Neutral kaon femtoscopic correlations in Pb-Pb collisions with ALICE at the LHC

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Outline

- Motivation
- Theory: $K^0_S K^0_S$ correlation function
- Analysis details
- Results
- Summary

Motivation for K^0_S femtoscopy

Femtoscopy

- Spatial & temporal characteristics of the particle emission
- Collective motion; particle freeze-out
- Constraints on system evolution models,
  e.g. time-scales and scattering amplitudes

Kaons: complement to $\pi\pi$

- Extend k_T and m_T range
- Check for common ("universal") m_T-scaling
- Smaller feed-down contribution

K^0_S and K^{ch}

- Consistency check: different analysis methods
  - Charged tracks vs. vertex reconstruction
  - Final state interactions (FSI): Coulomb(-dominated) vs. strong

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$K^0_S K^0_S$ system

Weak eigenstates:

$$\left|K^0_{S,L}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle \pm \left|\bar{K}^0\right\rangle\right)$$

Two-kaon state:

$$\left|K^0_S K^0_S\right\rangle \sim \left|K^0 K^0\right\rangle + \left|\bar{K}^0 \bar{K}^0\right\rangle + \left|K^0 \bar{K}^0\right\rangle + \left|\bar{K}^0 K^0\right\rangle$$

✔ Symmetrized
- identical bosons

✗ Strong FSI
- scattering length ~ 0.1 fm

✔ Symmetrized
- CP=+1 state of boson-antiboson pair

✔ Strong FSI
- scattering length ~ 1.0 fm
-- f_0(980), a_0(980)

Femtoscopic correlation functions: QS + FSI

"quantum statistics"

Koonin-Pratt: $$C(\vec{q}) = \int S(\vec{r}) |\psi(\vec{q},\vec{r})|^2 d^3 r$$

Identical non-interacting bosons
$$\psi_{sym} = \frac{1}{\sqrt{2}} \left(e^{-i\vec{k}\cdot\vec{r}} + e^{i\vec{k}\cdot\vec{r}} \right) \qquad \vec{k} = \vec{p}_{PRF} = \frac{1}{2}\vec{q}_{PRF}$$

$$|\psi_{sym}|^2 = 1 + \cos(2\vec{k}\cdot\vec{r}) \longrightarrow C(\vec{q}) = 1 + e^{-q_i^2 R_i^2 - \ldots}$$

Bosons interacting with strong interaction
$$\psi_{FSI} = e^{-i\vec{k}\cdot\vec{r}} + f(k)\frac{e^{-ikr}}{r}$$

Symmetrized bosons w/ strong interaction
$$\psi_{sym,FSI} = \frac{1}{\sqrt{2}} \left(e^{-i\vec{k}\cdot\vec{r}} + e^{i\vec{k}\cdot\vec{r}} + 2 f(k) \frac{e^{ikr}}{r} \right)$$

$$|\psi_{sym,FSI}|^2 = 1 + \cos(2\vec{k}\cdot\vec{r}) + 2\frac{|f(k)|^2}{r^2} + 2\cos\vec{k}\cdot\vec{r}\left(f(k)\frac{e^{ikr}}{r} + f^*(k)\frac{e^{-ikr}}{r} \right)$$

Studying the theoretical $K^0_S K^0_S$ correlation function

$$C_{K^0_S K^0_S} = \frac{1}{2}\left(C_{K^0 K^0} + C_{K^0 \bar{K}^0}\right)$$

$$C(q) = \int S(r)\,|\psi(q,r)|^2\, dr$$

$$S(r) \sim e^{-r_o^2/4R_o^2 - r_s^2/4R_s^2 - r_l^2/4R_l^2}$$

$$|\psi_{K^0 K^0}|^2 = |\psi_{sym}|^2 = 1 + \cos(2\vec{k}\cdot\vec{r})$$

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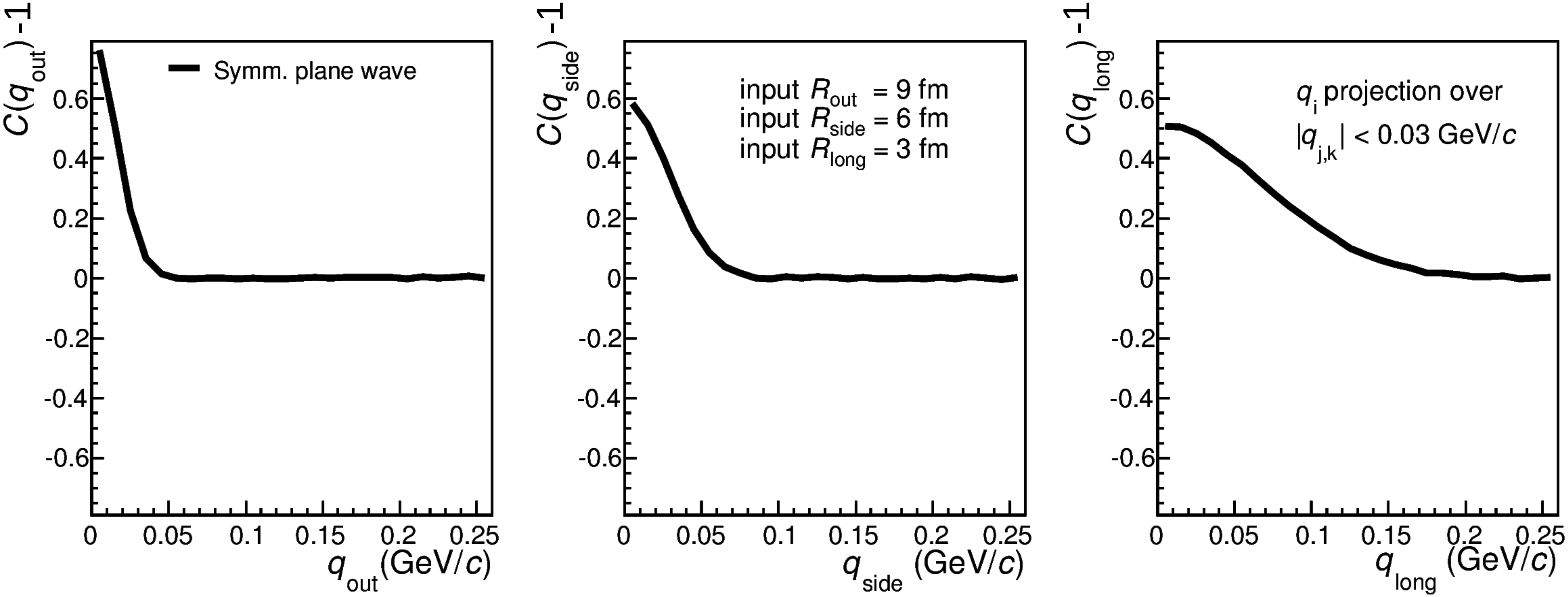

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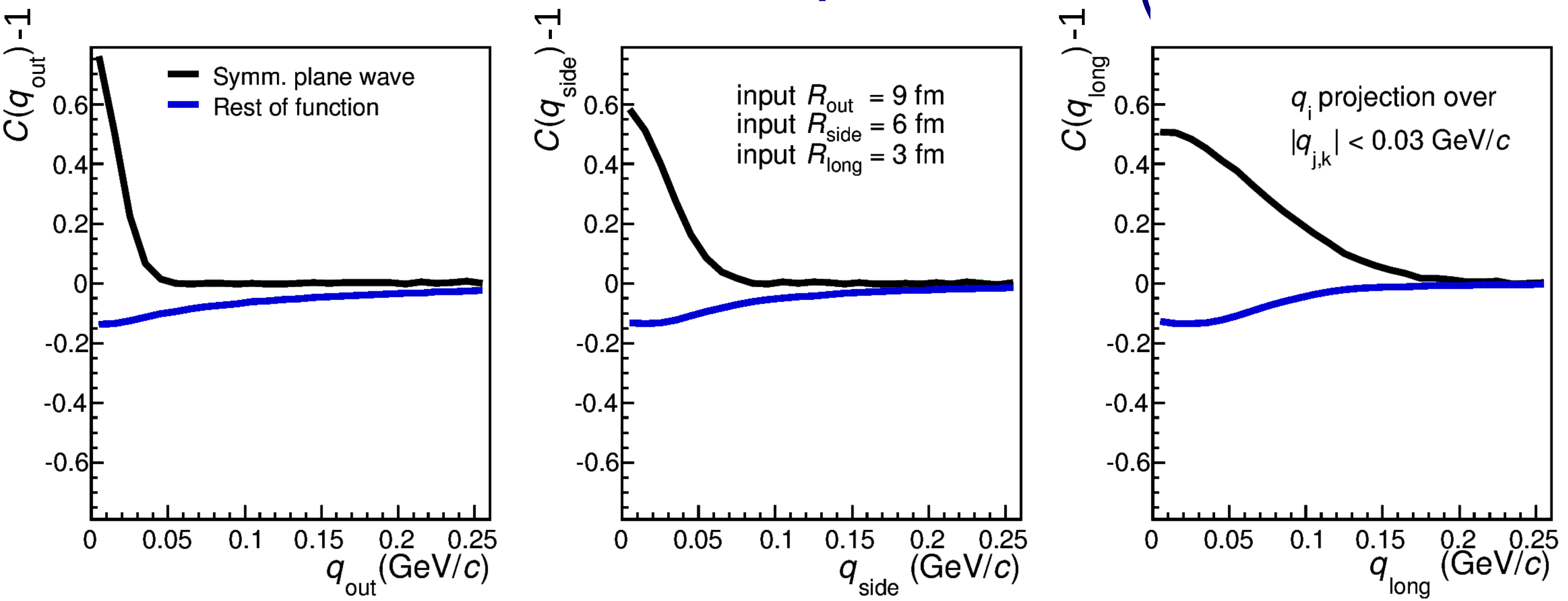

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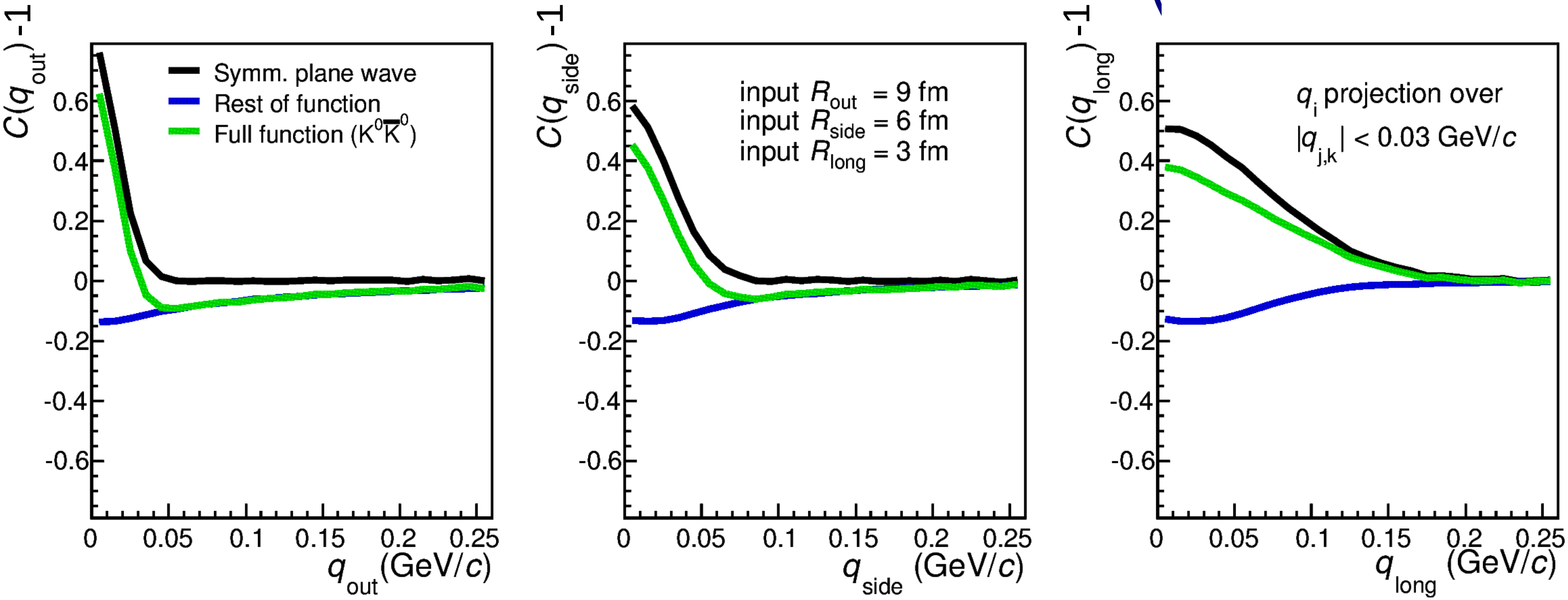

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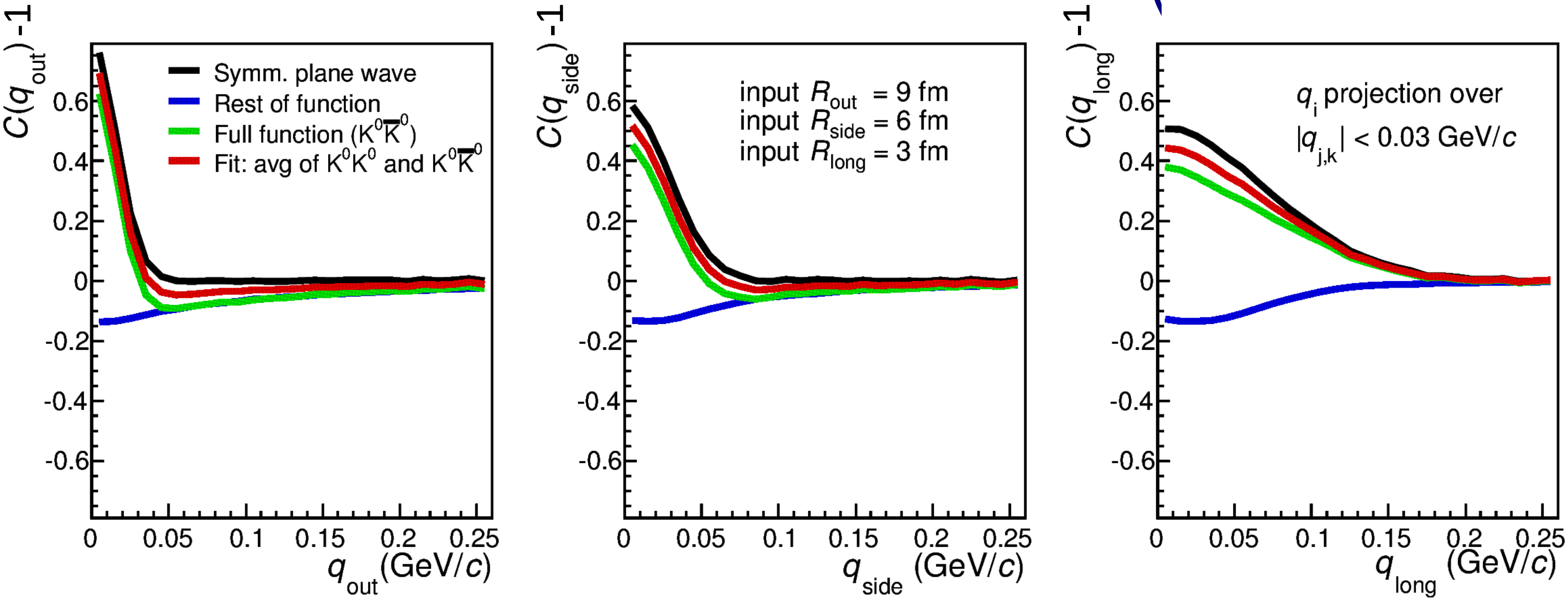

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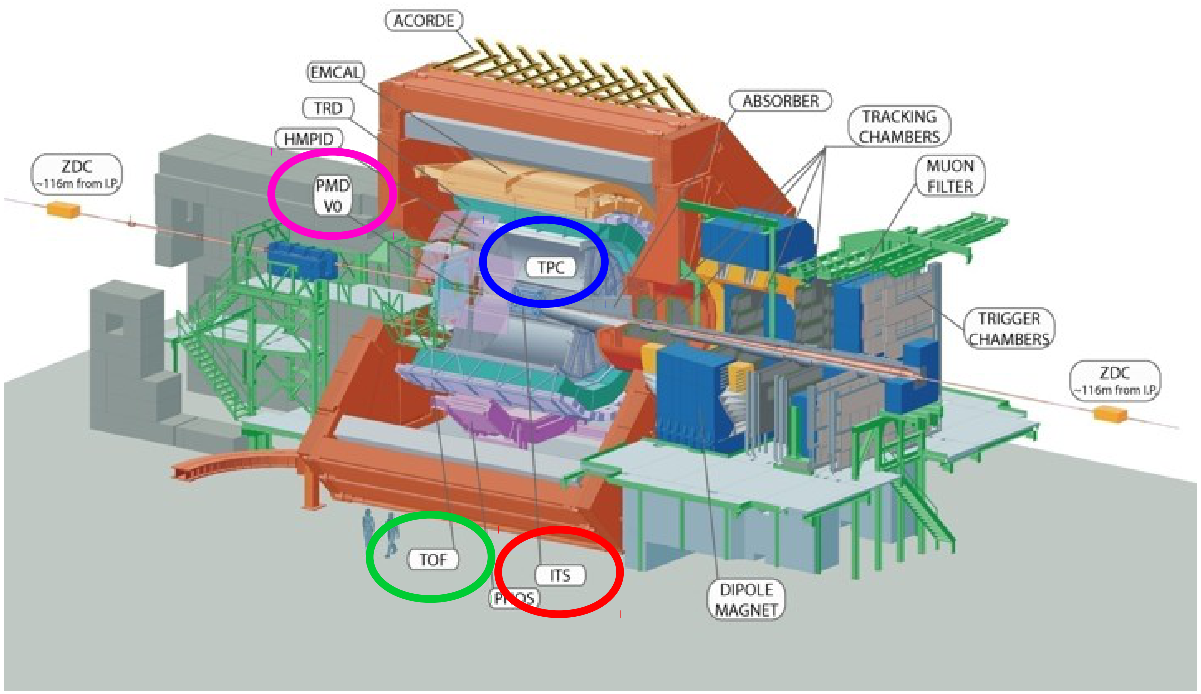
ALICE detector



Tracking and vertexing
- Time Projection Chamber (TPC) & Inner Tracking System (ITS)

Particle identification
- TPC & Time-of-Flight (TOF)

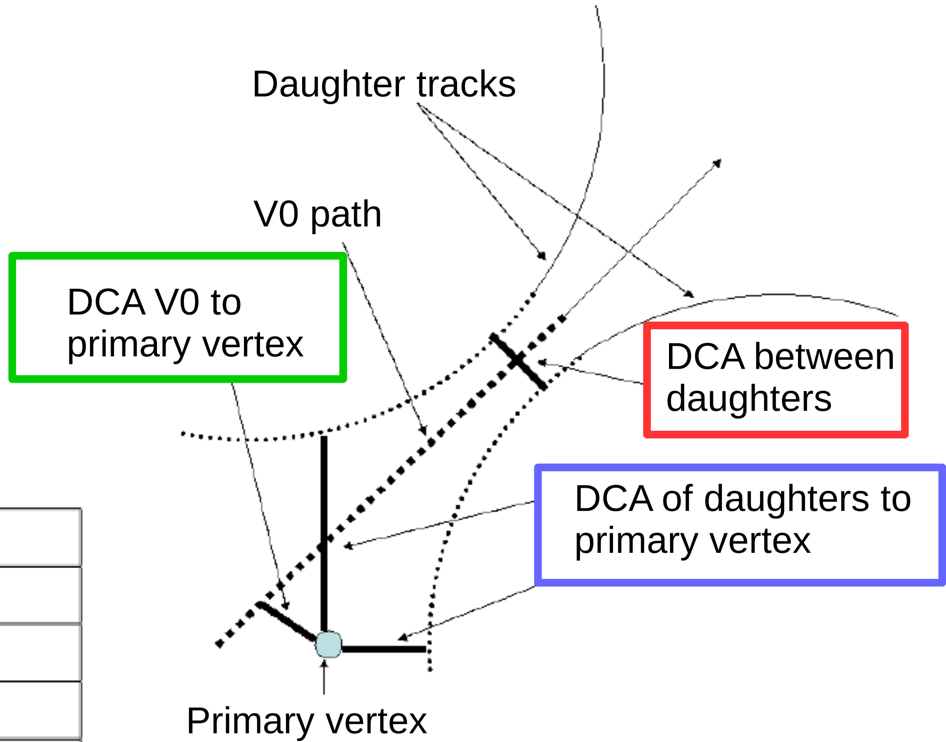
Centrality determination
- V0

Data collection
- 2010 & 2011
- 0-10%: 14M events
- 10-50%: 16M events

K^0_S reconstruction

$$K^0_S \rightarrow \pi^+ \pi^-$$

- $c\tau$ = 2.7 cm (15 m for K^0_L)
- branching ratio ≈ 70%



Pion (daughter) cuts	
p_T	> 0.15 GeV/c
$\lvert\eta\rvert$	< 0.8
DCA to primary vertex	> 0.4 cm
TPC PID of σ	< 3
TOF PID of σ (for $p > 0.8$ GeV/c)	< 3
K^0_S cuts	
$\lvert\eta\rvert$	< 0.8
$\pi^+ \pi^-$ DCA	< 0.3 cm
DCA to primary vertex	< 0.3 cm
decay length	< 30 cm
cosine of pointing angle	> 0.99
invariant mass	$.480 < m < .515$ GeV/c^2

- $$\frac{\text{Sig.}}{\text{Sig.+Bkg.}} \geq 95\%$$
- $$\left\langle N_{K^0_S} \right\rangle \approx 9$$

Experimental method & fitting procedure

$$C_{\exp}(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

same event pairs ("physics" + combinatorics)

mixed event pairs (combinatorics)

- **Mixing event classes**
  - centrality: 5%
  - primary vertex position (z): 2 cm
- **Normalized to "high-q" region**
- **Corrected for momentum resolution**

Fit: MC emission simulation + weight calculation

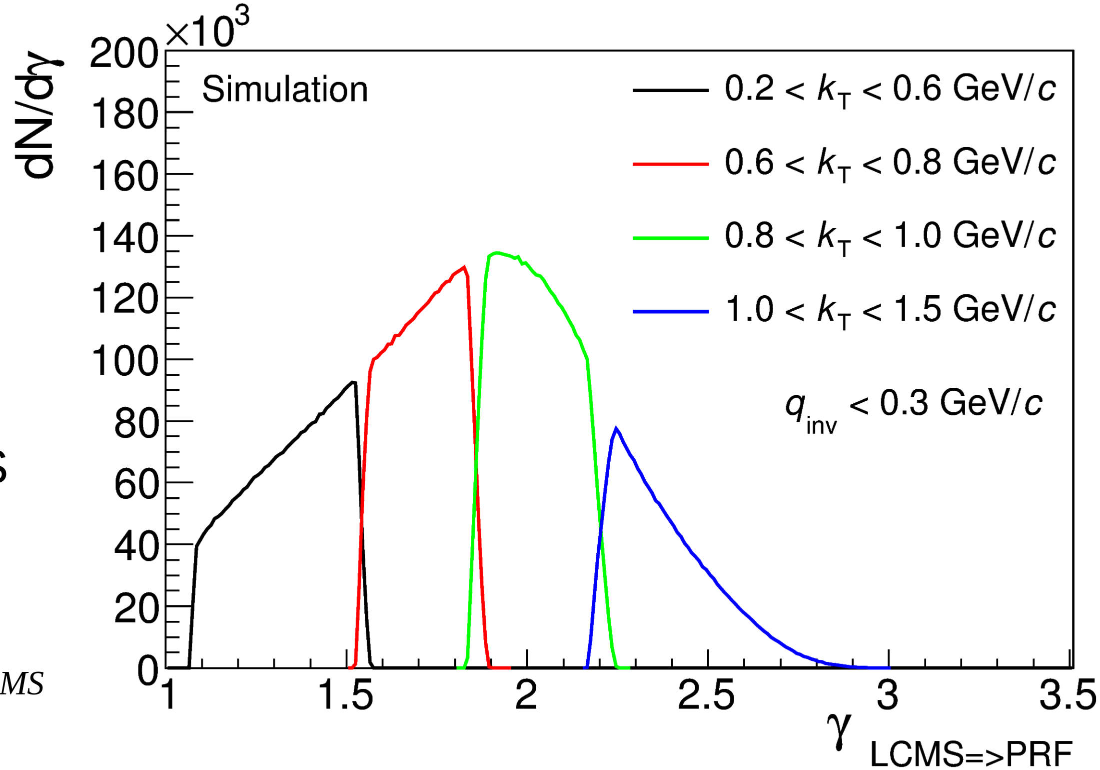
- MC $\vec{p}$ (data) and $\vec{x}$ (3D Gaussian)
- calculate $|\psi|^2$ weight

$$C_{theory}(\vec{q}) = \frac{A(\vec{q}, |\psi|^2)}{B(\vec{q}, 1)}$$

- both done in PRF; boost R_{out} to LCMS

$$R_{out,PRF} = \gamma\, R_{out,LCMS}$$

$$\gamma = \frac{1}{\sqrt{(1-\beta^2)}} \qquad \beta = \frac{p_{1,out} + p_{2,out}}{E_1 + E_2}\Big|_{LCMS}$$



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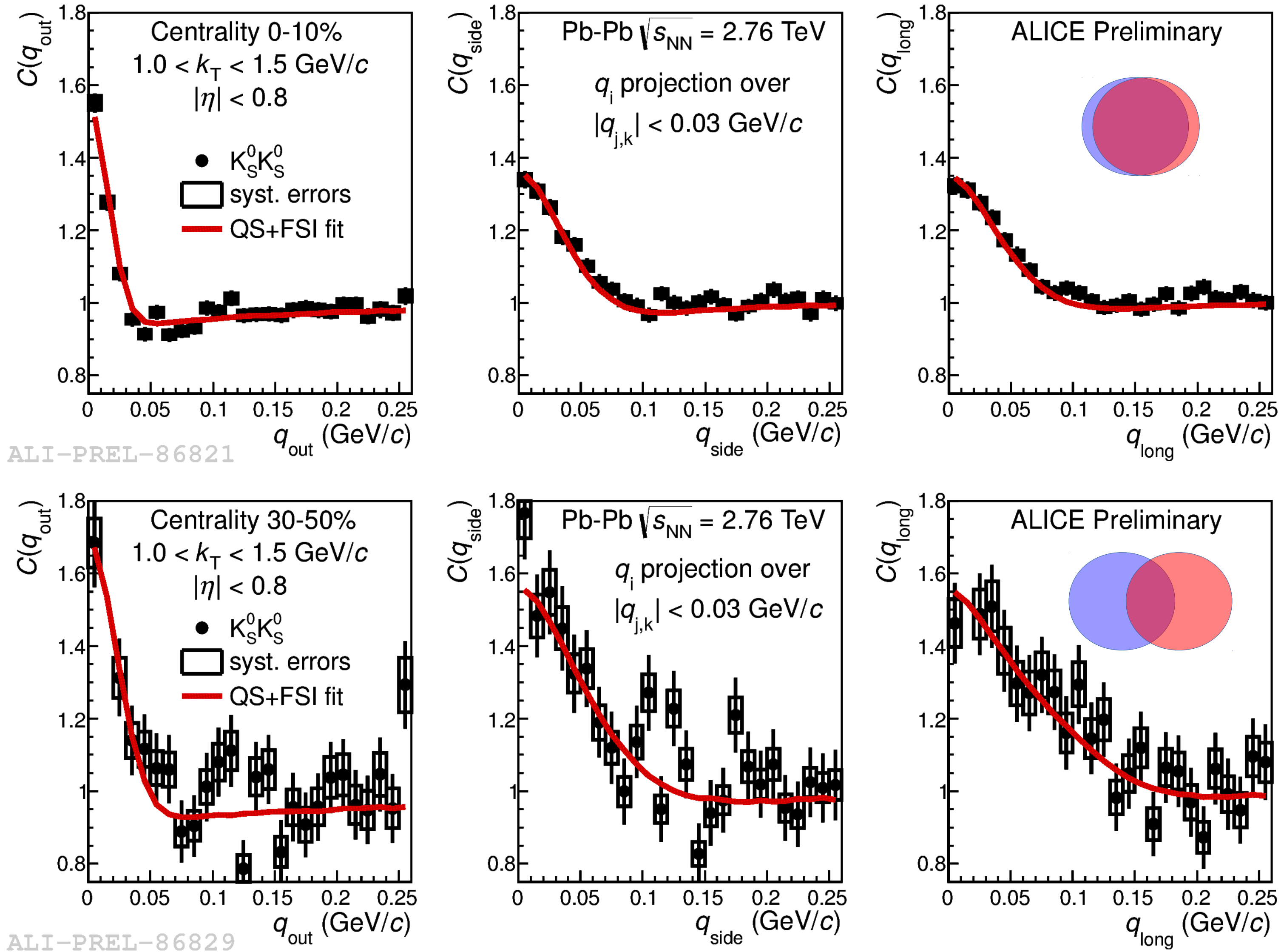
$K^0_S K^0_S$ femtoscopic correlation functions

3D correlation projected onto: q_{out} q_{side} q_{long}

Features:

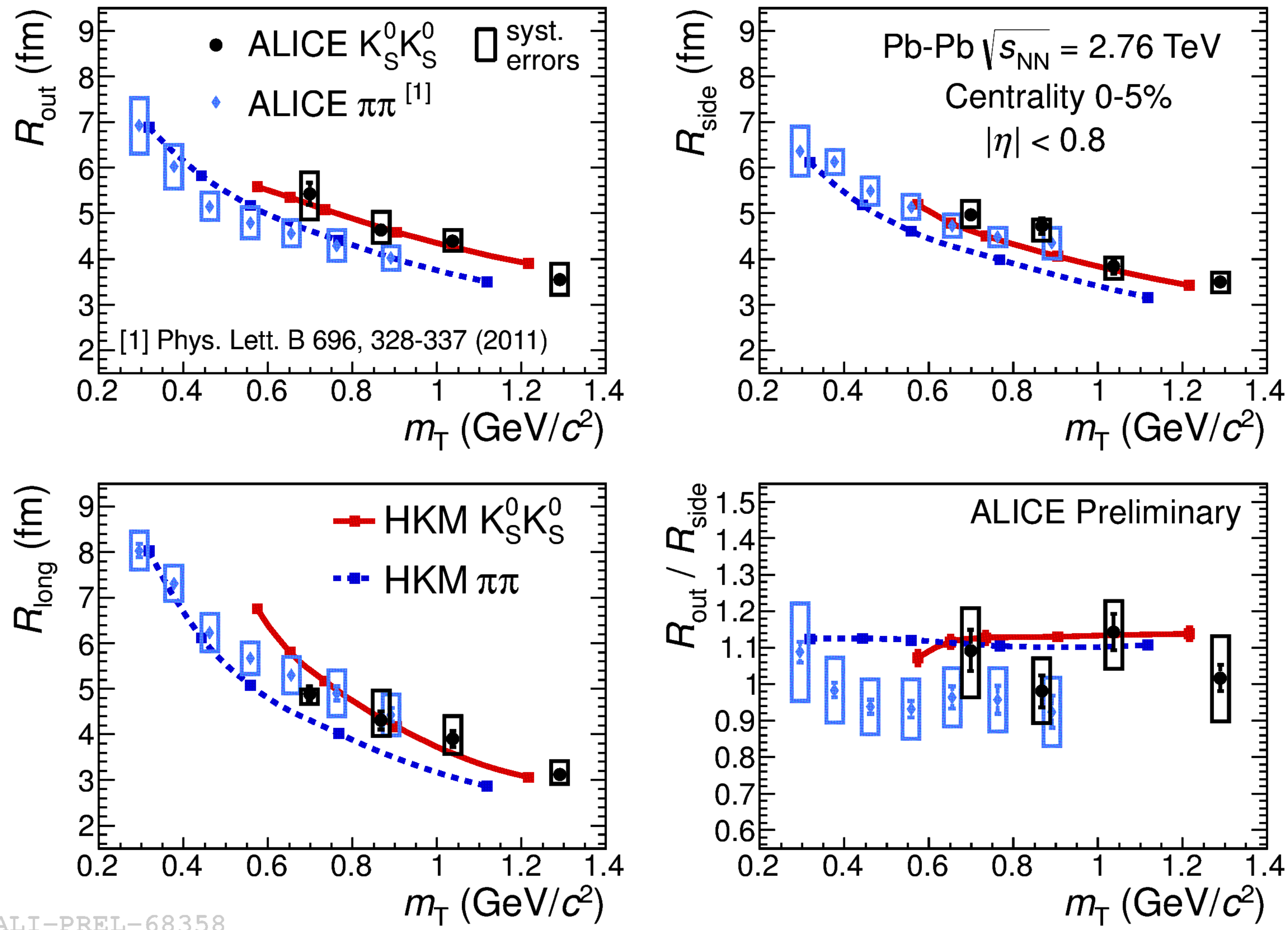
- Bose-Einstein enhancement
- FSI presence seen in dip below C = 1
- Flat background at large q

Pure Gaussian fit gives 10-40% larger radius



LCMS radii vs m_T: central collisions

shown with ALICE ππ and HKM† predictions



Kaon radii decrease with increasing m_T

- effect of collective flow

Kaon values match HKM predictions

Comparison with pions

- consistent for R_{side}, R_{long}
- no common scaling for R_{out}

R_{out}/R_{side} ratio

- flat, consistent with unity
- consistent with pions

† arXiv:1404.4501 [hep-ph]

LCMS Radii: centrality dependence, with $\pi\pi$

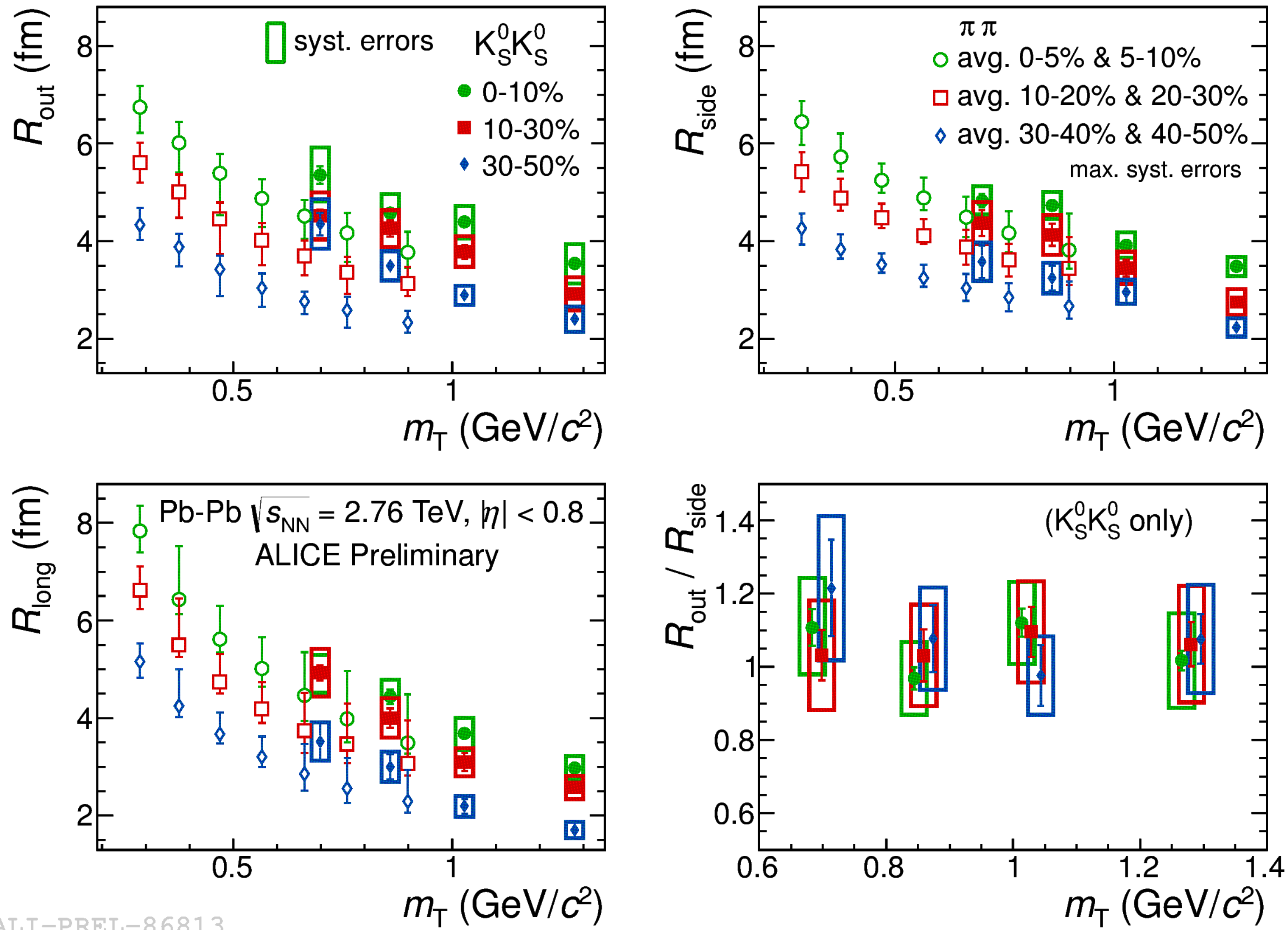
pion points averaged from smaller centrality bins (see plot legend)

Radii decrease for more peripheral collisions

- reflects change in system size

Comparison with pions

- roughly consistent for R_{side}, R_{long}
- no common scaling for R_{out}; kaons significantly larger



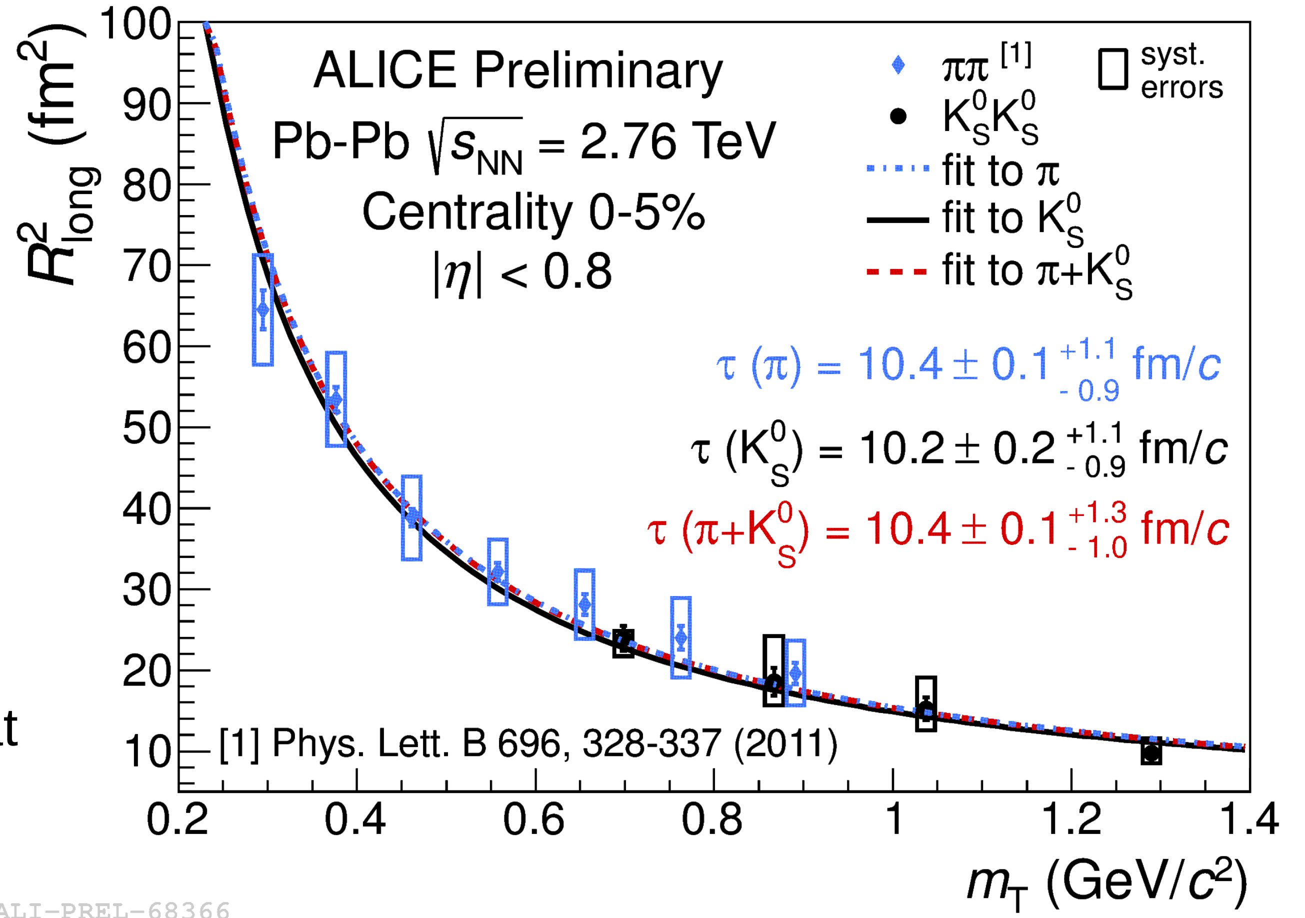
R_{out}/R_{side} ratio

- consistent with 1.0
- no dependence on centrality or m_T

R^2_{long} vs m_T: Freeze-out time

$$R^2_{long}(m_T) = \tau_f^2 \frac{T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}$$

A. N. Makhlin, Y. M. Sinyukov (1988)
M. Herrmann, G. F. Bertsch (1995)



τ_f = freeze-out proper time

- time of last interaction

Assumes a thermal emission at T = 120 MeV

Kaon emission time ~ 10 fm/*c*

Consistent with pions

Lambda parameter

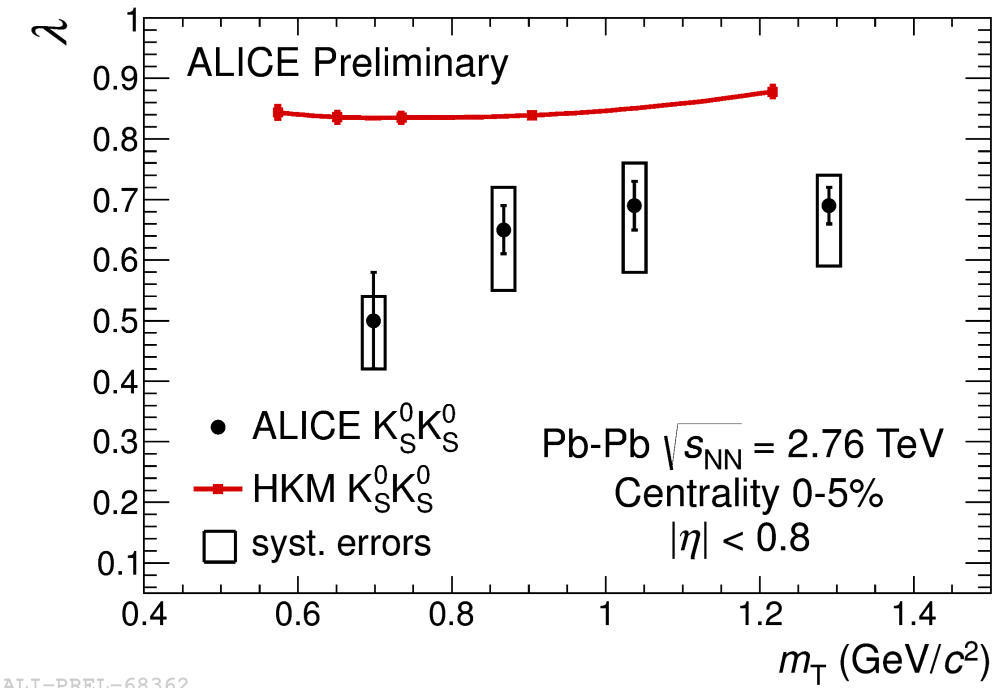
$$C_{fit}(\vec{q}) = N\left(1 - \lambda + \lambda C_{theory}(\vec{q})\right)$$

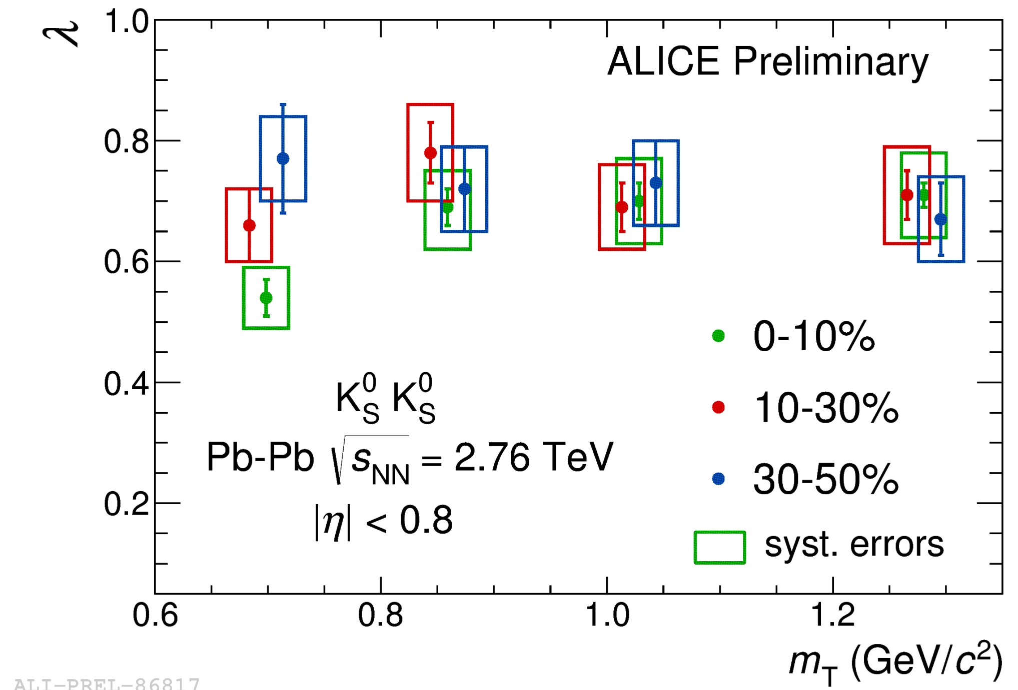
Factors that can affect *λ*:

- Pair purity (~90%)
- Decay products (direct kaons ~60%)
- Non-gaussian source
- Coherent emission

Results:

- λ ~0.7
  - consistent with Therminator predictions (including K* decays)
- no strong dependence on centrality or m_T
- ~20% below HKM predictions





Summary

First presentation of 3D analysis of $K^0_S K^0_S$ femtoscopic correlations for several centrality and m_T bins

Theoretical model using combination of quantum statistics and FSI necessary to fit the data

$K^0_S K^0_S$ LCMS radii show:

- decrease with increasing $m_{T,}$ with decreasing system size
- very good agreement with HKM predictions in central collisions
- “universal” m_T-scaling with pions?
  - consistent for R_{side}, R_{long}
  - significantly broken for R_{out} (all centralities)

Freeze-out time in central collisions extracted from R^2_{long} vs. m_T

- ~10 fm/c, consistent with pions

Lambda parameter ~0.7; no strong trends with centrality or m_T; 20% below HKM predictions for central collisions

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THANK YOU FOR YOUR ATTENTION!

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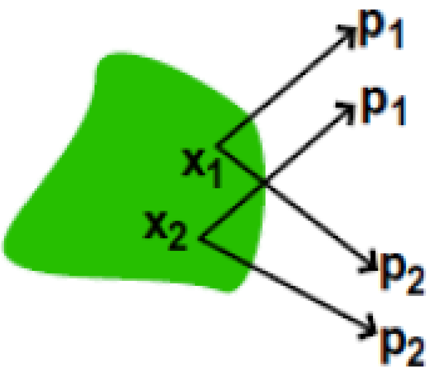
BACKUP SLIDES

Introduction

- Final state momenta <-> emission space-time information
- Relative momentum correlation functions
- Bose-Einstein enhancement
- Final state interactions (FSI)



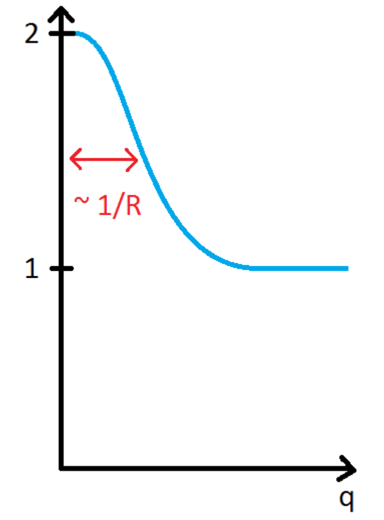
$$C_{\vec{k}}(\vec{q}) = \int S_{\vec{k}}(\vec{r}) |\psi(\vec{q}, \vec{r})|^2 dr$$

- 3D Gaussian source
- non-interacting bosons

$$C_{\vec{k}}(\vec{q}) = 1 + e^{-q_x^2 R_{x,\vec{k}}^2 - q_y^2 R_{y,\vec{k}}^2 - q_z^2 R_{z,\vec{k}}^2}$$

- *k*-dependence of correlation/radii
- “regions of homogeneity”

$$\vec{r} = \vec{x}_1 - \vec{x}_2$$
$$\vec{q} = \vec{p}_1 - \vec{p}_2$$
$$\vec{k} = \frac{\vec{p}_1 + \vec{p}_2}{2}$$



Motivations: universal m_T-scaling

Do different particle species flow and/or freeze-out together?

"m_T-scaling" of femtoscopic radii

$$R \sim m_T^{-\alpha} \qquad m_T = \sqrt{m^2 + p_T^2}$$

- longitudinal: boost invariance; affected by transverse flow
- transverse: generated by transverse flow
- Hydrodynamic picture suggests universal scaling independent of particle species

Common freezeout <=> common scaling

- flow-dominated freeze-out?
- or, are individual cross-sections important?

Remarks on lambda parameter - Purity

Results: Lambda parameter ~0.7

Therminator gives the following *sources* of K^0
- 60% direct
- 25% K* (semi long-lived, $c\tau$ ~4 fm)
- 5% phi (long-lived, $c\tau$ ~ 50 fm)
- 10% higher mss resonances

Single particle purity ~0.95 ---> pair purity ~0.90

If only direct kaons are correlated: $(0.6*0.95)^2$ = **0.32**
If also include K* products: $(0.85*0.95)^2$ = **0.65**

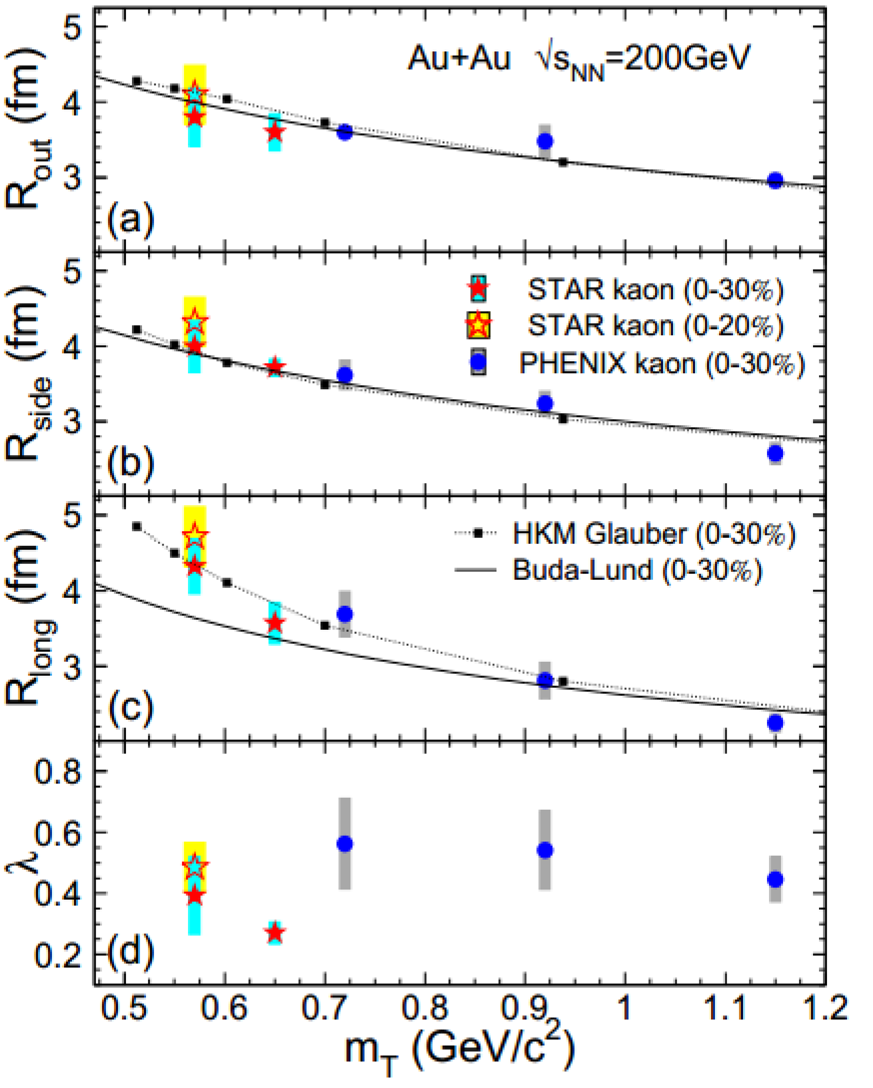
=> extracted lambda parameter is consistent with thermal model predictions based on sample purities

RHIC results for K^{ch}

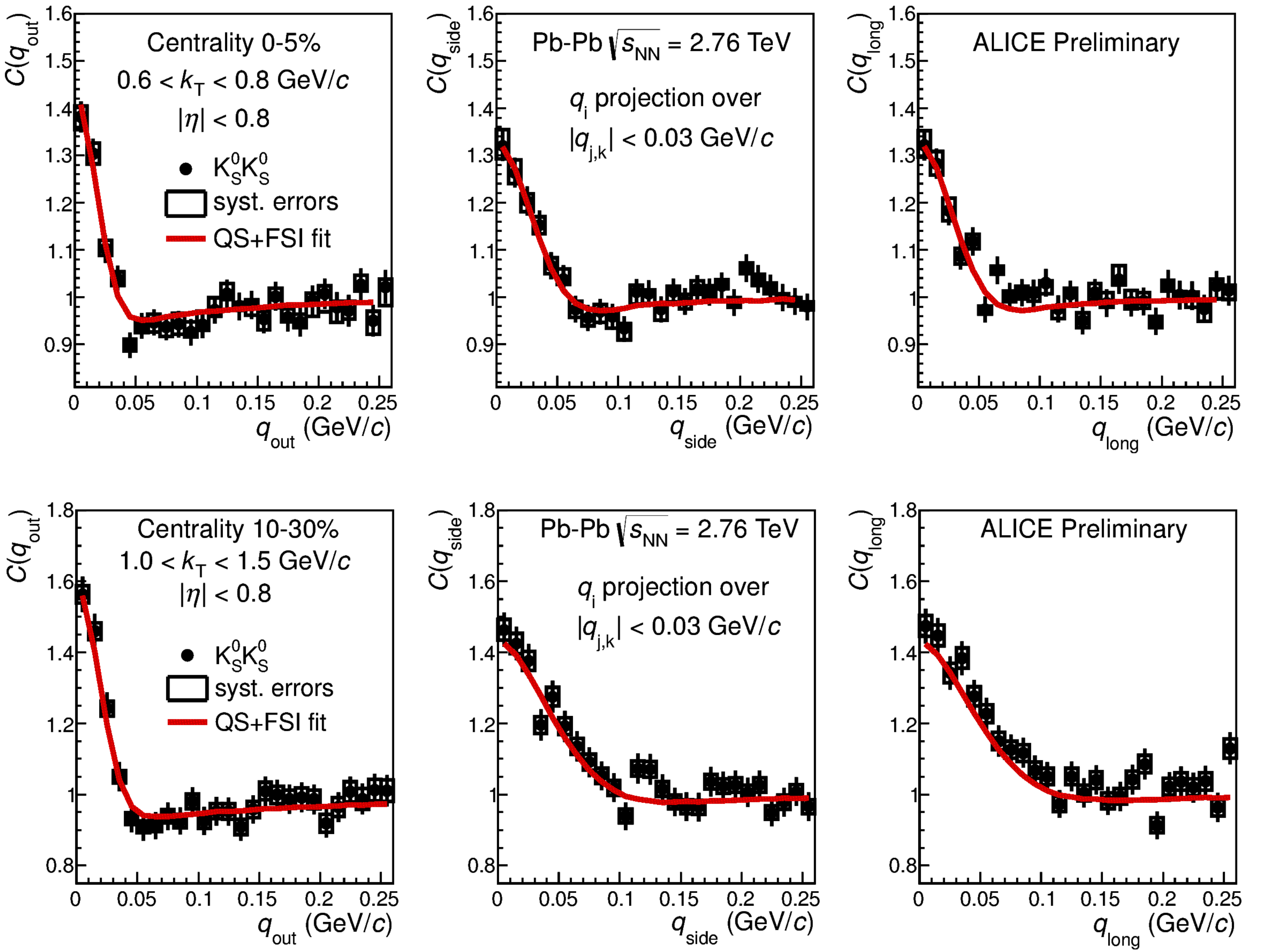
STAR and PHENIX results for "central" collisions (0-20% and 0-30%)

HKM and Buda-Lund predictions are shown
- models are consistent for out, side; HKM larger in long direction

Data follow HKM model when breaking away from pure hydro in long direction



Other projections



Fitting

– radii are input parameters to simulation; 1 billion pairs for every fit iteration
– to expedite process, use grid interpolation method
  - build 4 x 4 x 4 grid of simulated correlation functions
    R_o = [6,7,8,9](fm) $R_{s,l}$ = [2,3,4,5] (fm)
  - use quadratic interpolation between grid points to build $C_{fit}(q;R_{input})$
    - grid method used in 1D proton analysis
– statistical fluctuation: make several grids, take average
– use different FSI model parameters
  - made grids for each model parameter set (4)
  - take average of 12 fits (4 models X 3 grids each)

– fit using log-likelihood method
  - more accurate (than least squares) at low bin occupancy; equal at high
– fit to q_i = 0.25 GeV/c