3rd EMMI workshop: anti-matter, hypermatter and exotica production at the LHC
Wrap-up day 2

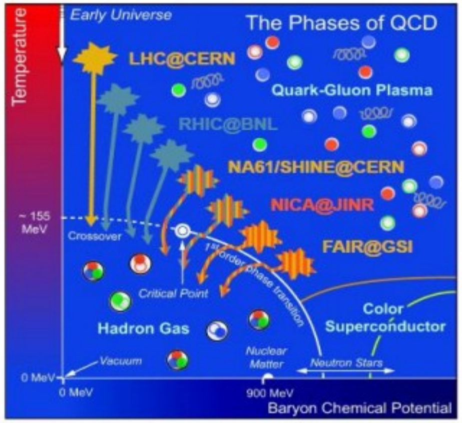
Ramona Lea

University and INFN (Trieste)

So… how are produced light nuclei?

The ‚holy grail' of heavy-ion physics:

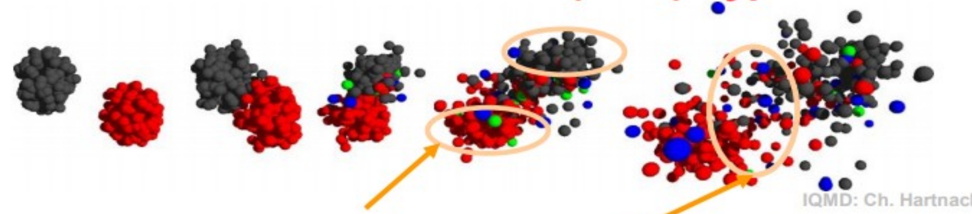
The phase diagram of QCD



Experimental observables:

…

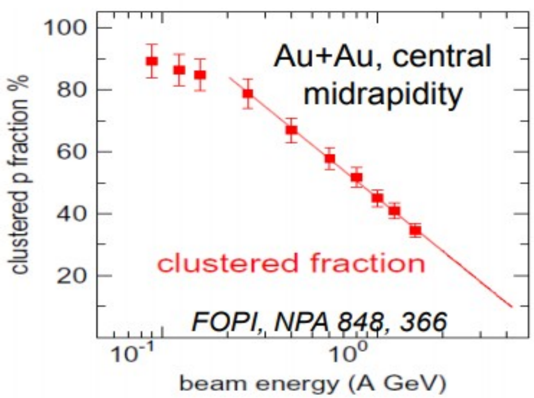
Clusters and (anti-) hypernuclei



- **projectile/target spectators➔ heavy cluster formation**
- **midrapidity➔ light clusters**

! Hyperons are created in participant zone

- **Clusters are very abundant at low energy**



(Anti-) hypernuclei production:

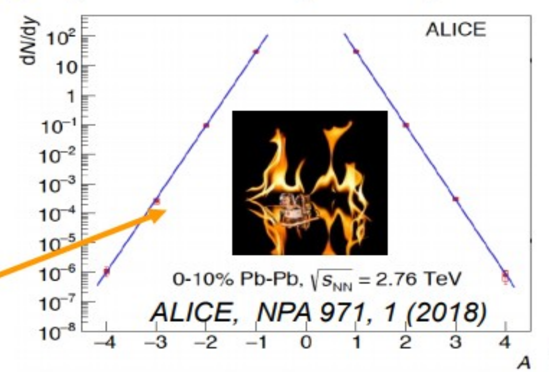
- at mid-rapidity by Λ coalessance during expansion

- at projectile/target rapidity by rescattering/absorption of Λ by spectators

High energy HIC:

‚Ice in a fire' puzzle:

how the weakly bound objects can be formed in a hot enviroment ?!



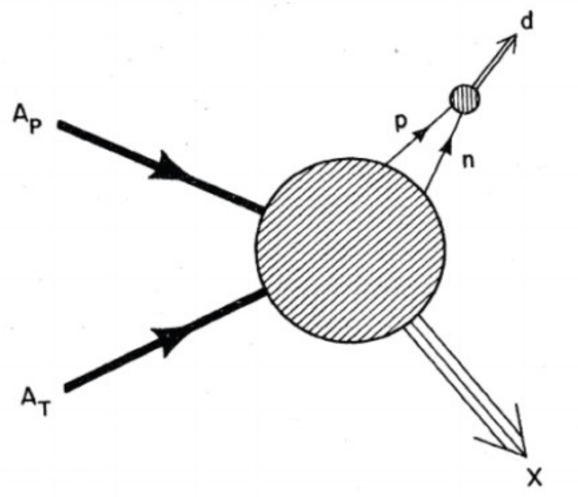
Elena BRATKOVSKAYA

Thermal vs coalescence

The sudden formation of clusters

Statistical model: describes very well the multiplicities in central collisions
but not the spectra (yield V,T,μ)
difficult to imagine how the cluster production takes place
d: E_b =2.2 MeV , rms radius = 1.7 fm
does not survive in heat bath of T>100 MeV
"ice in fire","snowball in hell"

Coalescence: goes back to Butler and Pearson PR129,836 (p+A)



d-production is a 3-body process
momentum has to be transferred to the third body

QM: in a static potential ~ $1/p^2$

$$n_d\,(p) \sim \frac{1}{p^2}\, n_n^{\,2}\left(\frac{p}{2}\right)$$

PHQMD 7

Prof. Joerg AICHELIN

Development of different models

Why does one need a new model ?

Present microscopic approaches:

- **VUU(1985), BUU(1985), HSD(1996), PHSD(2008), SMASH(2016) solve the time evolution of the one-body phase-space density in a mean field**
  → no dynamical fragments

- **UrQMD is a n-body model but makes clusterization via coalescence and a statistical fragmentation model**

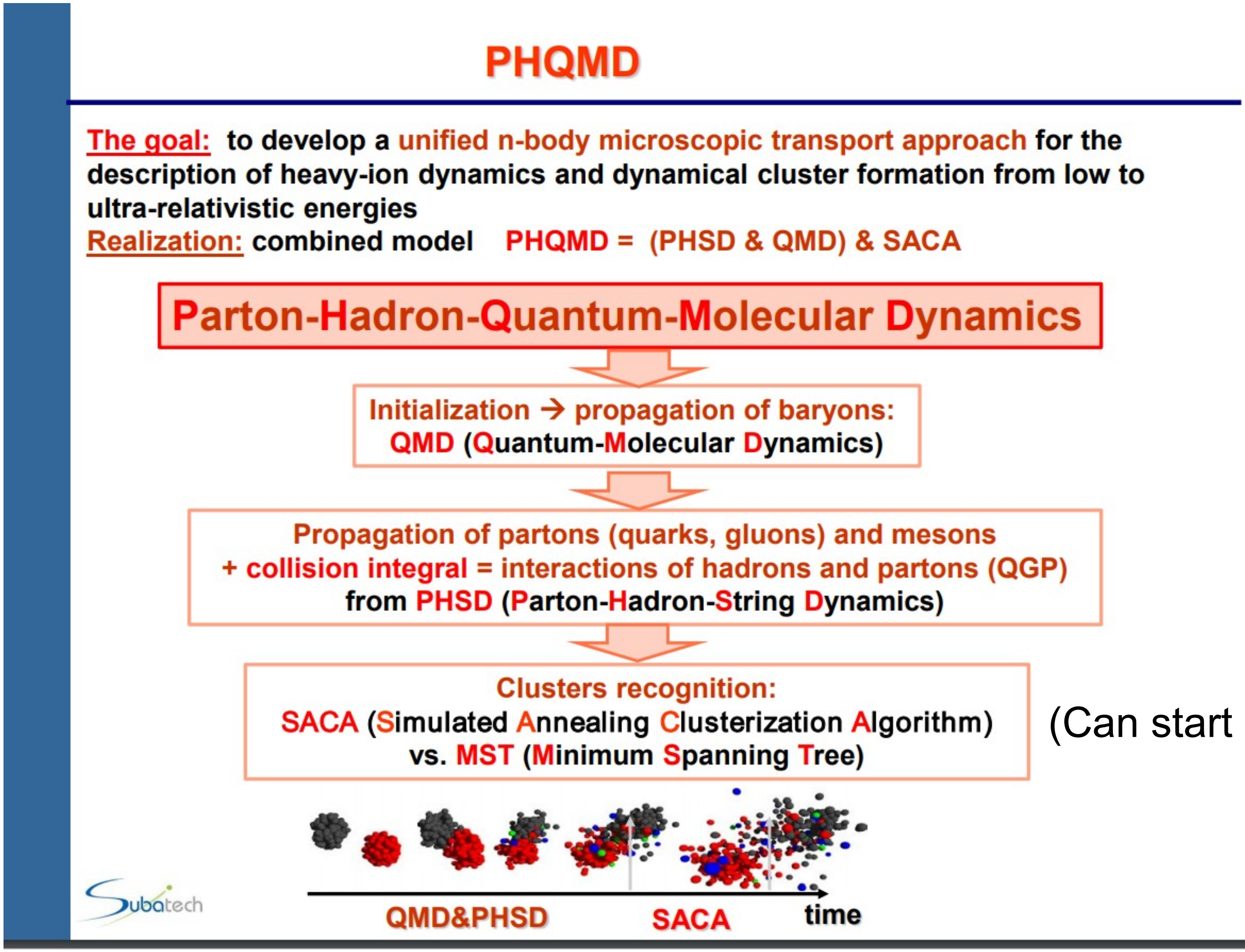
- **QMD is a n-body model but is limited to energies < 1.5 AGeV**
  → describes fragments at SIS energies,
  but conceptually not adapted for NICA/FAIR energies and higher

In order to understand the microscopic origin of cluster formation one needs:
- **a realistic model for the dynamical time evolution of HICs**
- **dynamical modelling of cluster formation based on interactions**

Dynamical modelling of cluster formation is a complex task which involves: the fundamental nuclear properties, quantum effects, variable timescales

Prof. Joerg AICHELIN

Development of different models



(Can start at any time)

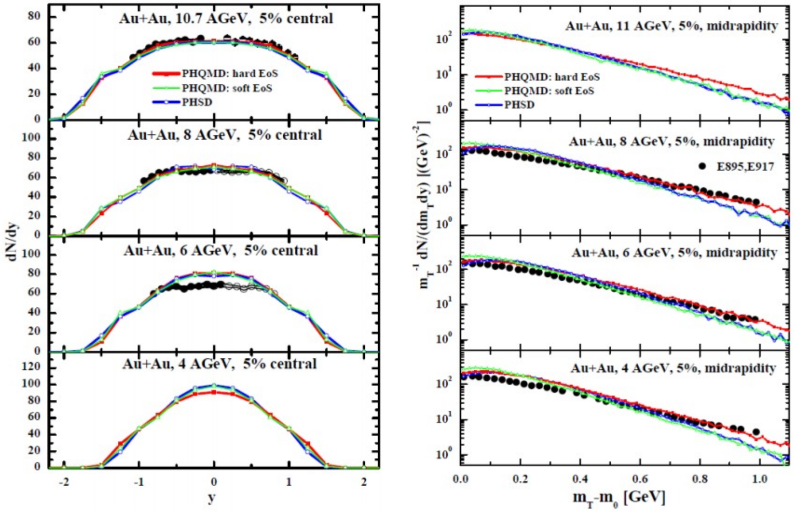
Prof. Joerg AICHELIN

SACA or SAHA?

Does microscopic approach work?

PHQMD: ‚bulk‘ dynamics at AGS/FAIR/NICA energies

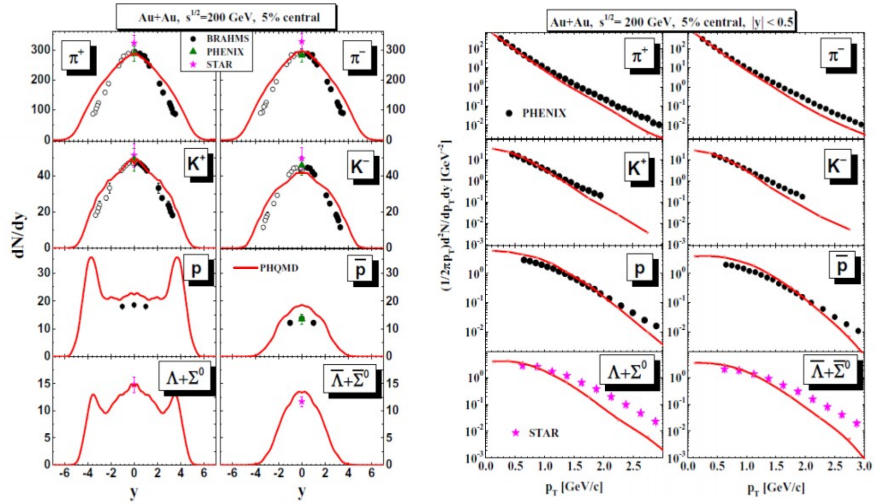
The rapidity and m_T distributions for protons from 5% central Au+Au collisions at 4, 6, 8, 10.7 A GeV



- the influence of EoS is slightly visible in rapidity spectra of protons
- m_T spectra of protons from PHQMD with a ‘hard’ EoS are harder then with ‘soft’ EoS
- PHQMD results for the m_T spectra with ‘soft’ EoS are in a good agreement with the PHSD spectra (using ‘soft’ EoS in default PHSD4.0 version)
  → QMD and MF dynamics gives similar results with similar EoS

PHQMD: ‚bulk‘ dynamics at RHIC

The rapidity and p_T distributions for p, anti-p, π^-, K^+, K^-, $\Lambda+\Sigma^0$, anti($\Lambda+\Sigma^0$) from 5% central Au+Au collisions at $s^{1/2}$ = 200 GeV

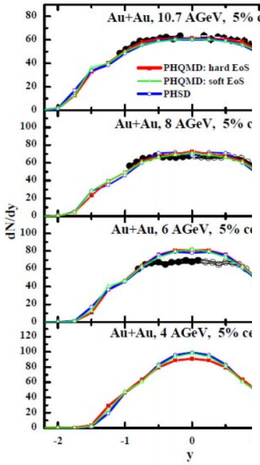


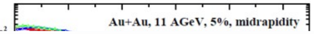
PHQMD: results are similar to PHSD - since at RHIC energies the dynamics is dominated by collisions of partons/hadrons rather than nuclear potential interactions!

Does microscopic approach work?

PHQMD: ‚bulk‘ dynamics at AGS/FAIR/NICA energies

The rapidity and m_T distributions for protons from 5% central Au+Au collisions at 4, 6, 8, 10.7 A GeV





- the influence of EoS is slightly
- m_T spectra of protons from PH
- PHQMD results for the m_T spe
spectra (using 'soft' EoS in de
→ QMD and MF dynamics giv

Summary

PHQMD

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation

combined model PHQMD = (PHSD & QMD) & SACA

PHQMD
- provides the good description of hadronic 'bulk' observables from SIS to RHIC energies
- shows sensitivity to EoS: m_T spectra of baryons
- predicts the dynamical formation of clusters from low to ultra-relativistic energies
- allows to understand the proton spectra and the properties of clusters (dn/dp_Tdy, v_1,v_2, fluctuations)
- allows to understand clusters formation in the participant and spectator region (consistent with available cluster data by ALADIN collaboration)
- allows to understand the formation of hypernuclei

❖ *PHQMD : under development*

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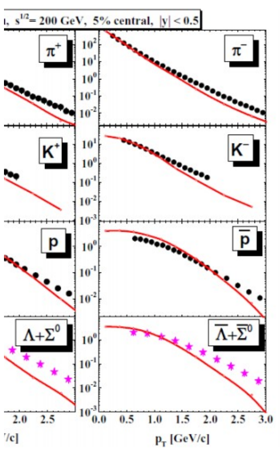
at RHIC

ti(Λ+Σ⁰) from 5% central Au+Au



ıergies the dynamics is
ı nuclear potential interactions!

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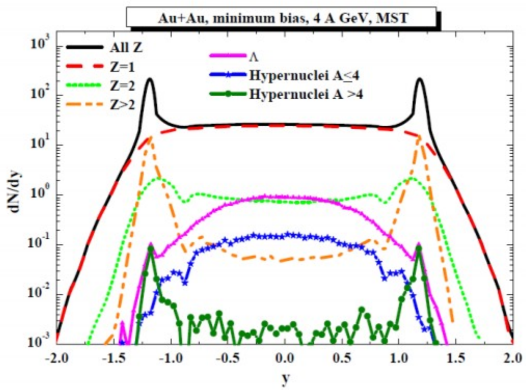
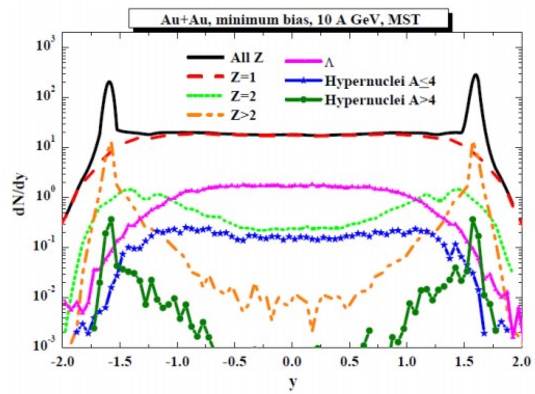
Hypernuclei production

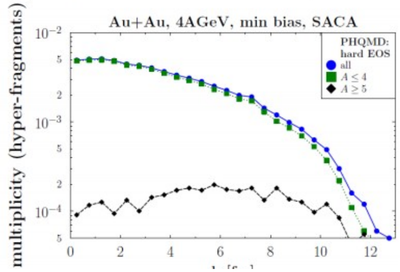
PHQMD: hypernuclei

PHQMD results (with a hard EoS and MST algorithm) for the rapidity distributions of all charges, Z = 1 particles, Z=2, Z>2, as well as Λ's, hypernuclei A≤4 and A>4 for Au+Au at 4 and 10AGeV





The multiplicity of light hypercluster vs. impact parameter b for Au+Au, 4 AGeV



- ❑ **Central collisions → light hypernuclei**
- ❑ **Peripheral collisions → heavy hypernuclei**

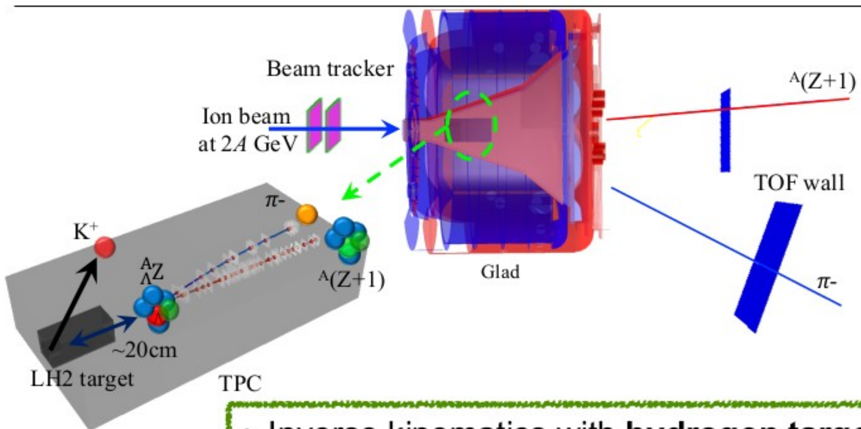
Penetration of Λ's, produced at midrapidity, to target/projectile region due to rescattering

→ Possibility to study ΛN interaction

Future plans for hypernuclei

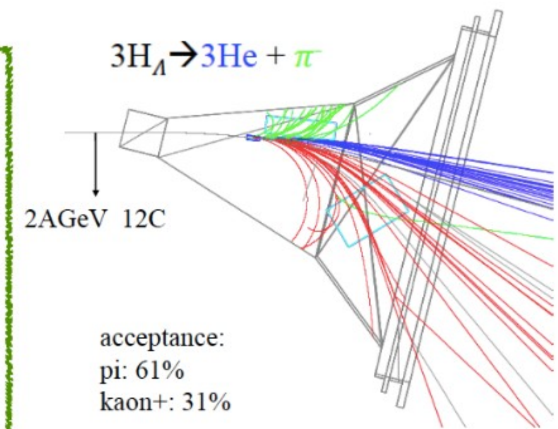
Future plans at R3B, GSI/FAIR

TECHNISCHE UNIVERSITÄT DARMSTADT



Hypernuclei production in inverse kinematics

- Inverse kinematics with **hydrogen target**
  - increase luminosity
  - reaction mechanism
  - decrease background
- Strangeness production by kaon tagging
- **TPC** inside GLAD dipole (invariant mass)
- Starting project (prototype under design)



Alexandre OBERTELLI

Future plans for hypernuclei

Future plans at R3B, GSI/FAIR

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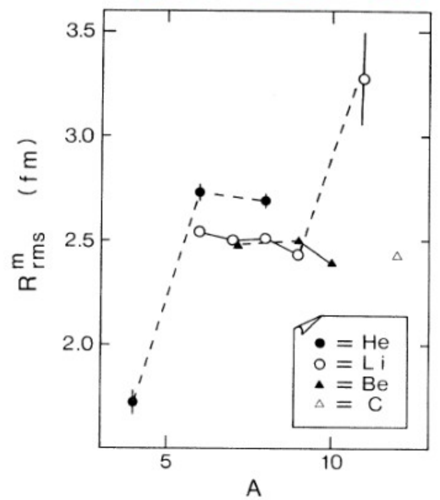
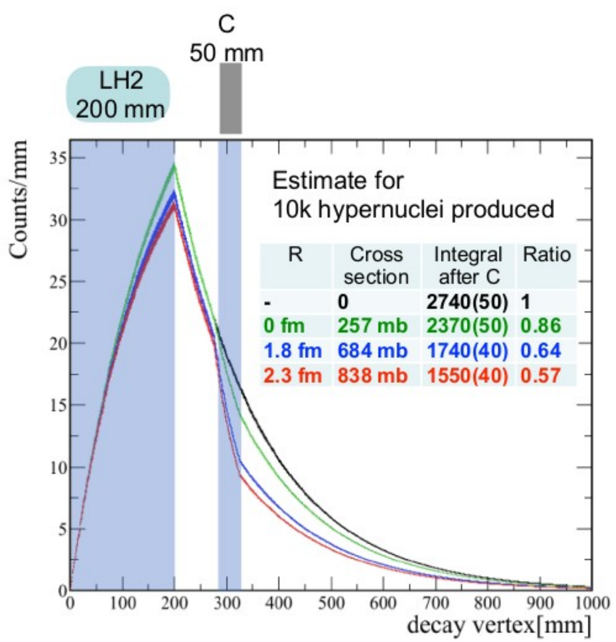
- "Are ^{3}H-lambda and ^{7}Be-lambda halos?"
- Hyper-version of the discovery of halo nuclei by Tanihata (1985)

$$\sigma_I(p,t) = \pi[R_I(p) + R_I(t)]^2$$



I. Tanihata et al., PLB 160 (1985)
I. Tanihata et al., PRL 55 (1985)



R	Cross section	Integral after C	Ratio
-	0	2740(50)	1
0 fm	257 mb	2370(50)	0.86
1.8 fm	684 mb	1740(40)	0.64
2.3 fm	838 mb	1550(40)	0.57

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Coalescence vs thermal

Can light nuclei exist in a fireball?

- Interparticle spacing in a hadron gas is about 1.5 fm at $T = 156$ MeV.
- Root mean square radius of a deuteron is 2.0 fm.
- Binding energy of a deuteron is $\varepsilon_B = 2.2$ MeV.
- A characteristic time of deuteron formation is $1/\varepsilon_B = 100$ fm/c.
- A hadron gas at $T = 156$ MeV is essentially a classical system.

- Snowflakes in hell ?
- No, snowflakes from hell.

4

Stanislaw MROWCZYNSKI

Coalescence from CF

Coalescence from correlation functions:

$$\mathcal{B}_2(p) \approx \frac{3}{2\,m} \int d^3q\,\mathcal{D}(\vec{q})\,\mathcal{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q})$$

R. Scheibl, U. Heinz, Phys.Rev. C59 (1999) 1585-1602

$$B_2 = \frac{3\,\pi^{3/2}\,\langle \mathcal{C}_\mathrm{d}\rangle}{2m_t\,\mathcal{R}_\perp^2(m_t)\,\mathcal{R}_\parallel(m_t)}\,. \qquad (6.3)$$

$$\langle \mathcal{C}_\mathrm{d}\rangle \approx \frac{1}{\left(1+\left(\frac{d}{2\,\mathcal{R}_\perp(m)}\right)^2\right)\sqrt{1+\left(\frac{d}{2\,\mathcal{R}_\parallel(m)}\right)^2}}\,. \qquad (4.12)$$

Using this approach to coalescence, the same results obtained by Scheibl and Heinz (but here no hydro is needed) and by Mrowczynzki using WF

S. Mrowczynski, Acta Phys.Polon. B48 (2017) 707

assumed: 1D GSM $\quad D(\mathbf{r}) = \frac{e^{-\frac{\mathbf{r}^2}{4R_{\mathrm{kin}}^2}}}{(4\pi R_{\mathrm{kin}}^2)^{3/2}} \Rightarrow C_2^{\mathrm{PRF}} = e^{-R_{\mathrm{kin}}^2 q^2}$

$\gamma_d \to 1$

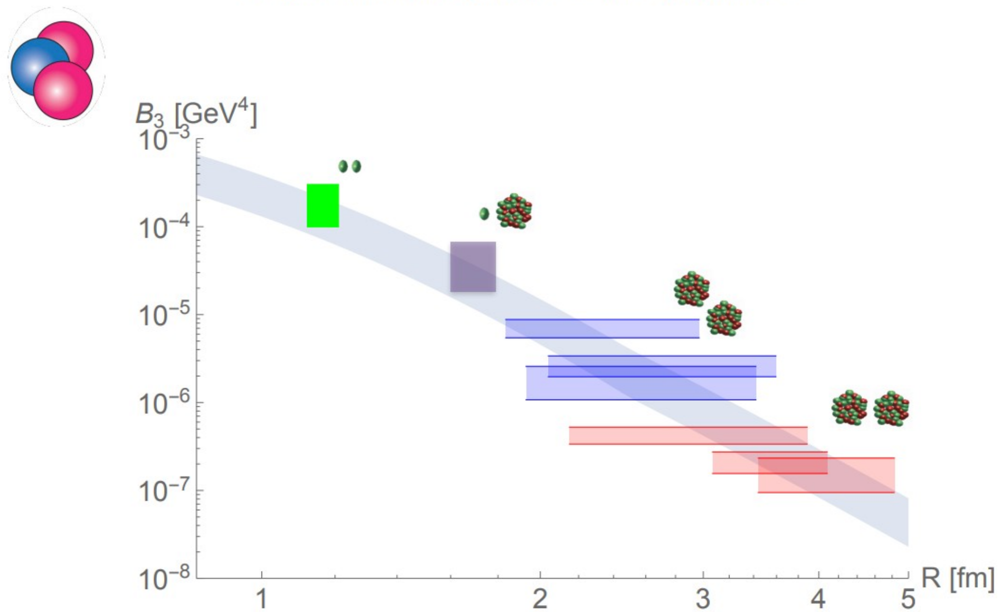
obtained: $\quad \frac{dN_d}{d^3\mathbf{p}} = \mathcal{A}\frac{dN_p}{d^3\left(\frac{1}{2}\mathbf{p}\right)}\frac{dN_n}{d^3\left(\frac{1}{2}\mathbf{p}\right)}, \quad \mathcal{A} = \frac{3}{4}\frac{\pi^{3/2}}{(R_{\mathrm{kin}}^2+R_d^2)^{3/2}} = \gamma_d \frac{m}{2} B_2$

Kfir BLUM

Coalescence from CF

Nuclear coalescence from correlation functions

KB, M. Takimoto, Phys.Rev. C99 (2019) no.4, 044913



Kfir BLUM

The theory seems to work, but one can see if it can be falsified.
How:
Reproduce “theoretical” results by using the same event, p_T and centrality intervals → bring together HBT and nuclei analyses
Measure accurately of HBT radii and multiplicity (→ calibrate the x-axis) : different model would have different dependencies.

Is it possible to falsify thermal model?

^{4}He vs. ^{4}Li

- The thermal and coalescence models give different predictions on the ratio of yields of ^{4}Li to ^{4}He.
- In the thermal model the ratio of yields is independent of collision centrality.
- In the coalescence model the ratio is maximal for central collisions and rapidly decreases when one goes to peripheral collisions.
- Since ^{4}Li can be observed through the correlation function of ^{3}He-*p*, the correlation needs to be measured.

***h-D* correlations**

- Hadron-deuteron correlations carry information about source of deuterons.
- Measurement of *h-D* & *h-p* correlation function can tell us whether deuterons are directly emitted from a fireball like protons or deuterons are formed due to final state interactions.
- *p-D* correlation functions show a sufficient sensitivity to a size of particle source to falsify the thermal or coalescence model.

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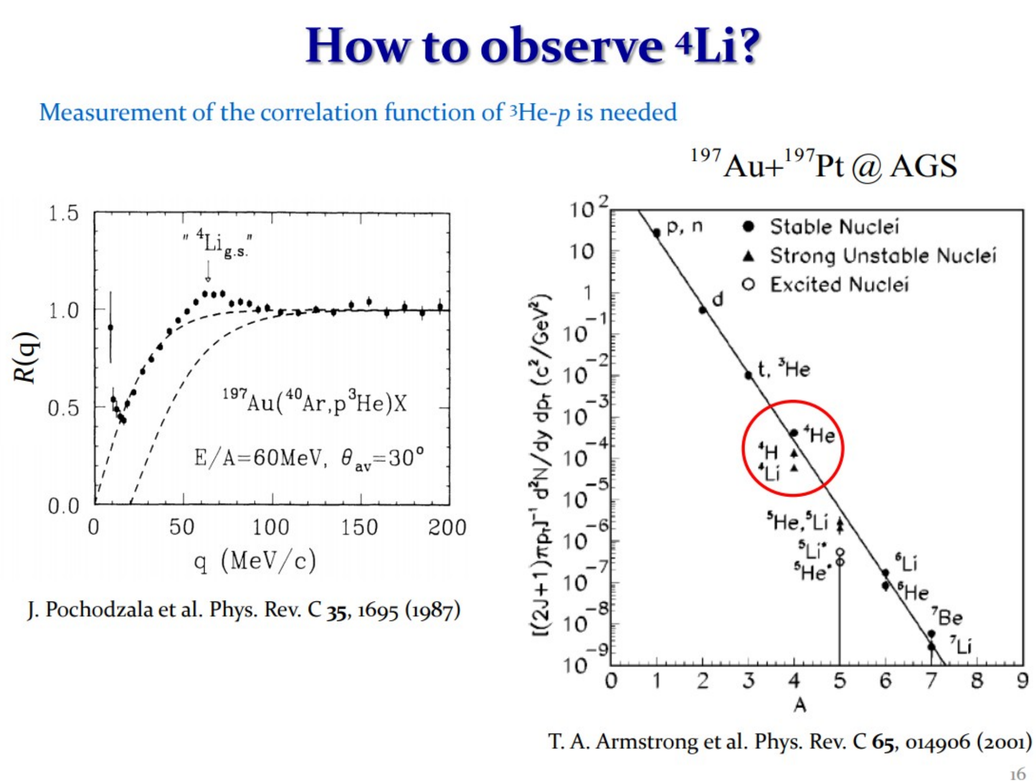
^{4}He vs ^{4}Li

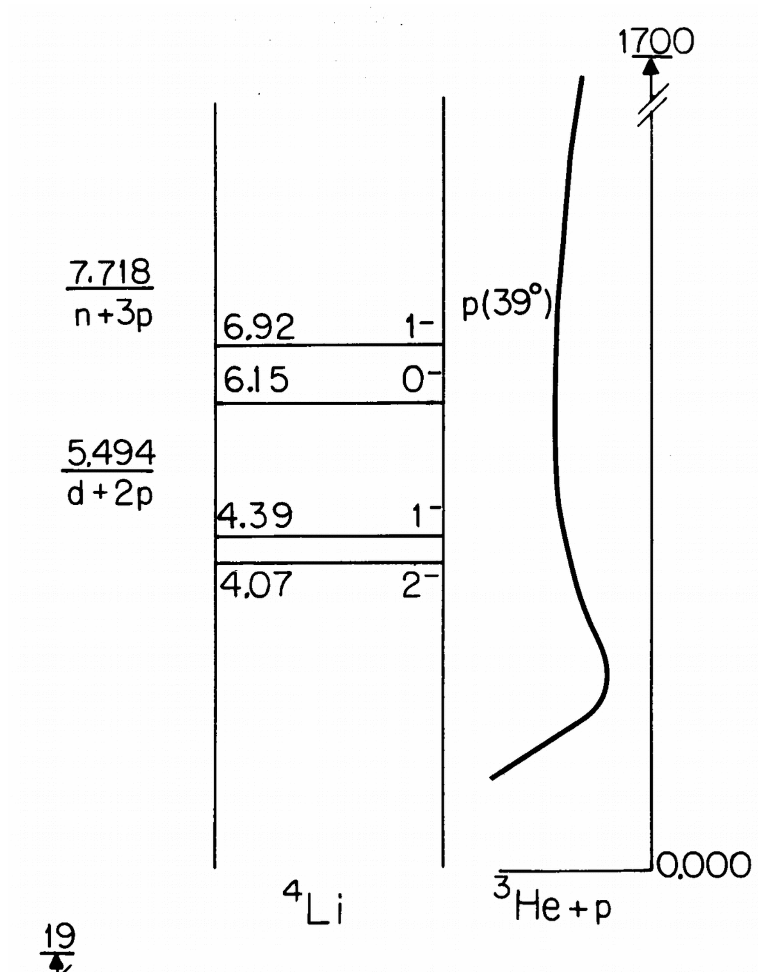

How to observe ^{4}Li?

Measurement of the correlation function of ^{3}He-p is needed

J. Pochodzala et al. Phys. Rev. C 35, 1695 (1987)

T. A. Armstrong et al. Phys. Rev. C 65, 014906 (2001)

16



A difference between 4He and 4Li should be seen in data.
Experimentally this is very difficult because of the production yield is small and 4Li is a wide and "complex" resonance.
→ One should maybe repeat the theoretical exercise to look at $^3_\Lambda$H and ^{3}He

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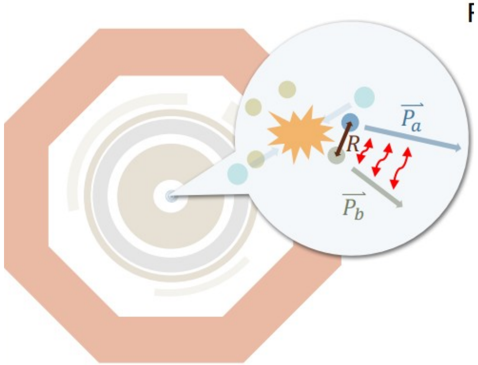
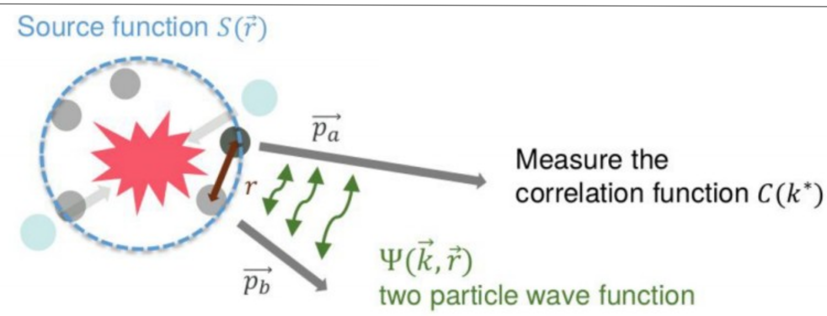
Two particle correlation





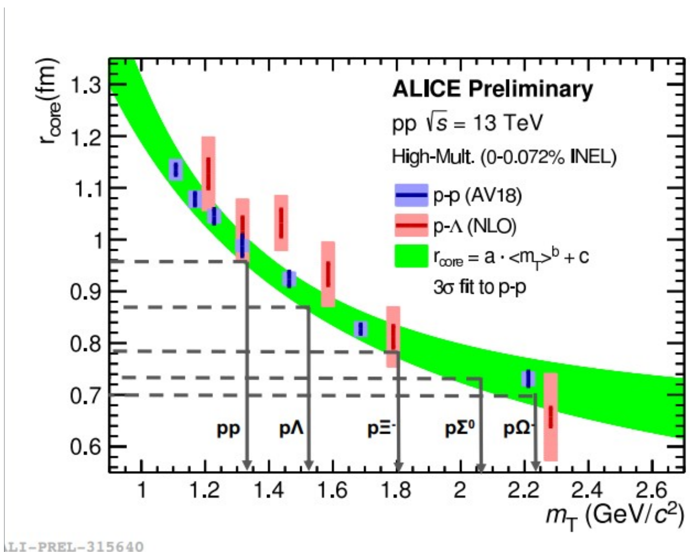
Experimental definition ***Theoretical definition***

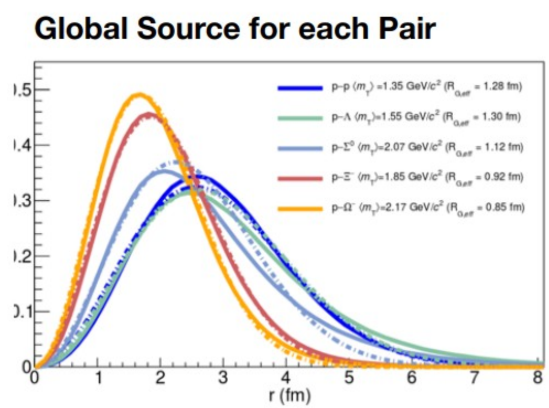
$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{Same}}(k^*)}{N_{\mathrm{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 d^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

>1 : **Attractive** Interaction

<1: **Repulsive** Interaction

Relative distance / reduced momentum in the rest frame of the pair



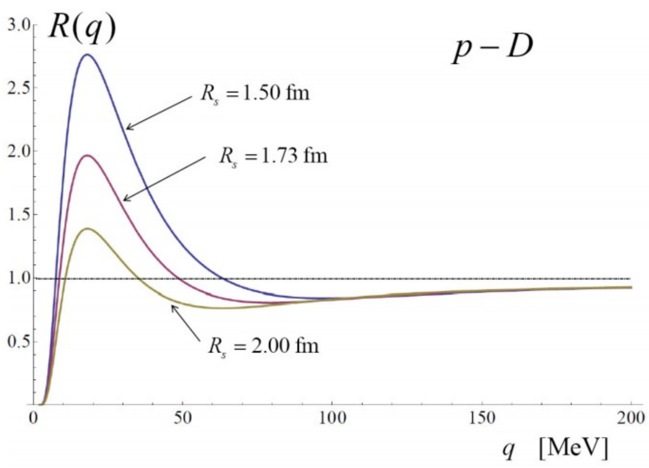


The source size is extracted from pp pairs and a common “core-baryon” source is obtained

Laura FABBIETTI

h-D correlation

p-D correlation functions



$$R(q) = \frac{1}{3} R_{1/2}(q) + \frac{2}{3} R_{3/2}(q)$$

$$a_{1/2} = 4.0 \text{ fm}$$

$$a_{3/2} = 11.0 \text{ fm}$$

$$2.00 = \sqrt{\frac{4}{3}}\, 1.73 = \frac{4}{3}\, 1.50$$

R_s from *p-D* correlation function vs. R_s from *p-p* correlation function

CF are sensitive to source radius so looking at p-p and p-d CF it would be possible to measure if the source size changes for the different particle pairs

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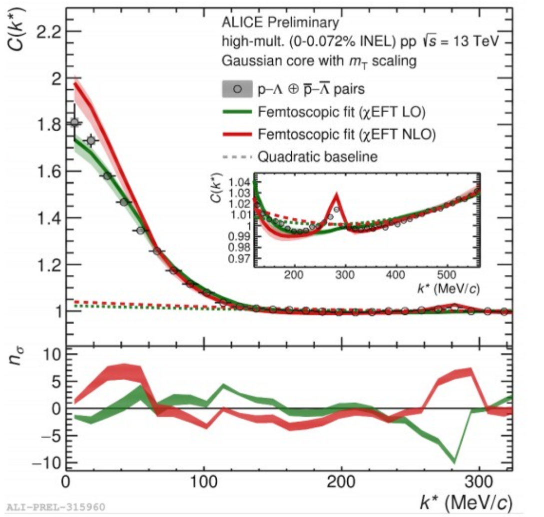
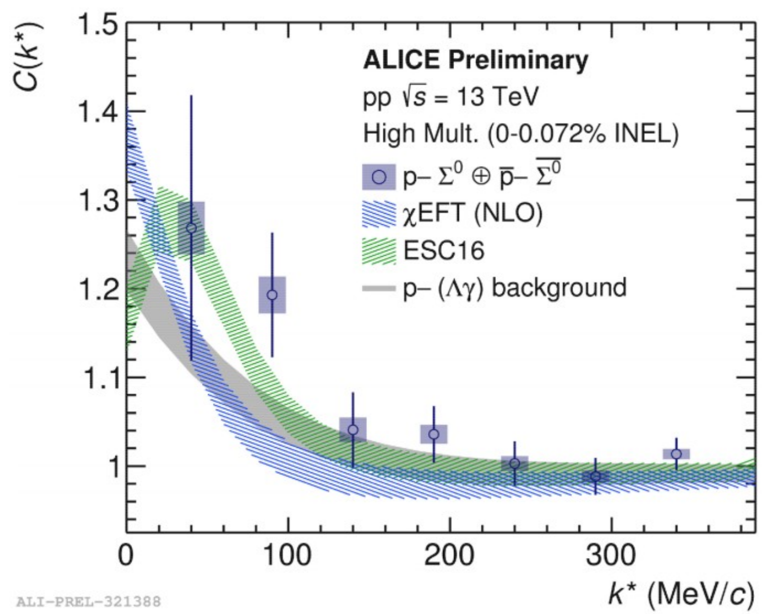
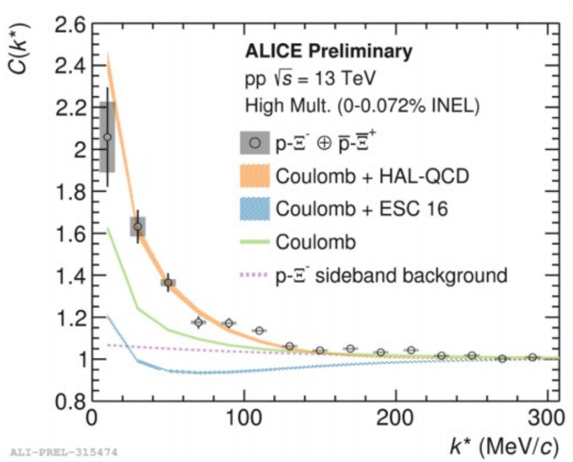
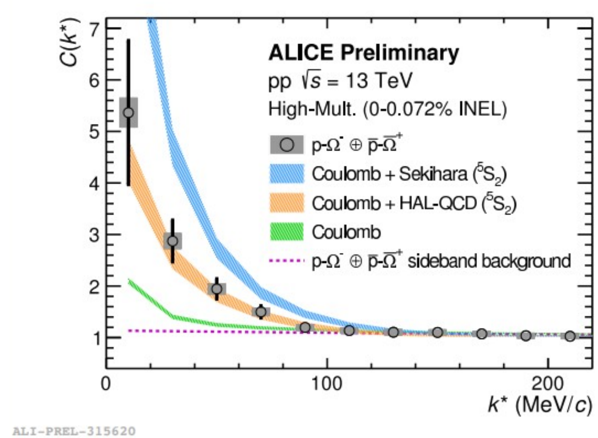
Study baryon-baryon interaction







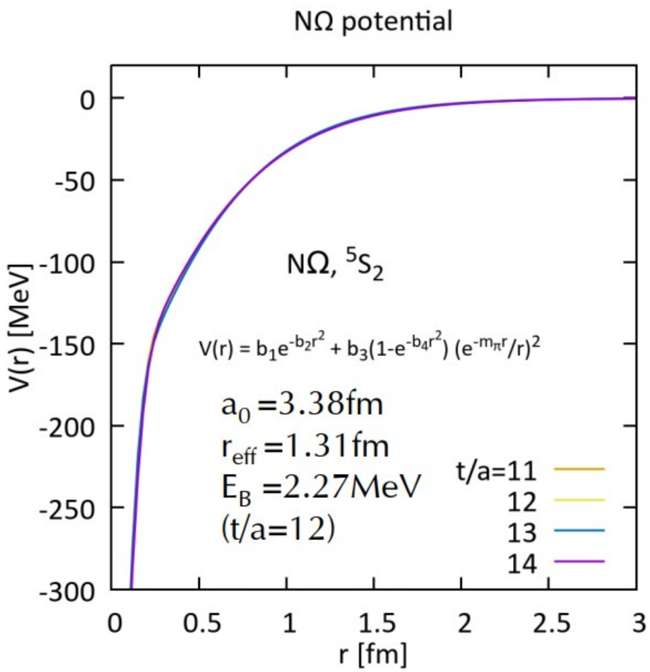


Plenty of new results that can be used to as alternative (or complementary) to scattering experiment to study very in detail the NY and YY interactions

CF from theory

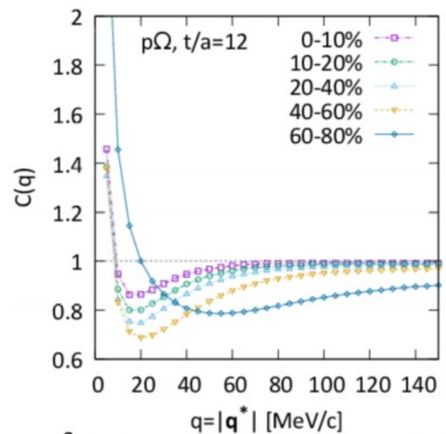
Example : pΩ Correlation

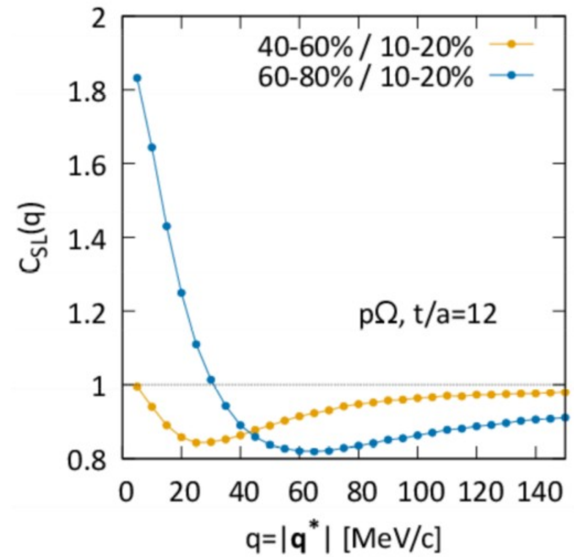
- Theory : HAL QCD potential + Expanding Source model

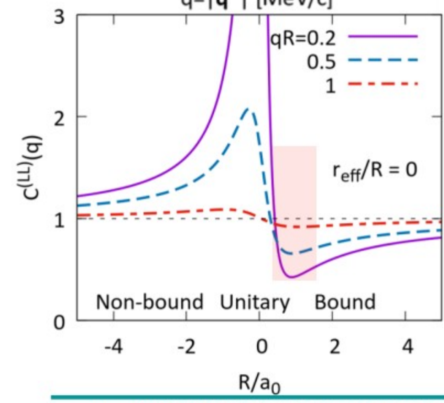


Example: pΩ Correlation

KM+ ‘19 (PRC in press)







40-60% Bound regime
60-80% Unitary regime

pp unitary measured: Need HI to confirm bound regime (STAR, but more statistics!)

QCD exotica

Search for $X(5568)$ in $B_s^0\pi^+$ state

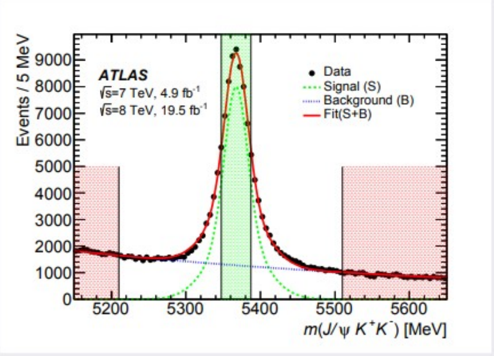
Phys. Rev. Lett. 120, 202007 (2018)

10

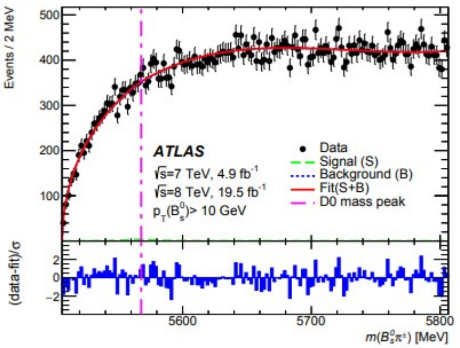
Analysis overview

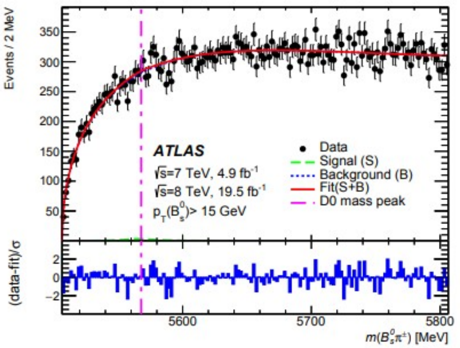
D0 reported evidence of a narrow structure, $X(5568)$, which was interpreted as a tetraquark with four different quark flavors: b, s, u, d. [PRL 117, 022003 (2016)]

- 4.9 fb^{-1} of pp collision data at 7 TeV and 19.5 fb^{-1} at 8 TeV
- Reconstruct B_s^0 mesons in their decays to $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$



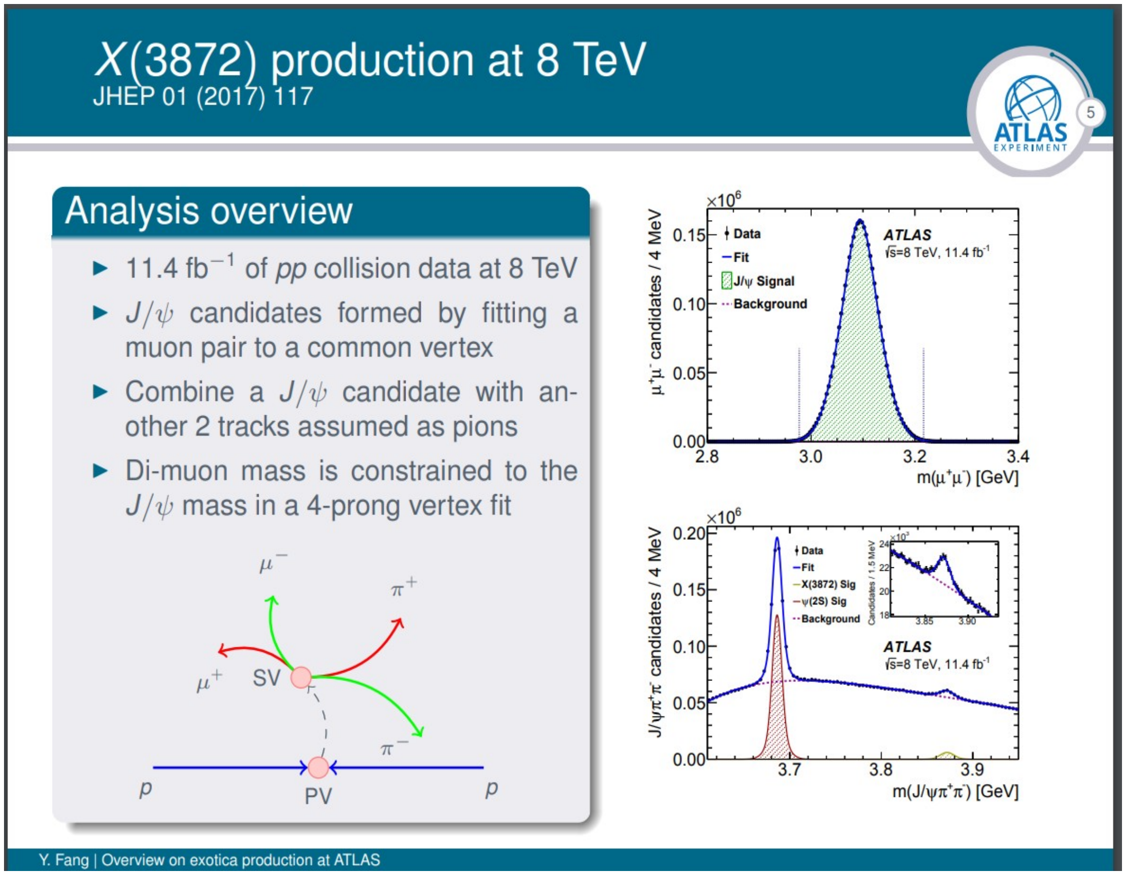
- Combine each of the tracks forming the selected PV with the selected B_s^0 candidate

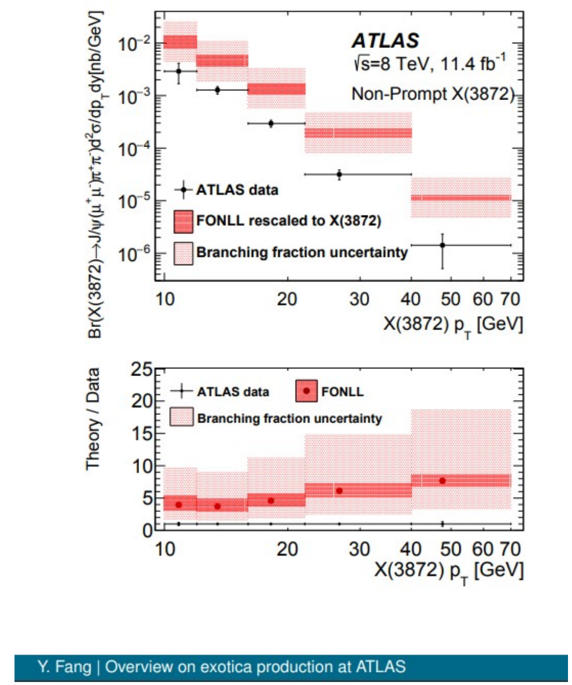




Y. Fang | Overview on exotica production at ATLAS

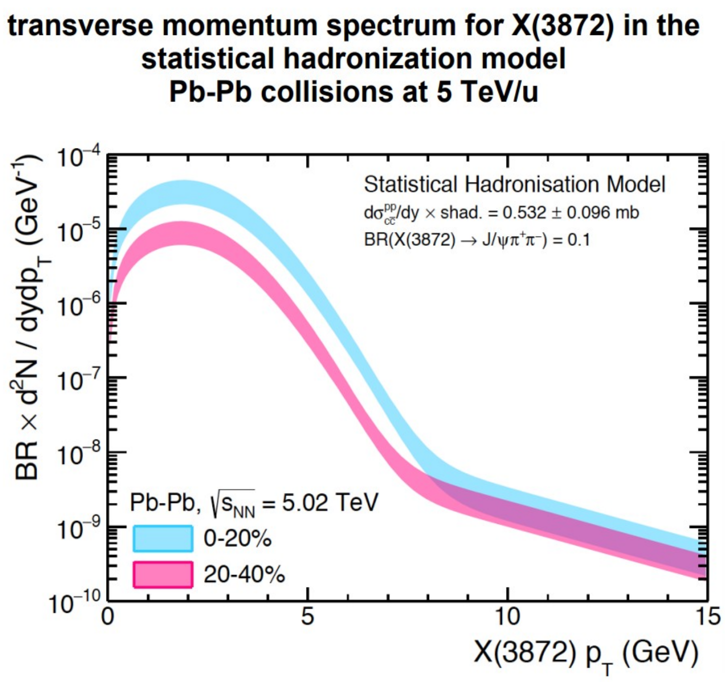
QCD exotica





Yi FANG

X(3872)



Measurement of X(3872)
→ relevant role in Pb-Pb collisions

Peter BRAUN-MUNZINGER

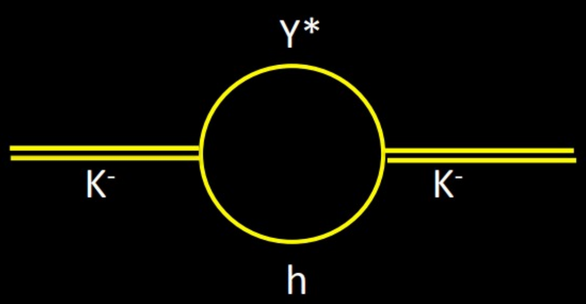
Back to particle production…

(Sub-Threshold) Strangeness Production

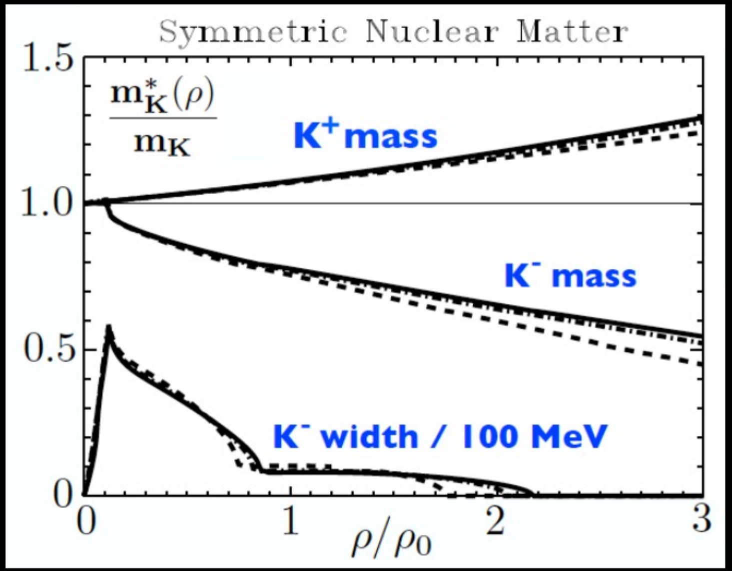
Unique observable:
Not produced in binary NN collisions at $\sqrt{s_{NN}}$= 2.4 GeV (no obvious elementary reference)

NN→NYK$^+$: $\sqrt{s_{NN}}$= 2.55 GeV,
NN→NNK$^+$K$^-$: $\sqrt{s_{NN}}$= 2.86 GeV
(strong K$^-$ suppression).

Energy must be provided from the system.



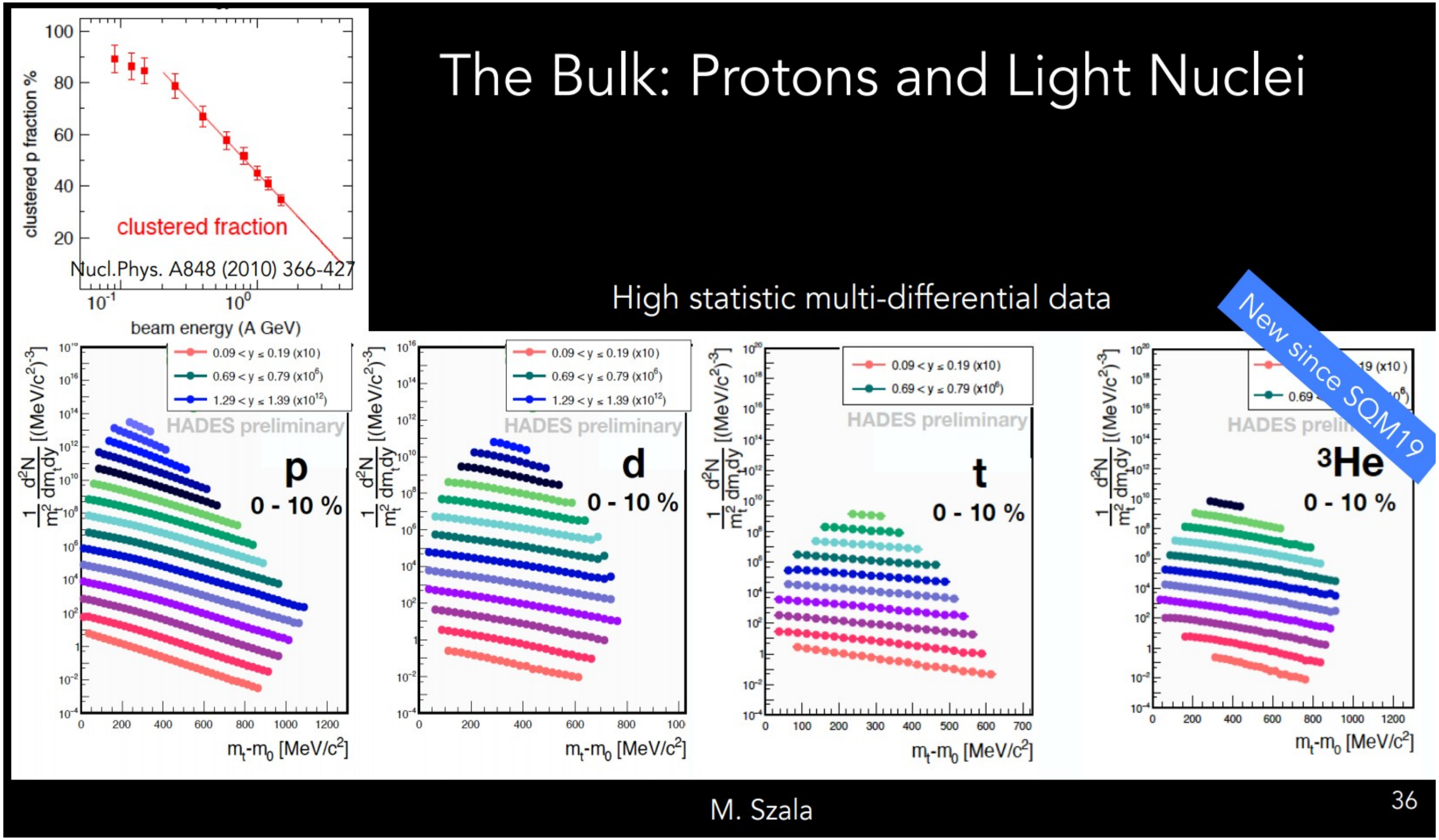
Coupling of K$^-$ to baryons
and strangeness exchange reactions
e.g. πY→NK$^-$.



Repulsive K$^+$N potential
Attractive K$^-$N potential → K$^-$ condensation?
(complicated form due to resonances)

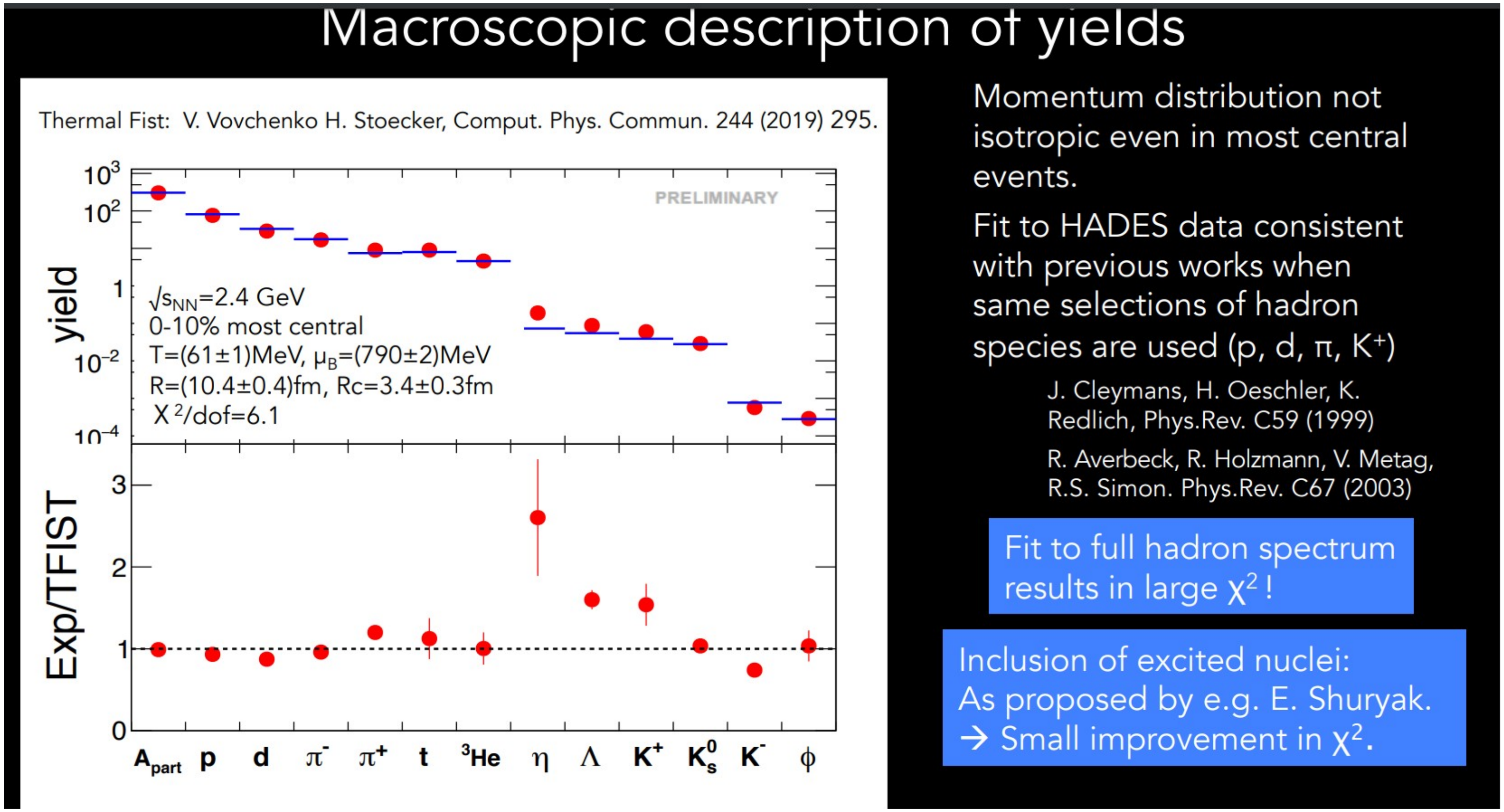
T. Waas, M. Rho and W. Weise Nucl. Phys. A617 (1997) 449-463
N. Kaiser et al. Nucl.Phys. A594 (1995) 325-345

Back to particle production…



Manuel LORENZ

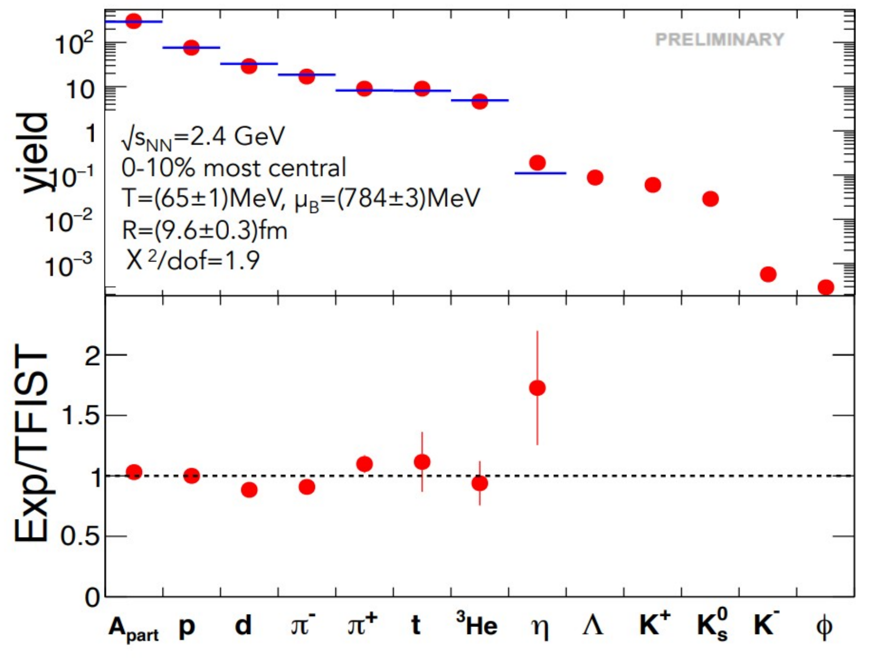
Thermal model applied to HADES data



Thermal model applied to HADES data

Macroscopic description of yields

Thermal Fist: V. Vovchenko H. Stoecker, Comput. Phys. Commun. 244 (2019) 295.



Momentum distribution not isotropic even in most central events.

Fit to HADES data consistent with previous works when same selections of hadron species are used (p, d, π, K^+)

J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999)

R. Averbeck, R. Holzmann, V. Metag, R.S. Simon. Phys.Rev. C67 (2003)

Fit excluding strangeness and but including excited nuclei results in small χ^2 !