
Mike Lisa

Correlations, spectra and conservation laws a case for collective (radial) flow in p+p collisions?

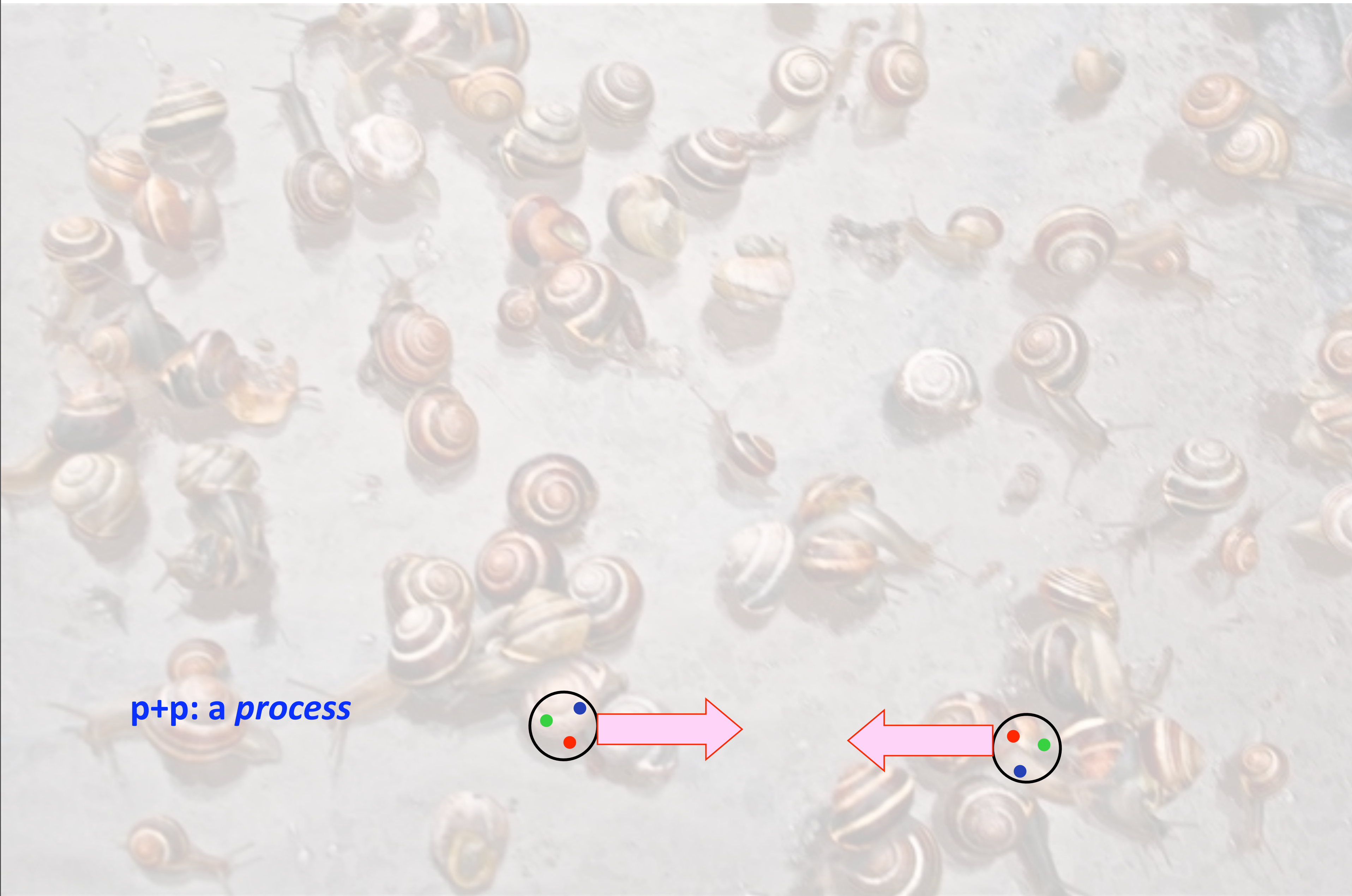
How big is big enough?

Mike Lisa
Ohio State University

Outline

- What is the importance of flow (what does it tell us)?
- What are the signals of <u>radial</u> flow at RHIC?
- 2-particle correlations in p+p collisions at RHIC
  - femtoscopic & phasespace-induced
- Single-particle spectra at RHIC. Effects of phasespace constraints
- Think similar to H.I.C.
  - flow “revealed”?
  - other similarities: yields, “proton anomoly,” <pT> vs Nch vs mass
- Panta Rhei?

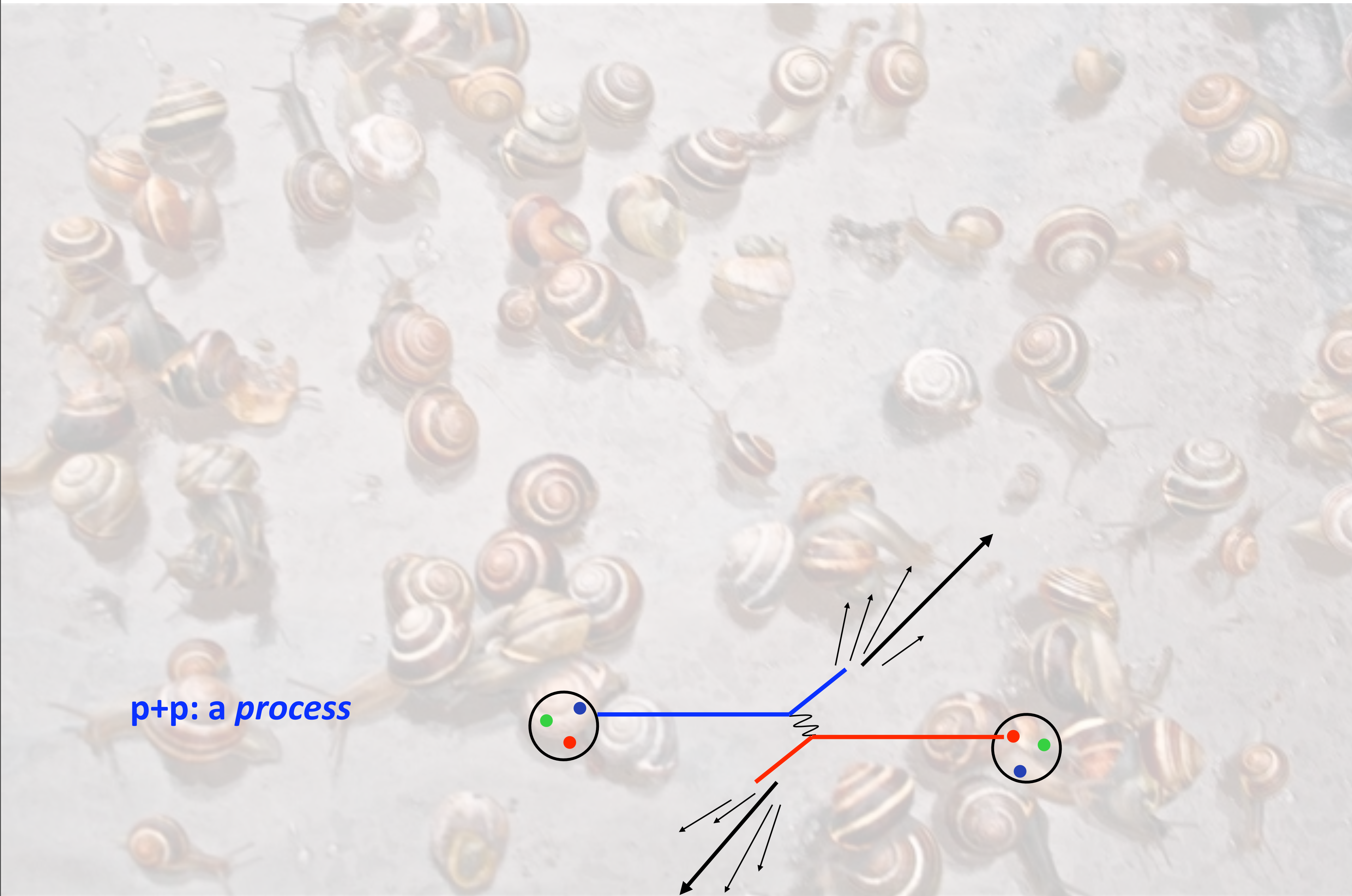
paradigms



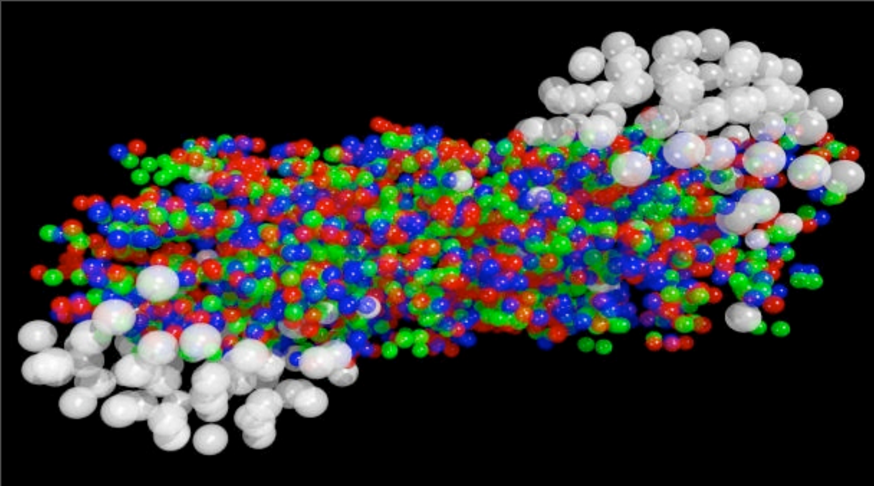
p+p: a *process*

paradigms

paradigms

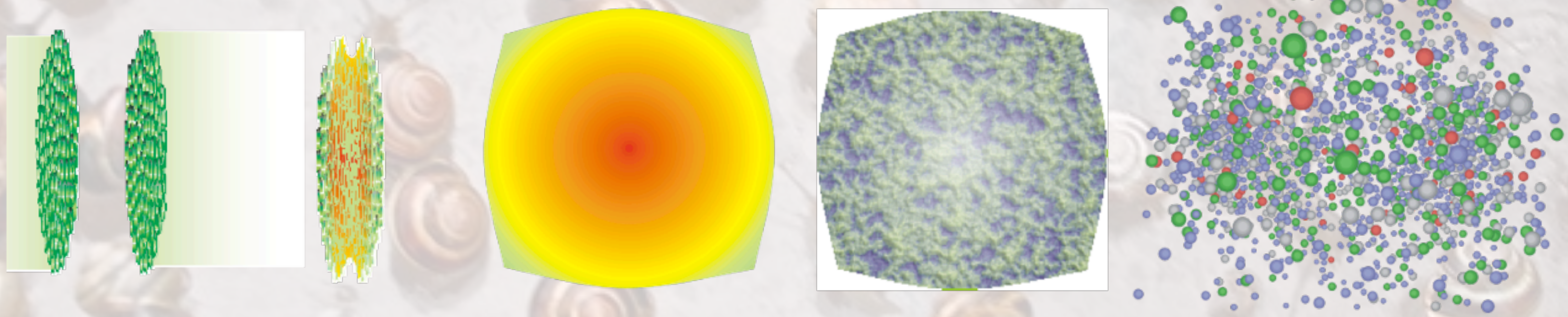


p+p: a *process*



paradigms

A+A → a *system*



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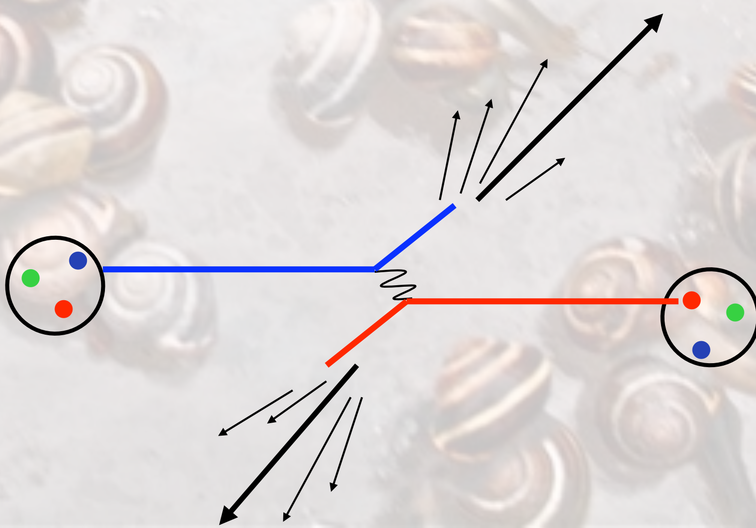
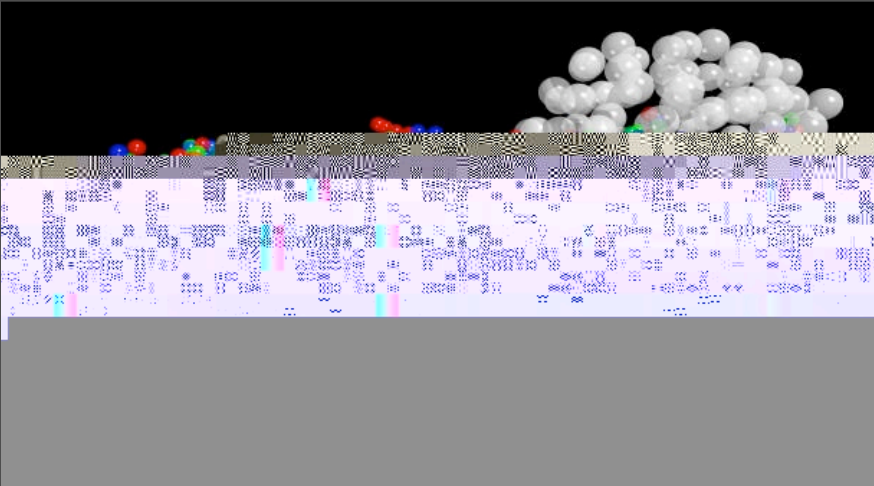


paradigms



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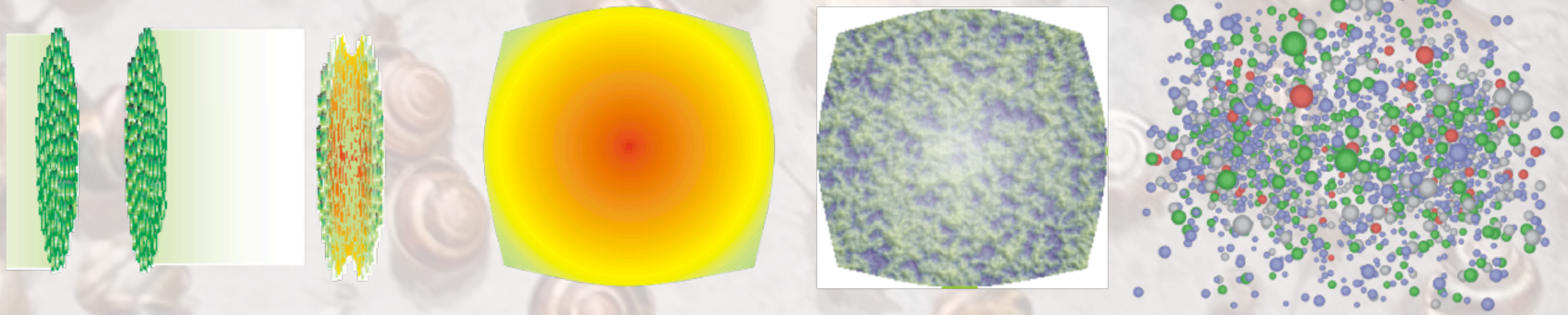
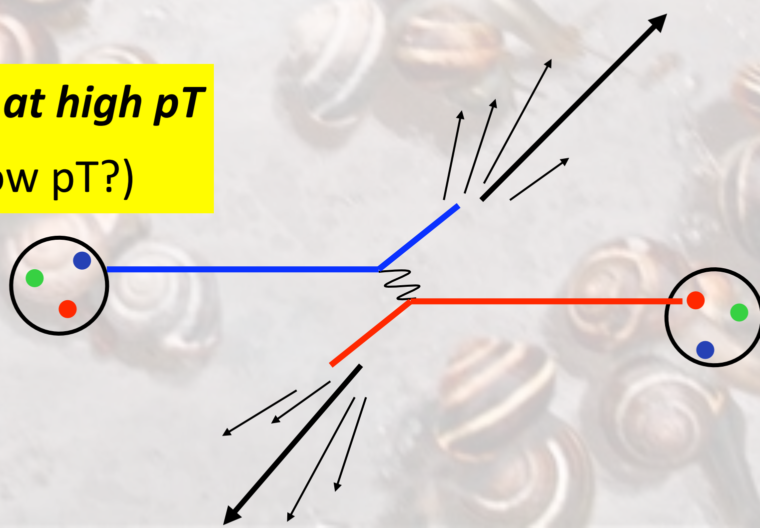
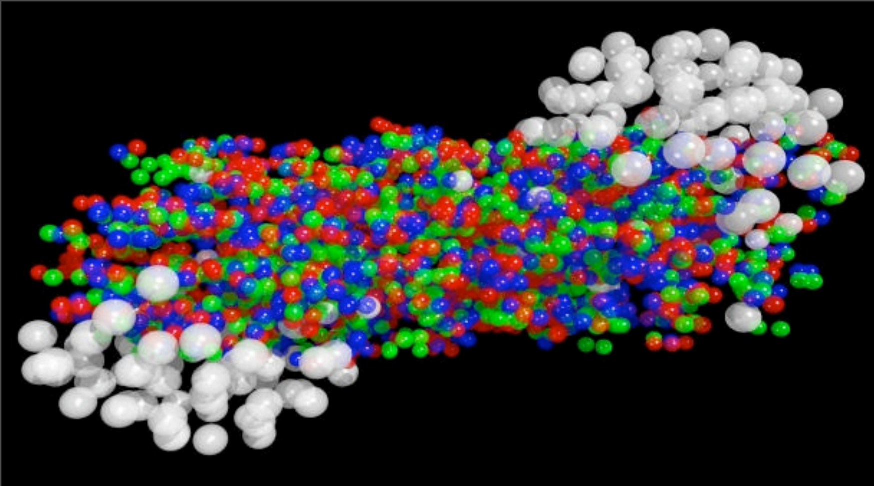


“Clean” p+p– a crucial reference ***at high pT***

(do we understand/care about low pT?)

p+p: a *process*





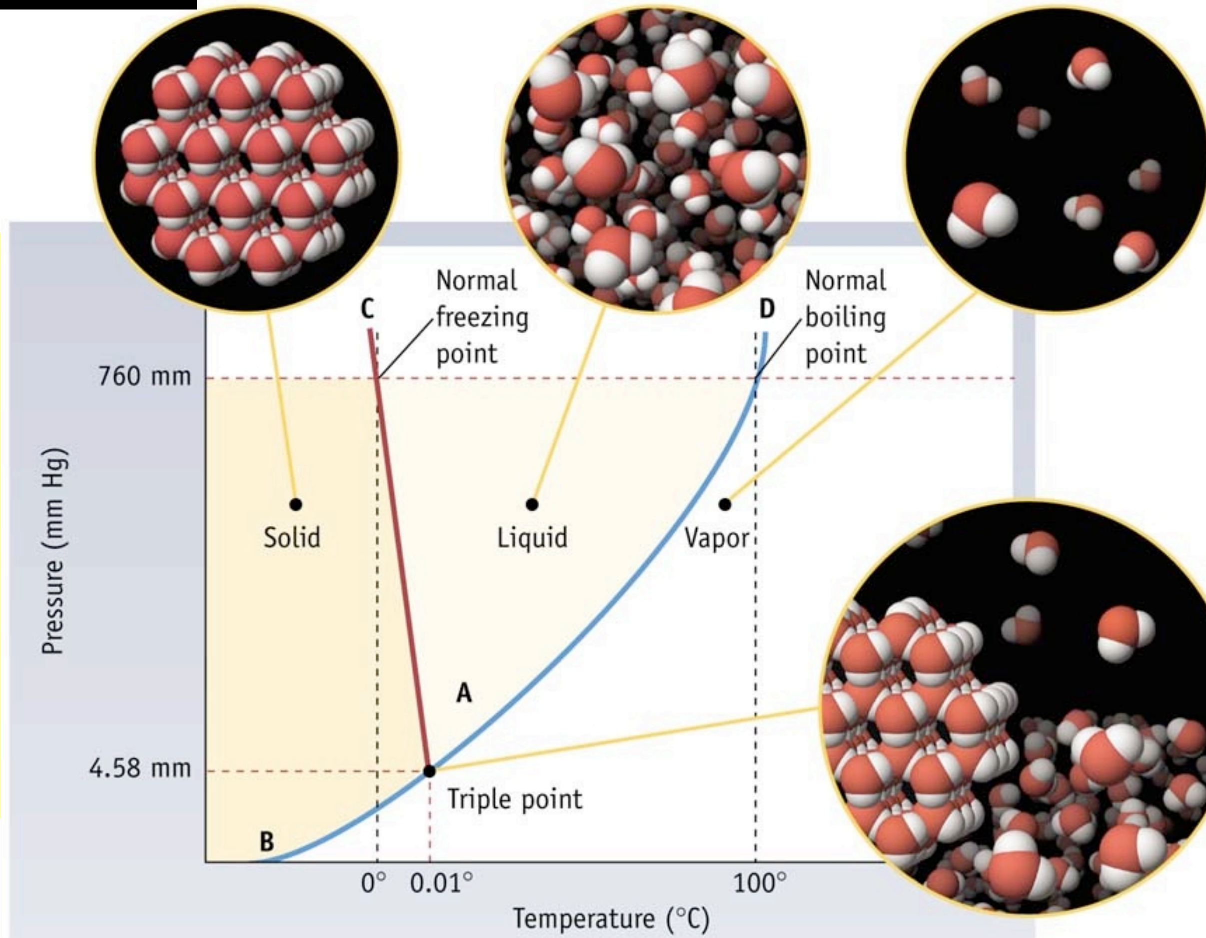
H.I.C. – a system

bulk physics

- superfluids
- superconductors
- metal/insulator
- …

Only for large *system*

- can't melt one H_20 molecule!



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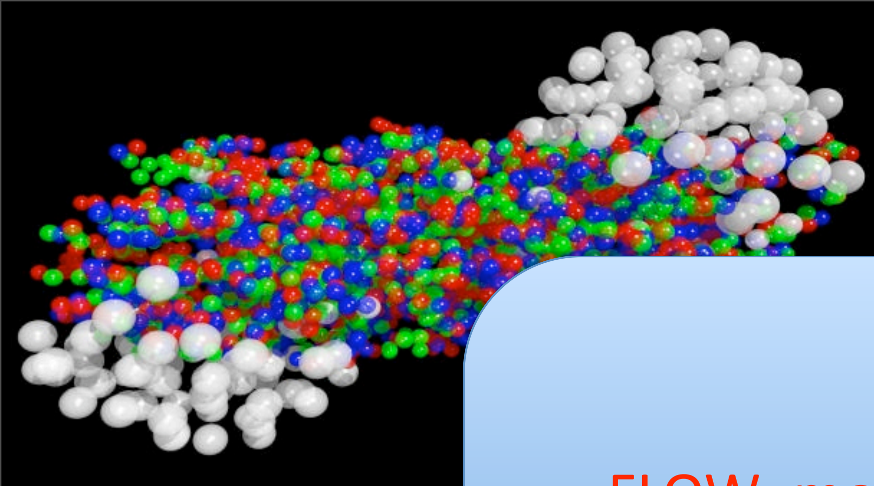
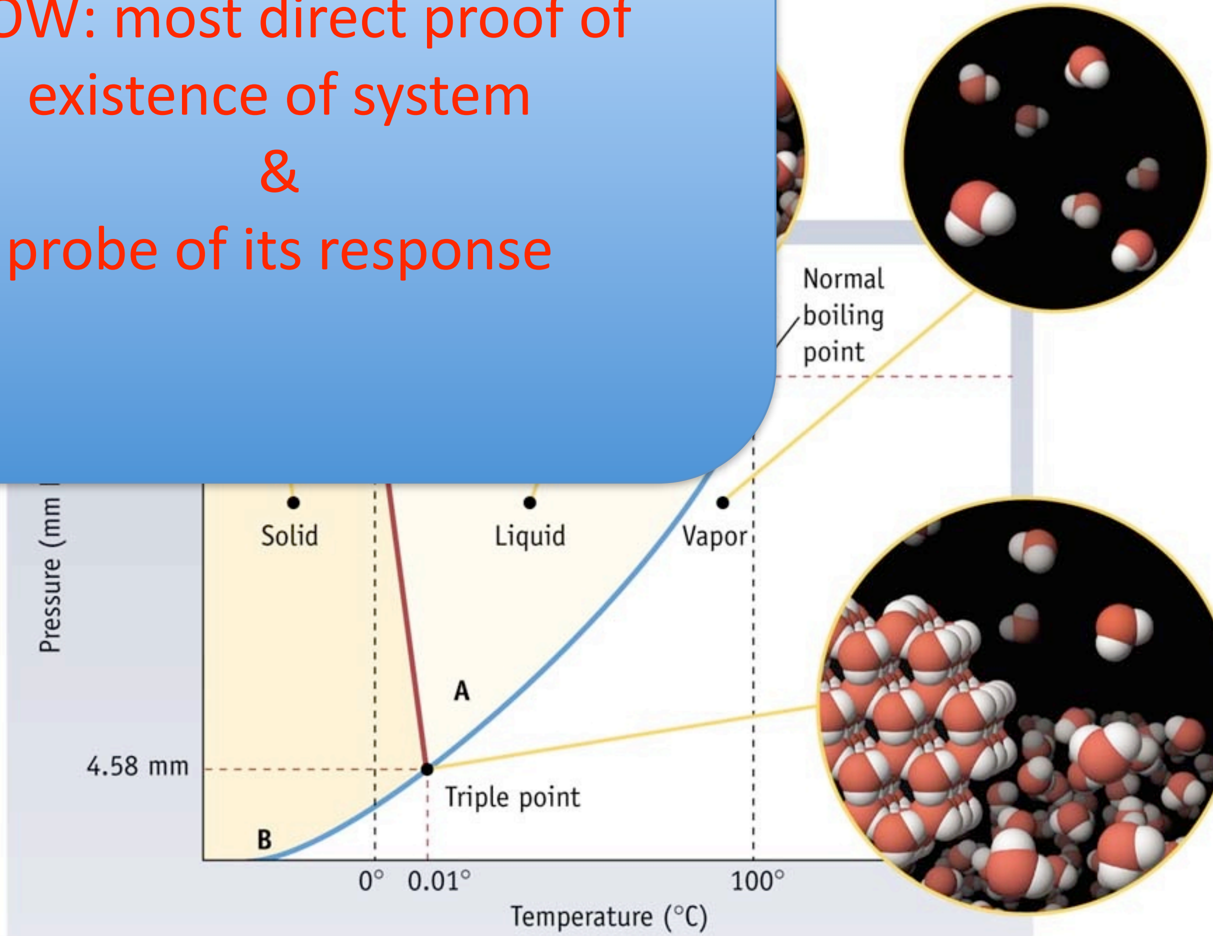
H.I.C. – a system



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

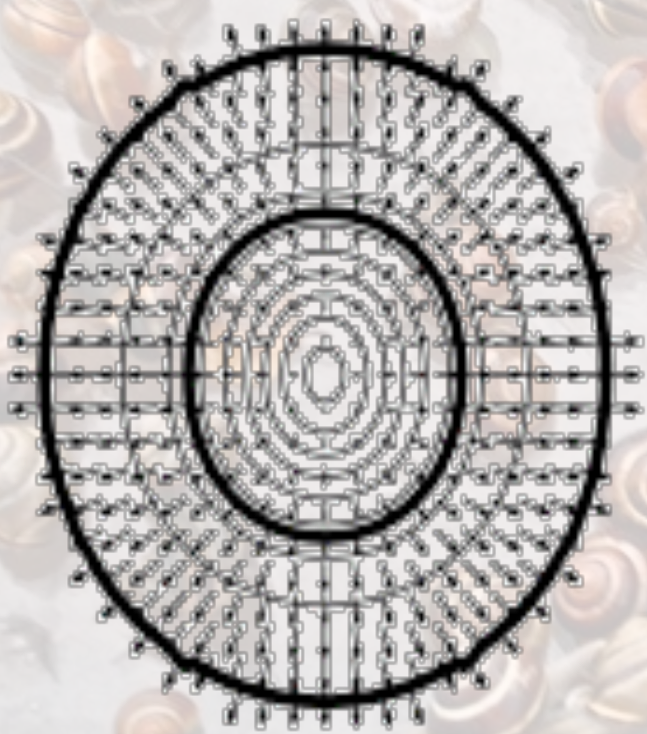
bulk physics
- superfluids
- superconductors
- metal/insulator
- …

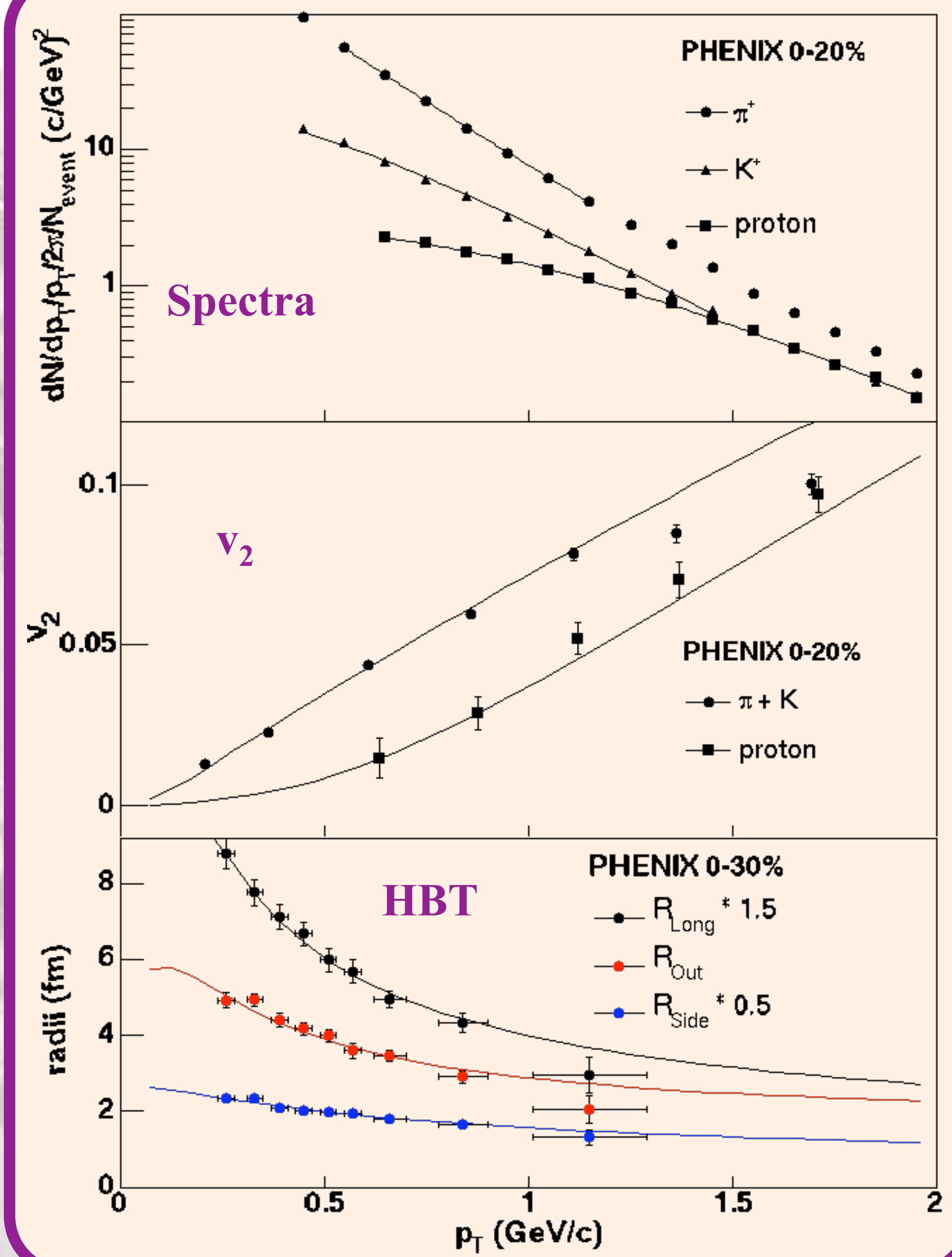
Only for large *system*
- can't melt one H_2O molecule!



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

calculable in hydrodynamics or toy "blast wave" models





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

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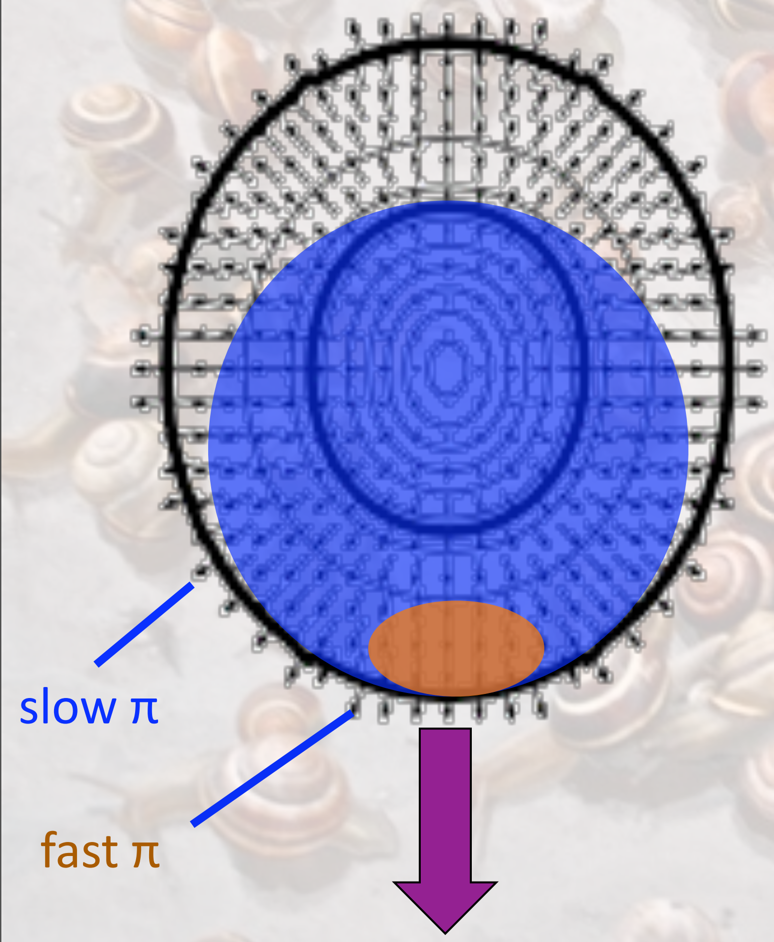

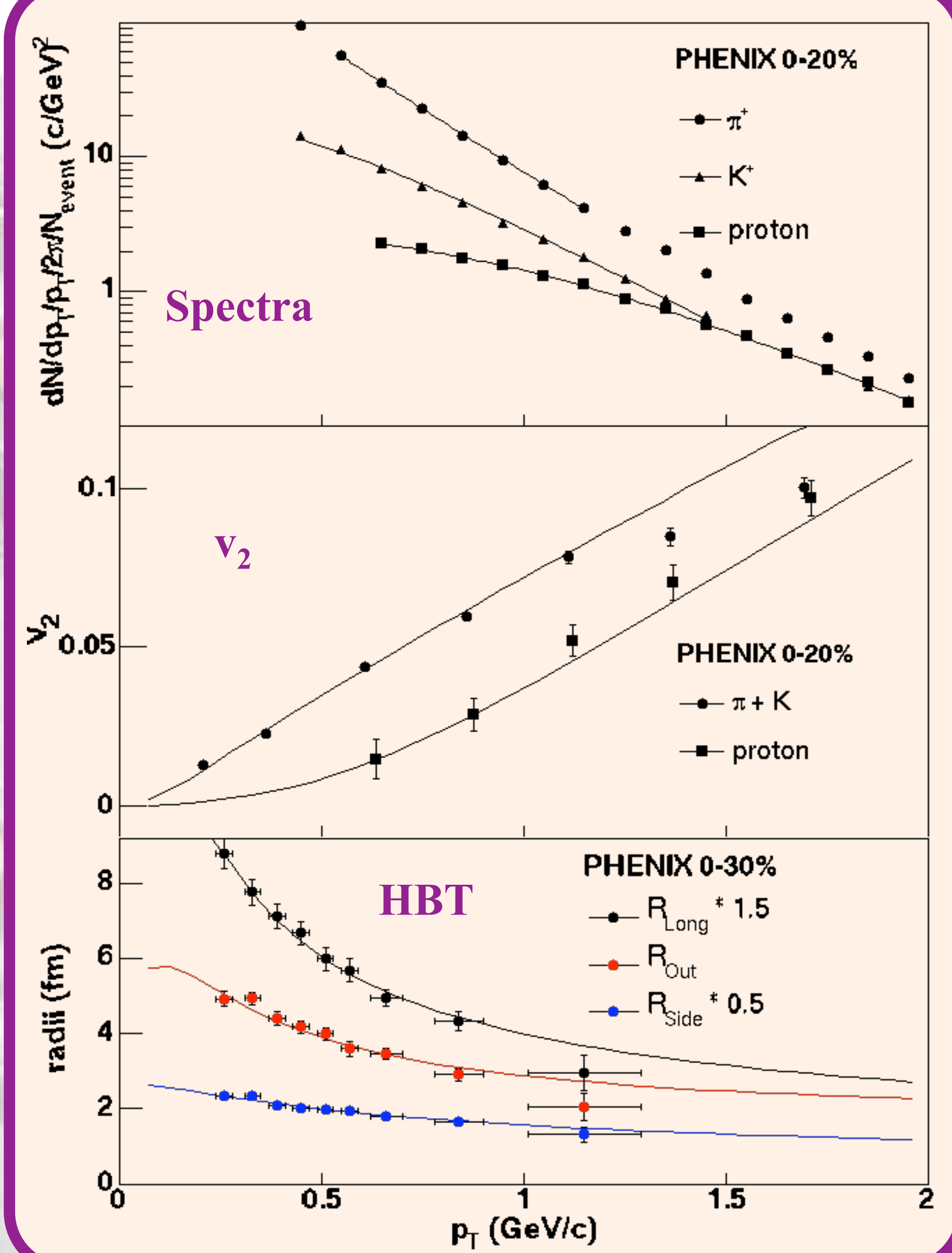

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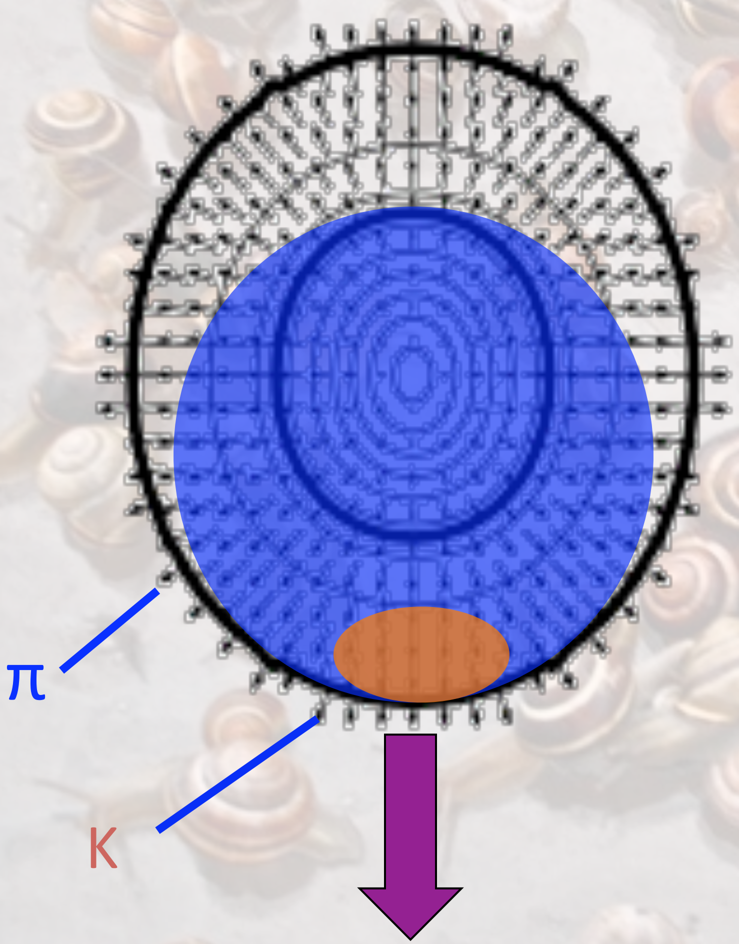

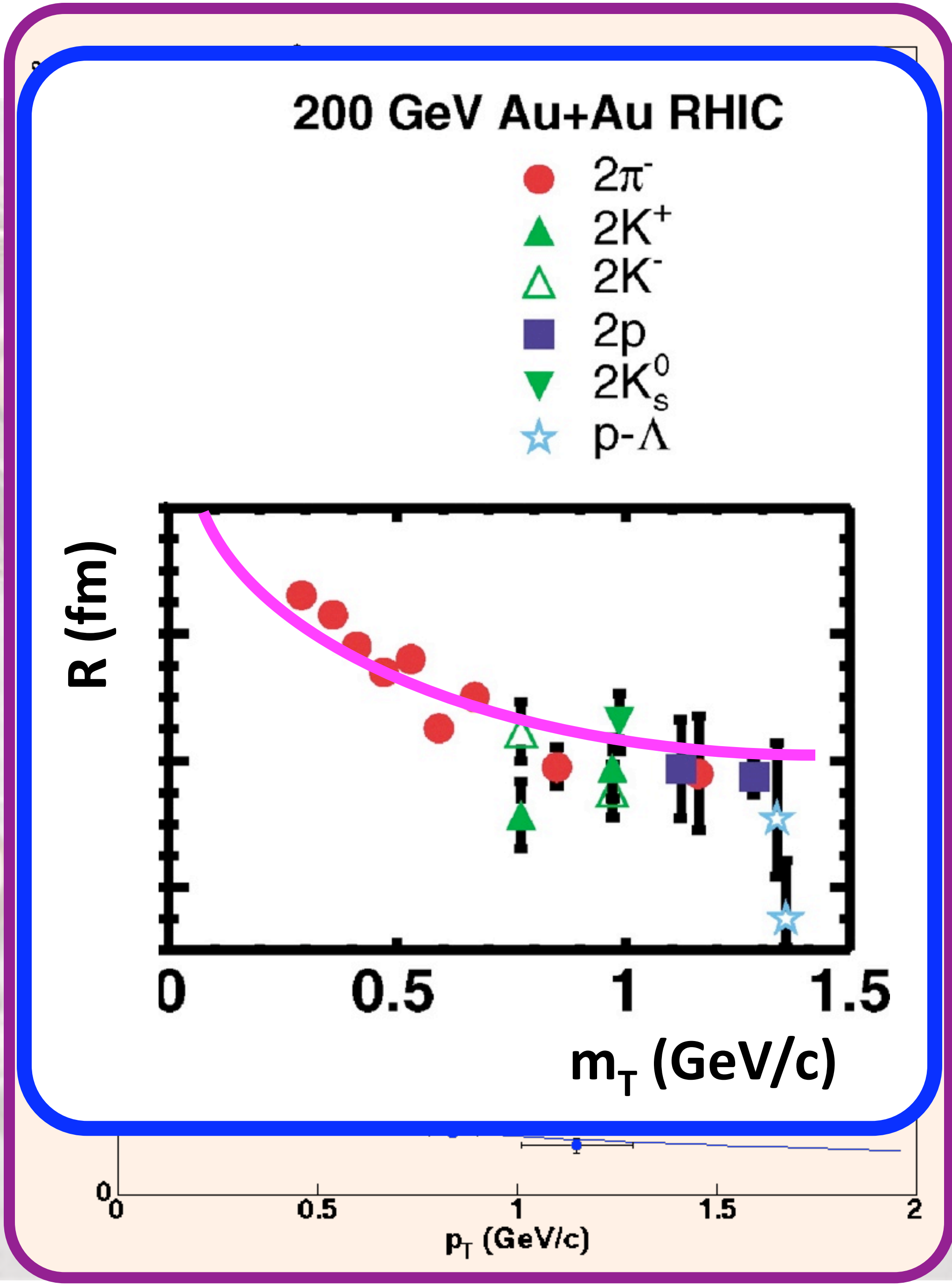

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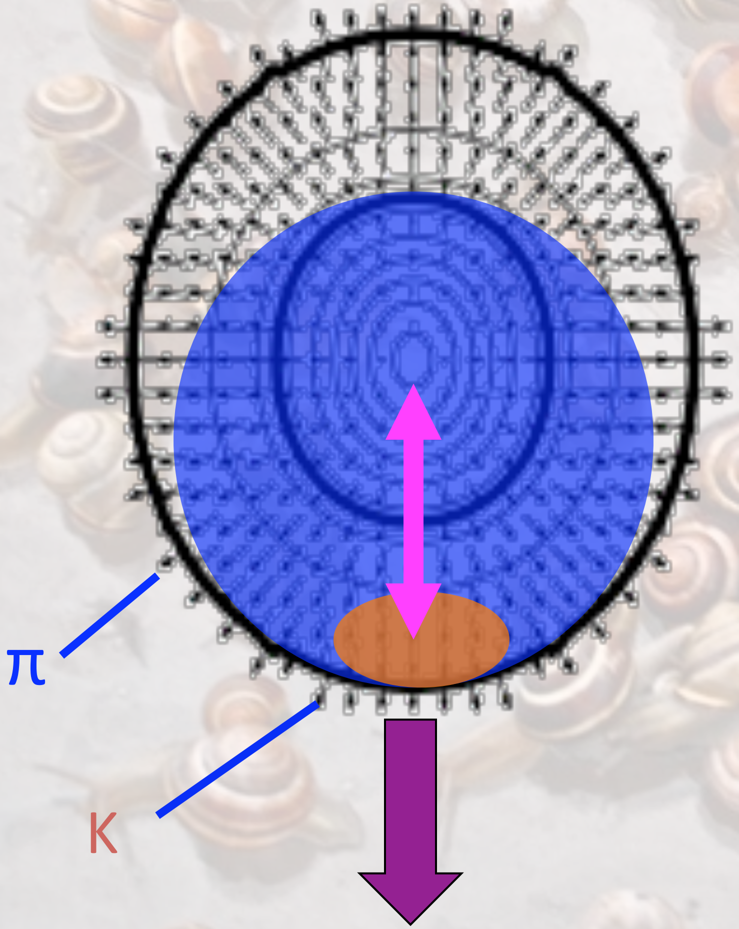

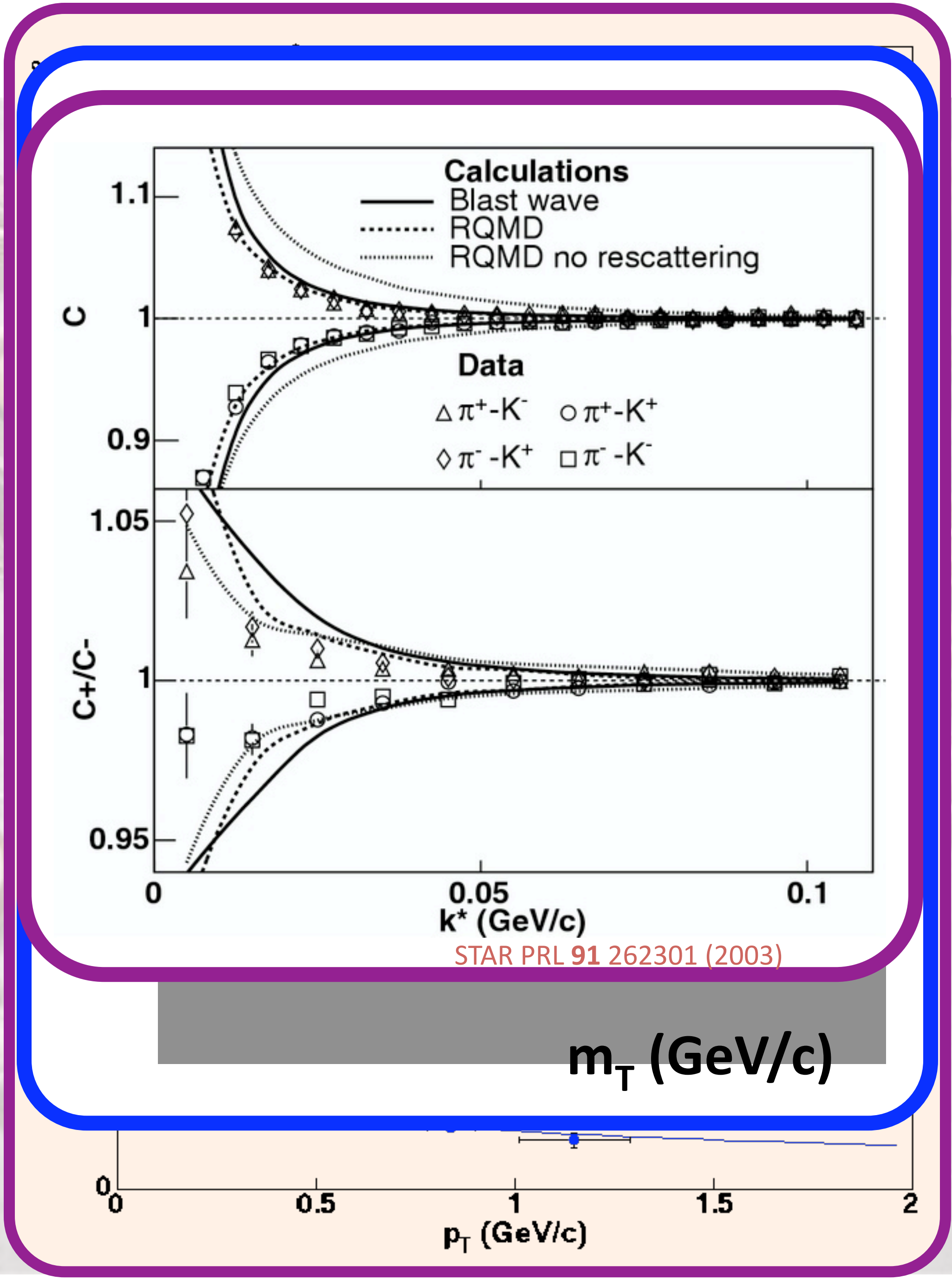

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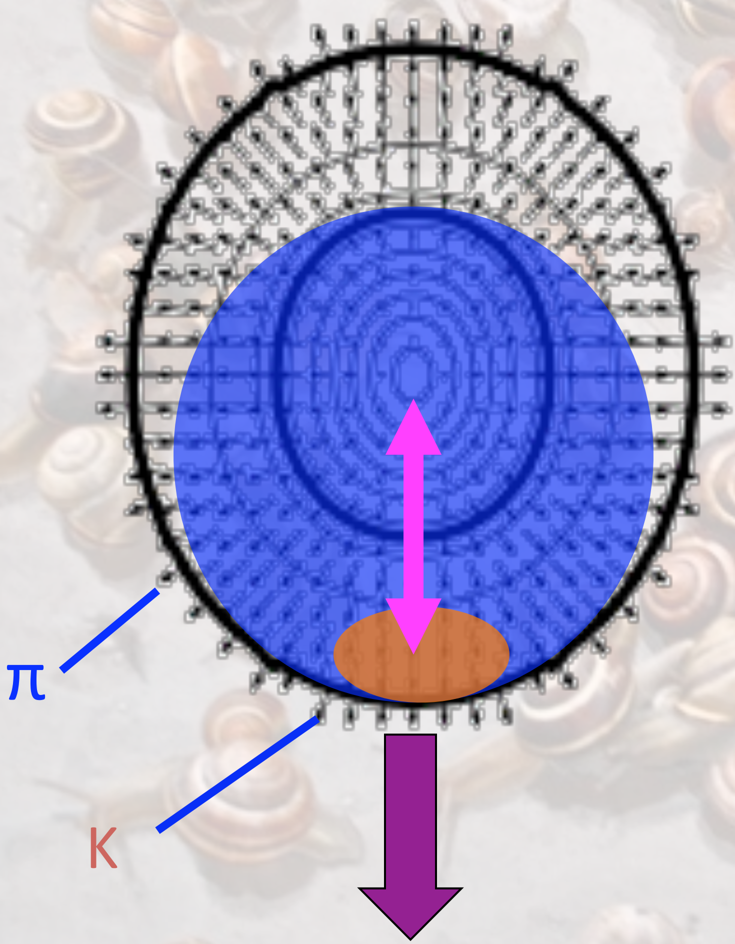

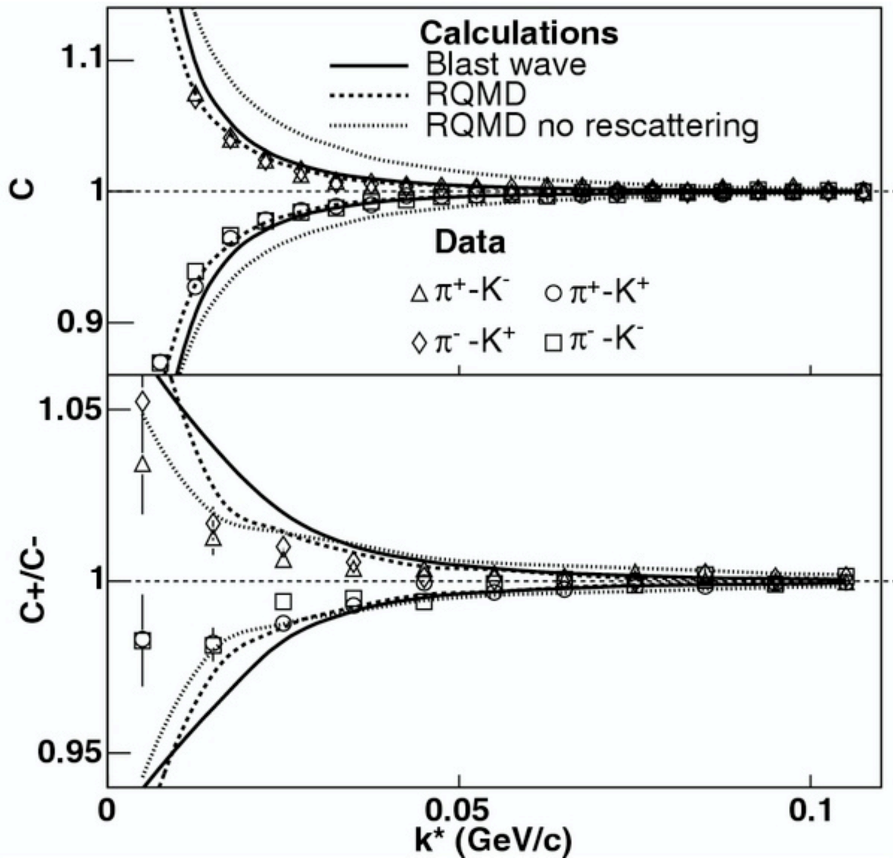

STAR PRL **91** 262301 (2003)

space-momentum substructure mapped *in detail*

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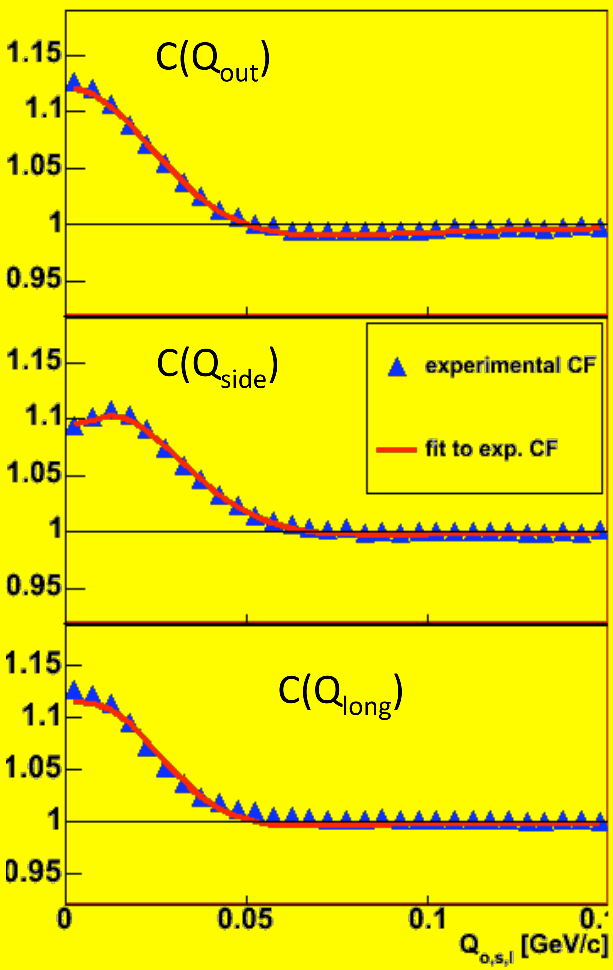
Obtaining 3D radii from 3D correlation functions

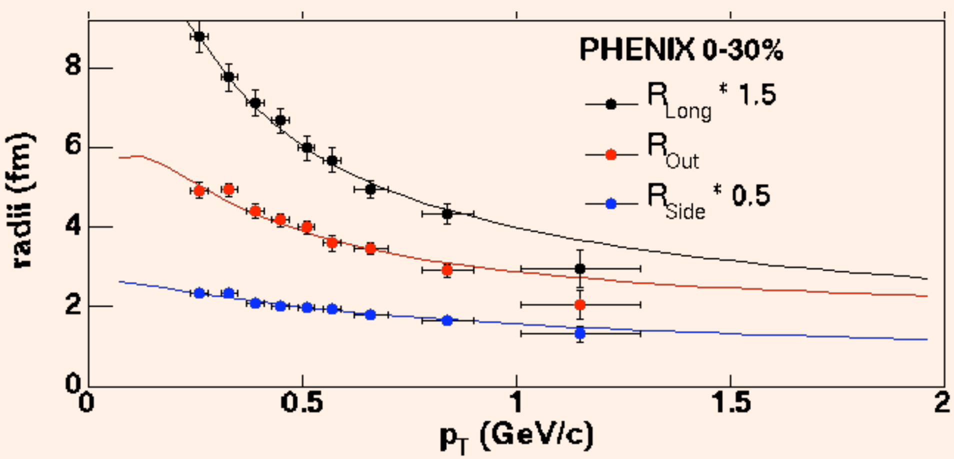
Au+Au: central collisions



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

typical "Gaussian" fitting function

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



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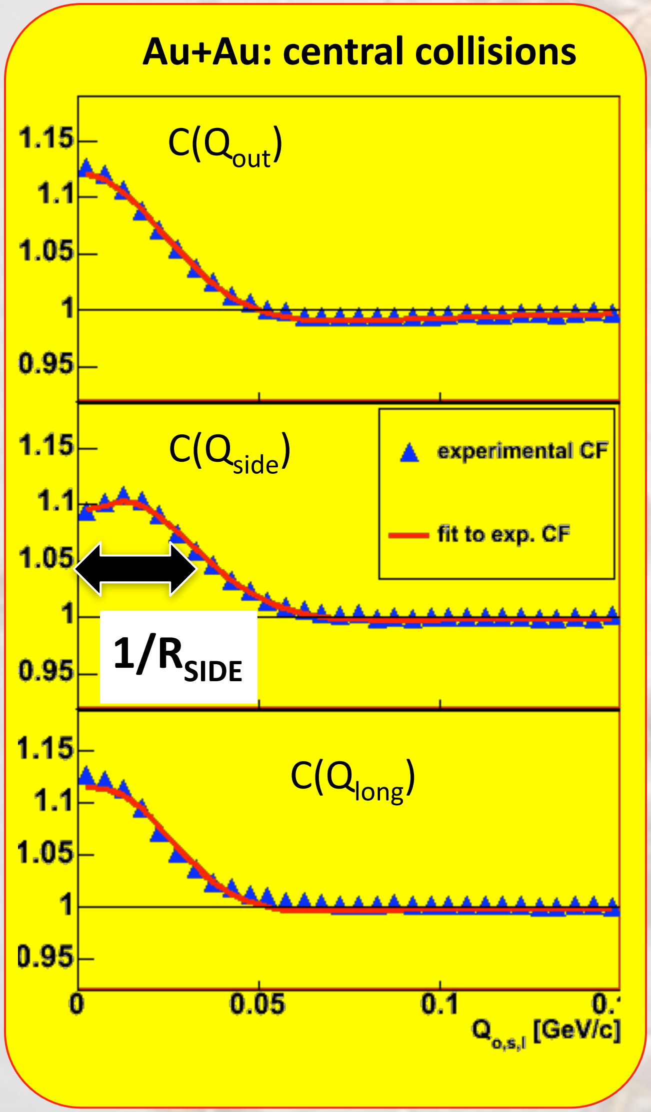

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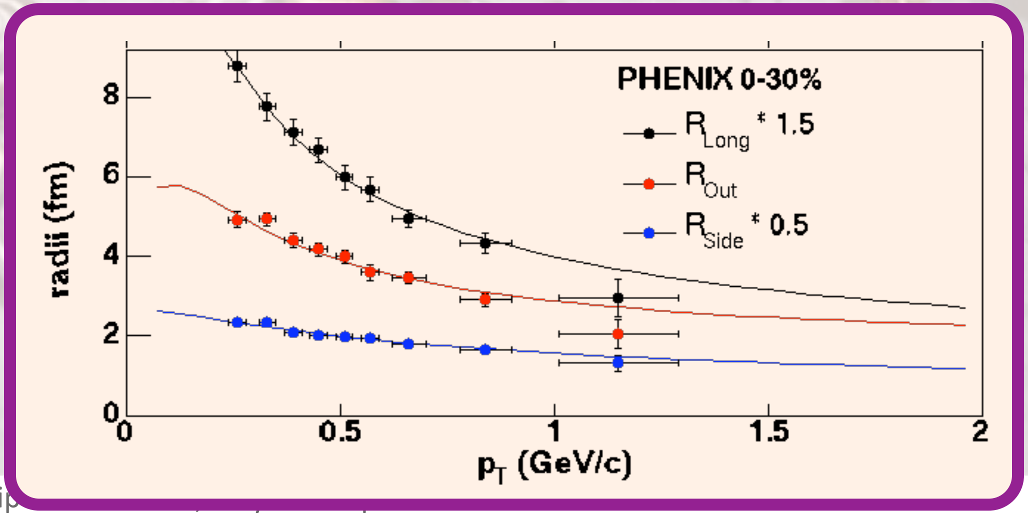

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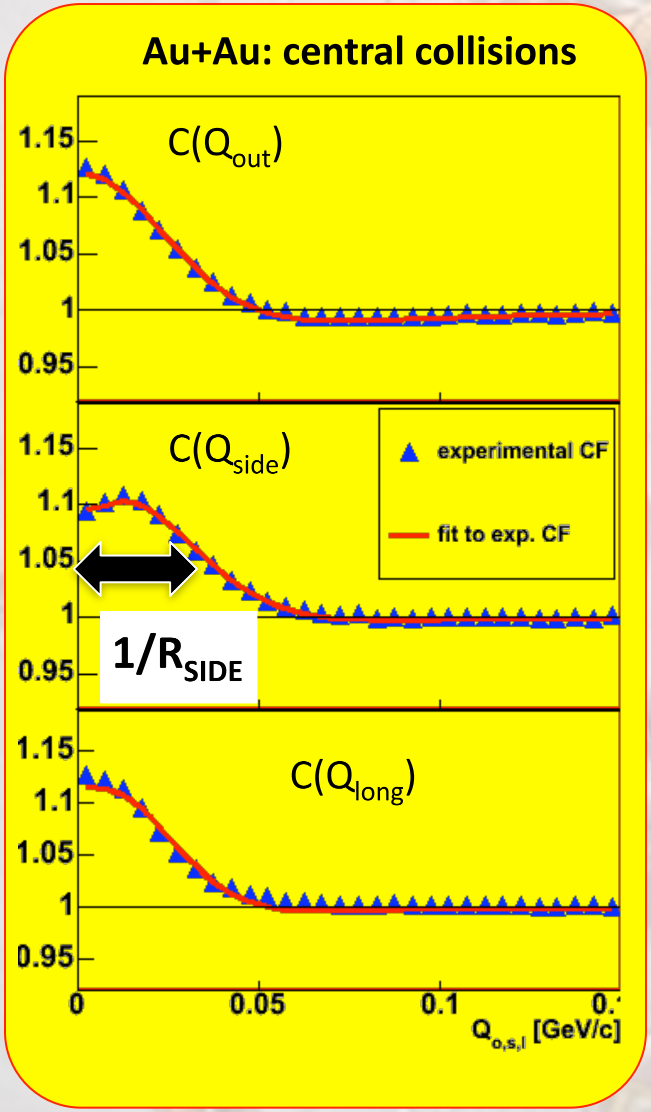

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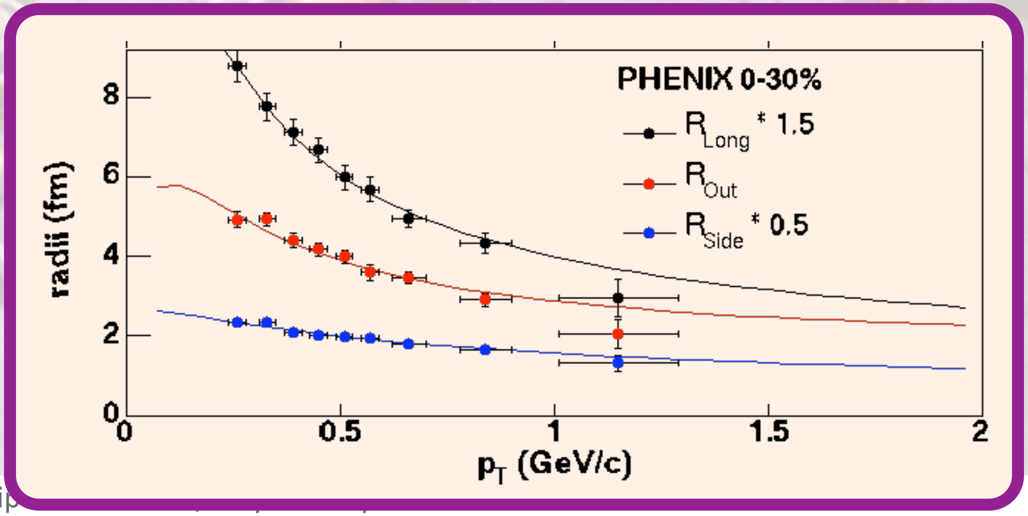
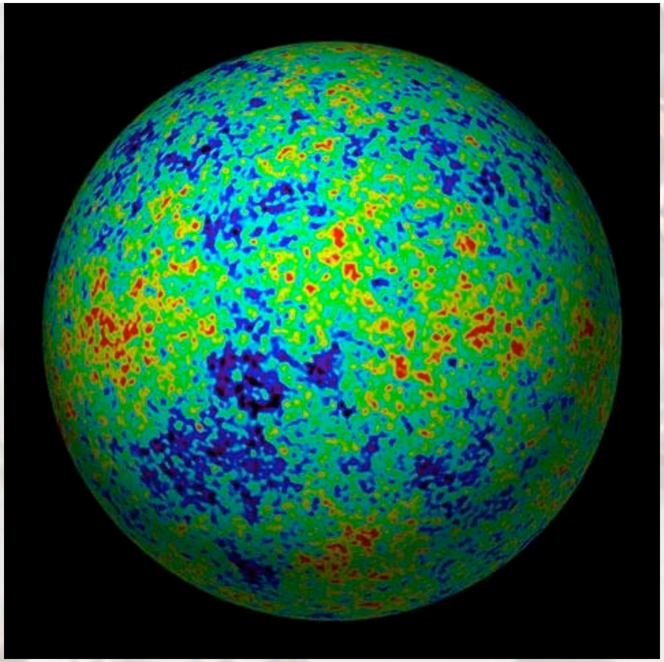
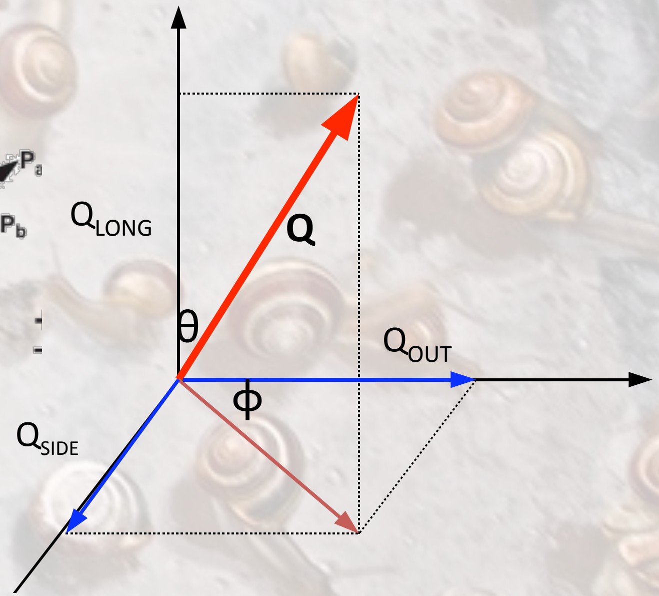
"set of zero measure" of full 3D correlation fctn



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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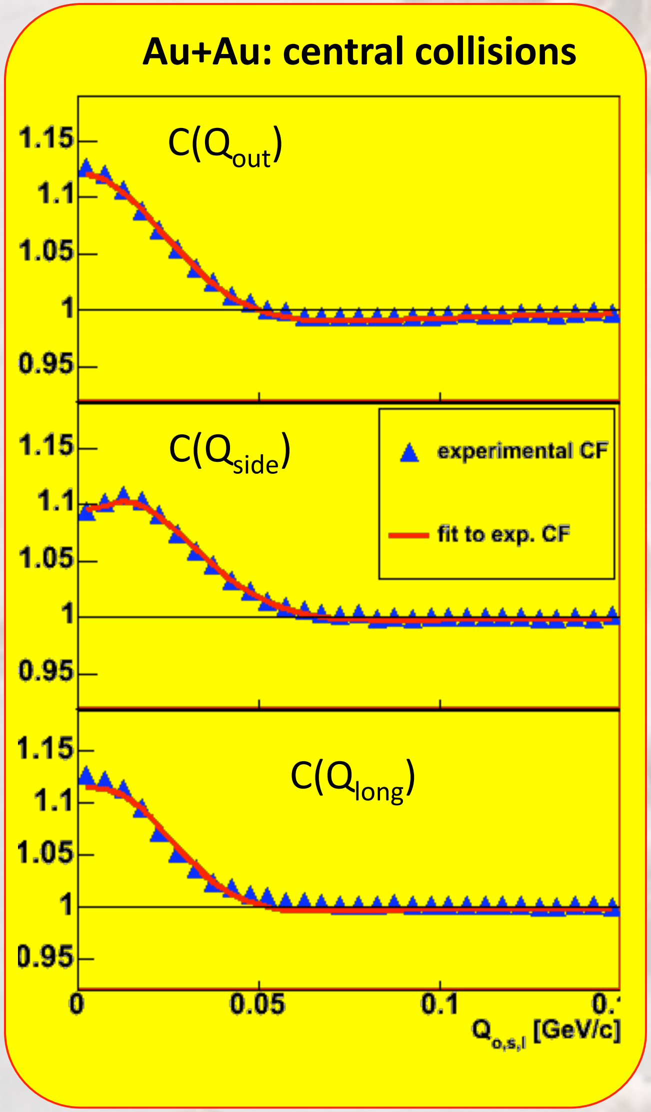

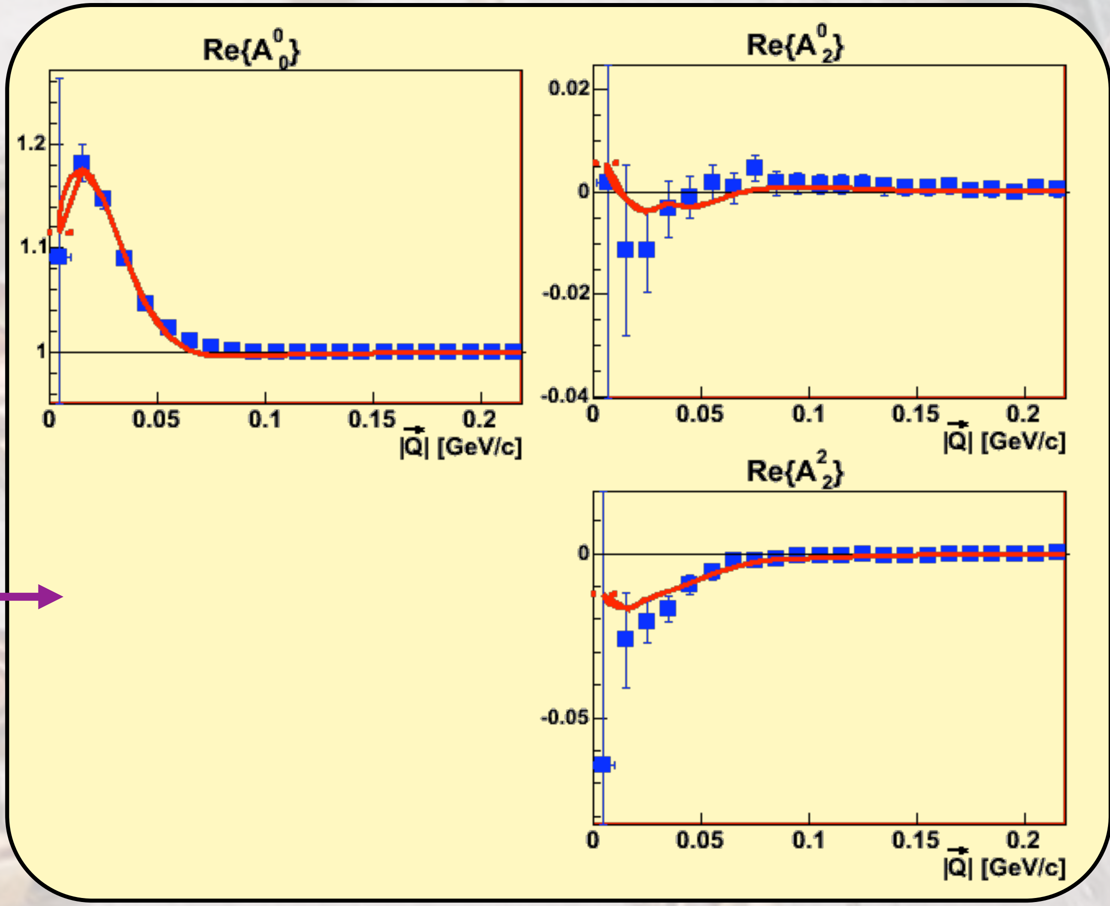

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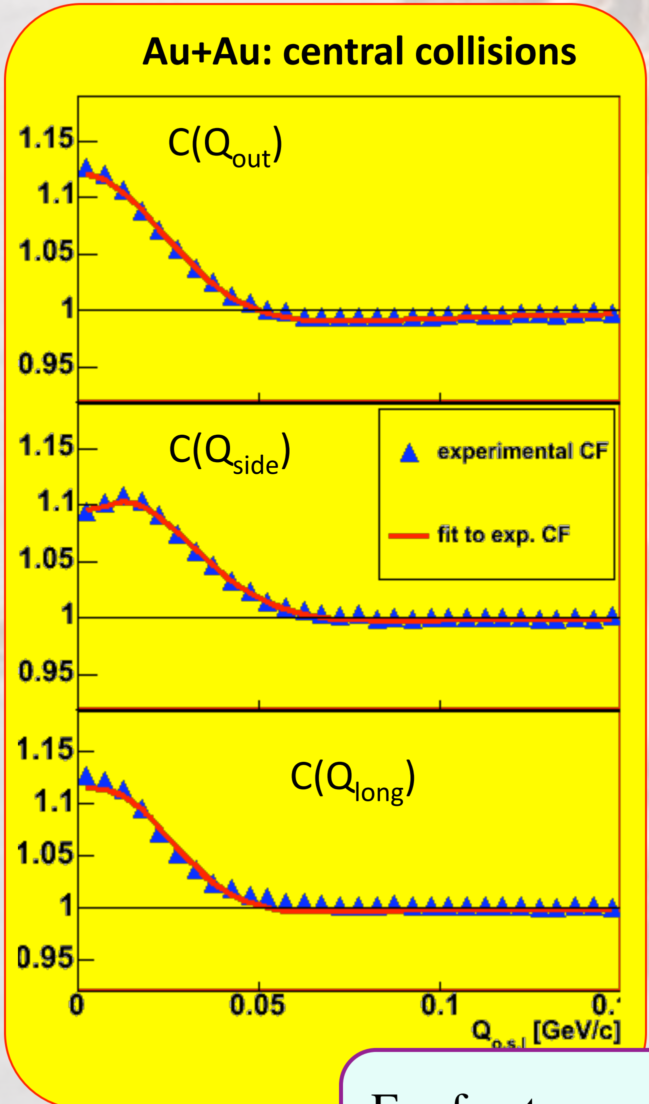

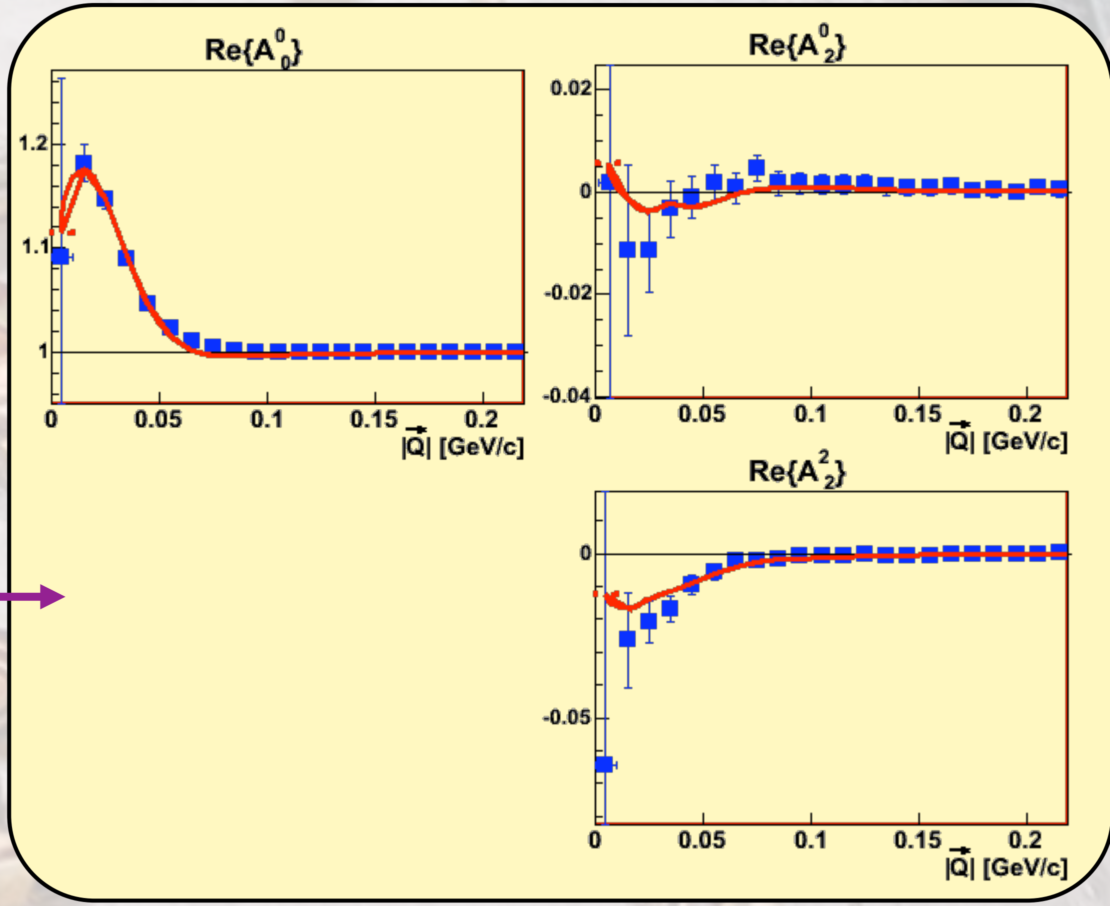

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For femtoscopic correlations:

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

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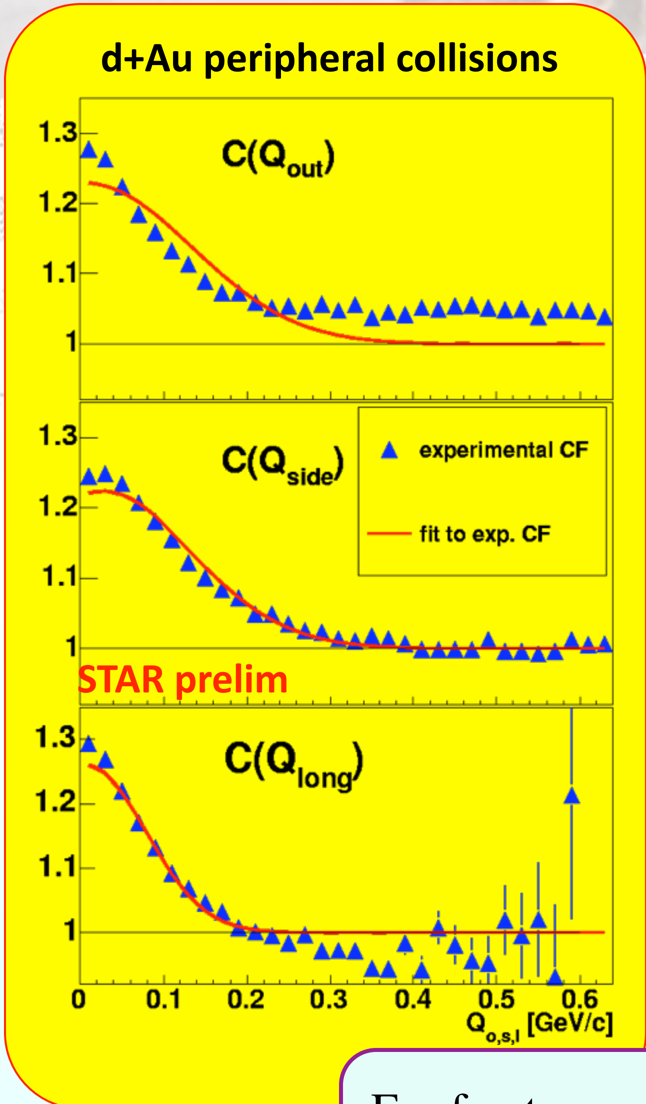

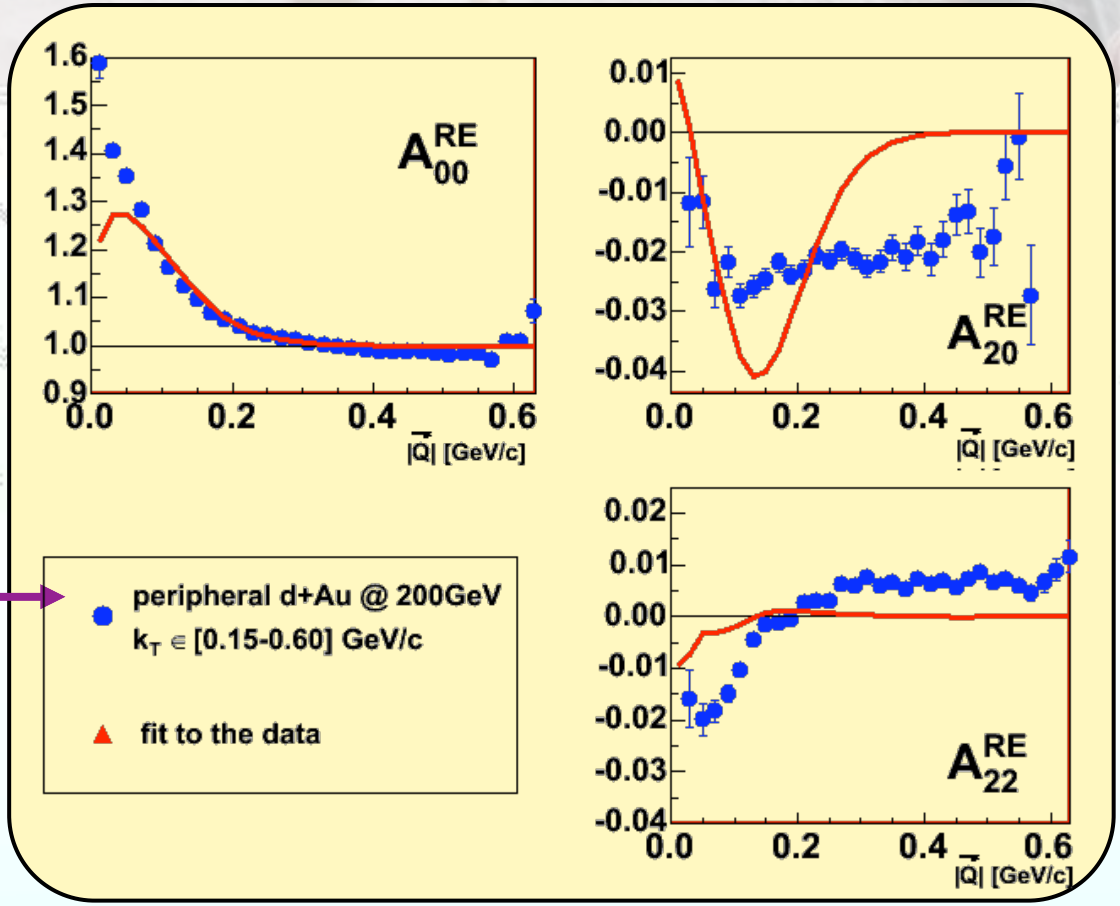

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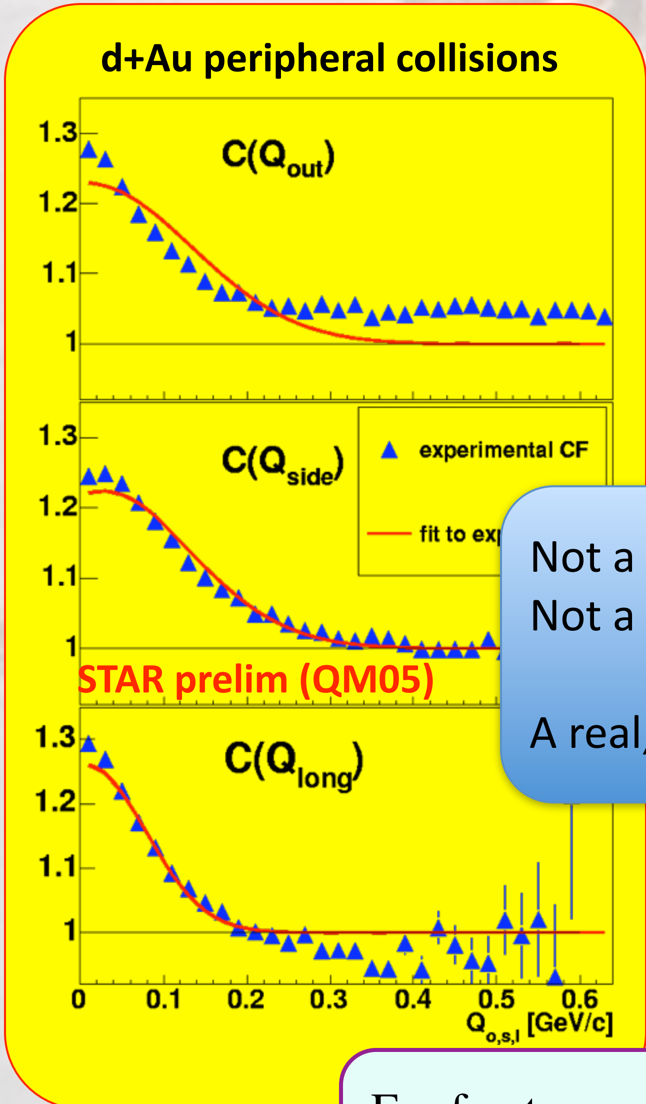

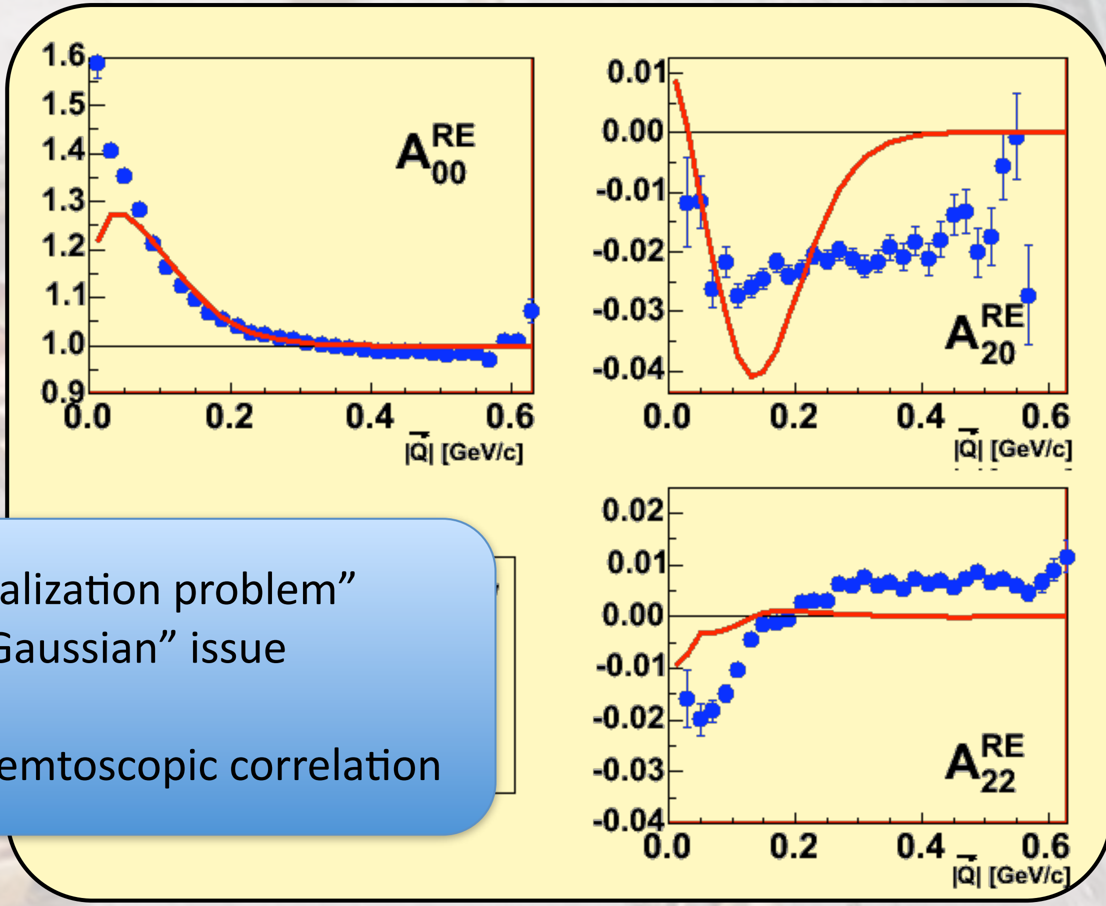

Not a "normalization problem"
Not a "non-Gaussian" issue

A real, non-femtoscopic correlation

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

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We are not alone...


We are not alone...

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

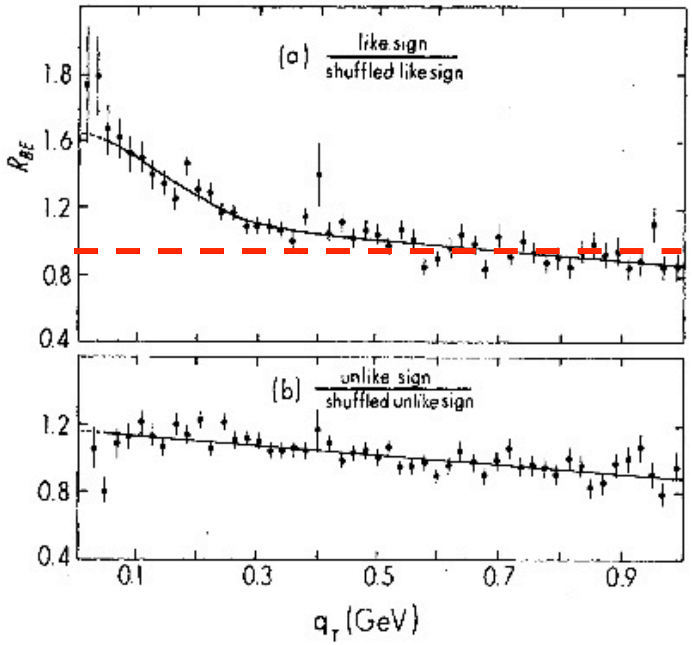

FIG. 9. (a) R_{BE} using a reference sample of shuffled like-si pairs; the fitted curve is according to Eq. (20), and (b) the ra of unlike-sign pairs to shuffled unlike-sign pairs.

CLEO PRD32 (1985) 2294

not alone...

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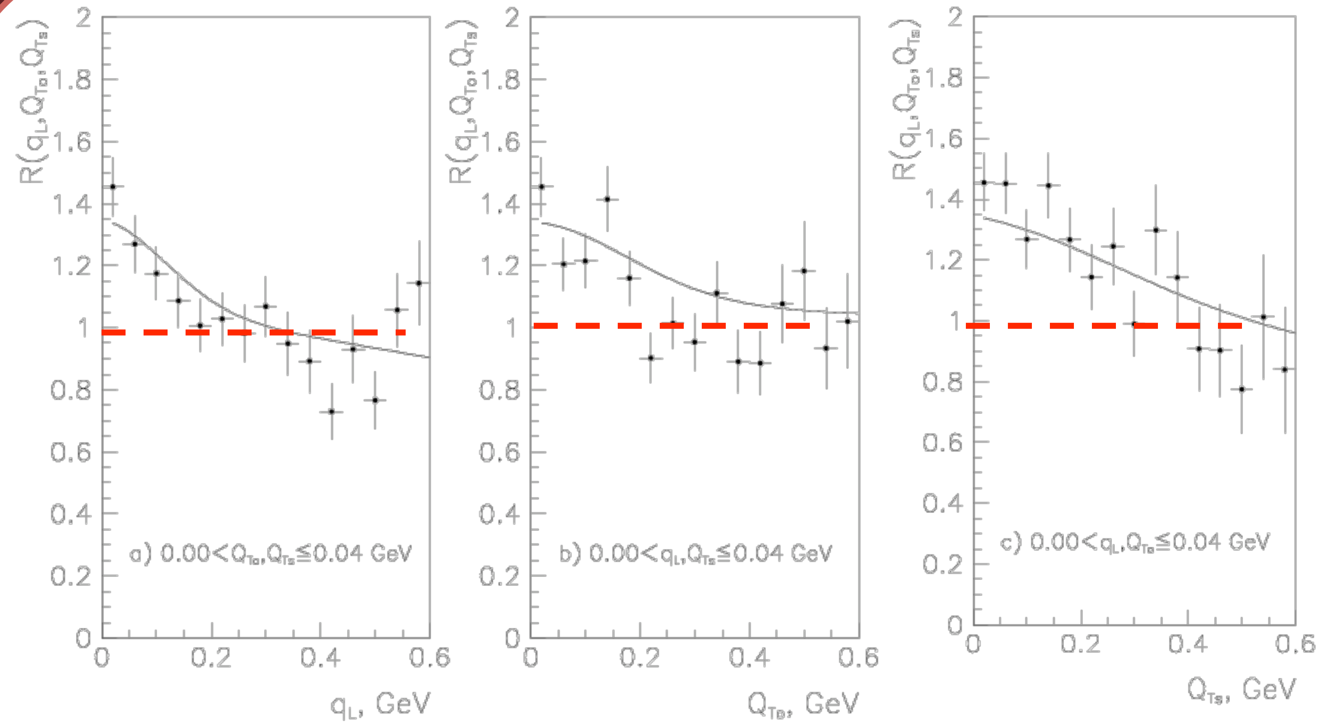

Q_x<0.04 GeV/c

NA22, Z. Phys. C71 (1996) 405

CLEO PRD32 (1985) 2294

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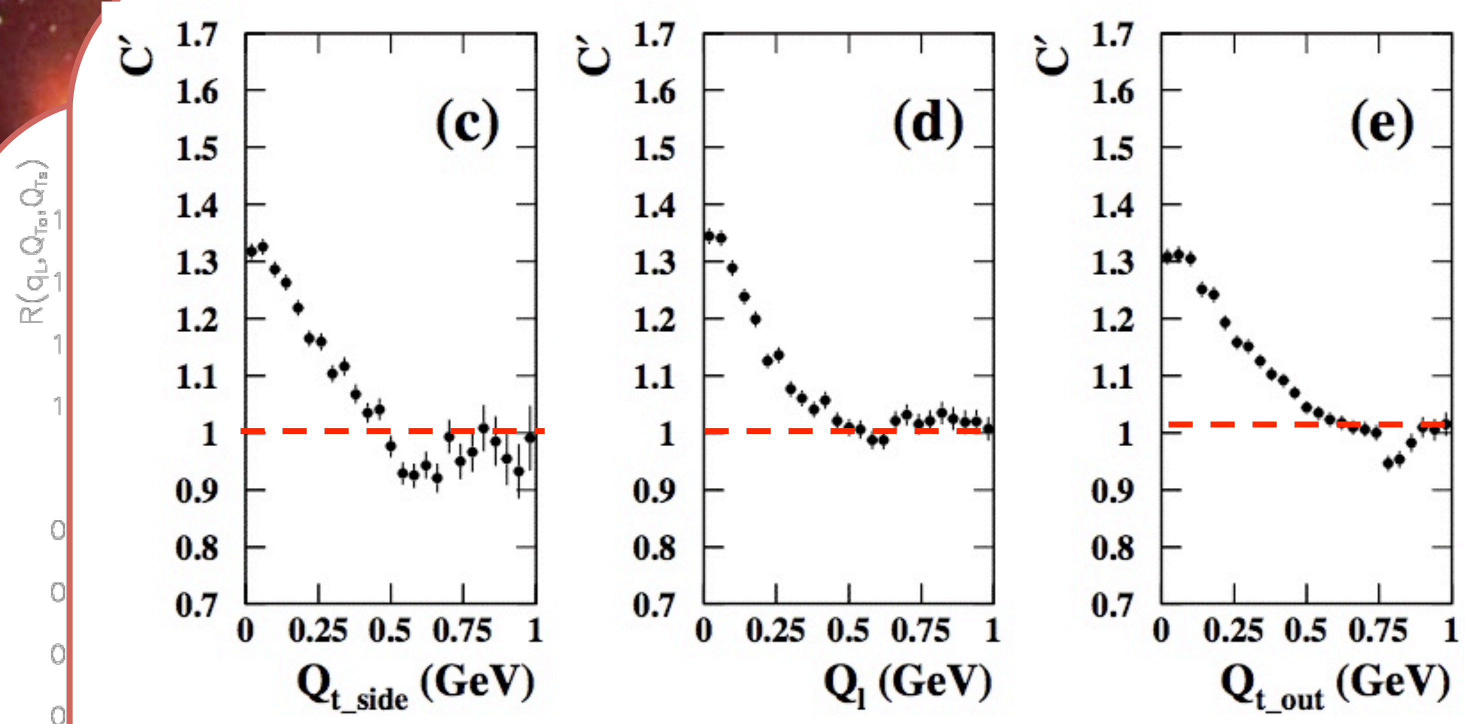

Q_x<0.2 GeV/c

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

NA22, Z. Phys. C71 (1996) 405

CLEO PRD32 (1985) 2294

Review: Z. Ch., Acta Phys.Polon.B 40 1119 (2009)

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)

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  Energy and **M**omentum **C**onservation **I**nduced **C**orrelations (**EMCICs**)?
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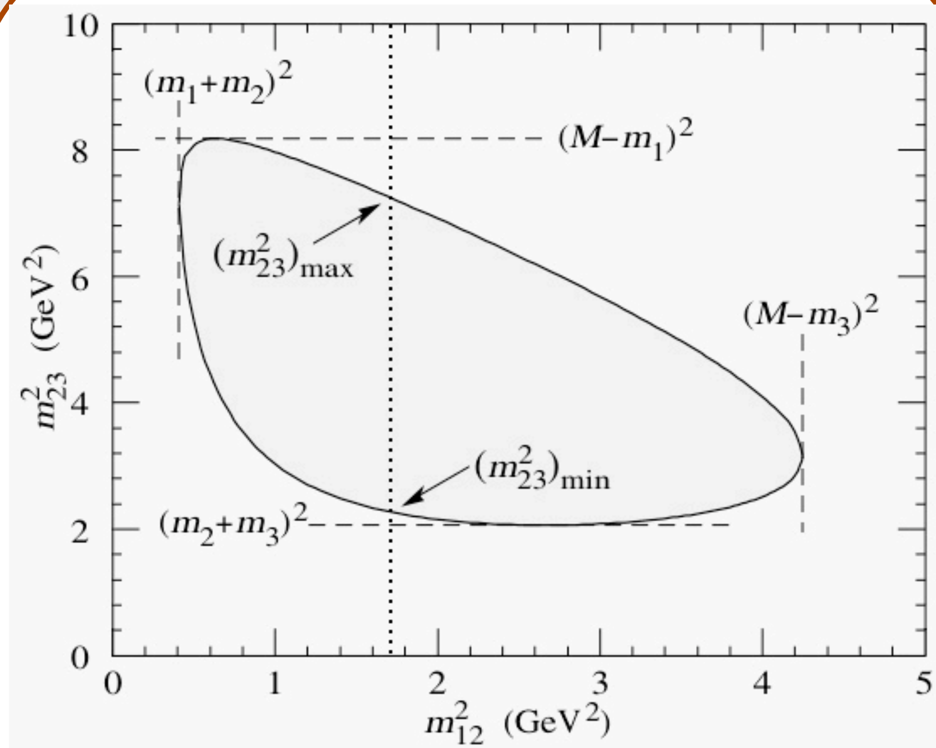
- see also
  – pT conservation effects on v1 (v2) [Danielewicz, Ollitrault & Borghini]
  – pT conservation on 3-particle "conical emission" observables [Borghini]
  – p and E conservation effects on single particle spectra [Chajecki & MAL]

Phasespace constraints impt @ low multiplicity

Phase-space constraints

Extreme case, N=3,
easily visible with Dalitz plot (k=2)

What about the effect for higher number of particles?



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

Fermi/Hagedorn factorization ("Golden rule")

Probability for an n-particle final state:

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

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

dynamics

kinematics

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dynamics

kinematics

$$\boxed{\frac{\Gamma(\mathrm{p\bar{p}} \to \pi\pi\pi)}{\Gamma(\mathrm{p\bar{p}} \to \pi\pi\pi\pi)} = \frac{\mathrm{R}_3(1.876;\pi,\pi,\pi)}{\mathrm{R}_4(1.876;\pi,\pi,\pi,\pi)}}$$

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

Single-particle spectrum

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

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

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

R. Hagedorn, *Relativistic Kinematics* 1963

Consider correlations arising (only) from conservation laws

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

$$\tilde{f}_c(p_1,\ldots,p_k) \equiv \left(\prod_{i=1}^{k} \tilde{f}(p_i)\right)$$

no other correlations

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what we measure

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

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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

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

where:

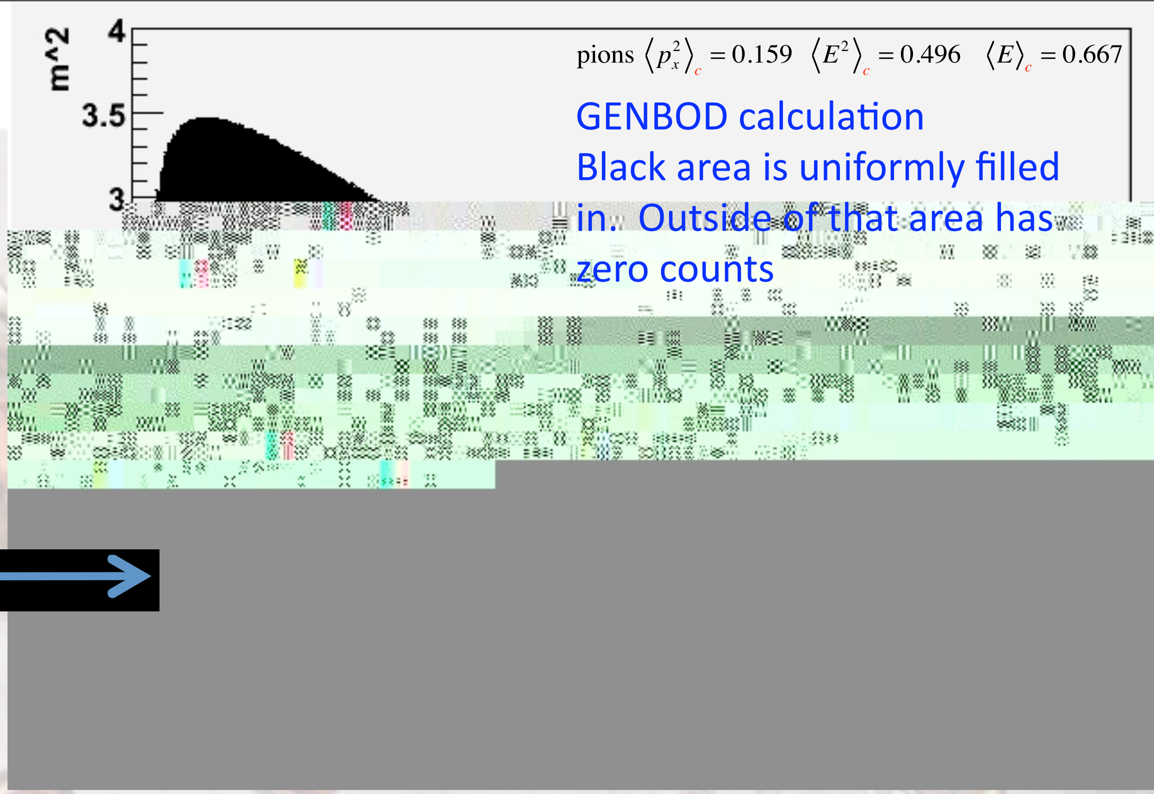
$$\sigma_\mu^2 = \langle p_\mu^2\rangle - \langle p_\mu\rangle^2$$

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

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

–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)

N-k=1 is not "large"



GENBOD calculation
Black area is uniformly filled in. Outside of that area has zero counts

Dalitz plot for 3-particle system:
N=3, k=2

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

calculated numerically by GENBOD* MC

* F. James, CERN 1964

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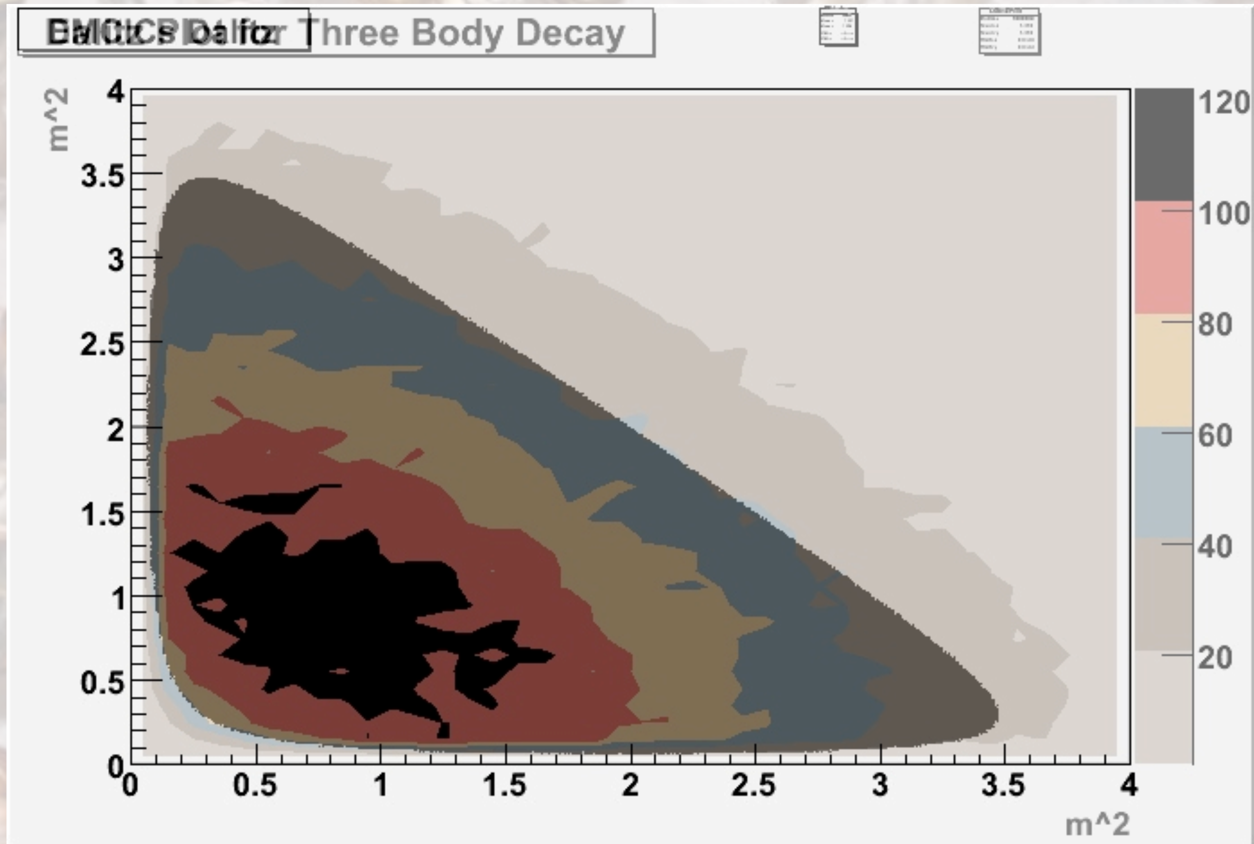
Overlaid



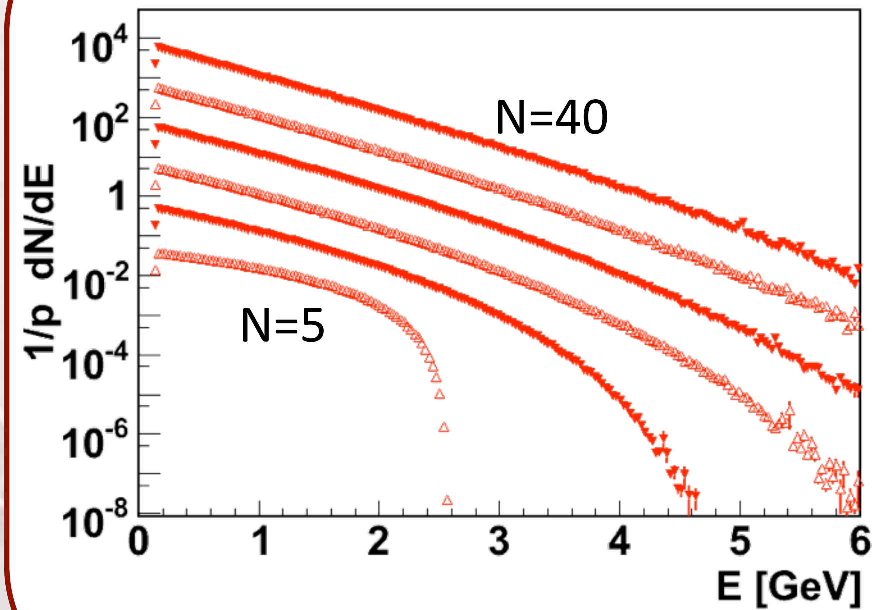
I actually didn't expect such good agreement in the N=3 case, especially on a Dalitz plot which has the sharpest possible behaviour.

Effects on single-particle distribution

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

We will return to this....

1-particle PS effect



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

k-particle correlation function

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

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

Dependence on "parent" distrib f vanishes,

except for energy/momentum means and RMS

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

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

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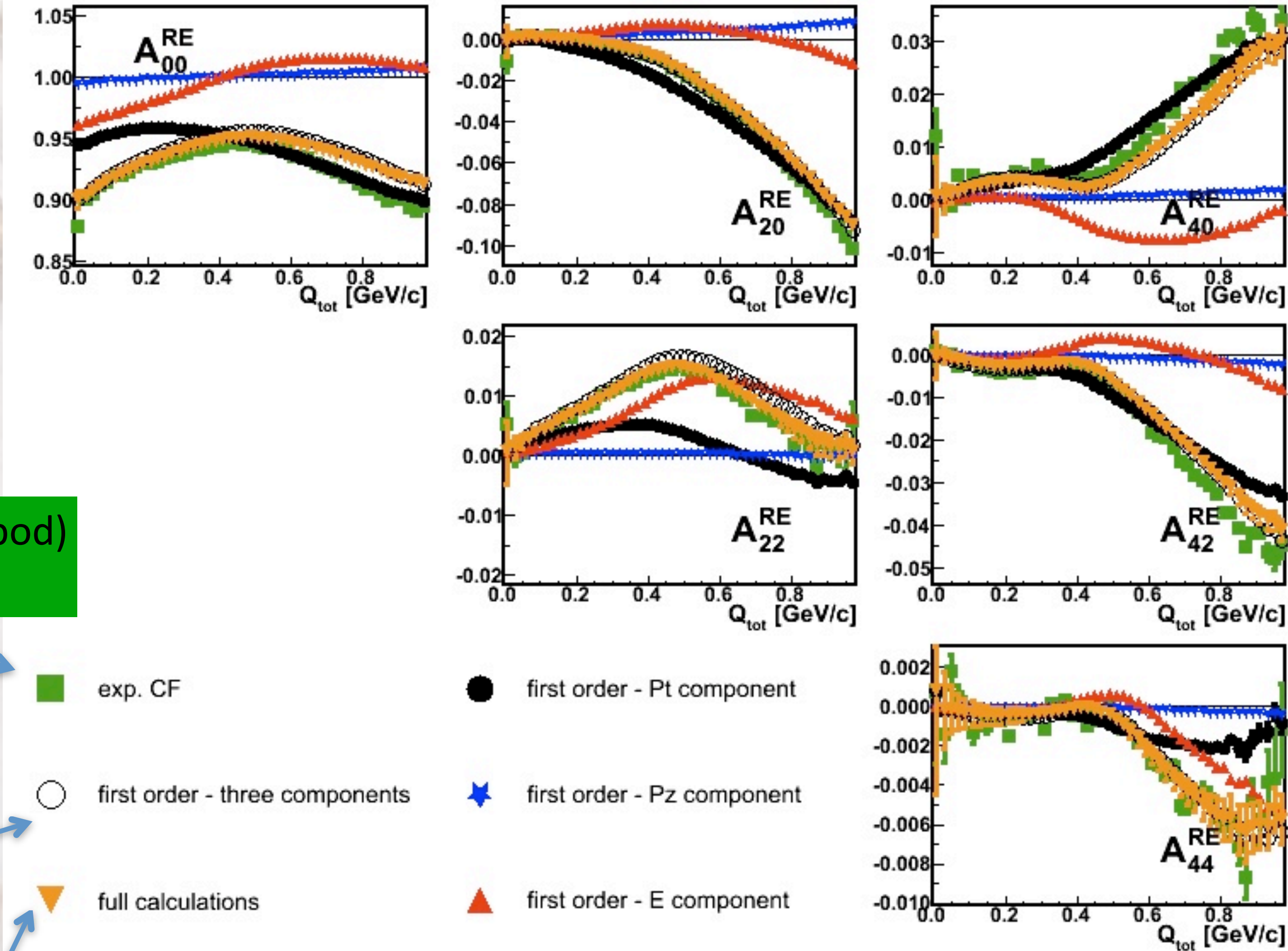
How do EMCICs look ? – nontrivial !

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



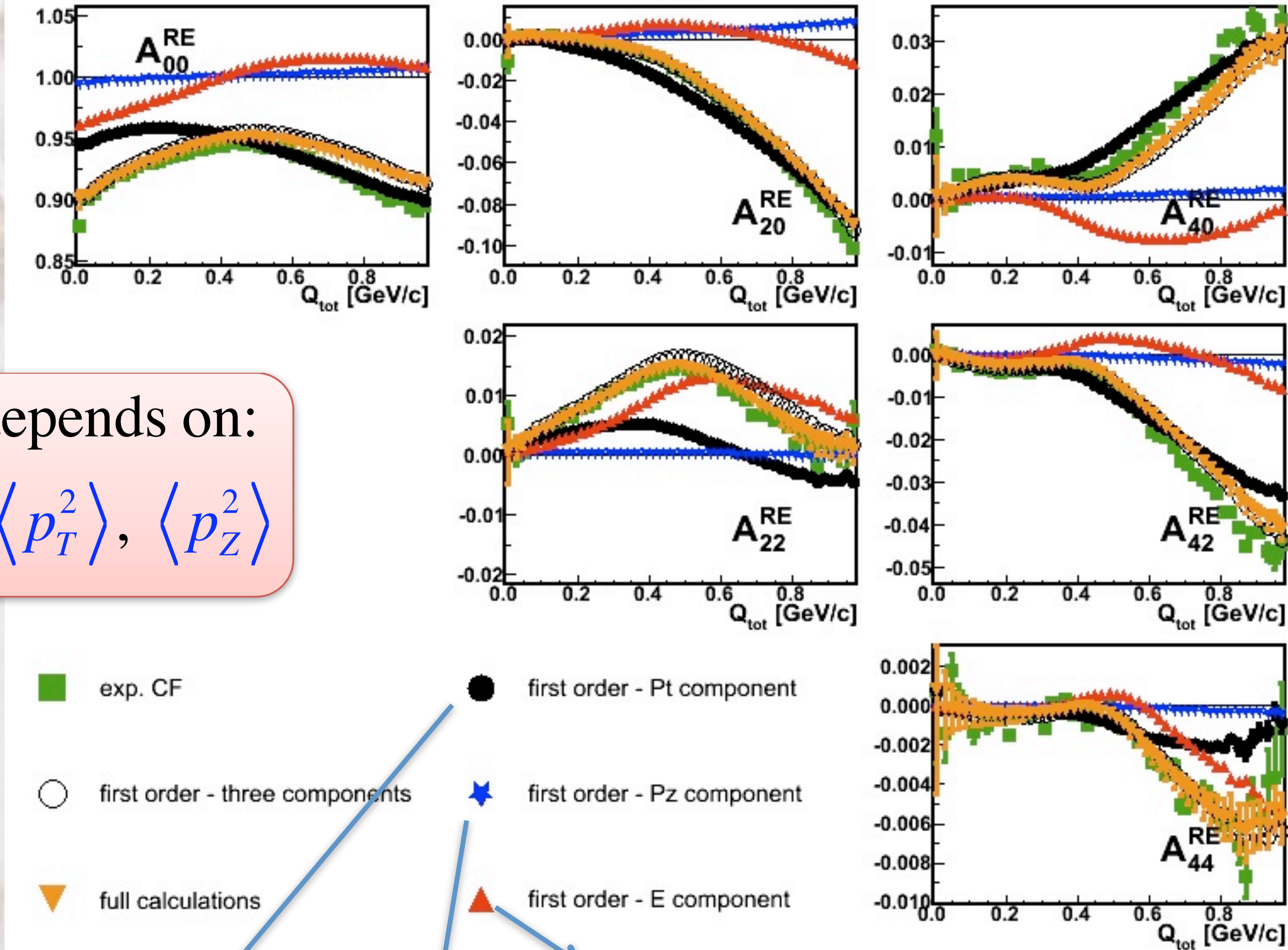
event generator (genbod) with only EMCICs

O(1/N) term in CLT approximation

CLT approximation

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

How do EMCICs look ? – nontrivial !

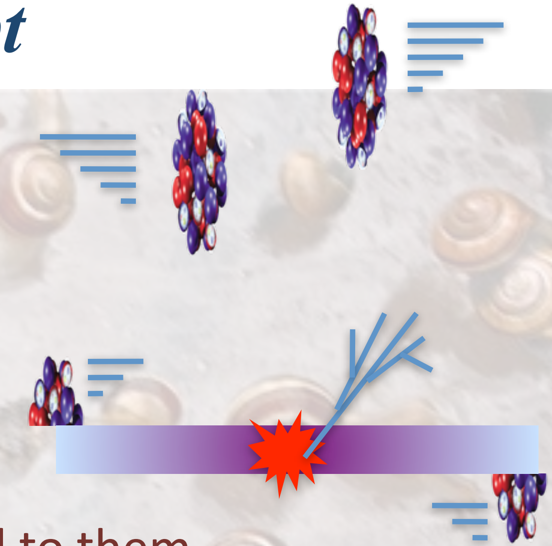


Detailed shape depends on:

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

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

"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

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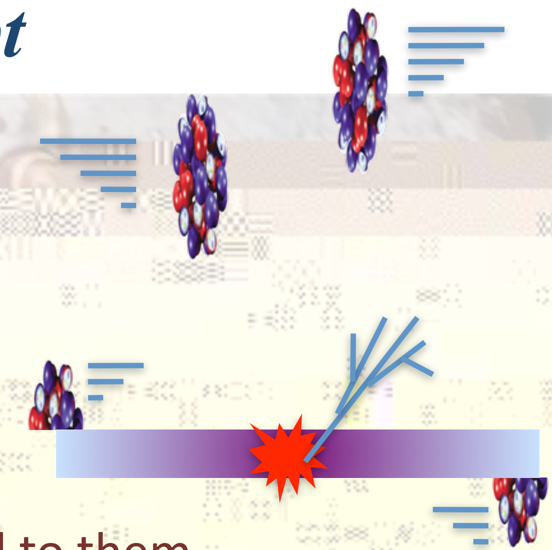

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1. *N* includes all primary particles (including unmeasured γ's etc)

2. secondary decay (resonances, fragmentation) smears connection b/t <E^2> and measured one

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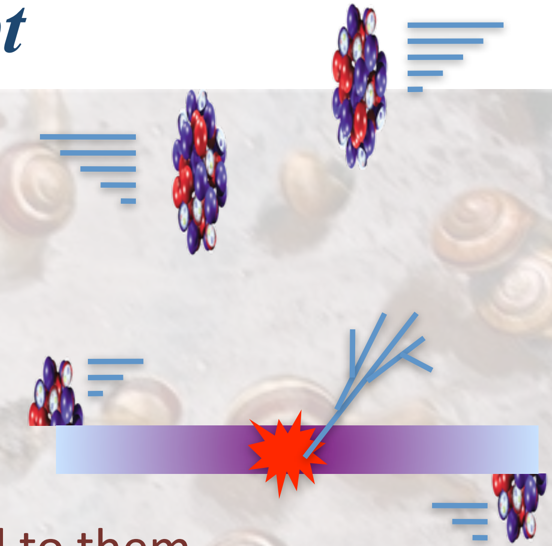

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3. <E^2> etc: averages of the *parent* distribution

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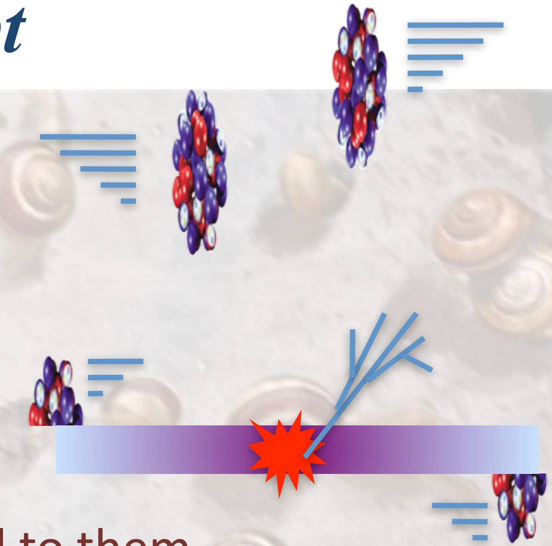

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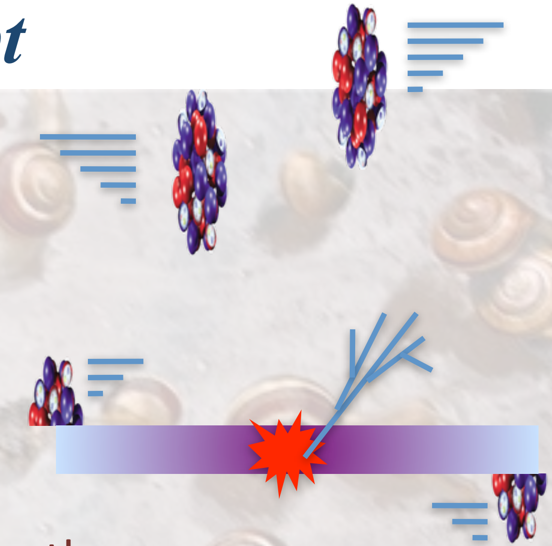
4. "relevant system" almost certainly not the "whole" (4π) system
   - e.g. beam fragmentation probably not relevant to system emitting at midrapidity
     - characteristic physical processes (strings etc): Δy ~ 1÷2
   - jets: "of the system" ??
     - or just stealing energy *from* "the system?"
  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

"the system"… a nontrivial concept



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

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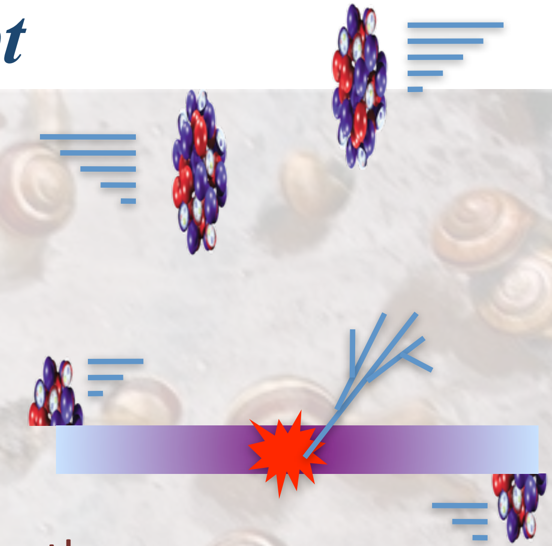
- Treat as parameters: what to expect?

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

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

"the system"… a nontrivial concept



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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.

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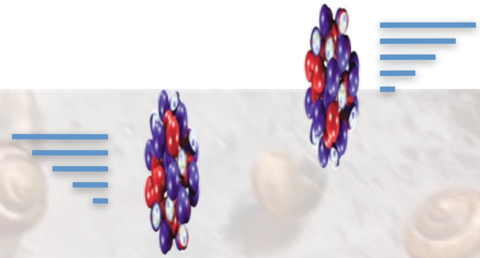

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- Treat as parameters: what to expect?

$$\text{Blastwave,}\quad T = 100\ \text{MeV}\quad \rho_0 = 0.9$$

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

$$\langle m_T\rangle_\pi = 0.435\ \ \text{GeV}$$

$$\langle m_T^2\rangle_\pi = 0.259\ \ \text{GeV}^2$$

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

	non-rel	ultra-rel	if $T = .15$ -
$\langle p_T^2\rangle$	$2mT$	$8T^2$	$0.045 \div 0.$
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Femtoscopic correlations and EMCICs (experimentalists' recipe)

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

$$\left[1-2M_1\overline{\left\{\vec{p}_{1,T}\cdot\vec{p}_{2,T}\right\}}-M_2\overline{\left\{p_{1,Z}\cdot p_{2,Z}\right\}}-M_3\overline{\left\{E_1\cdot E_2\right\}}+M_4\overline{\left\{E_1+E_2\right\}}-\frac{\left(M_4\right)^2}{M_3}\right]$$

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

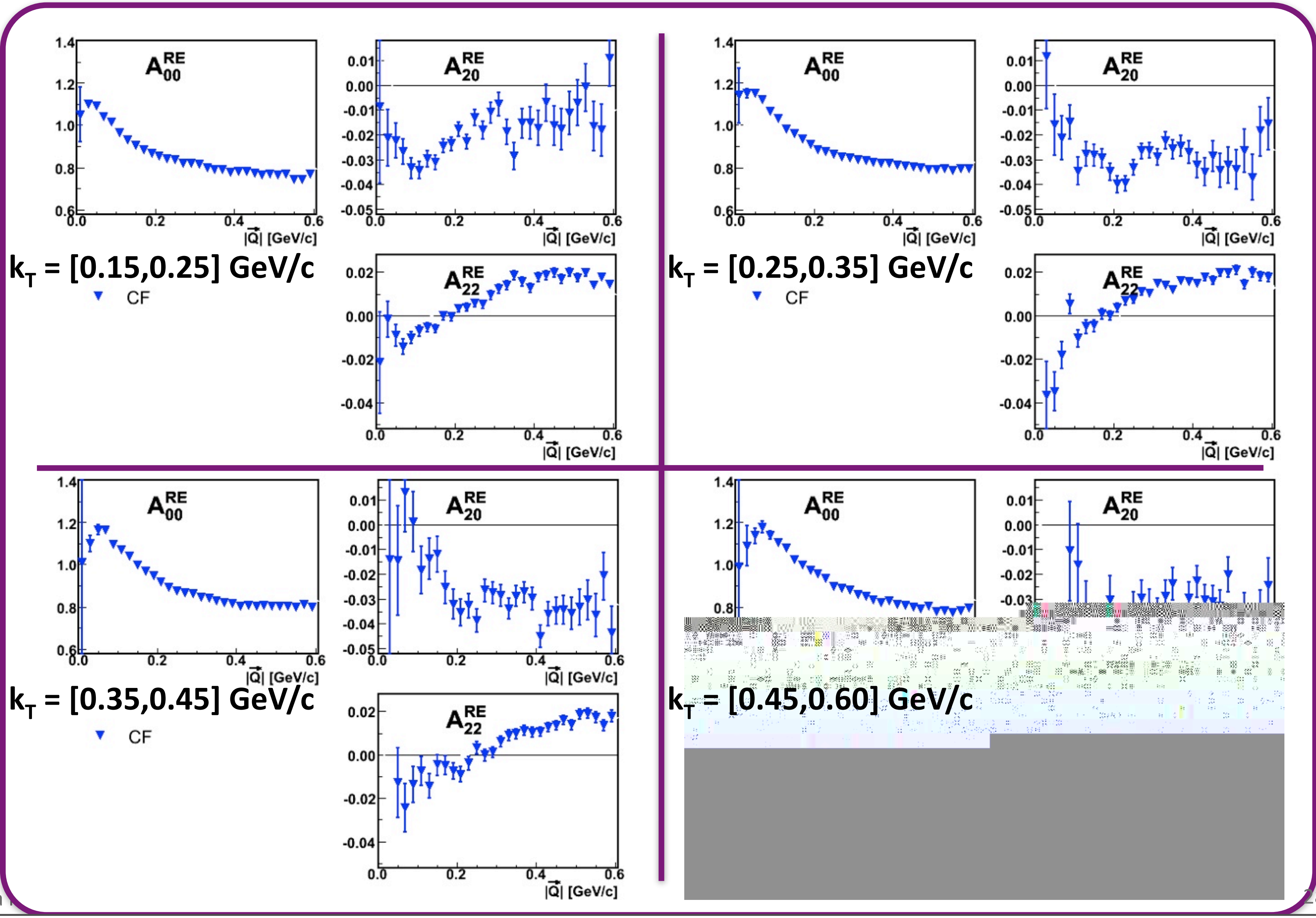
- Four parameters related to underlying parent distribution (*independent of k_T!*)

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

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

Fits to p+p data (STAR @ QM09)

STAR preliminary



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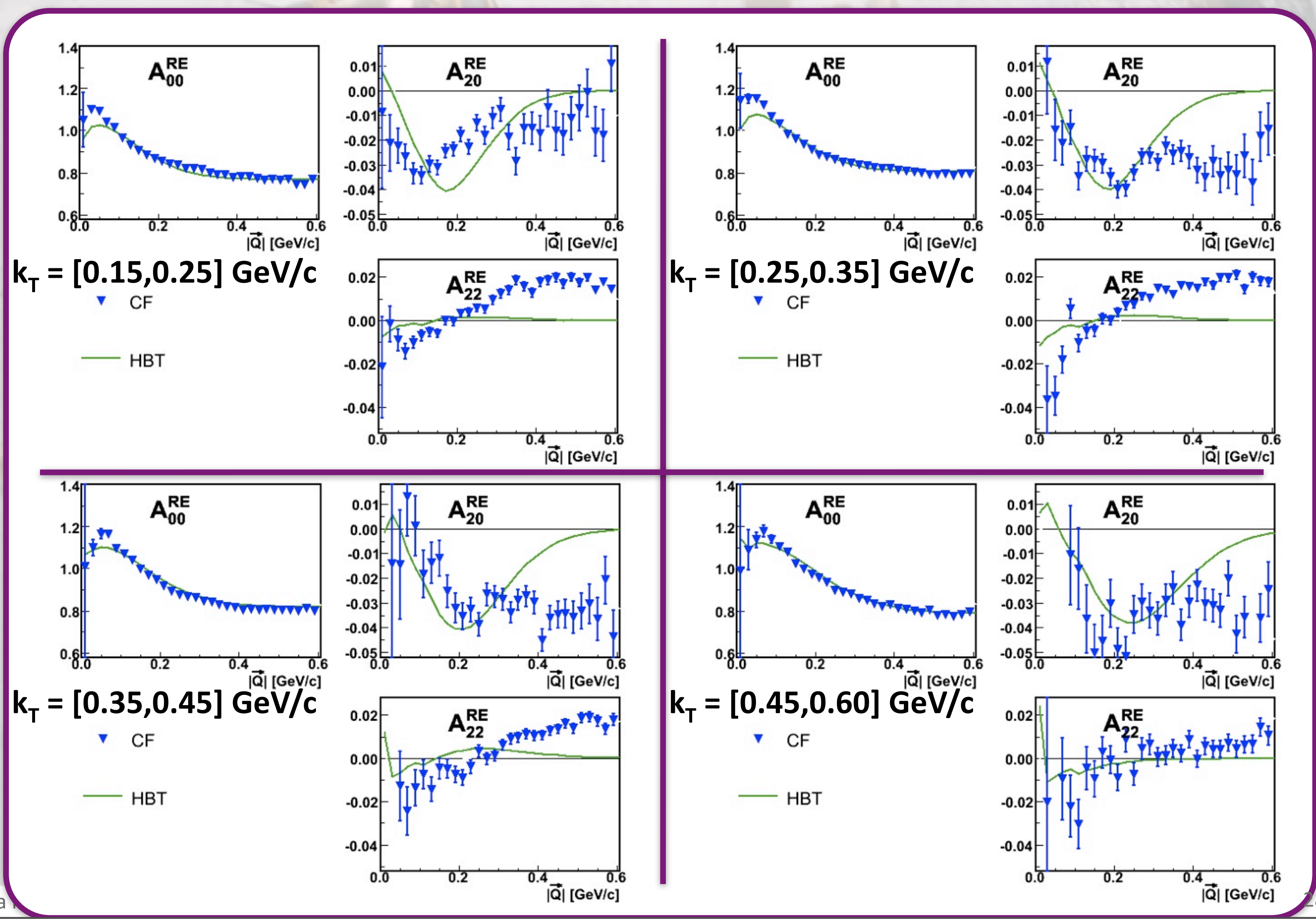

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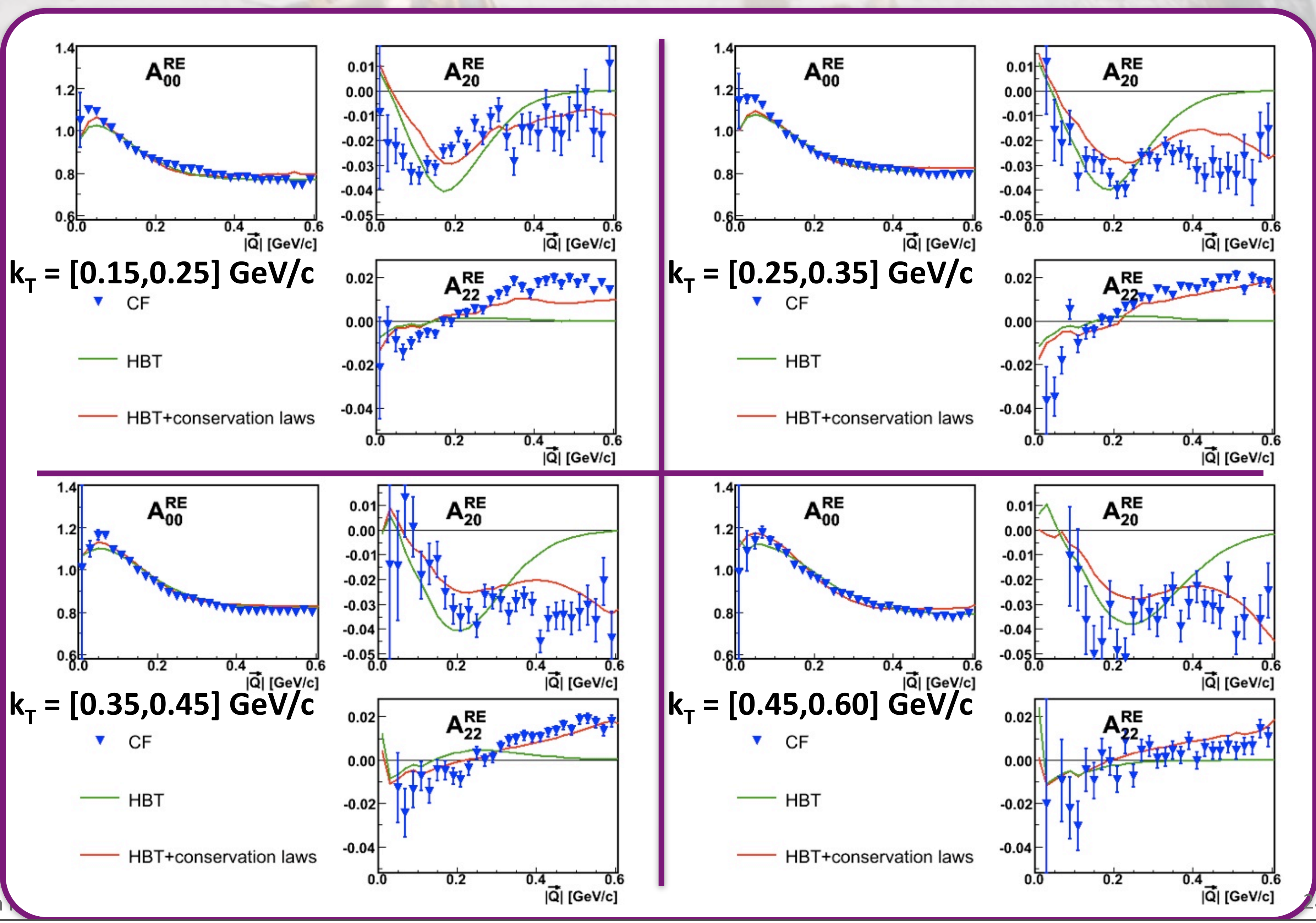
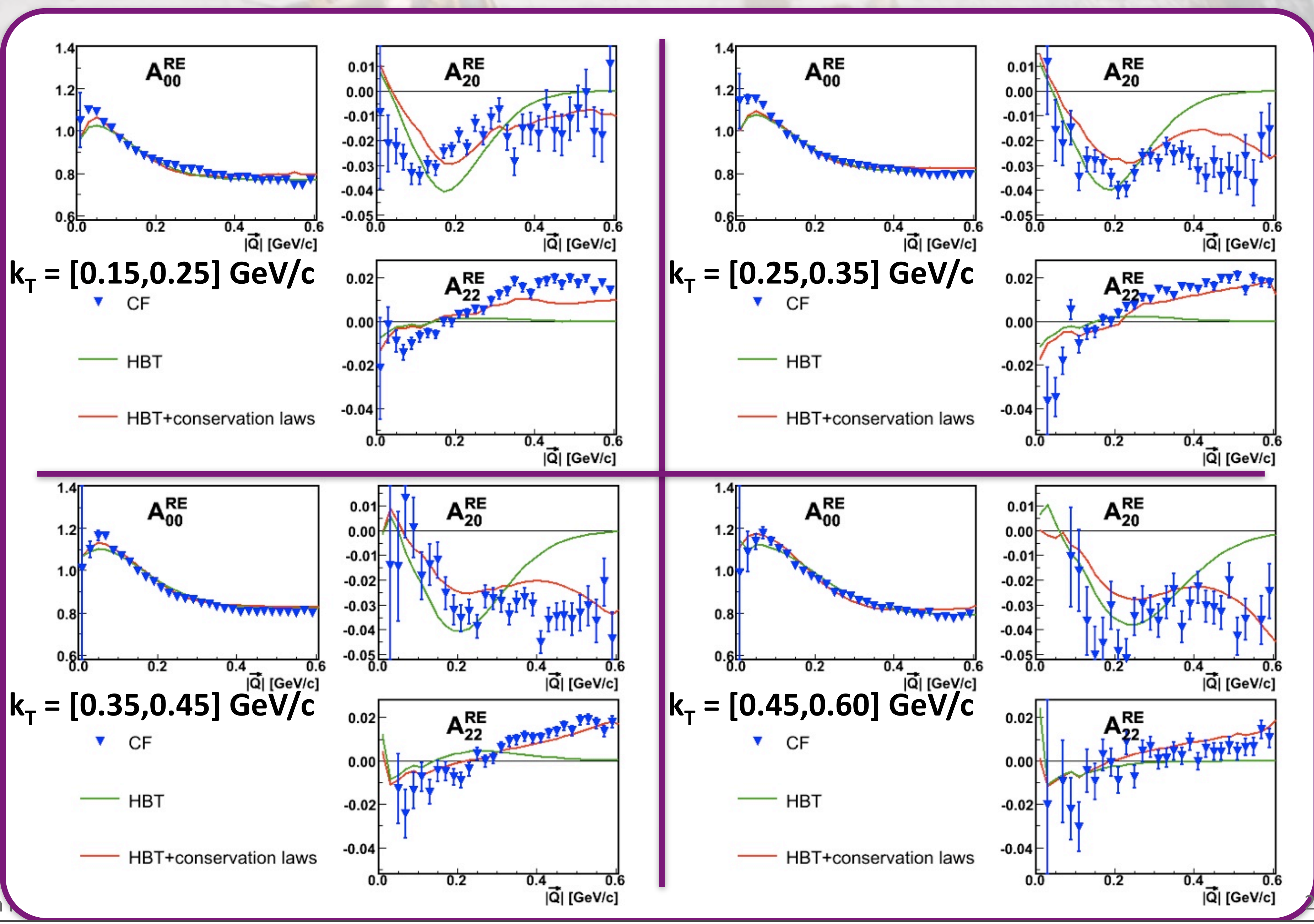


Wednesday, September 16, 2009

Fits to p+p data (STAR @ QM09)

STAR preliminary



Wednesday, September 16, 2009

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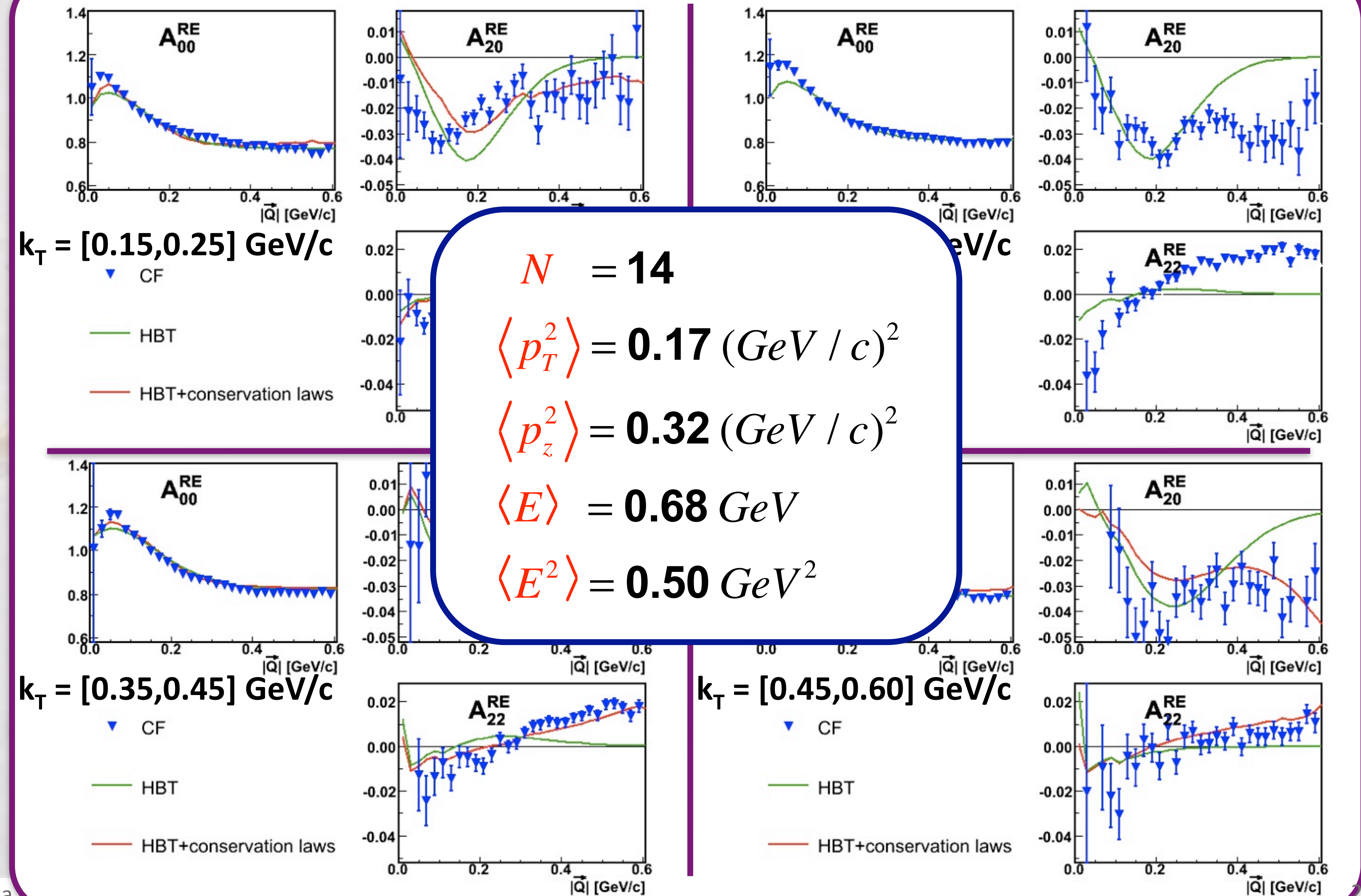


$$N = 14$$

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

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

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

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

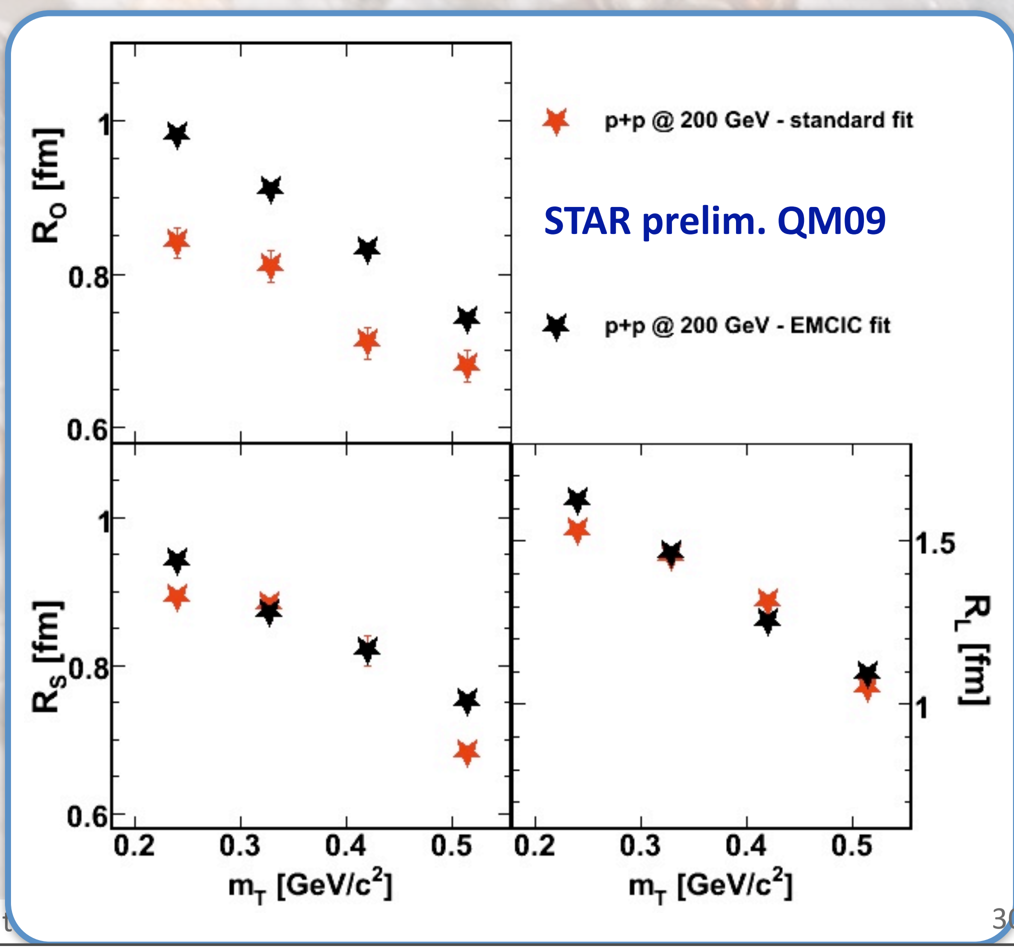
Wednesday, September 16, 2009

“HBT radii” in p+p (STAR@QM09)

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

same acceptance, *same* techniques

- unique opportunity to compare physics



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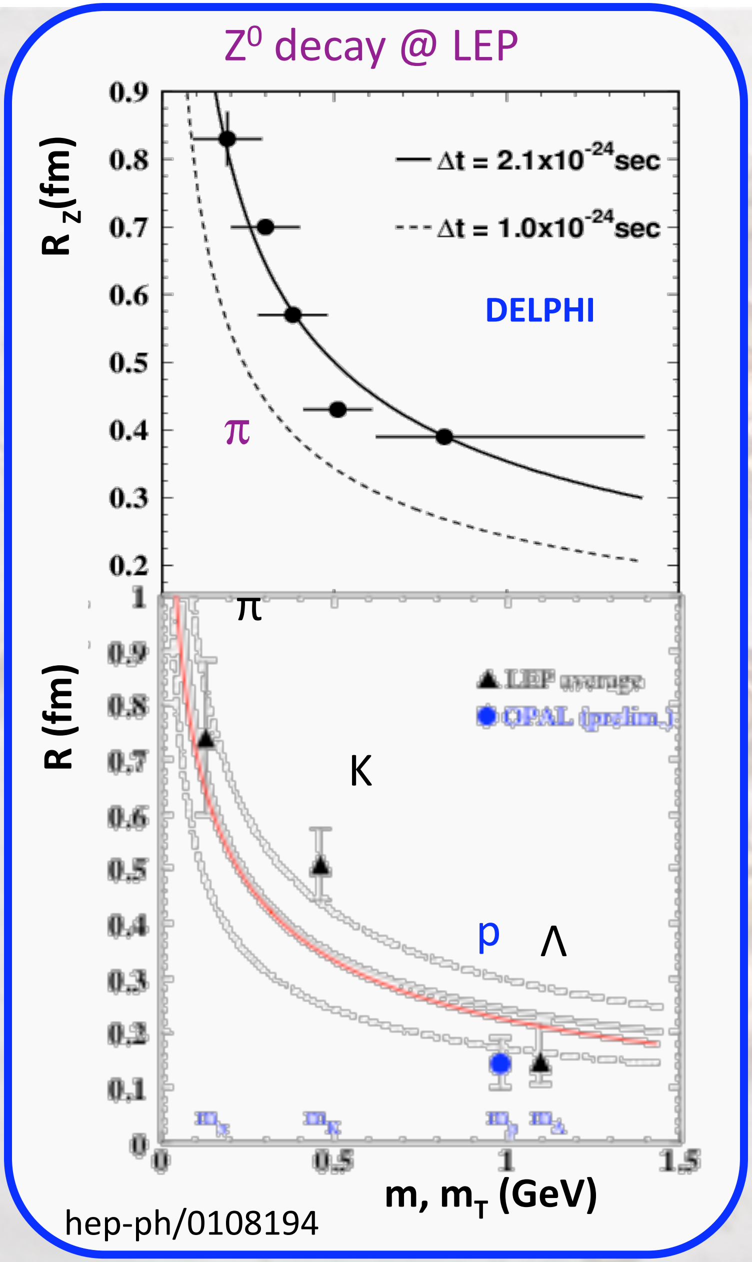

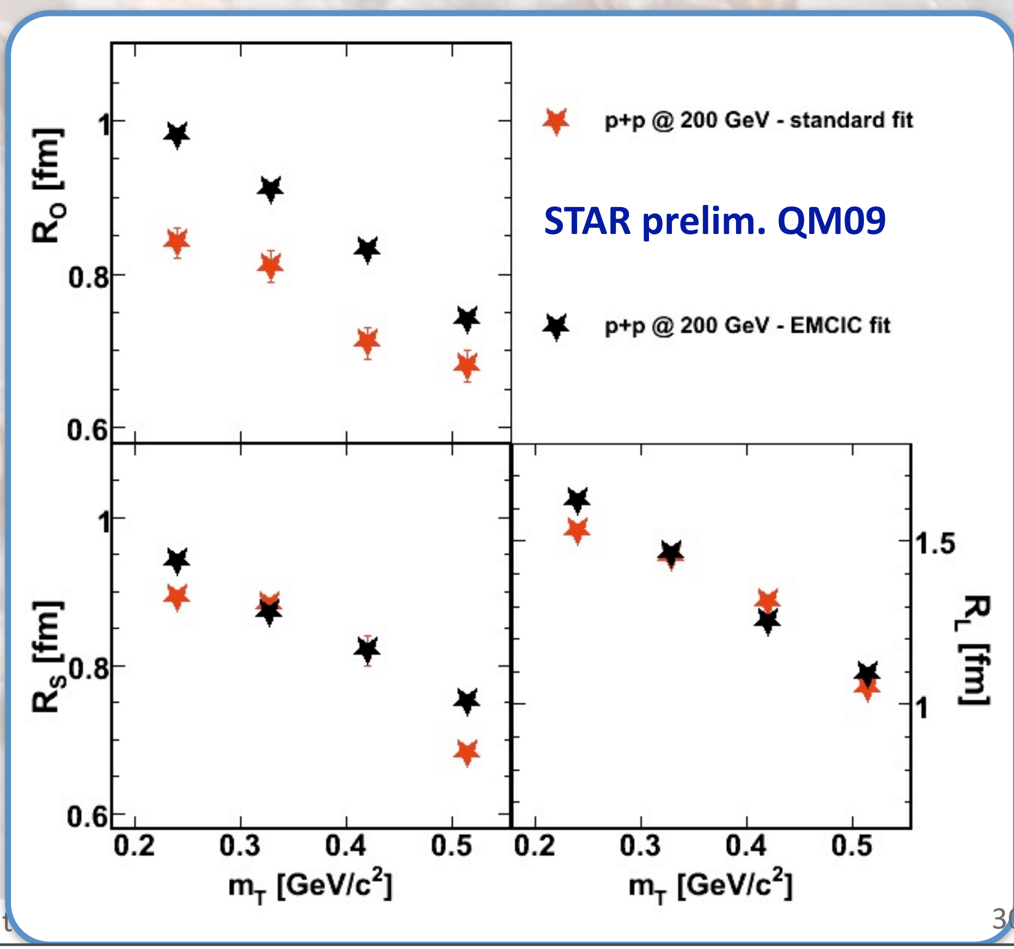

c.f. Z. Chajecki arXiv:0901.4078 [nucl-ex]

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

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

- Increasingly suggested in HEP experiments

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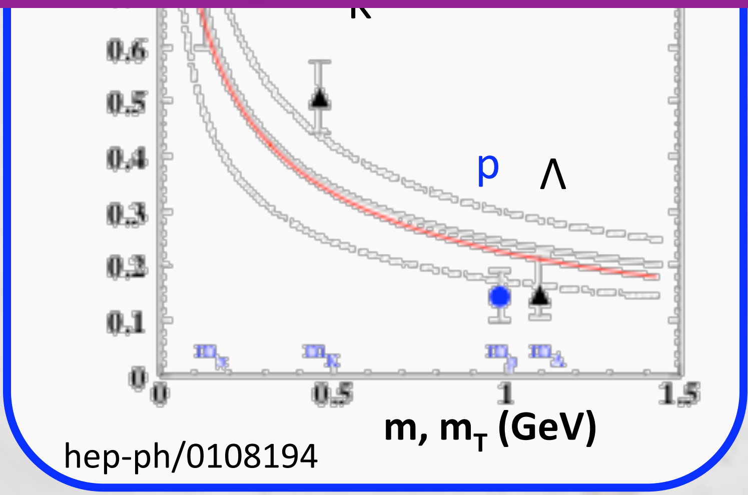

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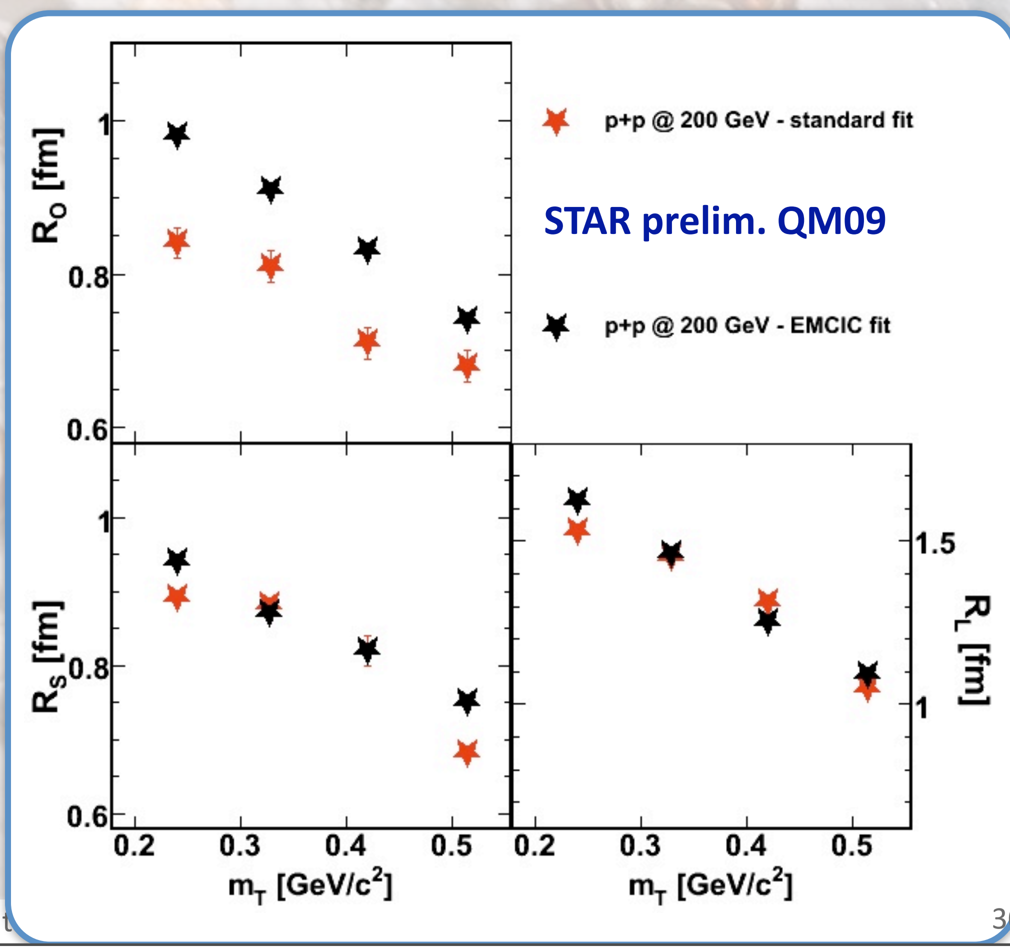

Zbigniew Chajecki QM05

femtoscopy in p+p @ STAR

1. Heisenberg uncertainty?

2. String fragmentation? (Lund)

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4. Flow???

- Increasingly suggested in recent experiments

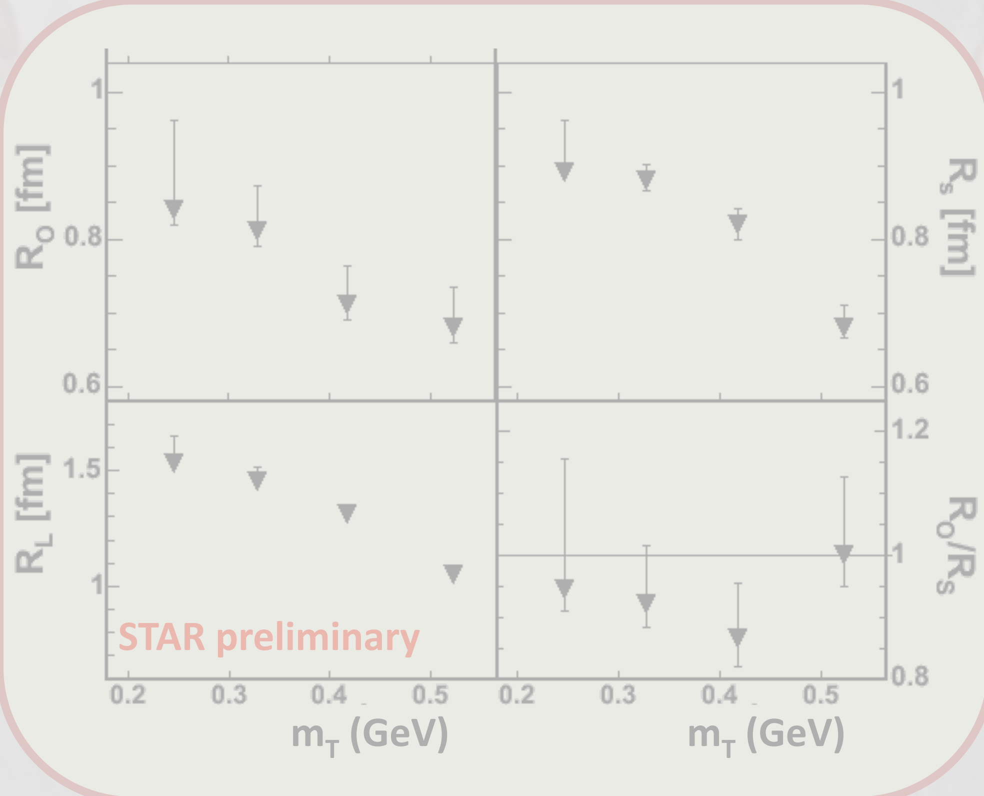
different effect than for Au+Au

Moriond 2000]

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?



Zbigniew Chajecki QM05

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Z^0 decay @ LEP

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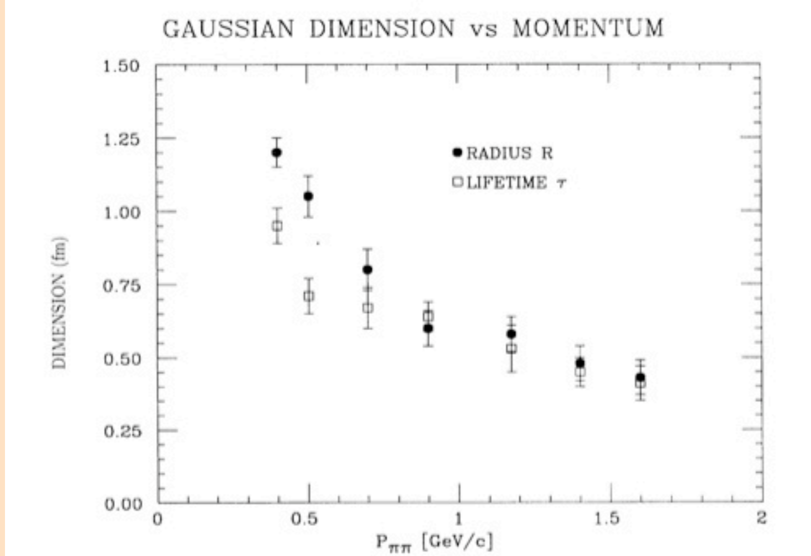

FIG. 9. Interaction "radius" and lifetime as a function of the total momentum $P_{\pi\pi}$ of the pion pair. R_G is primarily a source dimension along the beam direction. τ might possibly be interpreted as a source dimension transverse to the beam. Data are from Table III.

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

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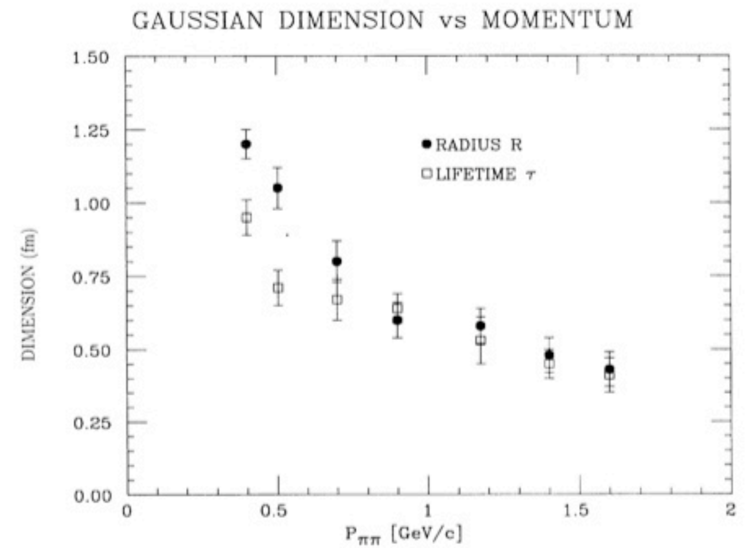
NA22 Collaboration Z. Phys. C 71, 405–414 (1996)
(hadron-hadron collisions)

[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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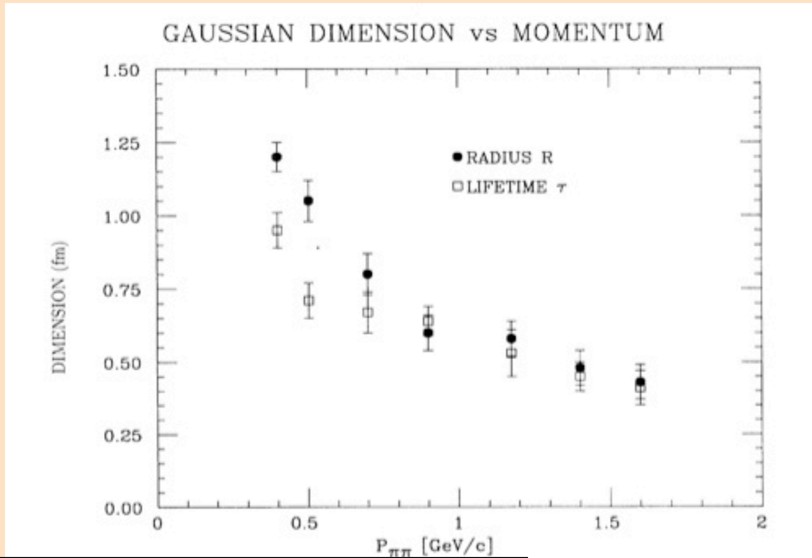

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1931 (1993)

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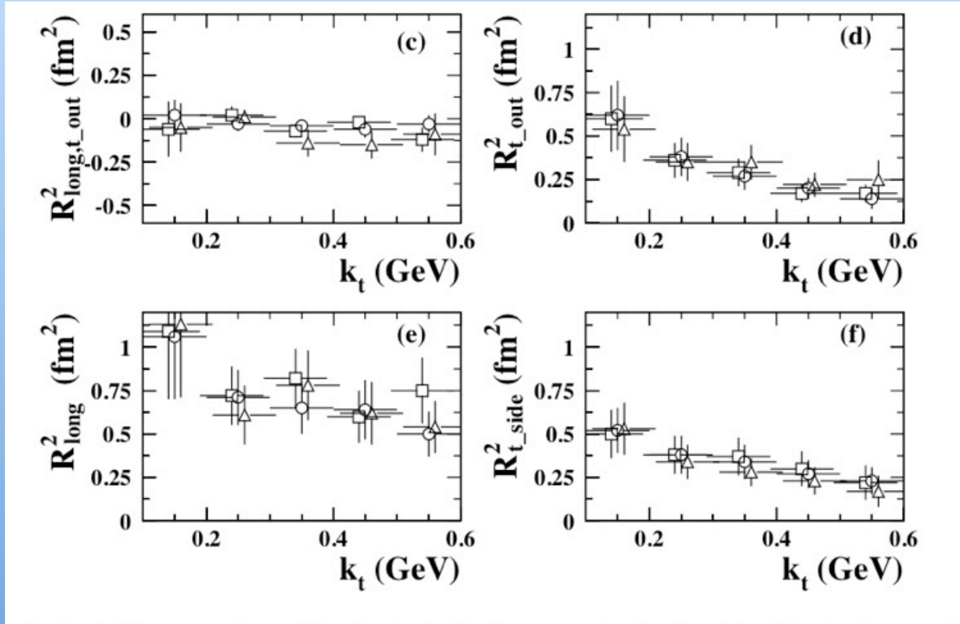
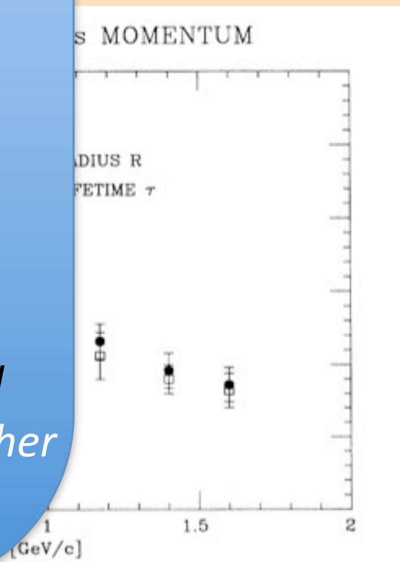
OPAL Collaboration, Eur.Phys.J.C52:787-803,2007; arXiv:0708.1122 [hep-ex]



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.



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

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…ectation from the

RHIC: "comparison machine"

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

- spectra
- femtoscopy

compare with a system we "know" is flowing

R2tsi…
The p…
their …
expands

[GeV/c]

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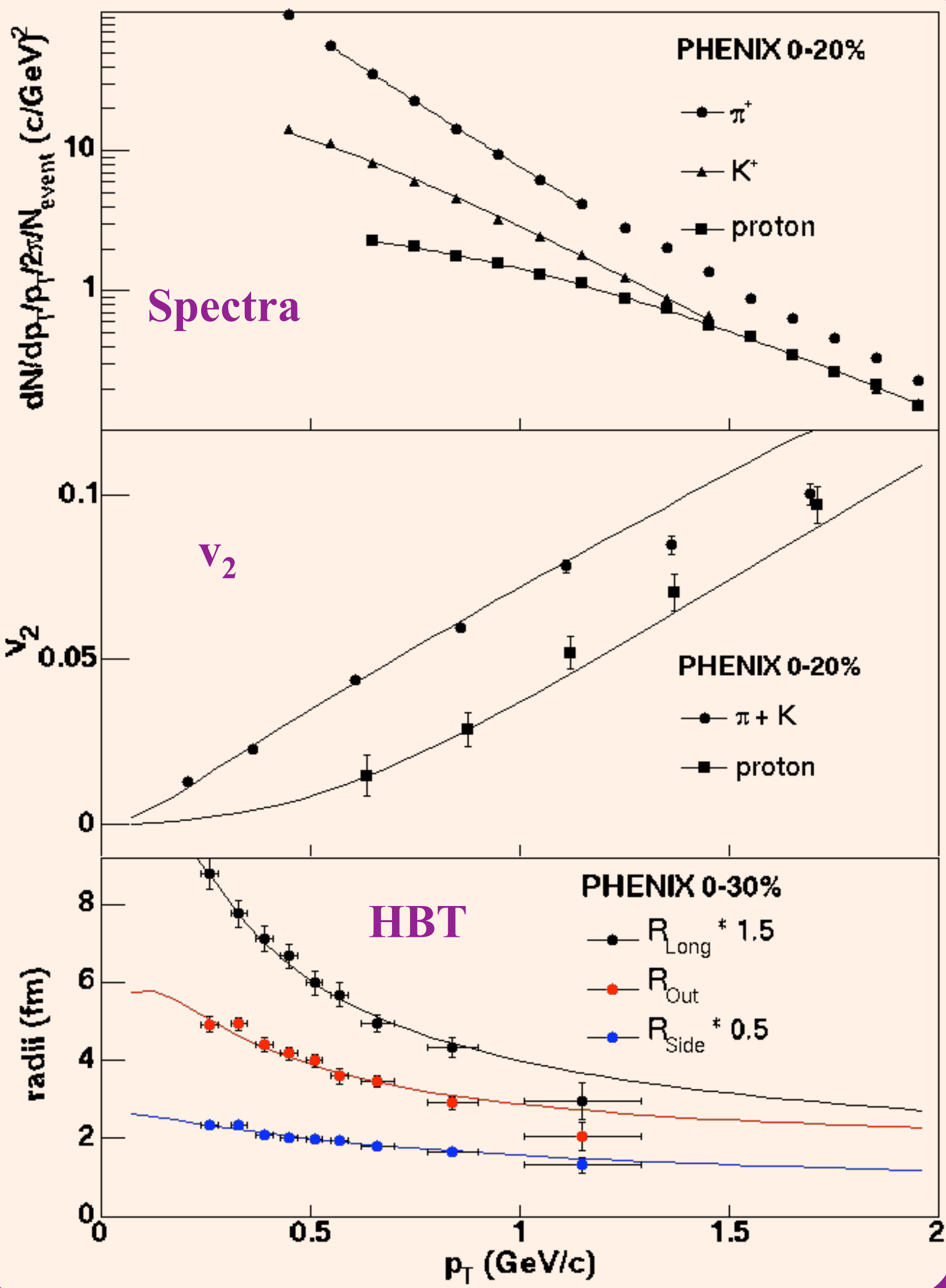


Wednesday, September 16, 2009

Apples:apples comparison…

Z. Chajecki, QM05

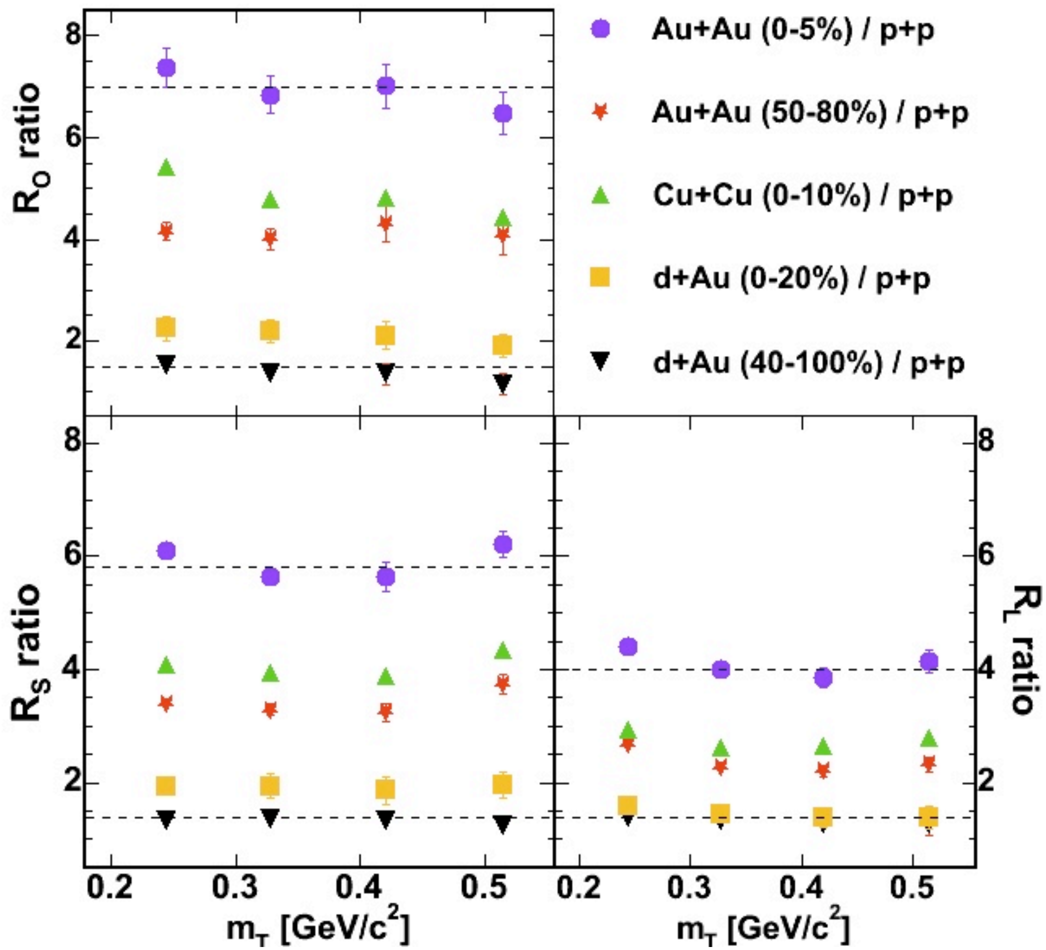
$R(p_T)$ taken as strong space-time evidence of flow in Au+Au

- 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

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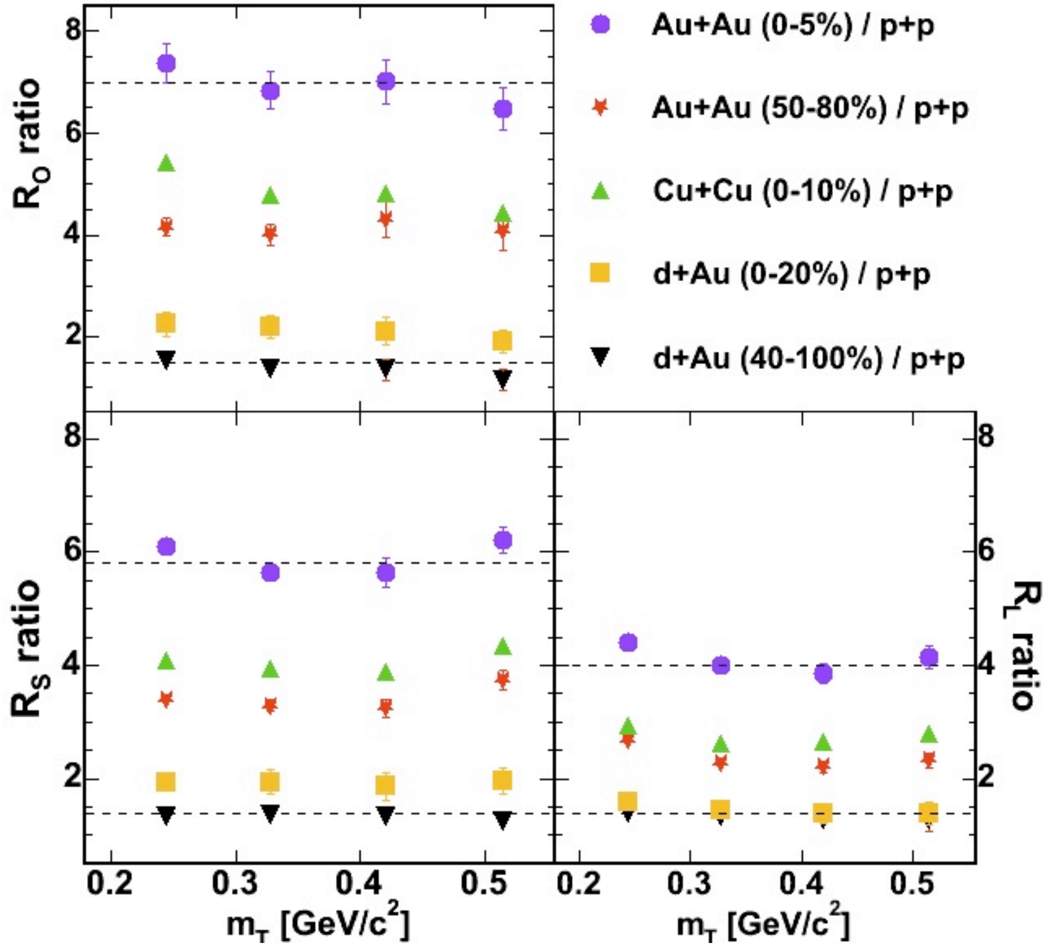

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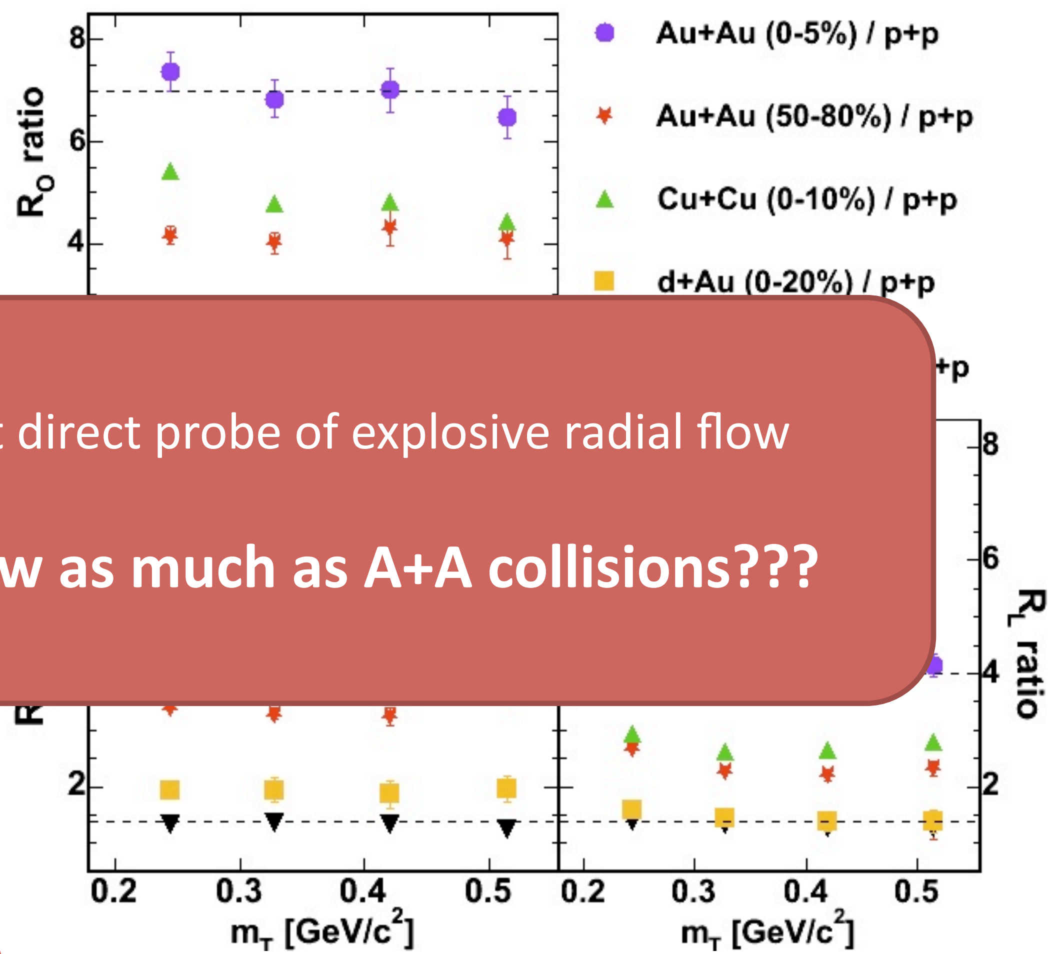


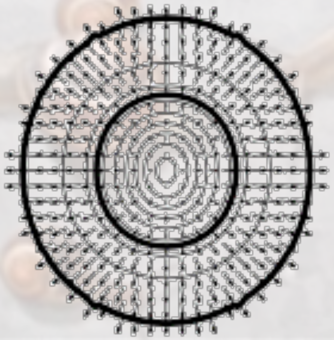
pp, dAu, CuCu - STAR preliminary

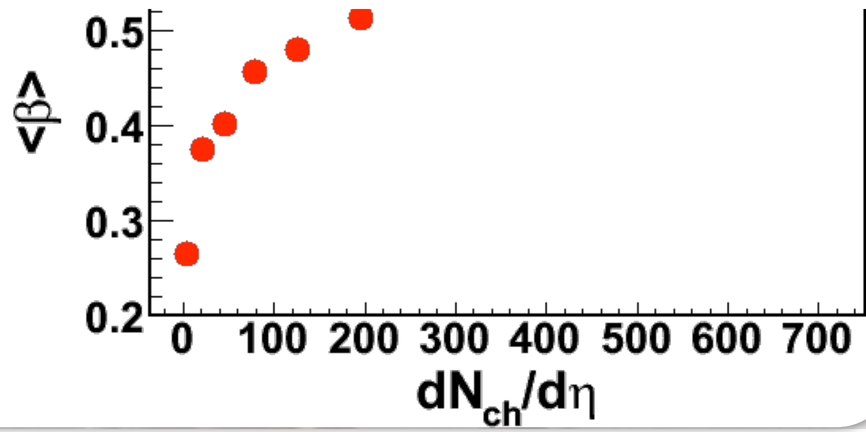
Femtoscopy is the most direct probe of explosive radial flow

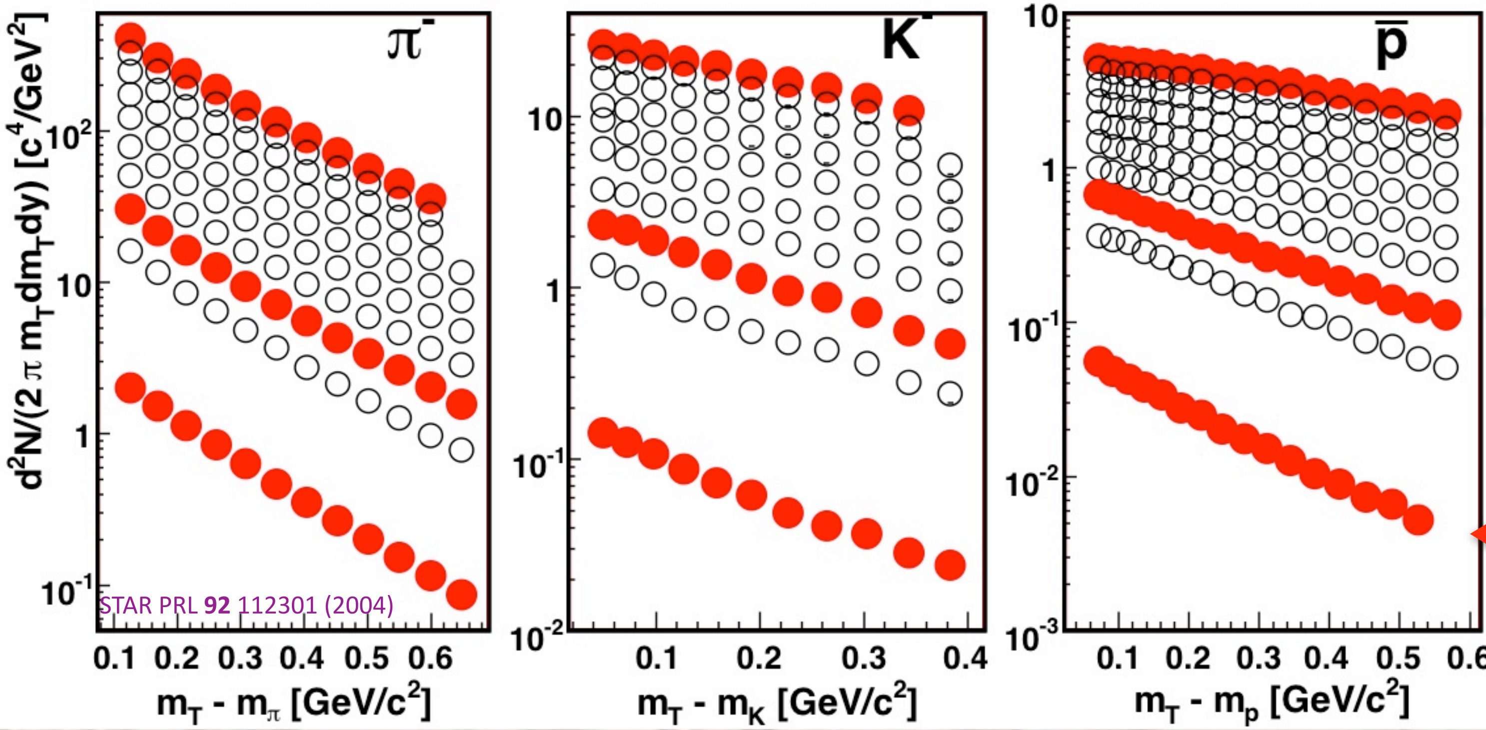
Do p+p collisions flow as much as A+A collisions???

Wednesday, September 16, 2009

NO.....

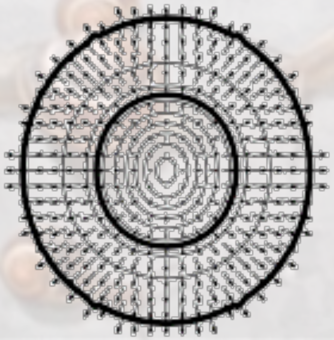


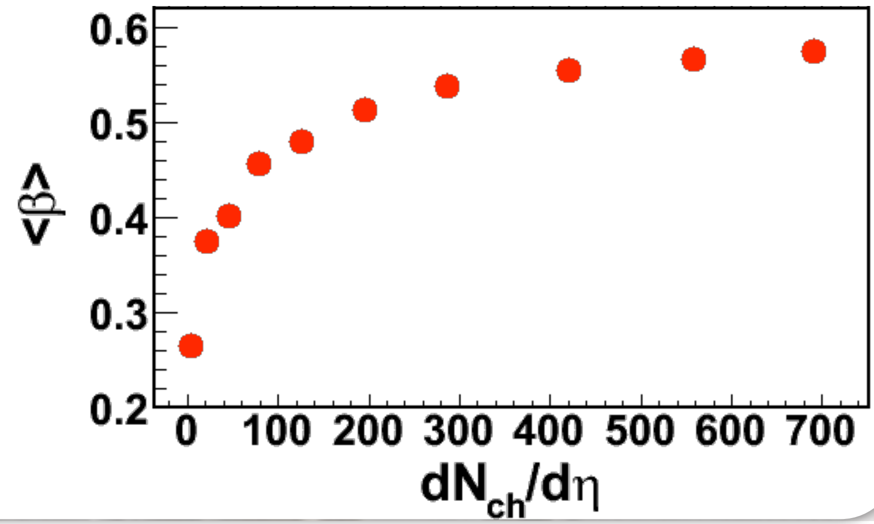




Blast-wave fit to spectra:

- much less explosive flow in p+p collisions





Wednesday, September 16, 2009

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

measured

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

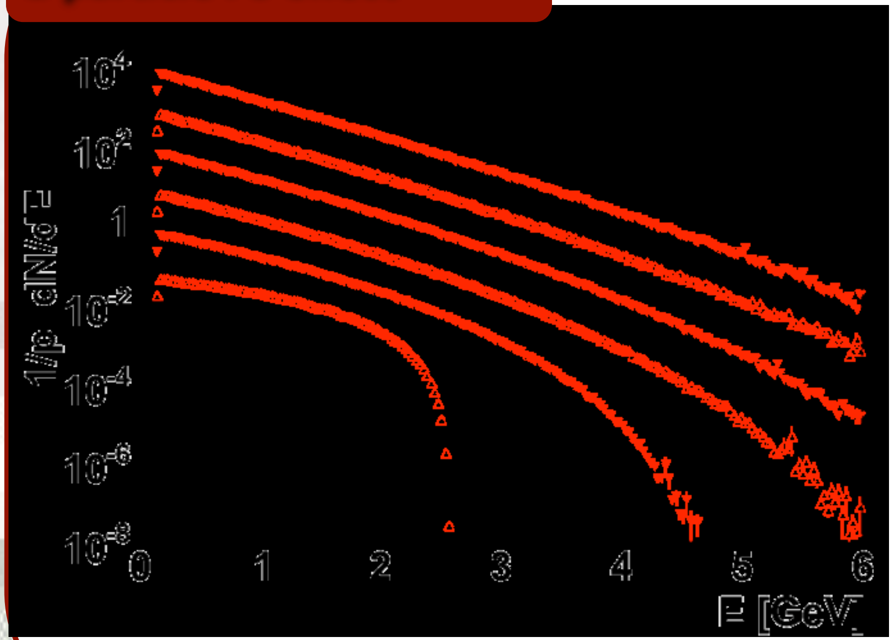
"matrix element"

"distortion" of single-particle spectra

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

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

1-particle PS effect



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

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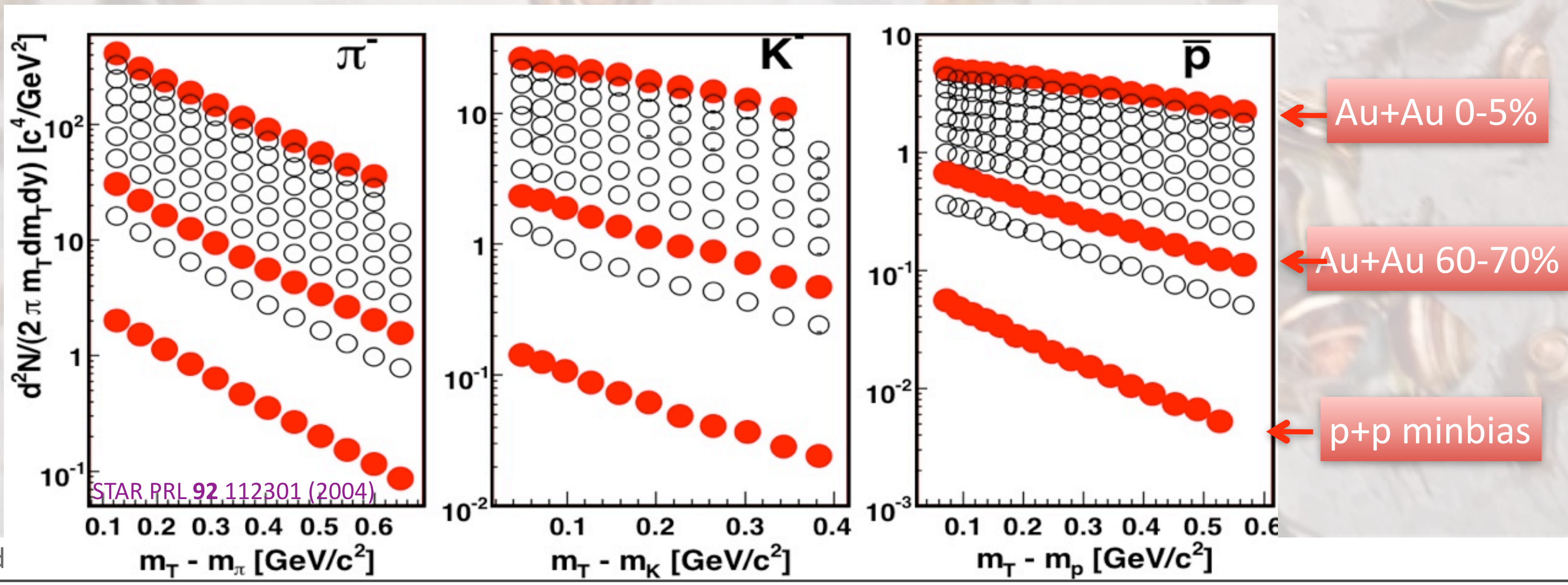
“matrix element”

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

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

** we remove this assumption soon*



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“matrix element”

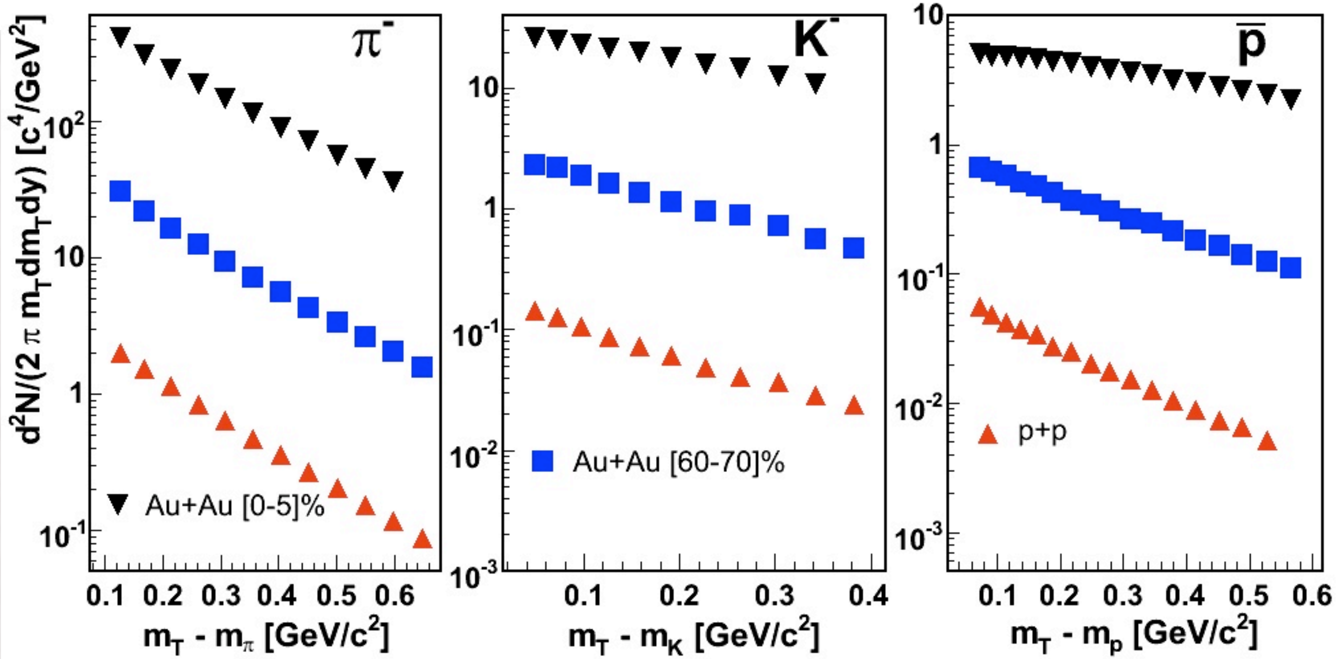
What if the only difference between p+p and A+A collisions was N?

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)



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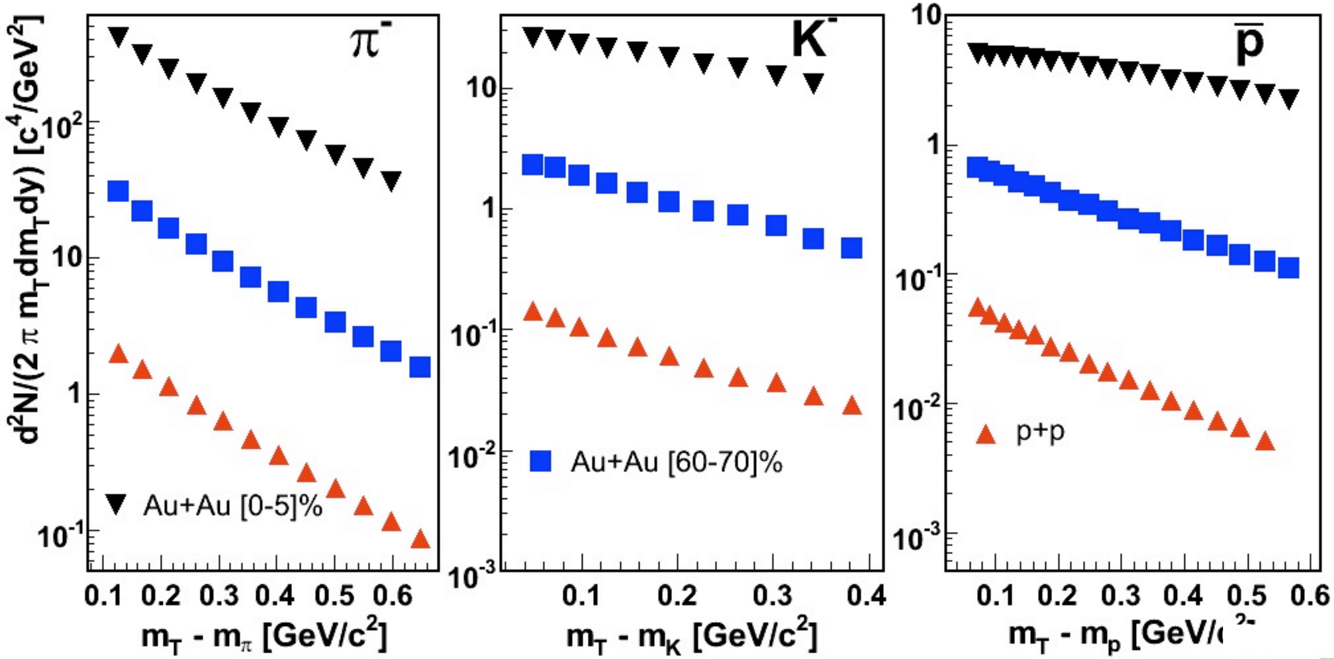

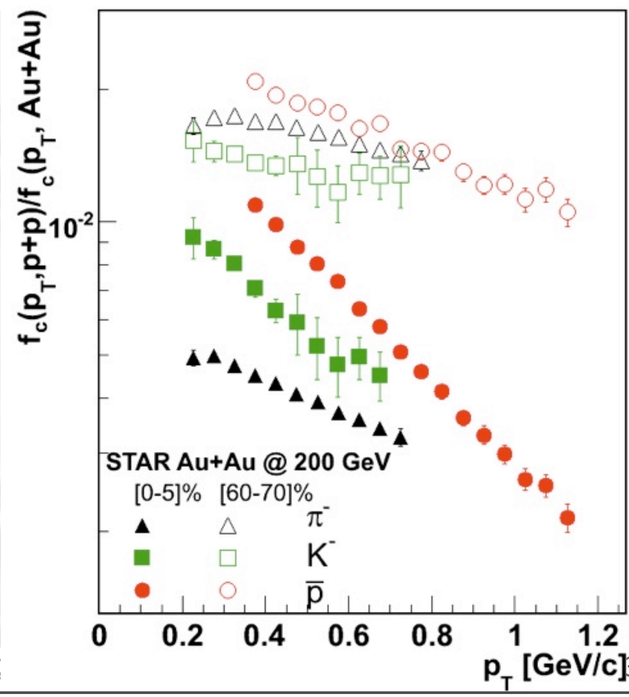

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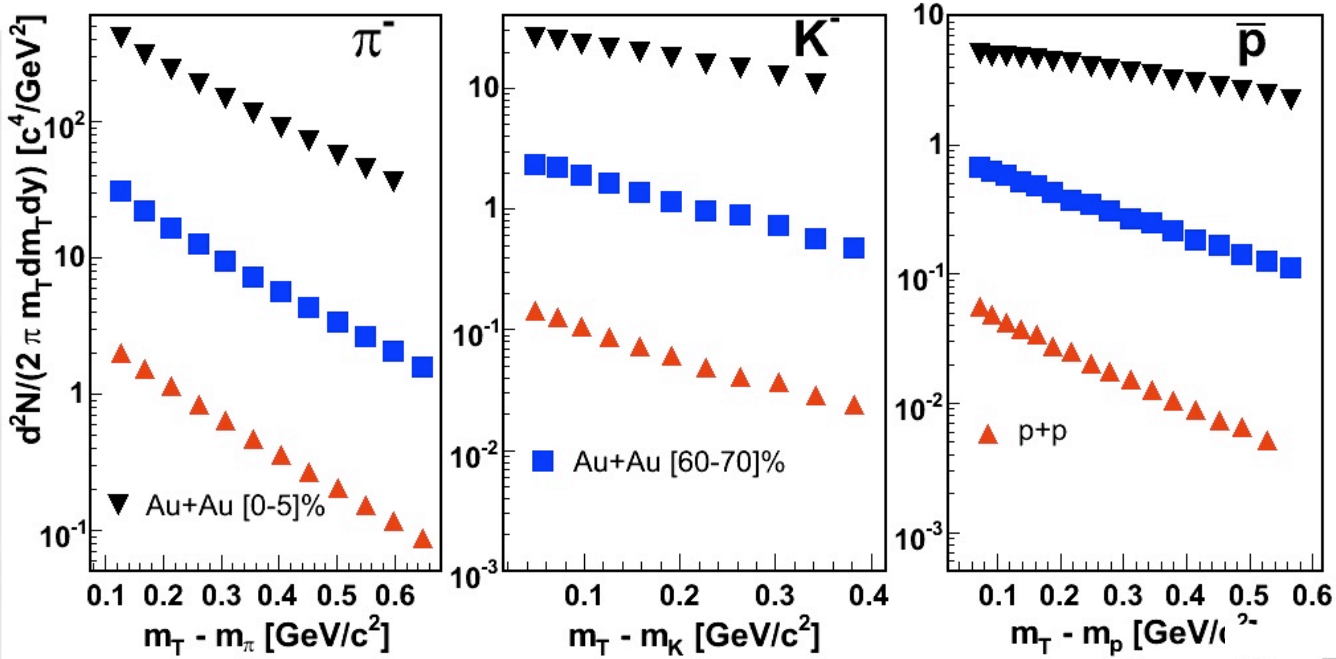
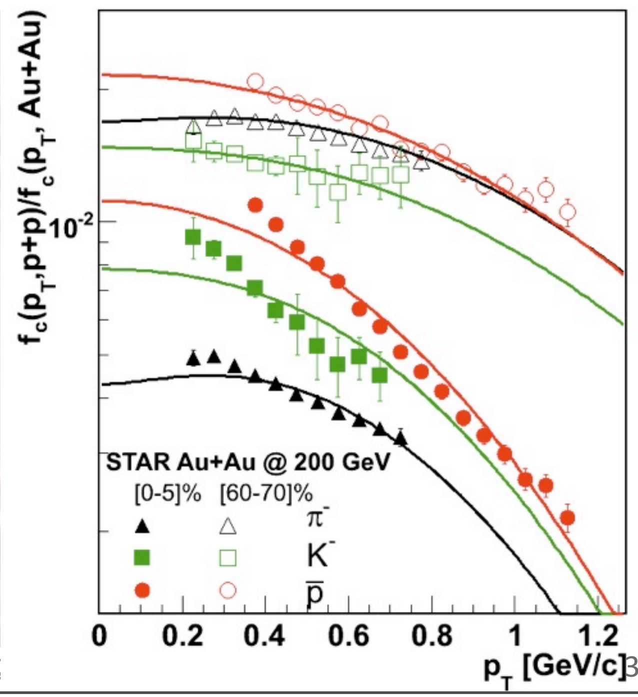


$$\frac{\tilde{f}_c^{pp}\left(p_{T,i}\right)}{\tilde{f}_c^{AA}\left(p_{T,i}\right)} \sim \exp\left(\left(\frac{1}{2\left(N_{AA}-1\right)}-\frac{1}{2\left(N_{pp}-1\right)}\right)\left(\frac{2p_{T,i}^2}{\left\langle p_T^2\right\rangle}+\frac{\left(E_i-\left\langle E\right\rangle\right)^2}{\left\langle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

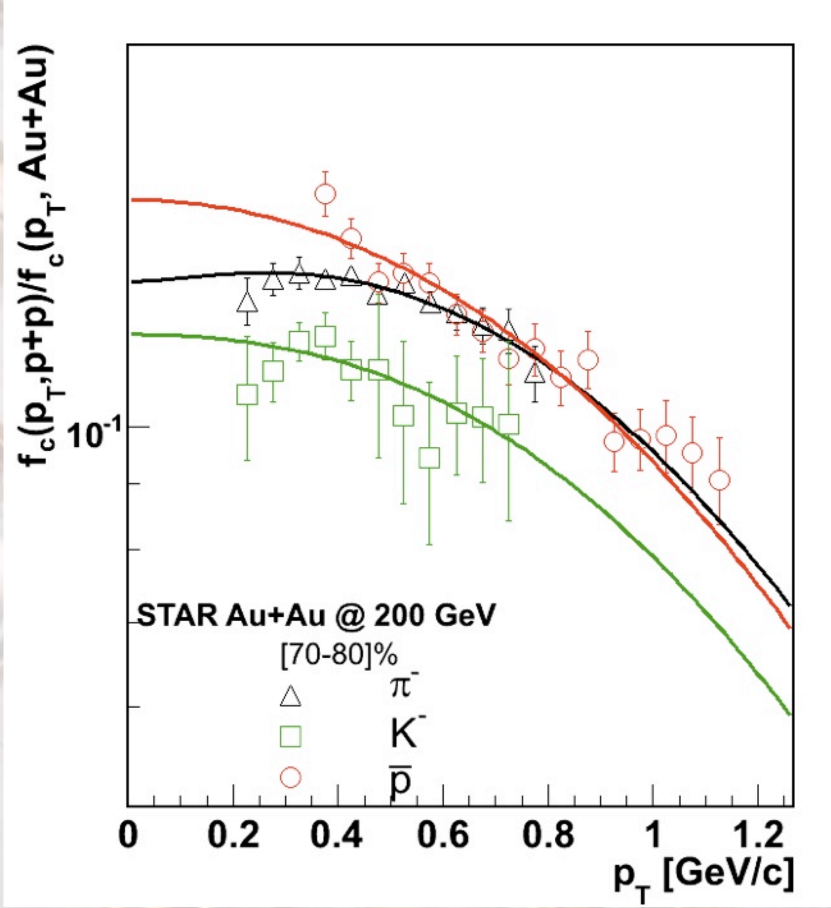
N evolution of spectra dominated by PS "distortion"

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



IMPT: What changes with multiplicity…?

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	”	”	”



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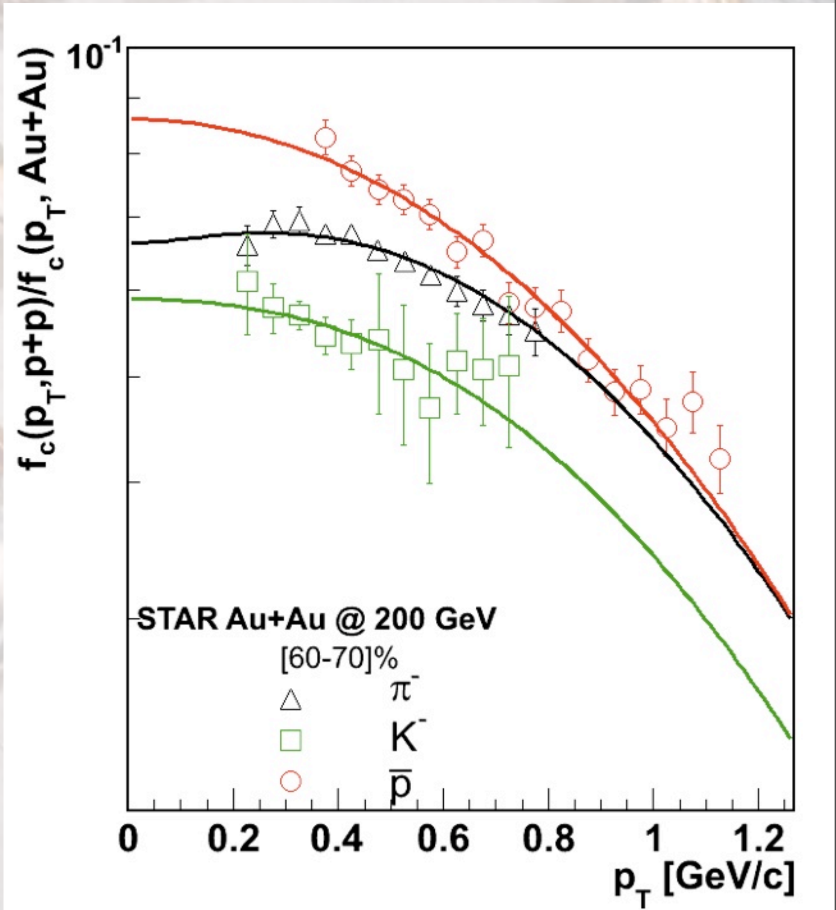

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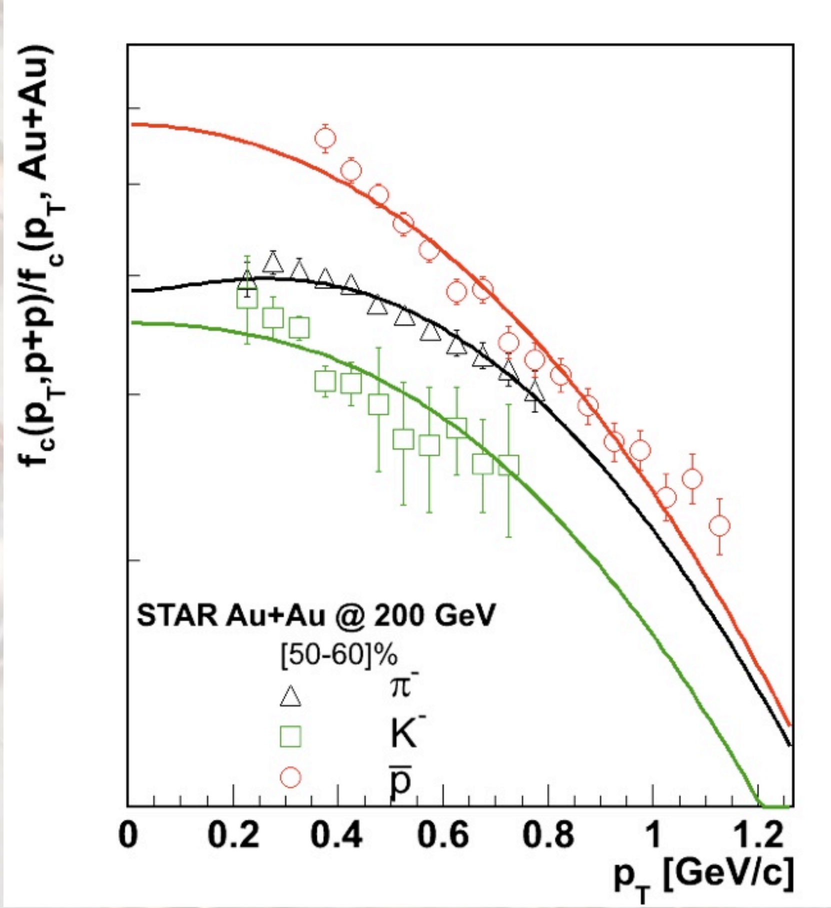

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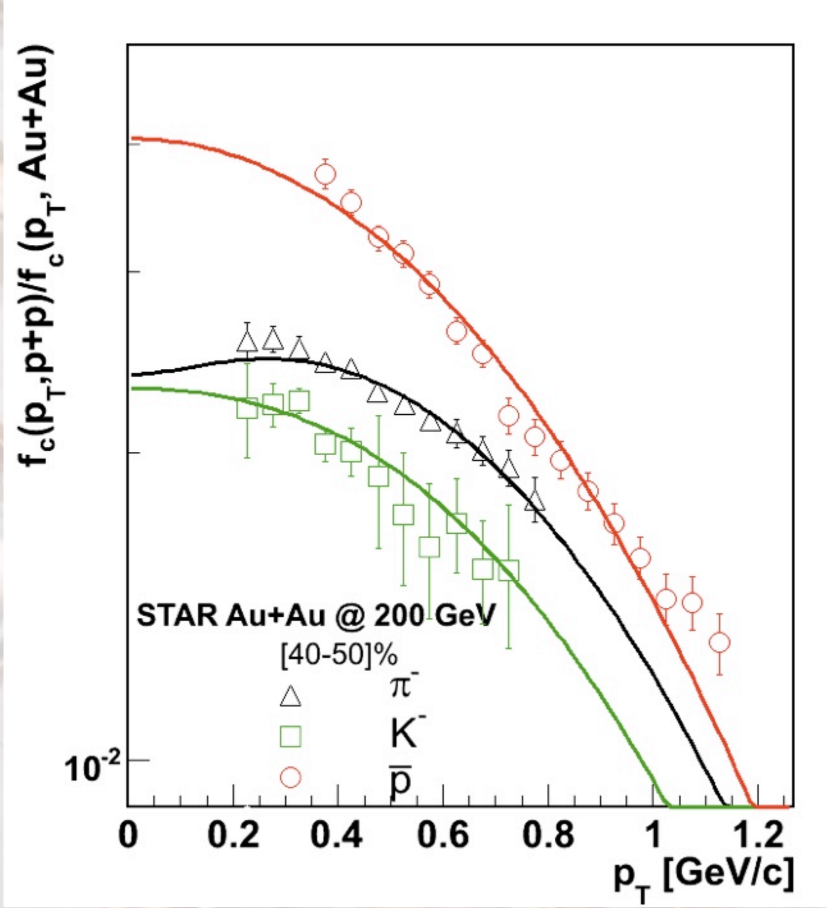
$Au+Au$ 40-50%	38.7	"	"	"



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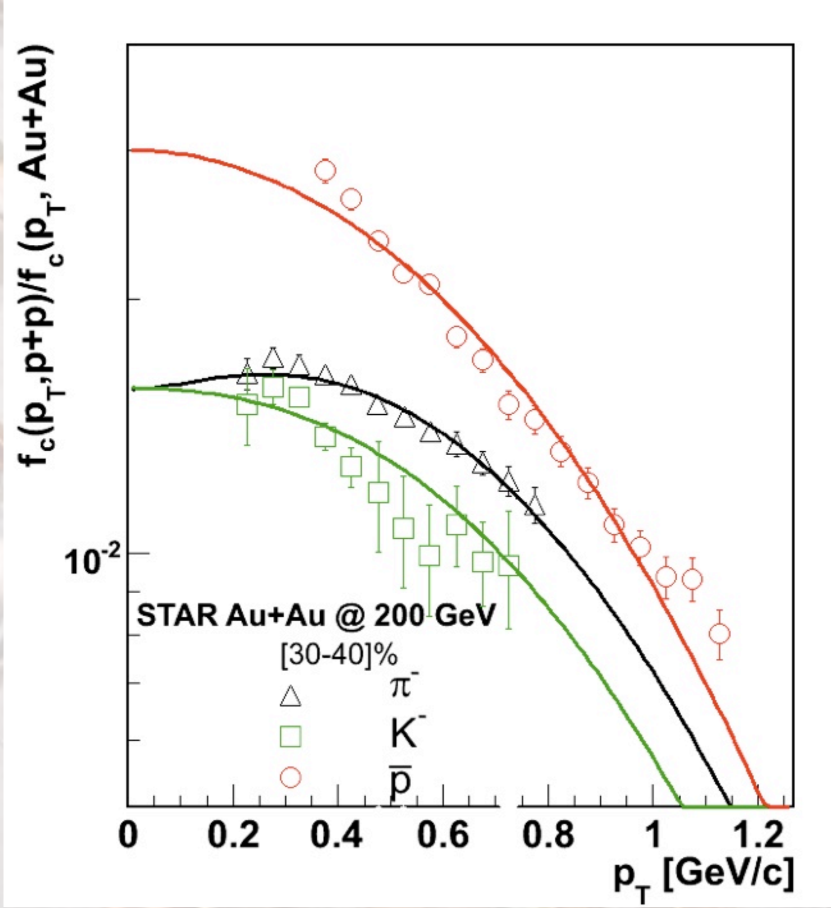
$Au+Au$ 40-50%	38.7	"	"	"
$Au+Au$ 30-40%	67.6	"	"	"



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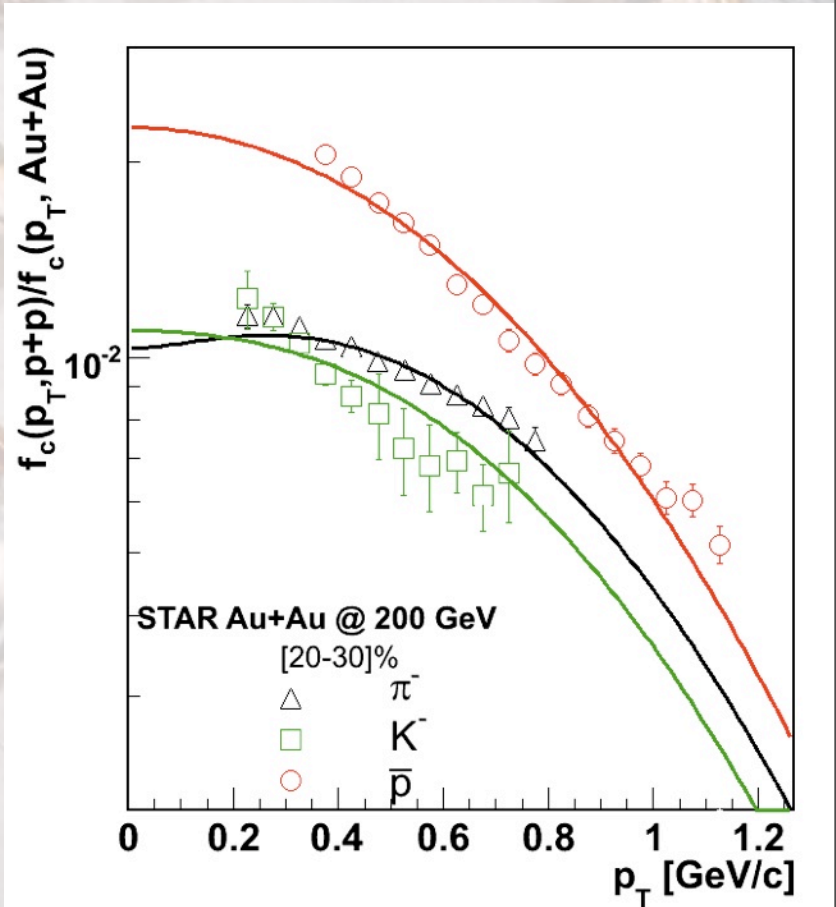
$Au+Au$ 30-40%	67.6	"	"	"
$Au+Au$ 20-30%	219	"	"	"



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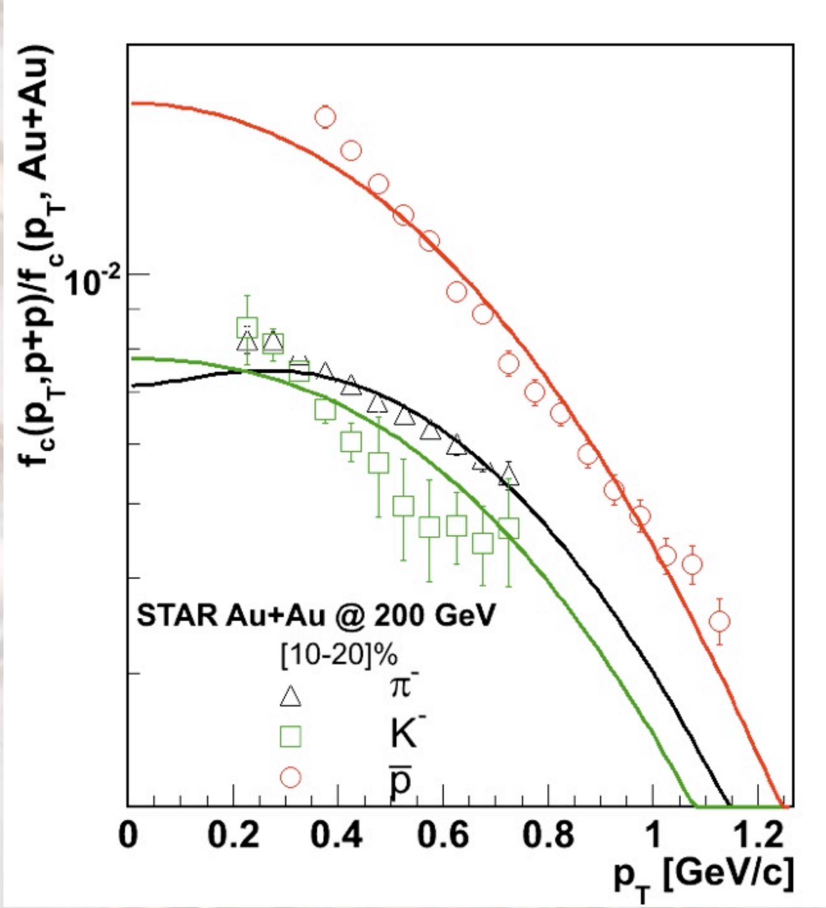
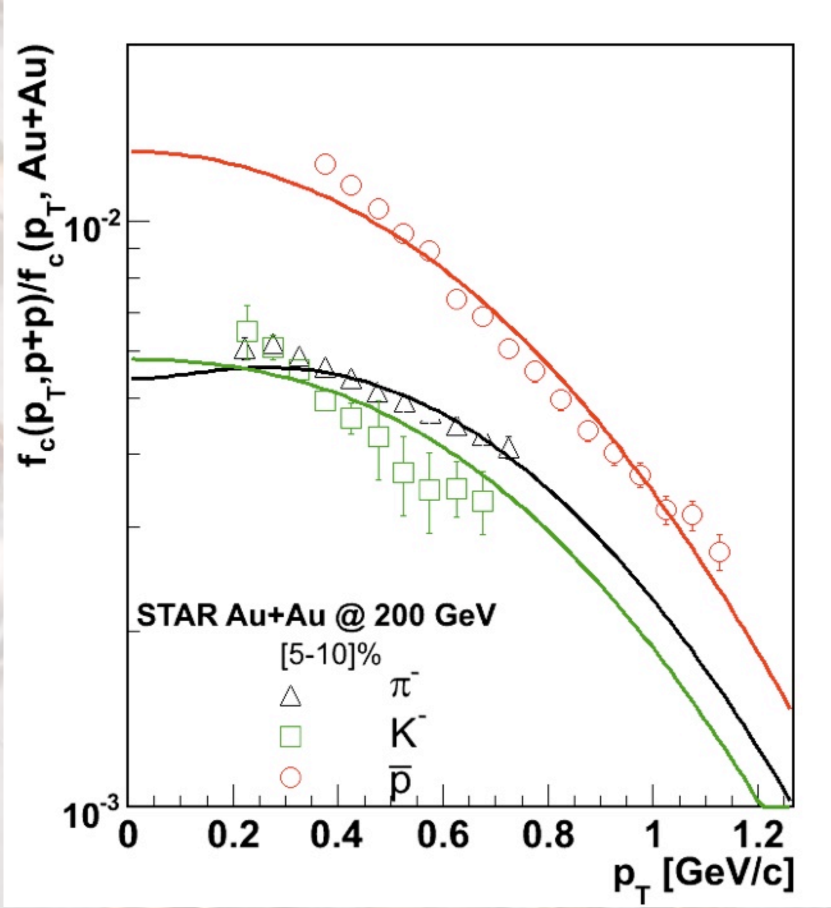
$Au+Au$ 20-30%	219	”	”	”
$Au+Au$ 10-20%	> 300	”	”	”



IMPT: What changes with multiplicity…?

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	"	"	"
$Au+Au$ 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	"	"	"



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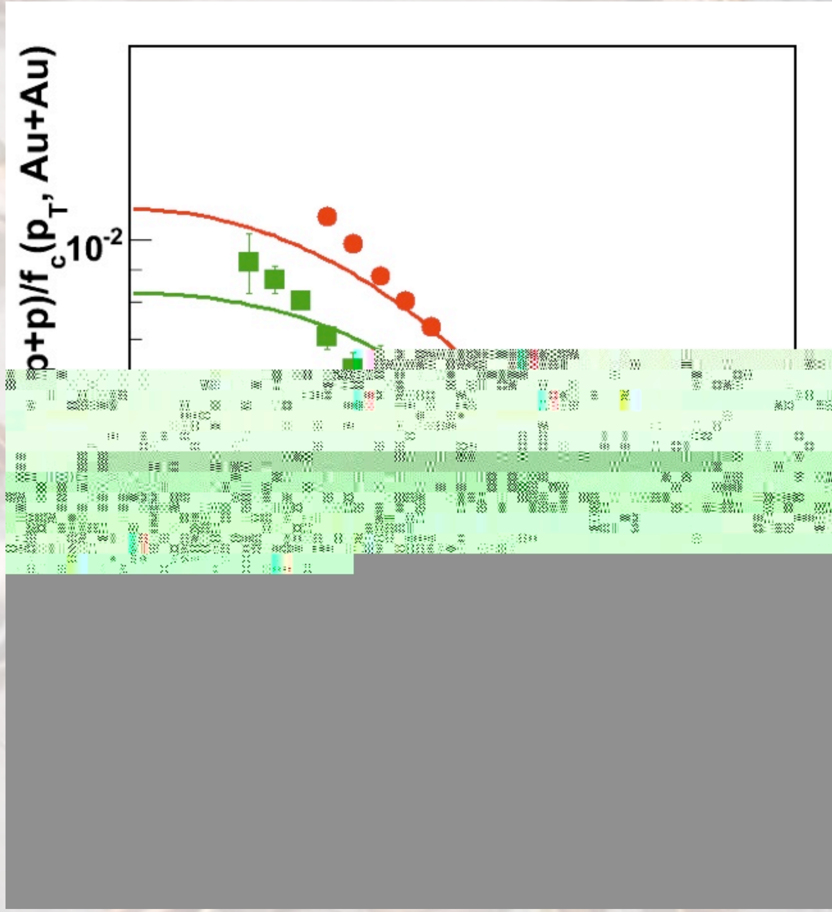
$Au+Au$ 5-10%	> 300	"	"	"
$Au+Au$ 0-5%	> 300	"	"	"



IMPT: What changes with multiplicity…?

multiplicity does !!

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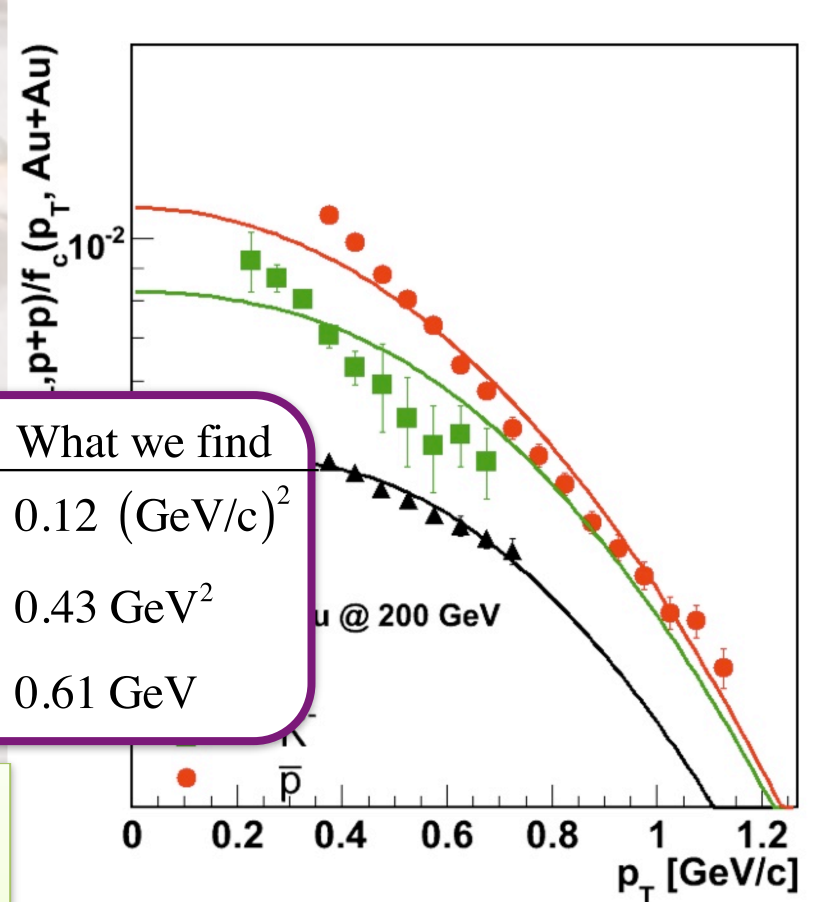
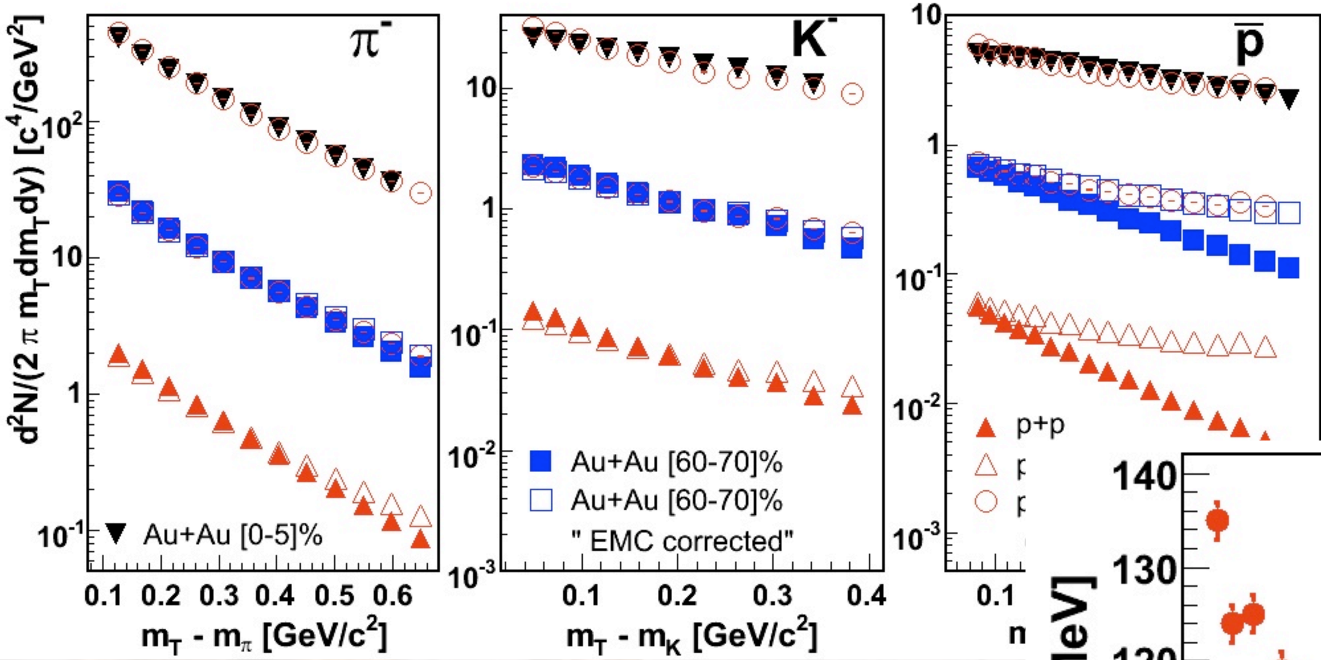


	non-rel	ultra-rel	if $T = .15 \div .35$	What we find
$\langle p_T^2 \rangle$	$2mT$	$8T^2$	$0.045 \div 0.98\ (\mathrm{GeV/c})^2$	$0.12\ (\mathrm{GeV/c})^2$
$\langle E^2 \rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5\ \mathrm{GeV}^2$	$0.43\ \mathrm{GeV}^2$
$\langle E \rangle$	$\frac{3}{2}T + m$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

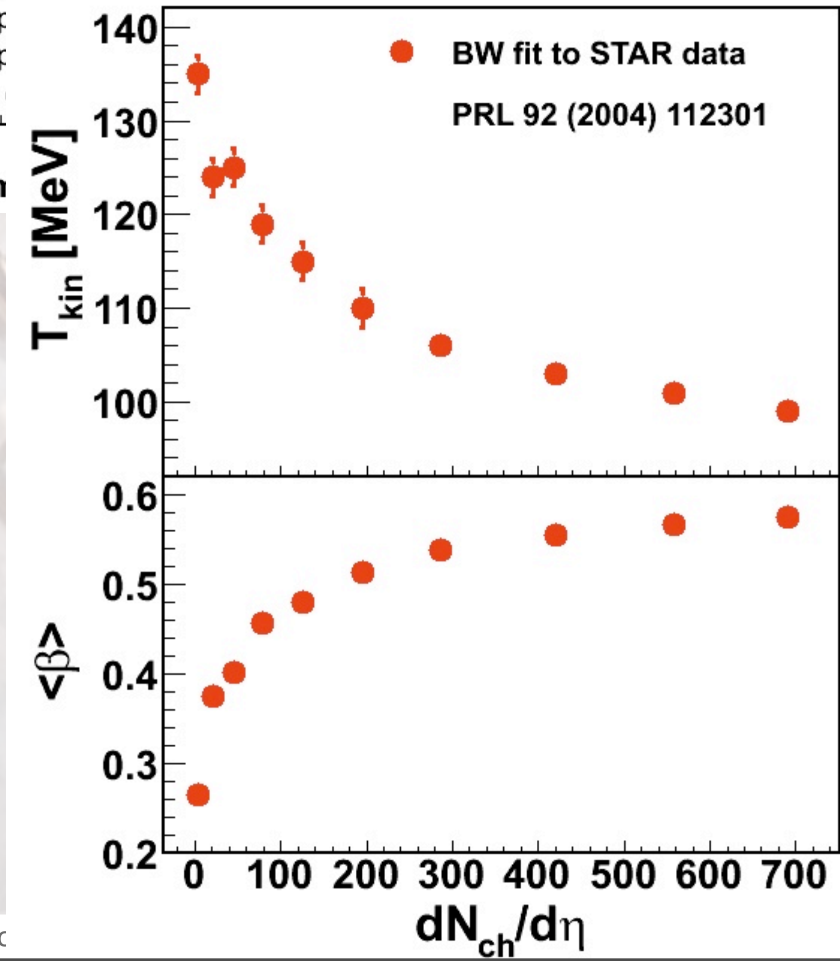
postulate of *same* parent consistent with *all* spectra

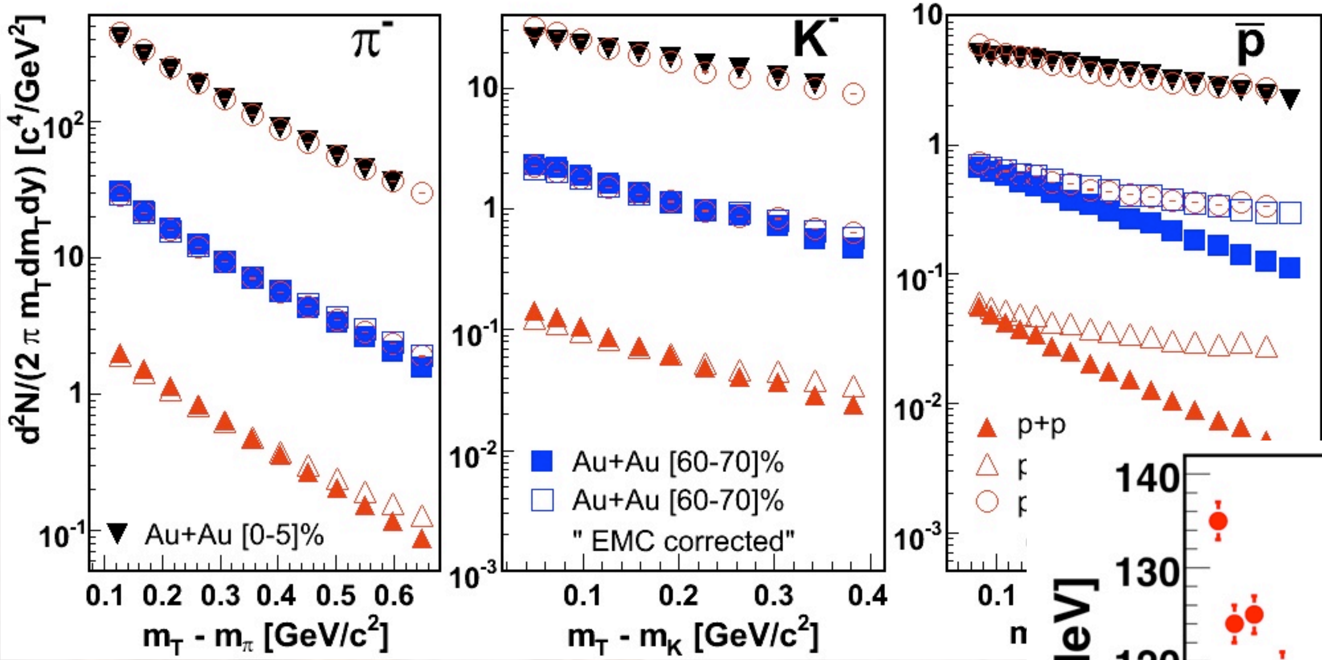
- magnitude
- pT dependence (shape)
- mass dependence



By popular demand

(you've already seen the impressive result)





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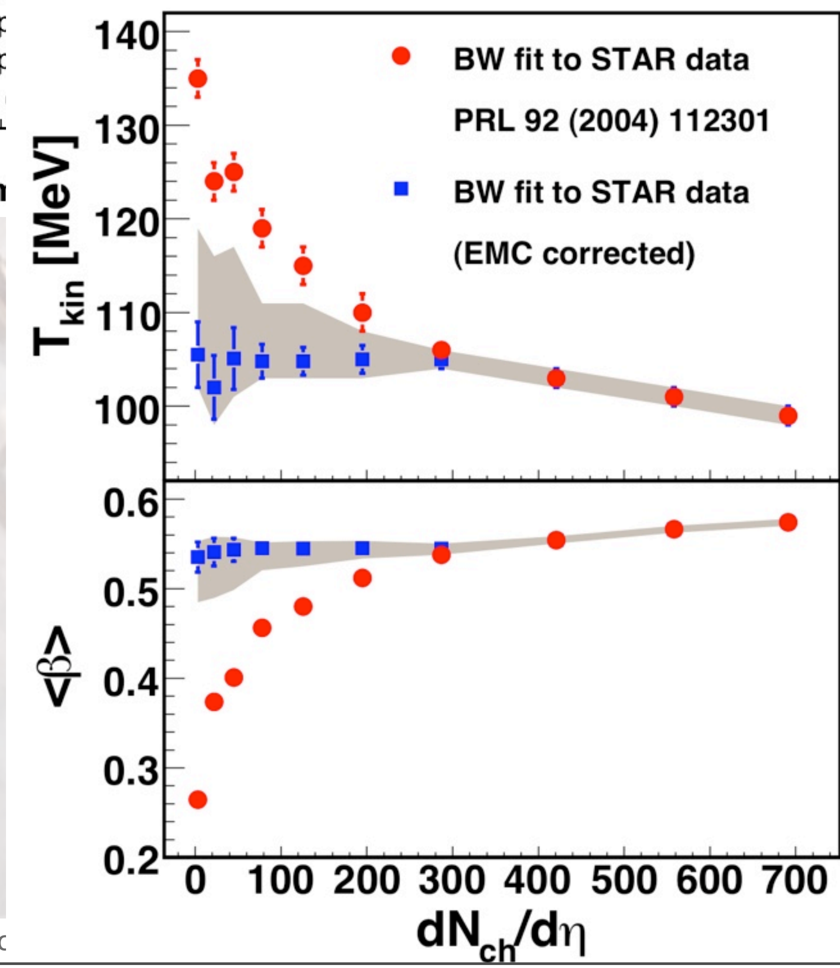
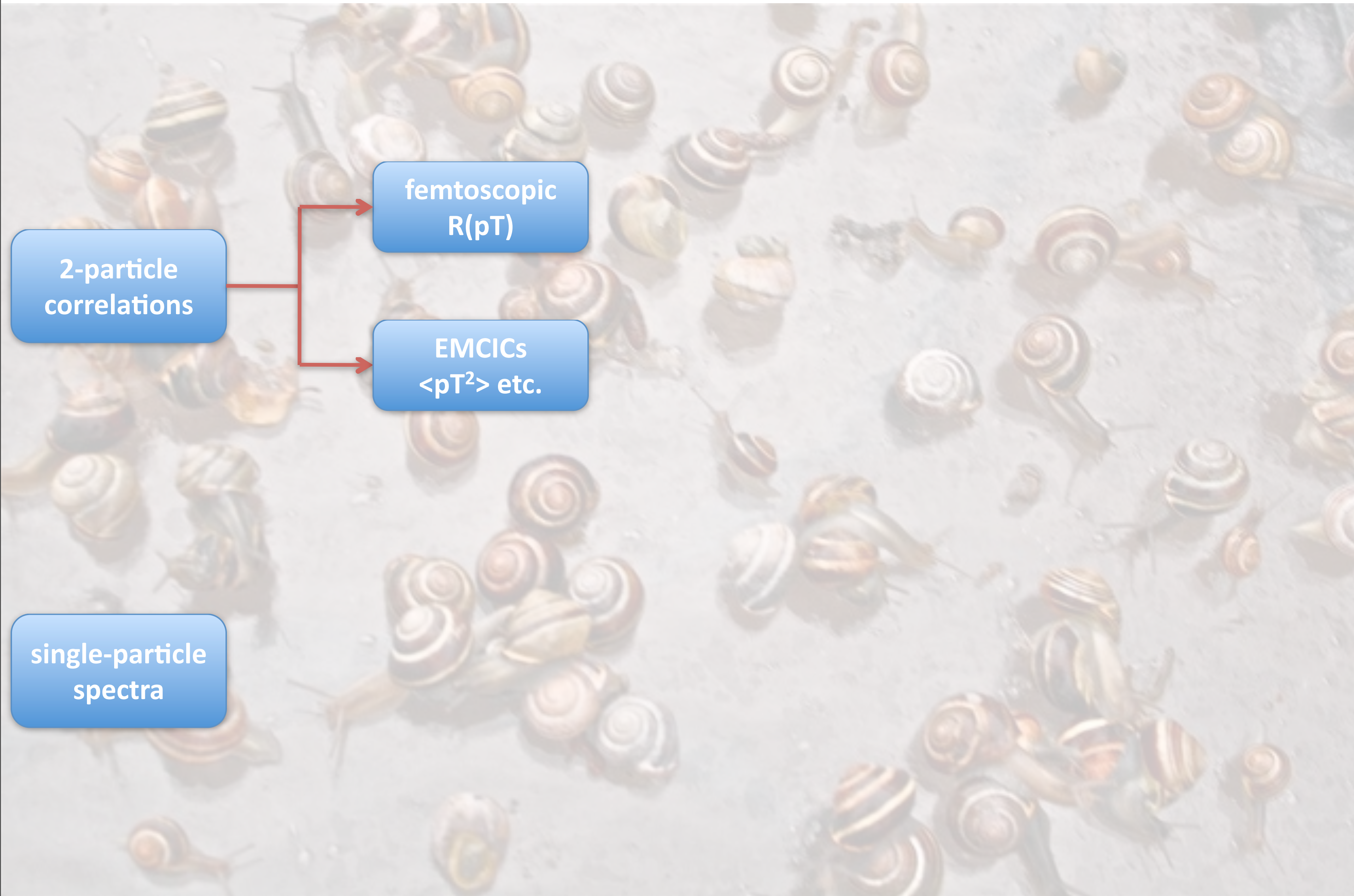


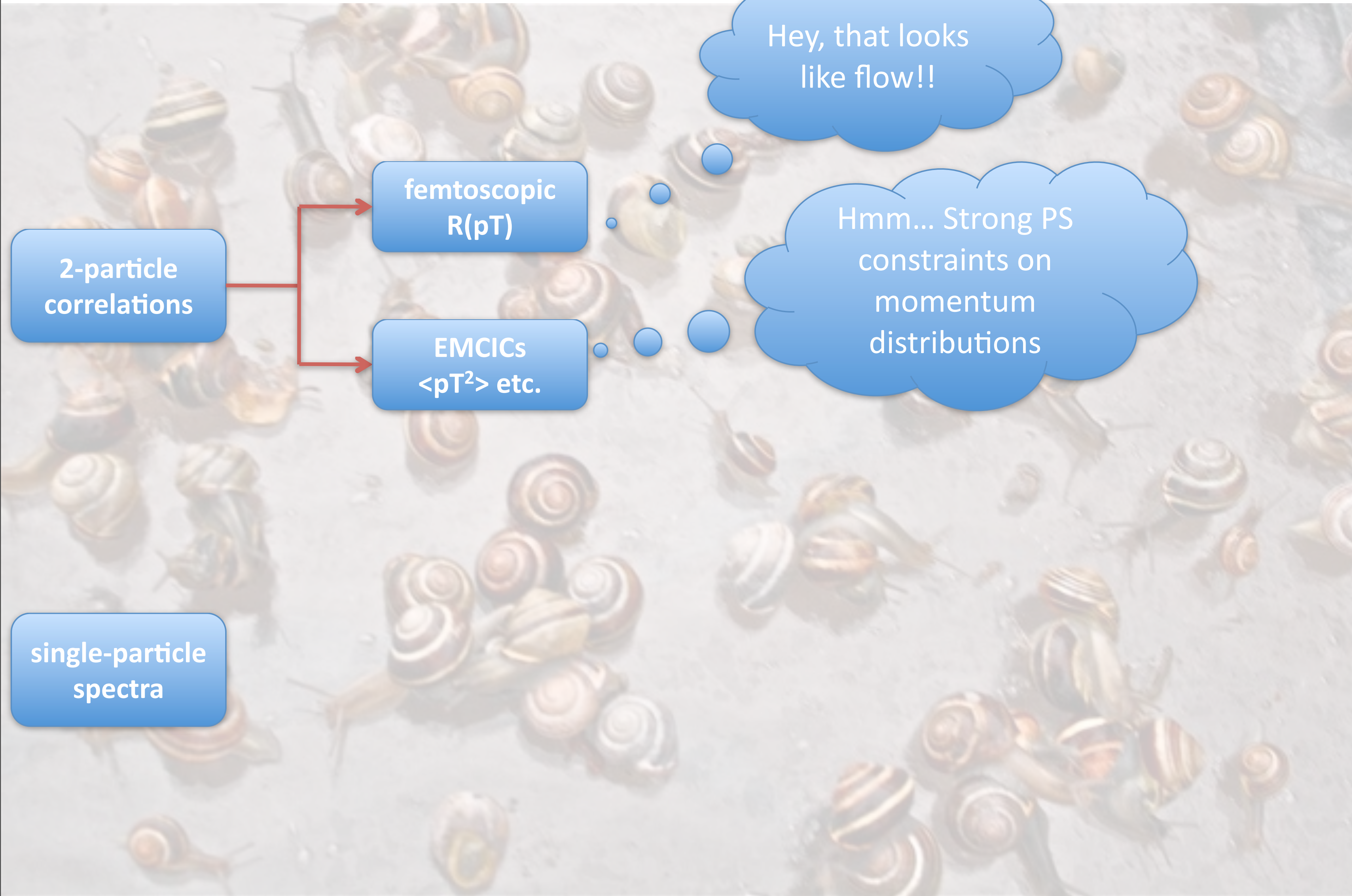
Almost universal "flow" & "temperature" parameters in a BlastWave fit

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

2-particle correlations

single-particle spectra


femtoscopic
R(pT)
2-particle
correlations
EMCICs
<pT²> etc.
single-particle
spectra



2-particle correlations

femtoscopic R(pT)

EMCICs $\langle p_T^2 \rangle$ etc.

Hey, that looks like flow!!

Hmm… Strong PS constraints on momentum distributions

single-particle spectra

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2-particle correlations

femtoscopic R(pT)

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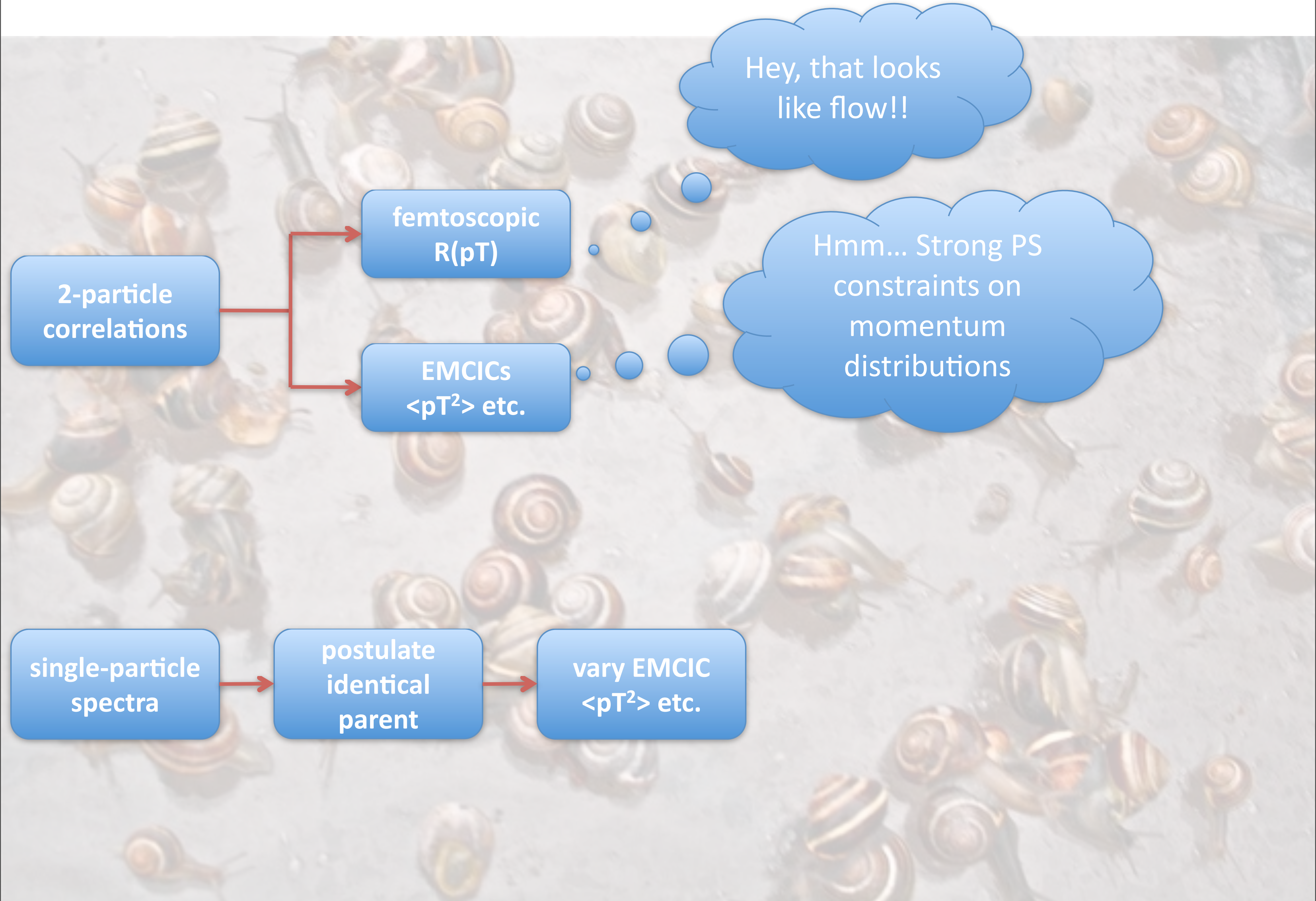
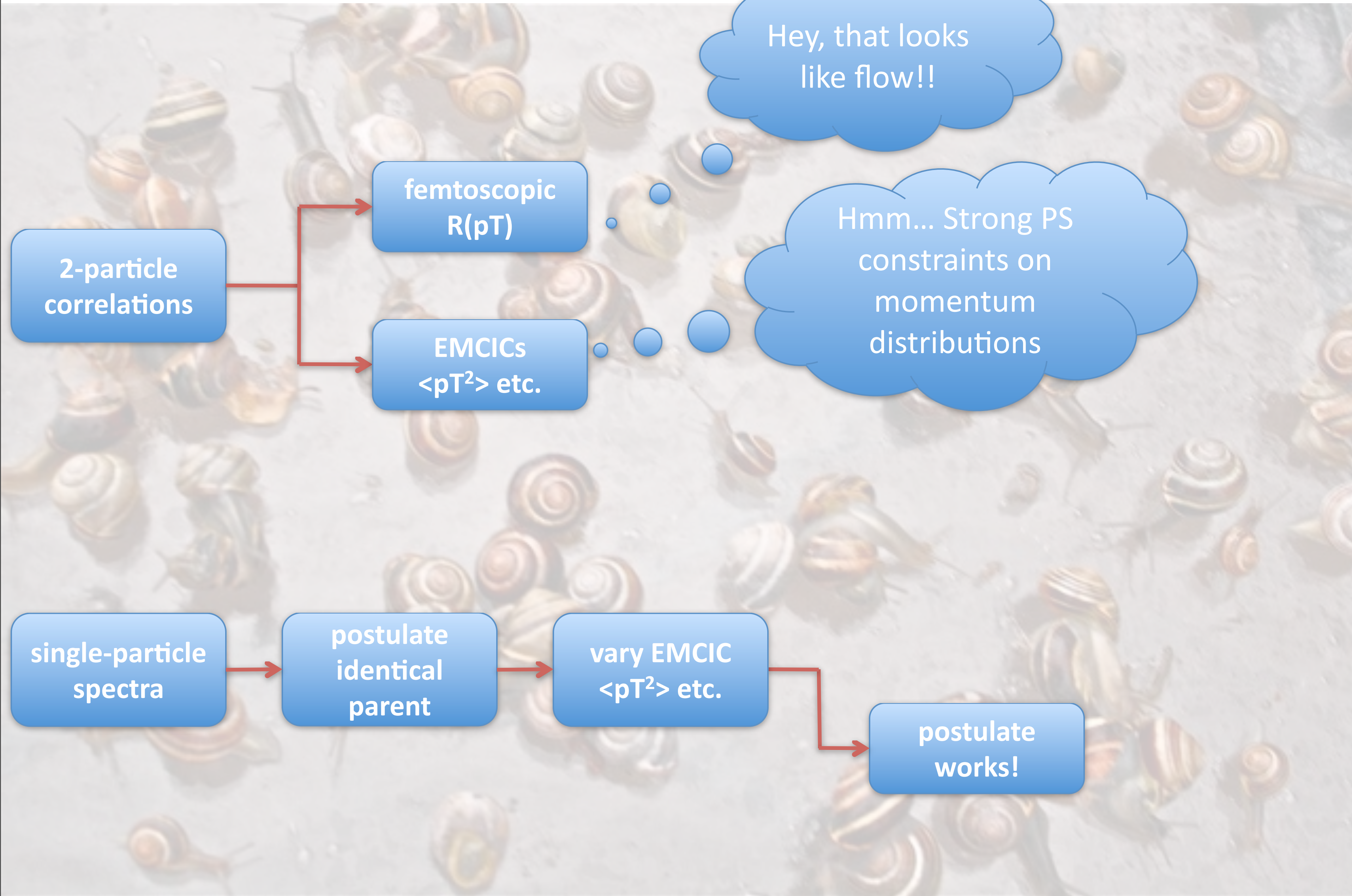
single-particle spectra

postulate identical parent


2-particle correlations
femtoscopic R(pT)
EMCICs <pT²> etc.
Hey, that looks like flow!!
Hmm... Strong PS constraints on momentum distributions
single-particle spectra
postulate identical parent
vary EMCIC <pT²> etc.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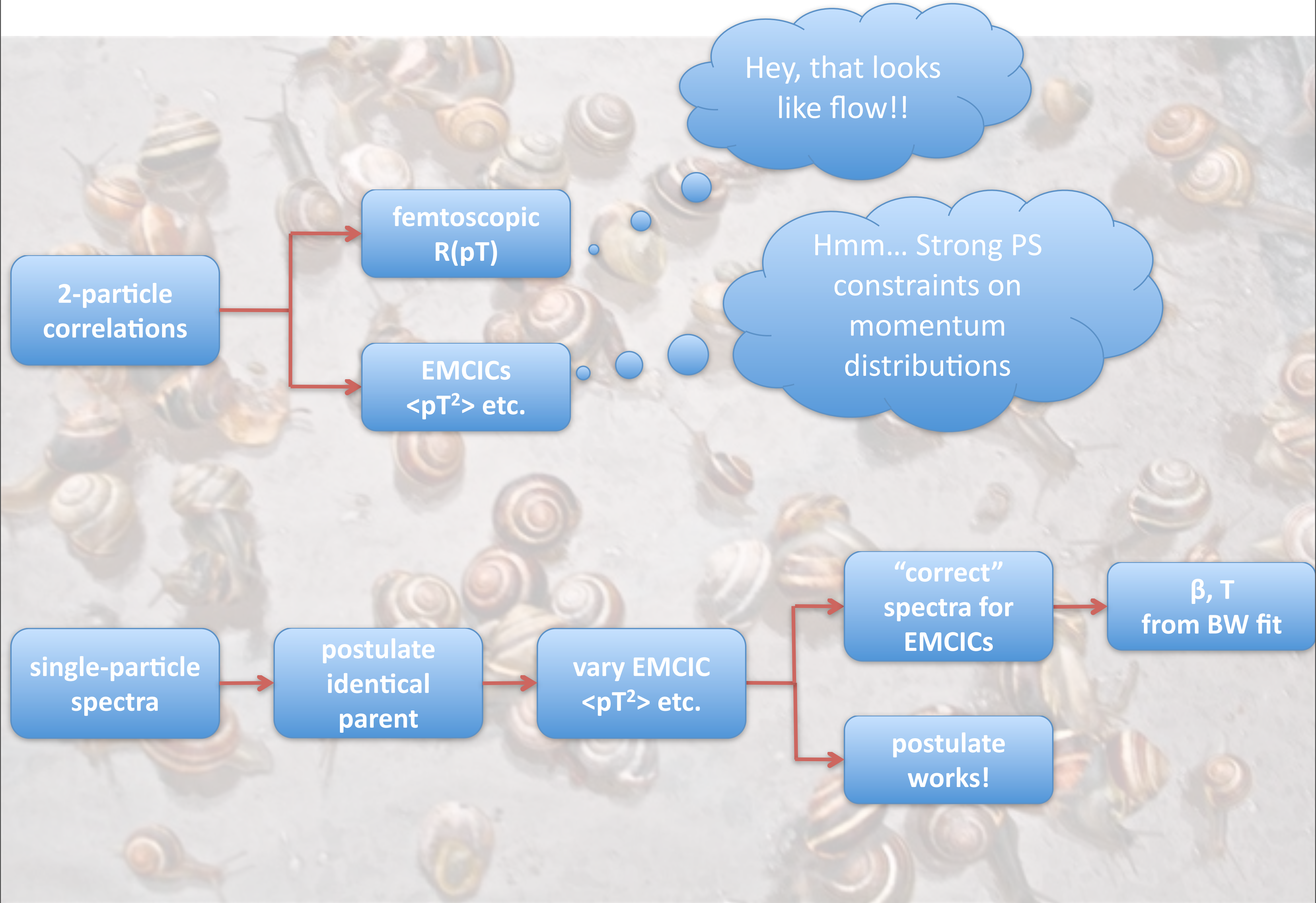
postulate works!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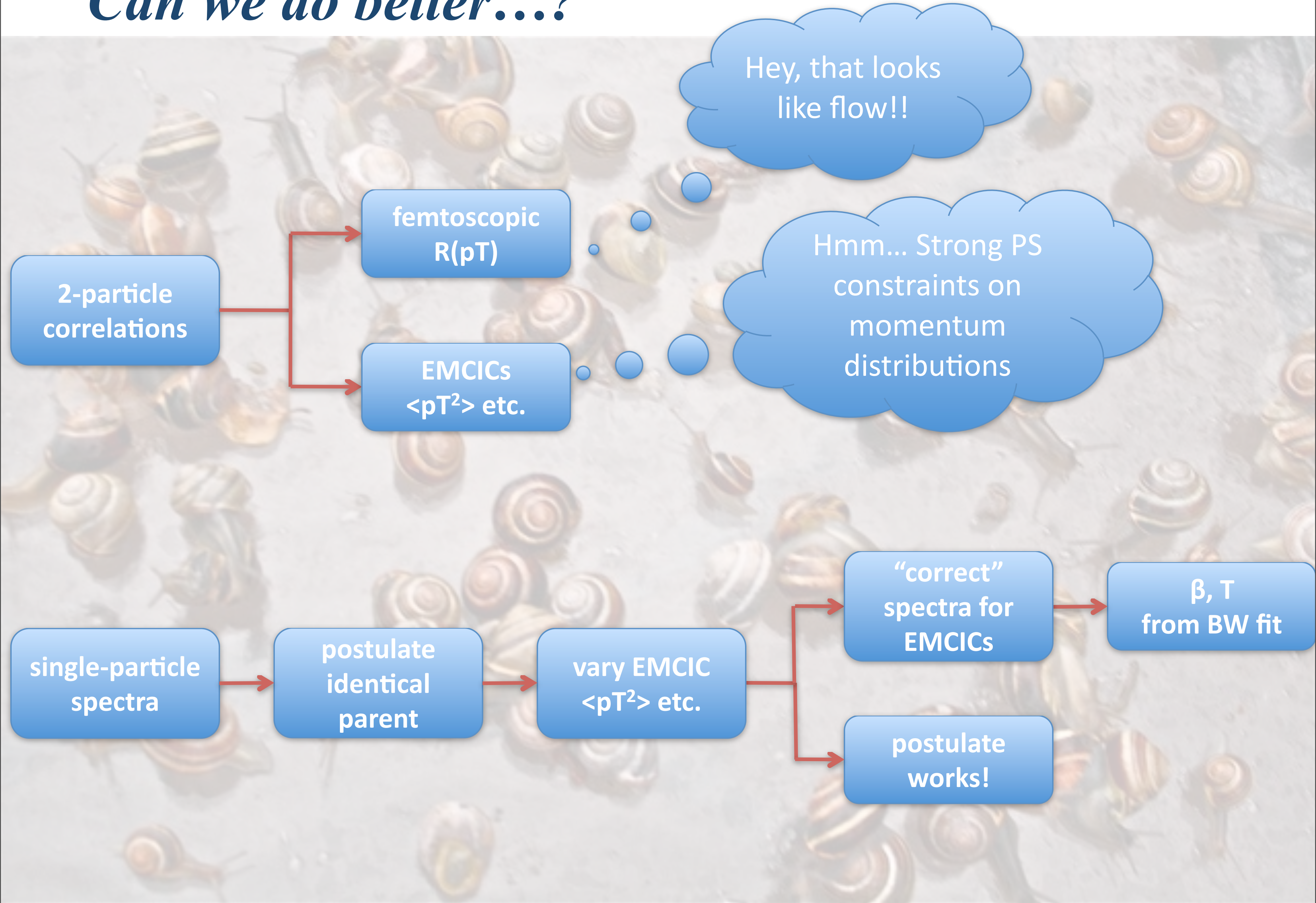
vary EMCIC <pT²> etc.
“correct” spectra for EMCICs
β, T from BW fit
postulate works!

Can we do better…?



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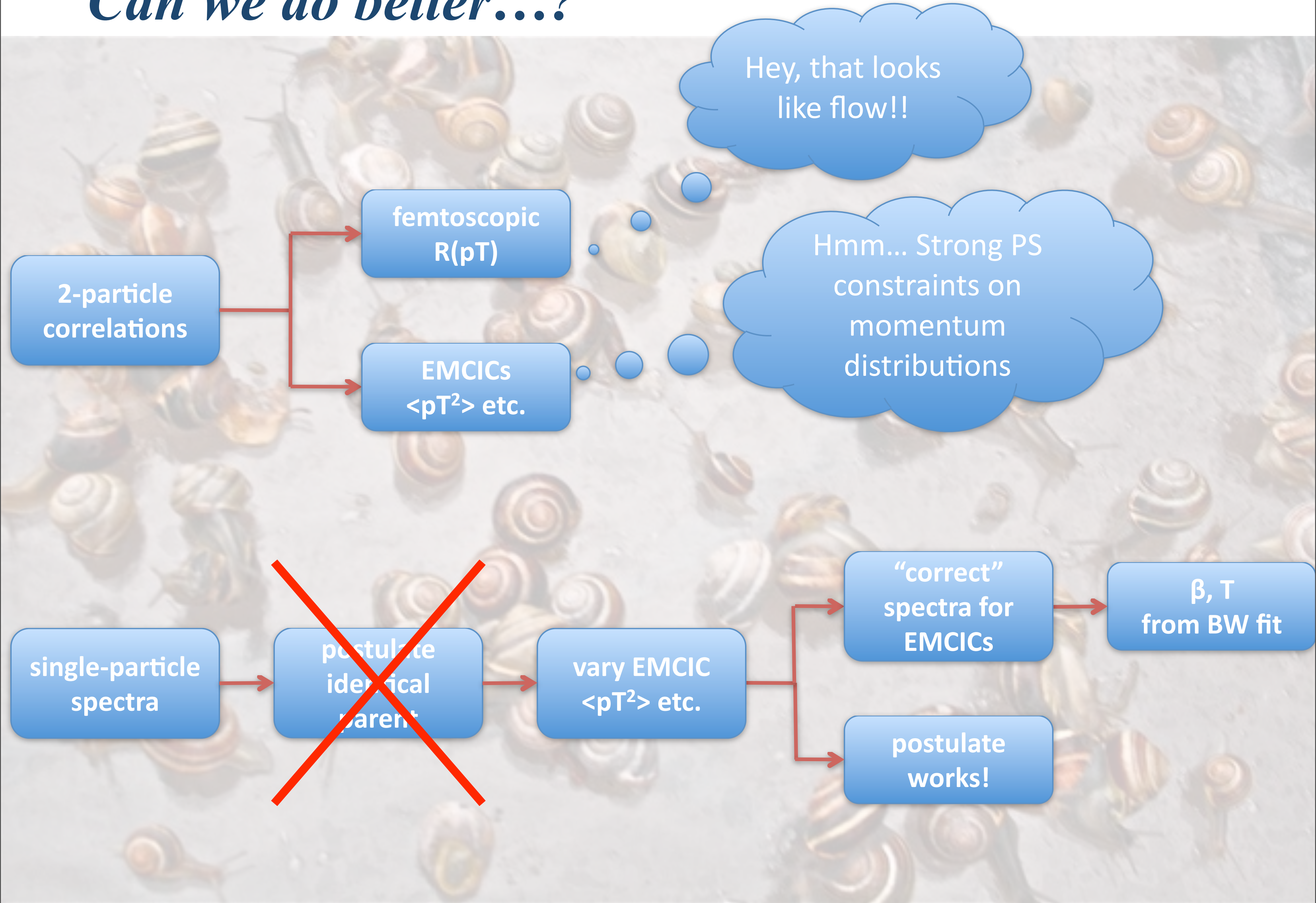

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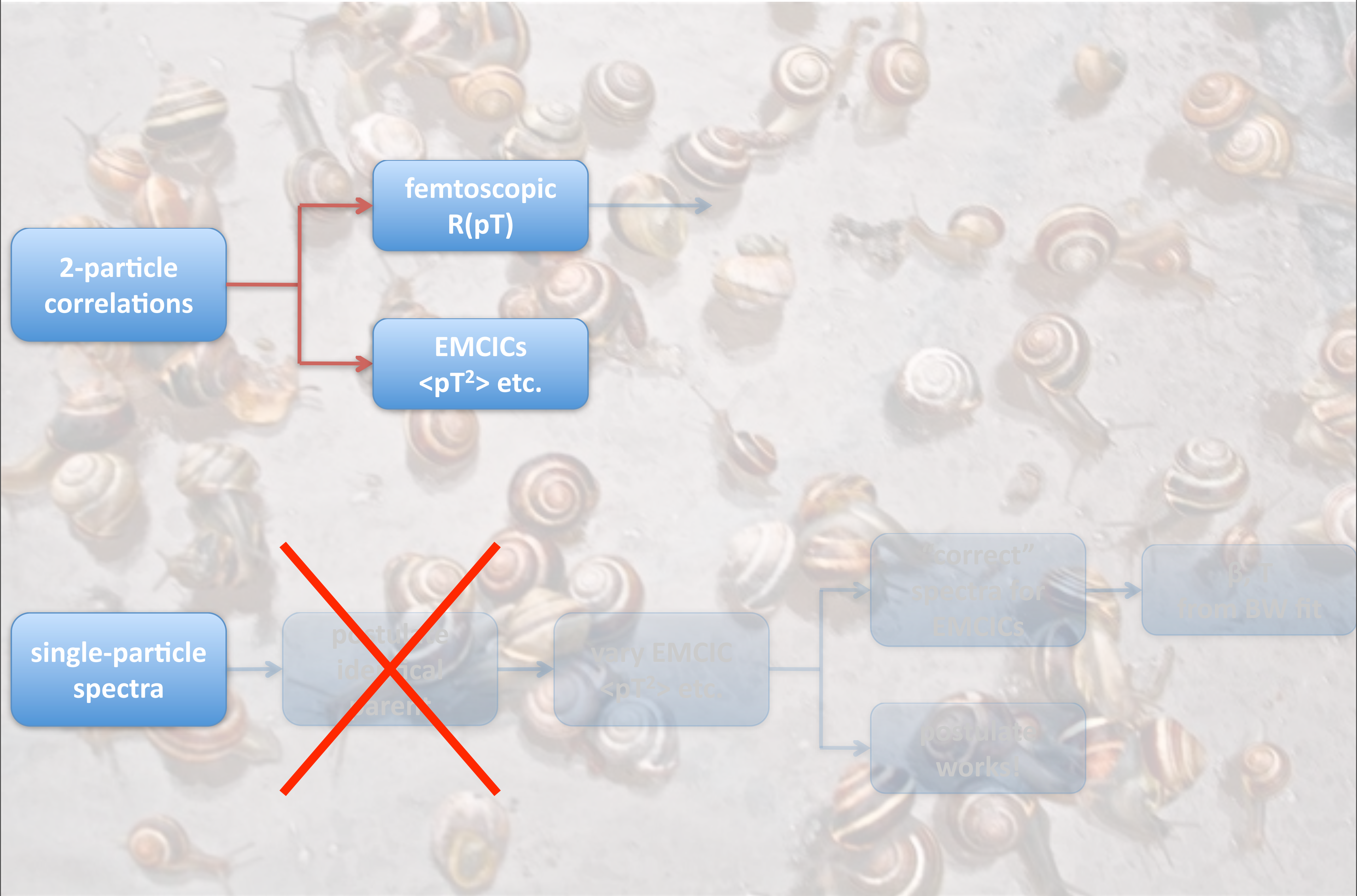


Can we do better…? *Yes we can!*

2-particle correlations → femtoscopic R(pT)

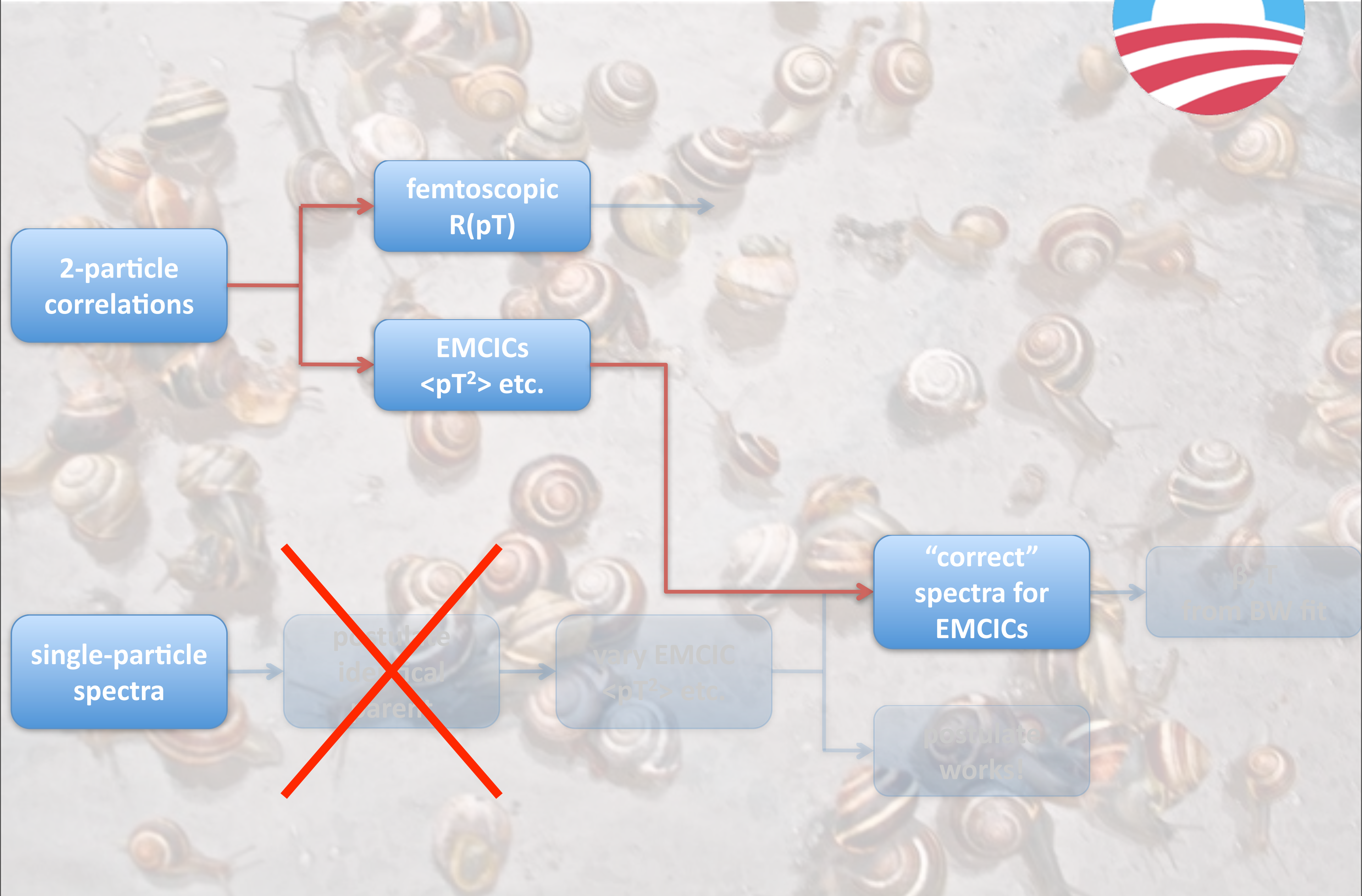
2-particle correlations → EMCICs $\langle p_T^2 \rangle$ etc.

single-particle spectra → postulate identical parent → vary EMCIC $\langle p_T^2 \rangle$ etc.

vary EMCIC $\langle p_T^2 \rangle$ etc. → “correct” spectra for EMCICs → β_T from BW fit

vary EMCIC $\langle p_T^2 \rangle$ etc. → postulate works!

Can we do better…? Yes we can!



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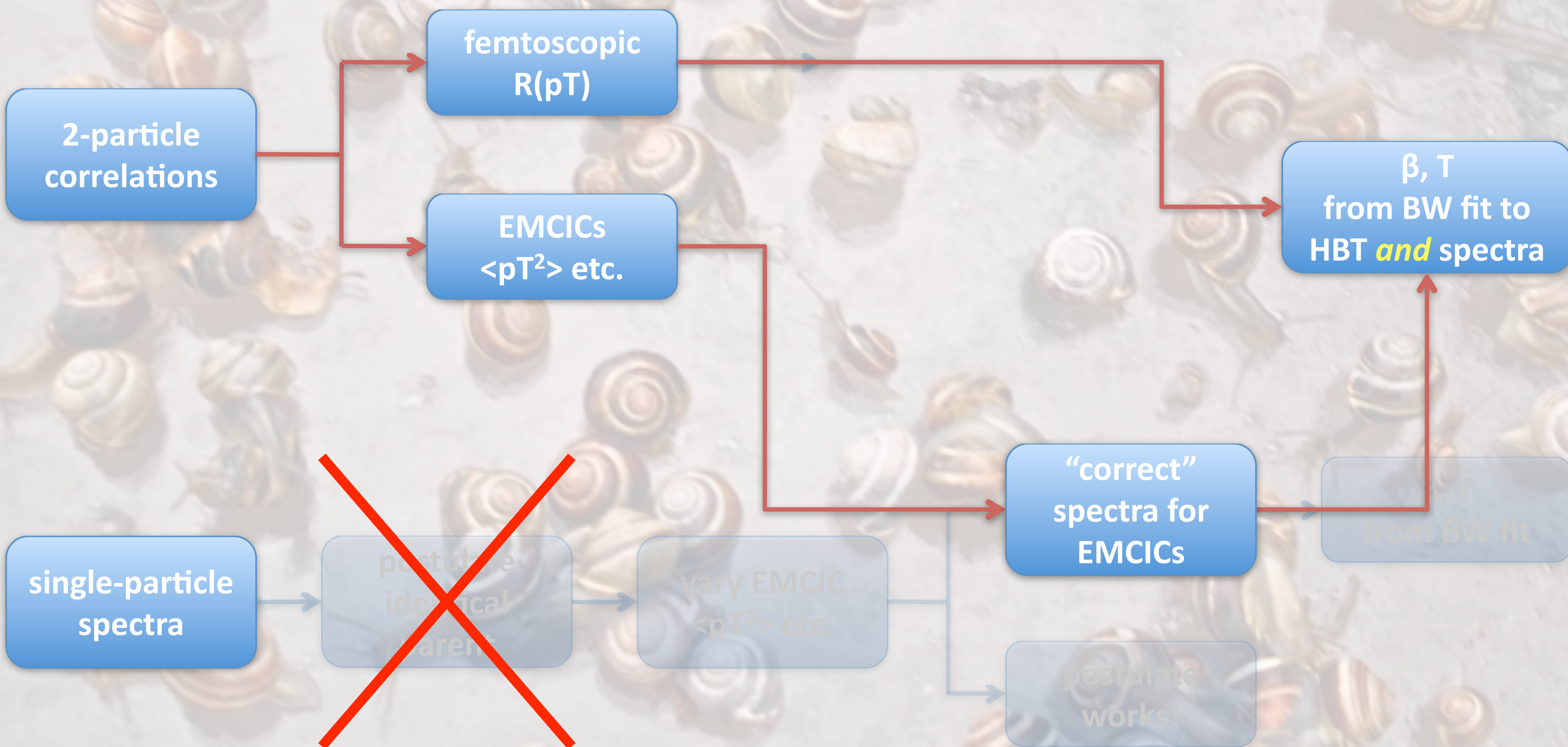
Can we do better…? *Yes we can!*



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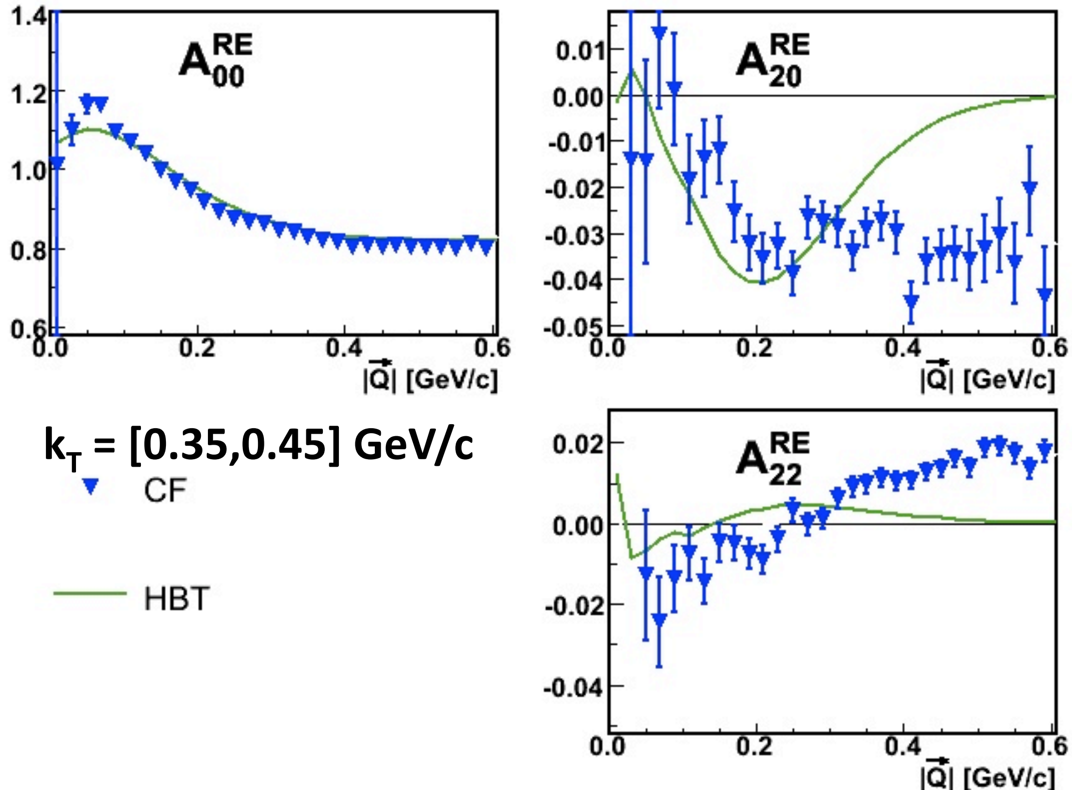
Combined fit: consistent flow-based description

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

STAR



Combined fit: consistent flow-based description

$$C(p_1,p_2) = a\left\{1 + ! \text{"}\$_{\%} K_{coul}(Q_{inv})\left(1+\exp\left(\# R_{out}^2 Q_{out}^2 \# R_{side}^2 Q_{side}^2 \# R_{long}^2 Q_{long}^2\right)\right) \# 1 \&' \right\} ($$

$$\$)_{)\%} 1 \# \frac{2 \text{"} \vec{p}_{1,T} \text{"} \vec{p}_{2,T}}{N\langle p_T^2\rangle} \# \frac{p_{1,Z} \text{"} p_{2,Z}}{N\langle p_z^2\rangle} \# \frac{\left(E_1 \# \langle E\rangle\right) \text{"} \left(E_2 \# \langle E\rangle\right)}{N\left(\langle E^2\rangle \# \langle E\rangle^2\right)} \&_{*\,*\,'}$$

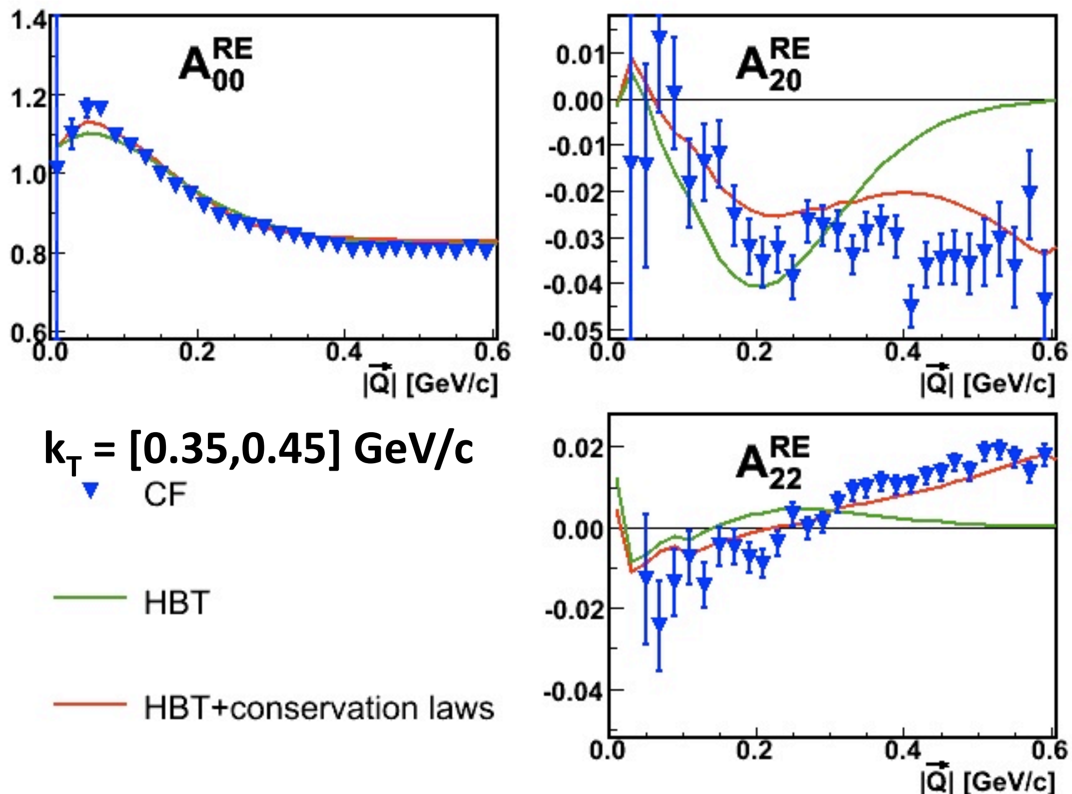
$N = \mathbf{14}$

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

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

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

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



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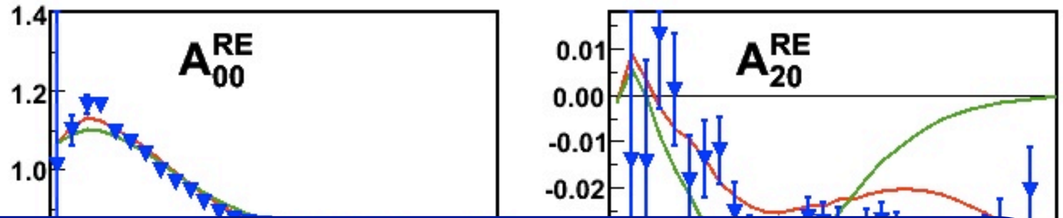
$$\left[1-\frac{2\cdot\vec{p}_{1,T}\cdot\vec{p}_{2,T}}{N\langle p_T^2\rangle}-\frac{p_{1,Z}\cdot p_{2,Z}}{N\langle p_z^2\rangle}-\frac{\left(E_1-\langle E\rangle\right)\cdot\left(E_2-\langle E\rangle\right)}{N\left(\langle E^2\rangle-\langle E\rangle^2\right)}\right]$$



STAR

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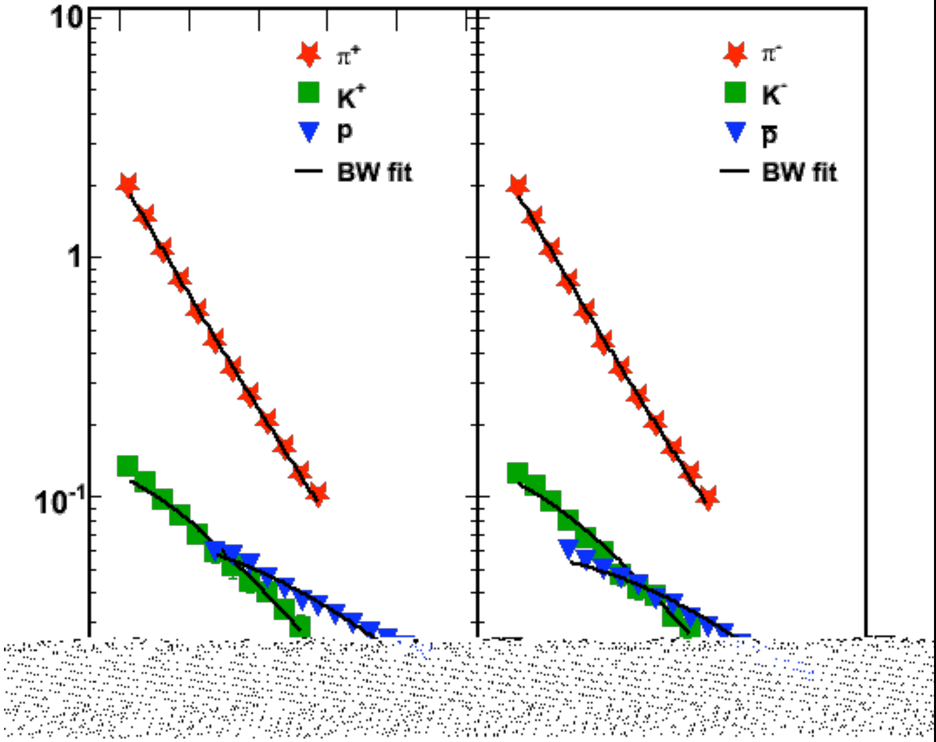
$\langle E\rangle = 0.68\ GeV$

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

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

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

Combined fit: consistent flow-based description



$T = 106 \pm 3$ MeV

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

$R = 2.09 \pm 0.04$ fm

$\tau_0 = 2.25 \pm 0.05$ fm/c

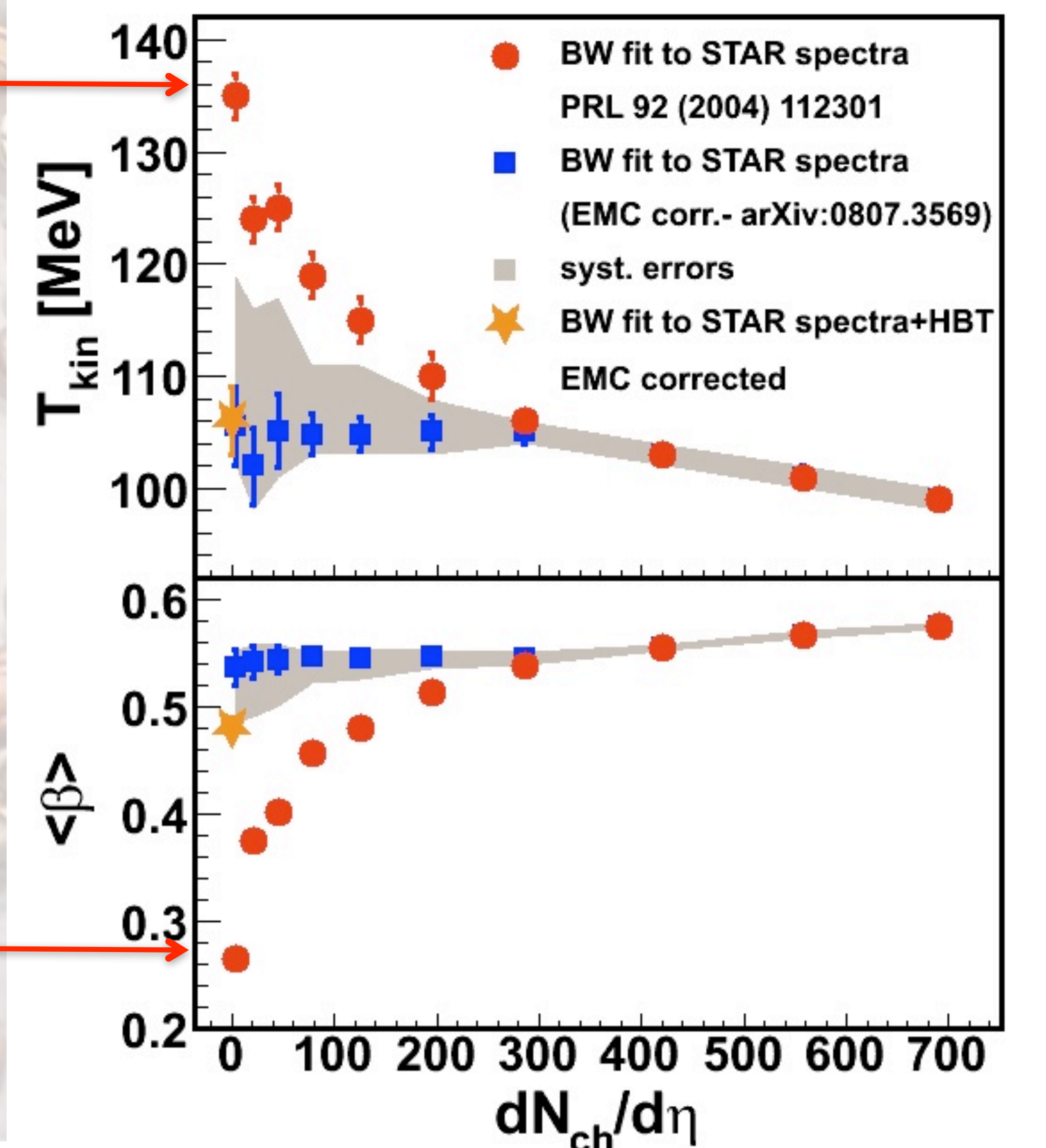
$\Delta\tau = 0.1 \pm 0.2$ fm/c

Blast-Wave Model:

F. Retiere, MAL, PRC70:044907,2004.

Combined fit: consistent flow-based description

"raw" (ignoring EMCICs)



"raw" (ignoring EMCICs)

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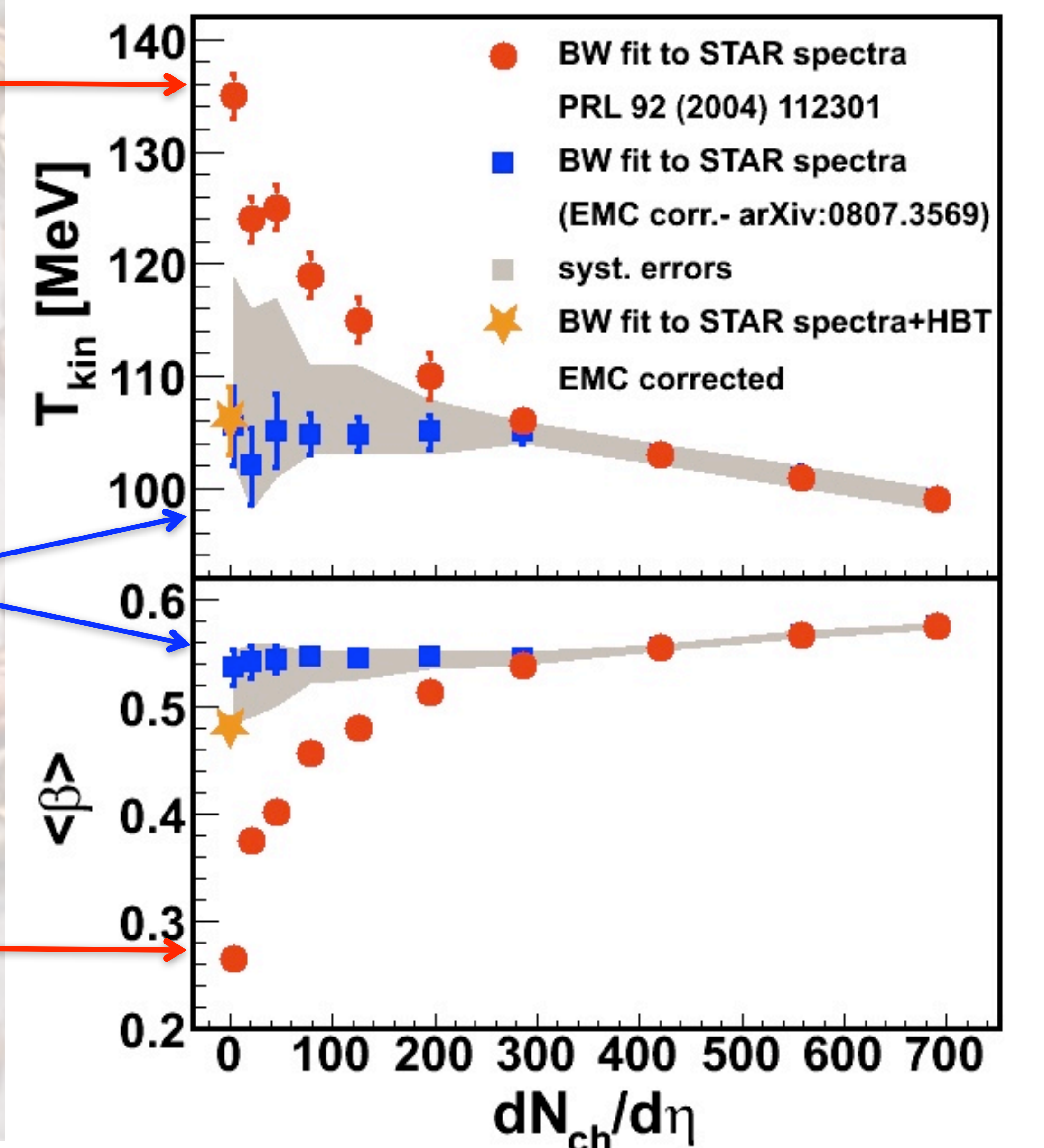
Combined fit: consistent flow-based description

"raw" (ignoring EMCICs)

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

"raw" (ignoring EMCICs)



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
Joint spectra/HBT BW fit

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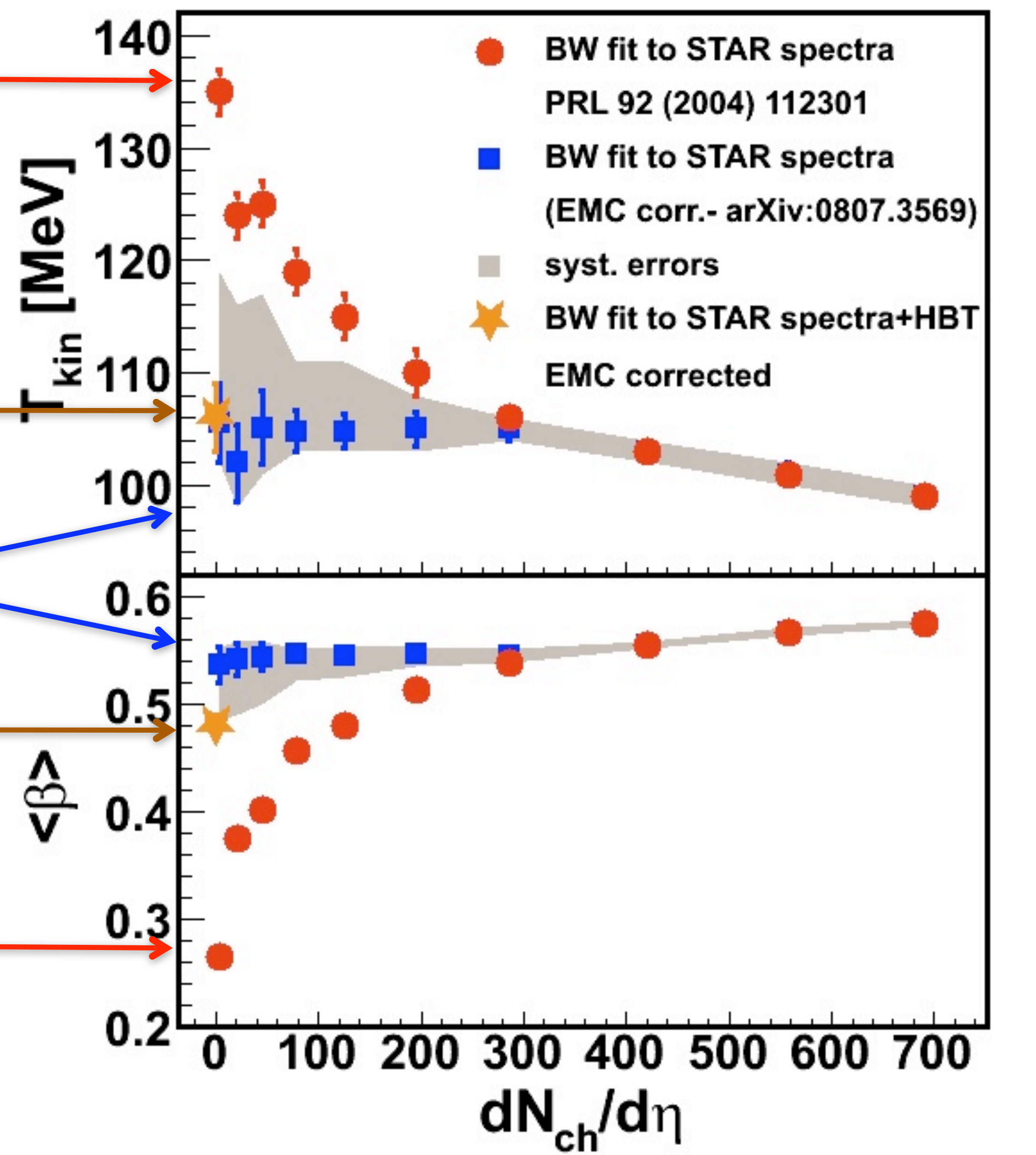

Wednesday, September 16, 2009

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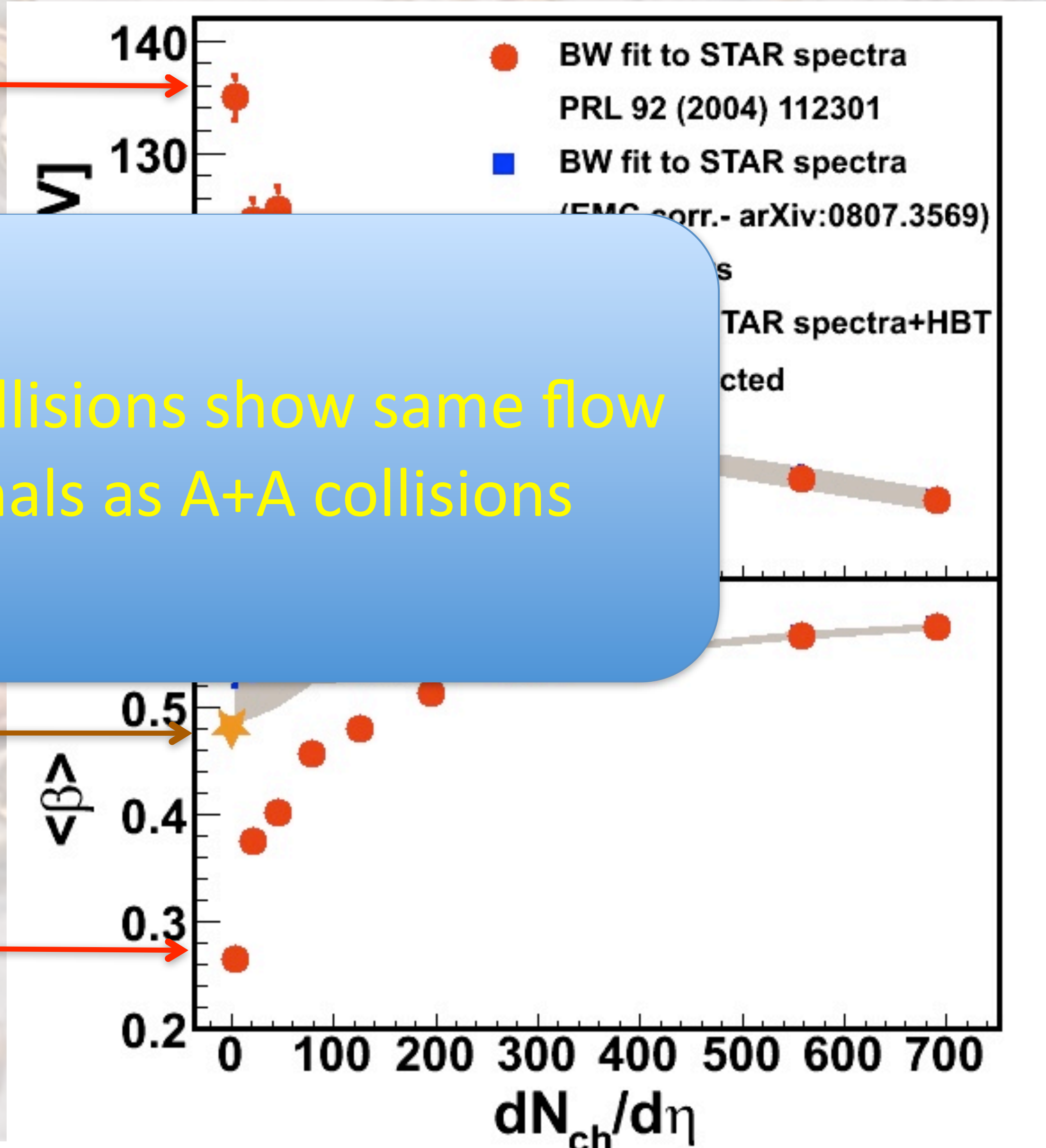

p+p collisions show same flow signals as A+A collisions

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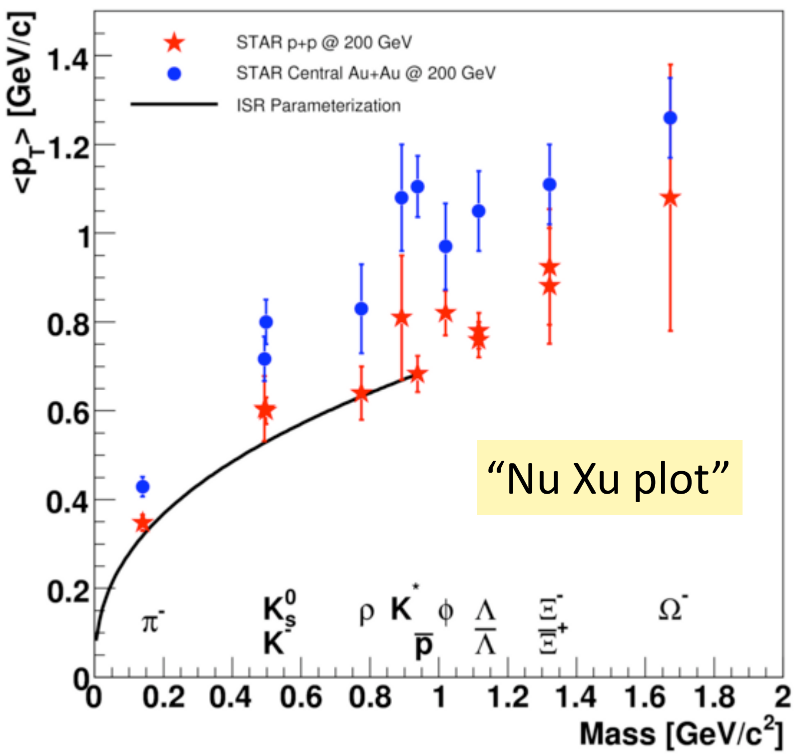
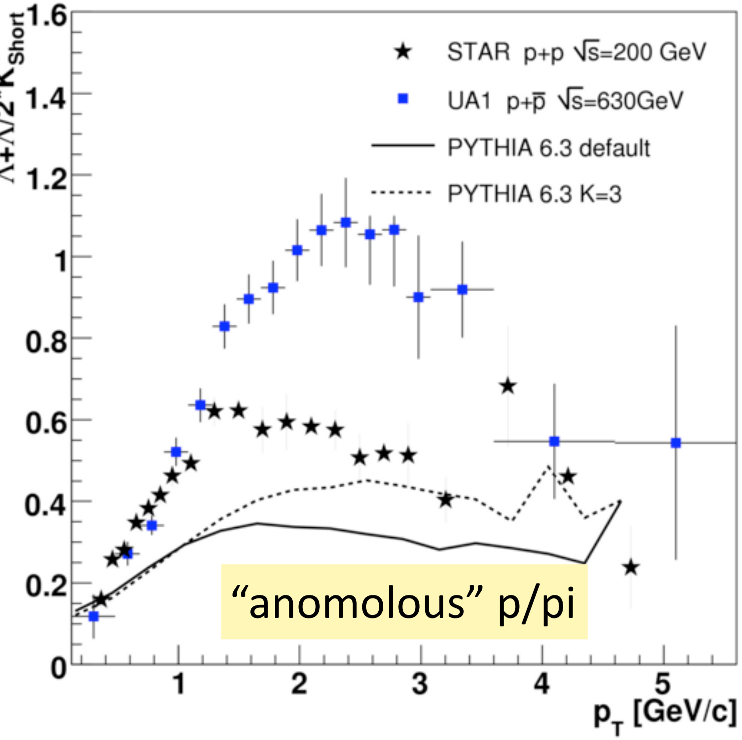
pp so different from AA?

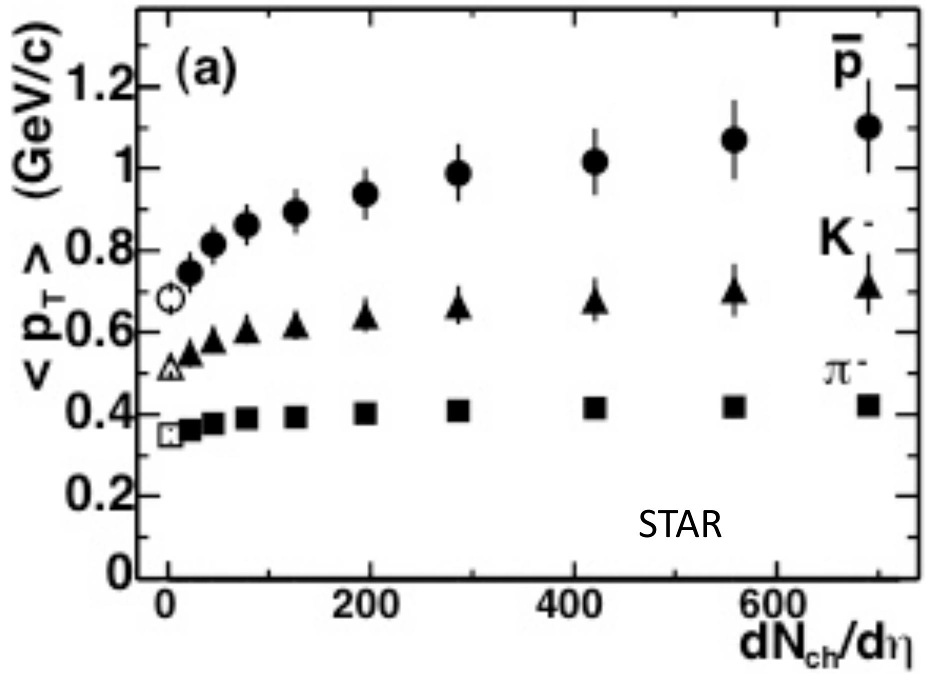


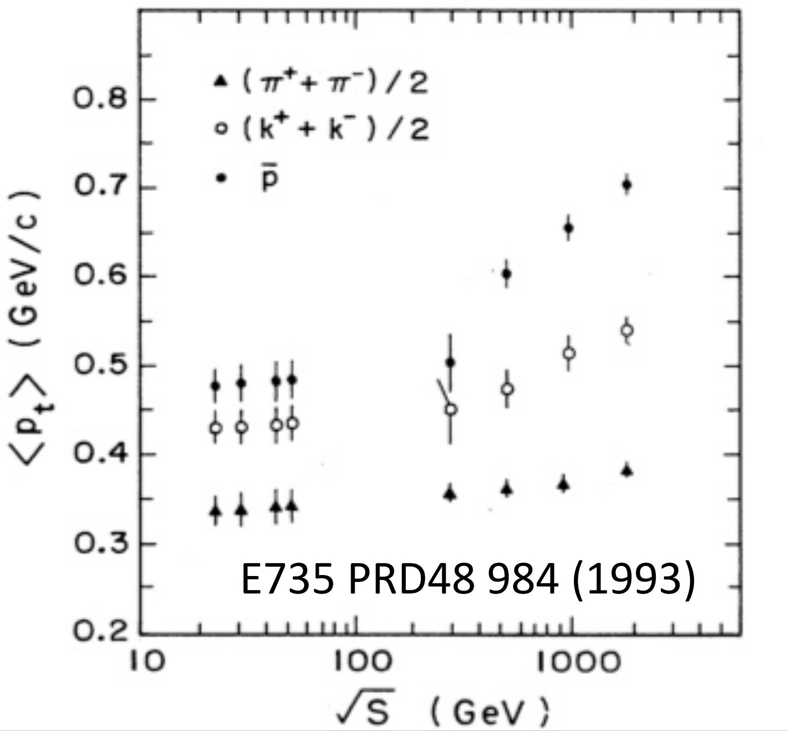


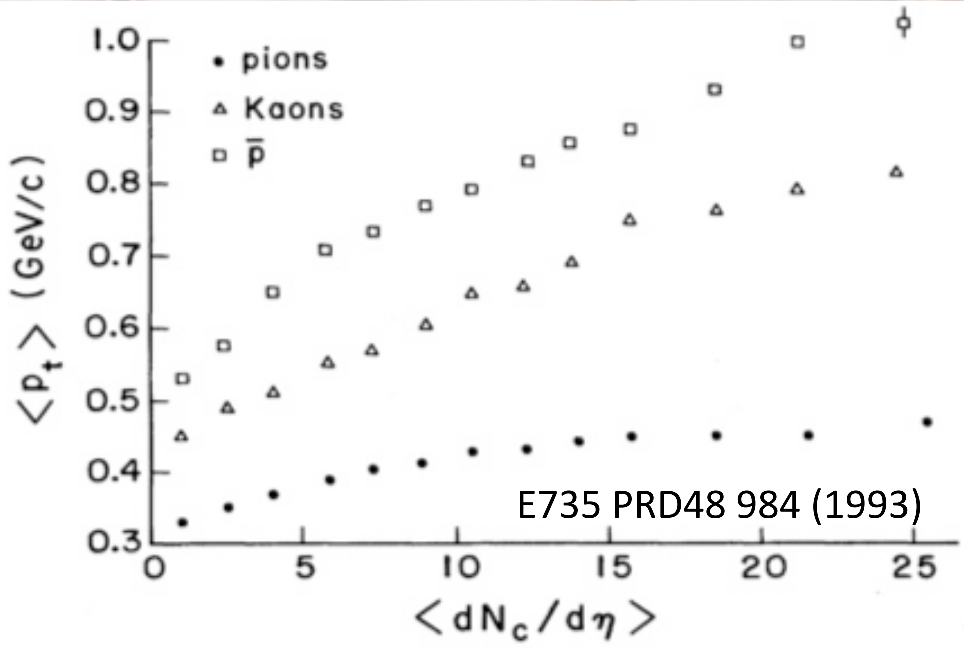
PID'd <pT> systematics

similar systematics AA vs pp

increasing flow
or
relaxed P.S
?







Summary

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- 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…]

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  - …*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…

Derek Teaney's Challenge – Haiku Summary

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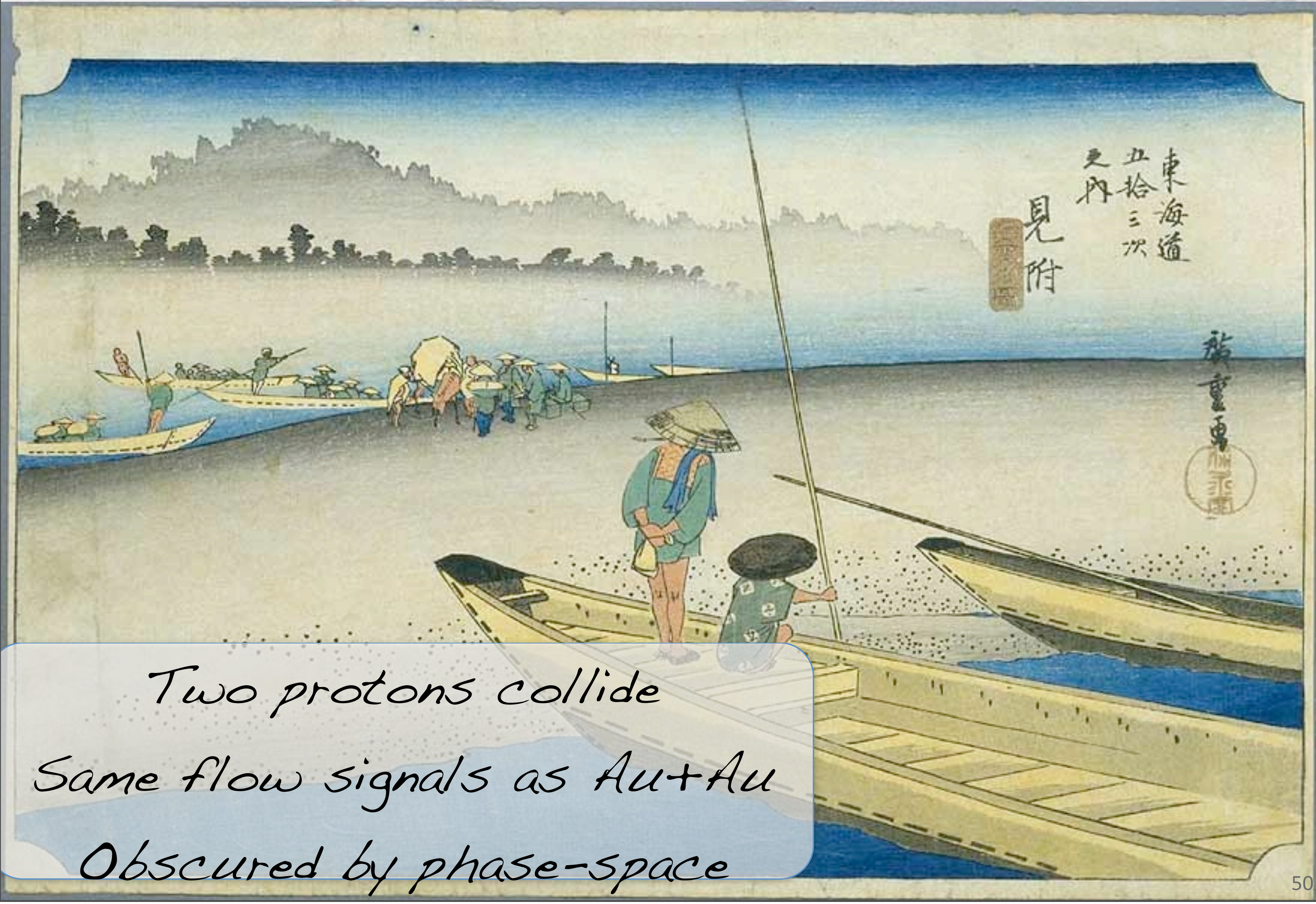

Two protons collide
Same flow signals as Au+Au
Obscured by phase-space