Terrestrial experiments to understand what is inside neutron stars

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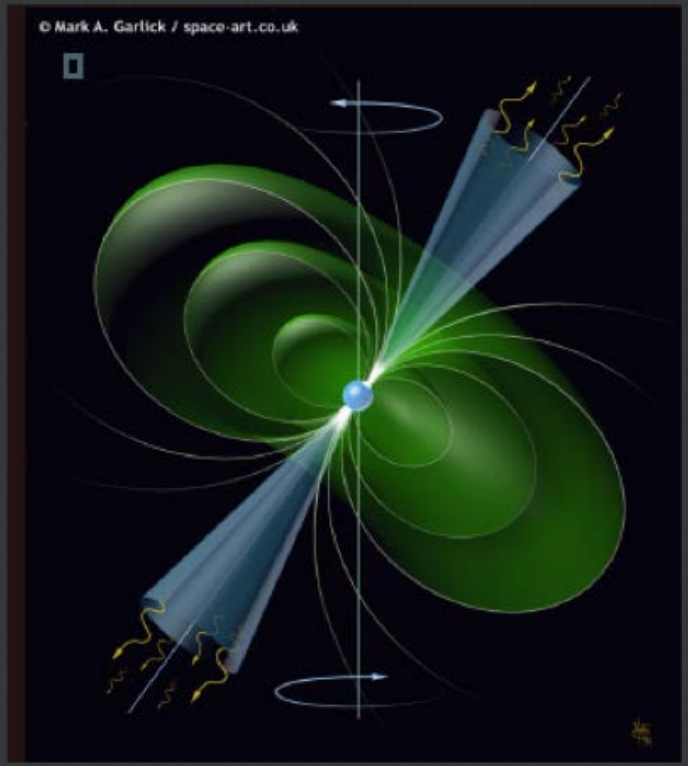
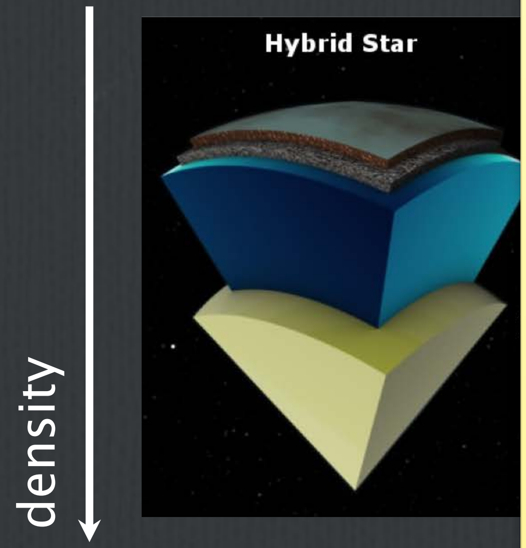
EMMI Colloquium, 24 May 2017

Facts about Neutron Sta



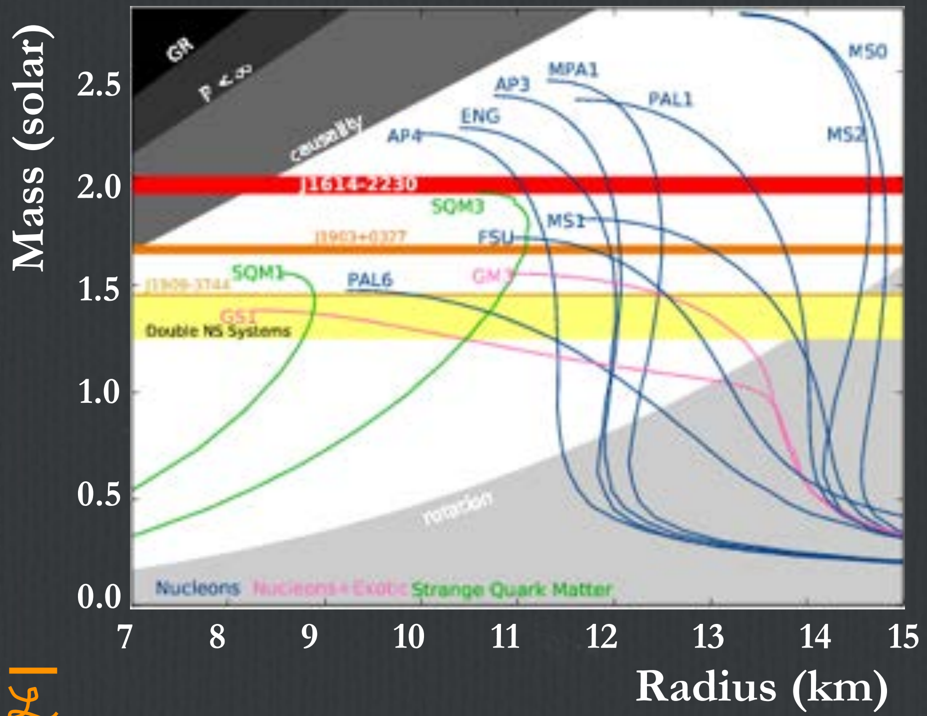
R ~ 10-15 km

M ~ 1.5 M⊙



additionally the study of strangeness has some impact on the modelling of neutron stars.

Scenarios with antikaon condensate is disfavoured but actually this strongly depends on the real antikaon-nucleon interaction
but there are other possibilities

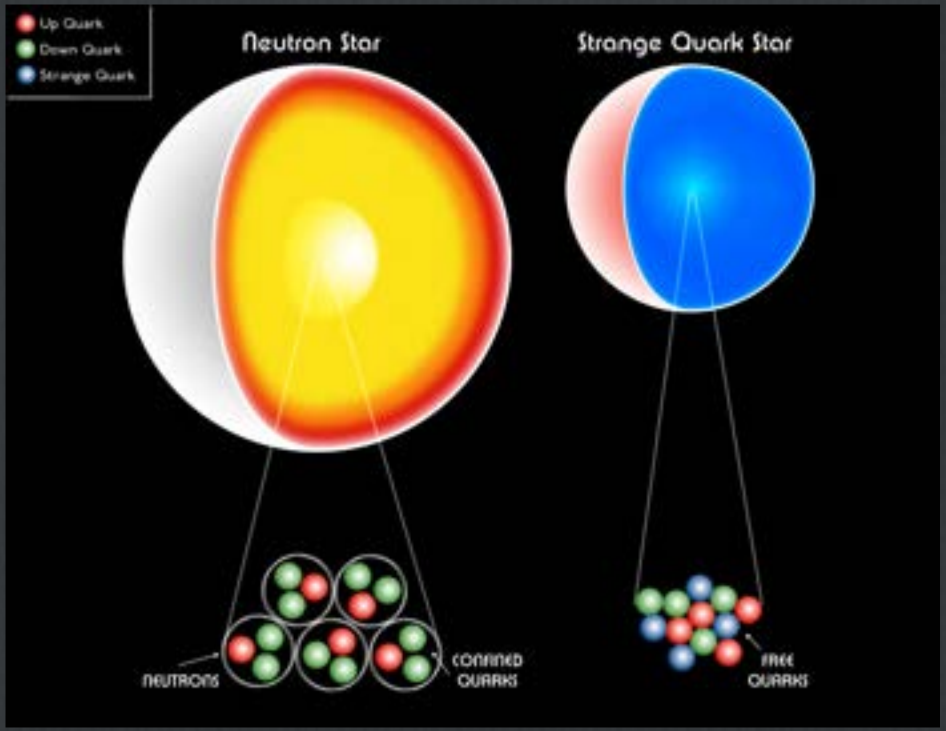

P. Demorest et al. Nature (467) (2010) 1081

- Very high density in the interior
- Strong magnetic fields
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement very difficult
- Masses ranging from 1.4 $M_\odot$ to 2 $M_\odot$

What is inside Neutron Stars??

Speculations about Neutron Stars

NSF, universetoday.com



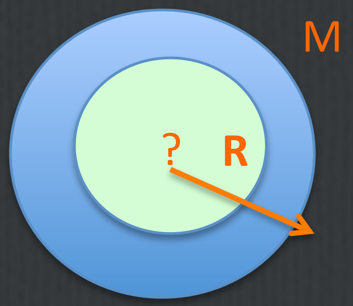
- Hadron composition
  - Only Nucleons
  - Antikaons-Nucleons condensate
  - Nucleons and Hyperons
- Nuclear Pasta
  - lasagne
  - spaghetti
- Quark star (Color super-conducting strange quark matter)

How to test different Hypotheses

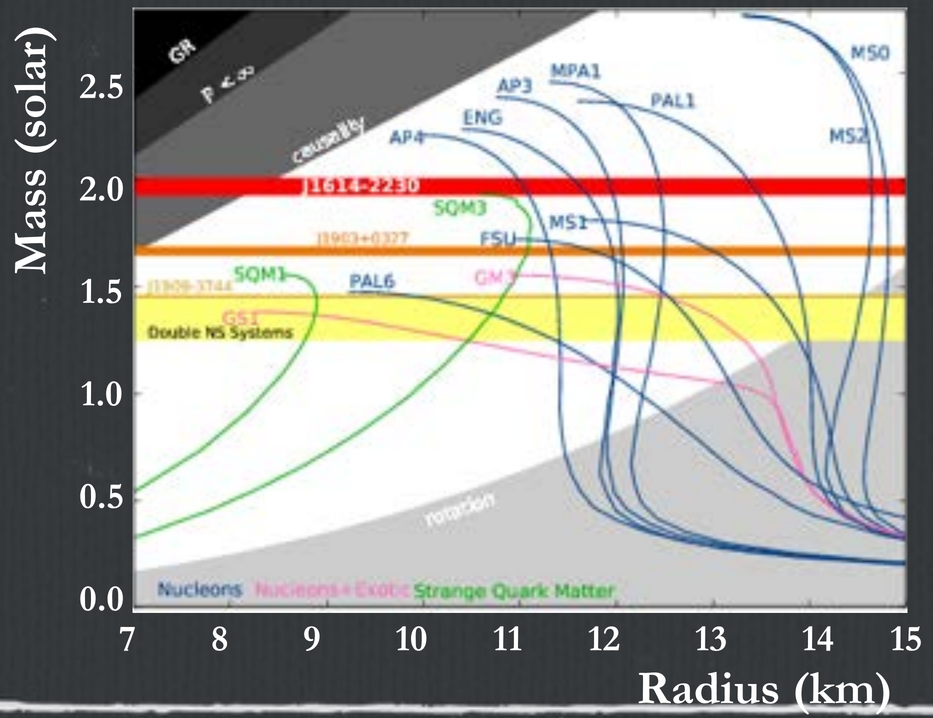
1) Equation of State (EoS): Dependency of the pressure upon the density

2) Given an object with a certain density the internal pressure must be compensated by gravity

3) From P(R)=0 -> the relation M(R) can be determined for each EOS as a function of the assumed density



P. Demorest et al. Nature (467) (2010) 1081



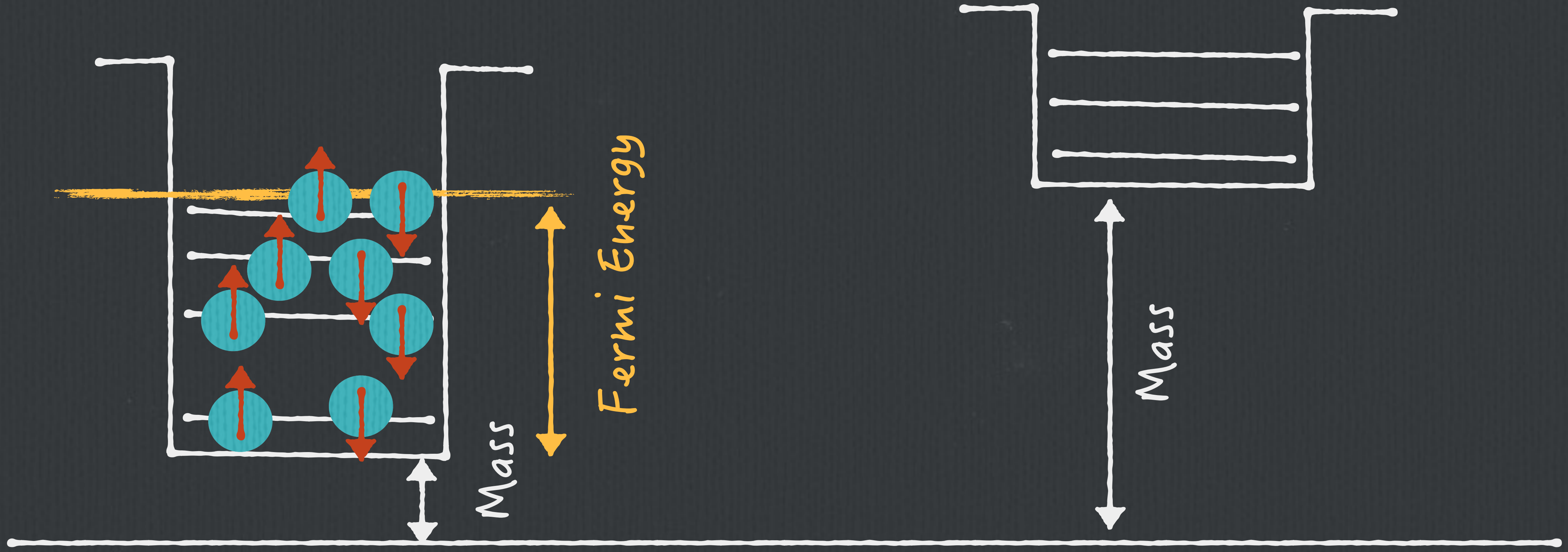
$\rho = 2-8\ \rho_0$??

It is not so easy to fix the density but the EOS must cross the measured values of the masses!

Strange Hadron Production in NS

Neutrons (uud, m= 938 MeV)

Λ Hyperons (uds, m= 1115 MeV)



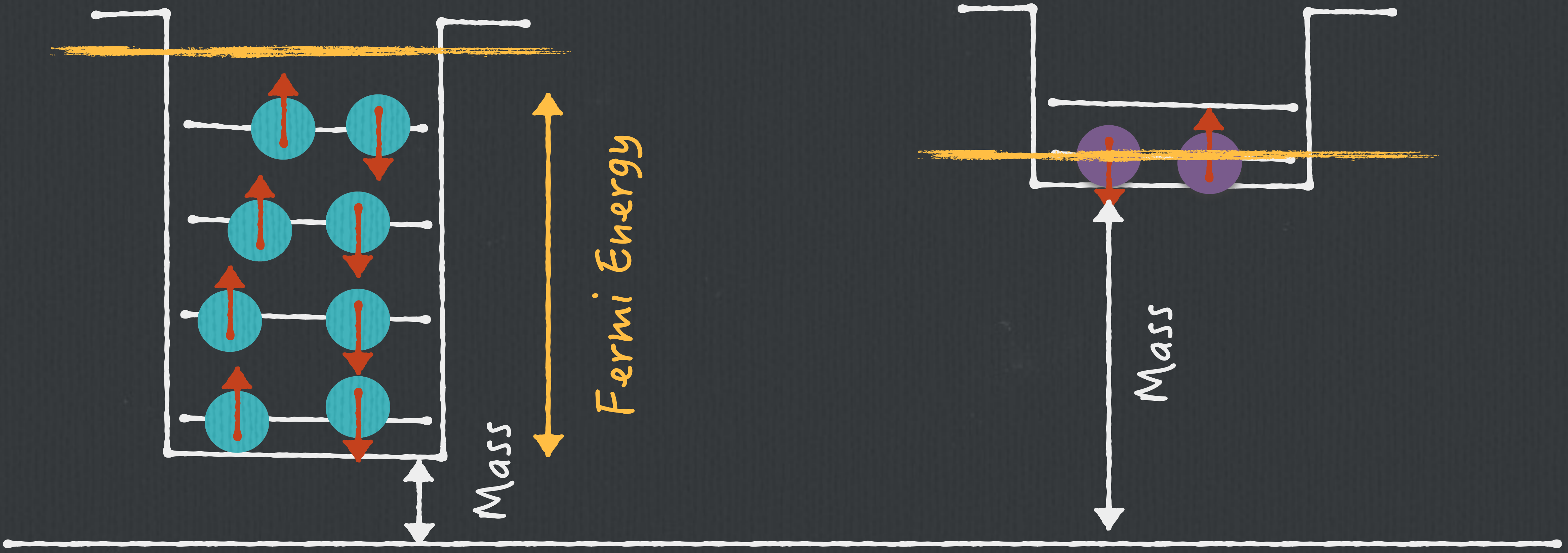
Chemical Potential $\mu = E_F + mass$

If the density increases also the Fermi Energy increases and hence the chemical potential

Strange Hadron Production in NS

Neutrons (uud, m= 938 MeV)

Λ Hyperons (uds, m= 1115 MeV)

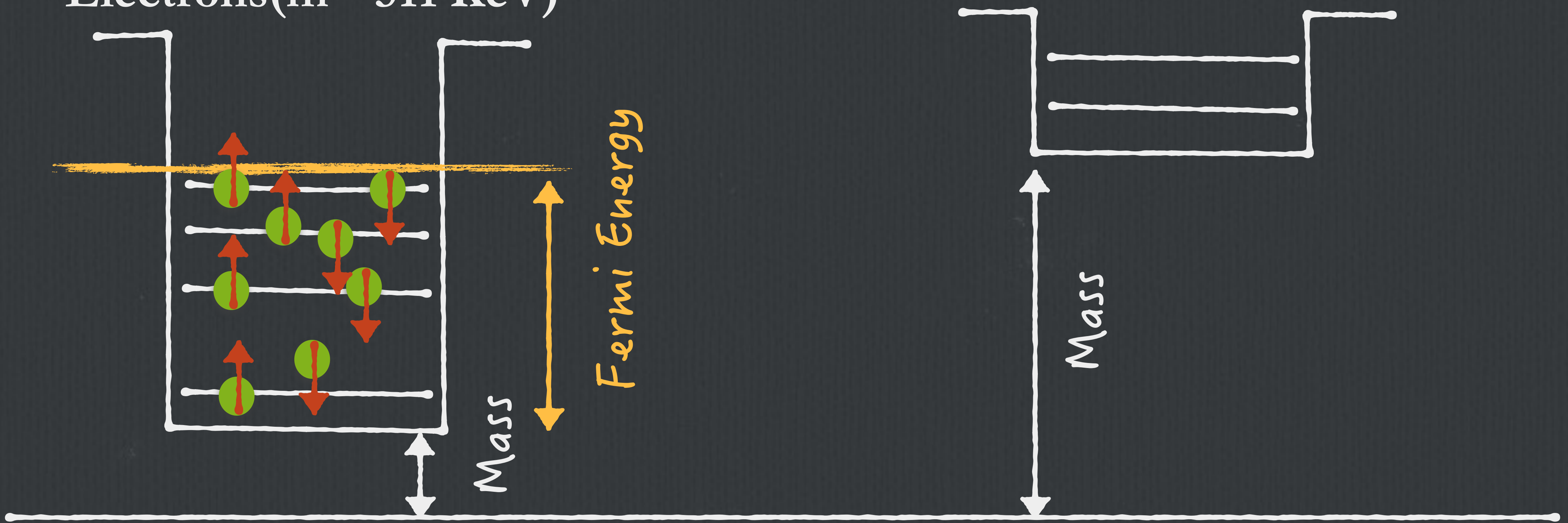


In order to have chemical equilibrium $\mu_{neutron} = \mu_\Lambda$

In this case it is energetically favourable to convert neutrons into hyperons

Strange Hadron Production in NS

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



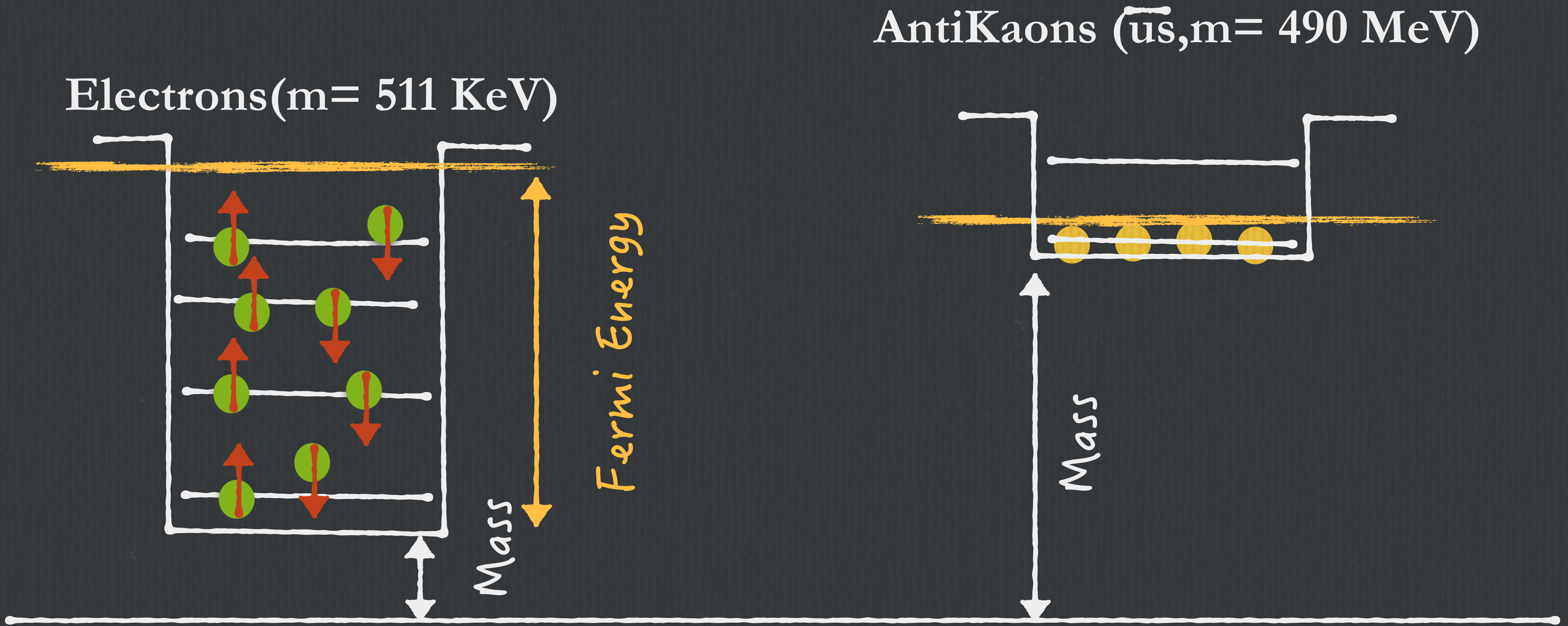
AntiKaons ($\overline{us}$,m= 490 MeV)

Electrons(m= 511 KeV)

Chemical Potential $\mu = E_F + mass$

Strange Hadron Production in NS

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Also in this case it can be energetically favourable to convert electrons into AntiKaons.
Furthermore: AntiKaons are bosons and hence they dont undergo Pauli blocking

Scenario Nr. 1: Kaon Condensate

Since hadrons interact with each others

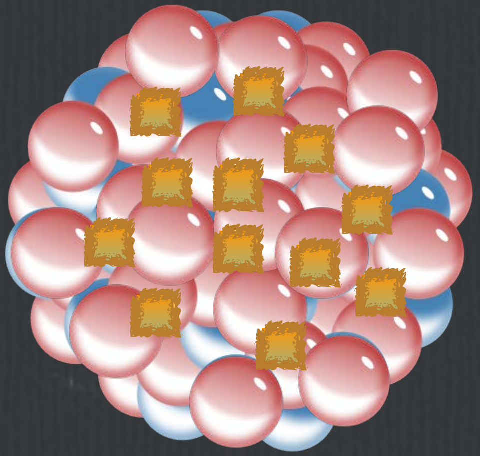
if the 'in-medium' mass of K- drop within dense nuclear matter it is even more favorable to produce strangeness

if $m_{K^{-*}} < \mu_{e^-}$

$$e^- \rightarrow K^- + \nu_e$$

$$n \rightarrow K^- + p$$

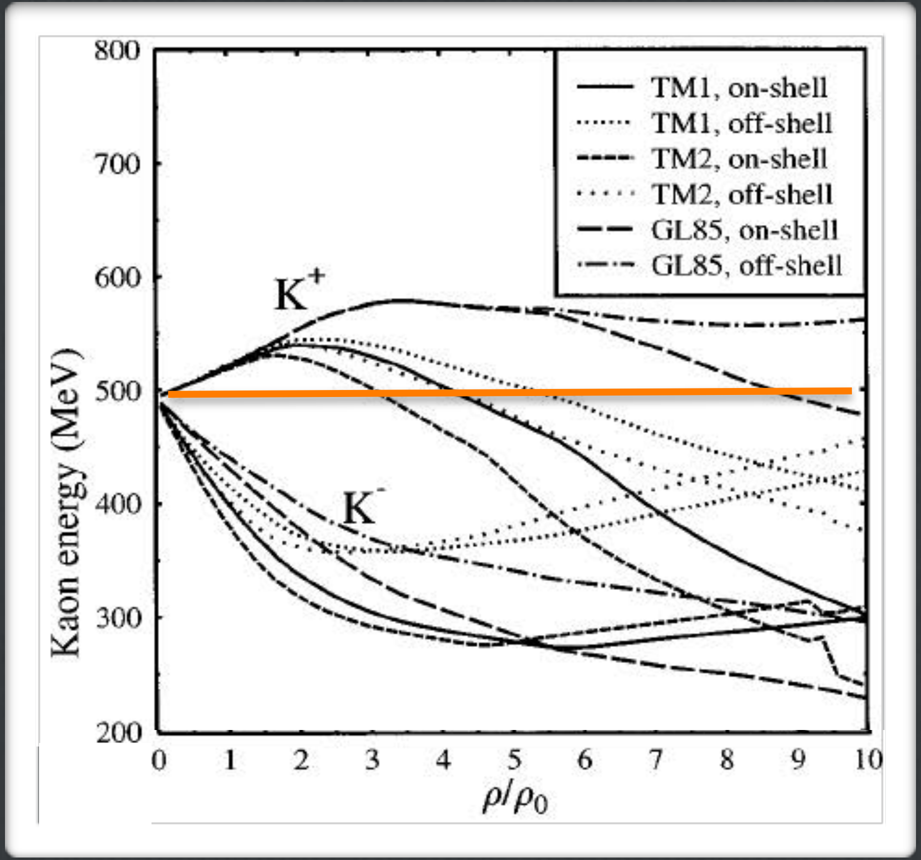
No Pauli Blocking!



● Neutron

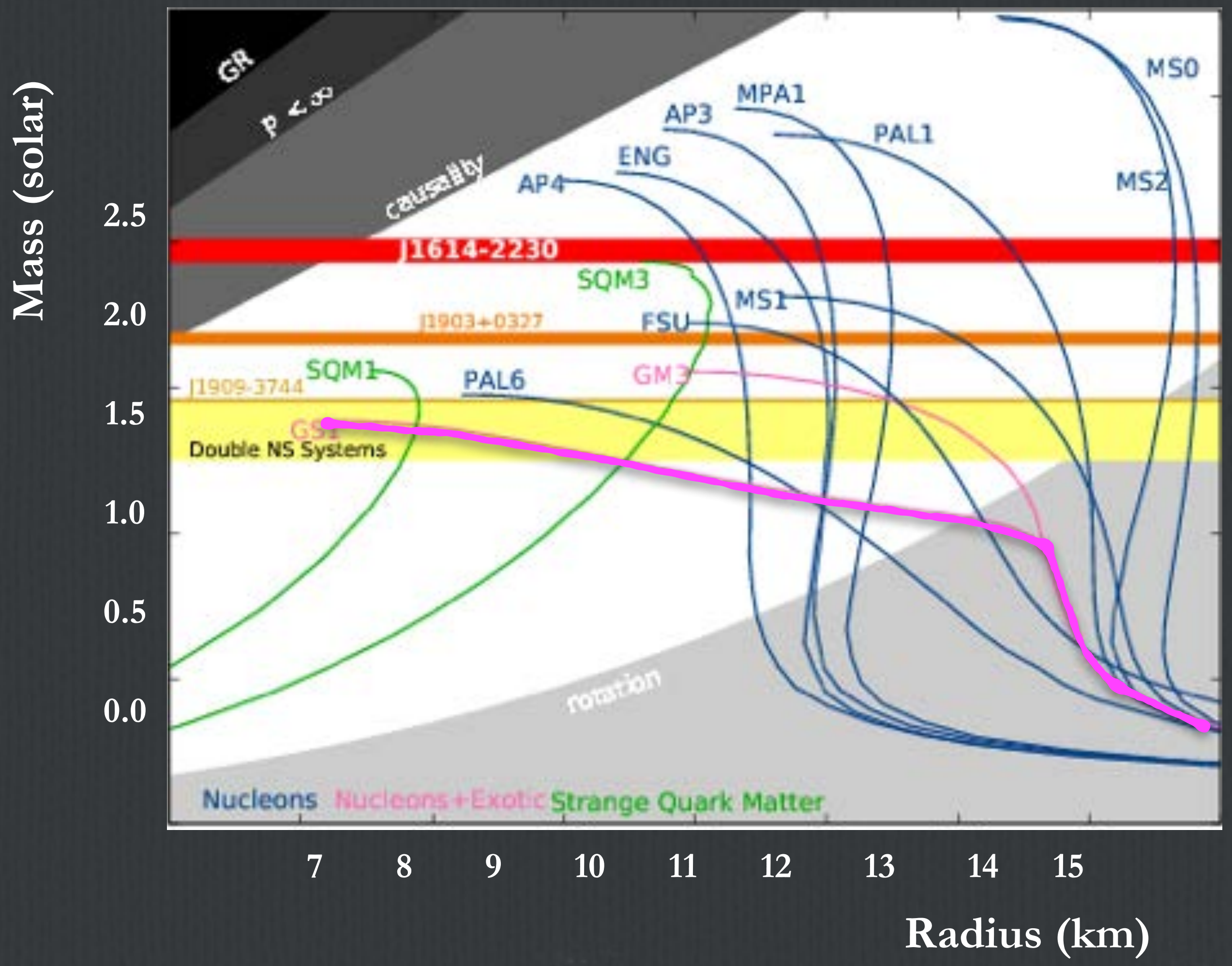
▨ Kaon

J. Schaffner and I. N. Mishustin
Phys. Rev. **C 53**, 3 (1996)



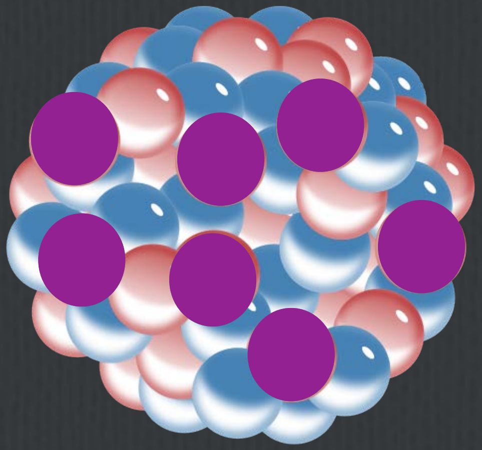
Large Masses Issue and Strangeness in NS

P. Demorest et al. Nature (467) (2010) 1081



- Production of strangeness is energetically favourable
- It relieves the Fermi pressure of neutrons and protons
- But… a decrease of the pressure softens the EOS
- Decrease of the maximum mass of neutron stars
- 2 $M_{\odot}$ neutron star measured
- EOS cannot be too soft
- Some EOS are disfavoured, for example Antikaon condensate

Scenario Nr. 2: Hyperon Star



● Neutron

● Λ

Possible Processes:

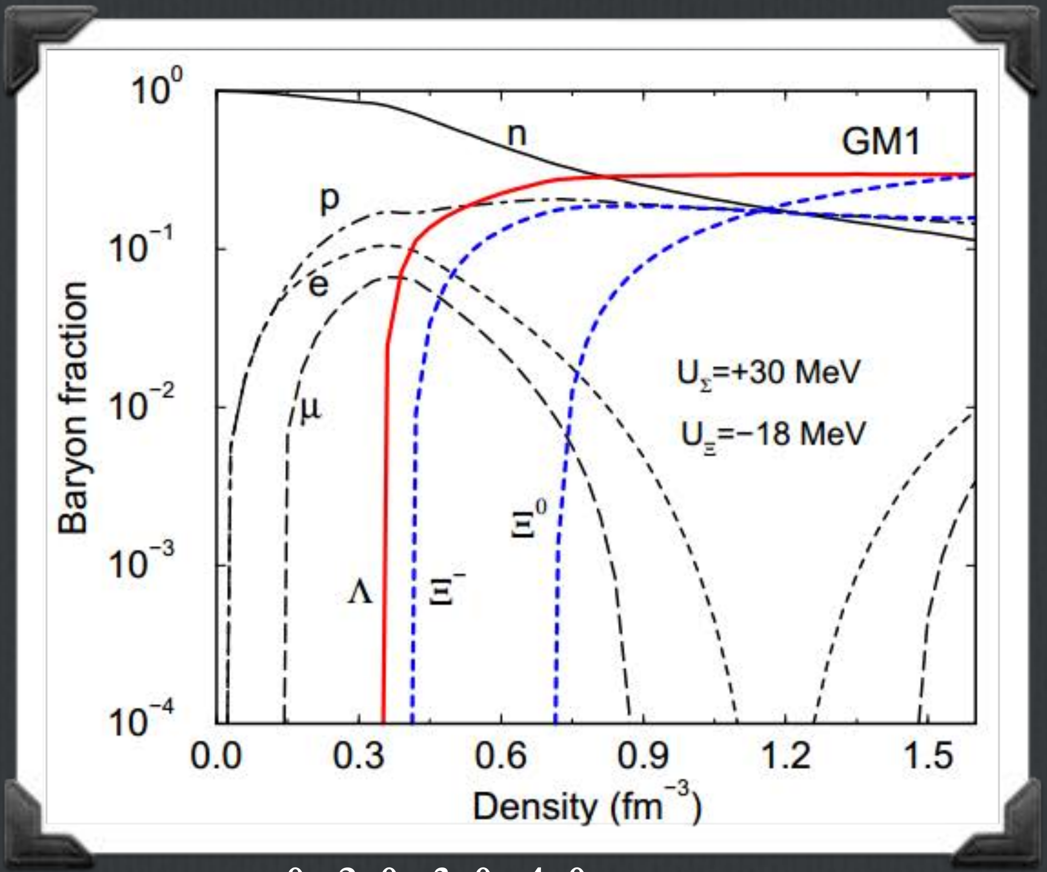
$$n + n \rightarrow n + \Lambda \; + \mathrm{K}$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-} \; + \mathrm{K}$$

$$n + n \rightarrow p + \Sigma^- \; + \mathrm{K}$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-} \; + \mathrm{K}$$

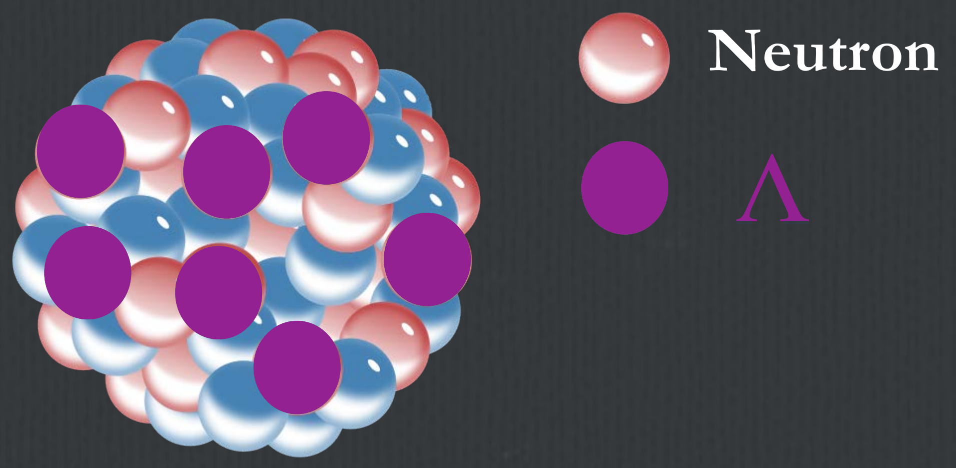
J. Schaffner-Bielich, **NPA 804** (2008)



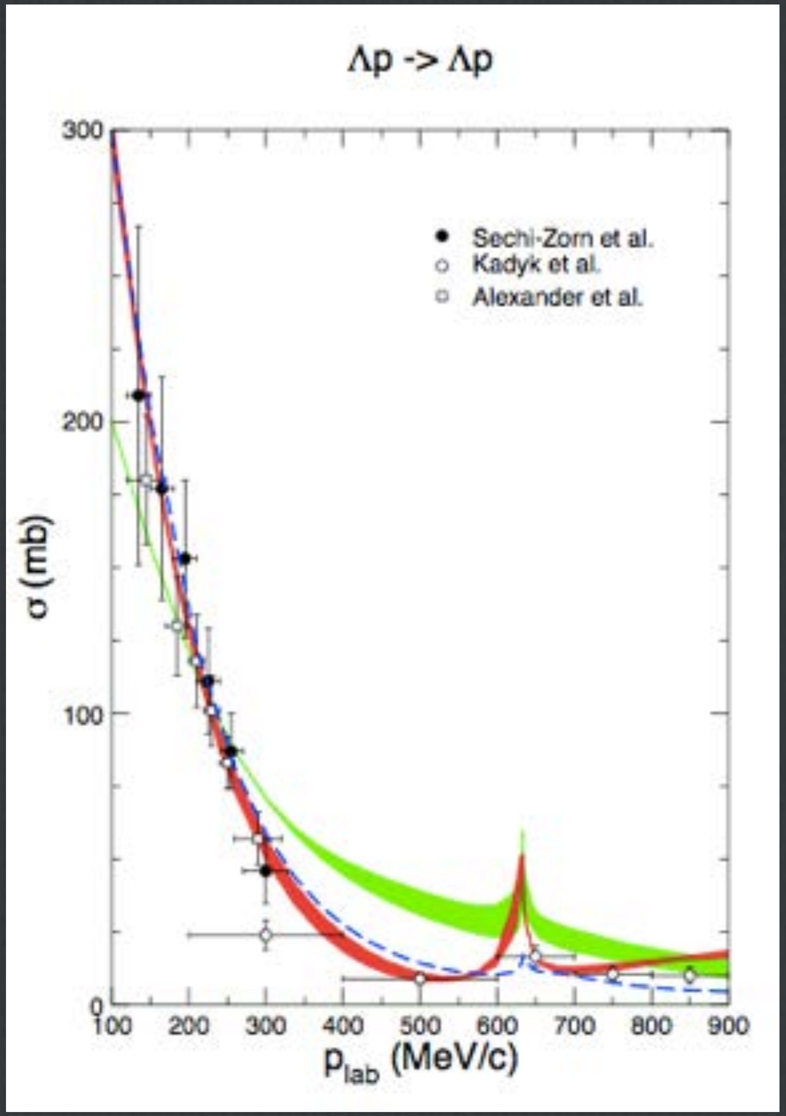
ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

This scenario might also be problematic since the hyperon appearance implies new degree of freedom and hence a softening of the EOS

Scenario Nr. 2: Hyperon Star



J. Haidenbauer, S. Petschauer et al.,
Nucl. Phys. A 915 (2013) 24



Possible Processes:

$n + n \rightarrow n + \Lambda$ + K

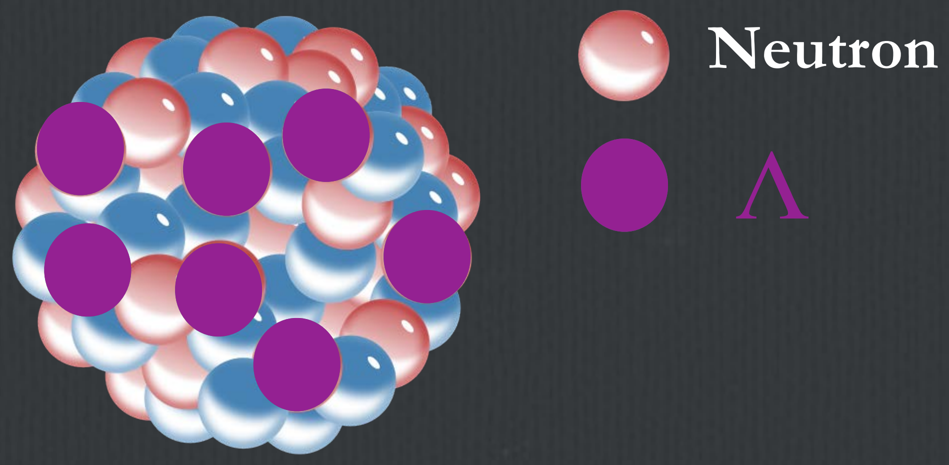
$p + e^{-} \rightarrow \Lambda + \nu_{e^{-}}$ + K

$n + n \rightarrow p + \Sigma^{-}$ + K

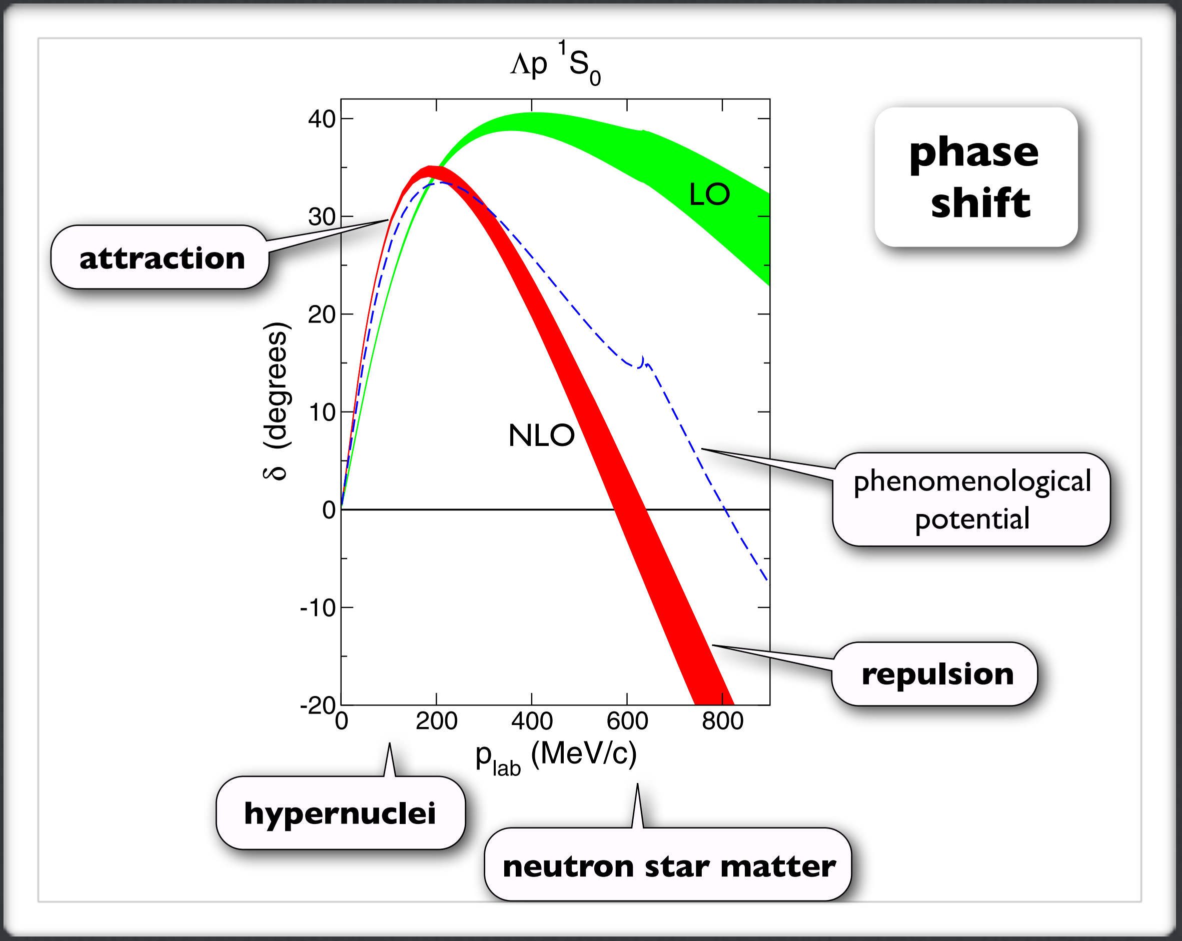
$n + e^{-} \rightarrow \Sigma^{-} + \nu_{e^{-}}$ + K

Λp scattering length extracted from scattering data and hypernuclei data for average Λp potential

Scenario Nr. 2: Hyperon Star



`J. Haidenbauer, S. Petschauer et al.,`
`Nucl. Phys. A 915 (2013) 24`



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$$p + e^- \rightarrow \Lambda + \nu_{e^-} + \mathrm{K}$$

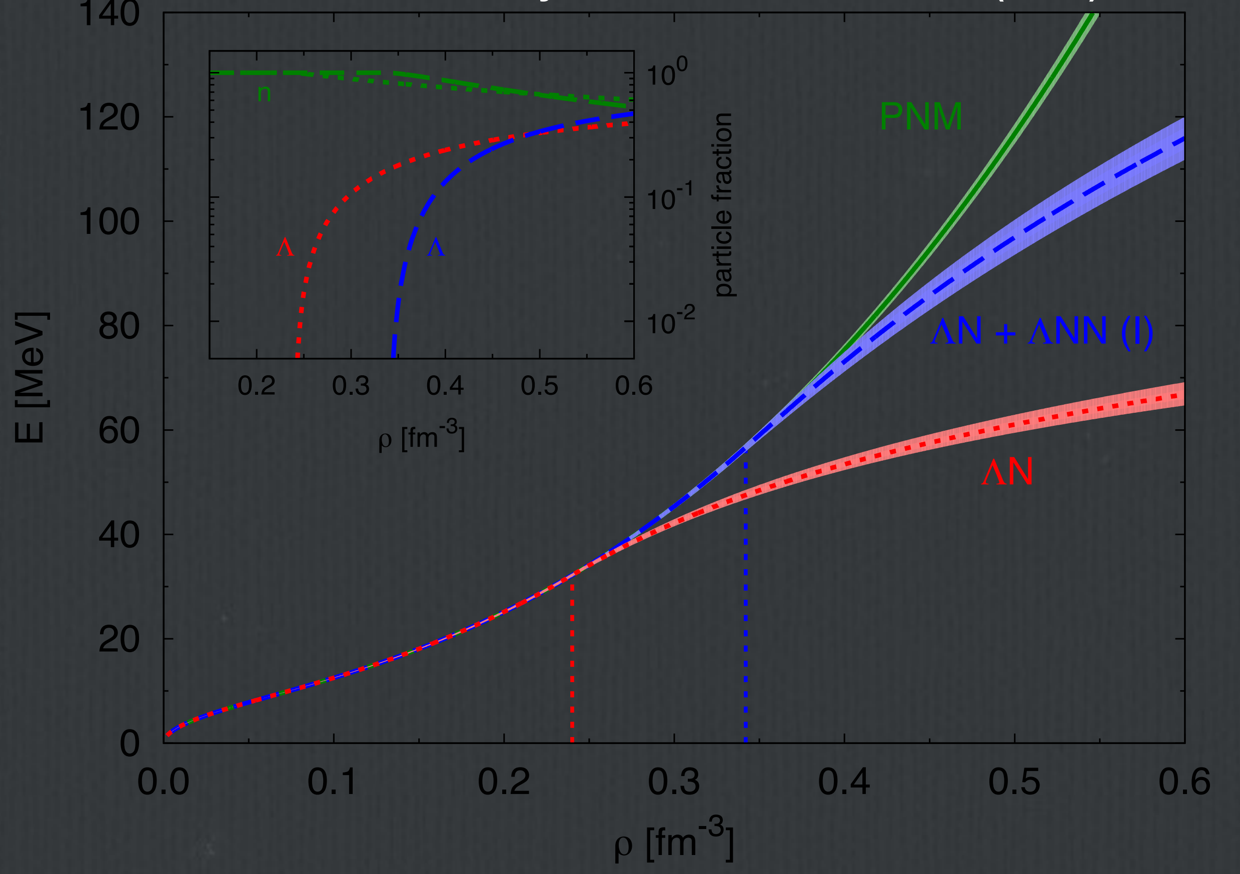
$$n + n \rightarrow p + \Sigma^- + \mathrm{K}$$

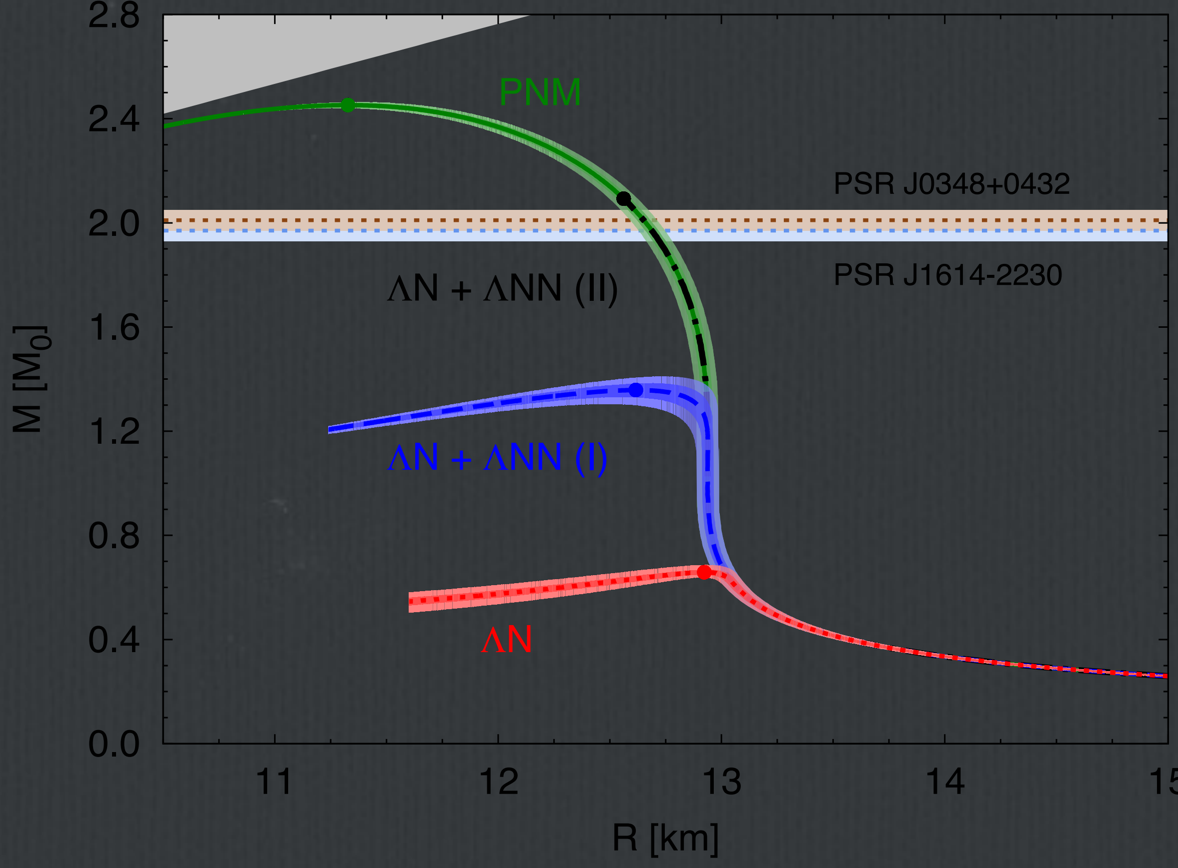
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-} + \mathrm{K}$$

It all depends upon the Λ-N and Λ-NN interaction and whether or not it has a repulsive core
This repulsive core could stiffen again the EOS allowing for heavy neutron stars

EOS with Hyperons

Lonardoni, et al. Phys. Rev. Lett. 114, 092301 (2015)





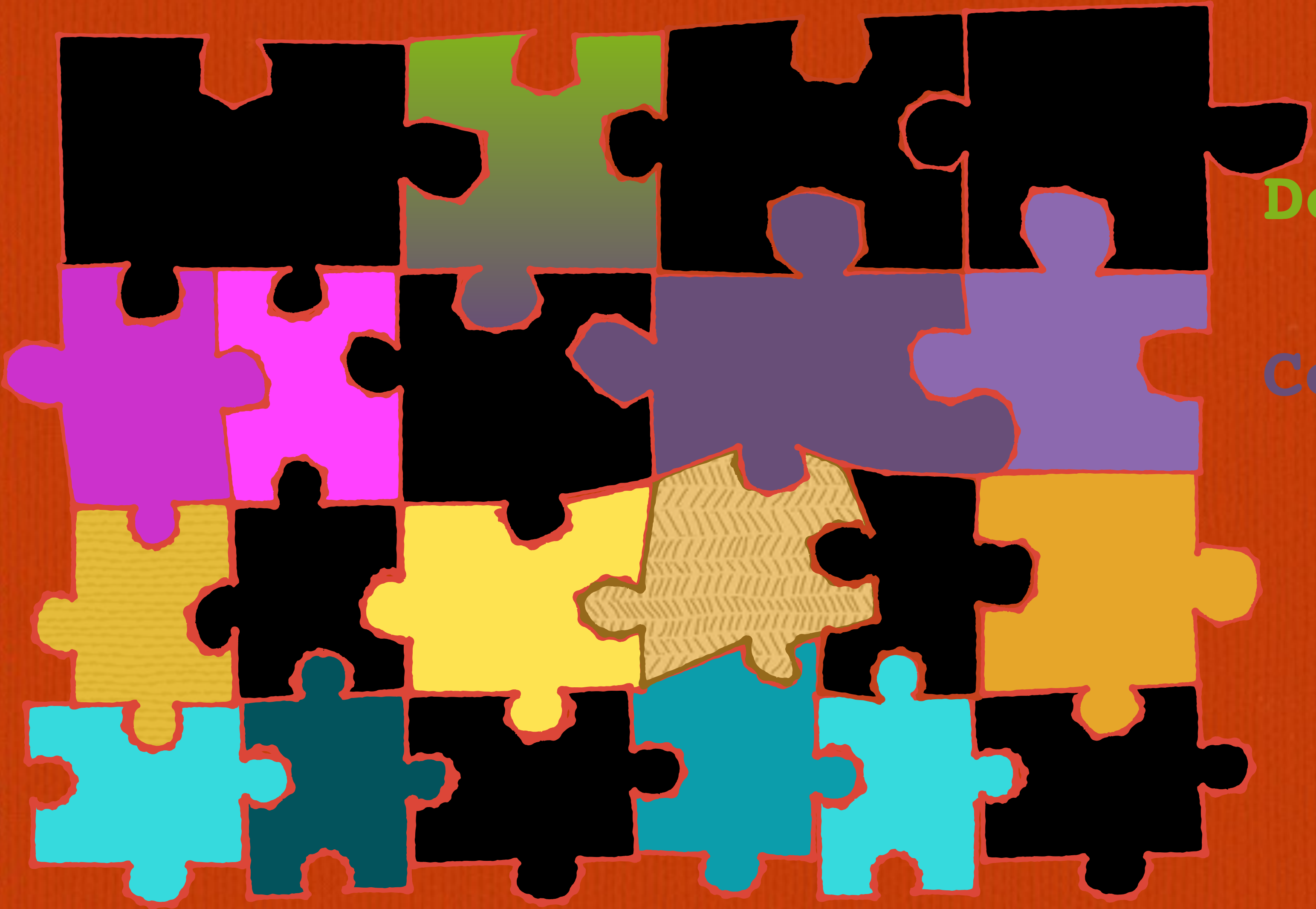
Λ-N, Λ-NN Interaction, in particular the short range repulsive part determines the fate of heavy hyperon stars.

Equation of state of dense hadron matter

Study of the strange-hadron properties within nuclear matter

Still a puzzle with many missing pieces

Knowledge of the interaction is needed to etract an EOS with neutrons and strange hadrons.



Dense Nuclear Matter

Cold Nuclear Matter

2/3-Body Interaction

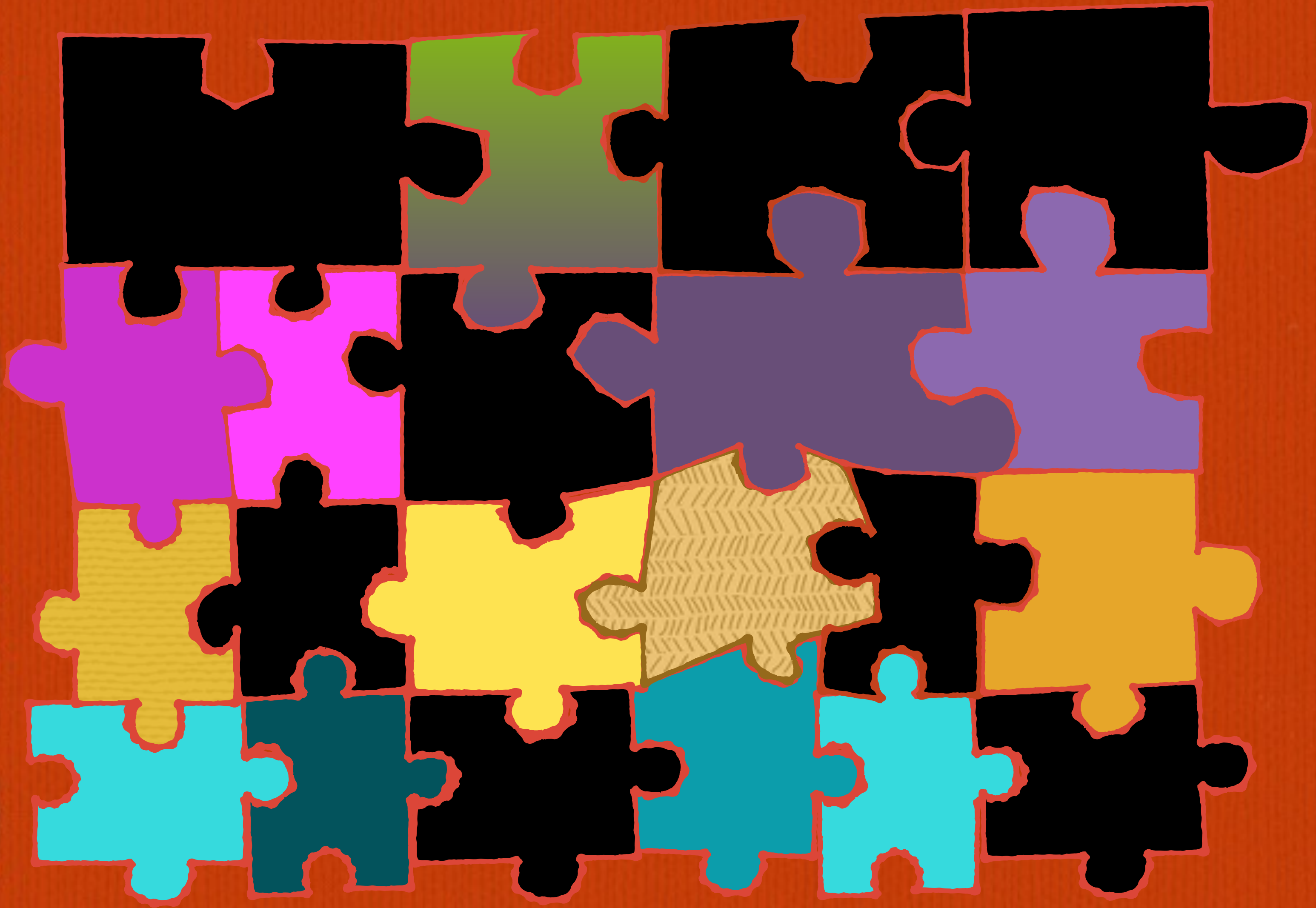
Production

Equation of state of dense hadron matter

Study of the strange-hadron properties within nuclear matter

Still a puzzle with many **missing pieces**

Knowledge of the interaction is needed to etract an EOS with neutrons and strange hadrons.



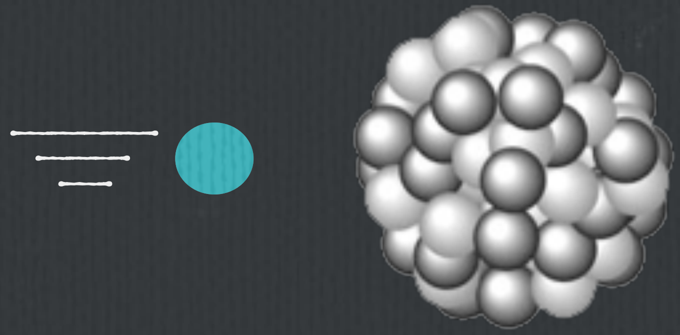
- Λ -Nucleon
- Λ -Nucleon-Nucleon

HADES at GSI

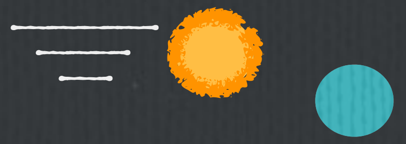
Fixed Target experiments, E_{kin}~ AGeV

proton-proton

proton-nucleus

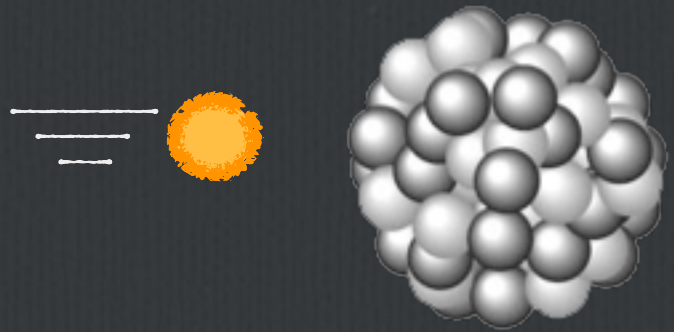


π-proton



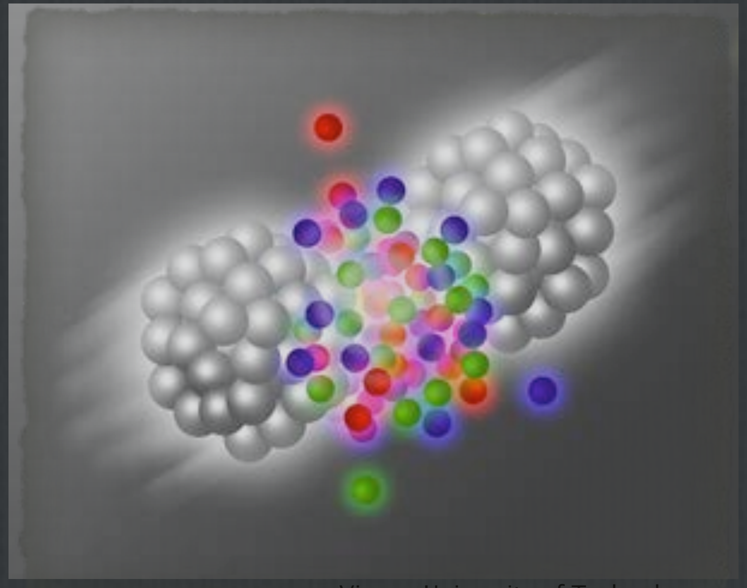
Vacuum

π-nucleus



$\varrho_B \sim \varrho_0$

Heavy-ion Collisions ϱ_B <2-3 ϱ_0



Vienna University of Technology

T~ 80-100 MeV

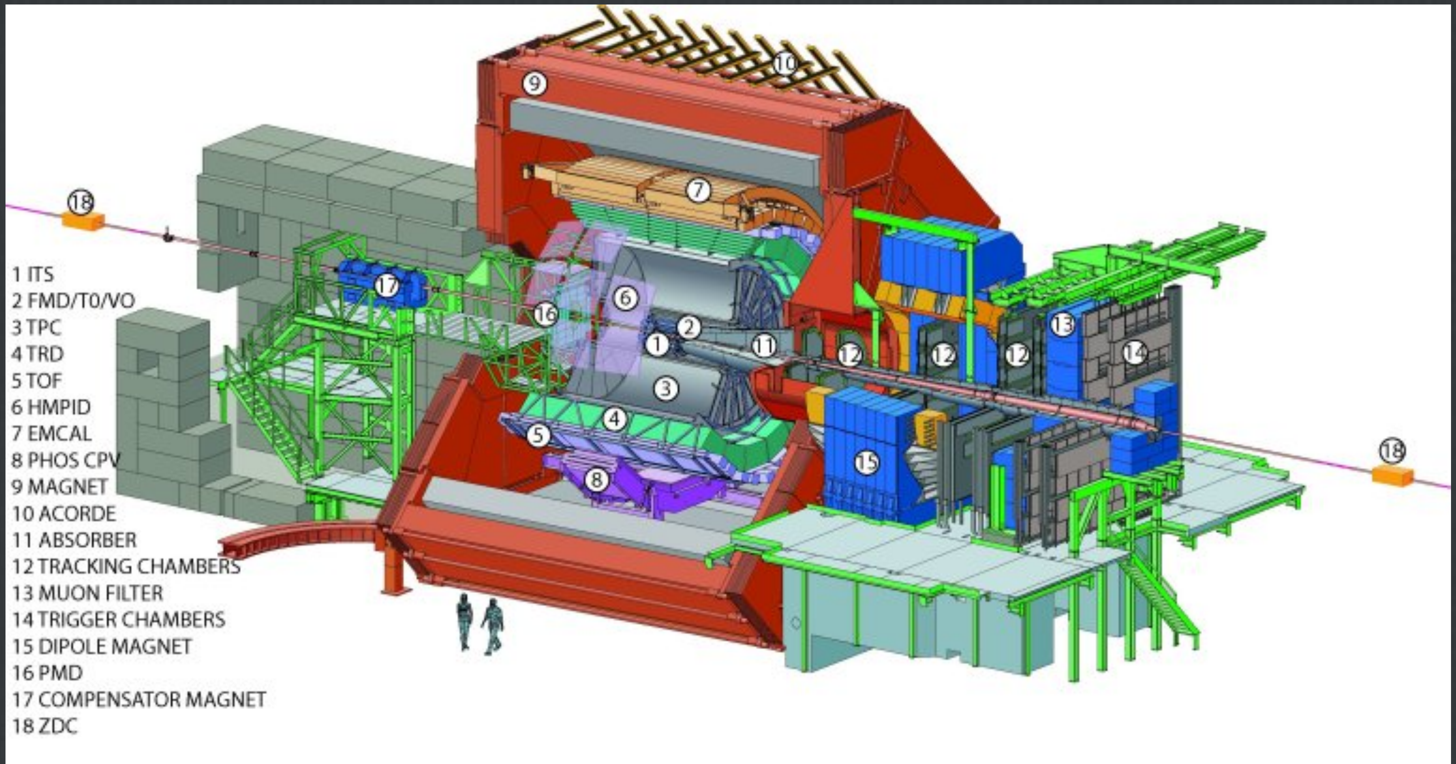
mention that elementary
collisions have been always
considered mainly as refere
for the hic, where densities
beyond nuclear matter can
formed.
This is one of the role they h
but there is more.

The reactions we are referri
here to happen at GeV, fixed
target and in particular the
Im going to show refer to …

The ALICE Experiment

Experiment at the LHC Collider

p+p at $\sqrt{s} = 7,\ 13\,\mathrm{TeV}$



Very good Particle Identification

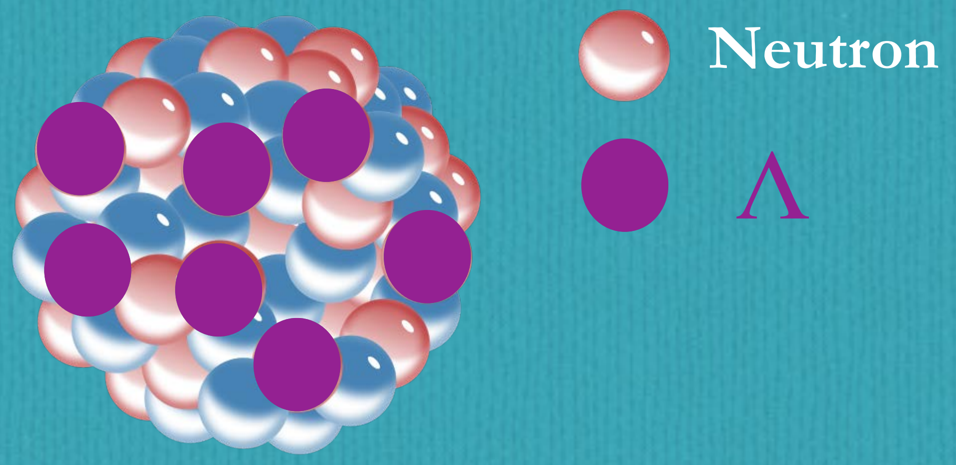
Energy Loss measurement in the large Volume

Time Projection Chamber

\+ Measurement of the time of flight

\+ + Excellent secondary vertex reconstruction capability

Scenario Nr. 2: Hyperon Star



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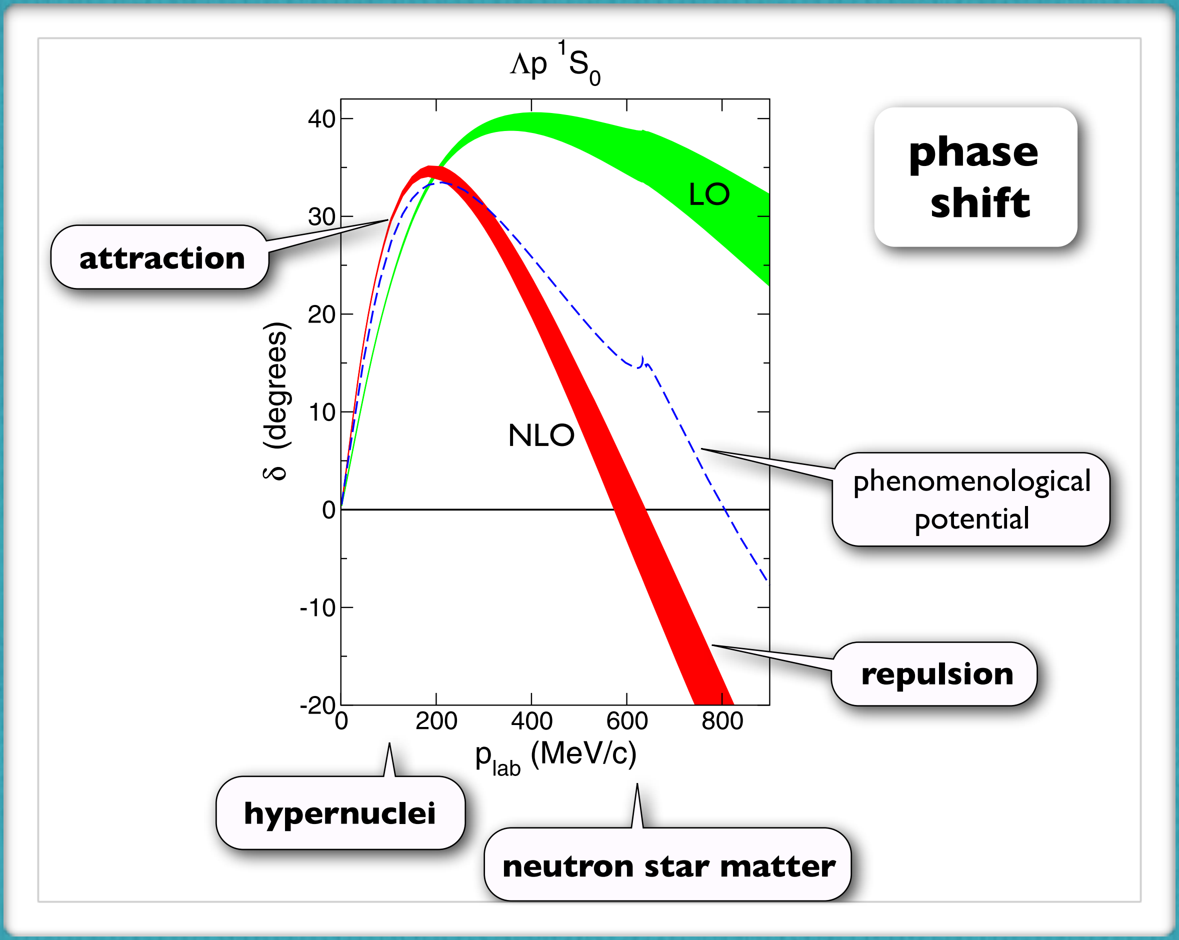
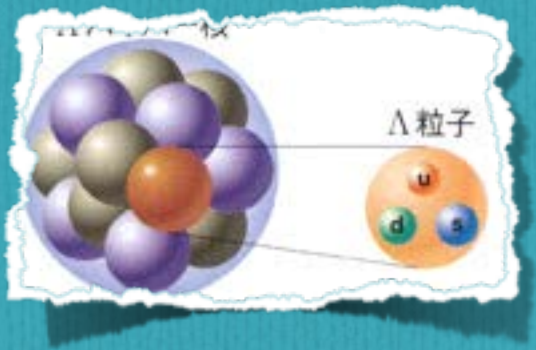
J. Haidenbauer, S. Petschauer et al., Nucl. Phys. A 915 (2013) 24



It all depends upon the Λ-N and Λ-NN interaction and whether or not it has a repulsive core

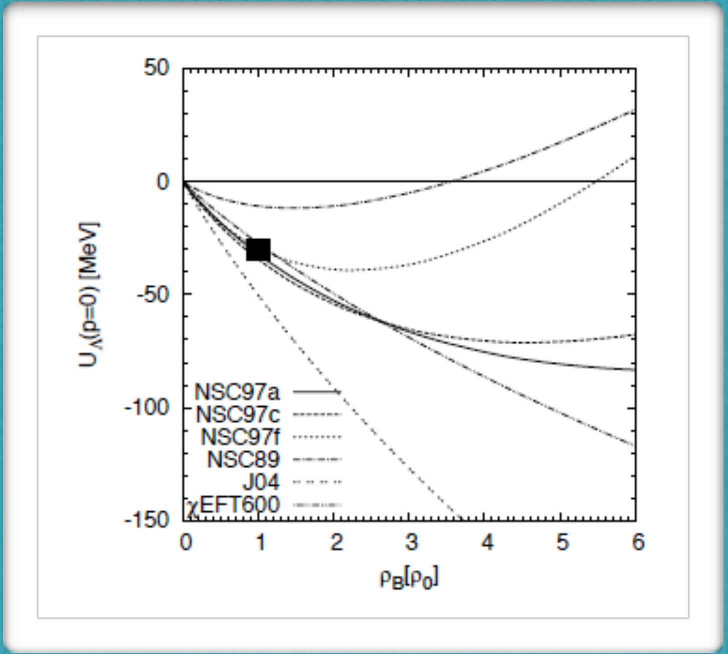
This repulsive core could stiffen again the EOS allowing for heavy neutron stars

Experimental Evidences



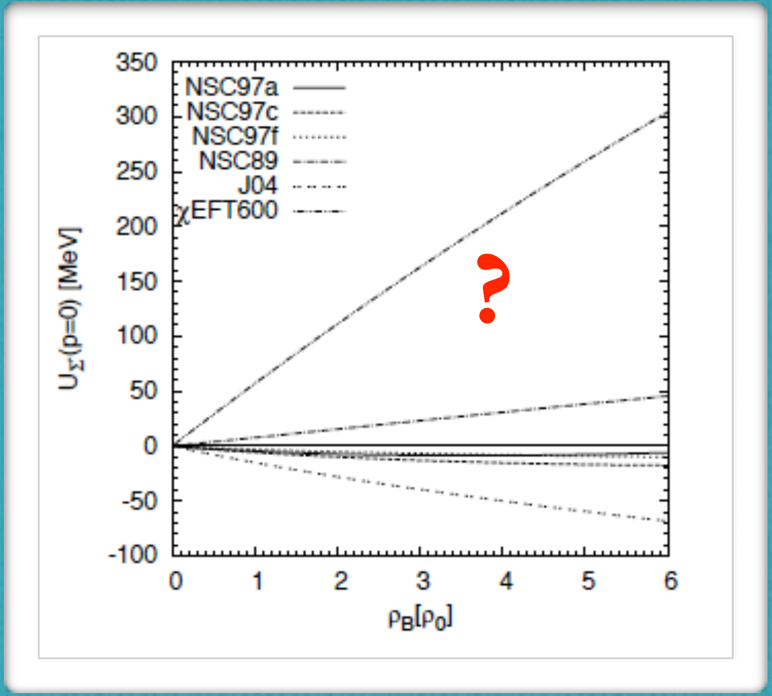
Λ Hypernuclei and Λ-p scattering

Λ-Nucleon Potential



U~ -30 MeV (attractive)
from Hypernuclei
No idea yet about the momentum and
density dependence

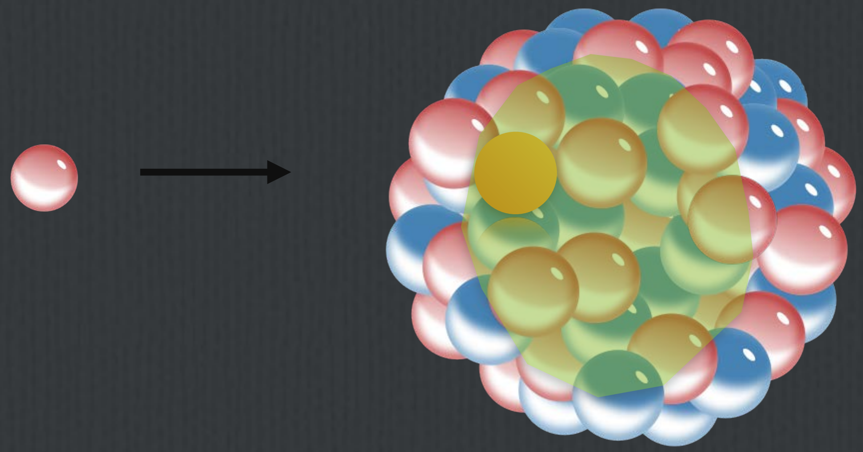
Σ-Nucleon Potential



No Idea at all

Femtoscopy in p+A/p+p reactions

p+Nb, 3.5 GeV



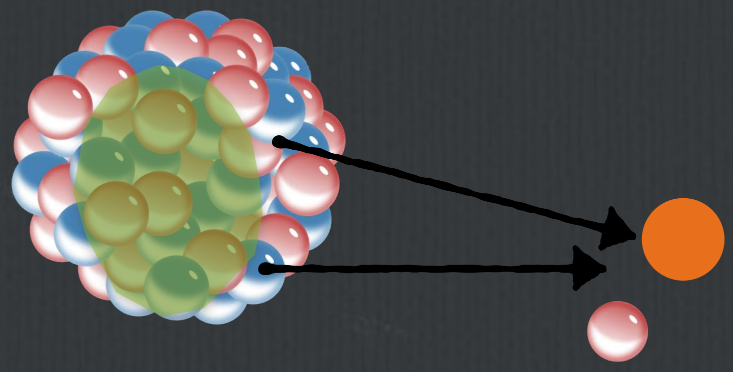
Λ

Interaction

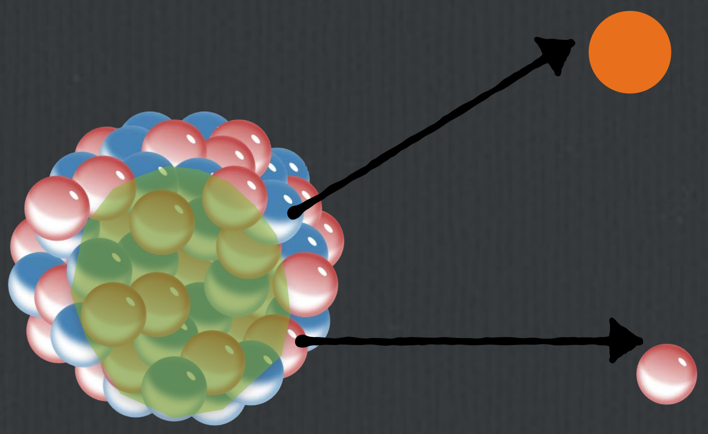
proton

Surface where particles are emitted from
Kinematic Freeze-out surface

Attractive Λ p Interaction

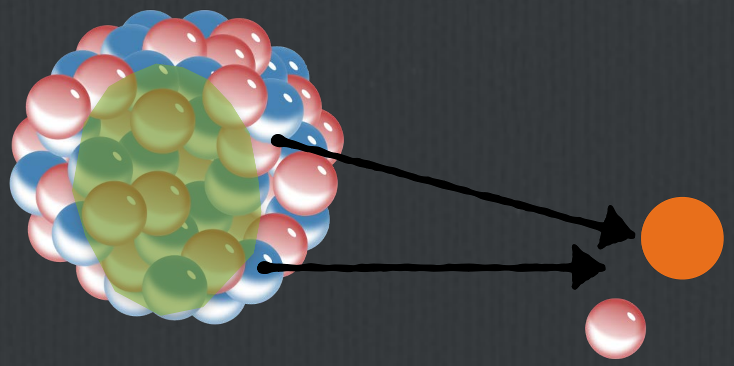


Repulsive Λp Interaction

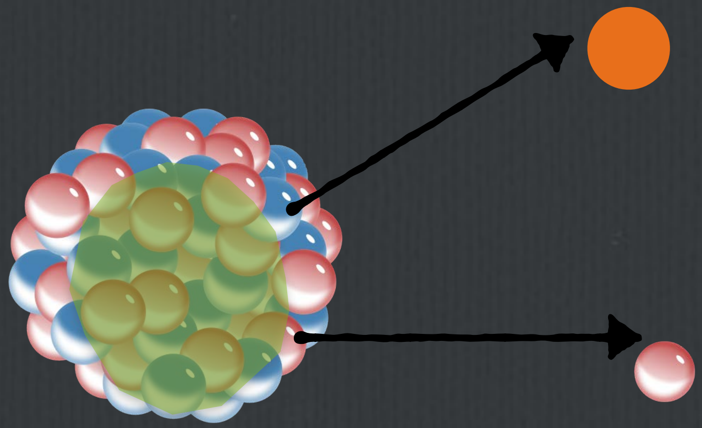


Femtoscopy in p+A/p+p reactions

Attractive Λ p Interaction



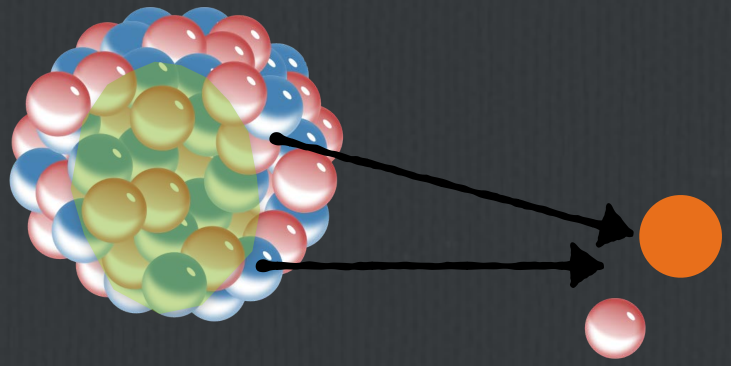
Repulsive Λp Interaction



- We can measure Λp pairs, their momentum and hence the distribution of the momentum difference.
- The source properties are taken from simulations.

- -> By looking at the distribution of the relative momentum we can infer on the final state interaction among the two particles

Correlation Function



Experimental Measurement

$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

$$k^* = \frac{1}{2}|\mathbf{p}_1^* - \mathbf{p}_2^*|$$

$$\mathbf{p}_1^* + \mathbf{p}_2^* = 0$$

Theoretical Function

F. Wang, and S.Pratt, Phys. Rev. Lett. **83** (1999) 3138

$$C(\vec{p}_a,\vec{p}_b) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} \approx \frac{\int d^4x_a\, d^4x_b\, S(p_a,x_a)S(p_b,x_b)|\phi_{rel}(\vec{p}_b-\vec{p}_a)|^2}{\int d^4x_a\, d^4x_b\, S_a(\vec{p}_a,x_a)S_b(\vec{p}_b,x_b)}$$

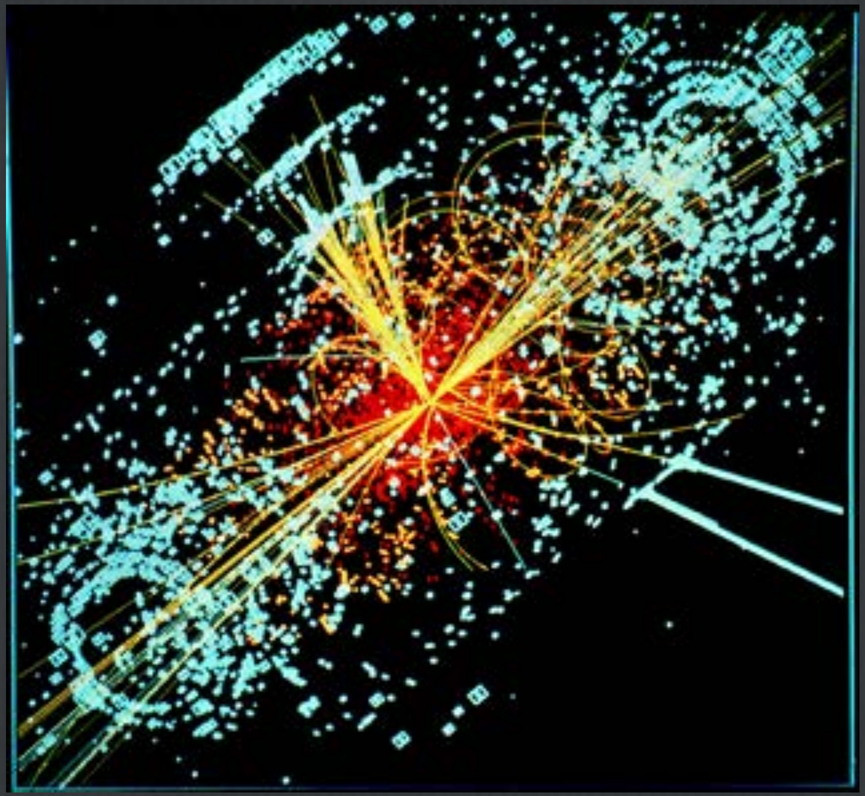
The theoretical function can be expressed in terms of the scattering parameters assuming that the source can be parametrised by f.e. a Gaussian function and that the correlation function does not provide information about the short-range part of the interaction.

The Experimental Data

p+p/A at 3.2 GeV

6 Particles/Evt

p+p/A at 7 TeV **RUN1**



2000 Particles/Evt

only 200.000 Λ/Σ but “clean” environment
better knowledge of the emitting source

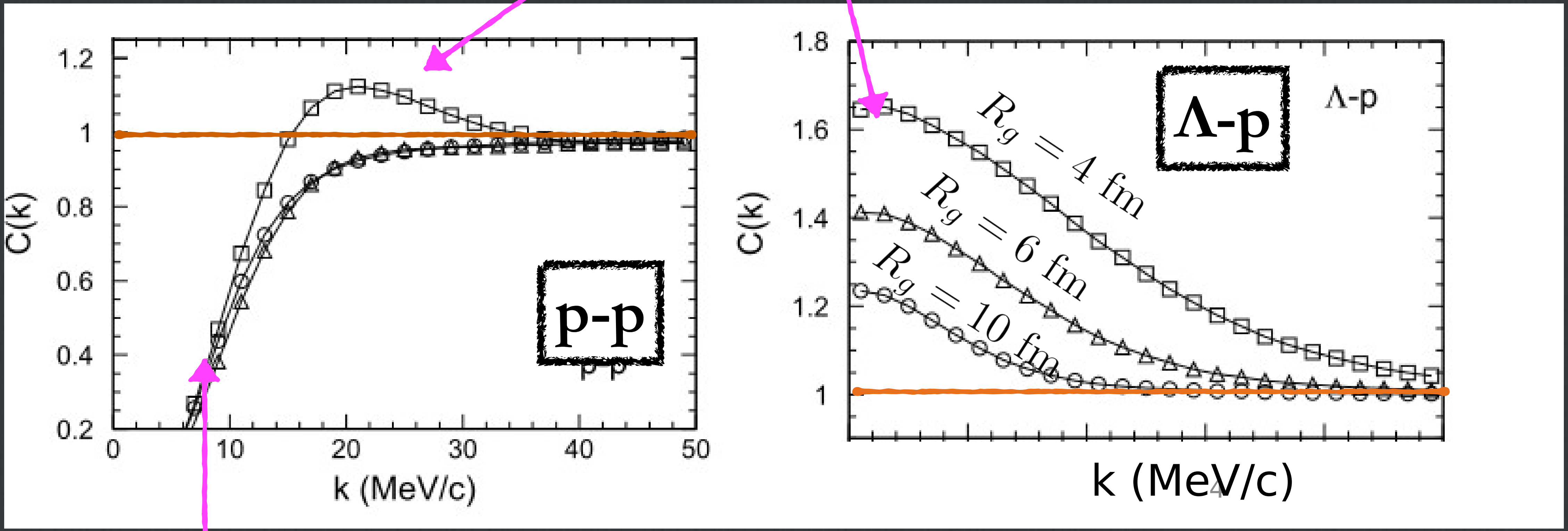
large Λ and Σ statistics (~ 3 Mevt) but
more complicated source to be described

The Experimental Data

Examples of Correlations from Calculations

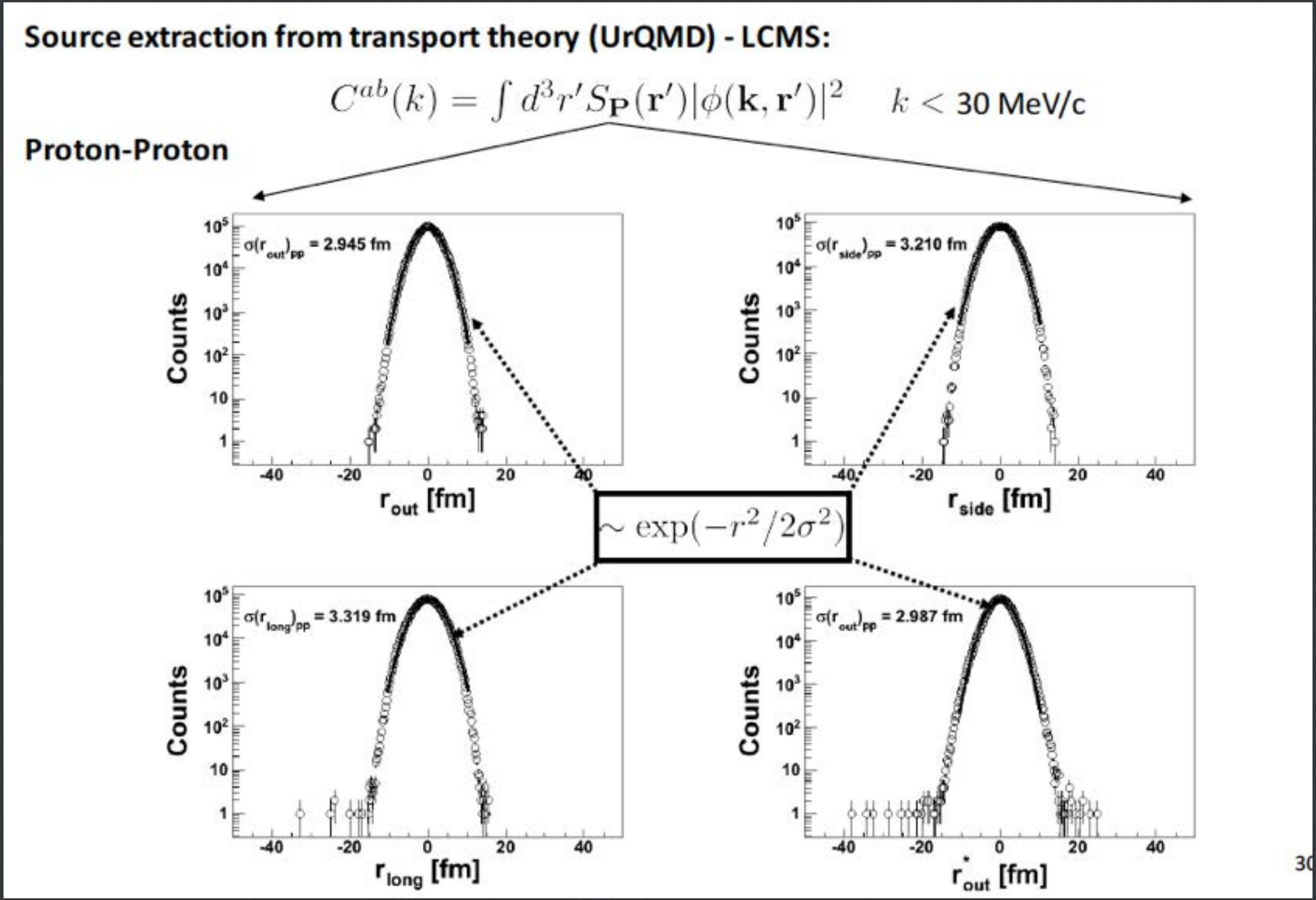
F. Wang and S. Pratt, Phys. Rev. Lett. 83, 3138 (1999).

Strong Attraction C(k)>1



Coulomb Repulsion C(k)<1

Sources from UrQMD



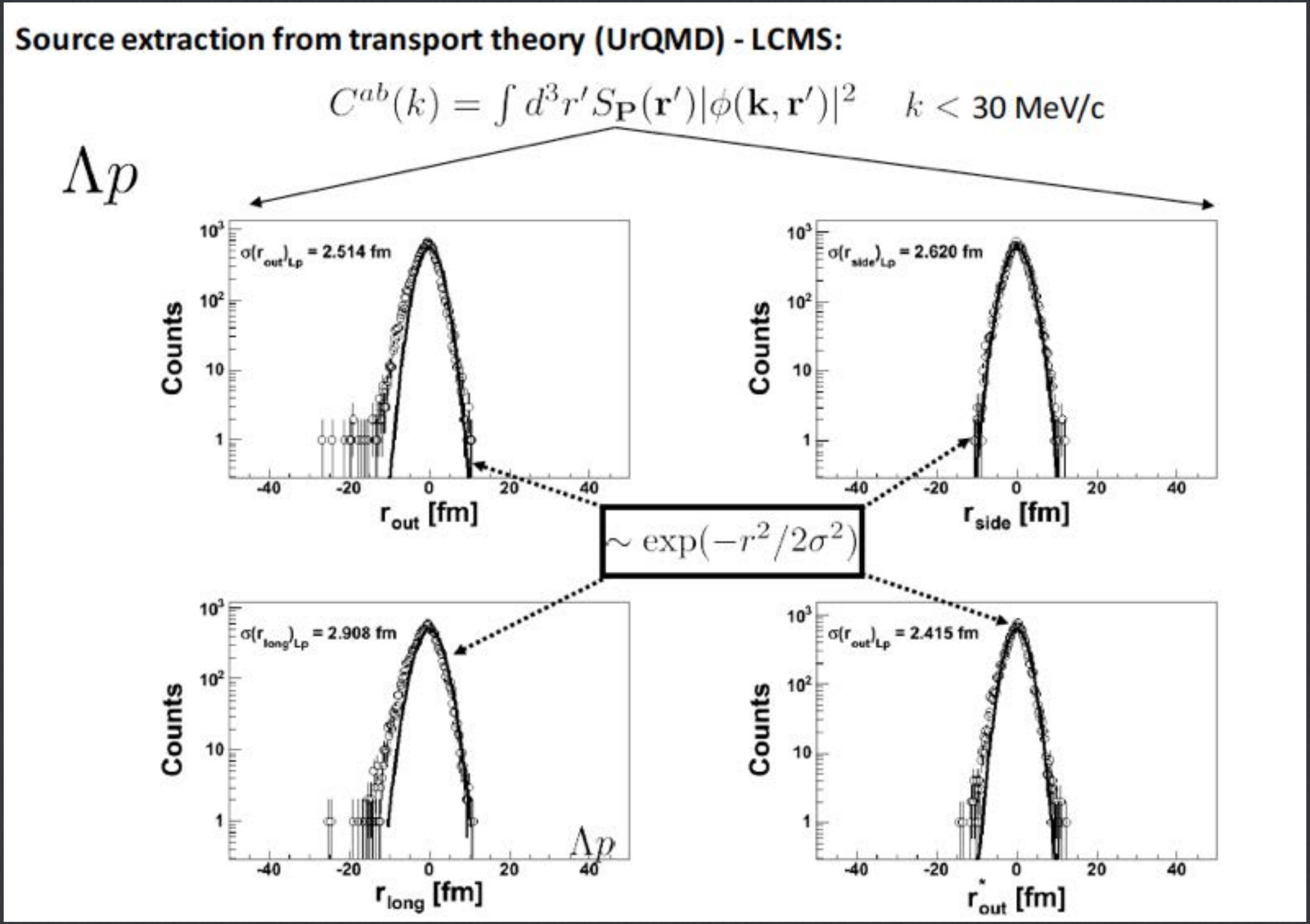
Source extraction from transport theory (UrQMD) - LCMS:

$$C^{ab}(k) = \int d^3r' S_{\mathbf{P}}(\mathbf{r}')|\phi(\mathbf{k},\mathbf{r}')|^2 \quad k < 30\ \mathrm{MeV/c}$$

Proton-Proton

$$\sim \exp(-r^2/2\sigma^2)$$

Sources from UrQMD



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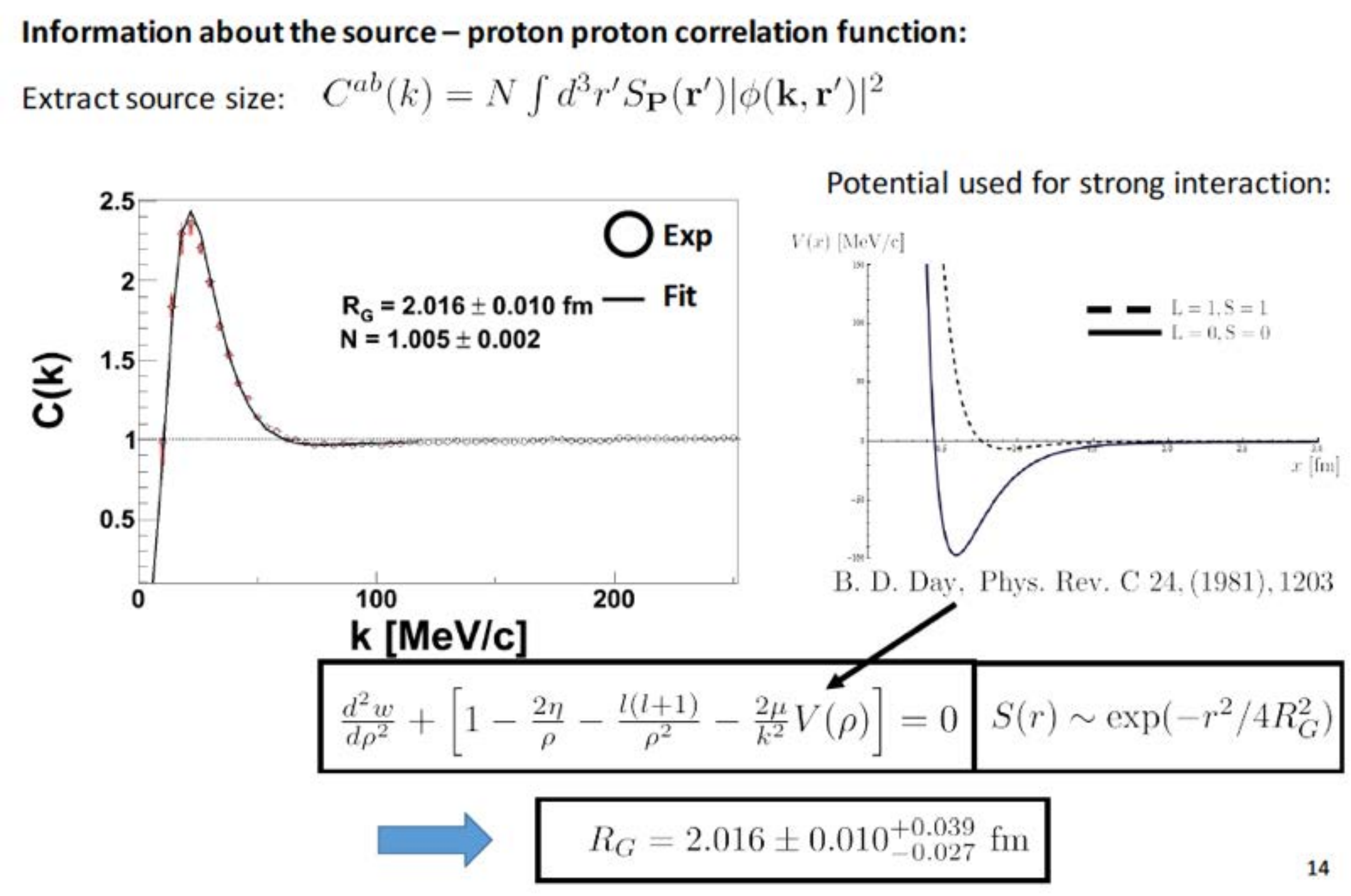
Λp

$\sim \exp(-r^2/2\sigma^2)$

p-p correlation in p+Nb collisions at 3.5 GeV

1.2 Billions evts



Information about the source – proton proton correlation function:

Extract source size: $C^{ab}(k) = N \int d^3r' S_{\mathbf{P}}(\mathbf{r}')|\phi(\mathbf{k},\mathbf{r}')|^2$

Potential used for strong interaction:

B. D. Day, Phys. Rev. C 24, (1981), 1203

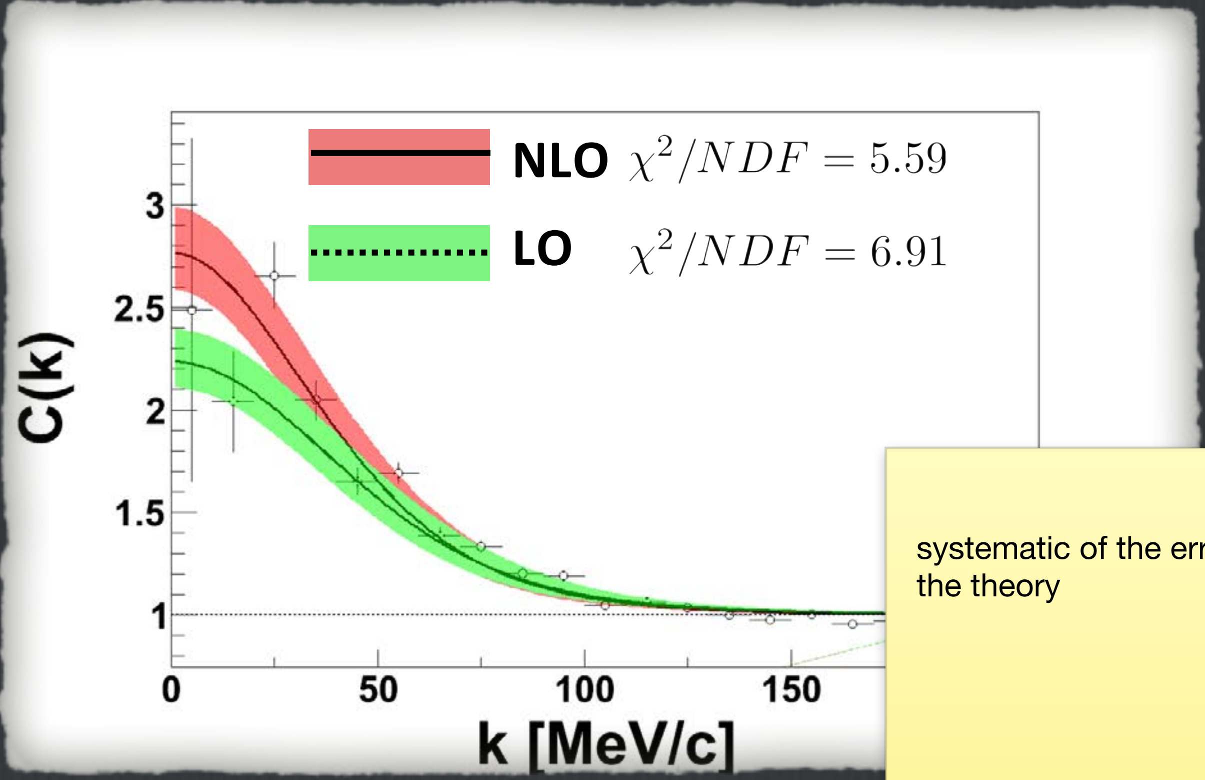
$$\frac{d^2w}{d\rho^2} + \left[1 - \frac{2\eta}{\rho} - \frac{l(l+1)}{\rho^2} - \frac{2\mu}{k^2}V(\rho)\right] = 0$$

$$S(r) \sim \exp(-r^2/4R_G^2)$$

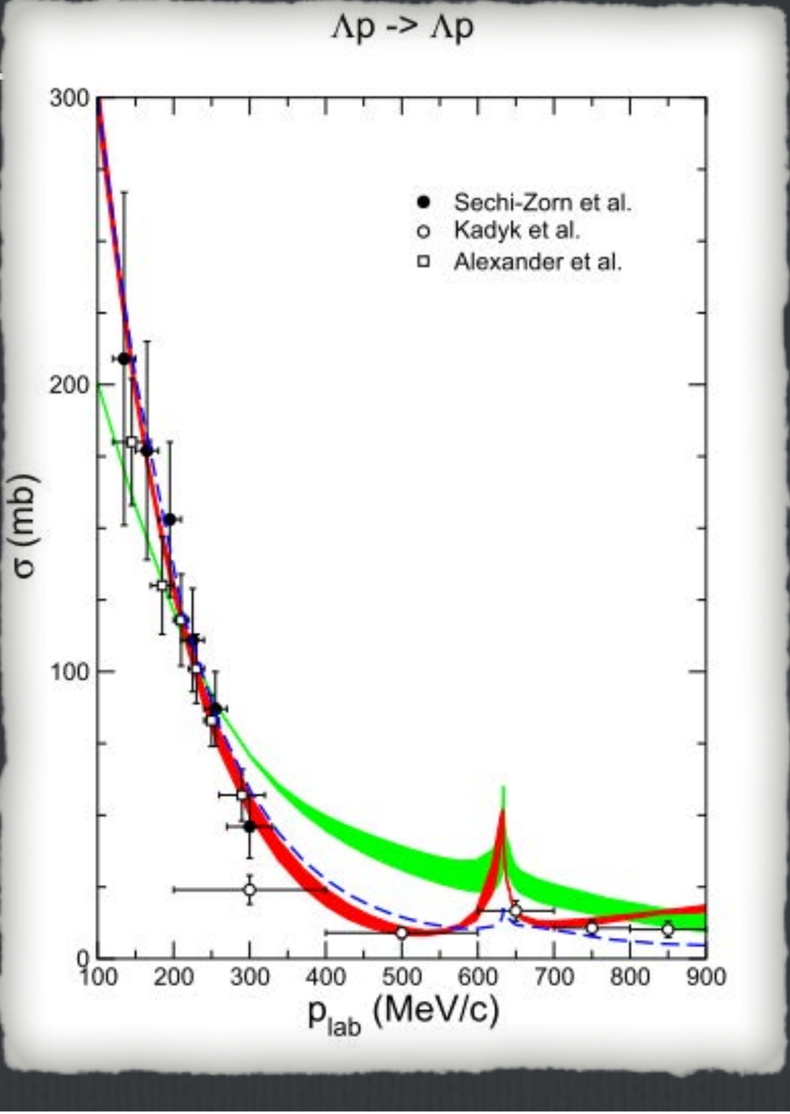
$$R_G = 2.016 \pm 0.010^{+0.039}_{-0.027} \text{ fm}$$

Λ-p Correlation in p+Nb collisions at 3.5 GeV

J. Adamczewski-Musch et al.,[HADES coll.] Phys. Rev. C. 94 (2016).



systematic of the error on the radius on the theory



$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

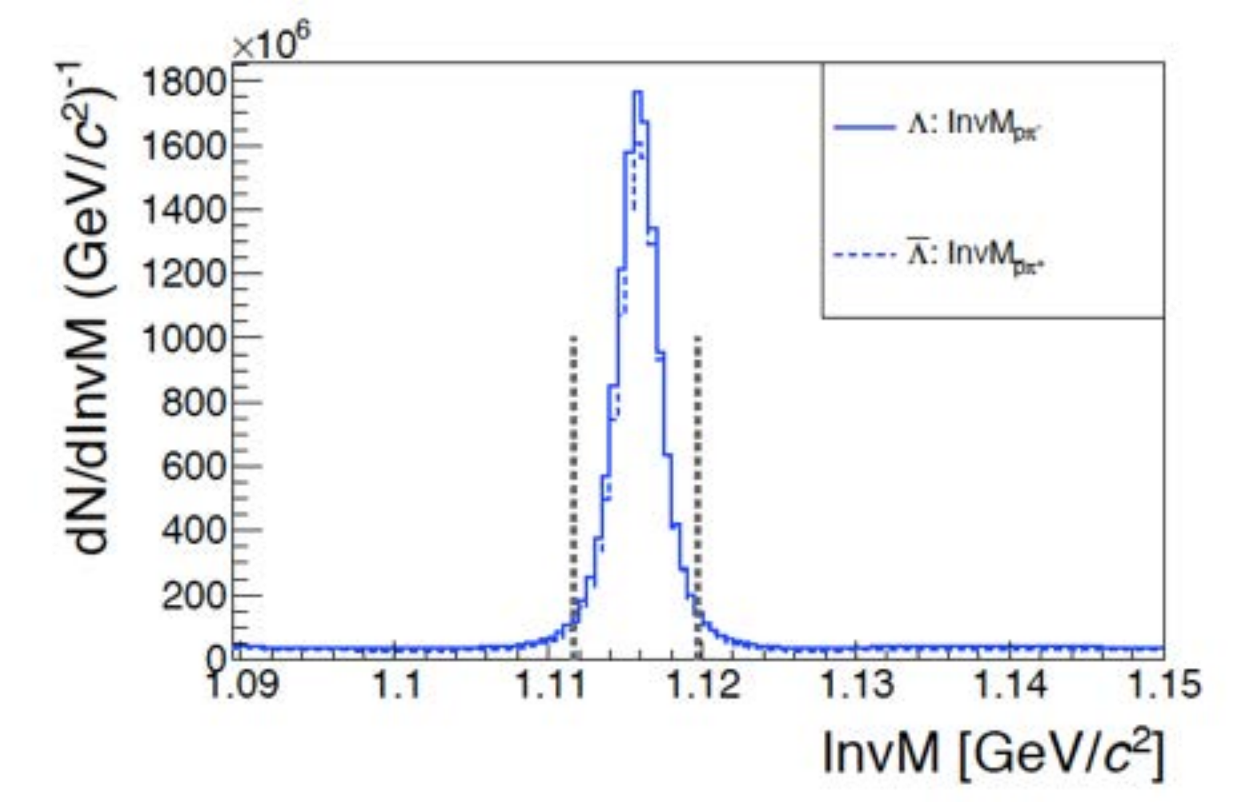
Λ-p correlation function obtained by subsituting the NLO and the LO scattering length values in the Lednicky's model.

Substitute scattering data!!

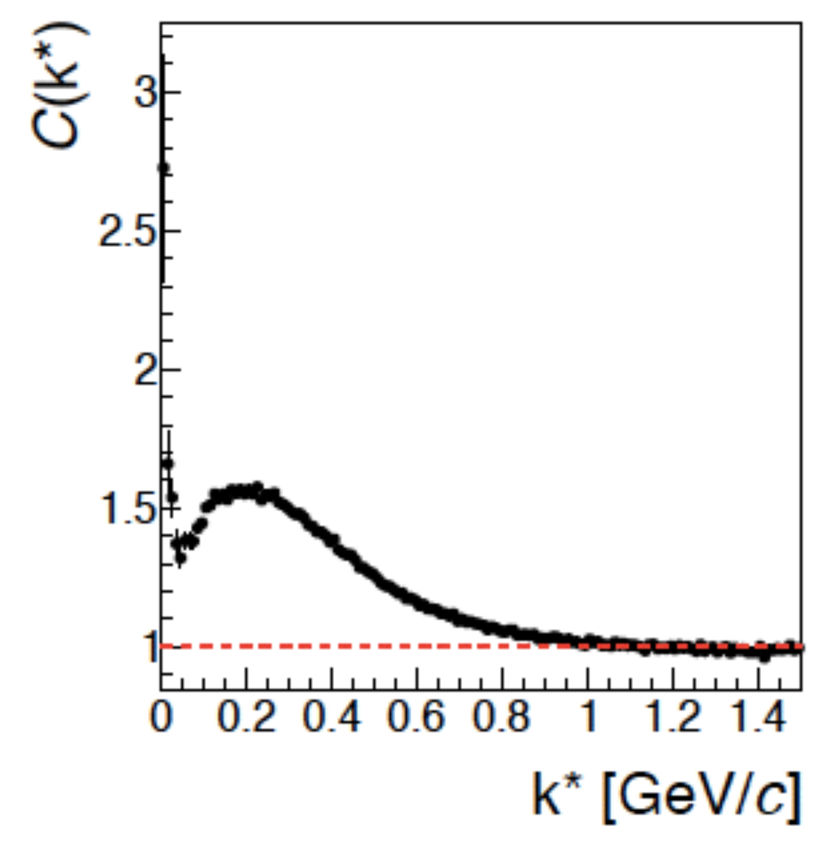
ALICE data

p+p 7 TeV, RUN 1 ~250 Millions Events

Excellent Purity for Λ



$p - \bar{p}$ Correlation



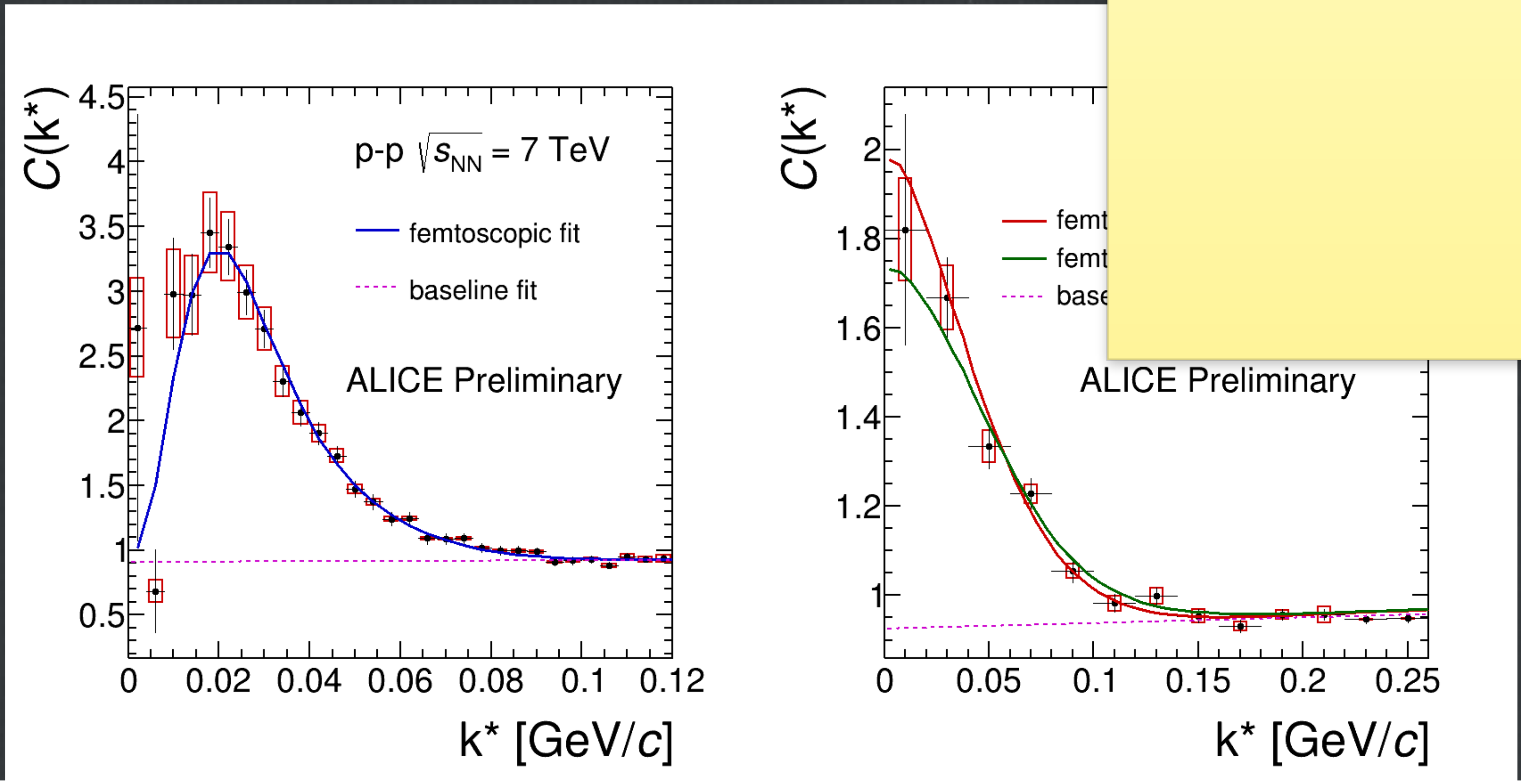
Minijets background present for Baryon-Antivaryon correlation
Not there for Baryon-Baryon correlation

p+p at much larger energ

systematic error only on the experimental data and extracted paprameters, radius in this case
Lines represent the fit for the standard case

p-p Correlation

Λp C



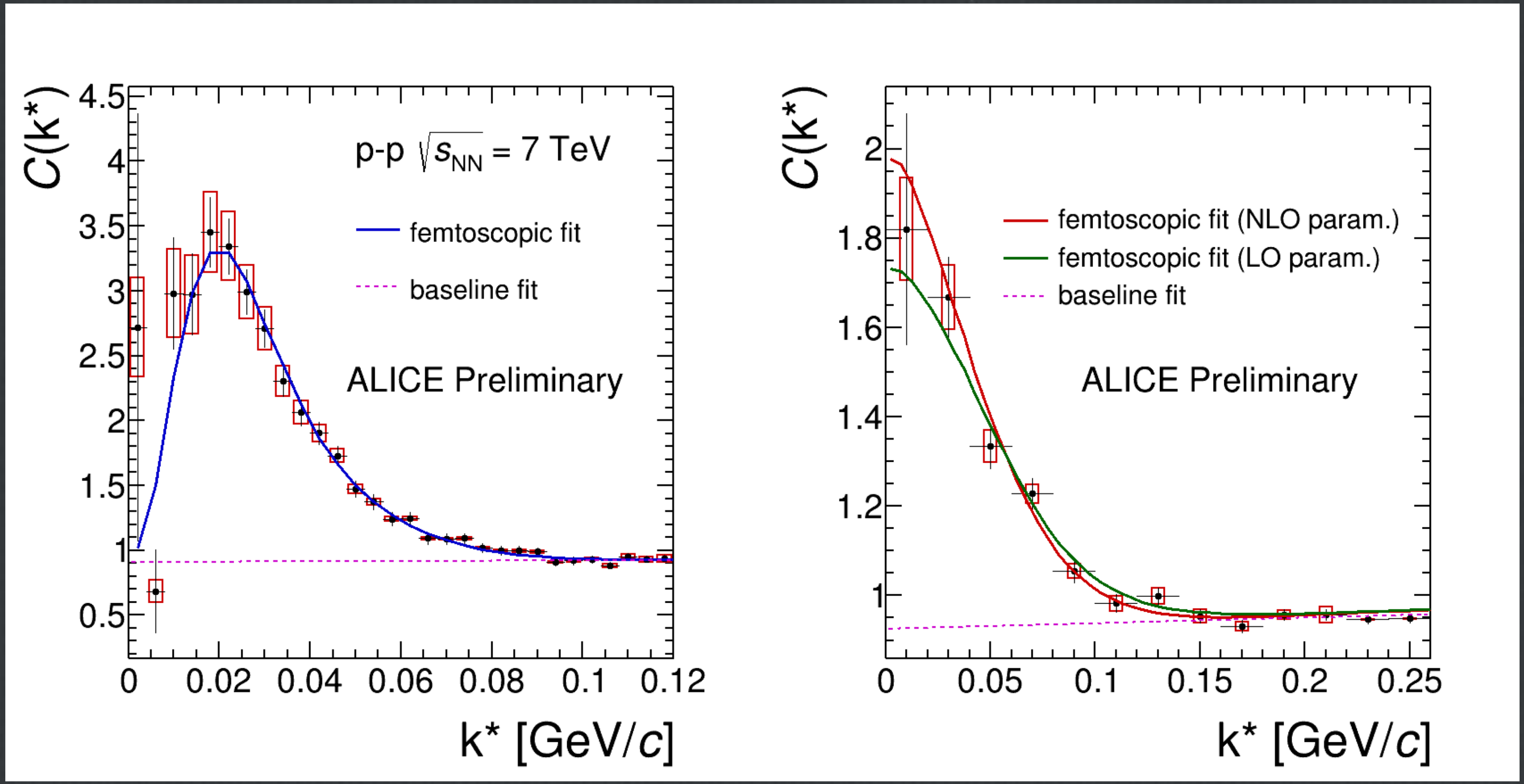
$$C(k^*)_{\mathrm{pp,tot}} = \mathcal{N}_{\mathrm{pp}}\left(1+\underbrace{\lambda_{\mathrm{pp}}}_{0.76}(C(k^*)_{\mathrm{pp}}-1)+\underbrace{\lambda_{\mathrm{p\Lambda}}}_{0.16}(C(k^*)_{\mathrm{p\Lambda}}-1)\right)C(k^*)_{\mathrm{baseline}}$$

$$C(k^*)_{\mathrm{p\Lambda,tot}} = \mathcal{N}_{\mathrm{p\Lambda}}\left(1+\underbrace{\lambda_{\mathrm{p\Lambda}}}_{0.53}(C(k^*)_{\mathrm{p\Lambda}}-1)+\underbrace{\lambda_{\mathrm{p\Sigma^0}}}_{0.17}(C(k^*)_{\mathrm{p\Sigma^0}}-1)+\underbrace{\lambda_{\mathrm{p\Xi^-}}}_{0.10}(C(k^*)_{\mathrm{p\Xi^-}}-1)\right)C(k^*)_{\mathrm{baseline}}$$

p+p at much larger energies (7 TeV)

p-p Correlation

Λp Correlation



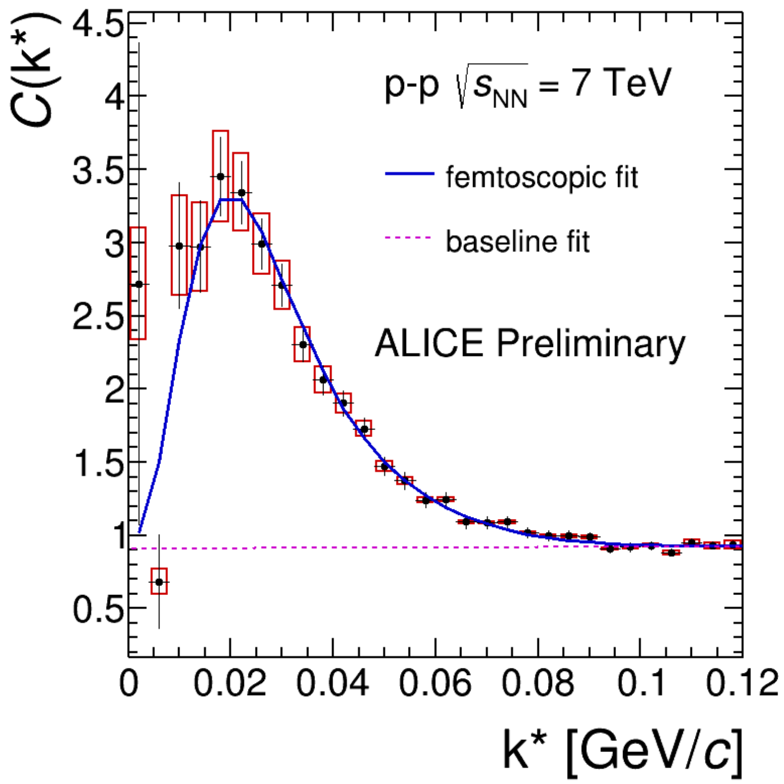
RUN1 Statistics

Factor 5 more available from RUN2 Statistics (middle of 2017)

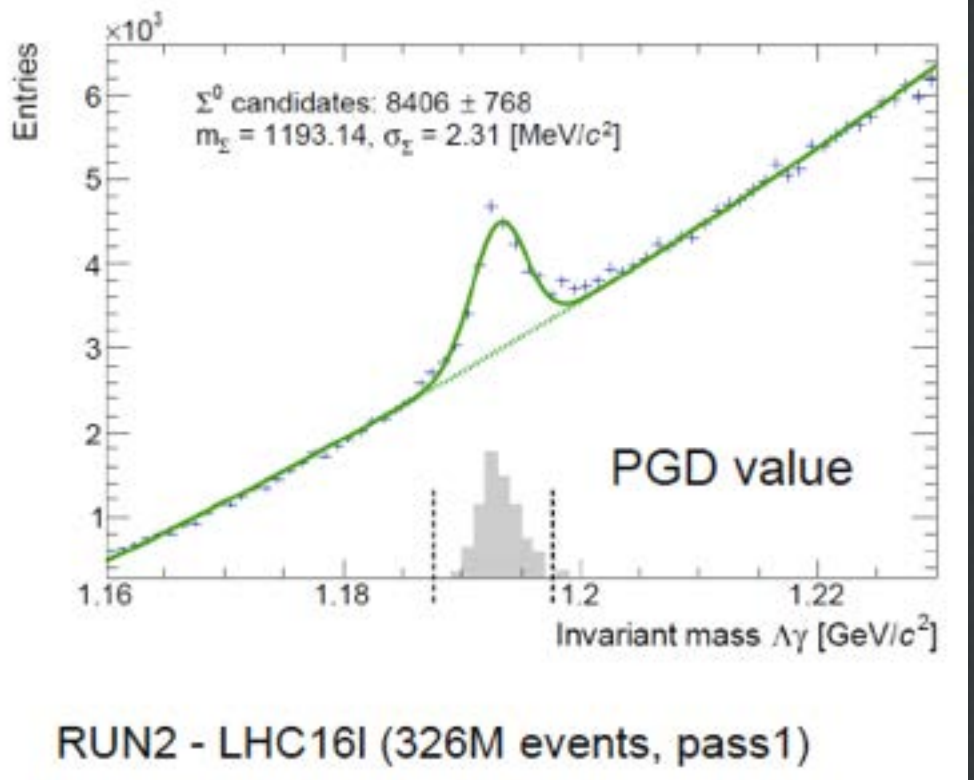
Extension to $\Sigma^0/\Sigma^+/\Xi - p$ correlations

p+p at much larger energies (7 TeV)

p-p Correlation



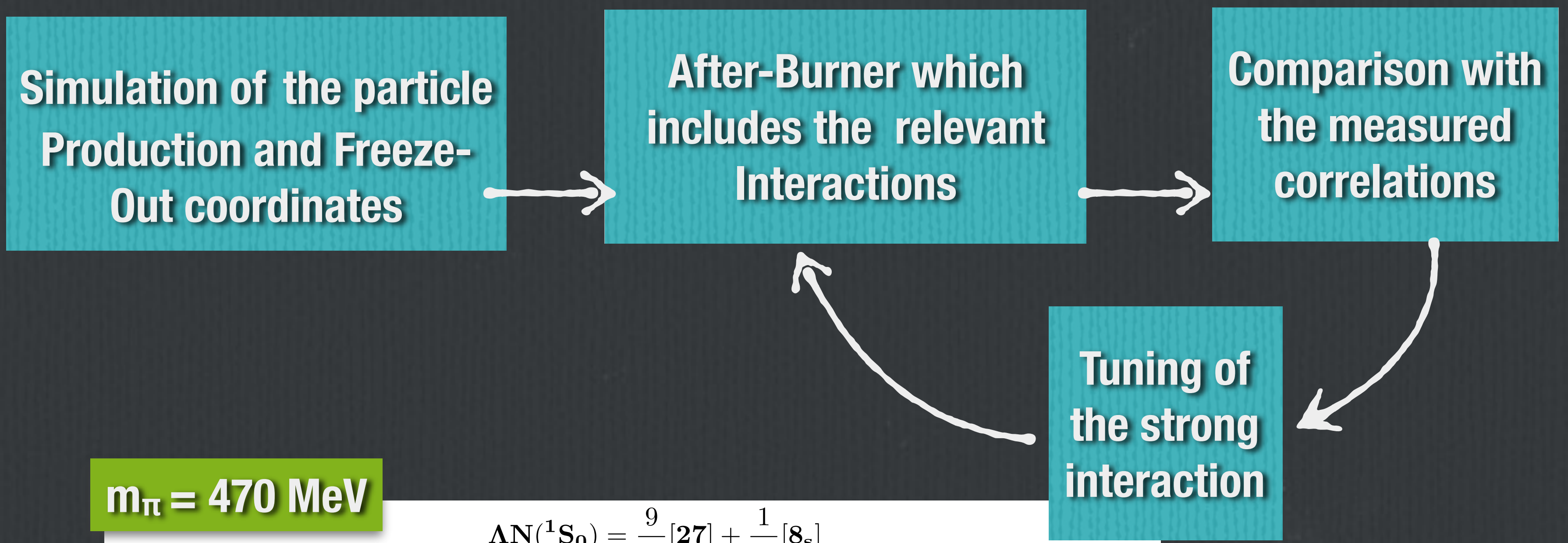
Λp Correlation



RUN2 - LHC16l (326M events, pass1)

RUN1 Statistics
Factor 5 more available from RUN2 Statistics (middle of 2017)
Extension to $\Sigma^0/\Sigma^+/\Xi - p$ correlations

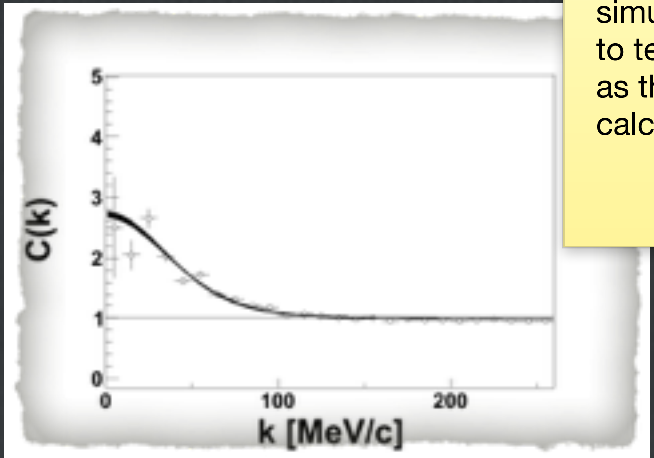
Test-Bed for Lattice Calculations


Simulation of the particle Production and Freeze-Out coordinates

After-Burner which includes the relevant Interactions

Comparison with the measured correlations

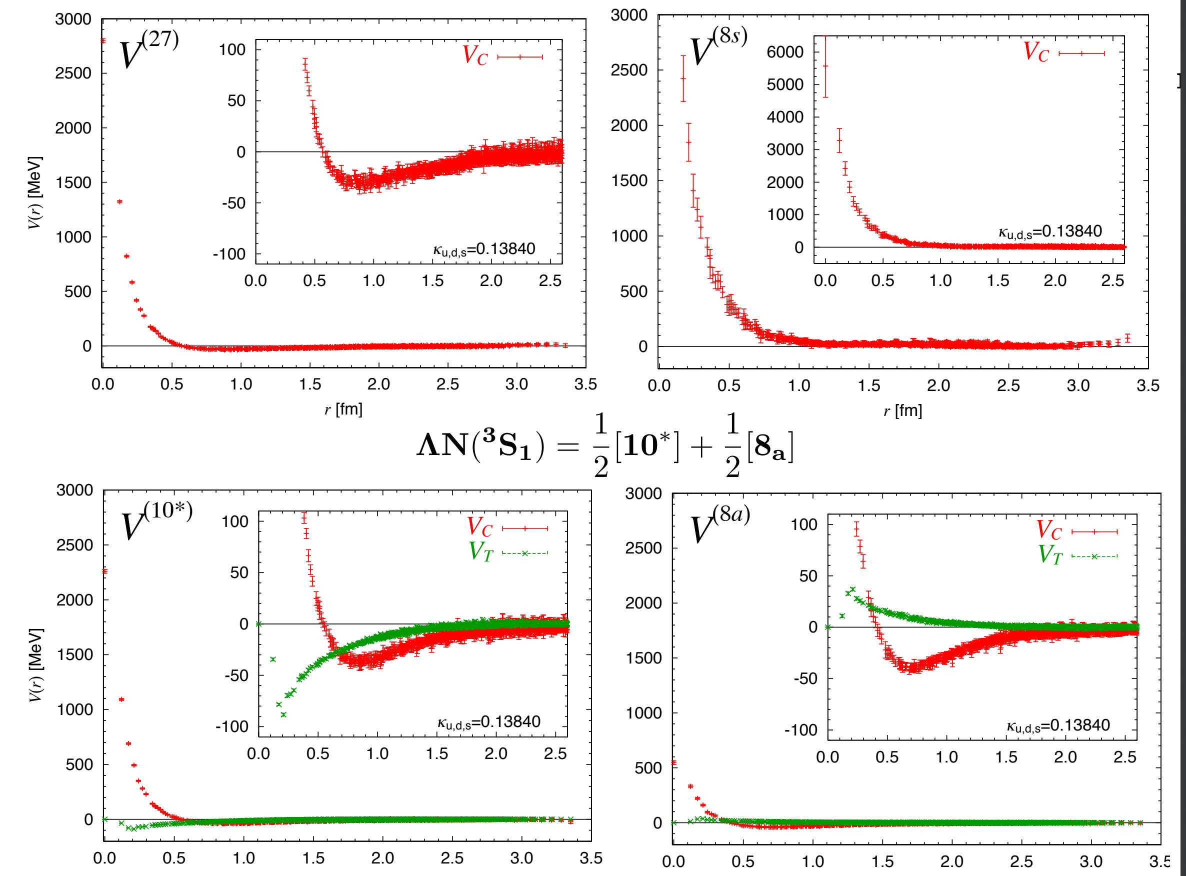
Tuning of the strong interaction



instead of fi
simulations
to test full s
as those res
calculations

m_π = 470 MeV

$$\Lambda N(^1S_0) = \frac{9}{10}[27] + \frac{1}{10}[8_s]$$



$$\Lambda N(^3S_1) = \frac{1}{2}[10^*] + \frac{1}{2}[8_a]$$

T. Inoue et al. Nucl. Phys. A881 (2012) 28

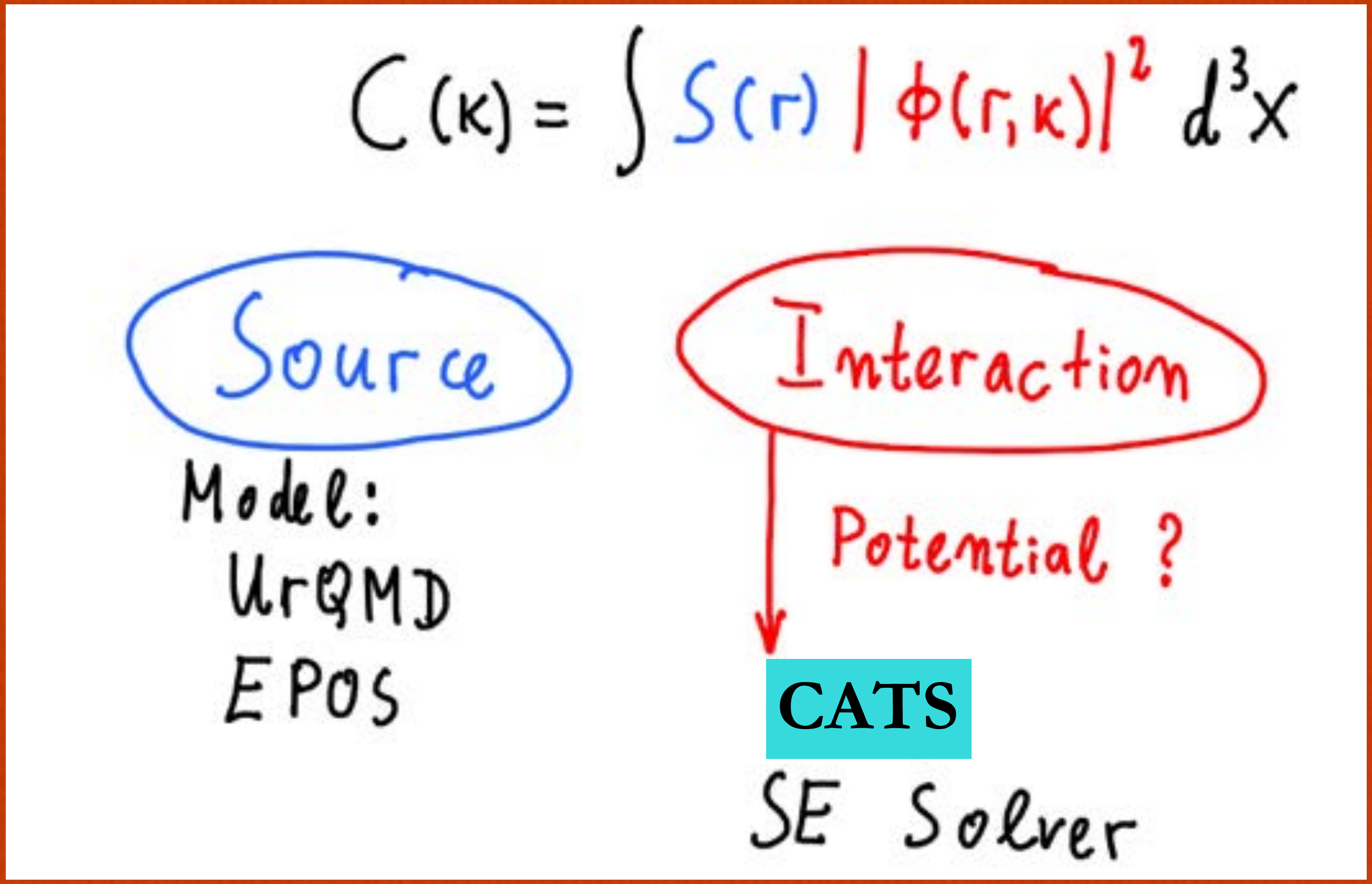
Hyperon-Nucleon Correlation
Hyperon-Nucleon-Nucleon Correlation??

Mainly a matter of statistics

Our Afterburner

Idea:

- Event generator (UrQMD or EPOS) or Gaussian distriburion for the source sampling
- Schrödinger equation solver



Output:

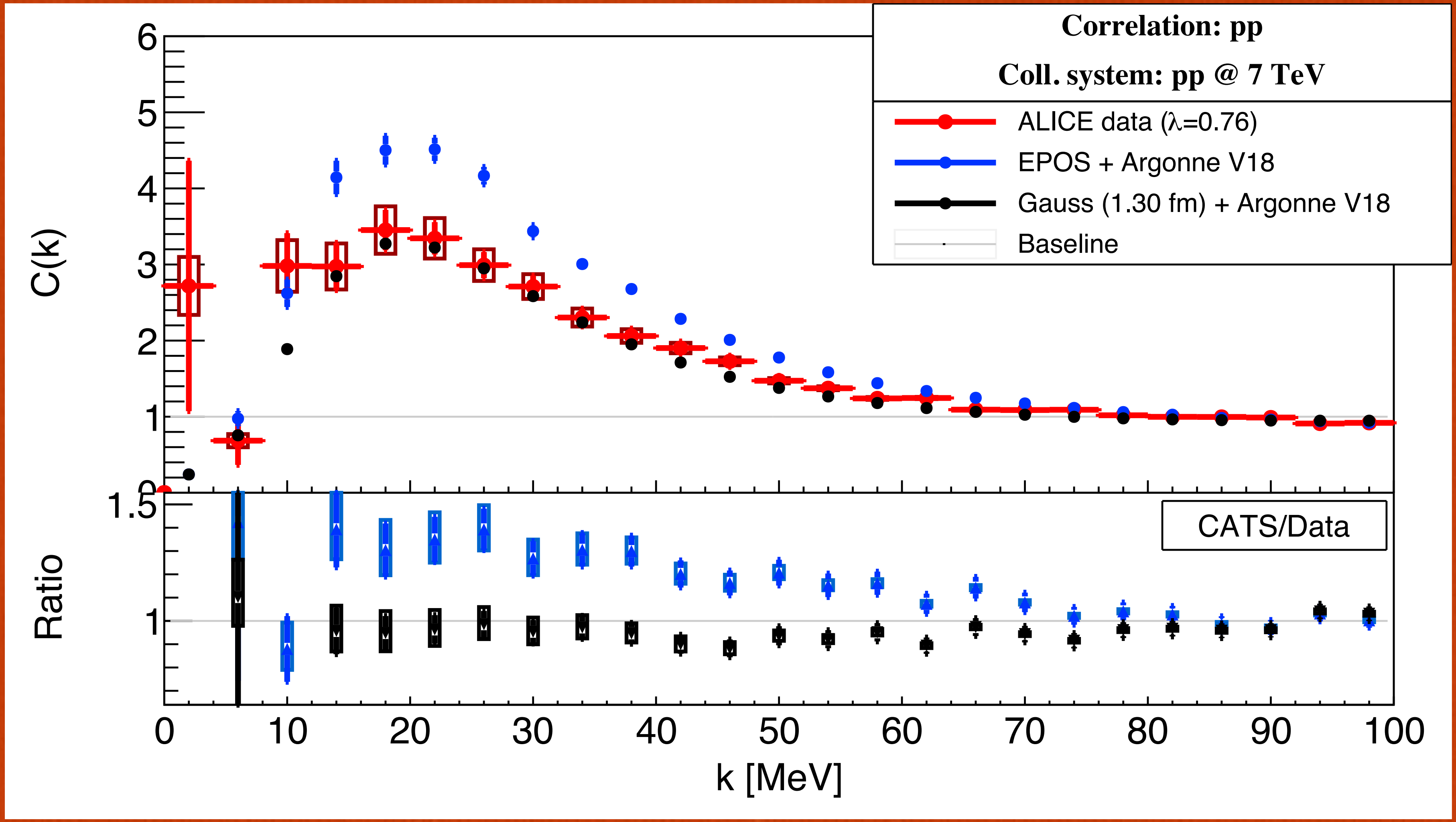
Theoretical correlation function to be compared with the experimental data

Correlation Analysis Tool using the Schrödinger equation

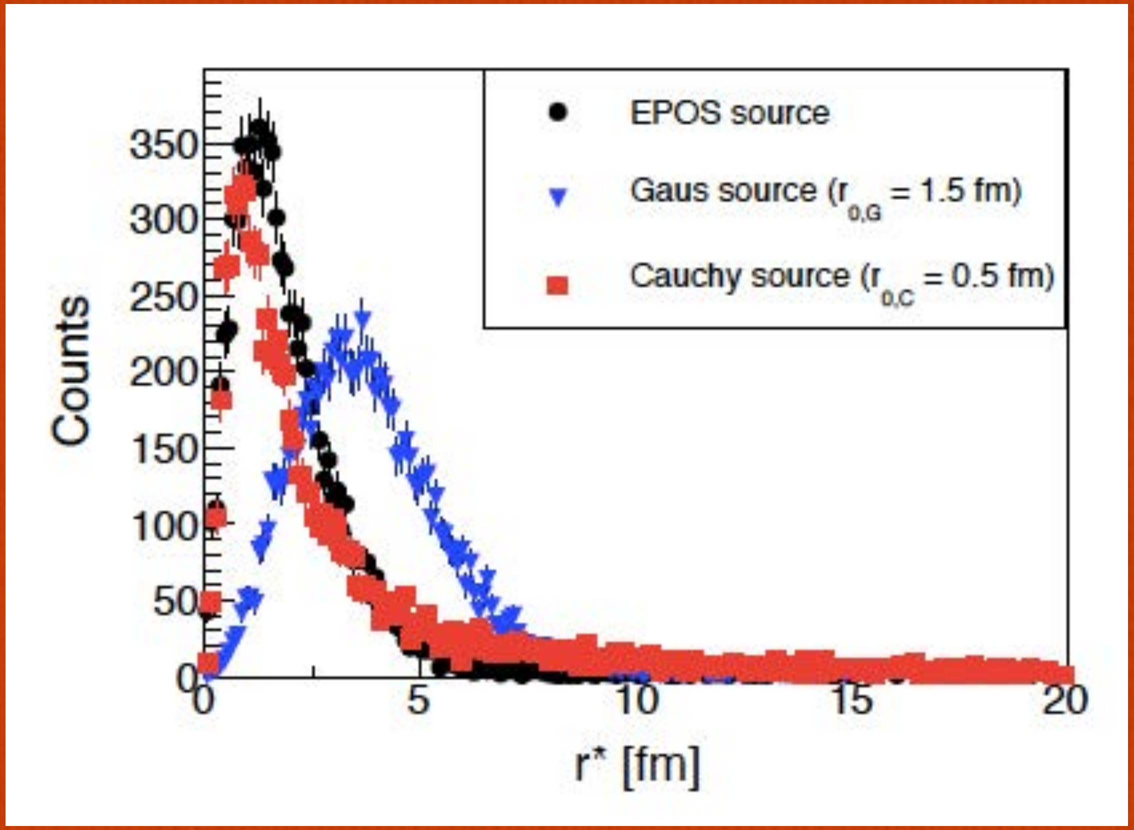
CATS

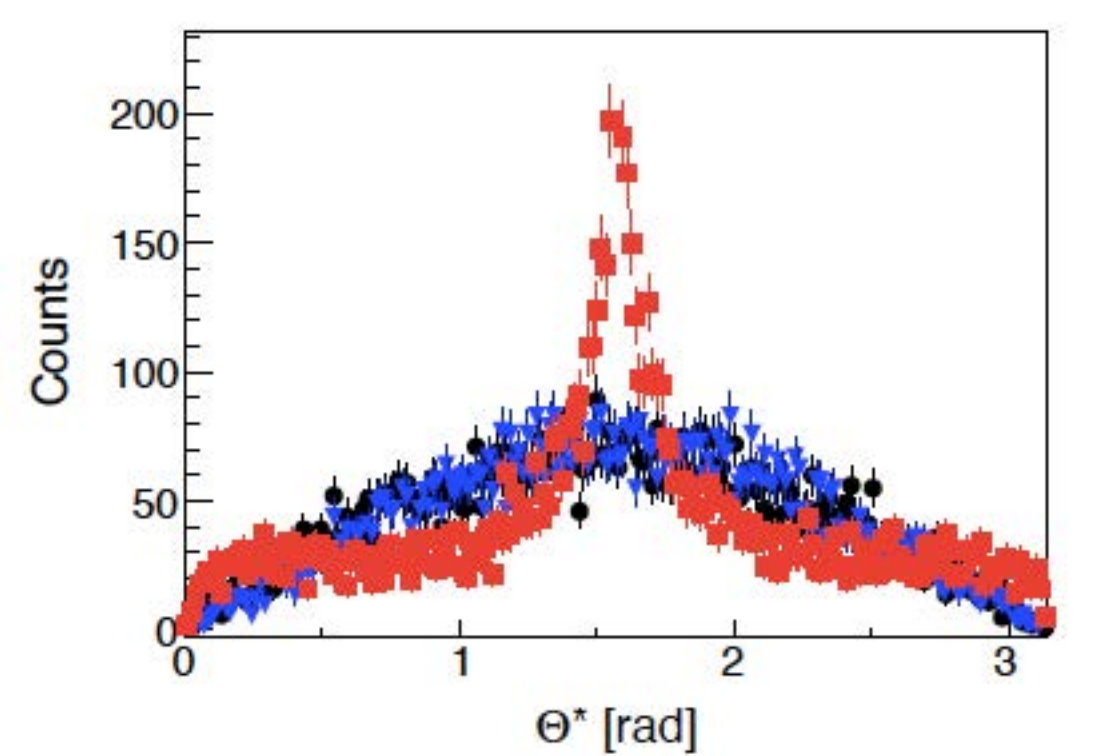
Exact solution, no asymptotic solution (large distances) as in CRAB*

* http://www.pa.msu.edu/~pratts/freecodes/crab/home.html



Source in EPOS





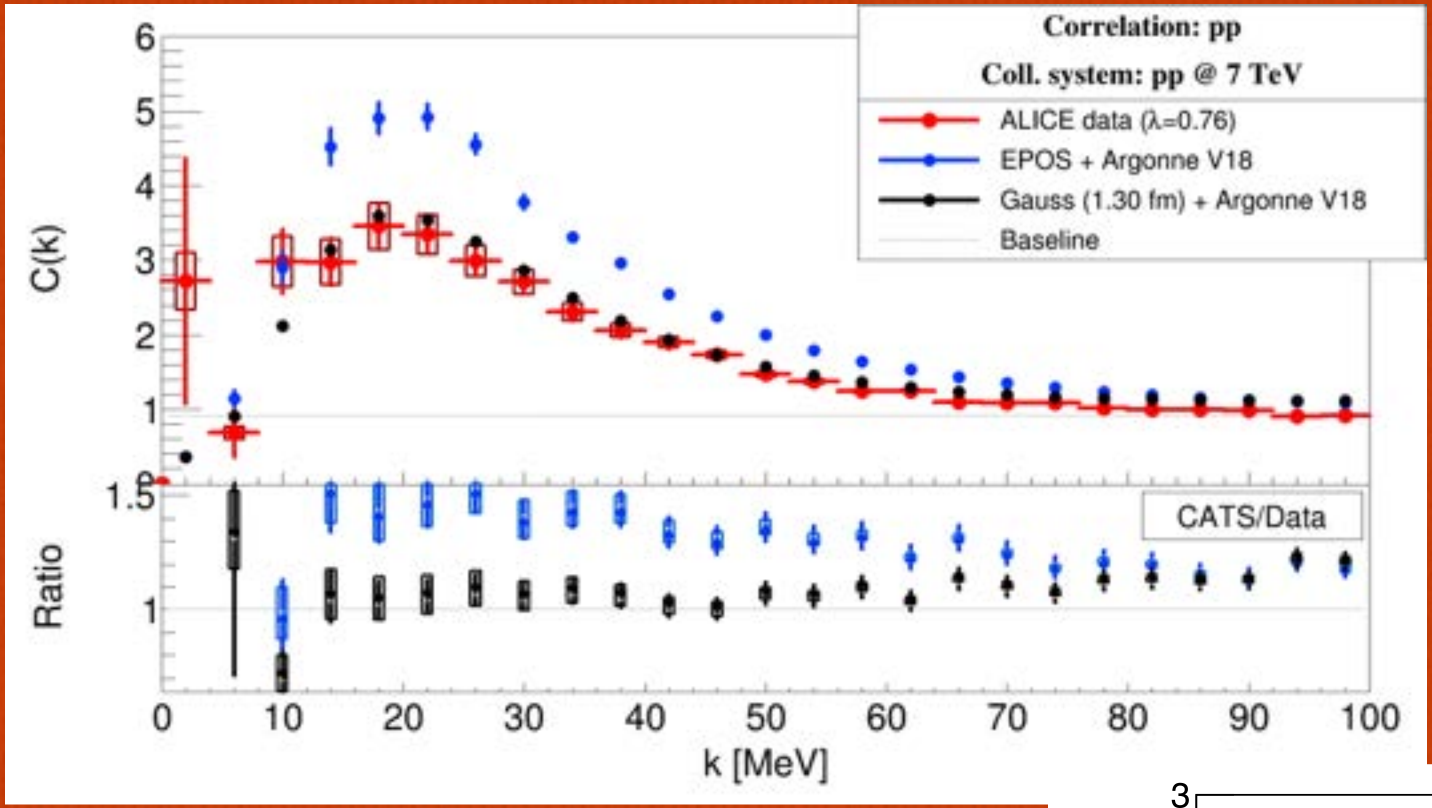
Cauchy Function:

$$f(x) = \frac{1}{\pi(1 + x^2)}$$

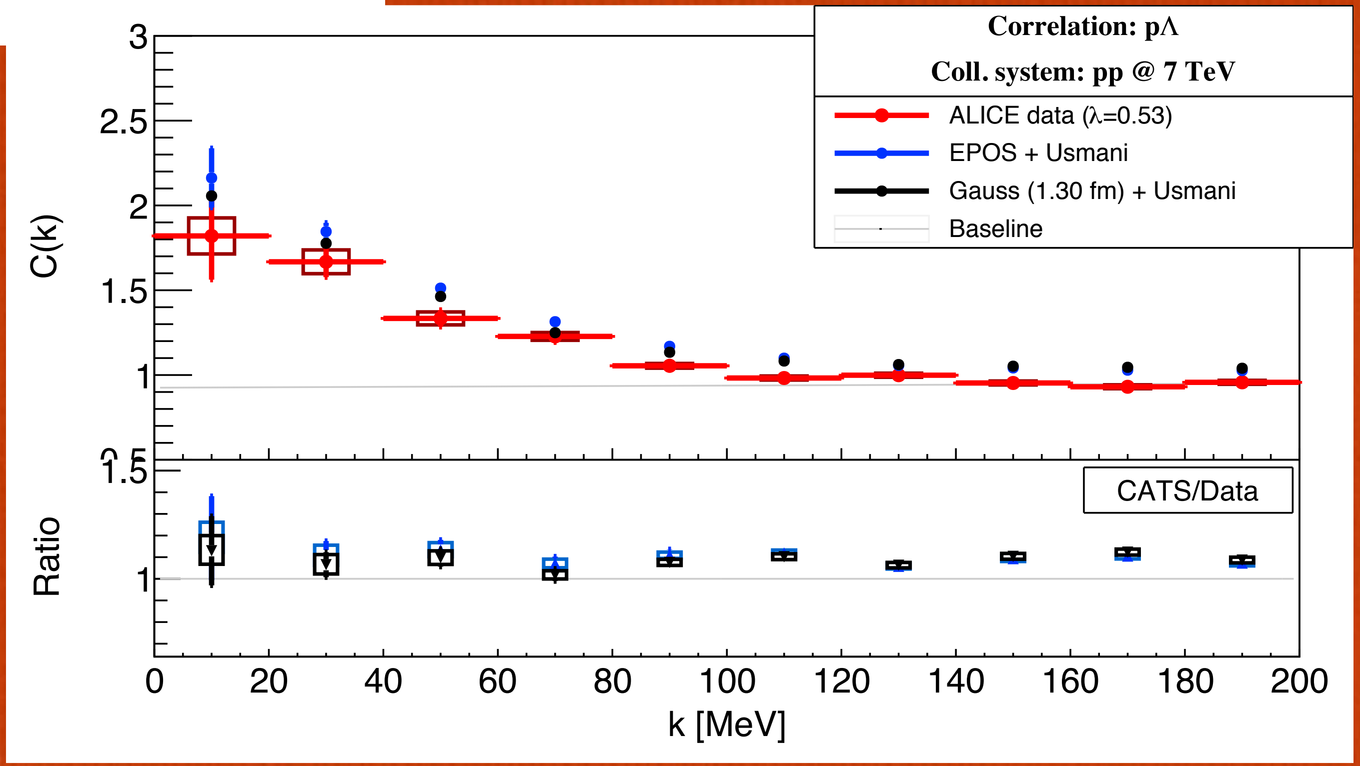
The EPOS generator does not deliver a Gaussian source!

CATS and ALICE data

proton-proton correlation



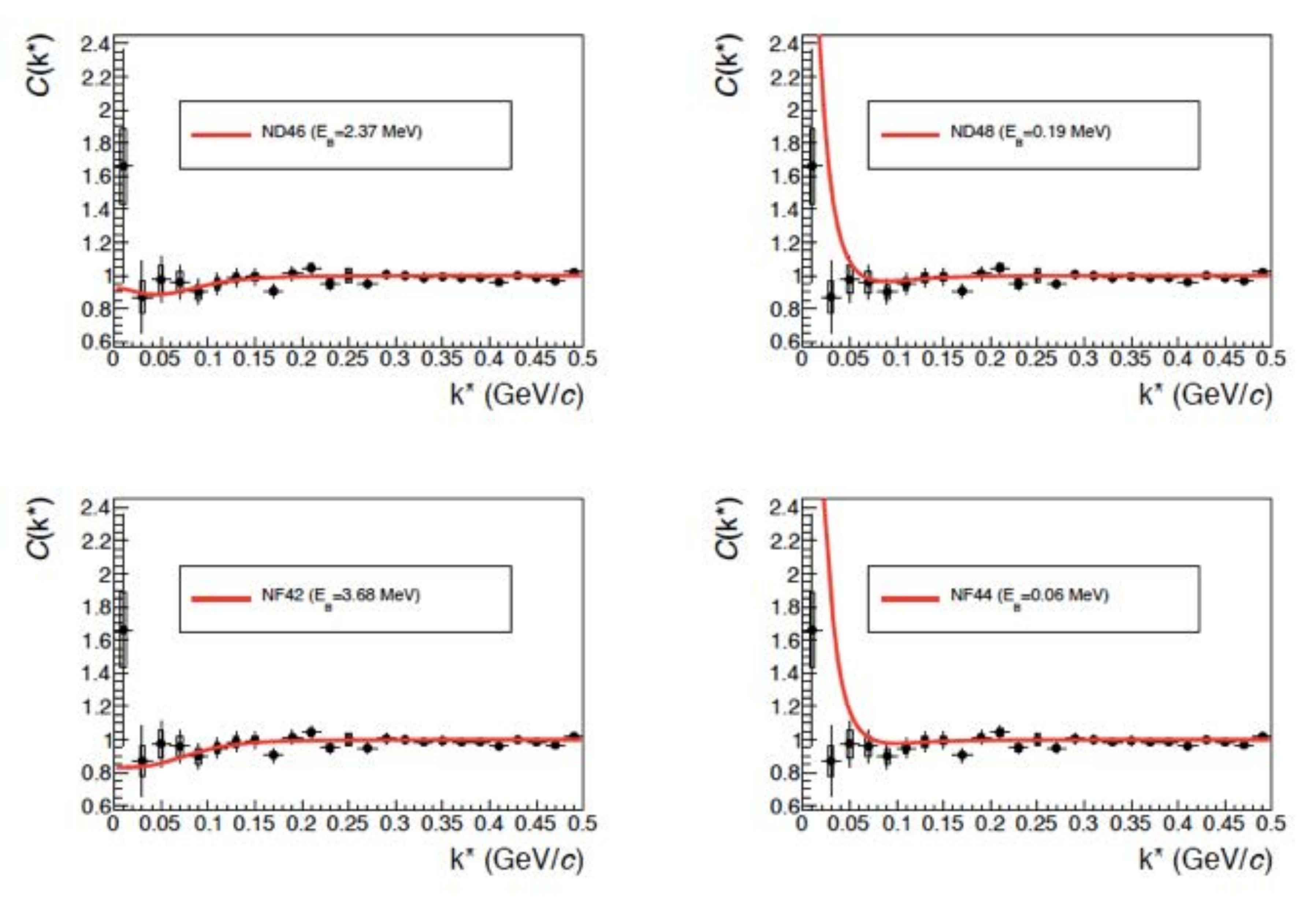
Λ -proton correlation



pp correlation are obtained with EPOS+CATS do not match the experimental data.
But a Gaussian source + CATS does it.

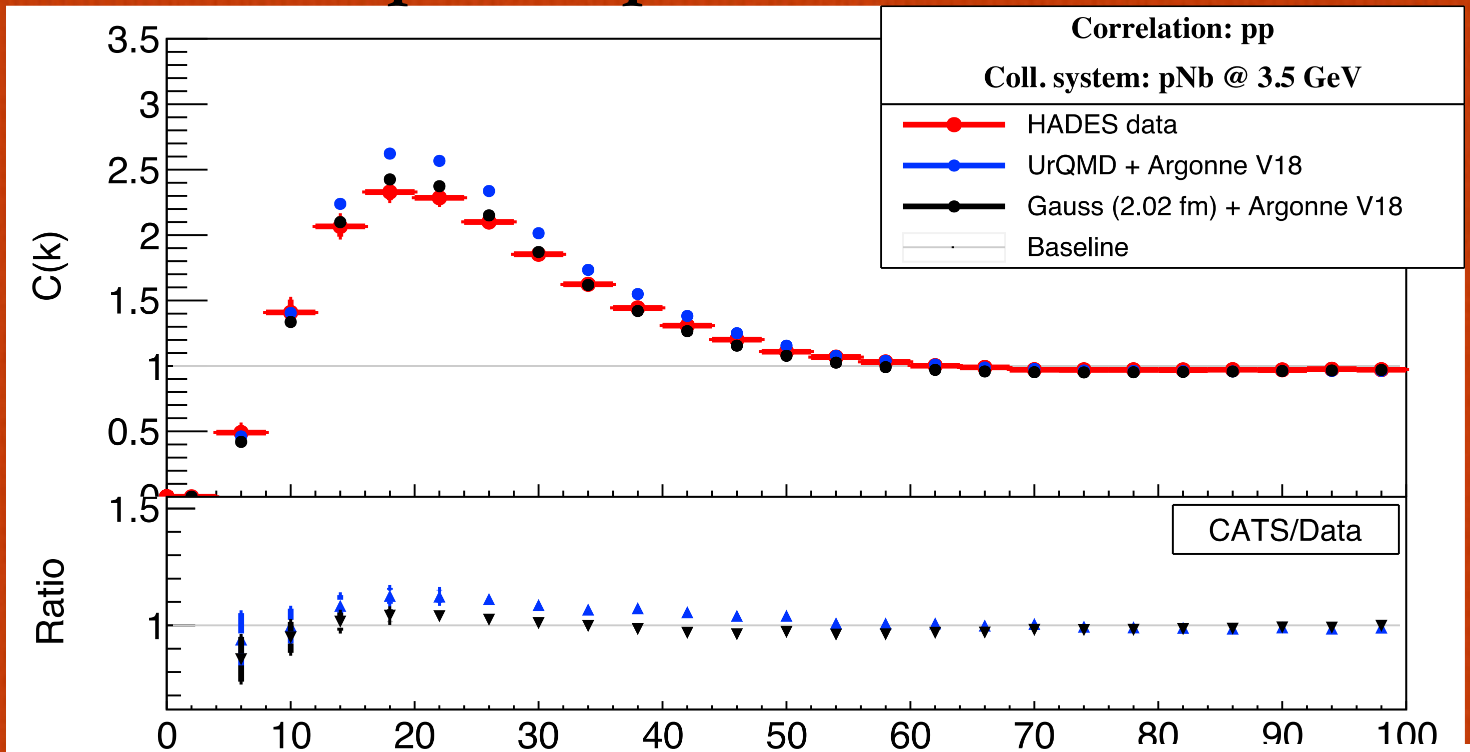
$\Lambda - \Lambda$ Correlation

$$E_B = \frac{(\hbar c)^2}{m_\Lambda}\kappa^2, \kappa = \frac{1}{d_0}\left(1 - \sqrt{1 - \frac{2d_0}{a}}\right)$$

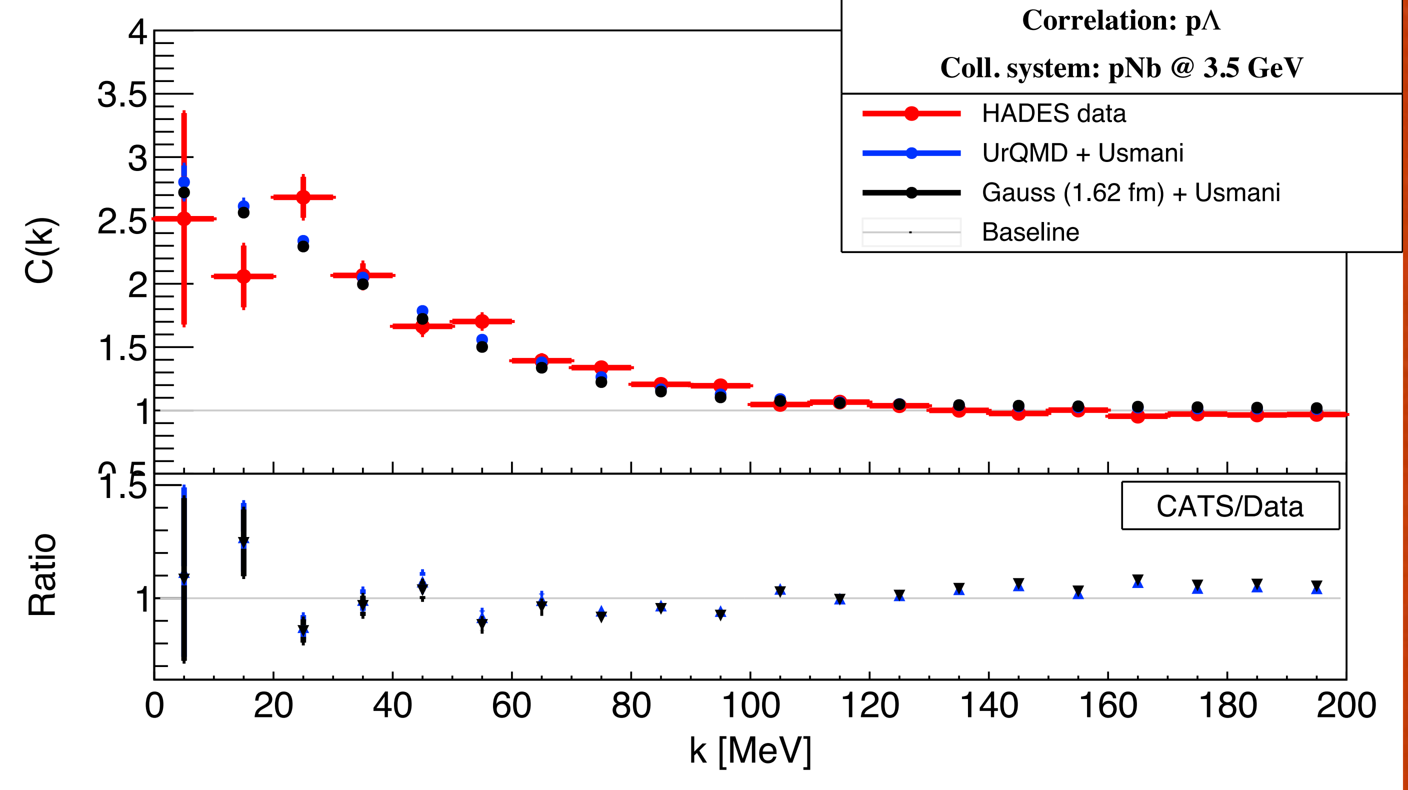


CATS and HADES data

proton-proton correlation



Λ -proton correlation



The agreement is more reasonable for UrQMD+ CATS

Summary and Outlook

- Hadron-Hadron interactions have to be understood in detail to compute a realistic EOS for neutron stars

- New tools to study Hyperon-Nucleon interaction:Femtoscopy in elementary reactions
- pp and Lambda-p correlations studied with the HADES and ALICE data.

Bundesministerium
für Bildung
und Forschung

sfb 1258 neutrinos darkmatter messengers

The Group

http://www.denseandstrange.ph.tum.de