NATIONAL SCIENCE CENTRE POLAND

EXCELLENCE INITIATIVE RESEARCH UNIVERSITY

Femtoscopy in heavy-ion collision experiments at various μ_B

Hanna Zbroszczyk

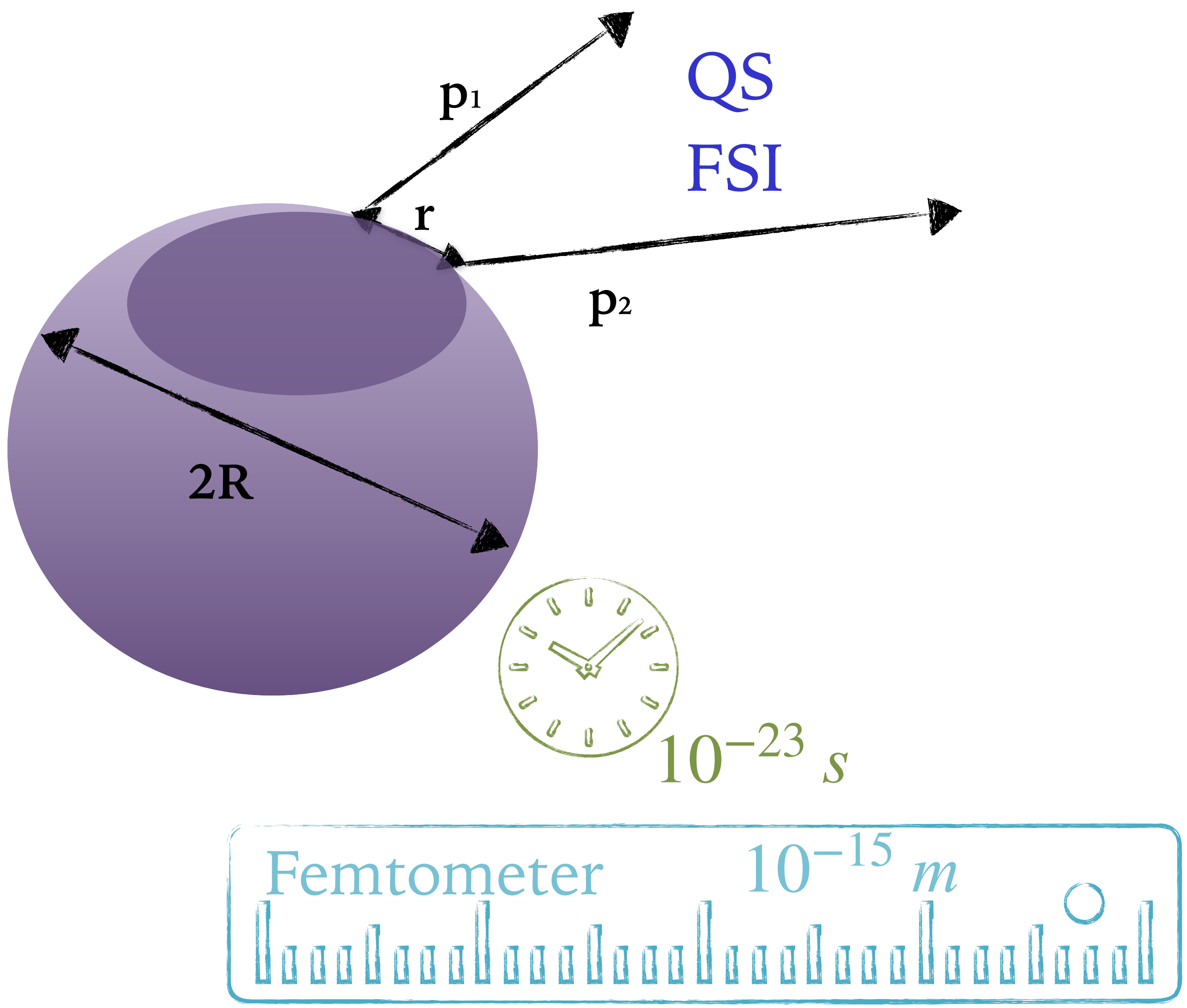
Introduction

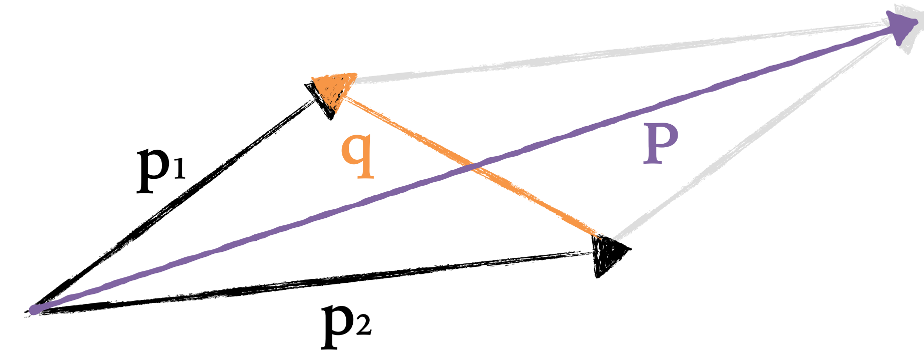
Scanning QCD phase diagram:

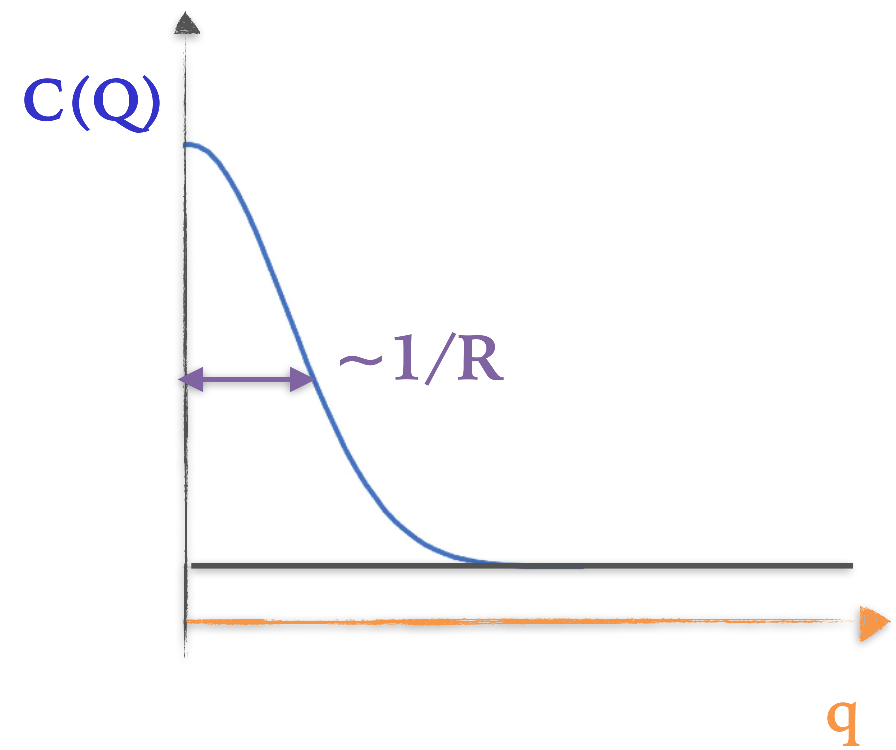
- neutron stars
- neutron star mergers
- phase transitions

Summary

Various faces of QCD, April 26-28 2024, Wrocław







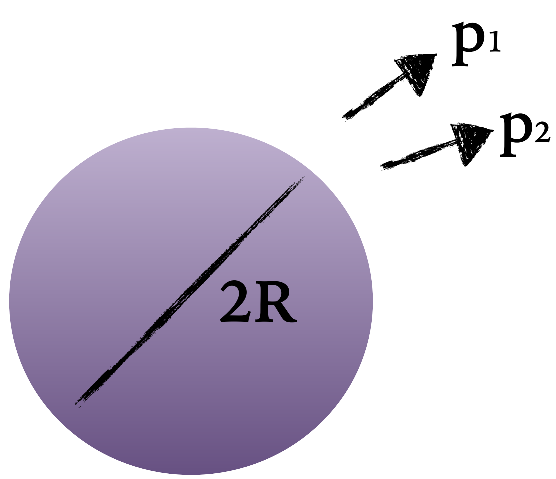
Femtoscopy

… 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.

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)

determined assumed measured

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

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

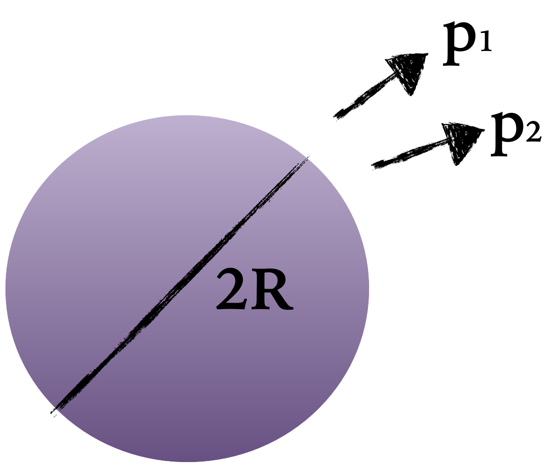
Gateway to study interactions

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)



assumed | determined | measured

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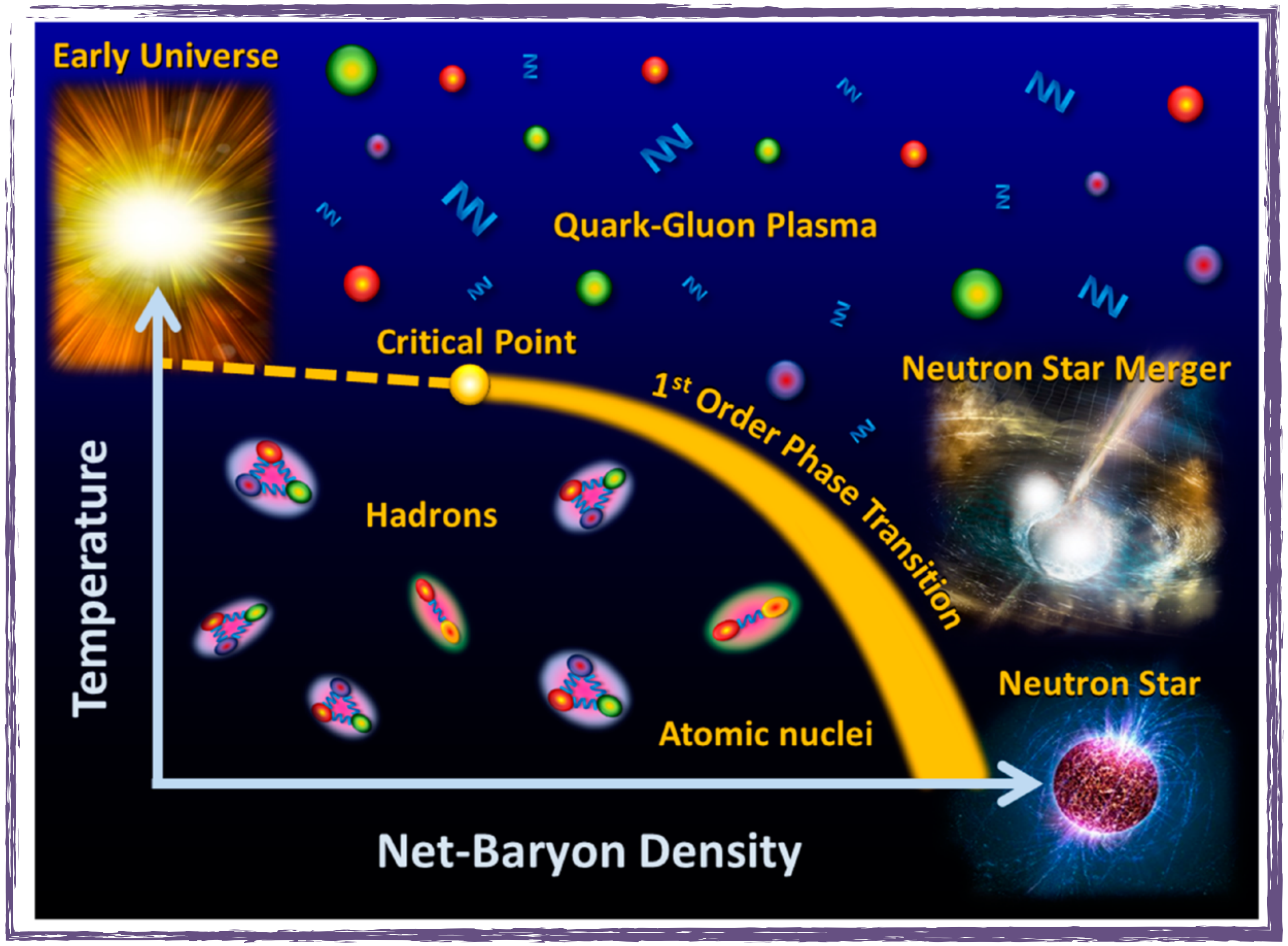

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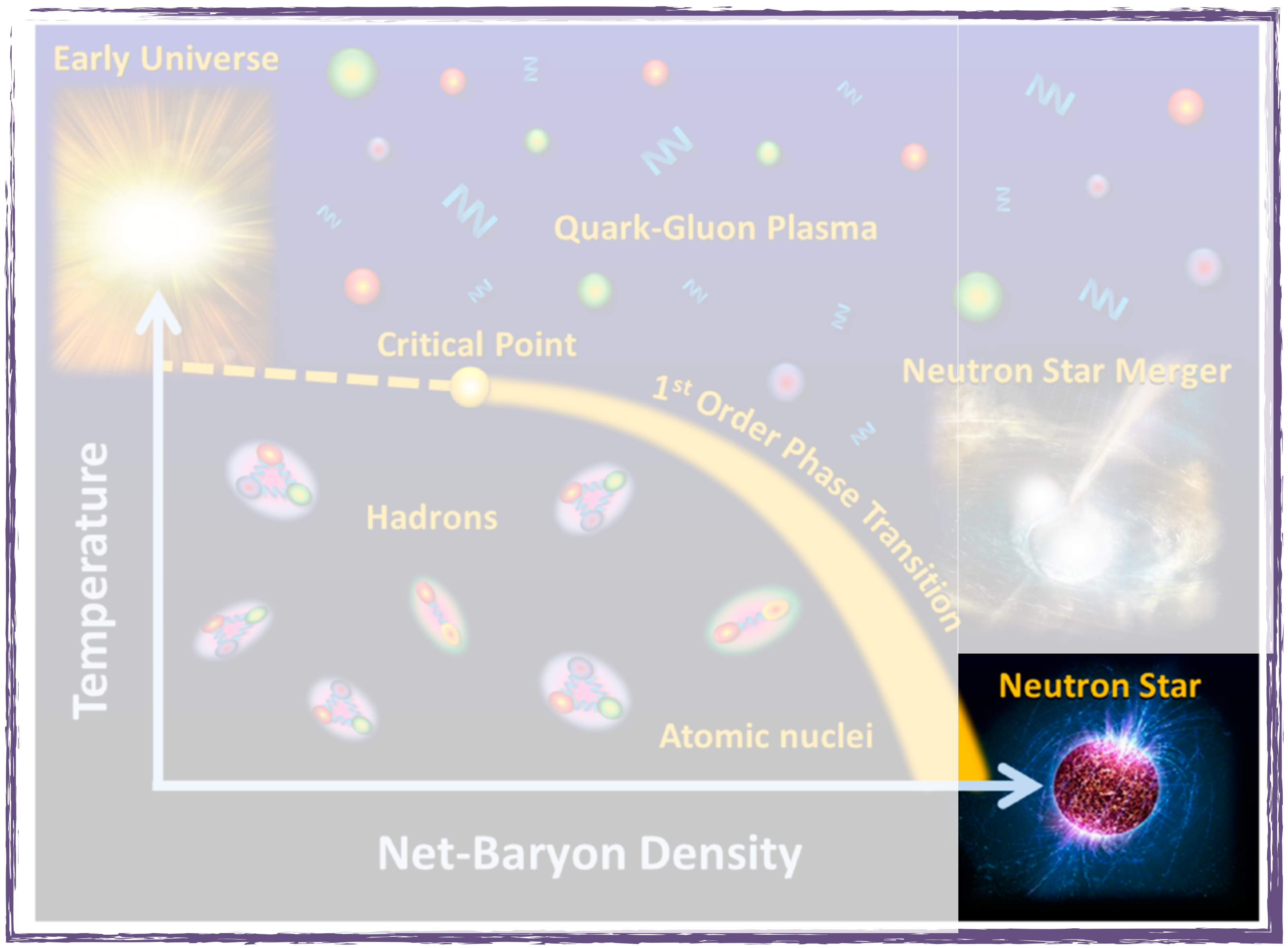
Scanning various μ_B

.. to study strongly interacting matter

.. to explore unknown QCD territory

Neutron stars

Exploration of unknown QCD territory: high μ_B



https://www.researchgate.net

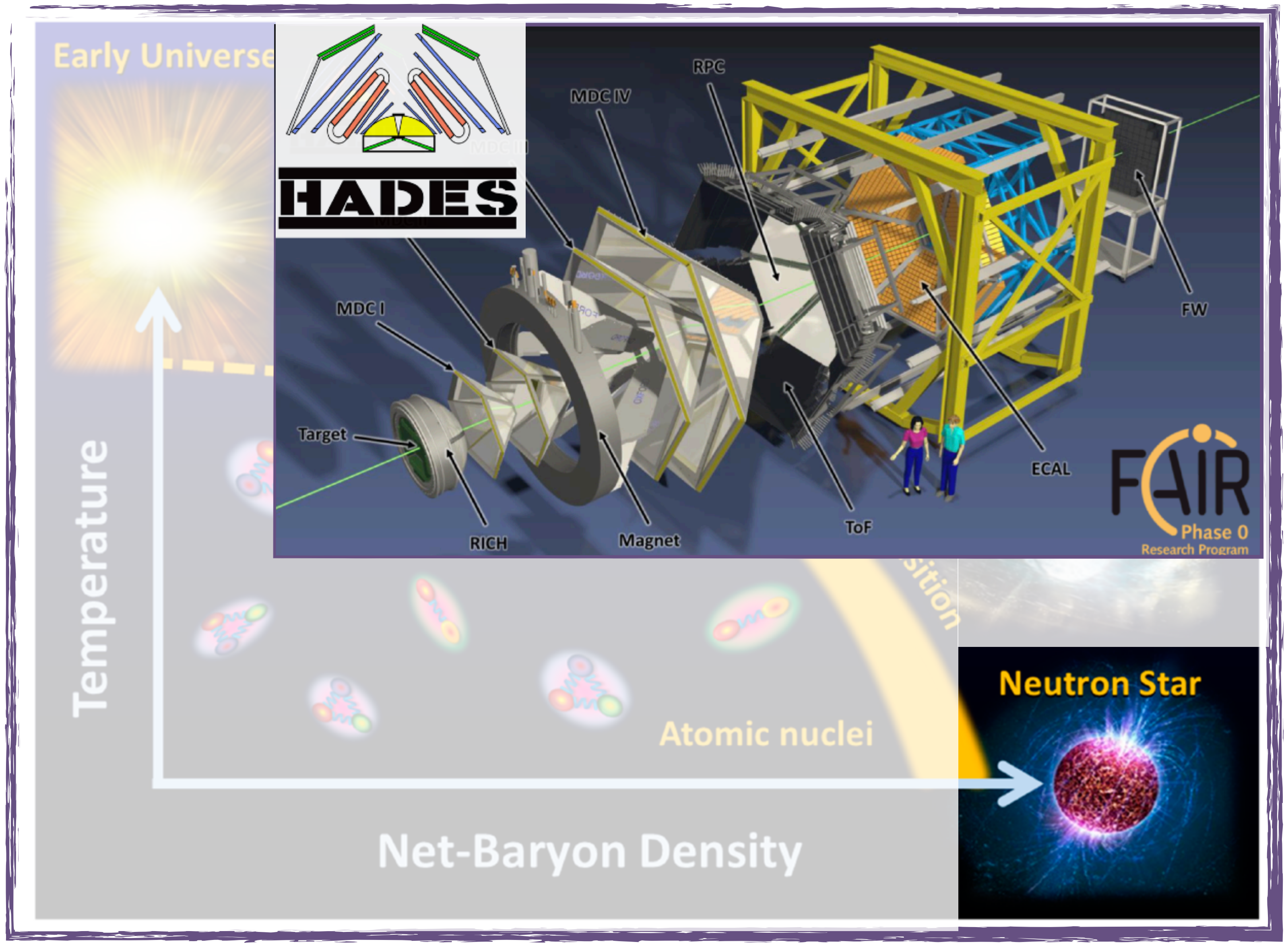
Temperature
T<10 MeV

Density
$n < 10n_0$

Lifetime
t ~ long

Neutron stars

Exploration of unknown QCD territory: high μ_B



https://www.researchgate.net

Temperature
T<10 MeV

Density
$n < 3n_0$

Lifetime
t ~ long

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.

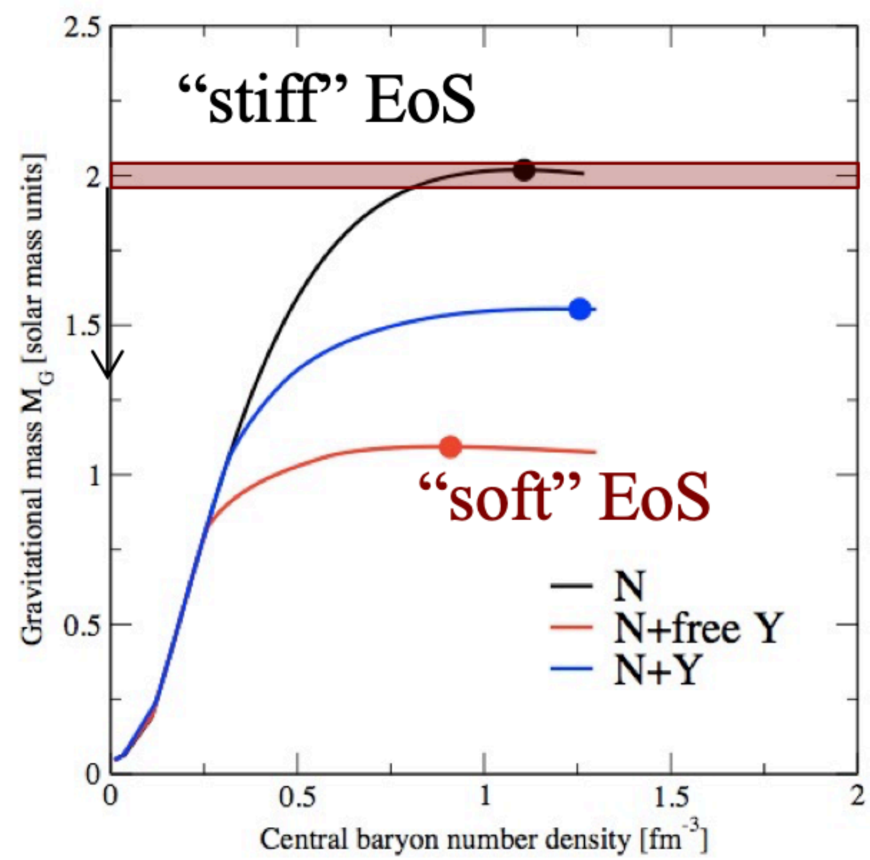
A few possible mechanisms, one of them:

Two-body YN & YY 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** or **YY bound states**.

$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx 10\text{-}12$ km
$\rho \approx 3 \div 5\ \rho_0$



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

Lednicky-Lyuboshitz model (pΛ example)

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

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

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

The correlated function can be calculated analytically by averaging $\mathbf{\Psi^s}$ over the total spin S and the distribution of the relative distances **S(r*)**

$$C(k^*) = 1 + \sum_S \rho_s \left[\frac{1}{2}\left|\frac{f^S(k^*)}{r_0}\right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0}\right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0)\right]$$

$$with\ F_1(z) = \int_0^z dx e^{x^2 - z^2}/z\ and\ F_2(z) = (1 - e^{-z^2})/z$$

Decomposition for spin channels :

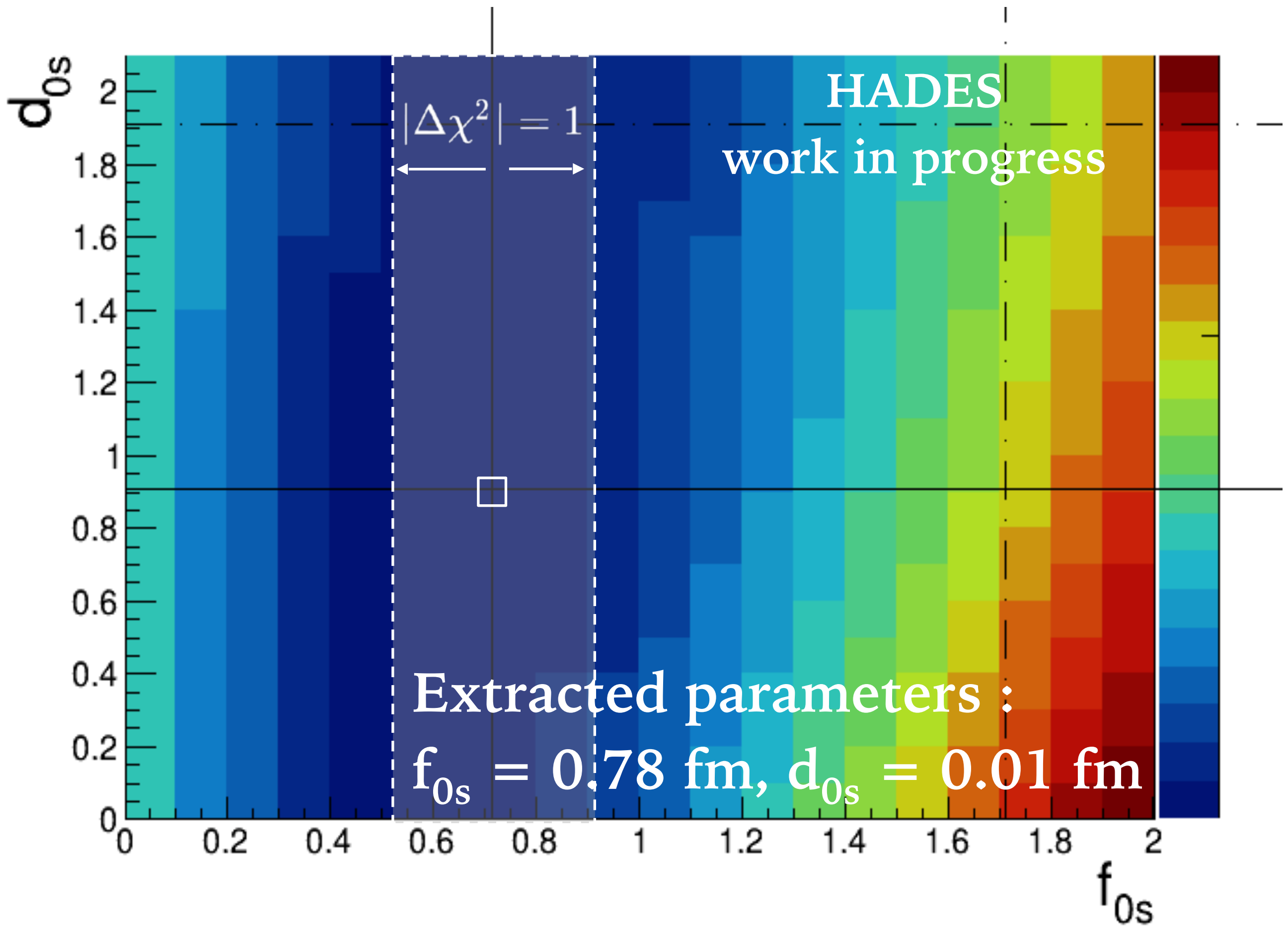
$$C(k^*) = \frac{1}{4}(1 + \lambda C(k^*, s = 0)) + \frac{3}{4}(1 + \lambda C(k^*, s = 1))$$

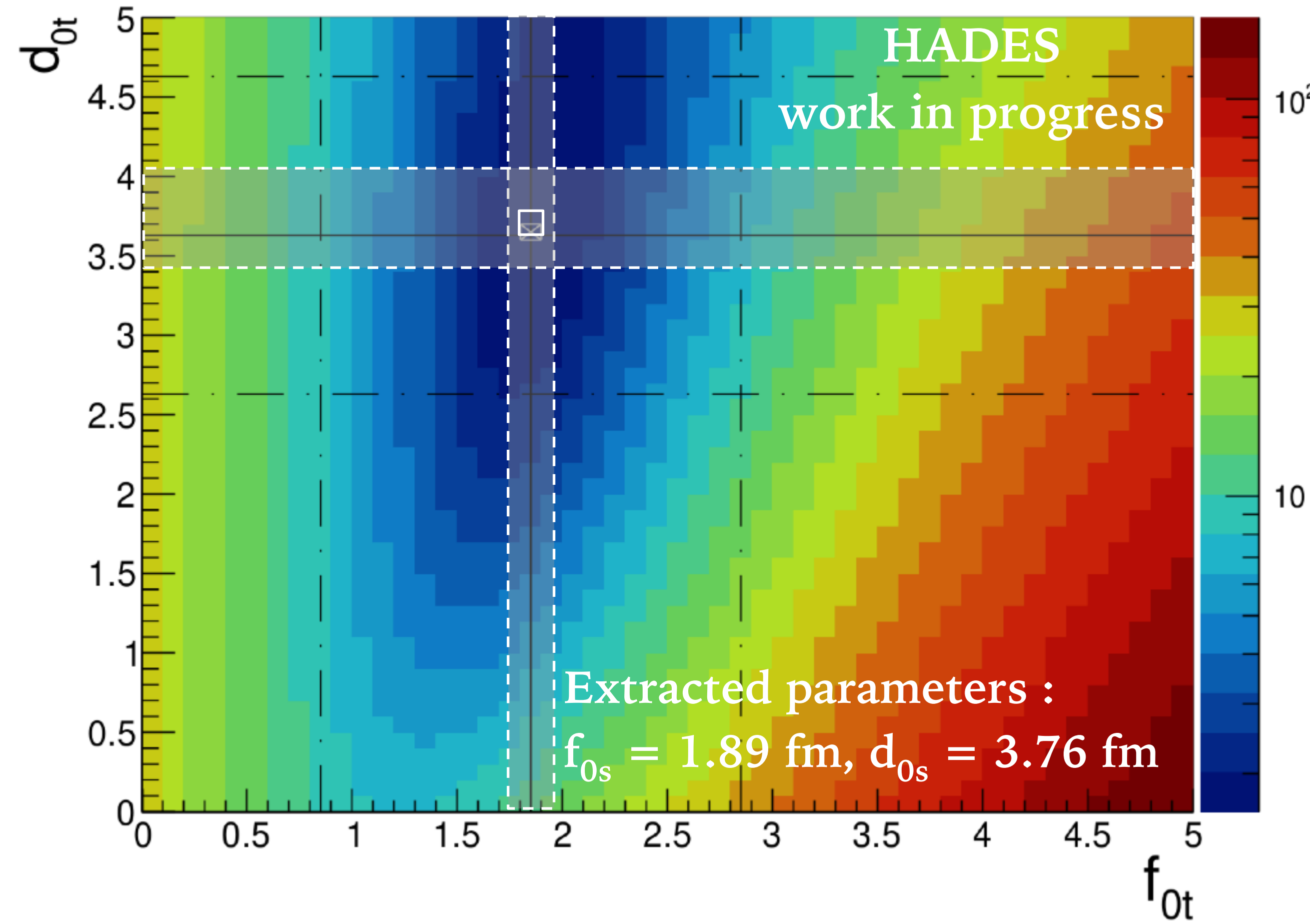
f_0 and d_0 - parameters of strong interaction.
Theoretical correlation function (k*) depends on: R, f_0 and d_0.

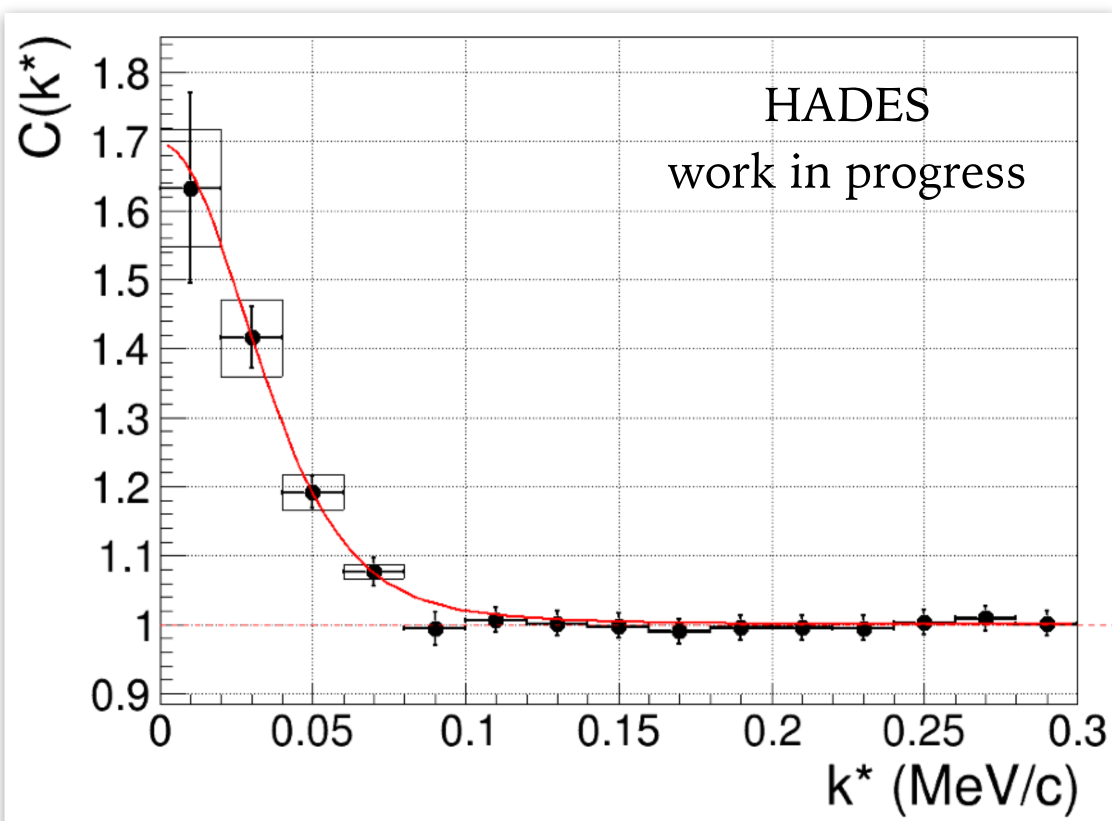
f_0 - the scattering length, determines low-energy scattering.
The elastic cross section, σ_e, (at low energies) determined by the scattering length, $\lim_{k \to 0} \sigma_e = 4\pi f_0^2$

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

YN ($p\Lambda$) correlations at HADES







$$\lambda = 0.74$$

$$f_{0s} = 0.80^{+0.39}_{-0.32}$$

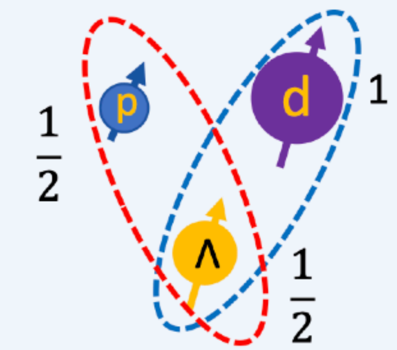
$$d_{0s} = 0.01$$

$$f_{0t} = 1.89^{+0.10}_{-0.09}$$

$$d_{0t} = 3.76^{+0.27}_{-0.25}$$

$$r = 2.24^{+0.12}_{-0.11}$$

YN correlations at STAR ($\sqrt{s_{NN}} = 3$ GeV)



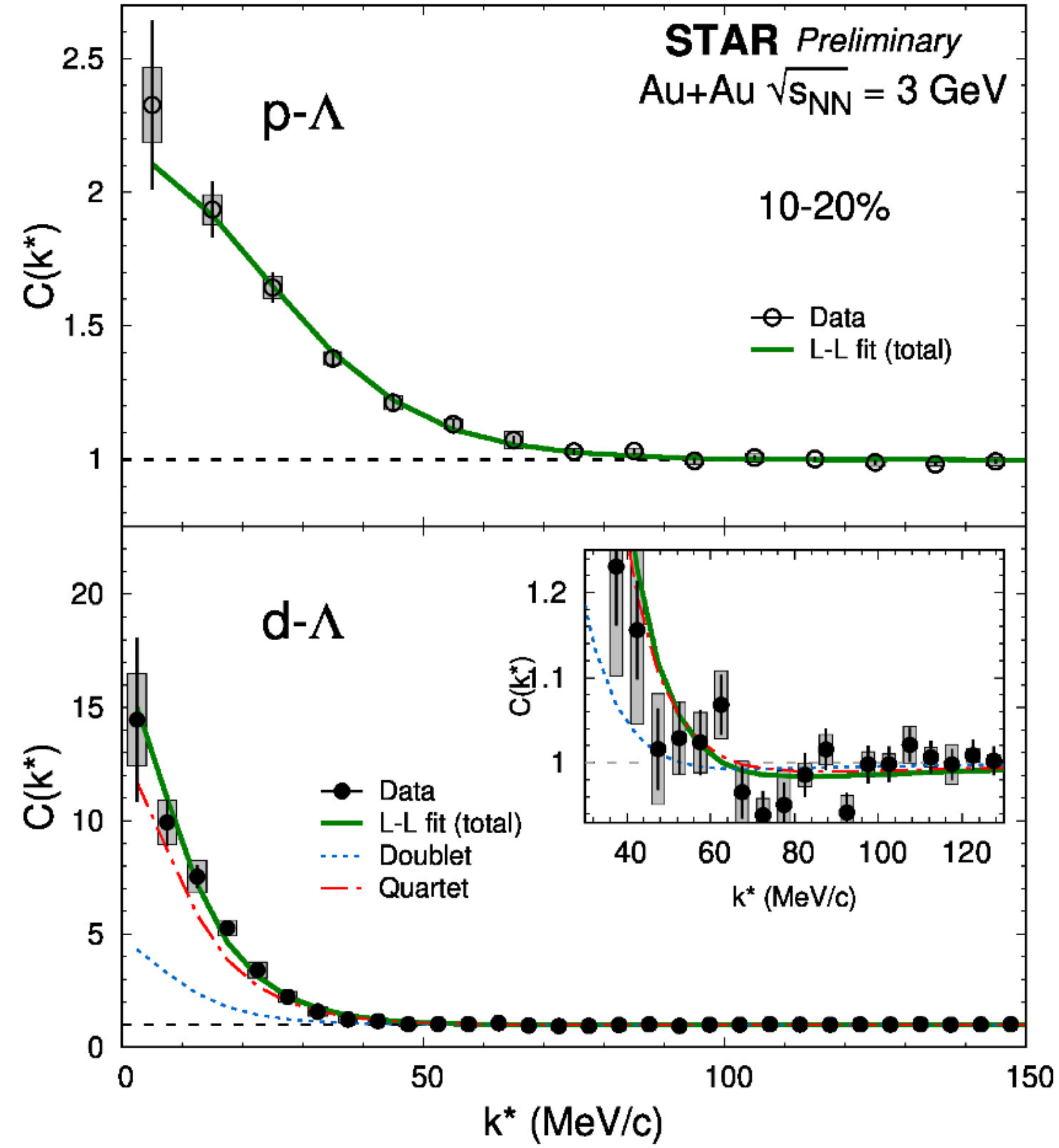
Singlet State	$^1S_0$	(S)
Triplet State	$^3S_1$	(T)

Doublet State	$^2S_{1/2}$	(D)
Quartet State	$^4S_{3/2}$	(Q)

p-Λ: $|\psi(r,k)|^2 \rightarrow \frac{1}{4}|\psi_0(r,k)|^2 + \frac{3}{4}|\psi_1(r,k)|^2$

d-Λ: $|\psi(r,k)|^2 \rightarrow \frac{1}{3}|\psi_{1/2}(r,k)|^2 + \frac{2}{3}|\psi_{3/2}(r,k)|^2$

- Different spin states with different f_0 and d_0 parameters
- **p-Λ correlation:** current statistics is not enough to separate two spin states → spin-averaged fit
- **d-Λ correlation:** very different f_0 for (D) and (Q) are predicted → **Spin-separated fit**

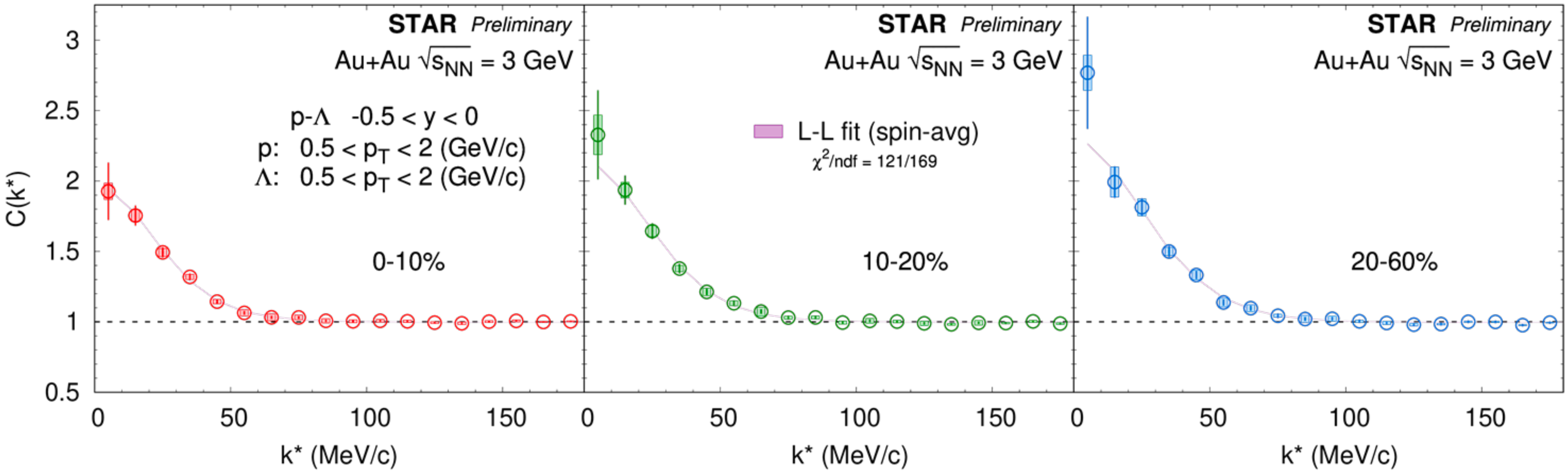


Different spin states with different FSI parameters

p-Λ correlation: currently spin-averaged fit

d-Λ correlation: spin-separated fit

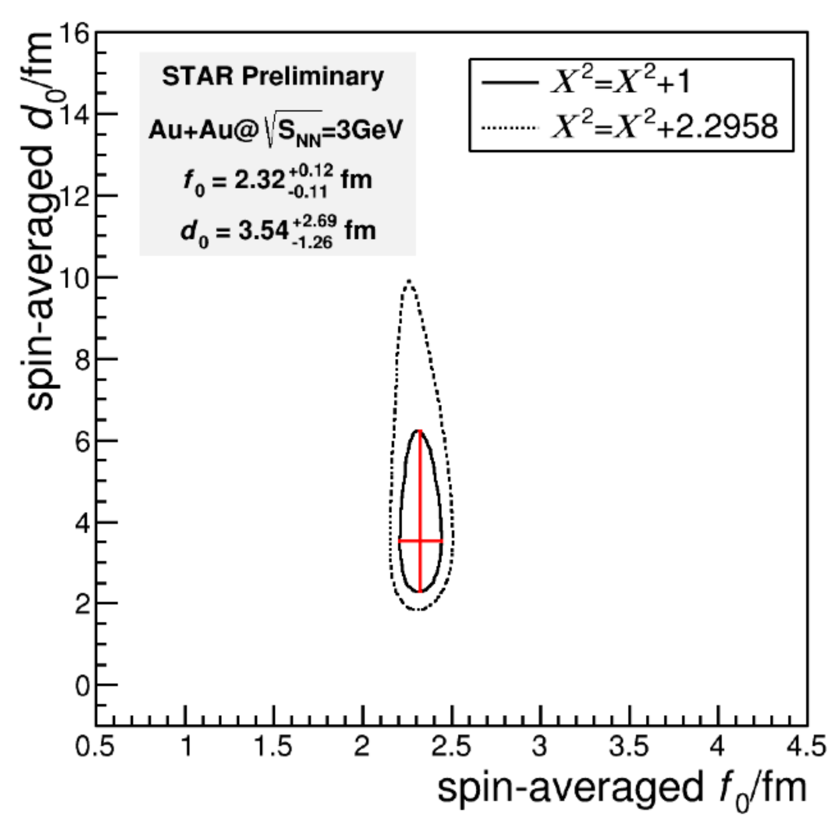
YN ($p\Lambda$) correlations at STAR



- 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:

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

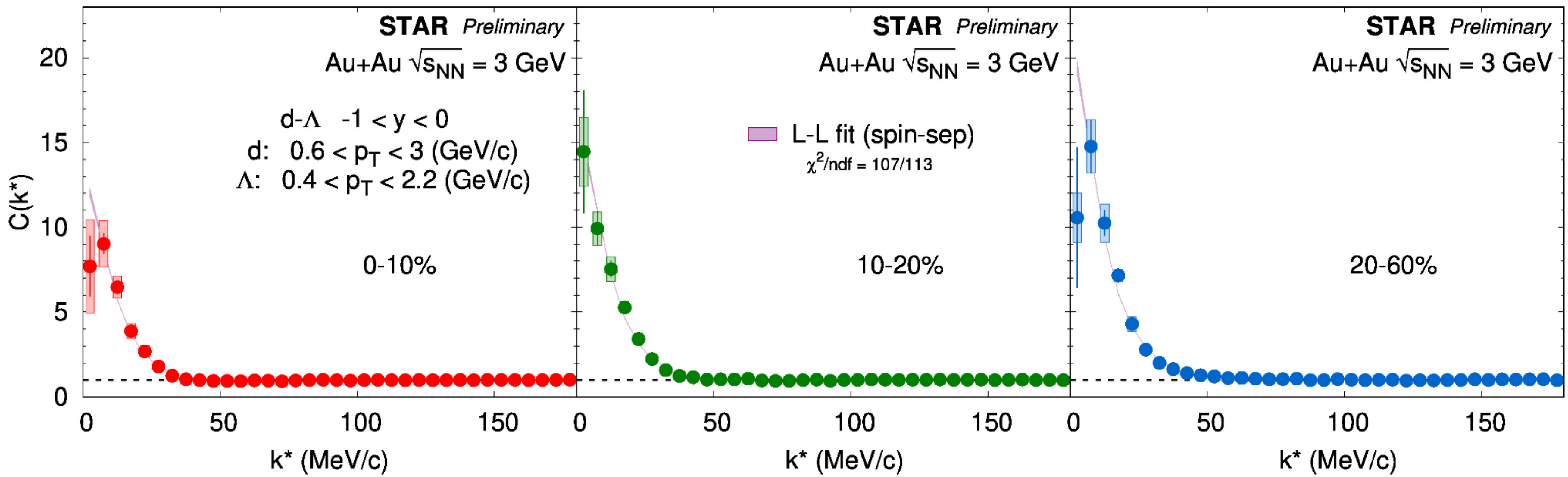
X^2 contour of spin-averaged d_0 and f_0 for $p\Lambda$ (-1<y<0)

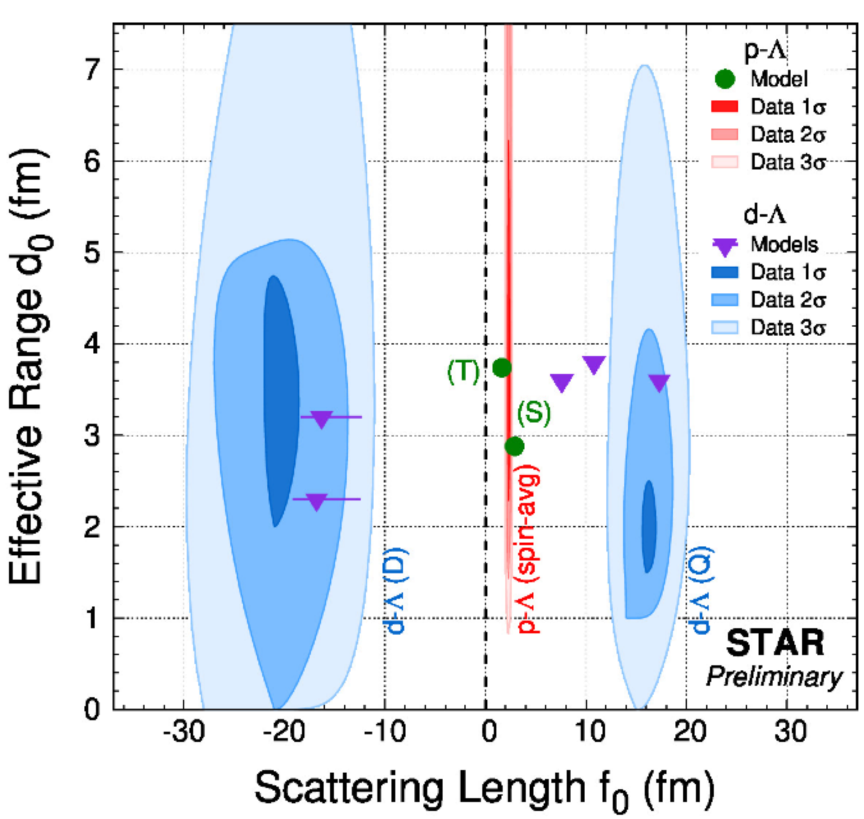


Source size extracted from the source assuming Gaussian shape;

Separation of emission source from the parameters of the final state interaction;

YN ($d\Lambda$) correlations at STAR





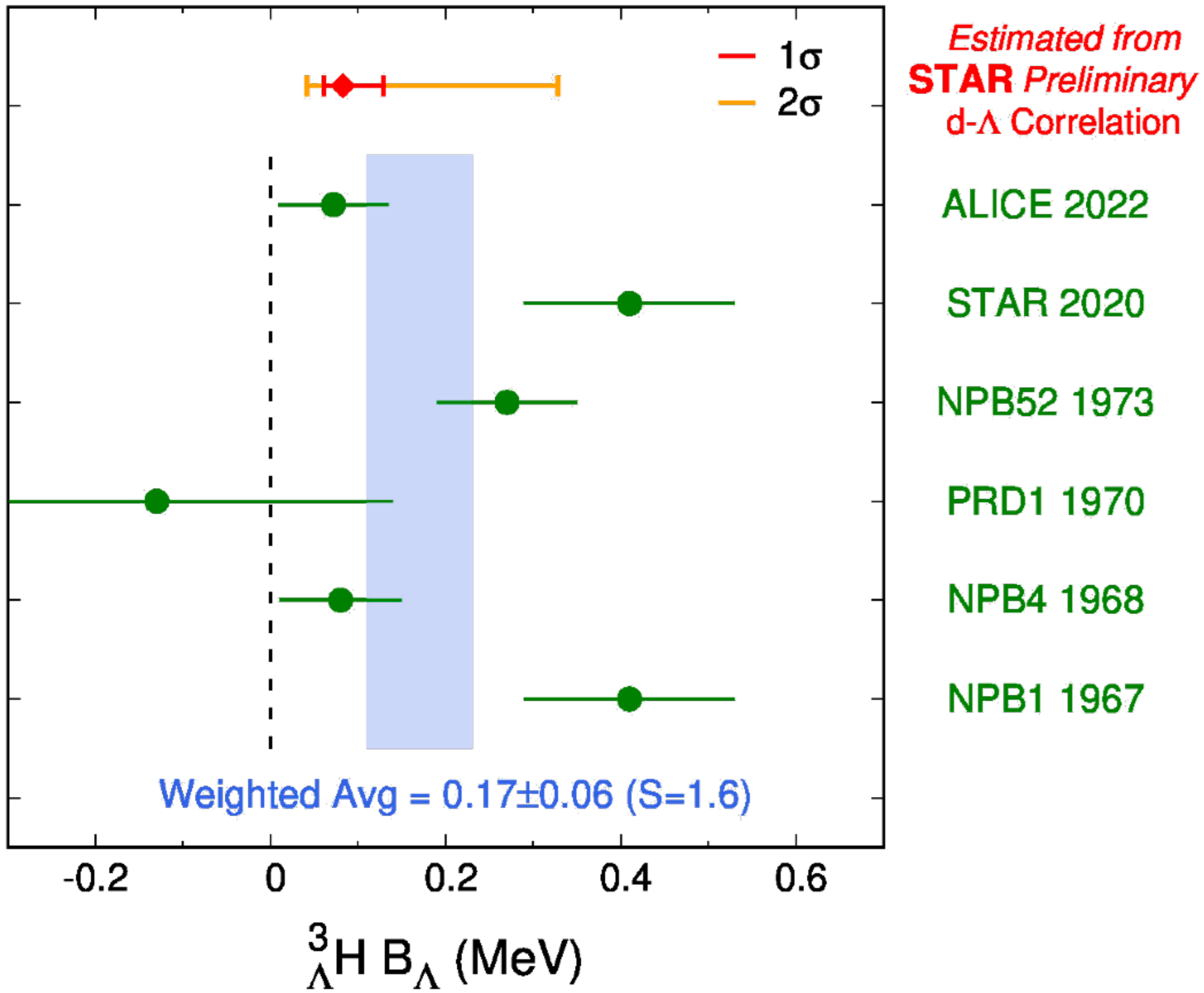
- Simultaneous fit to data in different centralities and rapidities;
- Source size R and parameters of SI: f_0 and d_0 with Lednicky-Lyuboshitz approach;
- Spin-separated scattering length and effective range:

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

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

H. W. Hammer, Nucl. Phys. A 705 (2002) 173
A. Cobis, et al. J. Phys. G 23 (1997) 401
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001
M. Schäfer, et al. Phys.Lett.B 808 (2020) 135614
G. Alexander, et al. Phys. Rev. 173 (1968) 1452
J. Haidenbauer, et al. Nucl. Phys. A 915 (2013) 24
F. Wang, et al. Phys.Rev.Lett. 83 (1999) 3138

YN ($d\Lambda$) correlations at STAR, binding energy



Bethe formula from Effective Range Expansion (ERE) parameters $f_0(D)$ and $d_0(D)$.

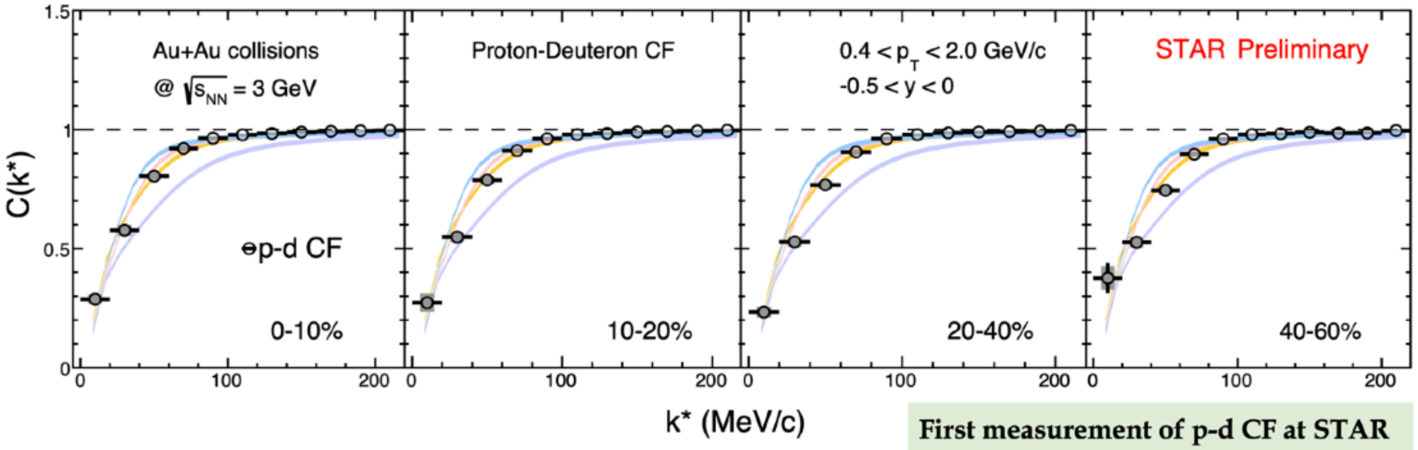
$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

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

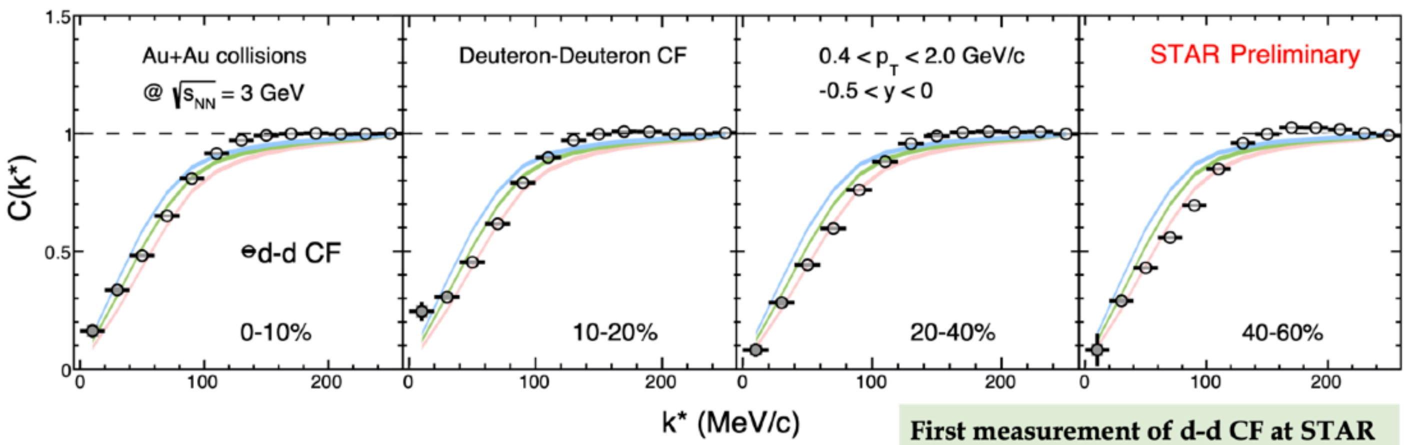
- $^{3}_{\Lambda}\mathrm{H}\ B_\Lambda = [0.04, 0.33]$ (MeV) @ 95% CL

  Consistent with the world average
- A new way to constrain the $^{3}_{\Lambda}$H structure

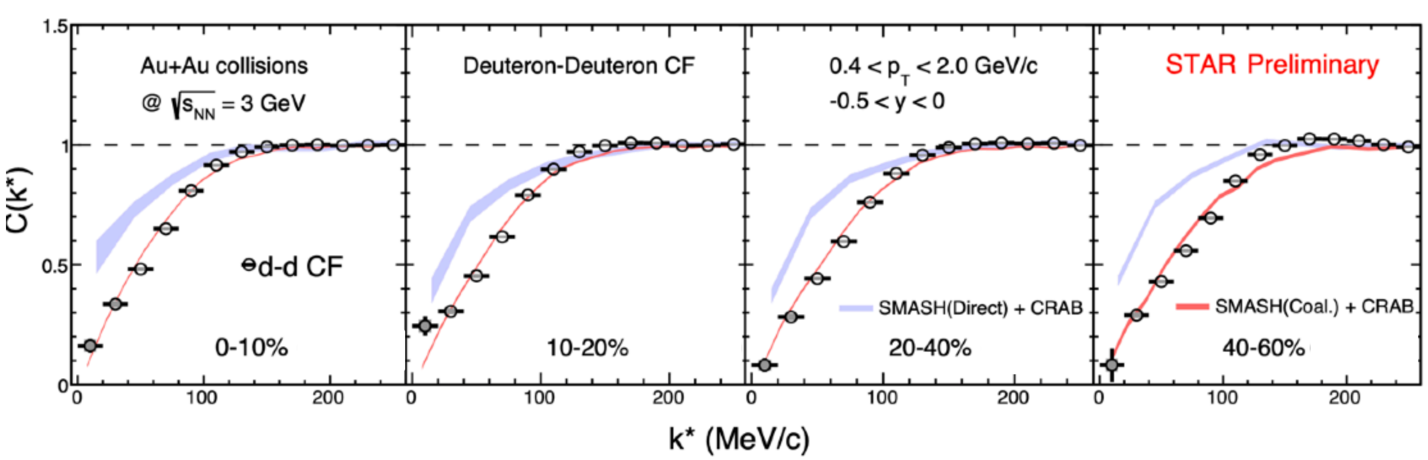
Light nuclei production at STAR



- First measurement of **proton-deuteron** and **deuteron-deuteron** correlation functions from STAR



- **Proton-deuteron** and **deuteron-deuteron** correlations qualitatively described by theory;



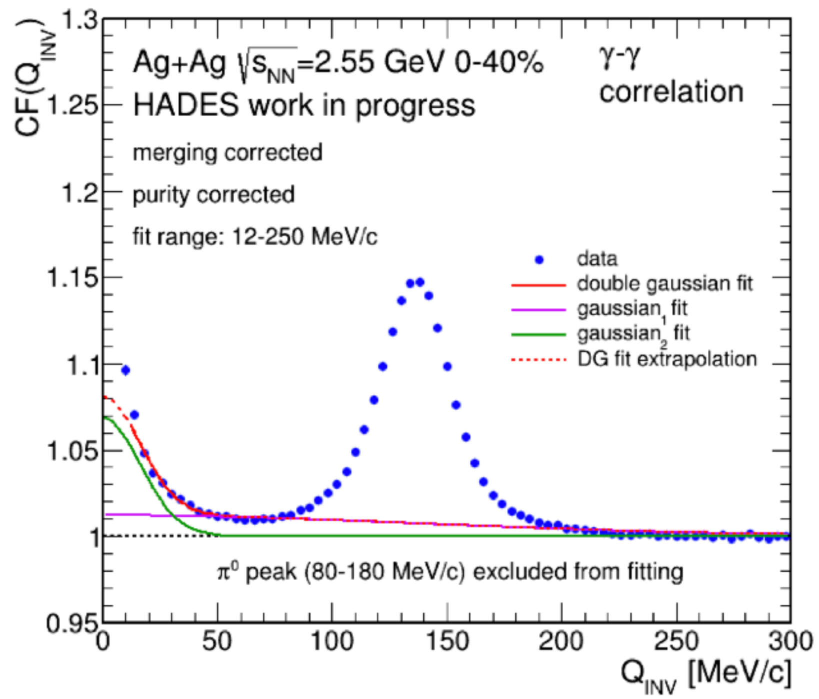
- Deuteron-deuteron correlations described better by the model including **coalescence**. Light nuclei are likely to be formed via coalescence.

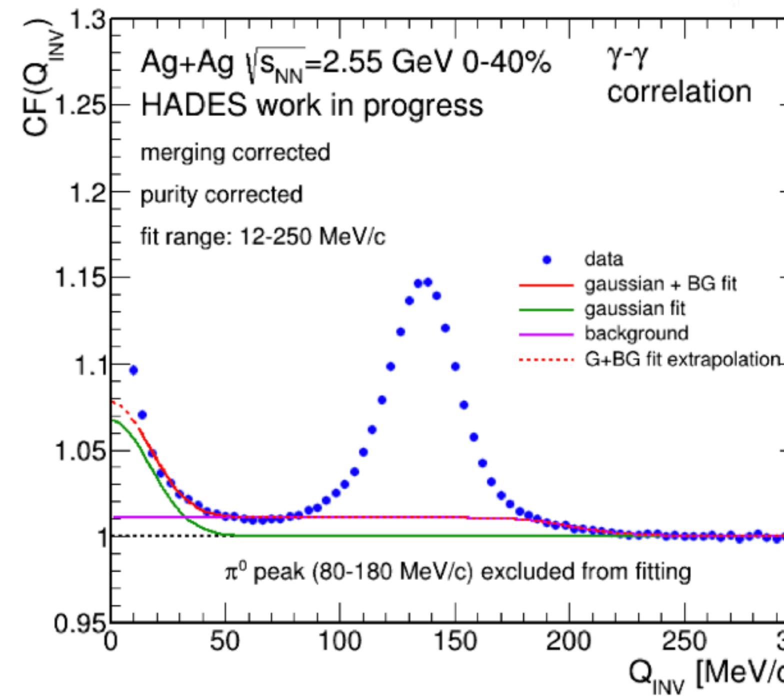
E-M probes at HADES

What if:
Non-interacting bosons → assuming 2 sources
(double gaussian or gaussian + some background)

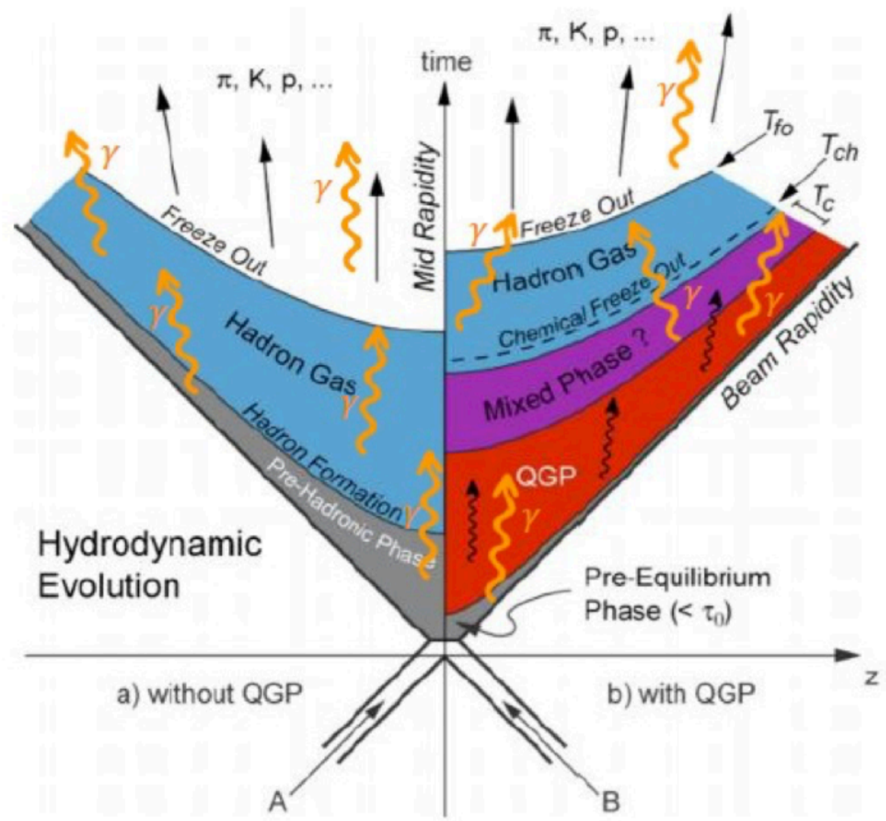
$$CF(Q_{inv}) = 1 + \lambda_1 e^{(-Q_{inv}{}^2 \cdot R_1{}^2)} + \lambda_2 e^{(-Q_{inv}{}^2 \cdot R_2{}^2)}$$

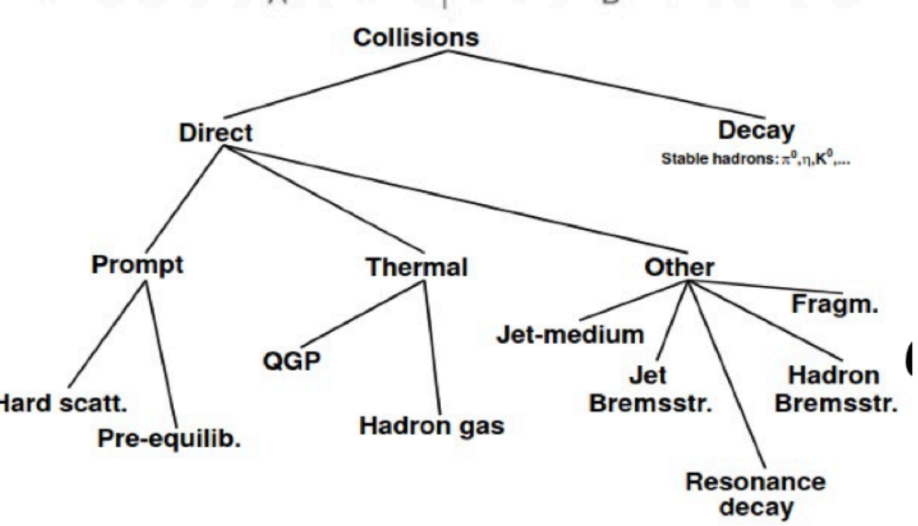
$$CF(Q_{inv}) = 1 + \lambda e^{(-Q_{inv}{}^2 \cdot R^2)} + \frac{a_0}{(1 + (a_1 \cdot Q_{inv})^{a_2})}$$





HADES work in progress

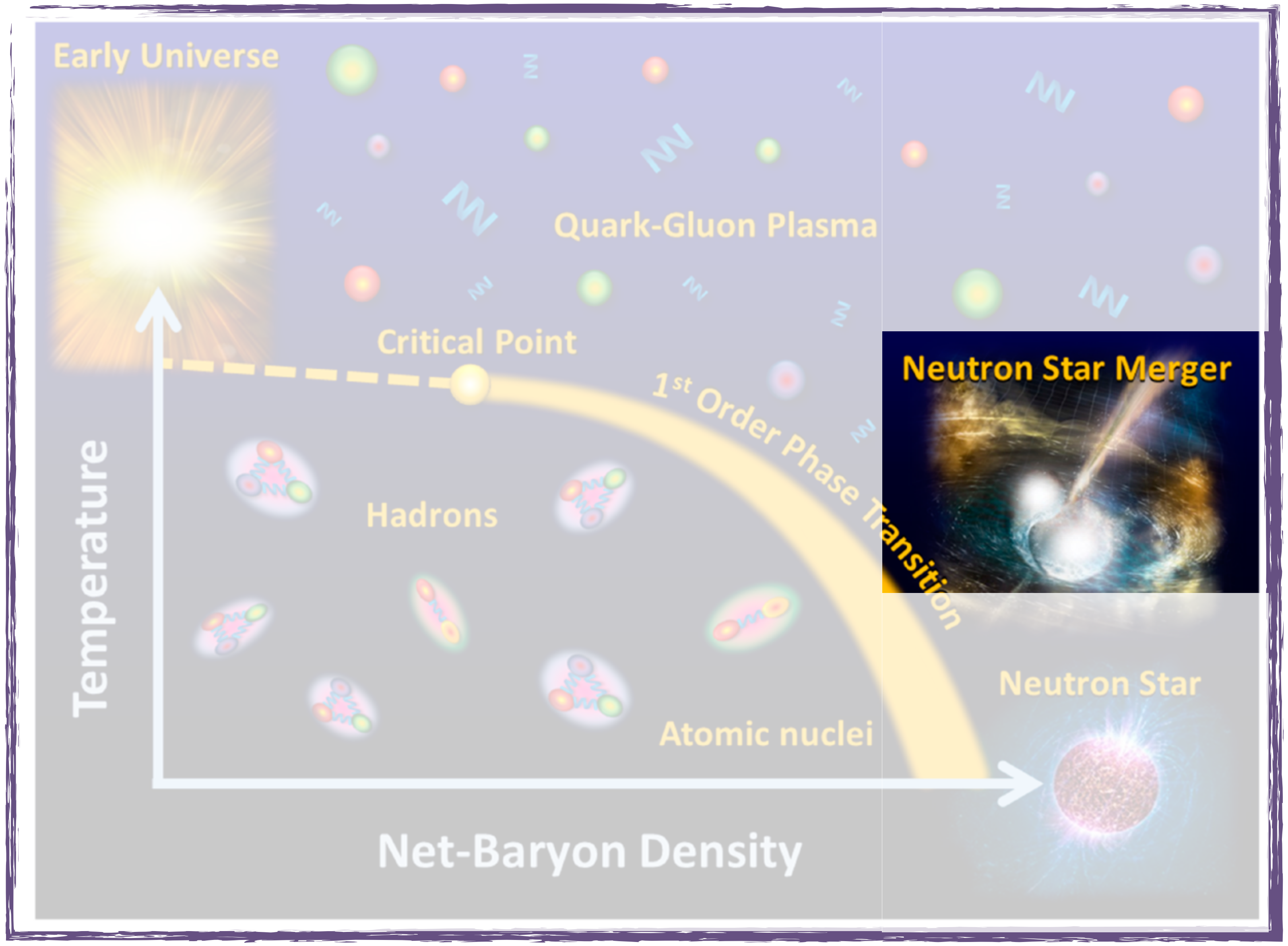




E-M probes signal various stages of the system's evolution;
Information about early stages (inaccessible for hadrons);
Access before freeze-out era;
A way to hunt for direct photons.

Neutron star mergers

Exploration of unknown QCD territory: still high μ_B



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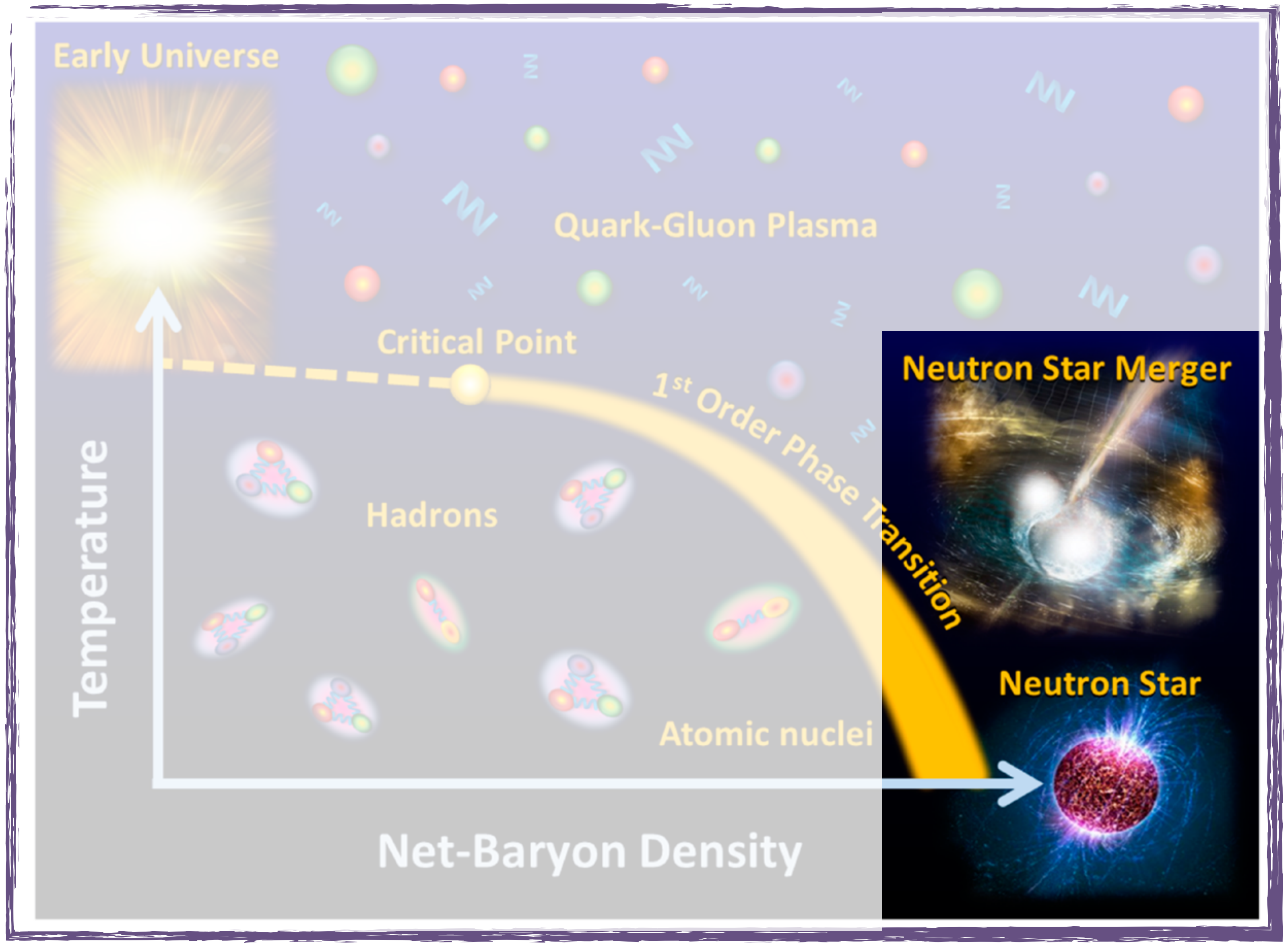
Temperature
T<50 MeV

Density
$n < 2 - 6n_0$

Reaction time
t ~ 10 ms
(GW170817)

Neutron star mergers

CBM and HADES future



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Temperature
T<50 MeV

Density
$n < 2 - 6n_0$

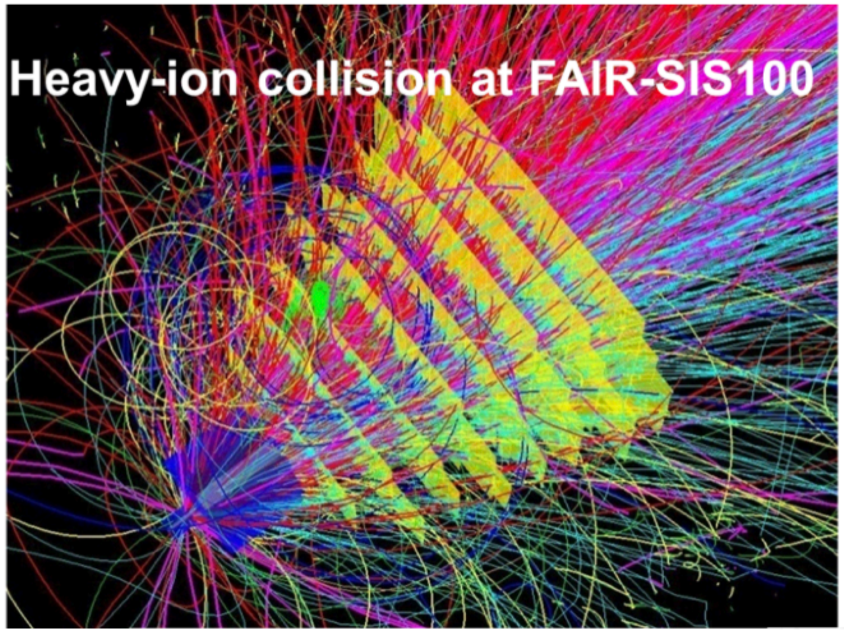
Reaction time
t ~ 10 ms
(GW170817)

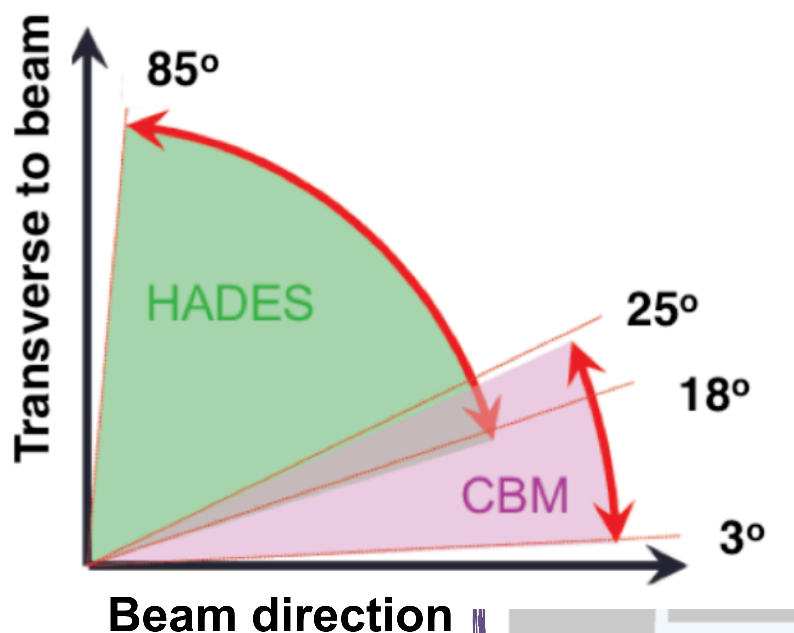
Temperature
T<10 MeV

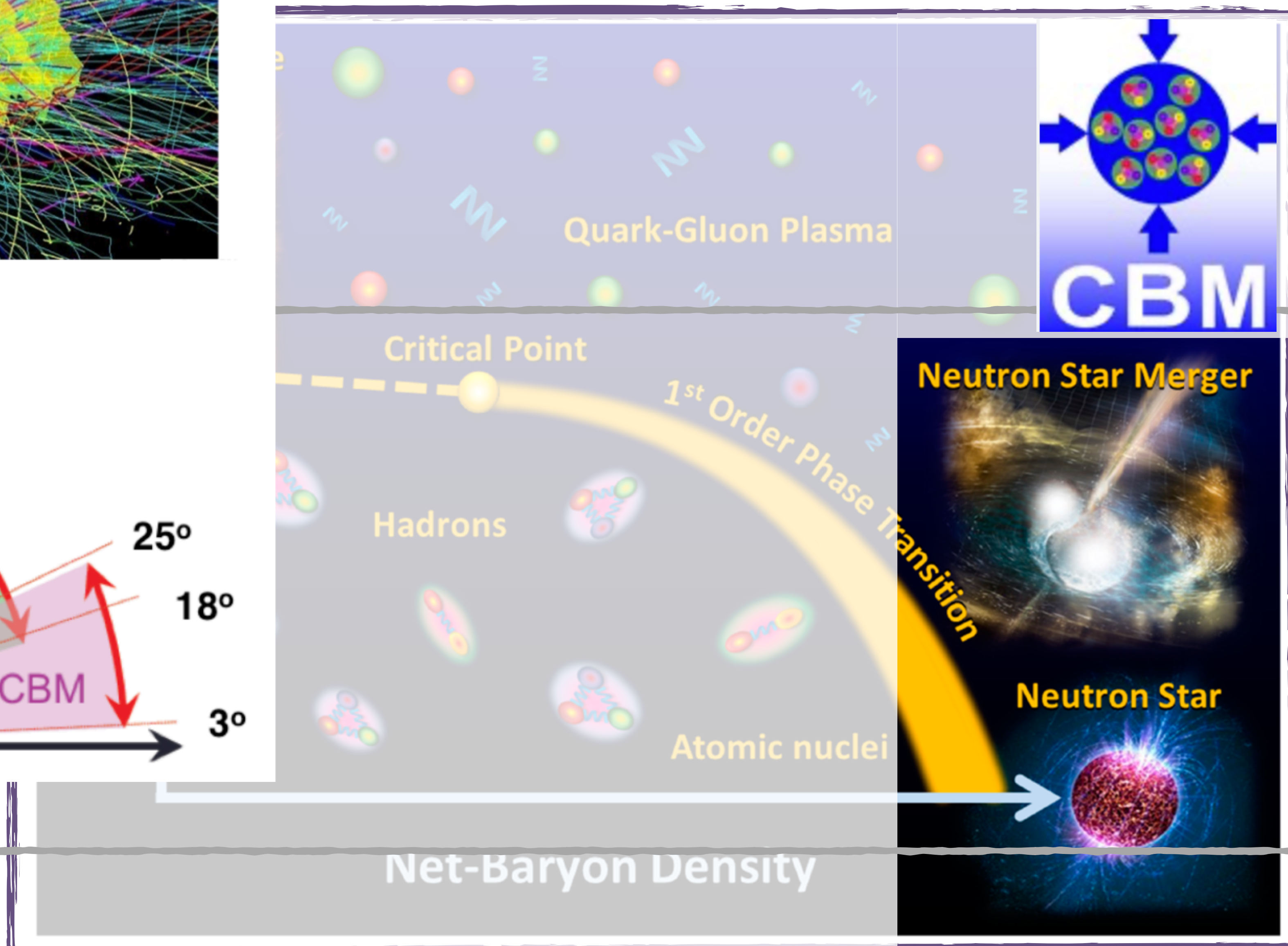
Density
$n < 10n_0$

Lifetime
t ~ infinity

CBM and HADES future







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Temperature
T<50 MeV

Density
$n < 2 - 6n_0$

Reaction time
t ~ 10 ms
(GW170817)

Temperature
T<10 MeV

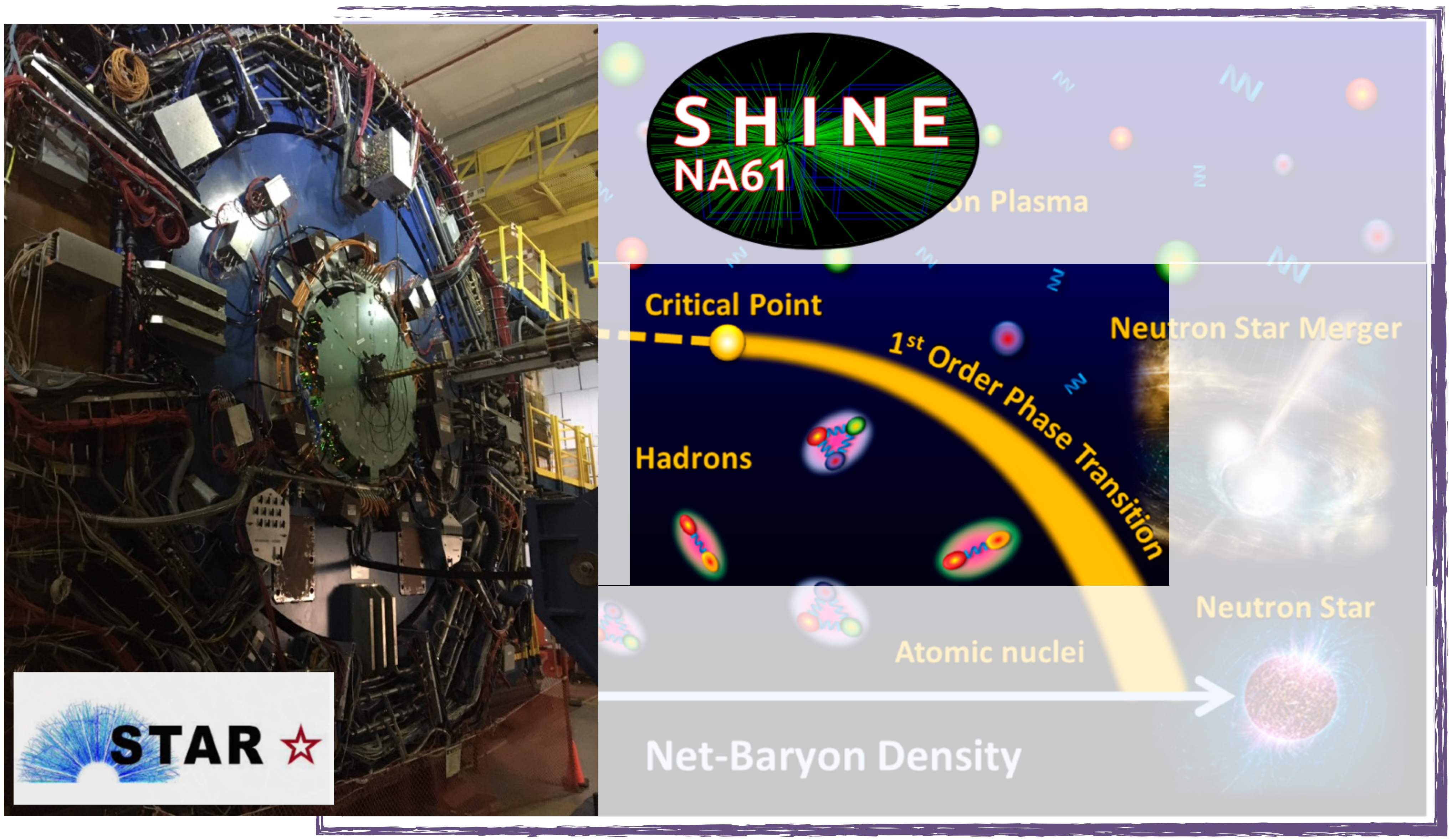
Density
$n < 10n_0$

Lifetime
t ~ infinity

SIS-100: Temperature T<120 MeV | Density $n < 8n_0$ | Reaction time t $\sim 10^{-23}$ s

Phase transitions

Exploration of unknown QCD territory: moderate μ_B



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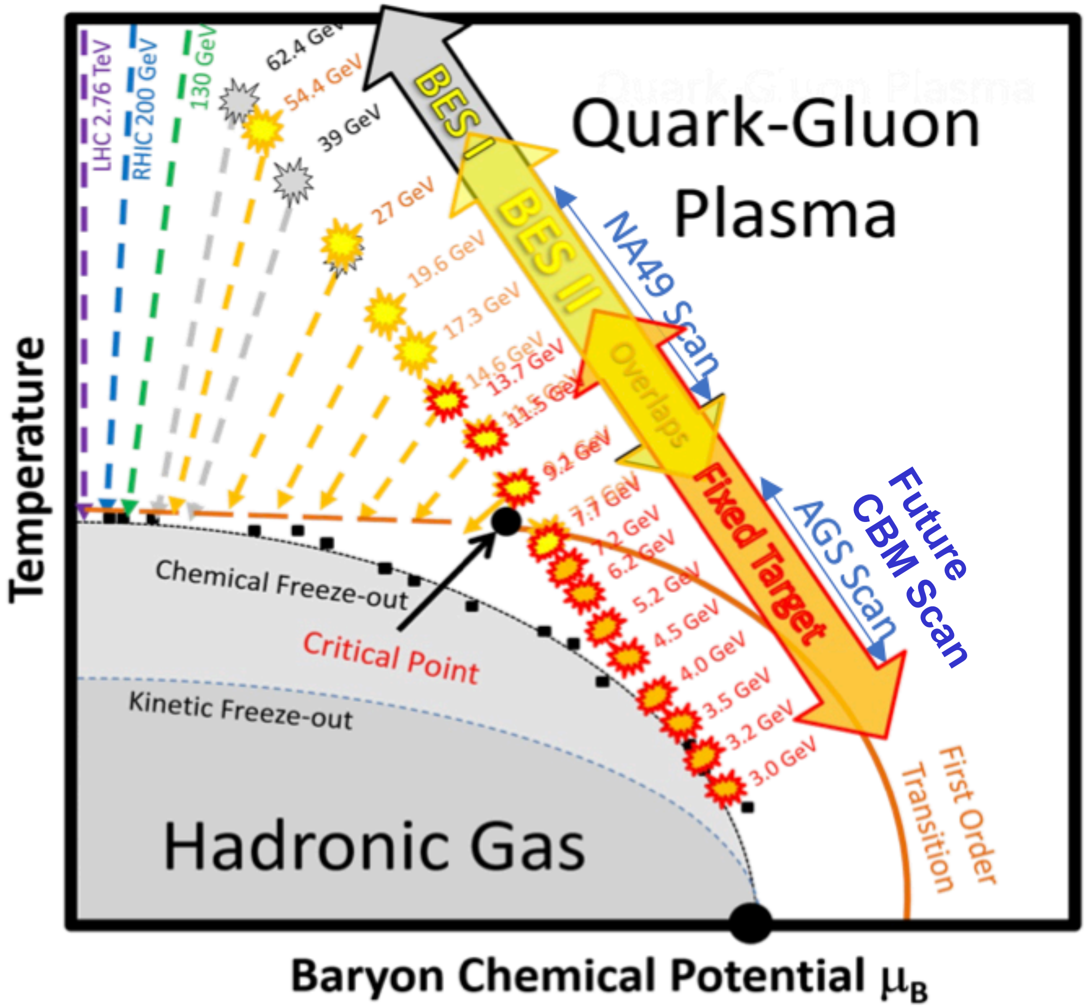
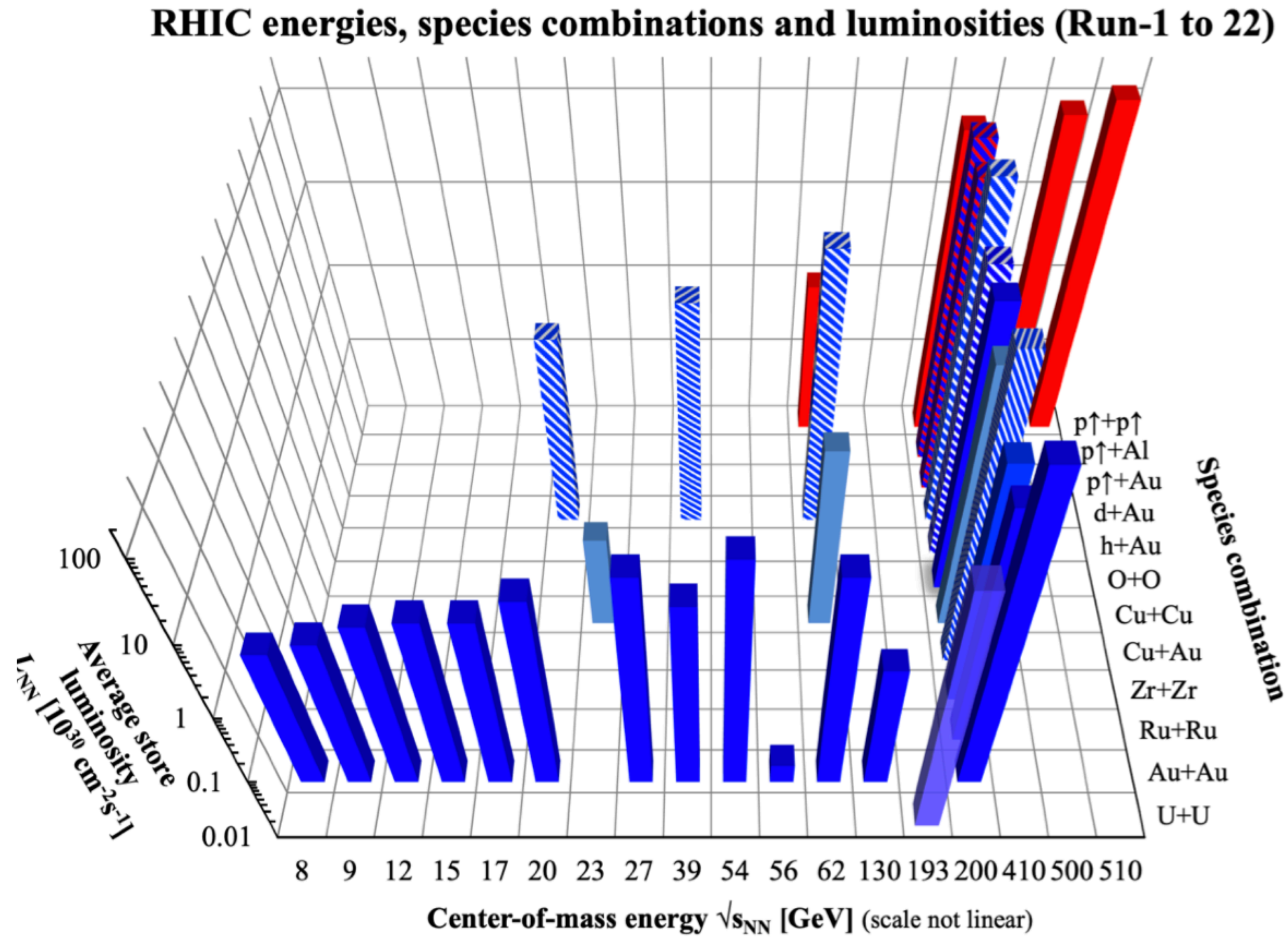
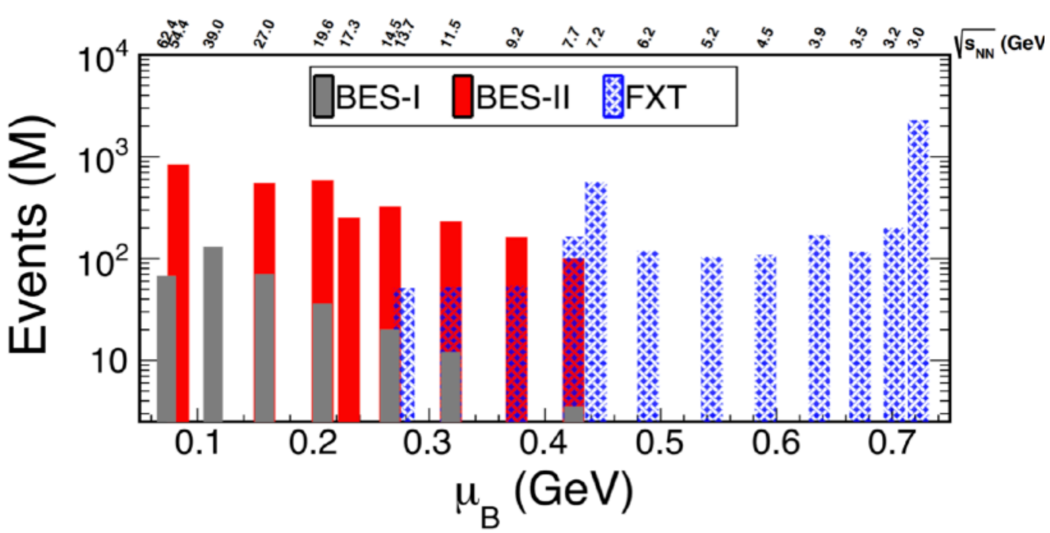
Searching for phase transitions signatures

Beam Energy Scan at STAR





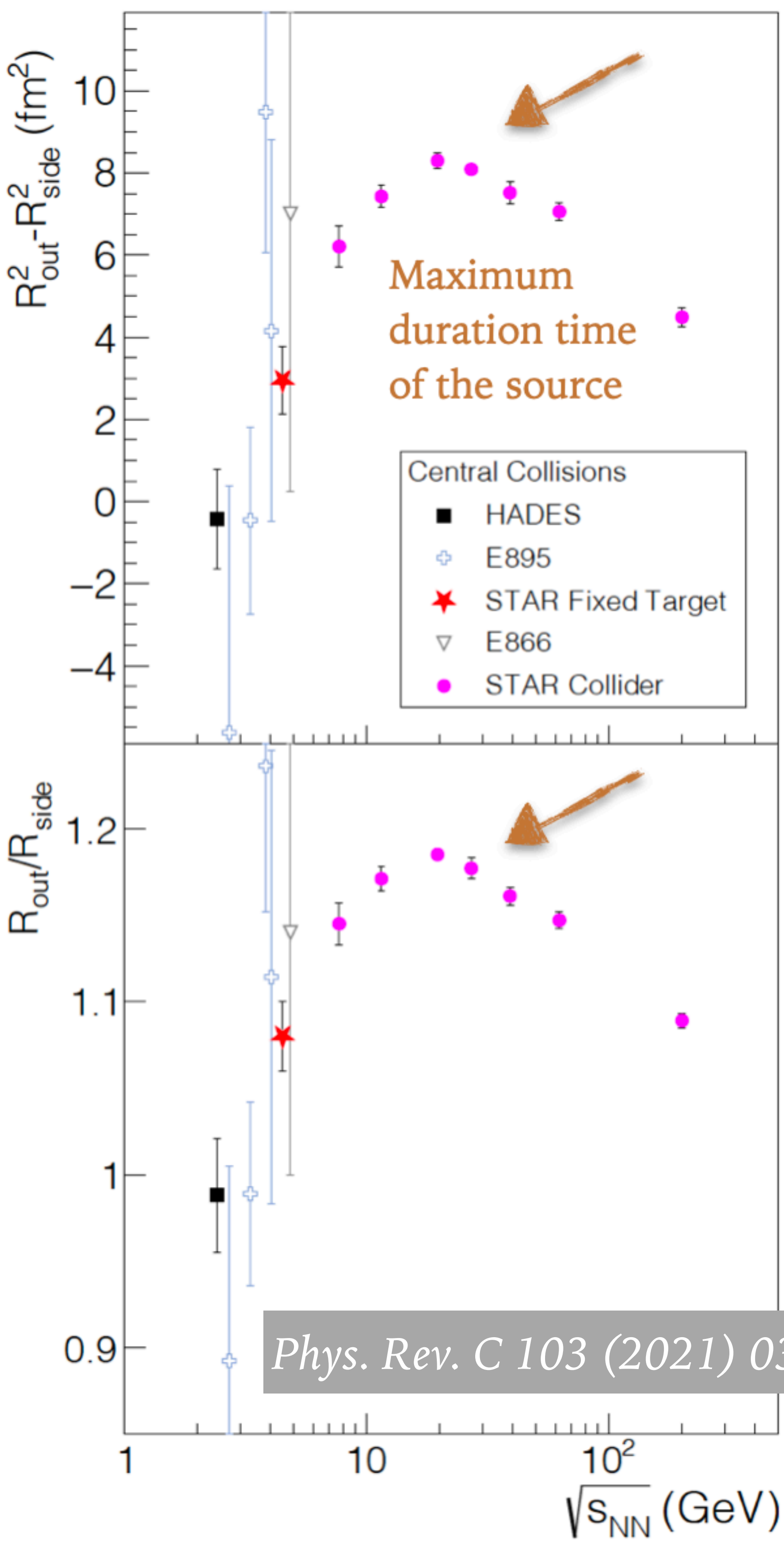


Beam Energy Scan: Au+Au 3-62.4 GeV

1. Search for **turn-off** of **QGP** signatures
2. Search for signals of the **first-order phase transition**
3. Search for QCD **critical point**

Fixed-Target Program: Au+Au: 3.0-13.7 GeV

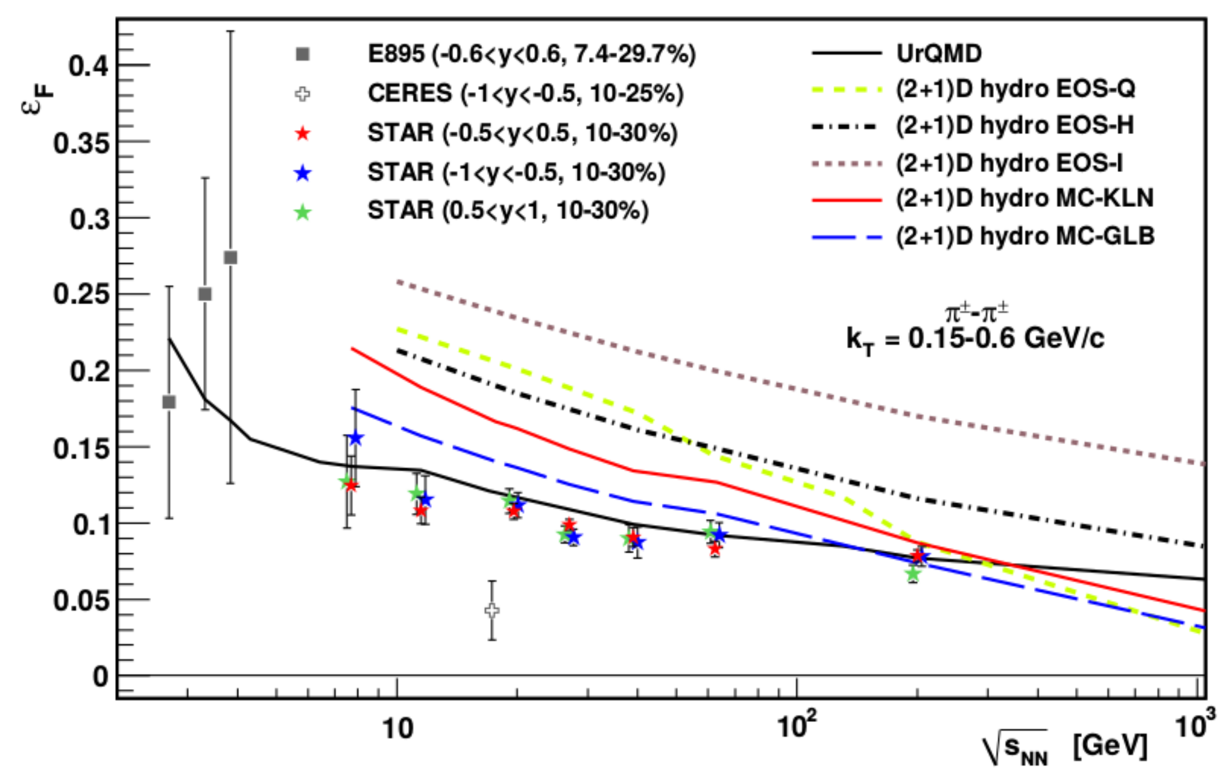
Looking for phase transition



Phys. Rev. C 103 (2021) 034908

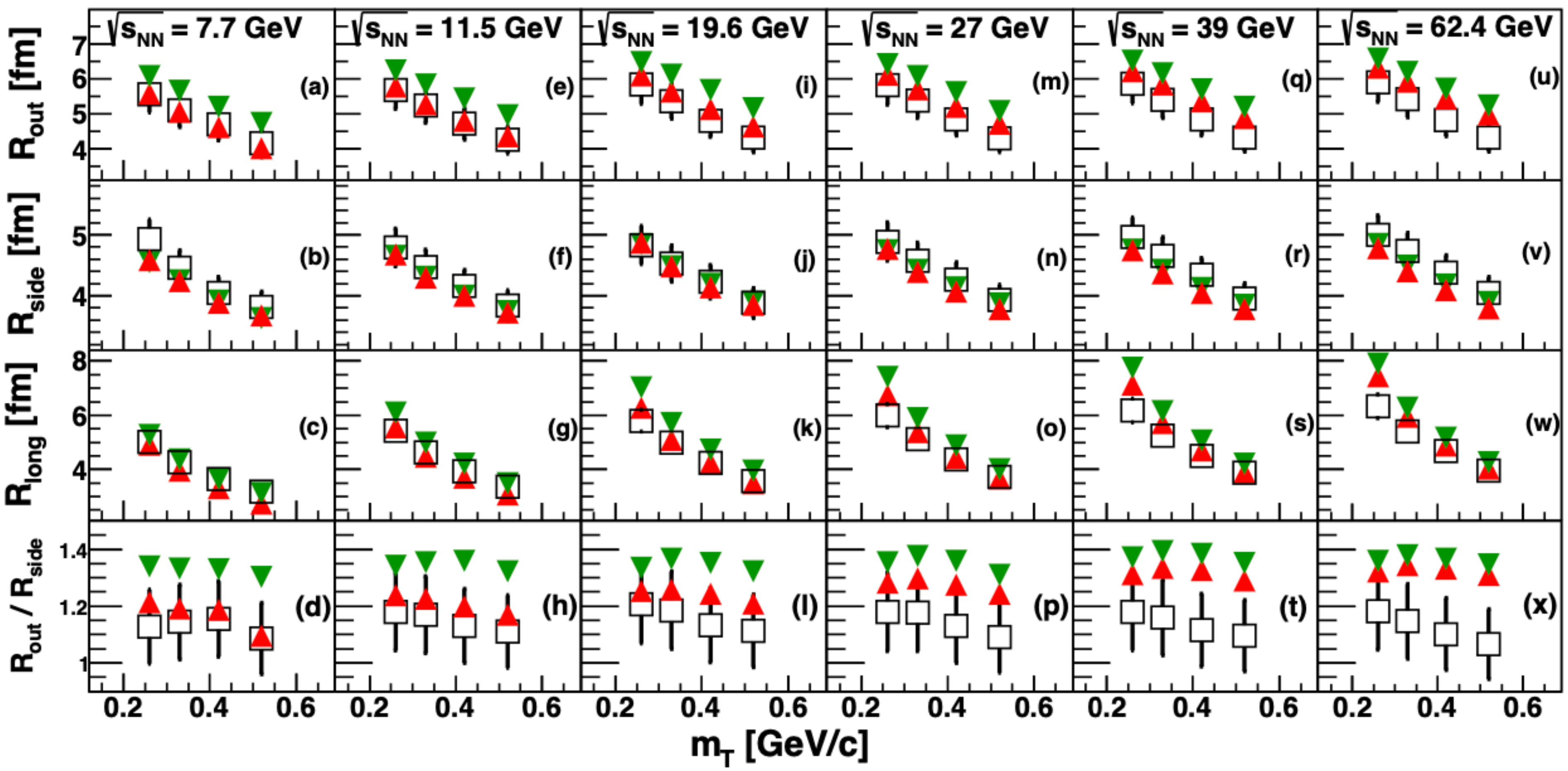
- R_{side} spatial source evolution in the transverse direction
- R_{out} related to spatial and time components
- R_{out}/R_{side} signature of phase transition
- $R_{out}{}^2$- $R_{side}{}^2 = \Delta\tau^2\ \beta_t{}^2$; $\Delta\tau$ – emission time
- R_{long} temperature of kinetic freeze-out and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

System evolves faster in the reaction plane



Phys. Rev. C 92 (2015) 14904

How to measure phase transition?



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)

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

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

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

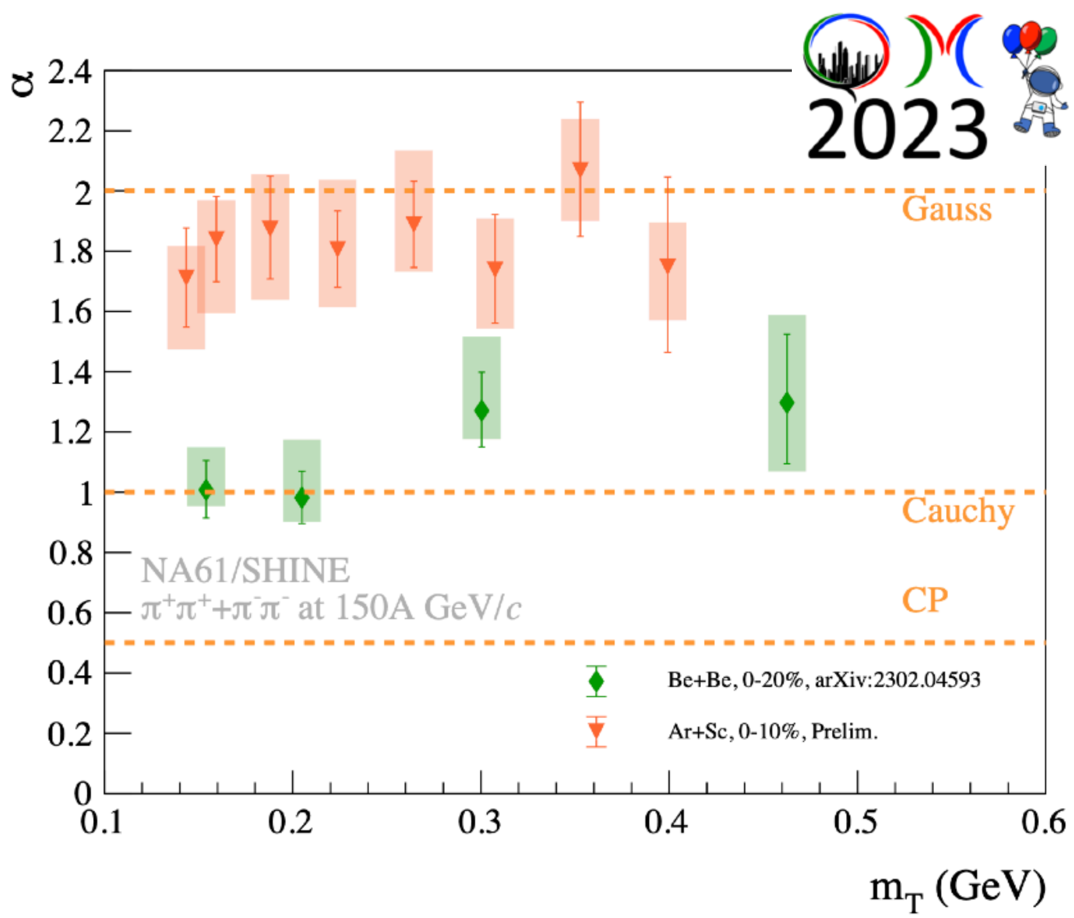
How to measure a phase transition? CP?

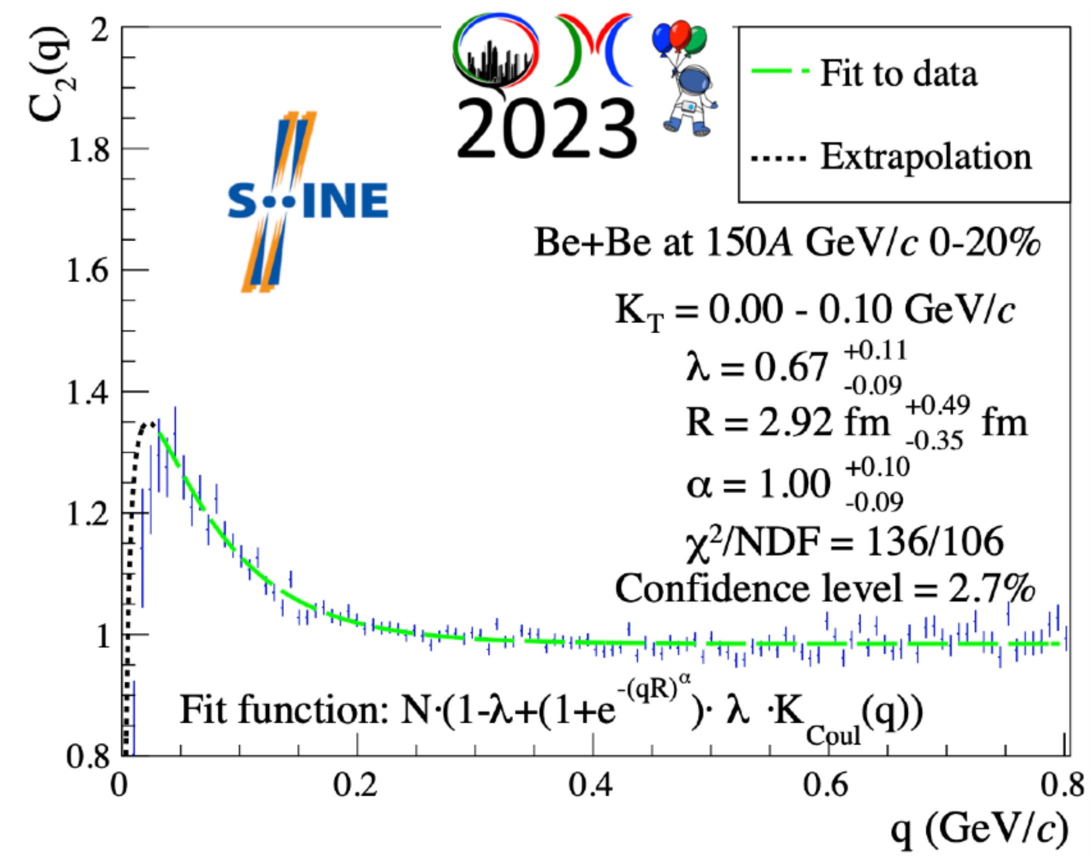
Levy-stability index

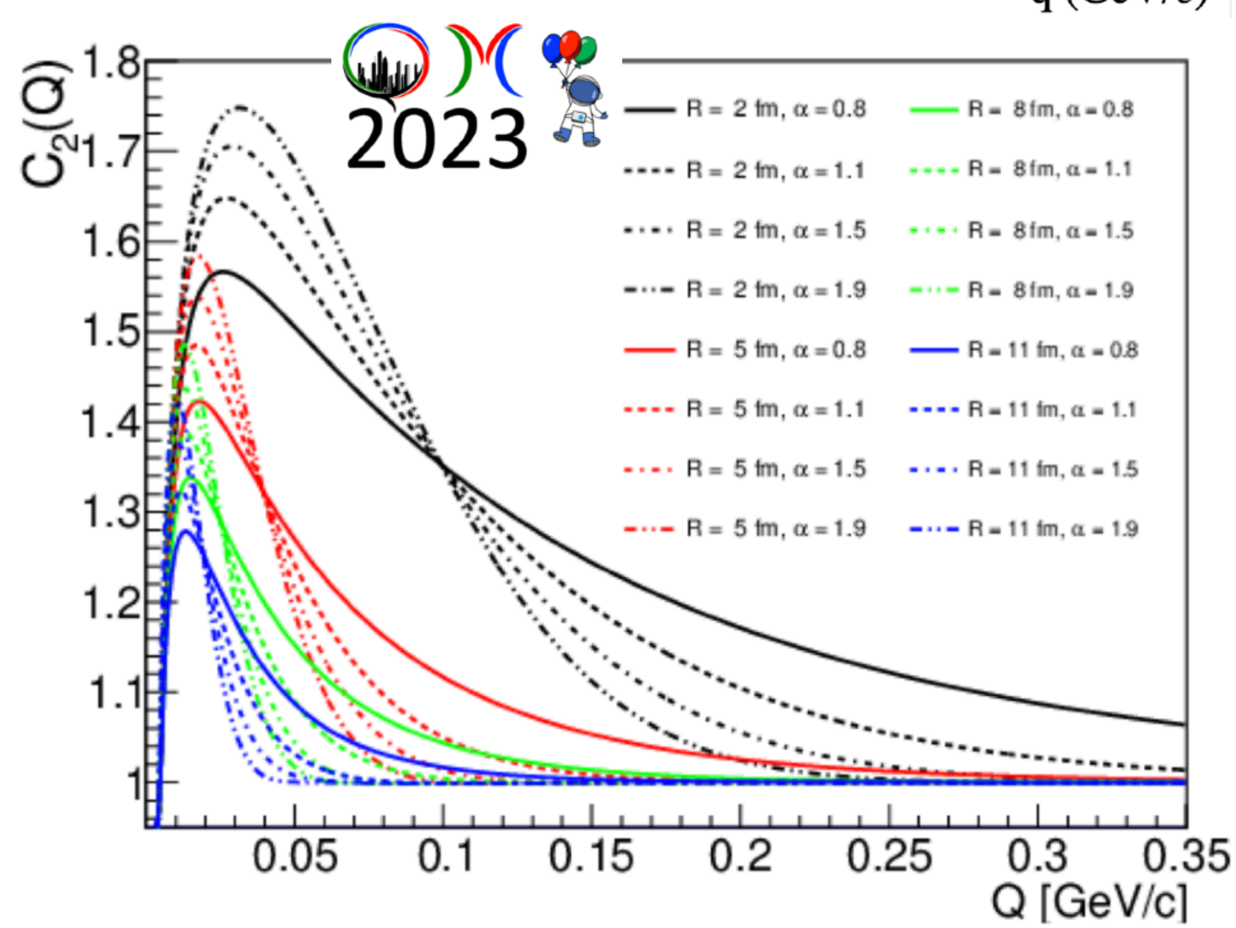
$\alpha = 2$ - Gauss

$\alpha = 1$ - Cauchy

$\alpha = 0.5$ - expected near the CP





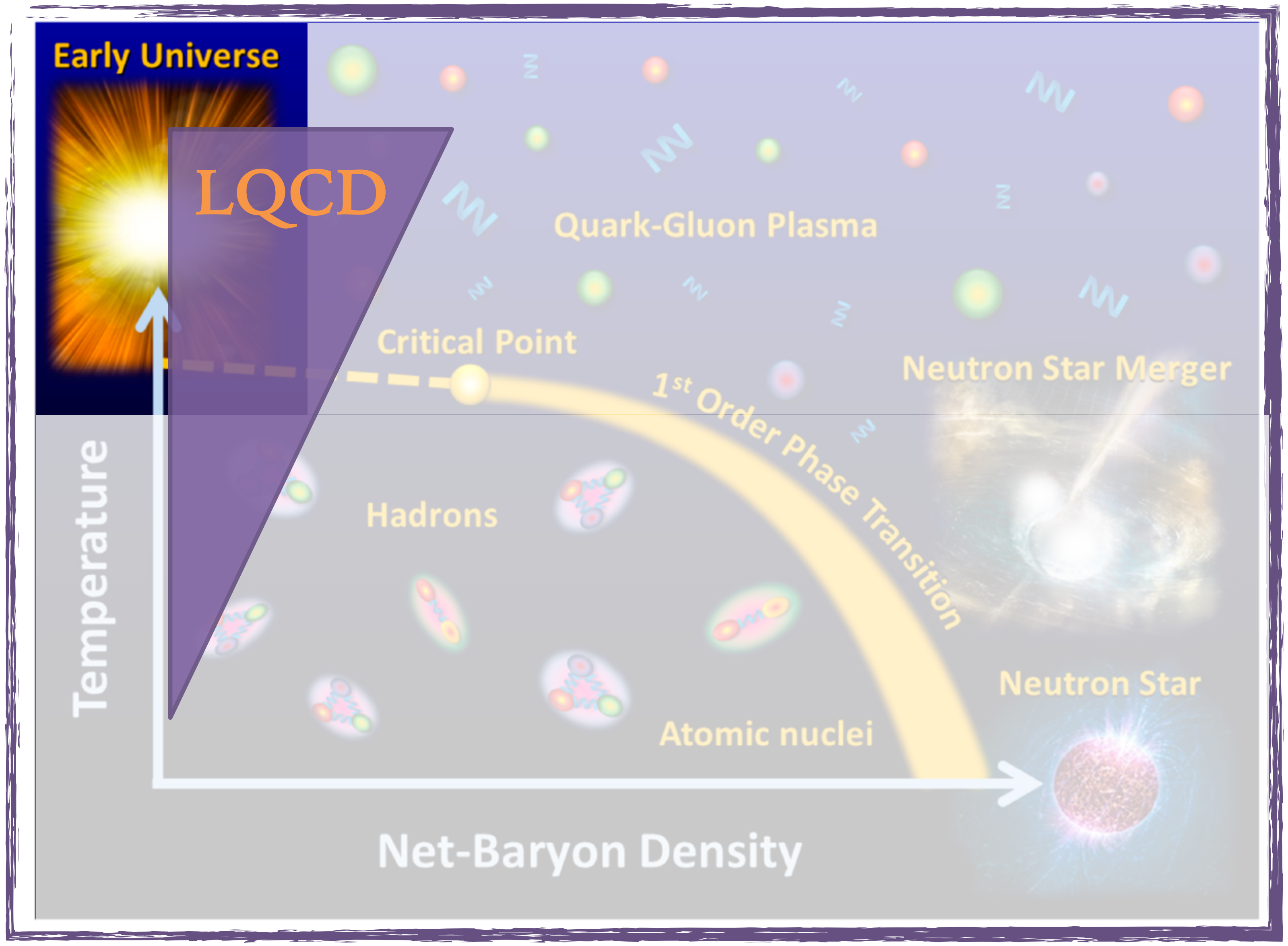


Levy-stability index

Far away from the CP

Early Universe

Exploration of ~~un~~**known** from lattice QCD: vanishing μ_B

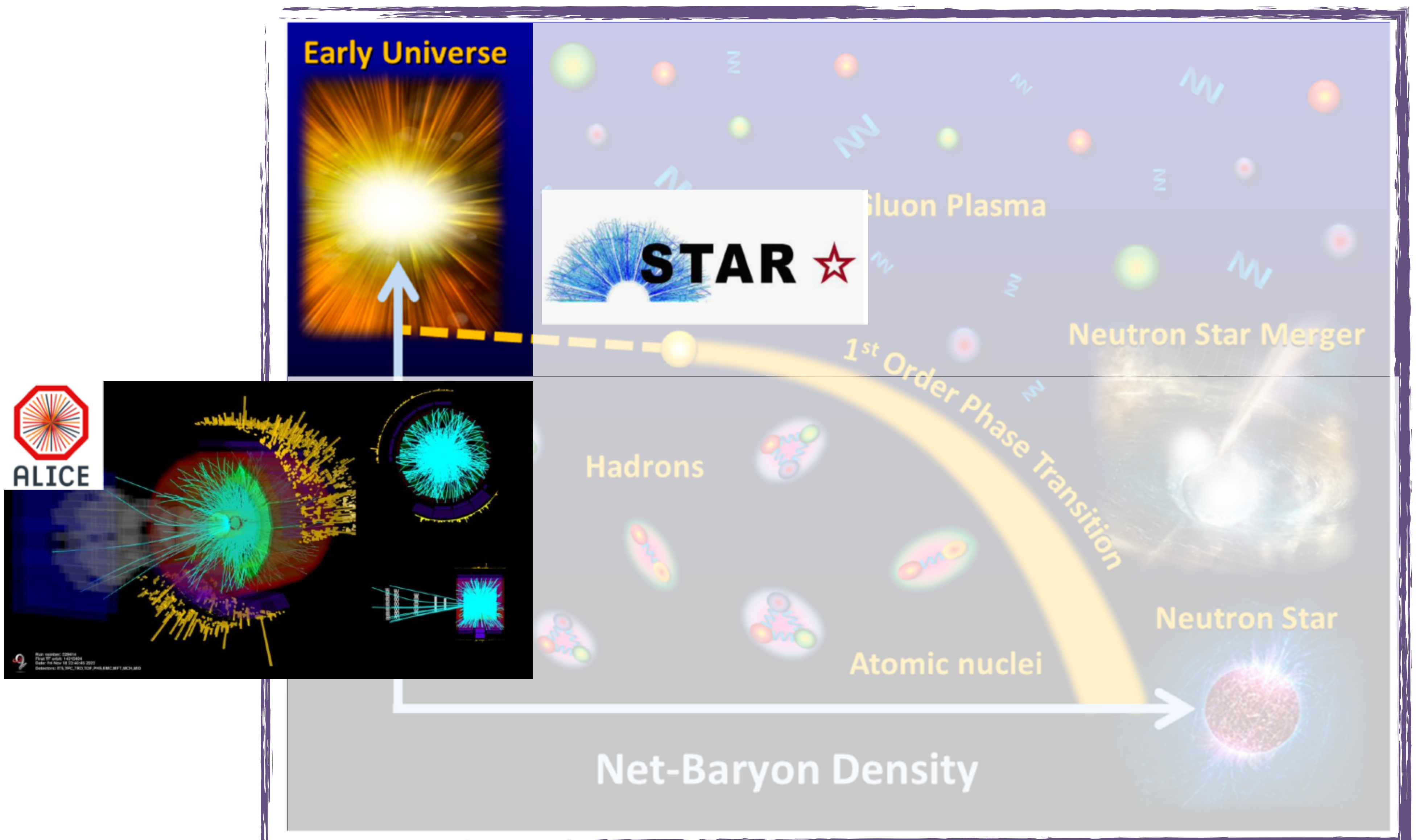


https://www.researchgate.net

Studies of Early Universe

Early Universe

Exploration of ~~un~~**known** from lattice QCD: vanishing μ_B

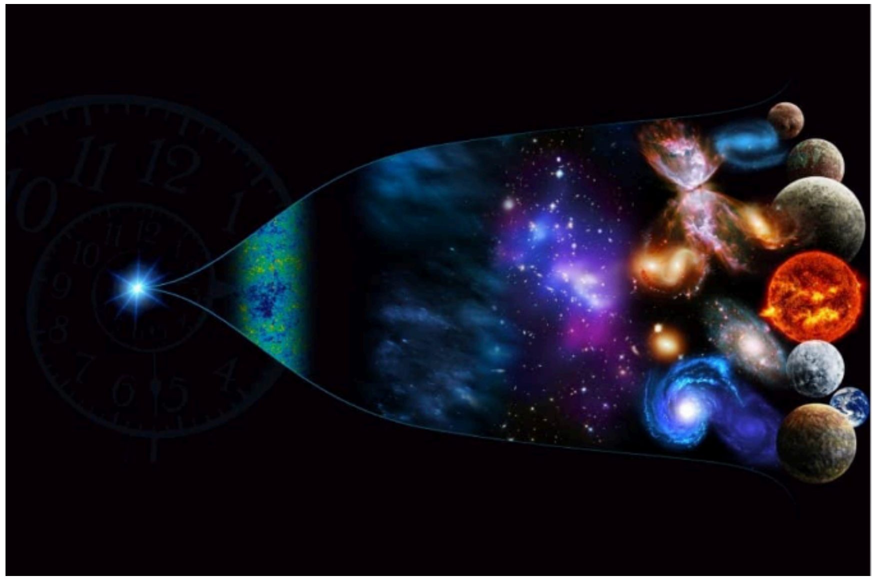


https://www.researchgate.net

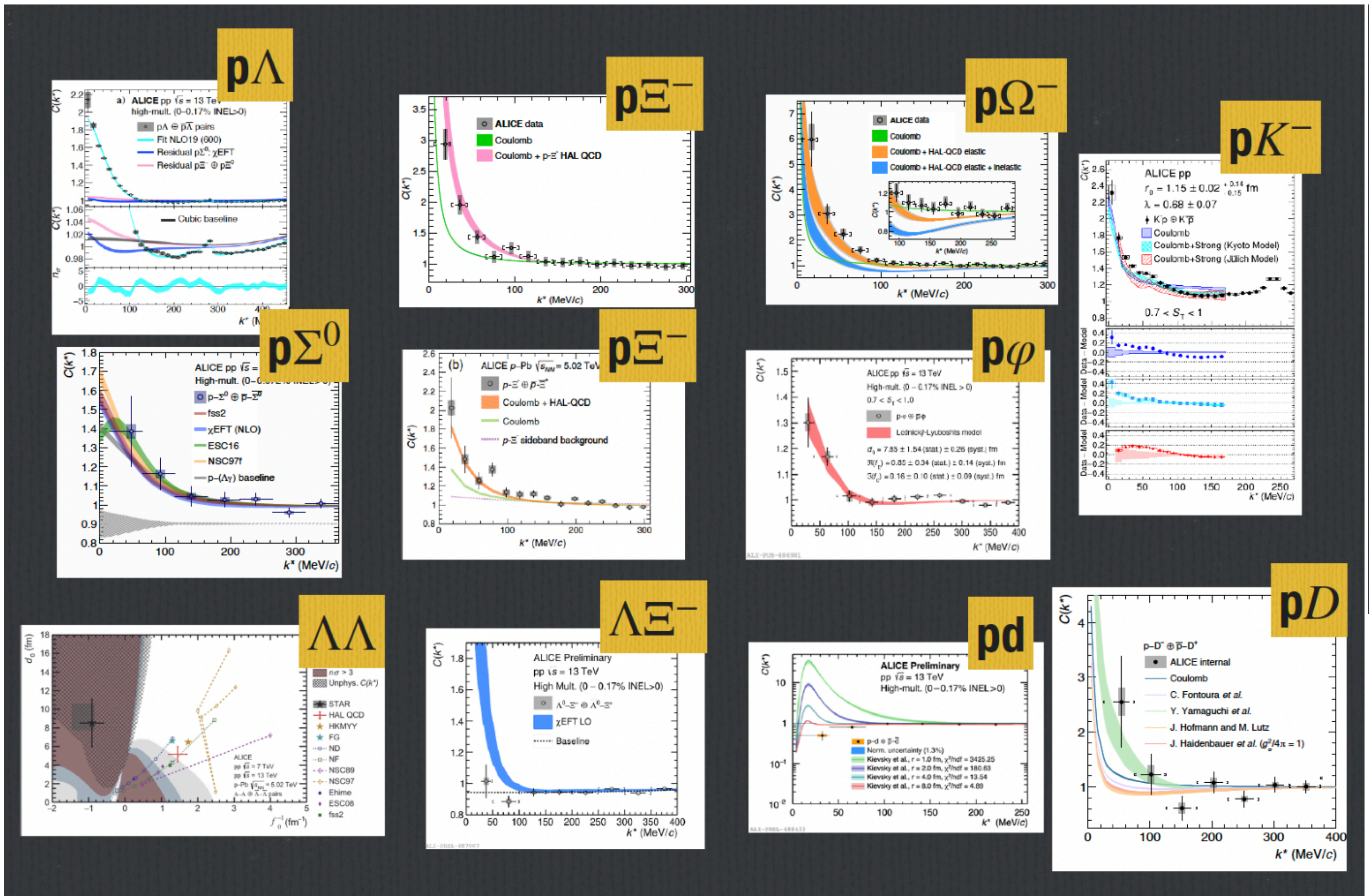
Studies of Early Universe

Early Universe, vanishing μ_B

- Probe the condition ~Early Universe,
- Very high abundances of particles produced,
- Statistical heaven to study exotic particles,
- Studies of heavy-flavor,
- Incredible laboratory of anti-matter.



https://insidetheperimeter.ca/the-universe-before-atoms/



CATS: EPJA 78 (2018)
Projector: EPJC 82 (2022)
Review 1: Prog.Part.Nucl.Phys. 112 (2020)
Review 2:Ann.Rev.Nucl.Part.Sci. 71 (2021)
p-ϕ bound state: arXiv:2212.12690
p-K: PRL 124 (2020) 092301
p-K: PLB 822 (2021), EPJC (2022)
p-p, p-Λ, Λ-Λ: PRC 99 (2019) 024001
Λ-Λ: PLB 797 (2019) 134822
p-Ξ: PRL. 123 (2019)
p-Ξ, p-Ω : Nature 588 (2020) 232–238
p-Σ⁰: PLB 805 (2020) 135419
p-φ: PRL 127 (2021)
$p-\bar{p}, \Lambda-\bar{\Lambda}, p-\bar{\Lambda}$: PLB 829 (2022)
p-Λ: PLB 832 (2022) 137272
$\Lambda-\Xi$: PLB 137223 (2022)
D-p: PRD **106**, 052010 (2022)
ppp, ppΛ: arXiv:2206.03344

Summary

Collisions of (heavy) ions give us access to:

High T, low μB

- Cross-over to QGP → Investigations of properties of QGP
- LQCD: no CP indication for $\mu_B/T < 3$

Lower T, high μB

- Phase structure?
  - first-order phase transition?
  - CP?
  - New phases of QCD?
- Characterization of dense matter,
- EOS?
- Properties of hadrons?

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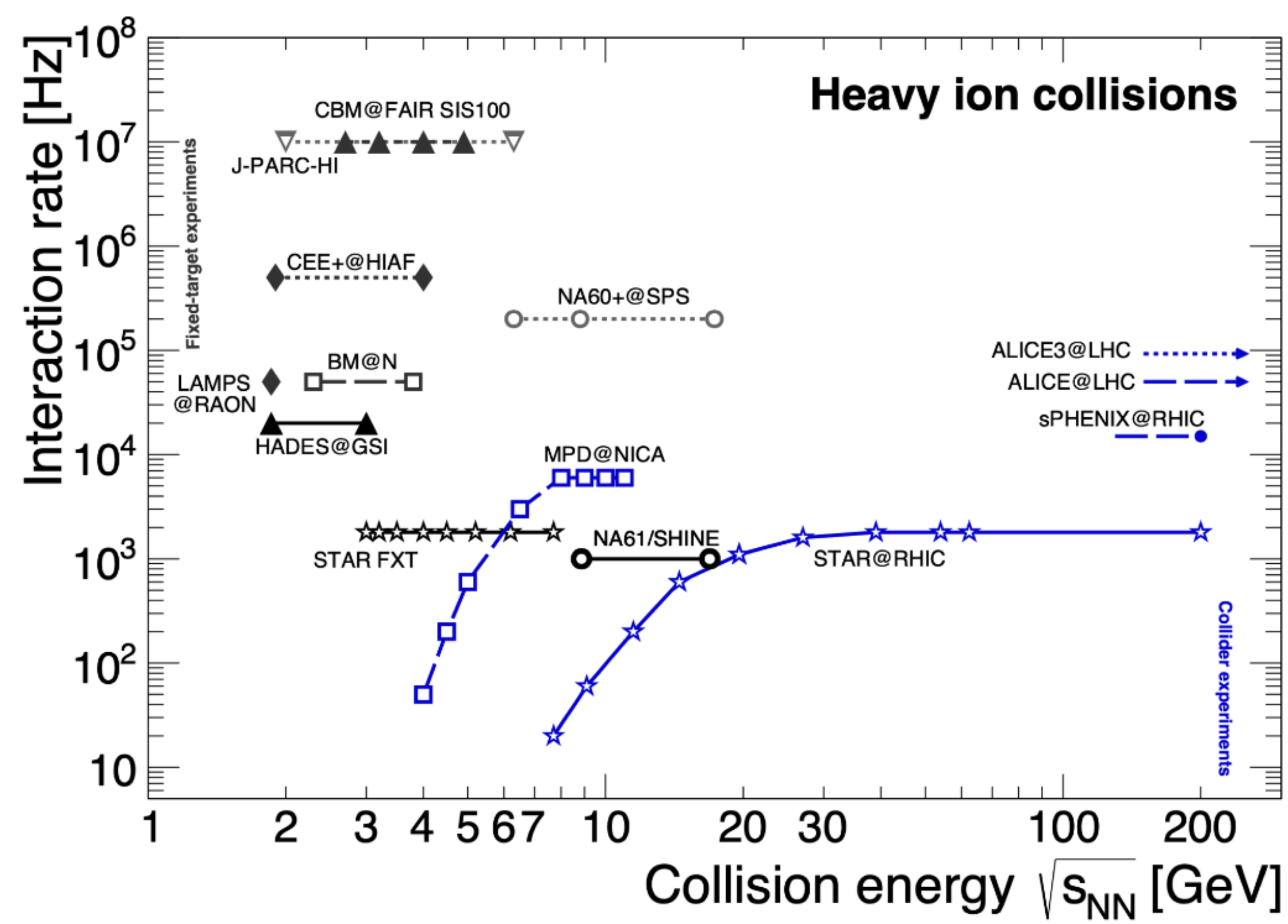
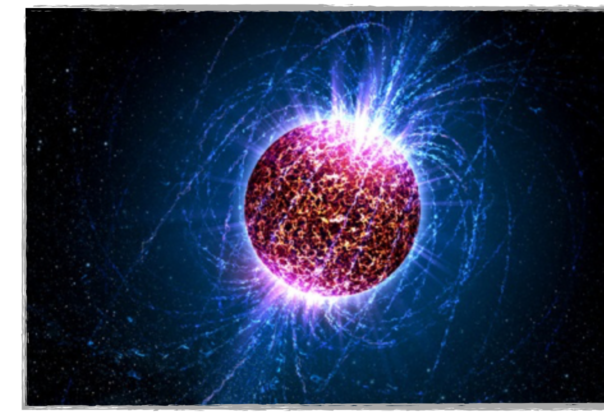
Thank you



NSM and HIC

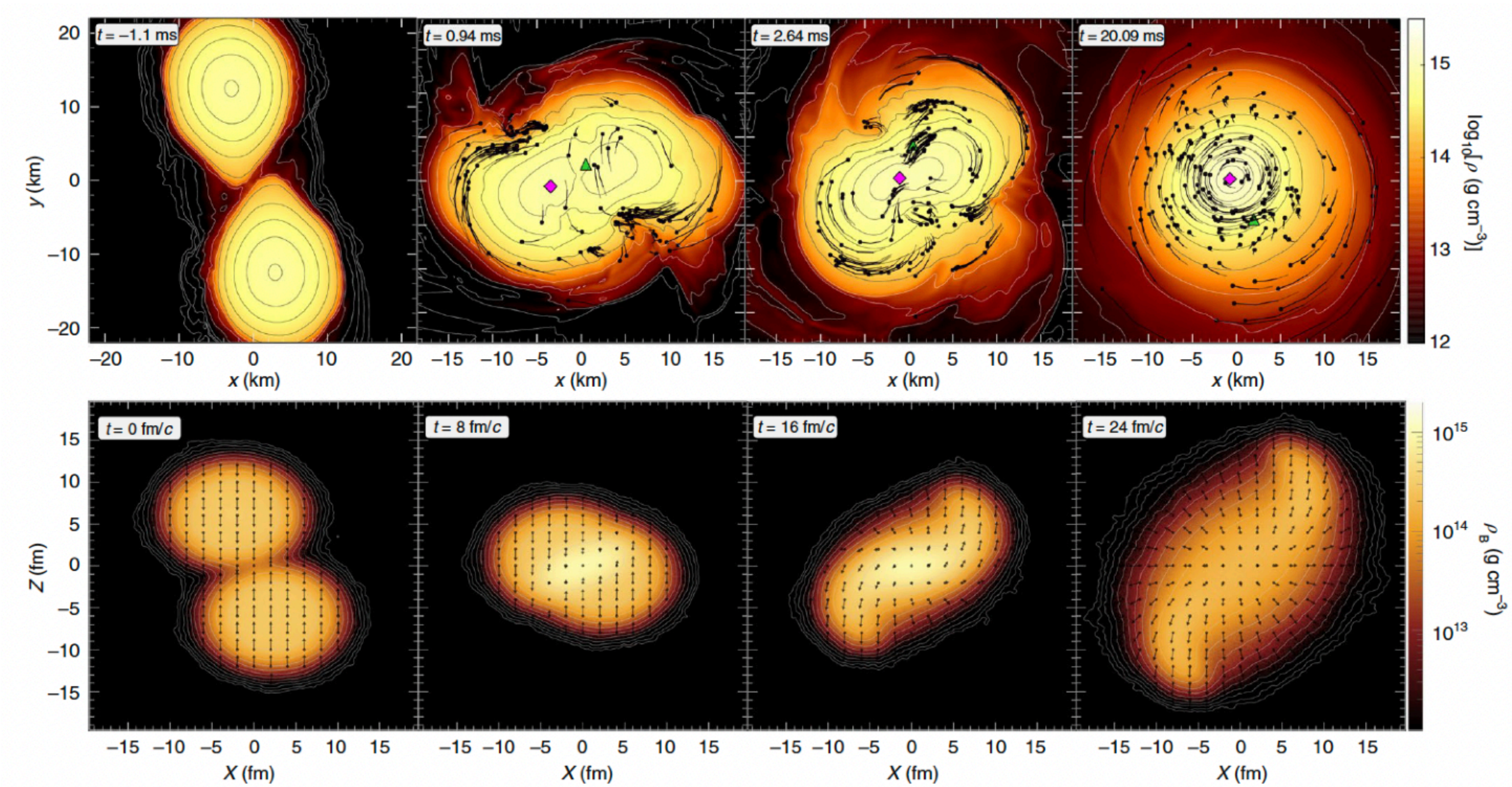


Top row: simulation of **neutron stars mergers**
2 neutron stars of 1.35 M⊙ each,
merging into a single object (2R ∼ 10 km, $n \simeq 5n_0$, $T \leq 20$ MeV).
Overlap region: $t \simeq 20$ms, $n \simeq 2n_0$, $T \simeq 75$ MeV

- max. temperature
- max. density

Bottom row: non-central-**collision Au+Au** at $\sqrt{s_{NN}} = 2.42$ GeV
$n \simeq 3n_0$, $T \simeq 80$ MeV

HADES, Nature Phys. 15, 1040–1045 (2019)



Similar **densities** and **temperatures** are achieved.

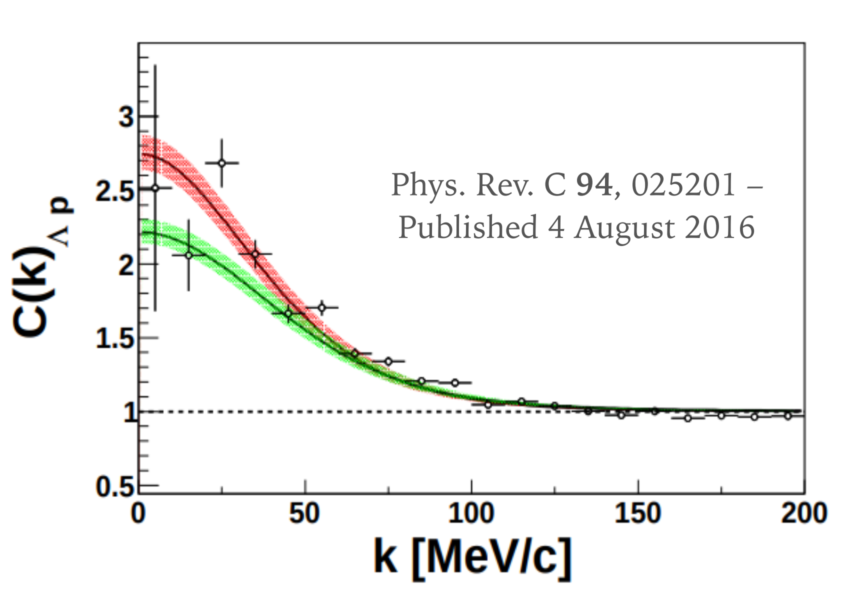
Space and **time** scales are vastly different (km - NS, fm - HIC).
The collision events differ in duration by 20 orders of magnitude.

Lednicky-Lyuboshitz model

Model		$f_0^{S=0}$ (fm)	$f_0^{S=1}$ (fm)	$d_0^{S=0}$ (fm)	$d_0^{S=1}$ (fm)	n_σ
ND [77]		1.77	2.06	3.78	3.18	1.1
NF [78]		2.18	1.93	3.19	3.358	1.1
NSC89 [79]		2.73	1.48	2.87	3.04	0.9
NSC97 [80]	a	0.71	2.18	5.86	2.76	1.0
	b	0.9	2.13	4.92	2.84	1.0
	c	1.2	2.08	4.11	2.92	1.0
	d	1.71	1.95	3.46	3.08	1.0
	e	2.1	1.86	3.19	3.19	1.1
	f	2.51	1.75	3.03	3.32	1.0
ESC08 [81]		2.7	1.65	2.97	3.63	0.9
χEFT	LO [25]	1.91	1.23	1.4	2.13	1.8
	NLO [26]	2.91	1.54	2.78	2.72	1.5
Jülich	A [82]	1.56	1.59	1.43	3.16	1.0
	J04 [83]	2.56	1.66	2.75	2.93	1.4
	J04c [83]	2.66	1.57	2.67	3.08	1.1

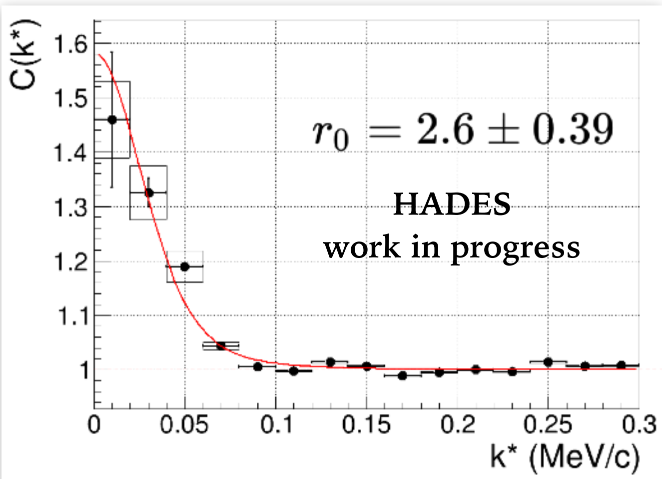
S. Acharya *et al.* Phys. Rev. C 99, 024001 – Published 13 Feb 2019
https://doi.org/10.1103/PhysRevC.99.024001

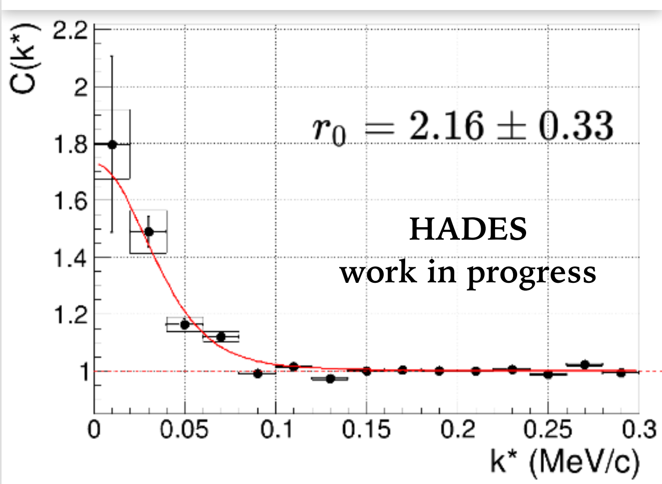
parameter scan boundaries : f_0 [0.01, 5.0], d_{0s} [0.01, 2.0] and d_{0t} [0.01, 5.0]

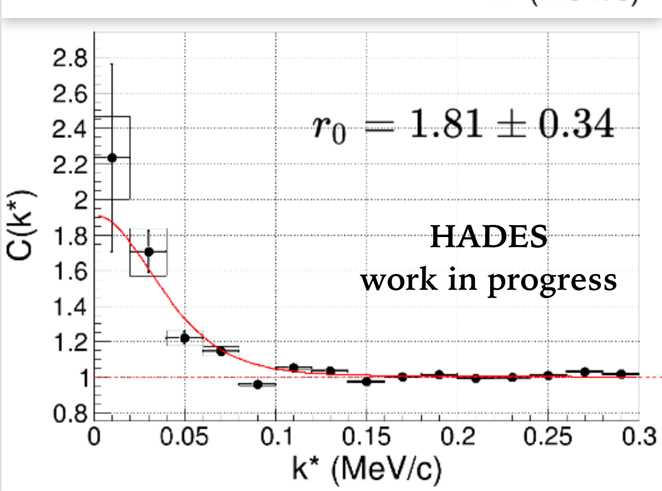


Parameters	p-Nb (LO)	p-Nb (NLO)
f_{0s}	1.91 fm	2.91 fm
d_{0s}	1.40 fm	2.78 fm
f_{0t}	1.23 fm	1.54fm
d_{0t}	2.13 fm	2.72fm
r_0	1.71±0.10	1.62±0.02

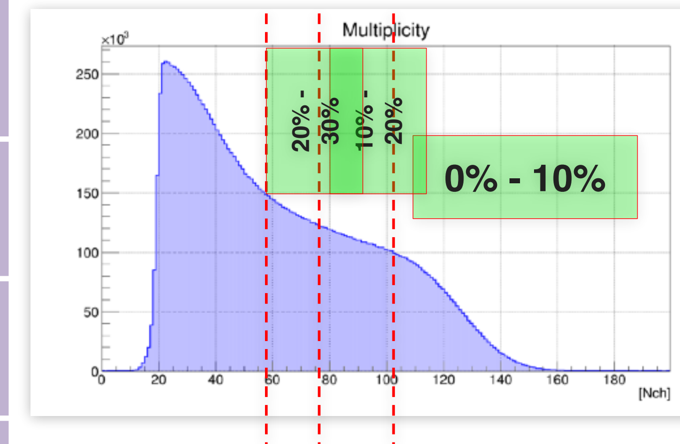
Results: centrality dependence

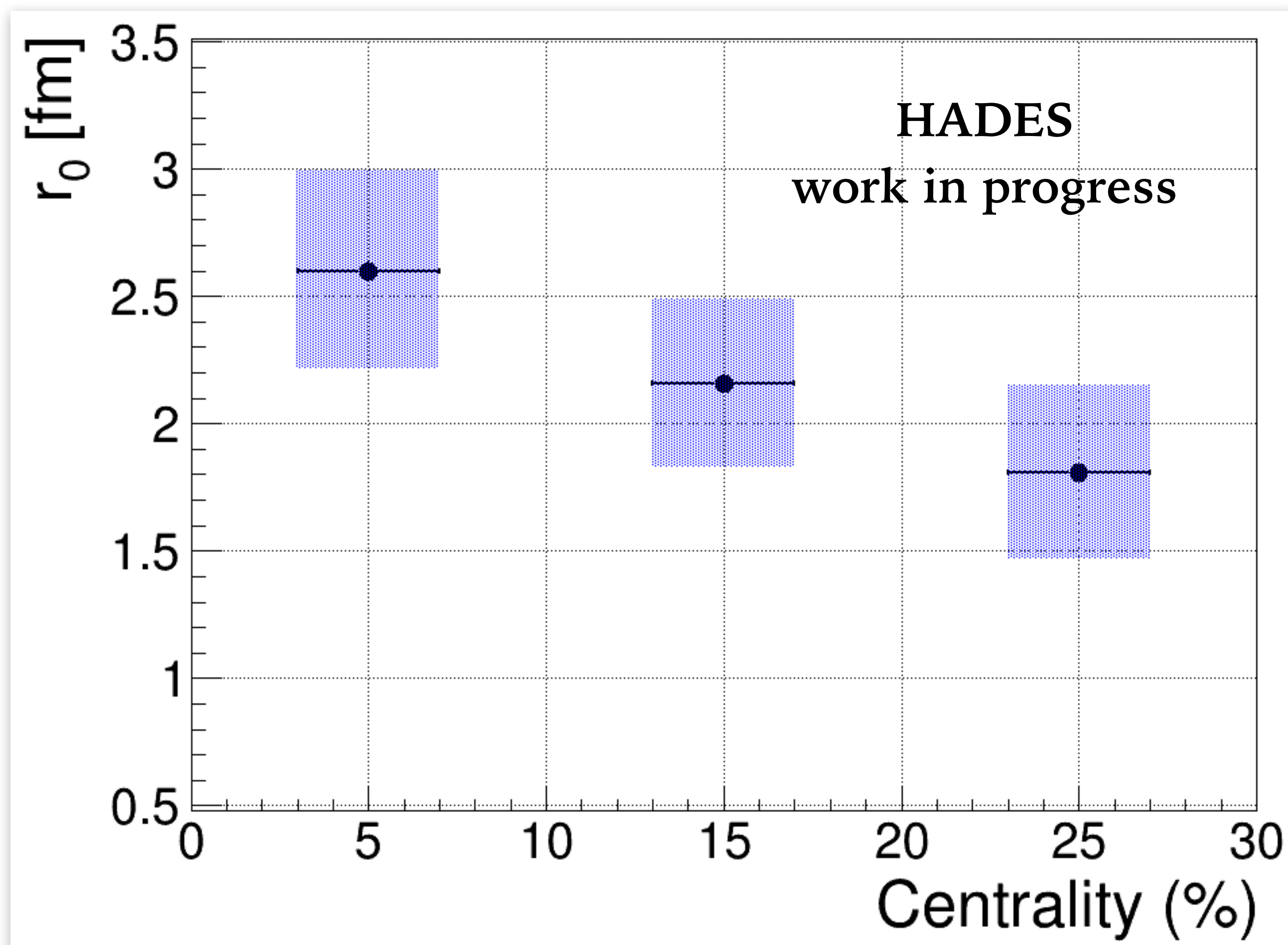




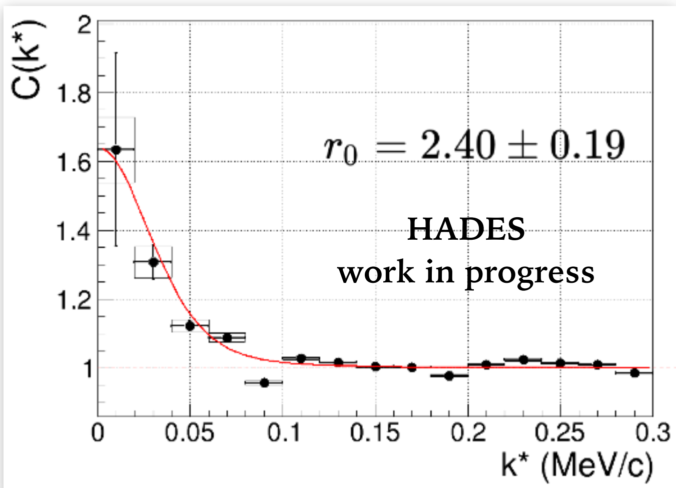


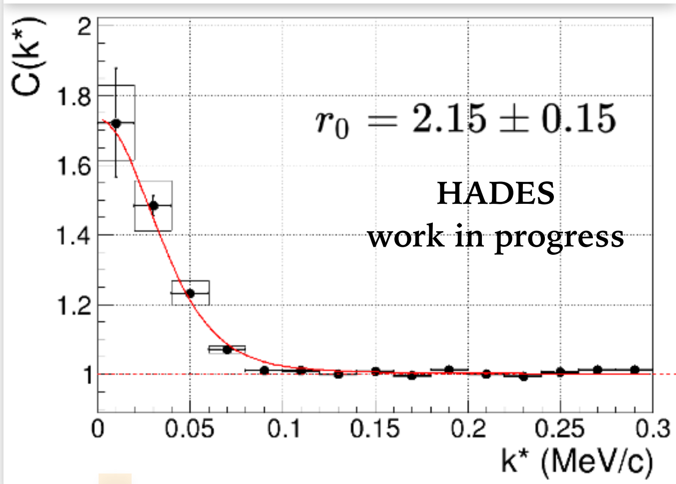
Centrality	Systematic Uncertainty
0 - 10 %	15.30 %
10 - 20 %	15.49 %
20 - 30 %	19.00 %

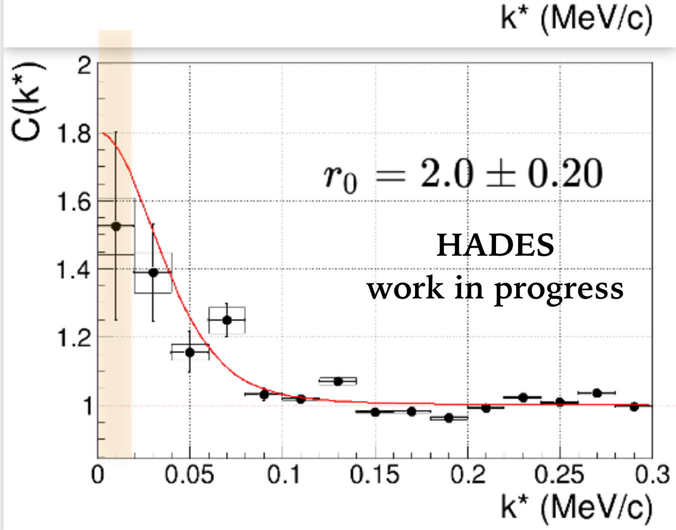




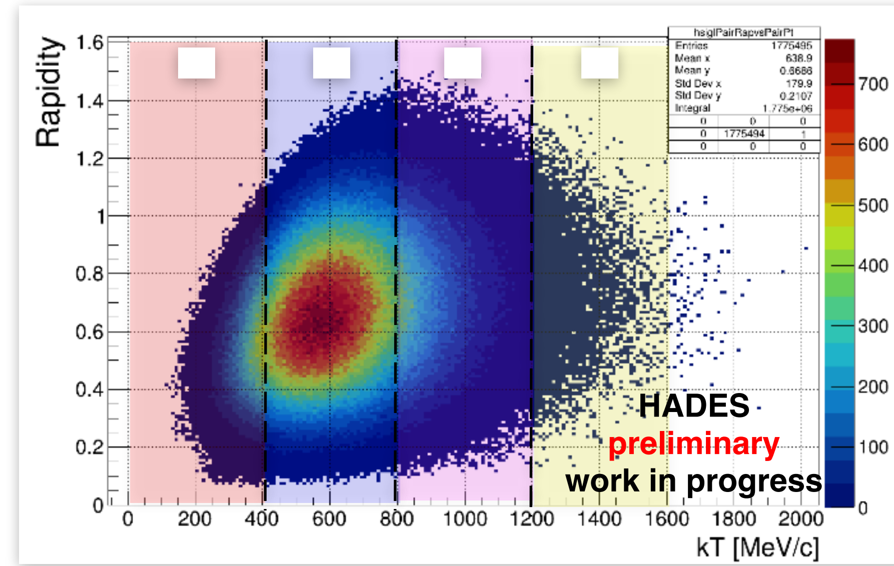
Results: k_T dependence

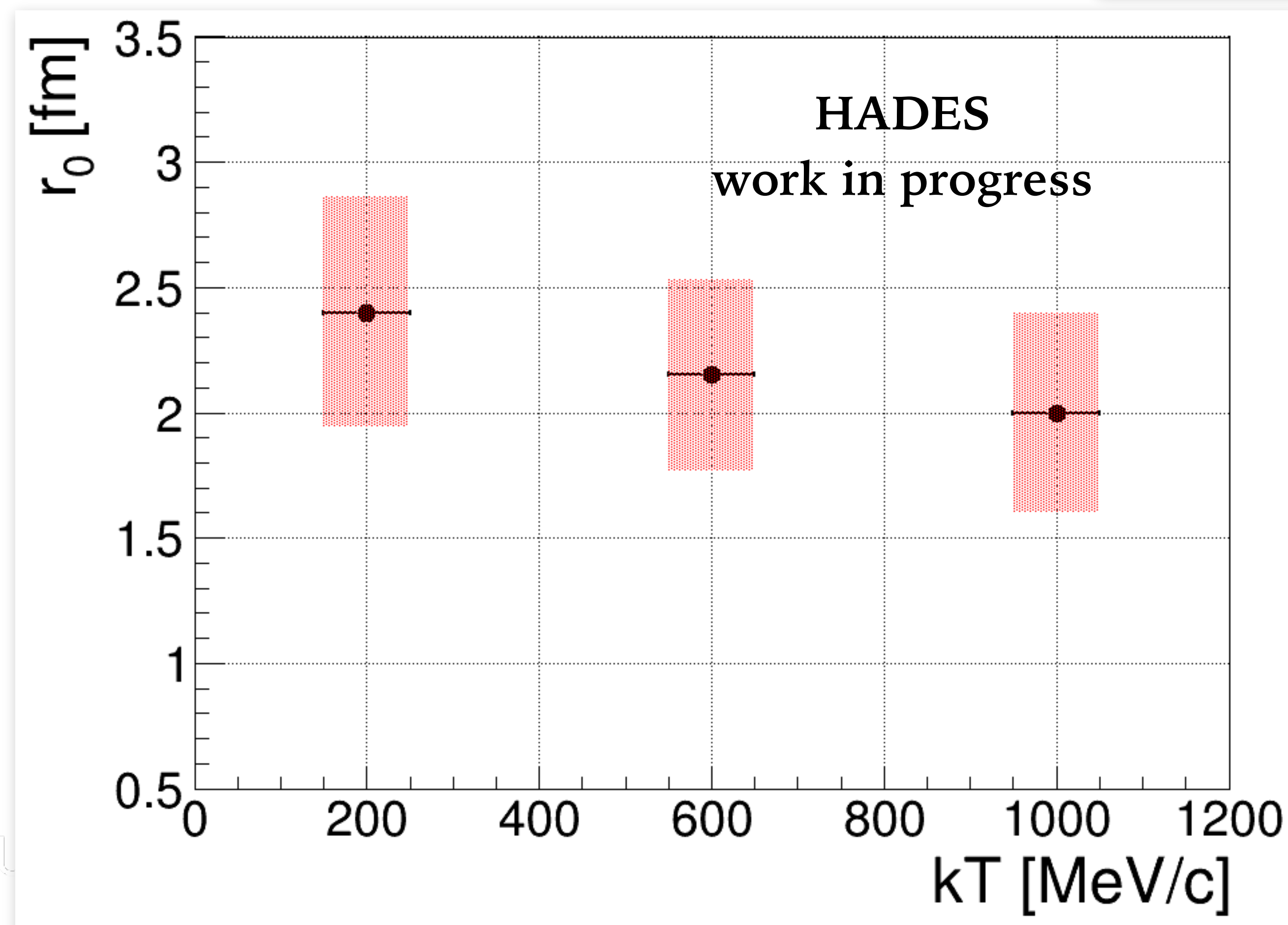






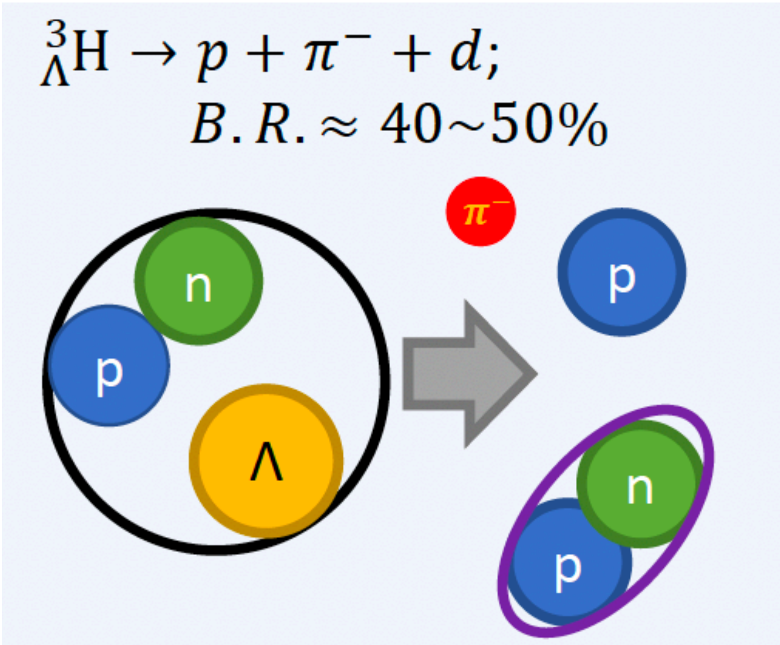
kT [GeV/c]	Systematic Uncertainty
0 - 400	19 %
400 - 800	15 %
800 - 1200	22 %

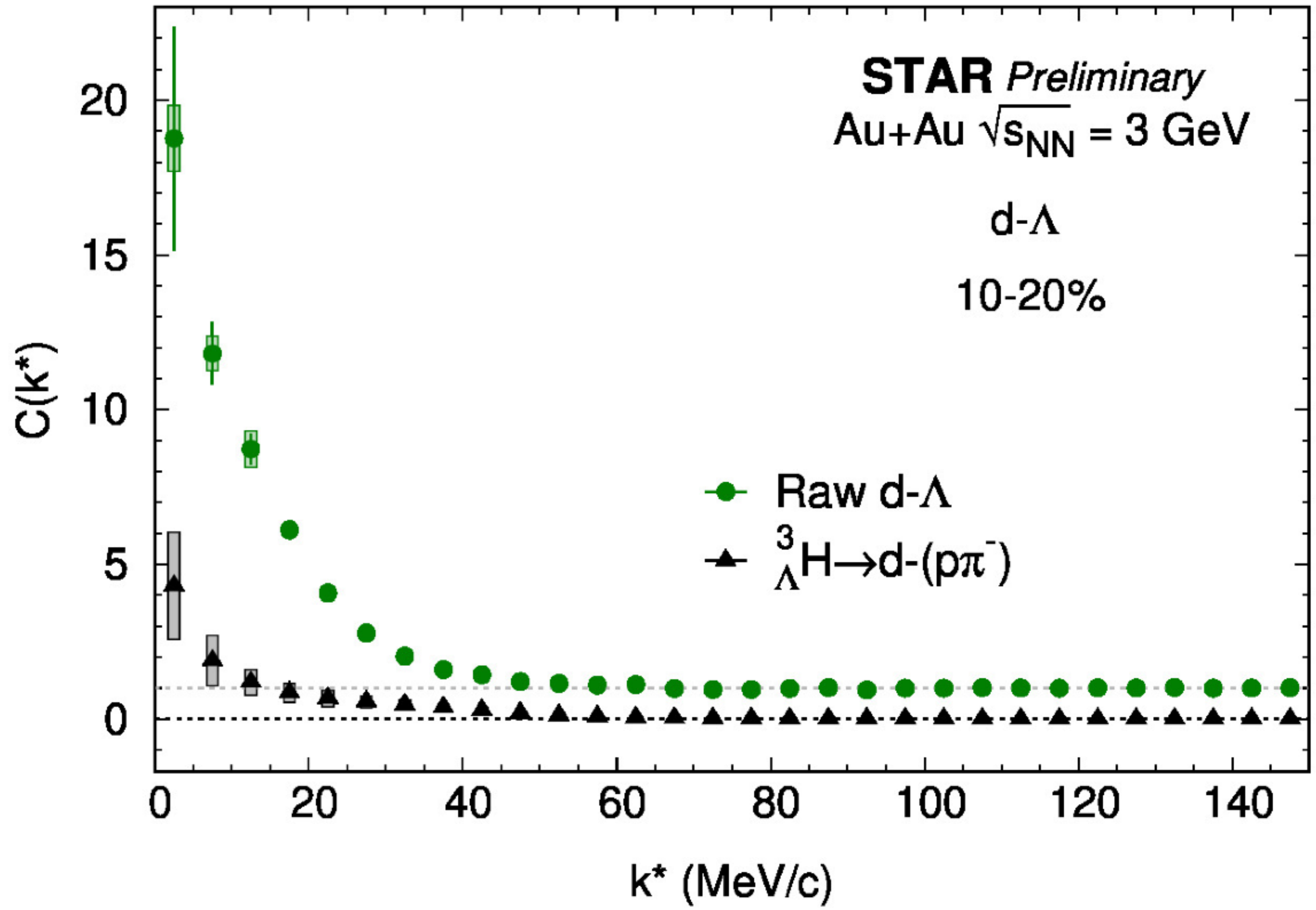




$$k_T = \frac{p_{T1} + p_{T2}}{2}$$

YN ($d - \Lambda$) correlations at STAR





Simulation based on STAR $^{3}_{\Lambda}H$ yield measurement:

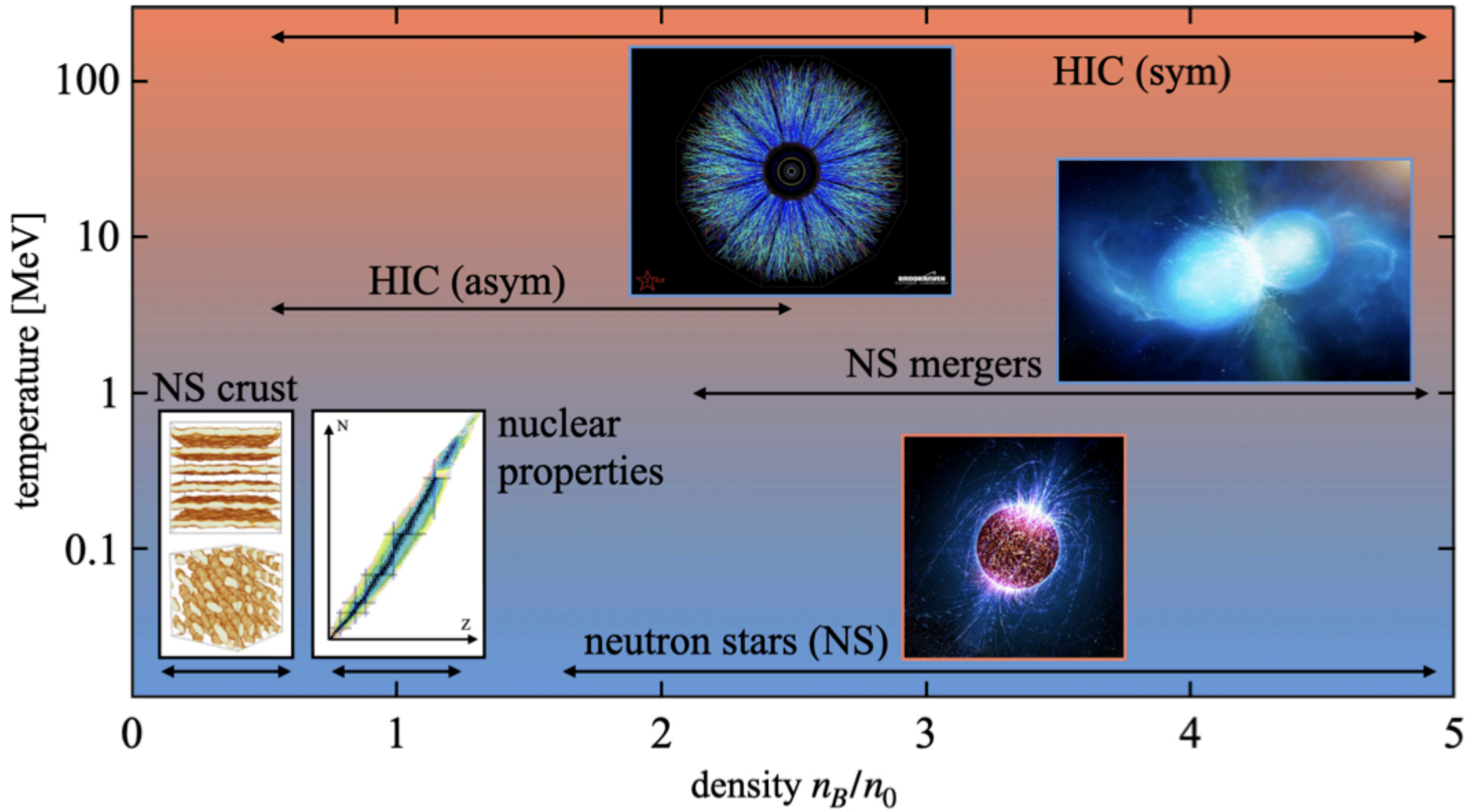
4 - 8% of $d - \Lambda$ entries come from $^{3}_{\Lambda}H$ decay for low k*;

Contamination subtracted from inclusive $d - \Lambda$ correlations;

Correlations of $^{3}_{\Lambda}H$ from $d - \Lambda$ and $d - (p - \pi^{-})$ are **not** experimentally **distinguishable.**

Various nuclear densities

A. Sorensen, HZ et al. arXiv:2301.13253 [nucl-th]



$\epsilon(n_n, n_p) = \epsilon_{SNM}(n) + S(n)\delta^2$

$\epsilon_{SNM}(n)$ - energy per nucleon of symmetric nuclear matter

$\delta > 0.8$ - neutron stars

HIC (asym): < 600 AMeV

HIC (sym): broad range of energy, including high-energies