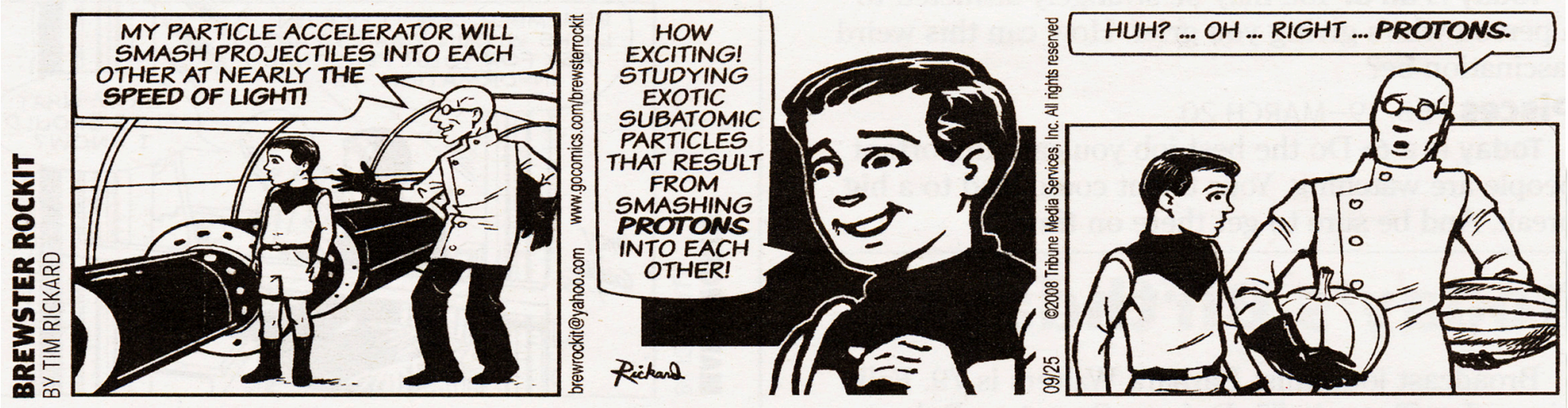
Z. Chajęcki & MAL PRC **78** 064903 (2008)
Z. Chajęcki & MAL PRC **79** 034908 (2009)
Z. Chajęcki Acta Phys. Polonica **B40** 1119 (2009)



How big is big enough?

Mike Lisa

Ohio State University

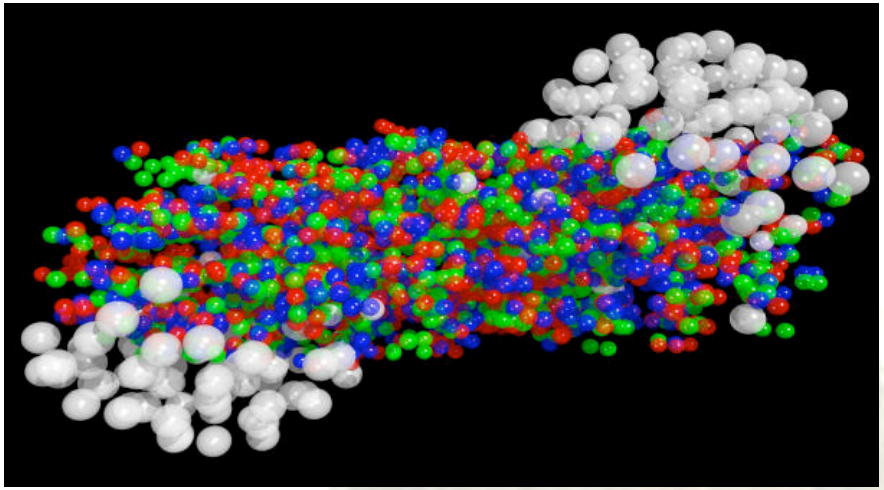
Outline

- Why collide watermelons rather than seeds
- Femtoscopic and phasespace-induced correlations in collisions at RHIC
- Effects of phasespace constraints on single-particle spectra: p+p & A+A
  - postulate of unchanging parent
- Putting it together: consistent treatment of 1- and 2-particle correlations
  - evidence of collectivity in p+p collisions
- Summary

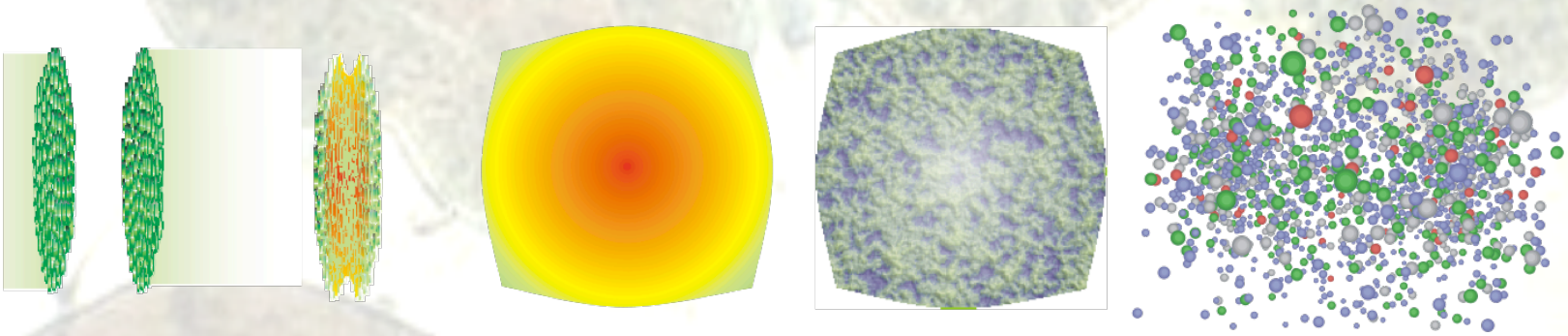
* EMCIC = "Energy and Momentum Induced Correlation"

** EMCIC = "Energy and Momentum Induced Constraint"

paradigms



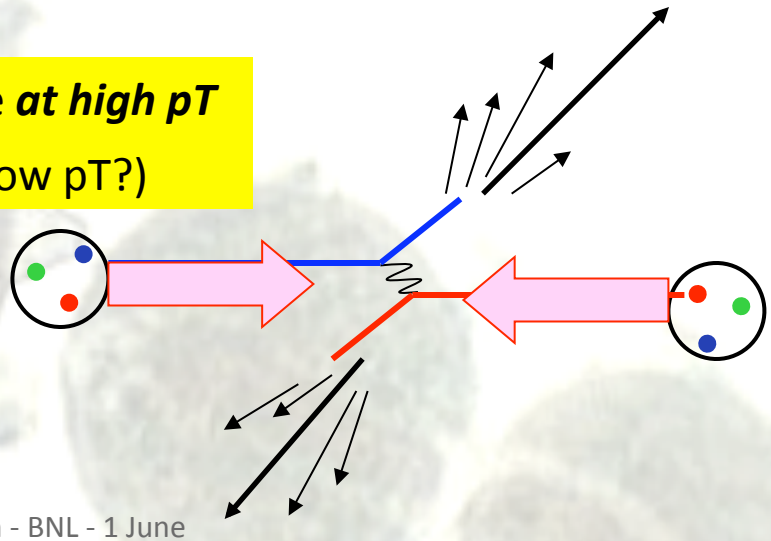
A+A → a *system*



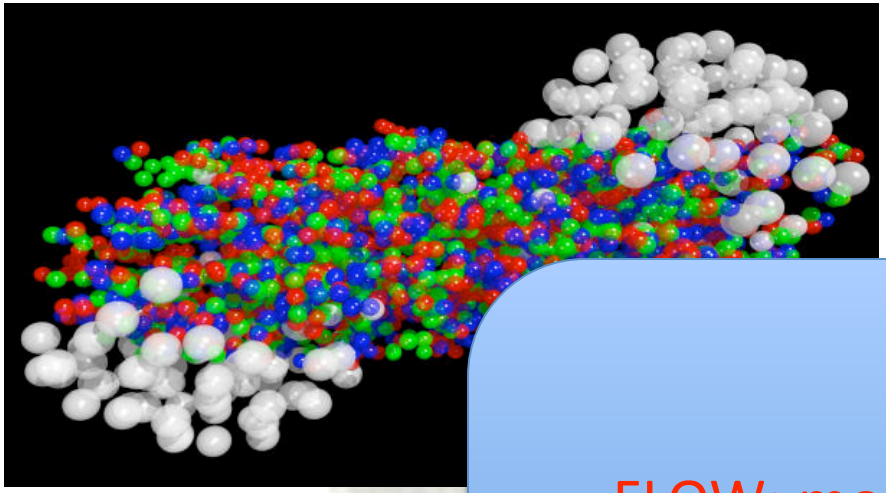
"Clean" p+p– a crucial reference ***at high pT***

(do we understand/care about low pT?)

p+p: a *process*



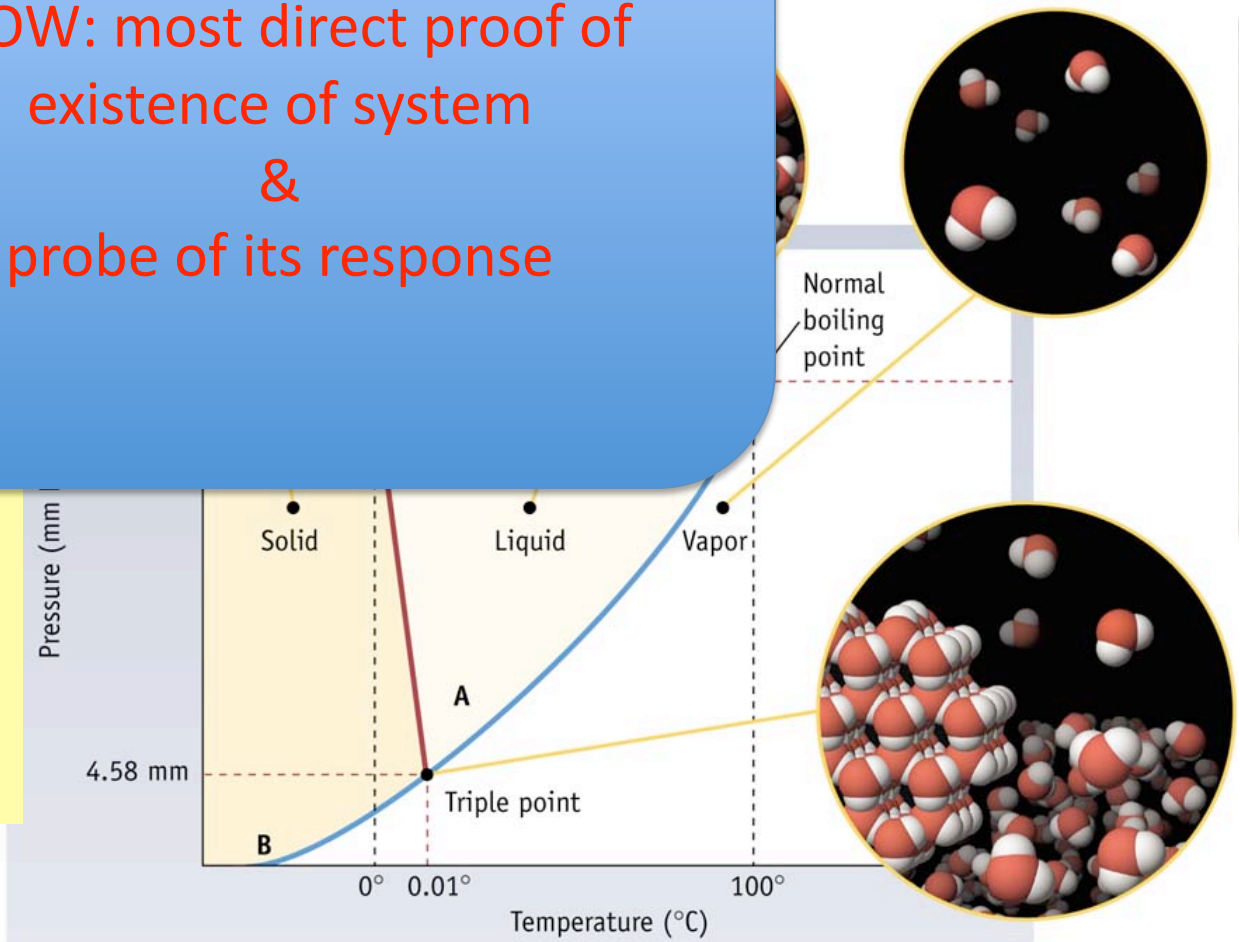
H.I.C. – a system



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

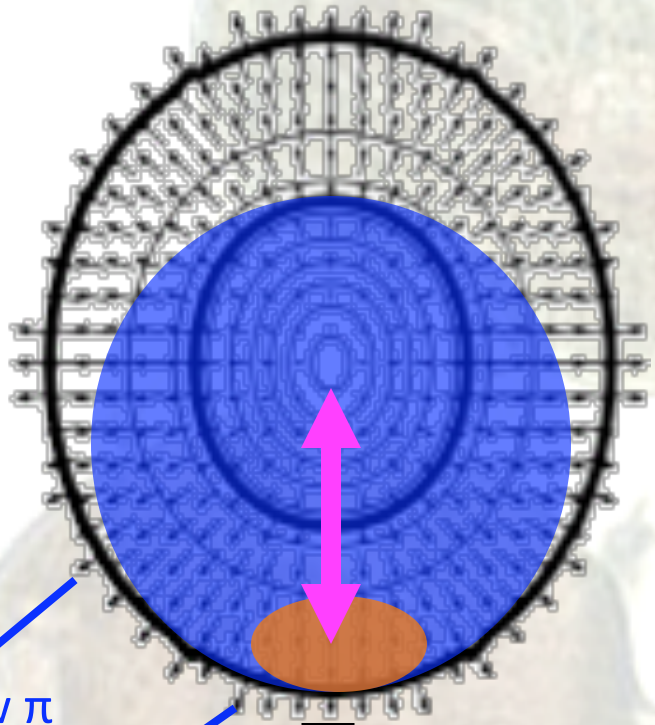
bulk physics
- superfluids
- superconductors
- metal/insulator
- …

Only for large *system*
- can't melt one H_2O molecule!



Explosive flow revealed through ***specific fingerprints*** on soft-sector observables

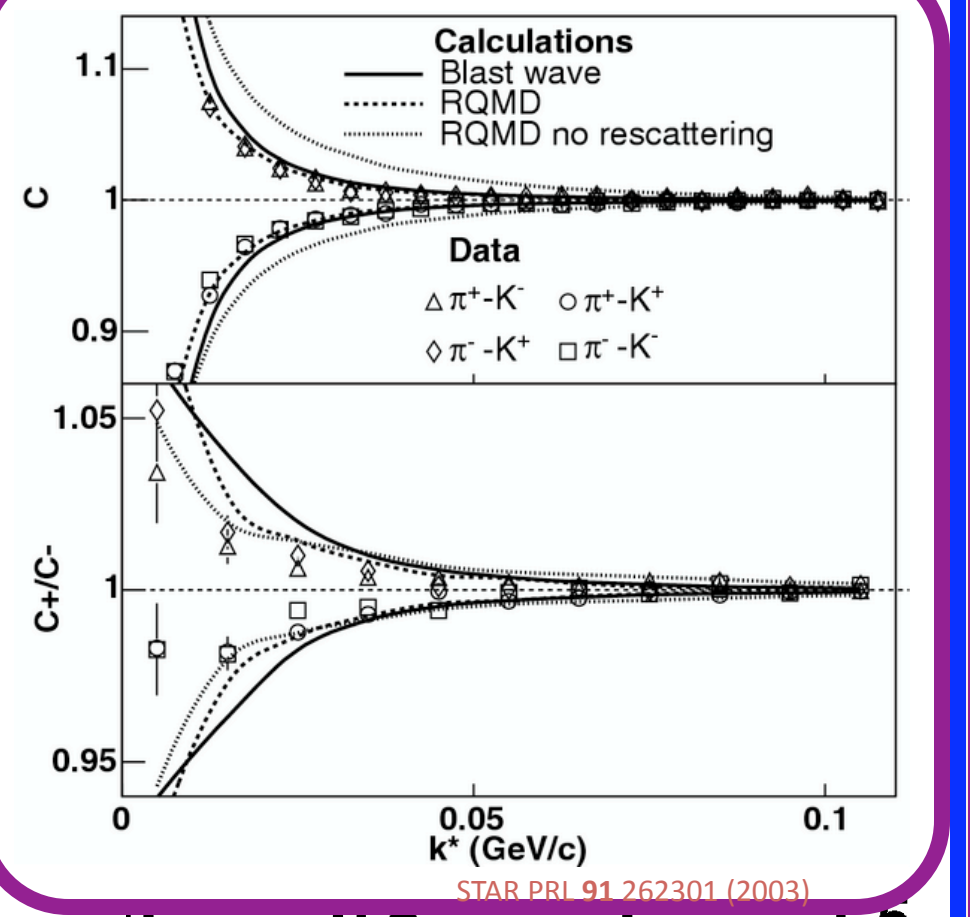
calculable in hydrodynamics or toy "blast wave" models



π
slow π

fast K π

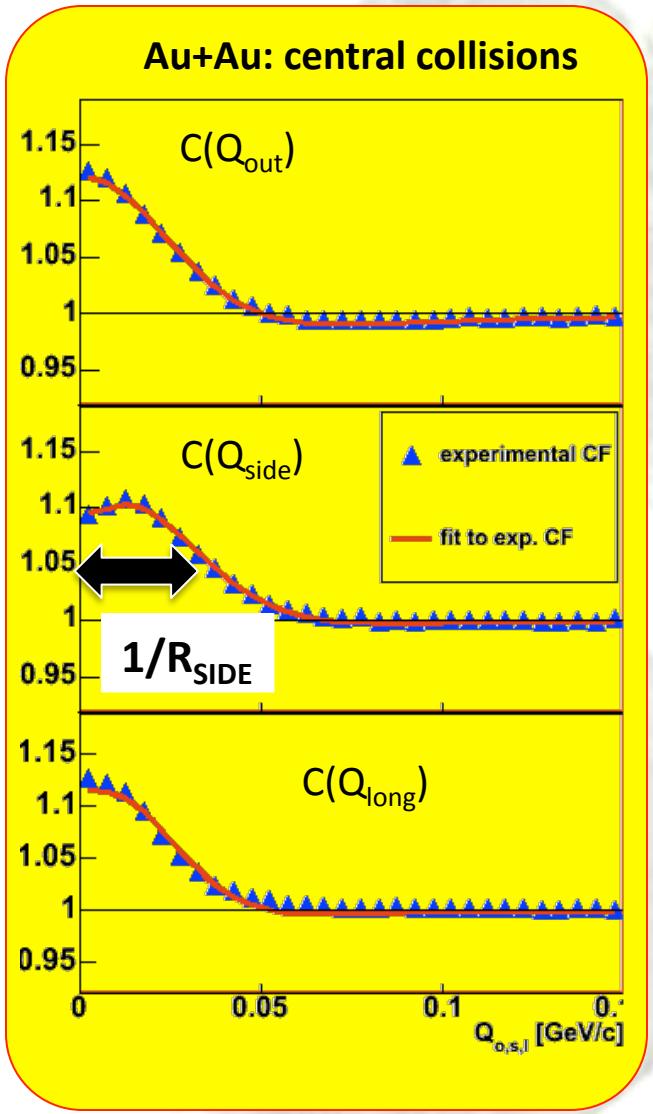
but the ***defining*** characteristic:
correlated position and boost direction



STAR PRL **91** 262301 (2003)

space-momentum substructure mapped *in detail*

Obtaining 3D radii from 3D correlation functions

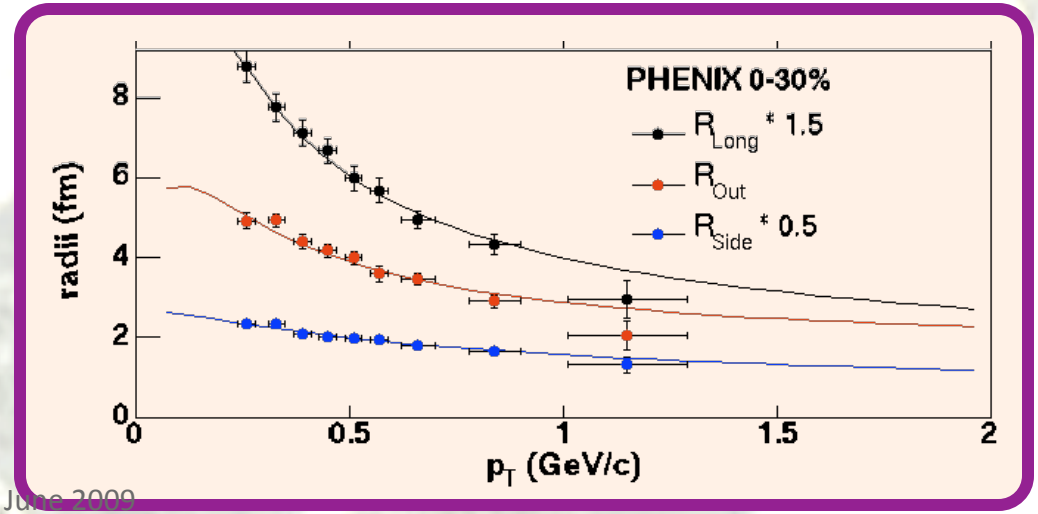


$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{ 1 + e^{-\left(q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2\right)} \right\} - 1 \right) \right]$$

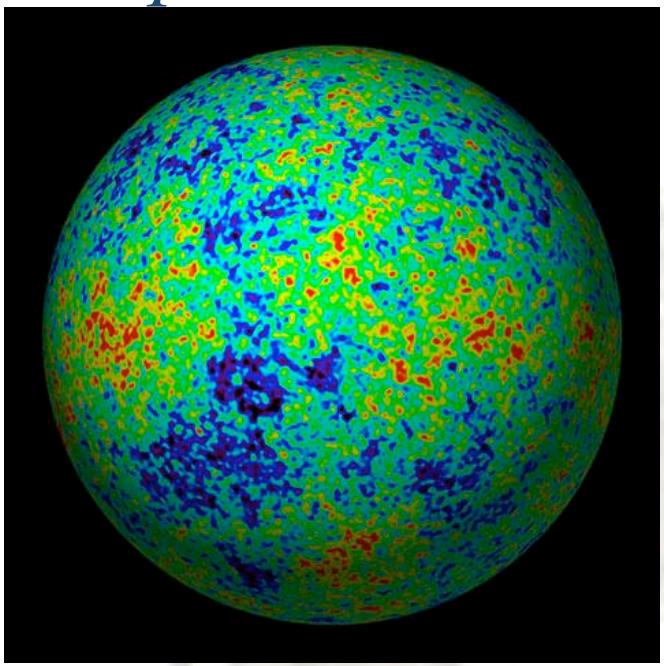
typical "Gaussian" fitting function

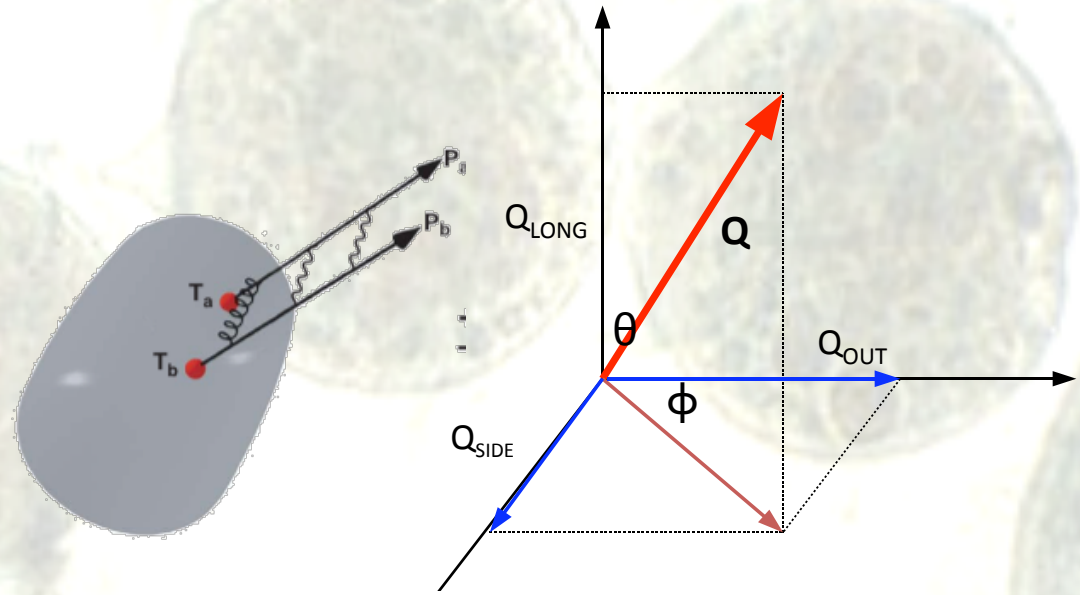
- Au+Au: "Gaussian" radii capture bulk scales
  - (resonance tails from imaging)
- $R(p_T)$ consistent with explosive flow

"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)

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

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

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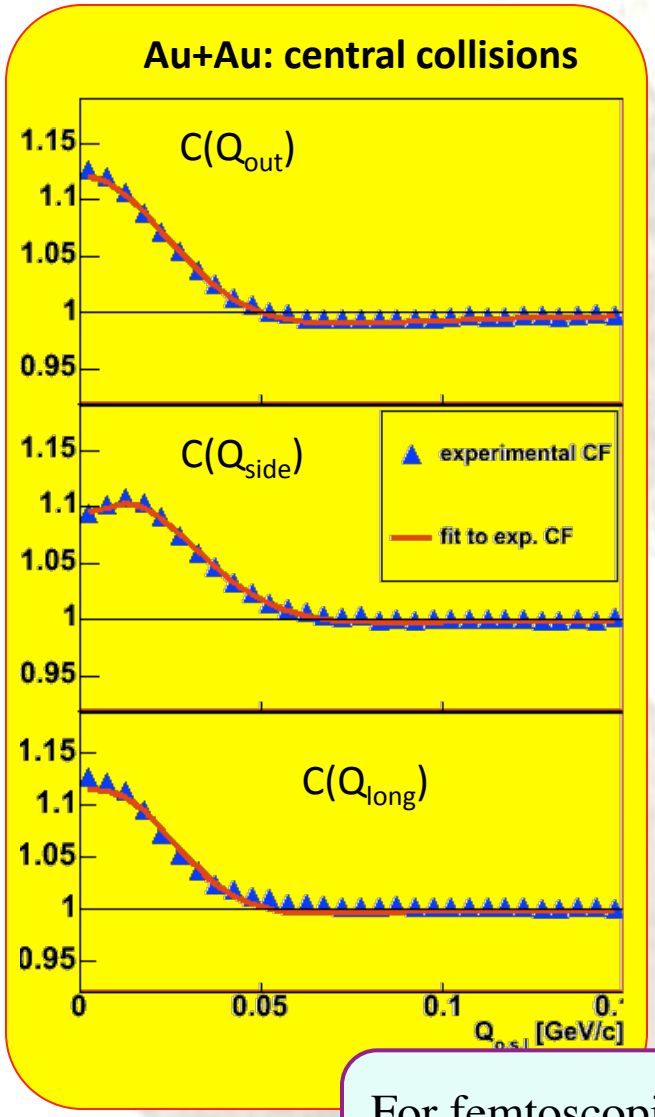
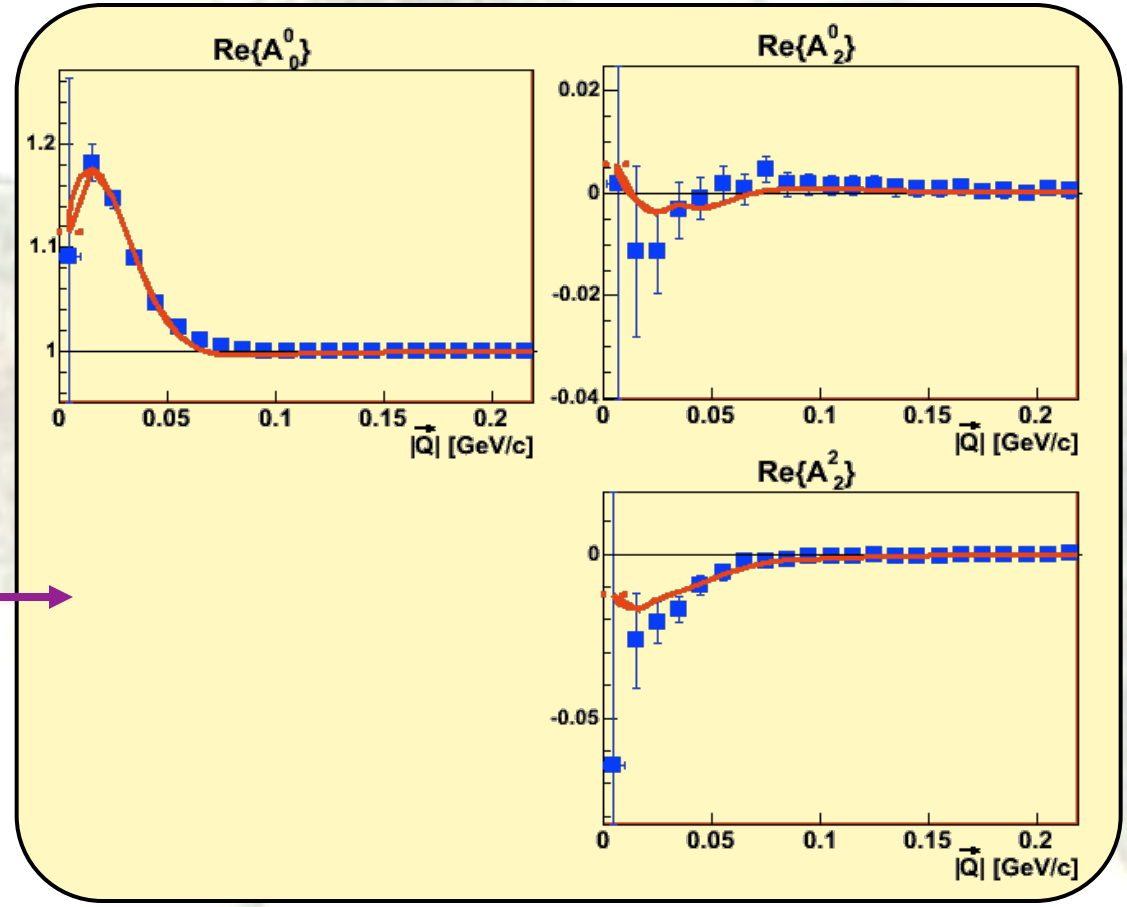




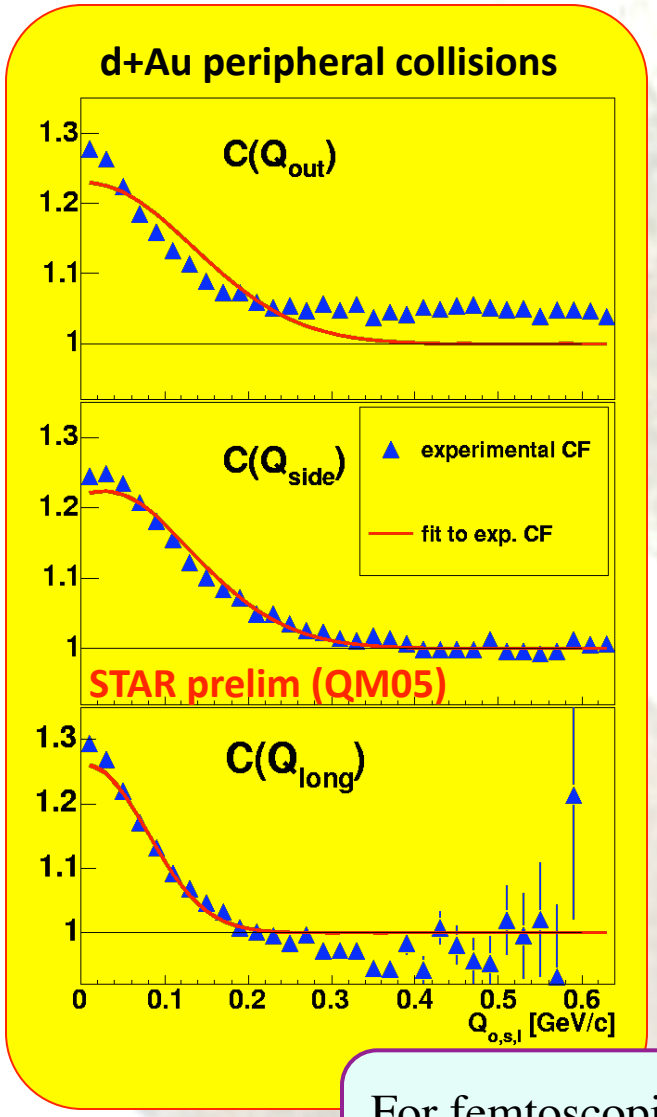
$$A_{l,m}\left(\left|\vec{Q}\right|\right) = \frac{\Delta_{\cos\theta}\Delta_{\phi}}{\sqrt{4\pi}} \sum_{i}^{bins} Y^{*}_{l,m}(\theta_i,\phi_i)\, C\left(\left|\vec{Q}\right|, \cos\theta_i, \phi_i\right)$$

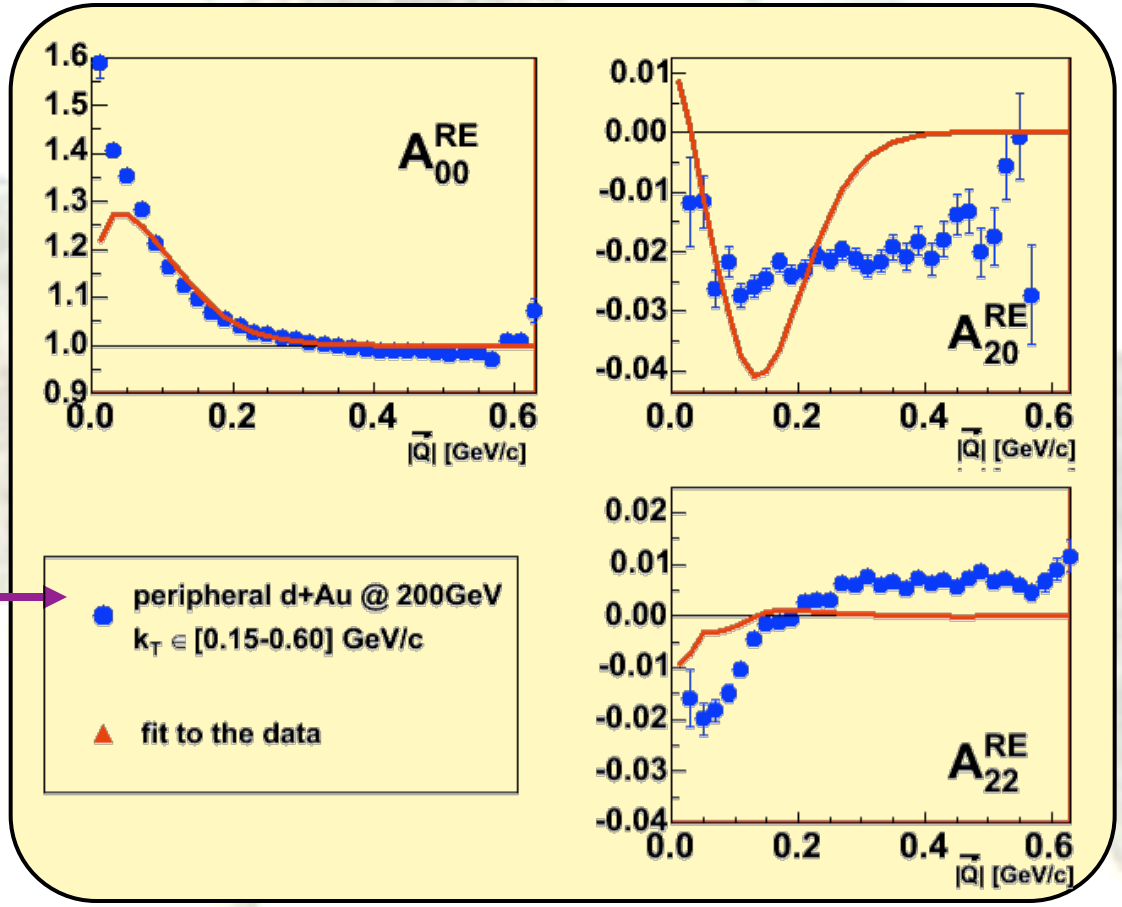
Z. Chajecki & MAL, PRC **78** 064903 (2008)

For femtoscopic correlations:

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

Spherical harmonic representation of 3D data





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

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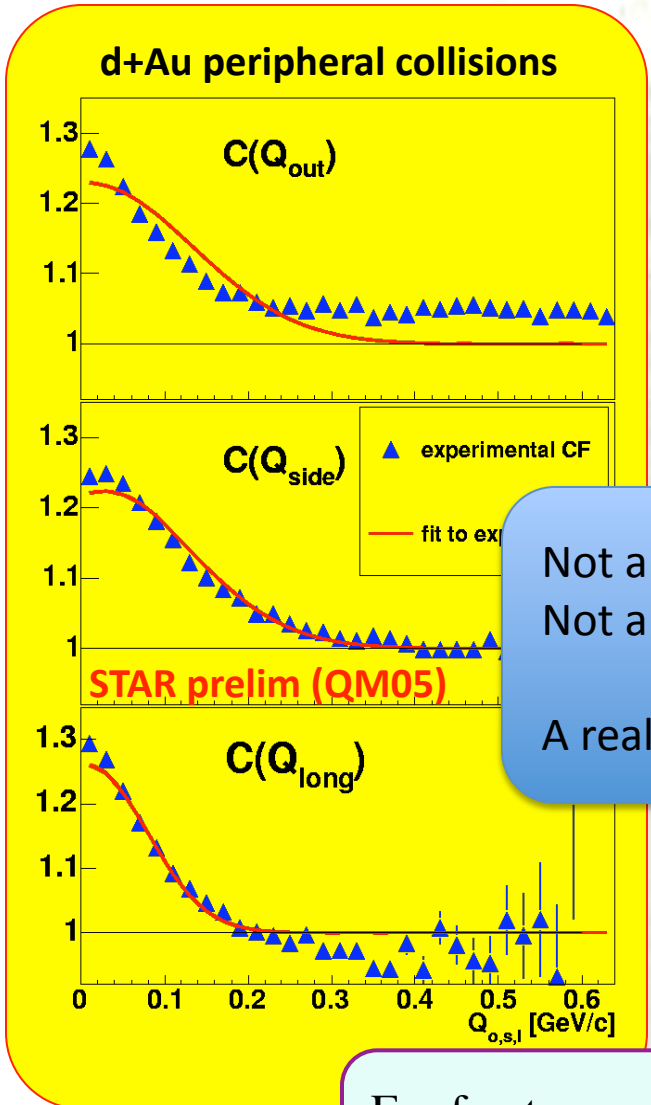
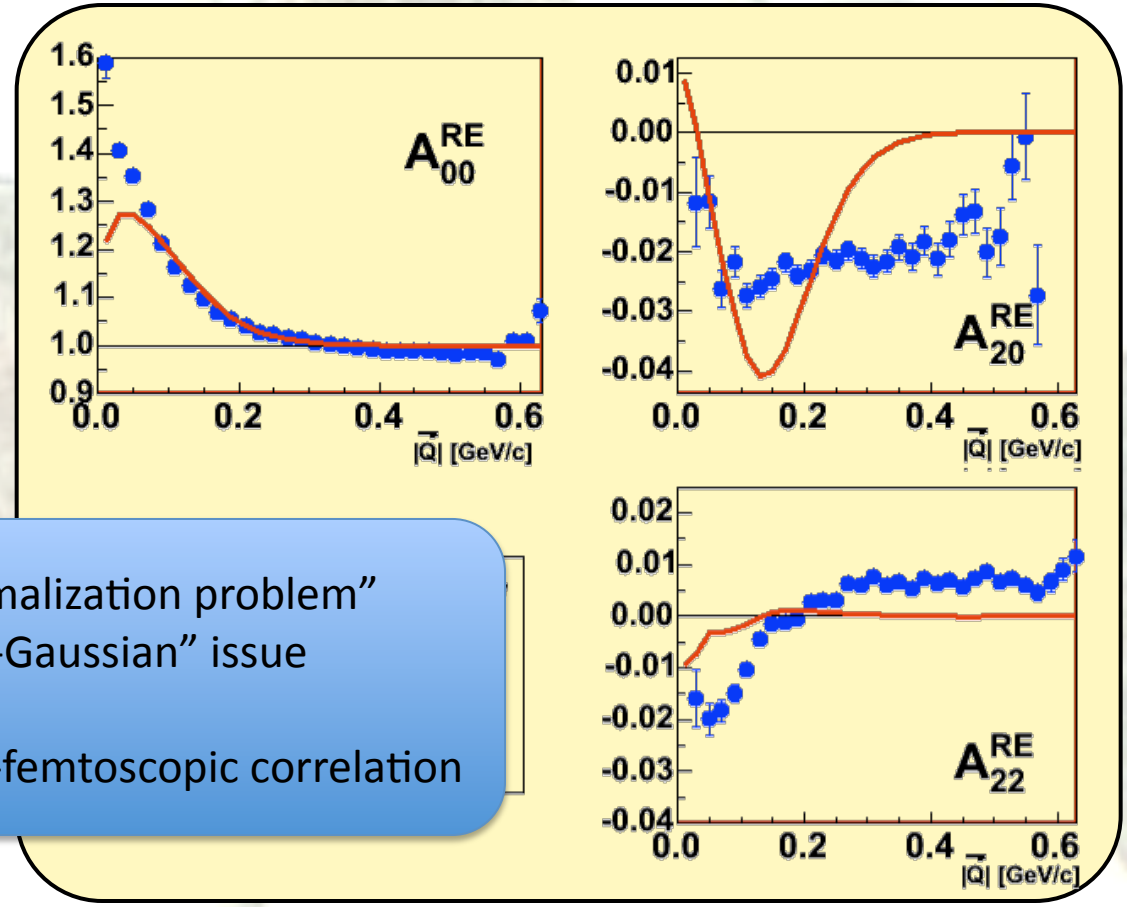




Not a "normalization problem"
Not a "non-Gaussian" issue

A real, non-femtoscopic correlation

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

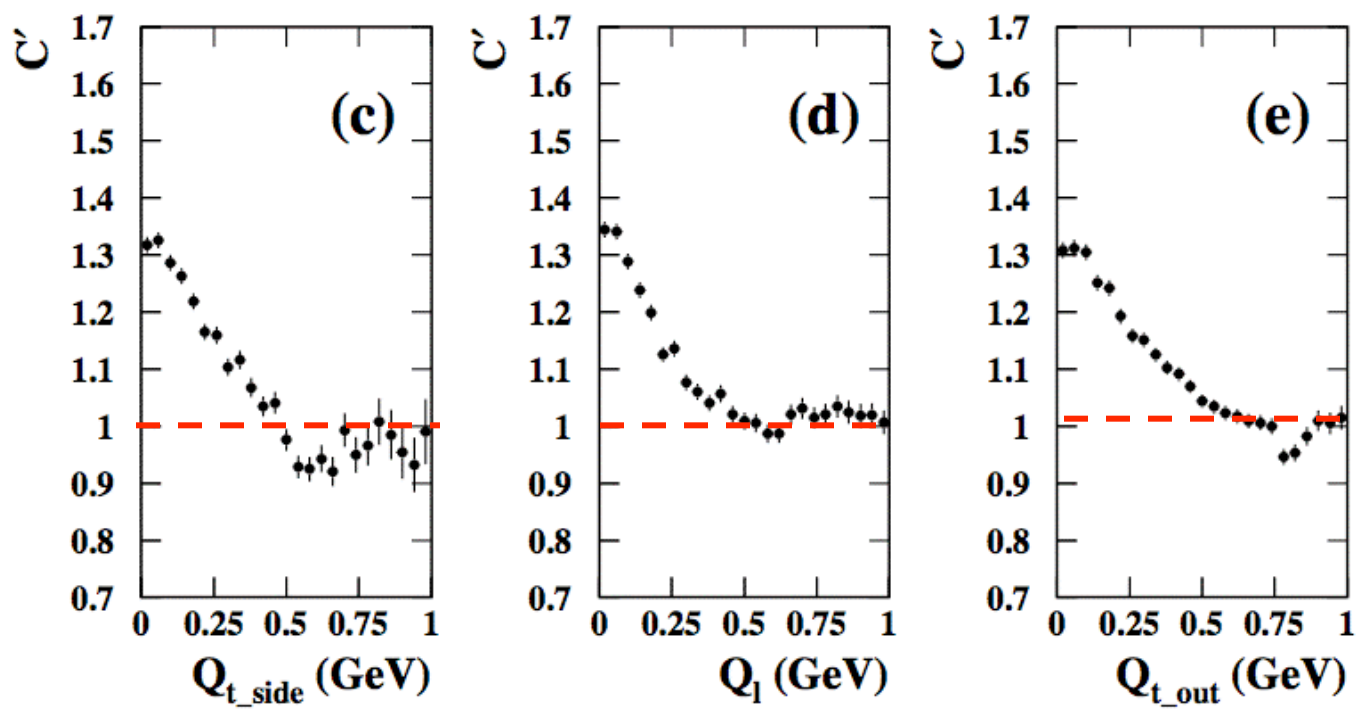
Z. Chajecki & MAL, PRC **78** 064903 (2008)

For femtoscopic correlations:

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

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-Q" 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)

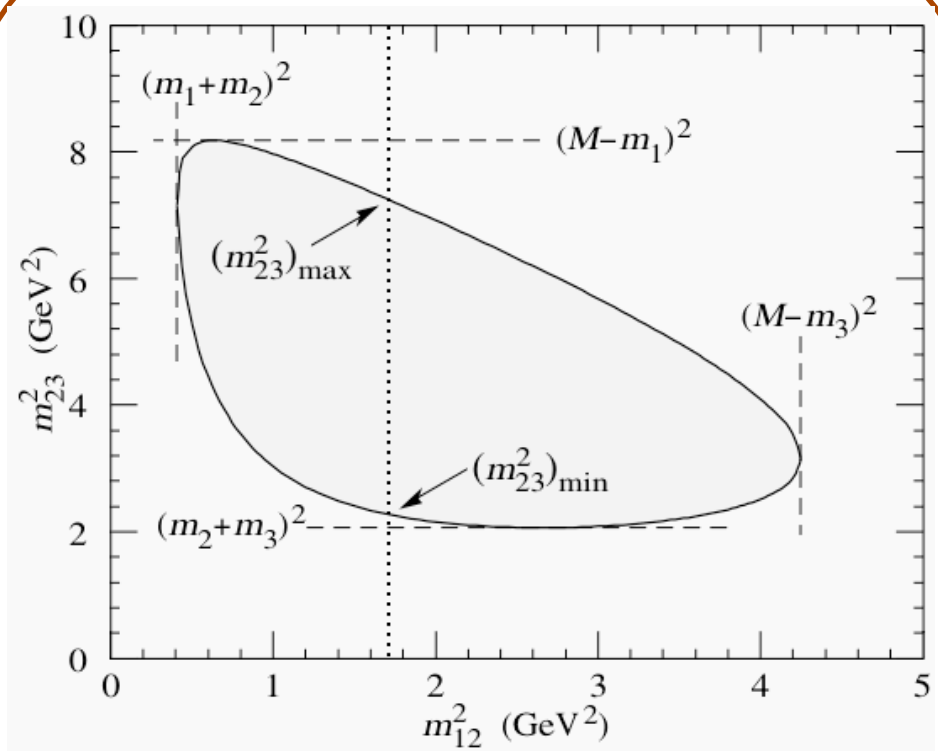
- see also
  – pT conservation effects on v2 [Danielewicz, Ollitrault & Borghini]
  – pT conservation on 3-particle "conical emission" observables [Borghini]
  – p and E conservation effects on single particle spectra [Chajecki & MAL]

Phase-Space varies with multiplicity

Phase-space constraints

Extreme case, N=3,
easily calculable with Dalitz plot

What about the effect for higher number of particles?



Dalitz plot for a three-body final state.
PDG 2008

Average matrix element - factorization

Probability for an n-particle final state:

$$P_n \propto \int \cdots \int \prod_{i=1}^{n} \delta\left(p_i'^2 - m^2\right) d^4 p_i' \times \delta^4\left(\sum_{j=1}^{n} p_j' - p_1 - p_2\right) S\left(p_1' \ldots p_n' \mid p_1, p_2\right)$$

$$\equiv \bar{S}_n \underbrace{\int \cdots \int \prod_{i=1}^{n} \delta\left(p_i'^2 - m^2\right) d^4 p_i' \times \delta^4\left(\sum_{j=1}^{n} p_j' - p_1 - p_2\right)}_{R_n}$$

dynamics

kinematics

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

Single-particle spectrum

$$W\left(p_1'\right) d^3 p_1' \propto d^3 p_1' \int \cdots \int \delta\left(p_1'^2 - m^2\right) dp_{01} \prod_{i=2}^{n} \delta\left(p_i'^2 - m^2\right) d^4 p_i' \times$$

$$\delta^4\left(\sum_{j=1}^{n} p_j' - p_1 - p_2\right) S\left(p_1' \ldots p_n' \mid p_1, p_2\right)$$

$$\equiv d^3 p_1' \cdot \bar{S}_n\left(p_1'\right) R_F$$

R. Hagedorn, *Relativistic Kinematics* 1963

Correlations arising (only) from conservation laws (PS constraints): The k-particle distribution

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

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

what we measure

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

no other correlations

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

CLT - for: $(N-k) >\sim 10, \quad E <\sim 3\langle E \rangle$

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

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

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

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

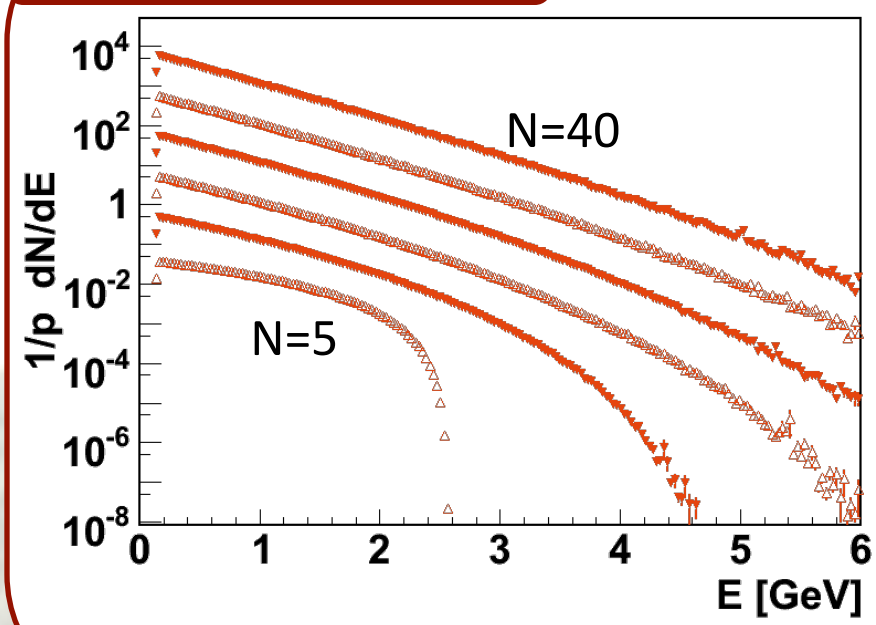
–Danielewicz *et al*, PR**C38** 120 (1988)
–Borghini, Dinh, & Ollitraut PR**C62** 034902 (2000)
–Borghini Eur. Phys. J. C30:381-385, (2003)
–Chajecki & MAL, PRC **78** 064903 (2008)

Effects on single-particle distribution

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

We will return to this….

1-particle PS effect



Z.Chajecki, MAL, PRC **79** 034908 (2009)

k-particle correlation function

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

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

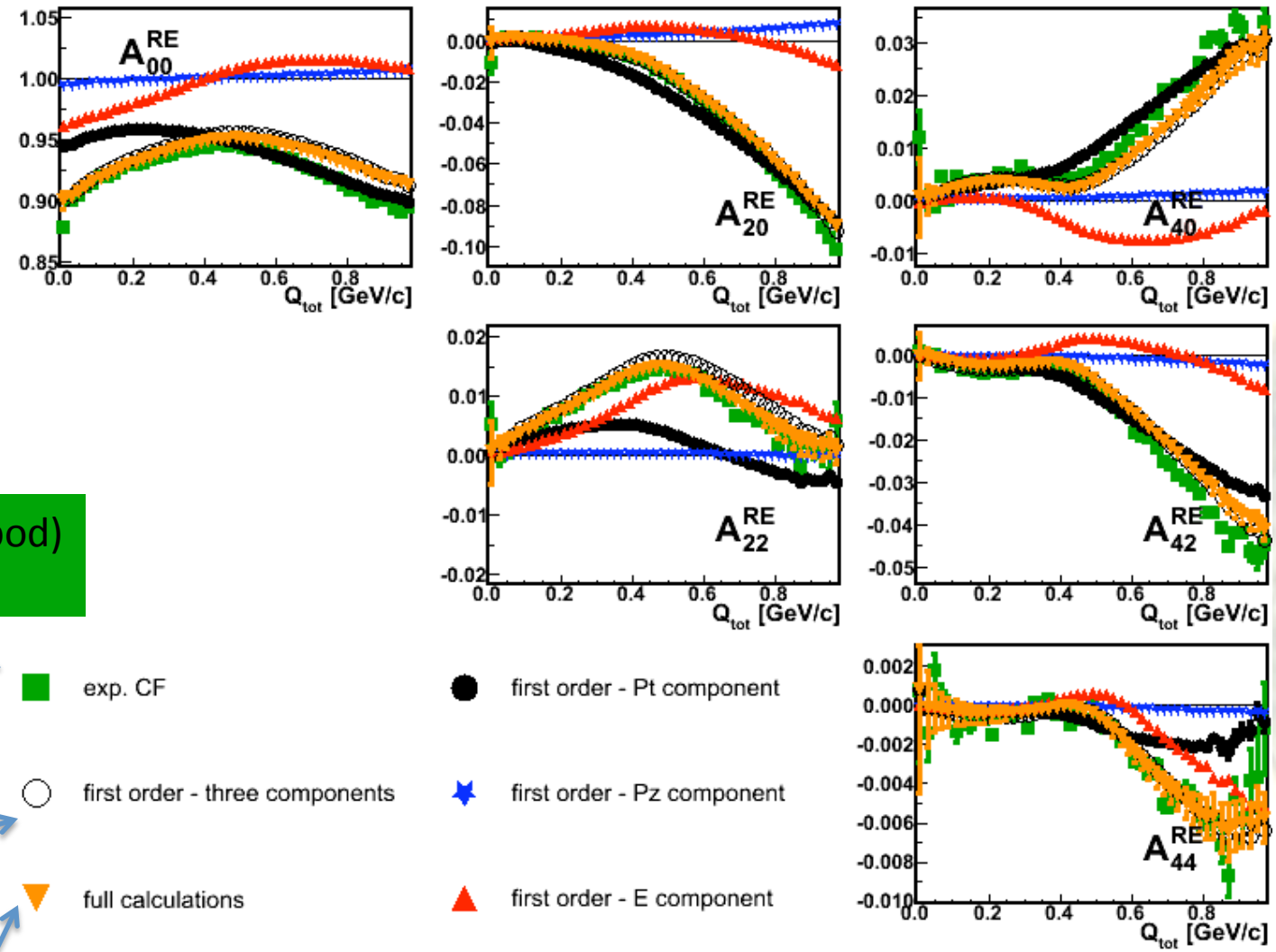
Dependence on "parent" distrib f vanishes,
except for energy/momentum means and RMS

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

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

How do EMCICs look ? – nontrivial !

Genbod N=18 <K>=0.9 GeV; PRF - |[illegible]|<0.5



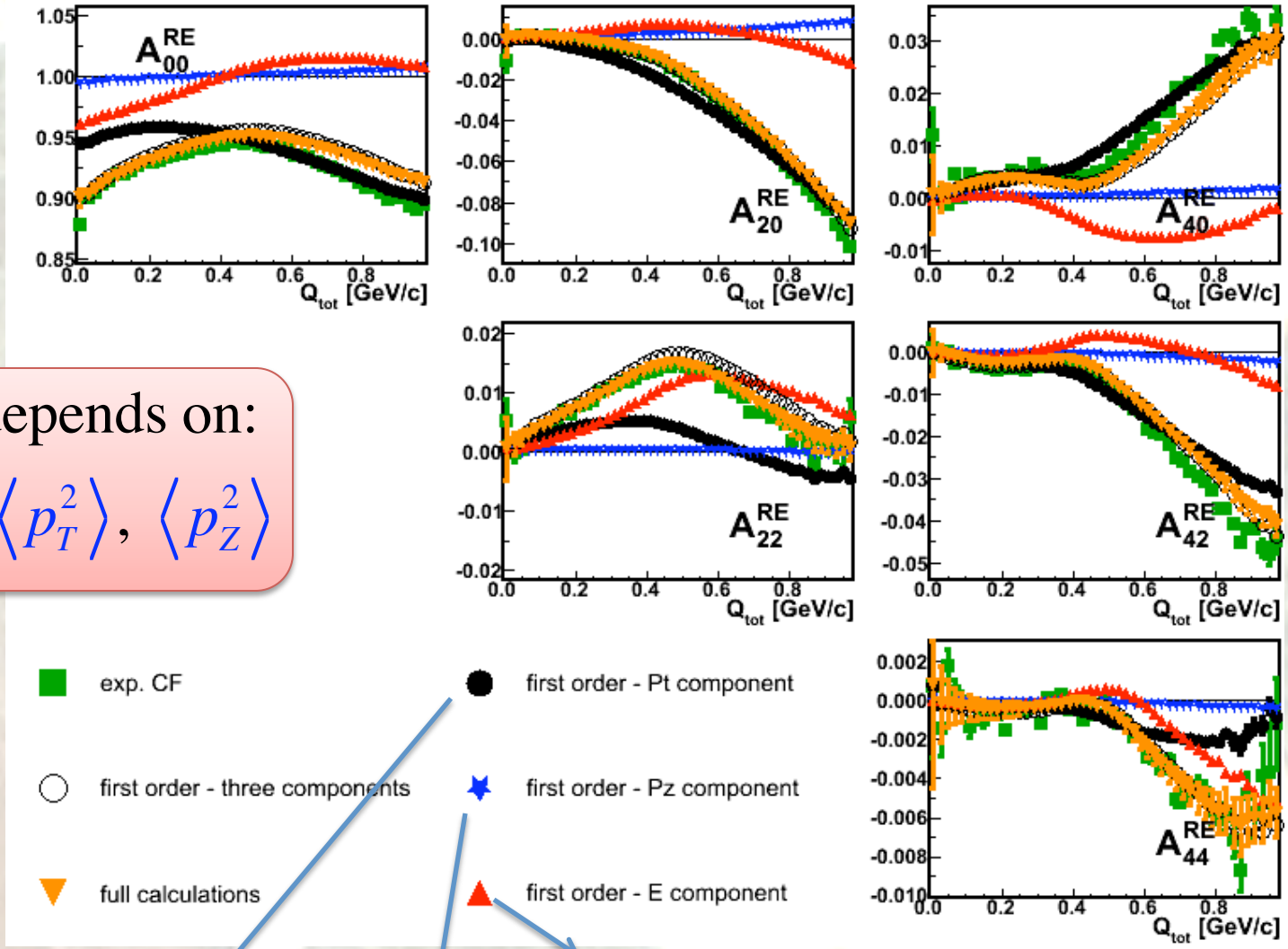
event generator (genbod) with only EMCICs

O(1/N) term in CLT approximation

CLT approximation

- **structure <u>not</u> confined to large Q**
- **kinematic cuts have strong effect**

How do EMCICs look ? – nontrivial !



Detailed shape depends on:

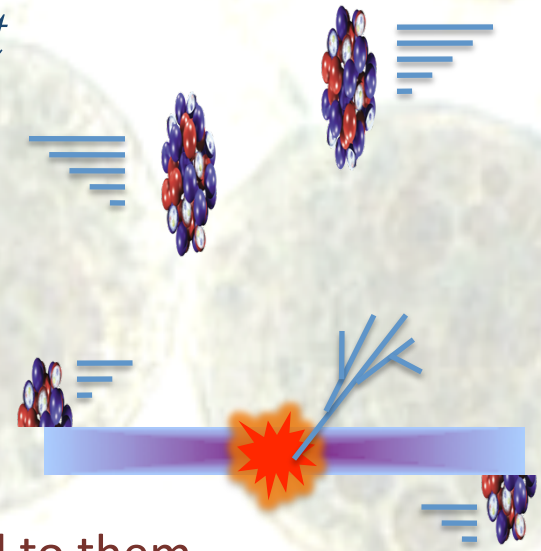
$N,\ \langle E\rangle,\ \langle E^2\rangle,\ \langle p_T^2\rangle,\ \langle p_Z^2\rangle$

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

"the system"... a nontrivial concept

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

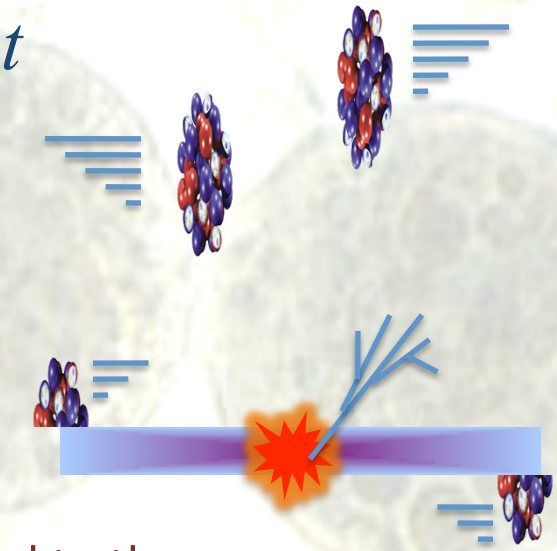
Characteristic scales of relevant system in which limited energy-momentum is shared



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

1. *N* includes all 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 $\langle p_\mu^2 \rangle \equiv \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}(p)}_{\text{unmeasured parent distrib}} \neq \int d^3p \cdot p_\mu^2 \cdot \underbrace{\tilde{f}_c(p)}_{\text{measured}}$
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" ??
     - or just stealing energy *from* "the system?"
   - 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

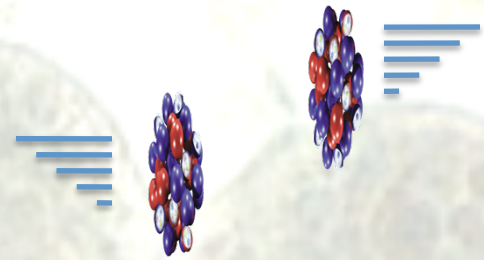
- Not known a priori
- should *track* measured quantities, but not be identical to them

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

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

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

"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 share

- 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 $\quad (\langle p_T \rangle_\pi = 0.405$ GeV$)$

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

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

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

	non - rel	ultra - rel	if $T = .15$ -
$\langle p_T^2 \rangle$	$2mT$	$8T^2$	$0.045 \div 0.$
$\langle E^2 \rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5$
$\langle E \rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1$ 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.

Femtoscopic correlations and EMCICs (experimentalists' recipe)

$$C(p_1,p_2) = \text{Norm}\cdot\left\{1+\lambda\cdot\left[K_{coul}(Q_{inv})\left(1+\exp\left(-R_{out}^2Q_{out}^2-R_{side}^2Q_{side}^2-R_{long}^2Q_{long}^2\right)\right)-1\right]\right\}\times$$
$$\left[1-2M_1\overline{\left\{\vec{p}_{1,T}\cdot\vec{p}_{2,T}\right\}}-M_2\overline{\left\{p_{1,Z}\cdot p_{2,Z}\right\}}-M_3\overline{\left\{E_1\cdot E_2\right\}}+M_4\overline{\left\{E_1+E_2\right\}}-\frac{(M_4)^2}{M_3}\right]$$

Z. Chajęcki & MAL PRC **78** 064903 (2008)

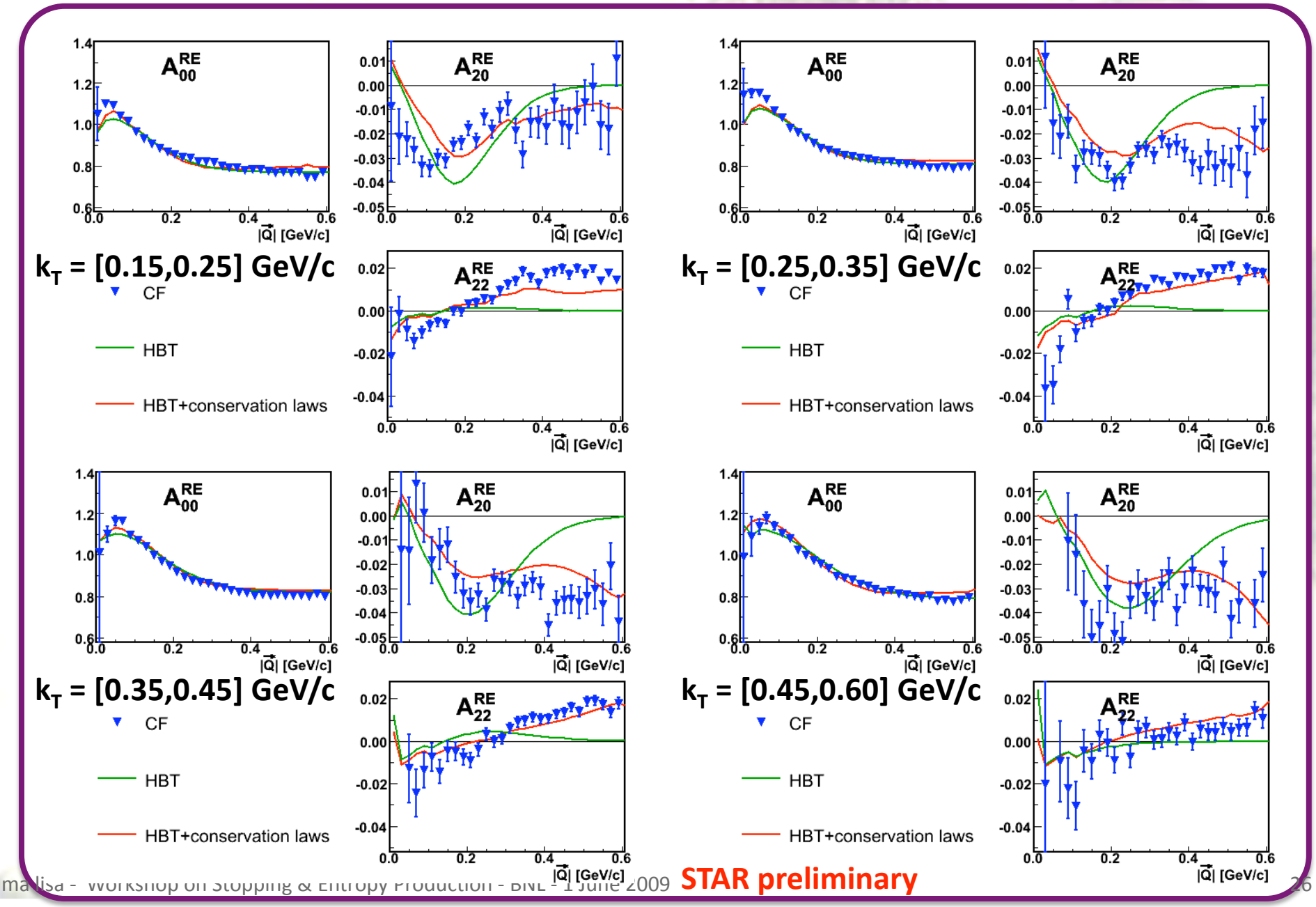
- Five parameters found in any femtoscopic analysis: R_{out}^2, R_{side}^2, R_{long}^2, λ, Norm

- Four parameters related to underlying parent distribution (*independent of* k_T*!*)

$$M_1 = \frac{1}{N\langle p_T^2\rangle} \qquad M_2 = \frac{1}{N\langle p_Z^2\rangle}$$

$$M_3 = \frac{1}{N\left(\langle E^2\rangle-\langle E\rangle^2\right)} \qquad M_4 = \frac{\langle E\rangle}{N\left(\langle E^2\rangle-\langle E\rangle^2\right)}$$

Fits to p+p data (STAR @ QM09)



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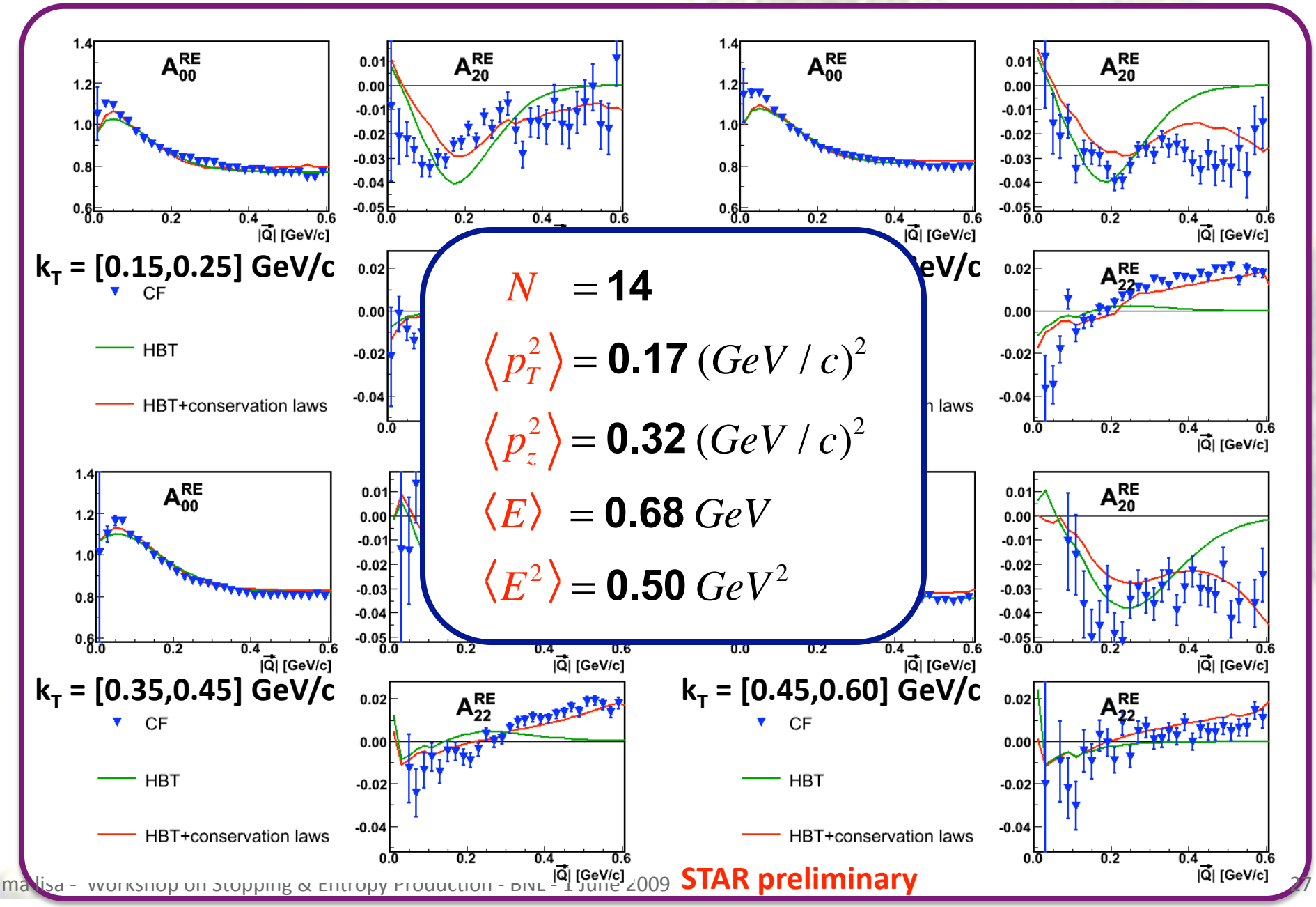


$$N = 14$$

$$\langle p_T^2 \rangle = 0.17\ (GeV/c)^2$$

$$\langle p_z^2 \rangle = 0.32\ (GeV/c)^2$$

$$\langle E \rangle = 0.68\ GeV$$

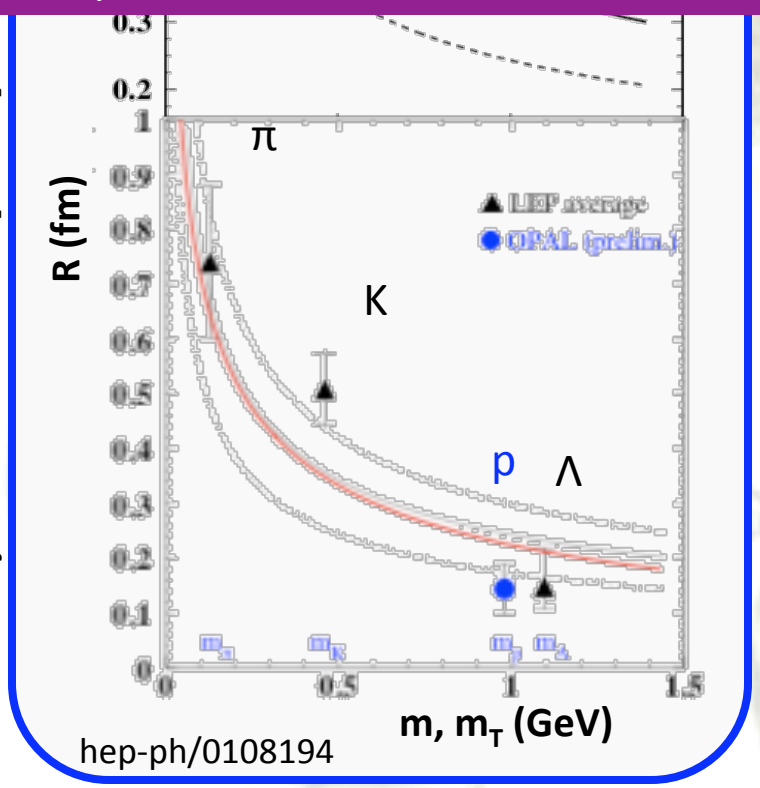
$$\langle E^2 \rangle = 0.50\ GeV^2$$

"HBT radii" in p+p (STAR@QM09)

1. **Heisenberg uncertainty?**
2. **String fragmentation? (Lund)**
3. **Resonance effects?**
4. **Flow???**

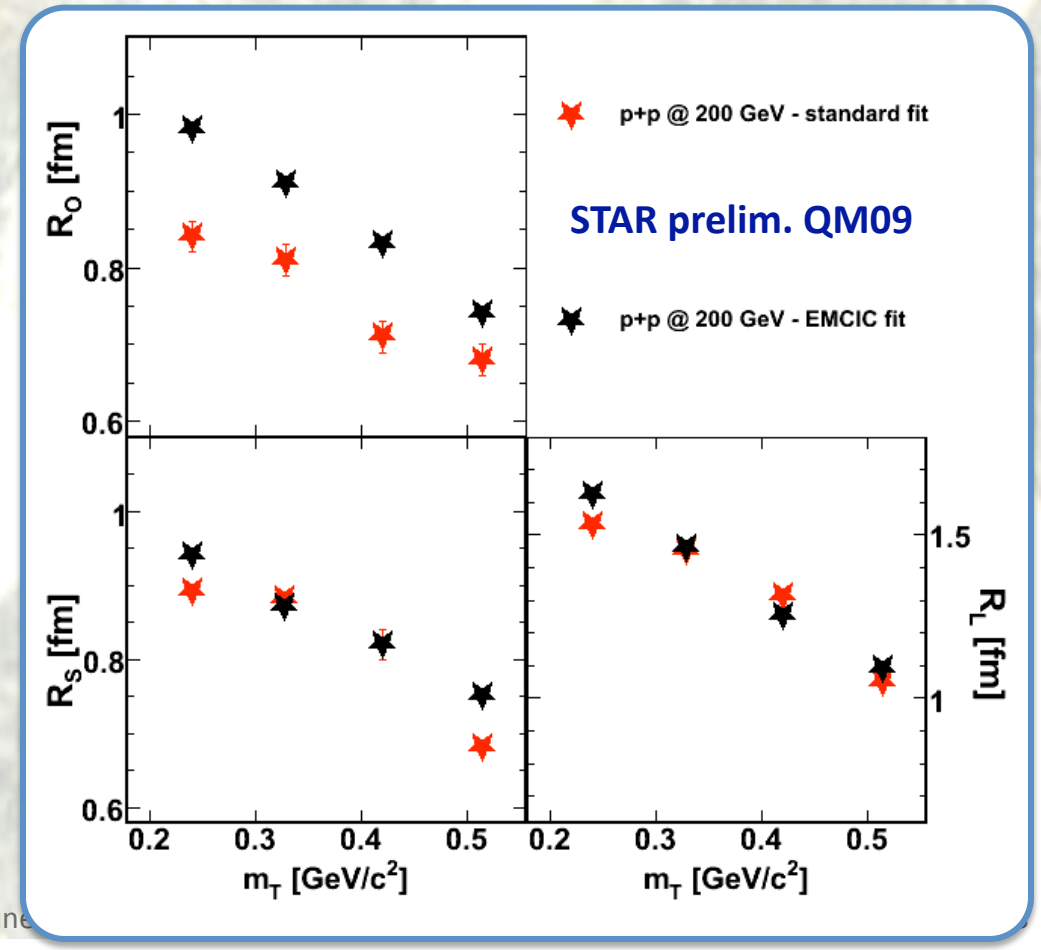
- Increasingly suggested in HEP experiments

c.f. Z. Chajecki arXiv:0901.4078 [nucl-ex]



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

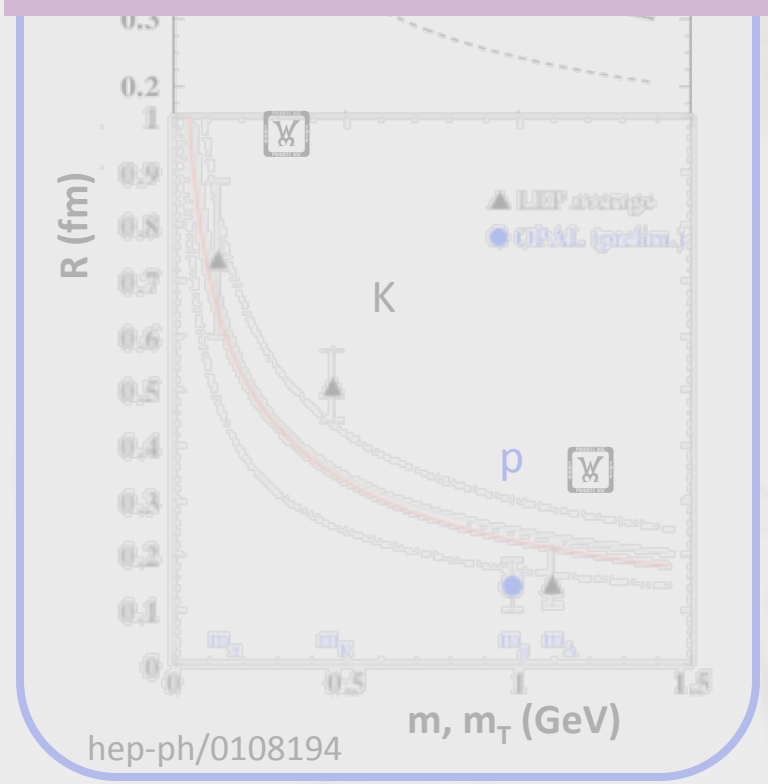
- unique opportunity to compare physics



femtoscopy in p+p @ STAR

1. Heisenberg uncertainty?
2. String fragmentation? (Lund)
3. Resonance effects?
4. Flow???

- Increasingly suggested in recent 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?

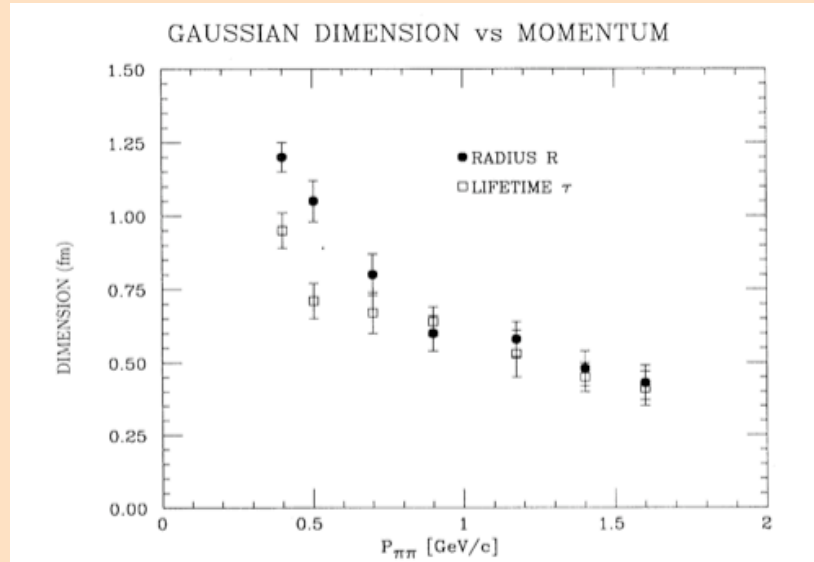


FIG. 9. Interaction "radius" and lifetime as a function of the total momentum $P_{\pi\pi}$ of the pion pair. R_G is primarily a source dimension along the beam direction. τ might possibly be interpreted as a source dimension transverse to the beam. Data are from Table III.

E735 Collaboration, PRD**48** 1931 (1993)
also PLB 2002
consistent with an expanding shell model.

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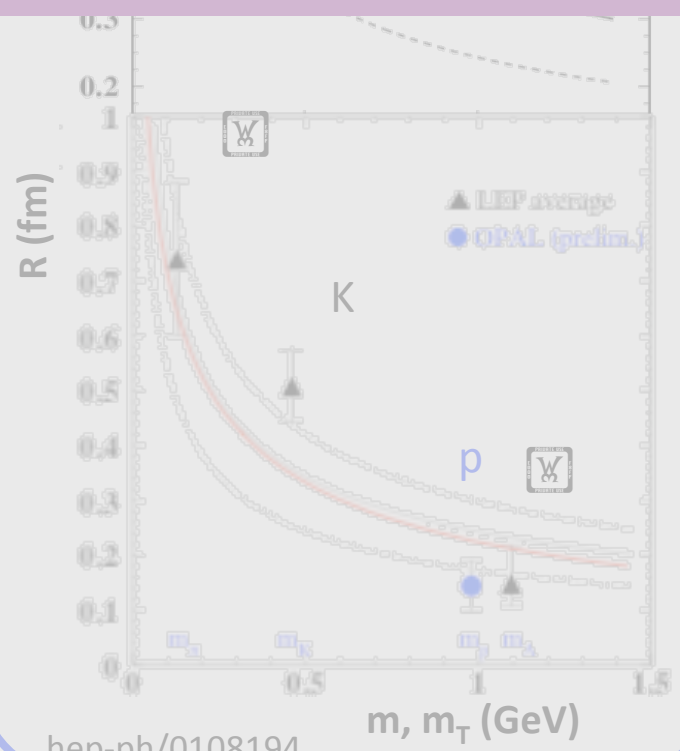
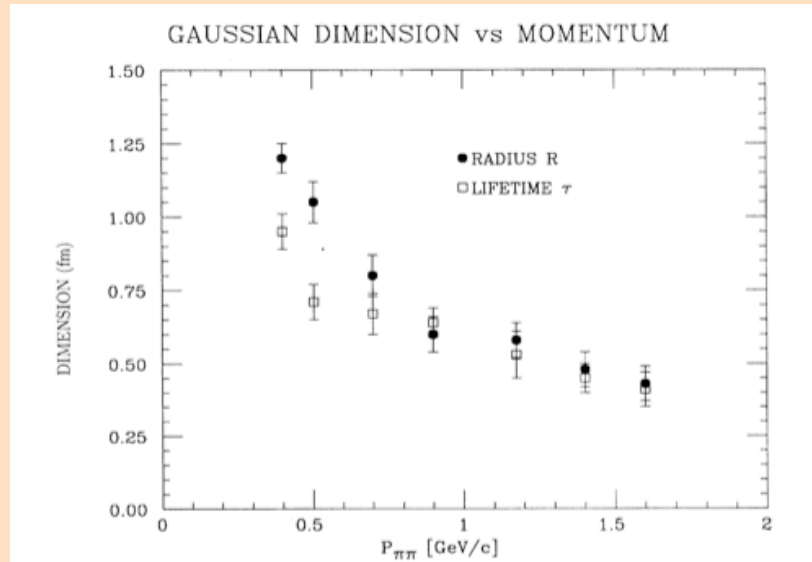


hep-ph/0108194

NA22 Collaboration Z. Phys. C 71, 405–414 (1996) (hadron-hadron collisions)

[based on shape of C(q)…]

Our data do not confirm the expectation from the string type model… A good description of our data is, however, achieved in the framework of the hydrodynamical expanding source model.



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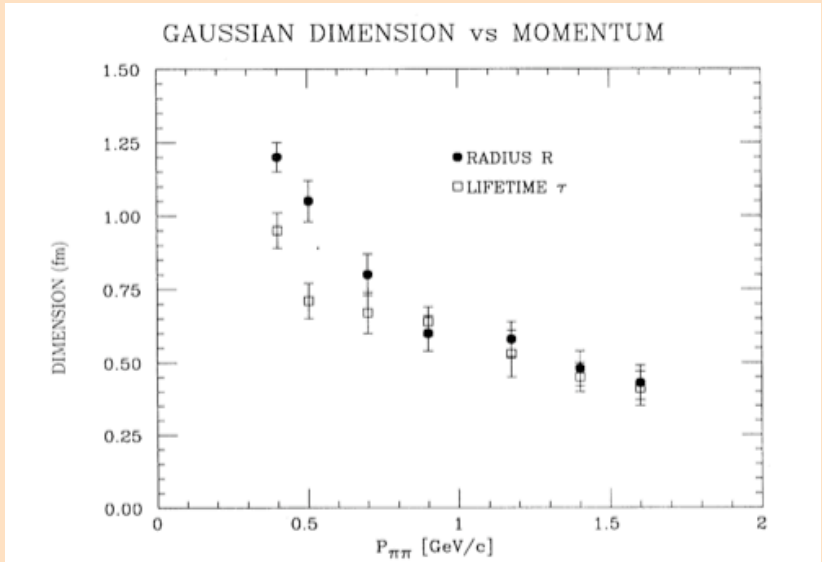

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8 1931 (1993)

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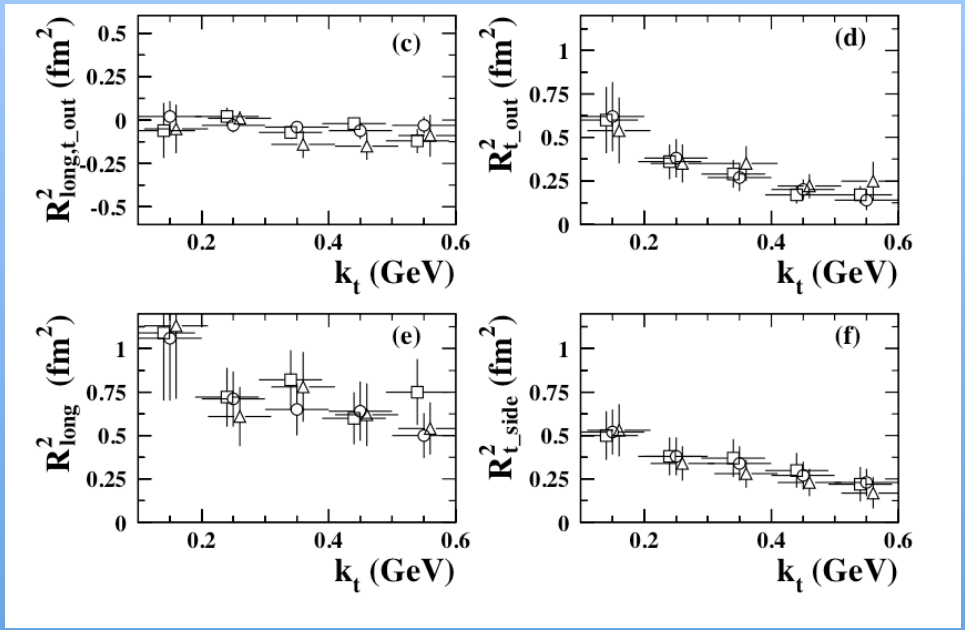
W. Kittel Acta Phys.Polon. B32 (2001) 3927 [Review article]

… 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.C52:787-803,2007; 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.

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

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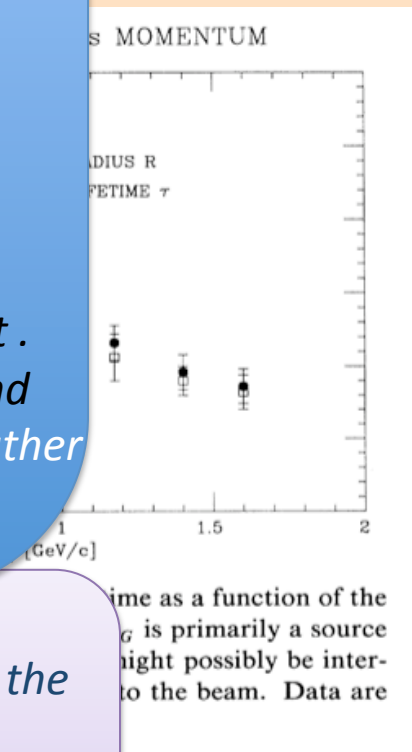

8 1931 (1993)

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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
expands

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

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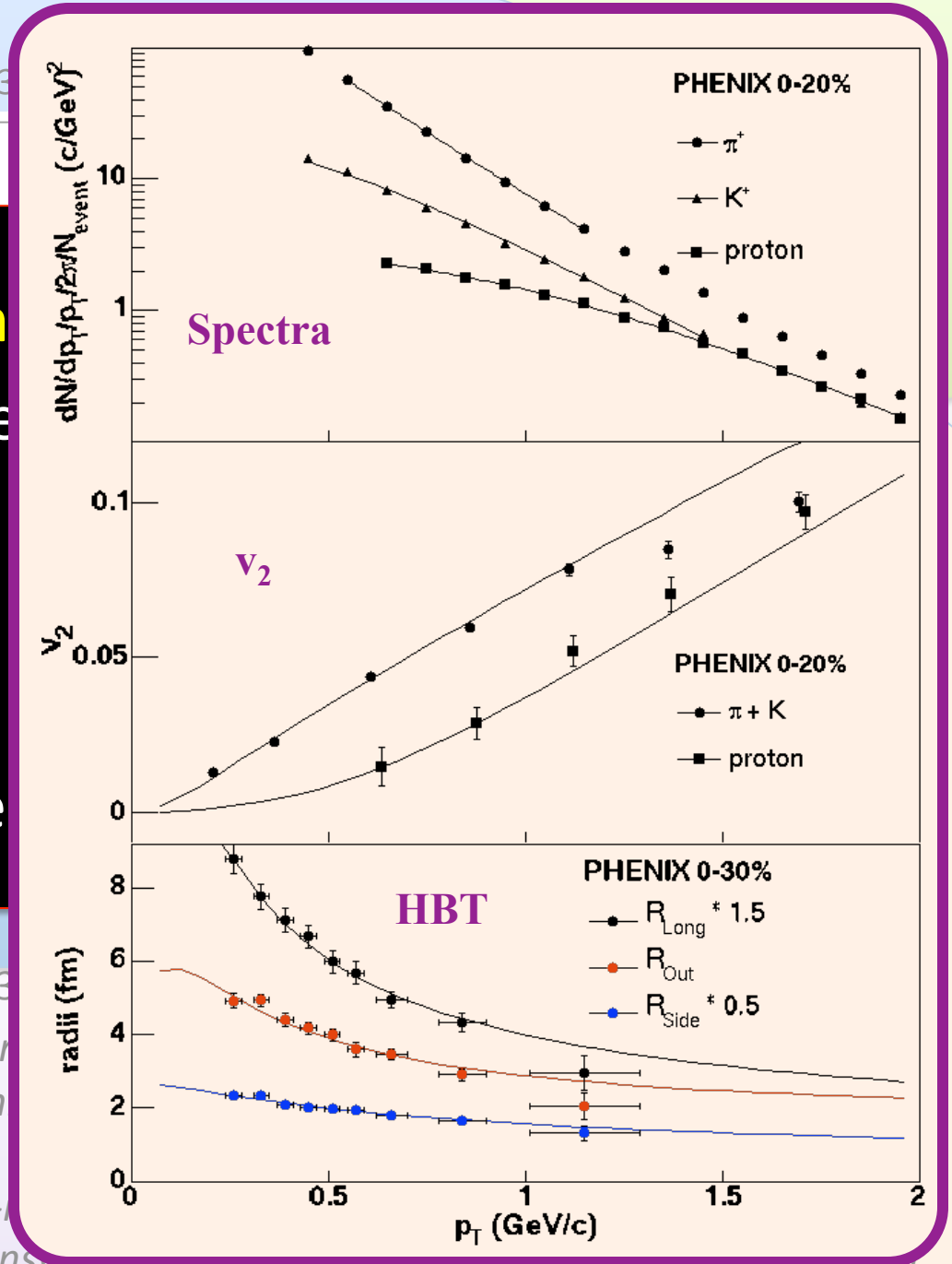

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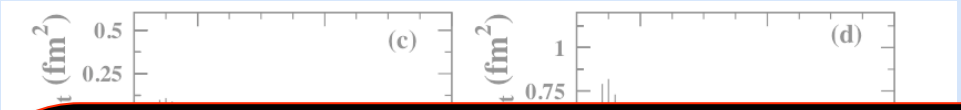

RHIC: “comparison machine”

Vary size. All else fixed. [acceptance, technique…]

- spectra
- femtoscopy

compare with a system we “know” is flowing

R2ts
The p
their
expands

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

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Apples:apples comparison…

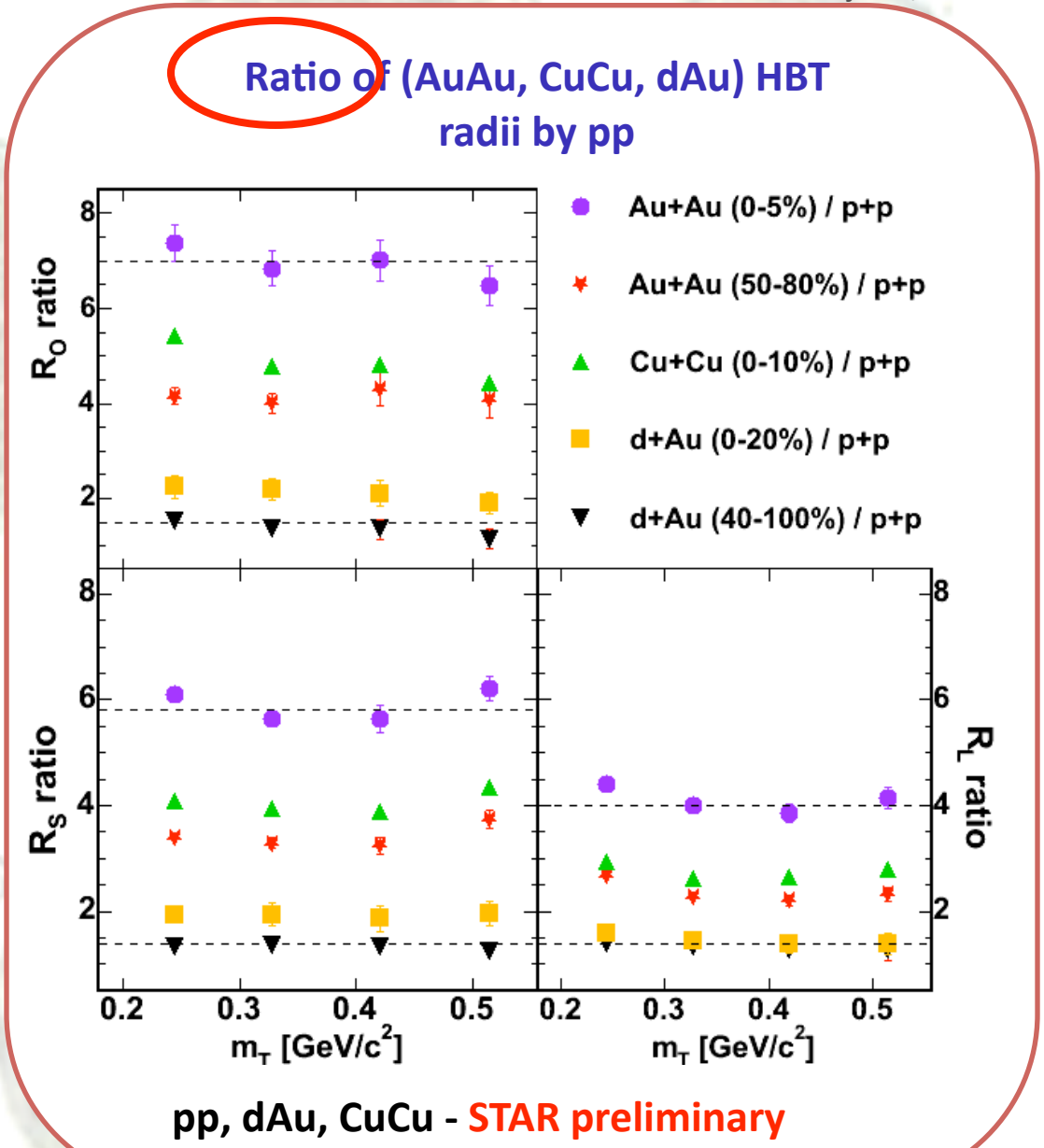
Z. Chajecki, QM05

$R(p_T)$ 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"...)



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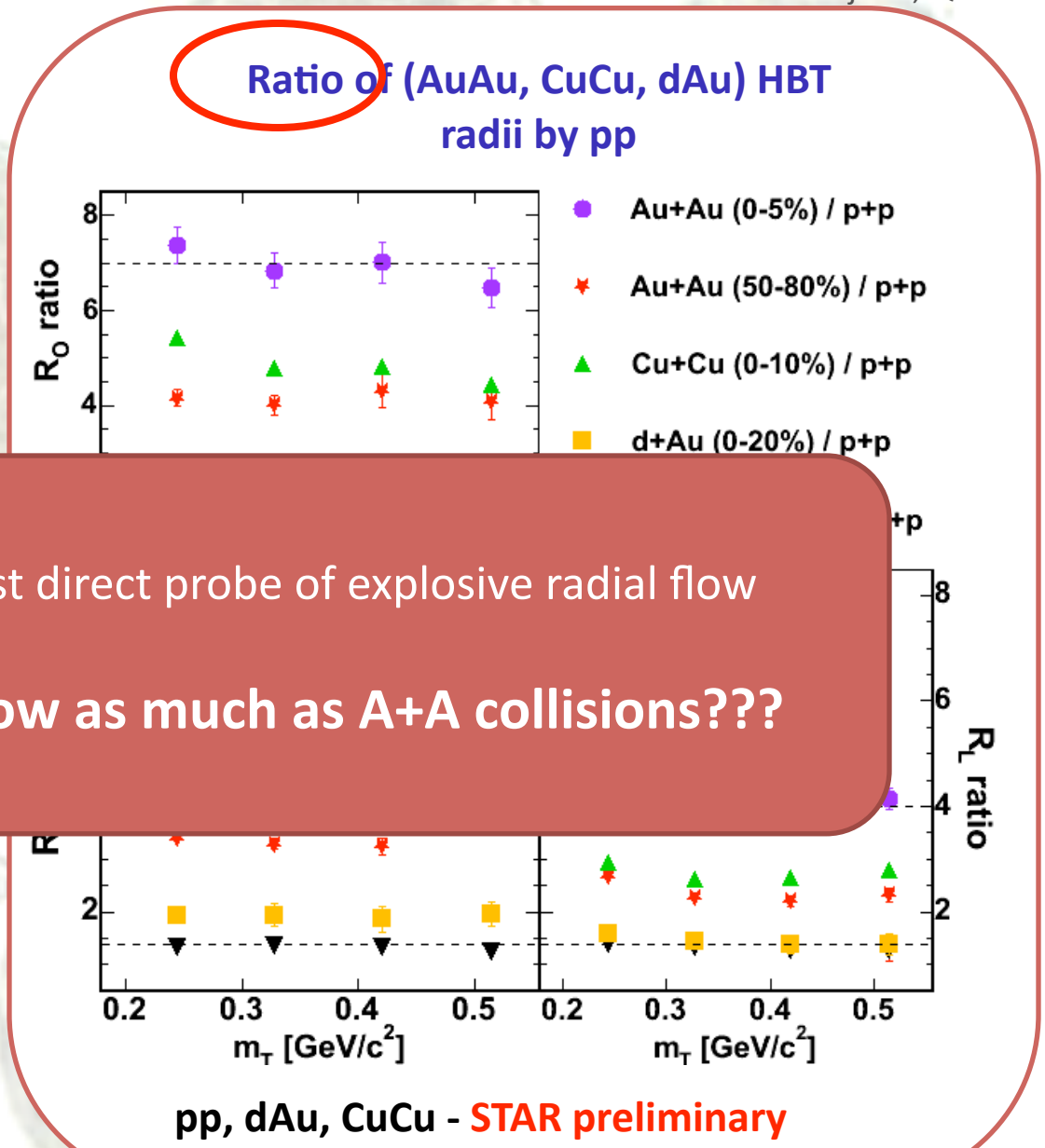


Femtoscopy is the most direct probe of explosive radial flow

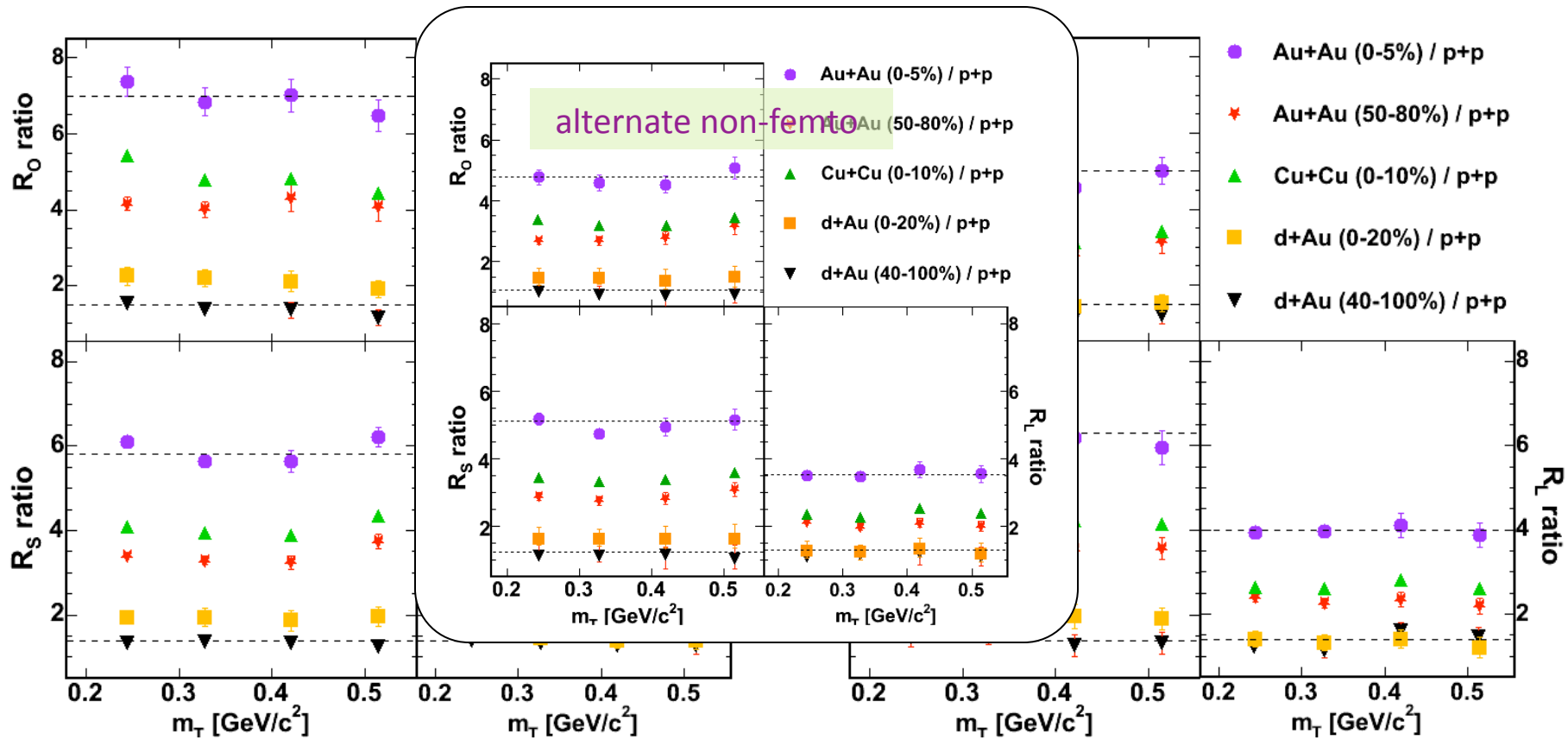
Do p+p collisions flow as much as A+A collisions???

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

STAR preliminary

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

radii by pp

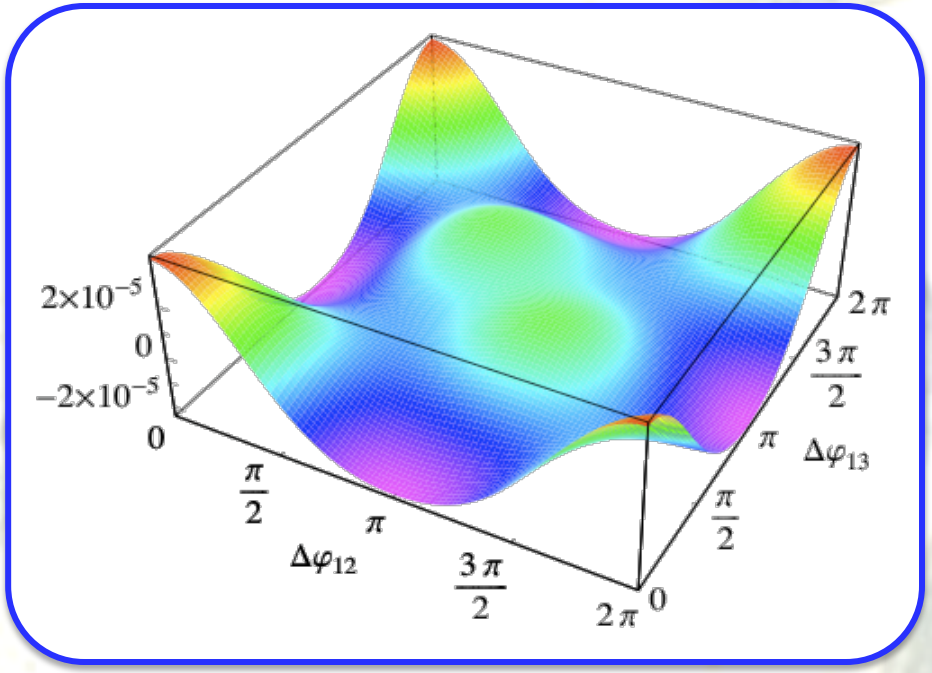


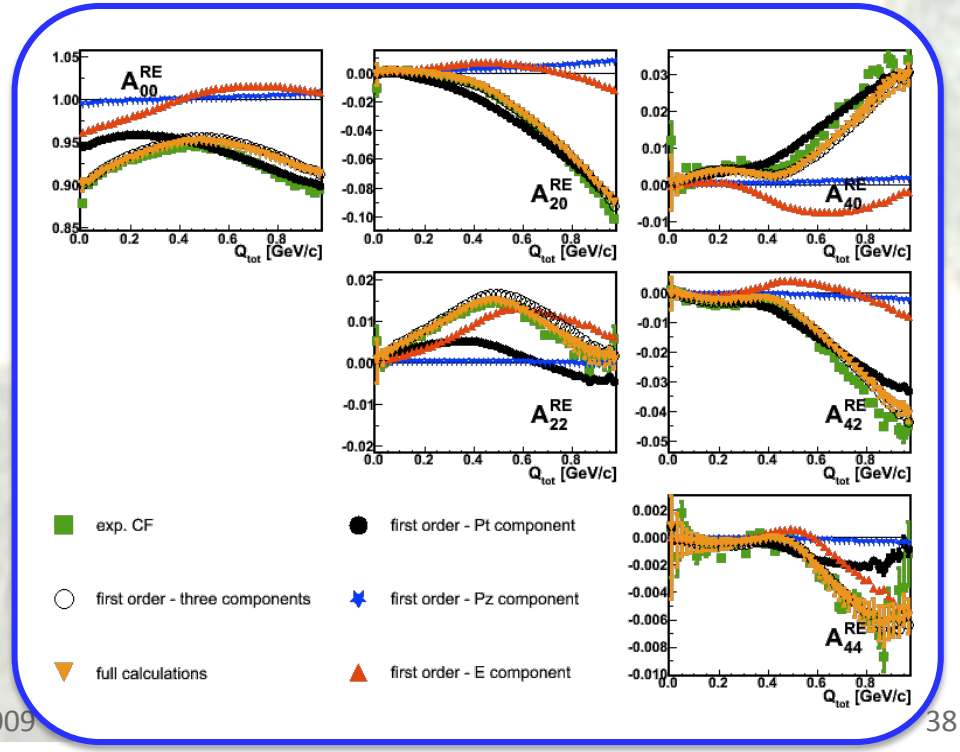
Fit w/o baseline parameterization

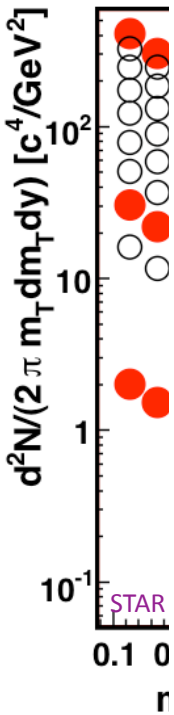
NEW fit w/ baseline parameterization

EMCIC effects for k =…

- **k=3 – conical flow?**
  - Borghini, PRC75:021904 (2007)
  - *EMCICs alone can mimic "conical emission"*
- **k=2 – directed flow**
  - Danielewicz, PLBB157:146 (1985)
  - Borghini et al, PRC66:014901,2002.
  - Borghini et al PRC62:034902,2000.
  - *"[EMCICs] alone large enough to reverse the sign of the proton directed flow measured by NA49"*
- **k=2 – femtoscopy**
  - Z. Chajęcki & MAL PRC **78** 064903 (2008)
  - *EMCIC effects of similar magnitude as femto correlations*







NO…..?

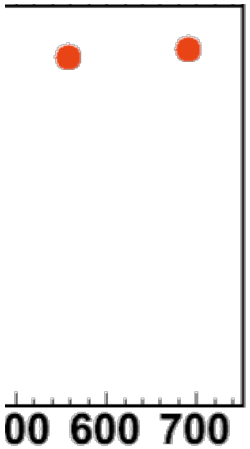
Au+Au 0-5%

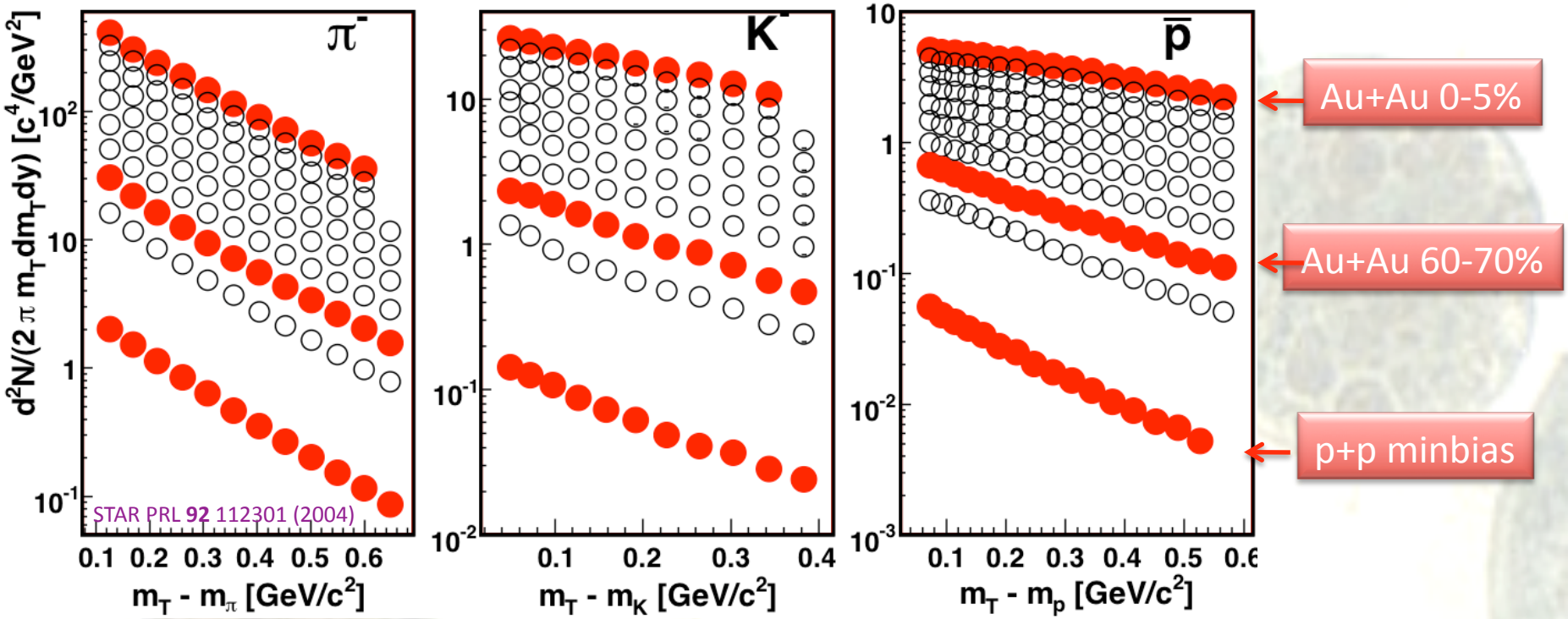
Au+Au 60-70%

p+p minbias

Blast-wave

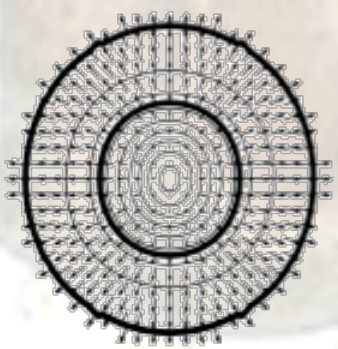
- much les

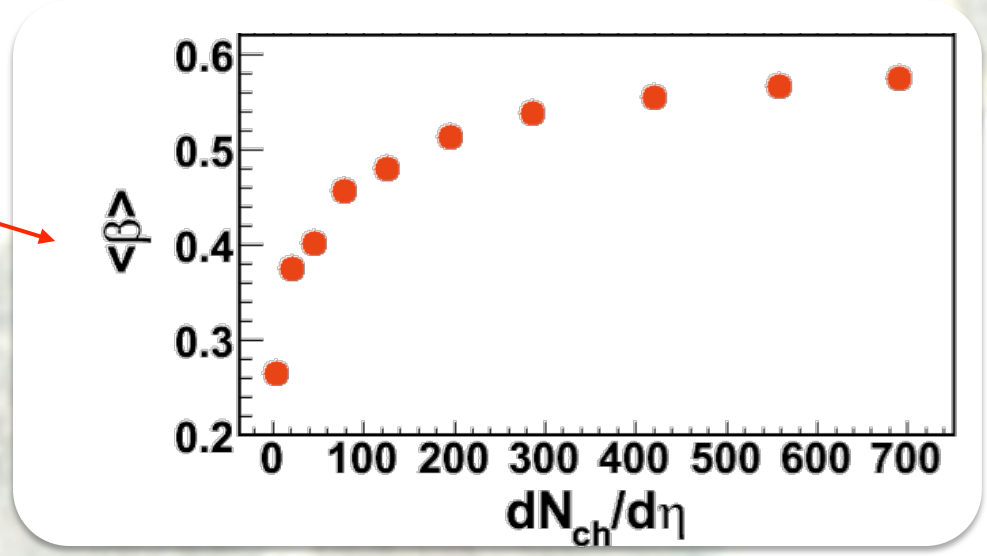




Blast-wave fit to spectra:

- much less explosive flow in p+p collisions





Don't forget - *EMCICs even for k=1*

measured

$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\underbrace{\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)}_{\text{"distortion" of single-particle spectra}}$$

"matrix element"

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

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

EMCICs even for k=1

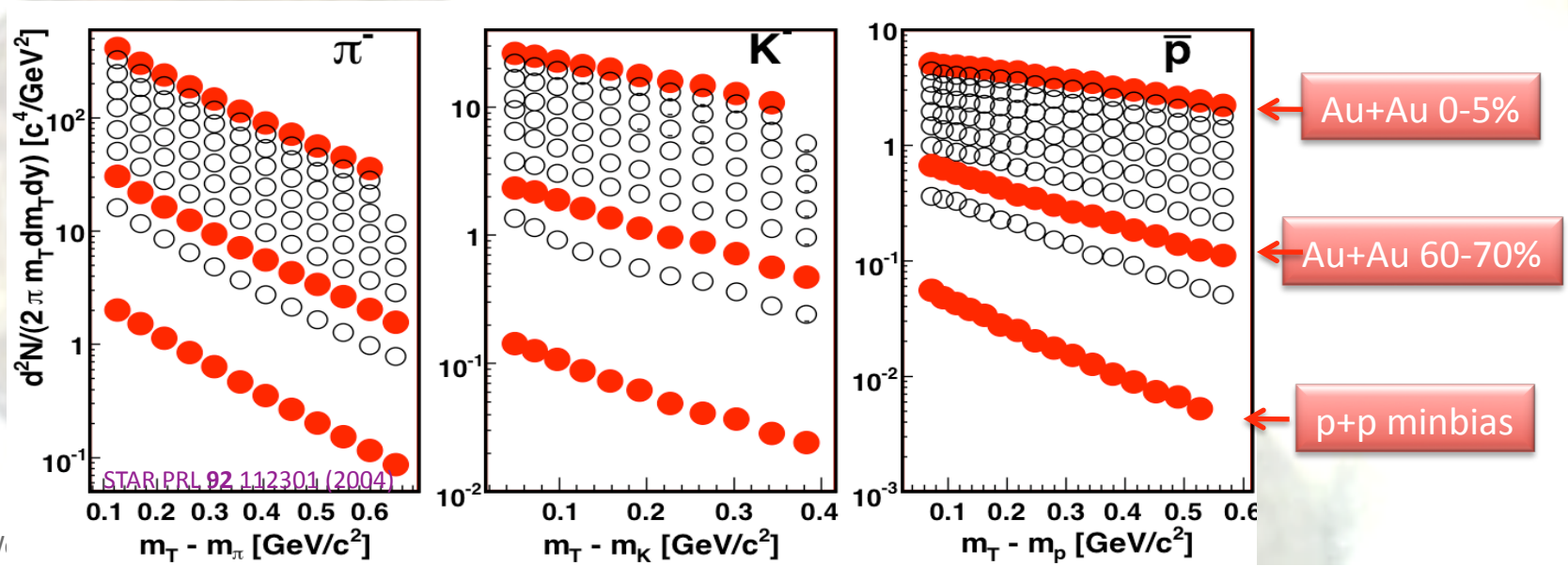
measured

$$\tilde{f}_c(p_i) = \tilde{f}(p_i)\underbrace{\left(\frac{N}{N-1}\right)^2 \exp\left(-\frac{1}{2(N-1)}\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{p_{z,i}^2}{\langle p_z^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)}_{\text{“distortion” of single-particle spectra}}$$

“matrix element”

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

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



EMCICs even for k=1

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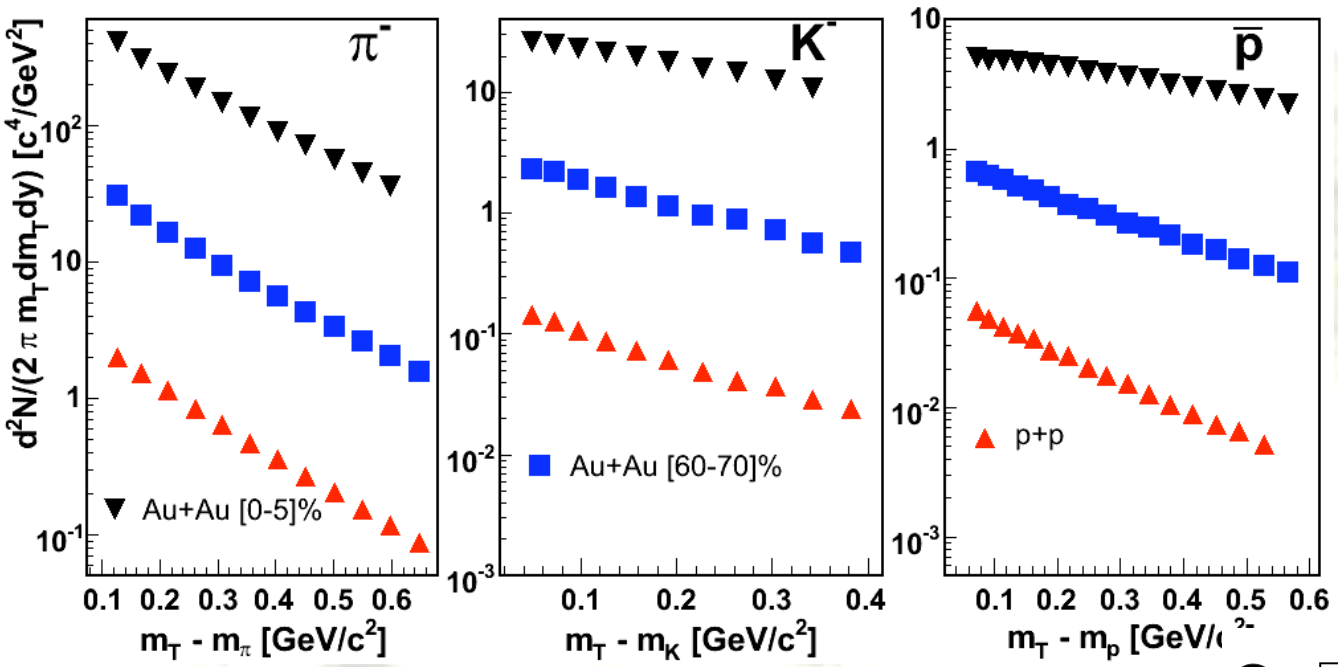
What if the only difference between p+p and A+A collisions was *N*?

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

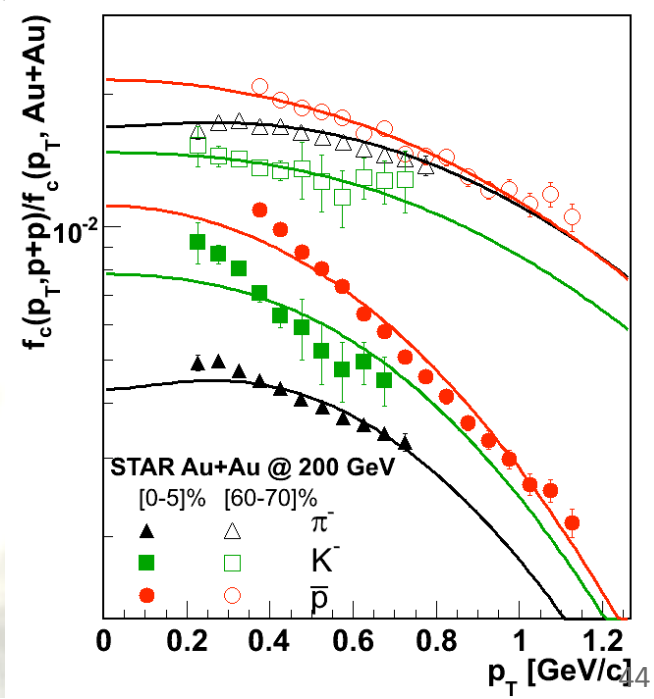
Then we would measure:

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

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



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



N evolution of spectra dominated by PS "distortion"

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

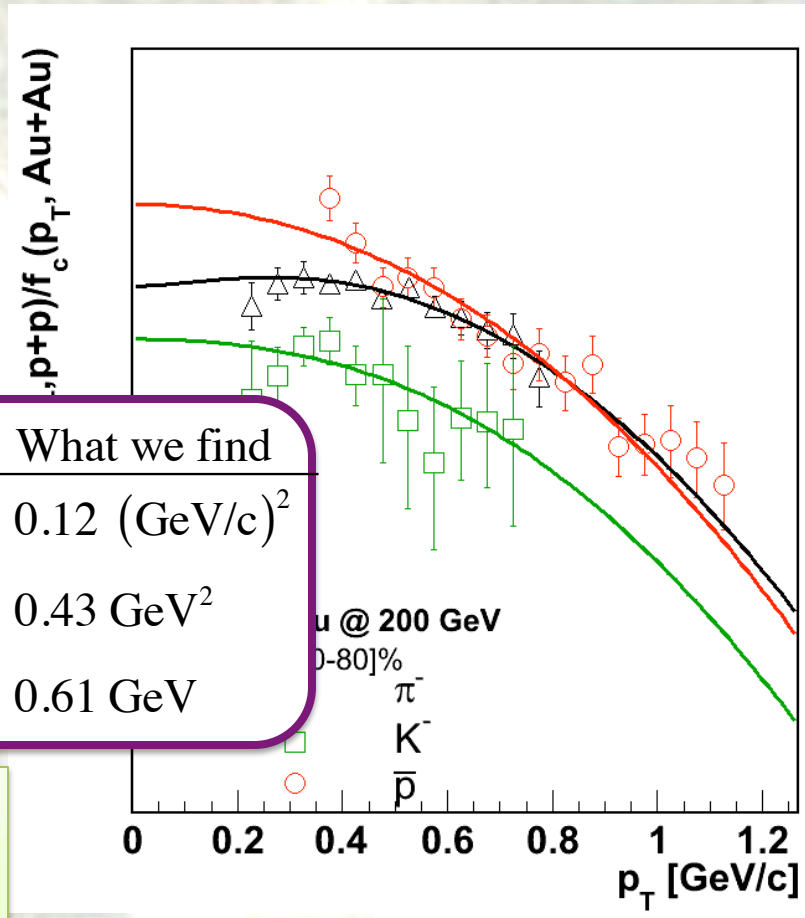
K ~ unity. driven by conservation of discrete quantum #s (strangeness, etc)

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	"	"	"

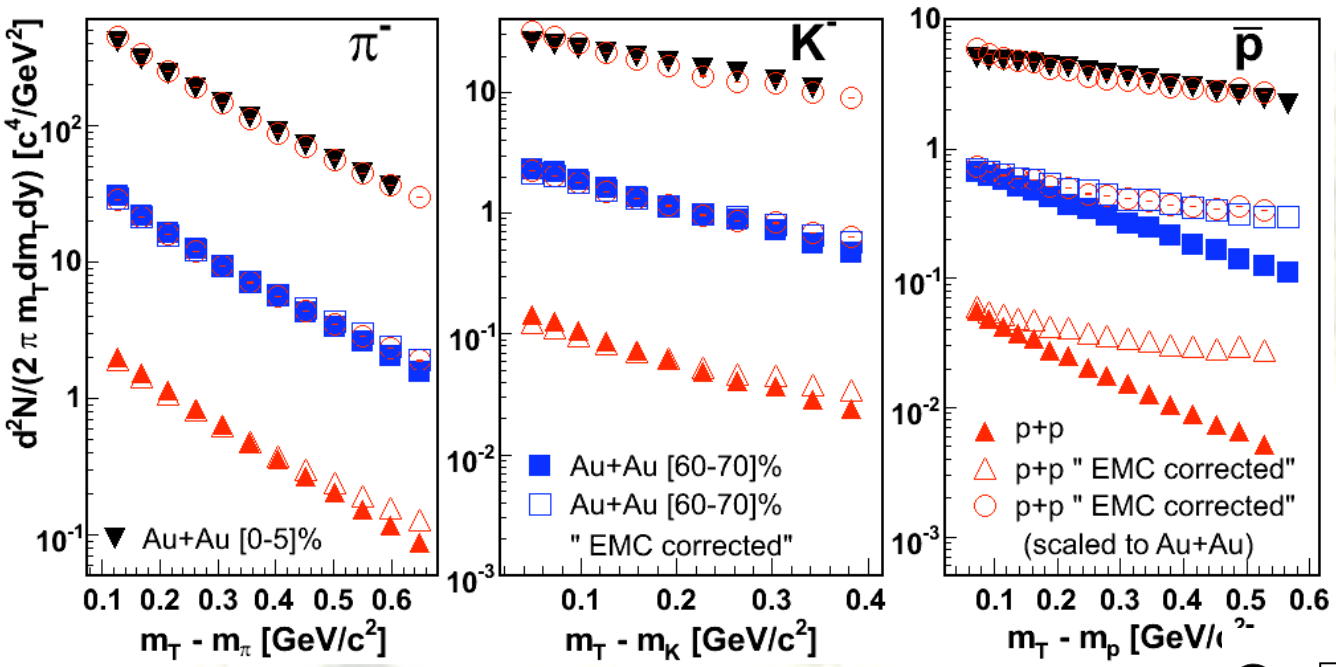
	non-rel	ultra-rel	if $T = .15 \div .35$	What we find
$\langle p_T^2 \rangle$	$2mT$	$8T^2$	$0.045 \div 0.98$ $(\mathrm{GeV/c})^2$	0.12 $(\mathrm{GeV/c})^2$
$\langle E^2 \rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5$ GeV^2	0.43 GeV^2
$\langle E \rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1$ GeV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



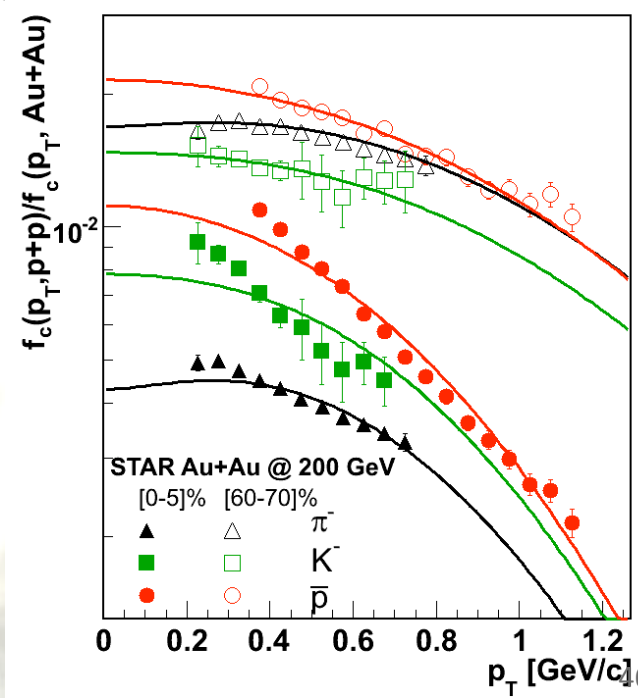
postulate of *same* parent consistent with *all* spectra

- magnitude
- pT dependence (shape)
- mass dependence

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



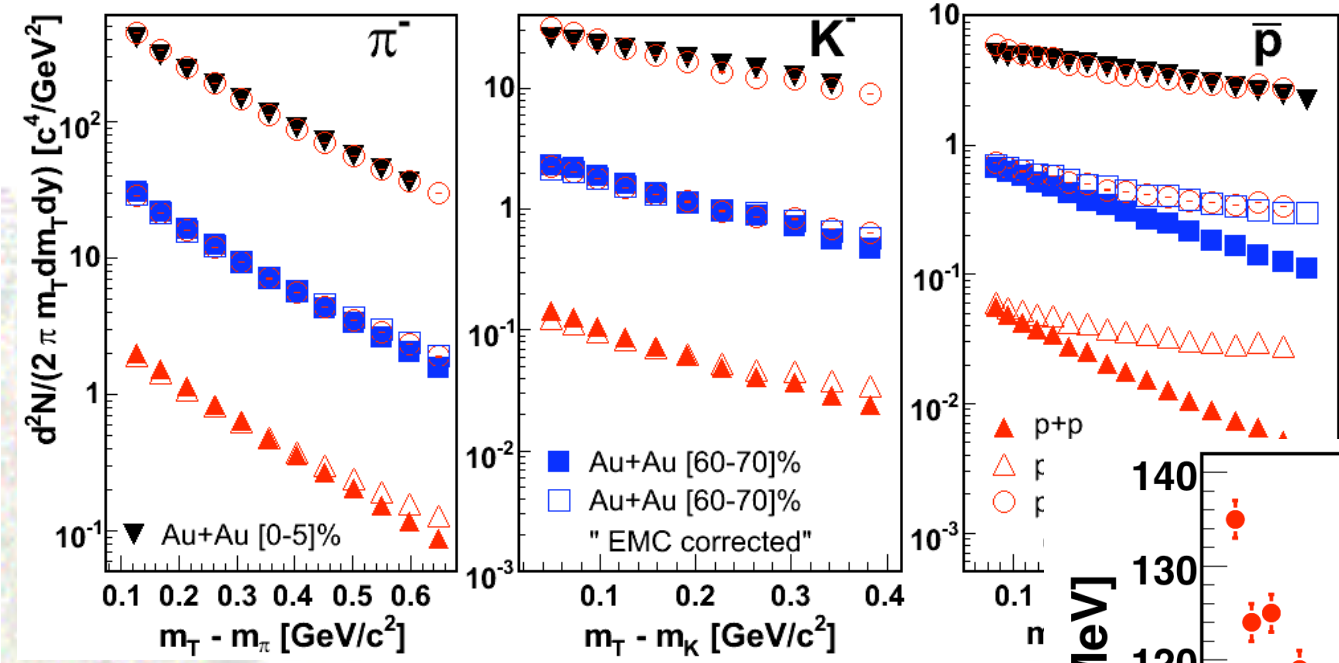
$$\frac{\tilde{f}_c^{pp}(p_{T,i})}{\tilde{f}_c^{AA}(p_{T,i})} \propto \exp\left(\left(\frac{1}{2(N_{AA}-1)} - \frac{1}{2(N_{pp}-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

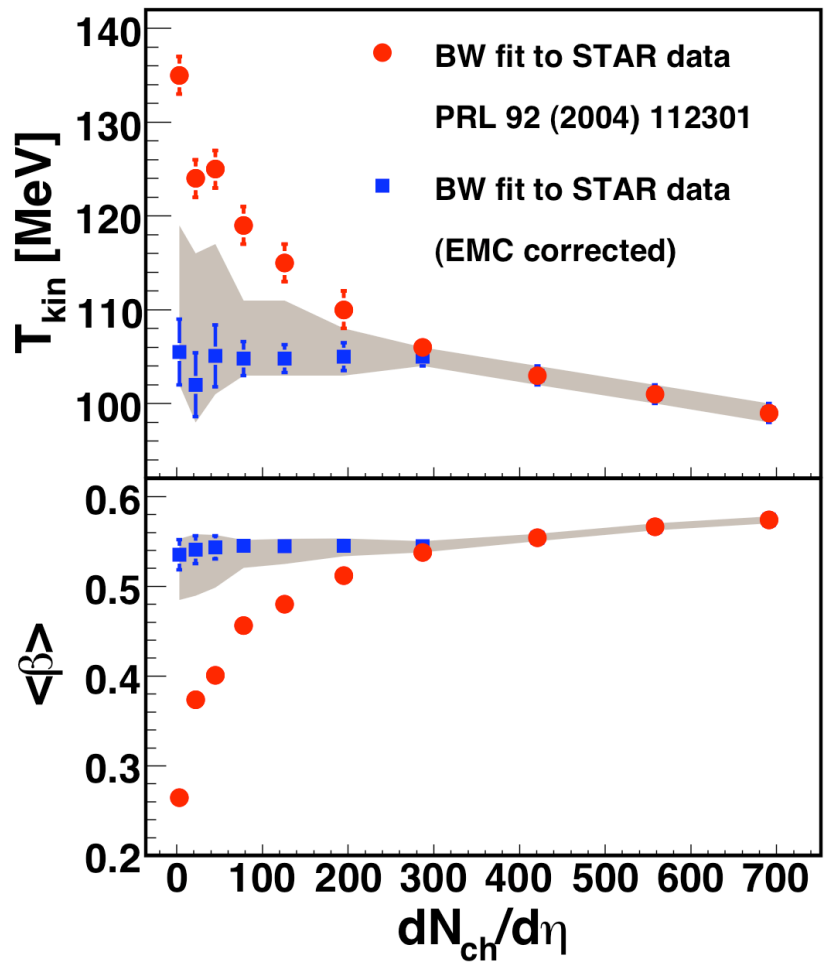


N evolution of spectra dominated by PS "distortion"

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

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





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 : simultaneous description of spectra, HBT

$T = 105.5$ MeV

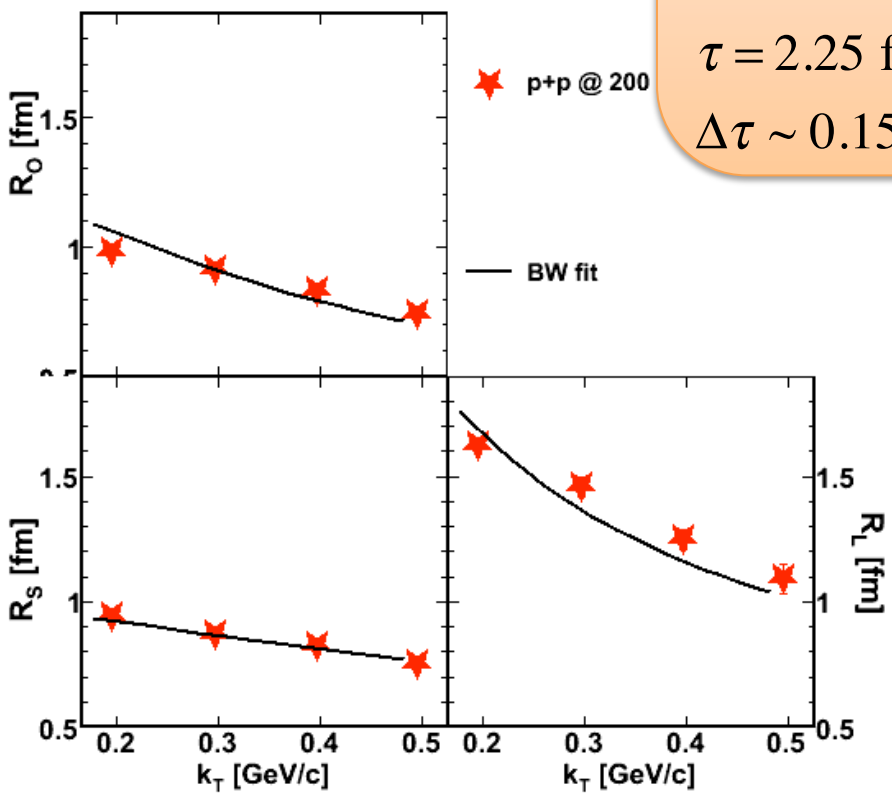
$\rho_0 = 0.934 \quad (\langle\beta\rangle = 0.535)$

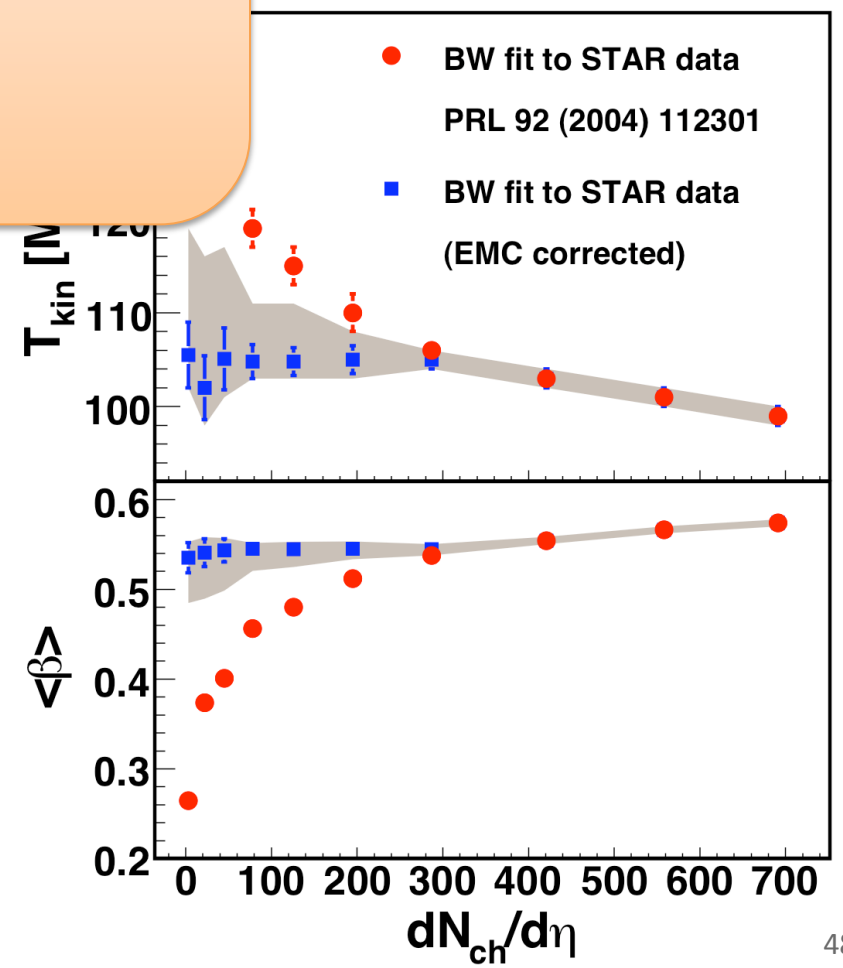
determined entirely by spectra

$R = 2.19$ fm

$\tau = 2.25$ fm/c

$\Delta\tau \sim 0.15$





Combined fit: consistent flow-based description

$$C(p_1,p_2) = a\left\{1+\lambda\cdot\left[K_{coul}(Q_{inv})\left(1+\exp\left(-R_{out}^2Q_{out}^2 - R_{side}^2Q_{side}^2 - R_{long}^2Q_{long}^2\right)\right)-1\right]\right\}$$

STAR Preliminary

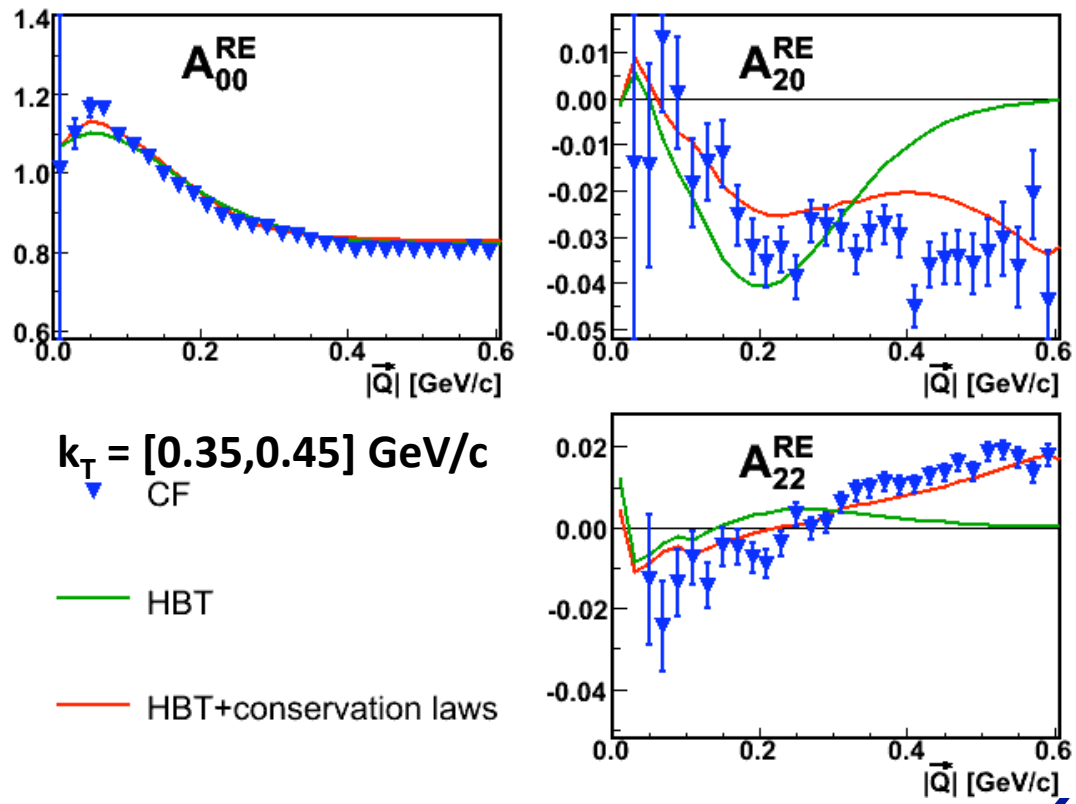
$N = \mathbf{14}$

$\langle p_T^2 \rangle = \mathbf{0.17}\ (GeV/c)^2$

$\langle p_z^2 \rangle = \mathbf{0.32}\ (GeV/c)^2$

$\langle E \rangle = \mathbf{0.68}\ GeV$

$\langle E^2 \rangle = \mathbf{0.50}\ GeV^2$



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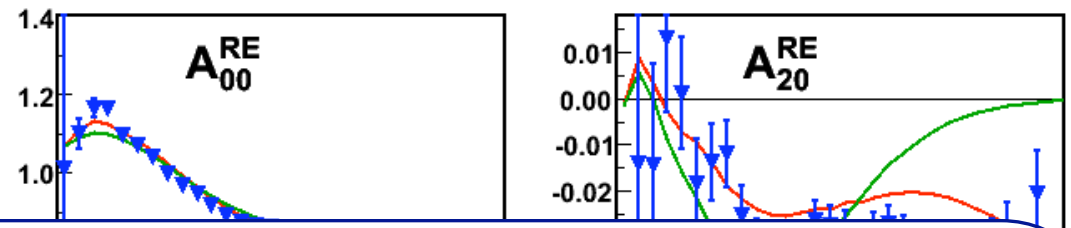

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$\langle E^2 \rangle = 0.50\ GeV^2$

Use parameters obtained from the fit to STAR femtoscopic correlation function and use them to "correct" spectra

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

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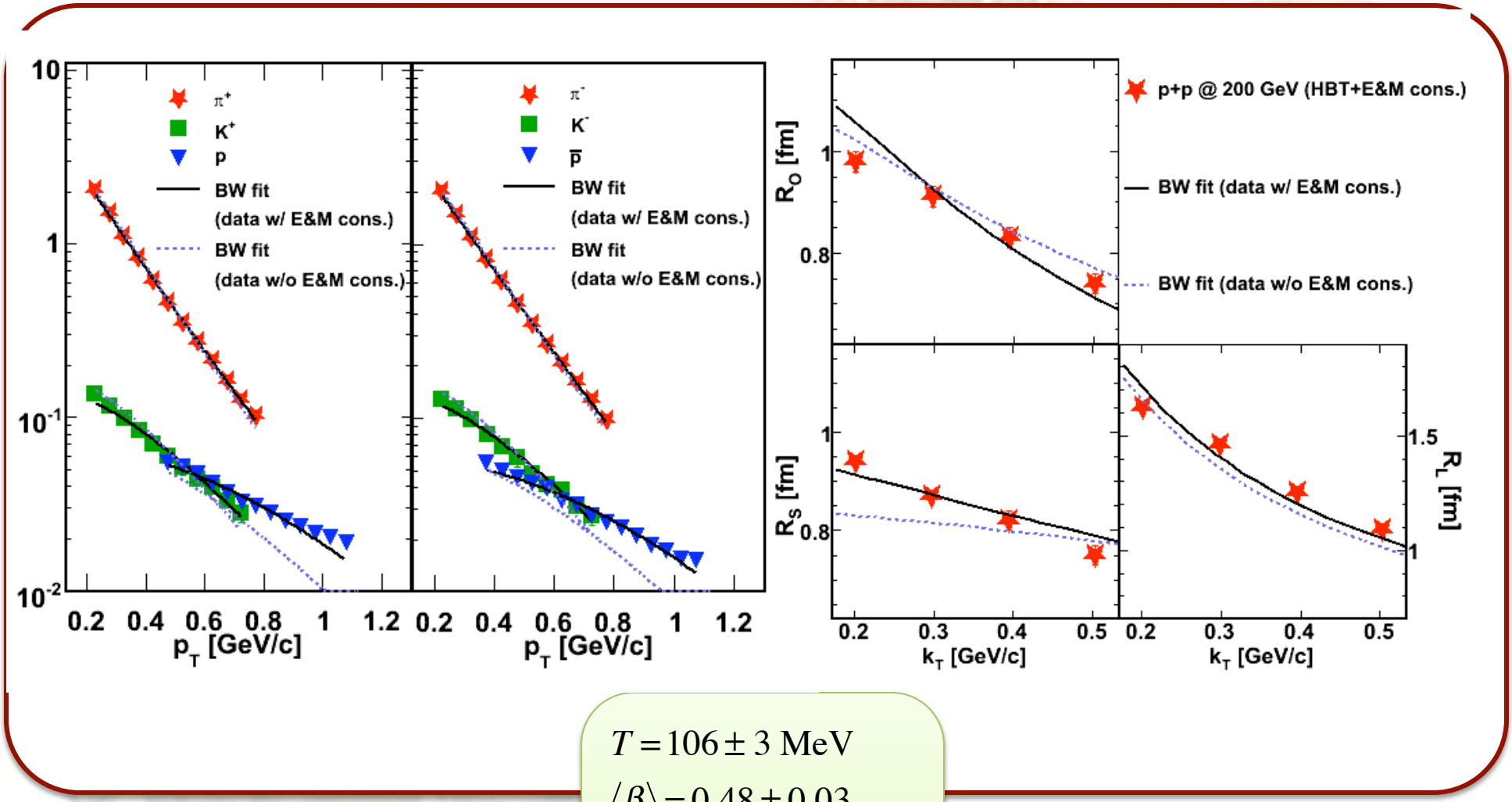

$$T = 106 \pm 3 \text{ MeV}$$
$$\langle \beta \rangle = 0.48 \pm 0.03$$
$$R = 2.09 \pm 0.04 \text{ fm}$$
$$\tau_0 = 2.25 \pm 0.05 \text{ fm/c}$$
$$\Delta\tau = 0.1 \pm 0.2 \text{ fm/c}$$

Blast-Wave Model:

F. Retiere, M. Lisa, PRC70:044907,2004.

Combined fit: consistent flow-based description

"raw" (ignoring EMCICs)

EMCICs **fixed by correlations**
Joint spectra/HBT BW fit

EMCICs **free adjusted**
to spectra & fit to spectra

EMCICs **fixed by correlations**
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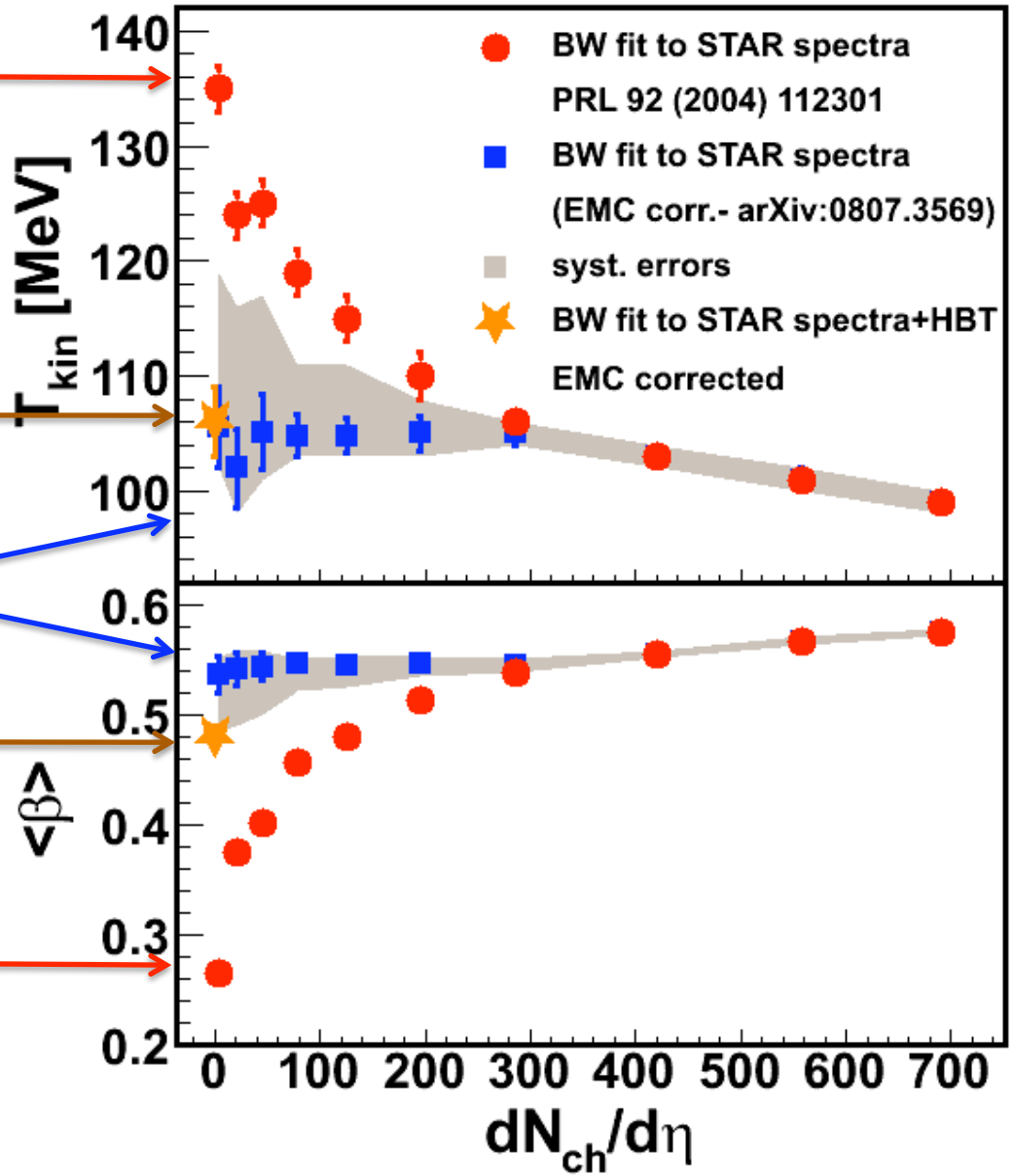
"raw" (ignoring EMCICs)



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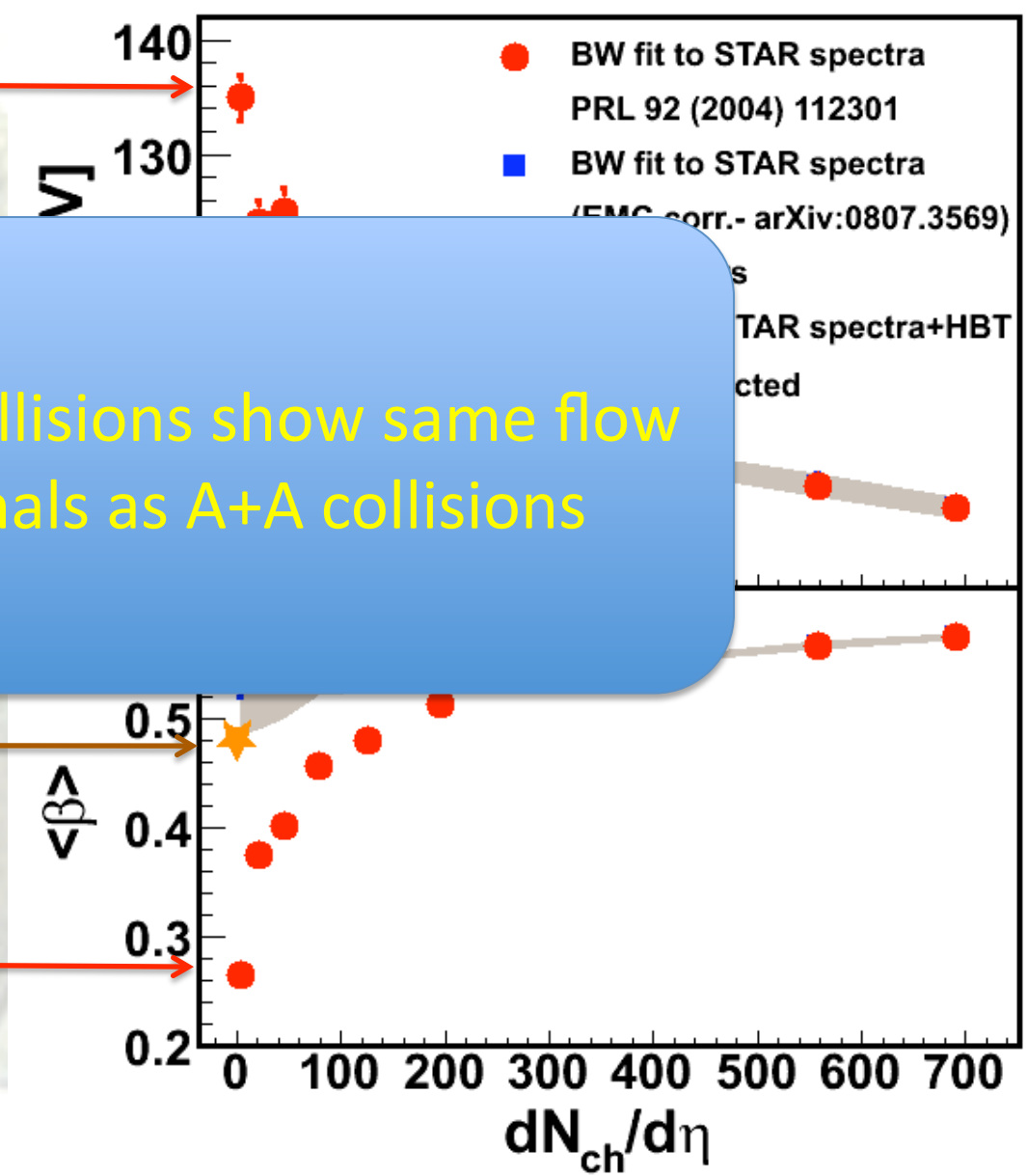
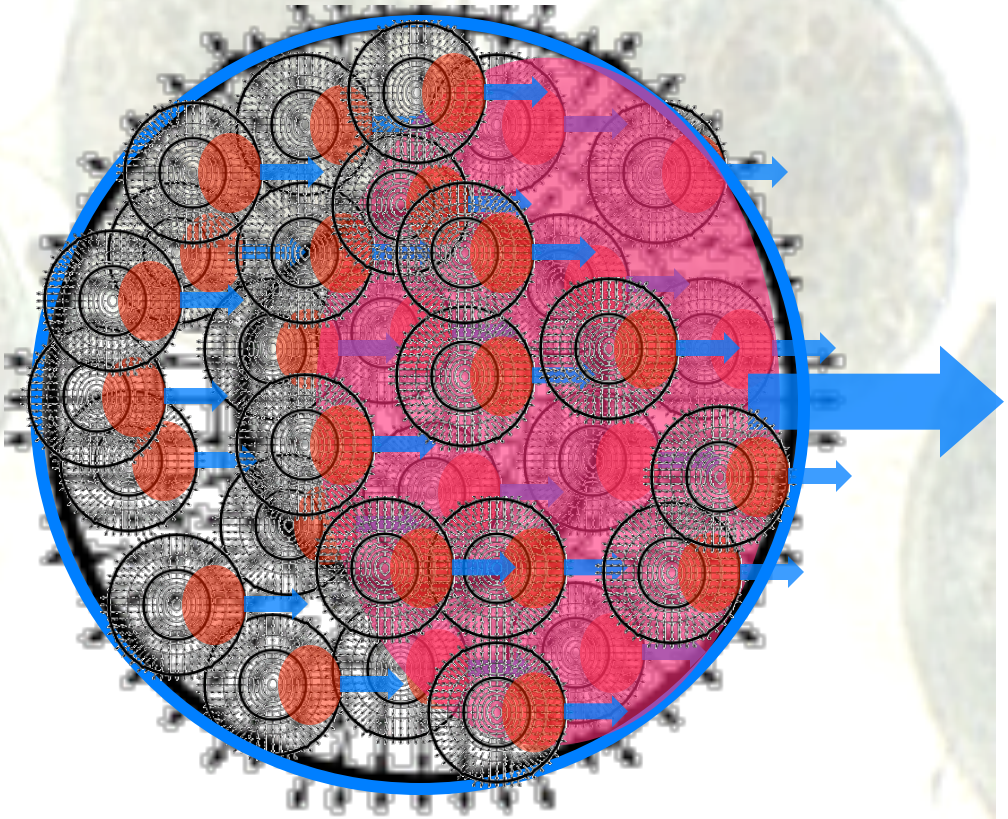


p+p collisions show same flow signals as A+A collisions

Implication: 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 BlastWaves
    - 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"

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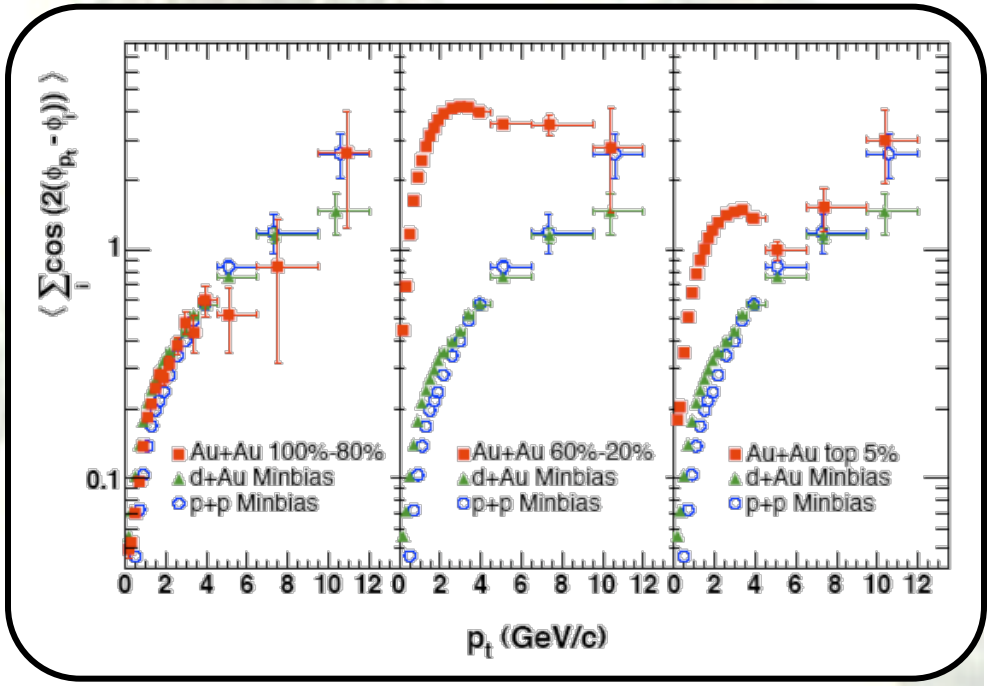
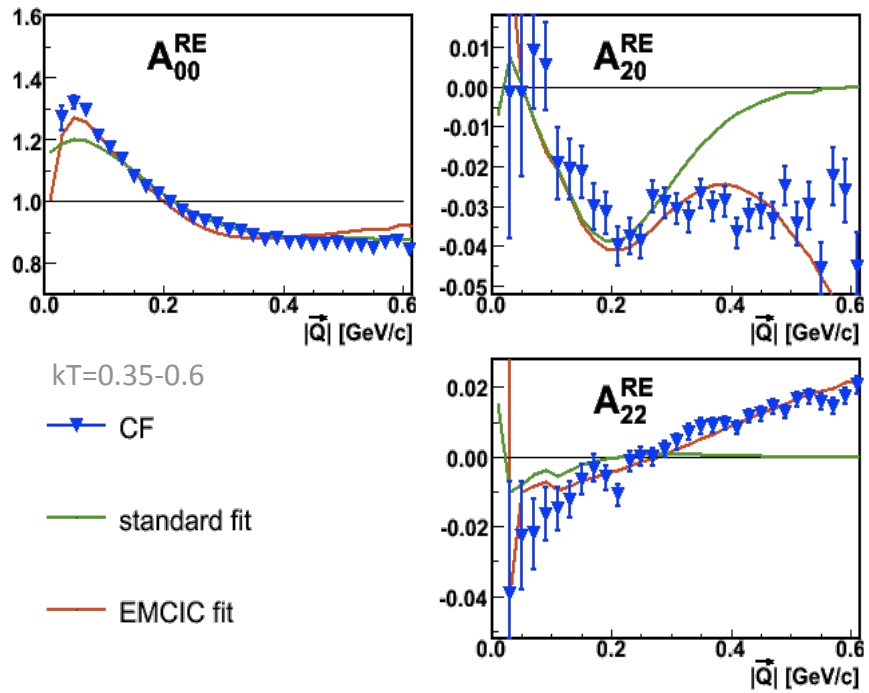


anisotropic flow

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

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")



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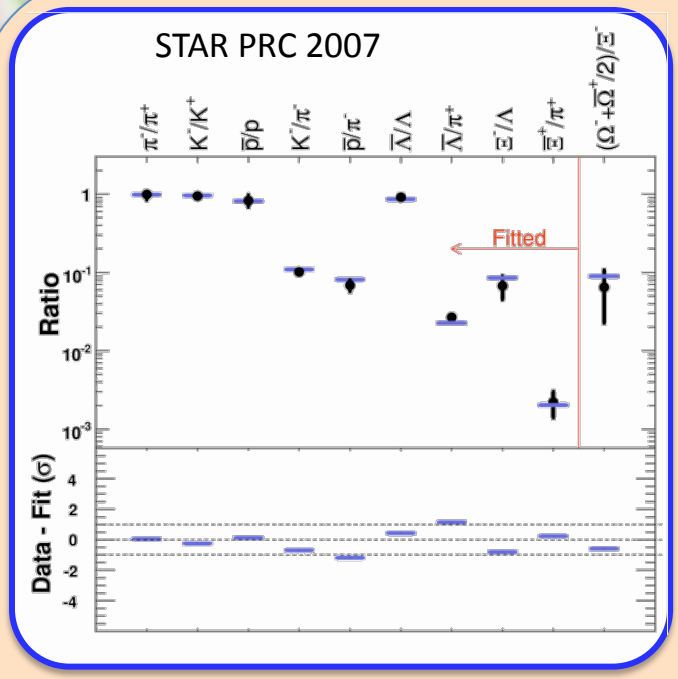
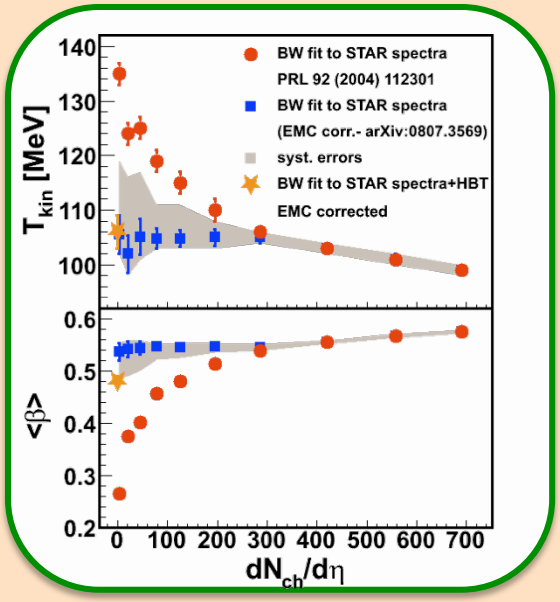
  - …*and* single-particle spectra (often neglected because no "red flags")

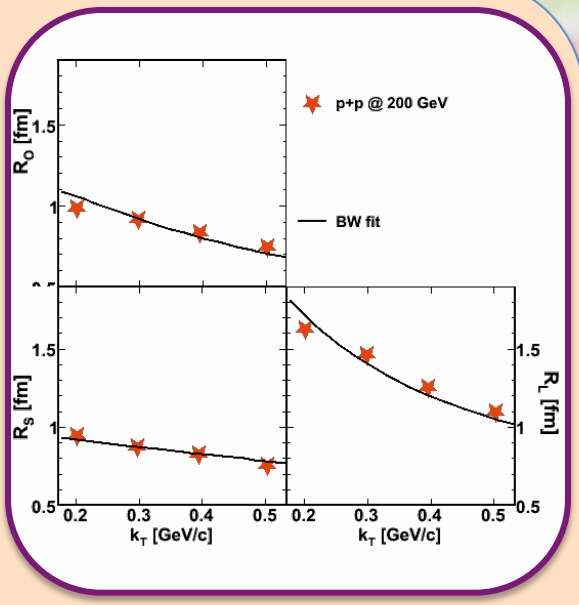
- Femtoscopy & Spectra
  - in H.I.C., well understood, detailed fingerprint of flow
  - RHIC – first opportunity for direct comparison with p+p
  - accounting for EMCICs, identical flow signals in p+p

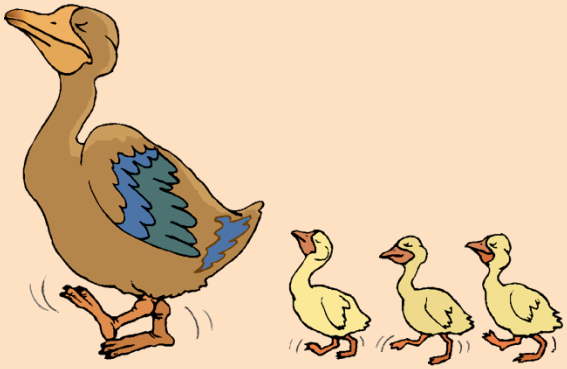
- is pp/AA physics very similar, or are measurements insensitive to diff physics?
- **Has AA become the reference system for pp in non-perturbative sector???**
- Thermalization, hadronization, very early color dynamics…

Summary









"It is a capital mistake to theorize before one has data."
– Sir Arthur Conan Doyle *[thanks to Debasish]*

"It is even worse, when one *has* data, to insist upon two orthogonal theoretical interpretations for the same systematics."
– Prof. Mike Lisa