Studying Dense Matter with the CBM Experiment

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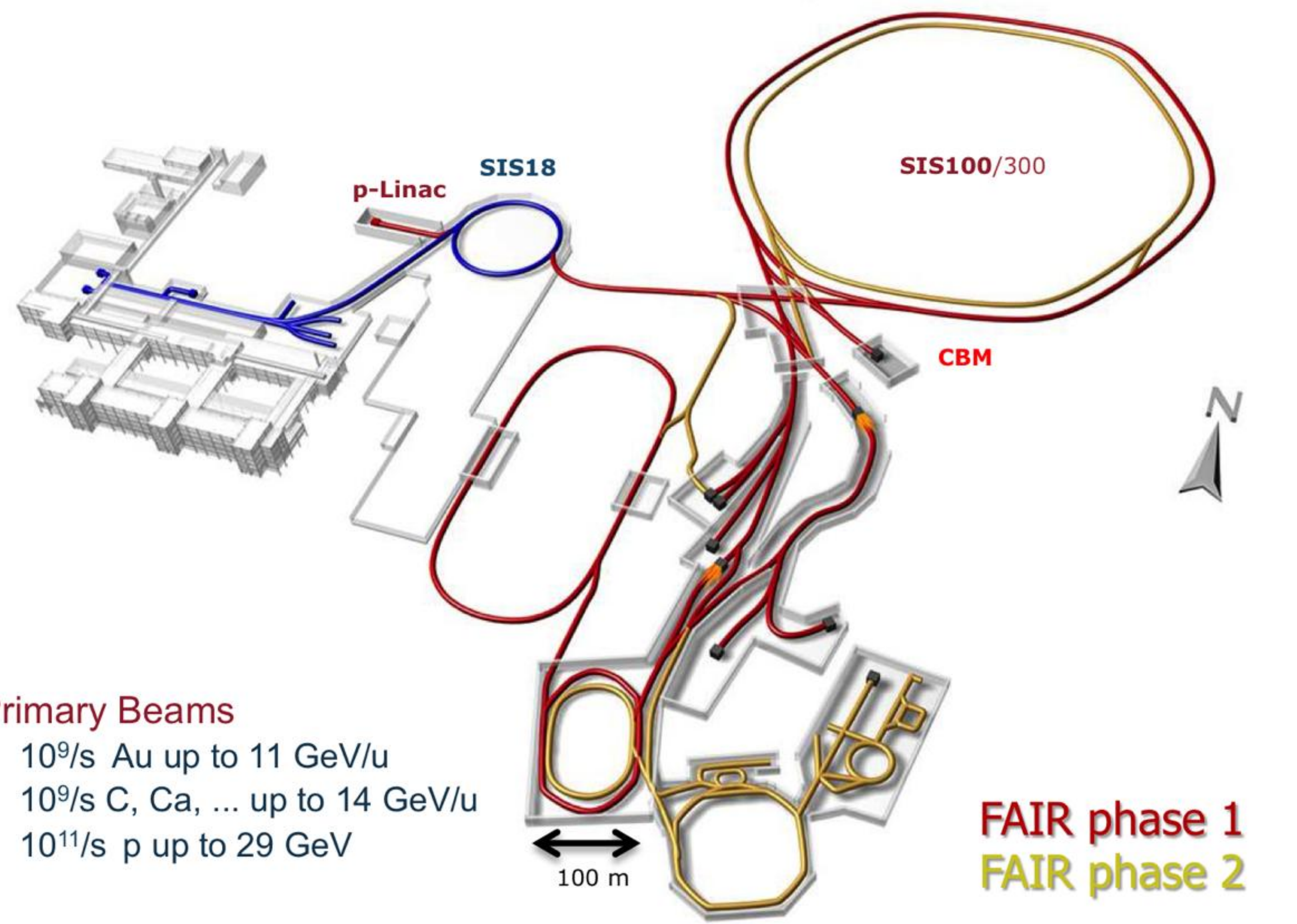
on behalf of the CBM Collaboration

ECT* Workshop “Phase diagram of strongly interacting matter”
Trento, 28 November 2017

FAIR Accelerator Complex



Primary Beams

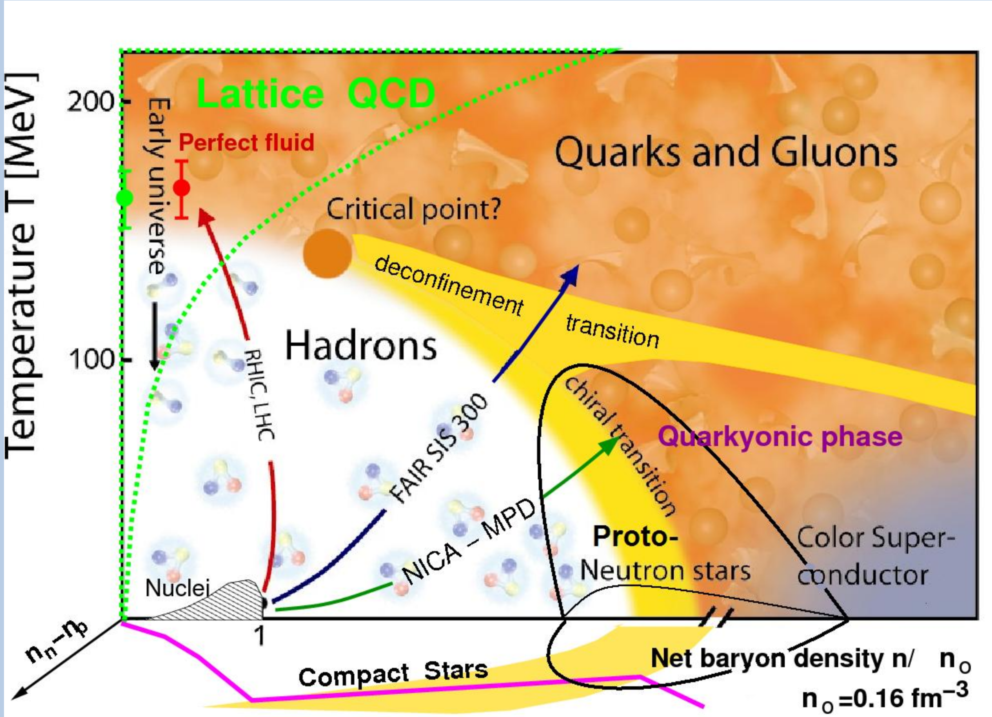
- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

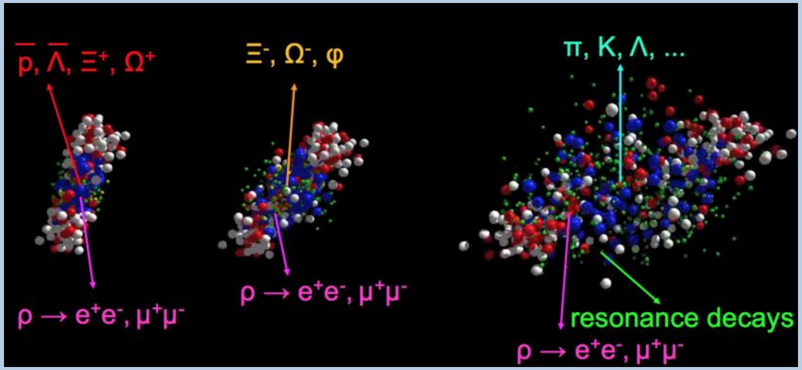
FAIR Accelerator Complex and CBM

Primary Beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

What We Are After





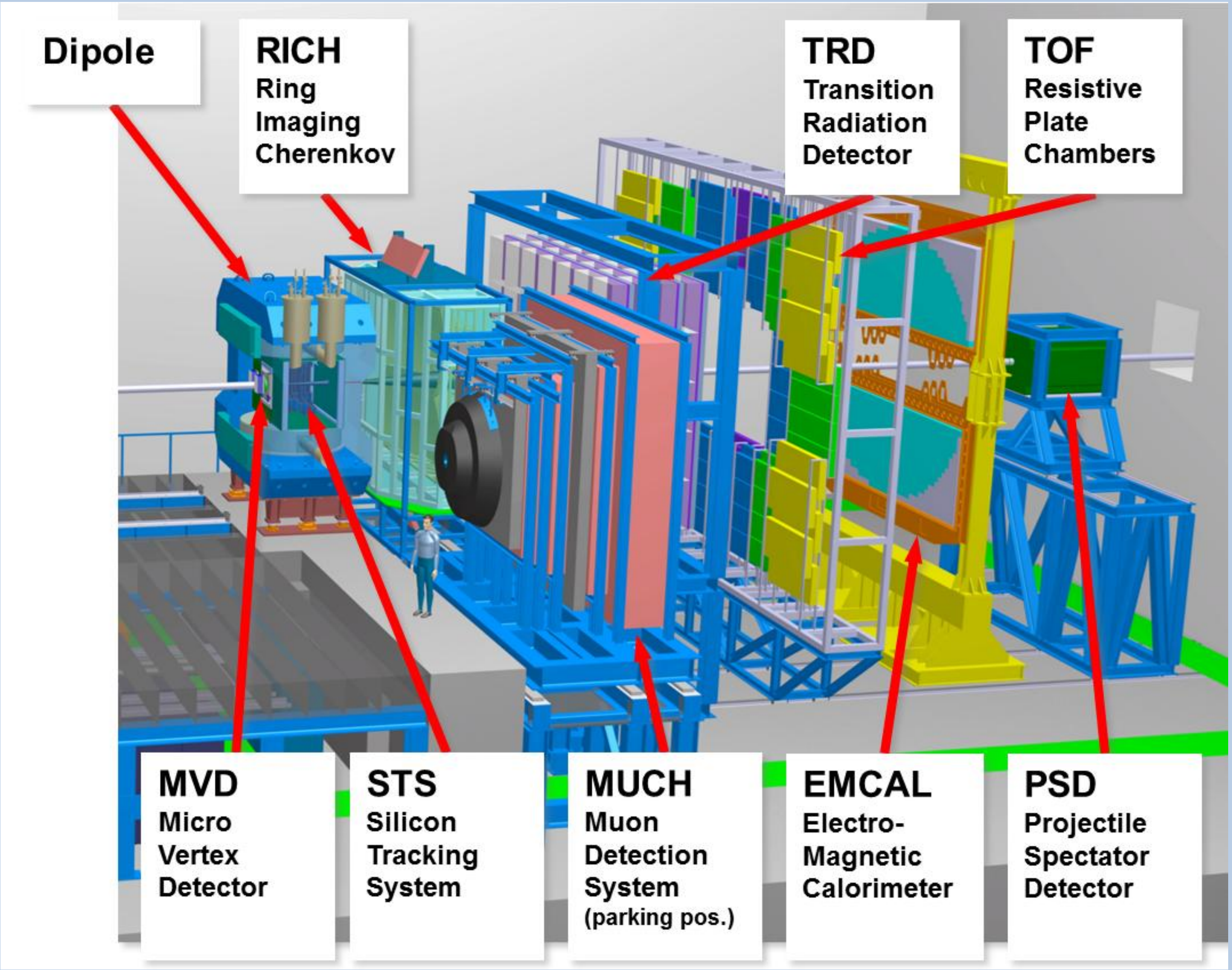
Theory, models

The quest: study properties of QCD matter at high net-baryon densities

- Equation-of-state
- Onset of deconfinement / chiral restoration
- Nature of transition (first-order?)
- Critical end-point

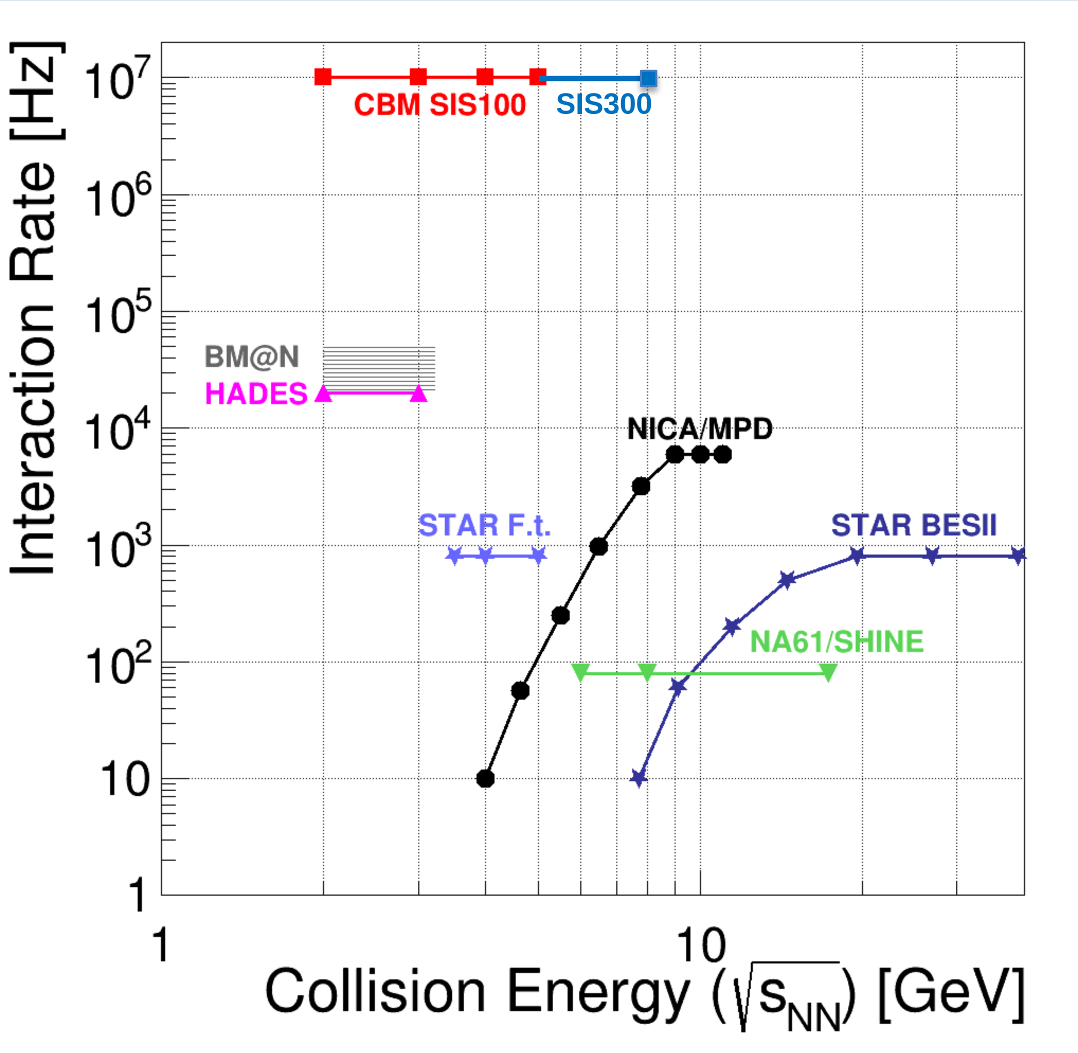
General experimental strategy: stay as open and flexible as possible; measure as many observables as you reasonably can.

CBM: Experiment Systems



- Large acceptance: 2.5° – 25°
- Identify:
  - Hadrons (TOF)
  - Electrons (RICH, TRD)
  - Muon (MUCH)
  - Neutral probes (ECAL)
  - Open charm (MVD)
- High rates: up to 10^7 events/s

CBM in the experimental landscape



Uniqueness of CBM: very high rate capability

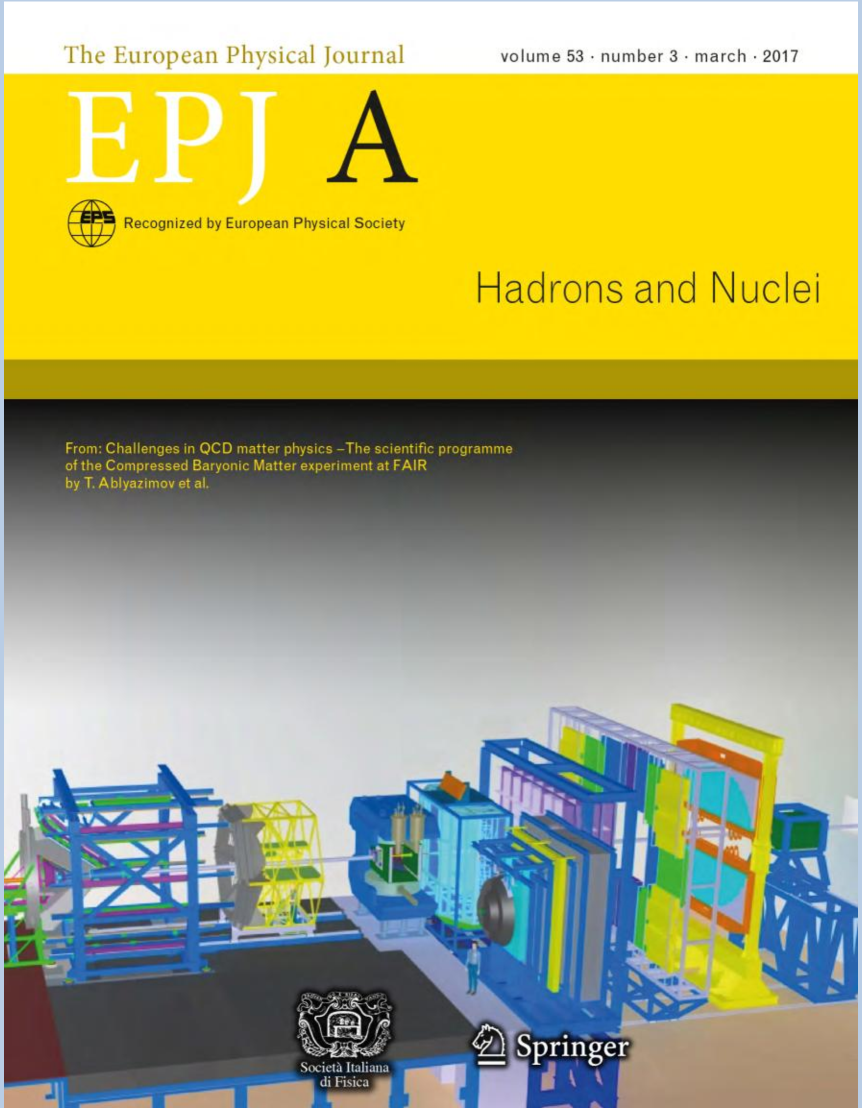
Comes with huge challenges in terms of:

- Speed and radiation hardness of detectors and read-out electronics
- Data processing on- and offline (no hardware trigger, free-running data acquisition, event reconstruction and selection in real-time)

SIS-100 and SIS-300

- SIS-100 and CBM are part of the FAIR Modularised Start Version (MSV)
- SIS-300 is agreed-on part of FAIR, but not of the start version; timeline is unclear
- we concentrate here on CBM@SIS-100
  - Au: 2A – 11A GeV
  - Ni: 2A – 15A GeV
  - p: up to 30 GeV
- staying open for SIS-300 as later upgrade

Physics Programme



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THE EUROPEAN PHYSICAL JOURNAL A

Review

Challenges in QCD matter physics —The scientific programme of the Compressed Baryonic Matter experiment at FAIR

T. Ablyazimov[1], A. Abuhoza[2,a], R.P. Adak[3], M. Adamczyk[4], K. Agarwal[5], M.M. Aggarwal[6], Z. Ahammed[7], F. Ahmad[8], N. Ahmad[9], S. Ahmad[8], A. Akindinov[10], P. Akishin[1], E. Akishina[1], T. Akishina[1], V. Akishina[13,1,2], A. Akram[12], M. Al-Turany[2], I. Alekseev[10], E. Alexandrov[1], I. Alexandrov[1], S. Amar-Youcef[13], M. Anđelić[14], O. Andreeva[15], C. Andrei[16], A. Andronic[2], Yu. Anisimov[17], H. Appelshäuser[13], D. Argintaru[18], E. Atkin[19], S. Avdeev[17], R. Averbeck[2], M.D. Azmi[9], V. Baban[18], M. Bach[11], E. Badura[2], S. Bähr[20], T. Balog[2], M. Balzer[20], E. Bao[12], N. Baranova[22], T. Barczyk[4], D. Bartoş[16], S. Bashir[8], M. Baszczyk[23], O. Batenkov[24], V. Baublis[25], M. Baznat[17], J. Becker[20], K.-H. Becker[26], S. Belogurov[1], D. Belyakov[1], J. Bendarouach[27], I. Berceanu[16], A. Bercuci[16], A. Berdnikov[28], Y. Berdnikov[28], R. Berendes[29], G. Berezin[17], C. Bergmann[29], D. Bertini[2], O. Bertini[2], C. Beşliu[18], O. Bezshyyko[30], P.P. Bhaduri[2,7], A. Bhasin[31], A.K. Bhati[6], B. Bhattacharjee[32], A. Bhattacharyya[21], T.K. Bhattacharyya[33], S. Biswas[3], T. Blank[20], D. Blau[34], V. Blinov[2], C. Blume[13], Yu. Bocharov[19], J. Book[13], T. Breitner[35], U. Brüning[36], J. Brzychczyk[4], A. Bubak[37], H. Büsching[13], T. Bus[13], V. Butuzov[19], A. Bychkov[17], A. Byszuk[38], Xu Cai[39], M. Cālin[18], Ping Cao[40], G. Caragheorgheopol[16], I. Carević[14], V. Cătănescu[16], A. Chakrabarti[21], S. Chattopadhyay[7,3], A. Chaus[42], Hongfang Chen[40], LuYao Chen[35], Jianping Cheng[43], V. Chepurnov[17], H. Cherif[13,2], A. Chernogorov[10], M.I. Ciobanu[2,b], G. Claus[44], F. Constantin[16], M. Csanád[45], N. D'Ascenzo[46], Supriya Das[3], Susovan Das[5], J. de Cuveland[11], B. Debnath[32], D. Dementiev[17], Wendi Deng[39], Zhi Deng[43], H. Deppe[2], I. Deppner[12], O. Derenovskaya[1], C.A. Deveaux[27], M. Deveaux[13], K. Dey[32], M. Dey[7], P. Dillenseger[13], V. Dobyrn[25], D. 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Kirejczyk[53], A. Kiryakov[52], M. Kiš[2], I. Kisel[11], P. Kisel[13,2,1], S. Kiselev[10], T. Kiss[54], P. Klaus[13], R. Kłeczek[23], Ch. Klein-Bösing[29], V. Kleipa[2], V. Klochkov[2,13], P. Kmon[23], K. Koch[2], L. Kochenda[25,19], P. Koczoń[2], W. Koenig[2], M. Kohn[29], B.W. Kolb[2], A. Kolosova[10], B. Komkov[25], M. Korolev[22], I. Korolko[10], R. Kotte[49], A. Kovalchuk[42], S. Kowalski[37], M. Koziel[13], G. Kozlov[11,1], V. Kozlov[25], V. Kramarenko[17], P. Kravtsov[25,19], E. Krebs[13], C. Kreidl[36], I. Kres[26], D. Kresan[2], G. Kretschmar[13], M. Krieger[36], A.V. Kryanev[1,19], E. Kryshen[25], M. Kuc[53], W. Kucewicz[23], V. Kucher[11], L. Kudin[25], A. Kugler[55], Ajit Kumar[7], Ashwini Kumar[41], L. Kumar[6], J. Kunkel[2], A. Kurepin[15], N. Kurepin[15], A. Kurilkin[17], P. Kurilkin[17], V. Kushpil[55], S. Kuznetsov[17], V. Kyva[42], V. Ladygin[17], C. Lara[35], P. Larionov[13,2], A. Laso García[49,d], E. Lavrik[5], I. Lazanu[18], A. Lebedev[2,1], S. Lebedev[27,1], E. Lebedeva[27], J. Lehnert[2], J. Lehrbach[35], Y. Leifels[2], F. Lemke[36], Cheng Li[40], Qiyan Li[13,39], Xin Li[40], Yuanjing Li[43], V. Lindenstruth[11,2], B. Linnik[13], Feng Liu[39], I. Lobanov[52], E. Lobanova[52], S. Löchner[2], P.-A. Loizeau[2], S.A. Lone[8], J.A. Lucio Martínez[35], Xiaofeng Luo[39], A. Lymanets[2,42], Pengfei Lyu[43], A. Maevskaya[15], S. Mahajan[31], D.P. Mahapatra[56], T. Mahmoud[27], P. Maj[23], Z. Majka[4], A. Malakhov[17], E. Malankin[19], D. Malkevich[10], O. Malyatina[19], H. Malygina[13,2,42], M.M. Mandal[56], S. Mandal[7], V. Manko[34], S. Manz[35], A.M. Marin Garcia[2], J. Markert[2], S. Masciocchi[2], T. Matulewicz[53], L. Meder[20], M. Merkin[22], V. Mialkovski[17], J. Michel[13], N. Miftakhov[25], L. Mik[23], K. Mikhailov[10], V. Mikhaylov[55], B. Milanović[13], V. Militsija[42], D. Miskowiec[2], I. Momot[13,2,42], T. Morhardt[2], S. Morozov[15], W.F.J. Müller[48,2], C. Müntz[13], S. Mukherjee[3], C.E. Muñoz Castillo[35], Yu. Murin[17],

CBM Physics: Strangeness

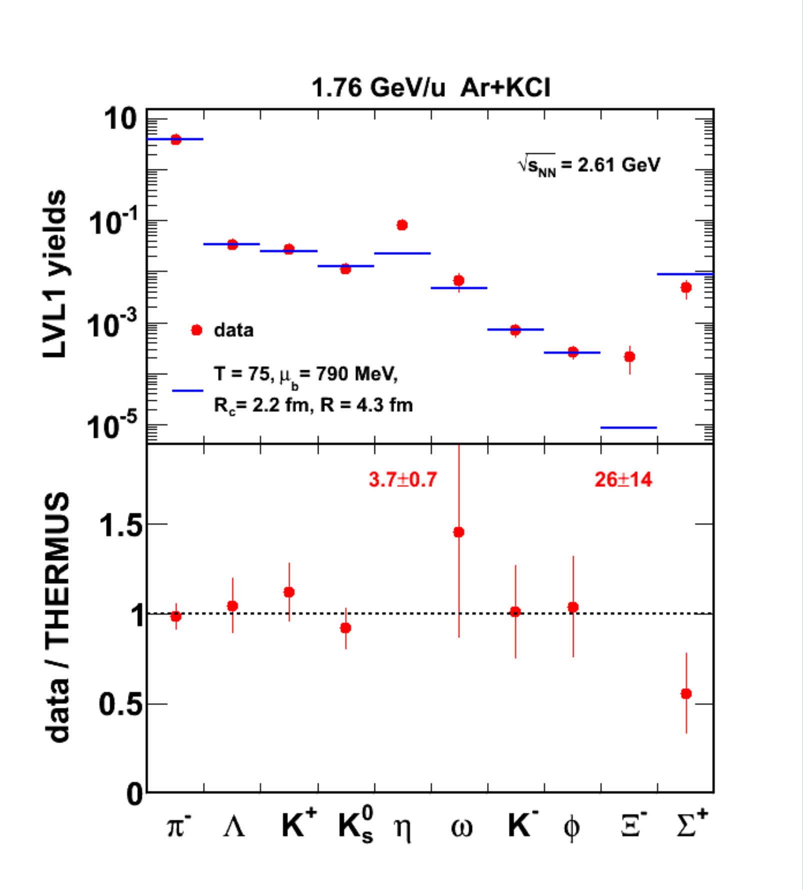
- One of the ”classical” observables:
  strangeness enhancement / canonical suppression
- Strangeness yields from are well described by the statistical model: strong argument for phase transition (no hadronic mechanism to equilibrate e.g. Omega)
- Model fits describe data at lower SPS and at AGS
  - But with a limited amount of particle species
  - Data on multi-strange baryons are scarce
- Following this: measuring strange baryon abundances at lower energies.
  - Down to which collision energies does the hadron gas model hold?

Breakdown of strangeness thermalisation?

HADES result for Xi^- at SIS-18 (1.76A GeV): Xi^- yield is off by an order of magnitude from the statistical model.

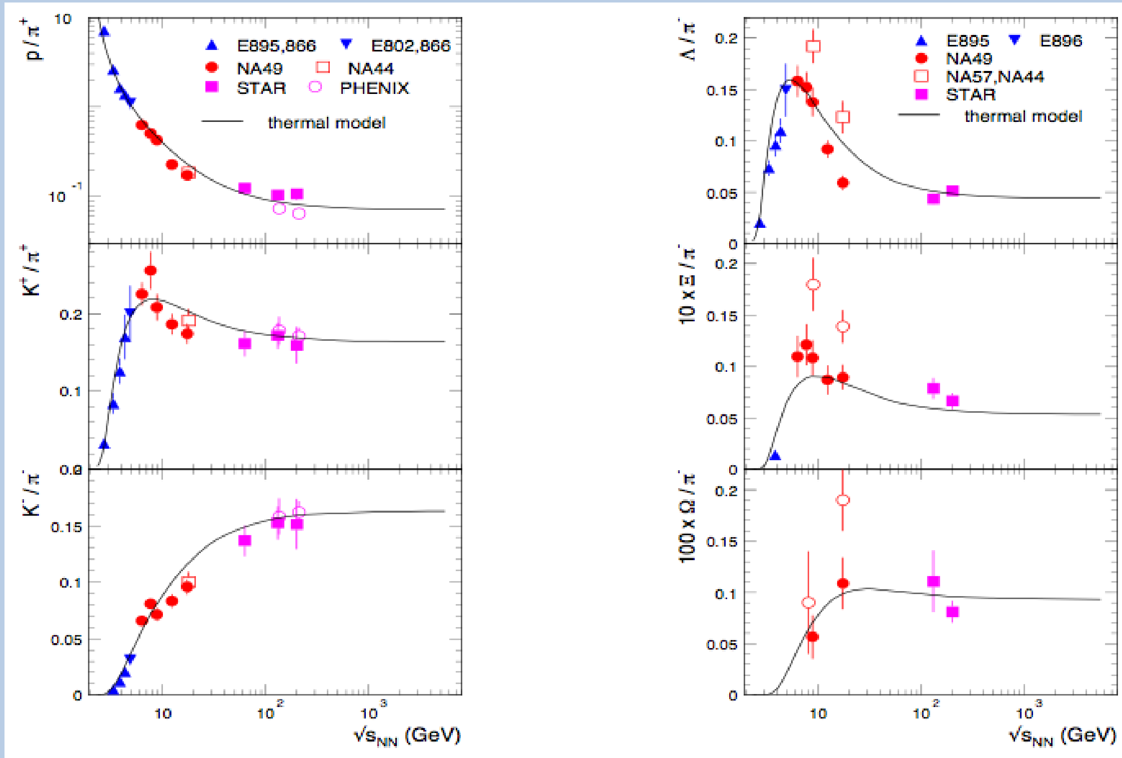
N.b.: This is deep sub-threshold. Production through multi-step processes:

$$\Lambda K \rightarrow \Xi\pi \quad \Lambda\Lambda \rightarrow \Xi^- p \quad \Xi K \rightarrow \Omega\pi$$



R. Holzmann, CBM Physics Workshop, April 2010

The need for data on multi-strange baryons

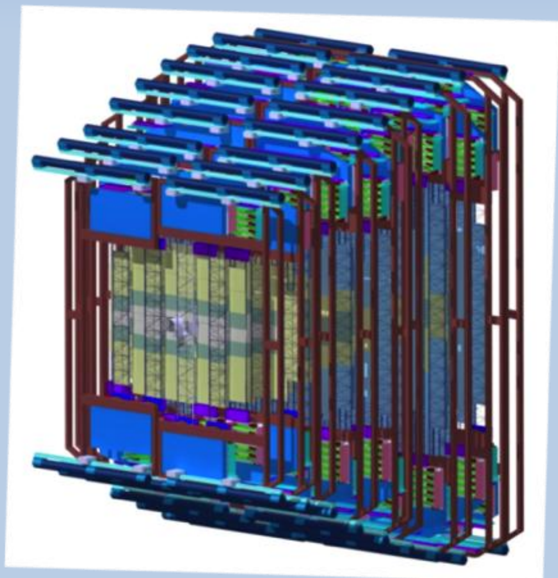


A long-lasting debate: pure hadronic description or signal of drastic change in matter properties?

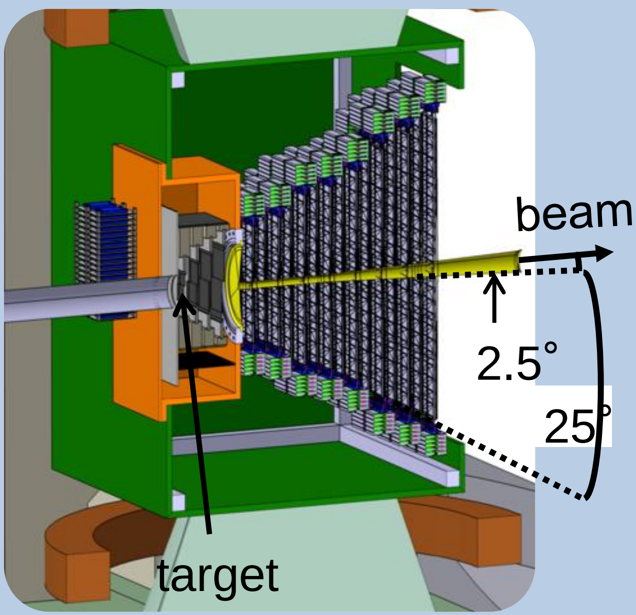
Data on multi-strange baryons will be decisive!

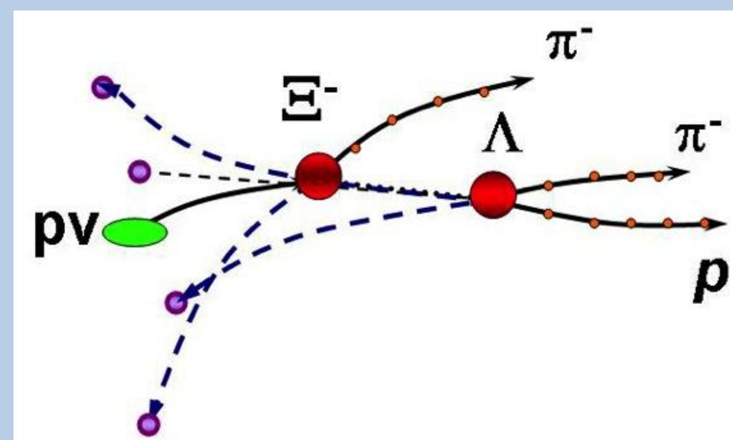
- “Onset” scenario: effect is due to increase in strangeness; sharp maximum at same location as K/pi; size of peak increases with strangeness content
- Hadron Gas Model: effect is due to net-baryon density; broad maximum; size of maximum decreases with strangeness content; position of maximum shifts

The Workhorse: Silicon Tracking System

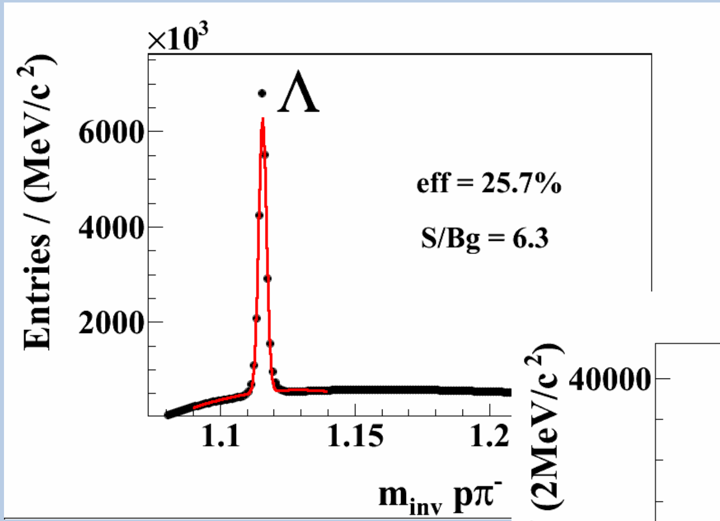


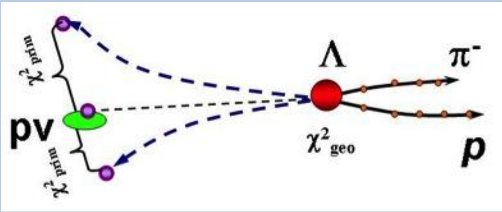
- *8 tracking stations in dipole magnet: between 0.3 m and 1 m from target*
- *Aperture: 2.5° < Θ < 25° (38°)*
- *Double-sided micro-strip sensors arranged in modules on low-mass, carbon-fiber supported ladders.*
- *1,220 sensors (4 m^2), 1.8 M channels*
- *Readout electronics at periphery*
- *Thermal enclosure, sensors at -5 °C*
- *CO_2 cooling (42 kW power dissipation)*

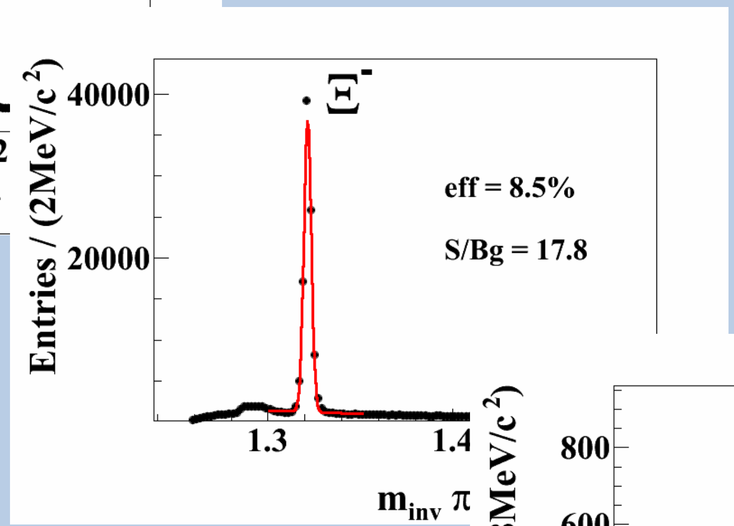


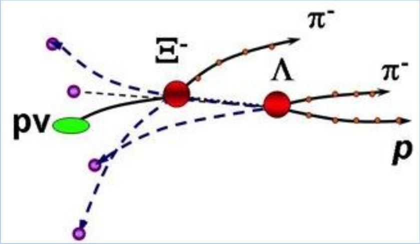


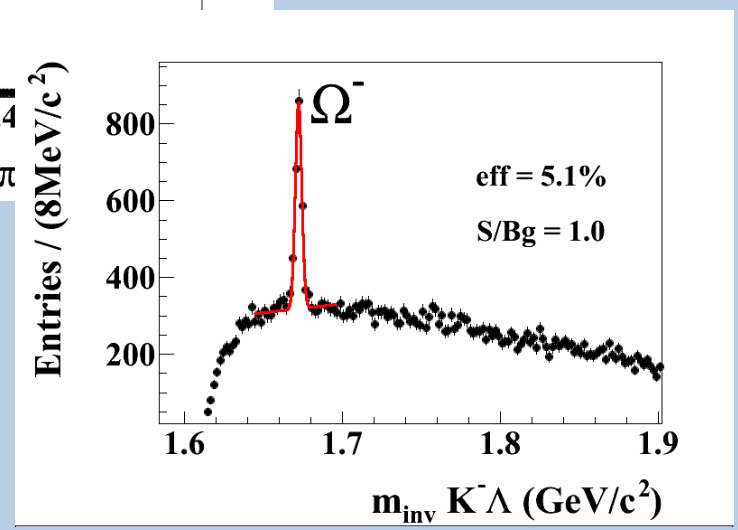
CBM Performance for Hyperons





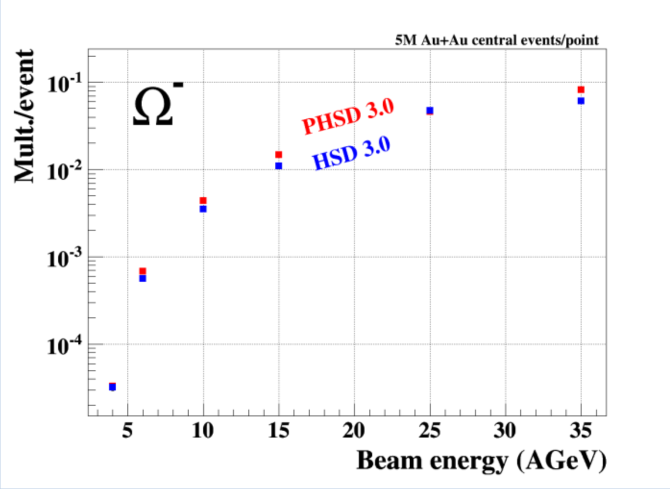


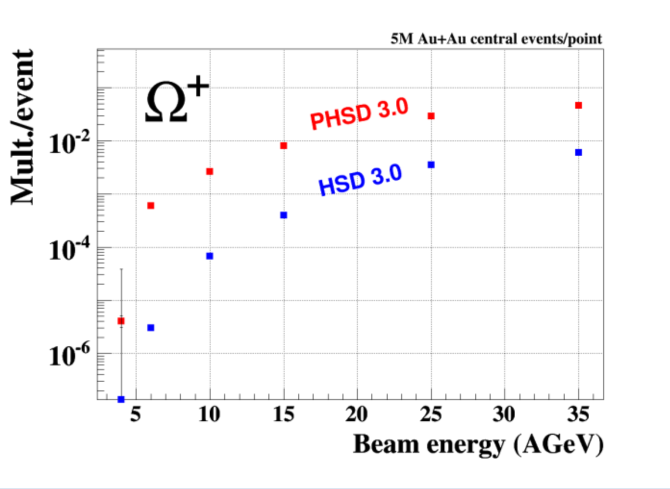




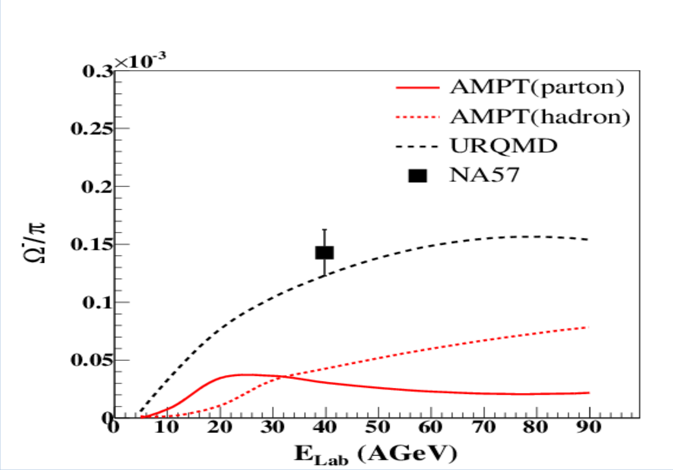
Input: UrQMD, central Au+Au, 10A GeV
Reconstruction from fully simulated detector response

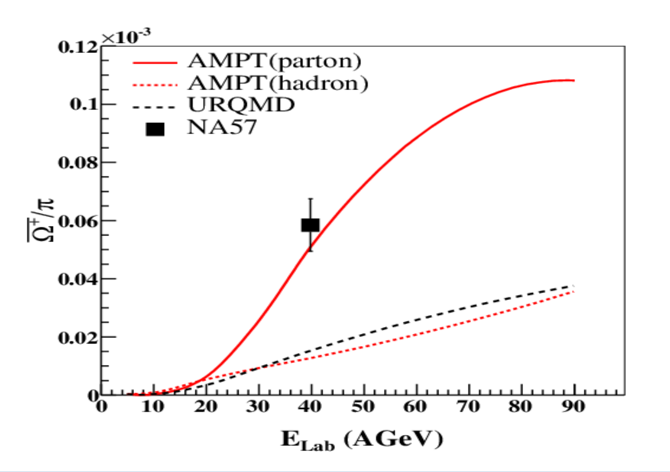
Strange anti-baryons at FAIR/NICA energies





HSD / pHSD

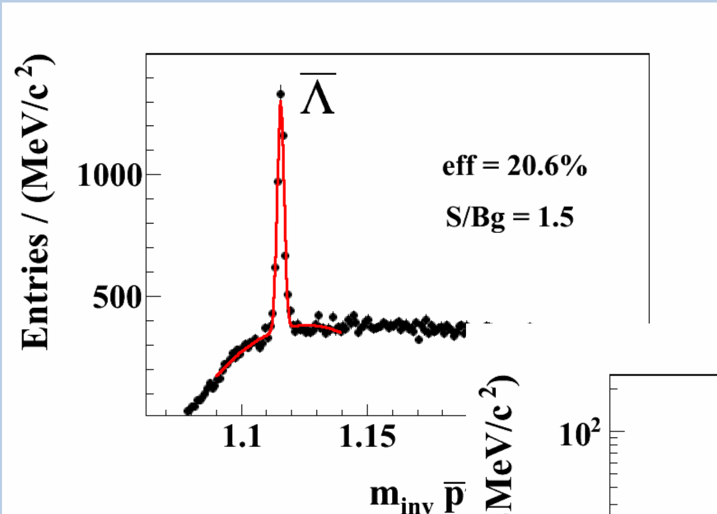


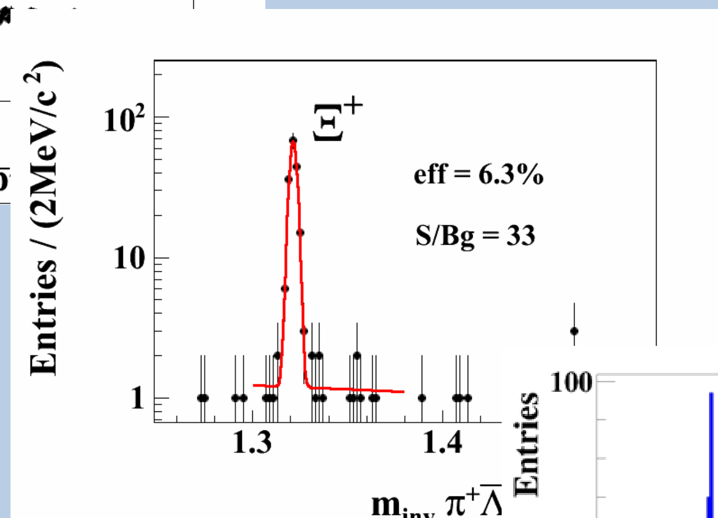


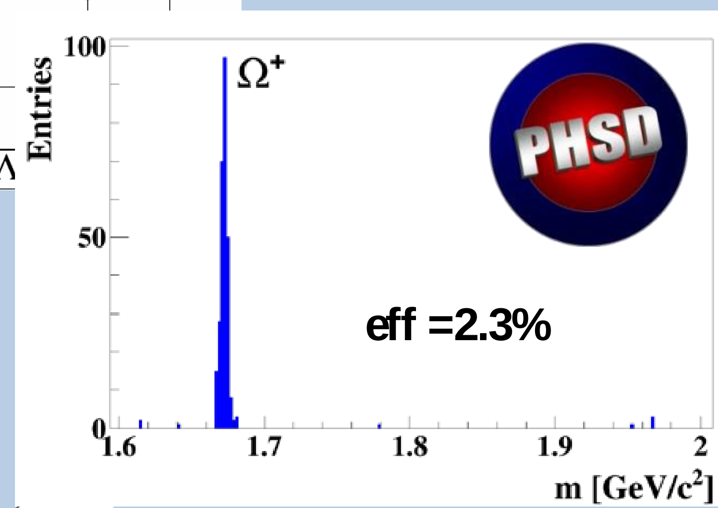
AMPT

Microscopic models (including partonic production) predict the anti-hyperons to be very sensitive to partonic production mechanisms (hyperons much less)

CBM Performance: Anti-Hyperons







Input: central Au+Au, 10A GeV
UrQMD (PHSD for Ω^+)

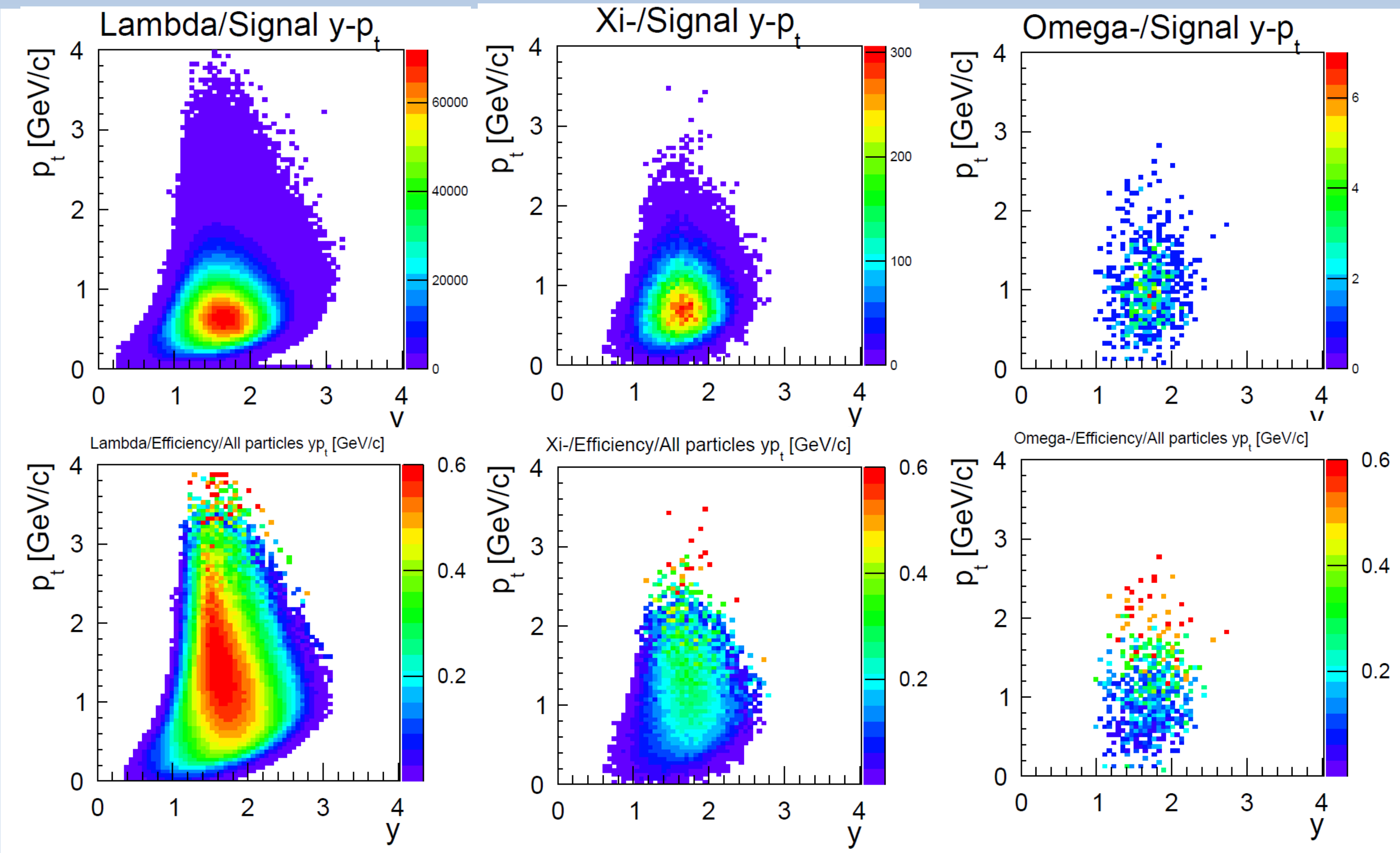
Very rare probes; require high interaction rates and online selection!

Hyperons: Expected Statistics

Au+Au 10 AGeV	Λ	Ξ^-	Ω^-	Ω^+
decay channel	$p\,\pi^-$	$\pi^- p\,\pi^-$	$K^- p\,\pi^-$	$K^+ \bar{p}\,\pi^+$
$M_{UrQMD\ 3.3}$	17.4	0.22	5.5E-3	6.7E-5
BR(%)	63.9	~100	67.8	67.8
total eff. (%)	**25.7**	**8.5**	**5.4**	**2.3**
$S/B_{2\sigma}$	**.3**	**17.8**	**1.0**	**~10**
Reco yield/sec. ~ 1MHz	**4.5M**	**20k**	**280**	**1.5**

Will allow systematic, differential studies also of rare particles!

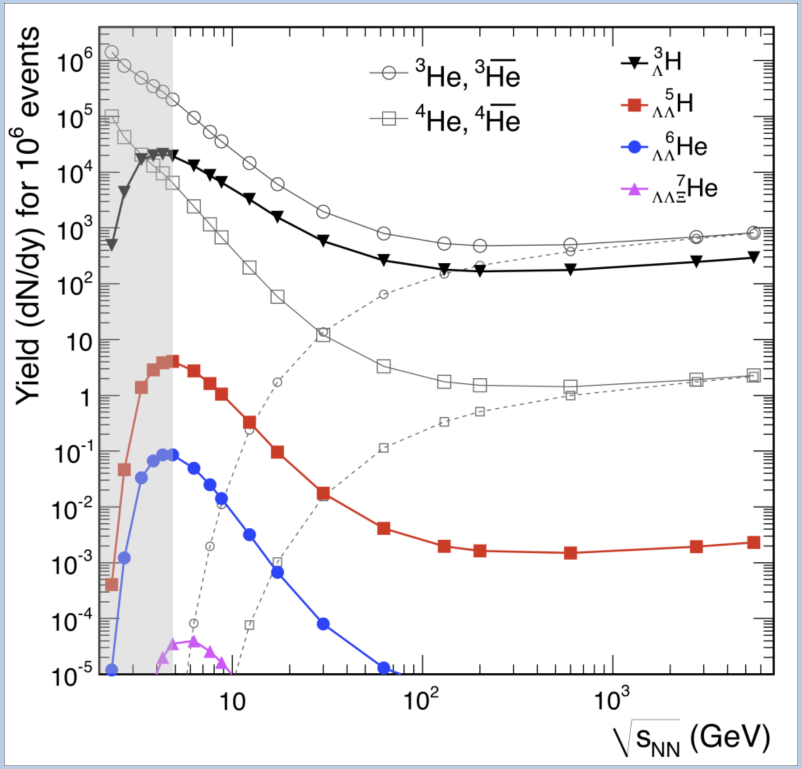
Hyperons: Acceptance and Efficiency



CBM Physics: Hyper-Matter

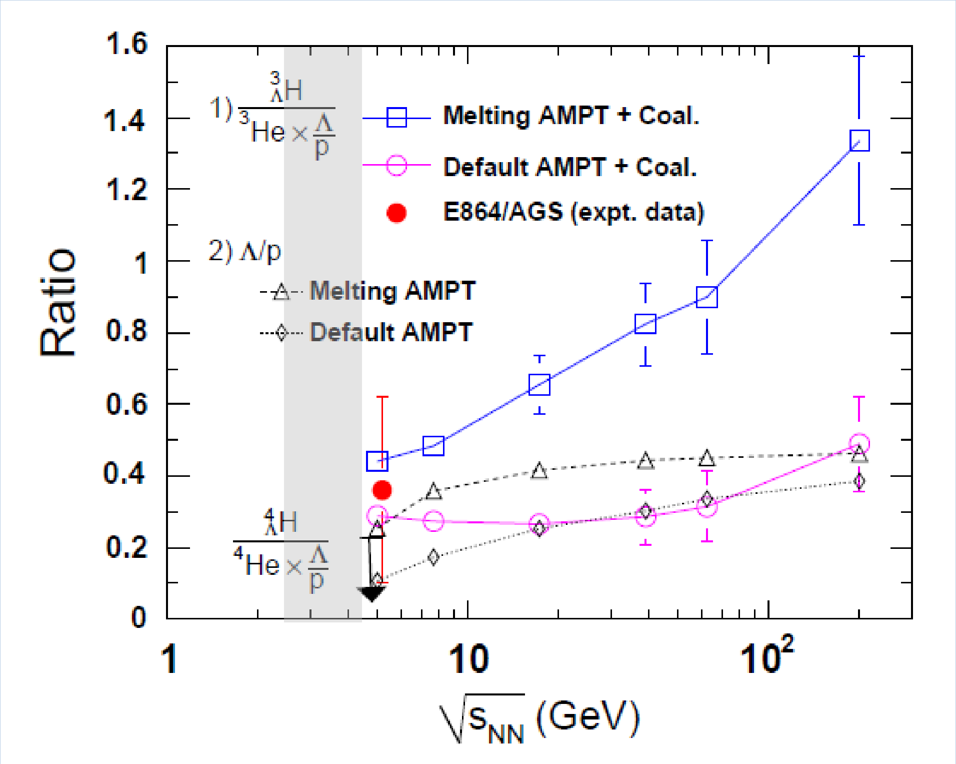
In heavy-ion collisions: produced through capture of Λ in light nuclei

A. Andronic et al., PLB 697 (2011) 203



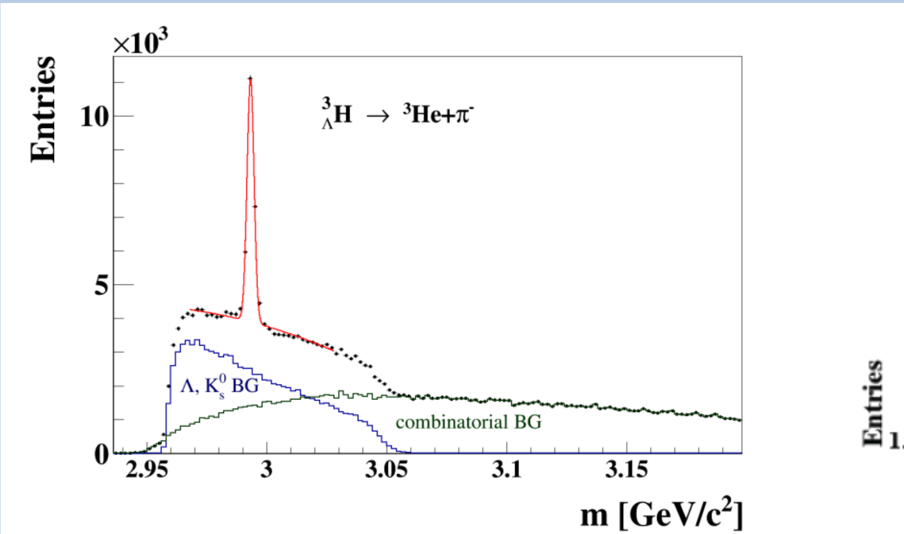
Thermal model: maximum production at CBM energies

S. Zhang et al., PLB 684 (2010) 224

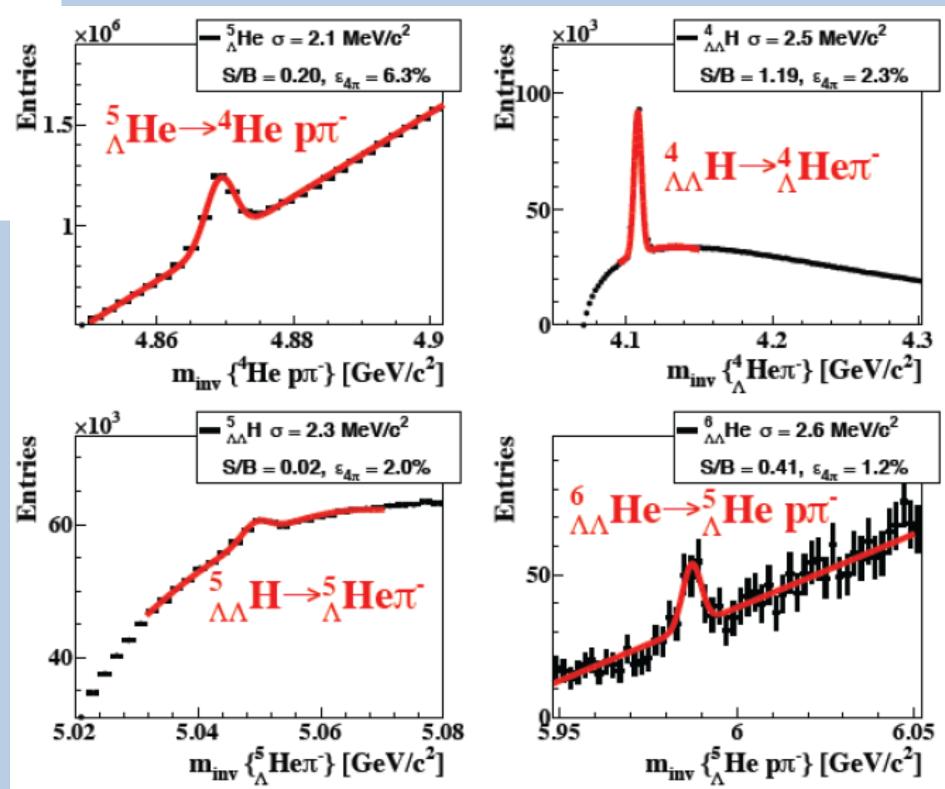


Transport: sensitive to medium properties (correlation of strangeness and baryon number)

CBM Physics: Hyper-Matter

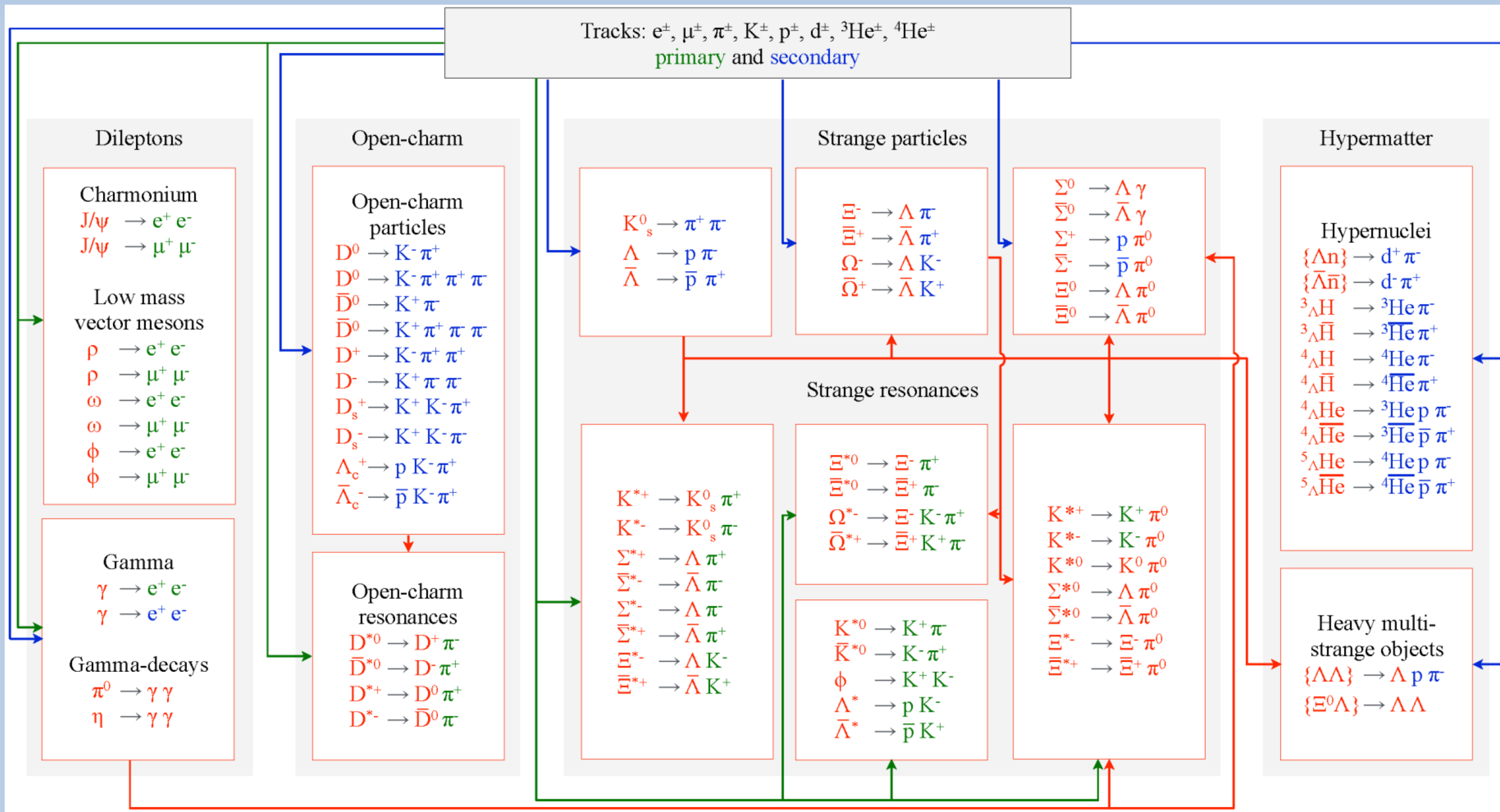


CBM Simulation
central Au+Au, 10A GeV
10^{12} events (3 weeks beamtime)



Prospects are good;
double-strange hyper-nuclei require maximal interaction rate

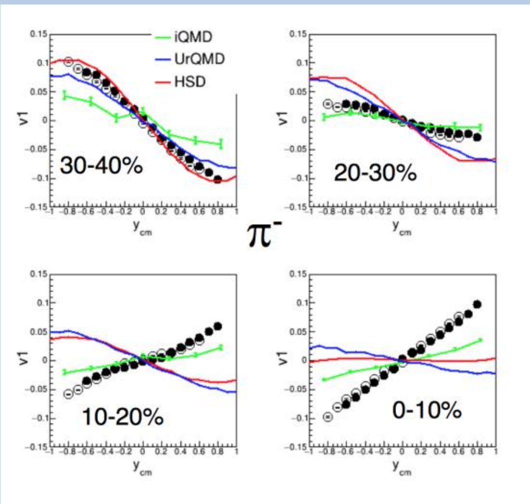
Particle reconstruction in real-time



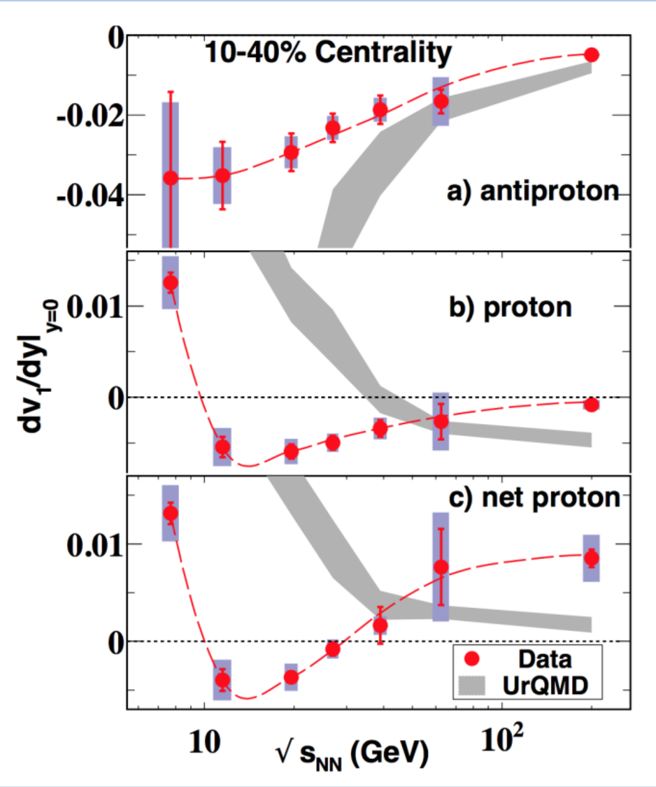
A multitude of particles will become accessible.
Real-time reconstruction allows online selection of rare probes.
Software becomes the key to the physics output.

CBM Physics: Flow

- The prime tool to study the equation-of-state
- Results at lower energies not understood in terms of transport models



HADES, Au+Au @1.23A GeV
(A. Kugler, ICNFP 2017)



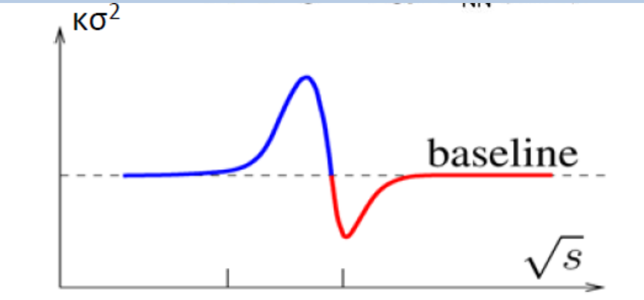
STAR, PRL 112 (2014) 162301

CBM will add flow data, also for weakly rescattering particles like φ or Ω

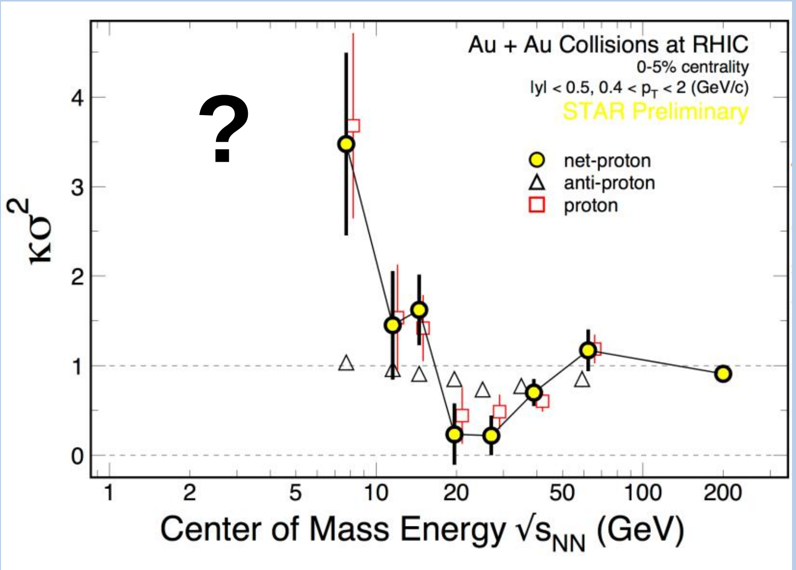
CBM Physics: Fluctuations

Should signal the critical point…

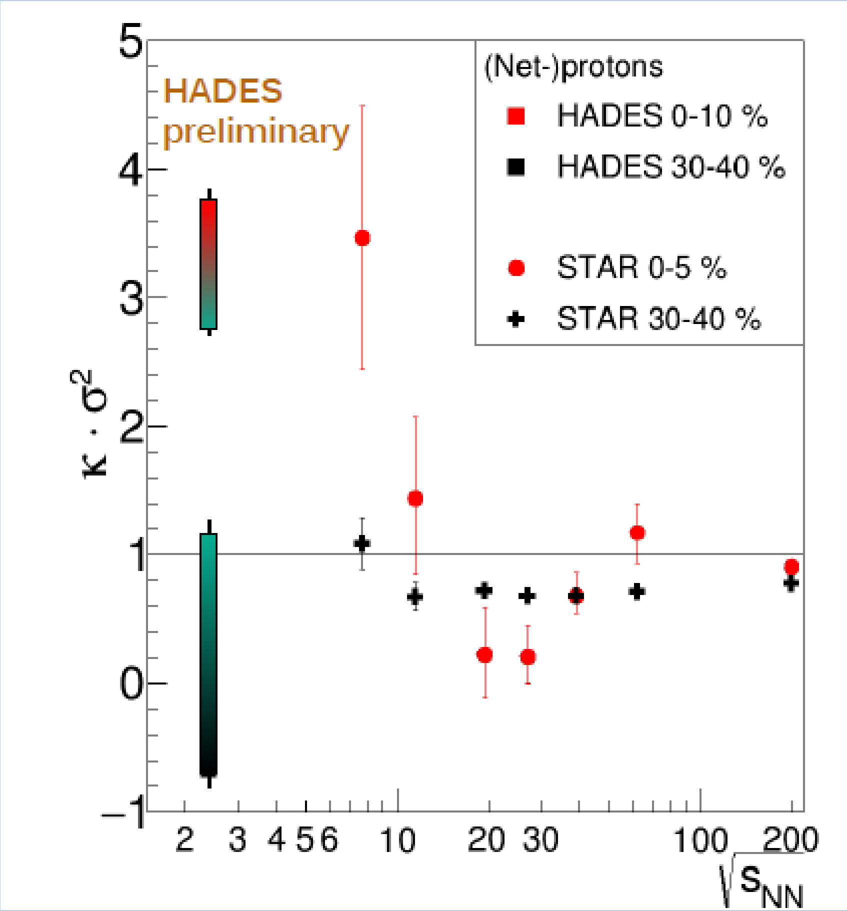
M. Lorentz, QM 2017



M. Stephanov. J. Physics G.: Nucl. Part. Phys. ***38*** (2011) 124147



STAR, NPA 956 (2016) 320c



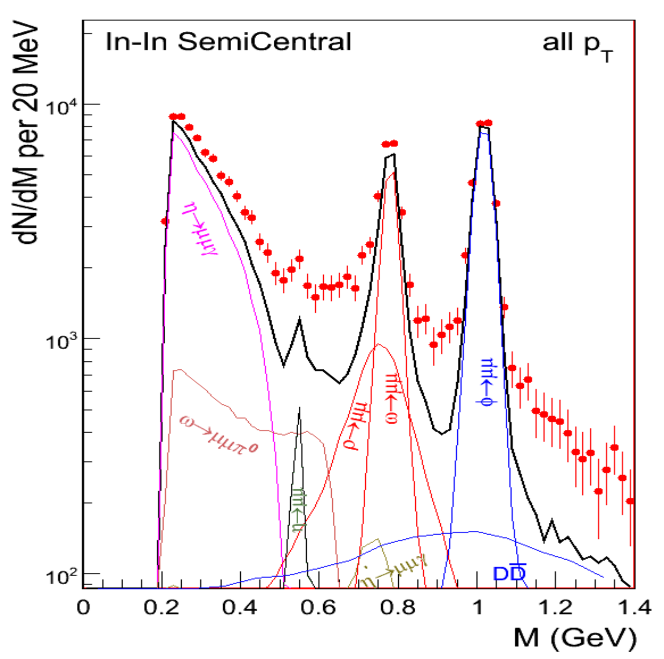
…or spinodial decomposition of a mixed phase?

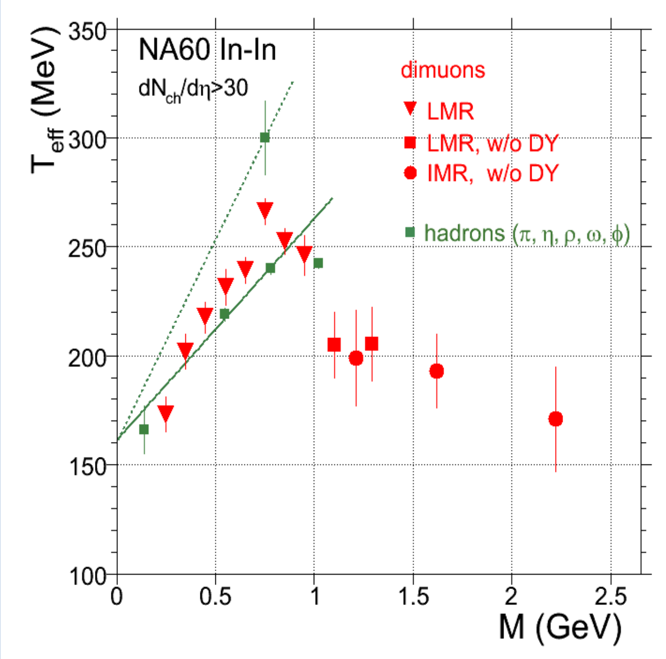
CBM Physics: Lepton Pairs

Emitted throughout the lifetime of the fireball: probe its space-time evolution

Low mass (< 1 GeV): in-medium properties of rho meson; excess yield (over vacuum hadronic cocktail) is sensitive to the lifetime of the system

Intermediate mass (1 – 2.5 GeV): no hadronic sources; measure directly the temperature of the fireball.



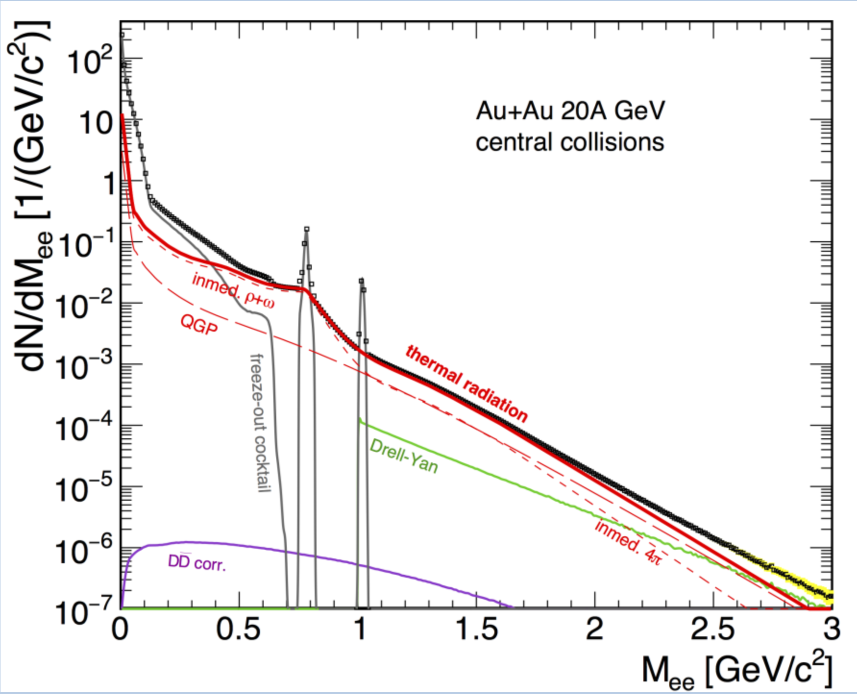


NA60, EPJC 59 (2009) 607

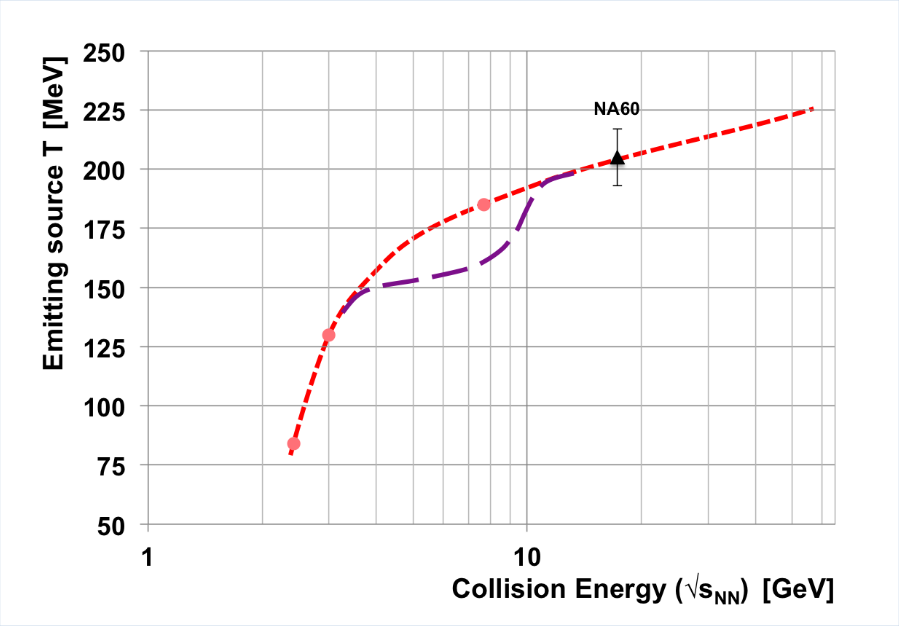
CBM Physics: Lepton Pairs

No di-lepton data exist between HADES and NA60!

CBM will provide di-lepton mass spectra and measure the caloric curve in the FAIR energy range. Interpretation almost model-independent!



CBM Simulation



Extracted temperature at intermediate masses; violet: speculated signature of a mixed phase

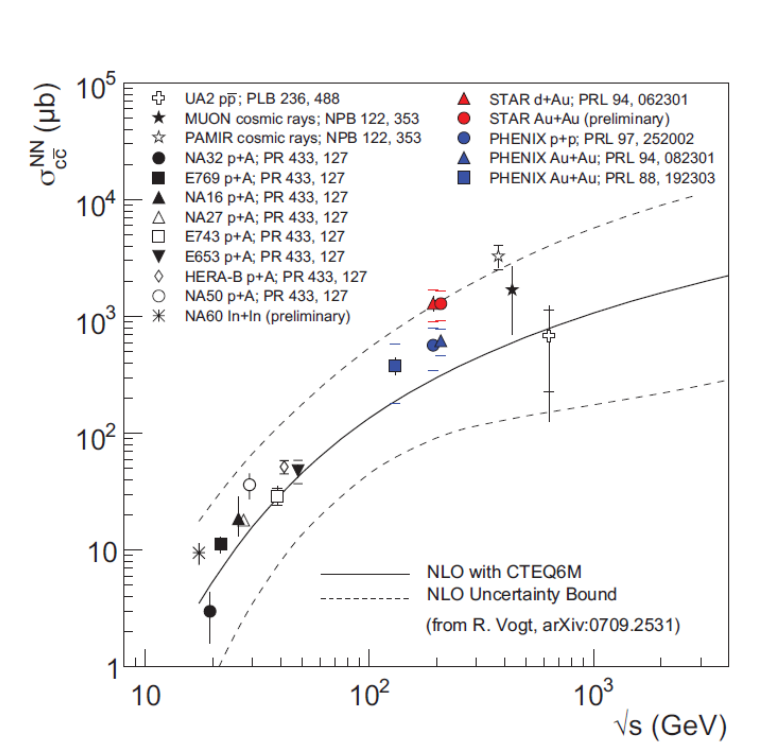
CBM Physics: Charm

- Important (if not decisive) probe of the created medium
  - that holds at all energies!
- Fraction of charm hadronising in J/psi is sensitive to the medium properties (e.g. suppression in QGP)
- Particular at lower energies (below top SPS):
  - N_{ccbar} << 1 -> no regeneration, ”clean” probe
  - Softer J/psi, longer-lived fireball: charm has a chance to see the medium
- Proper interpretation of data requires the measurement of both open and hidden charm
  - Important part of the CBM physics programme
  - CBM can provide both open and hidden charm from the same experiment setup

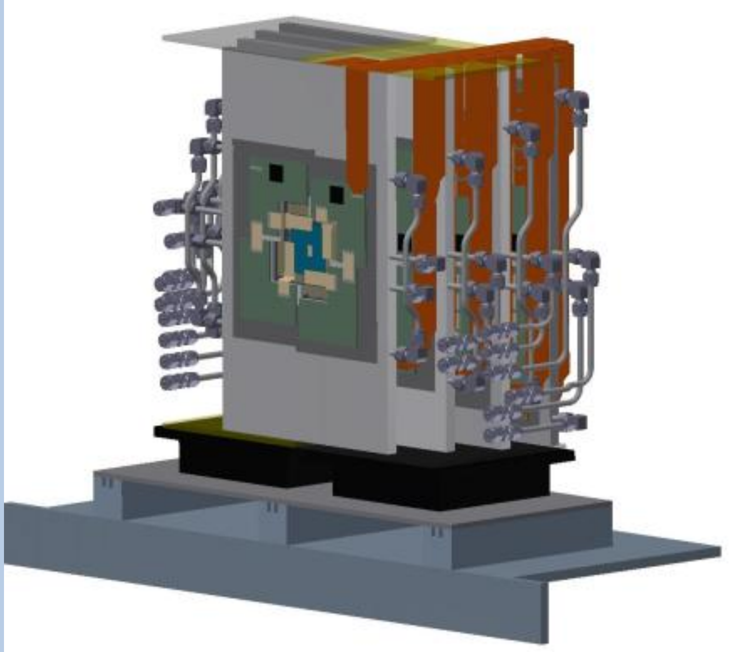
CBM Simulation, Au+Au @ 25A GeV

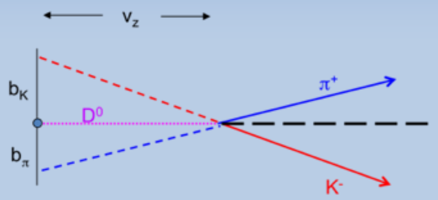
Charm Cross Section

- For the interpretation of charmonium data, the total c-cbar production cross section is required: need to measure also open charm.
  - cave: near threshold, $N_{J/\psi} << N_D$ not necessarily true
- Charm cross section close to threshold is experimentally unknown below √s = 20 GeV even in elementary reactions (let alone A+A)!
- pQCD calculations also come with large uncertainties.



Precision Vertexing: Micro-Vertex Detector

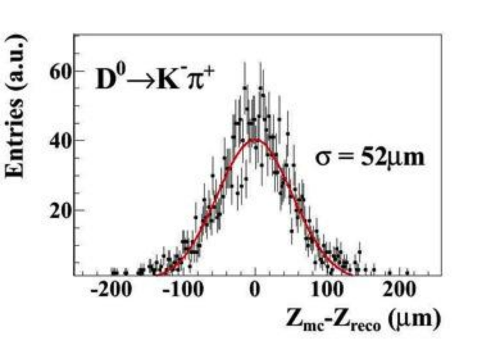




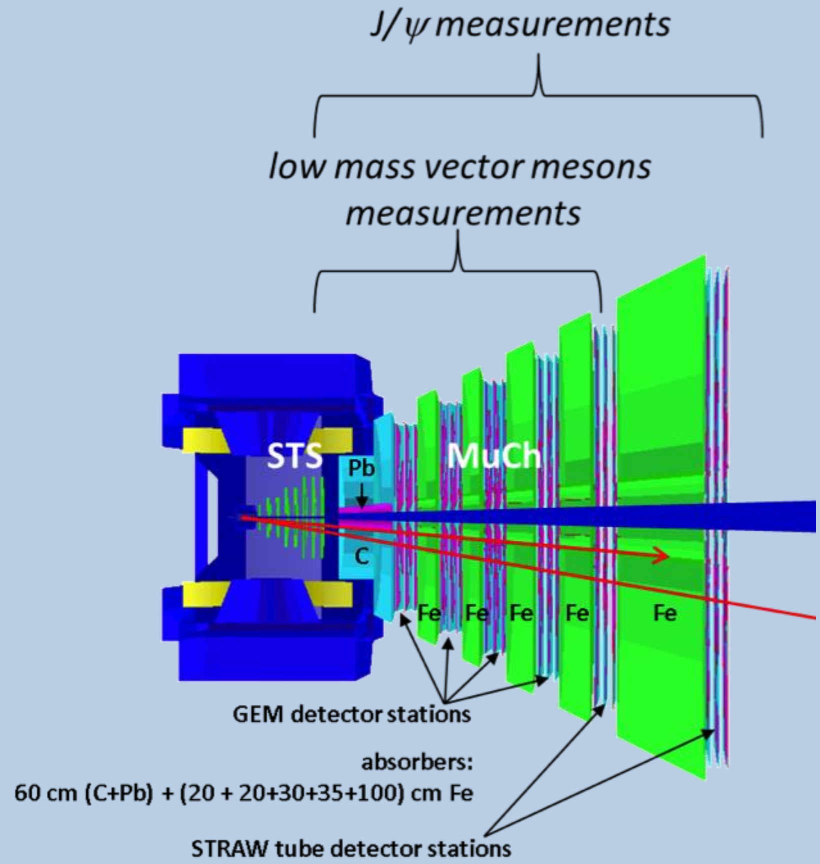
- *4 layers of Monolithic Active Pixel Sensors*
- *located at z = 5 cm - 20 cm*
- *pixel size 20 x 20 μm^2*
- *resolution 4 μm*
- *low-mass: < 0.5 % X_0 per layer*
- *operated in vacuum*
- *rad. hardness 10^{13} n_{eq}/cm^2 / 3 MRad*
- *sec. vertex resolution ≈ 50 μm along beam axis*

MIMOSA-26

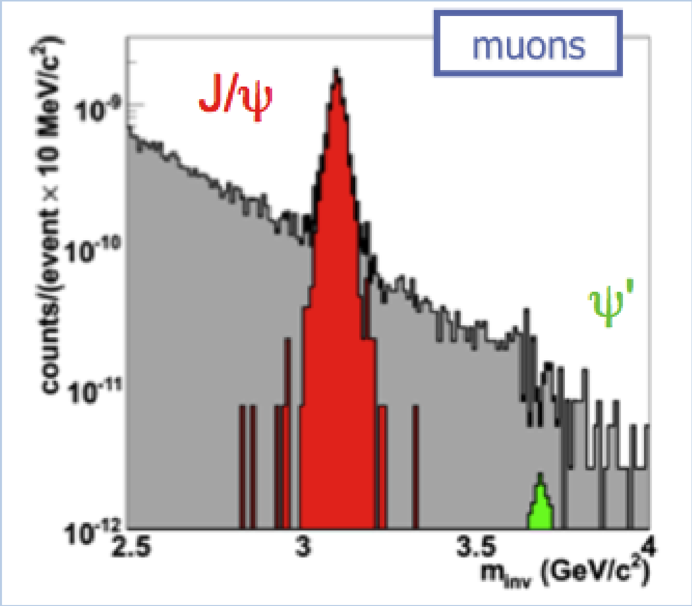
Prototype station



Muon Detector



- *active absorber system with tracking detectors (GEM/straw) sandwiched between absorber slices*
- *allows track following through the system*

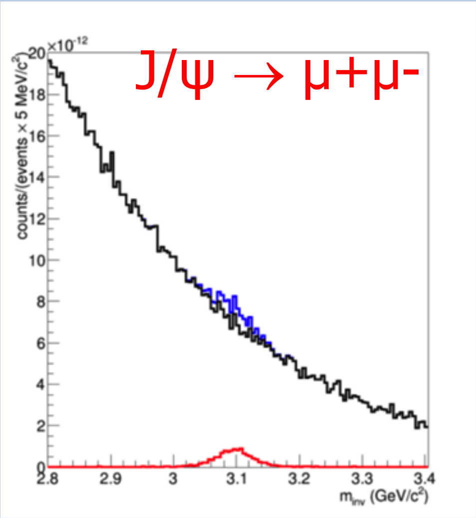


CBM Simulation, Au+Au @ 25A GeV

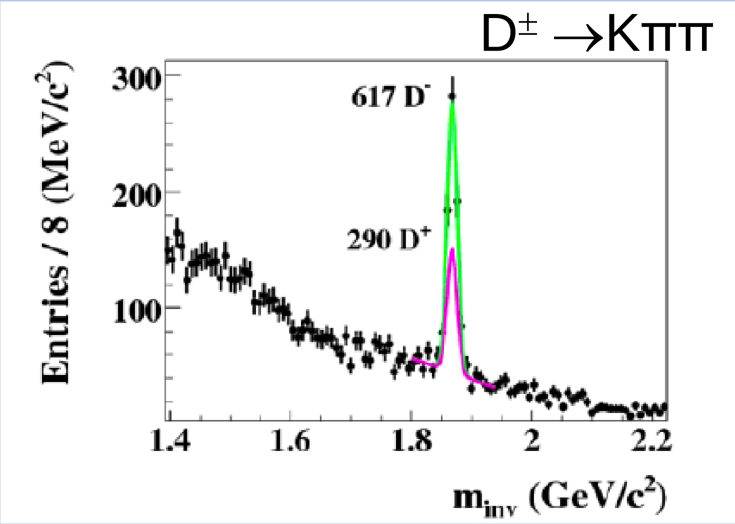
CBM Physics: Charm at SIS-100

- The CBM charm programme is tailored for SIS-300 energies
- At SIS-100:
  - charmonium at top energy: Au+Au, 10A GeV (sub-threshold, extremely challenging)
  - Z/A = 0.5 (e.g., Ni+Ni) @ 15A GeV (slightly above threshold)
  - open and hidden charm in p+A up to 30 GeV (c-cbar cross section, cold matter effects)

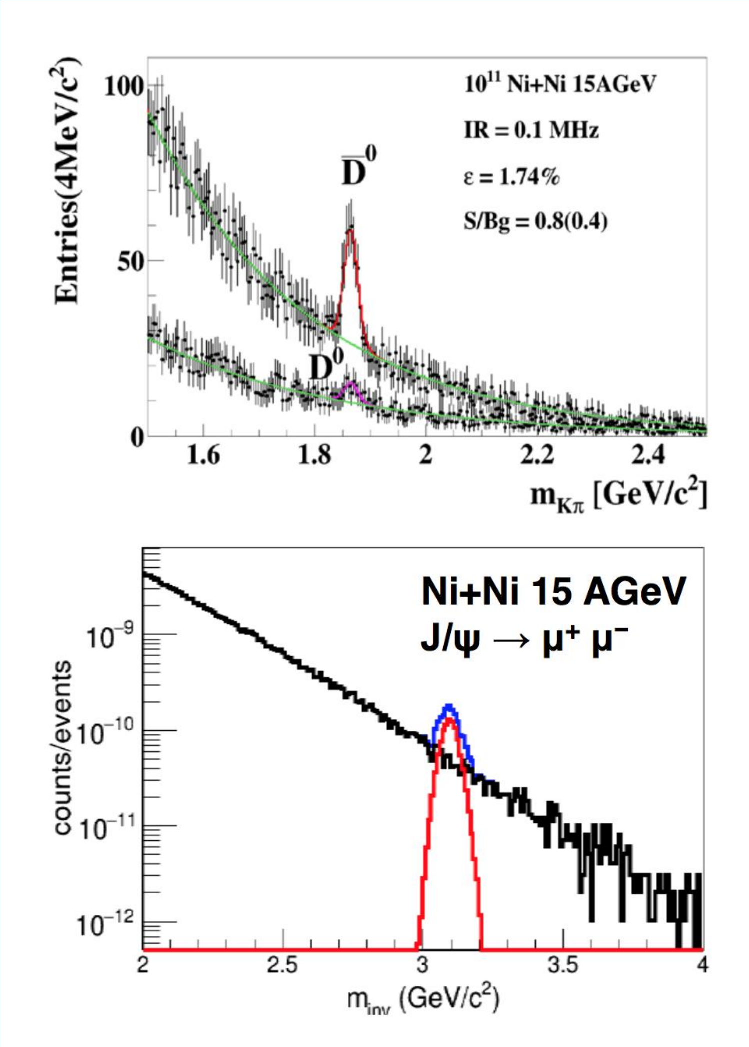
central Au + Au, 10A GeV



p + C, 30 GeV



CBM Physics: Open Charm at SIS-100



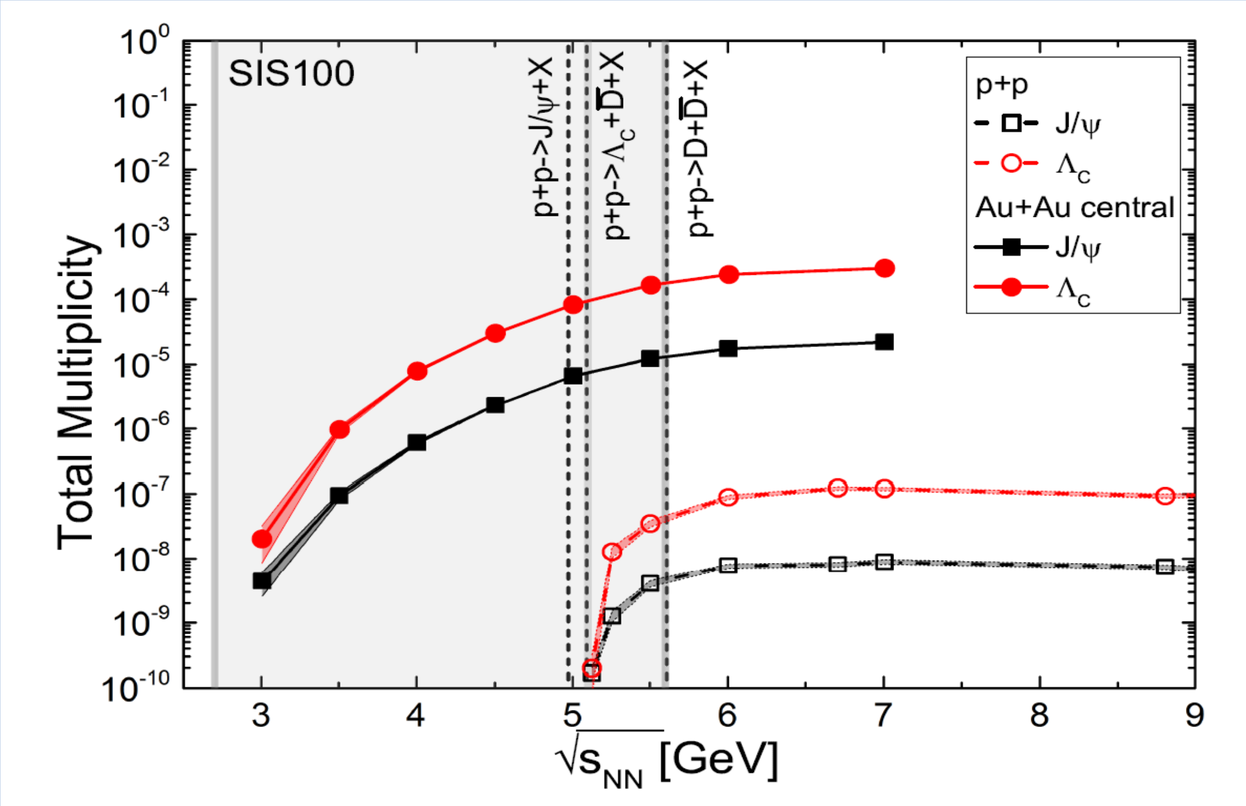
D mesons:
Interaction rate 0.1 MHz
260 $\overline{D}^0$ and 45 D^0 in 2 weeks

Acceptance down to zero p_t

Charmonium (muon channel):
Interaction 1 MHz
3300 J/Ψ in 2 weeks

Open Charm: Maybe There Is More Subthreshold

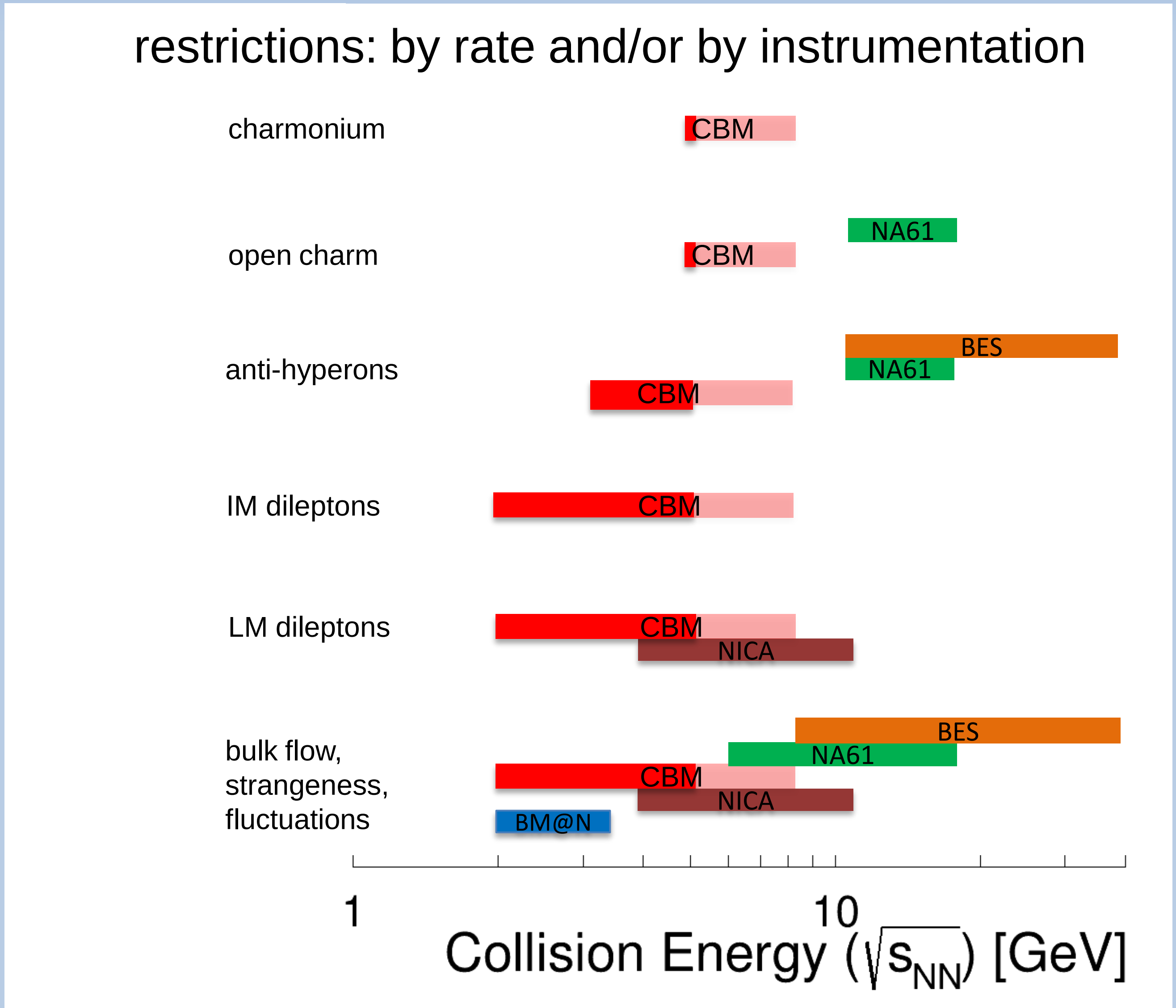
J. Steinheimer et al., PRC 95 (2017) 014911



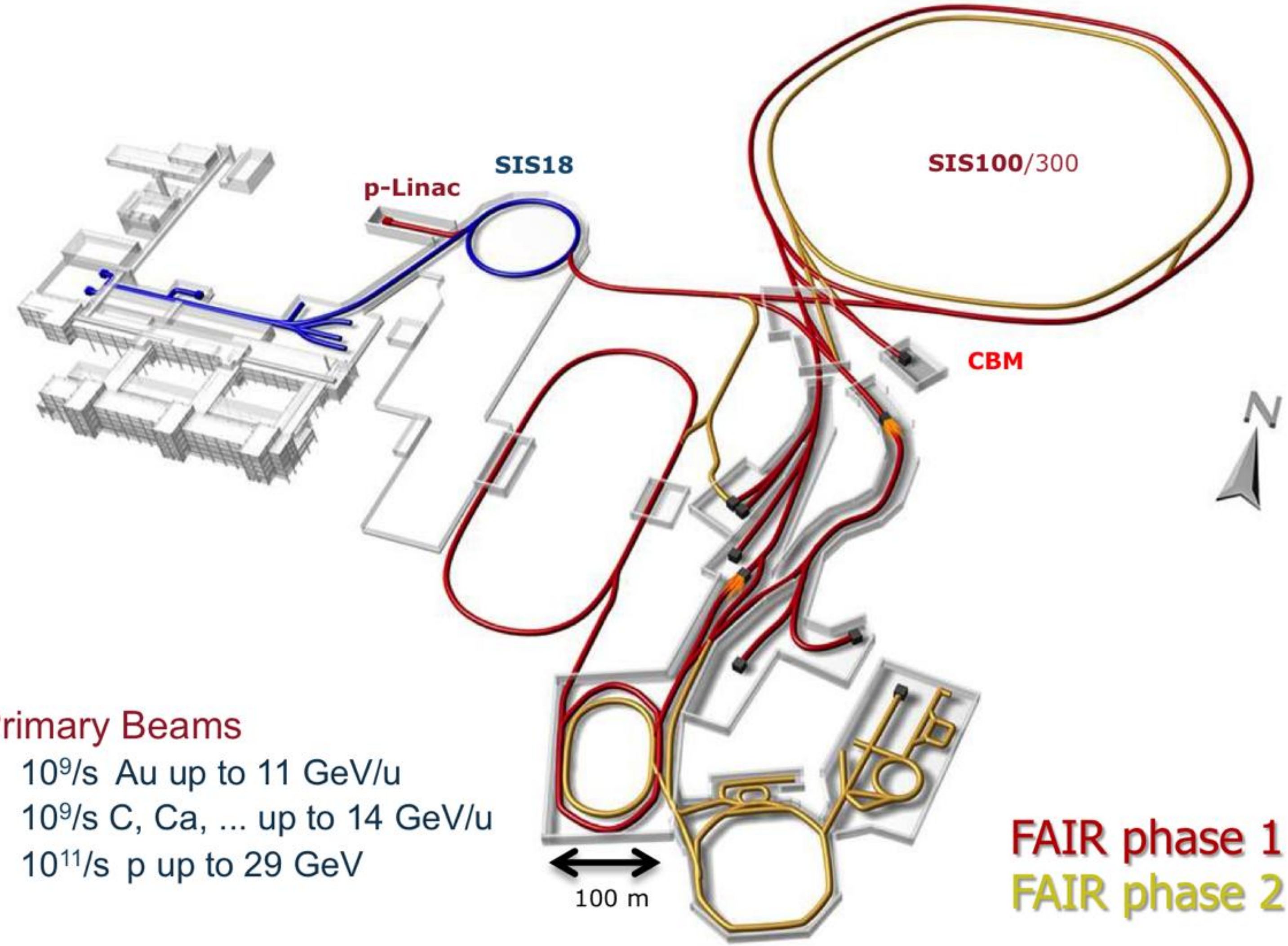
Sub-threshold production through heavy baryonic resonances:

$N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$

Comparison: Observables



The Times They Are A-Changin'



Primary Beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

The Times They Are A-Changin'

The Times They Are A-Changin'

First beams into the CBM cave in 2024

Summary

- The ambitious design of CBM, combining very high interaction rates with large acceptance and precision reconstruction, will allow the measurement of a multitude of particles originating from heavy-ion collision
  - At SIS-100 (AGS energy range) up to 10A GeV from 2024 on
  - After the installation of the second (booster) synchrotron up to 35A GeV (45 for symmetric nuclei)
- Systematic measurements (collision energy, system size) will address the nature of QCD matter at high net-baryon density:
  - Particle yields and spectra
  - Flow
  - Fluctuations
  - Lepton pairs
  - Charm