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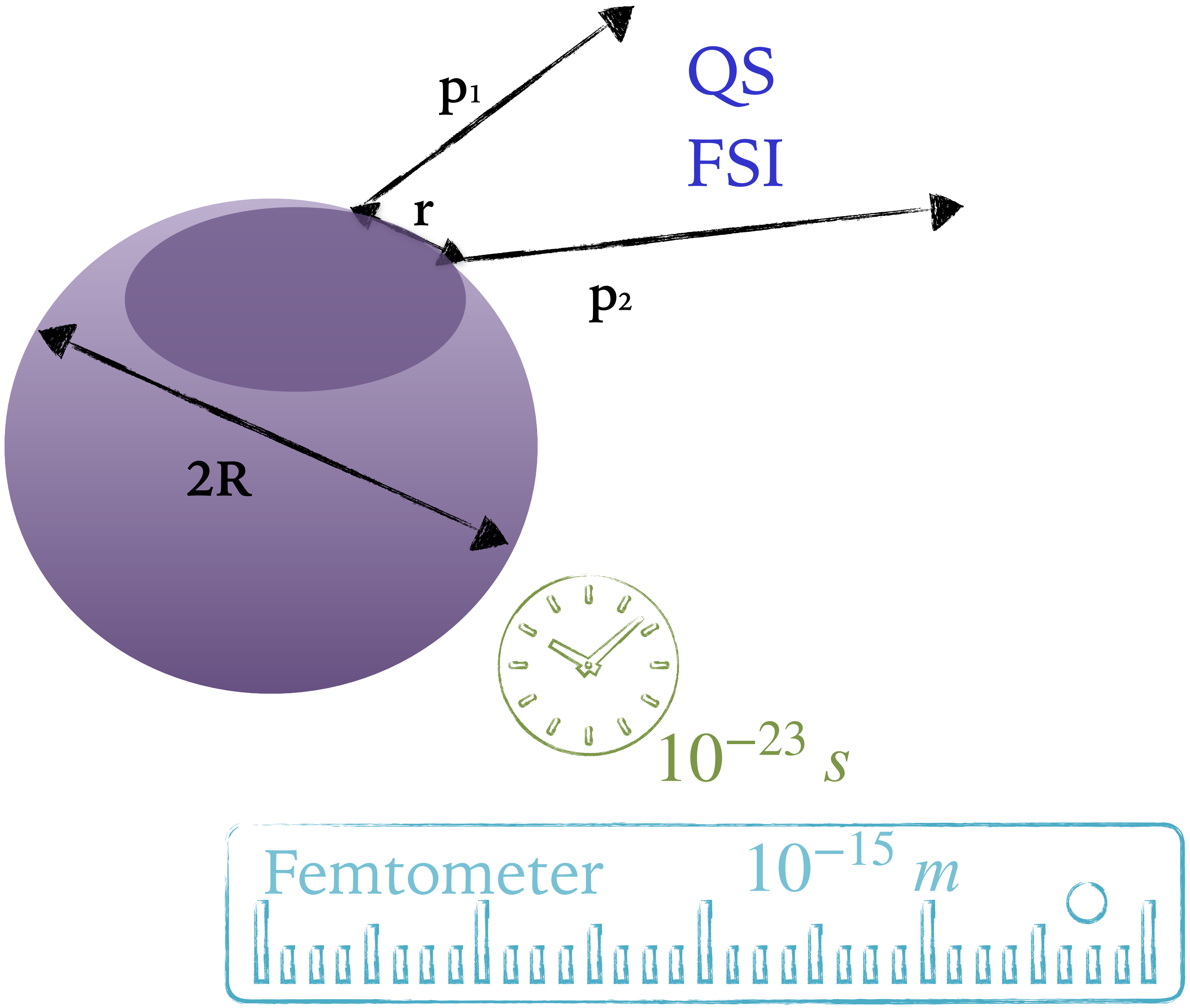
Probing Space-Time Evolution and Final-State Interactions in Relativistic Heavy-Ion Collisions via Femtoscopy

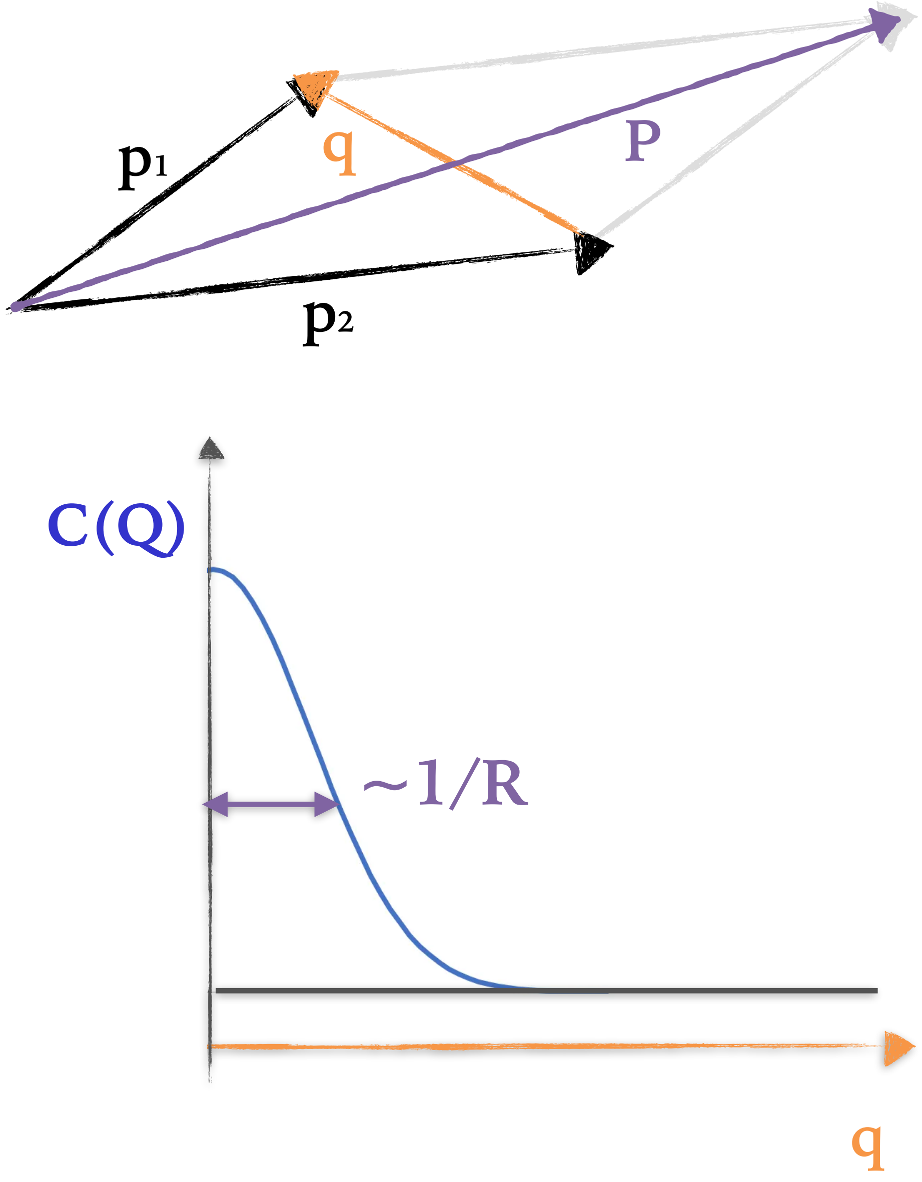
Hanna Zbroszczyk
Warsaw University of Technology
hanna.zbroszczyk@pw.edu.pl

Sizes femtoscopy
Interactions

In honor of Prof. Andrzej Białas

66. Cracow School of Theoretical Physics, Physics of Strong Interactions under Extreme Conditions, June 14-19, 2026

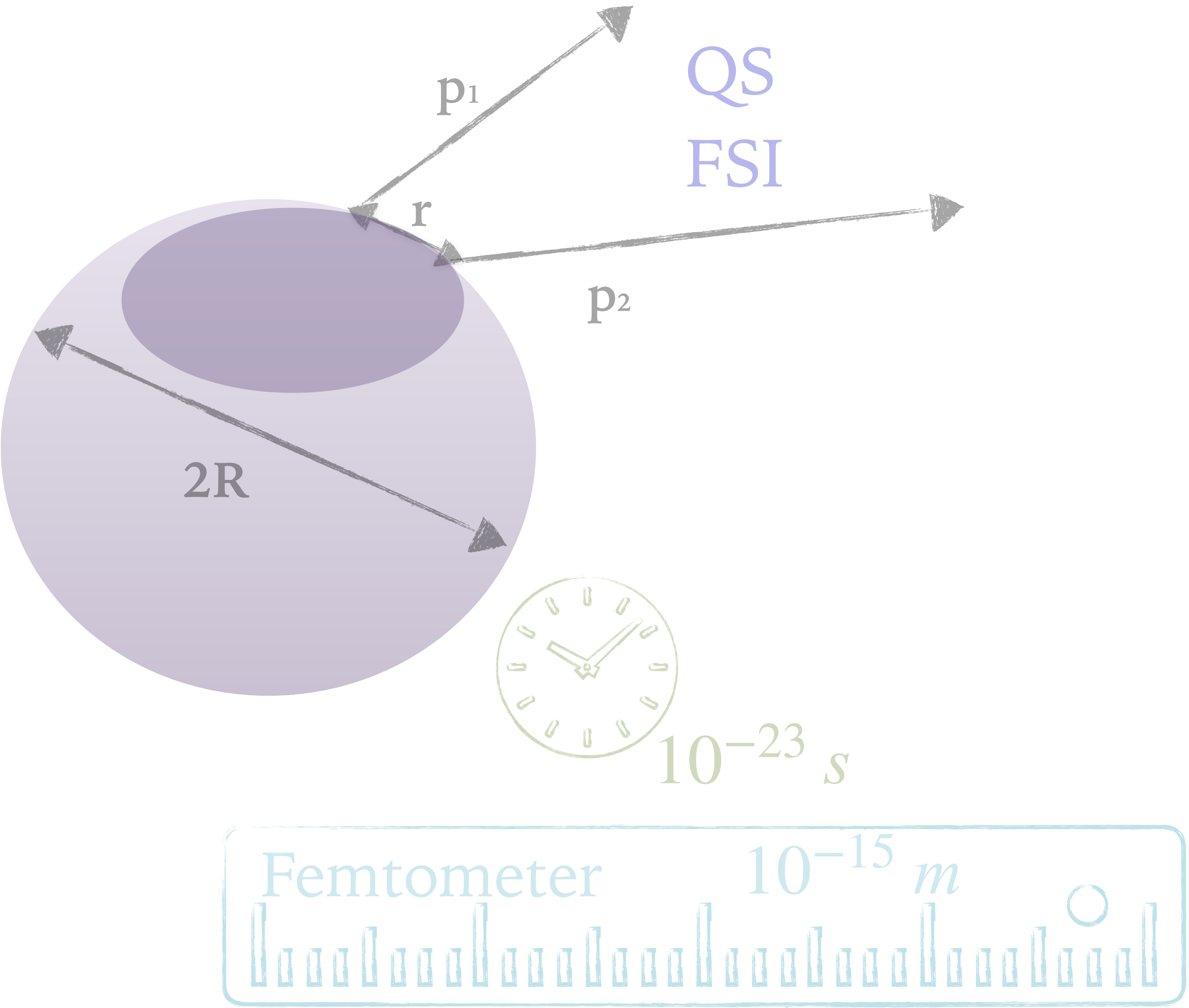


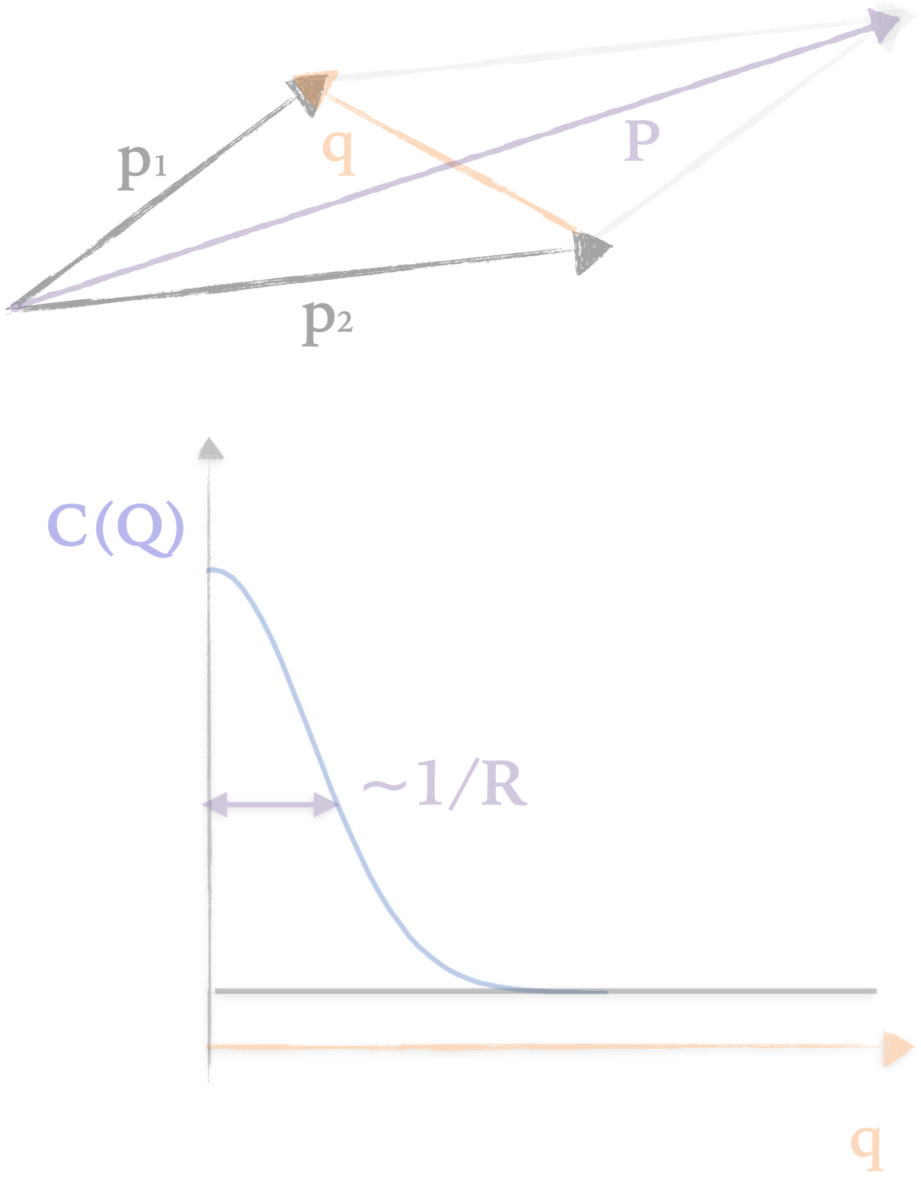


Femtoscopy

… the method to probe **geometric** and **dynamic** properties of the source (emission region, range of correlations-interactions, phase-space cloud, …)

Femtoscopy does not measure the whole source, but homogeneity length.





Sizes Femtoscopy

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Classic femtoscopy

Size: ~10^{-15} m (fm)
Time: ~10^{-23} s

Impossible to measure directly!

Femtoscopy (HIC) inspired by **Hanbury Brown and Twiss interferometry** method (Astronomy) - knows as **HBT technique**

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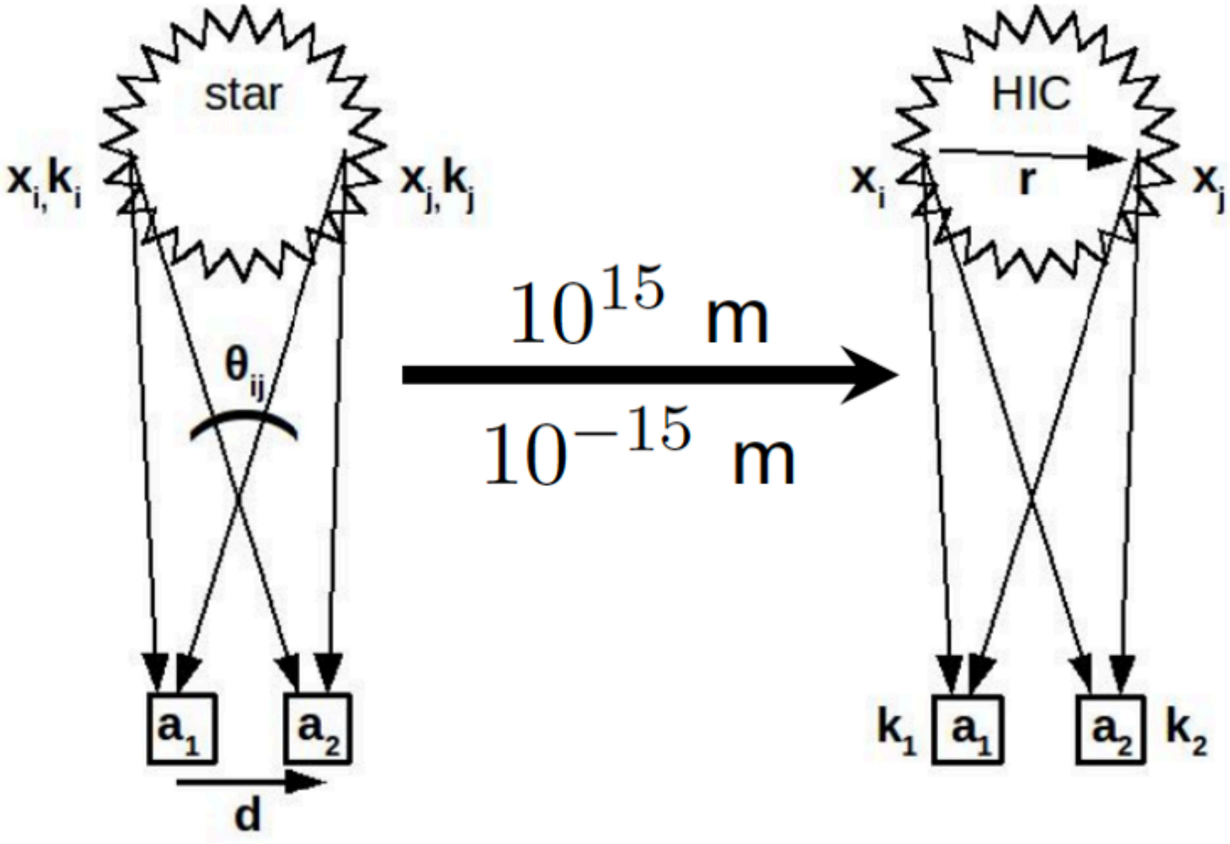
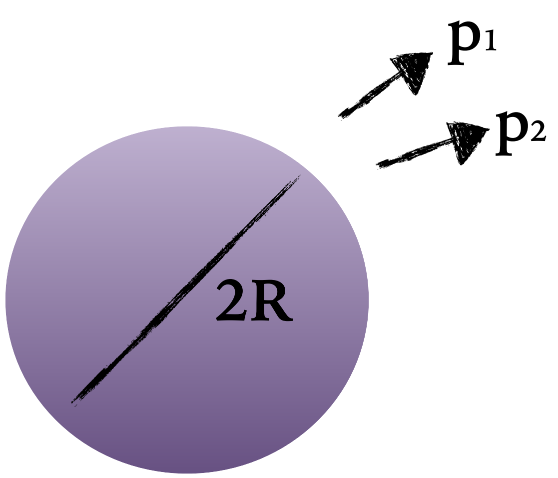


but!

- different scales,
- different measured quantities
- different determined quantities

Classic femtoscopy

Femtoscopy (originating from HBT):
the method to probe **geometric** and **dynamic** properties of the source



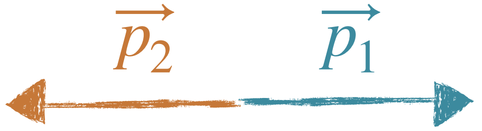
Space-time properties ($10^{-15}m$, $10^{-23}s$) determined thanks to two-particle correlations:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

$$C(k^*, r^*) = \overset{\text{determined}}{\int S(r^*)}\,\overset{\text{assumed}}{|\Psi(k^*, r^*)|}^2 d^3r^* = \overset{\text{measured}}{\frac{Sgnl(k^*)}{Bckg(k^*)}}$$

k^* - momentum of the first particle in the Pair Rest Frame reference



$S(r^*)$ - source function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

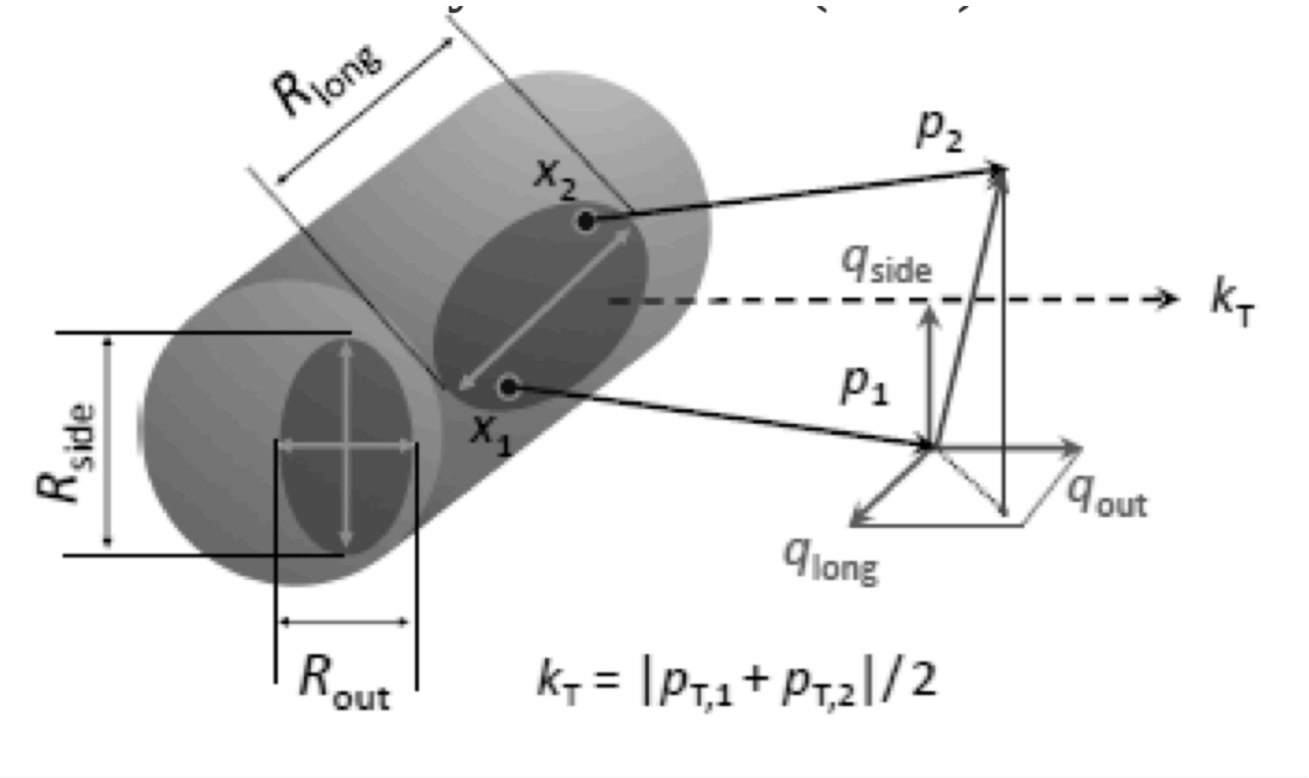
The Foundational Years (1970s)

Before the term „femtoscopy" became widely established, the community focused on understanding how two- and three-particle correlation functions, together with single-particle distributions, could be used to investigate correlations among produced particles. In particular, studies of negatively charged pions demonstrated the presence of correlations arising from energy and momentum conservation, while at high energies additional positive dynamic correlations between negative pions were found. One of the key questions addressed by Prof. Białas was whether particles produced in high-energy collisions were emitted independently or generated through intermediate correlated structures.

„Single-particle distributions and multi-particle correlations in inclusive experiments", A. Białas, K. Fiałkowski, R. Wit, *Nuclear Physics B*, Vol. 43 (1972) 413–433

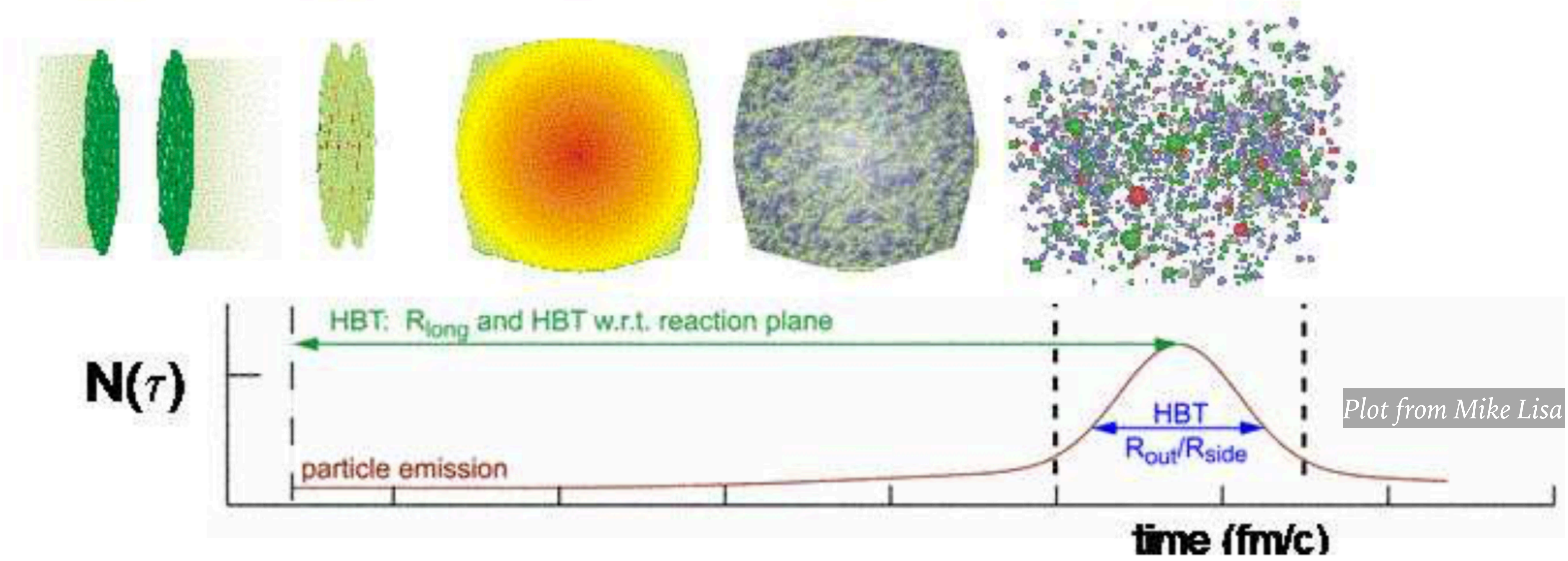
„Experimental investigation of two-particle correlations in the reaction
$p\,p \rightarrow \pi^{-}\pi^{-}$ anything",
A. Białas, K. Fiałkowski, R. Wit, *Phys.Lett.B* 39 (1972) 211-213

„Multiplicity distributions and correlations in inclusive processes",
A. Białas, K. Zalewski, *Nucl.Phys.B* 42 (1972) 325-332



Sizes and dynamics

Heavy ion collision (HIC) and the HBT method



Plot from Mike Lisa

Hadrons’ correlations probe the emission source properties at the moment of kinetic freeze-out

They offer indirect access to the source parameters and time properties

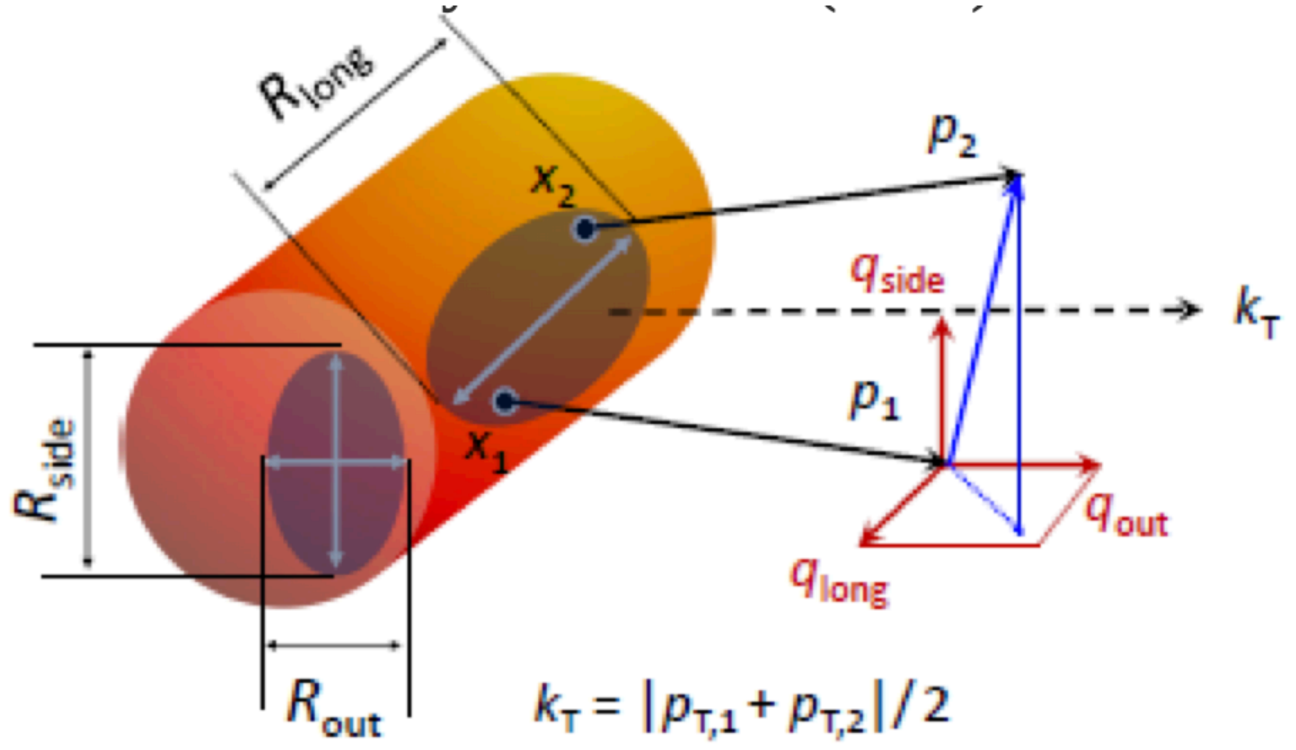
One of the primordial motivation was to probe formation of QGP (increased sizes)

Bertsch-Pratt parametrization, 3D- and 1D-dimensional cases

long - determined by the beam direction

out - determined by the pair trans. momentum

side - perpendicular to *long* and *side*



$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o q_s R_{os}^2 - 2 q_o q_l R_{ol}^2\right)$$

Bertsch-Pratt parametrization, 3D- and 1D-dimensional cases

→ R_{side} spatial source evolution in the transverse direction
→ R_{out} related to spatial and time components
→ R_{out}/R_{side} signature of phase transition
→ $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
→ R_{long} temperature of kinetic freeze-out and source lifetime

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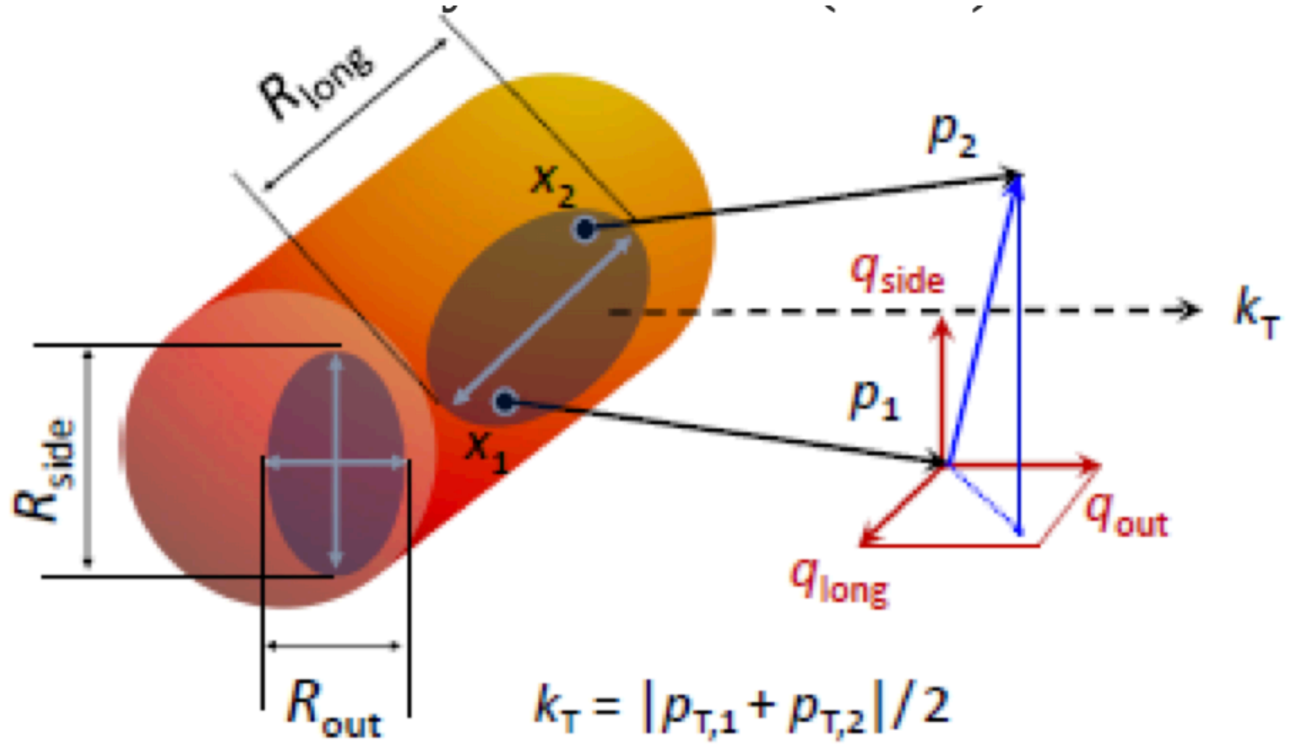

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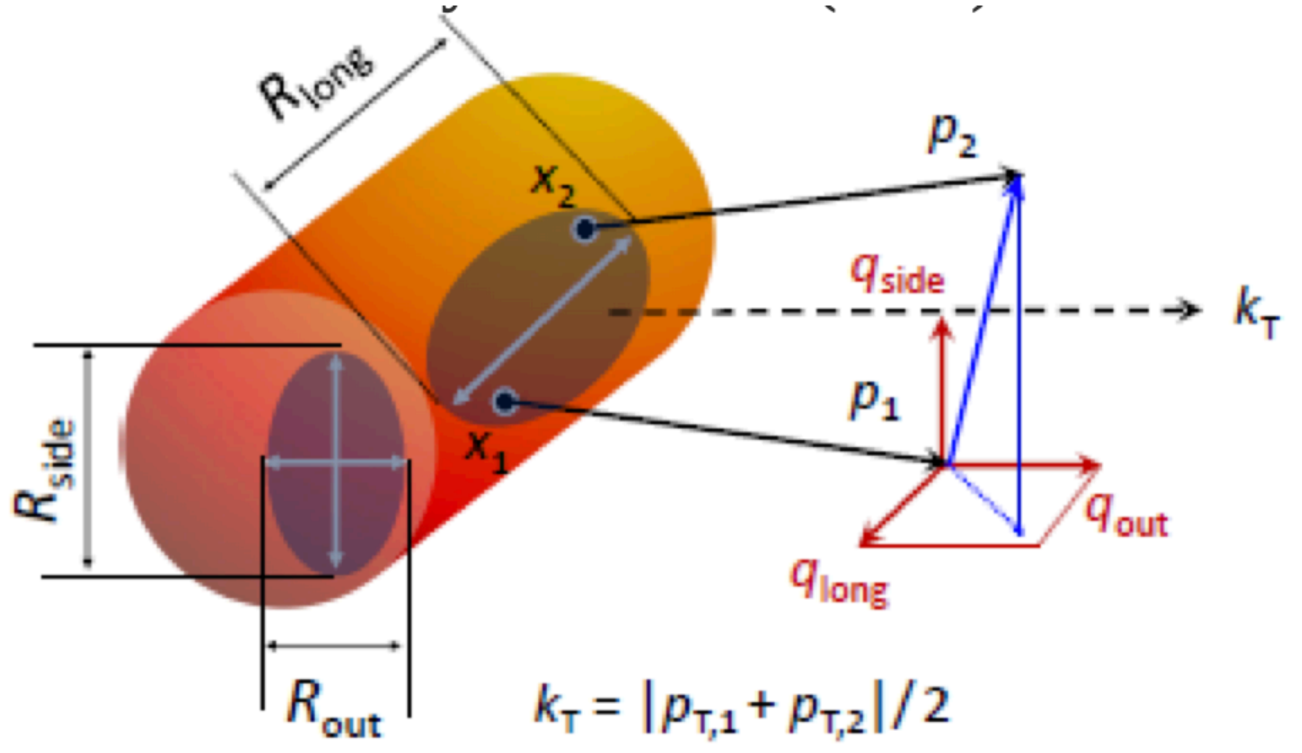
3D case is considered if statistics is enough and two-particle correlations are easy to describe (Quantum Statistics and Coulomb FSI).



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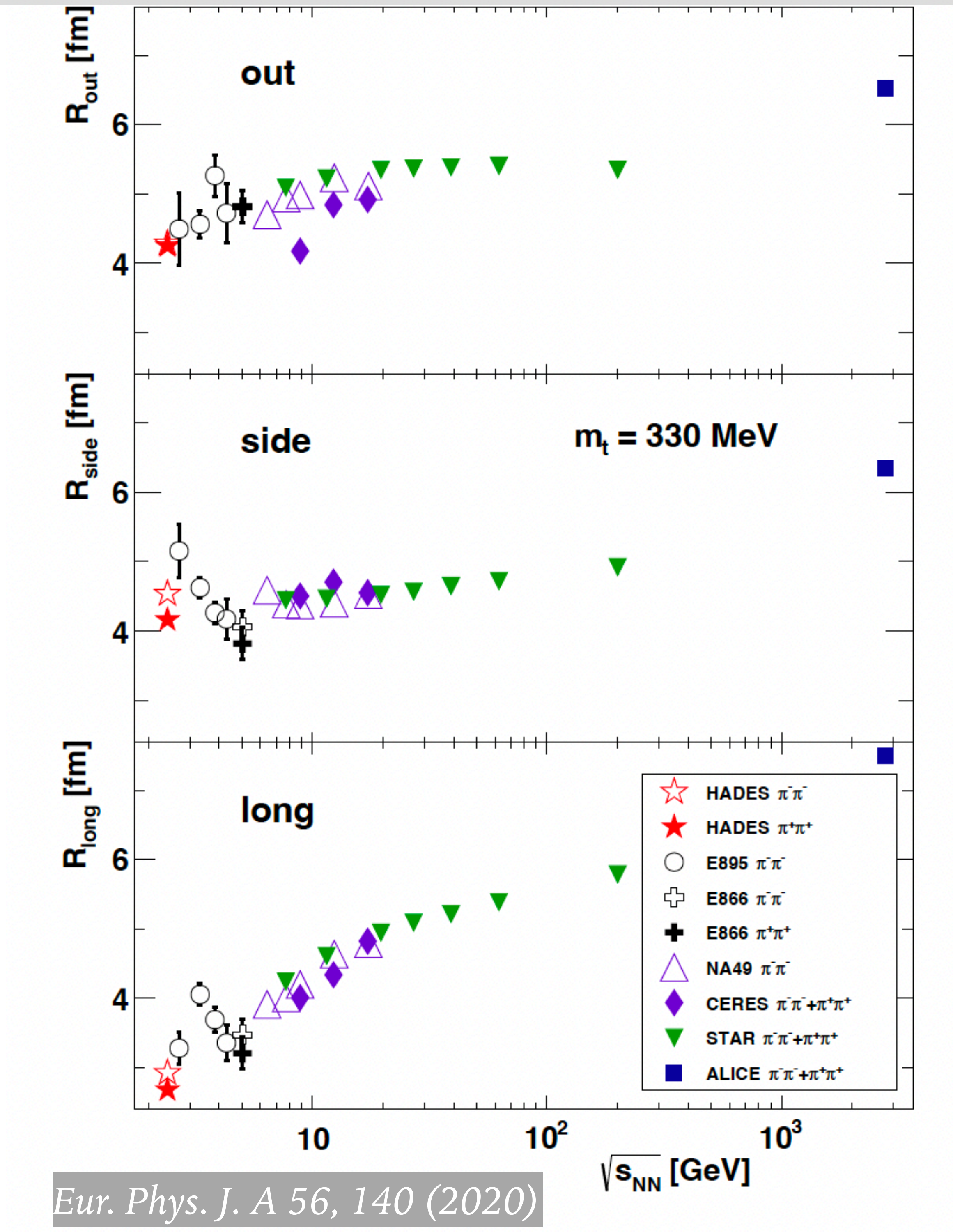
Identical pion femtoscopy ($\sqrt{s_{NN}}$)

HBT source sizes determined for wide range of collision energy
Non-monotonic behavior seen in three directions



Eur. Phys. J. A 56, 140 (2020)

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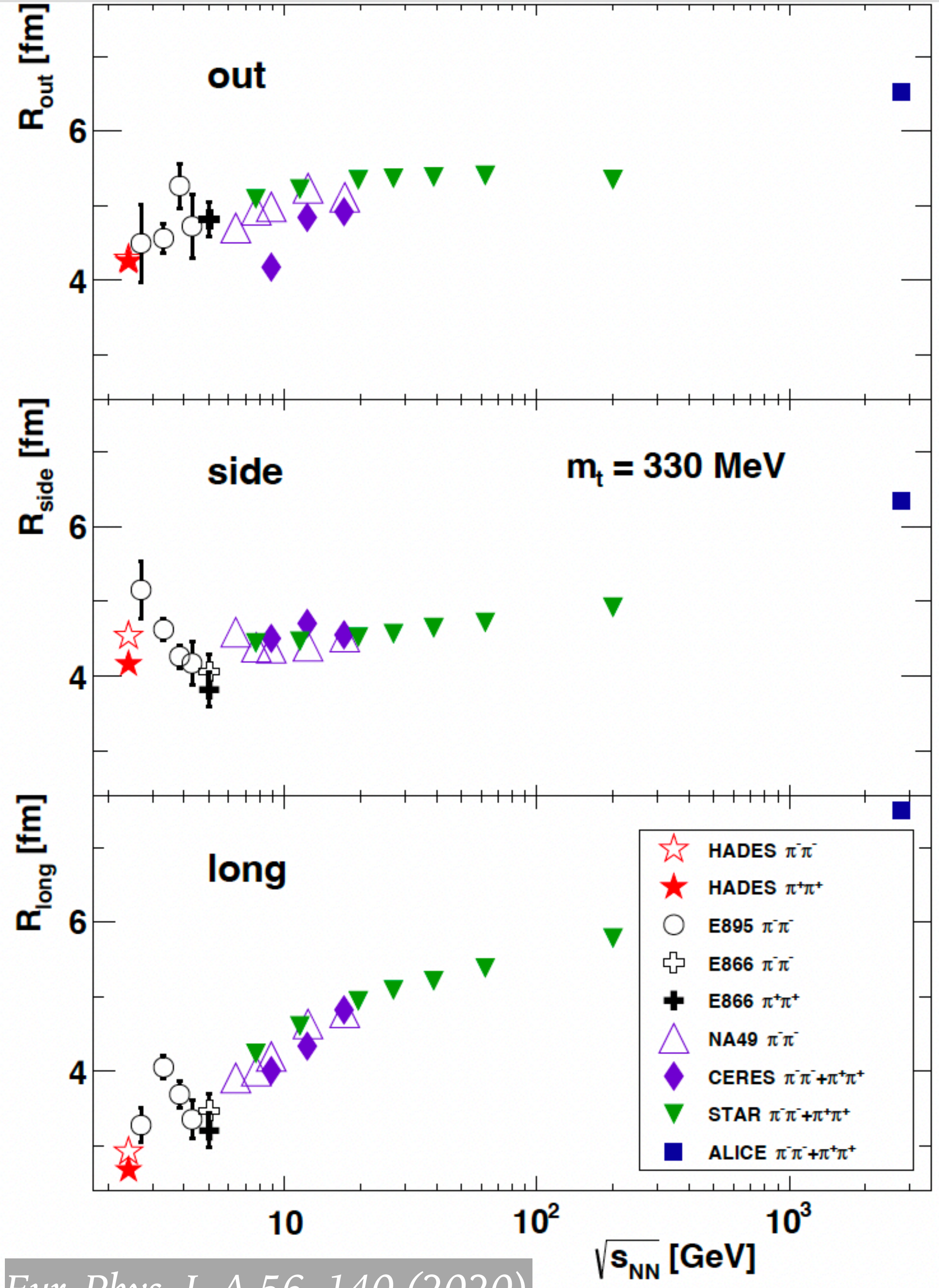
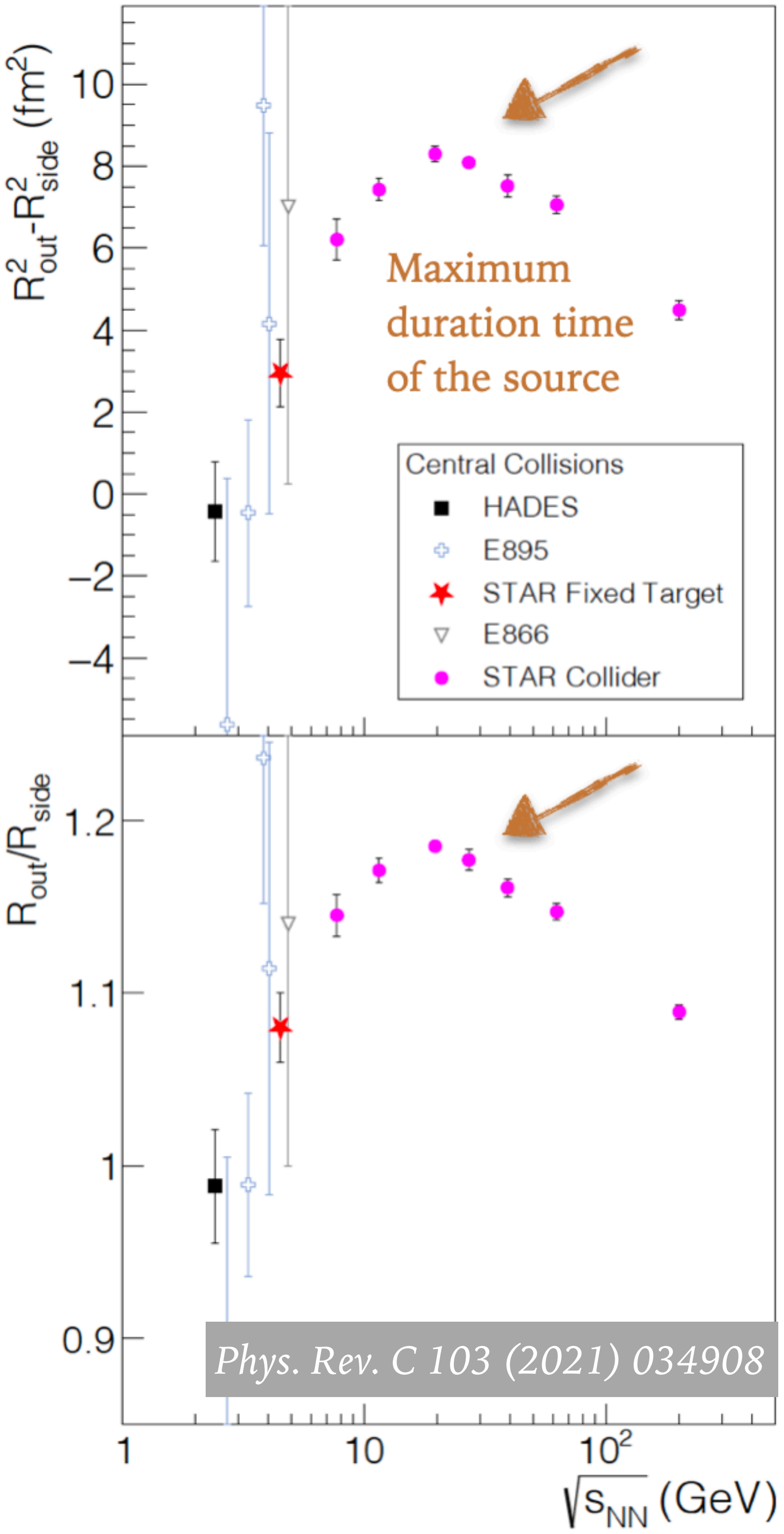


Eur. Phys. J. A 56, 140 (2020)

HBT parameters have been proposed as QGP signature

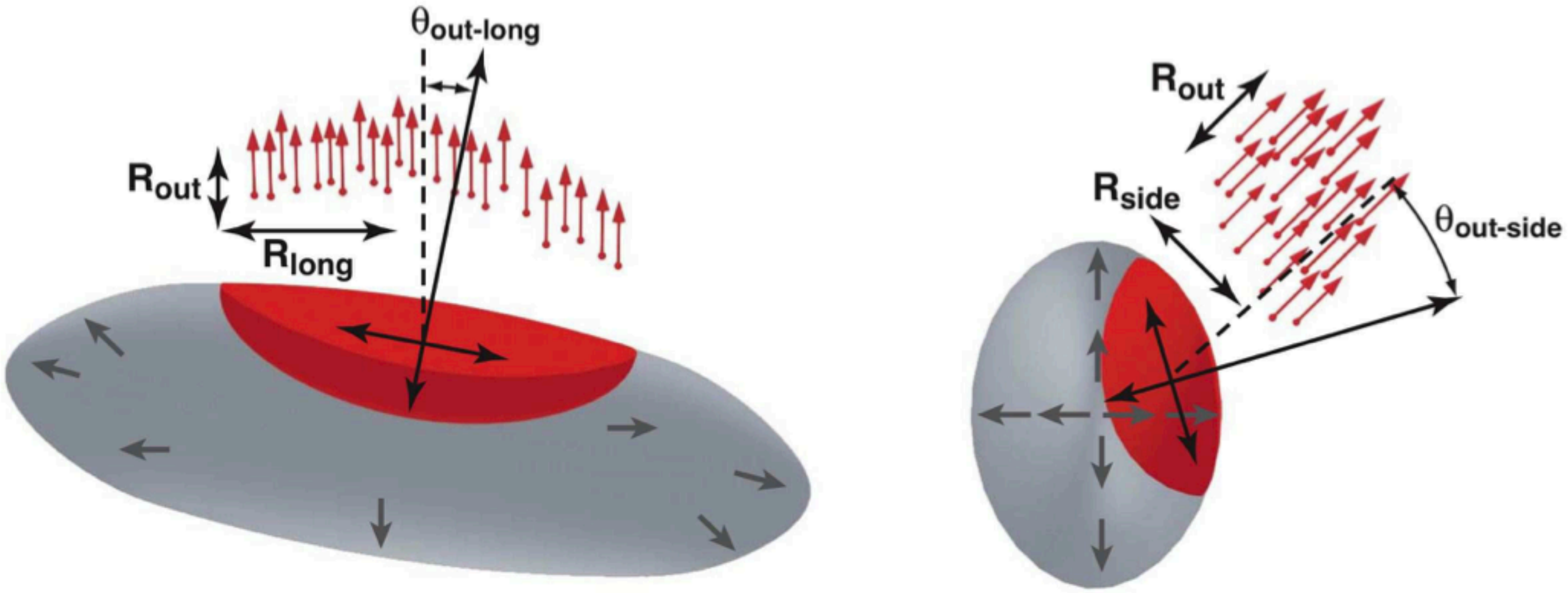
The focus was on R_{out}/R_{side} ratio and $R^2_{out} - R^2_{side}$



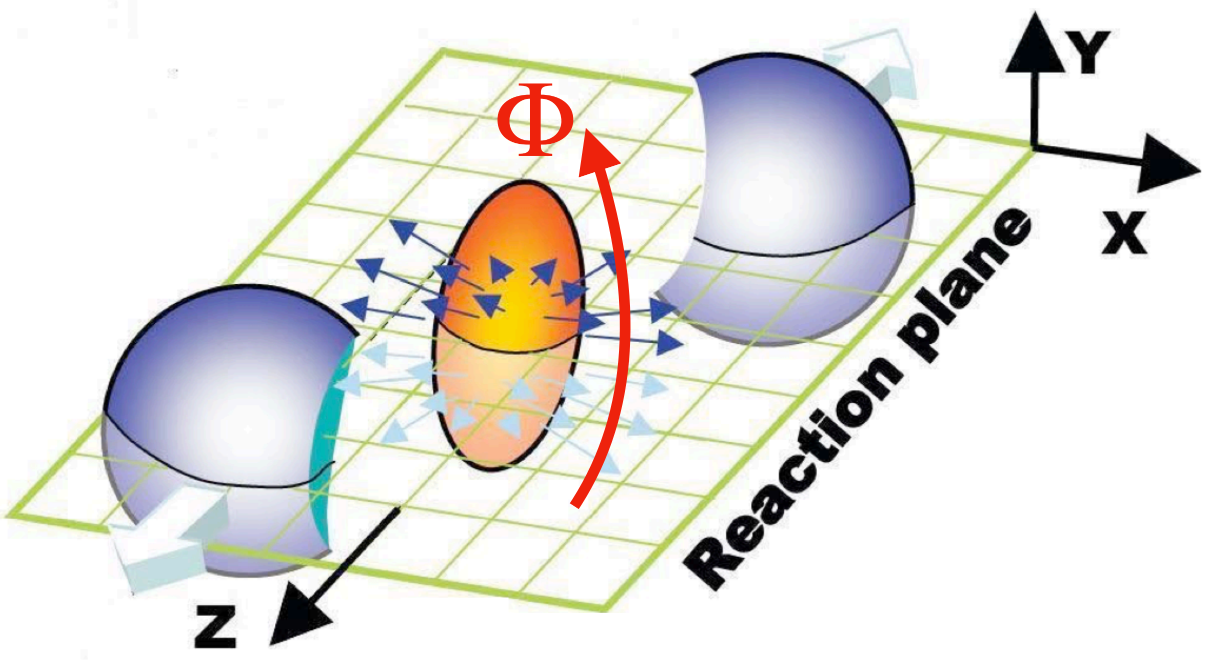
Maximum duration time of the source

Phys. Rev. C 103 (2021) 034908

Looking for phase transition



Looking at the source depending on orientation w.r.t. the reaction plane provides more complete information



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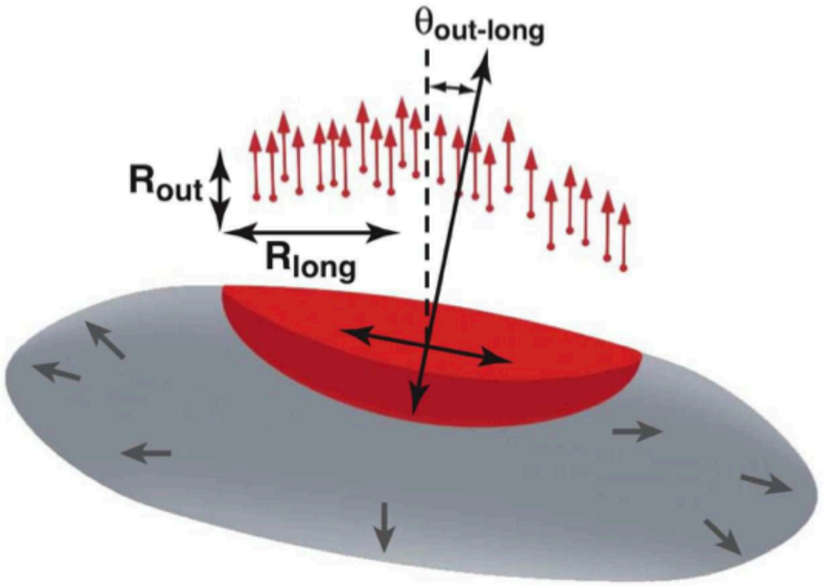

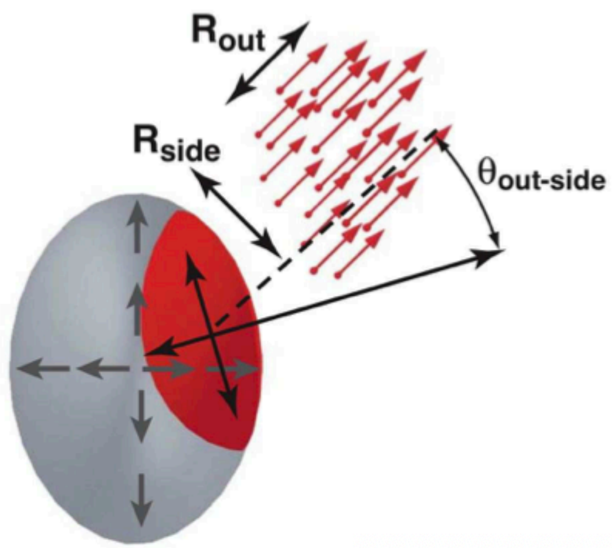

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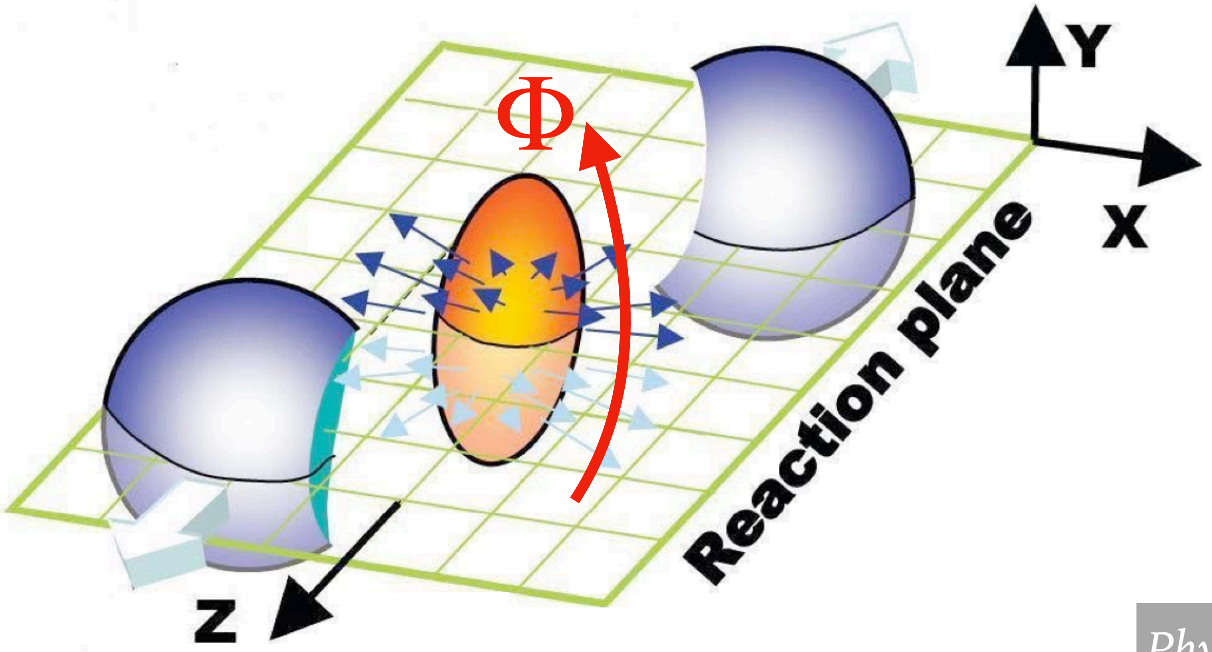
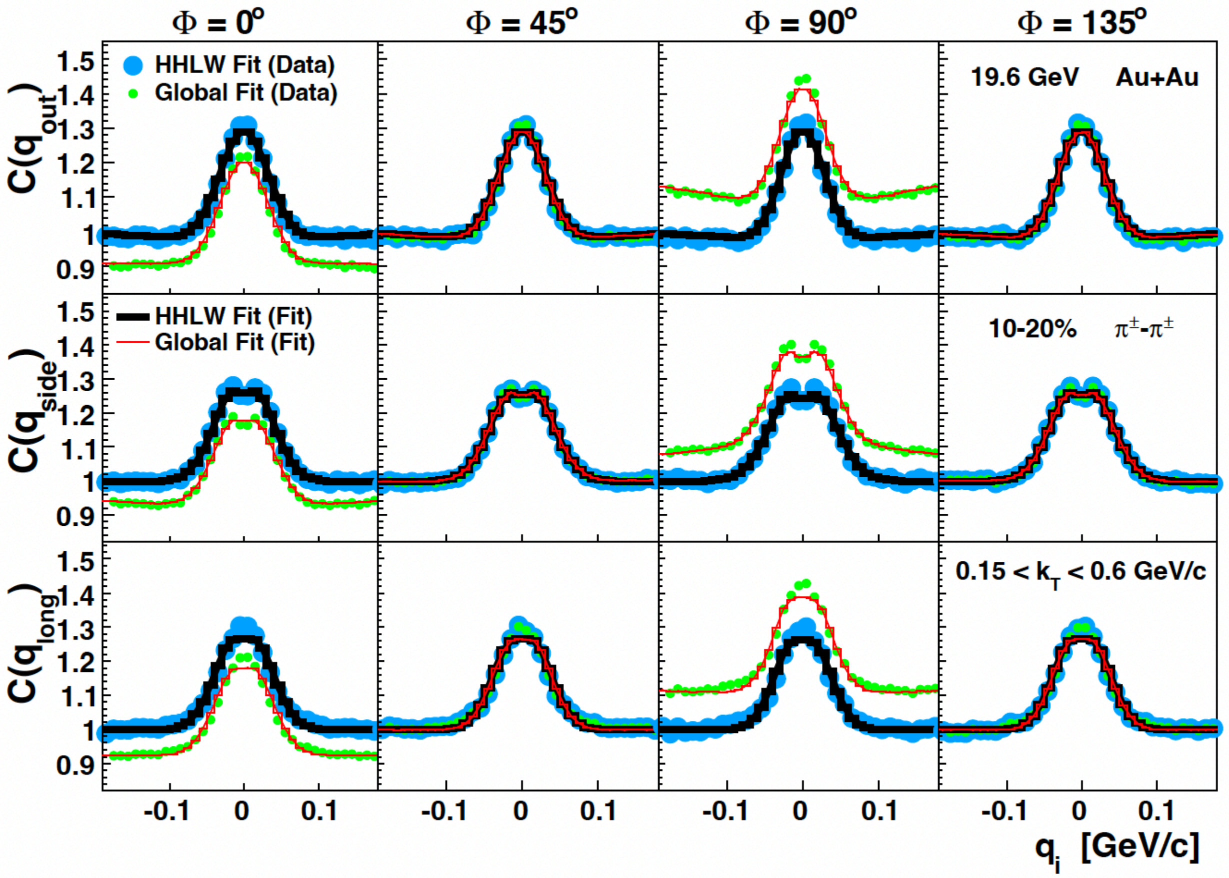
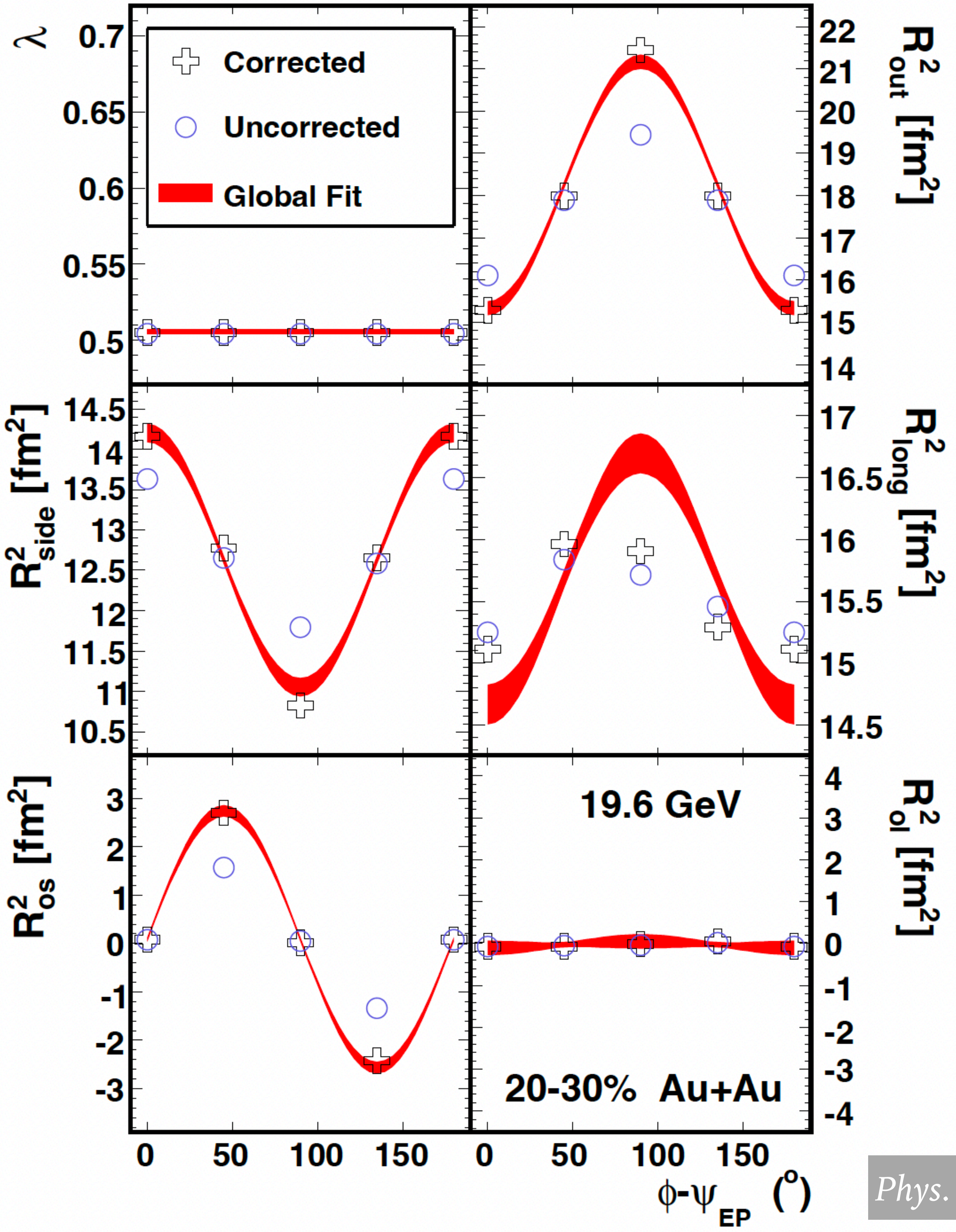




Phys. Rev. C 92 (2015) 14904

Looking for phase transition



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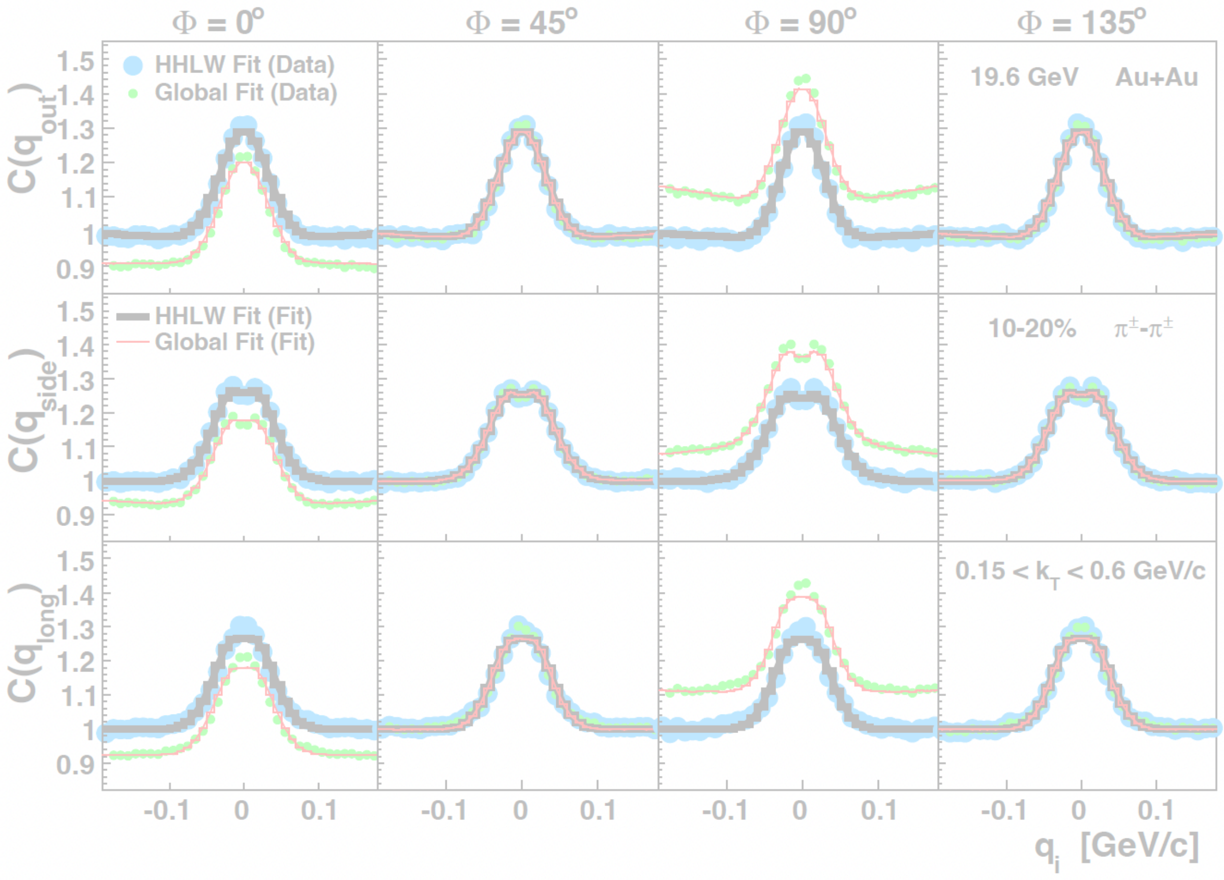


Phys. Rev. C 92 (2015) 14904

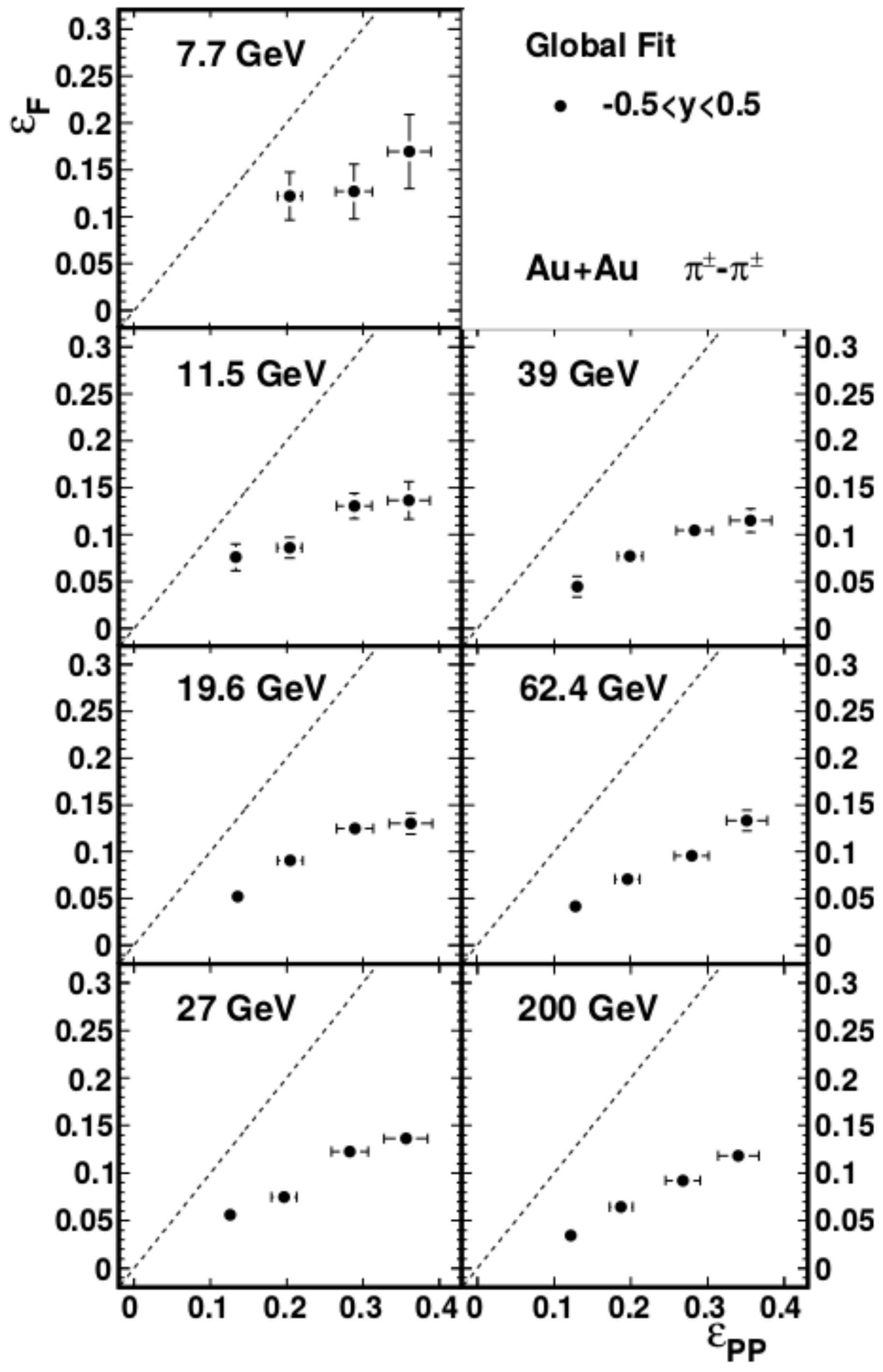
Looking for phase transition

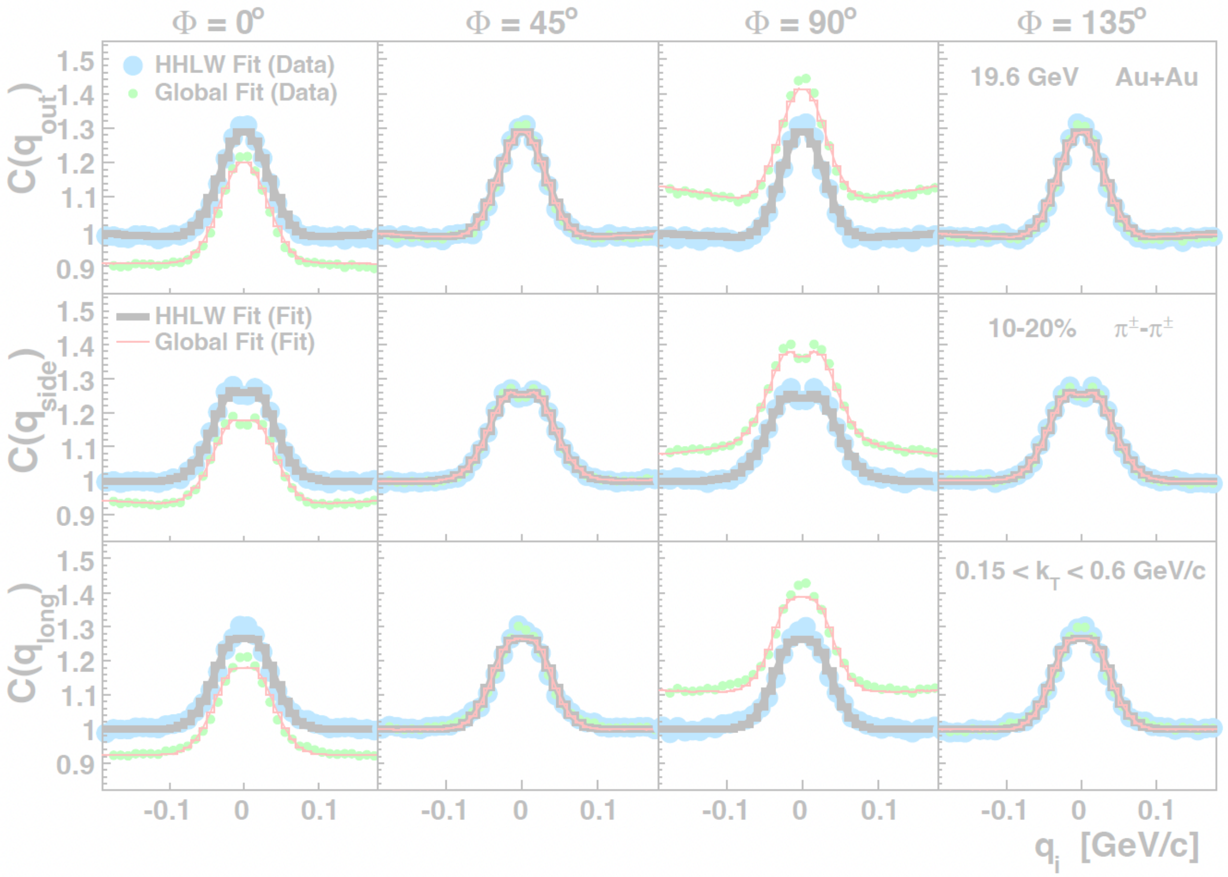
$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}. \qquad \varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

$$\sigma_x^2 = \{x^2\} - \{x\}^2 \text{ and } \sigma_y^2 = \{y^2\} - \{y\}^2$$

$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o, s, l, ol)$$

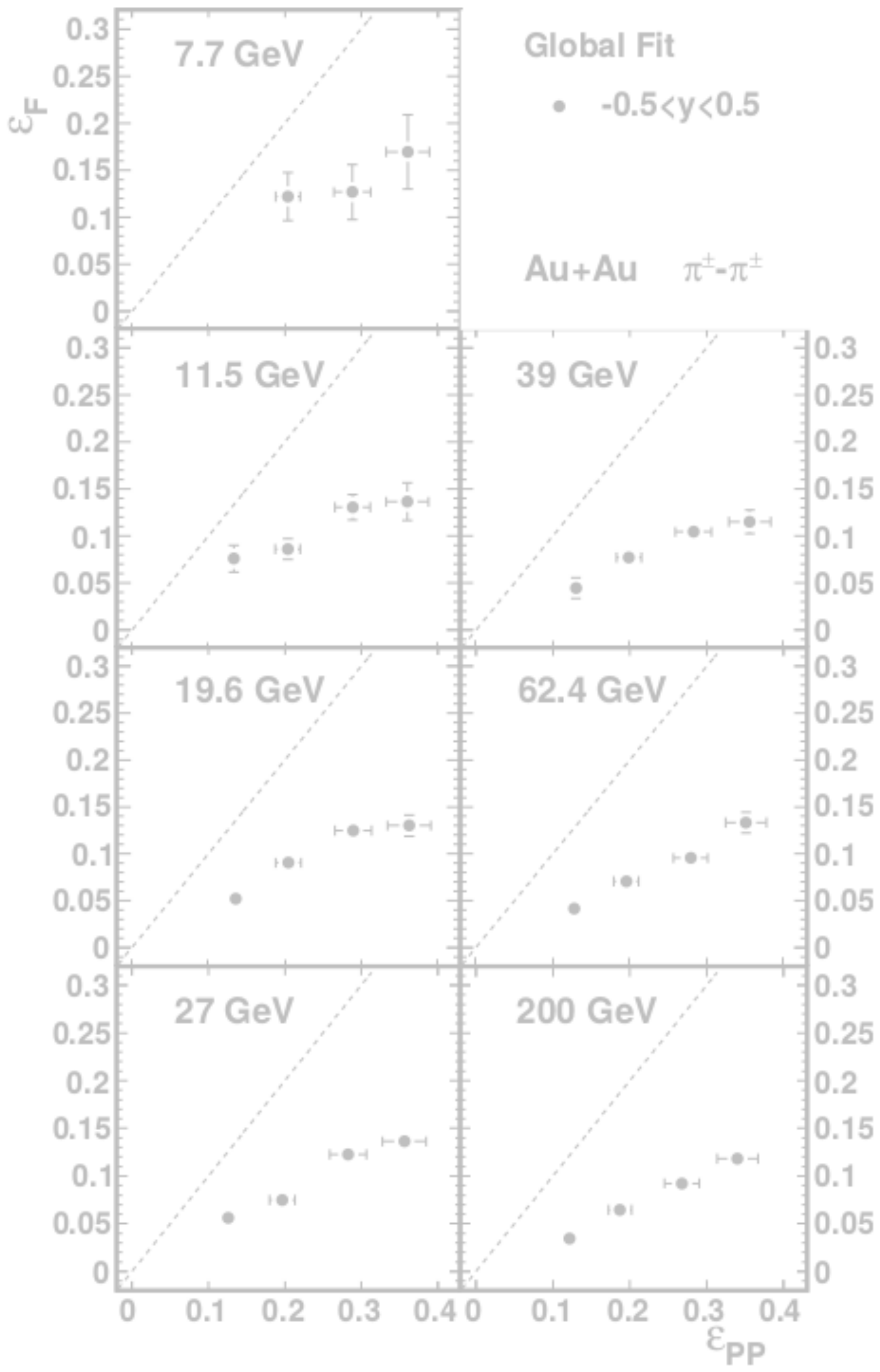
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$

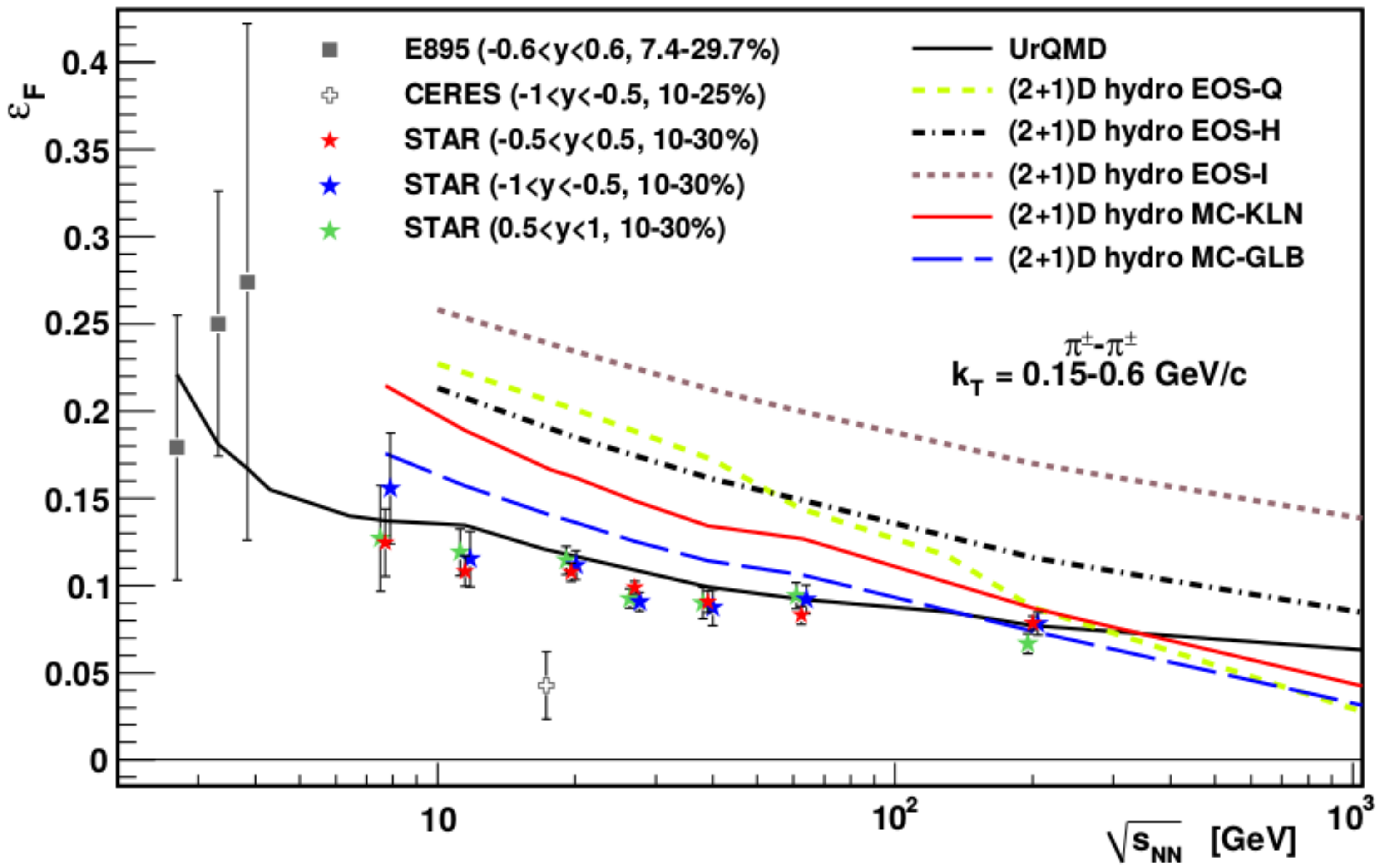




Phys. Rev. C 92 (2015) 14904

Looking for phase transition

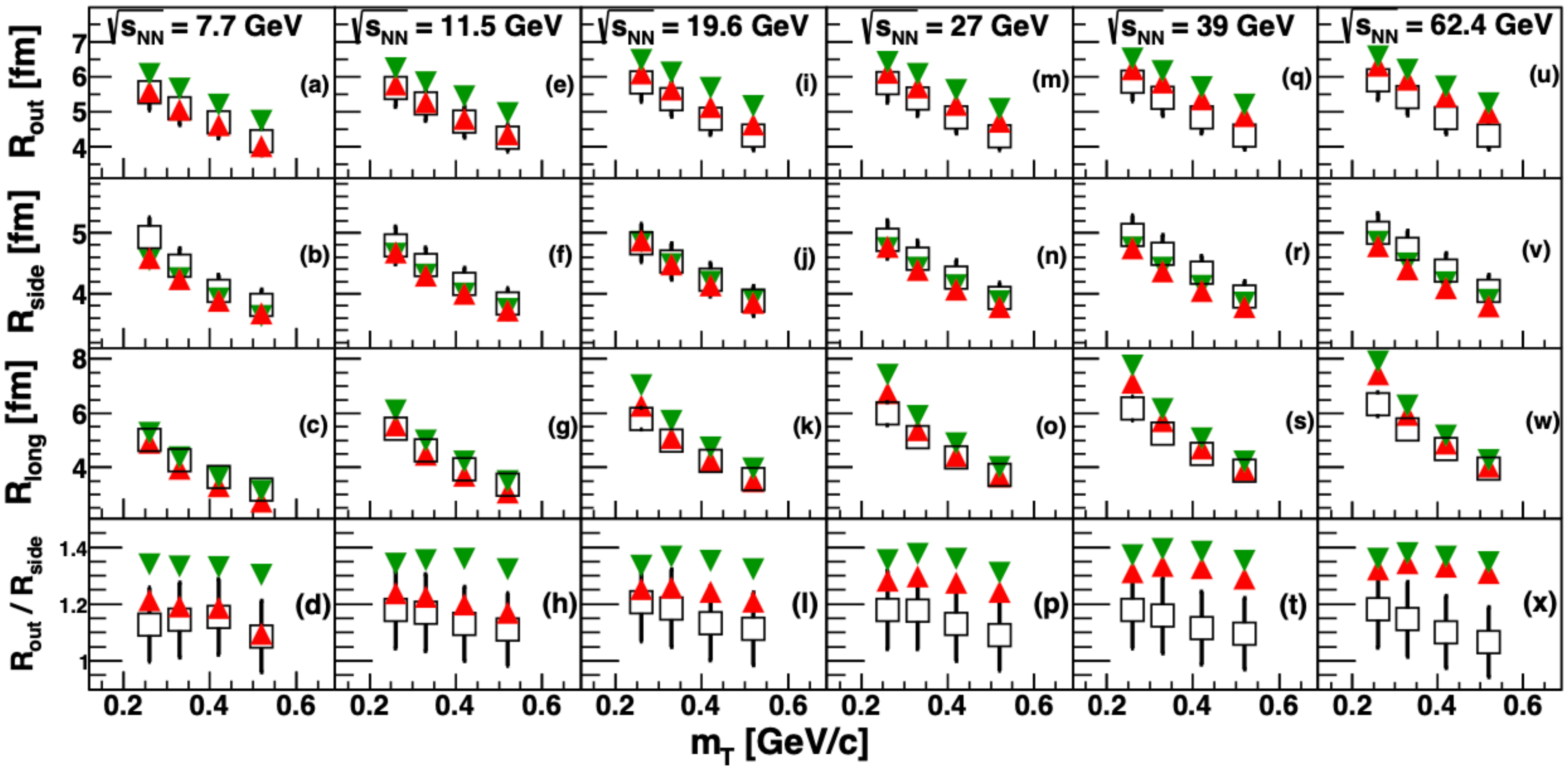




System evolves faster in the reaction plane

Phys. Rev. C 92 (2015) 14904

Looking for phase transition (models)



☐ STAR Data

🟩 1st order Phase Tr.

🟥 Cross-over Tr.

vHLLE (3+1)-D viscous hydrodynamics: Iu. Karpenko, P. Huovinen, H. Petersen, M. Bleicher; Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978, 1509.3751

Pre-thermal → Hydrodynamical phase → Hydronic cascades

UrQMD vHLEE UrQMD

HadronGas + Bag Model → 1^{st} order PT ; P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT); J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

vHLEE+UrQMD model verify **sensitivity of HBT measurements to the first-order phase transition**

Phys. Rev. C 96 (2017) no.2, 024911

The Intermittency (1980s - 1990s)

Prof. Białas investigated intermittency and random cascading processes in multiparticle production, demonstrating that standard and correlated factorial moments in rapidity provide stringent tests of characteristic intermittency patterns and can be used to search directly for the existence of underlying cascade mechanisms. His work also addressed the treatment of statistical effects and corrections necessary for reliable analyses. In addition, he showed that projections of inherently three-dimensional intermittent structures in momentum space onto rapidity and/or azimuthal variables may significantly reduce the extracted intermittency parameters and lead to deviations from the expected power-law behavior at very small phase-space intervals, emphasizing the importance of multidimensional approaches in the study of fluctuations.

„Random Cascading Models and the Link Between Long Range and Short Range Interactions in Multiparticle Production”,
A. Białas, R. Peschansky, *Phys.Lett.B* 207 (1988) 59-63

„Intermittency in Multiparticle Production at High-Energy”
A. Białas, R. Peschansky, *Nucl.Phys.B* 308 (1988) 857-867

„Strong intermittency in momentum space”,
A. Białas, J. Seixas, *Phys.Lett.B* 250 (1990) 161-163

The Intermittency (1980s - 1990s)

Prof. Białas explored the connection between intermittency phenomena and the possible formation of quark - gluon plasma in relativistic heavy-ion collisions, proposing anomalous dimensions extracted from particle spectra as potential signatures of the phase transition between deconfined and hadronic matter. He also introduced methods for studying intermittency in variables with uniform single-particle distributions, significantly reducing distortions caused by non-uniform particle densities. These developments led to a systematic framework for multidimensional intermittency analyses and improved the reliability of fluctuation studies in high - energy collisions.

„A New variable to study intermittency",
A. Białas, M. Gaździcki, *Phys.Lett.B* 252 (1990) 483-486

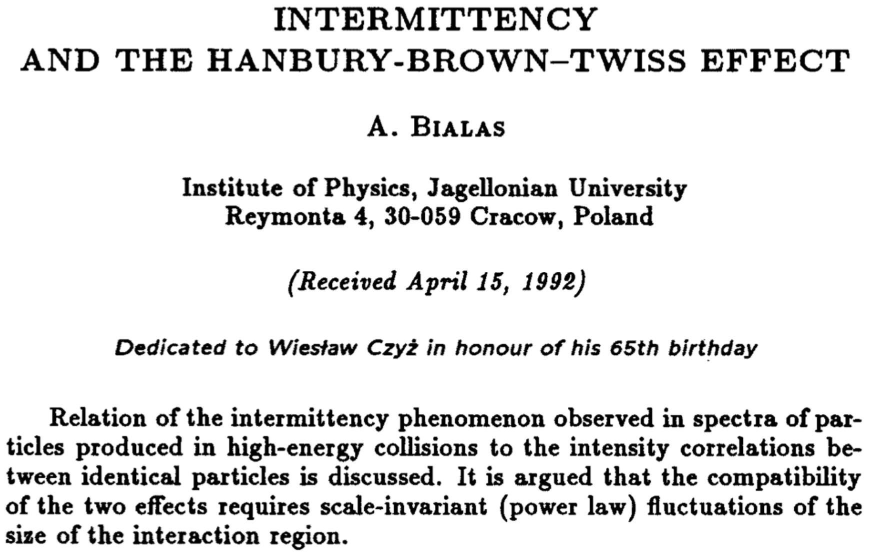
„Intermittency parameters as a possible signal for quark - gluon plasma formation",
A. Białas, R.C. Hwa, *Phys.Lett.B* 253 (1991) 436-438

The Intermittency (1980s - 1990s)

Prof. Białas investigated the relationship between intermittency observed in particle spectra from high-energy collisions and intensity correlations between identical particles (HBT correlations). He argued that consistency between these two phenomena requires scale-invariant, power-law fluctuations in the size of the particle-emitting source. Building on the idea that intermittency may be related to Bose–Einstein correlations among identical pions, he studied the origin of the observed power-law behavior of correlation functions. Analyses of higher-order correlations suggested that intermittency is not a consequence of incoherent superposition of many events, but rather an effect present within individual events. Moreover, the data indicate that uncorrelated emission from a space-time volume of arbitrary shape cannot account for the observed patterns. These findings point toward a genuine fractal-like structure of particle production in space-time.

„Intermittency and the Hanbury-Brown-Twiss effect"
A. Białas, *Acta Phys.Polon.B* 23 (1992) 561-567

„Space-time structure of hadron sources and intermittency"
A. Białas, B. Ziaja, *Acta Phys.Polon.B* 24 (1993) 1509-1518



INTERMITTENCY
AND THE HANBURY-BROWN–TWISS EFFECT

A. Bialas

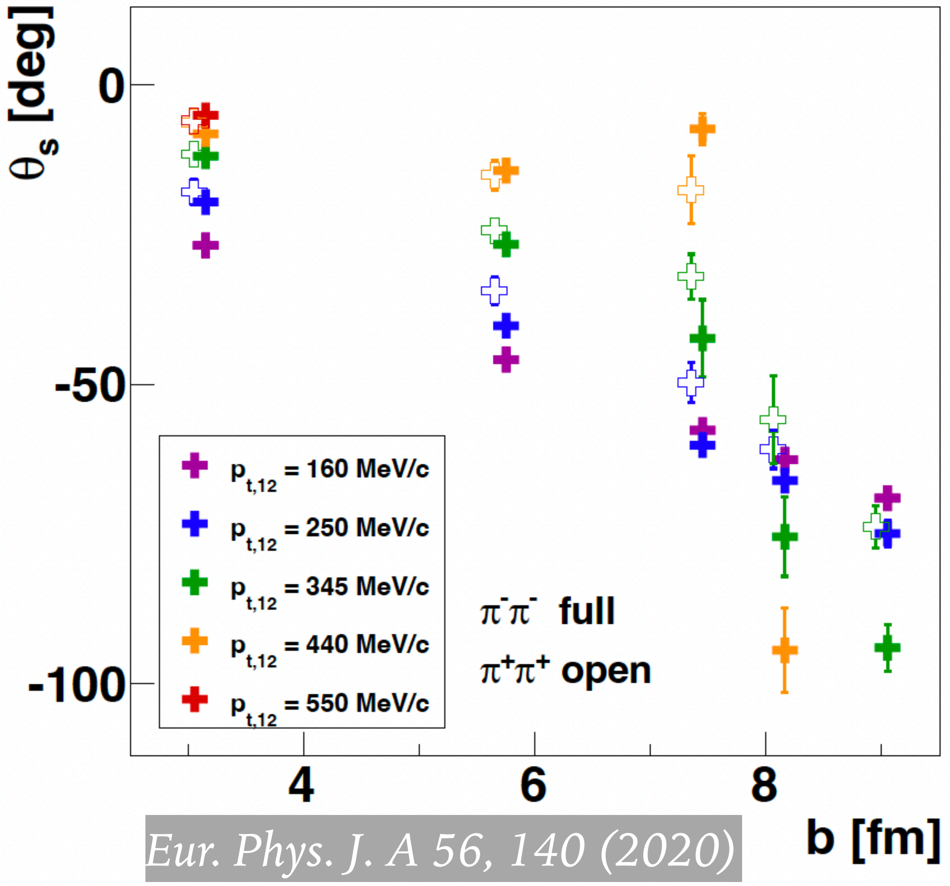
Institute of Physics, Jagellonian University
Reymonta 4, 30-059 Cracow, Poland

(Received April 15, 1992)

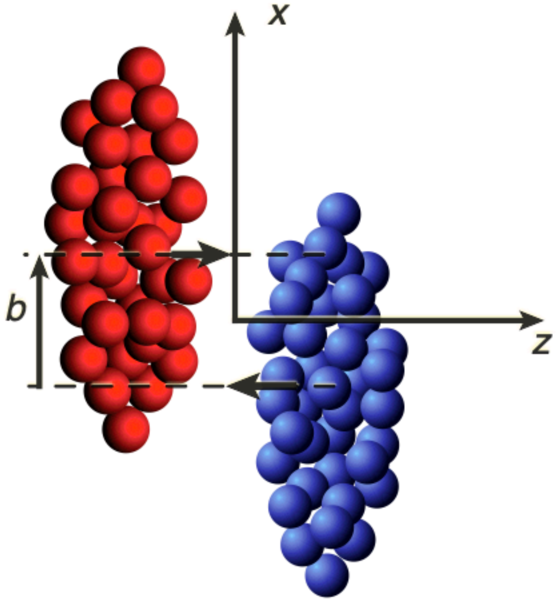
Dedicated to Wiesław Czyż in honour of his 65th birthday

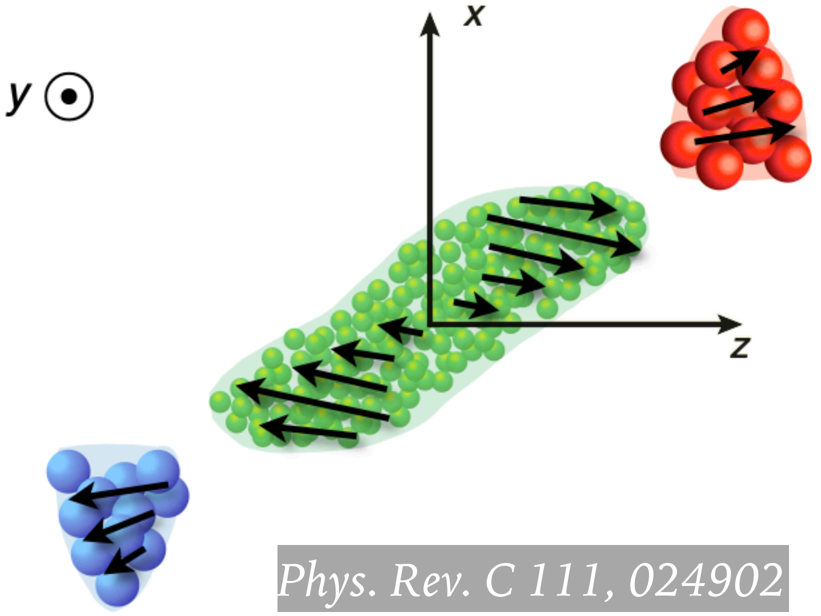
Relation of the intermittency phenomenon observed in spectra of particles produced in high-energy collisions to the intensity correlations between identical particles is discussed. It is argued that the compatibility of the two effects requires scale-invariant (power law) fluctuations of the size of the interaction region.

Collectivity from femtoscopy



Eur. Phys. J. A 56, 140 (2020)



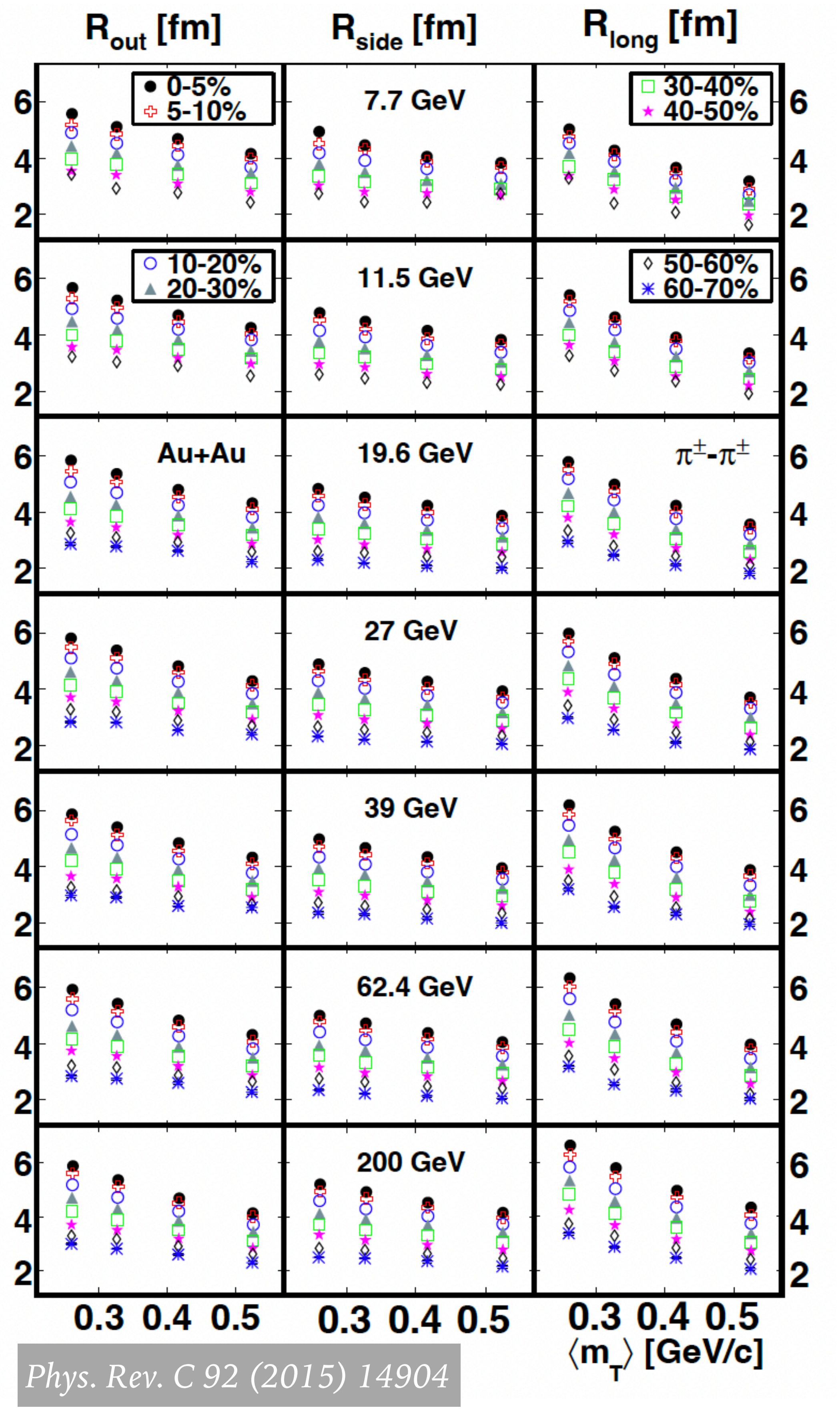


Phys. Rev. C 111, 024902

- Directed flow is attributed to the tilted source (from forward-backward asymmetry of the initial geometry).
- Tilt angle of the source describes the azimuthal distribution of the particles.

$$\theta_{out-long} = \frac{1}{2} tan^{-1}\left(\frac{4R^2_{out-long,1}}{R^2_{long,0} - R^2_{side,0} + 2R^2_{side,2}}\right) \qquad \theta_{side-long} = \frac{1}{2} tan^{-1}\left(\frac{4R^2_{side-long,1}}{R^2_{long,0} - R^2_{side,0} + 2R^2_{side,2}}\right)$$

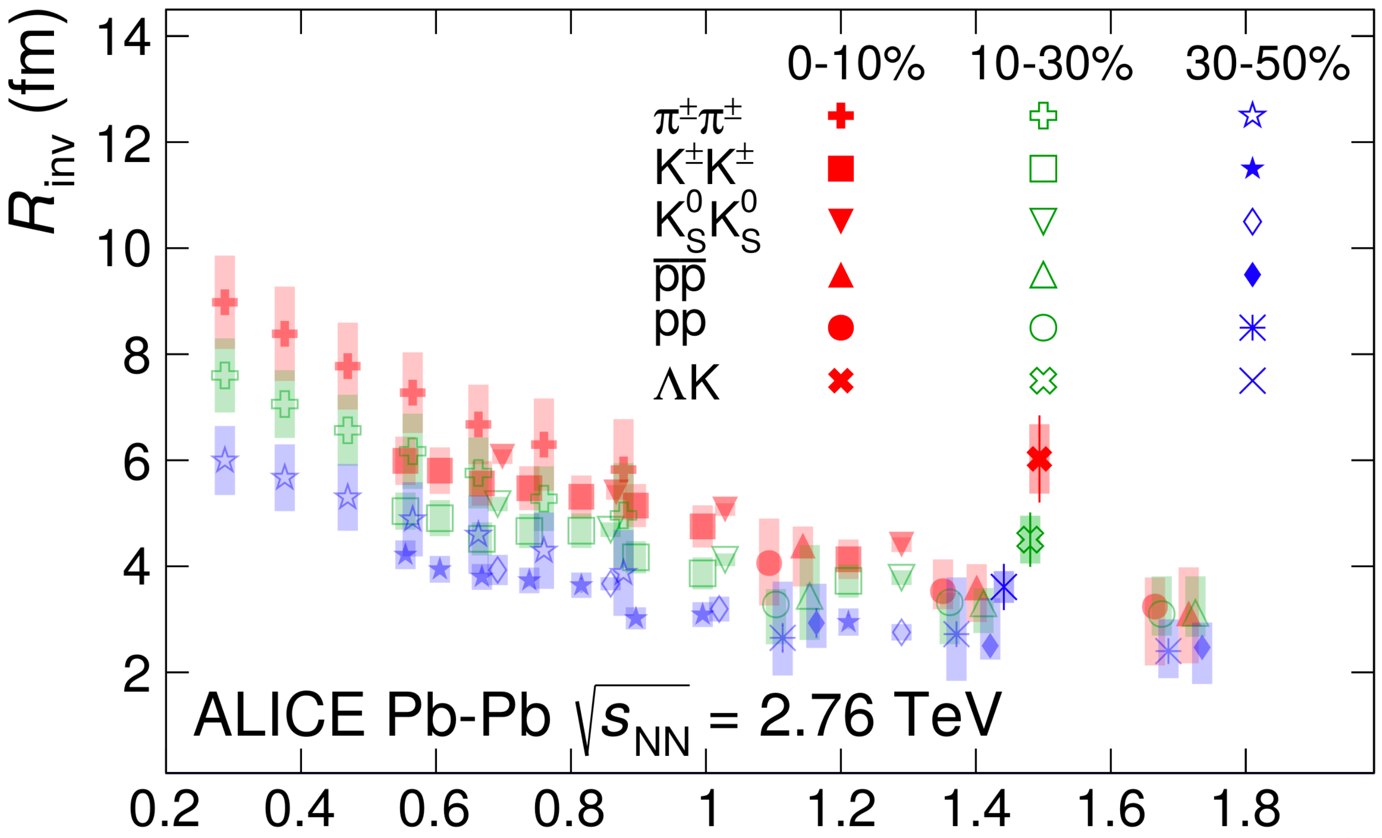
Collectivity from femtoscopy



Phys. Rev. C 92 (2015) 14904

Collectivity from femtoscopy

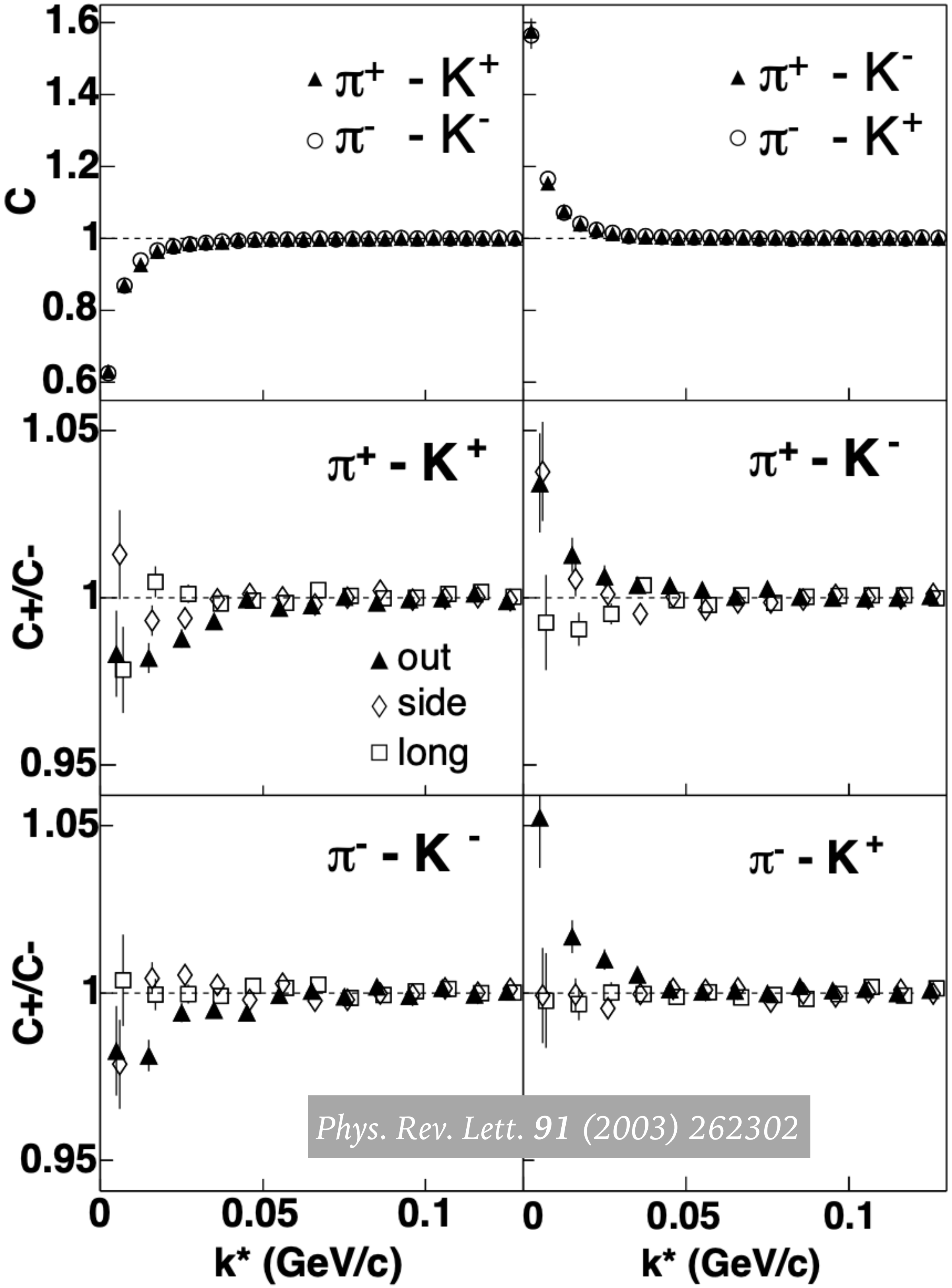
Phys. Rev. C 92 (2015) 14904



Phys. Rev. C 103 (2021) 5, 055201

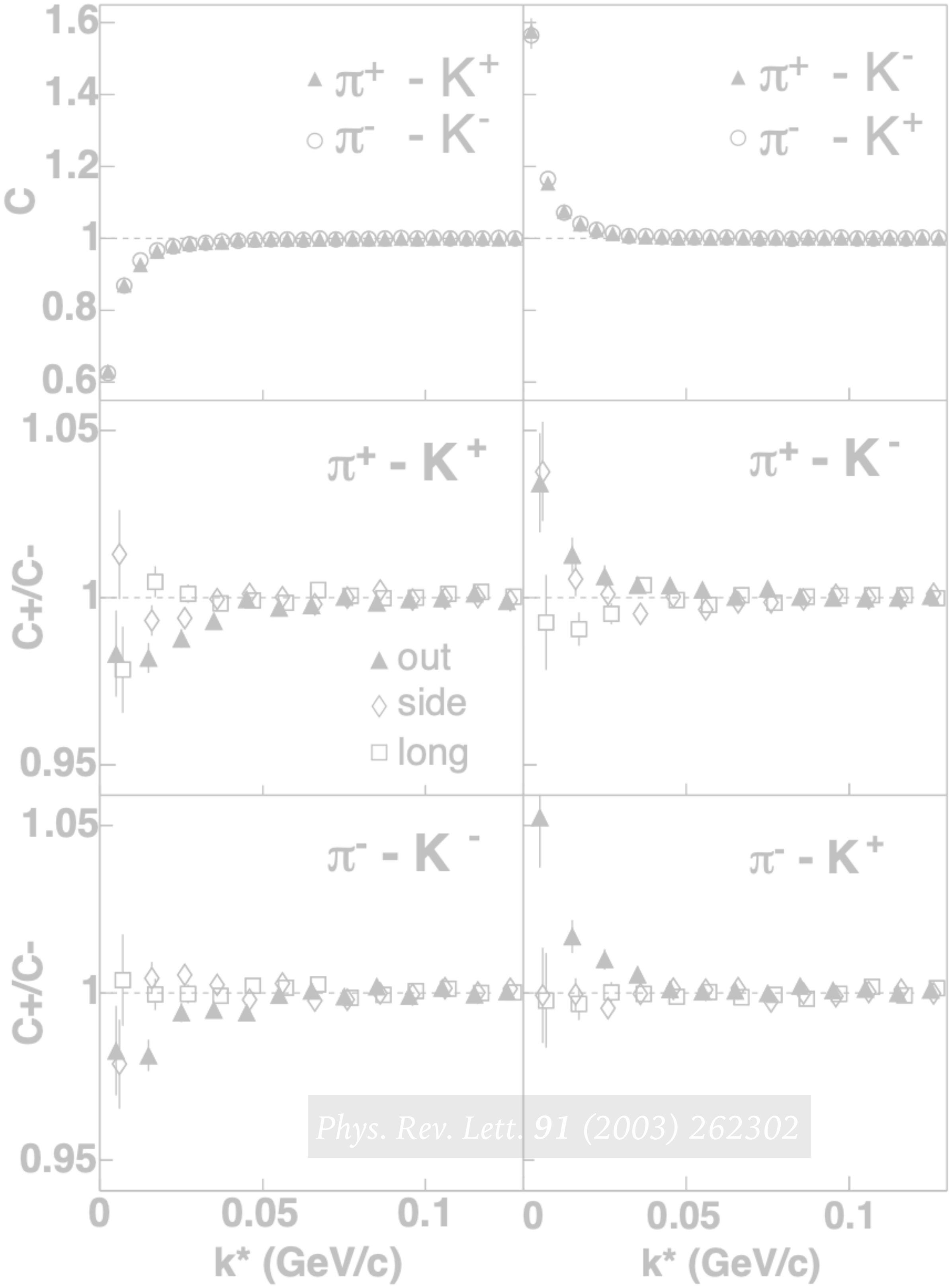
Signal of collective flow,
Confirmed by measurement of
non-identical particle correlations.

Collectivity from femtoscopy



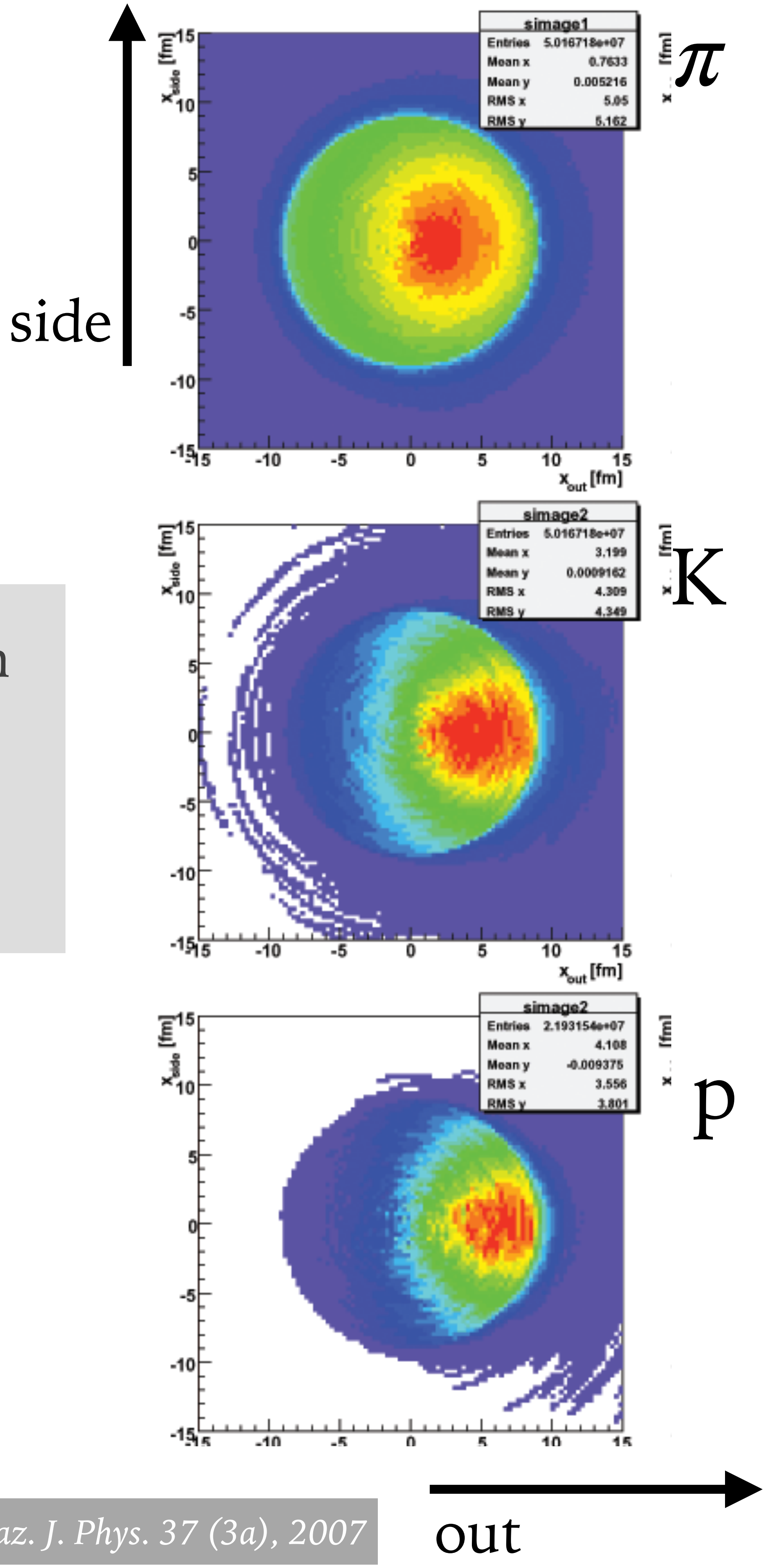
Phys. Rev. Lett. **91** *(2003) 262302*

Collectivity from femtoscopy



Phys. Rev. Lett. 91 (2003) 262302

Shift of the mean emission points toward „out” direction



Braz. J. Phys. 37 (3a), 2007

Precision @RHIC/LHC (2010s - 2020s)

Prof. Białas applied the blast-wave model to recent Hanbury - Brown and Twiss (HBT) measurements of femtoscopic radii in proton–proton collisions performed by the ALICE Collaboration. He showed that the data can be reasonably described with a relatively low kinetic freeze-out temperature of approximately T≃100 MeV and a transverse emission profile consistent with particle production from a thin shell. Within this framework, he extracted estimates of the size and lifetime of the produced system as a function of event multiplicity, providing insight into the space - time structure of particle emission in small collision systems.

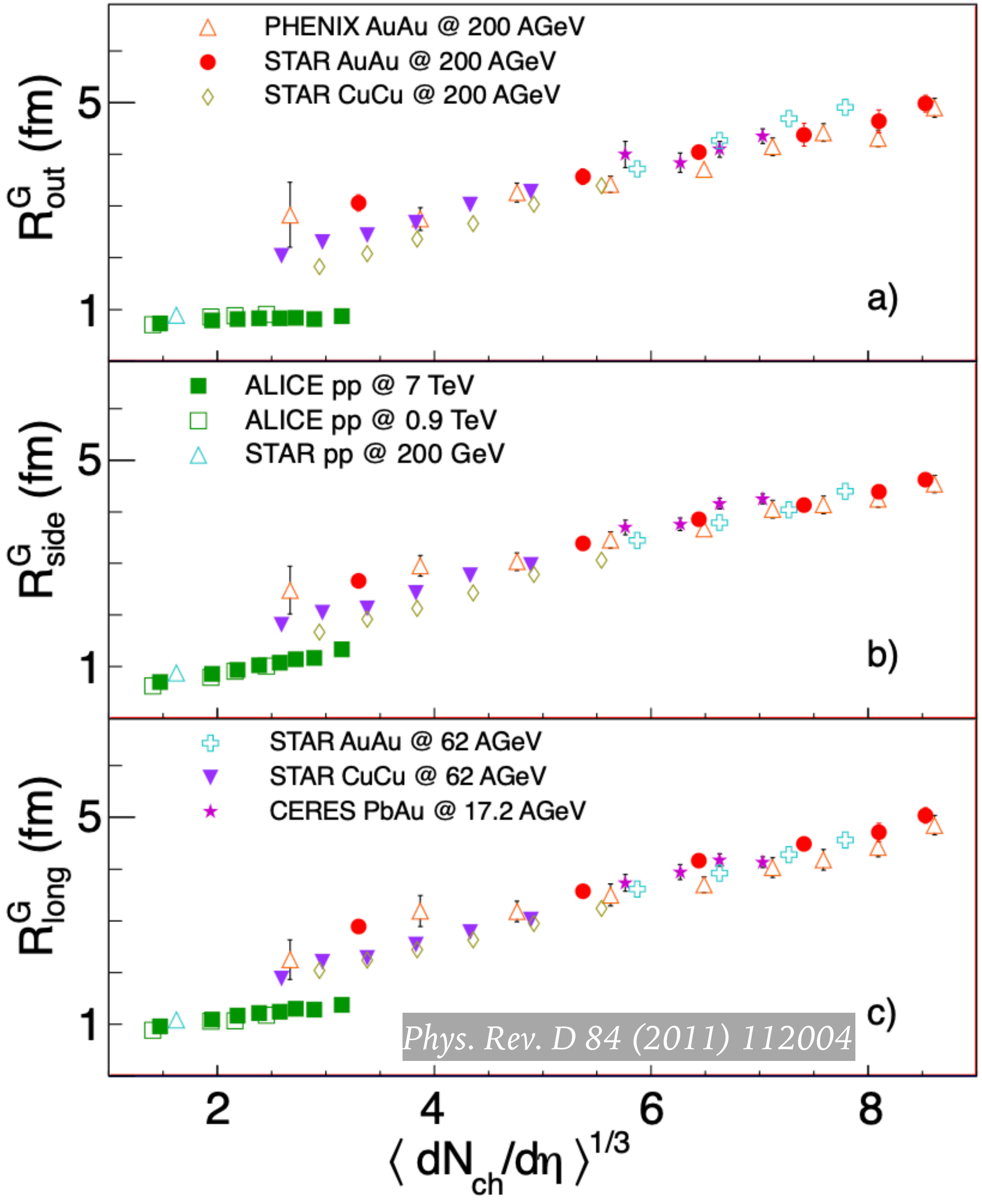
„Blast-wave model description of the Hanbury - Brown Twiss radii in pp collisions at LHC energies”
A. Białas, W. Florkowski, K. Zalewski, *J.Phys.G* 42 (2015) 4, 045001

Precision @RHIC/LHC (2010s - 2020s)

Prof. Białas studied how space - time correlations between produced particles, arising from the composite nature of hadrons, can modify the properties of correlation functions for identical particles. They showed that such effects can lead to characteristic changes in the observed correlations and estimated their magnitude using results from a blast - wave model analysis of proton–proton collisions at $\sqrt{s} = 7$ *TeV. This work provided a link between microscopic space - time structure and measurable femtoscopic observables in high-energy collisions.*

„Finite size of hadrons and Bose - Einstein correlations in pp collisions at 7 TeV"
A. Białas, W. Florkowski, K. Zalewski, *Phys.Lett.B* 748 (2015) 9-12

Identical pion femtoscopy ($dN_{ch}/d\eta$)

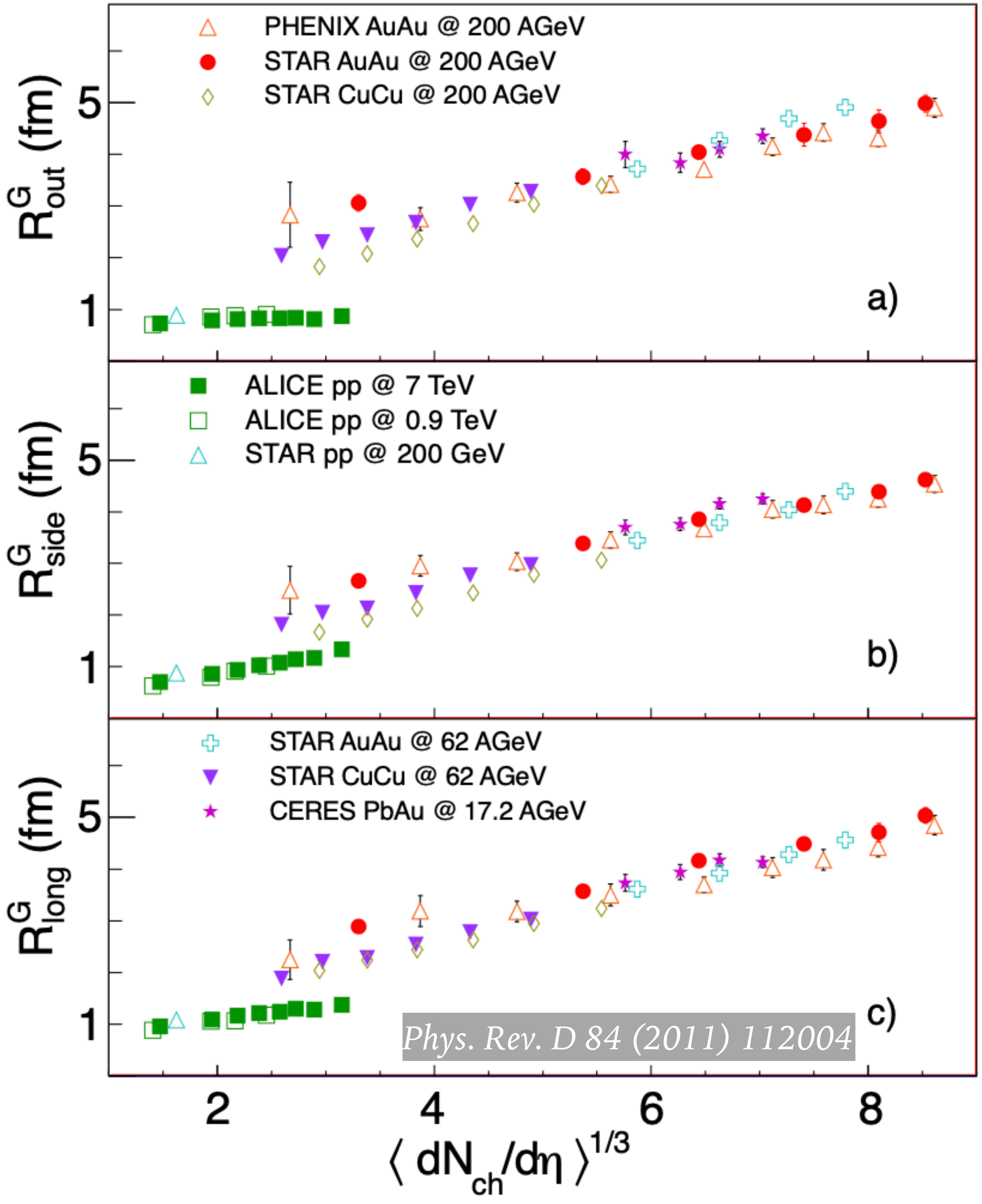


Phys. Rev. D 84 (2011) 112004

$< dN/d\eta >^{1/3}$ **scaling broken for p-p collisions.**

Possible scenario: two types of collisions at similar multiplicity.

Identical pion femtoscopy ($dN_{ch}/d\eta$)



Phys. Rev. D 84 (2011) 112004

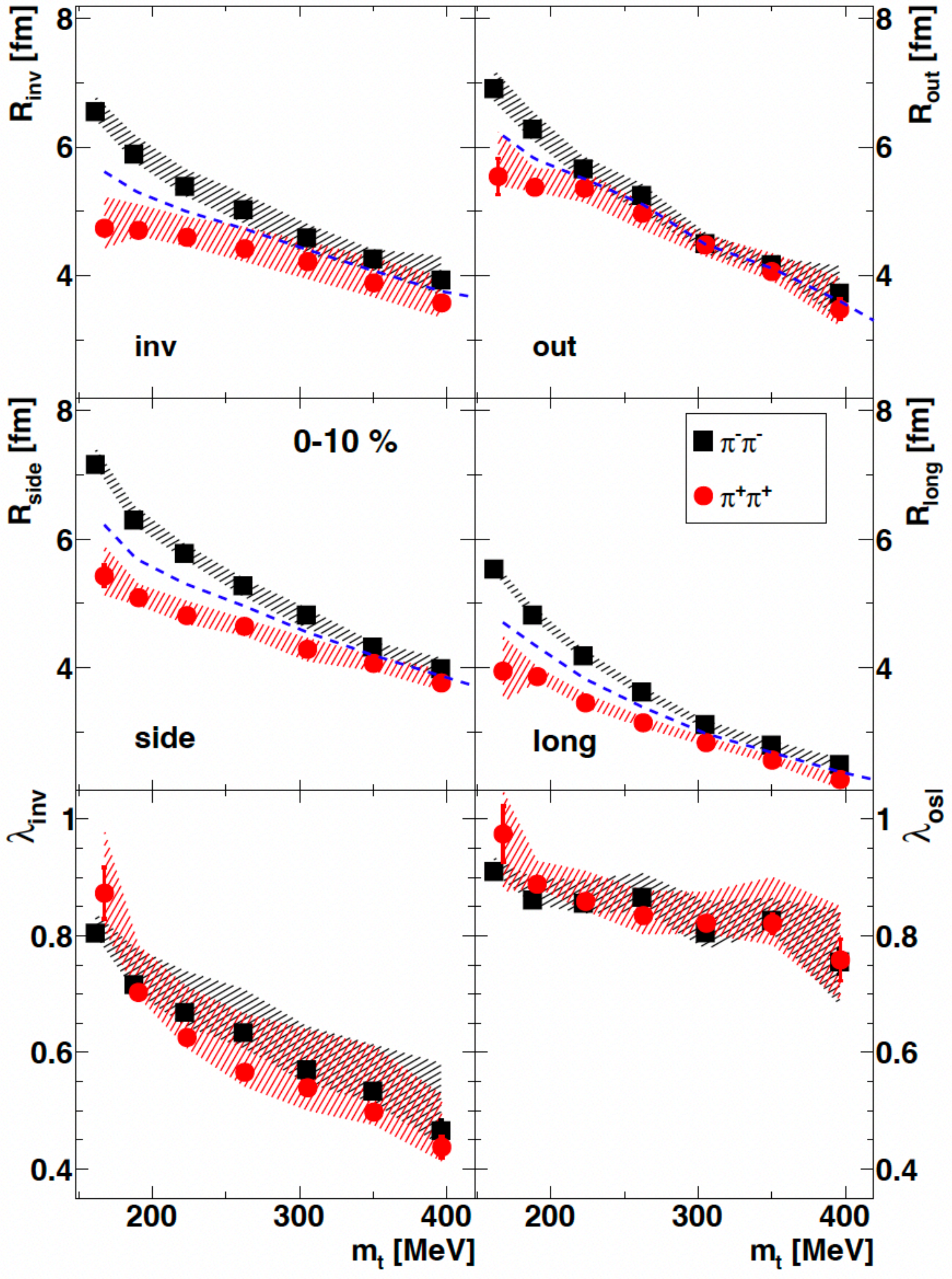
$< dN/d\eta >^{1/3}$ scaling broken for p-p collisions.
Possible scenario: two types of collisions at similar multiplicity.

p-p: production of many soft particles;
size of the region of particle's creation ~proton size;
the growth of $R(mult.)$ from particle's interactions;

Heavy-ions: many elementary nucleon scatterings, each producing a relatively low multiplicity.

Identical pion femtoscopy (charges)

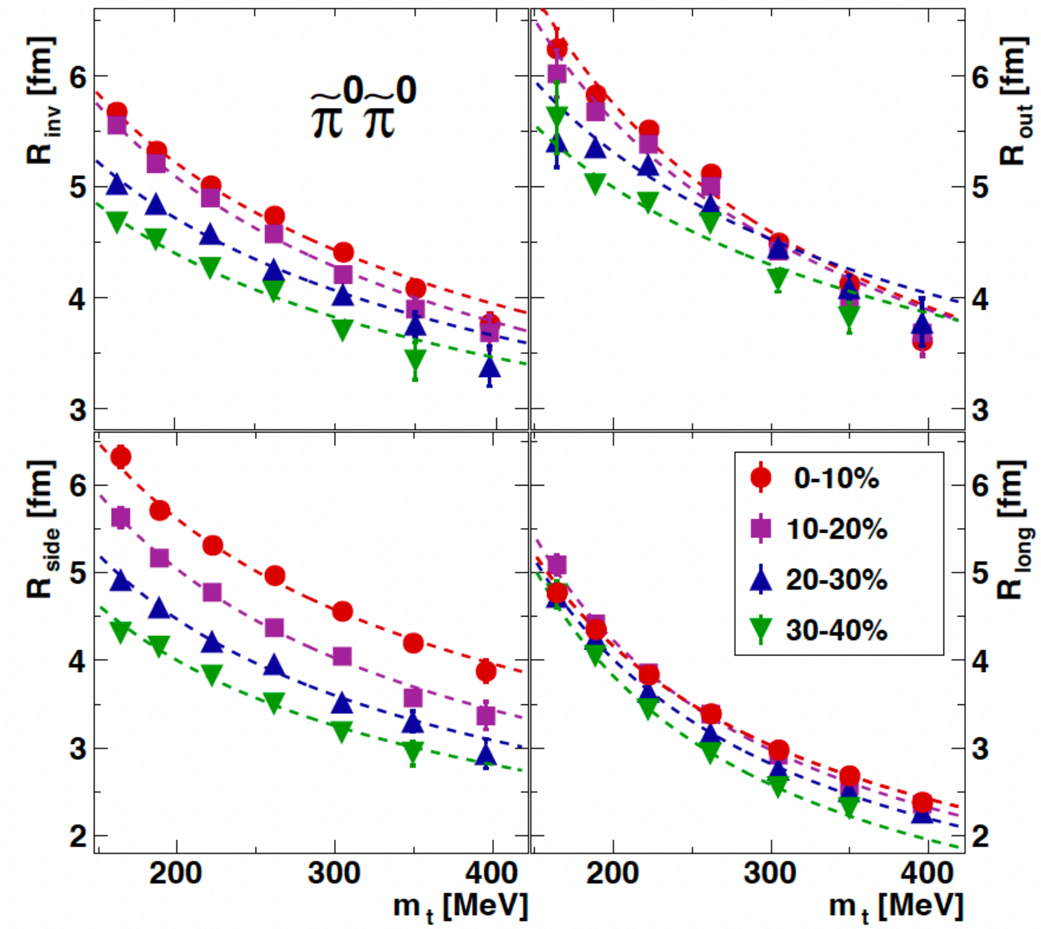
- 10% of most central collisions.
- 7 k_T intervals.
- Differences in HBT parameters for π^- and π^+ (especially low p_T) due to **Coulomb effect.**

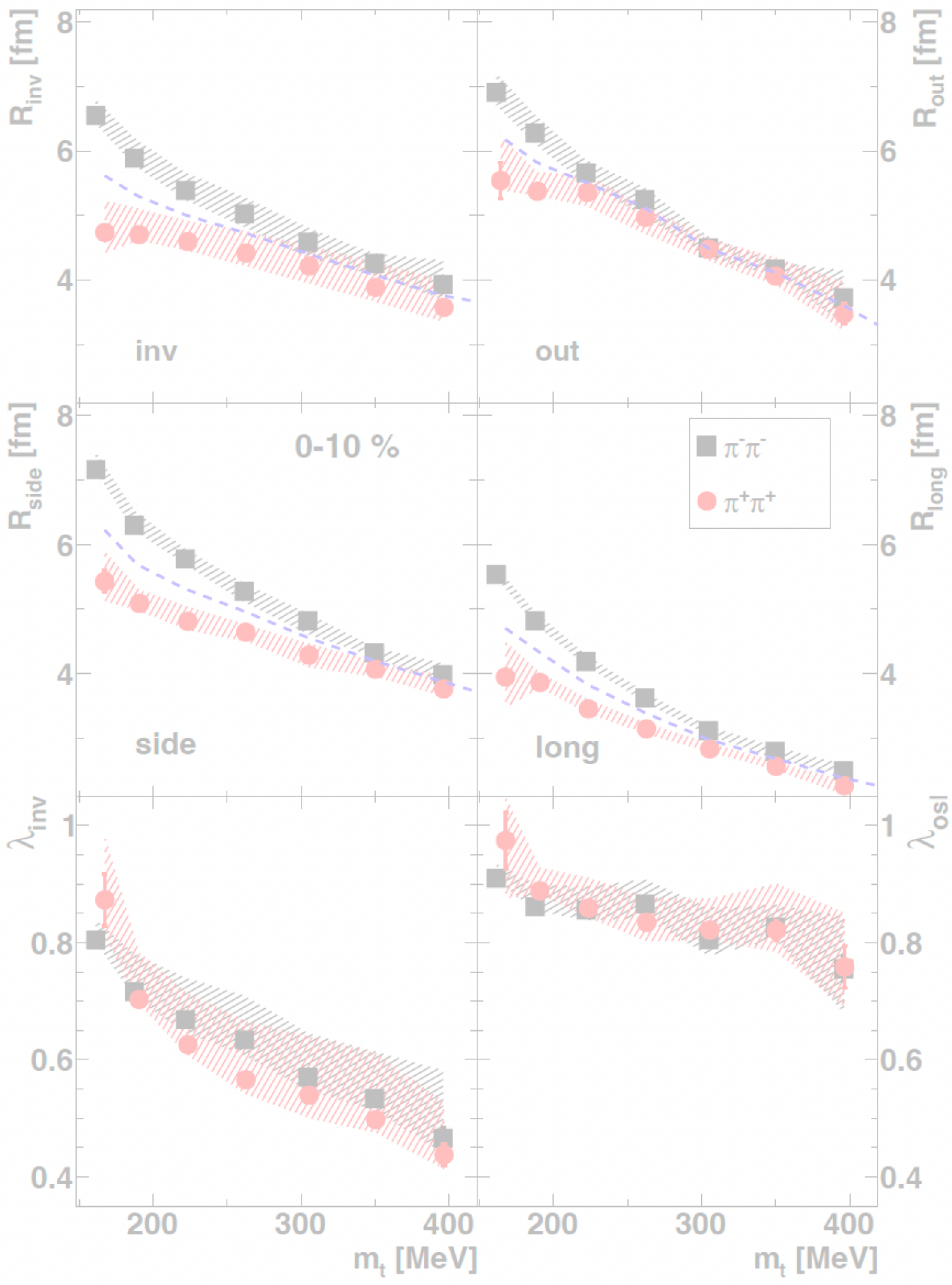


Eur. Phys. J. A 56, 140 (2020)

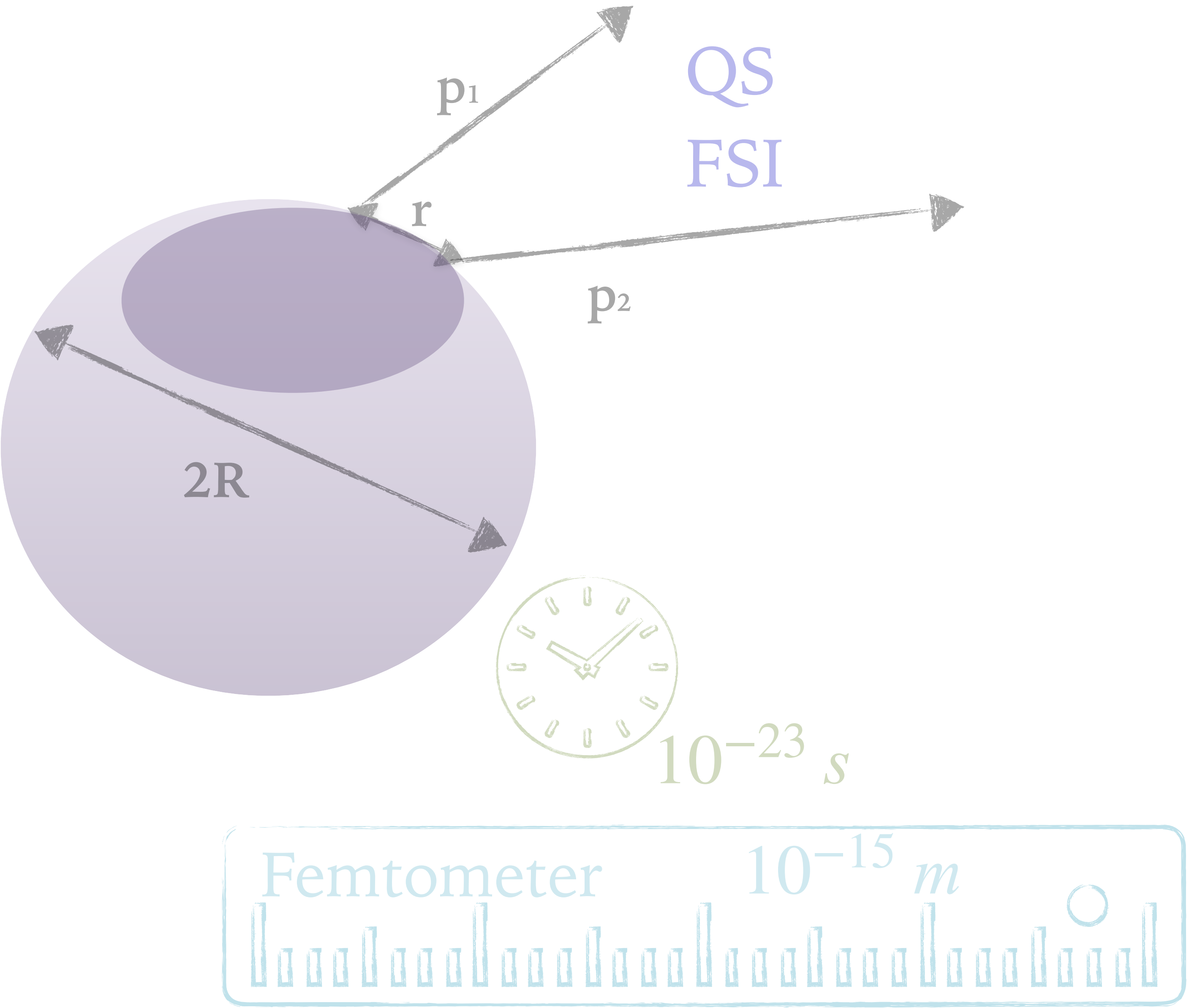
Identical pion femtoscopy (charges)

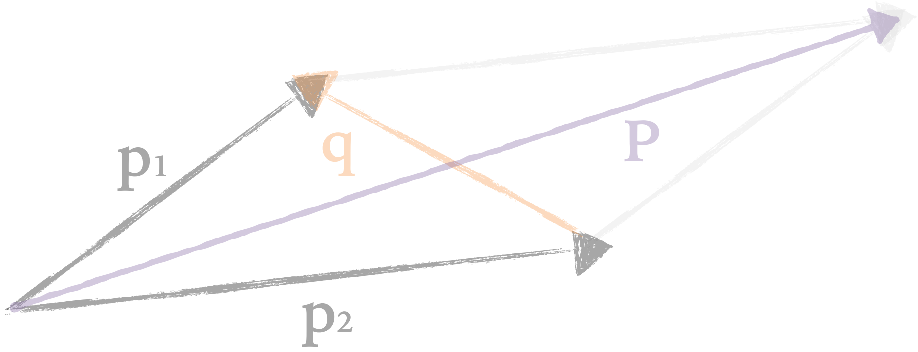
- 10% of most central collisions.
- 7 k_T intervals.
- Differences in HBT parameters for π^- and π^+ (especially low p_T) due to **Coulomb effect.**
- Neutral π deduced from interpolations of the charged π data.

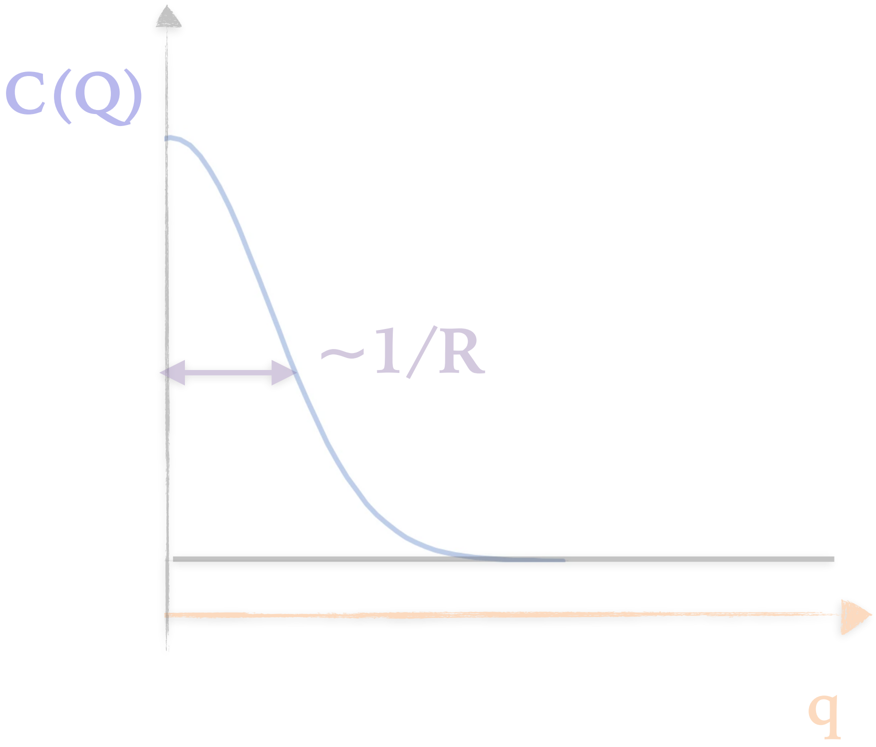




Eur. Phys. J. A 56, 140 (2020)







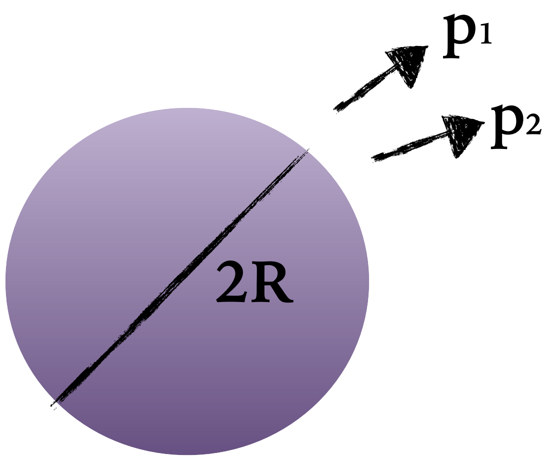
Interaction Femtoscopy

… the method to probe **geometric** and **dynamic** properties of the source (emission region, range of correlations-interactions, phase-space cloud, …)

Femtoscopy does not measure the whole source, but homogeneity length.

Gateway to study interactions

If we assume we know the source function, measured correlations are used to determine interactions in the final state.



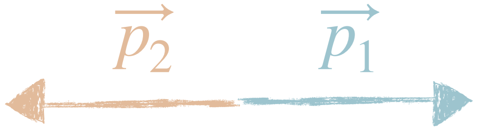
Space-time properties $(10^{-15}m,\ 10^{-23}s)$ determined thanks to two-particle correlations:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

$$C(k^*,r^*) = \int \overset{\text{assumed}}{S(r^*)}\,\overset{\text{determined}}{|\Psi(k^*,r^*)|^2}\, d^3r^* = \overset{\text{measured}}{\frac{Sgnl(k^*)}{Bckg(k^*)}}$$

k^* - momentum of the first particle in the Pair Rest Frame reference



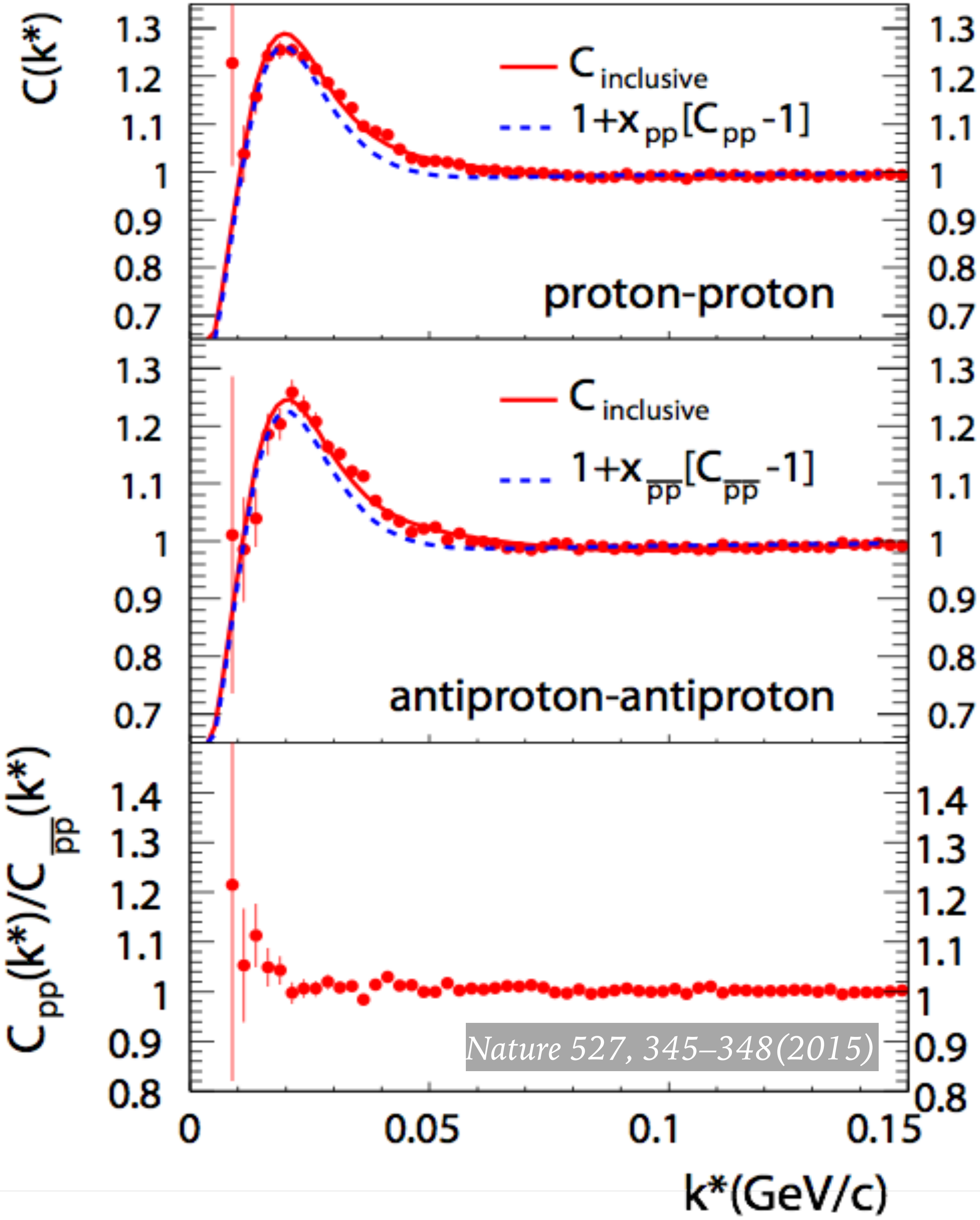
$S(r^*)$ - source function

$\Psi(k^*,r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

Matter - antimatter

Strong interactions between anti-nucleons



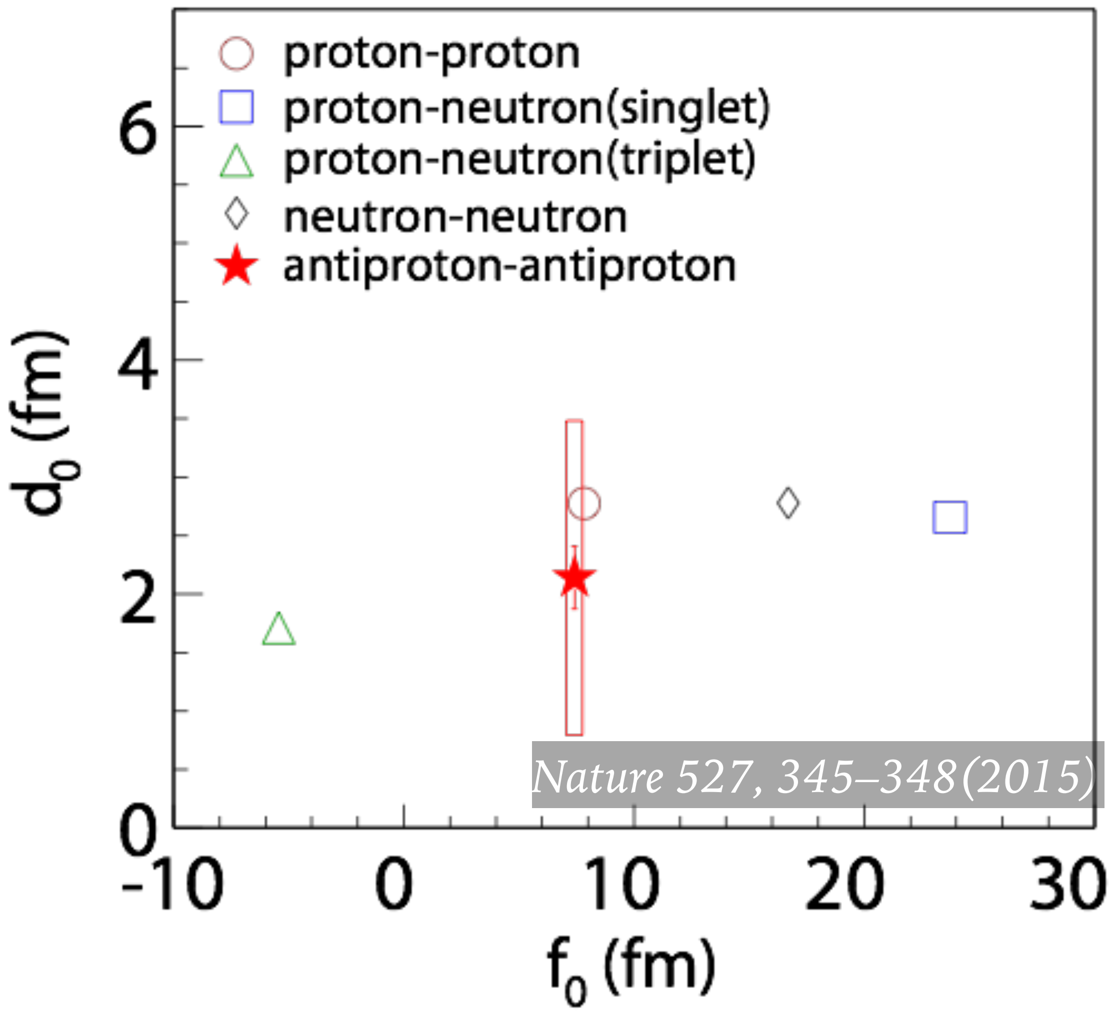
Nature 527, 345–348(2015)

The knowledge of **interaction** between two **anti-protons** fundamental to understand the properties of more sophisticated anti-nuclei.

$p-p$ and $\bar{p}-\bar{p}$ agrees within their uncertainties

Are they consistent within interaction parameters?

Strong interactions between anti-nucleons



Nature 527, 345–348(2015)

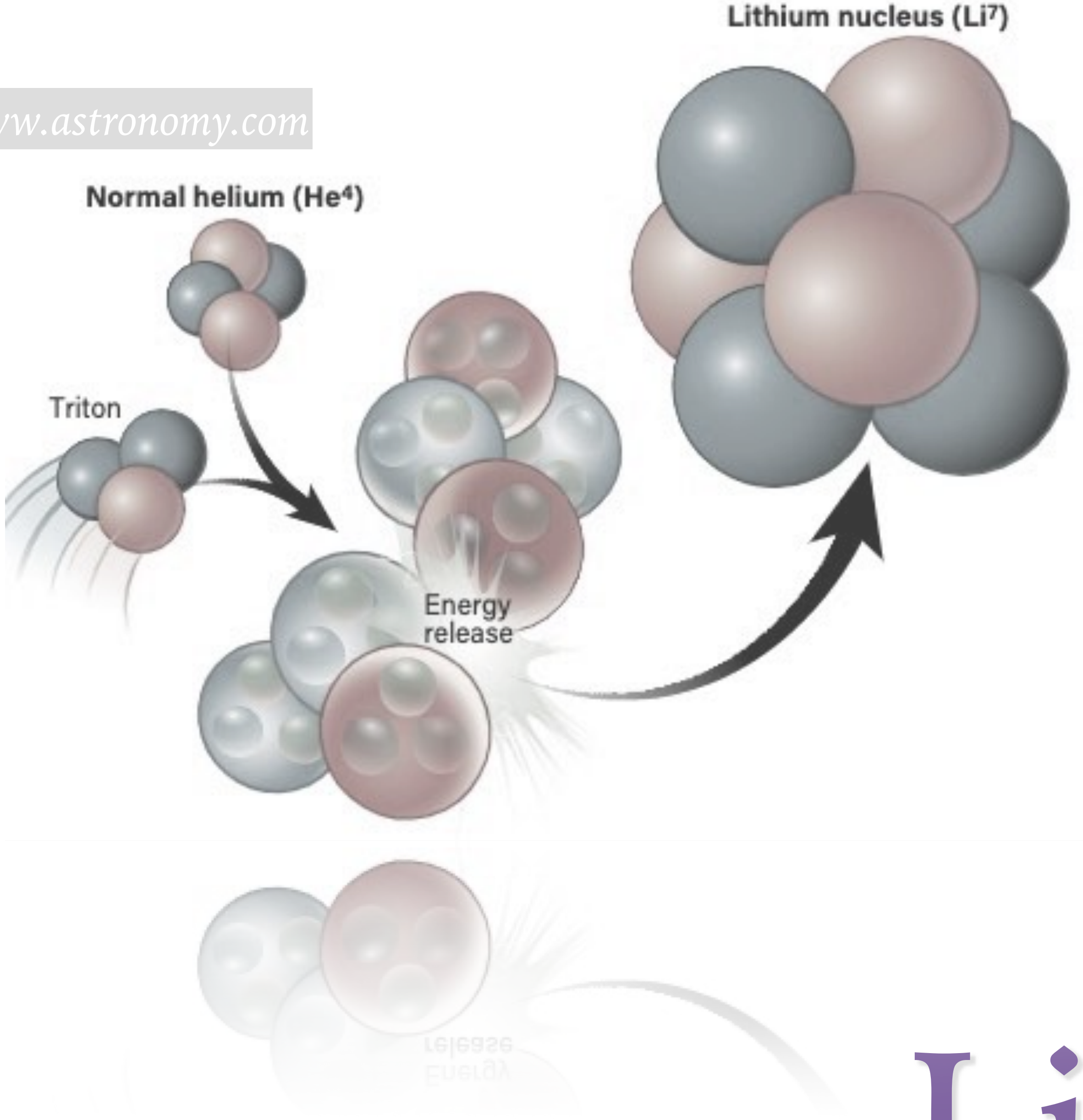
- f_0 and d_0 for $\bar{p}-\bar{p}$ interaction consistent with parameters for $p-p$ interaction;
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined;
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.

f_0 and d_0 - parameters of strong interaction.
Theoretical correlation function (k*) depends on: R, f_0 and d_0.

f_0 - the scattering length, determines low-energy scattering.
The elastic cross section, σ_e, (at low energies) determined by the scattering length,

d_0 - the effective range, corresponds to the range of the potential (simplified scenario - the square well potential.

https://www.astronomy.com



Light nuclei

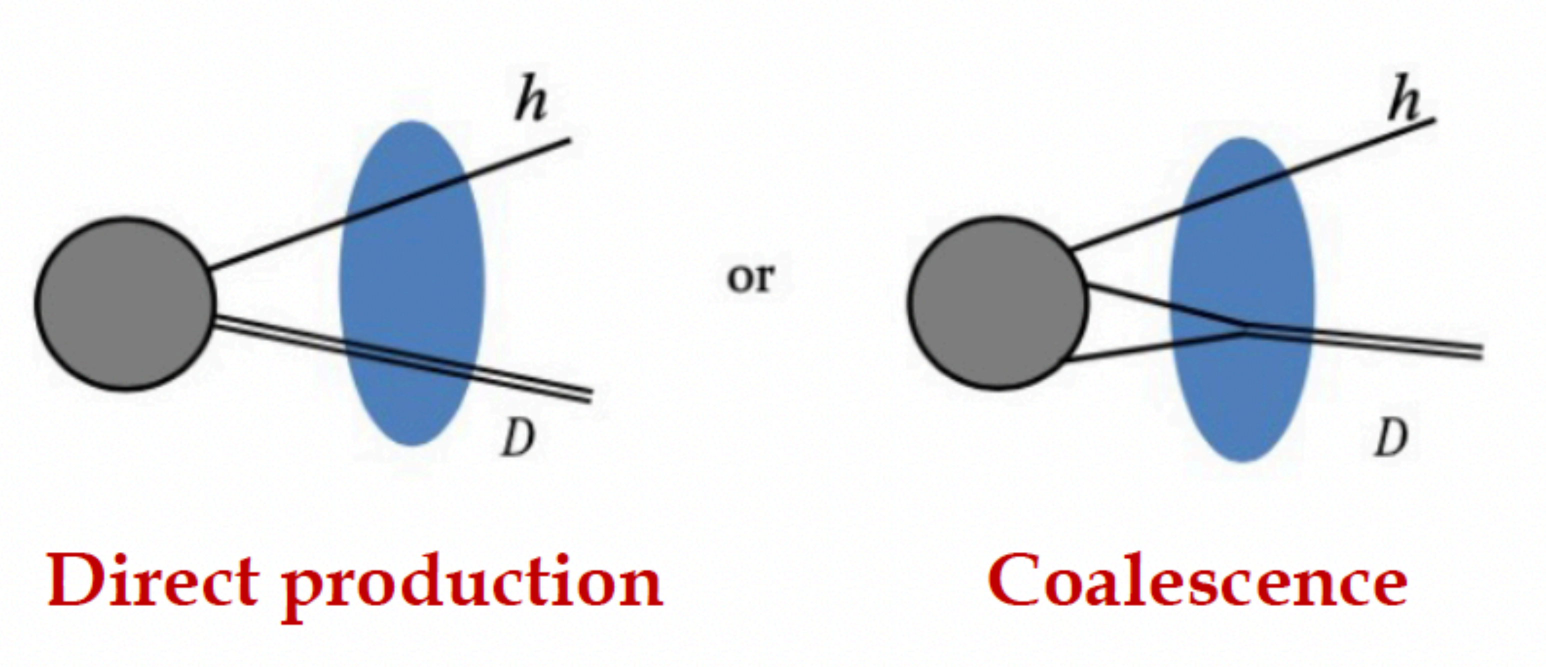
Precision @RHIC/LHC (2010s - 2020s)

Prof. Białas investigated longitudinal proton - proton femtoscopy within the Hanbury Brown - Twiss framework, motivated by the expectation that in heavy-ion collisions at $\sqrt{s_{NN}} \lesssim 20$ *GeV stopped protons are spatially separated in configuration space. He showed that the resulting correlation function exhibits a characteristic oscillatory structure that should be sufficiently strong to be observable experimentally. This proposed measurement provides a potential method for estimating the baryon density in the central rapidity region and may also be interpreted as an almost direct test of Lorentz contraction effects in fast-moving nuclei.*

„Femtoscopy of stopped protons"
A. Białas, A. Bzdak, V. Koch, *Physical Review C*, Vol. 99 (2019) 034906

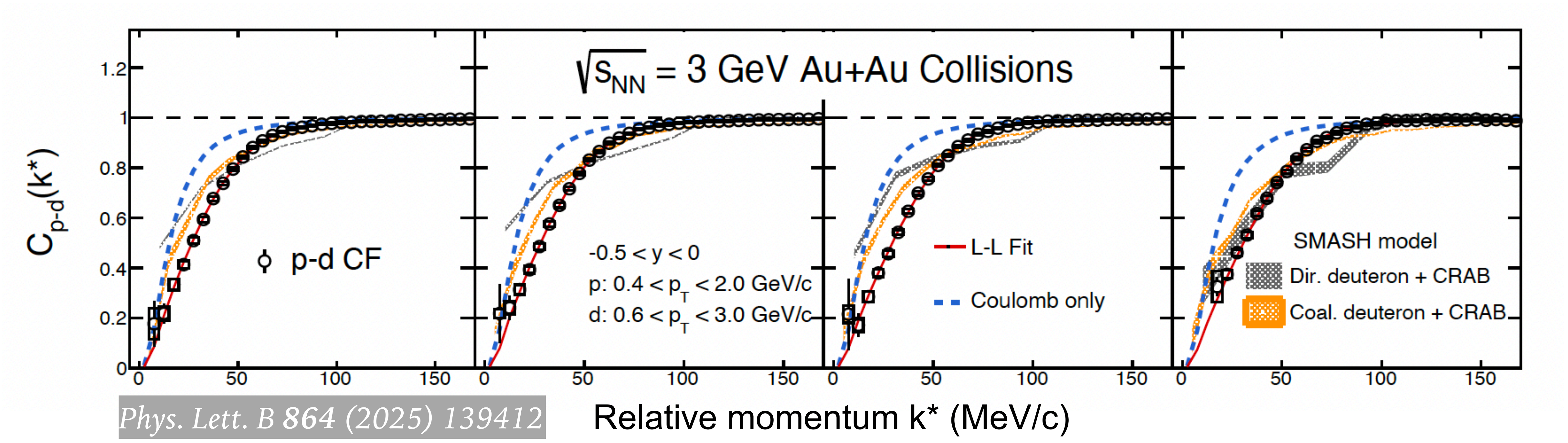
Light nuclei correlation: p-d, d-d correlations

1) A systematic measurement of **p-p**, **p-d**, and **d-d** correlations may tell us whether **deuterons** are directly emitted from the fireball or formed due to final-state interactions;
2) A large amount of light nuclei produced at Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV allows one for precision measurements.



S. Mrówczyński and P. Słoń, Acta Physica Polonica B 51, 1739 (2020)
S. Mrówczyński and P. Słoń, Physical Review C 104, 024909 (2021)

p-d correlations

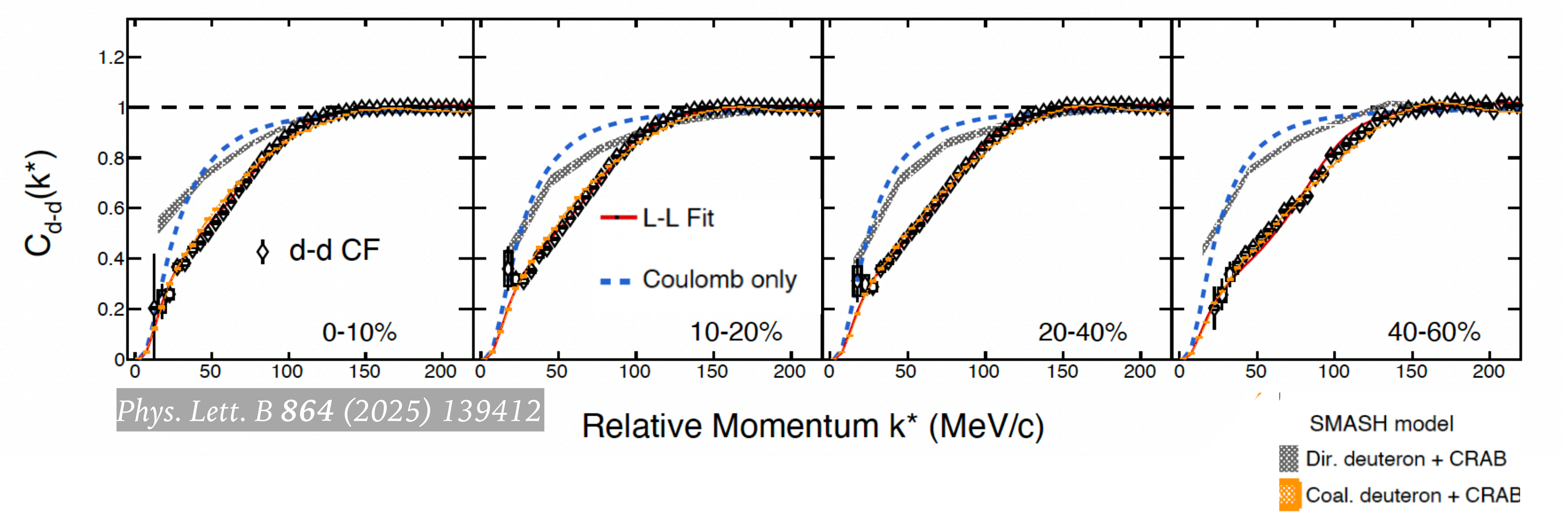


Phys. Lett. B ***864*** *(2025) 139412*

- Clear depletion at small k* range seen in data due to interactions in the final states;
- Coulomb only doesn’t describe data for any centrality class
- Lednicky - Lyuboshitz model describes data well;
- Two deuteron productions scenario considered: direct (~thermal) and coalescence
- Coalescence scenario fits data better
- A spherical source size with r = ~3 fm consistent with data.

.Lednický, R,Lyuboshitz, V; Sov.J.Nucl.Phys.35:770(1982)
.J. Arvieux, Nucl. Phys. A 221 (1974) 253–268

d-d correlations



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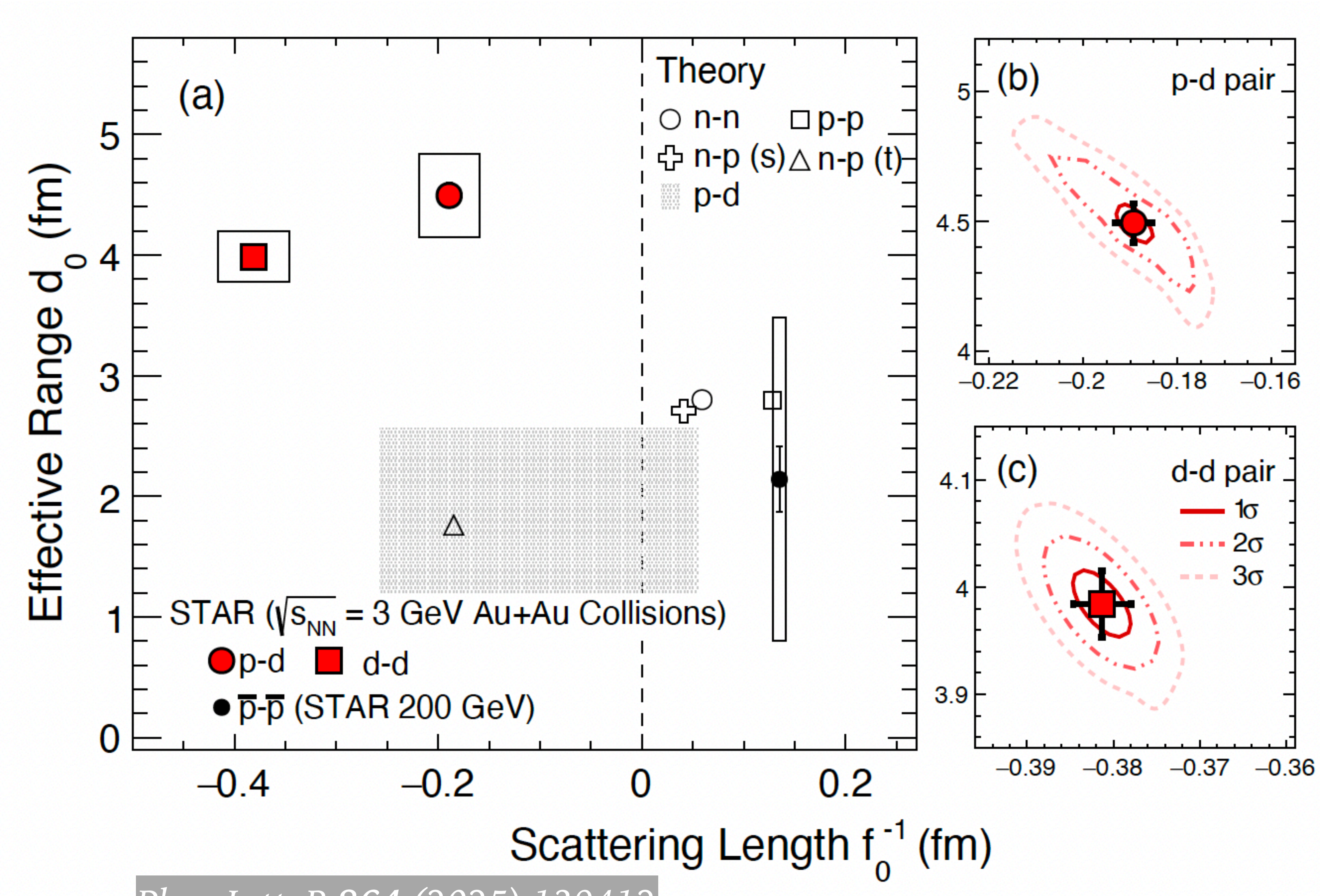
.Lednický, R,Lyuboshitz, V; Sov.J.Nucl.Phys.35:770(1982)
.J. Arvieux, Nucl. Phys. A 221 (1974) 253–268

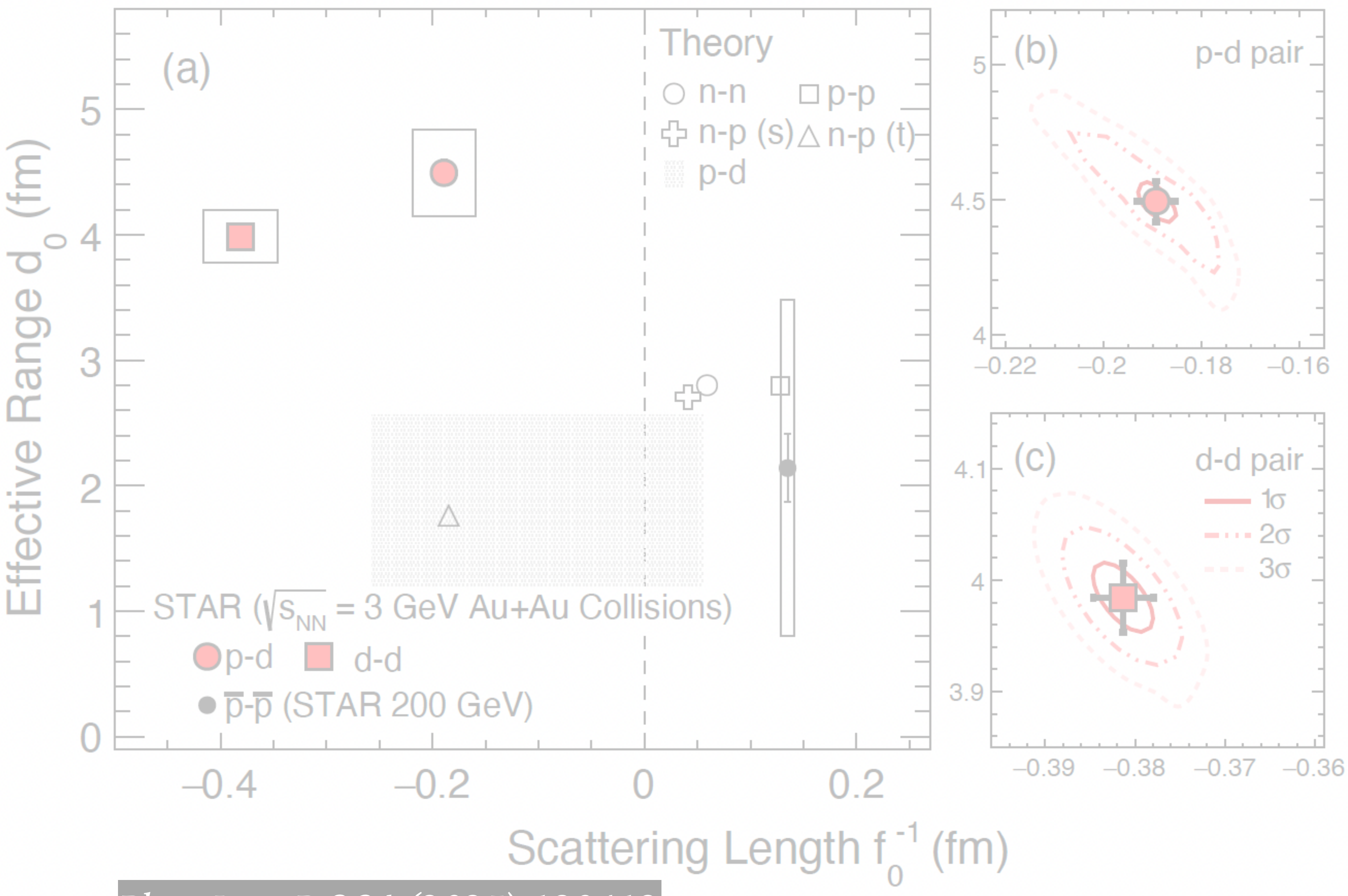
p (d) - d correlations

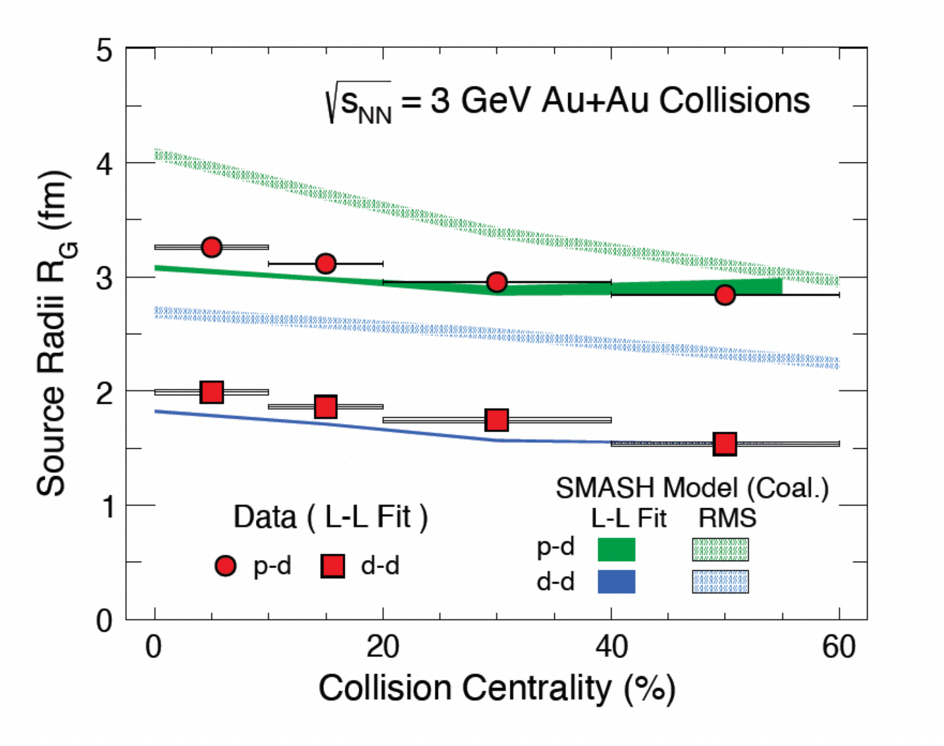


Phys. Lett. B ***864*** *(2025) 139412*

- Parameters of strong interaction extracted

p (d) - d correlations



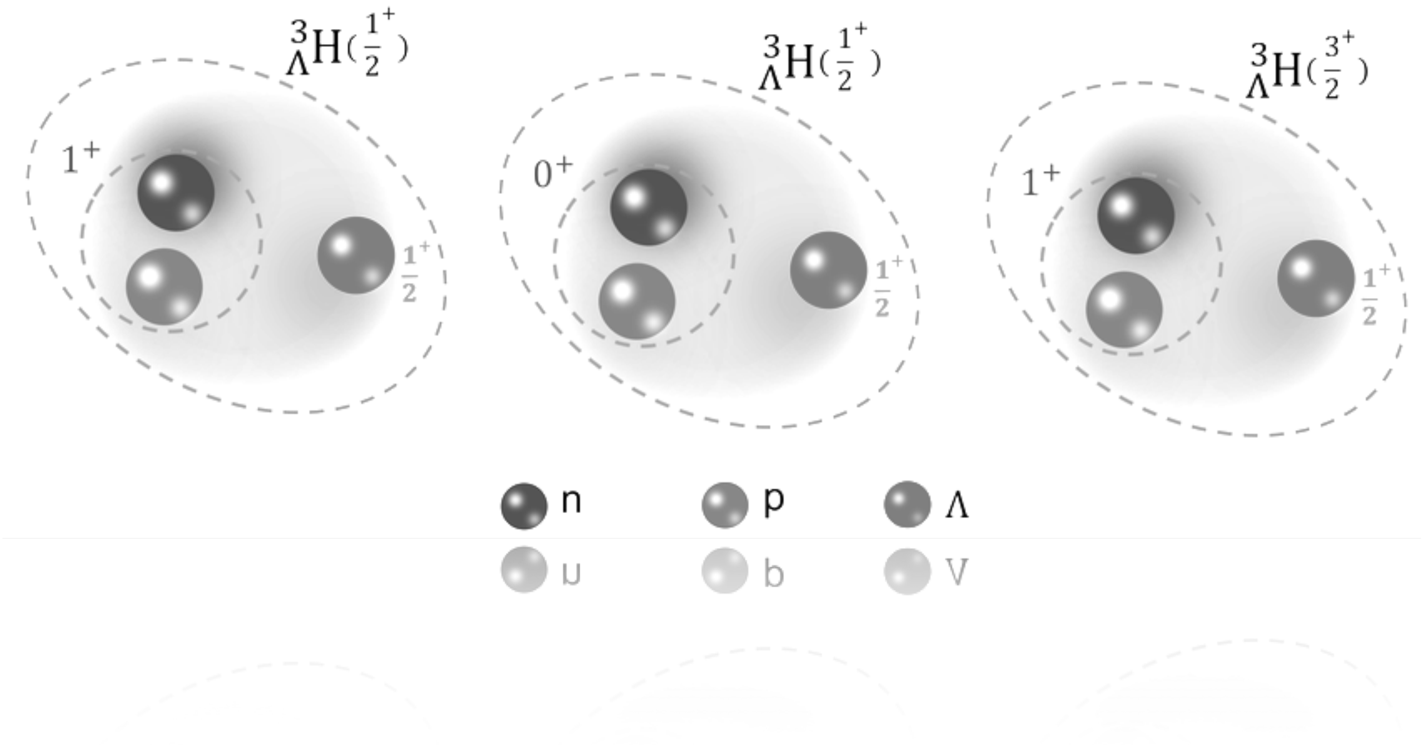


Phys. Lett. B ***864*** *(2025) 139412*

- Parameters of strong interaction extracted
- Source sized consistent with expectations (m_T scaling)

AI design

NN, NY, YY interactions



https://researchnet.gate

Hyperons

Neutron star puzzle

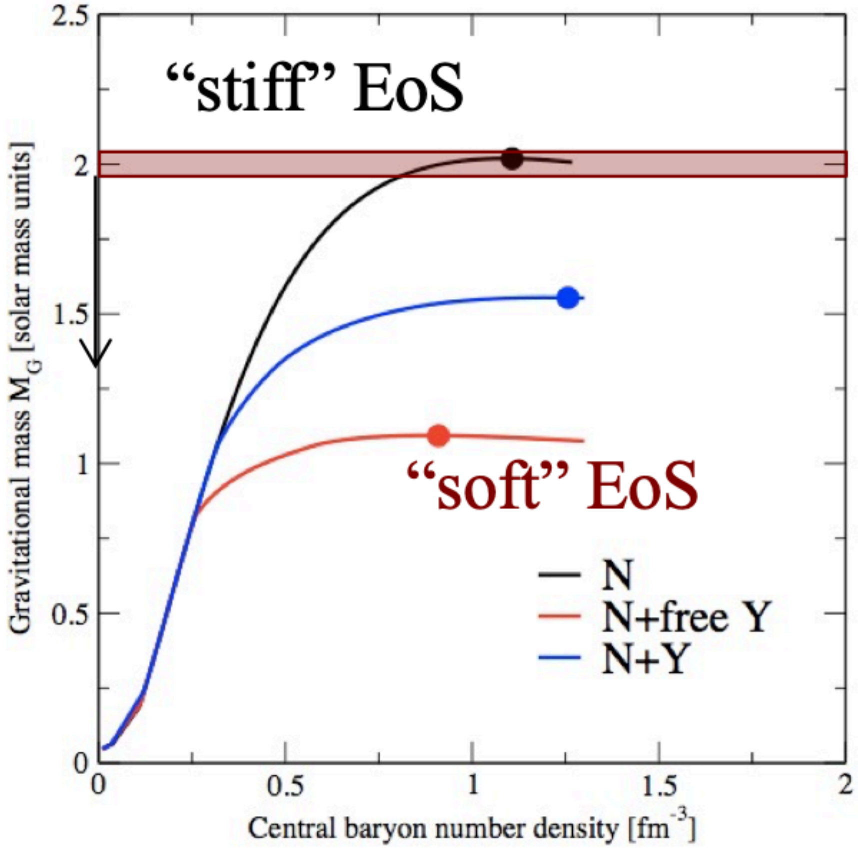
- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**
- Appearance of Y: The relieve of Fermi pressure → **softer EoS → mass reduction (incompatible with observation).**

The solution requires a mechanism that could provide the **additional pressure** at high densities needed to make the EoS stiffer.

$M_{NS} \approx 1 \div 2\ M_{\odot}$

$R \approx 10\text{-}12$ km

$\rho \approx 3 \div 5\ \rho_0$



$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

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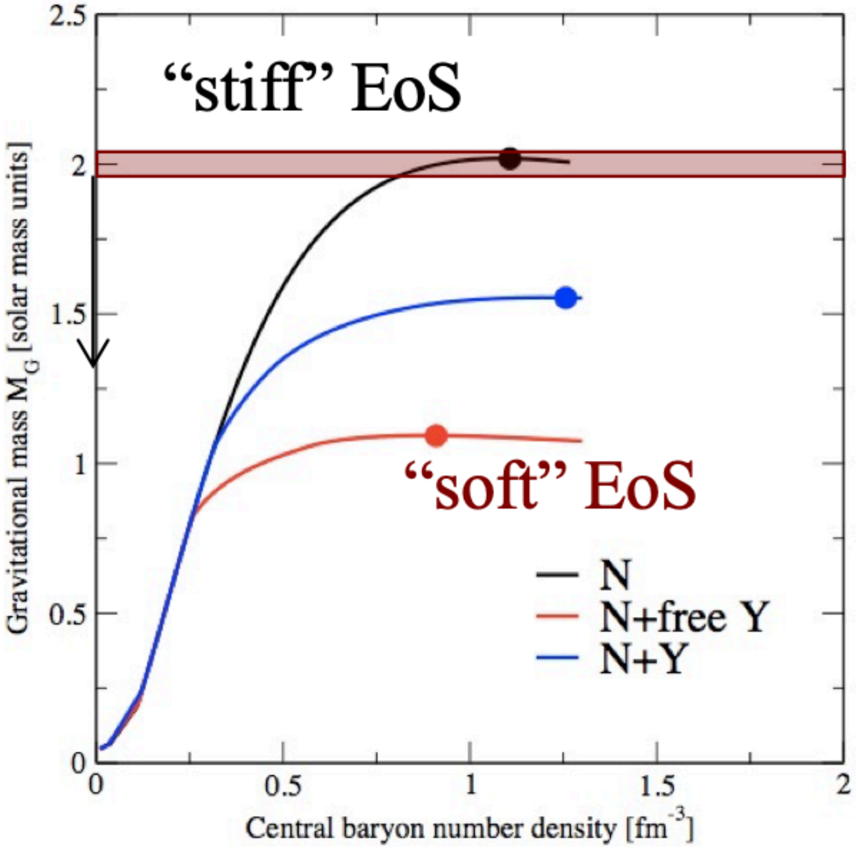


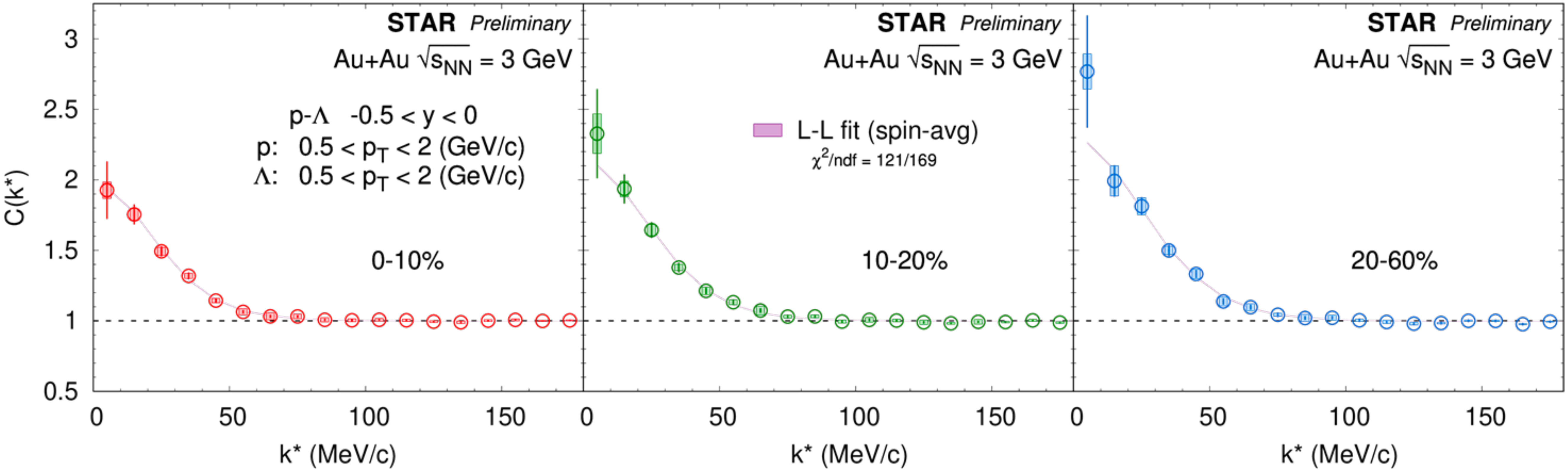
$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

A few possible mechanisms, one of them:

Two- (and more) body YN, YY, NNY, NYY, … interactions.

The existence of **hypernuclei** (confirmed by attractive YN interaction) → indicates the possibility to bind Y to N. The measurement of the YN and YY interactions leads to important implications for the possible formation of **YN, YY, NNY, NYY, … bound states**.

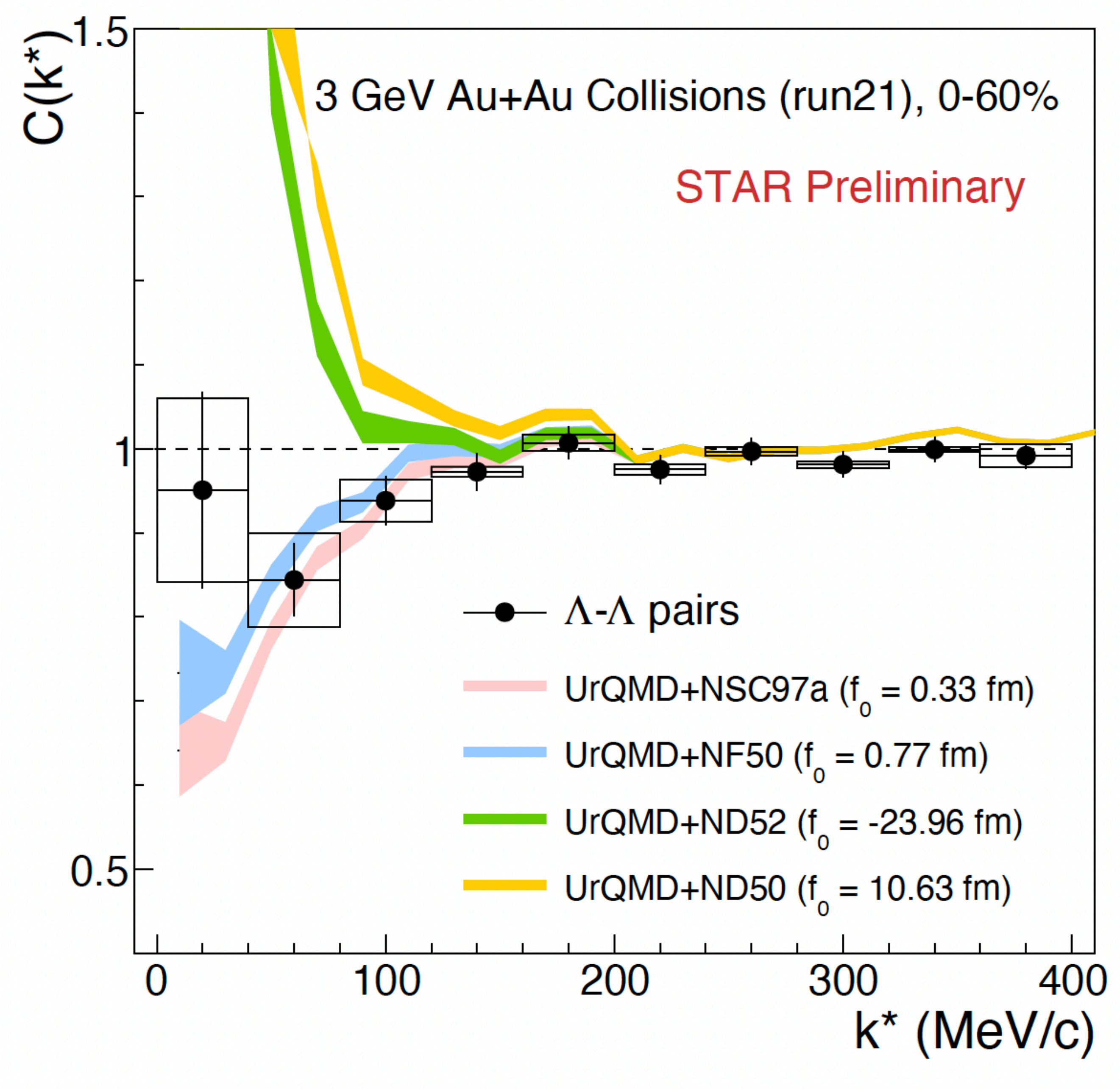
YN ($p-\Lambda$) interactions



- Simultaneous fit to data in different centralities and rapidities;
- Source size R and parameters of SI: f_0 and d_0 with Lednicky-Lyuboshitz approach;
- Spin-averaged scattering length and effective range:

$f_0 = 2.32^{+0.12}_{-0.11}\,fm$ and $d_0 = 3.5^{+2.7}_{-1.3}\,fm$.

YY ($\Lambda - \Lambda$) interactions

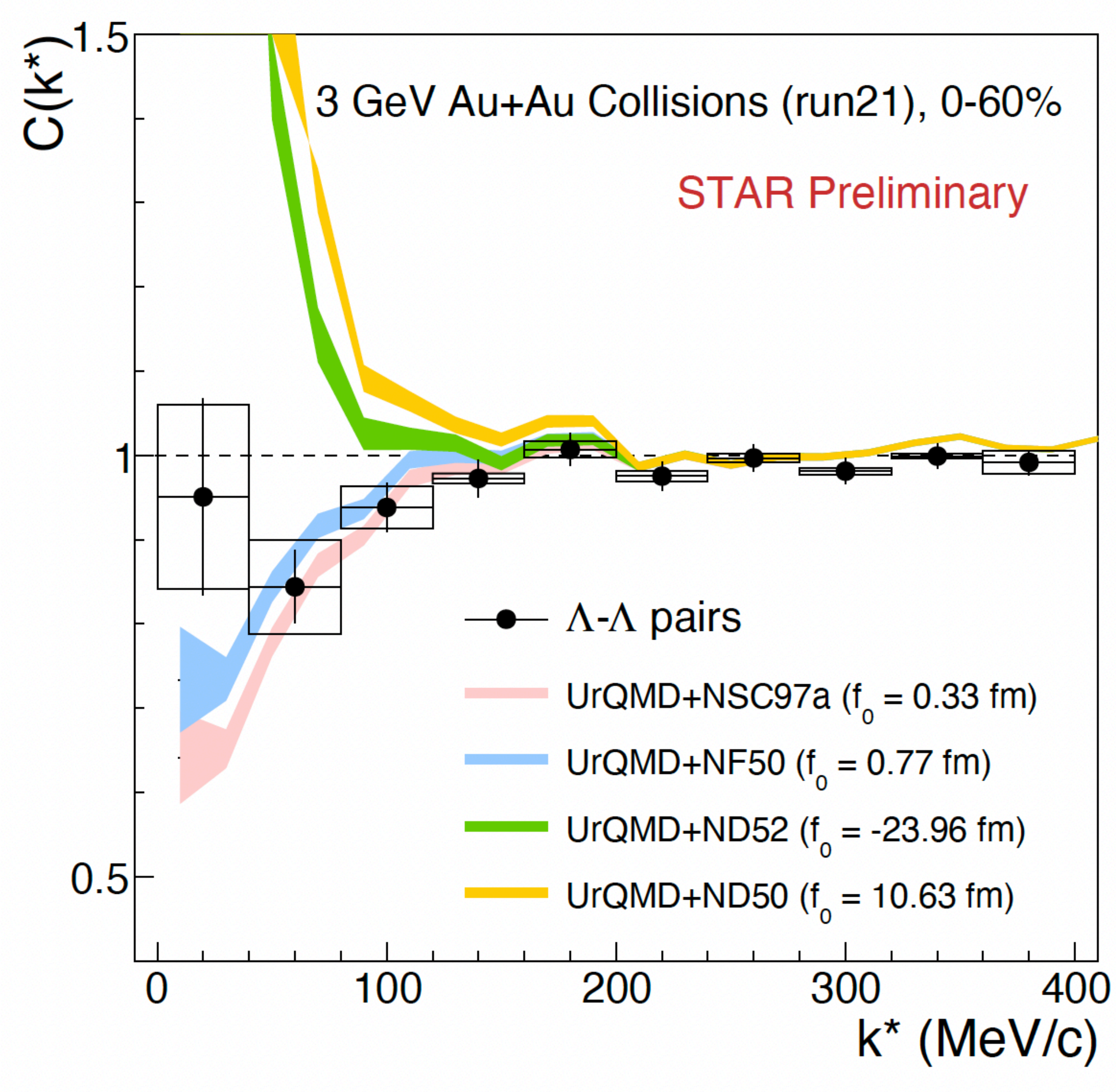


Λ-Λ correlation shows suppression at small k*

Smaller positive f_0 describes data better

Preferable attractive interaction in Λ-Λ

YY (Λ – Λ) interactions



Λ-Λ correlation shows suppression at small k*

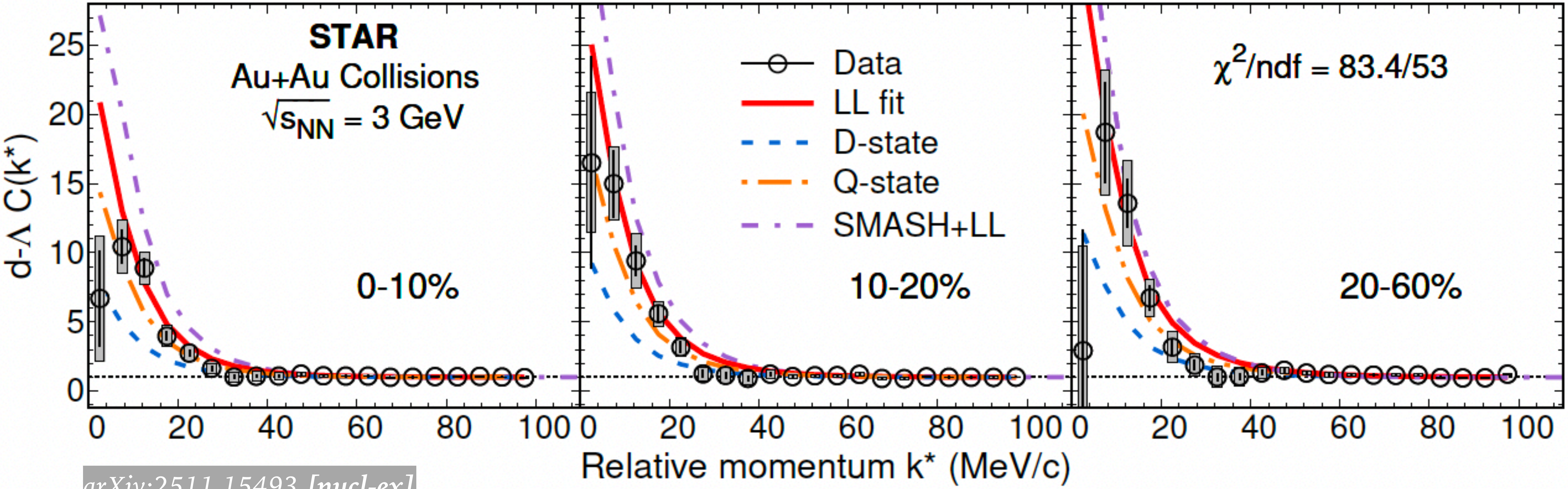
Smaller positive f_0 describes data better

Preferable attractive interaction in Λ-Λ

Potential	**f_0 (fm)**	**d_0 (fm)**	**Chi2/NDF**
NSC97a[1]	0.33	12.37	1.53
NF50[2]	0.77	4.27	1.61
ND52[3]	-23.96	2.59	2.24
ND50[3]	10.63	2.04	4.02

[1] P. M. M. Maessen, et al, Phys. Rev. C 40 (1989) 2226
[2] M. M. Nagels, et al, Phys. Rev. D 20 (1979) 1633
[3] M. M. Nagels, et al, Phys. Rev. D 15 (1997) 2547

YN ($d - \Lambda$) interactions



arXiv:2511.15493 [nucl-ex]
PRL accepted

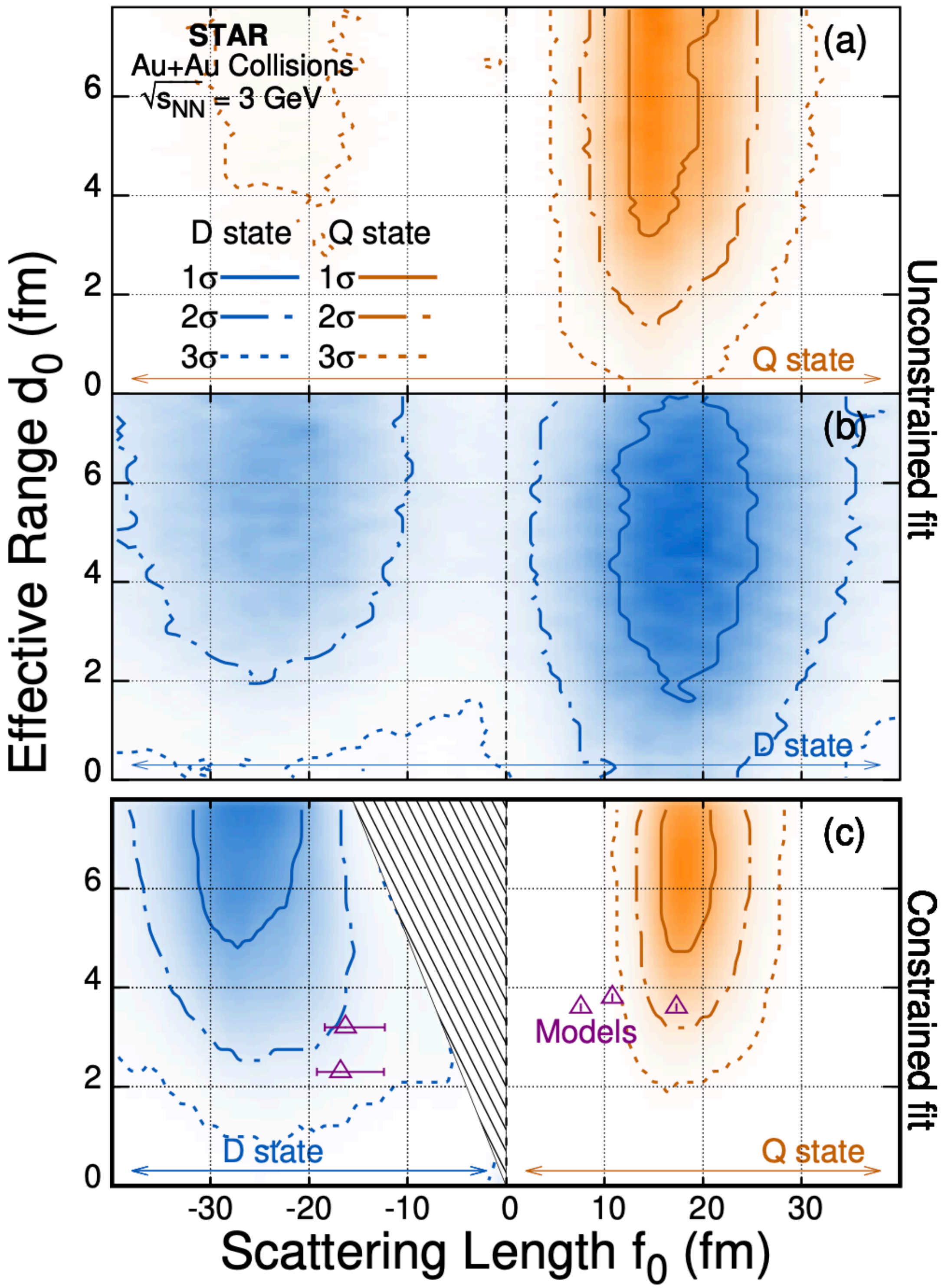
- Simultaneous fit to data in different centralities and rapidities;
- Source size R and parameters of SI: f_0 and d_0 with Lednicky-Lyuboshitz approach;
- Spin-separated scattering length and effective range:

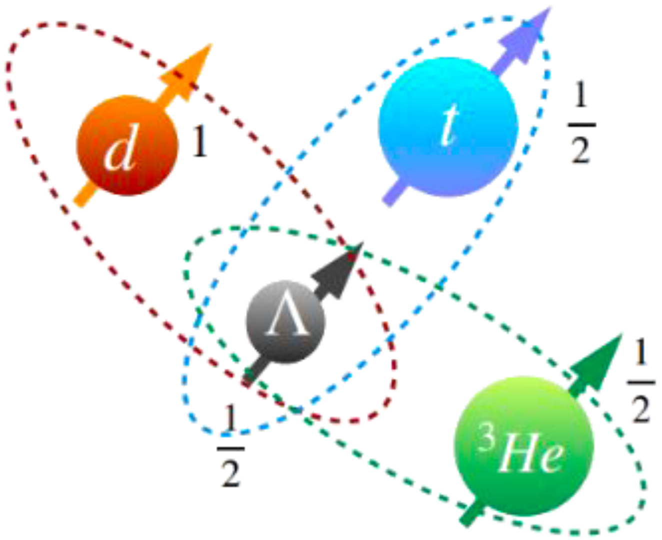
$$f_0(D) = 20^{+3}_{-3}\,fm;\ d_0(D) = 3^{+2}_{-1}\,fm;$$

$$f_0(Q) = 16^{+2}_{-1}\,fm;\ d_0(Q) = 2^{+1}_{-1}\,fm.$$

YN ($d-\Lambda$) interactions

arXiv:2511.15493 [nucl-ex]
PRL accepted

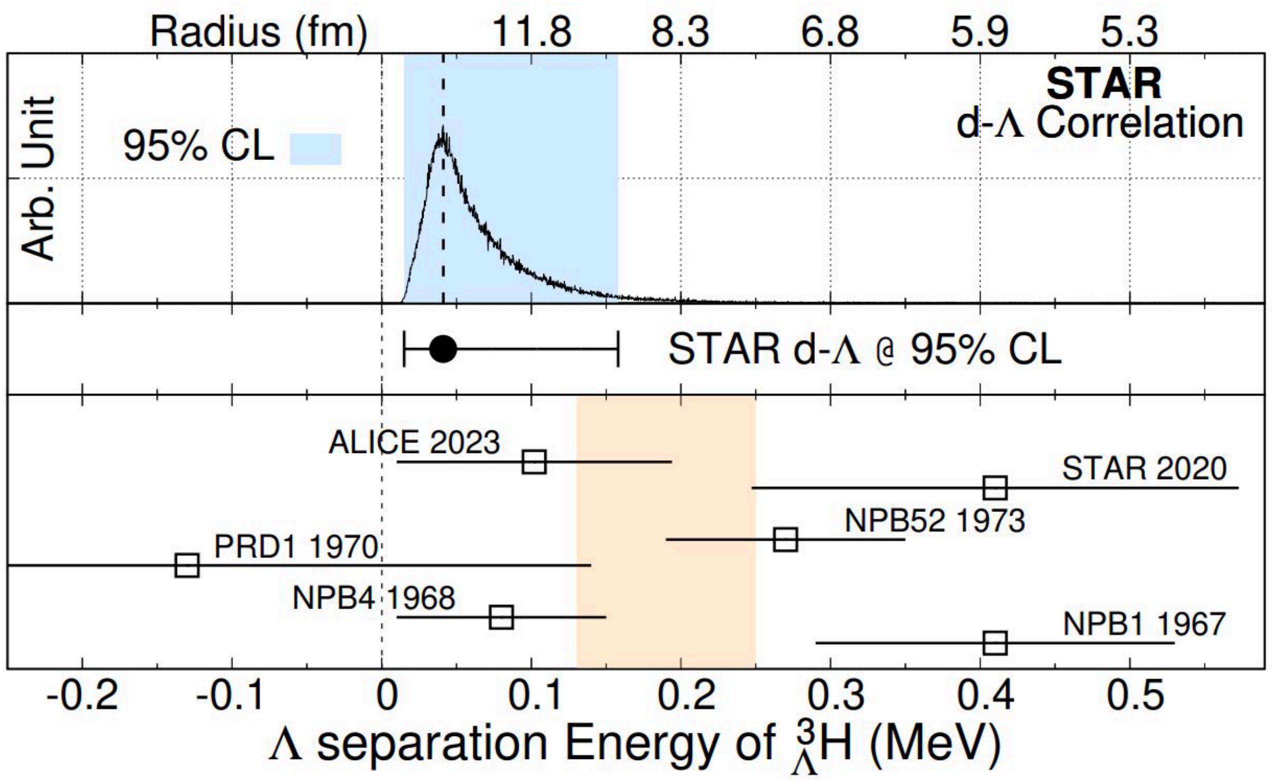




FSI parameters: f_0, d_0 for doublet and quartet spis-states separately

YN ($d - \Lambda$) interactions

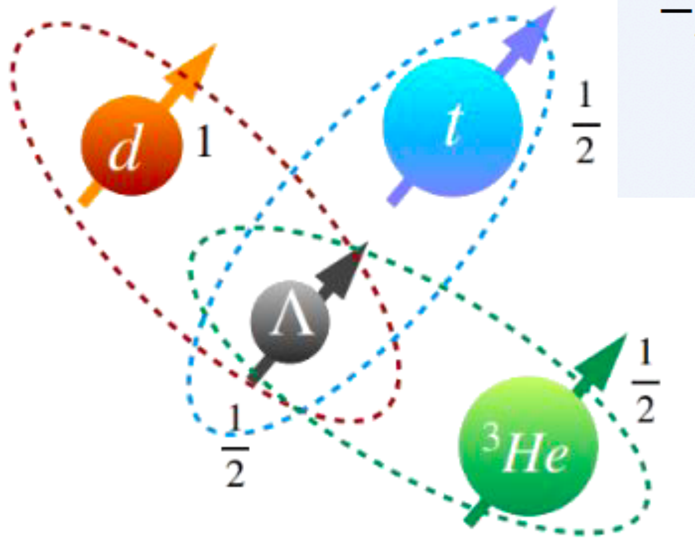
arXiv:2511.15493 [nucl-ex]
PRL accepted

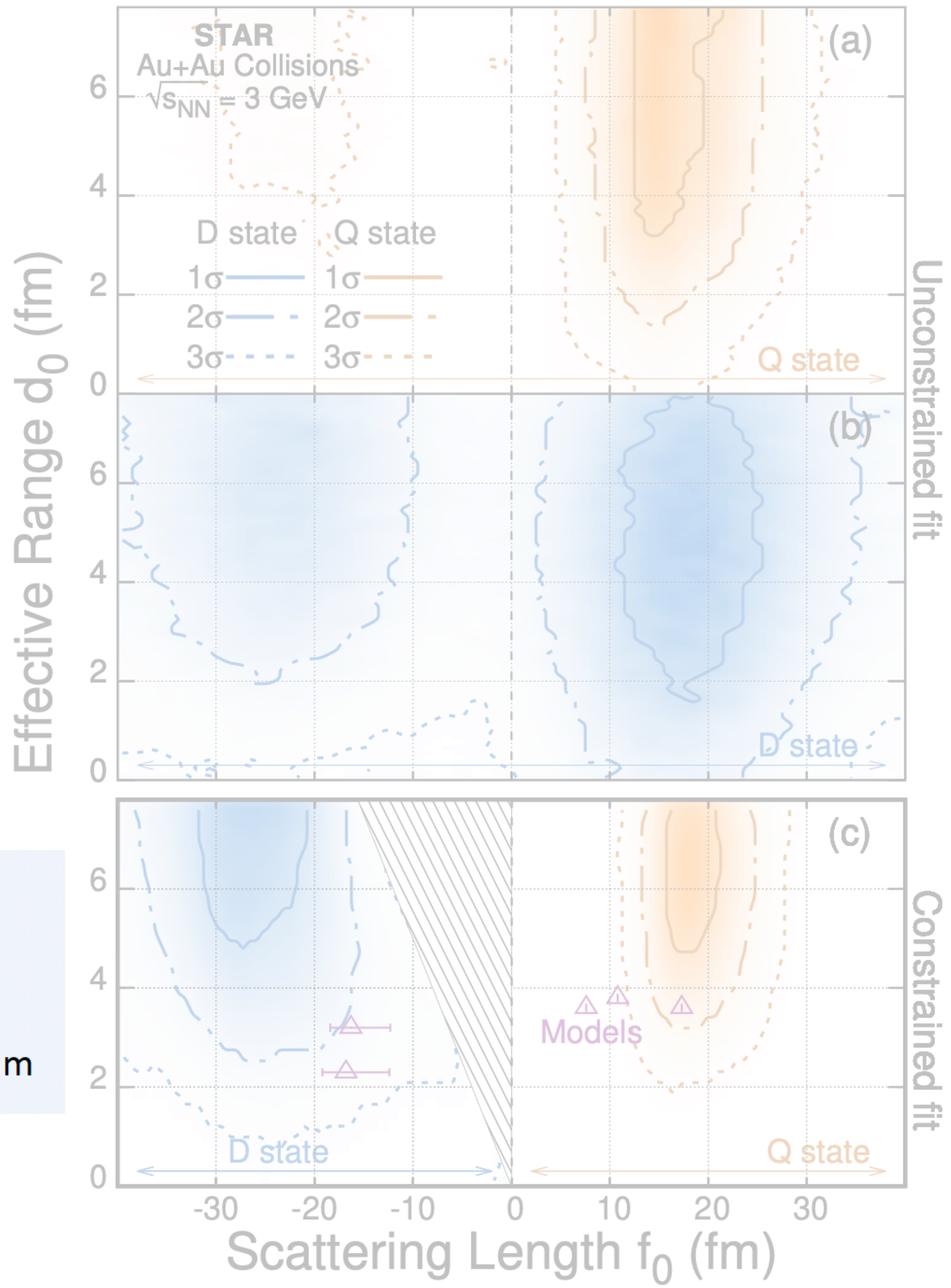


Precise extraction of hypertriton binding energy and radius using d - Λ correlations

$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

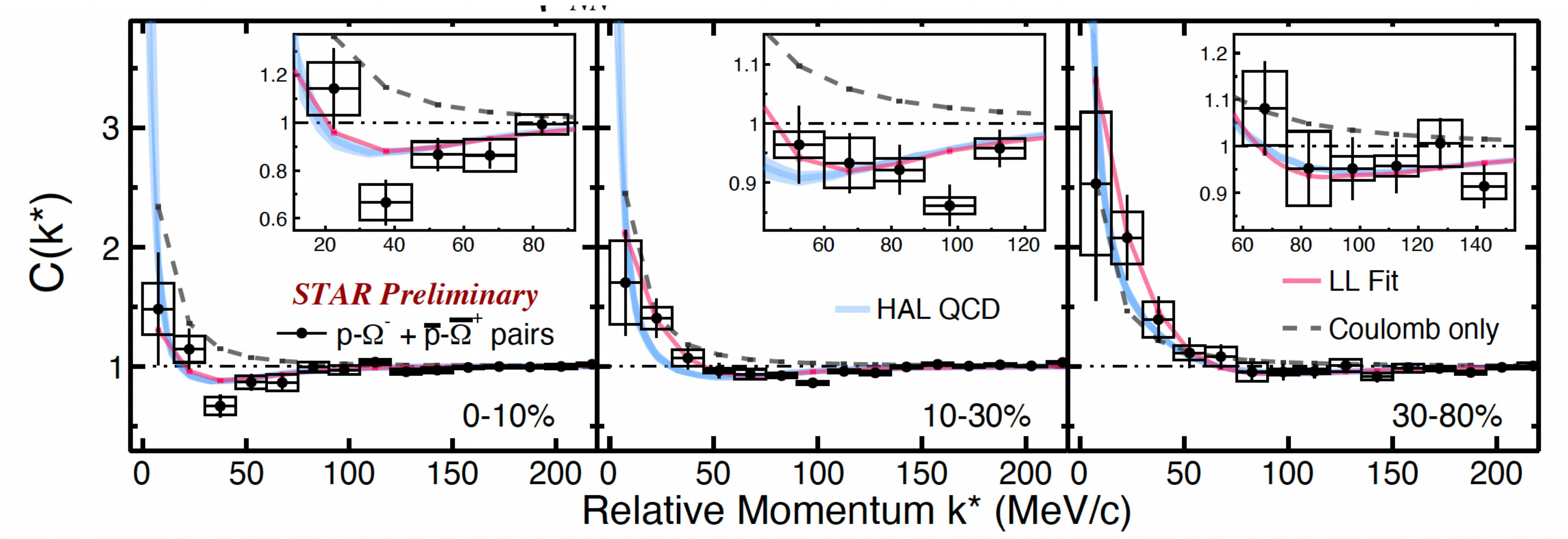
- ❖ $B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$
- ❖ $\mu_{d\Lambda}$: reduced mass
- ❖ γ: binding momentum





FSI parameters: f_0, d_0 for doublet and quartet spis-states separately

YN ($p - \Omega$) interactions

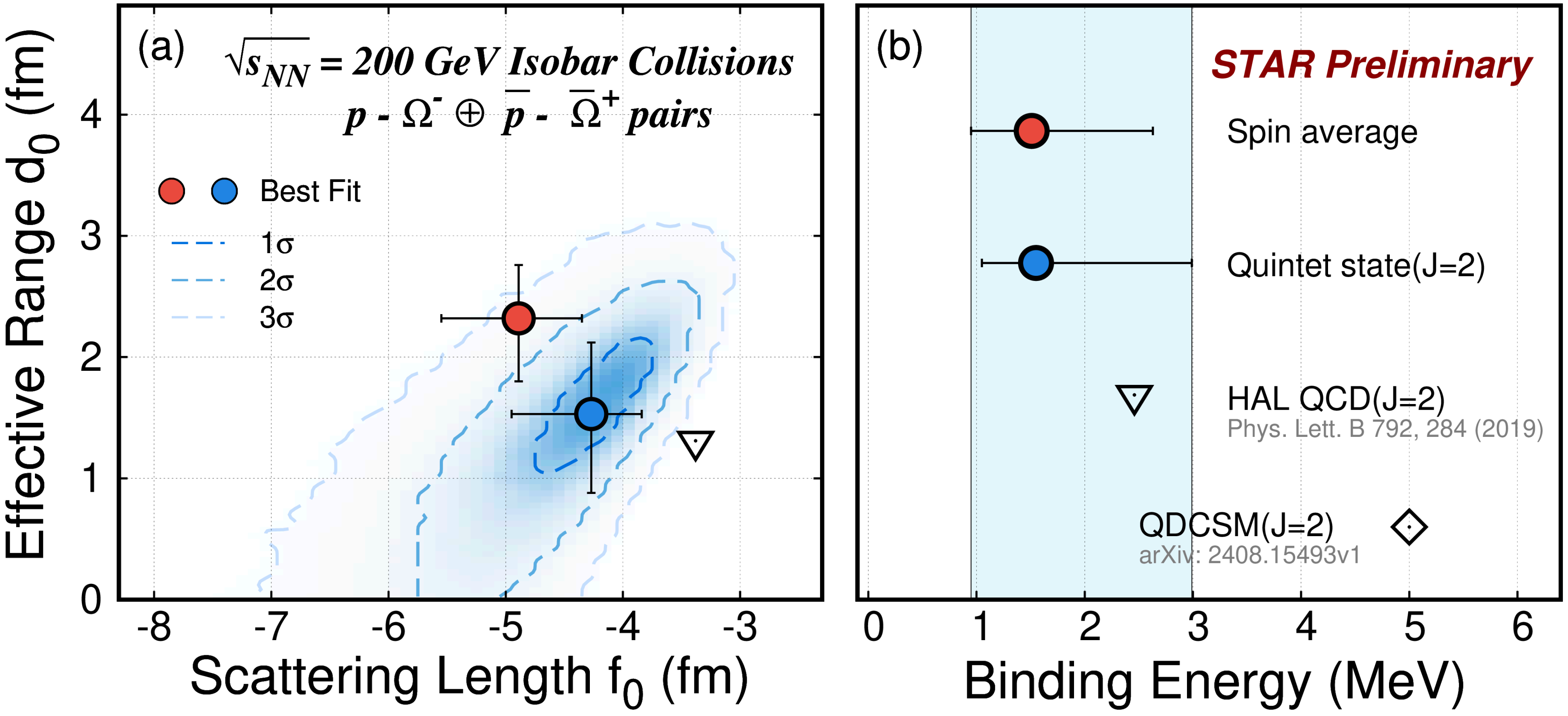


Interplay between Coulomb (the lowest k*) and strong FSI (k* around 30 - 100 MeV/c)

Lednicky-Lyuboshitz formalism used based on HAL QCD predictions

FSI parameters: f_0, d_0 for averaged and spin-separated states separately

YN ($p - \Omega$) interactions



First measurement of $p - \Omega^-$ correlations in HIC

FSI parameters: f_0, d_0 for averaged and quintet method

$|f_0| > 2d_0$ indicates a bound state

	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.9^{+0.5}_{-0.7}$	$-4.3^{+0.4}_{-0.7}$	-3.4
d_0 (fm)	$2.3^{+0.4}_{-0.5}$	$1.5^{+0.5}_{-0.7}$	1.3
BE (MeV)	$1.5^{+1.1}_{-0.6}$	$1.6^{+1.4}_{-0.5}$	2.3

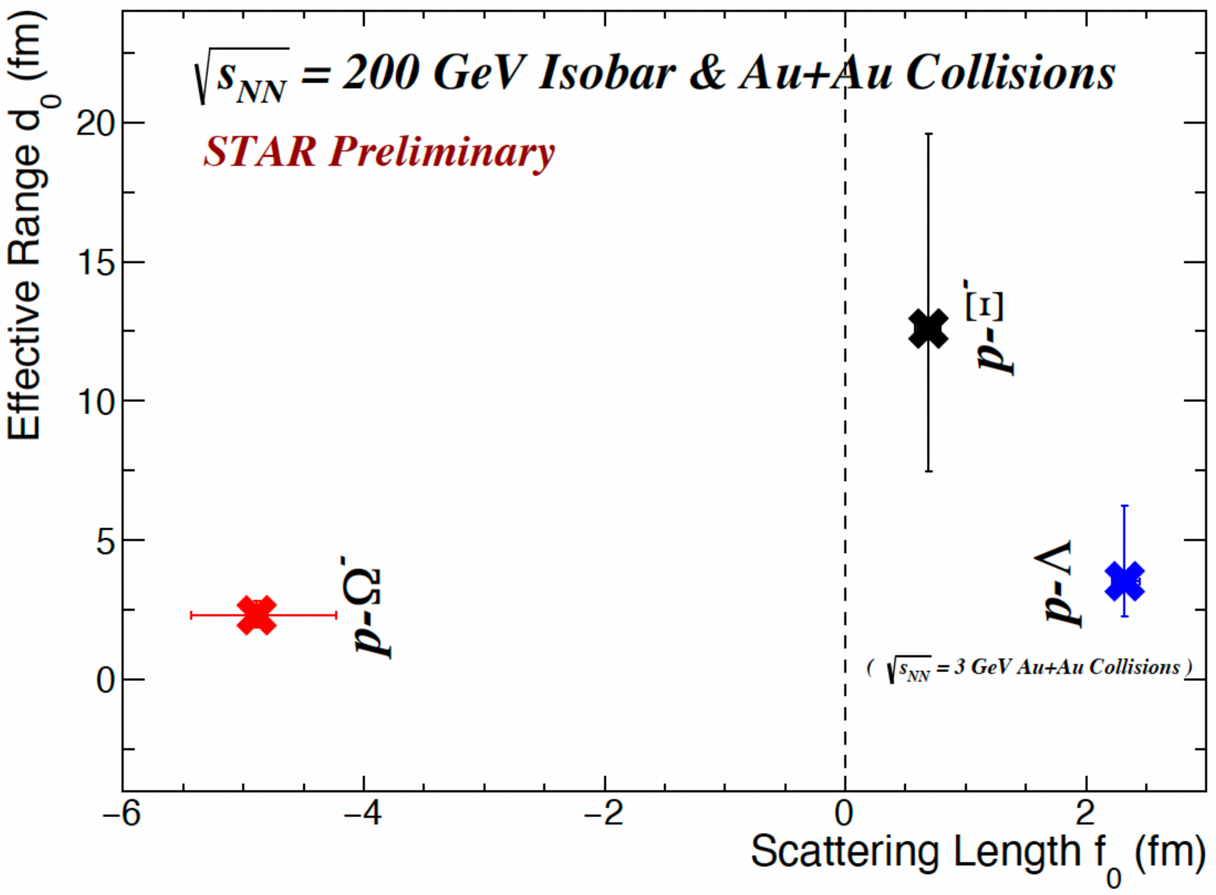
Binding energy

$$m_{p\Omega} = \frac{m_p m_\Omega}{m_p + m_\Omega}$$

$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}\left(1 - \sqrt{1 + \frac{2d_o}{f_0}}\right)^2$$

Consistent with HAL QCD predictions

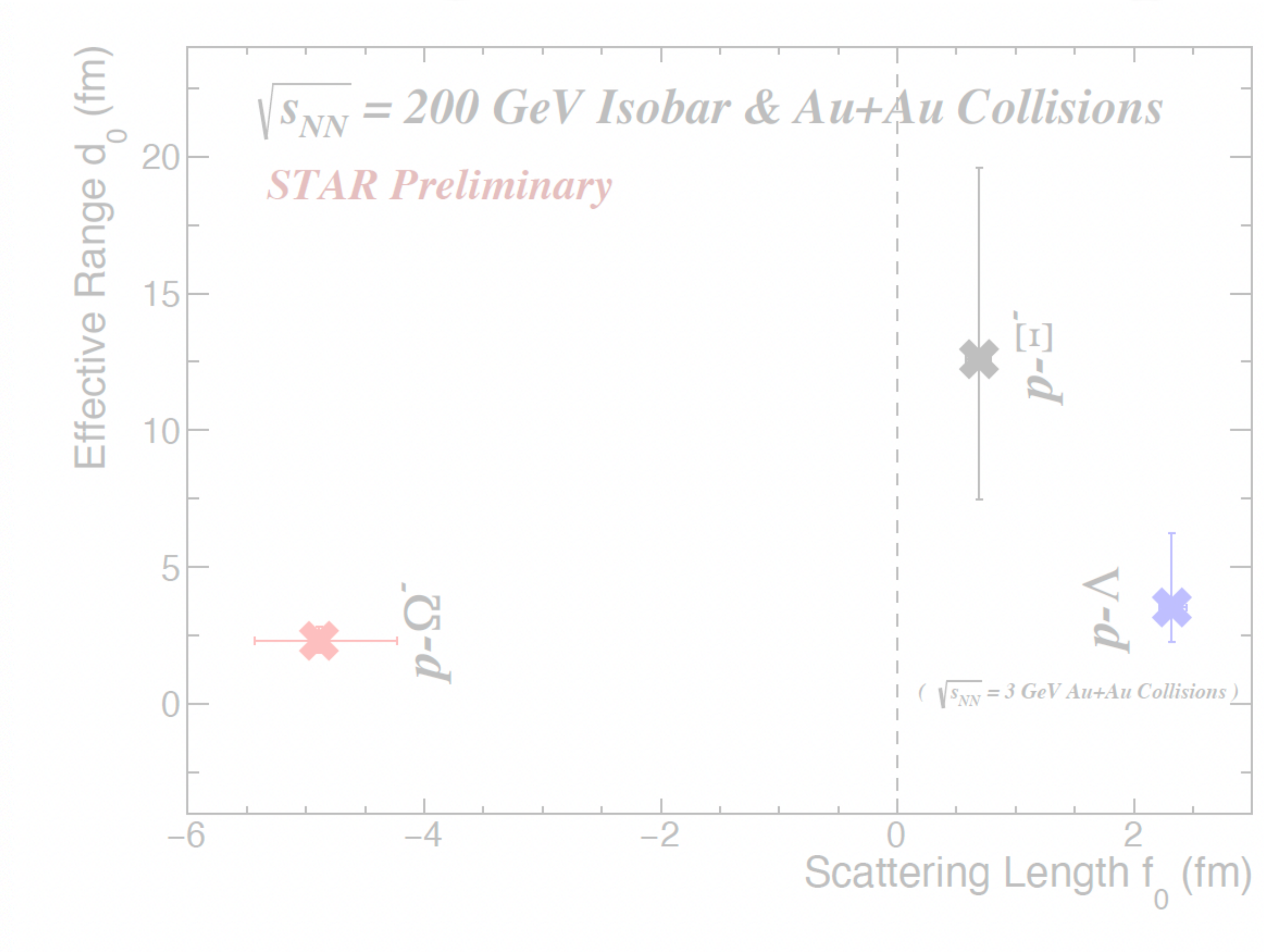
Strong interactions parameters

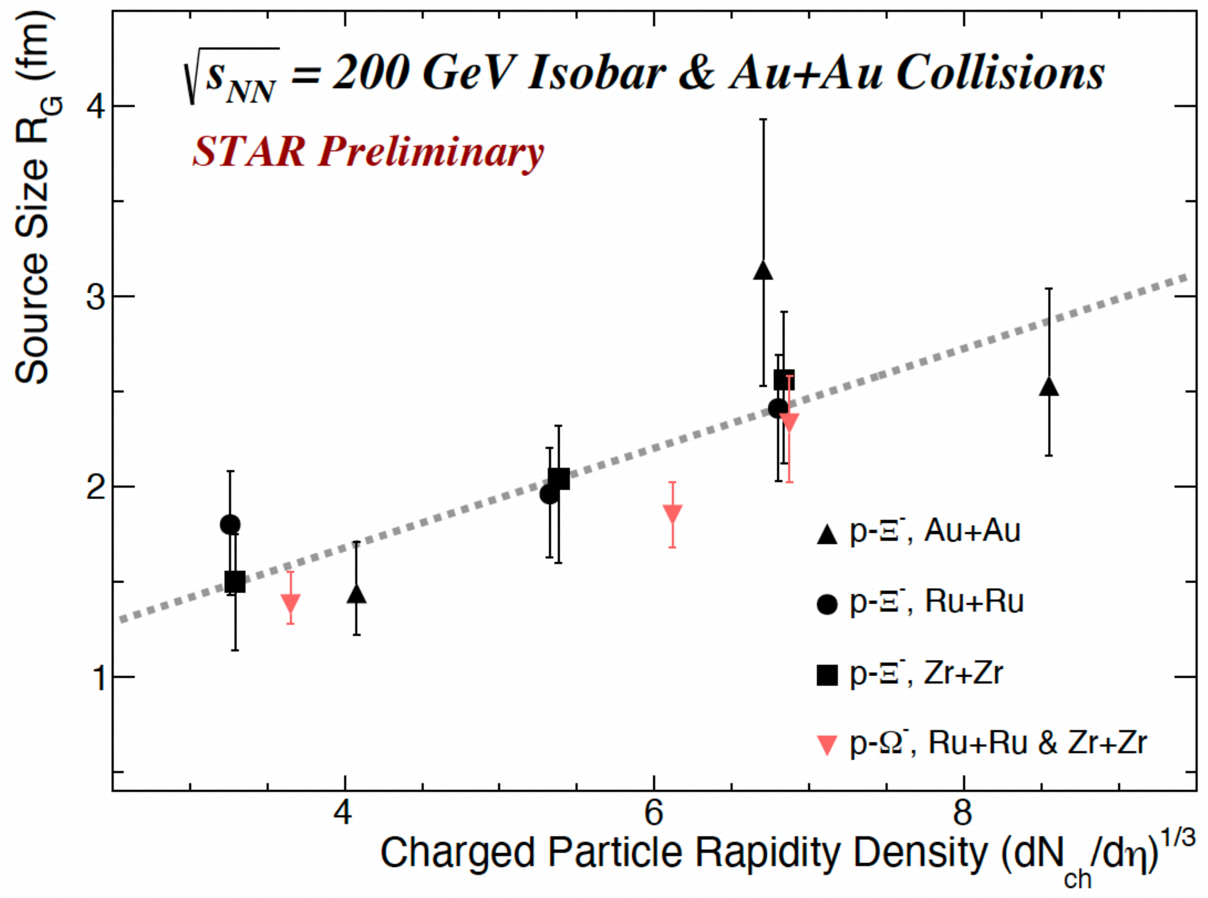


Extracted $f_0 > 0$ in $p - \Lambda$ and $p - \Xi^-$: Weakly attractive interaction

$f_0 < 0$ in $p - \Omega^-$: Attractive potential, possible bound state

Strong interactions parameters





Extracted $f_0 > 0$ in $p - \Lambda$ and $p - \Xi^{-}$: Weakly attractive interaction

$f_0 < 0$ in $p - \Omega^{-}$: Attractive potential, possible bound state

Extracted source sizes confirm a linear trend

Centrality dependence of the source size verified as well: $R_{central} > R_{peripheral}$

Summary

Summary
Femtoscopy

Source properties

- Geometric and dynamical characteristics of the source
- Source sizes, emission times, and lifetime
- Emission asymmetries in non-identical particle pairs

Bulk properties of matter

- EoS and possible phase transitions
- Collective dynamics complementary to flow observables

Hadron interactions

- Strong interaction parameters from correlation femtoscopy
- Bound states and binding energies
- NN, NY, and YY interactions relevant for neutron stars and neutron-star mergers

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Thank you!

Supporting slides

Lednicky-Lyuboshitz model

The correlation function can be calculated analytically by averaging **Ψ** over the total spin S and the distribution of the relative distances **S(r*)**

Ref : Lednicky, Richard & Lyuboshits, V.L.. (1982). Sov. J. Nucl. Phys. (Engl. Transl.); (United States). 35:5.

$$C(k^*) = \int S(r^*)\,|\Psi(r^*,k^*)|^2\, d^3r$$

The normalized pair separation distribution (source function) **S(r*)** is assumed to be Gaussian,

$$S(r^*) = (2\sqrt{\pi}r_0)^{-3} e^{-\frac{r^{*2}}{4r_0^2}},$$

$$\Psi^S(r^*,k^*) = e^{-ik^*r^*} + f^S(k^*)\frac{e^{ik^*r^*}}{r^*} \qquad f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2}d_0^S k^{*2} - ik^*\right)^{-1}$$

Strong

$$|\Psi^C(r^*,k^*)| = \sqrt{A_C}\, e^{-ik^*r^*} F(-i\eta,1,i\zeta) \qquad A_C(\eta) = \frac{2\pi}{k^* a_c}\left(exp\left(\pm\frac{2\pi}{k^* a_c}\right) - 1\right)^{-1}$$

Coulomb

F- confluent hypergeometric function

f_0 and d_0 - parameters of strong interaction.

Theoretical correlation function (k*) depends on: R, f_0 and d_0.

f_0 - the scattering length, determines low-energy scattering.

The elastic cross section, σ_e, (at low energies) determined by the scattering length, $\lim_{k\to 0}\sigma_e = 4\pi f_0^2$

d_0 - the effective range, corresponds to the range of the potential (simplified scenario - the square well potential.

For identical systems one has to include QS (Fermi-Dirac / Bose-Einstein) as well.

Strange hadronic matter in the inner core

The inner core of the neutron star is totally unknown. One of the most probable scenarios is that hyperons (baryons with strange quarks) appear at a density larger than (2–3) ρ_0

Λ hyperons, being free from Pauli exclusion principle by neutrons, are allowed to stay at the bottom of the attractive nuclear potential made by neutrons. When the kinetic energy of a neutron on the Fermi surface of the degenerate neutron matter exceeds the Λ-n mass difference of 176 MeV, it converts into a Λ hyperon via weak interaction.

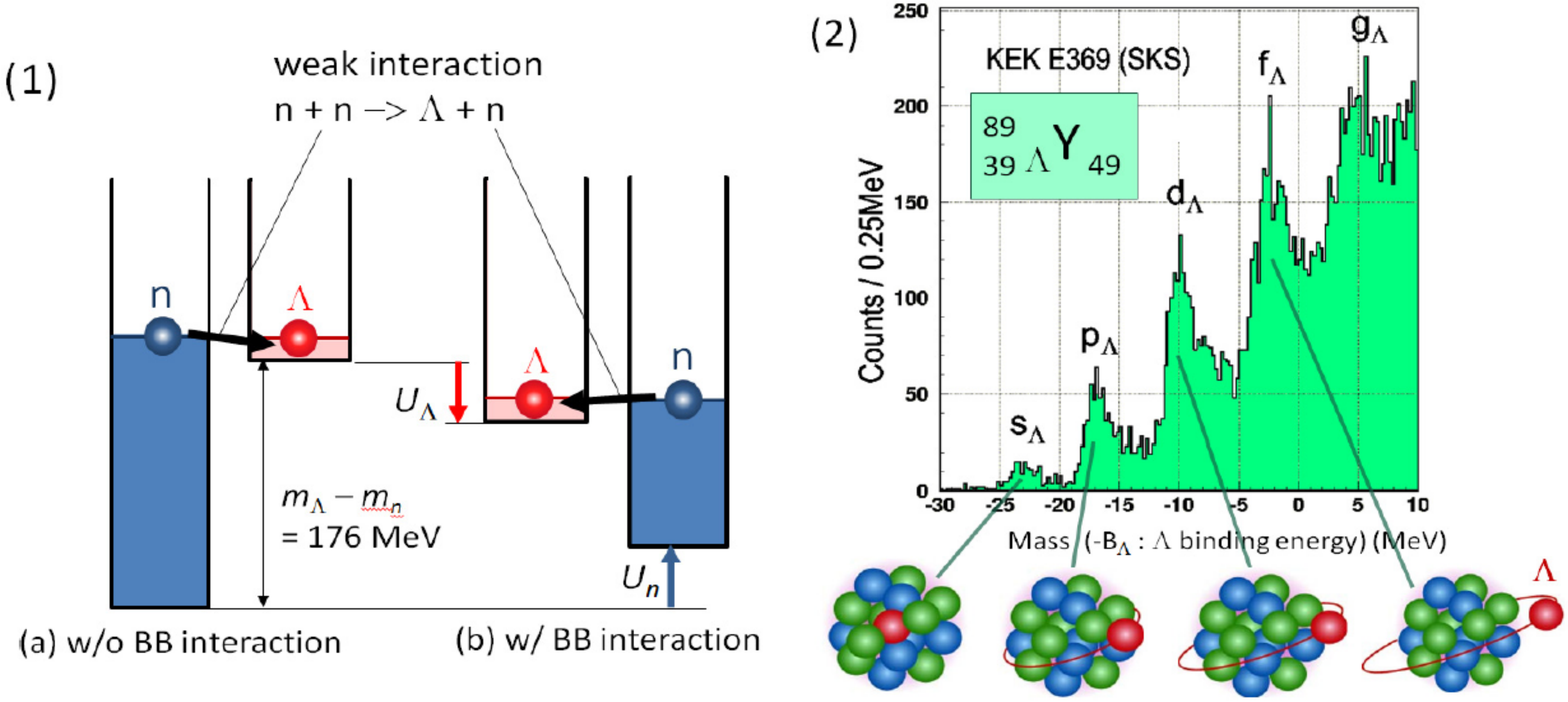

Fig. 3. (1) Energies of neutrons and Λ hyperons in high density neutron matter confined in the potential made by gravity. See text for details. (2) Excitation spectrum of a Λ hypernucleus $^{89}_{\Lambda}$Y via the (π^+,K^+) reaction on ^{89}Y target [6].