Femtoscopy in Relativistic Heavy Ion Collisions
Experimental Overview in the 3rd Decade *

Mike Lisa
Ohio State University

* or billion seconds

Outline

Broad topic! – Broad overview

- Data systematics & lessons: heavy ion decades 1 & 2
- Data systematics & lessons: heavy ion decade 3
- Puzzles & the most important open questions

<u>Not discussed</u>

- N>2 correlations, coherence: ALICE PRC89 024911 (2014); ALICE PLB739 139 (2014)
- extraction of scattering parameters: STAR Nature (2015)
- imaging PHENIX PRL98 132301 (2007), PRL103 142301 (2009)
  NA49 PLB685 41 (2010); STAR PRC88 034906 (2013)
- d+A, p+A (mentioned) ALICE PRC91 034906 (2015); PHENIX NPA931 (2014)
- asymmetry from non-id correlations: no recent (published) results

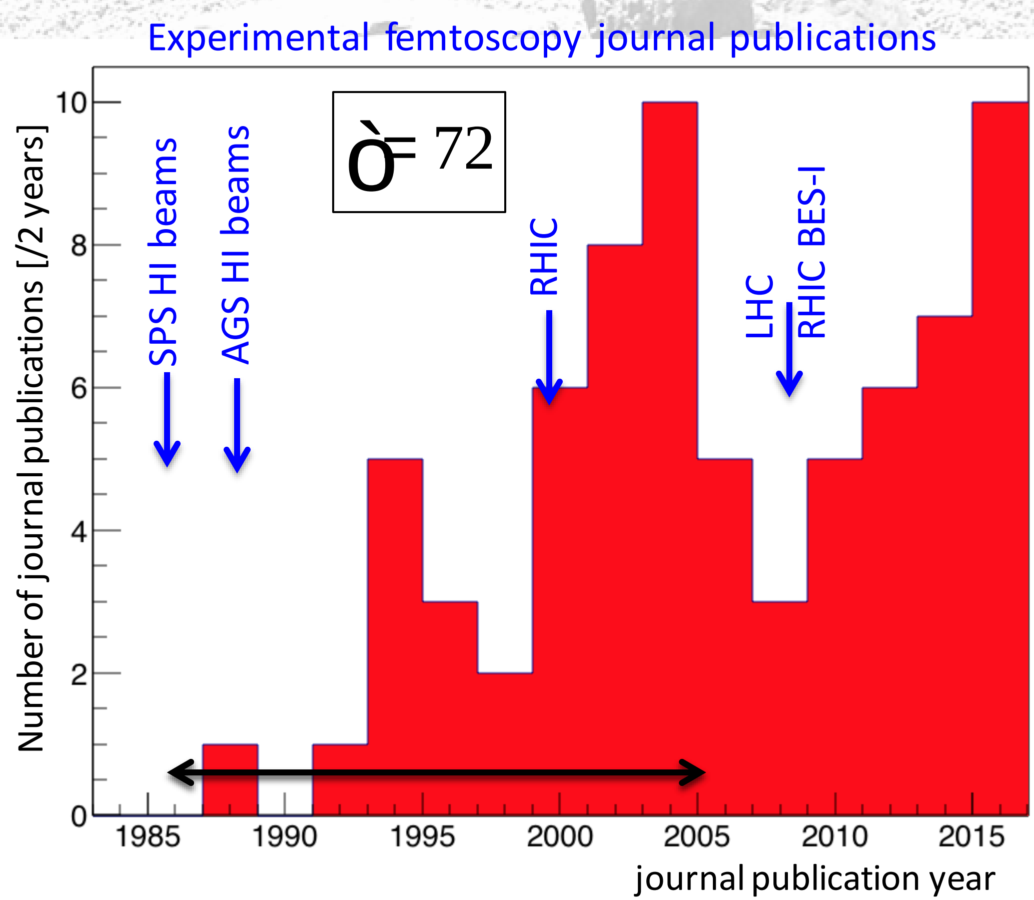
Decades 1 & 2
(Time & energy)

Ann. Rev. Nucl. Part. Sci. 55:357-402 (2005)

Femtoscopy in Relativistic Heavy Ion Collisions: Two Decades of Progress

MAL, S. Pratt, R. Soltz, U. Wiedemann

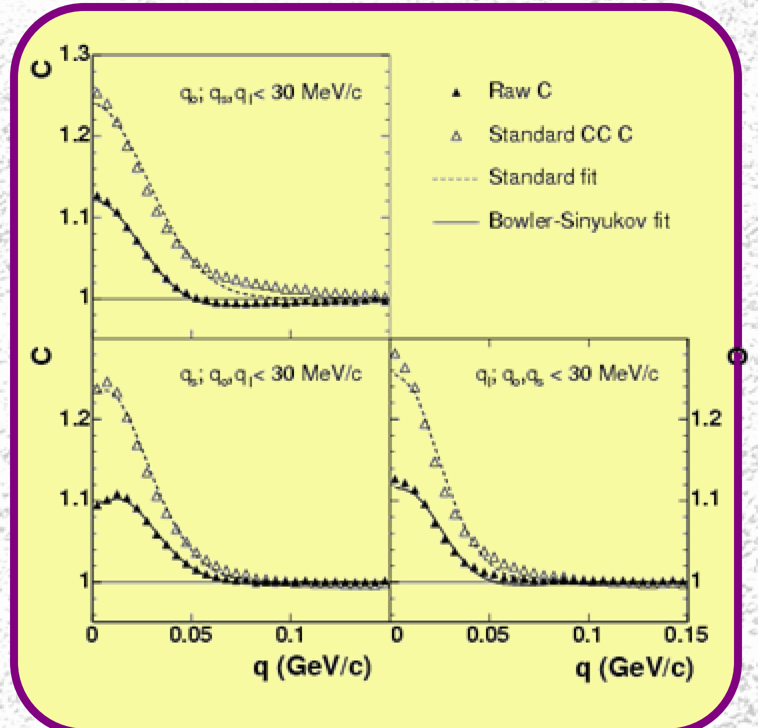
$\sqrt{s_{NN}} = 2$ ¸ 200 GeV

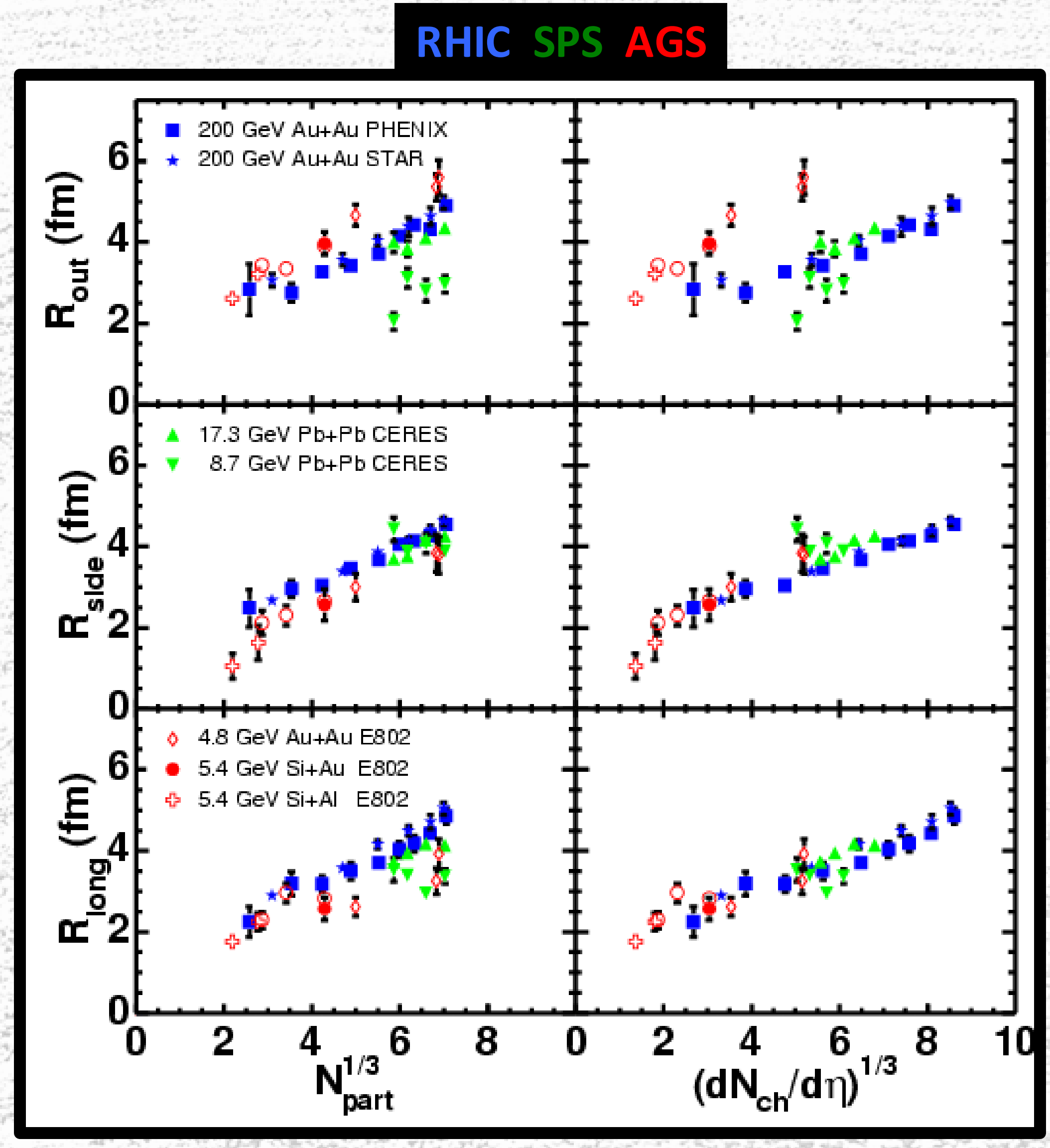


Decades 1 & 2
(Time & energy)

<u>First two decades (time & energy)</u>

- high-stats pion systematics
  - – N_{ch}, p_T, ϕ, (y)





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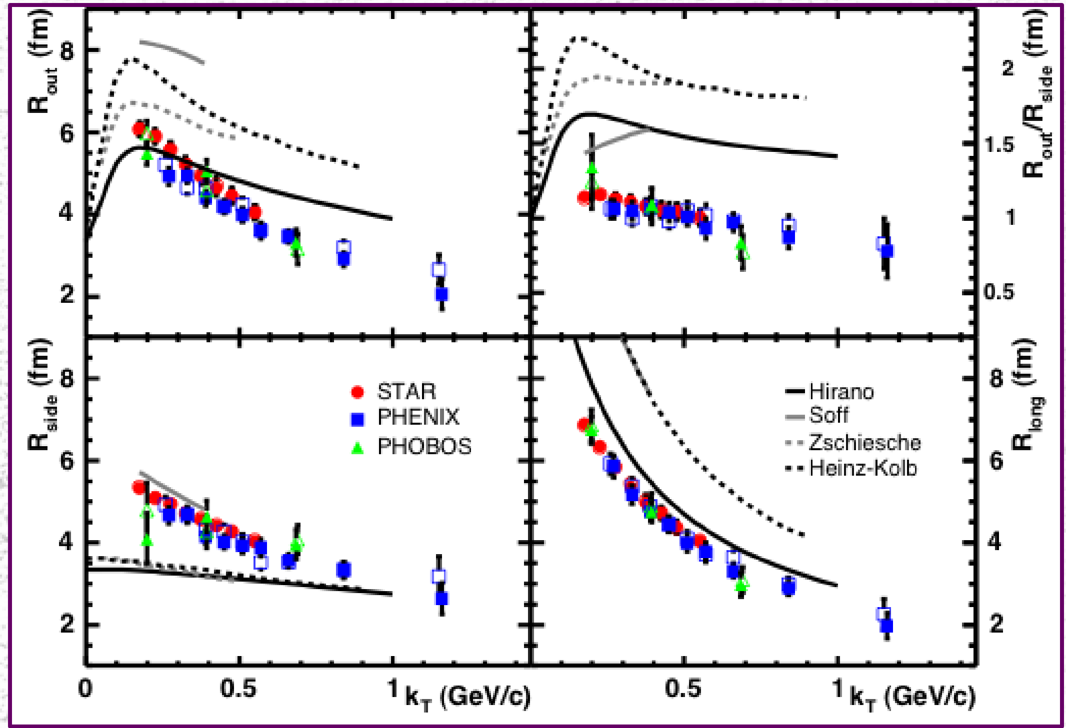

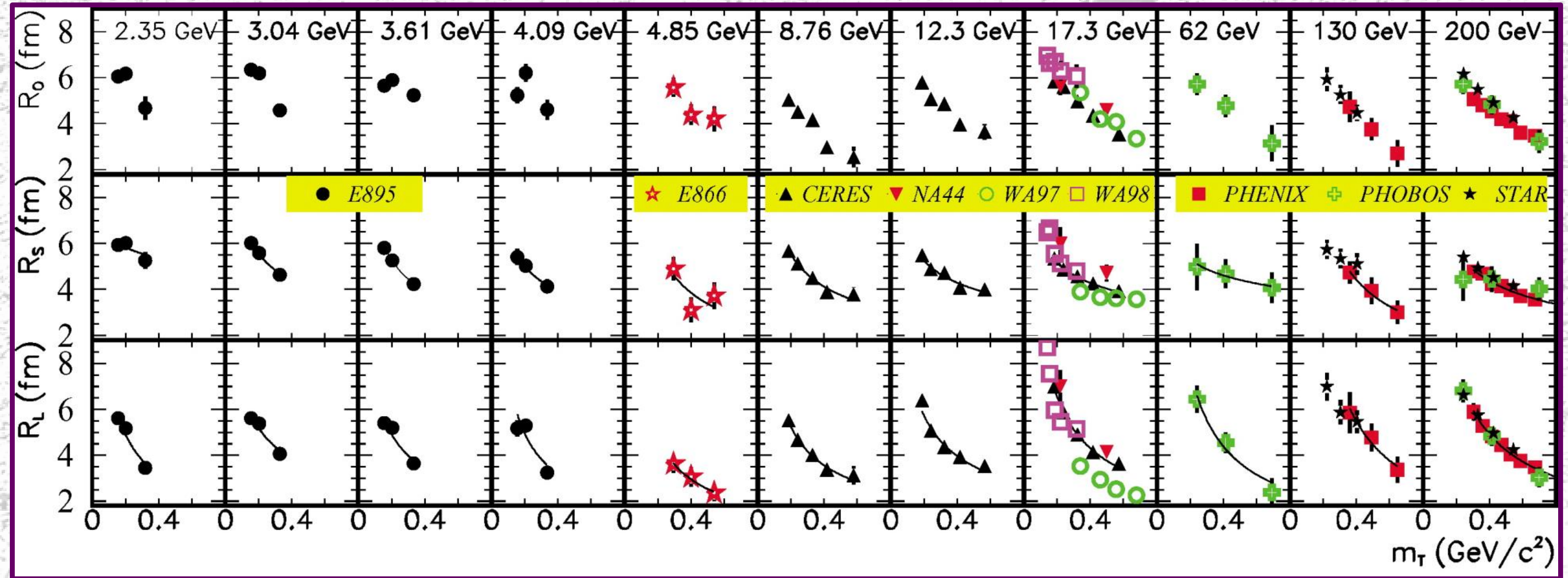

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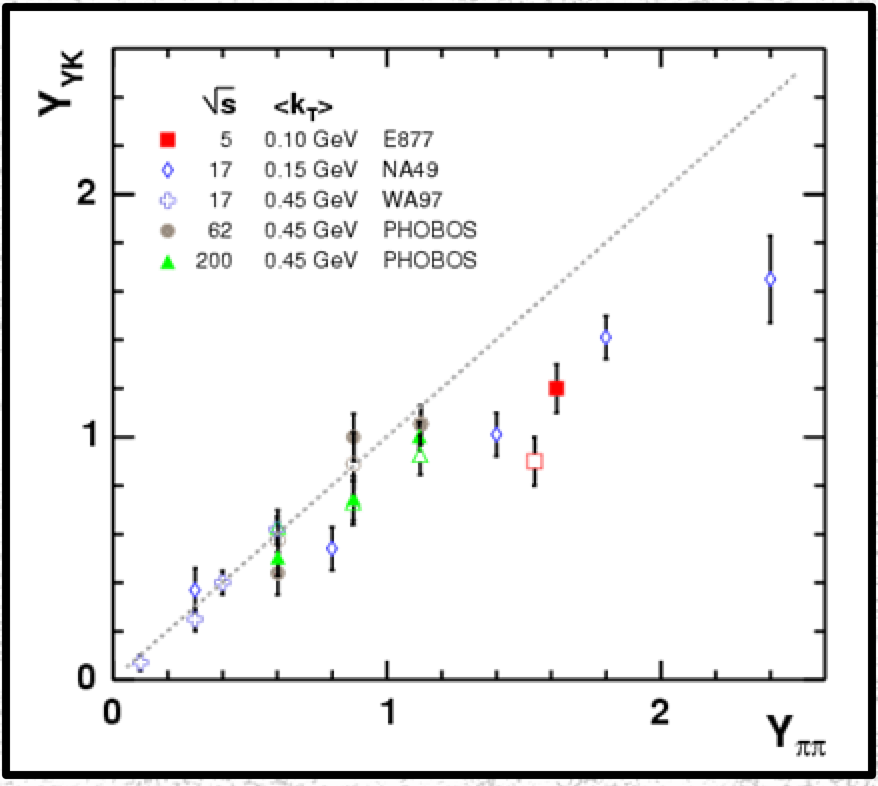

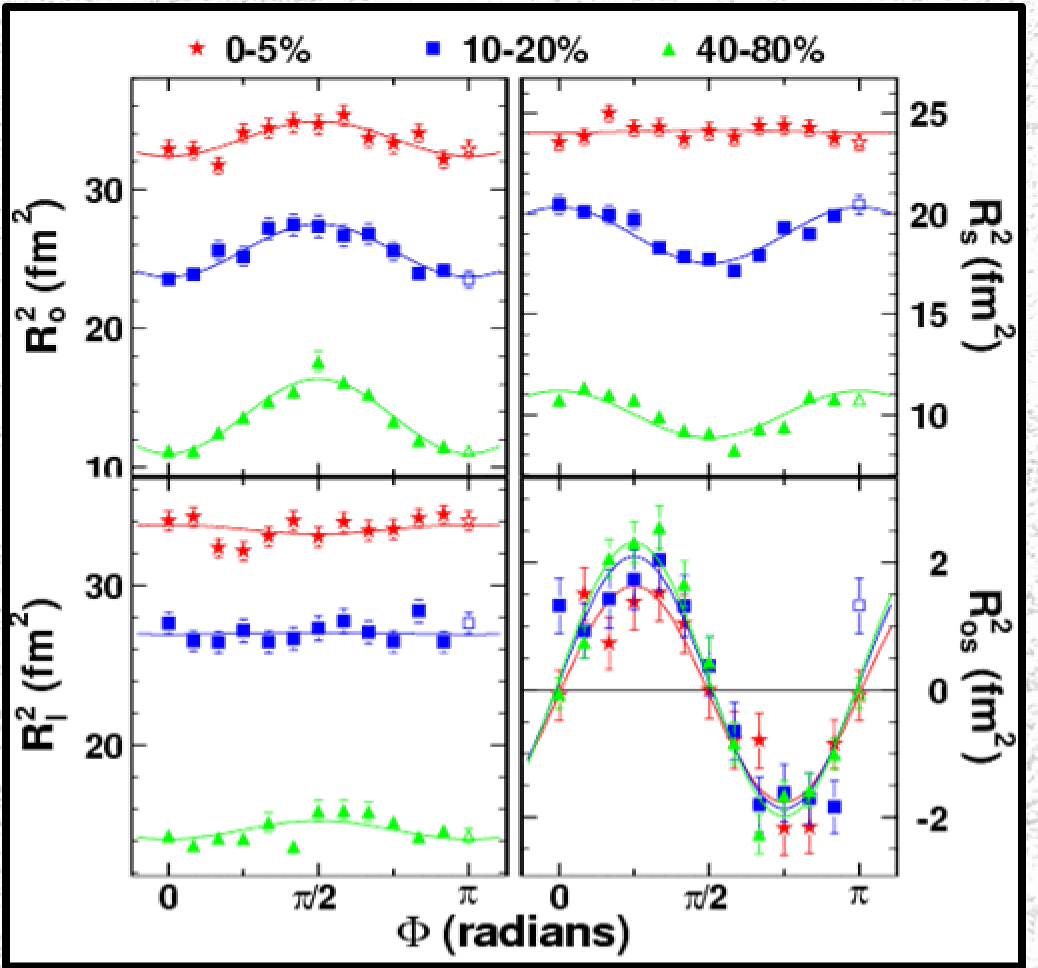

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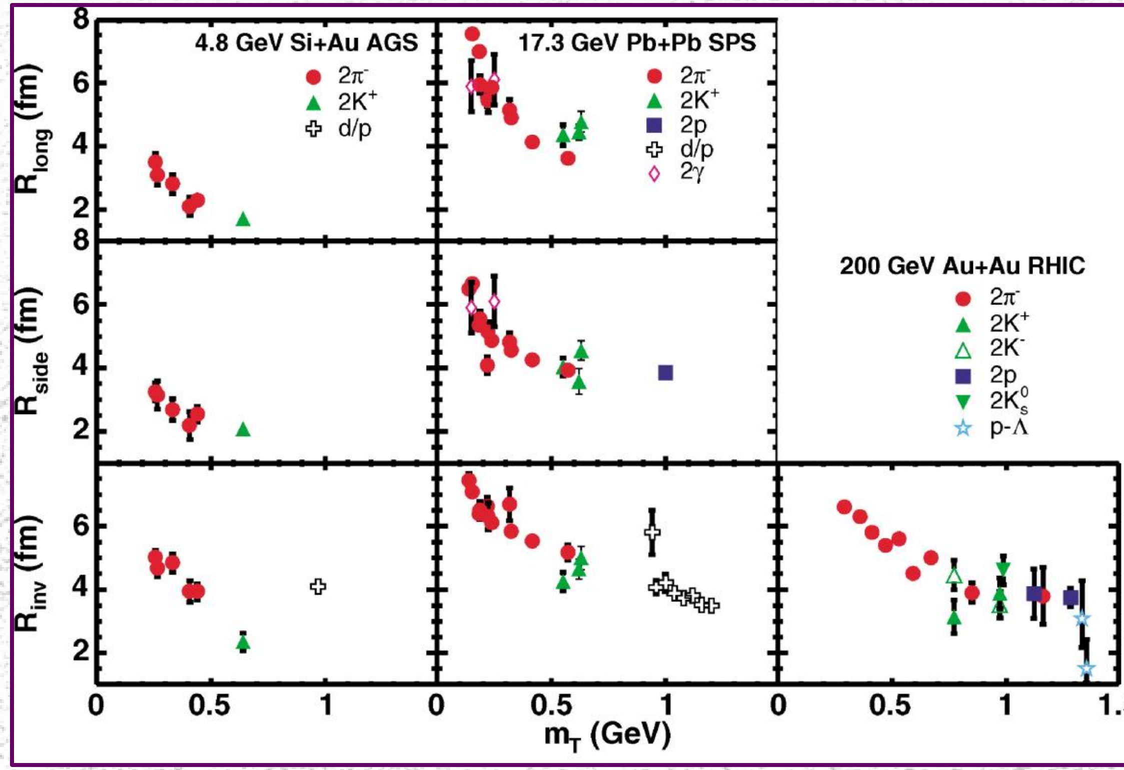

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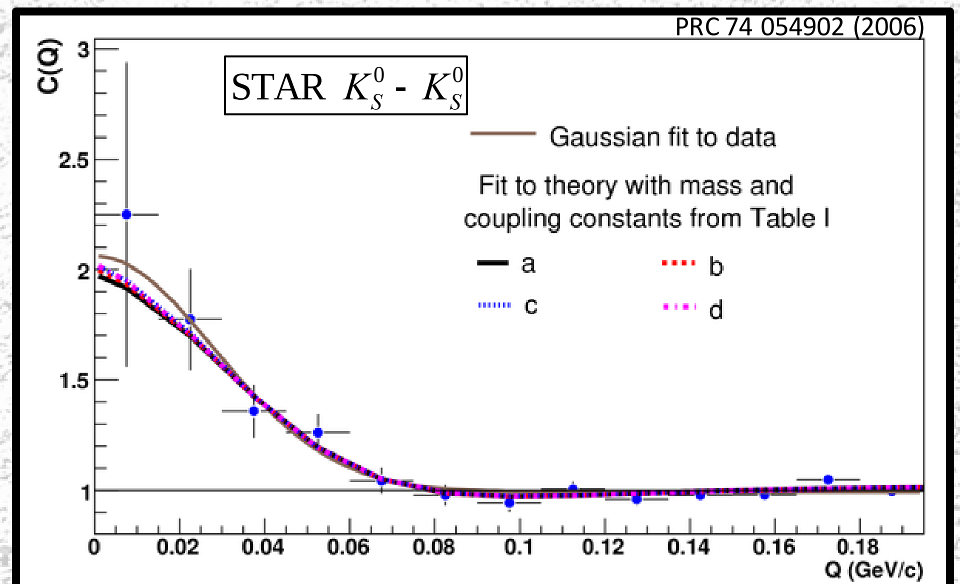
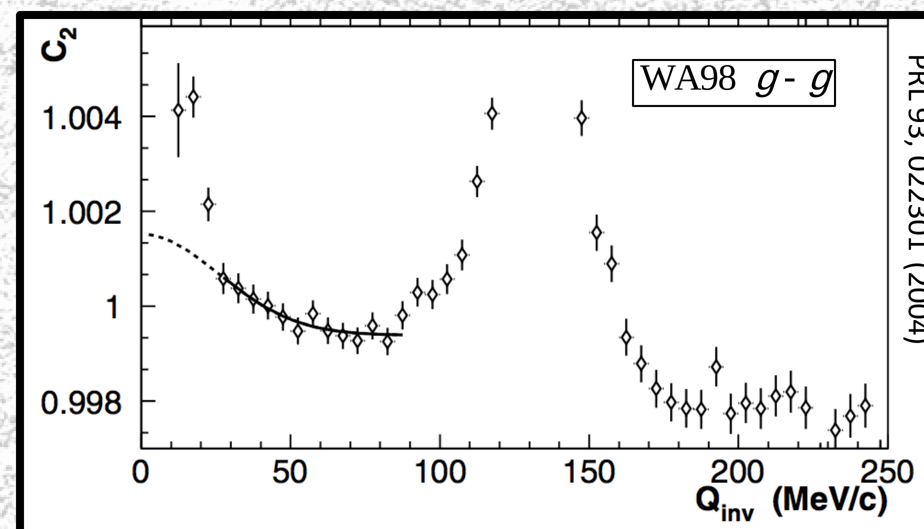
- other species
  - K^+, K^-, K^0, gamma, p, Lambda
  - nucleon coalescence





Decades 1 & 2 (Time & energy)

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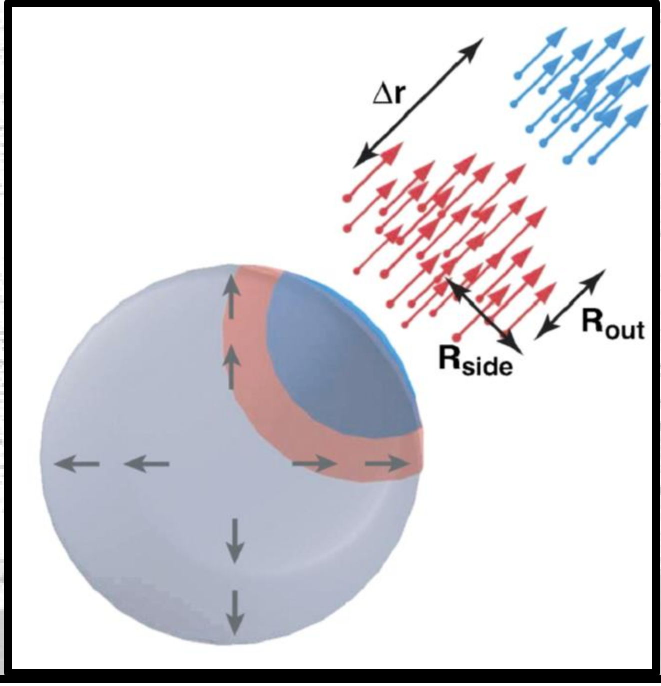
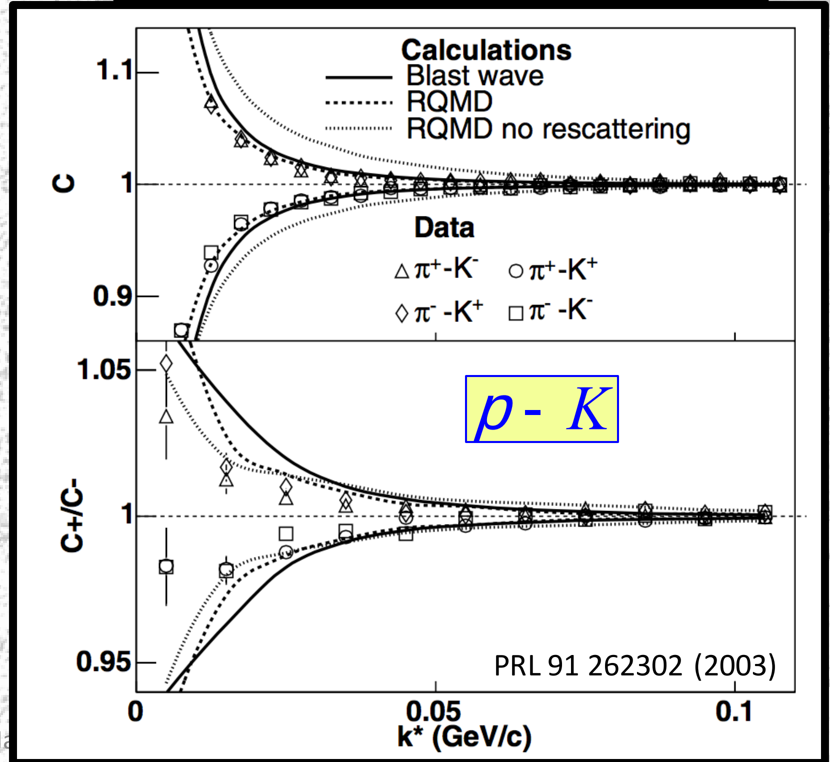
- non-id correlations
  - pi+pi-, p-Lambda, k-pi
  - (p-pi) (Xi-pi) (K-p) (p-pbar)
  - **multi-dimensional → unique information**





Decades 1 & 2
(Time & energy)

So, what did the first two decades teach us?

<u>First two decades (time & energy)</u>

- high-stats pion systematics
  - N_{ch}, p_T, ϕ, (y)
- other species
  - K^+, K^-, K^0, gamma, p, Lambda
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- non-id correlations
  - pi+pi-, p-Lambda, k-pi
  - (p-pi) (Xi-pi) (K-p) (p-pbar)
  - **multi-dimensional**
    → unique information
- extracting interaction parameters
- Source Imaging
- 3-pion correlations: chaoticity

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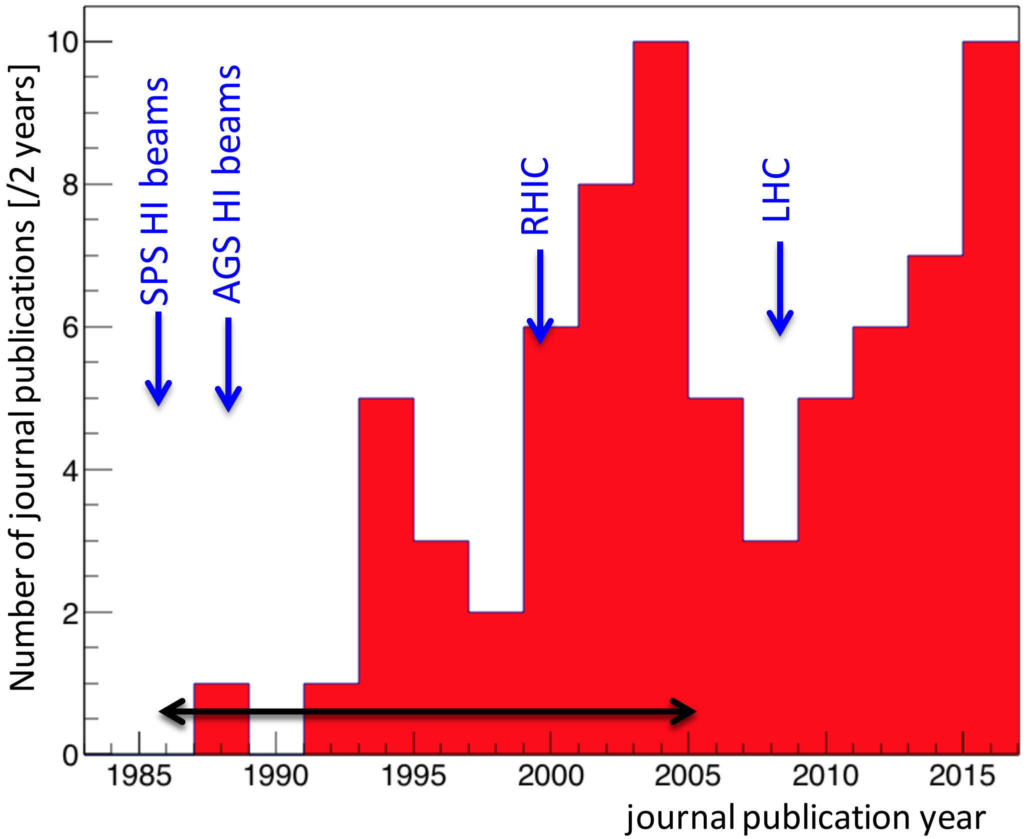
FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress

MAL, S. Pratt, R. Soltz, U. Wiedemann

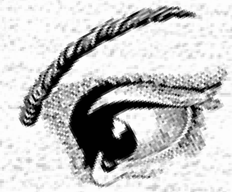
Experimental femtoscopy journal publications



The big items

- The “system” *is* a system.
- There is massive explosive radial flow, in all HI collisions
- The spatial **sub**structure of the flow is hydro-like
- There is not a large latent heat (not strongly first-order) @ top RHIC
- pre-equilibrium flow...
- The source at midrapidity is approximately boost invariant

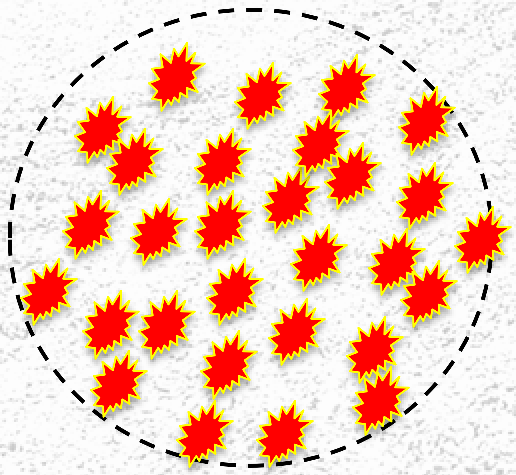
How we know what we “know”



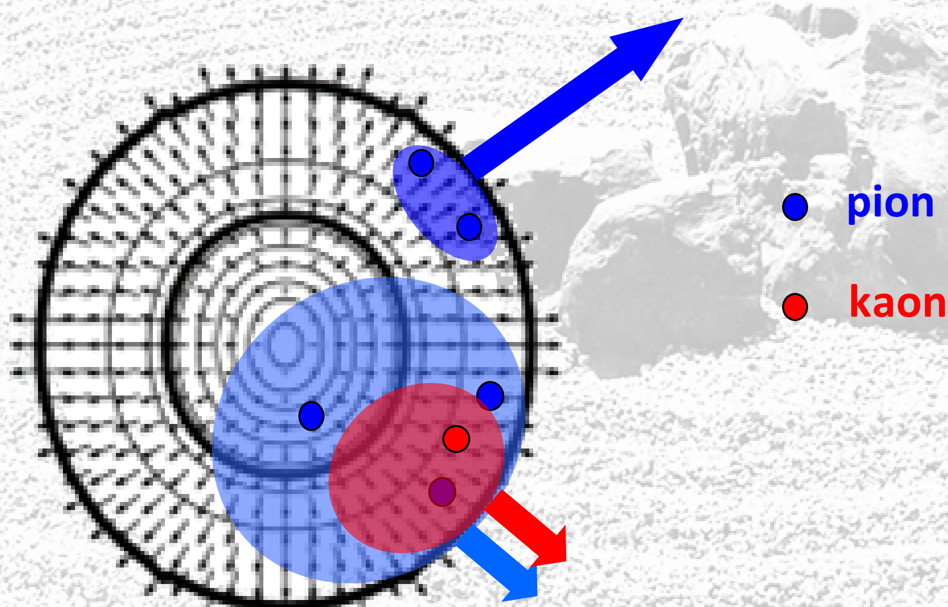
HI collisions create a “collective system of self-interacting matter”

How do we know that a central collision* creates a collective system?

- thermo-chemical fits? p_T spectra?



A collection of nearby, independent p+p collisions. **Not “matter”**



Matter is characterized by fields of bulk properties

* citing v_n systematics from an incompletely understood lumpy initial state, requiring very rapid thermalization via unclear mechanisms, is not compelling, if we cannot understand the zeroth order effects of simpler central collisions.

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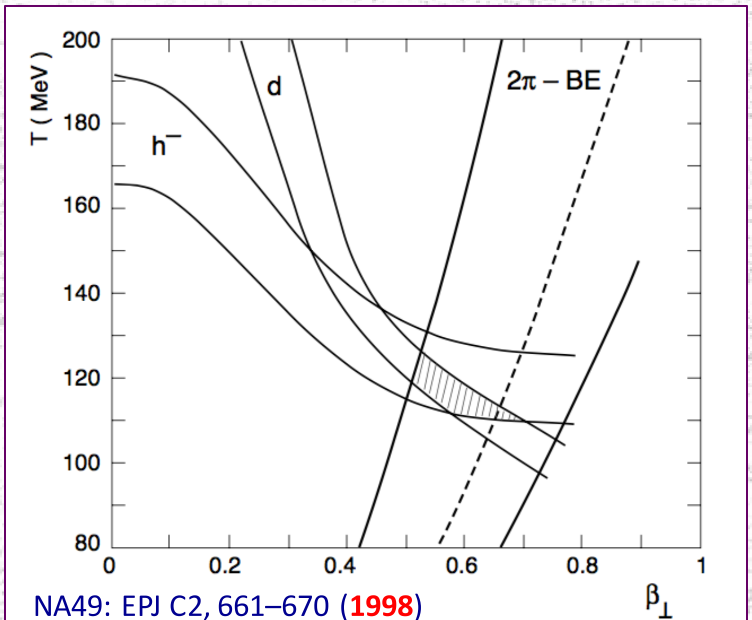
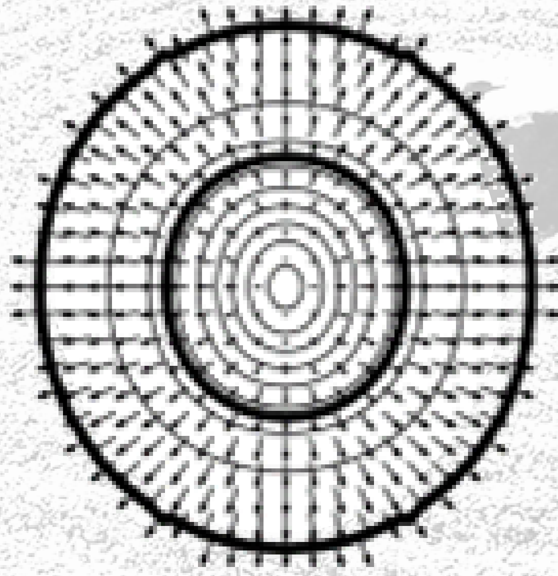
Constraining **freezeout configuration**



NA49: EPJ C2, 661–670 (**1998**)

c.f. all Blast-wave incarnations



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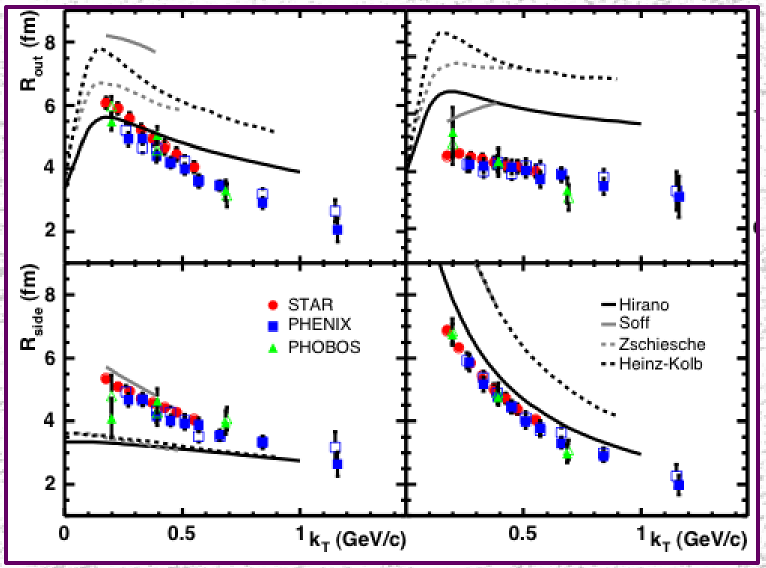
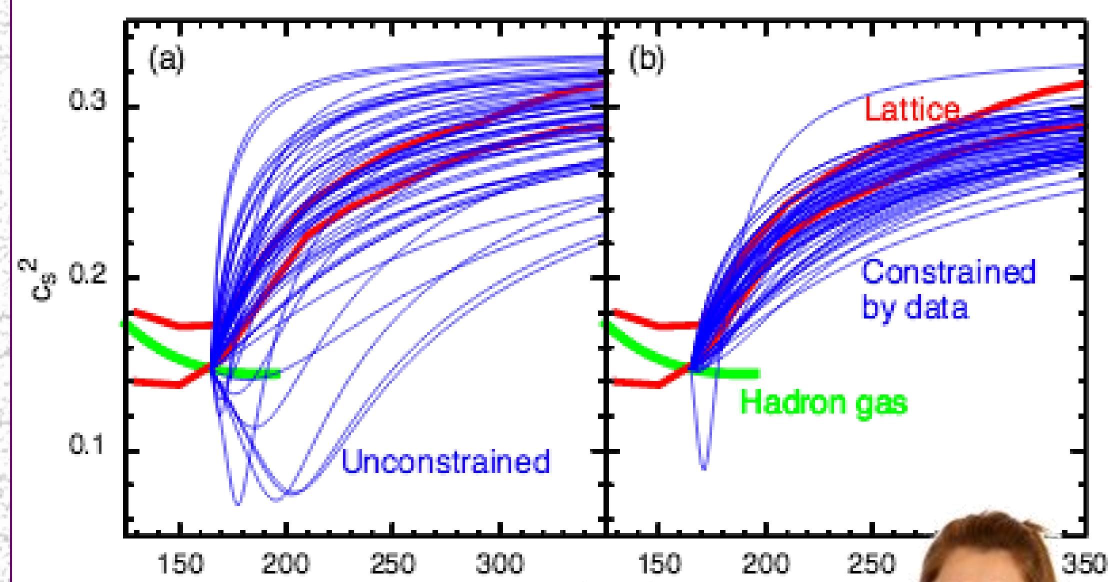
Constraining **hydro/transport**



Constraining **Equation of State**
femtoscopy the most constraining data



Pratt et al, 2015

confronting models with data

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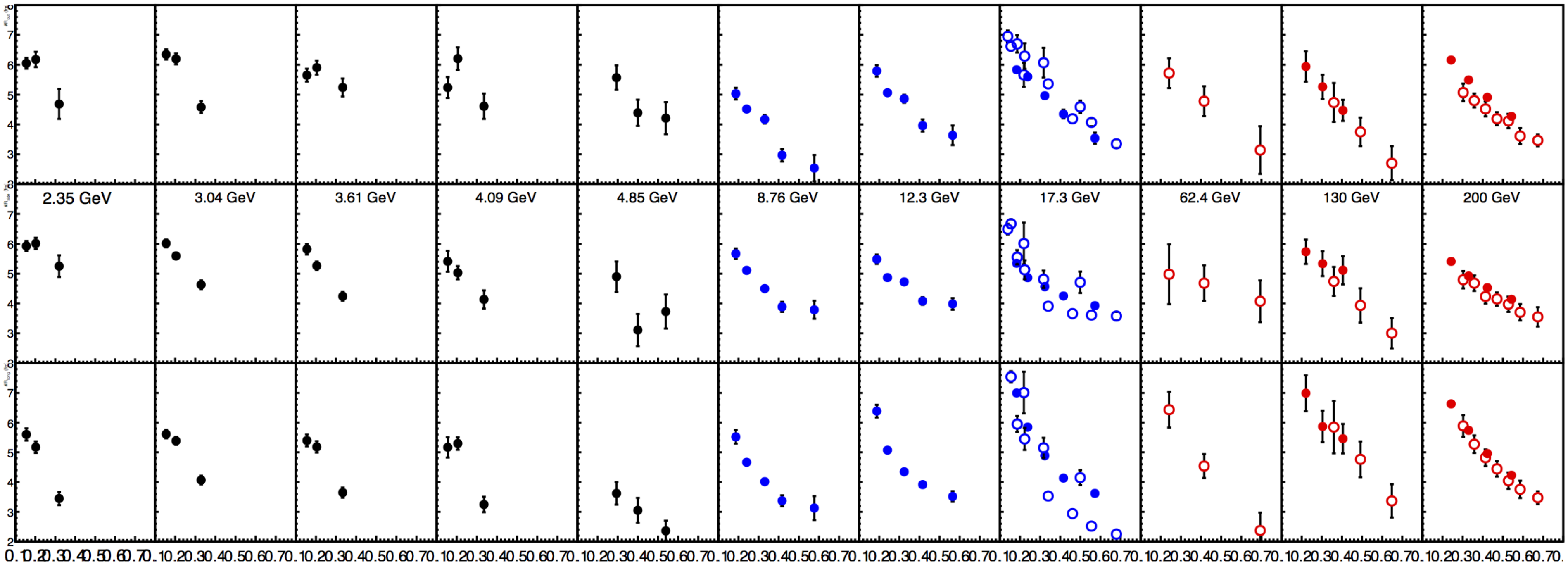
Decade 3

1985-2005 : dynamic range in root(s) = 10^2



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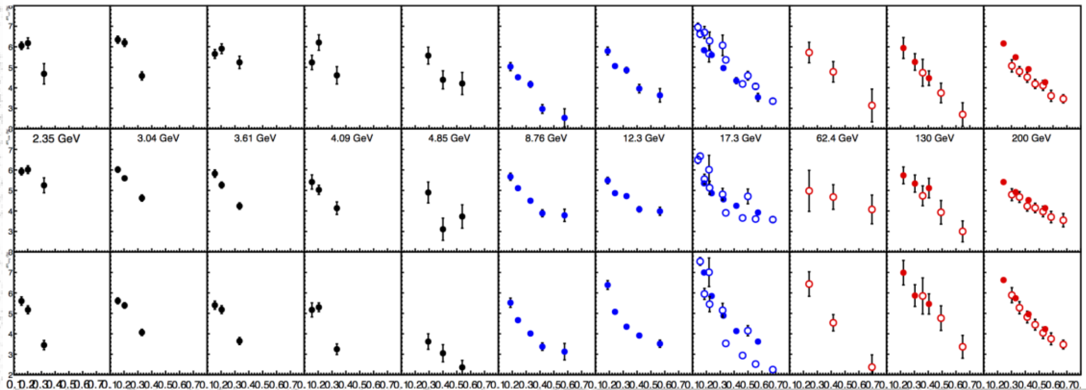
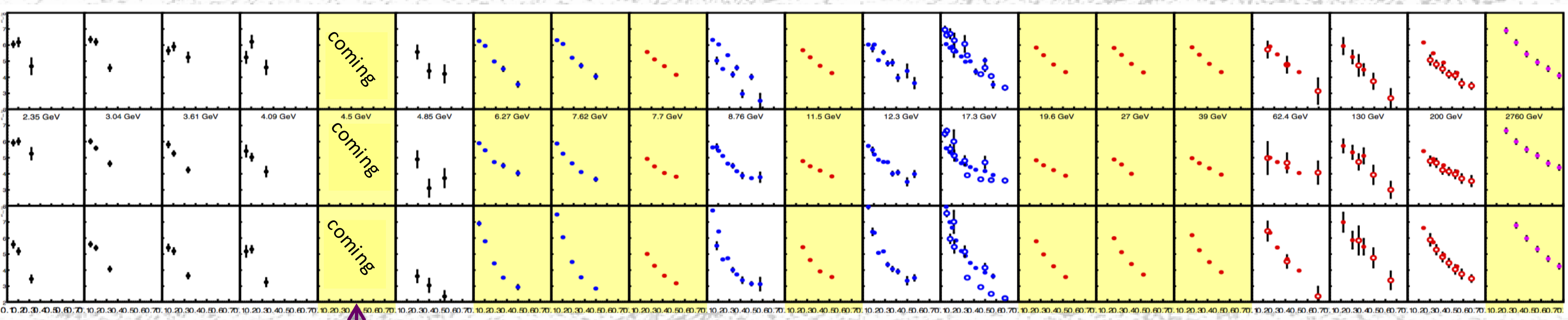


1985-2015 : dynamic range in root(s) = 10^3



STAR
Fixed Target

NA49 Scan

RHIC BES

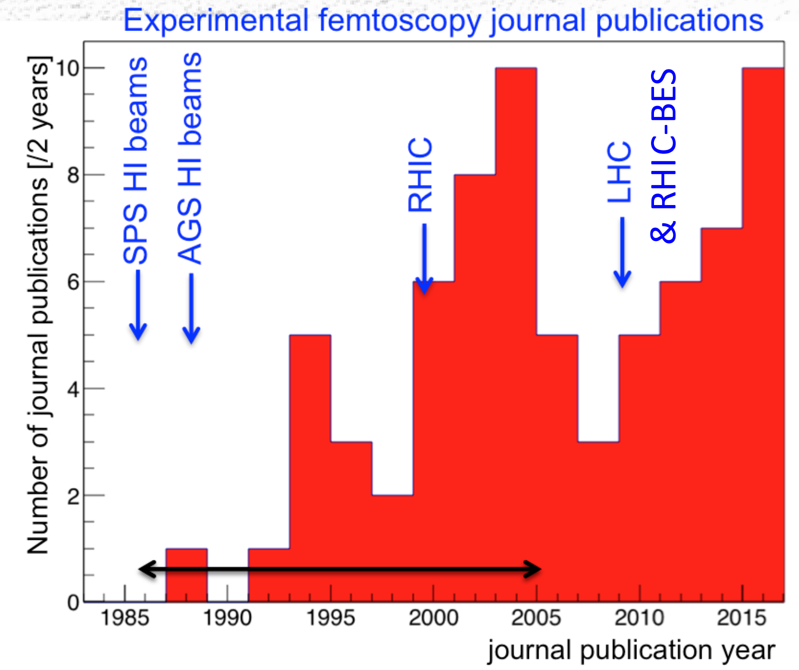
ALICE

Decade 3

- 43% (31/72) of papers published after 2006

	SPS	RHIC	LHC
A+A	4	10	6
p+p		1	9
p(d)+A		1	2

- Tech advances: residual correlations, SHD – no time ☹
- New species combinations
- N>2 correlations
- **Important new systematics**
- **focus on pp "a la HIC"**



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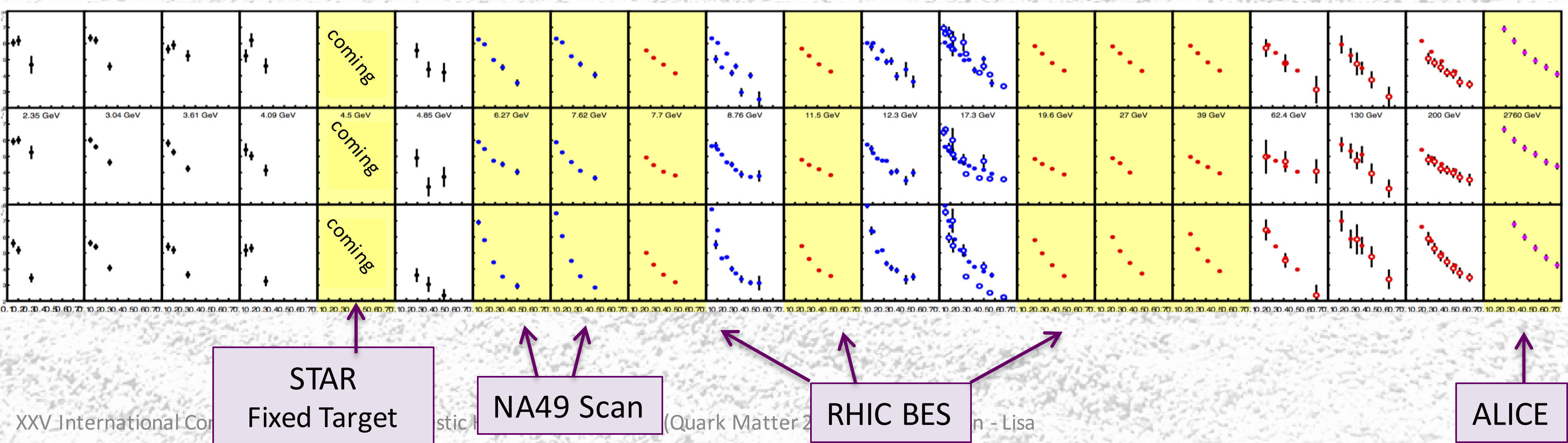
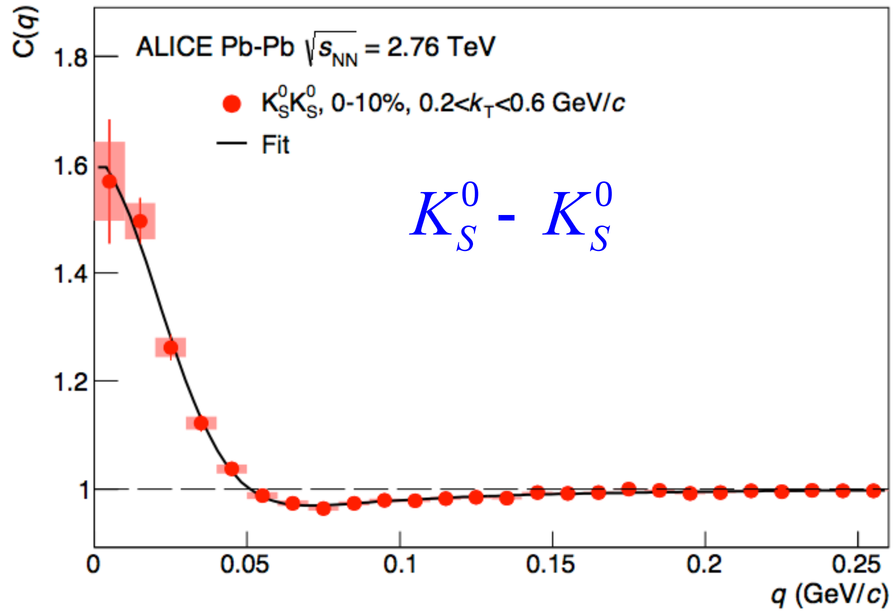
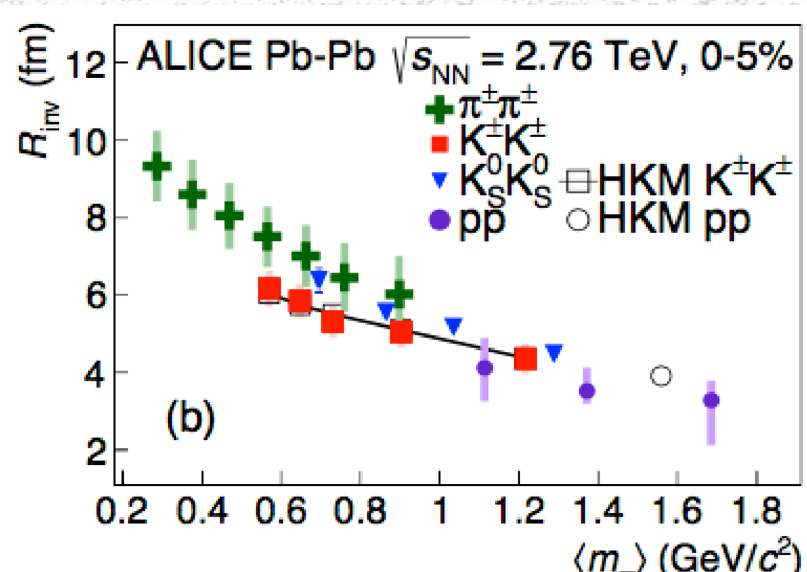


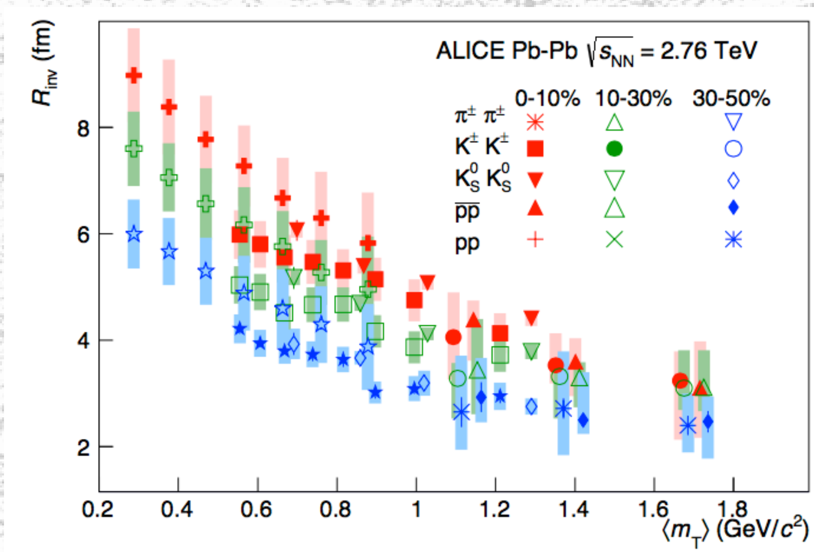
New species combos (& issues)

$$LHC: \pi^{\pm}-\pi^{\pm}, K^{\pm}-K^{\pm}, K_S^0-K_S^0, p-p, \bar{p}-\bar{p}$$



ALICE arxiv 1506.07884 (2015)





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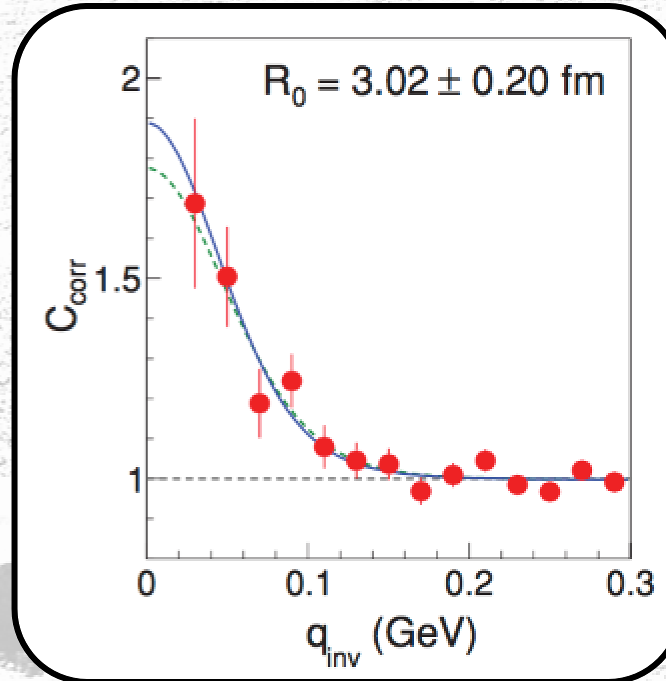
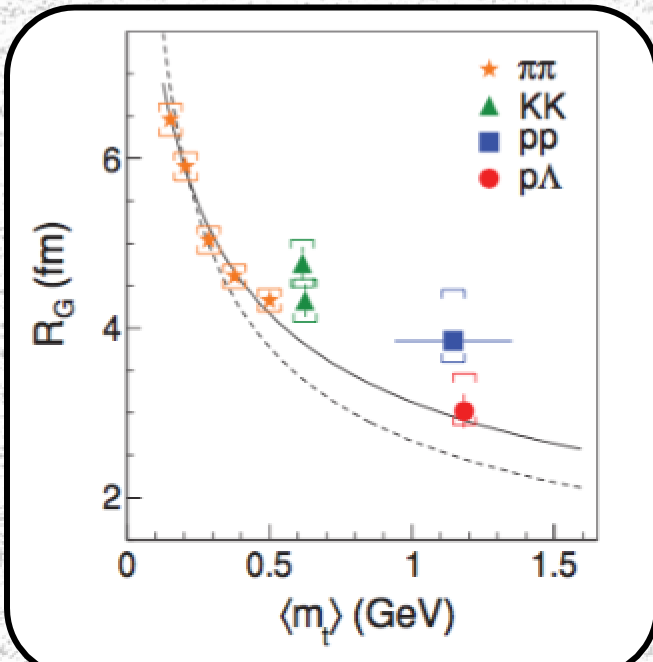
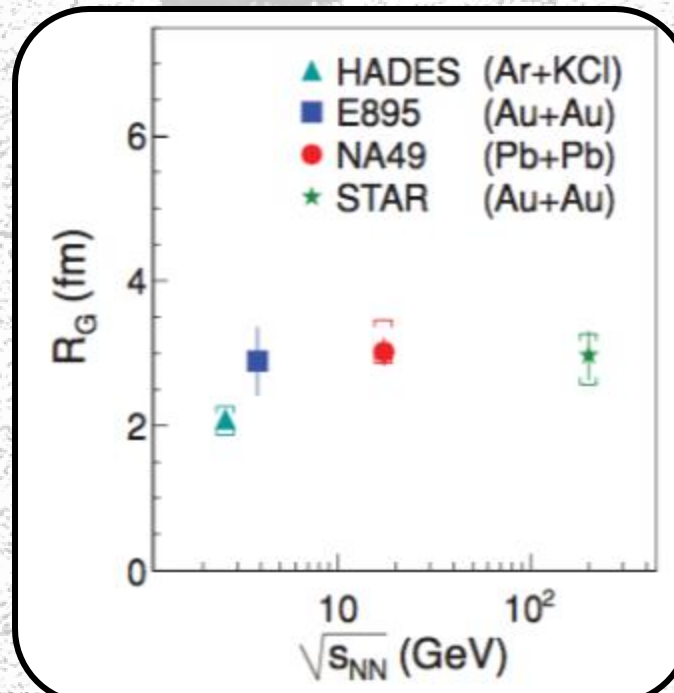


NA49 PRC 2011





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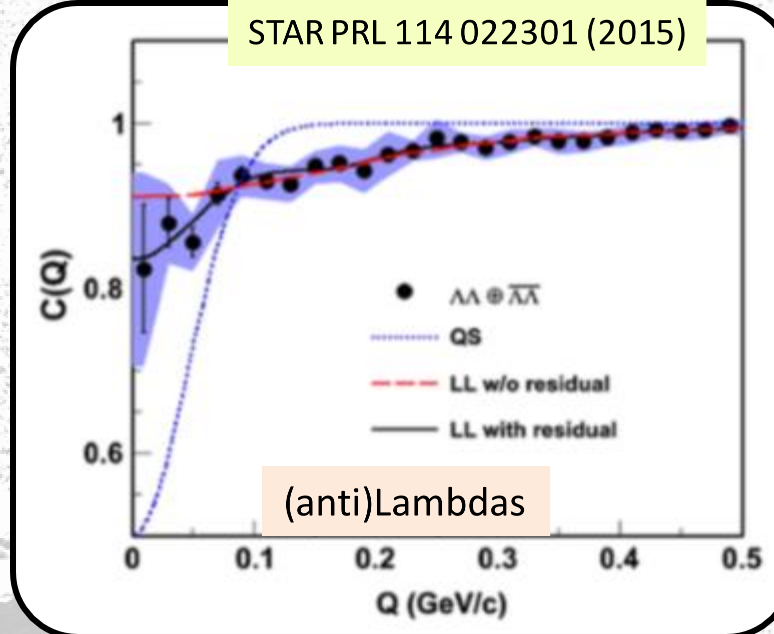
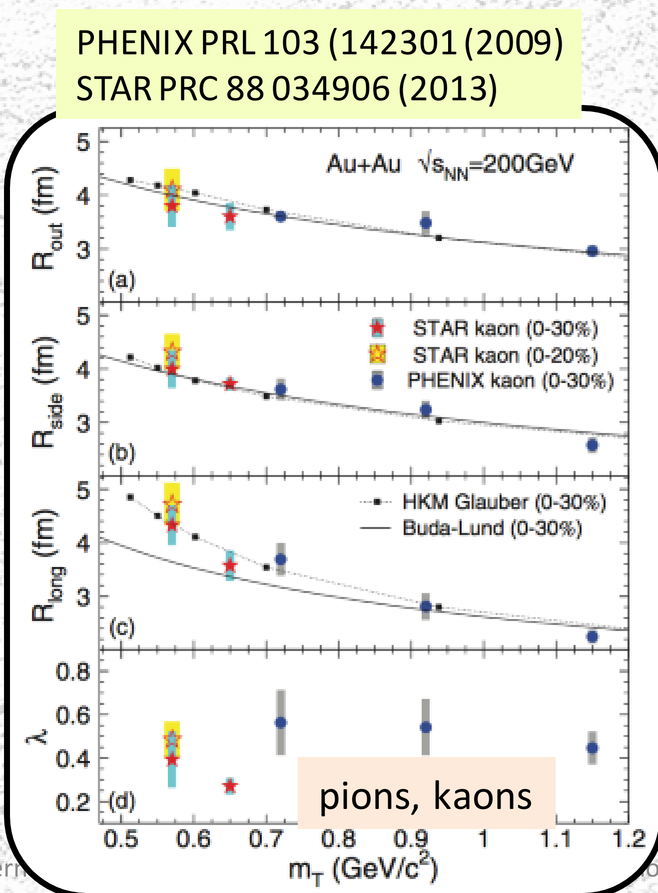
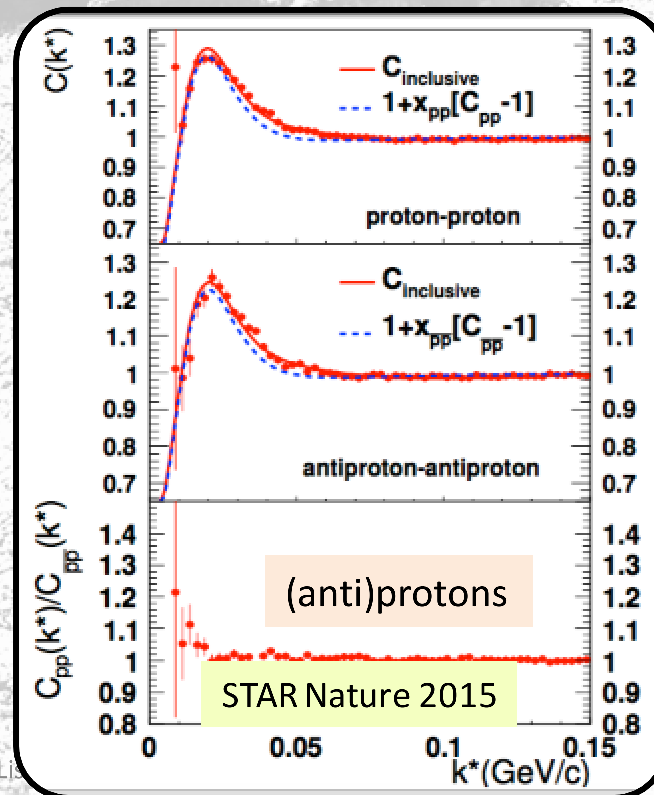
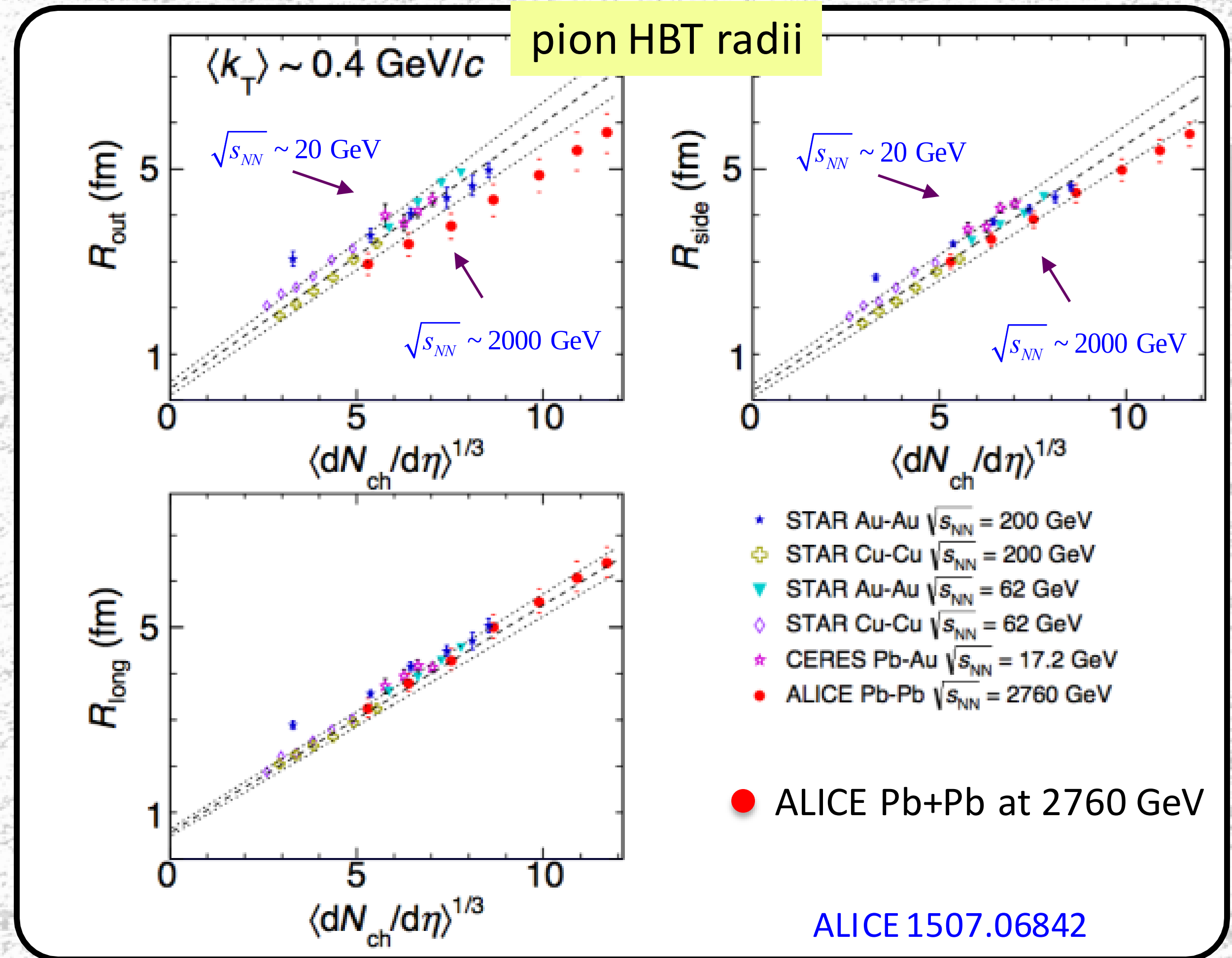






Decade 3 broad message

- New energies/species/techniques, higher statistics → reinforce earlier systematics
  - space and time scale ~ multiplicity$^{1/3}$



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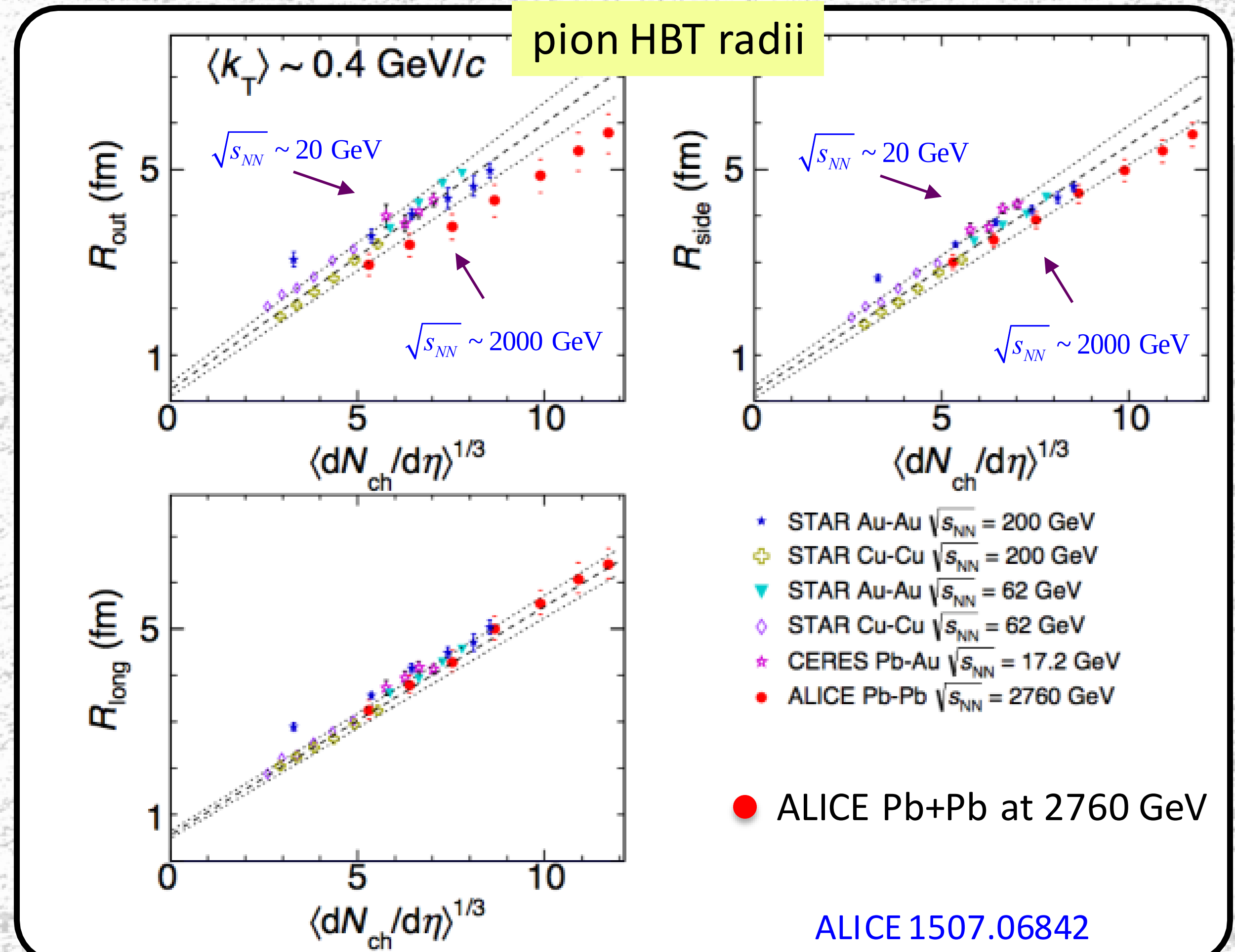
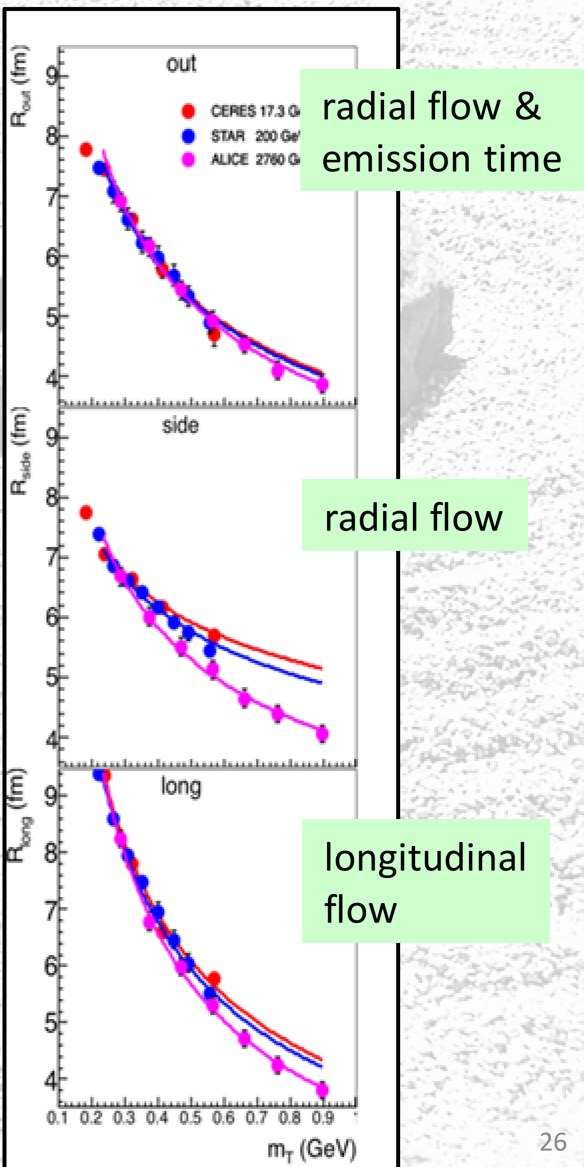
  - flow-induced falloff in m_T .
    - larger at LHC





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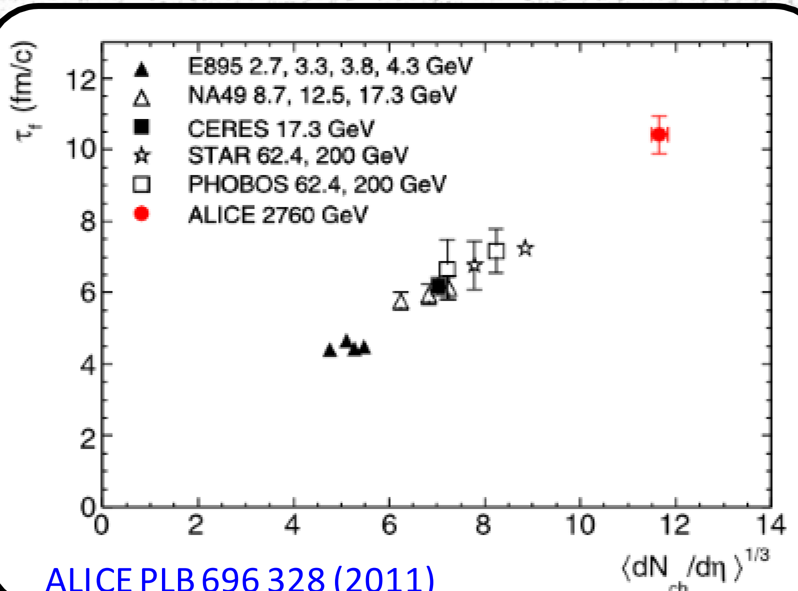
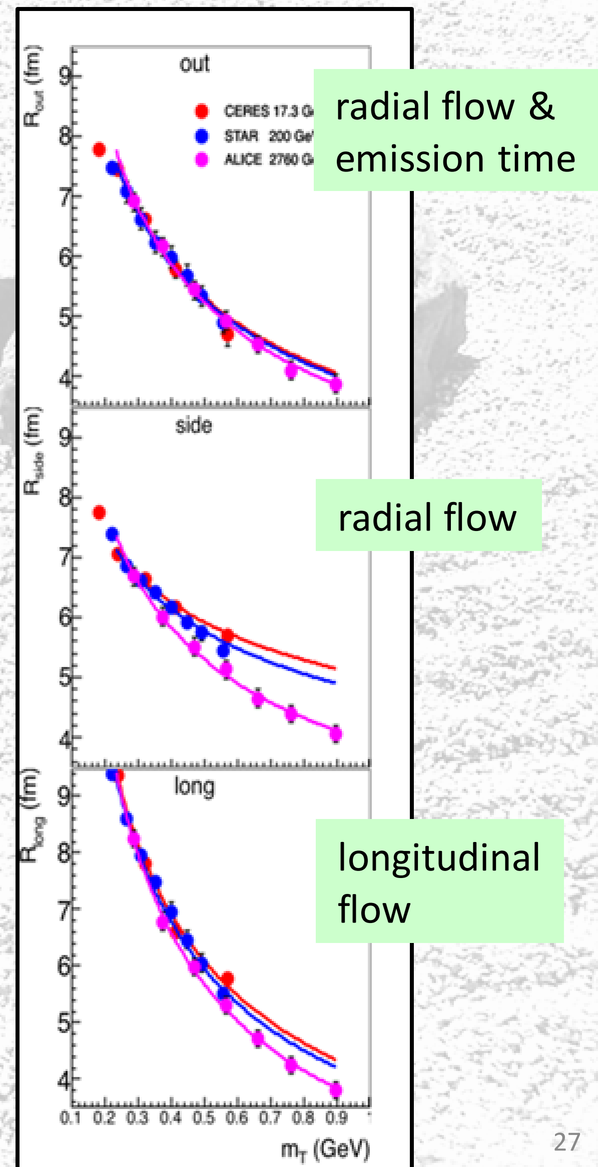
  - no sudden jumps in timescales (based on R_L and asHBT)

$$R_l^2 \approx \tau_0^2 \frac{T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}$$



ALICE PLB 696 328 (2011)



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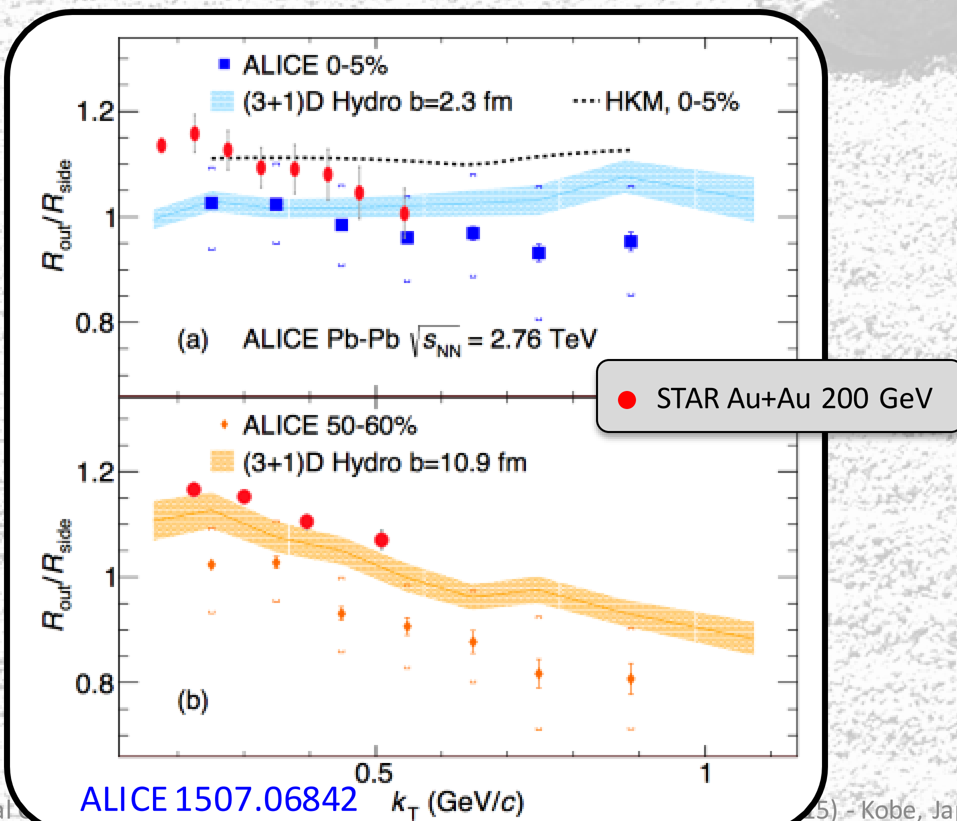
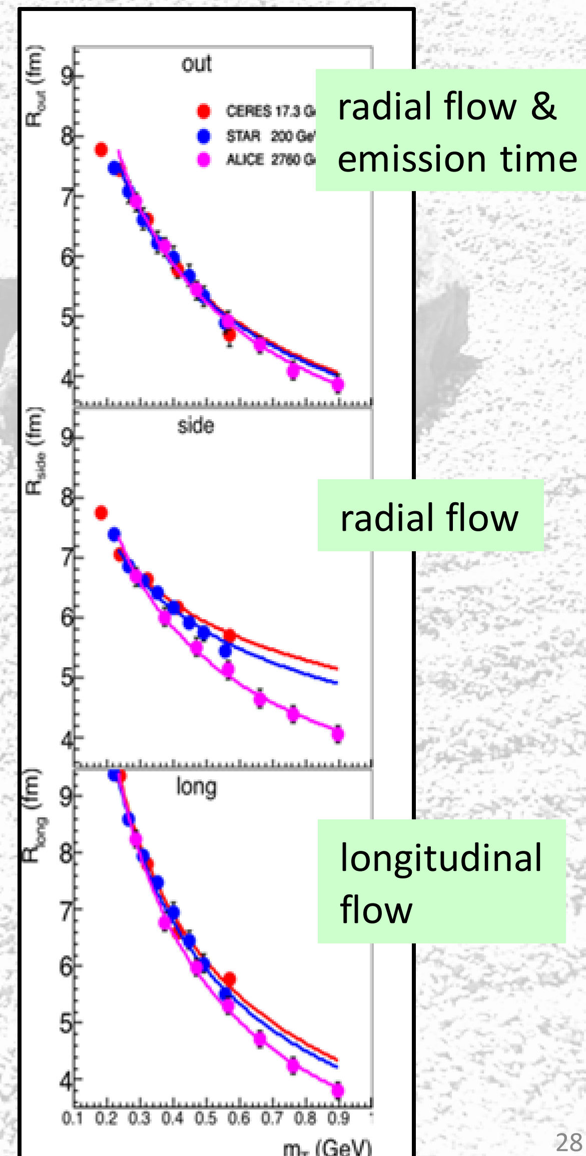
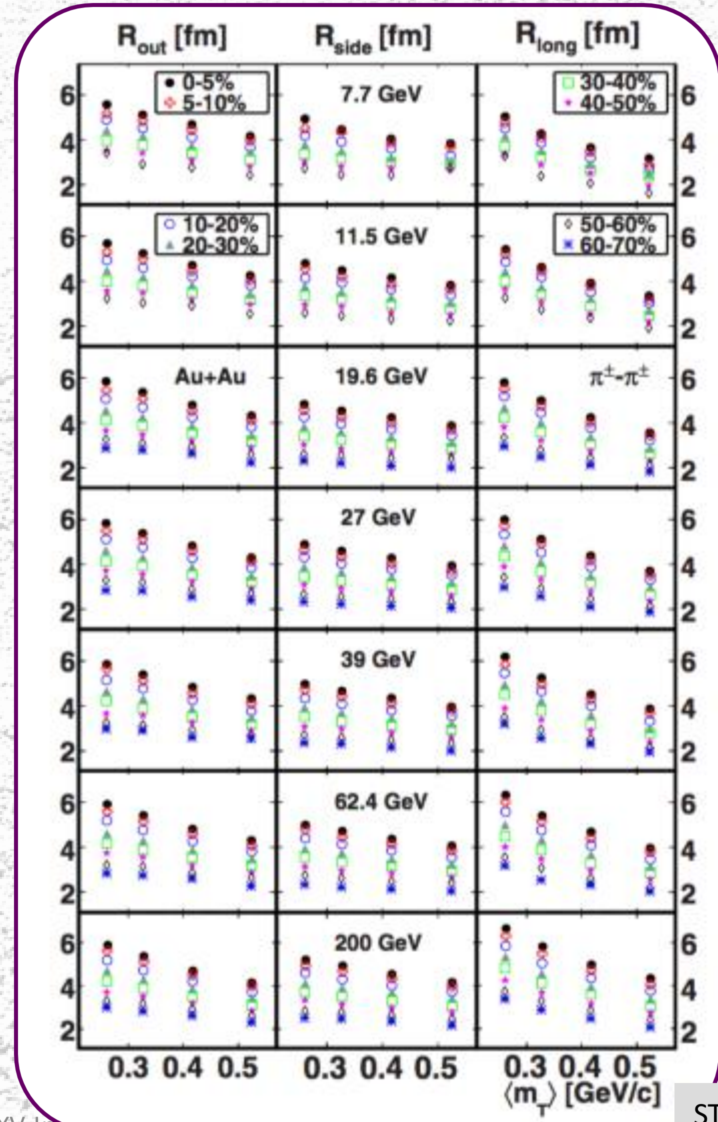
  - space and time scale ~ multiplicity$^{1/3}$
  - flow-induced falloff in m_T
    - larger at LHC
  - no sudden jumps in timescales (based on R_L and asHBT)
    - but sometimes important effects are small
    - ideally, study with *common* systematics

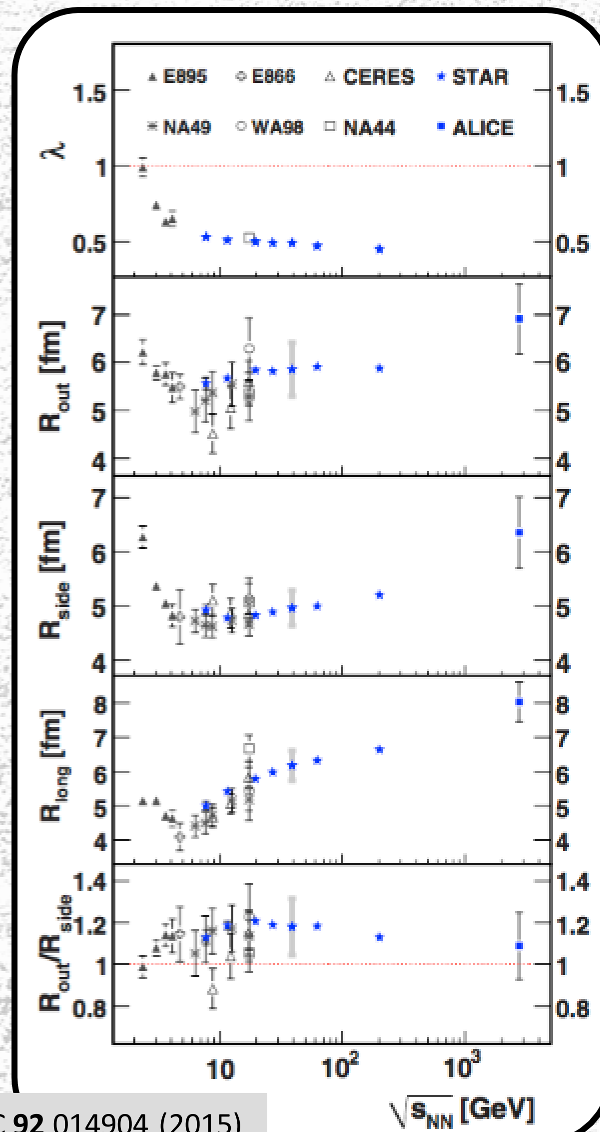




Systematic studies with ONE detector

- NA49, CERES, STAR: scans with common techniques, detectors
  - STAR: **broad** scan and fixed **acceptance**





STAR, PRC **92** 014904 (2015)

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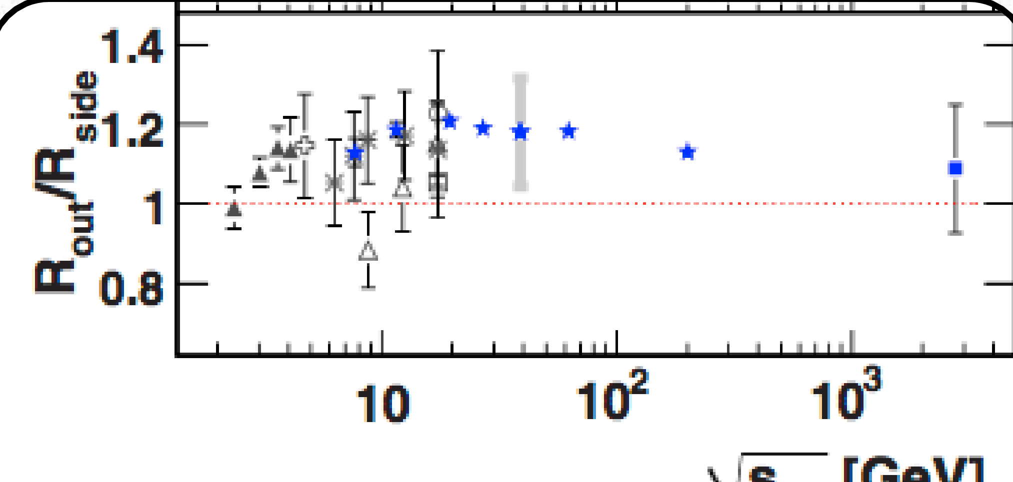

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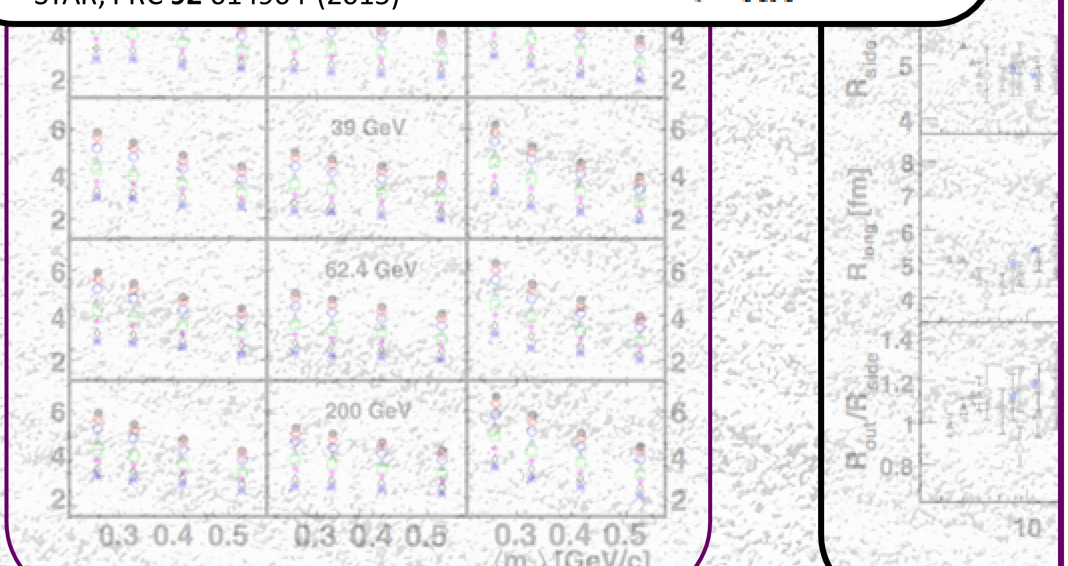
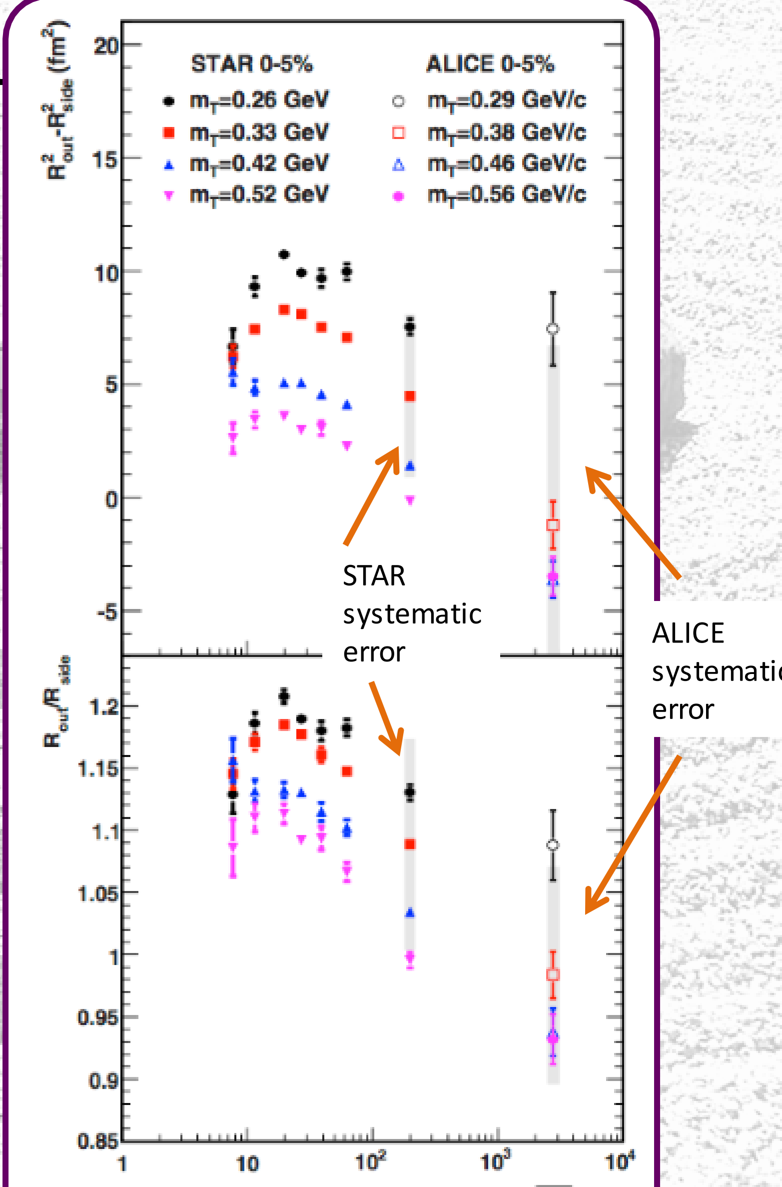


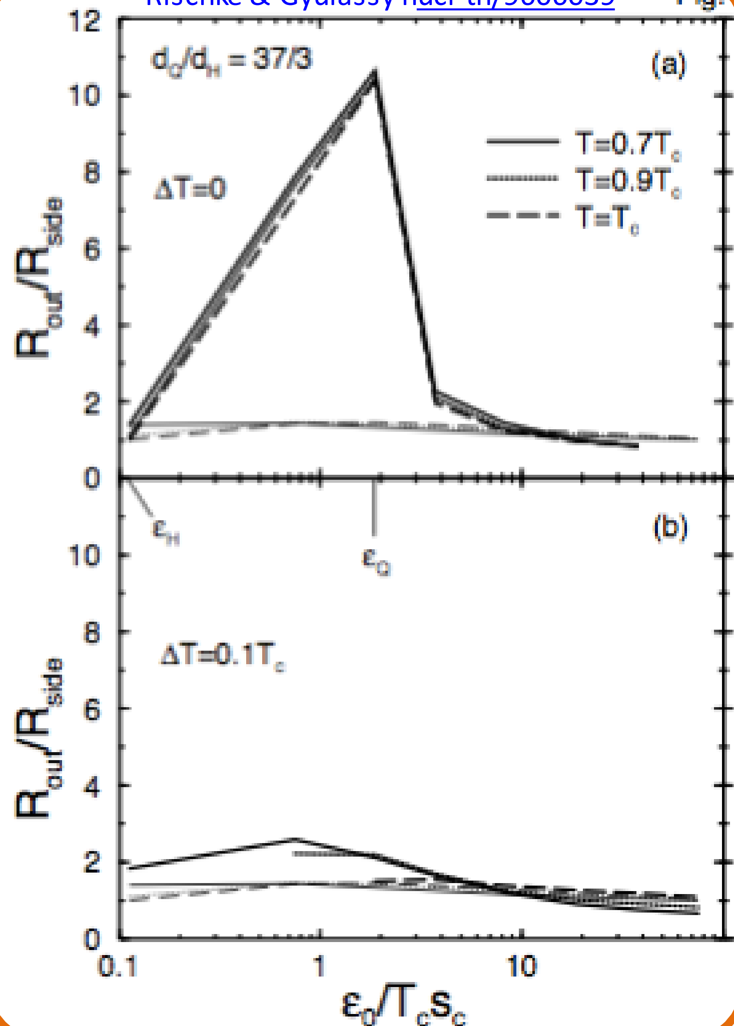


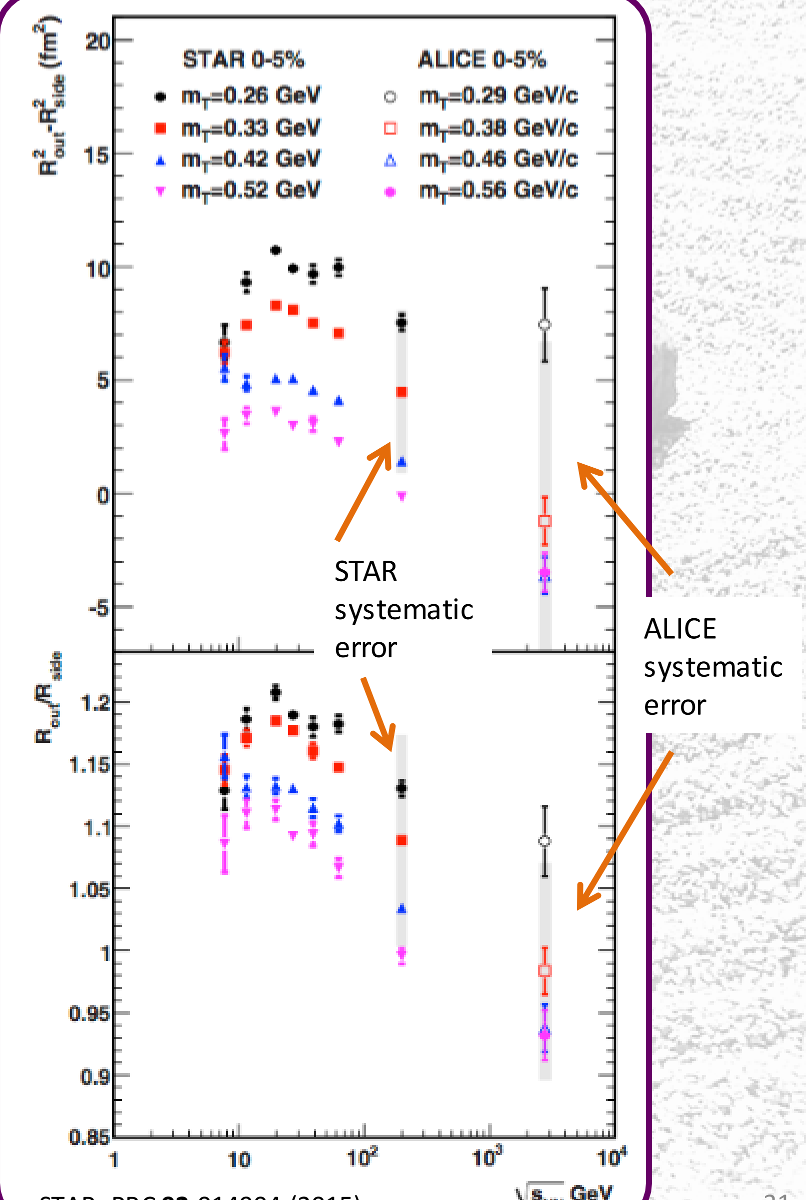
STAR, PRC **92** 014904 (2015)

Systematic studies with fixed acceptance

- The signal of latent heat, promised as a “sure thing” to be shown at QM 2001
  - **only 14.5 years late!**
  - more subtle than hoped
  - revealed only in detailed *scan*.

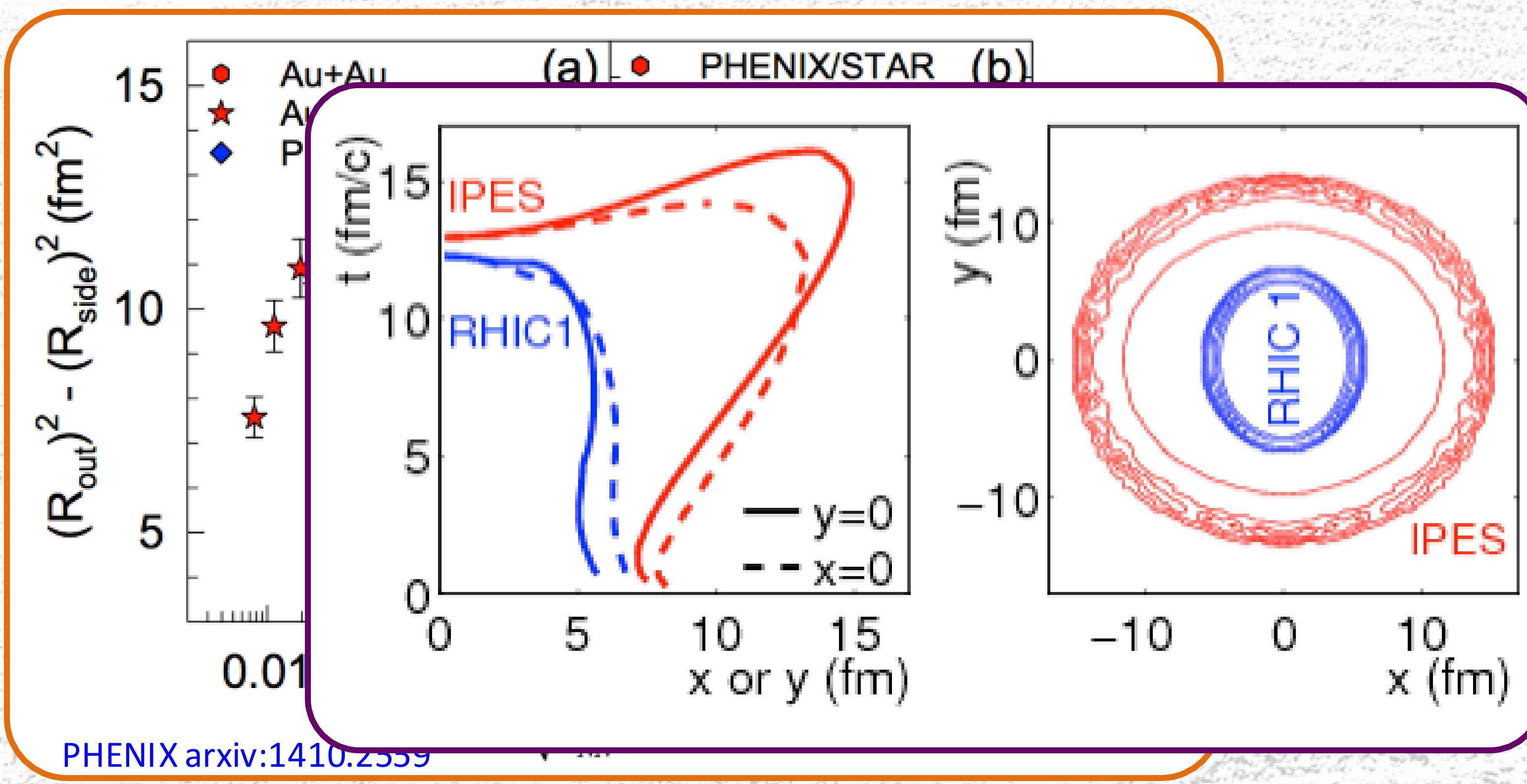
Rischke & Gyulassy nucl-th/9606039 Fig.

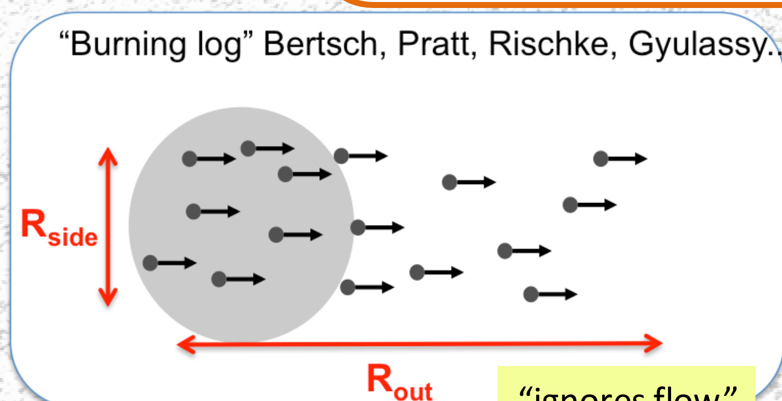




STAR, PRC **92** 014904 (2015)

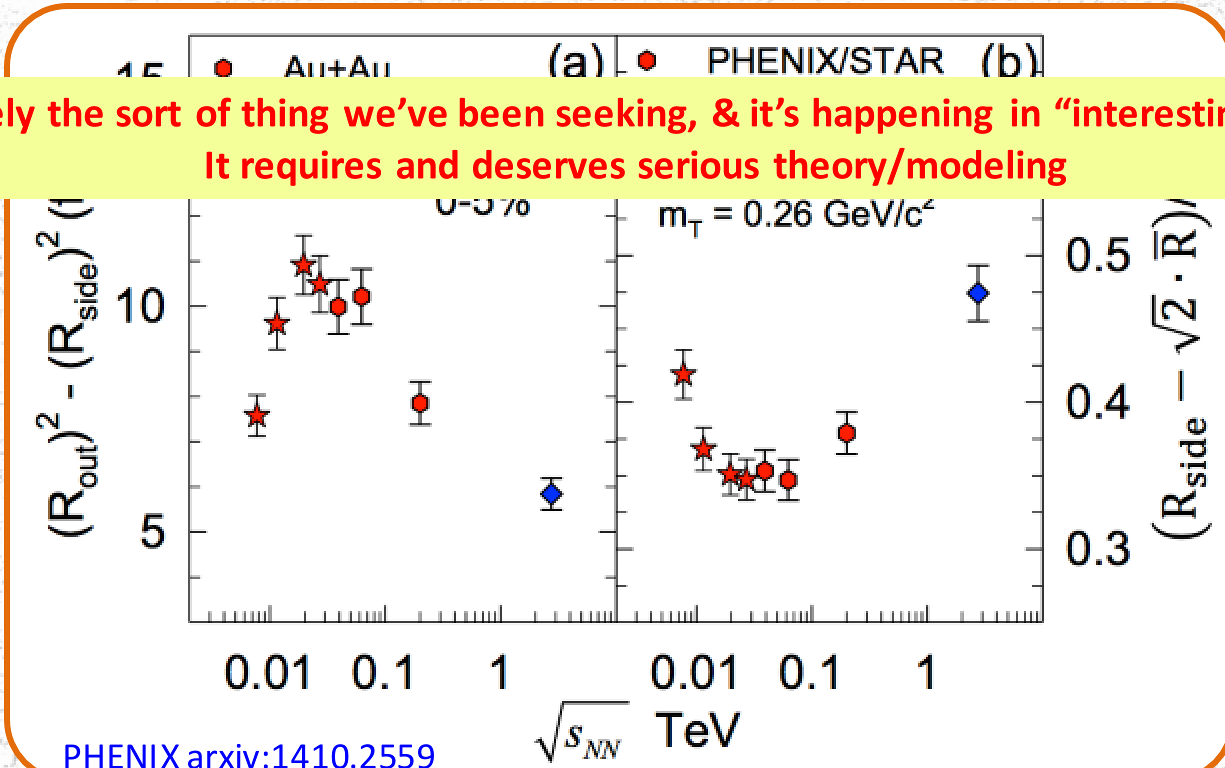
Elaborations...





$$R_o^2 - R_s^2 = \beta_\perp^2 \langle \tilde{t}^2 \rangle - 2\beta_\perp \langle \tilde{x}\tilde{t} \rangle$$

Elaborations...

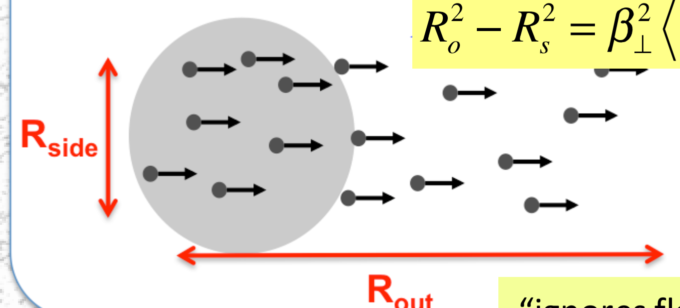


This is precisely the sort of thing we've been seeking, & it's happening in "interesting" BES energies. It requires and deserves serious theory/modeling

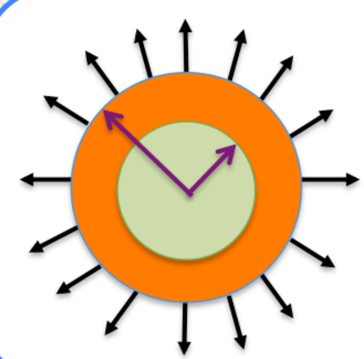
PHENIX arxiv:1410.2559

"Burning log" Bertsch, Pratt, Rischke, Gyulassy...

$$R_o^2 - R_s^2 = \beta_\perp^2 \langle \tilde{t}^2 \rangle - 2\beta_\perp \langle \tilde{x}\tilde{t} \rangle$$



"ignores flow"



$$\frac{R_s - \sqrt{2}\bar{R}_{\text{Glauber}}}{R_l}$$

$$\text{"}\sim\text{"} \quad \frac{R_{\text{final}} - R_{\text{initial}}}{c\tau_{\text{evolution}}}$$

$$\text{"}\sim\text{"} \quad \frac{v_{\text{expansion}}}{c}$$

Softening? Critical point??

More than just (!) softening? – finite size scaling

- at CP, susceptibilities diverge for *infinite* system
  - delta function
- for *finite* system (generic)
  - no divergence, just peaking
  - shifted peak position
  - broadened peaks

specifically:

height: $c_T^{\max}(V) \sim L^{g/n}$

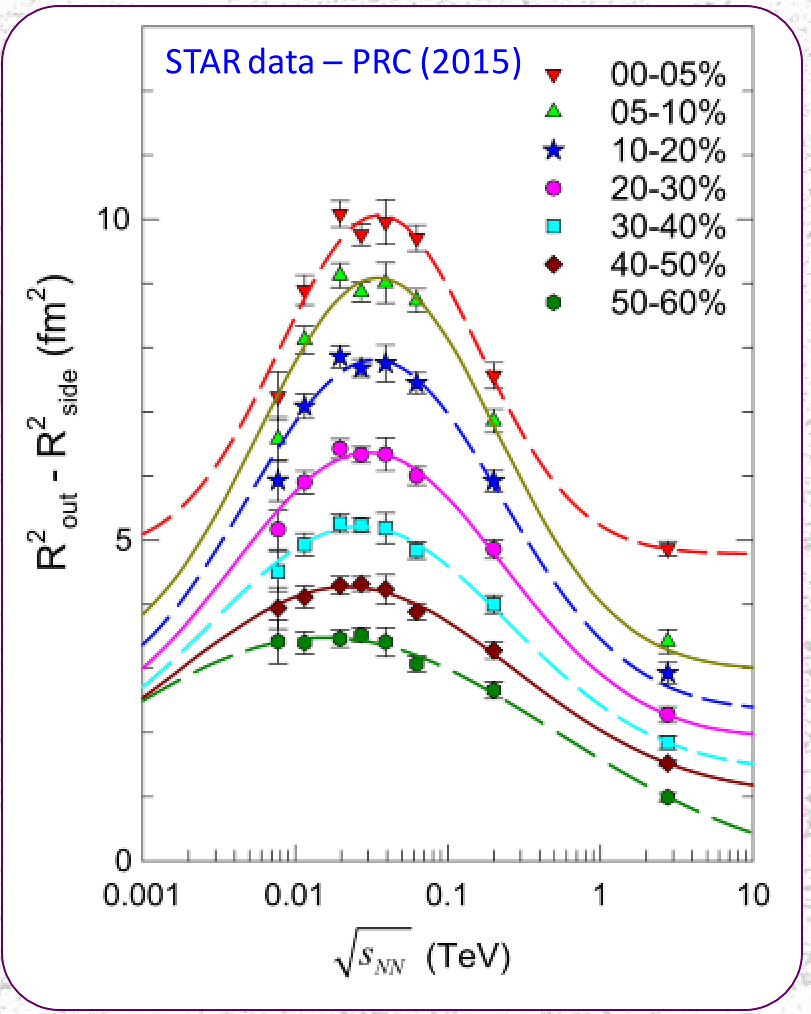
width: $dT(V) \sim L^{-1/n}$

position: $t_T(V) \sim T^{CEP}(V) - T^{CEP}(\text{¥}) \sim L^{-1/n}$

hypothesis

$R_o^2 - R_s^2 \leftrightarrow c_T$

$\bar{R}_{\text{Glauber}} \leftrightarrow L$



R. Lacey, PRL **114**, 142301 (April 2015)

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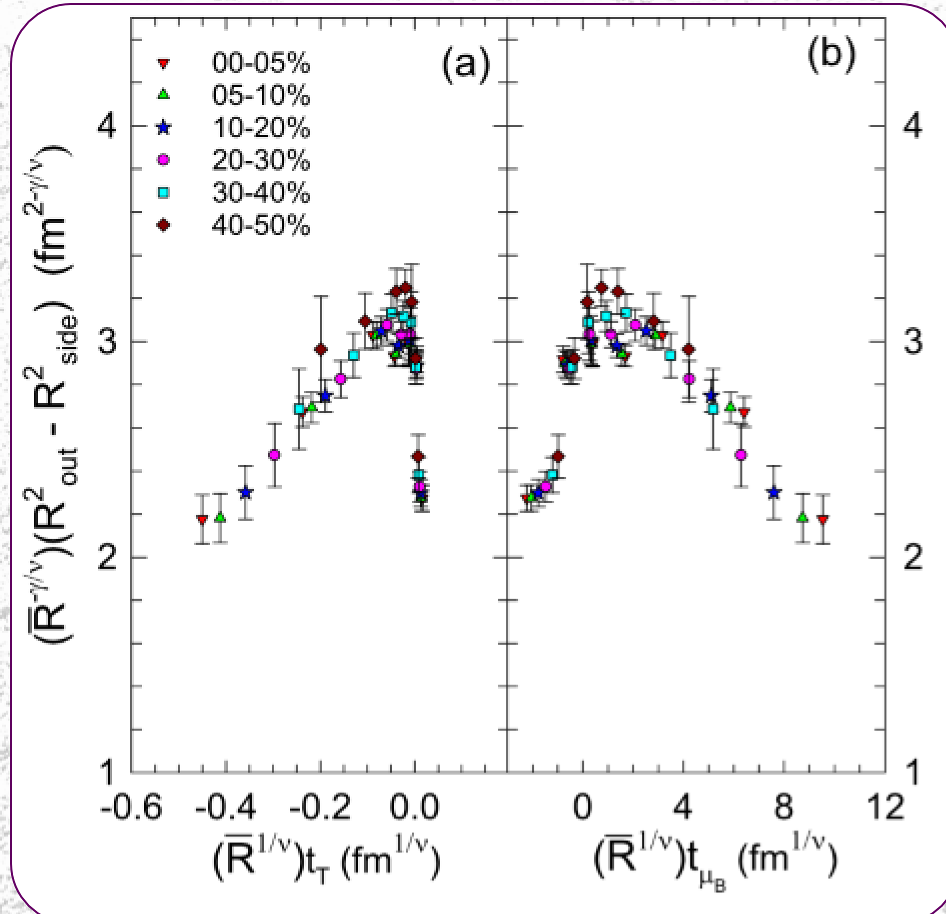
hypothesis

$R_o^2 - R_s^2 \leftrightarrow c_T$

$\bar{R}_{Glauber} \leftrightarrow L$

← reasonable?



$T^{CEP} \sim 165$ MeV $\quad m_B^{CEP} \sim 95$ MeV

g=1.15 $\quad n$=0.67 $\quad$ (3D Ising)

← excluded by Lattice?

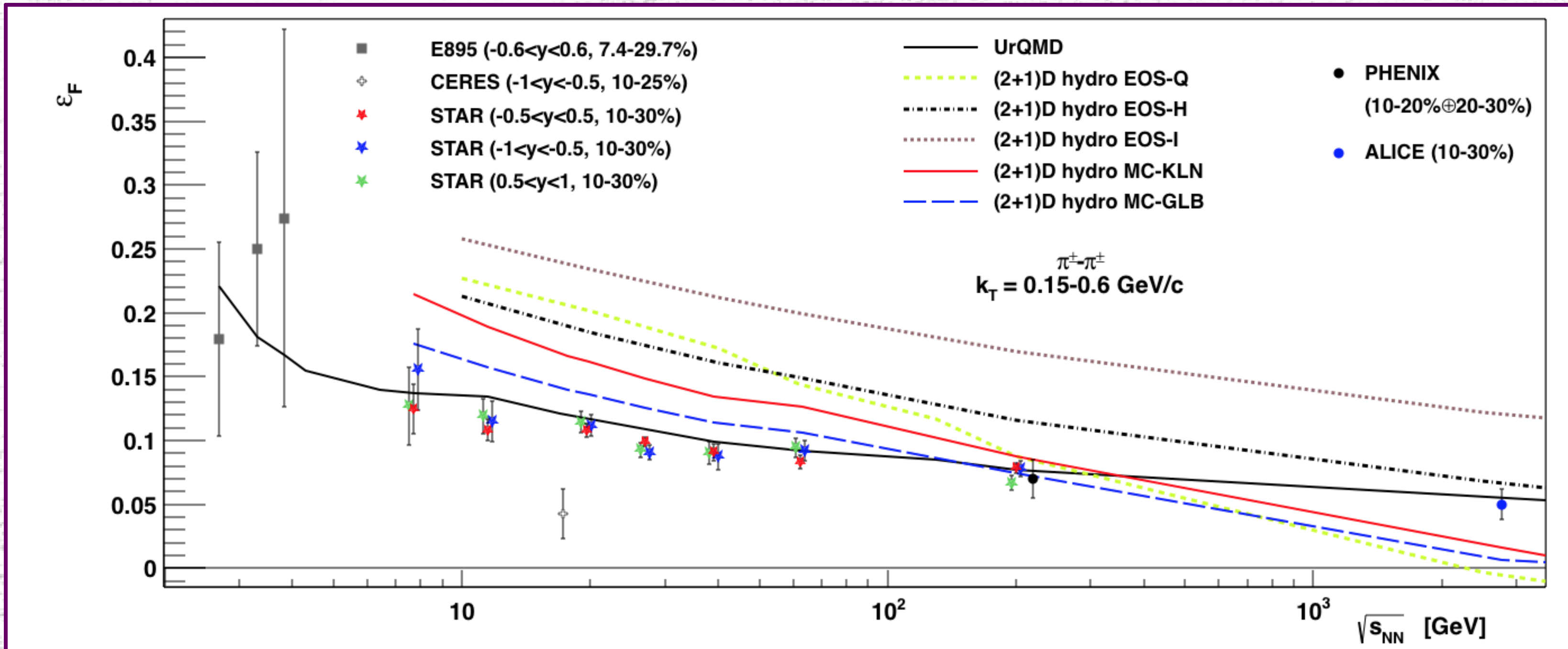
R. Lacey, PRL **114**, 142301 (April 2015)

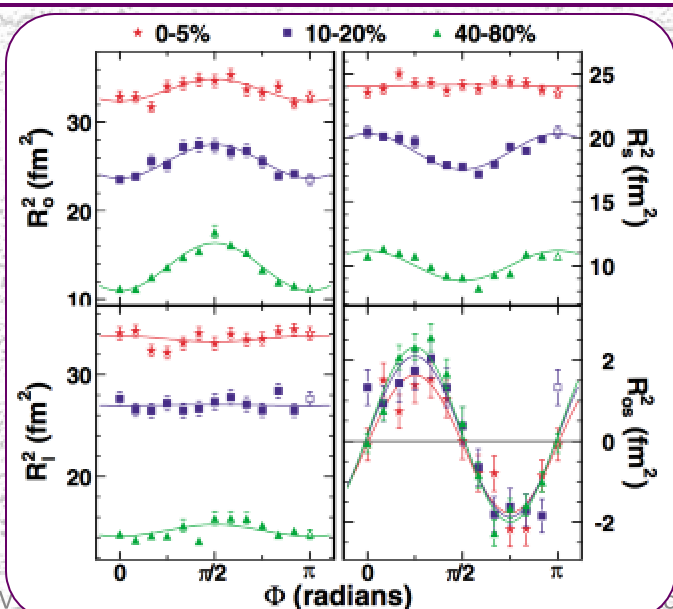
Dynamic *shape* evolution

STAR PRC92 014904

PHENIX
PRL 112 222301

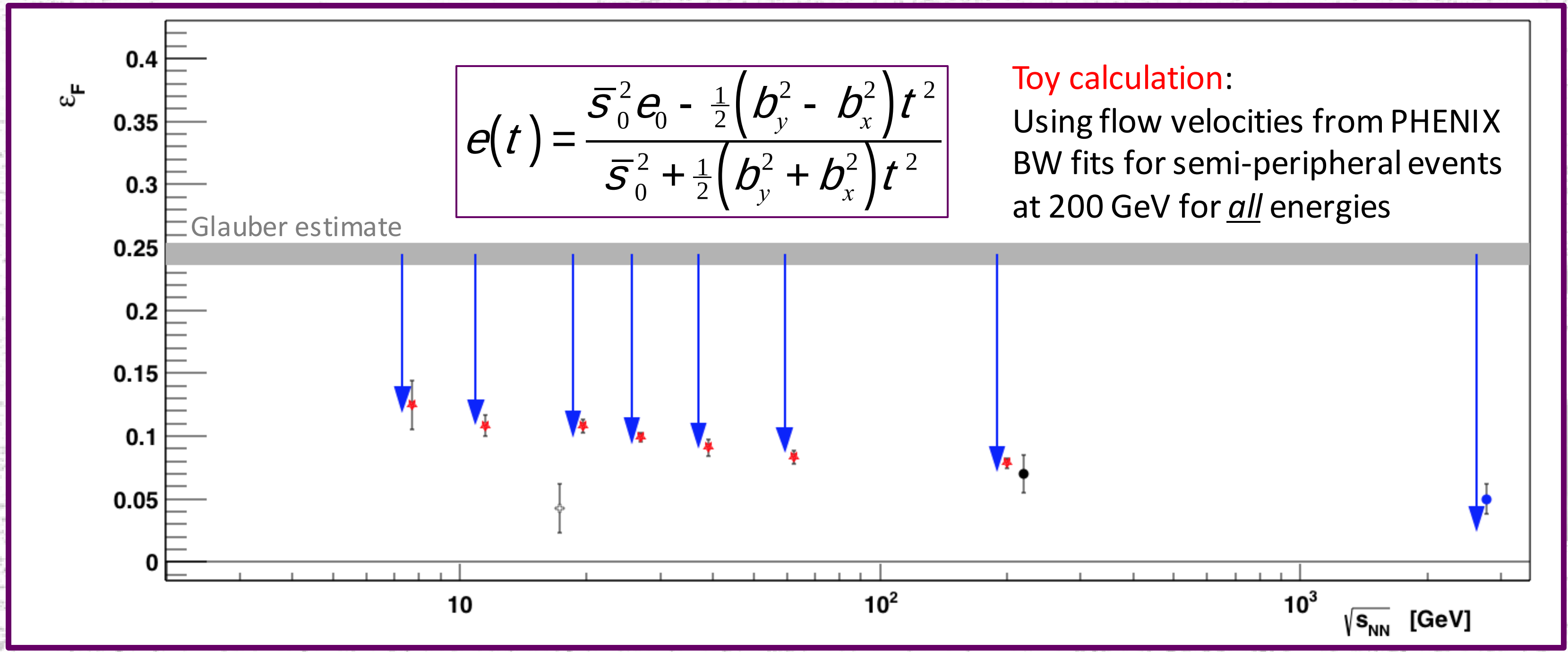
ALICE
NPA 931 1088

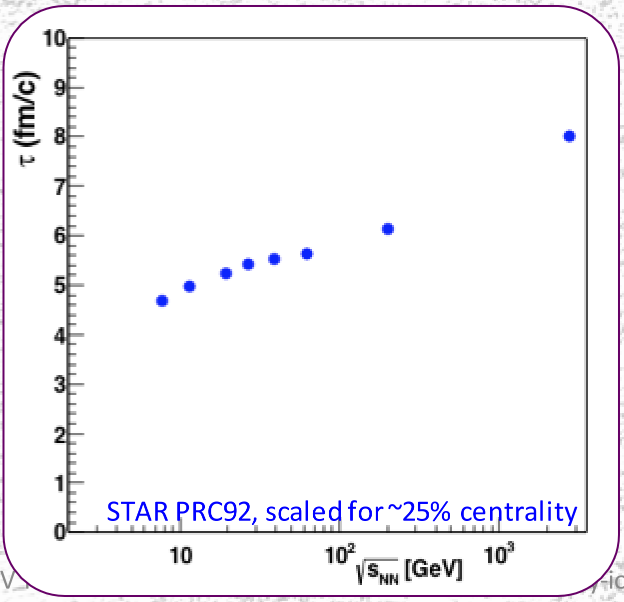




- HBT radii relative to 2nd-order plane reveal f.o. shape
- Sensitive to model parameters (EoS, init. cond., eta/s)
- Full excitation function in decade 3
- All collider experiments consistent with common curve… …which is UrQMD (?!)

Dynamic *shape* evolution





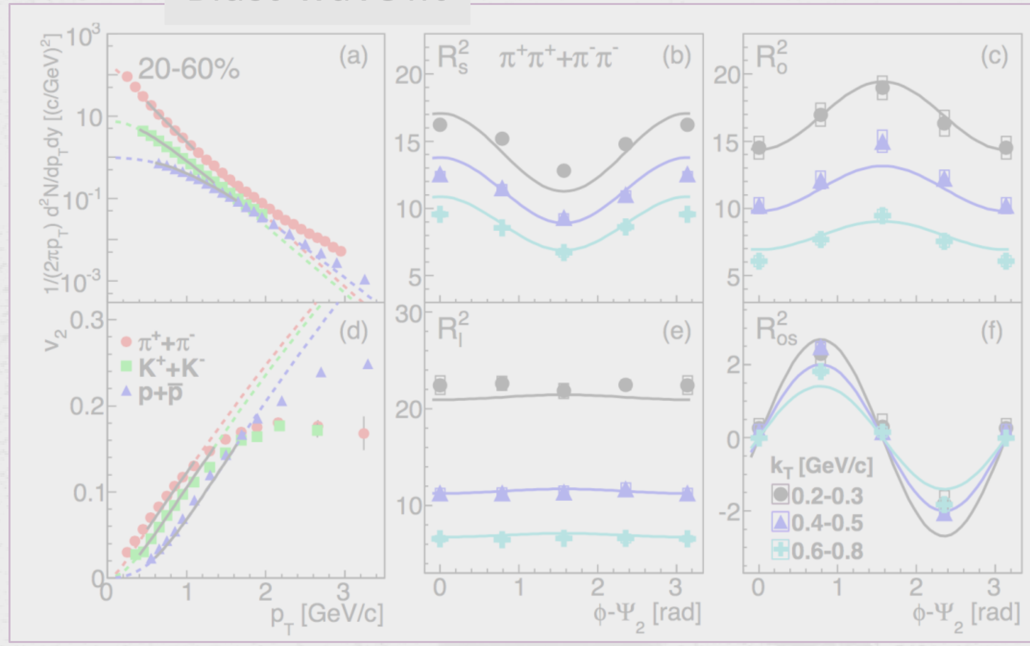
- HBT radii relative to 2^{nd}-order plane reveal f.o. shape
- Sensitive to model parameters (EoS, init. cond., eta/s)
- Full excitation function in decade 3
- All collider experiments consistent with common curve… …which is UrQMD (?!)
- final shape ~consistent with evolution time determined from R_{long} and flow velocity
  - But must go beyond toy models

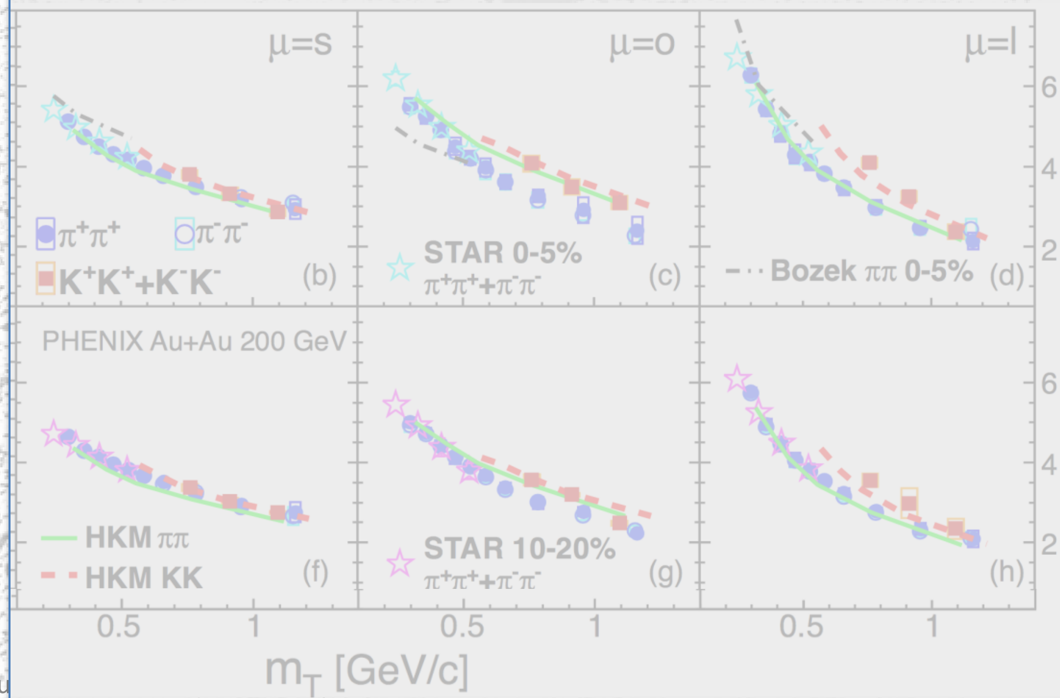
Extension to kaons

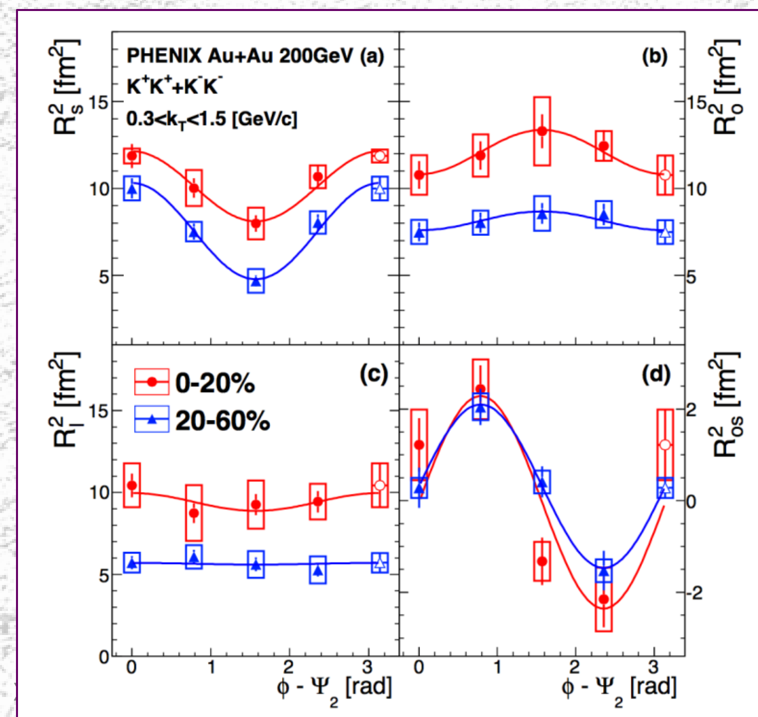
- kaon radius oscillations similar to pions
- m_T scaling for individual radii broken
- Blast-wave: decent fit to soft-sector data
- Hydro-kinetic model (HKM) and viscous hydro describe most femtoscopic data

Blast-wave fit

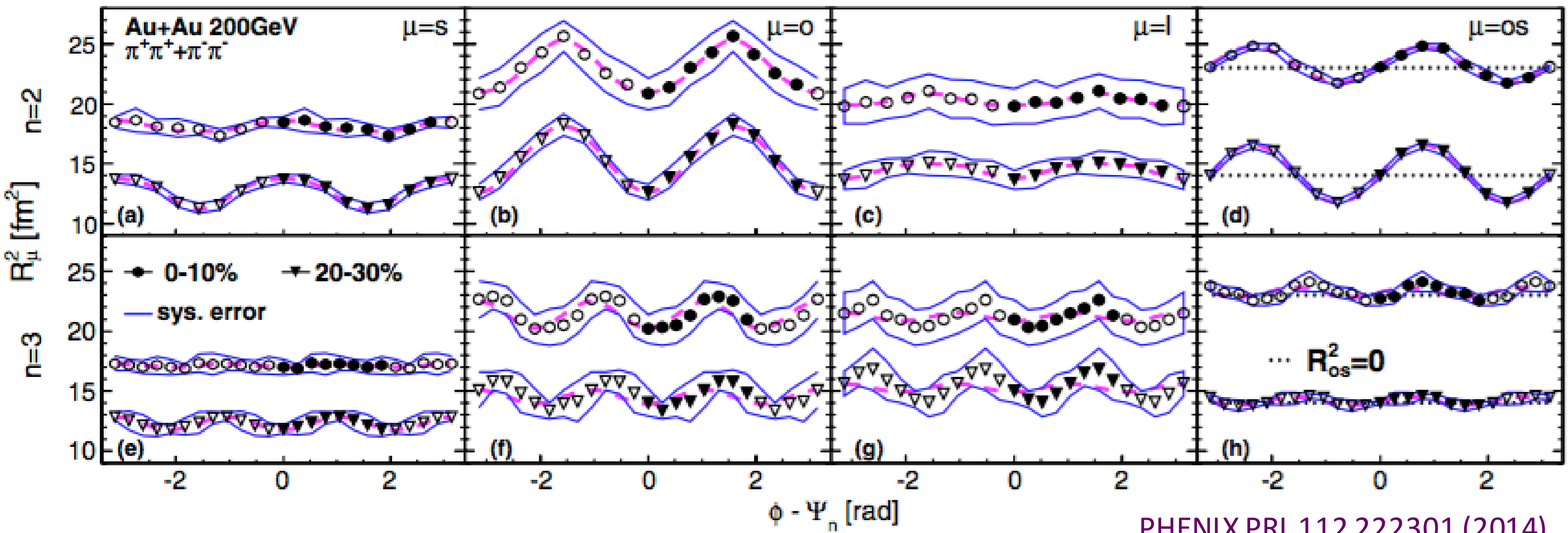
PHENIX arxiv:1504.05168



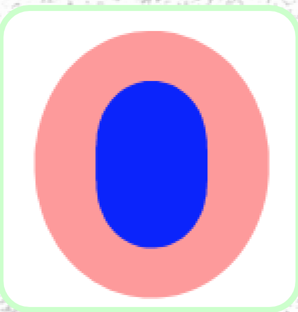




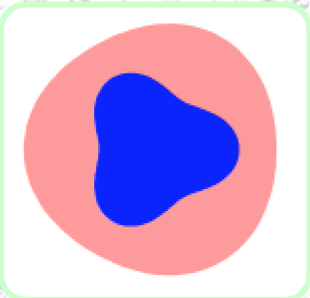
Higher-order geometrical substructure: n=3



PHENIX PRL 112 222301 (2014)



transverse size increases ~x2



consistent w/ 3+1D E-by-E viscous hydro calculations (& *pre*dictions)
– Bozek 2014

n=2
- oscillations dominated by system geometry
- ellipticity reduced ~x3
- ~consistent w/ evolution lifetime (R_{long})

n=3
- oscillations determined by flow gradients
- triangularity ~eliminated / slightly reversed
- distinguishes differing flow scenarios (Plumberg & Heinz, 2013)

Femtoscopic heavy ion story in Decade 3

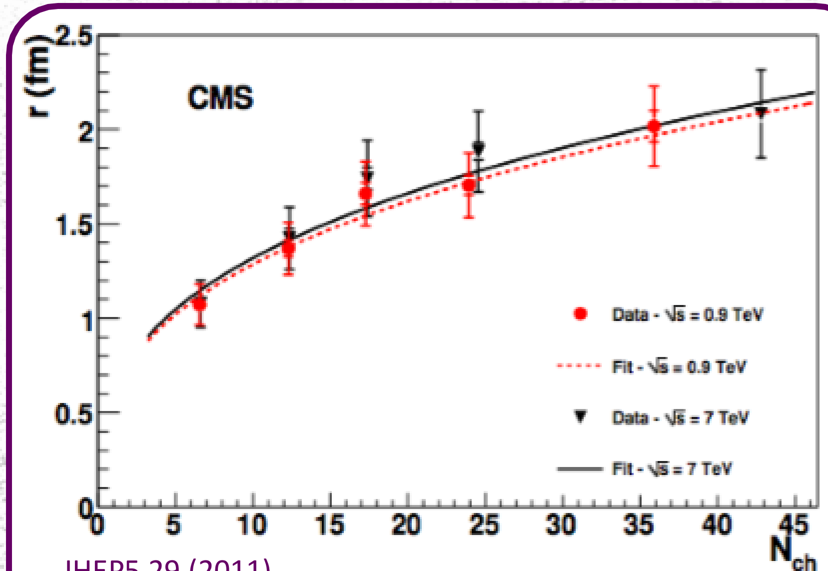
- New levels of detail with precision data and new techniques
  - dynamically-generated geometric substructure probed (asHBT)
  - SHD and images with spatially-extended tails
  - correlations between new species
  - residual correlations resolve "anomalies" in systematics

- Overall, very similar message over three orders of magnitude
  - freezeout radii ~Mult$^{1/3}$, largely independent of collision energy
  - flow-dominated substructure revealed in m_T dependence of scales
    - at all root(s) & multiplicity ranges
    - for all species
  - shape evolution sensitive to geometric gradients and timescales

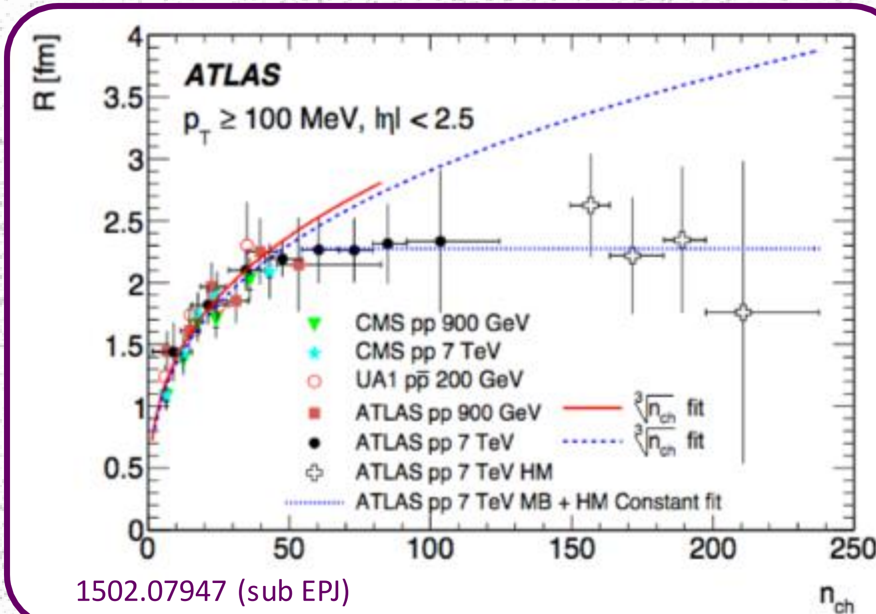
p+p versus A+A?

- Qualitatively most interesting physics: possible softening at sqrt(s) ~ 20 GeV
  - may corroborate several other qualitatively intriguing signals in RHIC BES program
  - revealed by systematically varying colliding system with fixed detector, methods

Femtoscopy in p+p: Multiplicity dependence



JHEP5 29 (2011)



1502.07947 (sub EPJ)

- Similar to A+A collisions, radii depend almost solely on multiplicity $\mu\ N_{ch}^{1/3}$, not $\sqrt{s}$
  - Fluctuations at extreme multiplicity violate the bulk trend
    - Pomeron picture? [Schegelsky et al, PLB (2011)]

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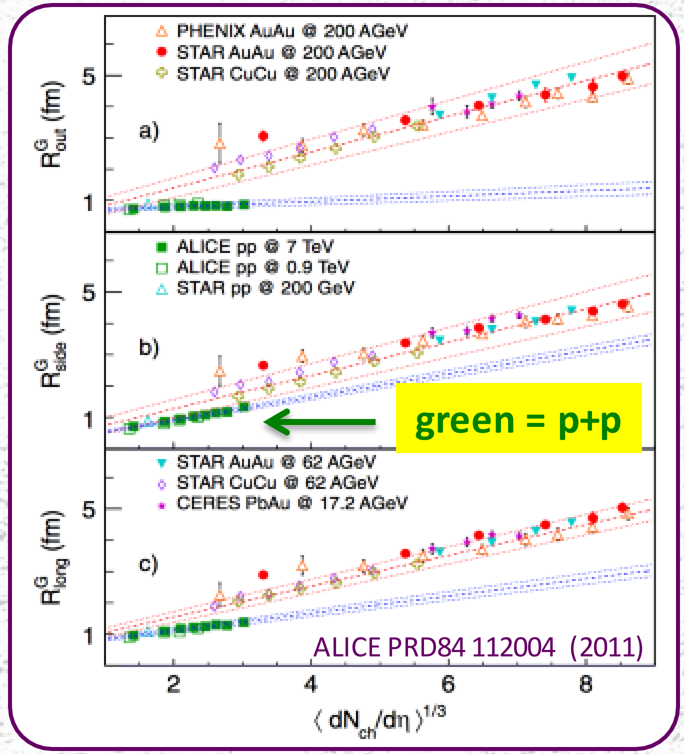

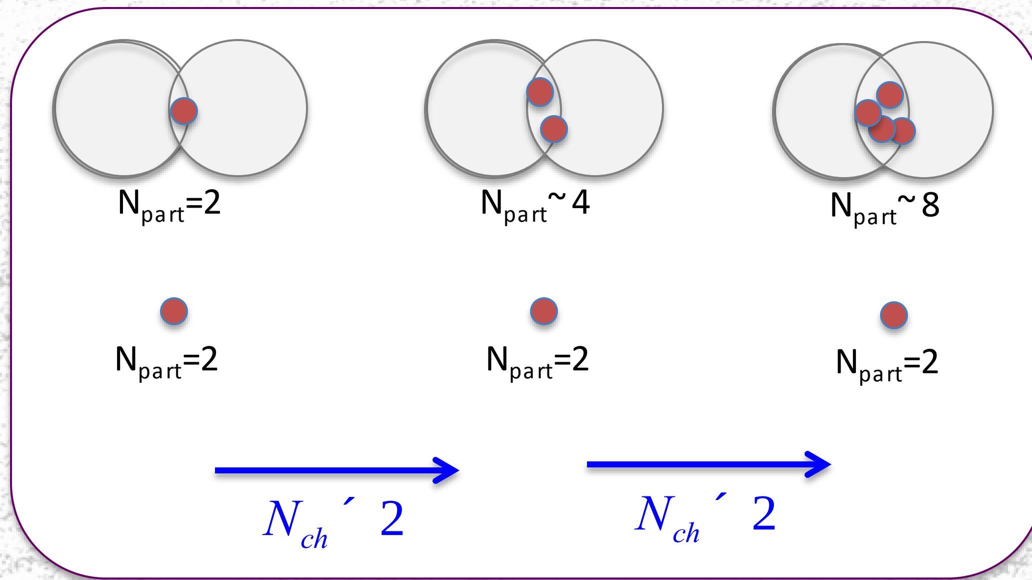

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- Proportionality constant differs from A+A case
  - relevance of initial geometry
  - p+p: multiplicity fluctuations in fixed (?) volume: expansion? jets? [Paic & Skowronski 2005]
  - A+A additional "trivial" initial geometry-N_{part} fluctuation

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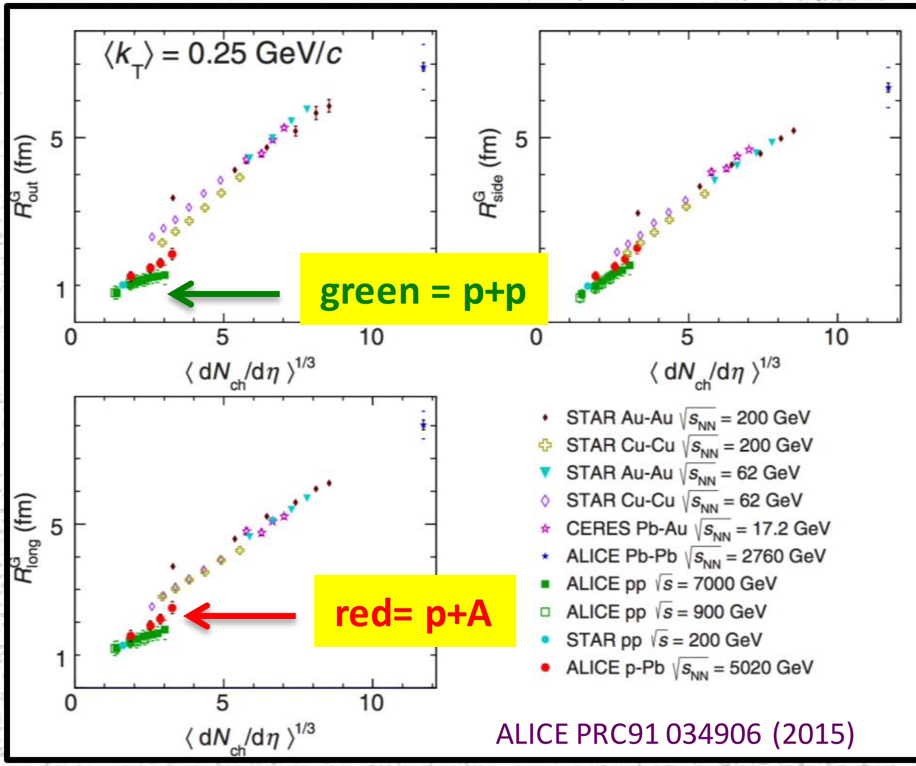

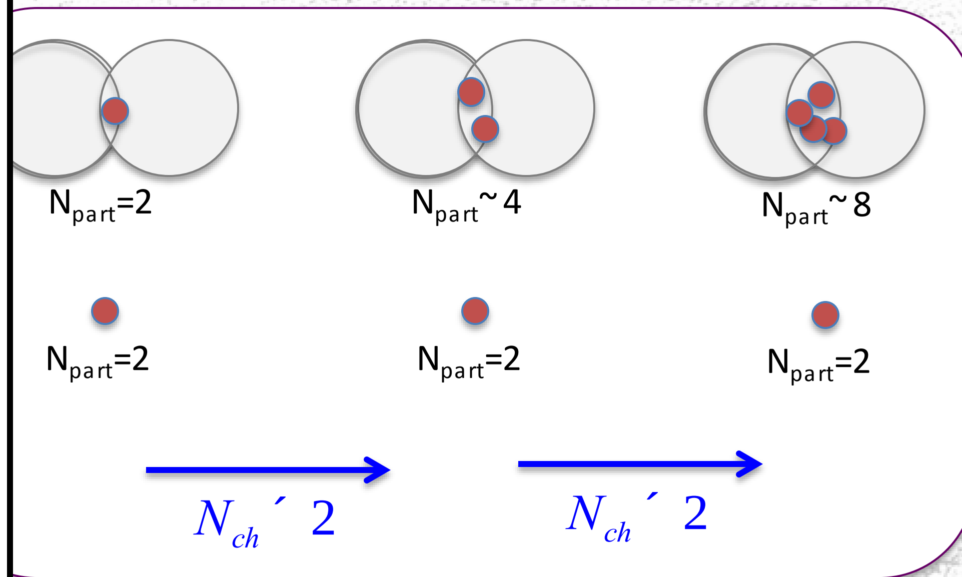

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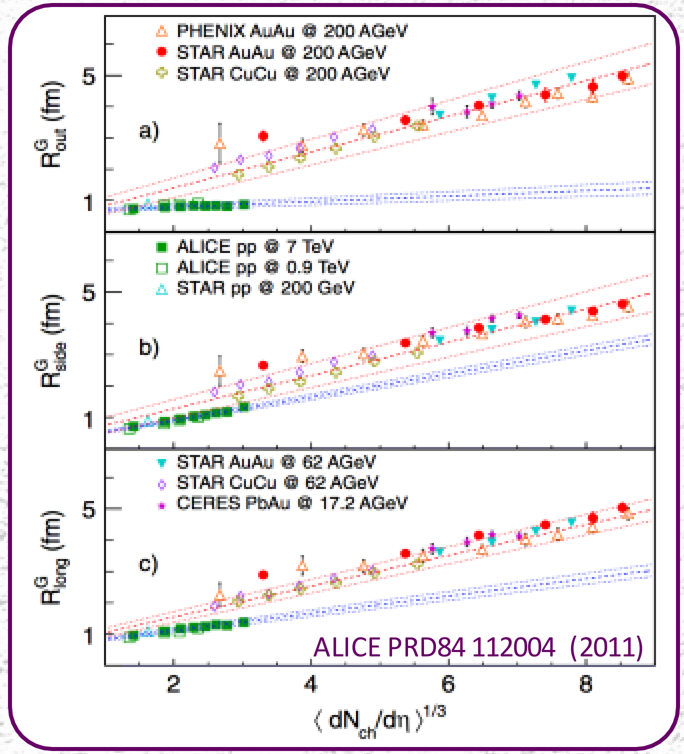

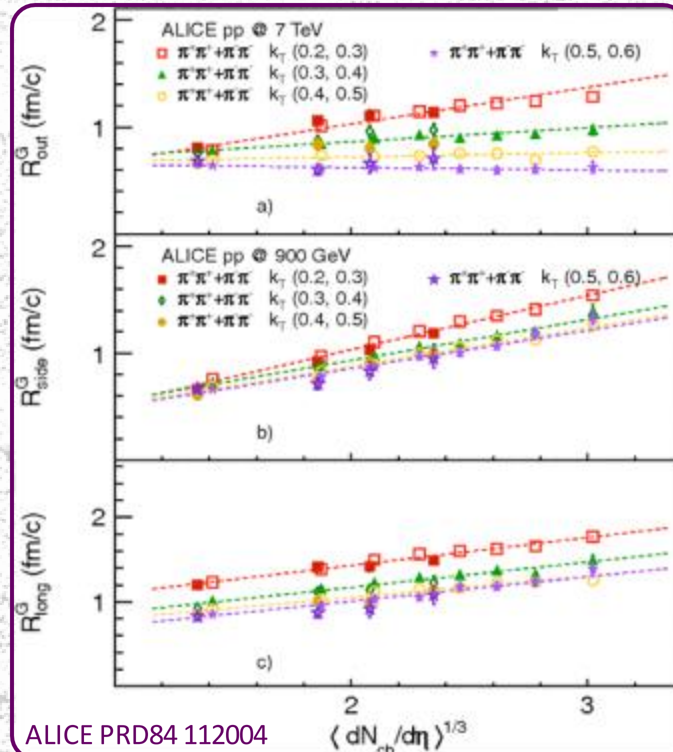

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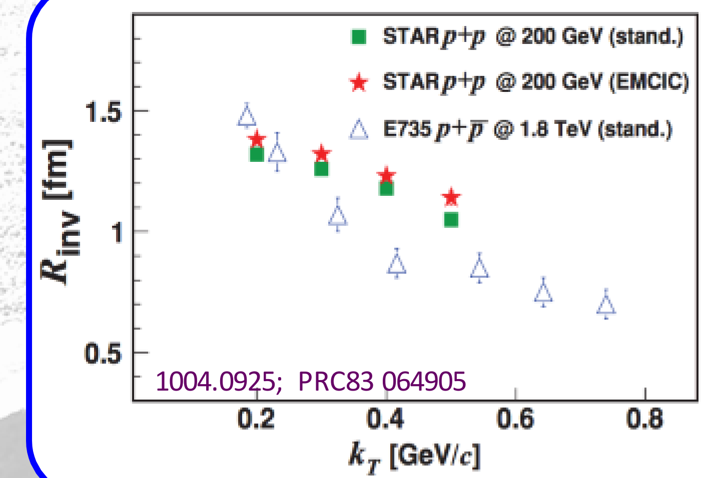
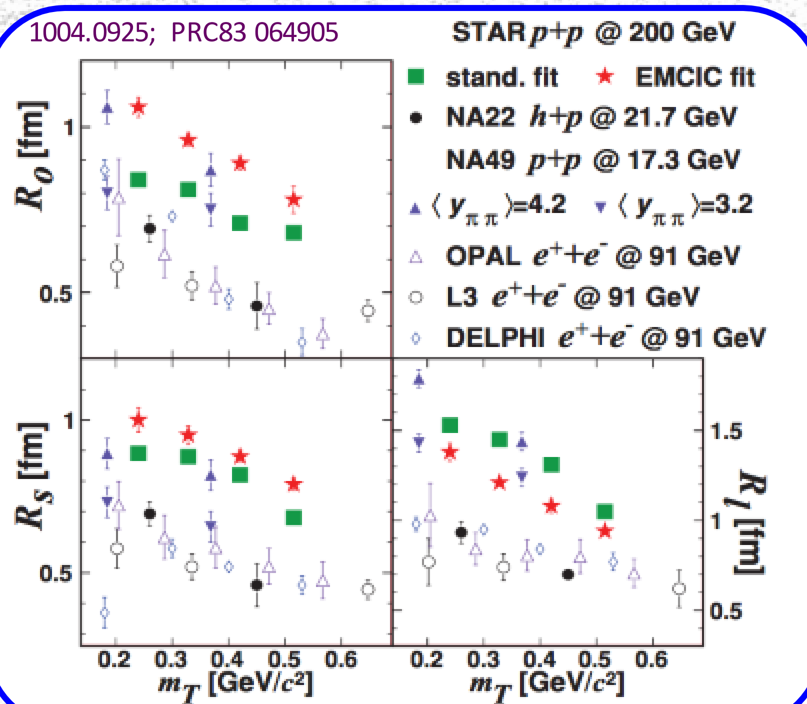
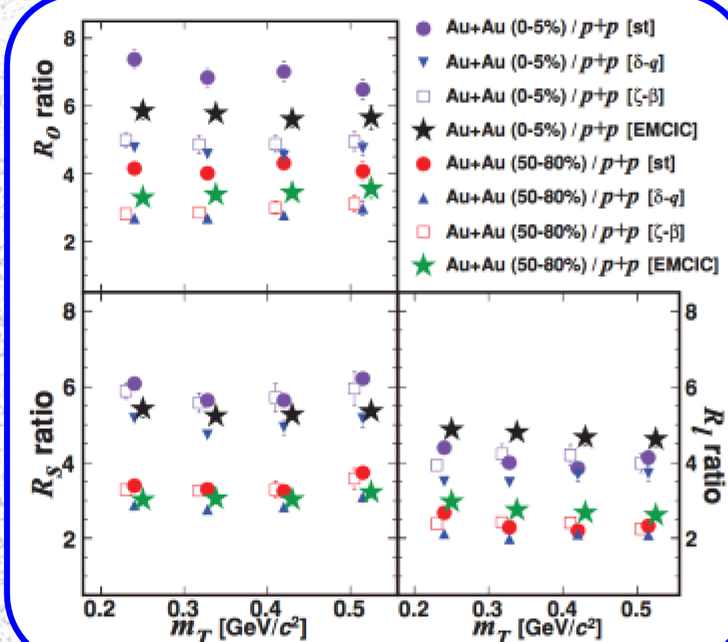
  - A+A additional "trivial" initial geometry-N_{part} fluctuation
  - p+A "between" p+p and A+A – longitudinal-only (naive picture) fluctuations
- Similar to A+A: additional k_T-dependence → bulk dynamics?

Strange suggestions from RHIC

STAR reports k_T dependence in *minbias* p+p @ 200 GeV
- requiring 2 midrapidity pions → bias toward high mult
- quantitatively similar to A+A @ RHIC - similar flow?



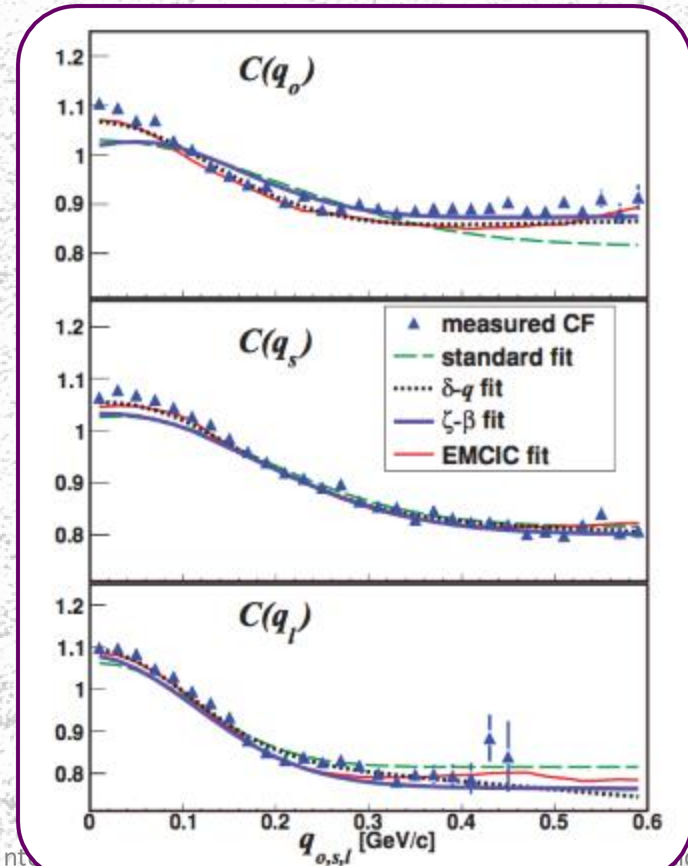




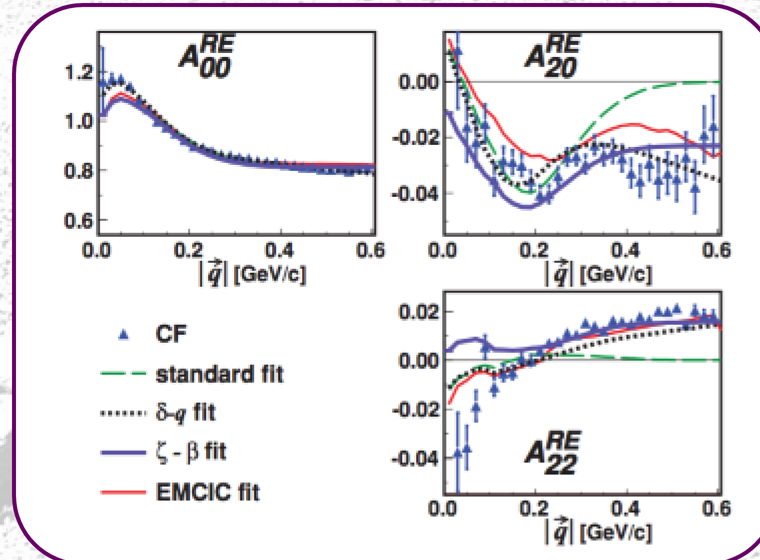
Strange suggestions from RHIC

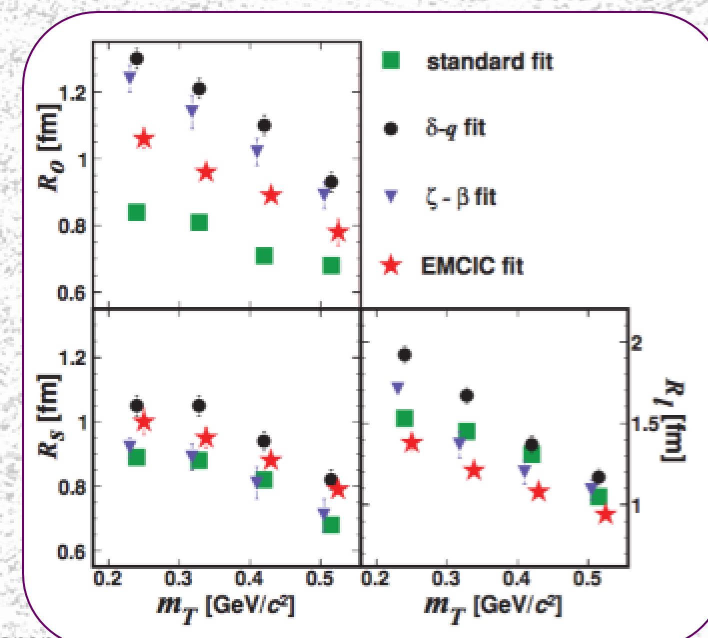
STAR reports k_T dependence in *minbias* p+p @ 200 GeV

- requiring 2 midrapidity pions →bias toward high mult
- quantitatively similar to A+A @ RHIC - similar flow?
- strong non-femto correlations → poor fit
  - energy & momentum conservation also distorts spectra, masking flow effects? [Chajecki & MAL PRC79 (2009)]



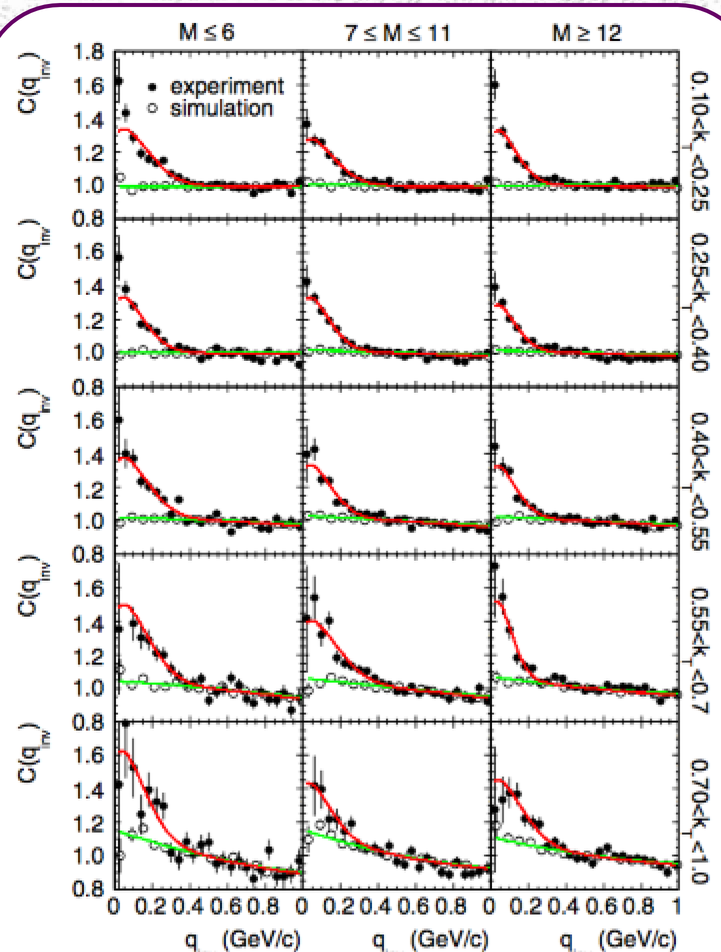
Harmonic decomposition



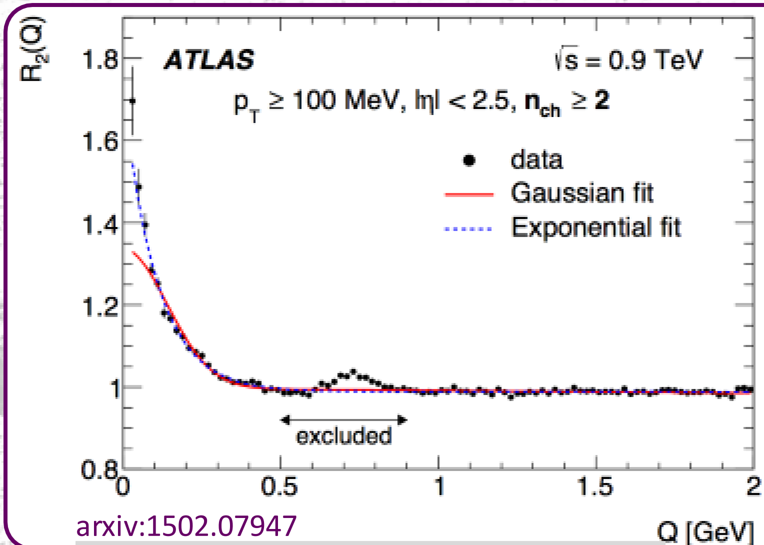


The message from LHC

- Much better (model-based) accounting of non-femto correlations
- 1D: exponential better than Gaussian fit

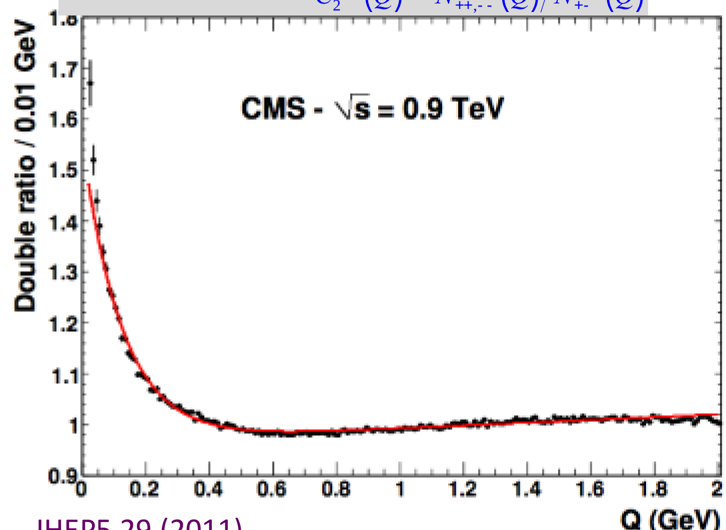


ALICE PRD82 052001 (2010)



arxiv:1502.07947

"double ratio" $R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)} = \frac{N_{++,--}(Q)/N_{+-}(Q)}{N_{++,--}^{MC}(Q)/N_{+-}^{MC}(Q)}$

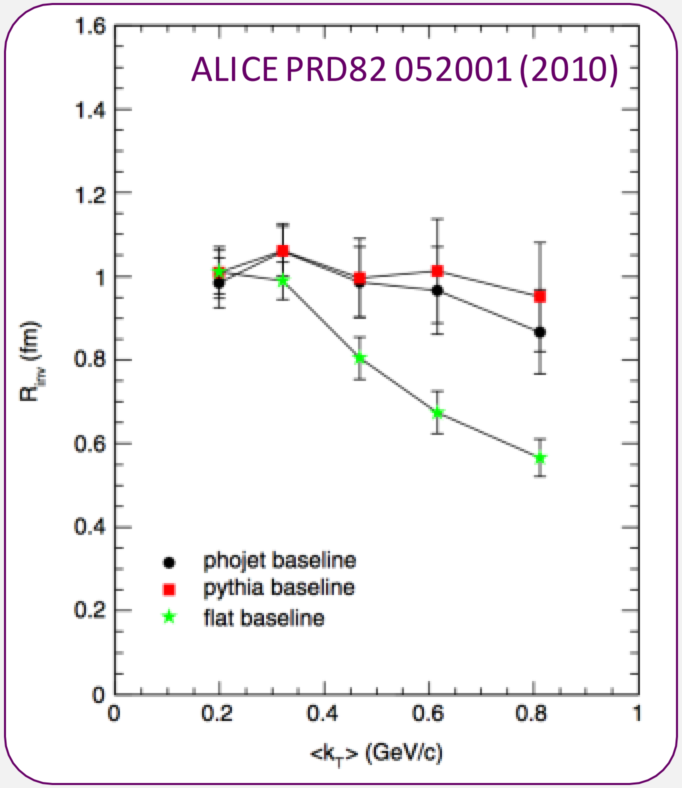


JHEP5 29 (2011)

Mixed message from LHC

- Much better (model-based) accounting of non-femto correlations
- 1D: exponential better than Gaussian fit
- k_T-dependence in minbias?

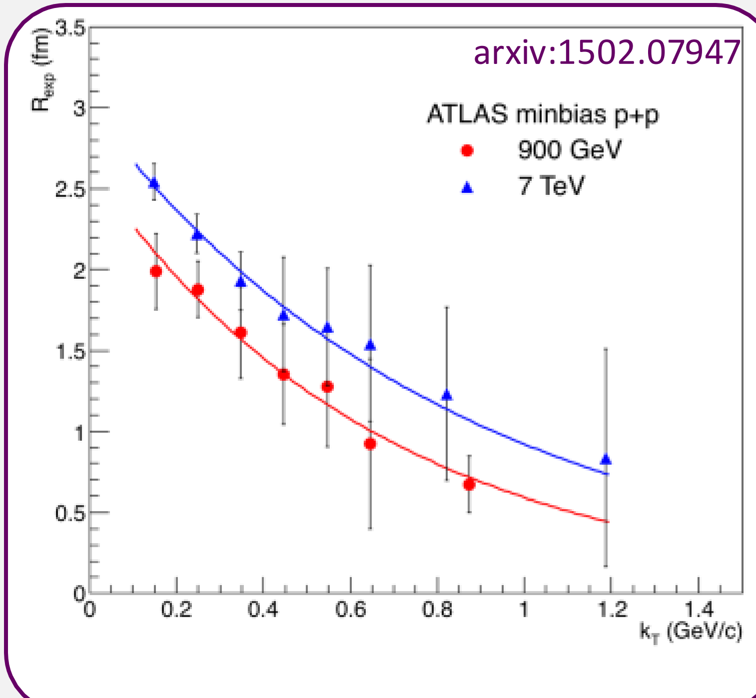
ALICE - Gaussian radius



k_T dependence **if** non-femto background ignored

No k_T dependence if background is accounted for

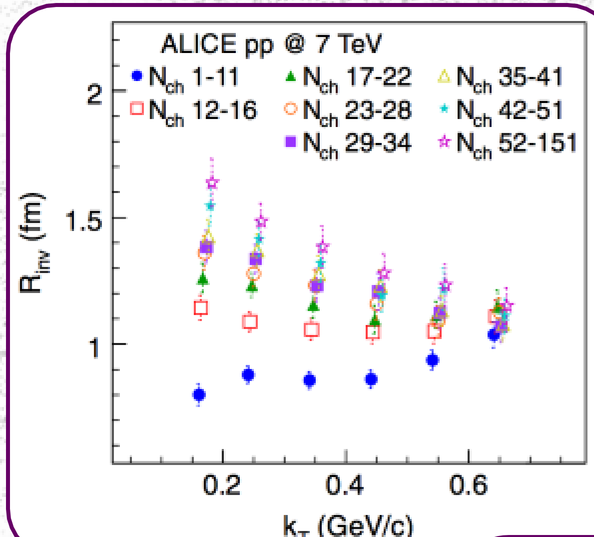
ATLAS - exponential radius



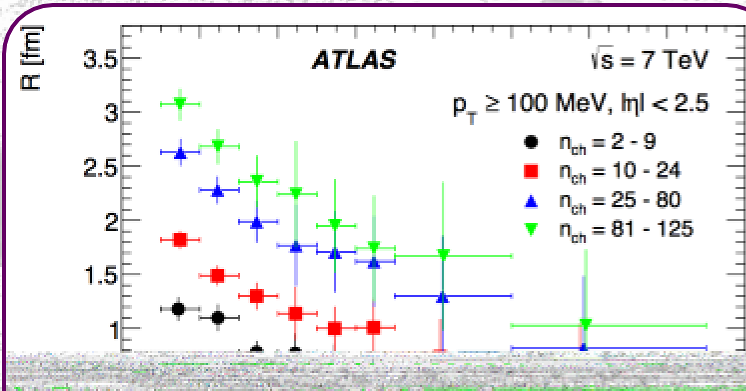
Strong k_T dependence (consistent w/ STAR, E735) even accounting for non-femto bkgd

k_T dependence @ LHC – beyond minbias

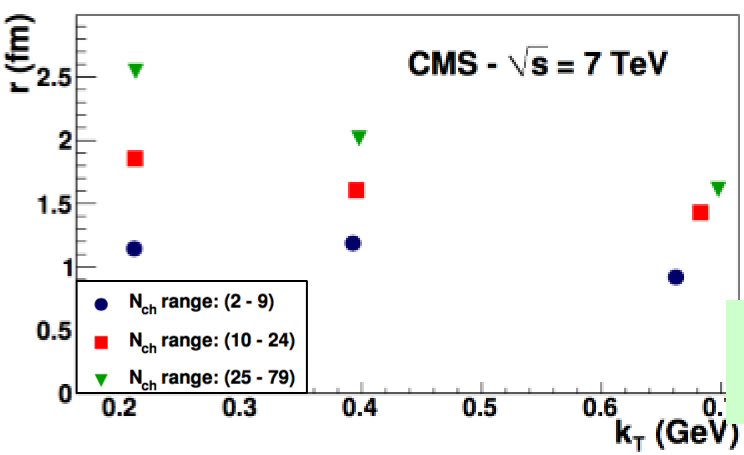
- Clearly a strong dependence for higher-multiplicity collisions
  - & need not go to "extreme" high multiplicity (good)
- what about the lowest multiplicity? (and implications for flow interpretations?)
  - mixed signals from ATLAS, ALICE, CMS (though techniques not identical)



low-multiplicity events *very* different *rise* with k_T



low-multiplicity events exhibit strong k_T dependence



low-multiplicity events exhibit small k_T dependence

k_T dependence @ LHC – beyond minbias

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  - & need not go to "extreme" high multiplicity (good)
- what about the lowest multiplicity? (and implications for flow interpretations?)
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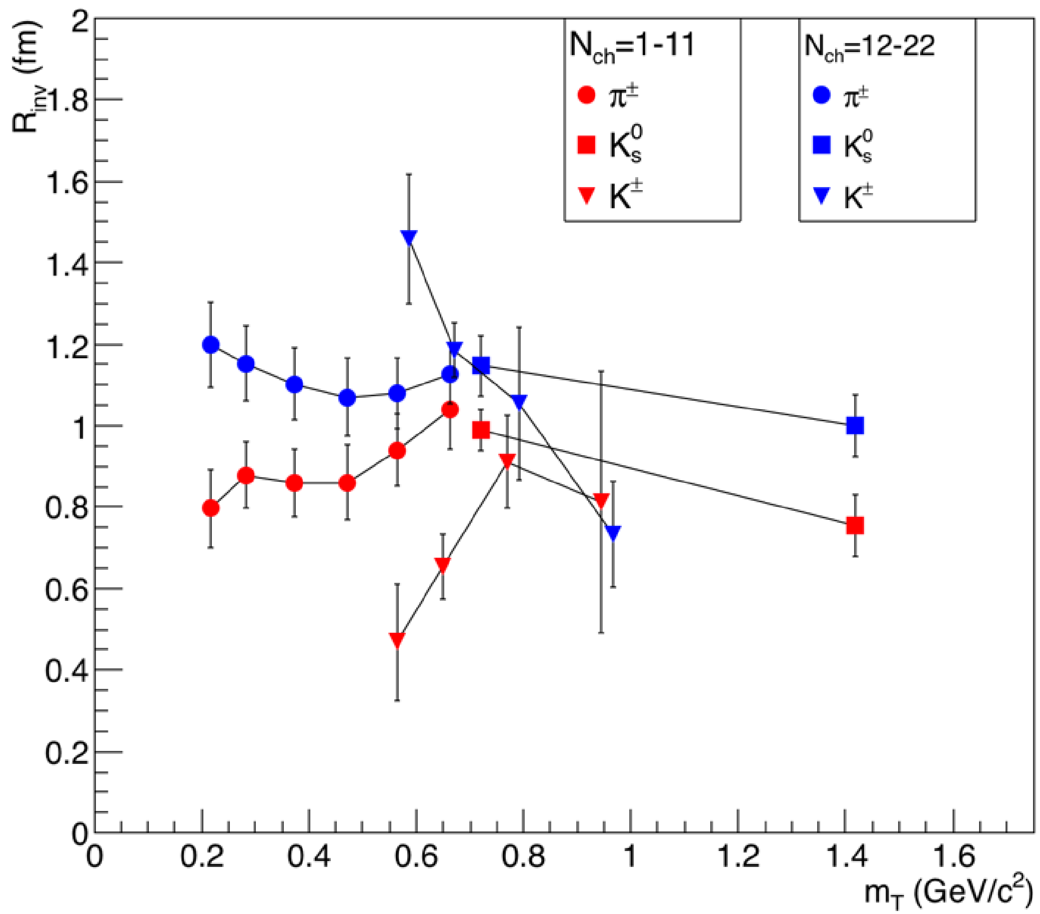
Overall, a very confusing picture from low-multiplicity p+p collisions



Summary

- Femtoscopy in RHI has taught us much of what we "know"
- Detailed geometric substructure paints a consistent picture
  - thermalized, flowing system, driven by spatial gradients
  - Evolution lifetime ~15 fm
- Third decade: tremendous extension of systematics: energy, size
  - improved statistics, techniques
  - heavy ion systematics: broad confirmation of existing trends at LHC
  - energy scan reveals crucial details – softening at "interesting" BES energies
  - an important light on the question of collectivity in p+p
    - high-multiplicity (not "extreme"): resembles A+A flow
    - low-multiplicity – flow?
      - experimentally extremely challenging
      - no clear picture as of now
- These two issues are the most compelling in the field overall

What's next? (Experimentally)

- RHIC BES-II
  - pion imaging – change of F.O. configuration?
  - asHBT[3] – probe of viscous effects (needs theory foundation)
  - asHBT[1] - tilt
  - non-id correlations (pi-K)
  - **Baryon-AntiBaryon correlations – map net baryon density**

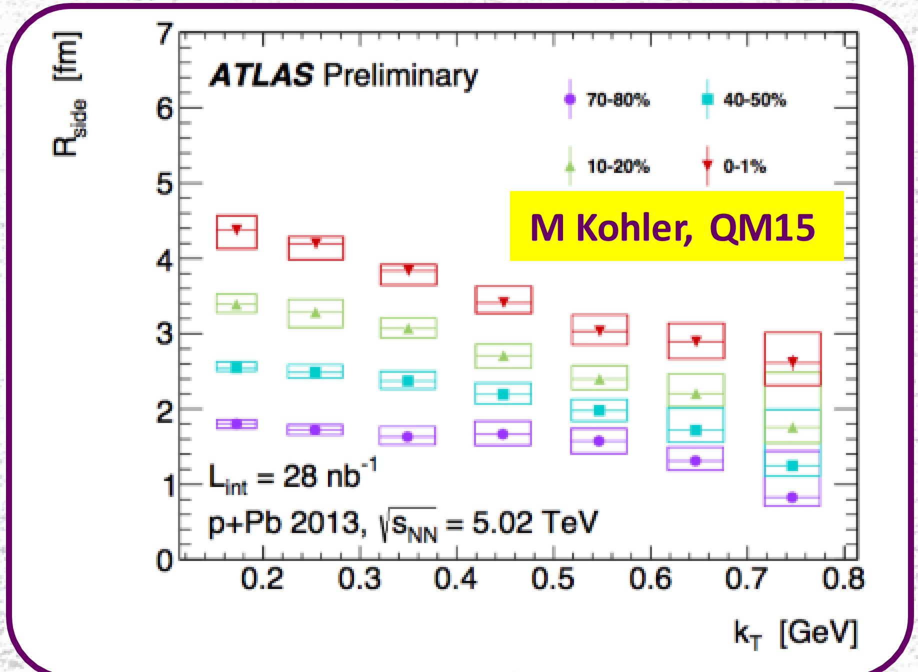
- p+p (RHIC & LHC)
  - **non-id (pi-K)** – more strictly test flow hypothesis; huge non-femto problems
  - **3D radii from ATLAS** – do p-Pb fall faster than p+p (& Pb+Pb)?

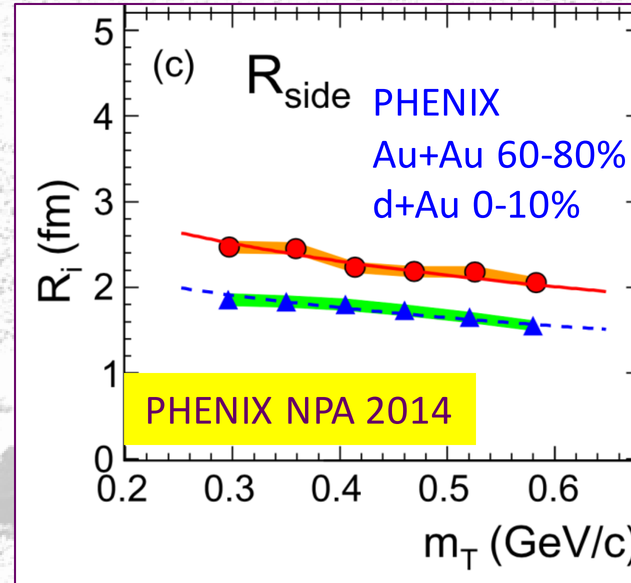
- Pb+Pb (LHC)
  - N>2 correlations – stricter signal for coherent fraction
    - already a 2-sigma signal for 25% [ALICE PRC89 024911 (2014)]
    - physics impact?
  - new partner species – extract scattering parameters

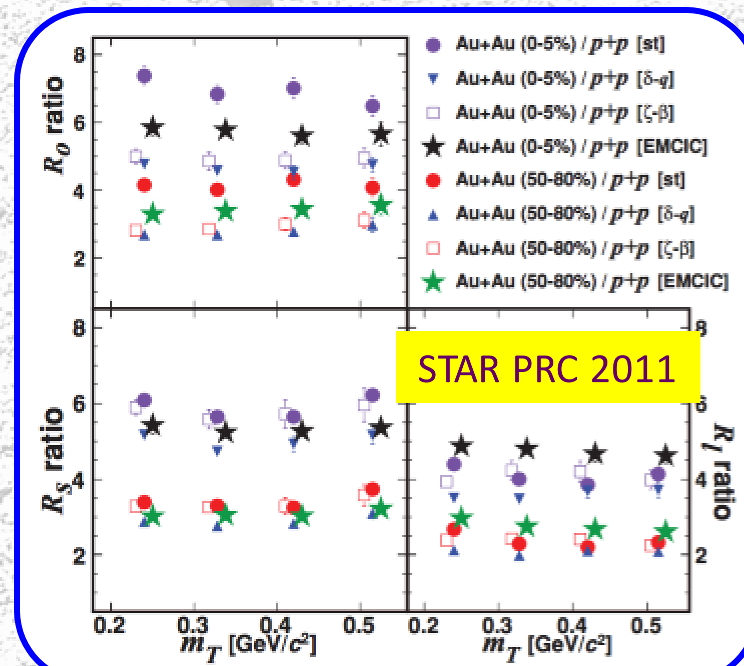
Conference series discussing femtoscopic developments in detail
https://indico.cern.ch/event/387606/
-- registration still open!

END

More radial flow in small systems than AA?







STAR: ~identical dependence p+p, A+A

- identical flow

PHENIX: ~identical d+A, A+A

- identical flow

ALICE: high-mult pp ~ p+Pb, lower than central Pb+Pb

- slightly larger flow in Pb+Pb than p+Pb, p+p

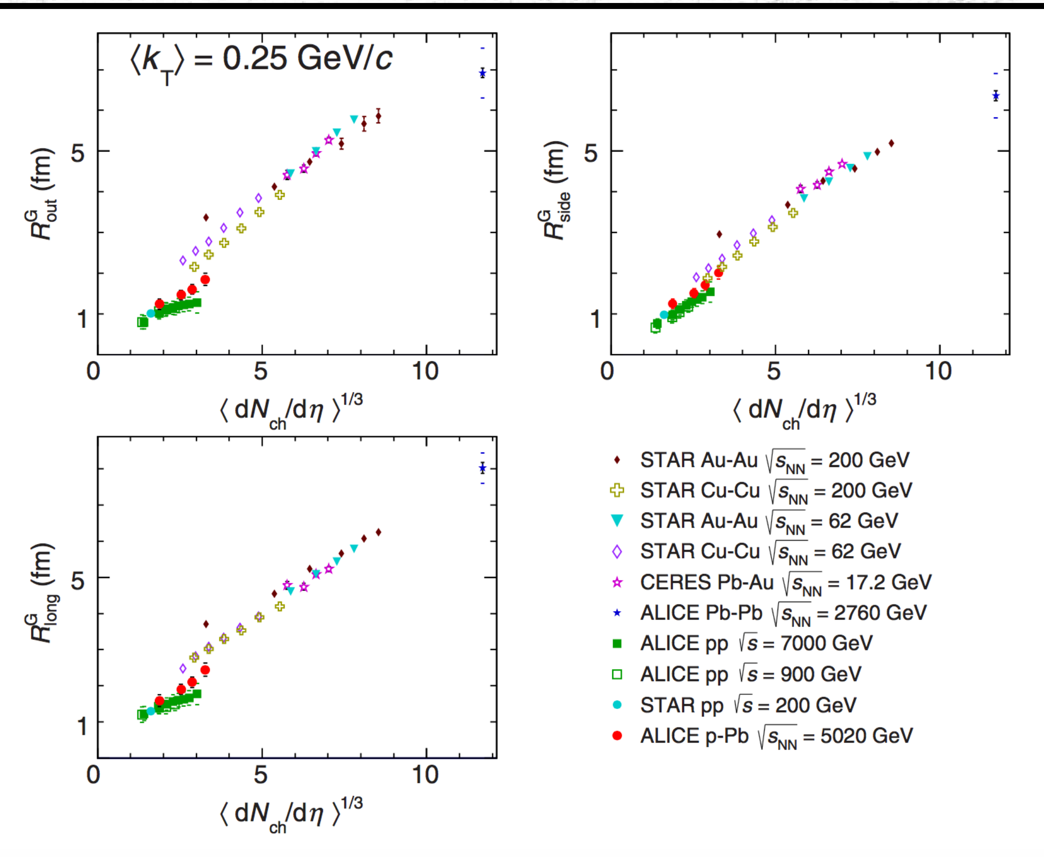
ATLAS: only p+Pb available (exponential)

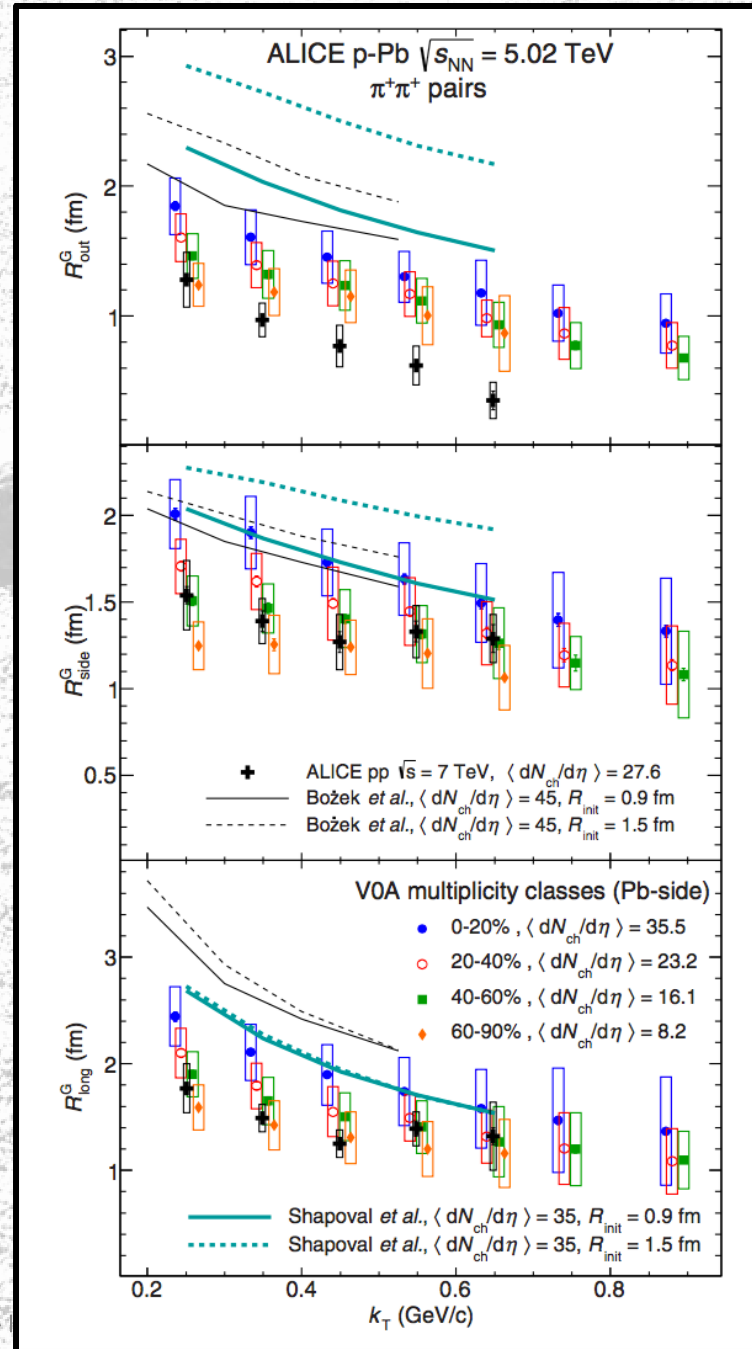
- larger than ALICE falloff for p+Pb
- 3D radii in p+p & A+A needed!

P+A

ALICE PRC91 034906 (2015)

p+A

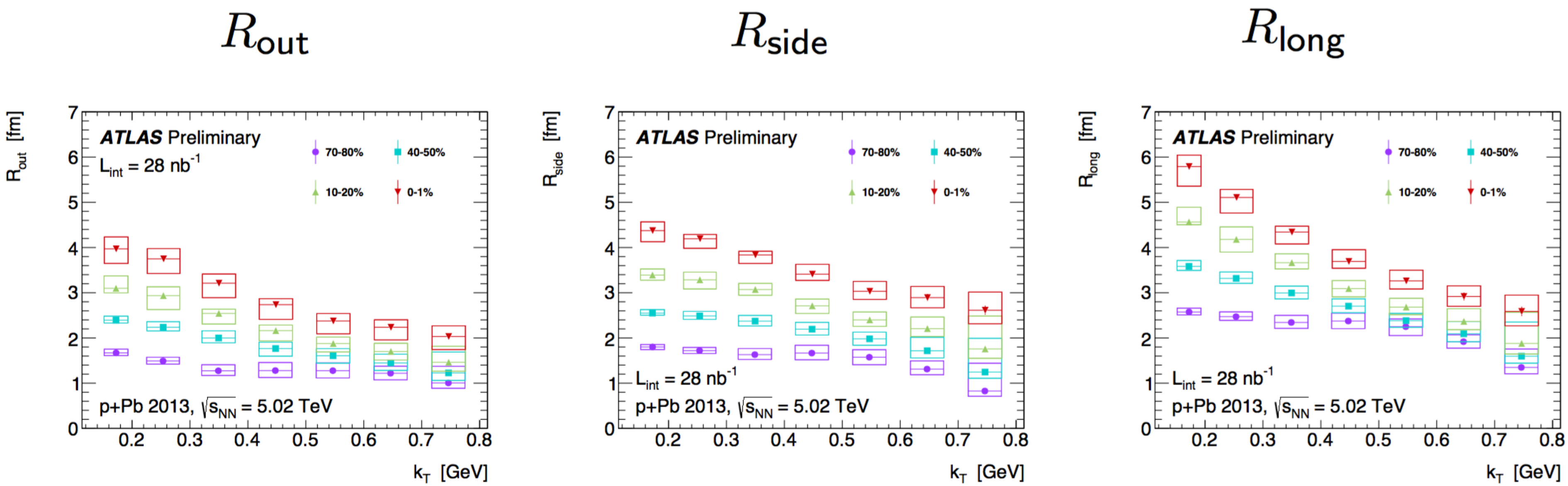




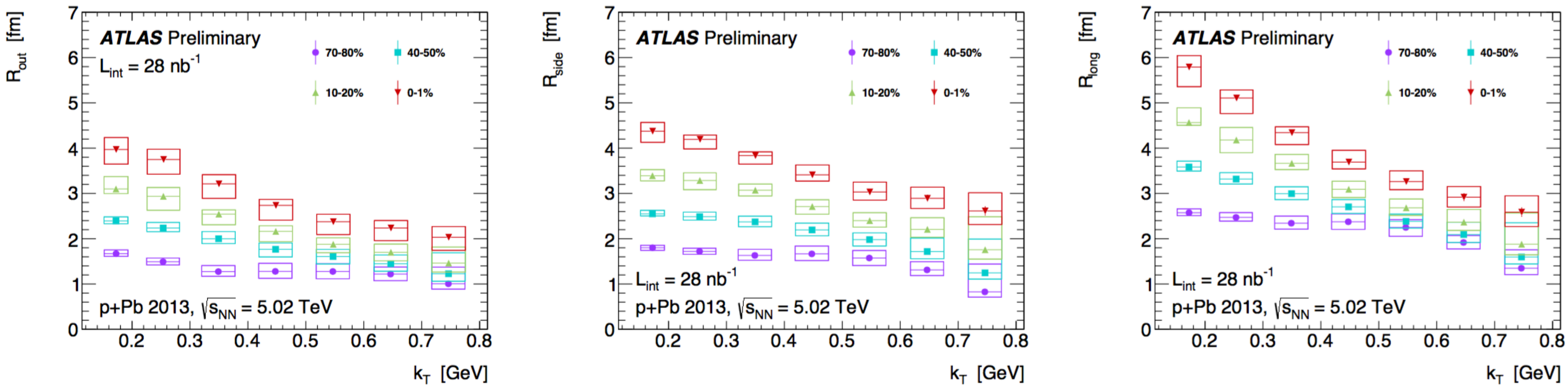
- Radii ~20% larger than p+p at equivalent mult.
- kT-dependence similar
- scale with N^{1/3}, with slope between AA, pp
    - again, *initial* geometry matters

ATLAS p+Pb

M. Kohler, Tuesday



R_{out} R_{side} R_{long}



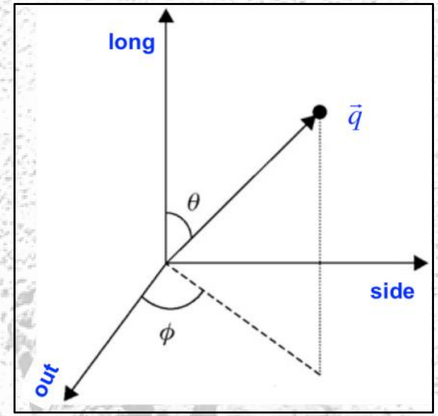
IMAGING

SHD & Imaging

Danielewicz & Pratt, PRC**75** (2007)
Chajecki & Lisa PRC**78**, (2008)
Kisiel & Brown PRC**80** (2009)

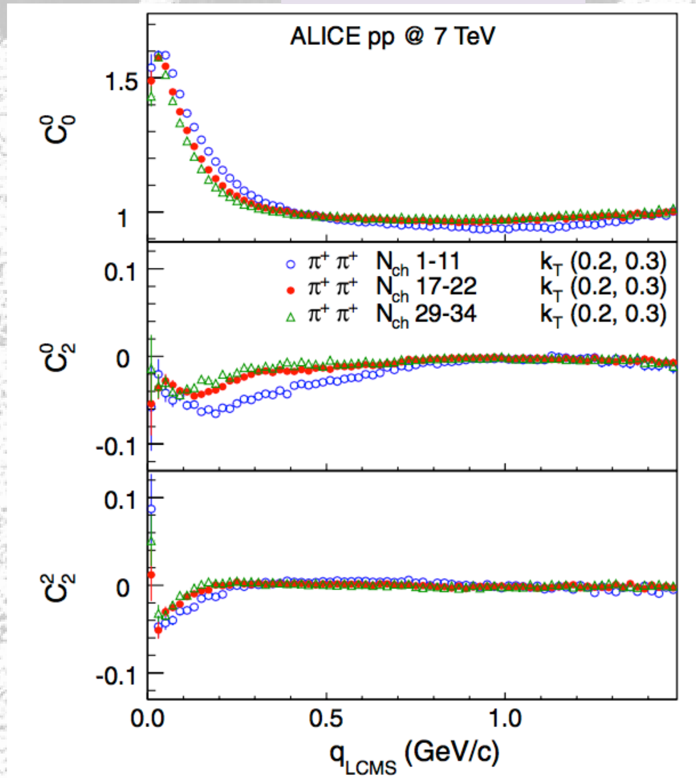
Spherical (or Cartesian) Harmonic Decomposition

$$R_l^m(|\vec{q}|) = \frac{1}{\sqrt{4\pi}} \int d\phi \, d(\cos\theta) \, R(|\vec{q}|, \theta, \phi) \, Y_l^m(\theta, \phi)$$

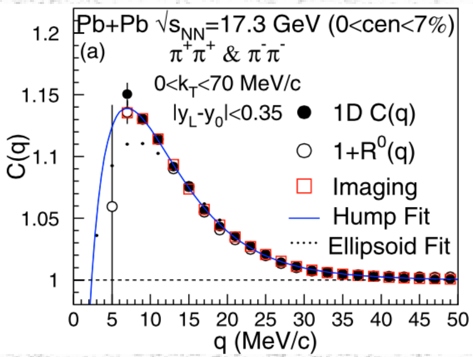


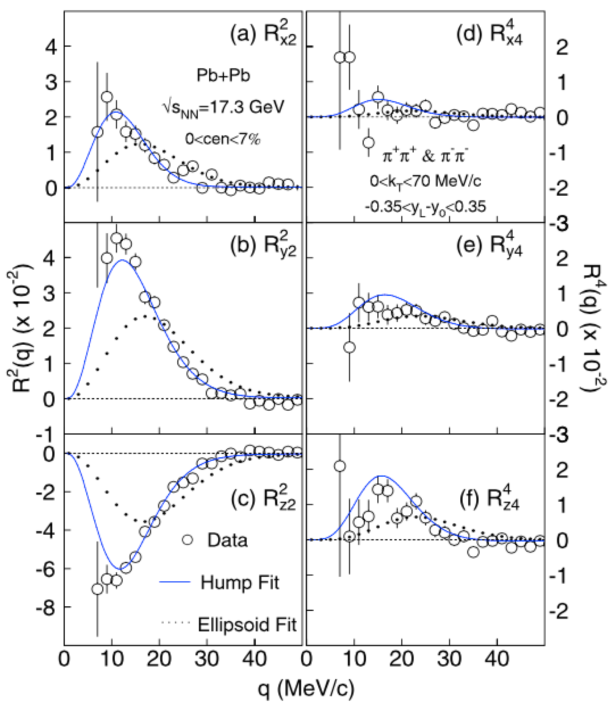
- maximum use of symmetries
- efficient, simpler visualization
  - important for poorly-understood correlations hidden in 3D space

ALICE PRD (2011)



NA49 PLB (2010)





SHD & Imaging

Brown & Danielewicz 2000
Danielewicz & Pratt, PRC**75** (2007)

Spherical (or Cartesian) Harmonic Decomposition

$$R_l^m\left(|\vec{q}|\right)=\frac{1}{\sqrt{4\pi}}\int d\phi\, d(\cos\theta)\, R\left(|\vec{q}|,\theta,\phi\right)Y_l^m(\theta,\phi)$$

$$S_l^m\left(|\vec{r}|\right)=\frac{1}{\sqrt{4\pi}}\int d\phi\, d(\cos\theta)\, S\left(|\vec{r}|,\theta,\phi\right)Y_l^m(\theta,\phi)$$

$$R_l^m\left(|\vec{q}|\right)=4\pi\int dr\; r^2 K_l\left(|\vec{q}|,|\vec{r}|\right)S_l^m\left(|\vec{r}|\right)$$

3D Imaging

- Term-by-term (l=0,1,2...) correspondence between correlation function and 2-particle "image" moments
- reveals non-Gaussian tails (resonances, etc)
- restricts model freezeout parameters

NA49 PLB (2010)