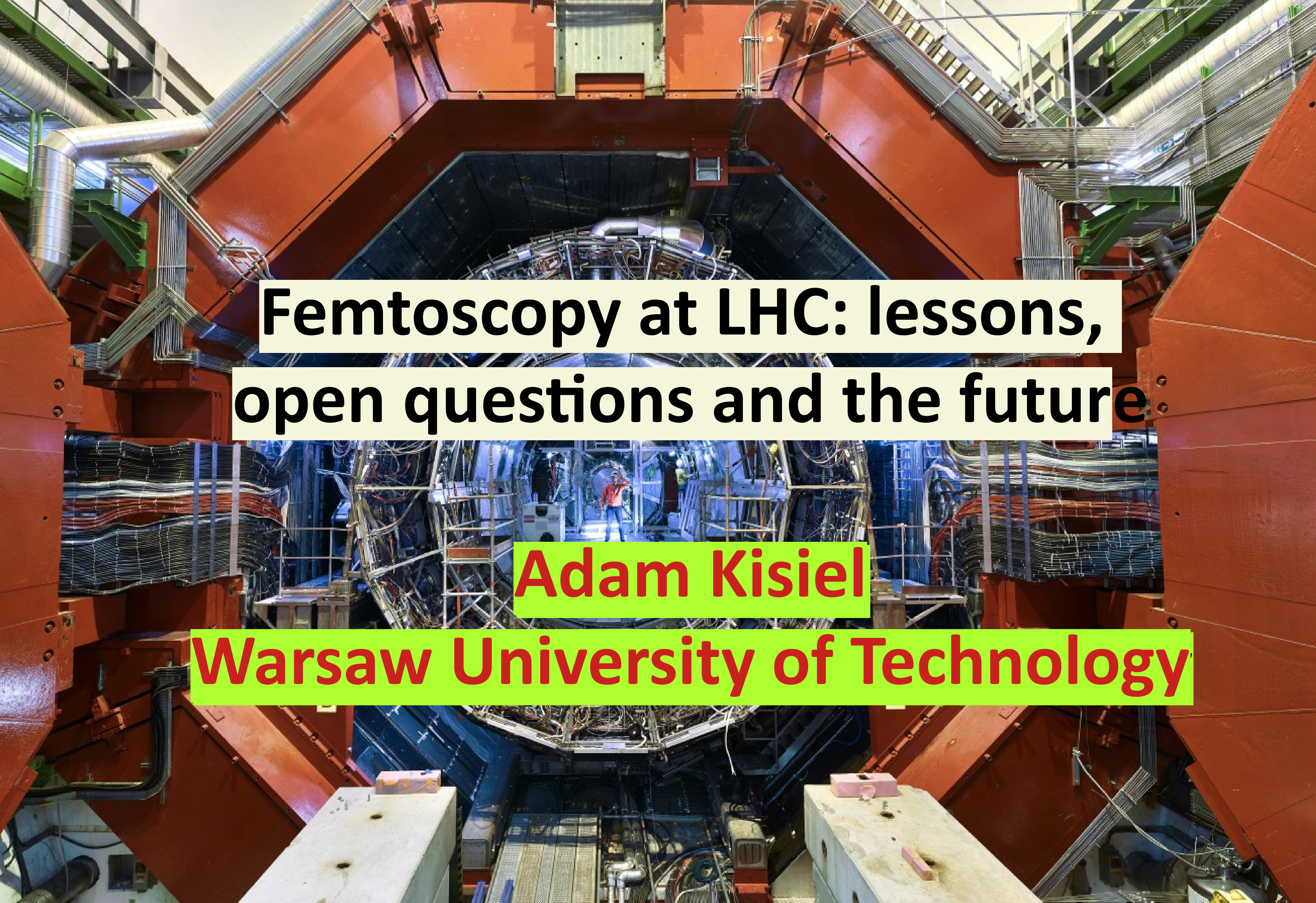
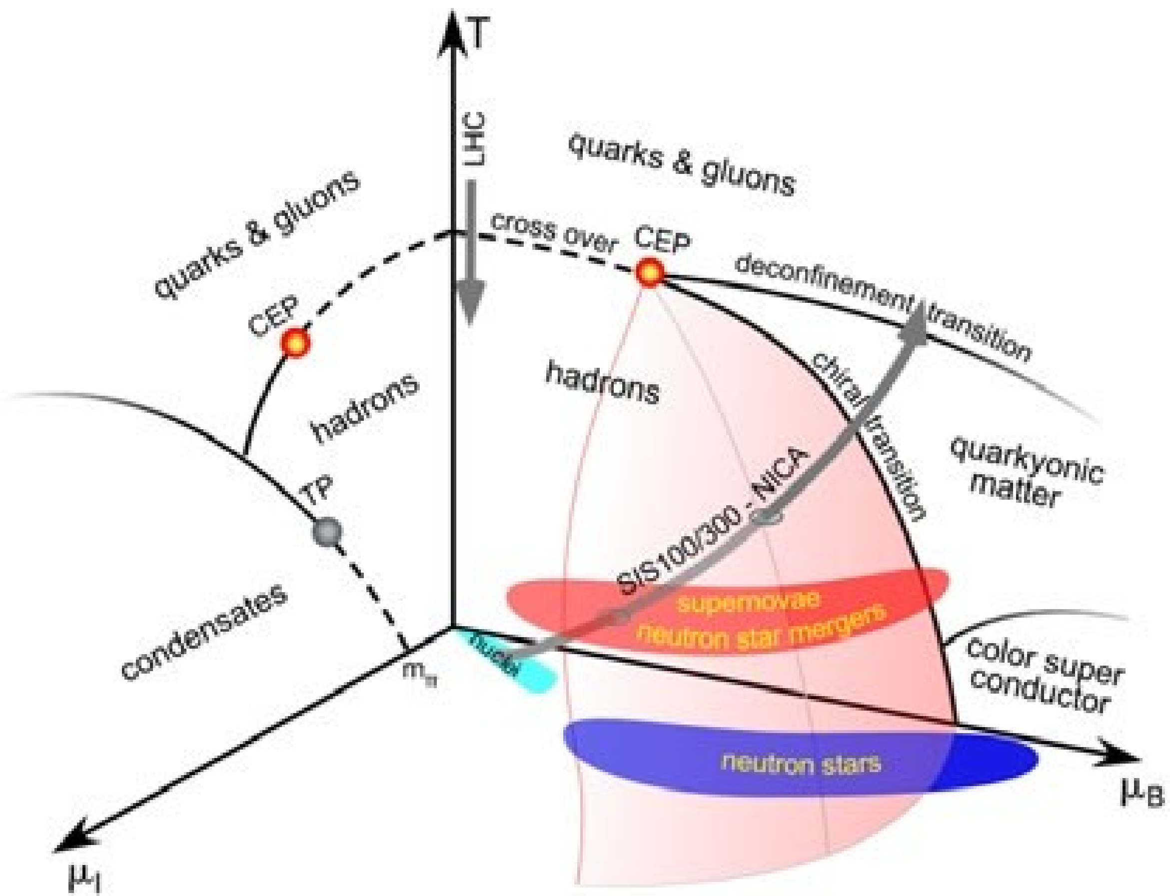


Femtoscopy at LHC: lessons, open questions and the future

Adam Kisiel
Warsaw University of Technology

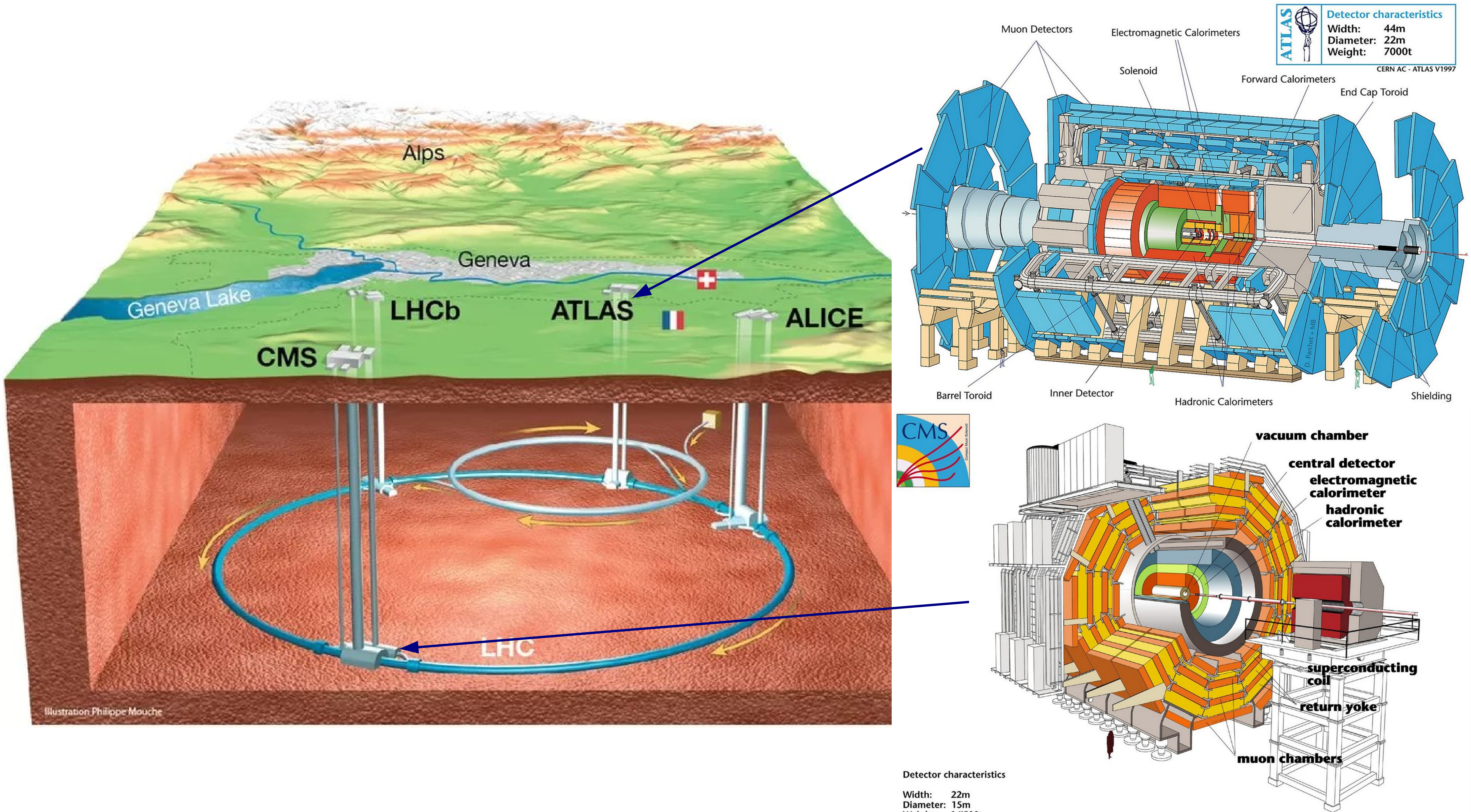
Exploring QCD phase diagram



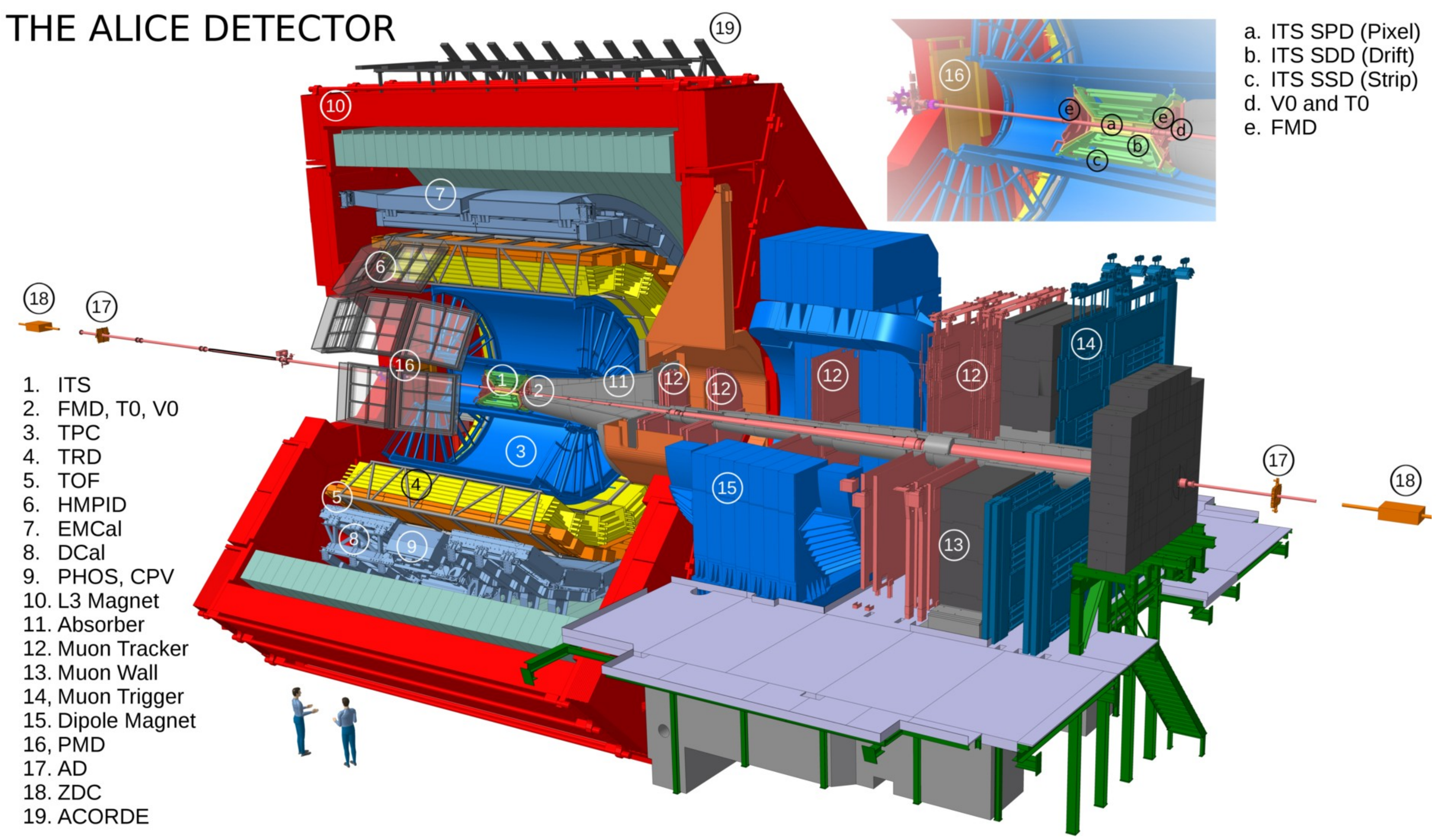
NuPECC Long Range Plan 2017

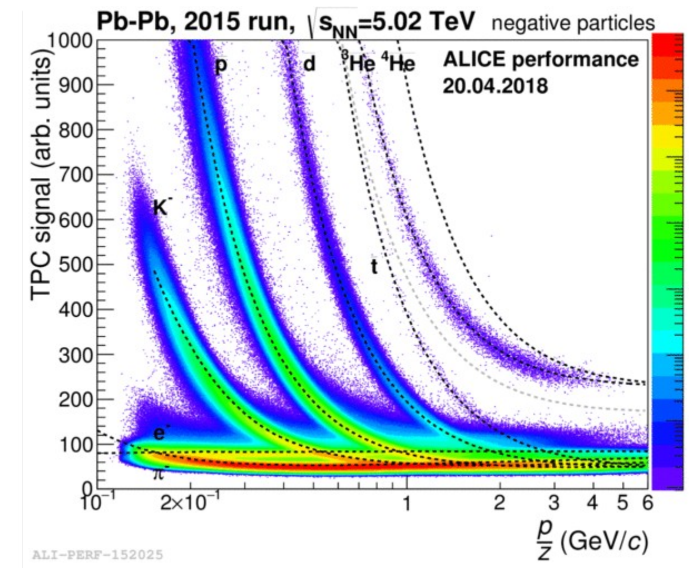
- QCD phase diagram: main goal of high energy physics
- QCD phase diagram probed by matter created in ion collisions and astrophysical phenomena
- Various colliders produce matter at different regions in the diagram
- Significant overlap of collider physics and astrophysics

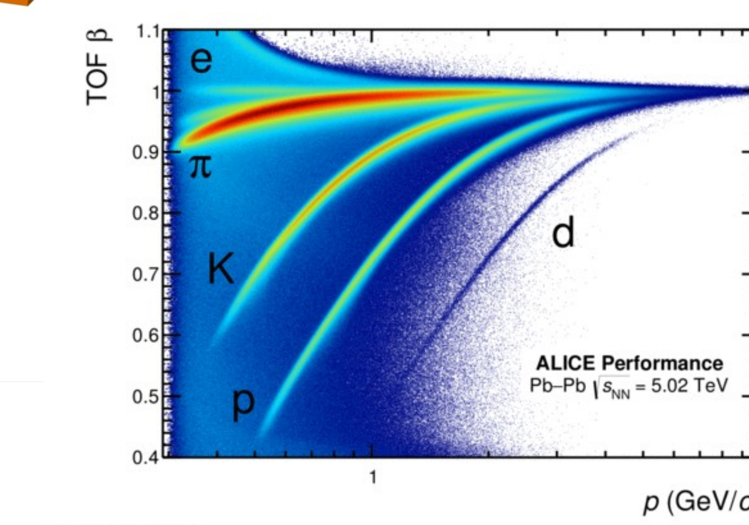
Exploring QCD: Large Hadron Collider



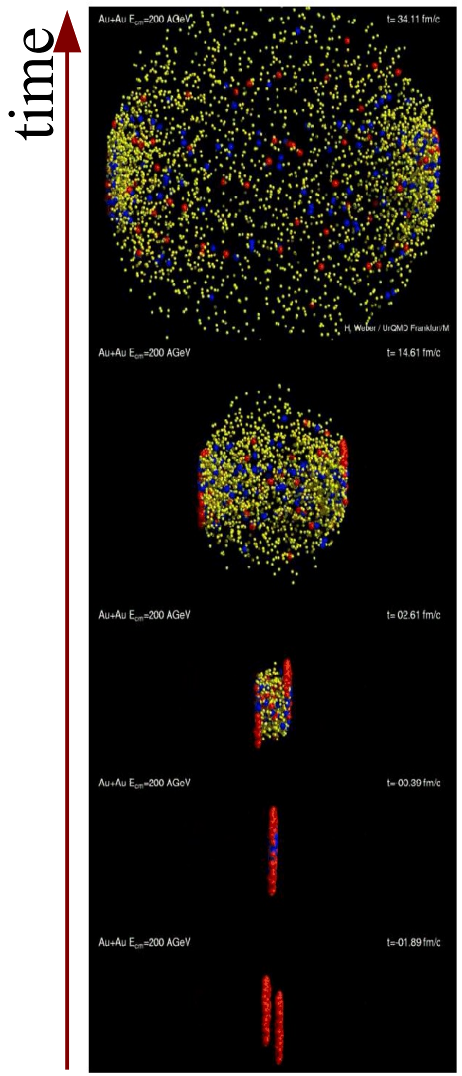
Experiments at LHC: ALICE

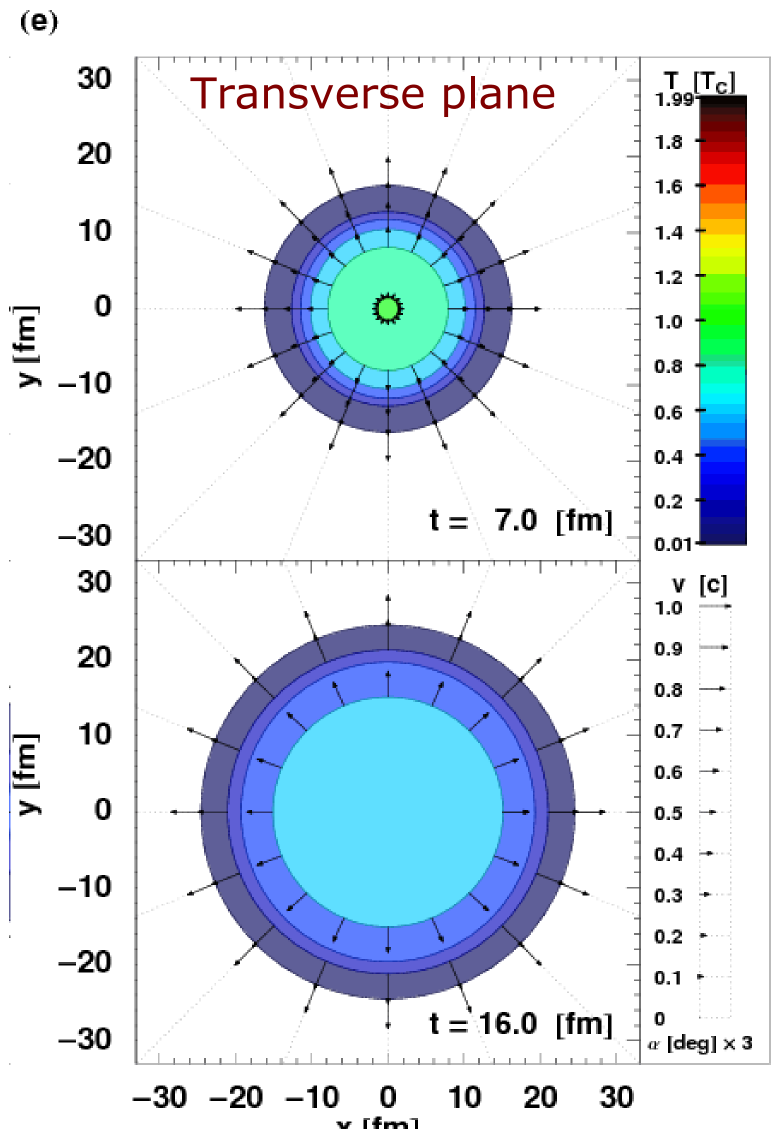






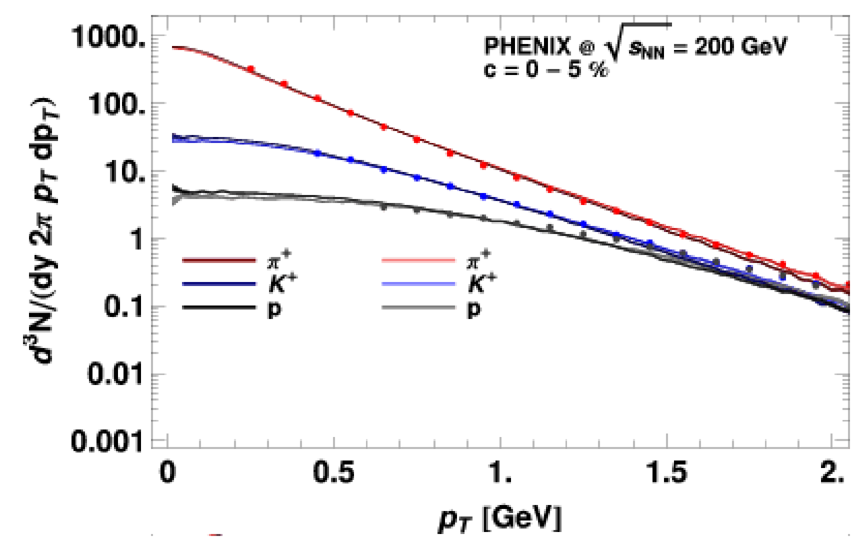
Heavy-ion collision evolution



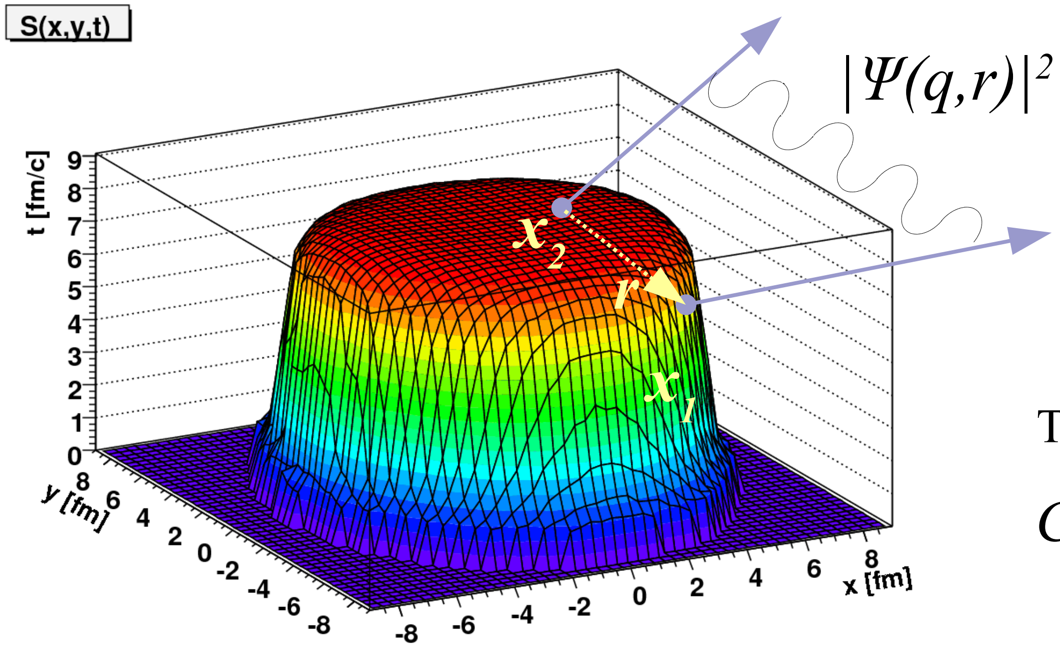


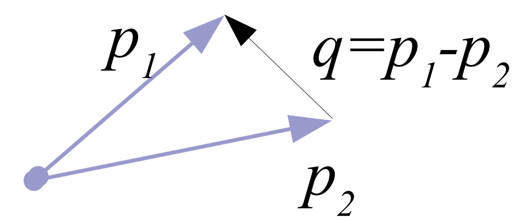
M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification



Measuring space-time extent: femtoscopy



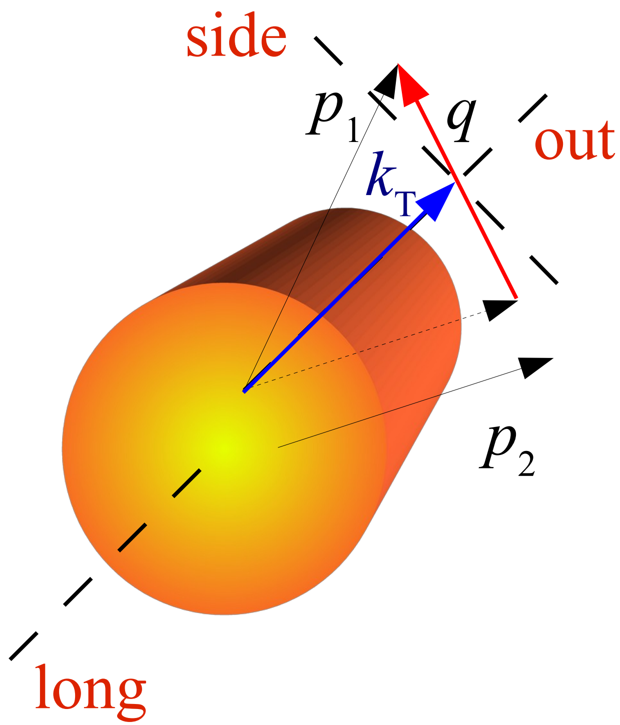


The Integral Equation for Correlation

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

- Use two-particle correlation, coming from the interaction Ψ (quantum statistics (HBT), coulomb and/or strong)
- Measure $C(q)$
- Try to invert the Koonin-Pratt eq. to gain information about S from known Ψ and measured C

Sizes accessible via femtoscopy



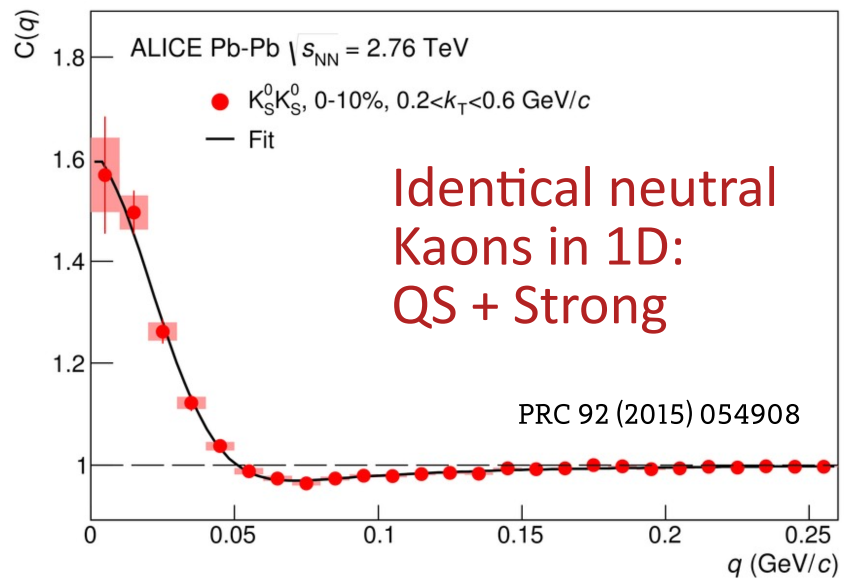
$m_T = \sqrt{k_T^2 + m_\pi^2}$

Longitudinally Co-Moving System (LCMS):

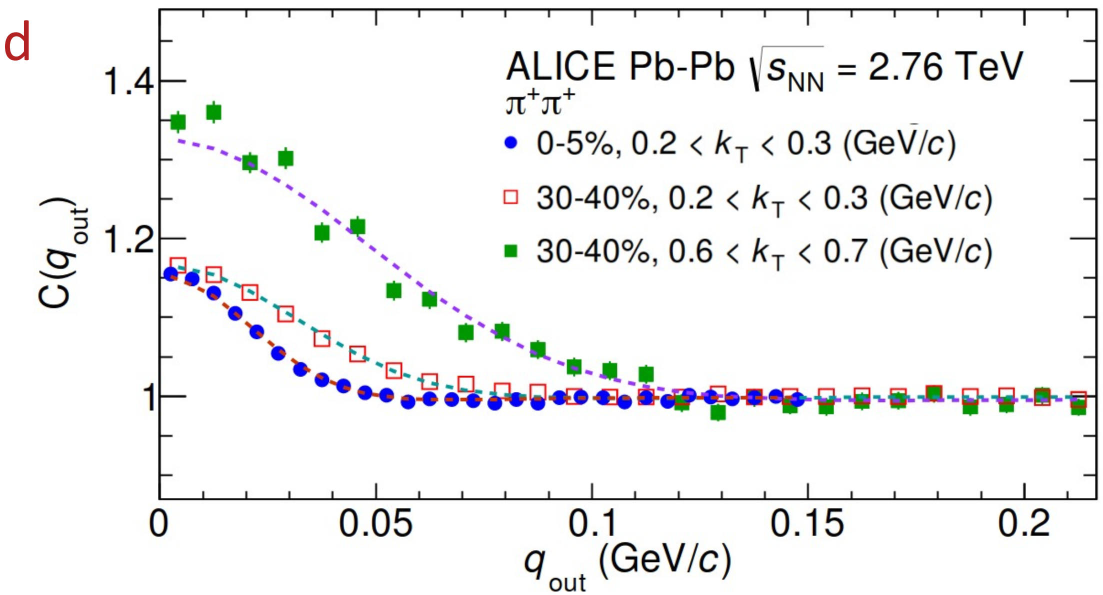
$p_{1,long} = - p_{2,long}$

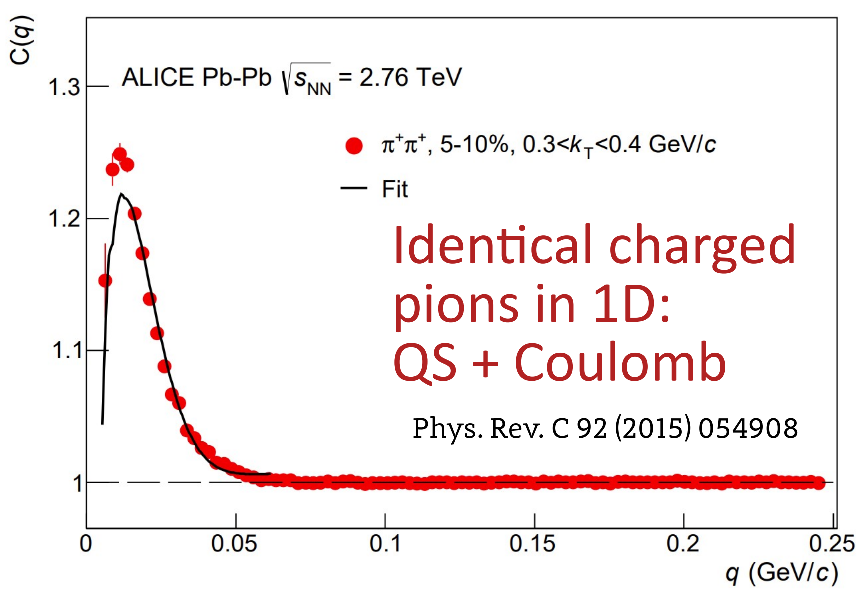
- For large statistics – measurement in 3 dimensions, giving 3 independent sizes in Longitudinally Co-Moving System
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive to geometrical size, emission time and space-time correlation
  - Side (perpendicular to Long and Out): sensitive to geometrical size
- For statistically challenged analyses, measurement in one dimension (giving only one size) in Pair Rest Frame

Femtoscopy: various shapes and sizes

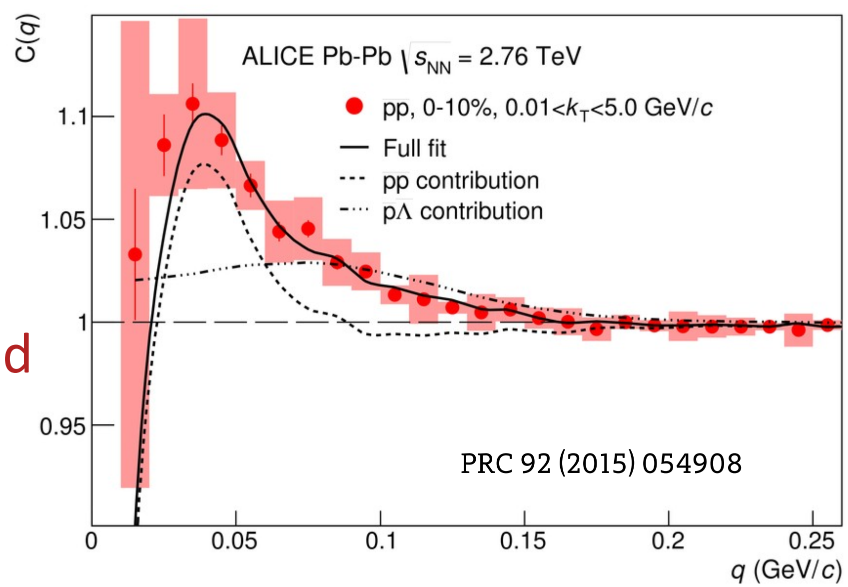


Identical charged pions in 3D (projection): QS + Coulomb

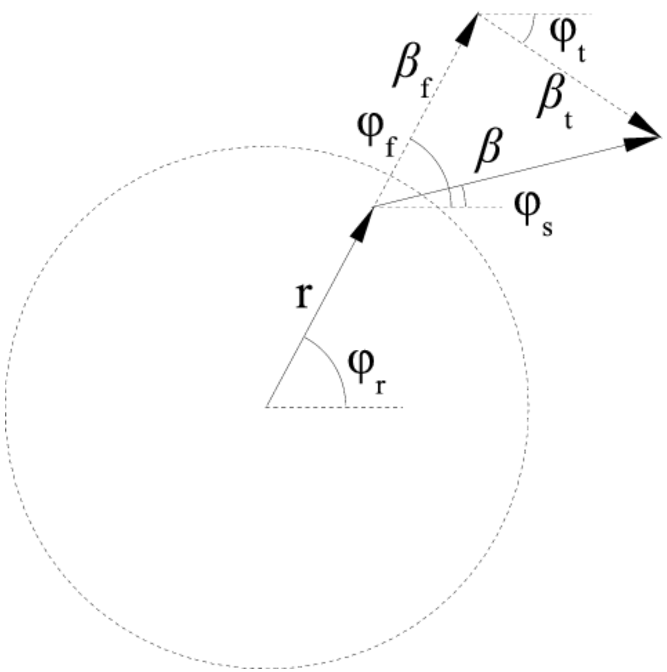




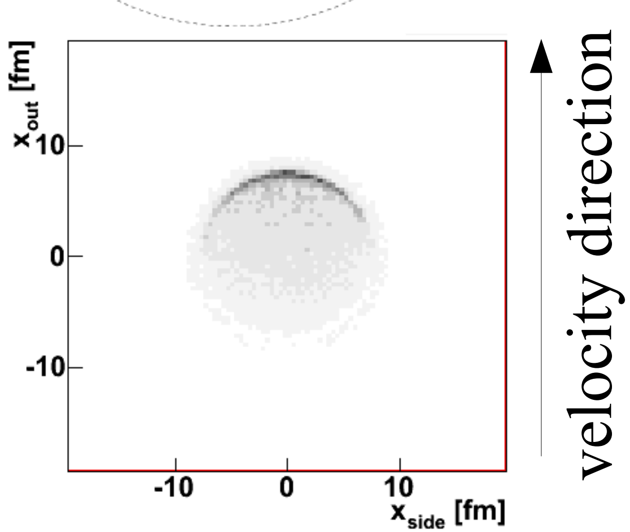
Identical charged protons in 1D: QS + Coulomb + Strong

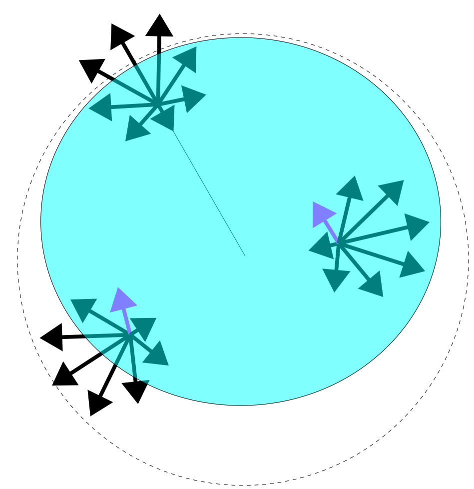


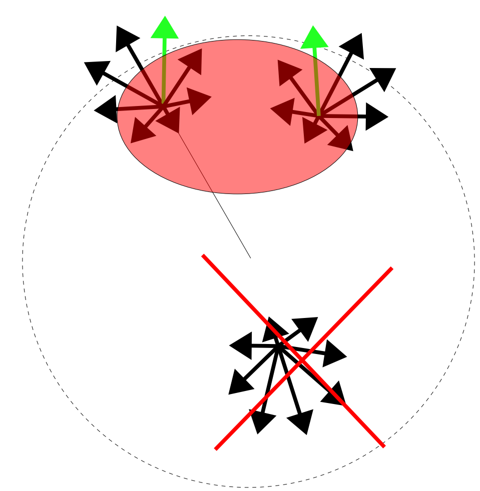
Thermal emission from collective medium



- Particle emitted from medium has collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source

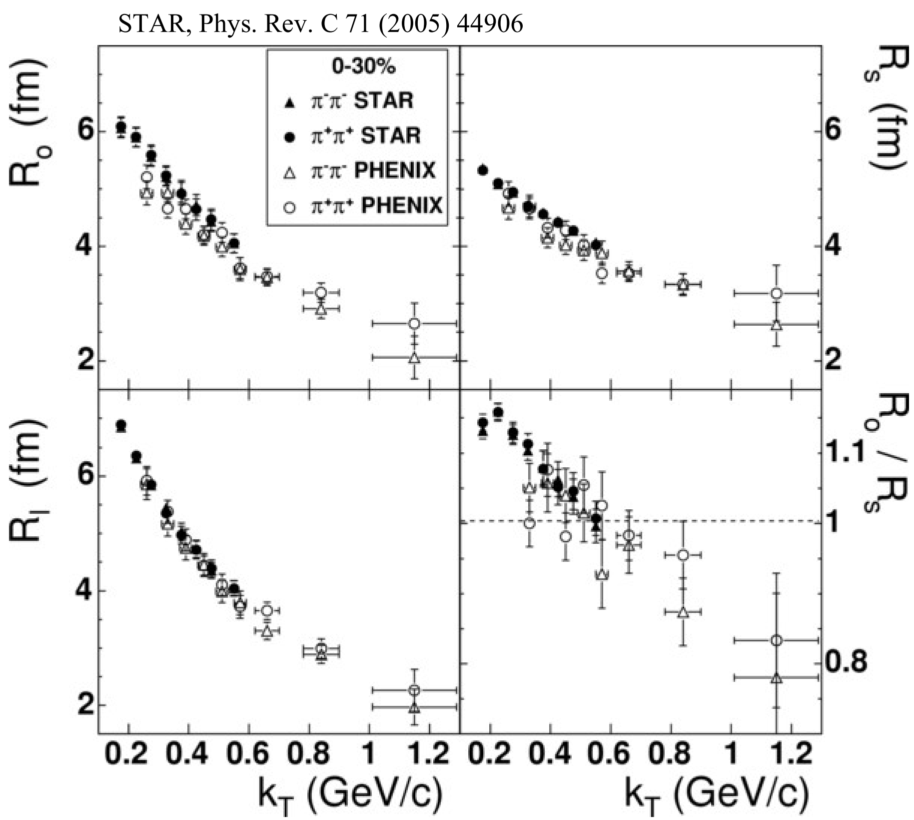


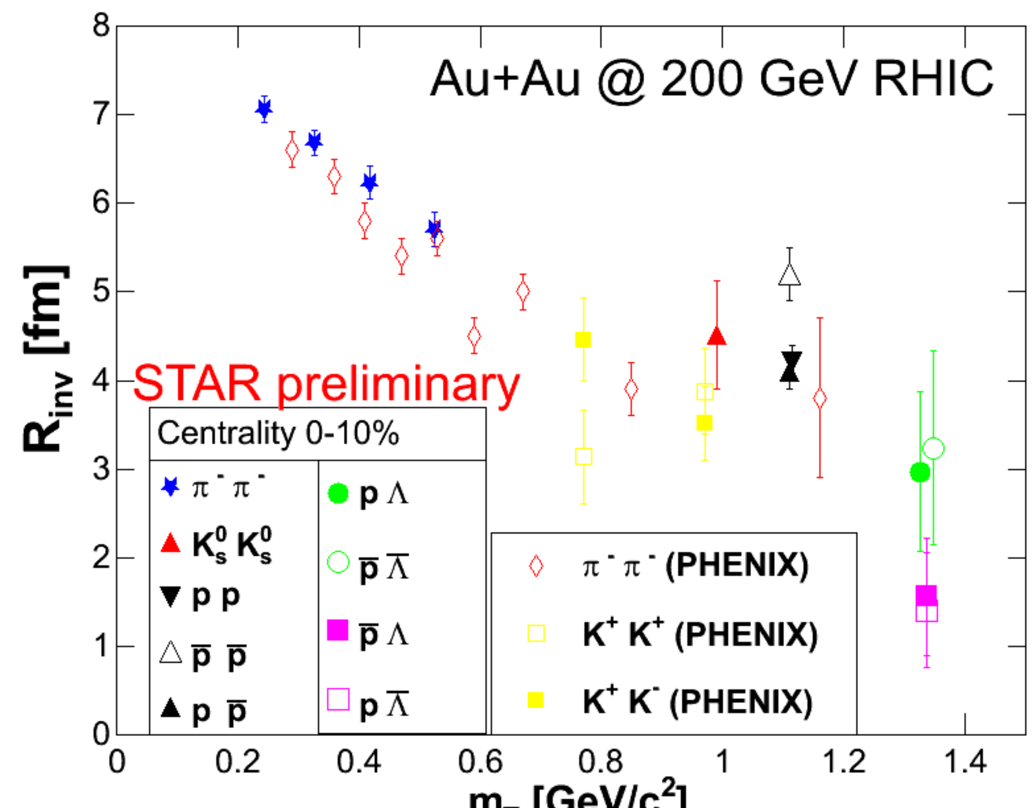




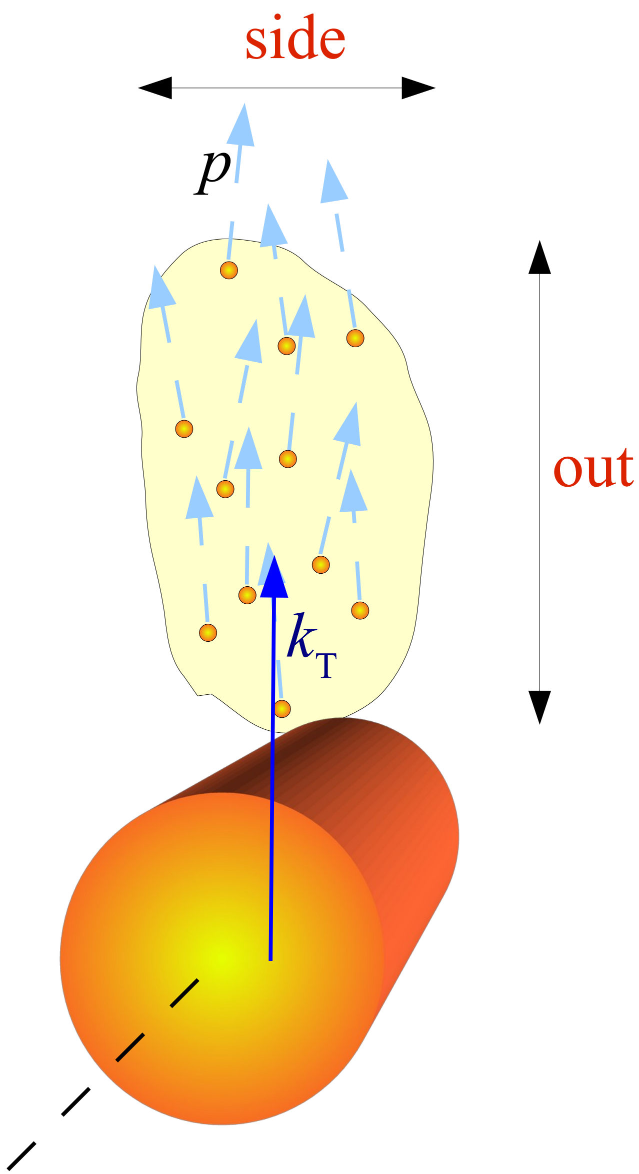
m_T dependence at RHIC

- A clear m_T dependence is observed, for all femtoscopic radii and for all particle types: but is it hydrodynamic like? Can we tell?





Emission duration



- Particles emitted “earlier” travel some distance in “out” (direction of velocity β)
- Radii have components from:
  - Geometrical size x (width of the space point distribution)
  - Emission duration t (width of the emission time distribution)
  - Space-time correlations

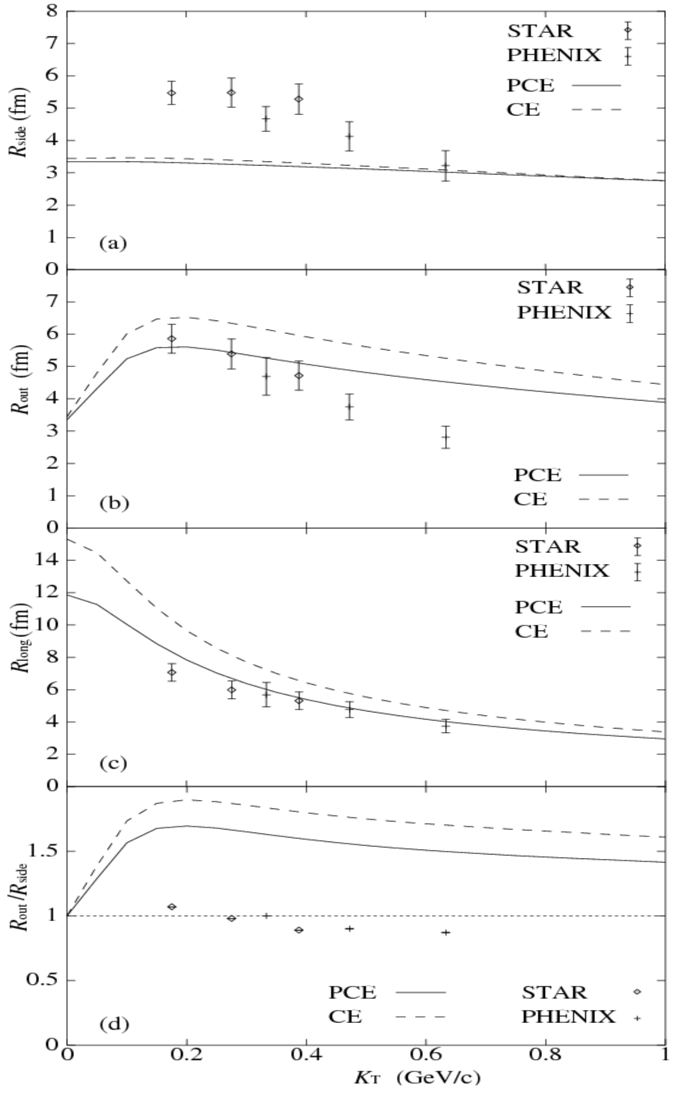
$$R_{out} = var\{x\} + \beta\, var\{t\} - \langle \beta\, t\, x \rangle$$

$$R_{side} = var\{x\}$$

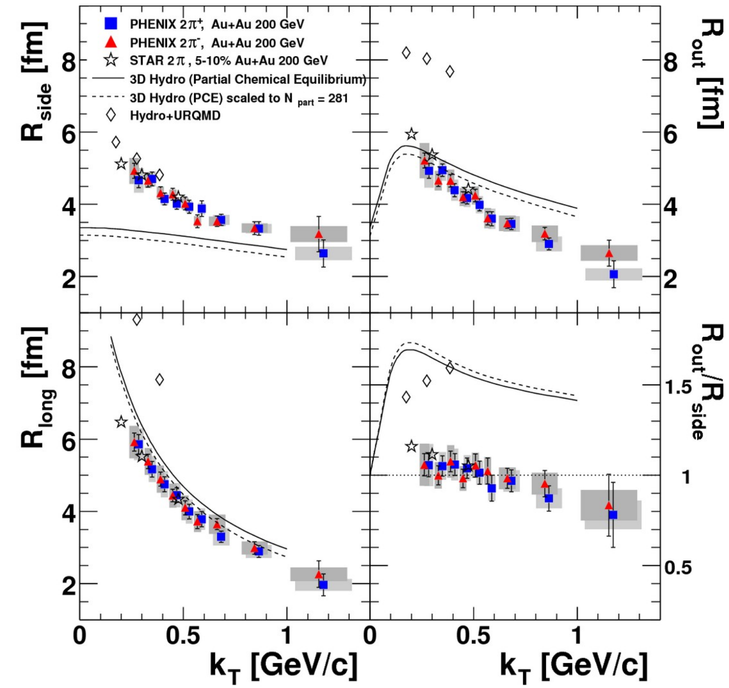
- What will R_{out}/R_{side} be?

RHIC Hydro-HBT puzzle

T. Hirano, K. Tsuda, nucl-th/0205043
Phys.Rev.C66:054905,2002.



- First hydro calculations struggled to describe femtoscopic data: predicted too small R_{side}, too large R_{out} – too long emission duration
- R_{out}/R_{side} sensitive to emission duration, which is large for first order phase tr.

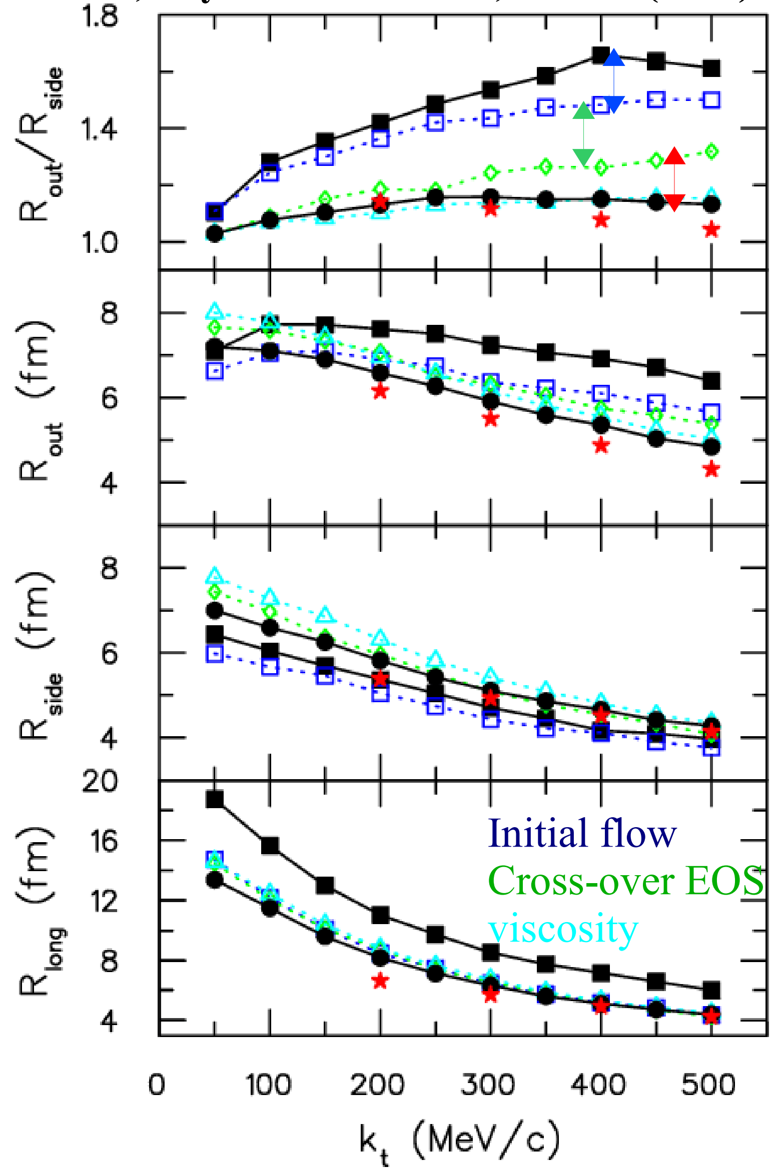


U. Heinz, P. Kolb, hep-ph/0204061

Phys. Rev. Lett. 93, 152302 (2004) ,

Modifying hydrodynamics assumptions

S. Pratt, Phys. Rev. Lett. 102, 232301 (2009)

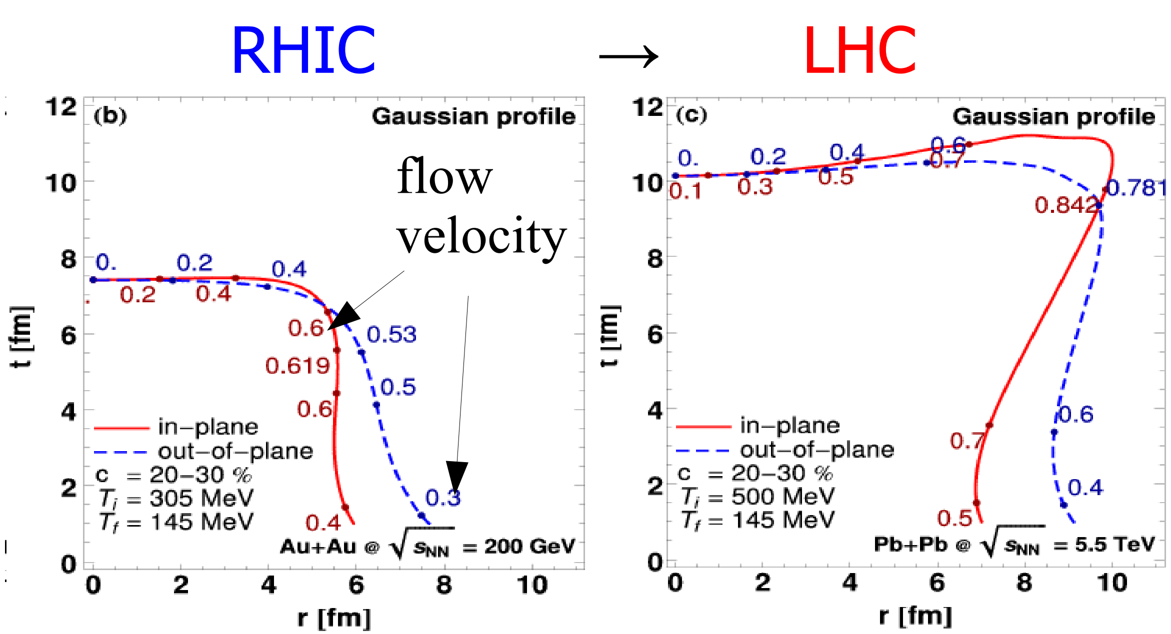


- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition at RHIC and LHC – smooth cross-over is needed
- Resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity

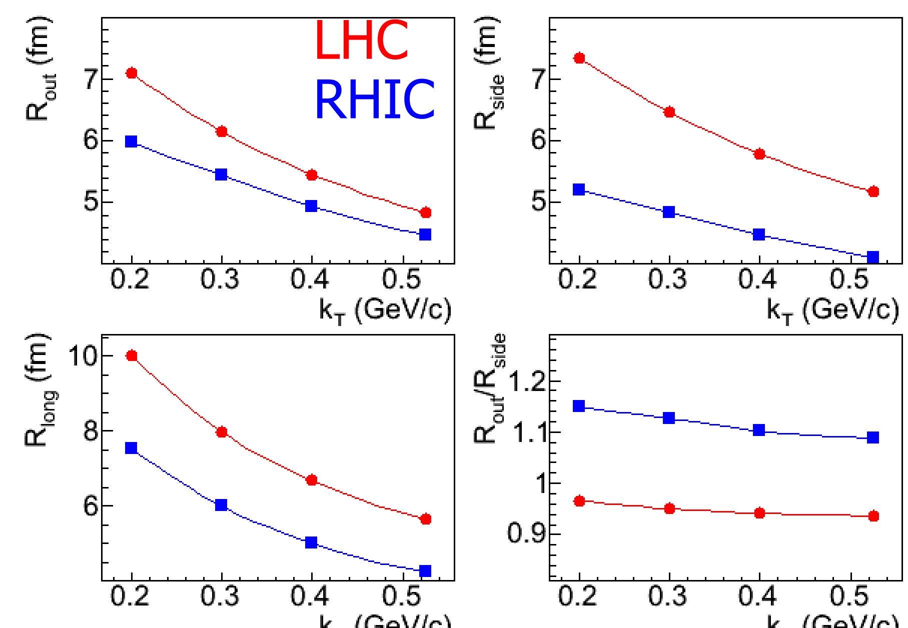
Expectations for the LHC

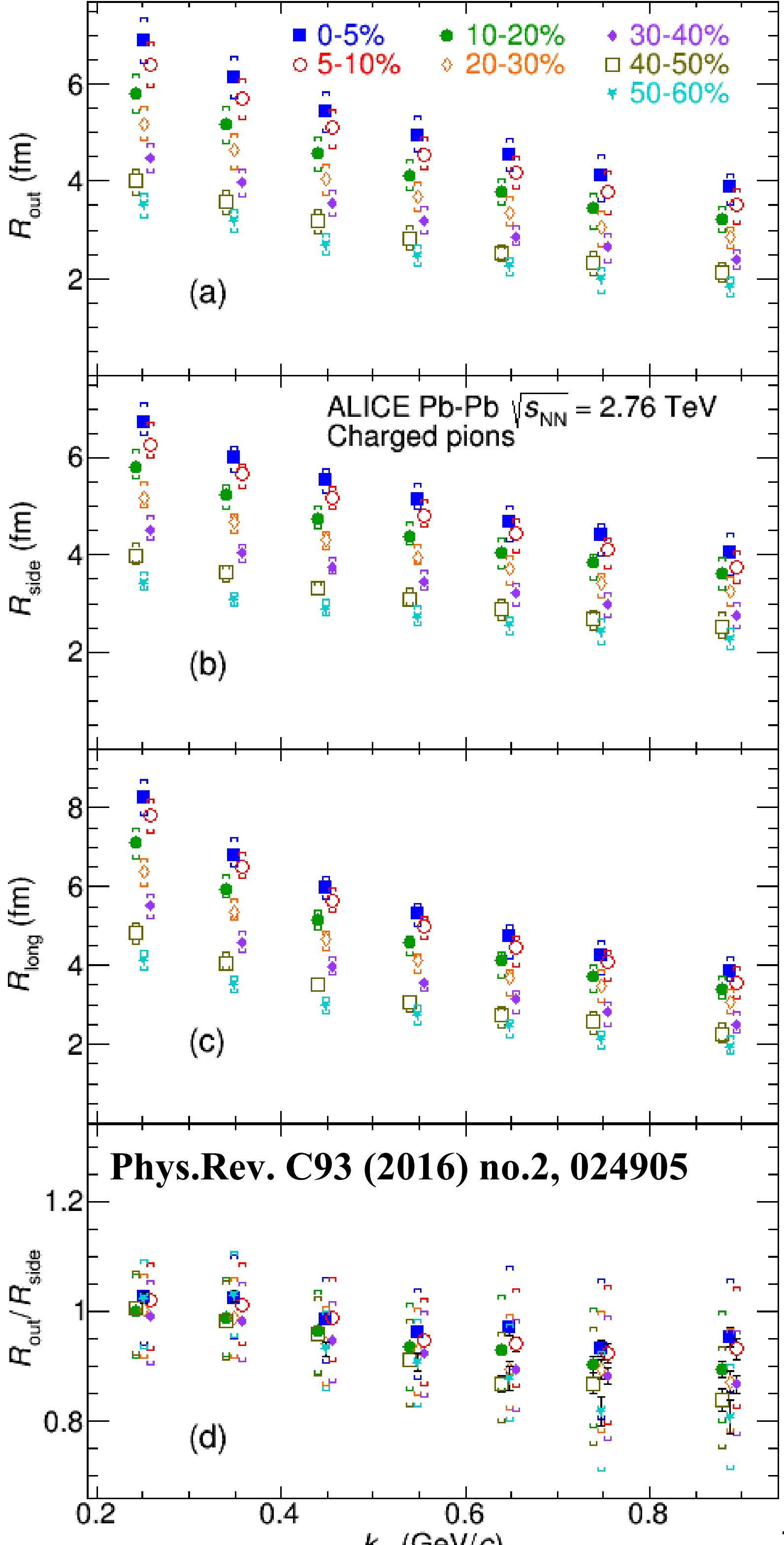
- Lessons from RHIC:
  - "Pre-thermal flow": strong flows already at $\tau_0 = 1$ fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important

- Extrapolating to the LHC:
  - Longer evolution gives larger system → all of the 3D radii grow
  - Stronger radial flow → steeper k_T radii dependence
  - Change of freeze-out shape → lower R_{out}/R_{side} ratio



AK, W. Broniowski, W. Florkowski, et al. Phys.Rev.C79:014902,2009

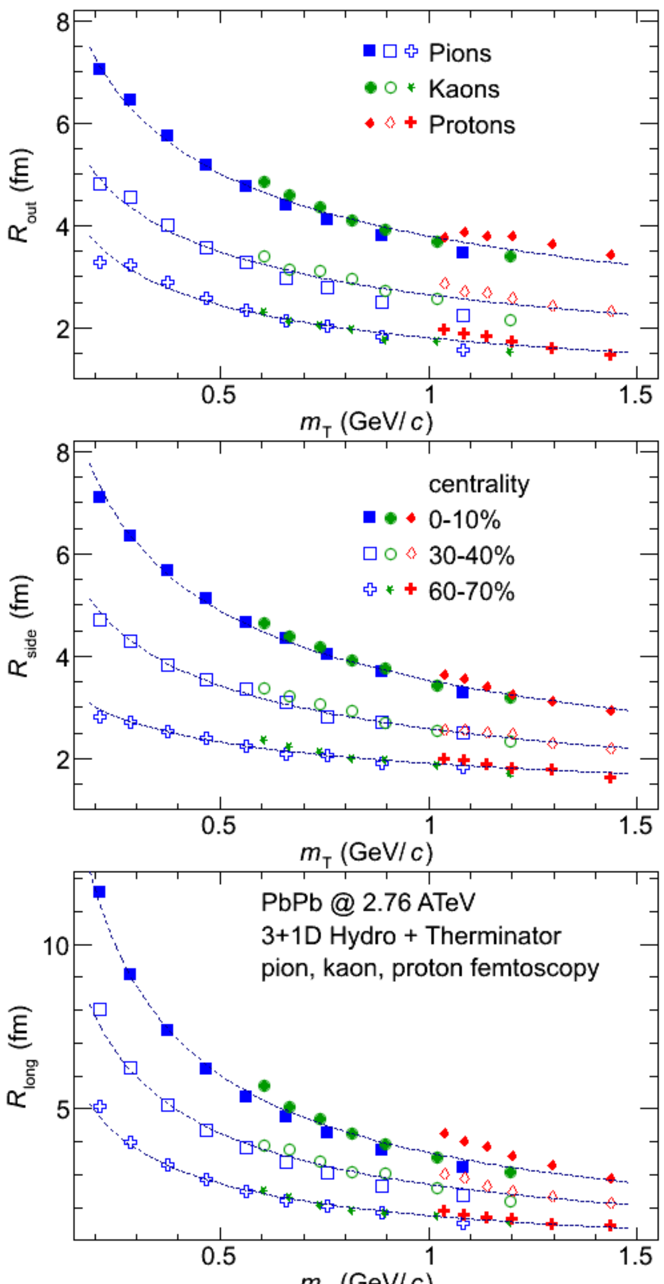




ALICE Data on radii vs. centrality and k_T

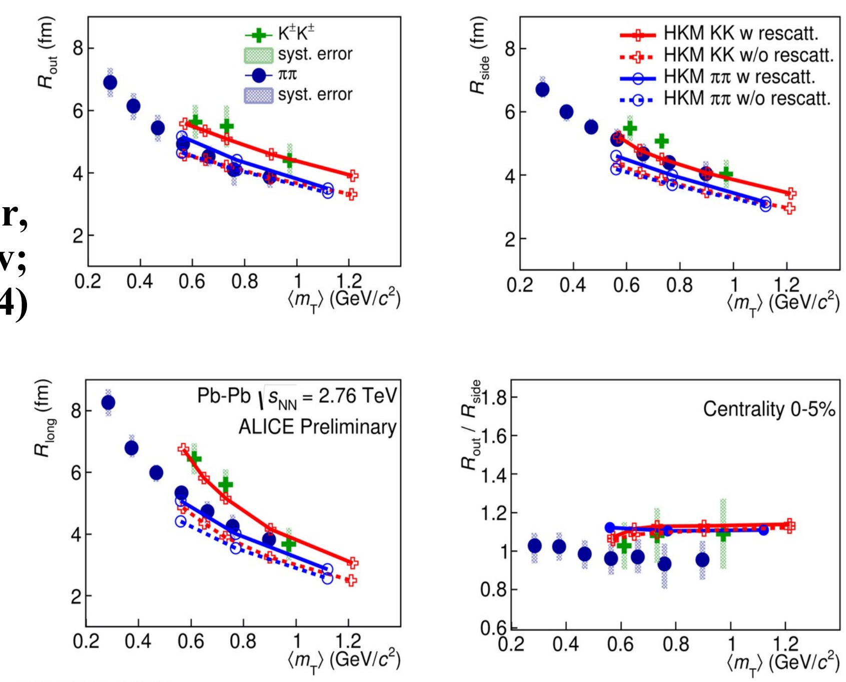
- Femtoscopic radii vs. k_T for 7 centrality classes in central rapidity region
- Radii universally grow with event multiplicity and fall with pair momentum
- Both dependencies in agreement with calculations from collective models (hydrodynamics), both quantitatively and qualitatively
- When compared to results from RHIC – all expected trends visible (larger size, steeper k_T dependence, R_{out}/R_{side}~1)

m_T scaling for heavier particles



- "Collective" flow should apply to all particles
  - Ideal 1D hydro → m_T scaling for all particles
  - "Real" 3+1D hydro + viscosity (no rescattering) → approximate scaling in LCMS
  - "Hydro" + rescattering → breaking of scaling

M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; Nucl.Phys. A 929 (2014)

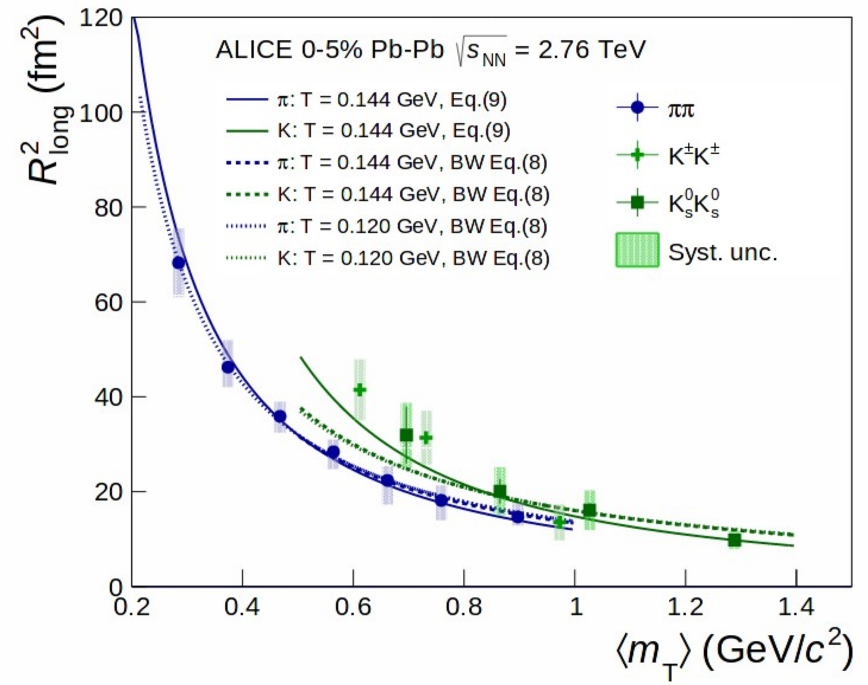


AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

Emission delay in pion and kaon data

- ALICE kaon data in hydro-based parameterization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance (**not included** in blast-wave or Therminator 2 or hydro)

ALICE, Phys.Rev. C96 (2017) no.6,



method	T (GeV)	α_π	α_K	τ_π (fm/c)	τ_K (fm/c)
fit with BW Eq. (8)	0.120	-	-	9.6 ± 0.2	10.6 ± 0.1
fit with BW Eq. (8)	0.144	-	-	8.8 ± 0.2	9.5 ± 0.1
fit with Eq. (9)	0.144	5.0	2.2	9.3 ± 0.2	11.0 ± 0.1
fit with Eq. (9)	0.144	4.3 ± 2.3	1.6 ± 0.7	9.5 ± 0.2	11.6 ± 0.1

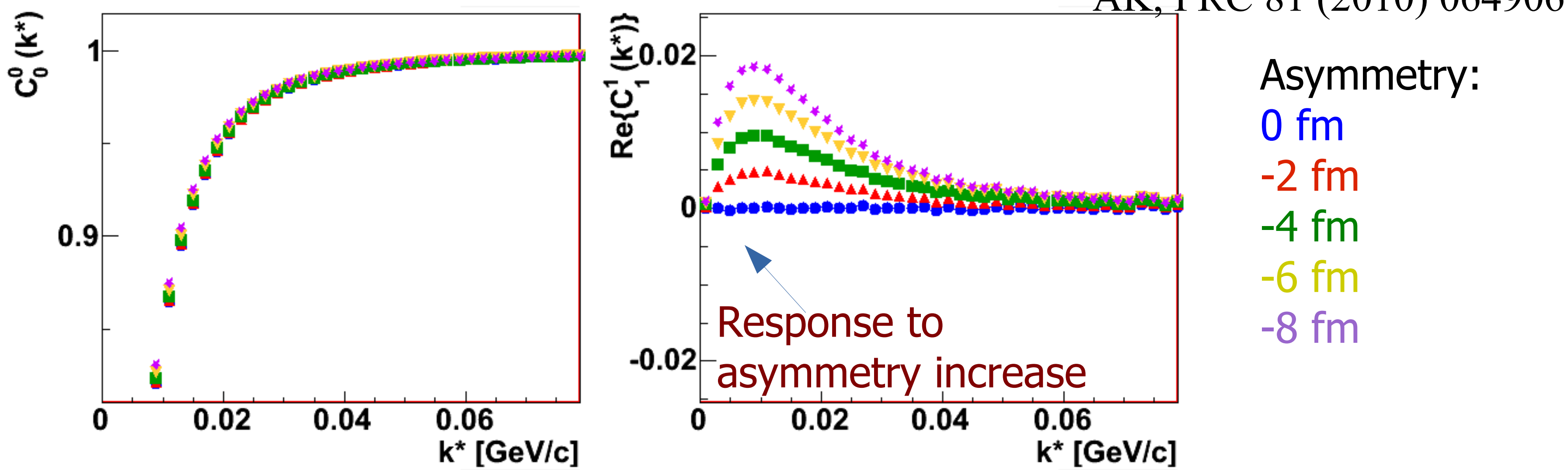
Table 4: Emission times for pions and kaons extracted using the Blast-wave formula Eq. (8) and the analytical formula Eq. (9).

V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; **Nucl.Phys. A929 (2014) 1-8**

Asymmetry via non-identical correlations

$$\Re\{C_1^1\} \sim \int C(\phi, \cos(\theta)) \cos(\phi) \, d\phi \, d\cos(\theta)$$

AK, PRC 81 (2010) 064906



- The non-identical particle femtoscopy sensitive to the emission asymmetry between non-identical particle types
- Measurement sensitive to the difference of the spatial and time asymmetries, not possible to distinguish between them

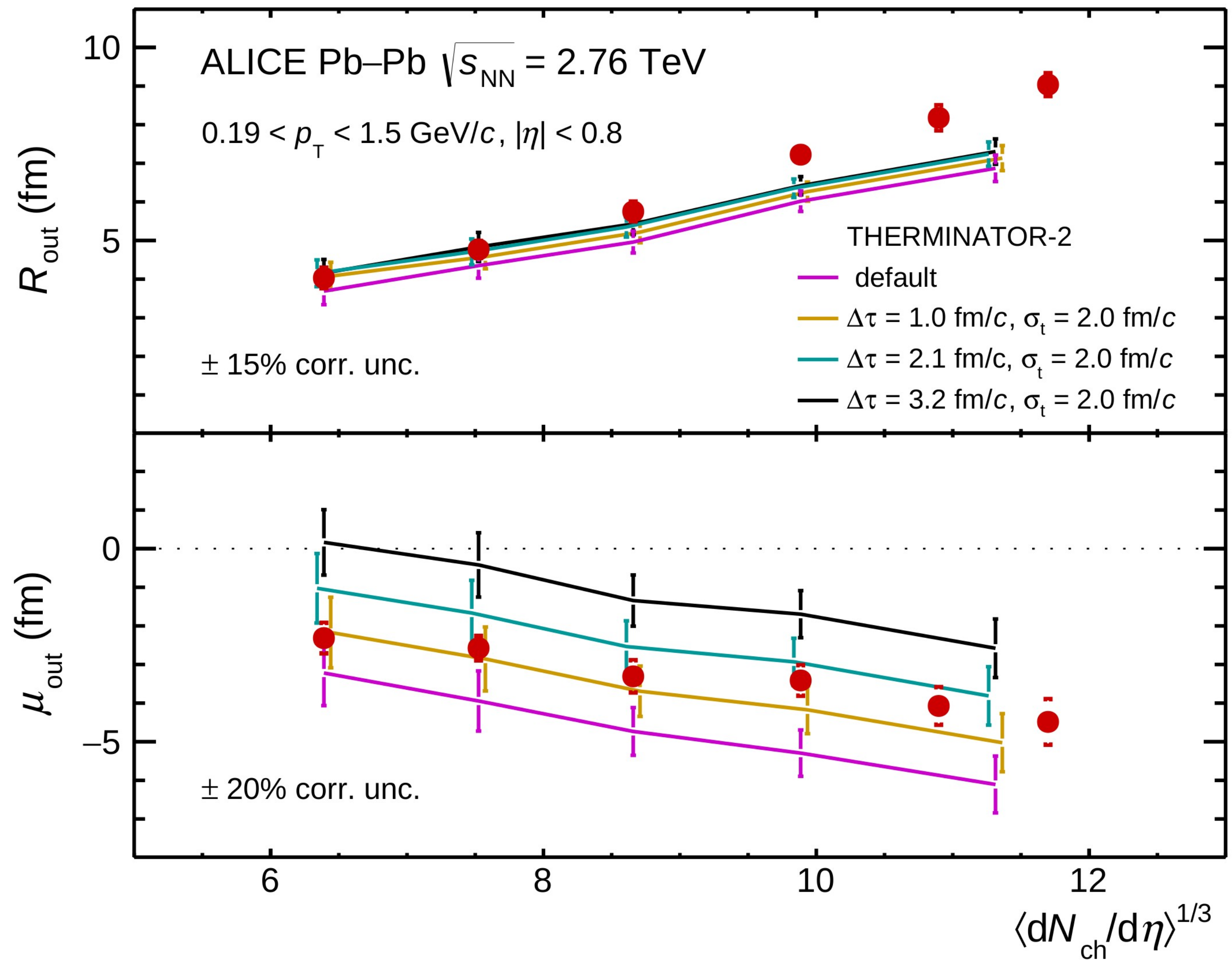
$$\mu_{out} = \langle r^*_{out} \rangle = \langle \gamma r_{out} - \beta \gamma \Delta t \rangle$$

- "Spatial" asymmetry r_{out} in flowing medium, difficult to produce otherwise
- "Time" asymmetry Δt from various origins, some not connected to flow

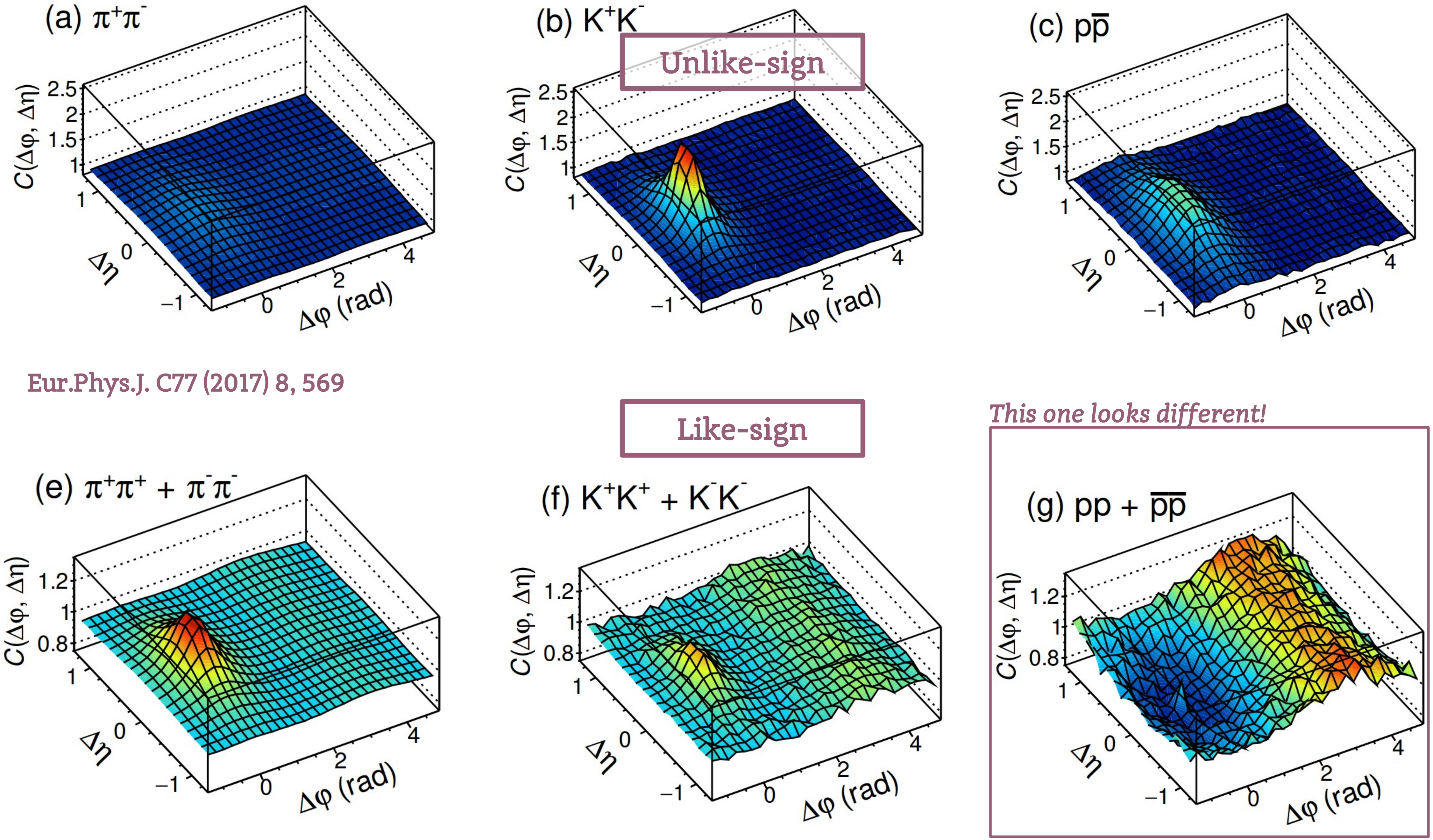
Measuring rescattering phase duration

- ALICE has published first pion-kaon results from LHC
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry from "default" hydro case larger than in data
- Asymmetry with additional 2.1 fm/c kaon delay consistent with data: internal consistency with identical kaon femtoscopy

ALICE; Phys.Lett.B 813 (2021) 136030; arXiv: 2007.08315 [nucl-ex]



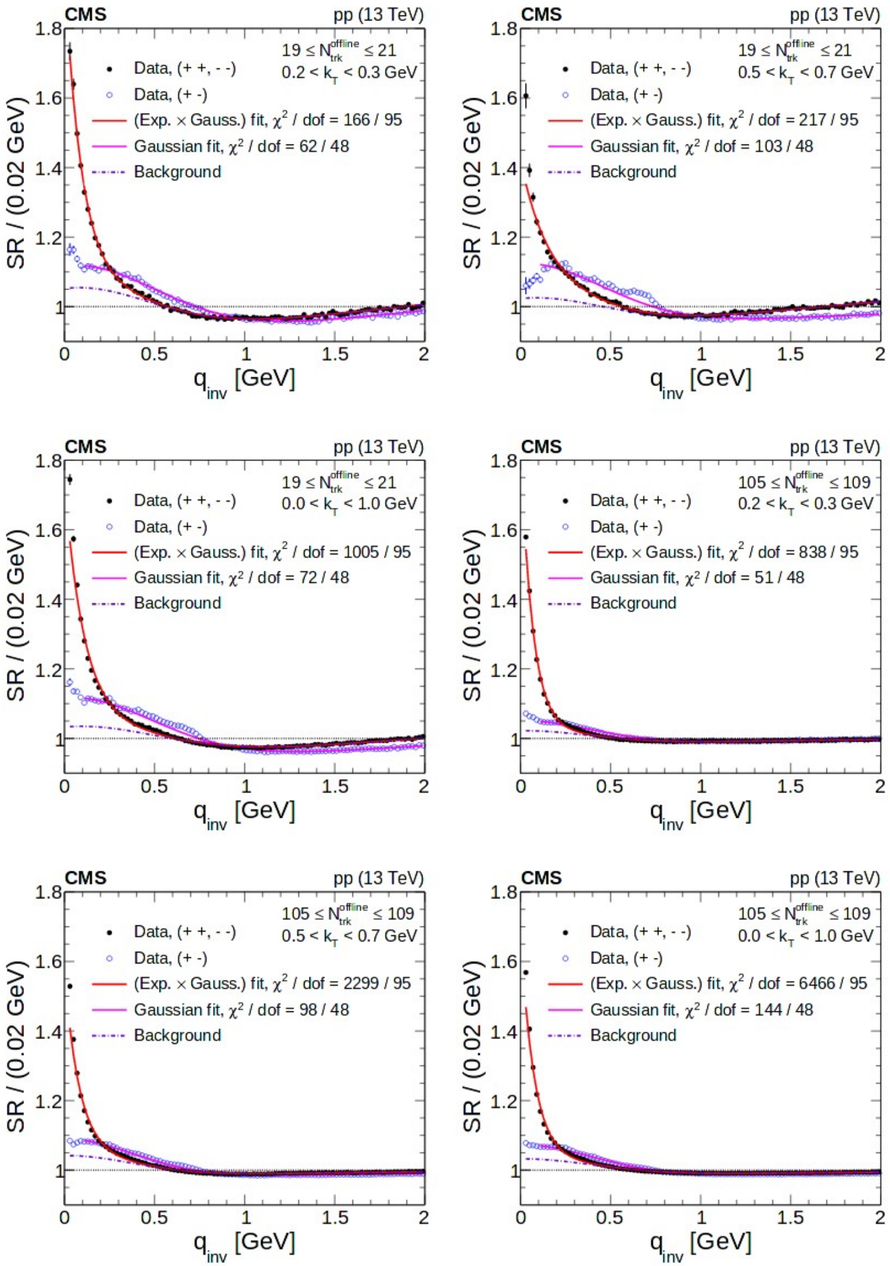
Small systems and mini-jet background



Eur.Phys.J. C77 (2017) 8, 569

Measuring size in 1D at LHC

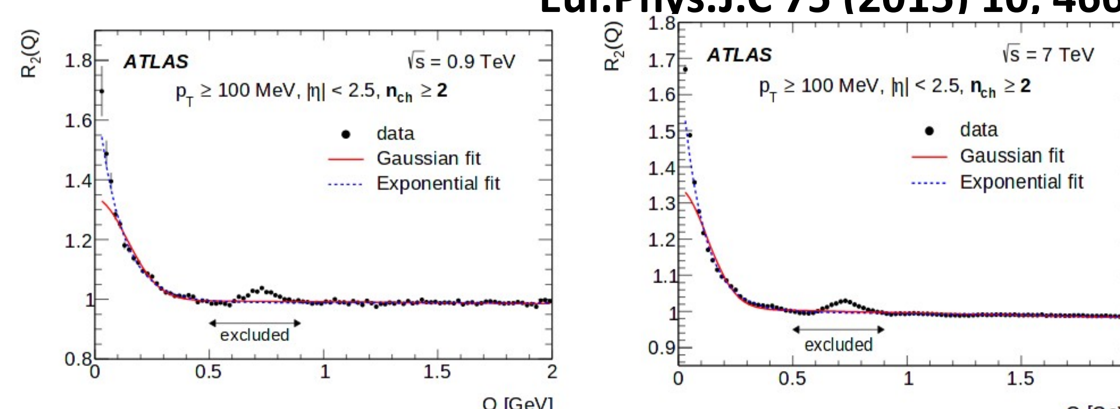
JHEP 03 (2020) 014



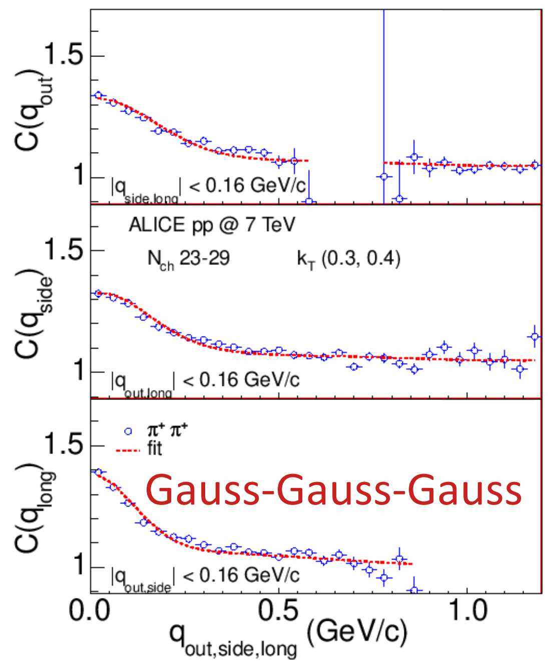
$$C(q) = \lambda[1 + \exp(-(Rq)^{\alpha})]$$

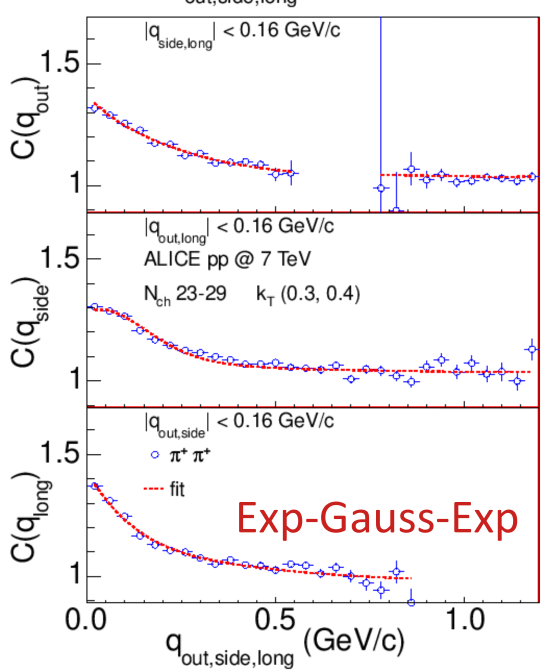
- Femto analysis in pp performed in 1D femto show non-gaussian shapes (ALICE, CMS, ATLAS, LHCb)
- Fits and radii presented for exponential form
- Background (from mini-jets) estimated based on 1D femto correlation function
- Analysis performed usually in narrow multiplicity slices, but only in 1D, integrated over transverse momentum, often in wide rapidity range

Eur.Phys.J.C 75 (2015) 10, 466



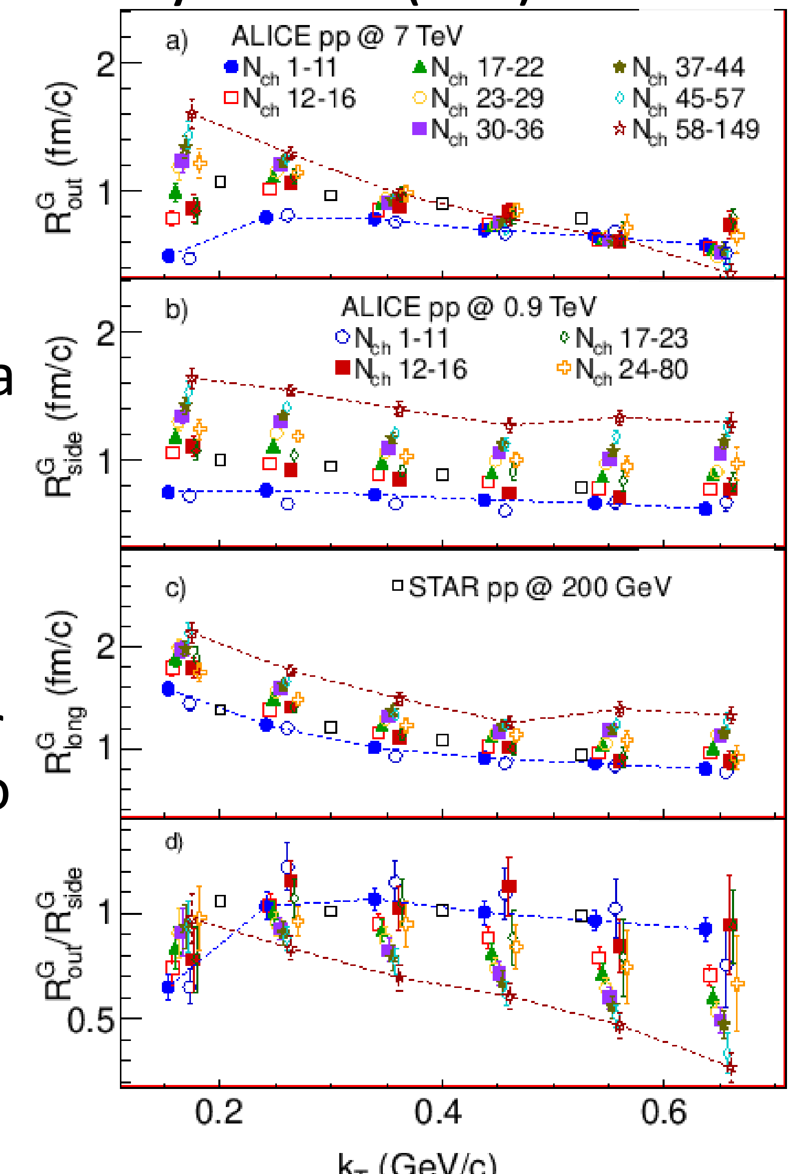
Full 3D analysis in pp collisions



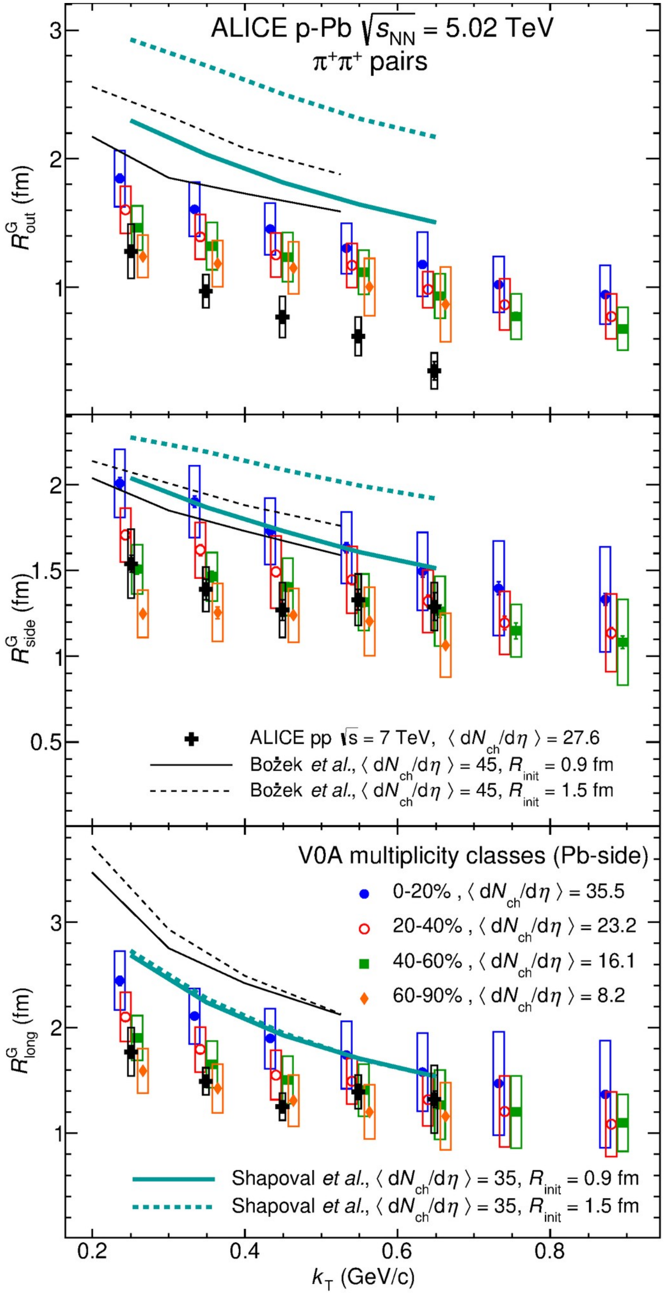


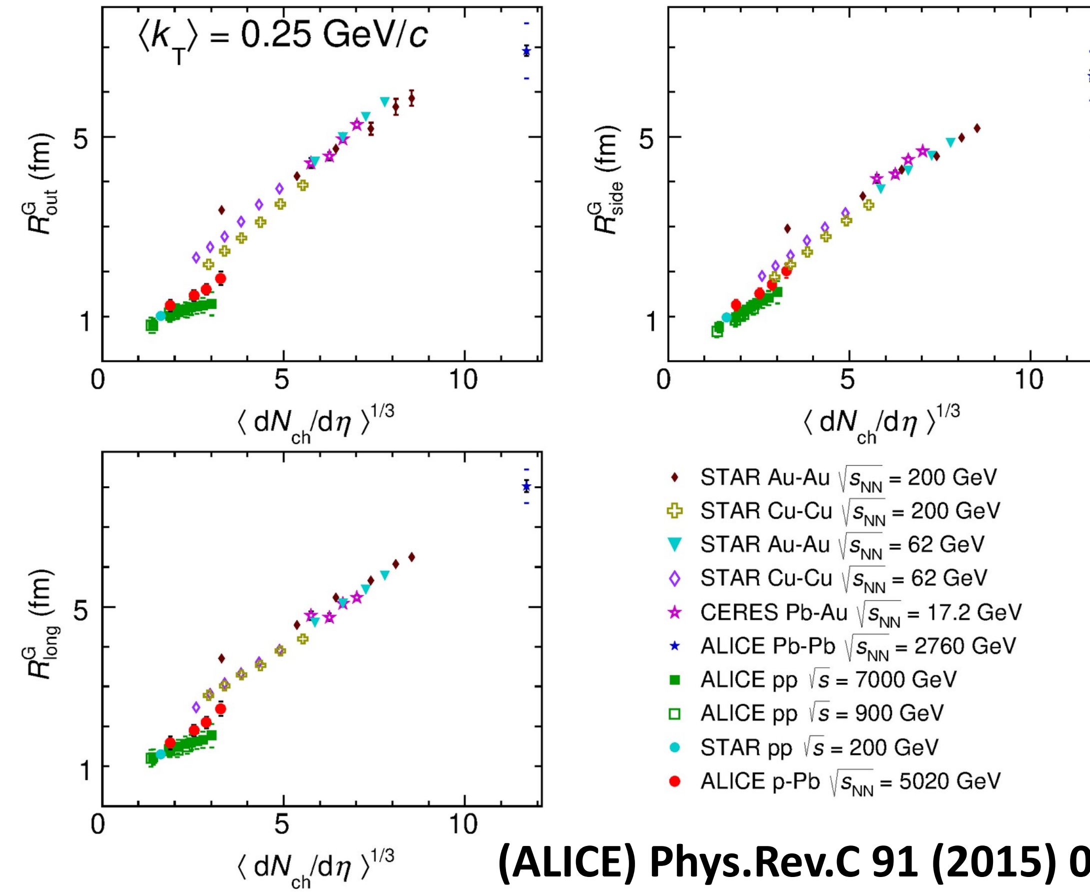
- ALICE measured pion source in pp collisions with extreme precision vs. collision energy*, multiplicity, pair transverse momentum in **3D**
- Source is reasonably gaussian in 3D, although the best fit is provided by a fit exponential in out and long (directions where pair velocity is non-zero) and Gaussian in side
- Extremely rich physics in **3D radii** dependence on multiplicity and pair momentum, not fully explored up to now
- No theoretical understanding of the source size behaviour, especially at low multiplicity
- 3D analysis also in CMS

Phys.Rev.D 84 (2011) 112004



Transition from small to large: p-Pb collisions



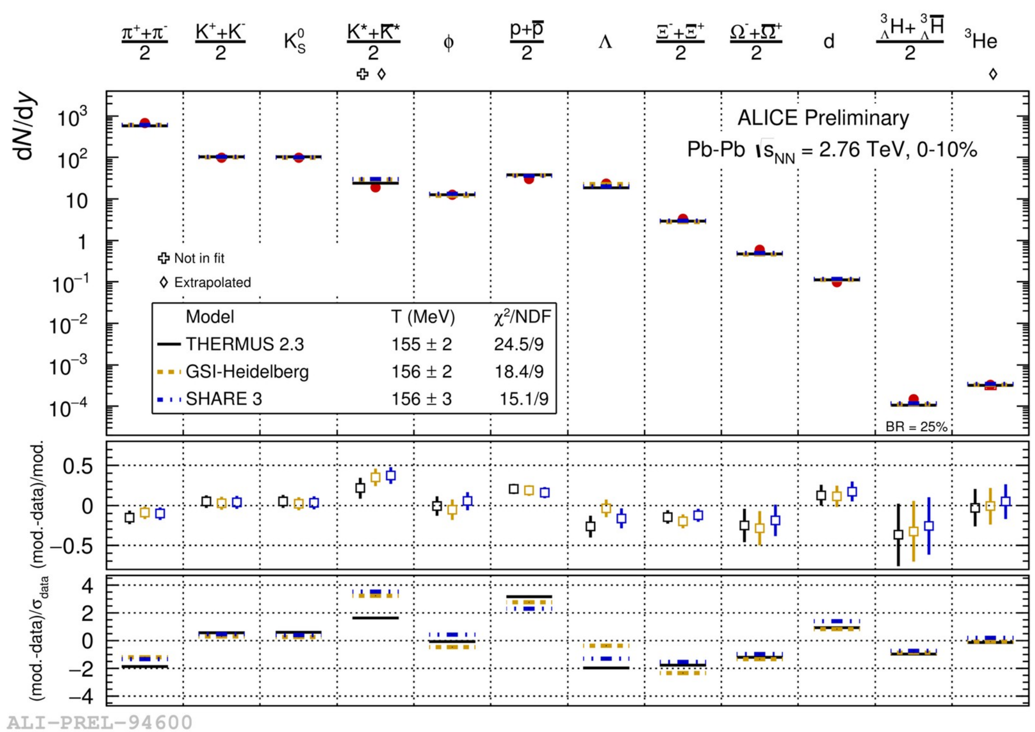


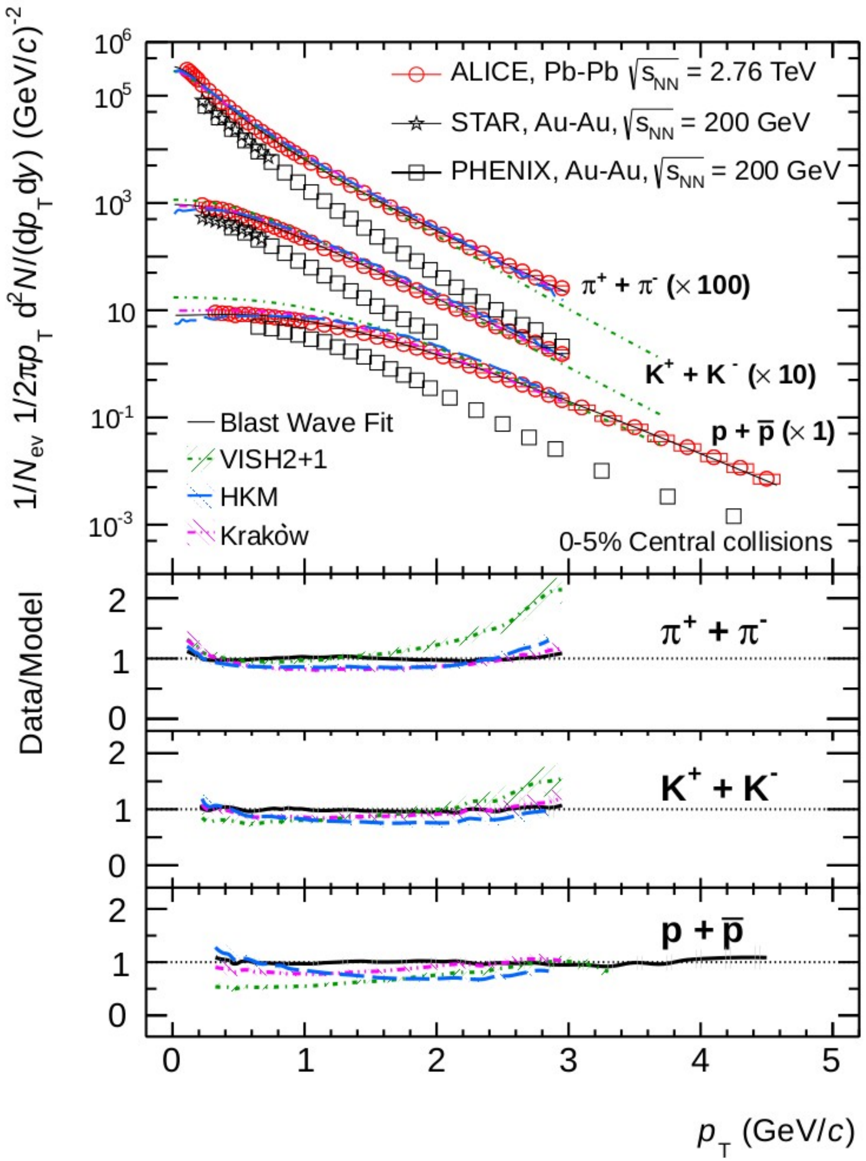
(ALICE) Phys.Rev.C 91 (2015) 034906

- Pion 3D data in p-Pb not fully described by hydro – question about collectivity in „intermediate" system
- Dependencies similar to pp at small multiplicity
- p-Pb a transition from small to large system

(Anti-)Baryon production in HIC

- Similar no. of baryons and anti-baryons produced at RHIC and LHC, at low-p_T, PID needed (STAR, ALICE)
- HIC are matter-antimatter pair factories (p, Λ, Ξ, Ω, ...)



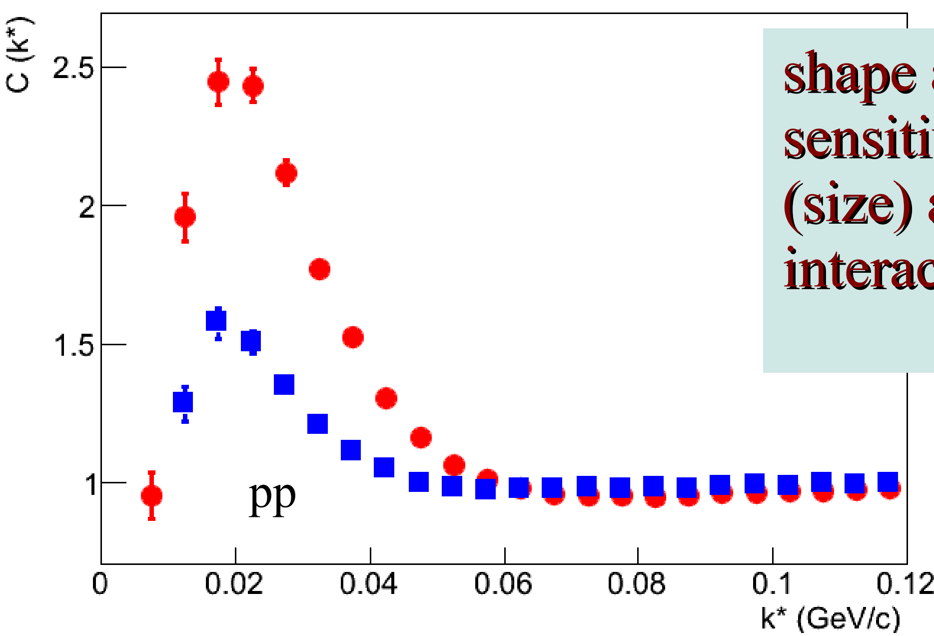


Baryon femtoscopy

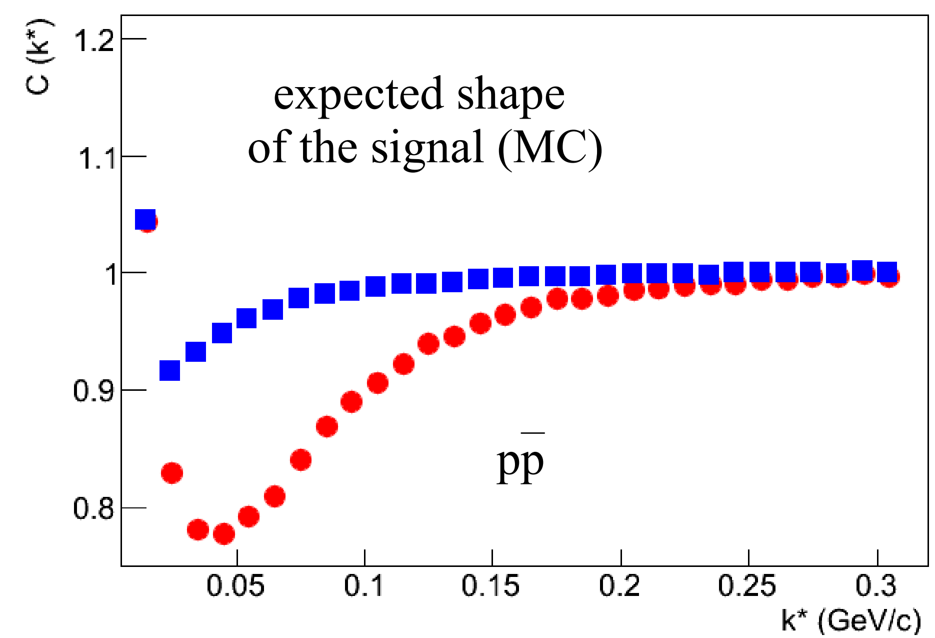
- Femtoscopy: use two-particle correlation function C and known interaction Ψ to extract information on the source emission function S

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

measured correlation — emission function (radius) — cross-section



shape and magnitude sensitive to source shape (size) and two-particle interaction (cross-section)



- The procedure can be reversed: study Ψ with known S

Lednicky&Lyuboshitz formula

- For the case of pure strong interaction, the integral equation for C performed analytically for a Gaussian source S:

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

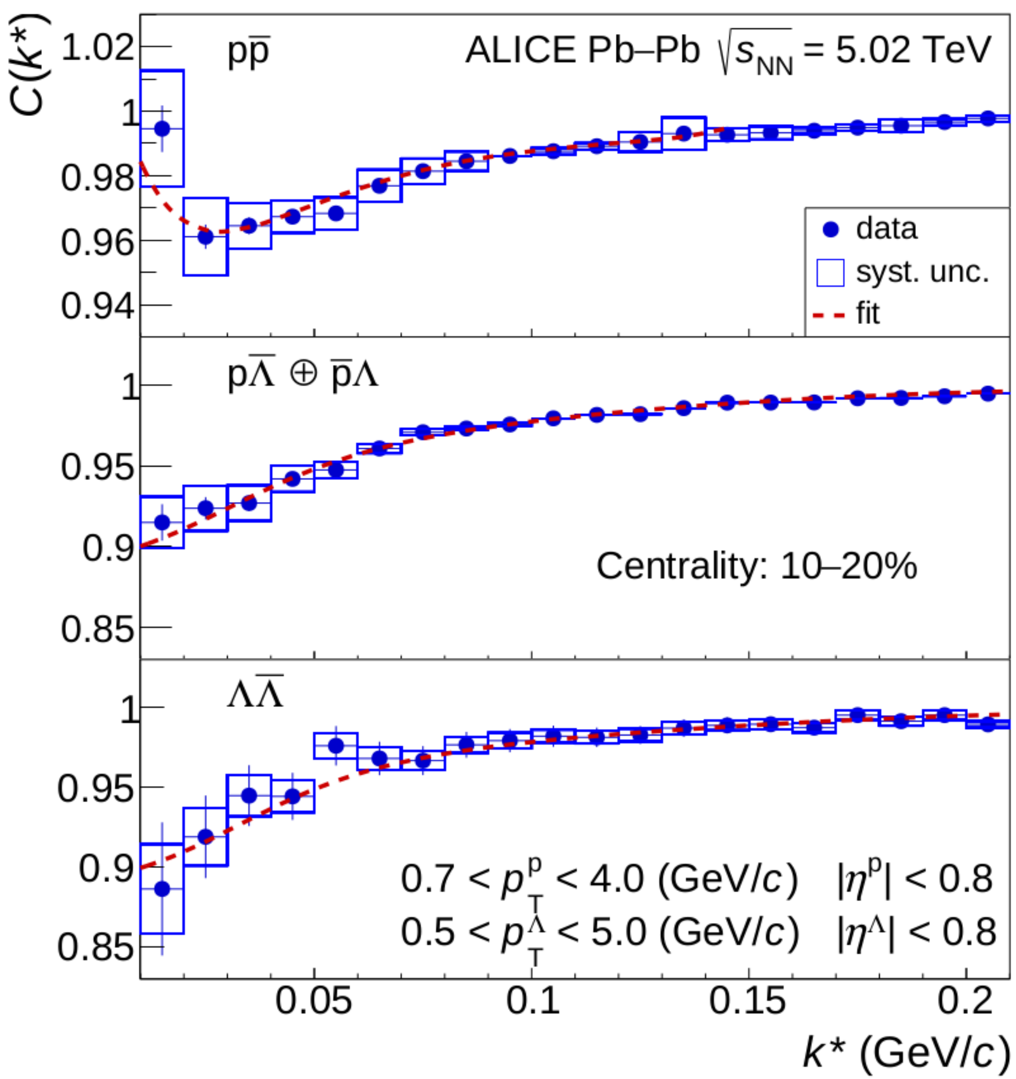
  where ρ_S are the pair spin fractions, F_1 and F_2 are known functions, R is the Gaussian source width (variance)

- Scattering length f_0 and effective range d_0 appear directly in the correlation function form, real and imaginary part of f have distinctly different contributions

- Not realistic to fit R and interaction parameters (f_0, d_0) simultaneously, at least one must be fixed

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

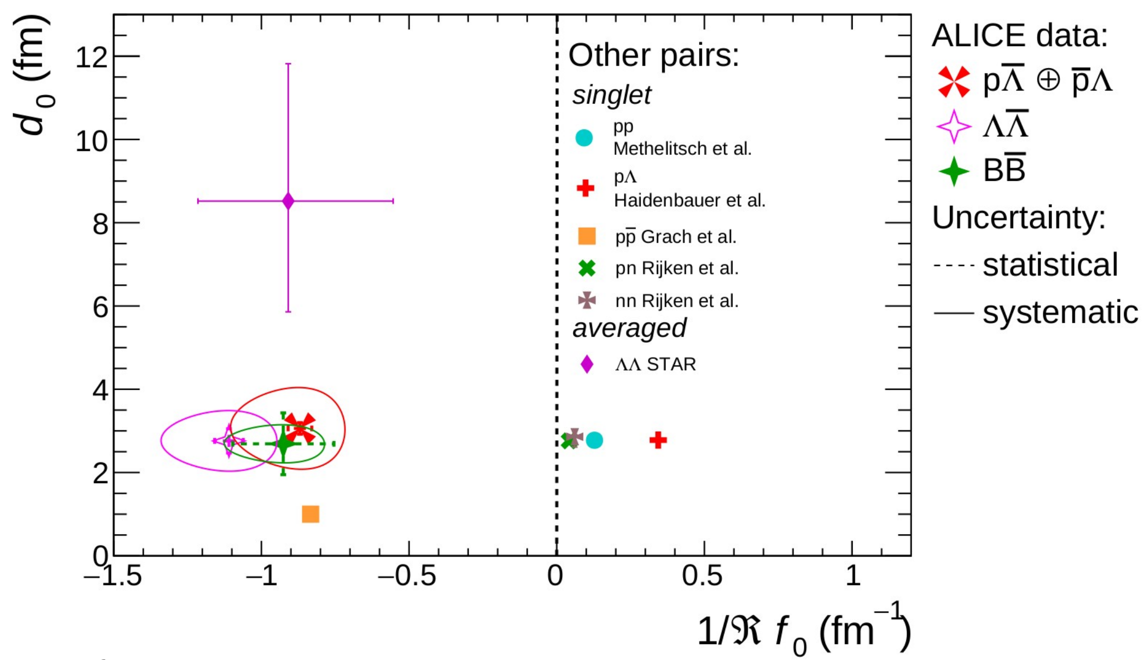
Baryon-Antibaryon in ALICE

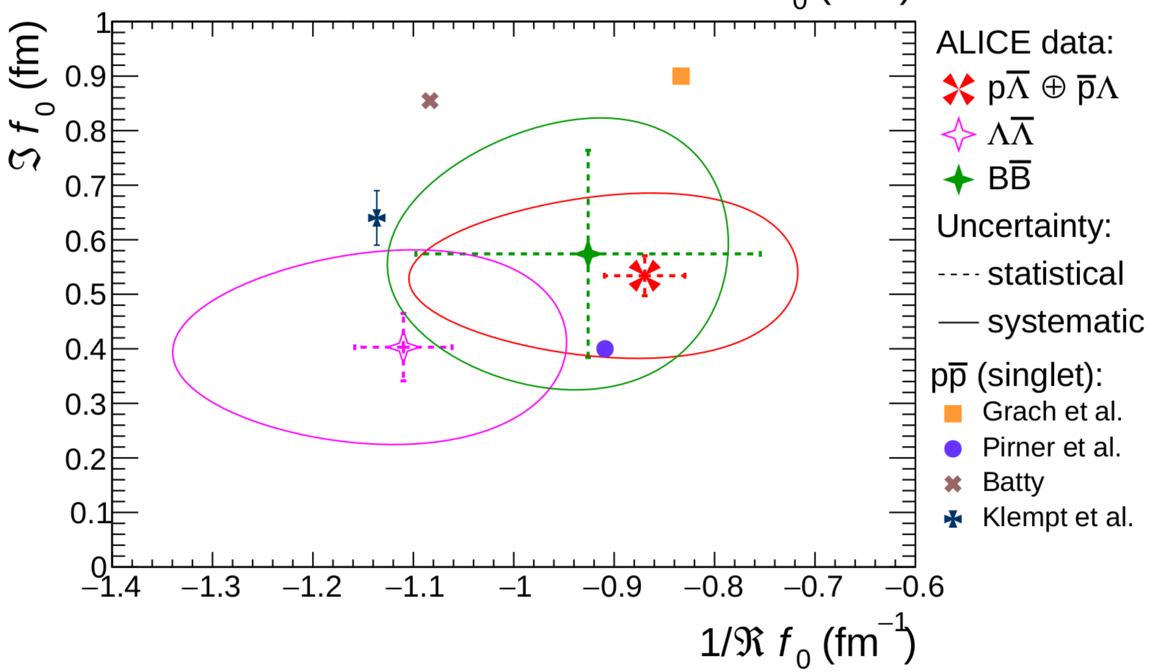


L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017
ALICE, arXiv: 1903.06149, Phys.Lett.B 802 (2020) 135223

- All combinations of baryon-antibaryon correlation functions with pairs containing protons and lambdas
- Fit fully including the web of residual correlations
- Combined fit to 6 centralities x 2 collision energies x 3 systems
- Interaction parameters free in the fit (3 sets)
- Sizes constrained to m_T scaling predictions

Measurement of strong $B\bar{B}$ interaction

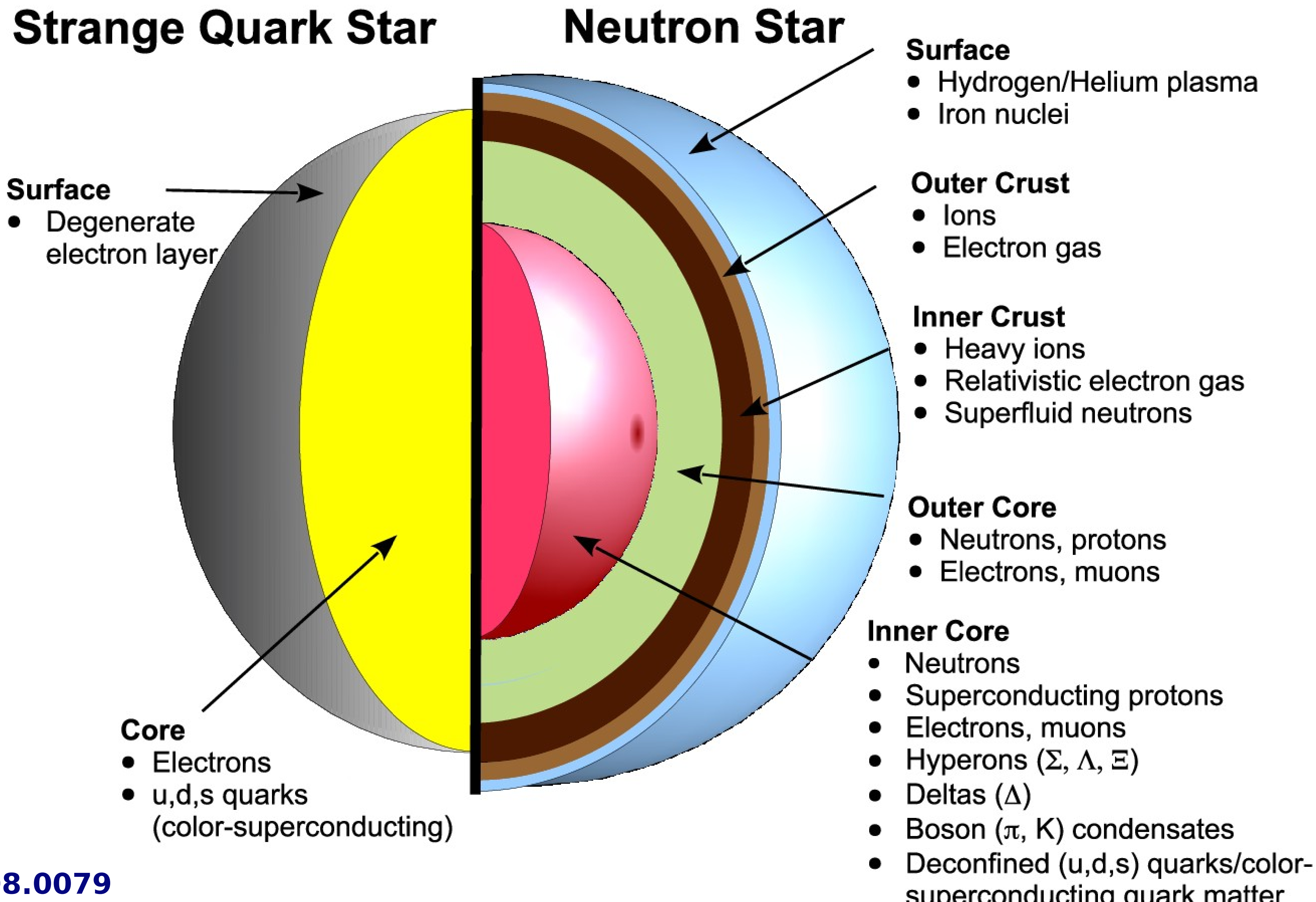




- Estimation of the scattering length and effective range
- Assumption of d_0=0 not necessary
- Non-zero negative value of the real part of f_0
- Non-zero value of imaginary part of f_0 (annihilation), comparable for all pair types

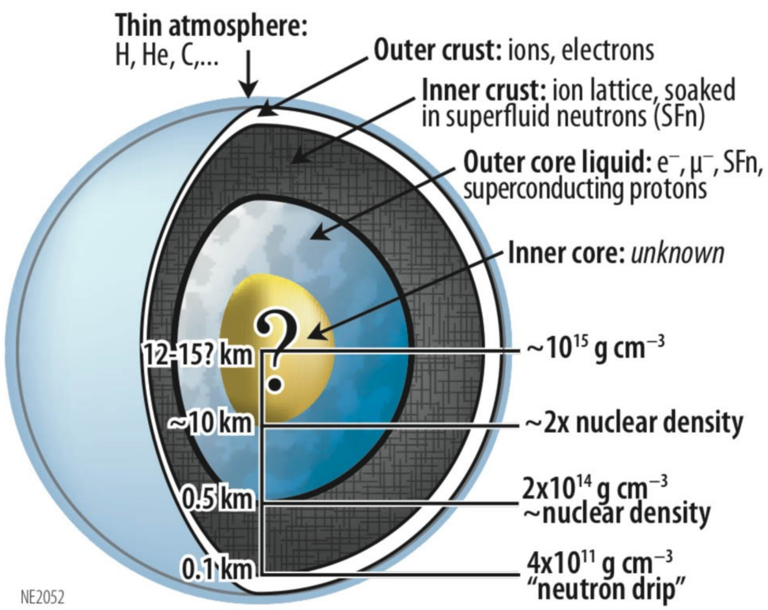
L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017
ALICE, arXiv: 1903.06149, Phys.Lett.B 802 (2020) 135223

Compact stellar objects



arXiv: 1408.0079

NICER measuring NS size

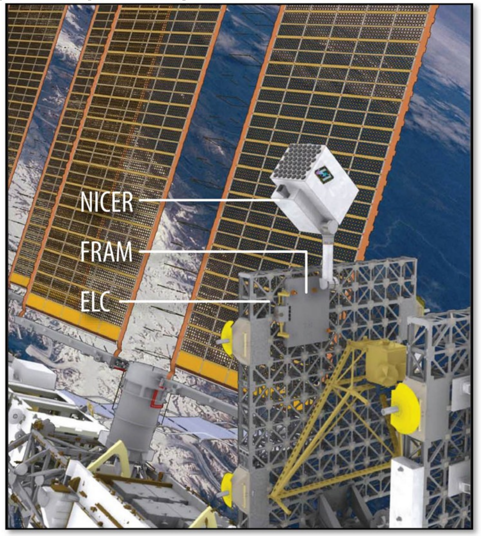


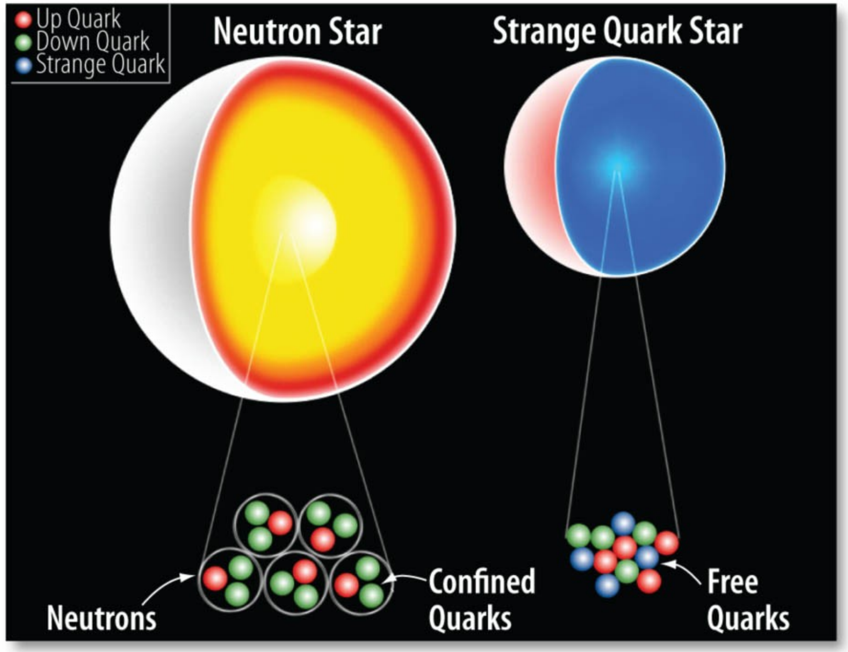
https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html

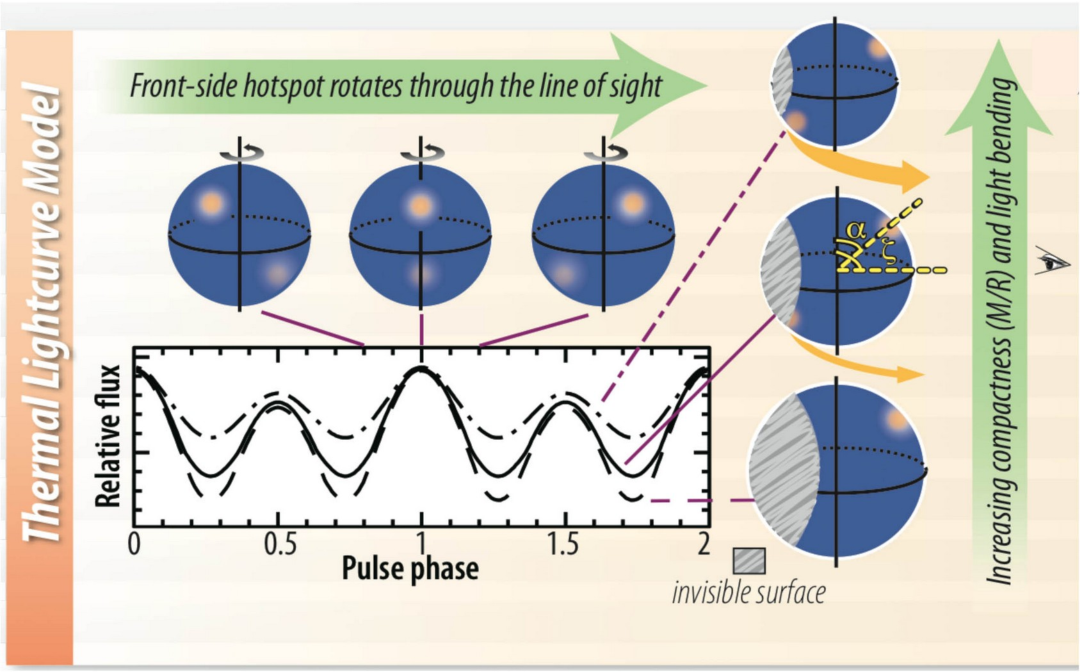
NICER mission on ISS

Signals from pulsars with precise (ns) timing

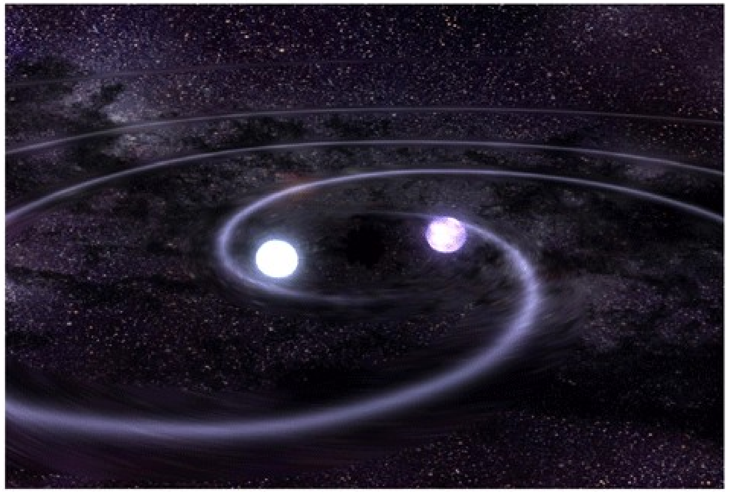
Ability to measure NS size via precise timing of hotspot pulses bent in gravitational well of NS

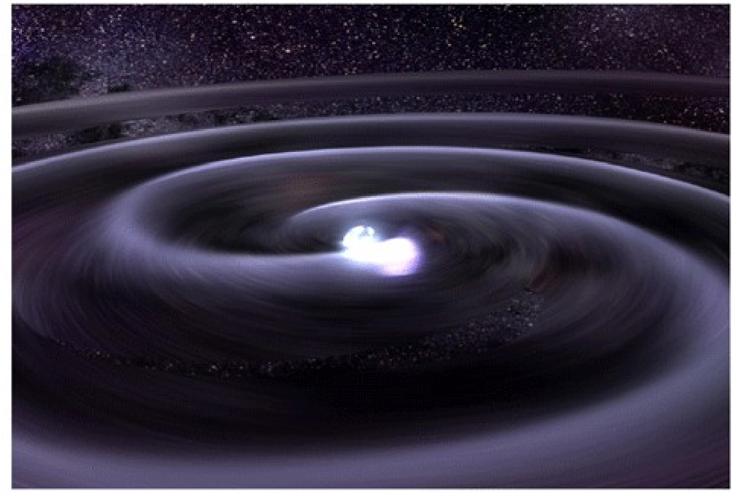


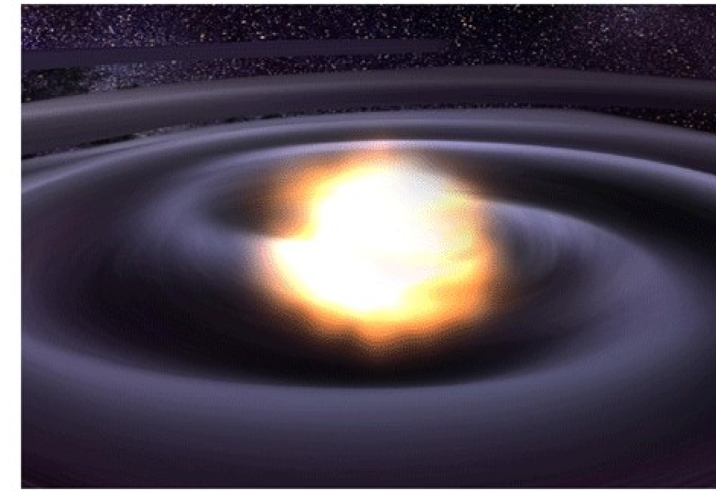


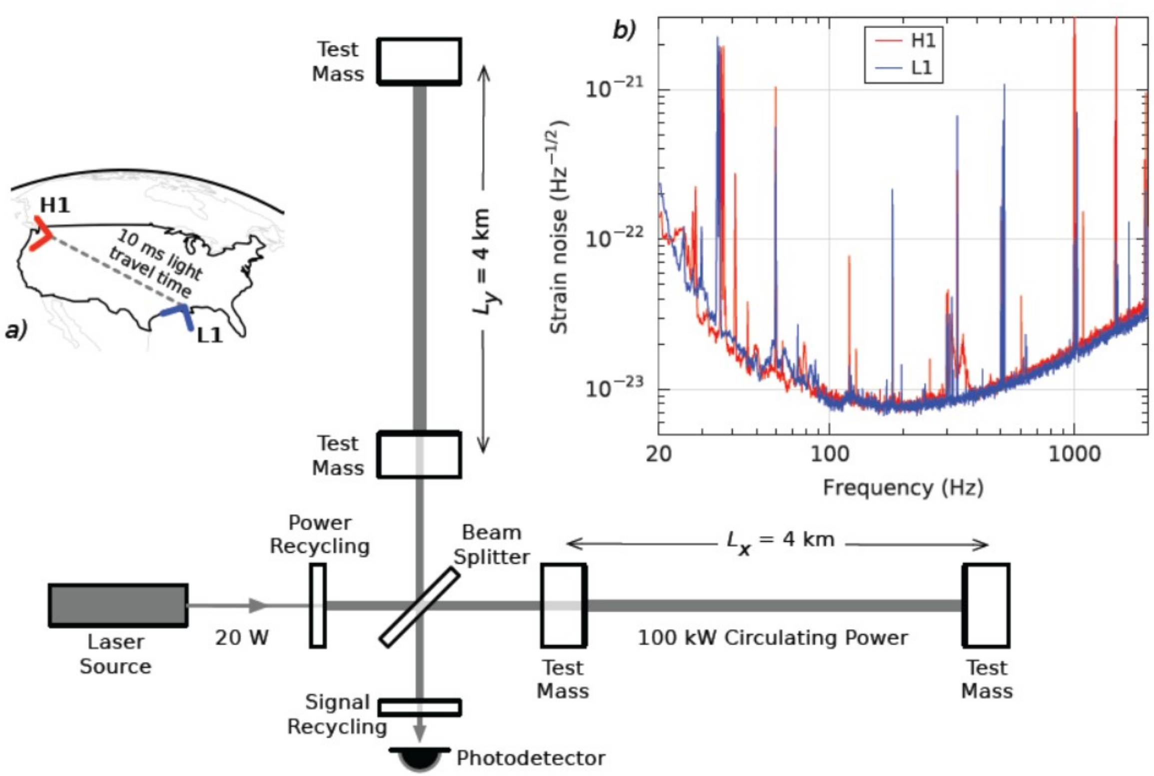


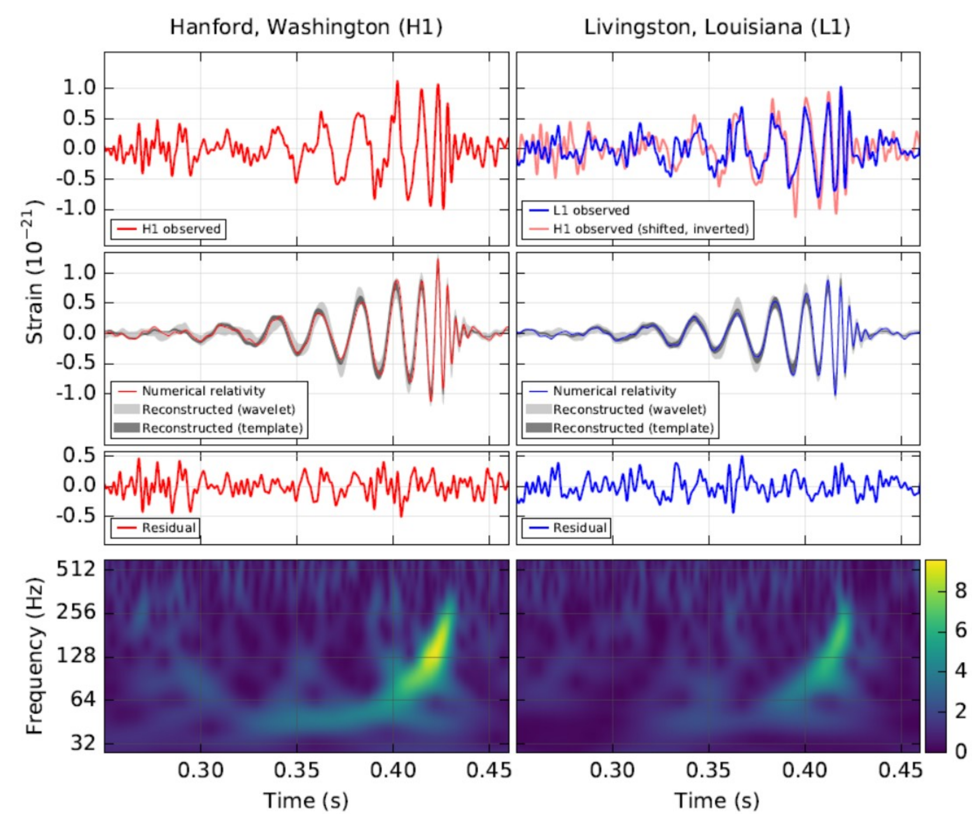
LIGO and gravitational waves





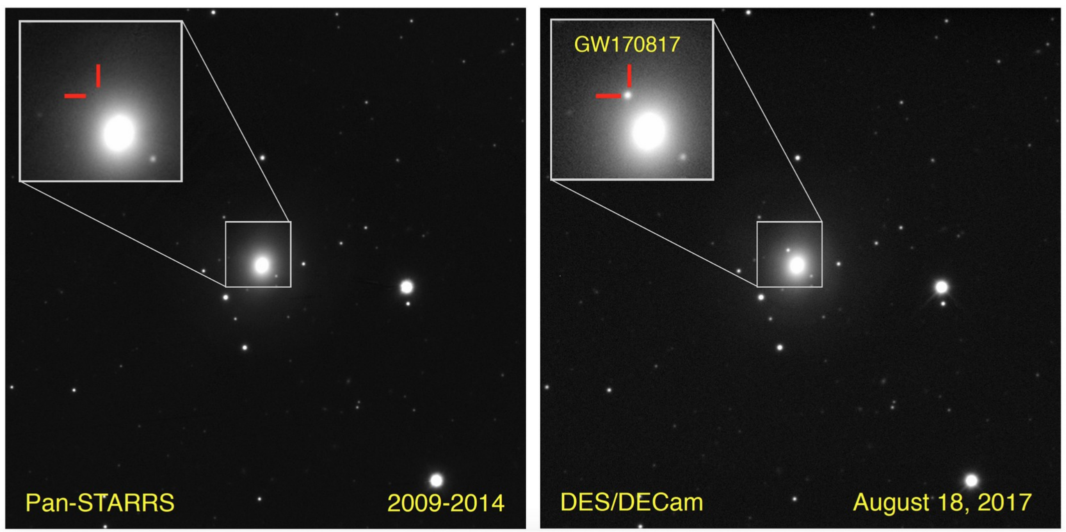


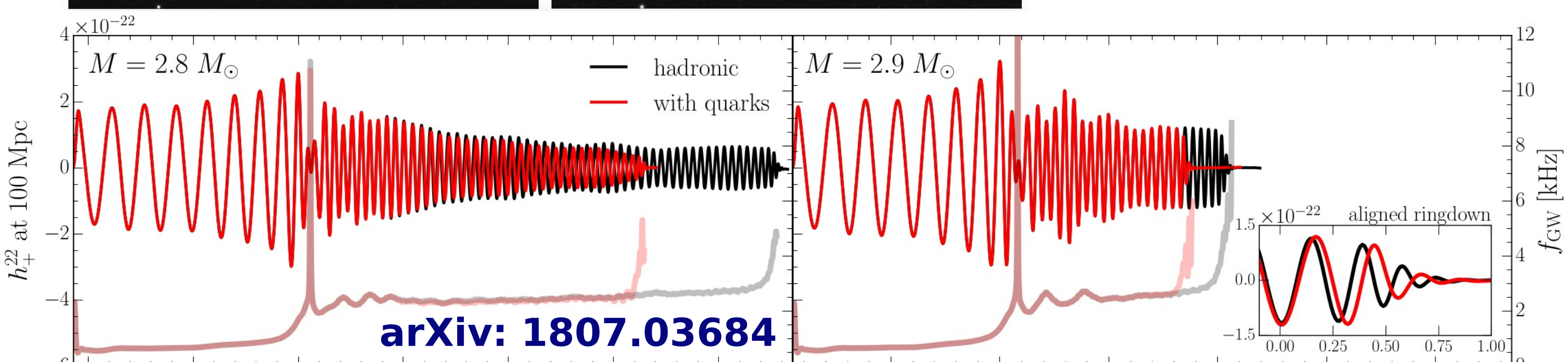


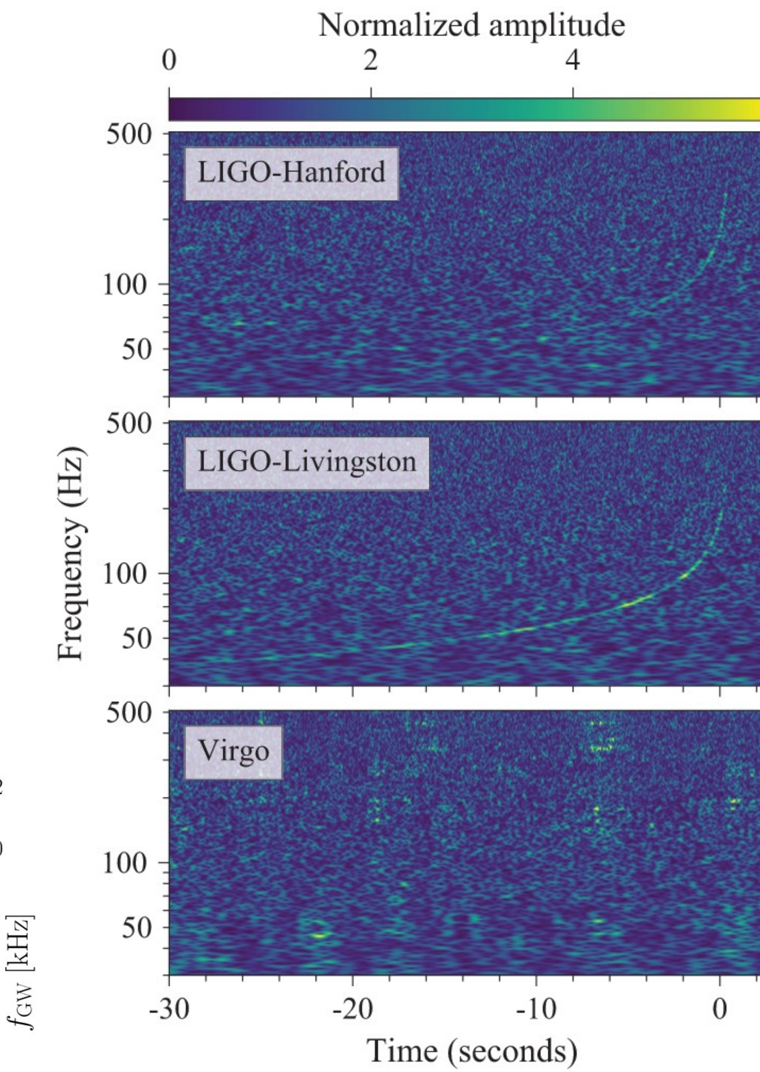


Neutron star merger

- LIGO observed NS merger GW170817 with EM counterpart – beginnig of multi-messenger astronomy
- Simulating merger with/without quarks







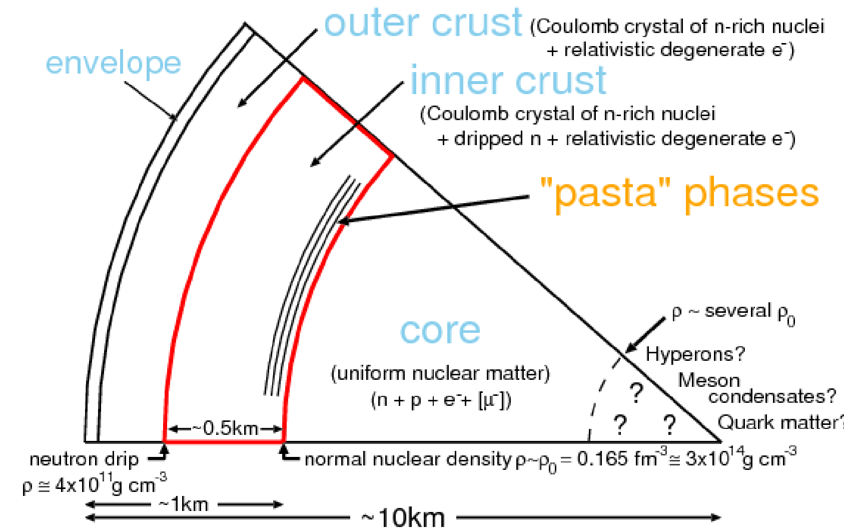
PRL 119, 161101 (2017)

Neutron star mergers

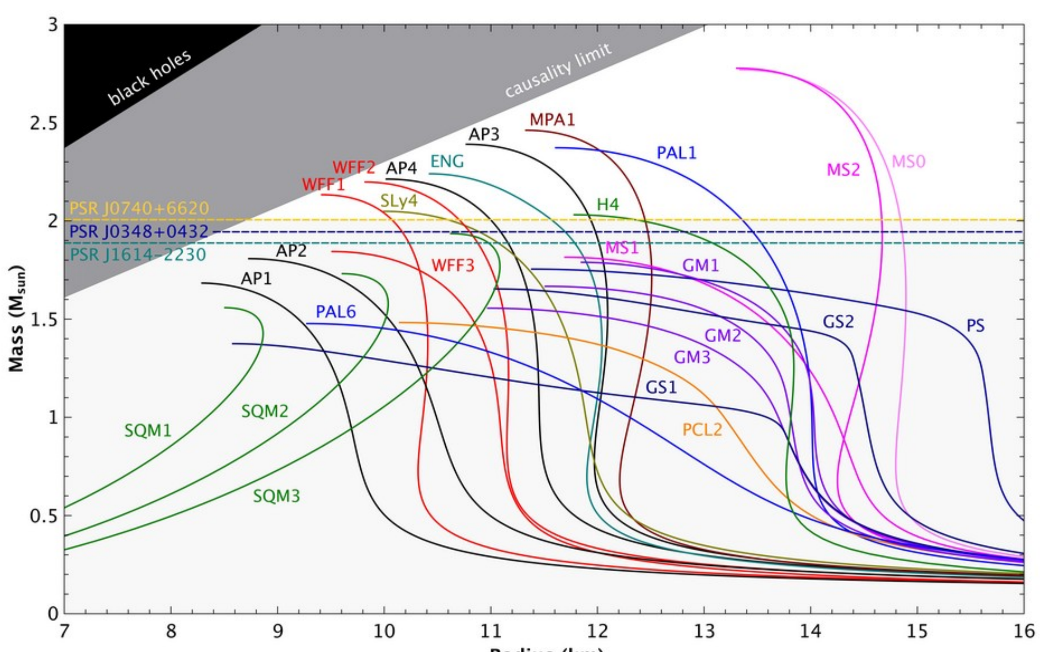
core of neutron stars reaches density several times nuclear density

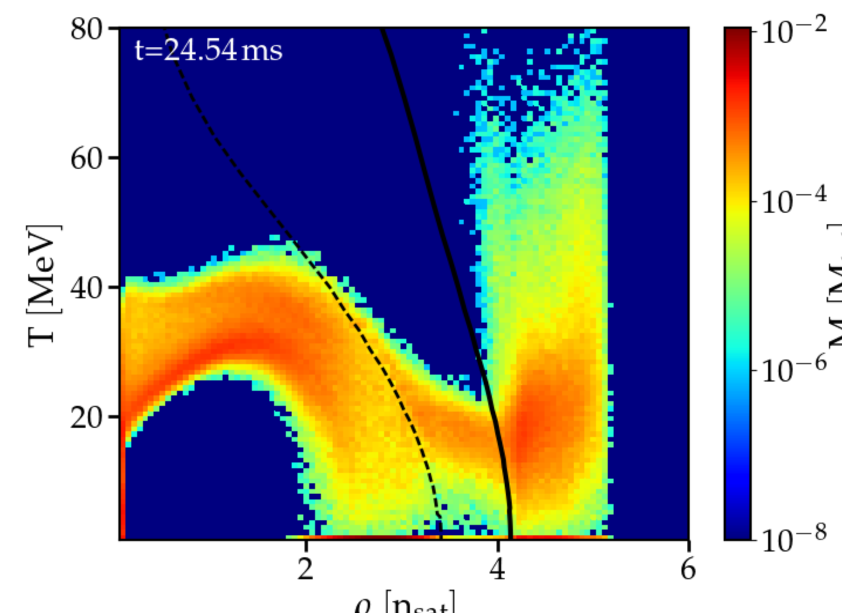
Credit: LIGO Collaboration

appearance of strangeness changes Equation-of-State, depends on strangeness-nucleon interaction

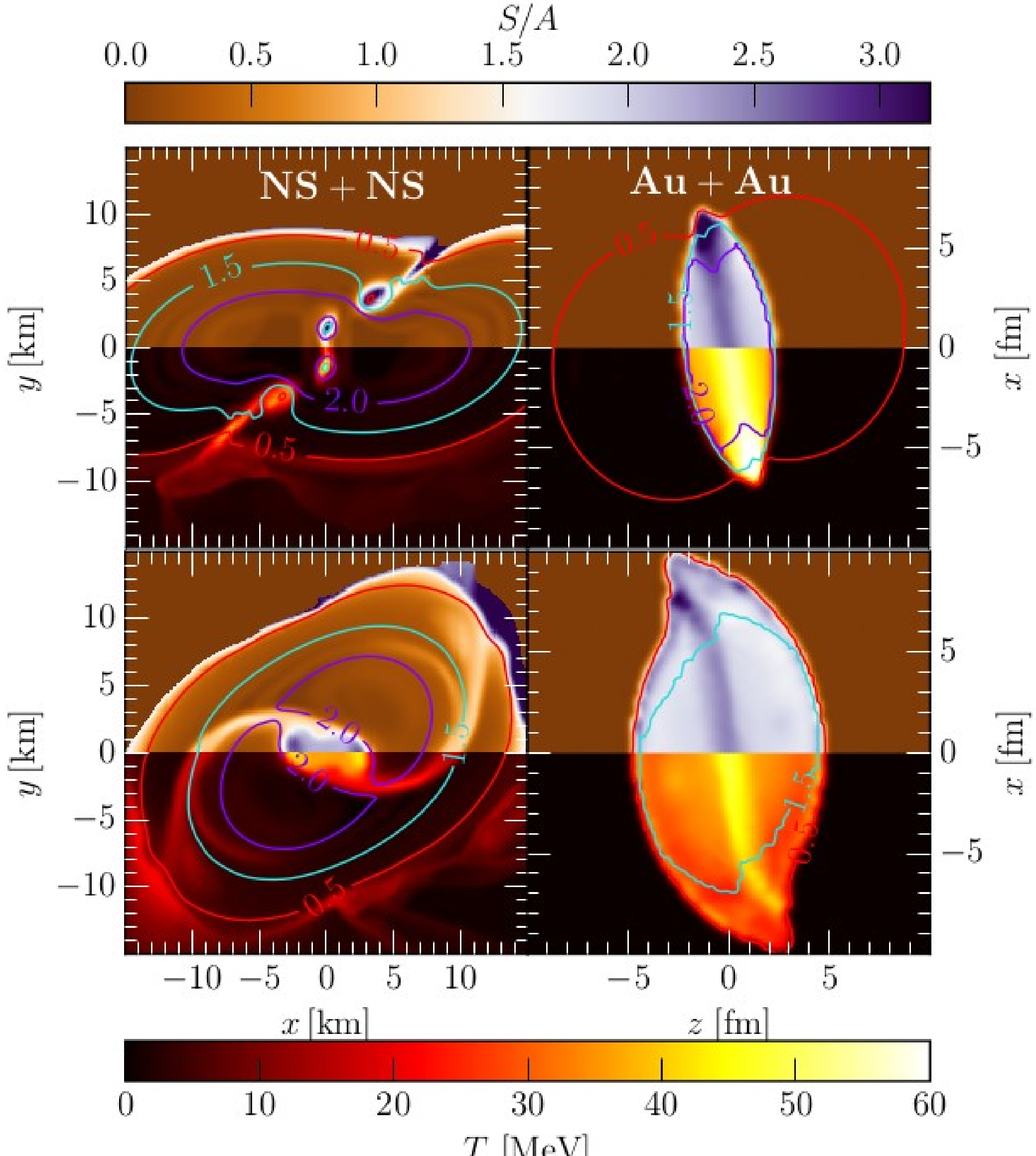


Demorest et al., Nature 467, 1081

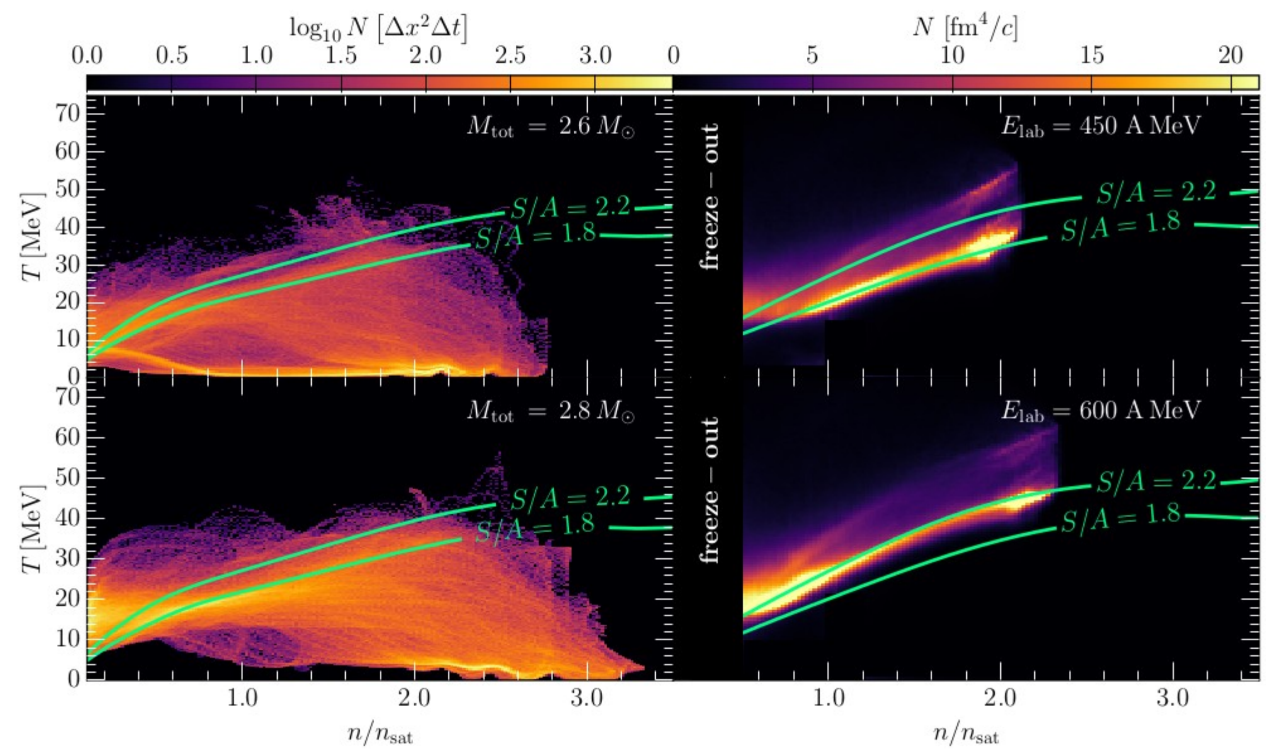




Comparing NS and HI collisions



- Comparing a merger of 2.9 M_{sun} NS and E_{lab}=450 MeV HI (Au-Au) collision



arXiv: 2201.13150

- Similar geometry and parameters across 18 orders of magnitude

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 (*nn* → *n*Λ) as illustrated in Fig. 3 (1)(a). It takes place at a density of 5 ρ_0

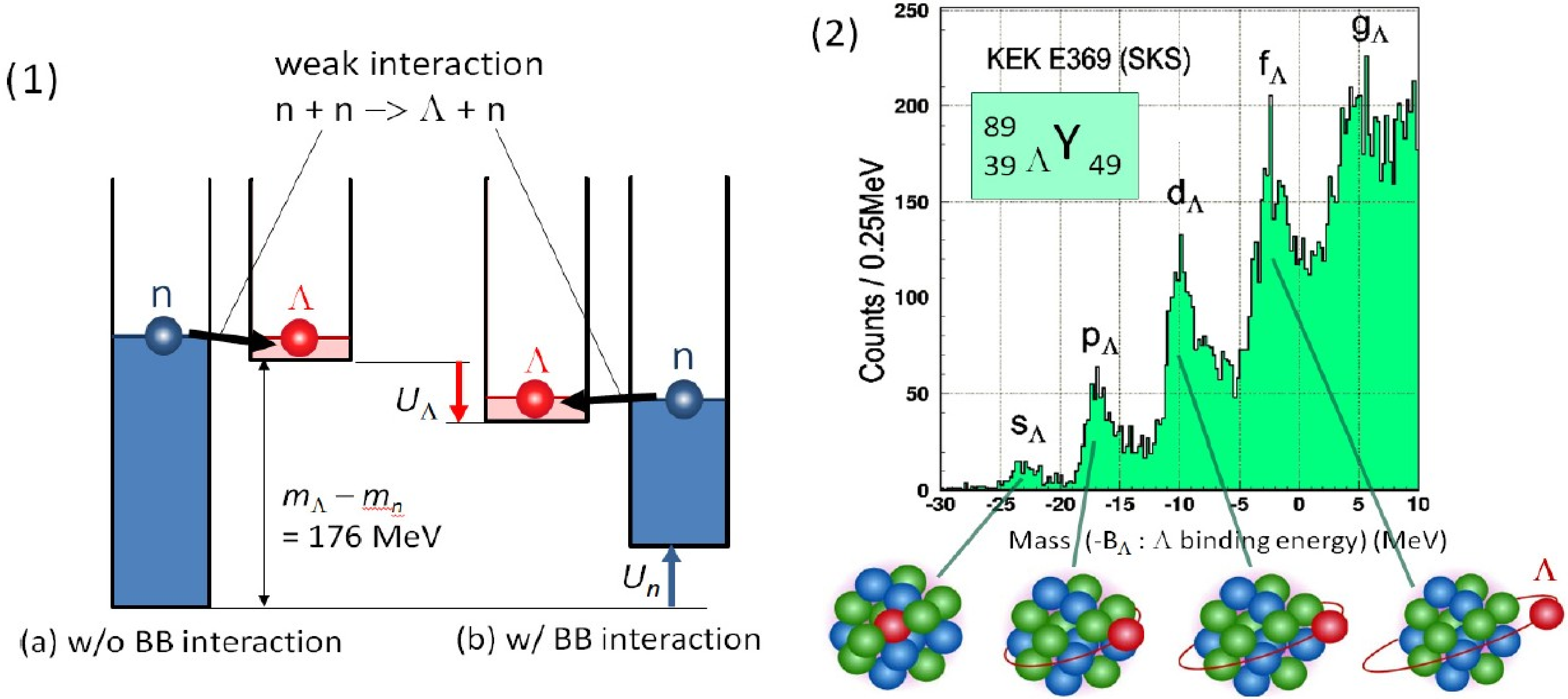
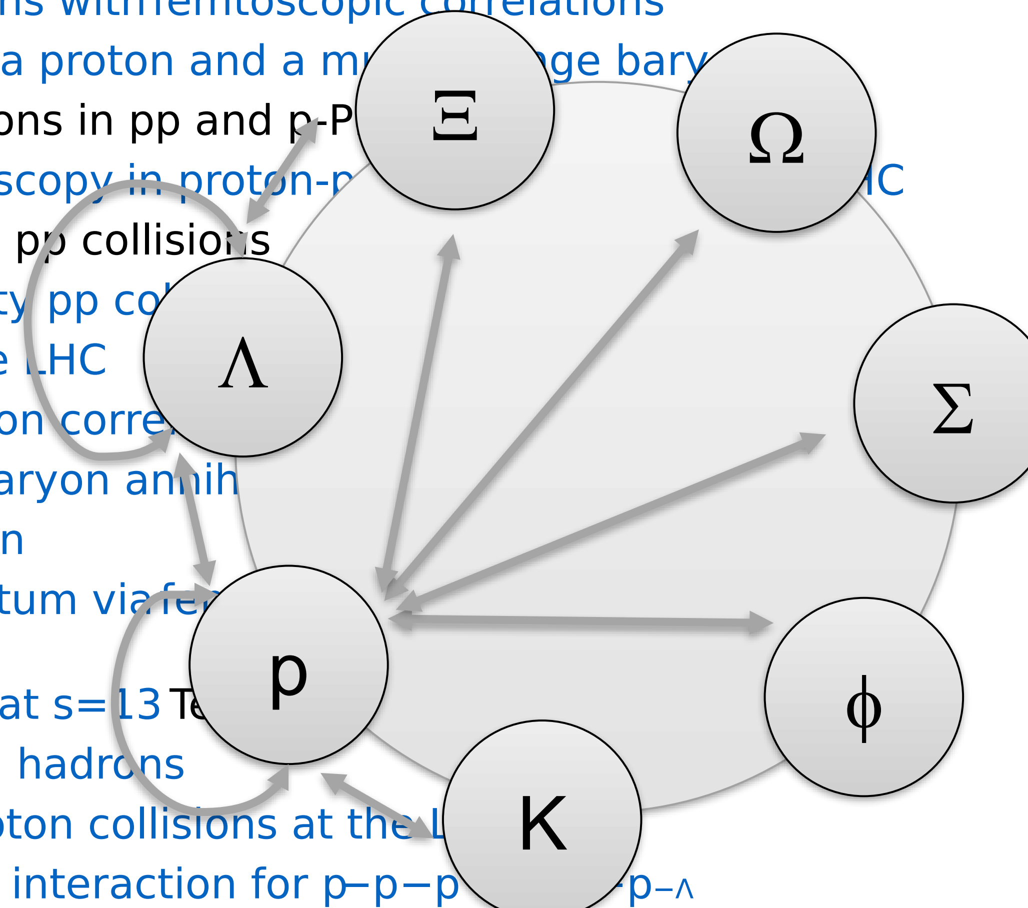


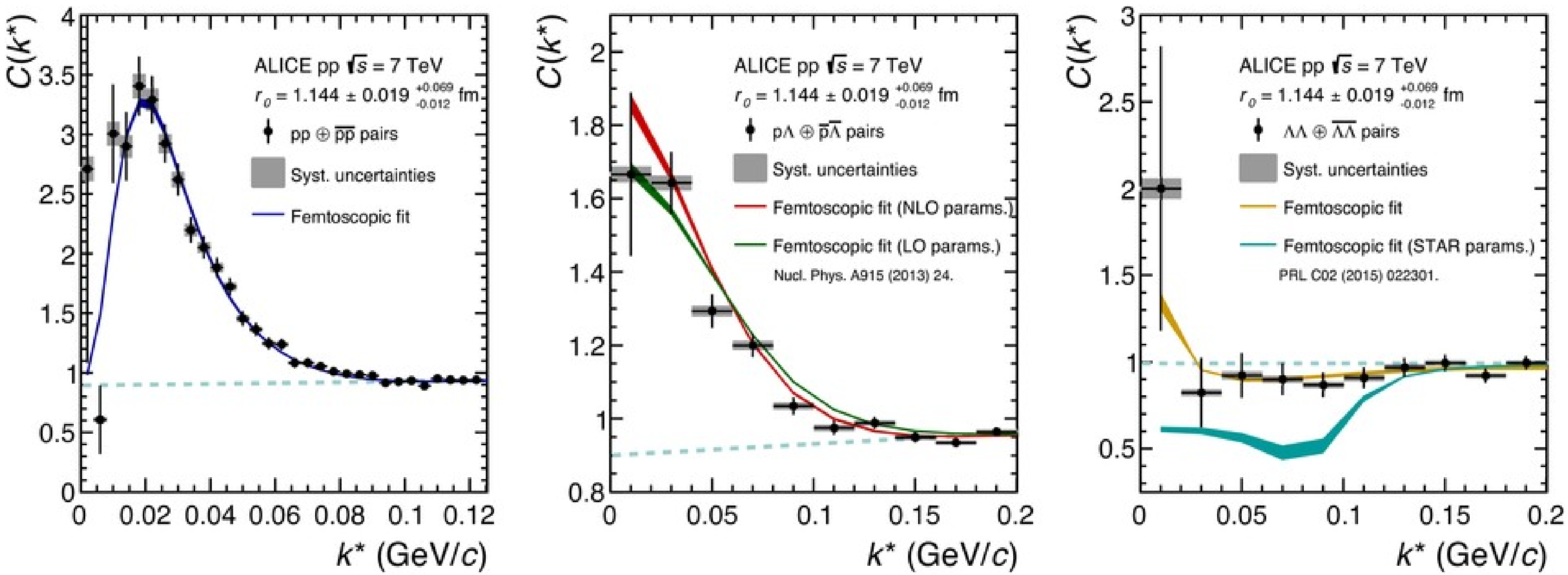
Fig. 3. (1) Energies of neutrons and Λ hyperons in high density neutron matter confined in the potential made by gravity. See text for details. (2) Excitation spectrum of a Λ hypernucleus $^{89}_{\Lambda}$Y via the (π^+,K^+) reaction on ^{89}Y target [6].

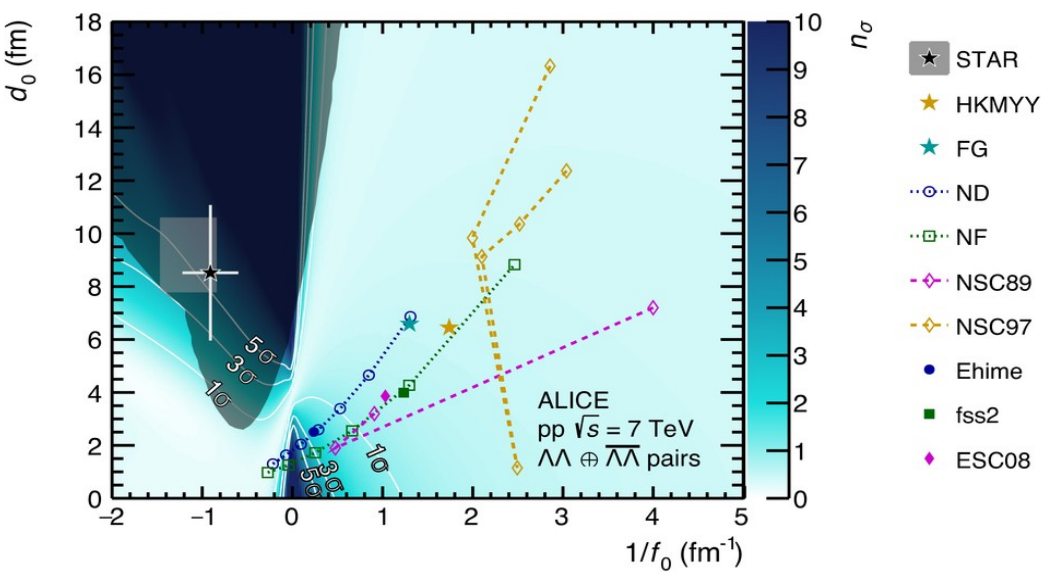
ALICE interaction papers

1. p-p, p-Λ and Λ-Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$ = 7 TeV
2. Measurement of strange baryon-antibaryon interactions with femtoscopic correlations
3. First observation of an attractive interaction between a proton and a m… …ge bary…
4. Study of the Λ-Λ interaction with femtoscopy correlations in pp and p-P…
5. Scattering studies with low-energy kaon-proton femtoscopy in proton-p… …IC
6. Investigation of the p-Σ0 interaction via femtoscopy in pp collisions
7. Search for a common baryon source in high-multiplicity pp co…
8. Unveiling the strong interaction among hadrons at the LHC
9. Exploring the NΛ-NΣ coupled system with high precision corre…
10. Investigating the role of strangeness in baryon−antibaryon annih…
11. Experimental evidence for an attractive p-φ interaction
12. Kaon-proton strong interaction at low relative momentum via fe… in Pb-Pb collisions at the LHC
13. K^0_SS0- and (anti-)Λ-hadron correlations in pp collisions at s=13 Te…
14. First study of the two-body scattering involving charm hadrons
15. First measurement of the Λ-Ξ interaction in proton-proton collisions at the L…
16. Towards the understanding of the genuine three-body interaction for p−p−p … -p−Λ



Baryon interactions in pp collisions

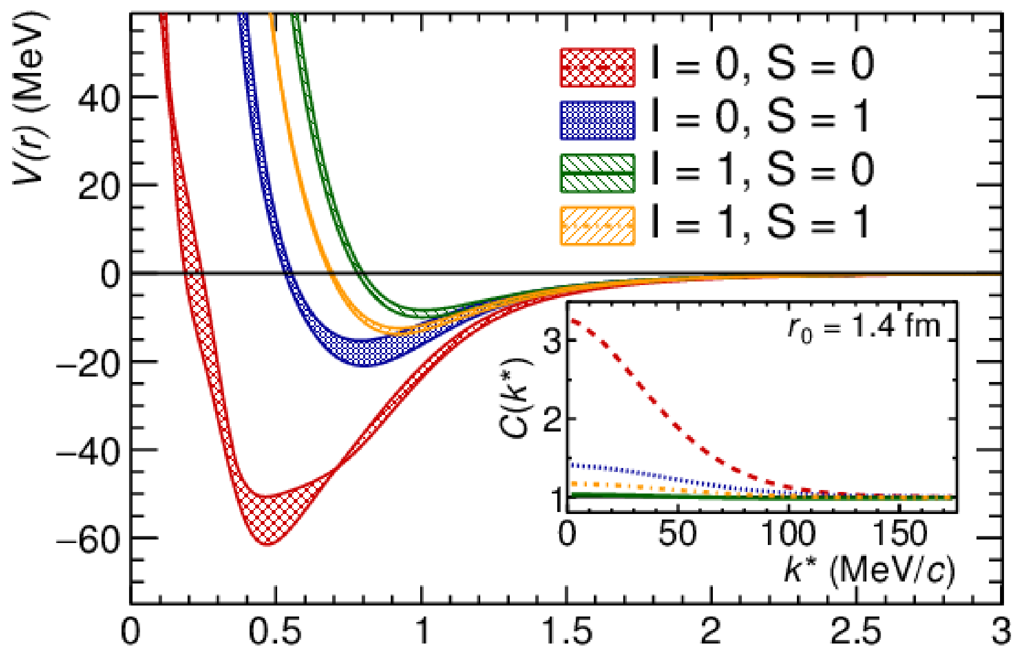




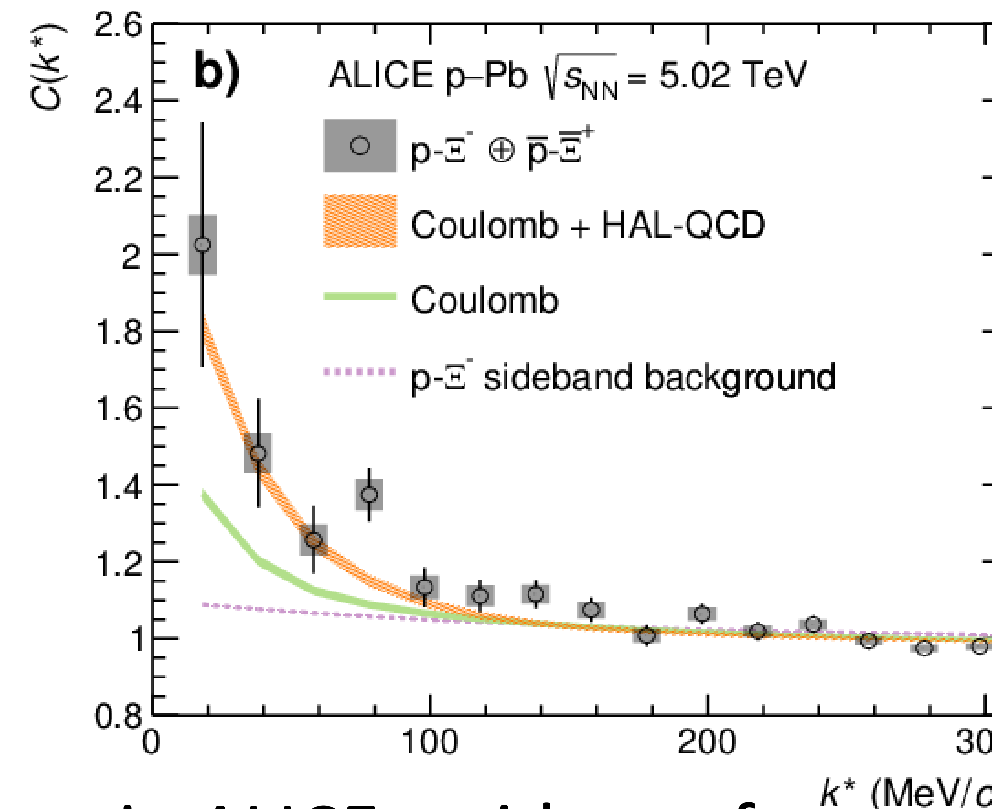
- p+p collisions – smaller system, probe potential at small distances
- Strict test of state-of-the-art calculation of intereaction potentials

ALICE, Phys.Rev. C99 (2019) no.2, 024001

Pioneering measurements



ALICE, arXiv:1904.12198

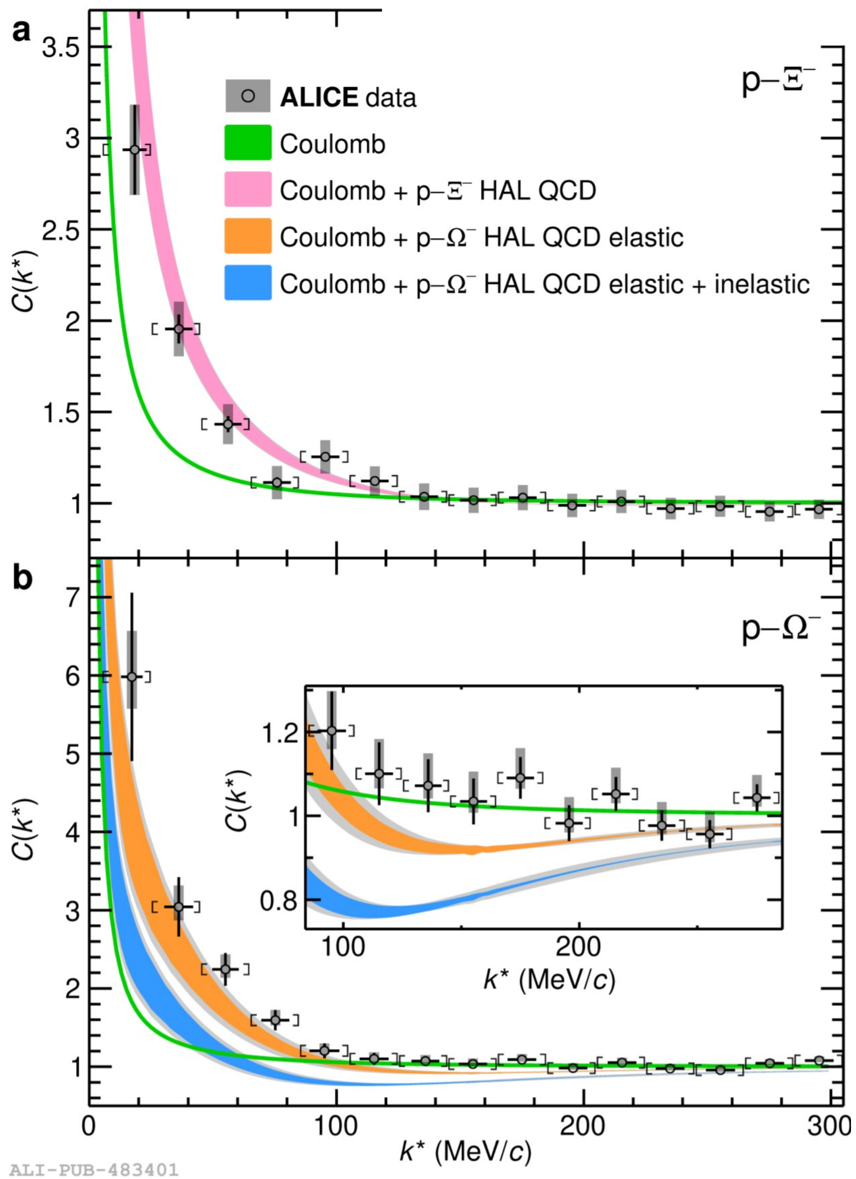


- Proton-Xi correlations in p+p collisions in ALICE: evidence for attractive strong interaction potential
- Direct relevance to strange matter appearance in neutron star cores: the same calculation shows shallow repulsive interaction between Xi- and neutron matter, implying stiffer NS EOS

Measurements of hadron-hadron interaction with strangeness

pΞ pΩ

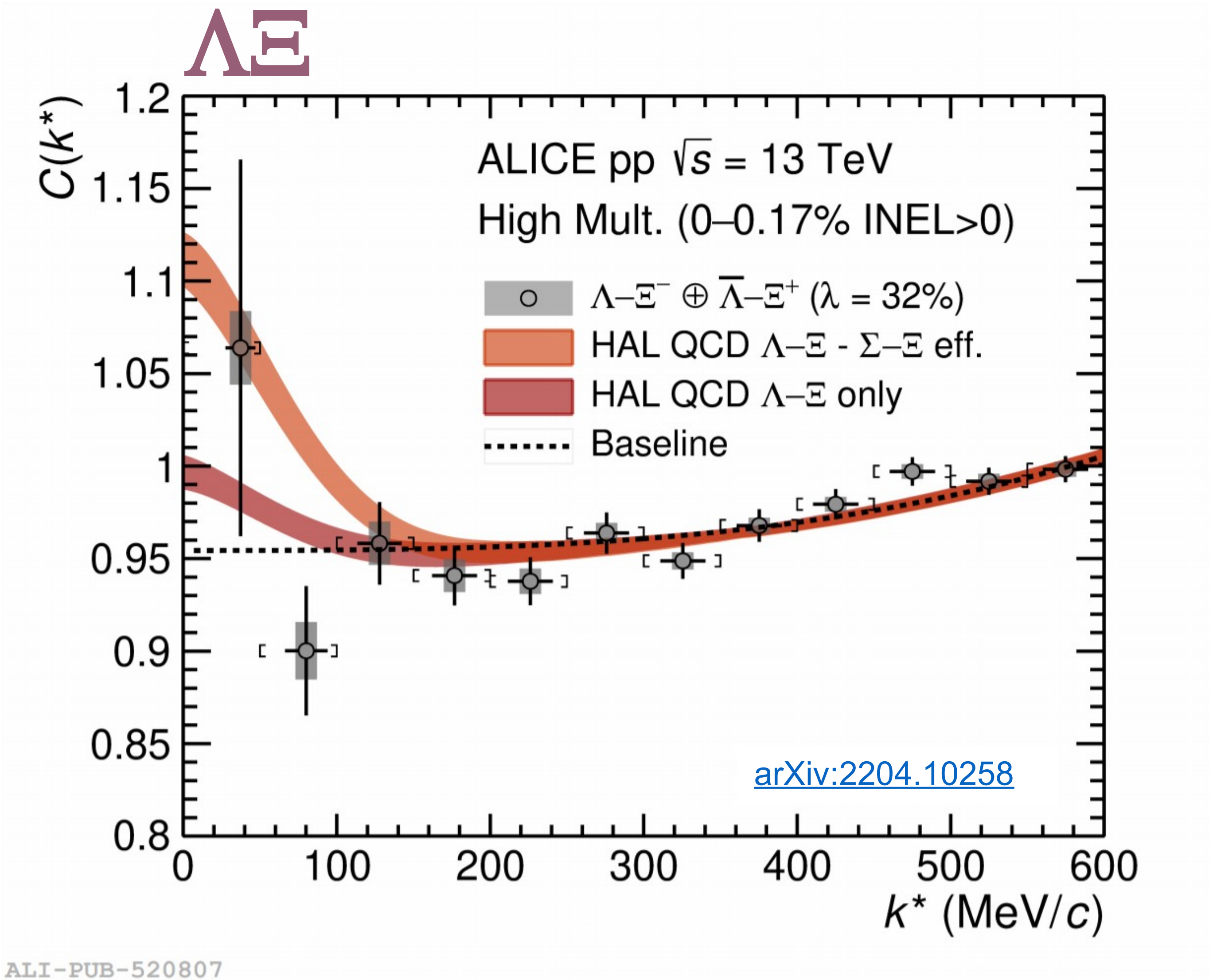
Nature 588 (2020) 232-238
arXiv:2005.11495



Measurements of the strong interaction for **pΞ pΩ** pairs

- Evidence for the attractive strong interaction potential
- Can be studied with precision similar to, and compared with, predictions from lattice calculations.
  - The correlation functions predicted by HAL QCD are in agreement with the measurements for the p–Ξ – interaction
  - For the p–Ω– interaction, the inelastic channels are not yet accounted for quantitatively within the lattice QCD calculations.

Measurements of hadron-hadron interaction with strangeness



First measurement of the ΛΞ- interaction :

- three units of strangeness,
- constraints for lattice QCD calculations and chiral potentials,
- more precision needed.

Summary

- **Lesson:** Femtoscopy of pions in 3D a mature way to probe details of the collision dynamics at LHC
- **Lesson:** Observed excellent agreement with hydrodynamic predictions
- **Lesson:** Heavier particles and non-identical particle correlations confirm detailed dynamic predictions but also access rescattering
- **Open question:** Detailed 3D pion femtoscopy in small systems at LHC presents puzzling results, no current model explanation available
- **Lesson:** Strong FSI for baryons can be probed using femtoscopic correlations, both in AA and pp collisions
- **Future:** Excellent prospects for baryons in LHC Run3 at 10x statistics