Particle Correlation Measurements from

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for the PHENIX Collaboration

HBT results presented here:
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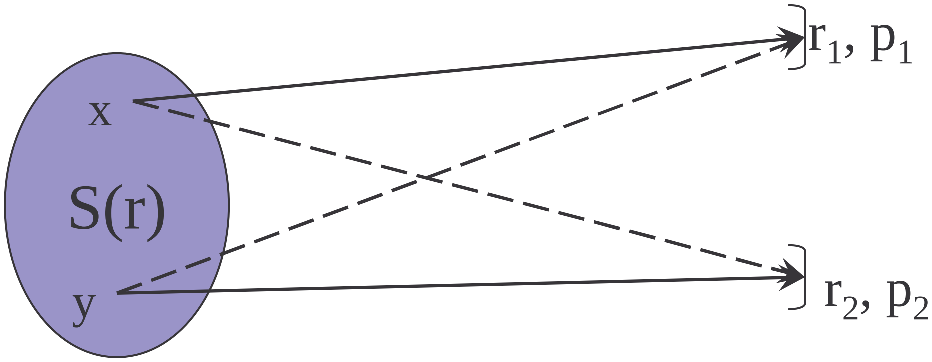
The Physics of Hanbury-Brown Twiss



Amplitude for this diagram:

$$A = \frac{1}{\sqrt{2}}\left[e^{ip_1(r_1-x)}e^{ip_2(r_2-y)} + e^{ip_1(r_1-y)}e^{ip_2(r_2-x)}\right]$$

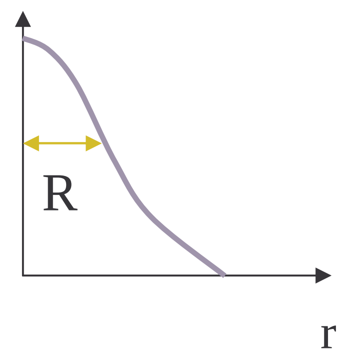
$$A^2 = 1 + e^{i(p_1-p_2)(y-x)}$$

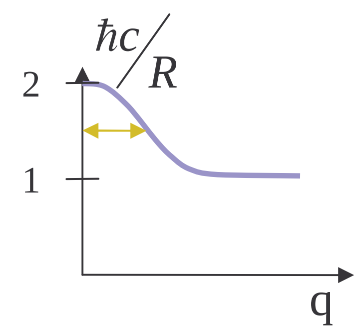
$$\approx 1 + \cos(\Delta p \Delta x)$$

Corresponding normalized probability:

$$P = \int dxdy|A|^2 S(x)S(y) = 1 + \left|\tilde{S}(q)\right|^2 \equiv C_2(q)$$

- Consider a source S(r) of identical bosons (γ or π) whose wave functions can be described as plane waves.
- Assume:
  - Production amplitudes independent of momentum
  - Mutually incoherent





Some details:

In principle:

$$C_2 = \frac{\langle n \rangle^2}{\langle n(n-1) \rangle} \frac{dn/dp_1 dp_2}{\left(dn/dp_1\right)\left(dn/dp_2\right)}$$

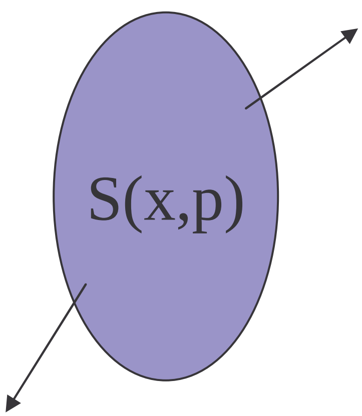
In practice:

$$C_2 = \frac{A(q)}{B(q)}$$

Pairs from same event

Pairs from 'mixed' events

- One dimension works fine when measuring stars:
  - Static
  - Isotropic emission (no position momentum correlations)
- Heavy Ion Collisions are anything but
  - Consider a more complicated source



$$E\frac{dN}{d^3p} = \int d^4x S(x,p)$$

$$q = p_1 - p_2$$

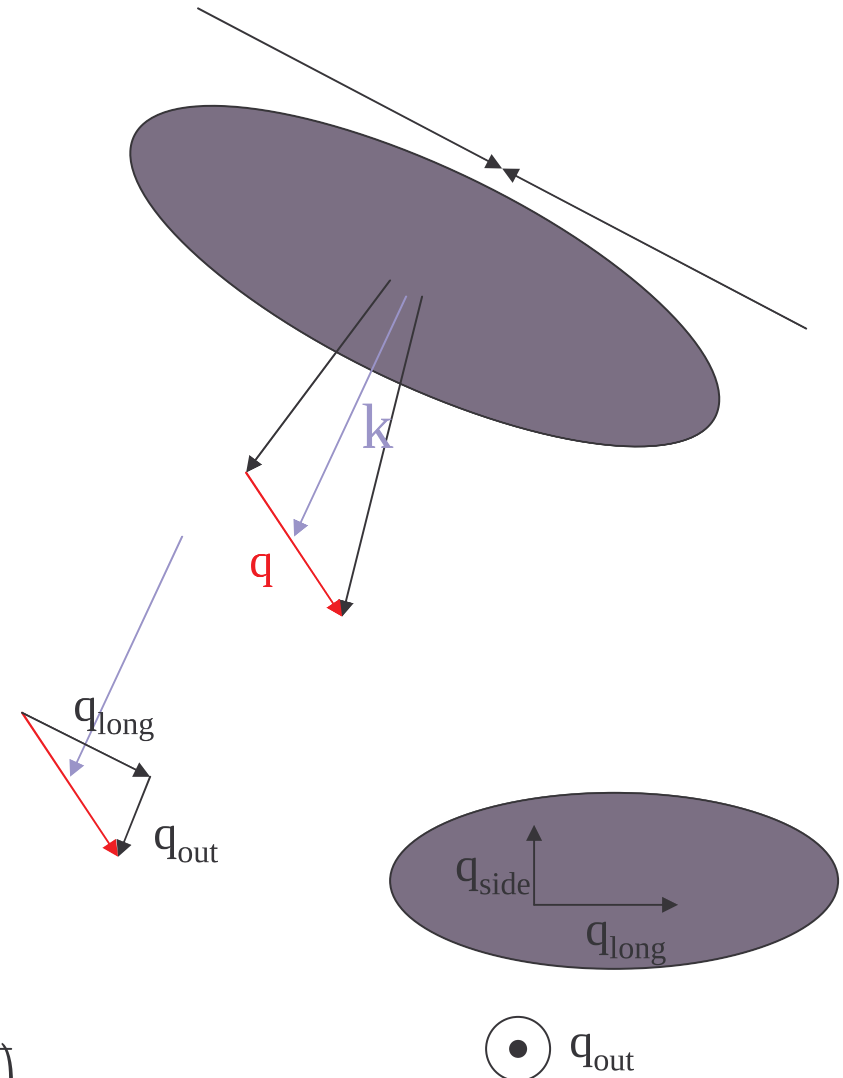
$$k = \frac{p_1 + p_2}{2}$$

$$C_2(q,k) = 1 + \frac{\left| \int d^4x S(x,k) e^{iq\cdot x} \right|^2}{\int d^4x S\left(x, k + \frac{1}{2}q\right) \int d^4y S\left(y, k - \frac{1}{2}q\right)}$$

- S() – effective single particle Wigner phase space density
  - Often replaced by a classical phase-space density in practical calculations
- Note: due to mass shell constraints, the function is non-invertible (model assumptions).

Kinematic Variables

- Currently the field tends to consider projections of the momentum difference into:
  - q_{long}, q_{side}, q_{out}
- q_{long}Ł R_{long} ~longitudinal extent
- q_{side}/q_{out} Ł R_{side}/R_{out} ~transverse extent

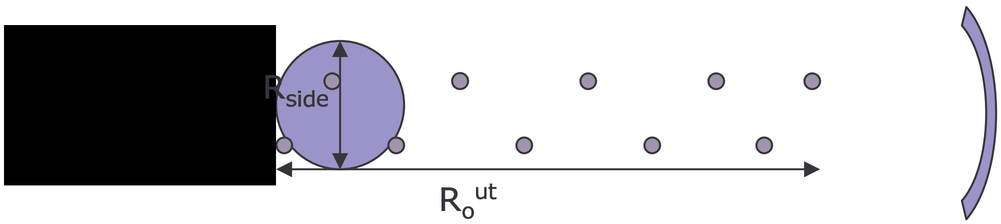


$$q = p_1 - p_2$$
$$k = {p_1 + p_2}/{2}$$

$$C_2(q,k) = 1 + \frac{\left|\int d^4x S(x,k) e^{iq\cdot x}\right|^2}{\int d^4x S\left(x, k + {1}/{2}\, q\right) \int d^4y S\left(y, k - {1}/{2}\, q\right)}$$

HBT and the QGP

- “Naïve” picture:
  - $R_{out}^2 = R_{side}^2 + (\beta_{\mathbf{pair}}\tau)^2$



- Concrete predictions are few:
  - Pratt PRD 1314 (`86): fireball and EOS Ł $\tau \sim 90$ fm/c
  - Bertsch NPA 173 (89) QGP + cascade Ł $\tau \sim 12$ fm/c
  - Hydro calculation of Rischke & Gyulassy expects $R_{out}/R_{side} \sim 2\text{->}4$ @ $k_t = 350$ MeV.
  - Result robust to T_{freeze}, d_Q/d_H, 1st order vs. rapid cross-over.
- Response: can hadronic rescattering mask this prediction?

D.H. Rischke, M. Gyulassy/Nuclear Physics A 608 (1996) 479–512

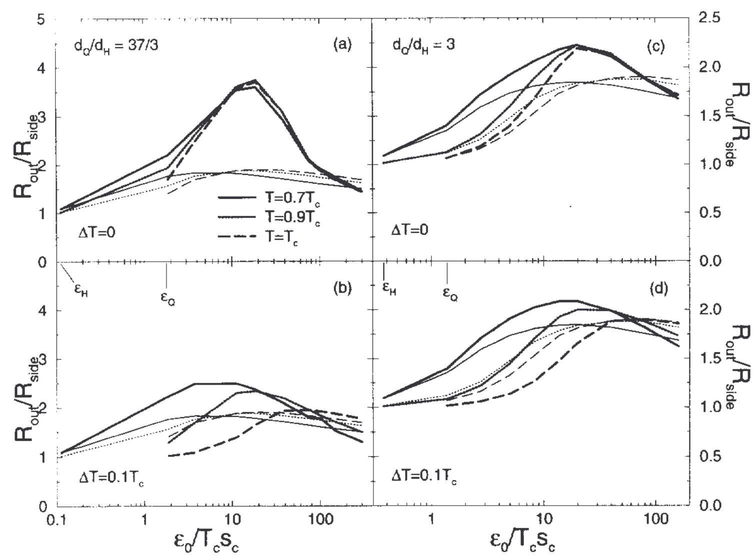
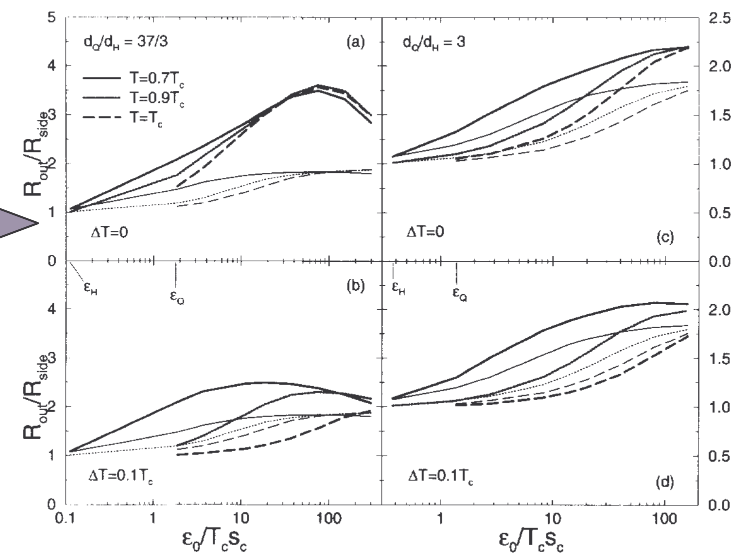


Fig. 17. The same as in Fig. 12, but for the ratio R_{out}/R_{side}.



One step closer

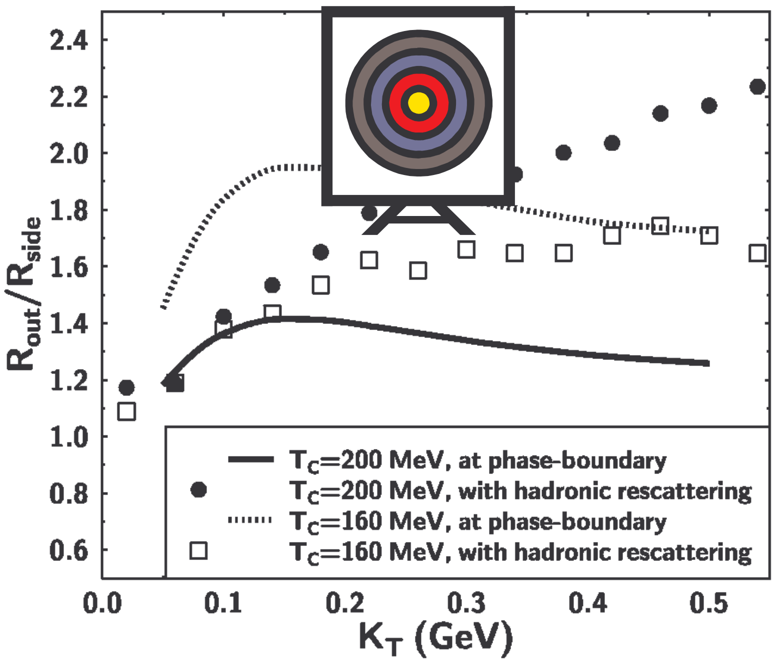


FIG. 3. R_{out}/R_{side} for RHIC initial conditions, as a function of K_T at freeze-out (symbols) and at hadronization (lines).

- Soff, Bass, Dumitru (PRL 86)
  - Couple microscopic transport to hydro with phase transition
  - Still expect R_{out}/R_{side}>1 Ł measurements at high k_t are very interesting.
- Note:
  - Hydro: $R_o/R_s(200)<R_o/R_s(160)$
    - Longer time at phase transition
  - Transport: $R_o/R_s(200)>R_o/R_s(160)$
    - Longer time rescattering

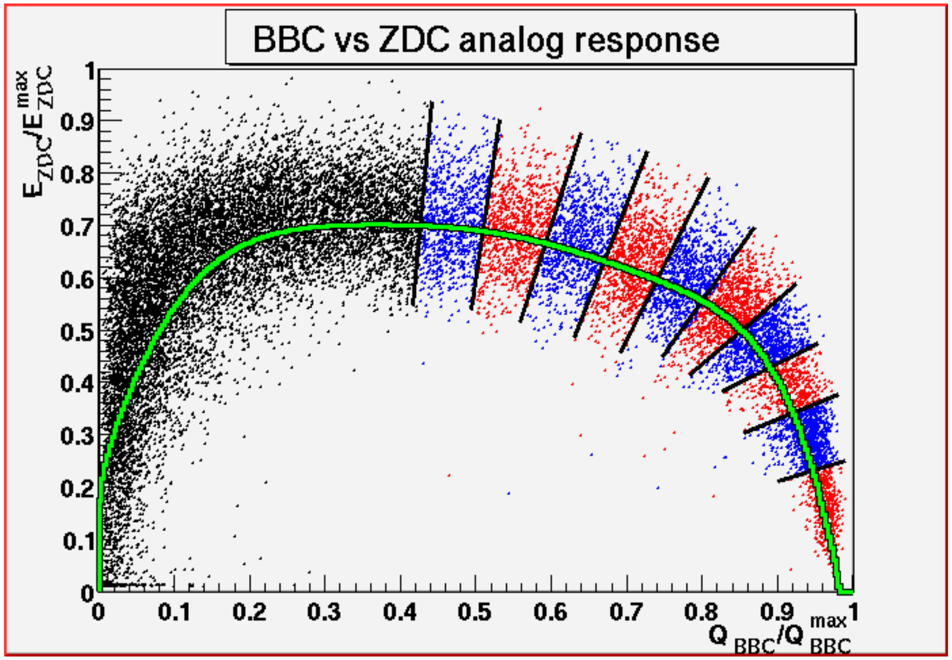
PHENIX – Year 1 Configuration

- Both arms provide hadron PID (contrary to popular belief)
- East:
  - DC + TOF (~100 ps)
  - π/K separation to 2 GeV/c
- West:
  - DC + PbSc (~600 ps)
  - π/K separation to 1 GeV/c
- B-field + geometry limits lower k_t bound to 200 MeV.

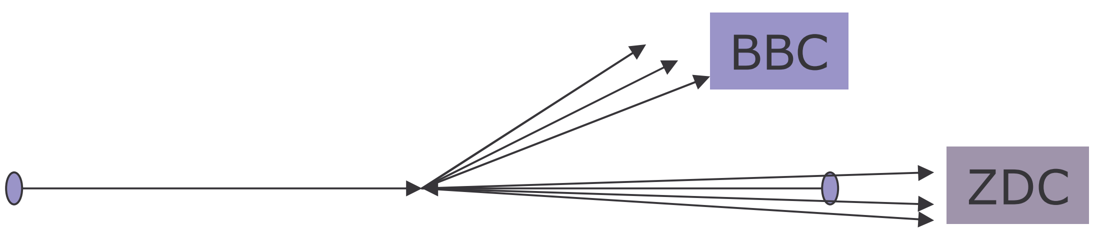
$$\frac{\partial p}{p} = 0.6\% \oplus 3.6\% p$$

I use 'electron' acceptance for this hadron

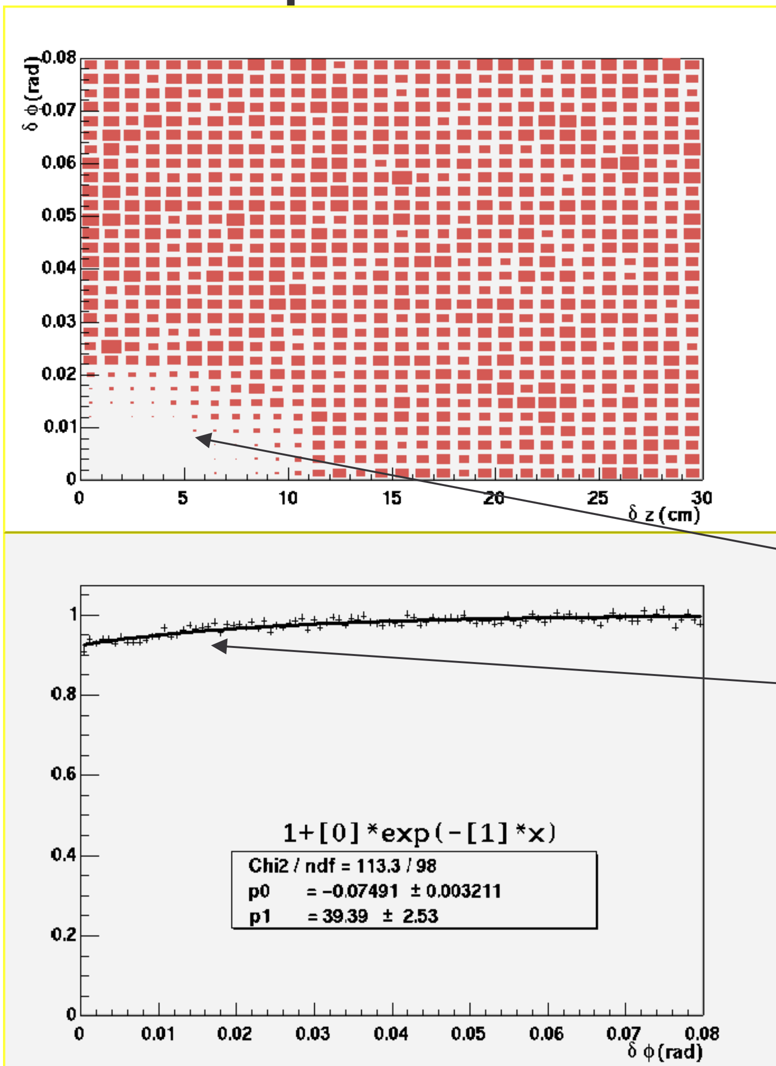
Centrality definition and sample



- This data sample uses the 30% most central collisions
  - <cent$_{pairs}$> = 10%
  - 493k events
- After all analysis cuts:
  - 3.1M π^+ pairs
  - 3.3M π^- pairs



Pair acceptance and corrections



- π definition Ł <1.5σ from π peak && >2.5σ from K peak
- Require pairs from mixed events to have reconstructed vertices within 1cm
  - Acceptance varies as a function of vertex position
- Remove pairs within 2cm in drift chamber
  - Ghosting
- Remove tracks with EMC clusters within 12cm of each other in both real and mixed sample
  - Shower + tower size in EMC
- Correct for two track inefficiencies at low relative ϕ in the drift chamber.
- Full Coulomb Correction modified for momentum smearing
  - Partial correction changes radii results marginally
- Residual correlations in event mixed background Ł <2% error
- Momentum smearing correction to correlation function

Systematic Errors:

R_{long} & R_{side}: 8%

R_{out}: 4.5%

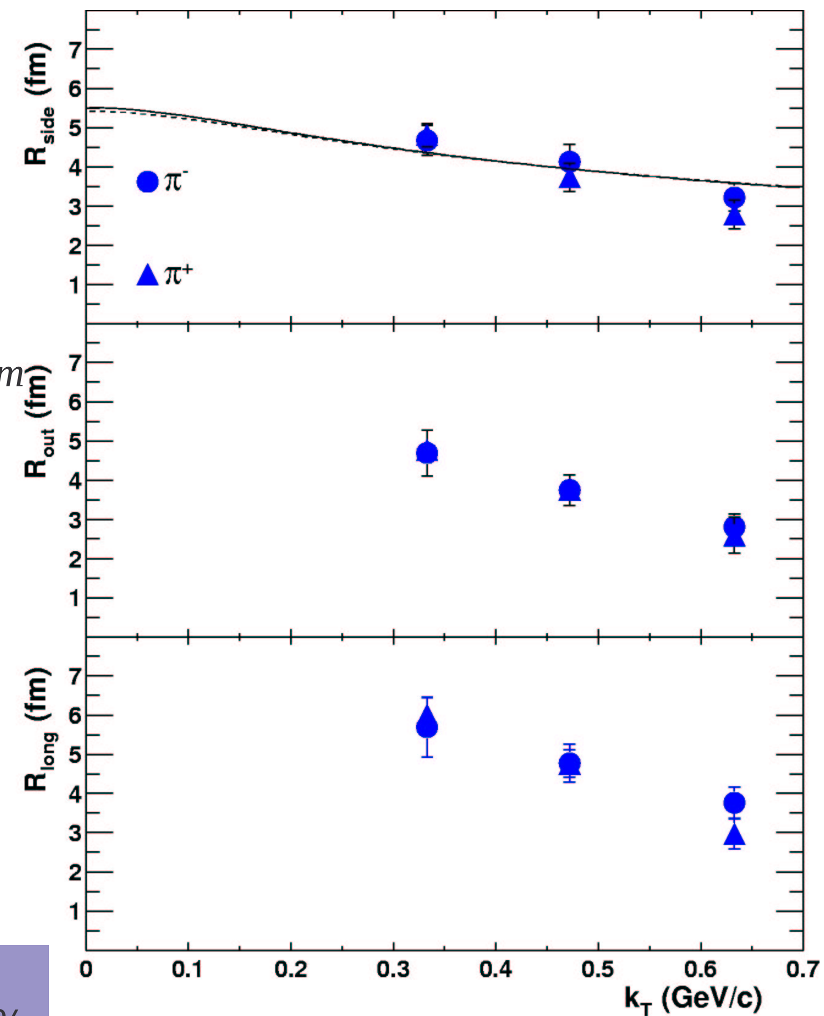
Results:

Assume T = 125 MeV, β_f = .69/η_f=.85
From fits to singles spectra in centrality region 5-15%
(J. Burward-Hoy)

- Theoretical hydro-inspired fits.
  - $$R_{side}^2(m_T) = \frac{R_{geom}^2}{1+\beta_f^2\left(\frac{m_T}{T}\right)} \Rightarrow R_{geom} = 6.7 \pm 0.2\ fm$$

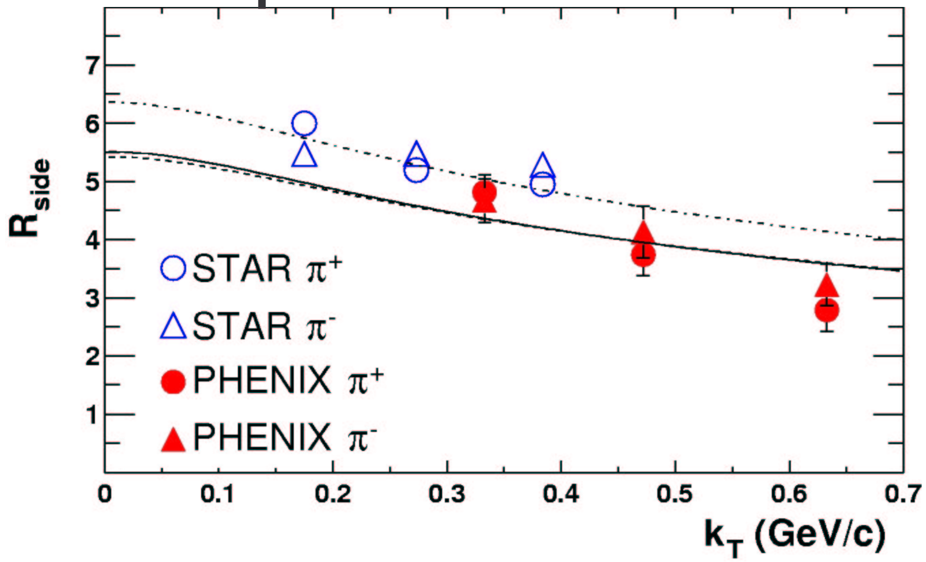
$m_t^2 = k_t^2 + m_\pi^2$

  - Chapman, Nix, Heinz PRC 52, 2694
  - $$R_{side}^2(m_T) = \frac{R_{geom}^2}{1+\eta_f^2\left(\frac{1}{2}+\frac{m_T}{T}\right)} \Rightarrow R_{geom} = 8.1 \pm 0.3\ fm$$
  - Wiedemann, Scotto, Heinz PRC 53, 918
- However, hydro calculations predict R_o than data, R_s, smaller.
- Much larger than comparable 1D RMS Au radius of 3.07fm
- k_t dependence suggest larger β_f/T (η_f/T) than fits to singles



Systematic Errors:
R_{long} & R_{side}: 8%
R_{out}: 4.5%

Compared to STAR

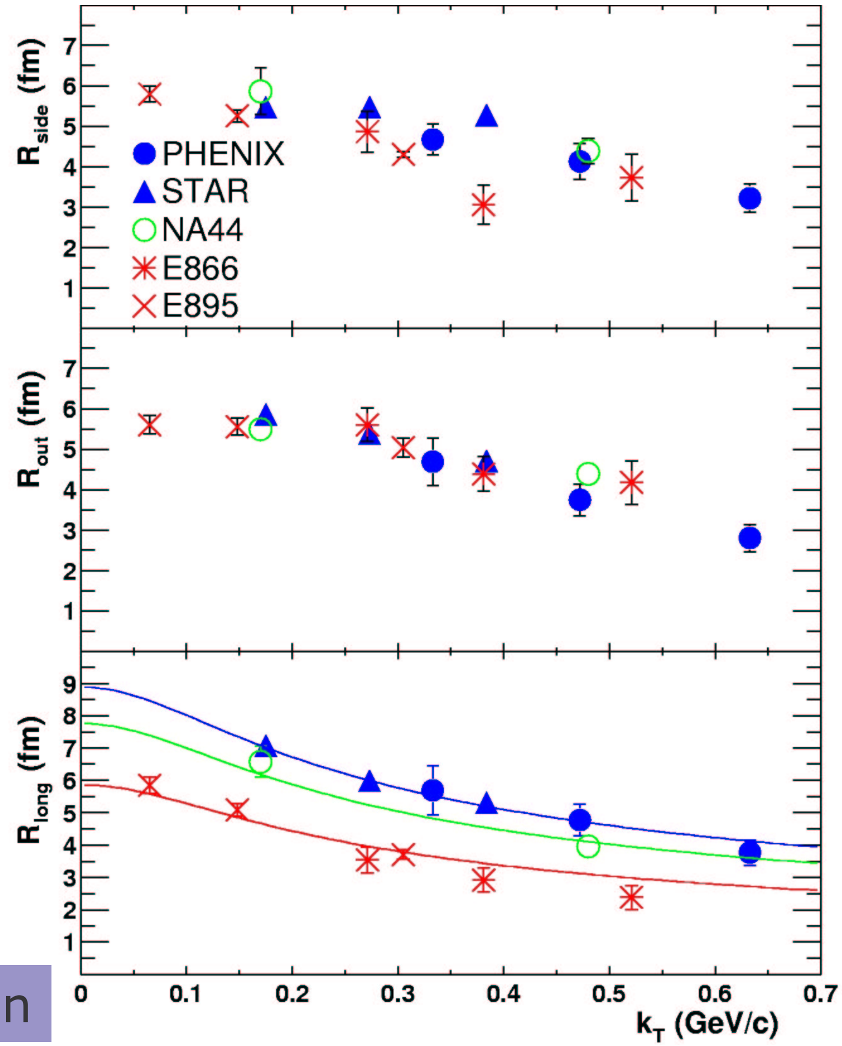


- Well described by hydro model if consider datasets separately.
  - But they indicate a much higher flow/temp ratio when taken together
  - Need to be careful about systematics between different measures.
  - Both experiments should be able to sort this out in the next dataset.
- Inconsistent with models of QGP that include an hadronic rescattering phase.

Energy dependence …

M. Lisa *et al.*, PRL **84**, 2798 (2000)
R. Soltz *et al.*, to be sub PRC
C. Ader *et al.*, PRL **87**, 082301
I.G. Bearden *et al.*, EJP **C18**, 317 (2000)

- R_{out} and R_{side} are energy independent within error bars.
- Smooth energy dependence in R_{long}
- No immediate indication of very different physics
- Fit R_{long} to: $\frac{A}{\sqrt{m_T}}$
- AGS: A = 2.19 +/- .05
- SPS: A = 2.90 +/- .10
- RHIC: A = 3.32 +/- .03



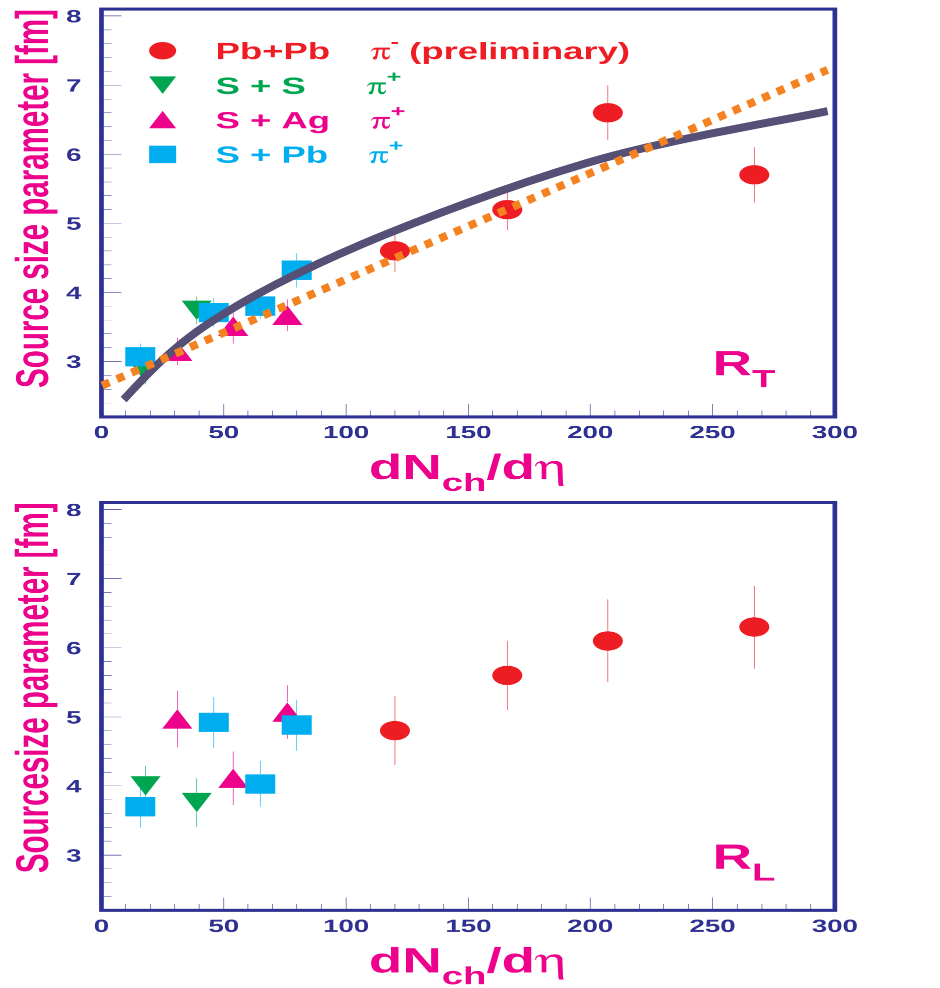
A = τ_0T in 1st order T/m_T calculation

τ_0 = average freeze-out proper time

Even an experimentalist can't predict this

- "A prognostication"
  - Local PHENIX HBT expert keeps his predictions on the web.
- Zajc at Nucleus-Nucleus 97 showed this slide
- Extrapolation to RHIC multiplicities?
  - $(dN/dy)^{1/3}$ => R ~ 9 fm
  - (dN/dy) => R ~20 fm
- Neither.
- What is happening here?
- **

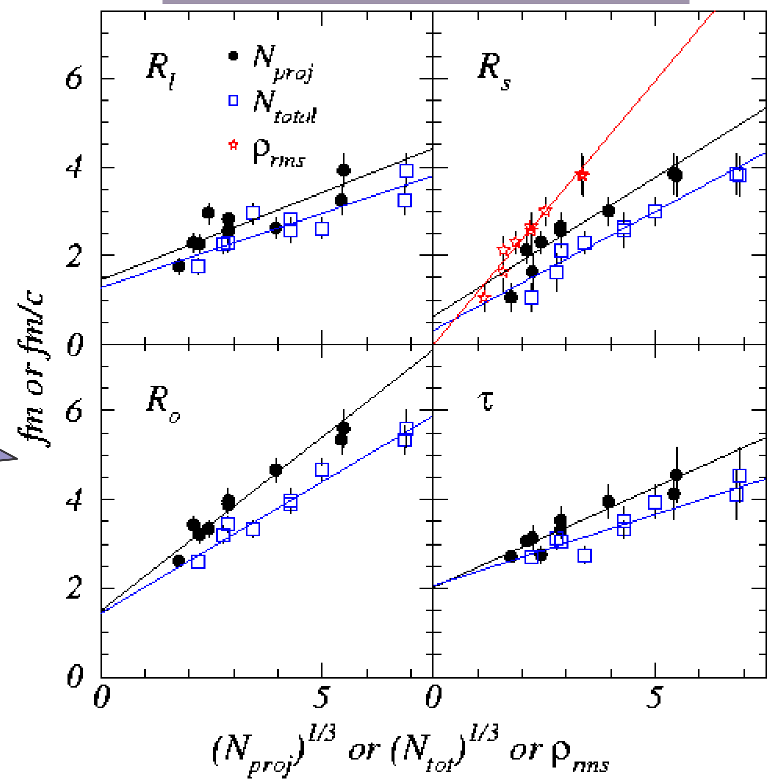
Multiplicity dependence of pion source size



** To be fair: Bill's radii predictions are way off. His guess at the charged particle multiplicity in the extrapolations…bang on

Q & A

- Q: Why are Rout and Rside ~identical over an order of magnitude of beam energy?
  - There is ample evidence at AGS and SPS of dependence of radii on # target+projectile nucleons
    - Even though the larger nuclei have larger flow the radii follow a simple scaling
    - Why no multiplicity/energy dependence?

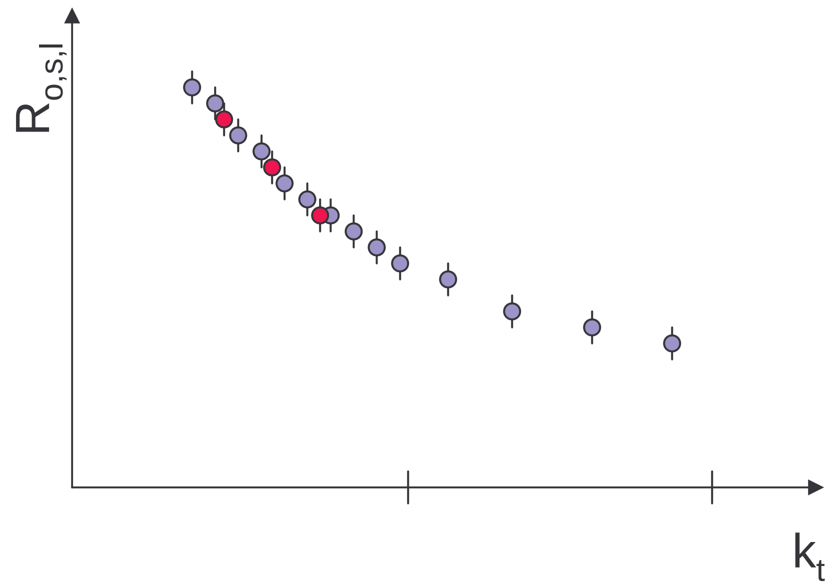


  - Q: Flow higher at RHIC leads to smaller radii?
    - HBT results suggest high flow but spectra imply flow comparable to SPS **
    - k_t dependence of radii is similar for different energies (competing mechanisms that create similar β_f/T?)
  - Q: Higher opacity at RHIC energies?
  - Why would opacity be higher at RHIC than at AGS?
    - $\pi n \rightarrow \Delta \rightarrow \pi n$ Ł $\pi\pi \rightarrow \rho \rightarrow \pi\pi$
    - And why would size and opacity effects identically cancel?
    - Red herring? – You can't create opaque source with smaller lifetime.
  - Q: Why is it only changing in the longitudinal direction?
    - Some surprise among theorists that the difference is so small.
    - Is there a quantitative expectation of the R_{long} dependence?

** To my knowledge no one has fit both SPS and RHIC results to same hydro model

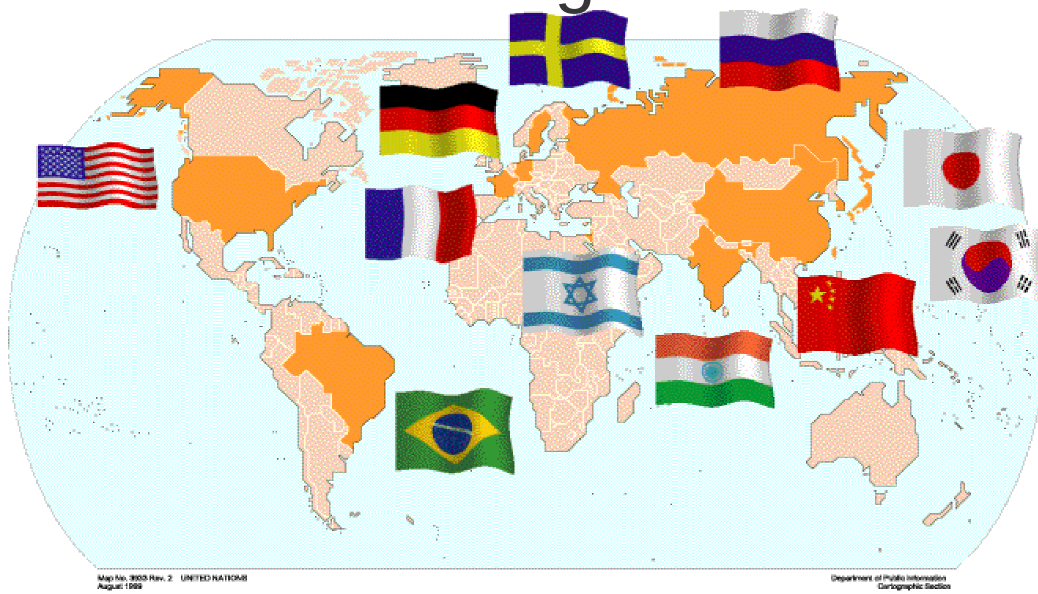
A taste of the future

- For year-1 we wrote ~5 million min. bias events.
  - 1/2 million events in this analysis after all cuts
- In the past run we wrote ~90 million min. bias events (+14 million rare event triggers)
- Therefore, for the year-2 pion correlations:
  - easily 10 high statistics bins in k_t from .2 to 1.0 GeV + a few bins from 1.0 to 2.0 GeV
    - Capability to exclude detailed theories
    - Systematic errors start to become the real problem
- Beyond pions:
  - 1D proton and kaon correlations
  - Non-identical correlations (πK, πp, etc.)
  - π^0
    - maybe possible in year 2 … year 3?
    - Probe of very high k_t.
  - anti-neutron correlations
    - Better than proton correlations Ł lack of coulomb.



The scientists that make me look good*

PH ENIX



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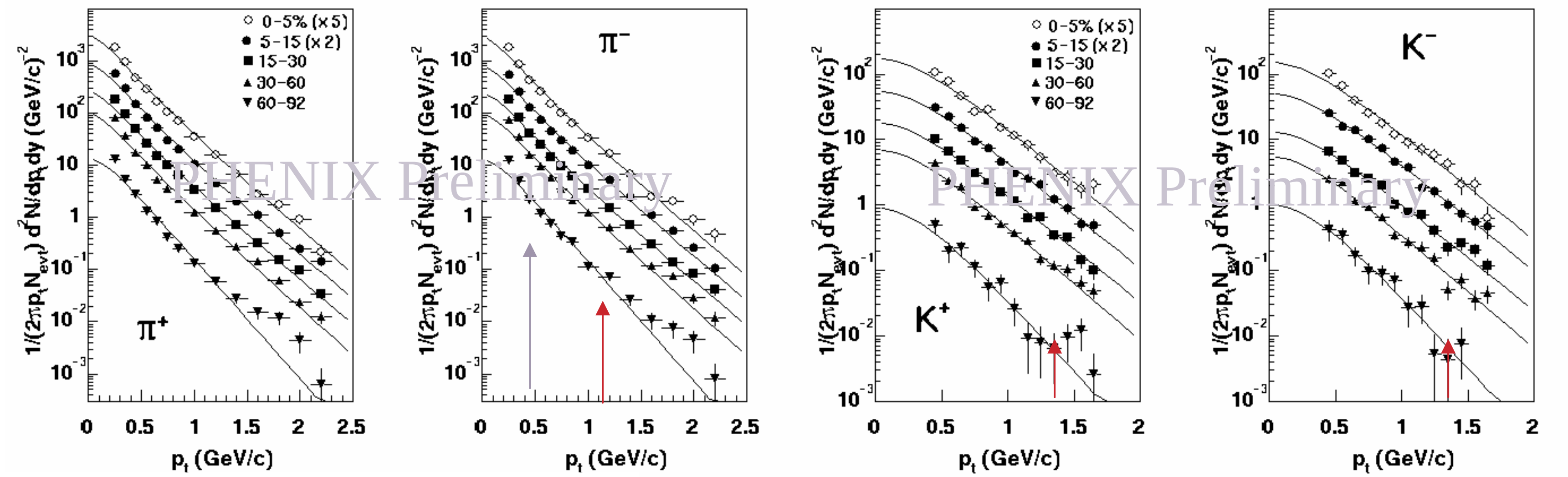
*or at least better than I normally do

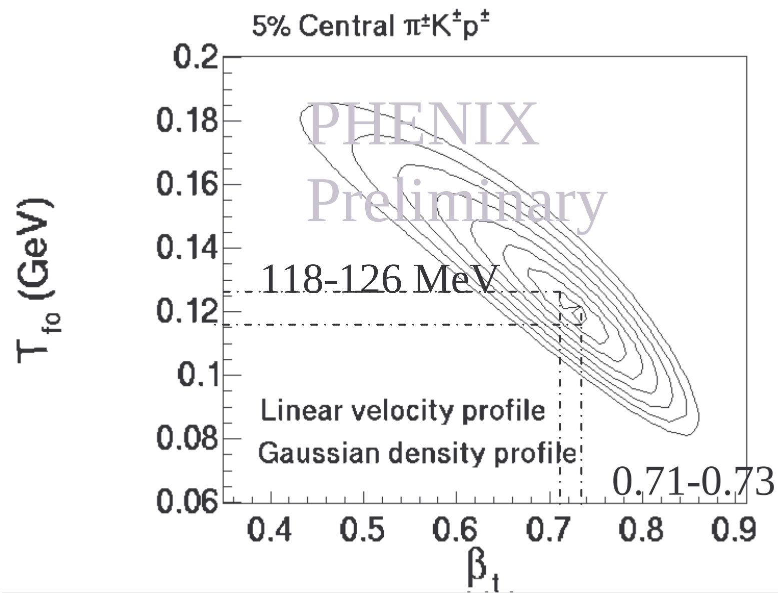
Supporting slides:

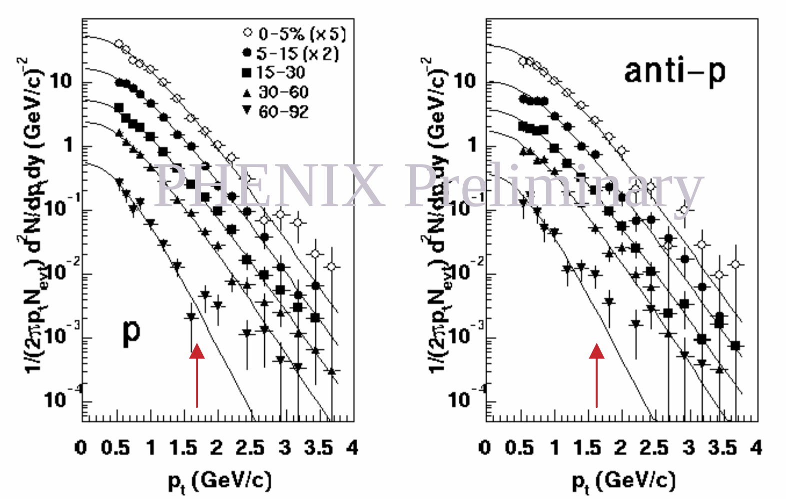
Fitting the Single Particle Spectra:

Jane Burward-Hoy (LLNL)

$$1/m_t\, dN/dm_t = A \int f(\xi)\, \xi\, d\xi\; m_T\;\; K_1(\, m_T /T_{fo} \cosh \rho\,)\; I_0(\, p_T /T_{fo} \sinh \rho\,)$$







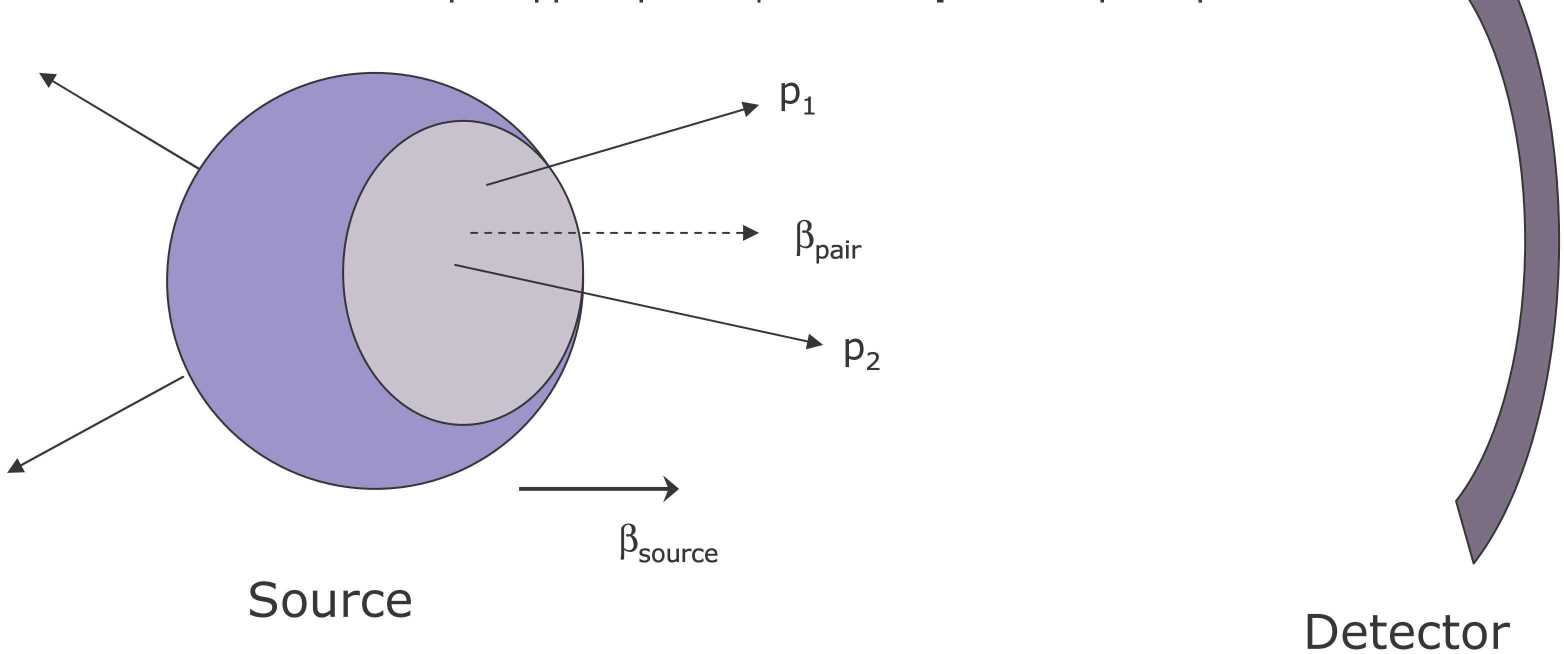
Switching frames

- Problem: radii extracted depend on the frame in which you measure
- Historically we have used:
  - Q_{inv} (1D pair rest frame)
  - Collision Center of Mass
    - AGS
  - LCMS (longitudinally co-moving frame)
    - Longitudinally boost invariant sources
    - SPS(?), RHIC
  - Jet frame
    - p-p collisions.
  - PCMS (pair center-of-mass – 3D version of Q_{inv})
  - …
- What is the ‘correct’ frame?? (= the frame in which the source is not moving)
- Can we bound it experimentally?

Our source??

2π HBT measurement is simultaneous in the PCMS frame

$$R_{OUT}^2 = \gamma_S^2 \{(1-\beta_P v_S)^2 R^2 + (\beta_P - v_S)^2 \tau^2\}$$



Pair rest frame != source rest frame

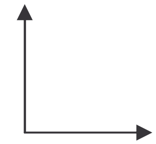
What is the β_{source}?

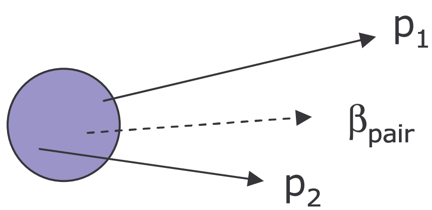
We don't know, but we can bound it:

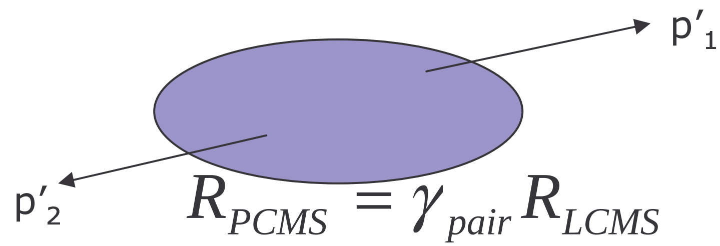
>0

$<\beta_{pair}$

LCMS vs. PCMS







$$R_{PCMS} = \gamma_{pair} R_{LCMS}$$

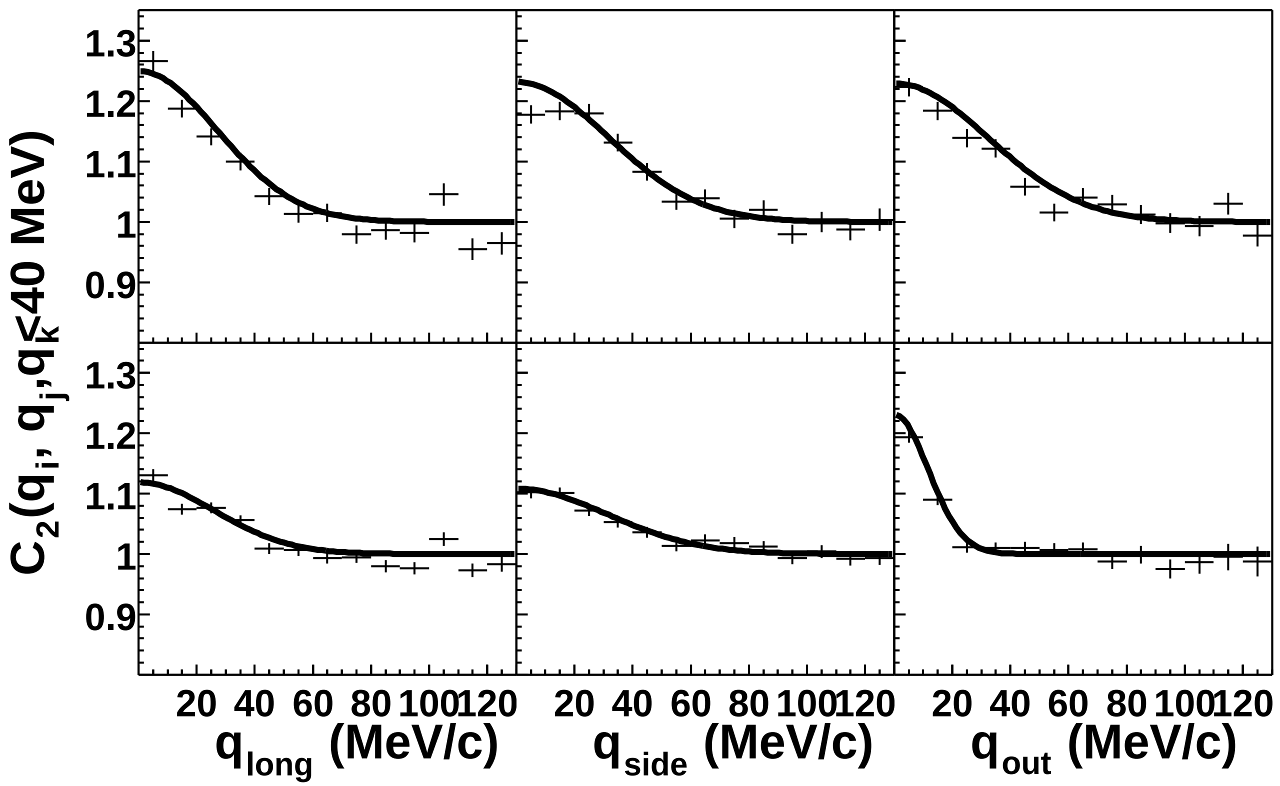
- LCMS
  - A Lorentz contracted measurement of the frame
- PCMS
  - A measurement of the length of the train in the train frame

unphysical

True frame

unphysical

Fits to entire dataset (π^-)



LCMS

PCMS*

*PCMS = Pair Center of Mass System

PCMS results

- R_{side} and R_{long} unchanged
  - And not plotted
- R_{out}^{PCMS} differs by $<\gamma_{pair}>$ from R_{out}^{LCMS}
- Be careful about deducing a lifetime from $R_{out}^2 = R_{side}^2 + (\beta_{pair}\tau)^2$
  - $\beta_{pair}=0$