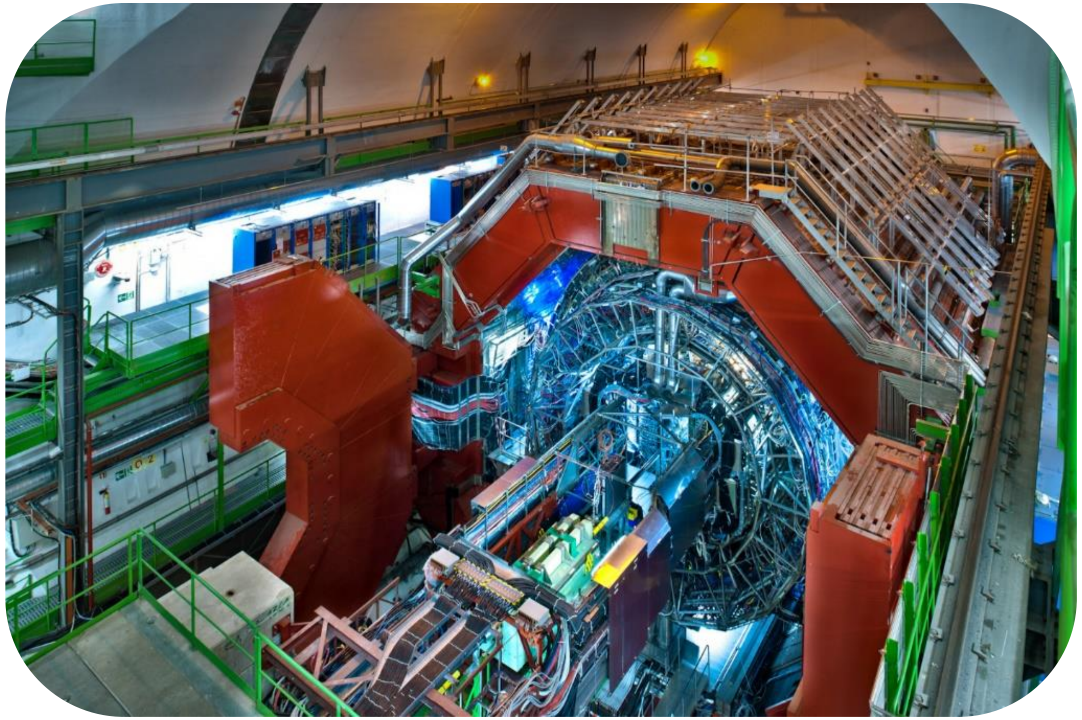
20th Rencontres du Vietnam July 7–13

ICISE

PASCOS 2024

Particle-emitting source dynamics via femtoscopy at the LHC energies with ALICE



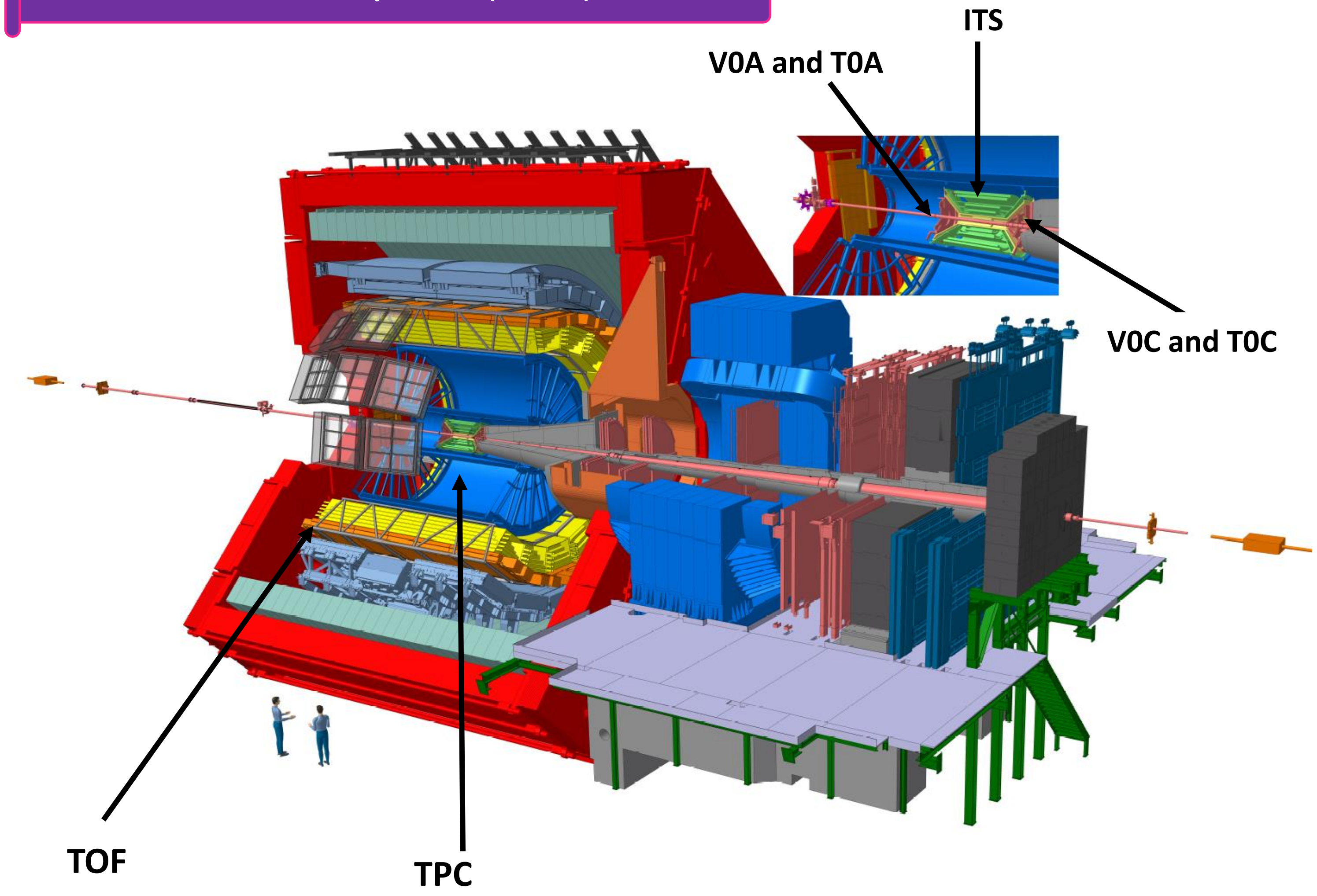
Rogochaya Elena

(JINR, Russia)

for the ALICE Collaboration

ALICE detector

ALICE, Int.J.Mod.Phys.A29(2014)1430044



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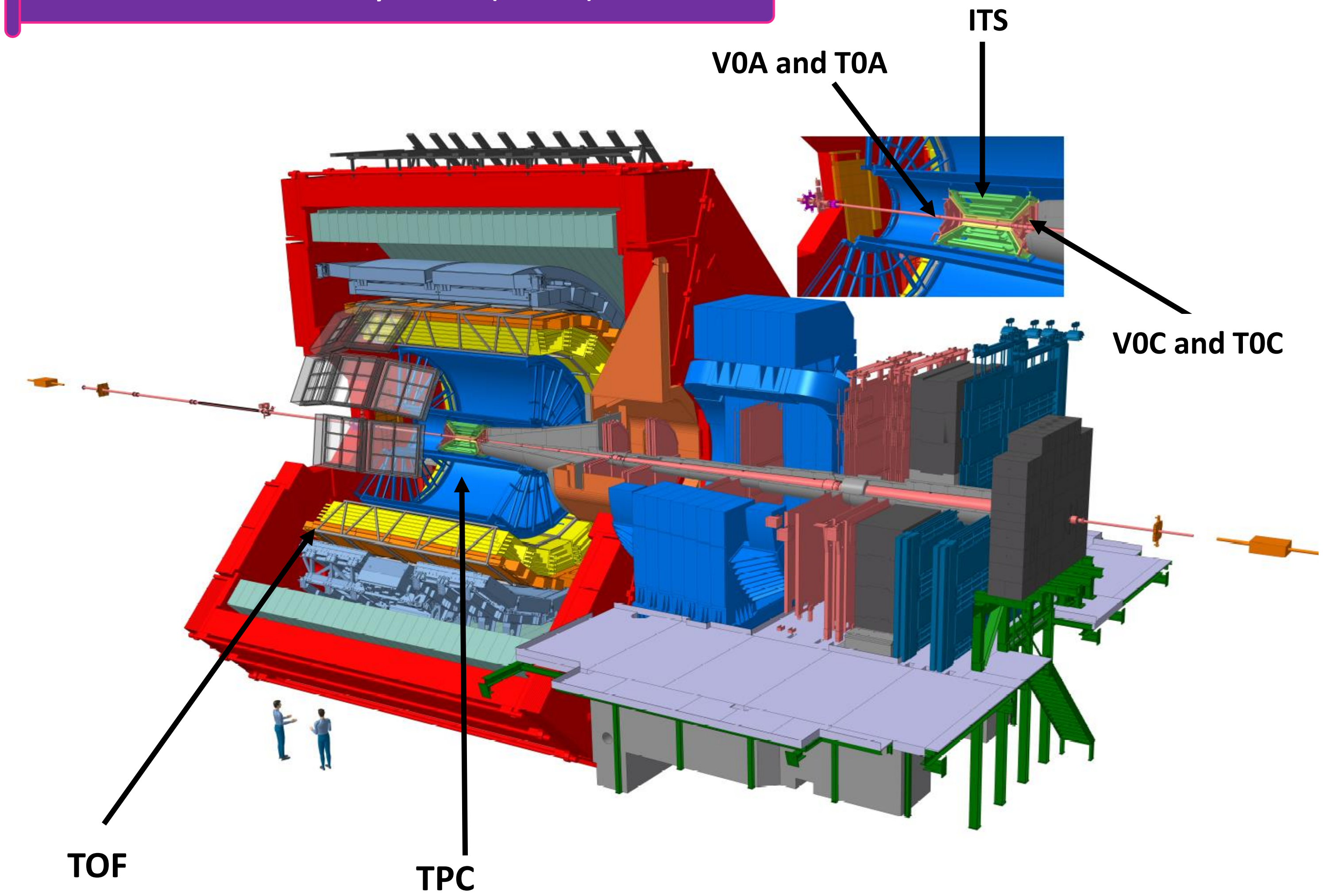

- *Abundant production of strange hadrons at the LHC*
- Good PID and momentum resolution → *good opportunity to study particle correlations in momentum space*

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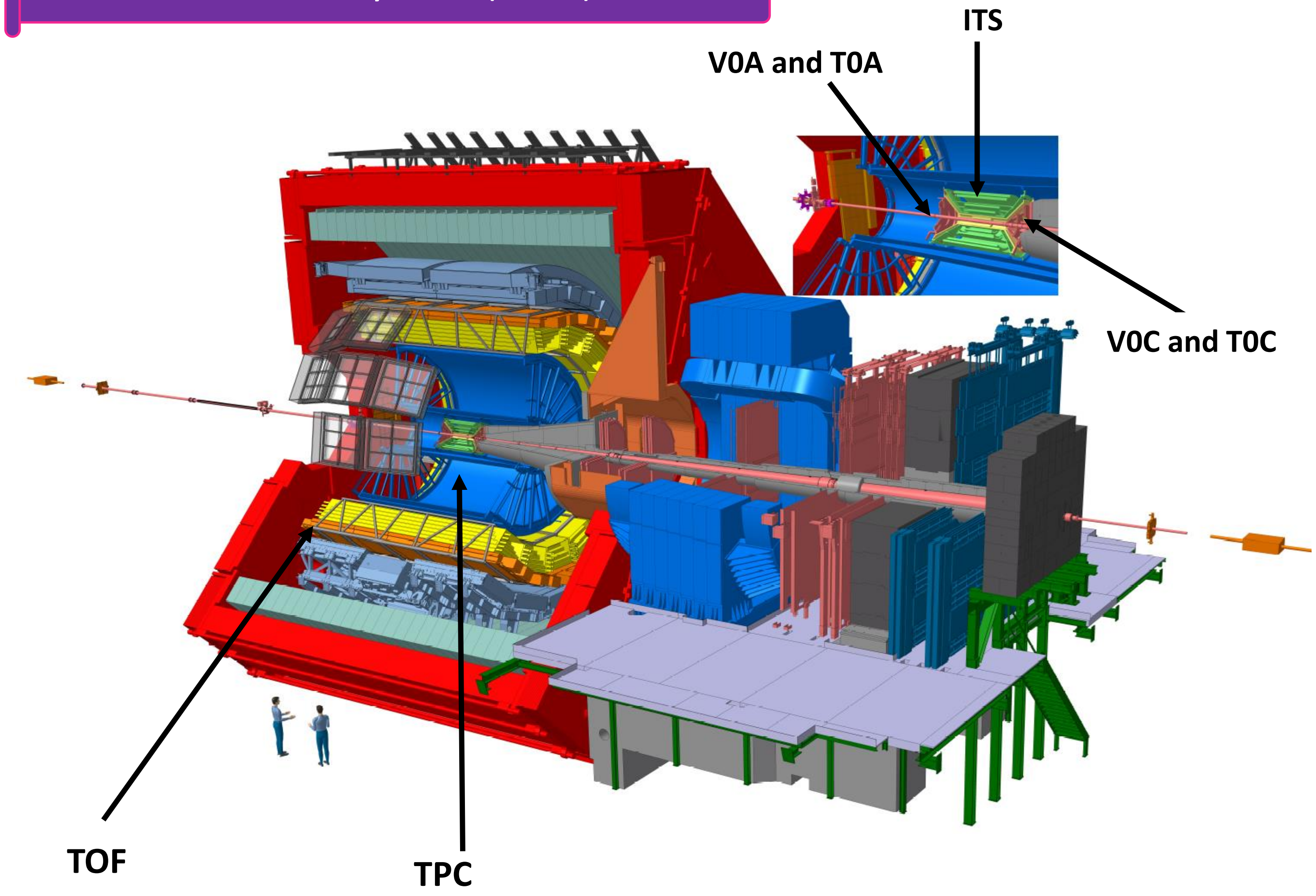

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Used data sets (Run 2):

- p–Pb 5.02 TeV (250 M minimum bias events)
- Pb–Pb 5.02 TeV (270 M minimum bias events)
- Direct detection of charged particles (p, K, π)

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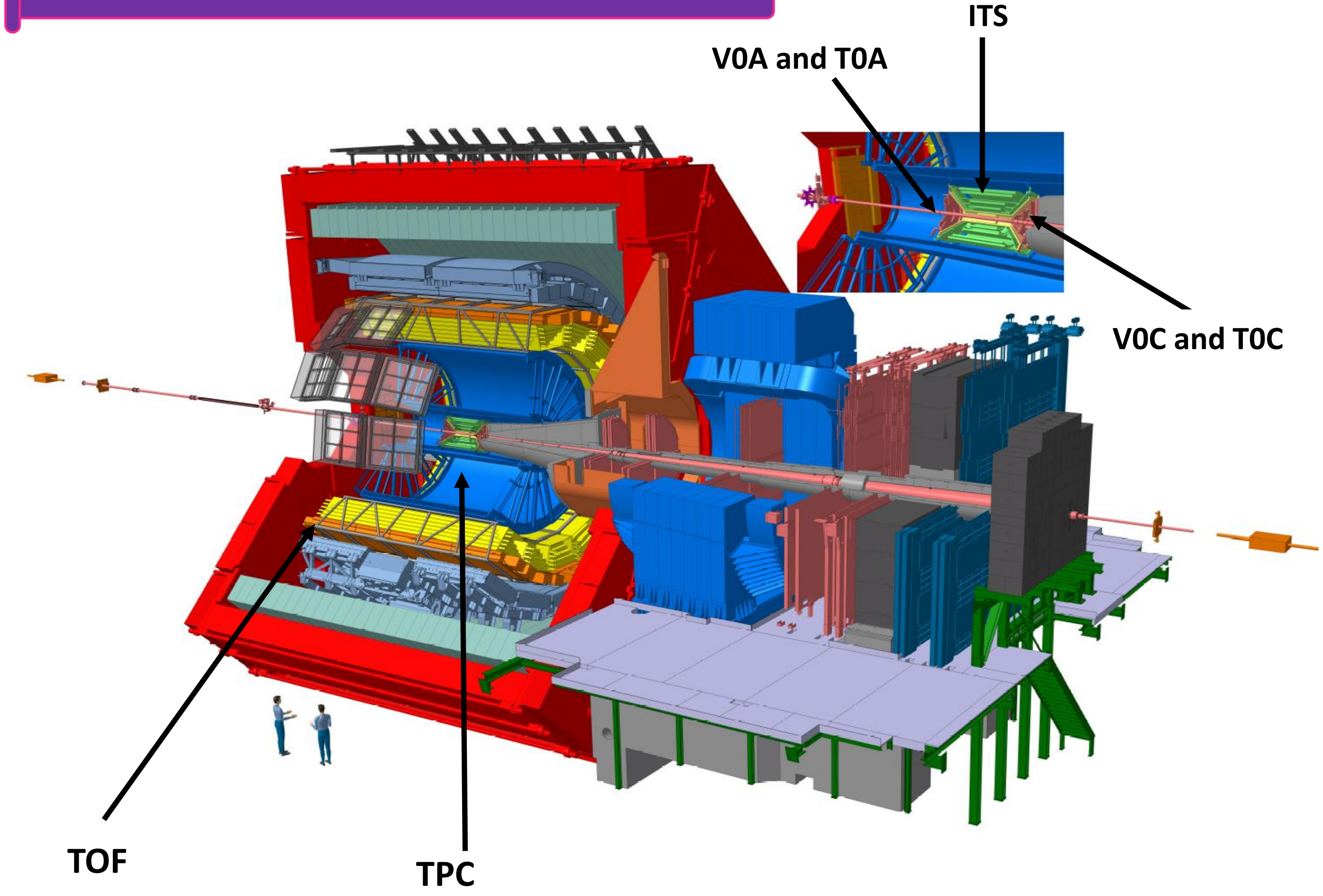

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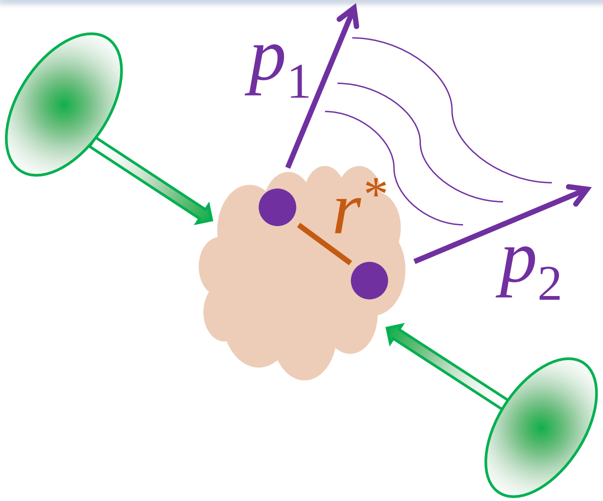
The very good PID capabilities of the detector result in very pure samples!

Two-particle femtoscopy



Correlation femtoscopy: measurement of space–time characteristics R, $c\tau$ ~fm of particle production source using particle correlations in momentum space due to the effects of quantum statistics (QS) and final-state interactions (FSI).

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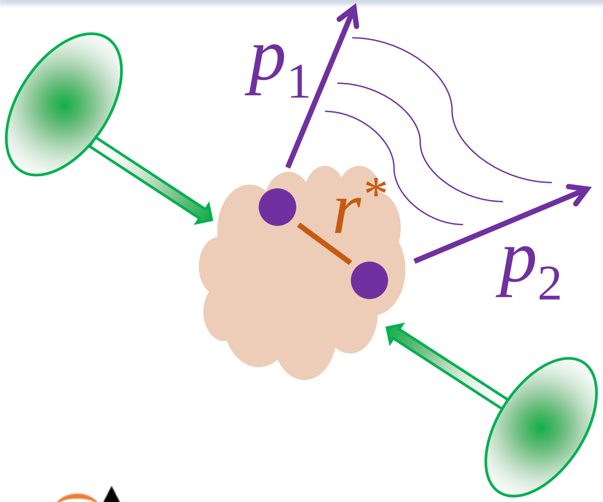

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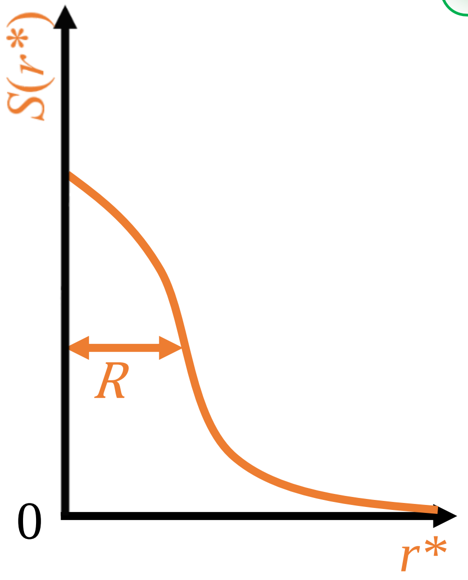

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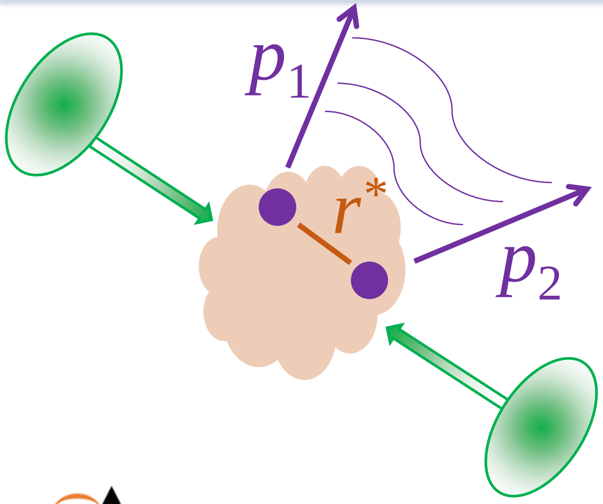

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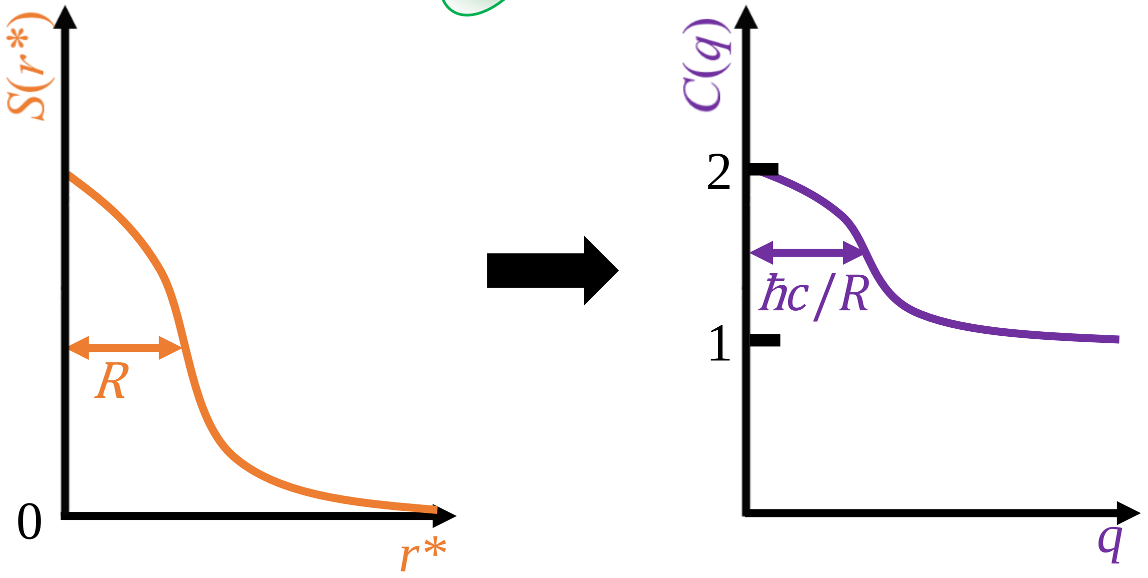

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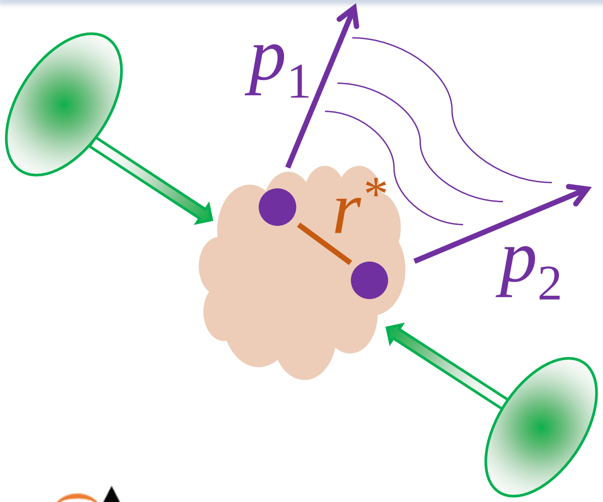

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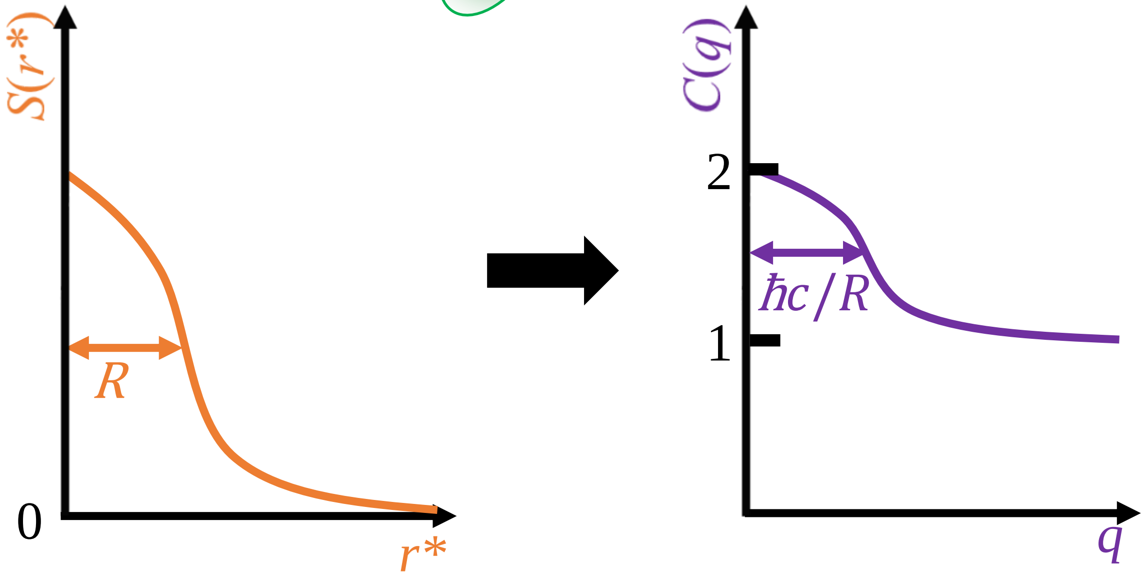

Two-particle correlation function $C(q)$:

Theory: $C(q) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}$, $C(\infty) = 1$

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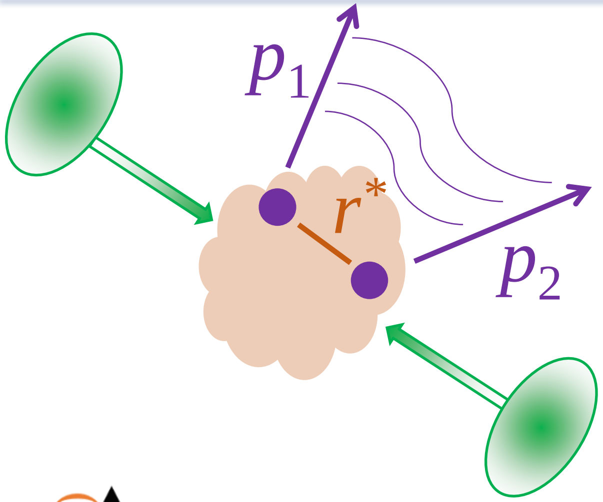

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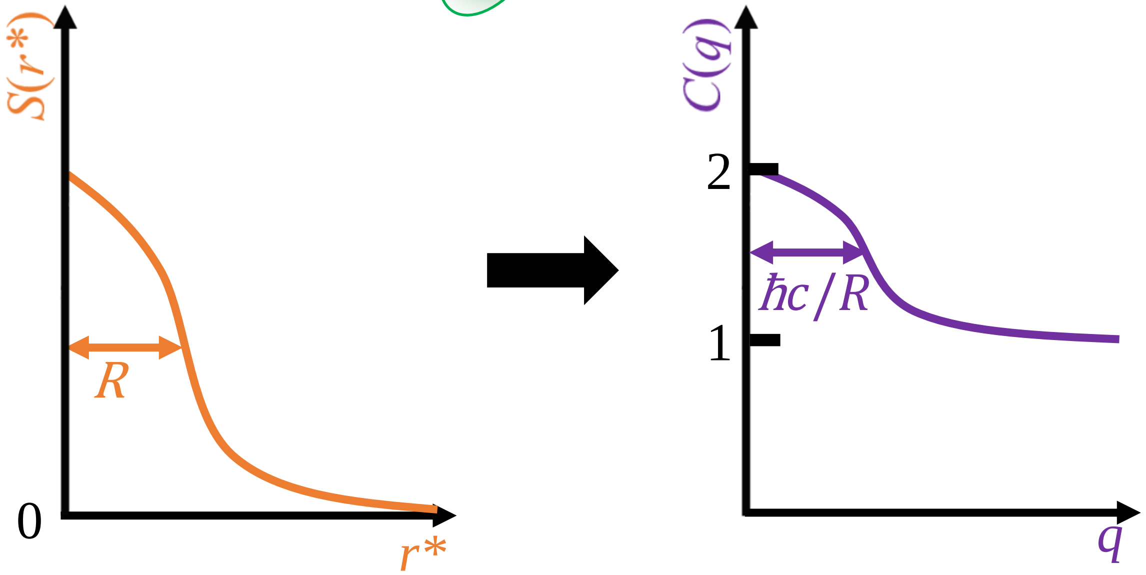
N_{same} (N_{mixed}) - pairs from same (different) event(s)



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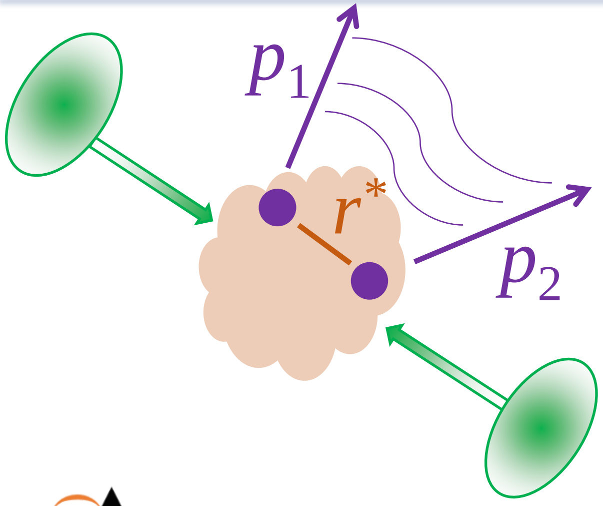

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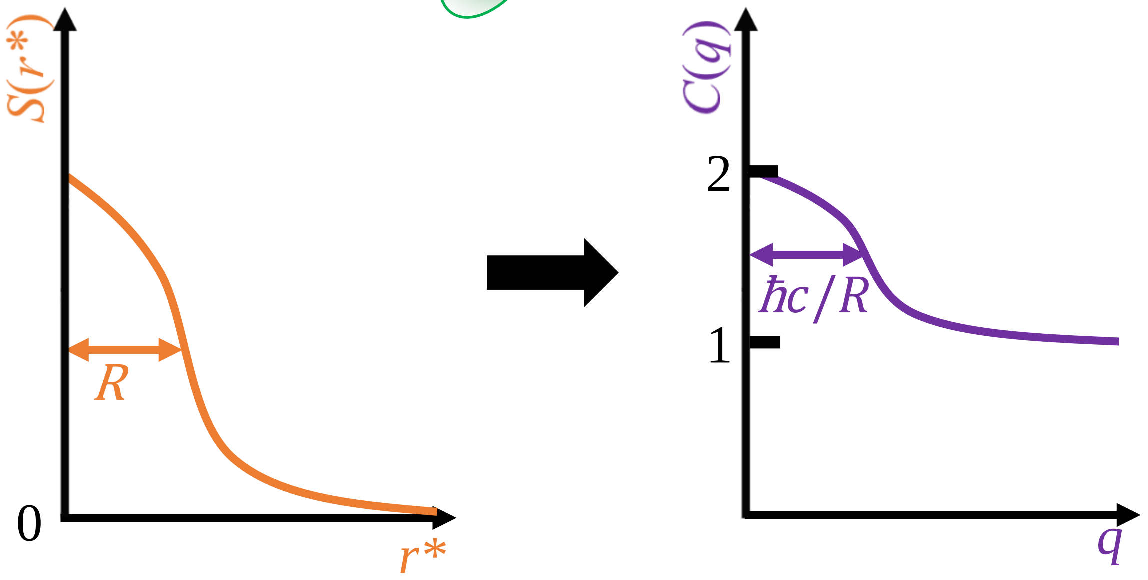

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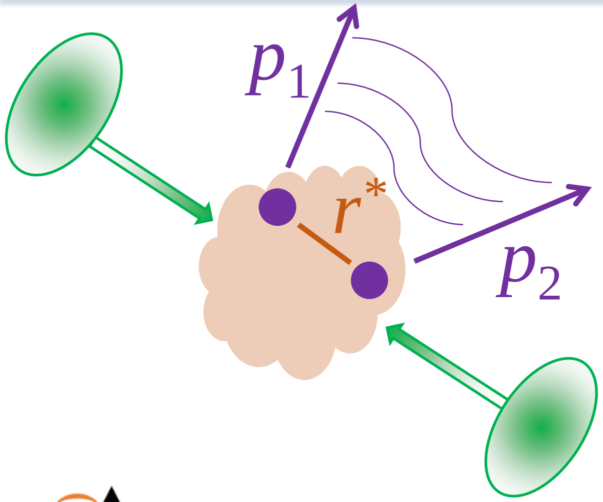
R_{inv} – source size in *Pair Reference Frame*

λ – correlation strength

Two-particle femtoscopy



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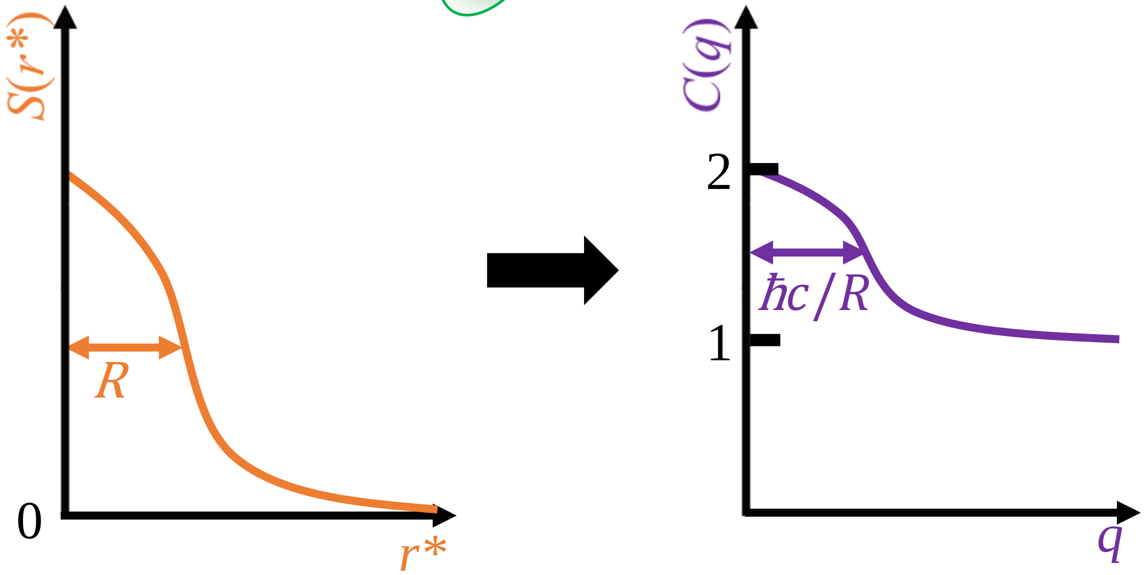


1D: $C(q_{inv}) = 1 + \lambda e^{-R_{inv}^2 q_{inv}^2}$

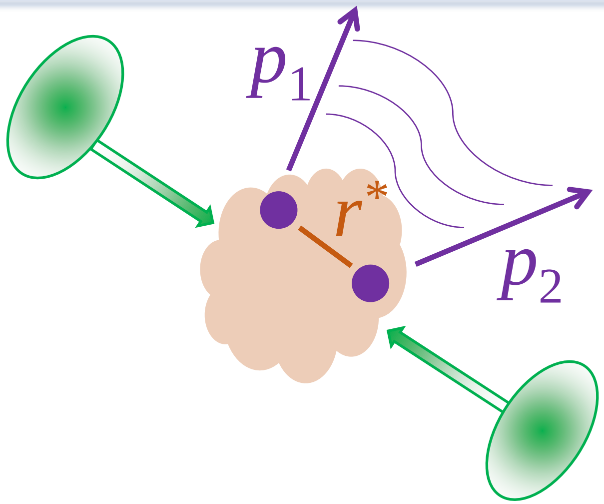
R_{inv} – source size in *Pair Reference Frame*

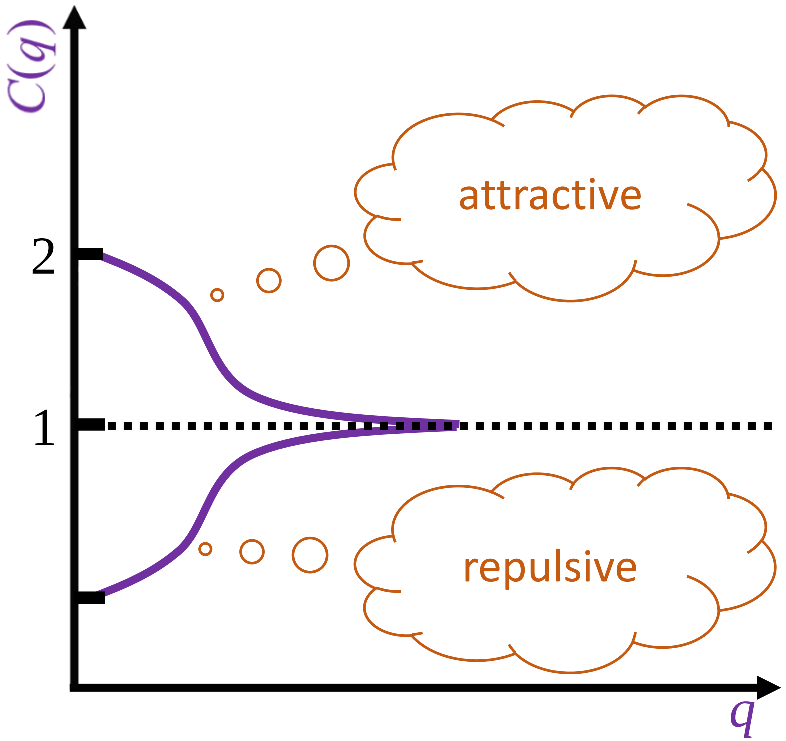
λ – correlation strength

3D: $C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$

R_{out}, R_{side}, R_{long} – source size in *Longitudinally Co-Moving System*

What femtoscopy can study?





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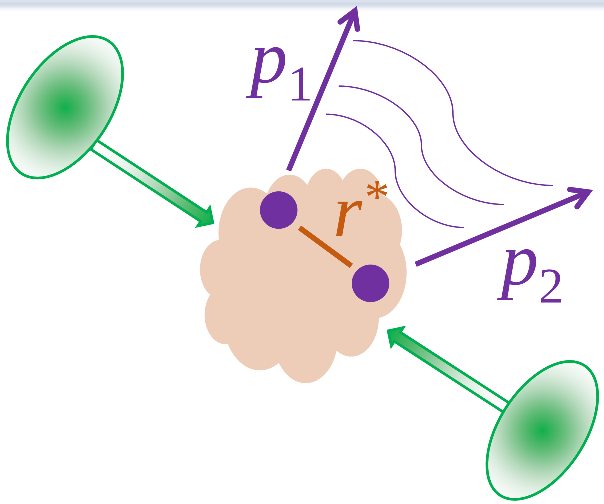

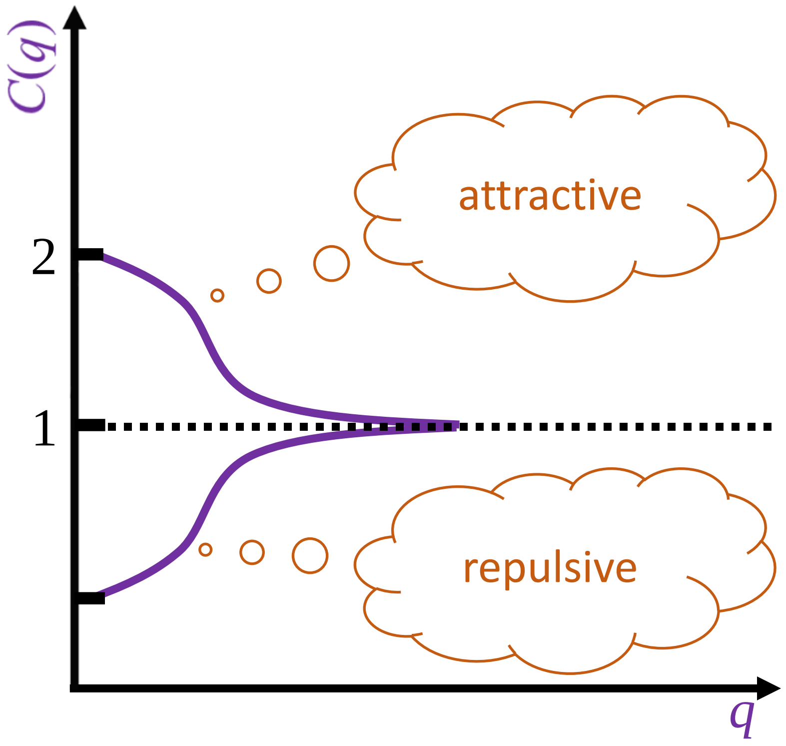

- Dynamics of medium created in high-energy collisions to test (hydrodynamic) models of hadron interactions

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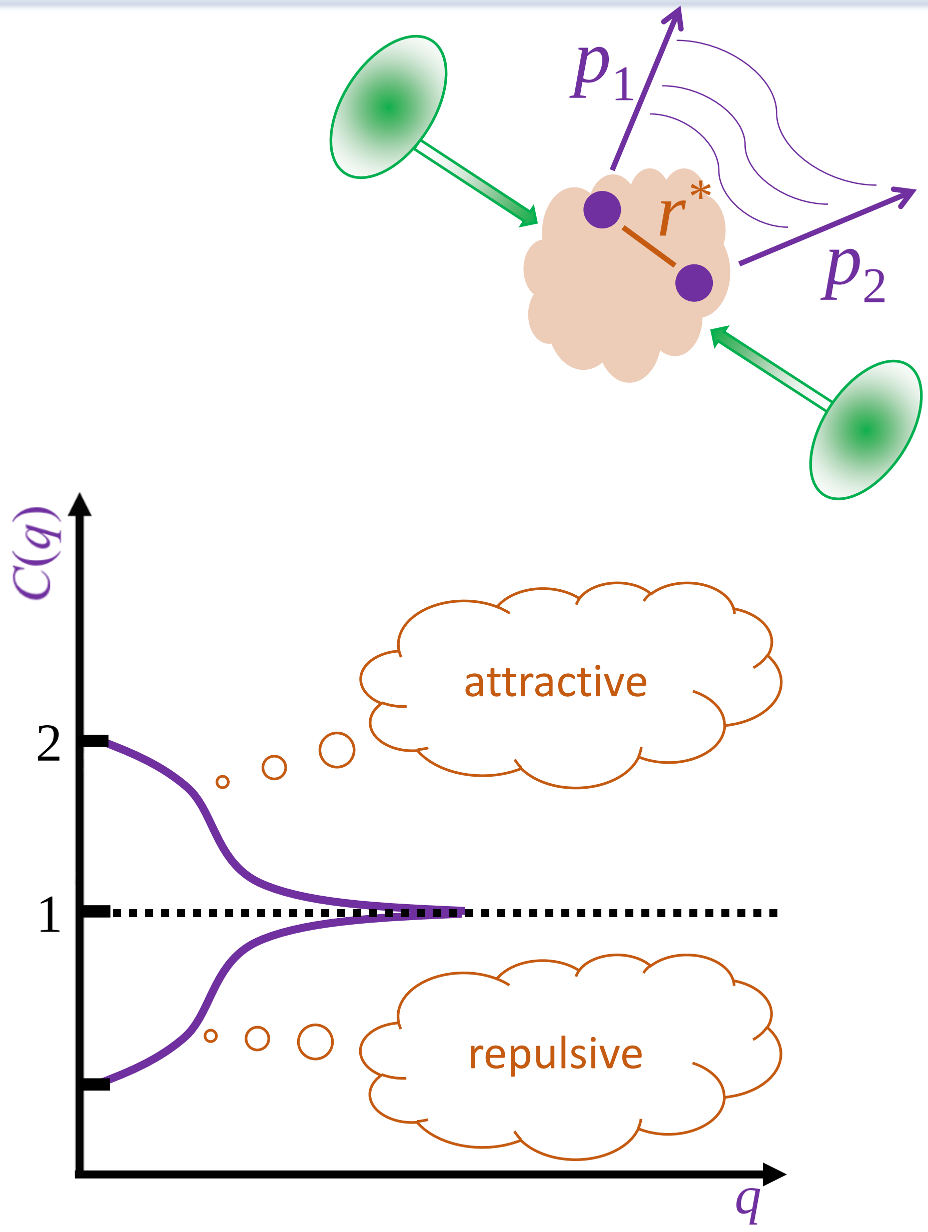

- Dynamics of medium created in high-energy collisions to test (hydrodynamic) models of hadron interactions
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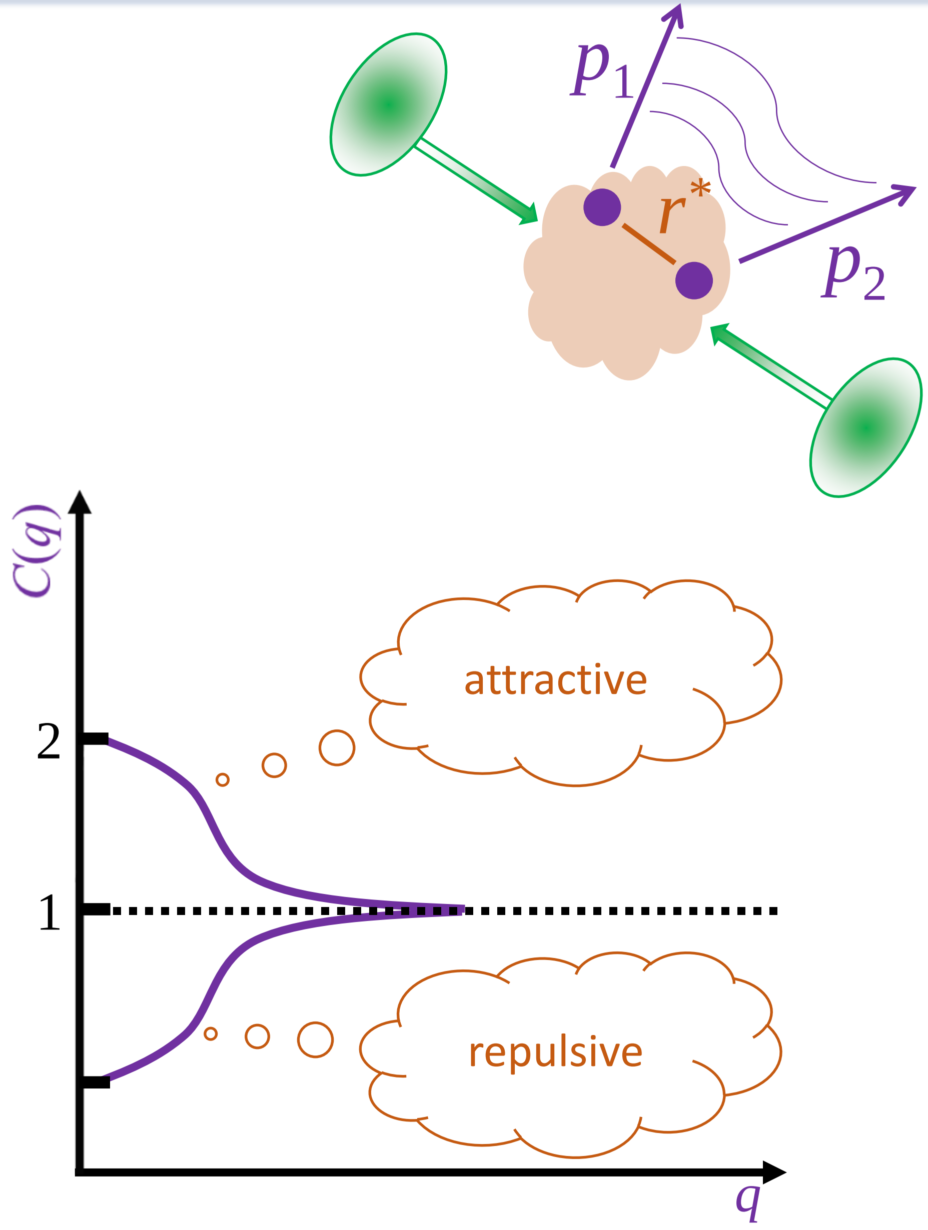

- Dynamics of medium created in high-energy collisions to test (hydrodynamic) models of hadron interactions
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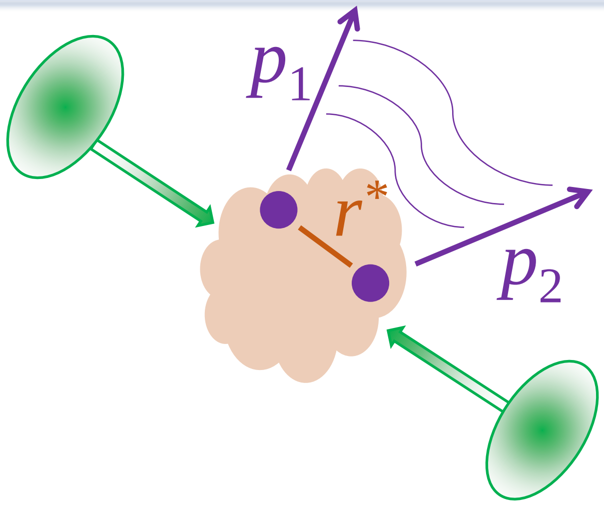

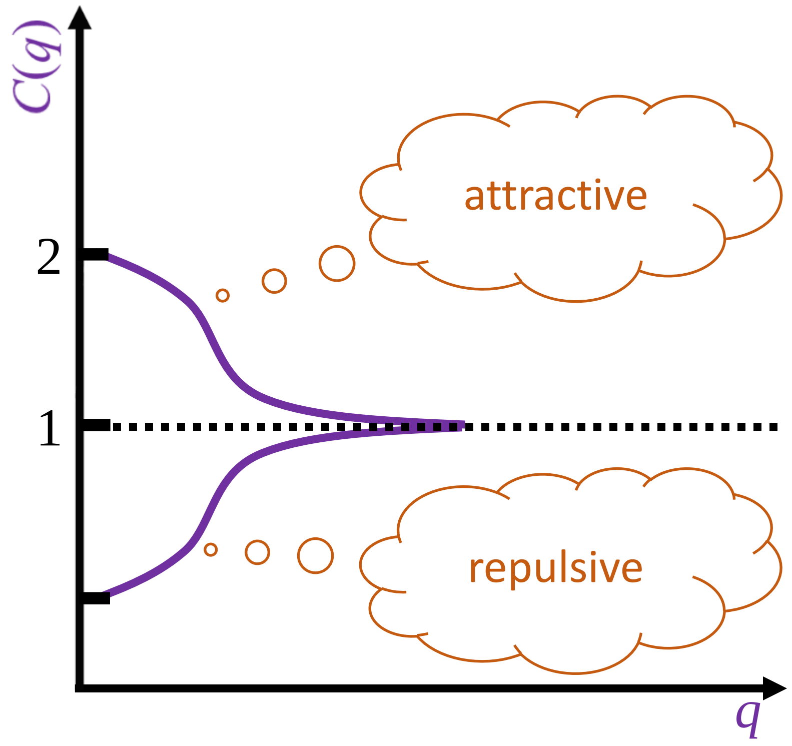

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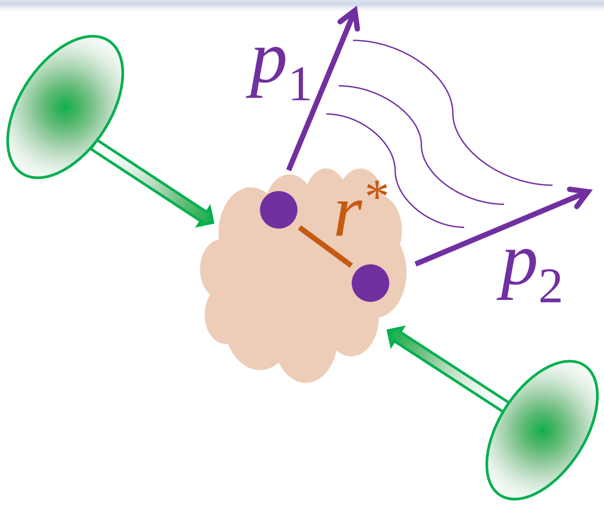

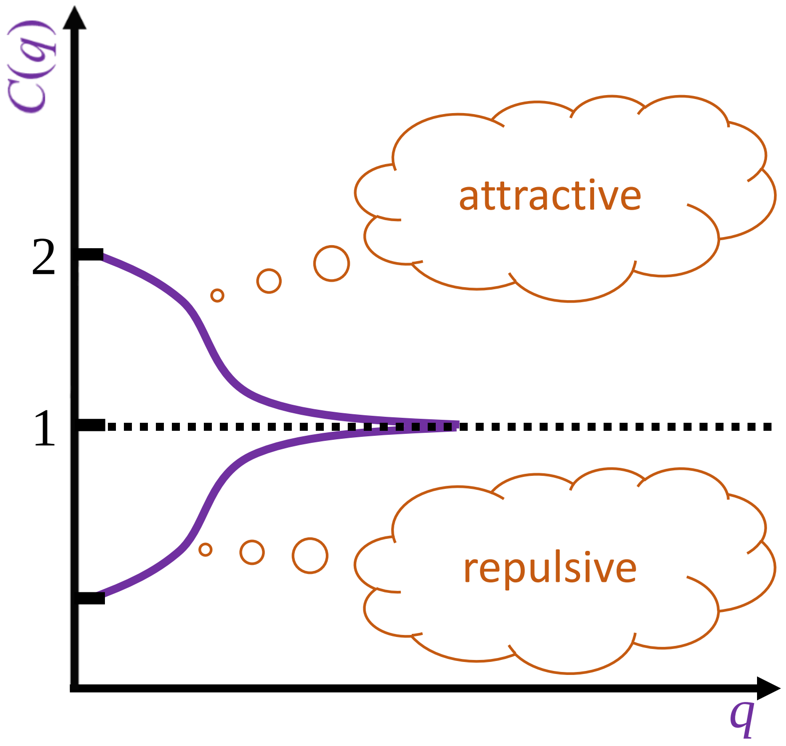

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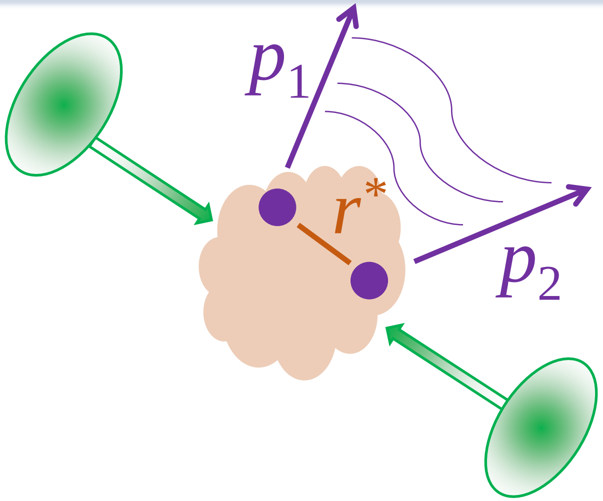
$K^{\pm}K^{\pm}$ femtoscopy in p–Pb



$K^{\pm}K^{\pm}$ femtoscopic correlations in p–Pb@5.02TeV

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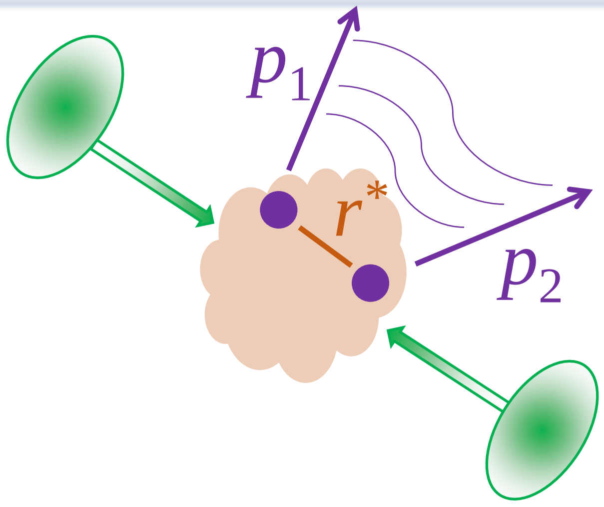

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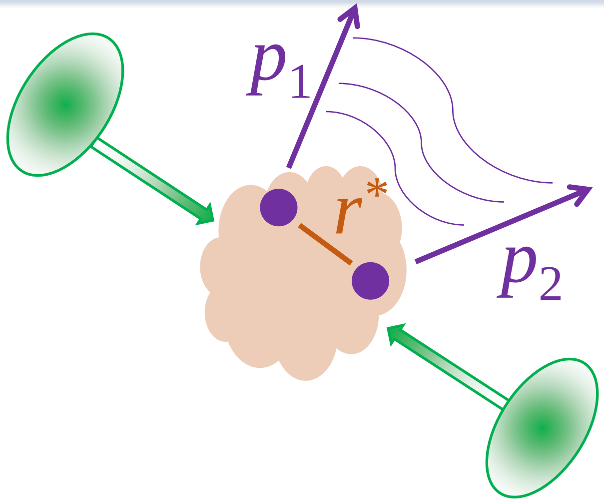

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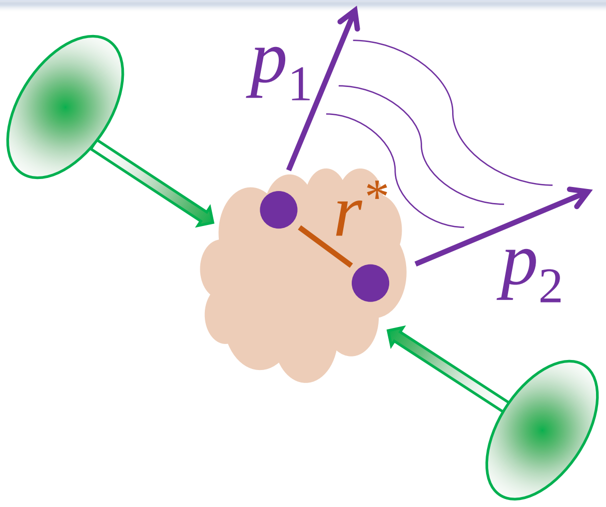

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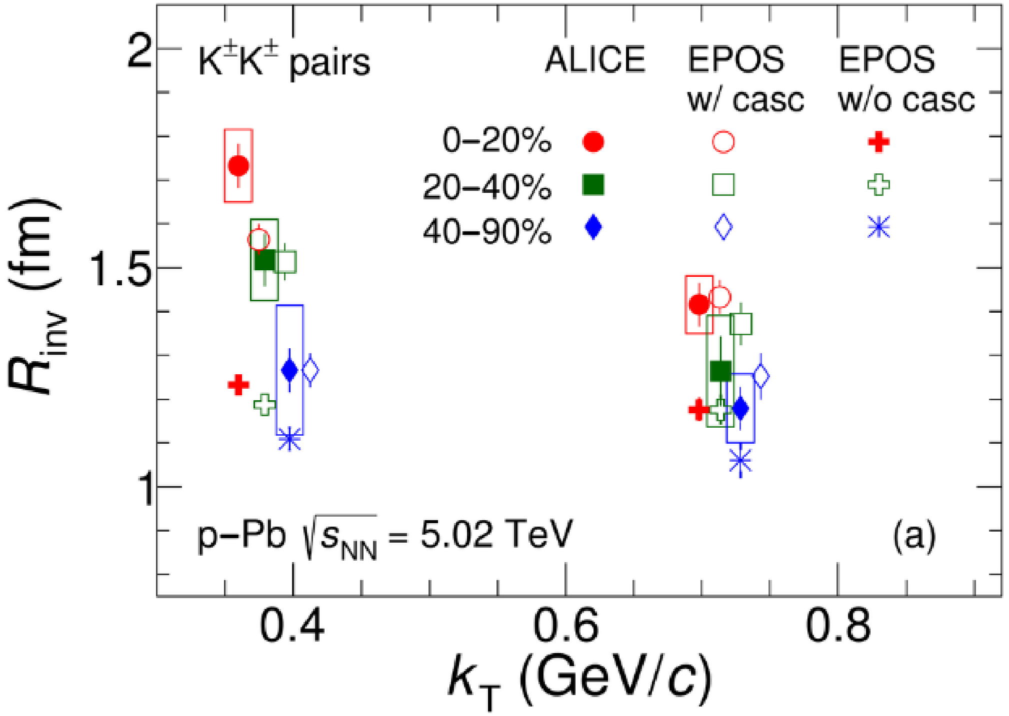
- Kaons – the second most copiously (after pions) produced particles
- Kaons – purer signal (not as many resonances decay to kaons as to pions)
- p–Pb (asymmetric collision system) – no consensus on the nature of matter created (collectivity?)

1D $K^{\pm}K^{\pm}$: experiment vs EPOS

ALICE, PRC100(2019)024002



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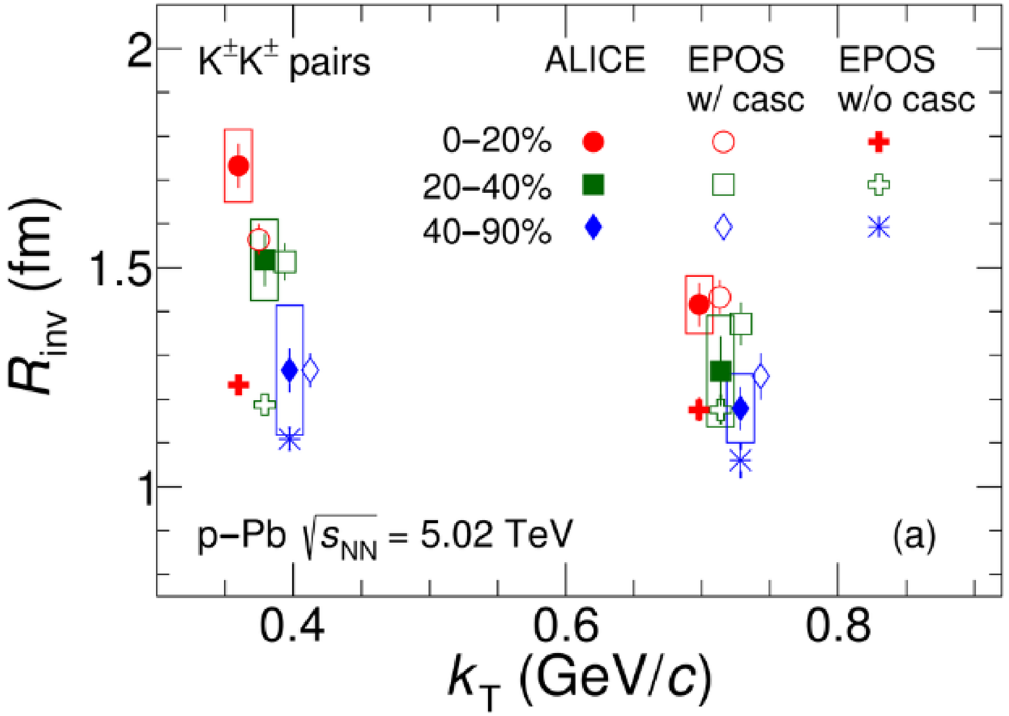

- R_{inv} decreases with increasing $k_{\mathrm{T}} = |\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}|/2$ and decreasing centrality → *hydrodynamic expansion of matter created in p–Pb collisions*
- EPOS with UrQMD cascade describes R_{inv}

K.Werner et al., PRC89(2014)064903

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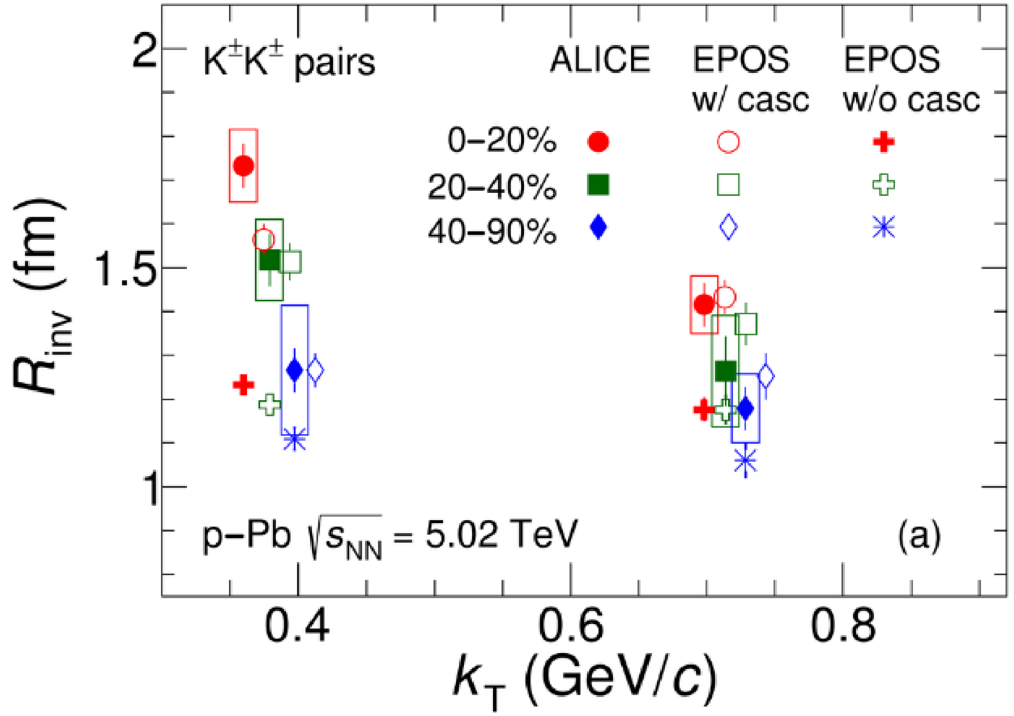

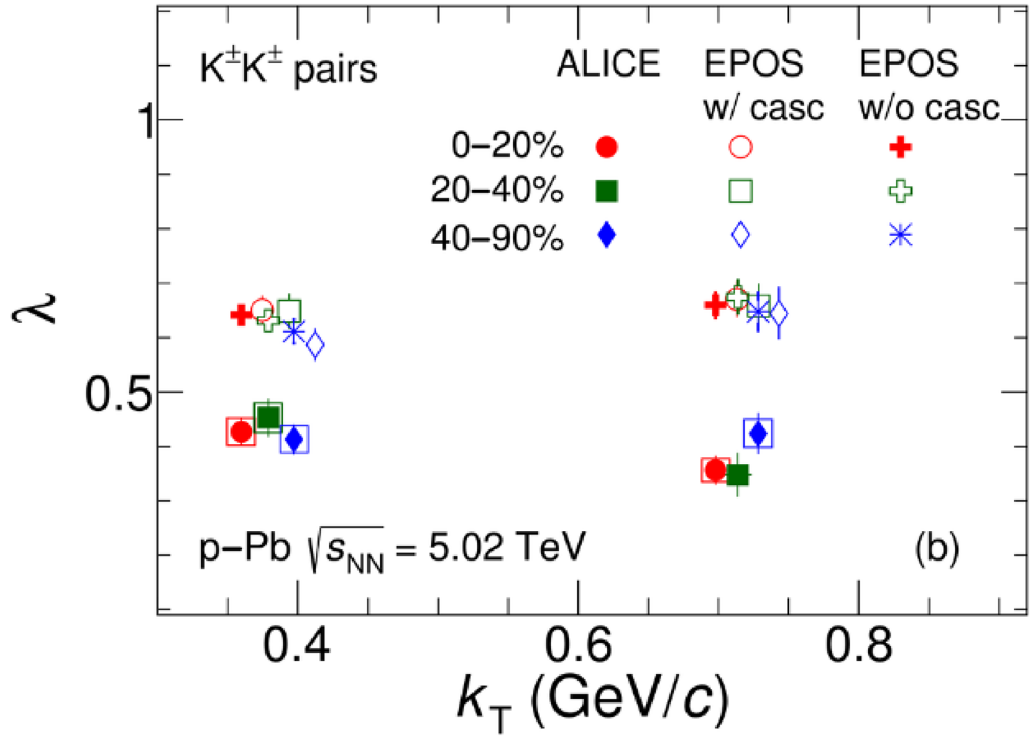

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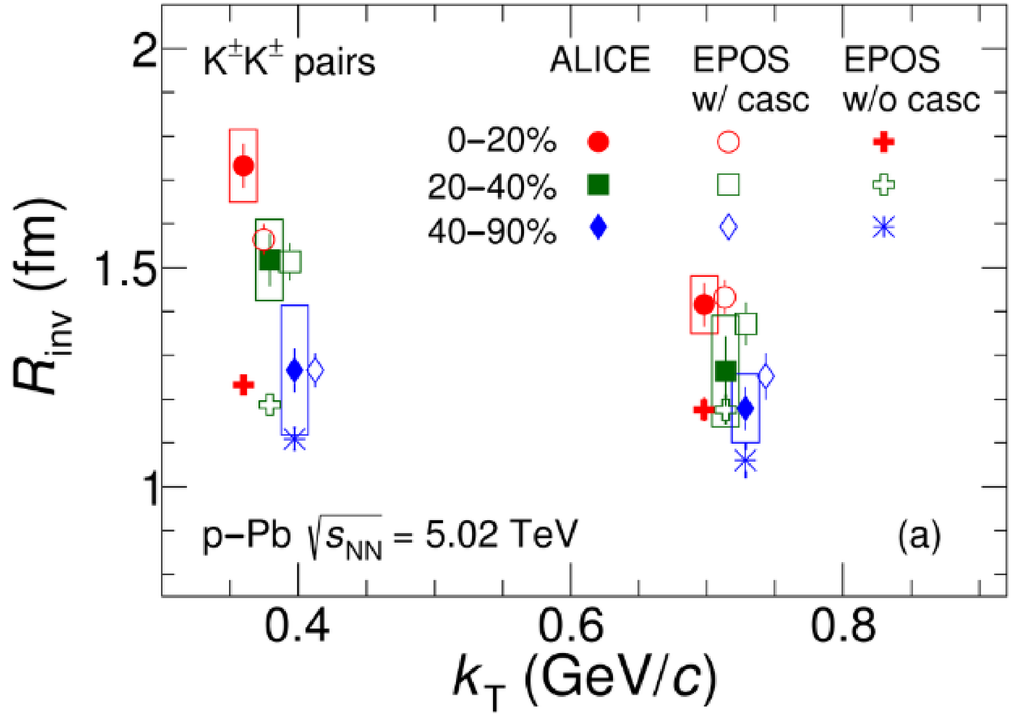

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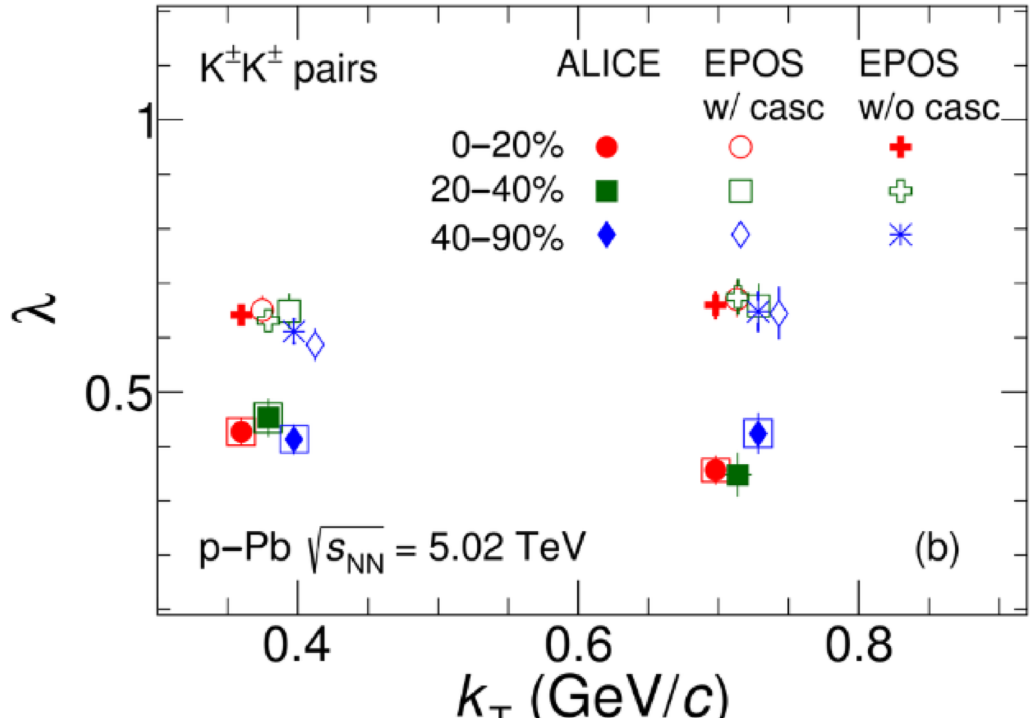

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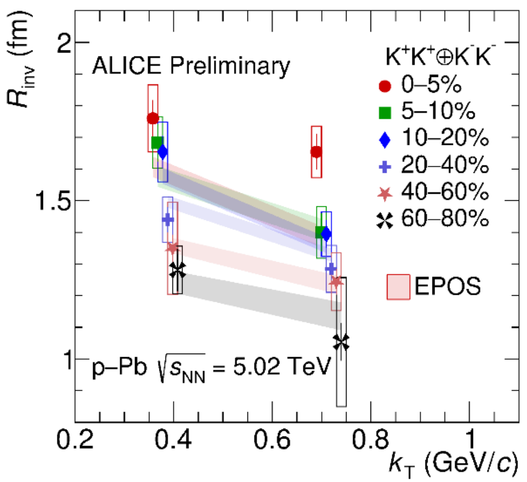
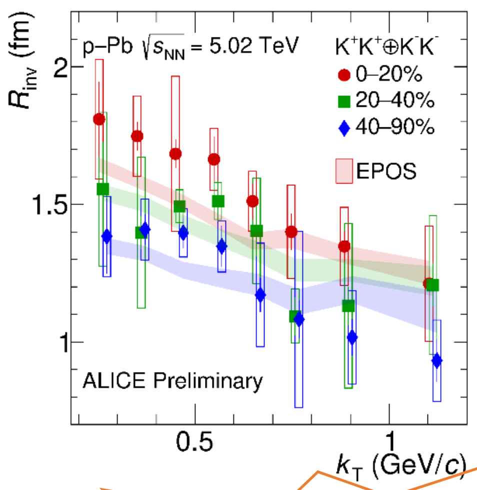


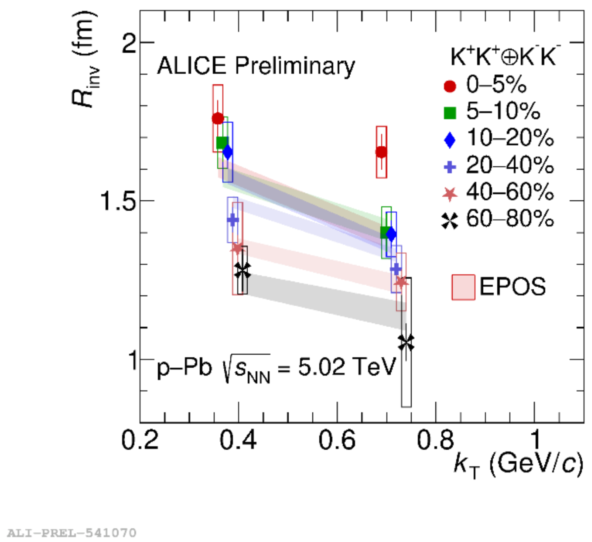
ALI-PREL-541070

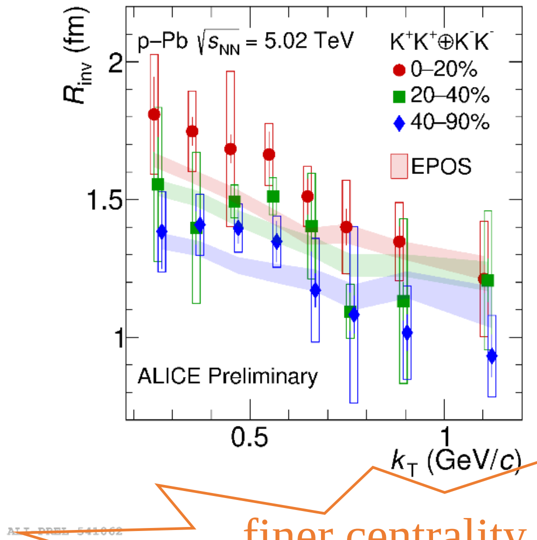


ALI-PREL-541062

finer centrality
and k_T ranges

1D $K^{\pm}K^{\pm}$: experiment vs EPOS – new





finer centrality and k_T ranges

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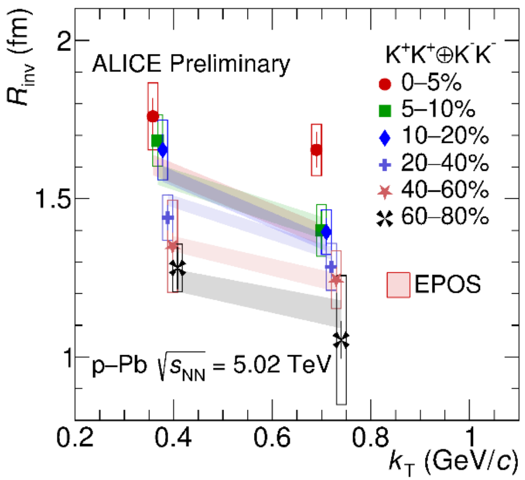
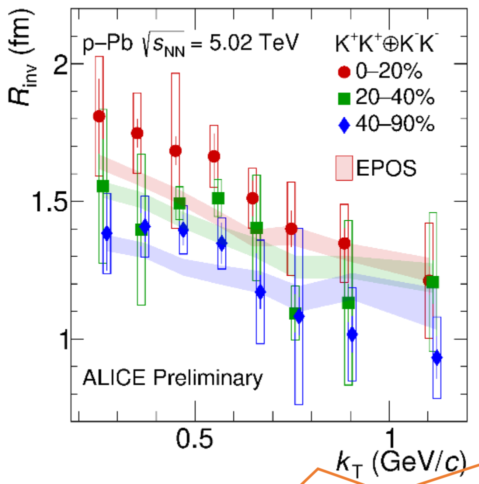
1D K±K±: experiment vs EPOS – new



ALI-PREL-541070



ALI-PREL-541062

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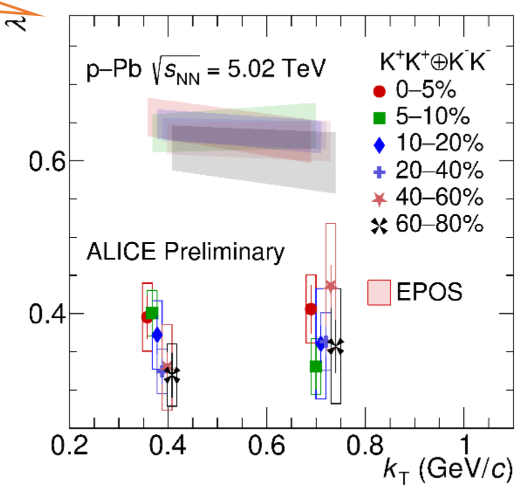
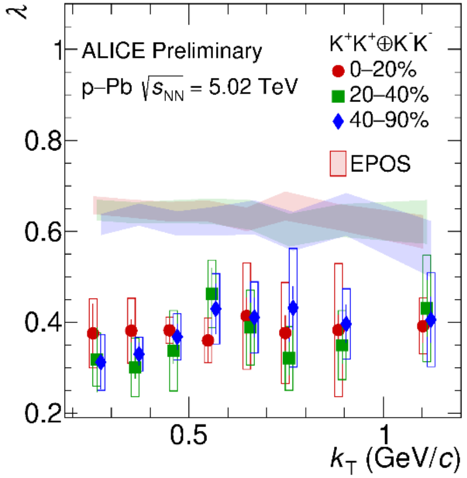
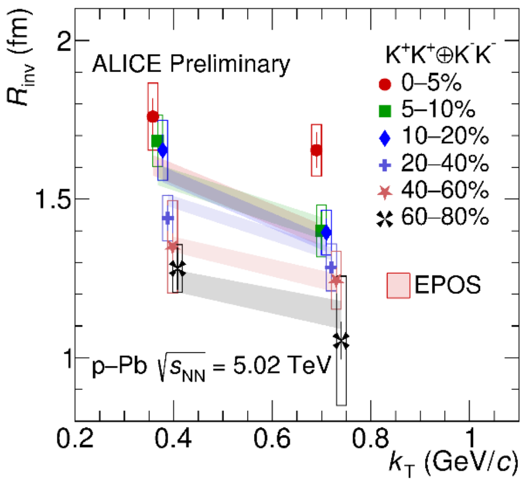


ALI-PREL-541074



ALI-PREL-541066

1D $K^{\pm}K^{\pm}$: experiment vs EPOS – new



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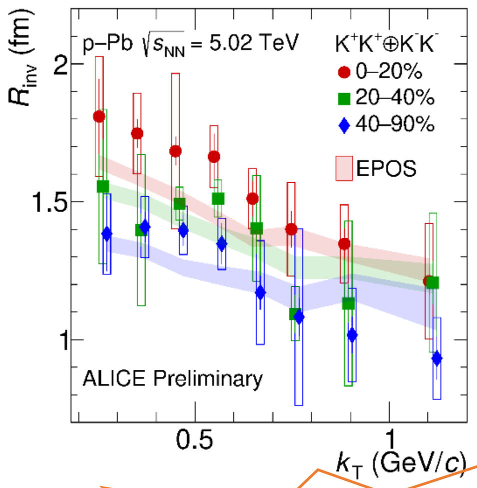

ALI-PREL-541062

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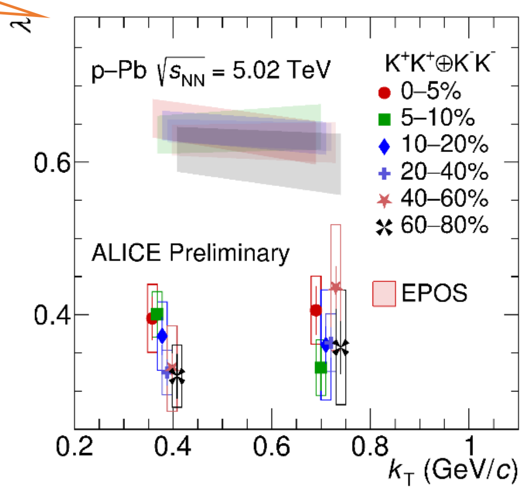

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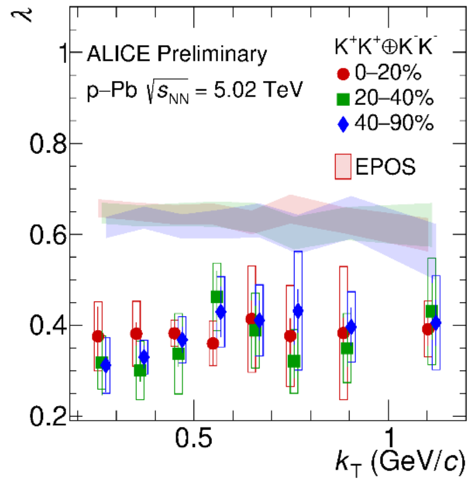
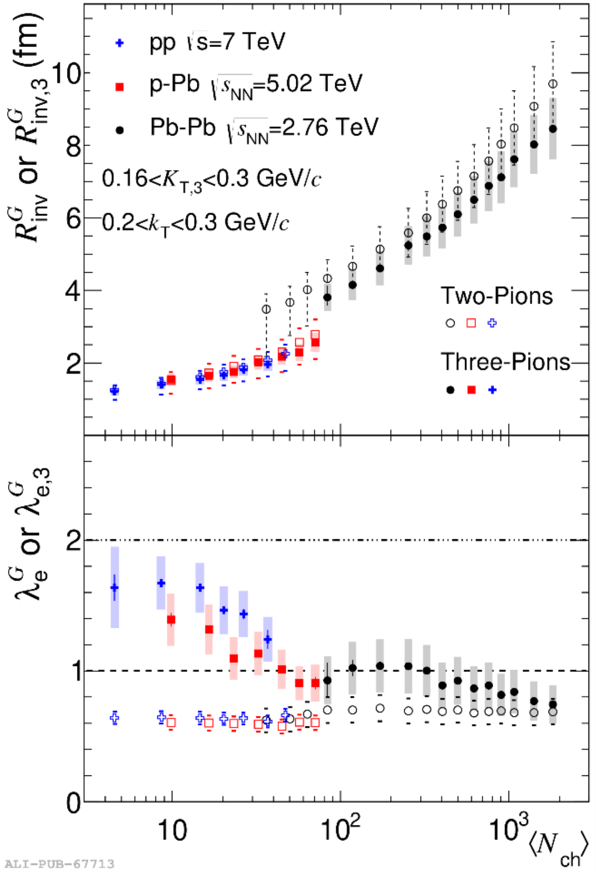


ALI-PREL-541066

1D K±K±: pp, p–Pb, Pb–Pb

ALICE, PLB739(2014)139



At similar multiplicity:

π±π± : indication that

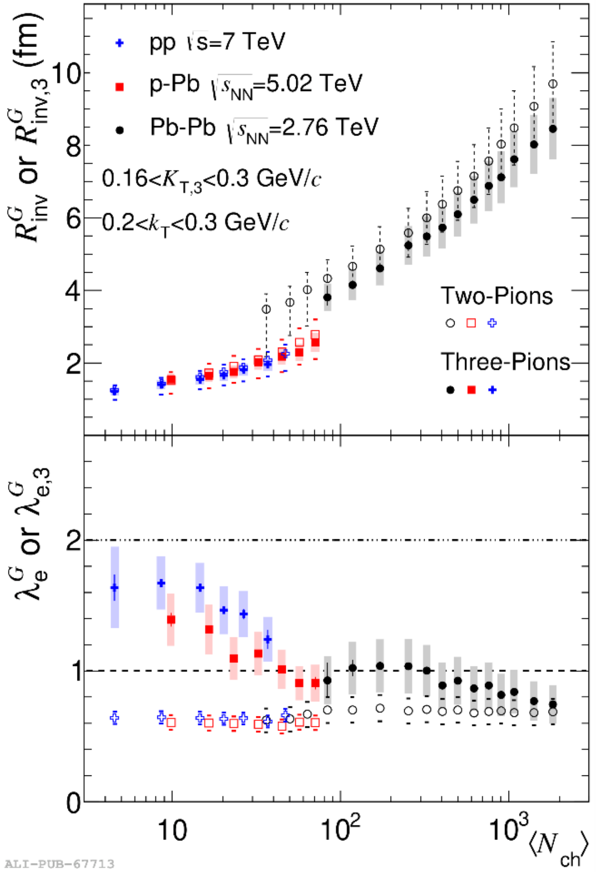
R_{inv} (pp)≈R_{inv}(p–Pb)

R_{inv}(Pb–Pb)>R_{inv}(p–Pb)

- *disfavors models which incorporate substantially stronger collective expansion in p–Pb as compared to pp collisions*
- *importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb*

1D $K^{\pm}K^{\pm}$: pp, p–Pb, Pb–Pb

ALICE, PLB739(2014)139



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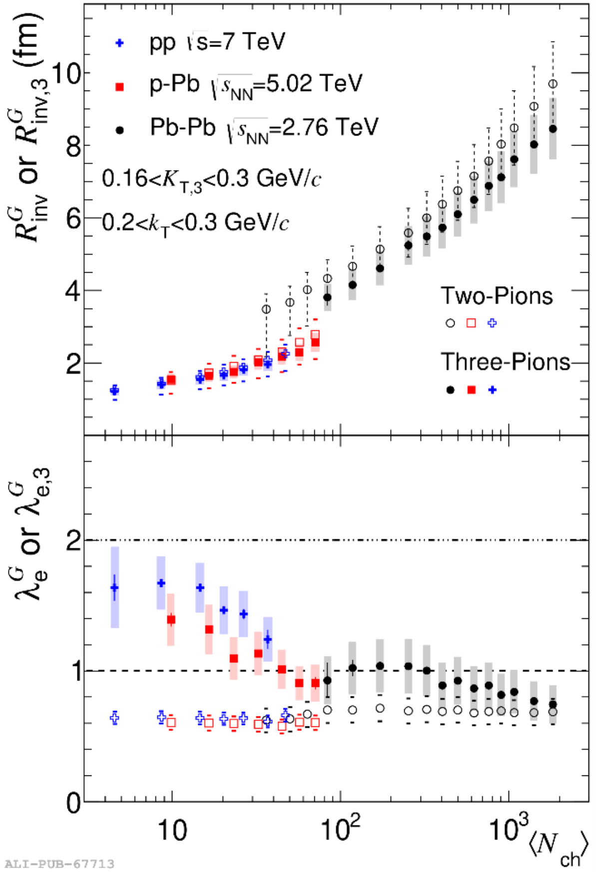
ALICE, PLB739(2014)139



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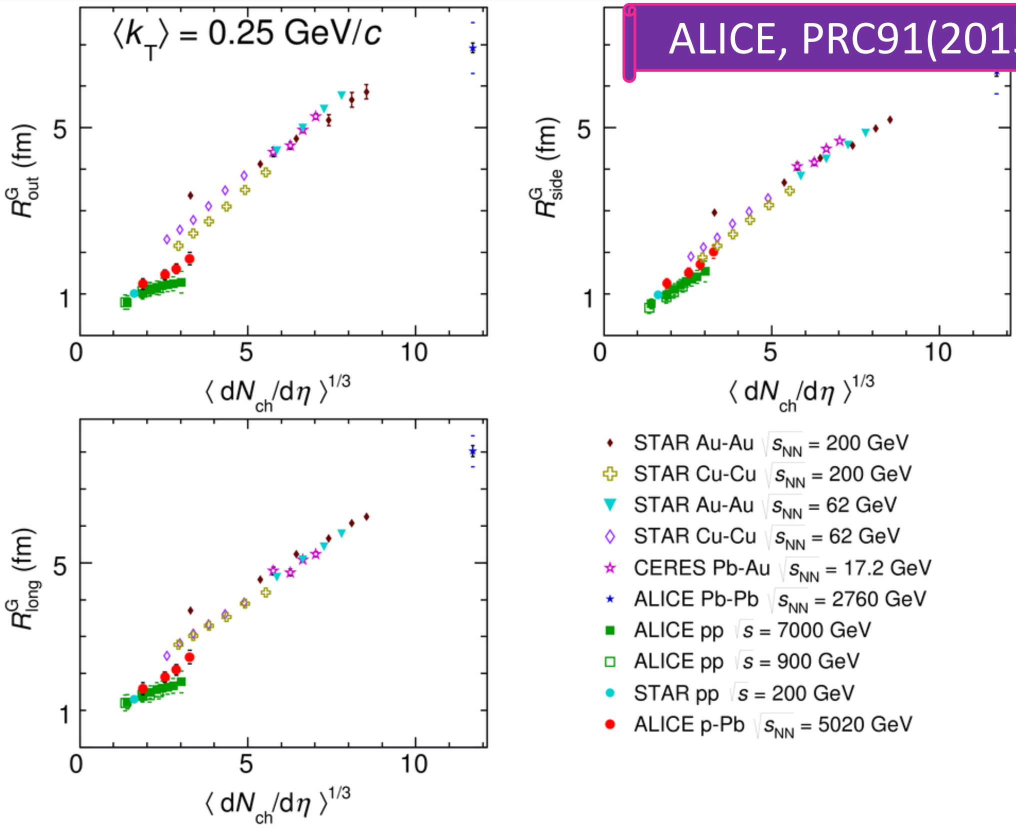
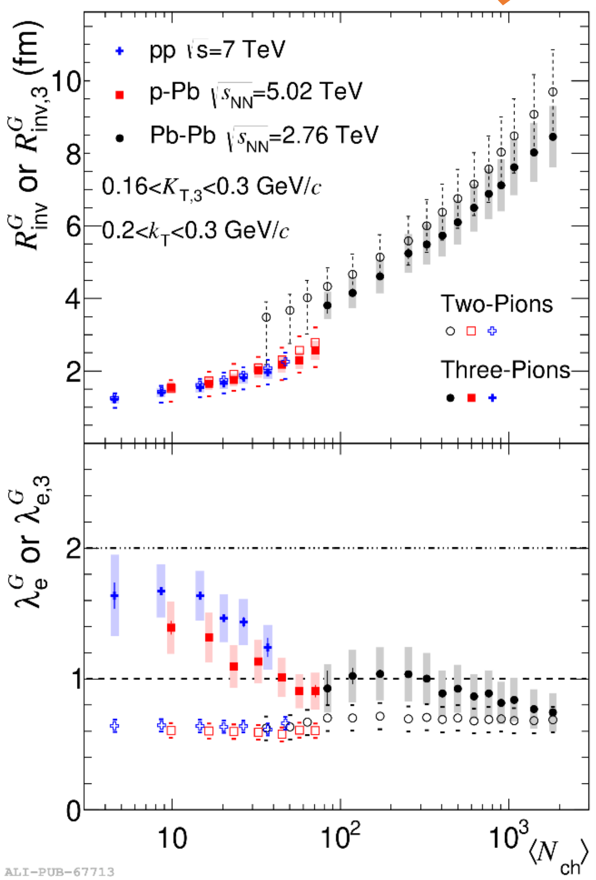
ALICE, PRC91(2015)034906



1D K$^\pm$K$^\pm$: pp, p–Pb, Pb–Pb

ALICE, PLB739(2014)139



At similar multiplicity:

$\pi^\pm\pi^\pm$: indication that

R_{inv} (pp)≈R_{inv}(p–Pb)

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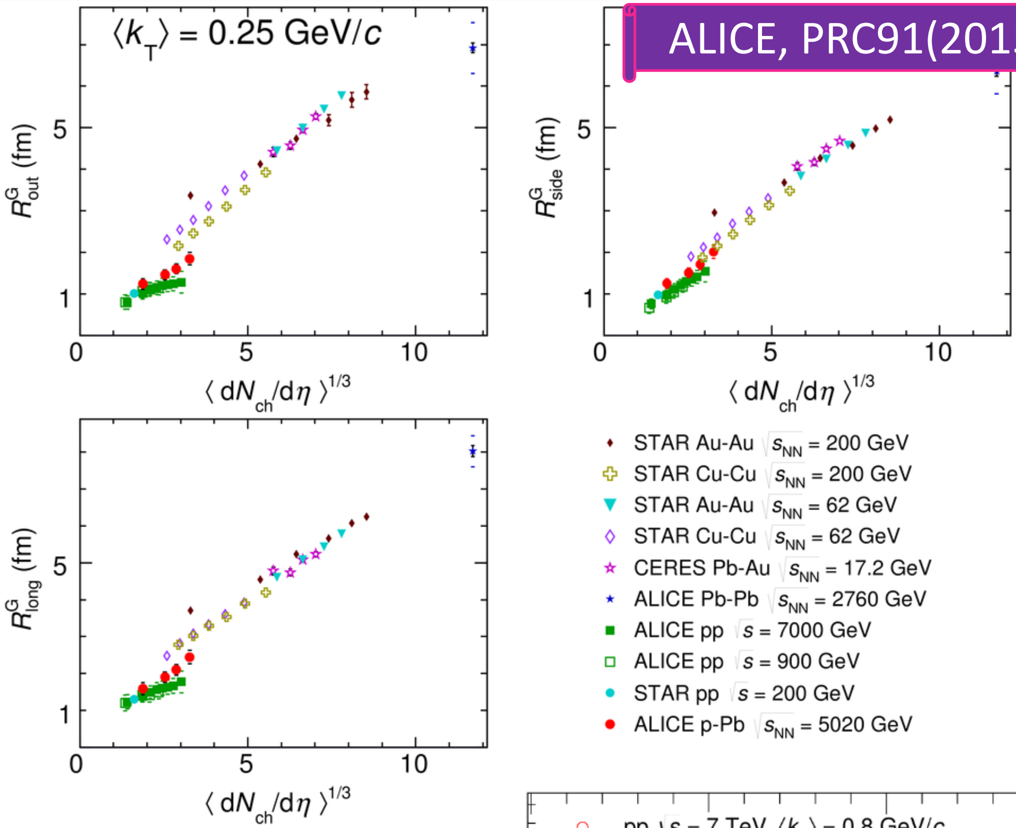
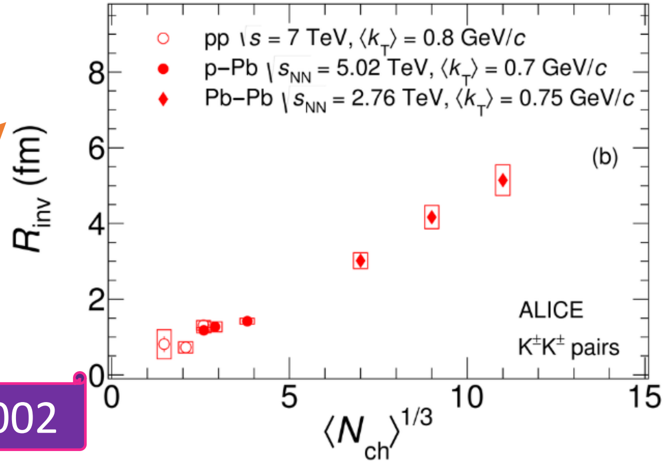
- *disfavors models which incorporate substantially stronger collective expansion in p–Pb as compared to pp collisions*
- *importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb*

What about **K$^\pm$K$^\pm$**?

ALICE, PRC91(2015)034906

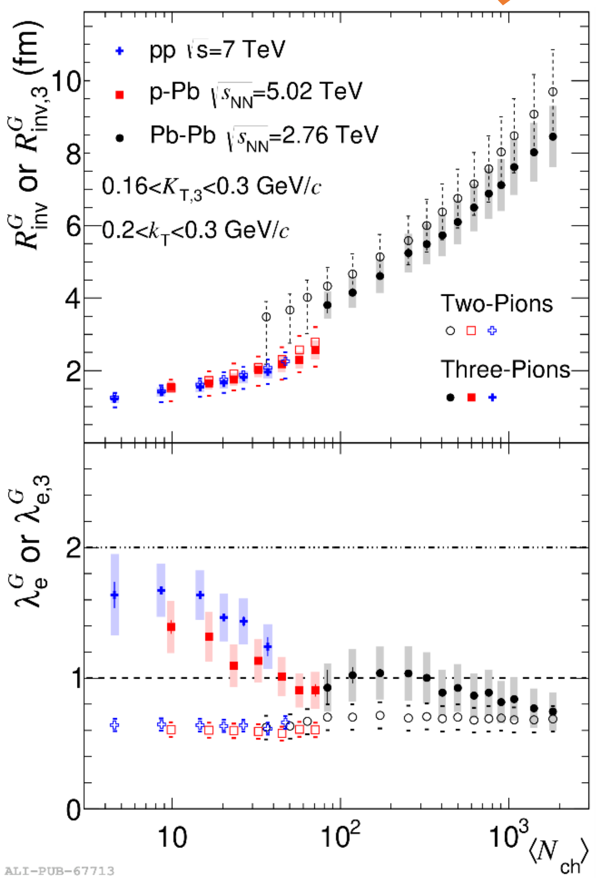




ALICE, PRC100(2019)024002

1D K±K±: pp, p–Pb, Pb–Pb

ALICE, PLB739(2014)139



At similar multiplicity:

$\pi^{\pm}\pi^{\pm}$: indication that

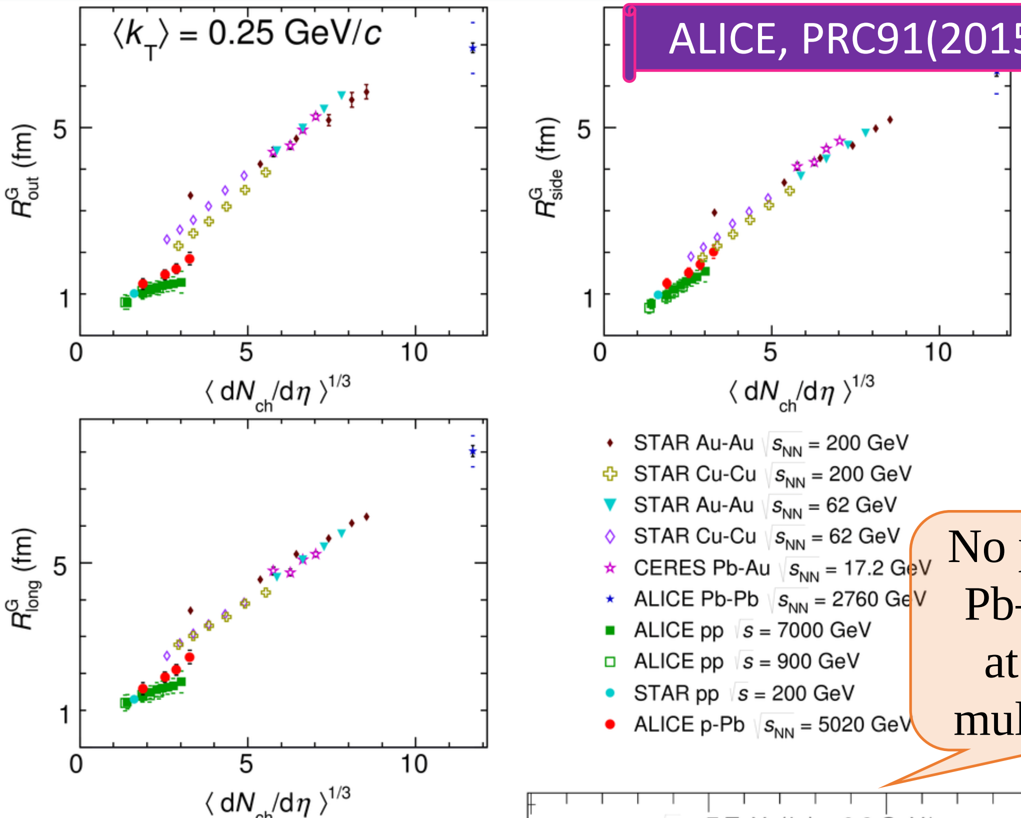
R_{inv} (pp)≈R_{inv}(p–Pb)

R_{inv}(Pb–Pb)>R_{inv}(p–Pb)

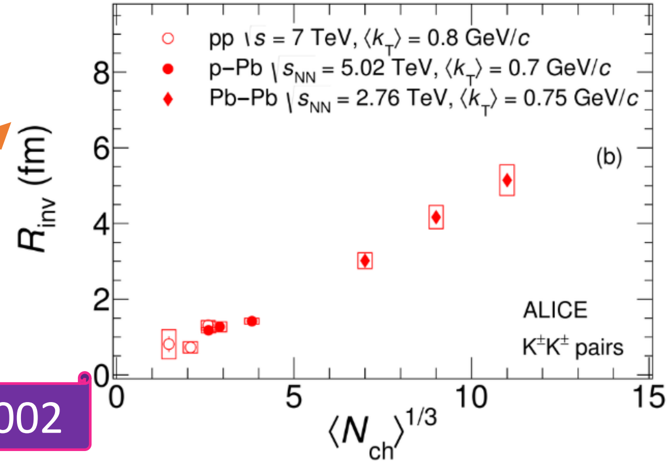
- *disfavors models which incorporate substantially stronger collective expansion in p–Pb as compared to pp collisions*
- *importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb*

What about **K±K±**?

ALICE, PRC91(2015)034906

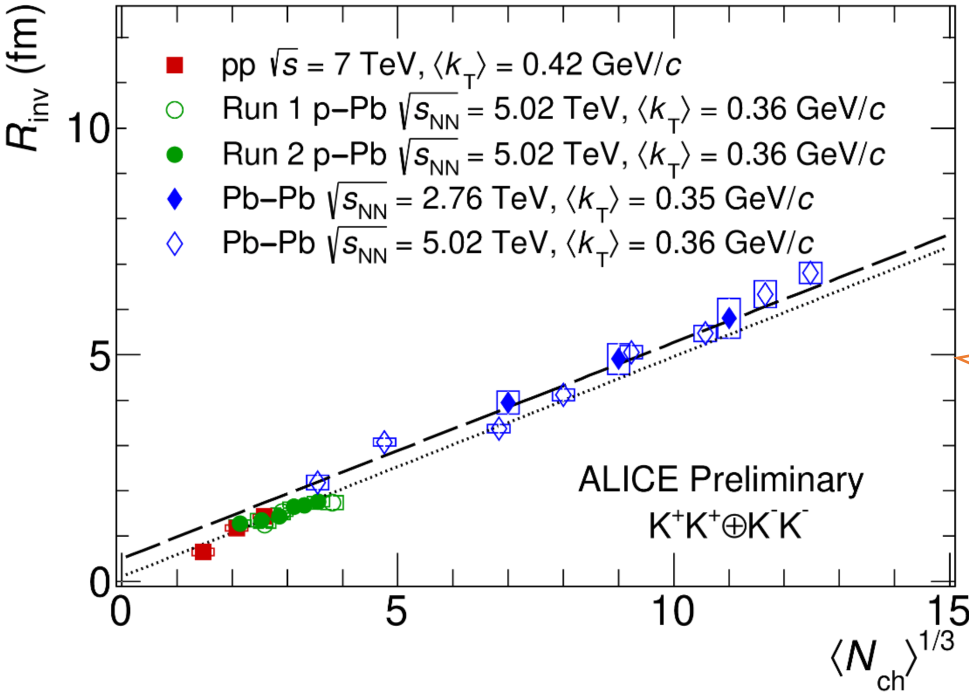


No p–Pb and Pb–Pb data at similar multiplicity!



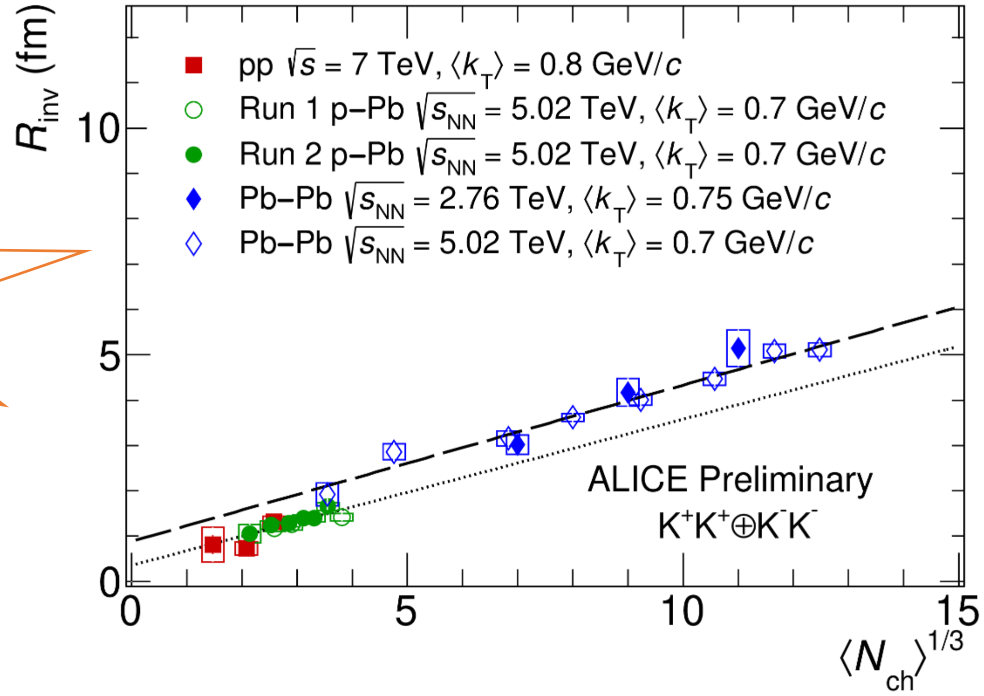
ALICE, PRC100(2019)024002

1D K±K±: pp, p–Pb, Pb–Pb – new



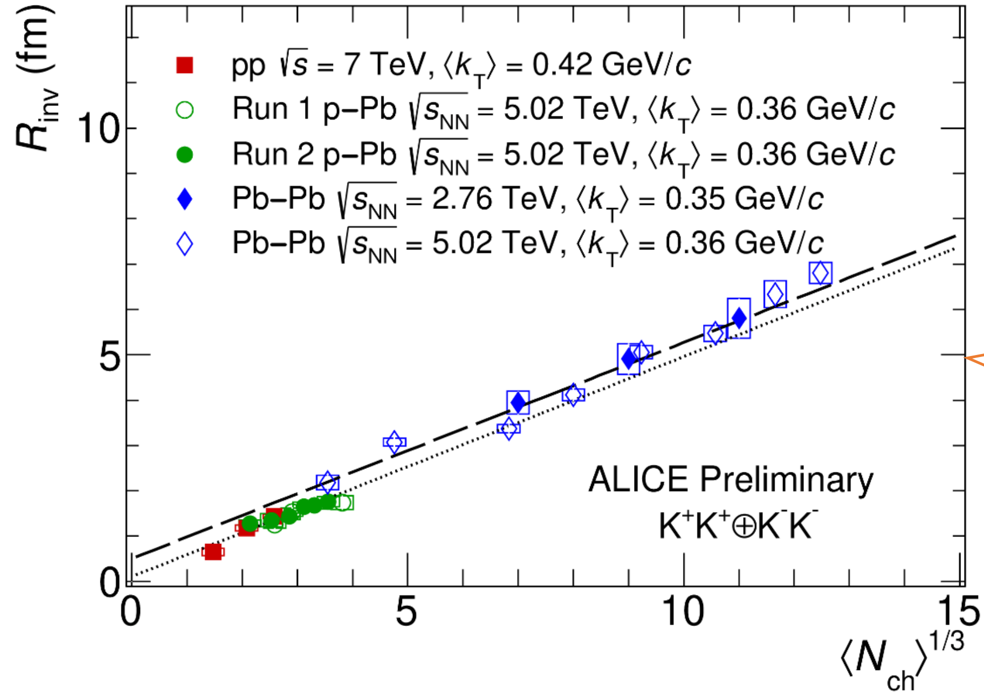
ALI-PREL-541028

more p–Pb and Pb–Pb points

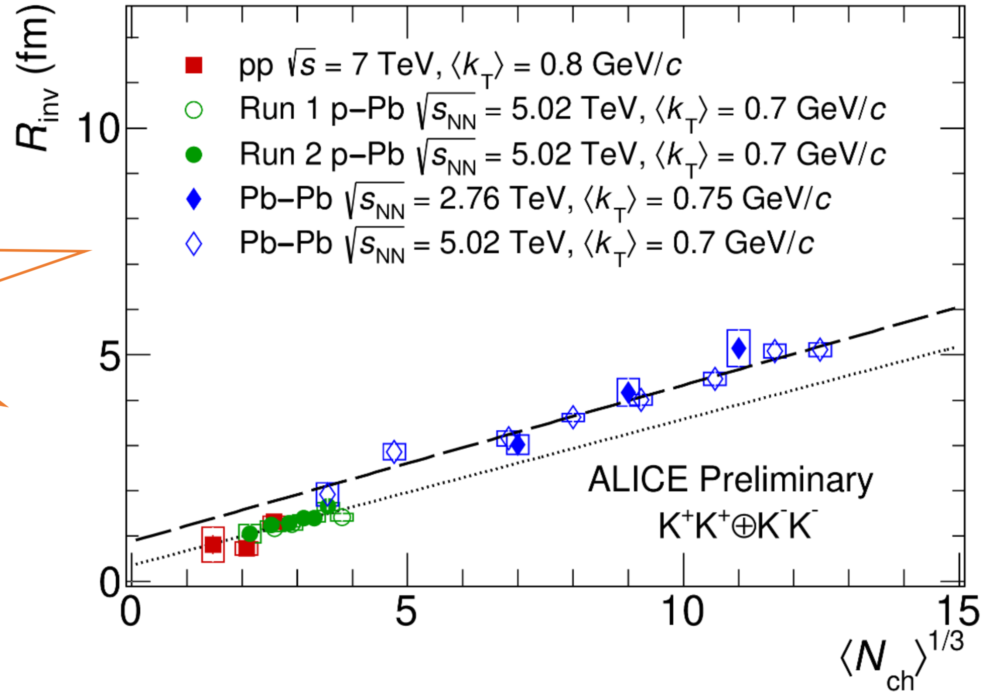


ALI-PREL-541025

1D $K^{\pm}K^{\pm}$: pp, p–Pb, Pb–Pb – new



ALI-PREL-541028



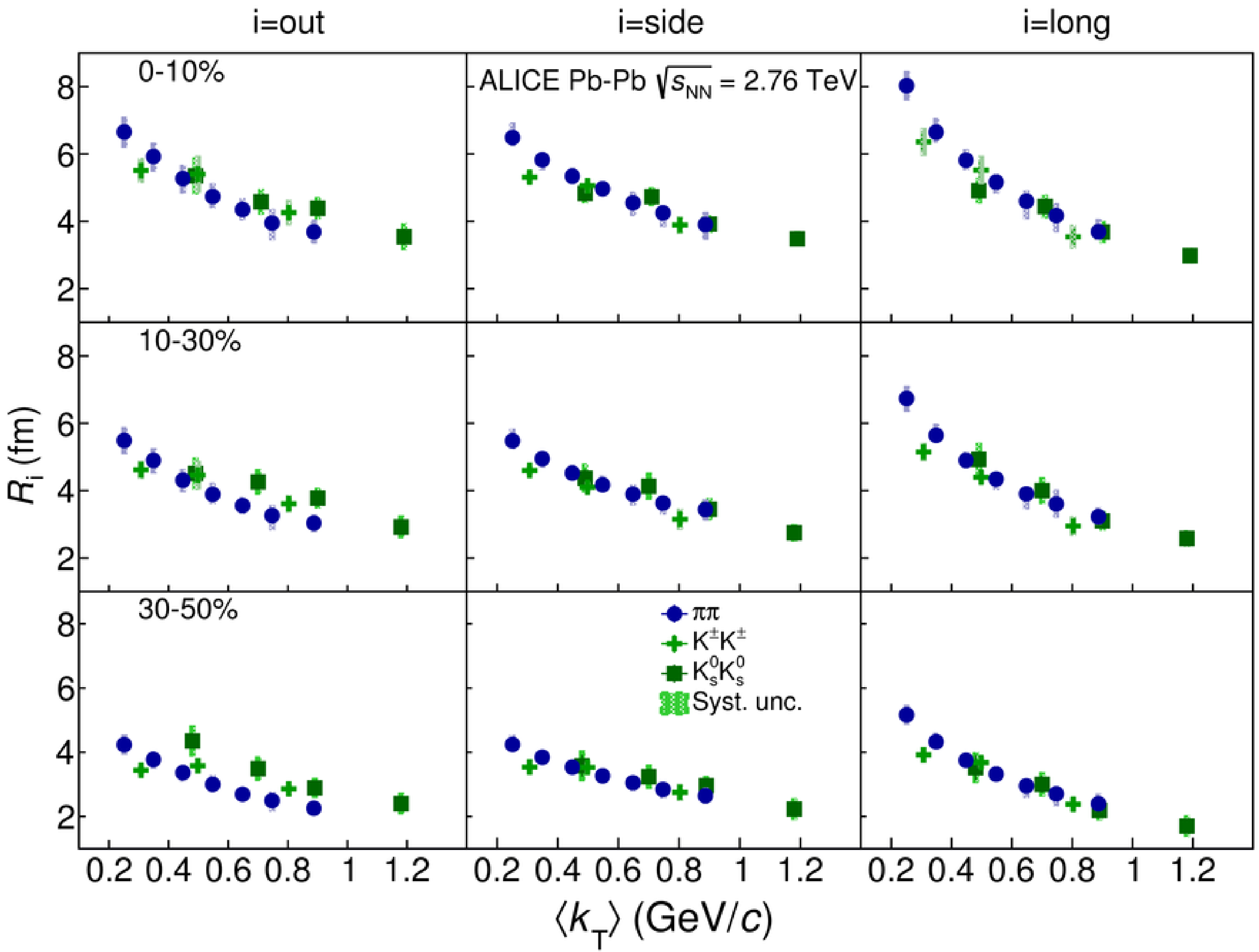
ALI-PREL-541025

more p–Pb and Pb–Pb points

- At similar multiplicity,
R_{inv}(p–Pb) ≈ R_{inv}(pp), R_{inv}(Pb–Pb) > R_{inv}(p–Pb)
- R_{inv}(pp&p–Pb) do not lie on the same curve as R_{inv}(Pb–Pb), gap increases with increasing k_T
- *Indication: Models predicting collective expansion in p–Pb are disfavored*
- *Indication: Importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb*

3D $K^{\pm}K^{\pm}$: Pb–Pb

ALICE, PRC96(2017)064613

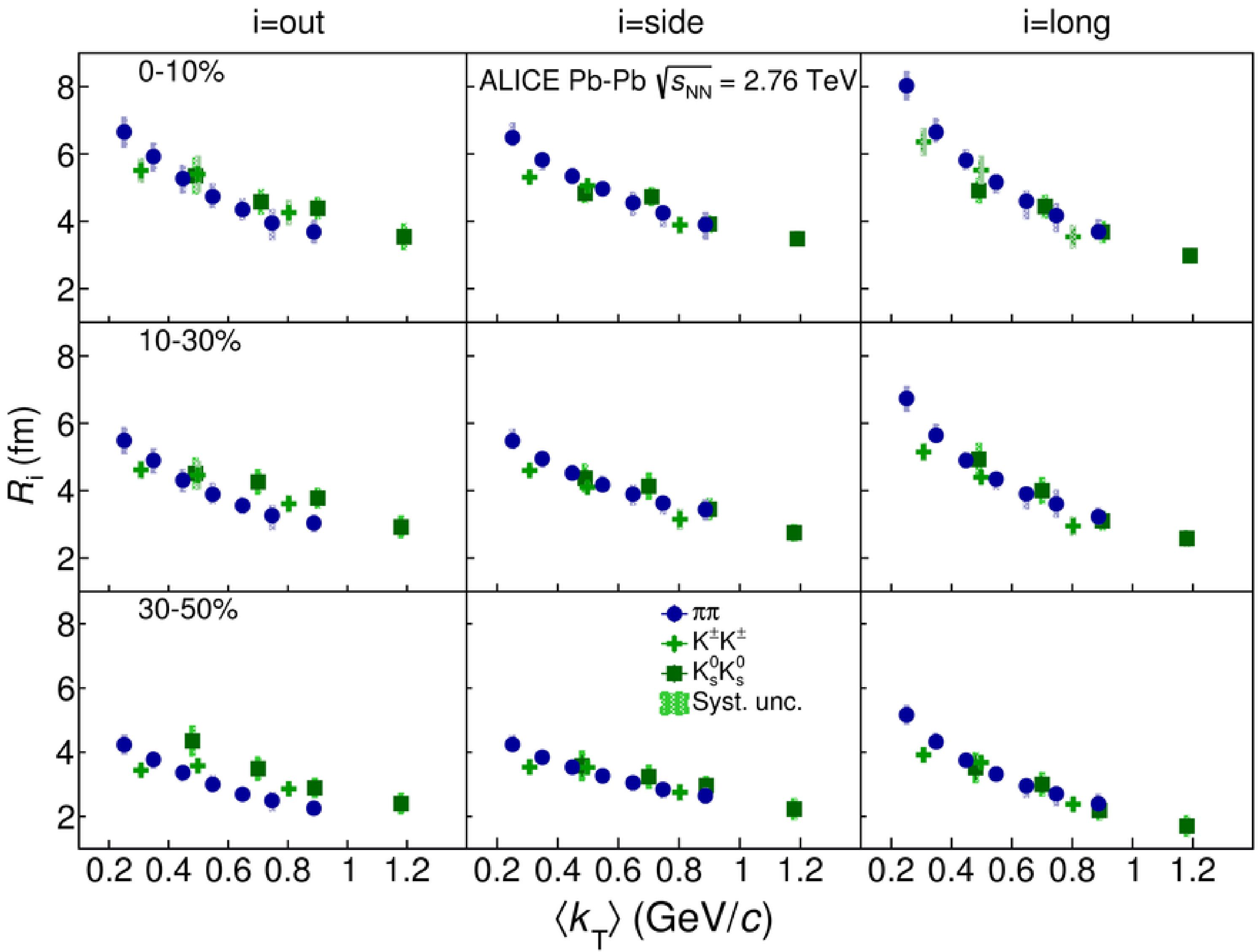


- R decrease with increasing pair transverse momentum k_T and for decreasing centrality → *hydrodynamic expansion of matter created in heavy-ion collisions*
- k_T scaling observed for pions and kaons *predicted by HKM+UrQMD cascade model*

Yu.M.Sinyukov et al., NPA946(2016)227

3D $K^{\pm}K^{\pm}$: Pb–Pb

ALICE, PRC96(2017)064613



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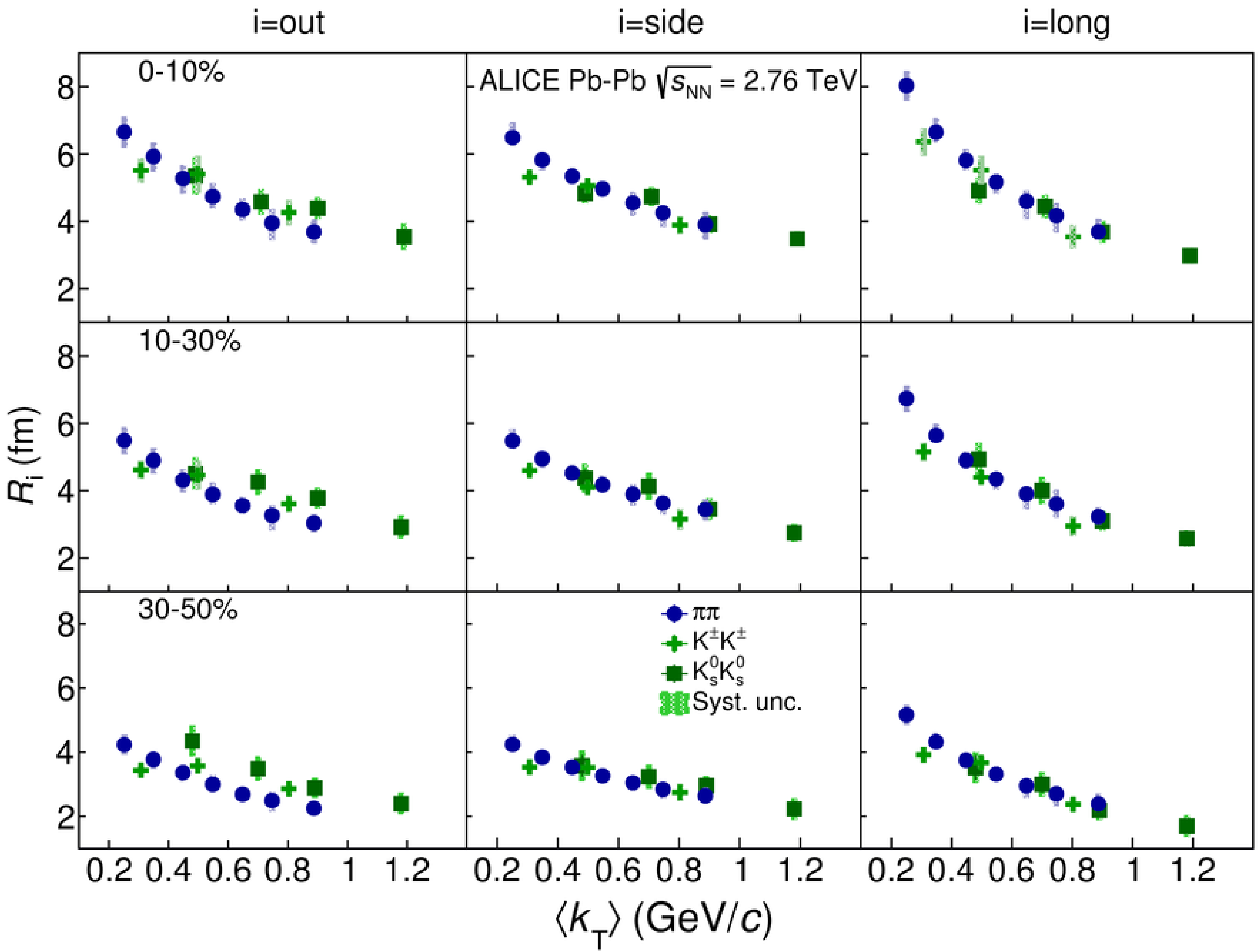
Yu.M.Sinyukov et al., NPA946(2016)227

3D $K^{\pm}K^{\pm}$: Pb–Pb

ALICE, PRC96(2017)064613



- R decrease with increasing pair transverse momentum k_T and for decreasing centrality →

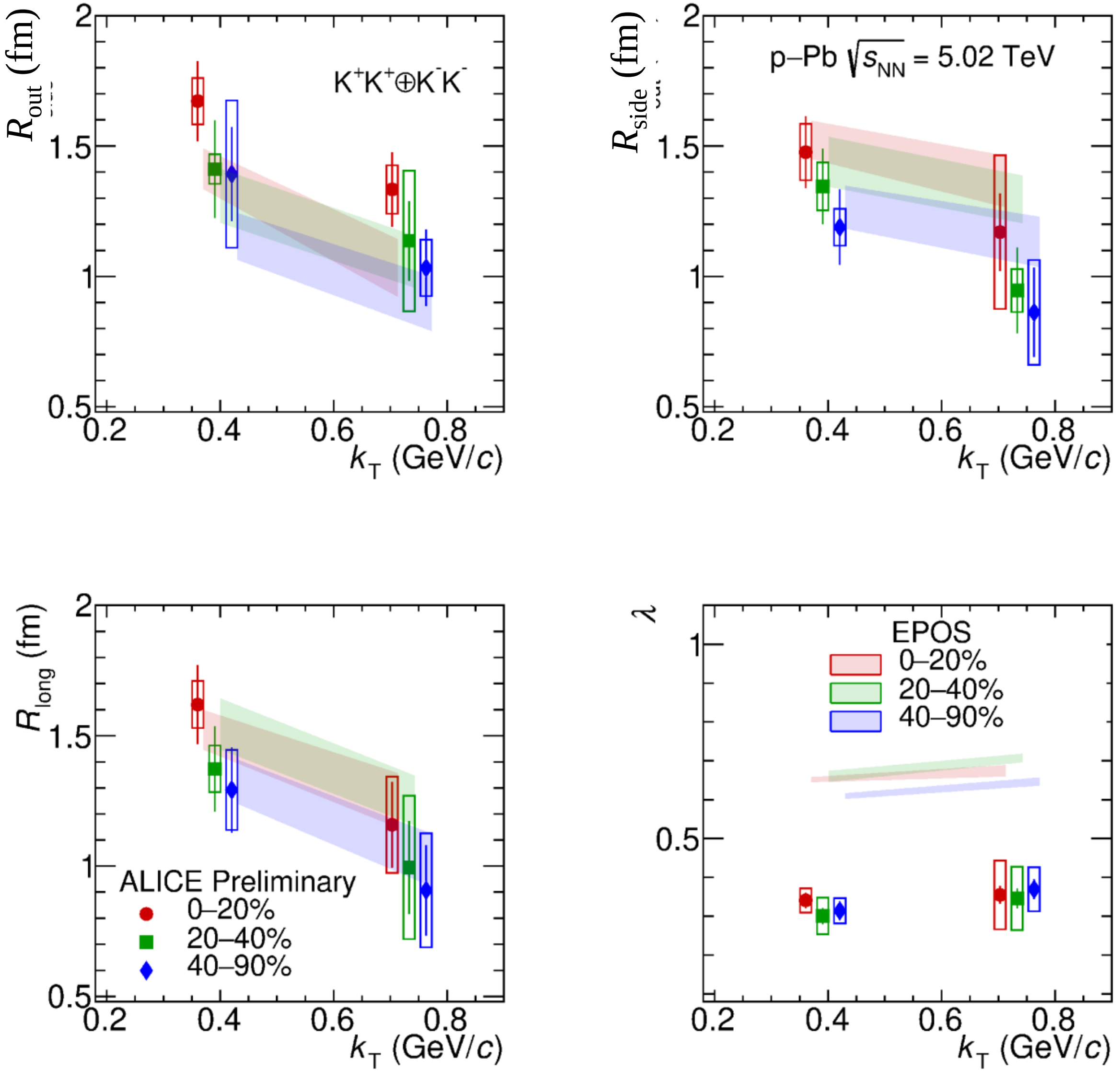
hydrodynamic expansion of matter created in heavy-ion collisions

- k_T scaling observed for pions and kaons

predicted by HKM+UrQMD cascade model

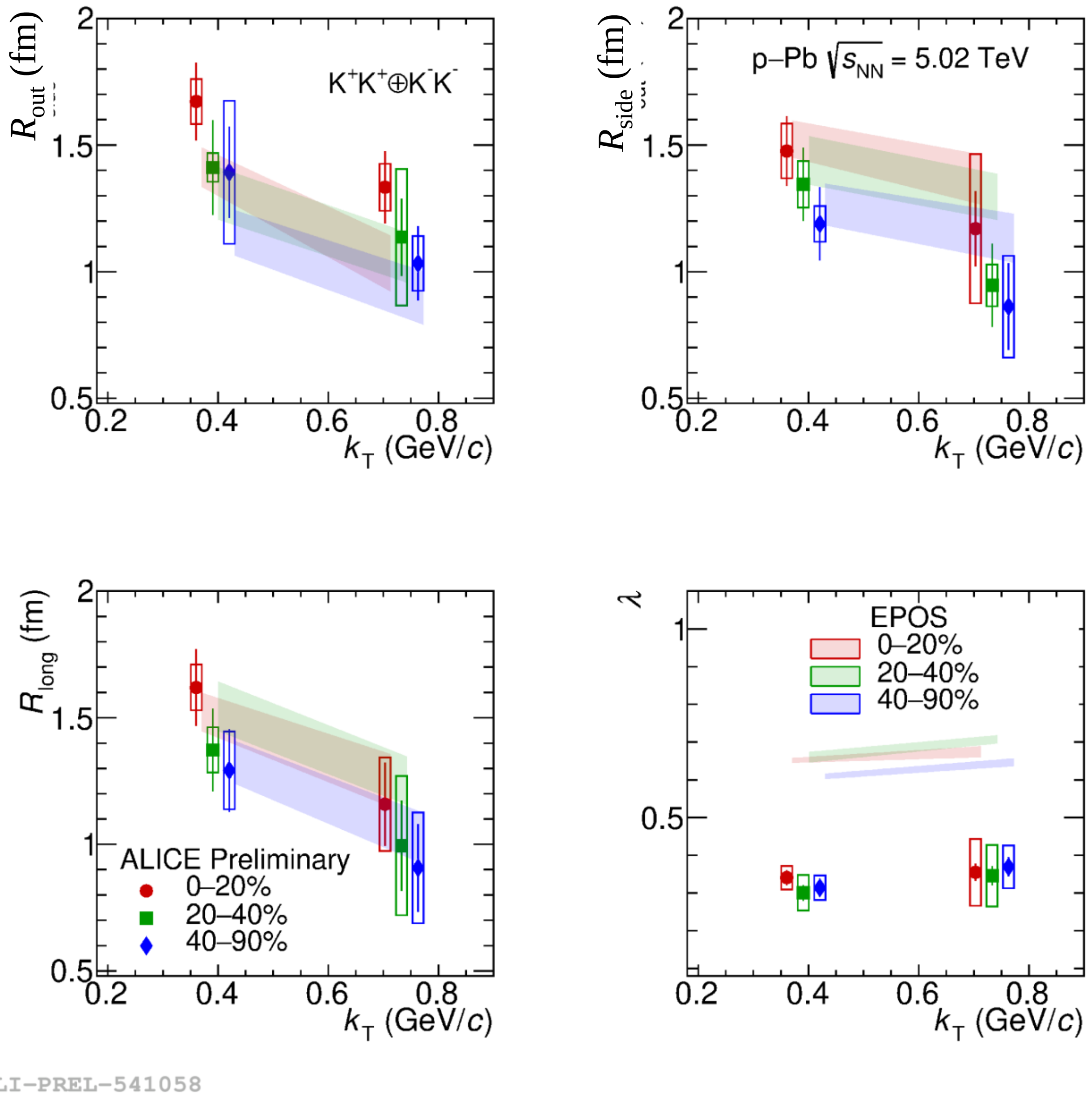
Yu.M.Sinyukov et al., NPA946(2016)227

3D K±K±: p–Pb



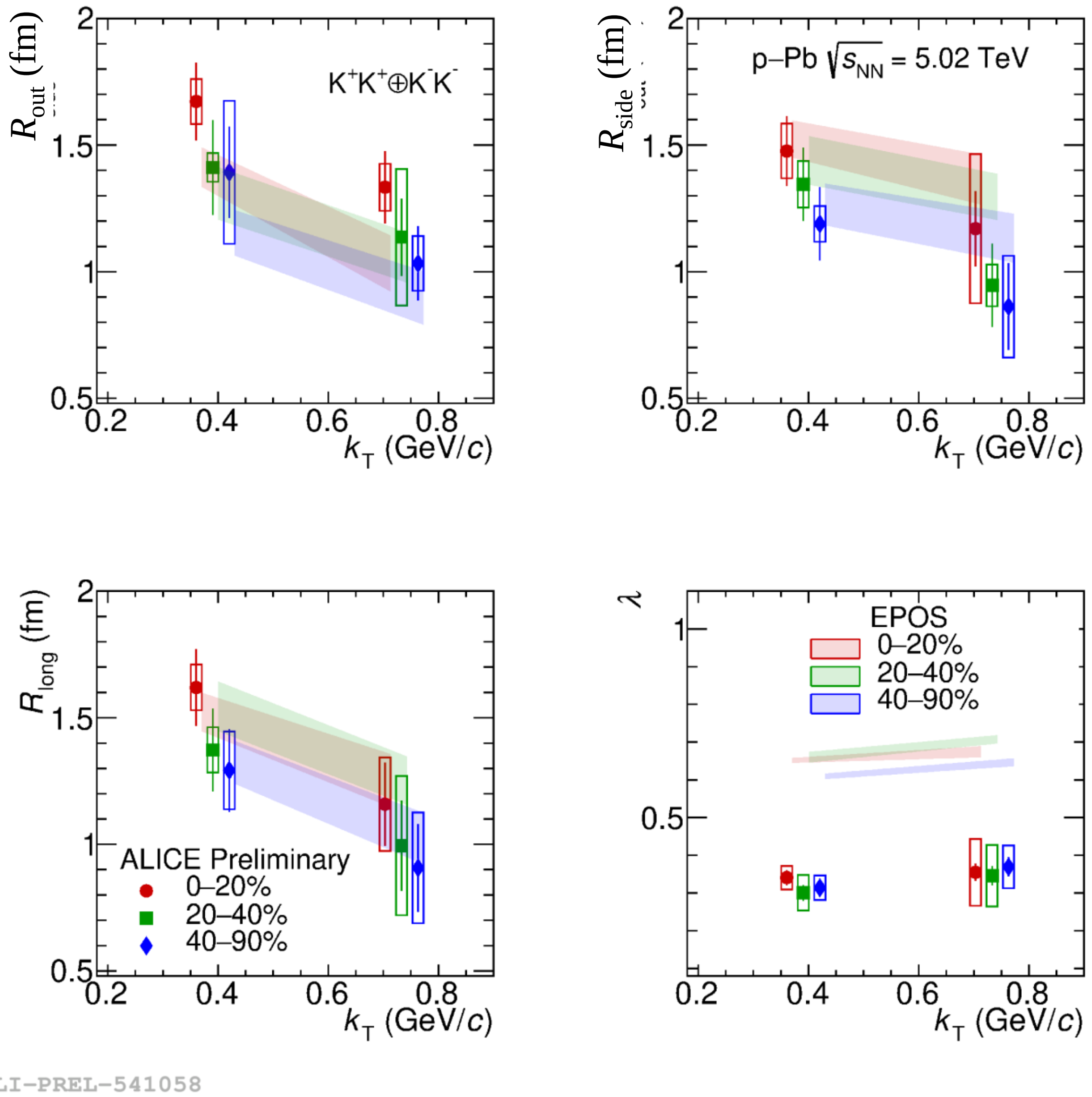
ALI-PREL-541058

3D $K^{\pm}K^{\pm}$: p–Pb



○ R decrease with increasing k_T and decreasing centrality → *hydrodynamic expansion of matter created in p–Pb collisions*

3D $K^{\pm}K^{\pm}$: p–Pb



○ R decrease with increasing k_T and decreasing centrality → *hydrodynamic expansion of matter created in p–Pb collisions*

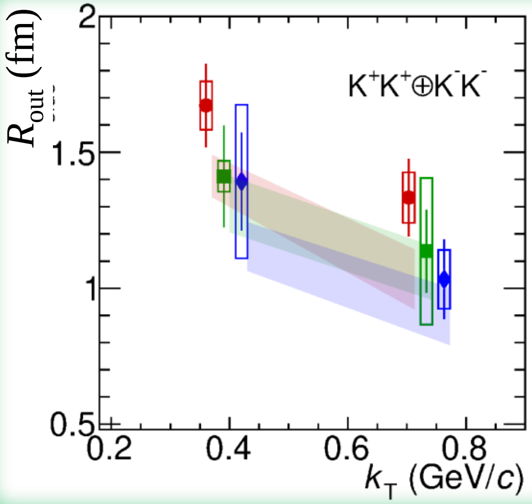
K.Werner et al., PRC89(2014)064903

○ EPOS describes R within uncertainties

○ Indication that EPOS underestimates R_{out} for central collisions

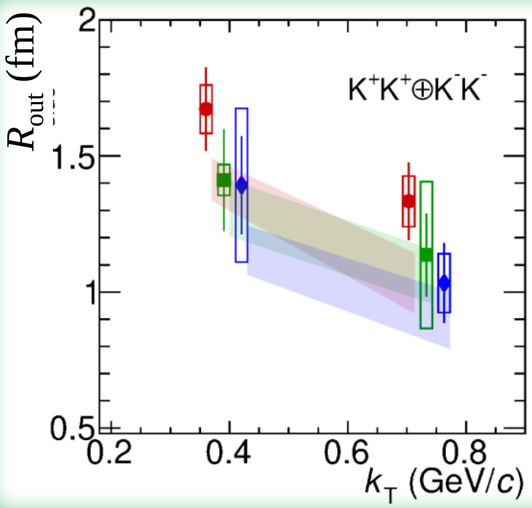
○ EPOS overestimates λ → *production of K from long-lived resonances like K* should probably be revised in the model*

3D: R_{out} problem



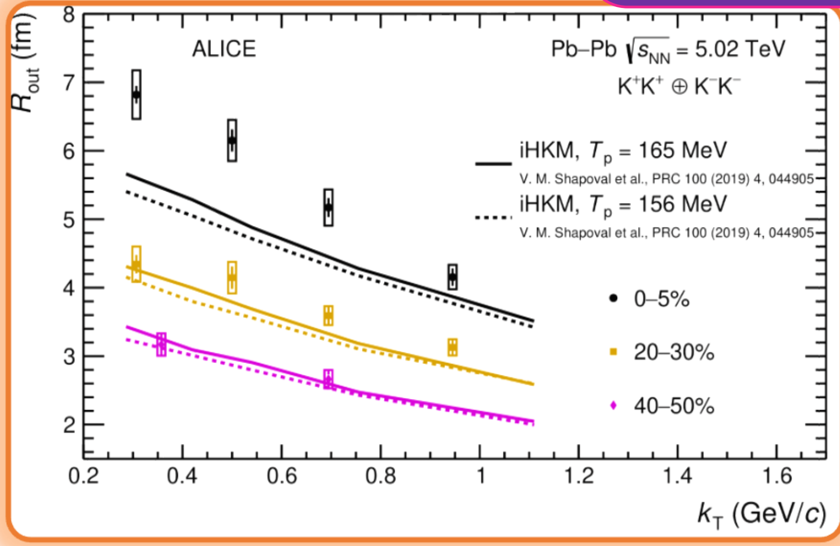
p–Pb@5.02 TeV: $K^{\pm}K^{\pm}$ vs EPOS 3

3D: R_{out} problem

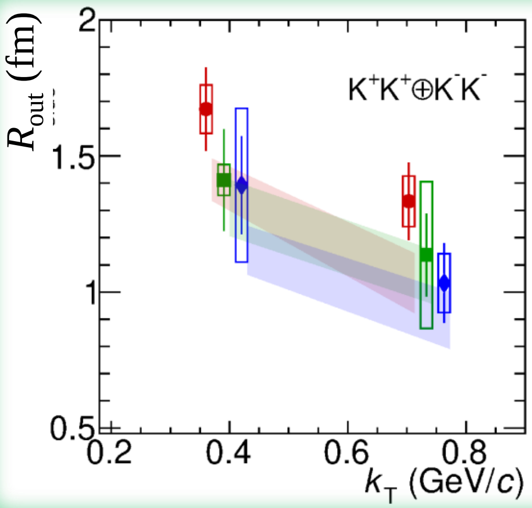


p–Pb@5.02 TeV: K±K±
vs
EPOS 3

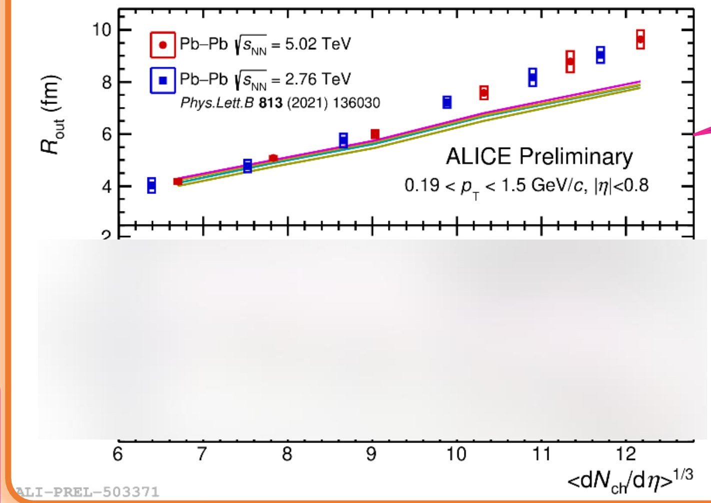
Pb–Pb@5.02TeV: K±K±
vs
iHKM



3D: R_{out} problem

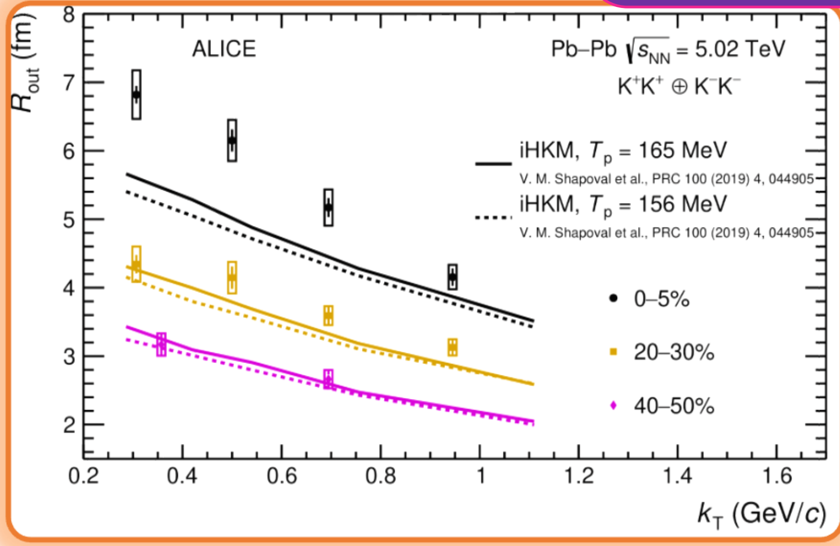


p–Pb@5.02 TeV: K±K± vs EPOS 3

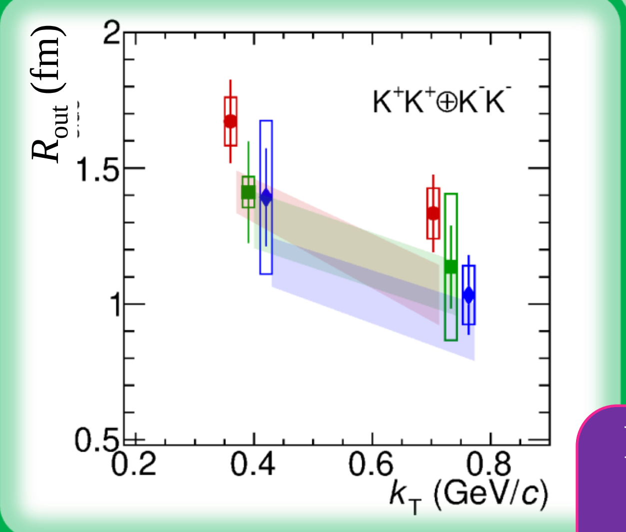


Pb–Pb@5.02TeV: π±K± vs THERMINATOR 2

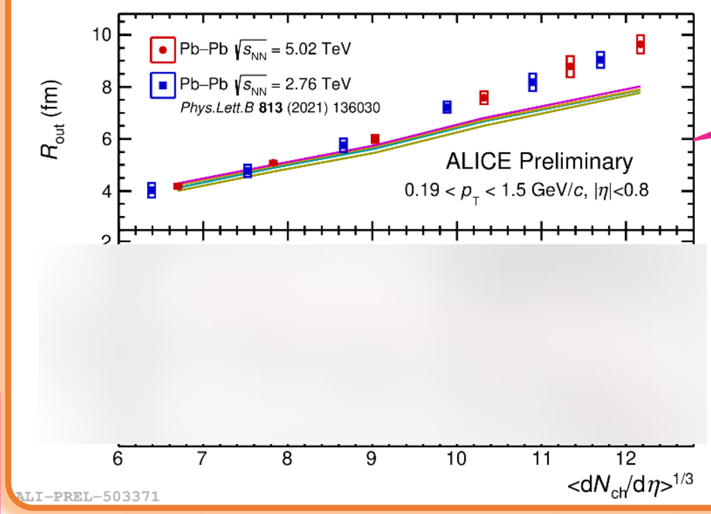
Pb–Pb@5.02TeV: K±K± vs iHKM



3D: R_{out} problem

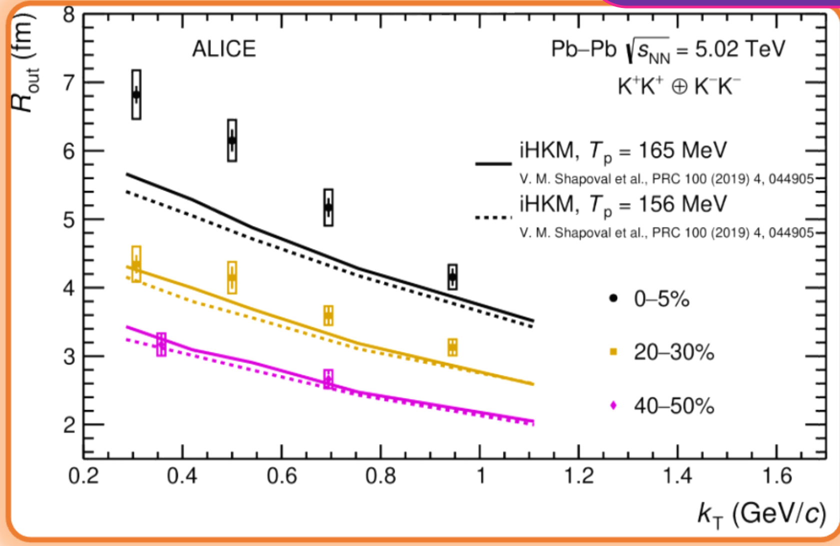


p–Pb@5.02 TeV: K±K± vs EPOS 3

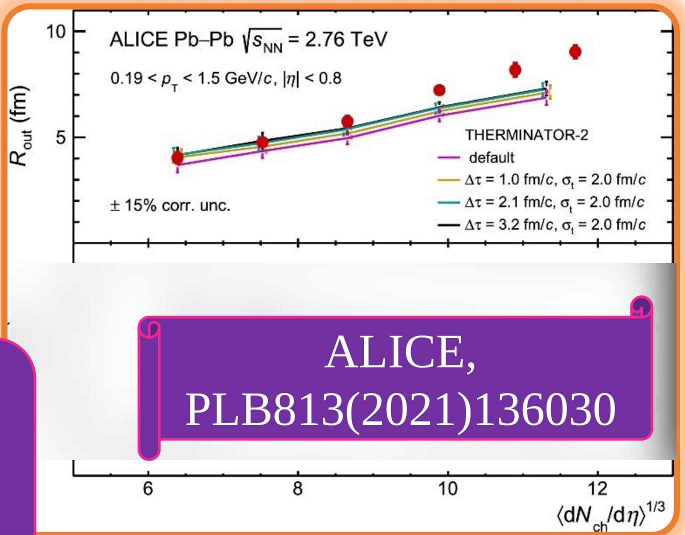


Pb–Pb@5.02TeV: π±K± vs THERMINATOR 2

Pb–Pb@5.02TeV: K±K± vs iHKM

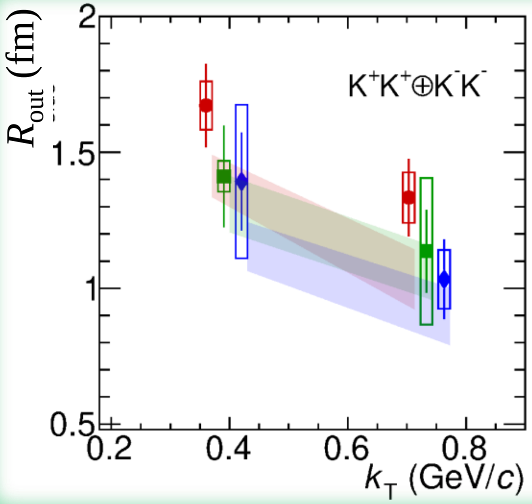


Pb–Pb@2.76TeV: π±K± vs THERMINATOR 2

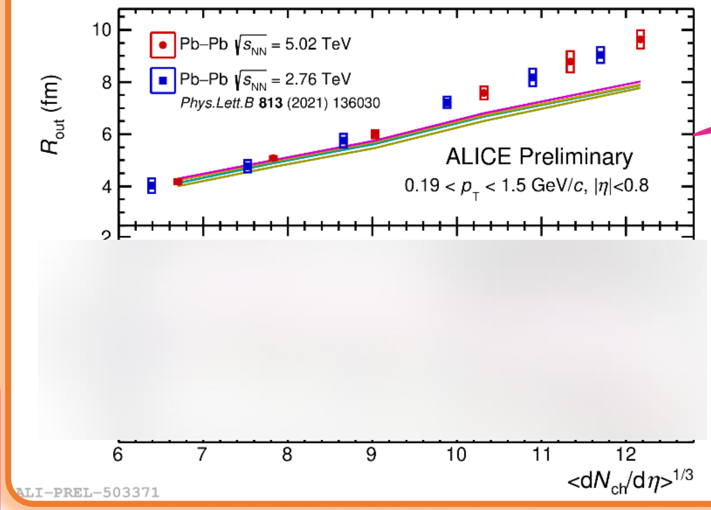


ALICE, PLB813(2021)136030

3D: R_{out} problem

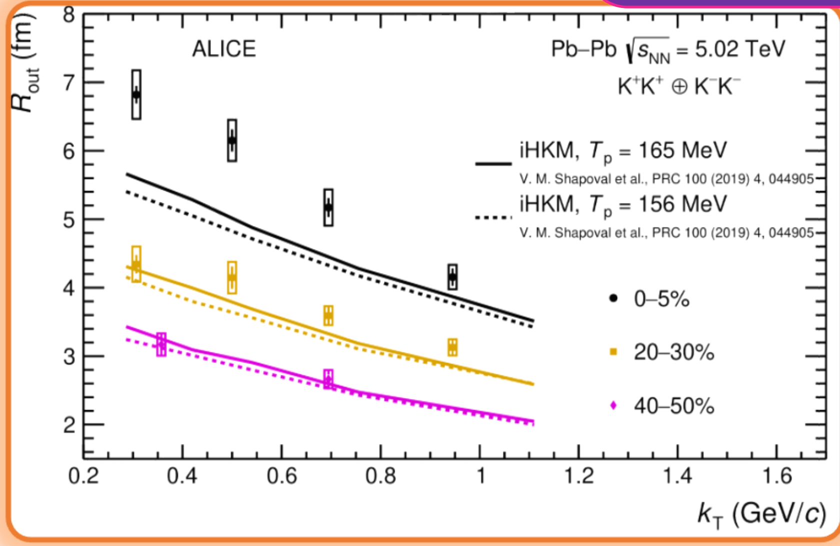


p–Pb@5.02 TeV: K±K± vs EPOS 3

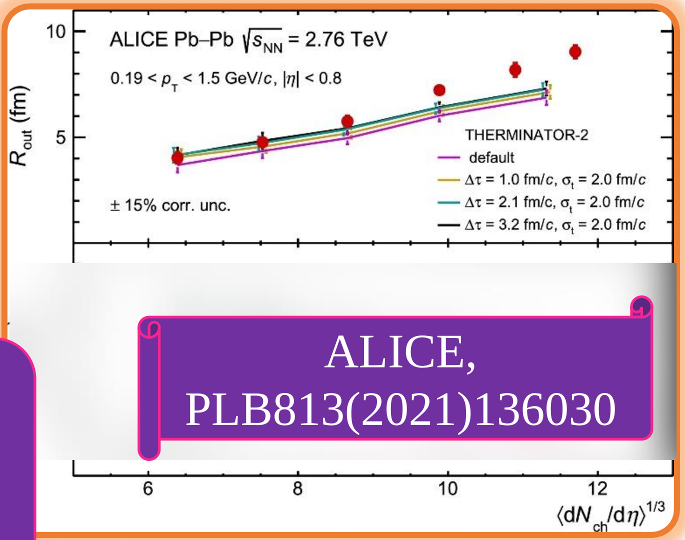


Pb–Pb@5.02TeV: π±K± vs THERMINATOR 2

Pb–Pb@5.02TeV: K±K± vs iHKM



Pb–Pb@2.76TeV: π±K± vs THERMINATOR 2

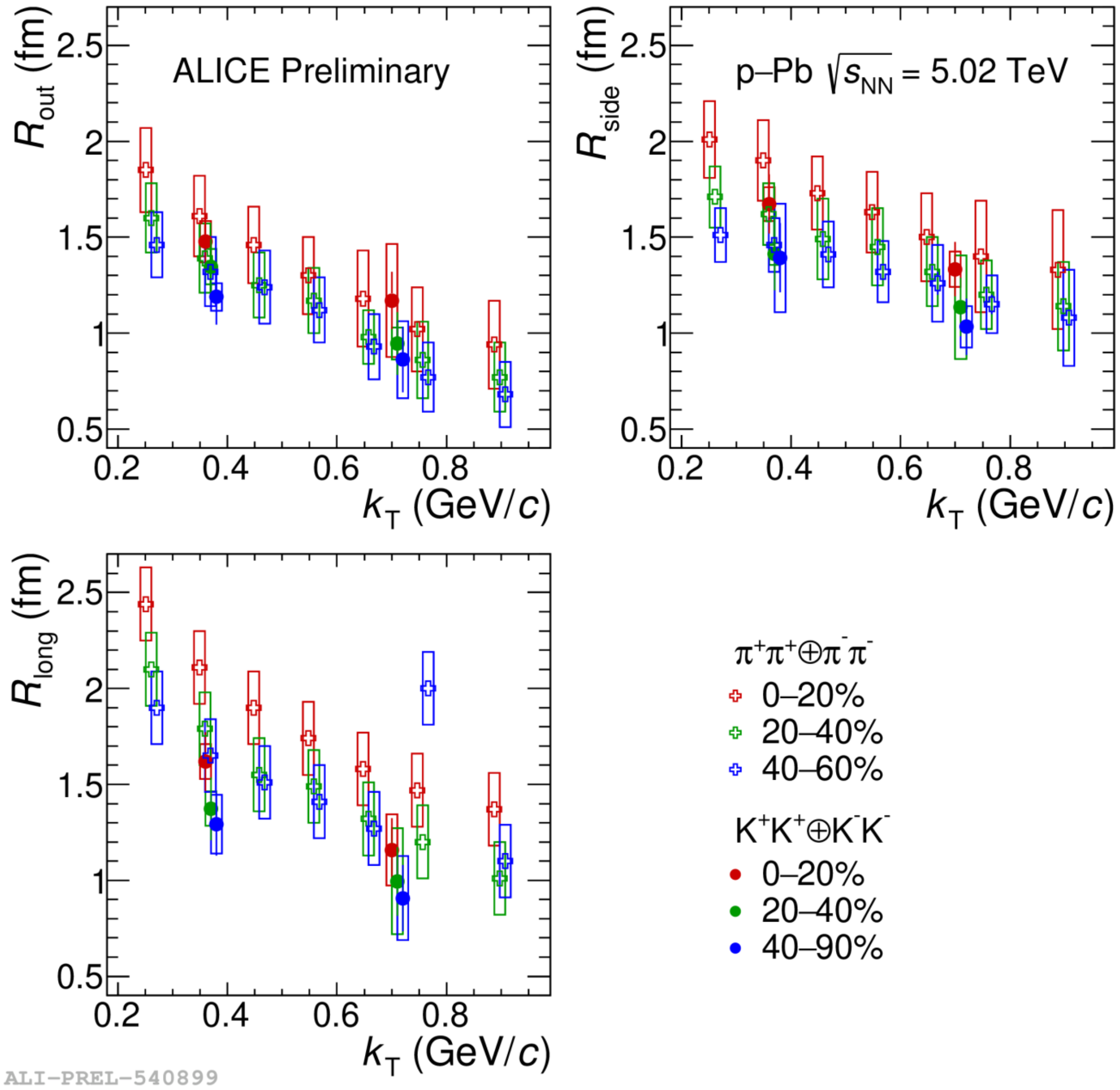


ALICE, PLB813(2021)136030

Hydrodynamic models do not manage to describe R_{out} for the most central events in p–Pb and Pb–Pb!

The reason is unknown.

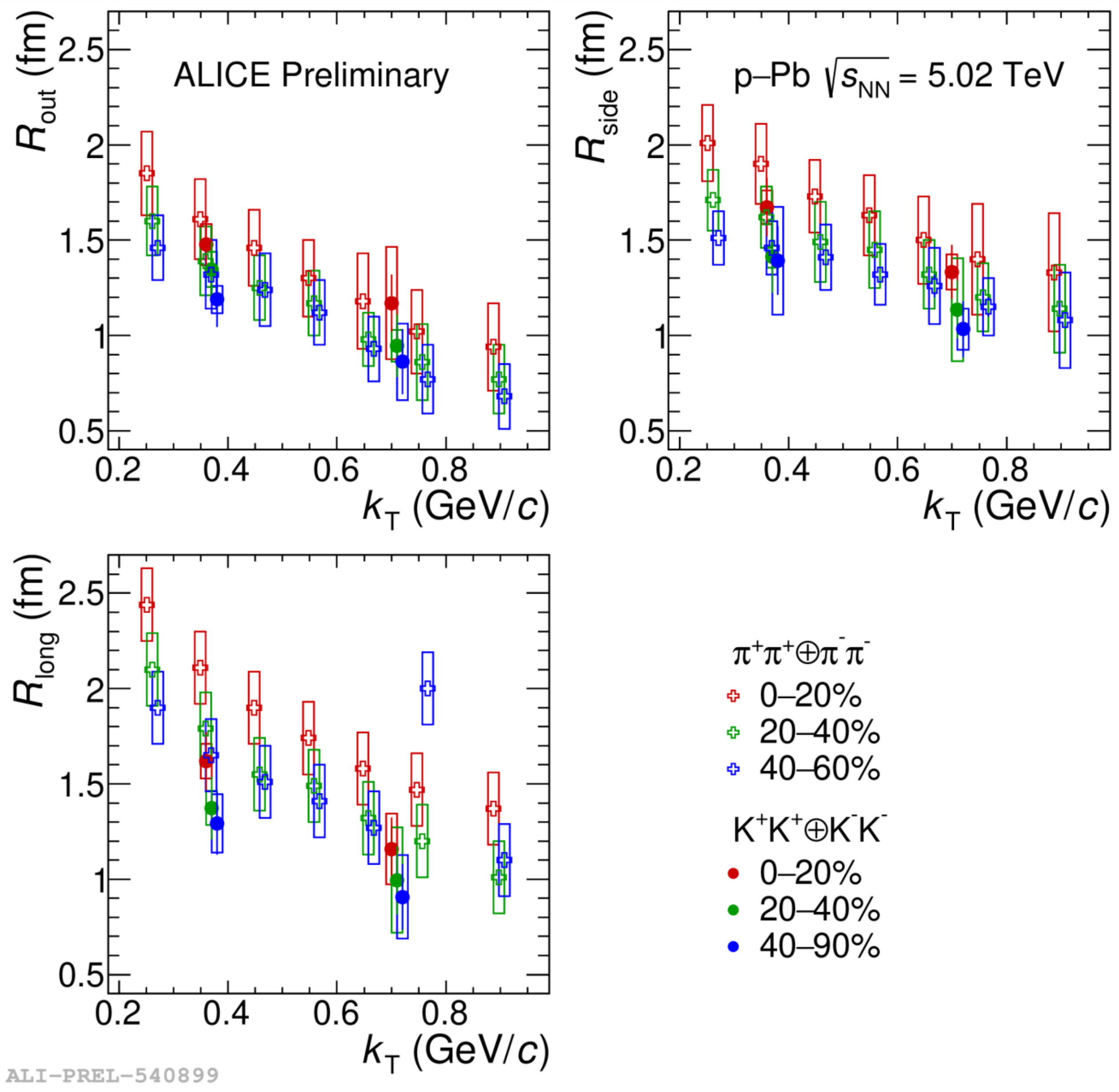
3D $\pi^{\pm}\pi^{\pm}$ vs $K^{\pm}K^{\pm}$: p–Pb



$\pi^{\pm}\pi^{\pm}$

ALICE, PRC91(2015)034906

3D $\pi^{\pm}\pi^{\pm}$ vs $K^{\pm}K^{\pm}$: p–Pb



$\pi^{\pm}\pi^{\pm}$

ALICE, PRC91(2015)034906

- At similar multiplicities, radii for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ agree within uncertainties →

π and K productions evolve similarly after collision

- Available data are not enough to say whether k_T/m_T scaling occurs in p–Pb

Maximal emission time

Yu.M.Sinyukov et al., NPA946(2016)227
V.M.Shapoval et al., EPJA56,10(2020)260

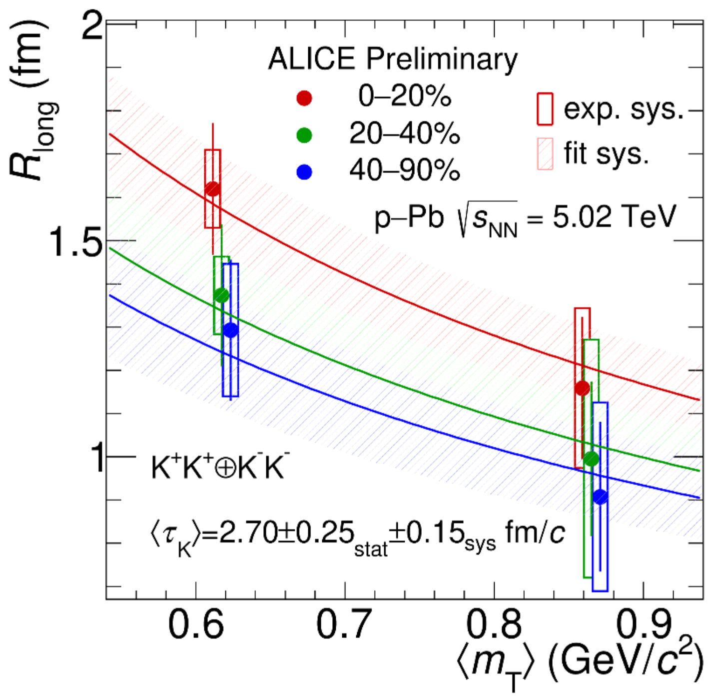
Estimate the lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximal.

Maximal emission time

Yu.M.Sinyukov et al., NPA946(2016)227
V.M.Shapoval et al., EPJA56,10(2020)260

Estimate the lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximal.

1. Fit pion and kaon p_T spectra → strength of collective flow α_π, α_K and temperature of maximal emission T extracted
2. Using T, fit kaon R_{long} → τ_K extracted



ALI-PREL-540893

Maximal emission time

Yu.M.Sinyukov et al., NPA946(2016)227
V.M.Shapoval et al., EPJA56,10(2020)260

Estimate the lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximal.

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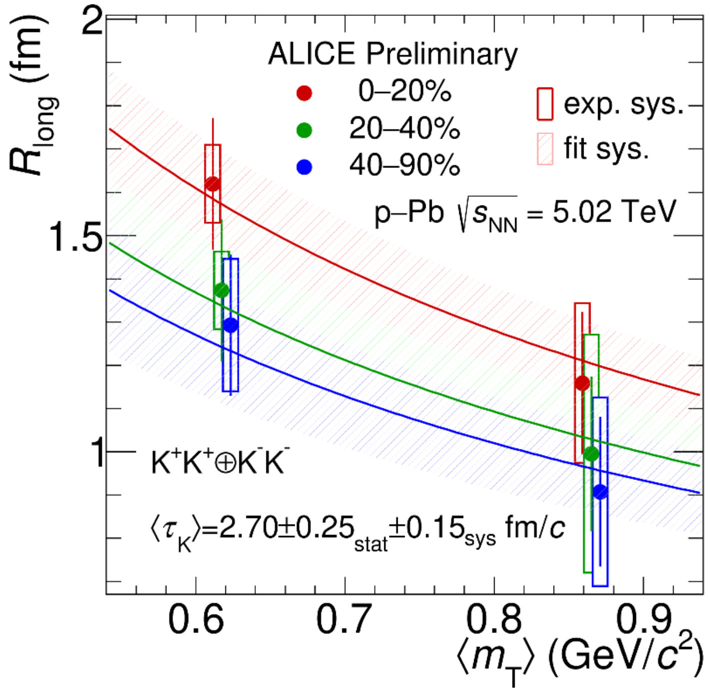
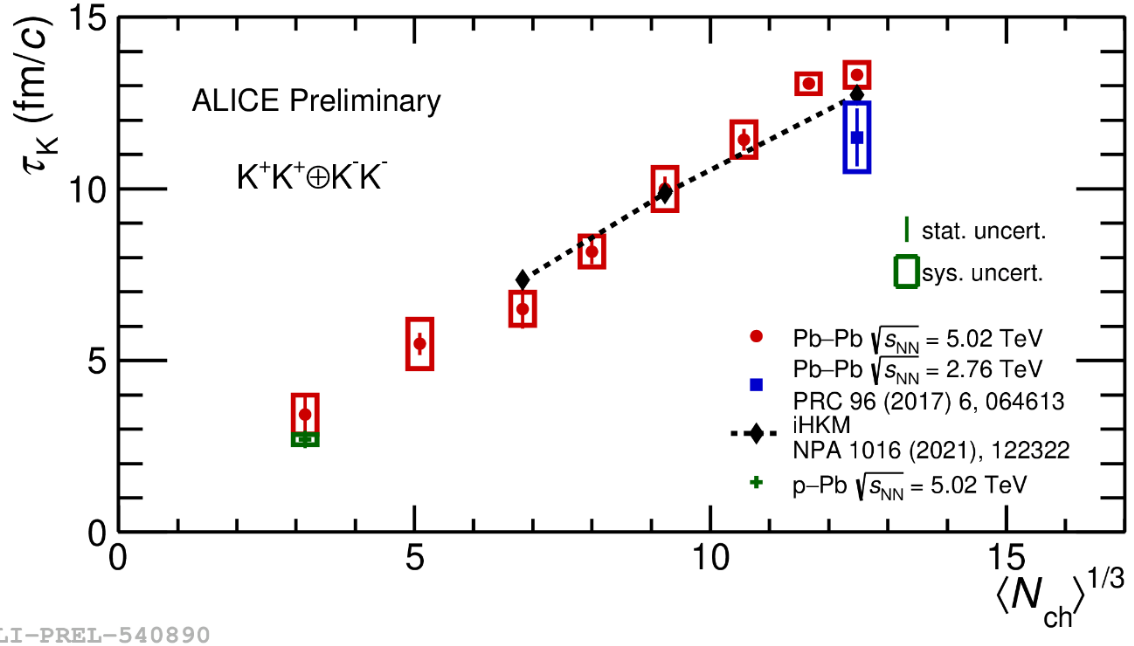


ALI-PREL-540893



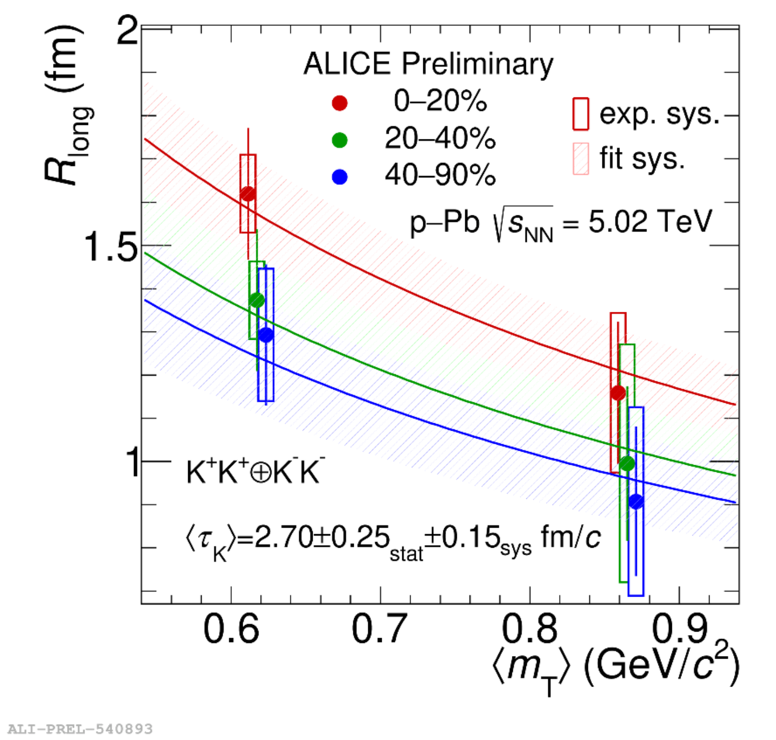
ALI-PREL-540890

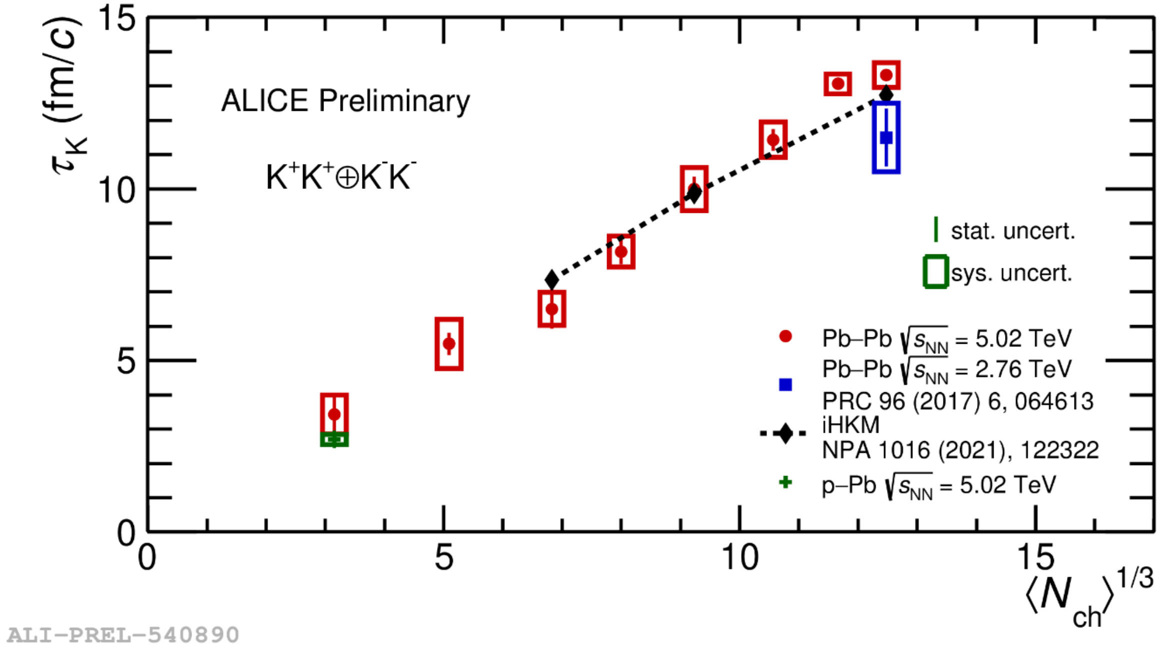
Maximal emission time

Yu.M.Sinyukov et al., NPA946(2016)227
V.M.Shapoval et al., EPJA56,10(2020)260

Estimate the lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximal.

1. Fit pion and kaon p_T spectra → strength of collective flow α_π, α_K and temperature of maximal emission T extracted
2. Using T, fit kaon R_{long} → τ_K extracted





- τ_K decreases for more peripheral events → *larger sources emit kaons slower*
- τ_K for p–Pb ≈ τ_K for the most peripheral Pb–Pb (70–90% centrality interval) at 5.02 TeV → *K production evolves similarly in p–Pb and peripheral Pb–Pb*
- More data are needed to see the trend of τ_K with multiplicity

Summary

- Hydrodynamic expansion of matter created in p–Pb and Pb–Pb
  - R for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ decrease with increasing k_T and decreasing multiplicity
- Importance of rescatterings to describe K correlations in p–Pb and Pb–Pb
  - R for $K^{\pm}$ are described by models if only they include UrQMD cascade
- Production of K from long-lived resonances like K* should probably be revised in EPOS
  - EPOS overestimates λ
- Models incorporating strong collective expansion in p–Pb as compared to pp collisions are disfavored
  - R for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ in pp and p–Pb agree at comparable multiplicities

Summary

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- Models incorporating strong collective expansion in p–Pb as compared to pp collisions are disfavored
  - R for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ in pp and p–Pb agree at comparable multiplicities
- Indication of importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb
  - R for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ in p–Pb and Pb–Pb disagree at comparable multiplicities
- Hydrodynamic models do not manage to describe R_{out} for the most central events
- π and K production in high-energy collisions evolves similarly
  - at similar multiplicities, R for $\pi^{\pm}\pi^{\pm}$ and $K^{\pm}K^{\pm}$ agree within uncertainties
- K production in p–Pb and peripheral Pb–Pb evolves similarly with time
  - τ_K in p–Pb agree within uncertainties with τ_K in very peripheral Pb–Pb
- Larger sources freeze-out later
  - τ_K decreases with decreasing multiplicity

new