Studies of baryonic matter properties @ FAIR

QCD various phases
26-28.04.2024

P. Salabura

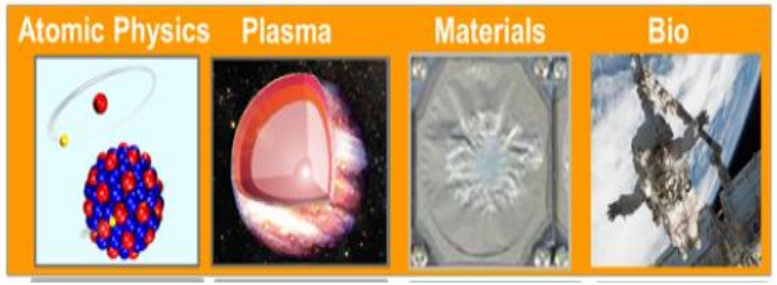
Uniwersytet Jagielloński, Kraków

- ✓ FAIR project: status and polish contributions
- ✓ Compressed Baryonic Matter : Hades & CBM
- ✓ Summary

FAIR : Facility for Antiproton and Ion Research

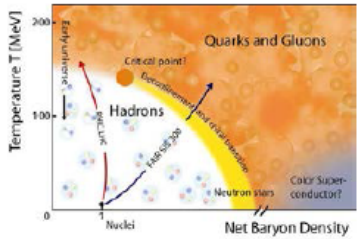
- FAIR founding convention signed in 2010 by 9 countries
- Construction started in 2016
- Jagiellonian University is a shareholder representing Poland (12 particpating Institutions) and managing in-kind contributions

FAIR: scientific pillars



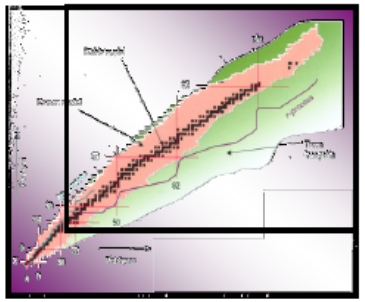
Atomic Physics, Plasma physics and applications

APPA



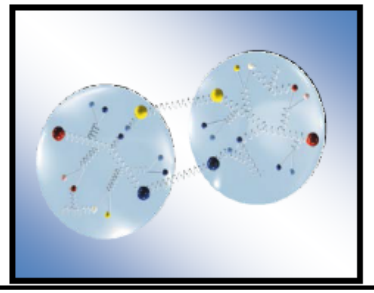
Compressed Baryonic Matter

CBM



Nuclear STructure Astrophysics and Reactions

NuSTAR



hadron structure with Antiproton ANihilation (at DArmstadt)

PANDA

FAIR: layout of facility & status

✓ SIS18 - SIS100 → protons 29 GeV, U^{92+} up to 11 GeV/u (14 GeV C,Ca)

(~ 250 superc. magnets, 11 ton He, 35 MW energy)

✓ High Intensity beams: 10^9 /s (U^{92+}), 10^{12} p/s

✓ storage rings : ions, antiprotons (HESR)

✓ High intenisty radioactive beams (Super-FRS)

- **Project status**

95% of civil construction completed

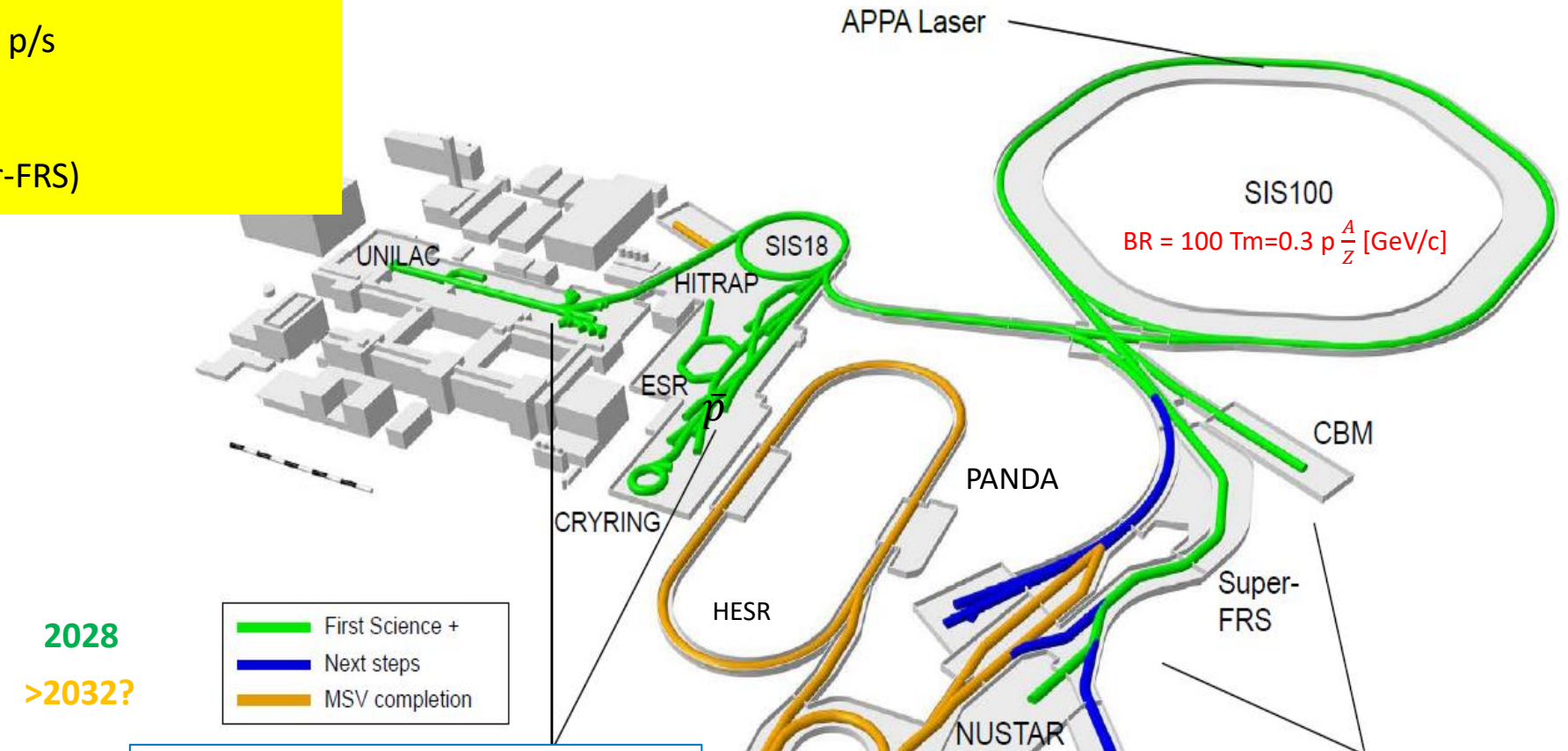
2025 - start of Installation of SIS100

and SFRS components

2028 completion of Instalation

2029 First Science : R3B@SFRS

& CBM (not yet fully funded)



2028

>2032?

Fair – Phase 0

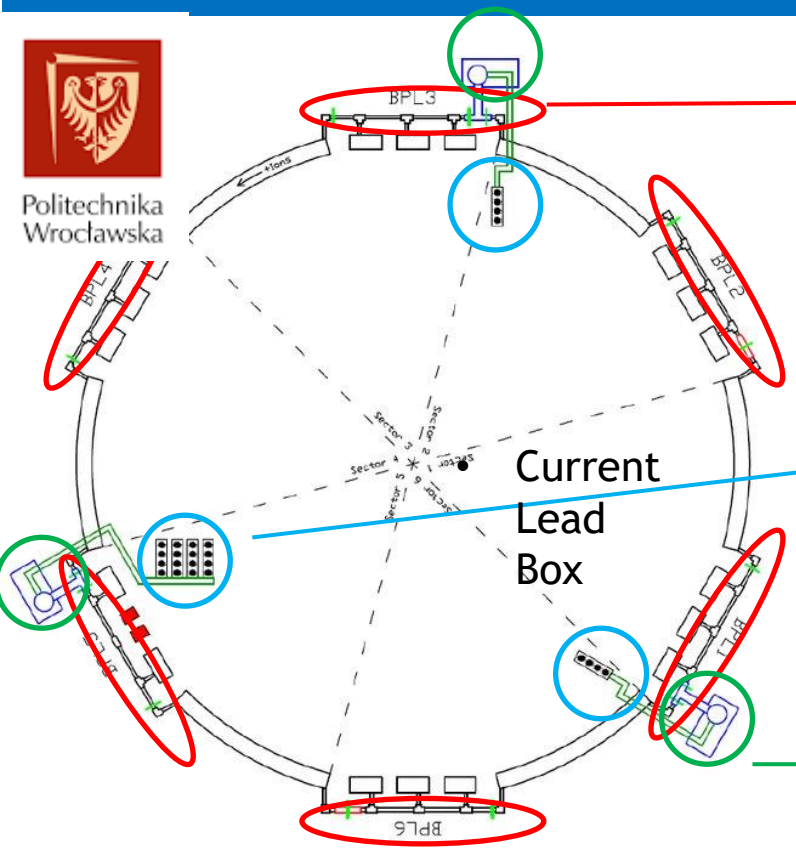
On-going physics programme SIS18 and pion seconadry beam with HADES

First Science+ (2029): NUSTAR (Super FRS), CBM , APPA

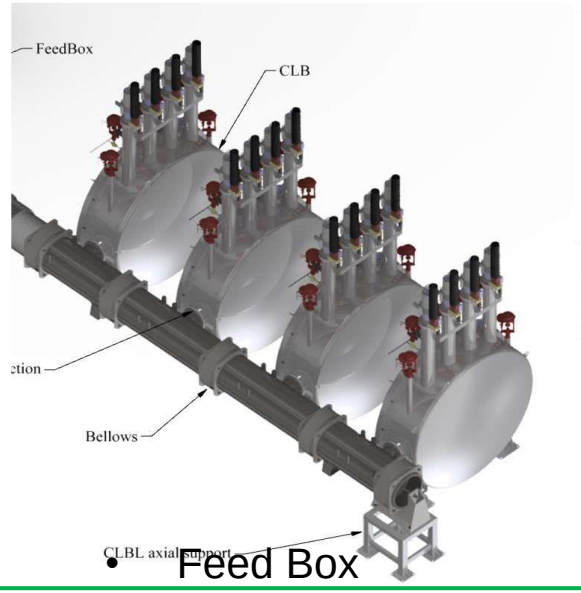
PANDA & HESR (>2032 ?)

Polish in-kind contribution to SIS100

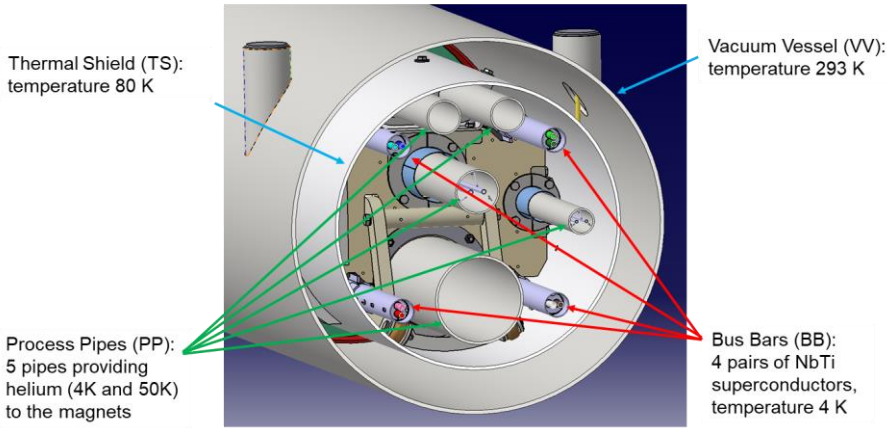
Politechnika Wrocławska

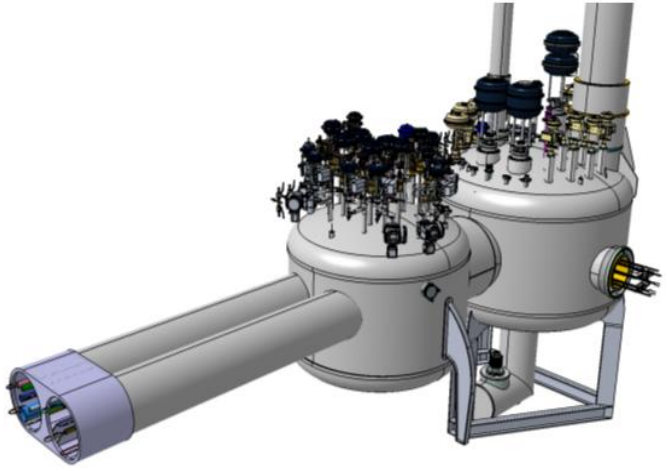


Bypass Lines (288m)



Cross-section of the Cryogenic Bypass Line



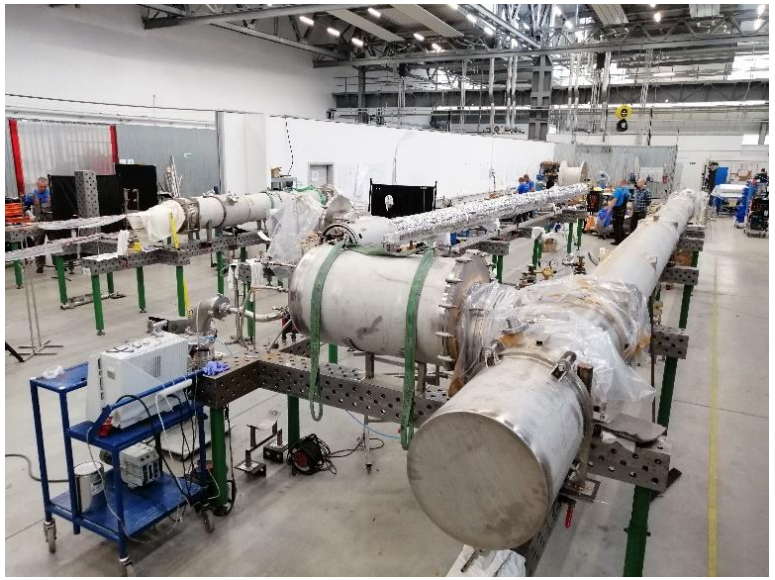


- Cryogenic and current (NbTi superconductors) distribution system for SIS100

Wrocław Technical University (M. Chorowski & co.): Design, production and installation

Key for First Science operation !

Production of ByPass lines for SIS100 in Kriosystem sp. z o.o., Wrocław

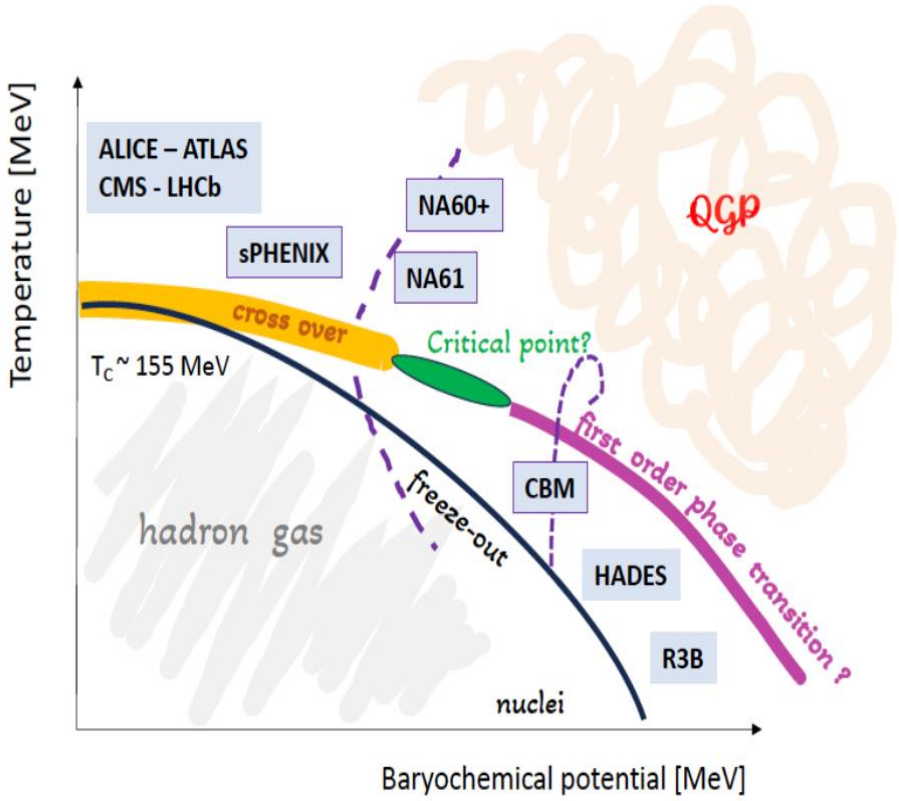


Politechnika Wrocławska

- ✓ Production completed..

Compressed Baryonic Matter @ FAIR

QCD phase diagramme
NuPECC LRP'2024

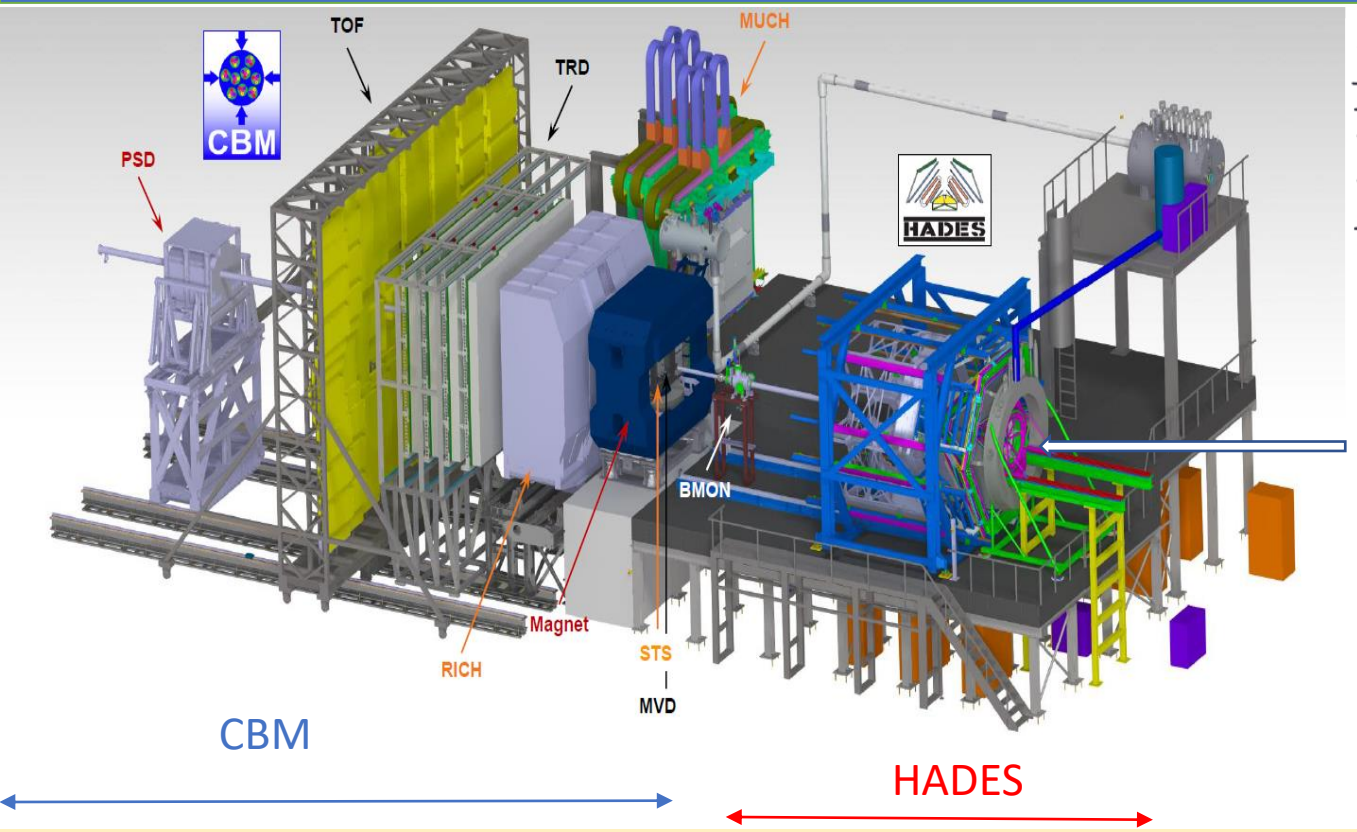


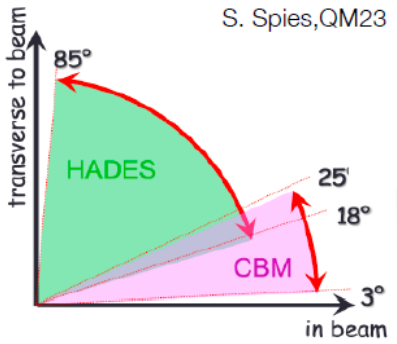
Key observables at FAIR

- ✓ Fluctuations –higher order cummulants (Critial Point)
- ✓ Hyperons (Ξ, Ω) production close to threshold (EOS), Y-N interactions
- ✓ hipernuclei
- ✓ Hyperon polarization in HIC
- ✓ Multi-differantial flow measurements ; EOS, symmetry energy,
- ✓ EM radiation (chrial symmetry restoration, diagnostic of early phase (T, ρ) , caloric curve)
- ✓ Charm production..

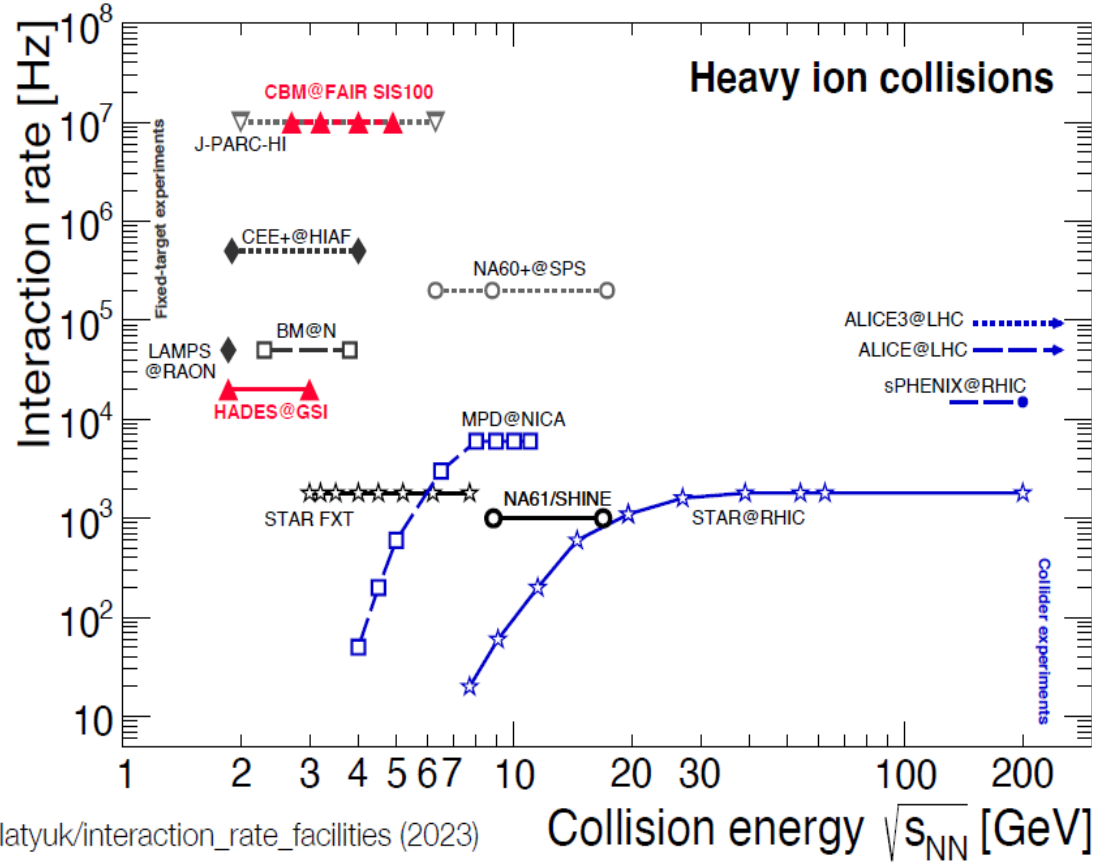
…

CBM & HADES at SIS100





Eur.Phys.J.A 53 (2017) 3, 60



- High rate capability (CBM 10 MHz , HADES 20 kHz)
- Complementary coverage
- Excelent PID (light fragments, p/pions/kaons/leptons)

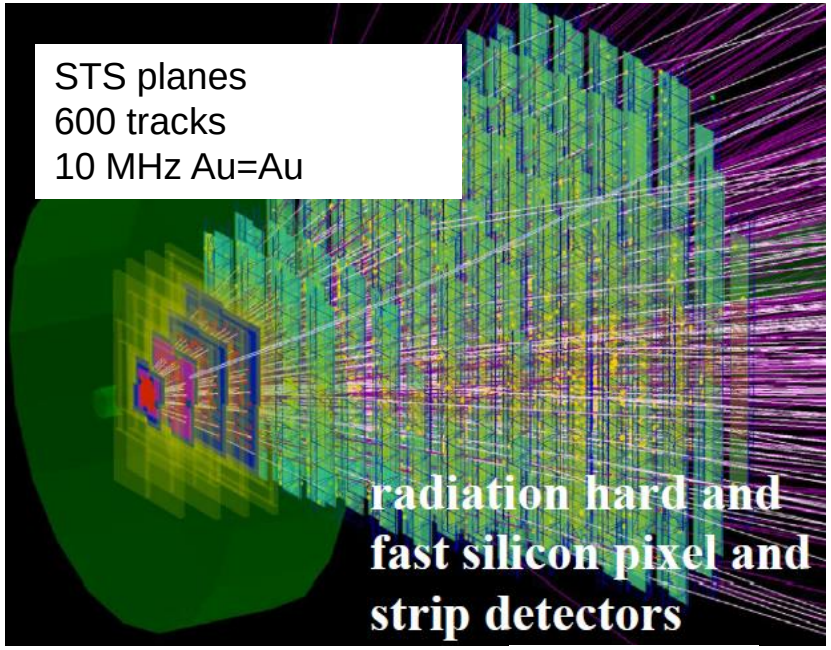
focus on rare probes :multistrangeness, dileptons, charm (CBM)

and momentum resolution (1-1.5%)

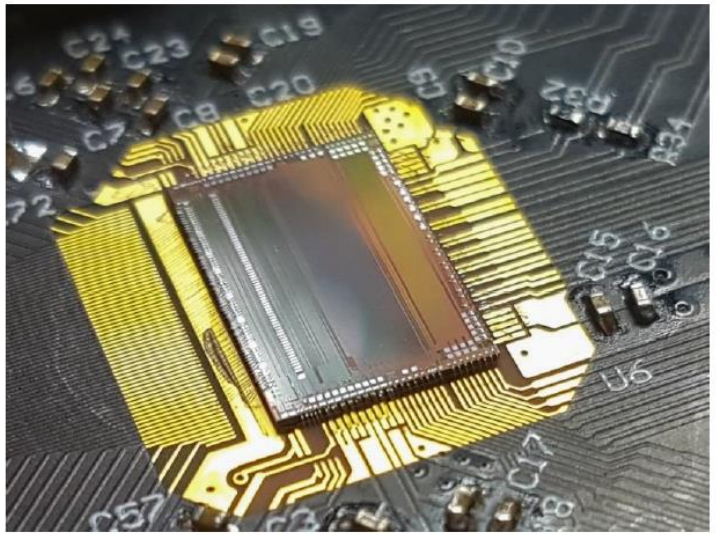
In kind polish contribution (hardware) to CBM

✓ Silicon Tracking Station : sensors, development and production of ASIC, read-out , tests and integration

STS: 1.8 mln channels : 25μm –resolution, 0.3-1% X_0 /plane

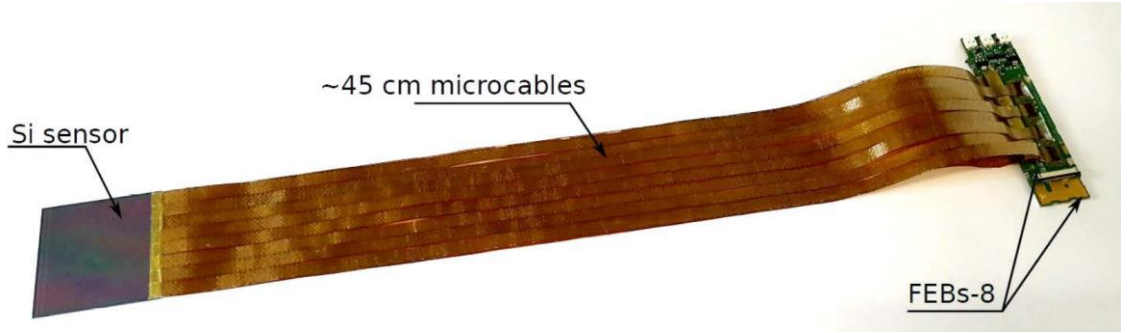


ASIC"STS-XYTER", radiation hard , 5ns resolution, 5 bit ADC



AGH

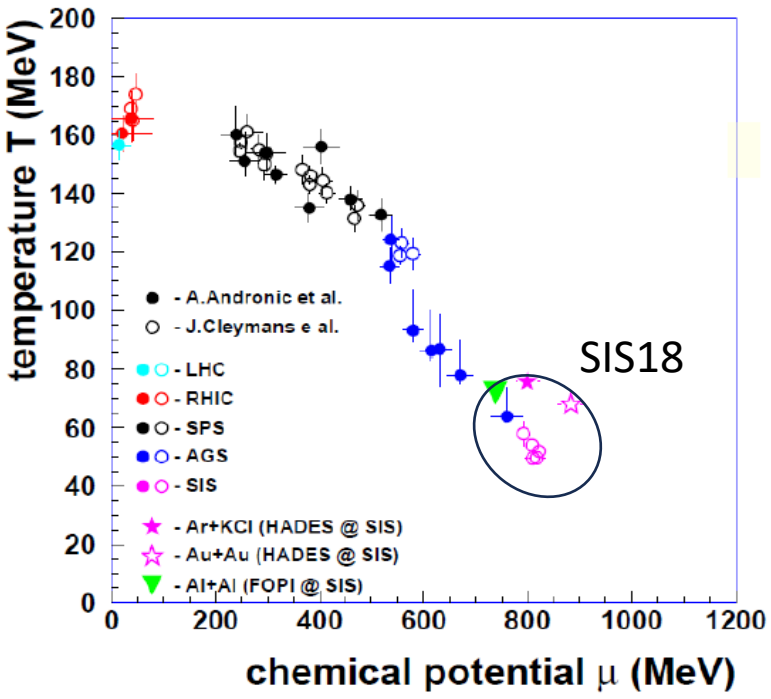
STS ladder



Readout board (FPGA) Politechnika Warszawska

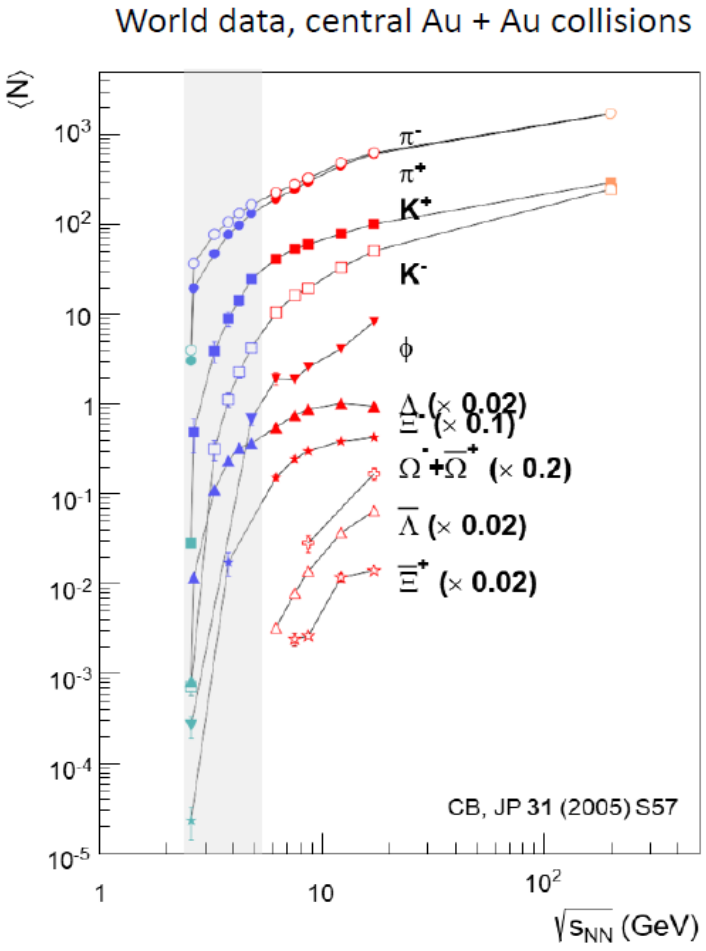
Integration UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE AGH

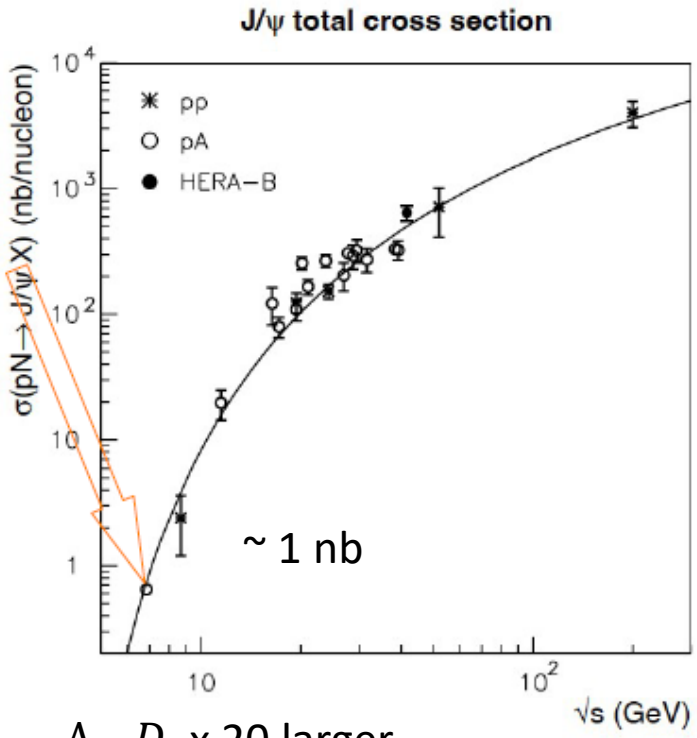
Particle production at SIS18-SIS100



Freeze-out data are well described by Statistical Hadronization Model

(deviations observed for Ξ, ϕ by HADES)



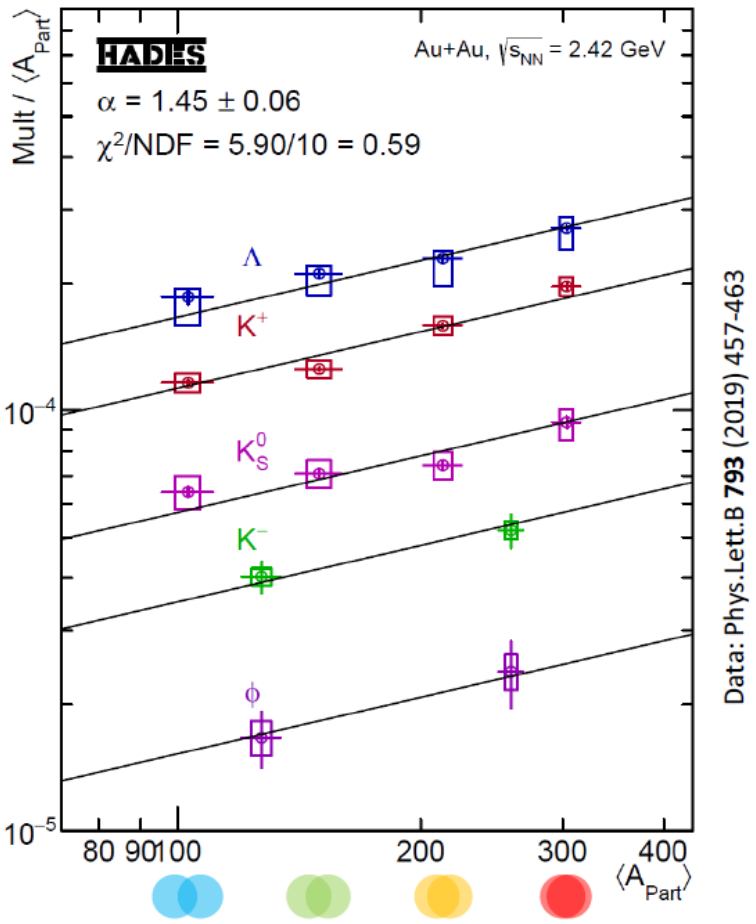


Λ_c, D x 20 larger

- Production mechanism ? particularly for charm, multistrangeness : hadronic (heavy N* resonances), string fragmentation? in HIC role of EOS (production close to threshold)
- Spectrum of hyperons , only few states known (6 Ξ* , 2 Ω*) !
- pp measurements @ SIS100 are mandatory ! on going discussion on physics programme

Strangeness Production at FAIR

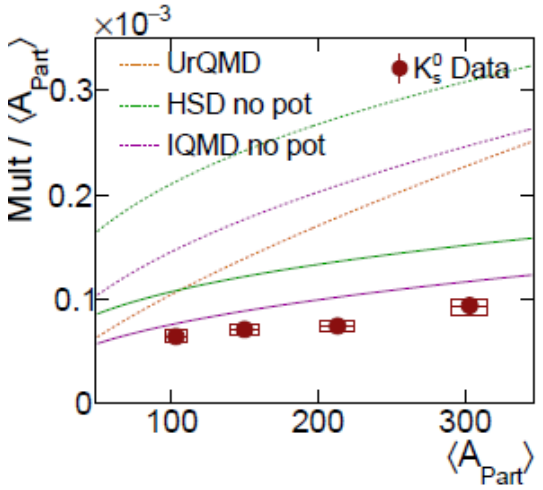
SIS18: subt-hreshold production

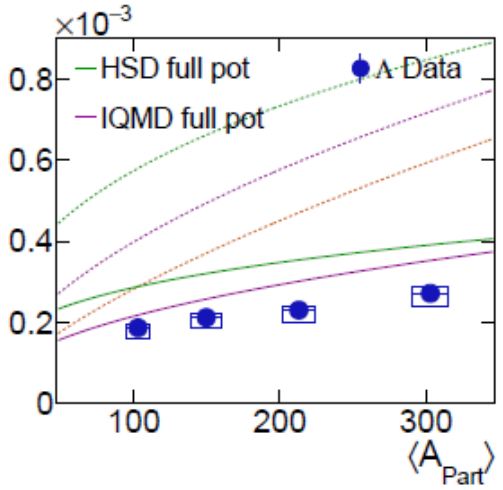


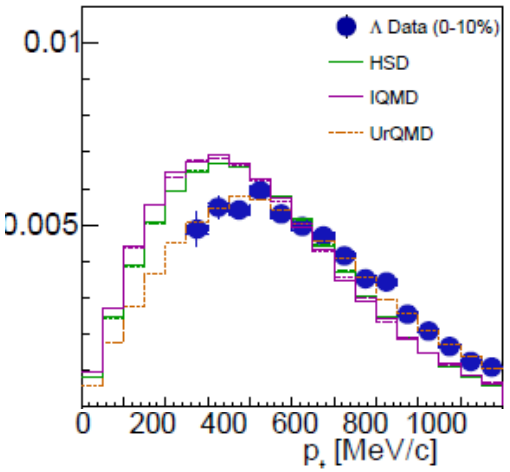
Data: Phys.Lett.B **793** (2019) 457-463

Mult $\propto \langle A_{Part} \rangle^{\alpha}$ with α_{Au+Au} = 1.45 ± 0.06

Universal law for centr. dependence suggests accumulation of energy during collsion till freeze-out to overcome threshold







IQMD,HSD with K-N, Λ-N potential improves agreement but shapes of pt and y are better described by UrQMD with no potential but assuming prodcution via heavy N* resonances. This model explains also ϕ/K-

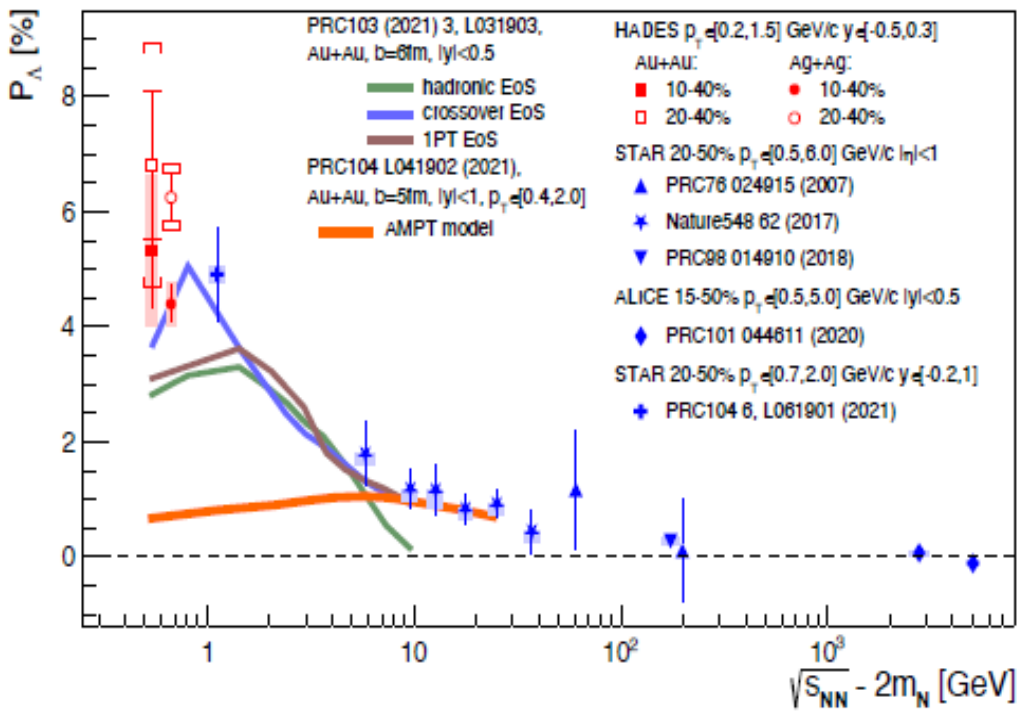
Lesson for studies of heavy hyperons production @ SIS100:

production of Ξ/Ω states below threshold is suggested as probe for EOS

$\rightarrow$ Reference measurements with pp are mandatory for the understanding of production mechanism (intermediate heavy resonances, partonic d.o.f)

Polarization of Hyperons in HIC

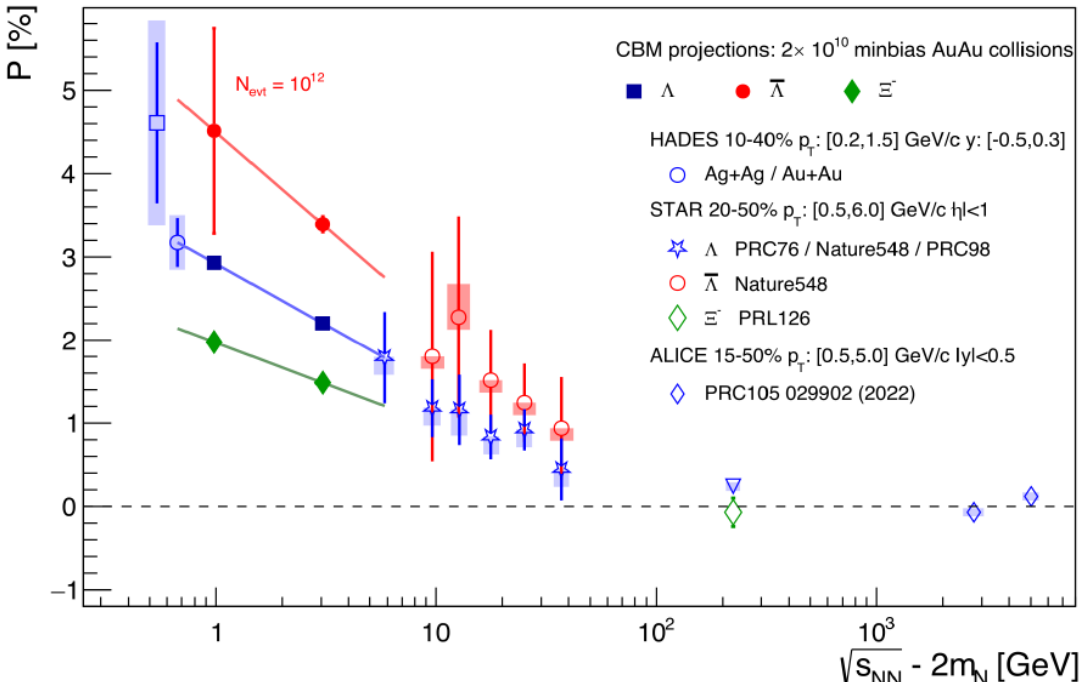
Λ polarizion

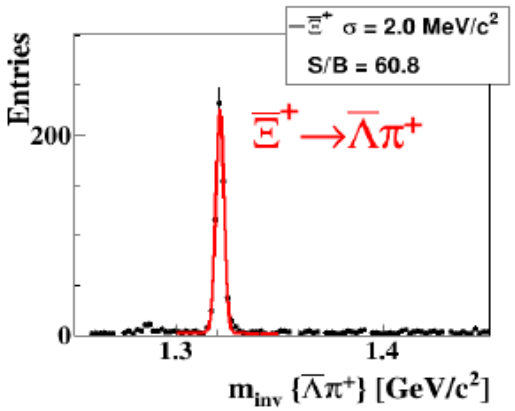


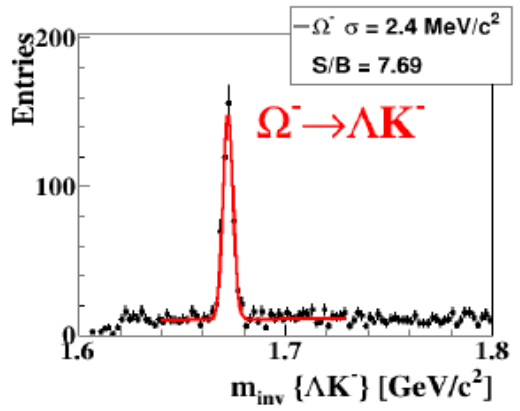
- HADES results show significant Λ polarization decreasing as function of centrality
- extension to $\overline{\Lambda}$, Ξ, Ω with CBM

Projections for CBM

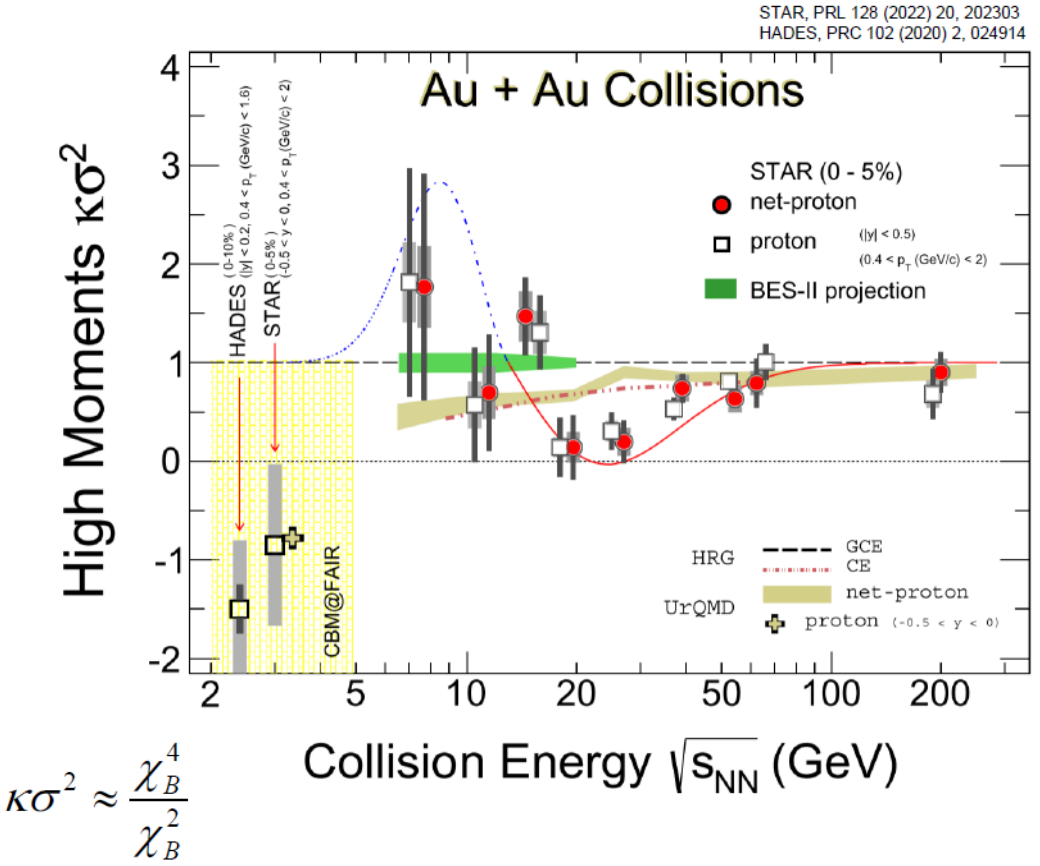
N.Herrmann, FAIR seminar, Krakow



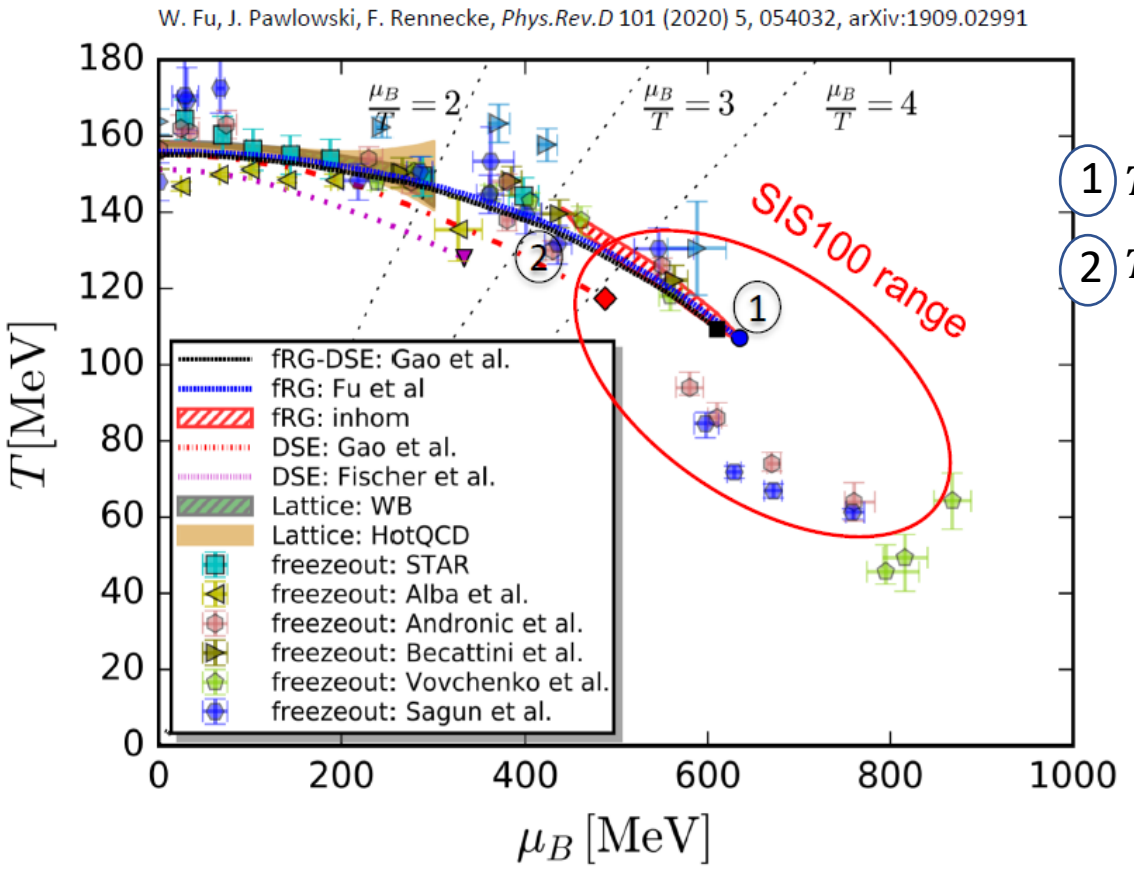




Fluctuations and location of Critical Point



$$\kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$



1 $T_{Lab} = 6\ GeV/u$

2 $T_{Lab} = 31\ GeV/u$

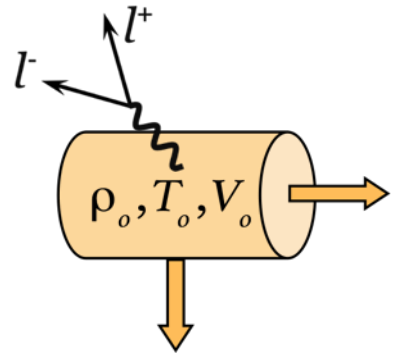
- Susceptibilities diverge at CP
- Ratios of moments of(net) proton multiplicty – non monotonic excitation function?
- CBM aims in measurements up to k_6

- fRG, DSE calculations predict CP location in SIS100 range…

Emissivity of QCD matter with dileptons

$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545



- Not disturbed by finite state interactions ! But needs integration over volume and time !
- *Π_{em} em. current-current correlator $q^2 < 1$ GeV : $q^2 > 1.5$GeV qq radiation pQCD (flat)*

Vector Meson Dominance

$$\mathrm{Im}\,\Pi_{em}^{\mathrm{had.}} = \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}\,D_V(M)\,.$$

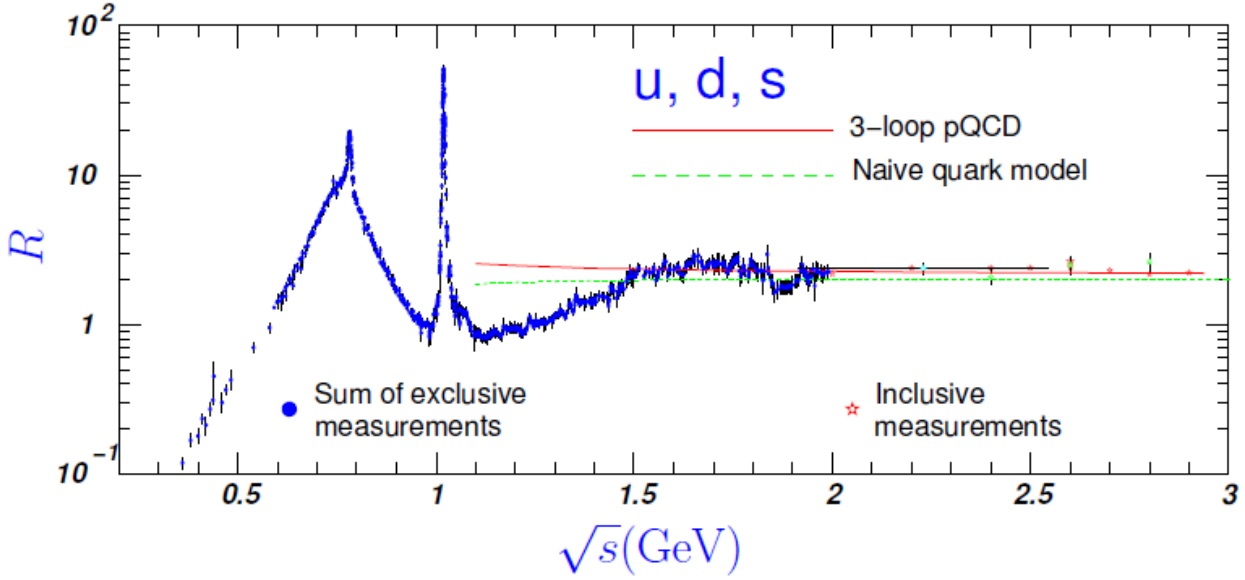
✓ *$q^2 < 1$ GeV* Low Mas
Π_{em} dominated by ρ in-medium propagator *D_ϱ*

✓ *$3 > q^2 > 1.5$ GeV* Intermadiate Mas Range

$f^{BE}(T)$ – thermometer

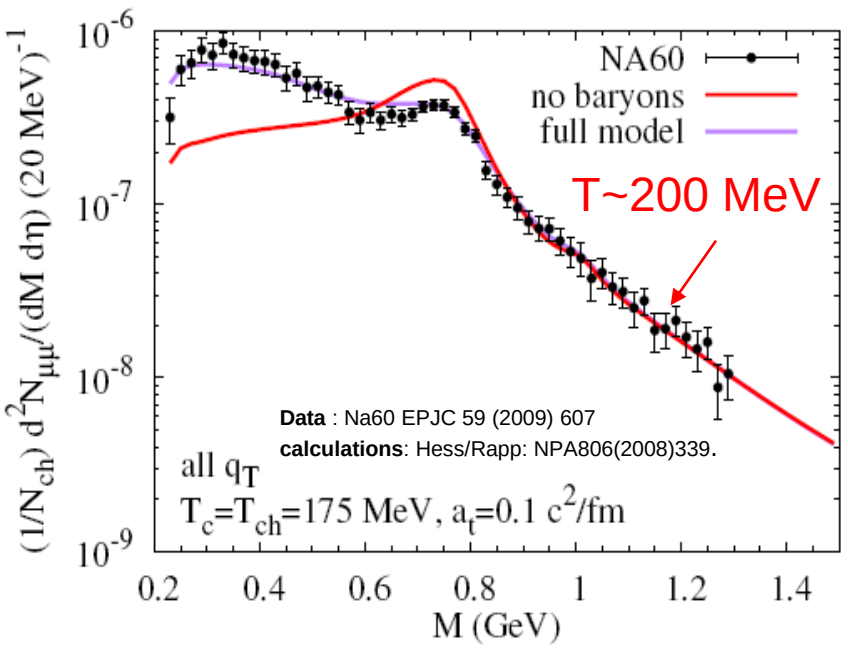
$1.0 < q^2 < 1.5$GeV ρ/a_1 mixing ?

$$R_{\mathrm{had.}} = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{1}{M^2}\,\mathrm{Im}\,\Pi^{em}$$

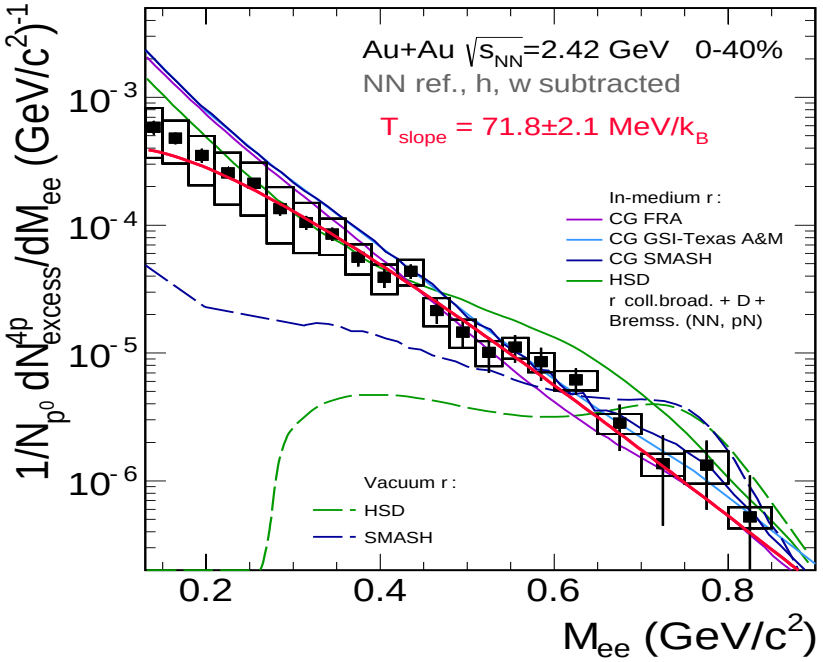


Dielepton thermal rates from HIC from SIS18 to SPS

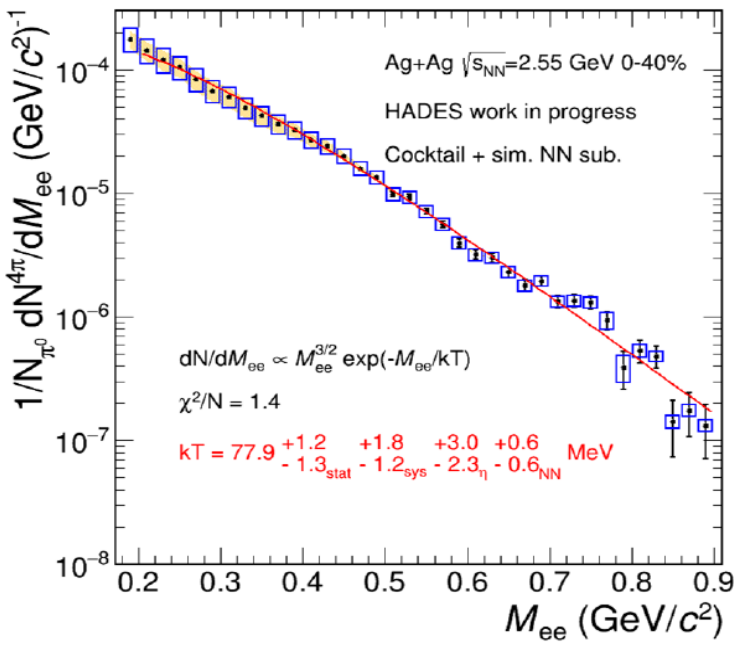
Na60 @ SPS In+In (μ+μ-) **√s=17.3 GeV**



HADES: Nature Phys. 15 (2019) 10, 1040-1045

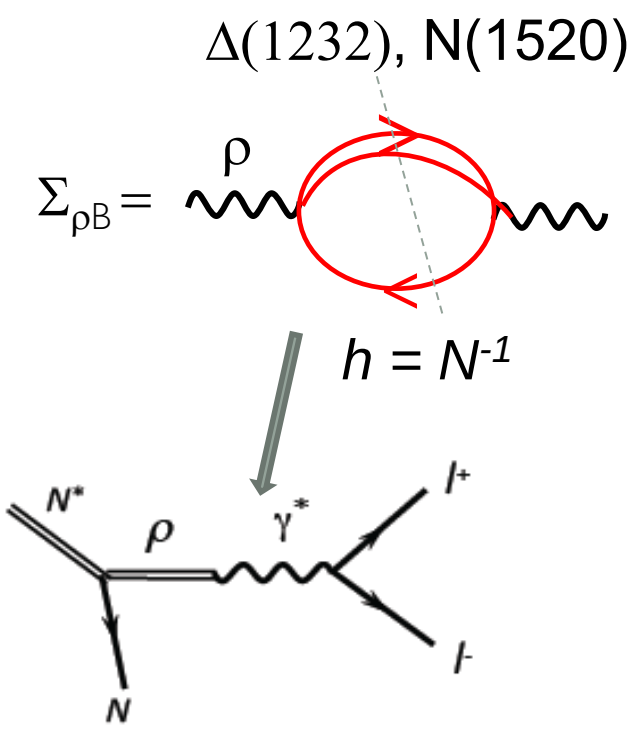


preliminary



- Successful description of dilepton excess yield over large energy region by thermal radiation from in-medium ρ with significant broadening – crucial input spectral function from many-body hadronic interactions (R. Rapp et. al)
- M_{ee} slope (not affected by blue shift) NA60: <T> ~ 200 MeV , HADES@SIS18 <T>~ 70-77 MeV
- next challenge : search for ρ/a_1 mixing: central point in ALICE3, NA60+, CBM

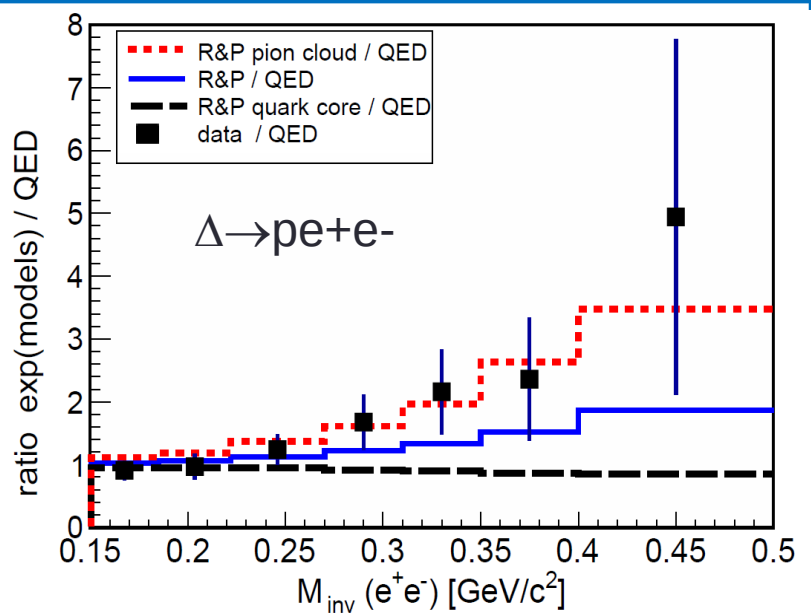
In medium ρ-B interactions–connection to Baryon Dalitz Decay

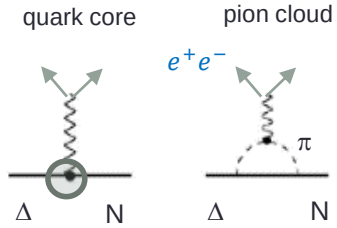


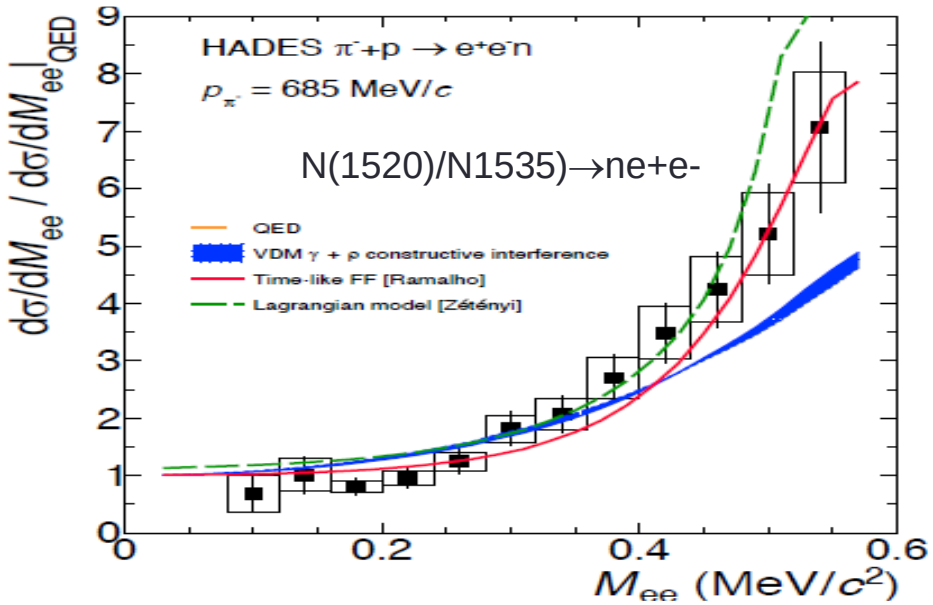
Baryon-rho interactions: important contribution to in-medium spectral functions

Baryon Dalitz decays → em. Transition Form Factors of baryons

N*/Δ Dalitz decays in πN collisions ! → dedicated HADES pion beam physics programme @ FAIR-Phase0



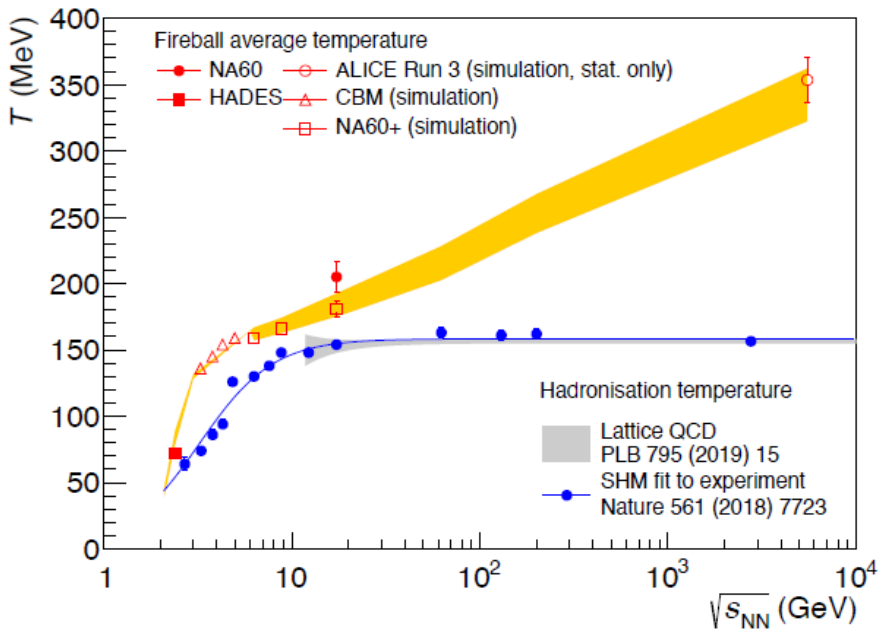




HADES Coll., arXiv:2205.15914

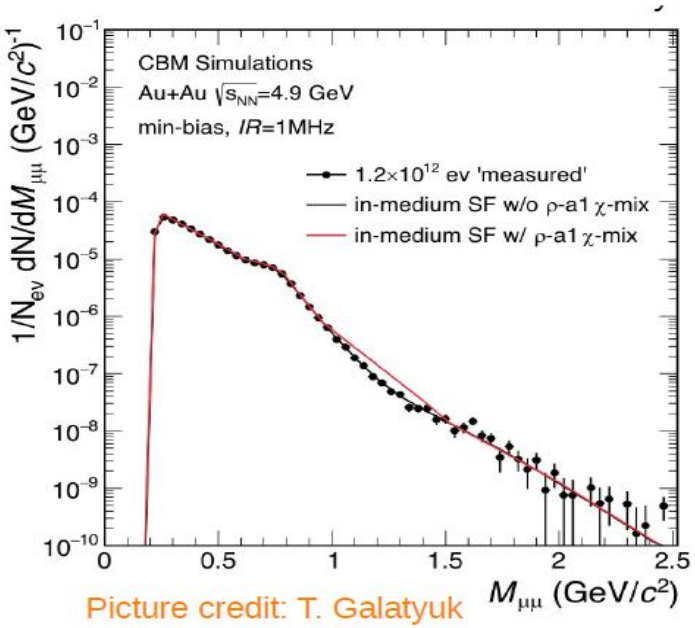
Projections for future dilepton measurements

Slope (T) extraction

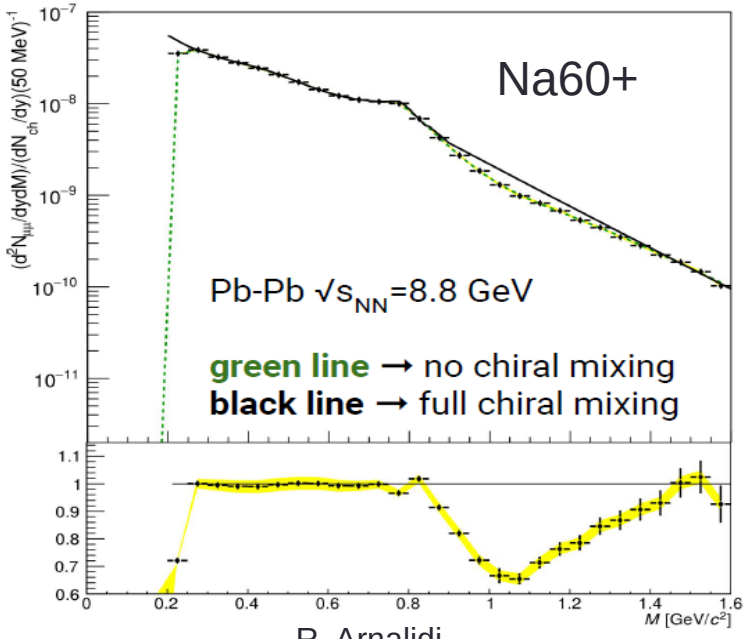


- Caloric Curve & dilepton rates

Flattening of caloric curve & Yield of thermal dileptons in LMR sensitive to phase transition



Picture credit: T. Galatyuk

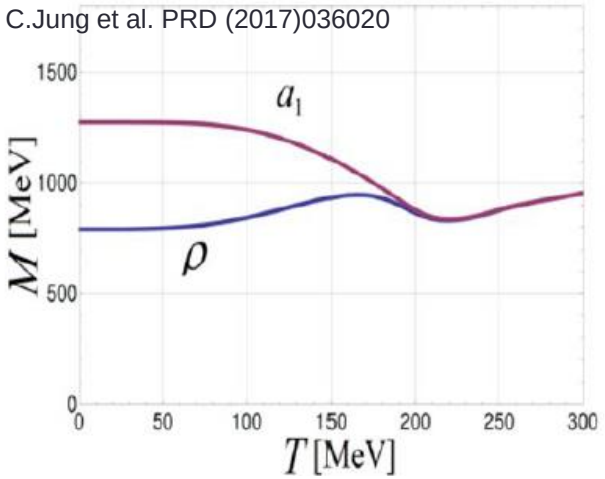


R. Arnaldi

- Search for for ρ/a_1 mixing

pp reference is mandatory

C.Jung et al. PRD (2017)036020



Charm production at SIS100

Exciting subject !

- pp , pA , and HI collisions- charm production and propagation

Measurements for all 3 collision systems is mandatory (H.Satz CBM charm workshop 2024)

no data at SIS100 energy – all 3 systems must be studied (open and hiden charm) !

pp collisions:

- charm content of nucleon - enhanced production close to threshold?
  (as discussed for ϕ in pp)

- trace anomaly and origin of proton, mass (Ji PRL74, PRD52, 1995 PRD104 Karzeev PRD104, 2021) via J/Ψ- N FSI ?

$F_{J/\Psi N}$ – J/Ψ - N scattering amplitude

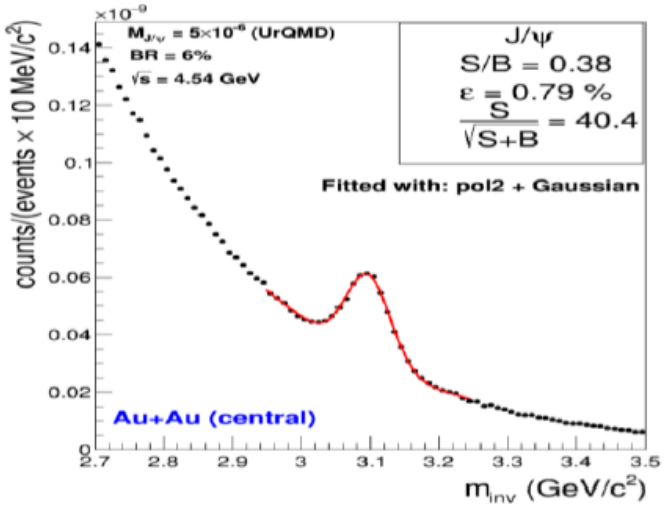
$$F_{J/\psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N\left|\sum_{i=u,d,s} m_i \bar{q}_i q_i\right|N\right\rangle\right)$$

$$\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right)$$

- J/Ψ – N bound system (pentaquark, molecular state? Cusp due to Λ_c D chanels?
  Close to threshold production simplifies description – Partial Wave Analysis

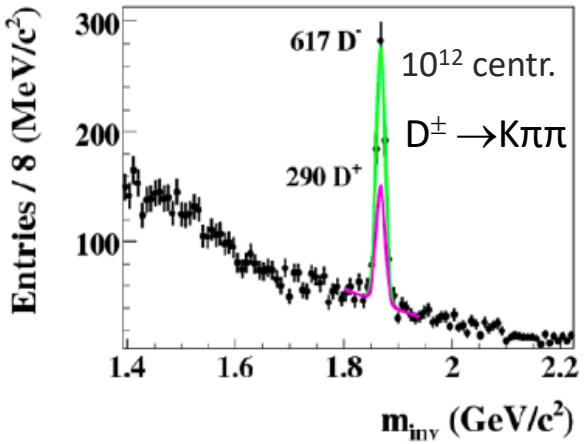
(complementary to photo-production studies GlueX,007@JLAB)

10 A GeV/c central Au+Au collisions



CBM projections for dimuon channel :
30 k J/Ψ in 4 weeks

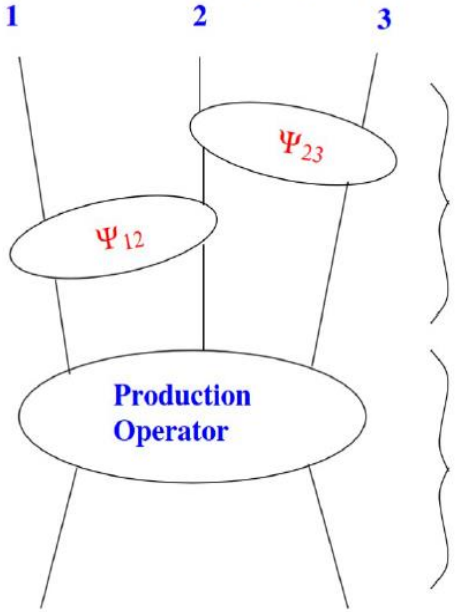
p+C collisions, 30 GeV



V. Friese CBM charm workshop 20024

Access to charm-N interactions via exclusive channels

- Dalitz plot analysis gives access to information about
  - 3-body final states
  - Final State Interactions (*e.g.* scattering lengths, get more dynamics from the data)
  - Resonances
  - Line shapes



Final state interaction

strongly energy dependent

sensitive to interactions of all subsystems; for more than 2 final particles: **Dalitz plot analysis!**

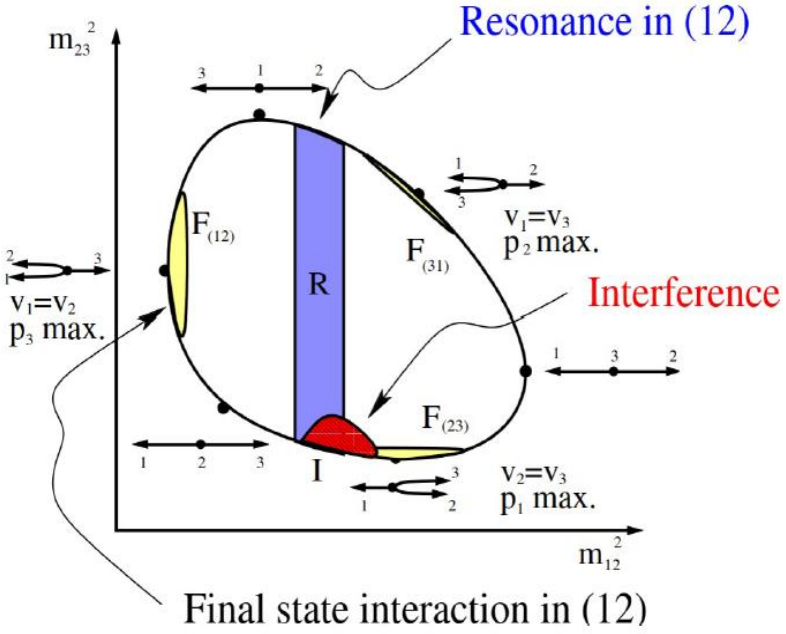
Production operator

weakly energy dependent;

selection rules!

(isospin, parity, Pauli principle ...)

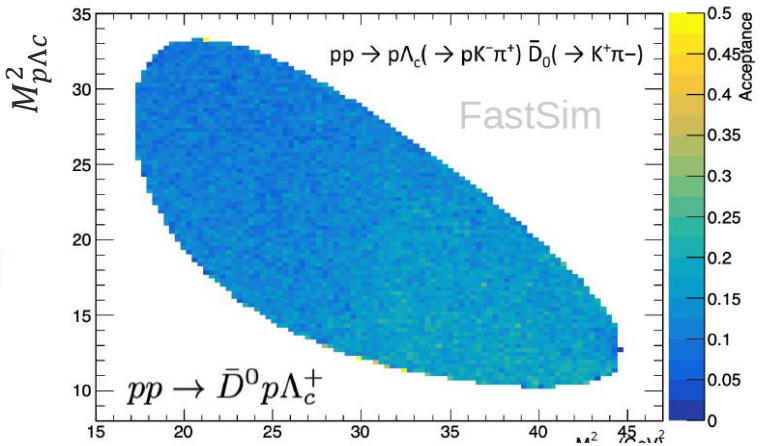
→ $d\sigma \propto |fM|^2$, where $M \simeq const.$ and $f = f[\Psi_{ij}]$.



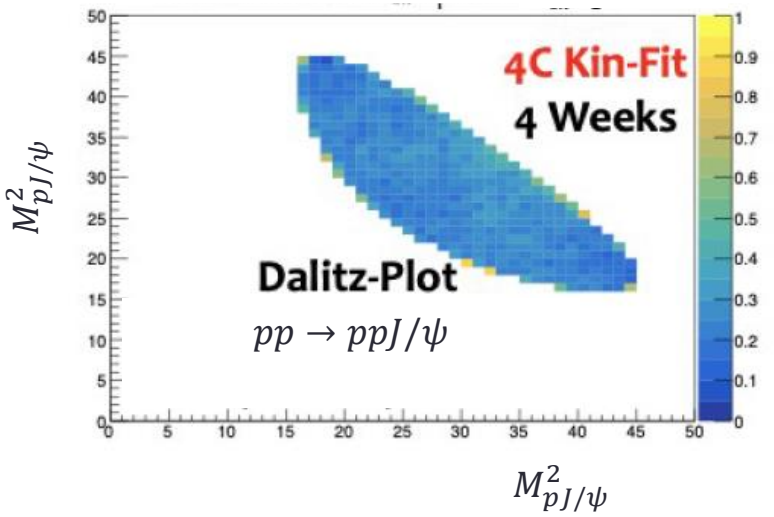
Picture Credit: Christoph Hanhart

CBM has excellent coverage for exclusive charm production !

pp@ 30 GeV



Johan Messchendorp



- Similar arguments holds also for studies of Ξ-N, Ω-N FSI and extraction of interaction hyperon- nucleon

Summary and outlook

- FAIR enters construction phase aims in completion of SIS100 machine and SFRS in 2028
- Compressed Baryonic Matter pillar with new detector CBM detector (First Science+) is not yet fully financed but is on good path to start operation in 2029.
- Polish in-kind contributions (cryogenic systems, detector components) are of critical importance for the project

Outlook into Future experiments in Phase-0

- Mini CBM performs integration and tests at SIS18
- HADES will continue his scienitic programme (running almost 20 years..) in 2025-2026

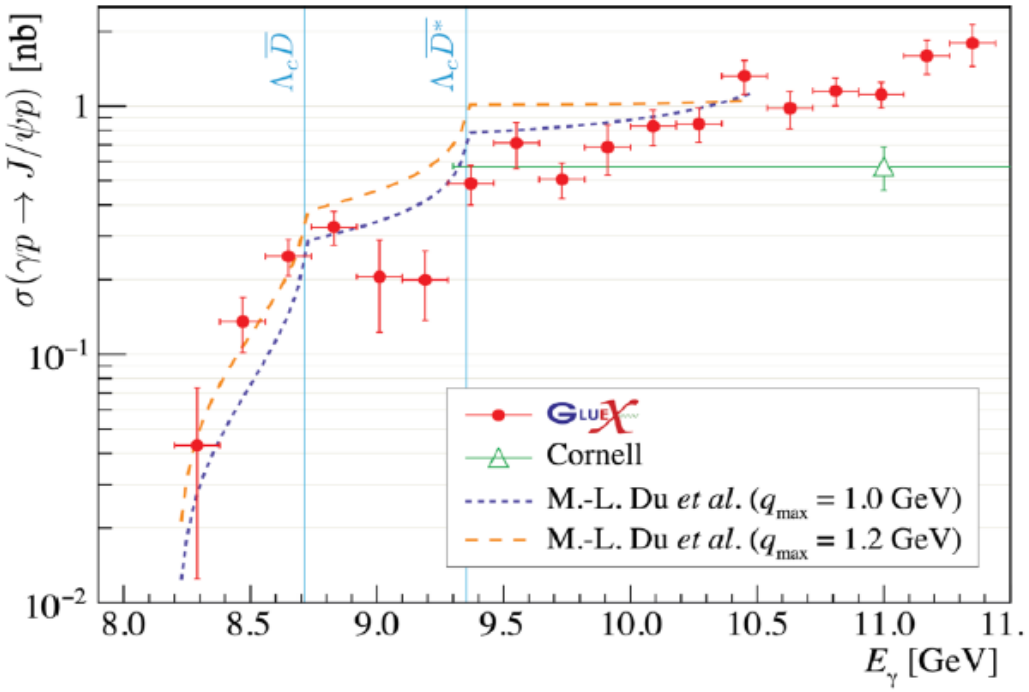
Beam Energy scan with Au+Au (200-800 AMeV)

studies of baryonic resonances with pion beam (third resonance region)

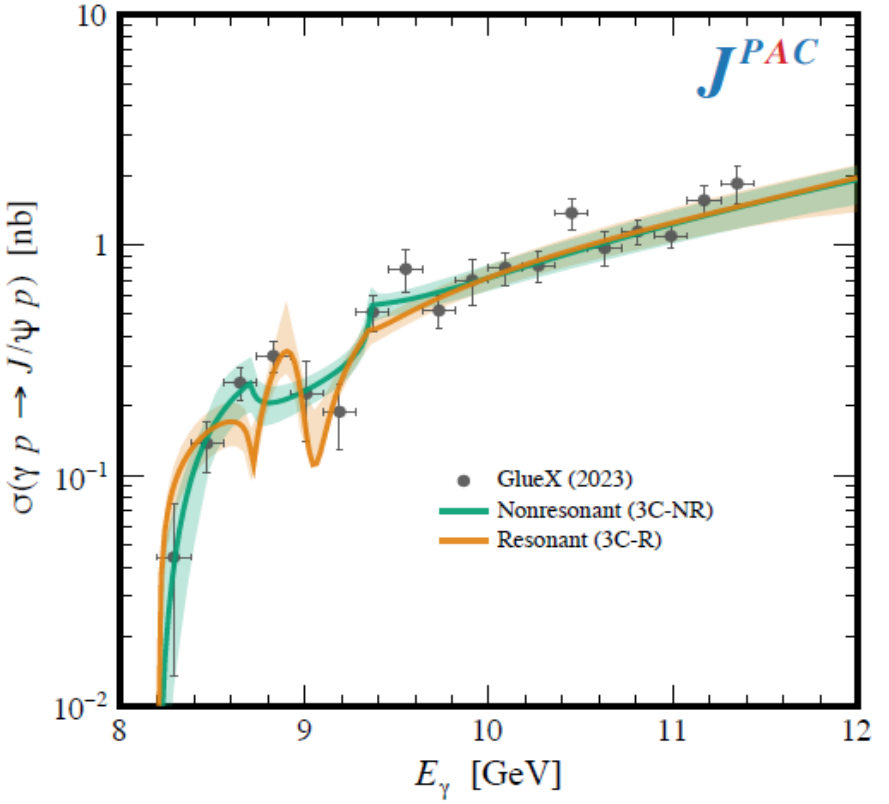
https://fair.uj.edu.pl/

Back-up

J/ψ photoproduction



PRC 108, 025201 (2023); EPJC 80, 1053 (2020)

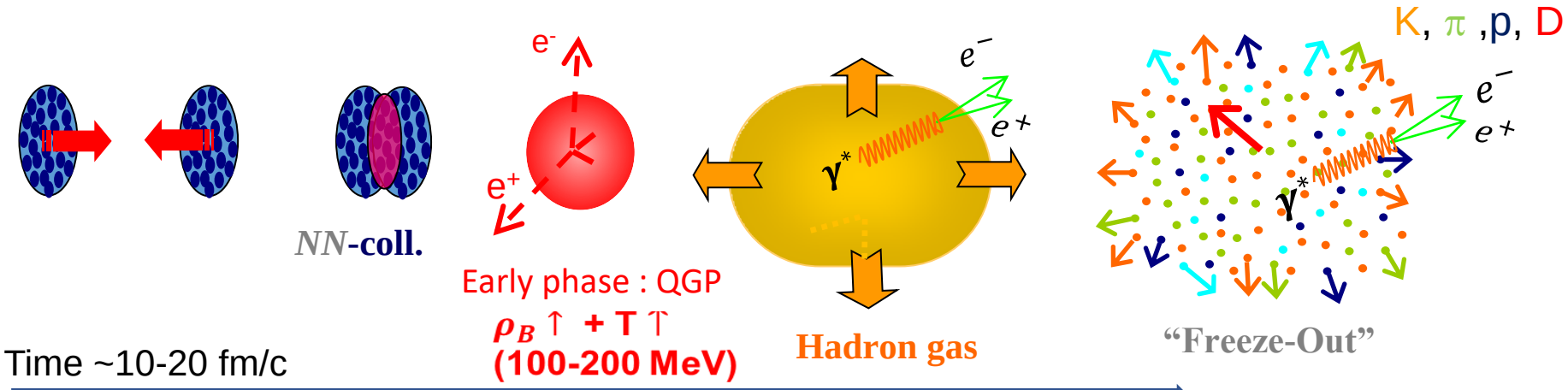


PRD 108, 054018 (2023)

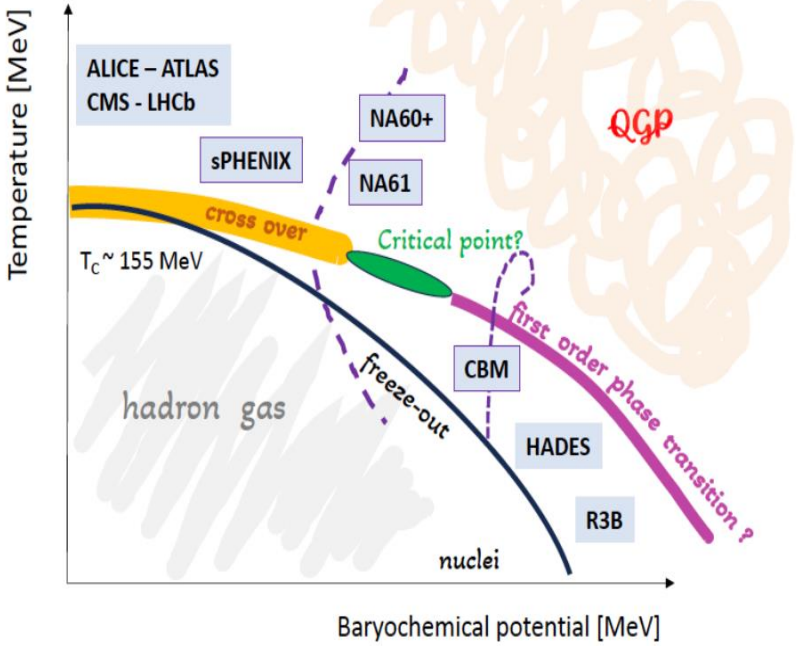
- Structures seen near open-charm thresholds
- More precision required — GlueX-II will provide factor ~3 more data
- Polarization observables can provide additional insight

QCD phase diagrame & URHIC

„standard model" of URHIC



QCD phase diagramme



Key observables at FAIR

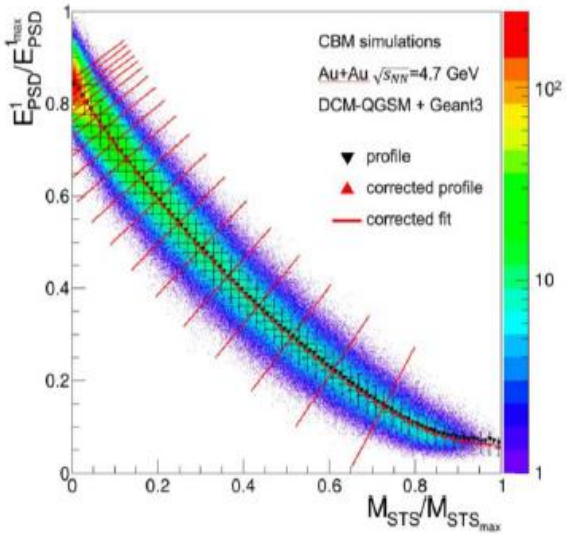
- ✓ Fluctuations –higher order cummulants (Critial Point)
- ✓ strangeness (|S|=2,3) production close to threshold (EOS), Y-N interactions
- ✓ hipernuclei
- ✓ Origin of hyperon polarization in HIC
- ✓ Multi-differantial flow measurements ; EOS, symmetry energy,
- ✓ EM radiation (chrial symmetry restoration, diagnostic of early phase (T, ρ) , caloric curve)
- ✓ Charm production..

…

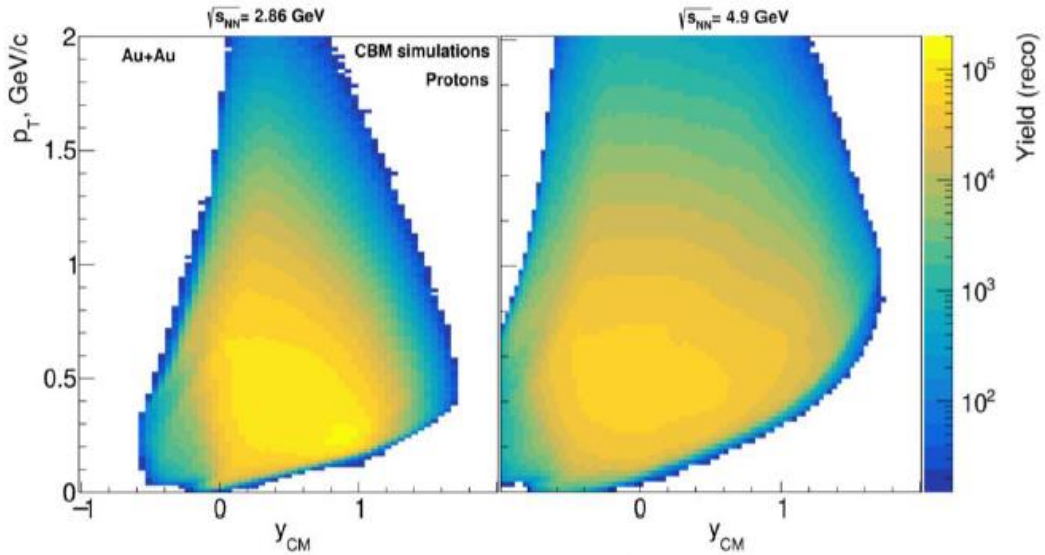
Net – proton fluctuations

- Corrections for volume fluctuations and conservation laws
- Event-by-event changes of efficiency
- Proper selection of $p_T - y$ bite
- (Net-)baryons vs. protons, neutrons, nuclei

Impact of the effects is being scrutinized

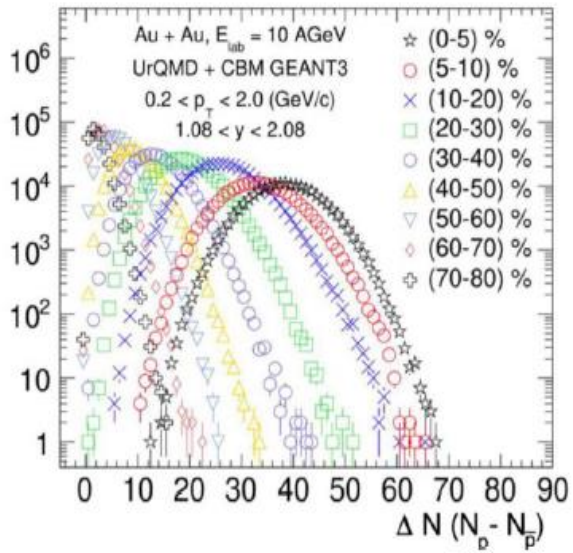


Crucial: centrality determination with independent detector → avoids bias on e-b-e fluctuation observables



Low p_T and midrapidity coverage

Reconstruction efficiency allows for precision measurement of cumulants



Statistics sufficient to study derivatives of order $> O(4)$

After 3 years of running:

- Completion of the excitation function for $\kappa_4(\mathrm{p})$
- First results on $\kappa_6(\mathrm{p})$
- Extension into strangeness sector $\kappa_4(\Lambda)$