Strangeness fluctuations as hadronization dynamics tests

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With R.Bellwied,C.Markert,G.Westfall

Our understanding of the heavy ion collision: Theorist view

Glauber
Color glass
AdS/CFT sheets

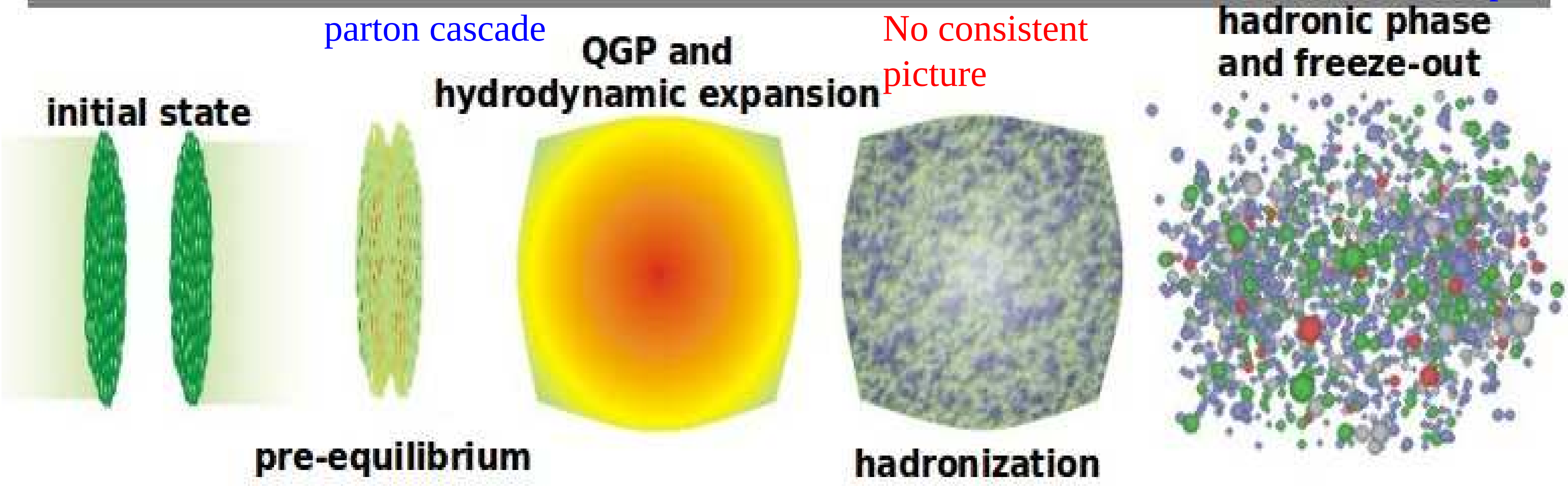
Glasma
"Weibel" Plasma
AdS/CFT
parton cascade

Hydro
parton cascade

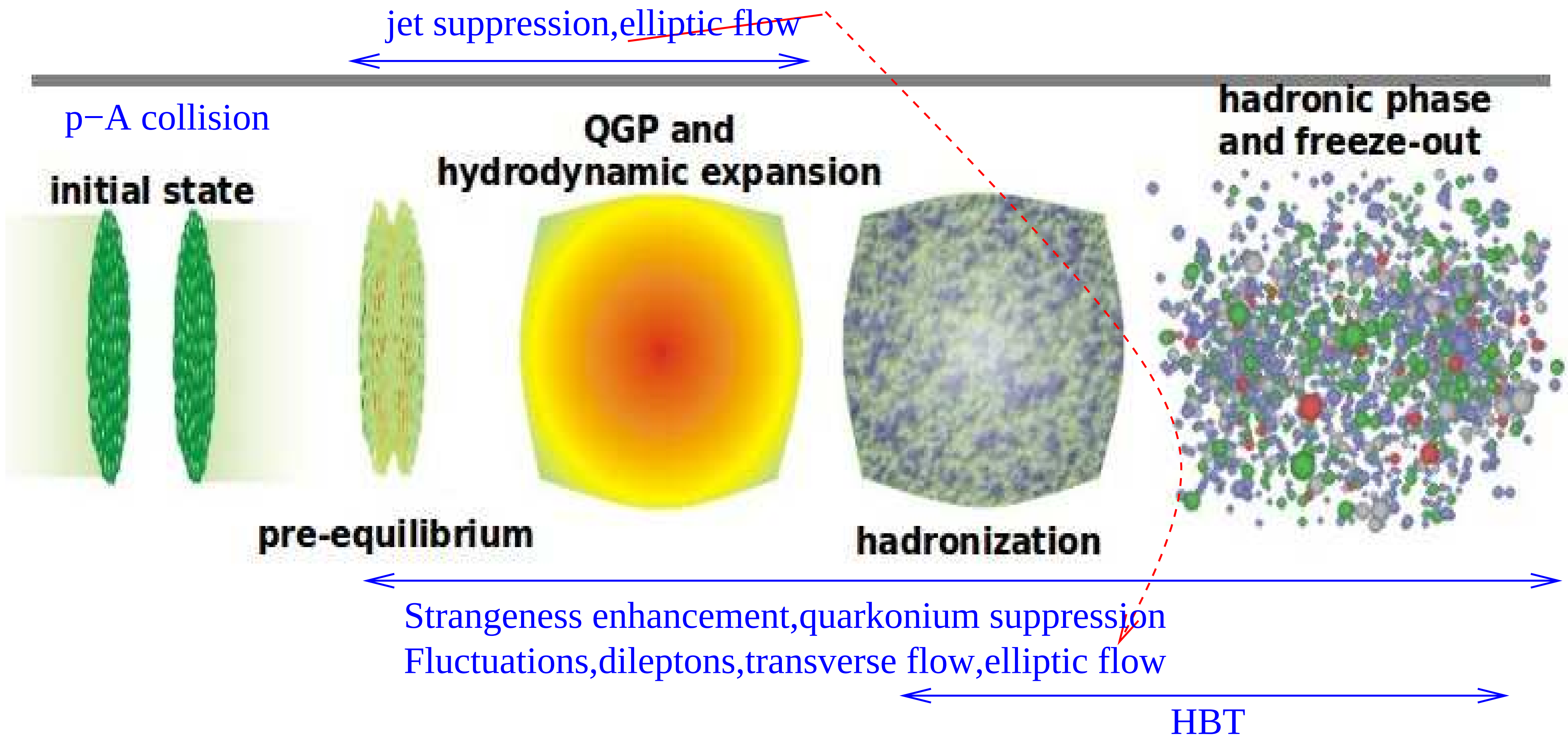
???????
Coalescence MODEL
Statistical MODEL

No consistent
picture

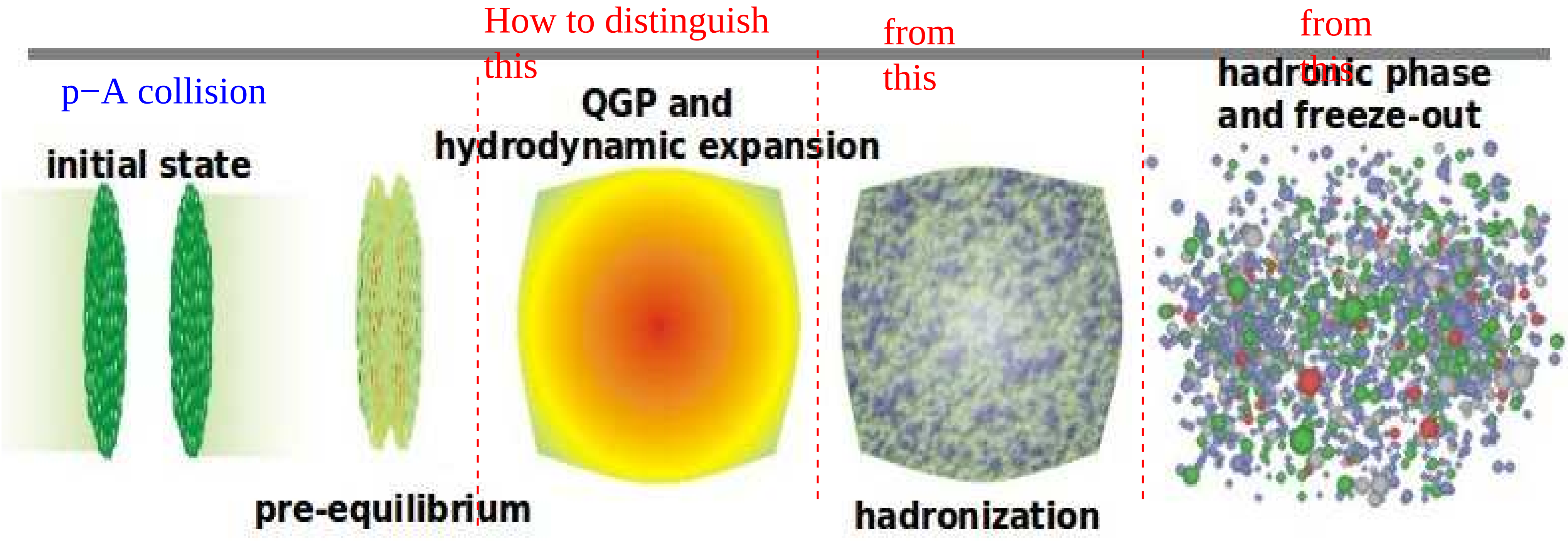
Hadronic EFTs
Hadronic transport



Our understanding of heavy ion collisions:Experimentalist view



Our understanding of heavy ion collisions:A problem



Strangeness enhancement,quarkonium suppression
Fluctuations,dileptons,transverse flow,elliptic flow

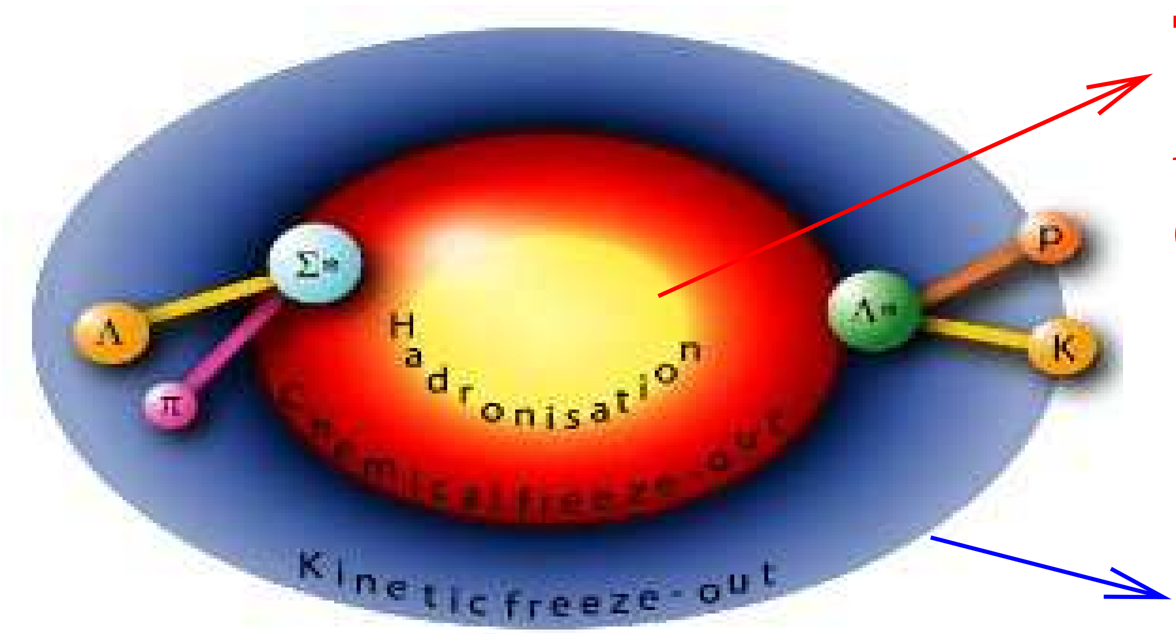
HBT

Briefly

How long is hadronization? The hadron gas phase?

What is the hadron gas's phase effect on signals of previeus dynamics? Early contribution of viscosity (quenching of flow gradients) as important as late one ($\Pi_{\mu\nu}$ in Cooper-Frye formula as important as anisotropy of flow, so can not ignore late hadronic stage even for v_2

Is there a way to minimize them?



Thermal freezeout
Abundances, correlations
of momentum fixed here

Chemical freezeout
Abundances,correlations
of flavor fixed here

The "traditional view": lengthy hadronization, substantial hadron gas phase, changing momentum spectra and some chemical abundances before freezeout.

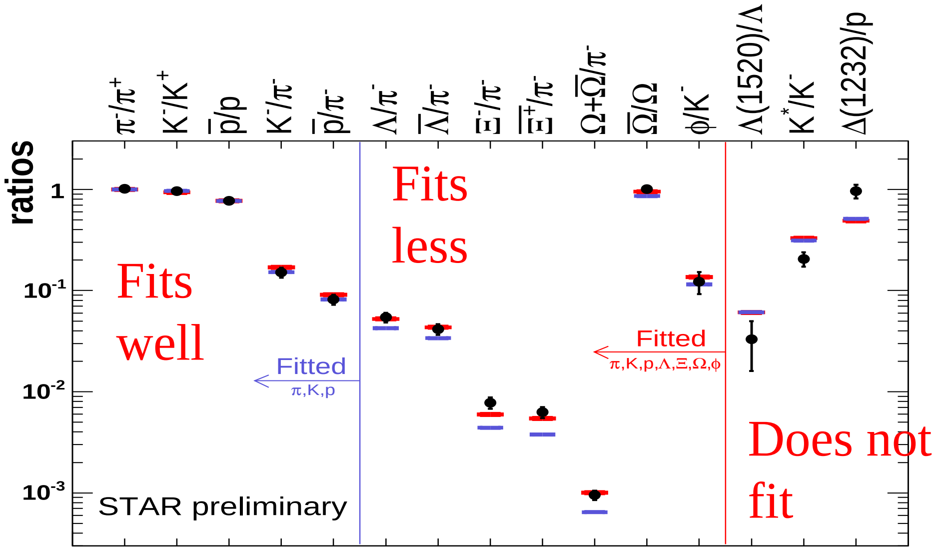
O.Barannikova (STAR)

Hot Quarks 2004

T, μ, γ_s fitted

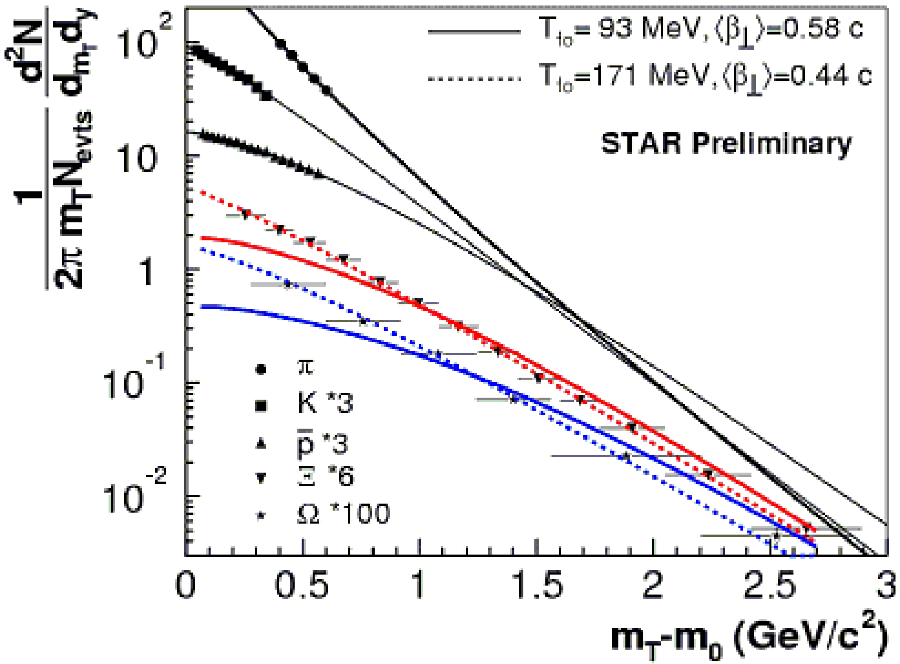
Braun−Munziger,Stachel,

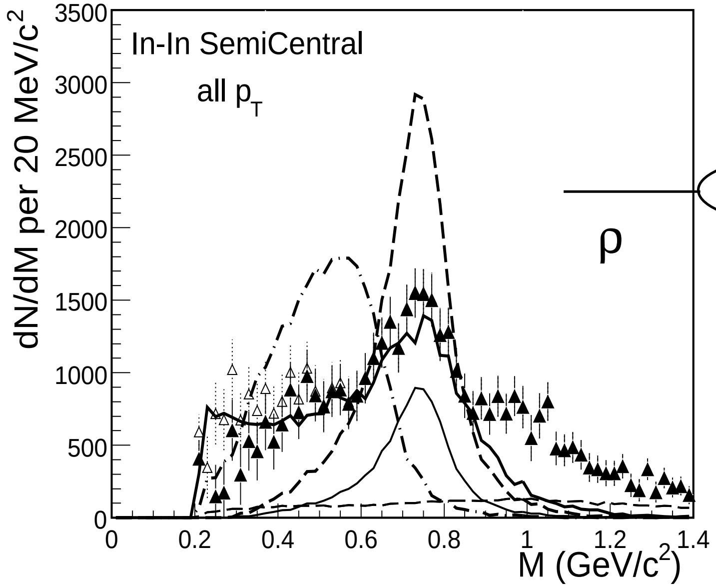
M.Kaneta,Nu Xu...

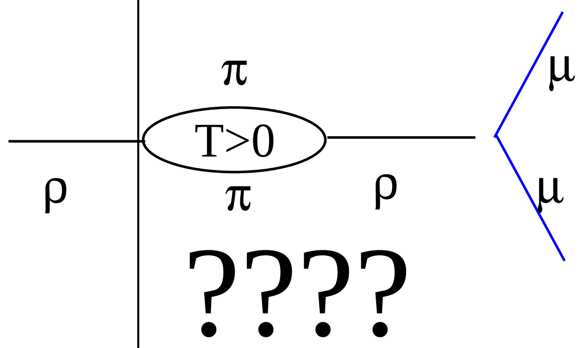


Why? Short-lived resonances do not fit! Need hadronic phase to bring it out of equilibrium

WHy? "Blast-wave" thermal freezeout temperature is lower than chemical freezeout temperature

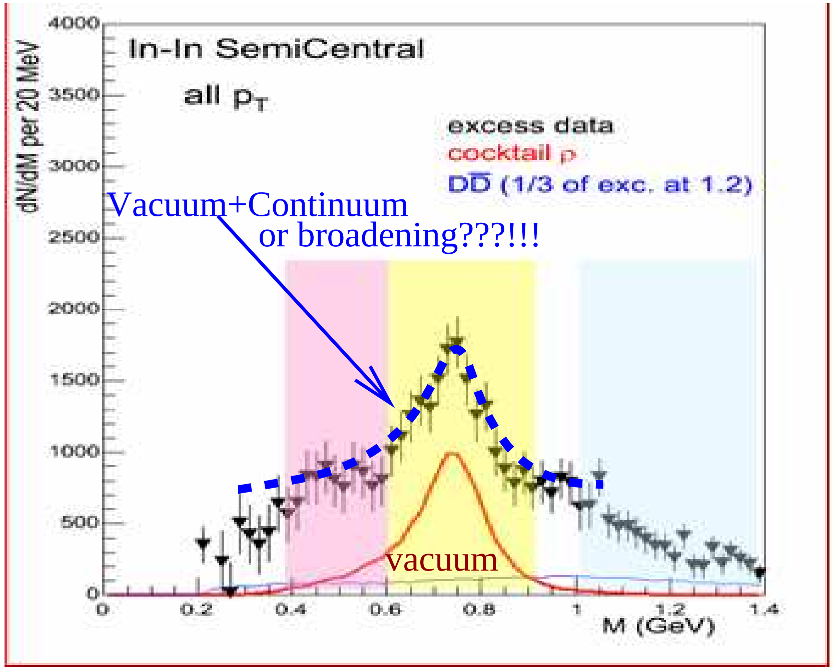






Why? $\rho \to \mu\mu$ broadened,seems to be related to mass shift in a hadron gas

Or is it?



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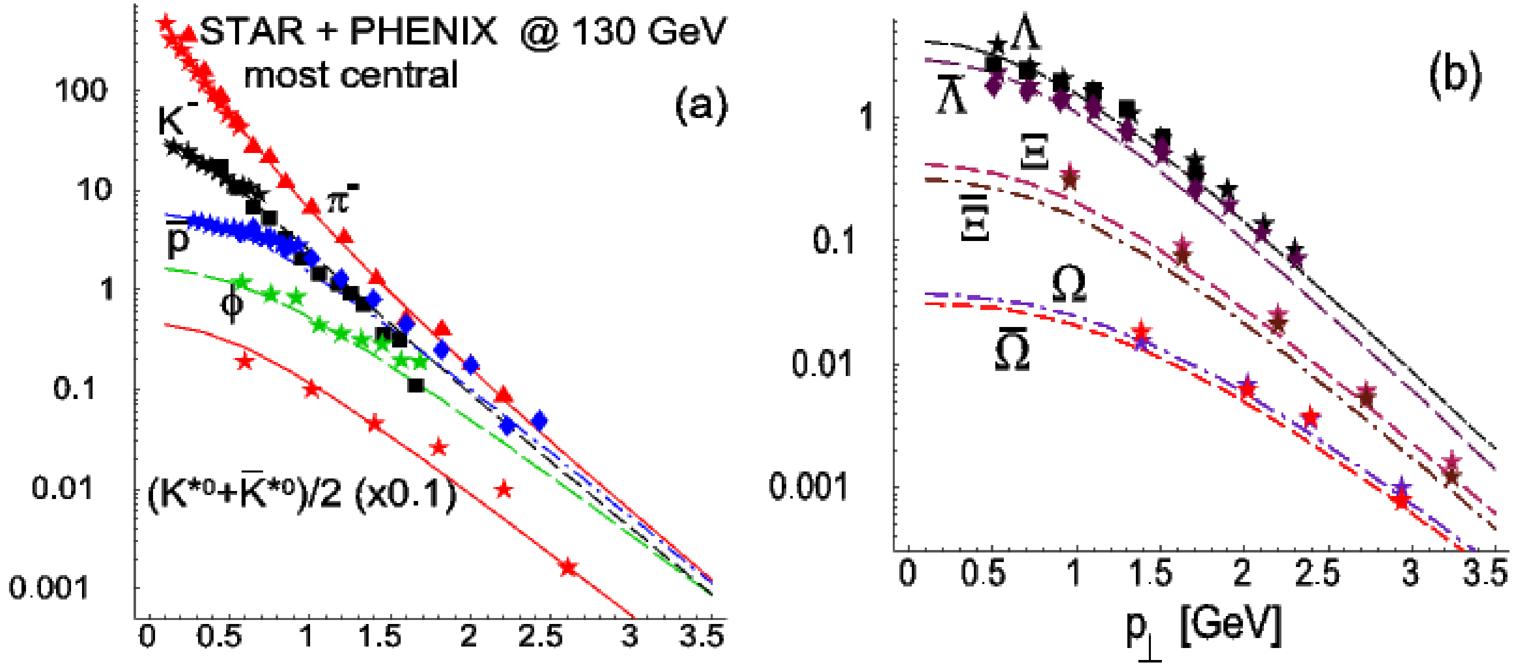
"broadening" actually looks more like a <u>continuum</u>

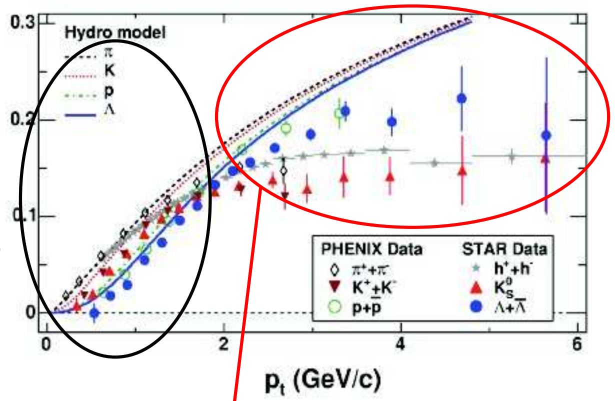
Or is it?



Baran,Florkowski and Broniowski... Chemical and thermal freezeout can be close if resonances properly included

Compilation by STAR collaboration

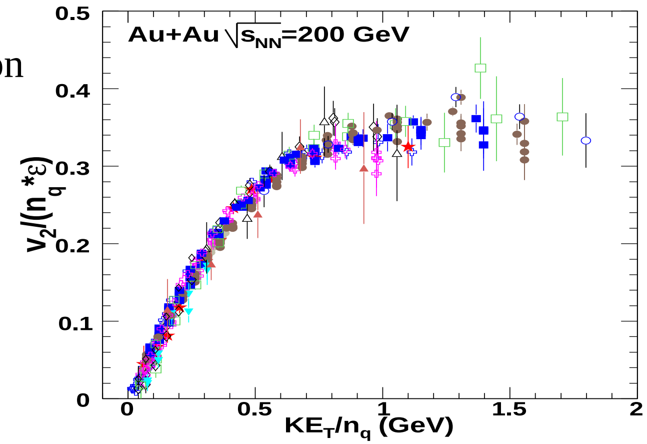
Hydro
+Cooper−Frye
applies
(mass scaling)



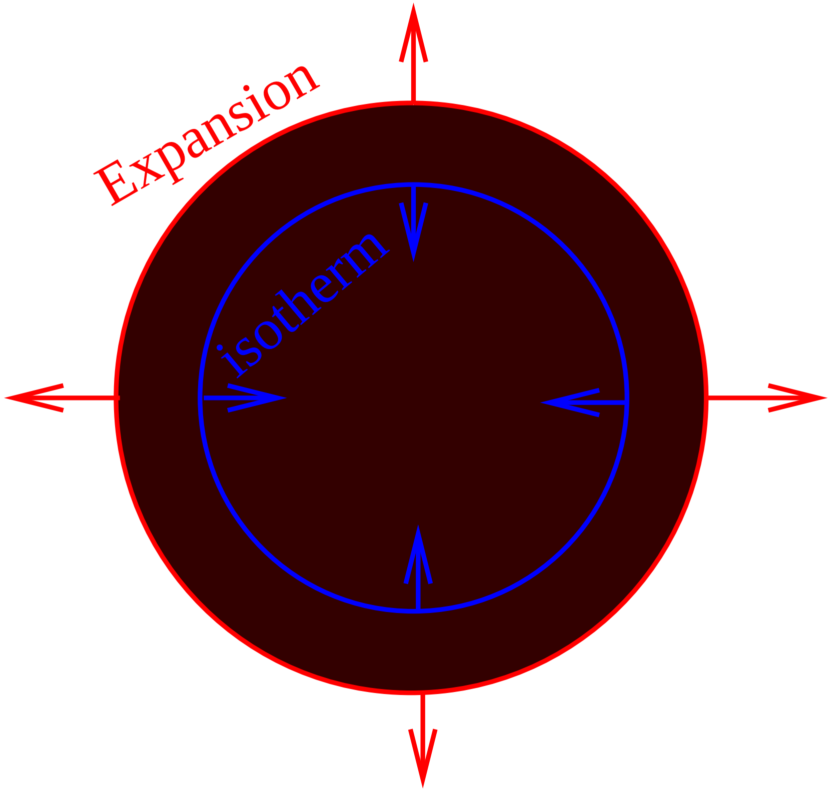
Hydro stops applying (Saturation)

VS

PHENIX
Collaboration
PRL 98
162301
(2007)



Or is it? Coalescence seems to imply hadronization period brief and straight-forward



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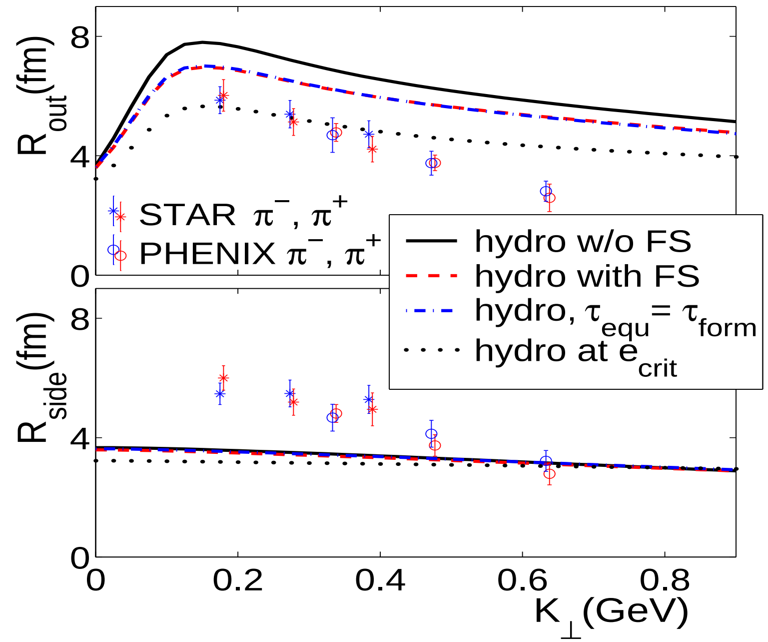
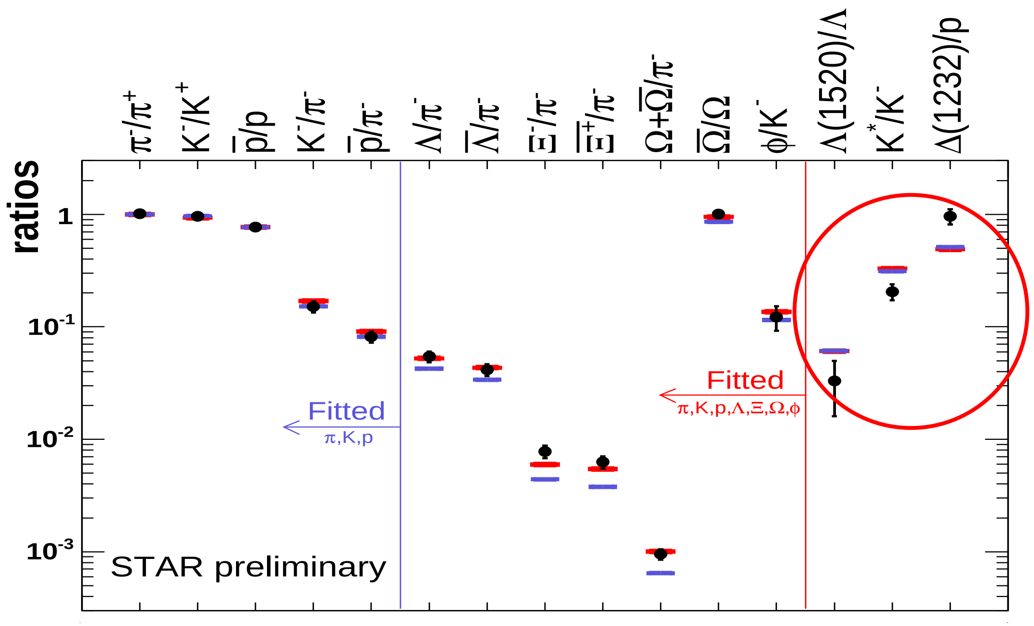
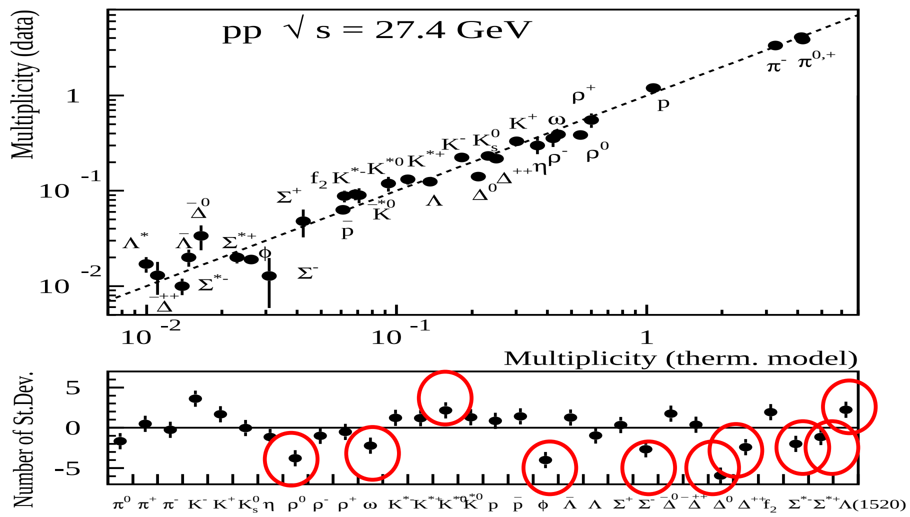


Or is it? HBT R_o/R_s could imply short decoupling time! (Baran et al s model fits well, "dynamical hydrodynamics" with low freezeout temperature typically fails)

Kaneta,Xu: RHIC Au−Au

Becattini et al:p−p,e+−e−





Or is it? Worse fit of resonances wrt stable particles <u>both</u> in big and small systems!

What we need: An observable fixed at "chemical freezeout", and another fixed at thermal freezeout to compare!

Fluctuations of ratios are fixed at chemical freezeout

Resonances are fixed at thermal freezeout

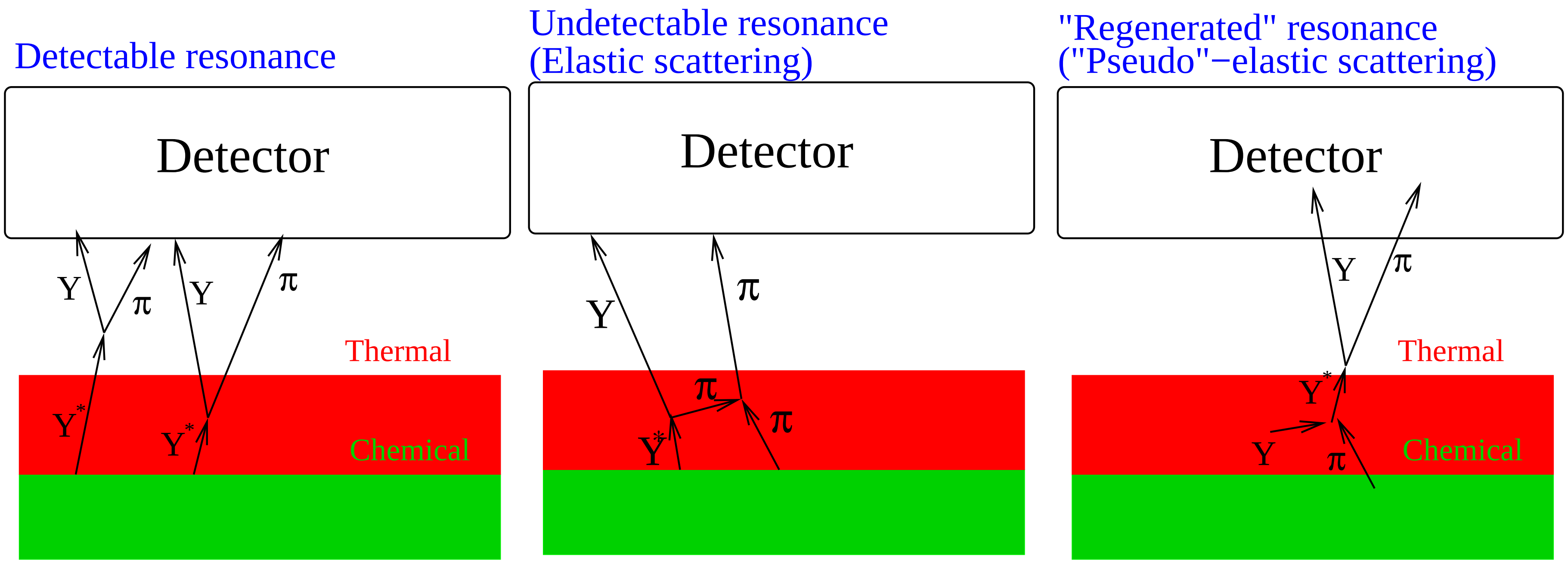
but both are related to each other in a quantitative calculable way

Abundance of resonances

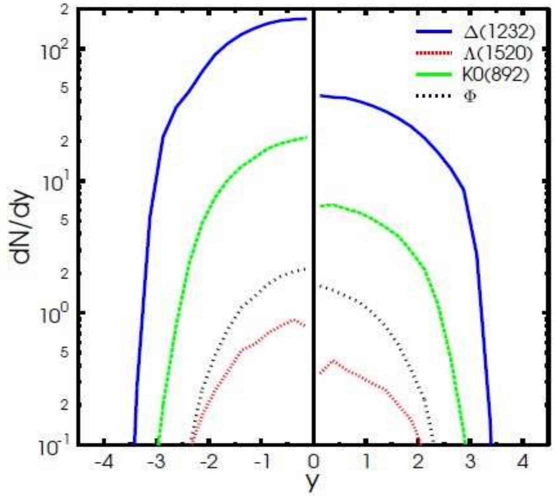
Detected by invariant mass reconstruction

Decay hadronically , so decay produces reinteract

Typical reinteraction capable of destroying resonances and creating new ones



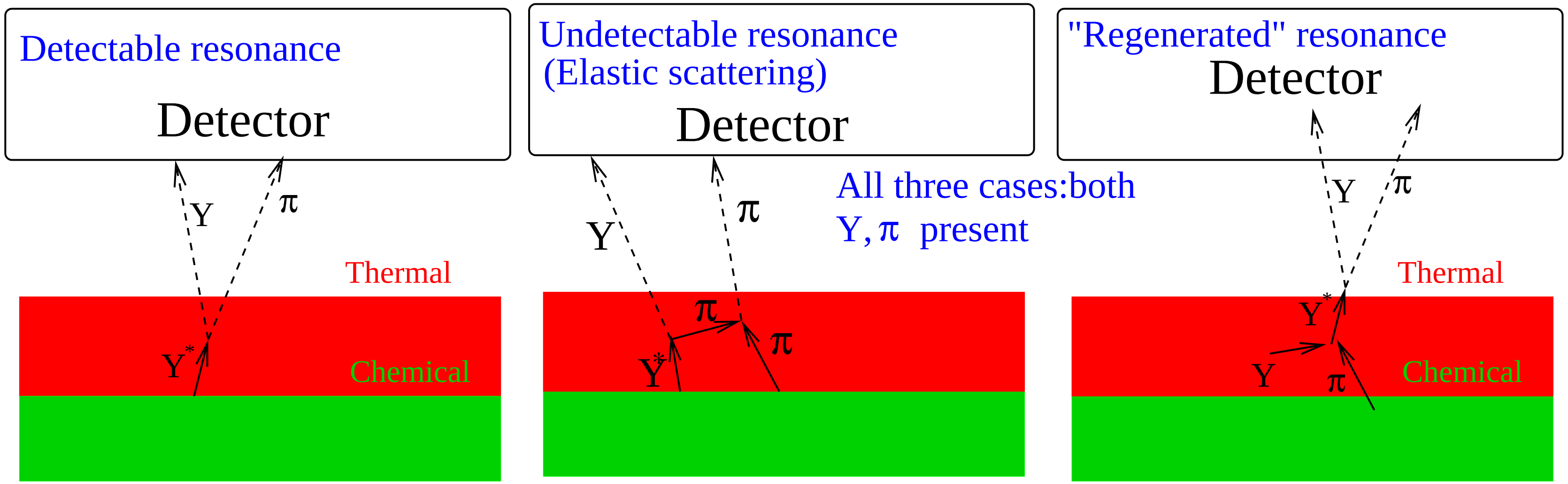
Molecular dynamics: In the long run destruction dominates



M.Bleicher,J.Aichelin

PLB530:81−87,2002

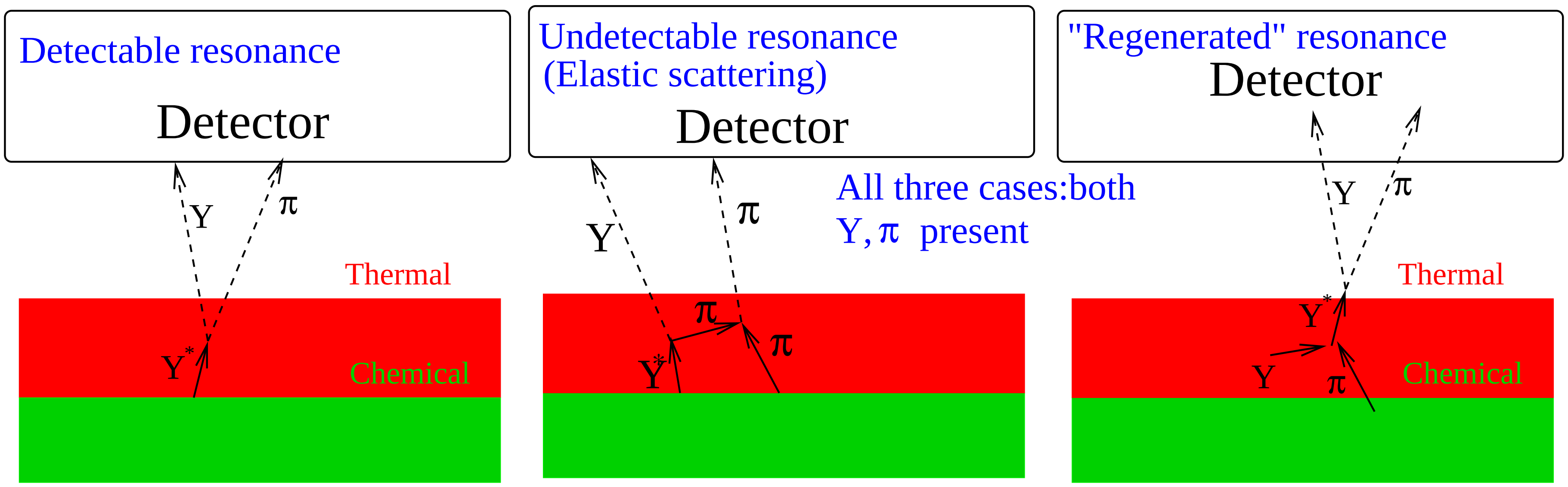
- If hadronic lifetime short , destruction more likely.
- If lifetime long , re-equilibration temperature is lower



Resonances correlate their decay products

Correlation fixed at chemical freeze-out

Hadronic elastic reinteractions might destroy observable resonance signal, but will maintain multiplicity correlation



So system with resonances@chemical freeze-out will have lower fluctuation than expectation without resonances, <u>even if</u> resonances <u>undetectable</u>

What is a ”good” fluctuation observable...

Volume fluctuations

These are difficoult to undestand in a model-independent way. Geometrical fluctuations provide initial stage,but not clear how they evolve (in viscous hydrodynamics this evolution can be non-trivial). So we eliminate them by considering fluctuations of ratios, $\sigma^2_{N_1/N_2}$. in the thermodynamic limit, volume fluctuation cancels out event-by-event

To see this, implement the thermodynamic limit at the level of particle distributions

$$F_1(N_1) = \int g(V) f_1\left(\frac{N_1}{V}\right) dV$$

$$F_2(N_2) = \int g(V) f_2\left(\frac{N_2}{V}\right) dV$$

where $f_{1,2}$ depend on thermodynamics and $g(V)$ on geometry,dynamics .

Now, the fluctuation of a ratio is

$$F\left(R = \frac{N_1}{N_2}\right) = \int F_1(N_1)F_2(N_2)\delta\left(\frac{N_1}{N_2} - R\right) = \int F_1(RN_2)F_2(N_2)dN_2$$

Expanding, we get

$$F(R) = \int\int\int g(V_1)g(V_2)f_1\left(\frac{RN_2}{V_1}\right)f_2\left(\frac{N_2}{V_2}\right)\underbrace{\delta\left(V_1 - V_2\right)}_{V_1=V_2=V \quad for \quad SHM} dV_1 dV_2 dN_2$$

folding

$$F(R) = \int g(V)^2 dV \int f_1\left(\frac{RN_2}{V}\right)f_2\left(\frac{N_2}{V}\right)dN_2$$

and substituting $\alpha = VN_2$ ...

$$F(R) = \underbrace{\int g(V)^2 V dV}_{Independent \quad of \quad R} \int f_1(\alpha R) f_2(\alpha) d\alpha$$

hence, $\mathcal{N} = \int g(V)^2 V dV$ appears equally in all cumulants, and quantities such as σ_{N_1/N_2} are strictly independent of it.

Physically , scaling σ_{N_1/N_2} is a good signature of statistical hadronization in the thermodynamic limit!

$$\sigma_{N_1/N_2} \simeq \frac{\left\langle (\Delta N_1)^2 \right\rangle}{\left\langle N_1 \right\rangle^2} + \frac{\left\langle (\Delta N_2)^2 \right\rangle}{\left\langle N_2 \right\rangle^2} - \frac{2 \left\langle \Delta N_1 \Delta N_2 \right\rangle}{\left\langle N_1 \right\rangle \left\langle N_2 \right\rangle}$$

The fluctuation term $\sim \left\langle N \right\rangle^{-1}$ if $\left\langle N_{1,2} \right\rangle \sim$ Poissonian

The correlation term $\sim \left\langle N^*_{\rightarrow N_1 N_2} \right\rangle$ Grand-canonically

A test for the statistical model applying within a single event is: To what extent are multiplicity and fluctuations described by the same parameters?

A different problem... Acceptance effects

- Particle (mis)identification
- Limited rapidity and momentum resolution
- Cuts (necessary to eliminate jets)

In fluctuations, these can be a lot more non-trivial than in averages. But should also appear in mixed events!

σ_{mix}:What is it?(Pruneau,Gavin,Voloshin, PRC66:044904,2002)

What it should be: A mixed event observable which should have no correlations if obtained from a sample of data from a perfect detector.

Why?We make the (good, not perfect) assumption that

$$\sigma^2 = \sigma^2_{physics} + \sigma^2_{acceptance}$$

$$\sigma^2_{mix} = \underbrace{\sigma^2_{trivial}}_{=\langle N_1 \rangle^{-1} + \langle N_2 \rangle^{-1}} + \sigma^2_{acceptance}$$

Therefore, concentrating on

$$\sigma^2_{dyn} = \sigma^2 - \sigma^2_{mix}$$

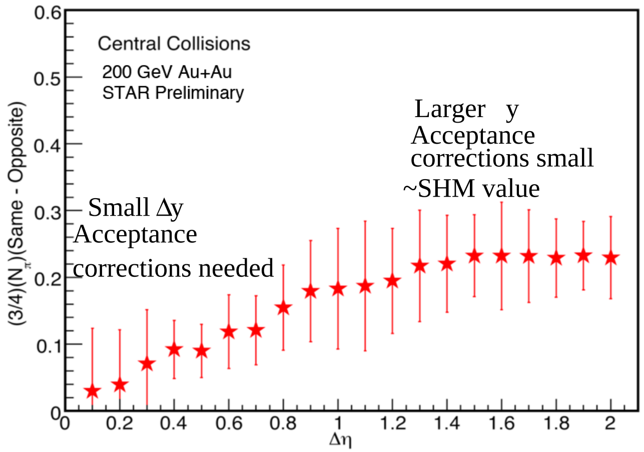
should eliminate acceptance effects.

Problem I:

In a narrow acceptance detector, resonance kinematics introduces a correlation into $\sigma^2_{acceptance}$ absent from σ^2_{mix} .

Partial solution: Vary acceptance until large enough that $N_1\sigma^{dyn}_{N_1/N_2}$ constant

G.Westfall [STAR] private communication



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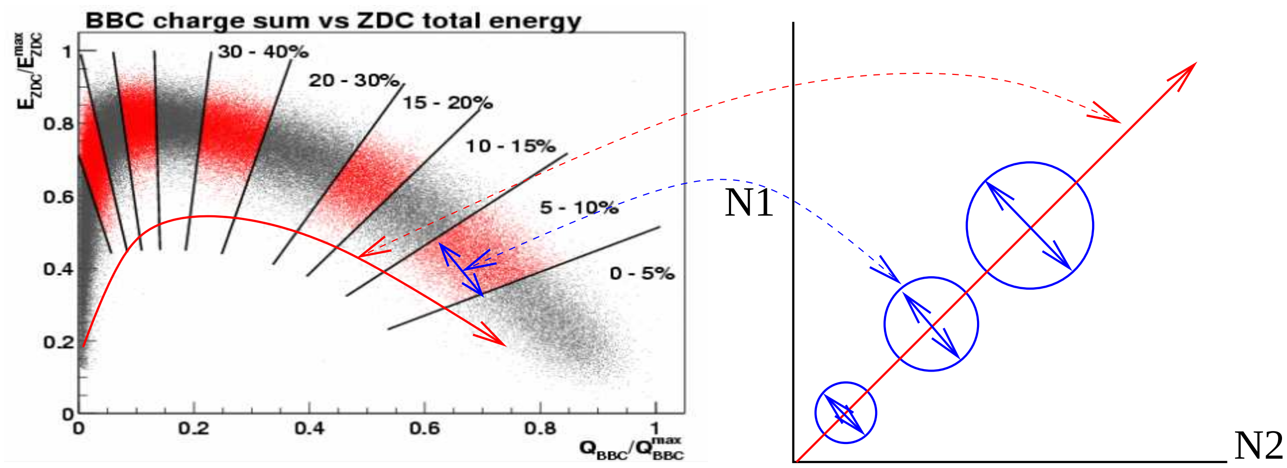
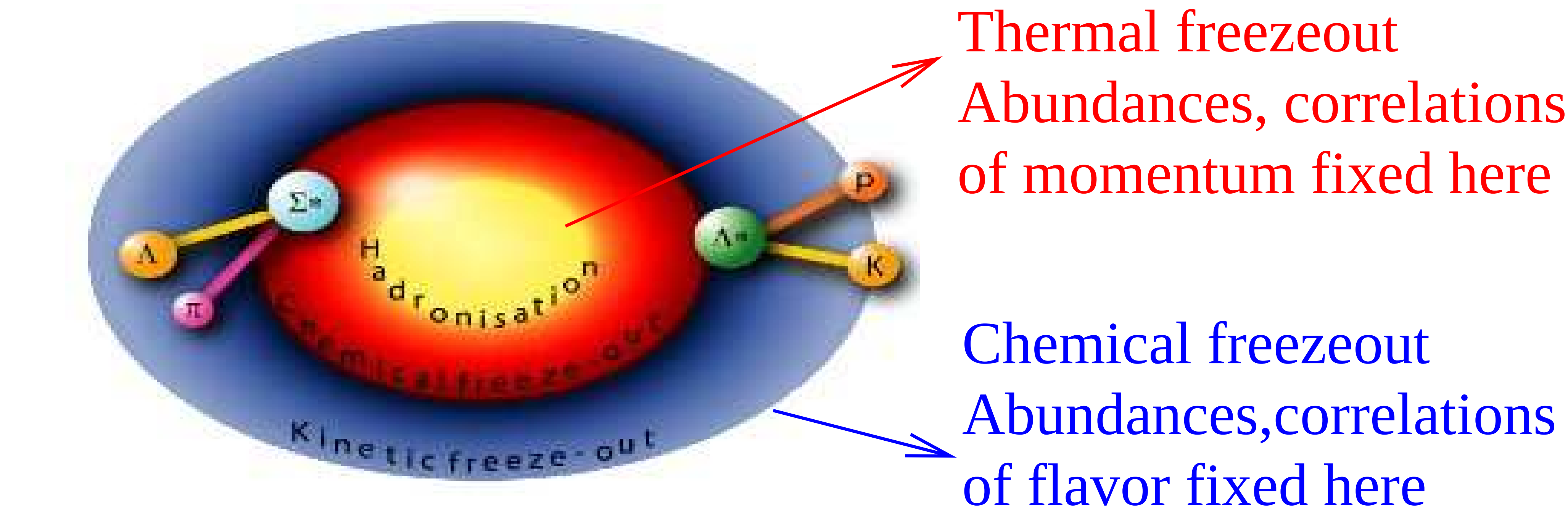
Problem II



Residual correlations left in σ_{mix} : If $\langle N_{ch} \rangle$ in mixed events experimentally determined, multiplicity correlations of real events remain in σ_{mix} (An event with greater multiplicity also has more N_1 and N_2 . Good scaling of $\sigma_{K/\pi}$ probably means effect is small, but it is there (M.Hauer,2010)

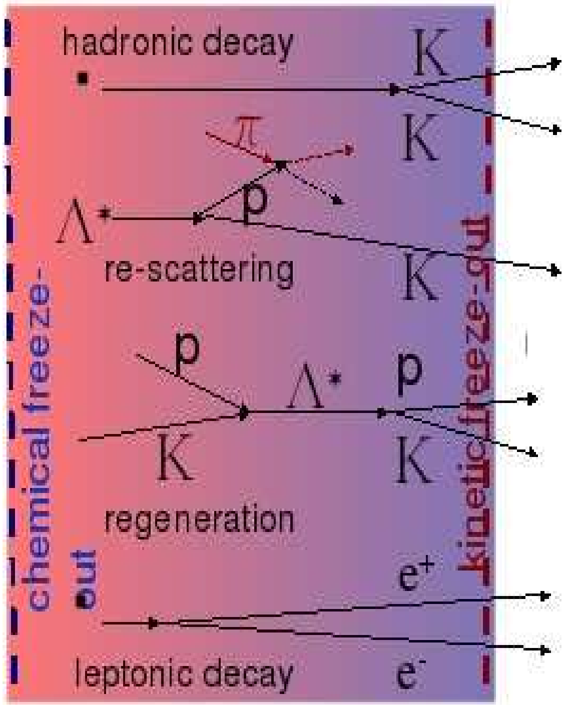
Possible Solution : Normalize mixed events by separate averages of $\langle N_{mixed} \rangle = \langle \pi \rangle + \langle K \rangle + \langle p \rangle$, to ensure no multiplicity correlations.

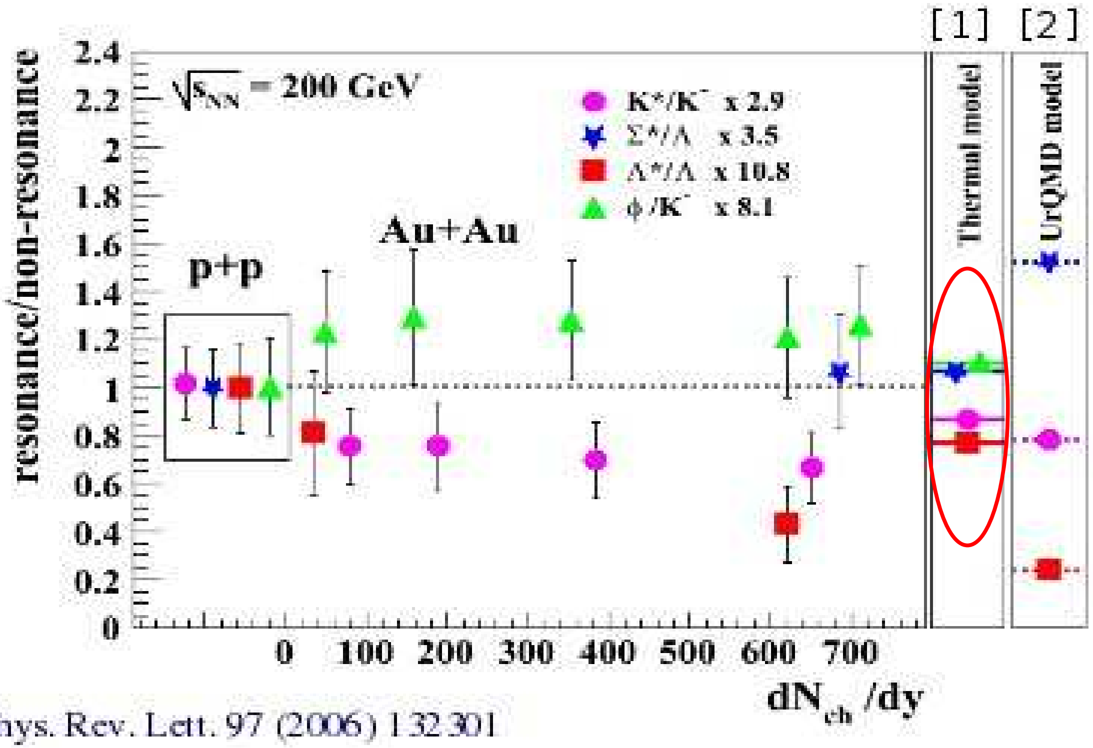


- Resonances reconstructed by invariant mass reconstruction carry information of all evolution up to last phase.

- Multiplicity fluctuations carry information of chemical freezeout phase

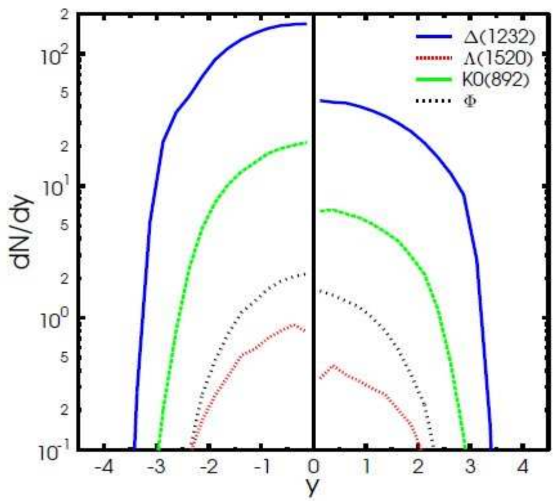
Experimentally, resonances do not fit the simplest thermal model





Different chemistry? $T \sim 140 + \gamma_q > 1$ Rescattering? all of the above?

In hadronic transport, rescattering usually dominates over regeneration (easy to understand, expected to be true up to detailed balance limit, since gas is cooling), reduces K^*/K^- by a factor of ~ 2



M.Bleicher,J.Aichelin

PLB530:81−87,2002

NBModels exist where such non-equilibrium hadronic phase expected to be suppressed. Eg, if freeze-out proceeds by bulk viscosity driven "cavitation" (GT+I.Mishustin+B.Tomasik,K.Rajagopal+N.Tripuraneni)

Two ways of definining K^* abundance

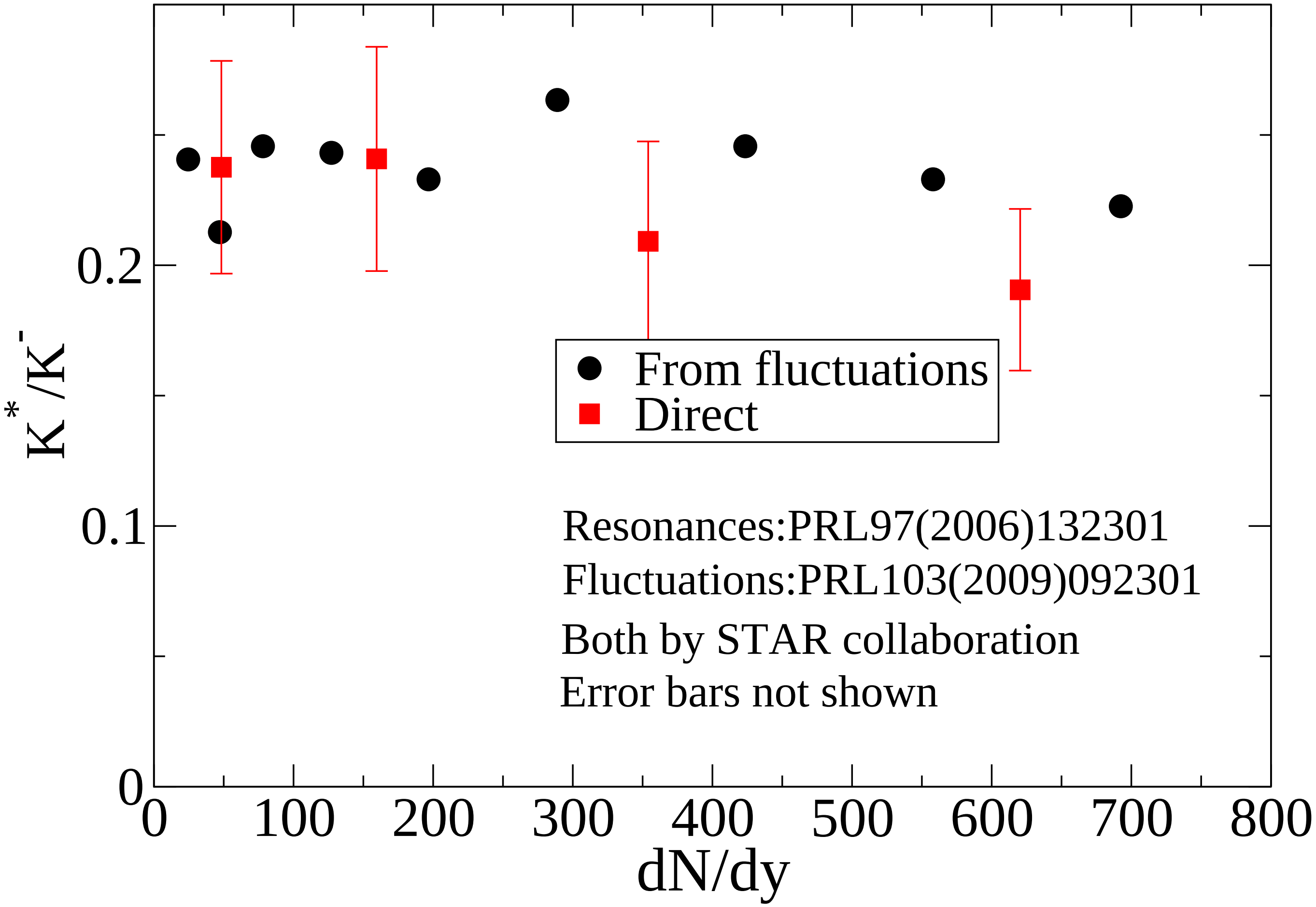
From fluctuations $\sigma_{dyn}^{K^+/\pi^-}$ correlated by K^* , $\sigma_{dyn}^{K^-/\pi^-}$ not correlated by anything! Therefore,

$$\underbrace{\frac{3}{4}}_{CG\ \ coefficient} \pi^- \left(\sigma_{dyn}^{K^+/\pi^-} - \sigma_{dyn}^{K^-/\pi^-}\right) \simeq 0.95 \frac{3}{8} \frac{dN_{ch}}{dy} \left(\sigma_{dyn}^{K^+/\pi^-} - \sigma_{dyn}^{K^-/\pi^-}\right)$$

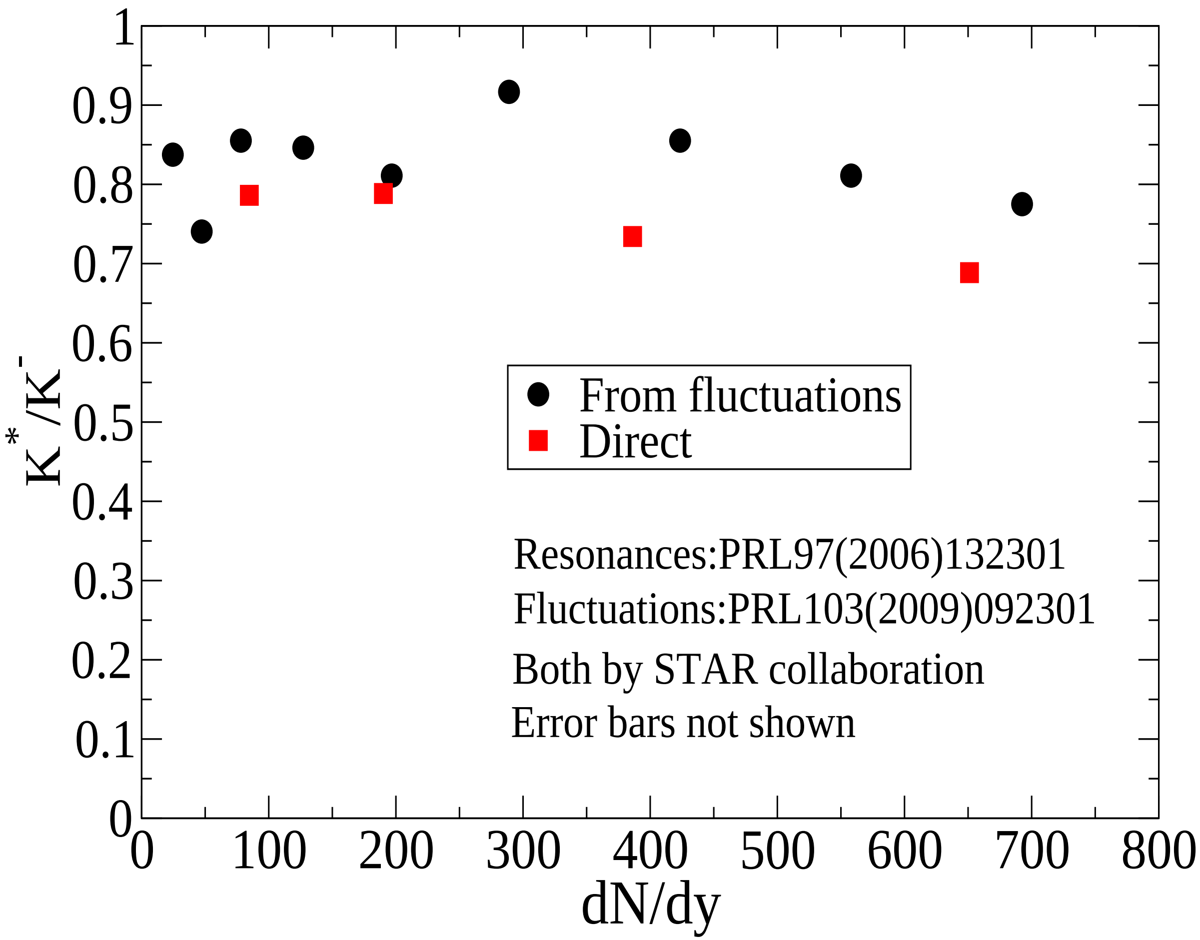
sensitive to K^*/K^- at chemical freeze-out
(S.Jeon,V.Koch, PRL83, 5435 (1999))

Directly K^*/K^- can be measured by invariant mass reconstruction. This only sees "last" K^* , at thermal freeze-out

Comparing the two $\rightarrow$ effect of hadronic rescattering



K*/K-
dN/dy
0
0.1
0.2
0
100
200
300
400
500
600
700
800
From fluctuations
Direct
Resonances:PRL97(2006)132301
Fluctuations:PRL103(2009)092301
Both by STAR collaboration
Error bars not shown



Two definitions of K* give surprisingly similar answers

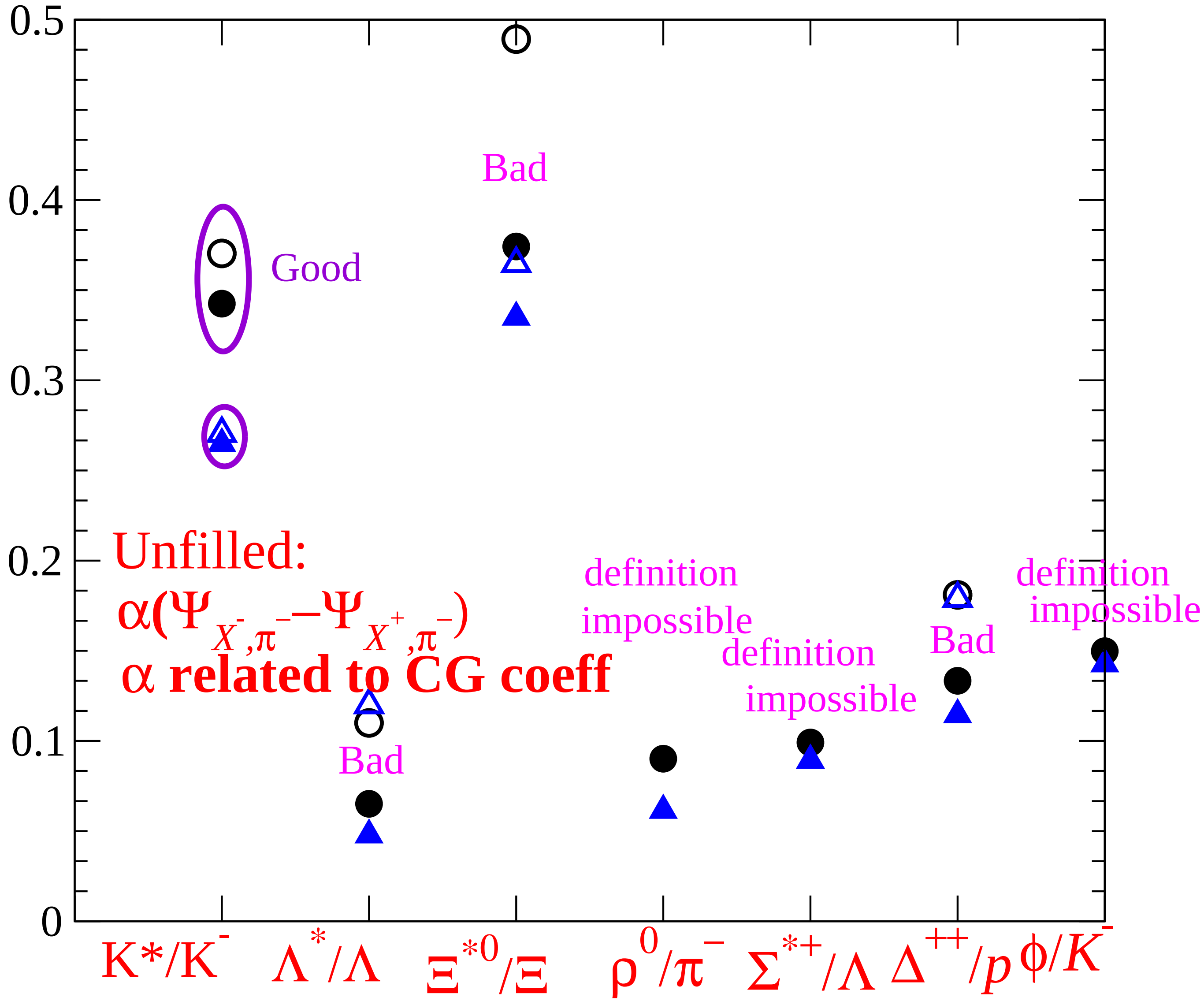
Very preliminary
no error bars
dN/d η
used for π

So,to be continued...

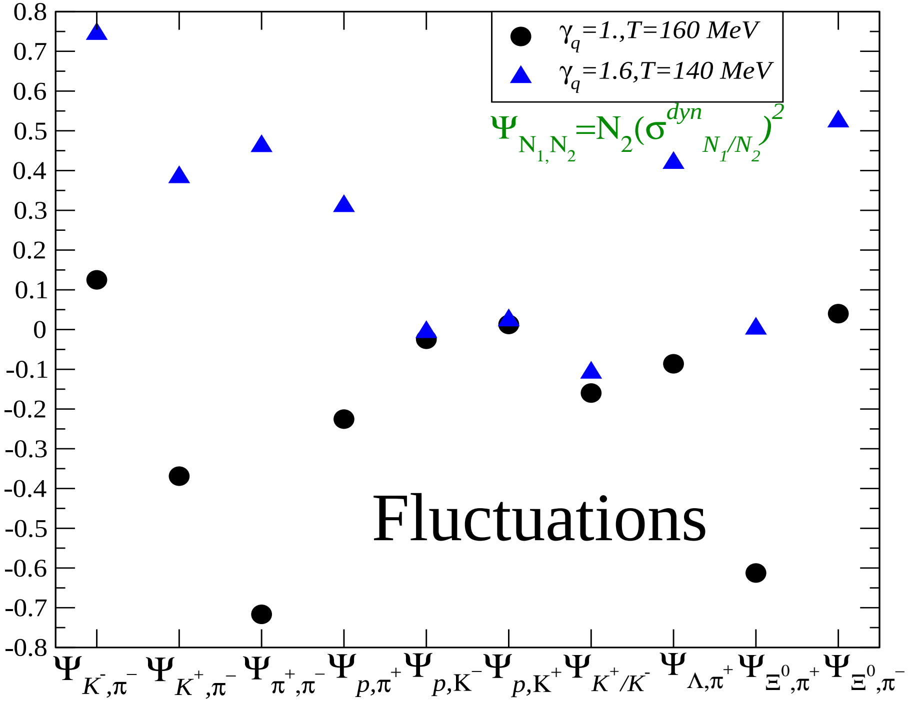
Problem: Lots of resonances, complicated decay trees

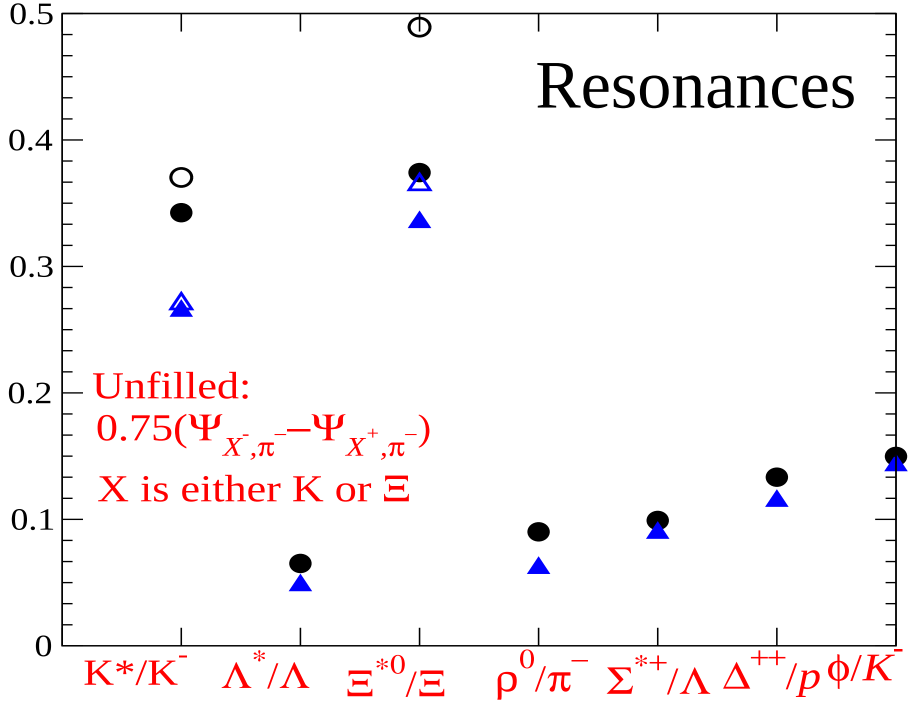
- K, π correlated only by K^* (other states much heavier)
- p, π correlated by Λ and Δ
- Λ, K correlated by $\Lambda(1520)$ and $\Lambda, \Sigma(1600)$
- Λ, π correlated by Ξ and Σ^*
- Ξ, π correlated by Ξ^* and $\Sigma^*(1690)$

Imposing a primary vertex cut takes out weak decays , but as not enough. Only K, π have "clean" light resonance! In addition, for many ratios, impossible to define corresponding fluctuation observable (eg $\rho^0/\pi, \Sigma^*/\Lambda$)



0.5
0.4
0.3
0.2
0.1
0
Good
Bad
Bad
Bad
definition impossible
definition impossible
definition impossible
Unfilled:
$\alpha(\Psi_{X^-,\pi^-} - \Psi_{X^+,\pi^-})$
α related to CG coeff
K^*/K^- Λ^*/Λ Ξ^{*0}/Ξ ρ^0/π^- Σ^{*+}/Λ Δ^{++}/p ϕ/K^-





We can still say something with large sample of resonances, fluctuations

Fluctuations fit, resonances dont Hadronic reinteraction phase long, changes particle abundance.
Direction of error allows us to distinguish between rescattering (under-prediction) and regeneration (over-prediction)

Both resonances and fluctuations fit Not much reinteraction!

Resonances fit, fluctuations dont Model is wrong!

NB: This way, the "Hagedorn thermalization model" (Noronha-Hostler, et al, PRL.100:252301,2008) could also be falsified,
since Hagedorn tree $\leftrightarrow$ Lots of resonance correlations)

Conclusions

- Fluctuation of particle ratios optimal for falsifying and constraining timescale between equilibration and freezeout, both in experiment and in models.

- A comparison of K^* abundance measured directly and $\sigma^{dyn}_{K^+/\pi^-} - \sigma^{dyn}_{K^-/\pi^-}$ consistent with no evidence for hadronic rescattering
  Short reinteracting phase, or balance with regeneration?

more fluctuation results, eg σ^{dyn}_{p/π^-},$\sigma^{dyn}_{\Lambda/\pi^-}$ essential for confirming these results. Stay tuned!