L'expérience CBM@FAIR : détecteur et potentiel de physique

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IPHC, Strasbourg

Plan de l'exposé :

- Contexte général (FAIR)
- Objectifs scientifiques de CBM
- Système de détection
- Etudes de faisabilité et de performance
- Conclusions

FAIR – Facility for Antiproton and Ion Research

GSI - Darmstadt

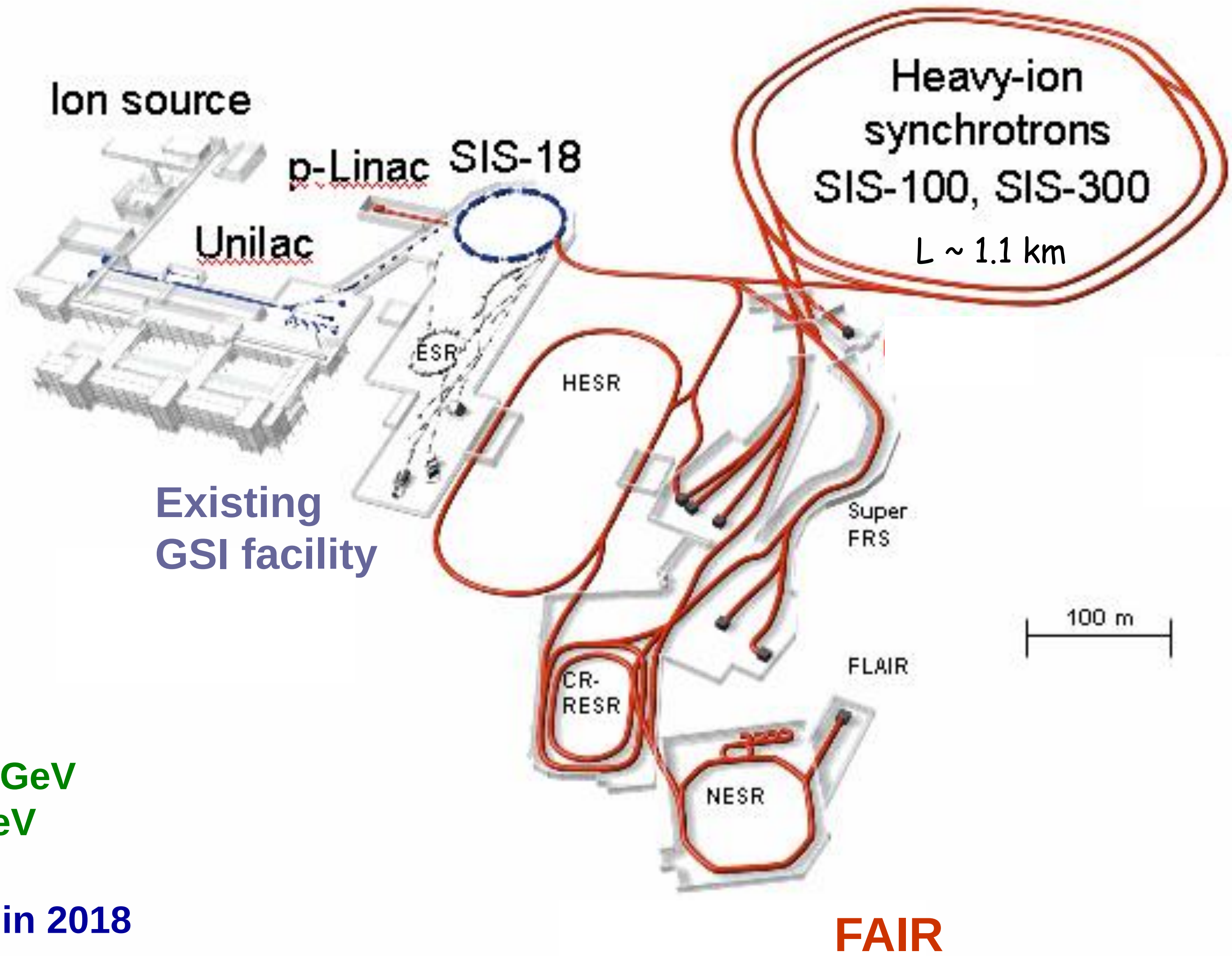
A large variety of high intensity primary and secondary beams

SIS-100
Ions : up to 14 AGeV
Protons : up to 29 GeV

SIS-300
Ions : up to 45 AGeV
Protons : up to 89 GeV

Secondary beams
Rare isotopes : up to 2 AGeV
Antiprotons : up to 30 GeV

→ First beams expected in 2018

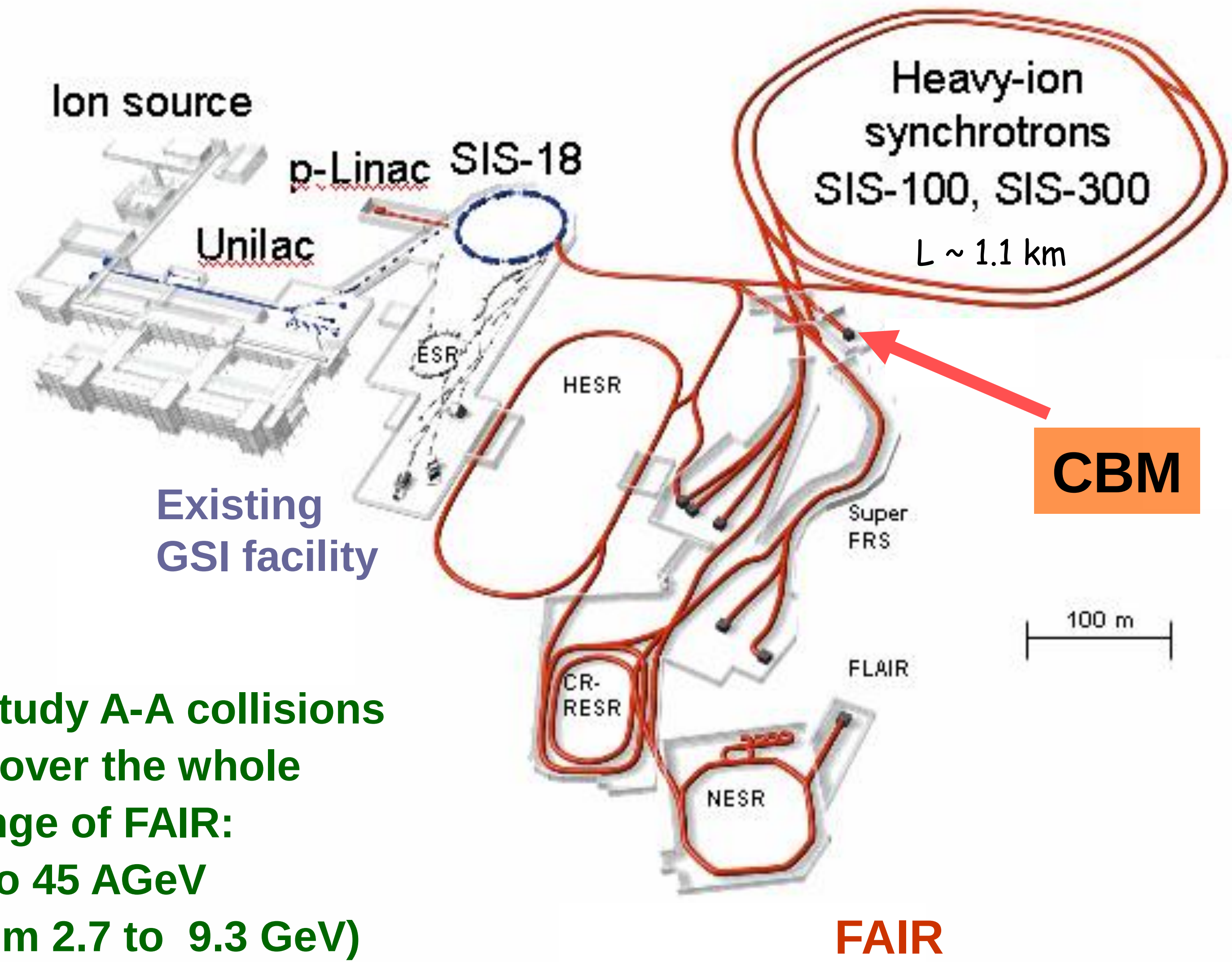


The Facility for Antiproton and Ion Research

photos by the FAIR GmbH
May 2013

The Compressed Baryonic Matter (CBM) experiment

→ One of the major experiments at FAIR

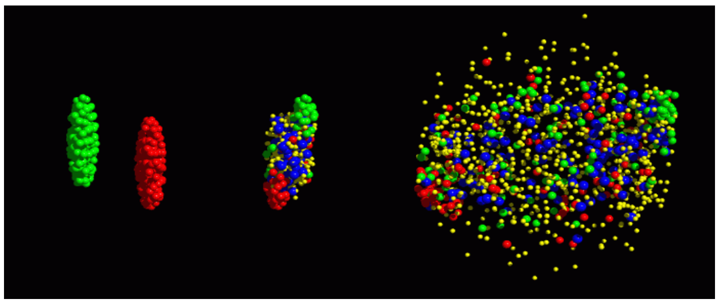


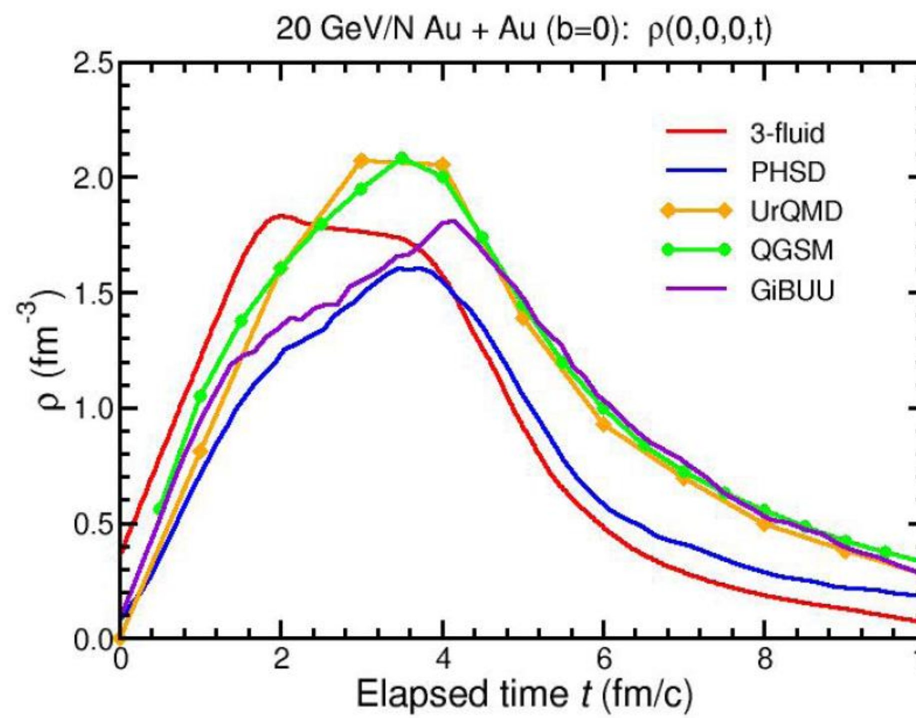
→ **CBM will study A-A collisions collisions over the whole energy range of FAIR:**
2 to 45 AGeV
($\sqrt{S_{NN}}$ from 2.7 to 9.3 GeV)

High Energy Heavy-Ion Collisions at FAIR

Specificity of the FAIR energy range (2 to 45 AGeV)

⇒ High net-baryon densities in A-A collisions





Theoretical models

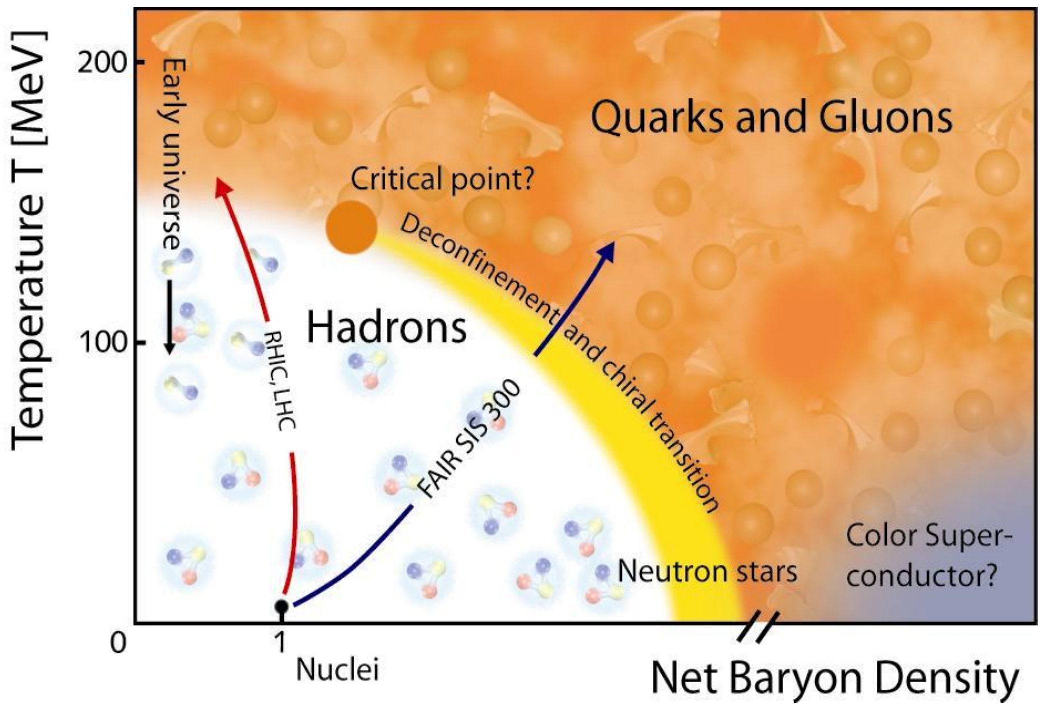
→ **Net baryon densities up to ~10×ρ_0 can be achieved**

→ **High density phase lasts for a time span of 3-4 fm/c**

I.C. Arsene et al., Phys. Rev. C 75 (2007) 034902

⇒ A-A collisions in the FAIR energy range will allow exploring a broad region of the QCD phase diagram extending up to very high baryon densities

Exploring the QCD phase diagram at high ρ_B



- **Deconfinement phase transition**
  - → **1st order phase transition**
  - → **QCD critical endpoint**
- **In-medium modifications of hadrons (at high baryon densities)**
  - → **chiral symmetry restoration**
- **Equation of state at high ρ_B**

Main topics of the CBM physics program

→ **Complementarity with RHIC et LHC (high T and low ρ_B)**

→ **Nuclear matter at high ρ_B of particular interest in the study of compact astrophysical objects (neutron stars)**

The CBM physics program*: Main topics and observables

Deconfinement phase transition at high ρ_B & QCD critical point

- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^{\pm}$, Λ_c)
- excitation function of dynamical event-by-event fluctuations

Chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons
  - $\rightarrow$ dileptons from the decay of light vector mesons, in both e^+e^- and $\mu^+\mu^-$
  - $\rightarrow$ production yield of D-mesons (at threshold)

The equation-of-state at high ρ_B

- excitation function of the collective flow of hadrons
- production of multi-strange baryons (Ξ, Ω) at threshold

CBM $\rightarrow$ detailed measurements with high statistics, including for

charmonium, open charm and lvm (rare probes)
$\rightarrow$ will be measured for the first time in the FAIR energy range

Thanks to:

- high beam intensities of FAIR (10^{10} ions/s for U up to 35 AGeV)
- new generation detector able to operate at extremely high coll rates (up to 10 MHz)

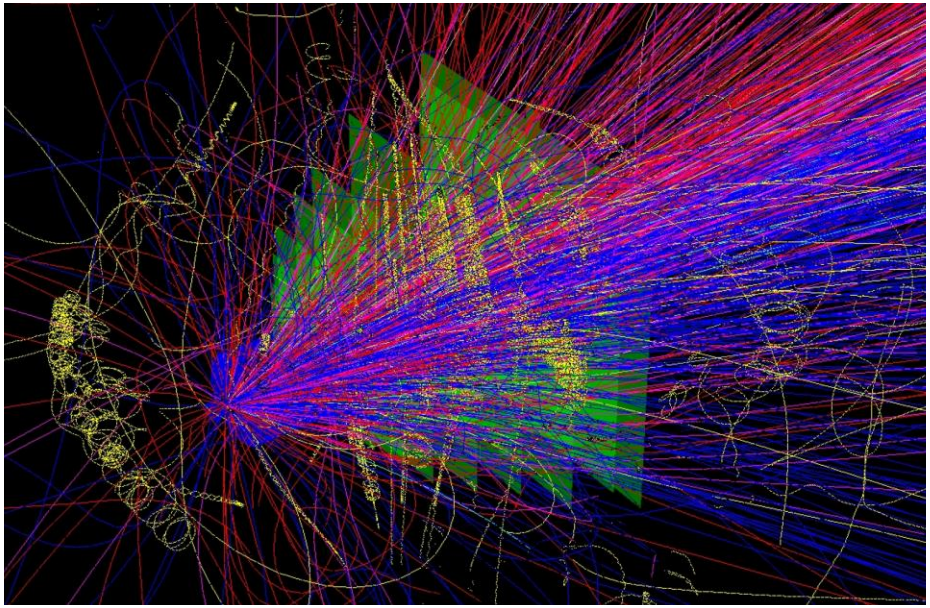
* The CBM Physics Book (2011), Springer Series: Lecture Notes in Physics, Vol. 814

Experimental challenges

High rate measurements (up to 10 MHz) require:

→ fast detectors + radiation tolerant
→ fast read-out electronics (free-streaming)
→ high speed data acquisition system
→ high performance computer farm for online event selection

→ identification of leptons and hadrons
→ large acceptance
→ determination of secondary vertices with high precision ($\sigma < 100\ \mu m$)



Central Au+Au at 25 A GeV / UrQMD + GEANT
160 p, 400 π^+, 400 π^+, 44 K^+, 13 K^-

The CBM Collaboration: 58 institutions, 500 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Germany:
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
Münster Univ.
Tübingen Univ.
Wuppertal Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

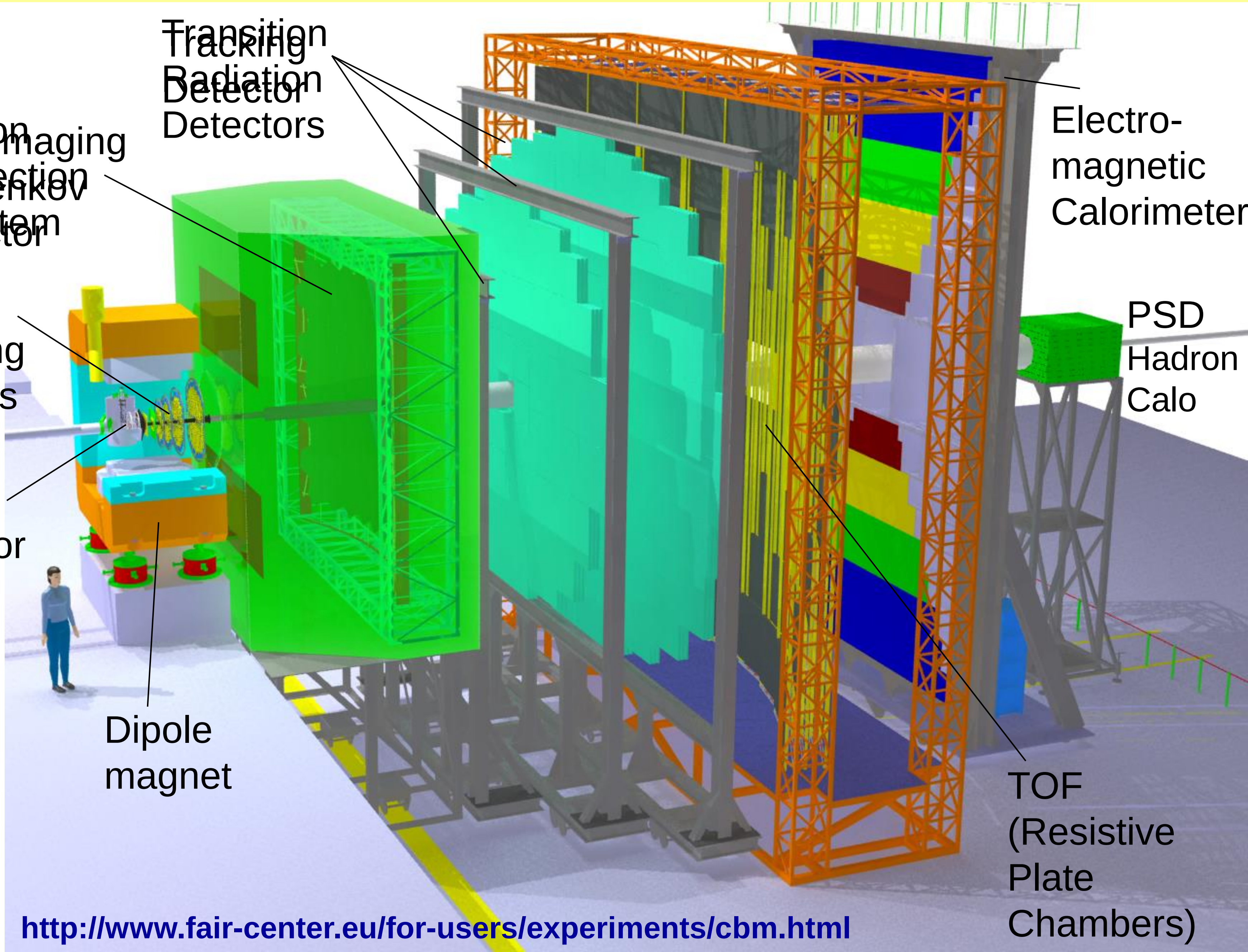
Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

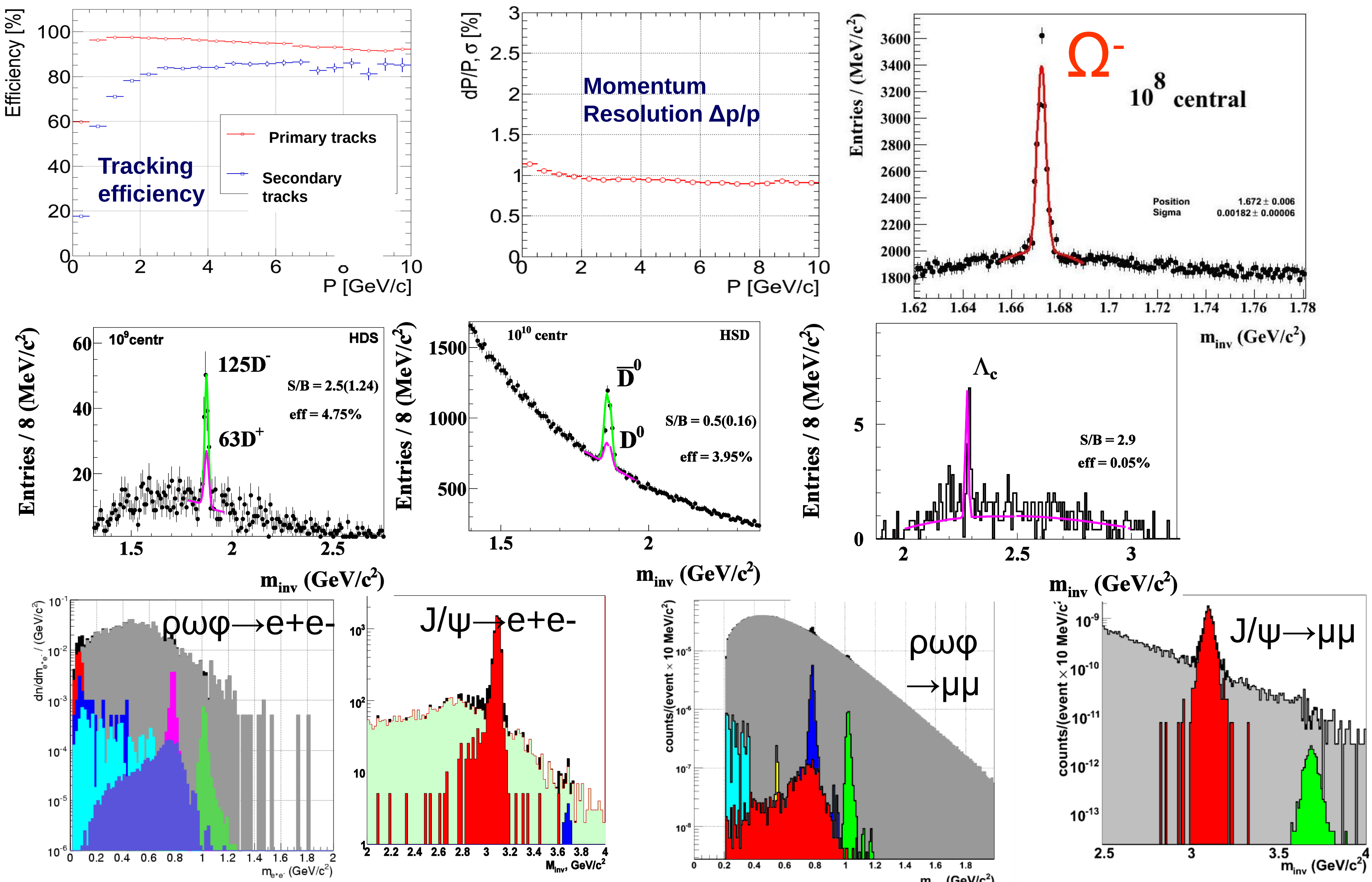
Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

19th CBM Collaboration Meeting, March 26-30, 2012, GSI Darmstadt

The Compressed Baryonic Matter Experiment



Some feasibility studies: Au+Au central collisions at 25 A GeV



CBM: Estimated particle yields for minimum bias Au+Au collisions at 25 AGeV

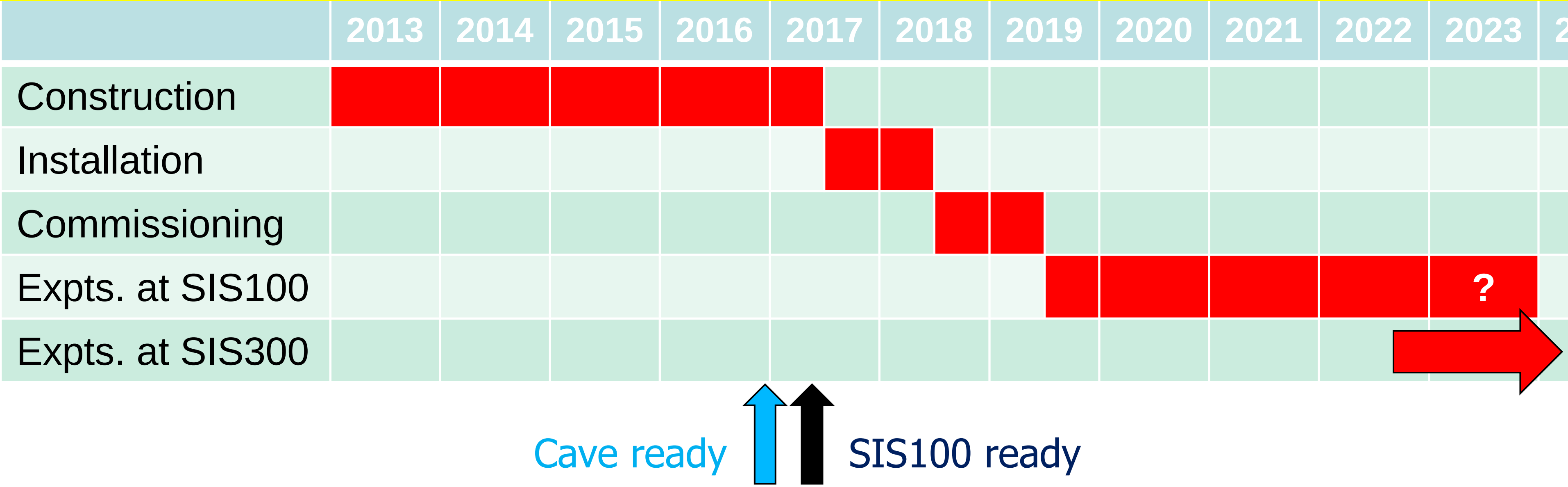
particle, mass (MeV)	N	decay mode	BR	R/s (MHz)	T	ε (%)	Y/s	Y/10 w
η (547)	6.6	$\mu^+\mu^-$	$5.8 \cdot 10^{-6}$	0.25	y	3	0.28	$1.7 \cdot 10^6$
K^+ (494)	8	-	-	0.025	n	20	$4 \cdot 10^4$	$2.4 \cdot 10^{11}$
K^- (494)	2.6	-	-	0.025	n	20	$1.3 \cdot 10^4$	$7.8 \cdot 10^{10}$
K_s^0 (497)	5.4	$\pi^+\pi^-$	0.69	0.025	n	10	$9.3 \cdot 10^3$	$5.6 \cdot 10^{10}$
ρ (770)	4.6	e^+e^-	$4.7 \cdot 10^{-5}$	0.025	n	5.4	0.29	$1.8 \cdot 10^6$
ρ (770)	4.6	$\mu^+\mu^-$	$4.6 \cdot 10^{-5}$	0.25	y	2.7	1.4	$8.6 \cdot 10^6$
ω (782)	7.6	e^+e^-	$7.1 \cdot 10^{-5}$	0.025	n	7.2	1	$6 \cdot 10^6$
ω (782)	7.6	$\mu^+\mu^-$	$9 \cdot 10^{-5}$	0.25	y	3.7	6.3	$38 \cdot 10^6$
ϕ (1020)	0.256	e^+e^-	$3 \cdot 10^{-4}$	0.025	n	9.6	0.18	$1 \cdot 10^6$
ϕ (1020)	0.256	$\mu^+\mu^-$	$2.9 \cdot 10^{-4}$	0.25	y	6	1.	$6.7 \cdot 10^6$
Λ (1115)	6.4	p π^-	0.64	0.025	n	10.6	$1.1 \cdot 10^4$	$6.5 \cdot 10^{10}$
Ξ^- (1321)	0.096	Λ π^-	0.999	0.025	n	2.1	50.4	$3 \cdot 10^8$
Ω^- (1672)	0.0044	Λ K^-	0.68	0.025	n	1	0.75	$4.5 \cdot 10^6$
D^0 (1864)	$7.5 \cdot 10^{-6}$	$K^-\pi^+$	0.038	0.1	y	3.25	$8.5 \cdot 10^{-4}$	$5.1 \cdot 10^3$
D^0 (1864)	$7.5 \cdot 10^{-6}$	$K^-\pi^+\pi^+\pi^-$	0.075	0.1	y	0.37	$2.1 \cdot 10^{-4}$	$1.3 \cdot 10^3$
$\bar{D}^0$ (1864)	$2.3 \cdot 10^{-5}$	$K^+\pi^-$	0.038	0.1	y	3.25	$2.6 \cdot 10^{-3}$	$1.6 \cdot 10^4$
D^+ (1869)	$8 \cdot 10^{-6}$	$K^-\pi^+\pi^+$	0.092	0.1	y	4.2	$3.1 \cdot 10^{-3}$	$1.9 \cdot 10^4$
D^- (1869)	$1.8 \cdot 10^{-5}$	$K^+\pi^-\pi^-$	0.092	0.1	y	4.2	$7 \cdot 10^{-3}$	$4.2 \cdot 10^4$
Λ_c(2285)	$4.9 \cdot 10^{-4}$	$pK^-\pi^+$	0.05	0.1	y	0.5	$1.2 \cdot 10^{-2}$	$7.4 \cdot 10^4$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	e^+e^-	0.06	1-10	y	14	0.032 - 0.32	$1.9 \cdot 10^{5-6}$
ψ′ (3686)	$5.1 \cdot 10^{-8}$	e^+e^-	$7.3 \cdot 10^{-3}$	1-10	y	15	$5.6 \cdot 10^{-(5-4)}$	$3.4 \cdot 10^{2-3}$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	$\mu^+\mu^-$	0.06	10	y	16	0.36	$2.2 \cdot 10^6$
ψ′ (3686)	$5.1 \cdot 10^{-8}$	$\mu^+\mu^-$	$7.3 \cdot 10^{-3}$	10	y	19	$7.1 \cdot 10^{-4}$	$4.3 \cdot 10^3$

Yield per 10 weeks

Huge statistics for bulk particles

10^4 – 10^6 for rare particles

CBM time line



- Present status: beginning of the construction phase
- Installation planned in 2017-2018, followed by commissioning of the detectors
- First physics data taking in 2019 at SIS100 $\rightarrow$ low energy part of the physics program (~ 5 years)
- The physics program will continue later at SIS300 to cover the high energy part

Conclusions

- The CBM experiment offers new perspectives for the exploration of the QCD phase diagram in the region of high baryon densities
  - → large discovery potential: 1st order phase transition, Critical point, Chiral symmetry restoration, EOS
- The detector is designed to operate at very high collision rates (up to 10 MHz)
  - → Measurements for the first time of rare diagnostic probes, highly sensitive to the physics under study
- The preparation of the experiment is already well advanced
- Currently, all the detectors are in prototyping or construction phase
- Installation planned in 2017-2018, followed by commissioning of the detectors
- First physics data taking in 2019 at SIS100 → low energy part of the physics program (~ 5 years)
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Backup slides

The CBM physics program*: Main topics and observables

Deconfinement phase transition at high ρ_B & QCD critical point (SIS300)

- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)
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- excitation function of dynamical event-by-event fluctuations

Chiral symmetry restoration at high ρ_B (SIS100, SIS300)

- in-medium modifications of hadrons
  $\rightarrow$ dileptons from the decay of light vector mesons, in both e^+e^- and $\mu^+\mu^-$
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The equation-of-state at high ρ_B (SIS100, SIS300)

- excitation function of the collective flow of hadrons
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CBM $\rightarrow$ detailed measurements with high statistics, including for

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Thanks to:

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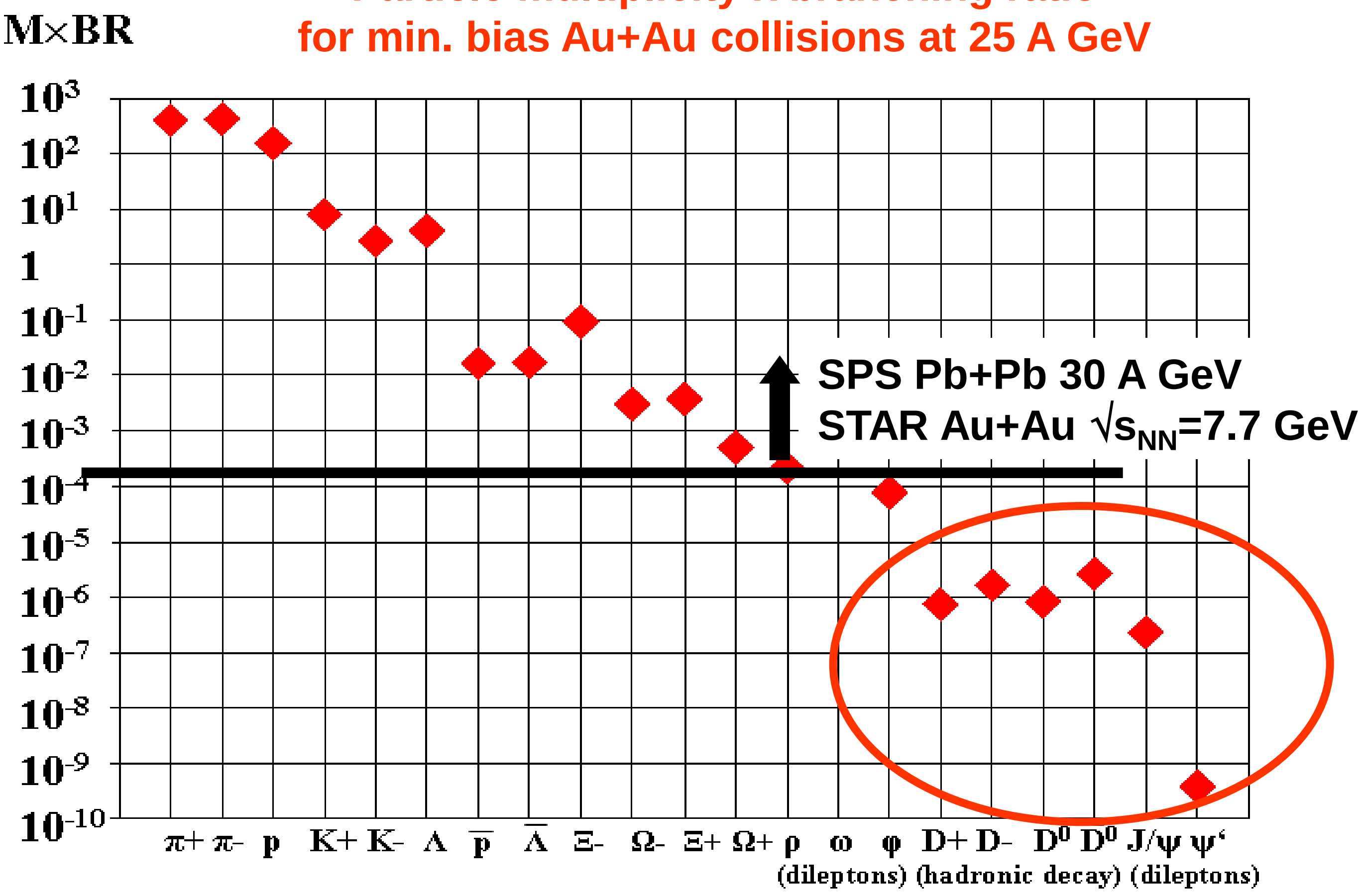
Measuring rare probes: Experimental challenges

Particle multiplicity x branching ratio
for min. bias Au+Au collisions at 25 A GeV



- ➢ CBM must be able to operate at very high collision rates: up to 10^7 collisions/sec

  → imposes strong constraints on the detector system: must be extremely fast and tolerant to high radiation doses + high precision vertex reconstruction

  → strong constraints also on the readout electronics and the DAQ system

Present and future experiments at high ρ_B

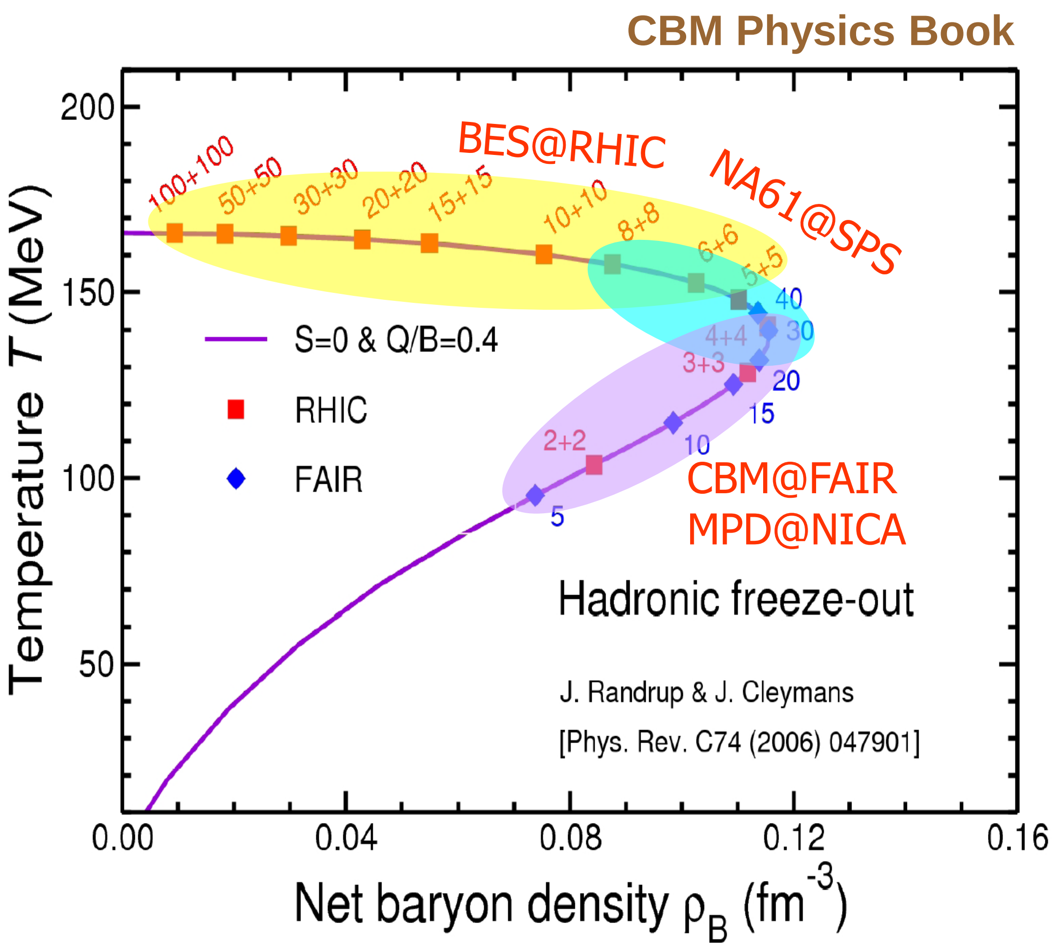
Experiment	Timeline	Energy range (Au/Pb beams)	Reaction rates Hz
STAR/PHENIX RHIC – BNL	BES-I: ongoing BES-II: 2018-2021	$\sqrt{s_{NN}}$ = 7 – 200 GeV BES-II: < 20 GeV	1 – 800 (*) (limitation by luminosity)
NA61 SPS – CERN	2009-2015	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD NICA – Dubna	Not yet funded > 2018 ?	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (design luminosity of 10^{27} $cm^{-2}s^{-1}$ for heavy ions)
CBM@FAIR Darmstadt	Start: 2018	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	up to10^7

Rare probes (new)

(*) before luminosity upgrade limitation to 800 due to TPC

Particularly sensitive to phase transitions and high baryon density effects

Density and **Temperature at freezeout**
for different beam conditions
(from hadron gas model)



- **Maximum net-baryon density reached at ~30 AGeV ($\sqrt{s_{NN}} \approx 8$ GeV)**
- **well within SIS300 range**

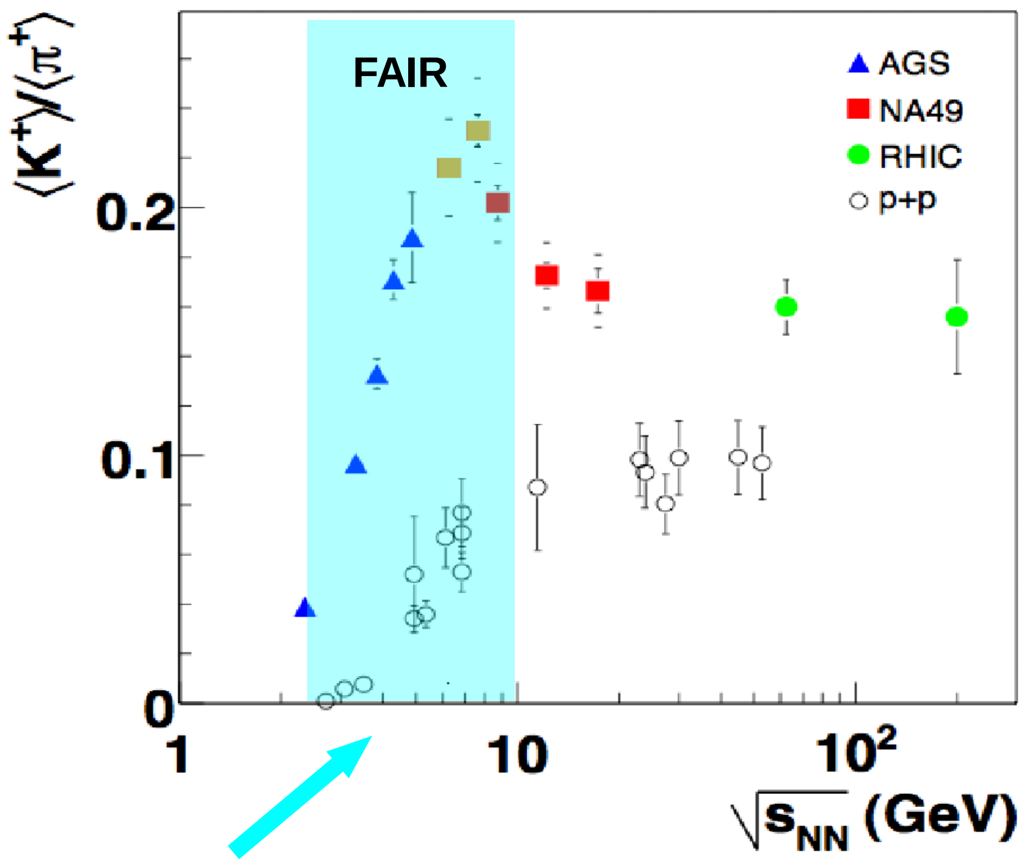
Onset of Deconfinement Phase Transition

- Structures in the excitation functions of several observables
- All at the same incident energy: ~ 30 AGeV ($\sqrt{S_{NN}}$ ~ 7 GeV)
- Typical of A-A collisions p-p → monotonic trend
- Cannot be reproduced by hadronic models

  → Onset of QGP formation?

- If due to QGP → 1st order phase transition

Results from SPS (NA49)



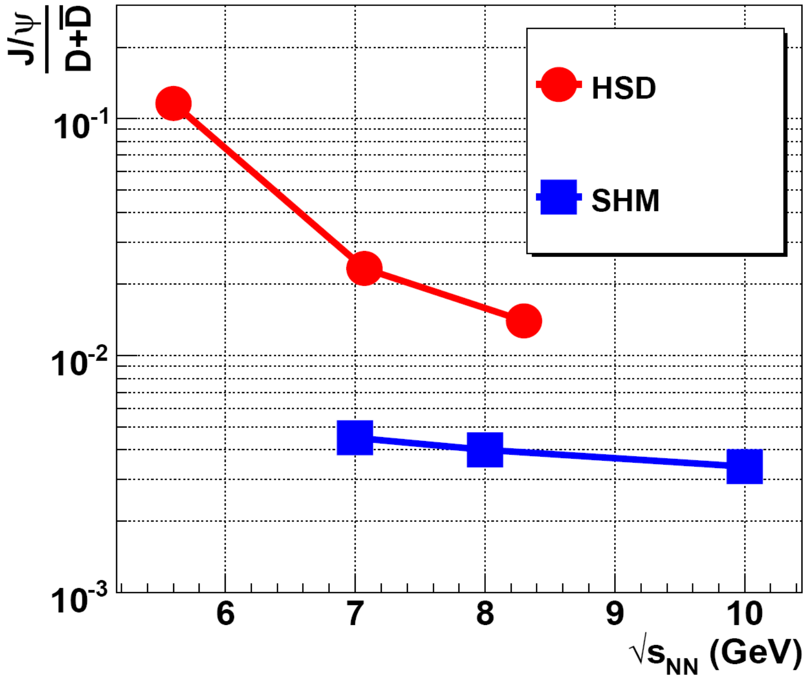
⇒ CBM will scrutinize this energy range with rare diagnostic probes (more sensitive to phase transition effects)

Deconfinement phase transition in CBM

⇒ CBM will measure several observables relevant for the deconfinement phase transition:

- The excitation function of yields, spectra, and collective flow of strange particles, including multi-strange baryons (Ξ, Ω)

- The excitation function of yields, spectra, and collective flow of charmed particles
  - → Open charm particles via their hadronic decay
  - → Charmonium (will be measured in both di-muon and di-electron channels)



Charmonium to open charm ratio sensitive to the nature of the medium in the early stage of the collision
→ can be used as a signature of the deconfinement phase transition

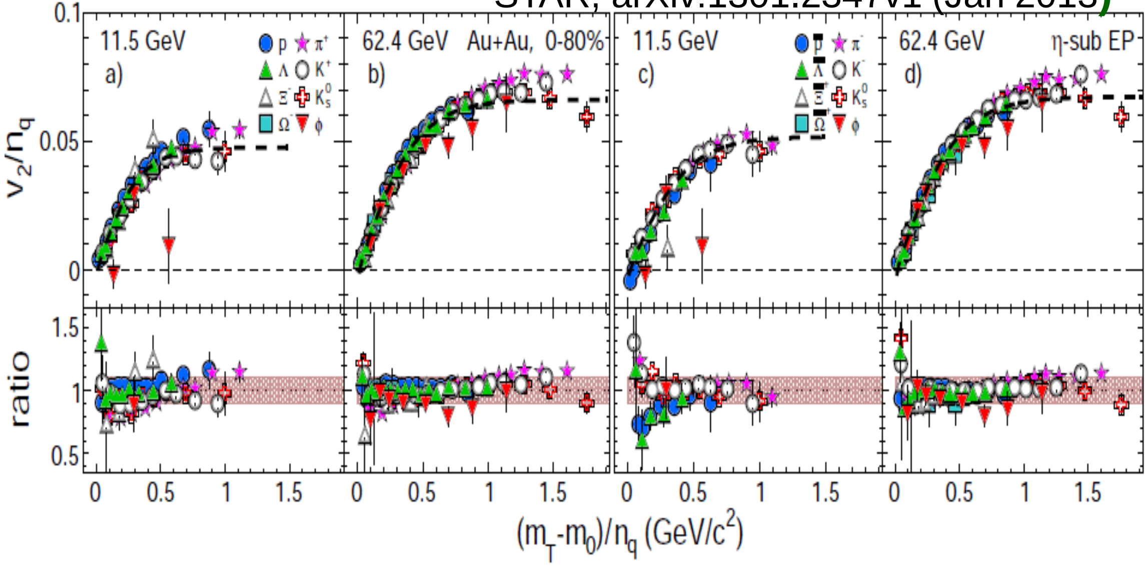
Results from BES-I at RHIC

- RHIC performed a scan in energy from $\sqrt{S_{NN}}$ ~ 200 GeV (top energy) down to 7.7 GeV
- Results → QGP signatures seem to disappear below 20 GeV

→ Main observations:

- High pt suppression not observed below 20 GeV
- v_2(particles) ≠ v_2(anti-particles) below 20 GeV → deviation w.r.t. the NCQ scaling
- $v_2(\Phi)$ is relatively small at 11.5 GeV (expected if predominant hadronic phase, due to their small hadronic interaction x-section)

STAR, arXiv:1301.2347v1 (Jan 2013)

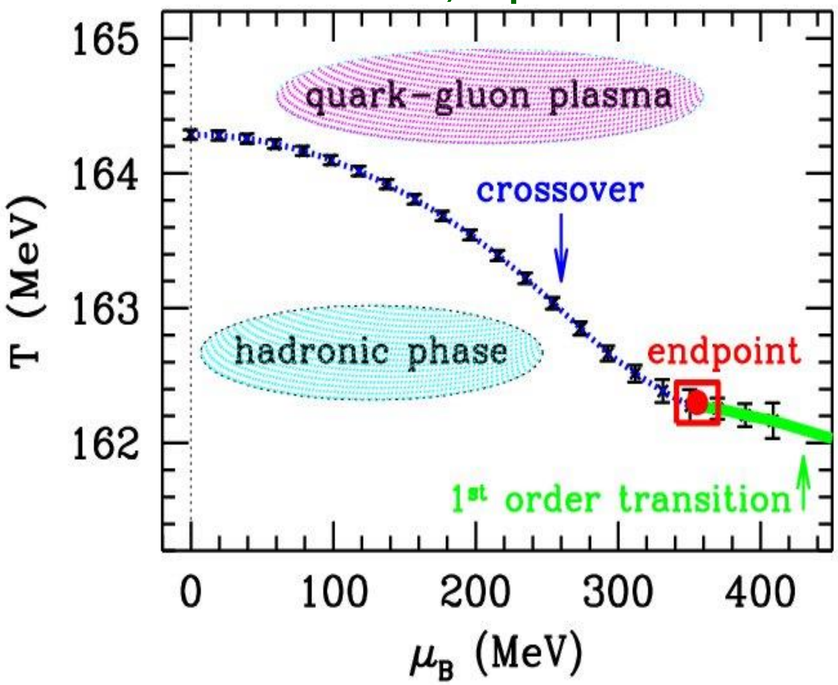


⇒ Needs to be confirmed with higher statistics measurements (BES-2)

⇒ CBM will extend these studies to multi-strange baryons and charmed particles

QCD critical point

LQCD calculations at $\mu_B \neq 0$
Fodor & Katz, hep-lat/0402006



- Depends on assumptions made
  → Number of quark flavours
  → m_q
- Localisation of the Critical Point
  → μ_B from 200 to 1000 MeV!
- Important to measure over a broad range in energy (→ broad range in μ_B)

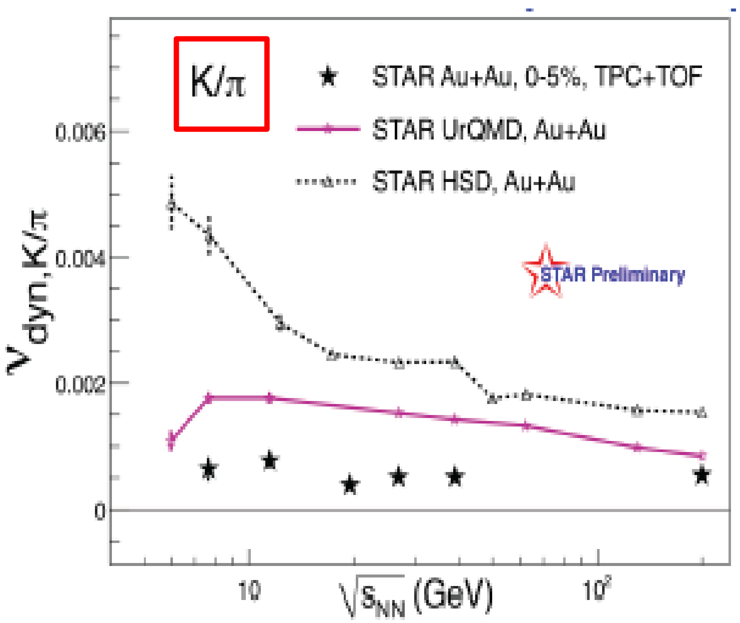
Experimental program	$\sqrt{s_{NN}}$ range (GeV)	μ_B range (MeV)
RHIC (BES)	5 - 30	150 - 580
SPS	4.9 - 17.3	220 – 600
FAIR	2 – 9.3	300 – 800

μ_B coverage

→ Complementarity between RHIC, SPS and FAIR (+ overlap)

Experimental observable: event-by-event fluctuations of conserved quantities like net baryon number, and net-charge
→ expect anomalies (non-monotonous change) in E-dependence near CP

Dynamical fluctuations in STAR BES



Constant ...

Particule ratio: K/π

Dynamical event-by-event fluctuations γ_{dyn} for the K/π ratio

→ dynamical := substracted from trivial statistical fluctuations (using mixed event ensembles)

NA49 data:
increase K/pion
… E-dependent acc, in fixed target !!

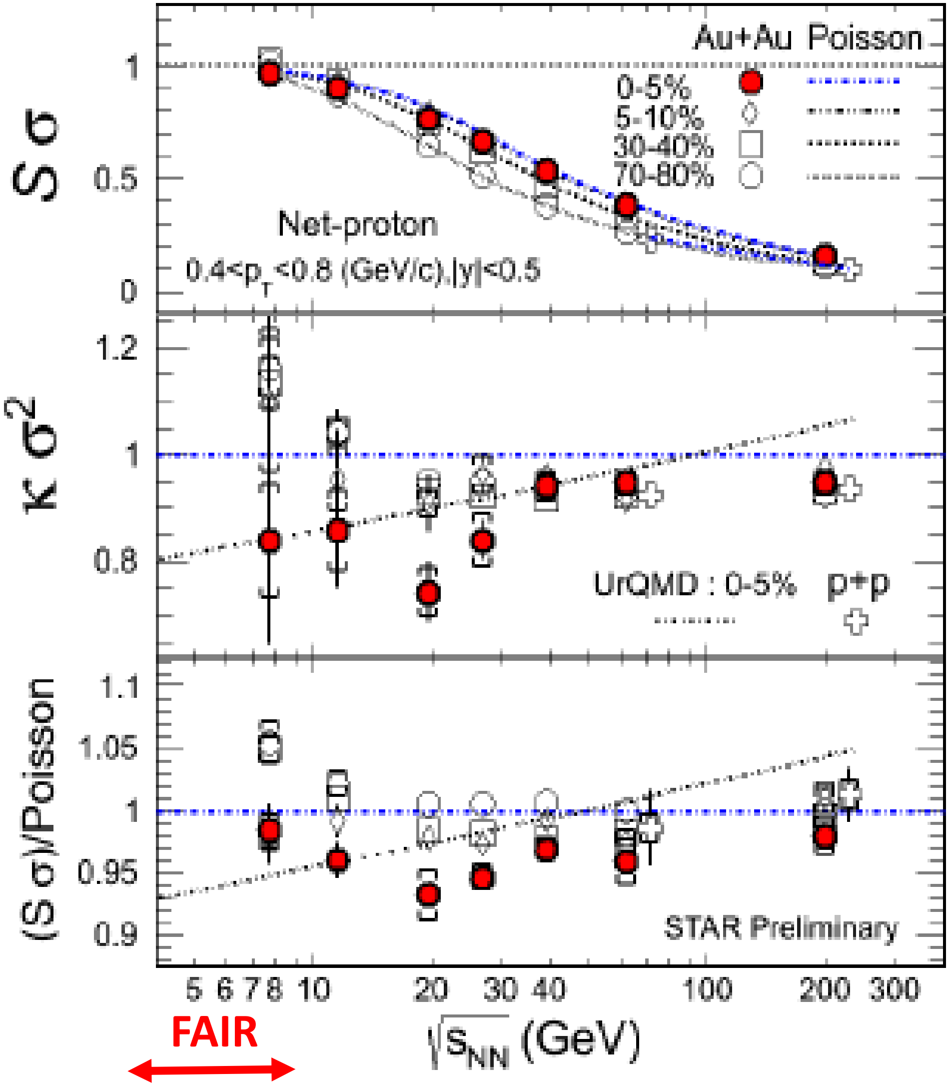
However: CP effects could be too small:

- correlation length « L » limited by system size & lifetime
- may be washed out by sub-sequent hadronic interactions

But: 2^{nd} moment ~ L^2 (only)

Higher moments: 3^d (skewness) & 4^{th} (kurtosis) ~ $L^{4\text{-}5\text{-}7}$
→ more sensitive to CP effects

Dynamical fluctuations in STAR BES



Fluctuations at higher moments of net-proton number distributions

$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$

$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$ Skewness

$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$ Kurtosis

Present results → CP (if it exists) should be below √s = 39 GeV

→ **At lower energies -> difficult to draw clear conclusions due to large statistical and systematic uncertainties**

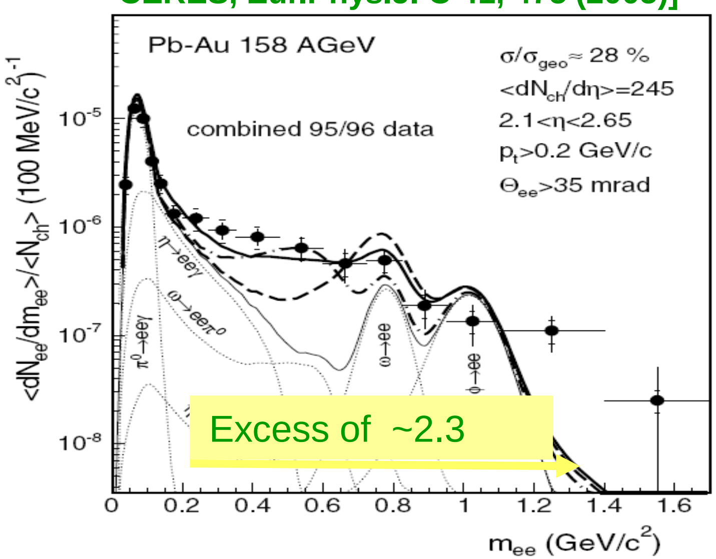
→ **BES II will provide more accurate data**

→ **CBM will provide high statistics data in the region below √s = 10 GeV**

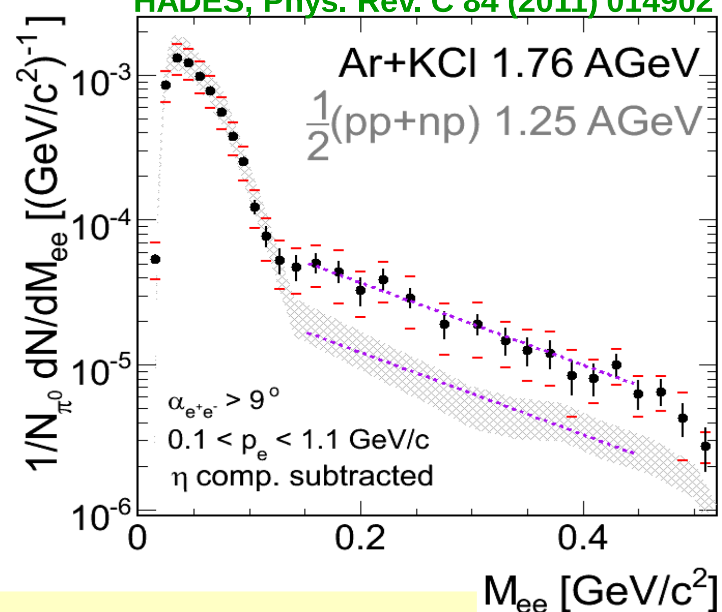
In-medium modification of hadron properties

- Indications on the chiral symmetry restoration ↔ origin of hadron mass
- A sensitive observable: light vector mesons (ρ, ω, Φ) in their leptonic decay channel
  - formed and decay inside the fireball (e.g. lifetime of ρ in vacuum = 1.3 fm/c)
  - leptons not affected by final state interactions → probe to study the properties of these mesons in a dense and hot medium
- Experimentally → measure dilepton spectra in the low mass region and compare to what is expected in the absence of medium effects (N-N reference)
- Measured at SPS (CERES, NA60) and at SIS18 (HADES)

CERES, Eur.Phys.J. C 41, 475 (2005)]



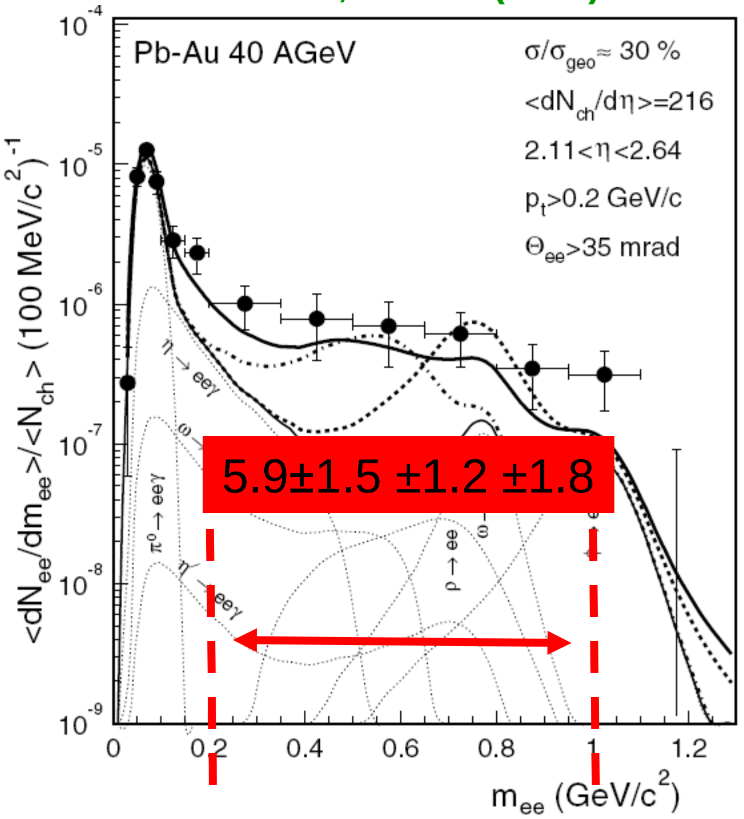
HADES, Phys. Rev. C 84 (2011) 014902



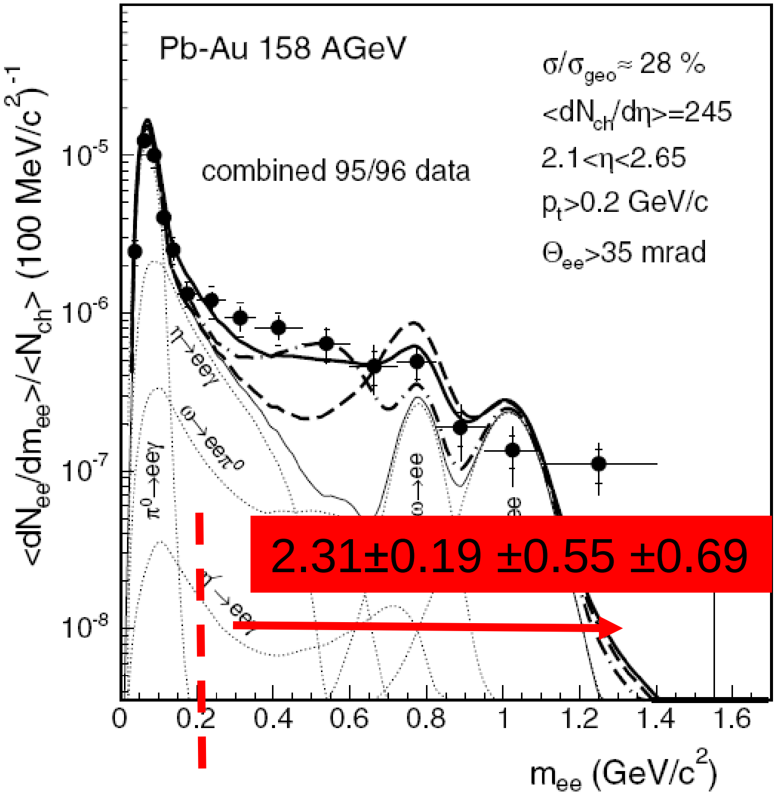
Recent theoretical studies indicate that these effects are more driven by baryon density than by temperature
⇒ Importance of high ρ_B measurements → FAIR energy range (CBM)

CERES data → excess factor higher at lower energy

PRL 91, 042301 (2003)



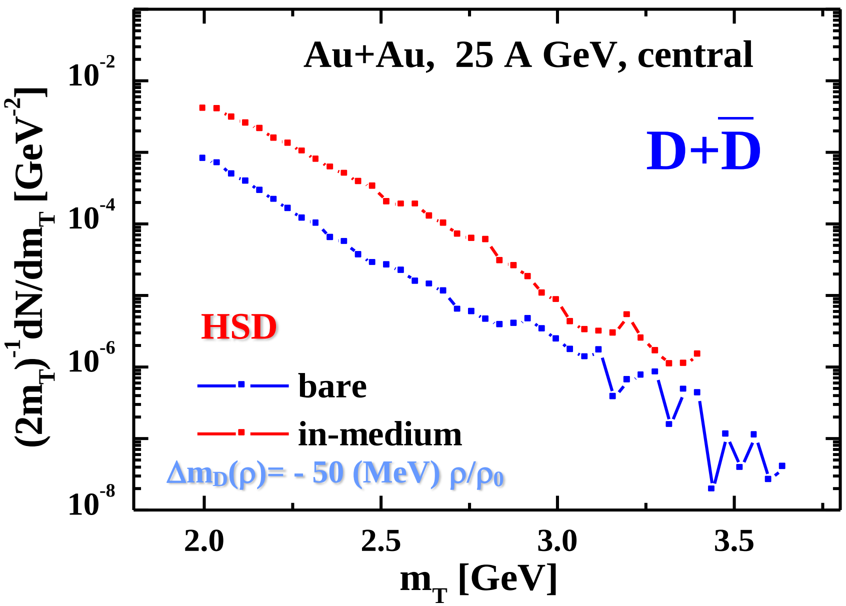
Eur.Phys.J.C 41, 475 (2005)



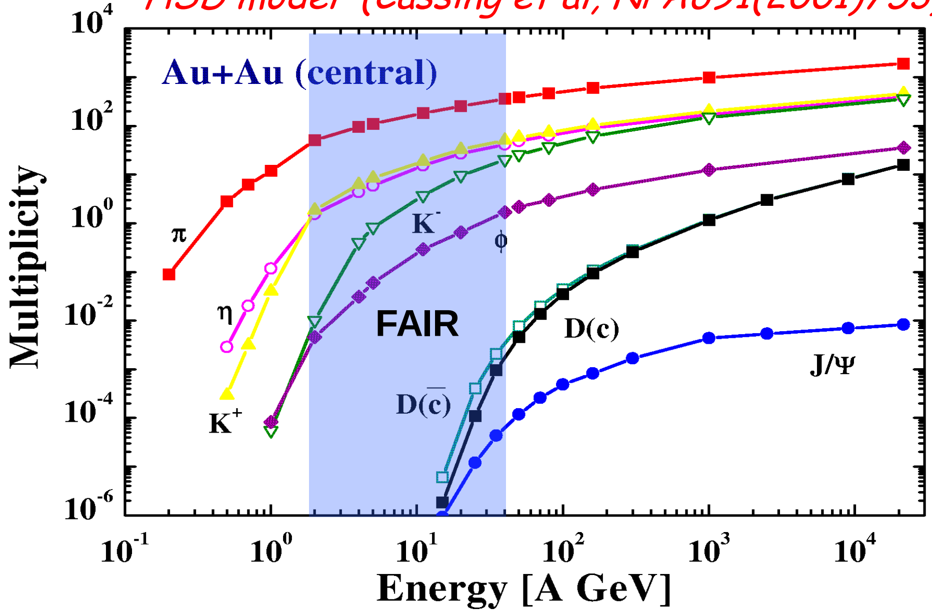
In-Medium Modifications of Hadron Properties
Open Charm

At FAIR energies, D-mesons are produced close to their kinematical threshold

→ At threshold, a modification of their mass (even very small) will lead to a substantial change in their production yields



HSD model (Cassing et al, NPA691(2001)753)



CBM

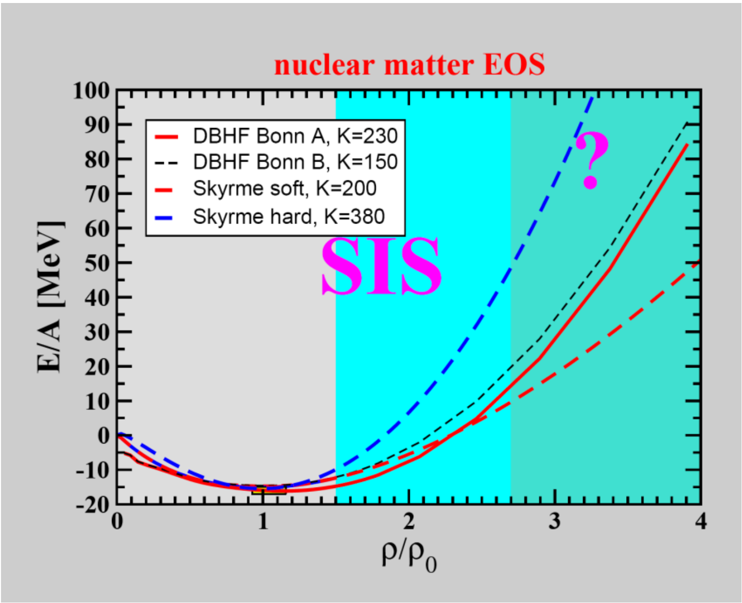
↓

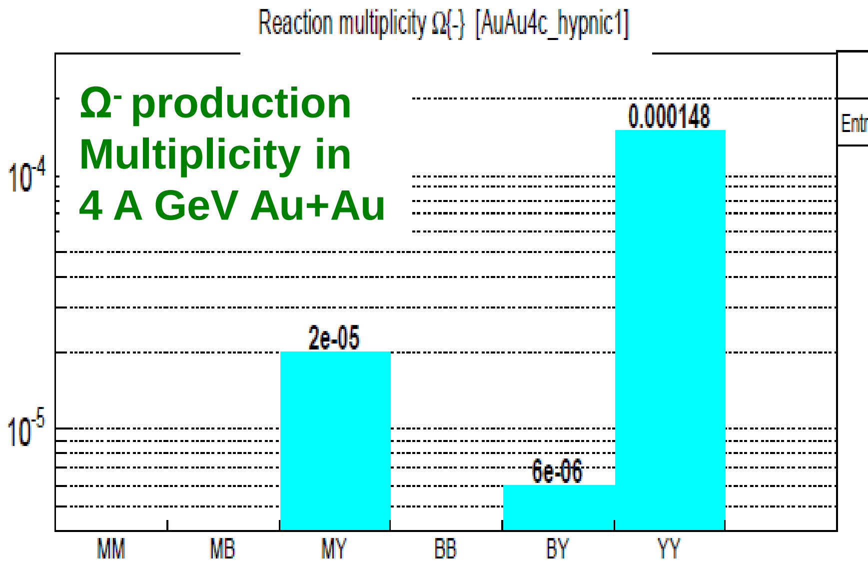
Detailed measurements of different types of open charm particles:
D^+, D^-, D^0, Λ_c
→ Yields, p_t spectra and flow

Not measured so far in A-A collisions!

Nuclear Matter Equation of State

CBM will contribute to the determination of the EOS in the region of high baryon densities



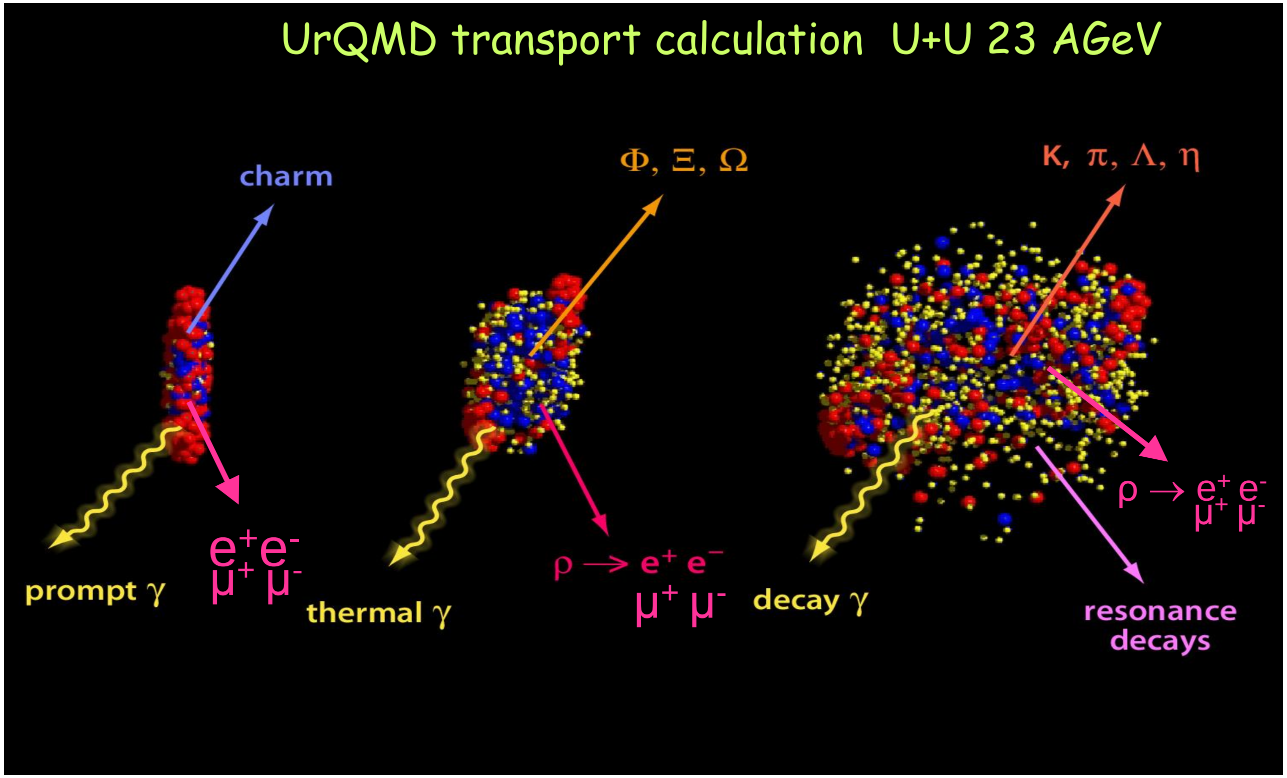


HYPQGSM calculations , K. Gudima et al.

To constrain the theory, CBM will measure two sensitive observables:

- **Collective flow of hadrons (driven by the pressure created in the early fireball)**
- **Production yield of multi-strange baryons at incident energies close to their kinematical threshold (2 to 10 A GeV)**

Messengers from the dense fireball



- Particles produced early in the collision are much more sensitive to the high density phase (fireball)
  - → Charmed particles formed very early (hard processes)
  - → Lepton pairs from the decay of light vector mesons are unperturbed by the effect of final state interactions (messengers from the fireball)
- These particles are produced with very low production yields → rare probes

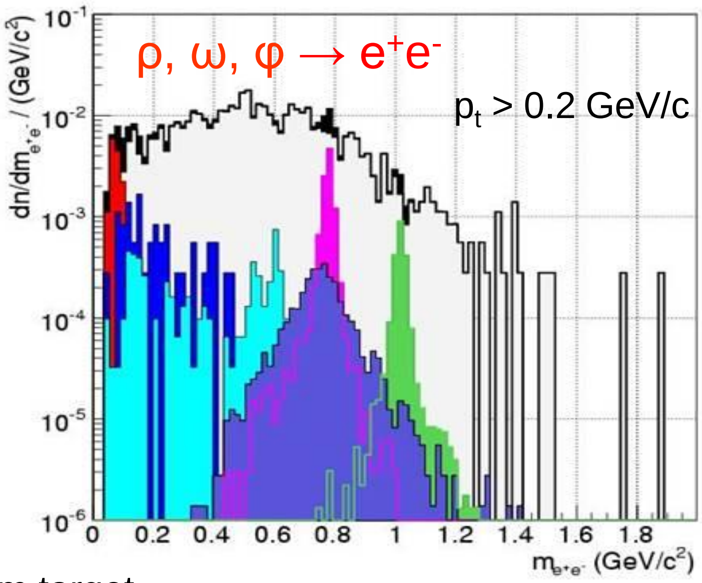
⇒ CBM will measure them for the first time in the FAIR energy range ($\sqrt{S_{NN}}$ < 10 GeV)

Electron pairs

- Electron id: TRD, RICH (combination → π suppression factor of 10^4)

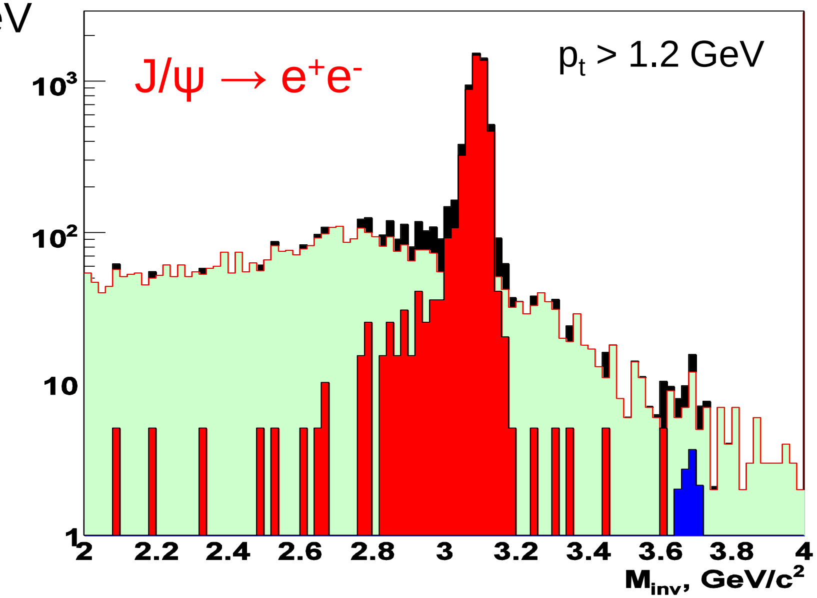
Central Au +Au
25 AGeV

2x10⁵ events



25 μm target

4x10¹⁰ events

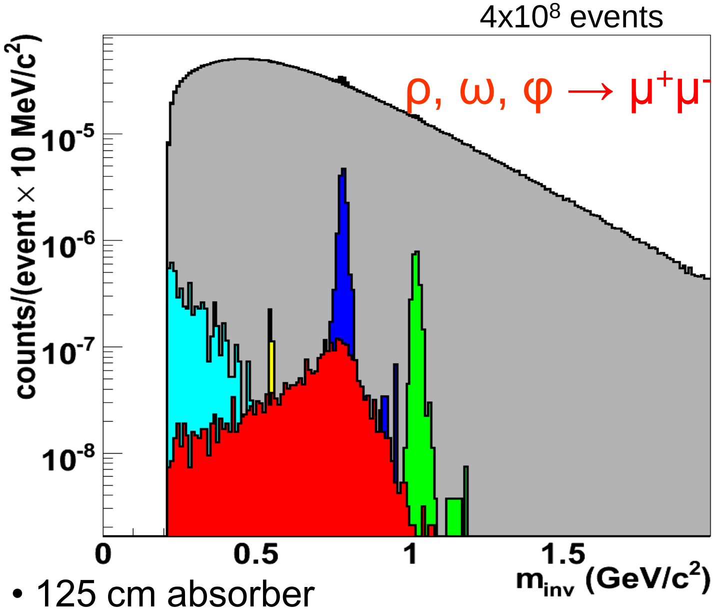


particle	S/B	ε (%)
ω	0.4	6.6
φ	0.32	9.4
ρ	0.008	4.7
J/ψ	13	14
ψ'	0.3	19

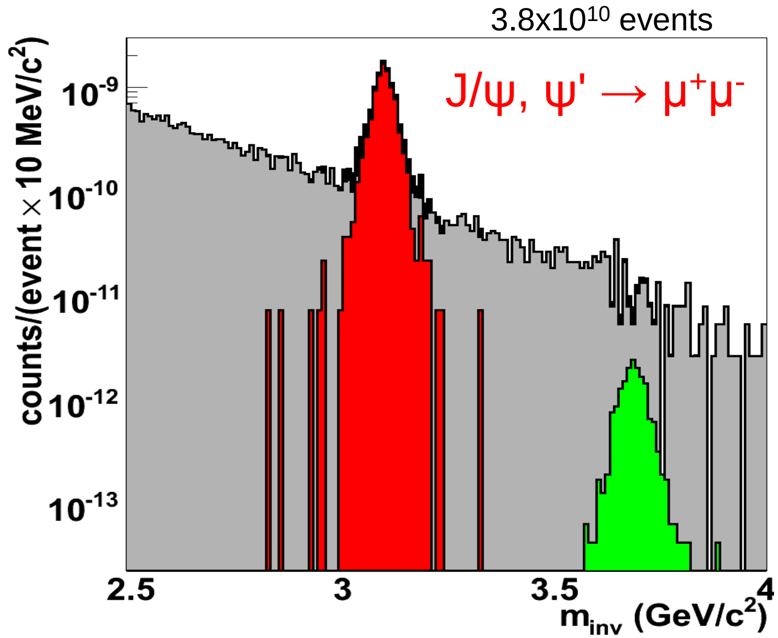
- **Background dominated (75%) by physical sources (mainly from π^0 Dalitz decays)**
- **Expected statistics per 10 weeks (Min bias)**
  - → **Light vector mesons ~ few 10^6 each**
  - → **J/ψ ~ 2 x 10^6, ψ' ~ 3 x 10^3**

Muon pairs

- Muon id: segmented hadron absorber + tracking stations
  - Iron absorber: 3x20 + 30 + 35 + 100 cm
  - 6 detector triplets: 3 GEM + 3 straw tubes



- 125 cm absorber (intrinsic p>1.5 GeV cut)



- 225 cm absorber
- p_t > 1GeV/c

- **Background dominated by muons from π and K decay (0.13/event)**
- **Expected statistics per 10 weeks (Min bias)**
  - **→ Light vector mesons ~ few 10^7 each**
    - **10 x higher than with dielectrons**
    - **but exclude the mass range below $2m_\mu$ ~ 200 MeV/c² (close to the edge of ρ)**
  - **→ J/ψ ~ 2 x 10^6, ψ' ~ 4 x 10^3**

particle	S/B	ε (%)
ω	0.11	4
φ	0.06	7
ρ	0.002	3
J/ψ	18	13
ψ'	1	16