Pion-pion and pion-proton correlations – new results from CERES*

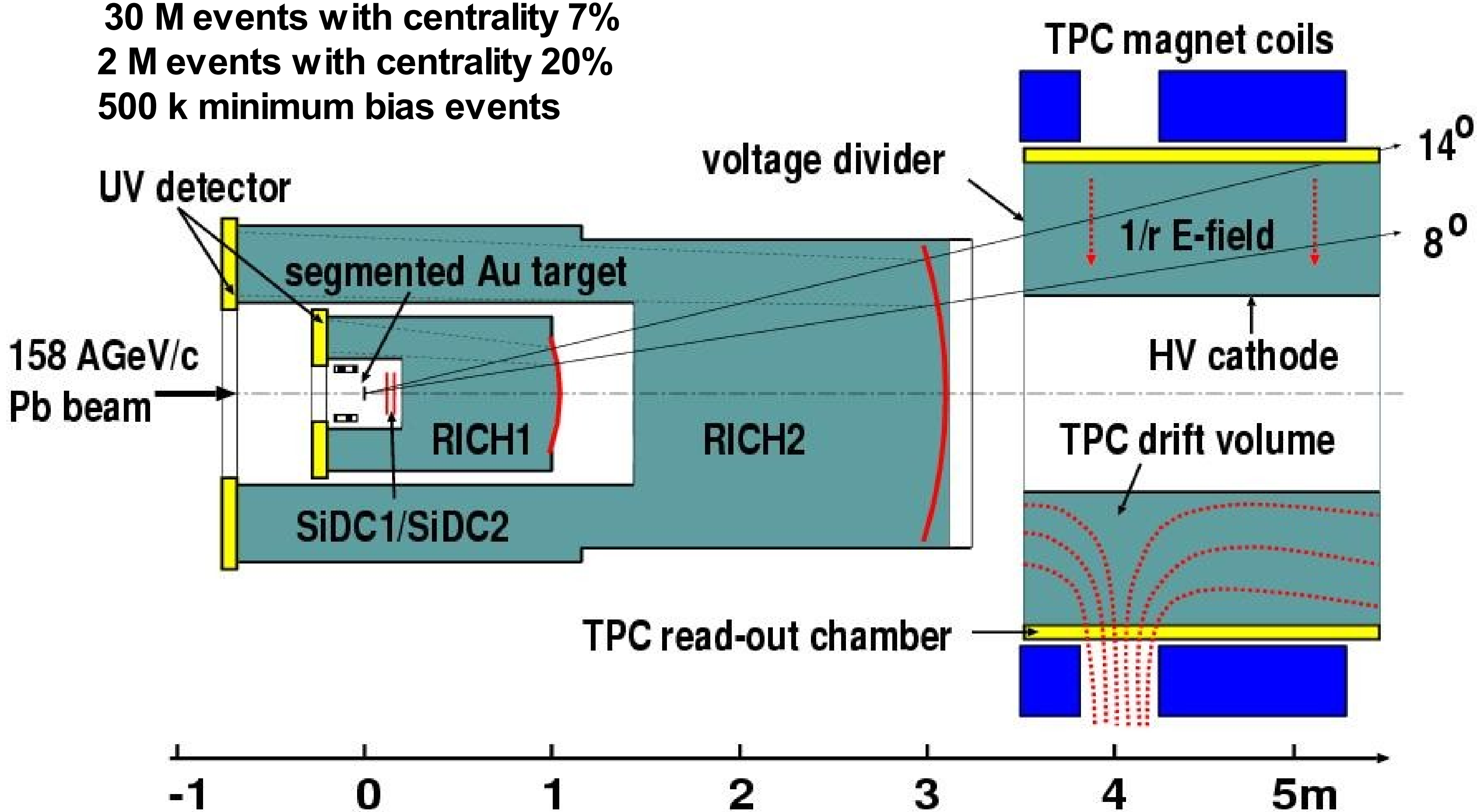
Dariusz Miskowiec, GSI Darmstadt

- intro: setup, data set, etc.
- standard HBT analysis
- pion-proton correlations
- reaction plane (in)dependence of HBT radii
- hydro and blast
- summary

*** Ph.D. work of Dariusz Antonczyk, GSI Darmstadt**

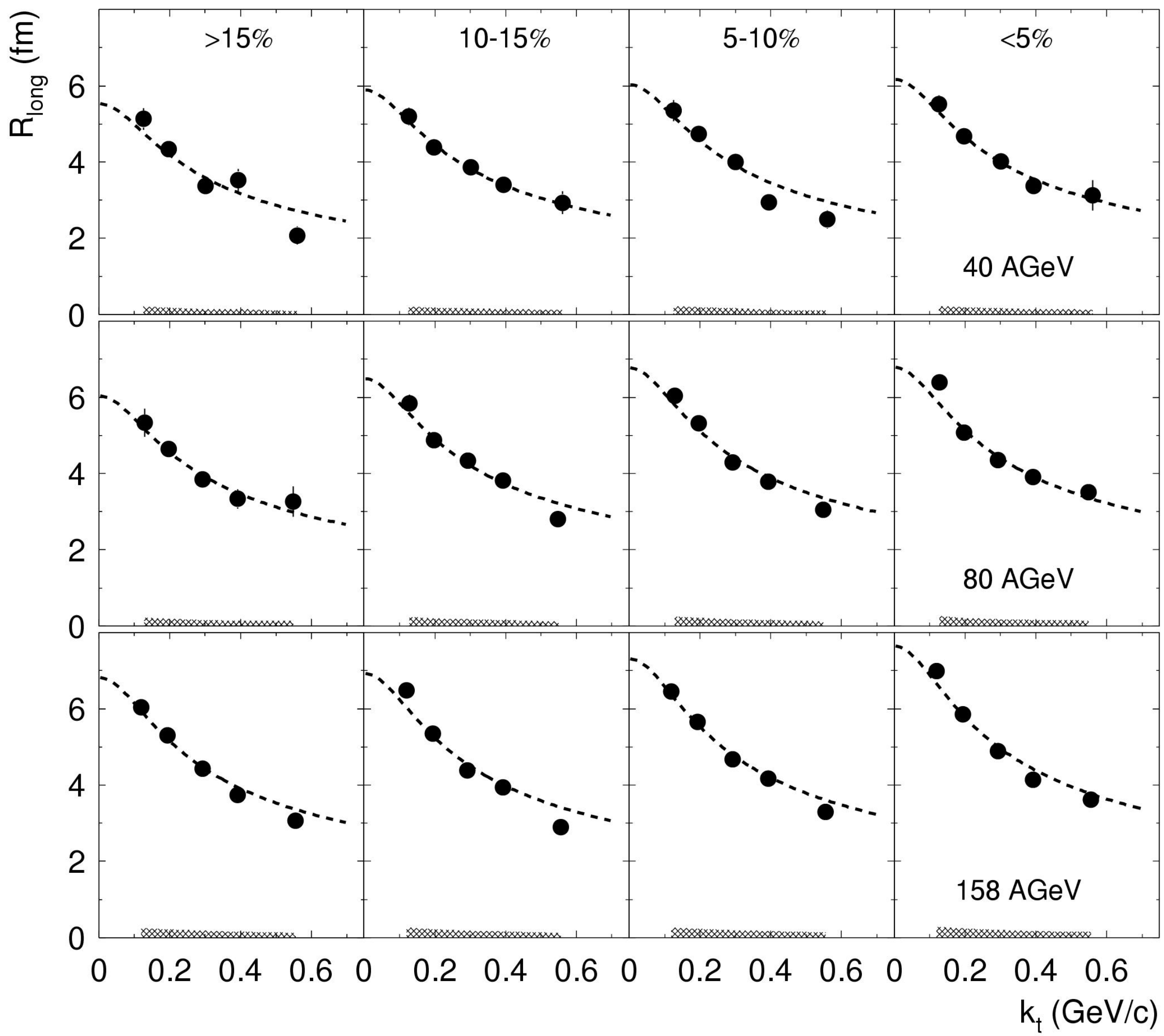
CERES run in 2000 – THE run with the TPC

run 2000: Pb+Au at 158 GeV per nucleon
30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events



Published HBT results from this run

analysis by Heinz Tilsner and Harry Appelshäuser



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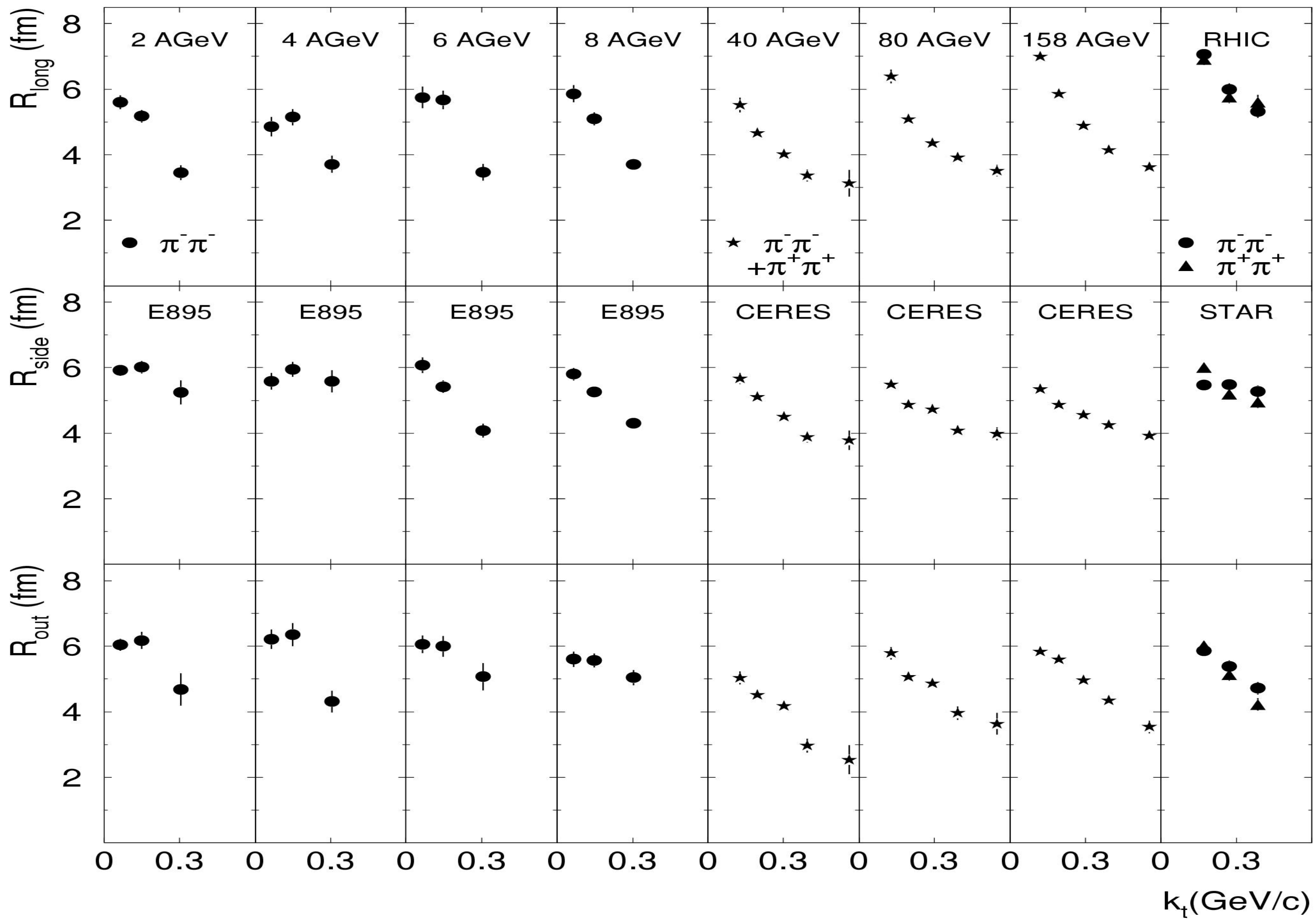
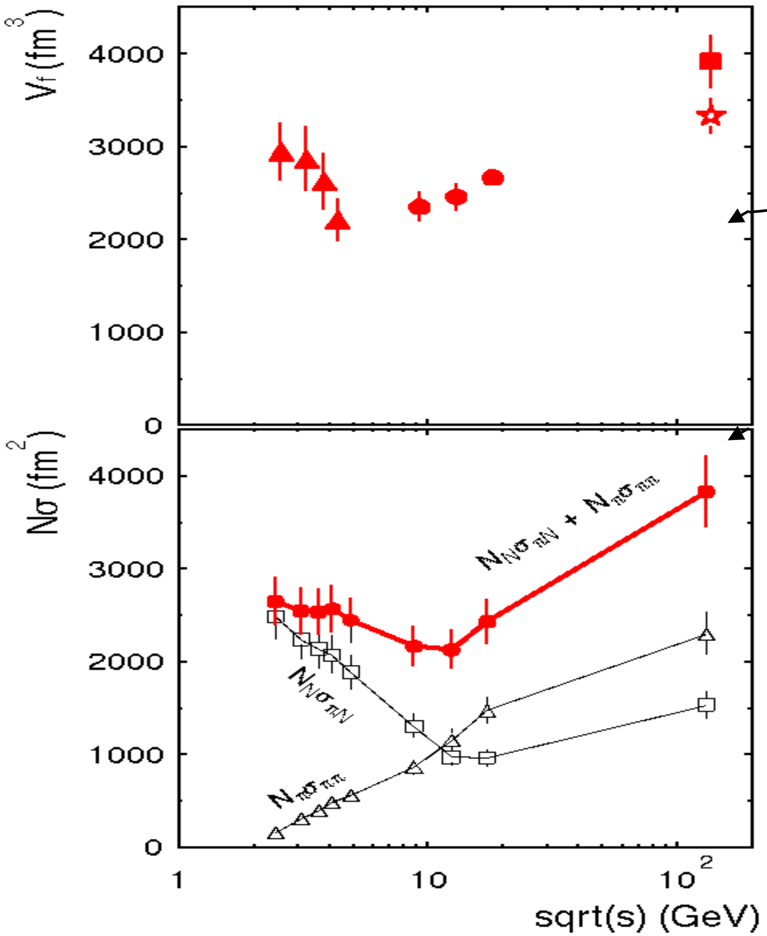


Published HBT results from this run

analysis by Heinz Tilsner and Harry Appelshäuser, PRL 90 (2003) 022301



Freeze-out volume
$V_f = (2\pi)^{3/2} R_{long} R_{side}^2$
has a minimum at a beam energy of 10-40 GeV per nucleon

Particle multiplicity times mean hadron-hadron cross-section Nσ has a similar beam energy dependence

$V_f / N\sigma = \lambda_f = 1$ fm
independent of beam energy

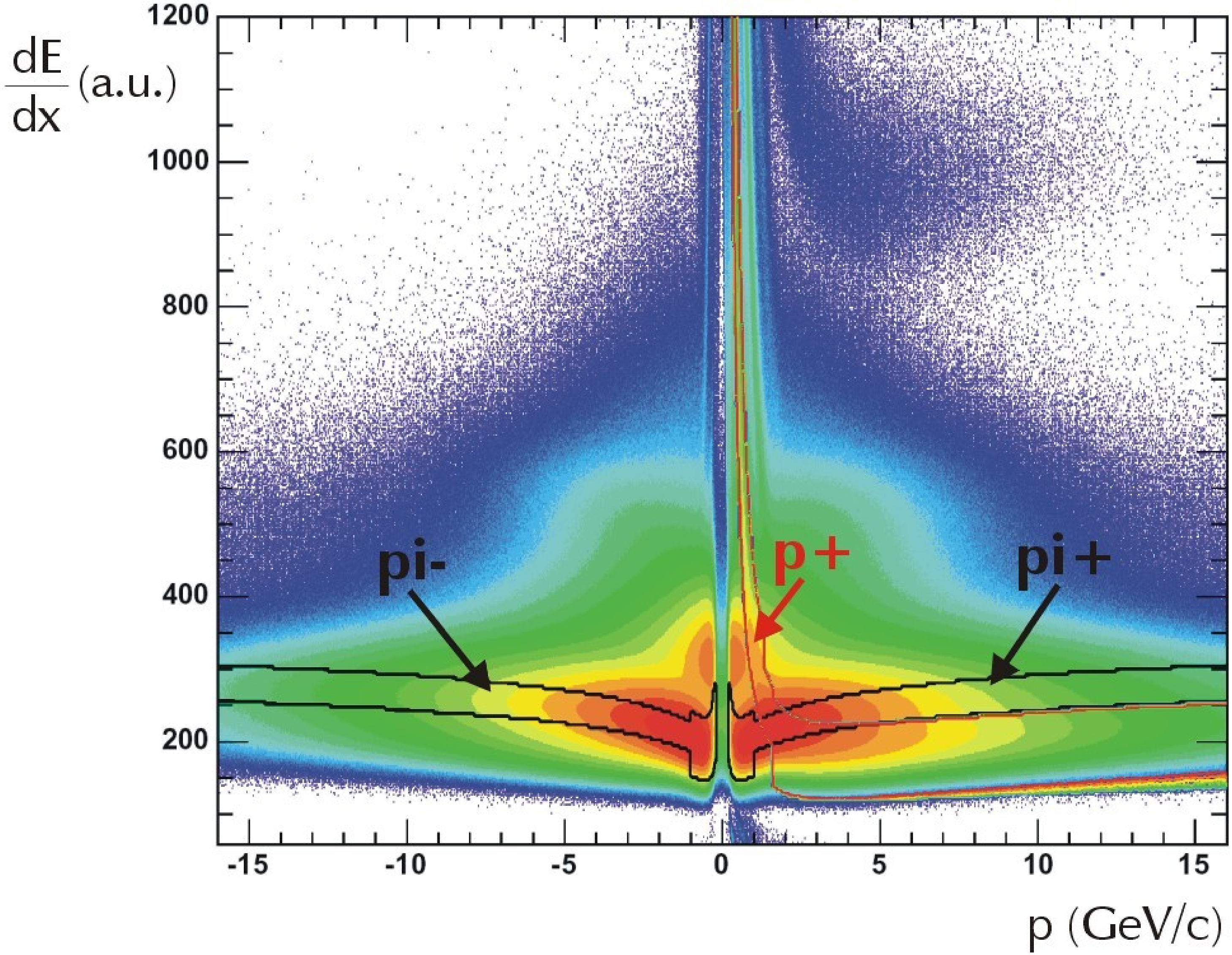
Freeze-out when mean free path ≈ 1 fm

New analysis

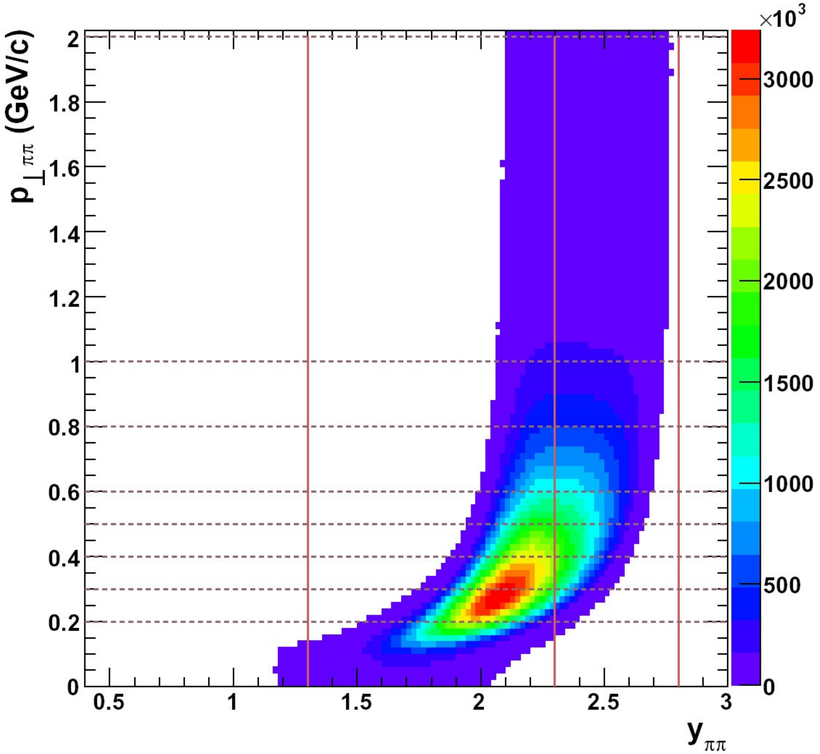
- better momentum, centrality, reaction plane resolutions
- better two-track separation cut
- full statistics (30 M events)
- emphasis on nonidentical and reaction plane dependence…

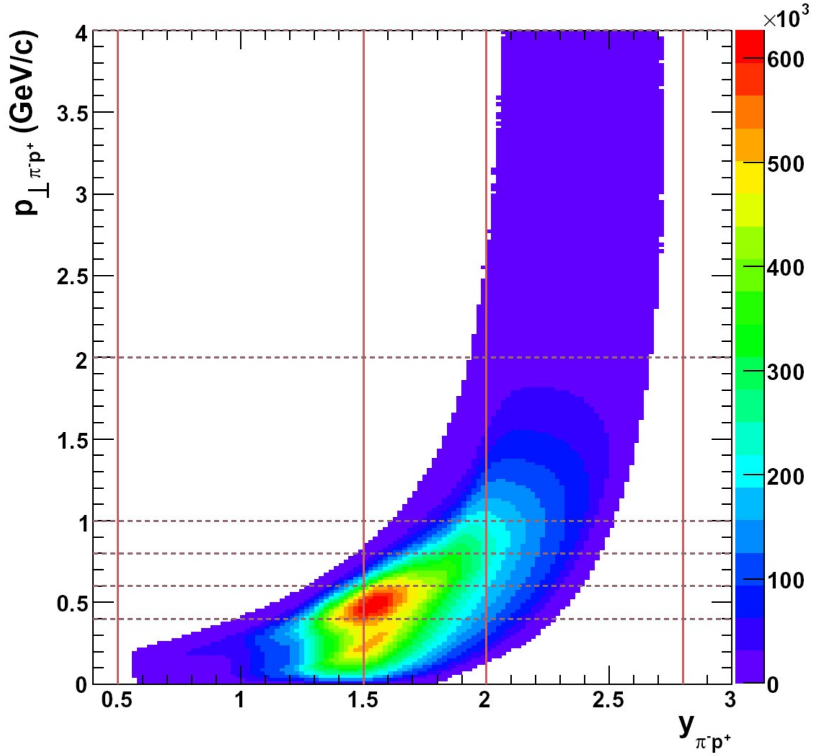
…however, most of the statistics central 7%

Partial identification of pions and protons via dE/dX



Pair acceptance

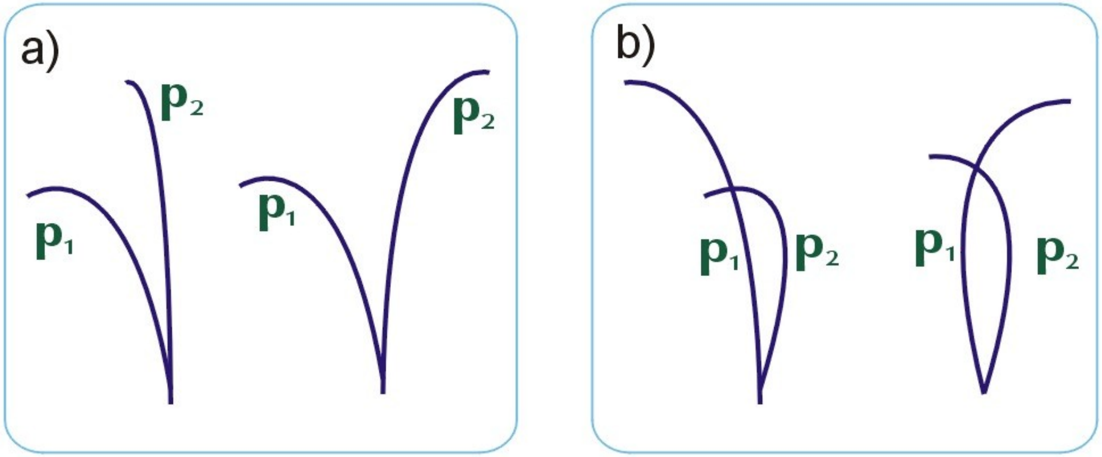




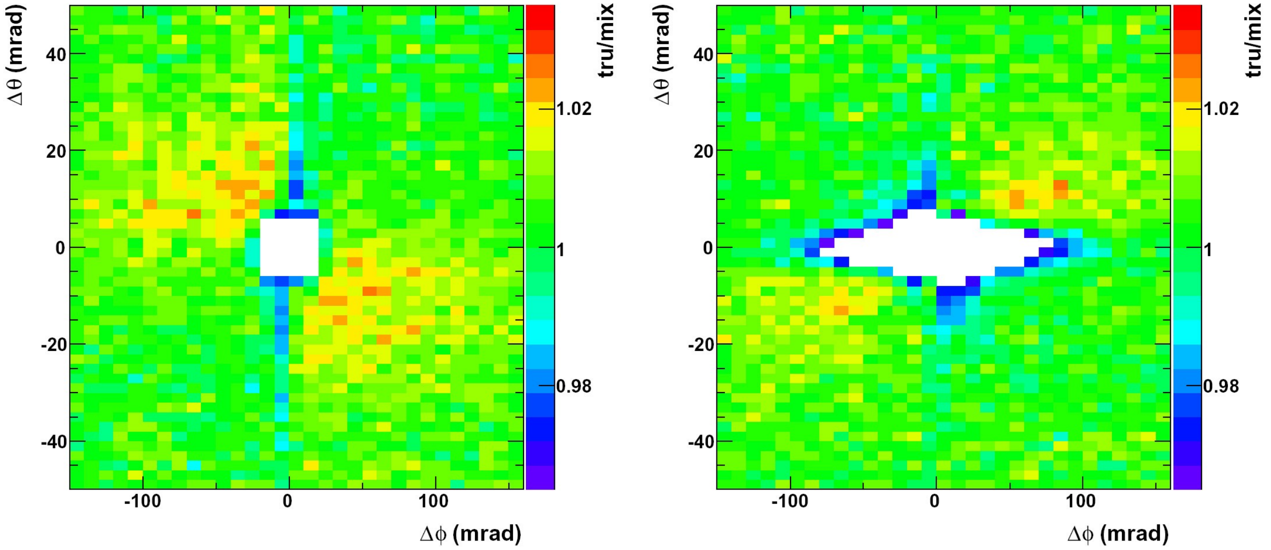
midrapidity: y=2.91

midrapidity

Two-track cut



Different cuts needed for the two topologies: sailor and cowboy

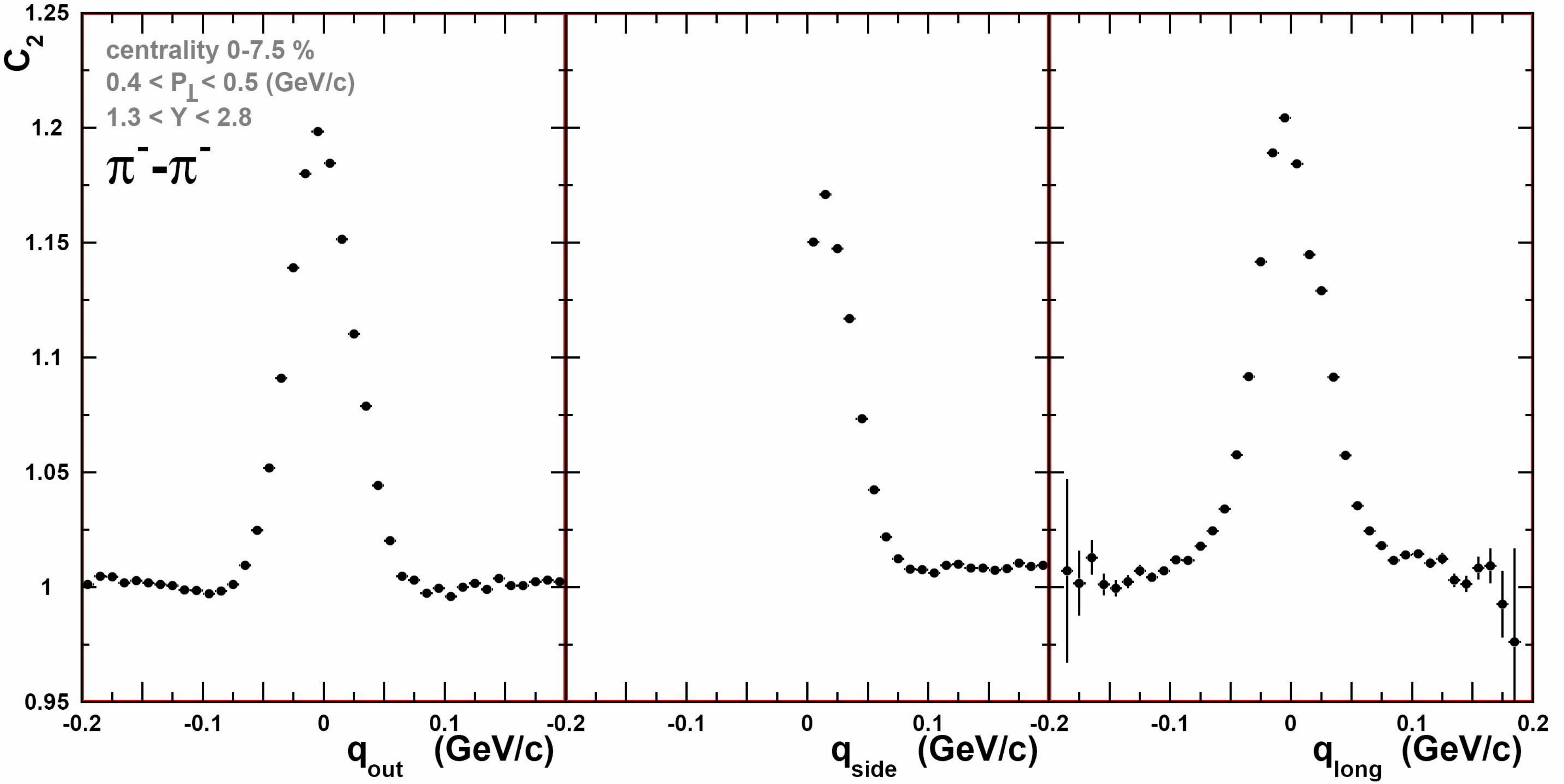


Analysis frame

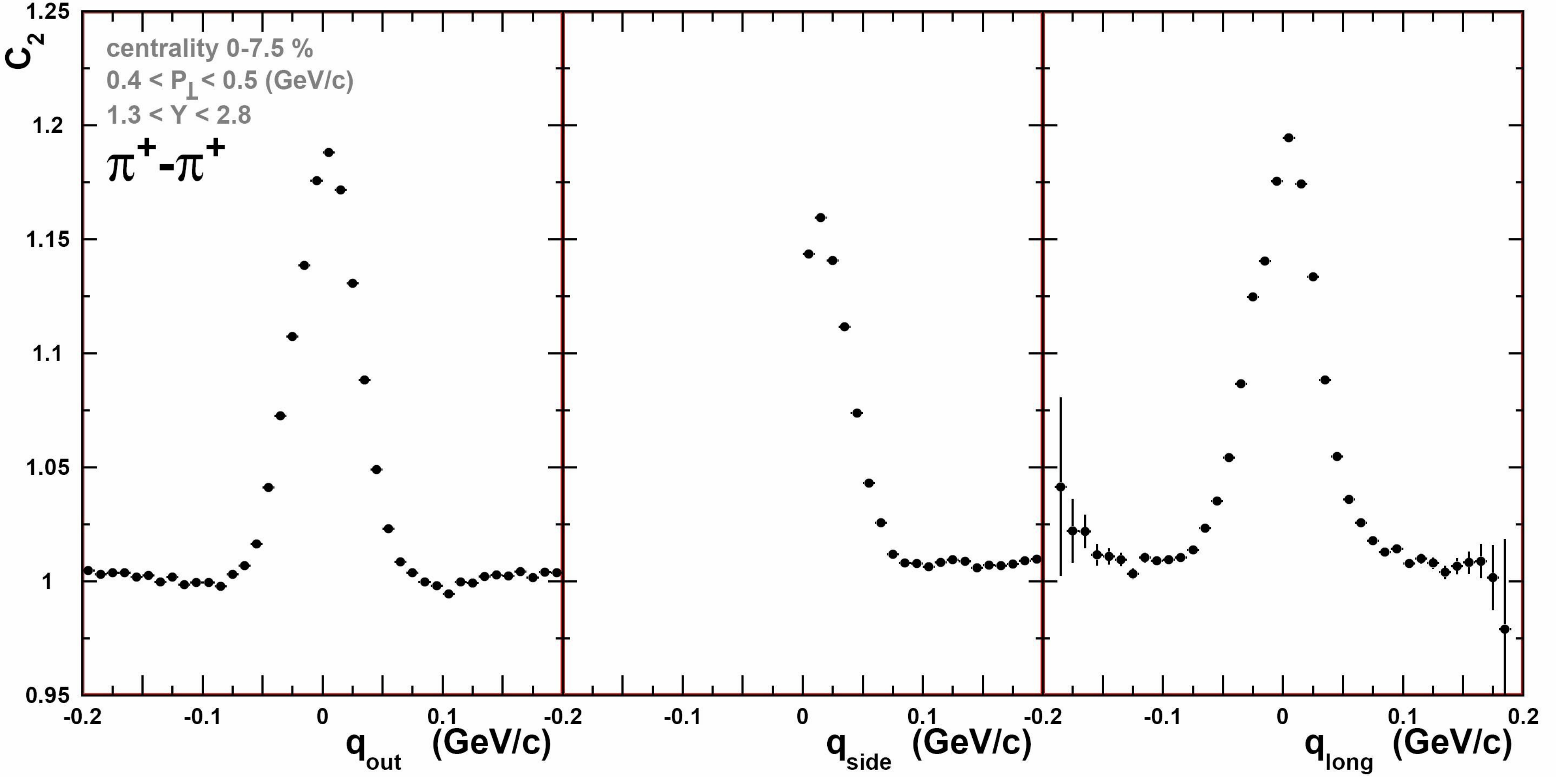
HBT analysis in the LCMS frame, $C(q_{out}, q_{side}, q_{long})$

nonidentical correlation analysis in the pair c.m.s., $C(q_{||}, q_{\perp})$
with $q_{||}$ being the component parallel to the pair $P_{\perp}$

$\pi^-\pi^-$ correlation function

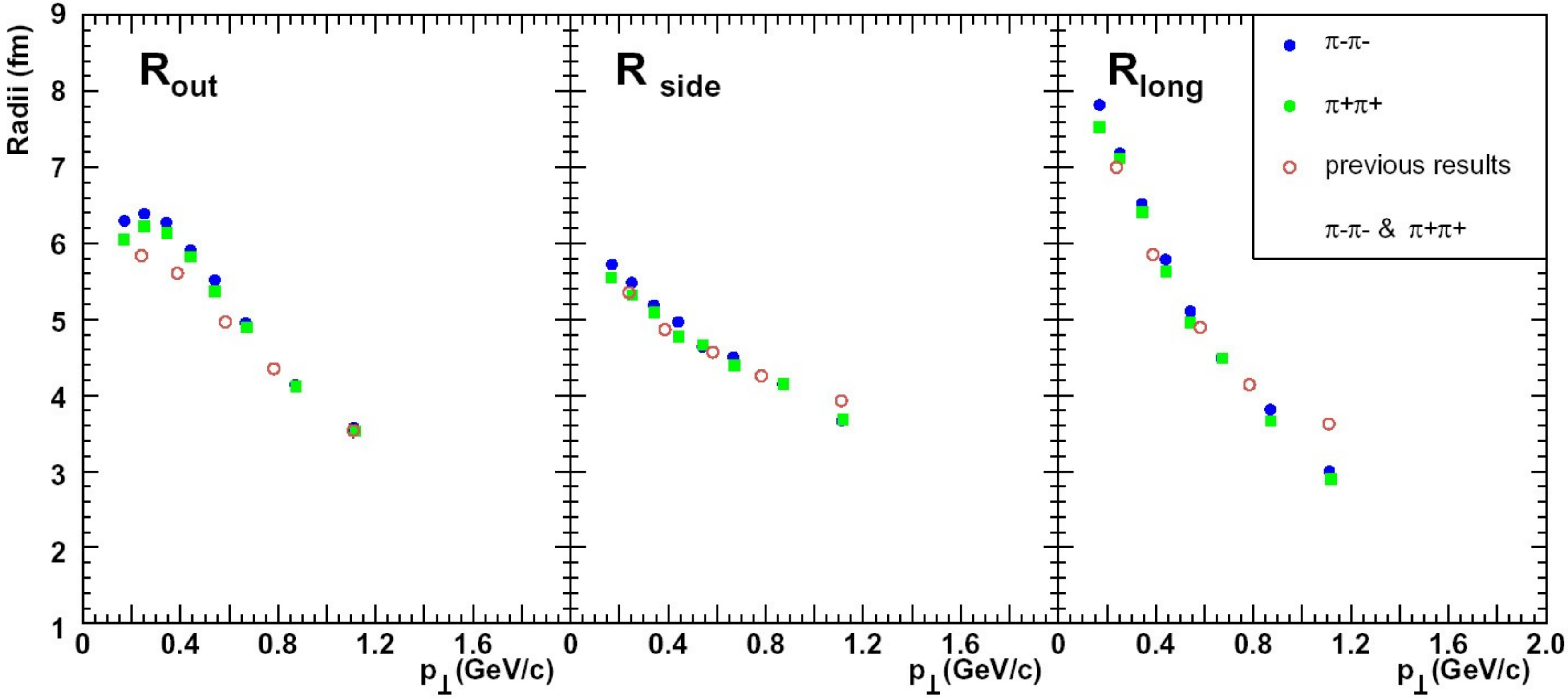


$\pi^+\pi^+$ correlation function



HBT radii vs. pair $P_\perp$

Comparison to the previous analysis, centrality 0-5%

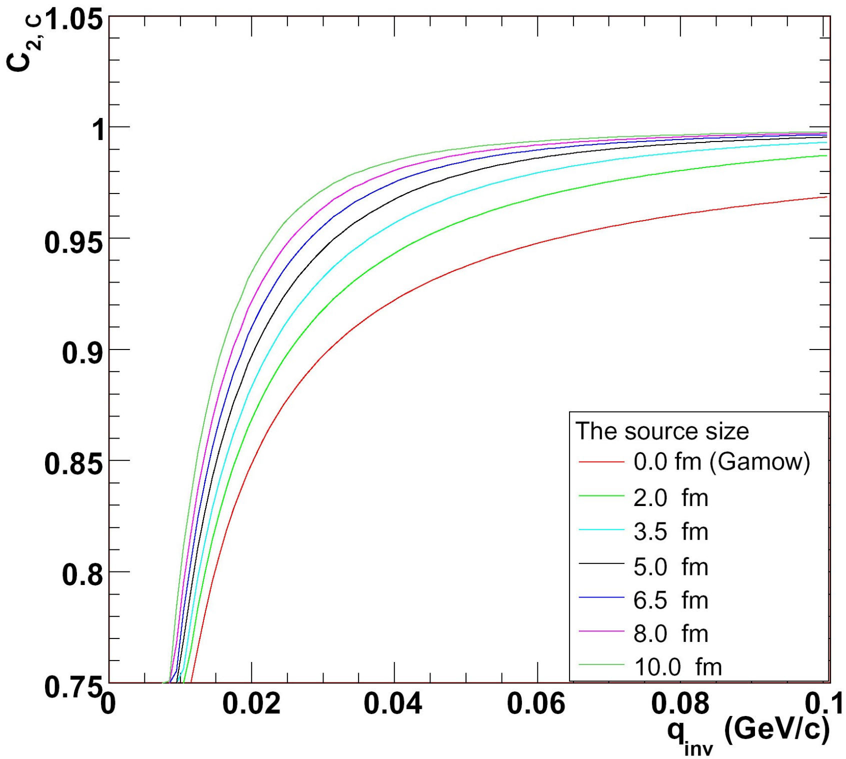


→**good consistency. Better at the edges (statistics!)**

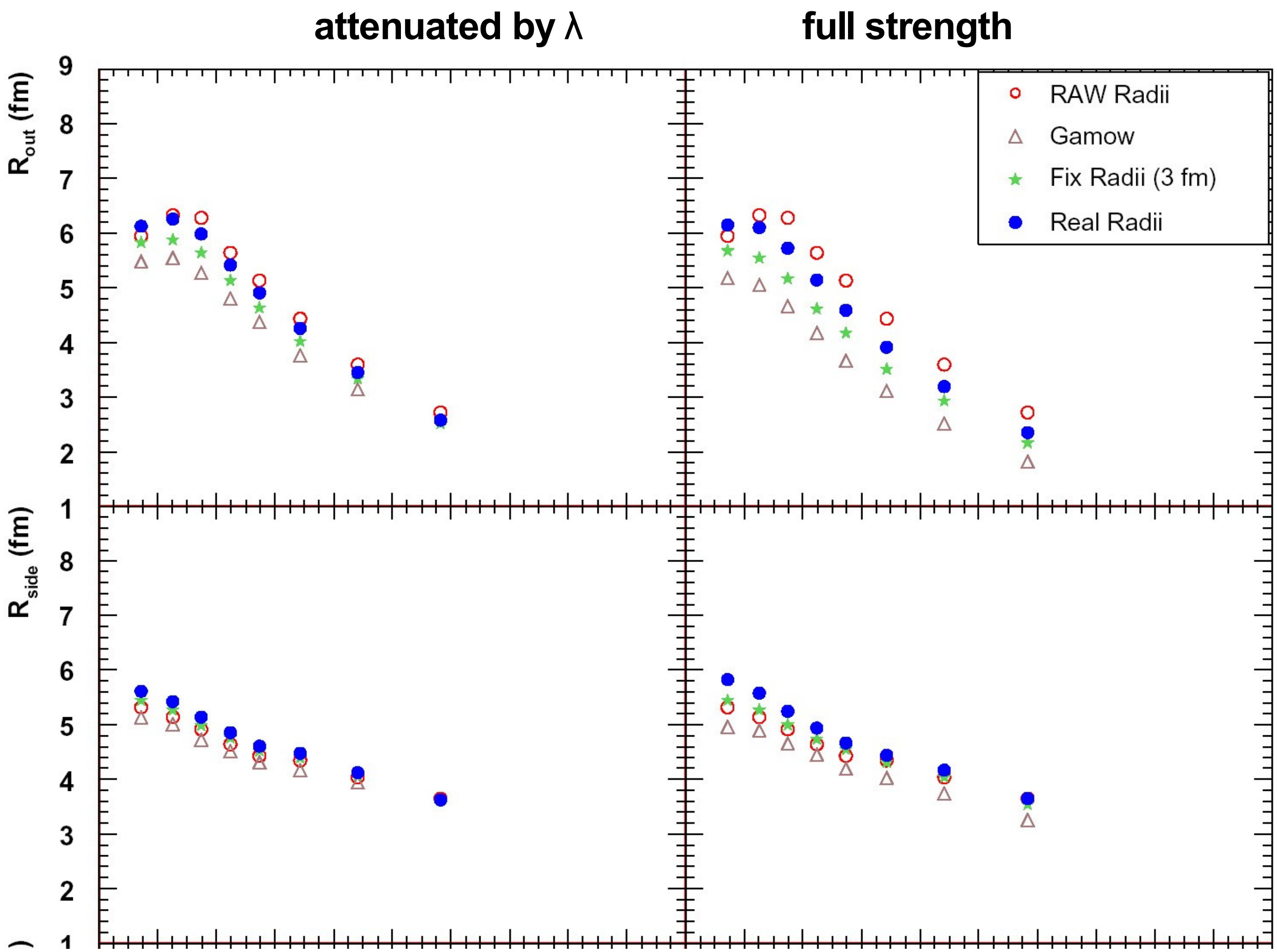
Fitting the HBT correlation functions

- standard Gaussian fit
- maximum likelihood assuming Poisson

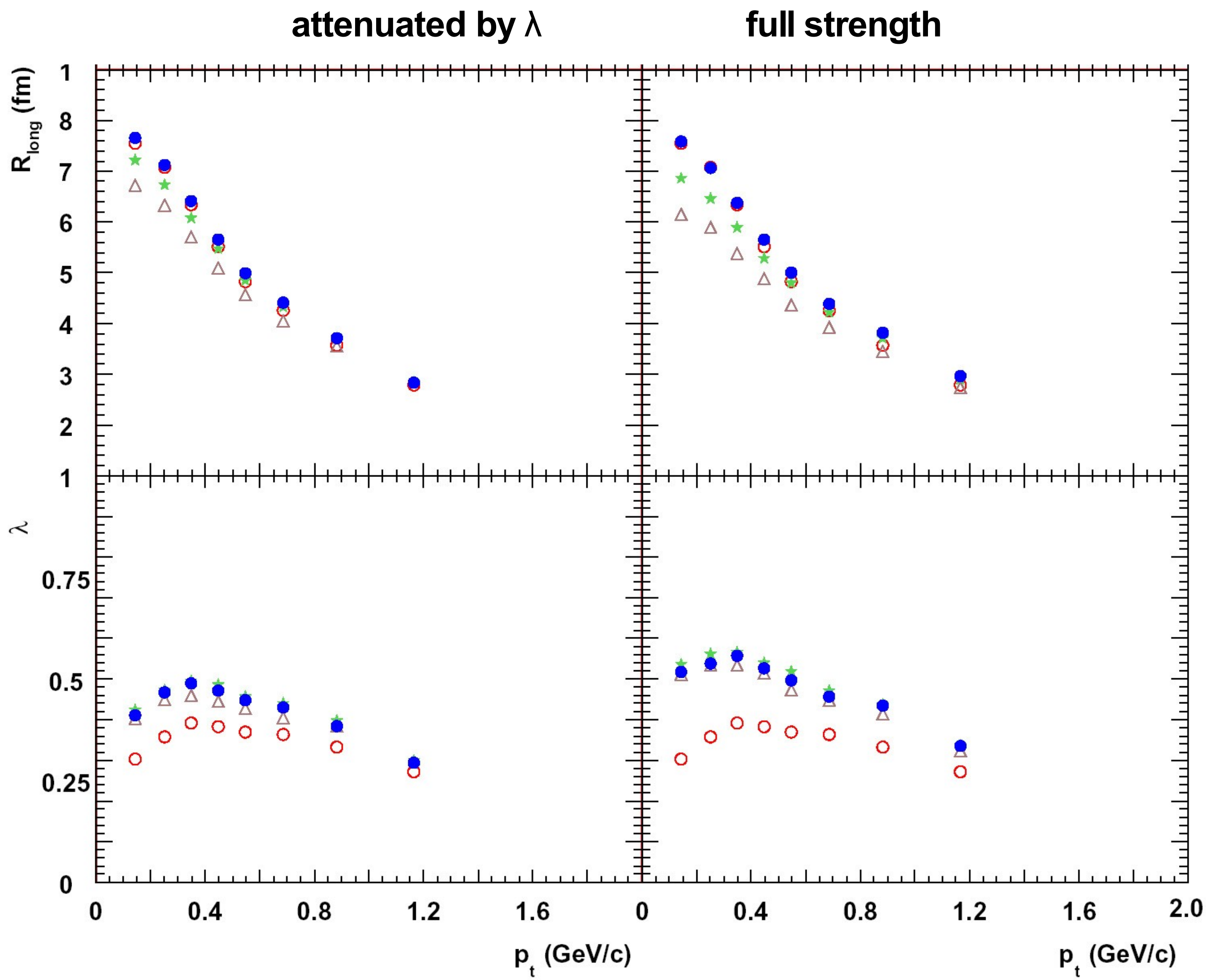
- Coulomb included in the fit
- Coulomb attenuated by the same factor λ and calculated for a similar source size
- Coulomb correlation calculated as the square of the Coulomb wavefunction, averaged over finite Gaussian source



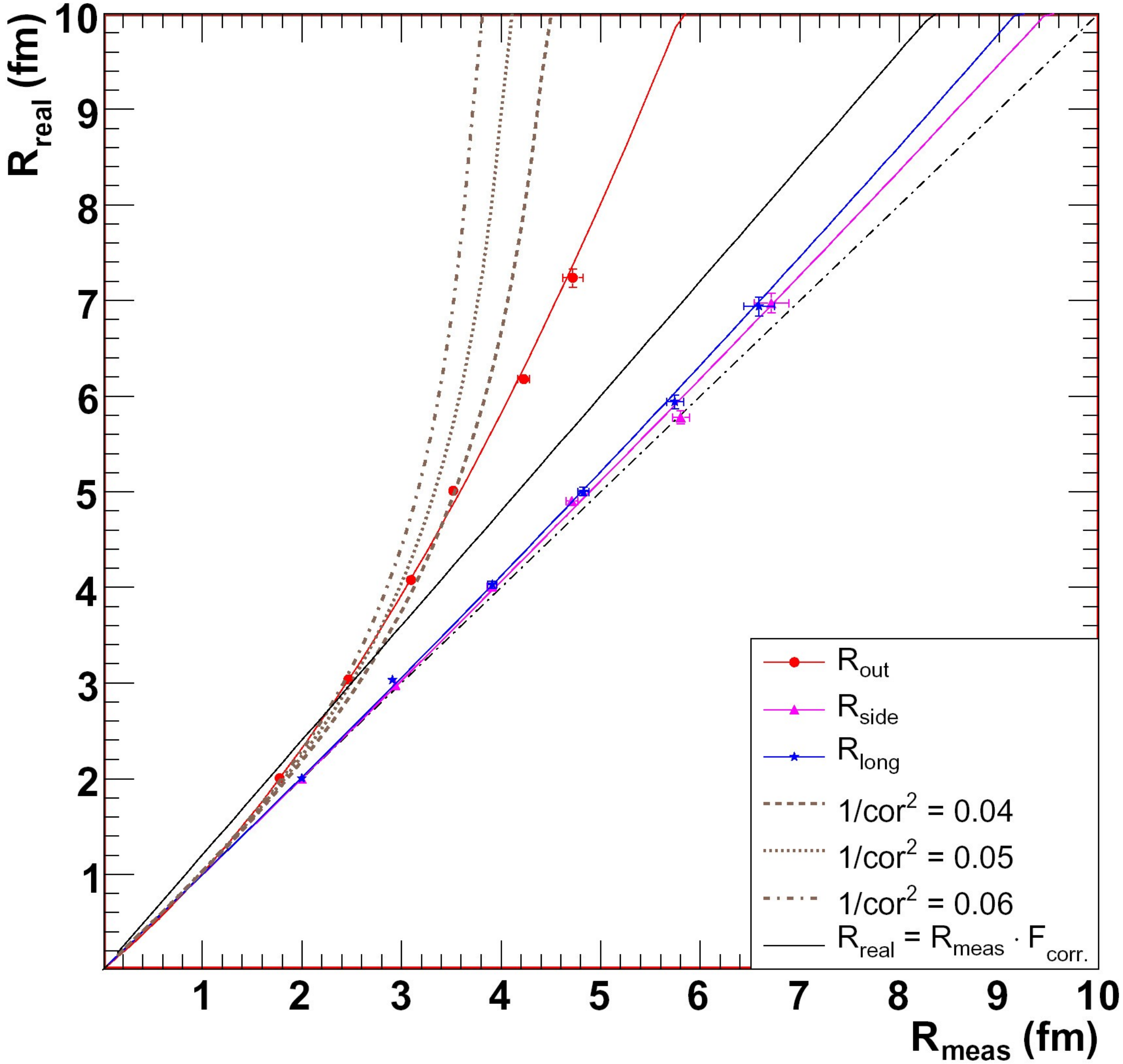
Effect of the Coulomb correction



Effect of the Coulomb correction



Correction for momentum resolution



example: highest pt bin (the largest correction)

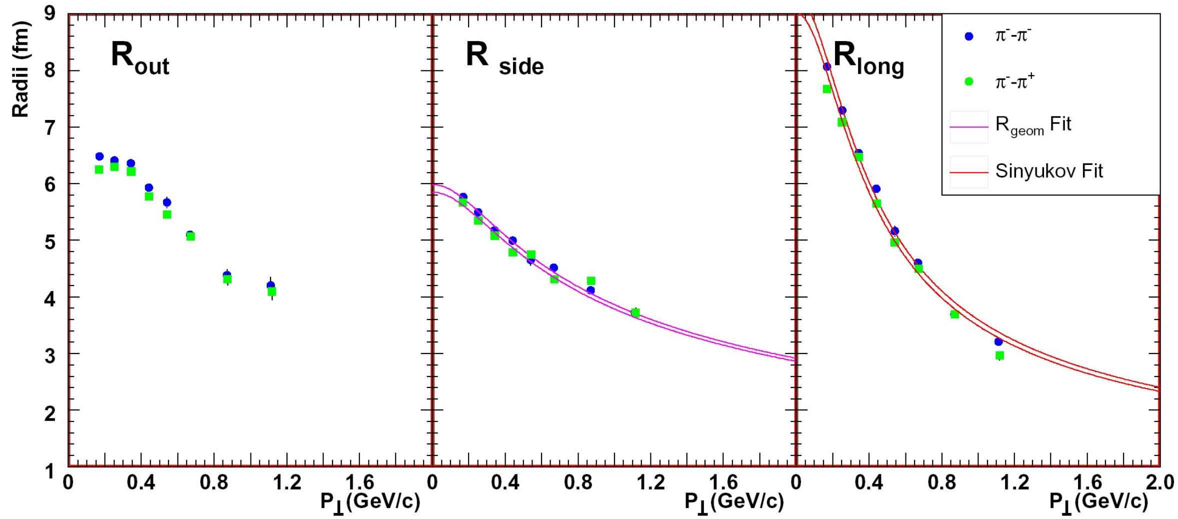
determined by Monte Carlo

lines: various attempts to parametrize

correction applied to the radii obtained from the fit

Fitting the radii with analytic forms

1.3<y<2.8

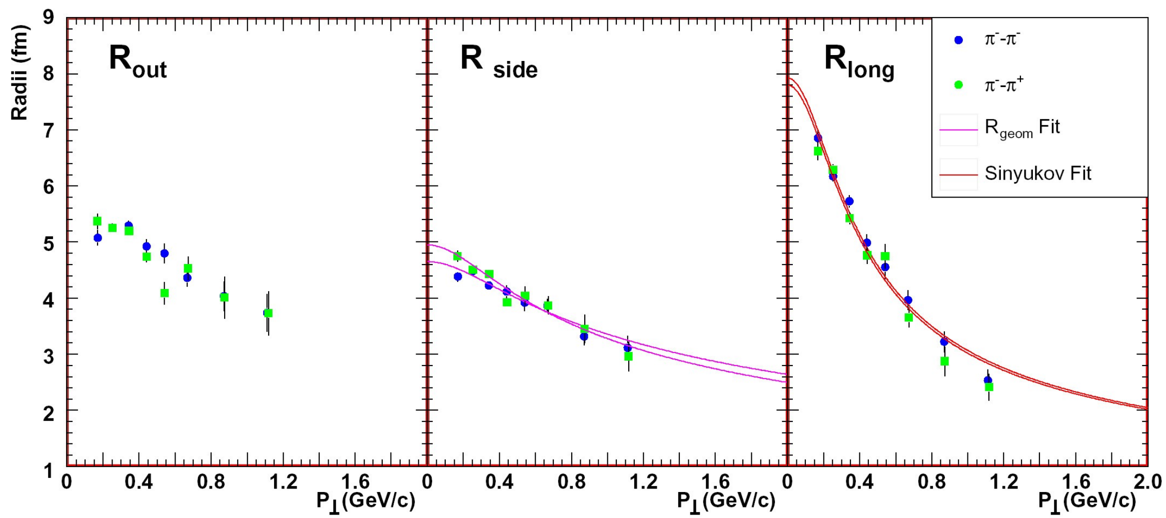


$$R_{side}(p_\perp) = \frac{R_G}{\sqrt{1+\frac{m_\perp \eta_f^{\,2}}{T}}}$$

$$R_{long} = \tau_0 \sqrt{\frac{m_\perp}{K}\frac{K_2(T/m_\perp)}{K_1(T/m_\perp)}}$$

(wrong formula!)

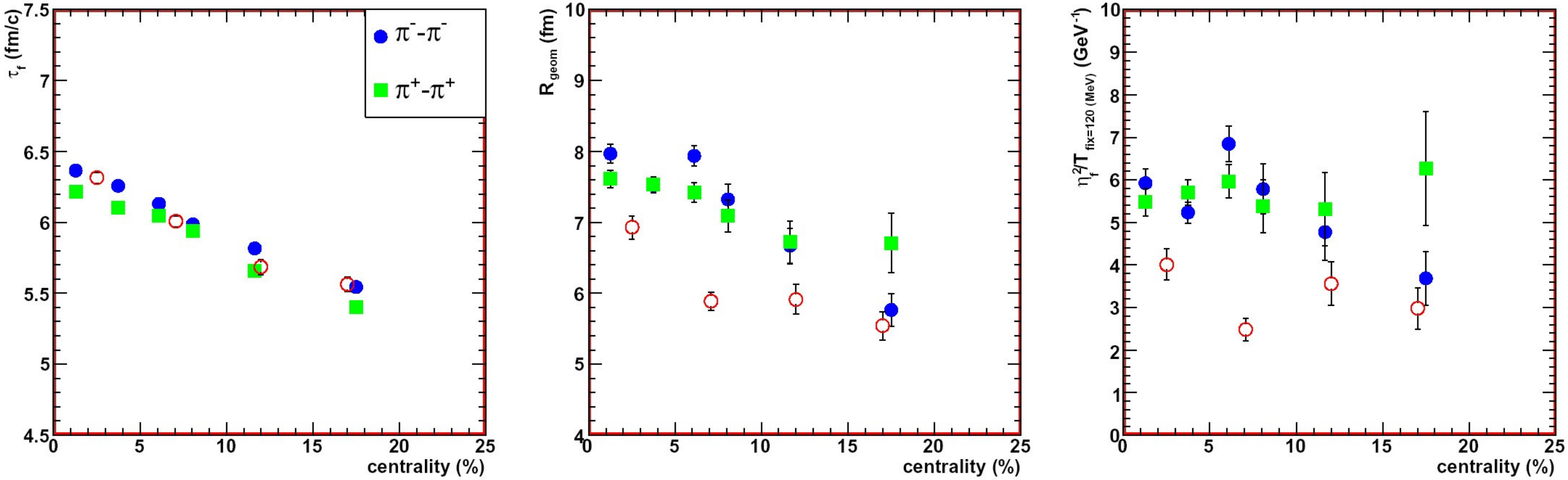
centrality 0-2.5%



centrality 15-35%
(mean about 18%)

Centrality dependence of τ_f , R_G, and η_f^2/T

1.3<y<2.8



Pion-proton correlations

pair c.m.s.

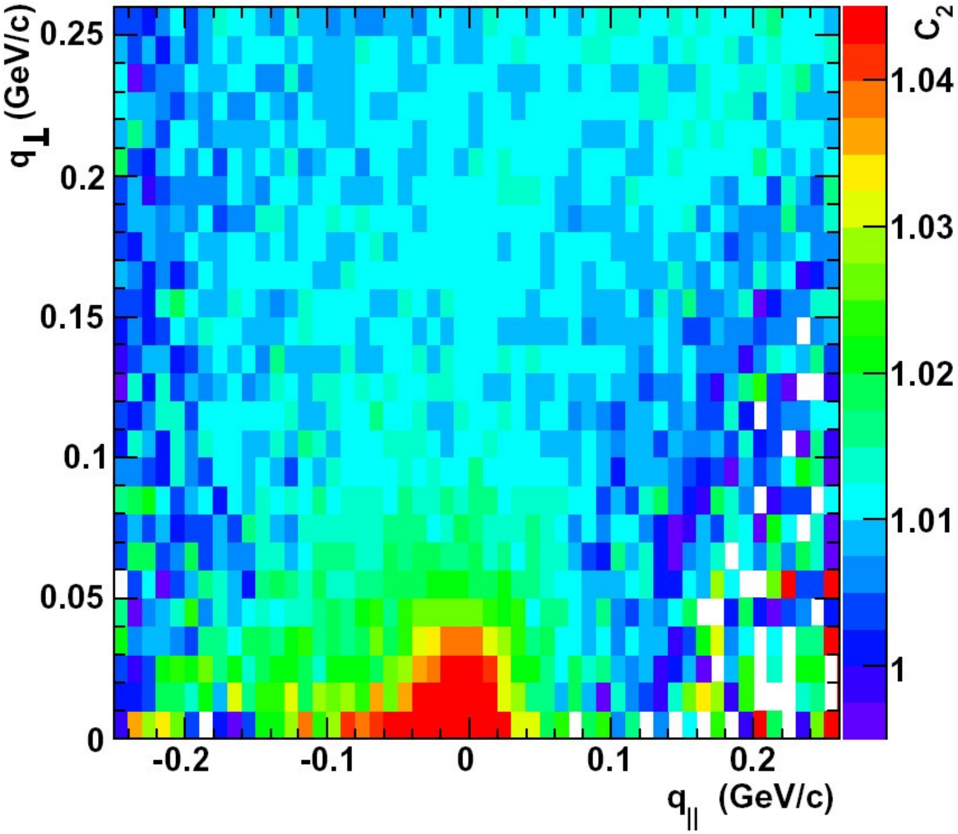
$q = p_{proton} - p_{pion}$

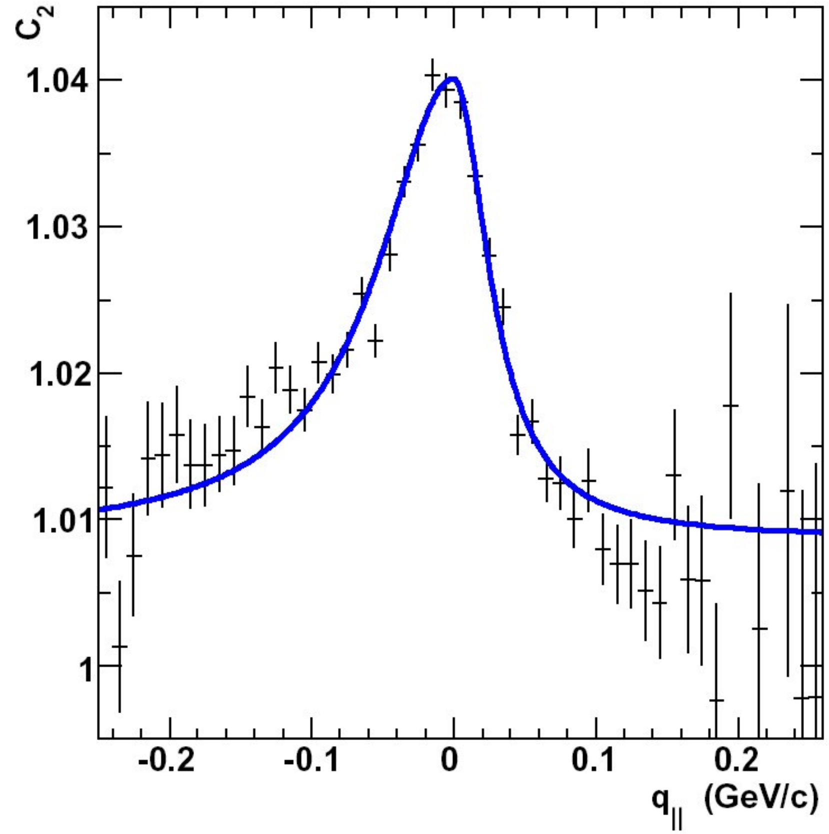
$C(q_{||}, q_{\perp})$

$q_{||}$ is the component parallel to the pair $P_{\perp}$

Extracting the asymmetry

π^- - proton correlation



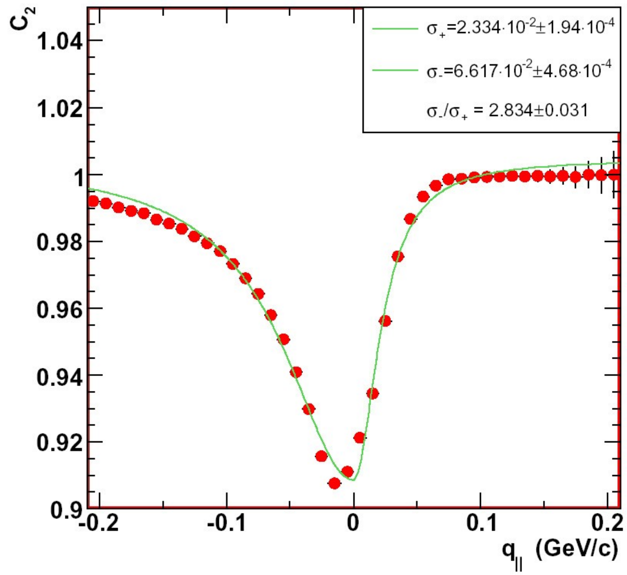


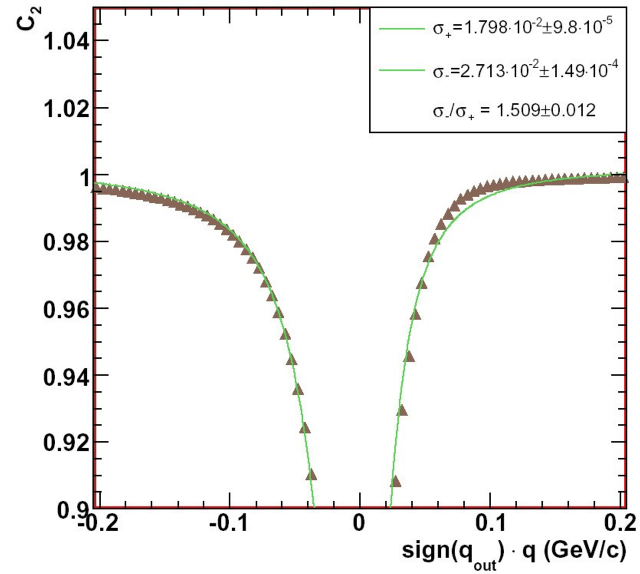
take a slice and project on $q_{||}$
fit each half separately with……..

$$C(q_{||}) = 1 + \frac{A}{1 + q_{||}^{\,2} / B^2}$$

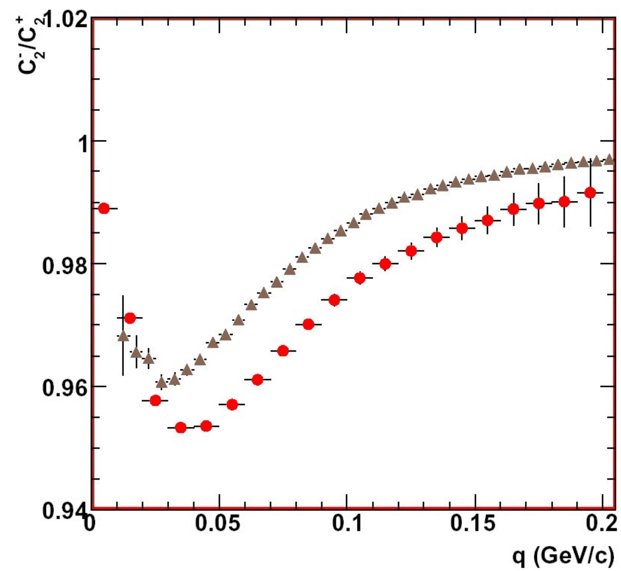
require same A
B is HWHM
asymmetry = B_{left}/B_{right}

Comparison to the traditional method (simulation)





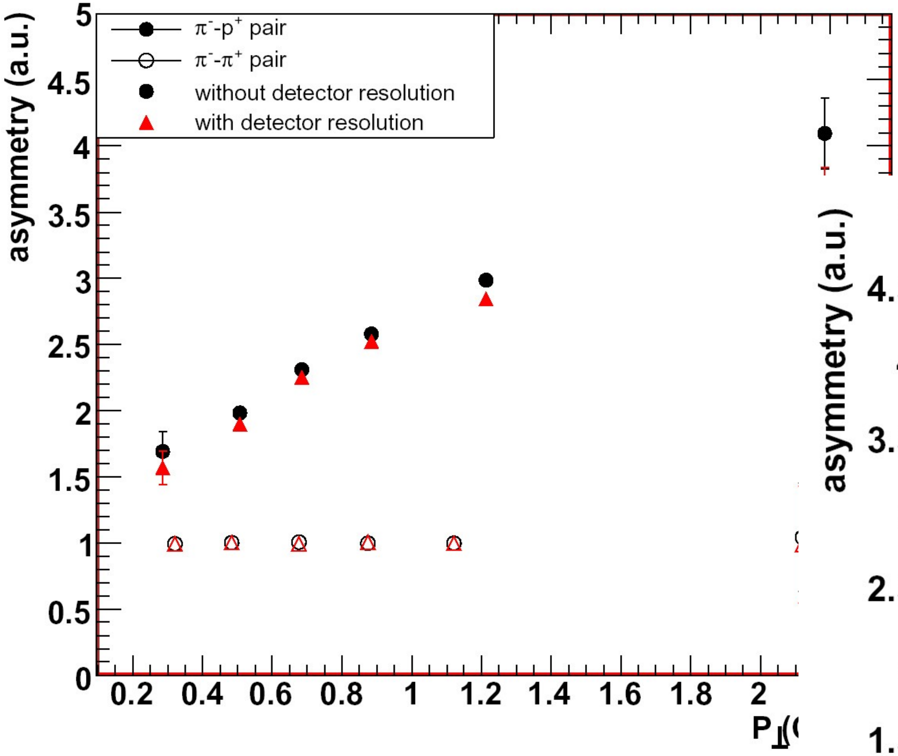
using a slice rather than the entire hemisphere gives a better significance (asymmetry-1)/error of 59 vs 42



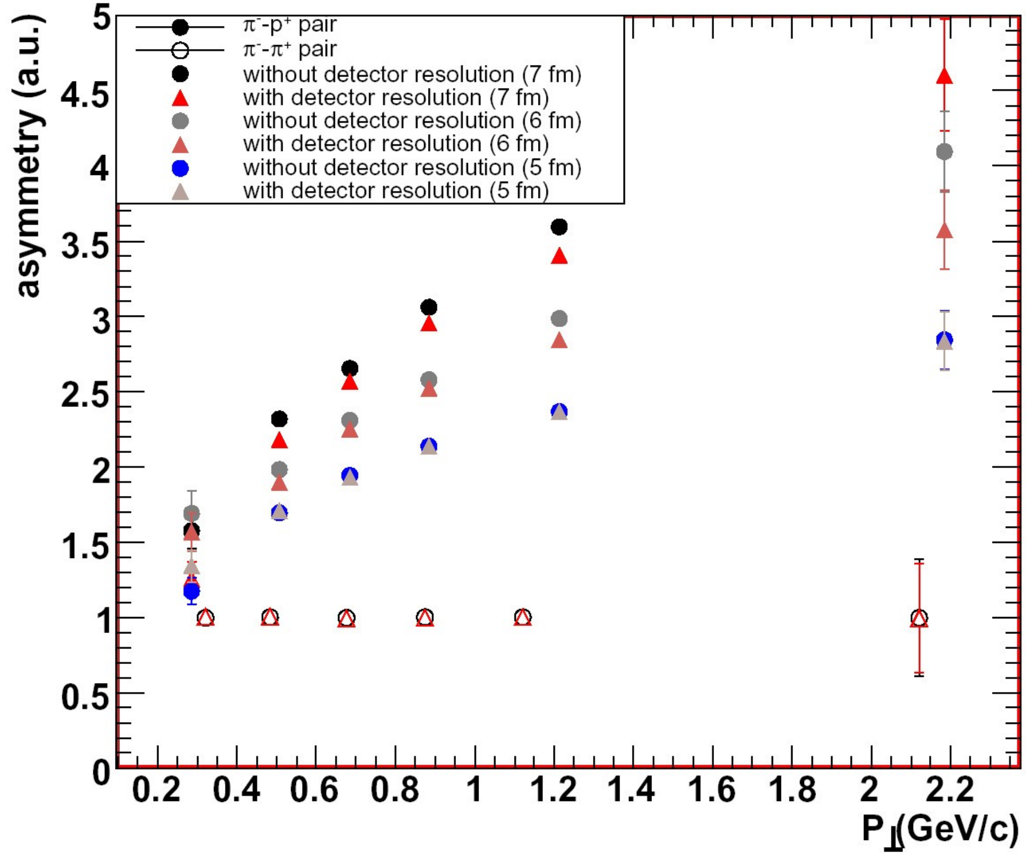
Correction for the finite momentum resolution

using Monte Carlo with realistic source sizes and displacements

6 fm displacement



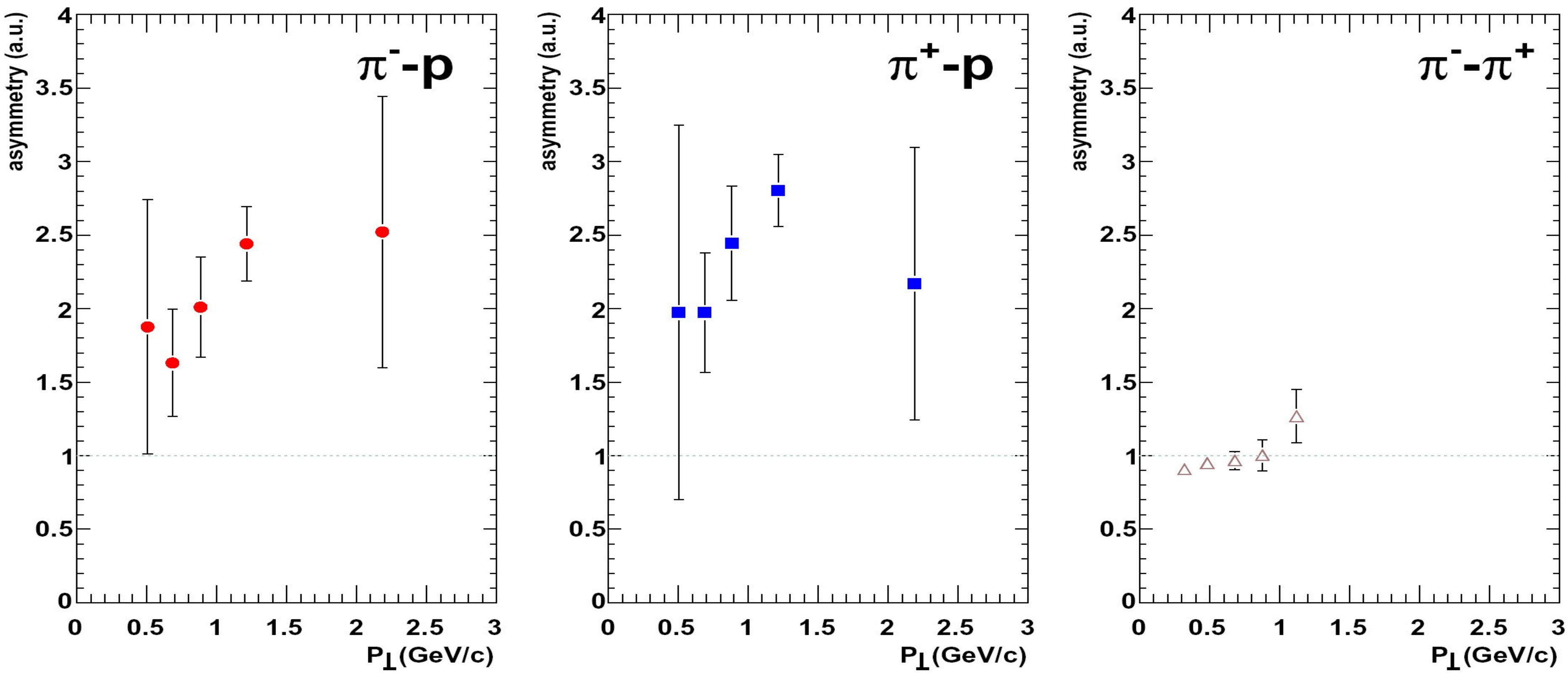
5,6,7 fm displacement



Asymmetry

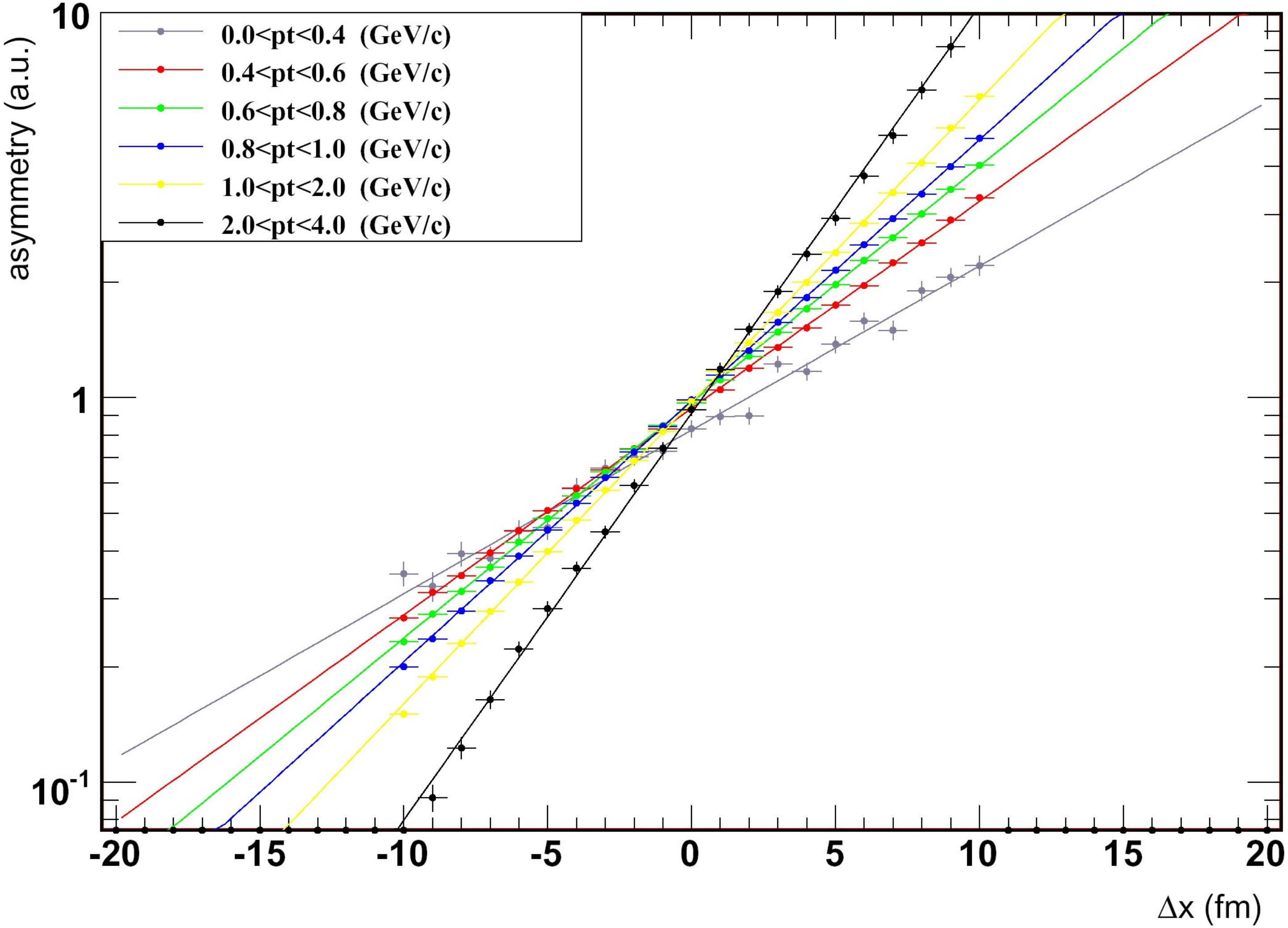
centrality 7%, 1.5<y<2.8

Pt is pair pt!

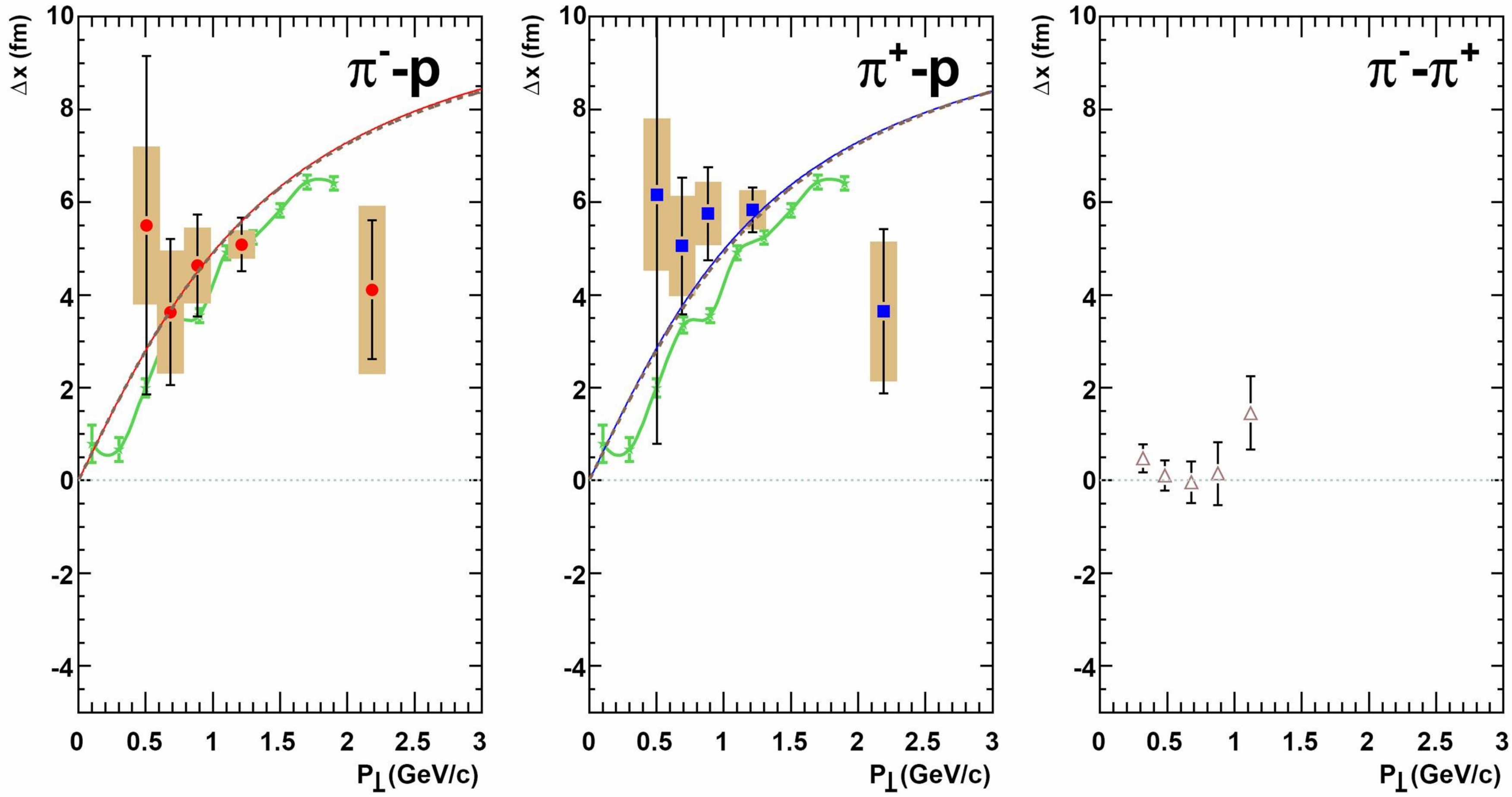


Translating asymmetry to displacement

using Monte Carlo with realistic pt-dependent source sizes



Displacement



green: UrQMD (only Δx, not Δt!)
blue and red: fit to Δx (see next slide)
brown dashed: same fit, but simultaneously to pi+ and pi-

Δx is the average displacement between protons and pions at freeze-out in the out-direction. Positive Δx – protons outside

Fitting R_{side} and Δx

$$R_{side}(p_\perp) = \frac{R_G}{\sqrt{1+\frac{m_\perp \eta_f^2}{T}}}$$

$$m_\perp = \sqrt{m_\pi + \left(\frac{P_\perp}{2}\right)^2}$$

U. Heinz, many many papers

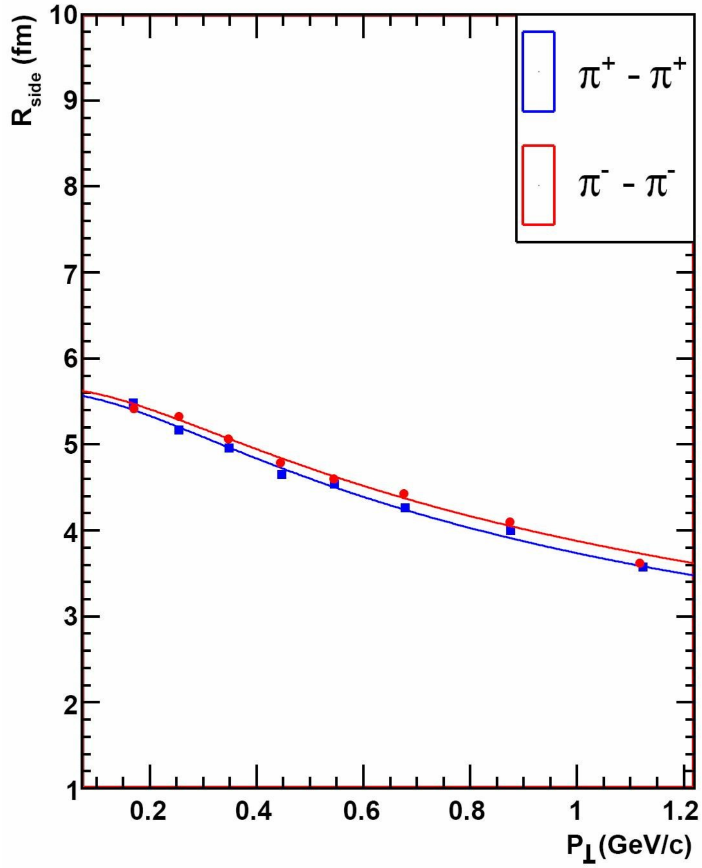
$$\langle \Delta x \rangle = \frac{R_G \, \beta_\perp \, \beta_0}{\beta_0^2 + \frac{T}{m_\perp}}$$

$$m_\perp = \sqrt{m_\perp^1 \, m_\perp^2}$$

$$\beta_\perp = \frac{1}{\sqrt{1+\left(\frac{m_\pi + m_p}{P_\perp}\right)^2}}$$

$$\eta_f = \frac{1}{2}\log\frac{1+\beta_0}{1-\beta_0}$$

R. Lednicky, nucl-th/0305027, based on Akkelin, Sinyukov Z.Phys.C 72(1996)501



R_{side} dominates the fit
Δx agrees reasonably well
→ all flow?

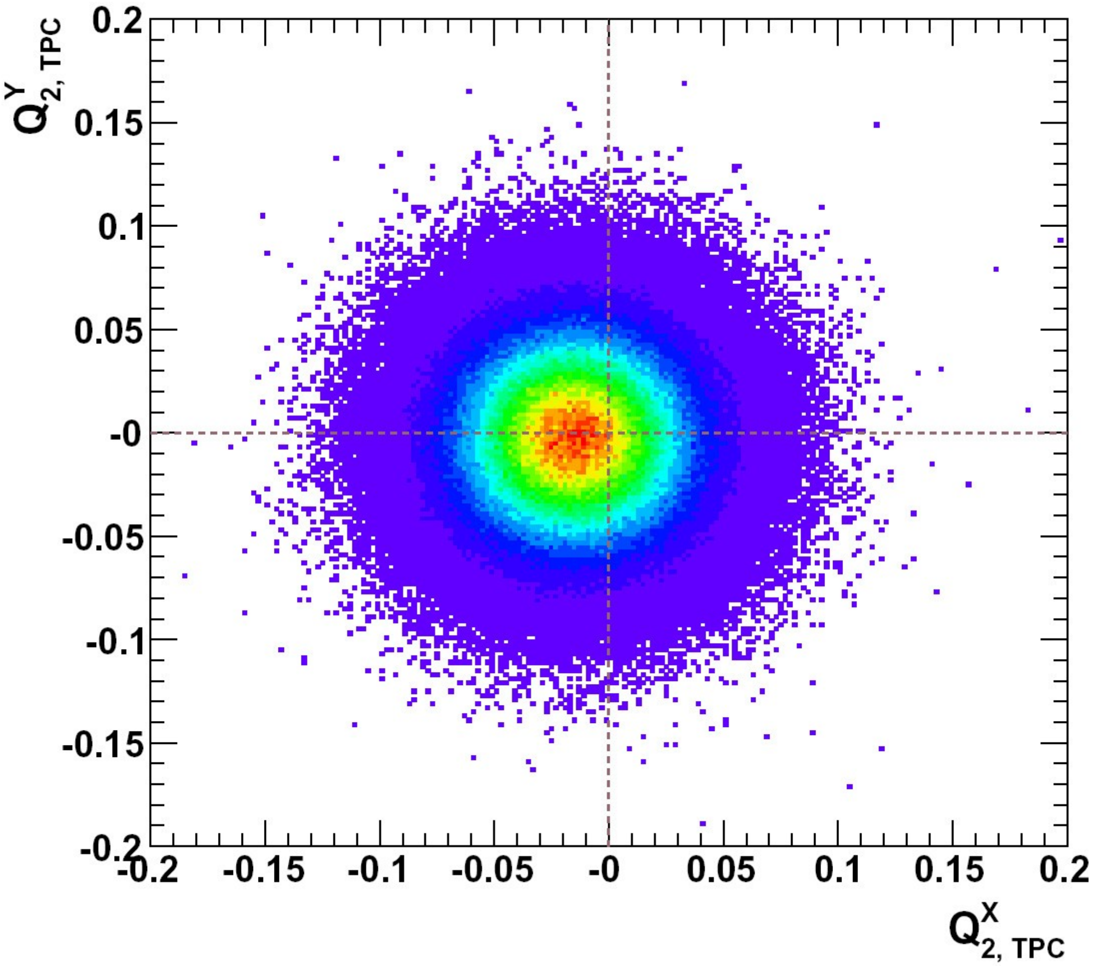
Fitting R_{side} and Δx

fixed T=120 MeV

	β_0	R_G (fm)
π^+ p	0.695 (7)	7.64 (7)
π^- p	0.655 (6)	7.41 (12)
π^+ p and π^- p	0.663 (4)	7.42 (12)

Reaction plane dependence of the HBT radii

Reaction plane

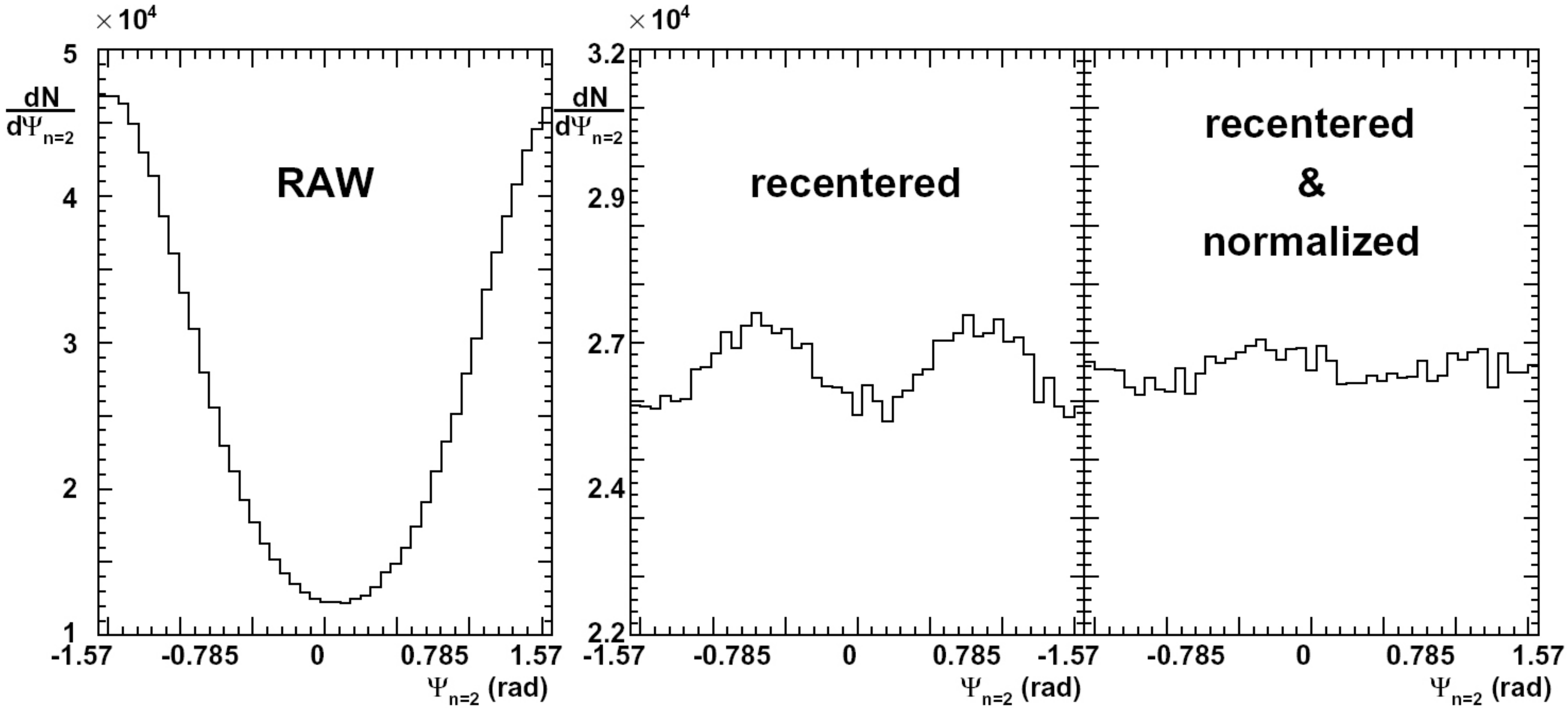


$$Q_2^X = \sum_i p_t \cdot \cos(2\phi_i)$$

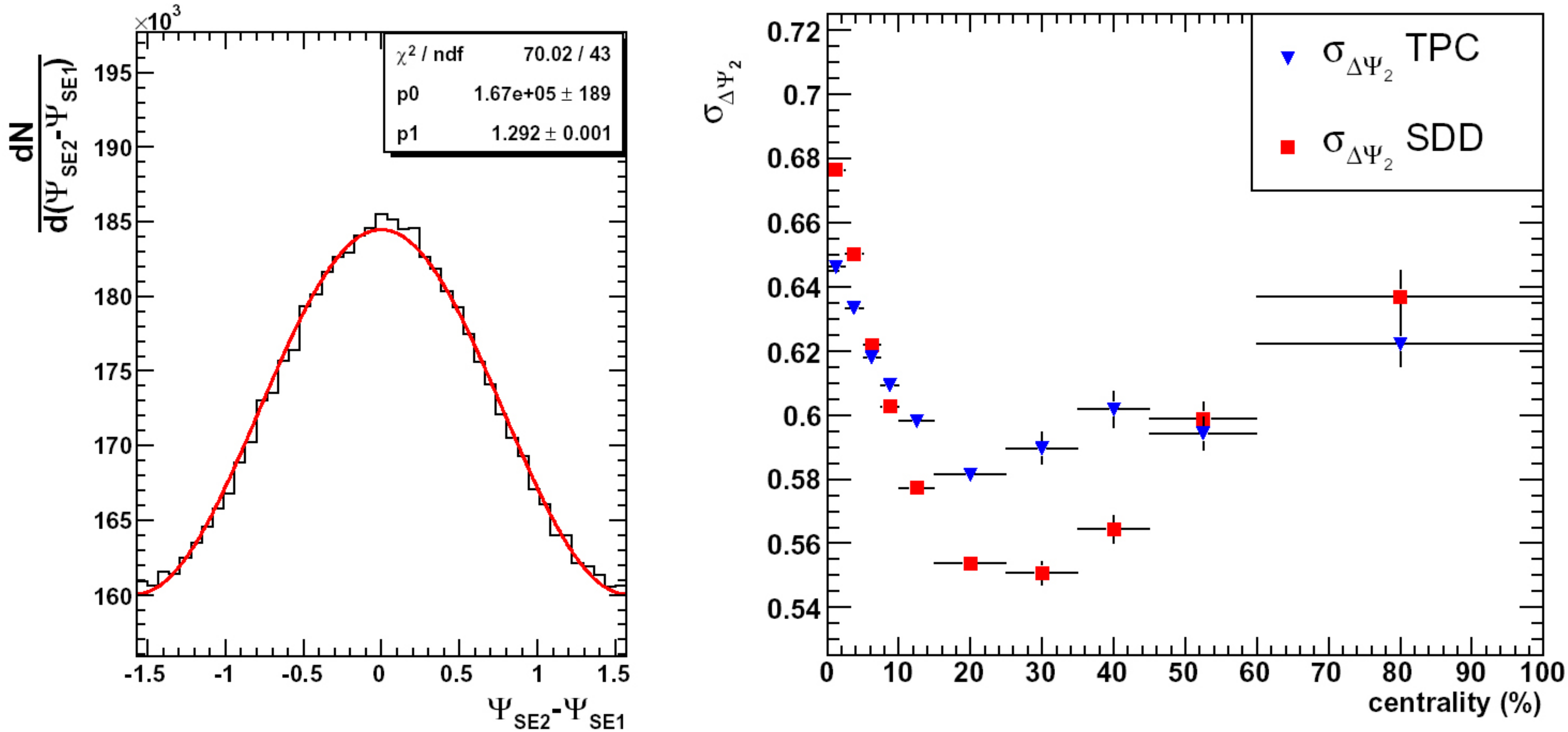
$$Q_2^Y = \sum_i p_t \cdot \sin(2\phi_i)$$

$$\Phi_{RP} = \frac{1}{2}\arctan\left(\frac{Y_2}{X_2}\right)$$

Distribution of the reaction plane angle

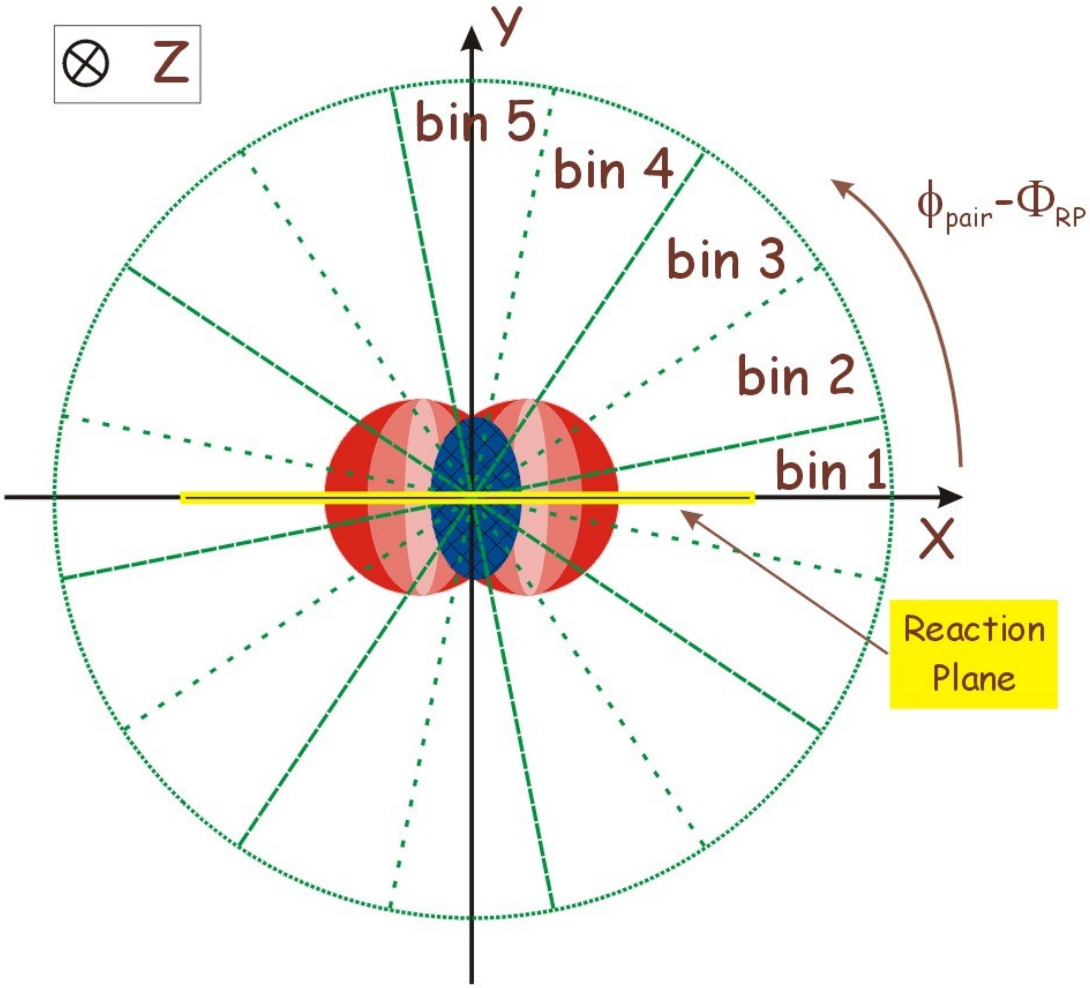


Resolution of the reaction plane



Obtained reaction plane resolution ⇒ 31°-38° (centrality dependence)

Bins in the azimuthal pair angle

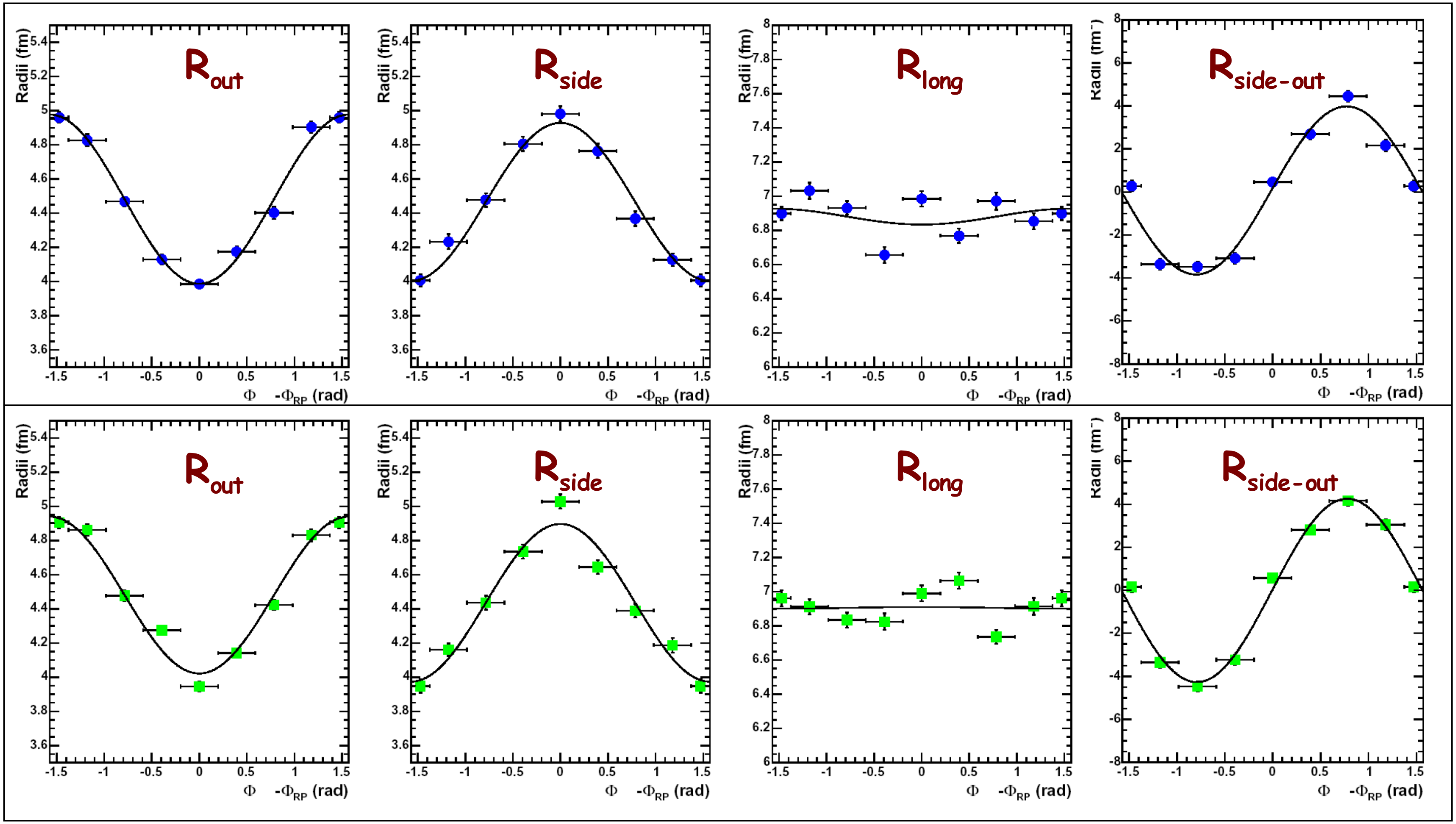


HBT vs Reaction plane - Simulation

- $\pi^-\pi^-$
- $\pi^+\pi^+$

Gaussian source parameterisation, constant radii size:

R_{out} = 4 (fm), R_{side} = 5 (fm), R_{long} = 7 (fm)

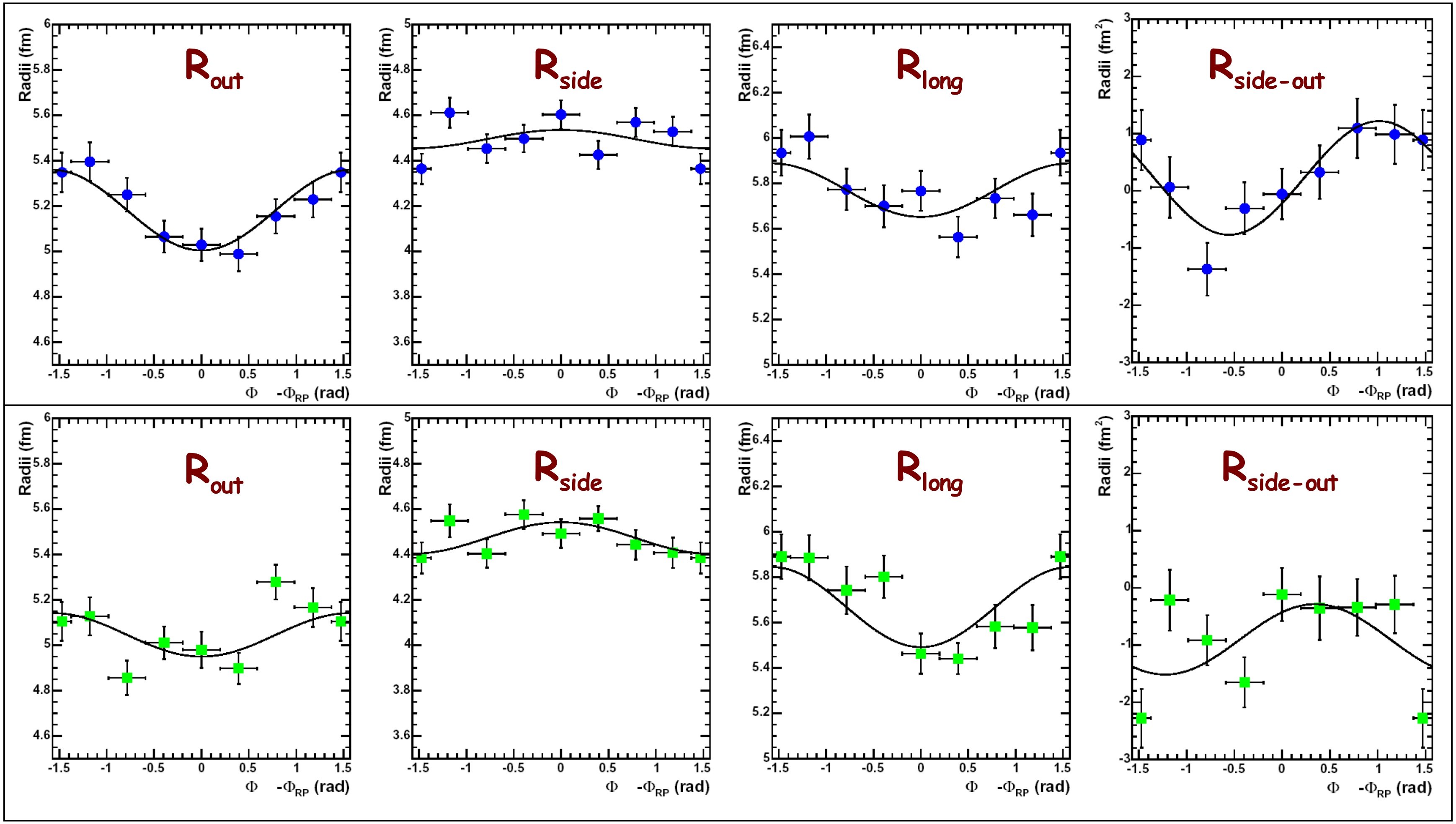


HBT vs Reaction plane - Data

- $\pi^-\pi^-$
- $\pi^+\pi^+$

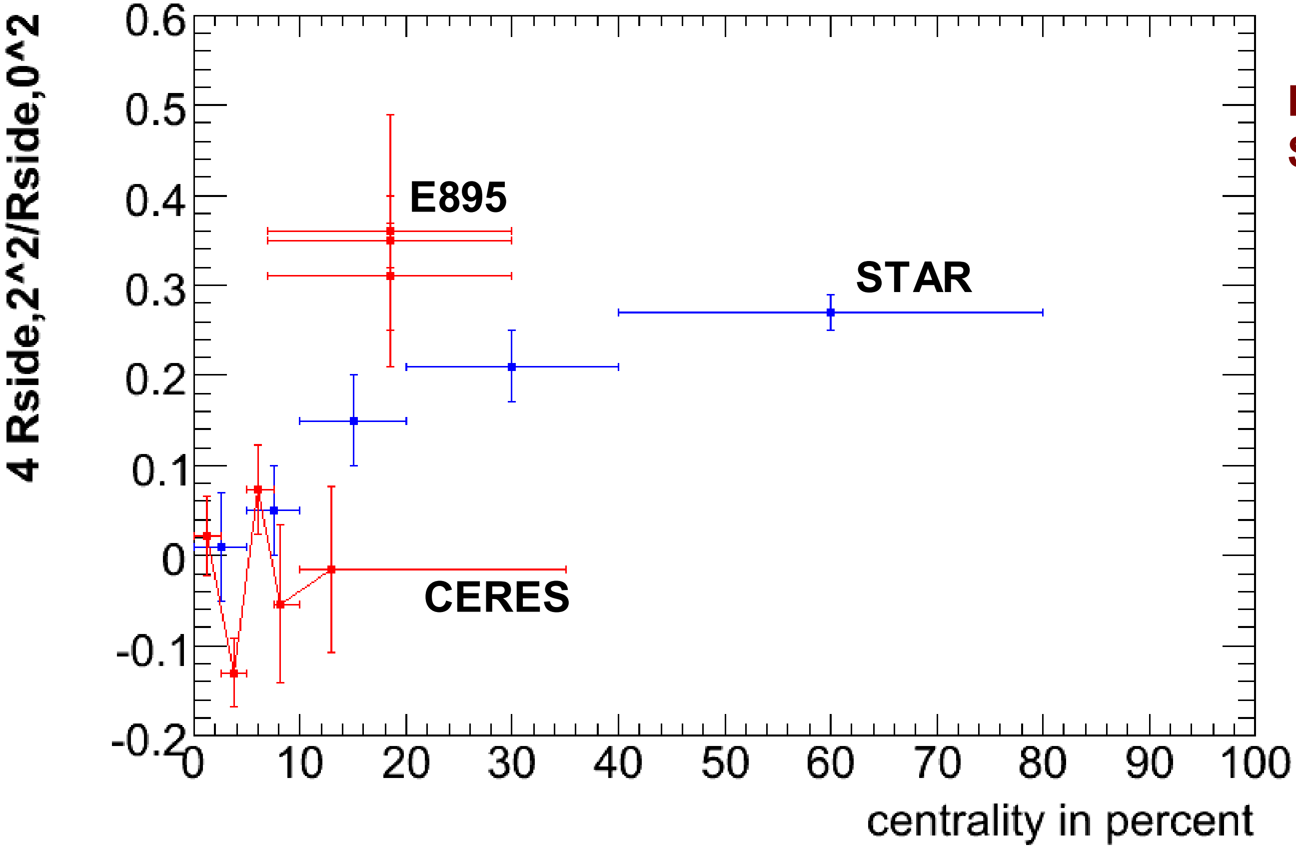
NOT Corrected for Reaction Plane resolution.

σ/σ_{geom} = 10-35 %



Why don't we see anything?

relative R_{side} asymmetry vs centrality



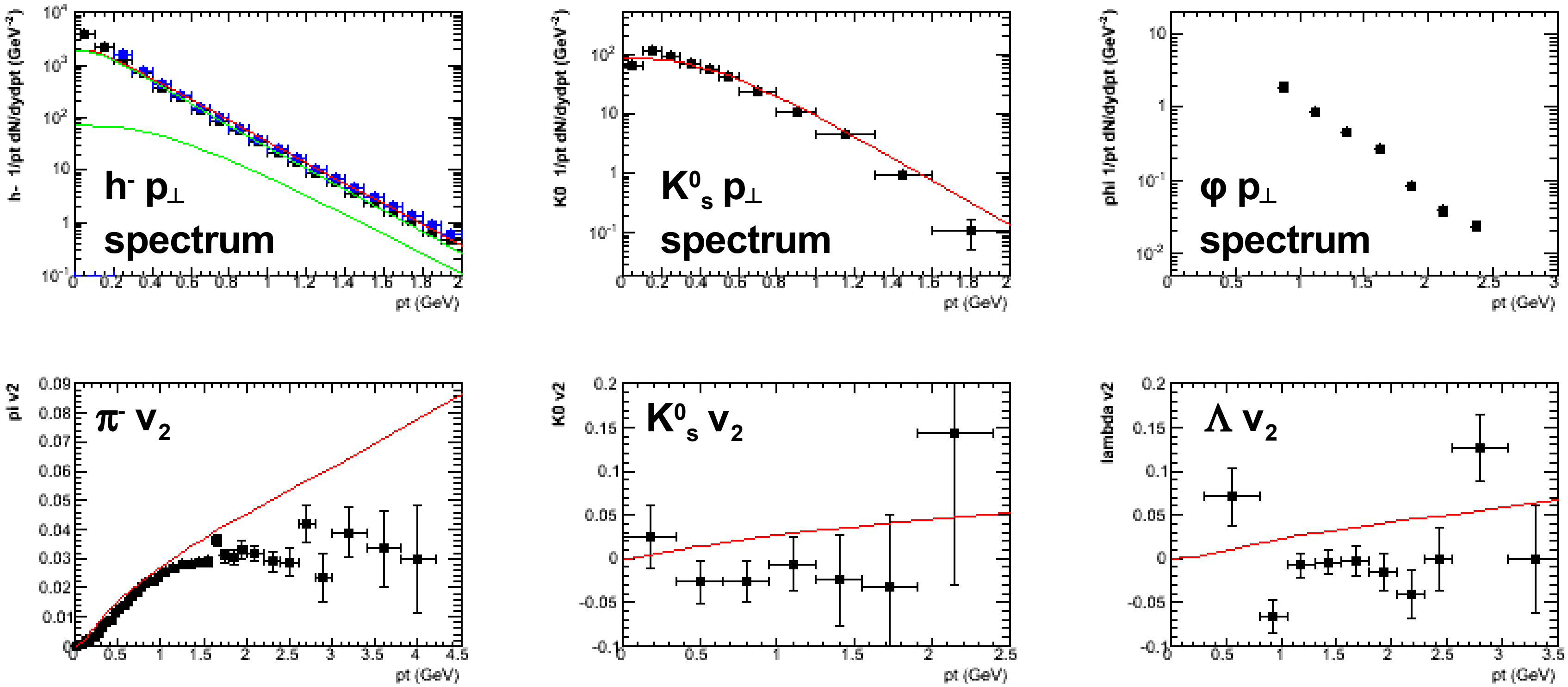
E895 PLB 496 (2000) 1
STAR nucl-ex/0312009

→our statistics dies out before the points have a chance to take off…

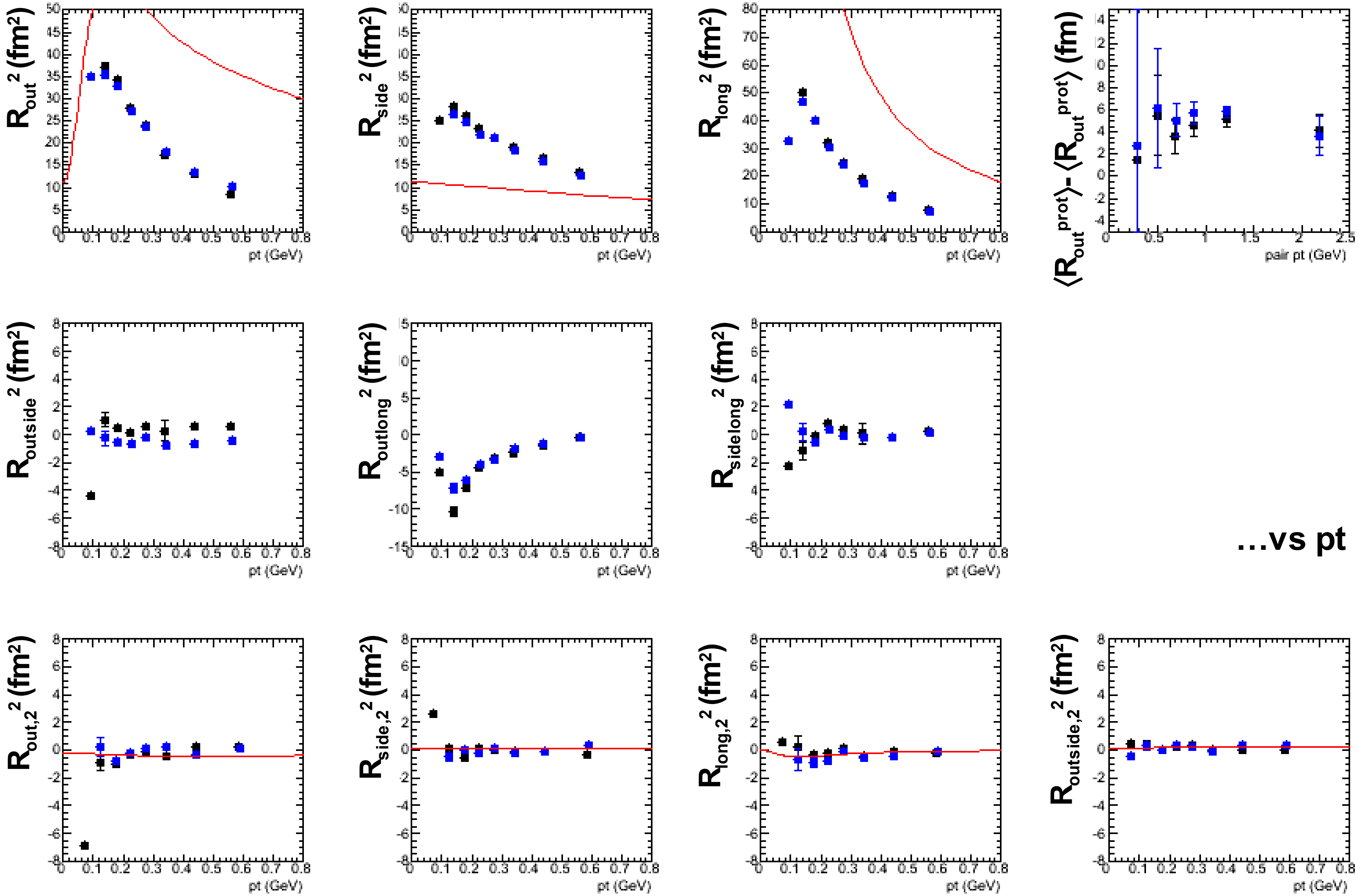
Try to reproduce all at once: hydro and blast

compared to our spectra and correlations at the 7% centrality

Comparison to hydrodynamics
Pasi Huovinen, T=120 MeV



Comparison to hydrodynamics
Pasi Huovinen, T=120 MeV

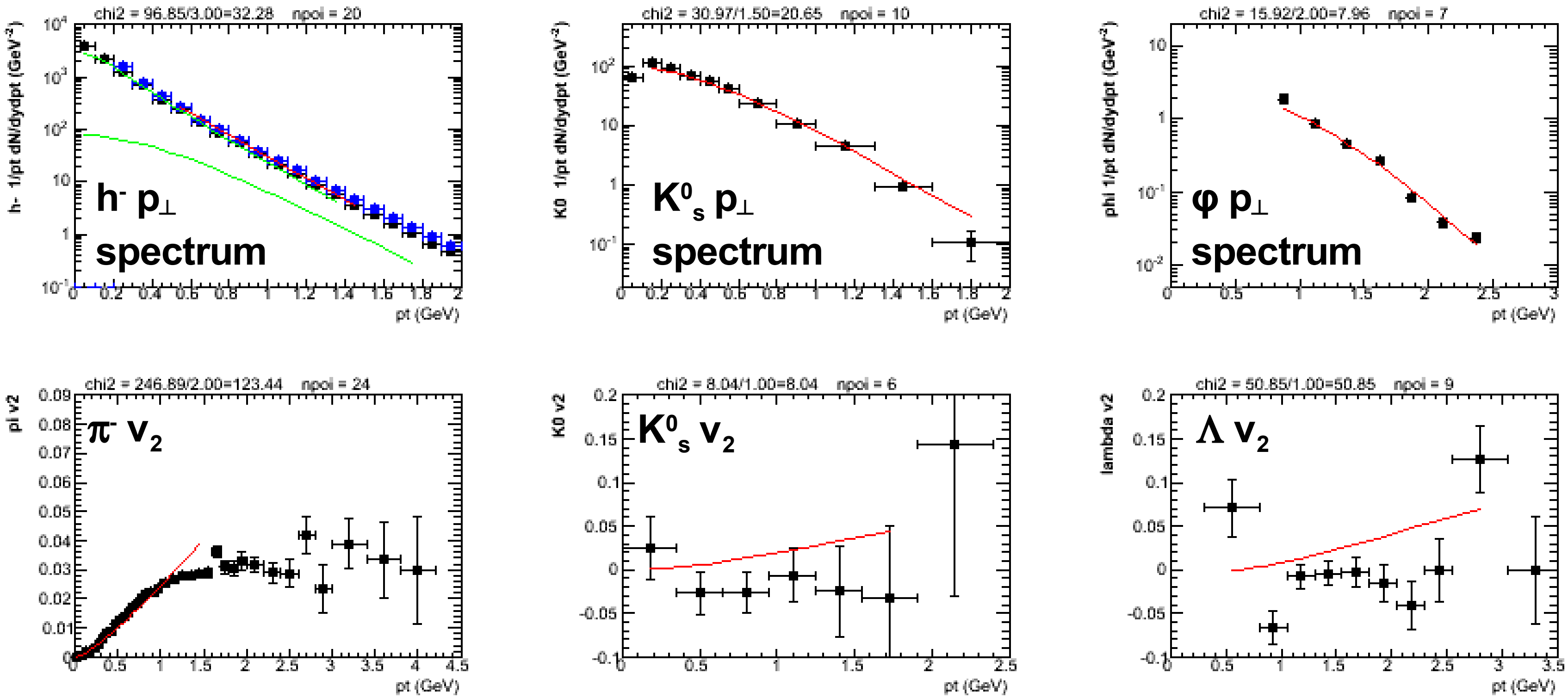


puzzle

hydro

~~RHIC~~ HBT puzzle

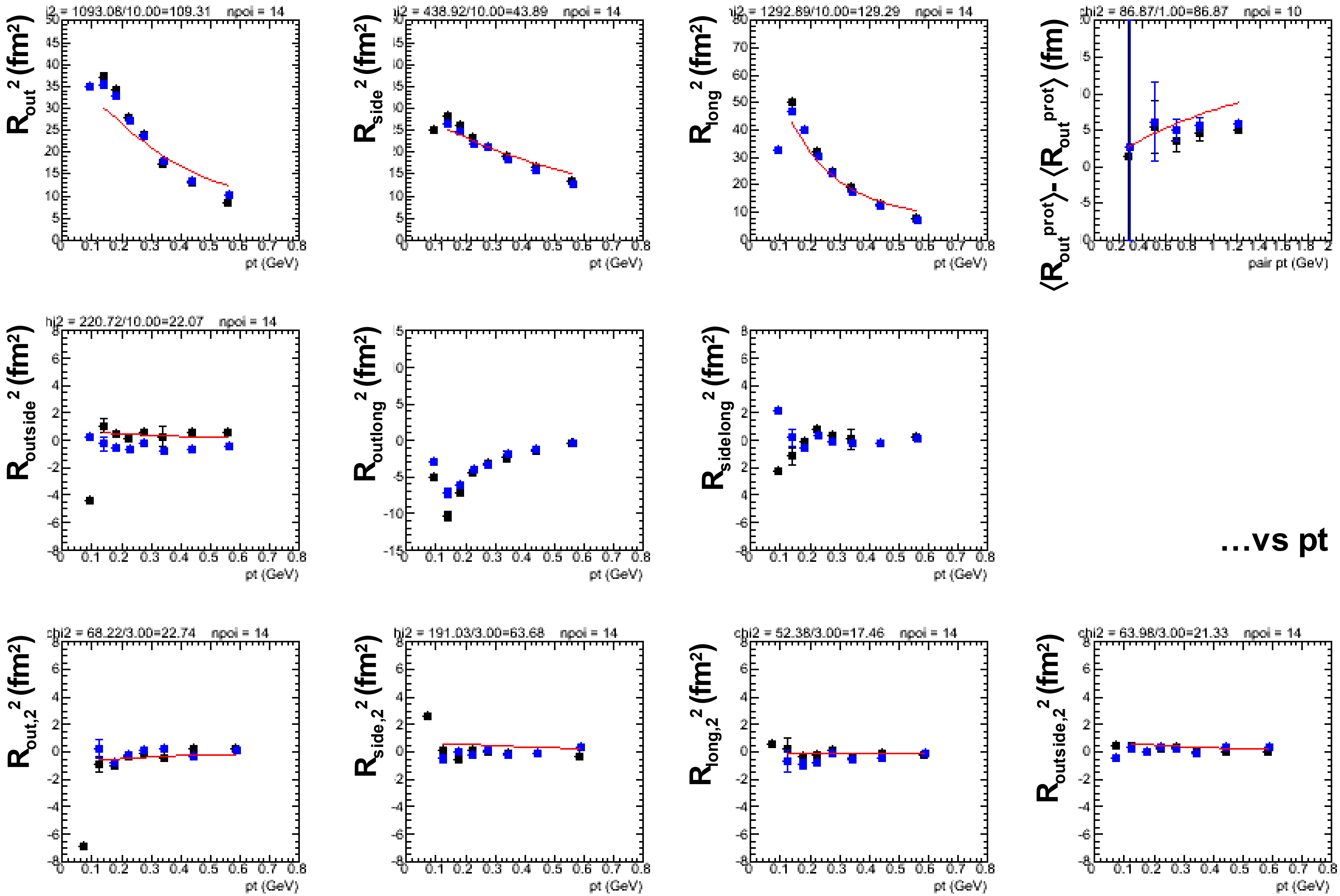
blast wave (Lisa-Retiere) T=100 MeV, sharp sphere



other->fPim = 152.7
other->fKa0 = 18.44
other->fPhi = 1.451
blast->fT = 0.100
blast->fRho0 = 0.87
blast->fRho2 = 0.016
blast->fRx = 11.26
blast->fRy = 11.42
blast->fAs = 0.010
blast->fTau0 = 7.37
blast->fDtau = 1.55

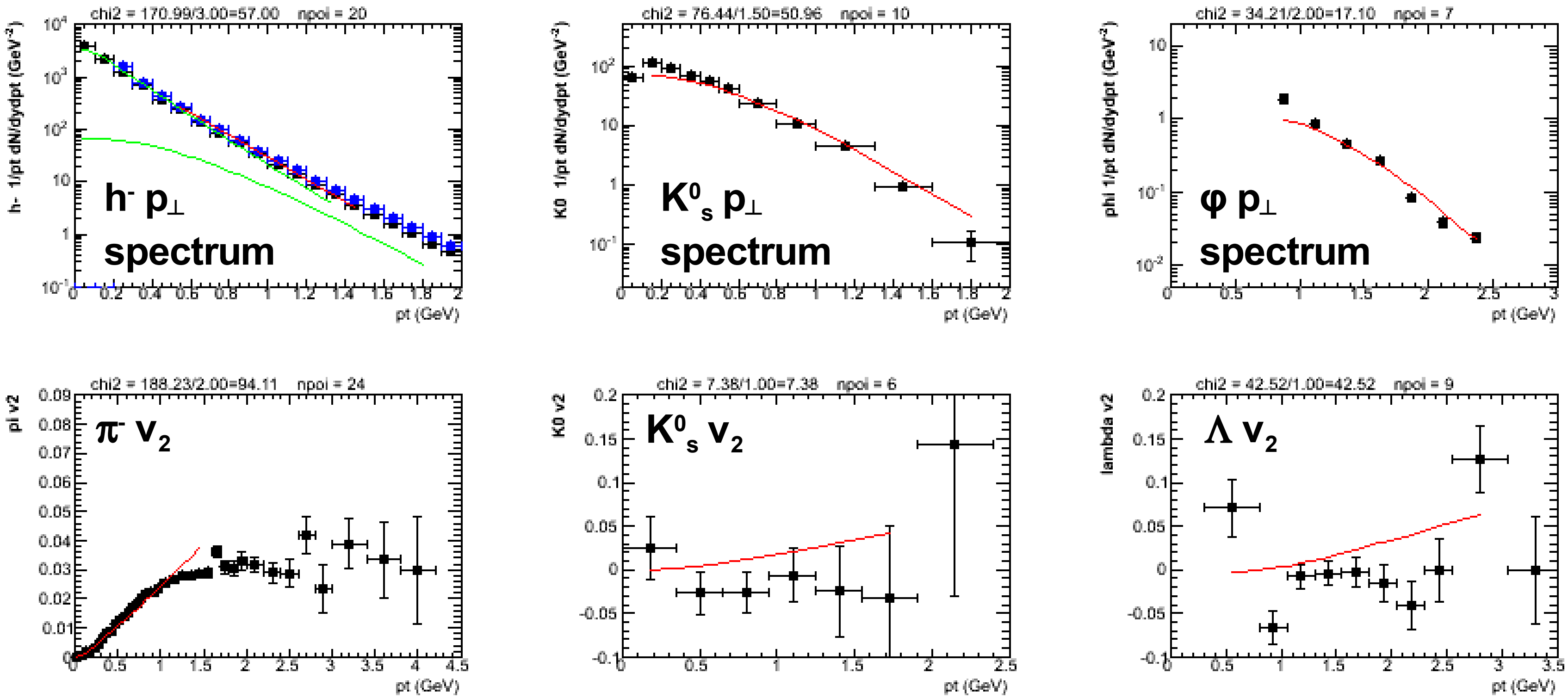
Pim = 152.7 +- 0.0
Ka0 = 18.44 +- 0.00
Phi = 1.451 +- 0.000
T = 0.100 +- 0.000
Rho0 = 0.87 +- 0.00
Rho2 = 0.016 +- 0.020
R = 11.34 +- 0.00
Ry-Rx = 0.16 +- 0.10
As = 0.010 +- 0.000
Tau0 = 7.37 +- 0.00
Dtau = 1.55 +- 0.00

blast wave (Lisa-Retiere) T=100 MeV, sharp sphere



…vs pt

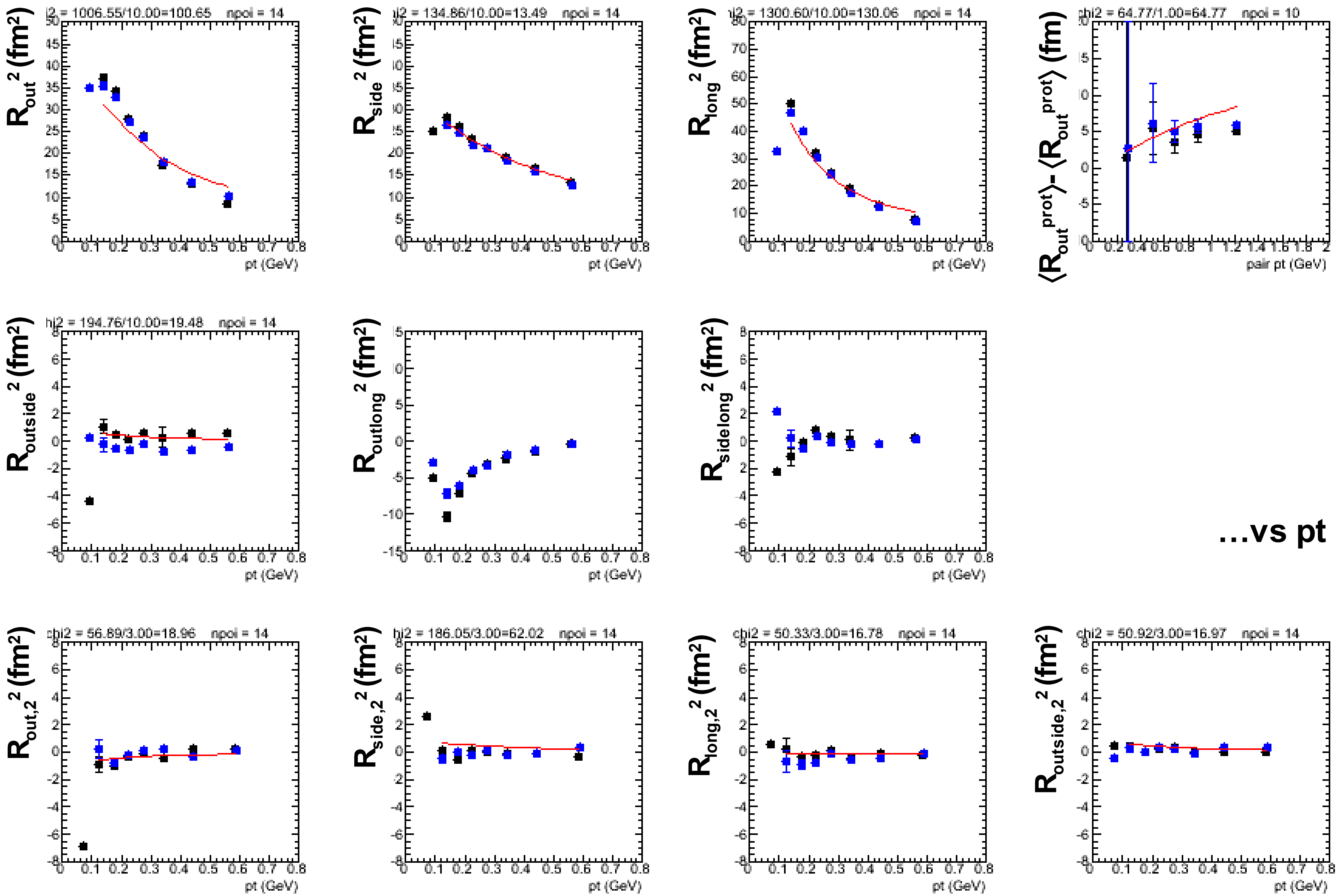
blast wave (Lisa-Retiere) T=80 MeV, sharp sphere



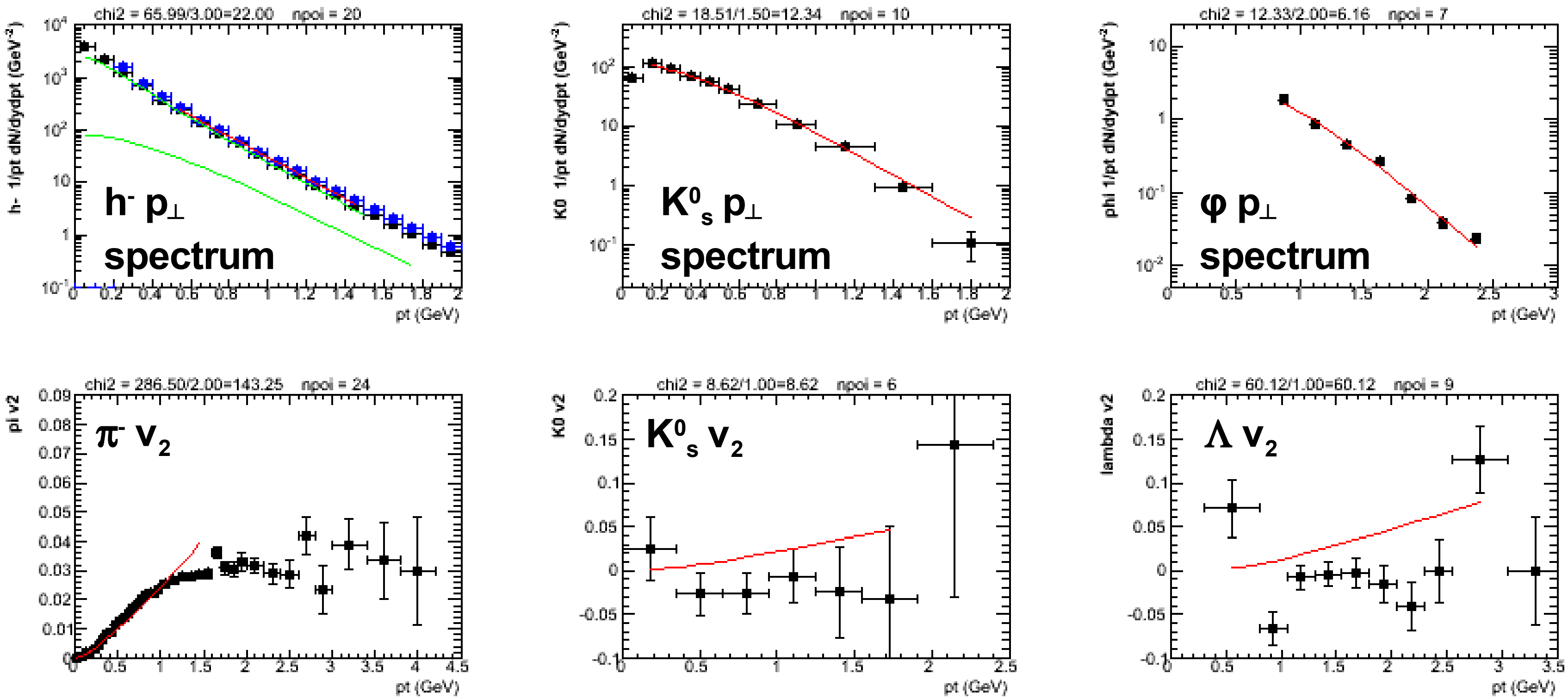
other->fPim = 165.0
other->fKa0 = 17.39
other->fPhi = 1.117
blast->fT = 0.080
blast->fRho0 = 1.02
blast->fRho2 = 0.014
blast->fRx = 12.62
blast->fRy = 12.79
blast->fAs = 0.010
blast->fTau0 = 8.69
blast->fDtau = 2.03

Pim = 165.0 +- 0.0
Ka0 = 17.39 +- 0.00
Phi = 1.117 +- 0.000
T = 0.080 +- 0.000
Rho0 = 1.02 +- 0.00
Rho2 = 0.014 +- 0.020
R = 12.70 +- 0.00
Ry-Rx = 0.17 +- 0.10
As = 0.010 +- 0.000
Tau0 = 8.69 +- 0.00
Dtau = 2.03 +- 0.00

blast wave (Lisa-Retiere) T=80 MeV, sharp sphere



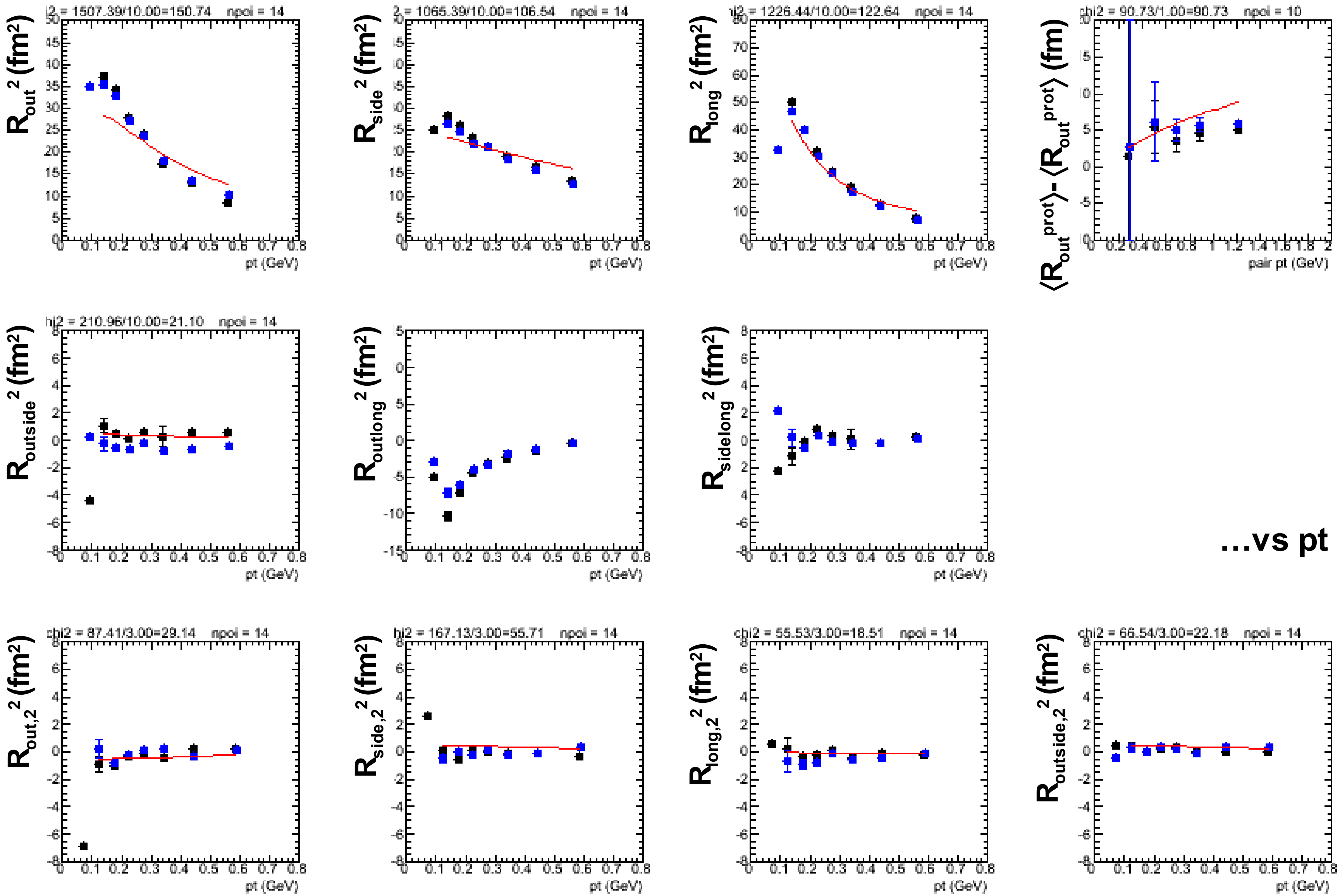
blast wave (Lisa-Retiere) T=120 MeV, sharp sphere



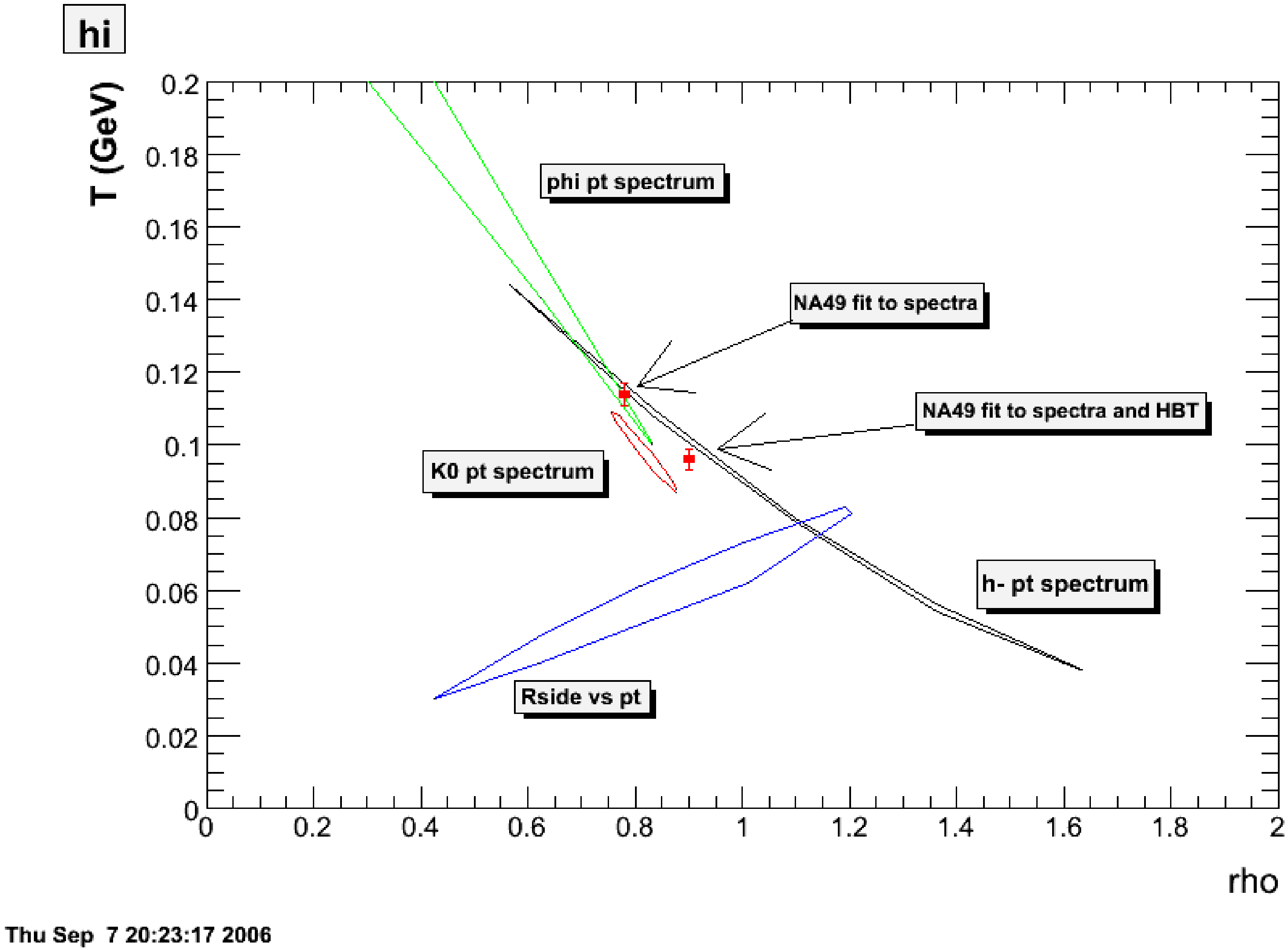

```
other->fPim  = 141.1
other->fKa0  = 19.04
other->fPhi  = 1.817
blast->fT    = 0.120
blast->fRho0 = 0.73
blast->fRho2 = 0.017
blast->fRx   = 10.34
blast->fRy   = 10.51
blast->fAs   = 0.010
blast->fTau0 = 6.60
blast->fDtau = 0.89
```

```
Pim   = 141.1 +-  0.0
Ka0   = 19.04 +-  0.00
Phi   = 1.817 +-  0.000
T     = 0.120 +-  0.000
Rho0  = 0.73 +-   0.00
Rho2  = 0.017 +-  0.020
R     = 10.43 +-  0.00
Ry-Rx = 0.17 +-   0.10
As    = 0.010 +-  0.000
Tau0  = 6.60 +-   0.00
Dtau  = 0.89 +-   0.00
```

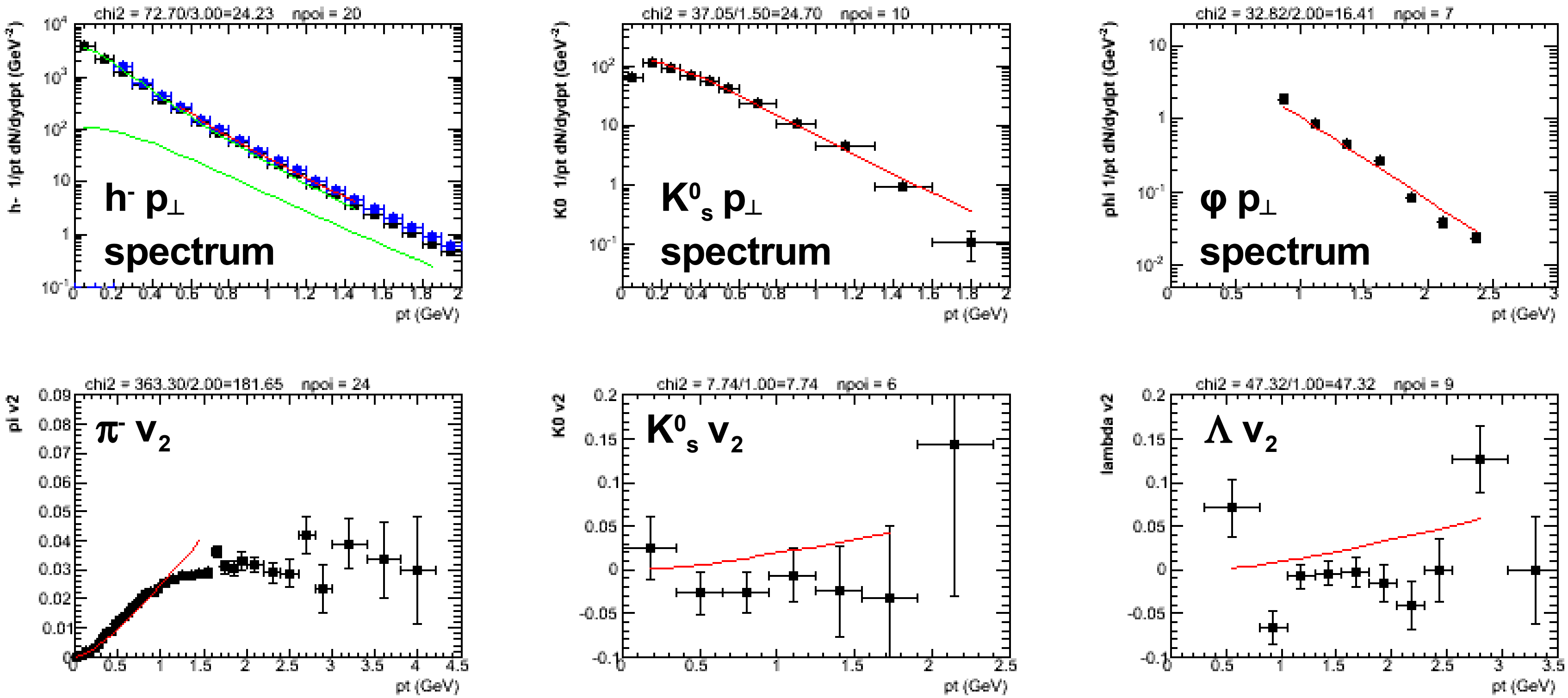
blast wave (Lisa-Retiere) T=120 MeV, sharp sphere



T - ρ contours


hi
T (GeV)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
rho
phi pt spectrum
NA49 fit to spectra
NA49 fit to spectra and HBT
K0 pt spectrum
h- pt spectrum
Rside vs pt
Thu Sep 7 20:23:17 2006

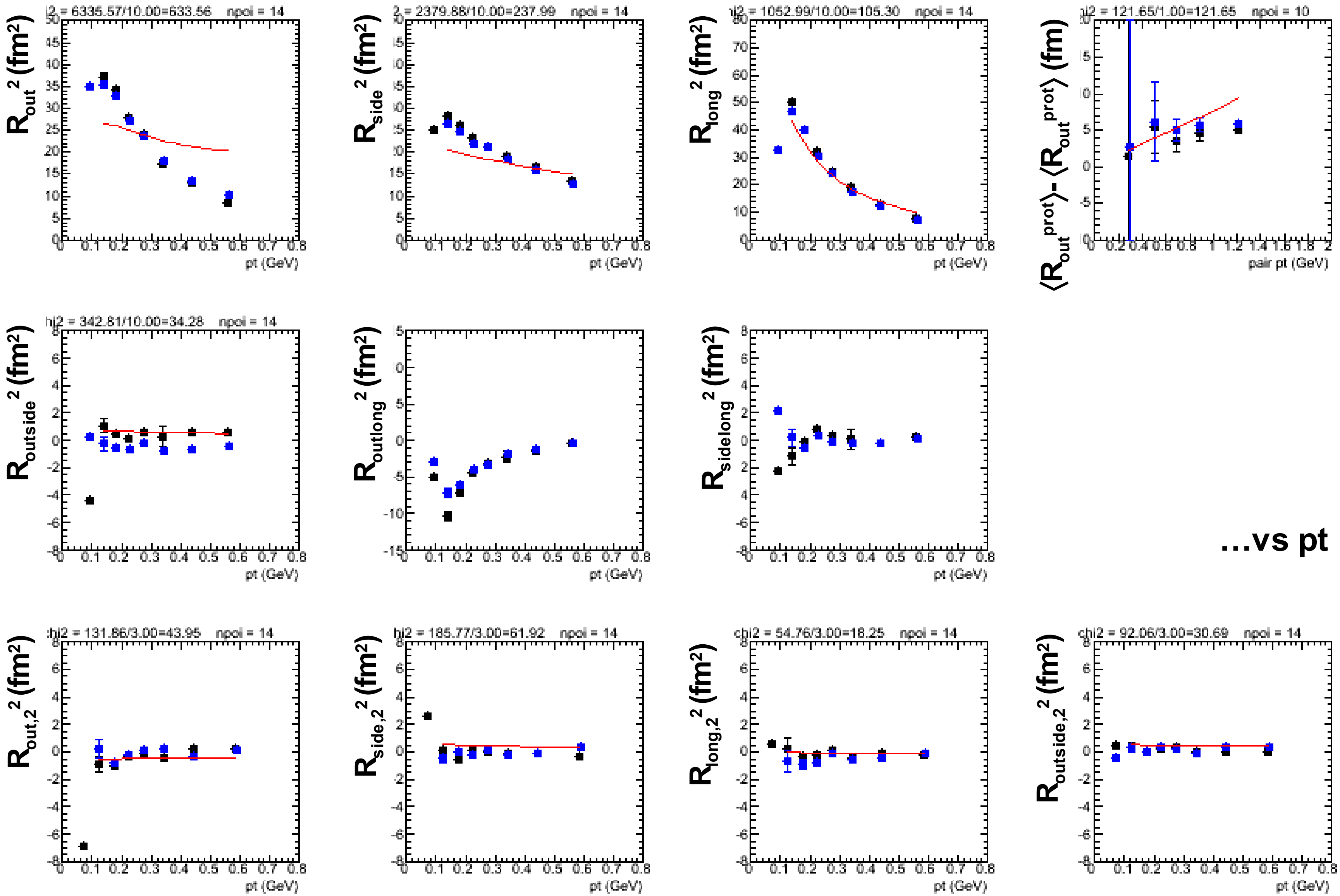
blast wave (Lisa-Retiere) T=100 MeV, gaussian-like



other->fPim = 169.6
other->fKa0 = 19.57
other->fPhi = 1.710
blast->fT = 0.100
blast->fRho0 = 0.52
blast->fRho2 = 0.009
blast->fRx = 6.96
blast->fRy = 7.07
blast->fAs = 0.300
blast->fTau0 = 7.65
blast->fDtau = 0.02

Pim = 169.6 +- 0.0
Ka0 = 19.57 +- 0.00
Phi = 1.710 +- 0.000
T = 0.100 +- 0.000
Rho0 = 0.52 +- 0.00
Rho2 = 0.009 +- 0.020
R = 7.01 +- 0.00
Ry-Rx = 0.11 +- 0.10
As = 0.300 +- 0.000
Tau0 = 7.65 +- 0.00
Dtau = 0.02 +- 0.00

blast wave (Lisa-Retiere) T=100 MeV, gaussian-like



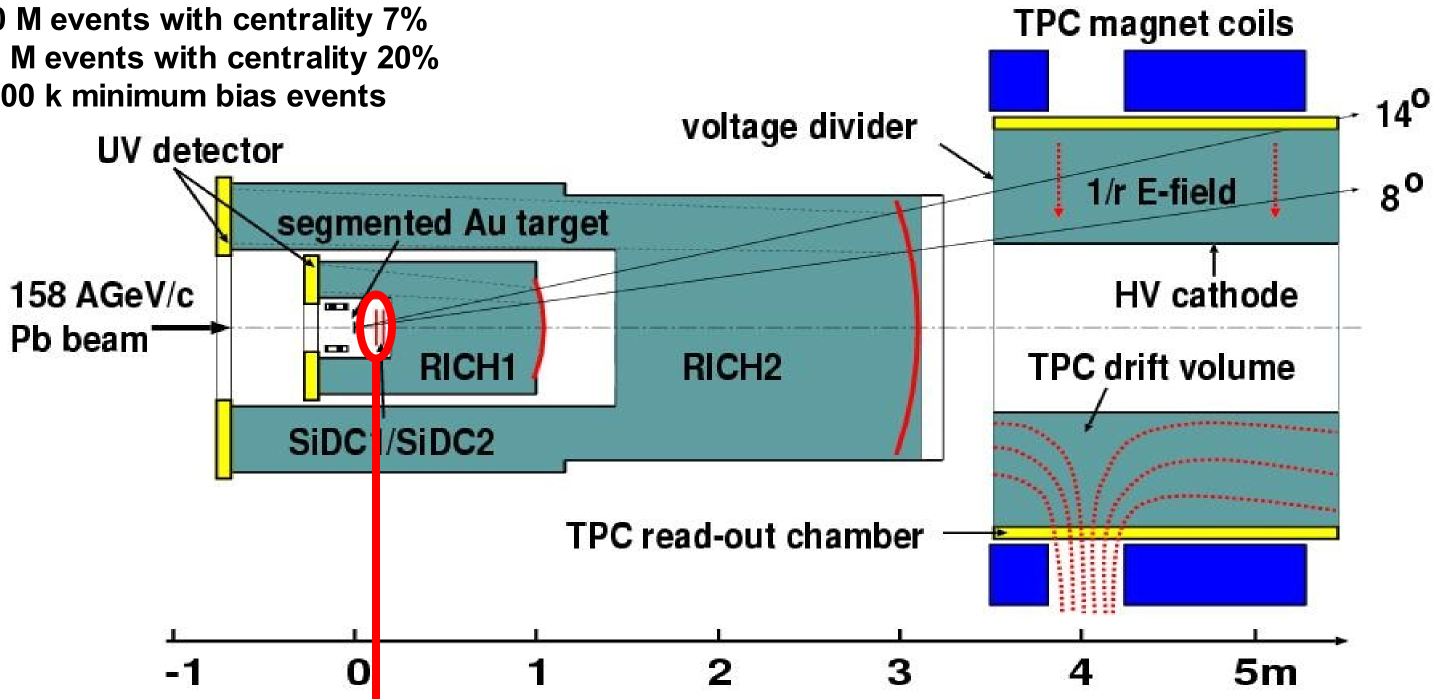
summary

- pion-proton correlation works very nicely… but is dominated by the radial flow, for which better tools exist
- no significant azimuthal anisotropy of the source observed
- hydro has a principal problem with source sizes
- blast wave fits in principle but not quite

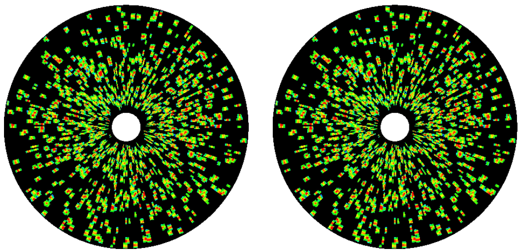
backup slides

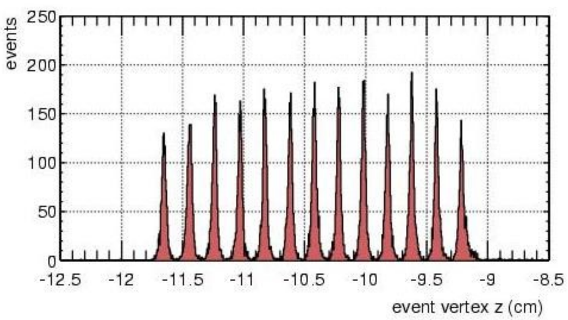
setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events



SD: event vertex, track vertex and angle

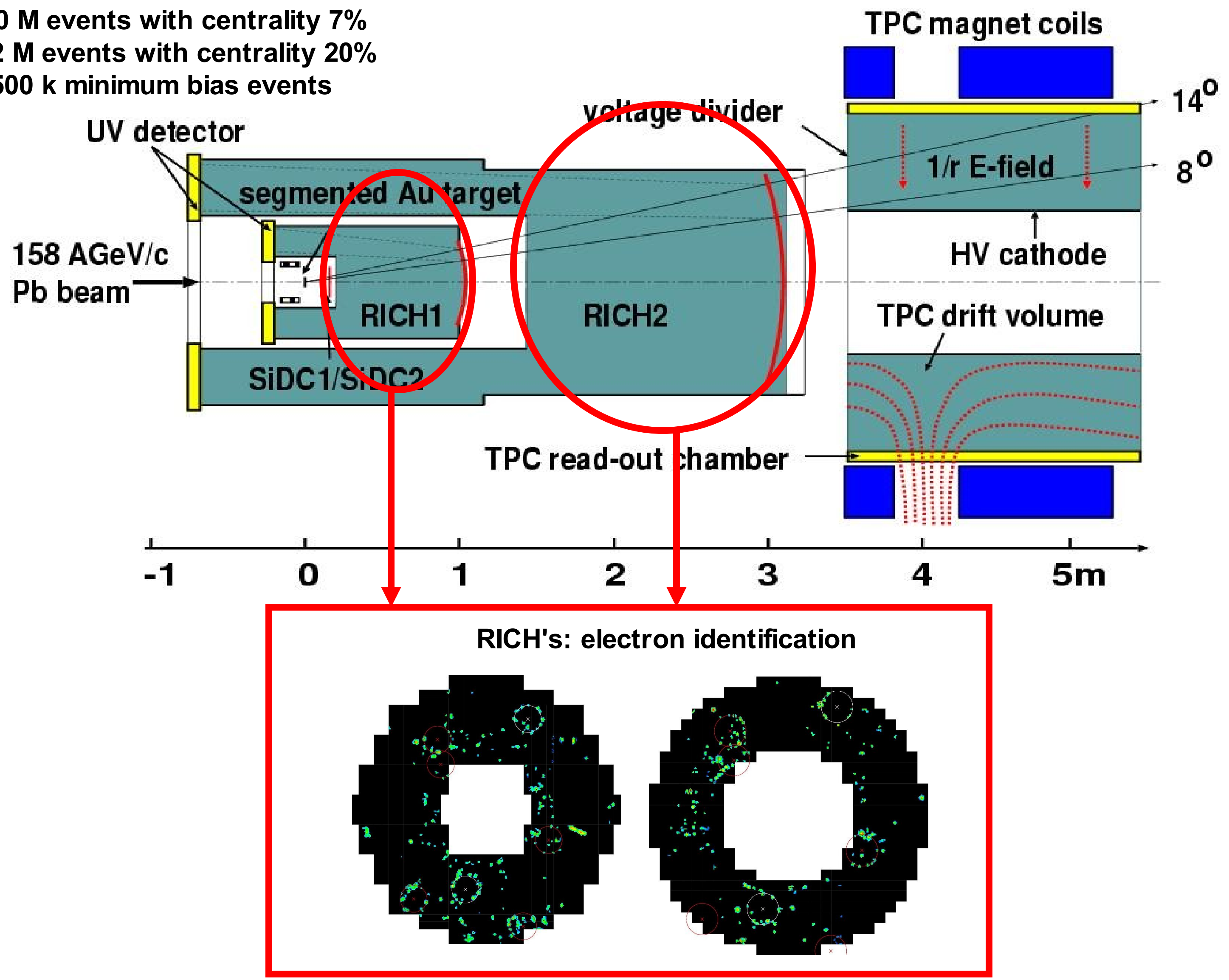




event Δz = 0.2 mm
track $\Delta\theta$ = 0.2 mrad
$\Delta\varphi$ = 2 mrad

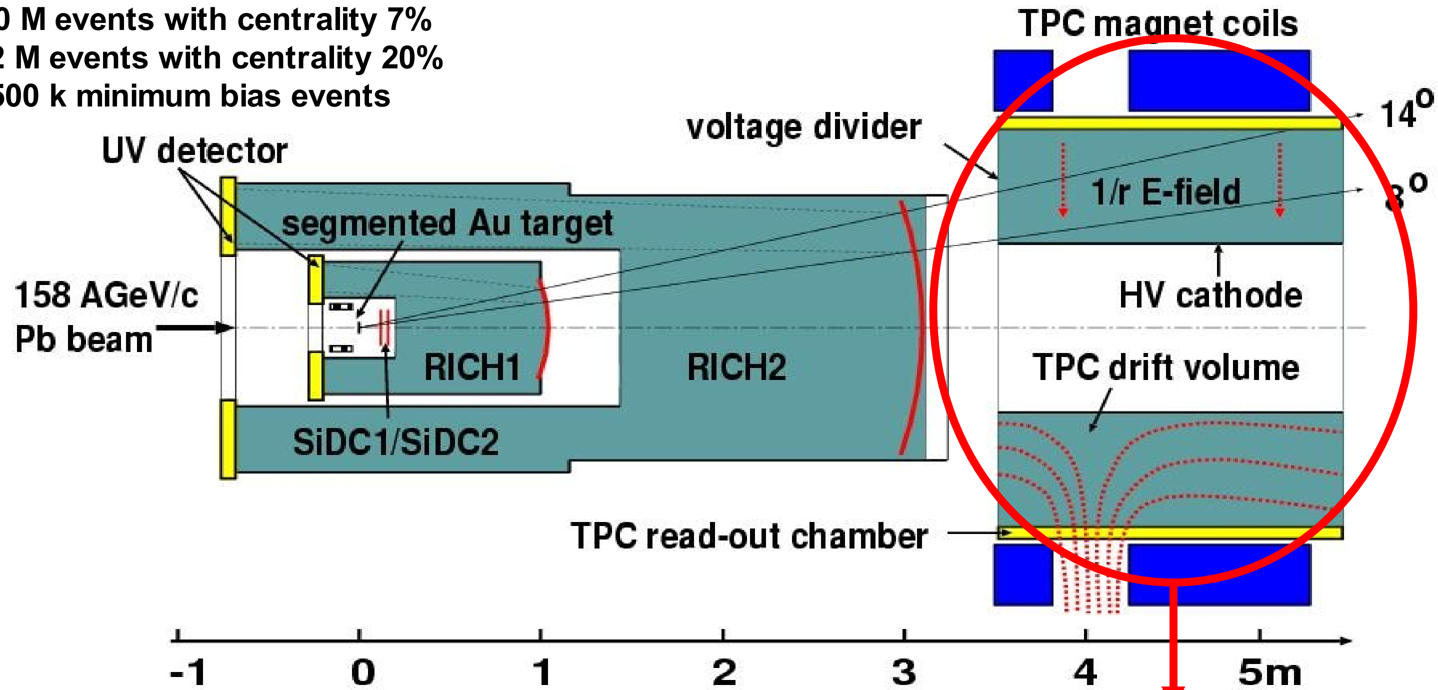
setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events

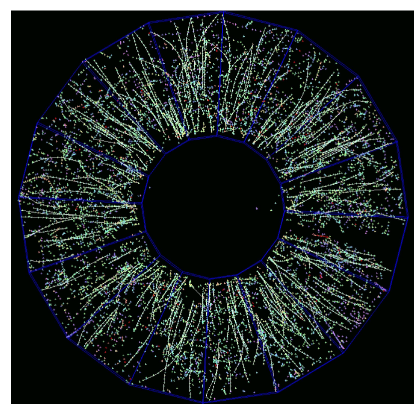


setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events



radial drift TPC: momentum and energy loss

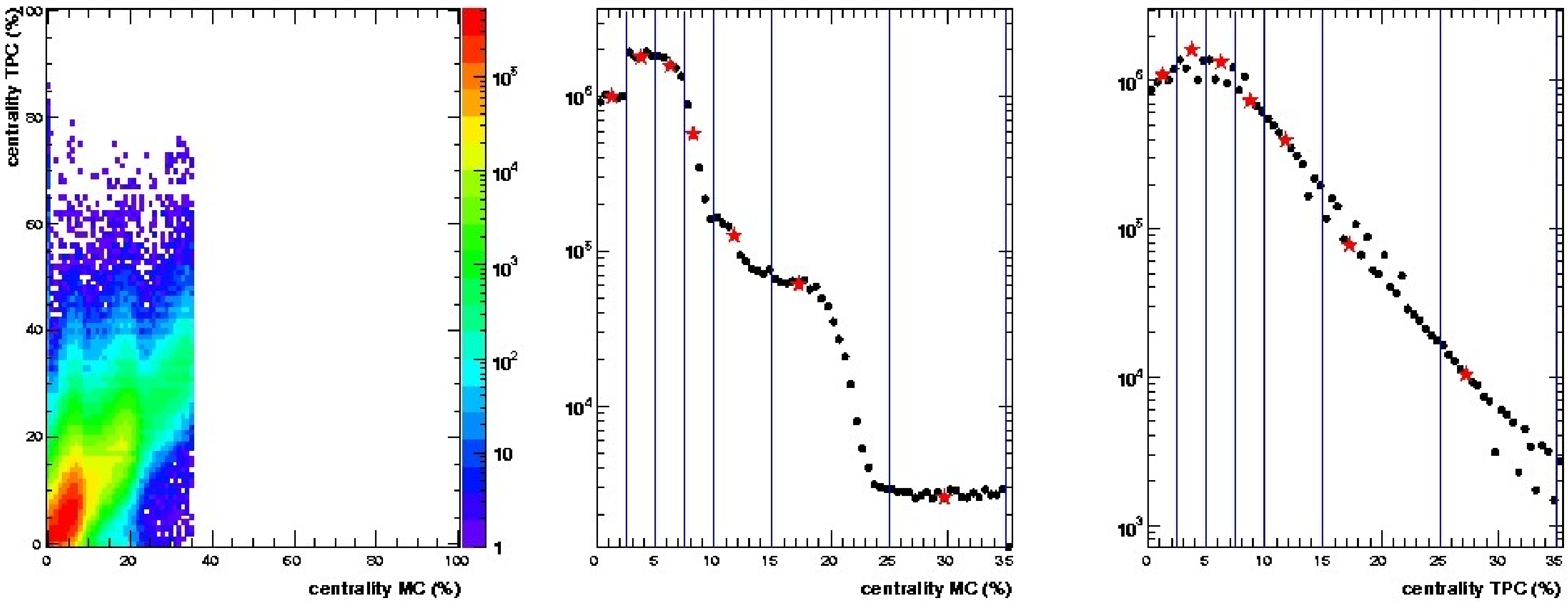


$\Delta p/p = 2\% \oplus 1\% * p/GeV$

$\Delta m/m$ = 3.8 % for ϕ

$\Delta(dE/dx)/(dE/dx) = 10\%$

centrality of the analyzed data set

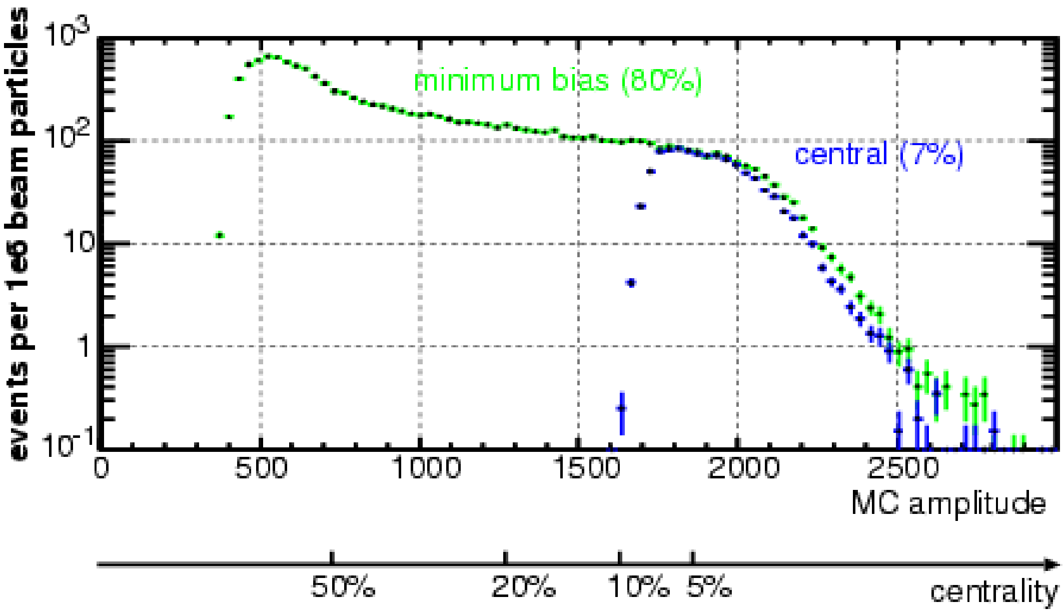


centrality determination

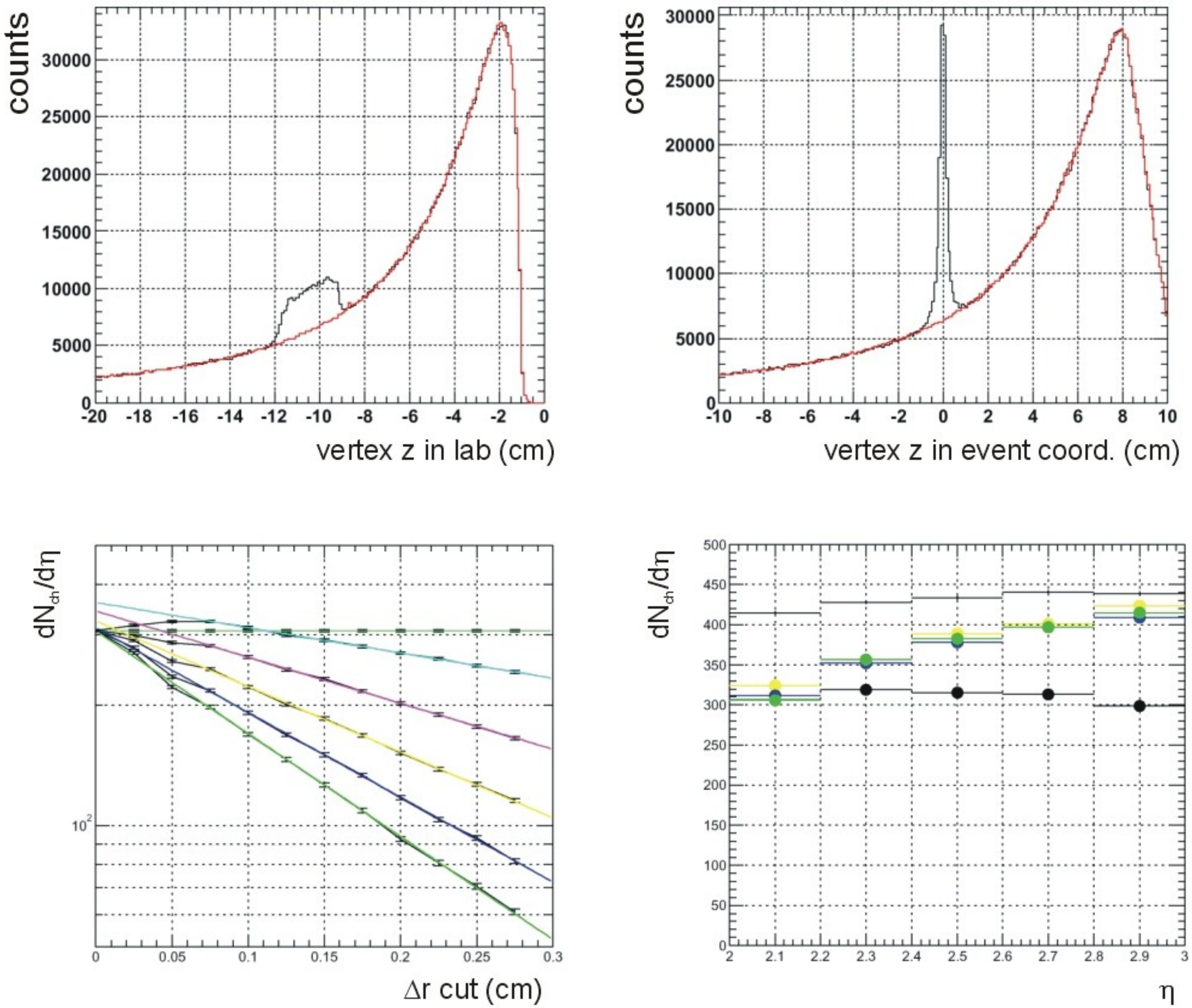
Pb+Au at 158 GeV per nucleon

centrality deduced from the multiplicity of charged particles around mid-rapidity

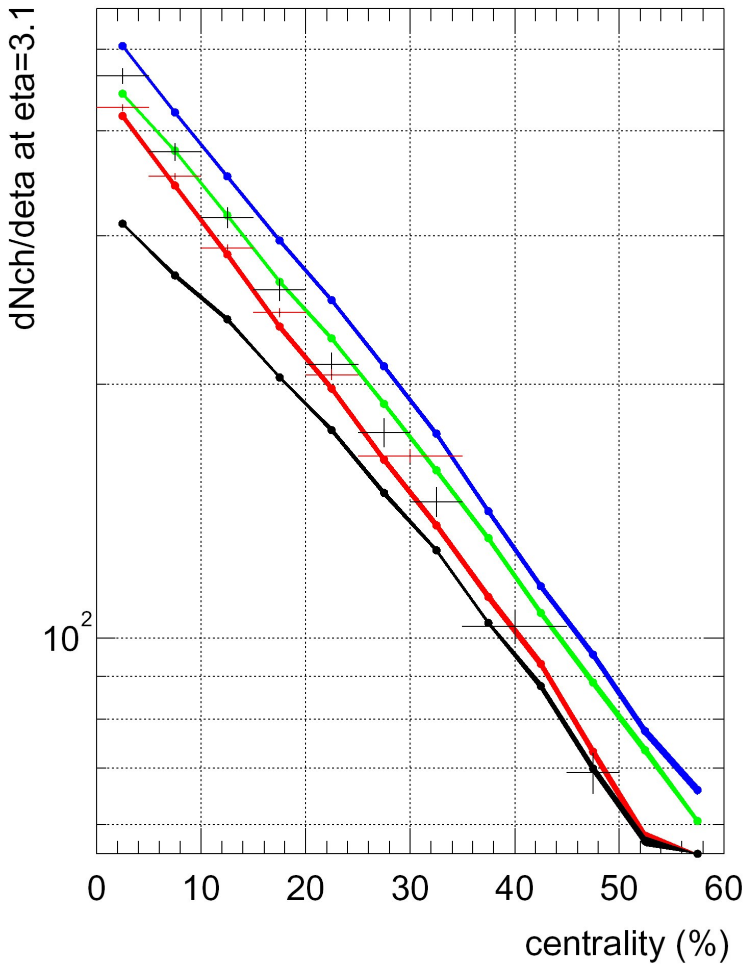
MC scintillator amplitude 2.95 < η < 4.05
TPC track multiplicity 2.10 < η < 2.80
mid-rapidity y = 2.91

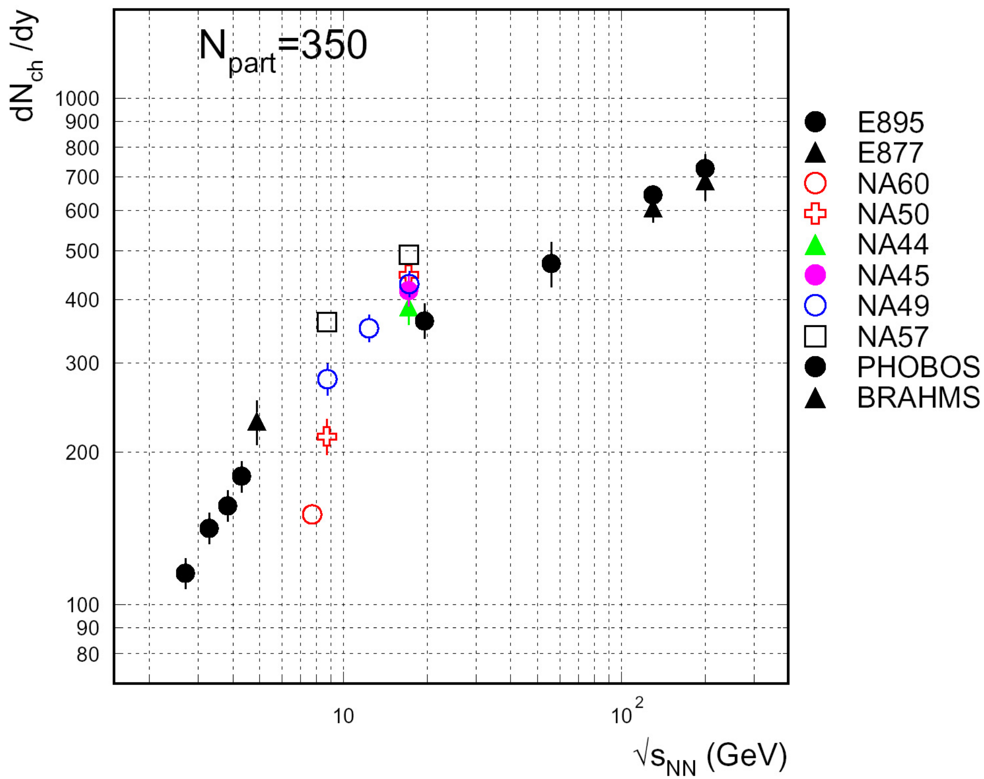


Absolute multiplicity of charged particles



Absolute multiplicity of charged particles

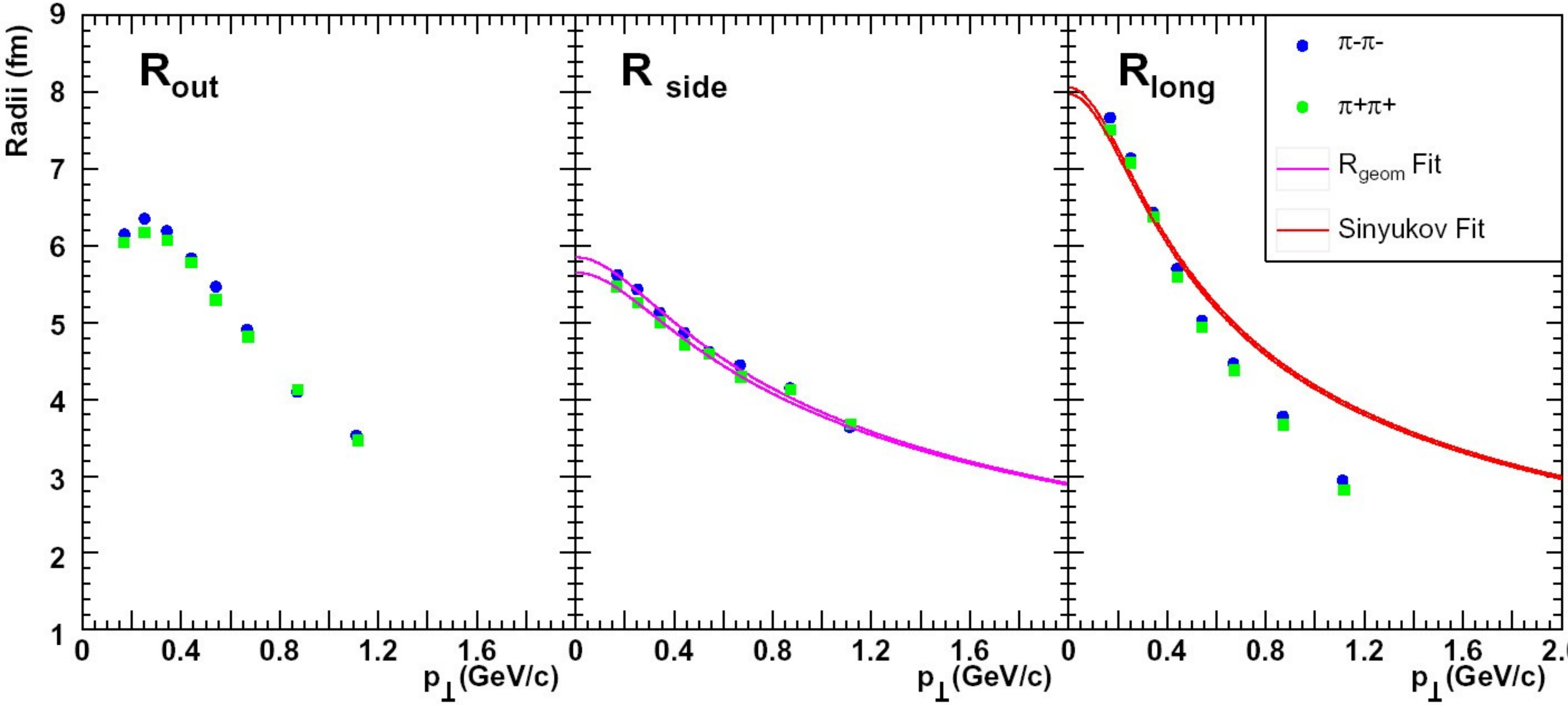




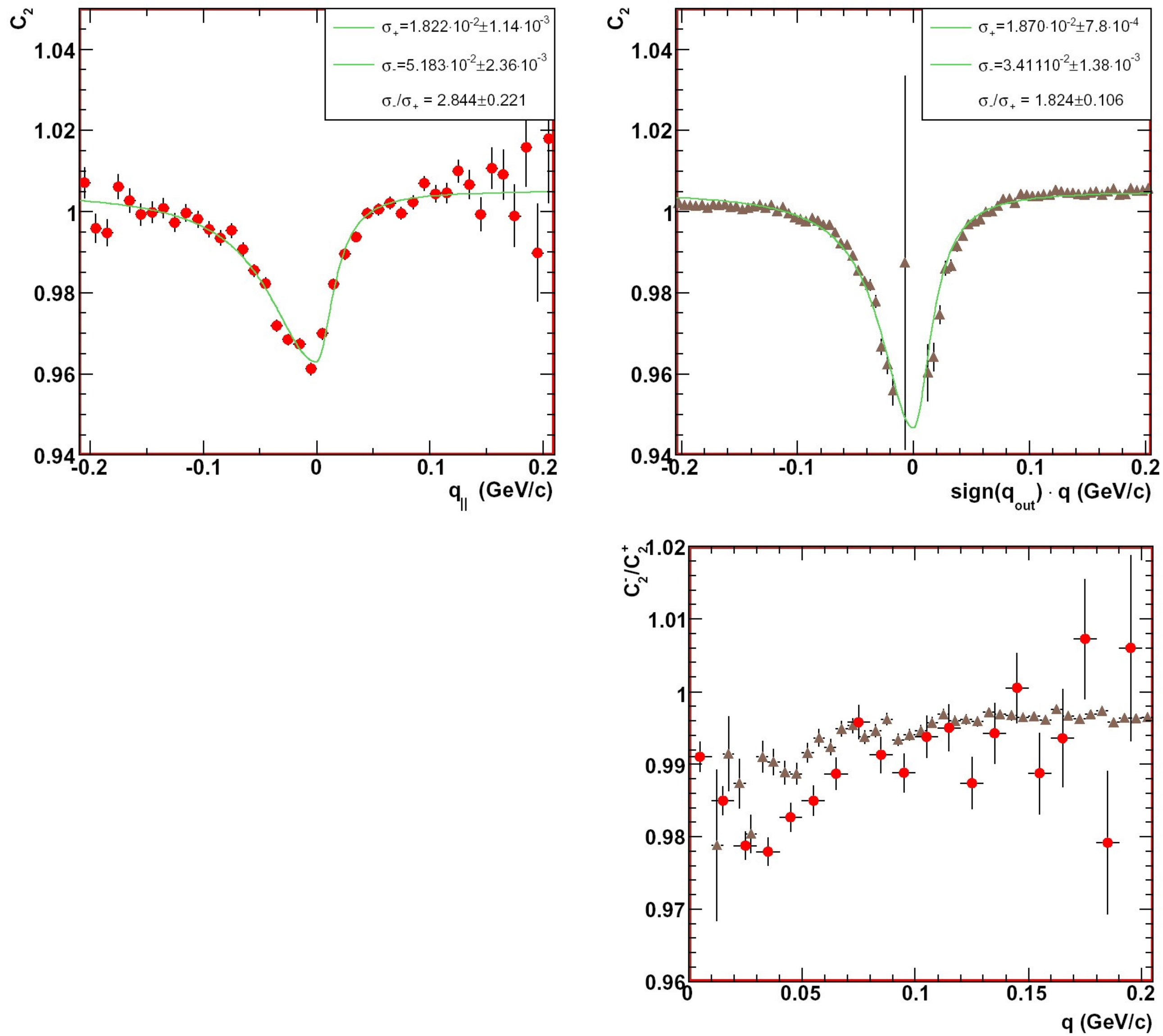
dNch/dy = 1.025 dNch/dη applied at SPS
dNch/dy = 1.1 dNch/dη applied at RHIC

Fit to R_{long} without the Bessel function term

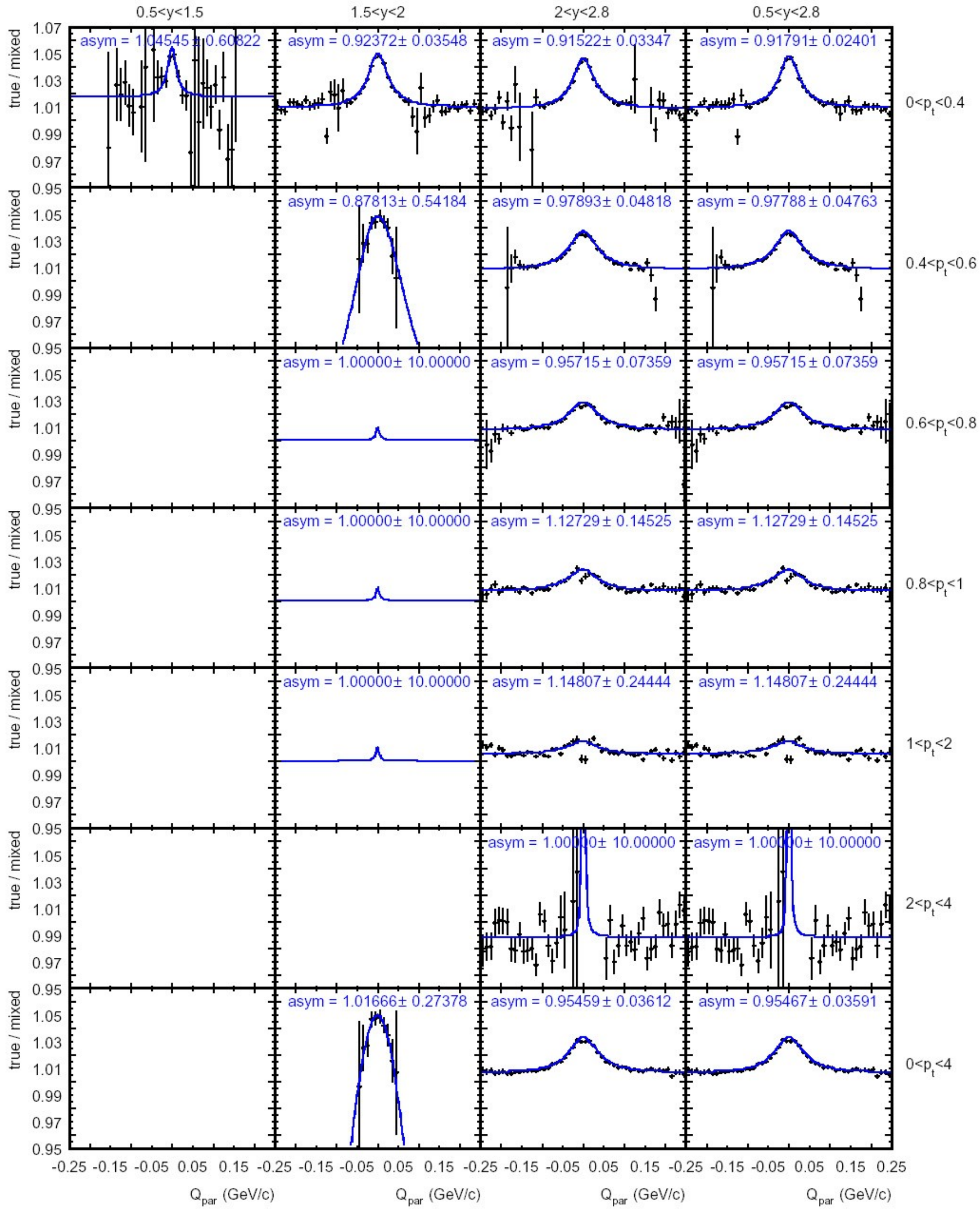
$$R_{long} = \tau_0 \sqrt{\frac{m_\perp}{K} \frac{K_2(T/m_\perp)}{K_1(T/m_\perp)}} \qquad R_{long} = \tau_0 \sqrt{\frac{m_\perp}{K}}$$



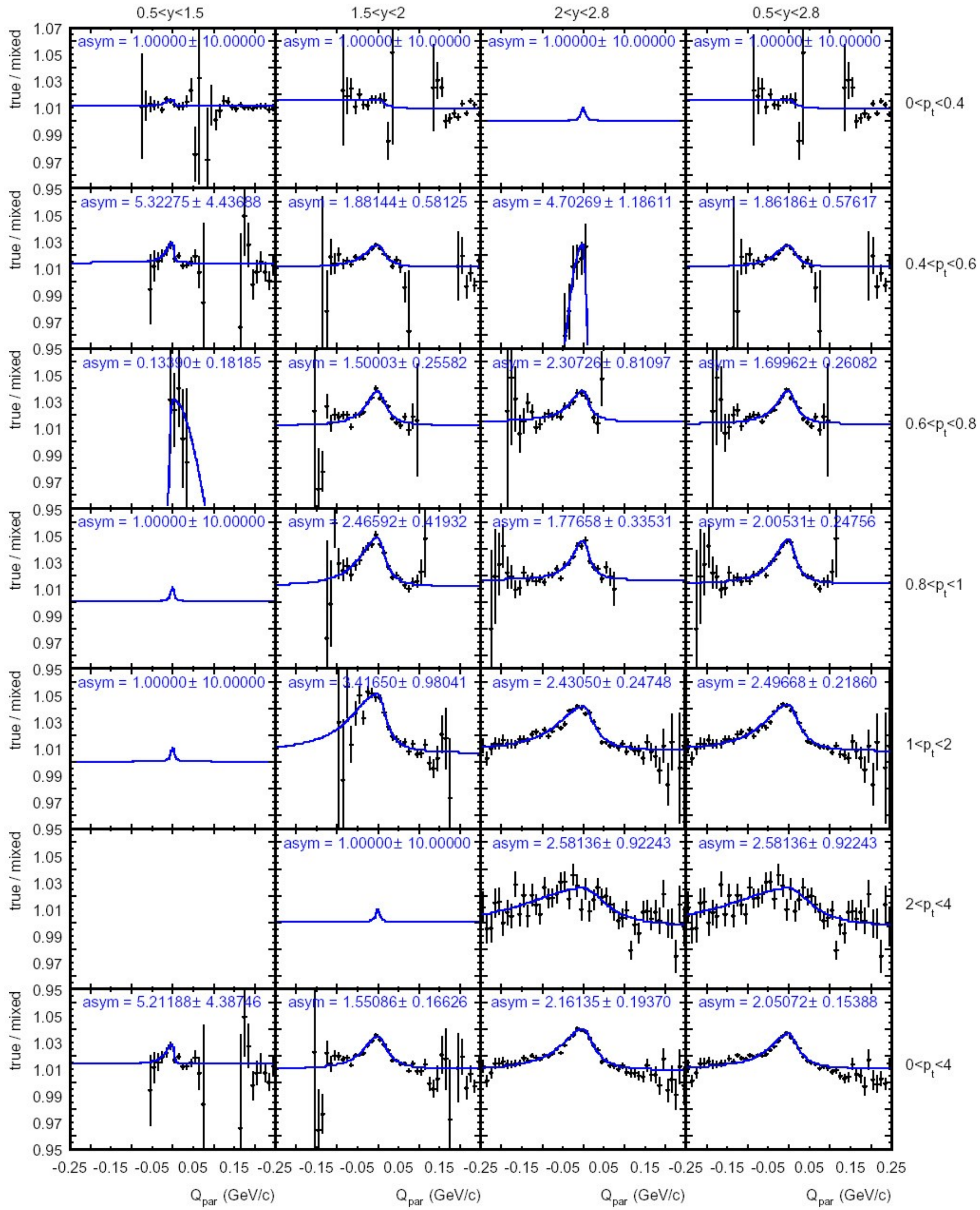
Comparison to the traditional method (experimental data)



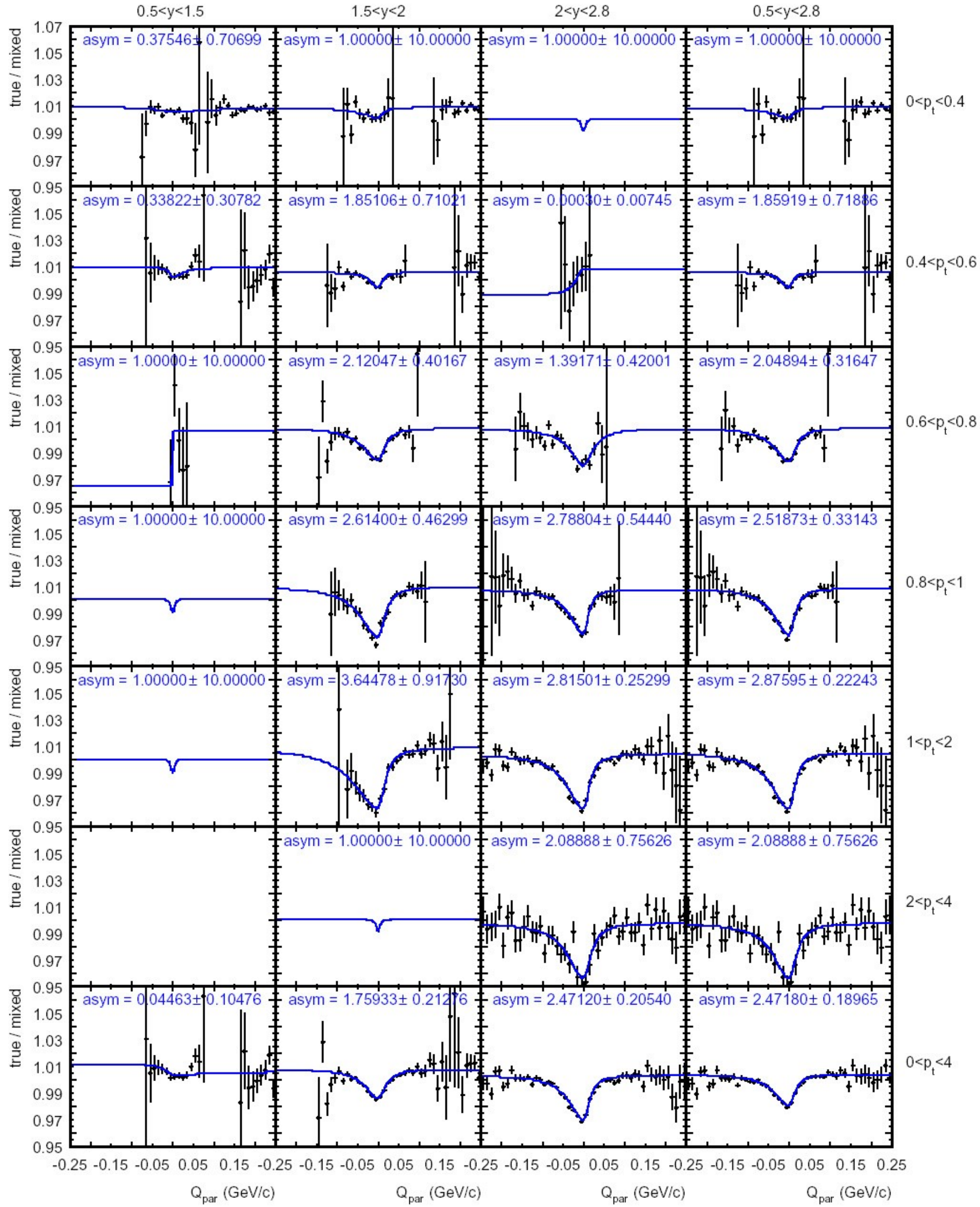
pi+ pi- correlation functions

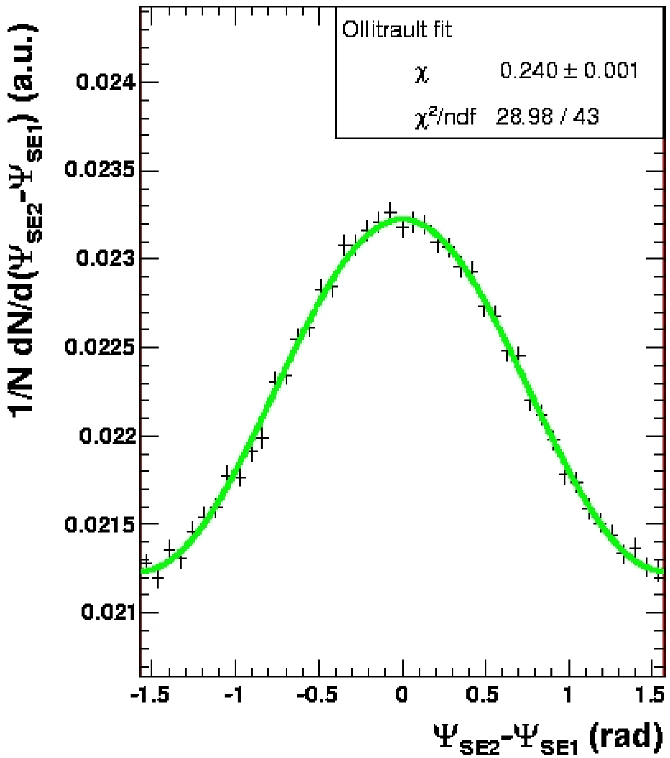


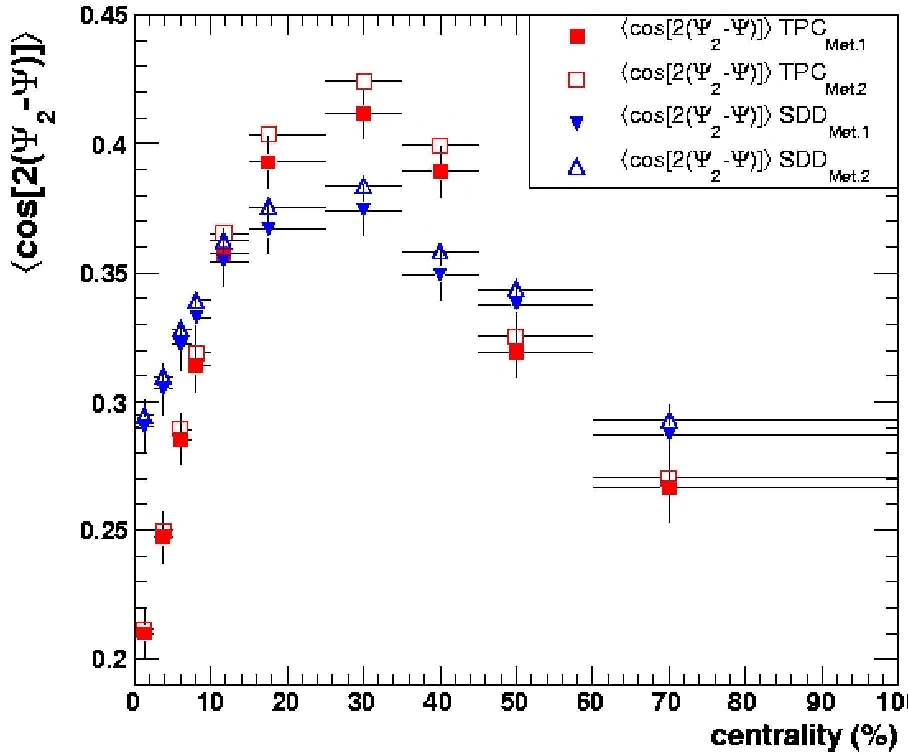
pi- proton correlation functions

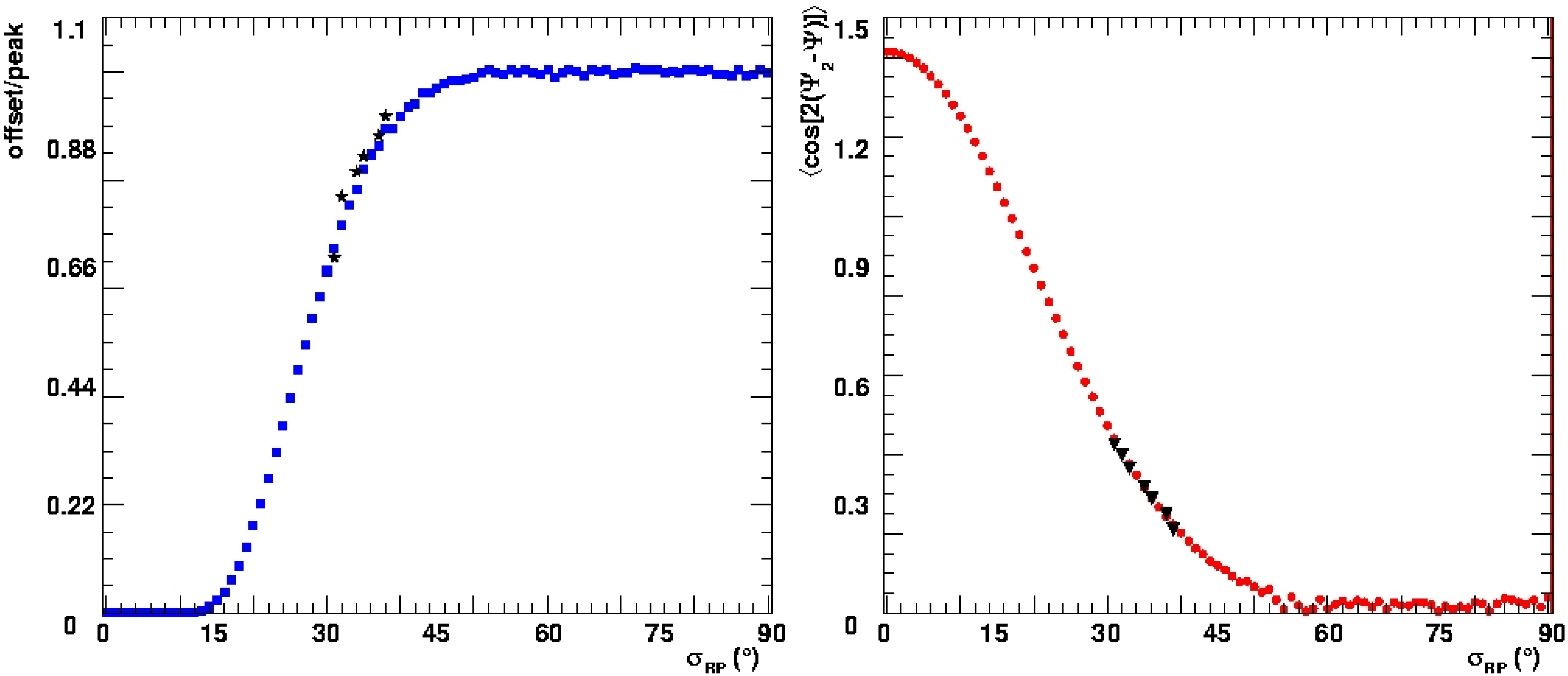


pi+ proton correlation functions

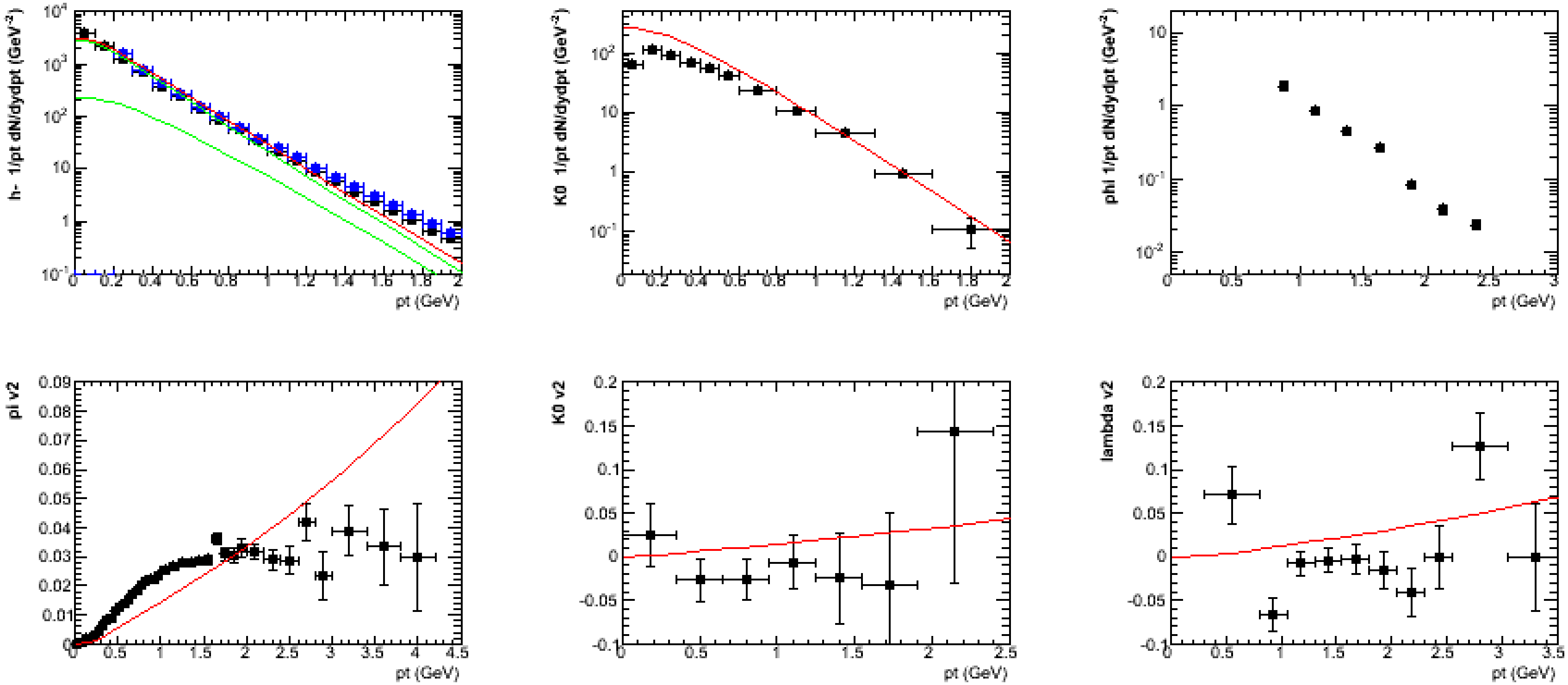



Ollitrault fit
χ 0.240 ± 0.001
χ²/ndf 28.98 / 43
1/N dN/d(Ψ SE2-Ψ SE1) (a.u.)
Ψ SE2-Ψ SE1 (rad)


⟨cos[2(Ψ2-Ψ)]⟩ TPC Met.1
⟨cos[2(Ψ2-Ψ)]⟩ TPC Met.2
⟨cos[2(Ψ2-Ψ)]⟩ SDD Met.1
⟨cos[2(Ψ2-Ψ)]⟩ SDD Met.2
⟨cos[2(Ψ2-Ψ)]⟩
centrality (%)


offset/peak
1.1
0.88
0.66
0.44
0.22
0
0
15
30
45
60
75
90
σ_RP (°)
⟨cos[2(Ψ_2-Ψ)]⟩
1.5
1.2
0.9
0.6
0.3
0
0
15
30
45
60
75
90
σ_RP (°)

Comparison to hydrodynamics
Pasi Huovinen, T=160 MeV



Comparison to hydrodynamics
Pasi Huovinen, T=160 MeV