Physics Opportunities With Protons from SIS100

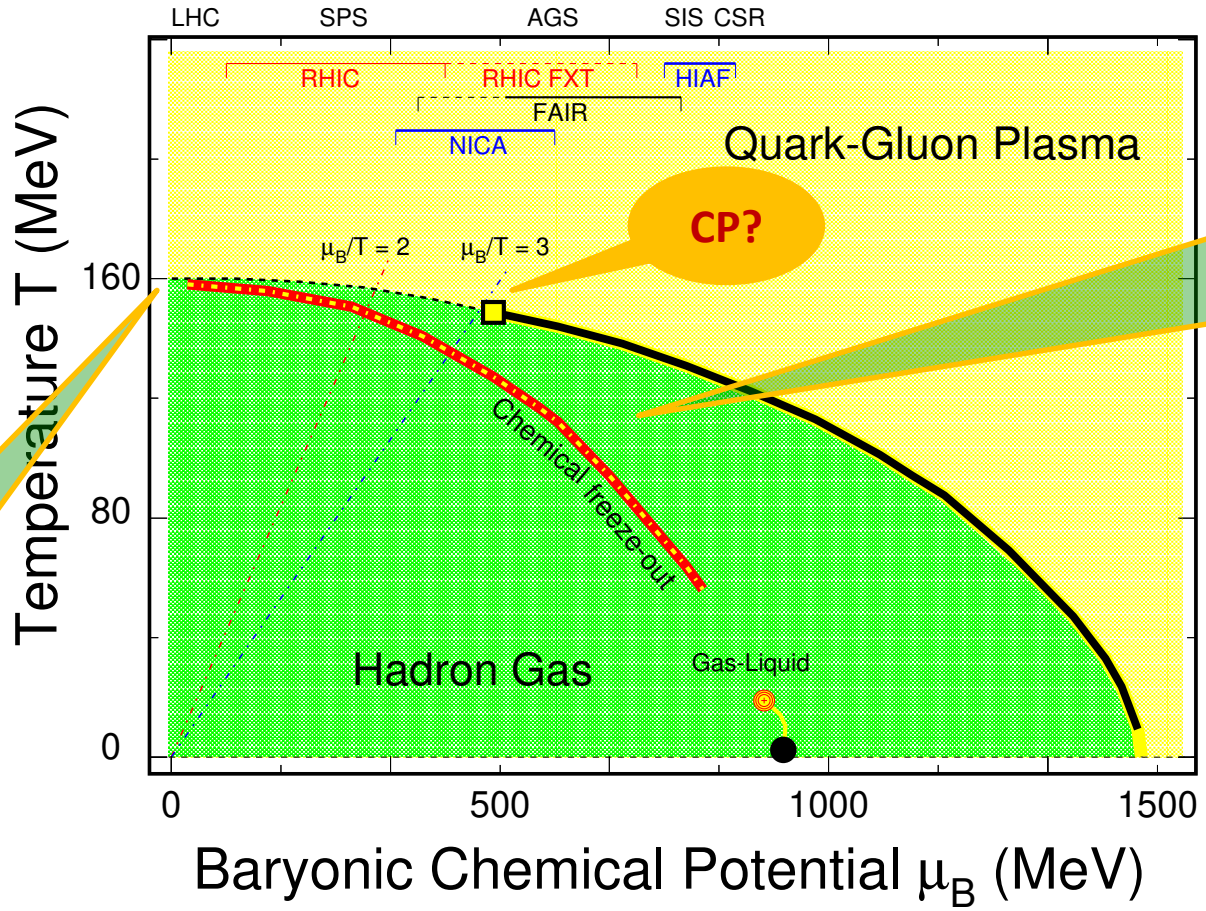
1) p+p collisions at extreme multiplicity;
2) Λ-polarization in p+p / p+A collisions

Nu Xu

GSI / LBNL

p+p Collisions at Extreme Multiplicity

- Properties of the smooth cross-over;
- p+p collisions;
- Full lepton distributions with **ALICE3**



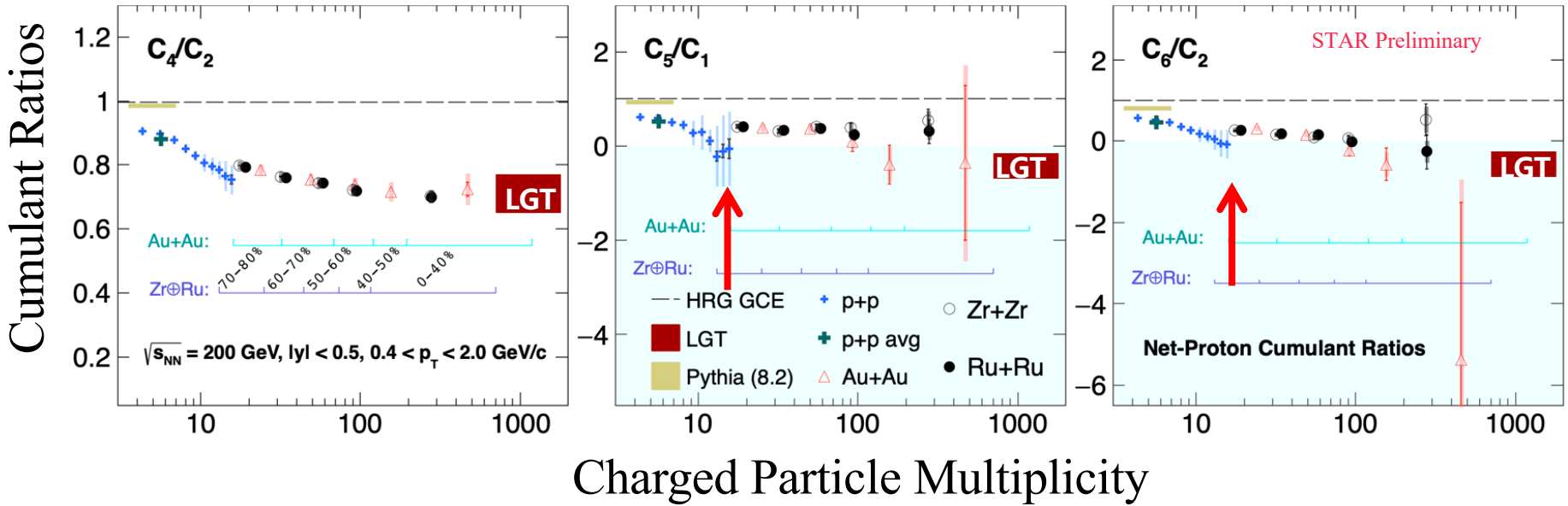
RHIC BES-II

CBM

ALICE at LHC

- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions

Net-p in 200 GeV p+p and Au+Au Collisions

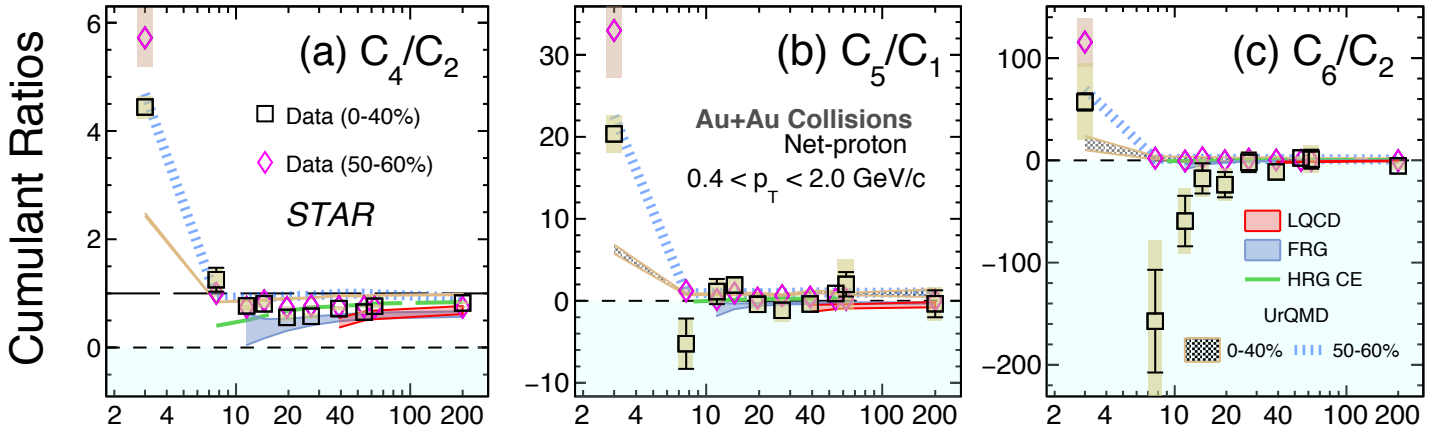


1) In 200GeV p+p collisions, at high multiplicity, C_5/C_2 and C_6/C_2 become negative as LGT predicted; *pp collisions are more efficient in producing QGP matter!*

2) Direct evidence for the QGP formation in 200GeV central collisions!

HotQCD Collaboration, PR**D101**, 074502 (2020)

C_4, C_5 and C_6 in Au+Au Collisions



$$\frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$$

Lattice prediction:
Phys. Rev. **D101**, 074502(2020)

STAR: Phys. Rev. Lett., **130**, 82301(2023)

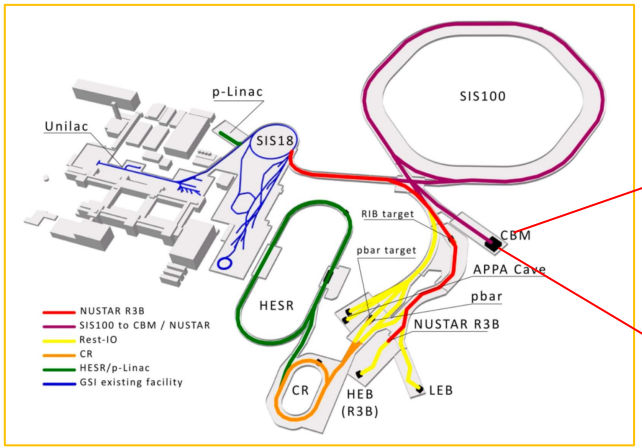
1) **C6/C2 < 0** from 200 GeV to 7.7 GeV consistent with LGT prediction for C_5/C_2 and C_6/C_2! HotQCD Collaboration, PR**D101**, 074502 (2020)

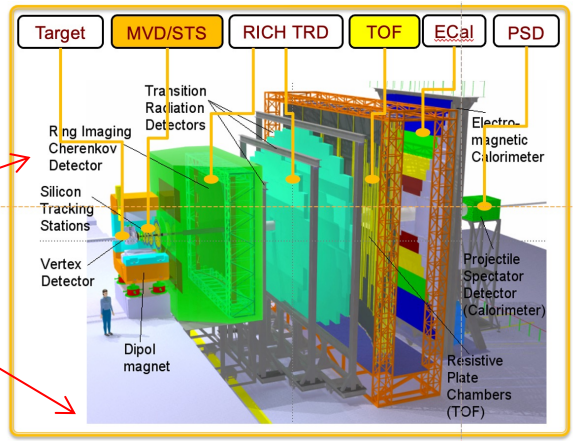
2) **Direct evidence for QGP formation in central Au+Au collisions 200 – 39 GeV!**

3) At 3 GeV: hadronic interactions dominant!

STAR: Phys. Rev. Lett., **128**, 202303 (2022)

Proposal I: Event Multiplicity Scan





Detector Requirement:

- Wide charged particle acceptance;
- Good particle ID;
- High rate capability

p + p→ $p + \bar{p} + x$ (p = 2 – 20 GeV/c,)

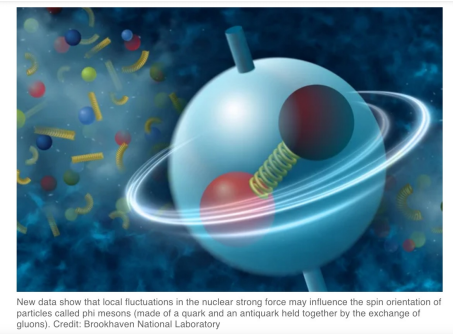
Precisely determine event multiplicity M_{event} and high moments of protons, net-p (κ_i: $i = 1, 2, 3, 4, 5, 6$)

→ Understand the EOS of the hot matter at high baryon density;

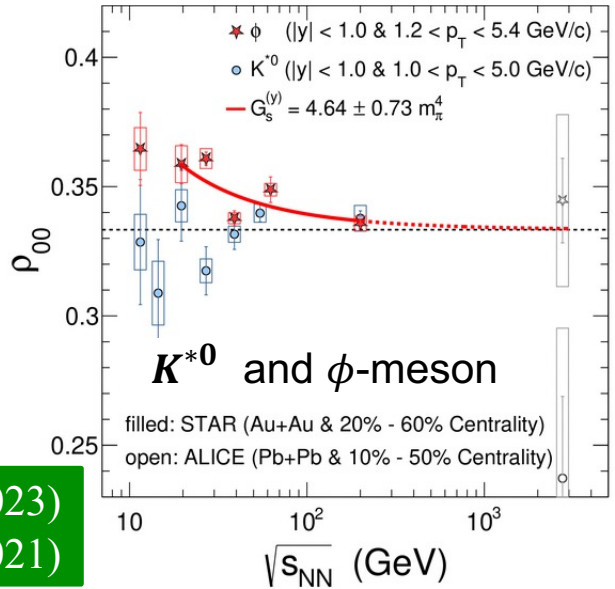
→ Compare with data from higher collision energies

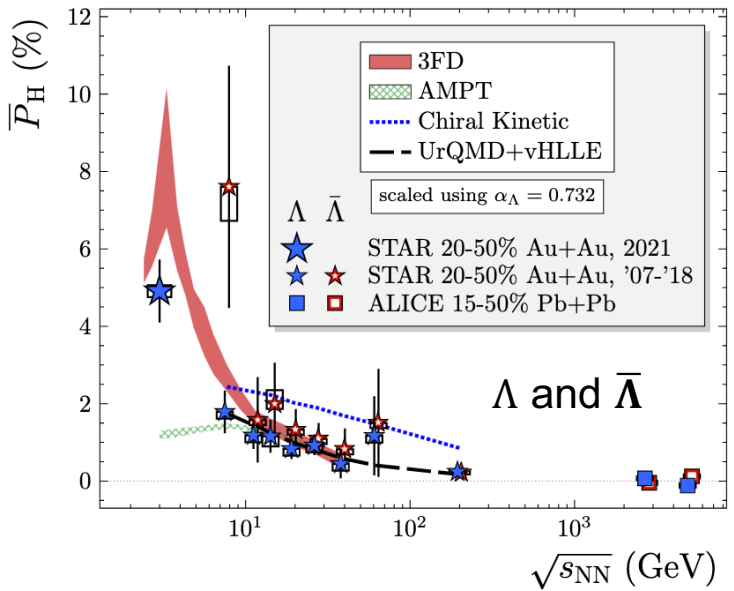
HIC

Global Spin Alignments in Heavy-Ion Collisions



New data show that local fluctuations in the nuclear strong force may influence the spin orientation of particles called phi mesons (made of a quark and an antiquark held together by the exchange of gluons). Credit: Brookhaven National Laboratory





STAR: *Nature*, **614**, 244(2023)
PR**C104**, 61901(2021)

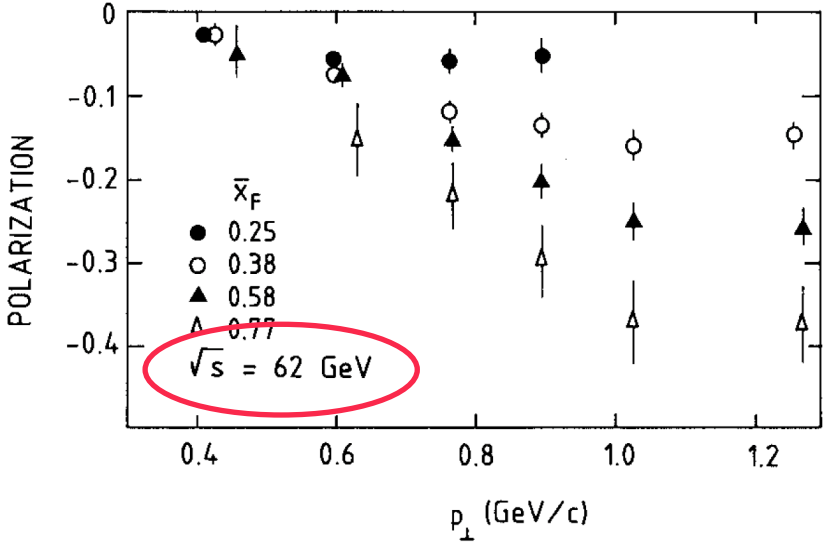
1) Unexpected large ρ_{00} for ϕ-meson: "*'Unbelievable' Spinning Particles Probe Nature's Most Mysterious Force*" – ***SCIENTIFIC AMERICAN*** February 2, 2023
2) ρ_{00} of K^{*0} ??
3) It is low energy phenomena!

Λ-polarization in p+p / p+A Collisions

"I am an engineer. I am after the facts, only the facts."

Harold Eugene Edgerton
(American, 1903–1990)

Λ-polarization in p+p Collisions



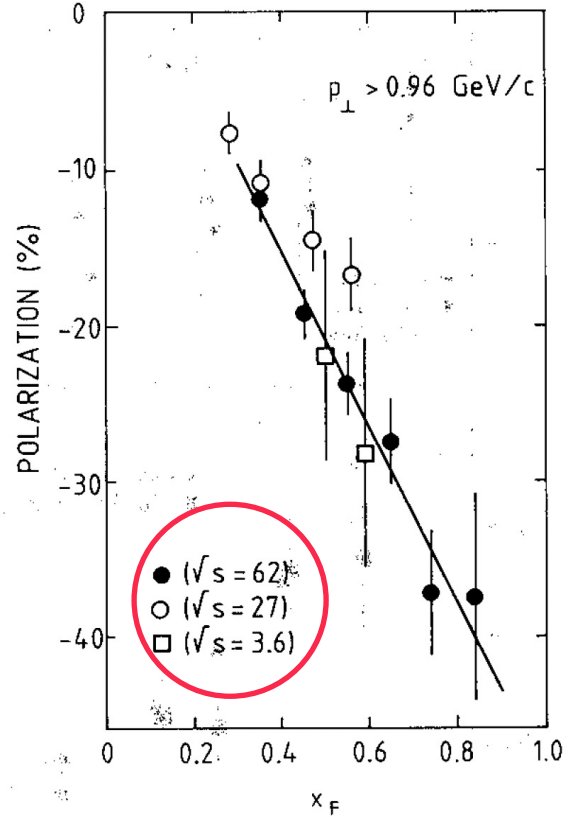
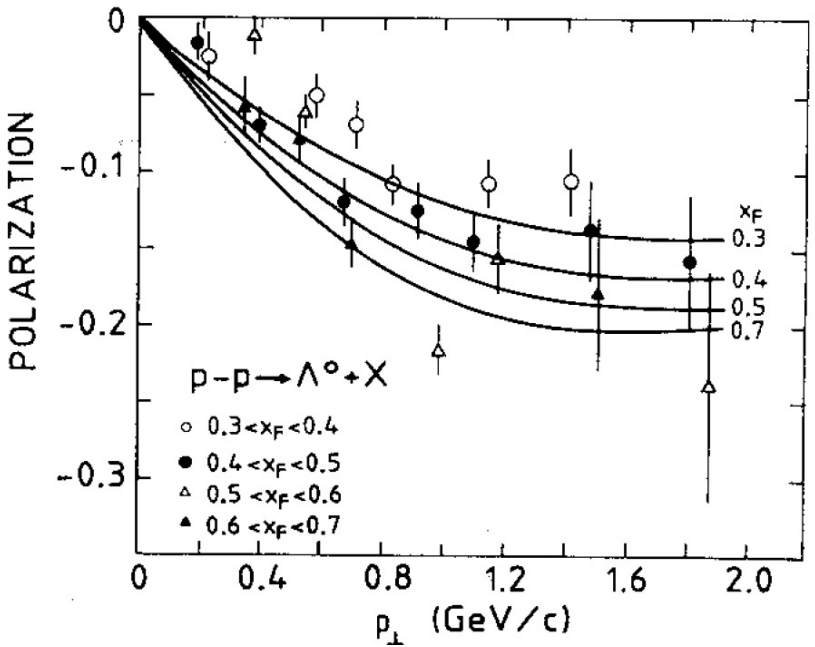


Fig. 35

p+p collisions:

1) Λs are negatively polarization;
2) The larger the x_f and the p_T, the stronger the polarization;
3) Up to 62 GeV, seems no energy dependence

Λ-polarization in p+p Collisions

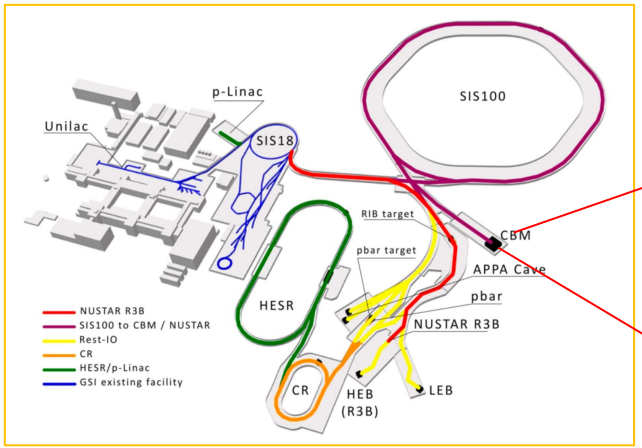


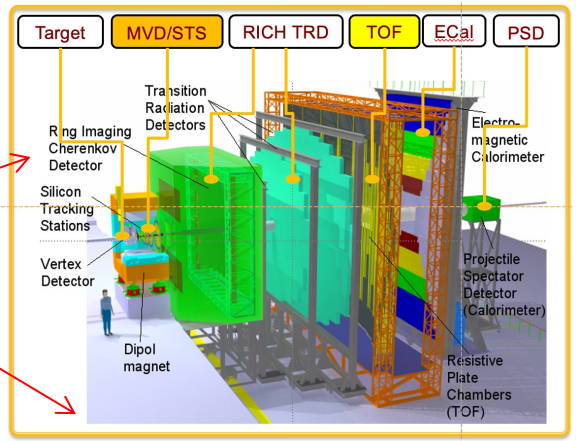
Model calculations:

1) Parton model: Polarization took place during the hadronization or quark recombination. In this picture, anti- Λ should not present any polarization in a similar proton collisions.
2) Polarization occurs at parton level!
3) All model calculations *over estimate the magnitudes* of the observed Λ-polarization.

- "Λ-polarization in *h-N*, *h-A* and *A-A* Interactions", by Apostolos D. Panagiotou, CERN, 1989;
- T. DeGrand and H.I. Miettnen, Phys. Rev. **D23**, (1981) 1227 and **D24** (1981) 2419;
- T.D. Lee, J. Steinberger, G. Feinberg, P.K. Kabir, C.N. Yang, Phys. Rev. **106** (1957)1367

Proposal II: Λ-polarization





Detector Requirement:

- Wide charged particle acceptance;
- Good particle ID;
- High rate capability;
- Secondary vertexing

(1) p + p $\rightarrow \Lambda + K^+ + x$ (p = 2 – 20 GeV/c, full event reconstruction)

Beam momentum scan, precisely determine Λ-polarization vs. x_f, p_T

→ Understand the mechanism of Λ-polarization and the structure of Λ

EIC

(2) p + A $\rightarrow \Lambda + K^+ + x$ (A = C, Cu, Au, Pb, U)

Target mass scan, precisely determine Λ-polarization vs. M_{event}, p_T

→ Understand the effect of re-scatterings and thermalization

HIC

Acknowledgements:

A. von Humboldt Foundation

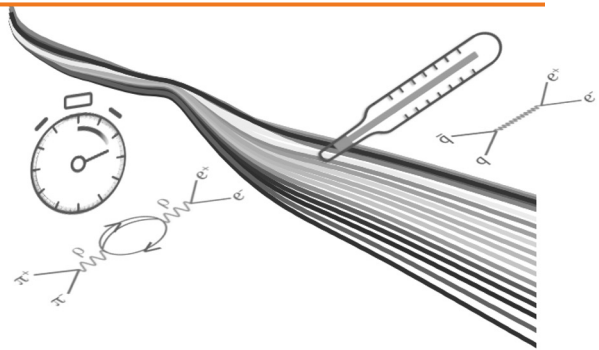
Thank you for your attention!

pp physics with SIS100

ELECTROMAGNETIC PROBES

Tetyana Galatyuk
GSI / Technische Universität Darmstadt

June 21, 2023
Krakow



Electromagnetic production rate

- em current-current correlation function

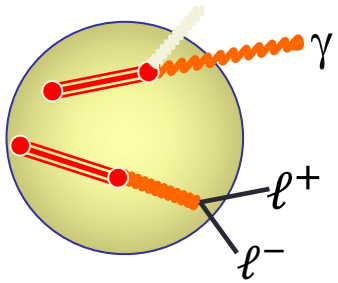
$$\Pi_{em}^{\mu\nu}(q_0, q) = -i \int d^4x\, e^{iq\cdot x}\theta(x^0)\langle[j^\mu(x), j^\nu(0)]\rangle$$

- Photons characterized by “transverse” momentum:

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{em}}{\pi^2} f^B(q\cdot u; T)\, Im\Pi_{em}(q_0 = q; \mu_B, T)$$

spectral function

determines both photon and dilepton rates



- Dileptons carry extra information: invariant mass
  → unique direct access to in-medium spectral function

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

lepton phase space factor

thermal Bose distribution

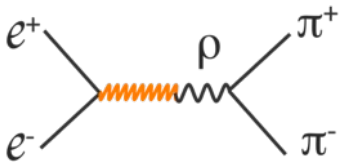
McLerran, Toimela, PRD 31, 545 (1985)
Weldon, PRD42, 2384-2387 (1990)
Gale, Kapusta, PRC 35, 2107 (1987) & NPB 357, 65-89 (1991)

Electromagnetic correlator in the vacuum

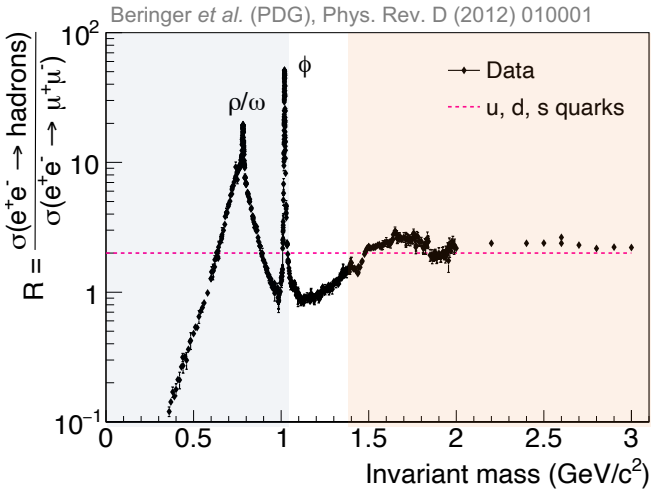
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

Low-mass regime LMR

em spectral function is saturated by light vector mesons (VMD $J^P = 1^-$ for both γ^* and VM, **ρ playing the dominant role**)

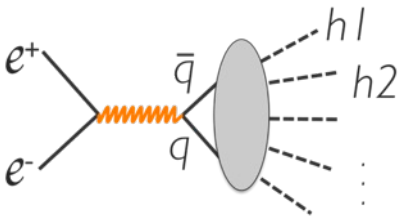


Beringer *et al.* (PDG), Phys. Rev. D (2012) 010001



Intermediate-mass regime IMR

perturbative QCD continuum (quark degrees of freedom)



$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

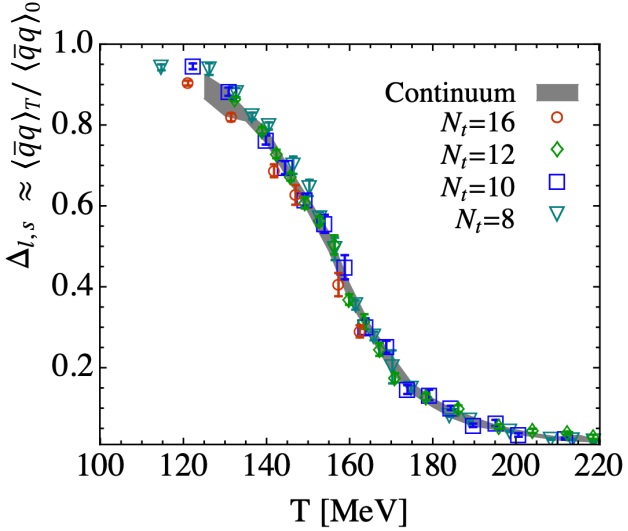
$$Im\Pi_{em}^{vac} = -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \cdots\right) N_c \sum_{q=u,d,s} (e_q)^2$$

Sakurai, Ann.Phys. 11 (1960)

Electromagnetic spectral functions

connection to chiral symmetry χ_c

- χ_c is broken spontaneously by dynamical formation of a quark condensate $\langle\bar{q}q\rangle$
- condensates $\langle\bar{q}q\rangle$ constrained by lattice QCD



Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

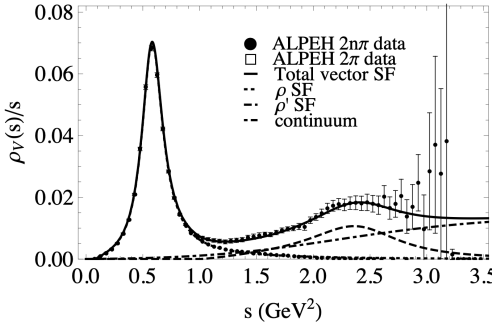
- QCD and chiral sum rules …

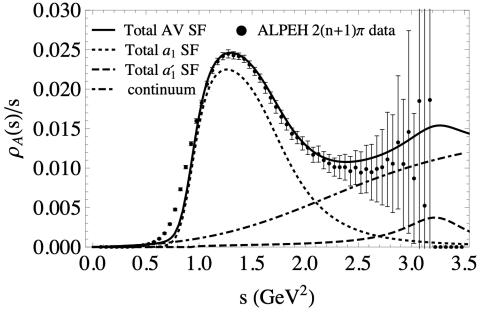
S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

- … accurately satisfied in vacuum

Hohler, Rapp, Annals Phys. 368 (2016)
Holt, Hohler, Rapp, PRD87 (2013) 076010



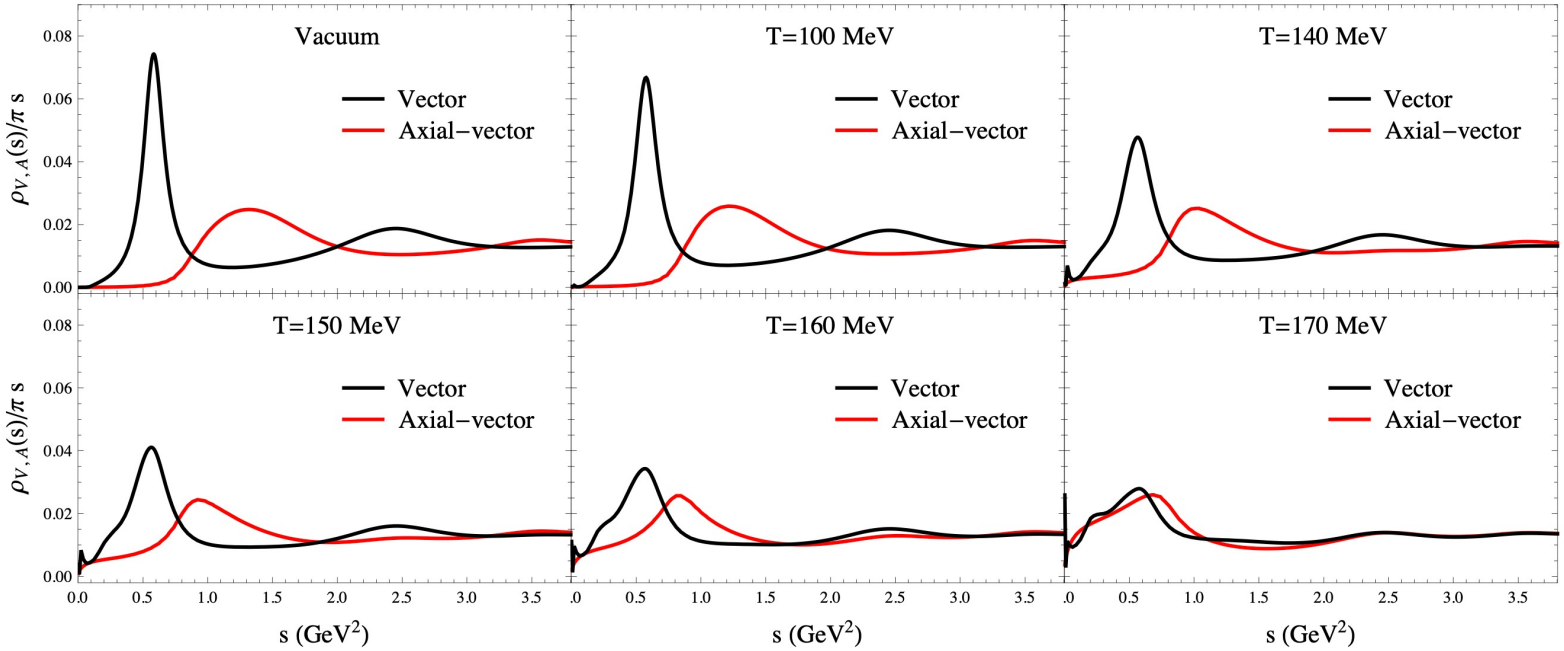


- … remain valid in medium

Kapusta, Shuryak, PRD49 (1994) 4694

How does chiral symmetry restoration at finite T and μ_B manifests itself?

In-medium *em* spectral functions – connection to chiral symmetry χ_c

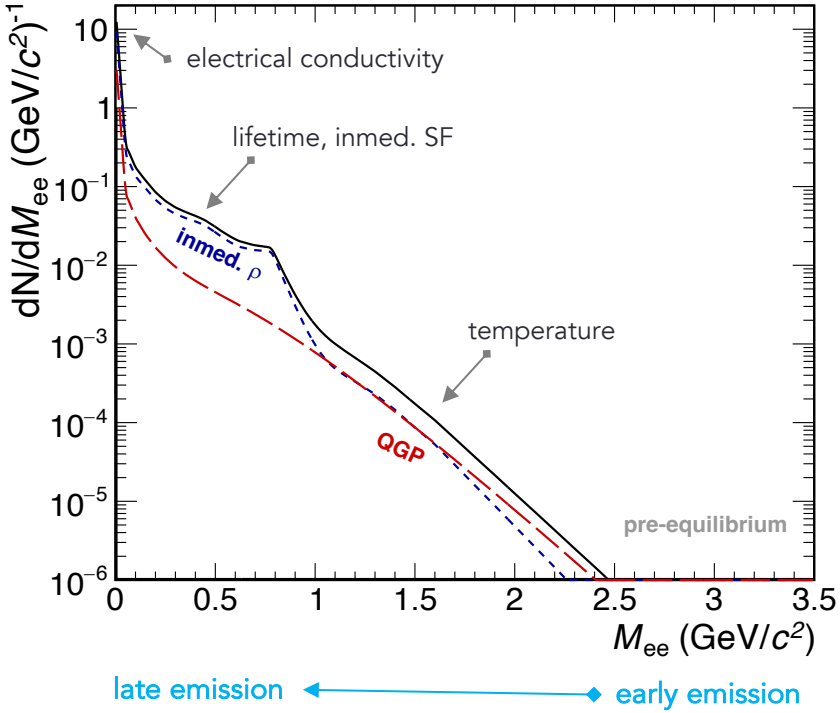


ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

Hohler and Rapp, PLB 731 (2014) 103

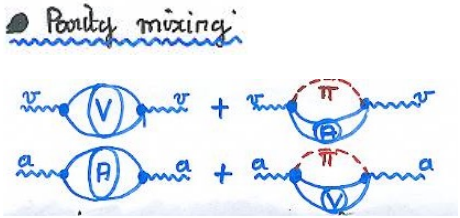
Electromagnetic production rate

- Encodes information on matter properties enabling unique measurements:
  - restoration of chiral symmetry
  - degrees of freedom of the medium
  - transport properties
  - fireball acceleration, polarization, fireball lifetime, average fireball temperatures (no blue-shift)

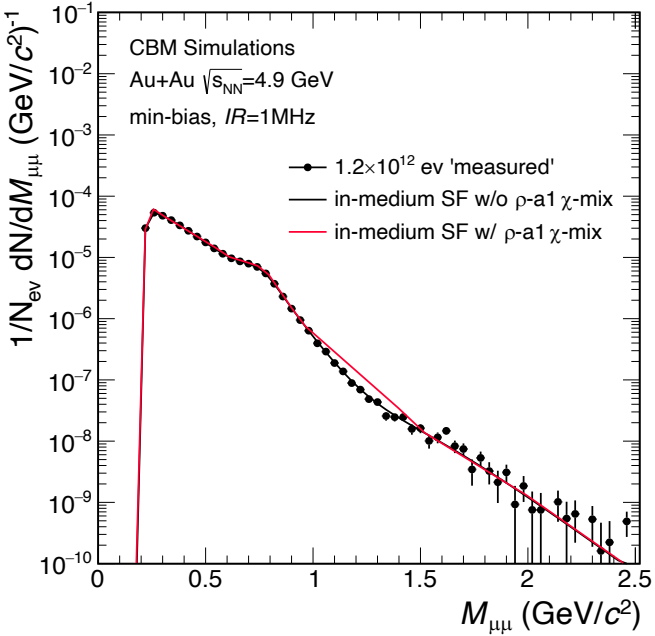


Signature for chiral symmetry restoration: $\rho - a_1$ chiral mixing

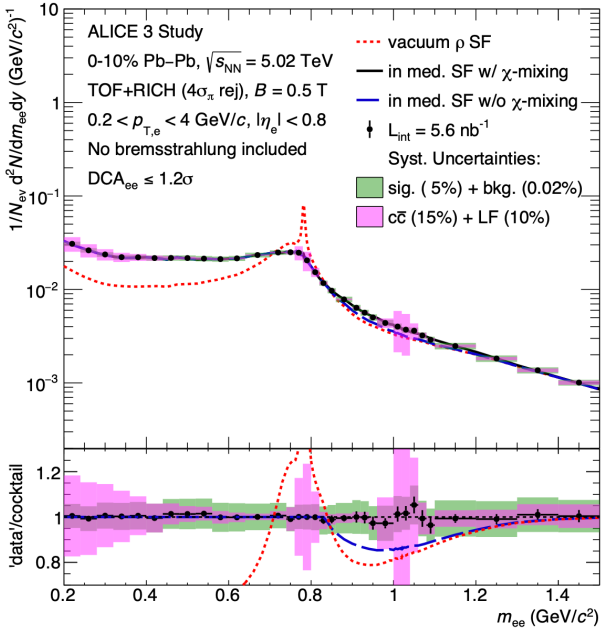
➥ experimental challenge: physics background ($M_{\ell\ell} > 1$ GeV)



Guy Chanfray, 1999 Lecture Notes



CBM energies: negligible correlated charm contribution, decrease of QGP, Drell-Yan contribution pp, pA



LHC energies: large contribution from $c\bar{c}, b\bar{b}$ and QGP, negligible Drell-Yan

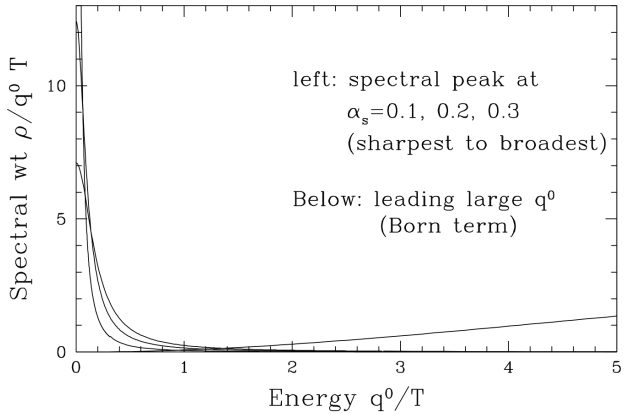
Transport properties of the medium

Electrical conductivity

can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

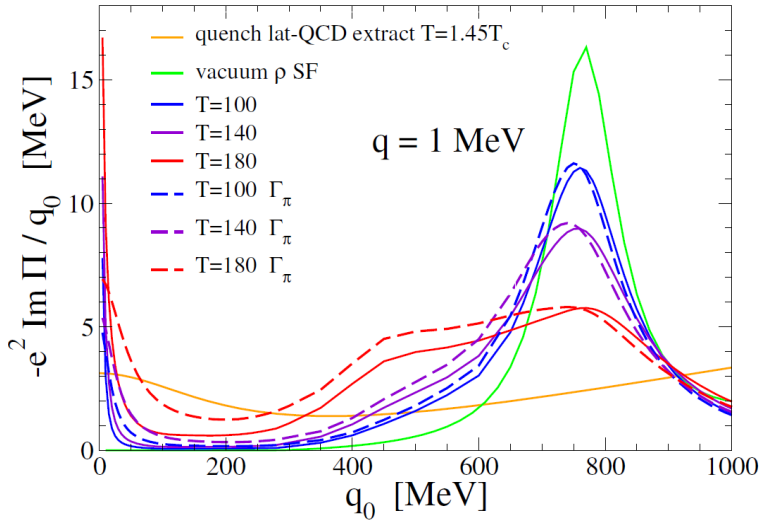
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Transport peak in the limit of very low mass and p_T



Moore and Robert, arXiv:hep-ph/0607172

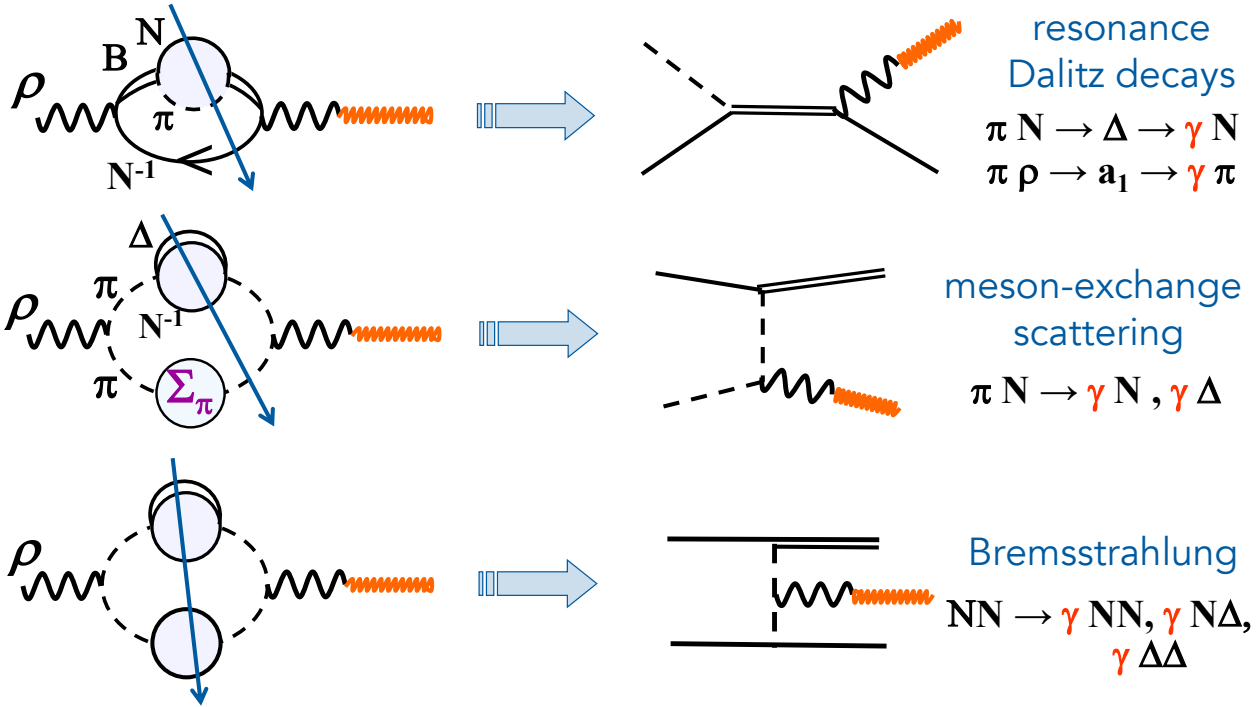
Rapp, EMMI RRTF 2021



- Conductivity is reduced when thermal-pion interactions included
- Transport peak broadens

Production Processes from ρ Spectral Function

→ Cuts (imag. parts) of Selfenergy Diagrams:



resonance Dalitz decays

$\pi N \rightarrow \Delta \rightarrow \gamma N$

$\pi \rho \rightarrow a_1 \rightarrow \gamma \pi$

meson-exchange scattering

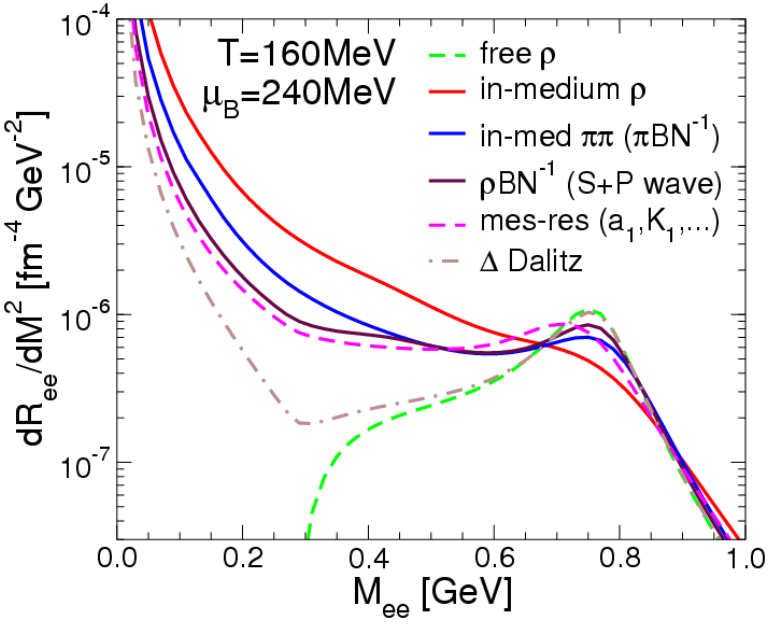
$\pi N \rightarrow \gamma N$, $\gamma \Delta$

Bremsstrahlung

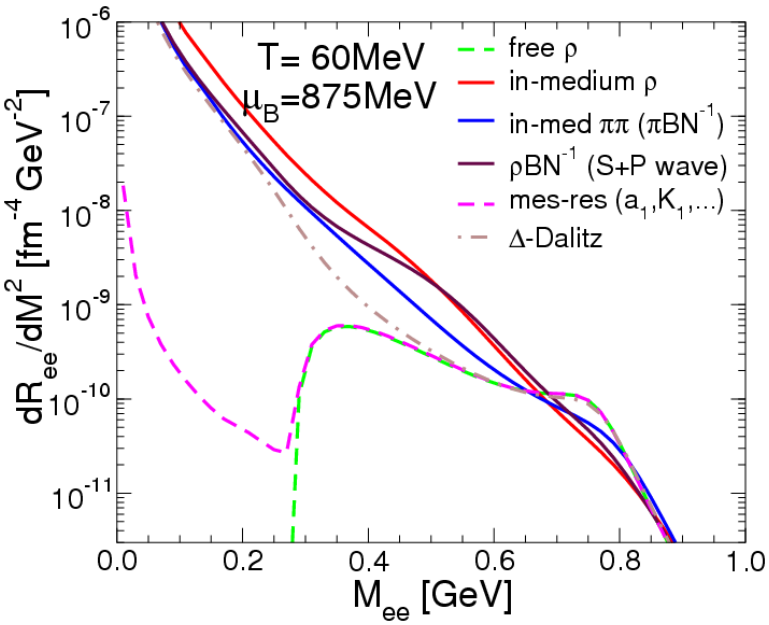
$NN \rightarrow \gamma NN$, $\gamma N\Delta$, $\gamma \Delta\Delta$

Decomposition of emission rates

SPS

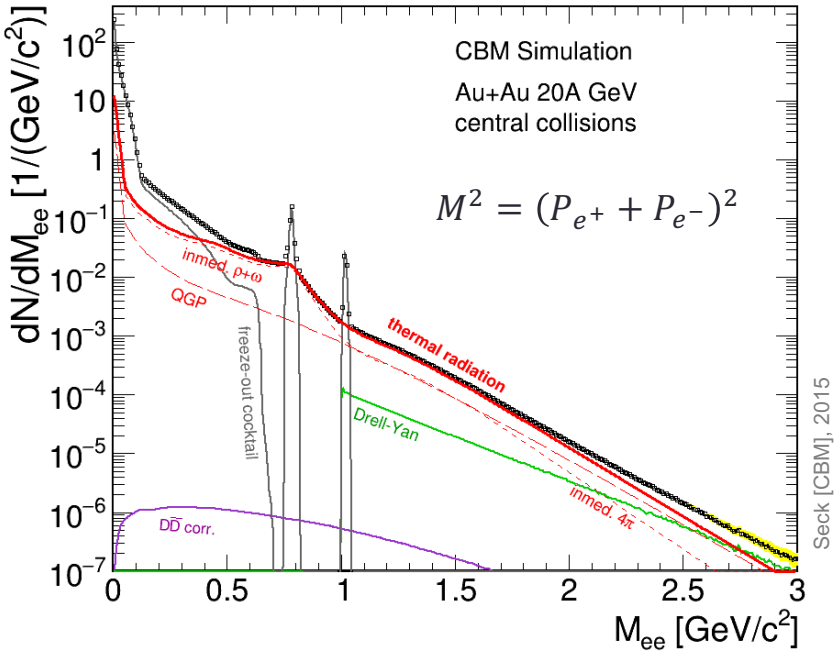


SIS



Thermal dilepton measurements

➥ **challenge: rare probe (in particular at few GeV collision energy)**



- Decisive parameters for data quality:
  - interaction rates (*IR*) and signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{\mathrm{eff}} \sim IR \times S/CB$
- Mid-rapidity, low-$M_{\ell\ell}$, low-p_{T} coverage (acceptance correction)
- Isolation of thermal radiation by subtraction of measured decay cocktail, "Resonance continuum", $\mathcal{D}$rell-Υan, $c\bar{c}$ $(b\bar{b})$

→ Measure $\ell^+\ell^-$ production in pp and pA collisions in Beam Energy Scan

- Inclusive production cross section of $\pi^0, \eta, \eta', \omega, \phi, \rho$ and a_1
- Mass and polarization of $\mathcal{D}$rell-Υan process
- "Resonance continuum" ($\ell^+\ell^-$ from multi-pion process)

e^+e^- inclusive invariant mass spectrum p+p 4.5 GeV

Study dilepton production mechanisms (baryon Dalitz-decay, vector meson decay, …), reference for medium effects (p/A+A at SIS100 energies)

- Signal-to-background ratio in the vector-meson region better than 150
- Mesons peaks are clearly seen, ω and φ
- Number of pairs allows multidifferential studies:
  - M_{e+e-}< 150 MeV/c^2: N_{e+e-} = 2.1×10^6
  - N_ω=1.1×10^4, N_φ=350
  - M_{e+e-}> 1020 MeV/c^2: N_{e+e-} = 112