Multi-pion Bose-Einstein correlations and the search for quantum coherence

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GDRE 2014

Microscopy (10^{-6})
Femtoscopy (10^{-15})

Femtoscopy = The study of particle correlations at low relative momentum

In high multiplicity events (M>~50)
such correlations are dominated by:
Bose-Einstein correlations (Quantum Statistics)
and
Final-State-Interactions (Coulomb+strong)

Only 2 sources of correlations make femtoscopy a clean probe of heavy-ion physics.

Use 1

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 femtoscopic ($\Delta x \sim 10^{-15}$ 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

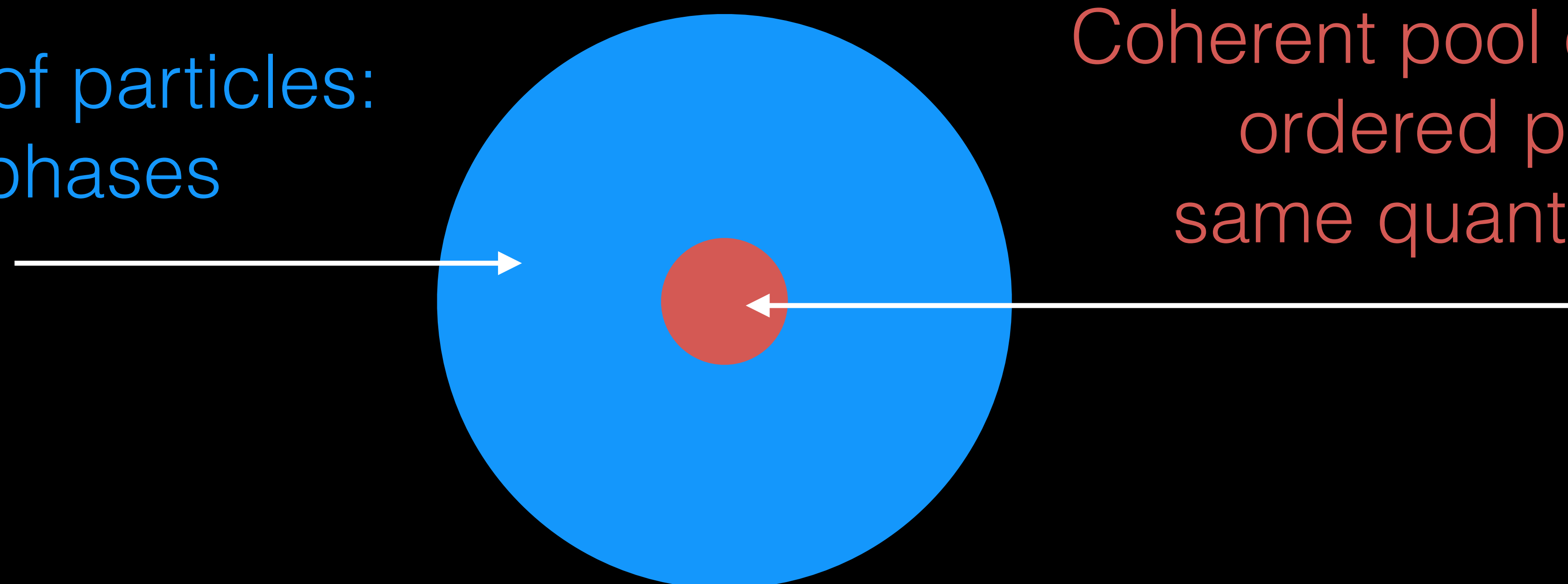
- Bose-Einstein correlations will be visible for $\Delta p <\sim 0.5$ GeV/c. Relative momentum correlations are sensitive to the relative separation at freeze out.

Use 2

Measuring the fraction of pions which are coherent

Chaotic pool of particles: random phases

Coherent pool of particles: ordered phases, same quantum state



Pion condensation, Disoriented Chiral Condensates, +…..
may create a coherent pool of pions.

Standard Correlation Functions

$$C_n = \frac{N_n(\mathbf{p_1}, \mathbf{p_2}, ..., \mathbf{p_n})}{N_1(\mathbf{p_1})N_1(\mathbf{p_2})...N_1(\mathbf{p_n})}$$

p = momentum

Projection Variables

$$q_{ij} = \sqrt{-(p_i - p_j)_\mu (p_i - p_j)^\mu}$$

$$k_T = |\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2}|/2$$

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

$$K_{T,3} = |\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2} + \vec{p}_{\mathrm{T}3}|/3$$

$$Q_4 = \sqrt{q_{12}^2 + q_{13}^2 + q_{14}^2 + q_{23}^2 + q_{24}^2 + q_{34}^2}$$

$$K_{T,4} = |\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2} + \vec{p}_{\mathrm{T}3} + \vec{p}_{\mathrm{T}4}|/4$$

Fitting 2- and 3-pion Bose-Einstein Correlations

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

Quantum-Statistics correlation

Suppression parameter related to incorrect fit functions and coherence

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

Edgeworth expansion for non-Gaussian features

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

Isolation and fitting of 3-pion Bose-Einstein <u>Cumulant</u>

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

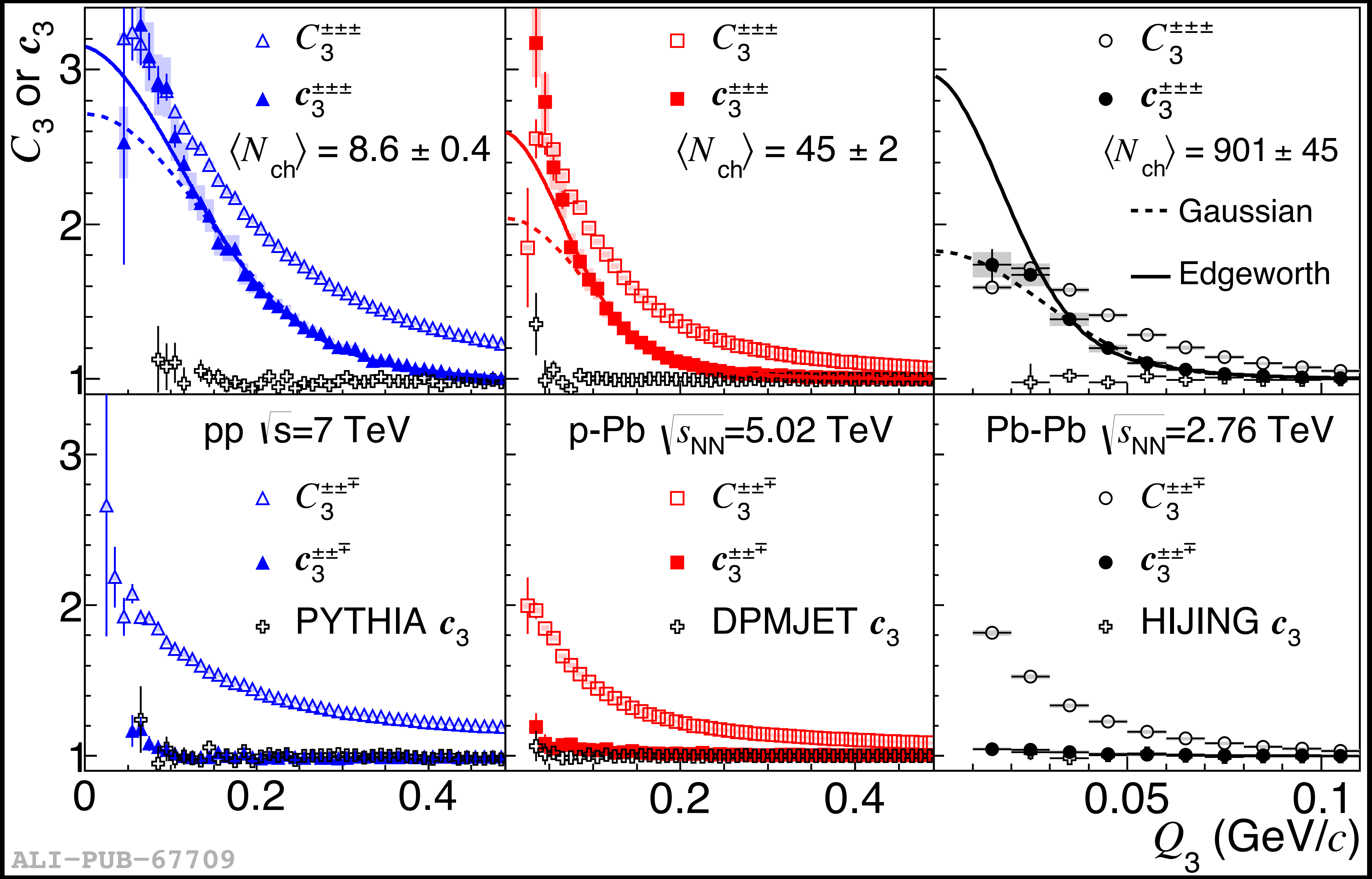
$$\mathbf{c}_3(q_{12}, q_{31}, q_{23}) = 1 + \lambda_3 E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{12})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{31})\, E_{\mathrm{w}}(R_{\mathrm{inv},3}\, q_{23})\, e^{-R_{\mathrm{inv},3}^2 Q_3^2/2}$$

3-pion suppression parameter

Edgeworth factors to account for non-Gaussian features

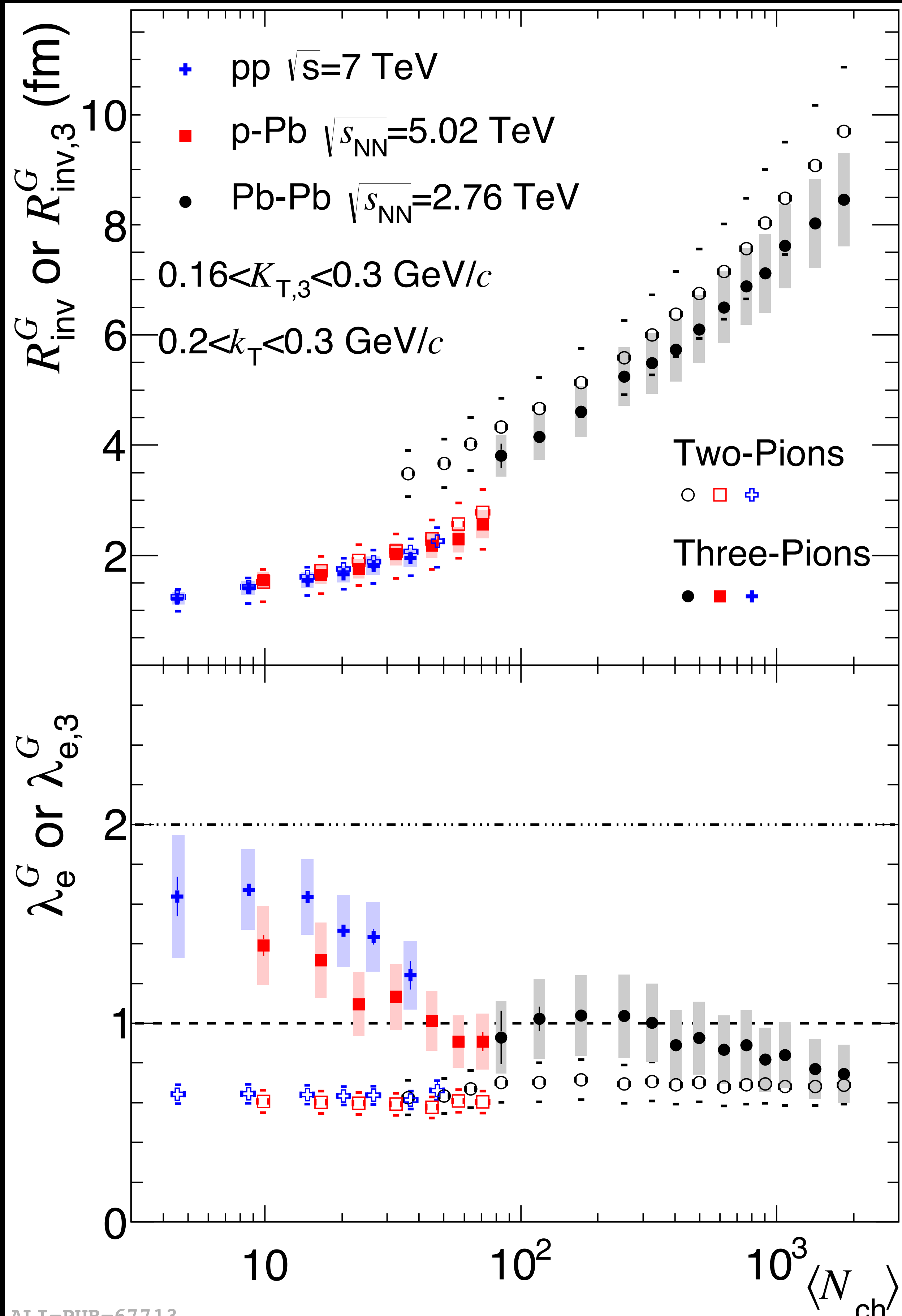
ALICE 2014
arXiv: 1404.1194

3-pion Femtoscopic Correlation Functions



ALICE 2014
arXiv: 1404.1194

1D source radii from 2- and 3-pion correlations in pp, p-Pb and Pb-Pb



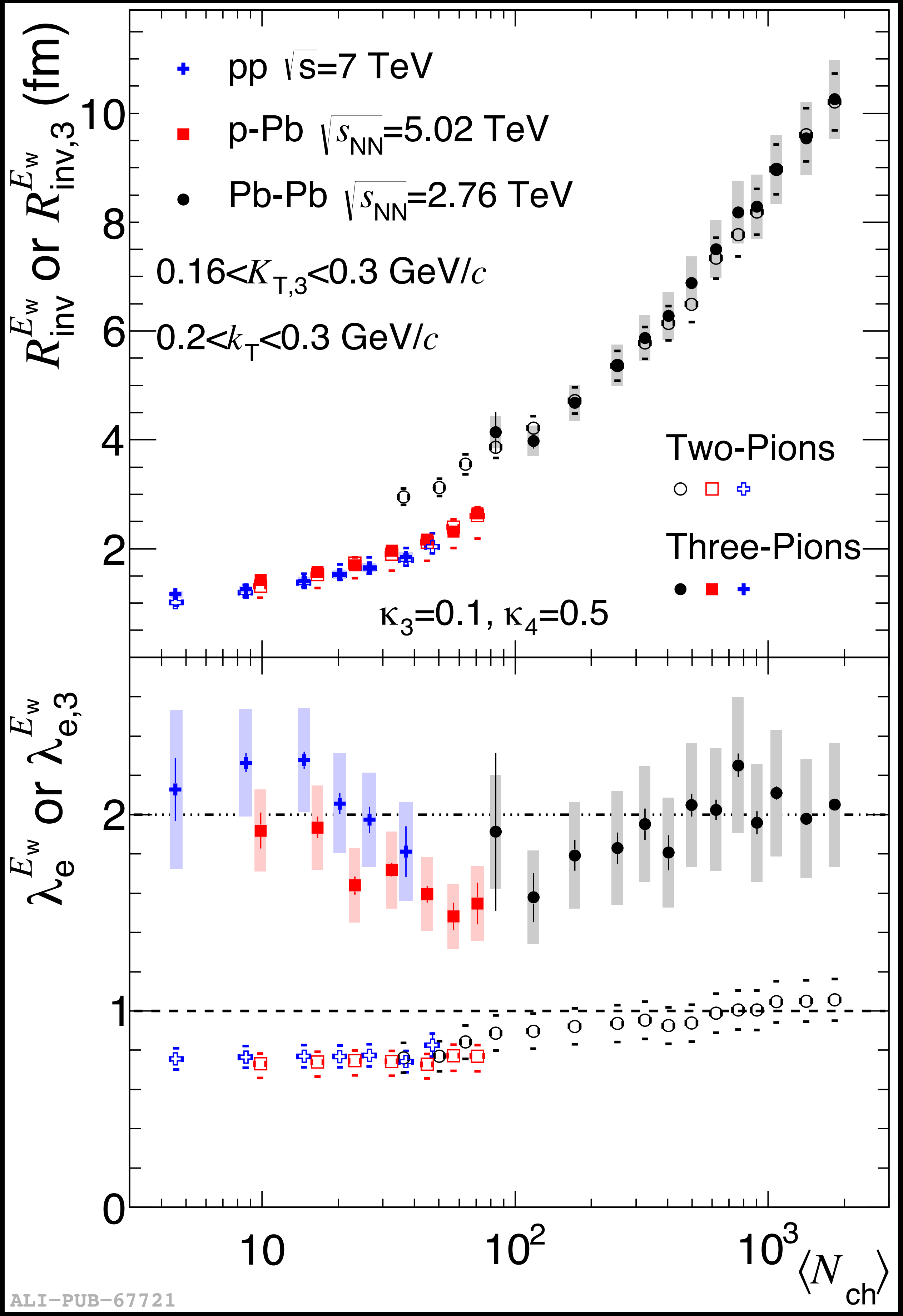
<u>Gaussian fits</u>

radii from 3-pion correlations somewhat smaller than from 2-pions.

Intercept parameters far below the chaotic limits.

ALICE 2014
arXiv: 1404.1194

1D source radii from 2- and 3-pion correlations in pp, p-Pb and Pb-Pb

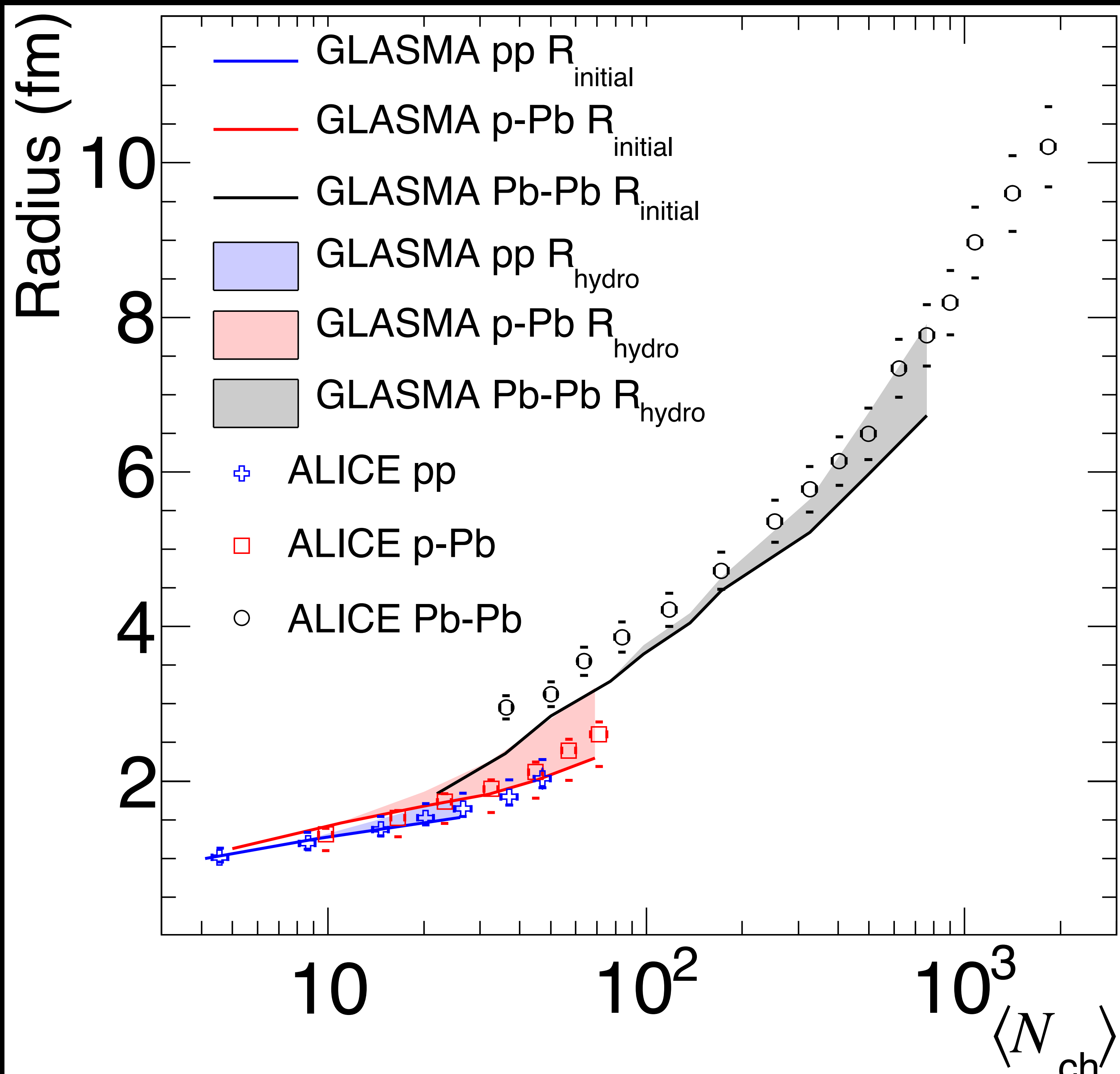


<u>Edgeworth fits</u>

radii from 3-pion correlations consistent with that from 2-pions.

Intercept parameters much more consistent with 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.

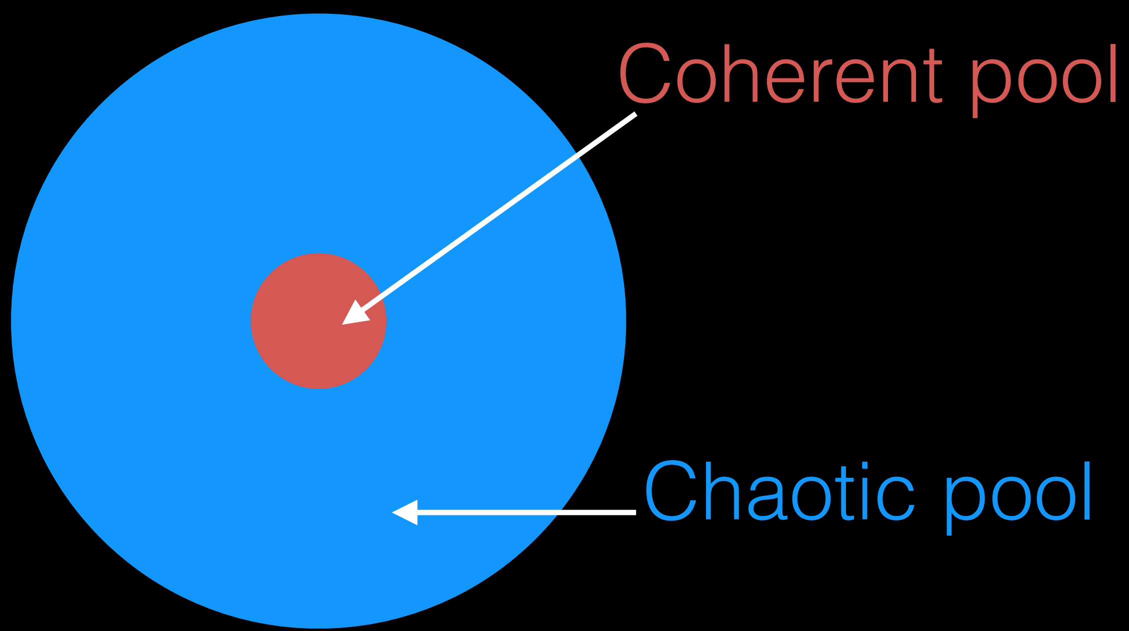
They can also be reproduced
with a hydrodynamic phase
in p-Pb.

Schenke & Venugopalan
arXiv:1405.3605

Use
2

Measuring the coherent fraction of pions

2-pion Bose-Einstein contributions



<u>2-pions</u>

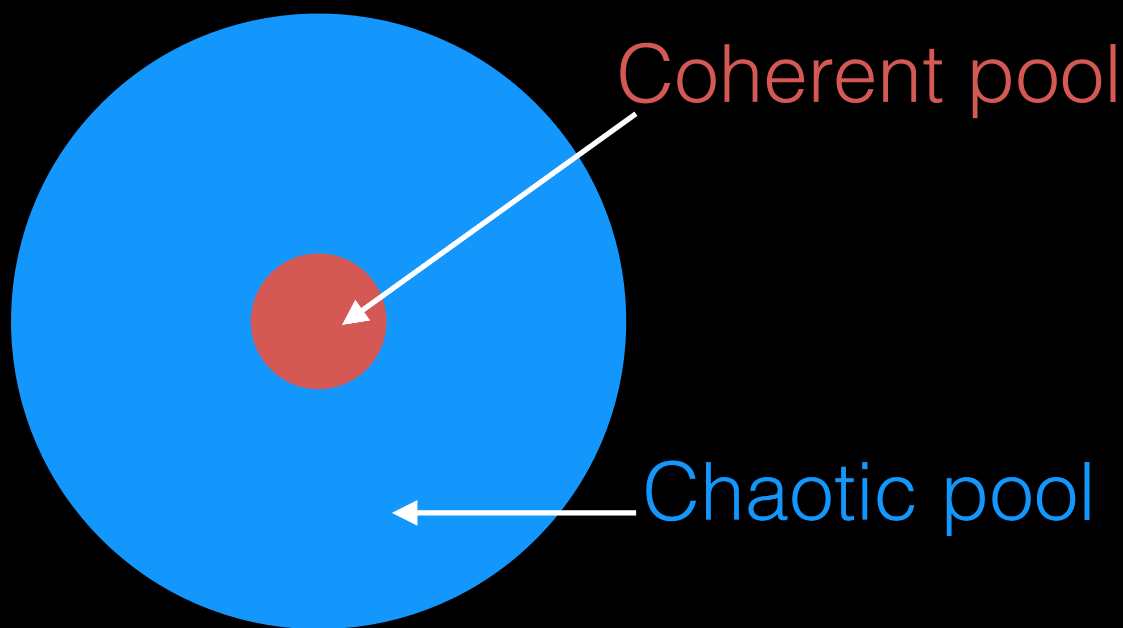
$\pi\ \pi$

$\pi\ \pi$

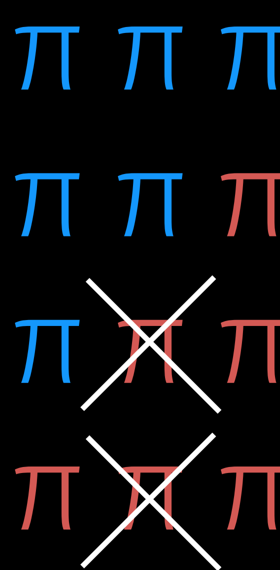
~~$\pi\ \pi$~~

1 suppressed combination

3-pion Bose-Einstein contributions

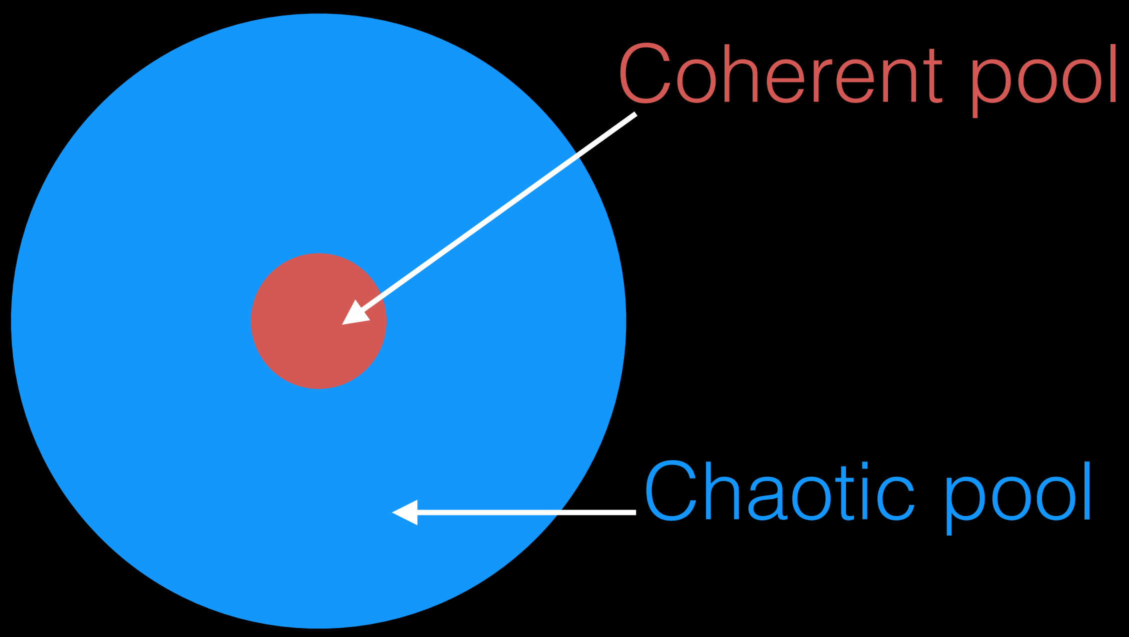


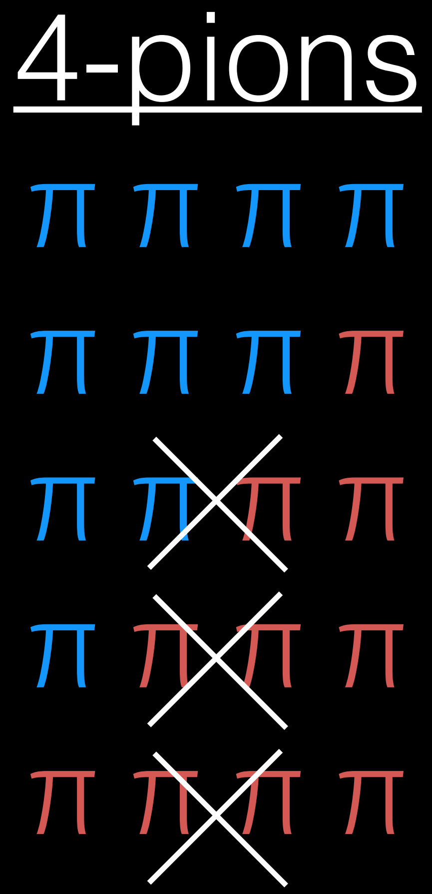
3-pions



2 suppressed combinations

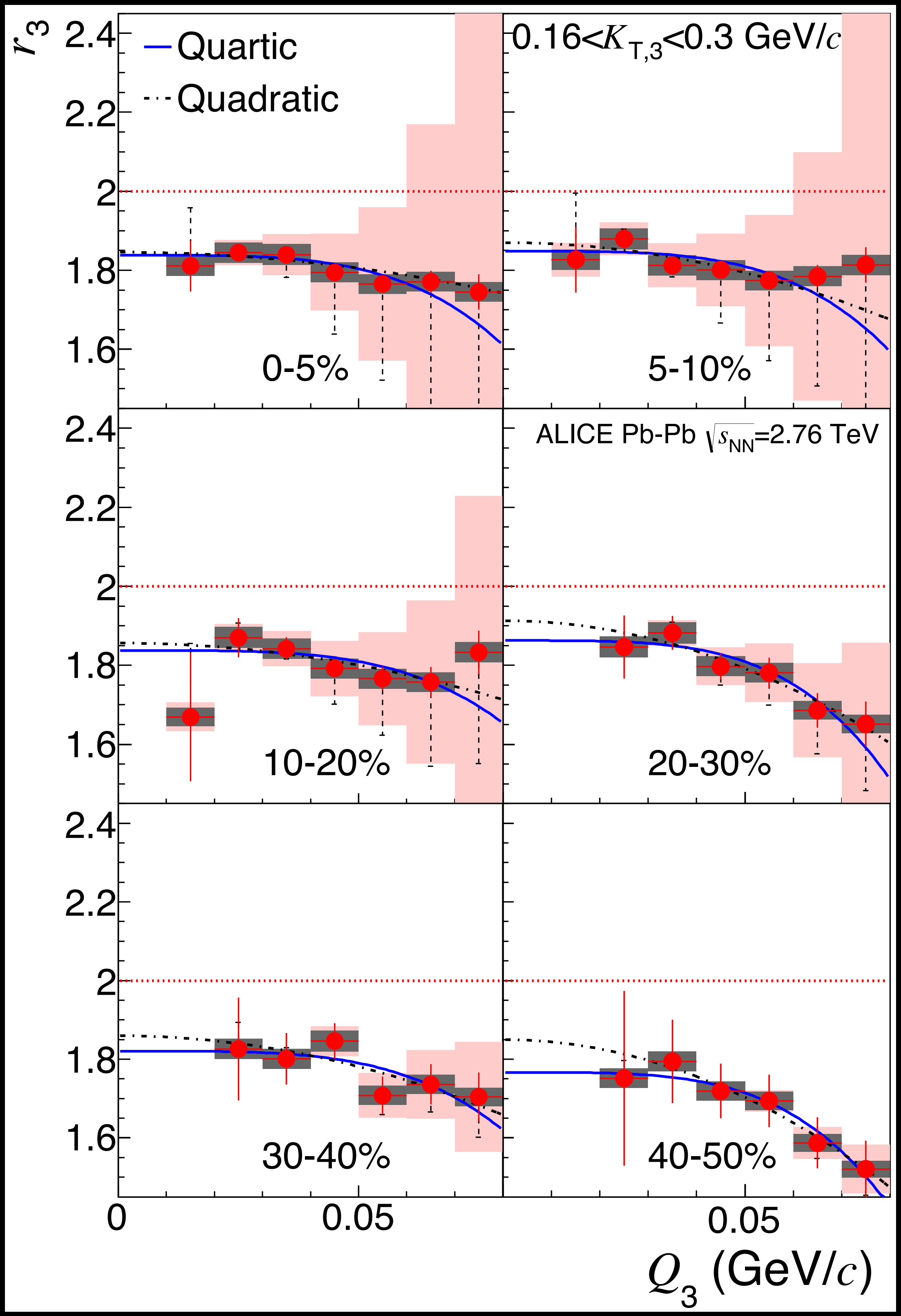
4-pion Bose-Einstein contributions





3 suppressed combinations

Resolution of coherence increases with the number of pions used.



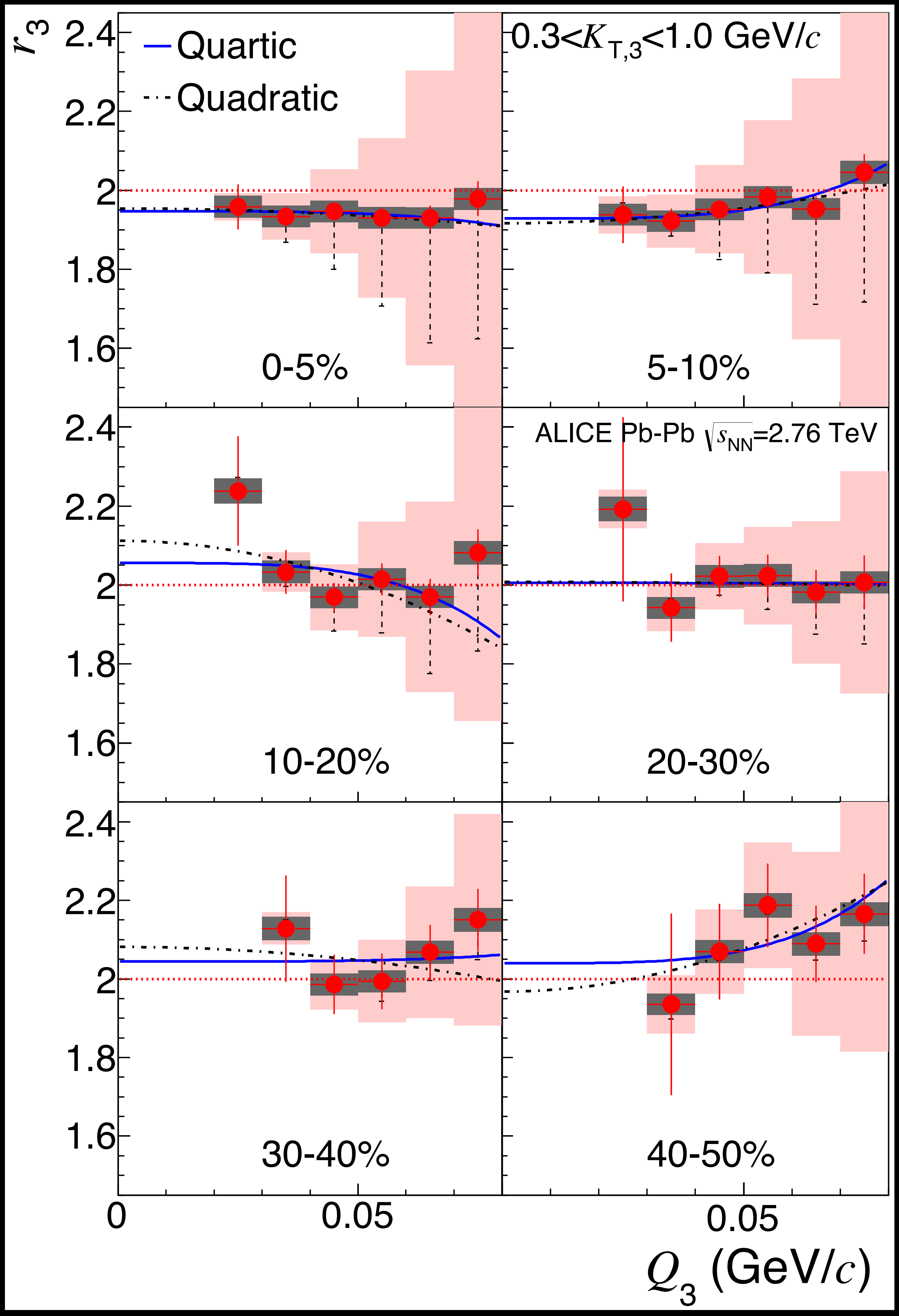
Measure of coherent fraction by comparing 3-pion to 2-pion correlation strength

$$r_3 = \frac{c_3(q_{12}, q_{23}, q_{31}) - 1}{\sqrt{(C_2(q_{12}) - 1)(C_2(q_{13}) - 1)(C_2(q_{23}) - 1)}}$$

All Correlations are first Coulomb corrected.

r_3 is suppressed below 2.0. Intercept corresponds to **~20% coherence at low p_T.**

ALICE 2014
PRC 89 024911 (2014)



Measure of coherent fraction by comparing 3-pion to 2-pion correlation strength

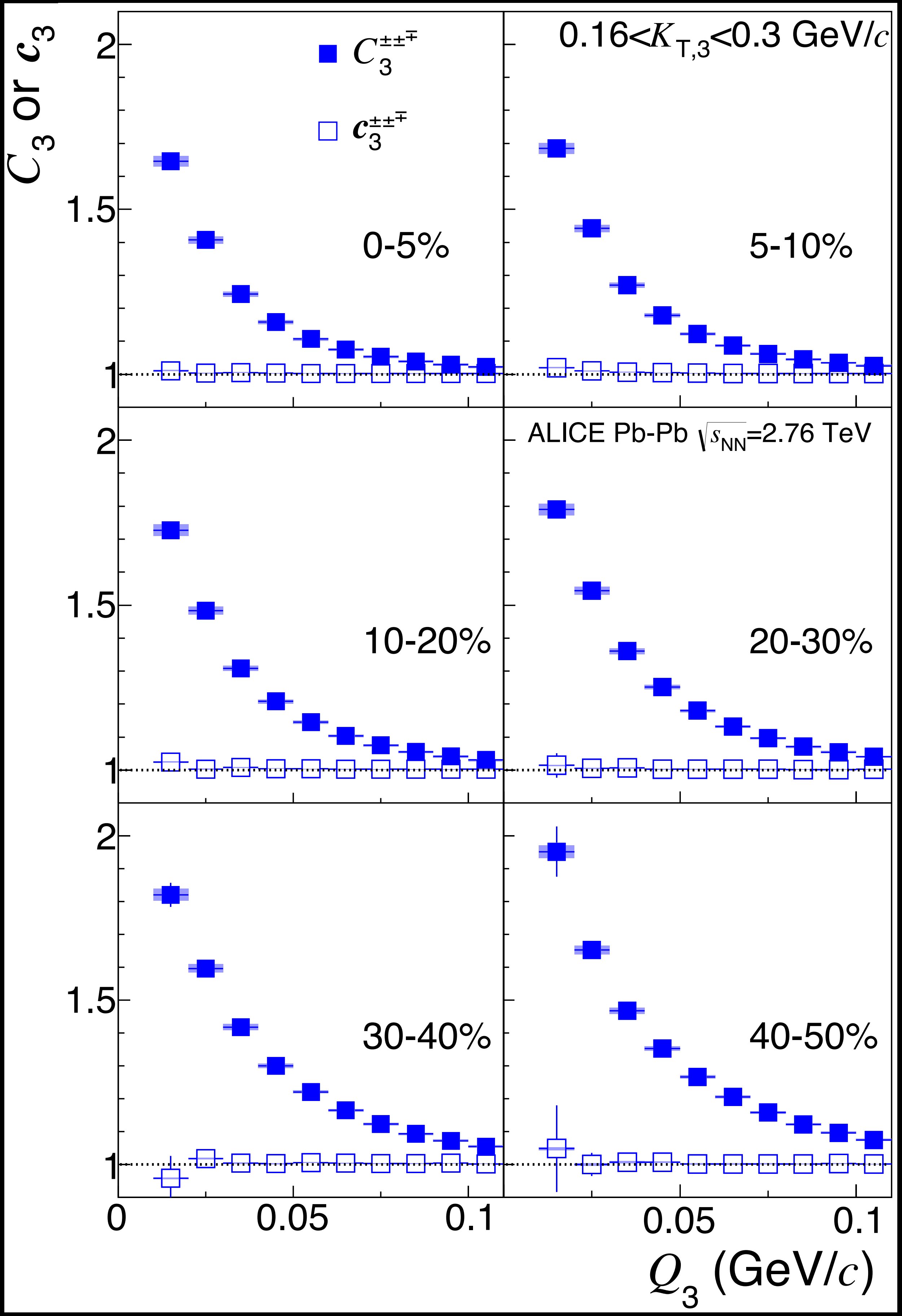
$$r_3 = \frac{c_3(q_{12}, q_{23}, q_{31}) - 1}{\sqrt{(C_2(q_{12}) - 1)(C_2(q_{13}) - 1)(C_2(q_{23}) - 1)}}$$

All Correlations are first Coulomb corrected.

r_3 is consistent with 2.0.
Intercept is consistent with **0% coherence at high p_T**

ALICE 2014
PRC 89 024911 (2014)

Check that 3-body Coulomb corrections work



The cumulant (hollow points) ais Coulomb corrected.

Consistency with unity demonstrates success of 3-body Coulomb ansatz

$K_3 = K_2^{12} * K_2^{13} * K_2^{23}$

ALICE 2014
PRC 89 024911 (2014)

Future measurements in ALICE

An interesting hint of coherence in Pb-Pb collisions has been observed with 3-pion correlations.

4-pion correlations are even more sensitive to coherence. The 4-pion analysis is already underway. Preliminary results expected for WPCF Aug 2014.

New method to extract coherent fraction— “Built” C_4^{QS}

$C_2(k_T, q_{Out}, q_{Side}, q_{Long})$ is statistically well defined.
It can be tabulated very differentially.

For fully chaotic pion emission:
$C_2^{QS}(q_{ij}) - 1.0 = T_{ij}^2$
(pair exchange amplitude squared).

Also for fully chaotic emission and neglecting
the multi-pion phases for 3-pion and 4-pion interchanges,
C_4^{QS} is entirely built from each of the 6 T_{ij}

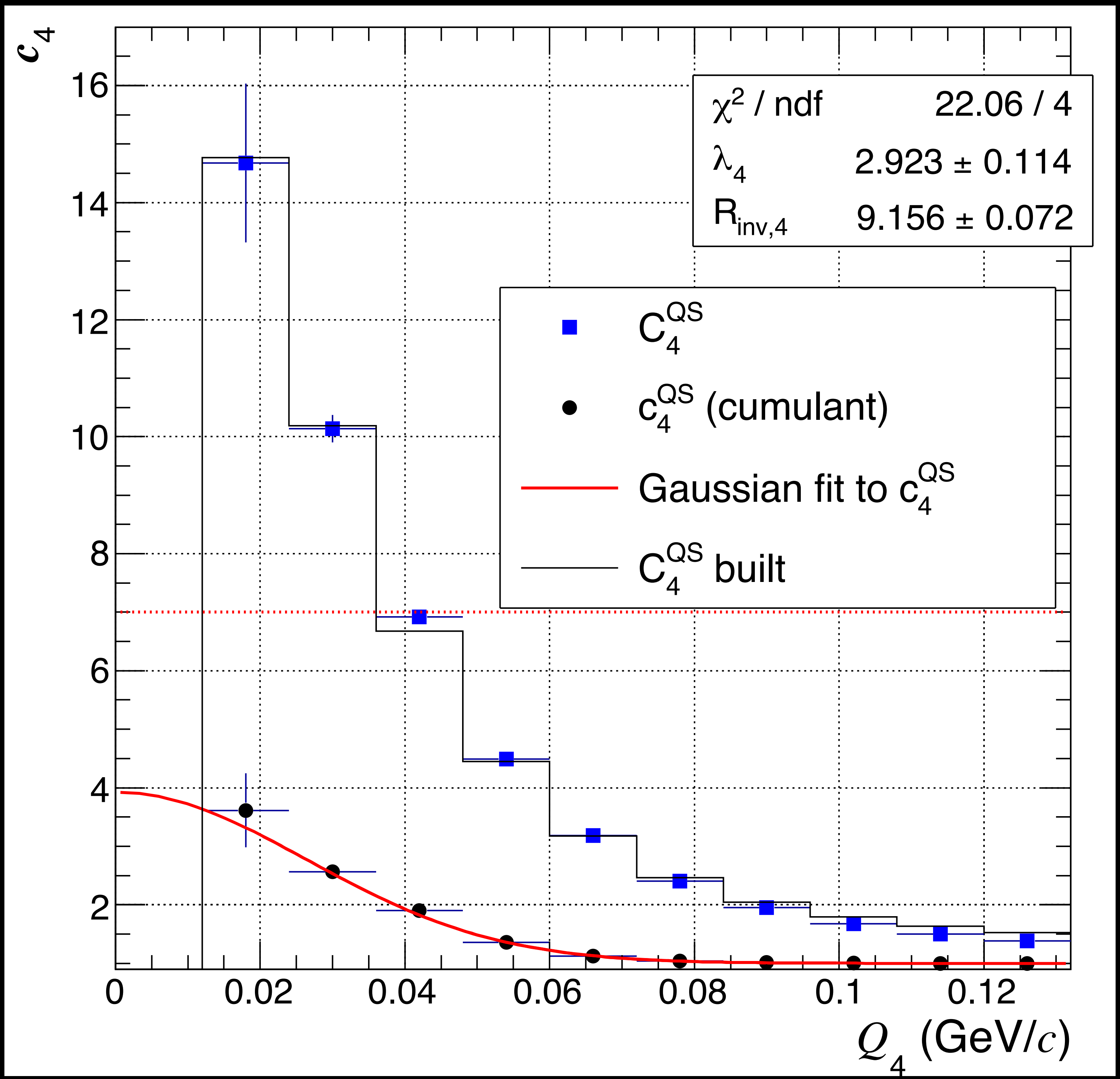
Equations to Build QS correlations with coherence

G = coherent fraction of pions

$$
\begin{aligned}
C_2^{QS} - 1 &= (1-G^2)T_{12}^2 & (52)\\
C_3^{QS} - 1 &= (1-G)^2(T_{12}^2 + T_{13}^2 + T_{23}^2) & (53)\\
&+ (6G(1-G)^2 + 2(1-G)^3)T_{12}T_{13}T_{23} & (54)\\
C_4^{QS} - 1 &= (1-G^2)(T_{12}^2 + T_{13}^2 + T_{14}^2 + T_{23}^2 + T_{24}^2 + T_{34}^2) & (55)\\
&+ (4G(1-G)^3 + (1-G)^4(T_{12}^2 T_{34}^2 + T_{13}^2 T_{24}^2 + T_{14}^2 T_{23}^2) & (56)\\
&+ (6G(1-G)^2 + 2(1-G)^3)(T_{12}T_{13}T_{23} + T_{12}T_{14}T_{24} + T_{13}T_{14}T_{34} + T_{23}T_{24}T_{34}) & (57)\\
&+ (8G(1-G)^3 + 2(1-G)^4)(T_{12}T_{13}T_{24}T_{34} + T_{12}T_{14}T_{23}T_{34} + T_{13}T_{14}T_{23}T_{24}) & (58)
\end{aligned}
$$

These equations valid for R_{coh}=R_{ch}
(coherent Radius = chaotic Radius).
We will also consider R_{coh}=0 (point source).

Proof of Principle



<u>Therminator model calculation (no coherence).</u>

Black line (Built) is in good agreement with Blue points —> 4-pion QS correlations are built from information already present at 2-pion level for the case of no coherence.

<u>Deviations from this expectation may be used to search for non-zero coherence.</u>

Summary

Radii Measurements (Use 1)

For the first time, femtoscopic radii have been extracted using 3-pion cumulant Bose-Einstein correlations.
3-pion cumulants are advantageous in low-multiplicity events such as in pp and p-Pb collisions.
They are less sensitive to background correlations.

Coherence Measurements (Use 2)

An unexpected hint of quantum coherence has been observed using 3-pion Bose-Einstein correlations in Pb-Pb collisions at the LHC.
The eventual 4-pion measurement should shed more light on the possibility of coherent pion emission.

Supporting Slides

Fitting 2-pion Bose-Einstein Correlations

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

Quantum-Statistics correlation

Suppression parameter related to incorrect fit functions and coherence

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

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)

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- $N_1(p_1)N_1(p_2)N_1(p_3)$ — 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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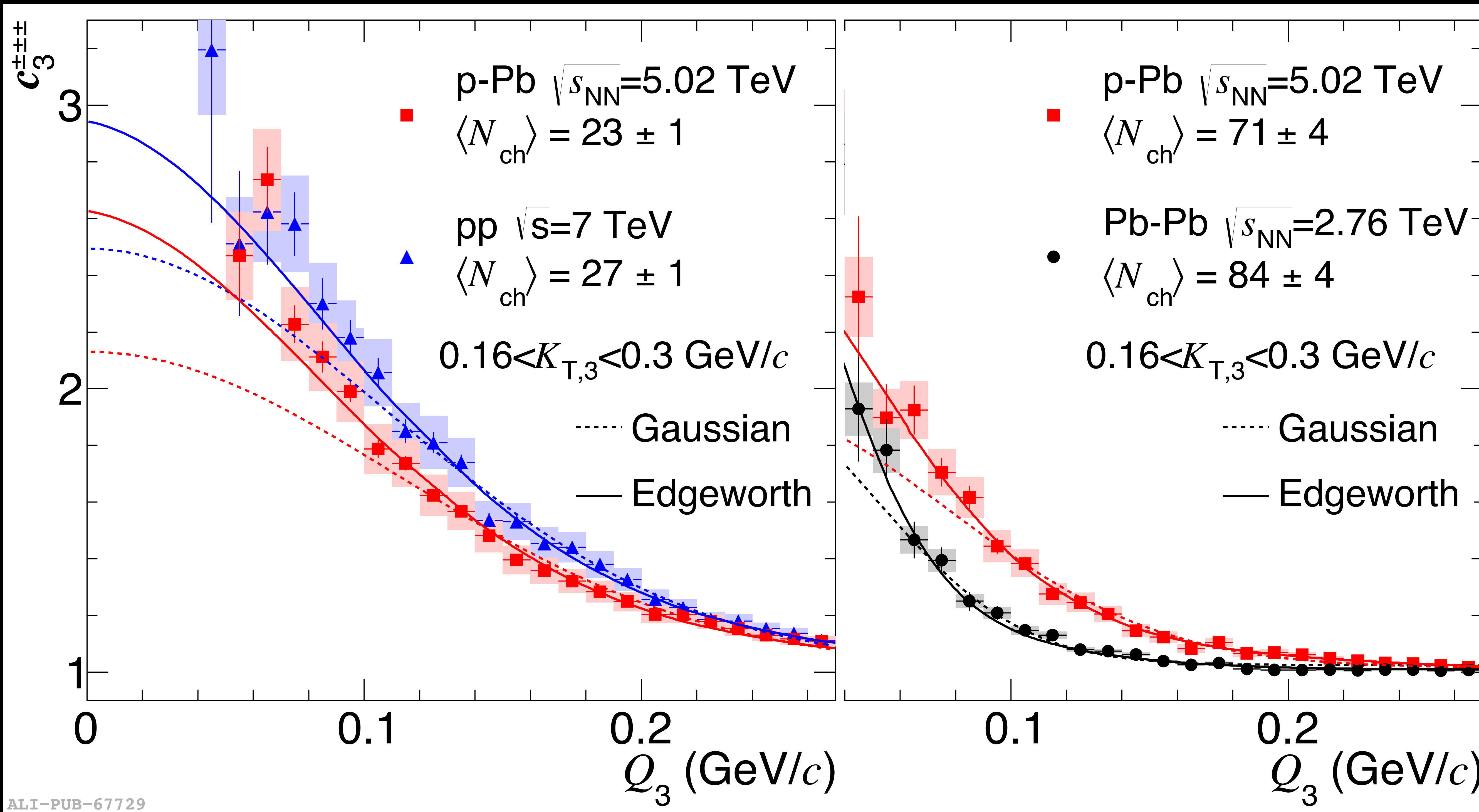
Cumulant fitting

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

3-pion suppression parameter (λ_3)

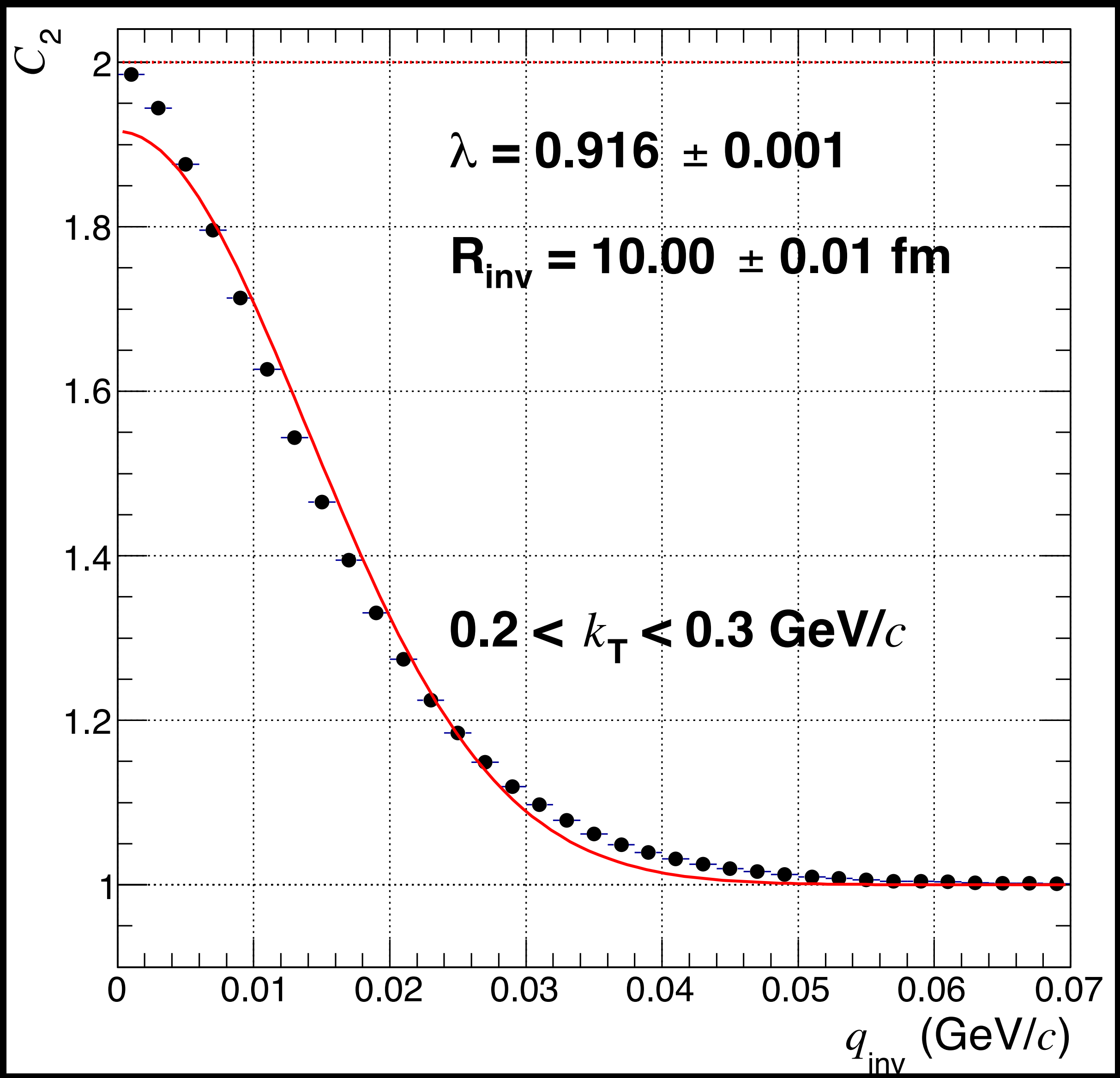
Edgeworth factors to account for non-Gaussian features (E_{w})

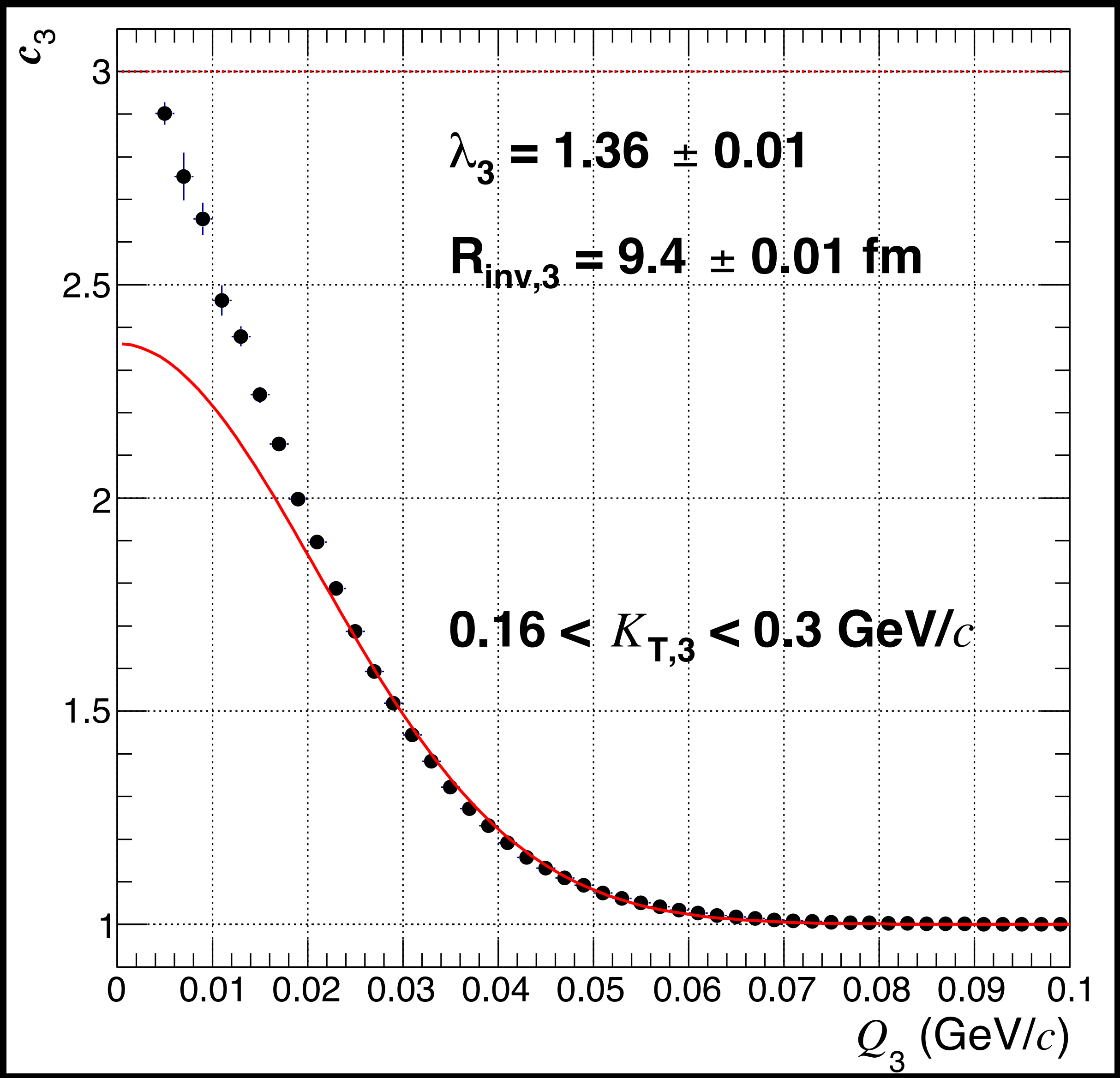


$c_3^{\pm\pm\pm}$
p-Pb $\sqrt{s_{NN}}$=5.02 TeV
$\langle N_{ch} \rangle$ = 23 ± 1
pp $\sqrt{s}$=7 TeV
$\langle N_{ch} \rangle$ = 27 ± 1
0.16<$K_{T,3}$<0.3 GeV/c
Gaussian
Edgeworth
p-Pb $\sqrt{s_{NN}}$=5.02 TeV
$\langle N_{ch} \rangle$ = 71 ± 4
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
$\langle N_{ch} \rangle$ = 84 ± 4
0.16<$K_{T,3}$<0.3 GeV/c
Gaussian
Edgeworth
Q_3 (GeV/c)
Q_3 (GeV/c)
ALI-PUB-67729

Therminator2
0-5% Pb-Pb

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





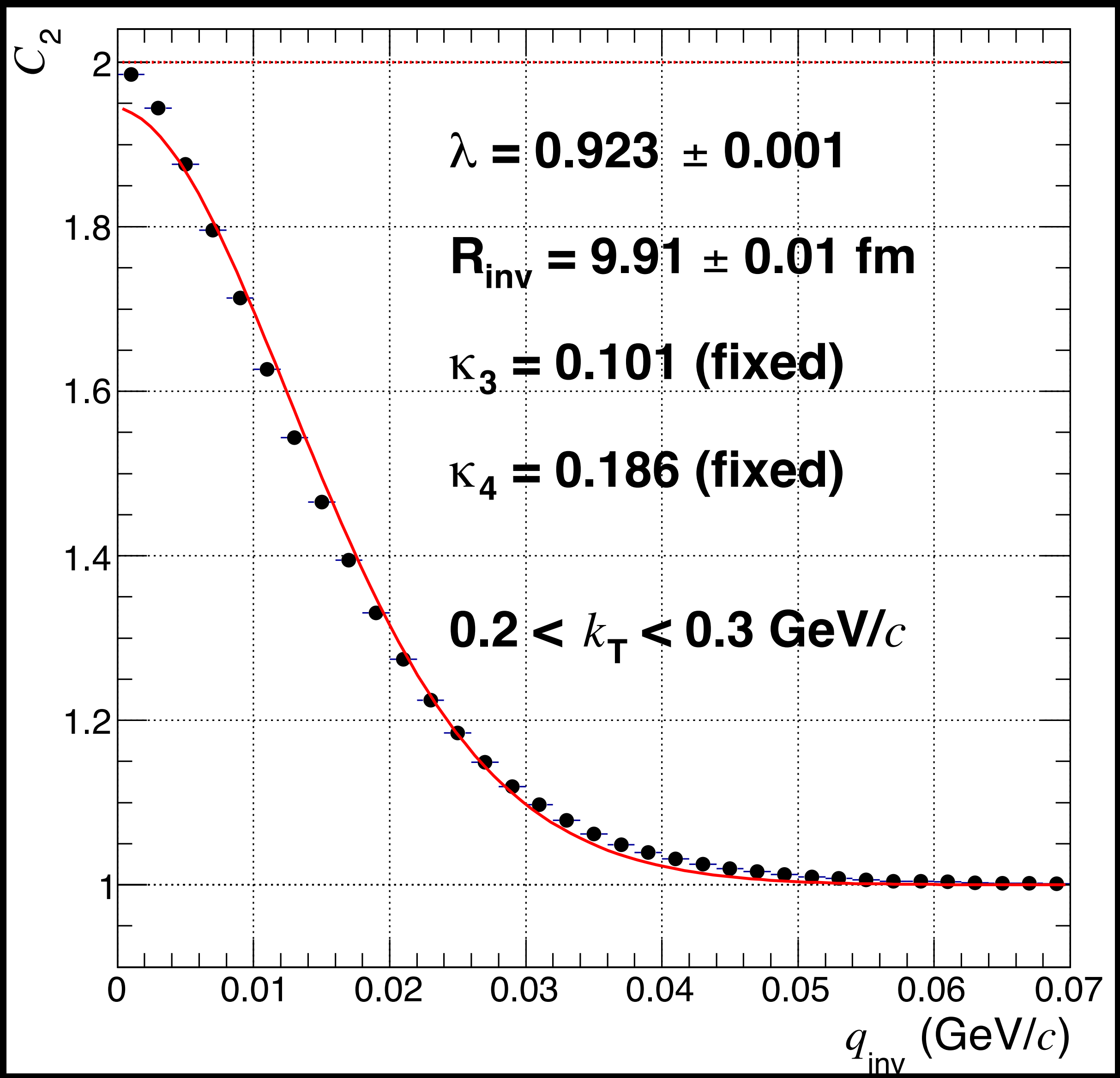
Gaussian fits in red.

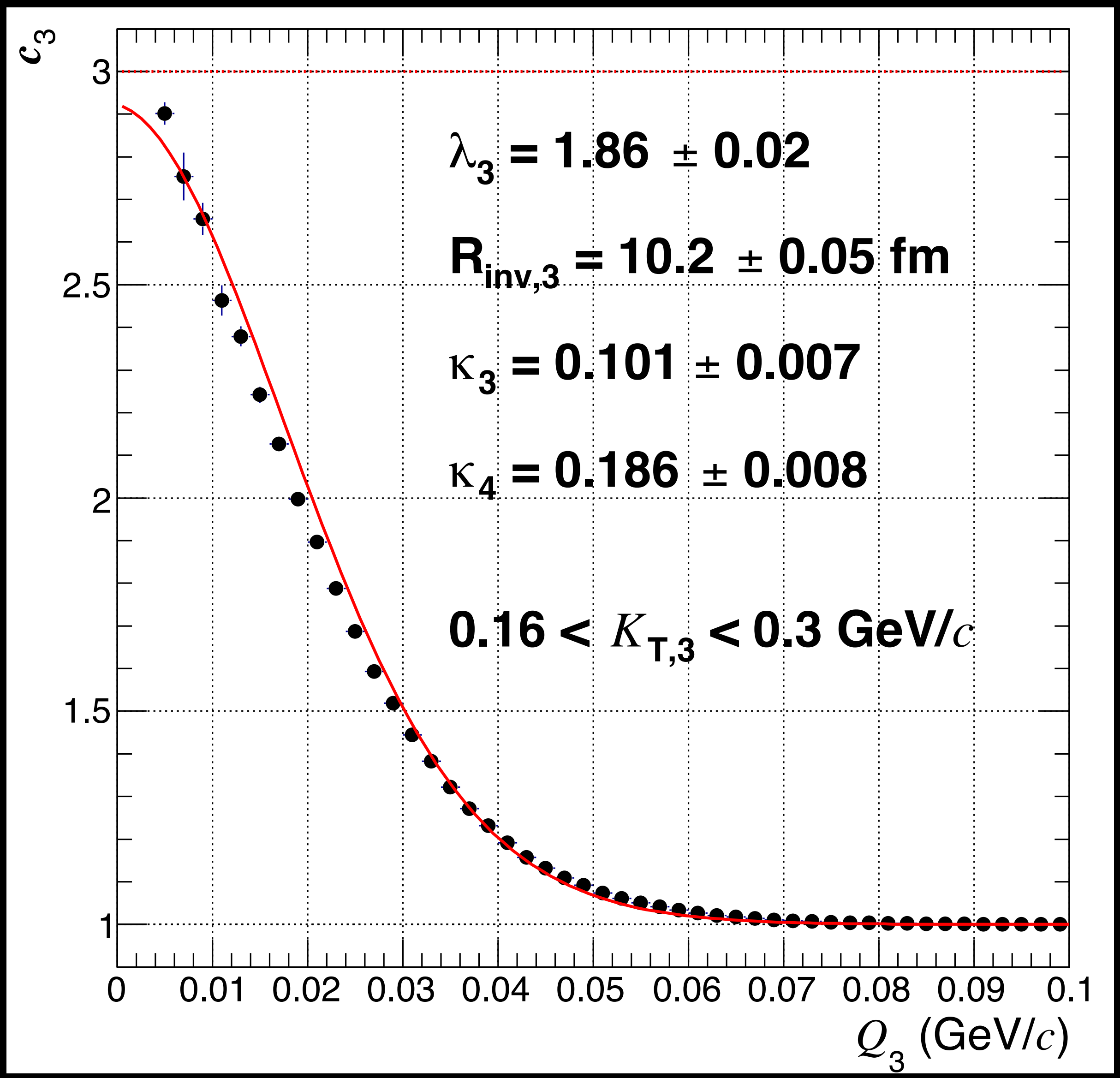
$R_{inv,3}$ smaller than R_{inv} by ~0.6 fm (6%).

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

Therminator2
0-5% Pb-Pb

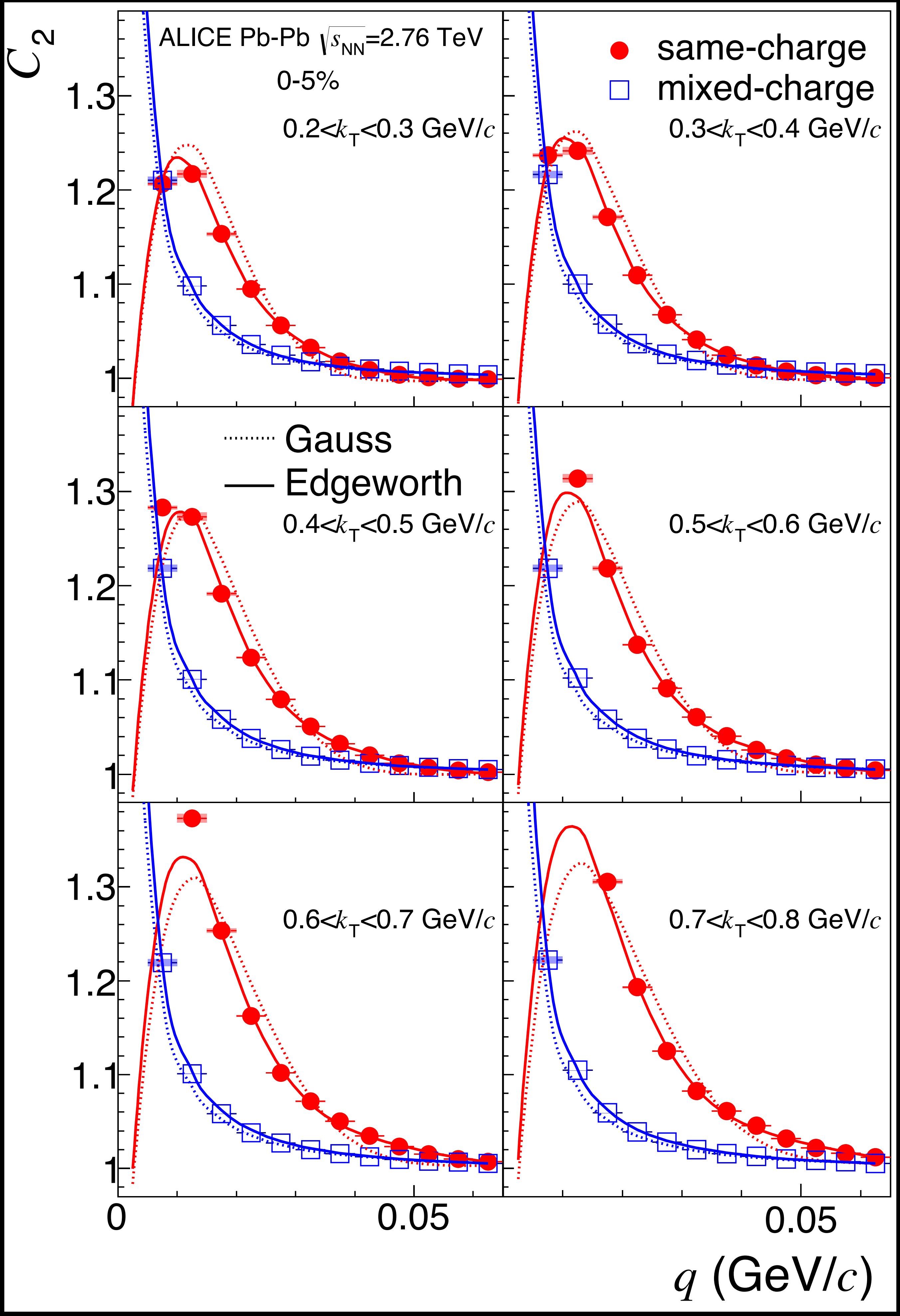




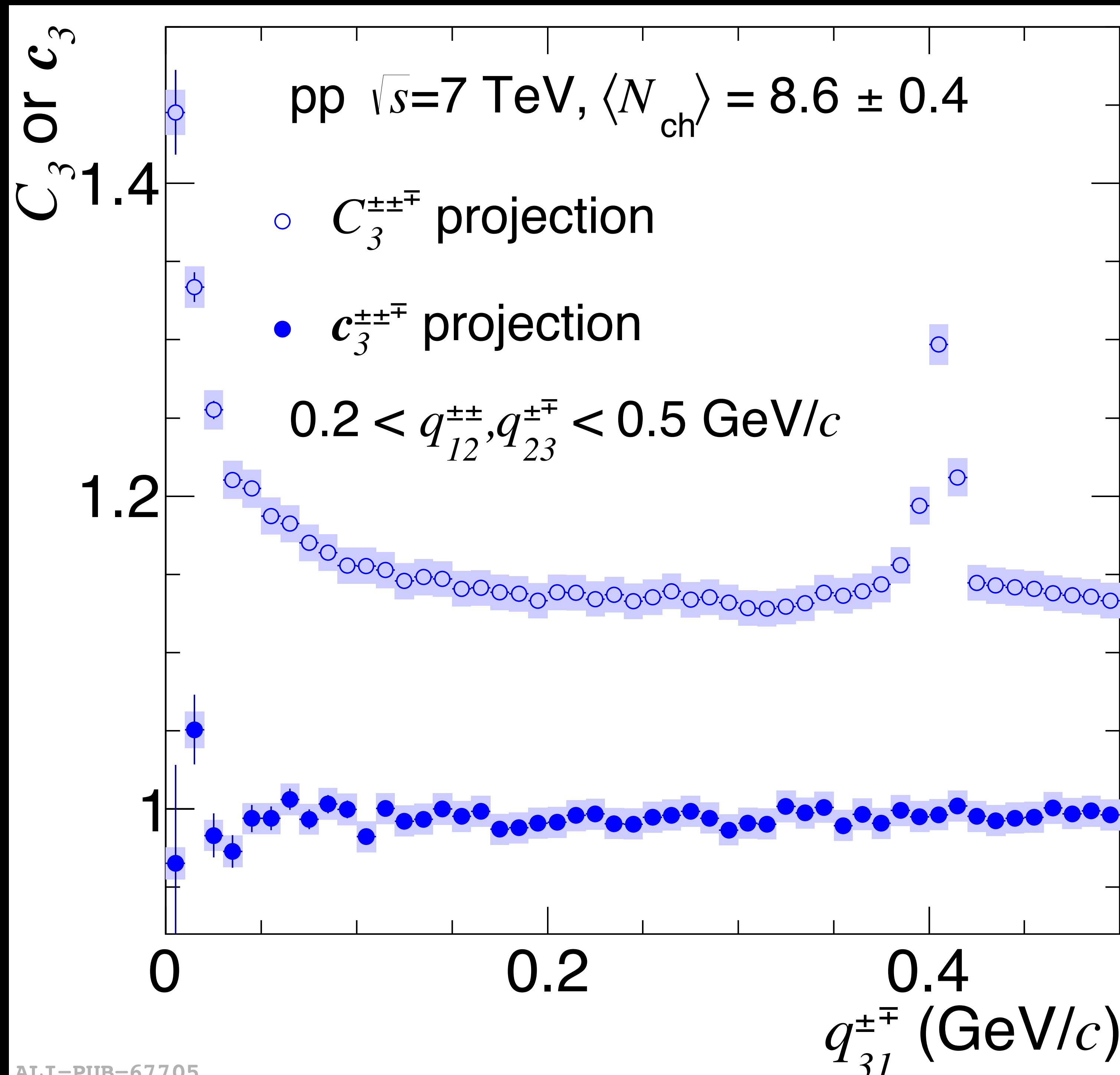
Edgeworth fits in red.

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

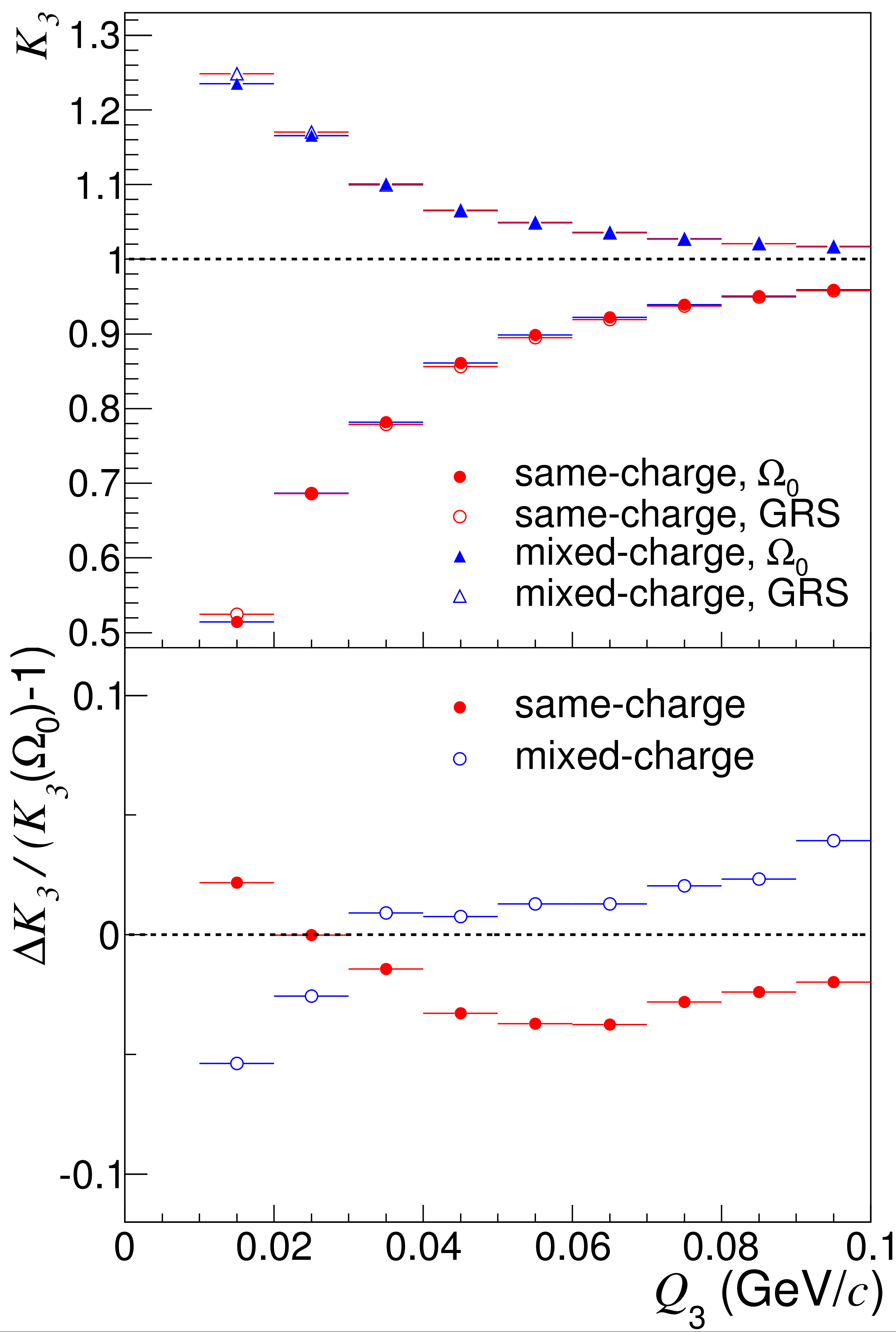
Therminator 2 (0-5% Pb-Pb)
Kisiel et al., Comput. Phys. Commun. 174, 669 (2006)
P. Bozek Phys. Rev. C 77, 034911 (2008)



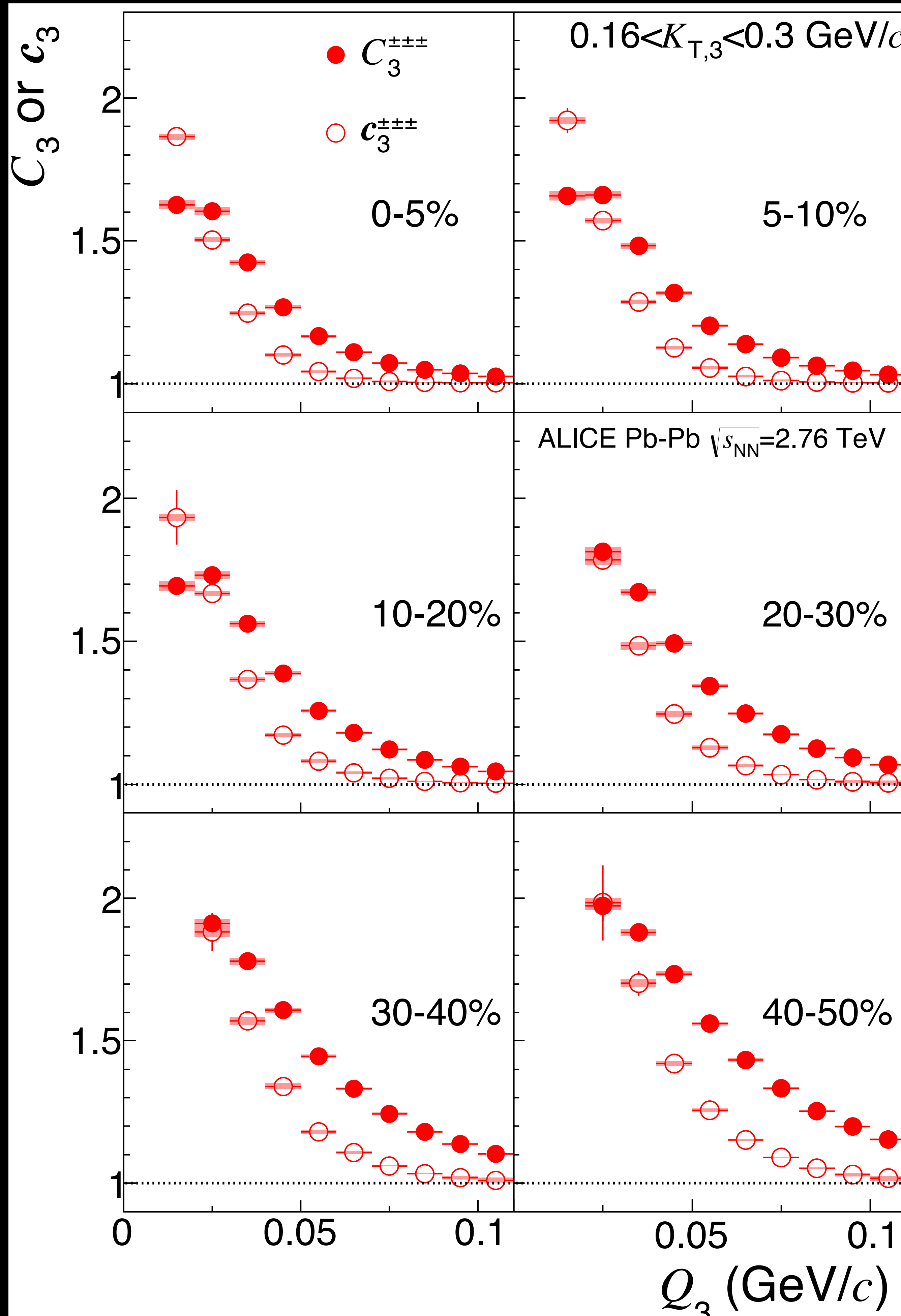
C_2
ALICE Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
0-5%
same-charge
mixed-charge
Gauss
Edgeworth
0.2<k_T<0.3 GeV/c
0.3<k_T<0.4 GeV/c
0.4<k_T<0.5 GeV/c
0.5<k_T<0.6 GeV/c
0.6<k_T<0.7 GeV/c
0.7<k_T<0.8 GeV/c
1.3
1.2
1.1
1
0
0.05
q (GeV/c)



pp √s=7 TeV, ⟨N ch⟩ = 8.6 ± 0.4
C3±±∓ projection
c3±±∓ projection
0.2 < q12±±,q23±∓ < 0.5 GeV/c
C3 or c3
1.4
1.2
1
0
0.2
0.4
q31±∓ (GeV/c)
ALI-PUB-67705

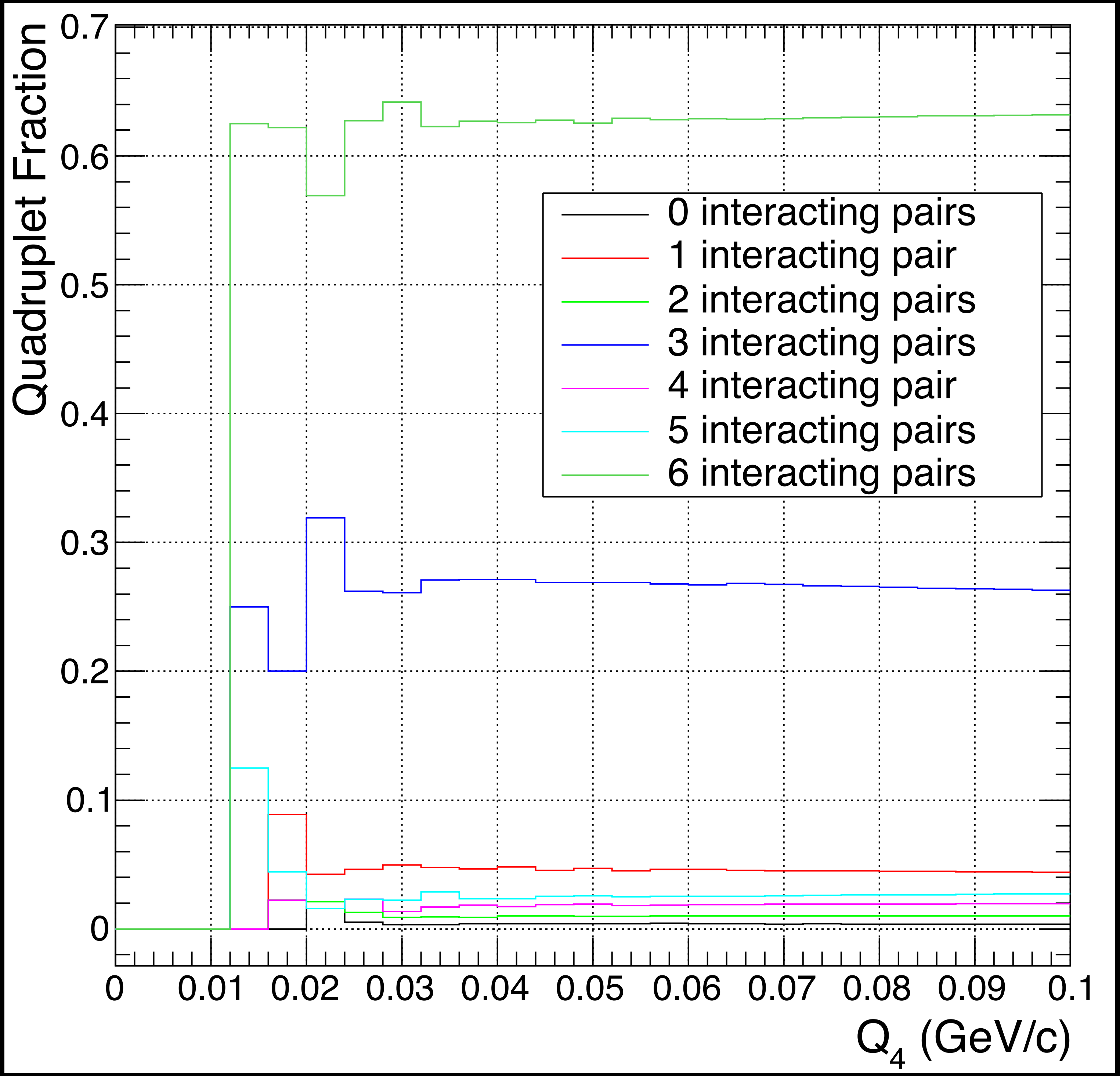


K_3
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
same-charge, Ω_0
same-charge, GRS
mixed-charge, Ω_0
mixed-charge, GRS
$\Delta K_3 / (K_3(\Omega_0)-1)$
0.1
0
-0.1
same-charge
mixed-charge
0
0.02
0.04
0.06
0.08
0.1
Q_3 (GeV/c)



C_3 or c_3
$C_3^{\pm\pm\pm}$
$c_3^{\pm\pm\pm}$
0.16<$K_{T,3}$<0.3 GeV/c
0-5%
5-10%
ALICE Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
10-20%
20-30%
30-40%
40-50%
Q_3 (GeV/c)

Quadruplet Fractions in Therminator



r_3 in Therminator