The XX International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", organized by the Joint Institute for Nuclear Research will be held October 4-9, 2010 in Dubna, Russia.

Femtoscopy application of the new EPOS model to the STAR and ALICE experiment

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Outline

- Motivation of the femtoscopy study with the Epos model
- Technical details of the Epos Femto package
- First results from Epos Femto package and comparison with STAR data
- Comparison with ALICE data and Non-femtoscopic effects
- Conclusions

Motivation

- EPOS is not a simple MC event generator, Epos is a physical event model which includes all stages of collision (init. conditions from flux tube, EbE procedure, 3+1 hydrodynamics, realistic EoS, complete resonance table, hardonic cascade)
- EPOS provides space-time coordinates of hadrons
- Possibility to study femtoscopy with EPOS
- EPOS is very wide energy range model

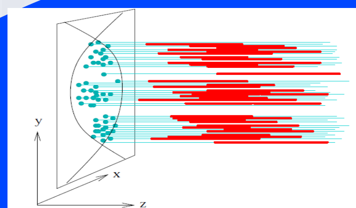
(applicability: pp, pA, AA, a tens GeV $< \sqrt{s} <$ a few TeV)

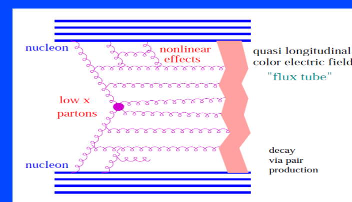
EPOS 2.05

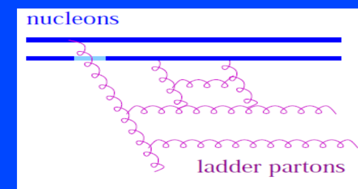
- Initial conditions obtained from flux tube approach (EPOS)
- Consider of the possibility to have a (moderate) initial collective transverse flow
- Event-by-event procedure
- Core-corona separation
- 3+1 hydrodynamic equation
- Realistic EoS
- Complete hadron resonance table
- Hadronic cascade after hadronization
- *All these above are applied to pp@LHC (completely new)!*

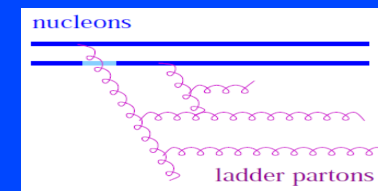
Epos and Femto

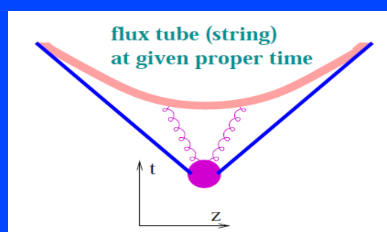
EPOS code v.2 [arxiv.org/abs/1004.0805]

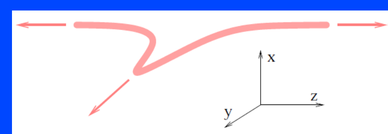


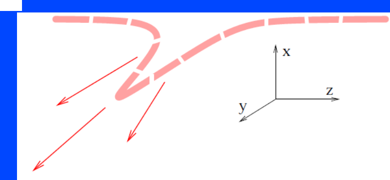


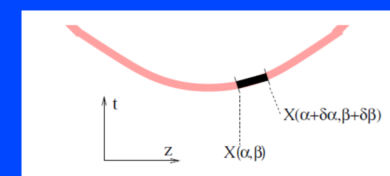




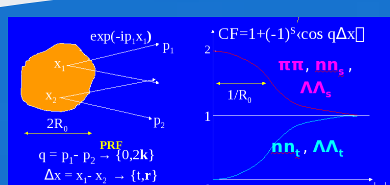




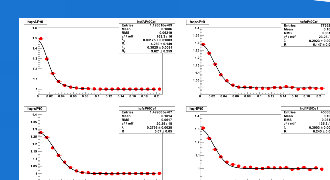




Connection via Epos Tree



Femtoscopy analysis
1d, 3d, ππ,KK,pp,
πp,pΛ,...



Radii, k_T (m_T) dependence, centrality dependence, etc

Epos Femto Package features

- Epos Femto package is a part of Epos2 code
- Femto could be used as a stand alone code (input Epos Root Tree events)
- Femto is a C++ code based on root framework
- The correlation function is calculated with event mixing technique: $C= (dN_{real}/dQ)/(dN_{mixed}/dQ)$
- The correlation weight is provided by R.Lednicky code
- All pairs of particles which are in Lednicky's code could be studied in Epos Femto package
- It is possible to smear the momentum of the particle according to the detector response

Go to the First results

K. Werner, Iu. Karpenko, T. Pierog,
M. Bleicher, K. Mikhailov

http://arxiv.org/abs/1004.0805

http://arxiv.org/abs/1010.0400

Correlation Function

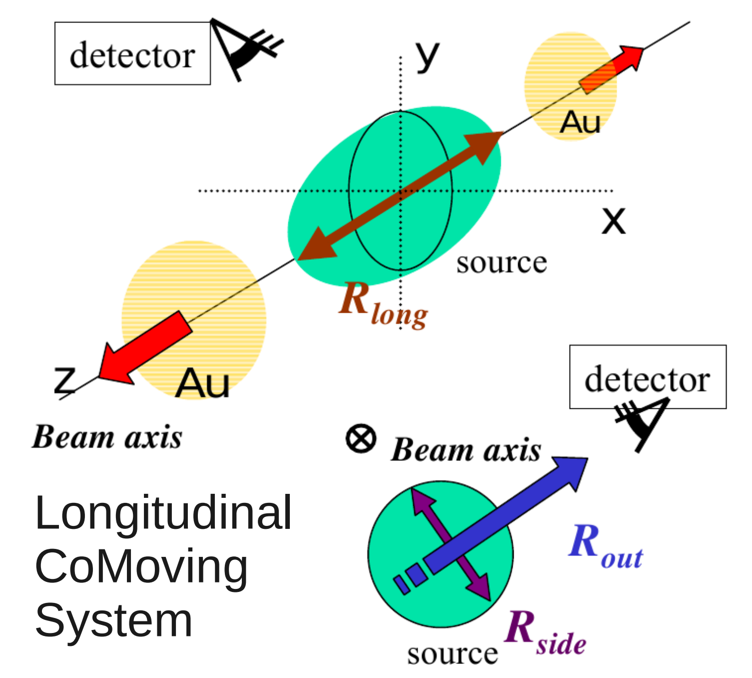
Provides source function $S(\mathbf{P}, \mathbf{r}')$ – probability of emitting a pair of hadrons with total momentum **P** and relative distance **r'** (from EPOS simulation).
Under certain assumption, S is related to the measurable correlation function $C(\mathbf{P},\mathbf{q})$ as:

$$C(\mathbf{P},\mathbf{q}) = \int d^3r' \, S(\mathbf{P},\mathbf{r}') \, |\Psi(\mathbf{q}',\mathbf{r}')|^2$$

q-relative momentum, Ψ outgoing two-particle wave function (Lednicky's code), q' amd r' relative momentum and distance in pair CMS

CF parametrized by :

$$C(\mathbf{P},\mathbf{q}) = 1 + \lambda \exp\left(-R_{\text{out}}^2 \, q_{\text{out}}^2 - R_{\text{side}}^2 \, q_{\text{side}}^2 - R_{\text{long}}^2 \, q_{\text{long}}^2\right)$$



Fit parameters λ, R_{out}, R_{side}, and R_{long} are determined for different centrality classes and for different m_T, with

$$m_T = \sqrt{k_T^2 + m^2}, \; k_T = \frac{1}{2}\left(|\vec{p}_T(\text{hadron } 1) + \vec{p}_T(\text{hadron } 2)|\right).$$

Simulation: software and input

- EPOS 2, model details in http://arxiv.org/abs/1004.0805
- Compare with STAR HBT ππ in AuAu collisions at √s=200 GeV

  [PHYSICAL REVIEW C 71, 044906 (2005)]

- Analysis of Epos events

  ~0.5 M events of AuAu collisions at 200 GeV ,
  5 centrality regions: 0–5%,5–10%, 10–20%, 20–30%, 30–50%, and 50–80%

- k_T regions: 150-250,250-350,350-450,450-600 MeV/c
- STAR accepnace: $0.15<P_T<0.8$ GeV/c, $|\eta|<0.5$
- Only Q.S. weight for $\pi+\pi+$ pairs
- Fit function (3d):

$$1+\lambda\exp(-R_{out}^2 Q_{out}^2 - R_{side}^2 Q_{side}^2 - R_{long}^2 Q_{long}^2)$$

Different Epos model scenarios

We will compare three scenarios:

1.) The full scenario:
flux tube+hydro+hadronic cascade

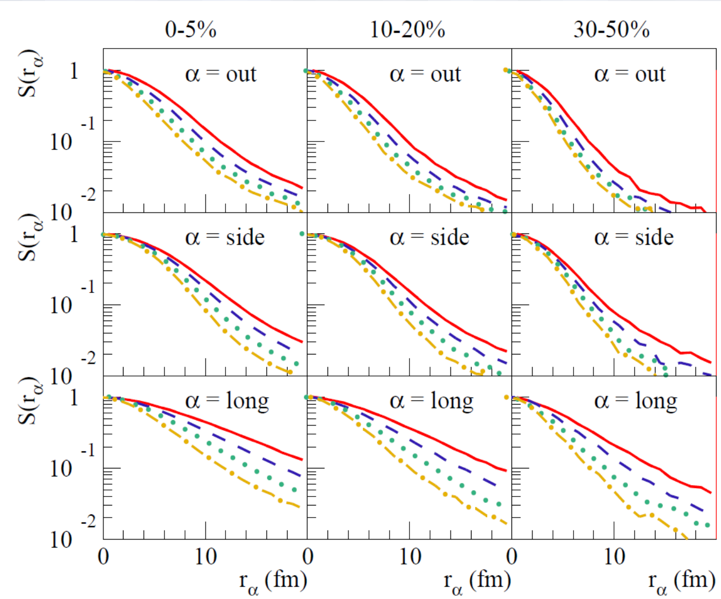
2.) The calculation without hadronic cascade:
with final freeze out at 166 MeV

3.) The fully thermal scenario:
hydrodynamical evolution till a late freeze-out
at 130 MeV and no hadronic cascade afterwards

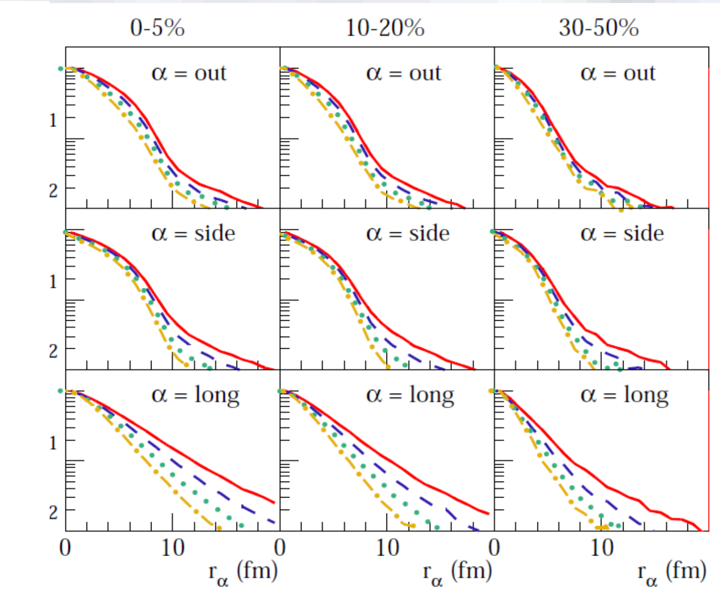
Source functions

The source functions as obtained from our simulations, for three different centralities (0-5%, 10-20%, and 30-50%), representing the distribution of the space separation of the emission points of the pairs, in LCMS. Full curves – first k_T bin, dashed – second k_T bin, and so on. The curves get narrower with increasing k_T (decreasing radii). The curves get narrower with decreasing centrality (decrease of radii with decreasing centrality).

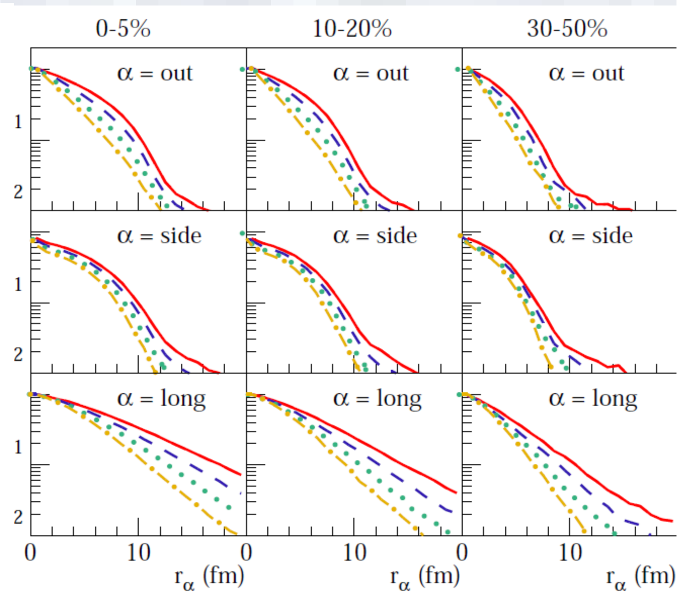
1. full scenario



2. without hadronic cascade



3. fully thermal scenario

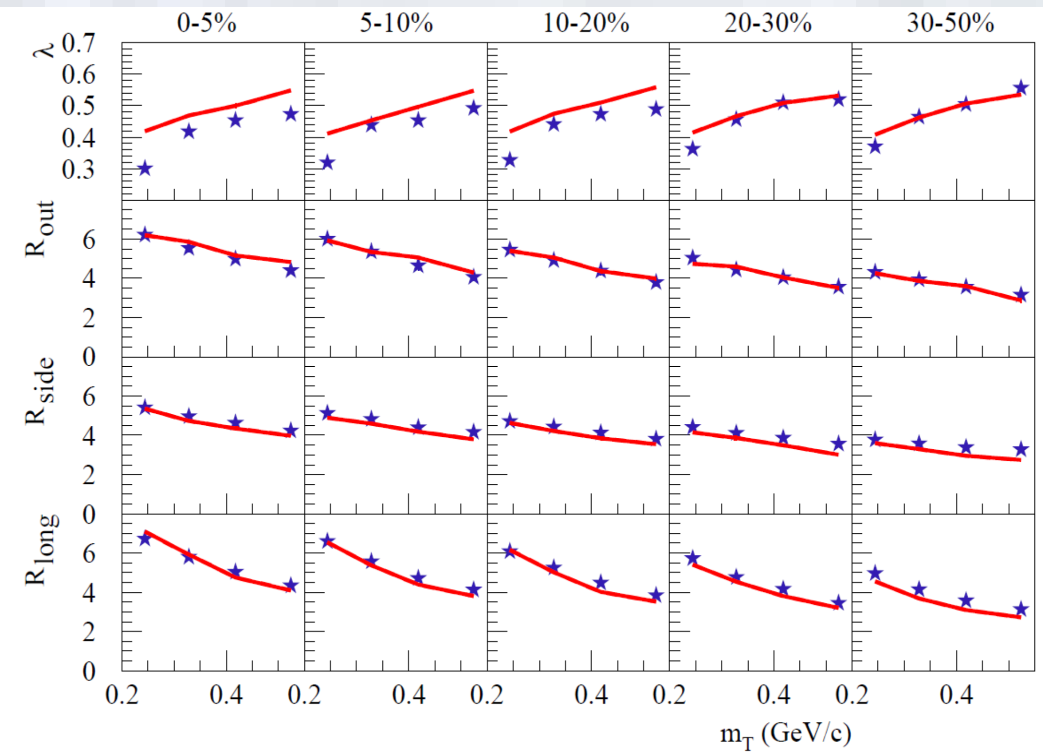


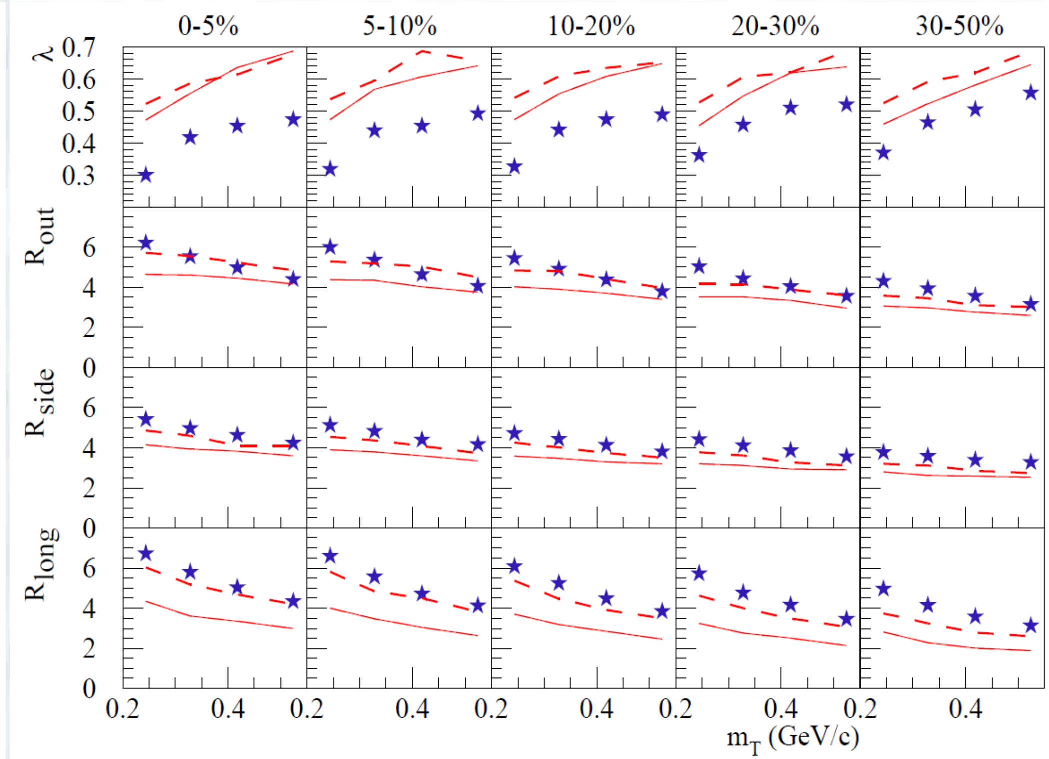
The fitting procedure based on the hypothesis that the source function Gaussians and it does not sensitive to the non-Gaussian tails.

One can expect similar results for scenario 1 and 3.

Femtoscopic radii (differnt scenarios)

R_{out}, R_{side}, and R_{long} as a function of m_T for different centralities (0-5% most central, 5-10% most central, and so on). The star sybols are the data of STAR.
Left: Thick full line - full calculation, hydro&cascade (scenario 1).
Right: Thin full line - the calculations are done without hadronic cascade (scenario 2).
Dashed lines - with a hydrodynamic evolution through the hadronic phase with freeze-out at 130 MeV (scenario 3).



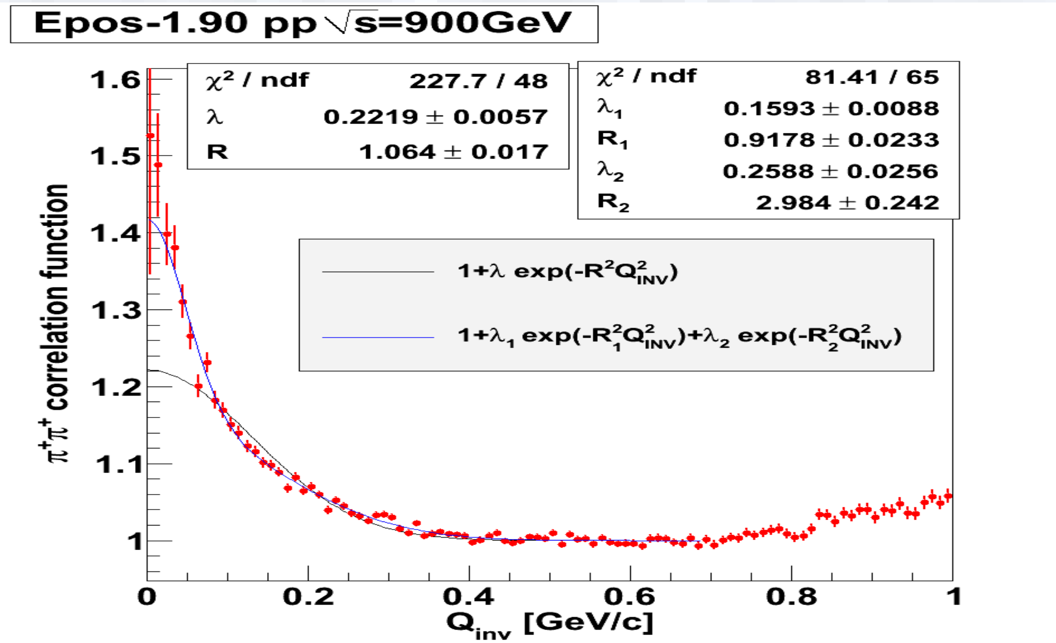


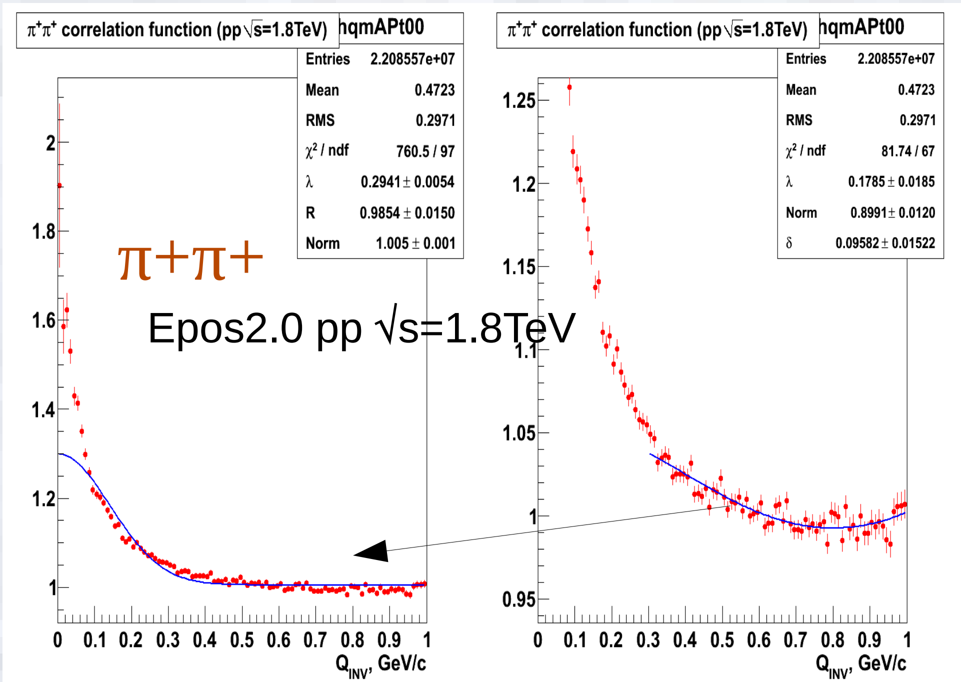
Scenario 1, scenario 3, and the data are similar.
It could be better to compare the shape of CF, not only radii

ALICE pp and Non-femtoscopic effects...

Long range correlation

These correlations (so-called “long-range correlations "— LRC) arise mainly from momentum conservation for real events, which is not a requirement for mixed pairs. LRC cause a smooth increase of CF with q, which reflects the fact that due to momentum conservation the probability of two particles emitted in the same direction is smaller than that of two particles emitted in opposite directions. Empirically, LRC can be parametrized as R ∝exp(b cos ψ), in which ψ is the angle between the two particles and b is a constant [A. V. Vlassov et al., Phys. At. Nucl. 58, 613 (1995)]. Practically, accounting for such a weak dependence of the correlation function on q is usually taken into account by introducing into data fit a factor (1 + const q^2)





PYTHIA 7e5 pp events √s=14 TeV

$\pi^+\pi^+$ correlation function

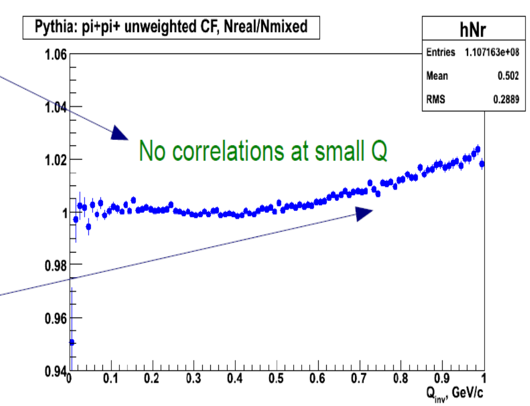
Cuts:

- $0.1 < P_T < 1.0$ GeV/c
- $-1. < \eta < +1.$

CF=Real/Mixed

Energy and Momentum Conservation-Induced Correlations:

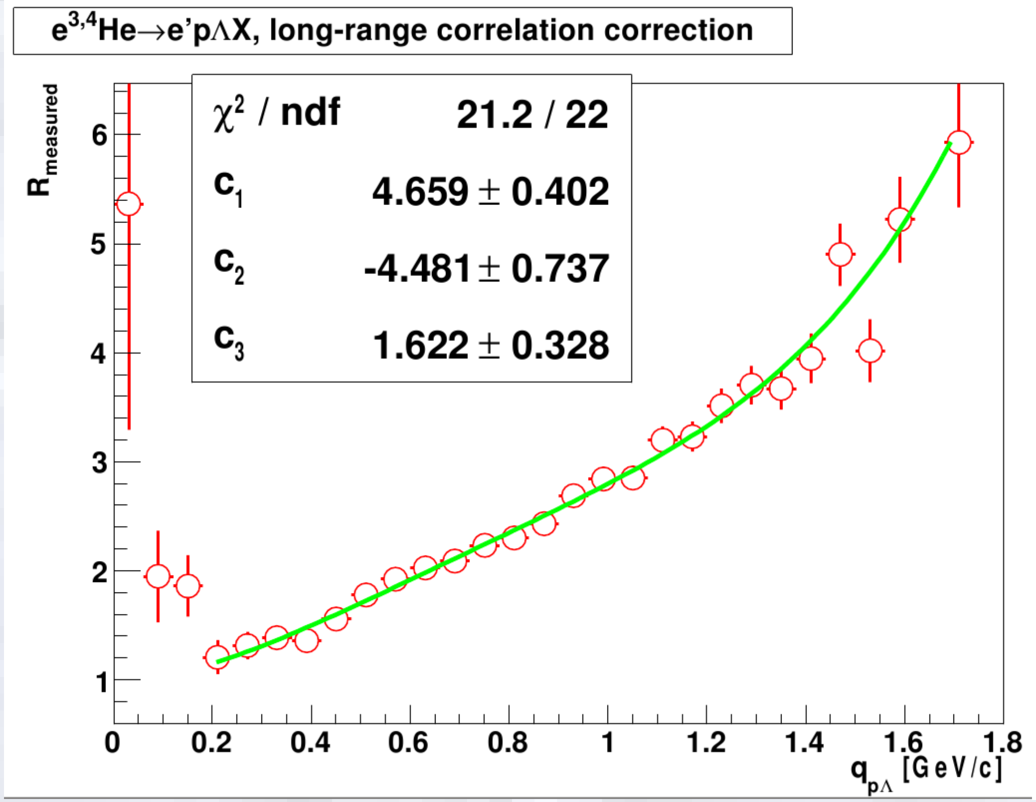
Due to energy-momentum conservation probability of two particle emitted at same direction is smaller than in opposite direction

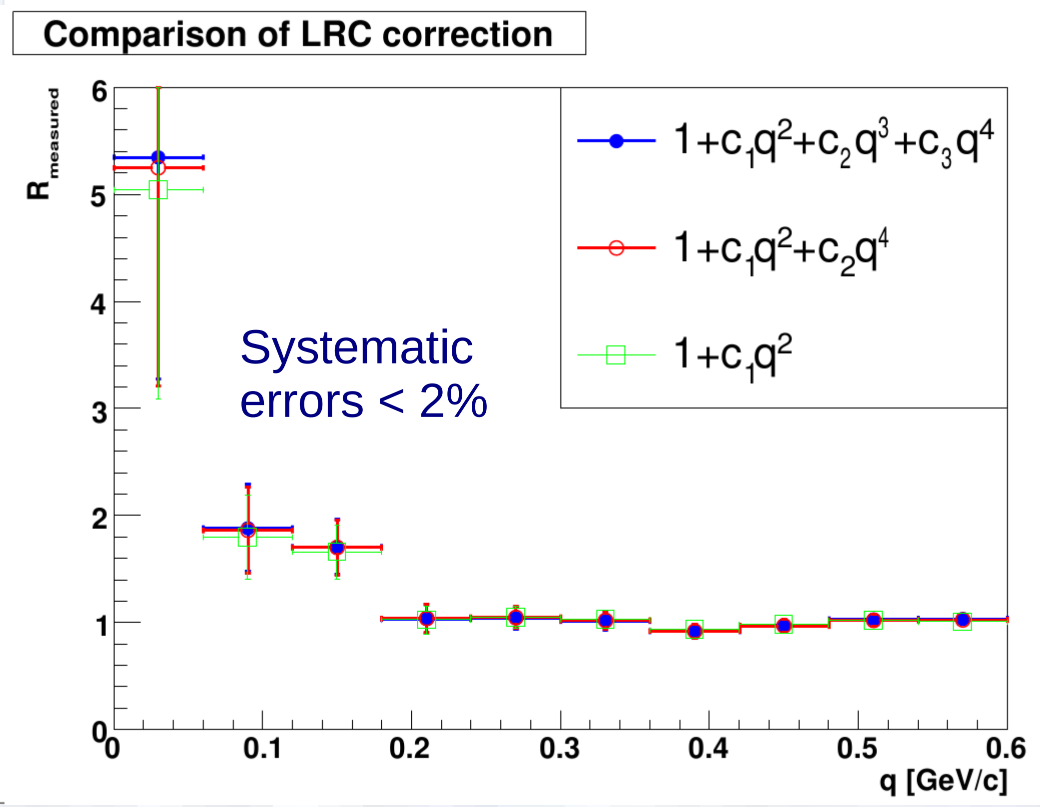


CEBAF data

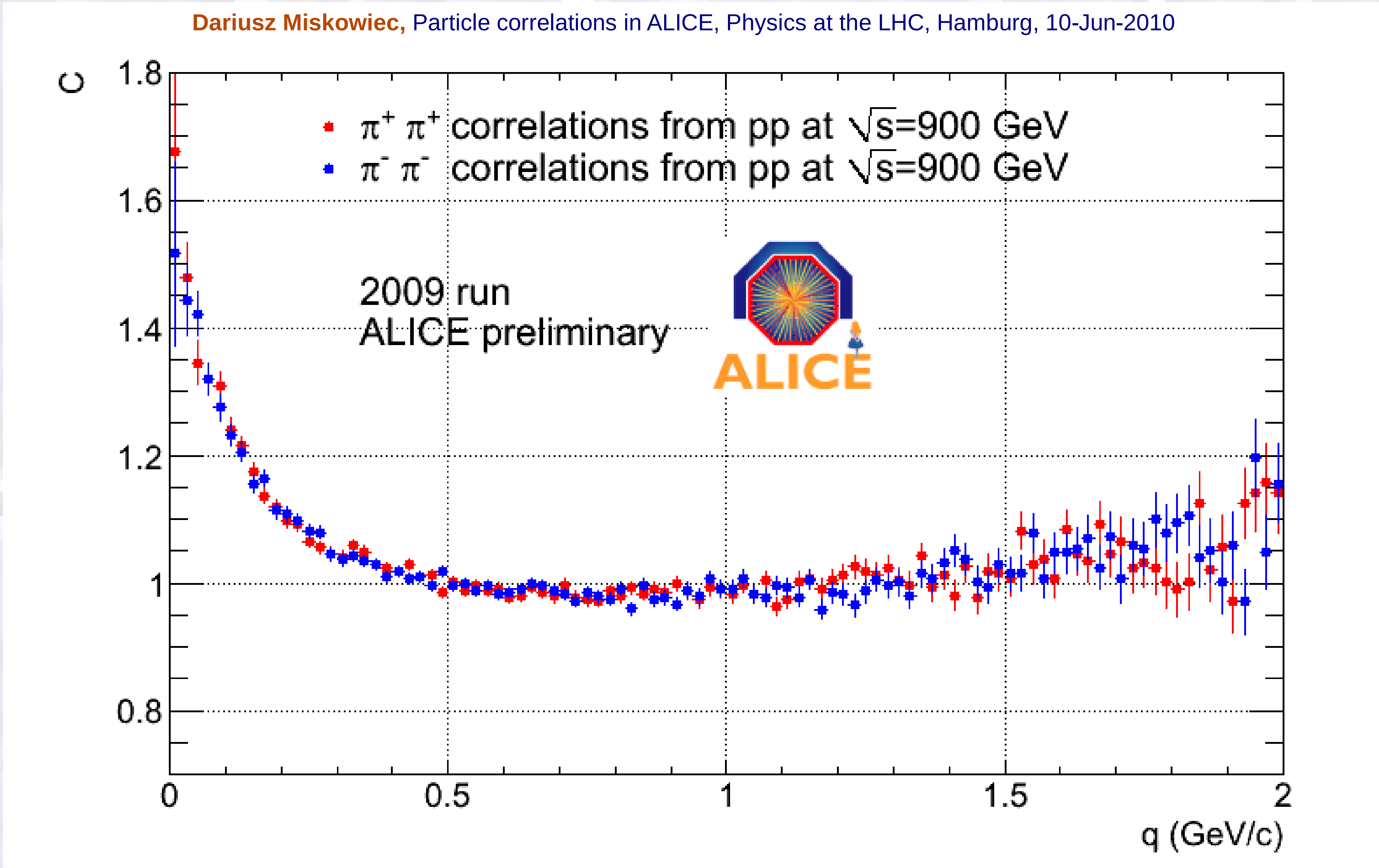
Source-Size Measurements in the $e^3He(^4He) \rightarrow e'p\Lambda X$ Reaction

[Physics of Atomic Nuclei, 2009, Vol. 72, No. 4, pp. 668–674.]





LRC in ALICE


Dariusz Miskowiec, Particle correlations in ALICE, Physics at the LHC, Hamburg, 10-Jun-2010
C
1.8
1.6
1.4
1.2
1
0.8
π+ π+ correlations from pp at √s=900 GeV
π- π- correlations from pp at √s=900 GeV
2009 run
ALICE preliminary
ALICE
0
0.5
1
1.5
2
q (GeV/c)

Non-femtoscpic effects with EPOS

- ππ correlation in pp at √**s**=900GeV Epos 2.05 model calculation
- k_T intervals [100,250],[250,400],[400-550],[550-700],[700-1000] MeV/c
- High multiplicity $dN_{ch}/d\eta(0)=12.9$
- Full correlation function with mixing procedure (femto and non-femto):

$CF = [dN_{real}/dq_{inv} *W(r,p)] / [dN_{mixed}/dq_{inv}]$

- Pure femtoscopic correlation function (femto):

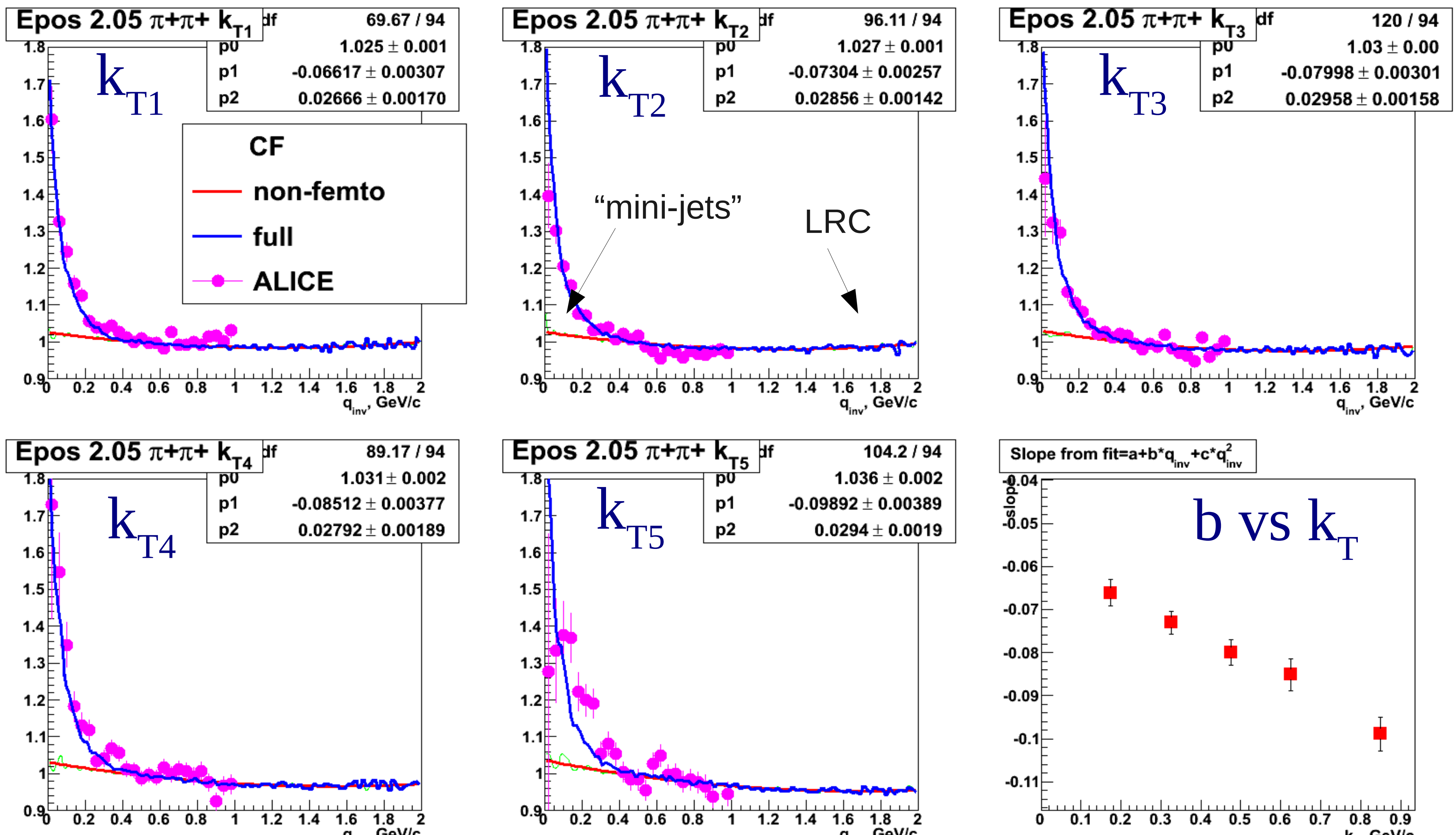
$CF= [dN_{real}/dq_{inv} *W(r,p)] / [dN_{real}/dq_{inv}]$, where W is pure femtoscopic weight from Lednicky's code (QS only)

- Pure Epos correlation function (non-femto):

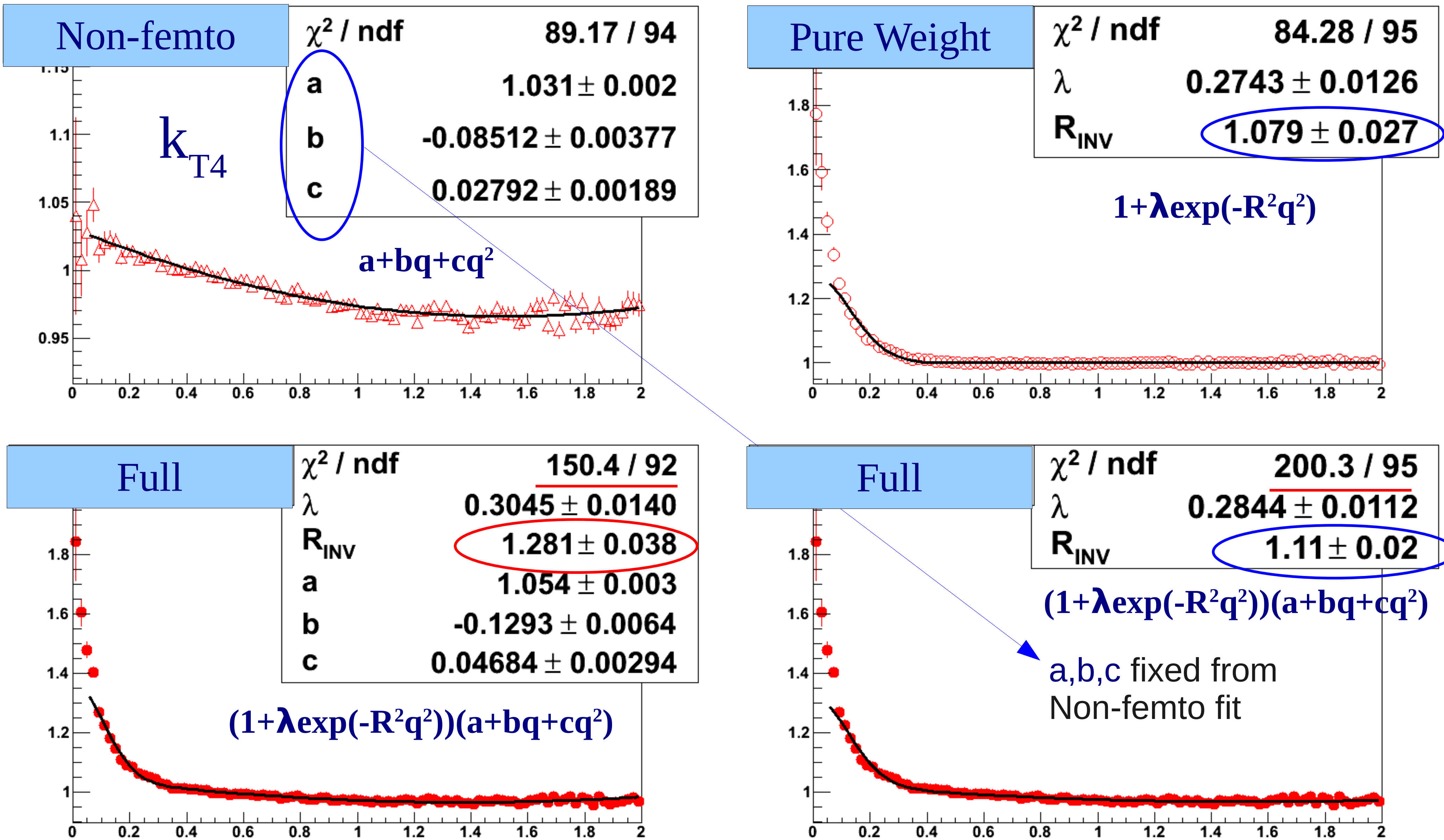
$CF = [dN_{real}/dq_{inv}] / [dN_{mixed}/dq_{inv}]$

Epos non-femto: $a+bq_{inv}+cq_{inv}^2$

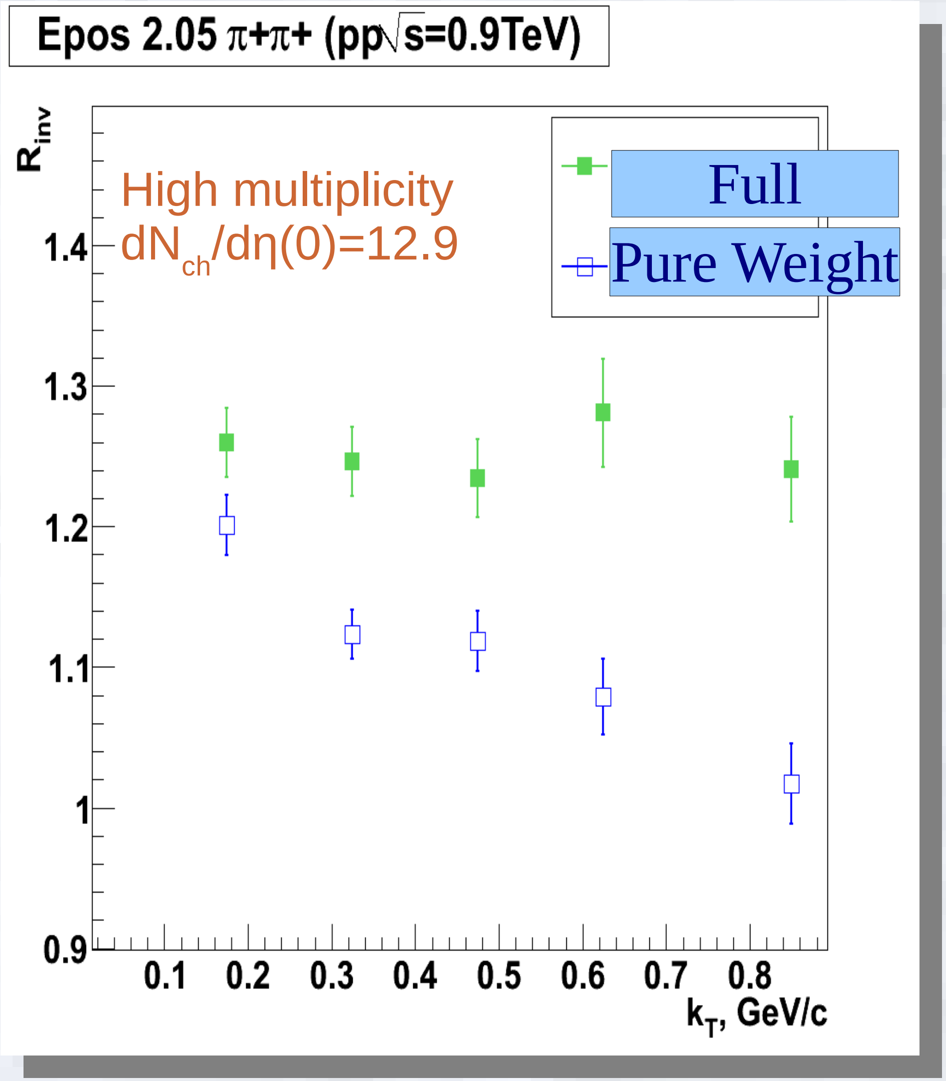
Points are ALICE ππ correlation in pp$\sqrt{S}$=900GeV data [arXiv:1007.0516v1 hep-ex]
Blue curves are the full scenario simulation with EPOS [arXiv:1010.0400v1 nucl-th]

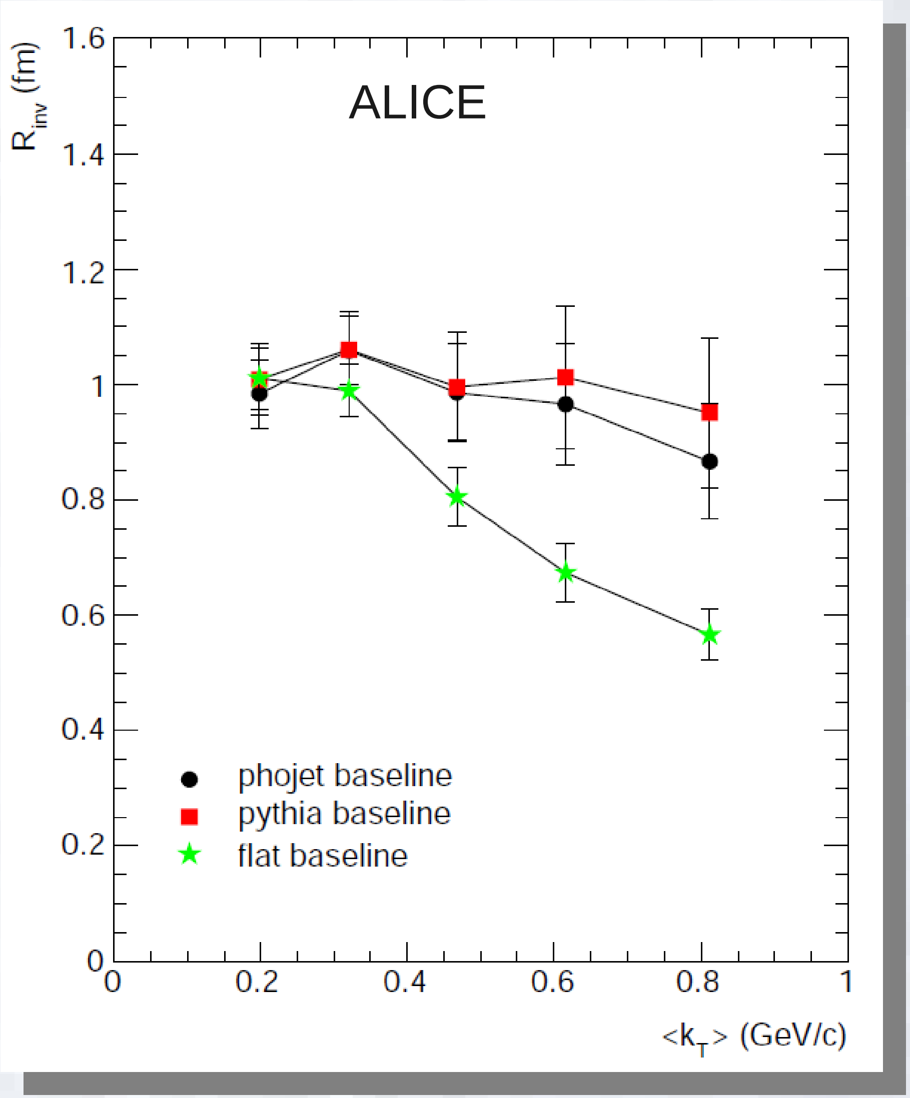


Epos: non-femto, pure, real/mix



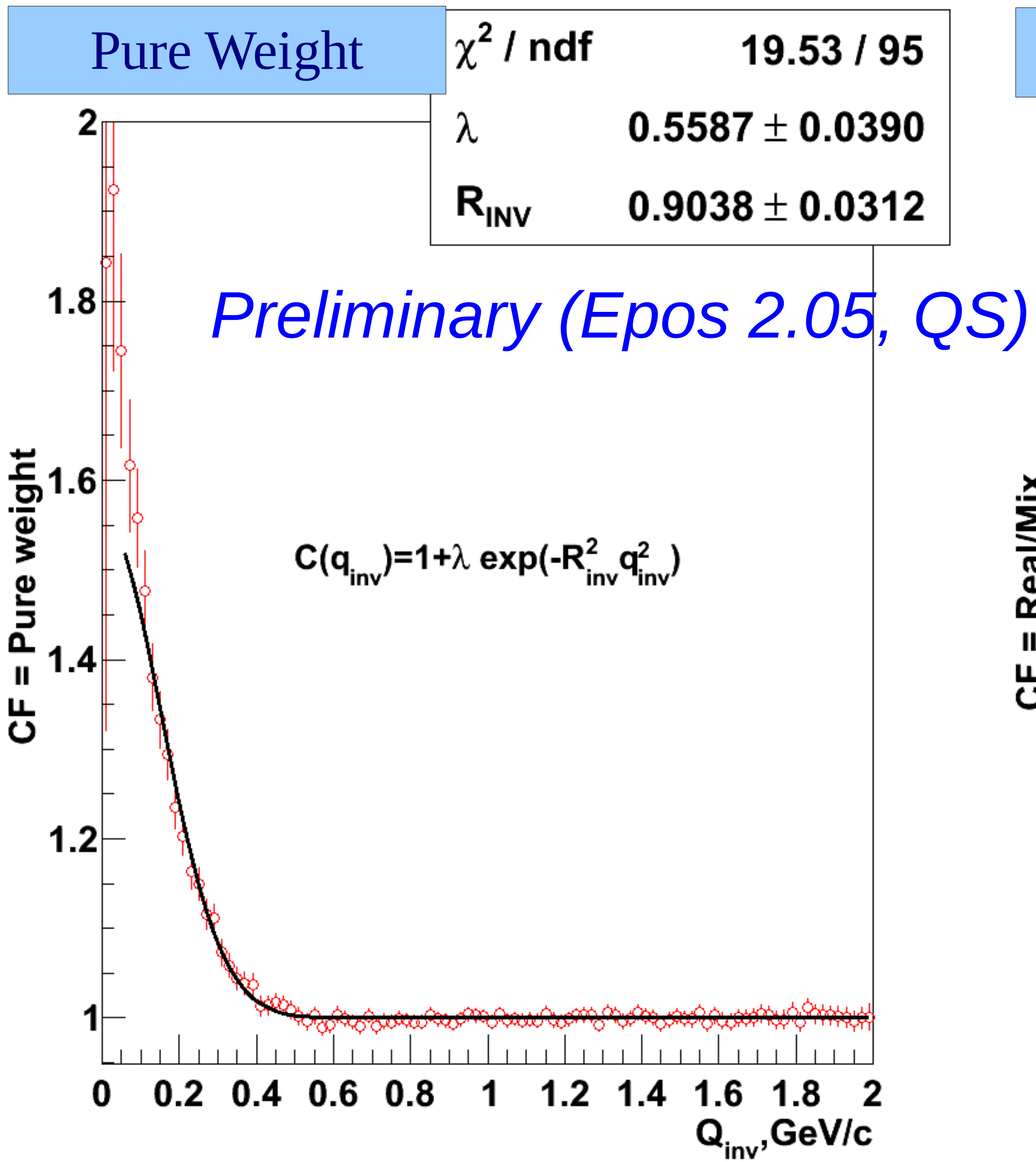
R_{inv} pure and full

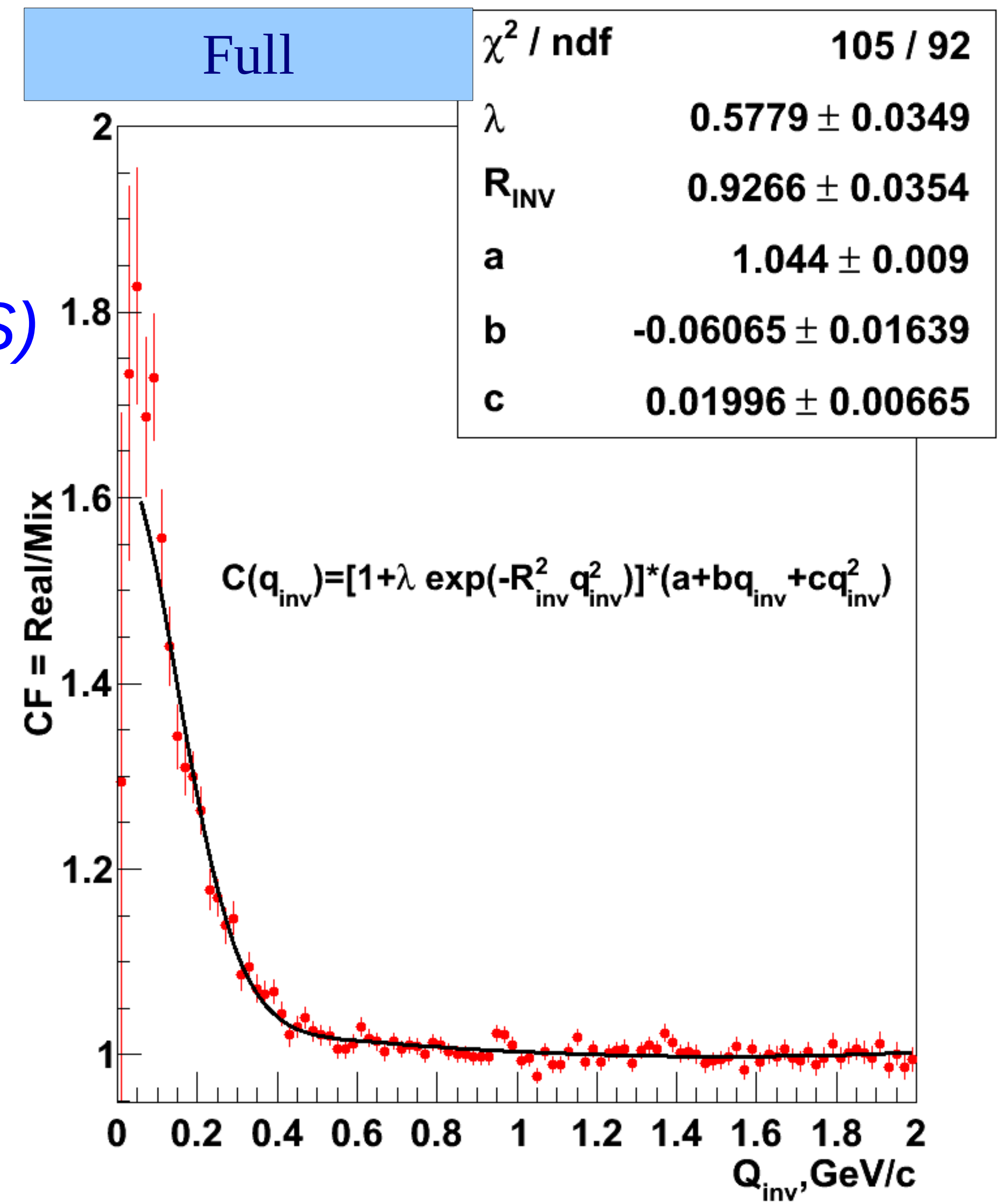




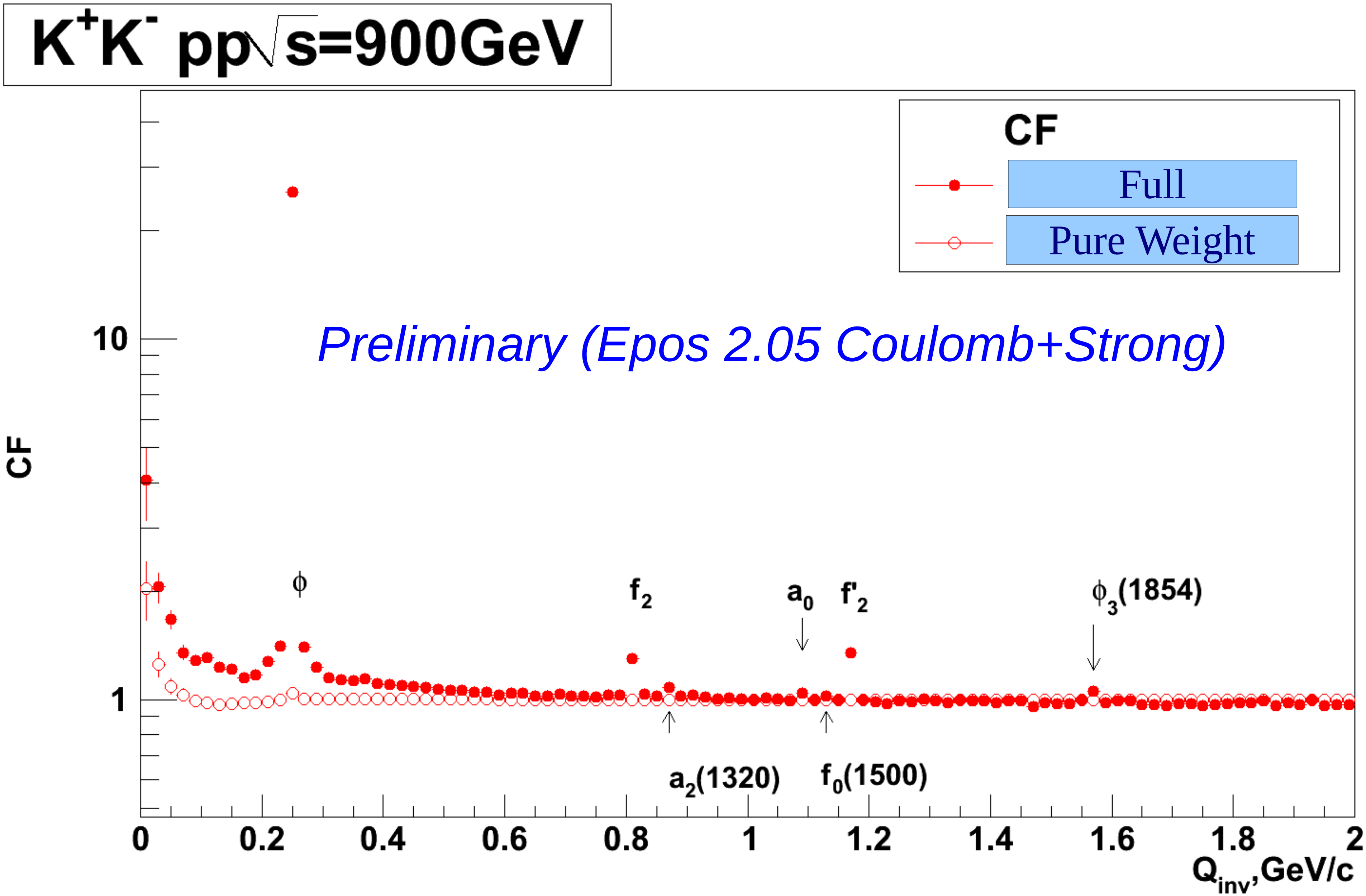
KK in Epos 2.05 (Preliminary)

Epos 2.05 K+K+ pp $\sqrt{s}$=900GeV





Epos 2.05 K+K- pp √s=900GeV



Conclusion

1. The Epos Femto package exists and works
2. STAR HBT pipi data was described with new Epos2+Femto
3. New studies (pp collisions at LHC energies) with Epos Femto are in progress [http://arxiv.org/abs/1010.0400]
4. Non-femtoscopic effects could be very important in case of low multiplicity, e.g. pp collisions

Thank you for your attention!

Extra Slides

Histograms

- Source function histograms:
  ΔR_{out}, ΔR_{side}, ΔR_{long} in LCMS

- 1D correlation function histograms:
  dN_{real}/dQ, projections: dN_{real}/dQ_{out}, dN_{real}/dQ_{side}, dN_{real}/dQ_{long}
  dN_{mix}/dQ, projections: dN_{mix}/dQ_{out}, dN_{mix}/dQ_{side}, dN_{mix}/dQ_{long}
  CF(Q), projections: $CF(Q_{out})$, $CF(Q_{side})$, $CF(Q_{long})$

- 3D correlation function histograms:
  $d^3N_{real}/dQ_{out}dQ_{side}dQ_{long}$
  $d^3N_{mix}/dQ_{out}dQ_{side}dQ_{long}$
  $CF(Q_{out},Q_{side},Q_{long})$

- A few technical histograms in addition

Fit functions

- 1D fit function:

  $1+\lambda \exp(-R_{inv}^2 Q_{inv}^2)$

  $1+\lambda_1 \exp(-R_1^2 Q_{inv}^2)+\lambda_2 \exp(-R_2^2 Q_{inv}^2)$

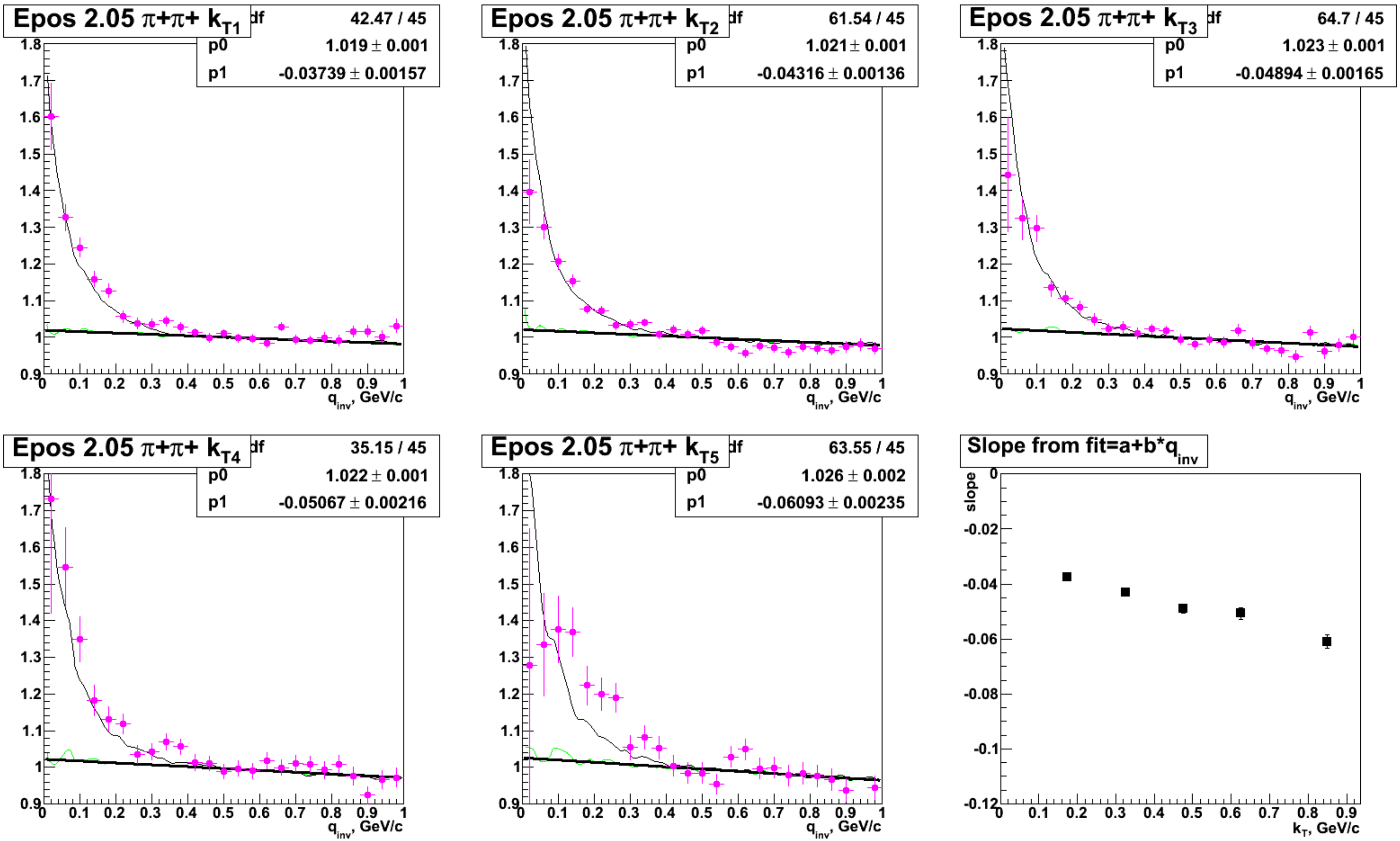
  $(1+\lambda \exp(-R_{inv}^2 Q_{inv}^2))*(1+\delta Q_{inv}^2)$

  $(1+\lambda \exp(-R_{inv}^2 Q_{inv}^2))*(a+bQ_{inv}+cQ_{inv}^2)$

- 3D fit function:

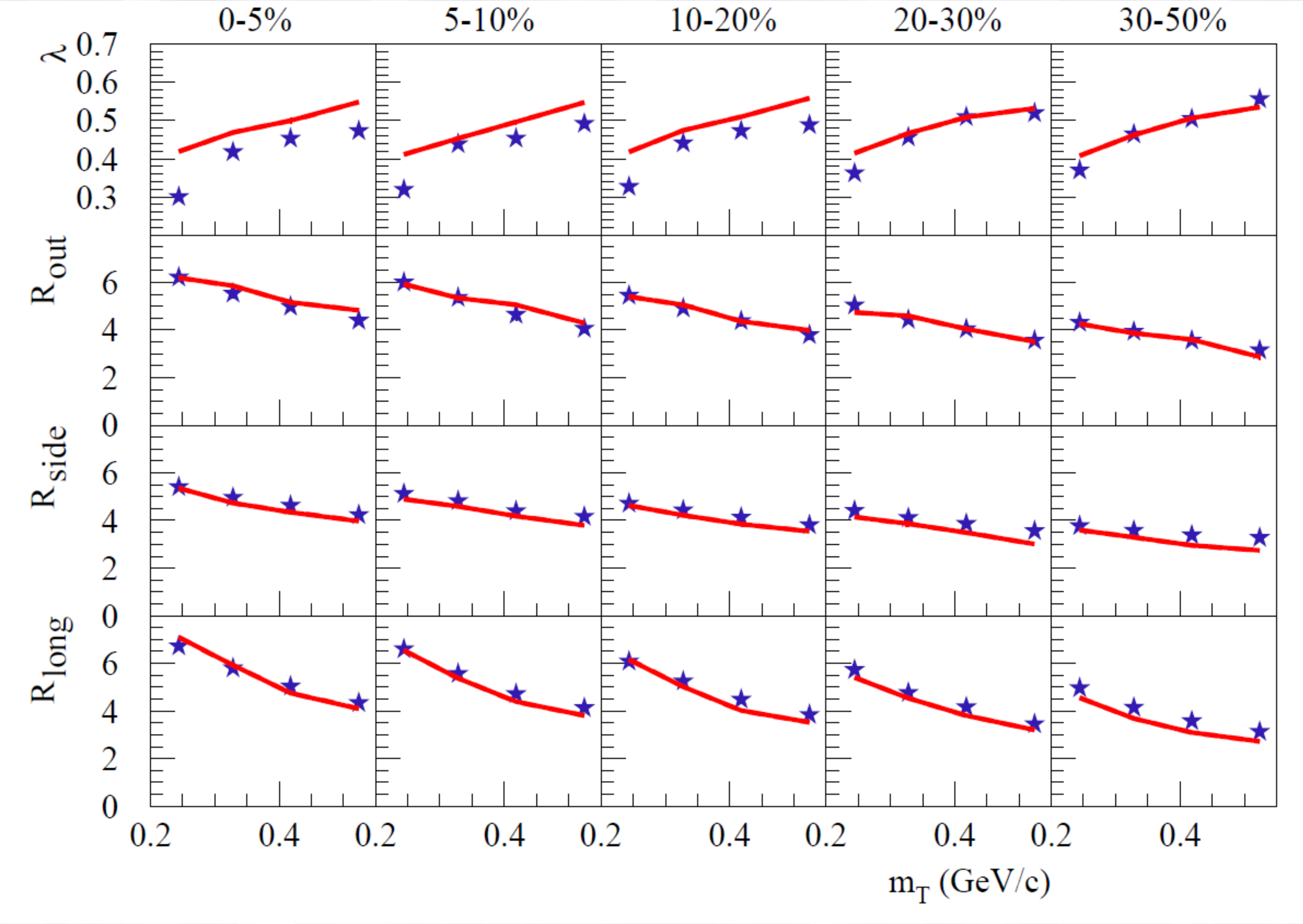
  $1+\lambda \exp(-R_{out}^2 Q_{out}^2 - R_{side}^2 Q_{side}^2 - R_{long}^2 Q_{long}^2)$

$a+bq_{inv}$ in $\pi^+\pi^+$ CF

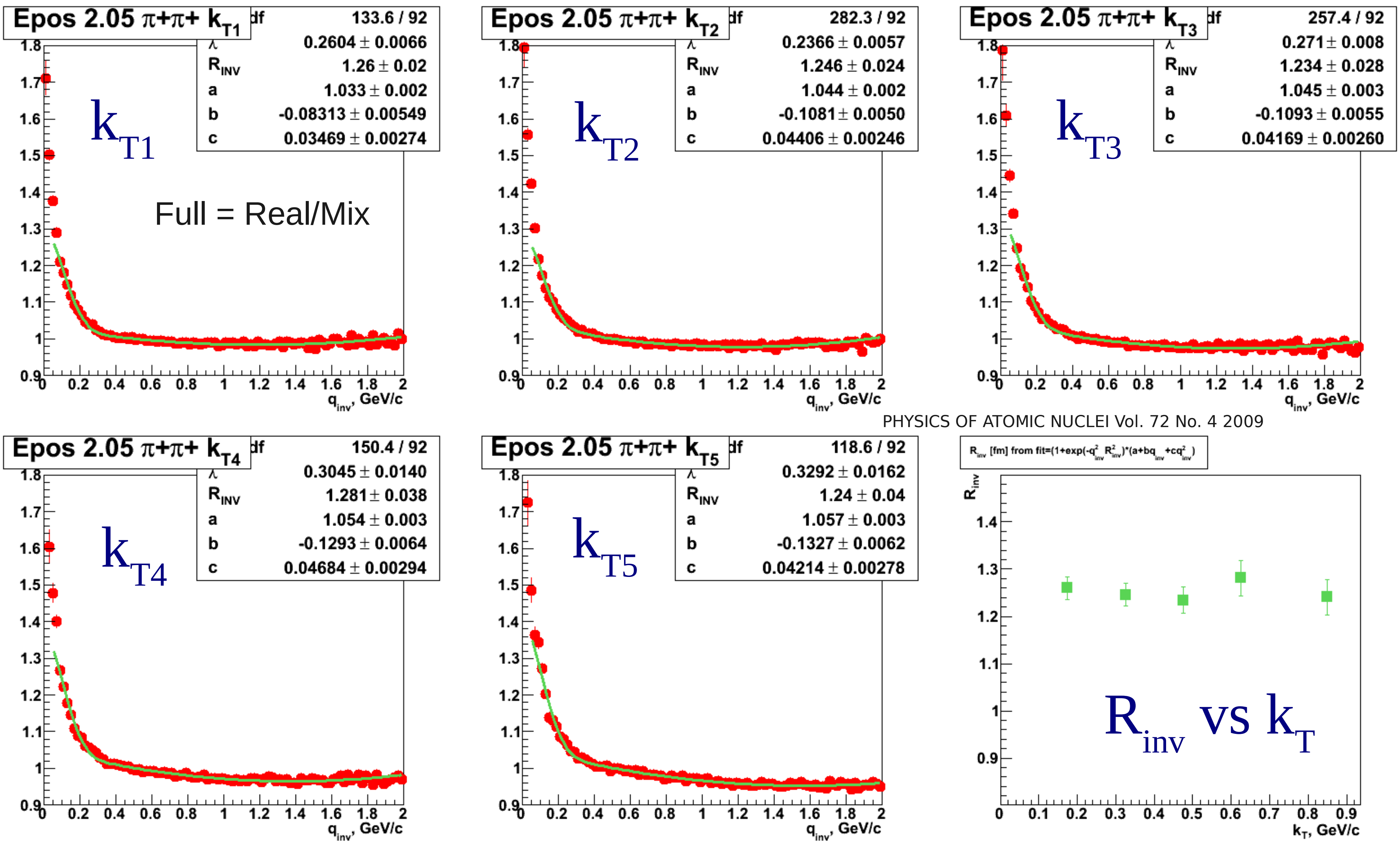


Femtoscopic radii (full calculation)

Rout, Rside, and Rlong as a function of m_T for different centralities (0-5% most central, 5-10% most central, and so on). The full lines are the full calculations (including hadronic cascade), the stars data of STAR

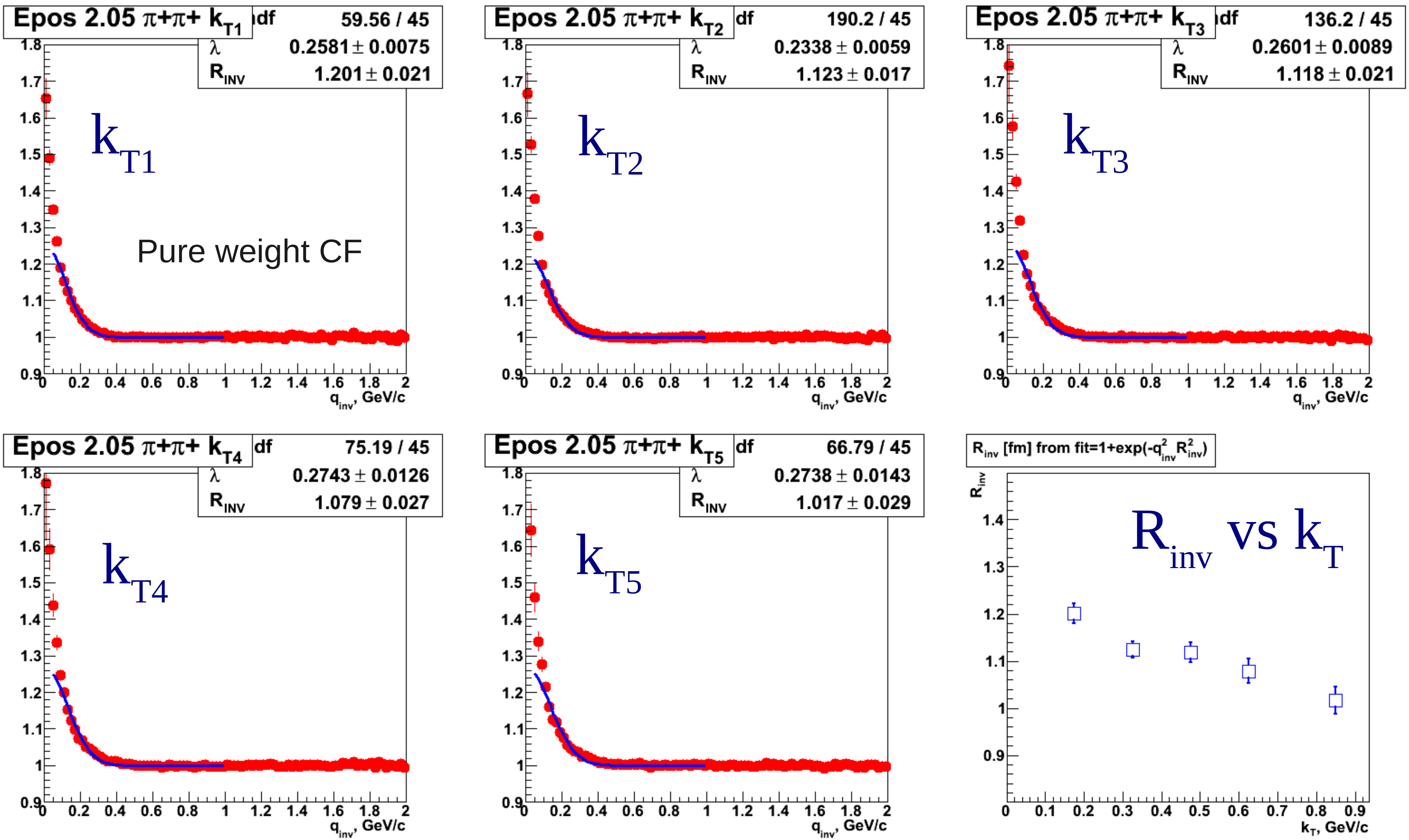


Epos full: $(1+\lambda \exp(-R^2q^2))(a+bq+cq^2)$



PHYSICS OF ATOMIC NUCLEI Vol. 72 No. 4 2009

Epos pure weight: $(1+\lambda \exp(-R^2q^2))$

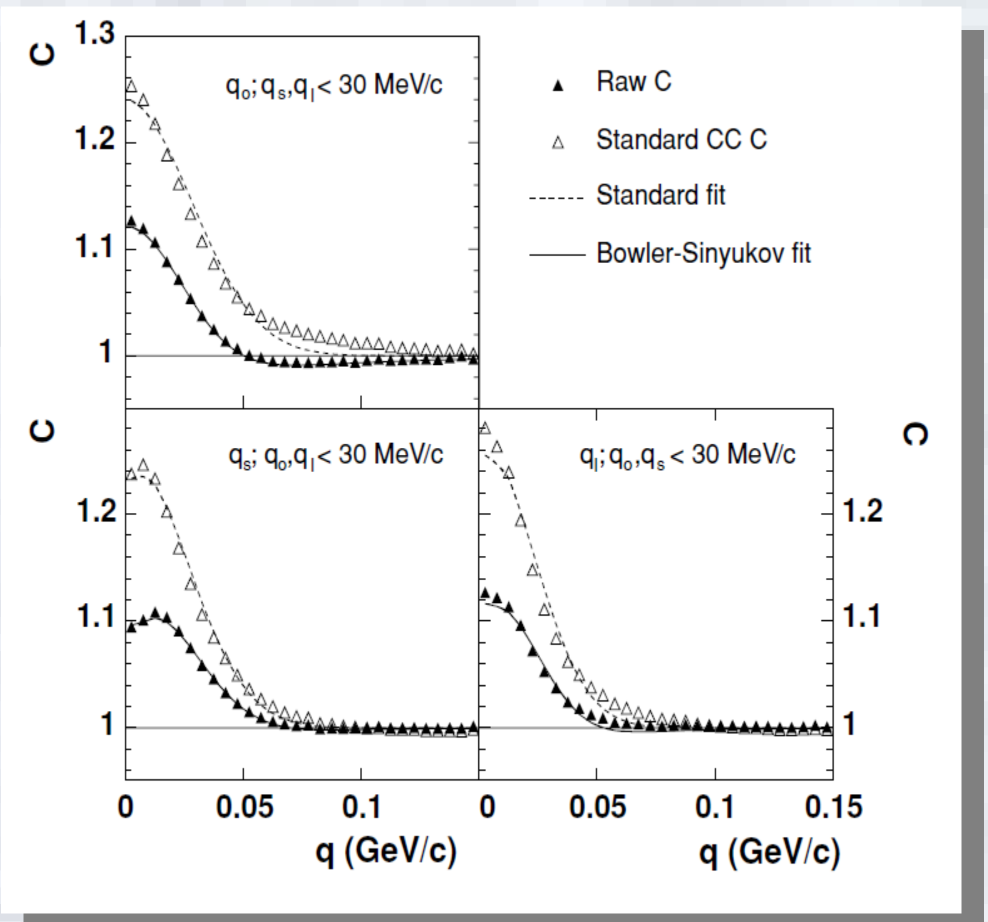


STAR experimental results

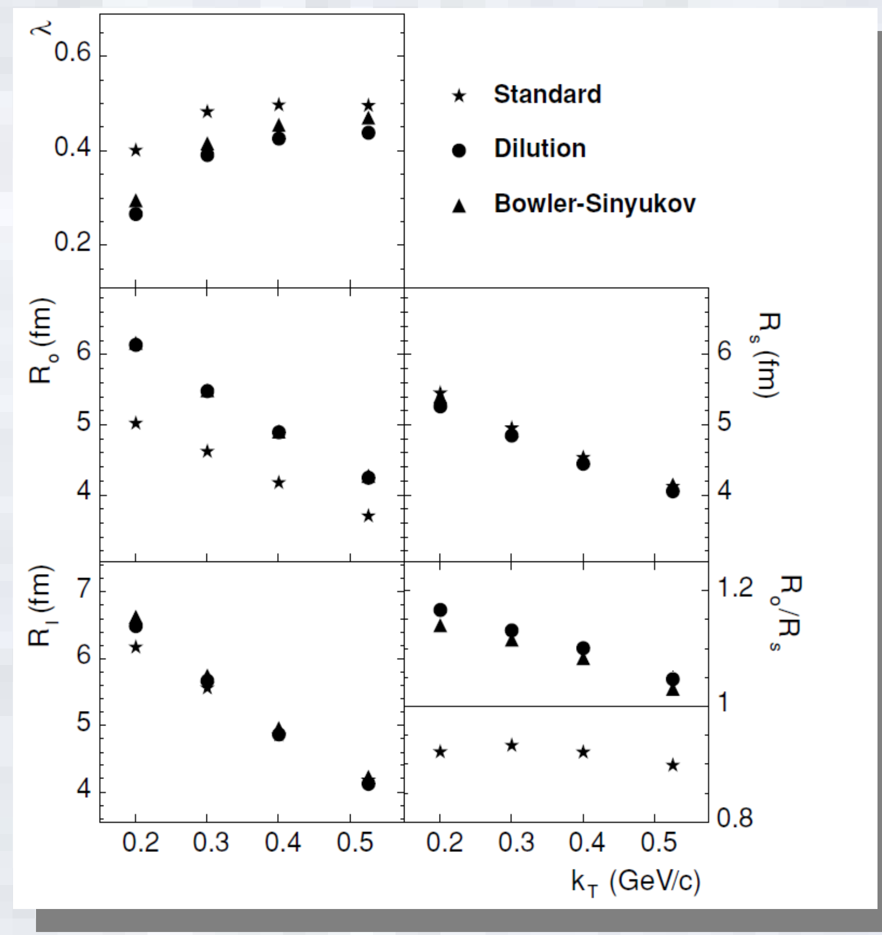
RHIC-STAR: ππ femtoscopy for Au+Au $_{NN}$=200GeV

[PHYSICAL REVIEW C 71, 044906 (2005)]

Projection of 3-d correlation function

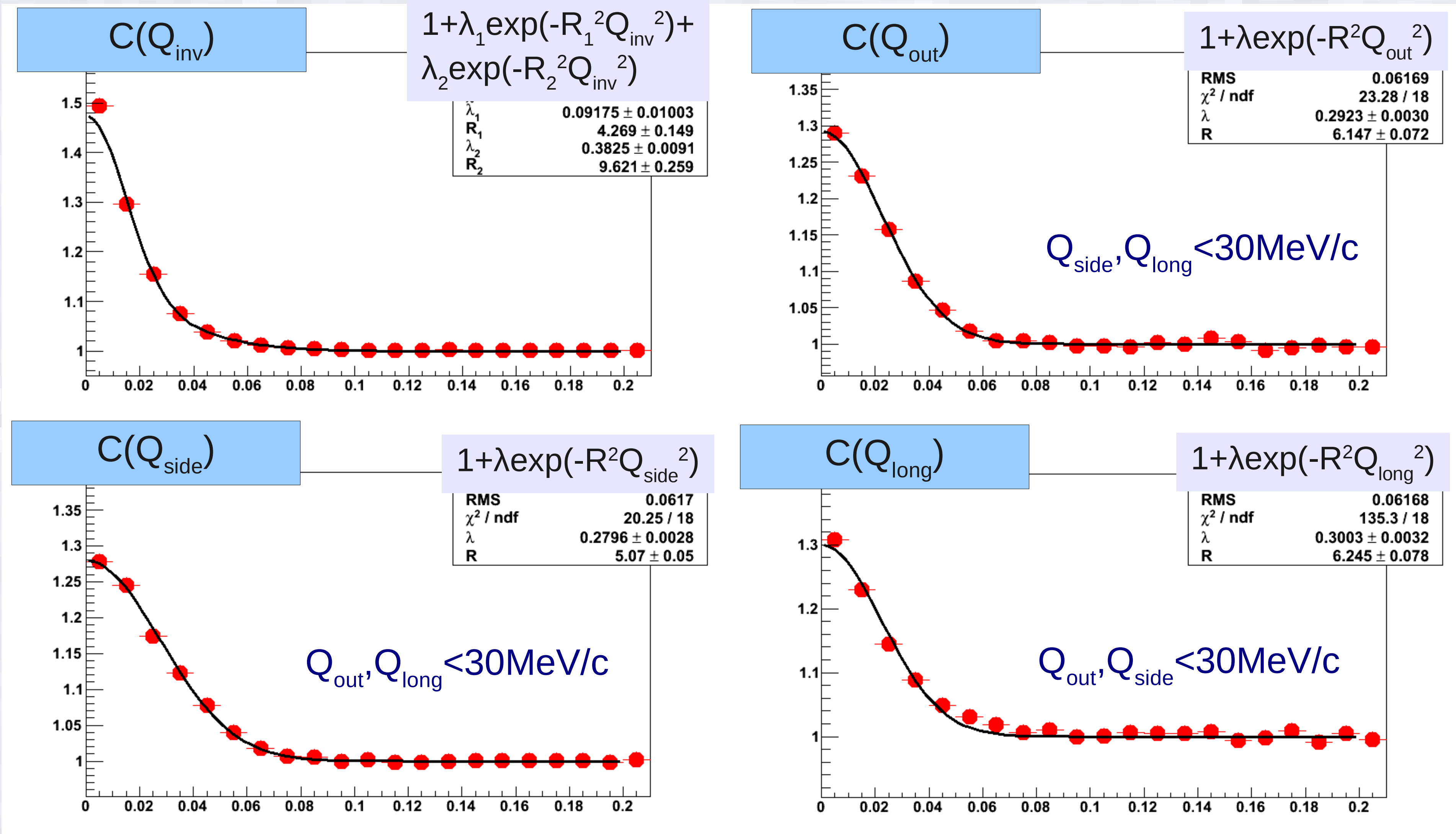


3-d fit results (3 variants of Coulomb)



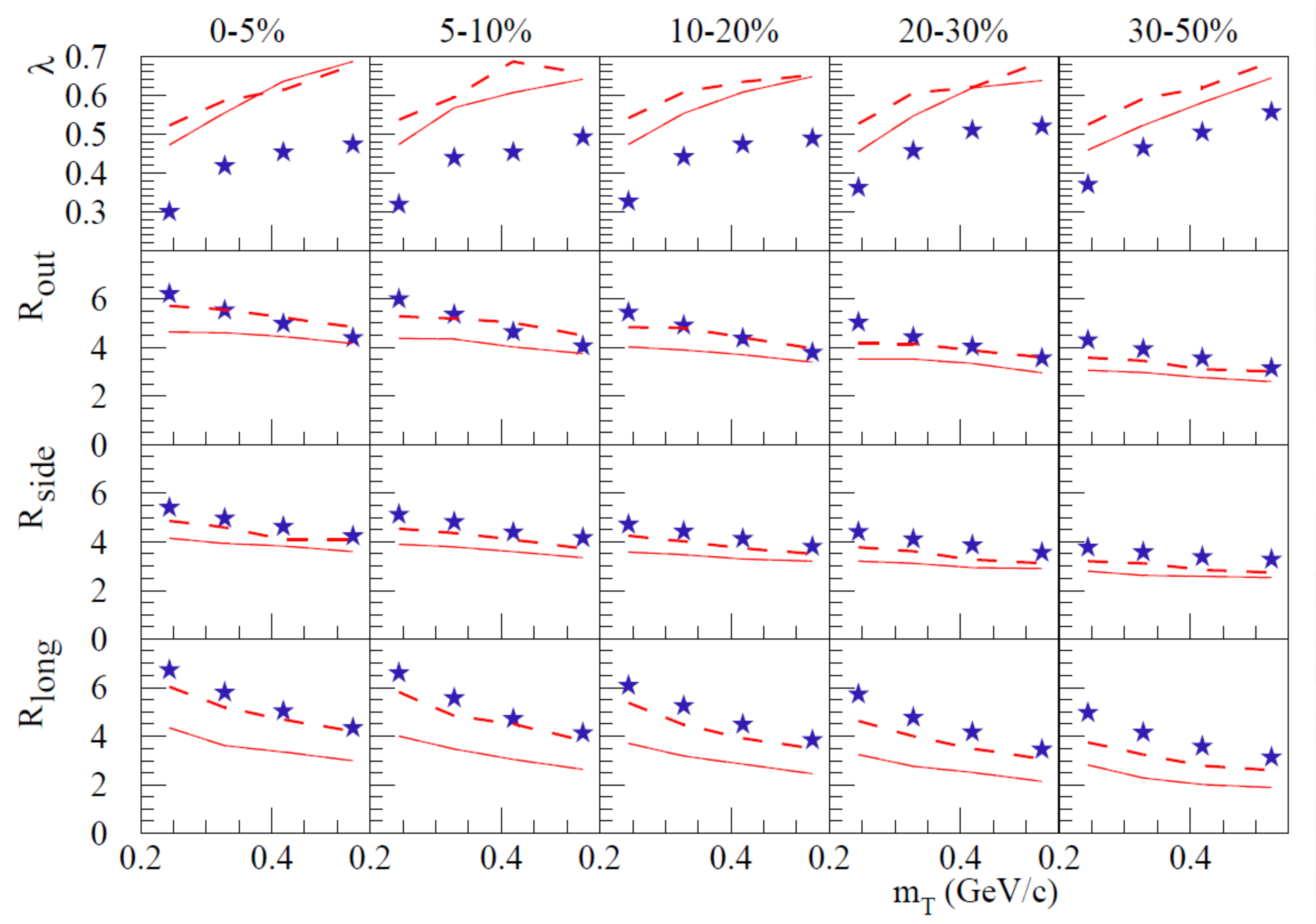
Femto package: 1d CF

Example of 1d pi+pi+ correlation function for central events



Femtoscopic radii (other scenarios)

Full line the calculations are done without hadronic cascade (scenario 2).
Dashed lines with a hydrodynamic evolution through the hadronic phase with freeze-out at 130 MeV (scenario 3).



Flux tube

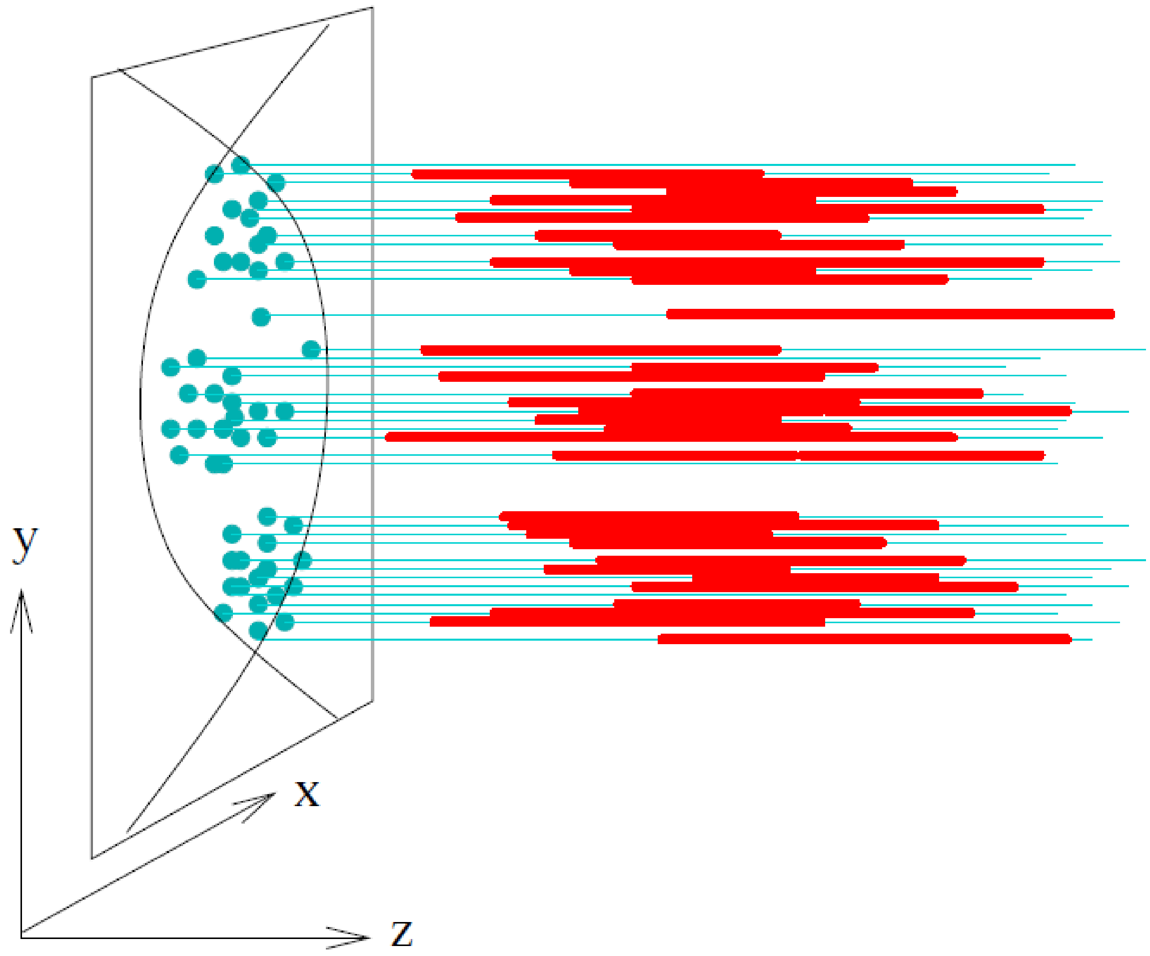


Figure 1: Macroscopic flux tubes (three in this example), made out of many individual ones, of variable length.

3+1 Hydro

Core evolves according to the equations of hydrodynamics:

local energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0, \quad \nu = 0, ..., 3\,,$$

and the conservation of net charges,

$$\partial N_k^\mu = 0, \quad k = B, S, Q\,,$$

with B, S, and Q referring to respectively baryon number, strangeness, and electric charge.

Here: ideal hydrodynamics:

$$T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}\,, \quad N_k^\mu = n_k u^\mu,$$

where u is the four-velocity of the local rest frame (unknowns: $\varepsilon(x)$, $u(x)$, $n_k(x)$.

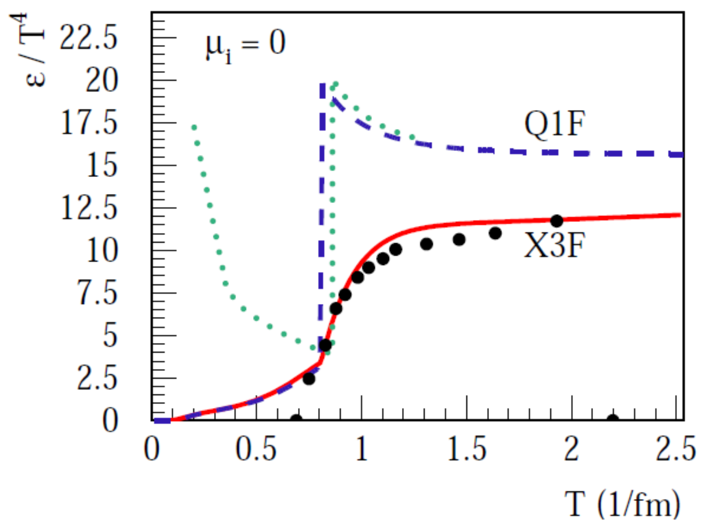


Figure **11**: Energy density versus temperature, for our equation-of-state X3F (full line), compared to lattice data [66] (points), and some other EoS choices, see text.

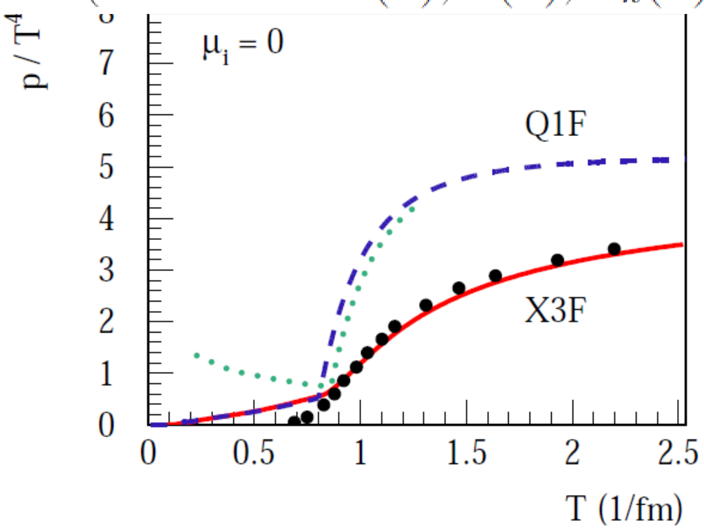
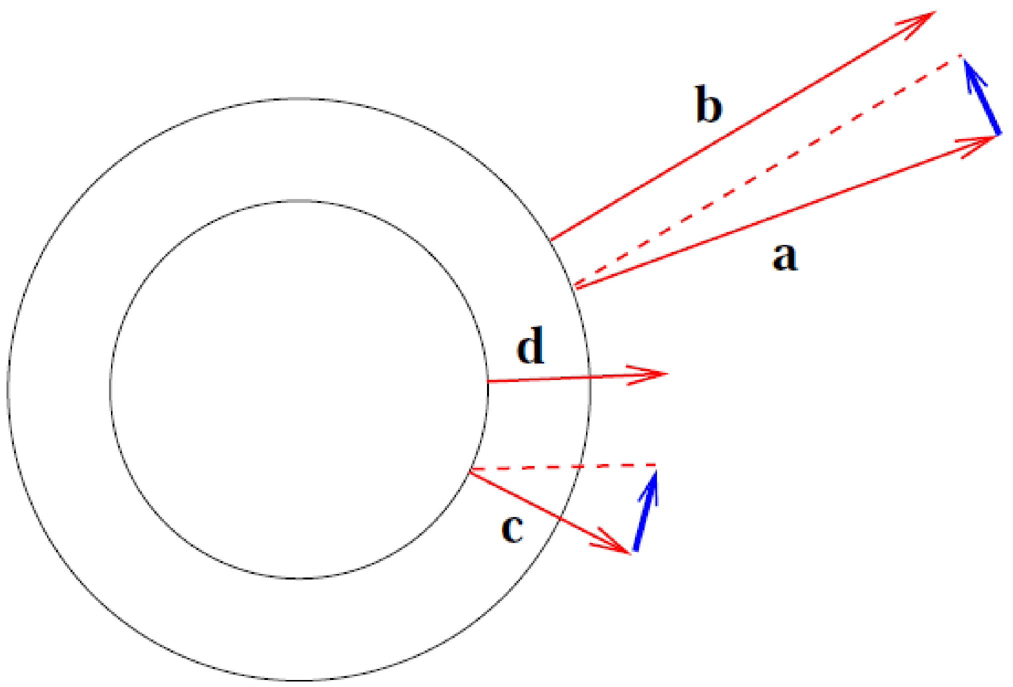


Figure **12**: Pressure versus temperature, for our equation-of-state X3F (full line), compared to lattice data [66] (points), and some other EoS choices, see text.

Radial flow effect on m_T dependence of femtoscopic radii:



distances get smaller outwards for fixed momentum differences

Basics of EPOS(parton model)

Klaus Werner. Nucl.Phys.175-176(2008)81-87

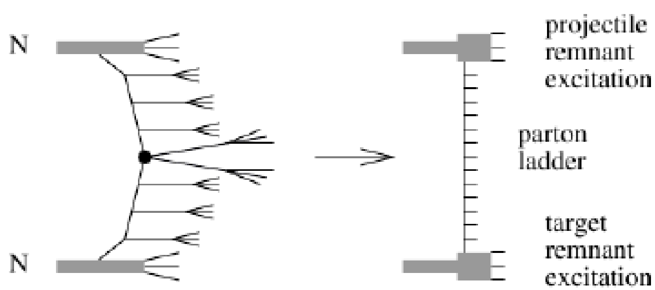
EPOS is a sophisticated multiple scattering approach based on partons and Pomerons (parton ladders), with special emphasis on high parton densities. The latter aspect, particularly important in proton-nucleus or nucleus-nucleus collisions, is taken care of via an effective treatment of Pomeron-Pomeron interactions, referred to as parton ladder splitting. In addition, collective effects are introduced after separating the high density central core from the peripheral corona. EPOS is the successor of the NEXUS model.

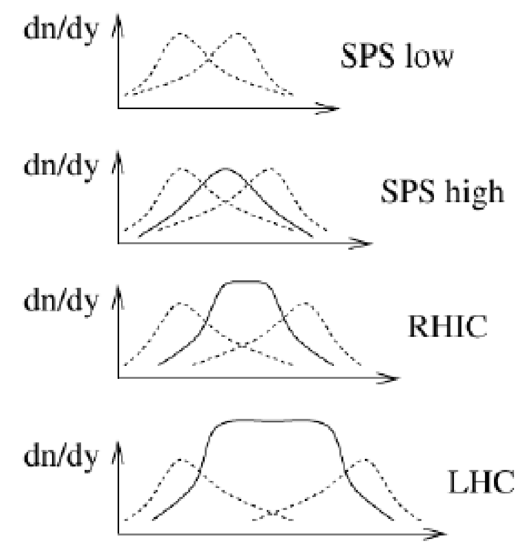
Energy conserving quantum mechanical multiple scattering approach based on

Parton (parton ladders)

Off-shell remnants, and

Splitting of parton ladders





4 Tests

- **Check basic "soft physics" RHIC data (only AuAu ≥ 200 distributions)**
  - **Particle yields and eta distributions**
    - STAR and PHENIX
      average yields and mean pt of pions, kaons, protons, lambdas, xis vs centrality
    - BRAHMS
      eta distr for different centralities 0-5% 5-10% 10-20% 20-30% 30-40% 40-50%
      rapidity distr of pions, kaons, protons(central)
      mean pt vs rapidity of pions, kaons (central)
  - **pt spectra**
    - PHOBOS: pt distributions of charged particles at centralities 0-6%, 6-15%, ..., 45-50%
    - BRAHMS: pt distributions of pions, kaons, protons at given rapidity (central)
    - PHENIX: pt distributions of pions, kaons, protons for different centralities:
      0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-92%
    - STAR: mt distributions of pions, kaons, protons for different centralities
      0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80 %
    - STAR pt distributions of strange baryons for different centralities:
      0-5%, 10-20%, 20-40%, 40-60%, 60-80%
  - **v2:**
    - PHOBOS: v2 vs eta for different centralities: MB, 3-15, 15-25, 25-50, 0-40
      v2 vs centrality v2 vs pt of charged particles, 0-50
    - STAR v2 vs pt of pi, K, prt for different centralities
      MB, 0-5, 20-30, 40-50; Λ and K_s 10-40, 40-80
    - PHENIX v2 vs pt of π, K, p for 0-60, 20-60