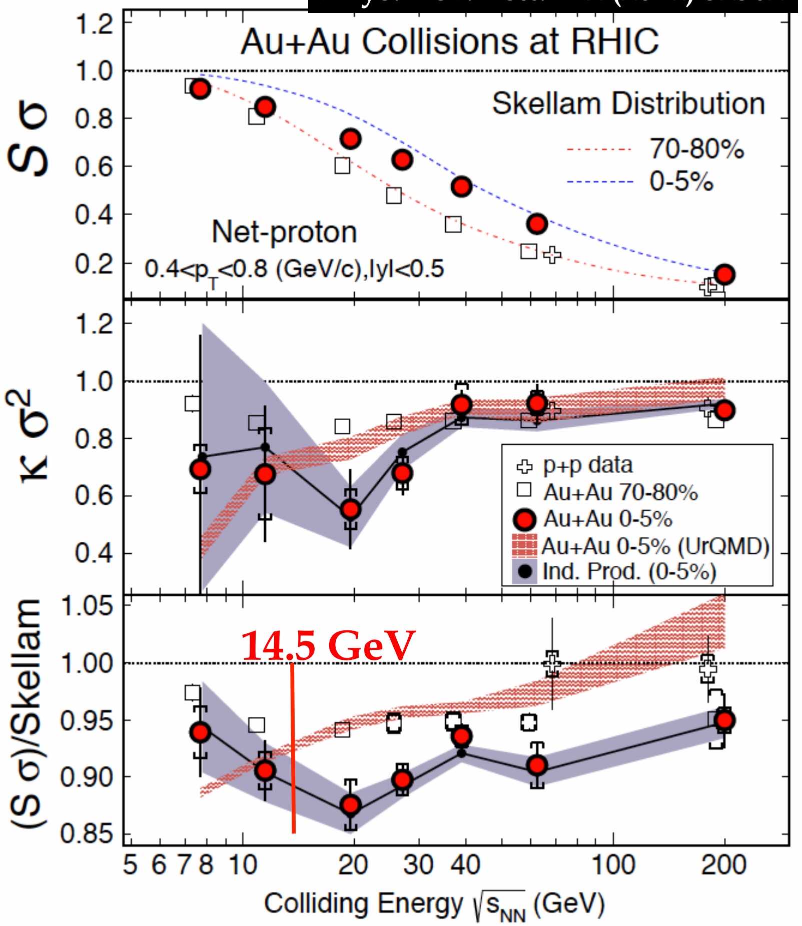




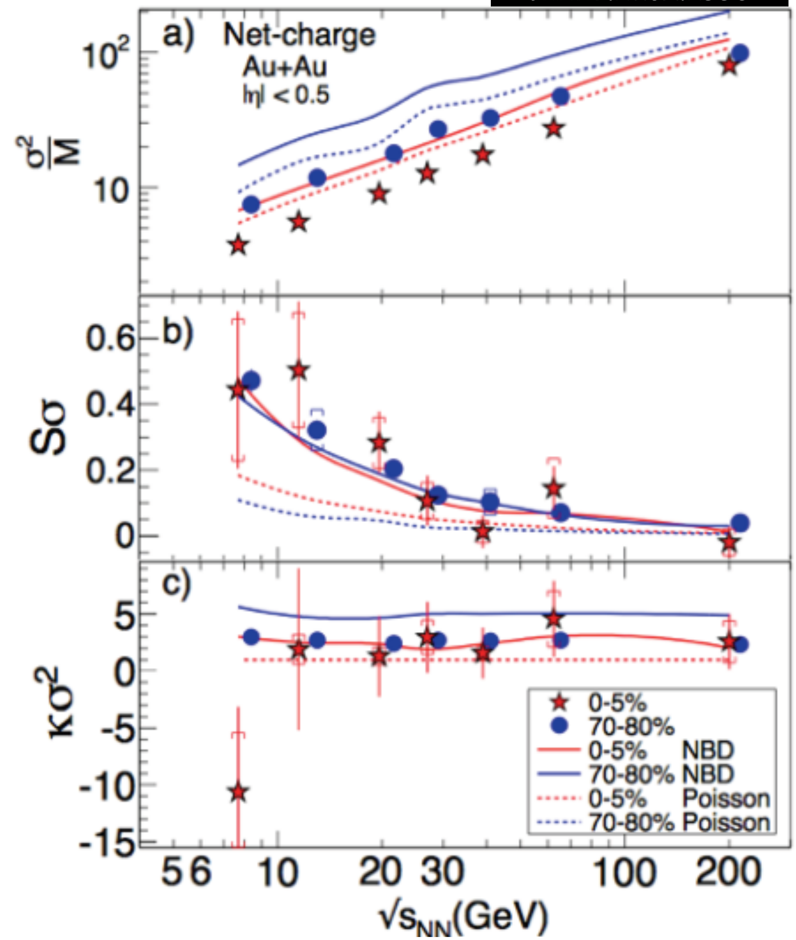
Searching for the critical point

Measuring higher moments of net-charged and net-protons (STAR)

Phys. Rev. Lett. 112 (2014) 32302



arXiv:1402.1558



Independent production (what does it mean ?)

STAR describes the data with 'independent production' : The data apparently do not require that the proton and anti-proton production is correlated. Data can be described when using the measured proton and anti-proton distributions separately.

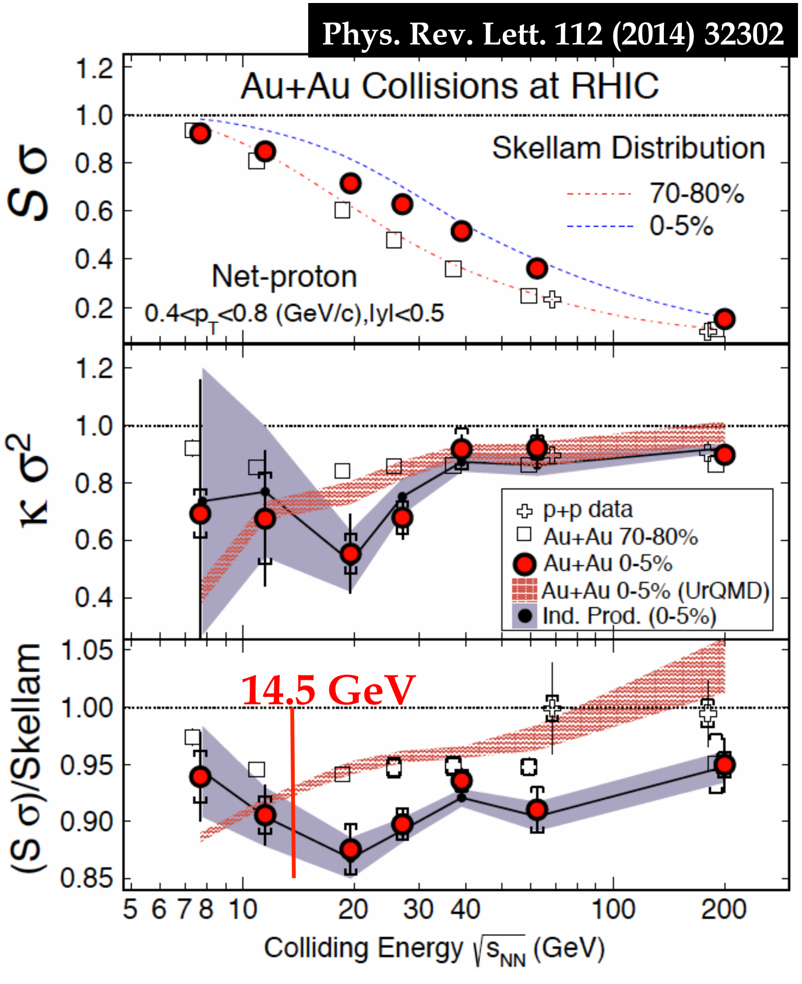
Remember: at low energies the net-proton fluctuations are dominated by the the primordial protons. Almost no anti-proton production, pbar/p < 10%.

Non-Linear Sigma Model (NLSM) : The conserved quantum number argument can still survive since according to the single particles couple to Sigma field (like quarks coupling to Higgs field). The larger the mass the stronger the coupling ($p>k>\pi$) .

Caveat 1: Single particle fluctuations might be affected by rescattering in hadronic phase (Kitazawa, QM 2014). The critical fluctuations wash out in the hadronic phase if the final (kinetic) freeze-out occurs sufficiently far from the critical point (more likely at higher temperatures). The exchange particle in the rescattering causes the fluctuations in the first place (Stephanov & Hatta)

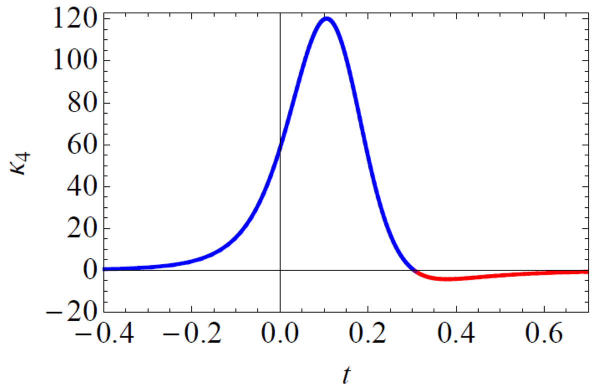
Caveat 2: Most of the measured protons are due to the baryon stopping of the colliding system and are not 'produced'. Therefore any fluctuation in the baryon stopping will be a fluctuation in the final number of protons and is not related to the quantum number conservation during particle production from the deconfined phase.

What goes down must come up….

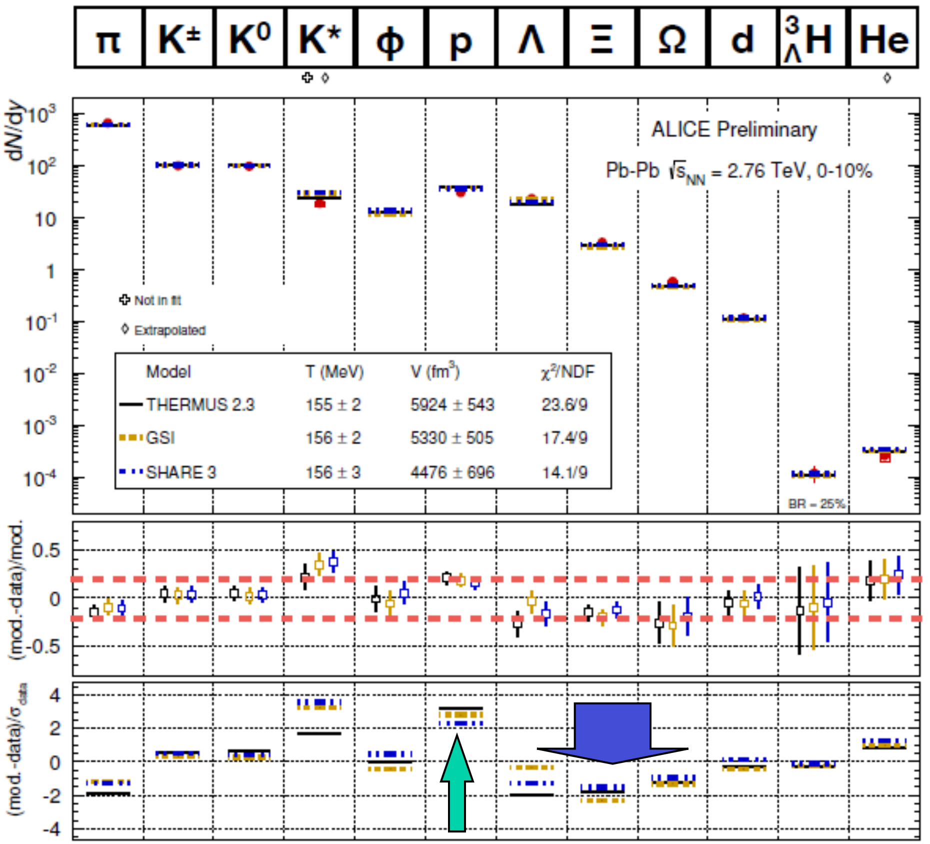


The lack of structure in the net-charge compared to the net-protons can be understood by the different coupling of specific species to the sigma field

But the negatvie kurtosis that might cause the dip near 20 GeV needs to be followed by a strong enhancement (positive kurtosis) at lower energies. The trends in the 14.5 GeV data provide a crucial test.



Chemical Freeze-out parameters



This looks like a good fit, but it is not

χ^2/NDF improves from 2 to 1 when pions and protons are excluded.

Fit to pions and protons alone yield a temperature of 148 MeV.

<u>Several alternate explanations:</u>

- Different T_{ch} for light and strange *(see talk by V. Mantovani)*
- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation

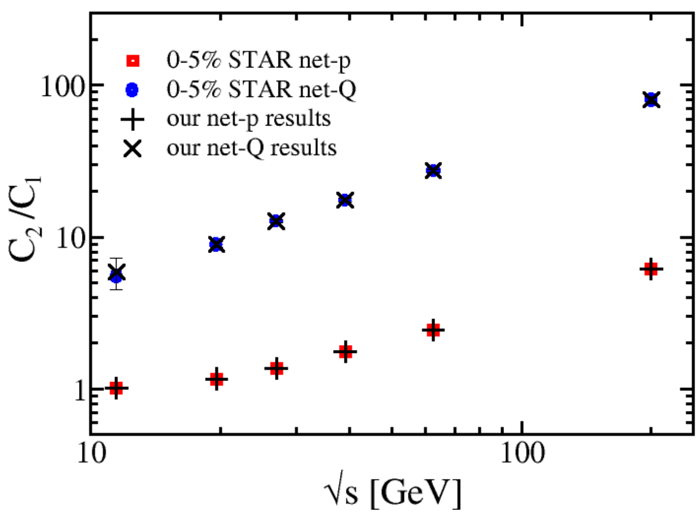
Determination through fluctuations (data)

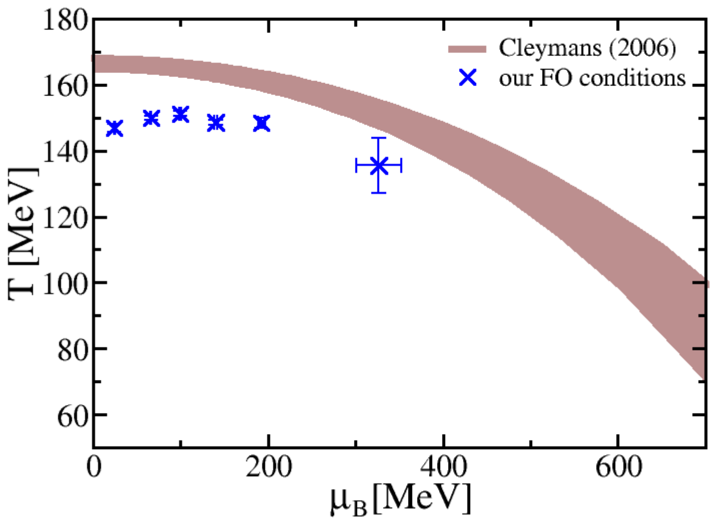
Use different higher moments ratios to determine the chemical freeze-out parameters (baryonometer, thermometer) from first principle lattice QCD and compare to HRG

$$\kappa_B\sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)}\left[\frac{1+\frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2+\ldots}\right]$$

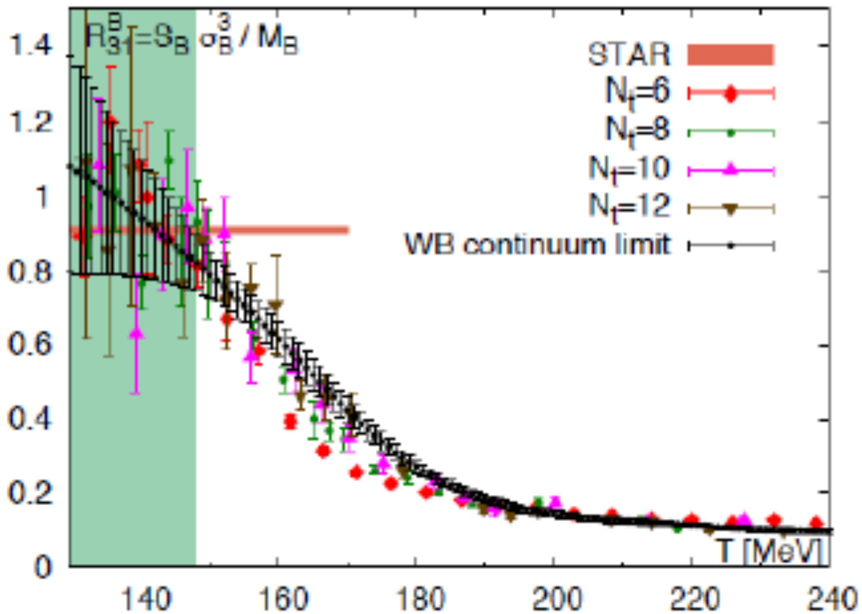
Simultaneous HRG fit to net-charge and net-protons

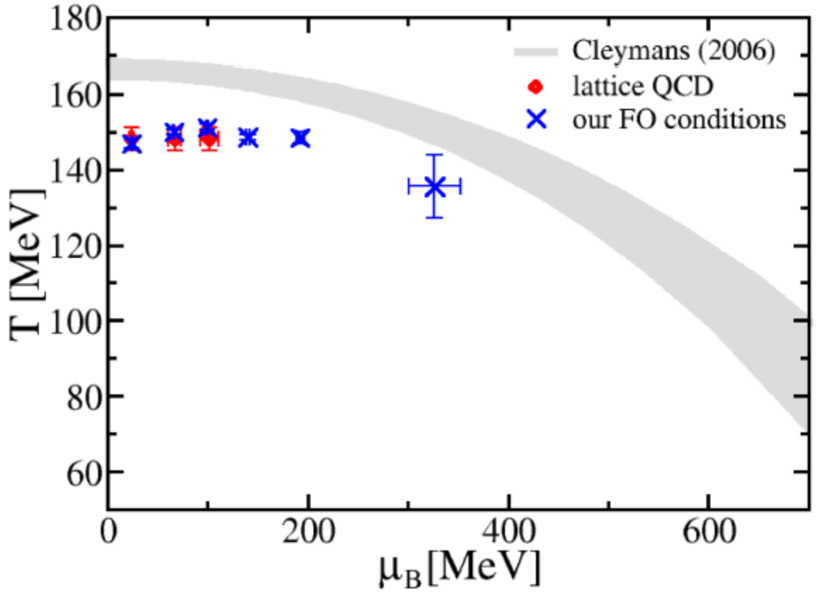
(P.Alba et al., arXiv: 1403.4903), *see talk by P. Alba on Tu afternoon*





Consistency between data, HRG, and lattice





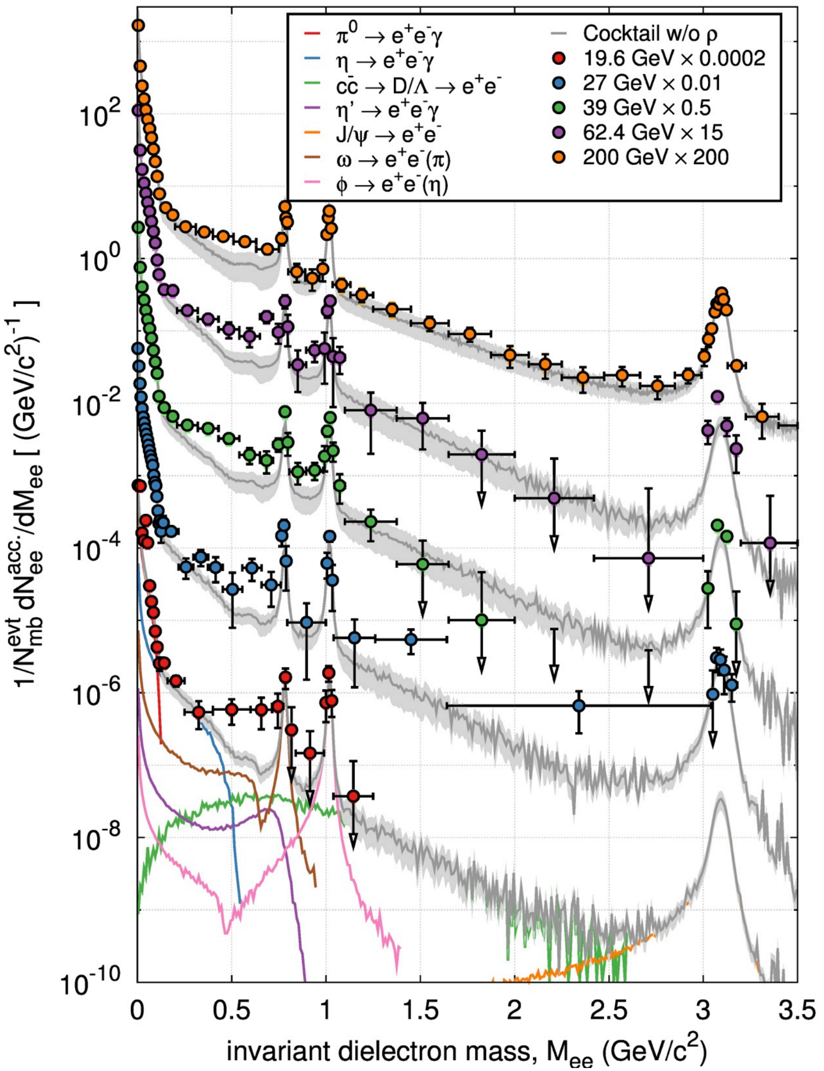
$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

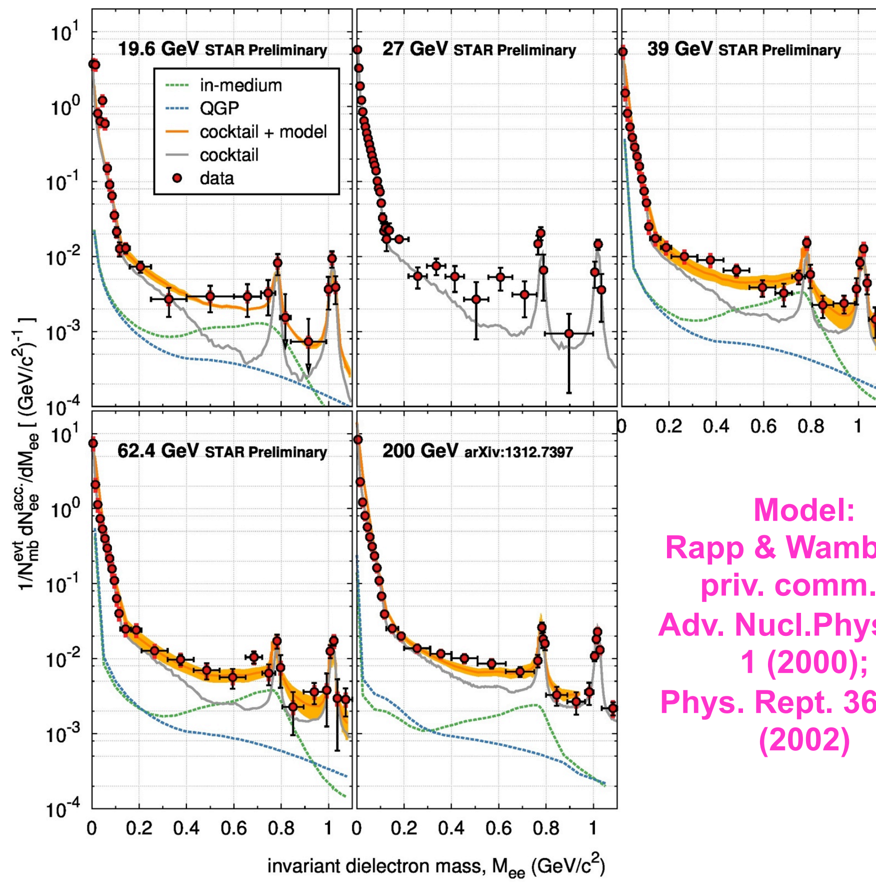
lattice QCD : S. Borsanyi et al., arXiv:1403.4576

(*see talk by C. Ratti on Tu morning*)

Maybe higher moments are more sensitive to freeze-out conditions than particle yields (*see talk by V. Mantovani on We afternoon*)

BES Low mass dileptons



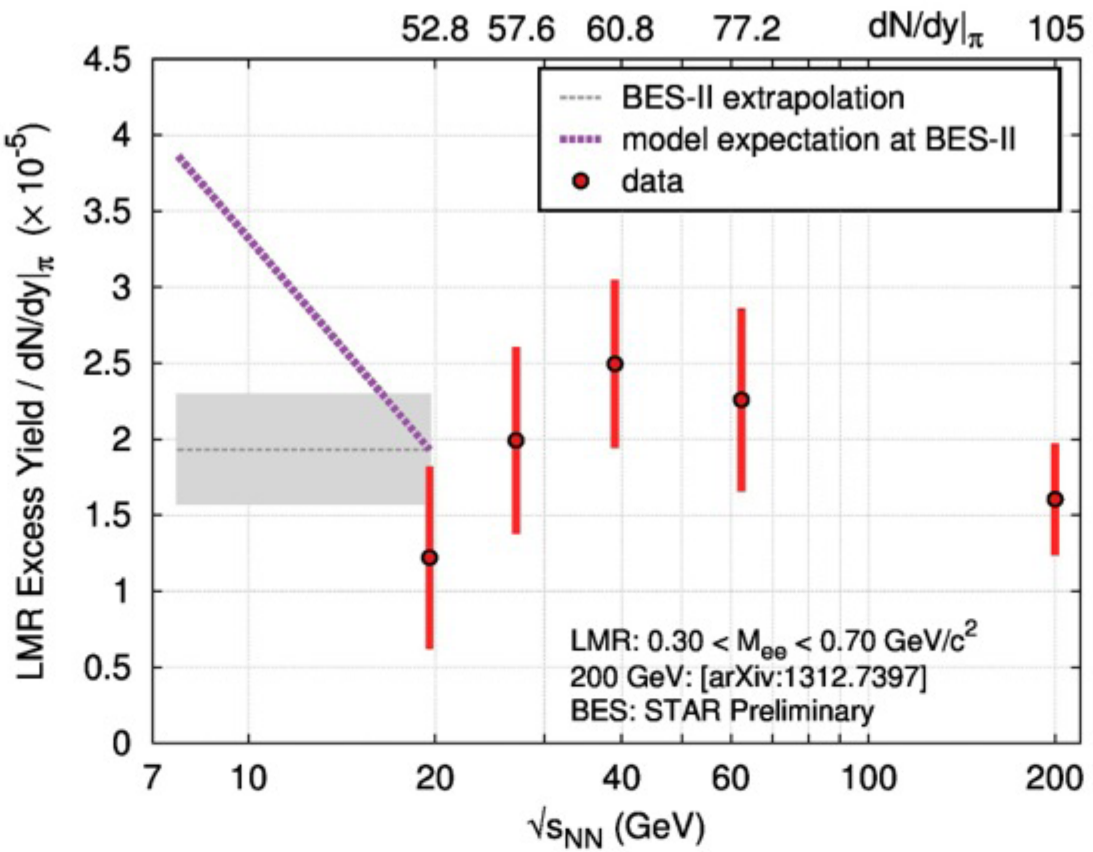


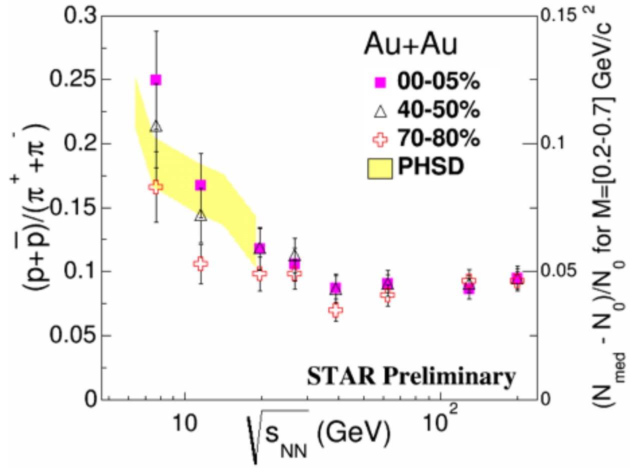
Model: Rapp & Wambach, priv. comm. & Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

A broadened ρ spectrum function consistently describes the low mass excess from 19.6 to 200 GeV in AA.

No modification in pp, dA, pA at RHIC and LHC.

Mass broadening should be baryon density dependent

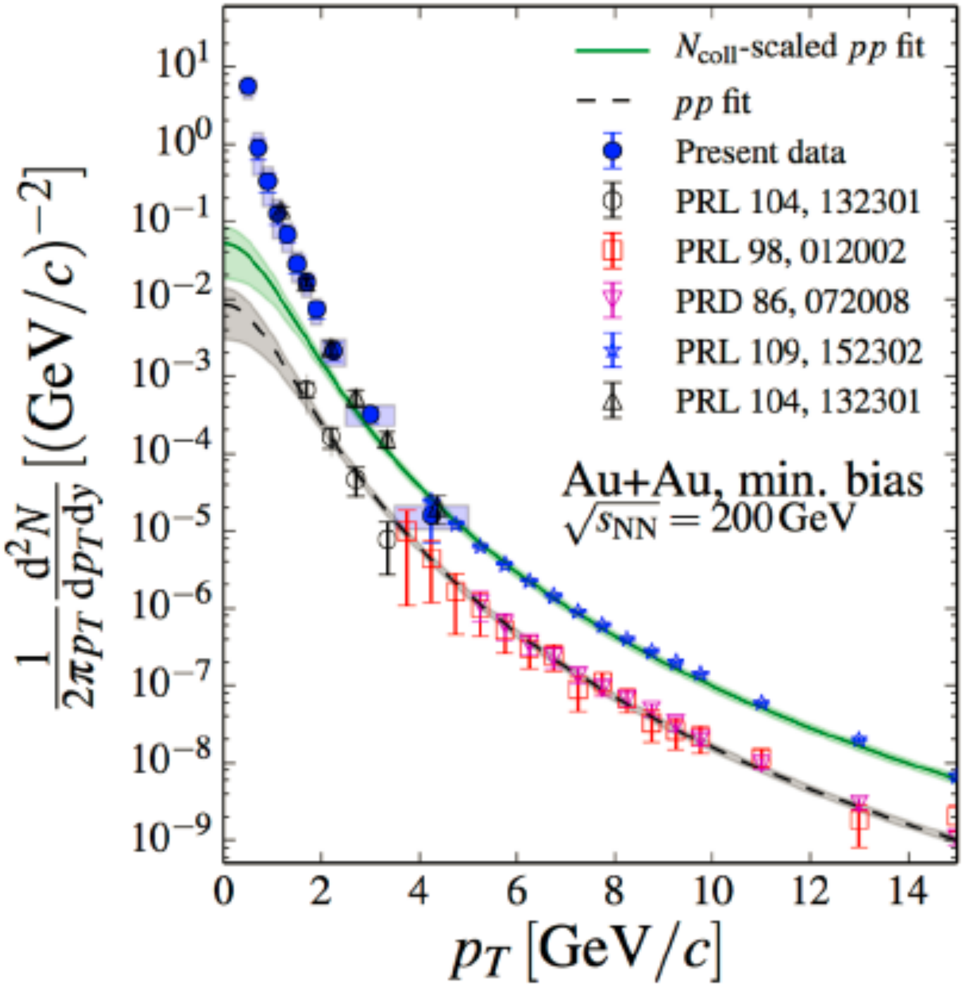




No evidence yet. Error bars too big, BES-II should help.

Particle Production, Hadronization & Flow

High precision thermal photon measurement



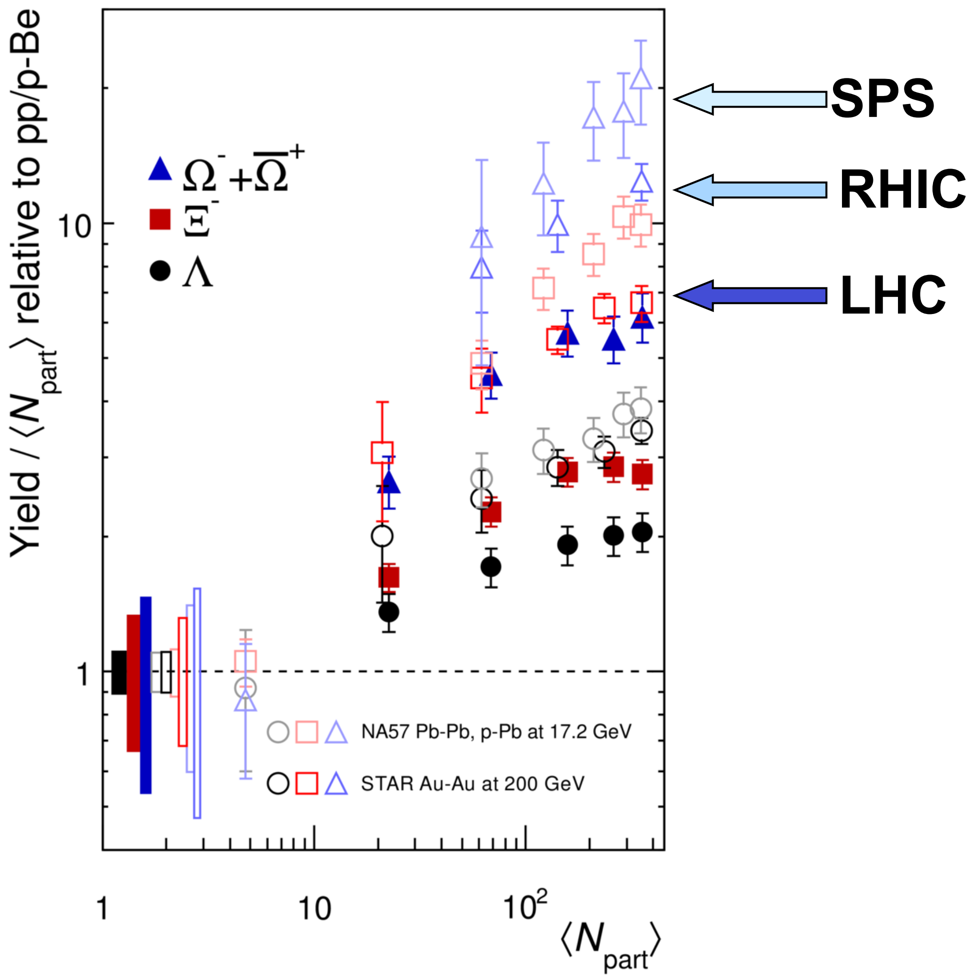
arXiv:1405.3940 (PHENIX)

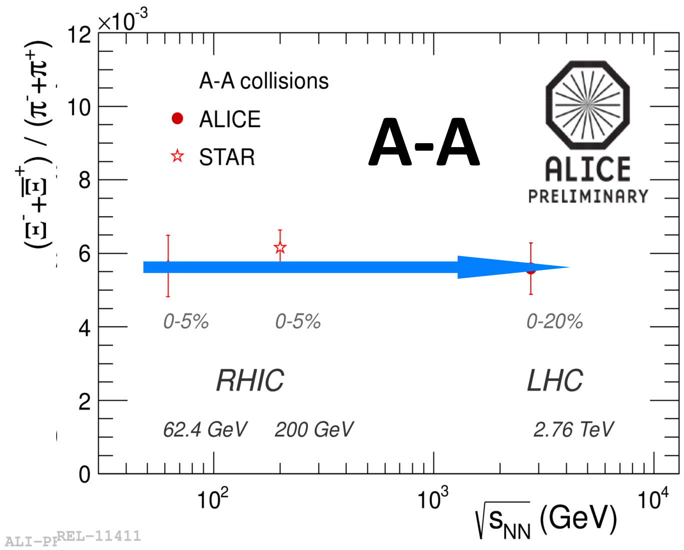
Exponential slopes of photon excess are centrality independent within uncertainties

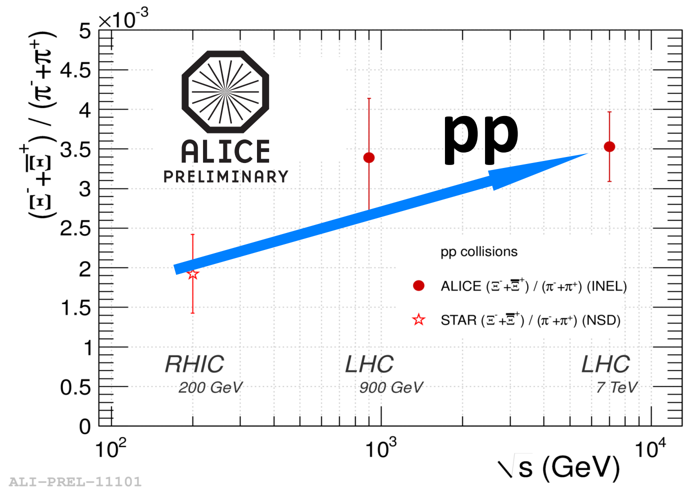
Yield = B exp(-pT/T)

T (0-20%) = 239 ± 25 ± 7 MeV
T (20-40%) = 260 ± 33 ± 8 MeV
T (40-60%) = 225 ± 28 ± 6 MeV
T (60-92%) = 238 ± 50 ± 6 MeV

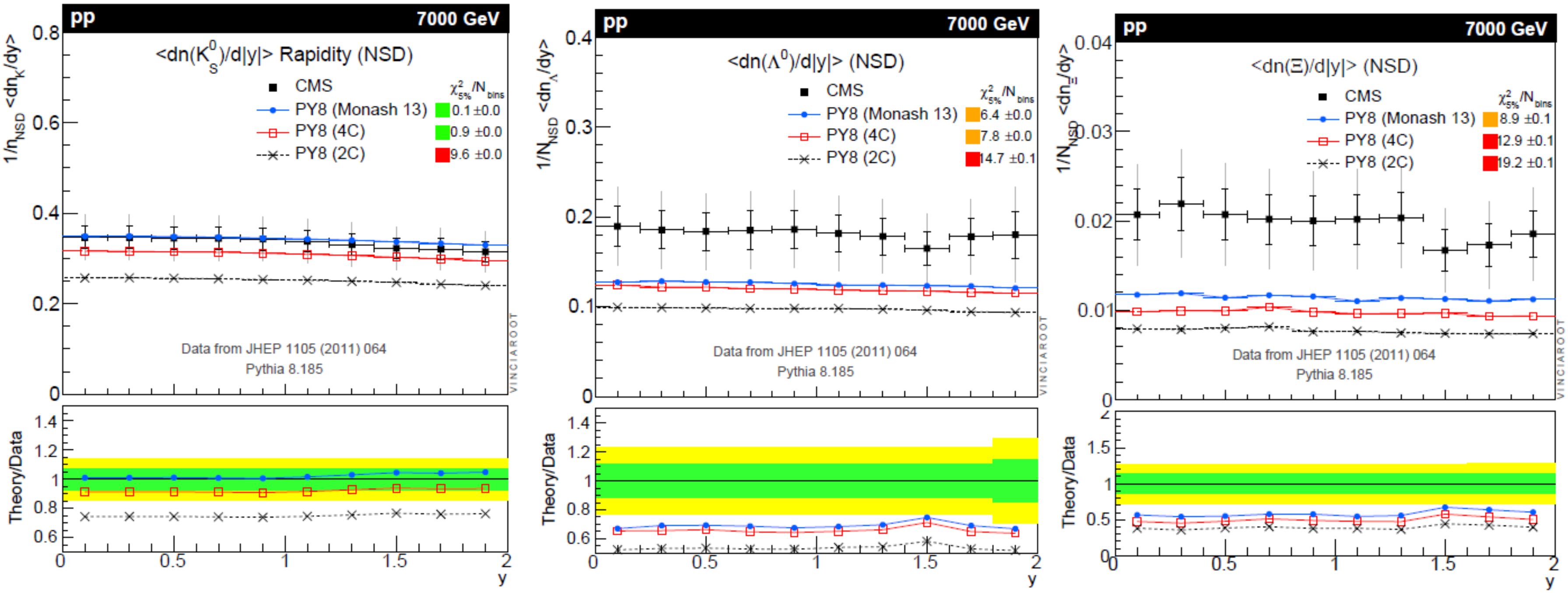
Energy dependent decrease in strangeness enhancement = reduction in strangeness suppression





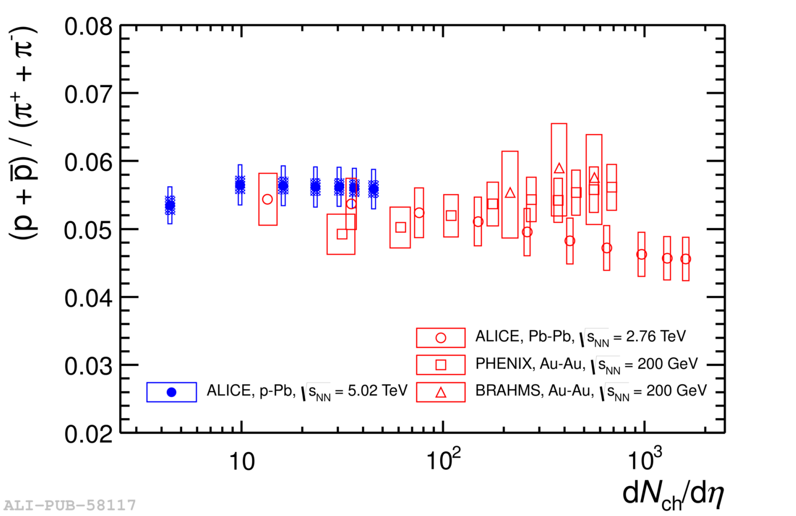


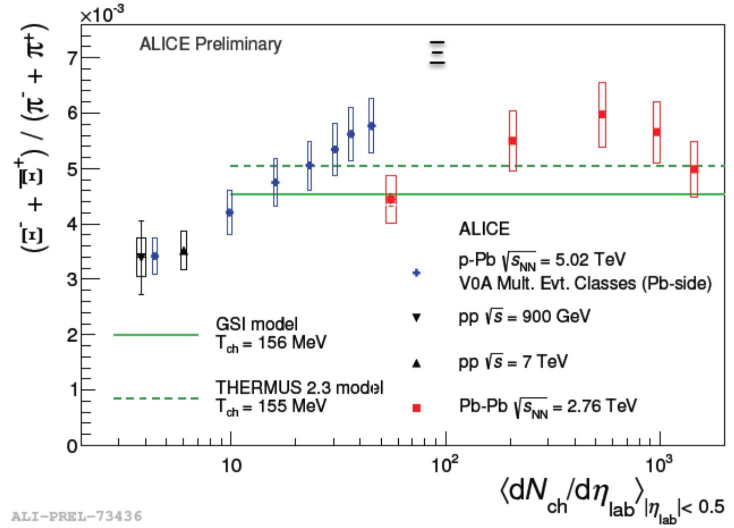
The very latest from PYTHIA 8.1 Monash tune (arXiv:1404.5630)

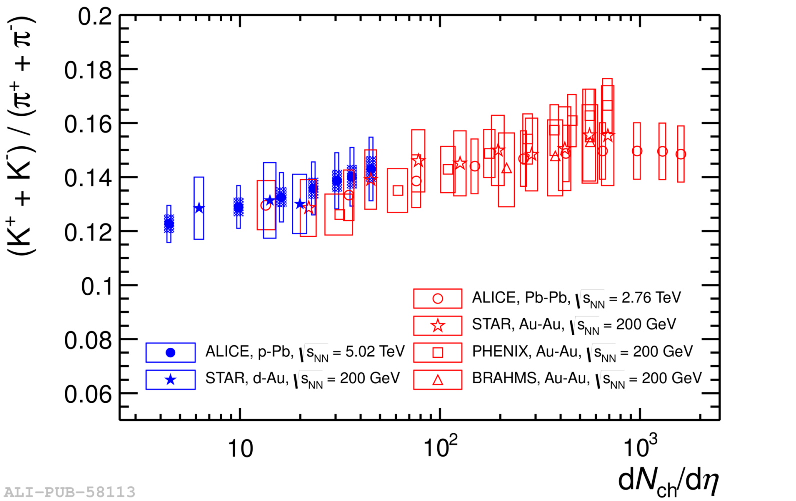


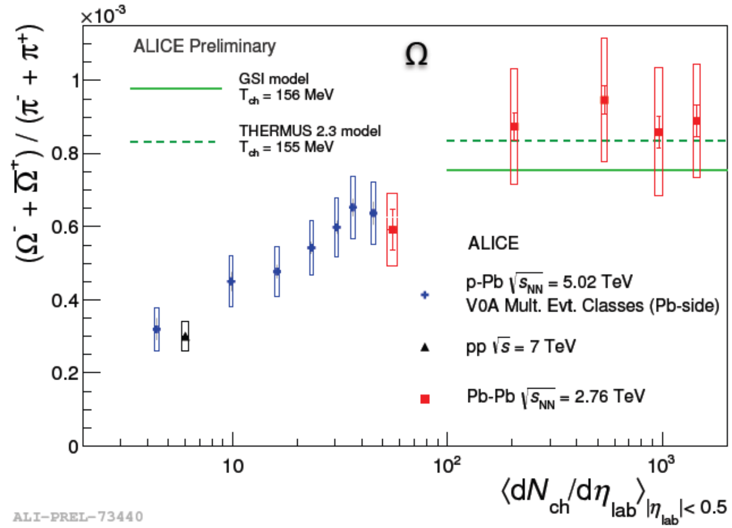
Things are still not well in baryon production

Particle production as a function of system size

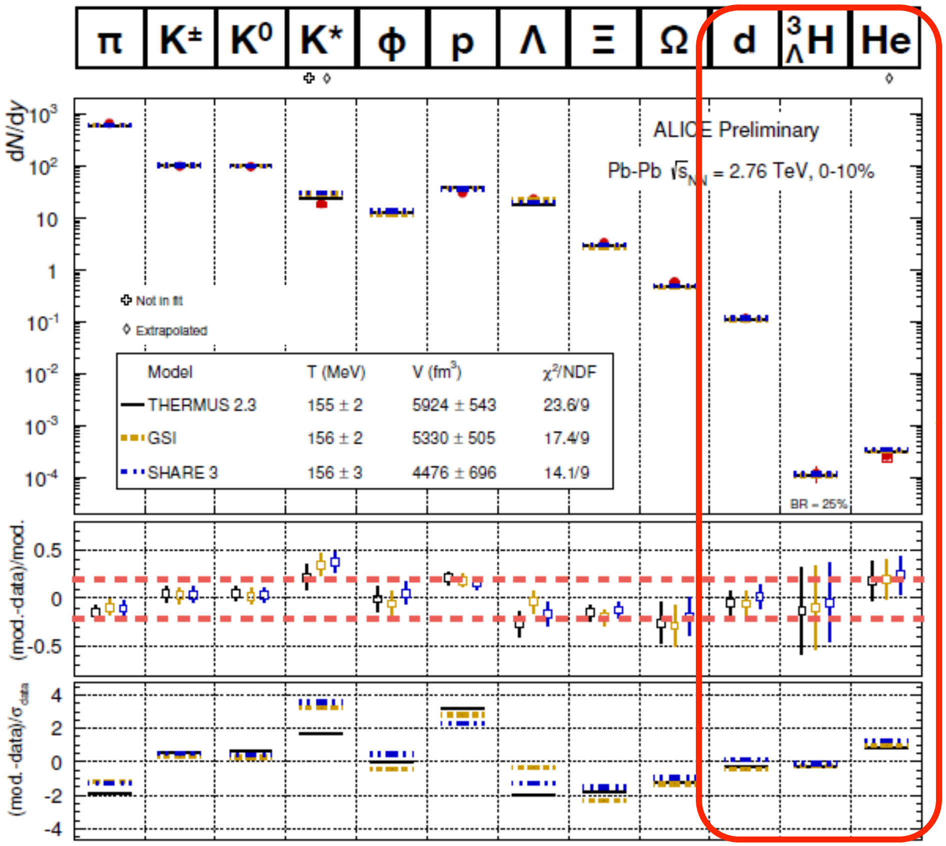








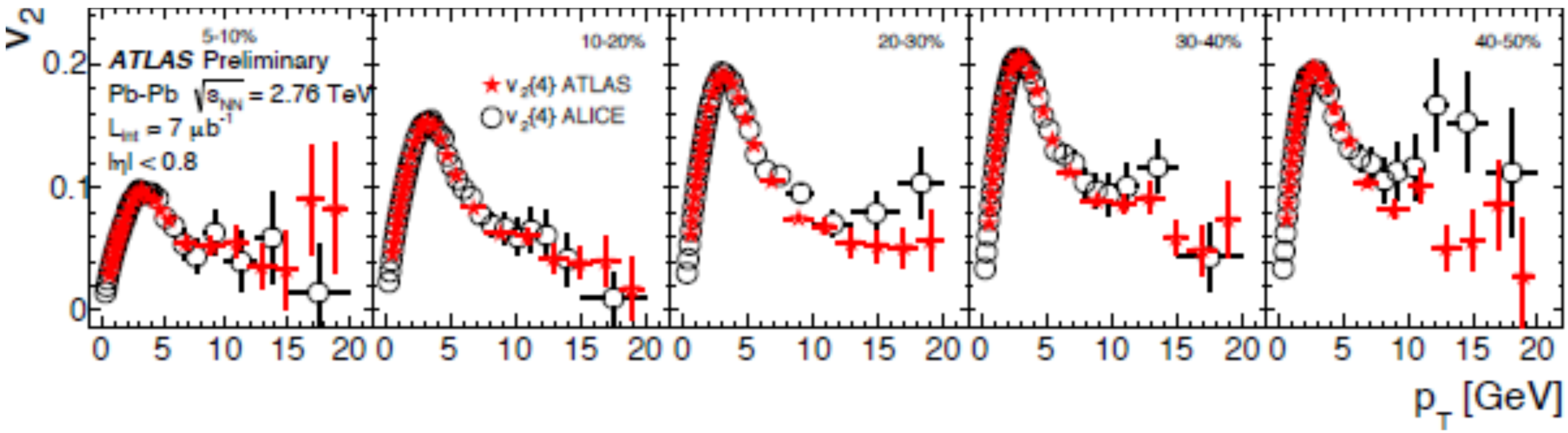
The fate of very loosely bound states

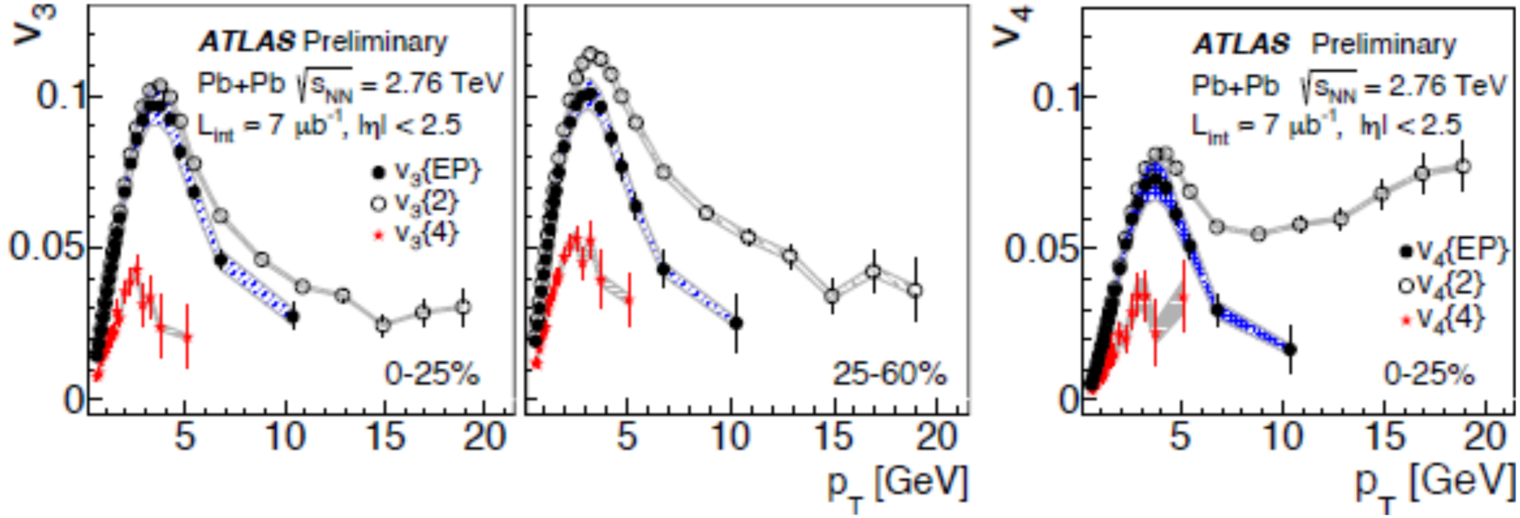


How can the yield of a bound state with binding energy 1/1000 of the temperature of the heat bath be determined at chemical freeze-out ?

Entropy conservation (PBM, Stachel) ? Is coalescence wrong ?

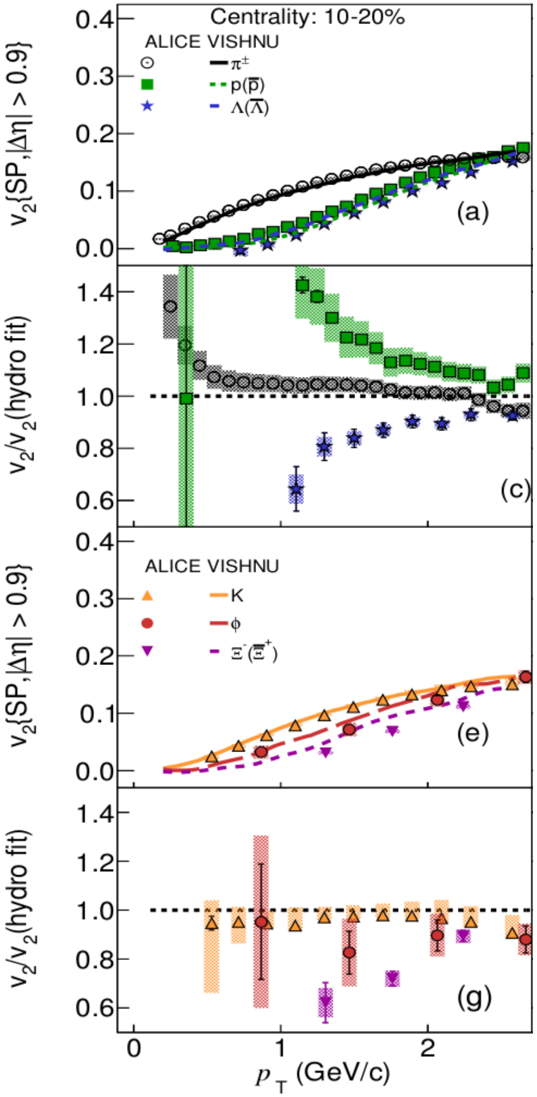
Heavy Ion Flow

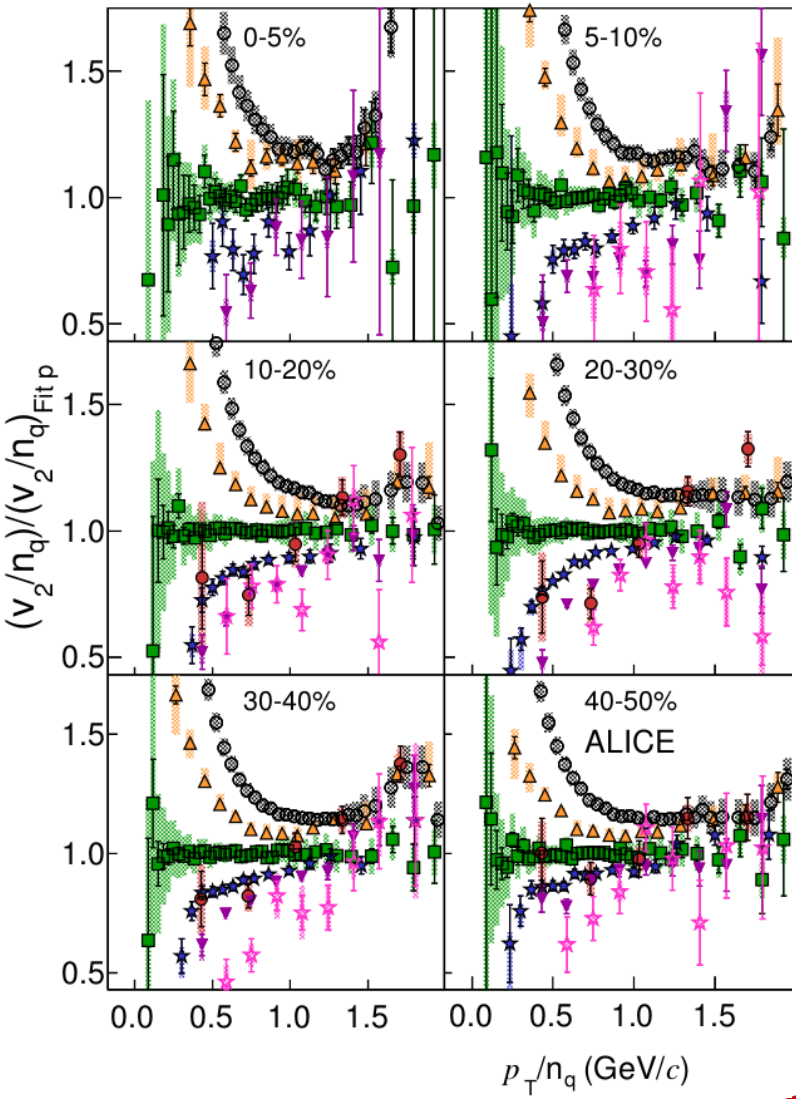




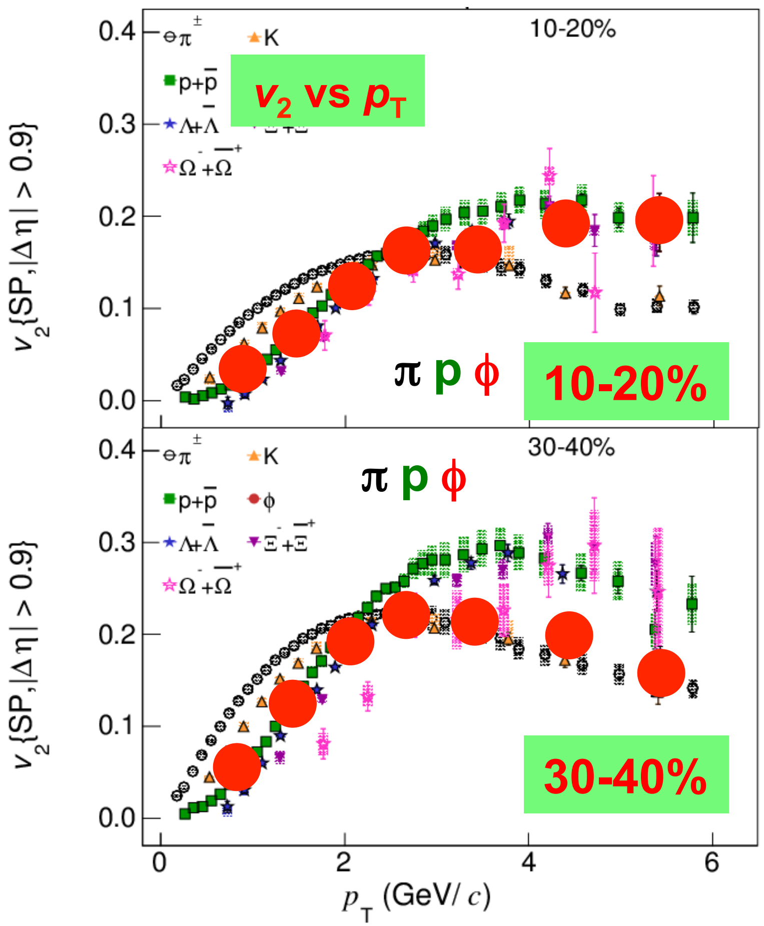
Significant precision to high pT and for higher order harmonics

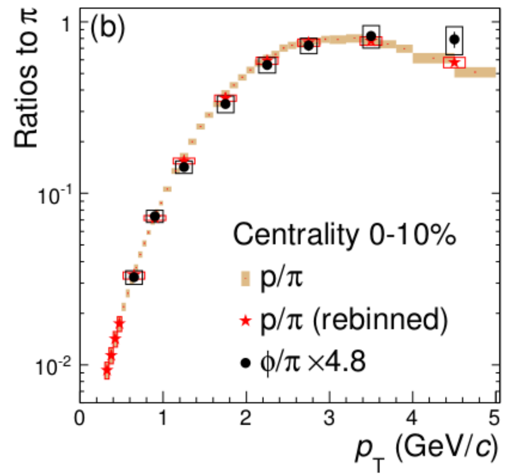
Is recombination dead ? Not yet

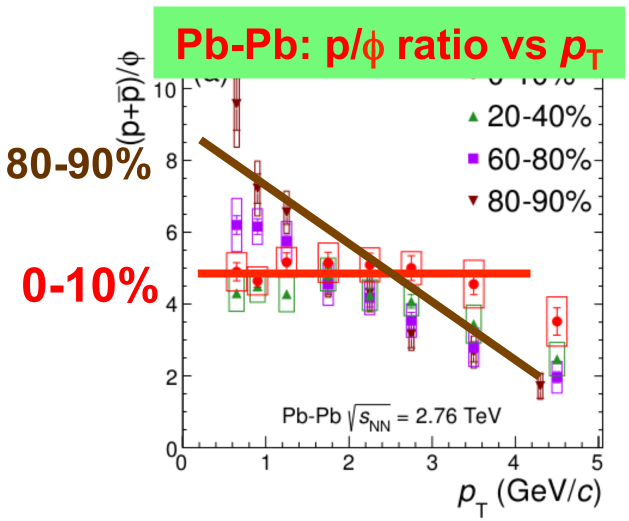




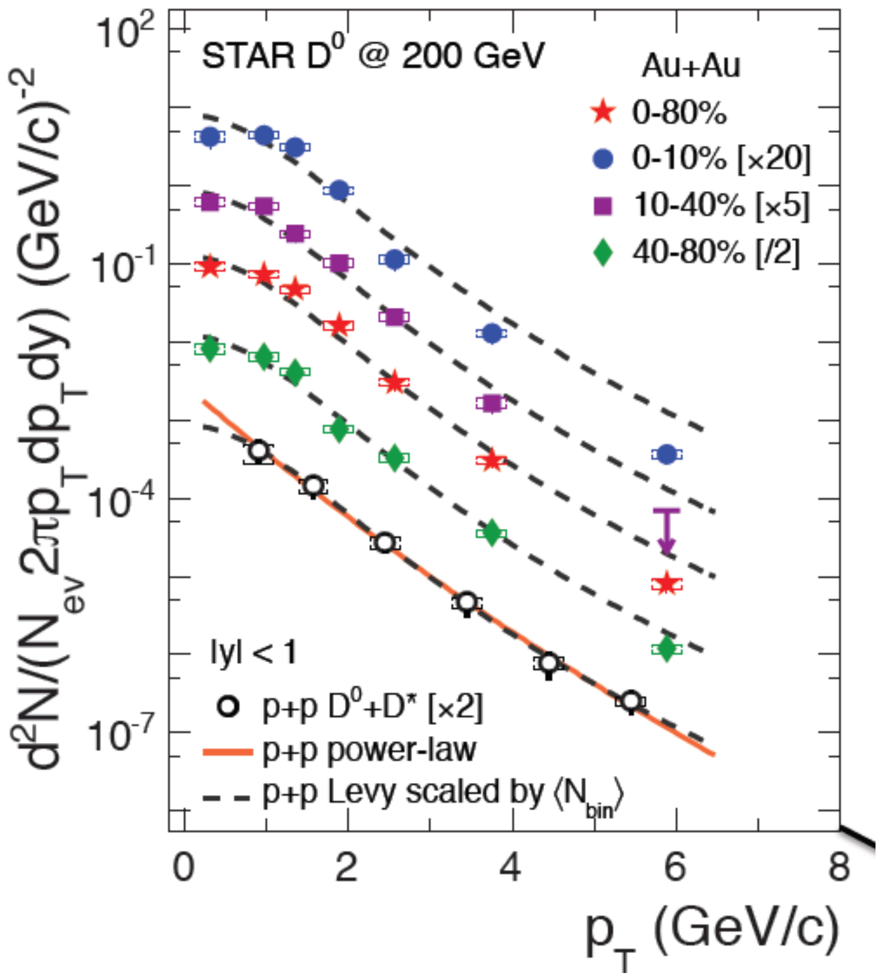
Is recombination dead ? Maybe







Is charm thermally produced and/or does it thermalize during the partonic phase evolution ?

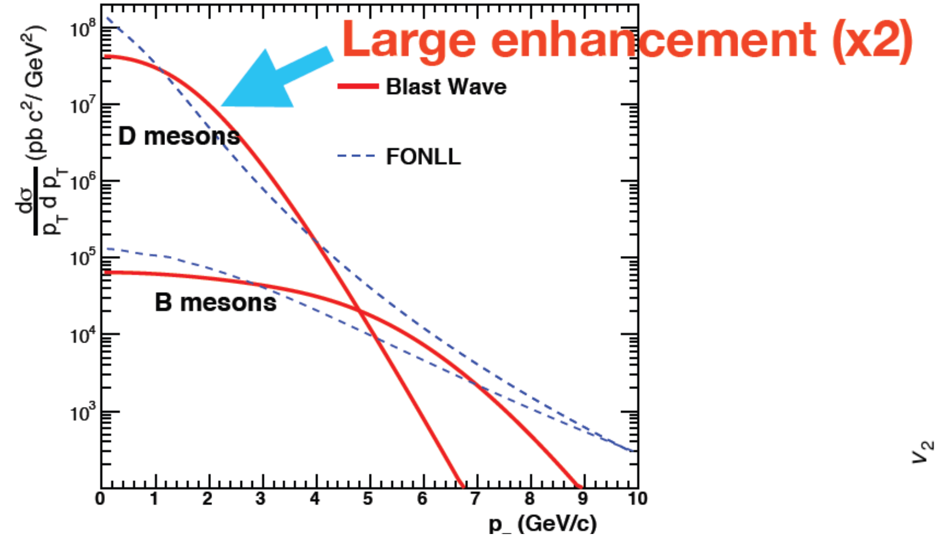


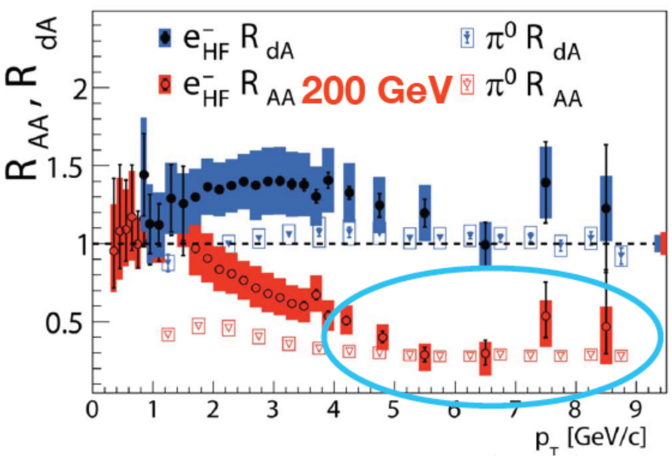
Production:
Not thermal at RHIC
Scales with <Nbin>

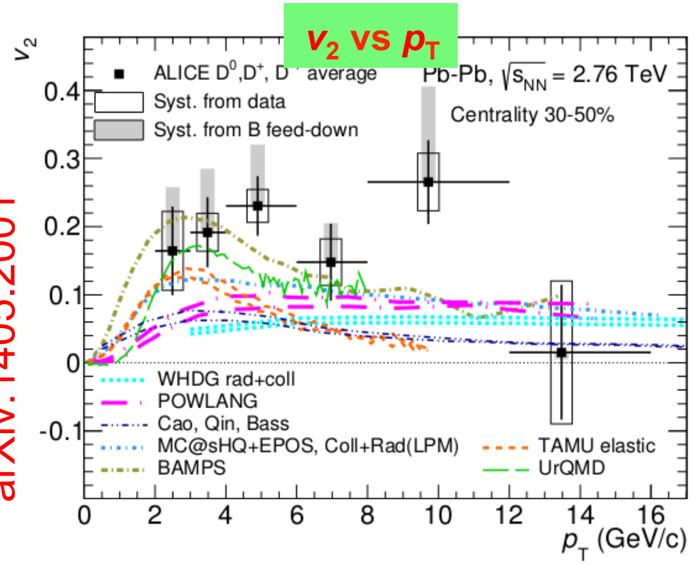
Spectral shape:
Changes from peripheral to central

Evidence for radial flow (Levy fit)

The thermalization of charm

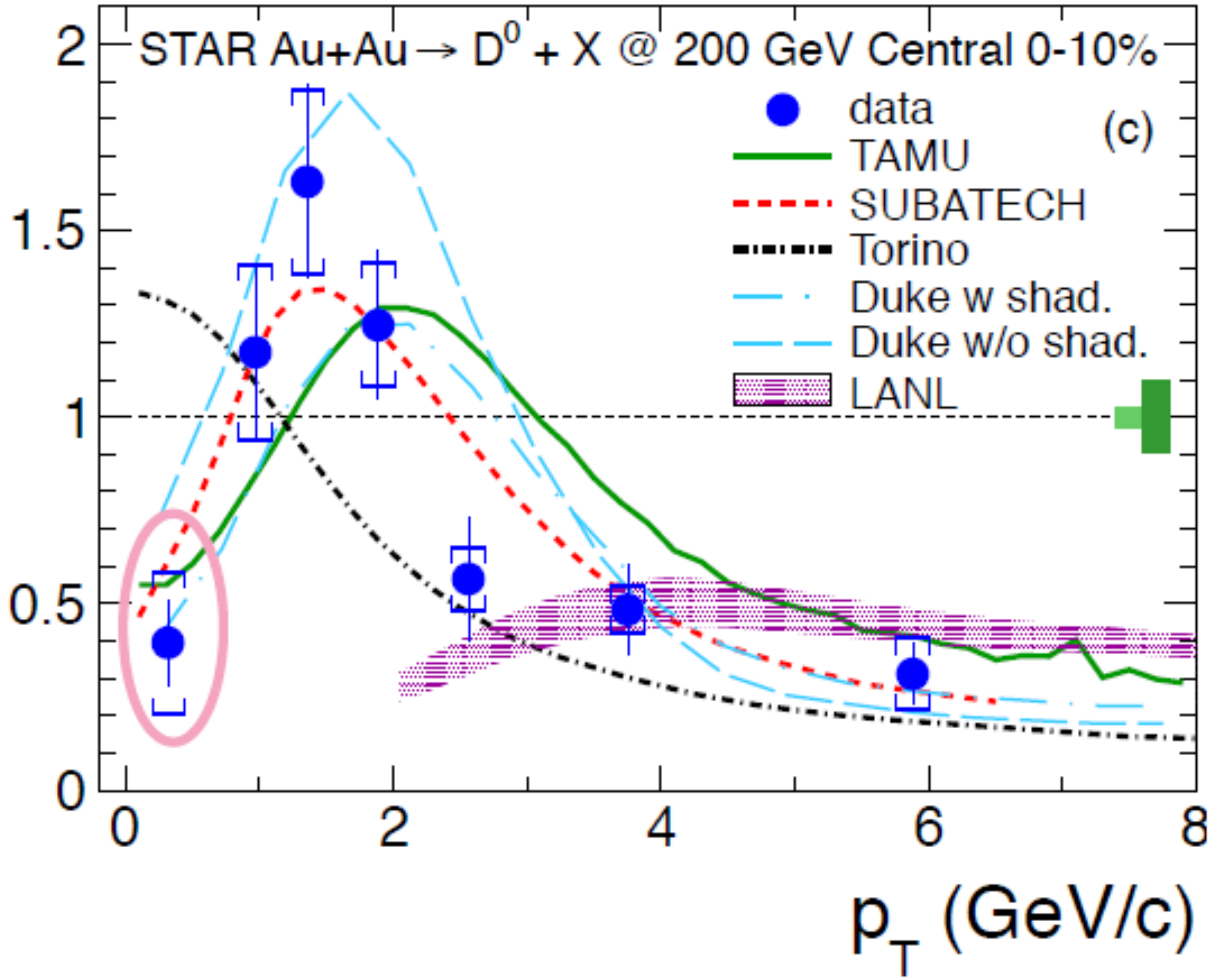






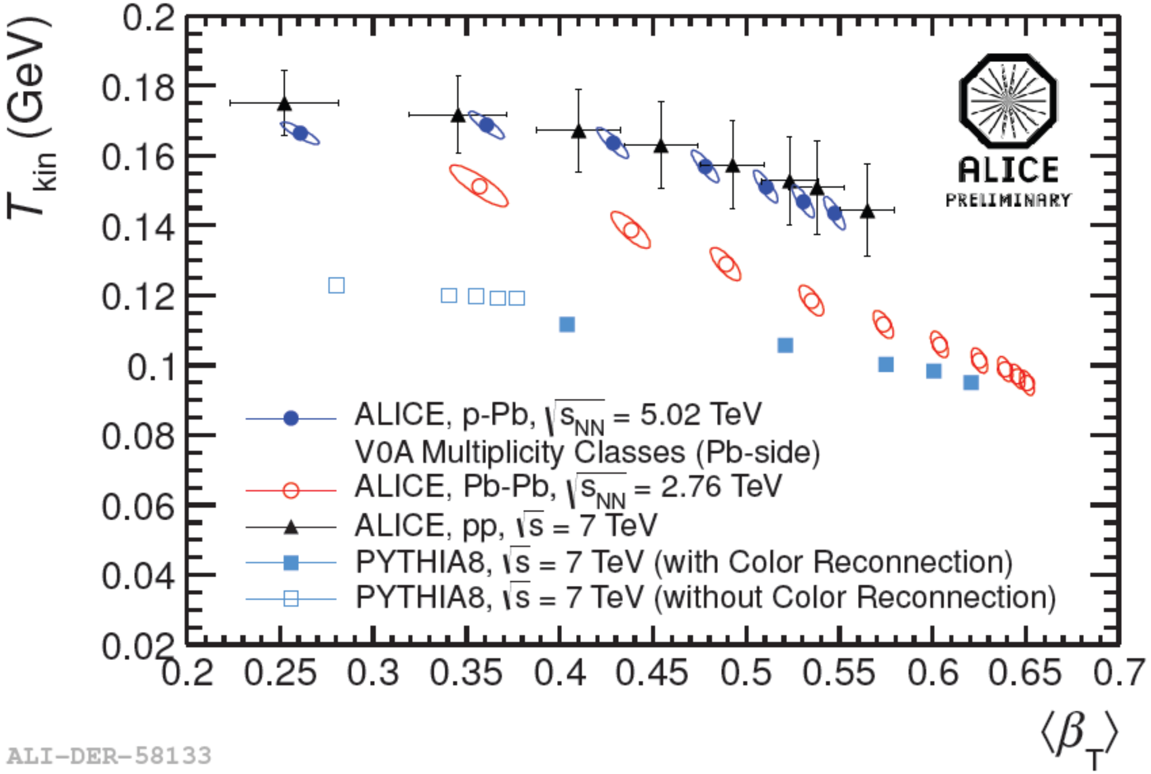
arXiv:1405.2001

Is recombination dead ? Not yet



Small Systems

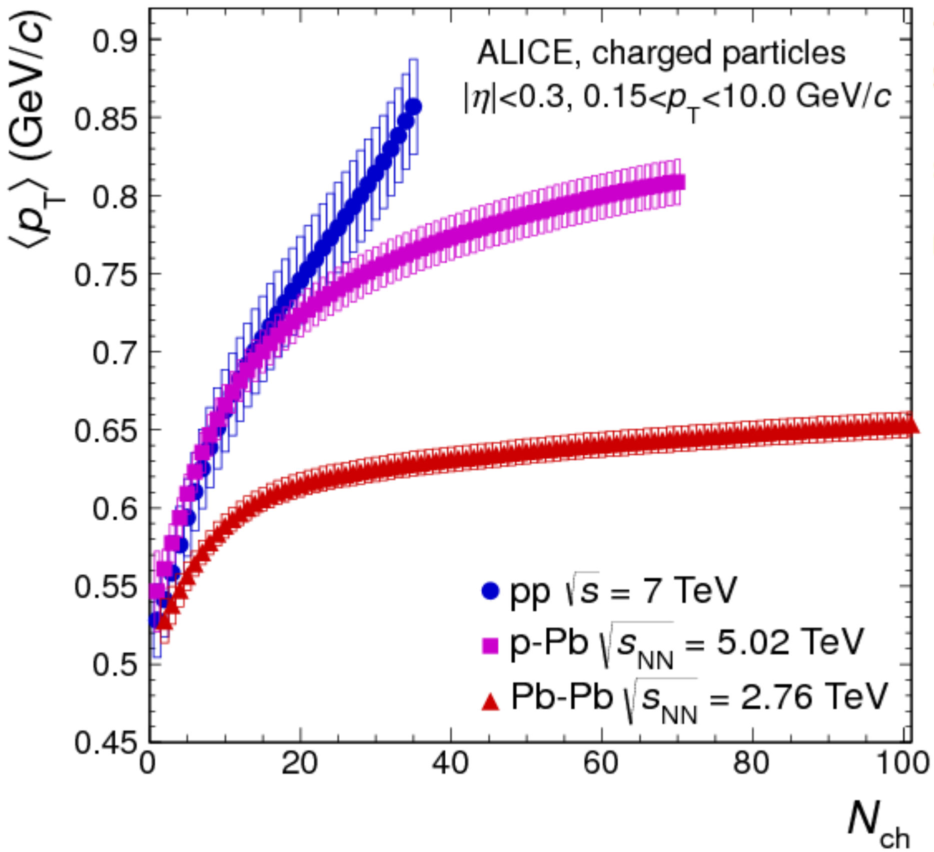
How small is too small ?

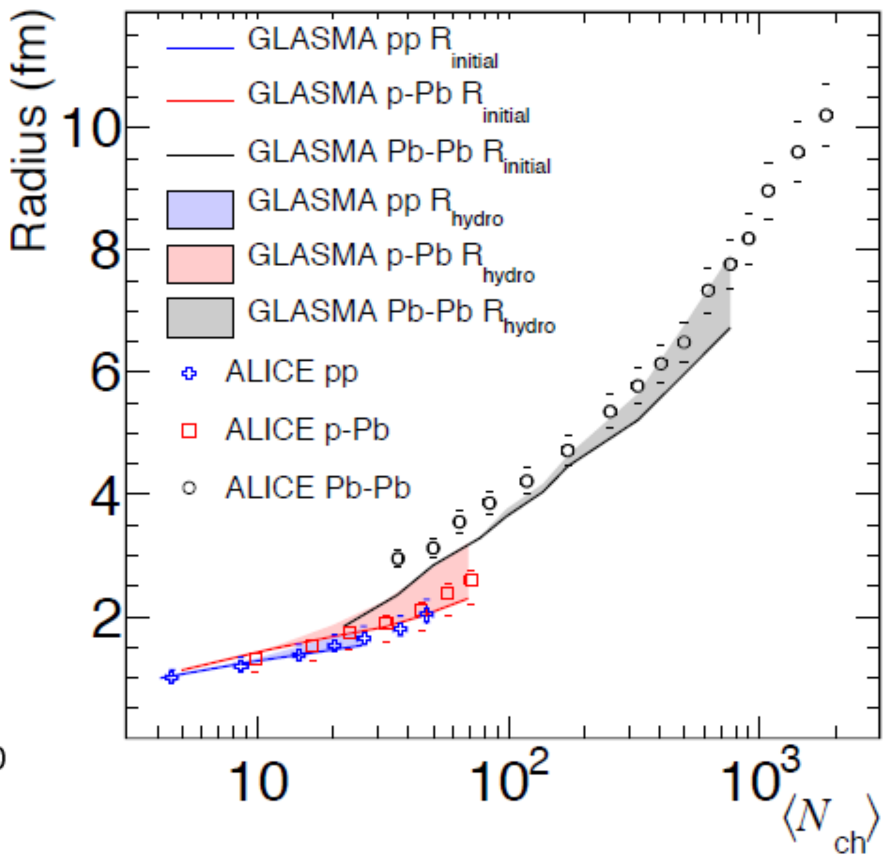


Buzz of the month:

multi-parton interactions = color reconnection = pomeron ladders = partonic cascade ?

System size evolution of kinematics and source





The model descriptions

From Initial State to Initial Conditions

Weakly coupled, strongly interacting system = high gluon density = CGC ?

multi-parton interactions = color reconnection = pomeron ladders

The evolution

Transport: multi-parton interactions = partonic cascade ?

(BAMPS, EPOS, AMPT)

Or

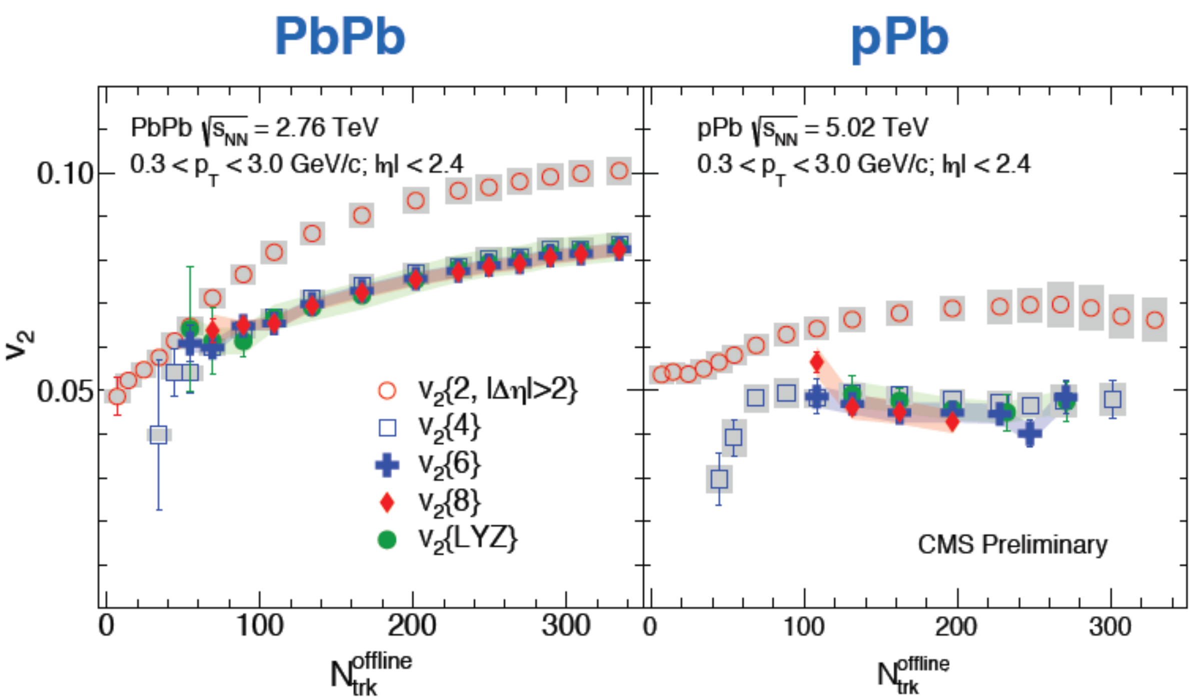
Hydrodynamics

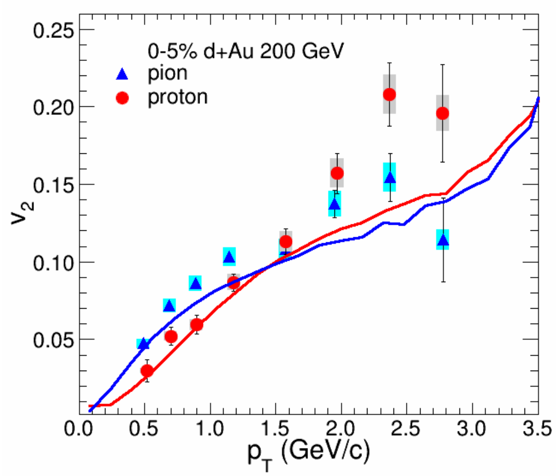
(hybrid codes, IP-Glasma, Echo-QGP, VISHNU)

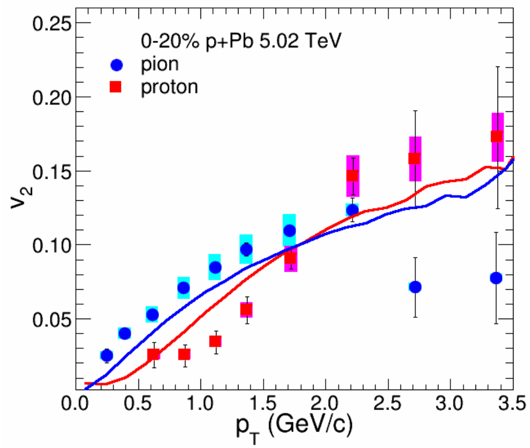
Hadronization

Cooper-Frye, lattice QCD, SHM-HRG

The dagger in the heart for non-flow explanations ?







This is a mass dependent multi-particle correlation

Instead of Conclusions – Discussion points

- for the critical point search the hope is that the kurtosis shows a more dramatic (and positive) turn between 7.7 and 19.6 GeV

- for the fluctuation analysis to determine chemical freeze-out we need to understand its sensitivity and measure net-strangeness

- for the low mass dileptons we need to measure between HADES and lower RHIC energies

- for particle production we need to measure more light nuclei and understand why they should follow thermal model predictions

- for intermediate p_T particle production we need to understand the vialbility of and necessity for recombination

- how thermal is charm, how thermal is beauty ?

- thermal QGP system size – how small is too small ?

- is hydrodynamics applicable down to N_{part} = 20 or even down to N_{part} = 2

- is CGC an alternative or a pre-equilibrium state before the hydro evolution ?