Overview on ALICE results on femtoscopy

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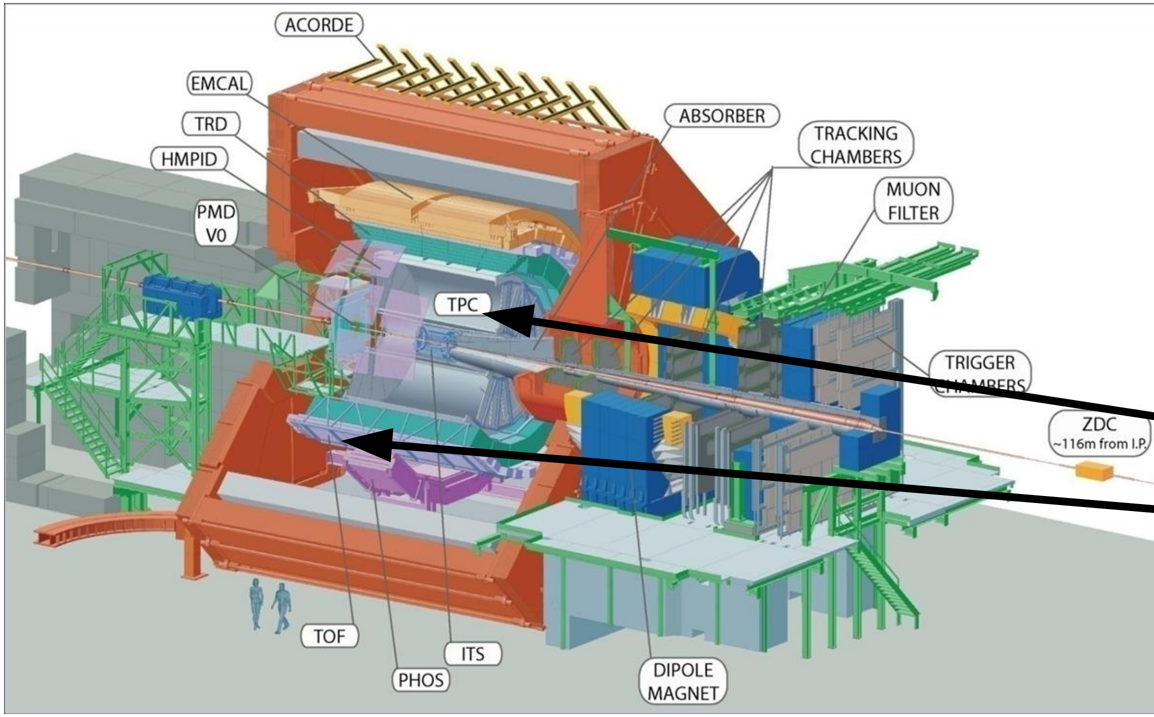
For the ALICE Collaboration

Cracow Epiphany Conference
on the physics after the first phase of the LHC

Overview

- Measuring size of particle emitting source (π, K, p)
- Wide range of pair transverse mass (m_T): test of dynamic evolution. Does collectivity go beyond pions?
- Different sources of correlations:
  - Quantum Statistics (QS)
  - Coulomb and Strong Final State Interactions (FSI)
- Possible measurements of unknown interaction potentials (p$\bar{\Lambda}$, $\Lambda\bar{\Lambda}$)

Experiment details



- pp collisions at 7 TeV ($\sim 300 \cdot 10^6$ events)
- Pb-Pb collisions at 2.76 ATeV ($\sim 30 \cdot 10^6$ events)
- Particle identification and tracking:
  - Time Projection Chamber
  - Time-of-Flight
- Single- and two-track effects taken into account

Correlation function: $C(q) = \dfrac{A(q)}{B(q)}$

q - pair relative momentum

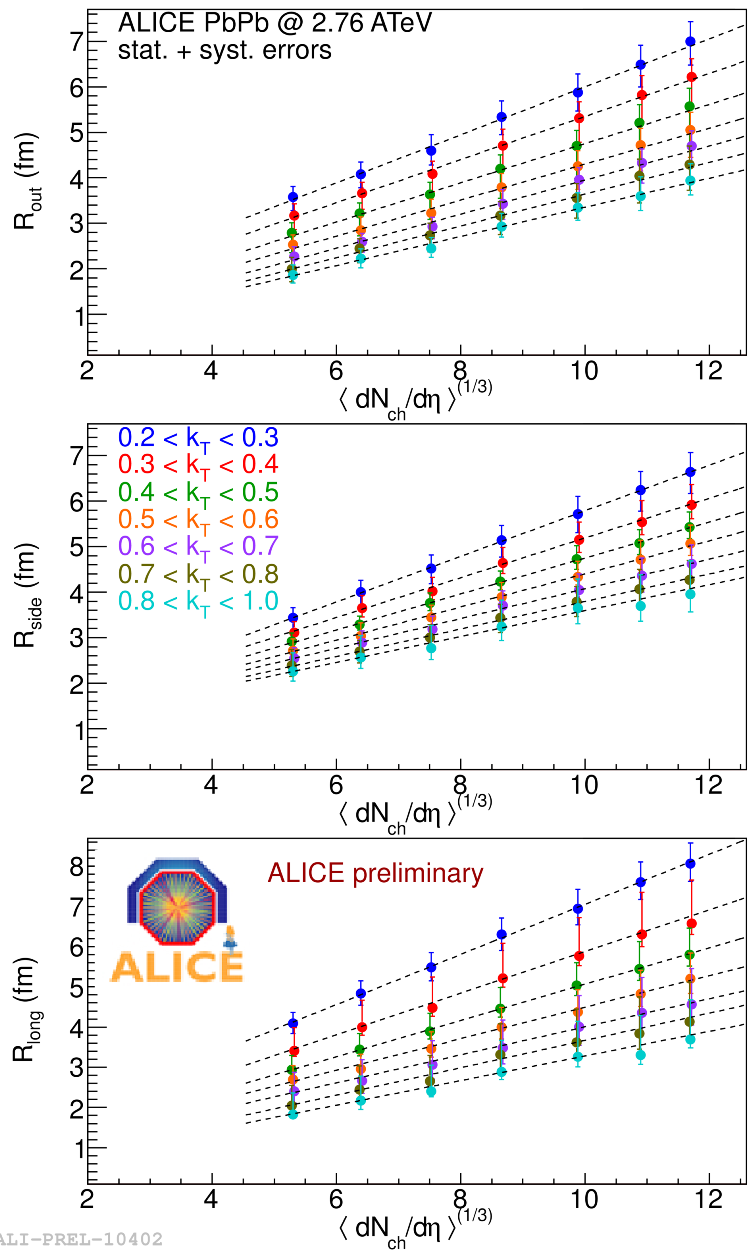
q → q_{inv} - 1D in Pair Rest Frame

q → $\vec{q}$ - 3D in Longitudinally Co-Moving System *(out, side, long)*

$A(q)$ - signal (both particles from the same event)

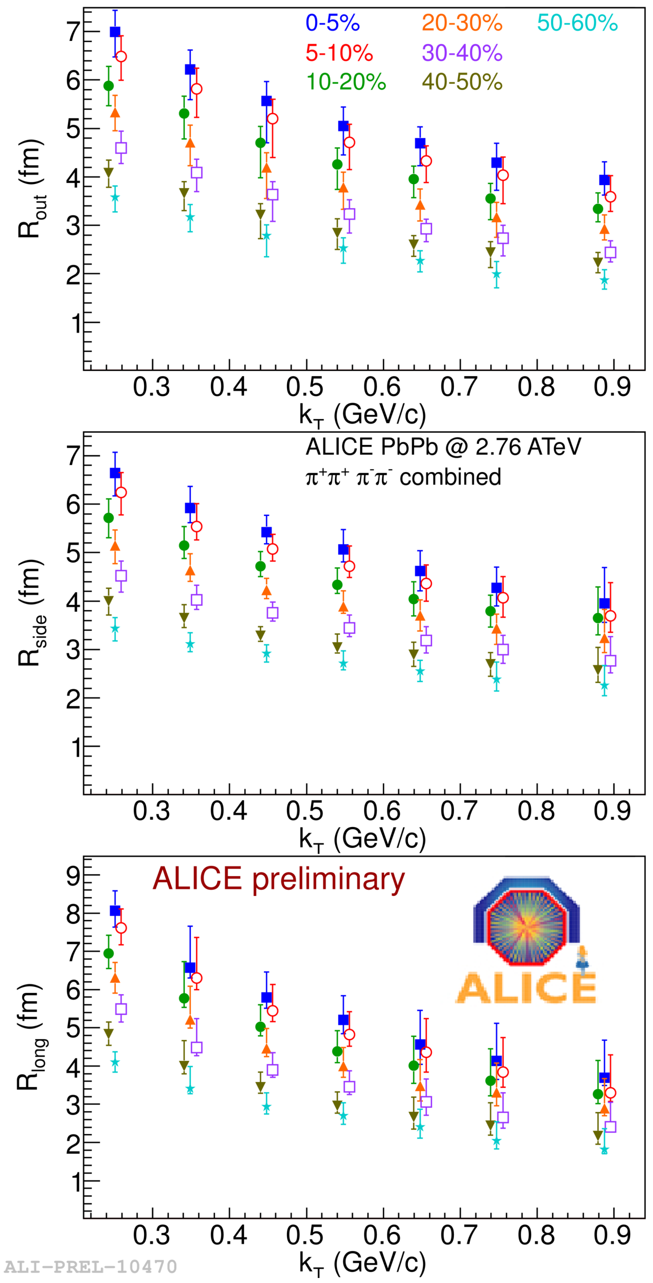
$B(q)$ - background (particles from two different events)

Pion radii vs. mulitplicity vs. k_T

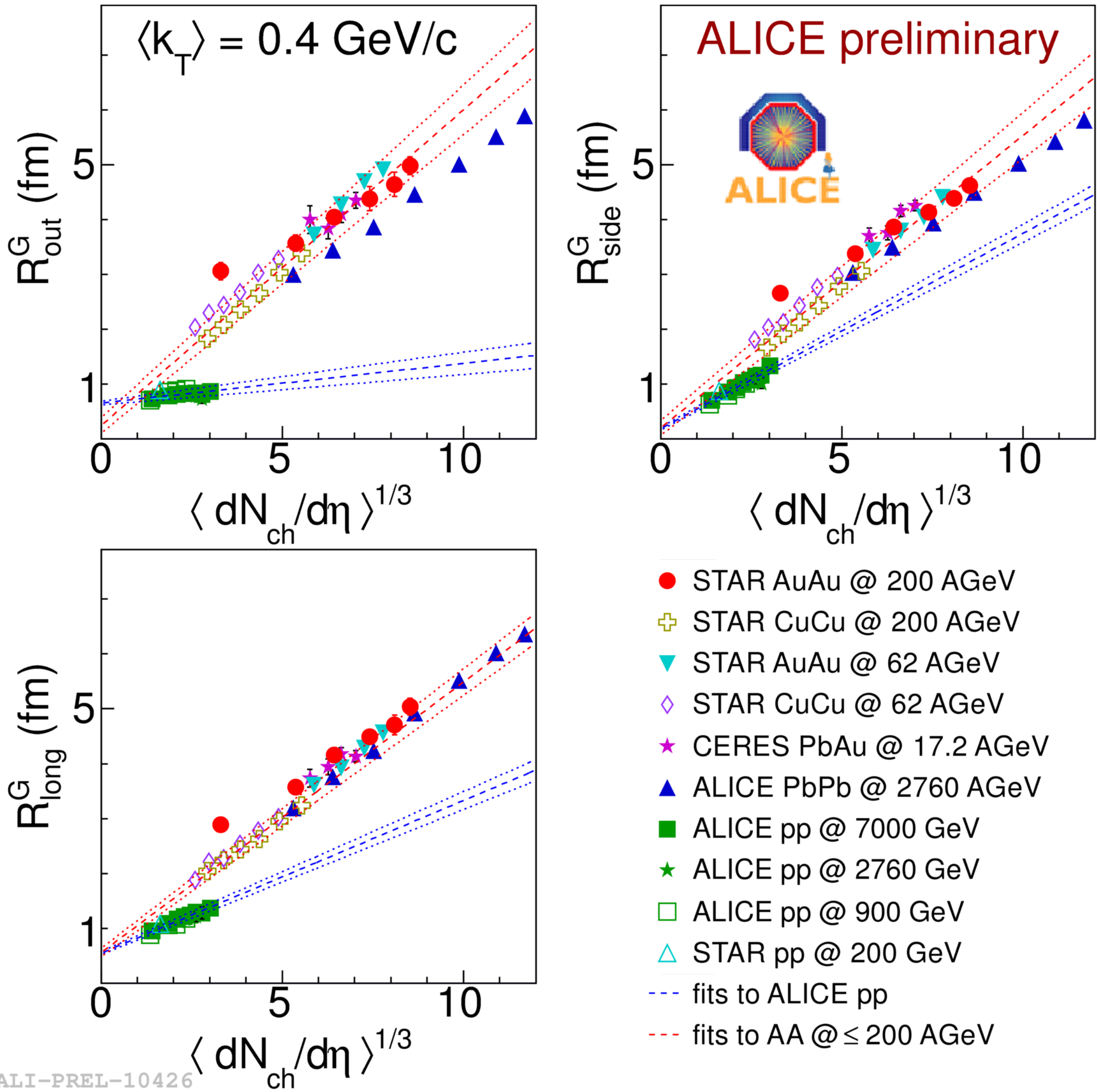


- Radii incerease with event multiplicity (larger initial size → larger size at freeze-out)

- Radii decrease with pair transverse momentum k_T (due to flow)



Pion femtoscopy in pp and AA

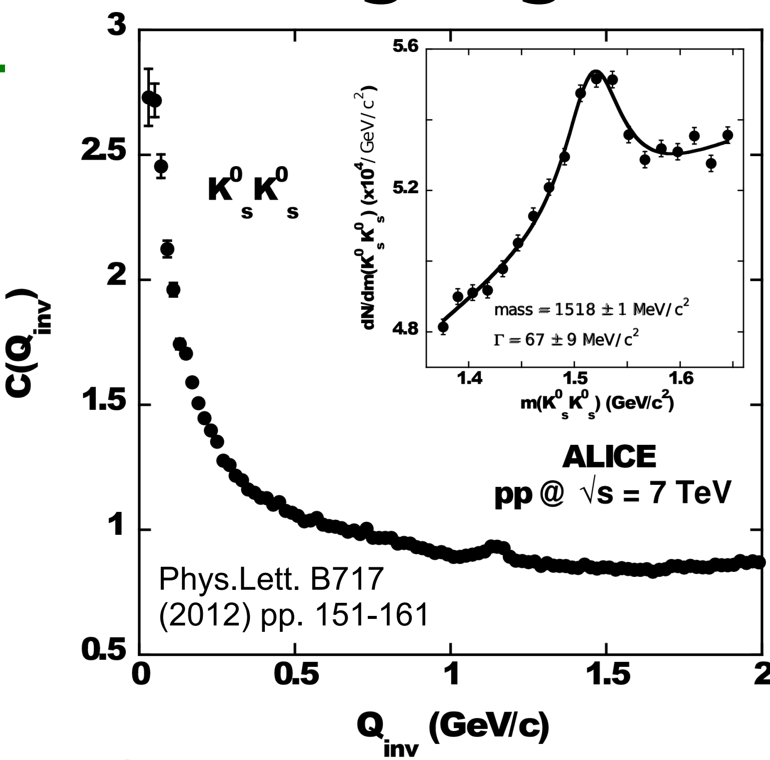


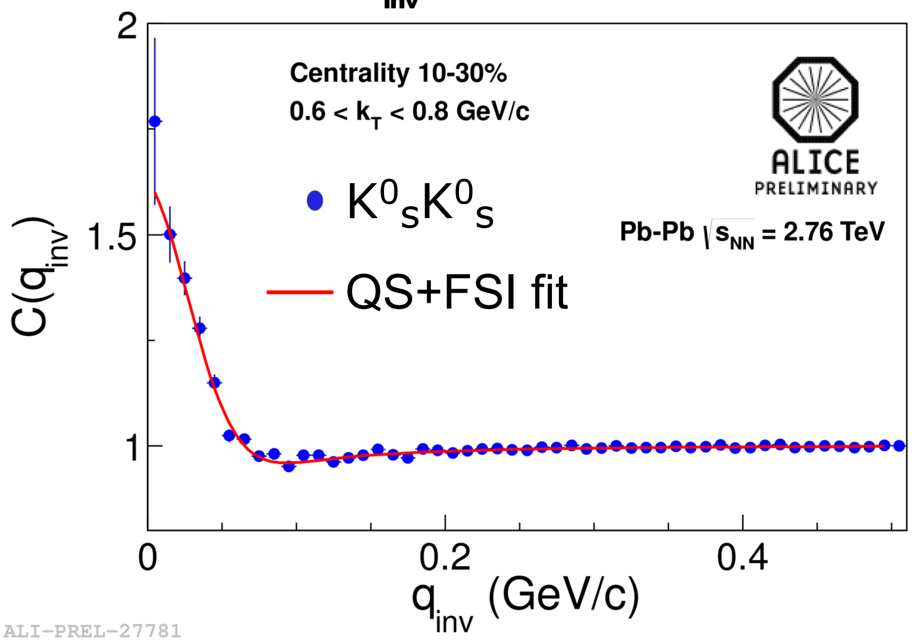
- In pp and AA, radii scale linearly, but with clearly different slope (initial size matters)
- Radii in "long" and "side" direction in a good agreement with data from lower energies
- Radii in "out" direction below the linear scaling, as predicted by hydrodynamics

Kaon femtoscopy

- Neutral kaons
  - PID via $\pi^+\pi^-$ decay channel (purity ~95%) - easily identified up to 2 GeV/*c*
  - Strong FSI and Quantum Statistics corroborate to create femtoscopic effect, both included in the fit (*Lednicky&Lyuboshitz model, Sov.J.Nucl.Phys. 35,770 (1982)*)
  - No Coulomb suppression
- Charged kaons
  - PID: TPC+TOF for considerable p_T range (up to 1.5 GeV/*c*)
  - Bowler-Sinyukov fit $C(q_{inv}) = (1-\lambda) + \lambda K(q_{inv})(1+\exp(-R_{inv}^2 q_{inv}^2))$
- Differential analysis in Pb-Pb
  - 3 centrality bins
  - Pair transverse momentum (k_T) bins: 4 (neutral kaons), 7 (charged kaons)

$K^0_sK^0_s$ and $K^{ch}K^{ch}$ in pp and Pb-Pb

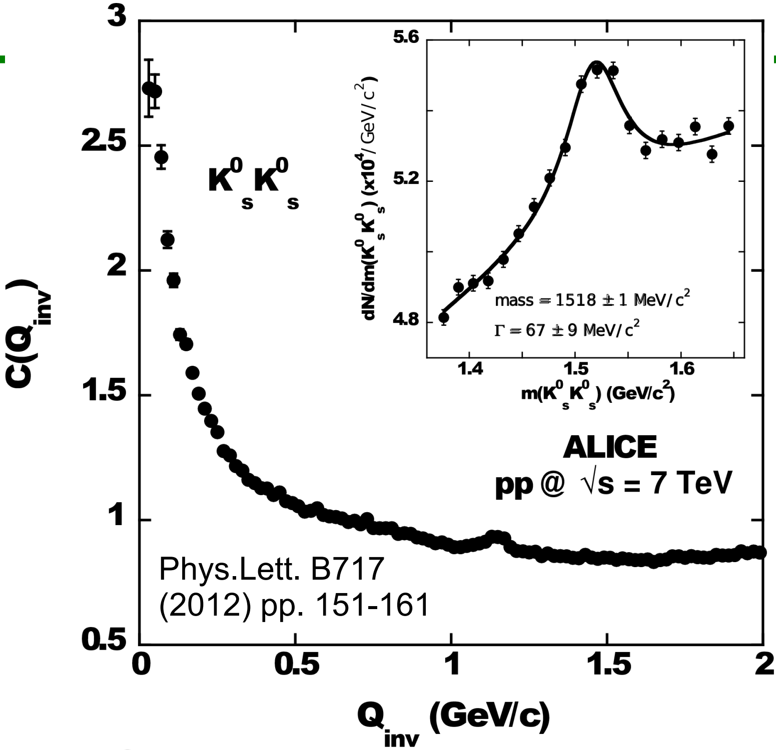




Neutral kaons

- In pp and Pb-Pb enhancement at low q_{inv}
- In pp non-flat background for q_{inv}>0.3 GeV/c
- The first observation of $f'_2(1525) \rightarrow K^0_sK^0_s$ in pp

$K^0_s K^0_s$ and $K^{ch}K^{ch}$ in pp and Pb-Pb



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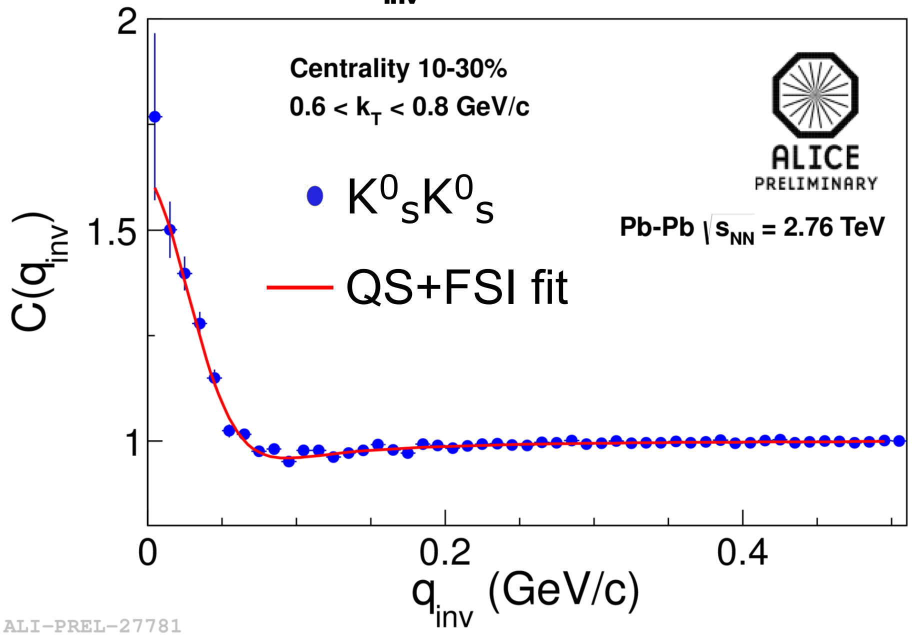
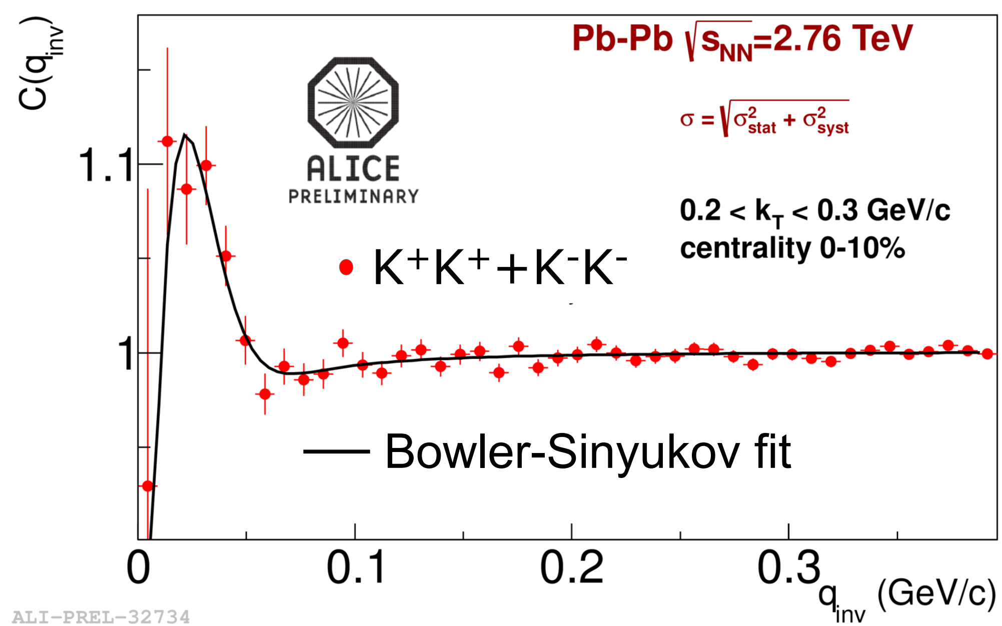
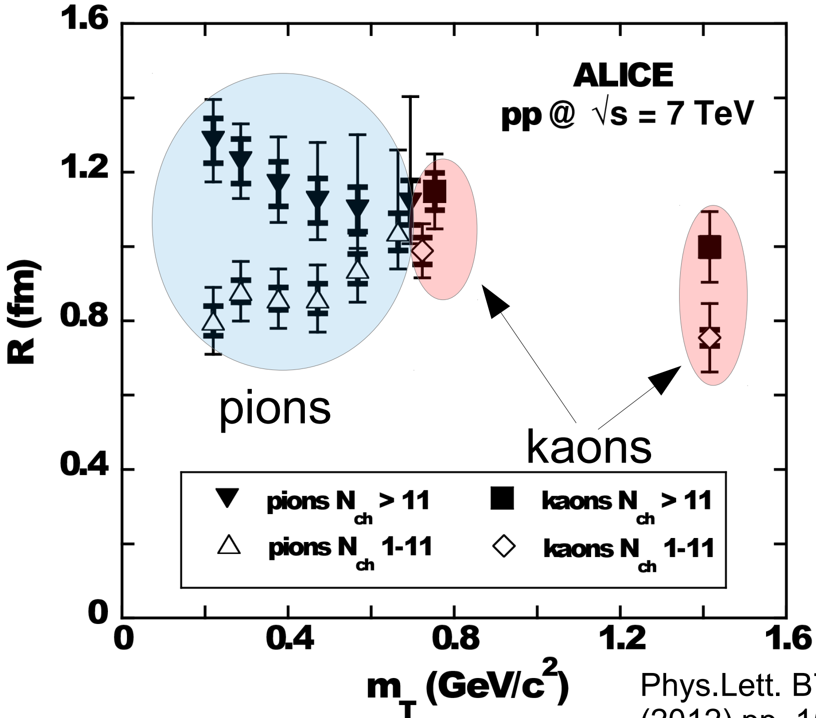
Charged kaons

- Bose-Einstein enhancement
- Coulomb repulsion





Kaon radii in pp and Pb-Pb



Phys.Lett. B717 (2012) pp. 151-161

- pp collisions
  - R_{inv} (for kaons) decreases with increasing m_{T}
  - R_{inv} increases with increasing multiplicity

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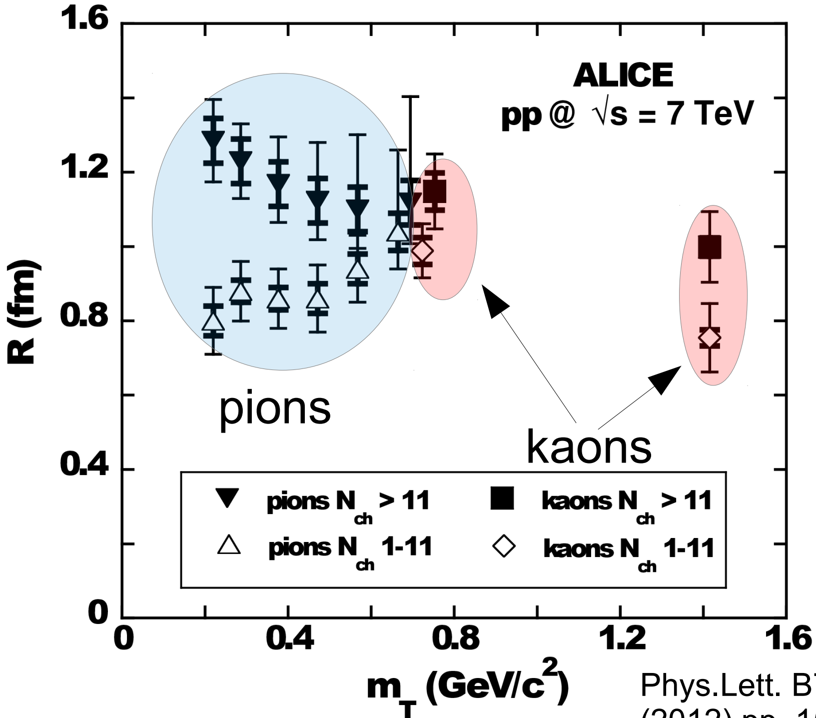

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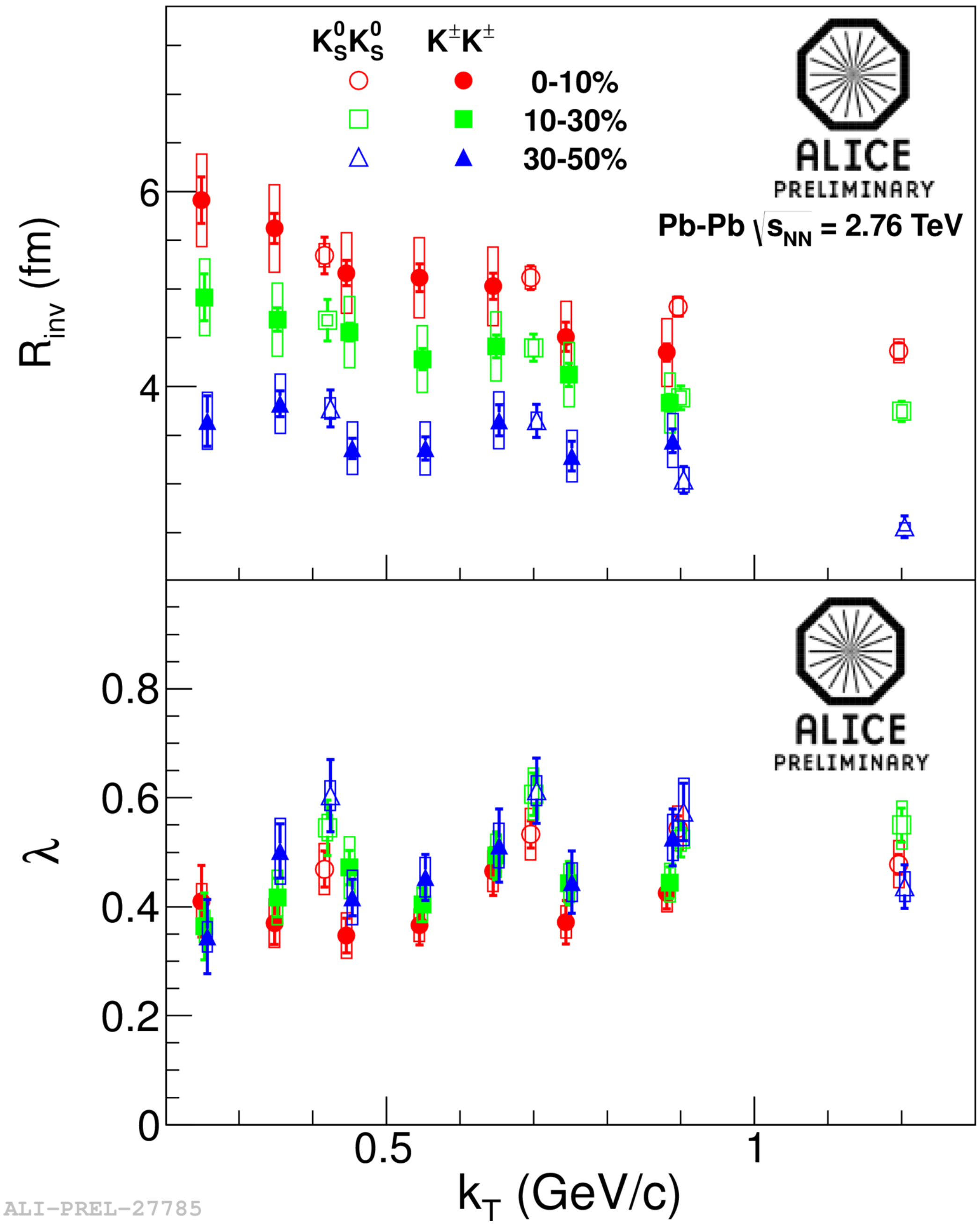
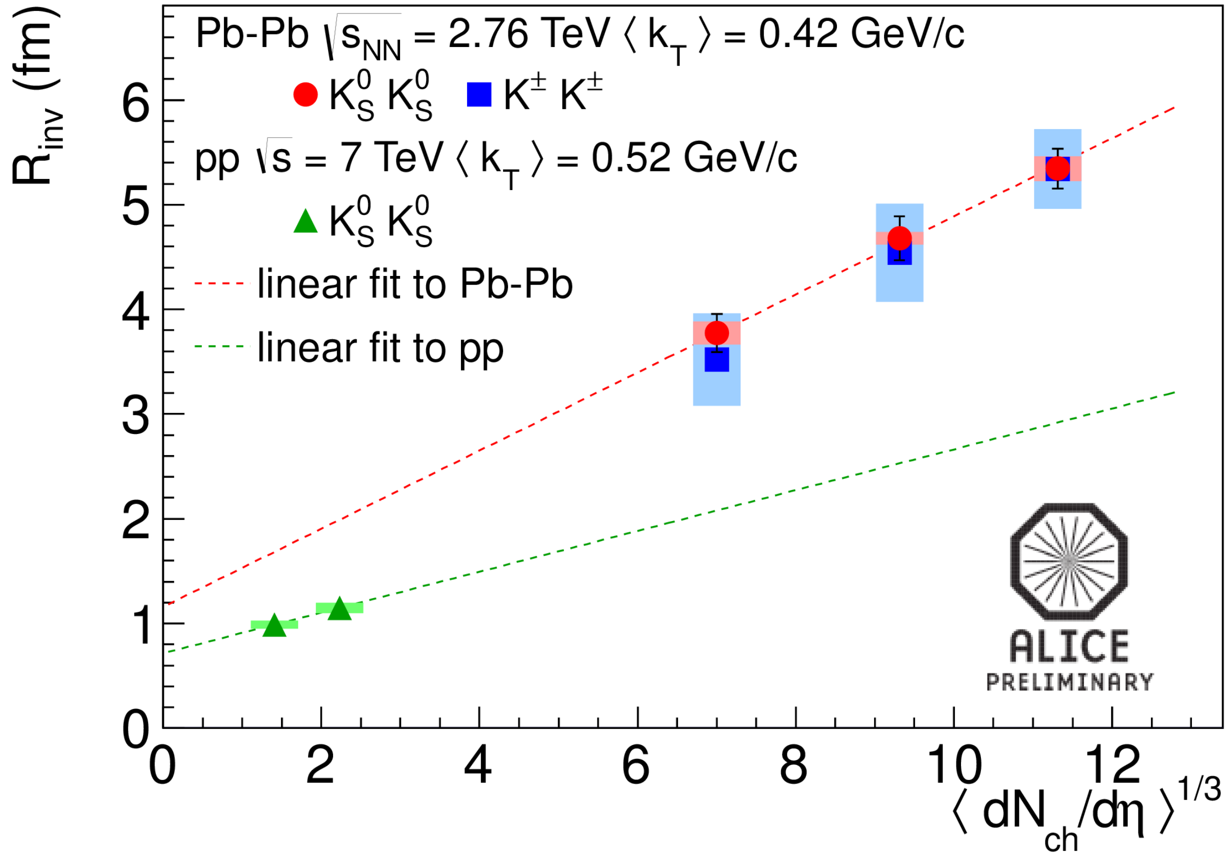


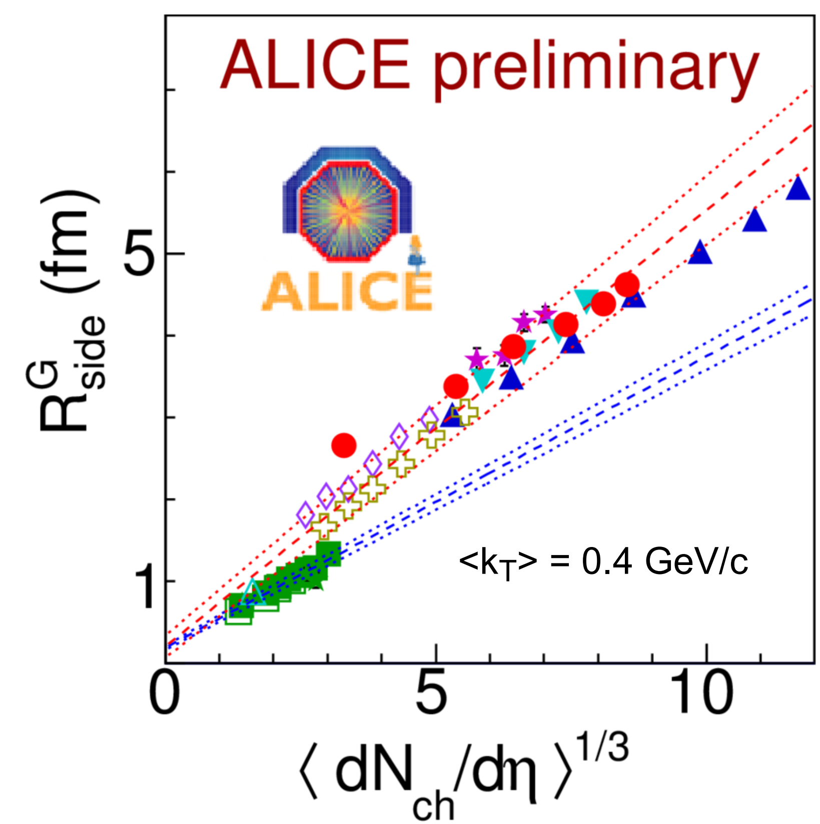
- pp collisions
  - R_{inv} (for kaons) decreases with increasing m_T
  - R_{inv} increases with increasing multiplicity
- Pb-Pb collisions
  - K^0_s and K^{ch} consistent
  - R_{inv} decreases with increasing k_T
  - R_{inv} increases with increasing multiplicity
  - $\lambda \sim 0.5$, not dependent on k_T

Kaon femtoscopy: pp vs. Pb-Pb



kaons

pions



- Linear scaling with multiplicity for Pb-Pb
- If we assume linear scaling for pp (as seen for pions), then the slope is different than for Pb-Pb

Baryon femtoscopy

$$C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r$$

measured correlation

emission function (radius)

cross-section

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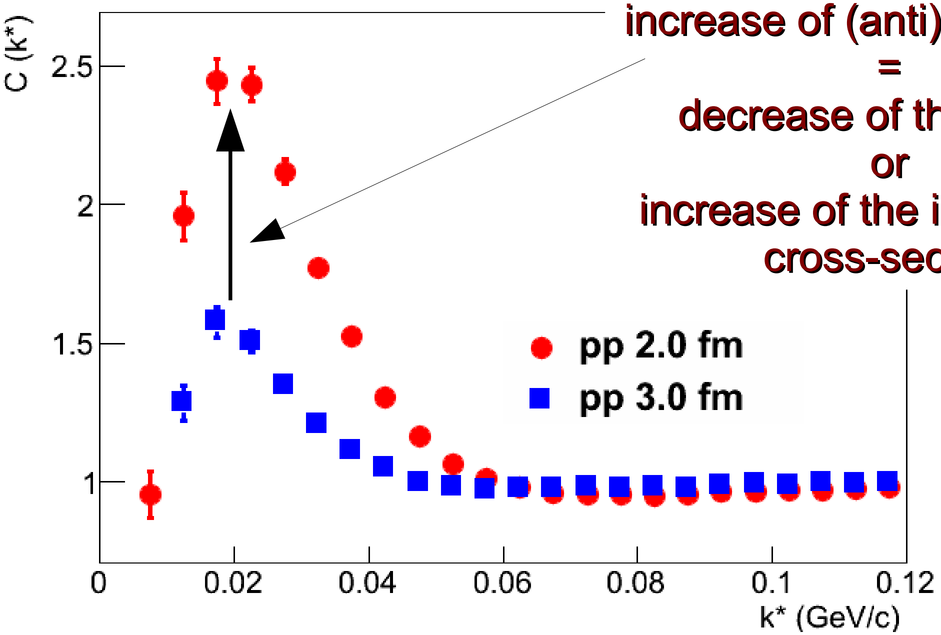
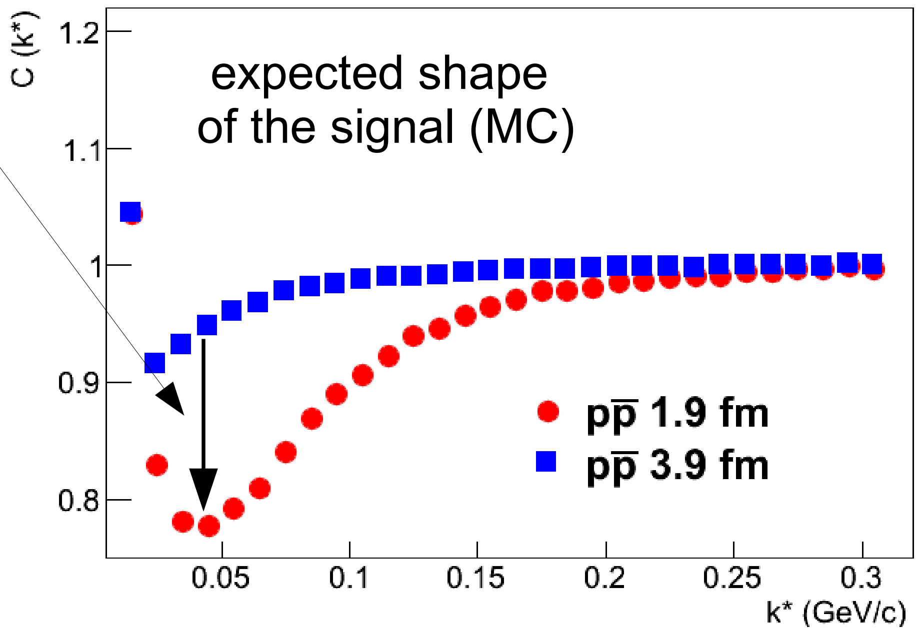


increase of (anti)correlation
=
decrease of the radius
or
increase of the interaction cross-section



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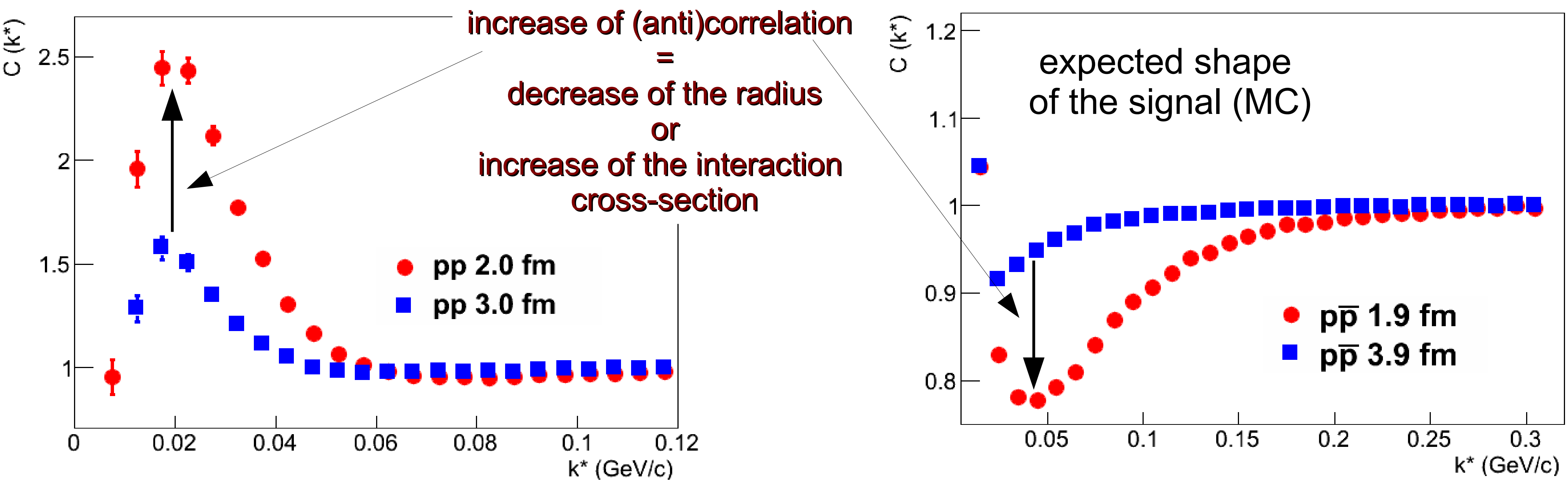


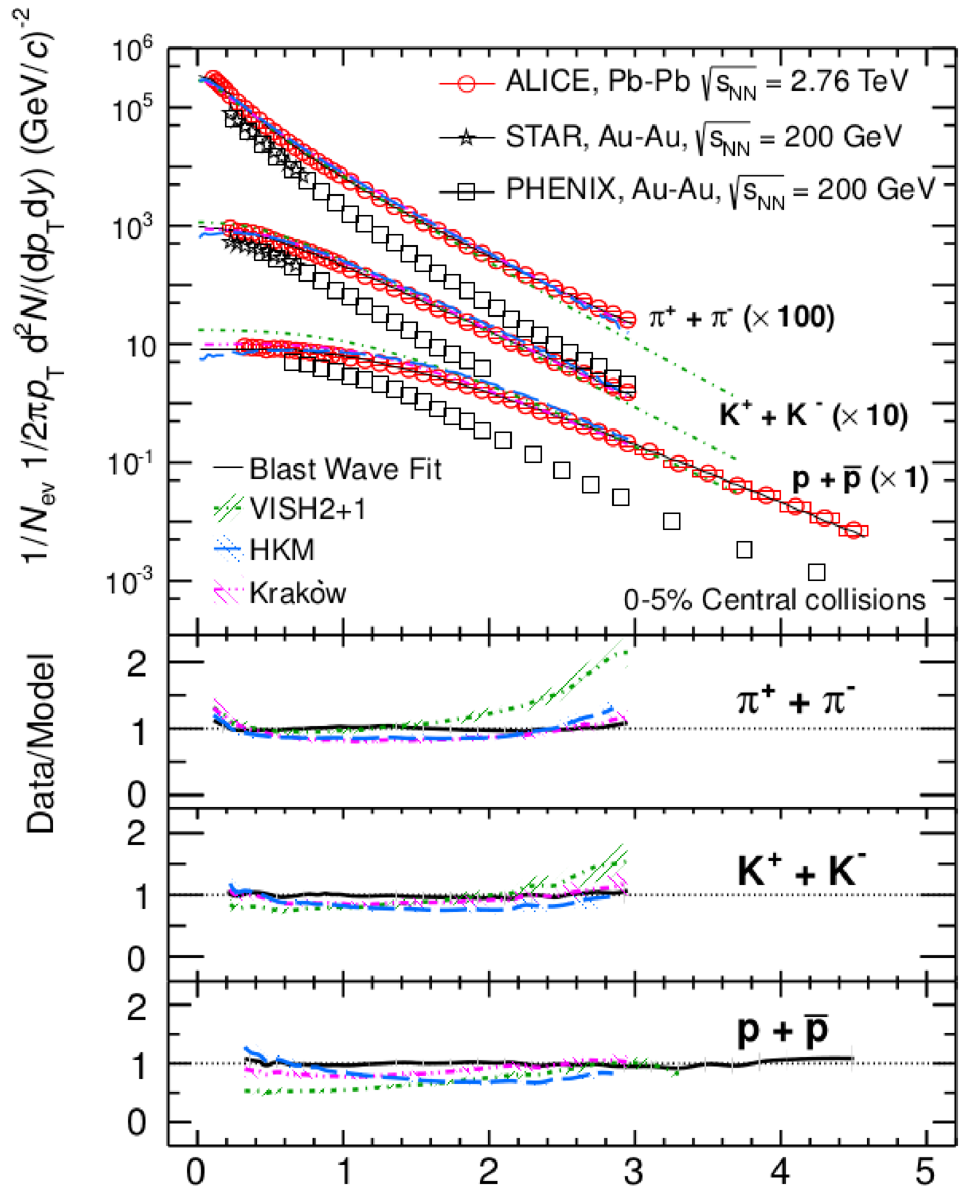
- For protons, cross-sections known, only radius can change
- For other systems (e.g. $\bar{p}\Lambda$, $\Lambda\bar{\Lambda}$), the radius and the cross-section not precisely known → only one can be a free parameter
- Possible constraints of the radius from p femtoscopy

Annihilation in baryon-antibaryon correlations

- Deviation of proton yields from thermal models expectations
  - "rescattering" phase should be taken into account while determining yields
    - Steinheimer, Aichelin, Bleicher; arXiv:1203.5302
    - Werner et al.; Phys.Rev. C85 (2012) 064907
    - Karpenko, Sinyukov, Werner; arXiv:1204.5351

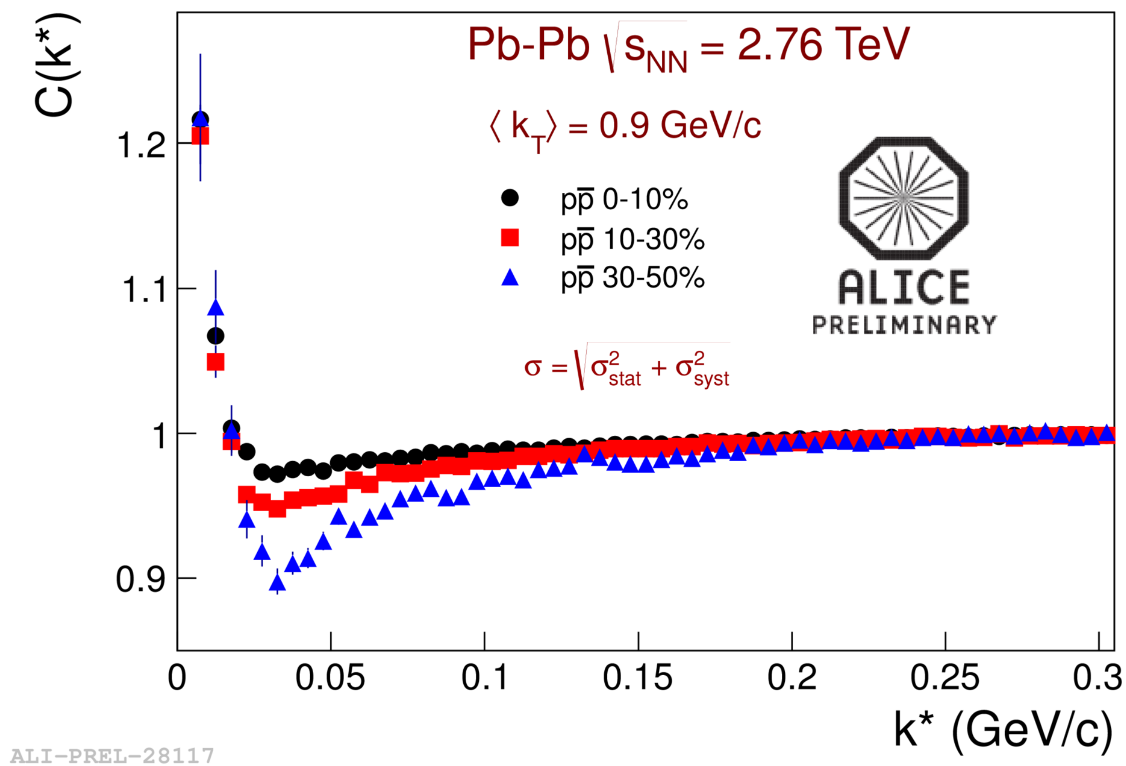
(...)switching $B\bar{B}$-annihilation on suppresses baryon yields, in the same time increases pion yield, thus lowering p/π ratio to the value 0.052, which is quite close to the one measured by ALICE(...)

  - if true → annihilation must be seen in baryon-antibaryon correlations



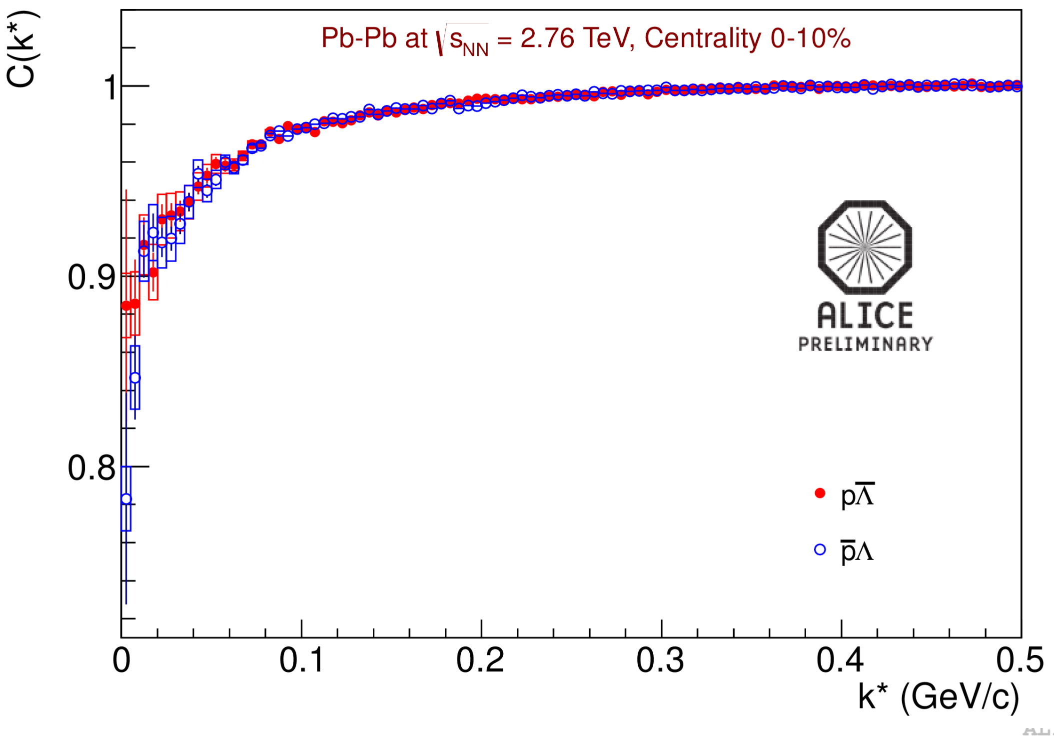
arXiv:1208.1974

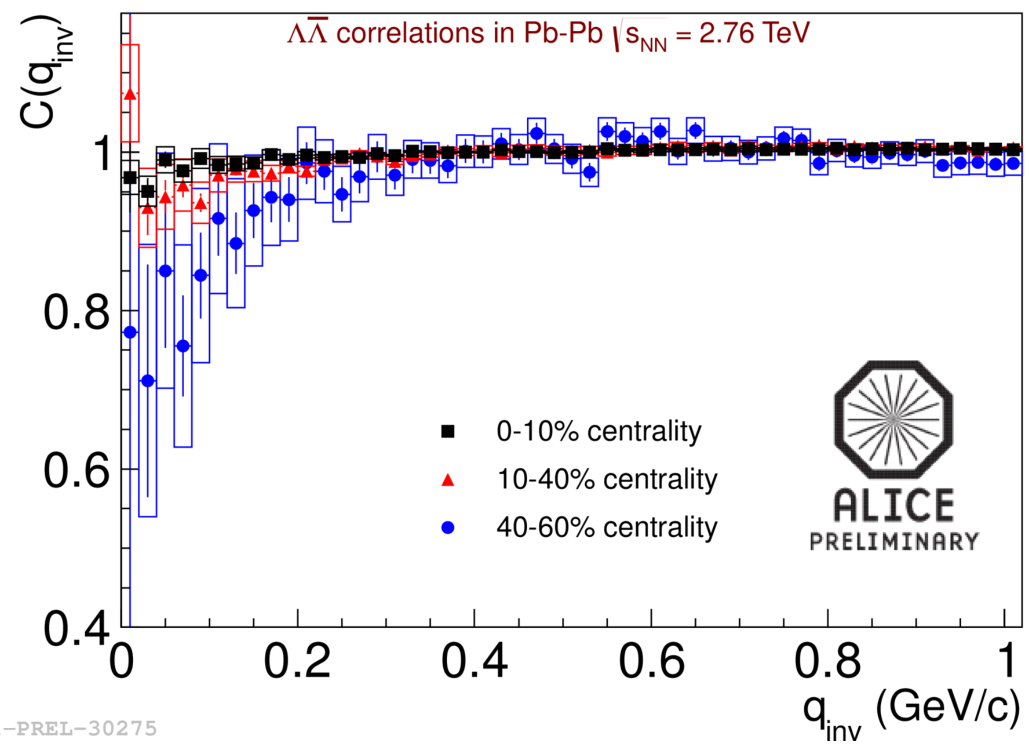
$p\bar{p}$ correlation functions



- Shape dominated by Coulomb and Strong FSI
- Significant annihilation (from strong FSI) expected and measured
- Femtoscopic effect very wide, better statistical handle on the system size (compared to pp)

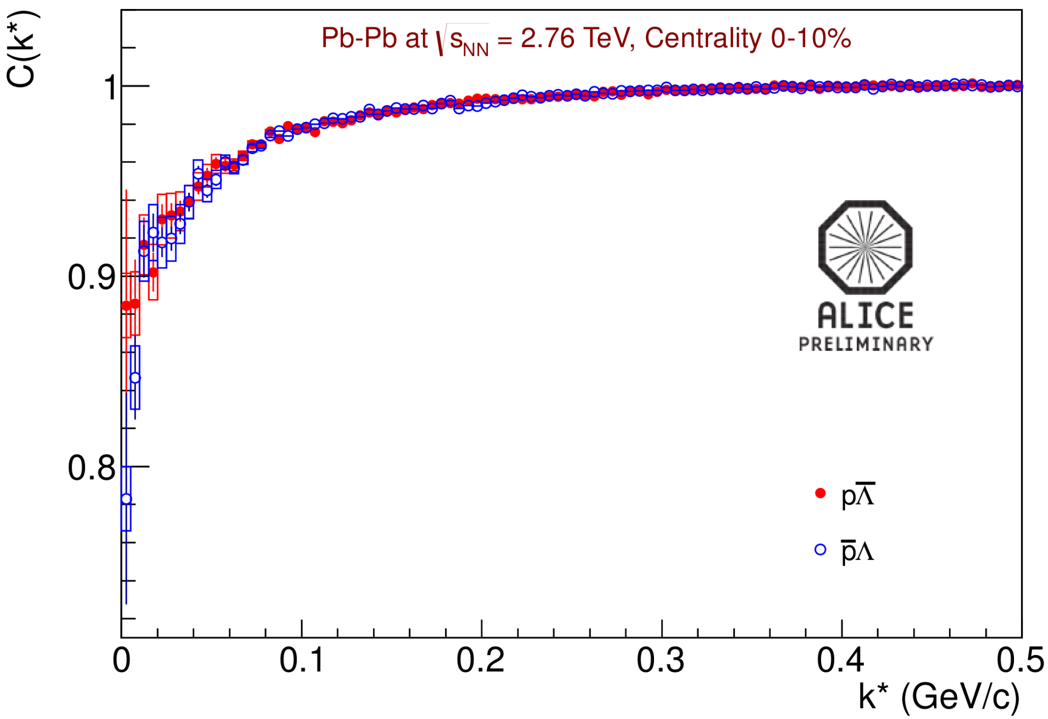
$p\bar{\Lambda}$, $\bar{p}\Lambda$, $\Lambda\bar{\Lambda}$ correlation functions

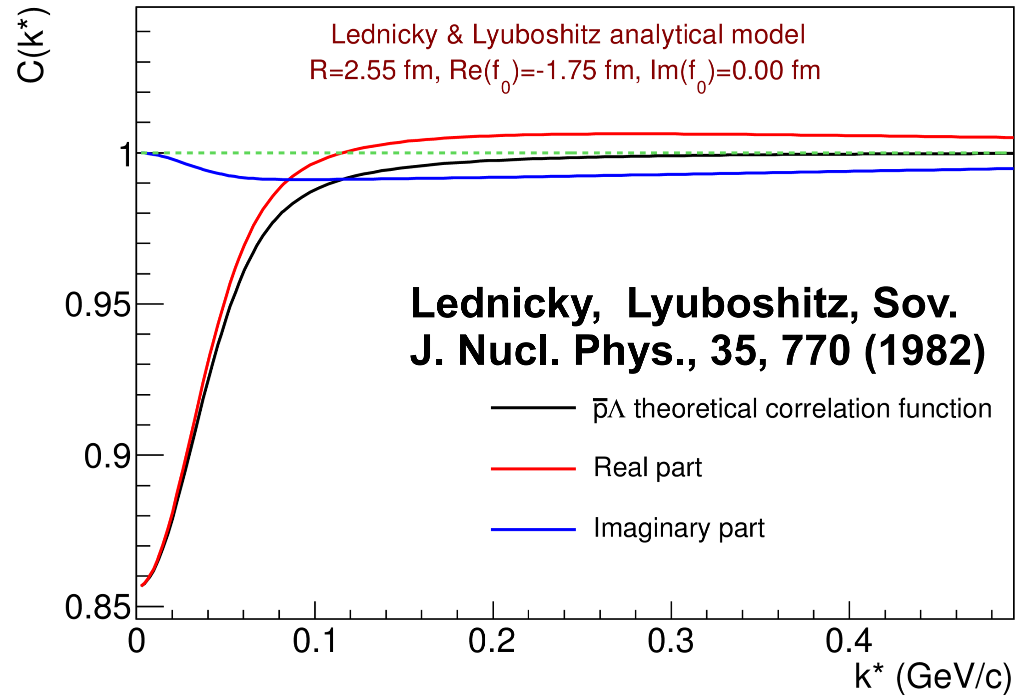




- Wide negative correlation, consistent with **annihilation** in the strong FSI
- Annihilation not limited to particle-antiparticle systems!
- Correlation strength increases with decreasing multiplicity (consistent with decrease of the system size)
- Possible influence from residual correlations (feed-up from $p\bar{p}$, feed-down correlations with $\bar{\Sigma}_0$, etc.)

$\bar{p}\Lambda$ correlations vs. analytical model





$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{R} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R} \right) + \frac{2 \Re f^S(k^*)}{\sqrt{\pi} R} F_1(QR) - \frac{\Im f^S(k^*)}{R} F_2(QR) \right]$$

- Contribution from Re{f(k*)} is either positive or negative but very narrow (few tens of MeV) in k*
- Only non-zero Im{f_0} (annihilation) can reproduce a wide (hundreds of MeV) negative correlation

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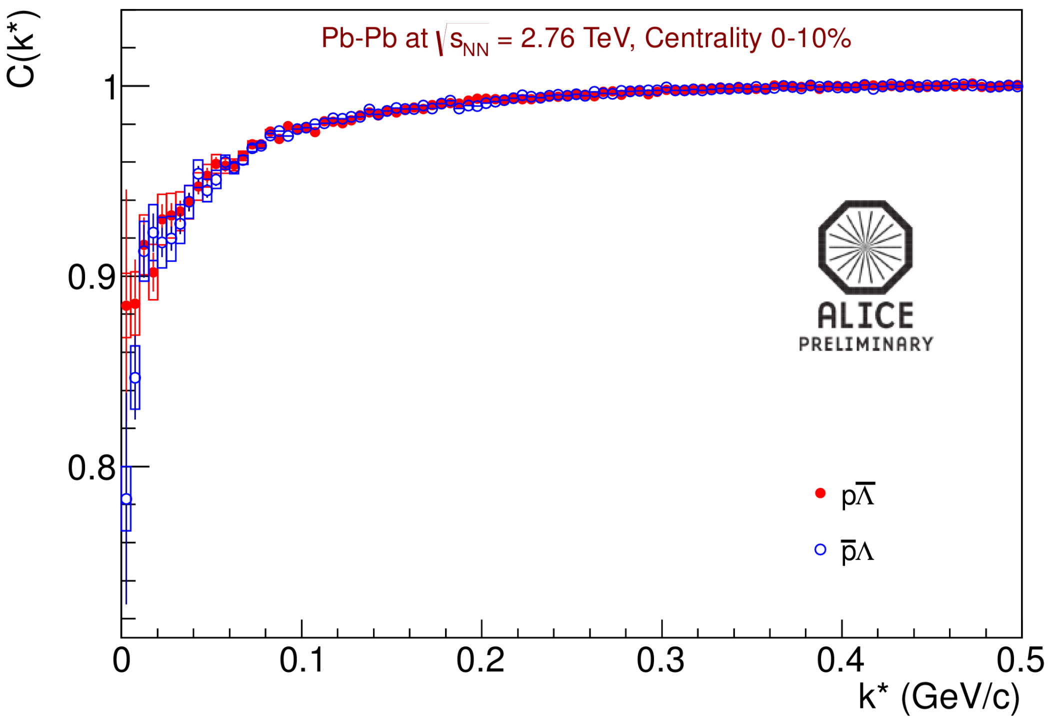

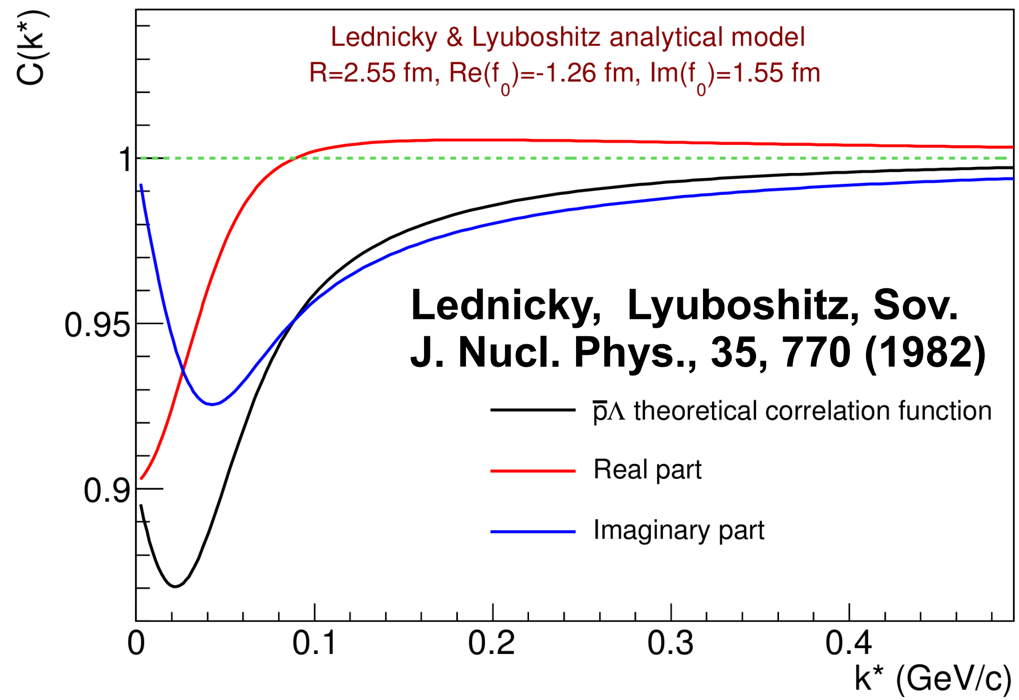

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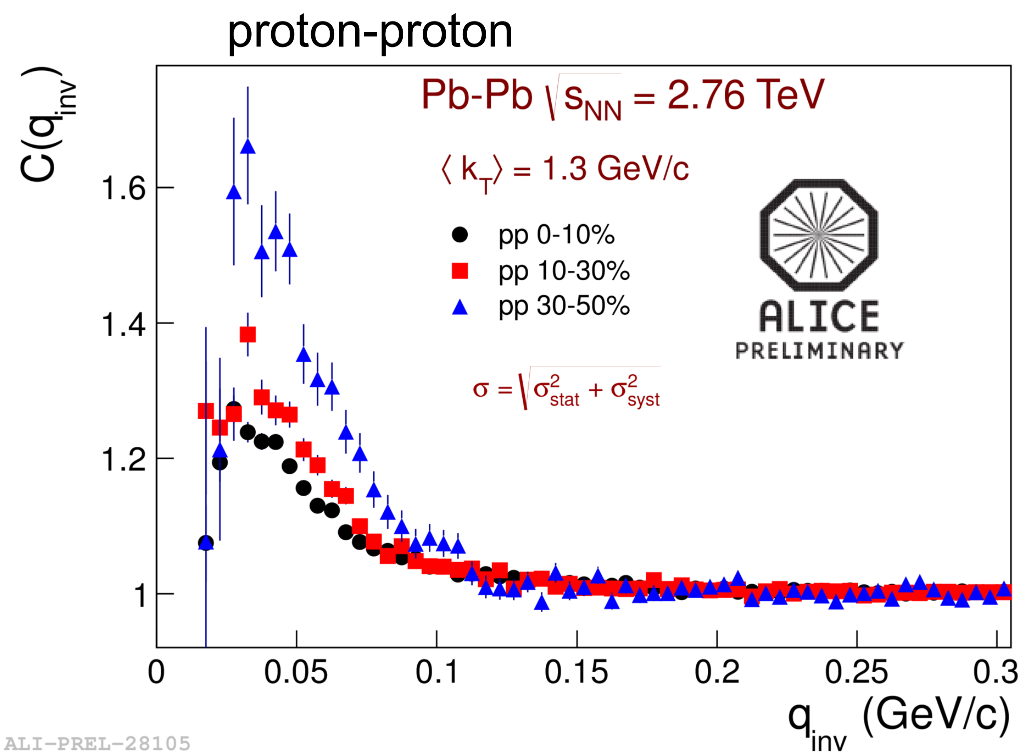
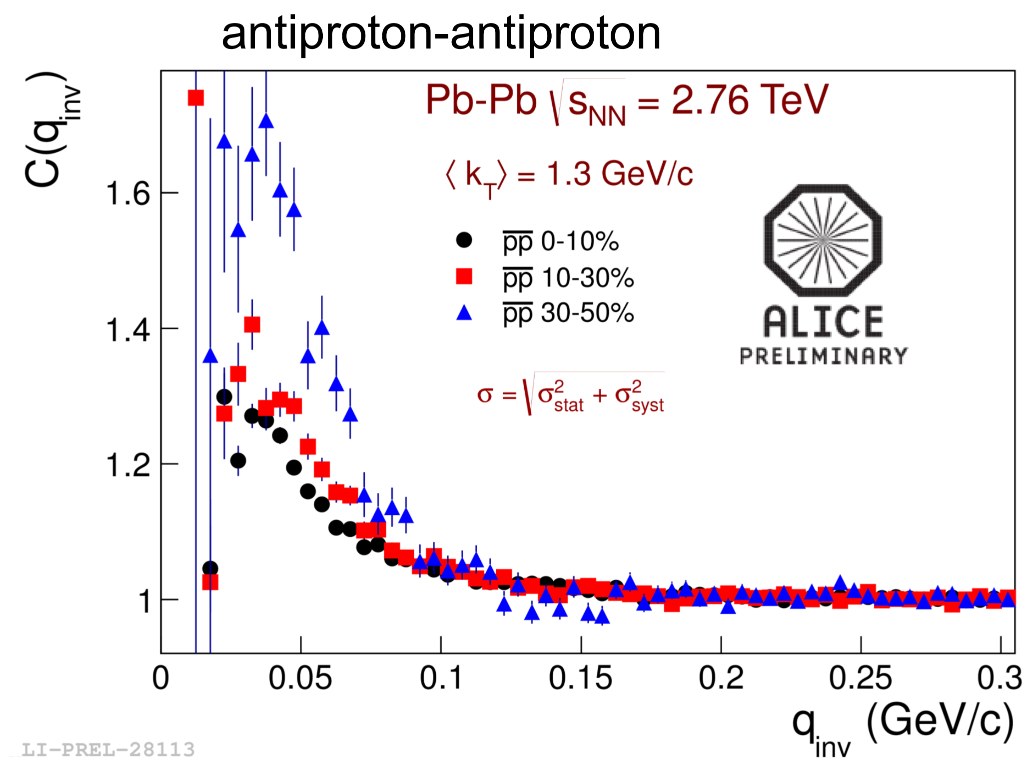
pp and $\overline{pp}$ correlation functions

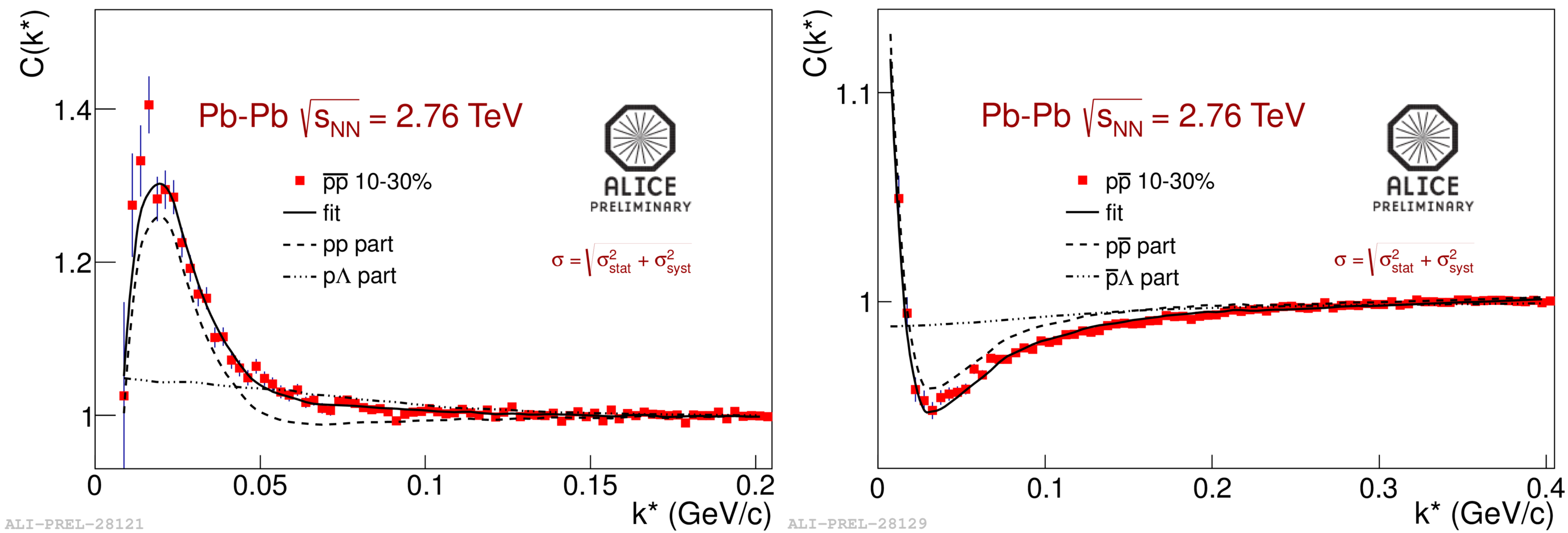




- Correlation effect increases for more peripheral events - size decreases with decreasing multiplicity
- QS, Coulomb and Strong FSI – all contribute to measured correlations
- Expected maximum for $q_{\mathrm{inv}}=2k^* \approx 40$ MeV/c

Fitting the baryon correlations

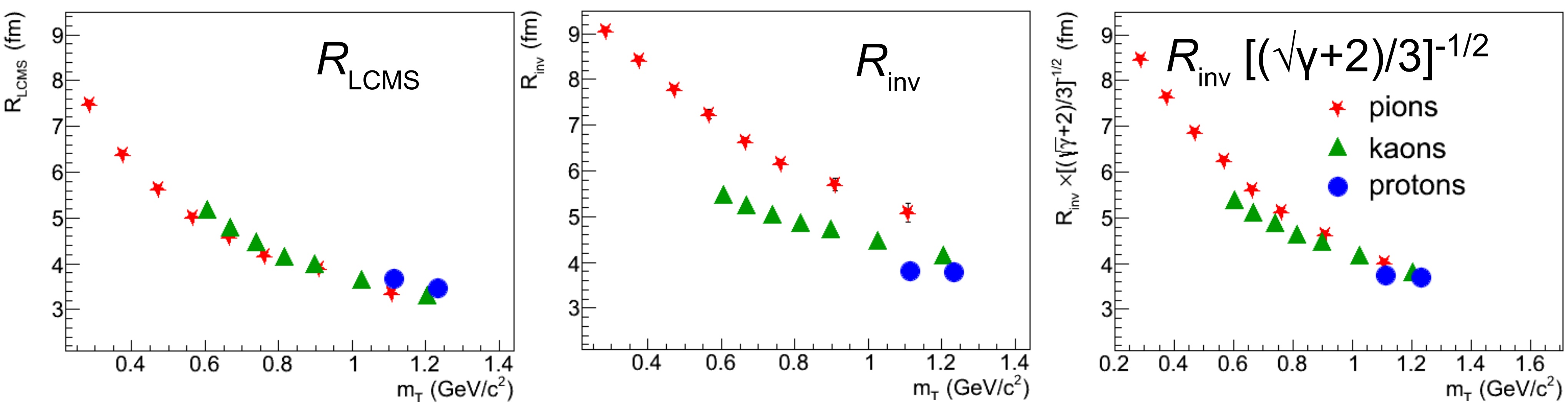
$$C_{meas}(k^*)=1+\lambda_{pp}(C_{pp}(k^*;R)-1)+\lambda_{p\Lambda}(C_{p\Lambda}(k^*;R)-1)$$



- Contribution from pp correlations describes the maximum at $k^*\approx 20$ MeV/c, cannot explain the broad excess from 0.05 to 0.1 GeV/c in k^*
- Excess correlation explained by residual correlations from pΛ
- Same combination of effects needed to describe $p\overline{p}$

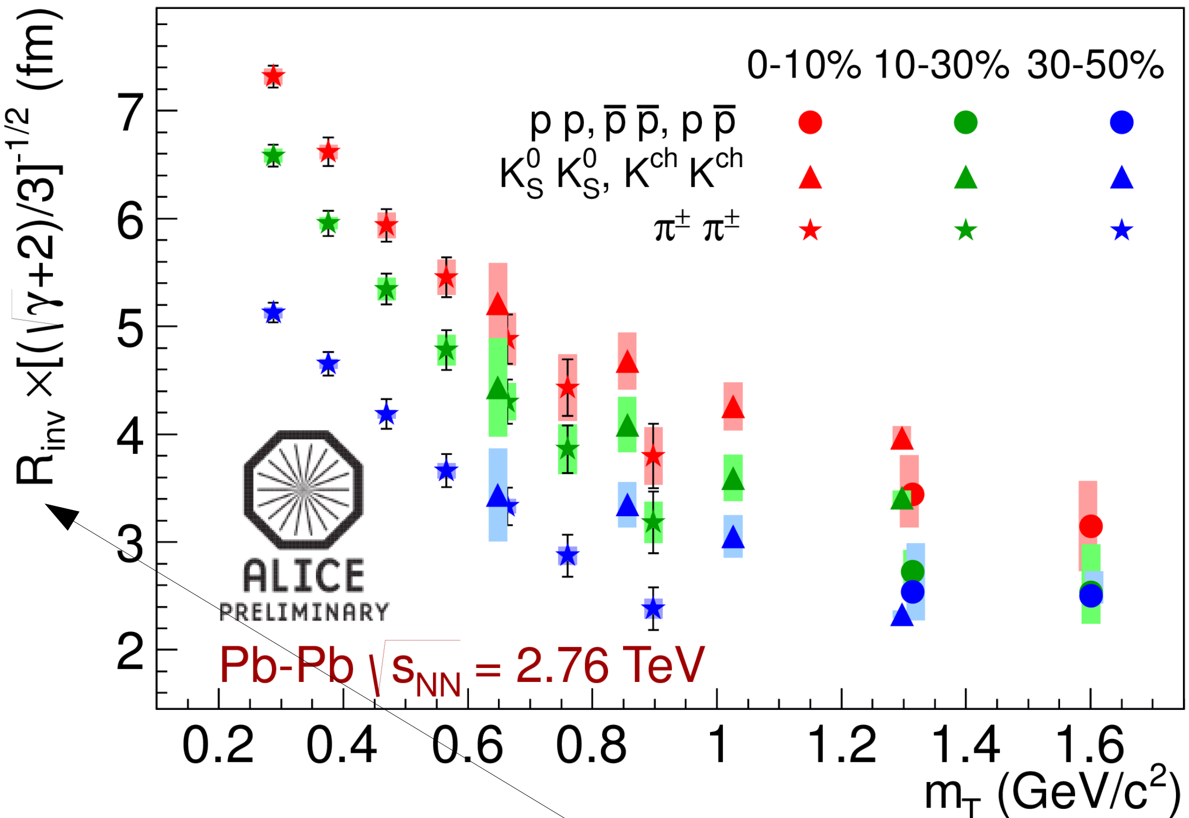
m_T scaling with different masses

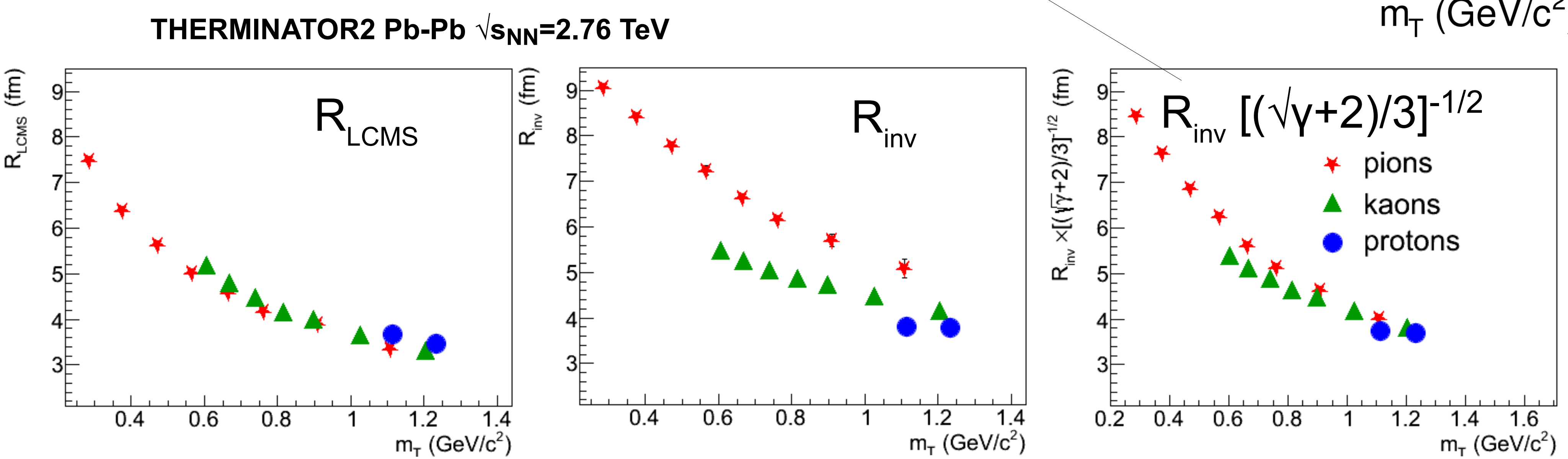
THERMINATOR2 Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV



m_T scaling with different masses

- 1st simultaneous measurement of π, K and p radii in multiple, overlapping m_T bins
- Approximate m_T scaling after taking into account kinematics, consistent with collectivity expectations





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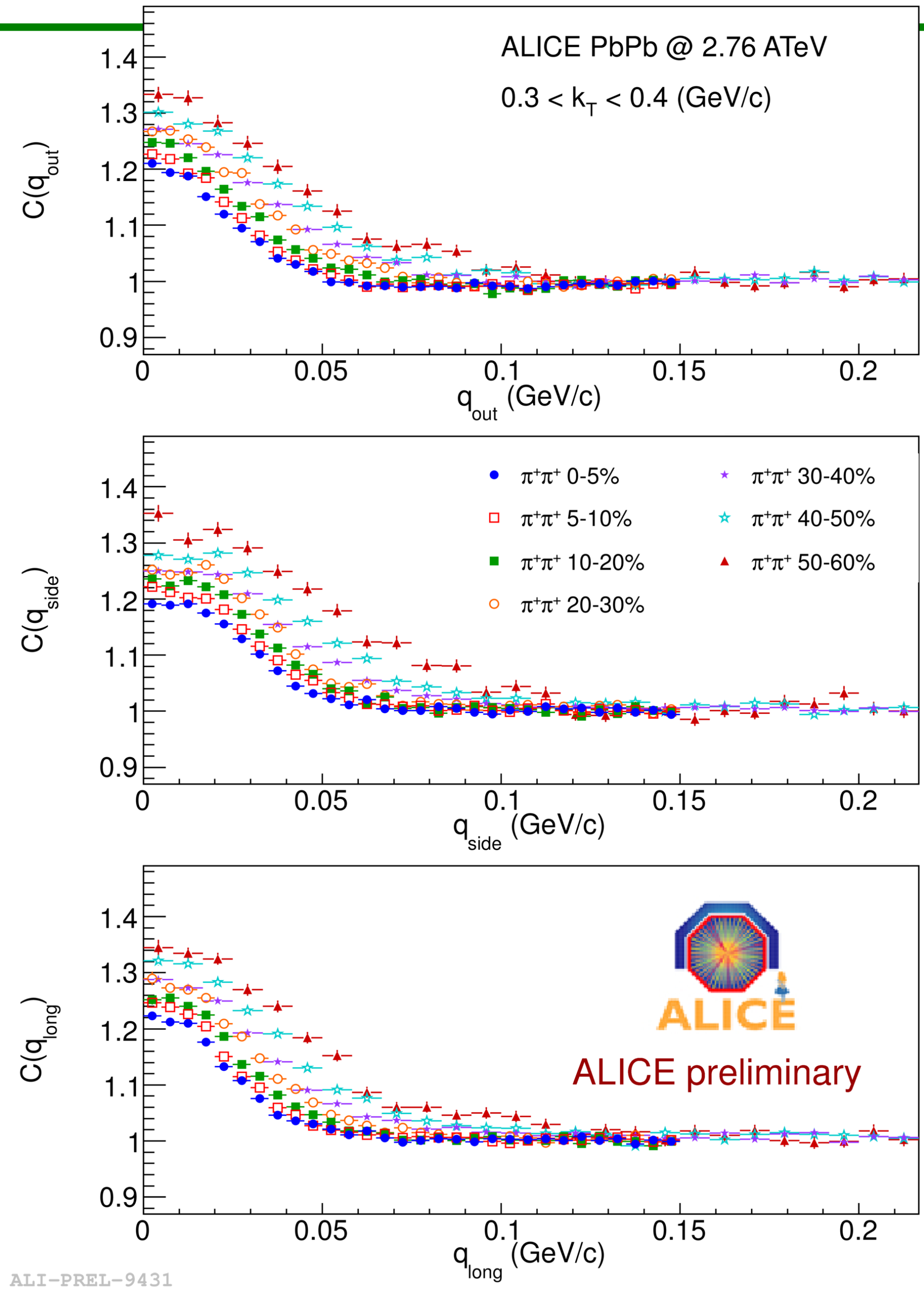
- Measurement of annihilation **cross-sections for poorly known systems** (e.g. $p\bar{\Lambda}$ and $\Lambda\bar{\Lambda}$) - new information for rescattering codes

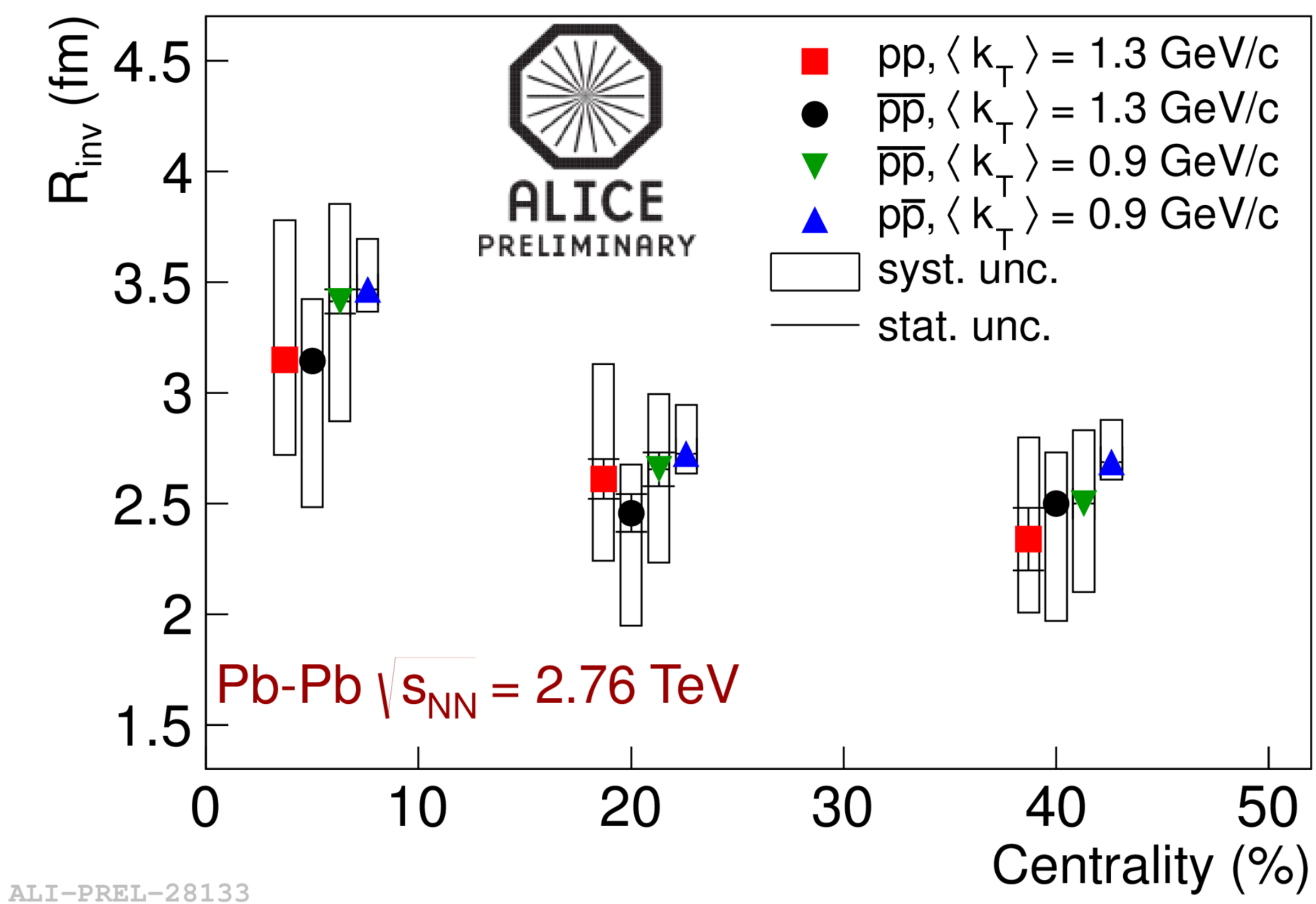
Backup slides

Pion correlations



- Projections of correlation functions for 7 centrality bins, for one pait transverse momentum bin
- Clear growth of the width of the correlation effect – decrease of the size with decreasing multiplicity
- Flat background at large *q*

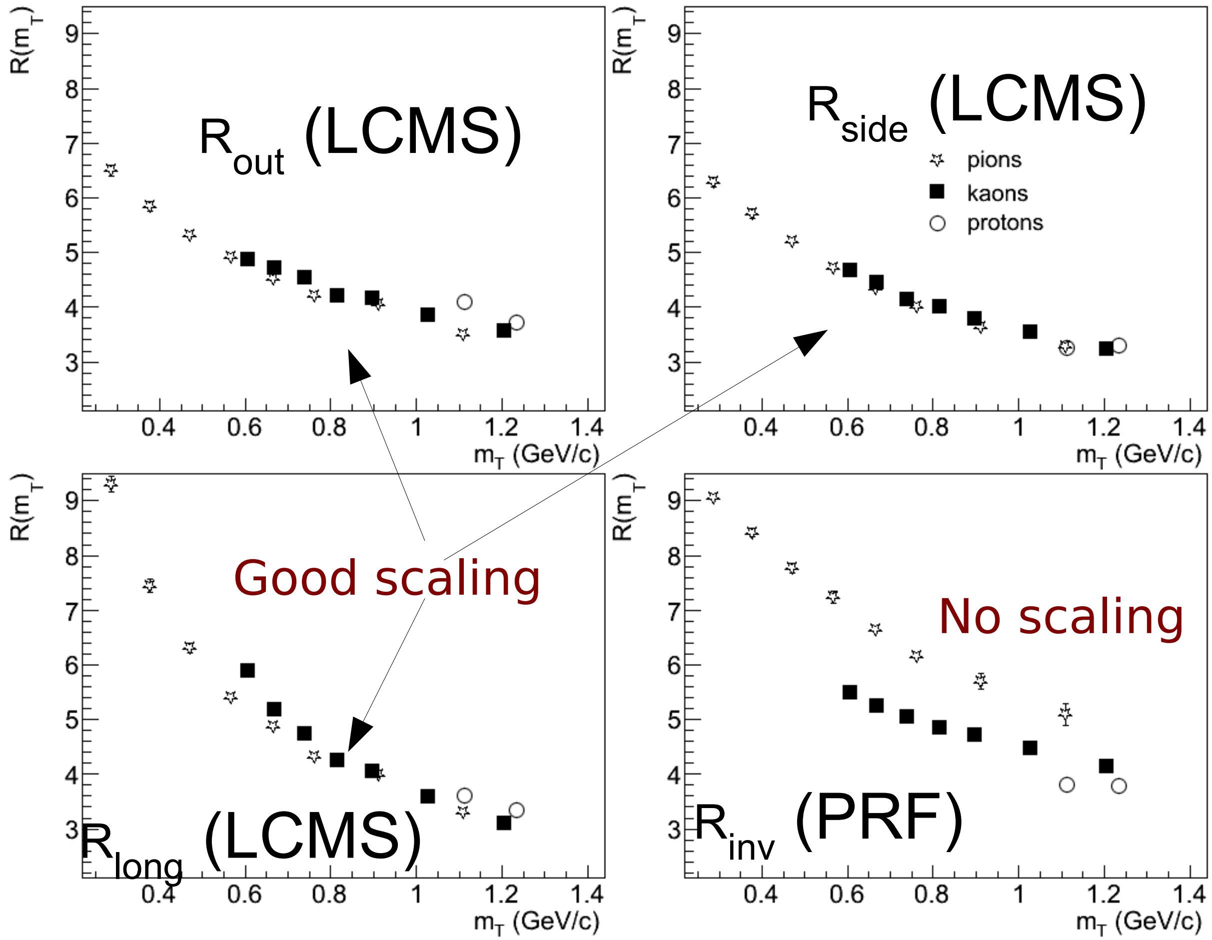
R_{inv} from proton femtoscopy



Radii increase with multiplicity, higher k_T gives smaller radii

What hydro actually predicts?

- Hydrodynamics + resonances calculation (THERMINATOR2) with parameters for PbPb collisions at 2.76 ATeV, clearly predicts m_T scaling in **LCMS** (Longitudinally Co-Moving System). But R_{inv} is calculated in **PRF** (Pair Rest Frame)!



THERMINATOR2
LHC PbPb@2.76ATeV

Recovering the scaling

- One can get an approximate 1D radius in LCMS with: which should also scale $R_{LCMS} = \sqrt{(R_{out}^2 + R_{side}^2 + R_{long}^2)/3}$
- But in PRF, we have:

$$R_{out}^{PRF} \sim \gamma R_{out}^{LCMS}$$

- The increase of R_{out} in PRF has two effects:
  - The overall radius of the system increases
  - The source becomes non-gaussian
- The interplay of the two effects can be accounted for with an approximate formula relating 1D sizes in LCMS and PRF

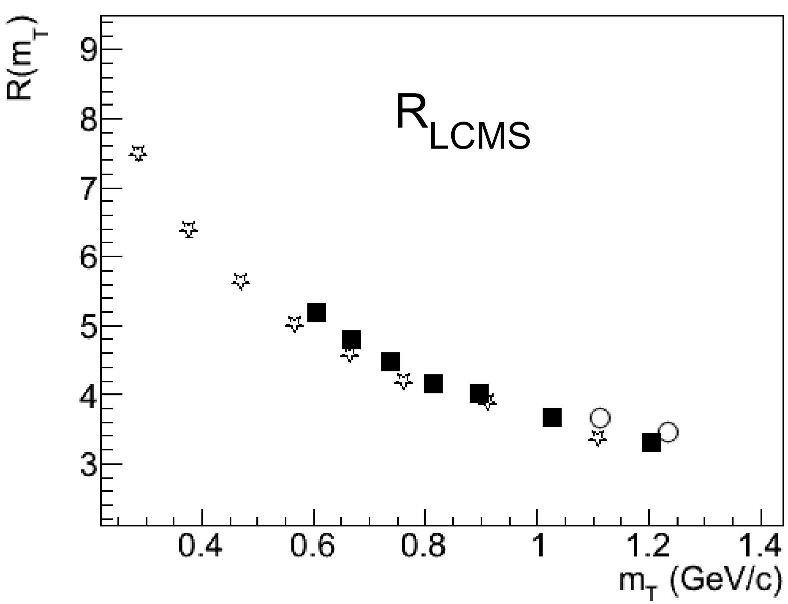
$$R_{PRF} \stackrel{\text{def}}{=} R_{inv} = \sqrt{(R_{out}^2 \sqrt{\gamma} + R_{side}^2 + R_{long}^2)/3}$$

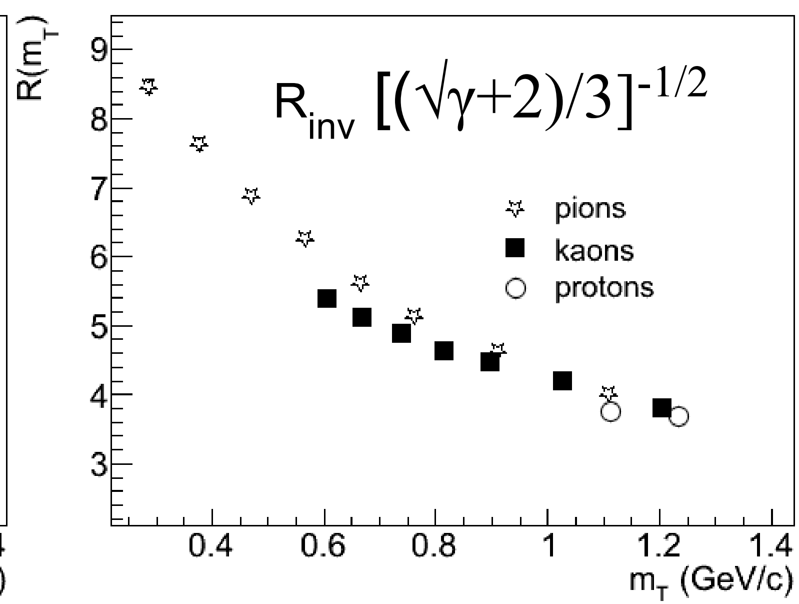
Testing the scaling formulas

- Therefore one can recover the R_{LCMS} from R_{inv} with a simple kinematic scaling:

$$R_{LCMS} = R_{inv}\left(\frac{\sqrt{\gamma}+2}{3}\right)^{-1/2}$$

- Please note that this is pure kinematics (not model dependent) and approximate (~10%, worse as gamma increases), but R_{inv} is an approximation in itself.





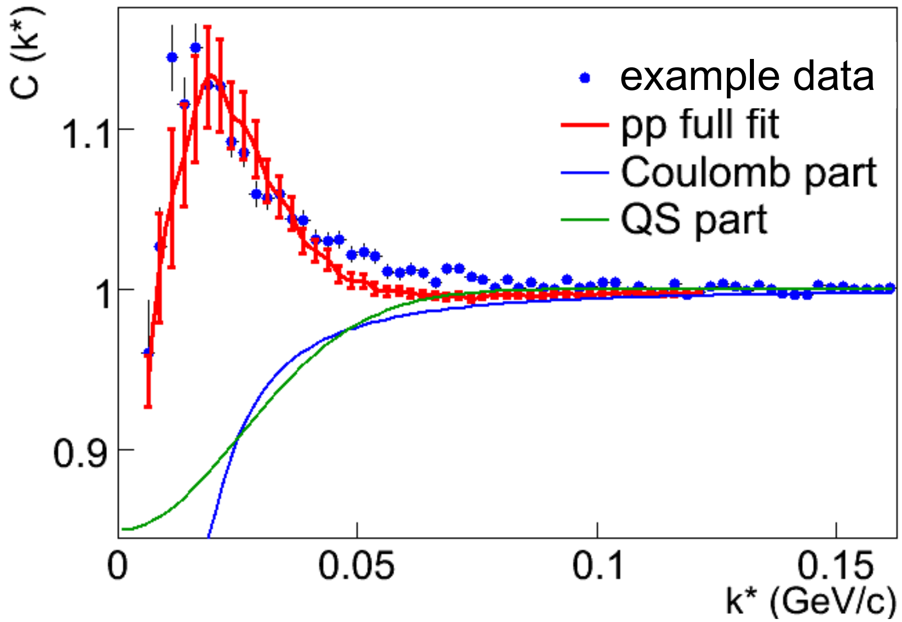
THERMINATOR2
LHC PbPb@2.76ATeV

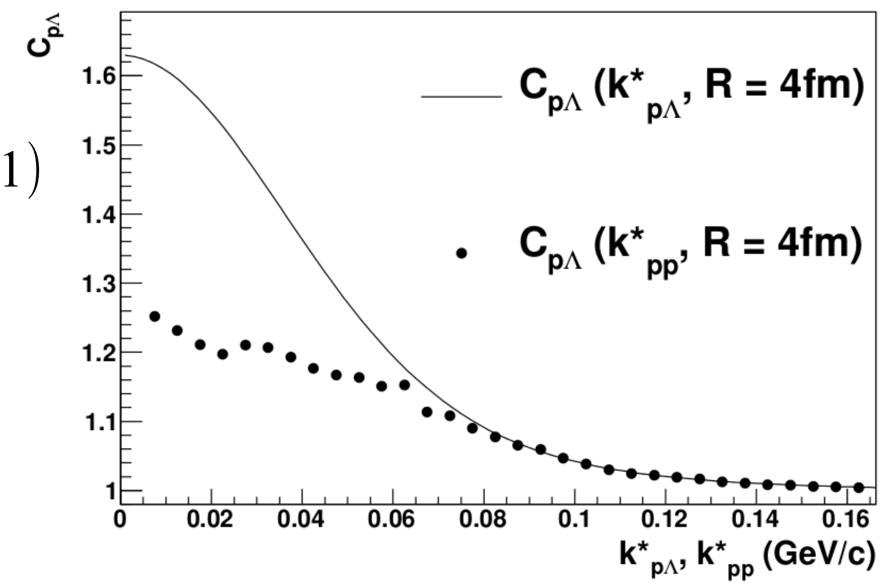
Fitting the baryon correlations

- The excess about 50 MeV/c in k* not explained by correlations coming from pp wave-function
- Possible explanation: residual correlations, main weak decay channel leading to protons: $\Lambda \rightarrow p + \pi^-$
- Fitting function calculated by quadratic interpolation between theoretical pp and pΛ

$$C_{meas}(k^*) = 1 + \lambda_{pp}(C_{pp}(k^*;R) - 1) + \lambda_{p\Lambda}(C_{p\Lambda}(k^*;R) - 1)$$

- Assumption of Gaussian source
- Decay kinematics taken into account
- Assumption regarding $R_{pp}/R_{p\Lambda}$ ratio





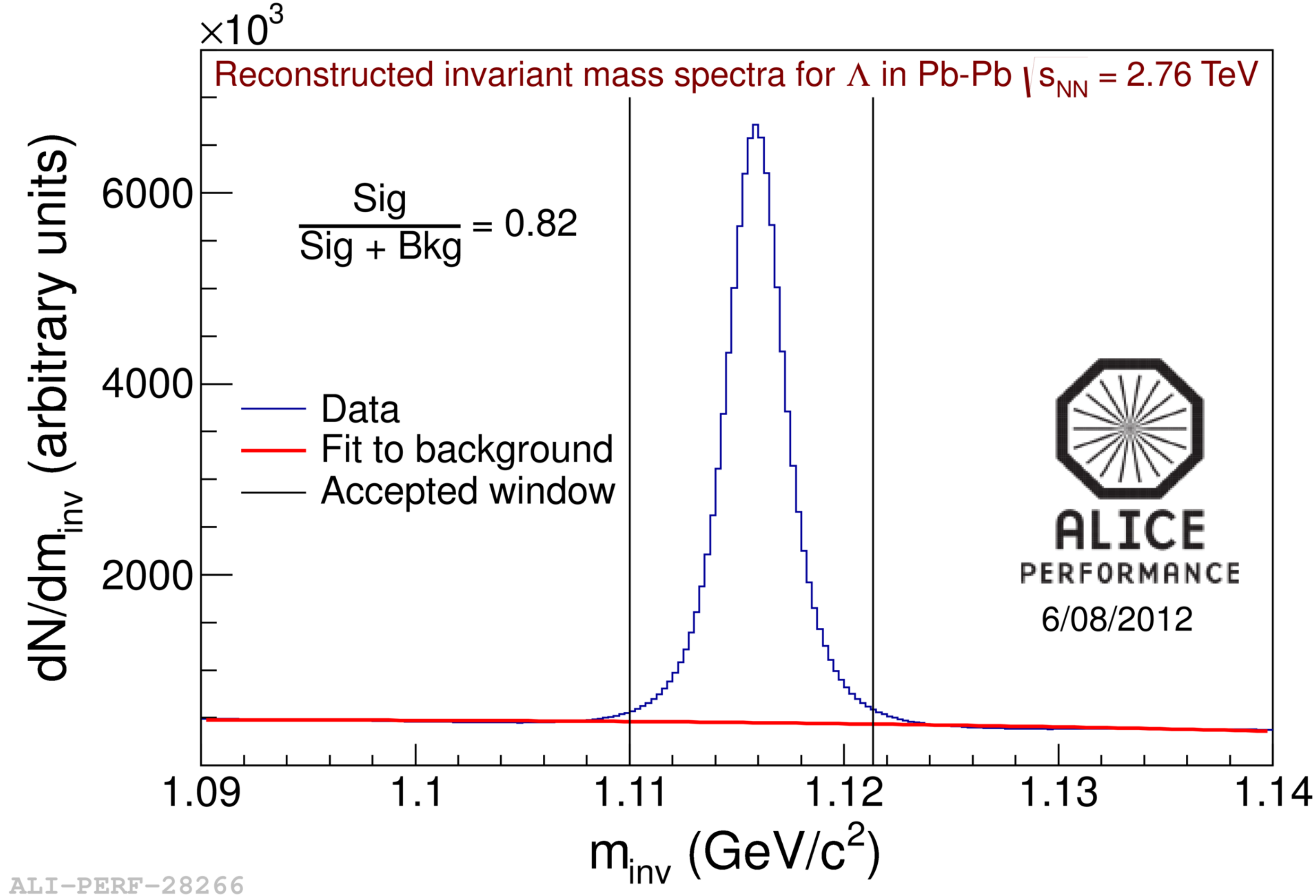
Dealing with λ_{pp}, $\lambda_{p\Lambda}$ parameters

- λ_{pp} – number of pp pairs where both particles are primary protons
- $\lambda_{p\Lambda}$ – number of pp pairs where one particle is a primary proton and the other is the product of Λ decay
- Ways to include in the fit:
  - Free fit paramters
  - Fixed to estimates from MC (model dependent)
  - Fixed to values from the "2nd" fit (pp vs. $p\bar{p}$) – consistency check

Proton correlations – analysis details

- Event selection
  - ~35M Pb-Pb events at $\sqrt{s_{NN}}$=2.76 TeV
- Particle identification
  - TPC + TOF (number of σ's method)
- Track selection
  - $|\eta| < 0.8$
  - $p_t > 0.5$ GeV/c (for protons, to reduce contamination from material)
  - $DCA_{xy} < 0.1$ cm, $DCA_z < 2$ cm
- Correlation functions
  - 1D representation
  - 3 centrality and 2 k_t bins

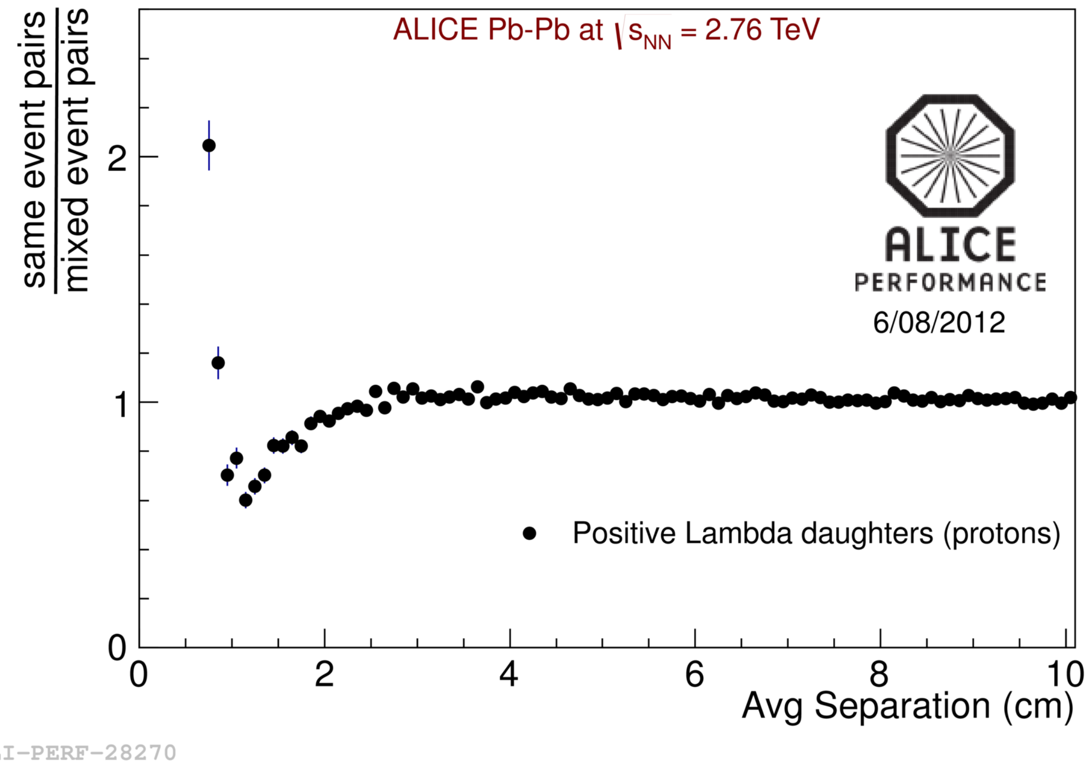
Λ Femtoscopy – invariant mass spectrum



Λ Femtoscopy – Two-Track Cuts

Average separation of daughter tracks.

Computed using the global position of each track at nine different radii in the TPC



The average separation distance is computed for same-event pairs and mixed event pairs.

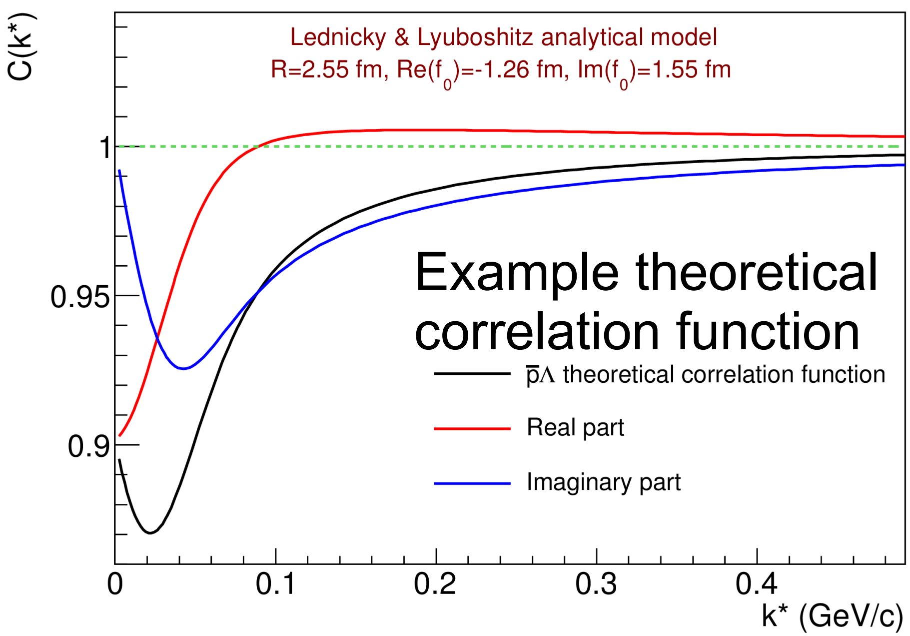
Correlation function is constructed from the ratio.

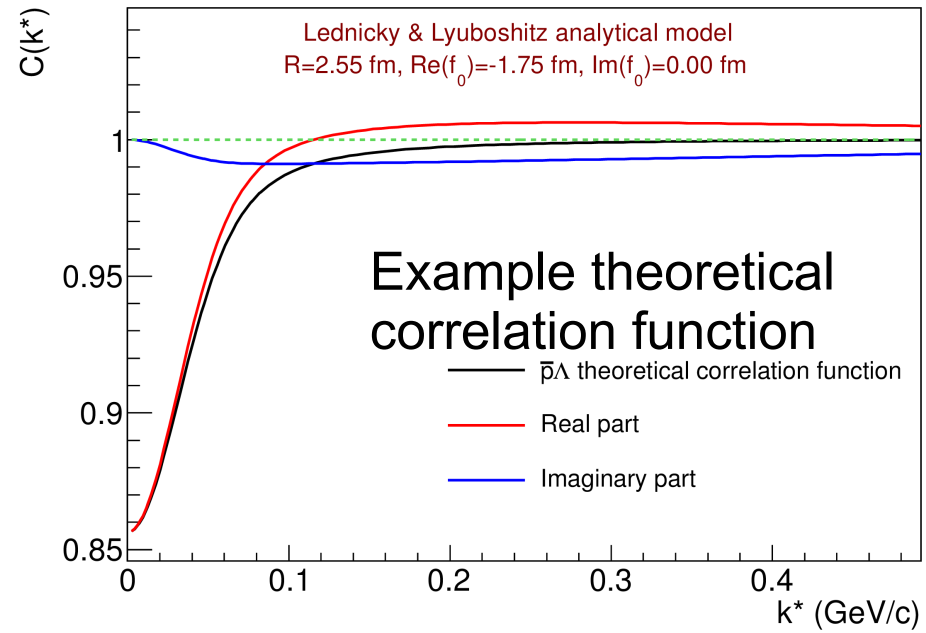
Peak from 0 < AvgSep < 1 cm – **splitting**
Dip from 1< AvgSep < 3 cm – **merging**

λ parameter for kaons

- λ (number of correlated pairs) 0.5-0.6 is observed
- For charged kaons understood as a consequence of PID purity
- But K^0_s have purity ~95%
- Chemical model with freeze-out tempearure 145 MeV predicts:
  - 60% primary kaons
  - 5% from Φ (long-lived)
  - 25% from K0* (semi long-lived)
  - The rest from higher-mass resonances (lifetime similar to K0*)
- Two extreme estimated of λ
  - Only Φ "non-correlated": λ ~ 0.8
  - K0* also "non-correlated": λ ~ 0.3
- Measured value 0.5-0.6 reasonably within chemical model estimates

$\bar{p}\Lambda$: analytical model





- In $\bar{p}\Lambda$ correlations the Lednicky & Lyuboshitz analytical model can be used to determine the interaction potential:

Lednicky, Lyuboshitz, Sov. J. Nucl. Phys., 35, 770 (1982)

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{R} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}R} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}R} F_1(QR) - \frac{\Im f^S(k^*)}{R} F_2(QR) \right]$$

$$f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2} d_0^S k^{*2} - ik^* \right)^{-1} \qquad F_1(z) = \int_0^z x e^{x^2 - z^2} / z \, dx \qquad F_2(z) = (1 - e^z)/z$$

$f^{singlet} = f^{triplet} = f$

Spin (S) dependence neglected

Effective radius $d_0 = 0$

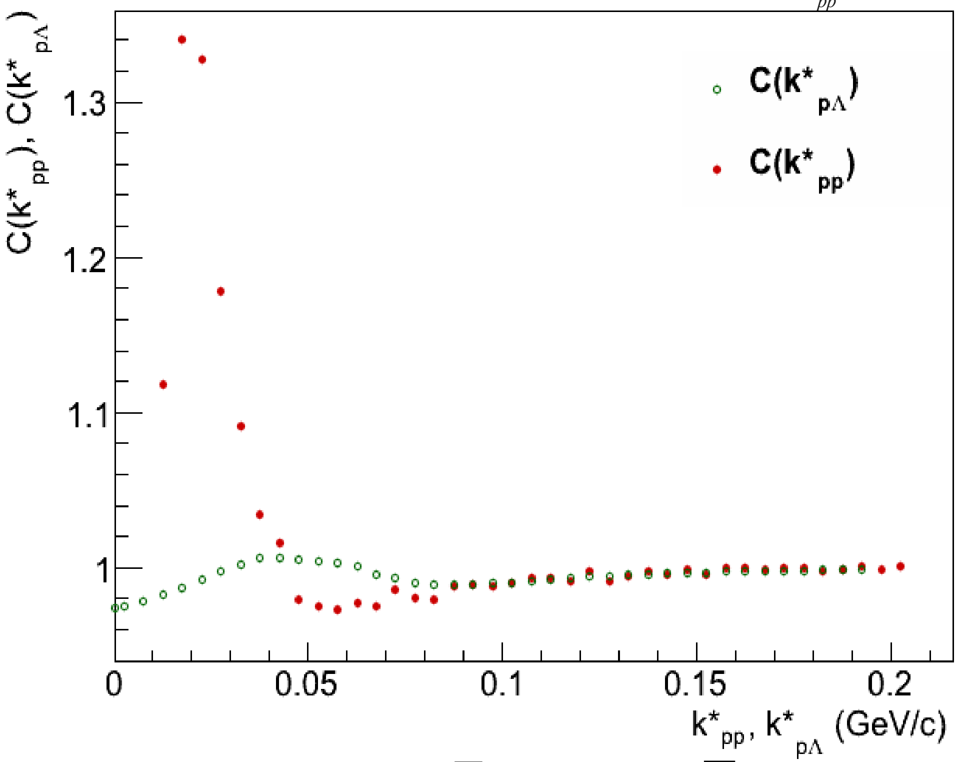
f_0 – scattering length

Q – relative momentum

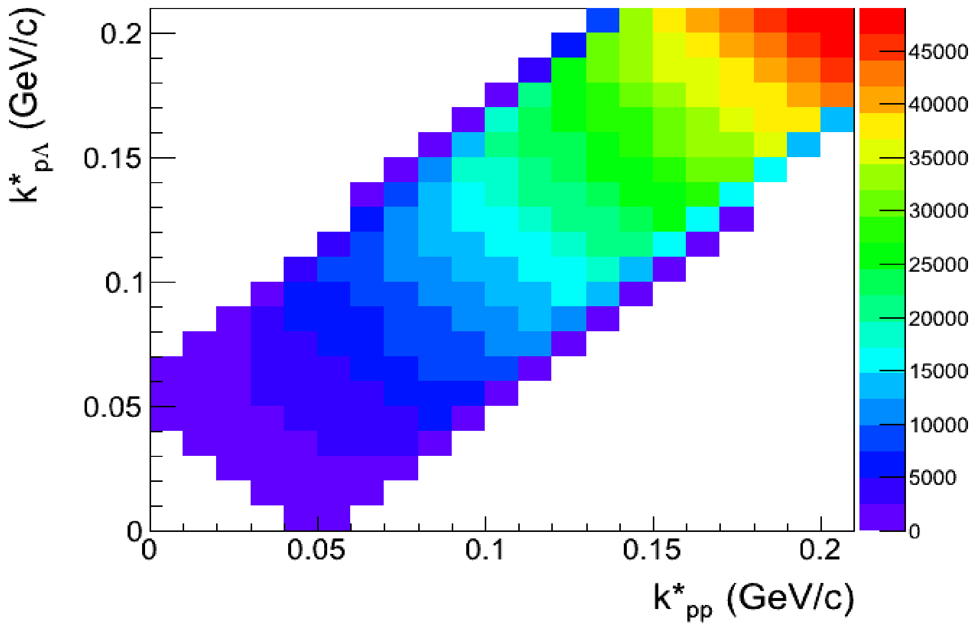
Study of residual correlations

Study of residual correlations

$$C(k^*_{p\Lambda}) = \sum_{k^*_{pp}} C(k^*_{pp}) T(k^*_{pp}, k^*_{p\Lambda})$$



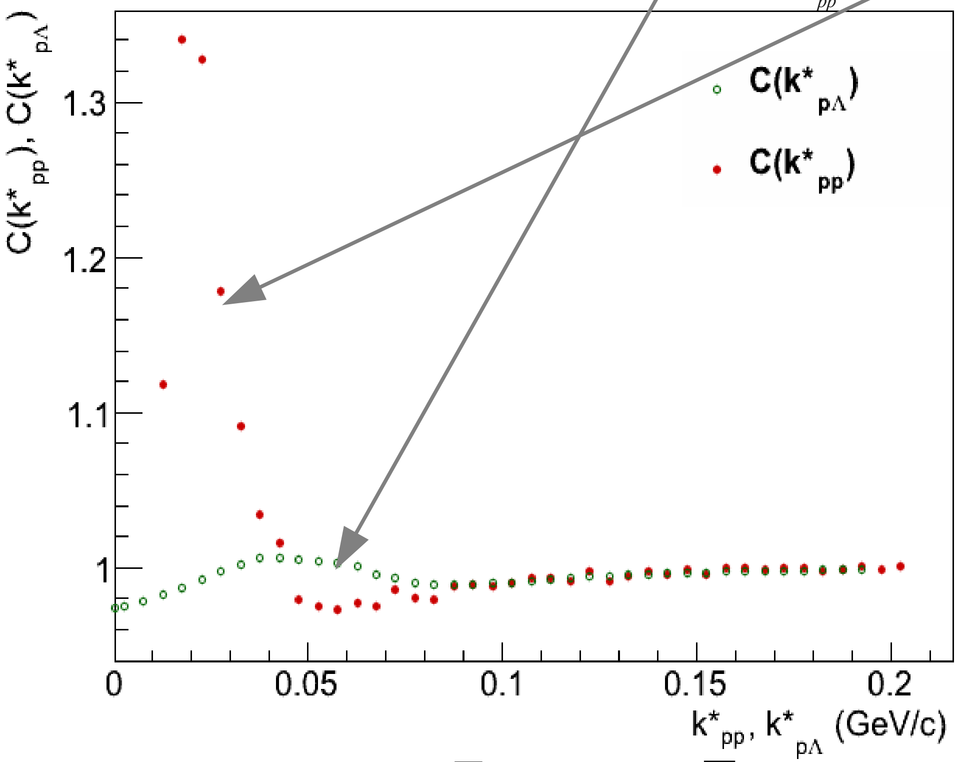
Transformation matrix



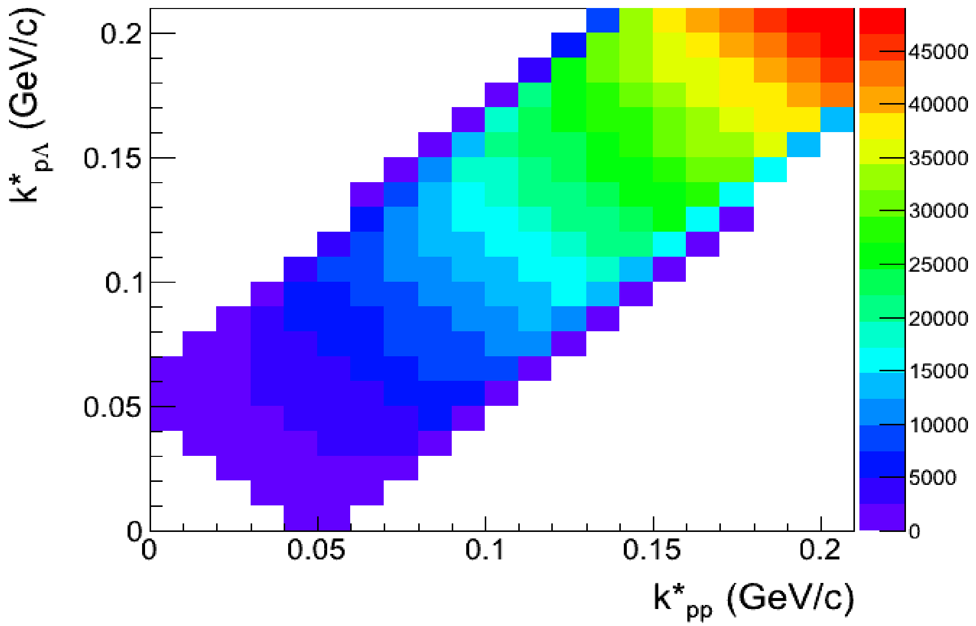
- Theoretical pp ($p\bar{p}$) or pΛ ($p\bar{\Lambda}$) correlation functions calculated using Lednicky's code.
- The Λ decay kinematics $T(k^*_{pp},k^*_{p\Lambda})$ calculated using THERMINATOR model.
- Transformation of theoretical $C(k^*_{pp})$ to $C(k^*_{p\Lambda})$ (or ($C(k^*_{p\Lambda})$ to $C(k^*_{pp})$) – residual correlation.

Study of residual correlations

$$C(k^*_{p\Lambda}) = \sum_{k^*_{pp}} C(k^*_{pp})\, T(k^*_{pp}, k^*_{p\Lambda})$$

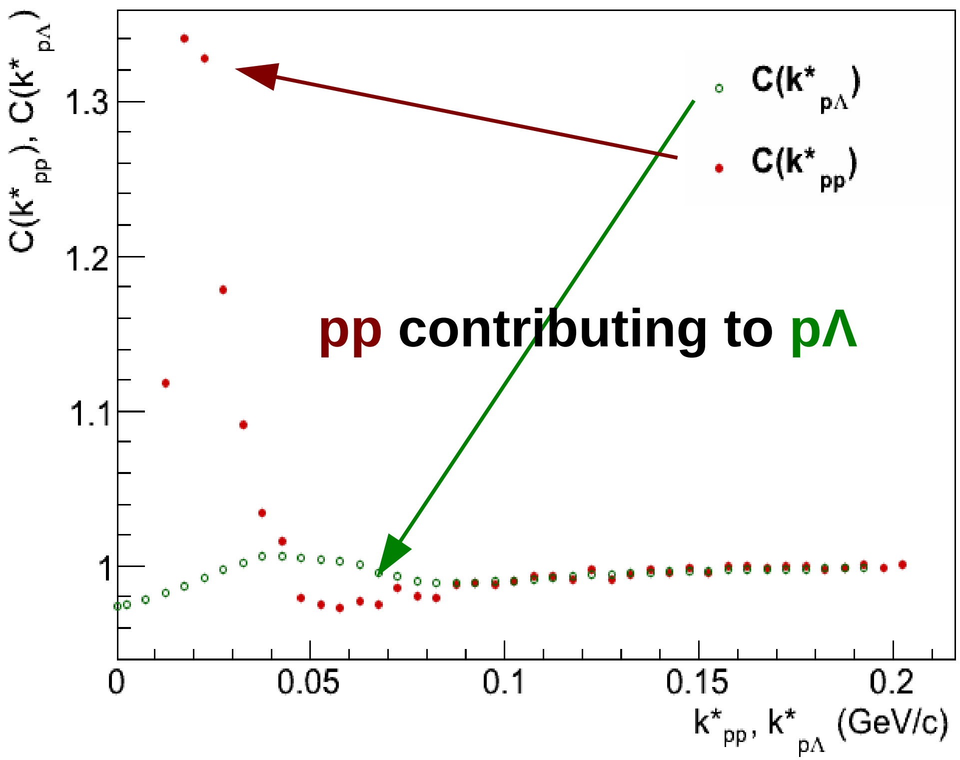


Transformation matrix

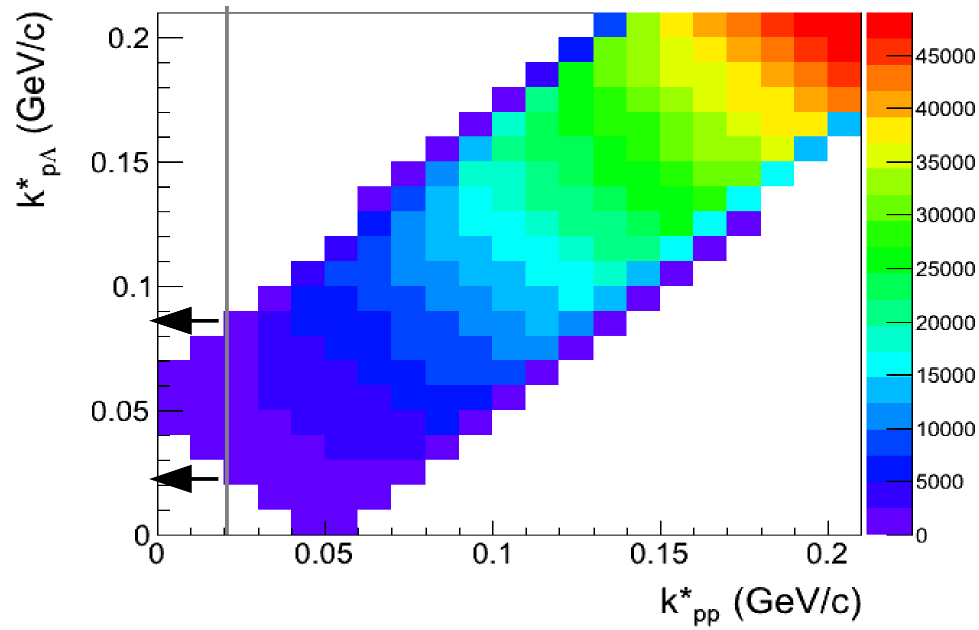


- Theoretical pp ($p\bar{p}$) or pΛ ($p\bar{\Lambda}$) correlation functions calculated using Lednicky's code.
- The Λ decay kinematics $T(k^*_{pp},k^*_{p\Lambda})$ calculated using THERMINATOR model.
- Transformation of theoretical $C(k^*_{pp})$ to $C(k^*_{p\Lambda})$ (or $(C(k^*_{p\Lambda})$ to $C(k^*_{pp}))$ – residual correlation.

Study of residual correlations - pΛ



Transformation matrix, THERMINATOR



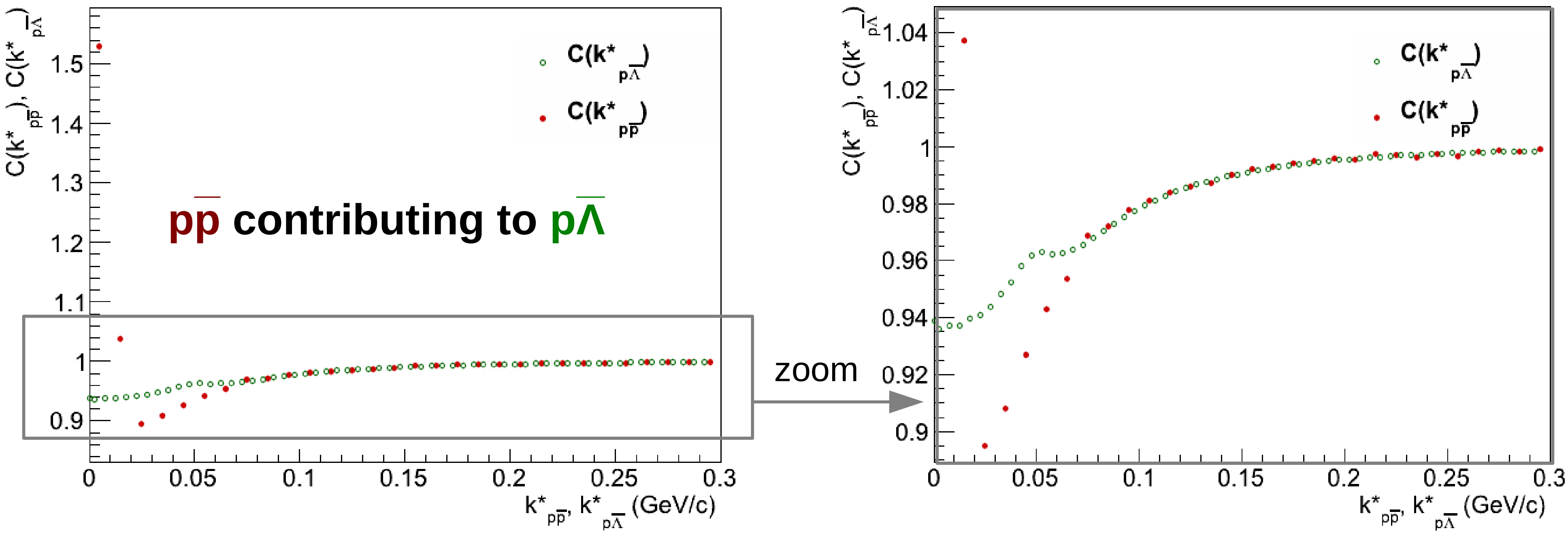
Peak in k^*_{pp} ~ 0.02 GeV/c → Peak in $k^*_{p\Lambda}$ ~ 0.05 GeV/c

Primary proton pairs in k^*_{pp} < 0.02 GeV/c are transformed to $k^*_{p\Lambda}$ from ~0.04 GeV/c to ~0.07 GeV/c.

Peak in k^*_{pp} ~ 0.02 GeV/c can create a structure in $k^*_{p\Lambda}$ ~ 0.05 GeV/c.

This is true also in the opposite way – pΛ residual correlation can be observed in pp.

Study of residual correlations - p$\bar{\Lambda}$



Peak ~ 0 GeV/c+ wide dip for k^*_{pp} → Dip+peak $k^*_{p\Lambda}$ ~ 0.05 GeV/c

Residual correlations from $p\bar{p}$ increase anticorrelation seen in $p\bar{\Lambda}$.
Also, they could create additional small bump at k^*_{pp} ~ 0.05 GeV/c.

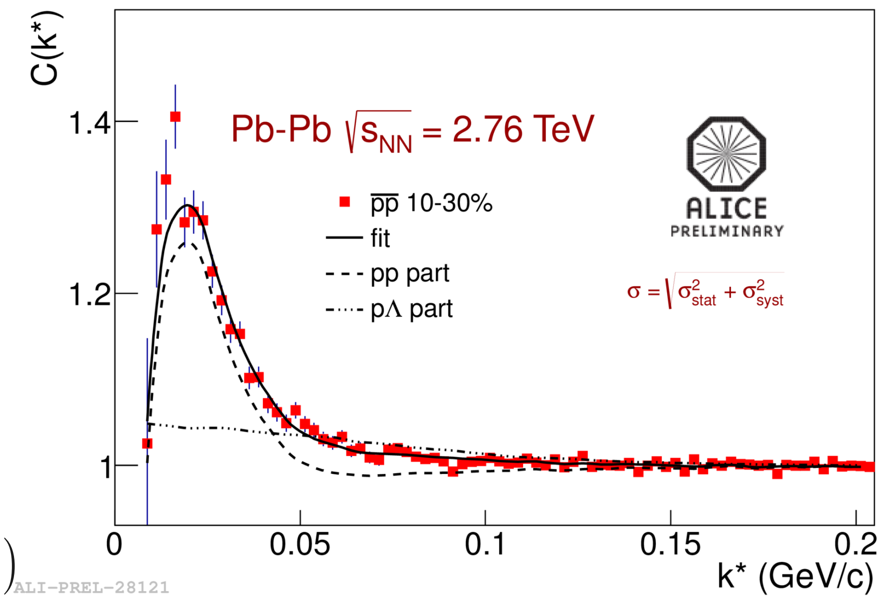
Study of residual correlations - pp

- The excess about 50 MeV/c in k* not explained by correlations coming from pp wave-function.
- Possible explanation: residual correlations, main weak decay channel leading to protons:

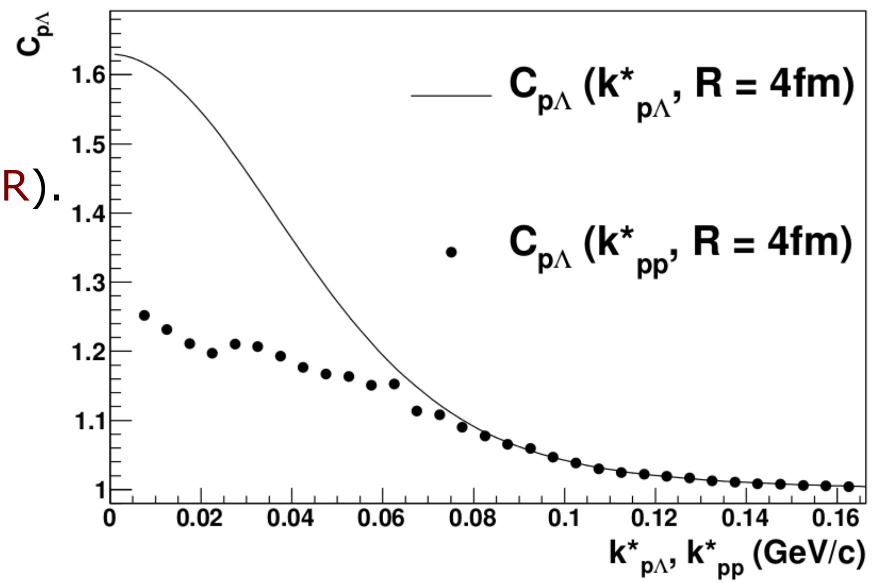
$$\Lambda \rightarrow p + \pi^-$$

- Fitting function calculated by quadratic interpolation between theoretical pp and pΛ:

$$C_{meas}(k^*) = 1 + \lambda_{pp}(C_{pp}(k^*;R) - 1) + \lambda_{p\Lambda}(C_{p\Lambda}(k^*;R) - 1)$$



- Details regarding residual correlations:
  - Assumption of Gaussian source.
  - Decay kinematics taken into account (THERMINATOR).
  - Assumption regarding $R_{pp}/R_{p\Lambda}$ ratio (equals to 1).



Study of residual correlations - $p\bar{p}$

- Similar residual correlation considerations are applicable for $p\bar{p}$ data.
- Instead of contribution from $p\Lambda$ in pp we have contribution from $p\bar{\Lambda}$ in $p\bar{p}$:

$$C_{meas}(k^*) = 1 + \lambda_{p\bar{p}}(C_{p\bar{p}}(k^*;R) - 1) + \lambda_{p\bar{\Lambda}}(C_{p\bar{\Lambda}}(k^*;R) - 1)$$

- After taking into account the residual correlations the shape of the correlation function is very well reproduced by the fit.