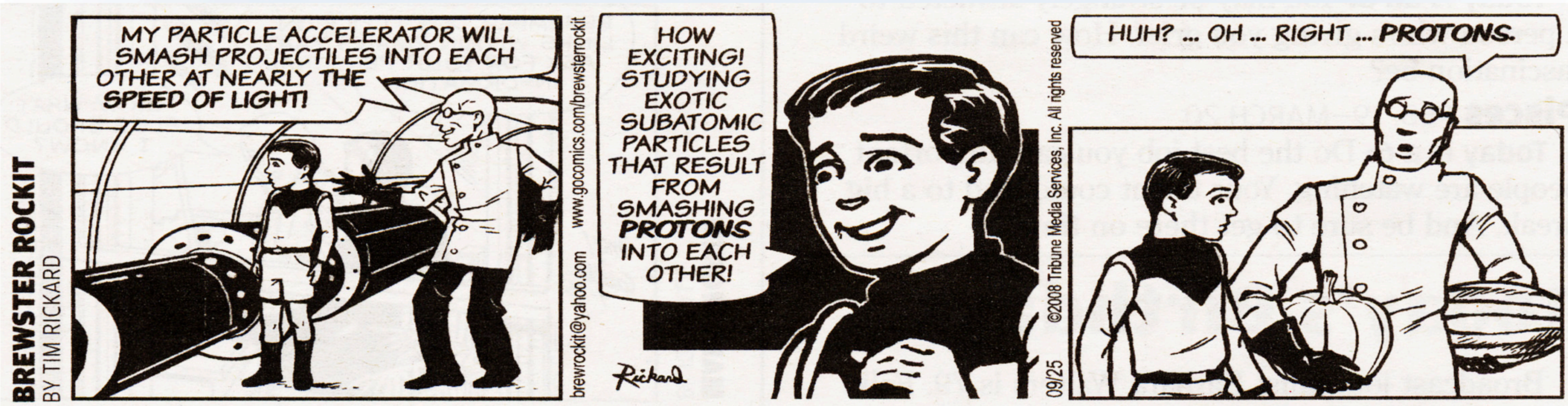
Z. Chajęcki & MAL PRC **78** 064903 (2008)
Z. Chajęcki & MAL arXiv:0807.3569 [nucl-th]
Z. Chajecki arXiv:0901.4078 [nucl-ex]
Z. Chajęcki & MAL, to be published



Oh, right... protons

A heavy ion approach to the soft-sector in hadron-hadron collisions

Mike Lisa

Ohio State University

Outline

- Why collide watermelons rather than seeds

- Collectivity and observable collective effects
  - spectral shapes (with PID!)
  - "elliptic flow"
  - femtoscopy ("HBT," "B.E.C." "GGLP")

  } how to *really* study the soft sector (in p+p: UE?)

- Claim (will not "prove/sell"): H.I.C. in soft sector extremely well-understood

- first (!) apples:apples comparison: p+p versus A+A
  - spectra
  - femtoscopy
  - importance of conservation laws

- Summary

From Peter's mail

*Your audience will instead be almost entirely unfamiliar with collective effects and… they are probably suspicious of both their theory and their modeling in heavy-ion, *as well* as their presence in pp…*

I don't think this is the right place to try to teach them hydrodynamics or convince them of its applications in heavy-ion physics…

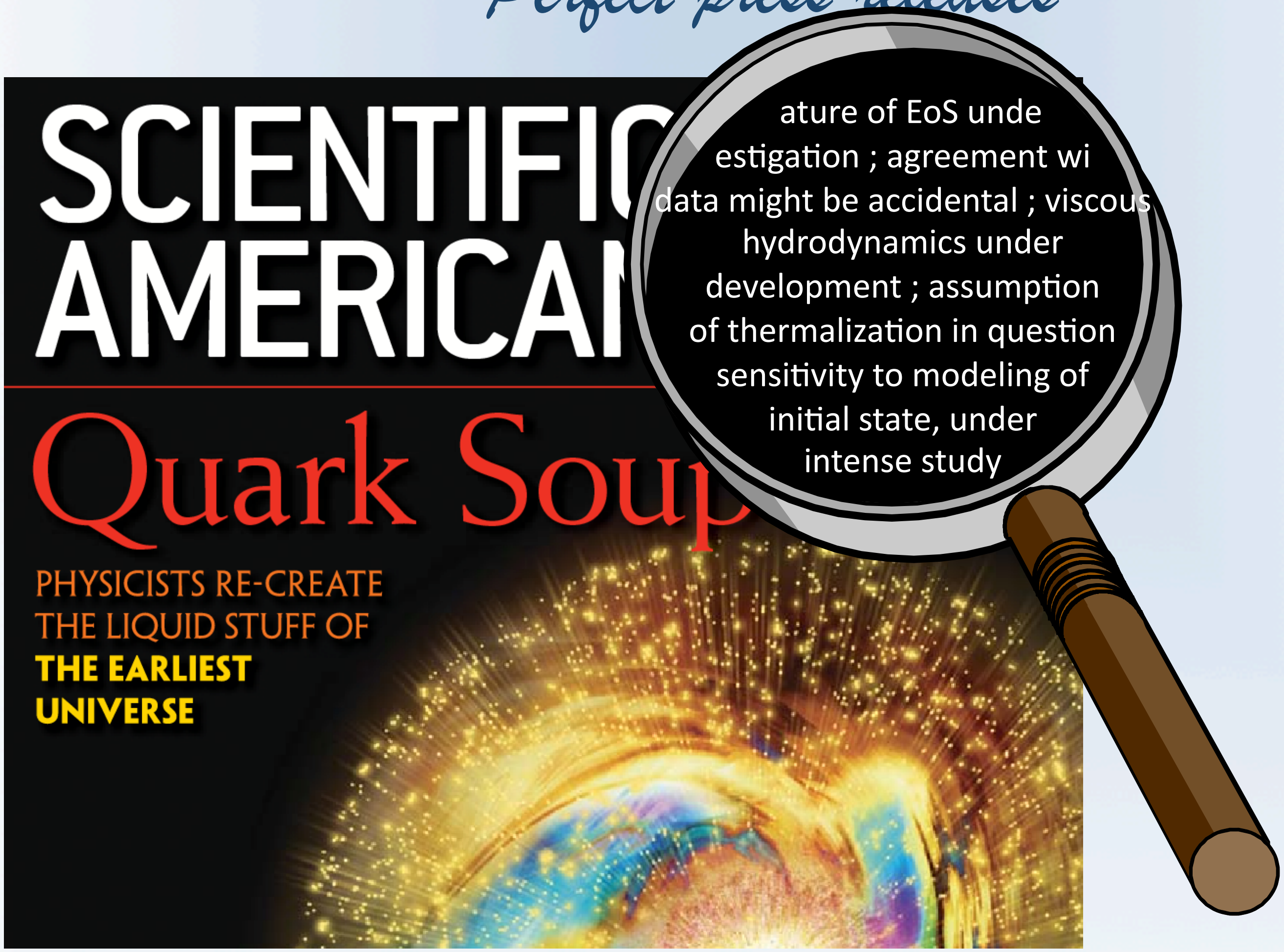
✓ **I will <u>mention</u> hydro, but focus on generic, measurable features of bulk collectivity**

I would prefer an attack angle that focuses more on the measurements themselves, the data, rather than their interpretation…

More like "this is what we see in pp, and oh by the way, it looks a lot like this effect we also see in heavy-ion, which is there interpreted as a collective effect, isn't that interesting?"

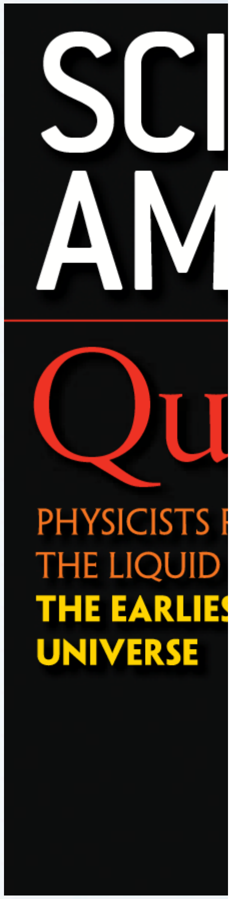
Well, a physics talk needs to go something beyond this, but we'll go a bit along this route.

Perfect press releases



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

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



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28 April 2009

Big Bang machine detectors will be 'even more perfect'

updated 4 hours, 10 minutes ago

STORY HIGHLIGHTS

- The Large Hadron Collider w
- Scientists have used the yea
- CMS uses about 100,000 co
- Experts hope to find the Hig

Next Article in Technology »

READ | DETAILS | MAP

By Elizabeth Landau
CNN

TEXT SIZE

(CNN) -- On a recent episode of "South Park," Mr. Marsh steals a particle accelerator magnet so his son, Stan, can win the Pinewood Derby. The magnet's power results in an alien encounter, and chaos ensues.

The Compact Muon Solenoid, shown here in December, is one of six experiments inside the collider complex.

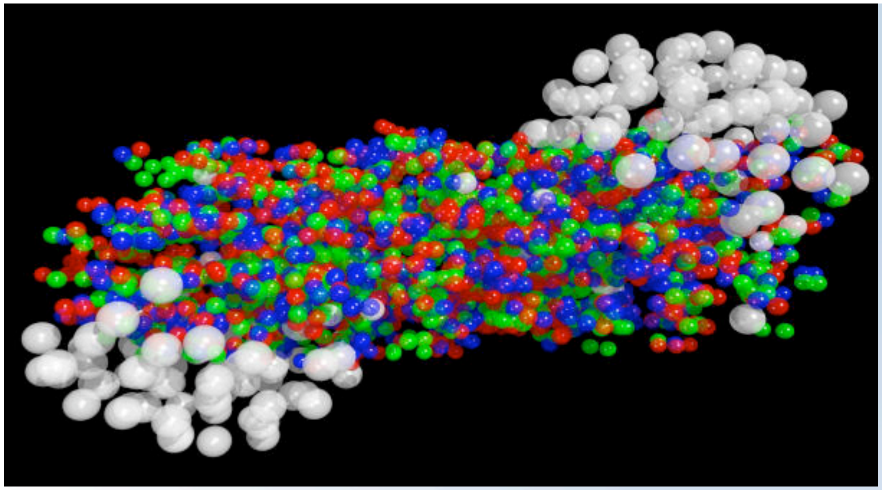
While the magnets at the real-life Large Hadron Collider may not reach extraterrestrials, scientists hope they will help lead to encounters with never-before-seen phenomena and answers to fundamental questions about the universe.

The collider, the world's most powerful particle accelerator, is being repaired after an electrical failure in September. Once it is fixed, the collider will circulate beams of particles with unprecedented energy. When these particles crash into each other, the resulting activity may help scientists figure out why the subമicroscopic stuff that makes up our universe behaves the way it does.

The Large Hadron Collider will start receiving current again in July, and will circulate this year's first proton beam by the end of September, said Lyn Evans, former project leader for the collider who is currently involved with the machine's repairs. The collider is located more than 300 feet below the French-Swiss border at CERN, the European Organization for Nuclear Research ... See it on a map »

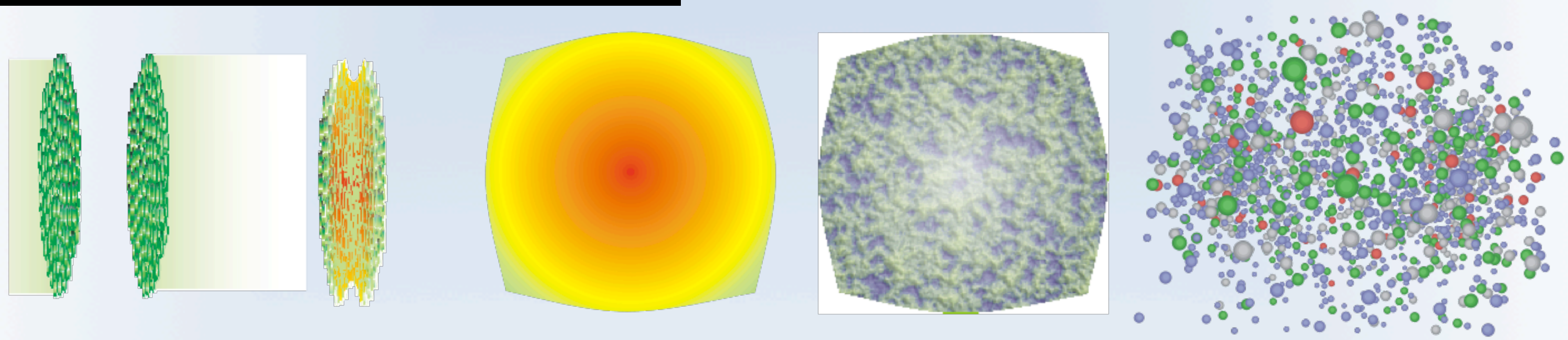
- Perfect or not, … ed - **flow**
- This system is v … ng it - R_{AA}

? ***Are these state***



paradigms

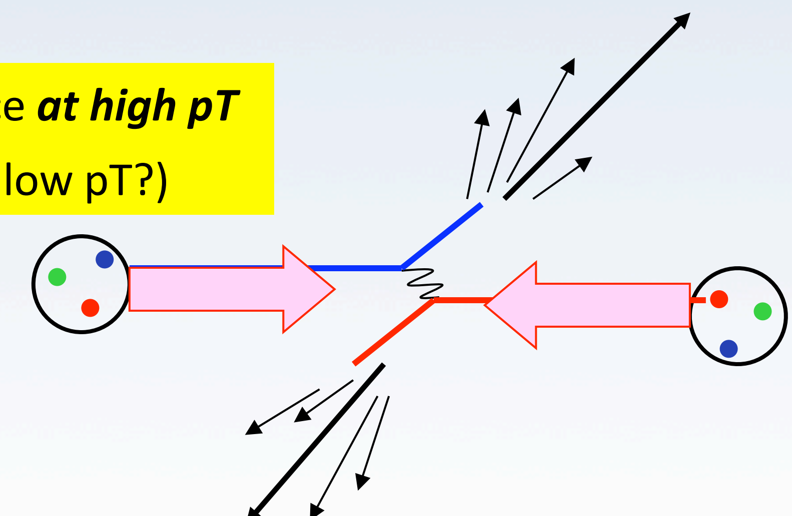
A+A → a *system*



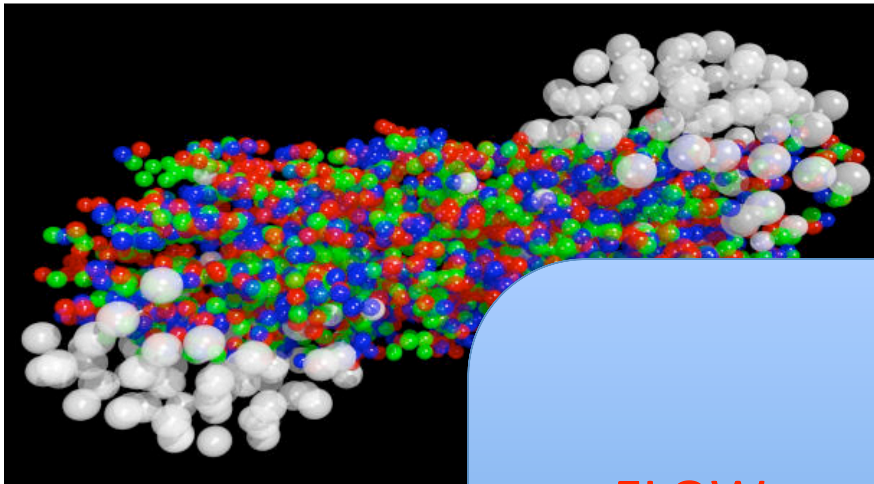
“Clean” p+p– a crucial reference ***at high pT***

(do we understand/care about low pT?)

p+p: a *process*



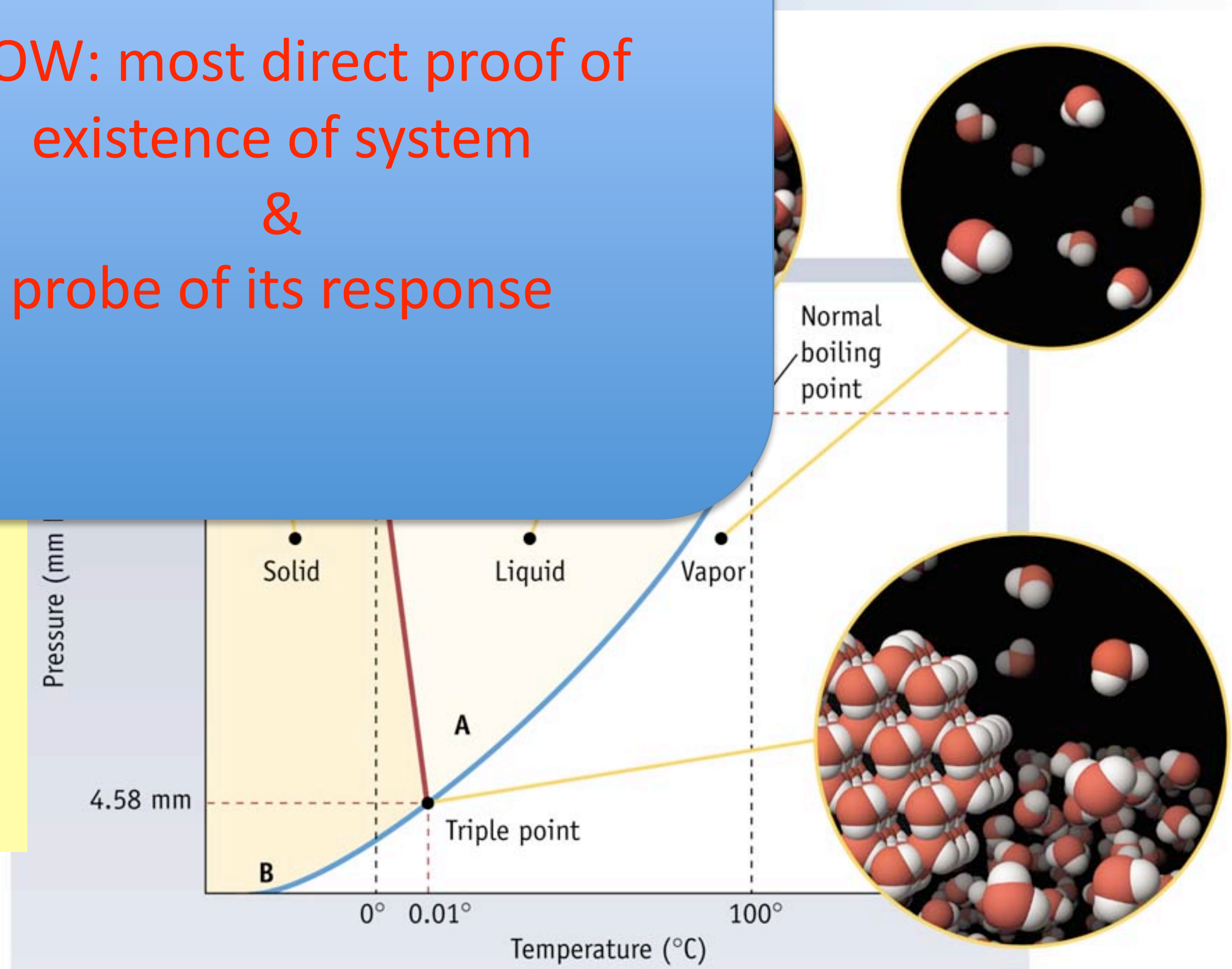
H.I.C. – a system



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_20 molecule!

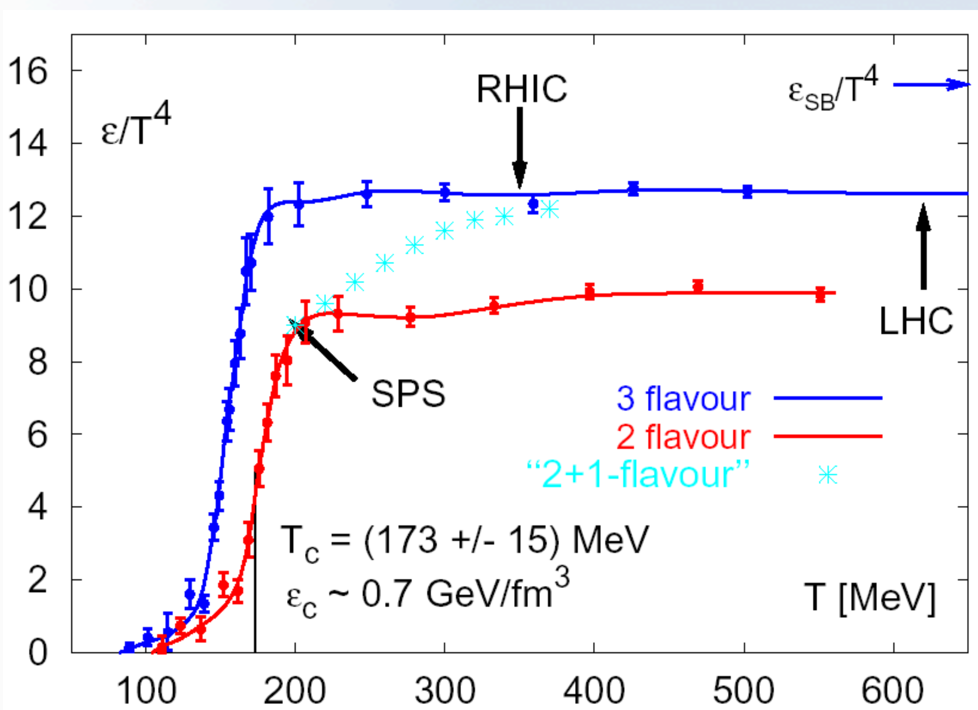


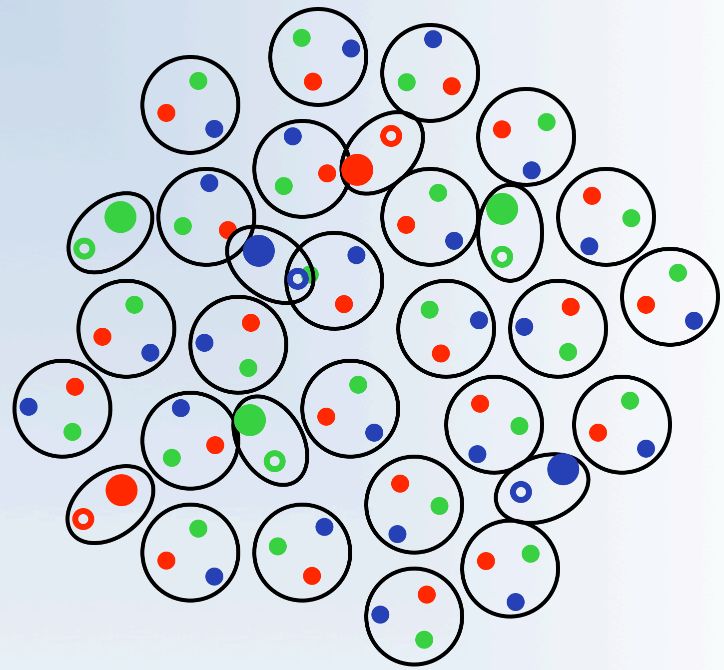
States of QCD Matter

Present understanding of Quantum Chromodynamics (QCD)

- heating
- compression

→ *deconfined color matter*

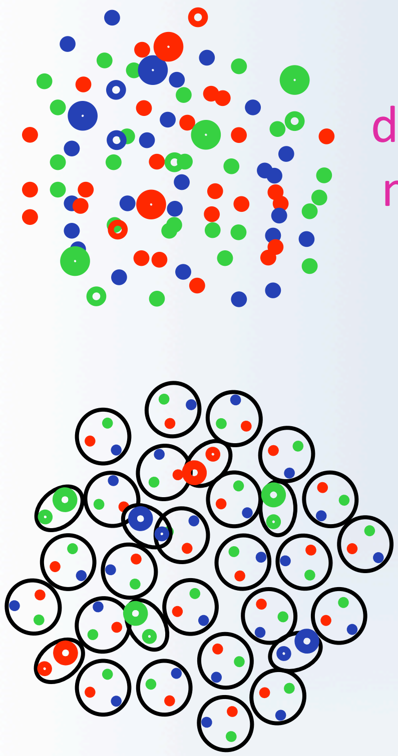




Quark Gluon Plasma / Nuclear Matter
(deconfined) / (confined)

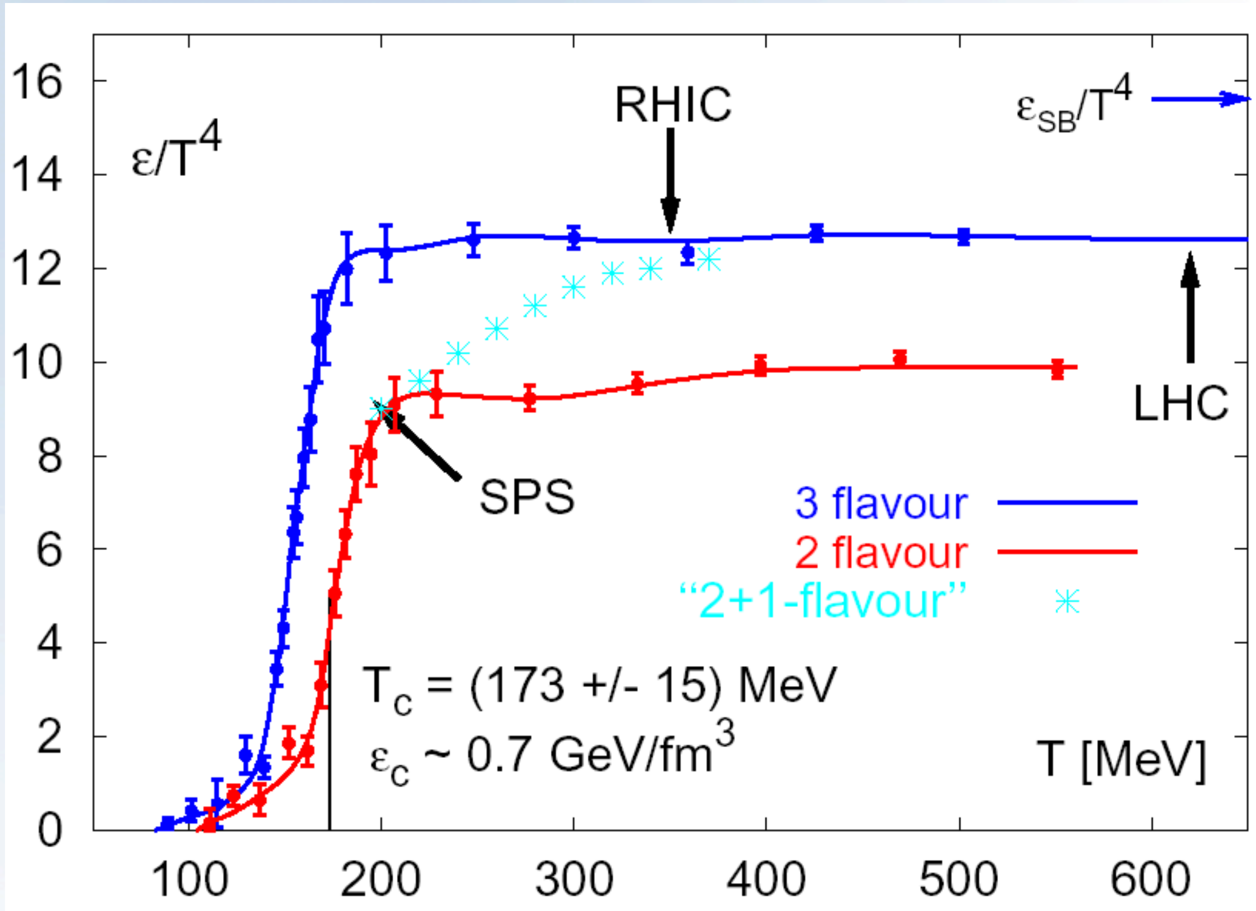
Expectations from Lattice QCD

ε/T^4 ~ # degrees of freedom



deconfined:
many d.o.f.

confined:
few d.o.f.



The hydrodynamics slide

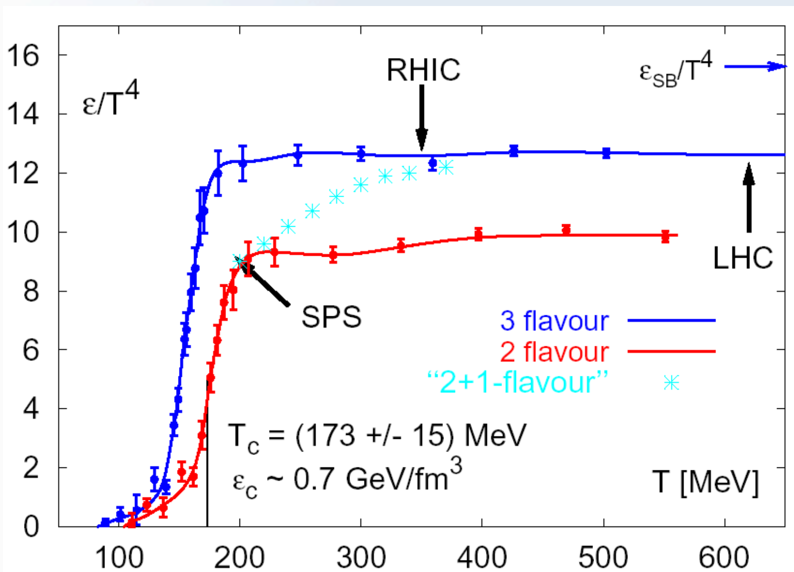
Ideal Hydrodynamics: Physics

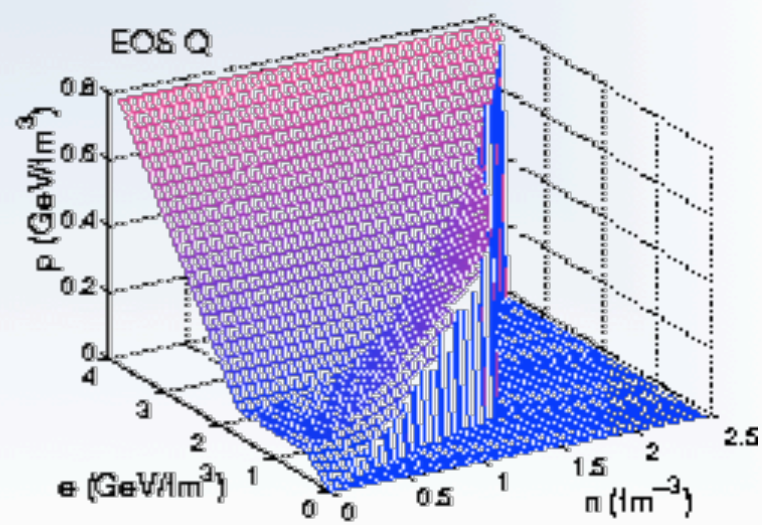
- Equations of motion:

$$\partial_\mu T^{\mu\nu} = \partial_\mu(e\, u^\mu u^\nu + p\, \Delta^{\mu\nu}) \quad = \quad 0$$
$$\partial_\mu N^\mu = \partial_\mu(n u^\mu) \quad = \quad 0$$

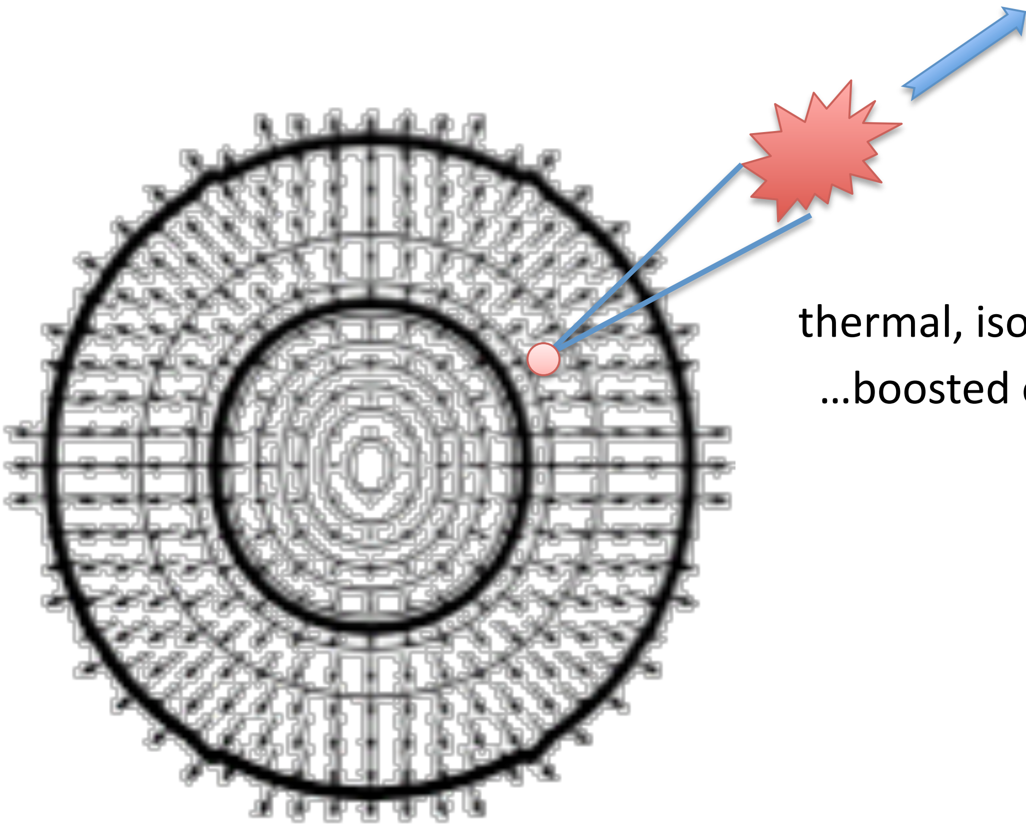
- Equation of State (EoS): $p(e,n)$

- Five Equations of Motion (T^{00}, T^{0i}, N^0) and Five unknowns $e, \mathbf{v}, n$.





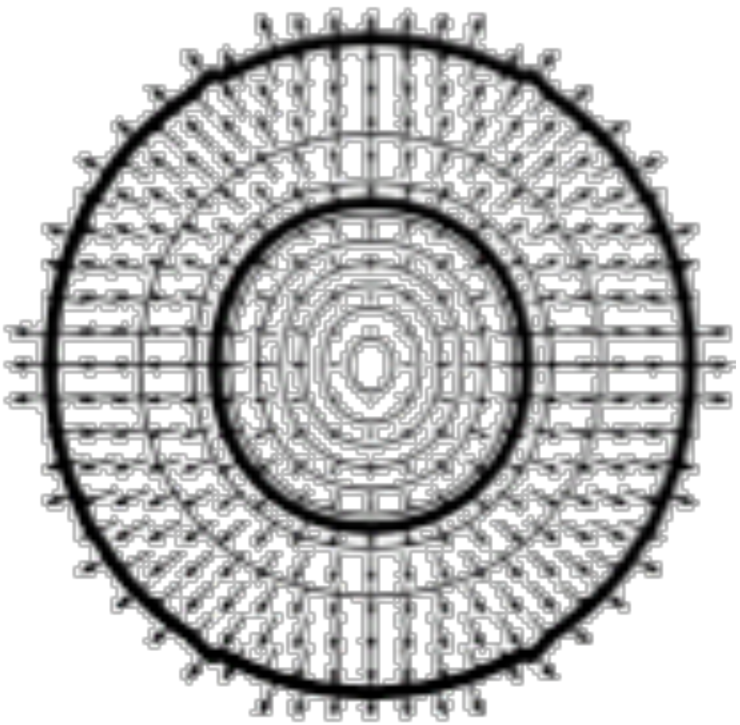
The other hydrodynamics slide



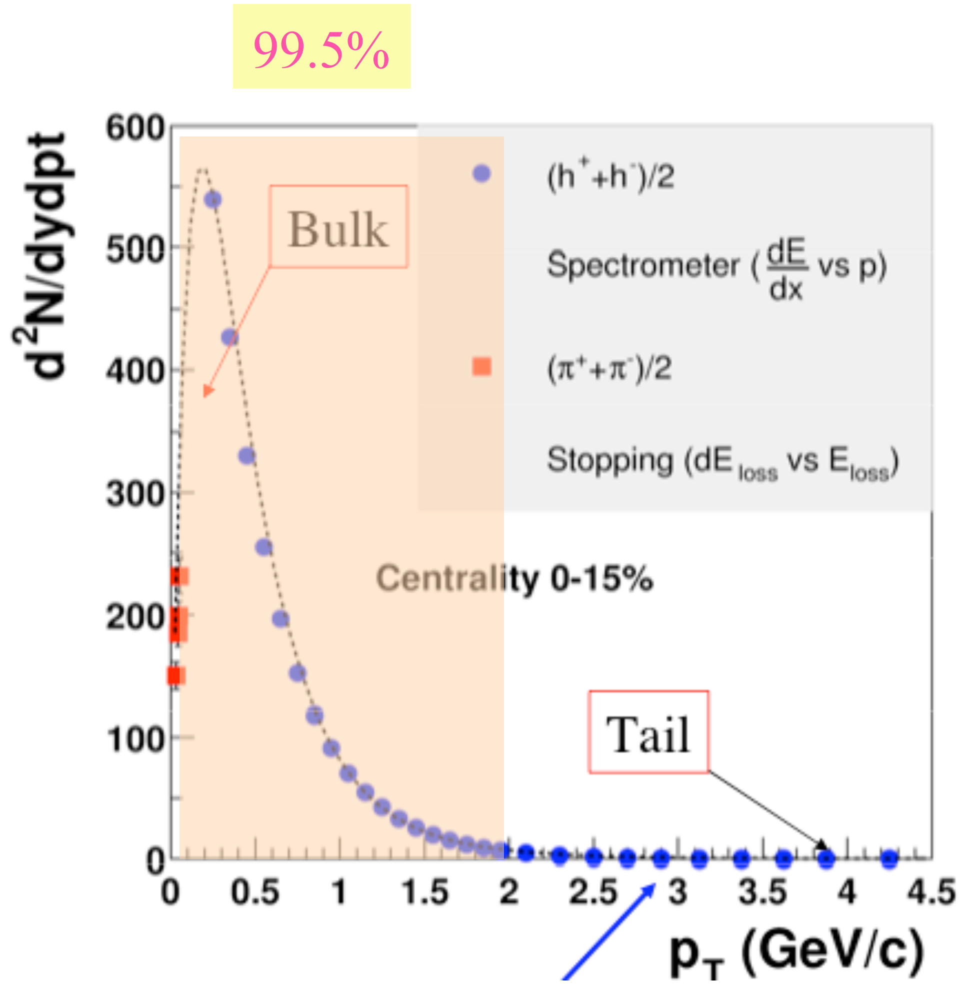
thermal, isotropically-emitting fluid cell
…boosted outward

The generic outcome
“Blast-wave”

The other hydrodynamics slide



The generic outcome
"Blast-wave"

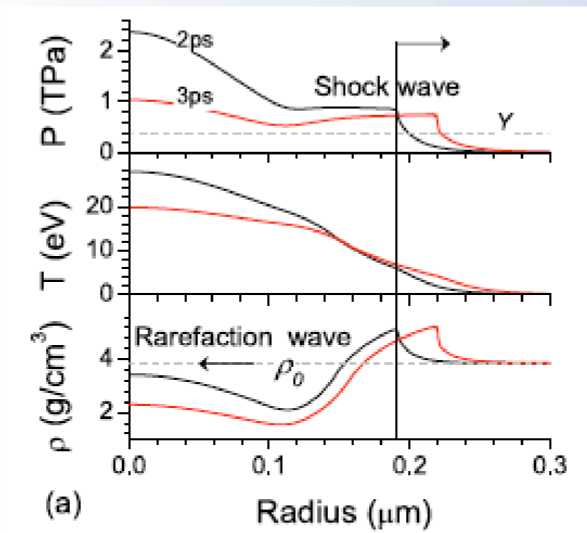


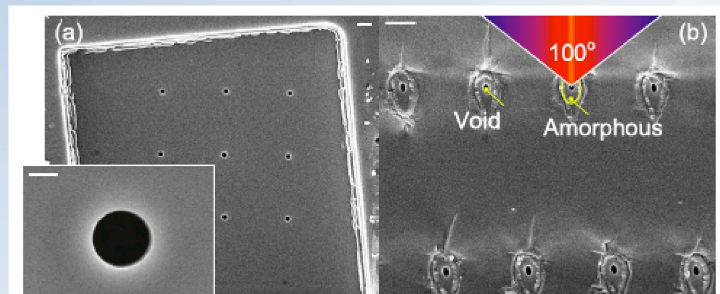
PRL 96, 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegabar Pressures

S. Juodkazis,[1] K. Nishimura,[1] S. Tanaka,[1] H. Misawa,[1] E. G. Gamaly,[2] B. Luther-Davies,[2] L. Hallo,[3] P. Nicolai,[3] and V. T. Tikhonchuk[3]

Extremely high pressures (~10 TPa) and temperatures (5×10^5 K) have been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/cm^2 converting material within the absorbing volume of ~0.2 μm^3 into plasma in a few fs. A pressure of ~10 TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by plasma hydrodynamics. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.





	Microexplosions	Femtoexplosions
√s	0.1 μJ	1 μJ
ε	10^{17} J/m^3	5 GeV/fm^3 = 10^{36} J/m^3
T	10^6 K	200 MeV = 10^{12} K
rate	10^{18} K/sec	10^{35} K/s

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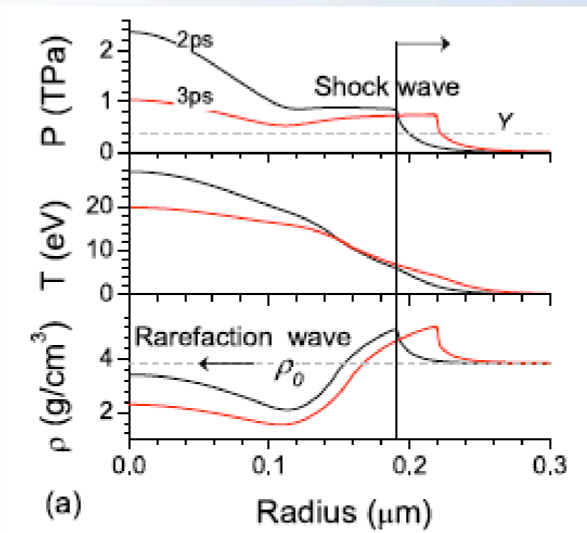
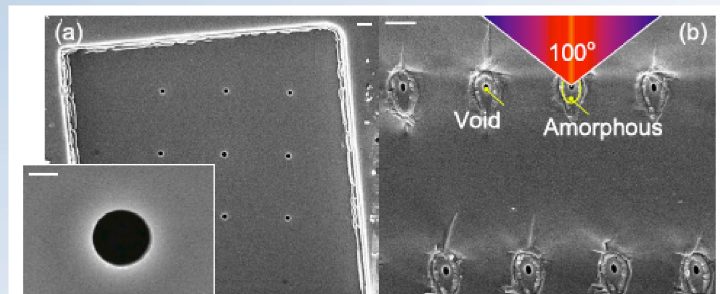


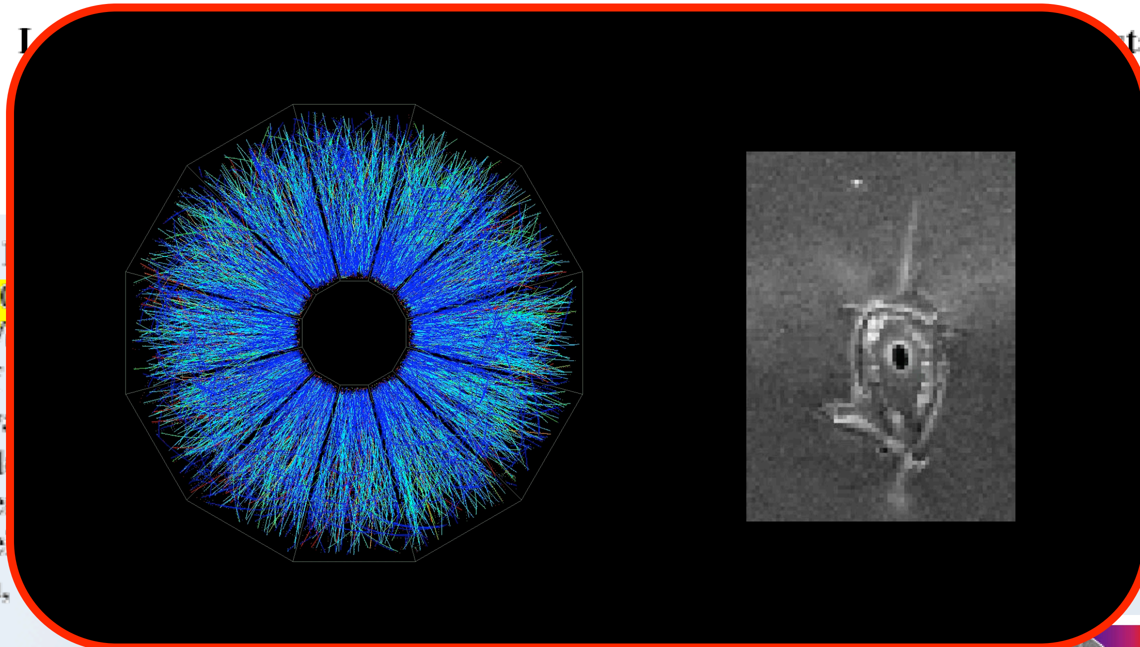


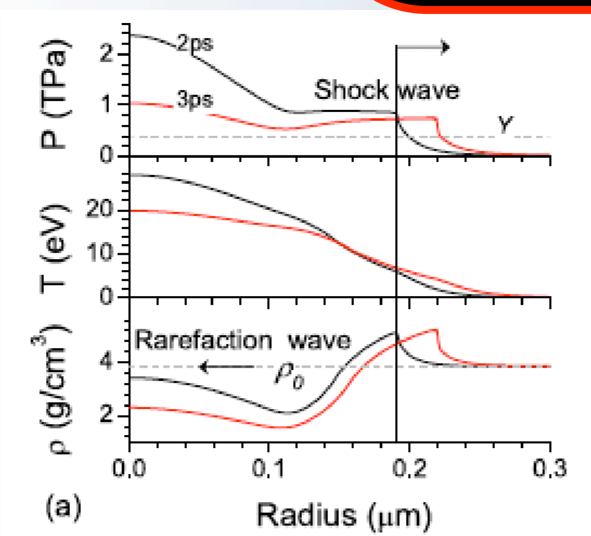
- energy quickly deposited
- enter plasma phase
- expand hydrodynamically
- cool back to original phase
- do ***geometric*** "postmortem" & infer momentum

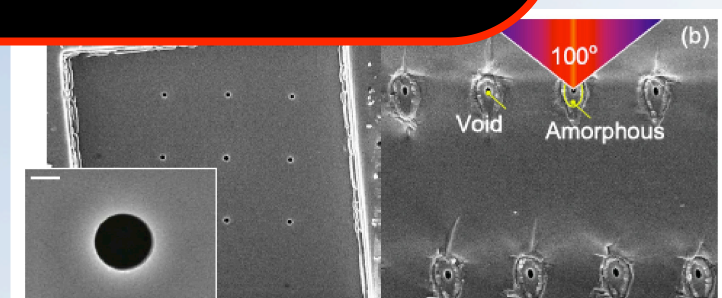
PRL 96, 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

I … tal:

Extremely … ing a single laser pulse (10 … an intensity over 10^{14} W/ … in a few fs. A pressure of … g shock and rarefaction w… ck-affected material insid… e versus the deposited ene… rvation laws and be mode… ing rates of 10^{18} K/s can,







- energy quickly deposited
- enter plasma phase
- expand hydrodynamically
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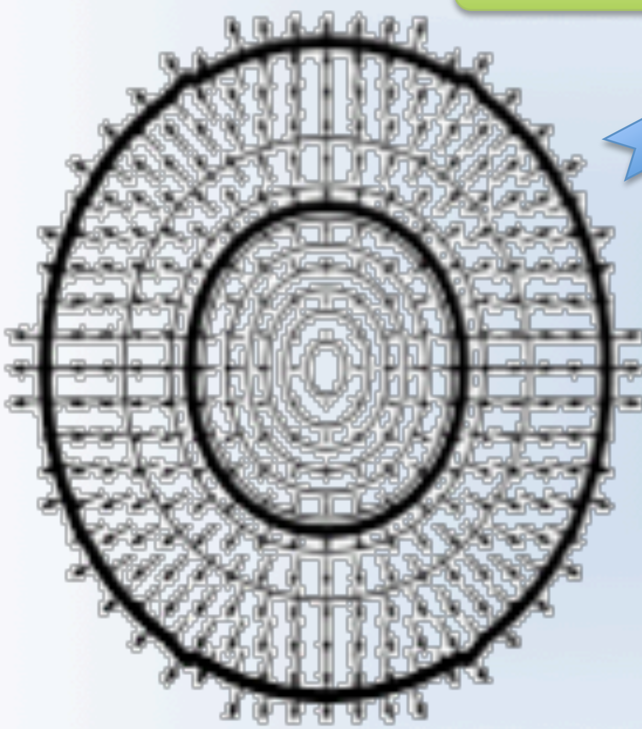
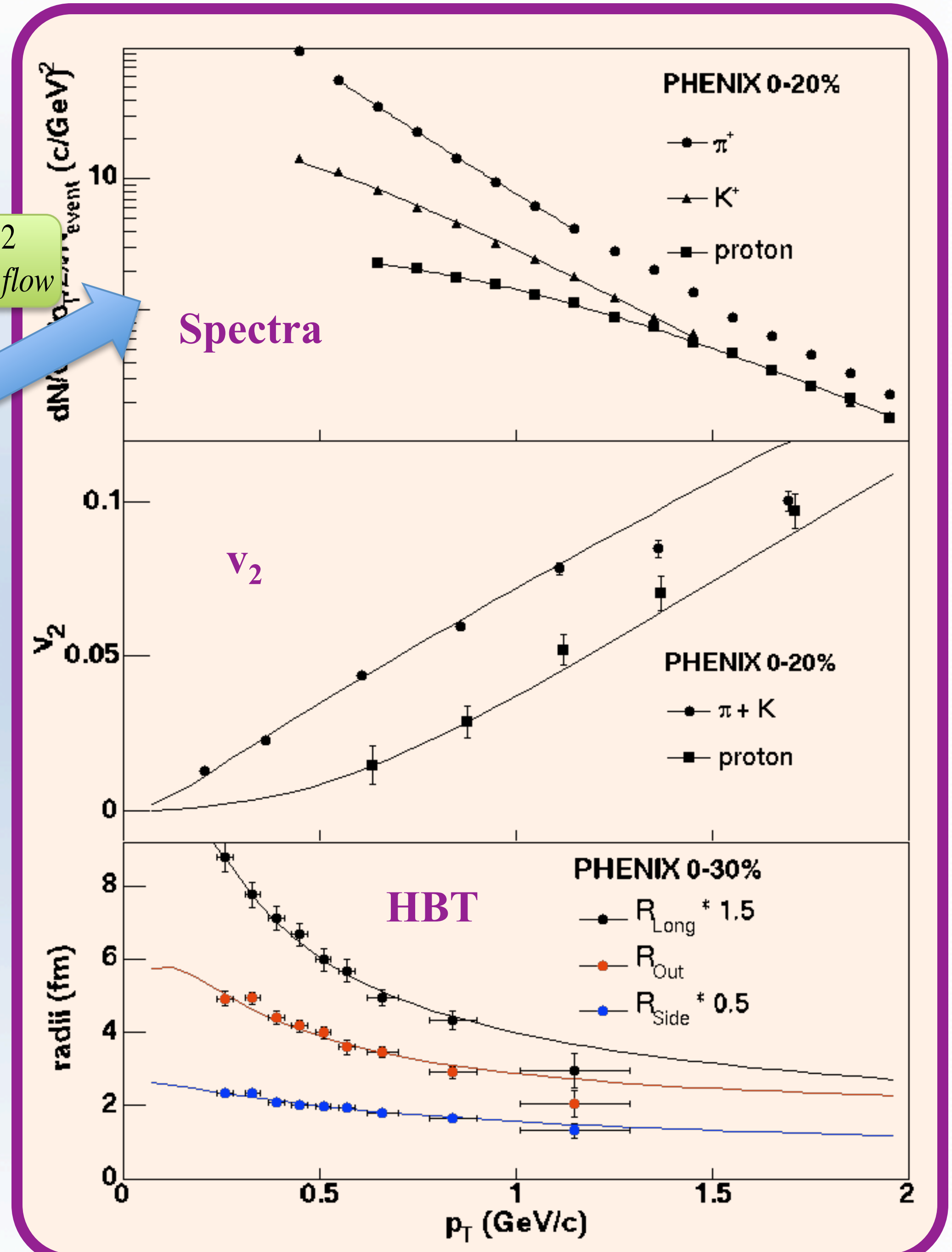
- do ***geometric*** "postmortem" & infer momentum

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

calculable in hydrodynamics or toy "blast wave" models

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



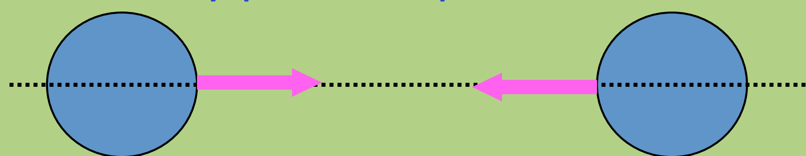


Impact parameter & Reaction plane

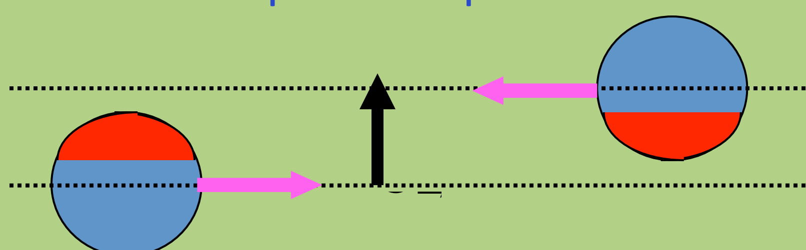
Impact parameter vector $\vec{b}$:

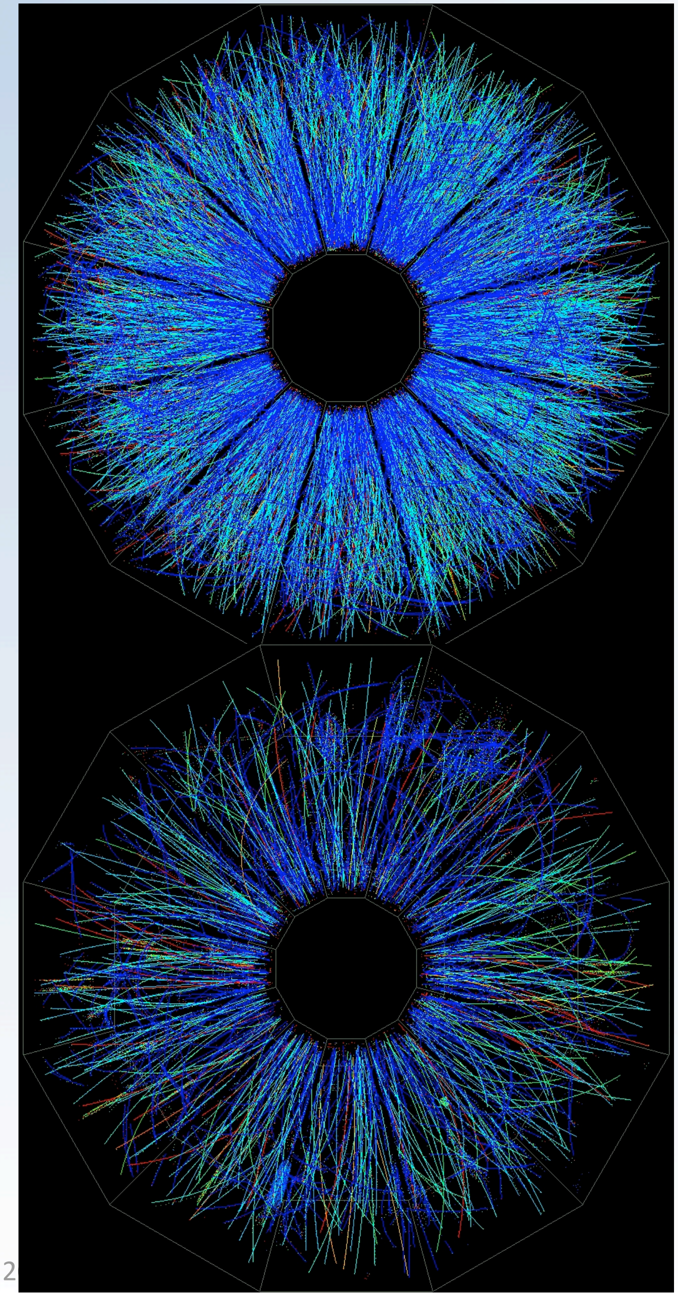
- $\perp$ beam direction
- connects centers of colliding nuclei

b = 0 : "central collision"
many particles produced



"peripheral collision"
fewer particles produced





Impact parameter & Reaction plane

Impact parameter vector $\vec{b}$:

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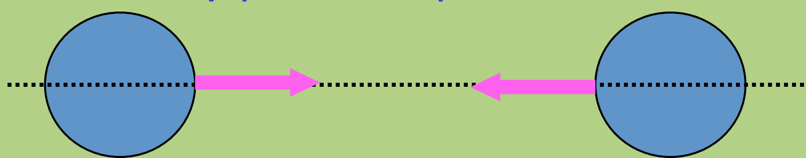
Reaction plane:

spanned by beam direction and $\vec{b}$

b = 0 : "central collision"
many particles produced



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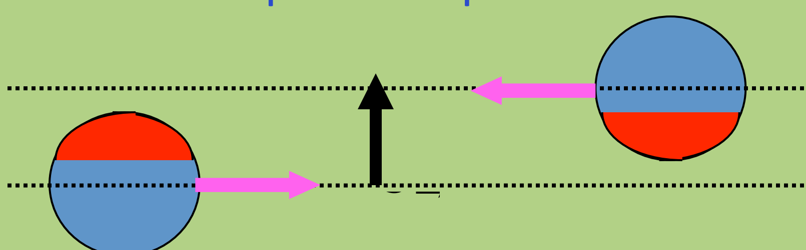
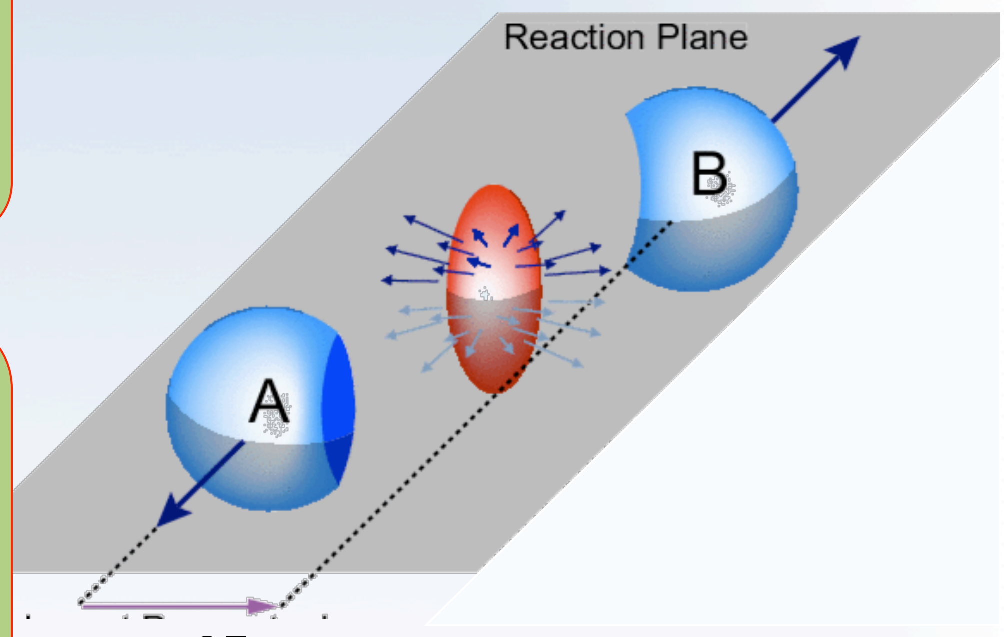
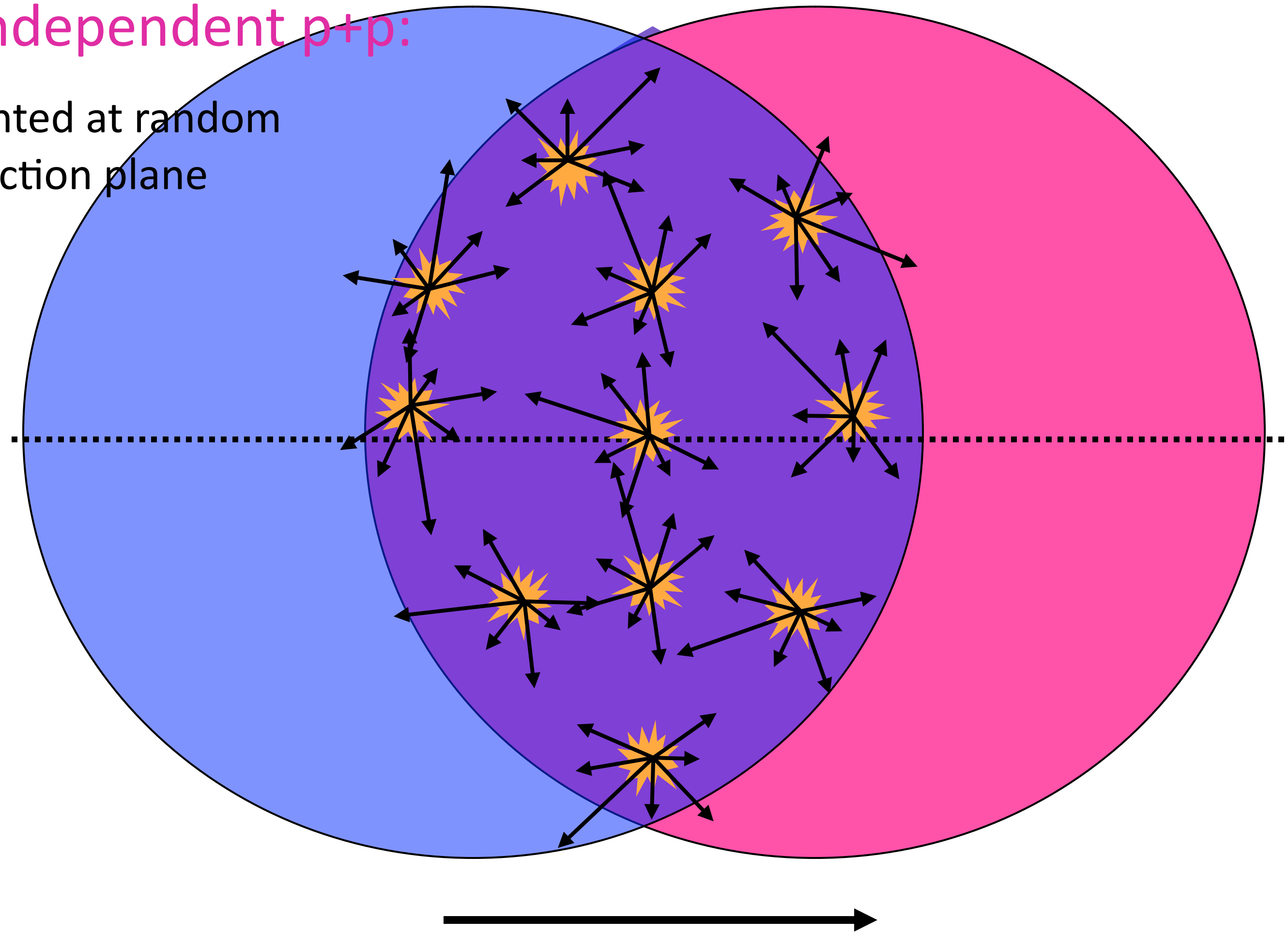




How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane



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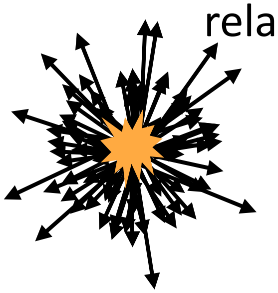
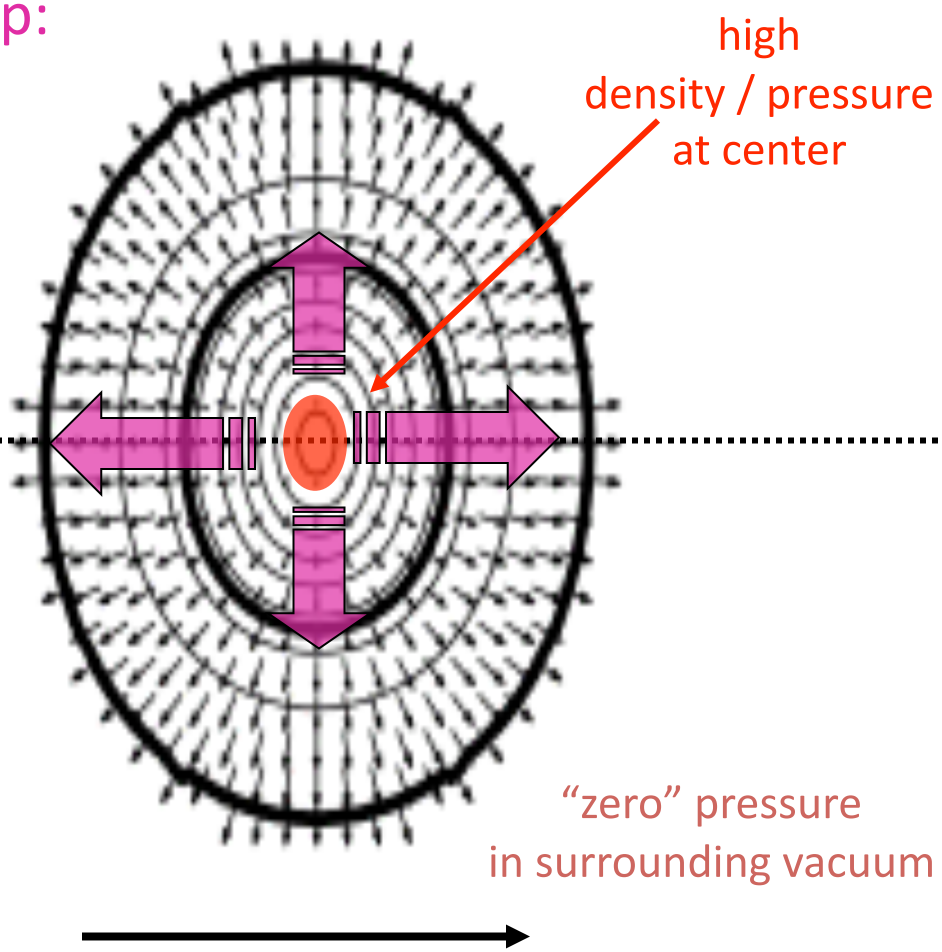
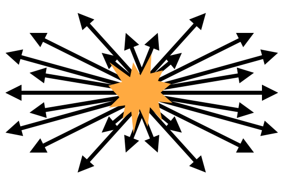


momenta pointed at random relative to reaction plane



2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane

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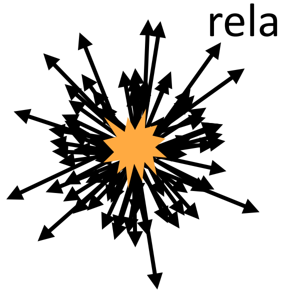

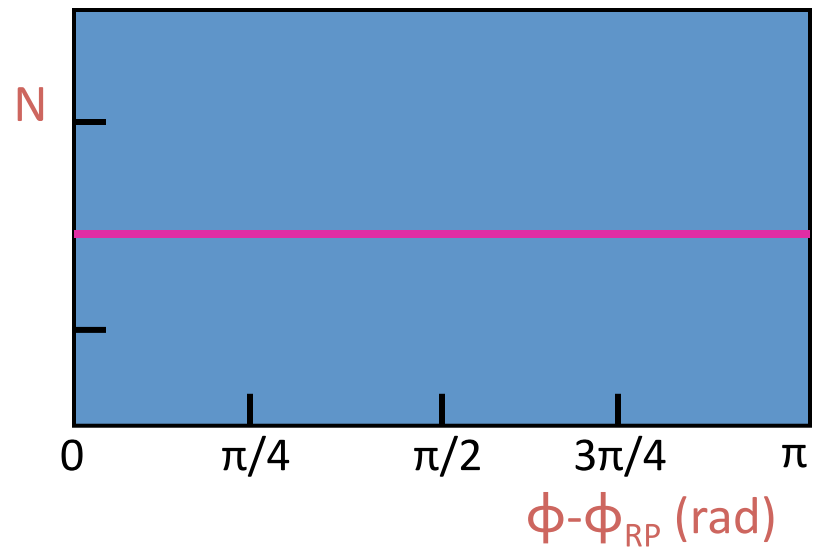

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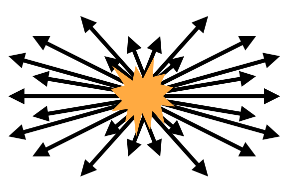

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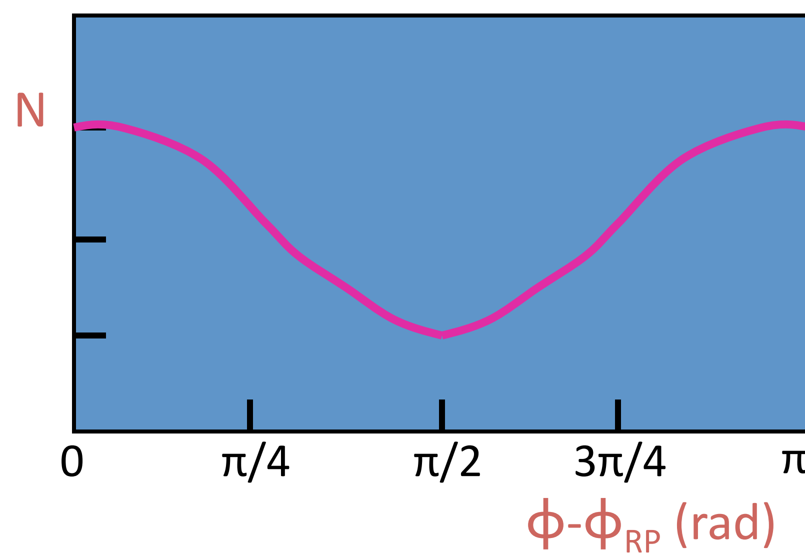
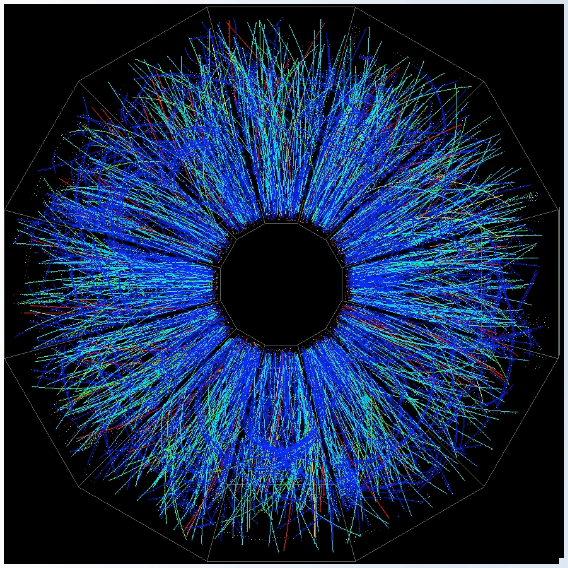


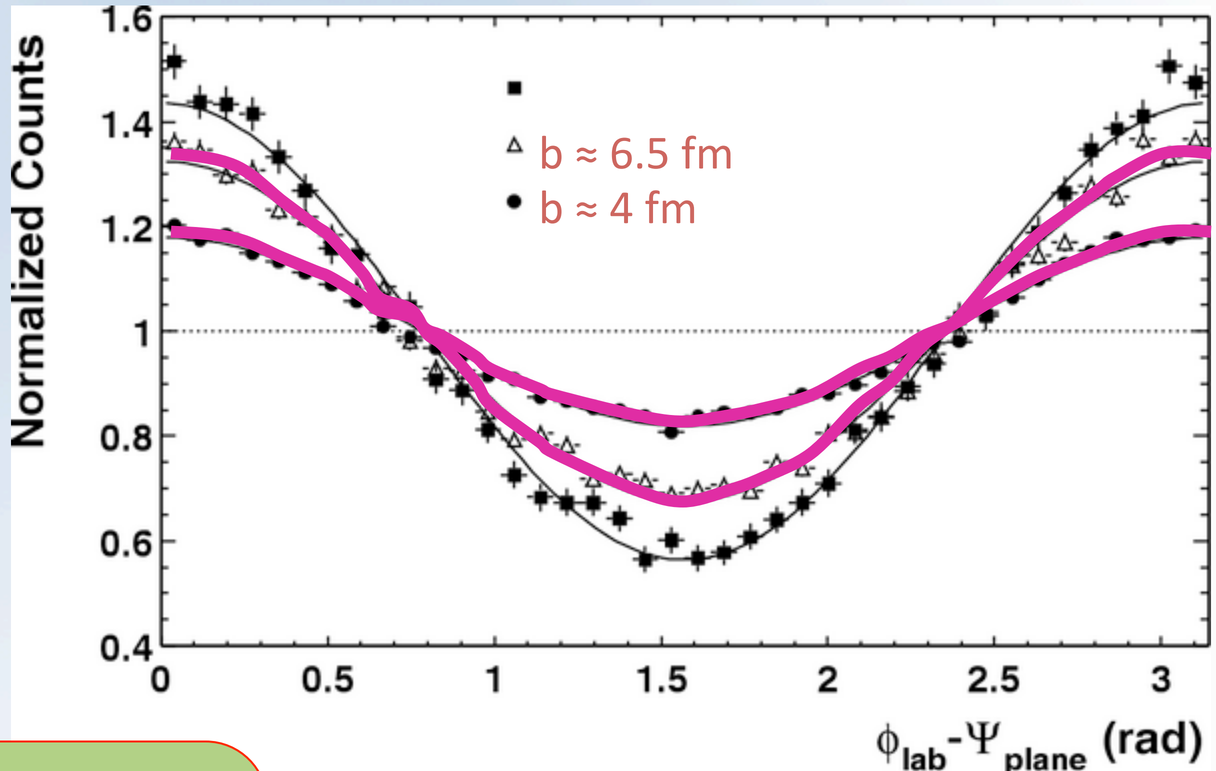
Azimuthal distributions at RHIC

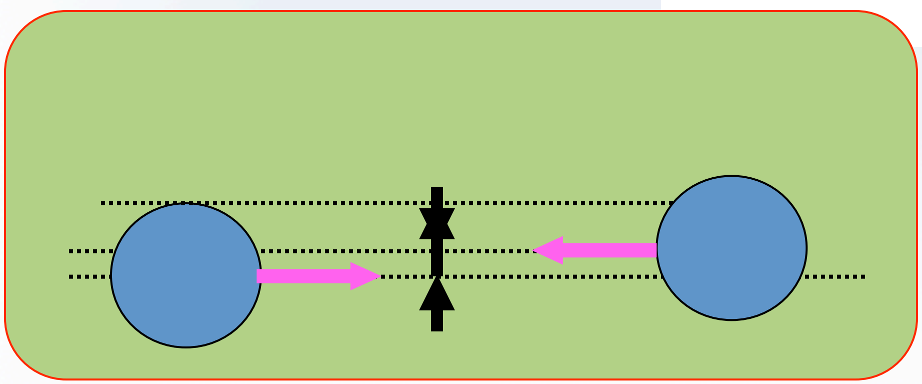


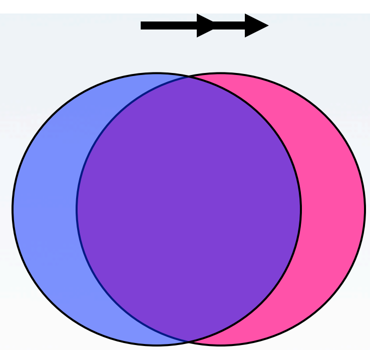
“central” collisions

mid-central collisions

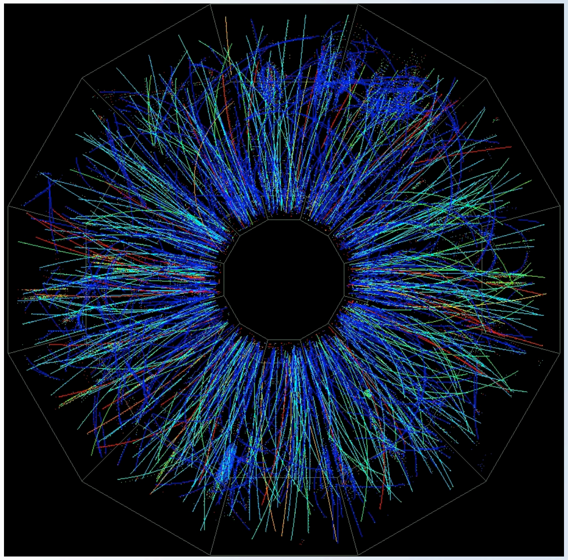
STAR, PRL**90** 032301 (2003)





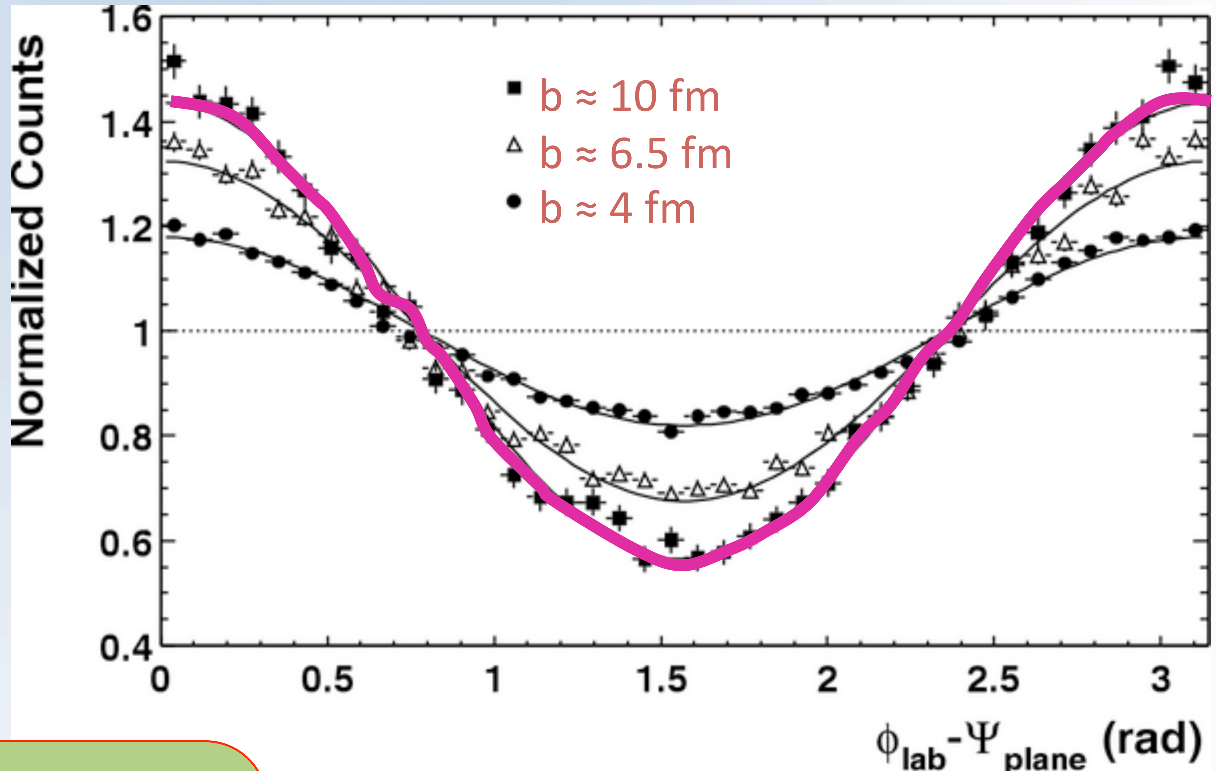


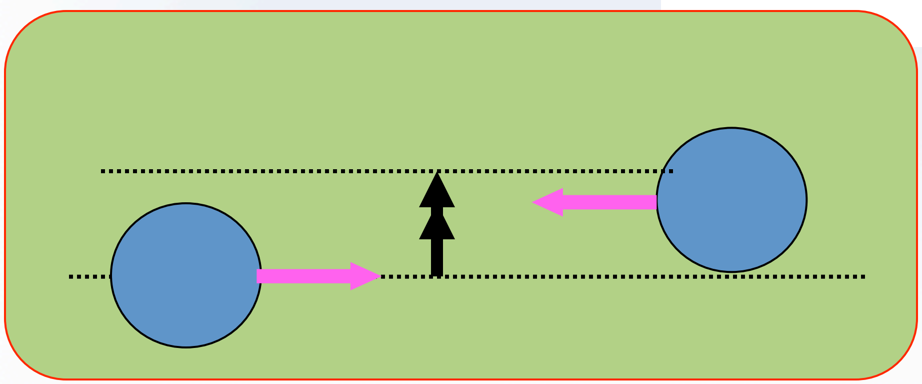
Azimuthal distributions at RHIC

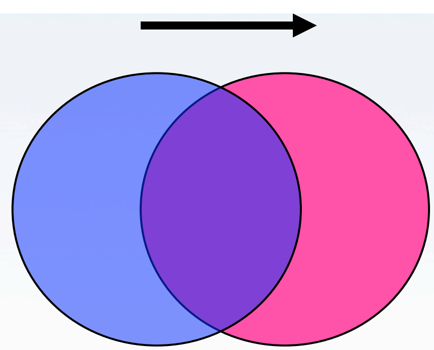


peripheral collisions

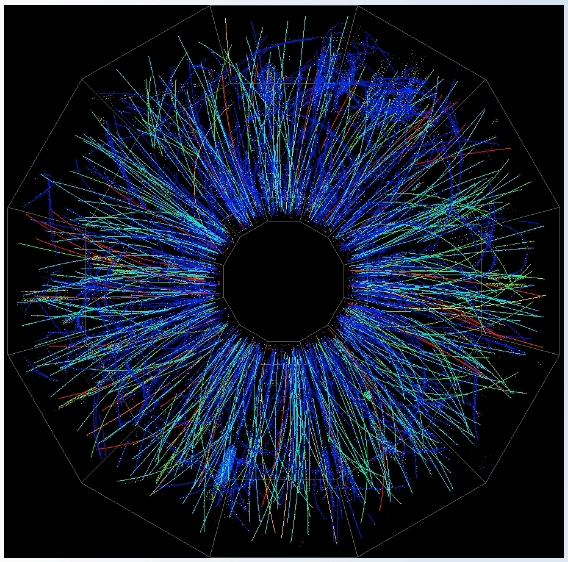
STAR, PRL**90** 032301 (2003)



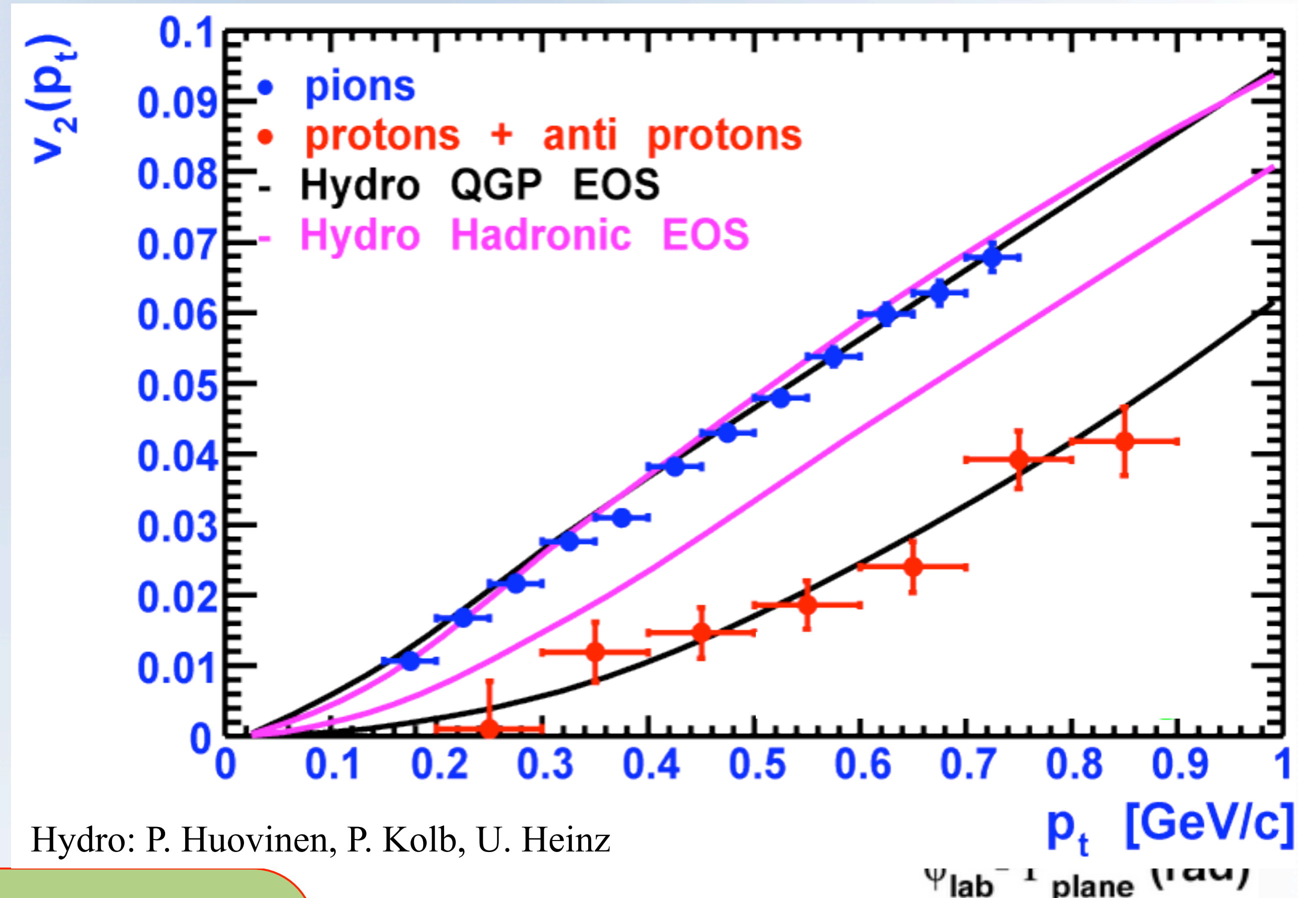


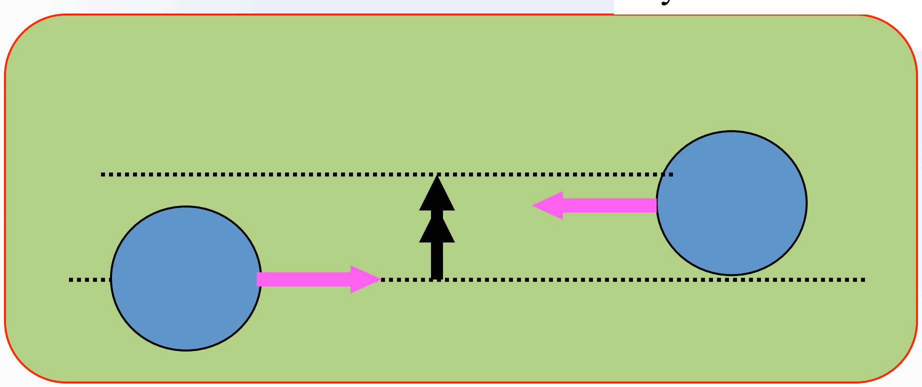


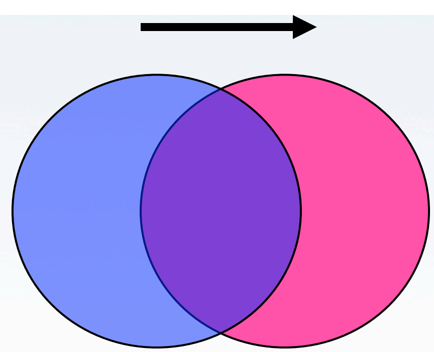
Azimuthal distributions at RHIC



peripheral collisions

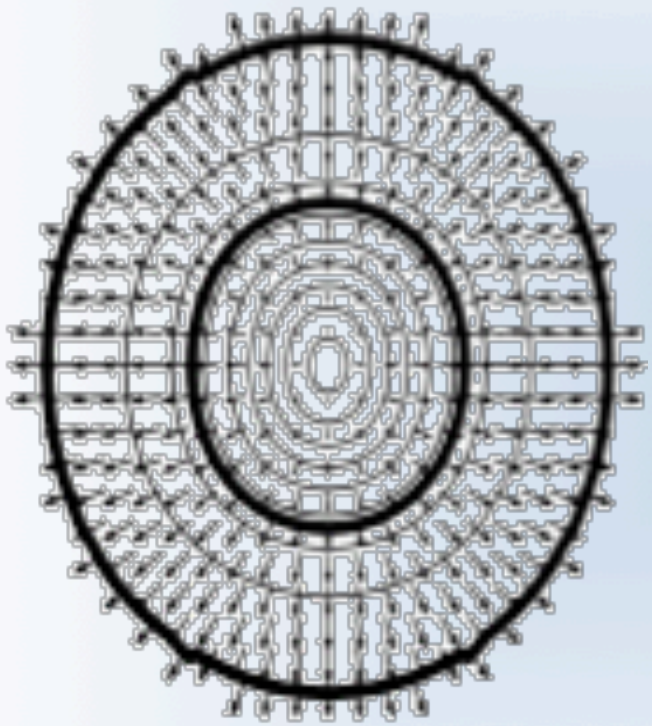


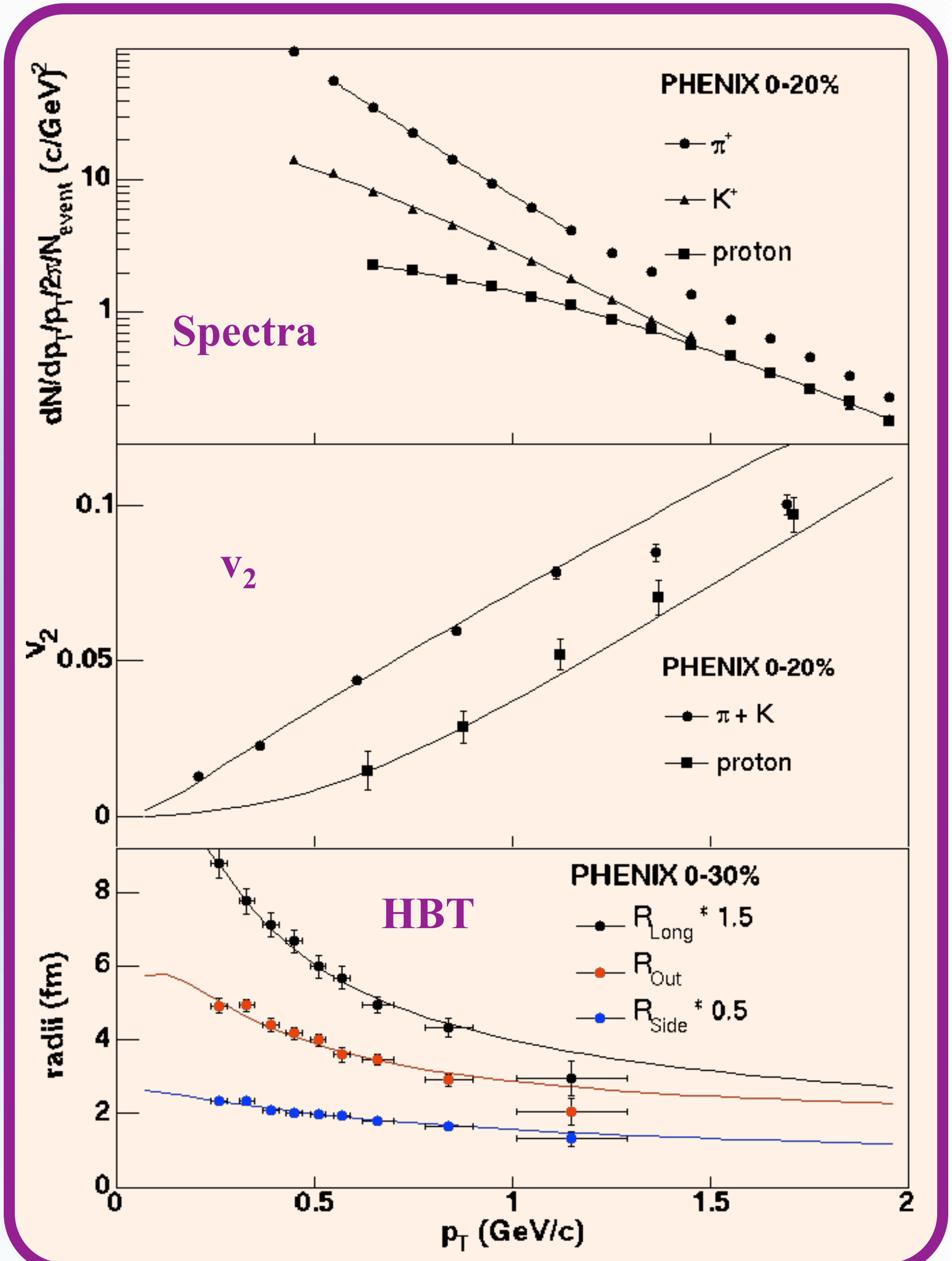




Explosive flow revealed through ***specific fingerprints*** on soft-sector observables

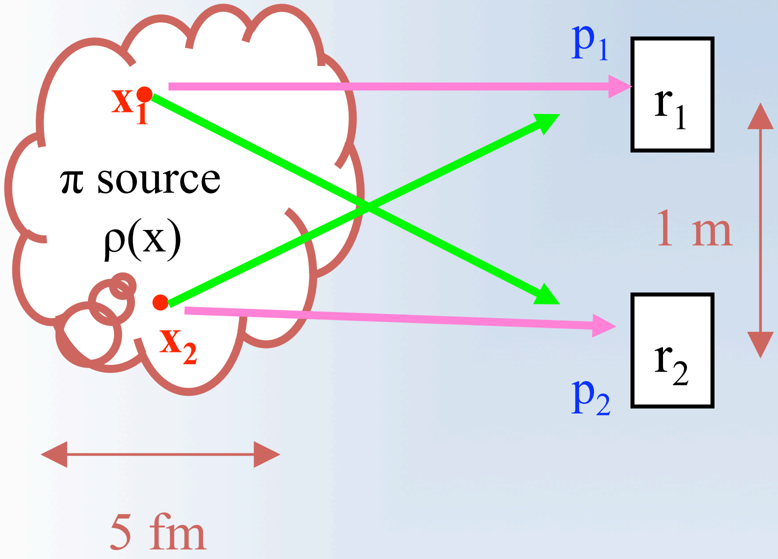
calculable in hydrodynamics or toy "blast wave" models





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

probing source geometry through interferometry



$$\psi_T = \frac{1}{\sqrt{2}}\{U(\vec{x}_1,\vec{p}_1)e^{i(\vec{r}_1-\vec{x}_1)\cdot\vec{p}_1}U(\vec{x}_2,\vec{p}_2)e^{i(\vec{r}_2-\vec{x}_2)\cdot\vec{p}_2} + U(\vec{x}_2,\vec{p}_1)e^{i(\vec{r}_1-\vec{x}_2)\cdot\vec{p}_1}U(\vec{x}_1,\vec{p}_2)e^{i(\vec{r}_2-\vec{x}_1)\cdot\vec{p}_2}\}$$

$$\psi_T^*\psi_T = U_1^*U_1 \cdot U_2^*U_2 \cdot \left(1+e^{iq\cdot(x_1-x_2)}\right)$$

Creation probability $\rho(x,p) = U^*U$

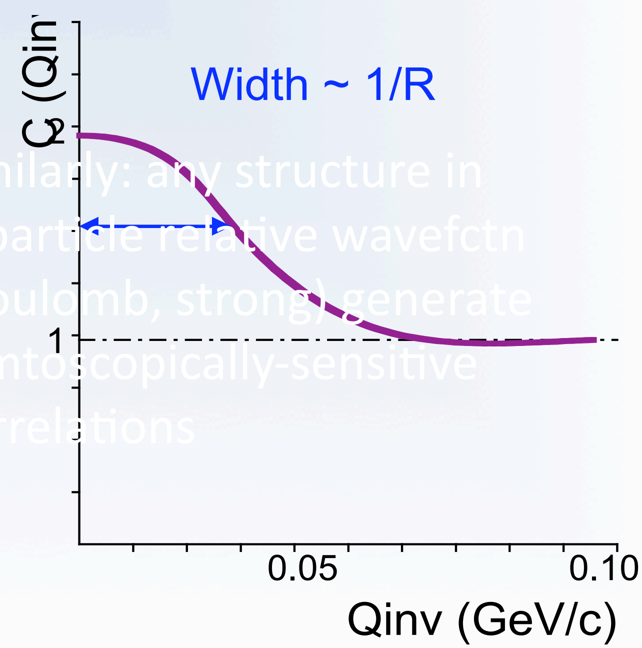
experimentally measuring this enhanced probability: quite challenging

$$C(p_1,p_2) = \frac{P(p_1,p_2)}{P(p_1)P(p_2)} = 1+\left|\tilde{\rho}(q)\right|^2$$

Measurable!

F.T. of pion source

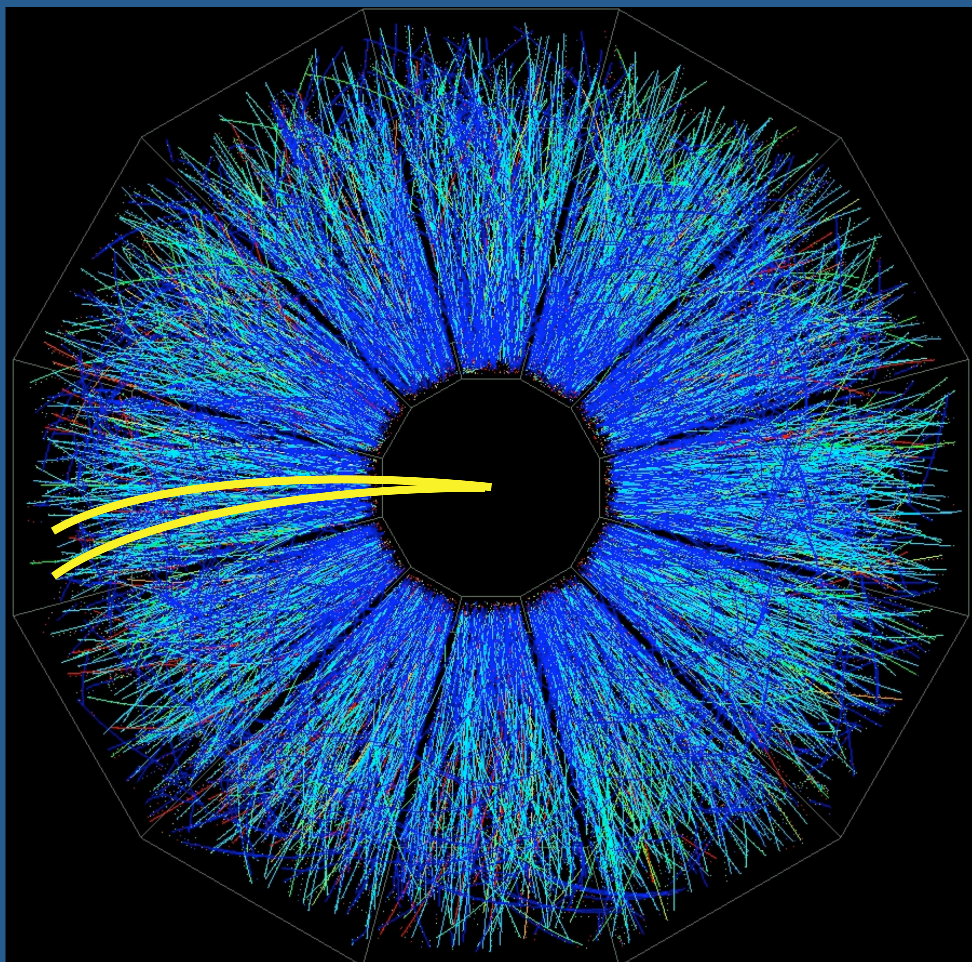
$$\vec{q} = \vec{p}_2 - \vec{p}_1$$



similarly: any structure in 2-particle relative wavefctn (Coulomb, strong) generate femtoscopically-sensitive correlations

The Bottom line…

if a pion is emitted, it is more likely to emit another pion *with very similar momentum* if the source is small



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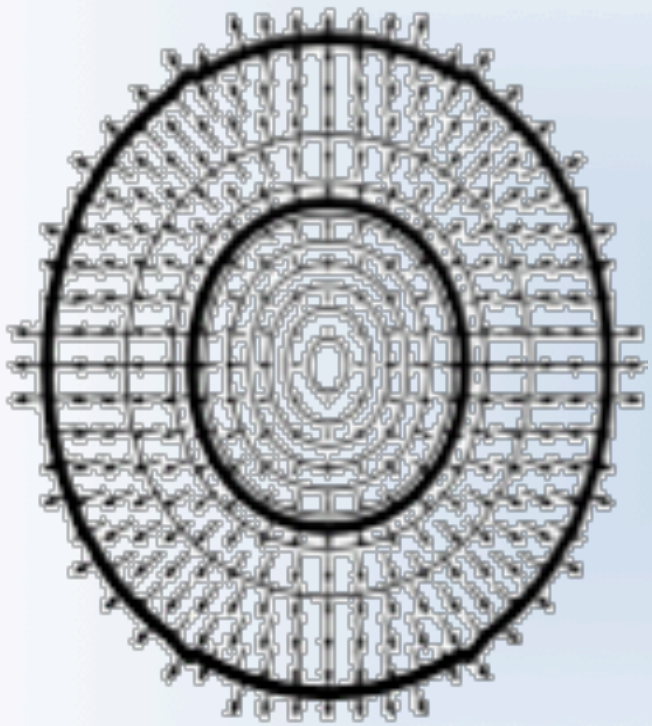
Explosive flow revealed through ***specific fingerprints*** on soft-sector observables

calculable in hydrodynamics or toy "blast wave" models



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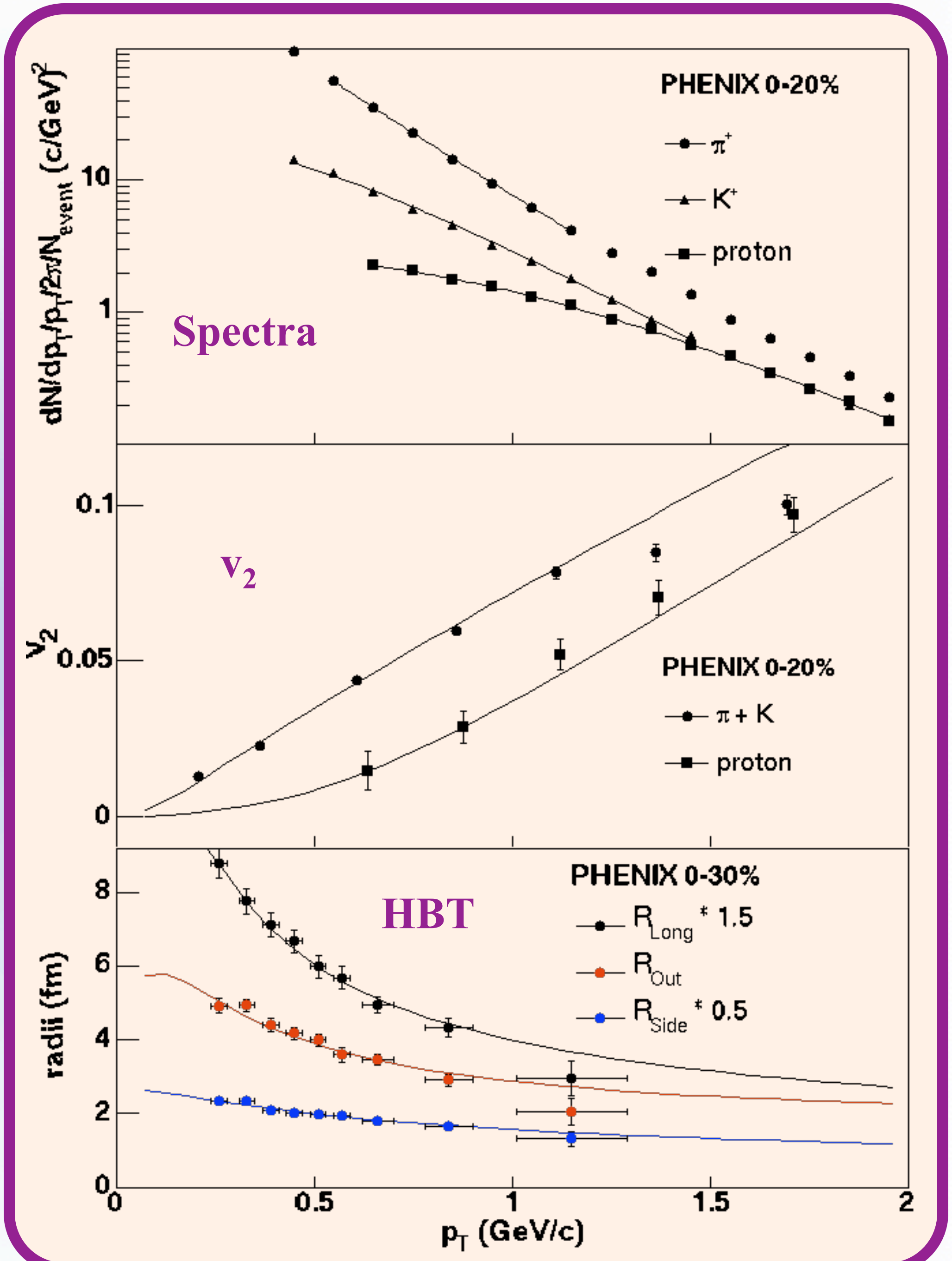
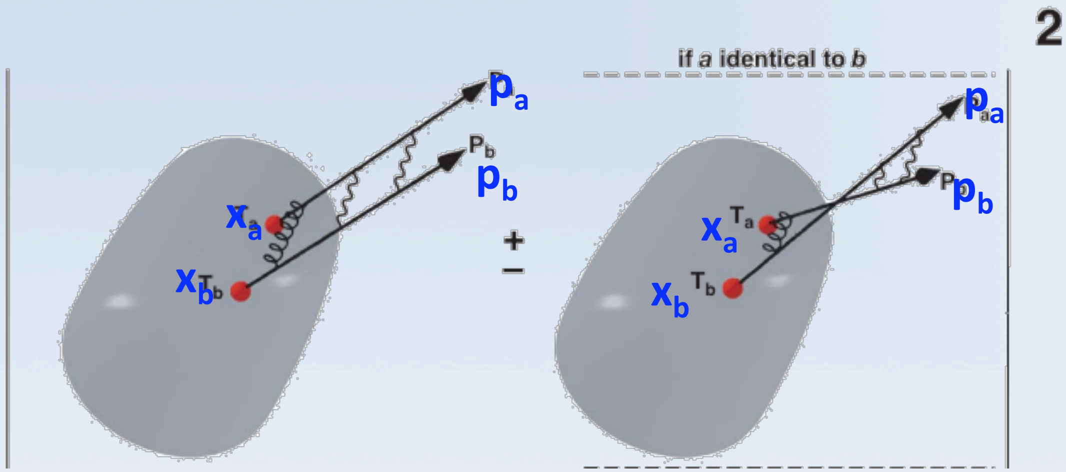


Femtoscopic information

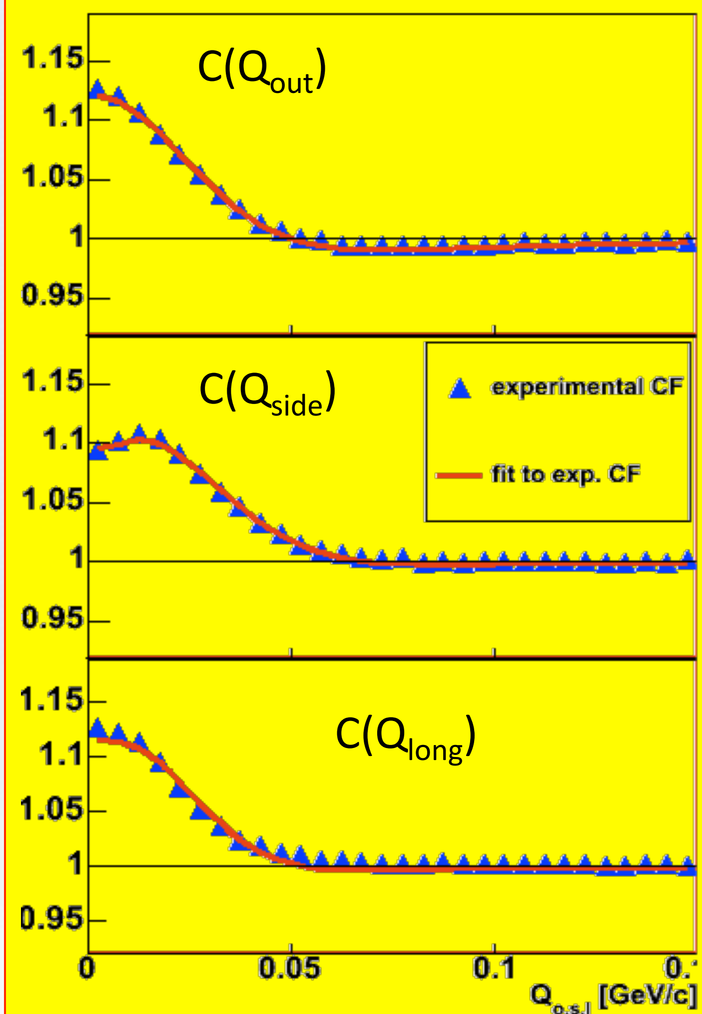
$S^{ab}_{\vec{P}}(\vec{r}\,') = (\vec{x}_a - \vec{x}_b)$ distribution

$\phi(\vec{q}\,',\vec{r}\,') = (a,b)$ relative wavefctn



$$C^{ab}_{\vec{P}}(\vec{q}) = \int d^3\vec{r}\,' \cdot S^{ab}_{\vec{P}}(\vec{r}\,') \cdot \left|\phi(\vec{q}\,',\vec{r}\,')\right|^2$$

- **femtoscopic correlation at low |q|**
- **must vanish at high |q|. [indep "direction"]**

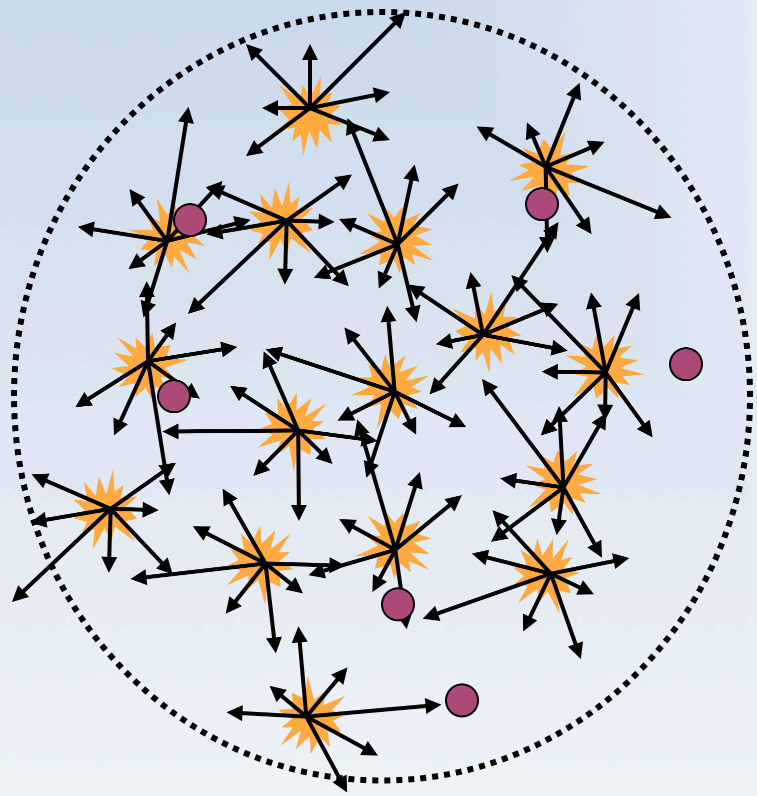


3 "radii" by using 3-D vector **q**

Geometric substructure?

random (non-)system:

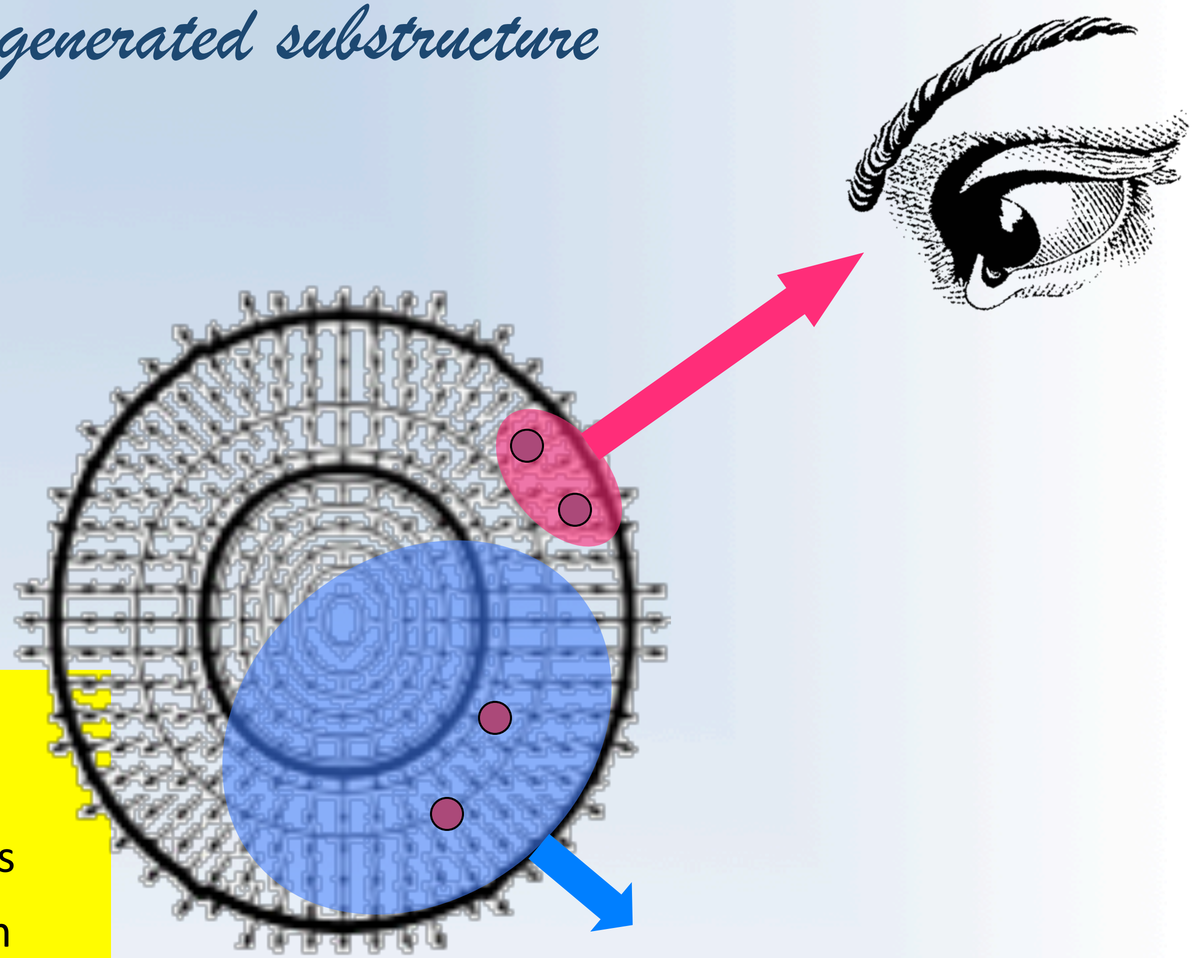
all observers measure the "whole source"



Flow-generated substructure

random (non-)system:

all observers measure the "whole source"

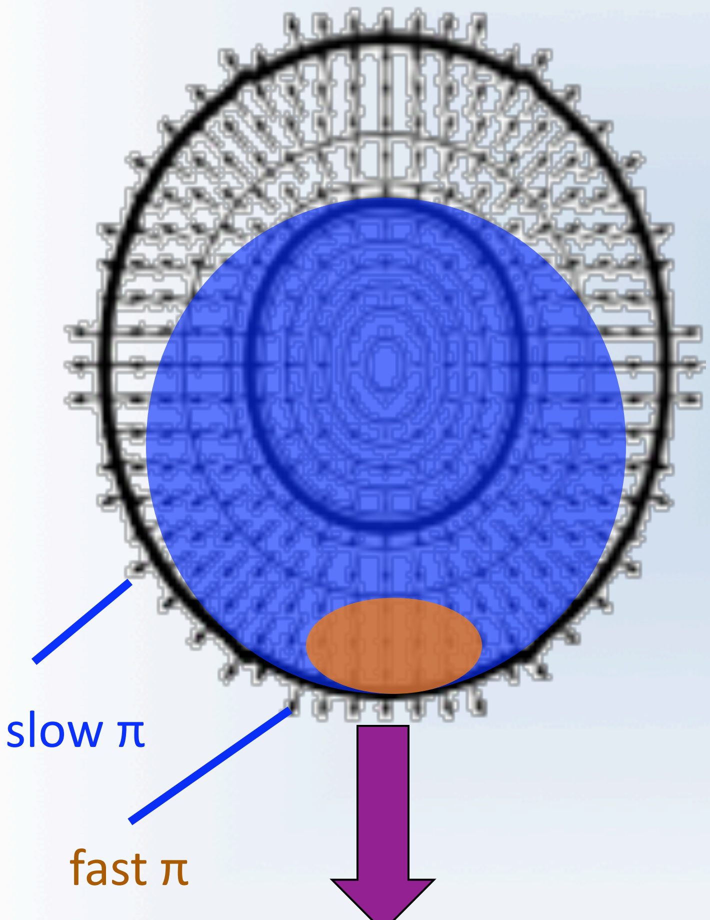


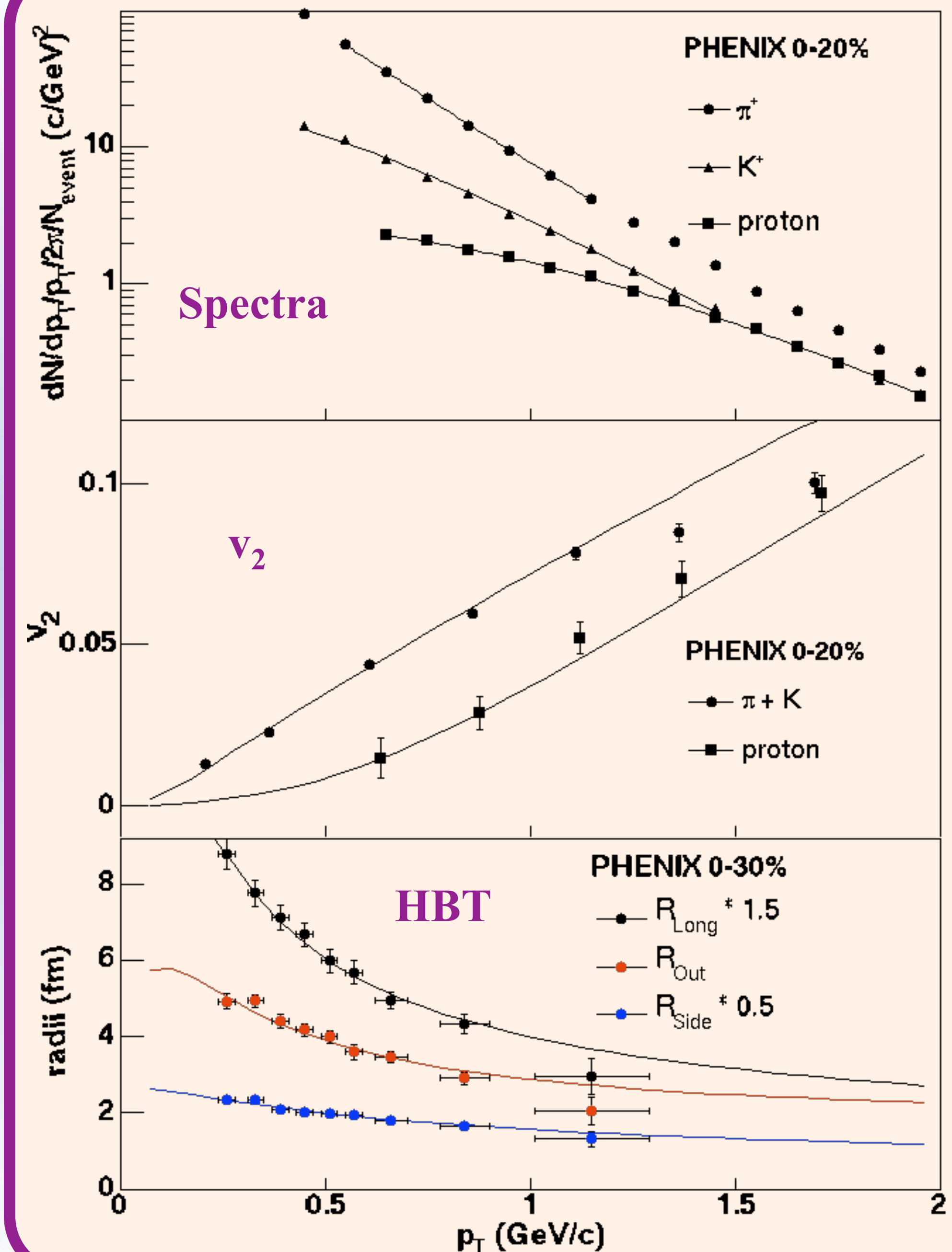
Specific predictions of bulk **global** collective flow:

- space-momentum (x-p) correlations
- faster (high pT) particles come from
  - **smaller** source
  - closer to "the **edge**"

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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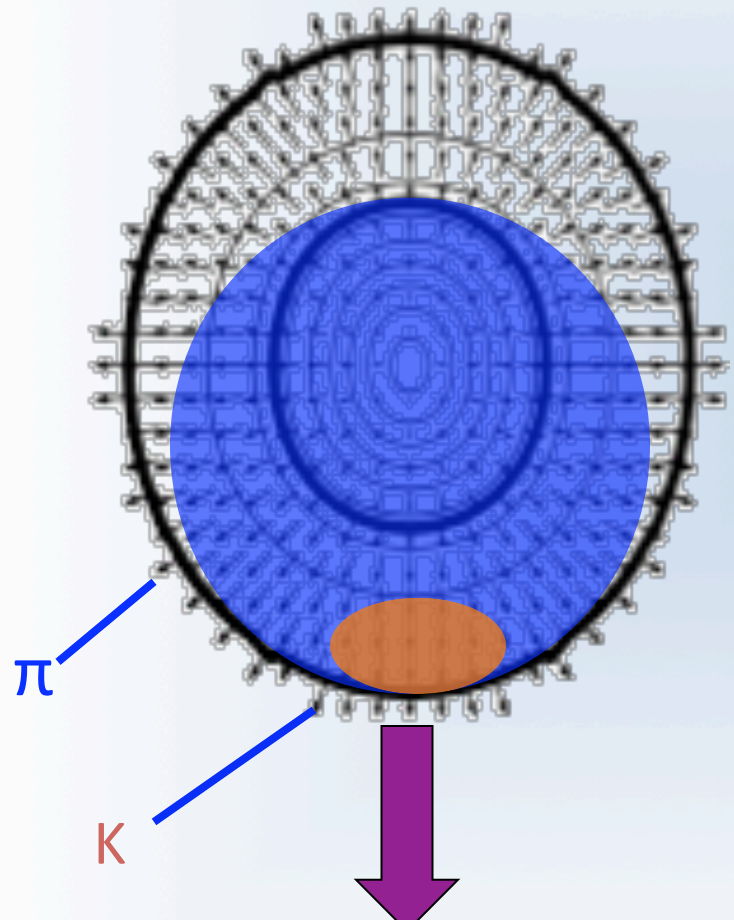

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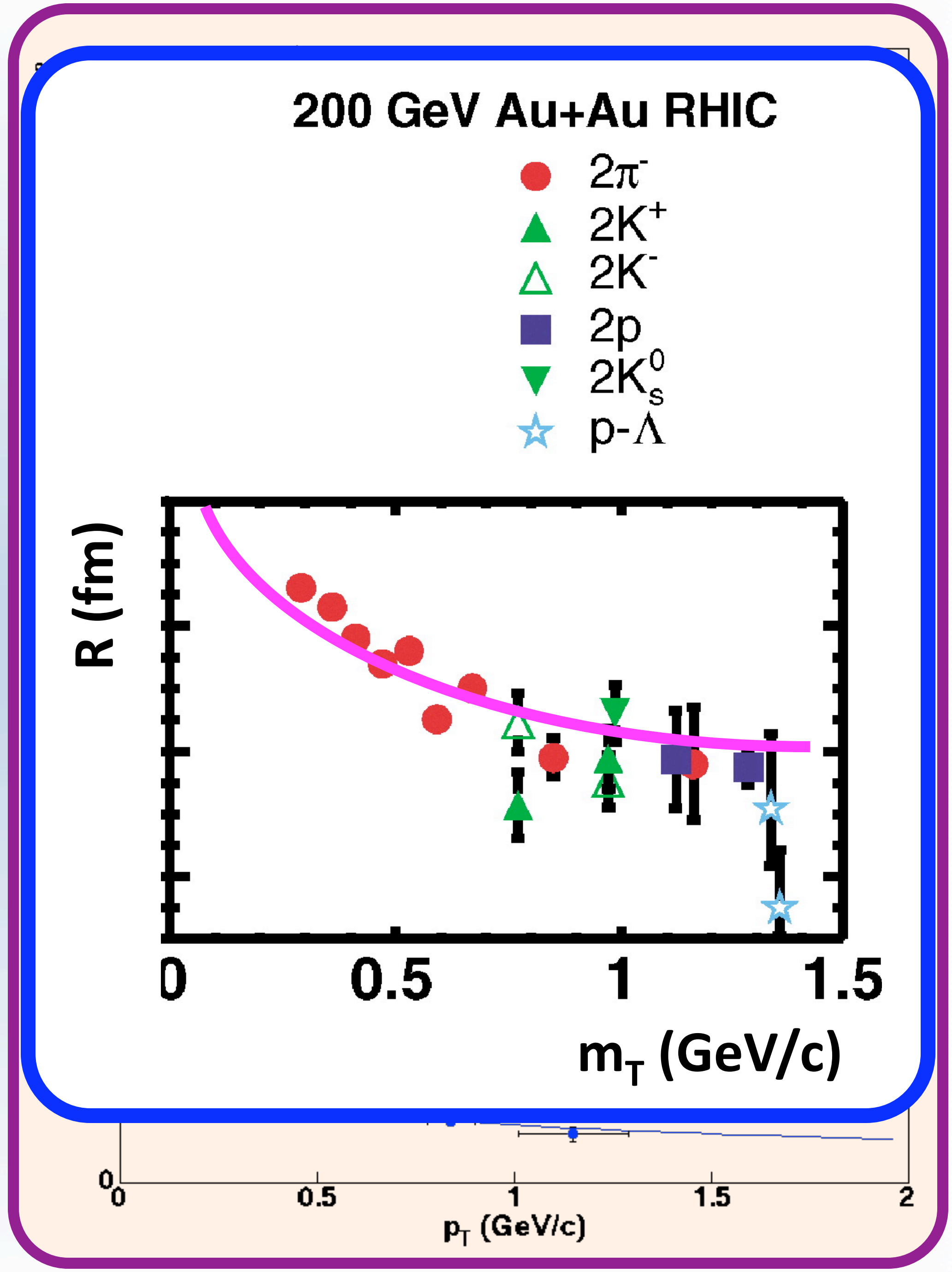

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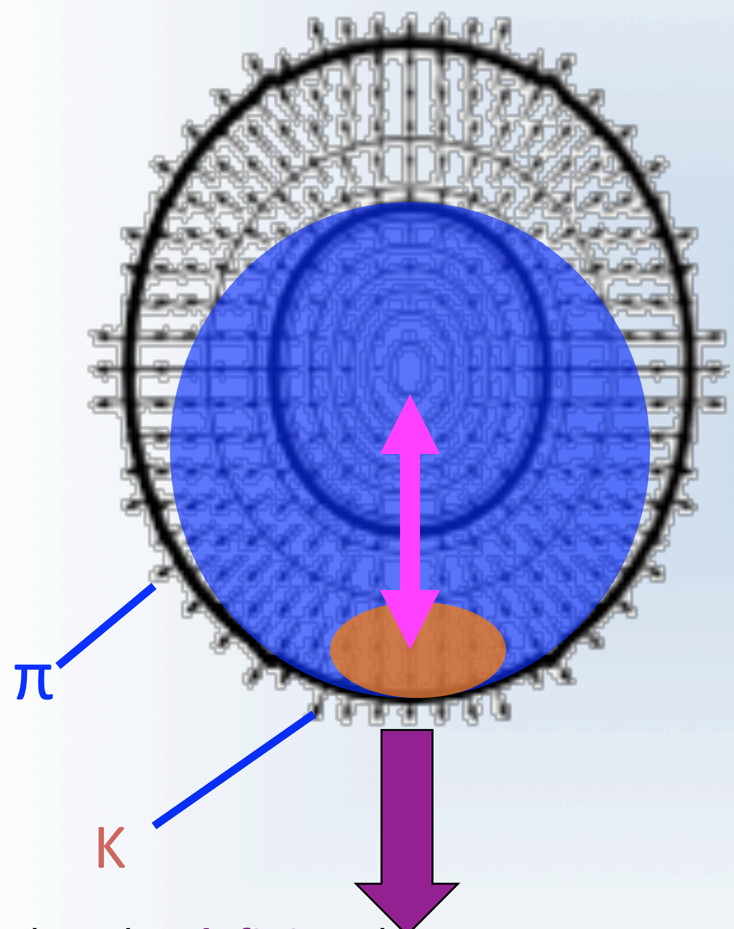

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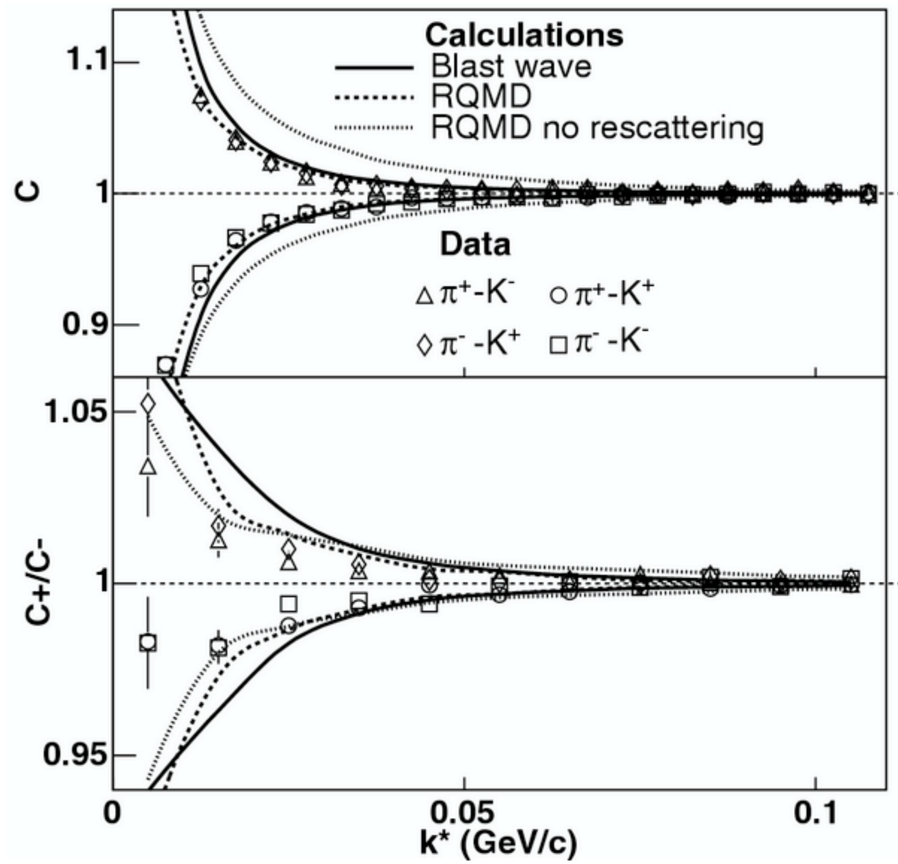
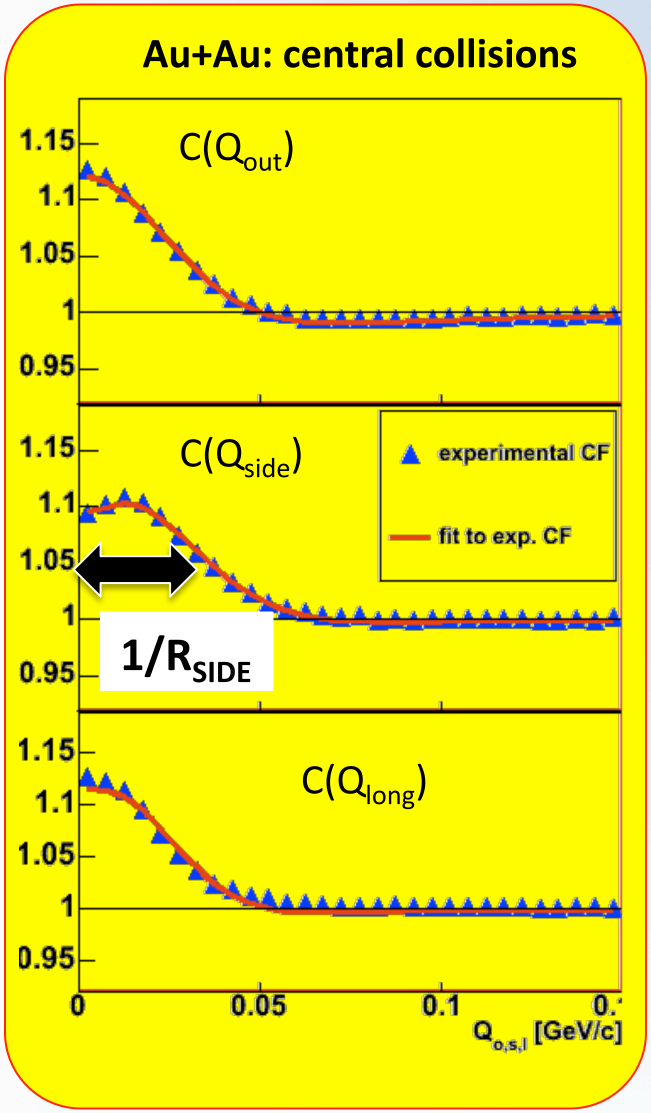


STAR PRL **91** 262301 (2003)

space-momentum substructure mapped *in detail*

Obtaining 3D radii from 3D correlation functions

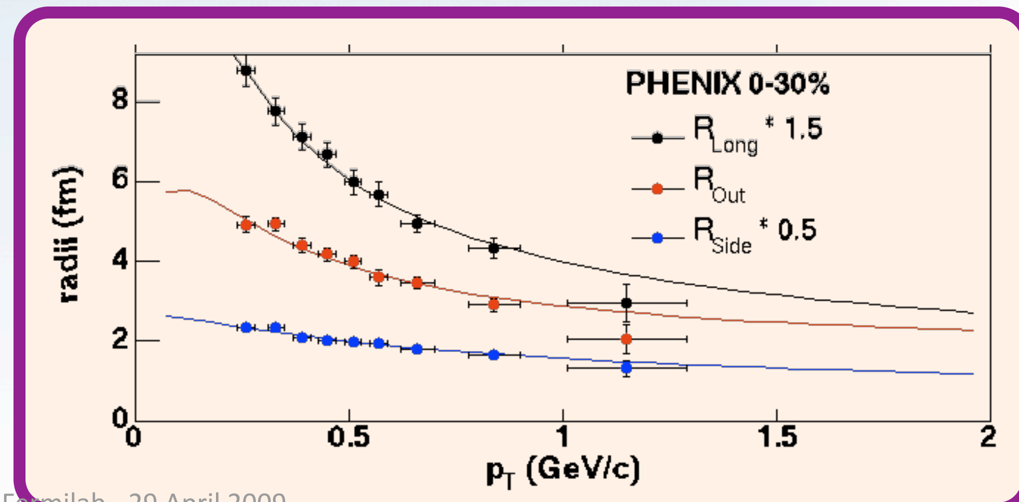


$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{ 1 + e^{-\left(q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2\right)} \right\} - 1 \right) \right]$$

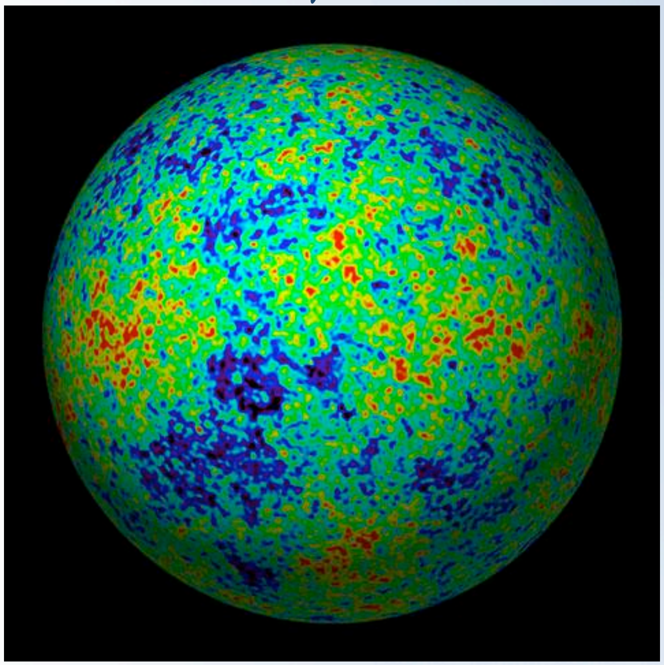
typical "Gaussian" fitting function

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

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



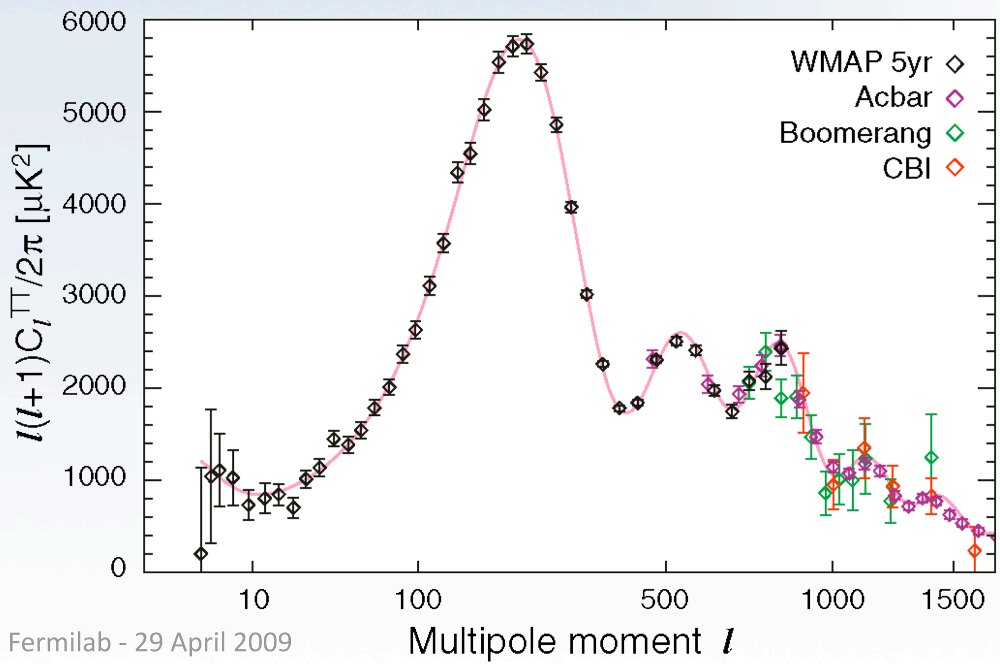
Spherical harmonic representation of 3D data



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

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

(average over m → no “special” direction)



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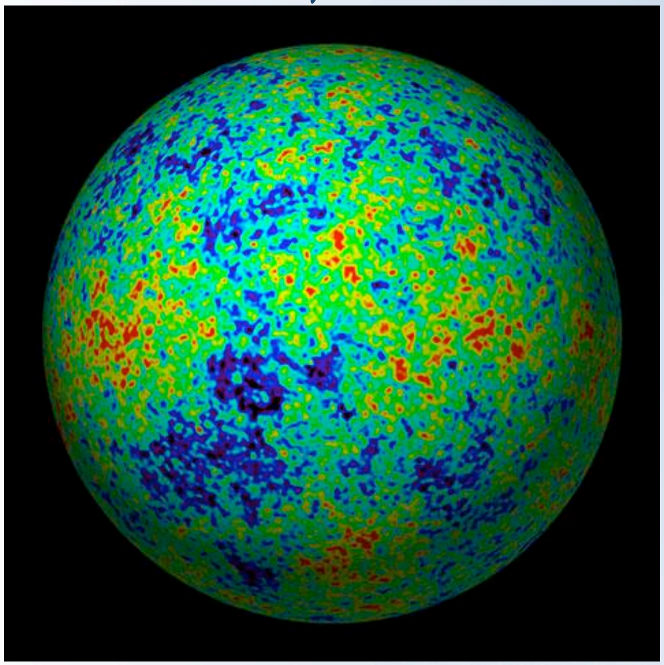

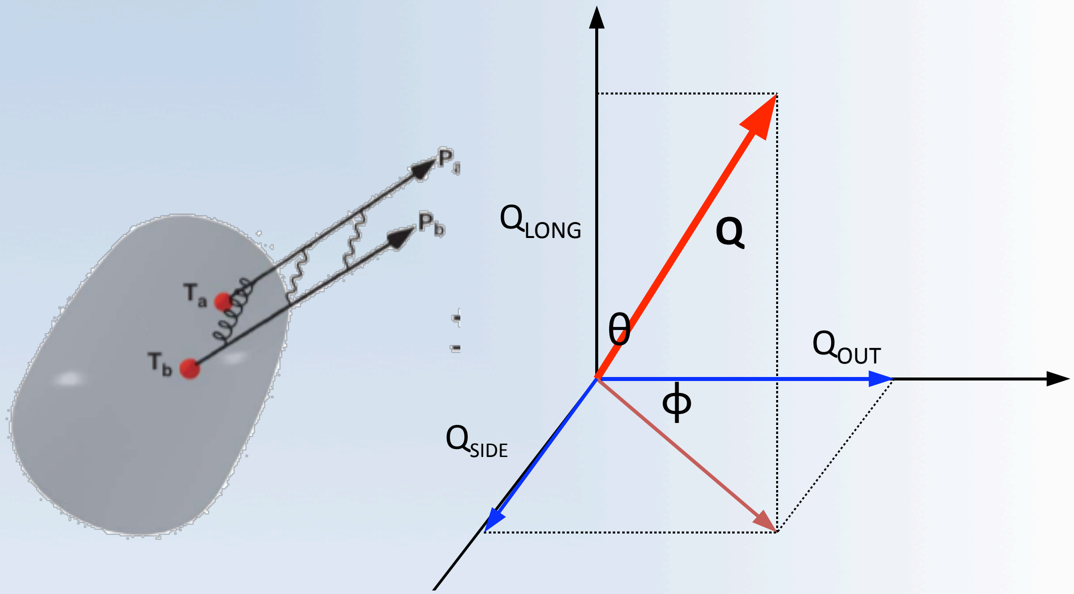

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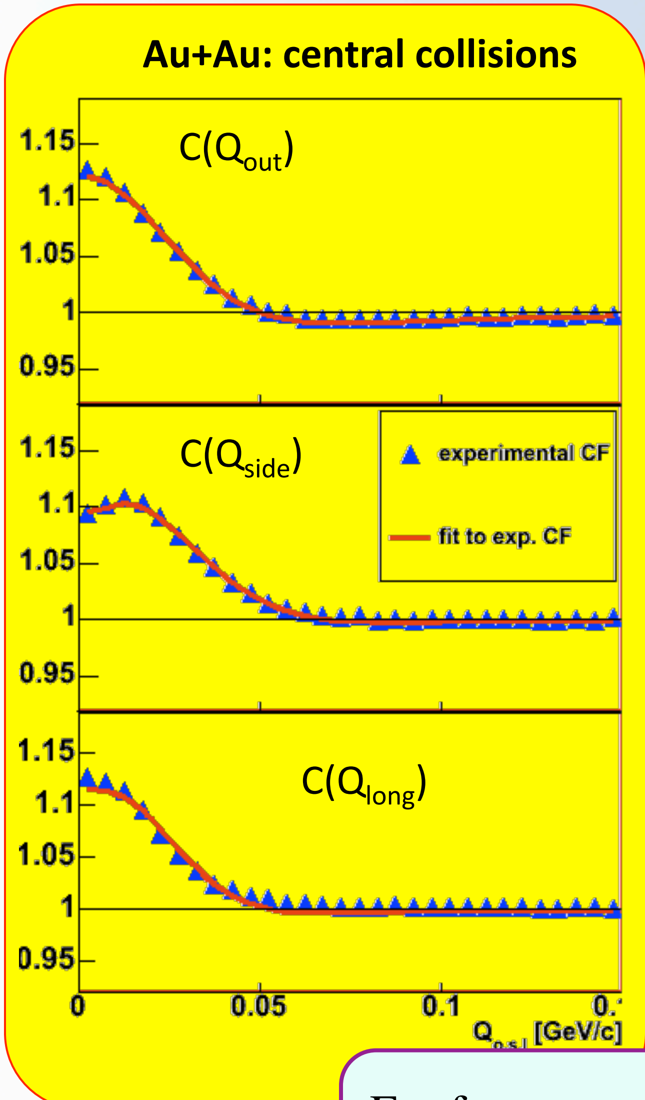
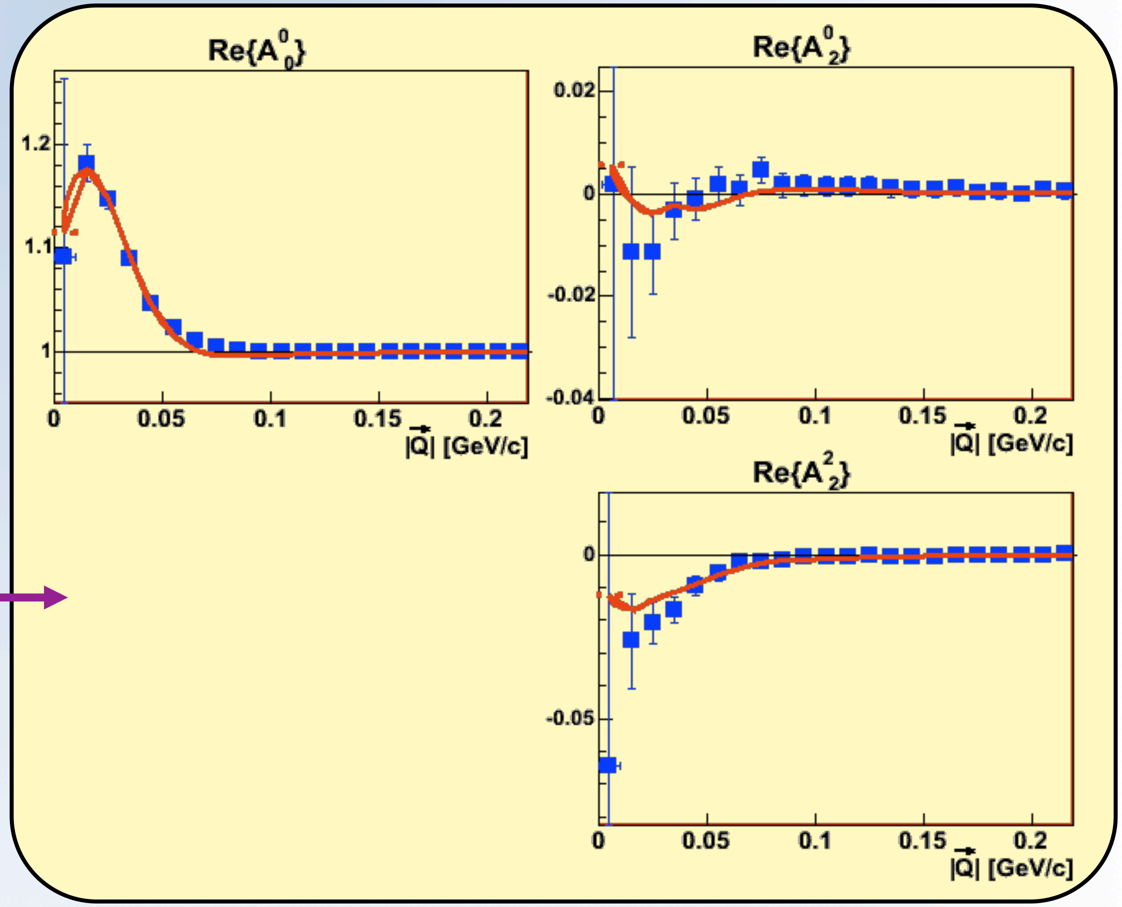
$$A_{l,m}\left(\left|\vec{Q}\right|\right) = \frac{\Delta_{\cos\theta}\Delta_{\phi}}{\sqrt{4\pi}} \sum_i^{bins} Y^{*}_{l,m}(\theta_i,\phi_i) C\left(\left|\vec{Q}\right|, \cos\theta_i, \phi_i\right)$$

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

(average over m ⇒ no "special" direction)

Spherical harmonic representation of 3D data





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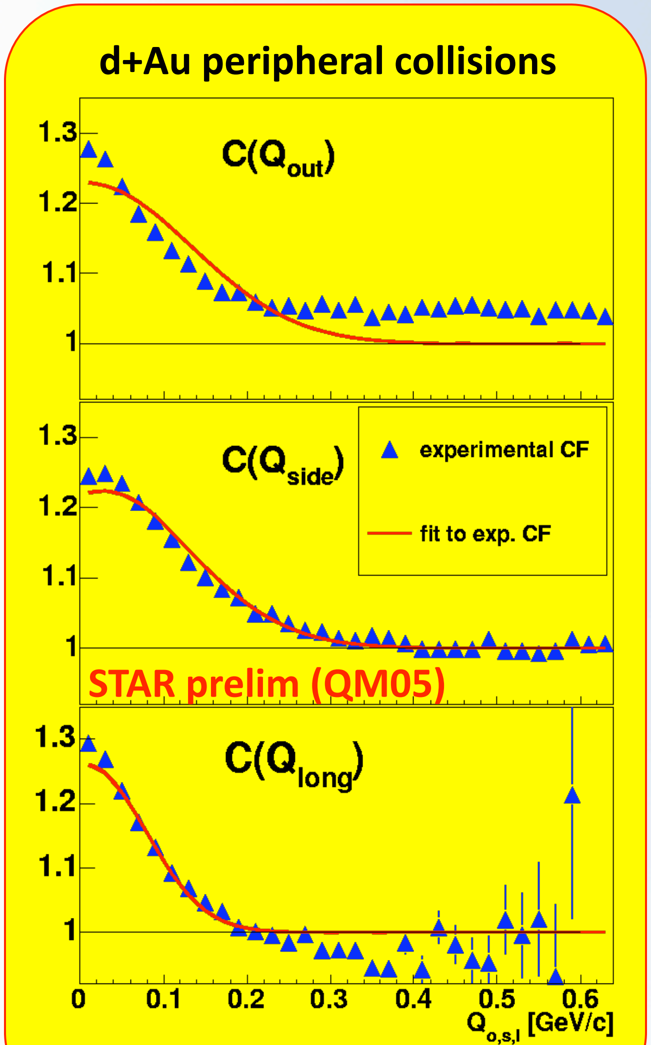
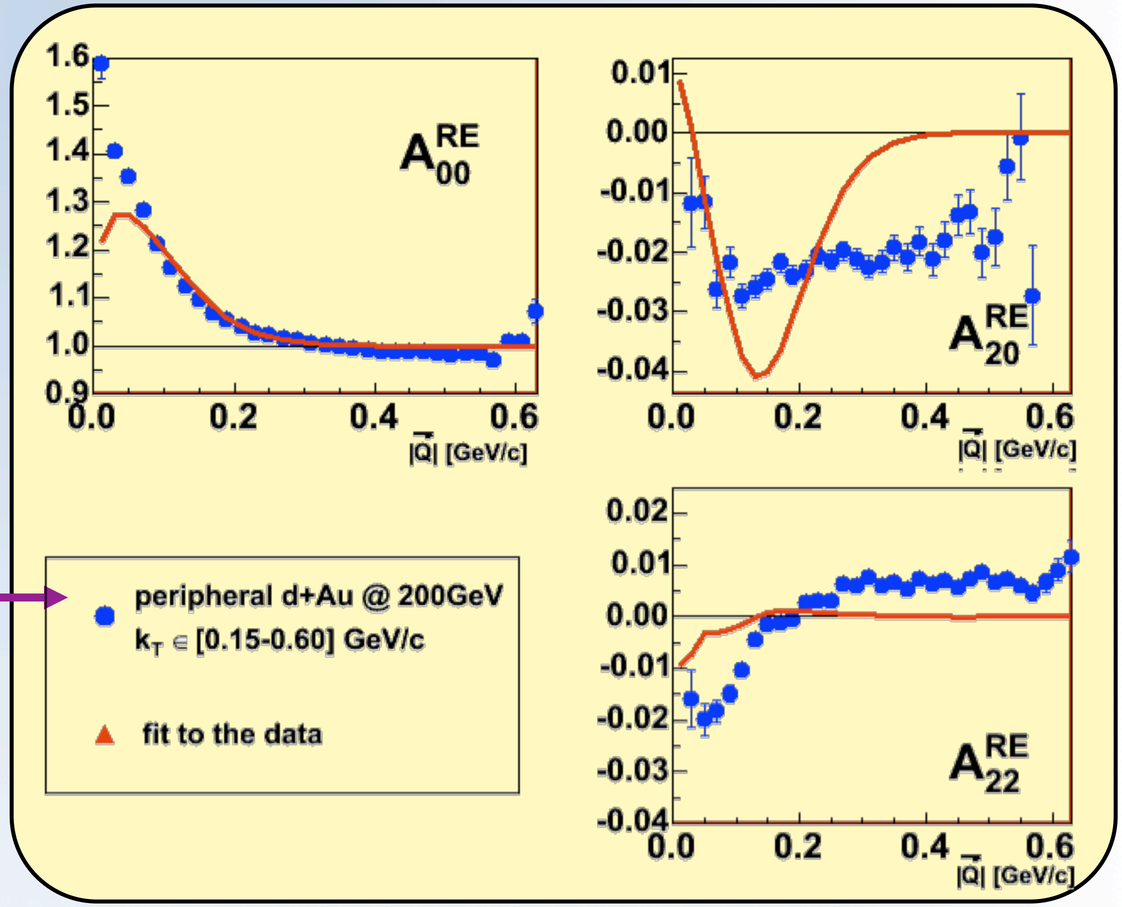
Z. Chajecki & MAL, PRC **78** 064903 (2008)

For femtoscopic correlations:

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

Spherical harmonic representation of 3D data





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

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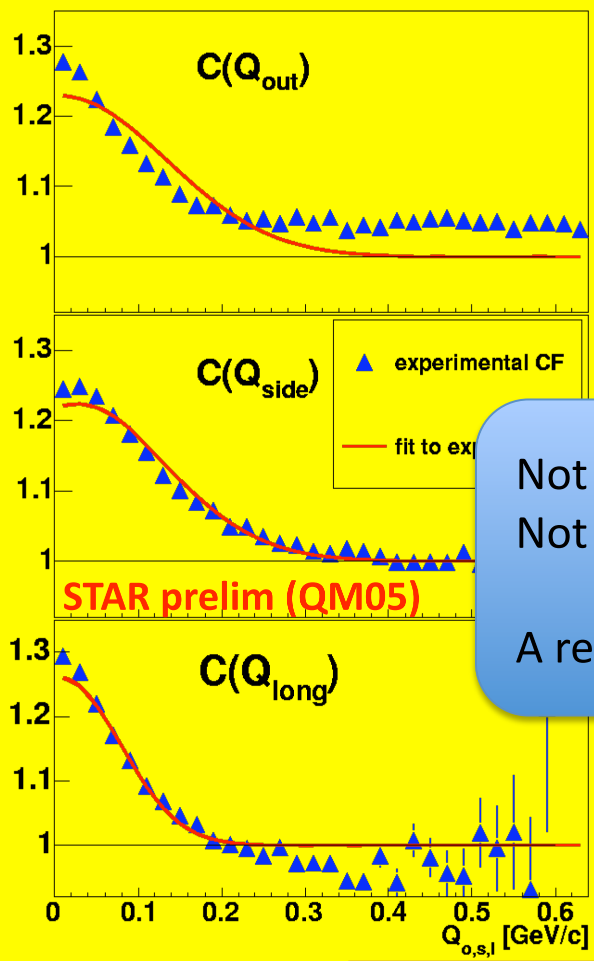
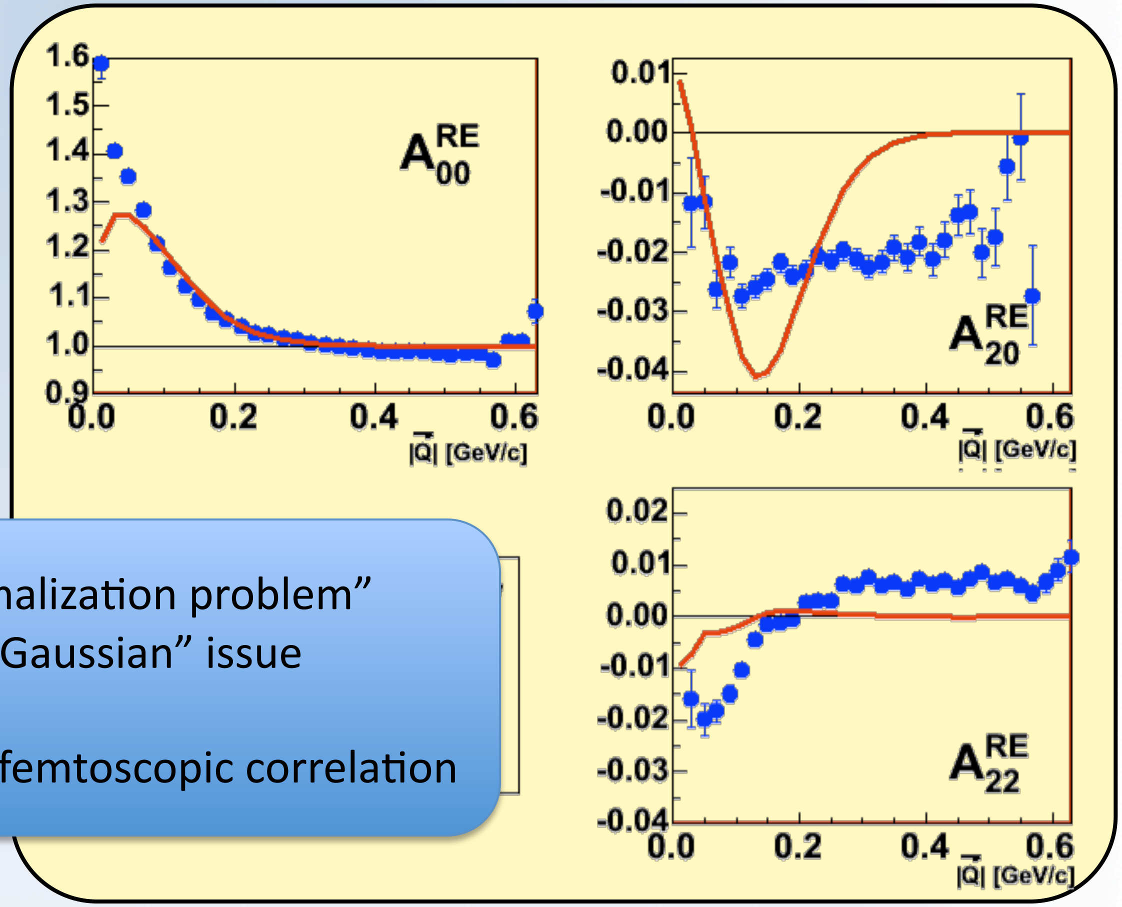
$$C\left(\vec{q};\left|\vec{q}\right|\to\infty\right)=C\left(\left|\vec{q}\right|\to\infty\right)\Rightarrow \mathrm{A}_{\ell\neq 0}^{m}\left(\left|\vec{q}\right|\to\infty\right)=0$$

Spherical harmonic representation of 3D data

d+Au peripheral collisions





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

A real, non-femtoscopic correlation

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

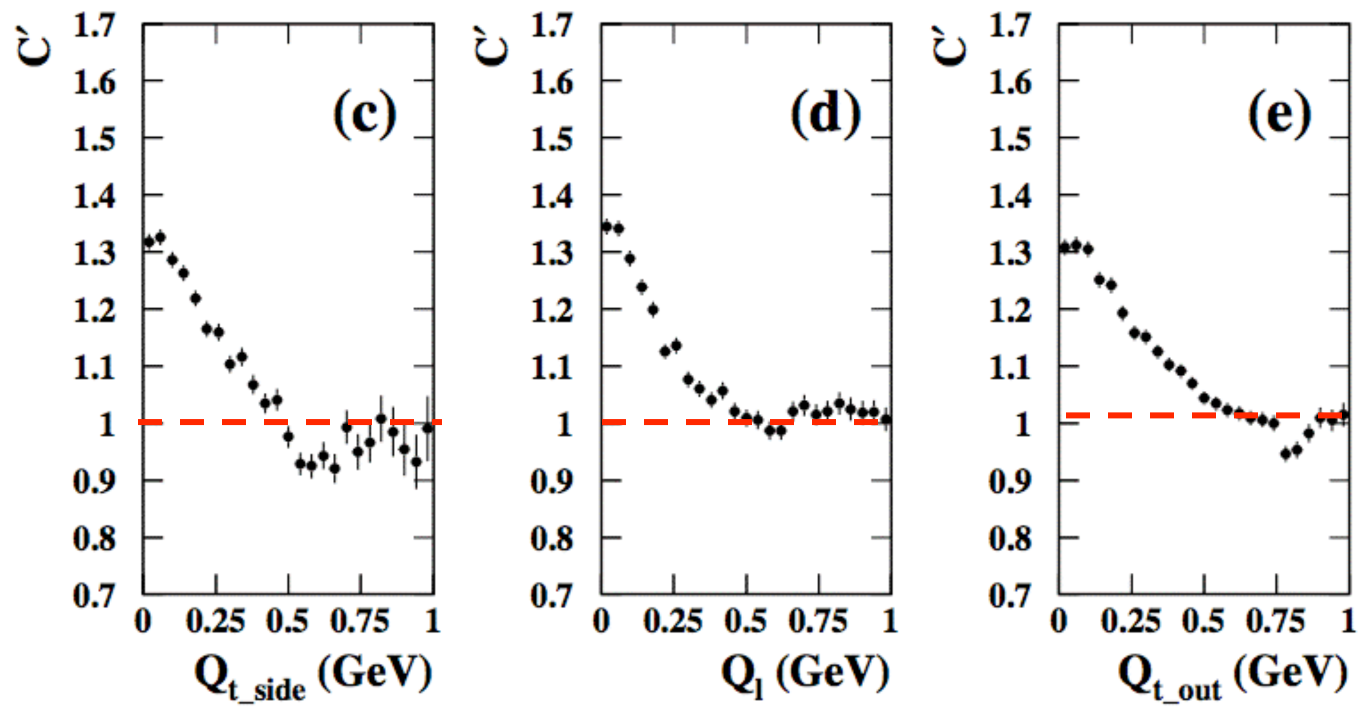
Z. Chajecki & MAL,PRC in press, arXiv:0803.0022 [nucl-th]

For femtoscopic correlations:

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


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

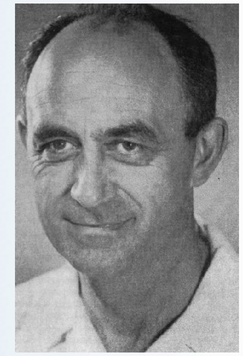
non-femto "large-Q" behaviour - various approaches

- ignore it
- various ad-hoc parameterizations
- divide by $\pi^+\pi^-$ (only semi-successful, and only semi-justified)

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

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

energy-momentum conservation in n-body states



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

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

where

$M =$ matrix element describing interaction

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

---

n-body Phasespace factor R_n

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

where

$P =$ total 4-momentum of n-particle system

$p_i =$ 4-momentum of particle i

$m_i =$ mass of particle i

statistics: "density of states"

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

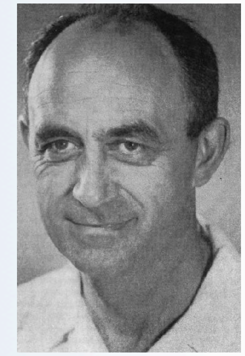
larger particle momentum [illegible] more available states

P[illegible] conservation

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

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

Example of use of total phase space integral



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

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

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

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

Hagedorn

- "spectrum of events":

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

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

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

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

Average matrix element - factorization

R. Hagedorn, *Relativistic Kinematics* 1963

Probability for an n-particle final state:

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

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

$$\equiv \bar{S}_n R_n$$

Single-particle spectrum

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

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

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

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

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

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

what we measure

no other correlations

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

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

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

Simplification for "large" N-k (1)

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

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

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

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

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

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

Simplification for "large" N-k (2)

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

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

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

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

$$\xrightarrow{\text{large } N-k}$$

$$\left(\prod_{i=1}^{k}\tilde{f}(p_i)\right)\cdot\left(\frac{N}{N-k}\right)^2\exp\left[-\left(\sum_{i=1}^{k}\left(p_i^{\mu}-\langle p^{\mu}\rangle\right)\right)\frac{b_{\mu\nu}}{2(N-k)}\left(\sum_{i=1}^{k}\left(p_i^{\nu}-\langle p^{\nu}\rangle\right)\right)\right]$$

averages $\langle X\rangle\equiv\int d^4p\cdot X\cdot\delta\left(p^2-m^2\right)\tilde{f}(p)$

covariance matrix $\left(b^{-1}\right)_{\mu\nu}=\langle p_\mu p_\nu\rangle-\langle p_\mu\rangle\langle p_\nu\rangle$

Fortunately, diagonal covariance matrix!

$$\left(b^{-1}\right)_{\mu\nu} = \left\langle p_\mu p_\nu \right\rangle - \left\langle p_\mu \right\rangle \left\langle p_\nu \right\rangle$$

- ✓ Work in global C.O.M. frame: $\left\langle p^\mu \right\rangle = \delta_{\mu,0} \left\langle E \right\rangle$

- ✓ No elliptic flow, etc: $\left(b^{-1}\right)_{1,2} = \left\langle p_x p_y \right\rangle = 0$

- ✓ No directed flow, etc: $\left(b^{-1}\right)_{1,3} = \left(b^{-1}\right)_{2,3} = 0$

- ✓ On-shell means momentum and energy obviously correlated... but covariance (second moment) vanishes. For $i \neq 0$:

$$\left(b^{-1}\right)_{0,i} = \left\langle E p_i \right\rangle - \left\langle E \right\rangle \left\langle p_i \right\rangle = \left\langle E p_i \right\rangle = \frac{\int dE \int d^3p \cdot E\tilde{f}(p)\delta\left(p^2 - m\right) \cdot p_i}{\int dE \int d^3p \cdot \tilde{f}(p)\delta\left(p^2 - m\right)} = 0$$

since $E\tilde{f}(p)\delta\left(p^2 - m\right)$ is even and p_i is odd

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

k-particle distribution in N-particle system

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

where

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

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

N.B.
relevant later

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

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

* "large": N > ~10

Effects on single-particle distribution

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

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

We will return to this….

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

k-particle correlation function

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

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

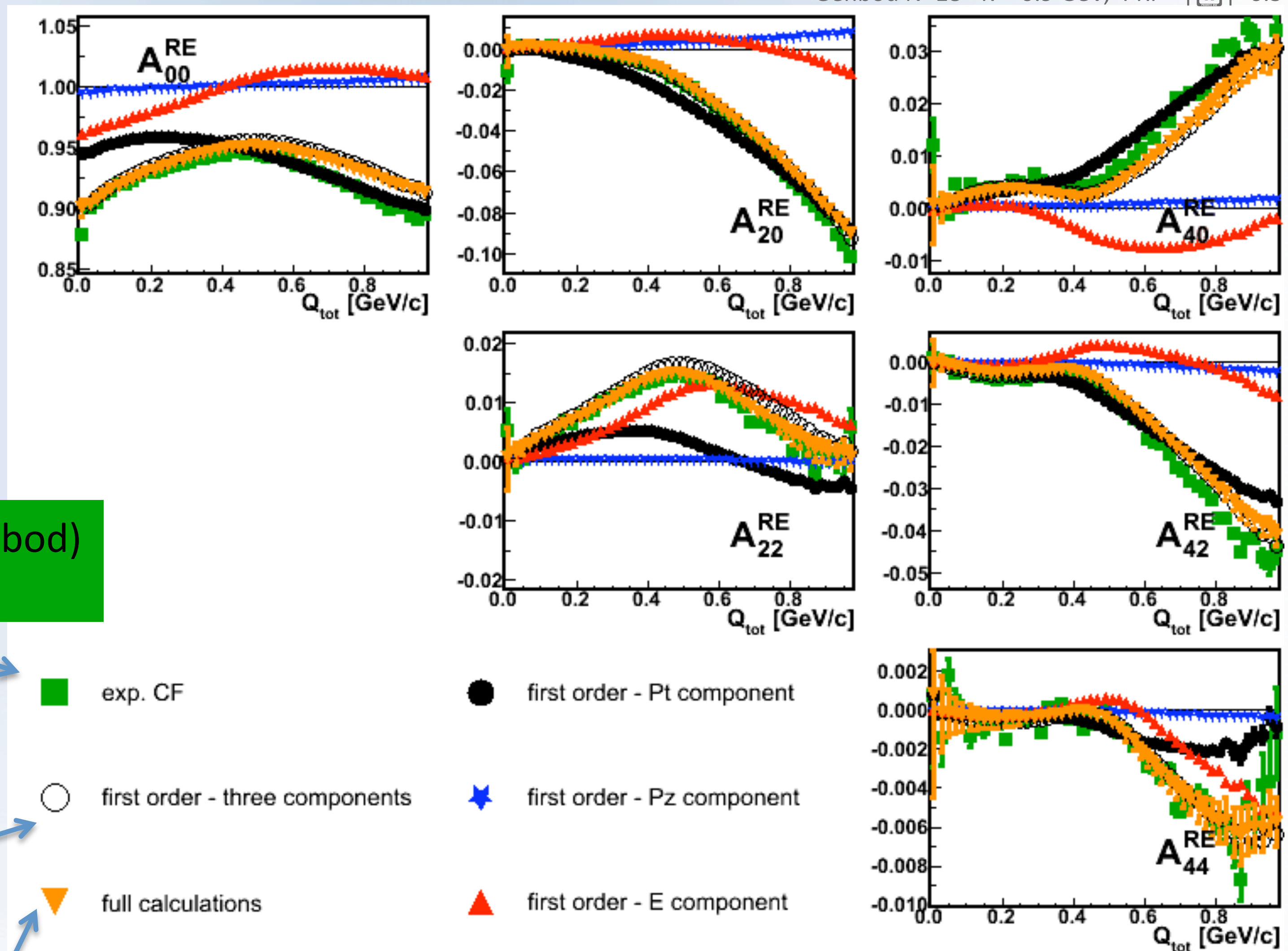
Dependence on “parent” distrib f vanishes,
except for energy/momentum means and RMS

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

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

How do EMCICs look ? – nontrivial !

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



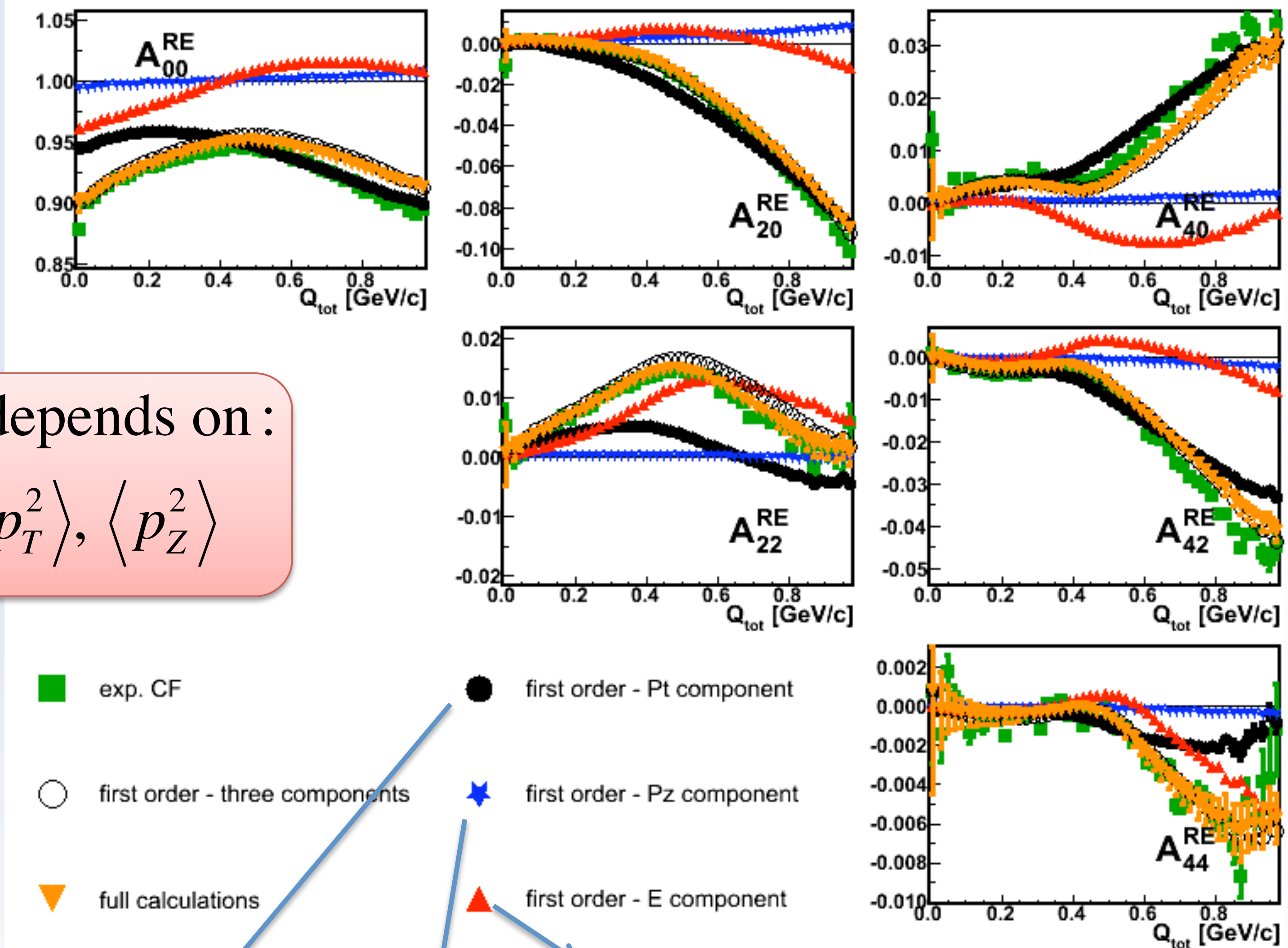
event generator (genbod) with only EMCICs

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 :

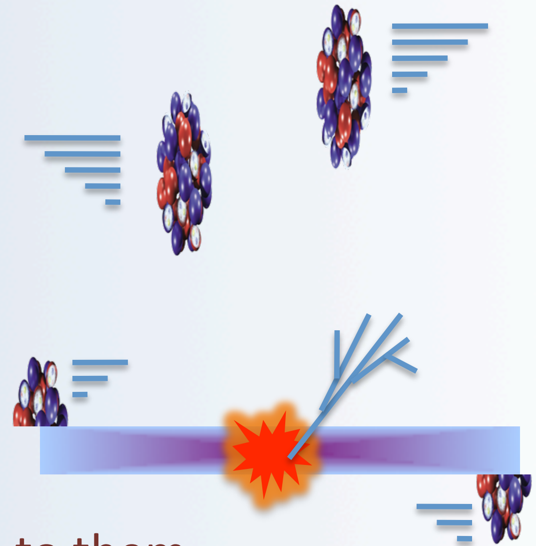
$N, \langle E \rangle, \langle E^2 \rangle, \langle p_T^2 \rangle, \langle p_Z^2 \rangle$

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

"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 <E^2> and measured one
3. <E^2> 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 underlying event appears indep of jet – CDF

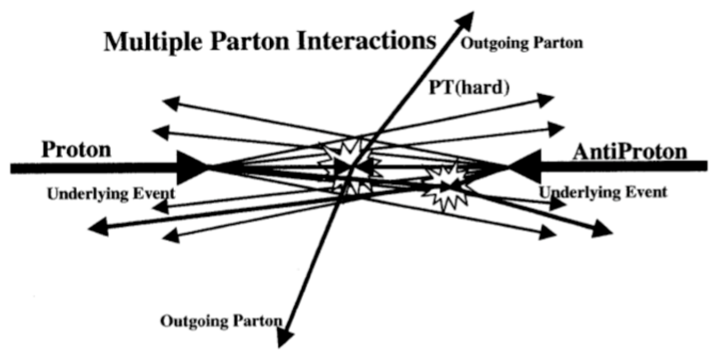
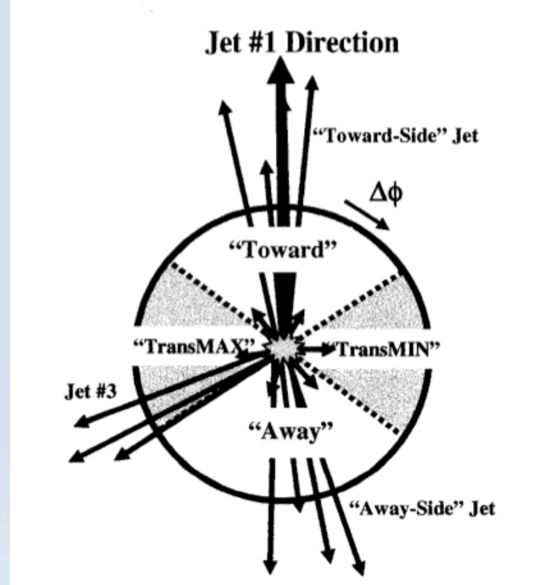
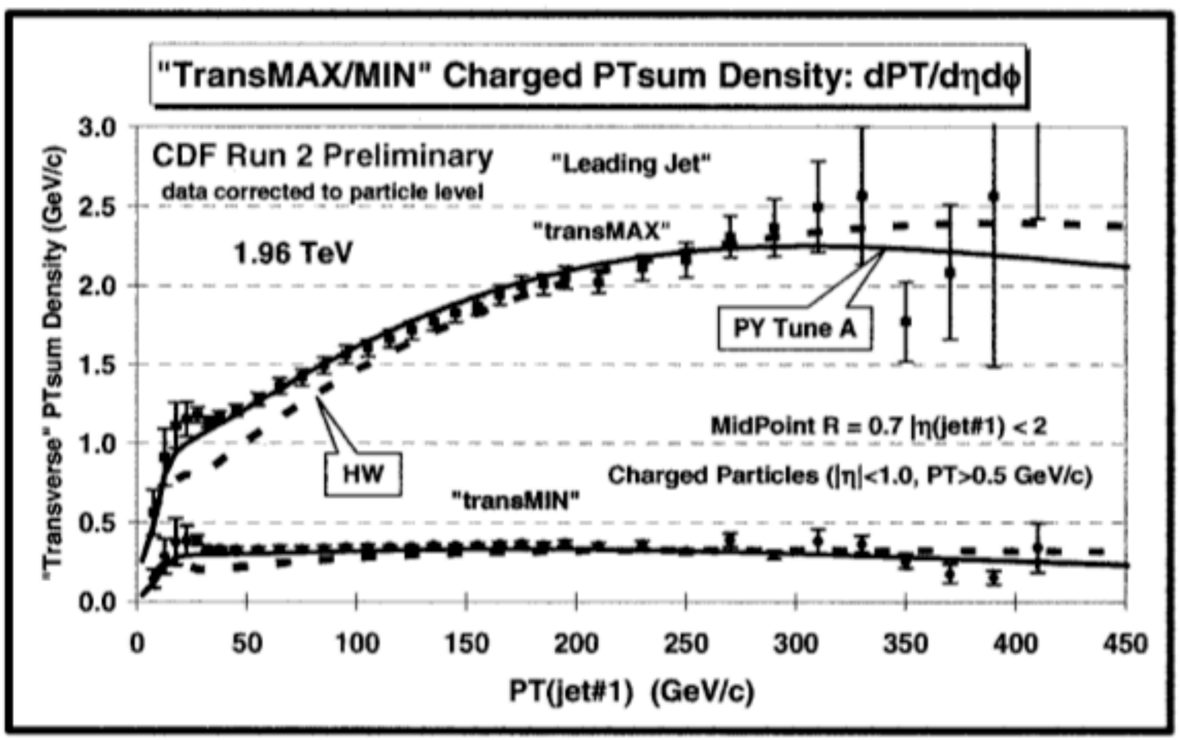


Fig. 1-5. Illustration of the way PYTHIA models the "underlying event" in proton-antiproton collision by including multiple parton interactions. In addition to the hard 2-to-2 parton-parton scattering with transverse momentum, P_T(hard), there is a second "semi-hard" 2-to-2 parton-parton scattering that contributes particles to the "underlying event".



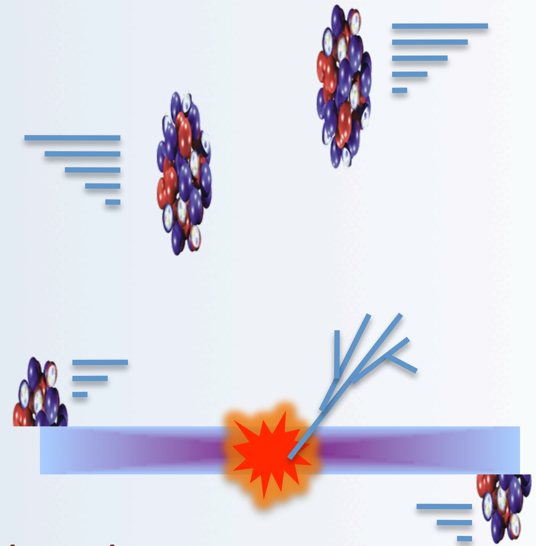


L.A. Cruz, PhD Thesis, U. Florida
"Underlying event at Tevatron" (2005)

"the system"... a nontrivial concept

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

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



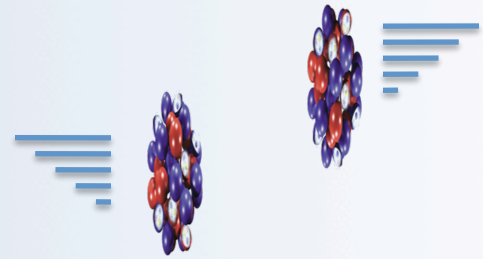
- Not known a priori
- should *track* measured quantities, but not be identical to them

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

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

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

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

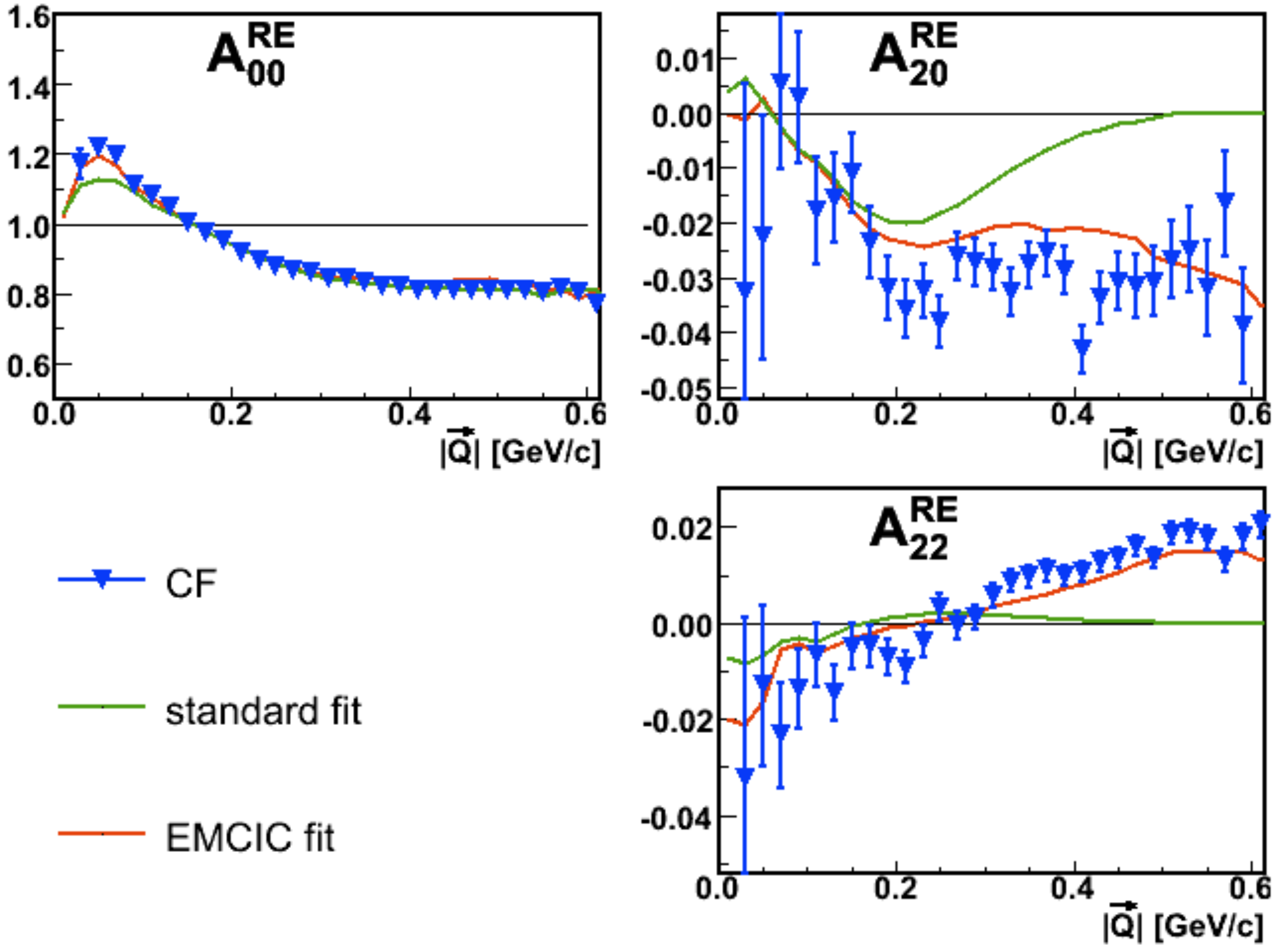
	non-rel	ultra-rel	if $T = .15$ -
$\langle p_T^2\rangle$	$2mT$	$8T^2$	$0.045 \div 0.9$
$\langle E^2\rangle$	$\frac{15}{4}T^2 + m^2$	$12T^2$	$0.10 \div 1.5$
$\langle E\rangle$	$\frac{3}{2}T + m$	$3T$	$0.36 - 1$ G

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

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

p+p minbias

STAR poster QM09



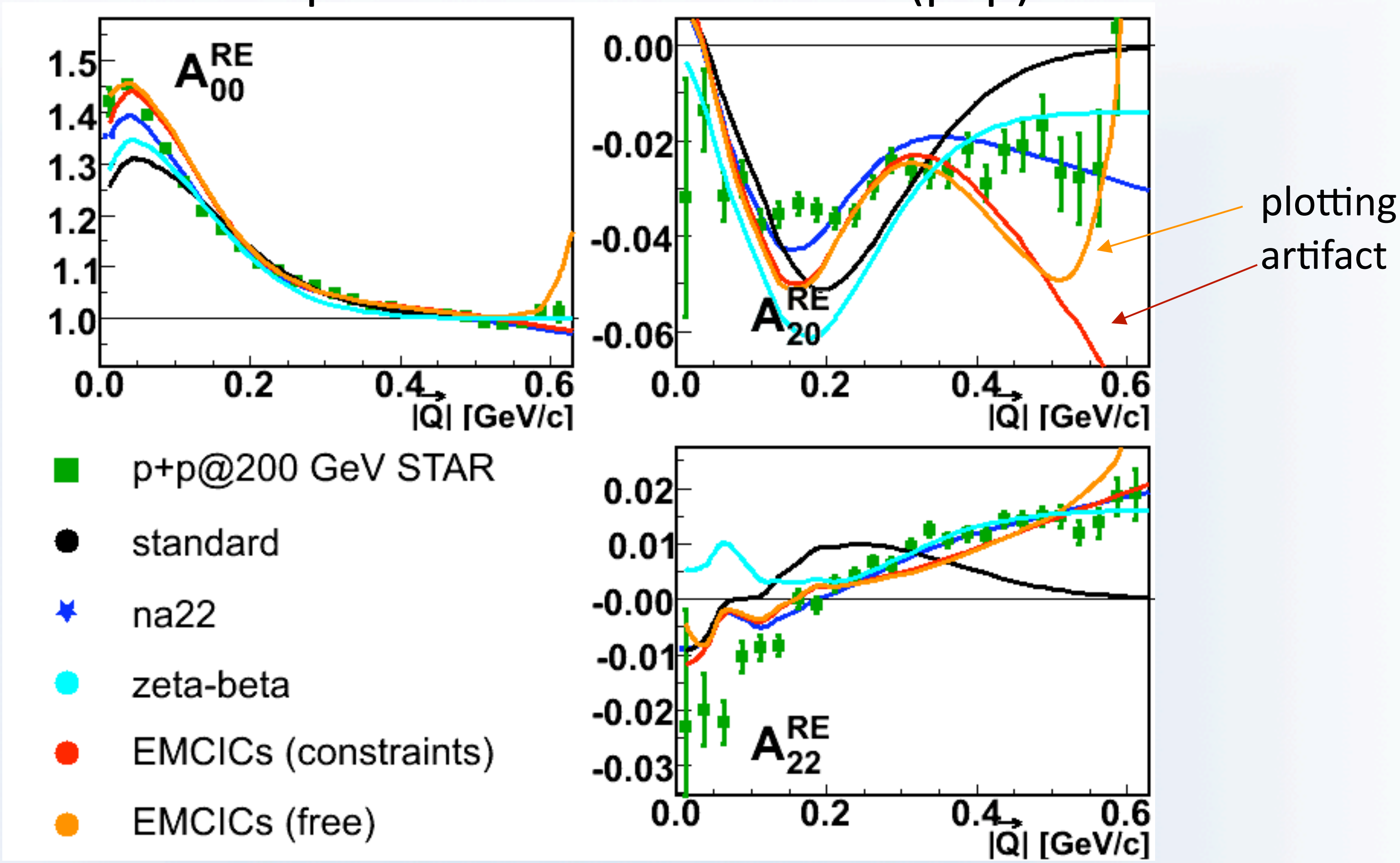
k_T = [0.35,0.45] GeV/c

λ = 0.38 ± 0.01
R_o = 0.81 ± 0.01 fm
R_s = 0.84 ± 0.02 fm
R_l = 1.29 ± 0.02 fm

λ = 0.69 ± 0.01
R_o = 0.96 ± 0.04 fm
R_s = 0.98 ± 0.03 fm
R_l = 1.26 ± 0.02 fm

N = 13.6
$\langle E \rangle$ = 0.68 GeV
$\langle E^2 \rangle$ = 0.54 GeV^2
$\langle p_T^2 \rangle$ = 0.17 GeV^2
$\langle p_z^2 \rangle$ = 0.33 GeV^2

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



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

Zbigniew Chajecki QM05

femtoscopy in p+p @ STAR

1. Heisenberg uncertainty?

2. String fragmentation? (Lund)

3. Resonance effects?

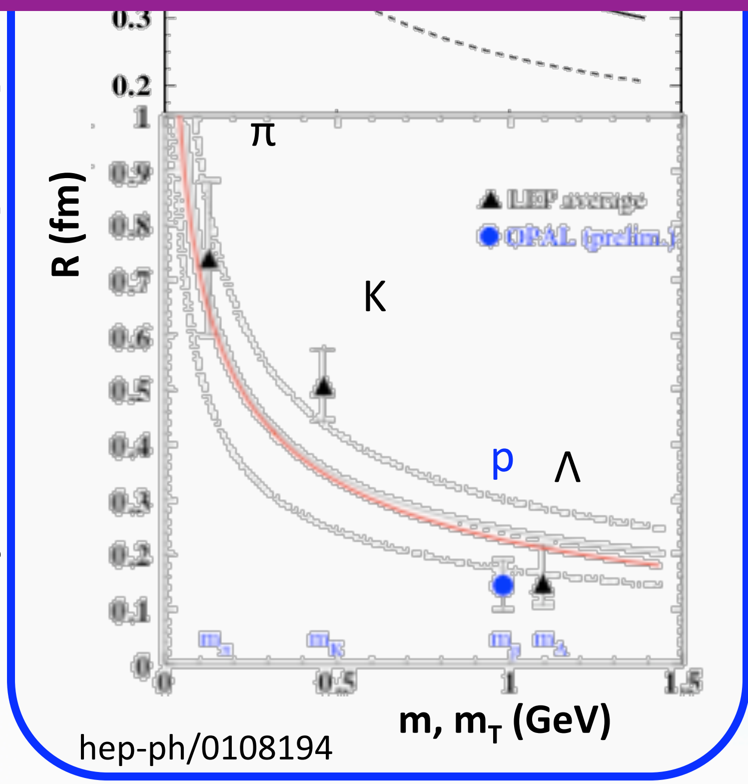
4. Flow???

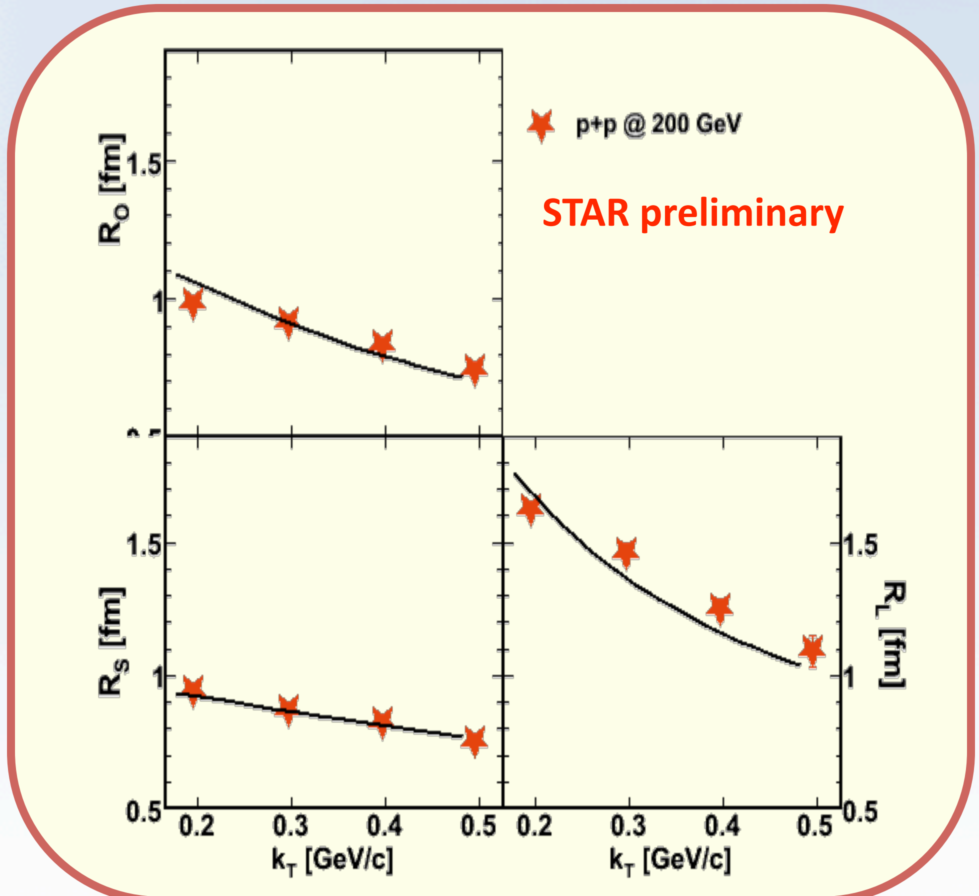
- Increasingly suggested in HEP experiments

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

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

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





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

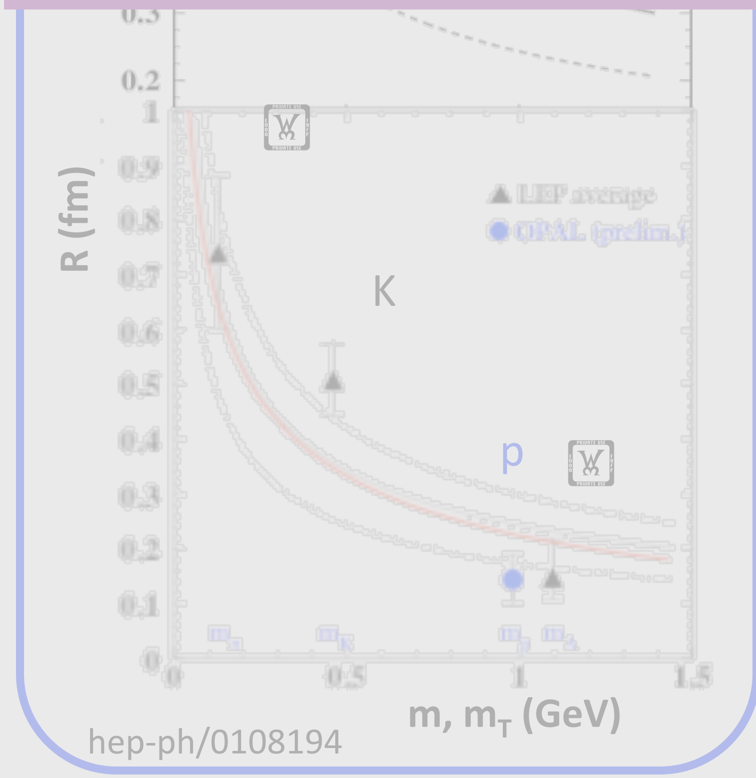
- Increasingly suggested in recent experiments

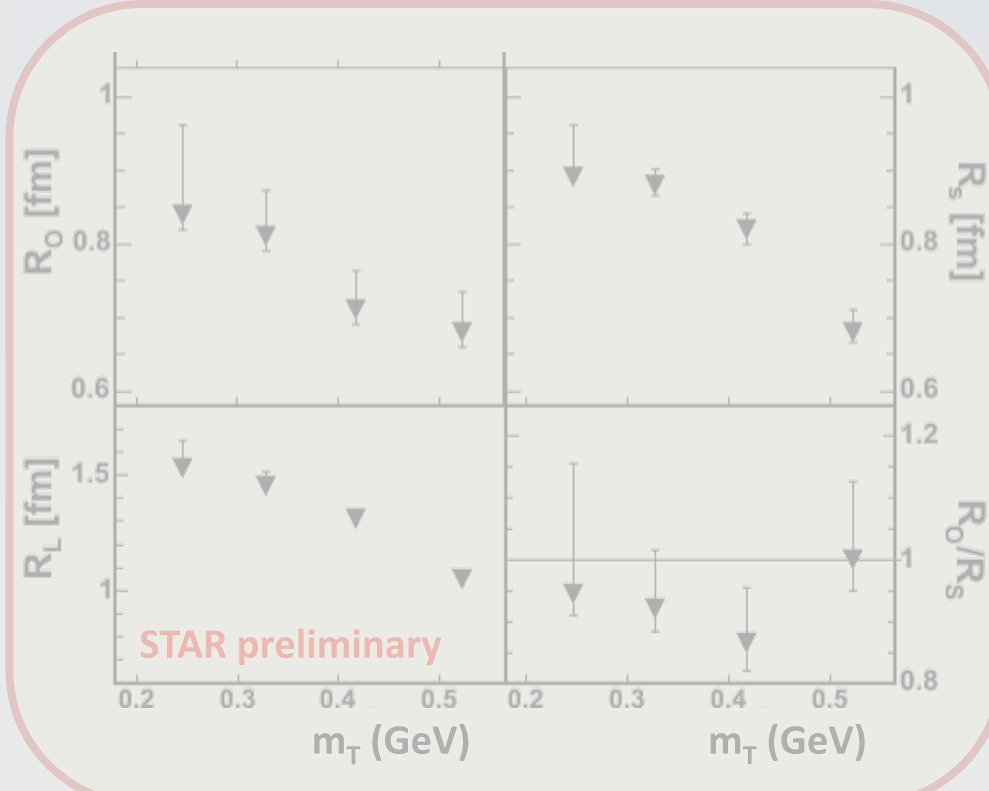
NA22 Collaboration Z. Phys. C 71, 405–414 (1996)
(hadron-hadron collisions)

[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.

•same cause as in A+A?





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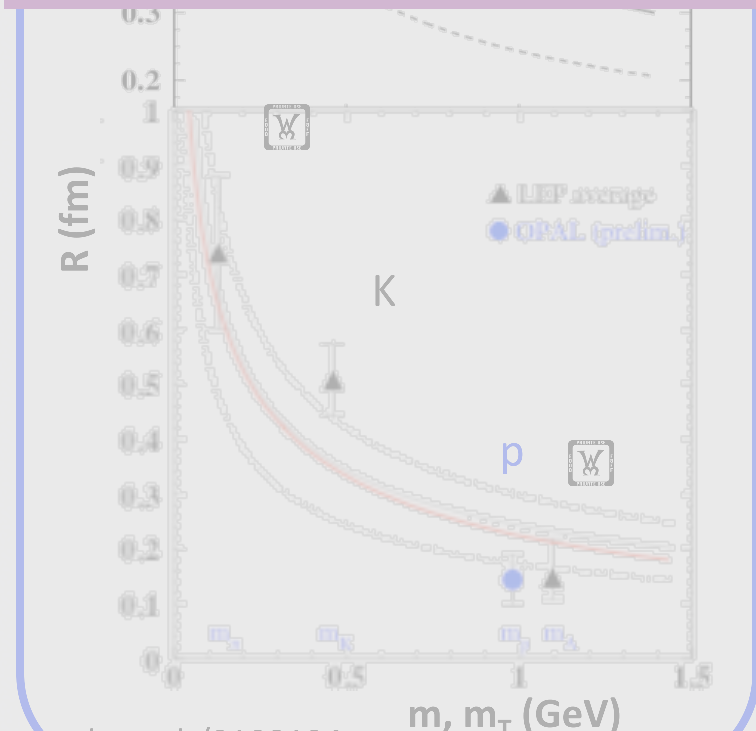

hep-ph/0108194

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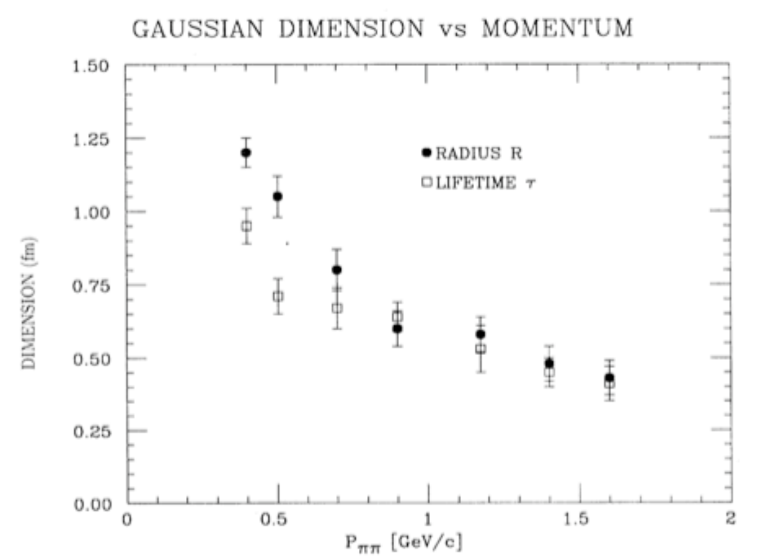


FIG. 9. Interaction "radius" and lifetime as a function of the total momentum $P_{\pi\pi}$ of the pion pair. R_G is primarily a source dimension along the beam direction. τ might possibly be interpreted as a source dimension transverse to the beam. Data are from Table III.

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

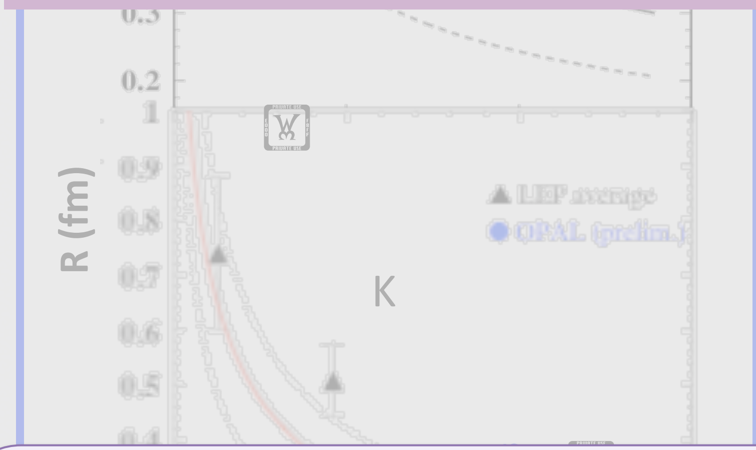
1. Heisenberg uncertainty?

2. String fragmentation? (Lund)

3. Resonance effects?

4. Flow???

- Increasingly suggested in recent experiments



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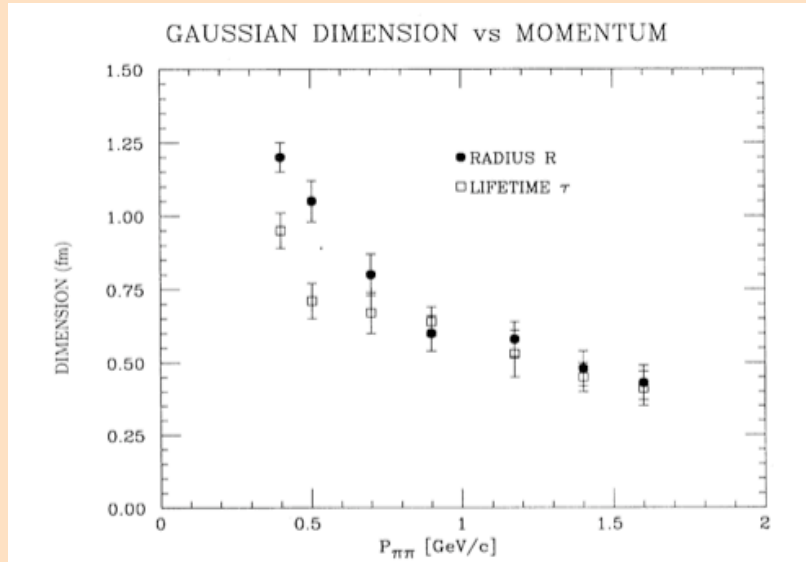


…ime as a function of the …$_G$ is primarily a source …might possibly be inter- …to the beam. Data are

…3 1931 (1993)

…*ling shell model.*

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

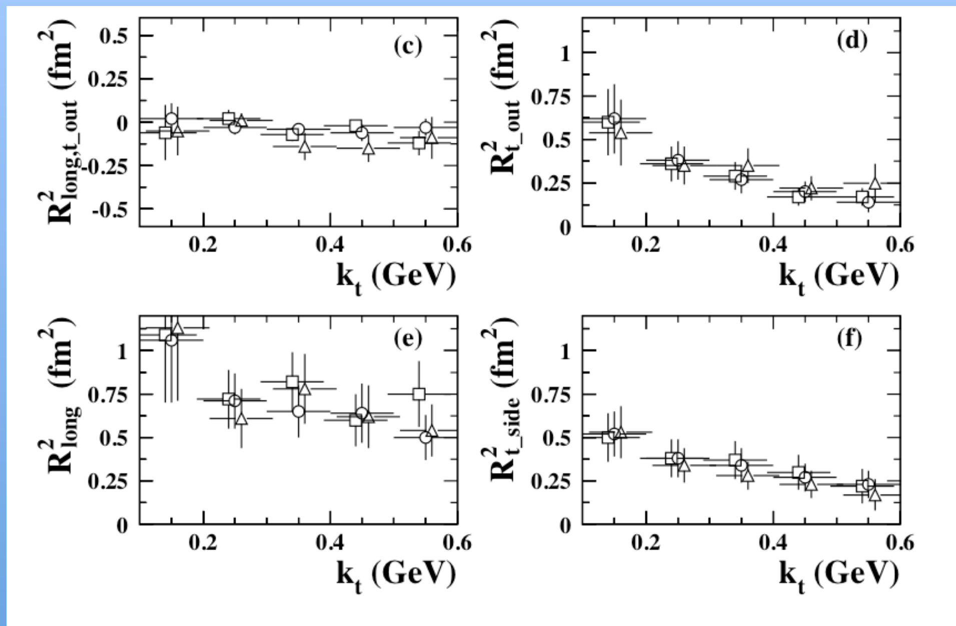
… and suggests the existence of an important "collective flow", even in the system of particles produced in e+e− annihilation!

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

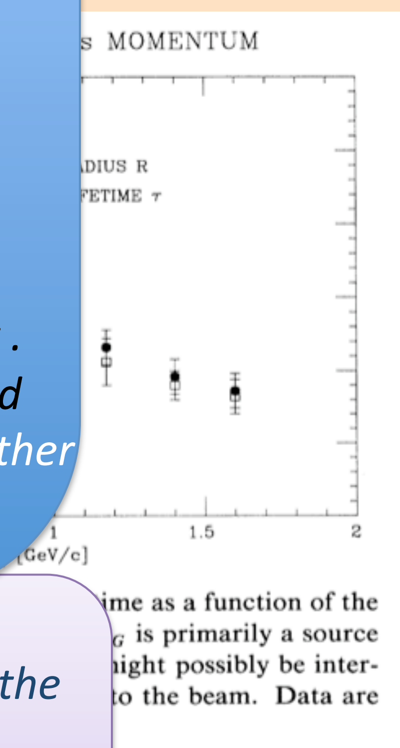
C 71, 405–414 (1996)

pectation from
description of
in the framework
ng source model.

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



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



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C 71, 405–414 (1996)

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

...ectation from
...f
...rk
...el.

RHIC: “comparison machine”

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

- spectra
- femtoscopy

compare with a system we “know” is flowing

R2ts...
The p...
their ...
expand...

...ime as a function of the ...G is primarily a source ...ight possibly be inter- ...to the beam. Data are

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

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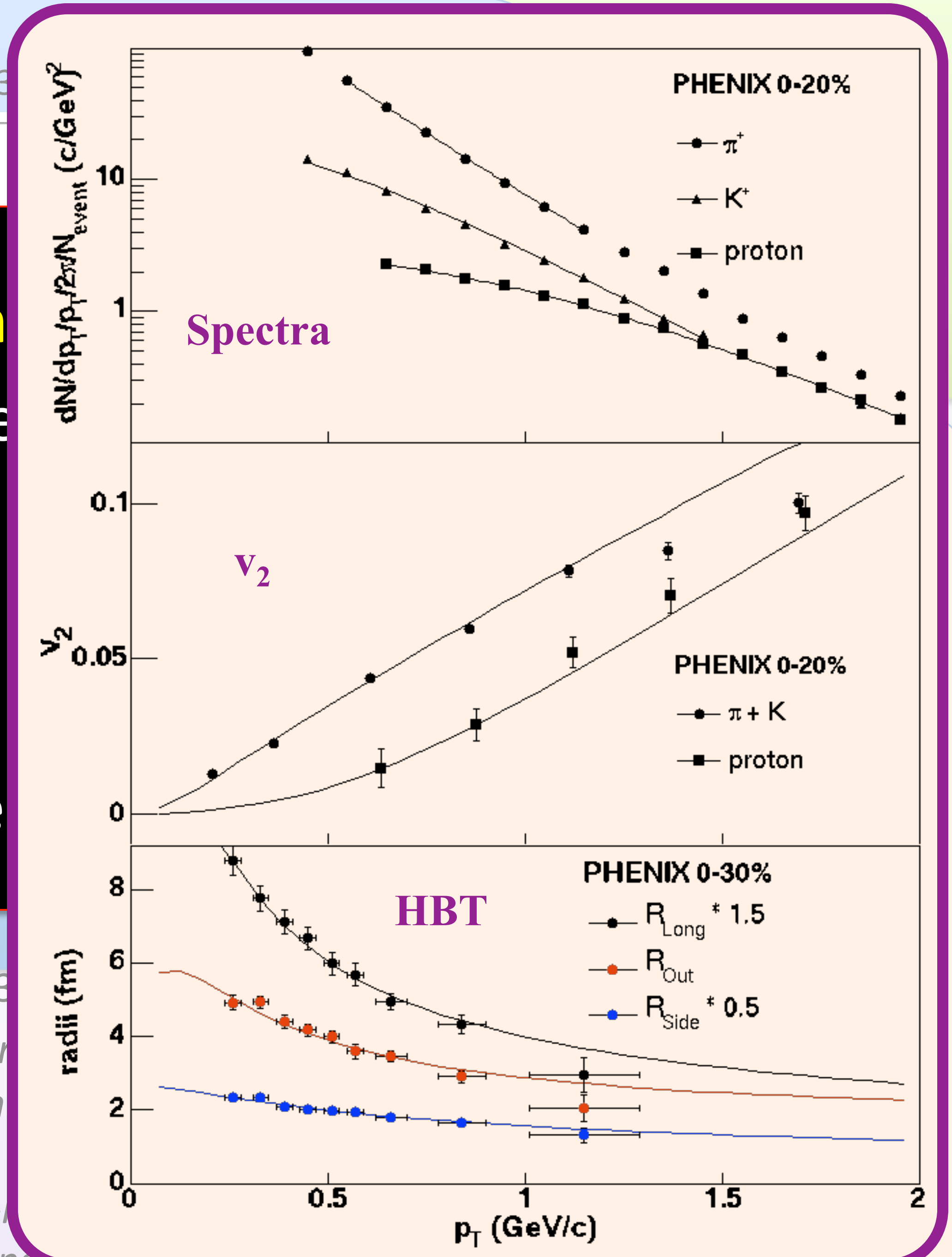


Apples:apples comparison…

Z. Chajecki, QM05

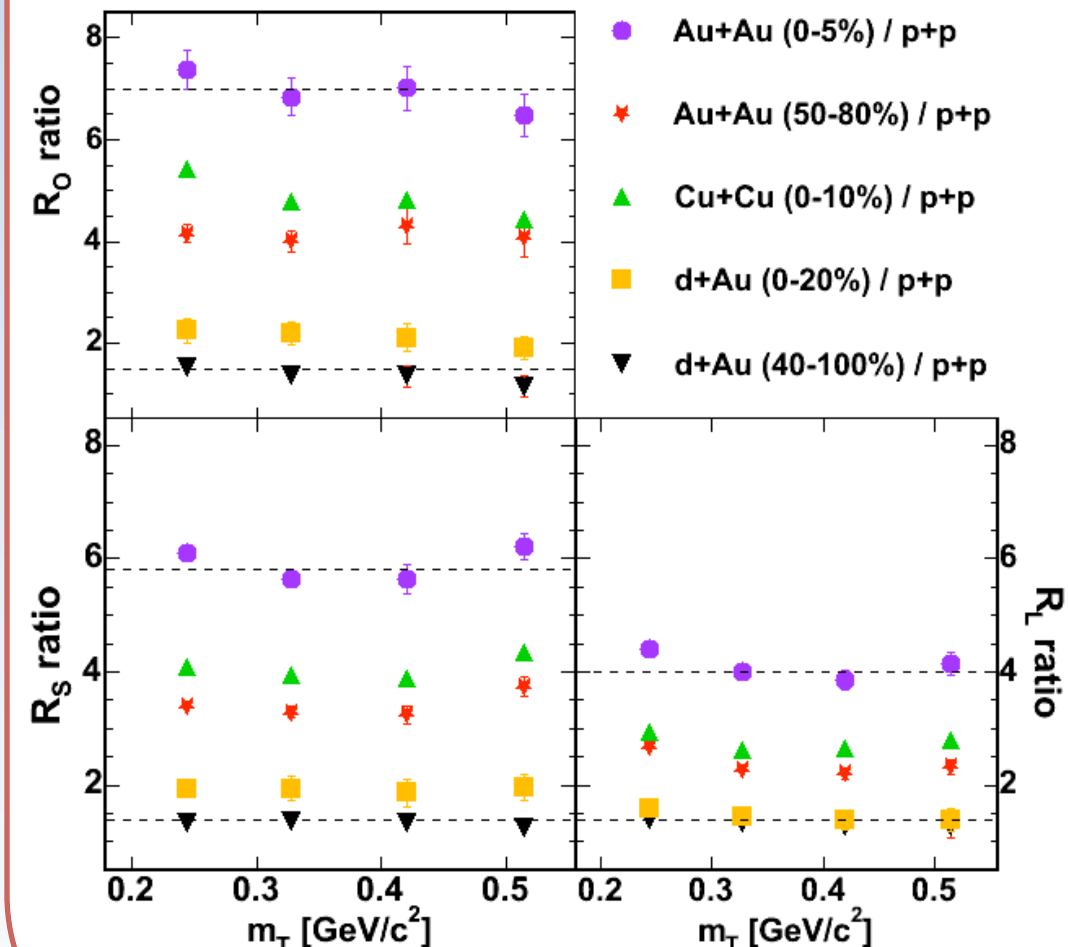
R(p_T) taken as strong space-time evidence of flow in Au+Au

- clear, quantitative consistency predictions of BlastWave

"Identical" signal seen in p+p

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

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

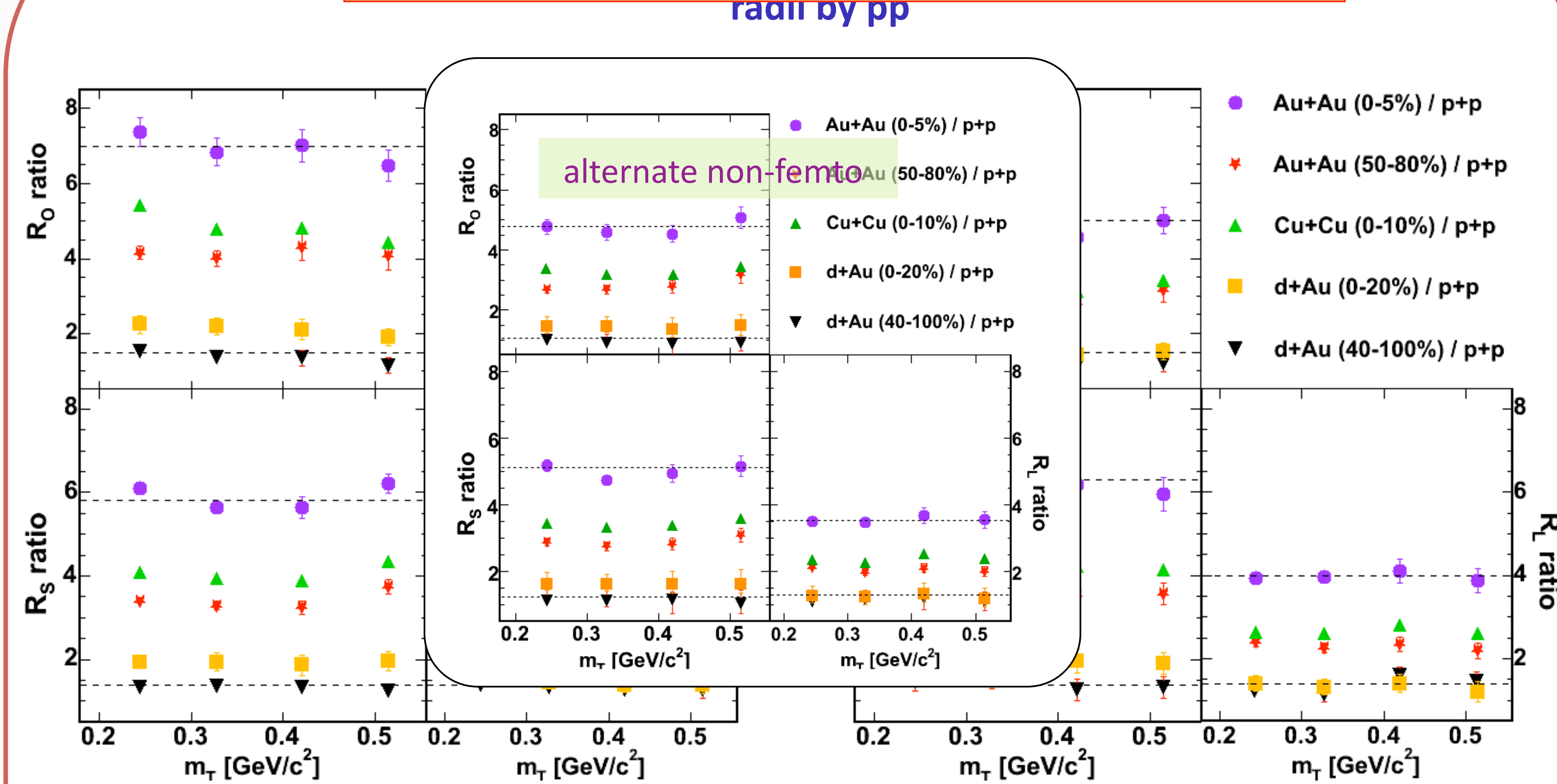


pp, dAu, CuCu - STAR preliminary

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

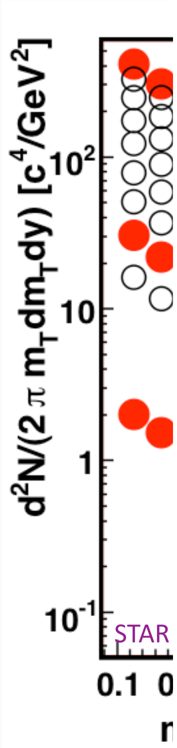
STAR preliminary

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



Fit w/o baseline parameterization

NEW fit w/ baseline parameterization



Au+Au 0-5%

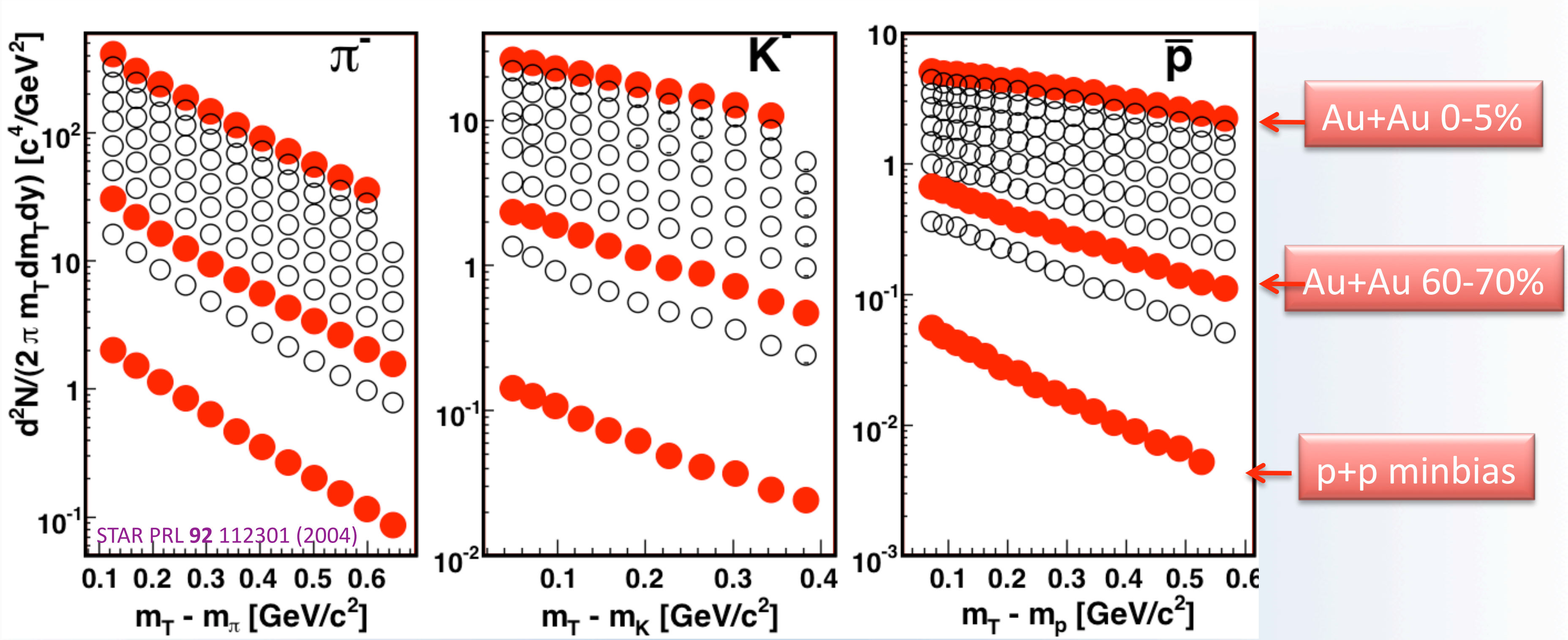
Au+Au 60-70%

p+p minbias

NO.....?

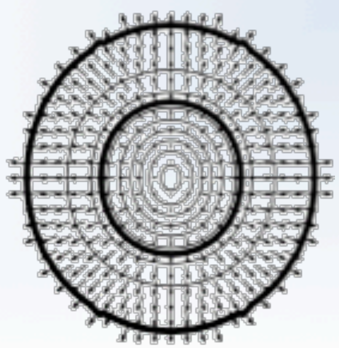
Blast-wave

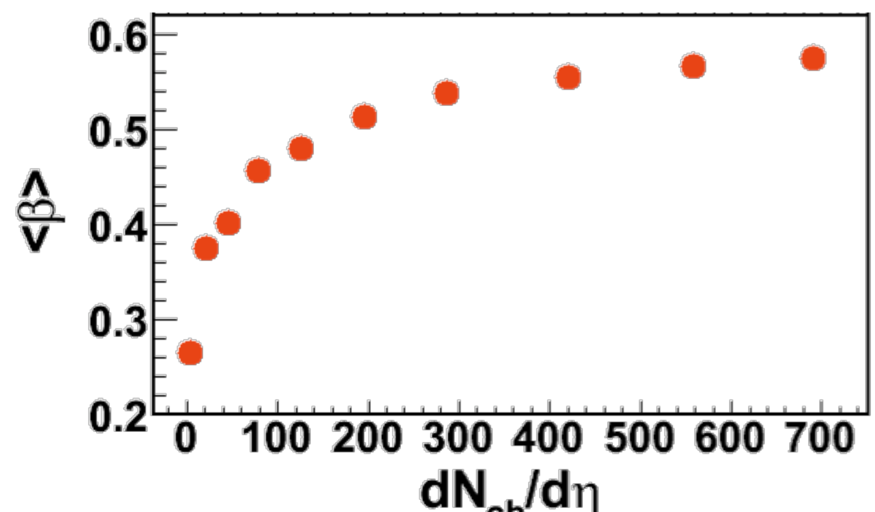
- much les



Blast-wave fit to spectra:

- much less explosive flow in p+p collisions





Don't forget - EMCICs even for k=1

measured

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

"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

EMCICs even for k=1

measured

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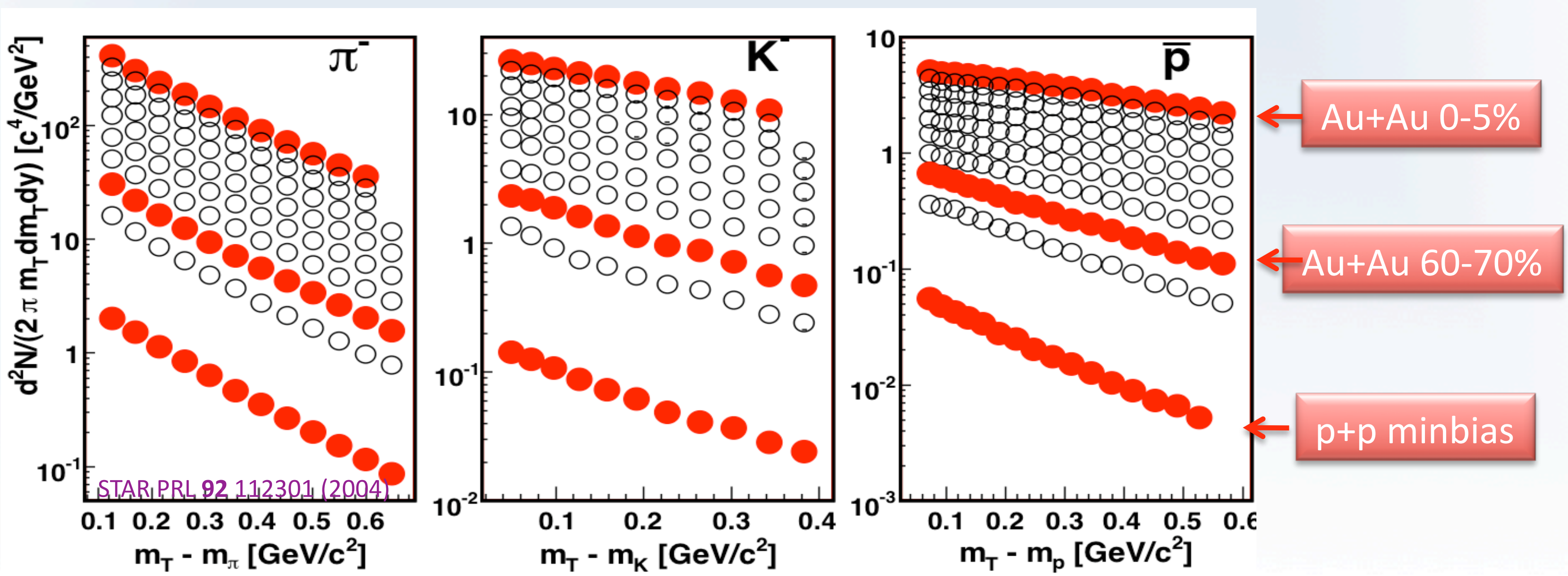
"matrix element"

"distortion" of single-particle spectra

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

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



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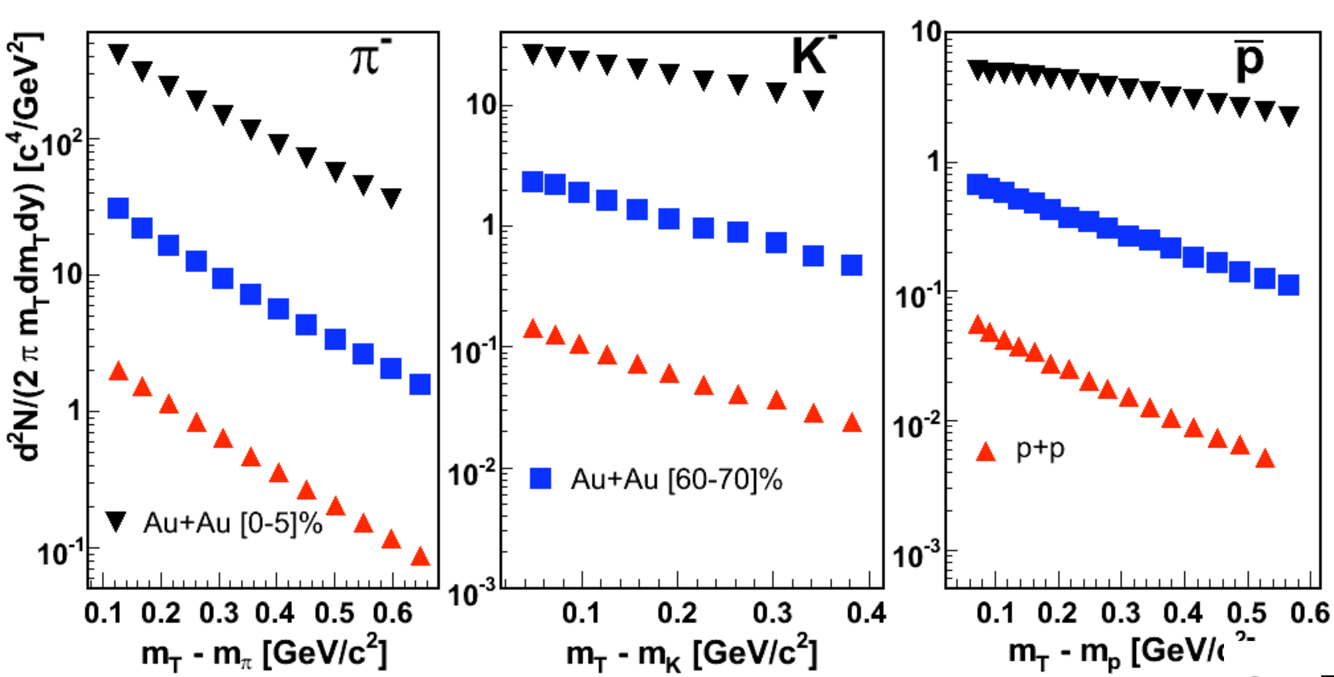
Then we would measure:

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

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

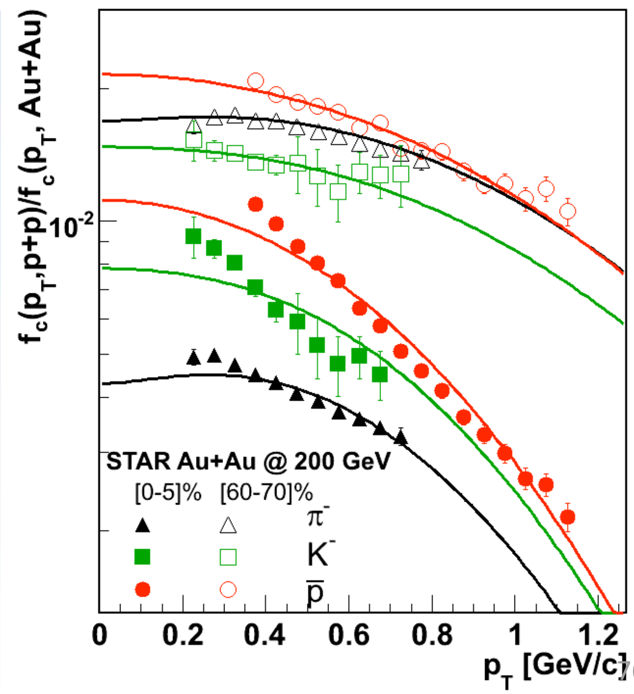


$$\frac{\tilde{f}_c^{pp}(p_{T,i})}{\tilde{f}_c^{AA}(p_{T,i})} \propto \exp\left(\left(\frac{1}{2(N_{AA}-1)} - \frac{1}{2(N_{pp}-1)}\right)\left(\frac{2p_{T,i}^2}{\langle p_T^2\rangle} + \frac{(E_i - \langle E\rangle)^2}{\langle E^2\rangle - \langle E\rangle^2}\right)\right)$$

N evolution of spectra dominated by PS "distortion"

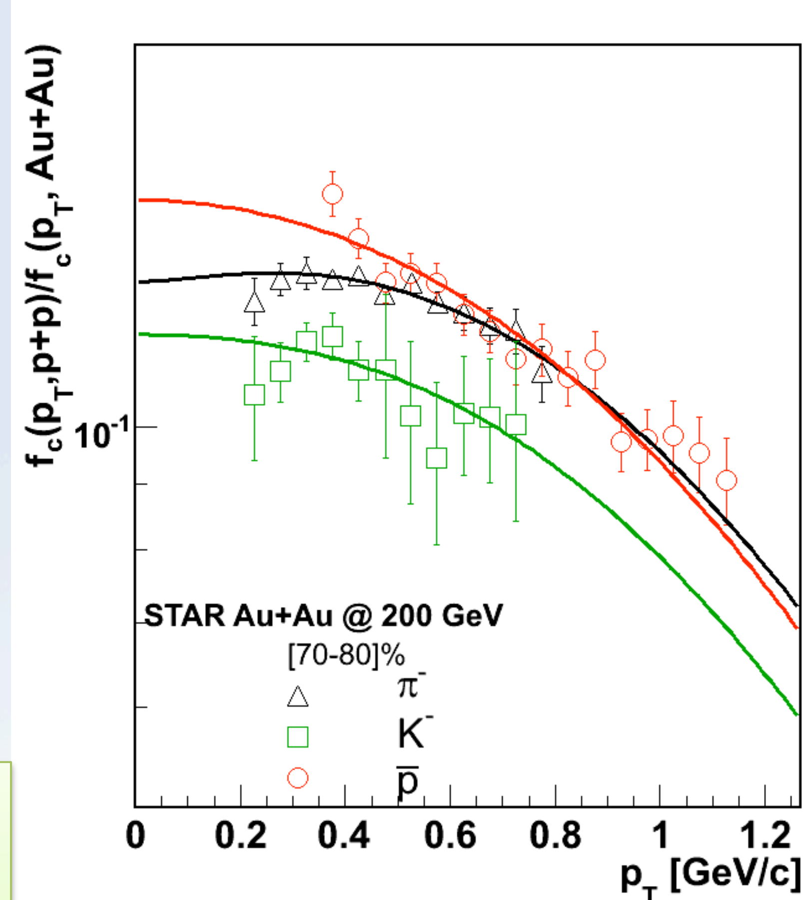
p+p system samples *same* parent distribution, but under stronger PS constraints

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



TMPT: 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	"	"	"
$Au+Au$ 60-70%	18.3	"	"	"
$Au+Au$ 50-60%	27.3	"	"	"
$Au+Au$ 40-50%	38.7	"	"	"
$Au+Au$ 30-40%	67.6	"	"	"
$Au+Au$ 20-30%	219	"	"	"
$Au+Au$ 10-20%	> 300	"	"	"
$Au+Au$ 5-10%	> 300	"	"	"
$Au+Au$ 0-5%	> 300	"	"	"



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

- magnitude
- pT dependence (shape)
- mass dependence

Kinematic scales of "the system"

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

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

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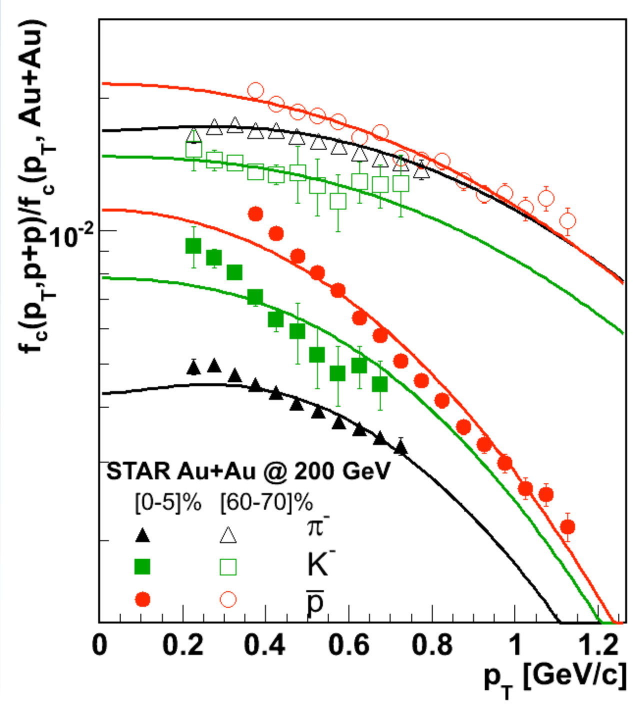
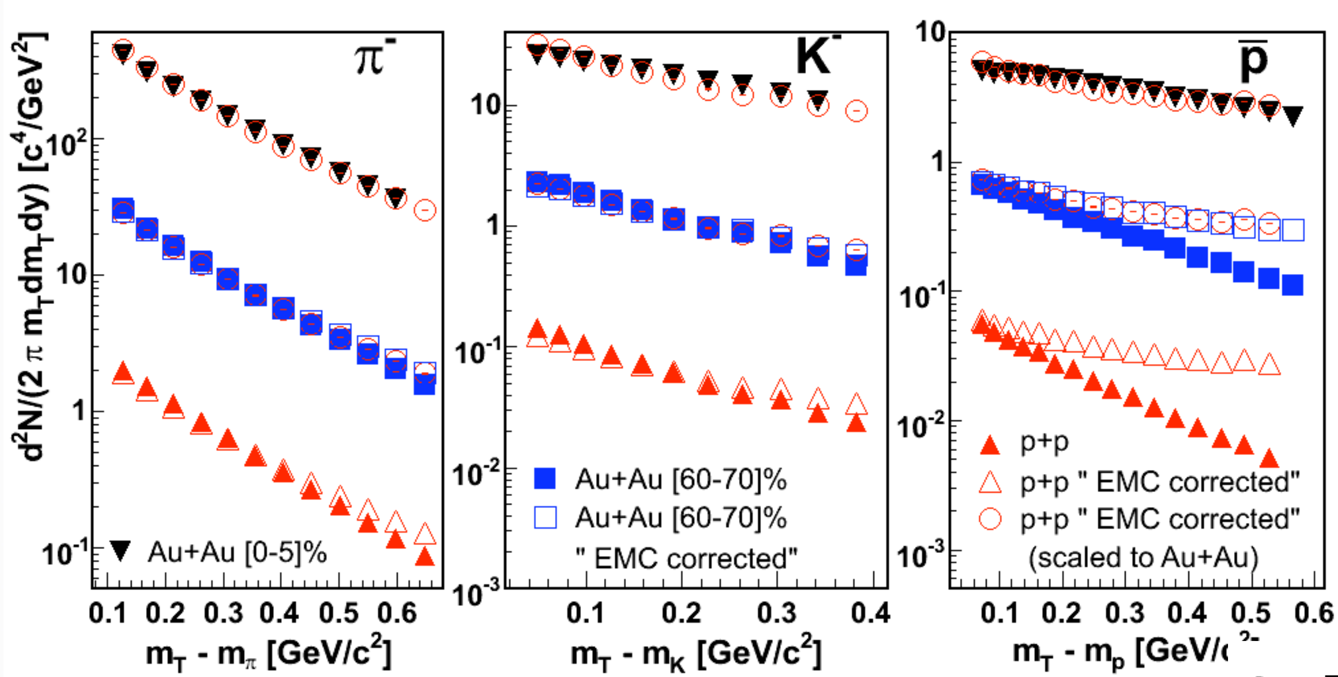
$Au+Au$ 5-10%	> 300	"	"	"
$Au+Au$ 0-5%	> 300	"	"	"

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



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



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

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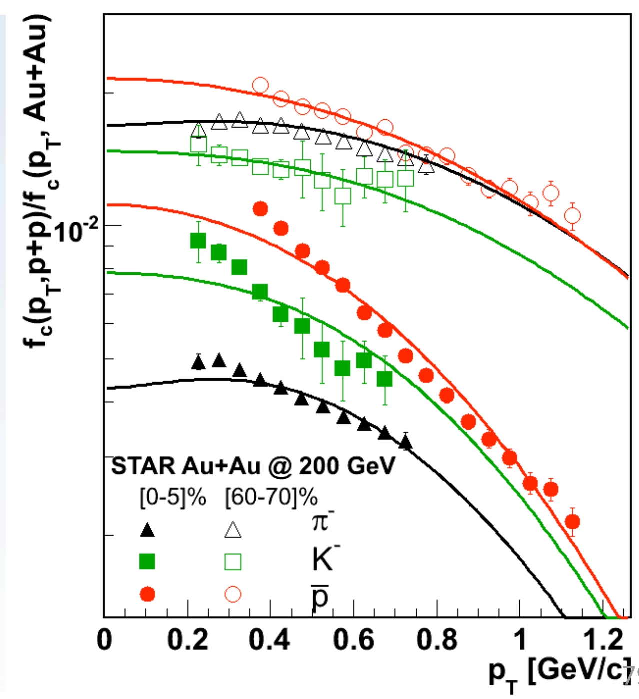

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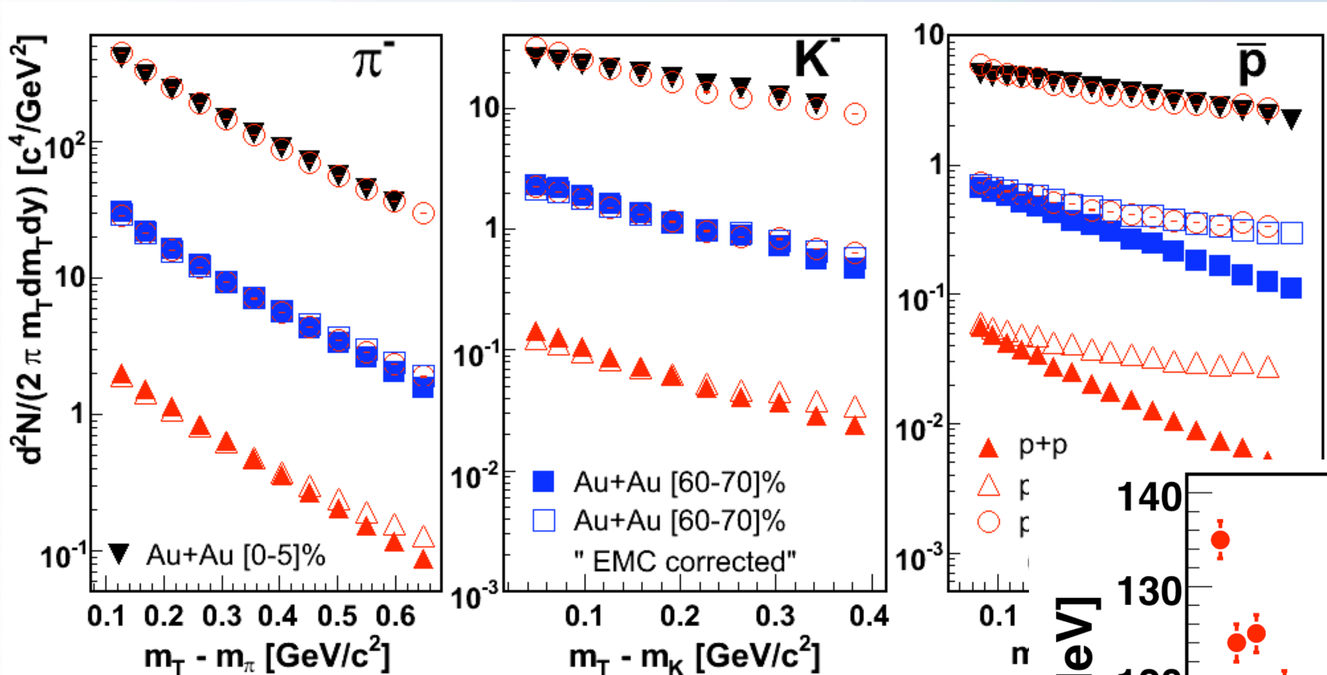
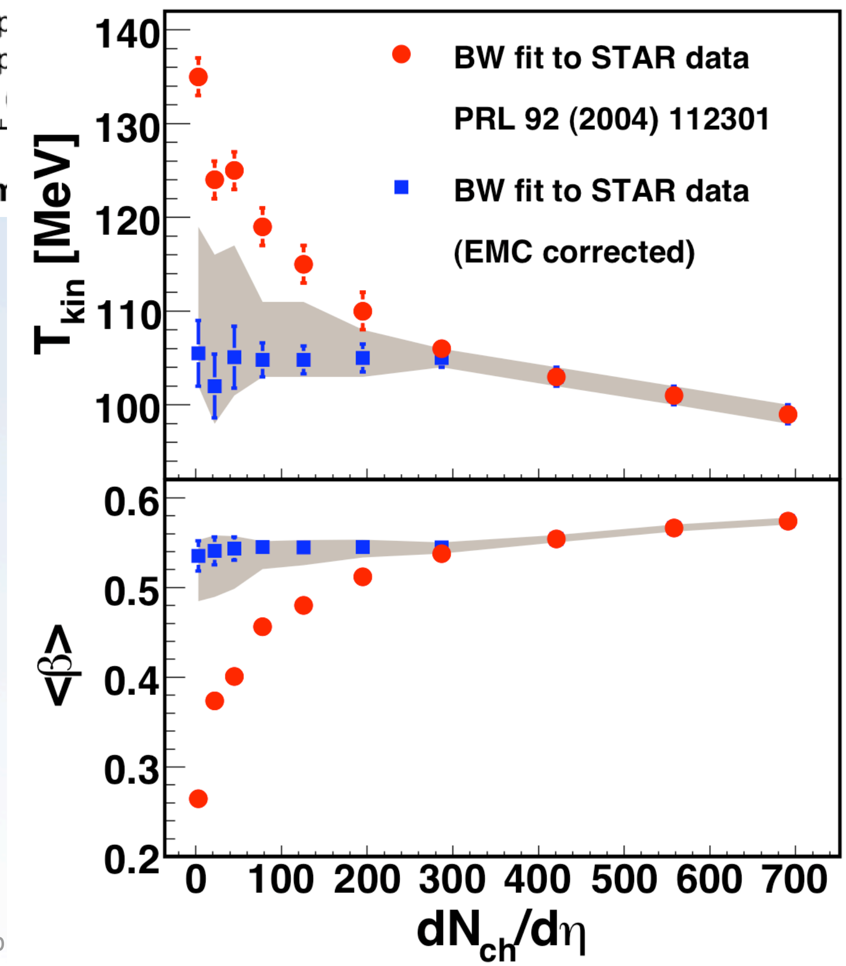


By popular demand



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

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

* EMCIC = Energy & Momentum Conservation Induced *Constraint*

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

$T = 105.5$ MeV

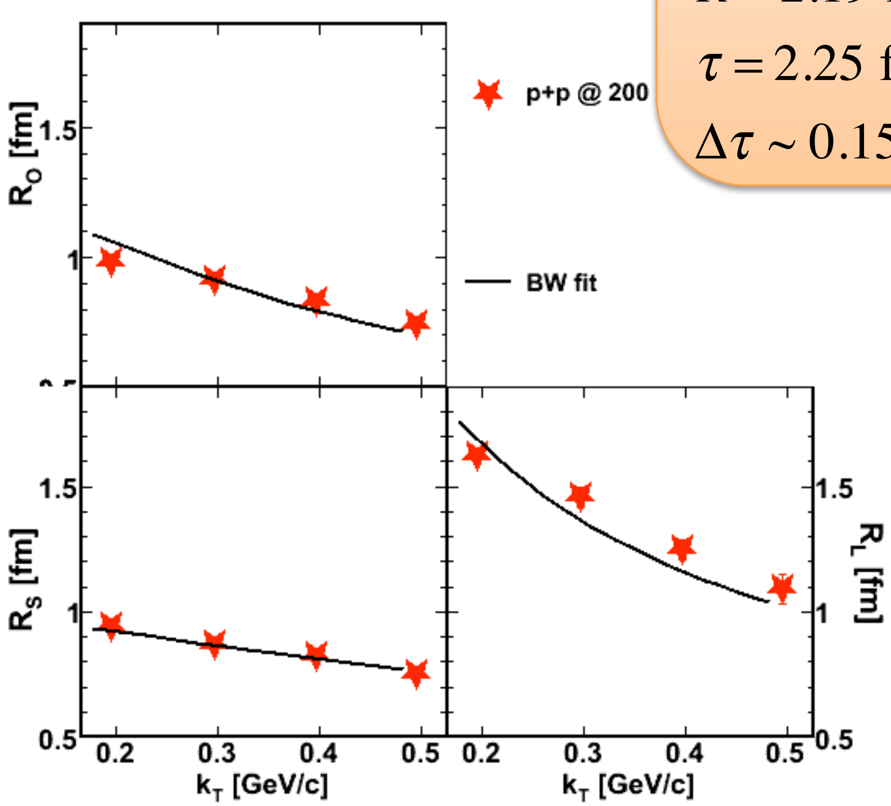
$\rho_0 = 0.934 \quad (\langle\beta\rangle = 0.535)$

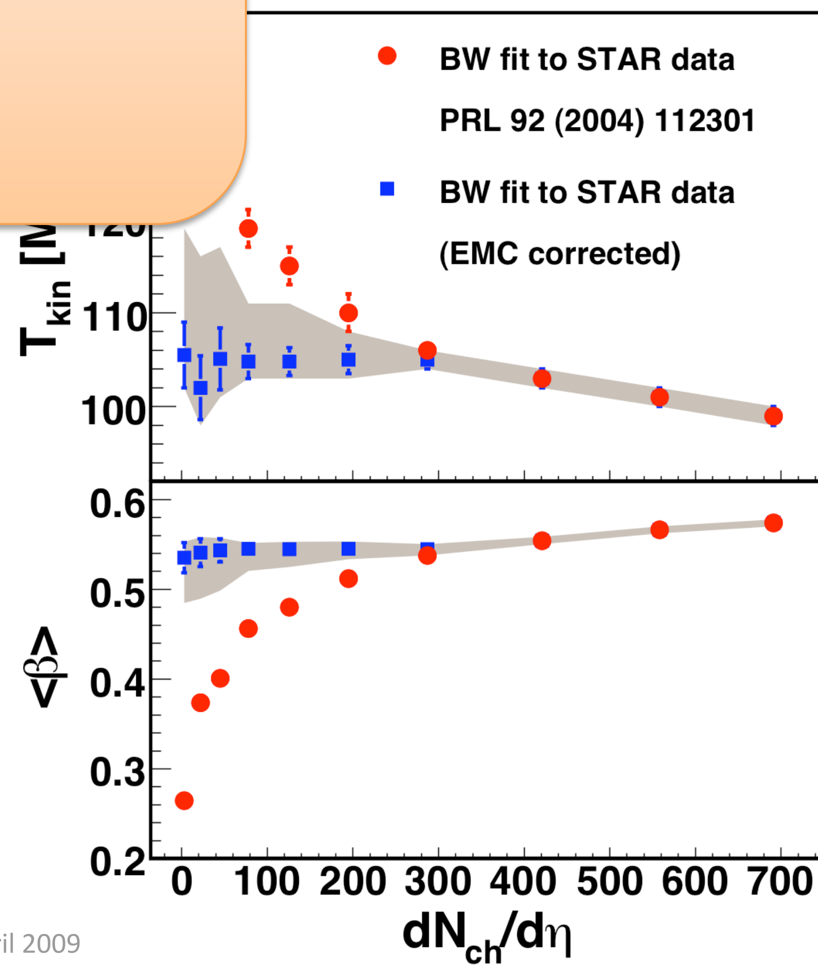
determined entirely by spectra

$R = 2.19$ fm

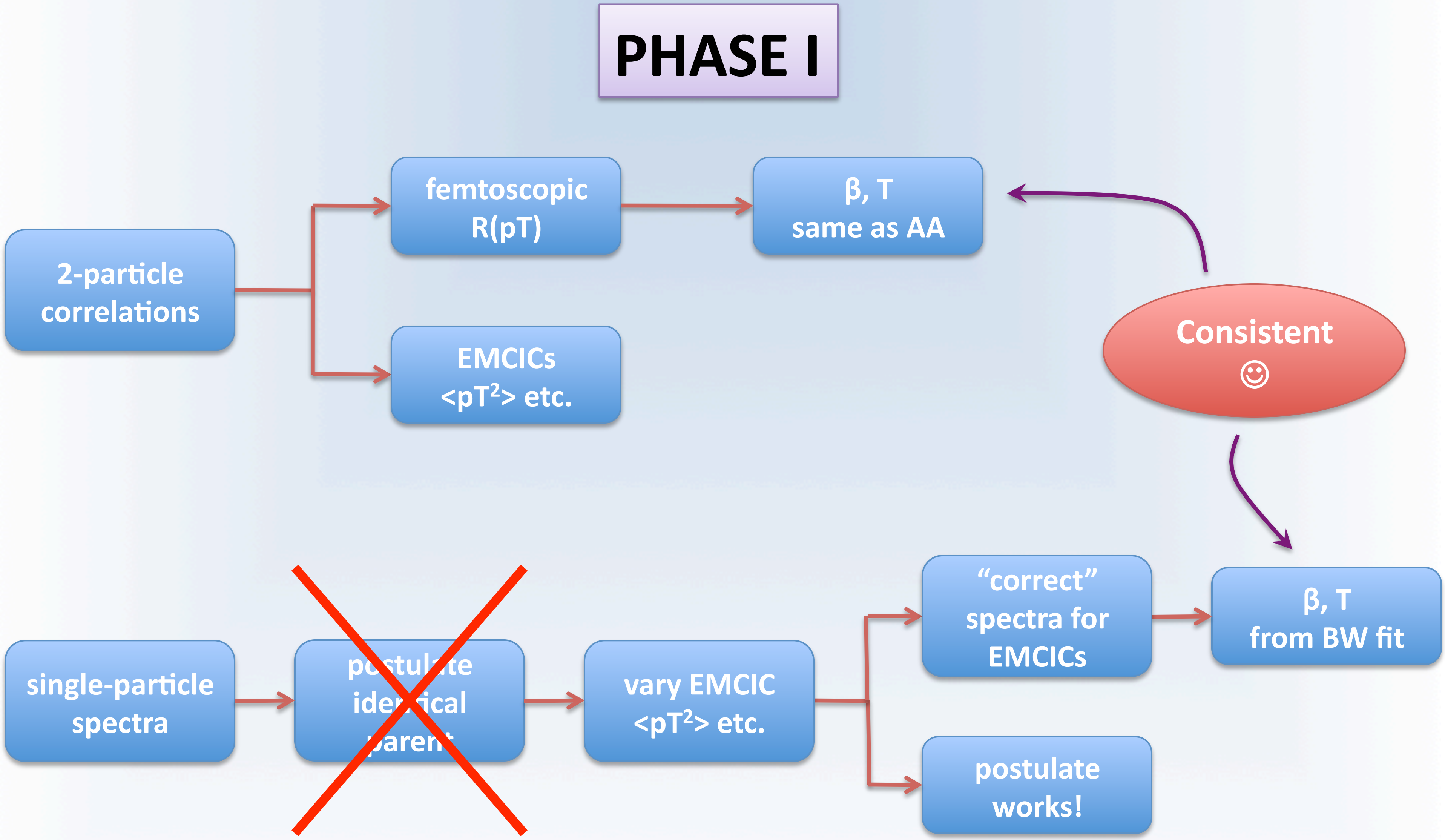
$\tau = 2.25$ fm/c

$\Delta\tau \sim 0.15$





Can't follow the game without a program…



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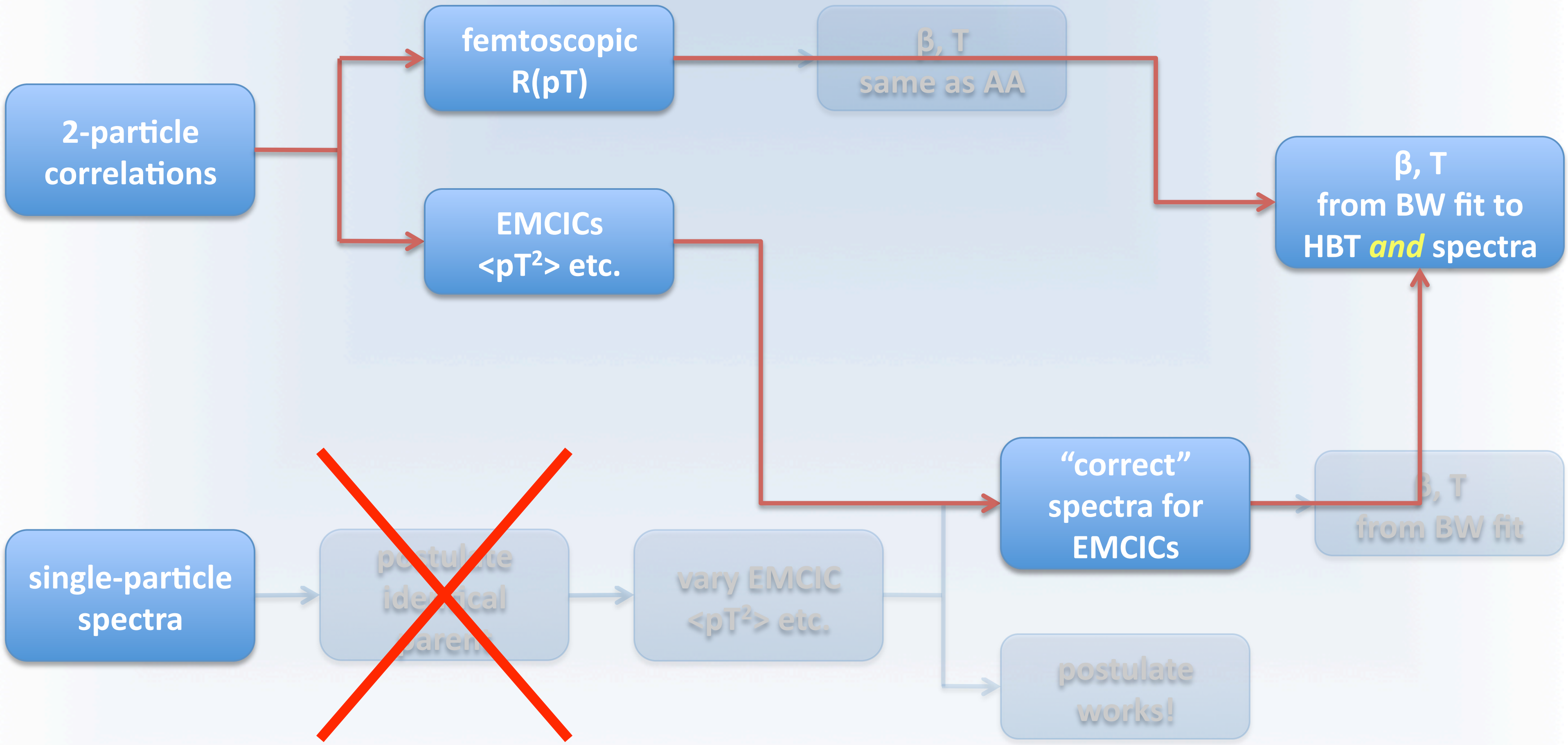
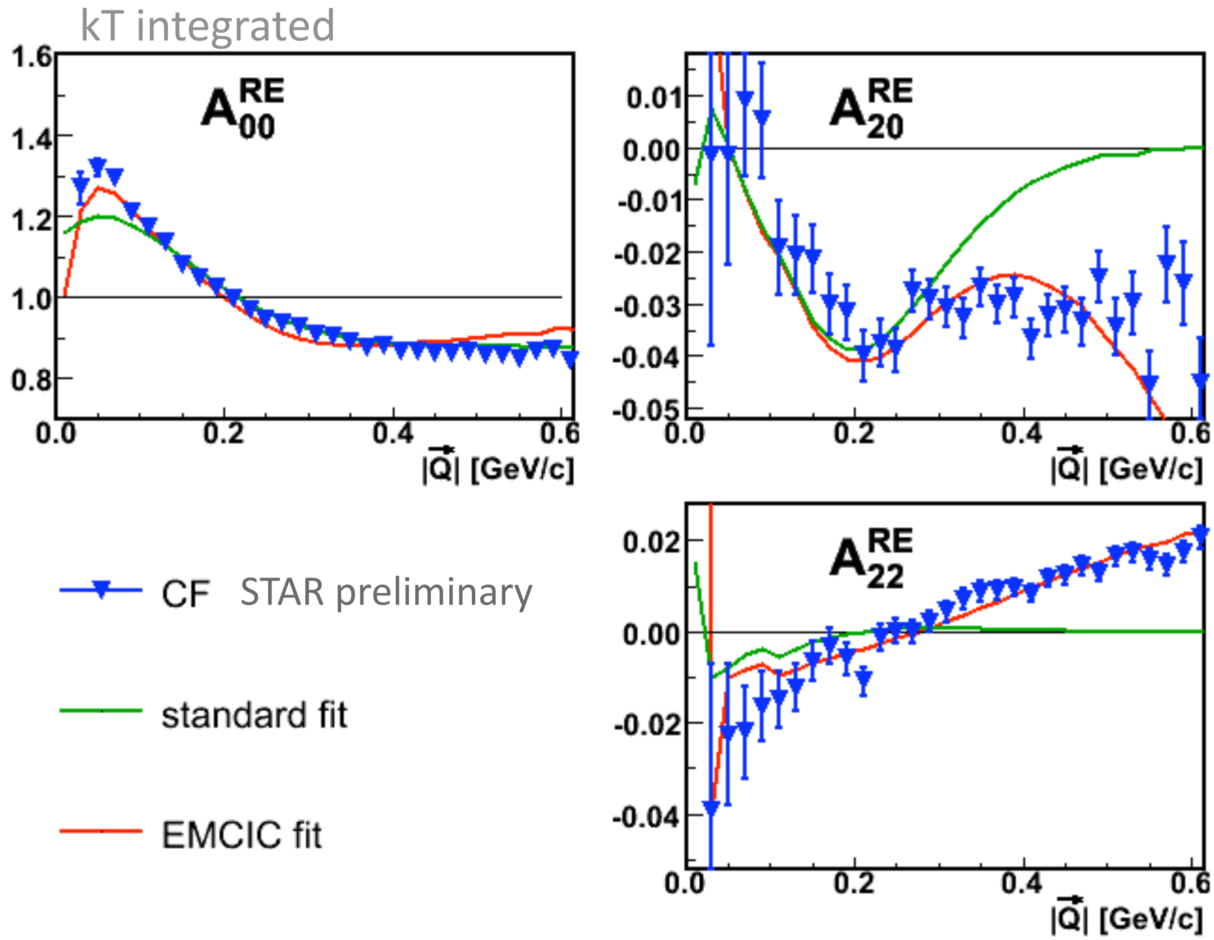
PHASE II



Femto and "system" parameters from 2-particle correlations

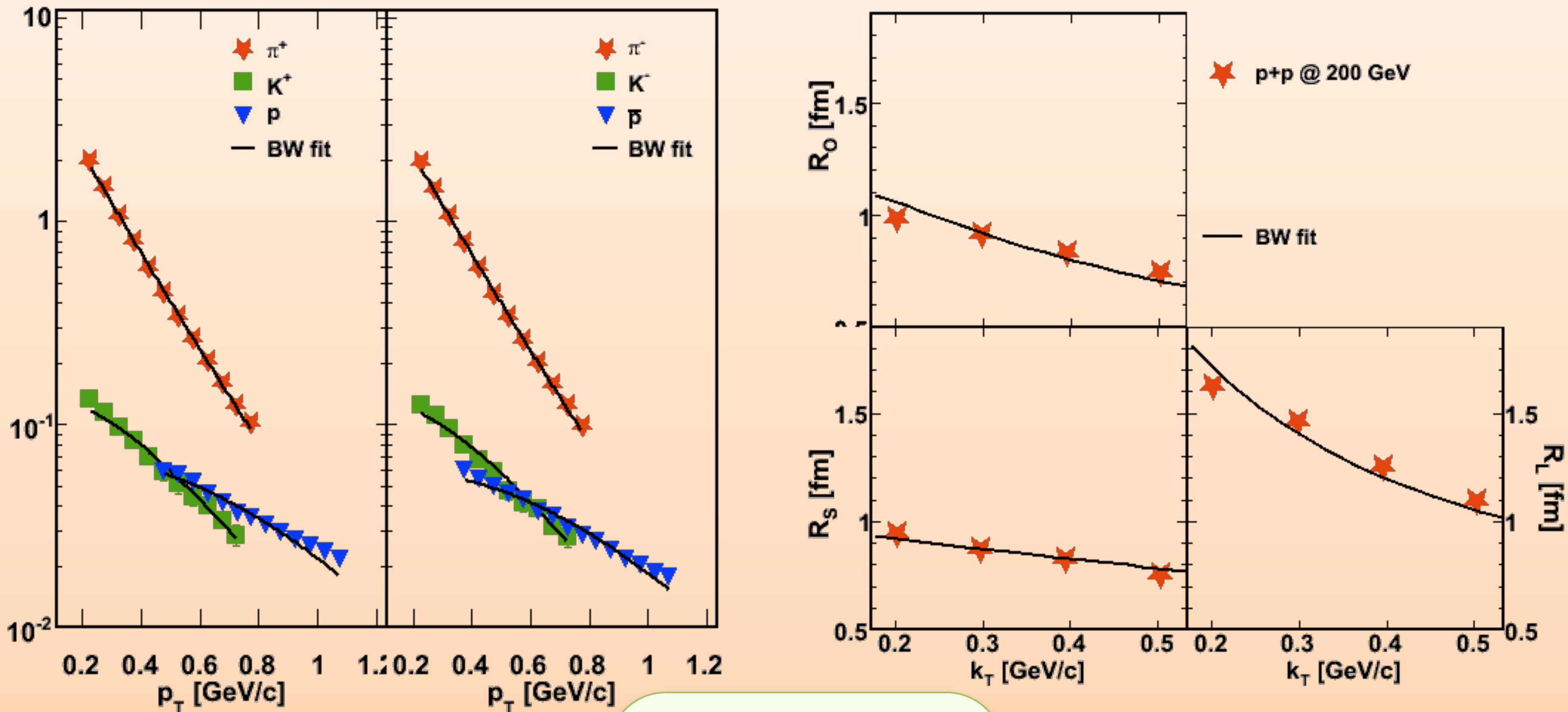


λ = 0.38 ± 0.01
R_o = 0.81 ± 0.01 fm
R_s = 0.84 ± 0.02 fm
R_l = 1.29 ± 0.02 fm

λ = 0.69 ± 0.01
R_o = 0.96 ± 0.04 fm
R_s = 0.98 ± 0.03 fm
R_l = 1.26 ± 0.02 fm

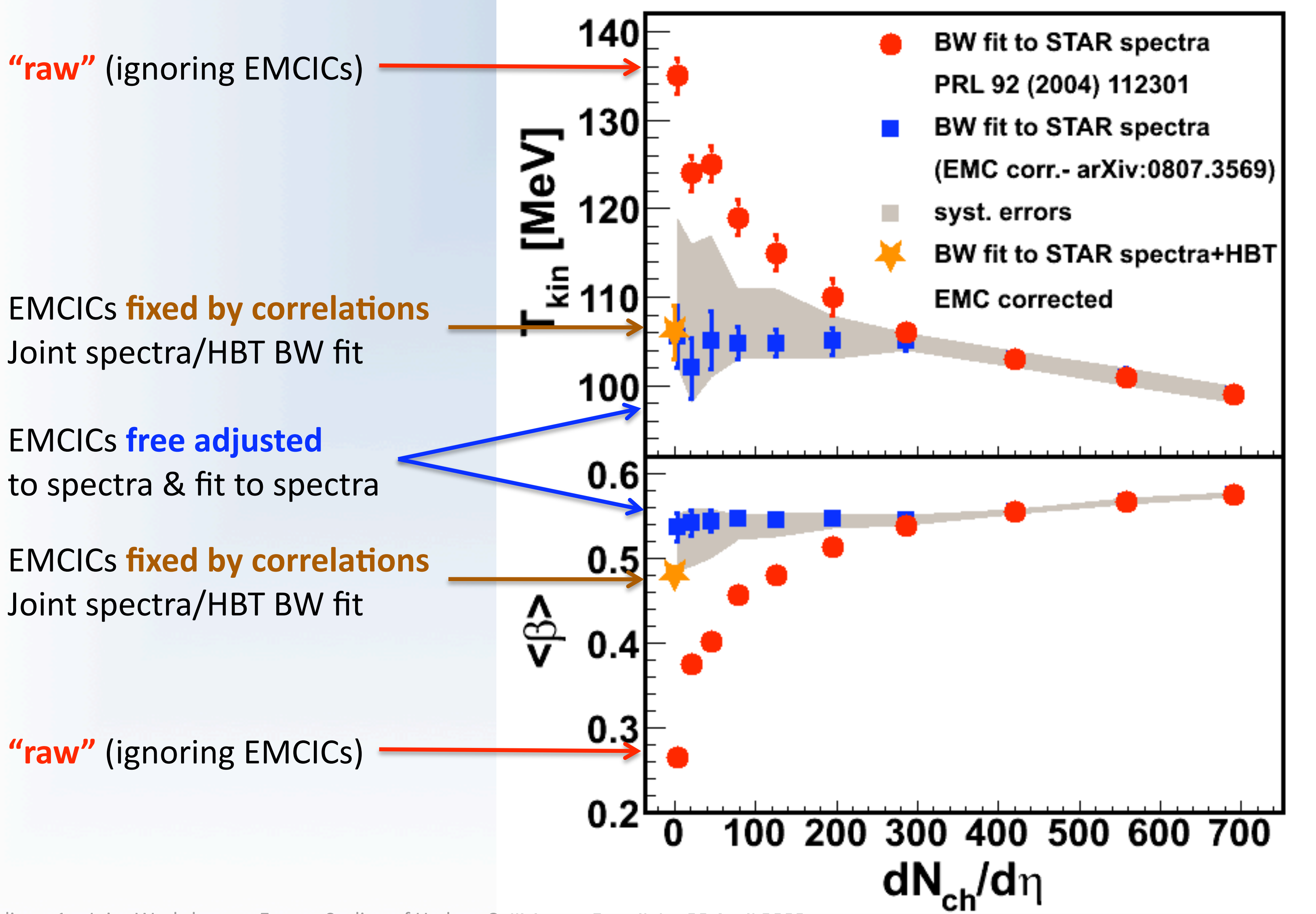
N = 13.6
$\langle E \rangle$ = 0.68 GeV
$\langle E^2 \rangle$ = 0.54 GeV^2
$\langle p_T^2 \rangle$ = 0.17 GeV^2
$\langle p_z^2 \rangle$ = 0.33 GeV^2

Combined fit: consistent flow-based description



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

Combined fit: consistent flow-based description



Combined fit: consistent flow-based description

"raw" (ignoring EMCICs)

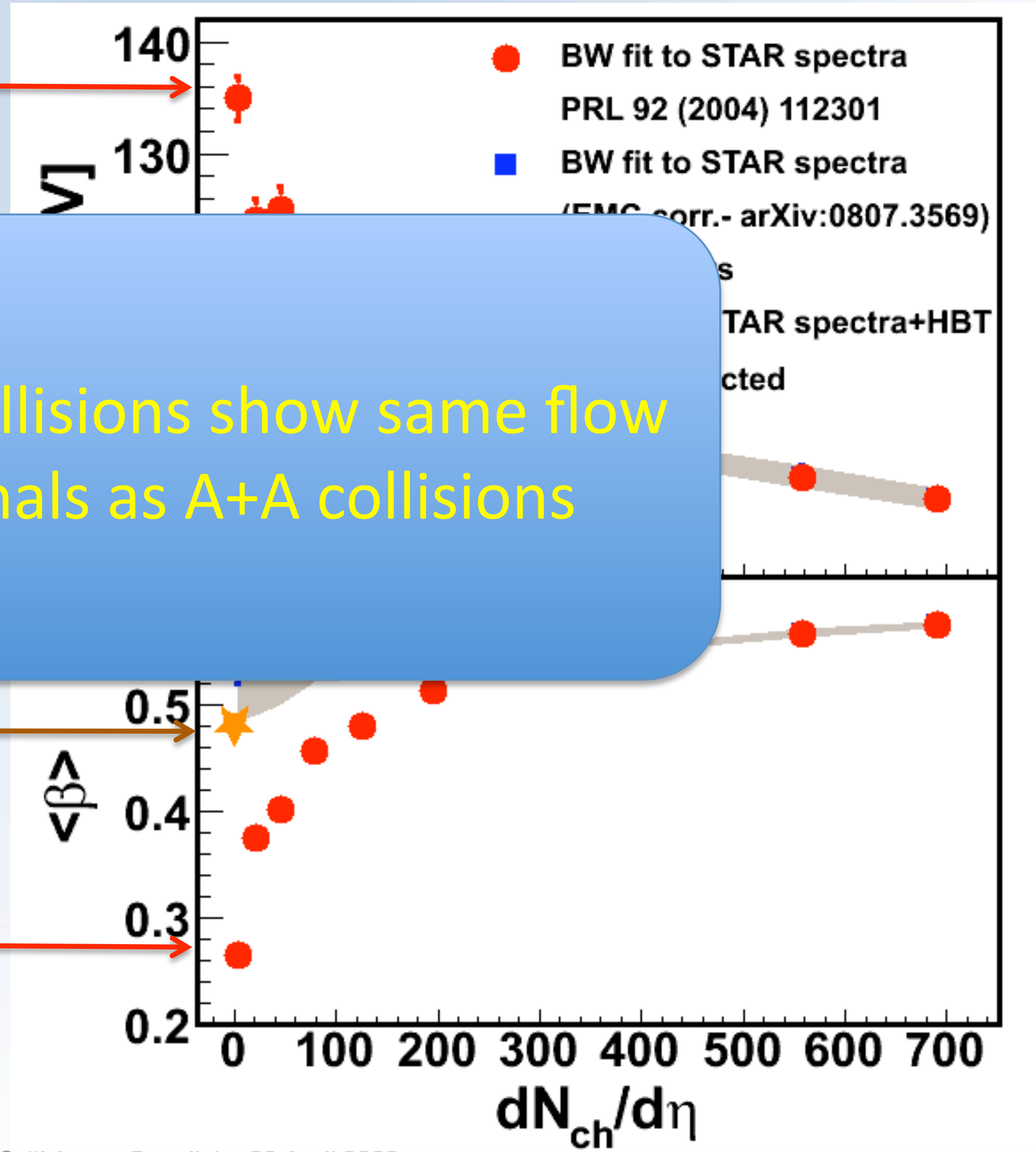
EMCICs **fixed by co**
Joint spectra/HBT B

EMCICs **free adjuste**
to spectra & fit to sp

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

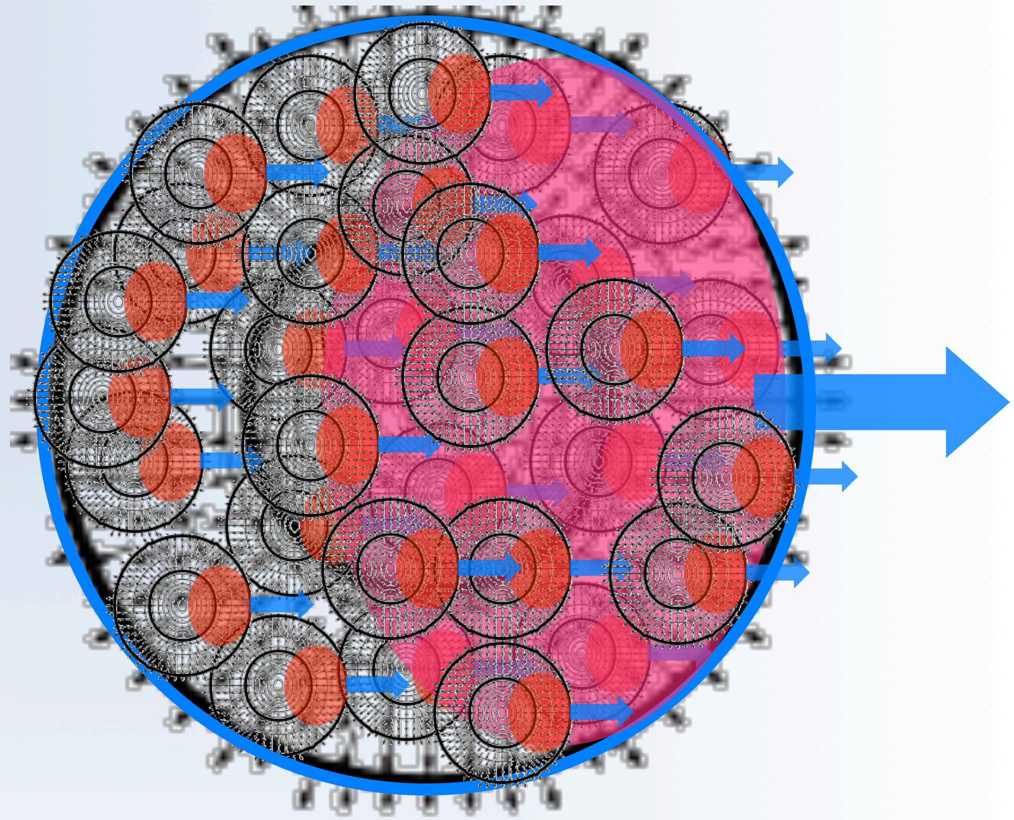
EMCICs **fixed by correlations**
Joint spectra/HBT BW fit

"raw" (ignoring EMCICs)



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”

1st Joint Workshop on Energy Scaling of Hadron Collisions

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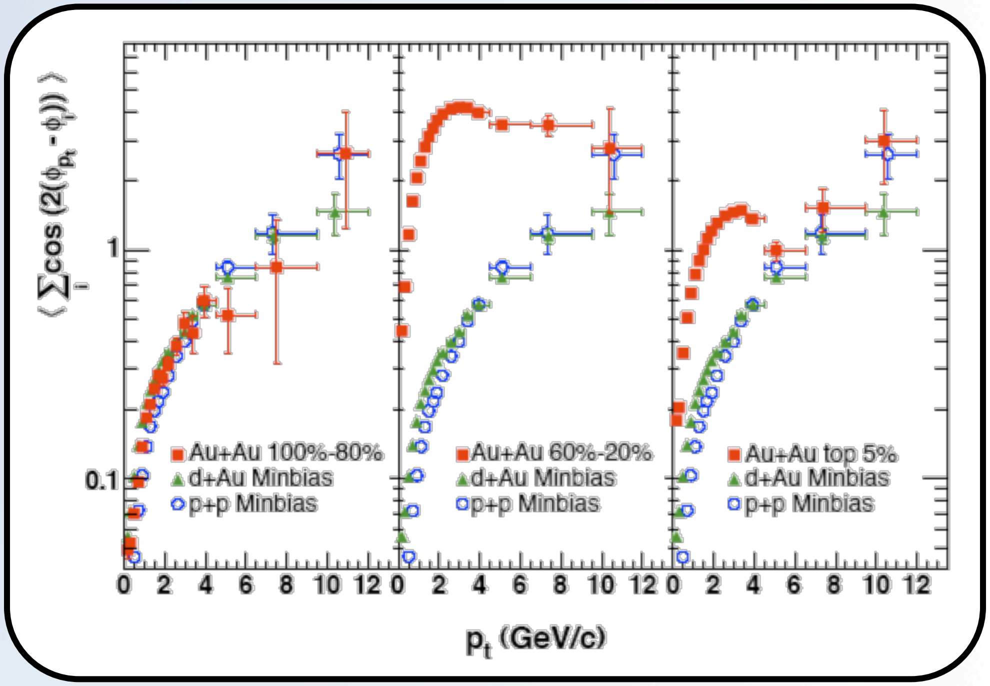
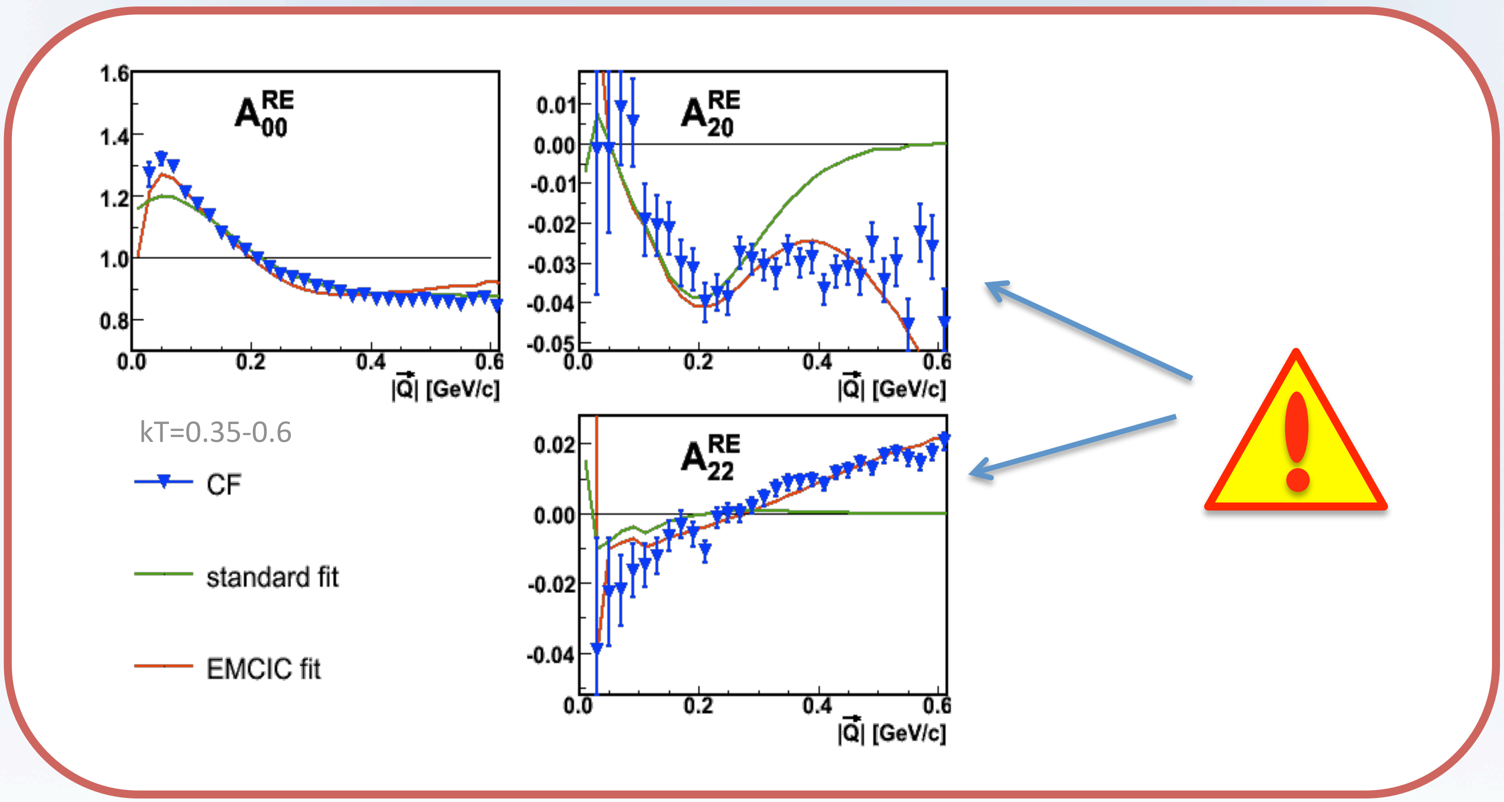


anisotropic flow

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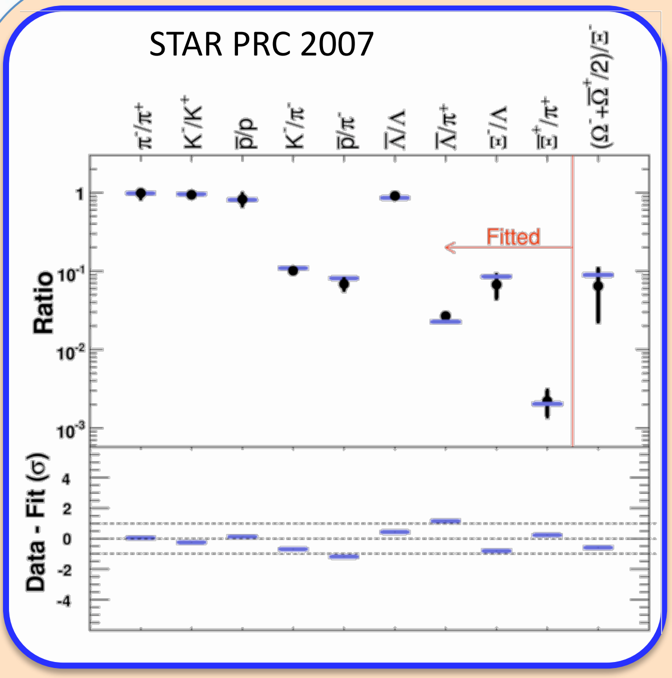
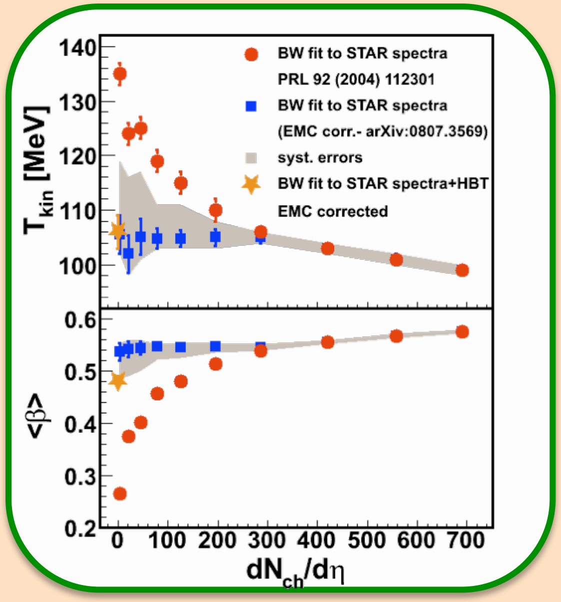
- Femtoscopy & Spectra
  - in H.I.C., well understood, detailed fingerprint of flow
  - RHIC – first opportunity for direct comparison with p+p
  - accounting for EMCICs, identical flow signals in p+p

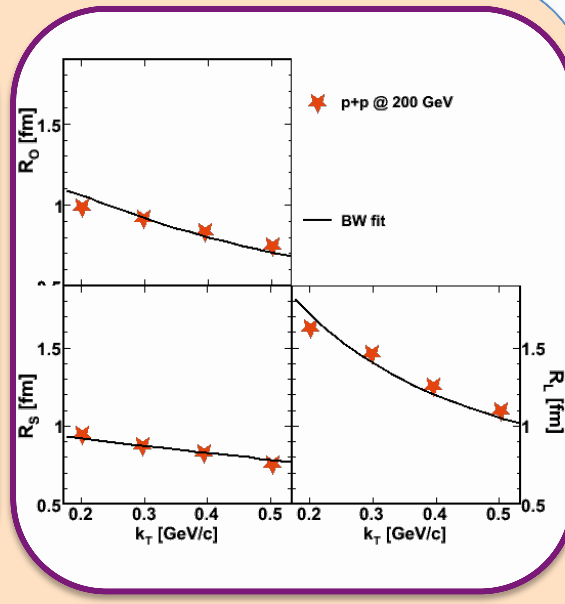
- is pp/AA physics very similar, or are measurements insensitive to diff physics?
- **Has AA become the reference system for pp in non-perturbative sector???**
- Thermalization, hadronization, very early color dynamics…

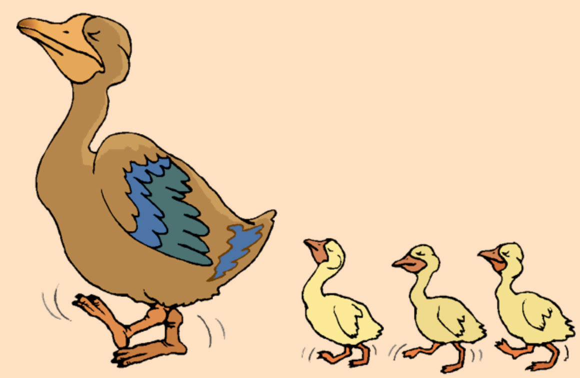
Summary

•









"It is a capital mistake to theorize before one has data."
– Sir Arthur Conan Doyle *[Debasish Das @ WWND09]*

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

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  - i… …sons
  - …]
  -
- S…
  -
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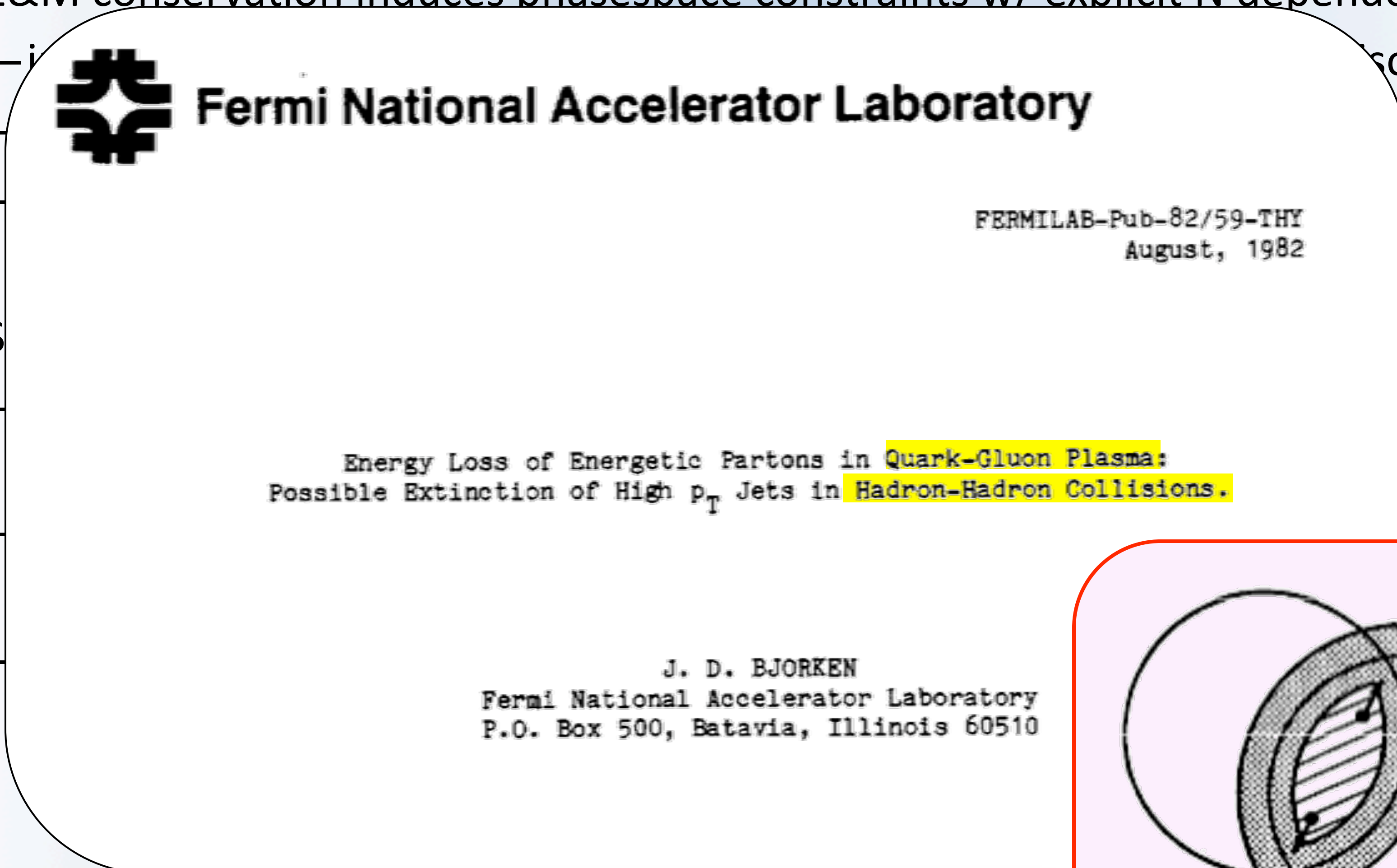
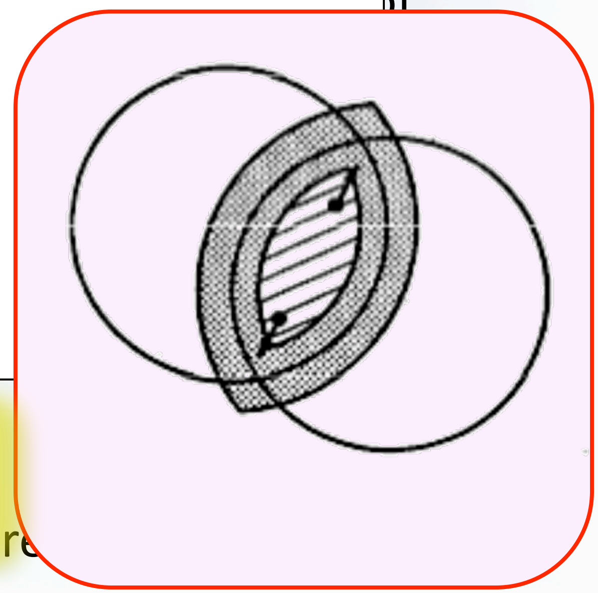

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510



- Well, anyway, account for the “trivial”
  - EMCICs do *not* explain N-dependence of spectra – pare…
  - EMCIC effects in p+p big, may modify physics conclusions