THE DILEPTON PHYSICS PROGRAM OF CBM

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40 Years Anniversary of IMP-GSI Cooperation,
CHST, Beijing, September 2017

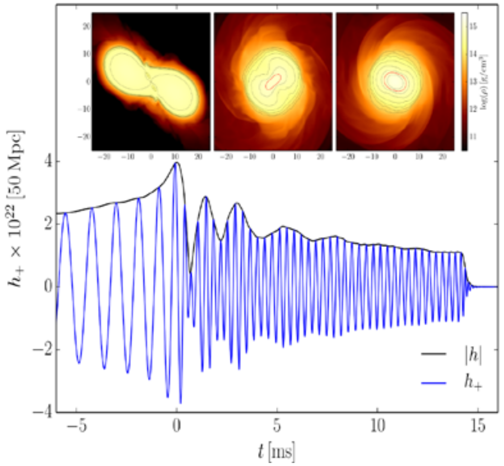
INTRODUCTION
MOTIVATION
DIMUONS
DIELECTRONS
PHASE-0

The QCD challenge

- From particles (quarks) to hadrons to nuclei and to matter (NS merger as site for r-process)
- Governed by non-perturbative QCD, ab-initio approach complicated
- Experimental approach to QCD matter: heavy-ion collisions, gravitational waves

supra-normal
nuclear densities

Density profile across a merging NS binary system. Taken $t = 1.4$ ms ($t = 0$ see below).



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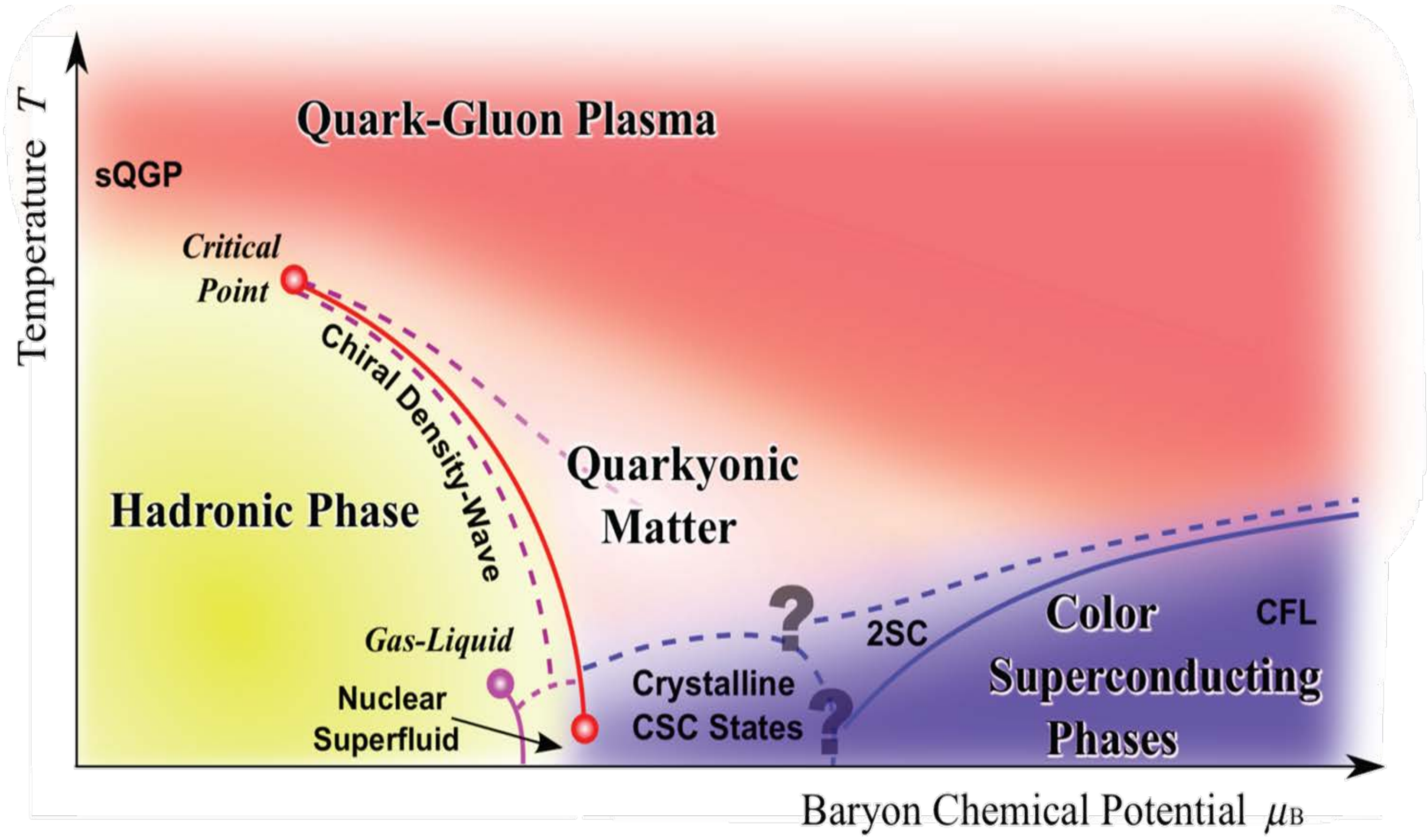
A. Bauswein et al. [1302.6530]

M. Hanauske, L. Rezzolla et al.   J.Phys.Conf.Ser. 878 (2017) no.1, 012031

The QCD phase diagram

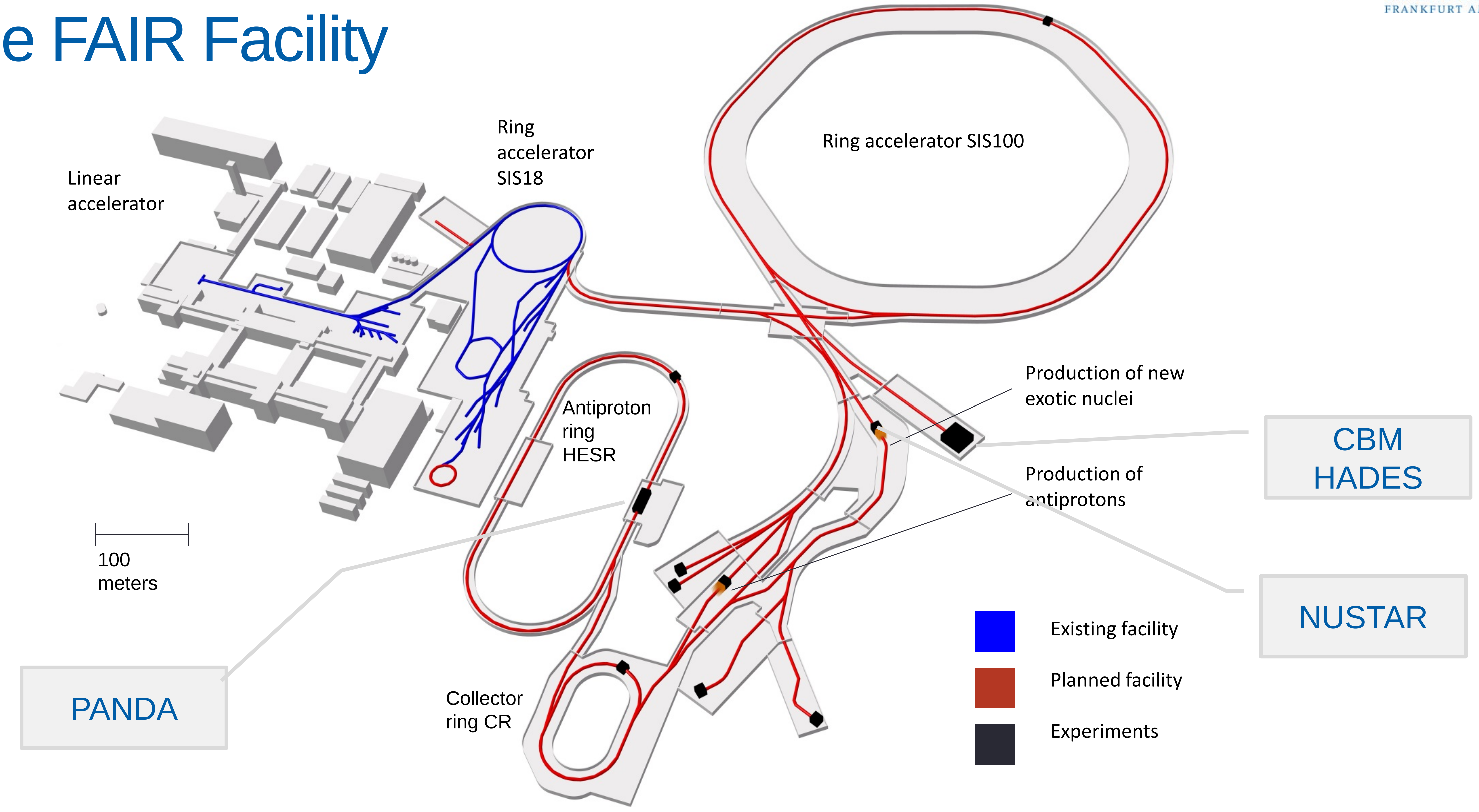


Courtesy of K. Fukushima & T. Hatsuda

Open questions:

- Origin of mass?
- Nature of confinement?
- Role of condensates?
- EOS of dense/hot matter

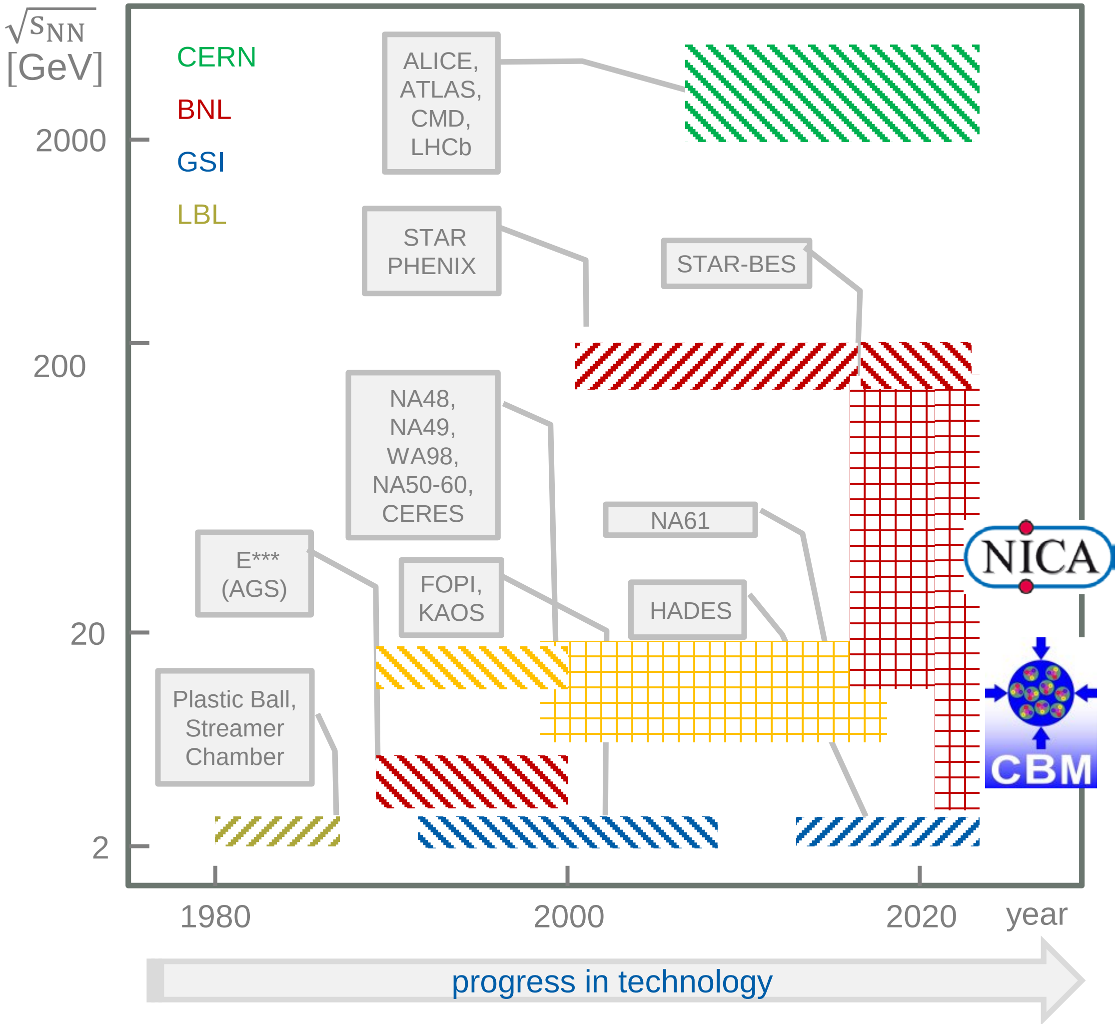
The FAIR Facility



QCD physics at FAIR

- Hadron- and Quark Matter Physics (CBM/HADES)
- Hadron Spectroscopy and Structure (PANDA)
- Properties and Reactions of Rare Isotope (NUSTAR)

Past and present relativistic heavy-ion programs



MOTIVATION

CBM - “nomen est omen” - Cloudy Bag Model ;)

A lot already known about nucleons and their excitations from (lattice) QCD:

- Confinement of light quarks nothing to do with flux tubes. Rather appears because the condensates are suppressed between the valence quarks.
- Resonance properties substantially driven by cloud-meson core final state interaction.

  L. Karatidis et al., arXiv:1608.03051
  J. M. M. Hall et al., arXiv:1411.3402

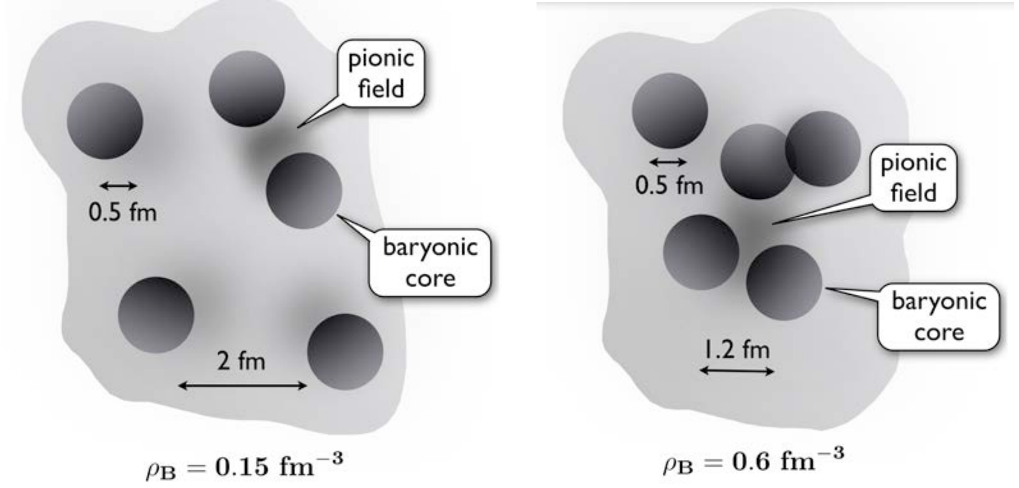
Chiral symmetry restoration

- in-medium a_1/ρ spectral functions. Trend seen like conjectured by Rapp/Hohler.

  H. Meyer et al. arXiv: 1212.4200 & INPC2016

- Likely no generation of mass without confinement.

What does it take, to force the quarks forming a giant bubble?



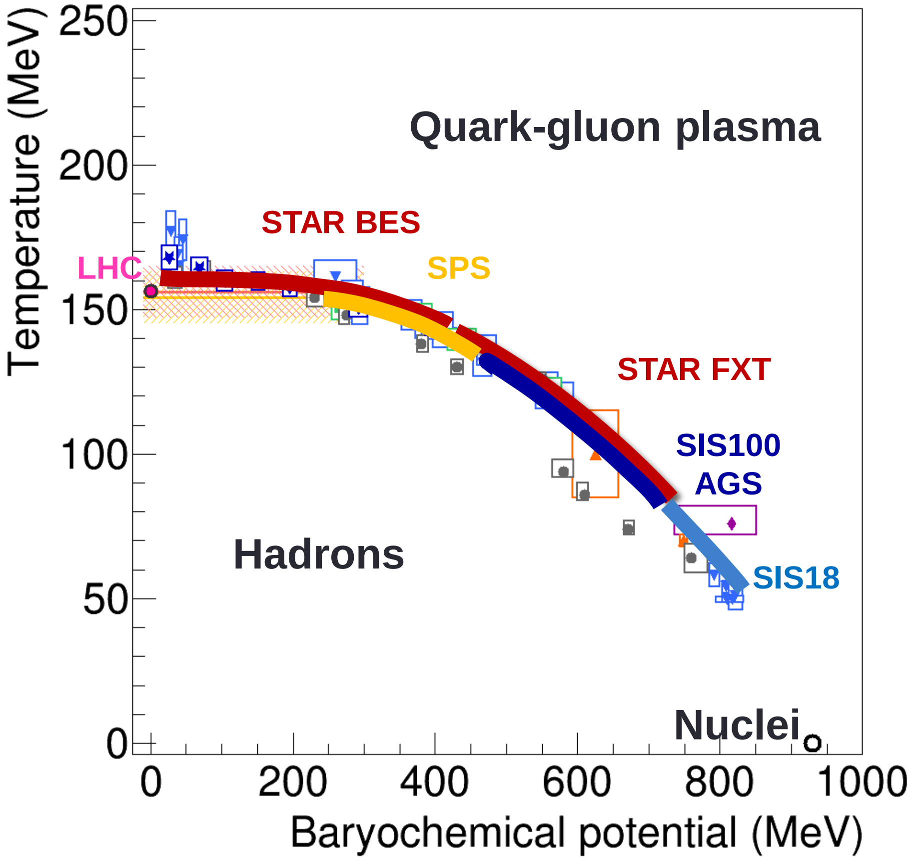
Chiral Perturbation Theory:

- Provides prediction for chiral order parameter a.f.o. baryon
- Sees strong repulsion (at low to moderate temperatures.

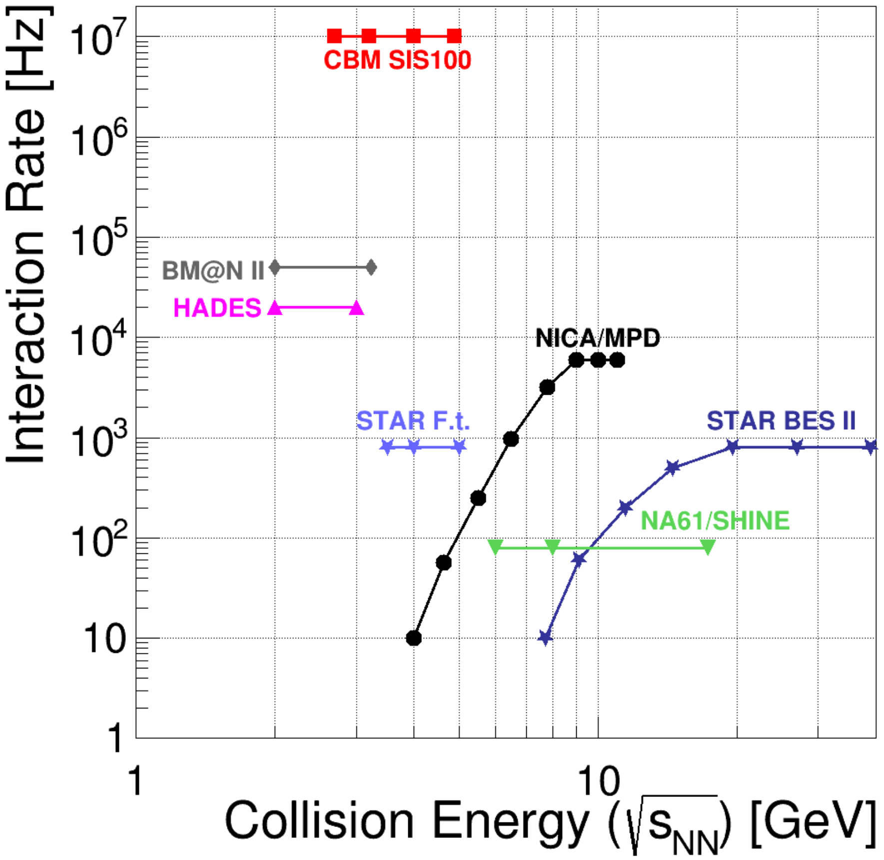
  J.W. Holt, M. Rho, W. Weise arXiv1411.6681

Exploration of the High-μ_B Region

Reach:
Temperature and chemical potential extracted from particle multiplicities and assuming thermalization



Speed:
Mean event rates before event selection.
Note the luminosity drop for colliders at low beam energy.

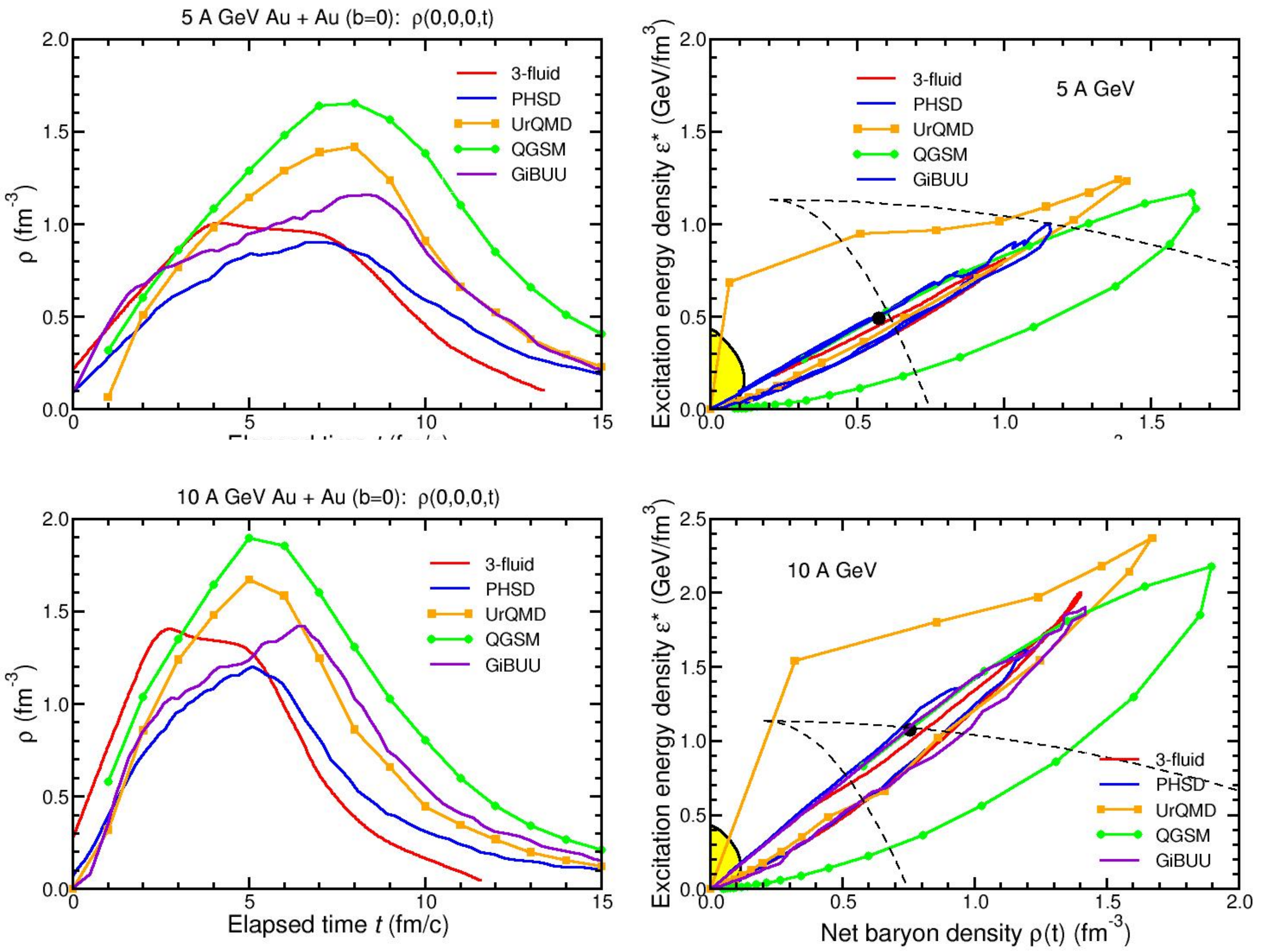


Heavy-ion collisions at SIS100 energies

- Nearly complete stopping leads to baryon-rich matter in the overlap zone.
- Generally shorter lifetime and larger densities as beam energy goes from 1 to 10 A GeV.

5 A GeV

10 A GeV



I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

Physics addressed by CBM

The QCD Equation-of-State

- Collective behavior (flow)
- Multi-strange baryons

Search for novel phases and 1st order phase transition

- e-b-e observables (higher-moments)
- Excitation function of hadron multiplicities and virtual photons

Path to restoration of chiral symmetry

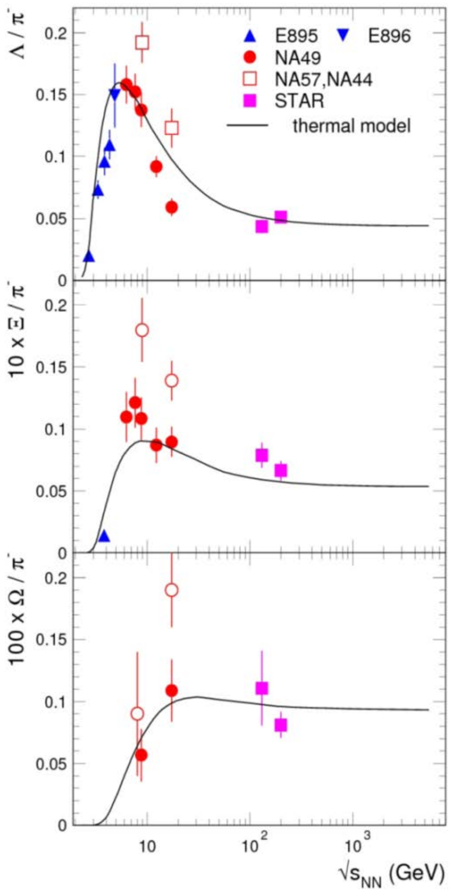
- High-precision invariant mass distributions low- and intermediate mass range

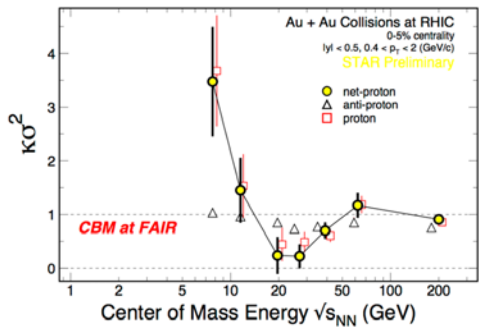
Strange matter

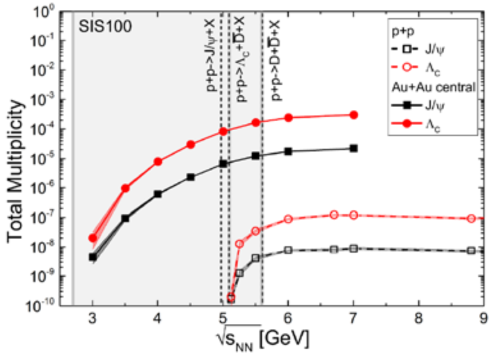
- (Double-) lambda hypernuclei
- Meta-stable objects (e.g. strange dibaryons)

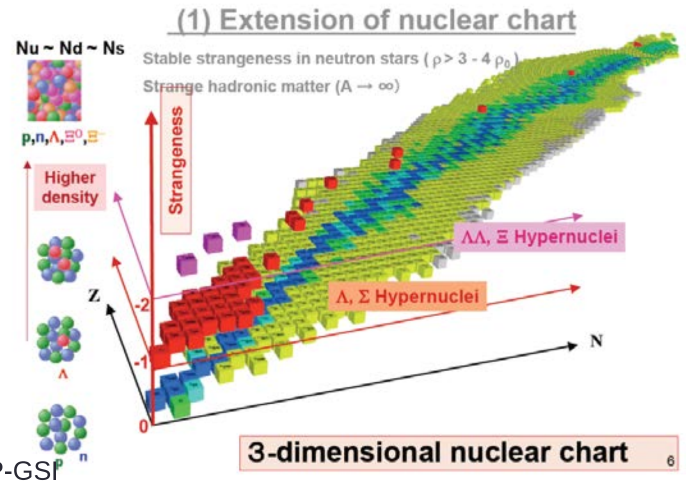
Charm production (and propagation) at threshold

- Open-charm in pp, pA
- Backward production in pA (R_{pA})

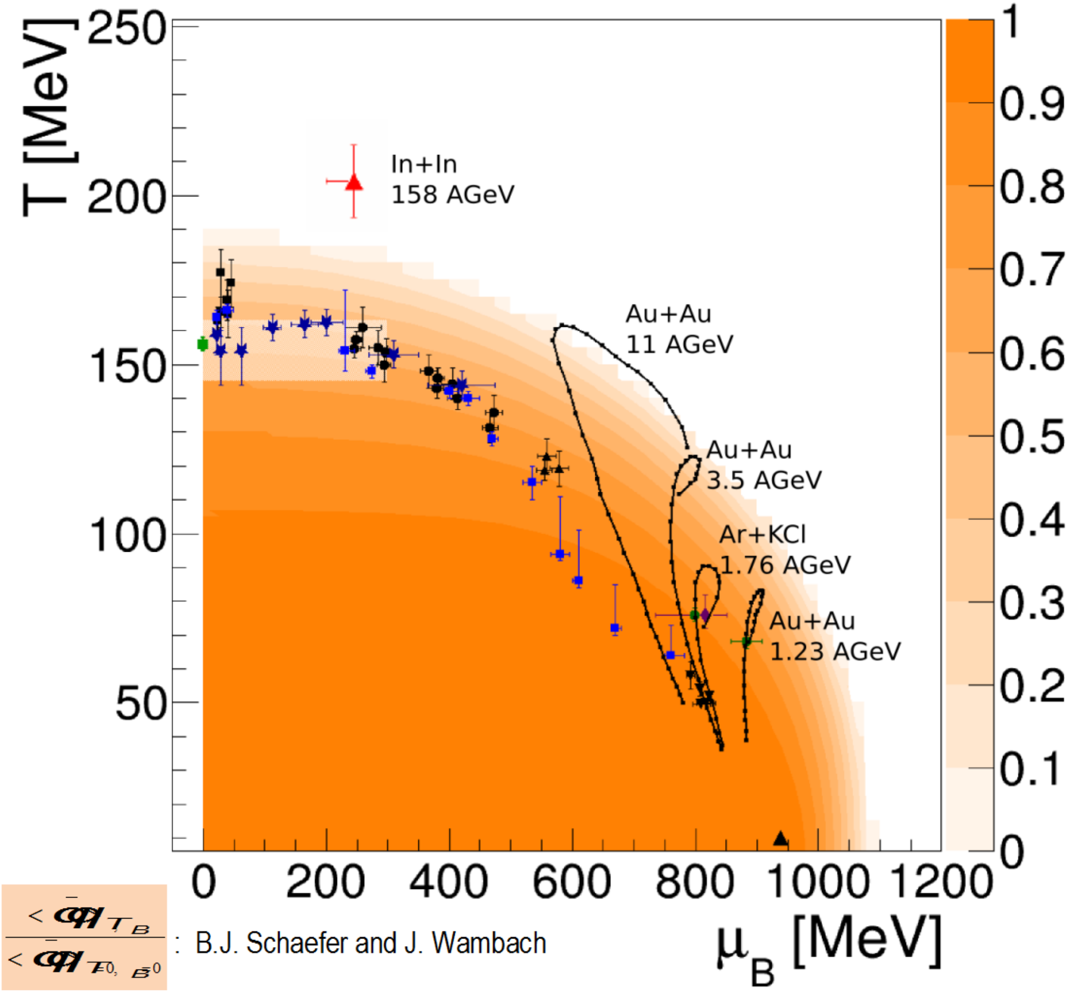








The Quest for In-medium Modifications



: B.J. Schaefer and J. Wambach

▲ NA60 (μ+μ-) : H.J.Specht: AIP Conf. Proc. 1322 (2010)

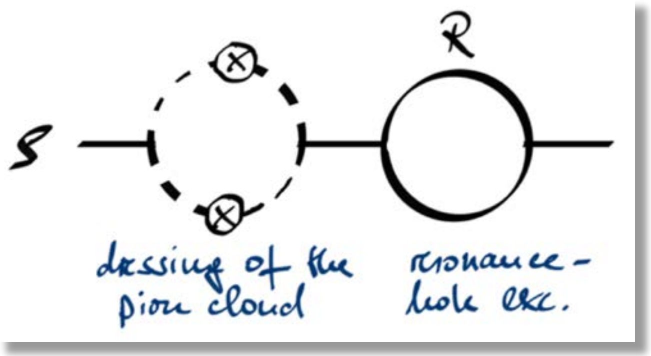
25 years ago:

- Brown/Rho, Hatsuda/Lee: meson shifts as a signal for the restoration of the sbχs.

$$m^* = m\left(1 - 0.18[^{\rho}/_{\rho_0}]\right) \text{ or } m^* = m\left(\langle q\bar{q}\rangle^* / \langle q\bar{q}\rangle\right)^u$$

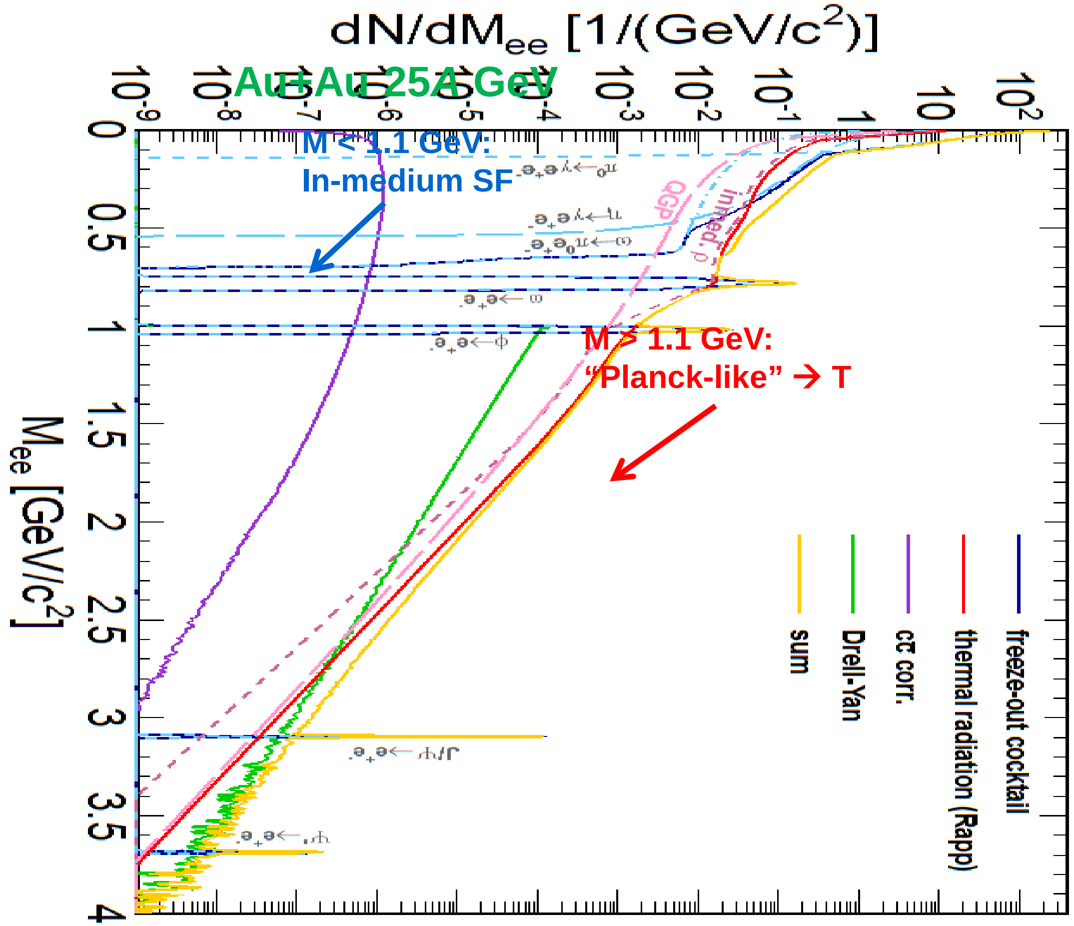
As of today:

- no real evidence for dropping masses,
- instead, ρ strongly broadened (in-medium ρ_0 propag.):

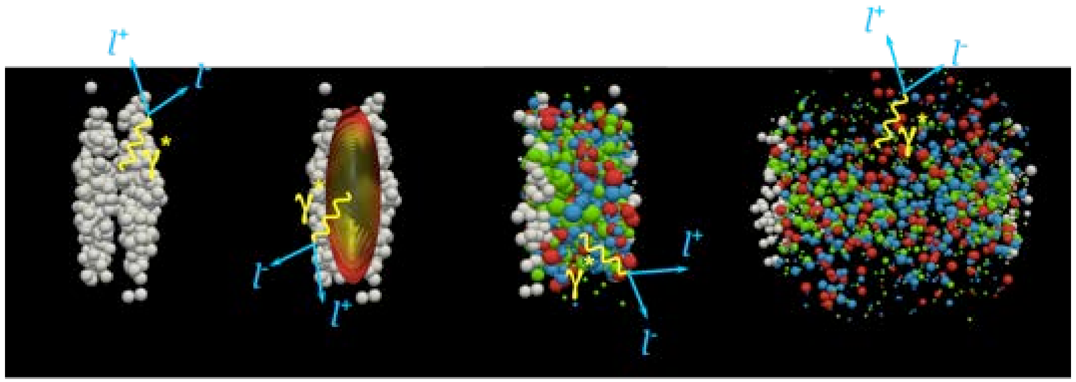


DILEPTON RADIATION

Features of dilepton invariant mass spectra



F. Seck (PhD)

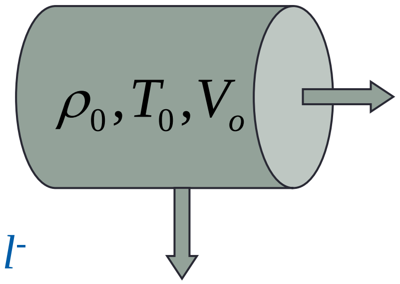


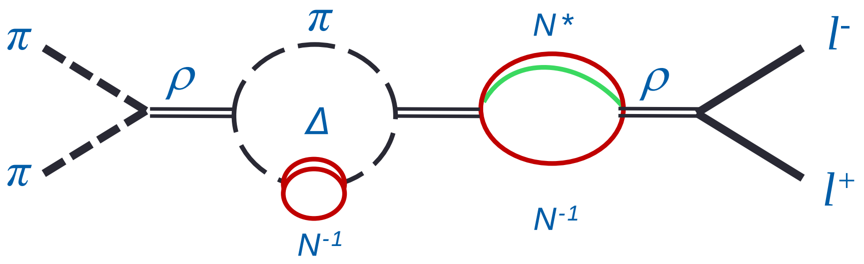
Dilepton spectra represent the space-time integral of electromagnetic radiation

- Drell-Yan (NN → l^+l^-X)
- Heavy-flavor: $c\bar{c}$ → l^+l^-
- Medium radiation:
  - QGP: $q\bar{q}$ → l^+l^-
  - In-medium ρ, ω → l^+l^-
  - “4π annihilation”: πa_1 → l^+l^-
- Final state decays (hadron cocktail): π^0, η, ω, ϕ

Dilepton Radiation in Theory

In-medium propagation of the ρ

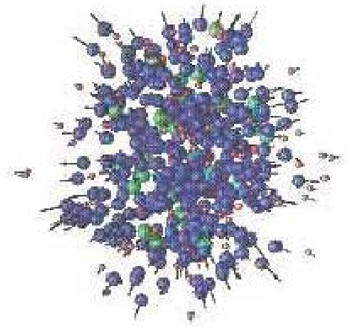




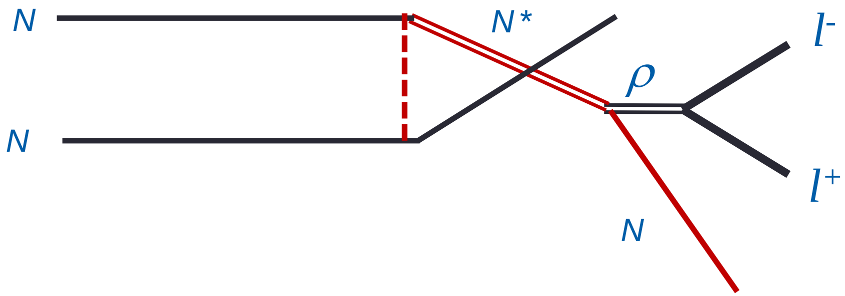
$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\ \mathrm{d}^4p} = -\frac{\alpha_{\mathrm{em}}^2}{\pi^3 M^2} f_B(q_0;T) \times \frac{1}{3} g_{\mu\nu} \mathrm{IM}\ \Pi_{em}^{\mu\nu}$$

Thermal emission rate

$$\frac{d^4N}{dM_{ee} dp_t d_Y d\alpha} \equiv \int dV \int dt\ \frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\ \mathrm{d}^4p} [T(x), \mu_B(x), v_{coll}(x), \dots],$$

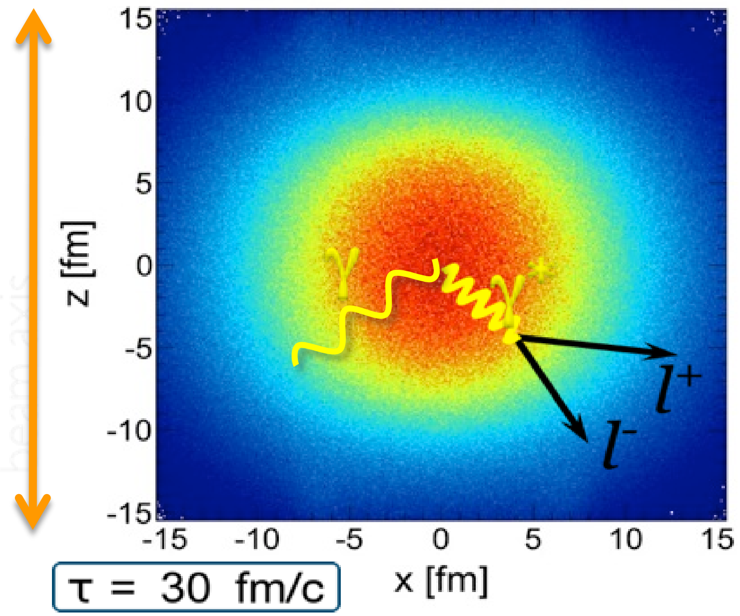


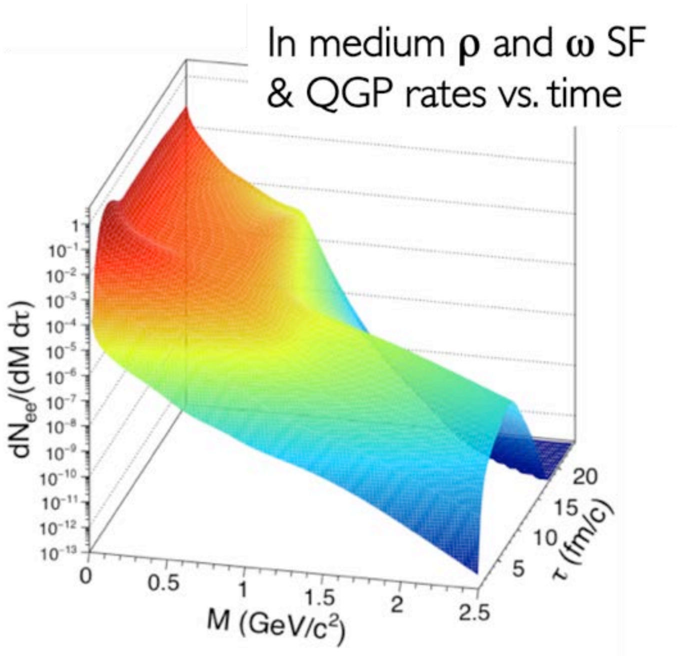
Microscopic transport approach UrQMD, HSD, iQMD



Follow up all resonances during the collision and let them (perturbatively) decay → SHINING

Coarse-grained UrQMD and Thermal Rates





Model: Ralf Rapp
STAR: QM2014,
NA60: EPJC 59 (2009) 607,
CERES: Phys. Lett. B 666 (2006) 425,
HADES: Phys.Rev.C84 (2011) 014902

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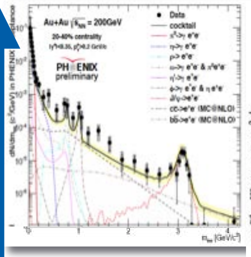
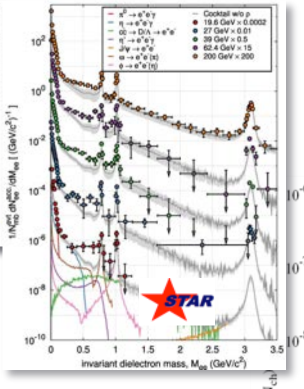
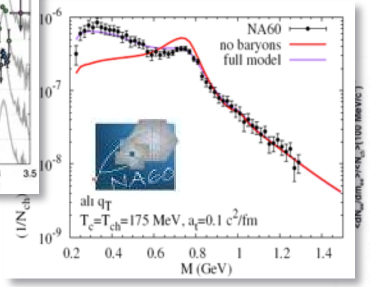
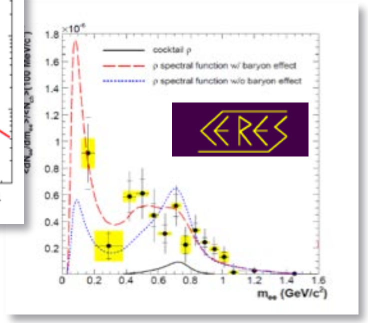
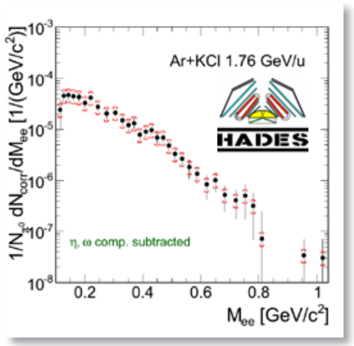






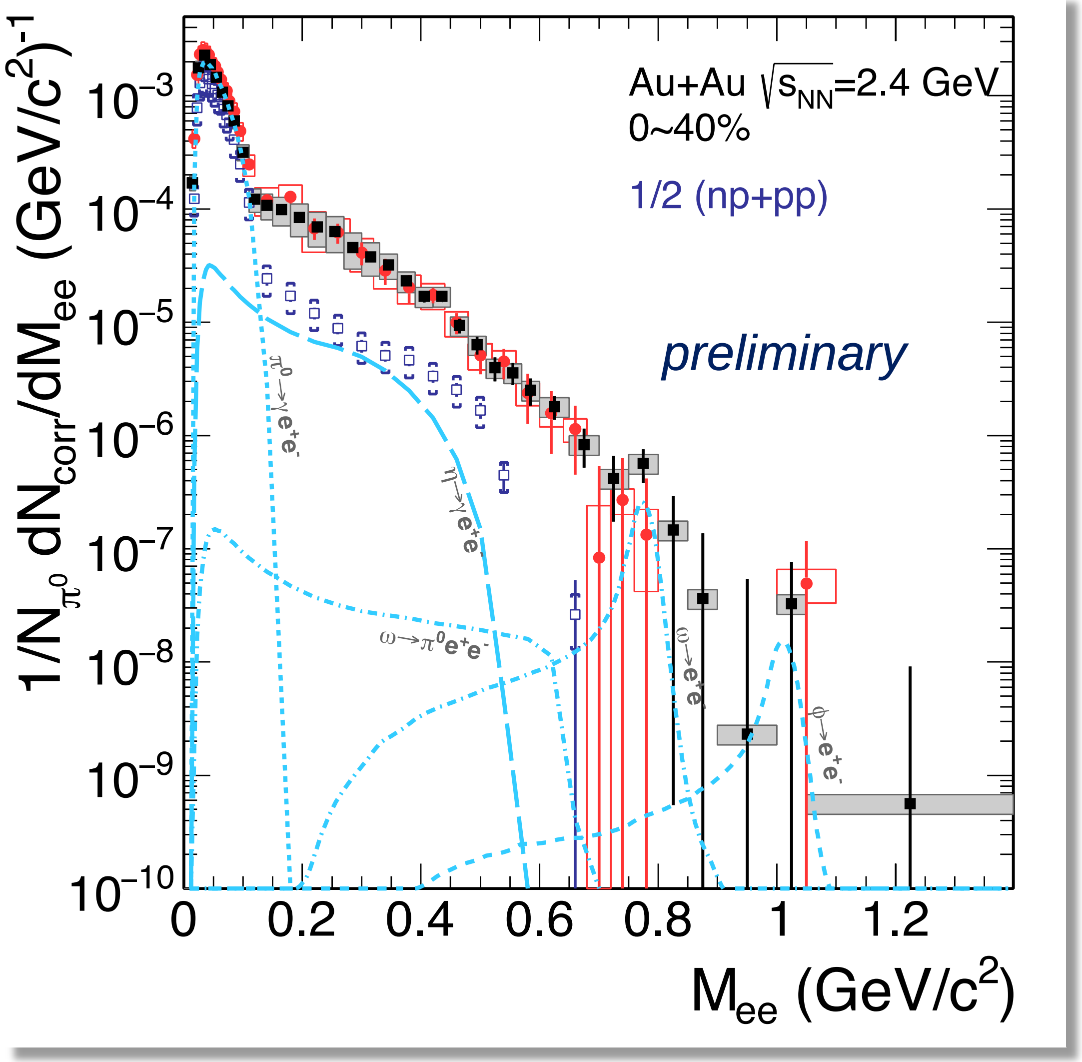


Highly interesting results from RHIC, SPS, SIS18
→ lepton pairs as true messengers
of the dense phase

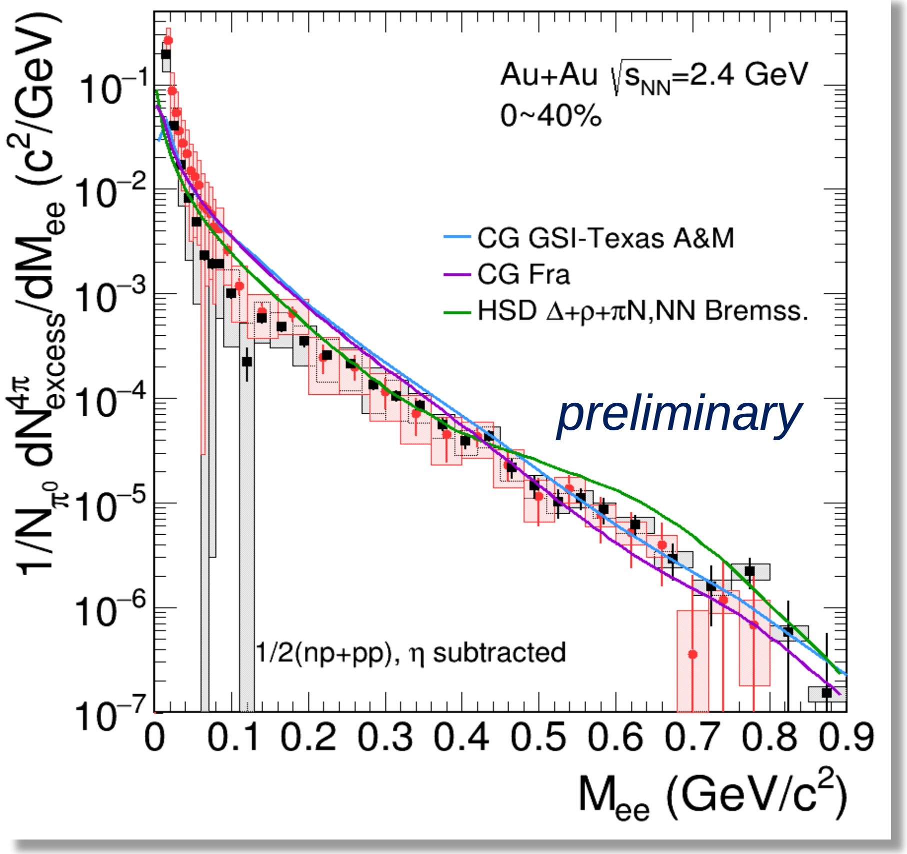


μ_B

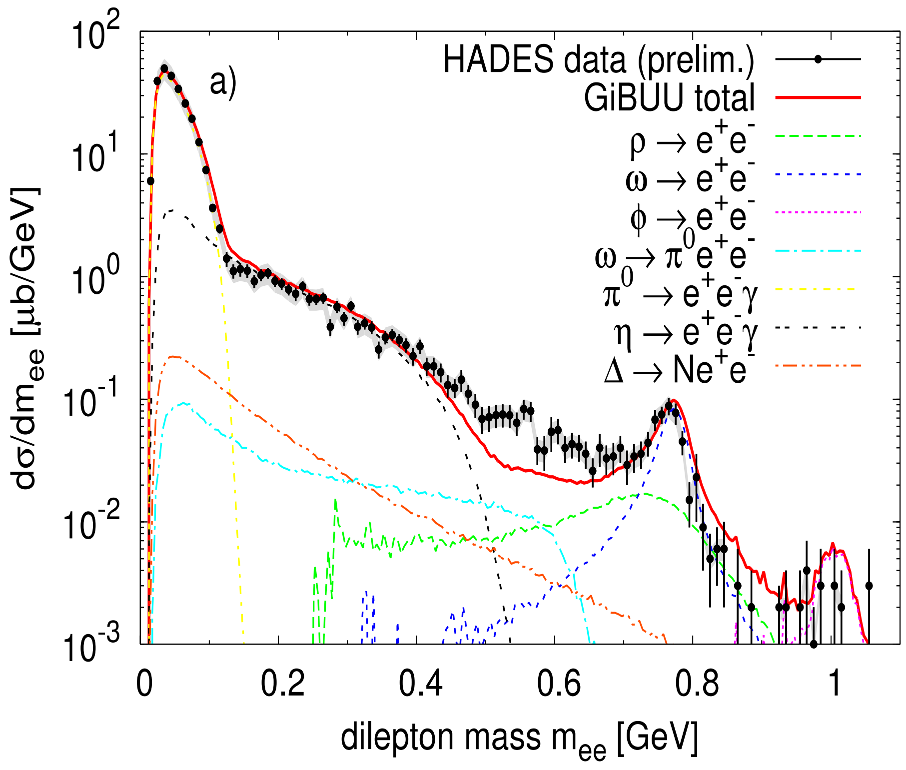
Dielectron Yields from $Au + Au$ ($\sqrt{s} = 2.4$ AGeV)



First measurement of excess radiation below SPS energies



Inclusive dilepton production in 3.5 pp collisions



Including a “VMD-like” formfactor for the Delta-Dalitz decay.

Data: HADES collaboration; arXiv:1112.3607

Particle production by PYTHIA, own tune.

Giessen group, J. Weil et al.: arXiv:1106.1344v1

Importance of baryon em transition form factors

THE DETECTOR SYSTEM

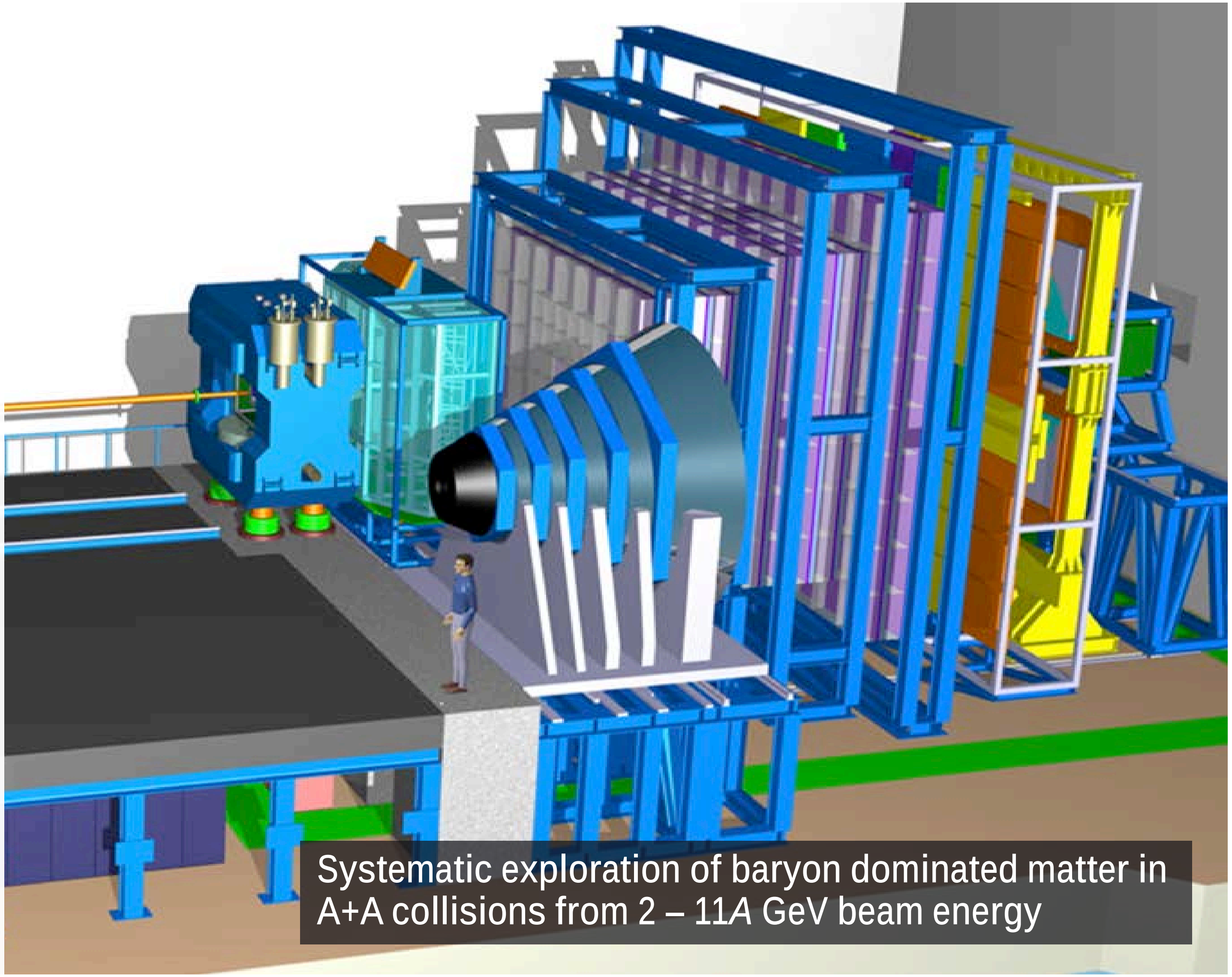
The CBM cave

The CBM experiment

- High-rate particle detector with free streaming data acquisition on real-time event reconstruction

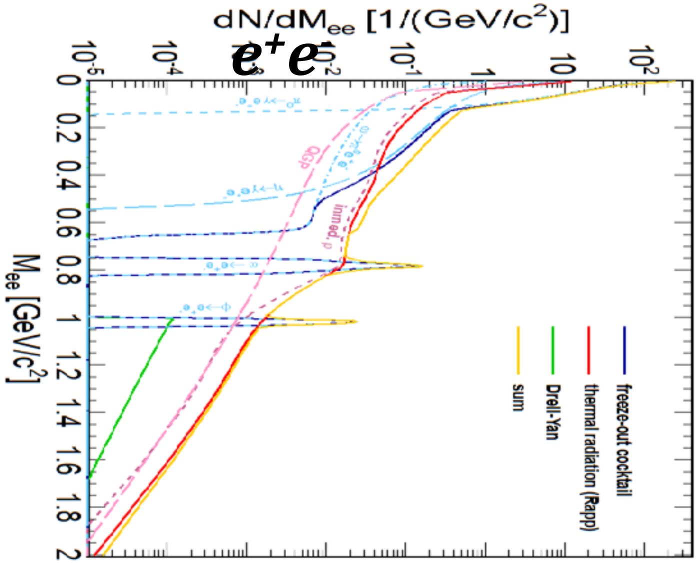
- Compact tracking with silicon in a 1 Tm magnetic field (dipole)
  - Double-sided silicon strip
  - MAPS based micro vertex detector

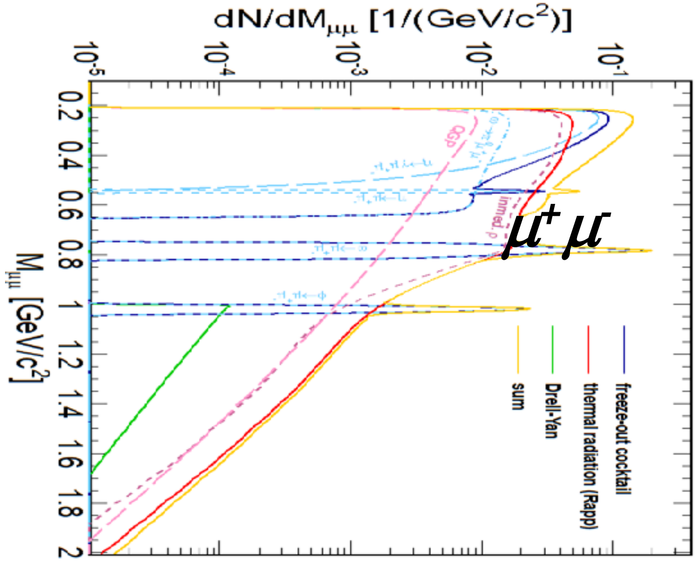
- Particle identification
  - Hadron ID: TOF
  - Photons, π^0, η: ECAL
  - Electrons: RICH, TRD
  - Muons: instrumented absorber (GEM, Straws)



Systematic exploration of baryon dominated matter in A+A collisions from 2 – 11*A* GeV beam energy

Dilepton spectroscopy with CBM





Aim:

- Isolation of excess pairs up to M=2.5 GeV/c^2
- Measurements of emitting source T
- Measurements of T_{eff} vs M_{ll}

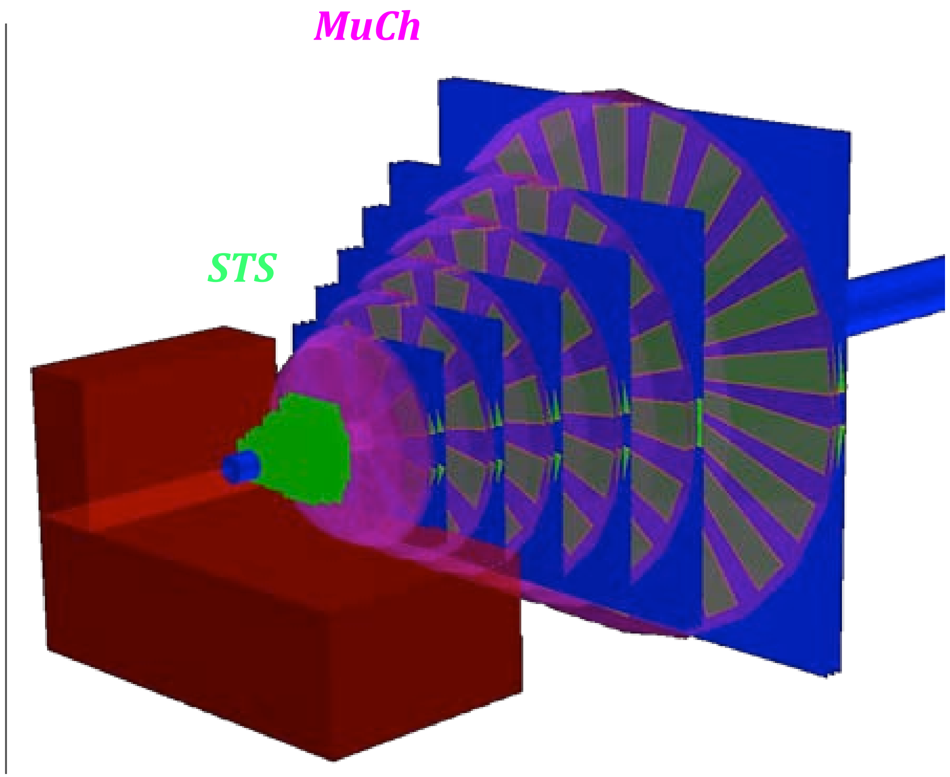
→precision of few MeV is required!

Performance studies:

- Hadronic “cocktail” generator Pluto (π^0, η, ω, ϕ)
- Thermal radiation – Rapp/Wambach Adv. Nucl.Phys.25, 1 (2000) Phys.Rept.363, 85 (2002)
- Hadron and photon BG – transport model calculations, Au+Au collisions, impact parameter: b_{max}= 0 fm and min-bias
- Simulations with realistic detector geometries, material budget, and response

THE MUON SETUP

CBM μ setup

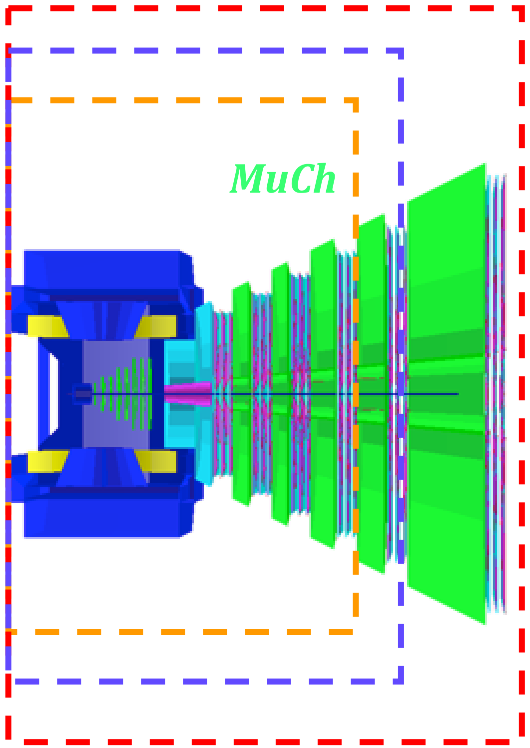


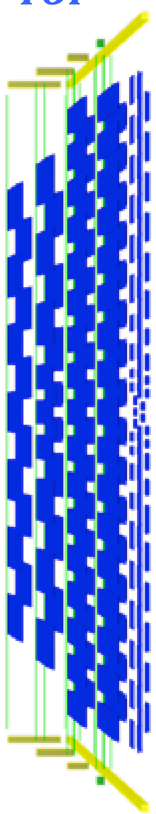
60 (C+Pb) + 20 Fe + 20 Fe + 30 Fe + 35 Fe + 100 Fe (cm)
30 cm gap between 2 absorbers

- Goal:
  - Clean dilepton signal for low- and intermediate mass pairs
- Challenge:
  - Muon detection at low energies
  - Efficient weak decay rejection
  - High areal particle rates in first detector:
  - 0.7 hit/cm2 ≅ 0.4 mA/cm2 (full intensity)
- Strategy:
  - Identification after hadron absorber with intermediate tracking layers
  - Triple GEM detectors with pad read-out

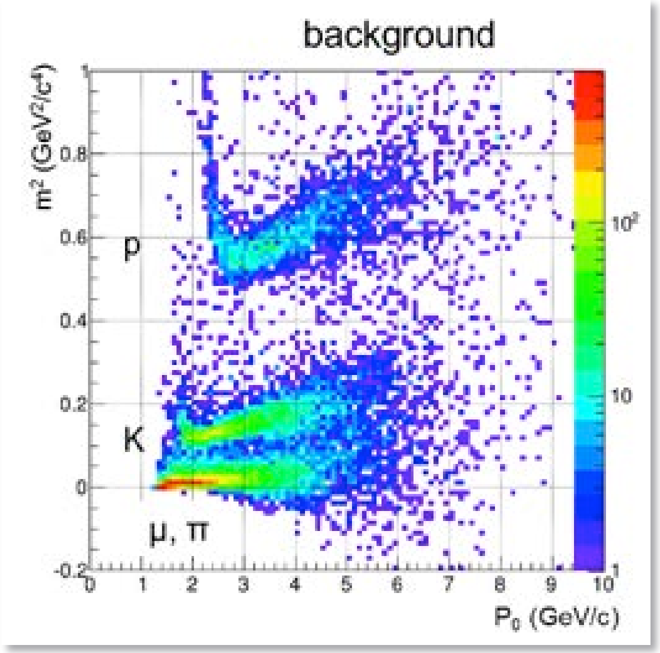
VECC , Kolkata

Muon background rejection

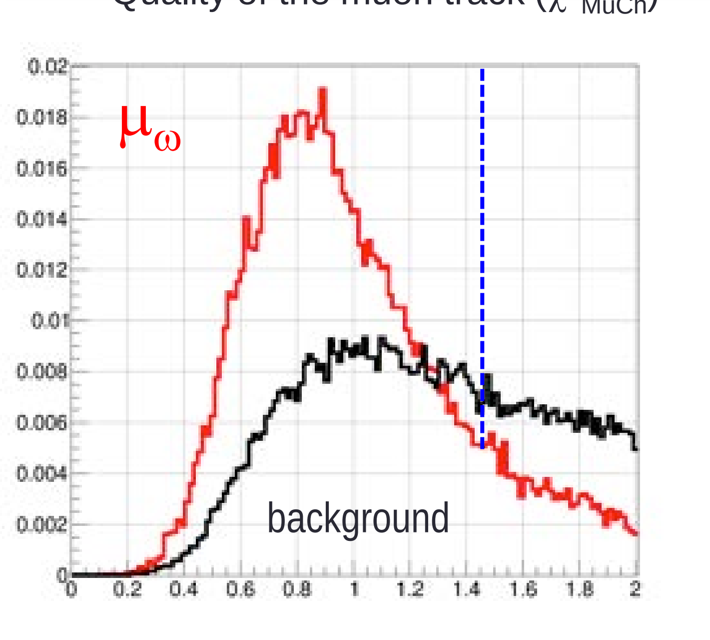




Punched through hadrons in ToF



Quality of the muon track (χ^2_{MuCh})



LMR-IMR @ SIS100

LMR-IMR @ SIS300

J/ψ at SIS100/300

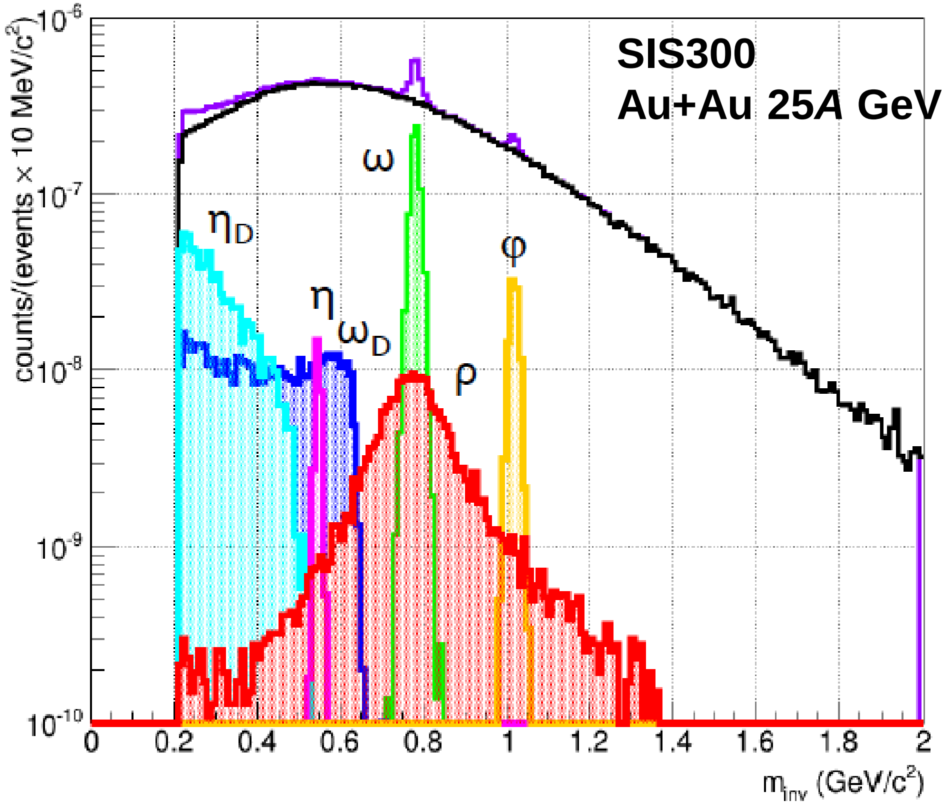
Rejection strategy

① Tracking: χ^2_{vertex}< 2 and 6 STS hits

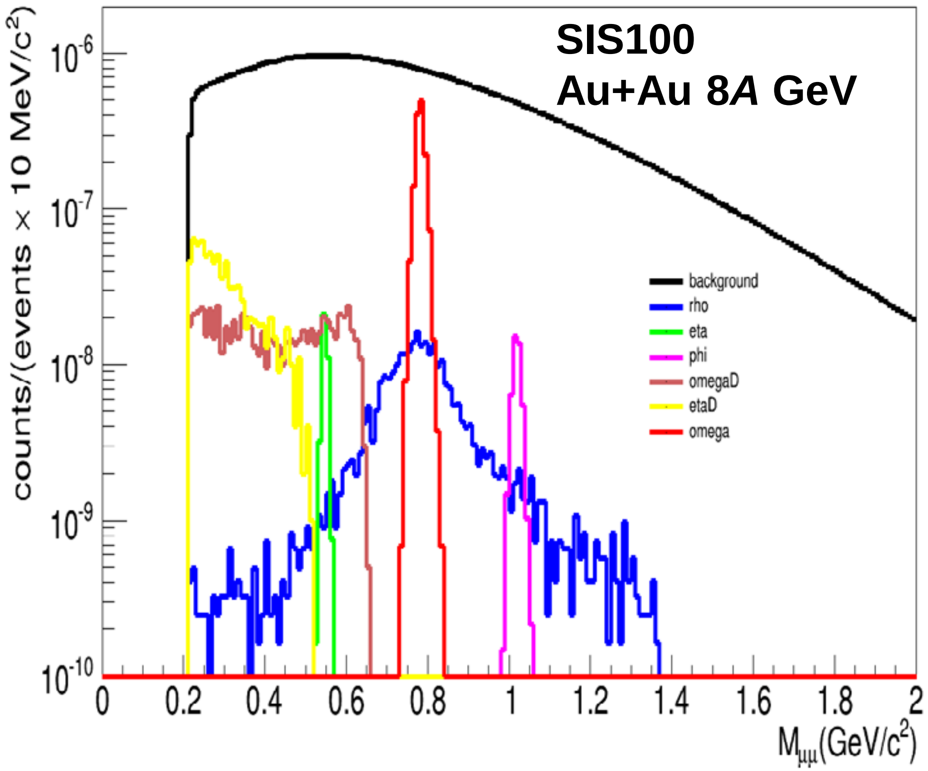
② MuCh: χ^2_{MuCh}< 1.25 and 14 MuCh hits

③ TOF: $m^2 < 0.01$

Dimuon results



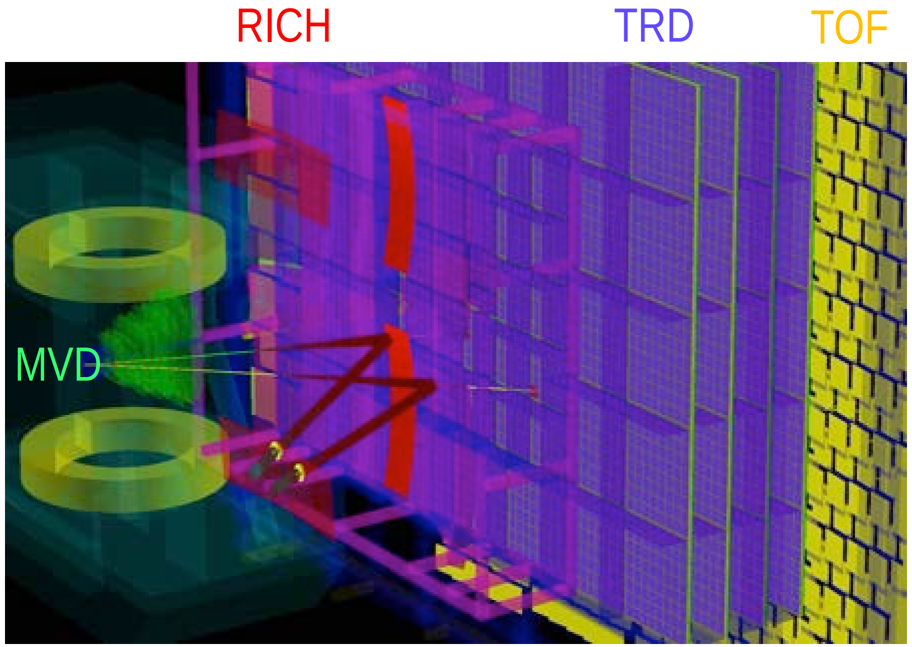
Anna Senger, GSI



Ekata Nandy, VECC

THE ELECTRON SETUP

CBM electron setup

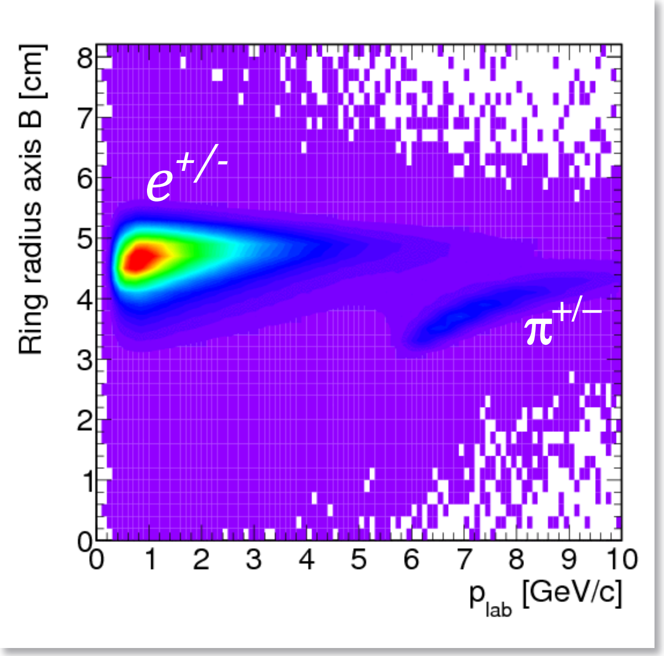


- MVD + STS: MAPS pixel sensors + silicon strip
- RICH: conventional design based on commercial products (Germany, Russia, Korea)
- TRD: thin gap design based on ALICE TRD (Germany, Romania)

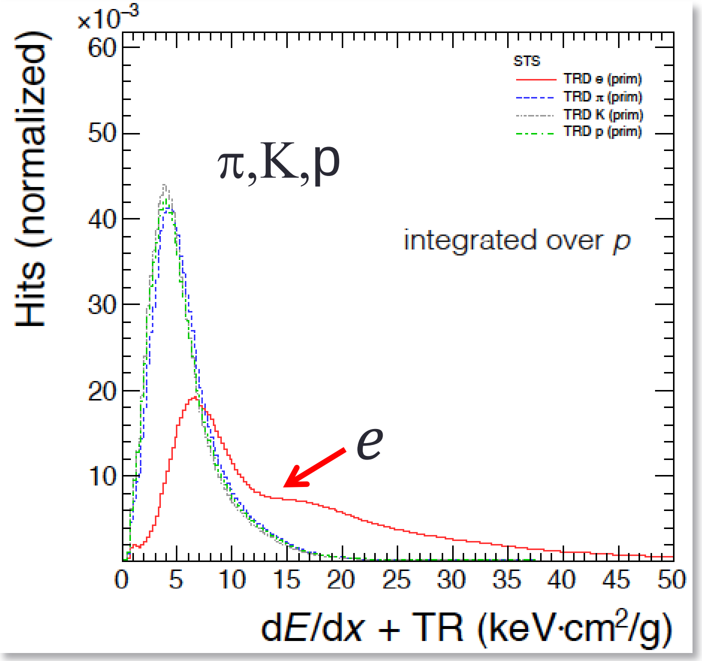
- Goal:
  - Clean dilepton signal for low- and intermediate mass pairs
- Challenge:
  - No electron identification before tracking
  - Background due to material budget of the tracking system
- Strategy:
  - Sufficient π discrimination
  - Reduction of background by reconstructing pairs from γ-conversion and π^0 Dalitz decay

Electron identification: Discriminating input variables

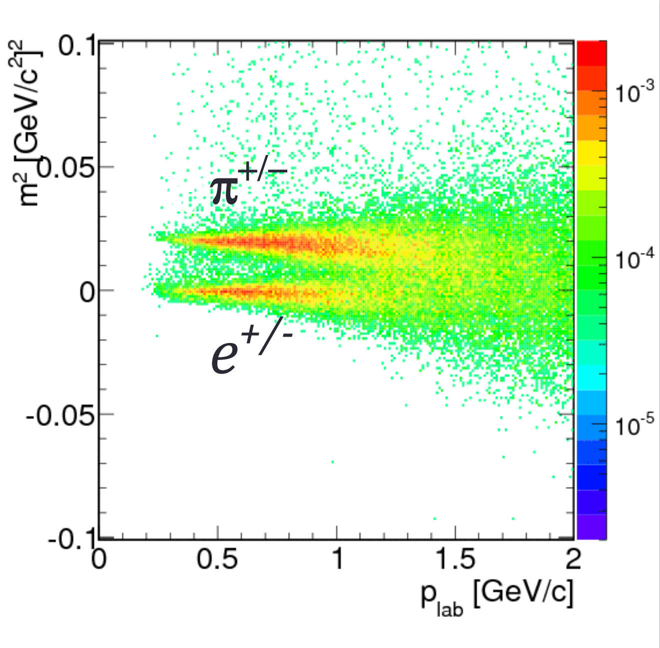
RICH ring radius vs. momentum



TRD signal for single hits with TR production



RICH identified electrons in TOF

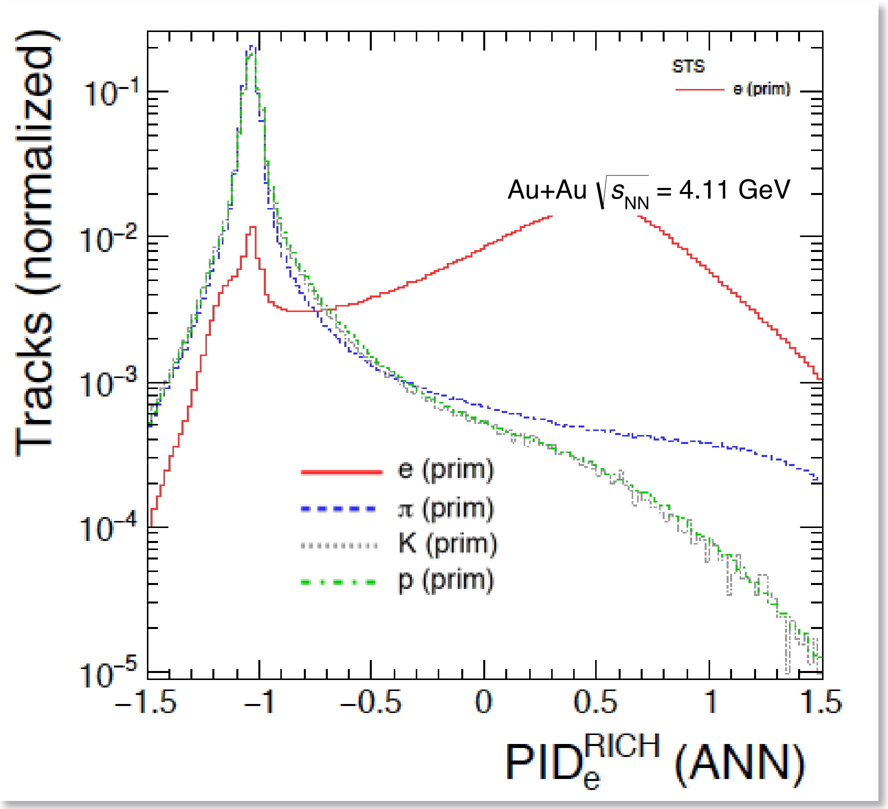


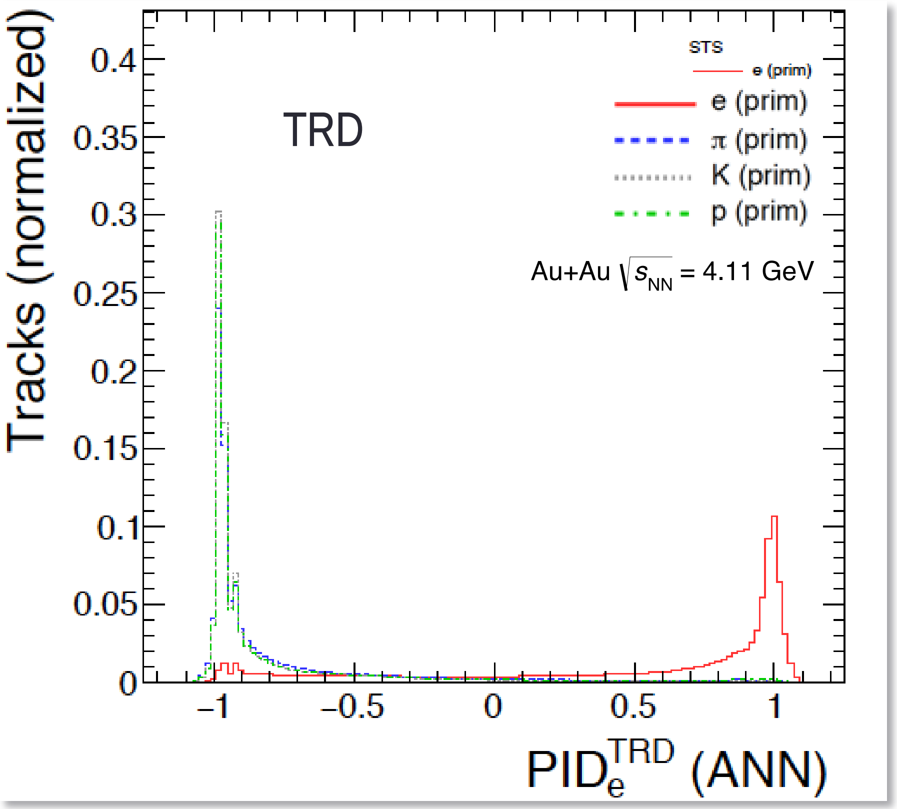
Nonlinear Analysis: Artificial Neural Networks are used to identify leptons

Neural network response function

Julian Book

Output: "probability", that the given particle belongs to **signal** (i.e. is a lepton)





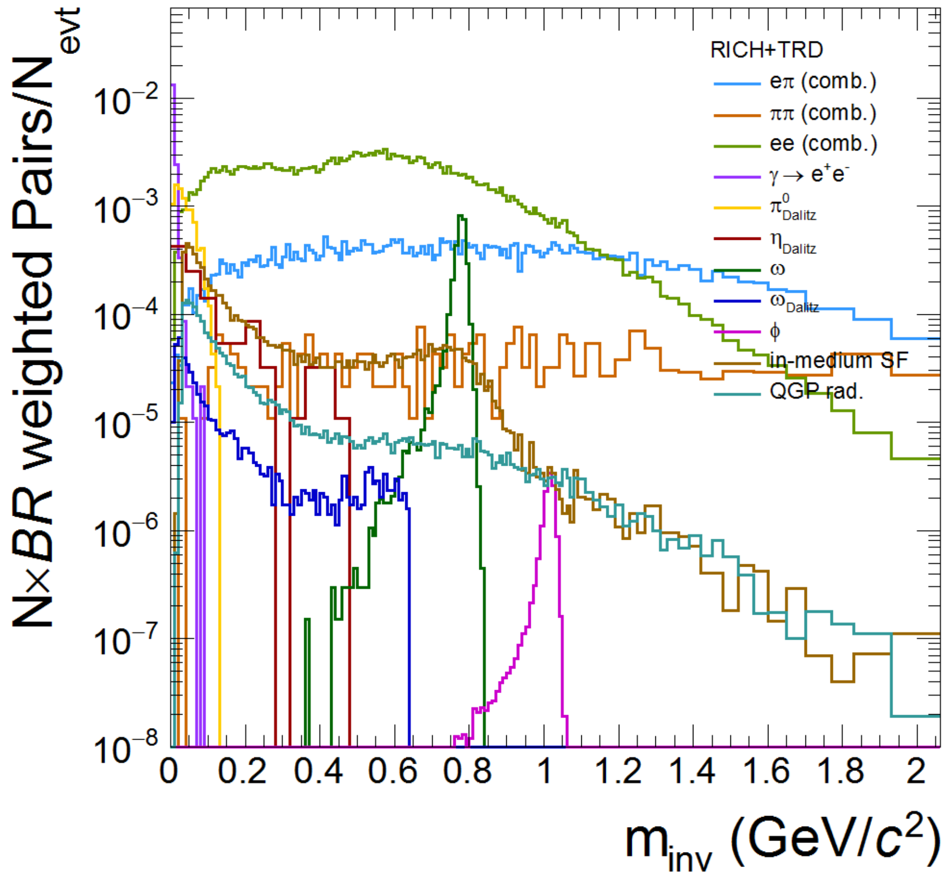
ANN-PID_e > -0.95 (90% e-eff.)

ANN-PID_e > -0.68 (90% e-eff.)

Invariant mass spectrum after *e* iD Cuts

CBM Simulation, Au-Au $\sqrt{s} = 4.1\ A\ \mathrm{GeV}, N_{evt} = 9\ \mathrm{M}$

Julian Book

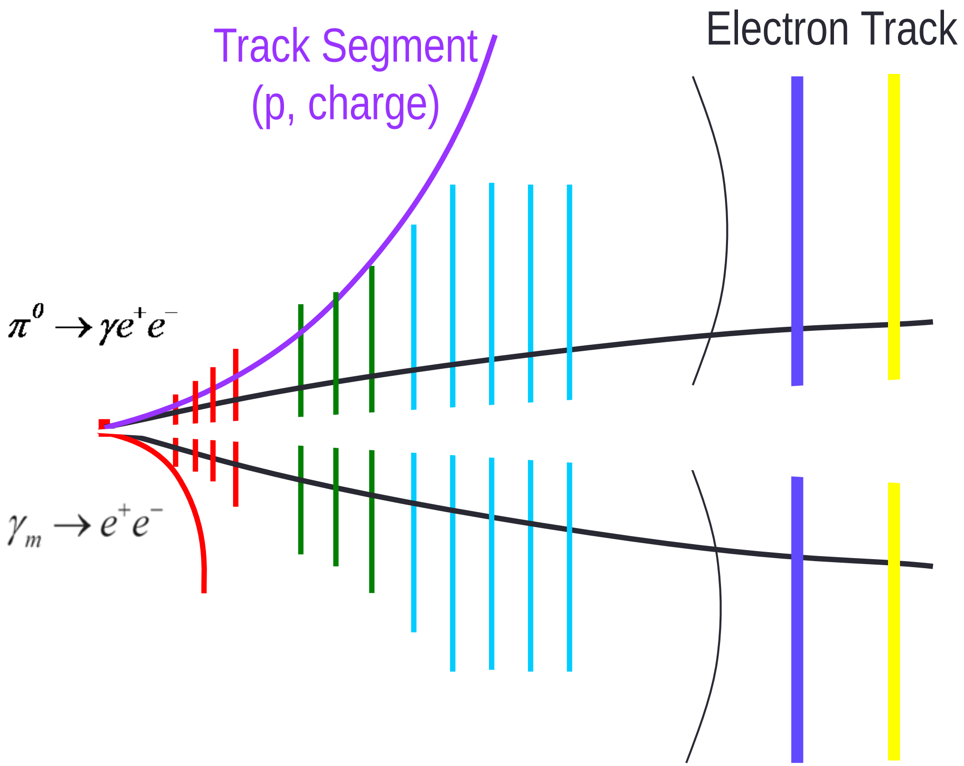


- Major combinatorial background from physical sources
  - Partially reconstructed γ-conversions in target and tracking system, π^0 Dalitz decays

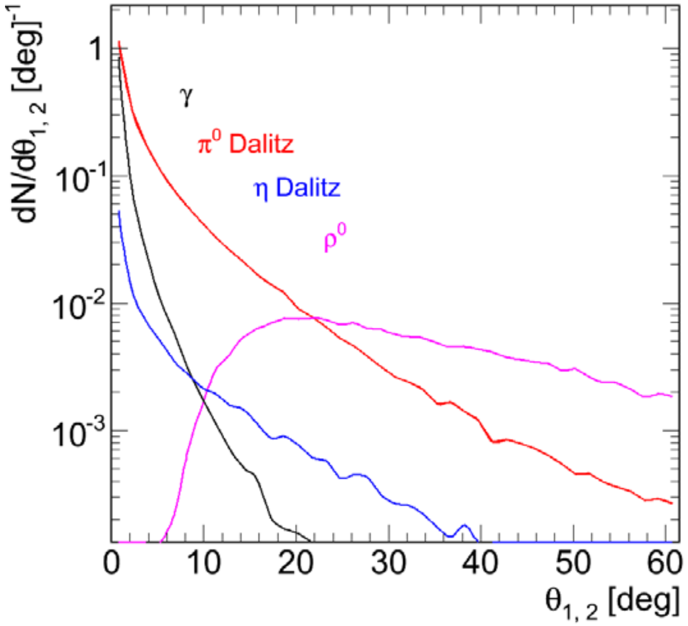
- Strategy:
  - Use topological cuts in order to reject this background

Track topology

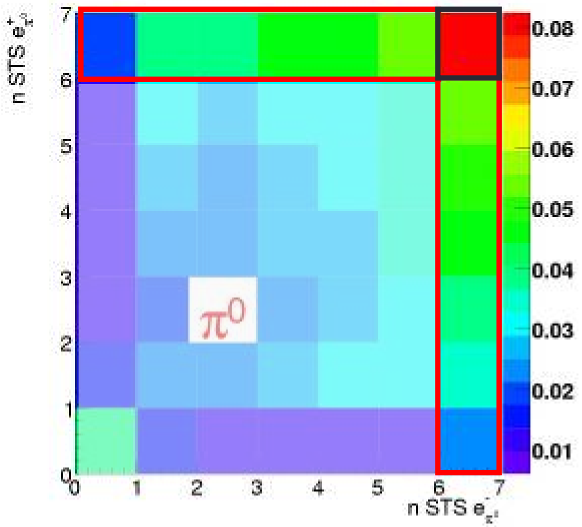
Erik Krebs



Opening angle distribution between e^+e^-

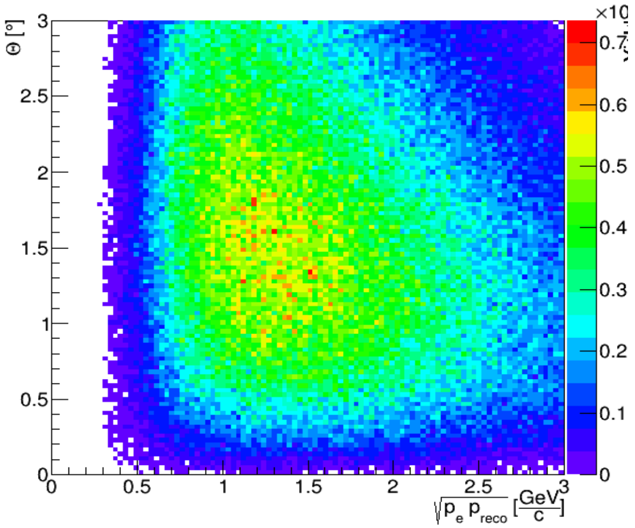


Correlation of the number of STS traversed by e^+e^- pairs from π^0-Dalitz

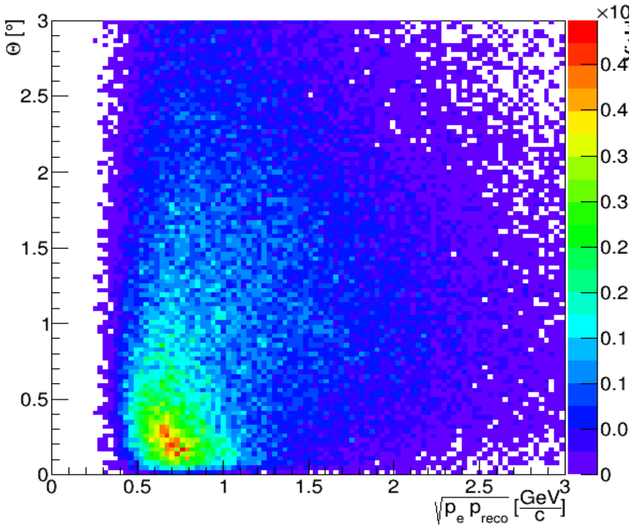


Background rejection strategy

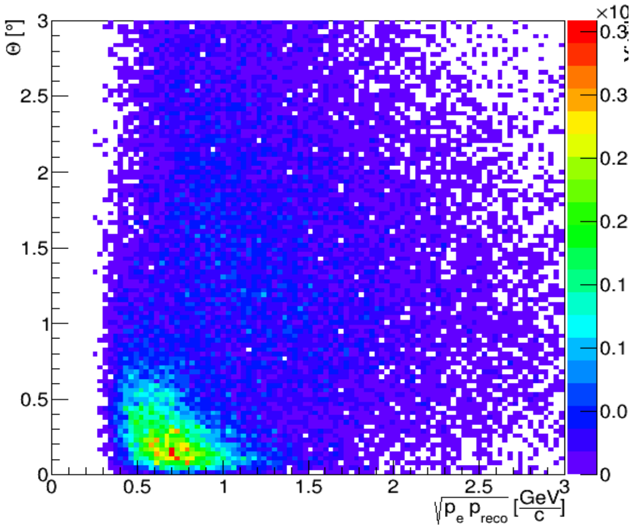
- Select closest neighbor track and plot opening angle θ versus $\sqrt{p_e p_{reco}}$
- Primary track cut
  - Extrapolate tracks to primary vertex and cut on deviation to the vertex
  - Tracks must have a hit in the first MVD station or be in its acceptance
- Track topology cut
  - Cut on opening angle and product of momenta



Signal



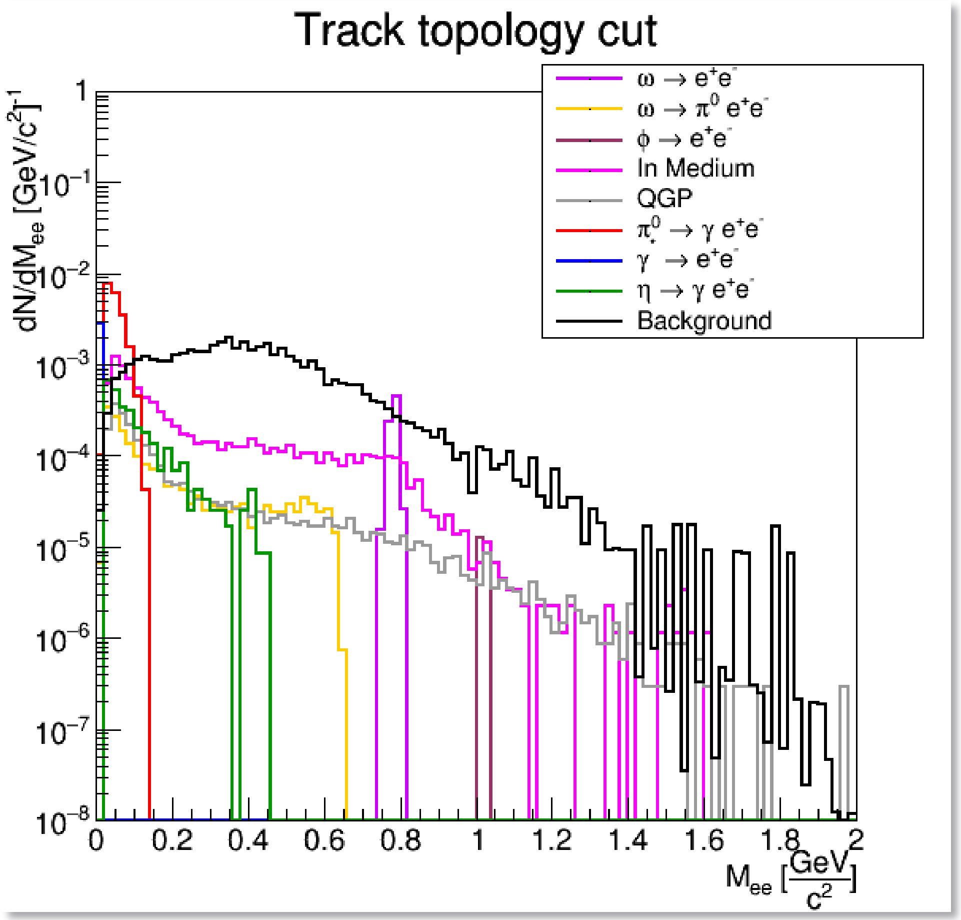
π^0-Dalitz

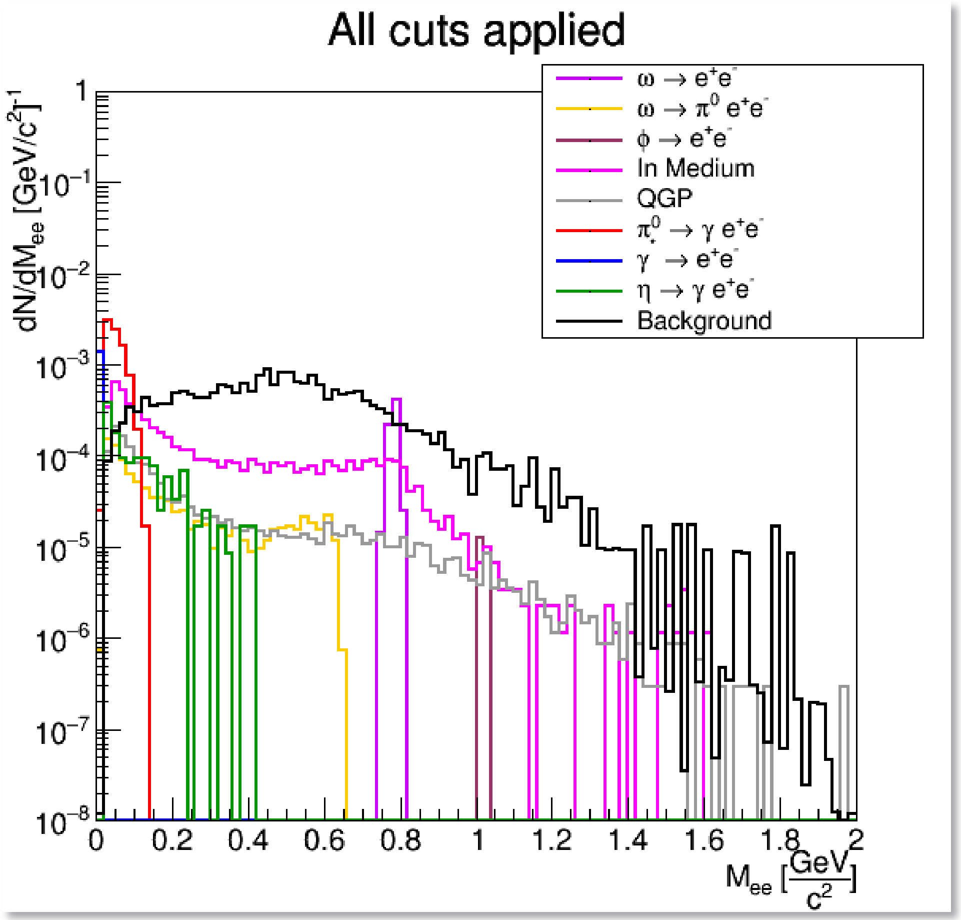


γ-conversions

Performance of the CB rejection cuts

CBM Simulation, Au-Au $\sqrt{s} = 4.1\ A\ \mathrm{GeV}, N_{evt} = 6\ \mathrm{M}$





CBM AT PHASE-0

HADES Upgrade

Detector upgrades

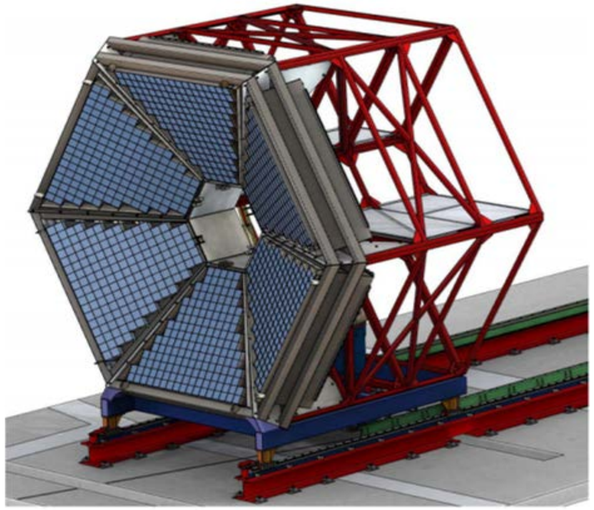
- ECAL (PSP 1.1.2.4)
- RICH-700 (synergy with CBM – UV detector)
- FW-Tracker (synergy with PANDA – straws)
- FW-RPC (detector elements mostly existing)
- MDC-FEE (PSP 1.1.2.4, 1.1.2.5)
- FW-Wall (synergy with CBM – PSD)
- START (synergy with CBM – t_0 detector)

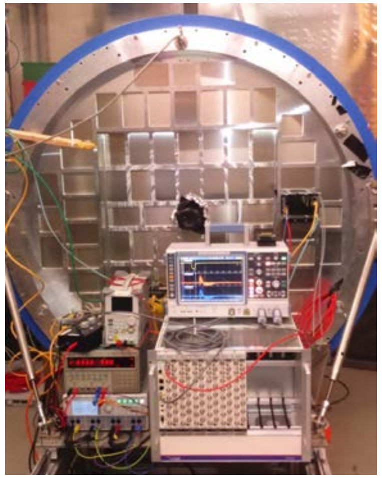
Up to 50 kHz interaction rate, improved electron-id, detection of photons, large acceptance for exclusive processes.

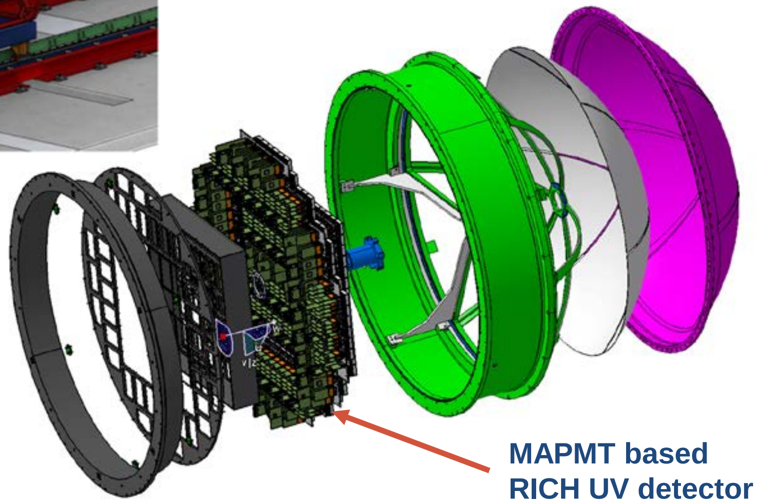
Planned physics runs (2018-2022)

- we anticipate three long runs, i.e.:
  - π+(CH2)n/LH2: baryon electromagnetic transition form factors, baryonic resonances with strangeness.
  - p+A/p+p: strangeness/vector mesons in medium. Hyperon spectroscopy.
  - A+A: medium system size at maximal energy, multi-strange baryons, dileptons.

ECAL based on OPAL lead glass







MAPMT based RICH UV detector

Secondary pion beam in combination with dilepton spectrometer is world-wide unique!

GSI

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Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
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Kiev Inst. Nucl. Research

The CBM Collaboration

60 institutions, 530 members

Summary

CBM scientific program at SIS100:

- Exploration of the QCD phase diagram in the region of neutron star core densities
  $\rightarrow$ large discovery potential.

Goals for the dilepton program:

- Establish a full excitation function of dilepton radiation
- Extract excess yields, temperatures and flow
- Search von non-monotonic behavior of these observables
- Study in detail the spectral distribution around 1 GeV to learn about the chiral symmetry restoration

FAIR Phase 0:

- HADES with CBM RICH photon detector
- Focus in particular on baryon transition form factors using pion-beam induced reactions
- Electromagnetic decays of hyperons