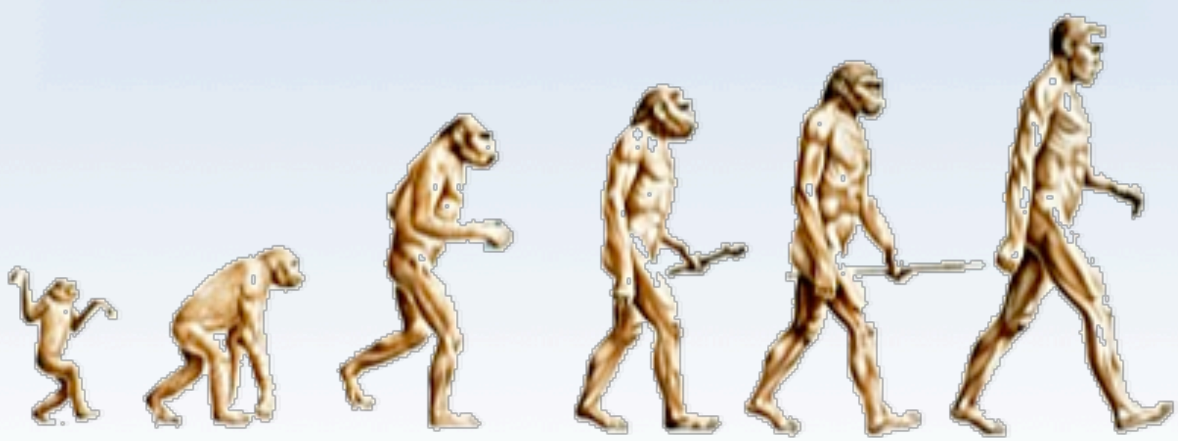
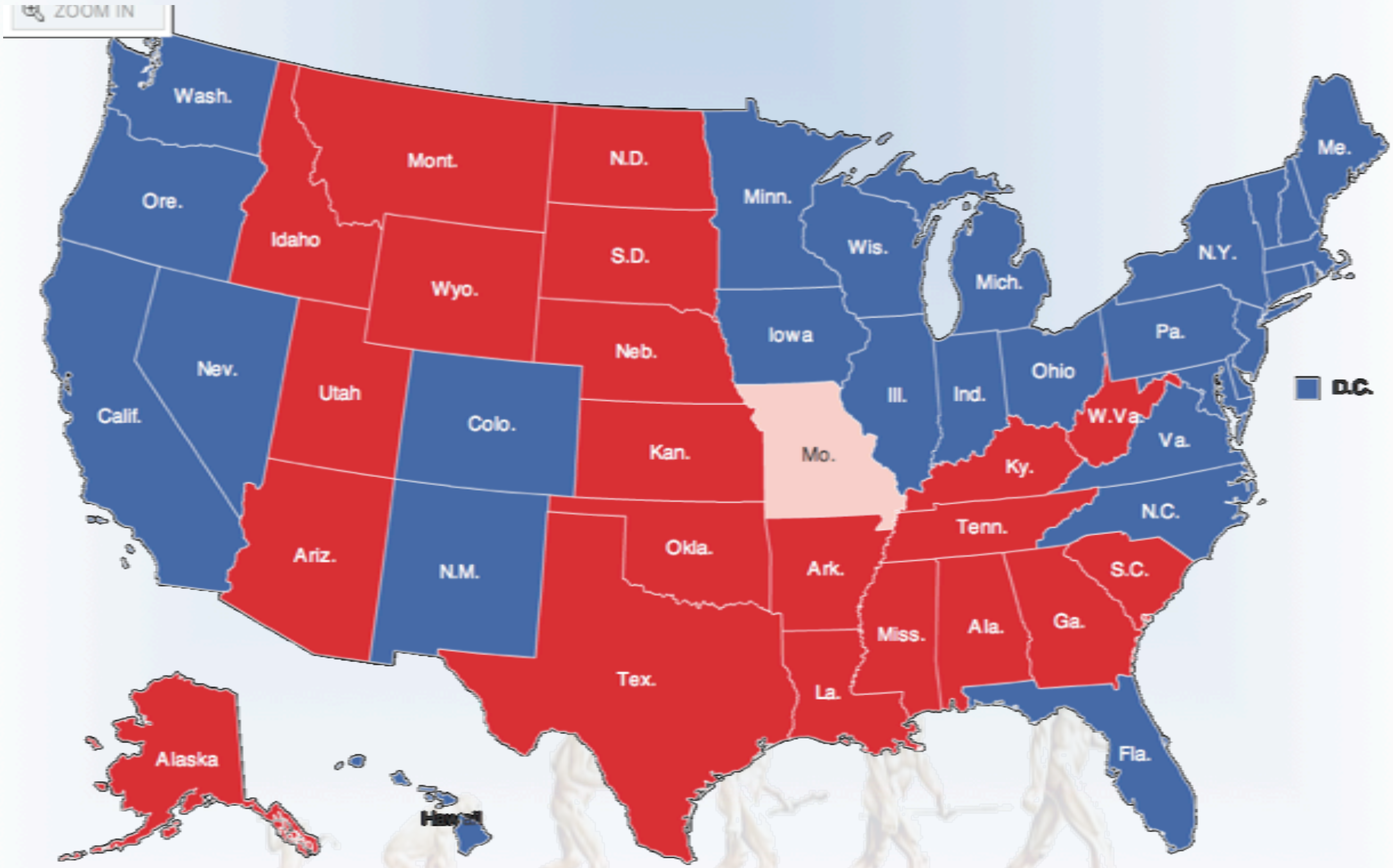
Z. Chajęcki & MAL arXiv:0807.3569 [nucl-th]
Z. Chajęcki & MAL PRC **78** 064903 (2008)

The evolution from p+p to A+A collisions at RHIC

Mike Lisa
Ohio State University

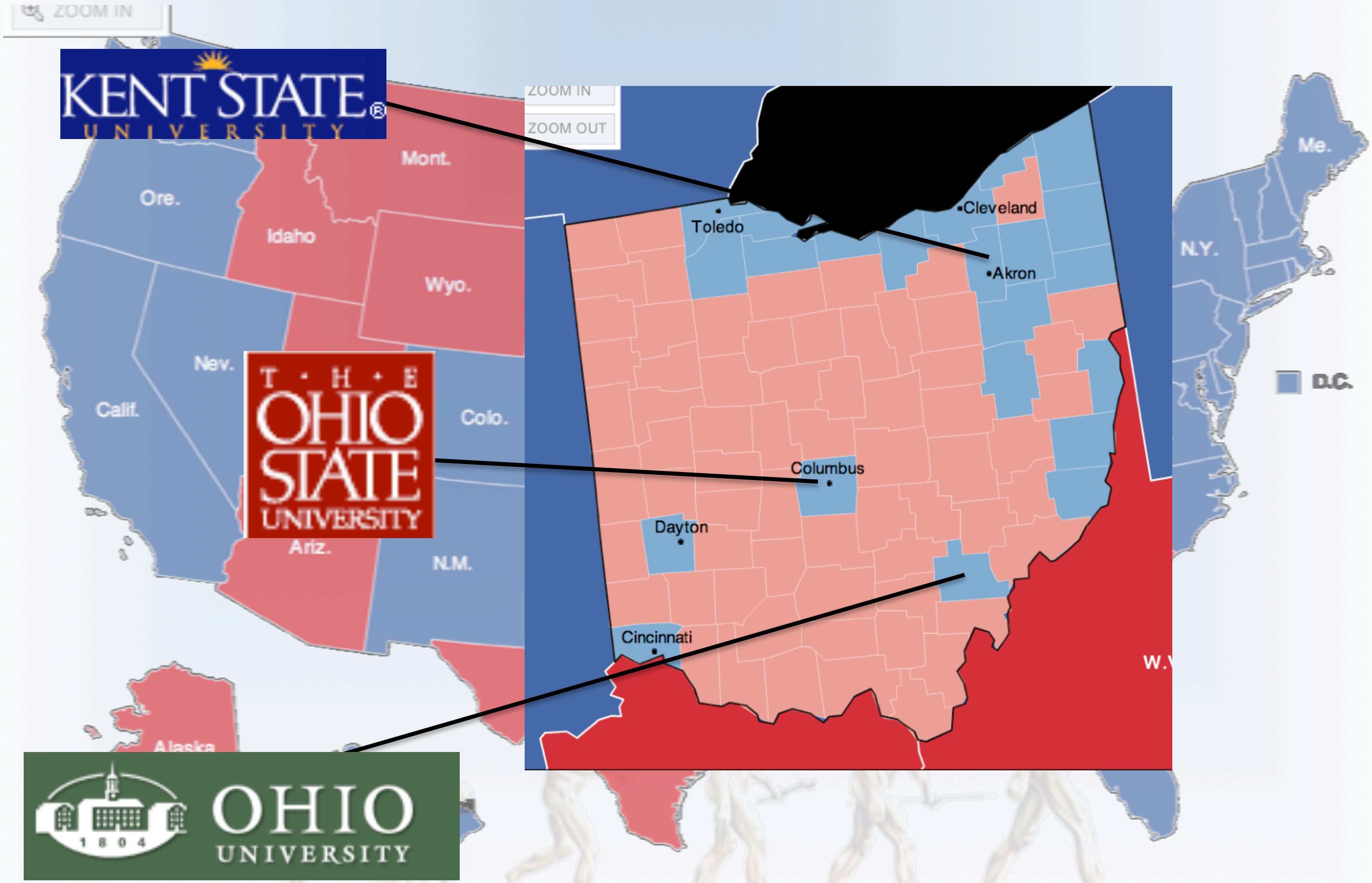


Where is Ohio?



MAL Weismann Institute Israel

Heavy Ion physics in Ohio



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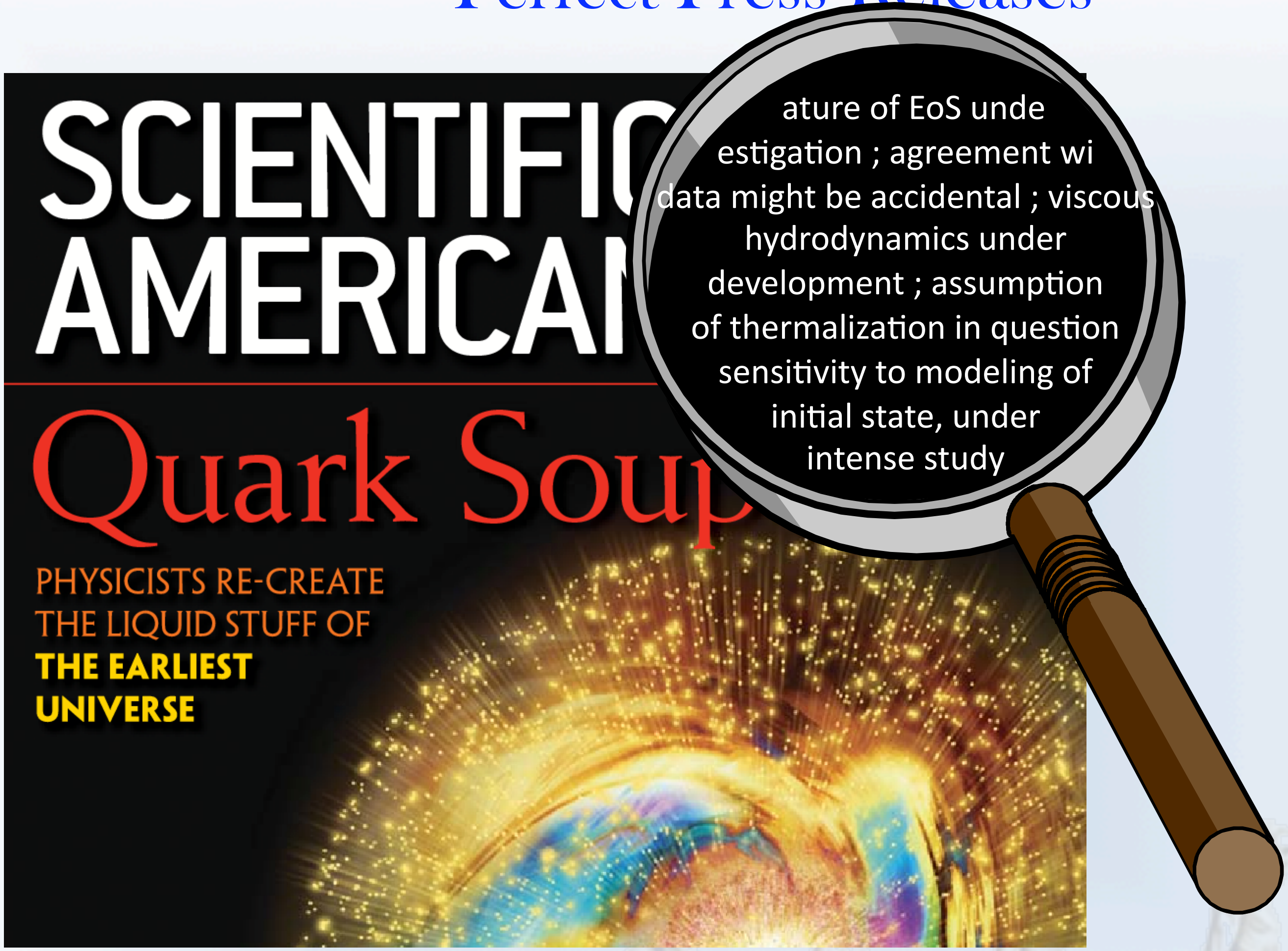
Outline

- 2 Prime Discoveries in (heavy ion) collisions at RHIC: flow & R_{AA}
- Femtoscopy :
  - most direct evidence of flow in A+A
  - increasing importance of **EMCICs*** in low-multiplicity collisions
  - A+A versus p+p – same flow signal??
- Spectra at low p_T
  - **EMCICs**** and the multiplicity evolution of spectra
  - A+A versus p+p – same "parent"? same flow?
- putting it together, with fewer assumptions
- Summary

* EMCIC = "Energy and Momentum Induced Correlation"

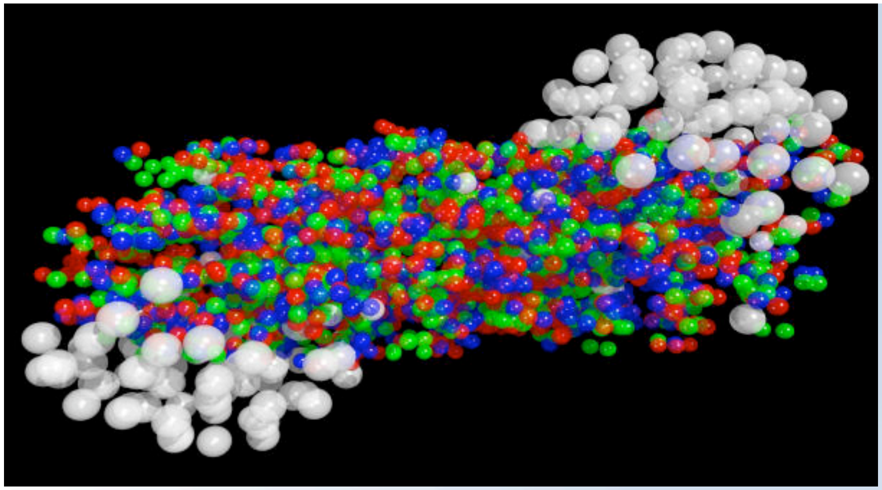
** EMCIC = "Energy and Momentum Induced Constraint"

Perfect Press Releases



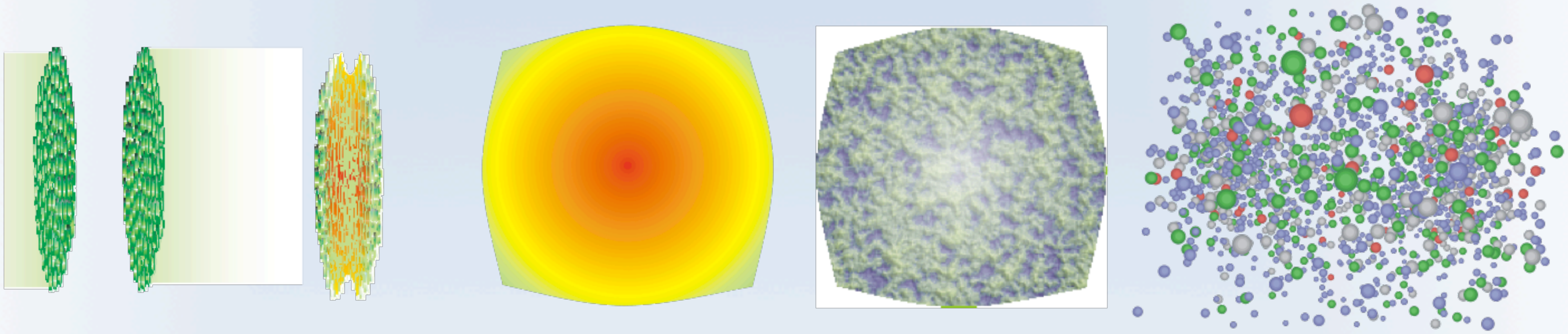
- Perfect or not, creation of a **bulk, collective** system at RHIC is established - **flow**
- This system is very color dense and largely **opaque** to partons traversing it - $\mathbf{R_{AA}}$

? ***Are these statements unique to A+A collisions?***

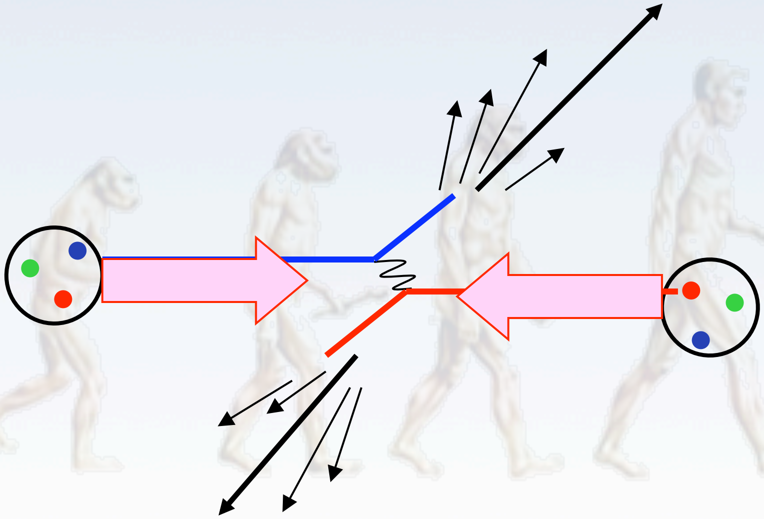


paradigms

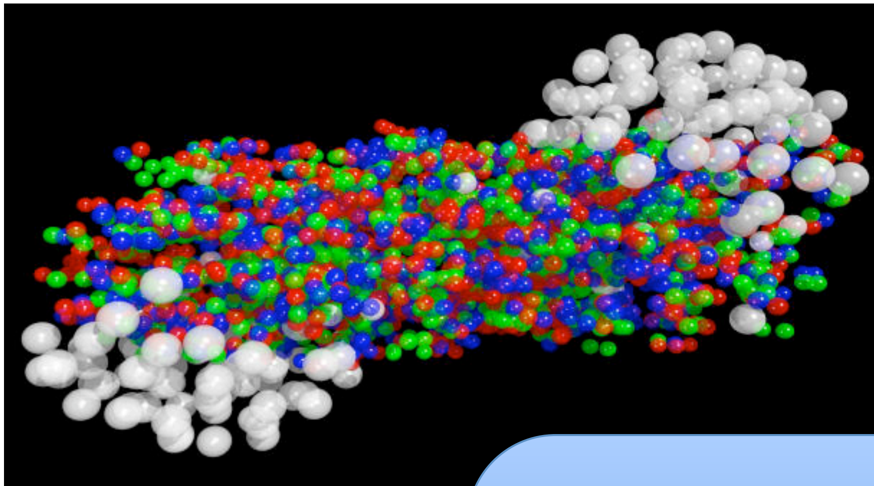
A+A → a *system*



p+p: a *process*



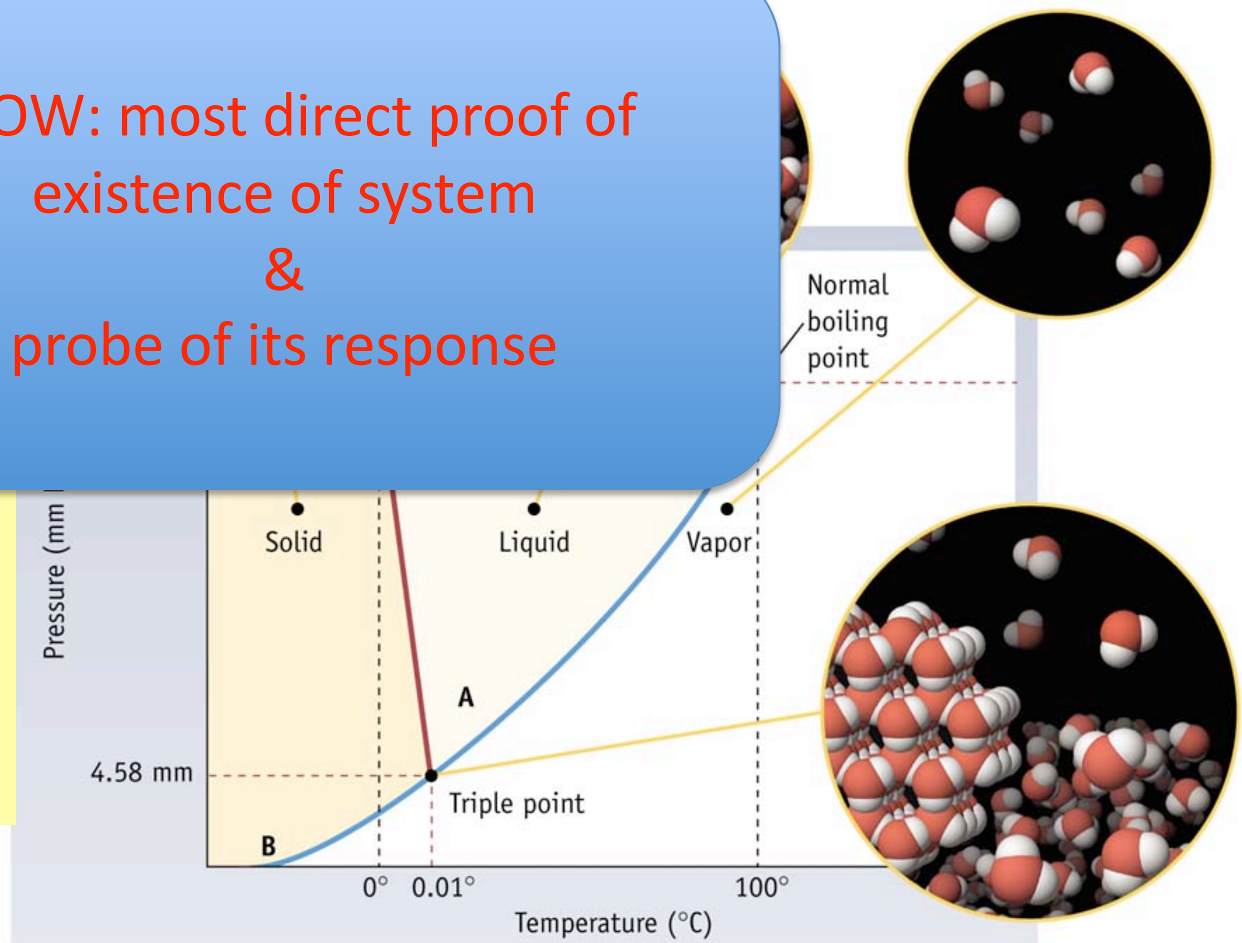
H.I.C. – a system



FLOW: most direct proof of
existence of system
&
probe of its response

bulk physics
- superfluids
- superconductors
- metal/insulator
- …

Only for large *system*
- cannot melt 1 H_20 molecule!

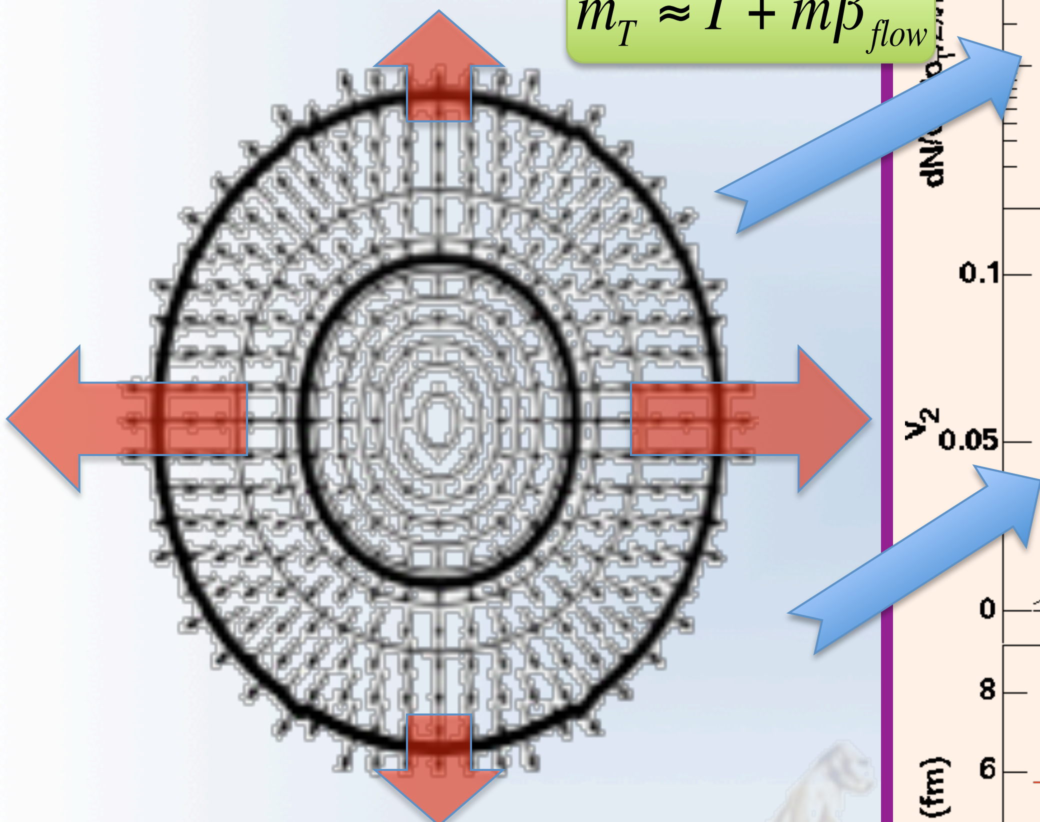


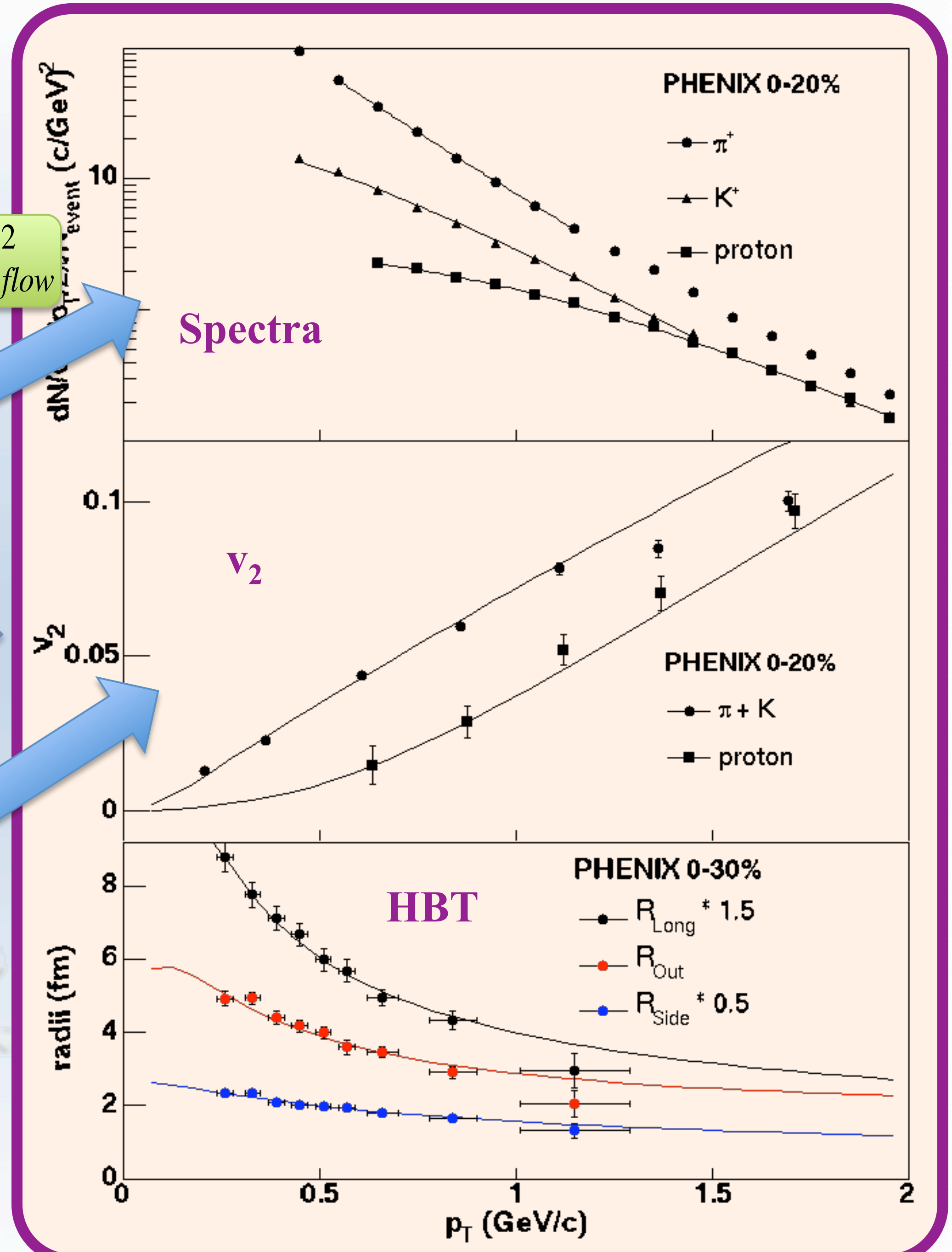
Flow-dominated “Blast-wave”

toy models capture main characteristics

e.g. PR**C70** 044907 (2004)

$$m_T \approx T + m\beta^2_{flow}$$





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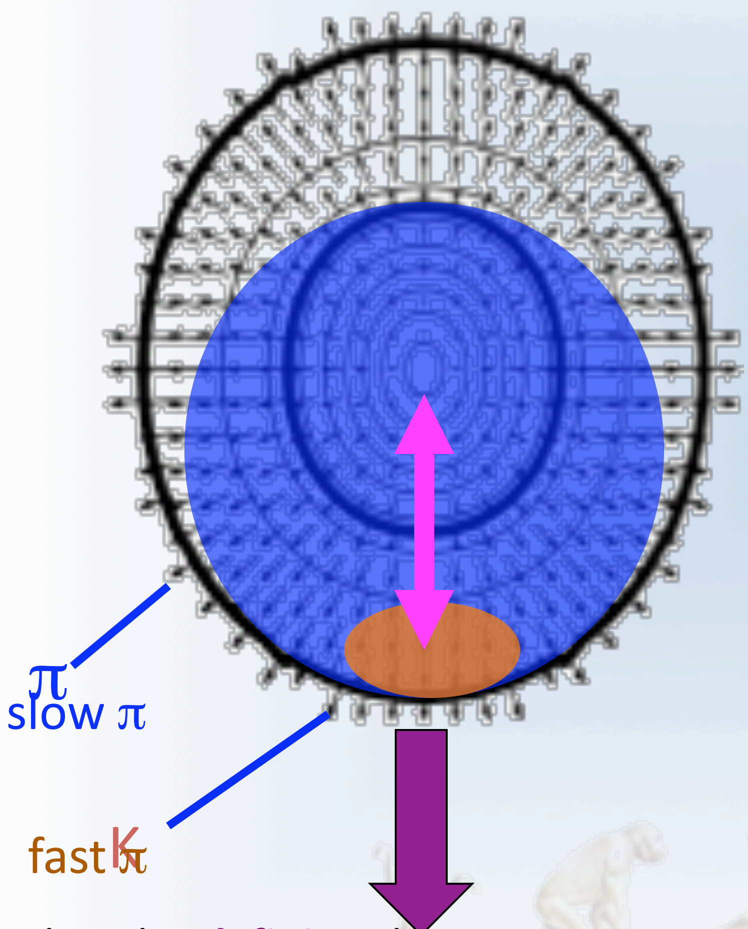
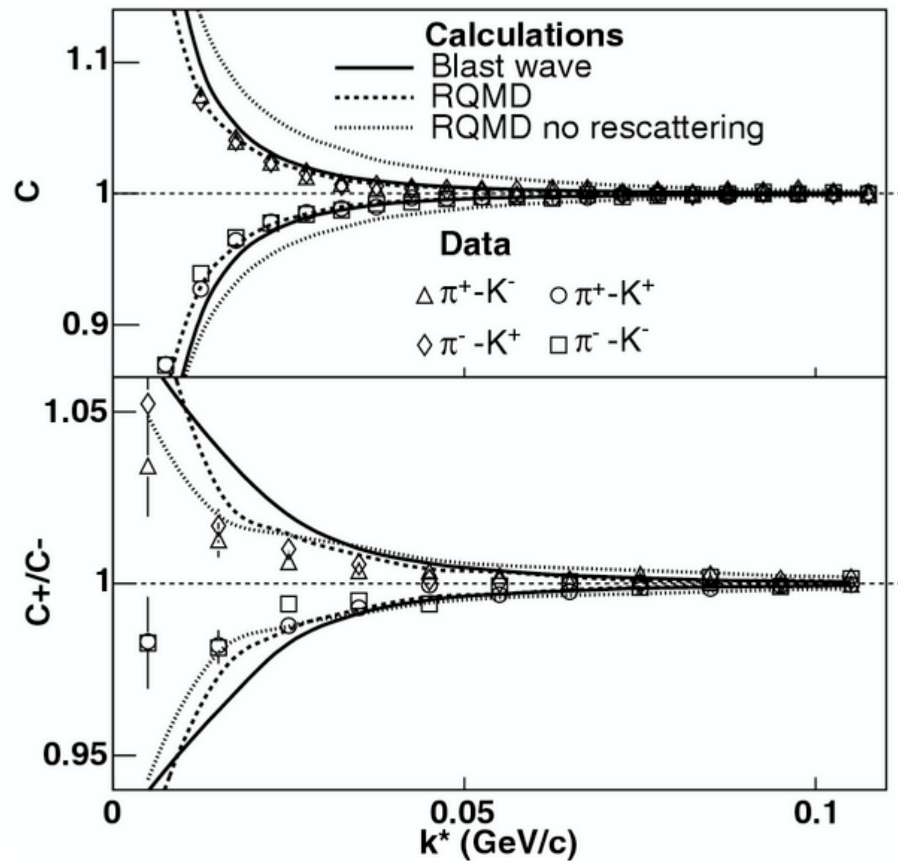


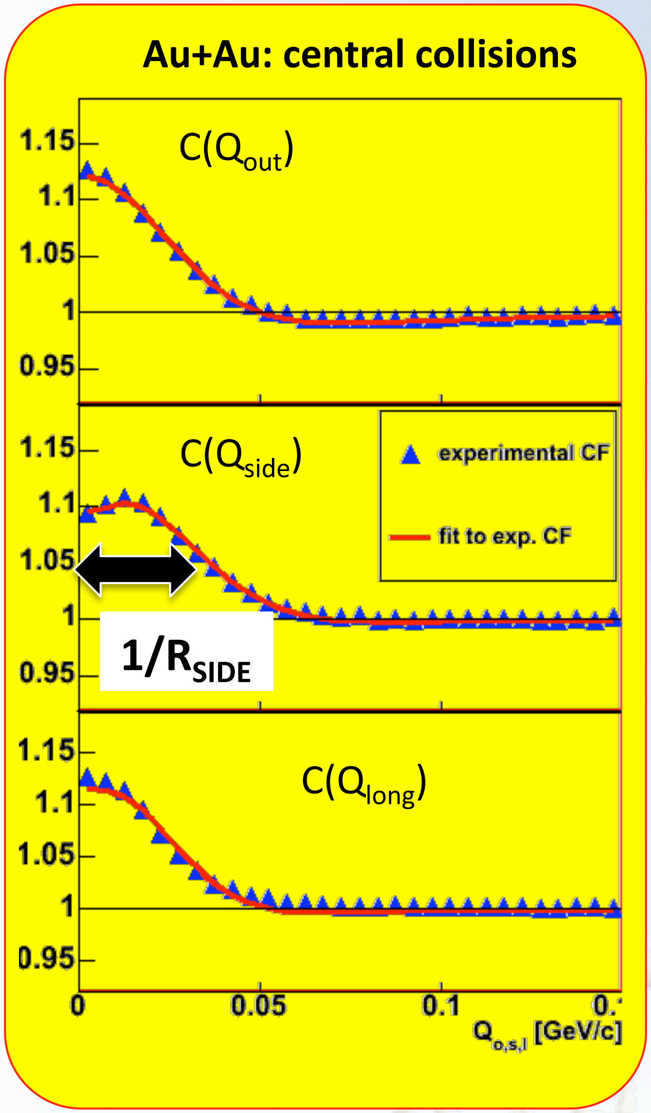
but the ***defining*** characteristic:
correlated position and boost direction



STAR PRL **91** 262301 (2003)

space-momentum substructure mapped *in detail*

Obtaining 3D radii from 3D correlation functions

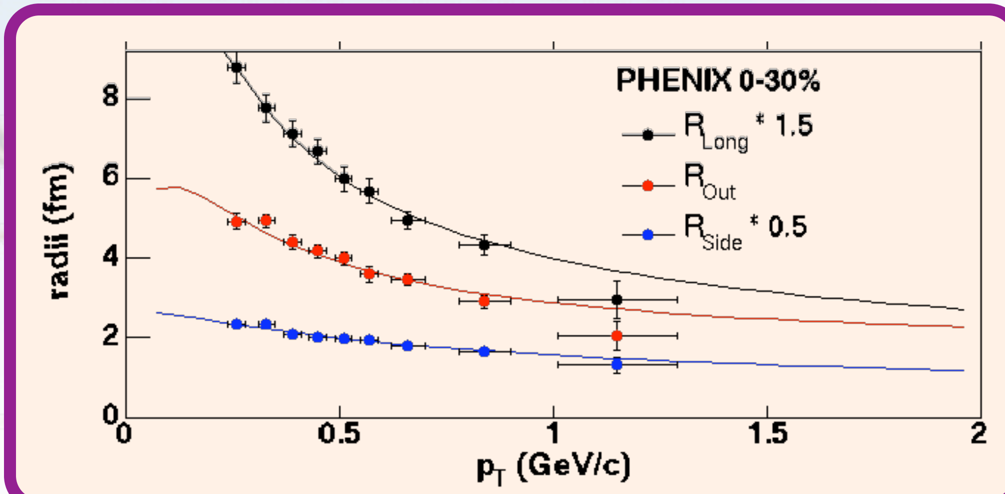


$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{ 1 + e^{-\left(q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2\right)} \right\} - 1 \right) \right]$$

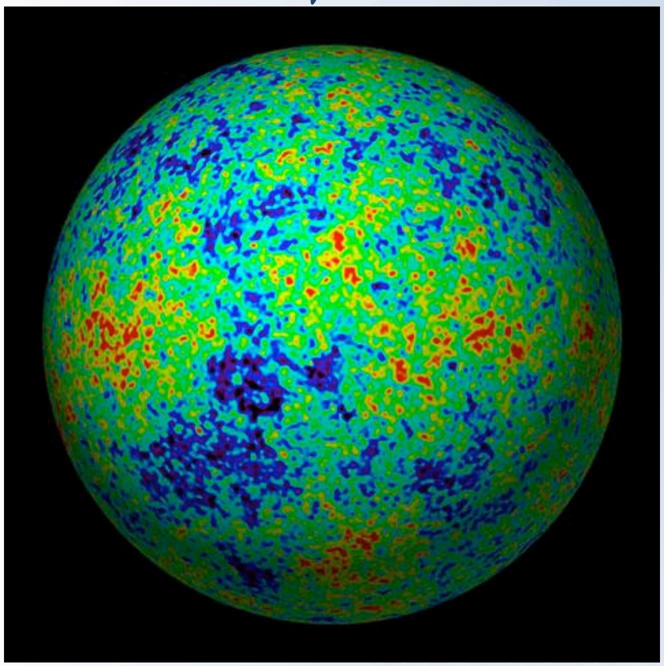
typical "Gaussian" fitting function

- Au+Au: "Gaussian" radii capture bulk scales
  - (resonance tails from imaging)
- $R(p_T)$ consistent with explosive flow

"set of zero measure" of full 3D correlation fctn



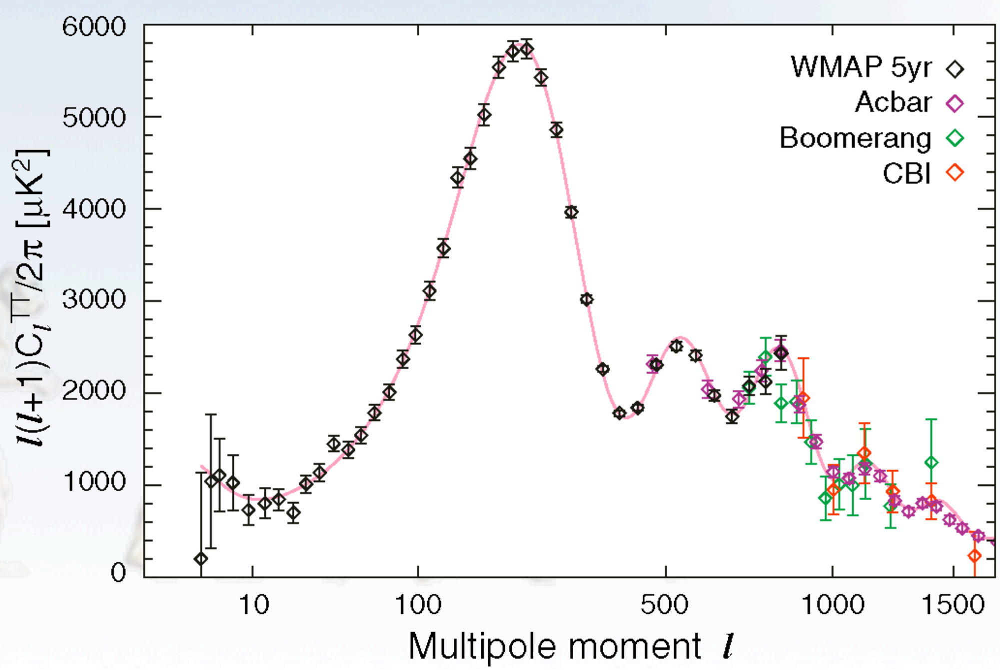
Spherical harmonic representation of 3D data



$$a_{l,m} \equiv \int d\Omega \cdot T(\theta,\phi) \cdot Y^*_{l,m}(\theta,\phi)$$

$$C_l^{TT} \equiv \left\langle \left| a_{l,m} \right|^2 \right\rangle_m$$

(average over m ↔ no "special" direction)



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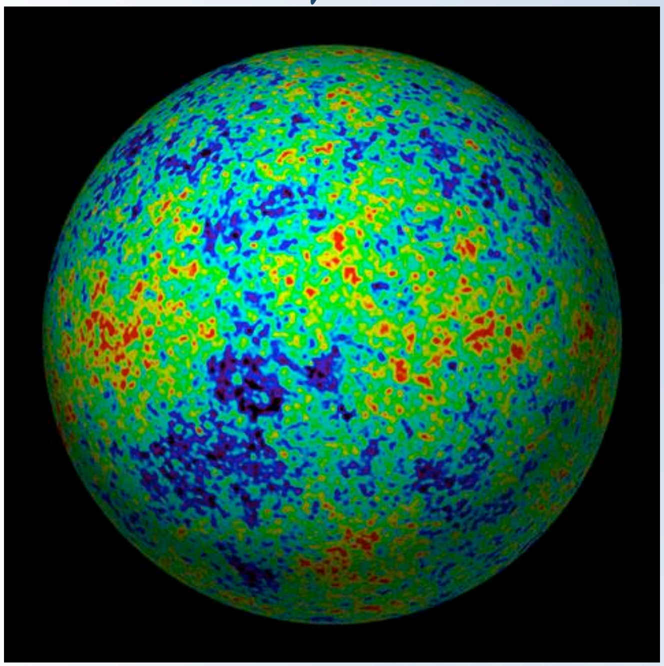

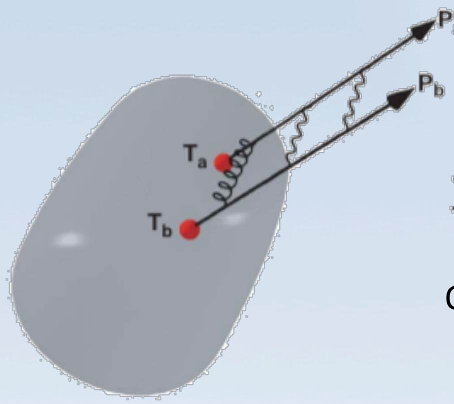

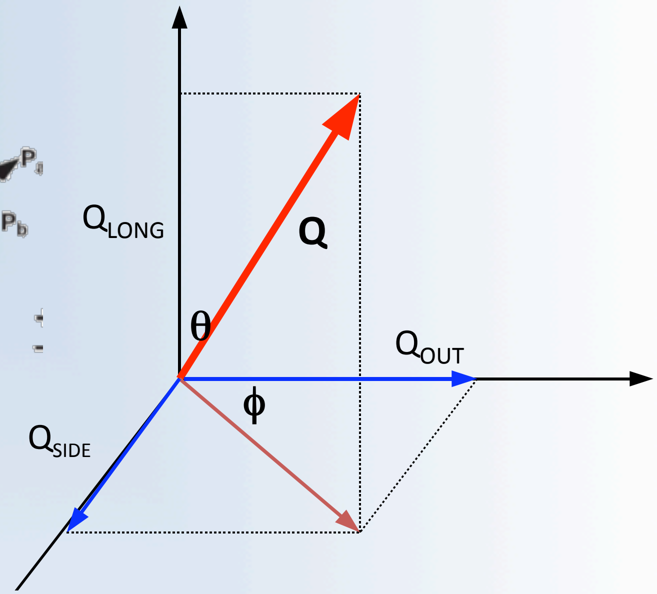

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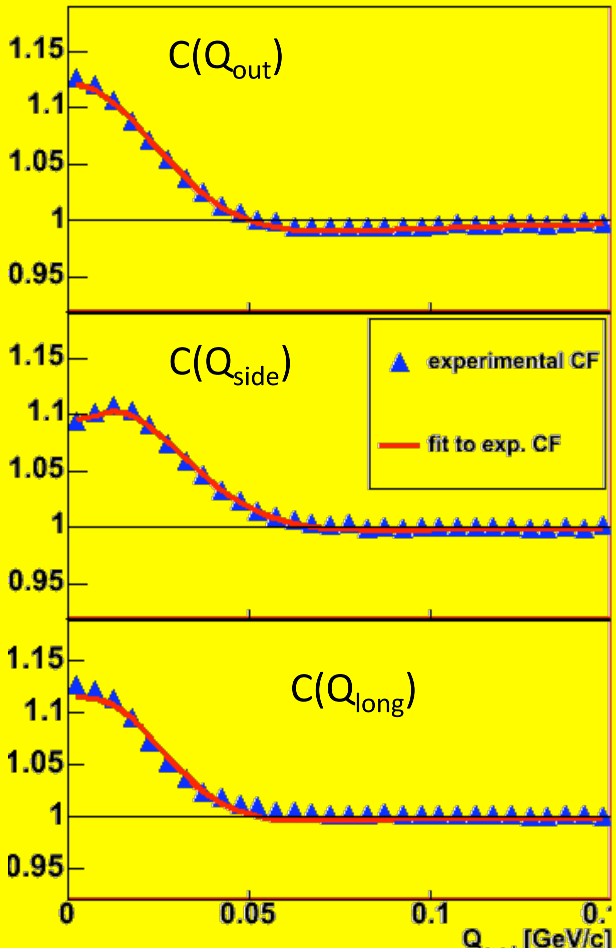
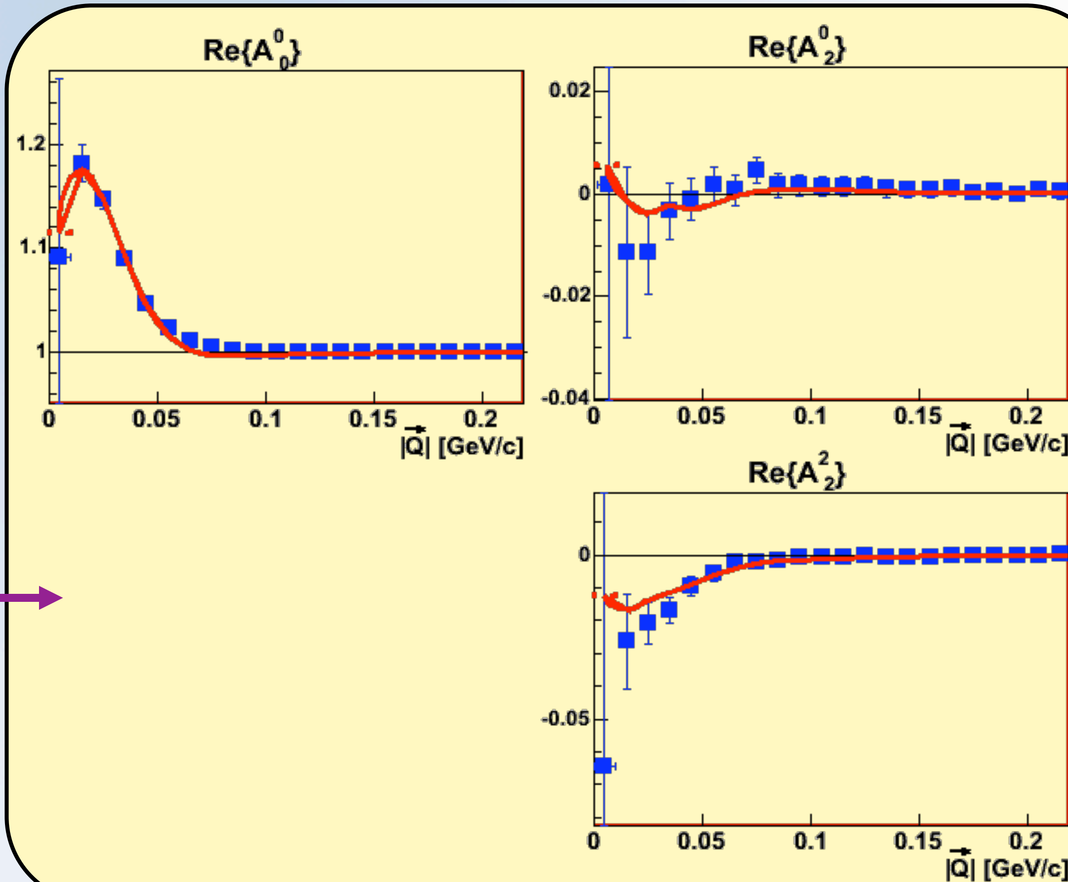
$$A_{l,m}\left(\left|\vec{Q}\right|\right) = \frac{\Delta_{\cos\theta}\Delta_\phi}{\sqrt{4\pi}} \sum_i^{bins} Y^*_{l,m}(\theta_i,\phi_i) C\left(\left|\vec{Q}\right|, \cos\theta_i, \phi_i\right)$$

Z. Chajecki & MAL, PRC **78** 064903 (2008)

Spherical harmonic representation of 3D data

Au+Au: central collisions





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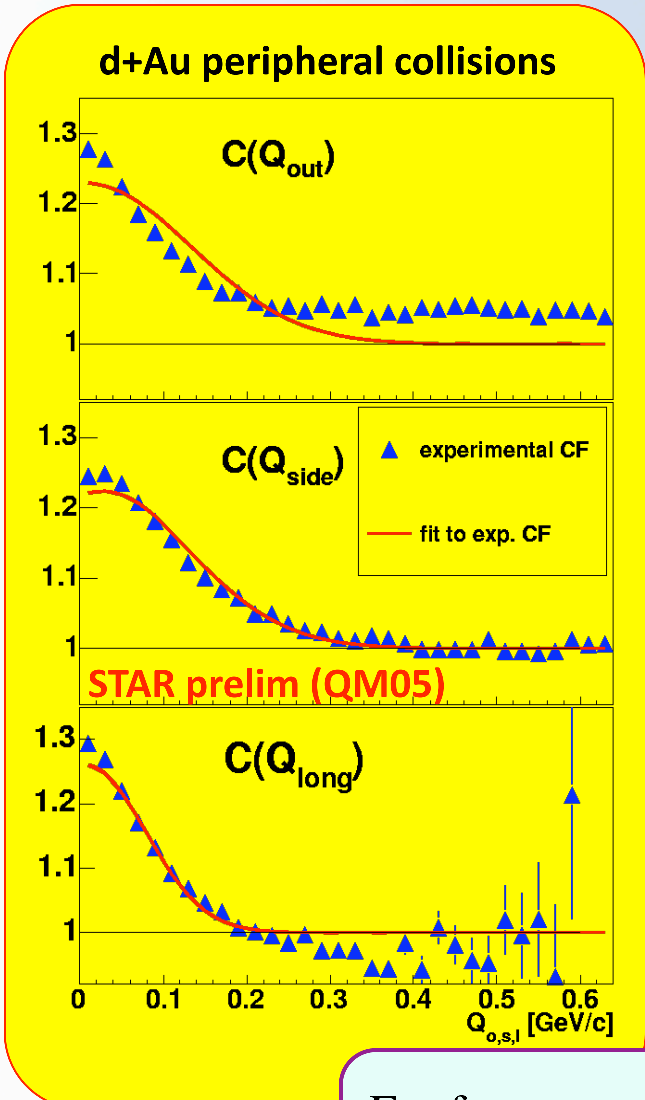
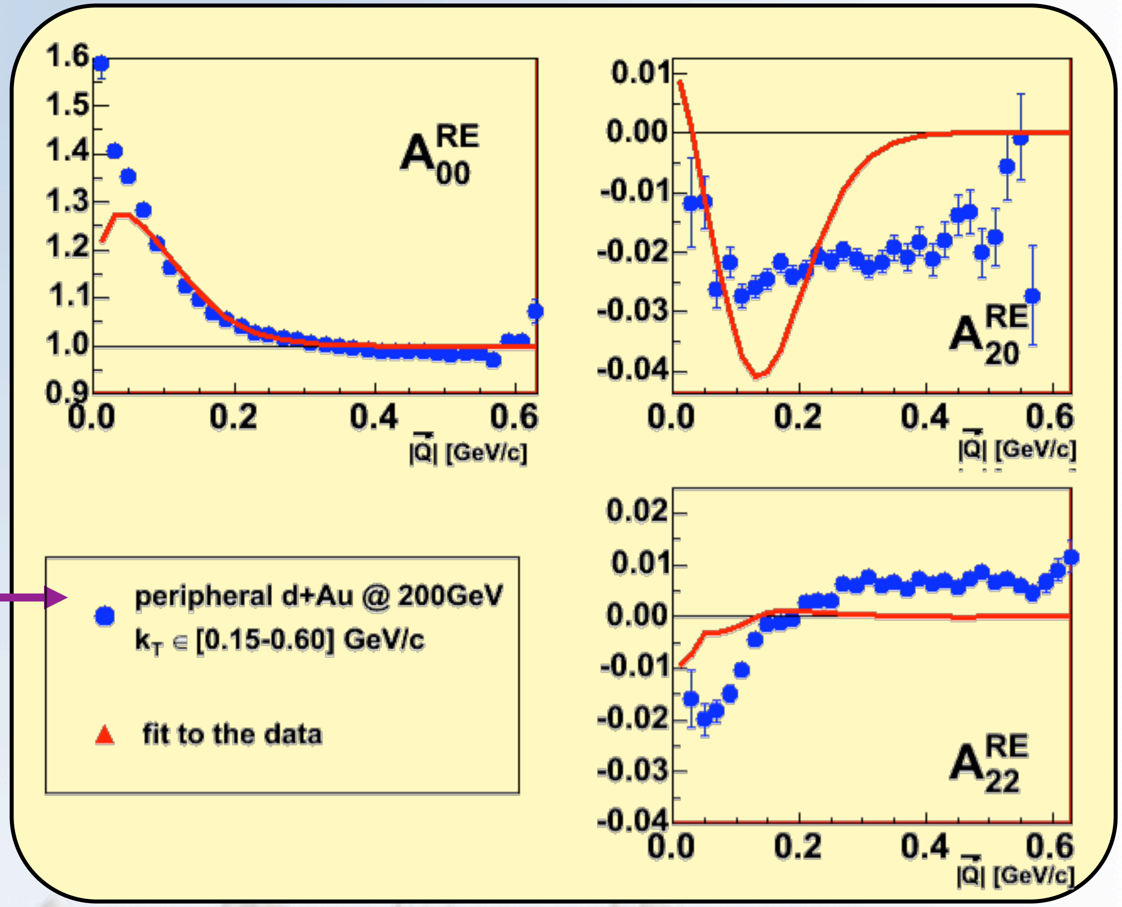
Z. Chajecki & MAL, PRC **78** 064903 (2008)

For femtoscopic correlations:

$$C\left(\vec{q};|\vec{q}|\to\infty\right)=C\left(|\vec{q}|\to\infty\right)\Rightarrow A^{m}_{\ell\neq 0}\left(|\vec{q}|\to\infty\right)=0$$

Spherical harmonic representation of 3D data





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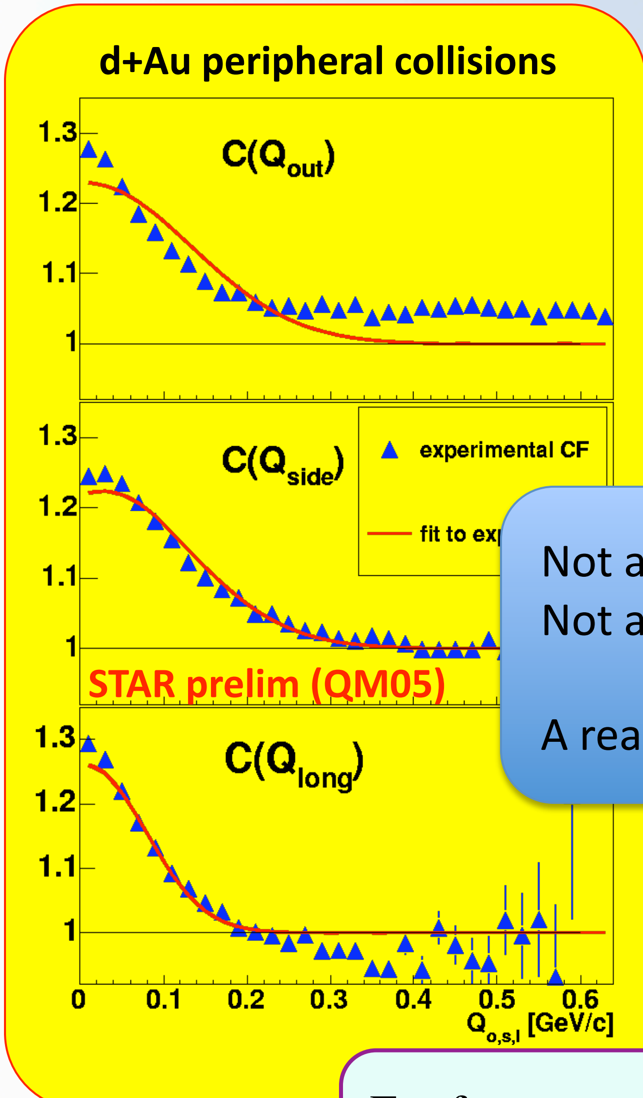
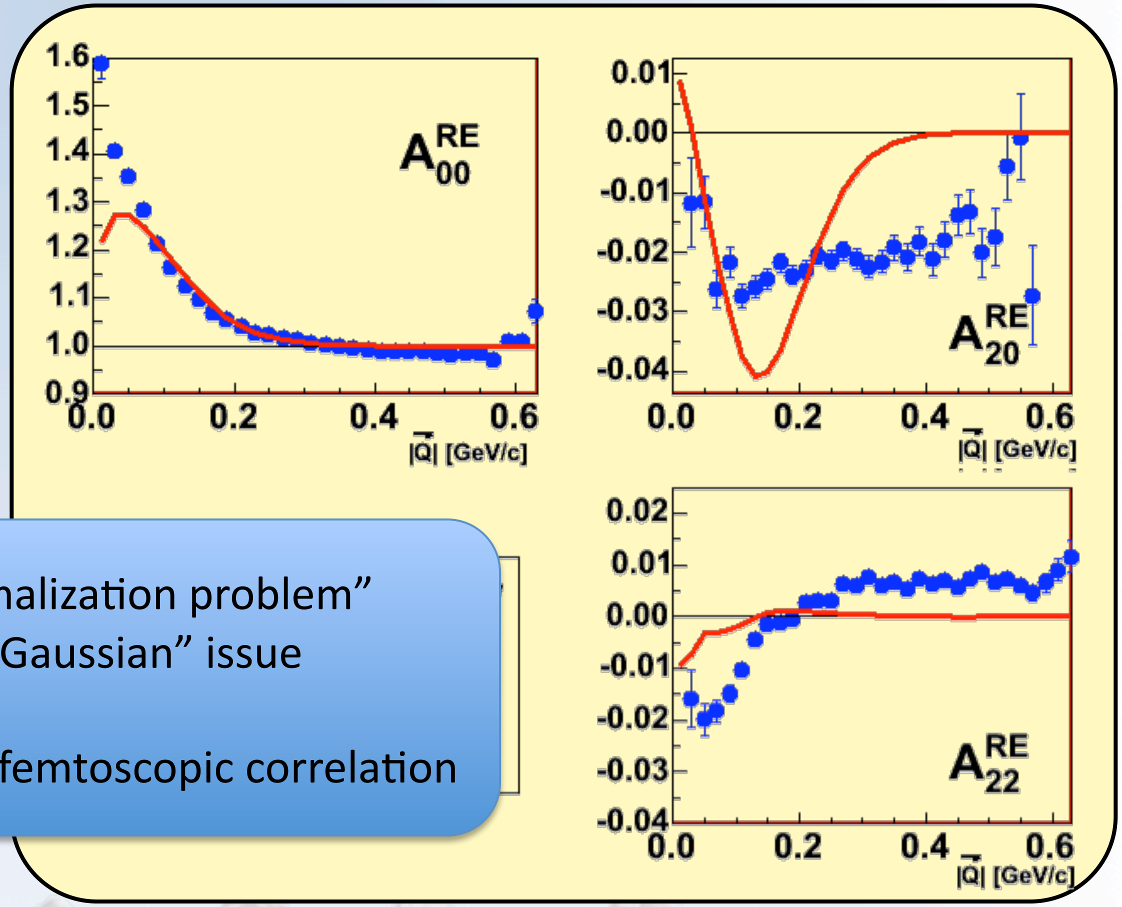
Z. Chajecki & MAL, PRC **78** 064903 (2008)

For femtoscopic correlations:

$$C\left(\vec{q};|\vec{q}| \to \infty\right) = C\left(|\vec{q}| \to \infty\right) \Rightarrow \mathrm{A}^{m}_{\ell\neq 0}\left(|\vec{q}| \to \infty\right) = 0$$

Spherical harmonic representation of 3D data





Not a "normalization problem"
Not a "non-Gaussian" issue

A real, non-femtoscopic correlation

$$A_{l,m}\left(\left|\vec{Q}\right|\right) = \frac{\Delta_{\cos\theta}\Delta_{\phi}}{\sqrt{4\pi}} \sum_{i}^{bins} Y^{*}_{l,m}(\theta_i,\phi_i)\, C\left(\left|\vec{Q}\right|, \cos\theta_i, \phi_i\right)$$

Z. Chajecki & MAL, PRC in press, arXiv:0803.0022 [nucl-th]

For femtoscopic correlations:

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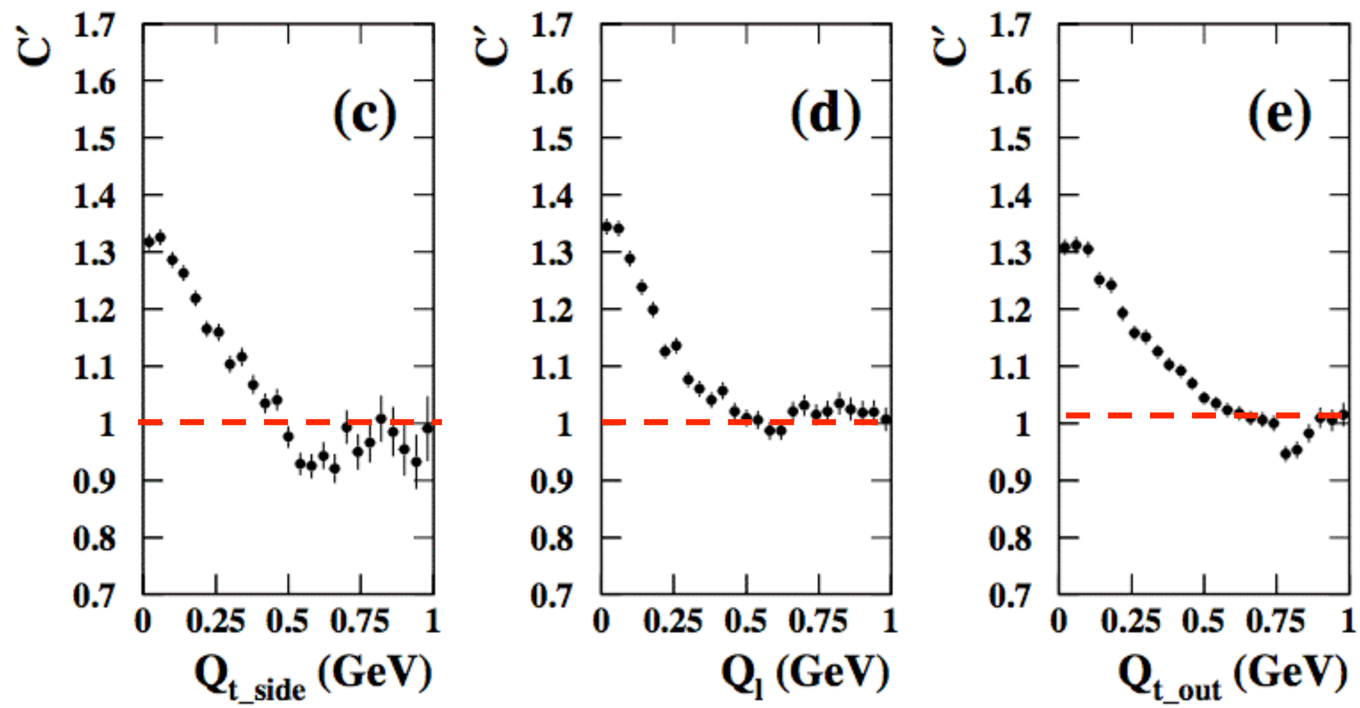
We are not alone...

Non-femto correlations in B-E analysis through the years:



Q_x<0.2 GeV/c

OPAL, CERN-PH-EP/2007-025
(submitted to Eur. Phys. J. C.)

NA22, Z. Phys. C71 (1996) 405

CLEO PRD32 (1985) 2294

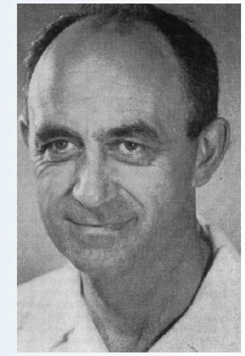
non-femto "large-2" behaviour - various approaches

- ignore it
- various ad-hoc parameterizations
- divide by $\pi^+\pi^-$ (only semi-successful, and only semi-justified)
- divide by MonteCarlo PYTHIA, tuning until tail is matched (similar to ad-hoc)

- Can we understand it in terms of simplest-possible effect–
  Energy and **M**omentum **C**onservation **I**nduced **C**orrelations (**EMCICs**)?
  - Z. Chajecki & MAL, PRC **78** 064903 (2008)

- see also
  - pT conservation effects on v2 [Danielewicz, Ollitrault & Borghini]
  - pT conservation on 3-particle "conical emission" observables [Borghini]
  - p and E conservation effects on single particle spectra [Chajecki & MAL]

energy-momentum conservation in n-body states



spectrum of kinematic quantity α (angle, momentum) given by

$$f(\alpha) = \frac{d}{d\alpha}\left(|M|^2 \cdot R_n\right)$$

where

M = matrix element describing interaction

(M = 1 $\rightarrow$ all spectra given by phasespace)

---

n-body Phasespace factor R_n

$$R_n = \int^{4n} \delta^4\left(P - \sum_{j=1}^{n} p_j\right) \prod_{i=1}^{n} \delta\left(p_i^2 - m_i^2\right) d^4 p_i$$

where

P = total 4-momentum of n-particle system

p_i = 4-momentum of particle i

m_i = mass of particle i

statistics: "density of states"

$$\delta\left(p_i^2 - m_i^2\right) d^4 p_i = \frac{|\vec{p}_i|^2}{E_i} d|\vec{p}_i| \cdot d(\cos\theta_i) \cdot d\phi_i$$

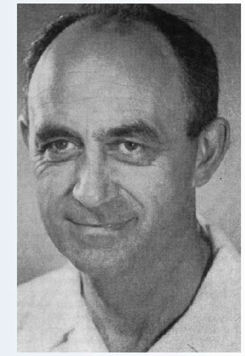
larger particle momentum $\rightarrow$ more available states

P_μ conservation

$$\delta^4\left(P - \sum_{j=1}^{n} p_j\right)$$

Induces "trivial" correlations (i.e. even for M=1)

Example of use of total phase space integral



- In absence of "physics" in *M* : (i.e. phase-space dominated)

$$\frac{\Gamma(p\bar{p} \to \pi\pi\pi)}{\Gamma(p\bar{p} \to \pi\pi\pi\pi)} = \frac{R_3(1.876;\pi,\pi,\pi)}{R_4(1.876;\pi,\pi,\pi,\pi)}$$

- single-particle spectrum (e.g. p_T):

$$W(p_i) = d^3 p_i \cdot \bar{S}_n(p_i) R_n$$

Hagedorn

- "spectrum of events":

In limit where "α"="event" = collection of momenta $\vec{p}_i$

$$\text{"spectrum of events"} = f(\alpha) = \frac{d}{d\alpha} R_n$$

$$\to \mathrm{Prob}_{\text{event }\alpha} \propto \frac{d^{3n}}{\prod_{i=1}^{n} dp_i^3} R_n$$

F. James, CERN REPORT 68-15 (1968)

Correlations arising (only) from conservation laws (PS constraints)

$$\tilde{f}(p_i) = 2E_i \frac{dN}{d^3 p_i}$$

single-particle "parent" distribution **w/o P.S. restriction**

what we measure

no other correlations

$$\tilde{f}_c(p_1,\ldots,p_k) \equiv \left(\prod_{i=1}^{k} \tilde{f}(p_i)\right) \cdot \frac{\int \left(\prod_{i=k+1}^{N} \frac{d^3 p_i}{2E_i} \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}{\int \left(\prod_{i=1}^{N} \frac{d^3 p_i}{2E_i} \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}$$

$$= \left(\prod_{i=1}^{k} \tilde{f}(p_i)\right) \cdot \frac{\int \left(\prod_{i=k+1}^{N} d^4 p_i \delta(p_i^2 - m_i^2) \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}{\int \left(\prod_{i=1}^{N} d^4 p_i \delta(p_i^2 - m_i^2) \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}$$

k-particle distribution (k<N) **with P.S. restriction**

Simplification for "large" N-k (1)

Numerator is the probability distribution of a sum of many (N-k) uncorrelated vectors

(i.e. the probability that they will add up to $P-\Sigma_{i=1}^{k}p_i$)

If (N-k) big →Multivariate Central Limit Theorem

$$\sum_{i=k+1}^{N} p_i - \left(P - \sum_{i=1}^{k} p_i\right)$$

$$= \left(\prod_{i=1}^{k} \tilde{f}(p_i)\right) \cdot \frac{\int \left(\prod_{i=k+1}^{N} d^4 p_i \delta(p_i^2 - m_i^2) \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}{\int \left(\prod_{i=1}^{N} d^4 p_i \delta(p_i^2 - m_i^2) \tilde{f}(p_i)\right) \delta^4\left(\sum_{i=1}^{N} p_i - P\right)}$$

Denominator is "just" a constant normalization (indep p_i)

Using central limit theorem ("large N-k")*

k-particle distribution in N-particle system

$$\tilde{f}_c(p_1,\ldots,p_k) = \left(\prod_{i=1}^{k} \tilde{f}(p_i)\right)\left(\frac{N}{N-k}\right)^2 \exp\left(-\sum_{\mu=0}^{3} \frac{\left(\sum_{i=1}^{k}\left(p_{i,\mu} - \langle p_\mu \rangle\right)\right)^2}{2(N-k)\sigma_\mu^2}\right)$$

where

$$\sigma_\mu^2 = \langle p_\mu^2 \rangle - \langle p_\mu \rangle^2$$

$$\langle p_\mu \rangle = 0 \quad \text{for} \quad \mu = 1,2,3$$

N.B.
relevant later

$$\langle p_\mu^2 \rangle \equiv \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}(p)}_{\substack{\text{unmeasured} \\ \text{parent distrib}}} \neq \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}_c(p)}_{\text{measured}}$$

–Danielewicz *et al*, PR**C38** 120 (1988)
–Borghini, Dinh, & Ollitraut PR**C62** 034902 (2000)
–Borghini Eur. Phys. J. C30:381-385, (2003)
–Chajecki & MAL, PRC **78** 064903 (2008)

* "large": N > ~10

Effects on single-particle distribution

$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\left(\frac{N}{N-1}\right)^2 \exp\left(-\sum_{\mu=0}^{3}\frac{\left(p_{i,\mu}-\langle p_\mu\rangle\right)^2}{2(N-1)\sigma_\mu^2}\right)$$

$$= \tilde{f}(p_i)\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{p_{x,i}^2}{\langle p_x^2\rangle}+\frac{p_{y,i}^2}{\langle p_y^2\rangle}+\frac{p_{z,i}^2}{\langle p_z^2\rangle}+\frac{\left(E_i-\langle E\rangle\right)^2}{\langle E^2\rangle-\langle E\rangle^2}\right)\right)$$

We will return to this….

in this case, the index i is only keeping track of particle type, really

k-particle correlation function

$$C(p_1,\ldots,p_k) \equiv \frac{\tilde{f}_c(p_1,\ldots,p_k)}{\tilde{f}_c(p_1)\ldots\tilde{f}_c(p_k)}$$

$$= \frac{\left(\frac{N}{N-k}\right)^2 \exp\left(-\frac{1}{2(N-k)}\sum_{i=1}^{k}\left(\frac{\left(\sum_{i=1}^{k} p_{x,i}\right)^2}{\langle p_x^2\rangle} + \frac{\left(\sum_{i=1}^{k} p_{y,i}\right)^2}{\langle p_y^2\rangle} + \frac{\left(\sum_{i=1}^{k} p_{z,i}\right)^2}{\langle p_z^2\rangle} + \frac{\left(\sum_{i=1}^{k}(E_i - \langle E\rangle)\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)}{\left(\frac{N}{N-1}\right)^{2k} \exp\left(-\frac{1}{2(N-1)}\sum_{i=1}^{k}\left(\frac{p_{x,i}^2}{\langle p_x^2\rangle} + \frac{p_{y,i}^2}{\langle p_y^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)}$$

Dependence on "parent" distrib f vanishes,

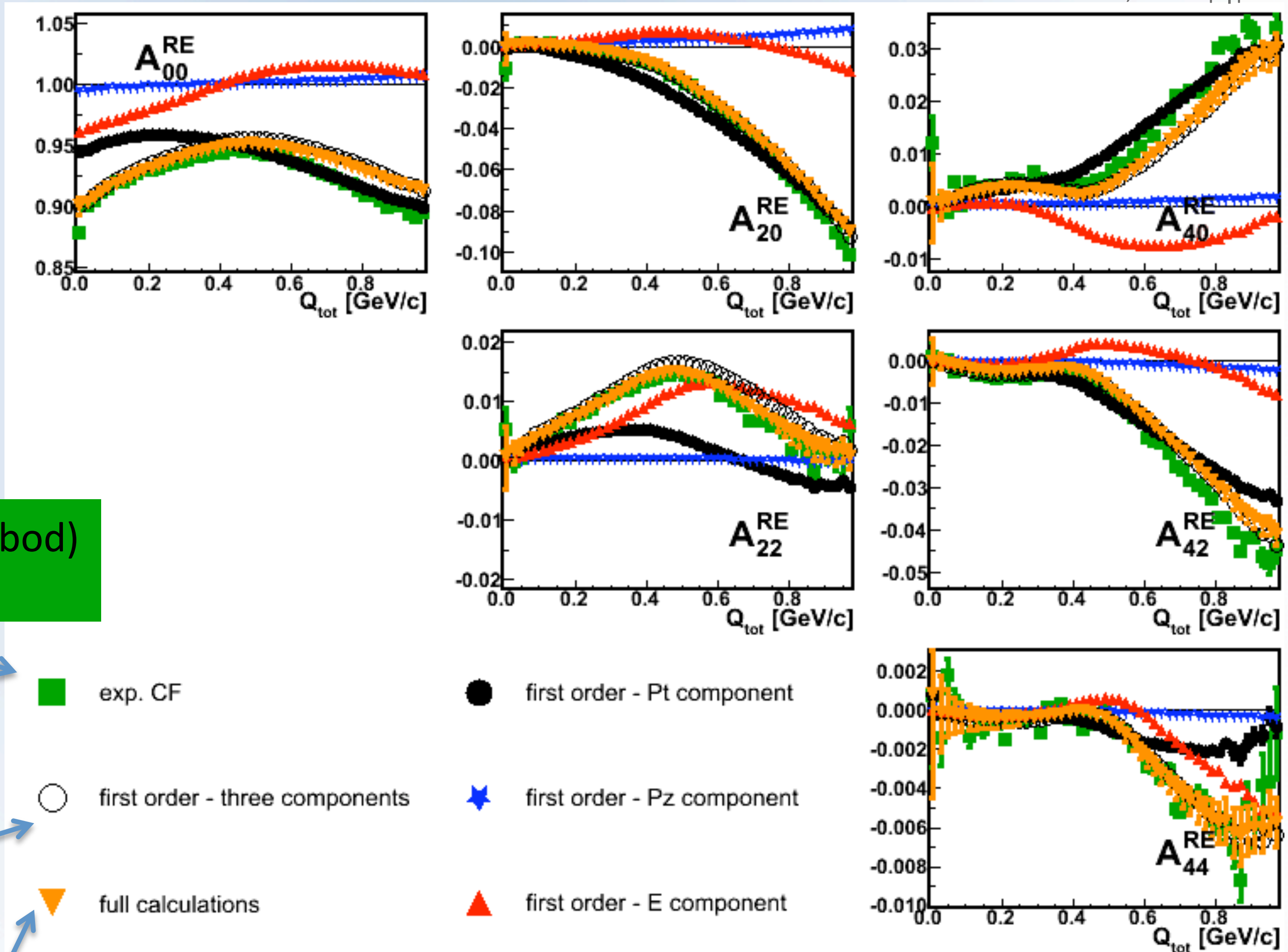
except for energy/momentum means and RMS

2-particle correlation function (1st term in 1/N expansion)

$$C(p_1,p_2) \cong 1 - \frac{1}{N}\left(2\frac{\vec{p}_{T,1}\cdot\vec{p}_{T,2}}{\langle p_T^2\rangle} + \frac{p_{z,1}\cdot p_{z,2}}{\langle p_z^2\rangle} + \frac{(E_1 - \langle E\rangle)\cdot(E_2 - \langle E\rangle)}{\langle E^2\rangle - \langle E\rangle^2}\right)$$

How do EMCICs look ? – nontrivial !

Genbod N=18 <K>=0.9 GeV; PRF - |η|<0.5



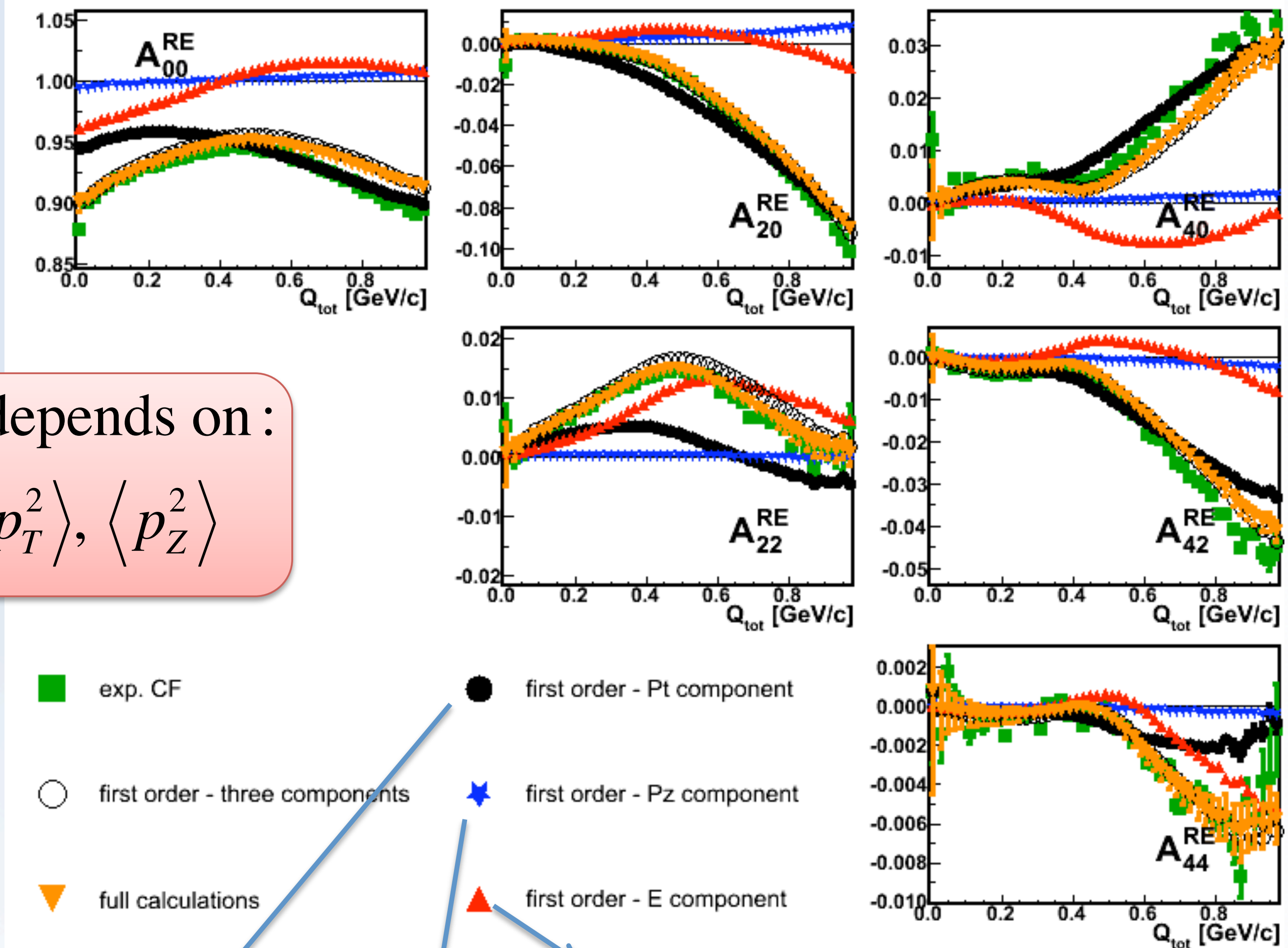
event generator (genbod) with only EMCICs

O(1/N) term in CLT approximation

CLT approximation

- structure not confined to large Q
- kinematic cuts have strong effect

How do EMCICs look ? – nontrivial !



Detailed shape depends on :

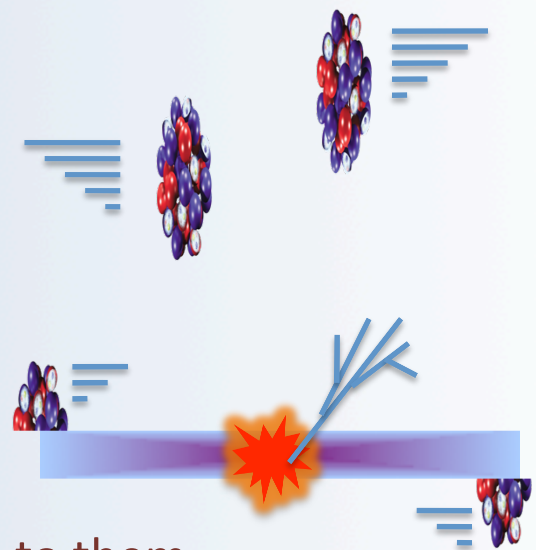
$N, \langle E \rangle, \langle E^2 \rangle, \langle p_T^2 \rangle, \langle p_Z^2 \rangle$

$$C(p_1,p_2) \cong 1 - \frac{1}{N}\left(2\frac{\vec{p}_{T,1}\cdot\vec{p}_{T,2}}{\langle p_T^2 \rangle} + \frac{p_{z,1}\cdot p_{z,2}}{\langle p_z^2 \rangle} + \frac{(E_1 - \langle E \rangle)\cdot(E_2 - \langle E \rangle)}{\langle E^2 \rangle - \langle E \rangle^2} \right)$$

"the system"... a nontrivial concept

$$N,\ \langle E\rangle,\ \langle E^2\rangle,\ \langle p_T^2\rangle,\ \langle p_Z^2\rangle$$

Characteristic scales of relevant system in which limited energy-momentum is shared



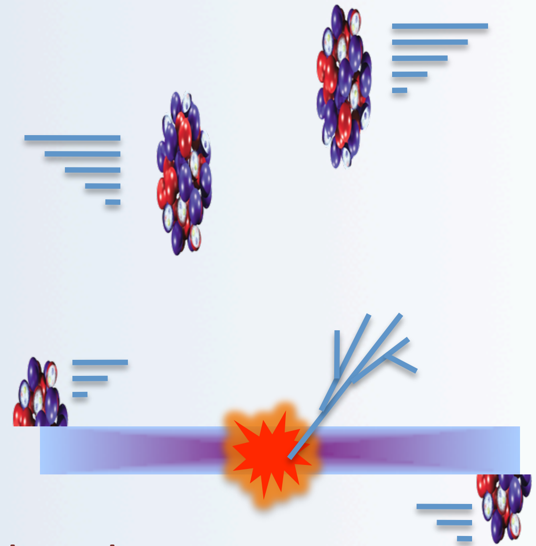
- Not known a priori
- should *track* measured quantities, but not be identical to them

1. *N* includes primary particles (including unmeasured γ's etc)
2. secondary decay (resonances, fragmentation) smears connection b/t $\langle E^2\rangle$ and measured one
3. $\langle E^2\rangle$ etc: averages of the *parent* distribution

$$\langle p_\mu^2\rangle \equiv \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}(p)}_{\substack{\text{unmeasured}\\ \text{parent distrib}}} \neq \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}_c(p)}_{\text{measured}}$$

4. "relevant system" almost certainly not the "whole" (4π) system
   - e.g. beam fragmentation probably not relevant to system emitting at midrapidity
     - characteristic physical processes (strings etc): Δy ~ 1÷2
   - jets: "of the system" ??
     - sim "leading baryon effect" in microcanonical thermal fits
   - if "relevant system" ≠ "whole system", then total energy-momentum ***will fluctuate*** e-by-e

"the system" ... a nontrivial concept



$$N,\ \langle E\rangle,\ \langle E^2\rangle,\ \langle p_T^2\rangle,\ \langle p_Z^2\rangle$$

Characteristic scales of relevant system in which limited energy-momentum is shared

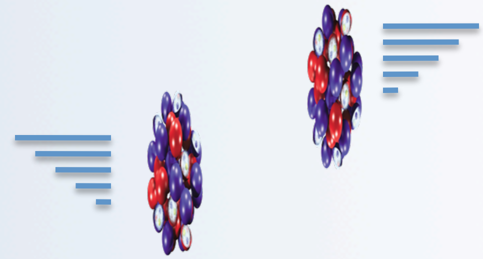
- Not known a priori
- should *track* measured quantities, but not be identical to them

- We will treat them as parameters: what to expect?

$$\text{Maxwell-Boltzmann parent}\ \frac{d^3N}{d^3p} \sim e^{-E/T}$$

	non-rel	ultra-rel	if $T = .15 \div .35$
$\langle p_T^2\rangle$	$2mT$	$8T^2$	$0.045 \div 0.98\ (\text{GeV/c})^2$
$\langle E^2\rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5\ \text{GeV}^2$
$\langle E\rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1\ \text{GeV}$

"the system"... a nontrivial concept



$$N, \langle E \rangle, \langle E^2 \rangle, \langle p_T^2 \rangle, \langle p_Z^2 \rangle$$

Characteristic scales of relevant system in which limited energy-momentum is shar

- Not known a priori
- should *track* measured quantities, b

- What to expect?

Blastwave, $T = 100$ MeV $\rho_0 = 0.9$

$\langle p_T^2 \rangle_\pi = 0.240$ GeV^2 $\left(\langle p_T \rangle_\pi = 0.405 \text{ GeV}\right)$

$\langle m_T \rangle_\pi = 0.435$ GeV

$\langle m_T^2 \rangle_\pi = 0.259$ GeV^2

Maxwell-Boltzmann parent $\frac{d^3N}{d^3p} \sim e^{-E/T}$

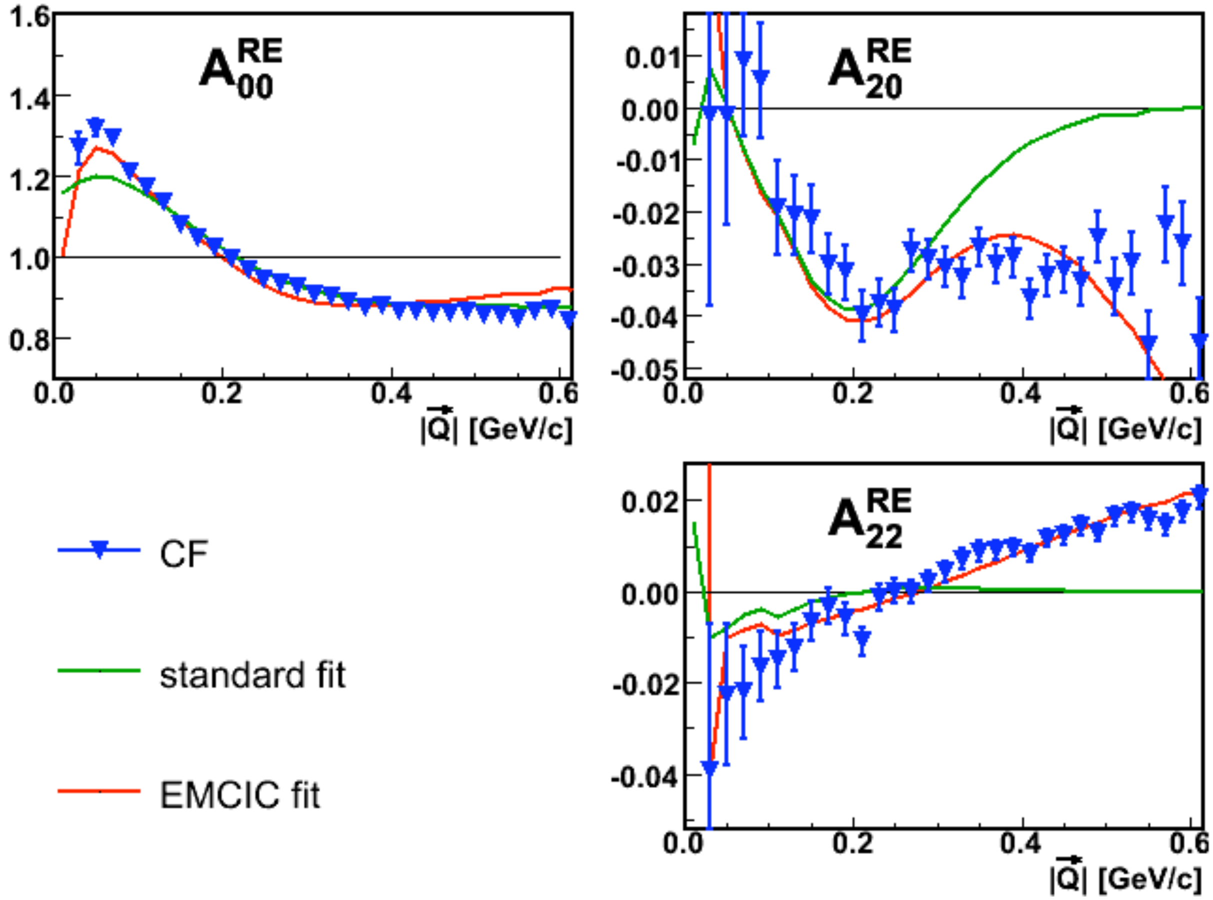
	non-rel	ultra-rel	if $T = .15$ -
$\langle p_T^2 \rangle$	$2mT$	$8T^2$	$0.045 \div 0.9$
$\langle E^2 \rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5$
$\langle E \rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1$ G

η_{max}	$\langle N \rangle$	$\langle p_T^2 \rangle_c$	$\langle p_z^2 \rangle_c$	$\langle E^2 \rangle_c$	$\langle E \rangle_c$
1.0	16	0.20	0.11	0.40	0.44
2.0	29	0.21	0.76	1.05	0.68
3.0	39	0.21	3.5	3.8	1.2
4.0	47	0.21	24	25	2.2
5.0	51	0.22	88	89	3.7

TABLE I: For a given selection on pseudorapidity $|\eta| < \eta_{max}$, the number and kinematic variables for primary particles from a PYTHIA simulation of $p+p$ collisons at $\sqrt{s_{NN}} = 200$ GeV are given. Units are GeV/c or (GeV/c)^2, as appropriate.

p+p minbias

Z. Chajecki, WPCF 2008

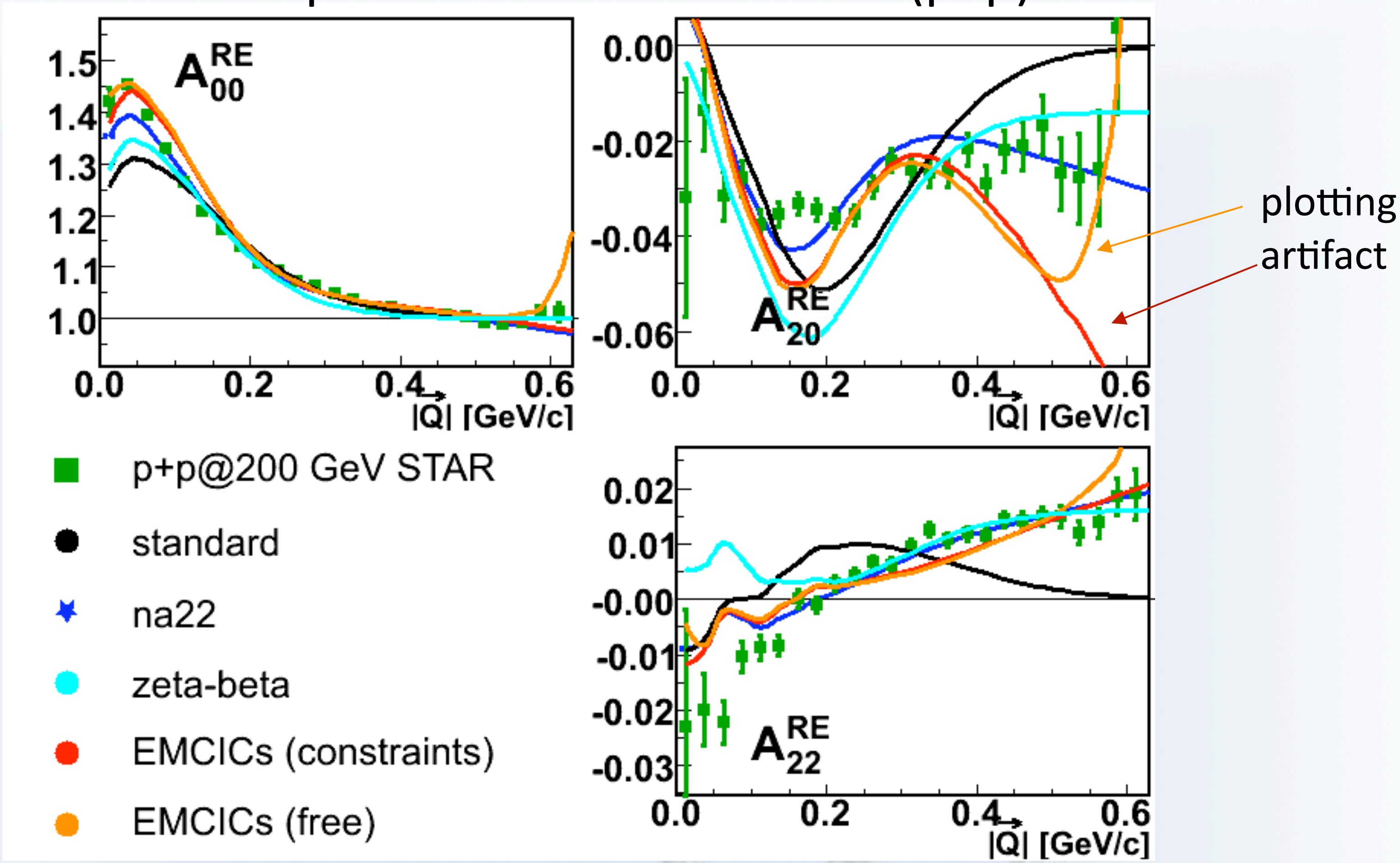


kT=0.35-0.6

λ	0.46
R_O	0.81 fm
R_S	0.84 fm
R_L	1.29 fm

λ	0.64	N	12.9
R_O	0.96 fm	$\langle p_T^2 \rangle$	0.2 (GeV/c)^2
R_S	0.88 fm	$\langle p_Z^2 \rangle$	0.39 (GeV/c)^2
R_L	1.26 fm	<E>	0.6 GeV
		$\langle E^2 \rangle$	0.43 GeV^2

Various fits to the pion correlation function (p+p)



fit method	R_{out} [fm]	R_{side} [fm]	R_{long} [fm]
standard	0.65 +/- 0.01	0.85 +/- 0.01	1.42 +/- 0.02
"NA22"	1.18 +/- 0.02	1.05 +/- 0.02	1.75 +/- 0.03
"zeta-beta"	1.01 +/- 0.03	0.79 +/- 0.03	1.52 +/- 0.05
EMCICs (constr.)	1.05 +/- 0.02	1.06 +/- 0.02	1.66 +/- 0.03
EMCICs(free)	1.06 +/- 0.02	1.08 +/- 0.02	1.69 +/- 0.03

femtoscopy in p+p @ STAR

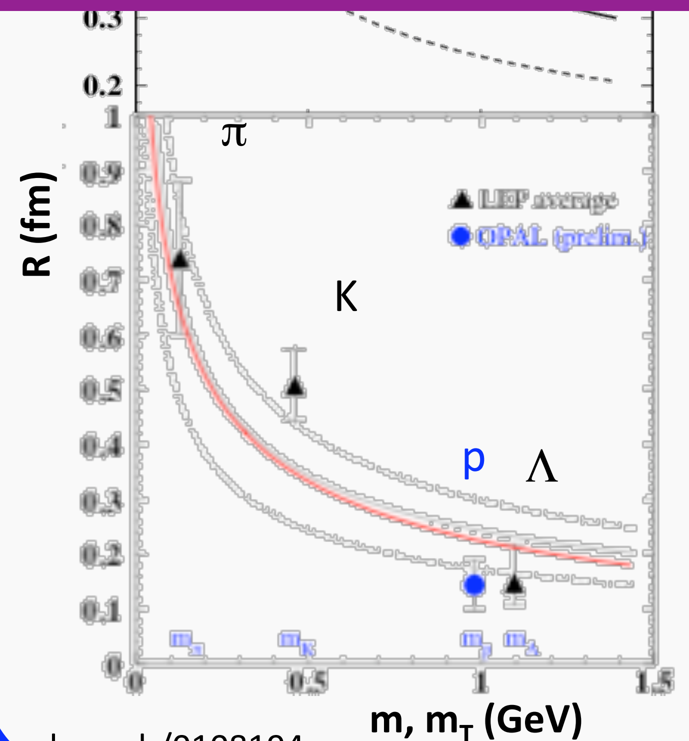
1. Heisenberg uncertainty?

2. String fragmentation? (Lund)

3. Resonance effects?

4. Flow???

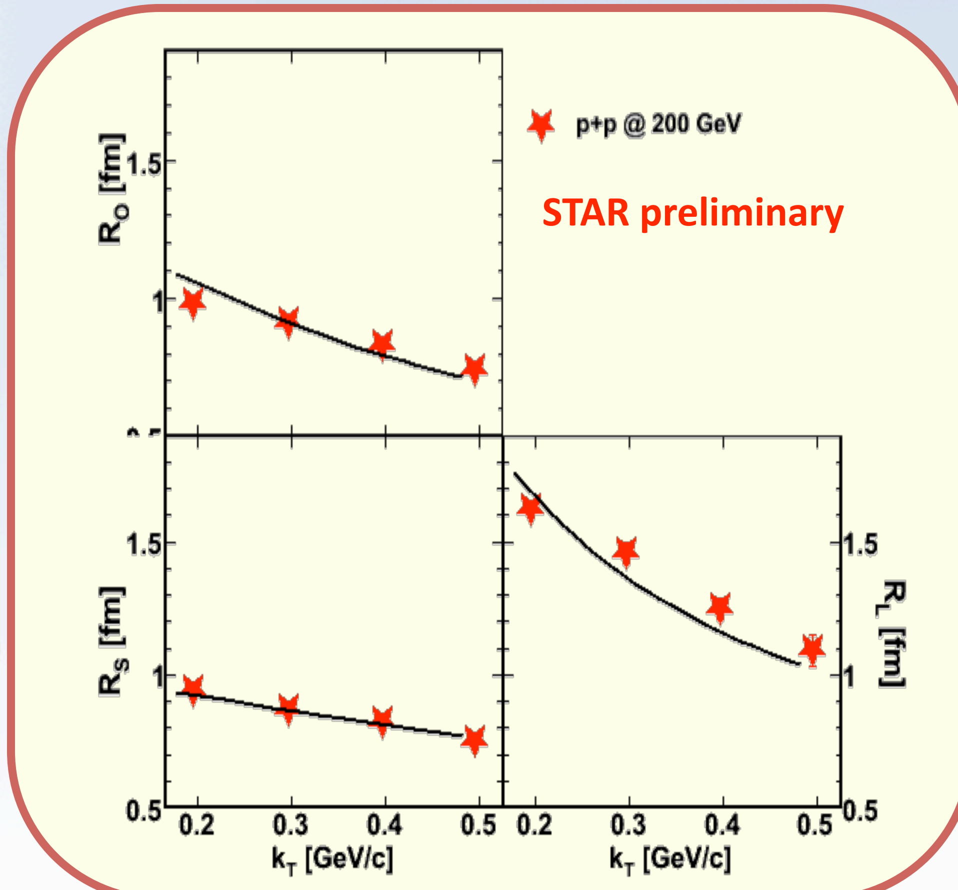
- Increasingly suggested in HEP experiments



hep-ph/0108194

p+p and A+A measured in *same* experiment, *same* acceptance, *same* techniques

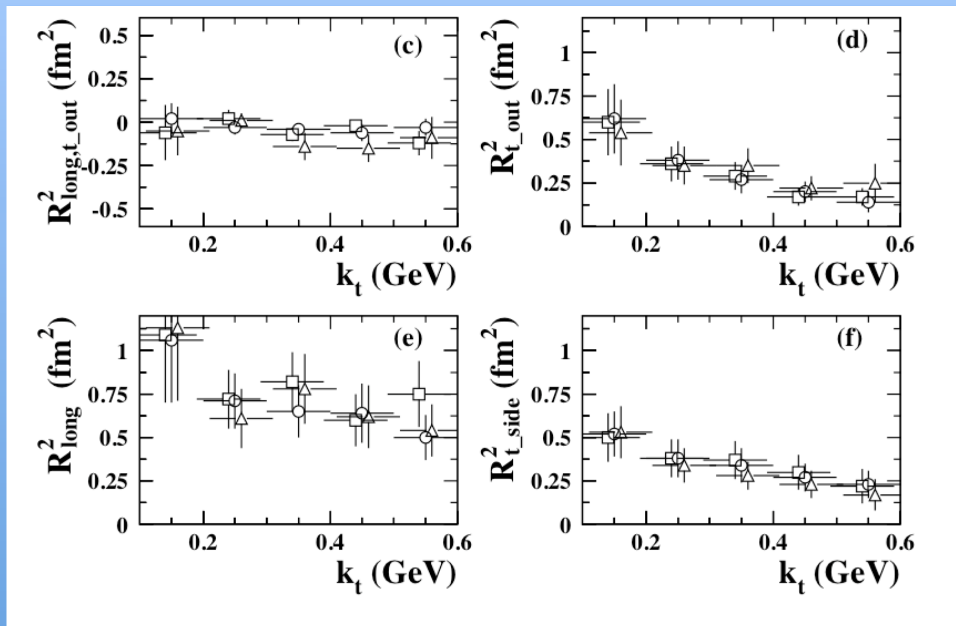
- unique opportunity to compare physics
- what causes p_T-dependence in p+p?
- same cause as in A+A?



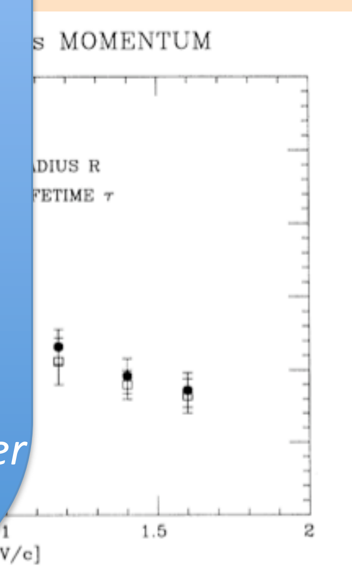
C 71, 405–414 (1996)

pectation from
description of
in the framework
ng source model.

OPAL Collaboration, Eur.Phys.J.C52:787-803,2007; arXiv:0708.1122 [hep-ex]



R2tside , R2tout and, less markedly, R2long decrease with increasing kt . The presence of correlations between the particle production points and their momenta is an indication that the pion source is not static, but rather expands during the particle emission process.



ime as a function of the
$_G$ is primarily a source
might possibly be inter-
to the beam. Data are

3 1931 (1993)

ling shell model.

W. Kittel Acta Phys.Polon. B32 (2001) 3927 [Review article]

… and suggests the existence of an important "collective flow", even in the system of particles produced in e+e− annihilation!

A 1/√m T scaling first observed in heavy-ion collisions is now also observed in Z fragmentation and may suggest a "transverse flow" even there!

OPAL Collaboration, Eur.Phys.J.C52:787-803

RHIC: “comparison m

Vary size. All else fixe

- spectra
- femtoscopy

compare with a syste

R2ts
The p
their
expand

W. Kittel Acta Phys.Polon. B32 (2001) 3

… and suggests the existence of an impor
system of particles produced in e+e− ann

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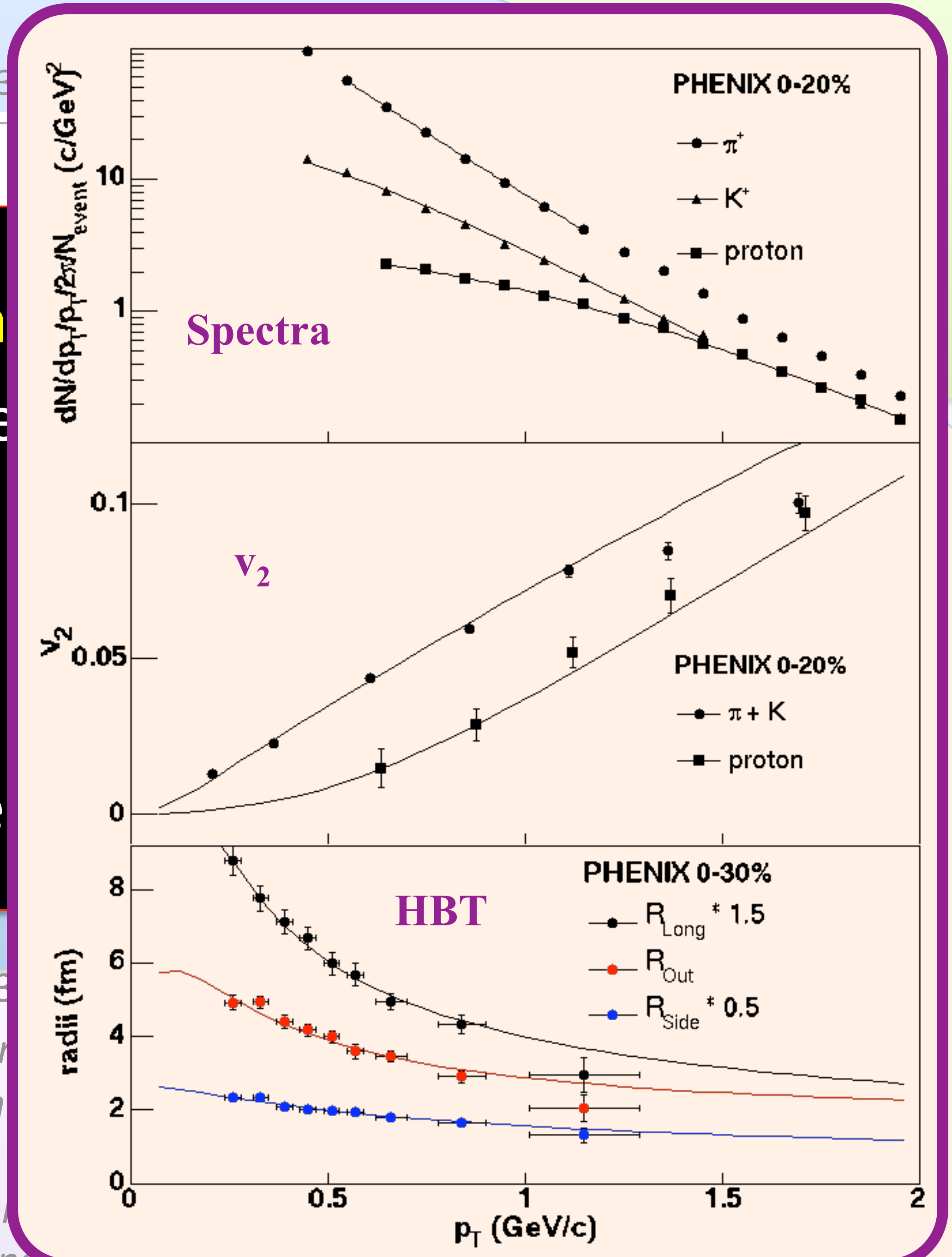


Apples:apples comparison…

Z. Chajecki, QM05

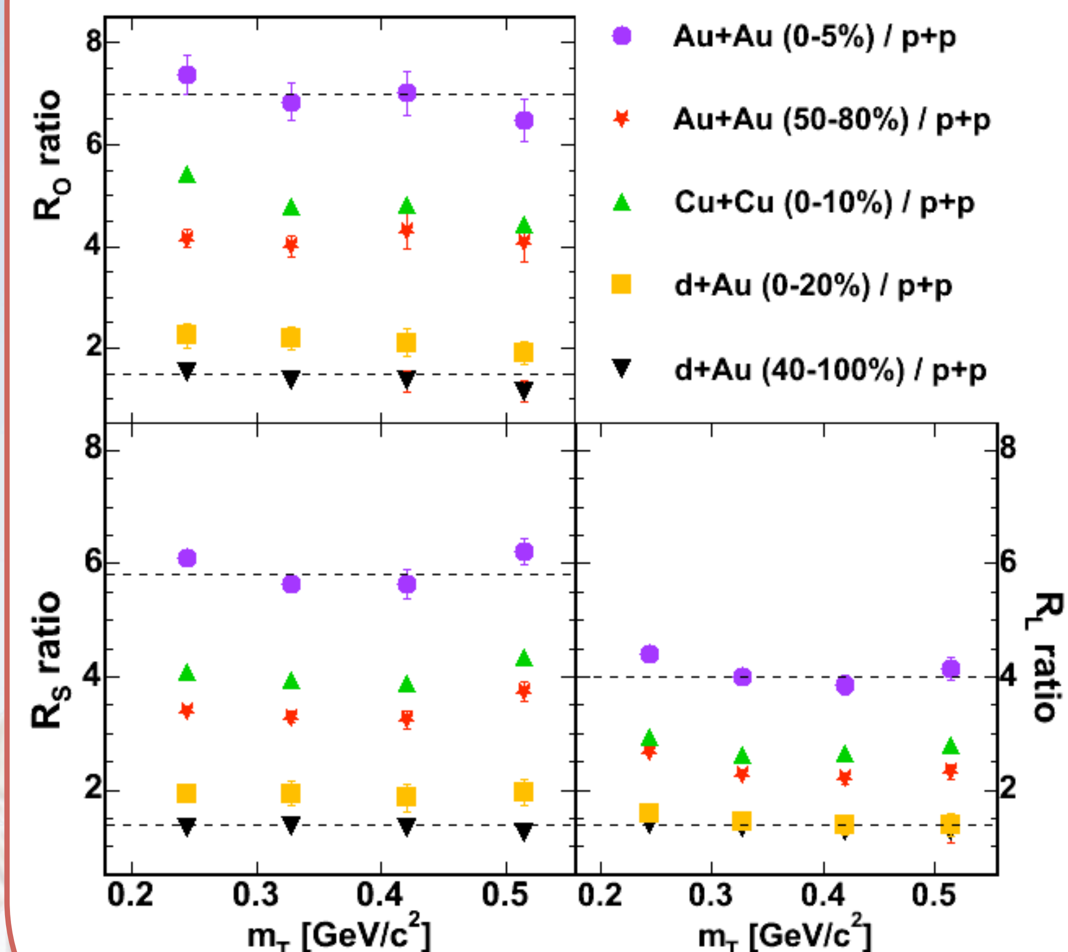
R(p_T) taken as strong space-time evidence of flow in Au+Au

- clear, quantitative consistency predictions of BlastWave

“Identical” signal seen in p+p

- cannot be of “identical” origin? (other than we “know it cannot”...)

Ratio of (AuAu, CuCu, dAu) HBT radii by pp

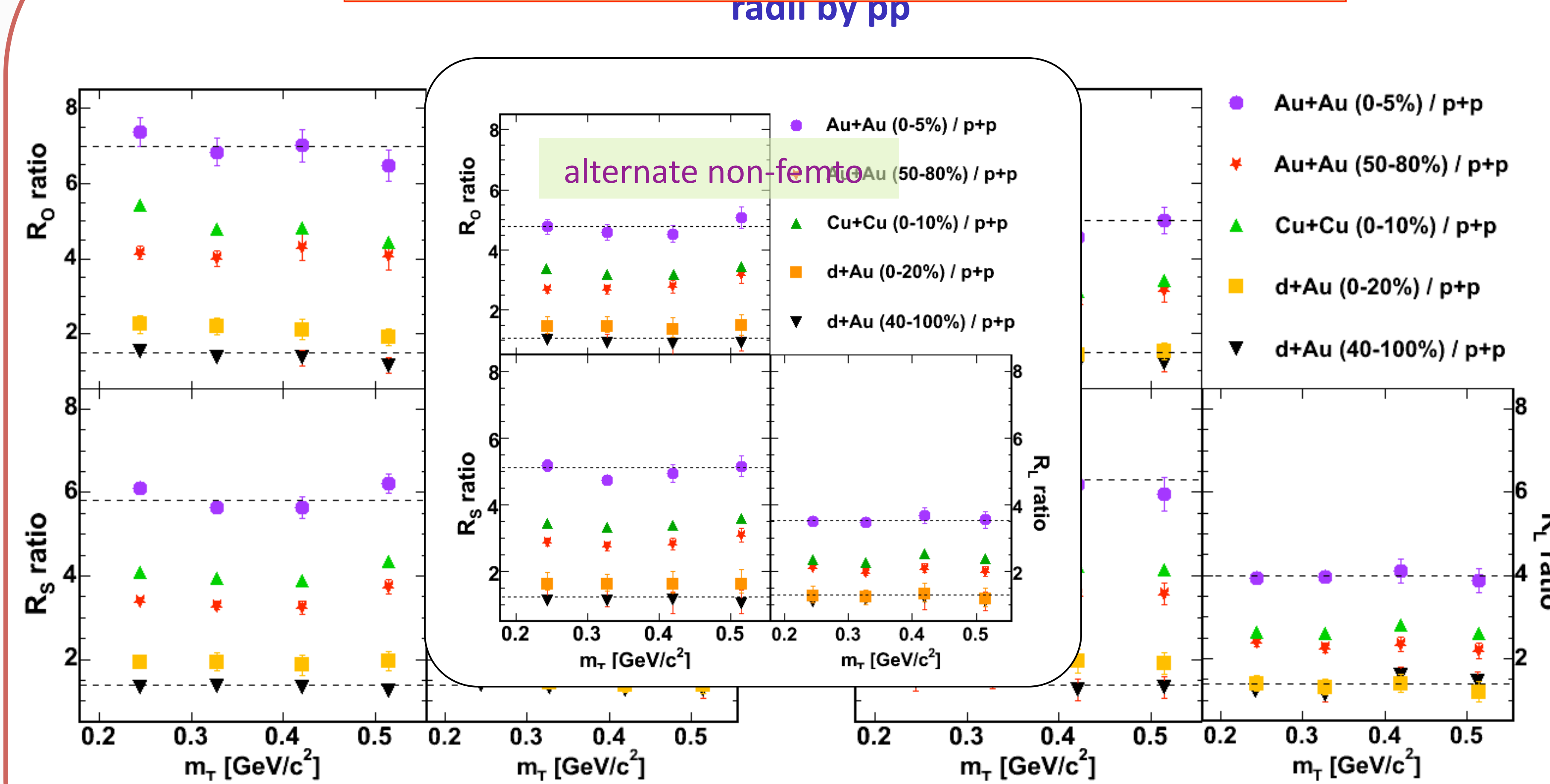


pp, dAu, CuCu - STAR preliminary

Significant non-femto correlations, but little effect on "message"

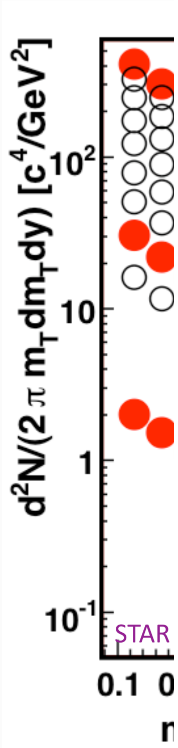
STAR preliminary

rather, "suggestion": explosive flow in p+p?



Fit w/o baseline parameterization

NEW fit w/ baseline parameterization



Au 0-5%

u 60-70%

minbias

BUT.....!

Blast-wave

- much les

But remember!

measured

$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{\left(E_i - \langle E\rangle\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

"matrix element"

"distortion" of single-particle spectra

But remember!

measured

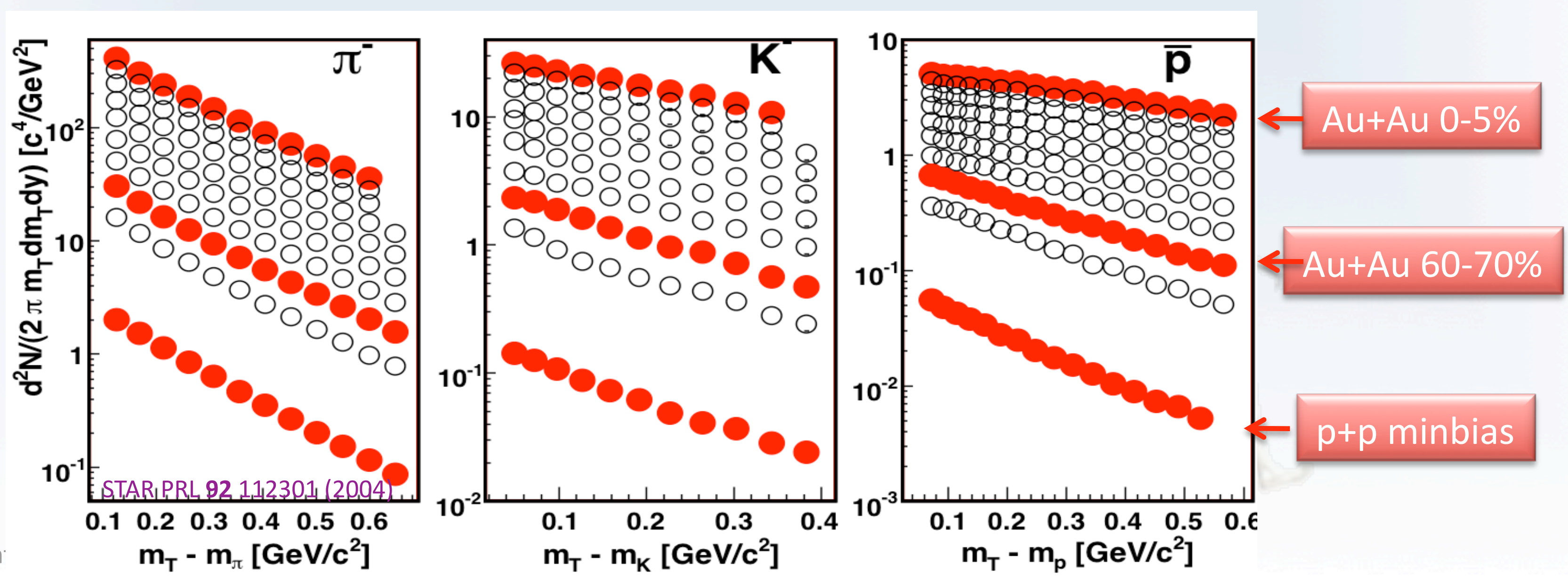
$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{\left(E_i - \langle E\rangle\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

"matrix element"

"distortion" of single-particle spectra

What if the only difference between p+p and A+A collisions was *N*?

$$\text{same } \tilde{f}(p)\ ,\ \langle p_T^2\rangle\ ,\ \langle E\rangle\ ,\ \langle E^2\rangle$$



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$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{\left(E_i - \langle E\rangle\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

"matrix element"

"distortion" of single-particle spectra

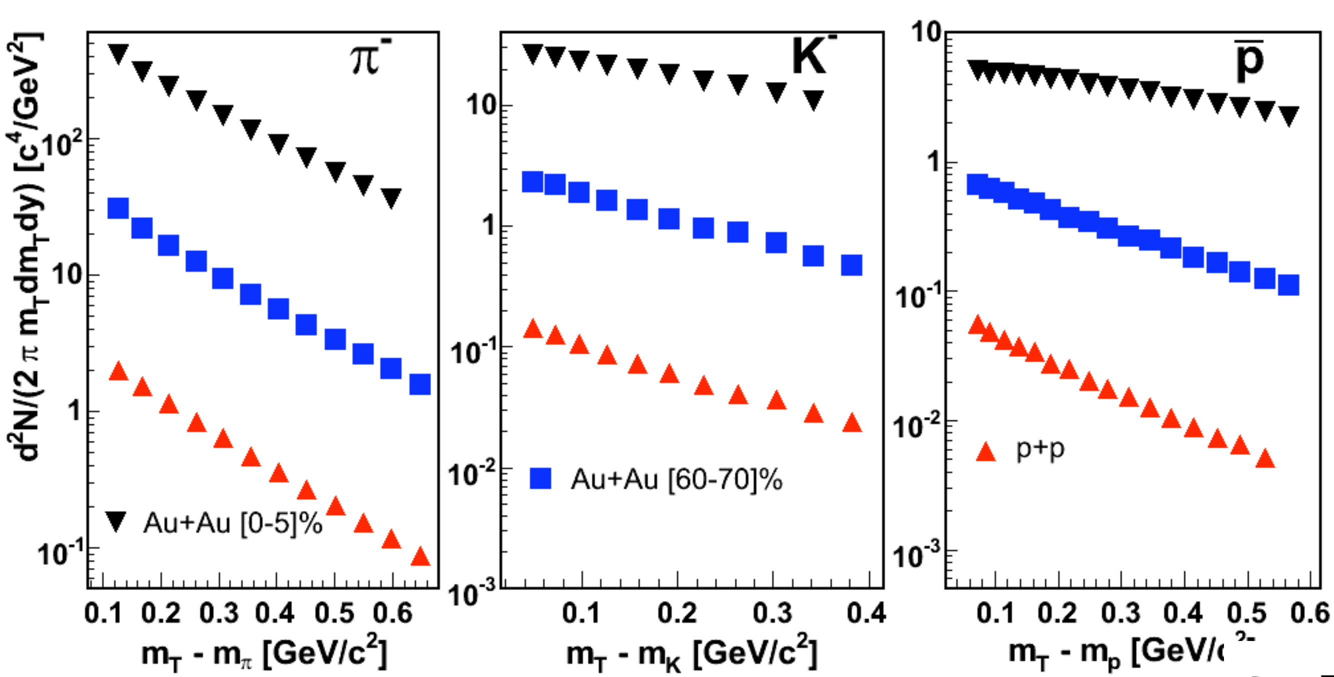
What if the only difference between p+p and A+A collisions was *N*?

$$\text{same } \tilde{f}(p)\ ,\ \langle p_T^2\rangle\ ,\ \langle E\rangle\ ,\ \langle E^2\rangle$$

Then we would measure:

$$\frac{\tilde{f}_c^{pp}\left(p_{T,i}\right)}{\tilde{f}_c^{AA}\left(p_{T,i}\right)} = \left(\frac{\left(N_{AA}-1\right)N_{pp}}{\left(N_{pp}-1\right)N_{AA}}\right)^2 \exp\left(\left(\frac{1}{2\left(N_{AA}-1\right)} - \frac{1}{2\left(N_{pp}-1\right)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{\left(E_i - \langle E\rangle\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

Multiplicity evolution of spectra - p+p to A+A (soft sector)

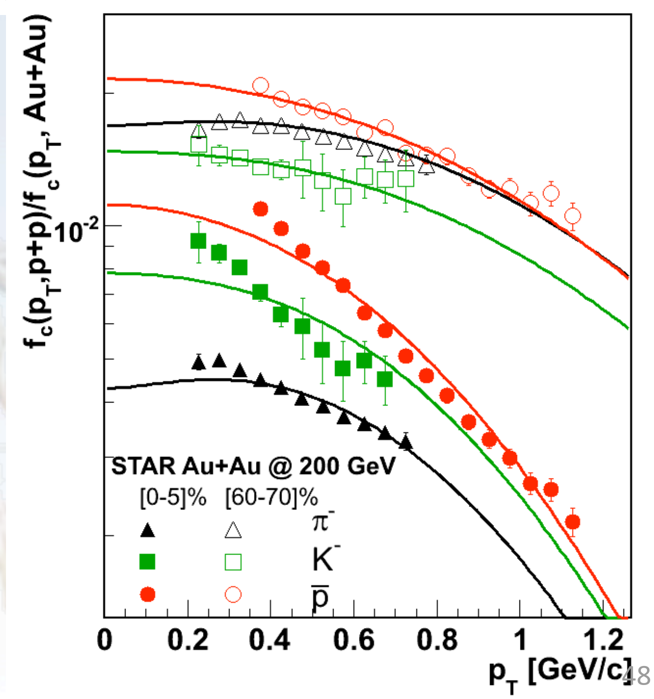


$$\frac{\tilde{f}_c^{pp}(p_{T,i})}{\tilde{f}_c^{AA}(p_{T,i})} \propto \exp\left(\left(\frac{1}{2(N_{AA}-1)} - \frac{1}{2(N_{pp}-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

N evolution of spectra dominated by PS "distortion"

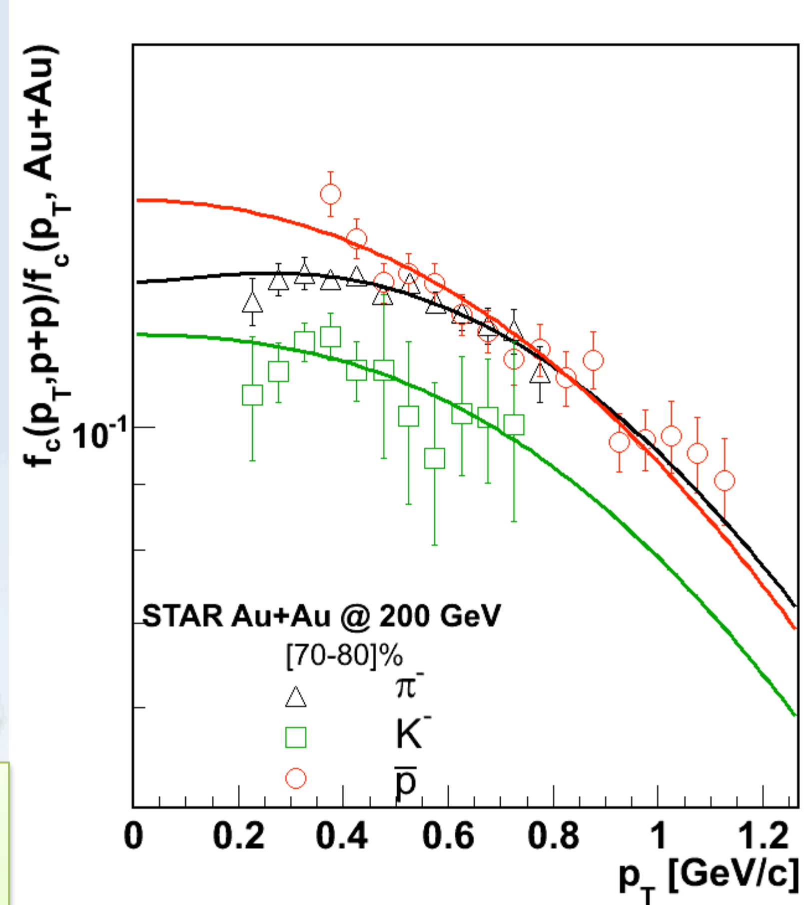
p+p system samples *same* parent distribution, but under stronger PS constraints

K ~ unity. driven by conservation of discrete quantum #s (strangeness, etc)



IMPT: What changes with multiplicity…? multiplicity does !!

Event selection	N	$\langle p_T^2 \rangle$ [(GeV/c)^2]	$\langle E^2 \rangle$ [GeV^2]	$\langle E \rangle$ [GeV]
$p+p$ min-bias	10.3	0.12	0.43	0.61
$Au+Au$ 70-80%	15.2	"	"	"



postulate of *same* parent consistent with *all* spectra

- magnitude
- pT dependence (shape)
- mass dependence

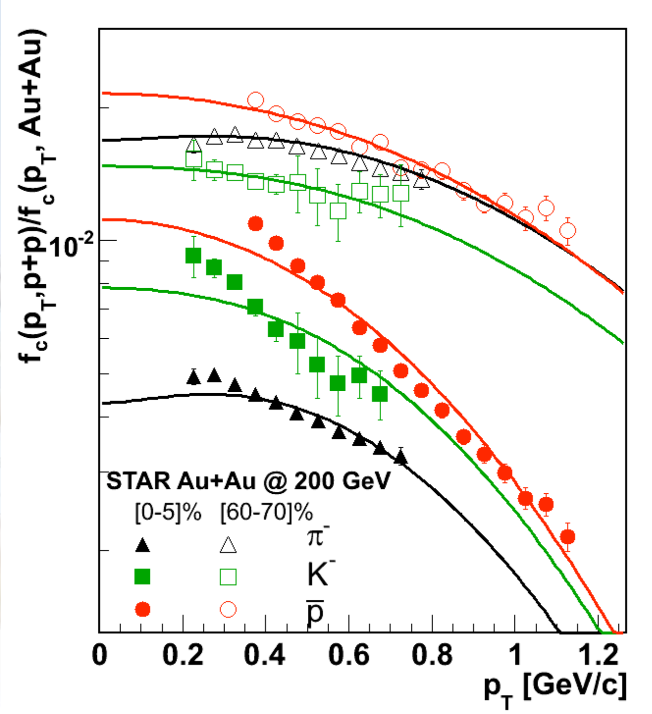
Kinematic scales of "the system"

$$\frac{\tilde{f}_c^{E_1}(p_{T,i})}{\tilde{f}_c^{E_2}(p_{T,i})} = \left(\frac{(N_2-1)N_1}{(N_1-1)N_2}\right)^2 \exp\left(\left(\frac{1}{2(N_2-1)} - \frac{1}{2(N_1-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

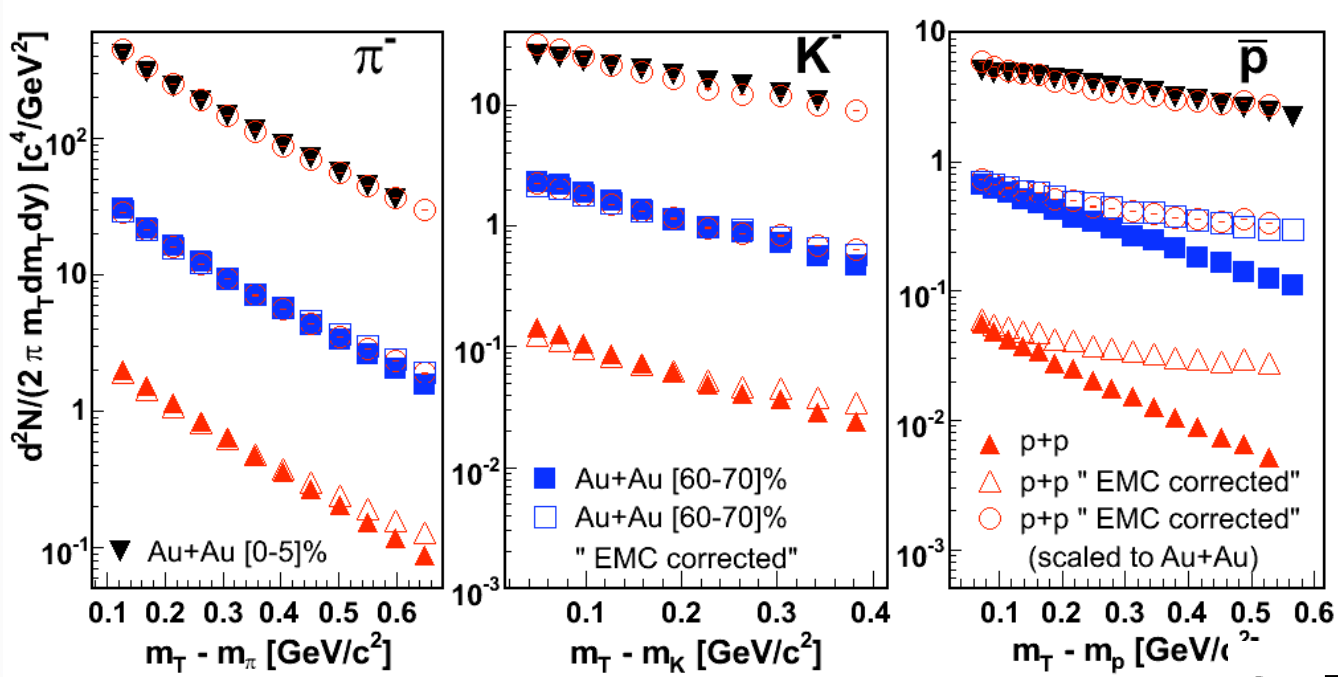
	non-rel	ultra-rel	if $T = .15 \div .35$	What we find
$\langle p_T^2\rangle$	$2mT$	$8T^2$	$0.045 \div 0.98\ (\mathrm{GeV/c})^2$	$0.12\ (\mathrm{GeV/c})^2$
$\langle E^2\rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5\ \mathrm{GeV}^2$	$0.43\ \mathrm{GeV}^2$
$\langle E\rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1\ \mathrm{GeV}$	$0.61\ \mathrm{GeV}$

Event selection	N	$\langle p_T^2\rangle$ [(GeV/c)^2]	$\langle E^2\rangle$ [GeV^2]	$\langle E\rangle$ [GeV]
$p+p$ minbias	10.3	0.12	0.43	0.61
$Au+Au$ 70-80%	15.2	"	"	"
$Au+Au$ 60-70%	18.3	"	"	"
$Au+Au$ 50-60%	27.3	"	"	"
$Au+Au$ 40-50%	38.7	"	"	"
$Au+Au$ 30-40%	67.6	"	"	"
$Au+Au$ 20-30%	219	"	"	"
$Au+Au$ 10-20%	> 300	"	"	"
$Au+Au$ 5-10%	> 300	"	"	"
$Au+Au$ 0-5%	> 300	"	"	"

TABLE II: Multiplicity and parent-distribution kinematic parameters which give a reasonable description of the spectrum ratios for identified particles in the soft sector. See text for details. Note that the multiplicity changes with event class; the parent distribution is assumed identical.



Multiplicity evolution of spectra - p+p to A+A (soft sector)



$$\frac{\tilde{f}_c^{pp}(p_{T,i})}{\tilde{f}_c^{AA}(p_{T,i})} \propto \exp\left(\left(\frac{1}{2(N_{AA}-1)} - \frac{1}{2(N_{pp}-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{\left(E_i - \langle E\rangle\right)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

N evolution of spectra dominated by PS "distortion"

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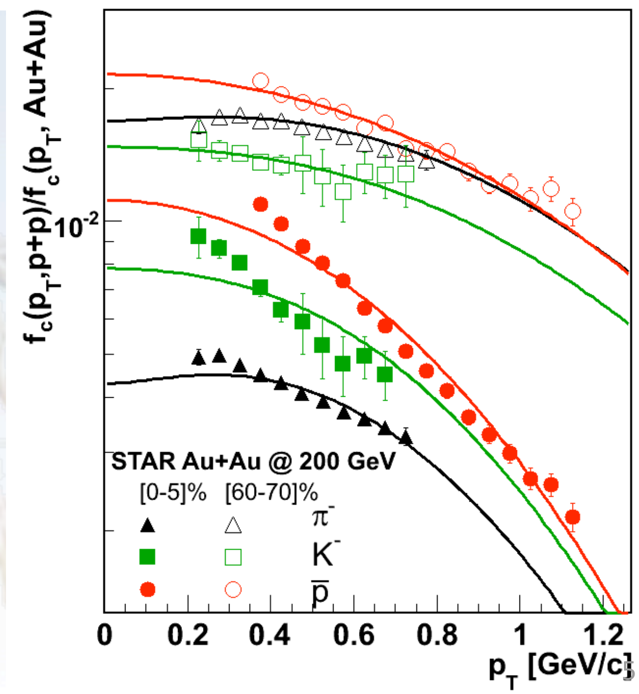
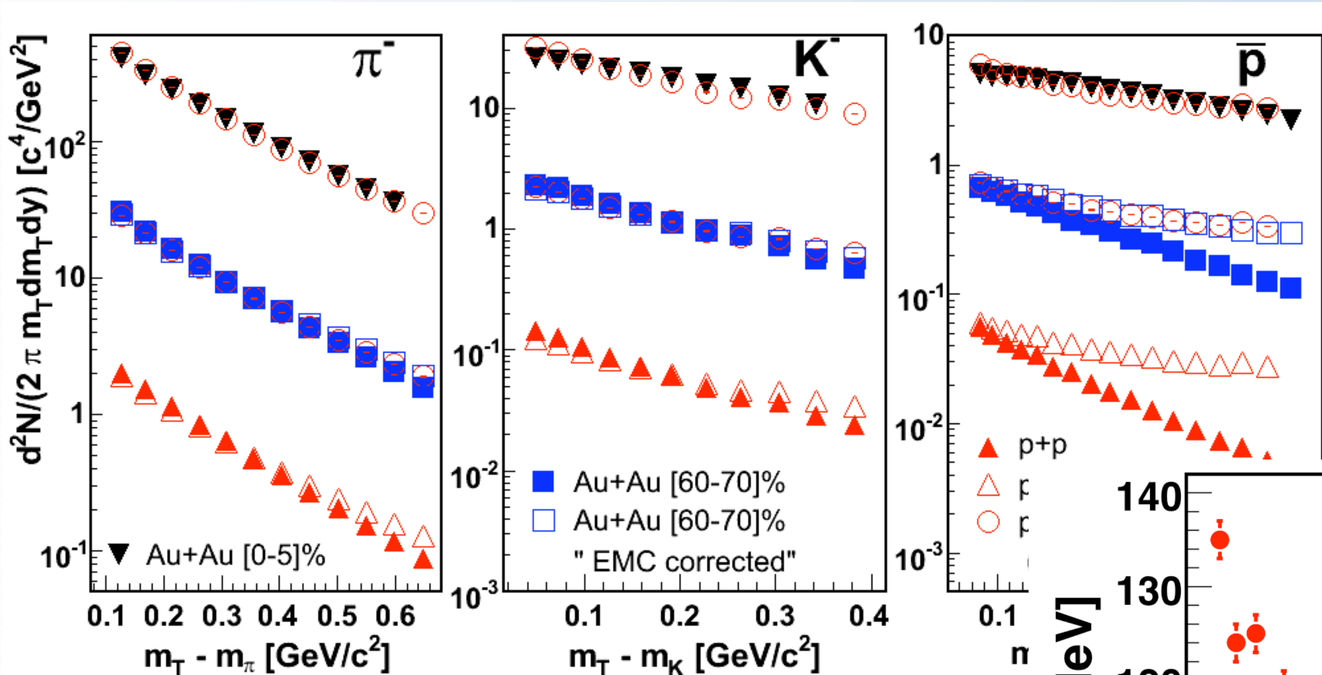
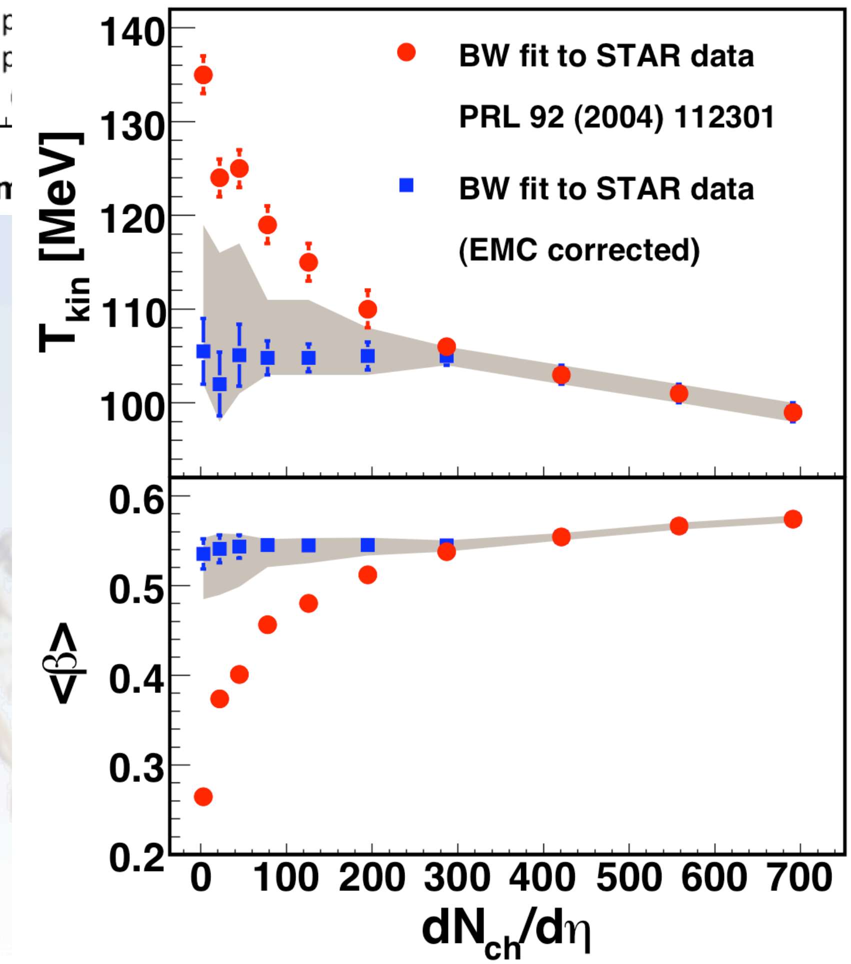




By popular demand



Almost universal "flow" & "temperature" parameters in a BlastWave fit

Apparent changes in β, T with dN/dη caused by EMCICs*

* EMCIC = Energy & Momentum Conservation Induced *Constraint*

Blast-wave in p+p: simultaneous description of spectra, HBT

$T = 105.5$ MeV

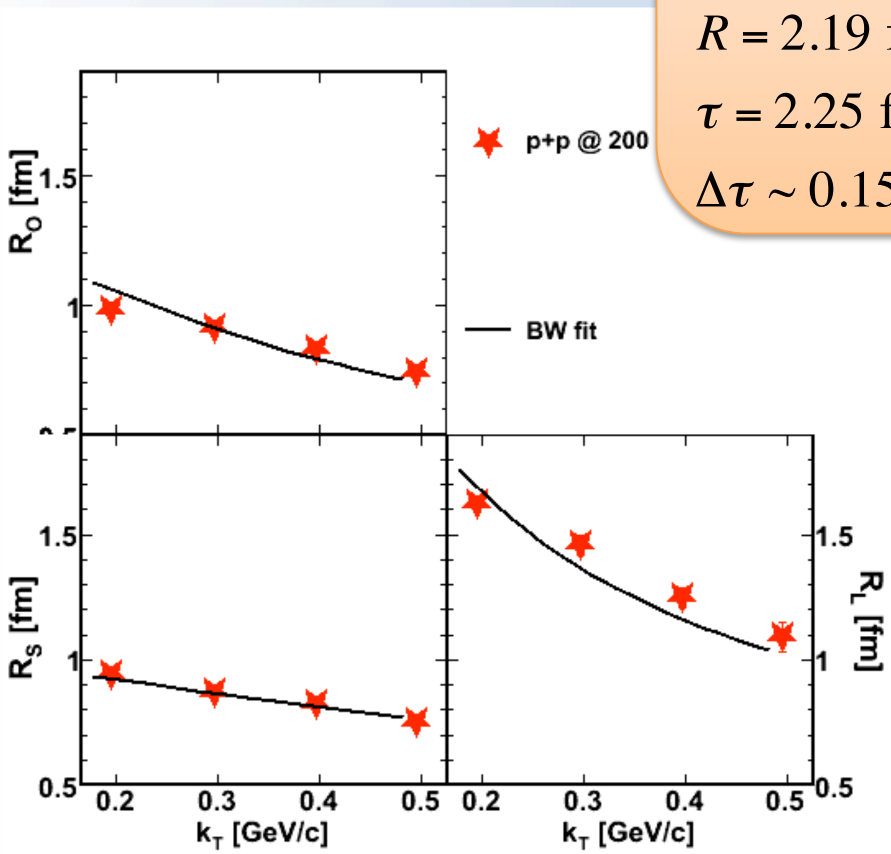
$\rho_0 = 0.934 \quad (\langle\beta\rangle = 0.535)$

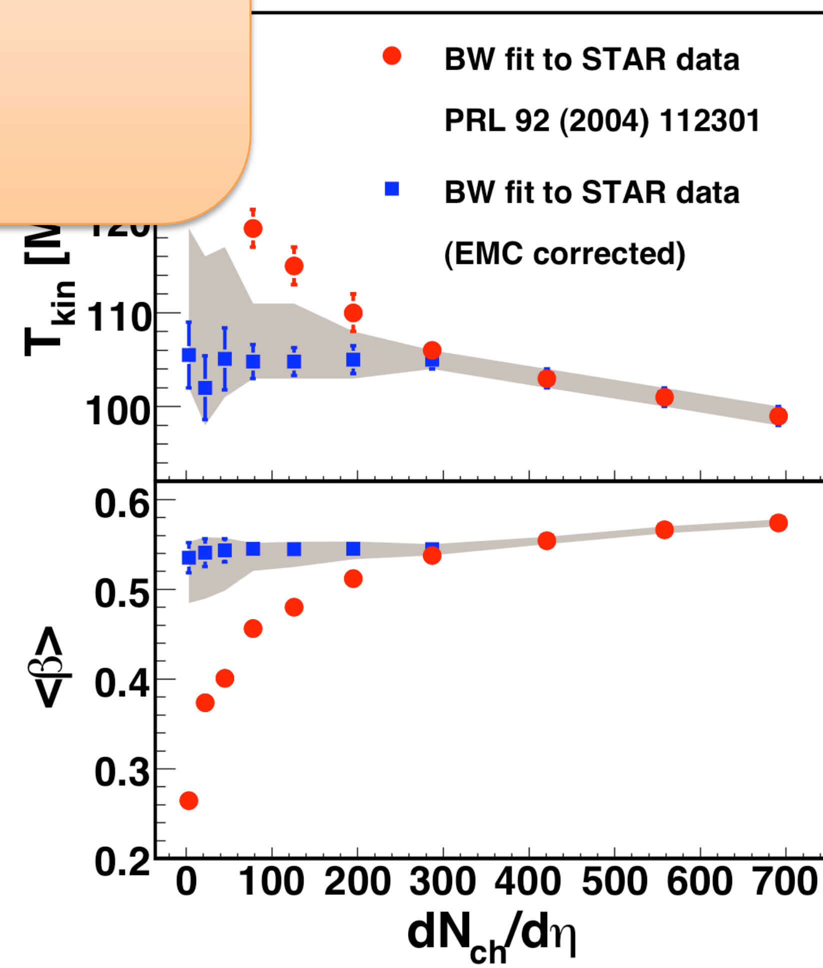
} determined entirely by spectra

$R = 2.19$ fm

$\tau = 2.25$ fm/c

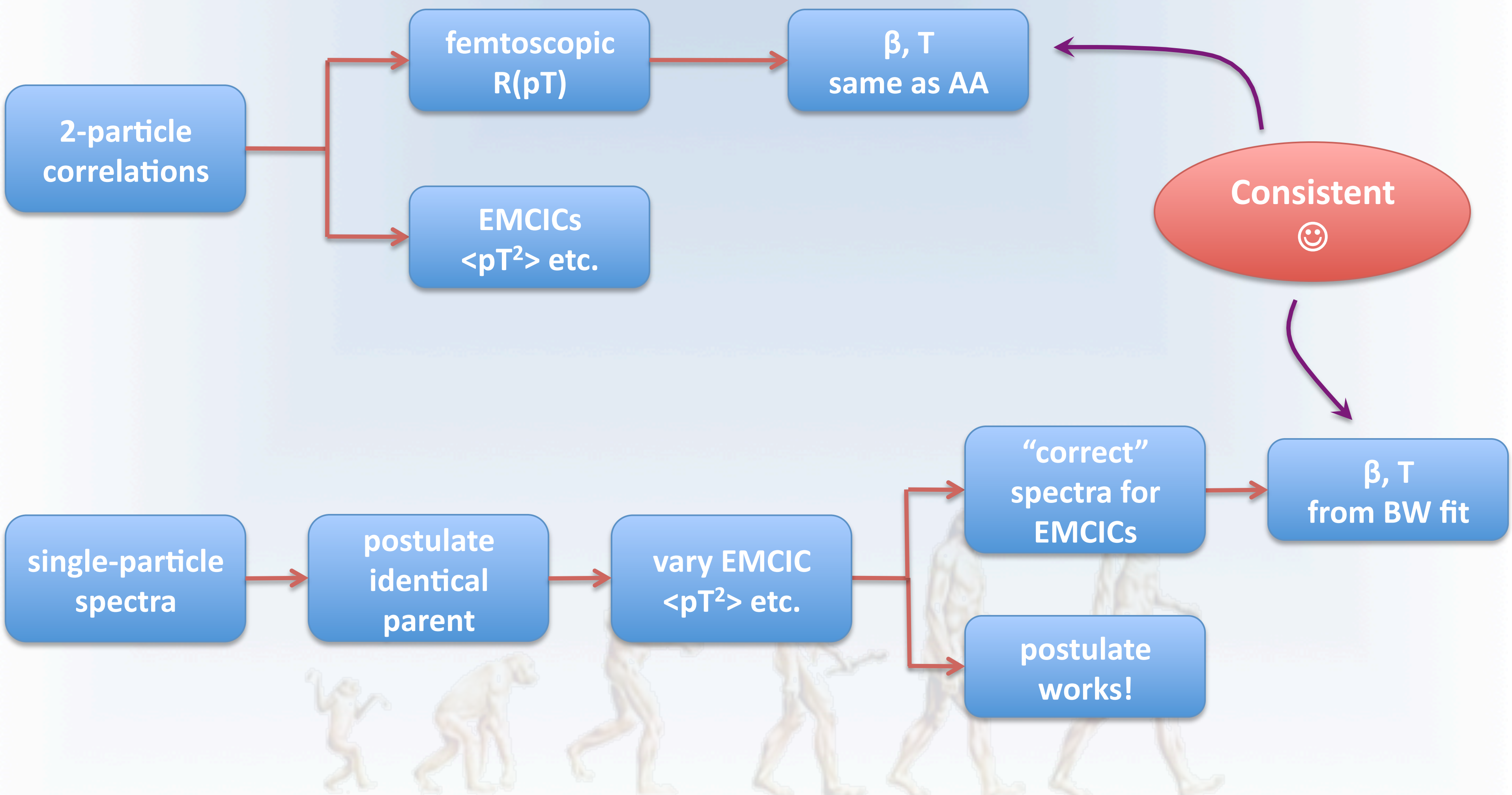
$\Delta\tau \sim 0.15$





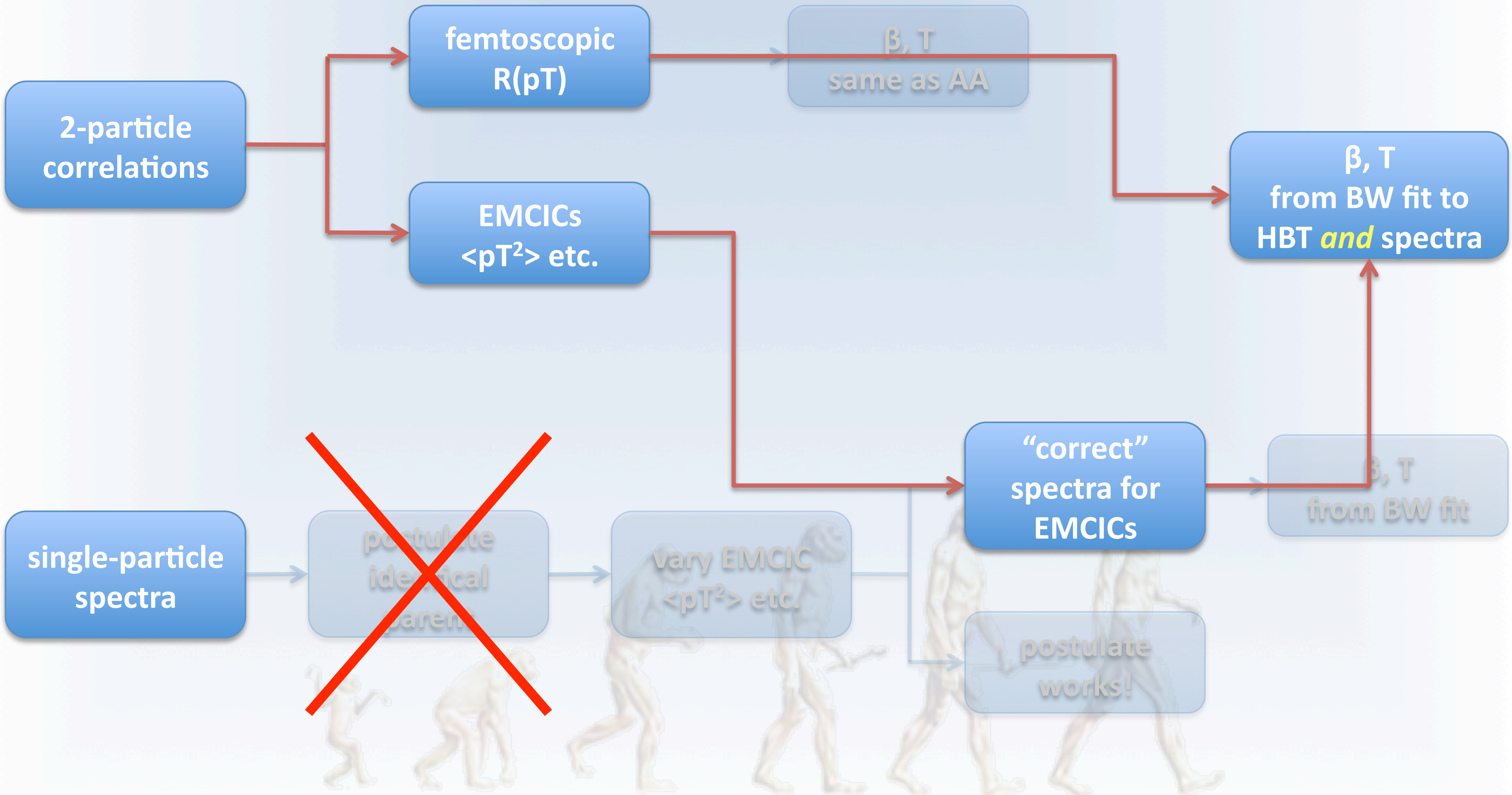
Can't follow the game without a program…

PHASE I

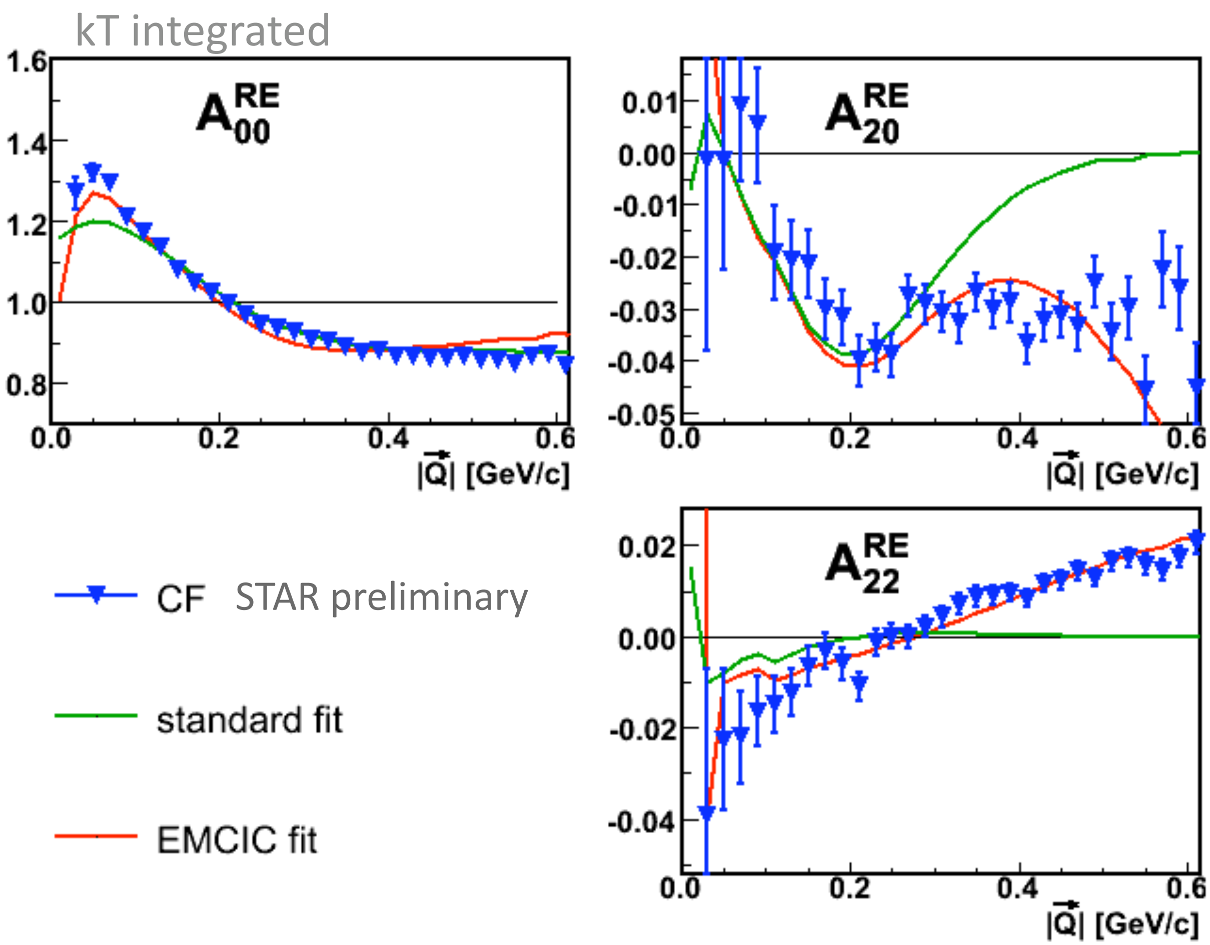


Can't follow the game without a program...

PHASE II



Femto and "system" parameters from 2-particle correlations

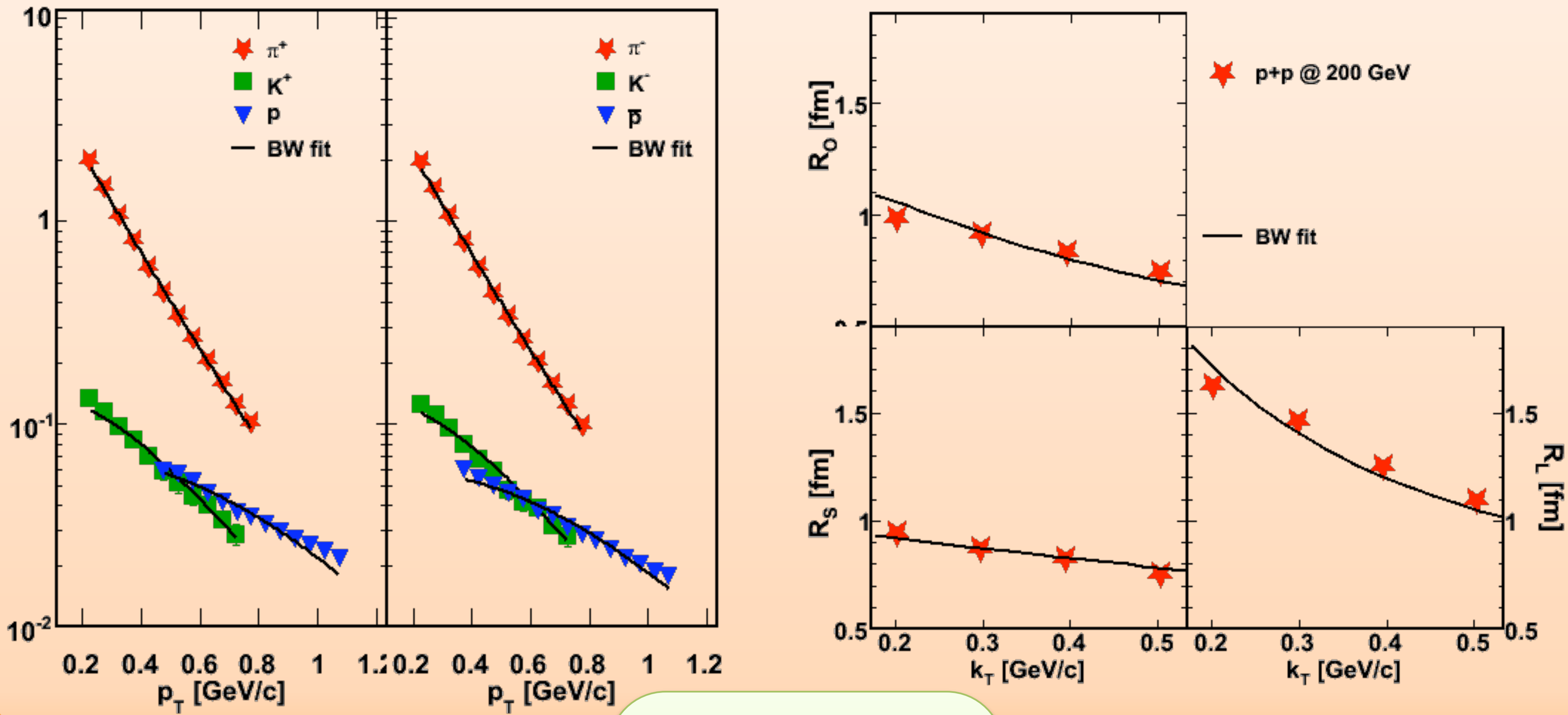


$\lambda = 0.38 \pm 0.01$
$R_o = 0.81 \pm 0.01$ fm
$R_s = 0.84 \pm 0.02$ fm
$R_l = 1.29 \pm 0.02$ fm

$\lambda = 0.69 \pm 0.01$
$R_o = 0.96 \pm 0.04$ fm
$R_s = 0.98 \pm 0.03$ fm
$R_l = 1.26 \pm 0.02$ fm

$N = 12.9$
$\langle E \rangle = 0.60$ GeV
$\langle E^2 \rangle = 0.40$ GeV^2
$\langle p_T^2 \rangle = 0.2$ GeV^2
$\langle p_z^2 \rangle = 0.4$ GeV^2

Combined fit: consistent flow-based description



$$T = 106 \pm 3 \text{ MeV}$$

$$\langle \beta \rangle = 0.48 \pm 0.03$$

$$R = 2.09 \pm 0.04 \text{ fm}$$

$$\tau_0 = 2.25 \pm 0.05 \text{ fm/c}$$

$$\Delta\tau = 0.1 \pm 0.2 \text{ fm/c}$$

Combined fit: consistent flow-based description

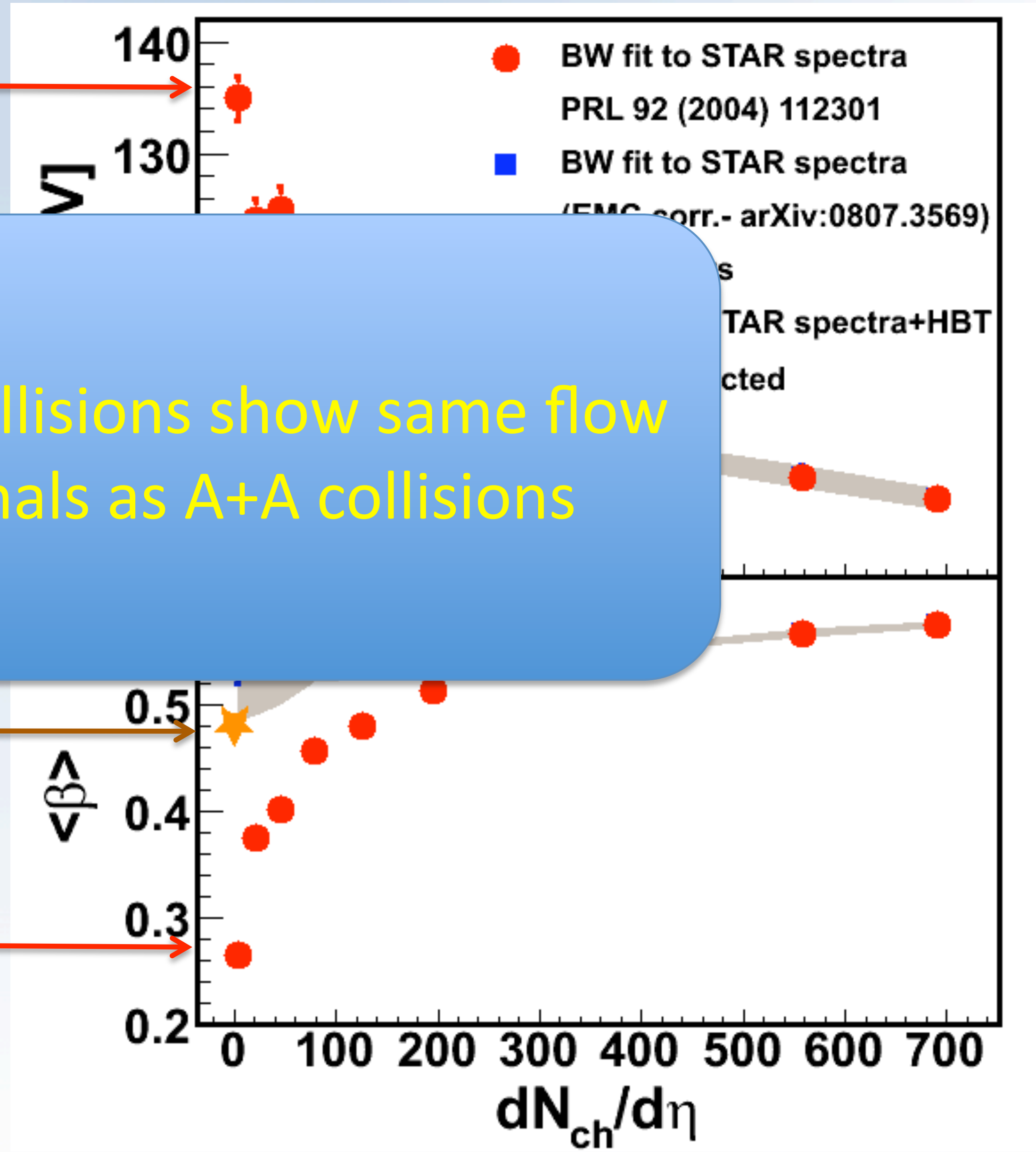
"raw" (ignoring EMCICs)

EMCICs fixed by co[rrelations]
and joint spectra/H[BT fit]

EMCICs free adjuste[d]
to spectra & fit to sp[ectra]

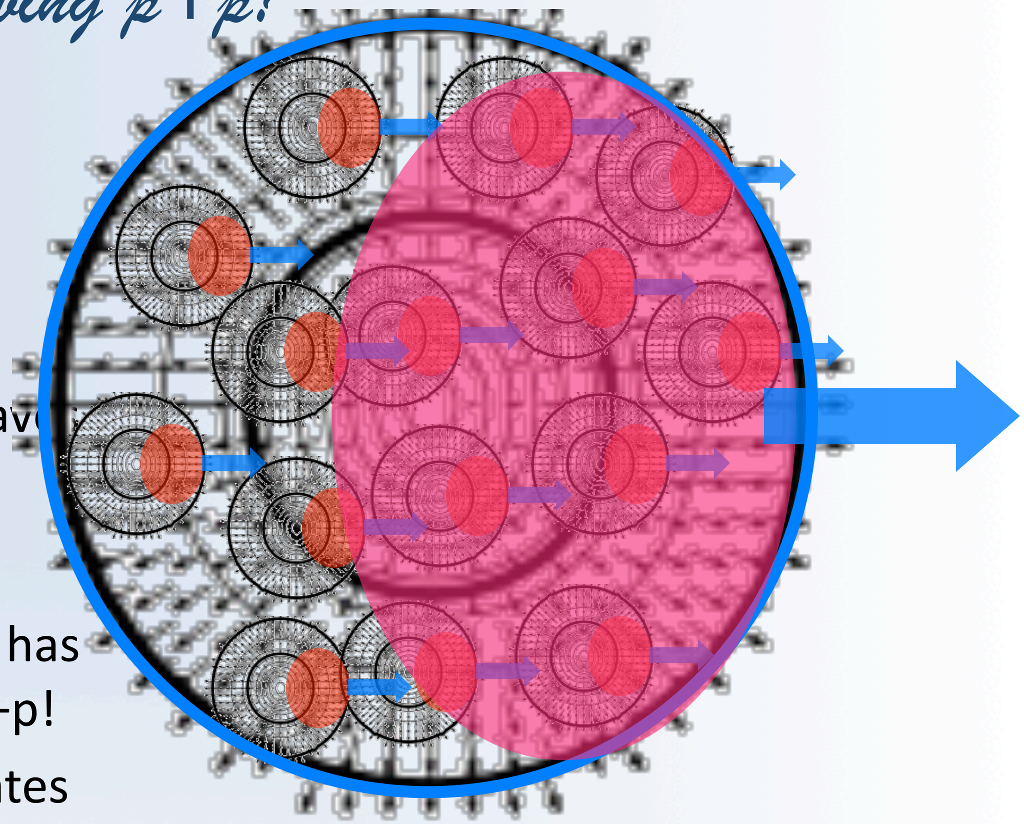
EMCICs fixed by correlations
and joint spectra/HBT fit

"raw" (ignoring EMCICs)



p+p collisions show same flow signals as A+A collisions

A+A is just a collection of flowing p+p?

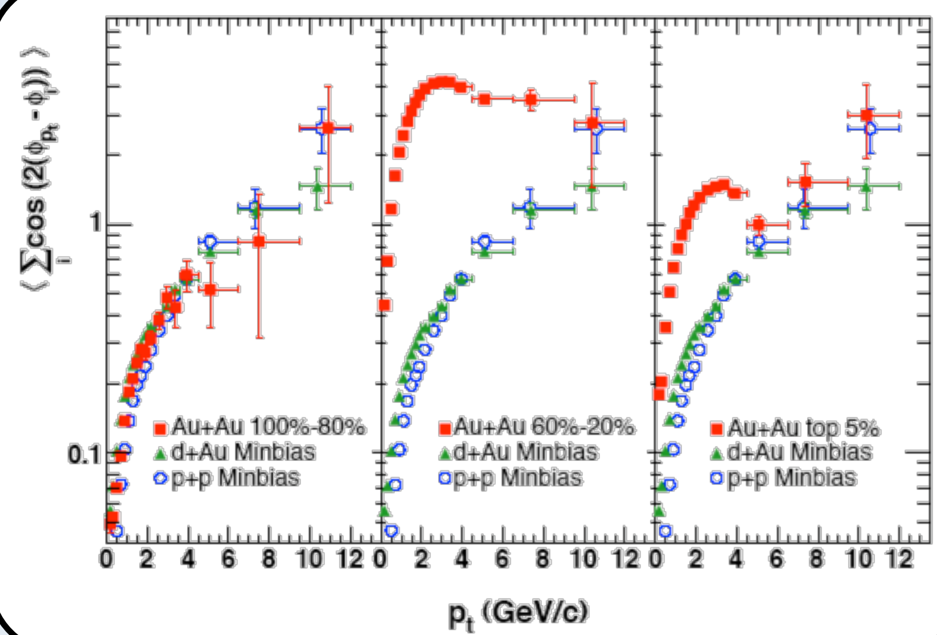


- No! Quite the opposite.
  - **femtoscopically**
    - A+A looks like a big BlastWave
    - *not* superposition of small BlastWav
    - A+A has thermalized globally
  - **spectra**
    - superposition of spectra from p+p has same shape as a spectrum from p+p!
    - relaxation of P.S. constraints indicates A+A has thermalized globally

- rather, p+p looks like a "little A+A"

A+A is just a collection of flowing p+p?

- No! Quite the opposite.
  - **femtoscopically**
    - A+A looks like a big BlastWave
    - *not* superposition of small BlastWav
    - A+A has thermalized globally
  - **spectra**
    - superposition of spectra from p+p h same shape as a spectrum from p+p
    - relaxation of P.S. constraints indicates A+A has thermalized globally



anisotropic flow

- A+A shows increased signal over superposition of p+p
- is the p+p signal "flow" ??

- rather, p+p looks like a "little A+A"

Summary

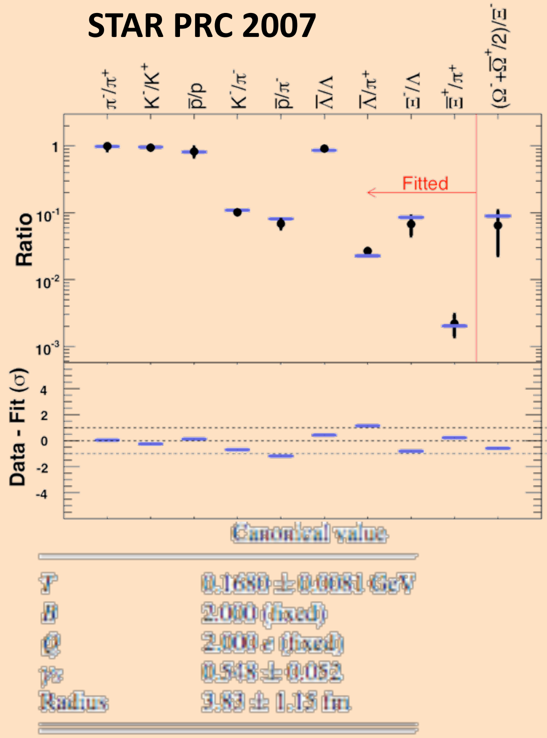
- E&M conservation induces phasespace constraints w/ explicit N dependence
  - should not be ignored in (crucial!) N-dependent comparisons
  - significant effect on 2- (and 3-) particle correlations [c.f. Ollitrault, Borghini, Voloshin…]
  - …*and* single-particle spectra (often neglected because no "red flags")

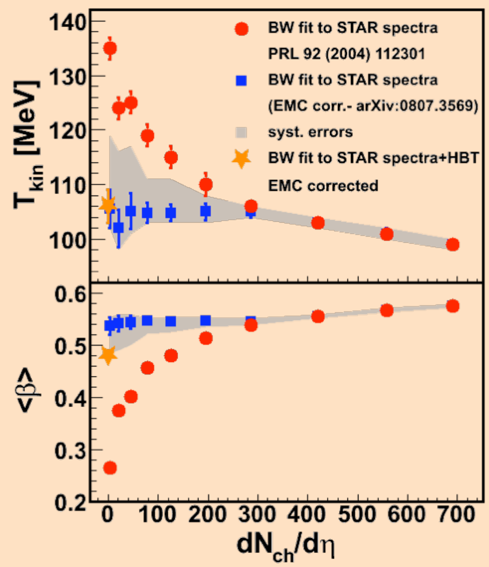
- Femtoscopy & Spectra
  - in H.I.C., well understood, detailed fingerprint of flow
  - RHIC – first opportunity for direct comparison with p+p
  - accounting for EMCICs, identical flow signals in p+p

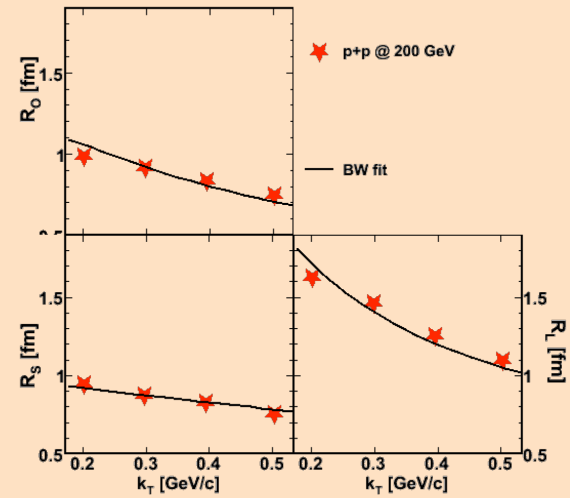
- is pp/AA physics very similar, or are measurements insensitive to diff physics?
- **Has AA become the reference system for pp in non-perturbative sector???**
- Thermalization, hadronization, very early color dynamics…

Summary

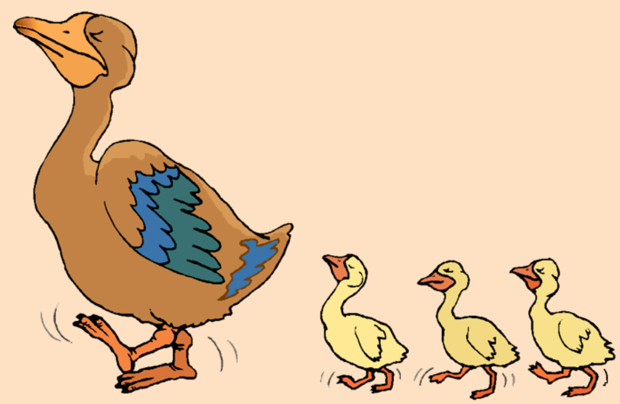
- E&M



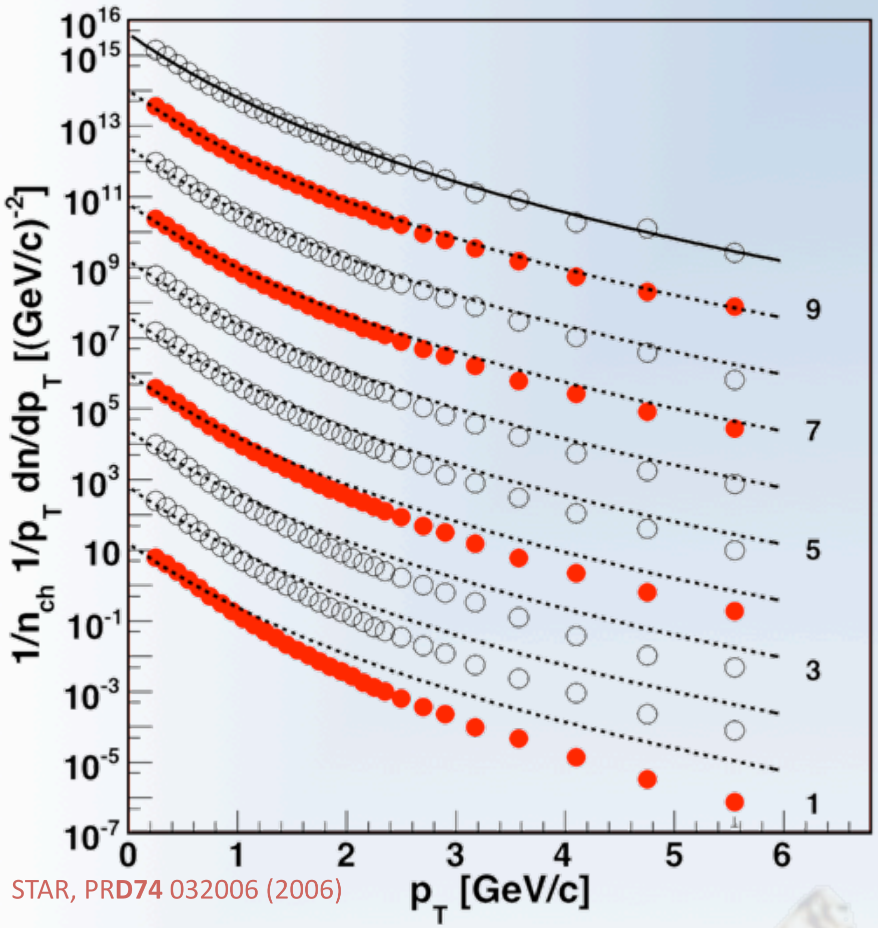




Other than our prejudices, what is evidence against transverse flow in p+p?



Multiplicity evolution of spectra - *within* p+p (soft sector)



STAR, PR**D74** 032006 (2006)

What if the only difference between multiplicity-selected p+p collisions was *N*?

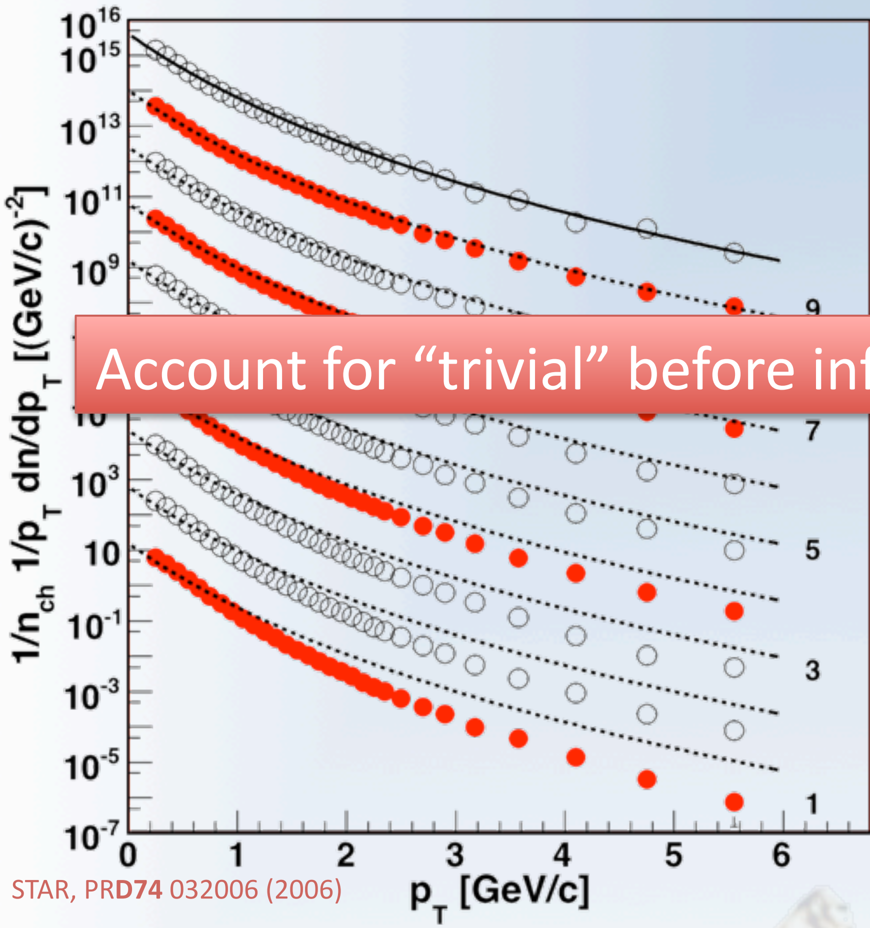
$$\text{same } \tilde{f}(p)\ ,\ \langle p_T^2 \rangle\ ,\ \langle E \rangle\ ,\ \langle E^2 \rangle$$

...Then we would measure:

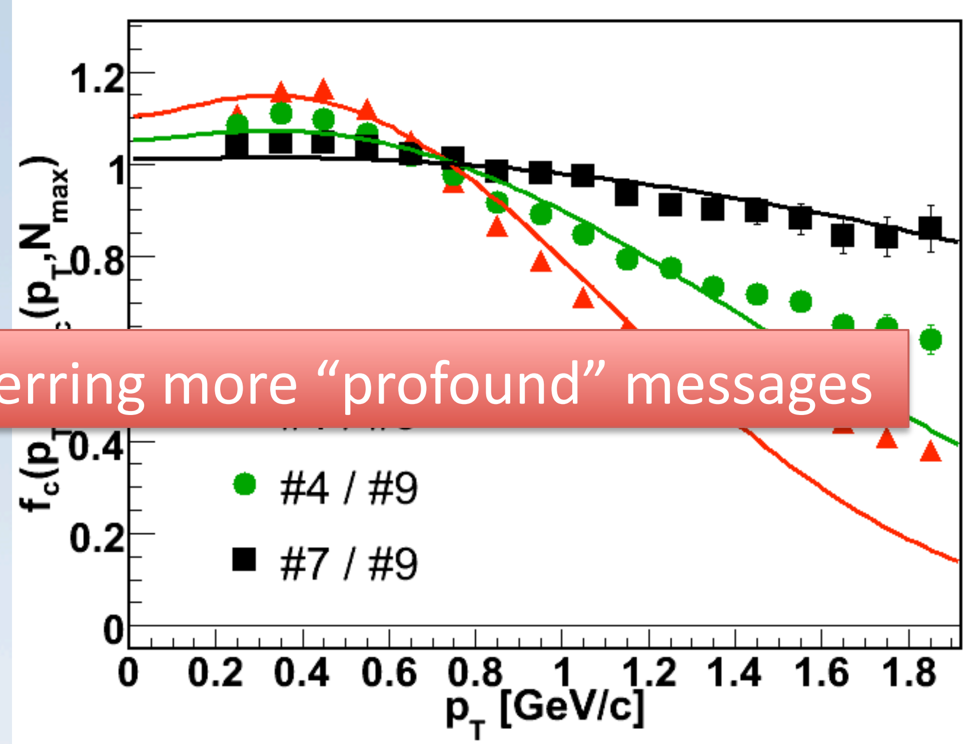
$$\frac{\tilde{f}_c^{N_1}(p_{T,i})}{\tilde{f}_c^{N_2}(p_{T,i})} = \left(\frac{(N_2-1)N_1}{(N_1-1)N_2}\right)^2 \exp\left(\left(\frac{1}{2(N_2-1)} - \frac{1}{2(N_1-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2 \rangle} + \frac{(E_i - \langle E \rangle)^2}{\langle E^2 \rangle - \langle E \rangle^2}\right)\right)$$

pion mass assumed

*Multiplicity evolution of spectra - **within** p+p (soft sector)*



STAR, PR**D74** 032006 (2006)



Account for "trivial" before inferring more "profound" messages

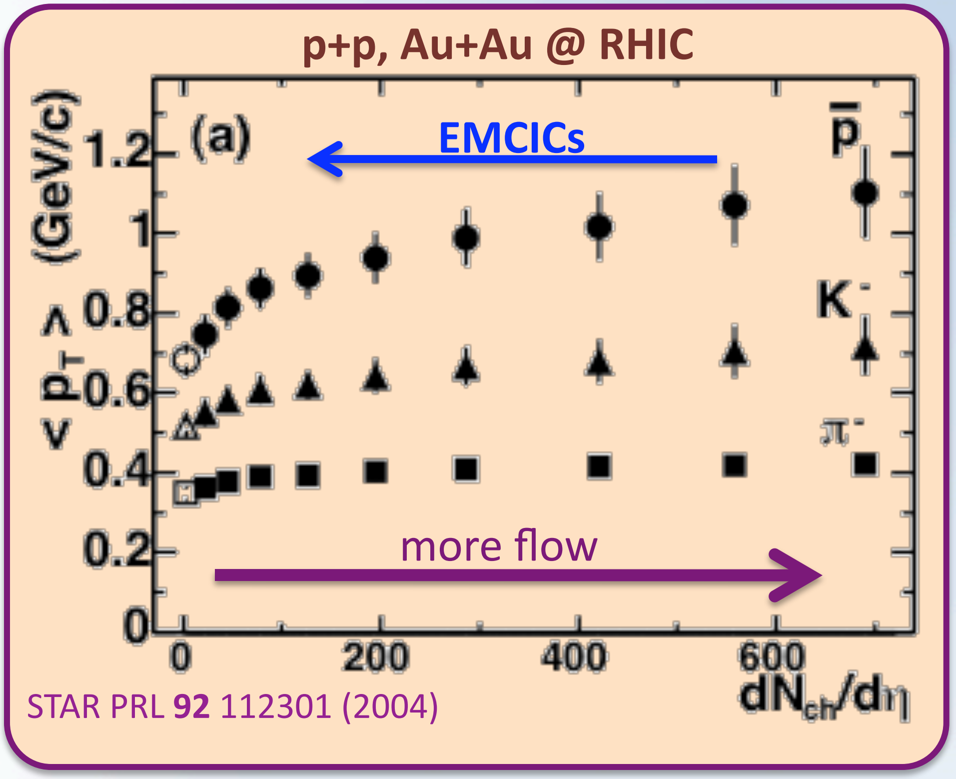
unidentified particles → cannot conclude that EMCICs is the *whole* story…

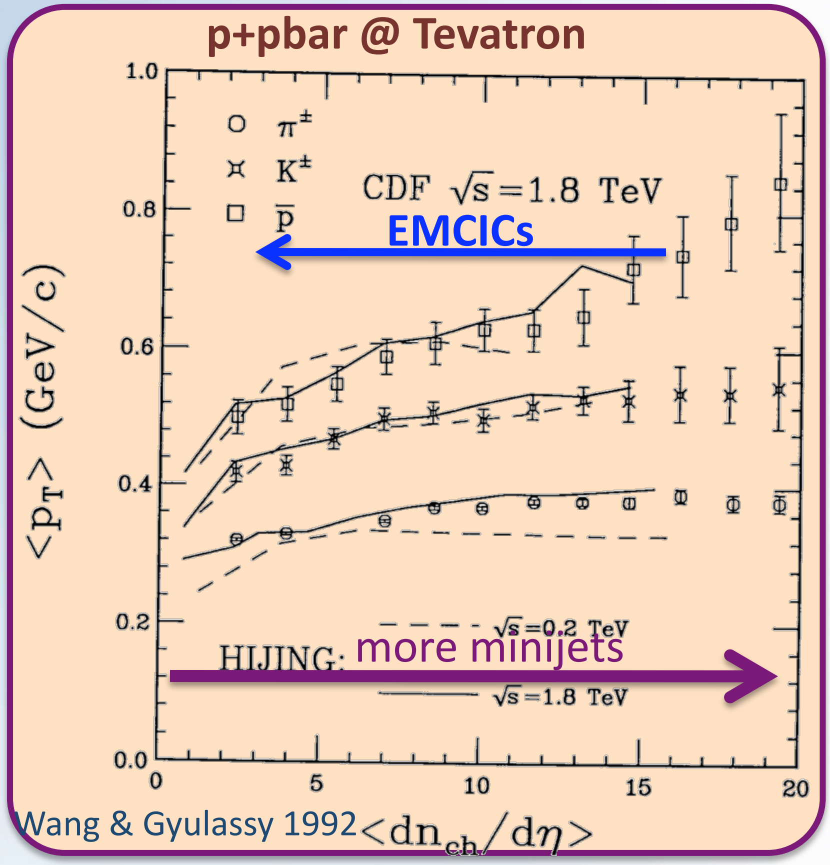
…but it may be *most* of it.

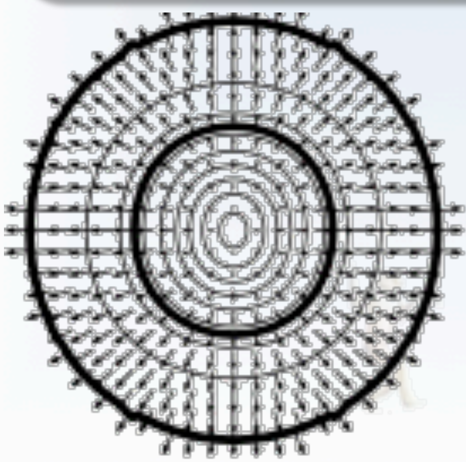
$$\frac{\tilde{f}_c^{N_1}(p_{T,i})}{\tilde{f}_c^{N_2}(p_{T,i})} = \left(\frac{(N_2-1)N_1}{(N_1-1)N_2}\right)^2 \exp\left(\left(\frac{1}{2(N_2-1)}-\frac{1}{2(N_1-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle}+\frac{(E_i-\langle E\rangle)^2}{\langle E^2\rangle-\langle E\rangle^2}\right)\right)$$

pion mass assumed

Coming back to HBT…







Geometric substructure argues against changing flow argument

…and for soft sector, a pure minijet mechanism (next page)

The End