Freeze-out radii extracted from 3-pion cumulants in pp, p-Pb and Pb-Pb

arXiv: 1404.1194
3-pion formalism from PRC 89 024911 (2014)

Dhevan Gangadharan (LBNL)
on behalf of the ALICE collaboration
Quark Matter 2014

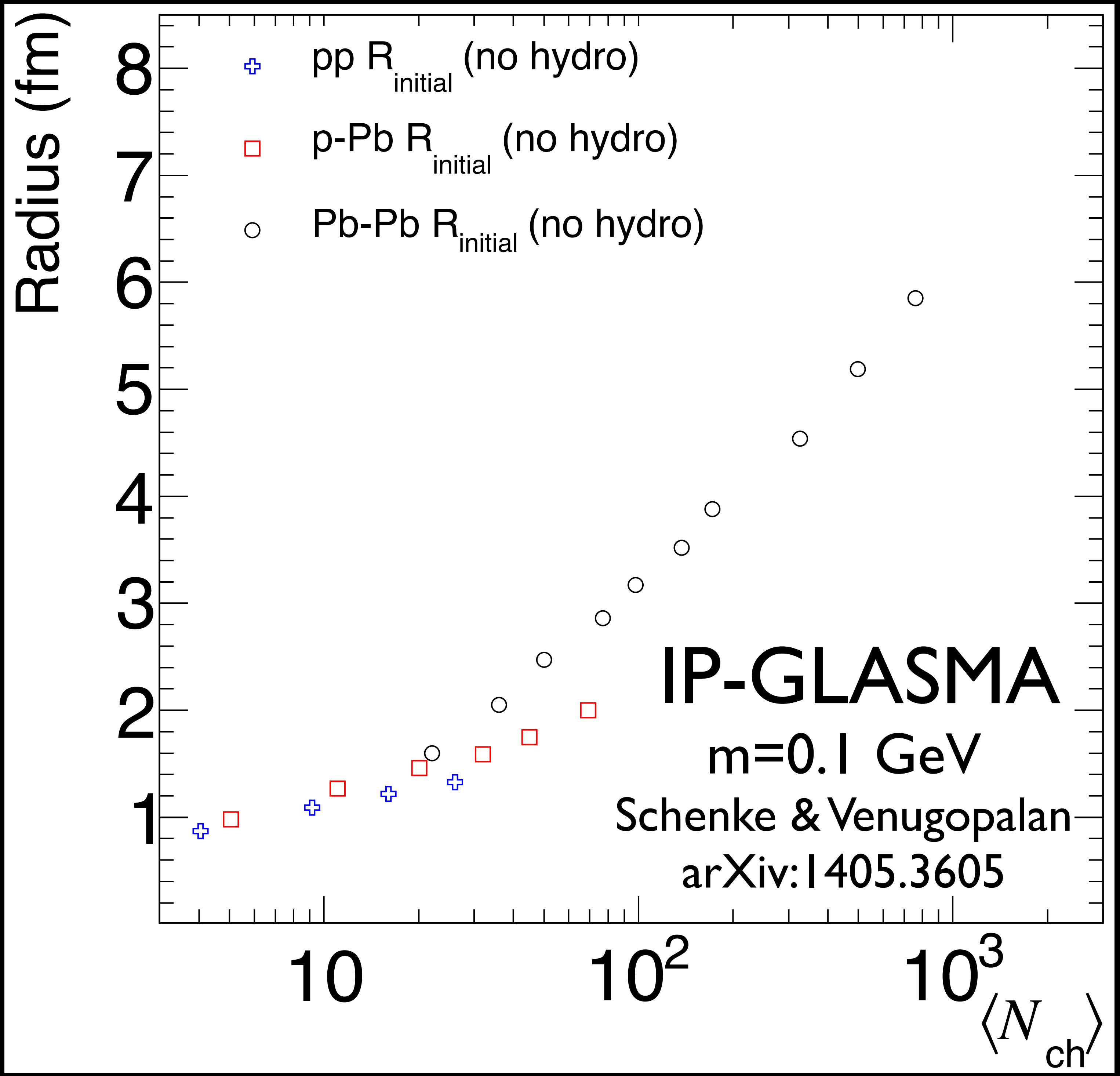
Why is the source radius important?

Hydrodynamic Evolution in p-Pb

vs.

Initial Conditions Alone in p-Pb

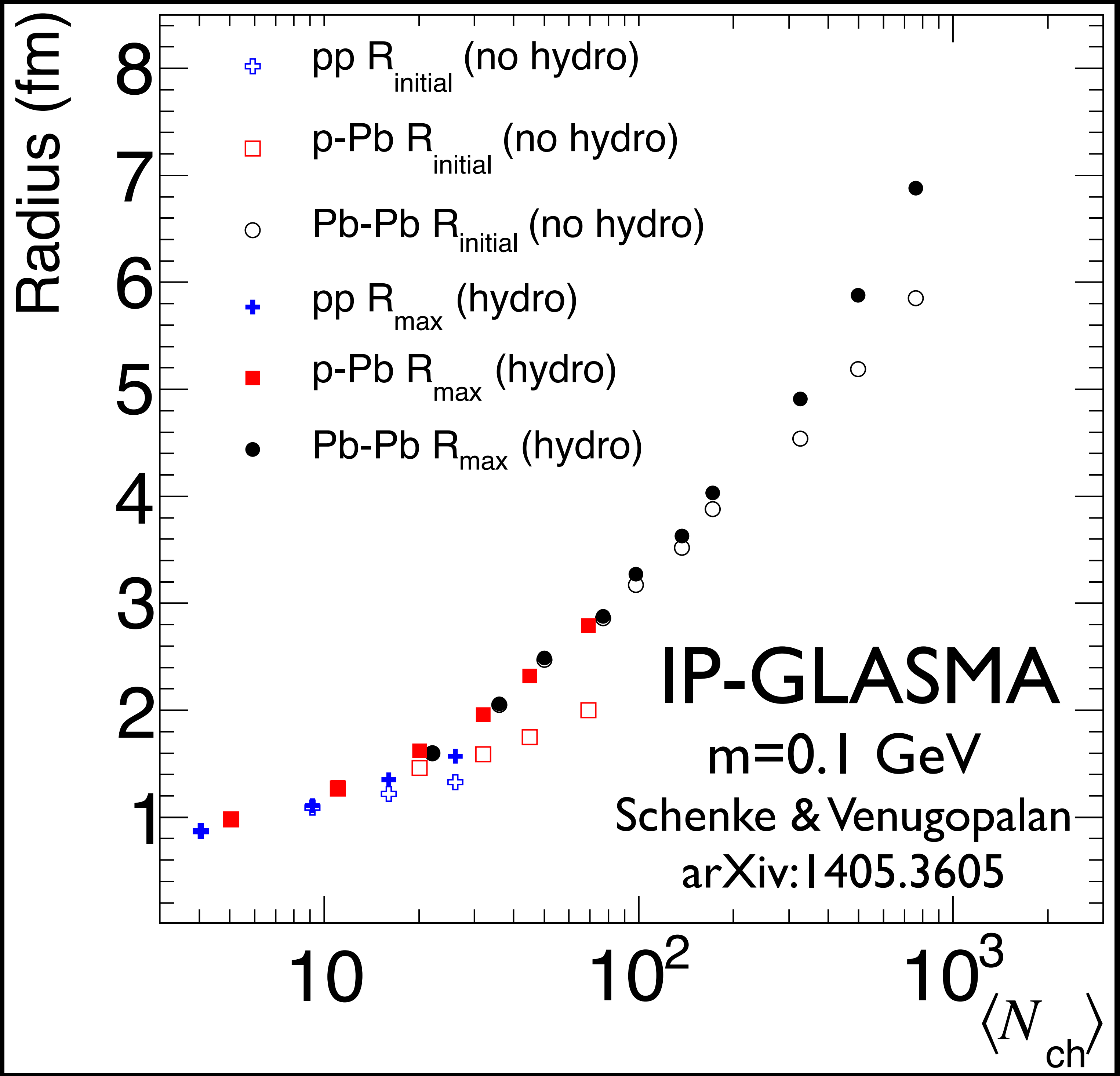
Why is the source radius important



IP-GLASMA initial conditions alone.

→ Similar freeze-out radius in p-Pb as compared to pp.

Why is the source radius important



IP-GLASMA initial conditions alone.
→ <u>Similar</u> freeze-out radius in p-Pb as compared to pp.

Hydrodynamic expansion
→ <u>Larger</u> freeze-out radius.
p-Pb more comparable to Pb-Pb

There are other hydrodynamic predictions as well:
Bozek and Broniowski,
Phys. Lett. B 720, 250 (2013)

Measuring the source radius ~ Δx

- The last stage of particle interactions is kinetic freeze out.
- At freeze out in high-energy particle collisions, the characteristic separation of particles is <u>femtoscopic</u> ($\Delta x \sim 10^{-15}$ m).

$$\Delta x \Delta p \gg 2\pi\hbar$$

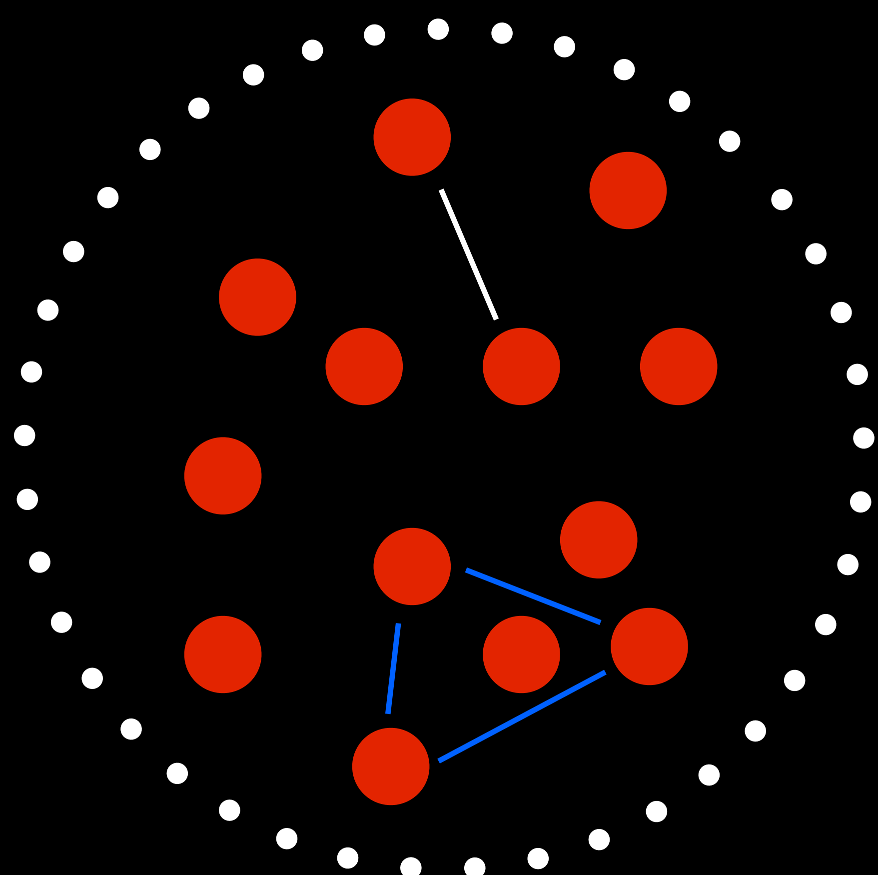
Classical:
no observable quantum phenomena

$$\Delta x \Delta p \sim 2\pi\hbar$$

Non Classical:
Bose-Einstein / Fermi-Dirac correlations

- Bose-Einstein correlations will be visible for $\Delta p <\sim 0.5$ GeV/c. <u>Relative momentum correlations are sensitive to the relative separation at freeze out.</u>

Freeze-out source profile



2-Pion correlations

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}$$

Projected onto invariant relative momentum

$$q_{12} = \sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}$$

3-Pion correlations

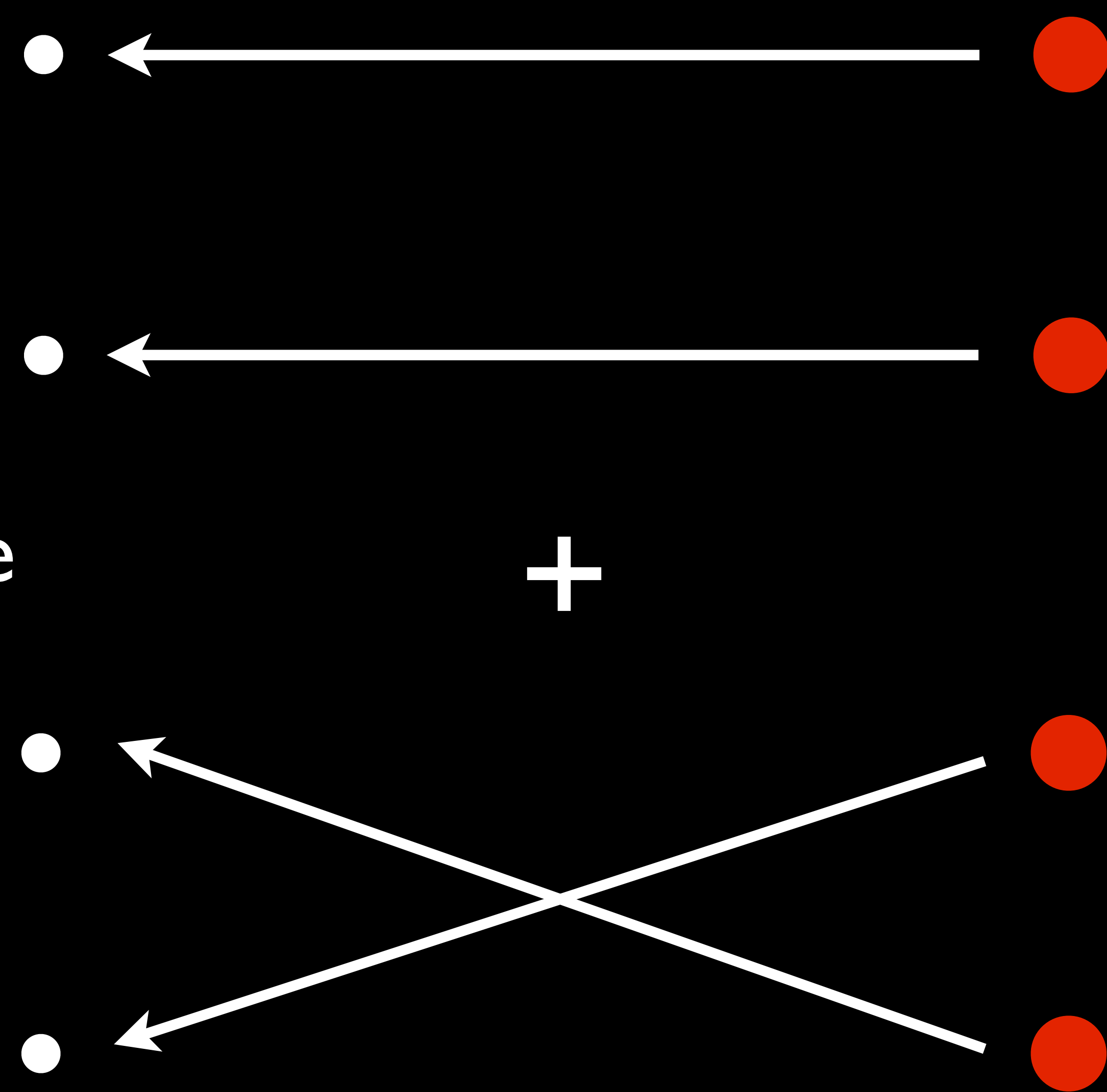
$$C_3(p_1, p_2, p_3) = \frac{N_3(p_1, p_2, p_3)}{N_1(p_1)N_1(p_2)N_1(p_3)}$$

Projected onto triplet relative momentum

$$Q_3 = \sqrt{q_{12}^2 + q_{13}^2 + q_{23}^2}$$

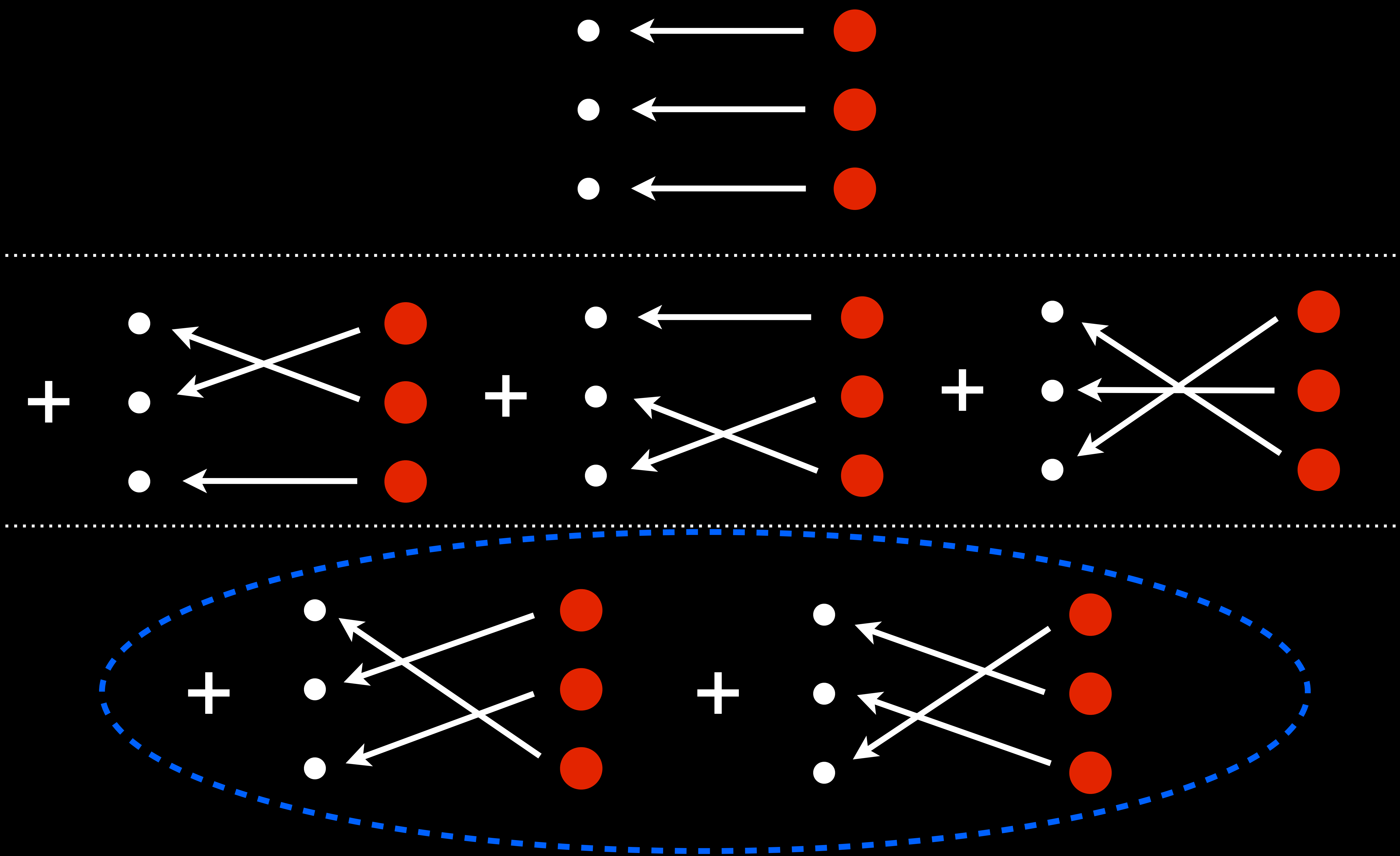
2-Pion Symmetrization

Detection Point Production Point



For Indistinguishable Bosons

3-Pion Symmetrization



Cumulant or Irreducible part

Isolation of 2-pion Bose-Einstein Correlations

$$C_2(q) = \mathcal{N}[(1 - f_c^2) + f_c^2 K_2(q) C_2^{QS}(q)]\, B(q)$$

Measured correlation function

Correlated fraction of pairs
Obtained from mixed-charge pion C_2.
(cleaner method to determine dilution).
$f_c^2 = 0.7 \pm 0.05$ in ALICE
PRC 89 024911 (2014)

Coulomb+strong FSI

Quantum-Statistics correlation

Non-femtoscopic background

Sinyukov et al.,
Phys. Lett. B 432, 249 (1998)

Fitting 2-pion Bose-Einstein Correlations

$$C_2^{\mathrm{QS}}(q) \;=\; 1 + \lambda\, E_{\mathrm{w}}^2(R_{\mathrm{inv}}\, q)\, e^{-R_{\mathrm{inv}}^2\, q^2}$$

Quantum-Statistics correlation

Suppression parameter related to incorrect fit functions and coherence

$$E_{\mathrm{w}}(R_{\mathrm{inv}}\, q) \;=\; 1 + \sum_{n=3}^{\infty} \frac{\kappa_n}{n!(\sqrt{2})^n} H_n(R_{\mathrm{inv}}\, q)$$

Edgeworth expansion for non-Gaussian features

Gaussian Fit when $E_{\mathrm{w}} = 1.0$

Non-Gaussian features parameterized with an Edgeworth expansion.

- κ_3 and κ_4 expansion parameters retained and extracted from 3-pion cumulants.
- Free fit performed for all 3 systems and all multiplicity bins.
- $\langle\kappa_3\rangle = 0.1$
- $\langle\kappa_4\rangle = 0.5$

Csorgo & Hegyi, Phys. Lett. B 489, 15 (2000)

Isolation and fitting of 3-pion Bose-Einstein Cumulant

c_3 = 3-pion cumulant correlation

Isolated using:

- $N_3(p_1, p_2, p_3)$ — 3 pions from same event
- $N_2(p_1, p_2)N_1(p_3)$ — 2 pions from same event
- $N_1(p_1)N_1(p_2)N_1(p_3)$ — All pions from different events
- $K_3 = K_2^{12} * K_2^{13} * K_2^{23}$ — 3-body Final-State-Interaction

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Cumulant fitting

$$\mathbf{c}_3(q_{12}, q_{31}, q_{23}) = 1 + \lambda_3 E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{12})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{31})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{23})\, e^{-R_{\mathrm{inv},3}^2 Q_3^2/2}$$

3-pion suppression parameter

Edgeworth factors to account for non-Gaussian features

Data and Track Selection

<u>Collision types</u>

pp $\sqrt{s}$ = 7 TeV

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

<u>Track Selection</u>

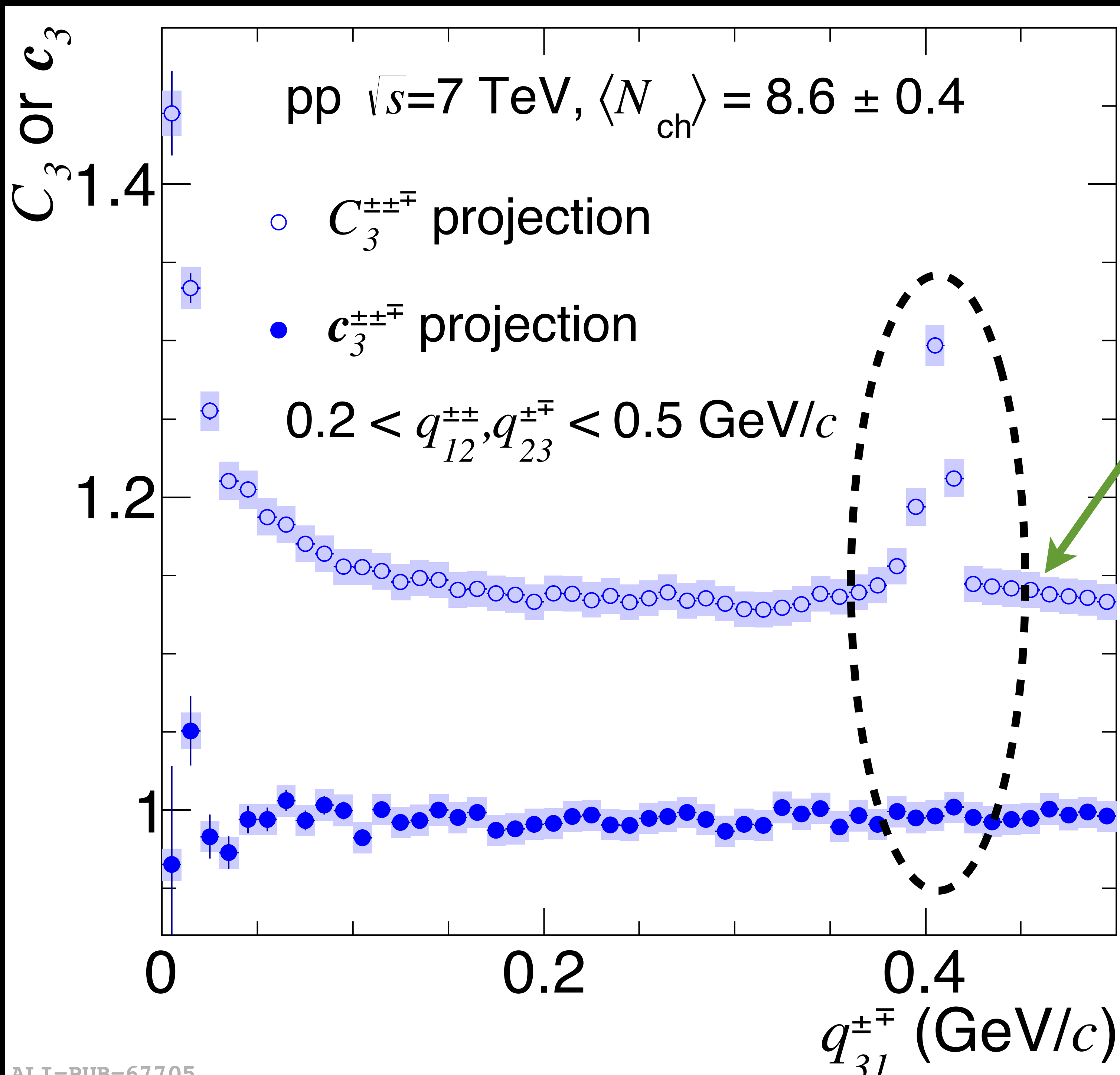
- <u>Pions</u> selected based on their specific energy loss in the Time Projection Chamber. Time of Flight also used for $p > 0.6$ GeV/c.
- $p_T > 0.16$ GeV/c
- $p < 1.0$ GeV/c
- $|\eta| < 0.8$

<u>Pair Cuts</u>

- Track merging and splitting: pair angular separation

- For 3-pions, pair cuts applied to all 3 pairs in the triplet.

3-pion cumulants remove 2-pion correlations



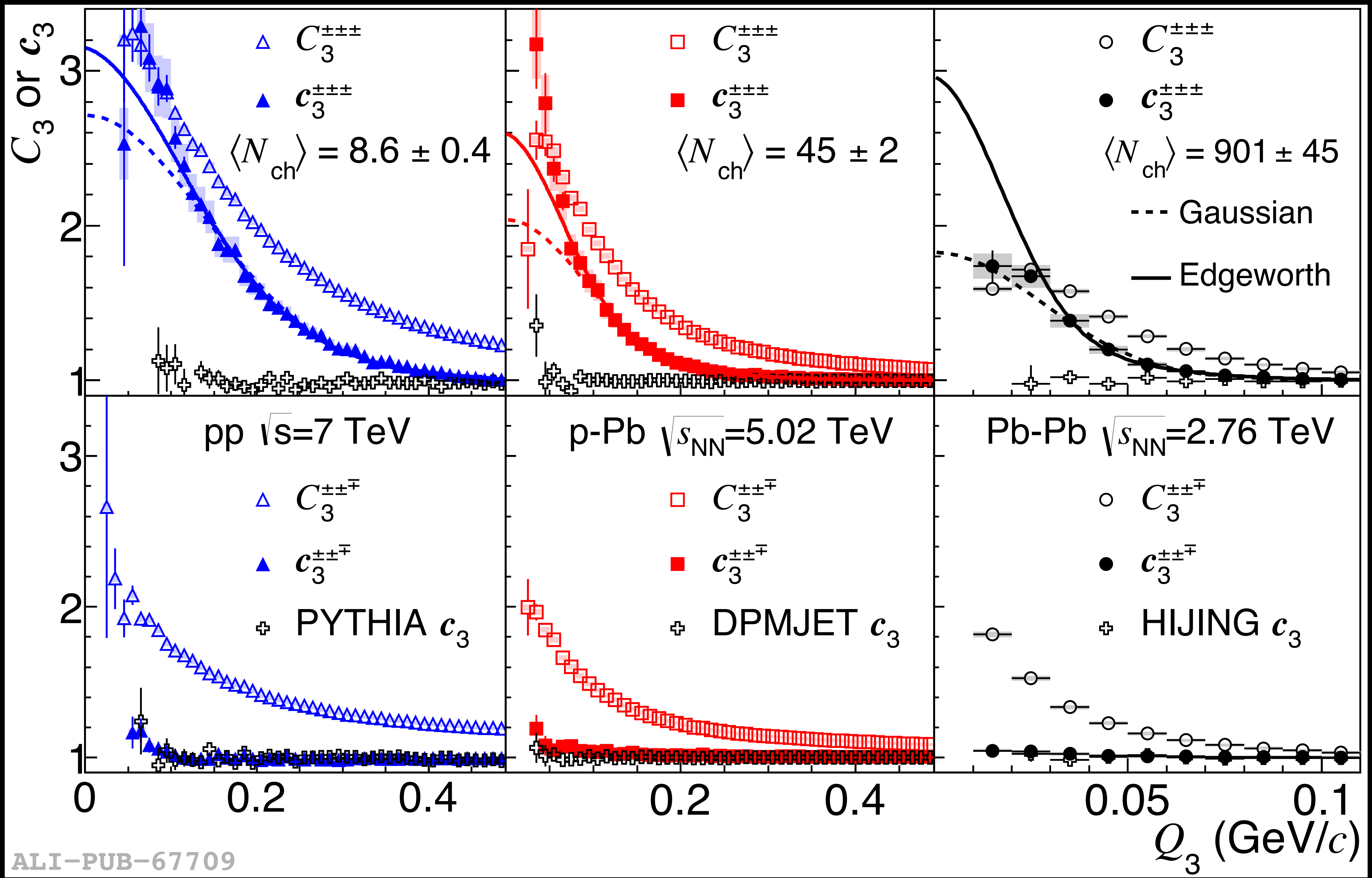
Hollow points:
K^0_s peak visible.

Solid points:
Cumulant.
K^0_s peak removed

3-pion Correlation Functions

Same Charge

Mixed Charge



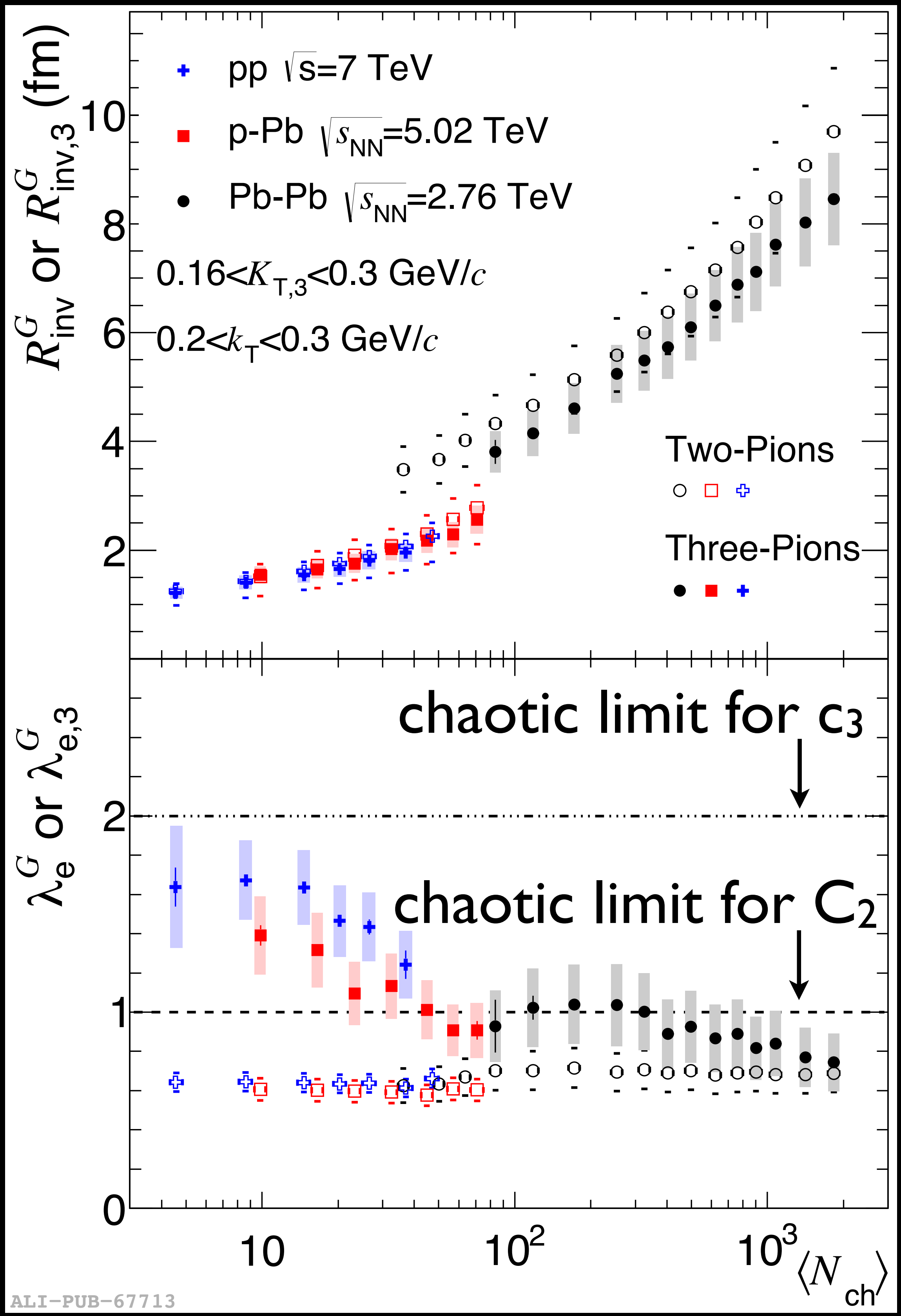
pp
low multiplicity

p-Pb
mid multiplicity

Pb-Pb
high multiplicity

3-body FSI correction ansatz works very well: $K_3 = K_2^{12} * K_2^{13} * K_2^{23}$

Gaussian Radii and Intercepts

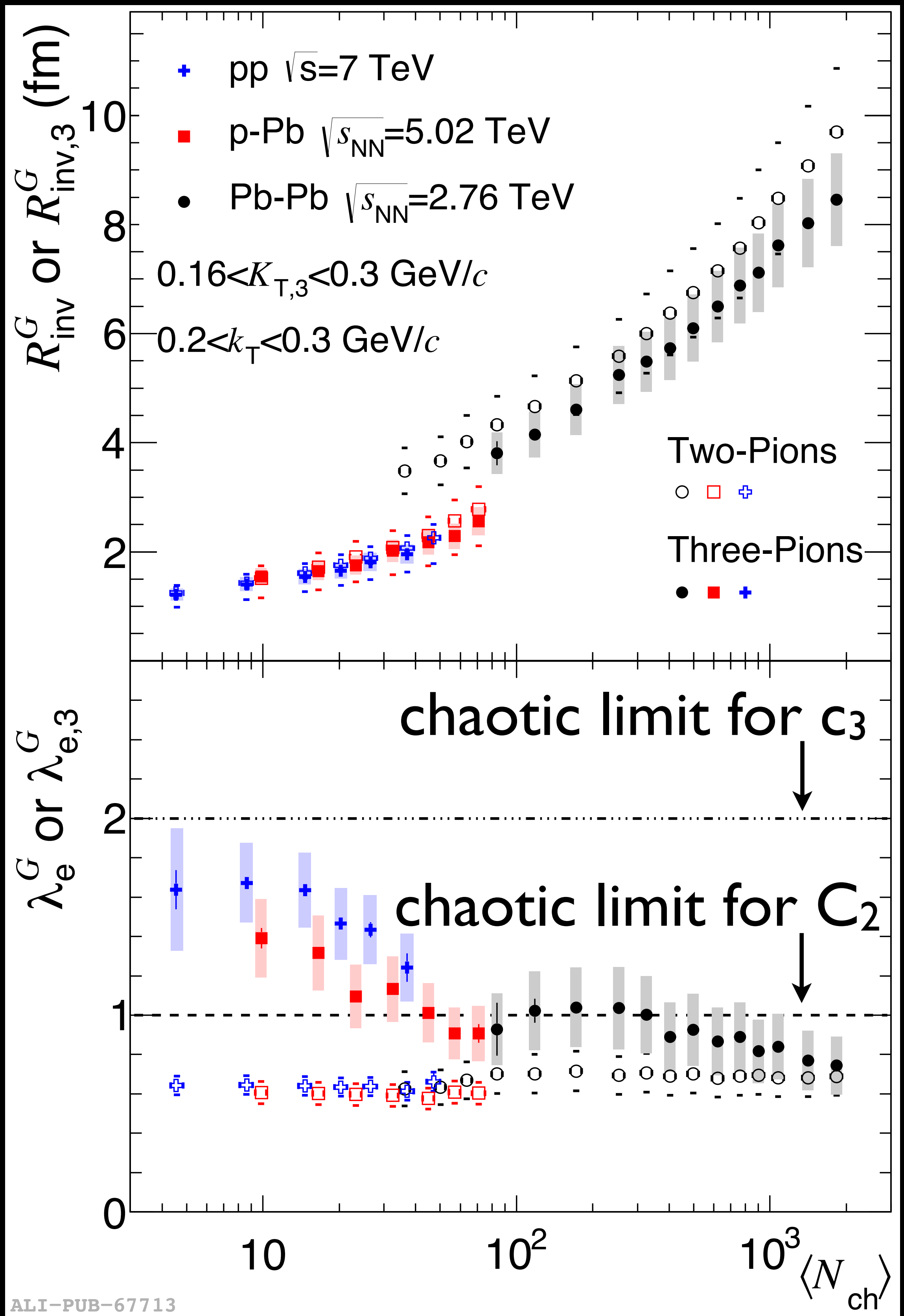


$$k_T = \frac{|\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|}{2}$$

$$K_{T,3} = \frac{|\mathbf{p}_{T,1} + \mathbf{p}_{T,2} + \mathbf{p}_{T,3}|}{3}$$

- 2- and 3-pion fit parameters shown in all 3 systems.
- 3-pion Gaussian radii smaller than 2-pion Gaussian radii.

Gaussian Radii and Intercepts



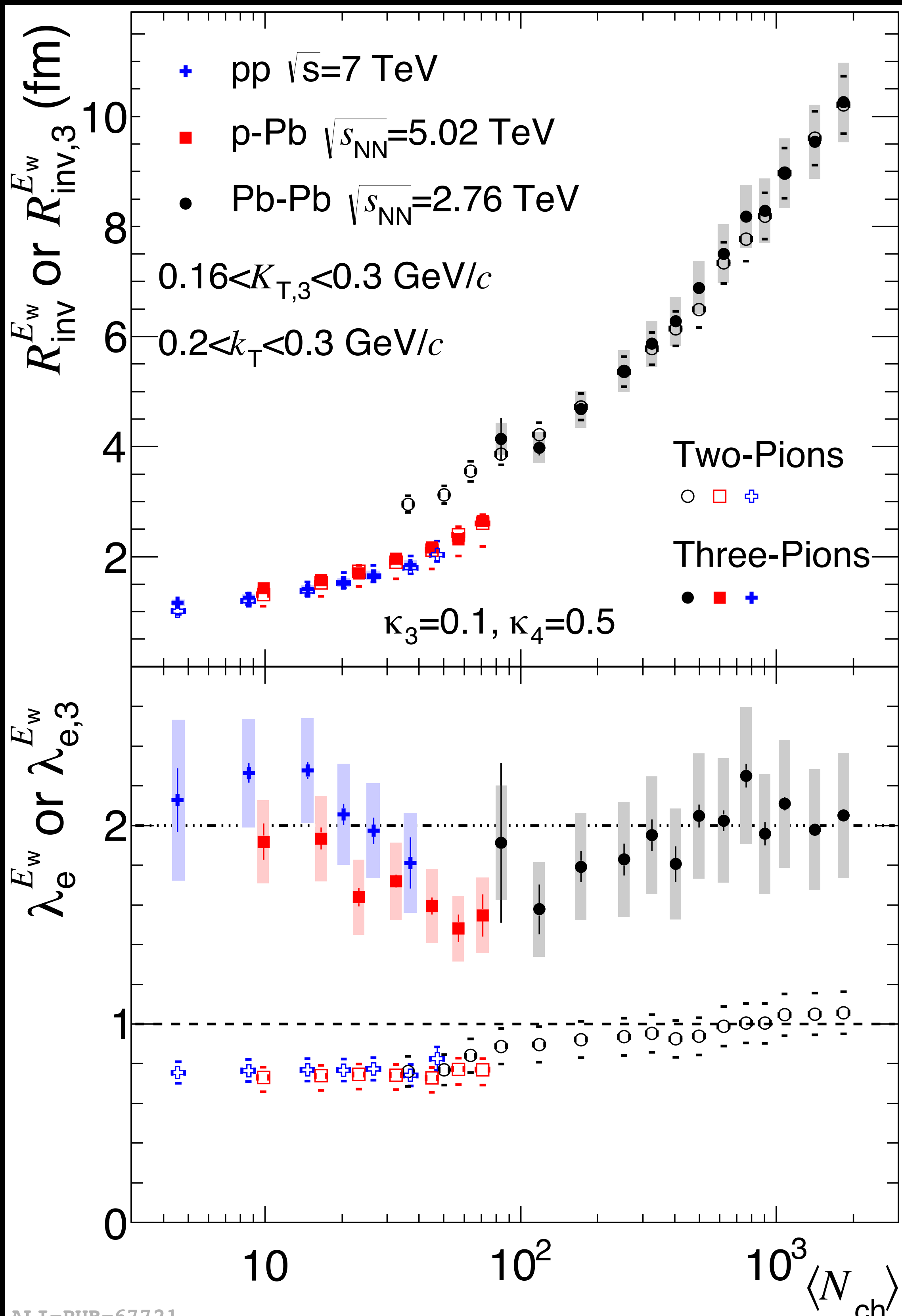
<u>Main Observation:</u>

For overlapping multiplicity:
Pb-Pb radii larger than p-Pb radii,
p-Pb radii similar to pp radii

<u>Also</u>

Intercept parameters (λ_e)
significantly below
their chaotic limits
→ Gaussian fits fail to explain
correlation function at low q.

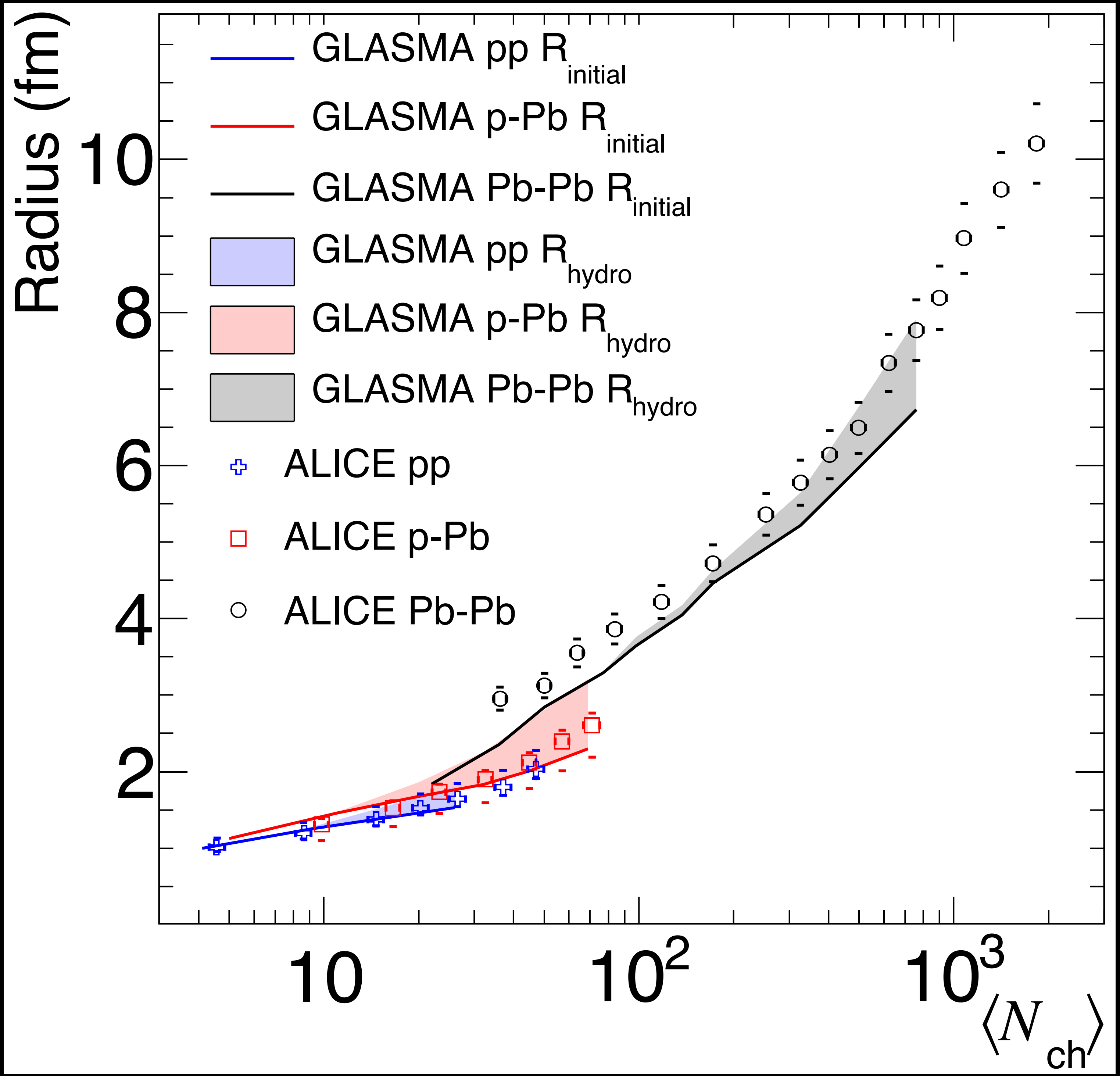
Edgeworth Radii and Intercepts



Better Estimate of the 1D Source Radius

- Non-Gaussian fits (Edgeworth) unite the 2- and 3-pion radii. Better fit of low q part of the correlation function.
- p-Pb similar to pp.
- Intercept parameters much closer to their chaotic limits.

Radii Comparison with IP-GLASMA



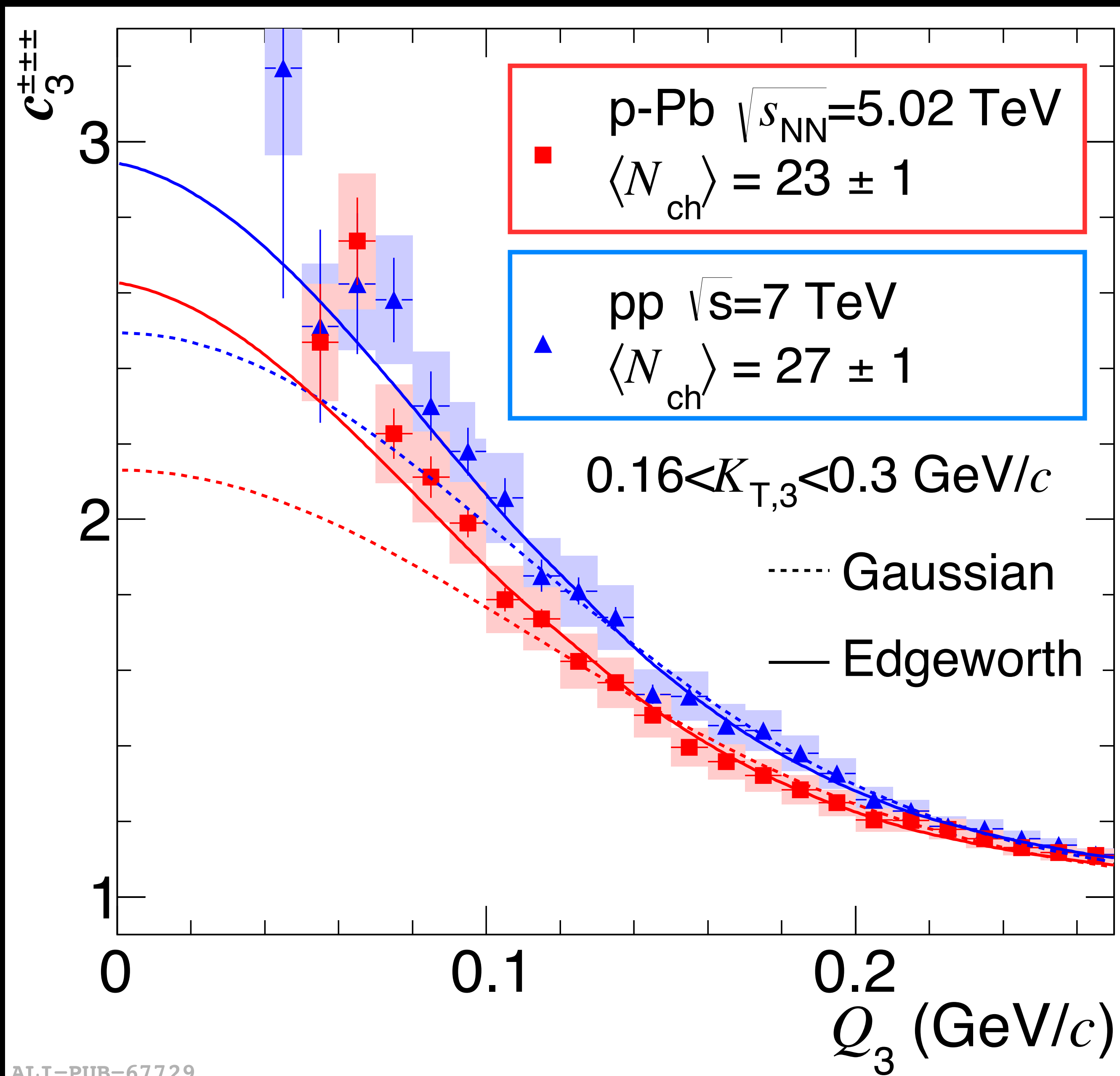
<u>Message:</u>
Similarity of ALICE radii in p-Pb and pp can be reproduced with GLASMA initial conditions alone.

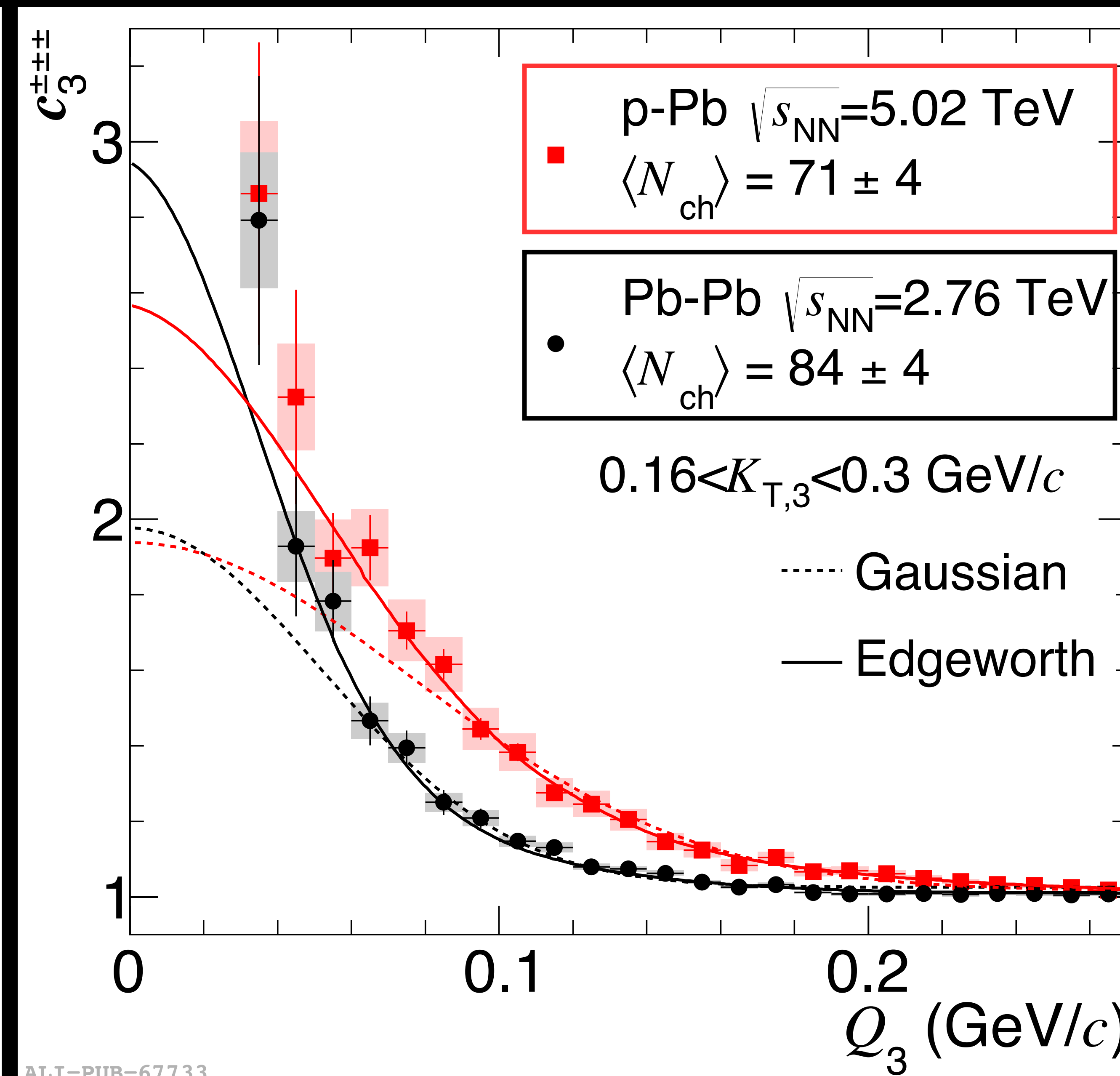
They can also be reproduced with a hydrodynamic phase in p-Pb.

Schenke & Venugopalan
arXiv:1405.3605

- GLASMA points are first scaled such that the calculations in pp match the ALICE pp data. Scale = 1.15. GLASMA calculations have uncertainty due to infrared cutoff (m=0.1 GeV).

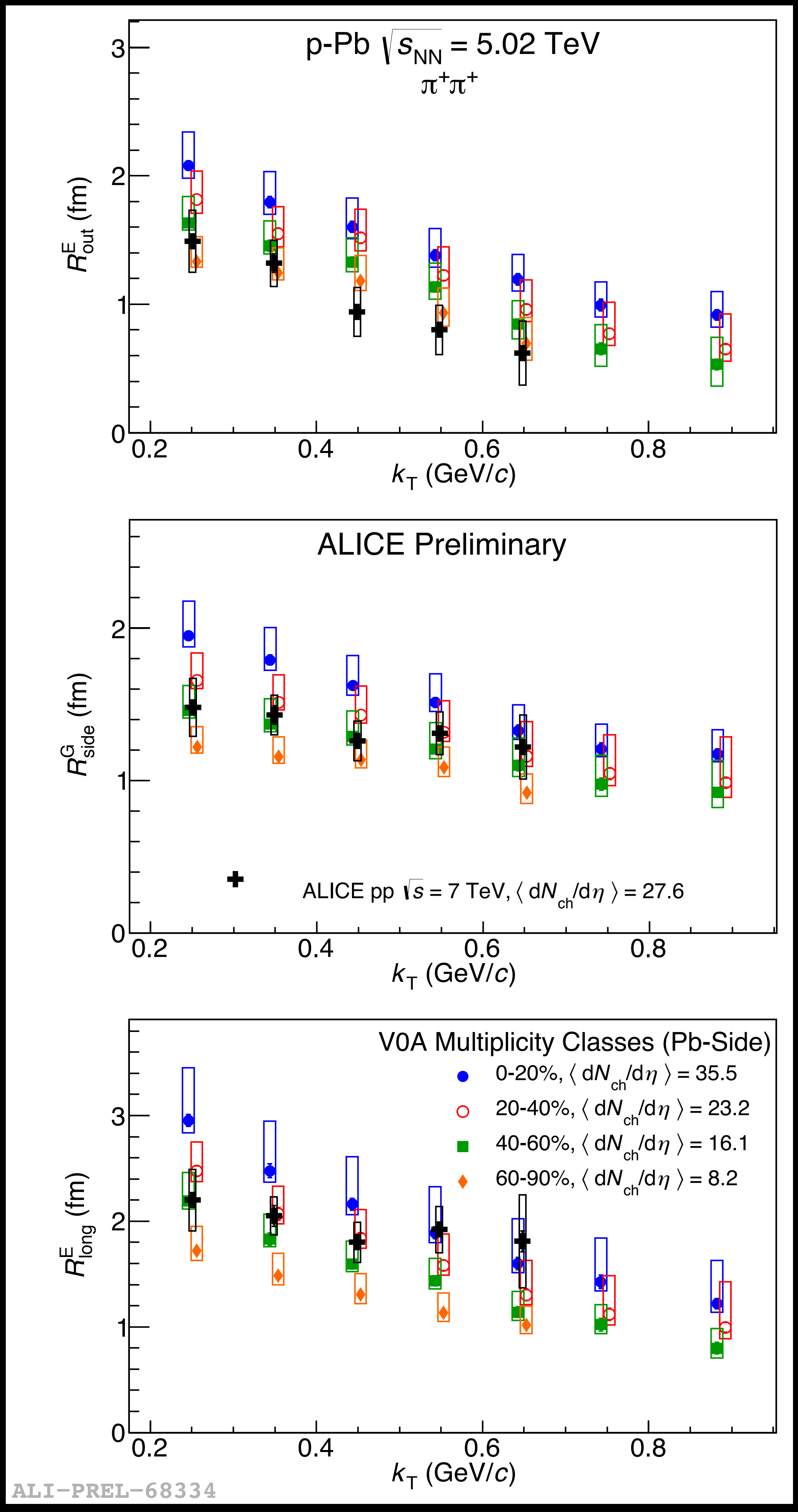
Comparison of c_3 at similar N_{ch}





Correlation functions <u>similar</u>

Correlation functions <u>different</u>



3D 2-pion Radii

See Poster by Lukasz Graczykowski I-13

- The 3D radii (R_{out}, R_{side}, R_{long}) have also been measured in p-Pb.
- k_T and multiplicity dependence studied.
- pp radii also shown.
- We conclude here as well that p-Pb radii are similar to pp radii.

Summary

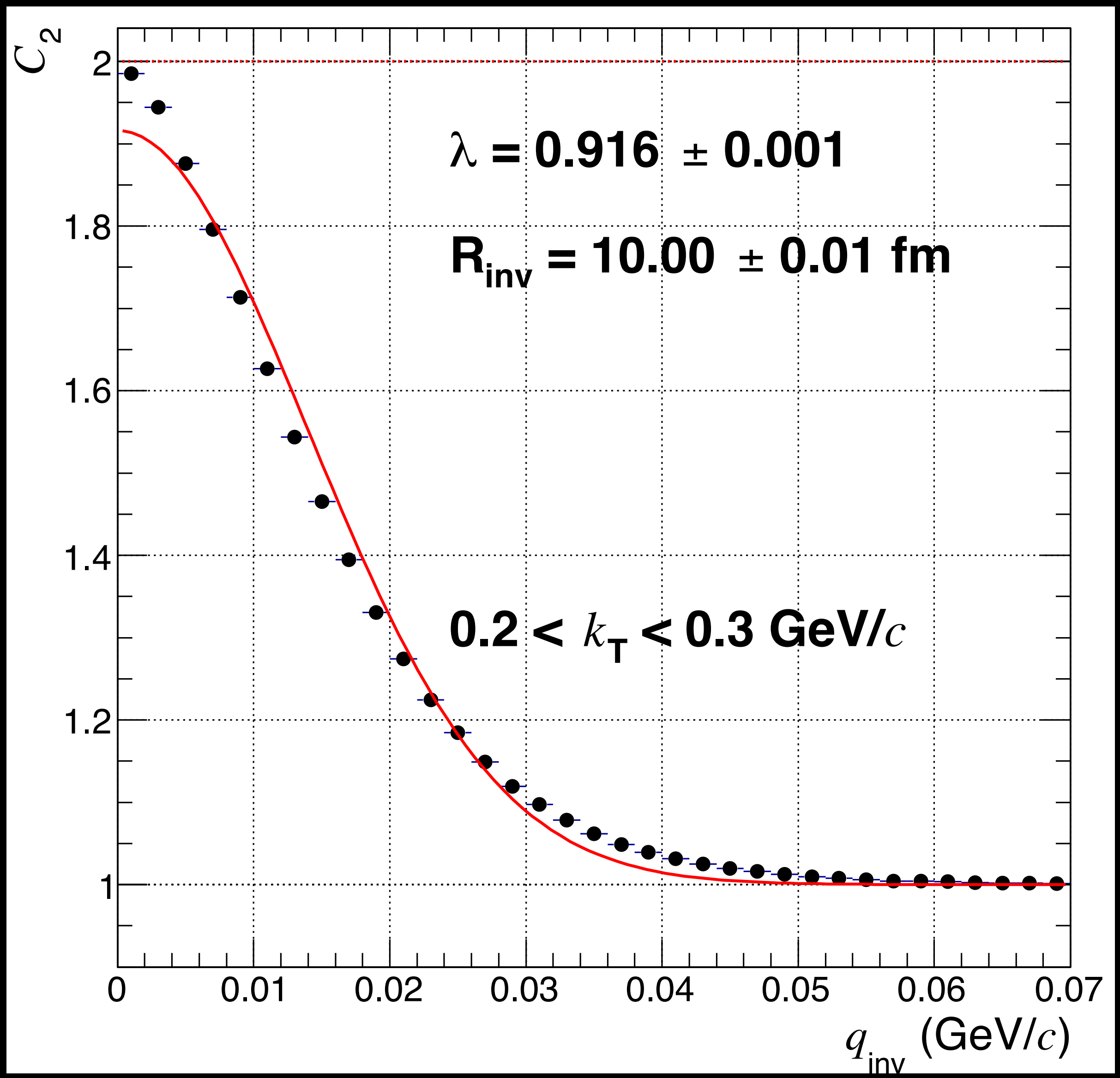
- 1st measurement of the source radius extracted from 3-pion cumulant Bose-Einstein correlations.
  - 3-pion cumulants remove 2-pion background correlations.
- 2- and 3-pion radii give compatible values when non-Gaussian features are treated.

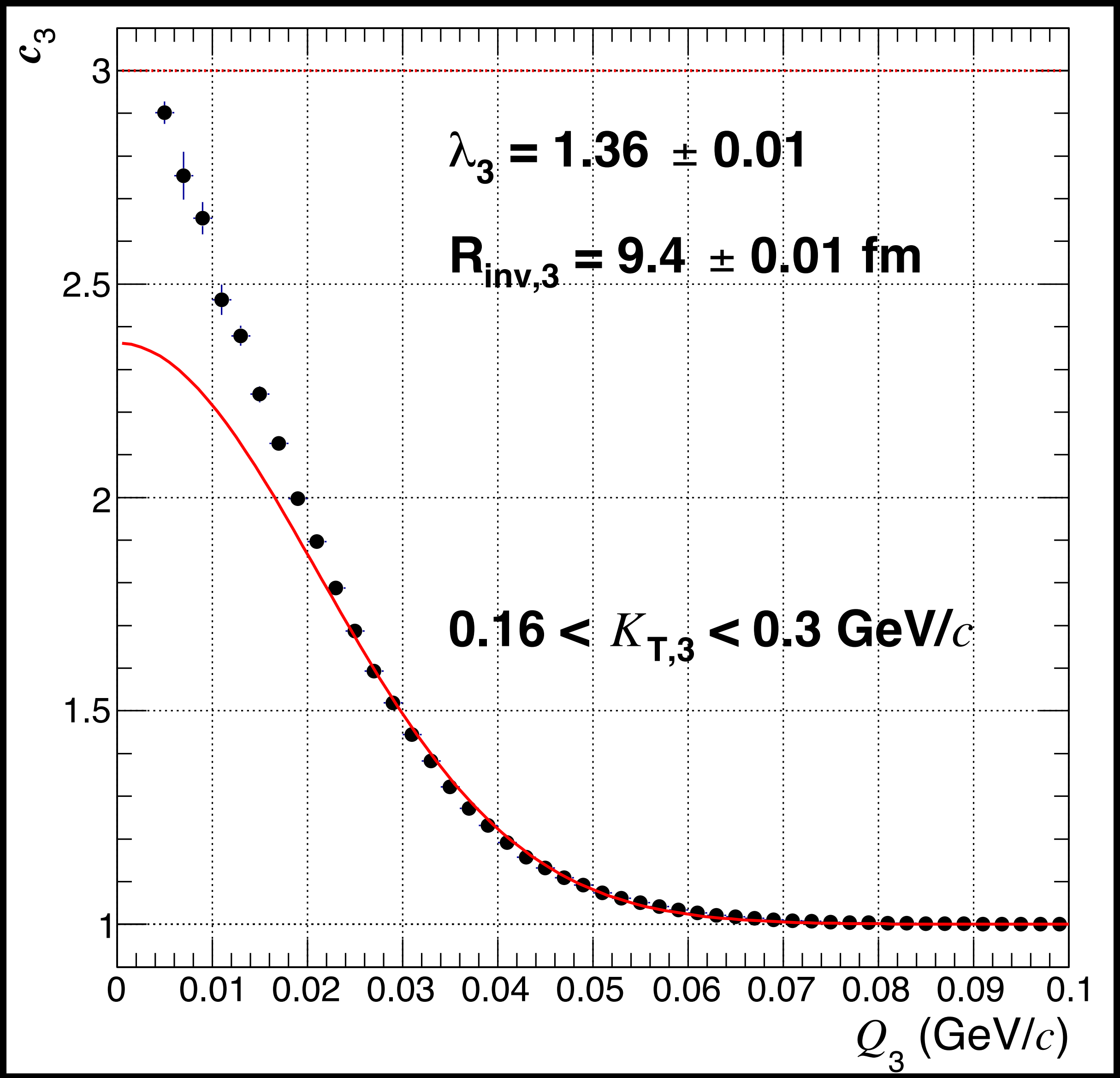
Conclusions

- p-Pb radii 5-15% larger than pp radii, at similar multiplicity.
  - The possibility of large initial radii in p-Pb radii is excluded.
  - There may or may not be hydrodynamic expansion in p-Pb.
  - If it is there, it must be similar in pp at the same dN/dy.
- Pb-Pb radii 35-55% larger than p-Pb, at similar multiplicity.

Supporting Slides

Therminator2 calculations of 2- and 3-pion Bose-Einstein correlations



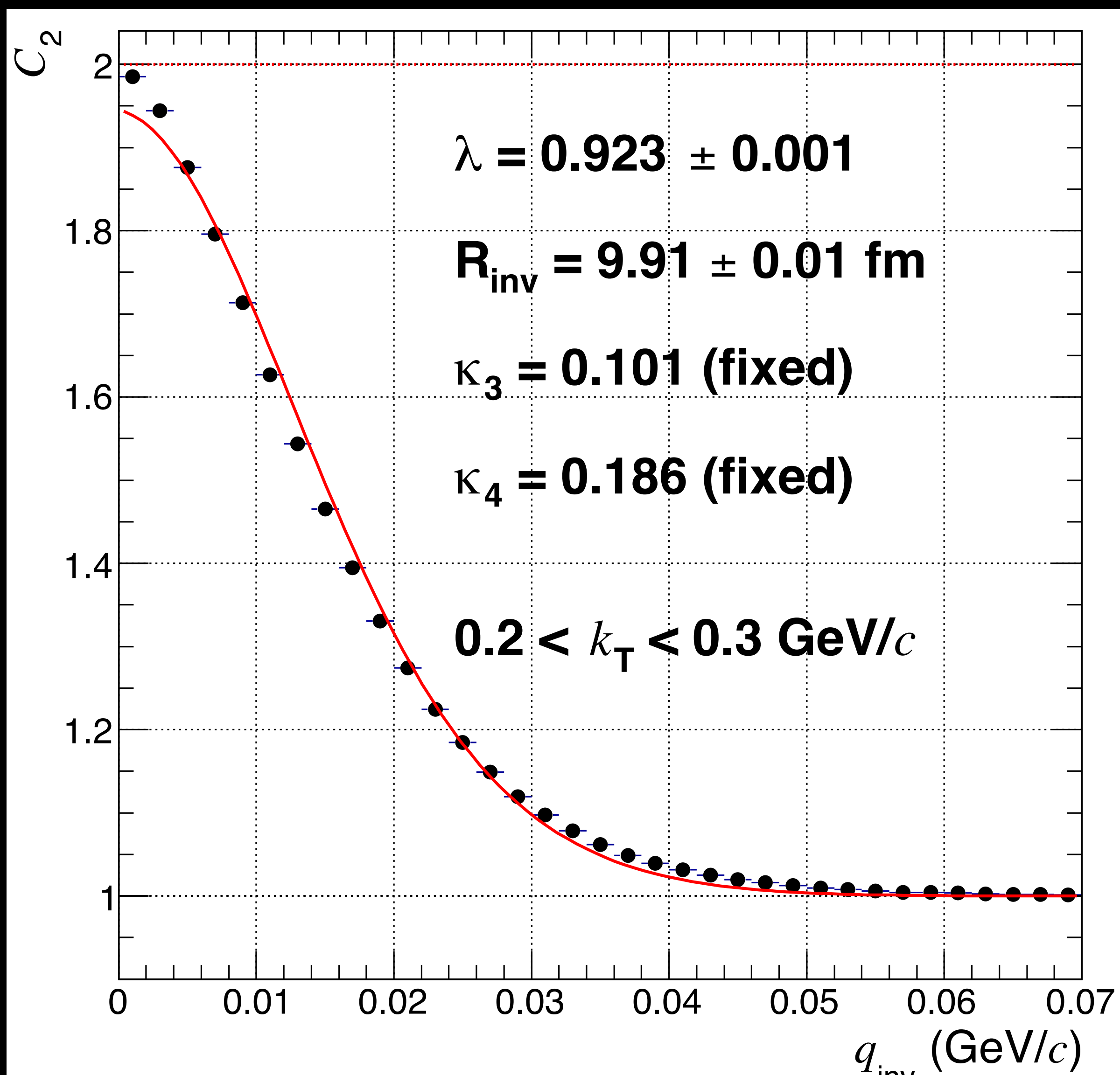


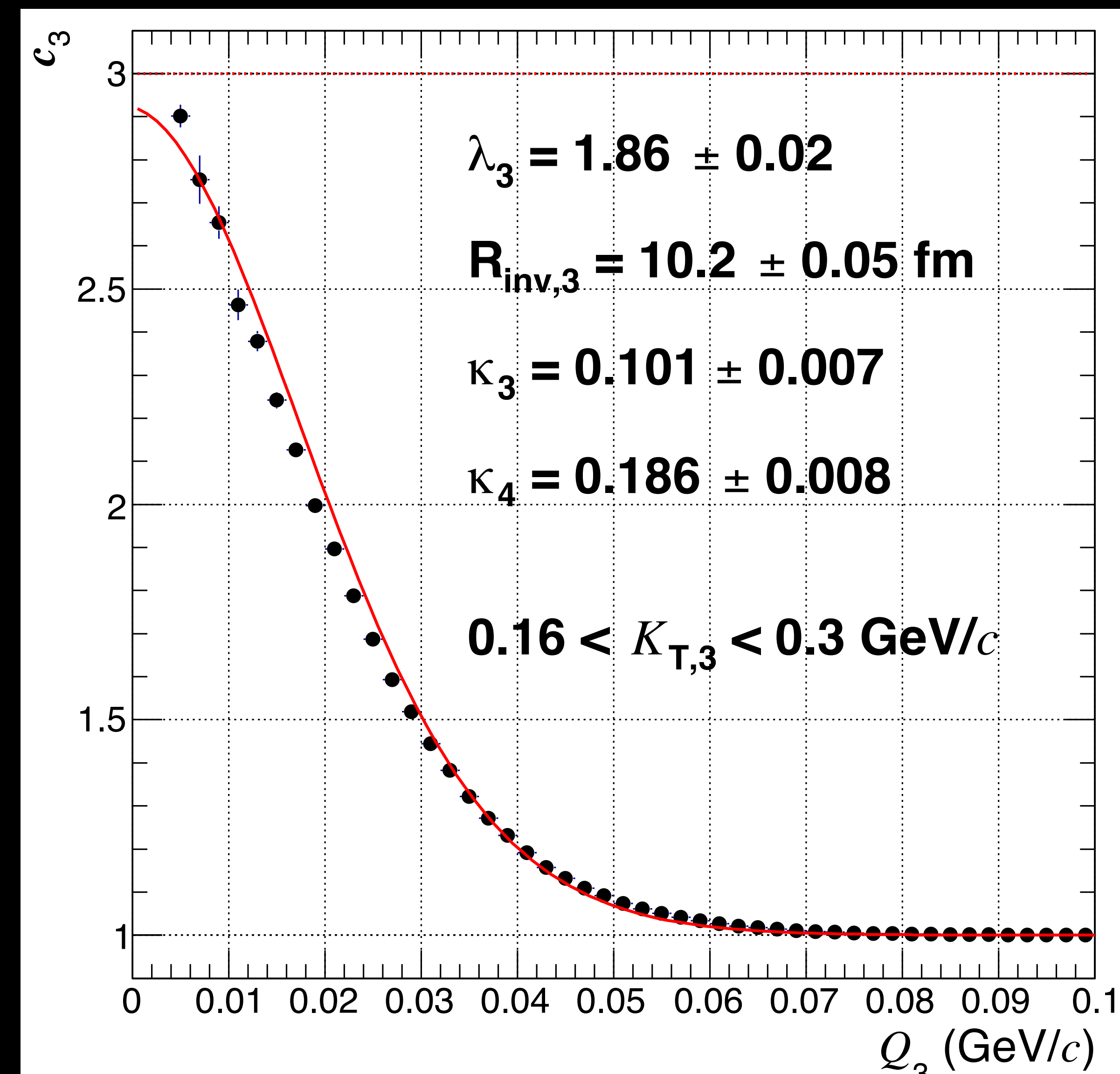
Gaussian fits in red.

$R_{inv,3}$ smaller than R_{inv} by ~0.6 fm (6%).

Therminator 2 (0-5% Pb-Pb)
Kisiel et al.,
Comput. Phys. Commun. 174, 669 (2006)
P. Bozek Phys. Rev. C 77, 034911 (2008)

Therminator2 calculations of 2- and 3-pion Bose-Einstein correlations



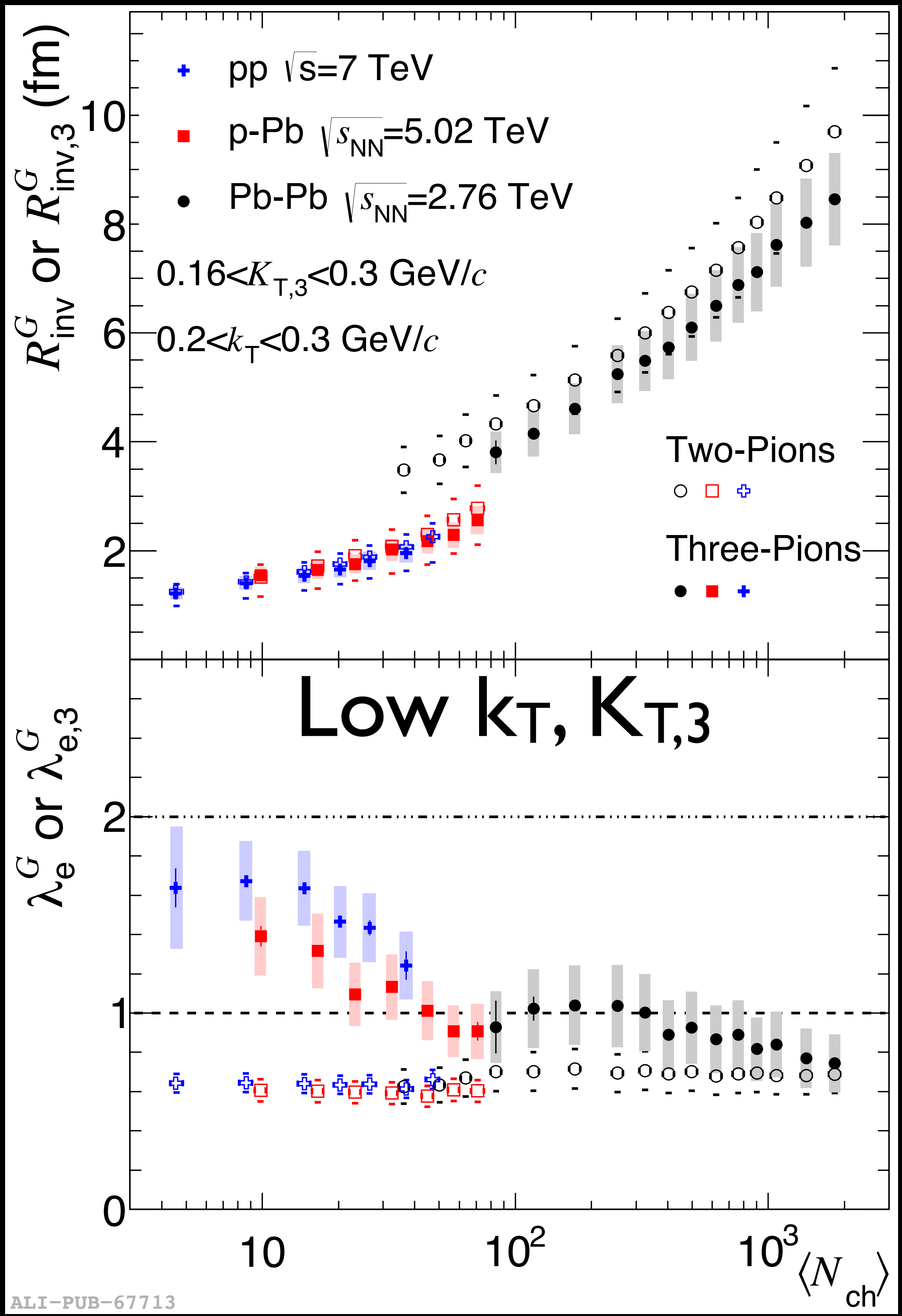


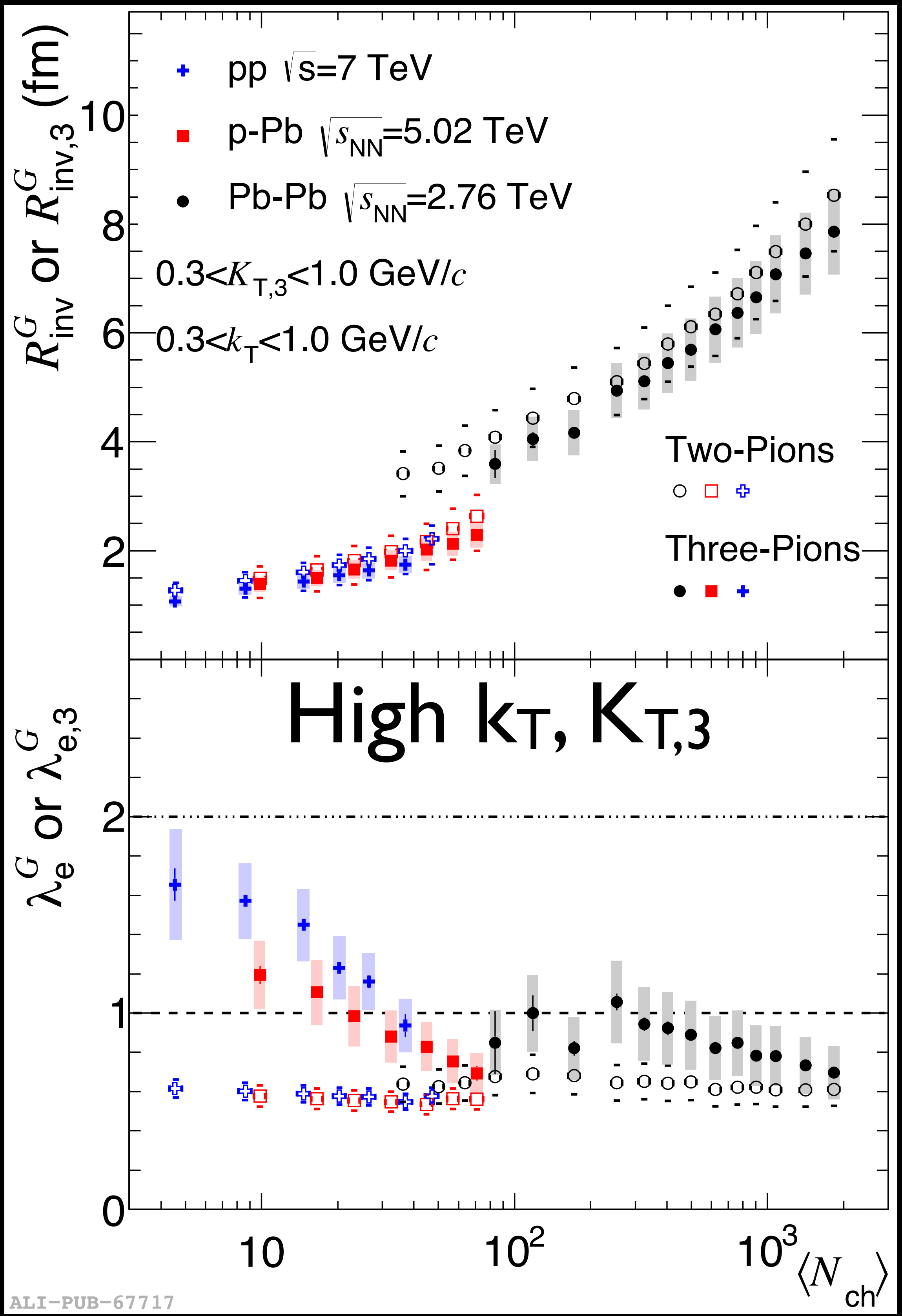
Edgeworth fits in red.

$R_{inv,3}$ similar to R_{inv} within ~0.3 fm (3%).

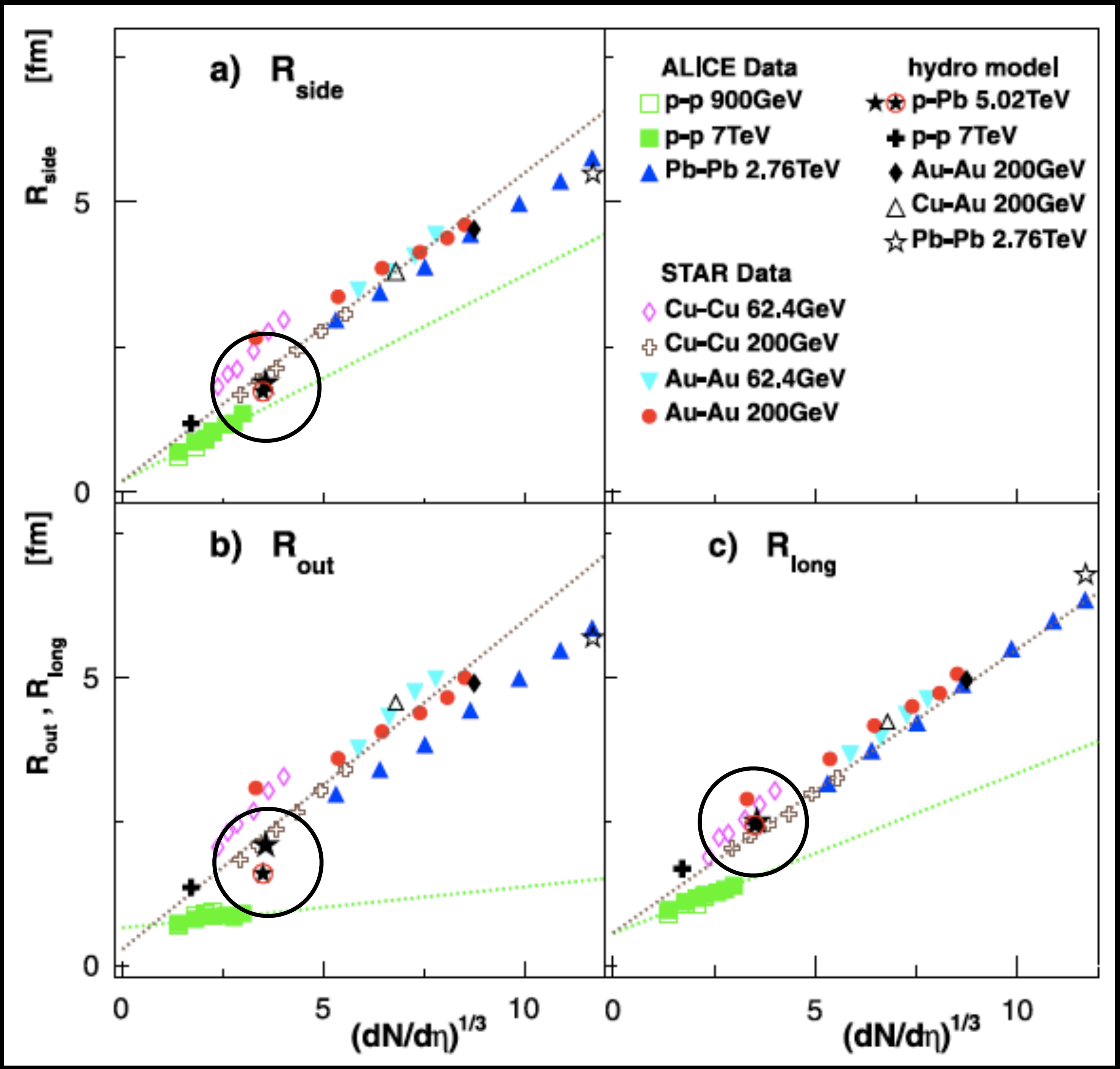
Therminator 2 (0-5% Pb-Pb)
Kisiel et al., Comput. Phys. Commun. 174, 669 (2006)
P. Bozek Phys. Rev. C 77, 034911 (2008)

Gaussian Radii and Intercepts





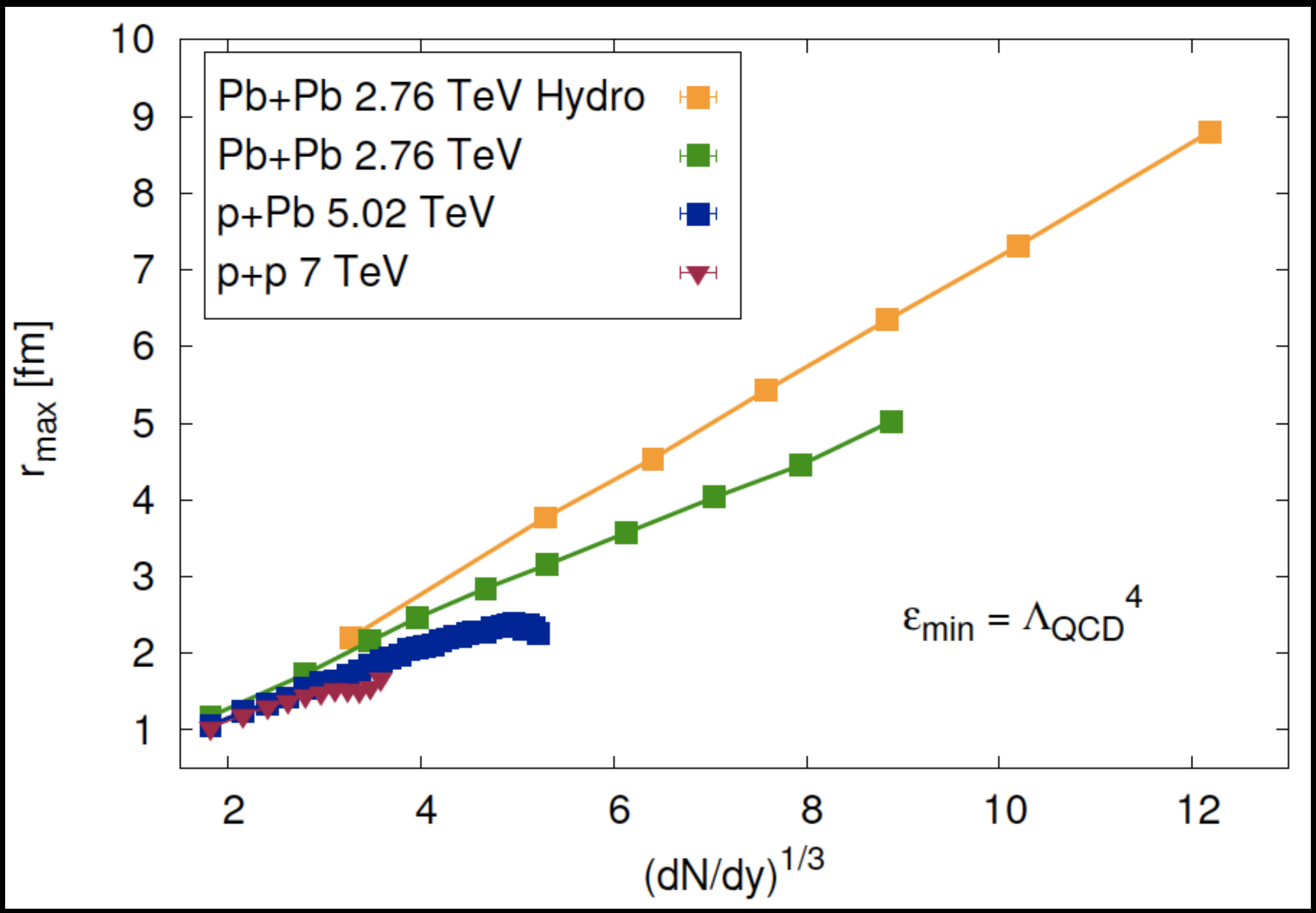
Why is the source radius important
Hydrodynamic Evolution



Hydrodynamic expansion
→ larger freeze-out radius in p-Pb as compared to pp.

Bozek and Broniowski,
Phys. Lett. B 720, 250 (2013)

Why is the source radius important
CGC IP-Glasma Initial Conditions



Initial conditions alone influence the freeze-out radius.

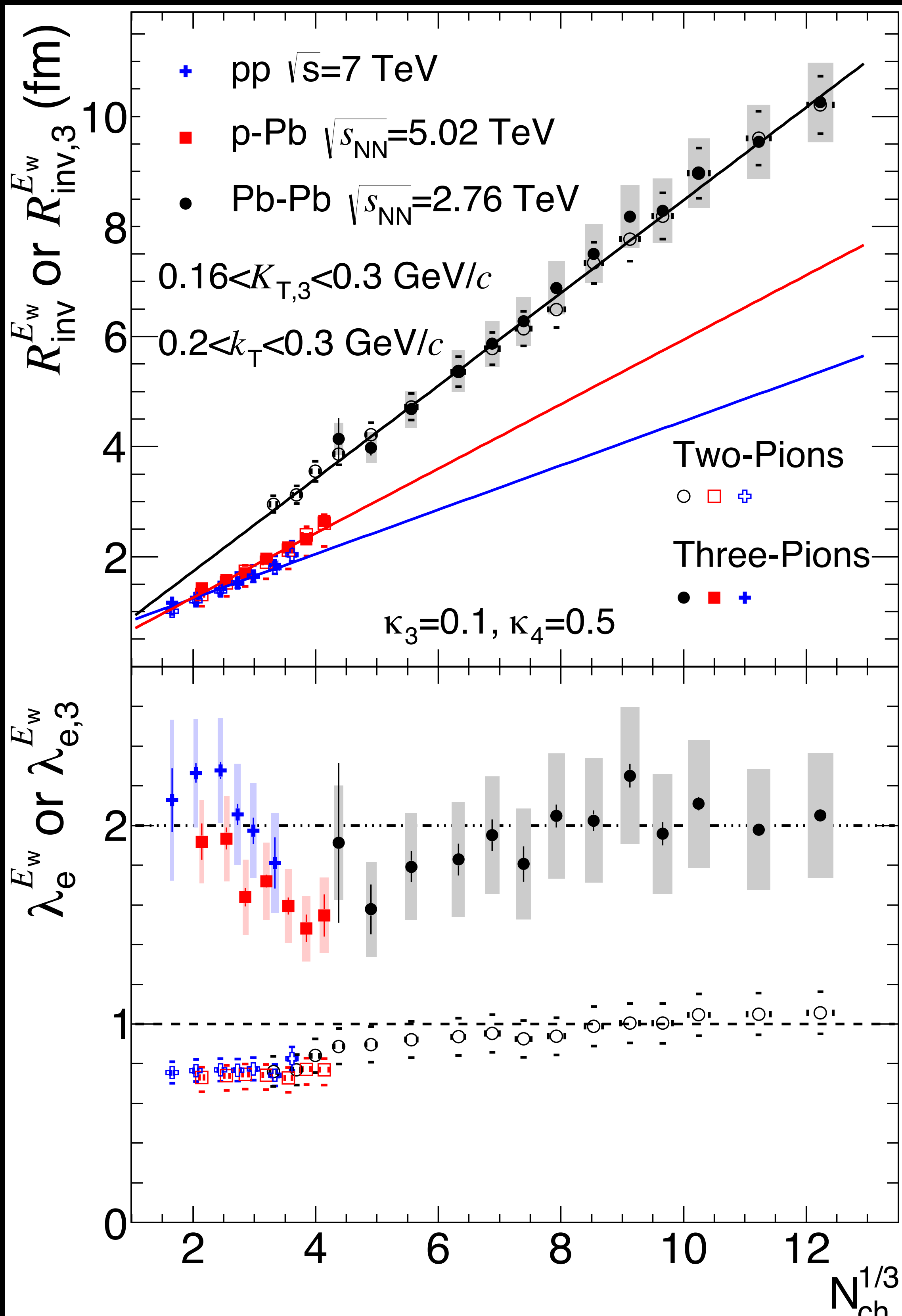
The initial conditions are clearly different in pp, p-Pb and Pb-Pb.

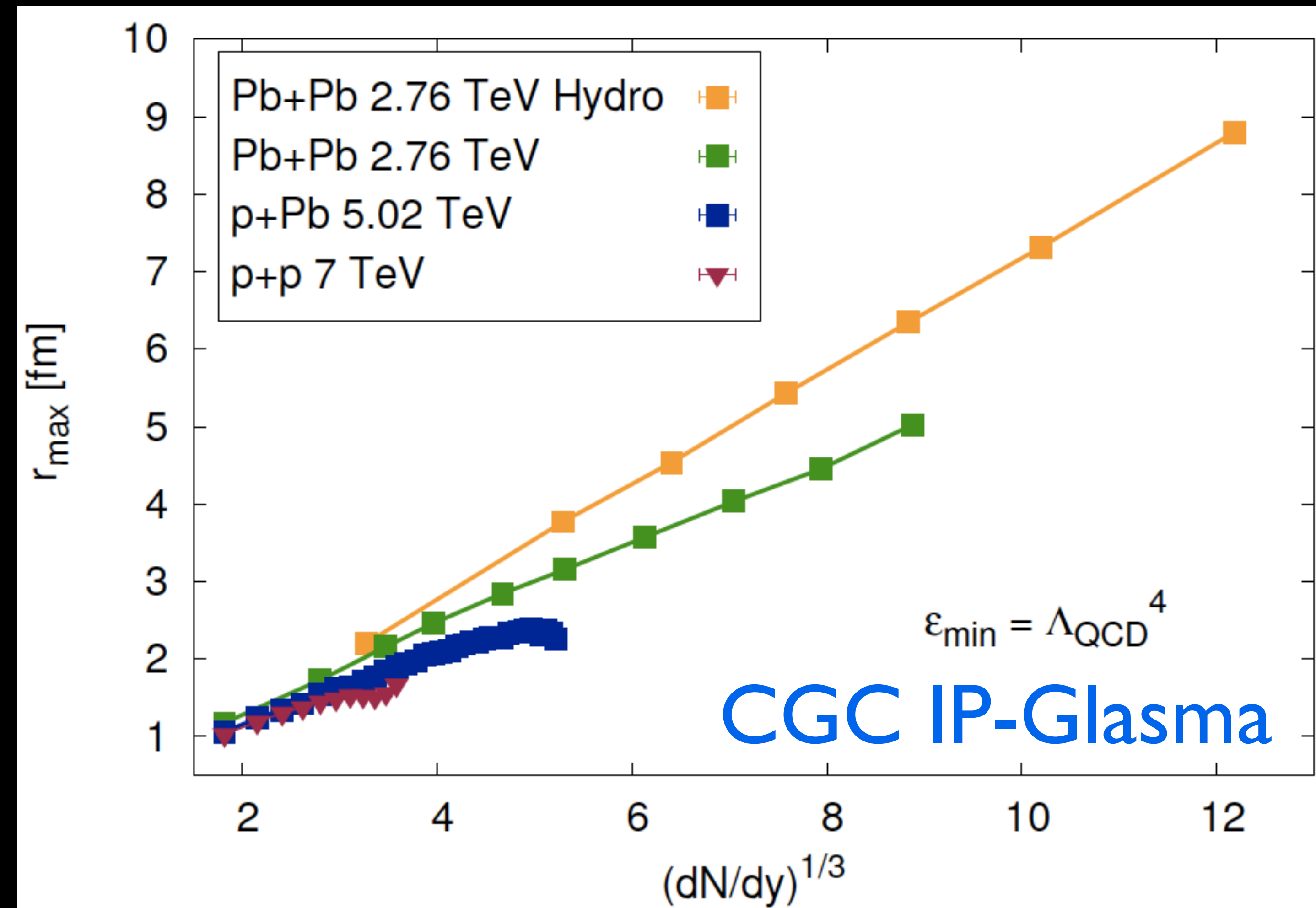
p-Pb and pp freeze-out radii similar.

From private communication with Bjoern Schenke

A. Bzdak et al., Phys. Rev. C 87, 064906 (2013)

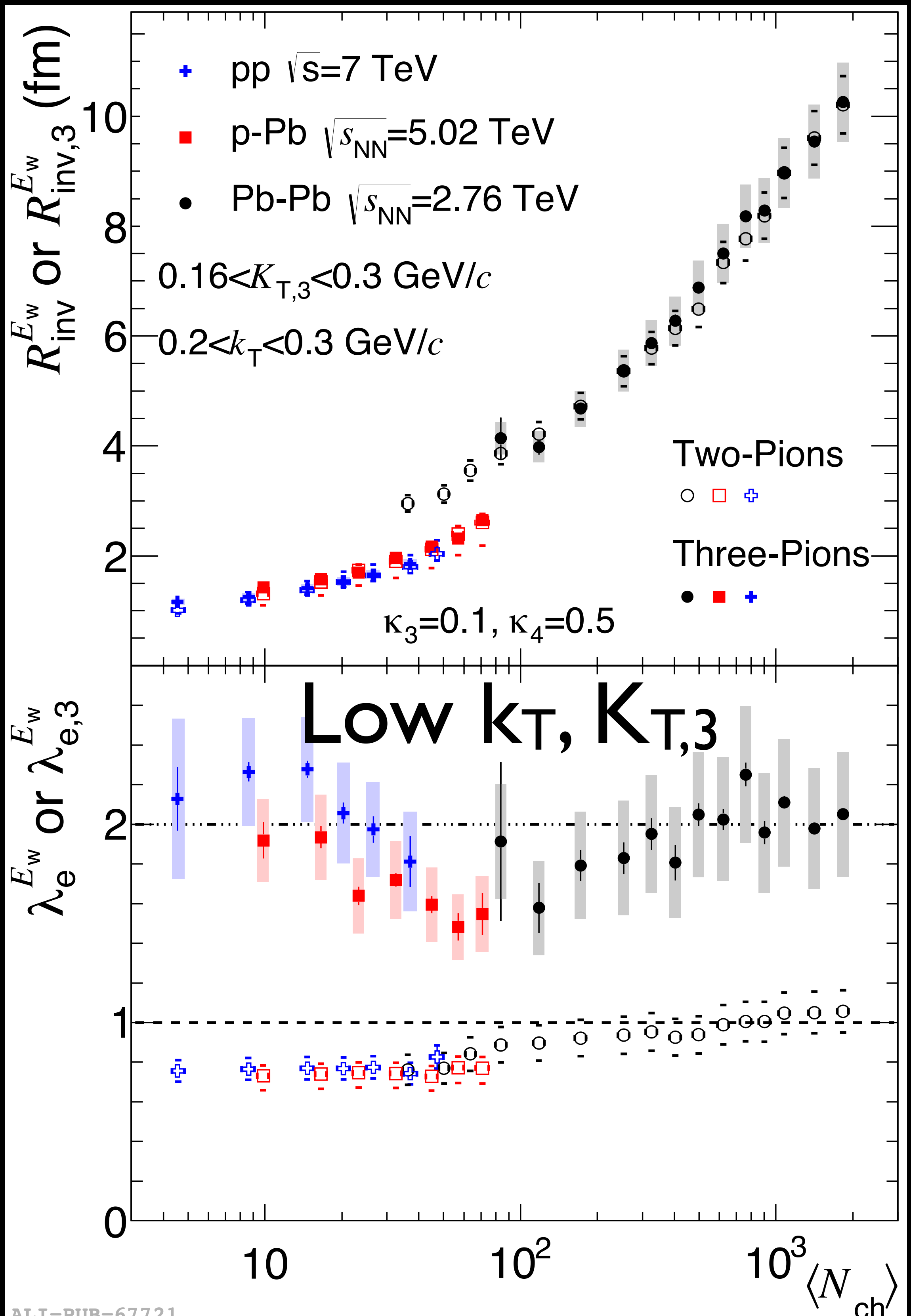
Edgeworth Radii vs $N_{ch}^{1/3}$

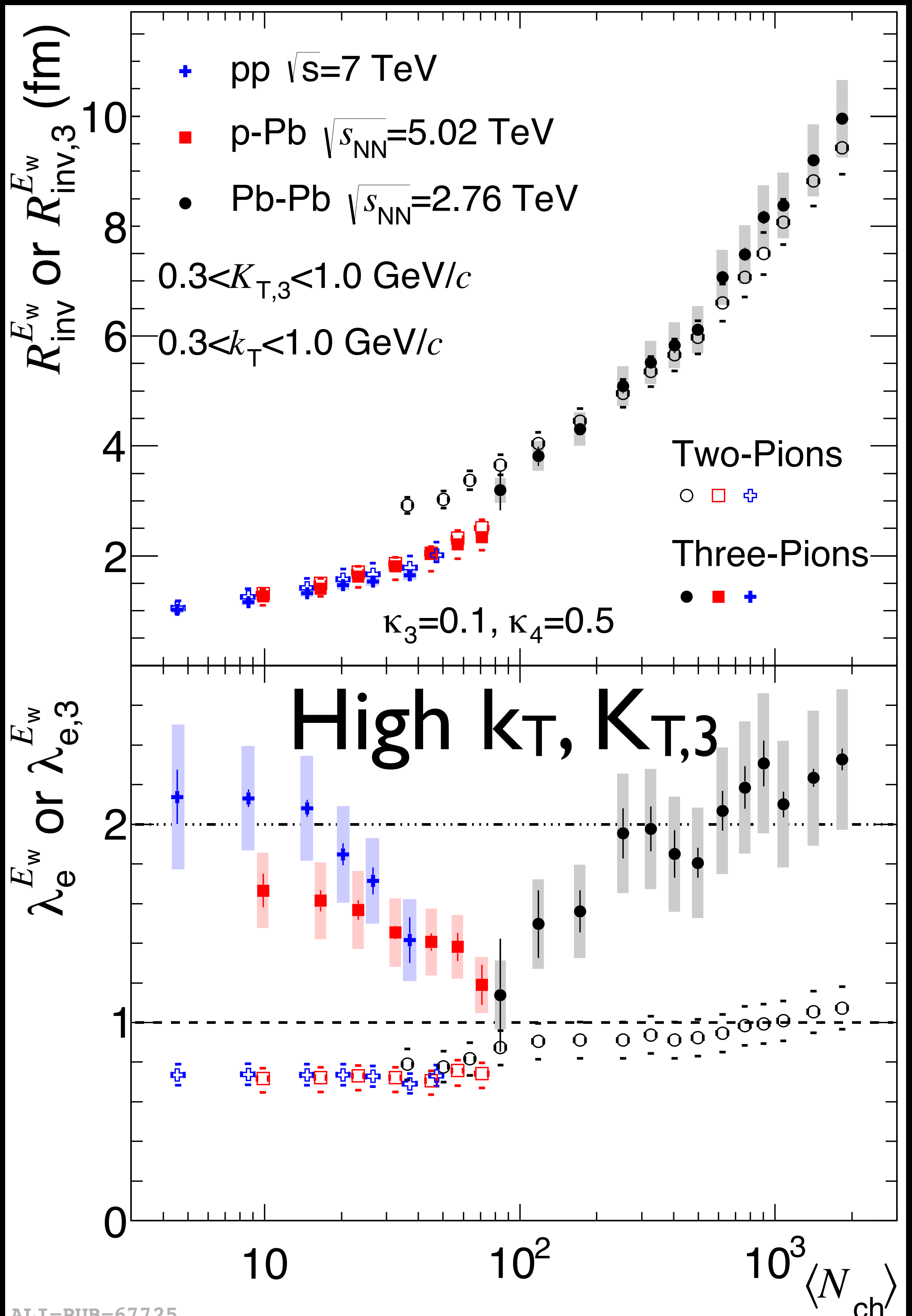




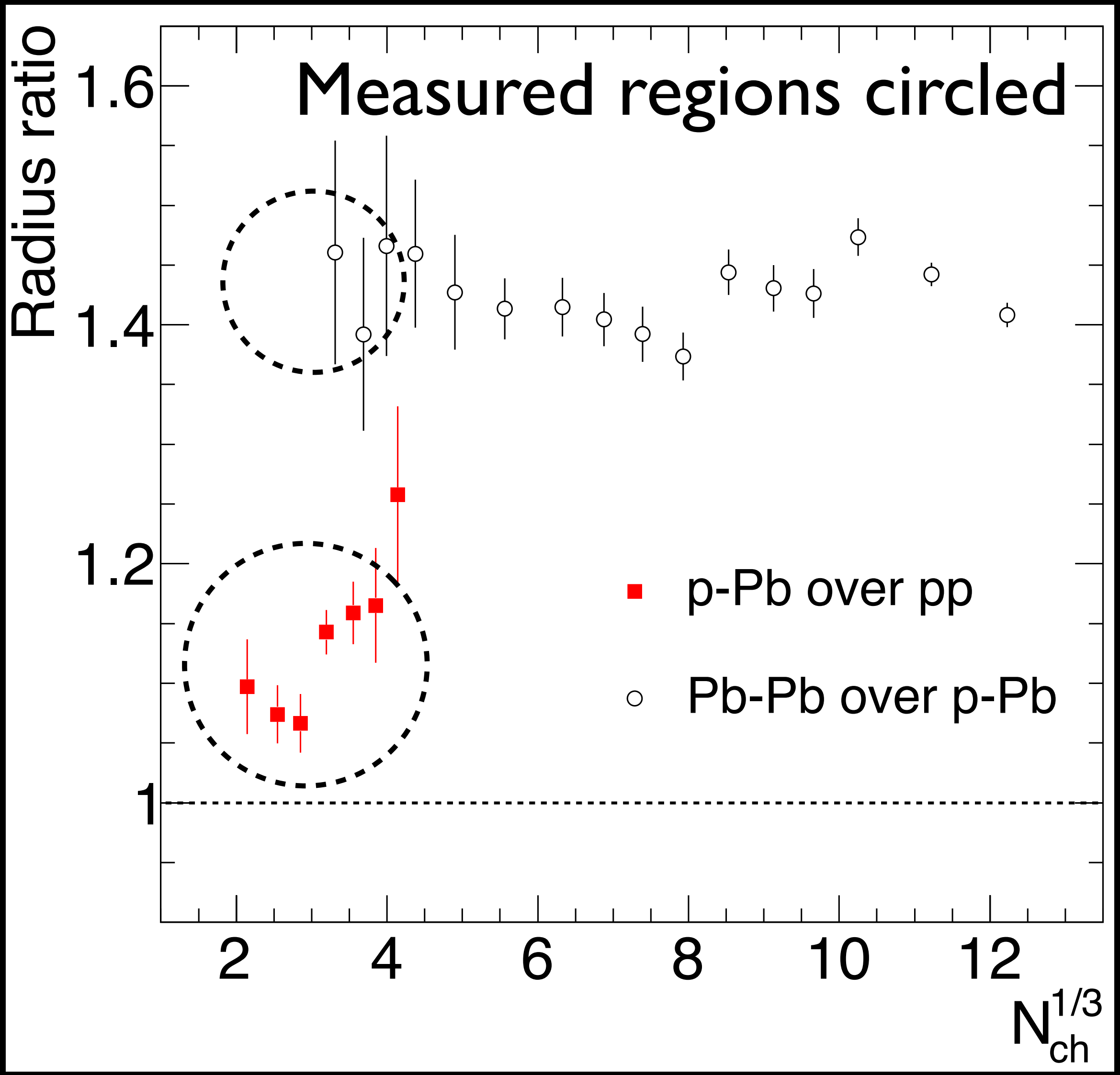
Linear scaling of radii versus $N_{ch}^{1/3}$. Qualitative features of radii in pp and p-Pb are reproduced with CGC initial conditions alone.

Edgeworth Radii and Intercepts



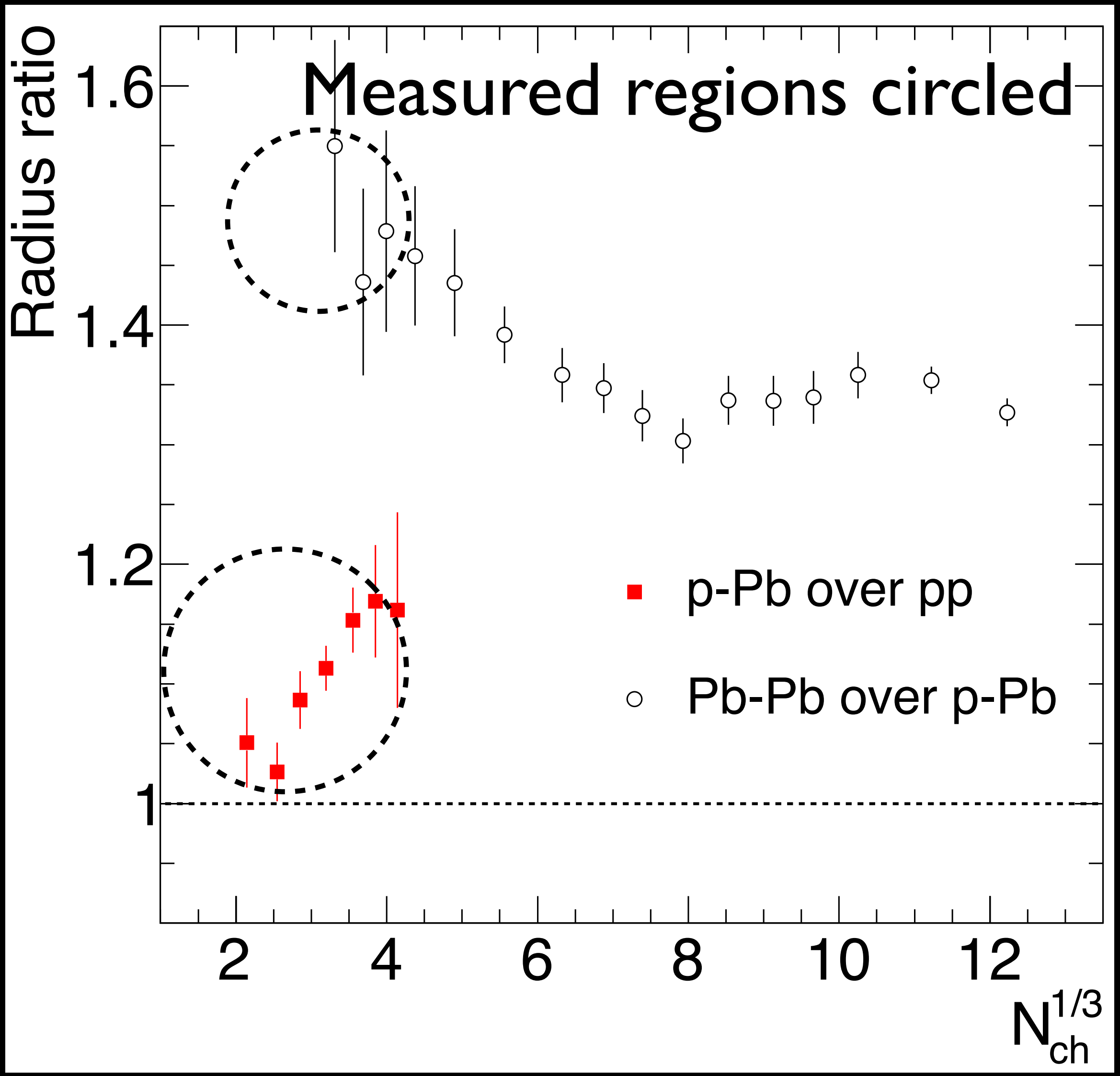


Edgeworth Radii Ratios



Low $K_{T,3}$

<u>pp Fit</u>: $R = 0.44 + 0.402*N_{ch}^{1/3}$
<u>p-Pb Fit</u>: $R = 0.08 + 0.586*N_{ch}^{1/3}$

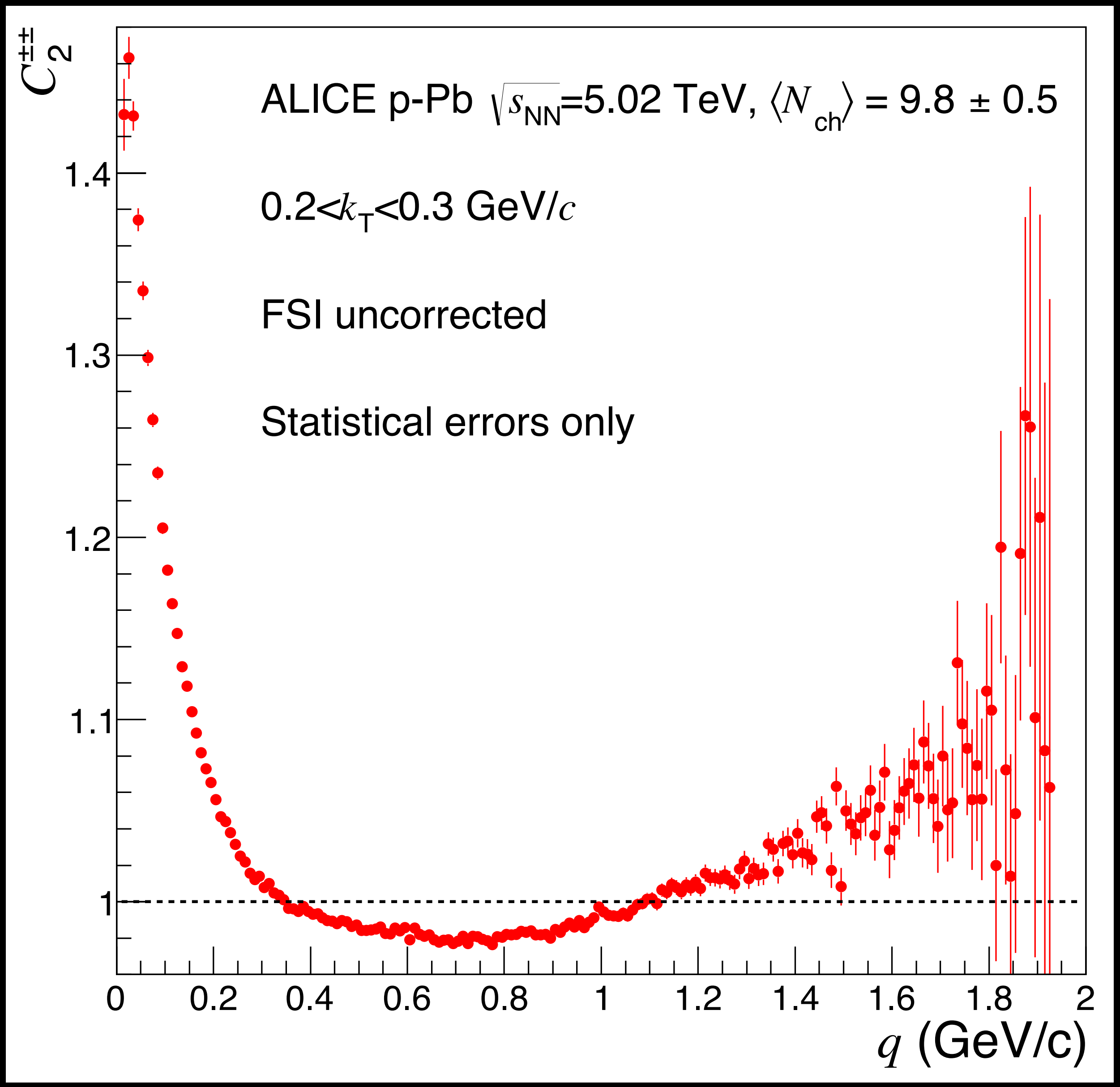


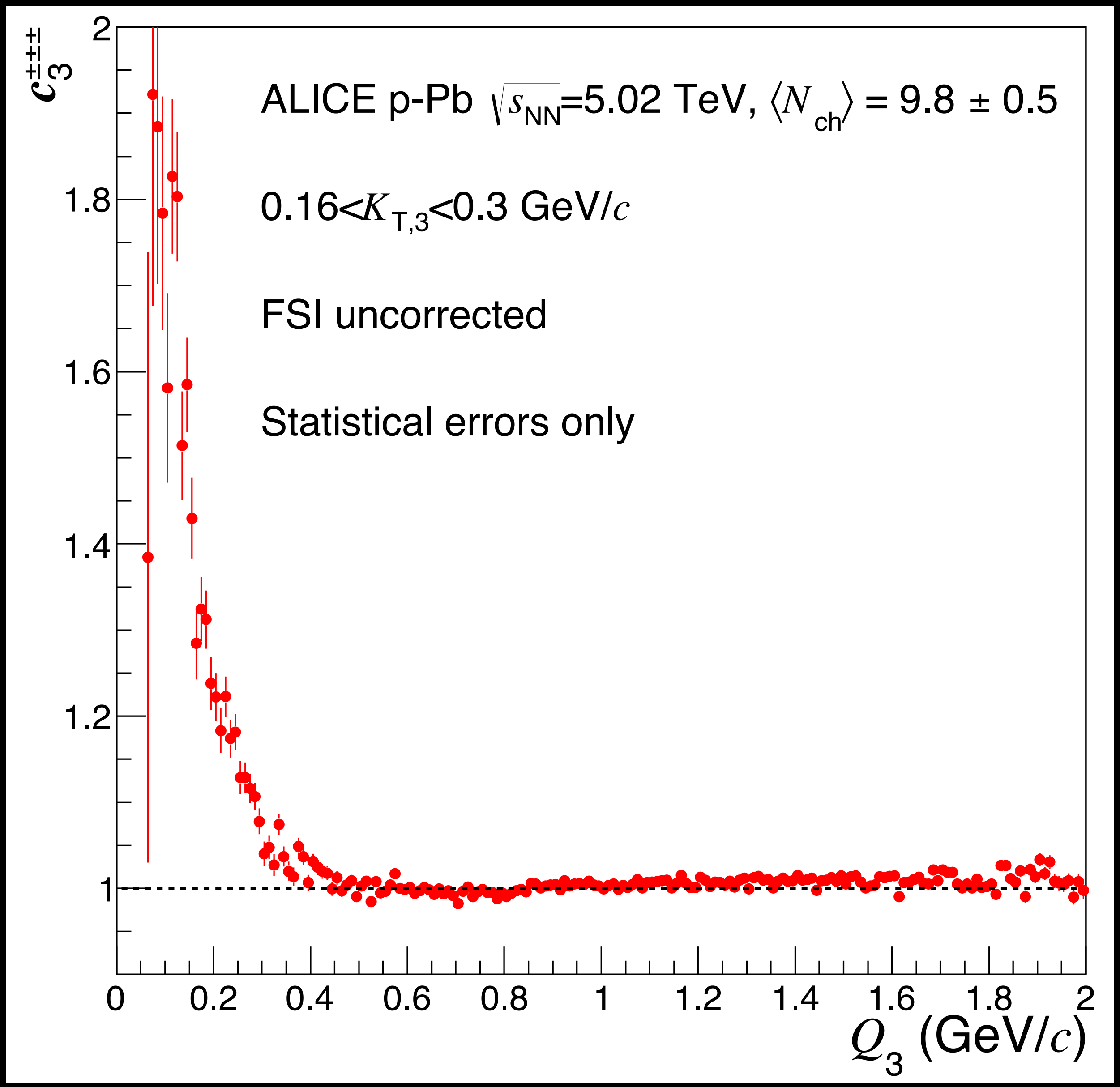
High $K_{T,3}$

<u>pp Fit</u>: $R = 0.33 + 0.405*N_{ch}^{1/3}$
<u>p-Pb Fit</u>: $R = -0.05 + 0.585*N_{ch}^{1/3}$

Red Points: p-Pb data divided by pp radii trend fit (linear with $N_{ch}^{1/3}$).
Black Points: Pb-Pb data divided by p-Pb radii trend.

C_2 & c_3 in an extended range





The baseline for 3-pion cumulants is more flat than for 2-pion correlations.

Isolation of 3-pion Bose-Einstein Correlations

3 pions from the same event

All 3 pions from different events

2 pions from the same event
Other pion from mixed event

$$
\begin{aligned}
N_3(p_1,p_2,p_3) &= f_1 N_1(p_1)N_1(p_2)N_1(p_3) \\
&+ f_2\left[N_2(p_1,p_2)N_1(p_3)+N_2(p_3,p_1)N_1(p_2)+N_2(p_2,p_3)N_1(p_1)\right] \\
&+ f_3 K_3(q_{12},q_{31},q_{23}) N_3^{\mathrm{QS}}(p_1,p_2,p_3)\,,
\end{aligned}
$$

3-pion FSI correlation

Full 3-pion
Quantum-Statistics
correlation

f_1, f_2 and f_3 are functions of f_c
$f_1 = -0.08$
$f_2 = 0.16$
$f_3 = 0.59$

Isolation and fitting of 3-pion Bose-Einstein Cumulant

Cumulant isolation

$$
\begin{aligned}
\mathbf{c}_3(p_1,p_2,p_3) &= \mathcal{N}_3 [1 + [2N_1(p_1)N_1(p_2)N_1(p_3) \\
&- N_2^{\mathrm{QS}}(p_1,p_2)N_1(p_3) - N_2^{\mathrm{QS}}(p_3,p_1)N_1(p_2) - N_2^{\mathrm{QS}}(p_2,p_3)N_1(p_1) \\
&+ N_3^{\mathrm{QS}}(p_1,p_2,p_3)]/N_1(p_1)N_1(p_2)N_1(p_3)],
\end{aligned}
$$

Cumulant fitting

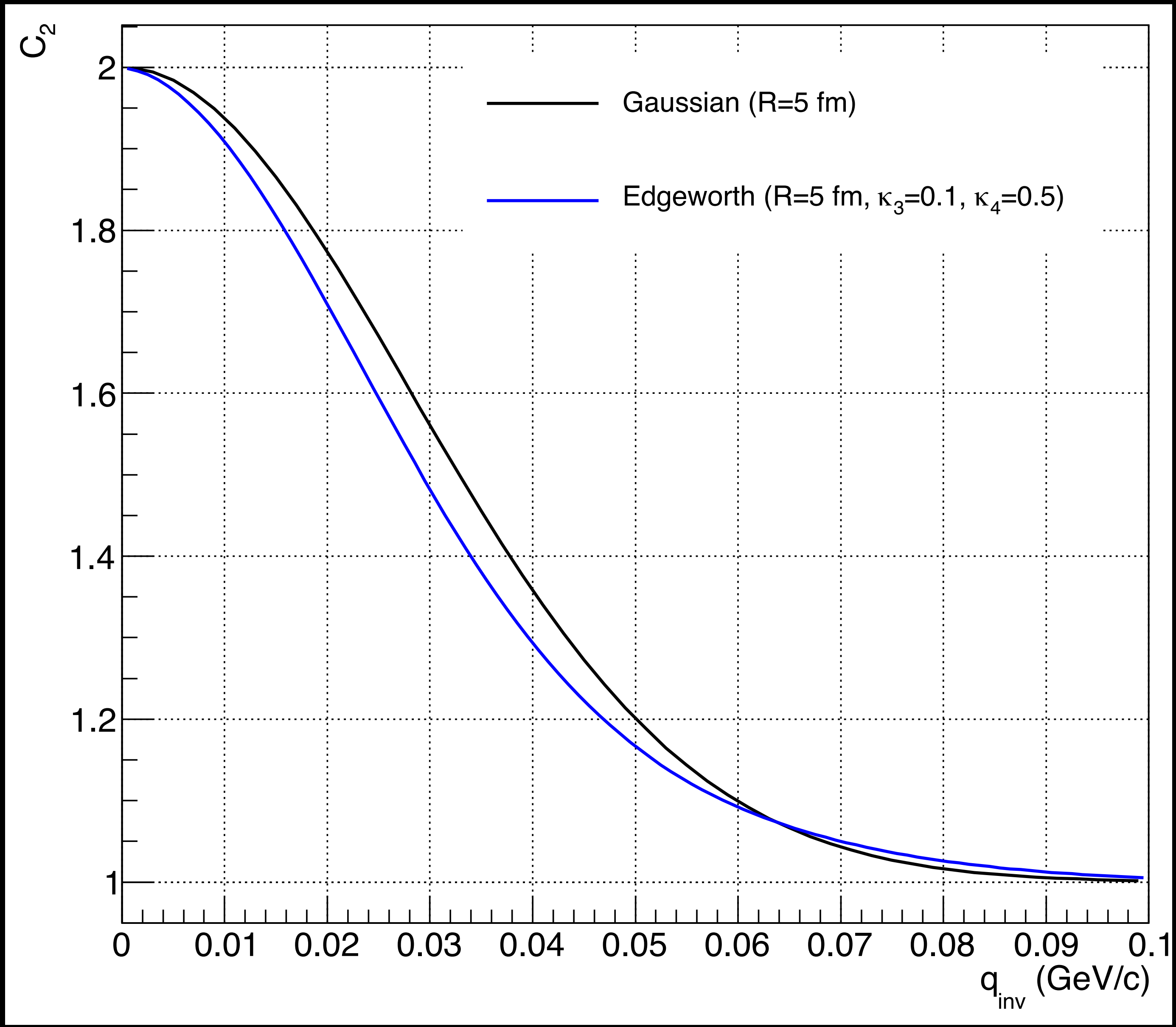
$$
\mathbf{c}_3(q_{12},q_{31},q_{23}) = 1 + \lambda_3\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{12})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{31})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{23})\, e^{-R_{\mathrm{inv},3}^2 Q_3^2/2}
$$

New suppression parameter

Edgeworth factors to account for non-Gaussian features

Edgeworth Expansion of a Gaussian Function

$$C_2^{\mathrm{QS}}(q) = 1 + \lambda E_{\mathrm{w}}^2(R_{\mathrm{inv}}\, q)\, e^{-R_{\mathrm{inv}}^2\, q^2}$$

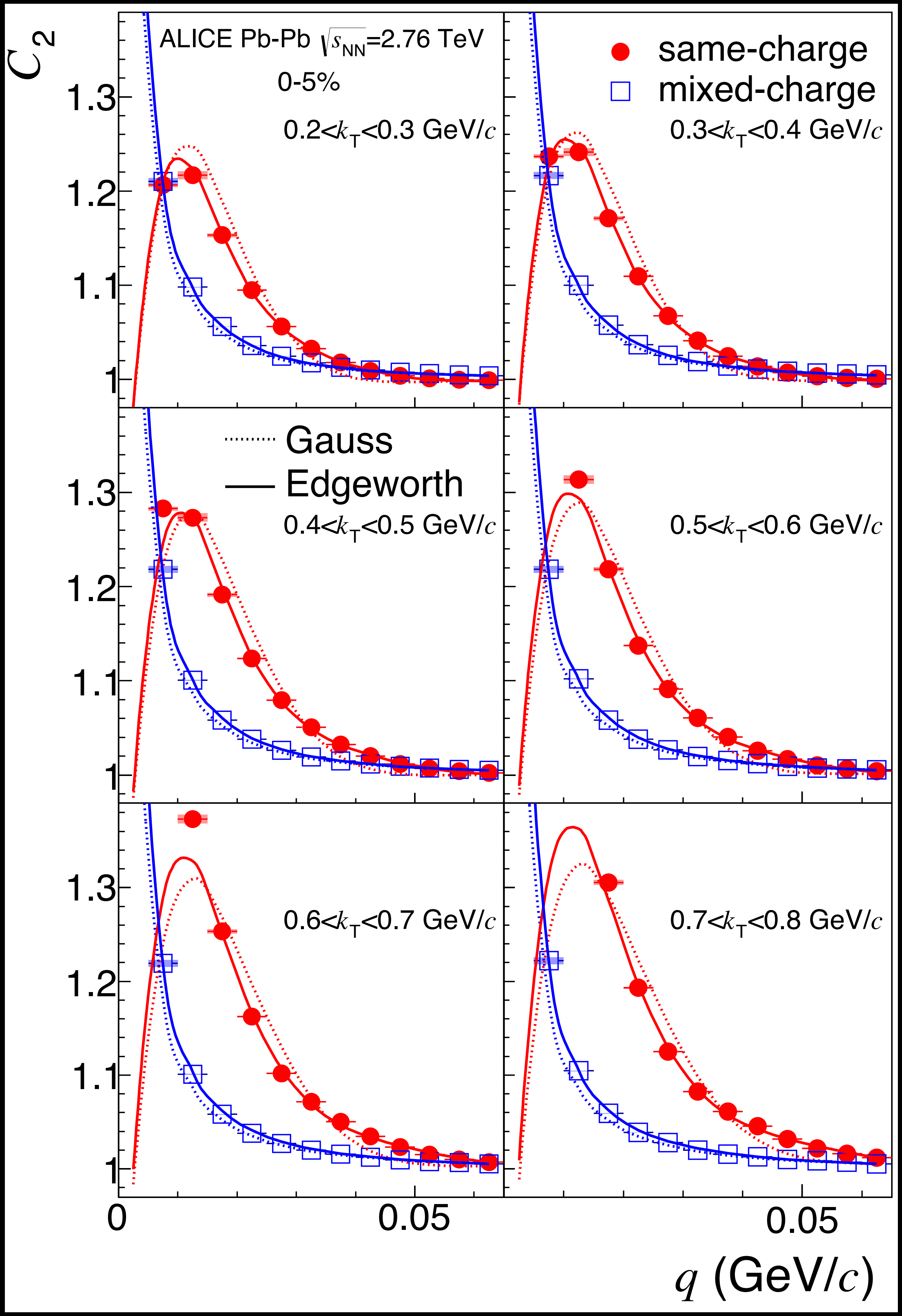


$$E_{\mathrm{w}}(R_{\mathrm{inv}}\, q) = 1 + \sum_{n=3}^{\infty} \frac{\kappa_n}{n!(\sqrt{2})^n} H_n(R_{\mathrm{inv}}\, q)$$

- κ_3 and κ_4 retained.
- Free fit performed for all 3 systems and all multiplicity bins.
- $\langle\kappa_3\rangle = 0.1$
- $\langle\kappa_4\rangle = 0.5$

Edgeworth correlation function <u>sharper</u> than Gaussian

f_c^2 -- dilution parameter

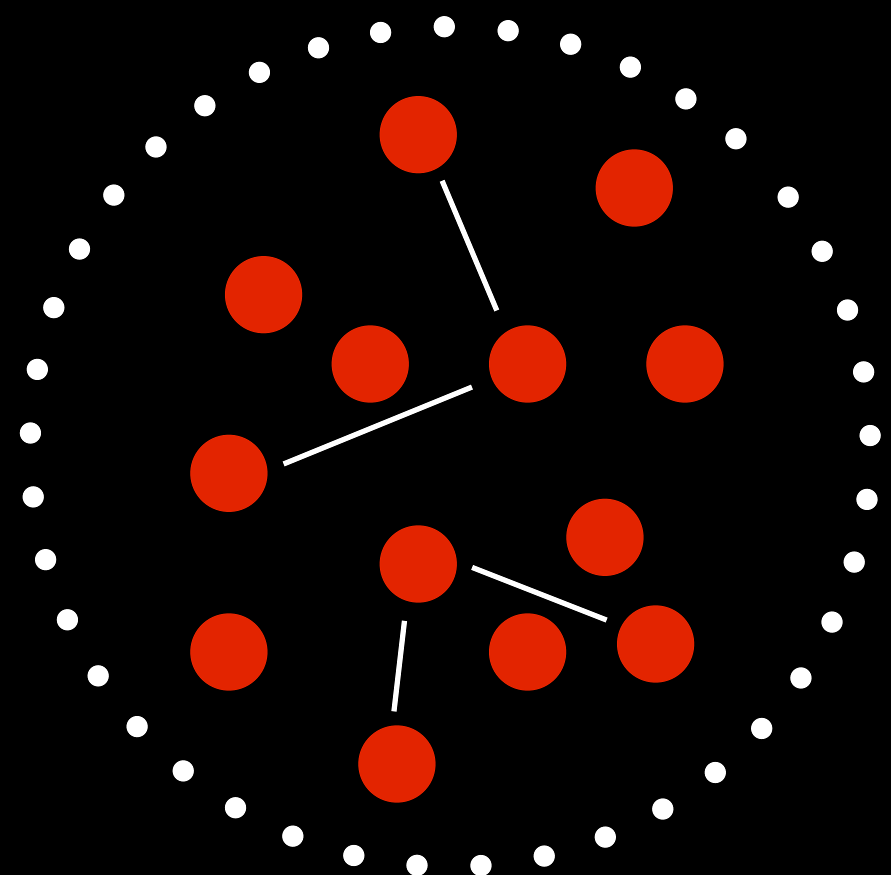


Mixed-charge Coulomb correlations greatly constrain the dilution parameter.

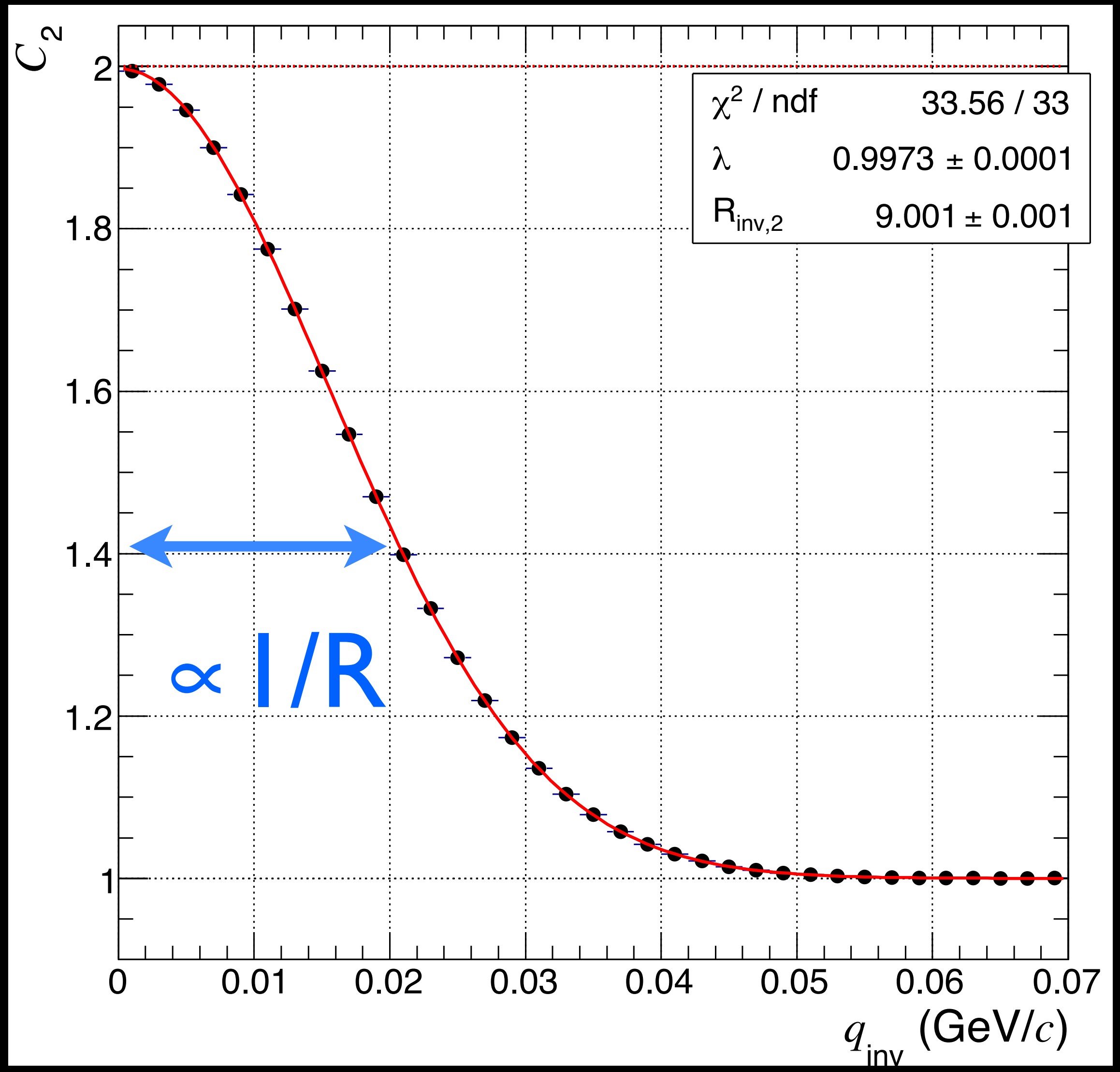
Global fits of same- and mixed-charge used to determine f_c^2.

Abelev et al (ALICE), Phys. Rev. C 89, 024911 (2014)

Freeze-out source profile with 2-Boson correlations

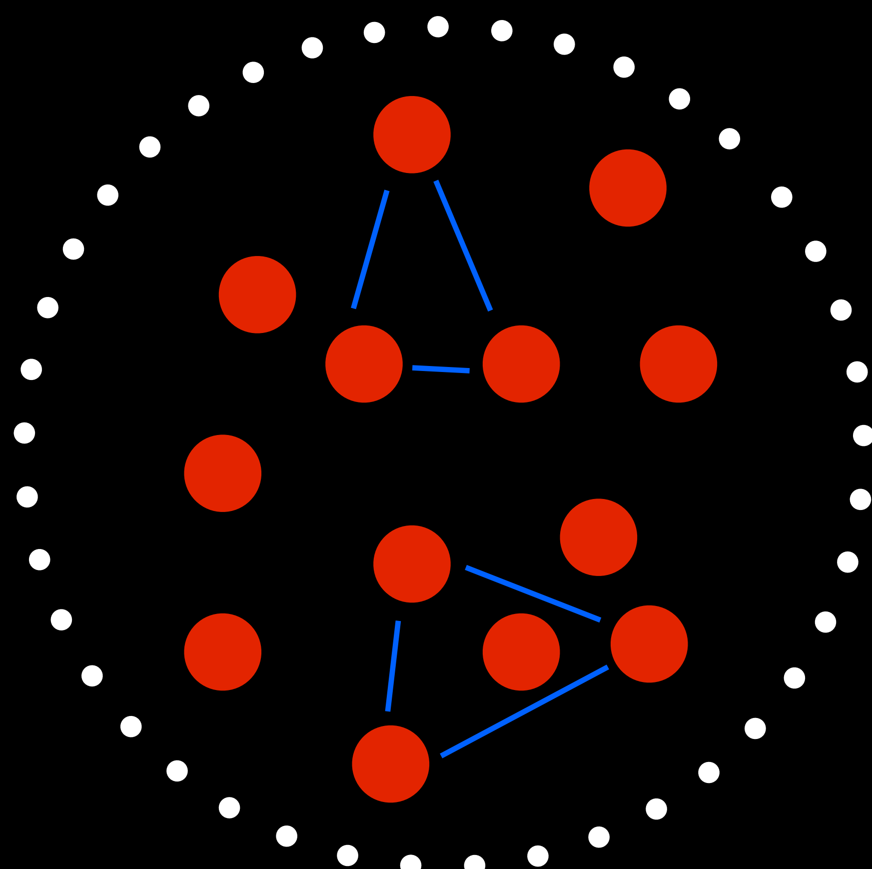


Gaussian model with R=9 fm

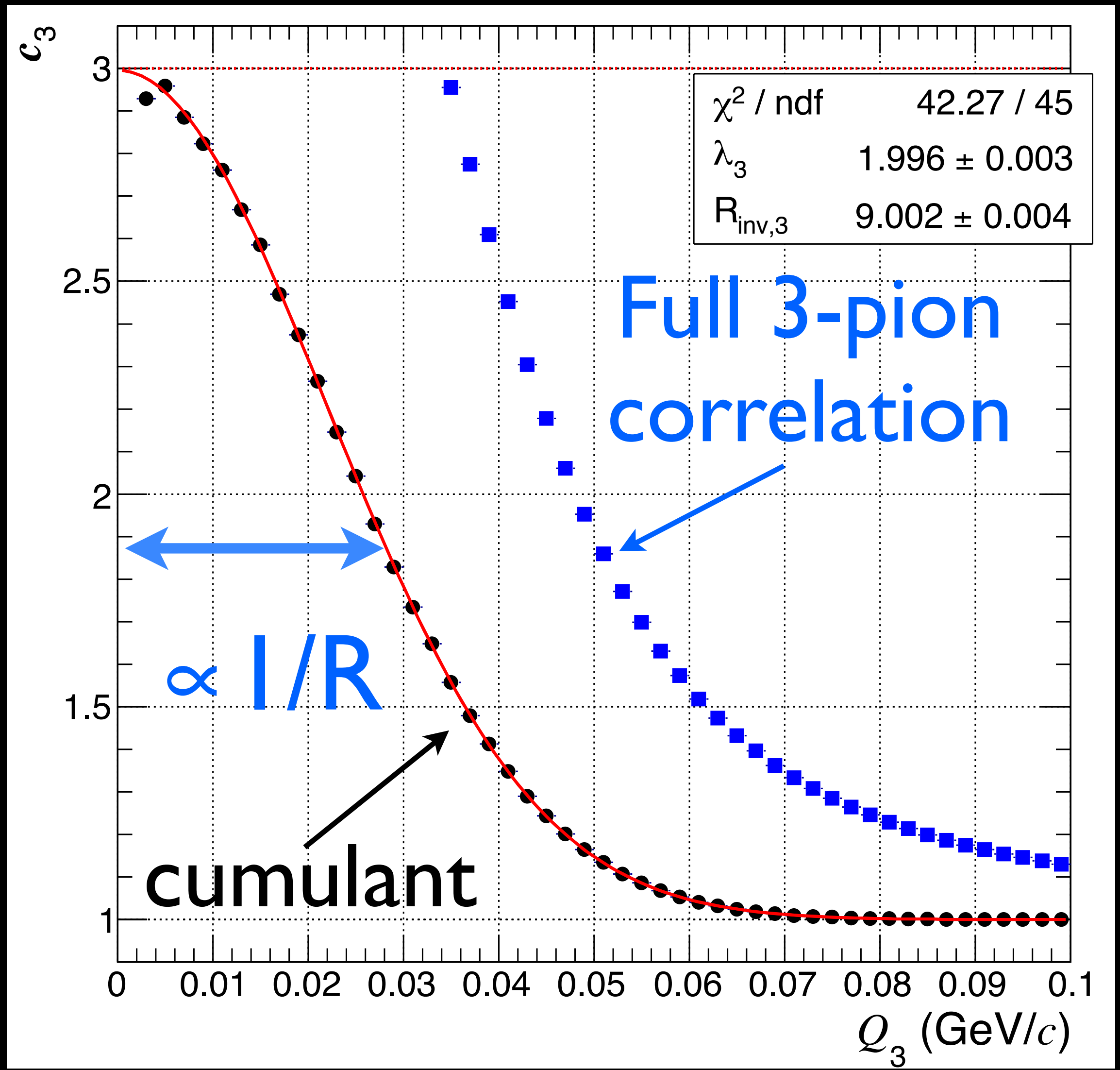


Width of Bose-Einstein peak inversely proportional to the source radius.

Freeze-out source profile with 3-Boson correlations



Gaussian model with R=9 fm



3-pion Bose-Einstein cumulant is <u>2x larger</u> than 2-pion cumulant