Dilepton production in transport models

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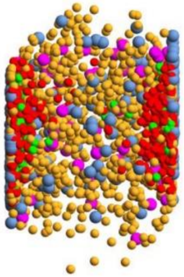
Workshop 'Prospects on various aspects of the dilepton probe in hadronic physics'
November 25, 2021
IJClab, France



Electromagnetic probes

❑ Dileptons and real photons :

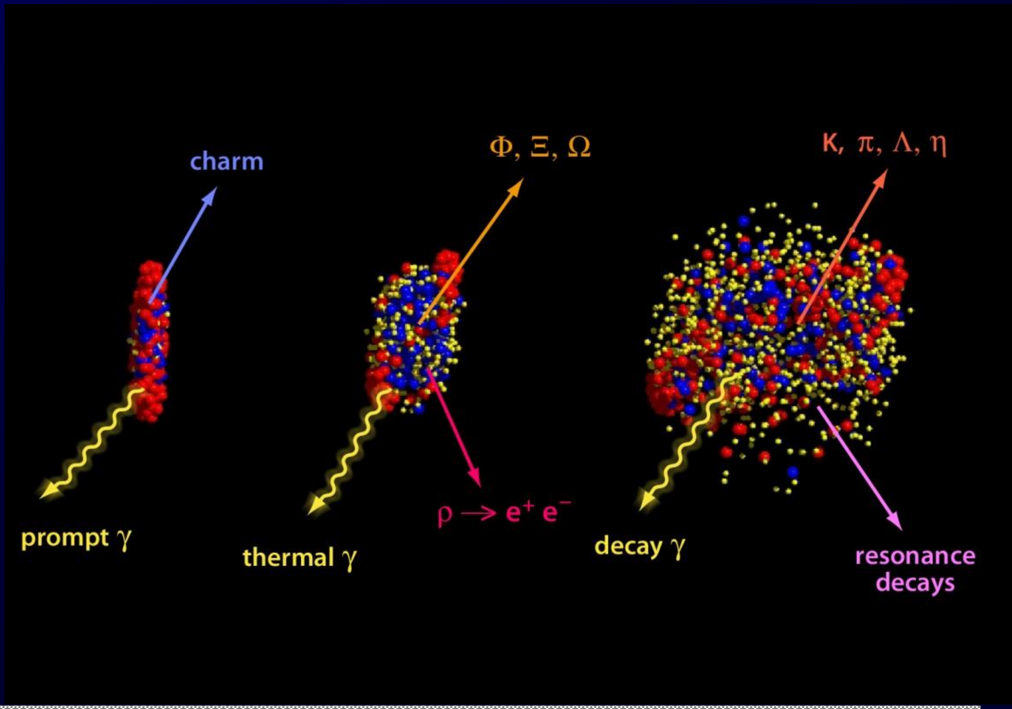
- not effected by final-state partonic and hadronic interactions
- promising signal of QGP – ‚thermal‘ photons and dileptons
- emitted from many production sources at different stages of the HIC

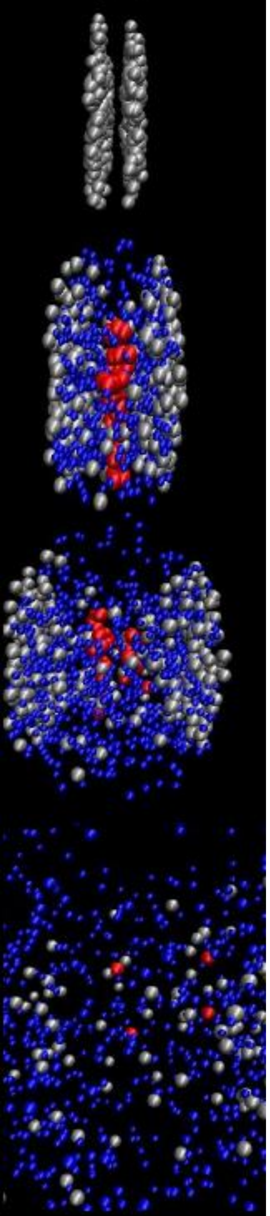
➔ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

⇩

Microscopic transport approaches

Theoretical laboratory - PHSD





Parton-Hadron-String-Dynamics (PHSD)

PHSD is a non-equilibrium transport approch with

- **explicit phase transition from hadronic to partonic degrees of freedom**
- **lQCD EoS for the partonic phase (‚crossover' at finite μ_q)**
- **explicit parton-parton interactions - between quarks and gluons**
- **dynamical hadronization and hadronic interactions**

❑ QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD

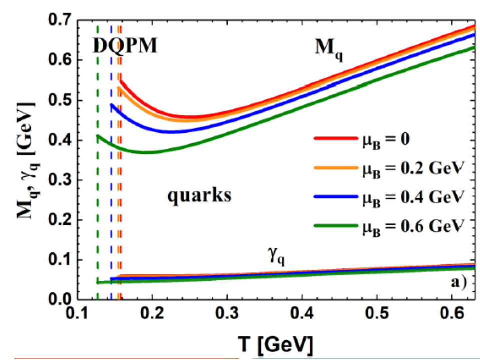
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

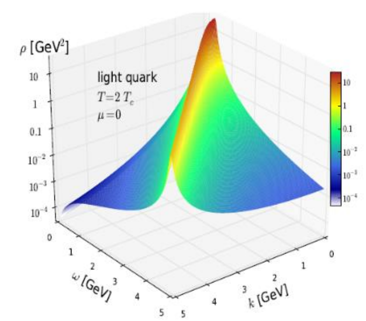
- **strongly interacting quasi-particles** **(non-perturbative QCD): massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in self-generated mean-field potential**

- **Spectral functions:**

$$\rho_i(\omega, T, \mu_B) = \frac{4\omega\Gamma_i(T,\mu_B)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T,\mu_B)\right)^2 + 4\omega^2\Gamma_i^2(T,\mu_B)}$$

$(i = q, \bar{q}, g)$





P. Moreau et al., PRC100 (2019) 014911;
O. Soloveva et al., PRC101 (2020) 045203

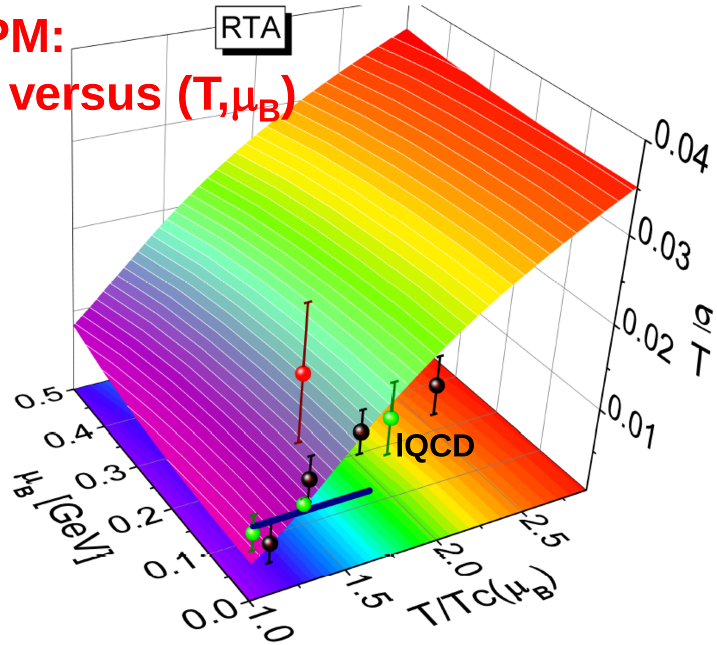
❑ Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting systems!)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3,
O. Linnyk at al, Prog. Part. Nucl. Phys. 87 (2016) 50

Transport coefficients: electric conductivity σ_0/T

σ_0 ➔ **Probe of electric properties of the QGP**

DQPM:
σ_0/T versus (T,μ_B)



- **Relaxation Time Approximation**

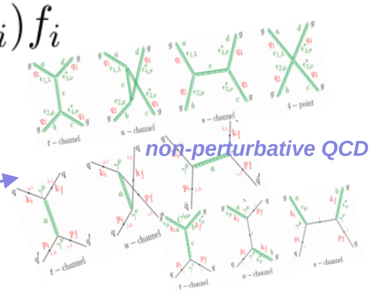
$$\sigma_0^{\mathrm{RTA}}(T,\mu_B) = \frac{e^2}{3T}\sum_{i=q,\bar{q}} q_i^2 \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^2}{E_i^2}$$

$$\times\ \tau_i(\mathbf{p},T,\mu_B) d_i (1-f_i) f_i$$

relaxation time

$$\tau_i(\mathbf{p},T,\mu_B) = \frac{1}{\Gamma_i(\mathbf{p},T,\mu_B)}$$

parton interaction rate

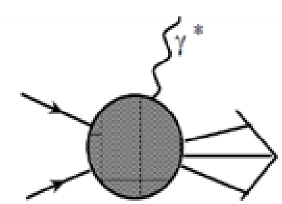


- **the QCD matter even at $T \sim T_c$ is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !**

Exp. observables – photon and dilepton spectra

- **Photon emission:** rates for $q_0 \to 0$ are related to **electric conductivity σ_0**

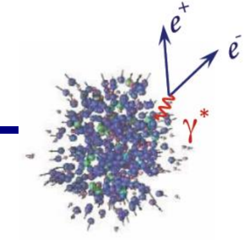
$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0\to 0} = \frac{T}{4\pi^3}\sigma_0$$



O. Soloveva et al., PRC110 (2020) 045203

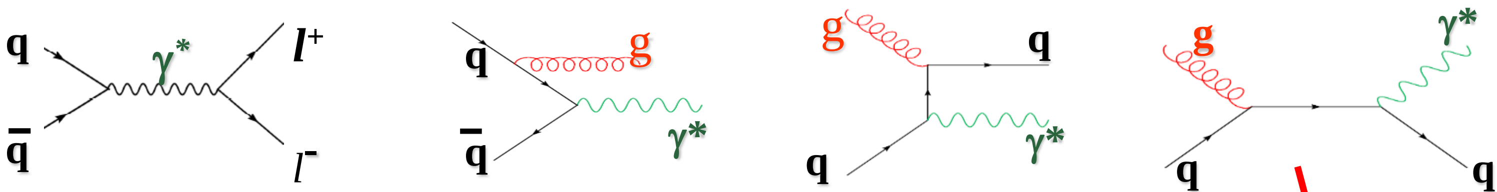
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

Dilepton sources



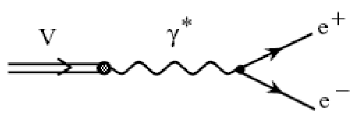
- **from the QGP via partonic (q,qbar, g) interactions:**

PHSD: non-perturbative QGP → DQPM (Dynamical Quasiparticle Model)

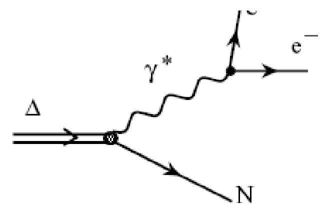


- **from hadronic sources:**

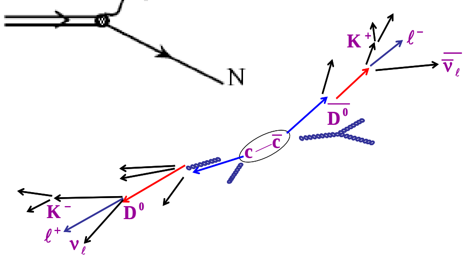
• **direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ')**



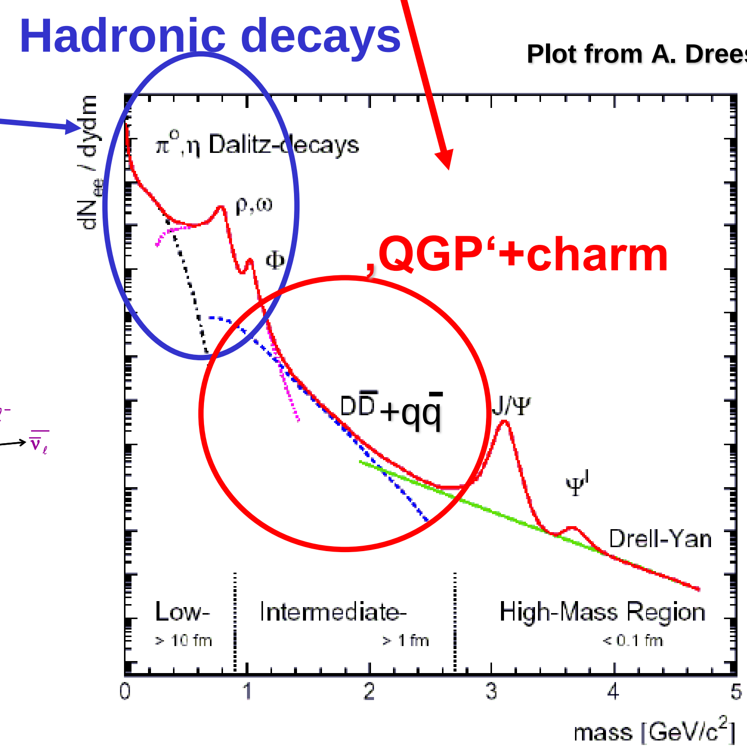
• **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**



• **correlated D+Dbar pairs**



• **radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π'**

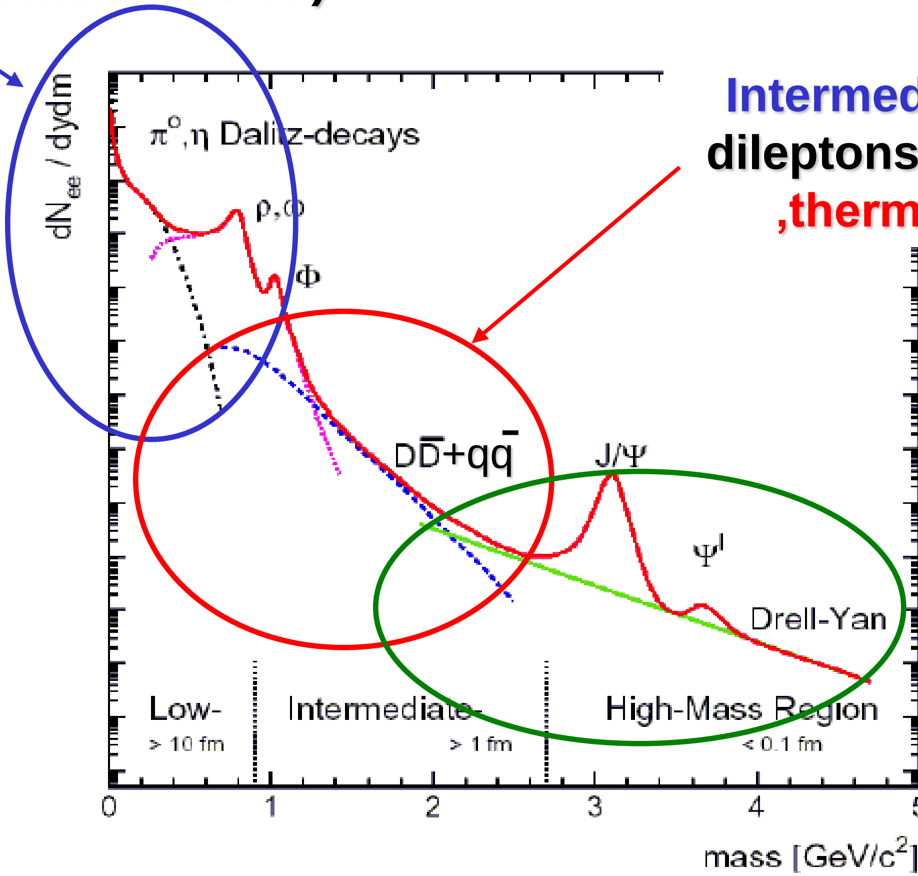


Cf. review: O. Linnyk, E. Bratkovskaya, W. Cassing, Prog. Part. Nucl. Phys. 87 (2016) 50

Physics with dileptons

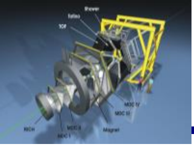
Low mass dileptons
-probe of hadronic in-medium effects
(late time emission)

Advantage of dileptons vs. photons:
additional „degree of freedom“ (*M*) allows to disentangle various sources



Intermediate mass dileptons – probe of ‚thermal QGP‘

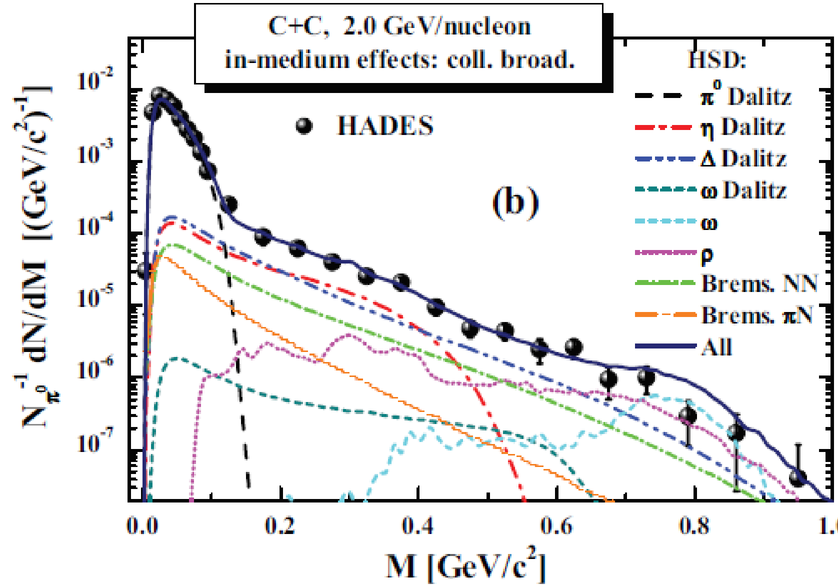
High-mass dileptons – probe of pQGP and hard probes (early time emission)



Dileptons at SIS energies - HADES

- **HADES: dilepton yield dN/dM scaled with the number of pions $N_{\pi 0}$**

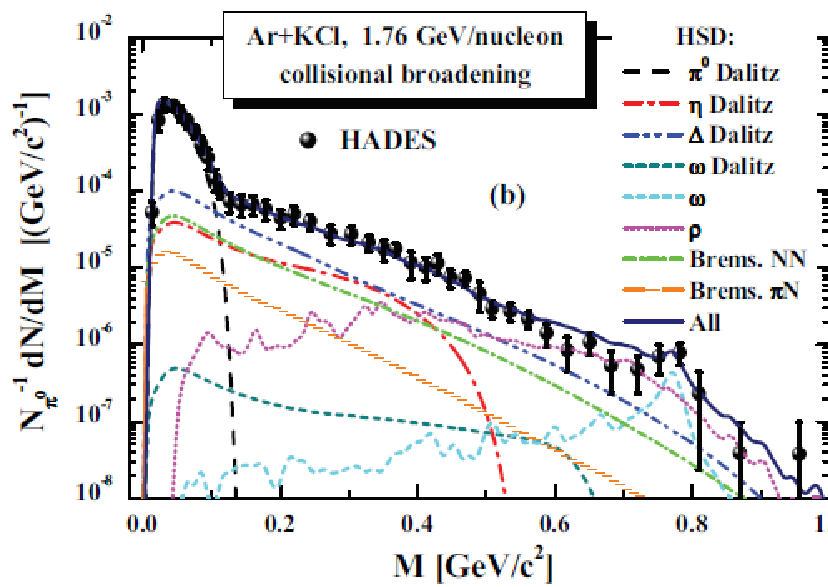
- **Dominant hadronic sources for $M>m_\pi$:**
  - **η, Δ Dalitz decays**
  - **NN bremsstrahlung**
  - **direct ρ decay**



➢ **ρ meson = strongly interacting resonance**
strong collisional broadening of the ρ width

- **In-medium effects are more pronounced for heavy systems such as Ar+KCl than C+C**

- **The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum**

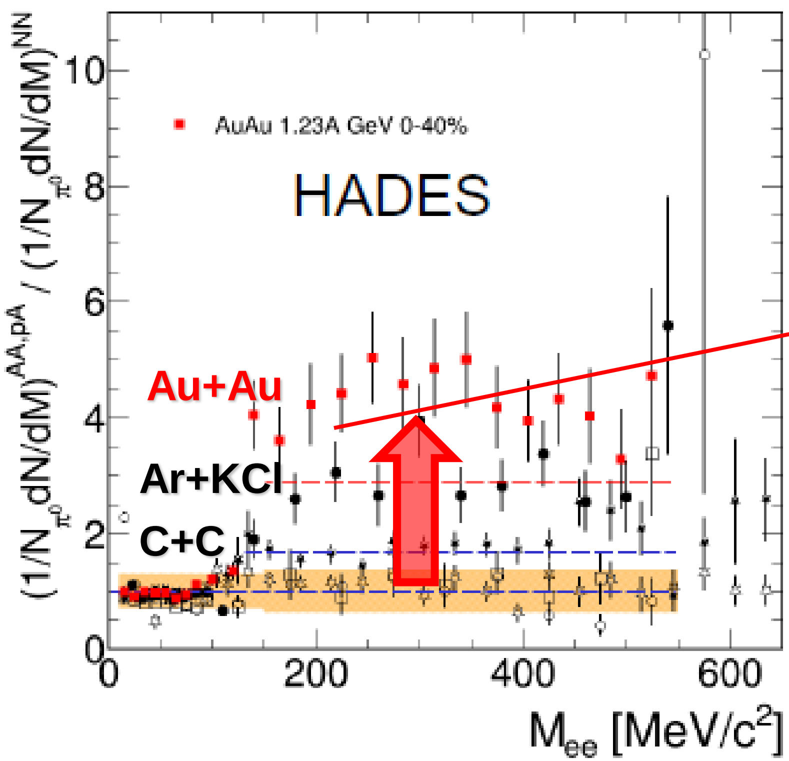


E. Bratkovskaya, J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

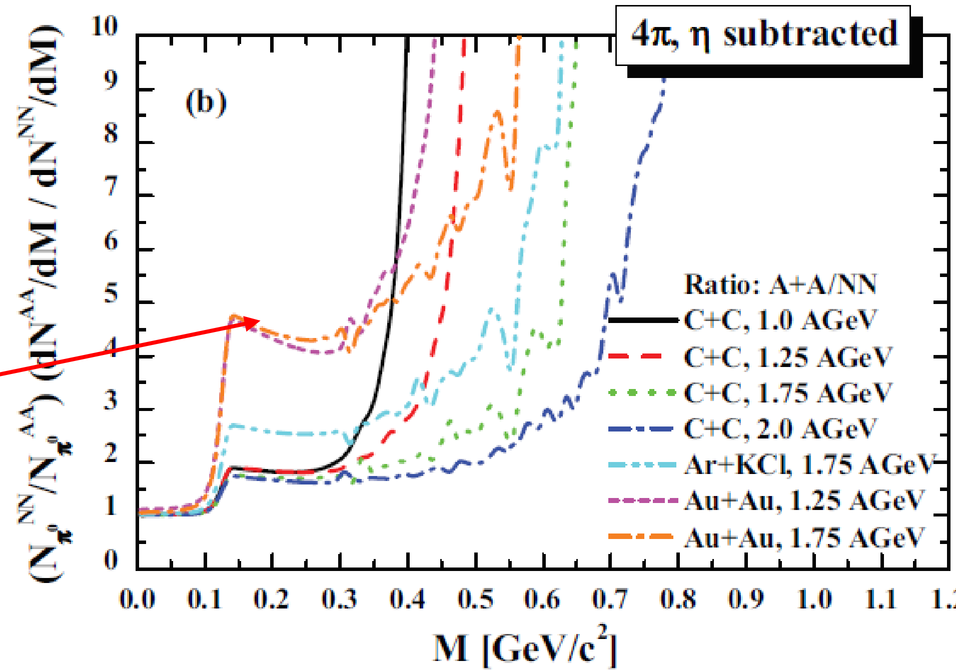
Dileptons at SIS (HADES): Au+Au

HADES, Nature Phys.15 (2019) 1040

HADES : Au+Au, 1.23 A GeV



- HSD predictions (2013)



- **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN
- **Increases with the system size!**

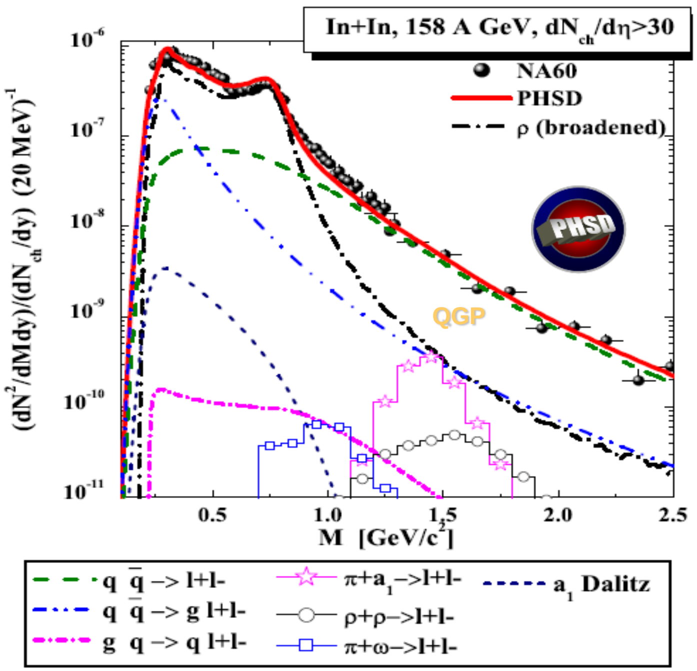
1) the **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

2) the **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions

E.B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

Lessons from SPS: NA60

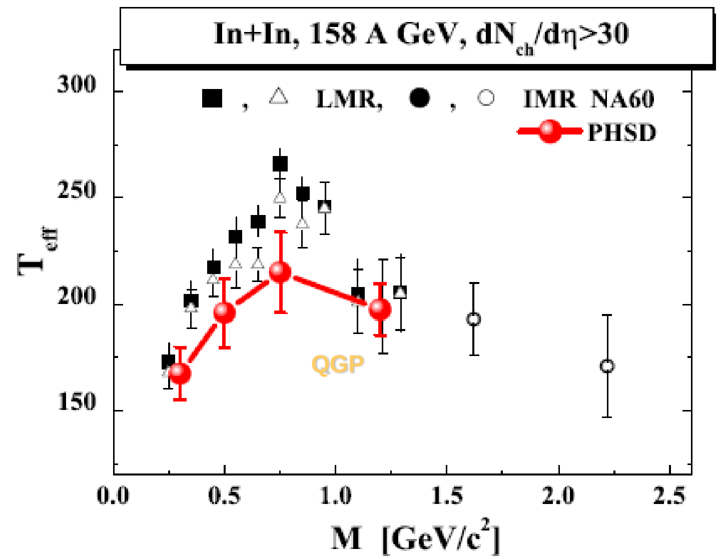
❑ Dilepton invariant mass spectra:



NA60: Eur. Phys. J. C 59 (2009) 607

❑ Inverse slope parameter T_{eff}:

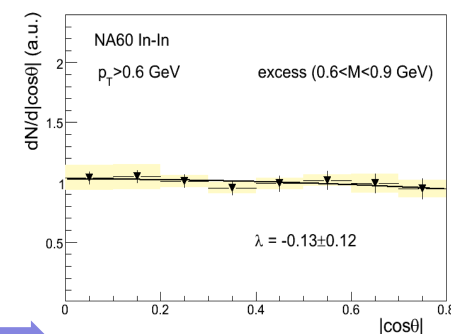
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed



PHSD:
Linnyk et al, PRC 84 (2011) 054917

Message from SPS: (based on NA60 and CERES data)

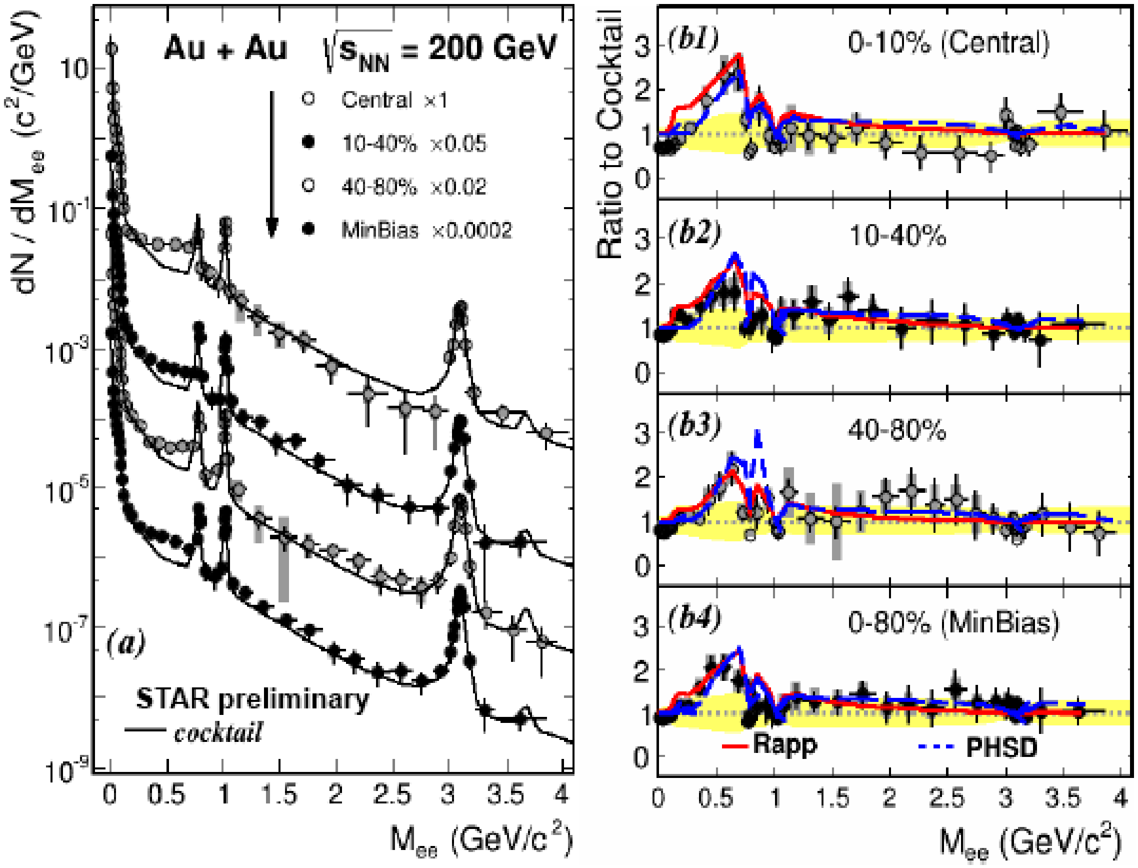
1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons



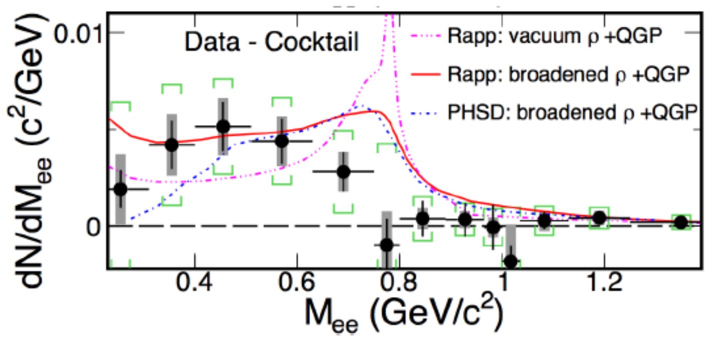
PRL 102 (2009) 222301

Dileptons at RHIC: STAR data vs model predictions

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



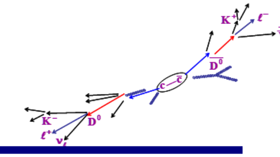
Models:
- **Fireball model – R. Rapp**
- **PHSD**

Low masses:
collisional broadening of ρ
Intermediate masses:
QGP dominant

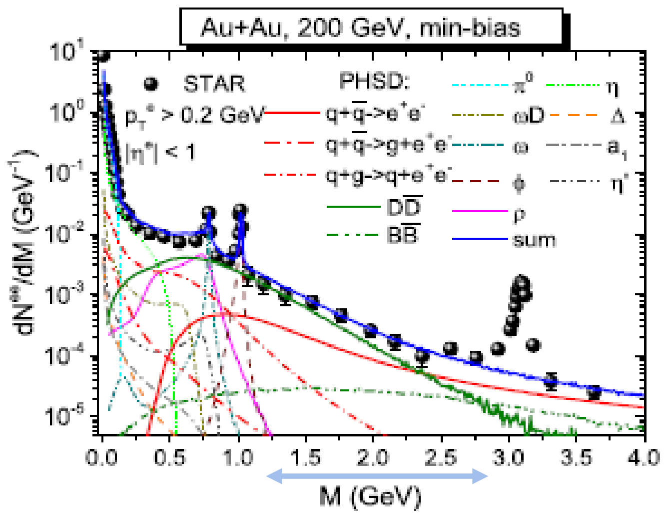
→ **STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP**

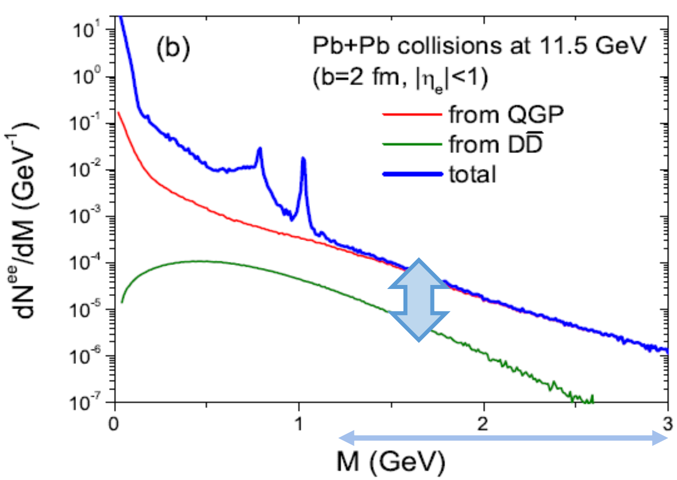
→ **In-medium effects are stronger for the central A+A collisions**

Dileptons: QGP vs charm

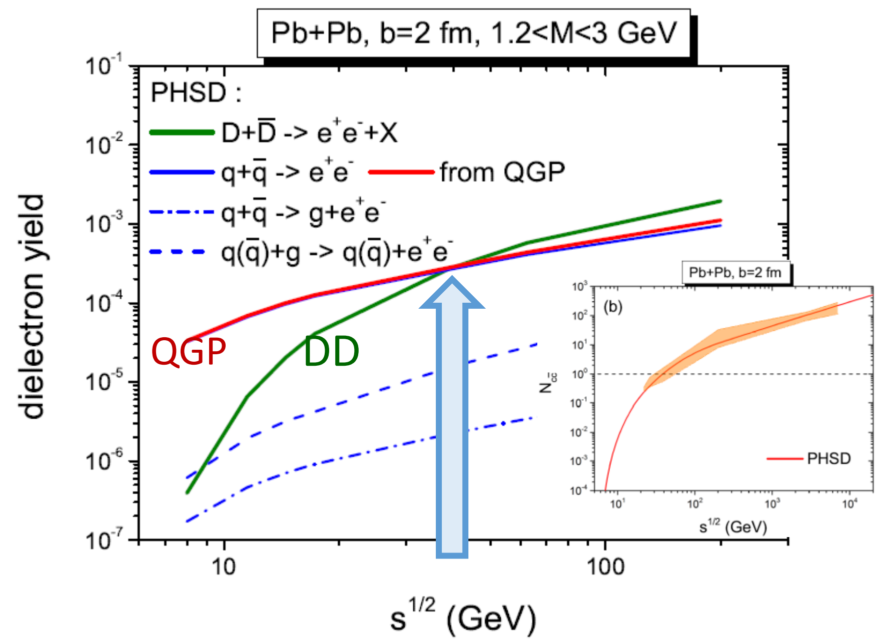


- ❑ STAR RHIC BES data and the ALICE data are described by PHSD within a **collisional broadening** scenario for the **vector meson** spectral functions + **QGP** + **correlated charm**





Excitation function of dilepton yield integrated for 1.2<M<3GeV



- ❑ **Dileptons from QGP overshine charm dileptons with decreasing beam energy!**

➔ **Good perspectives for FAIR/NICA and RHIC BES!**

T.Song, P. Moreau et al., Phys. Rev. C97 (2018), 064907; Phys. Rev. C98 (2018), 041901; Phys. Rev. D 98 (2018) 116007

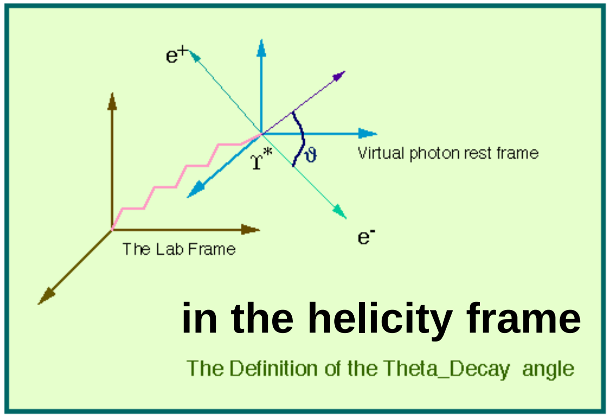
Polarization: Dilepton anisotropy coefficients

E.B., M. Schafer, W. Cassing, U. Mosel, O.V. Teryaev, V. D. Toneev, Phys. Lett. B 348 (1995) 283; B 348 (1995) 325; B 362 (1995) 17, B376 (1996) 12; Z. Phys. C75 (1997)197

$d\sigma/d(\cos\theta) \sim 1 + B\cos^2\theta$

$$B = \frac{3\rho_{11} - 1}{1 - \rho_{11}}$$

$$\rho_{00} + 2\rho_{11} = 1$$



Anisotropy coefficients for elementary channels:

- **pseudoscalar mesons (e.g. π^0 and η):**

  B = +1
- **vector mesons (e,g, ρ, ω and ϕ) from NN→VX: if no preferred spin orientation of VM**

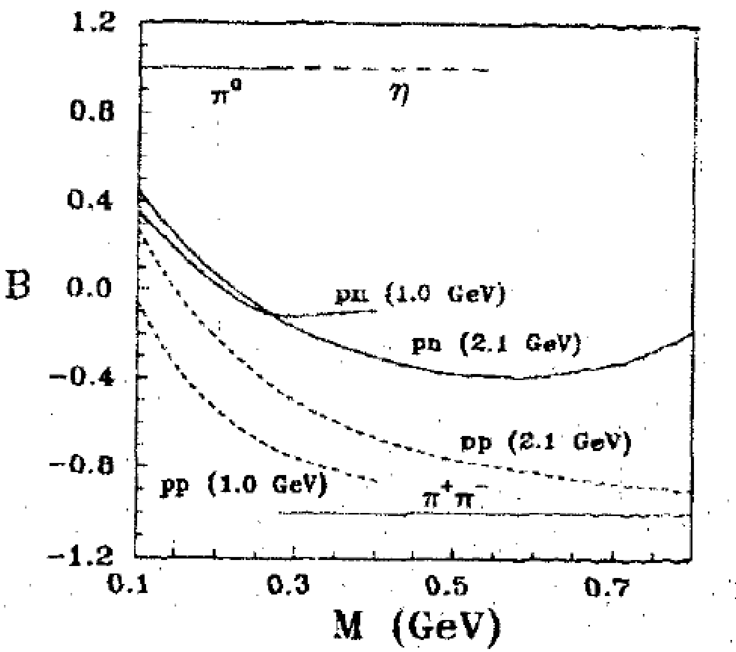
  B = 0
- **$\pi\,\pi$ annihilation: $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$:**

  p wave (L=1 $\perp$ to $\pi\,\pi$ scattering plane)

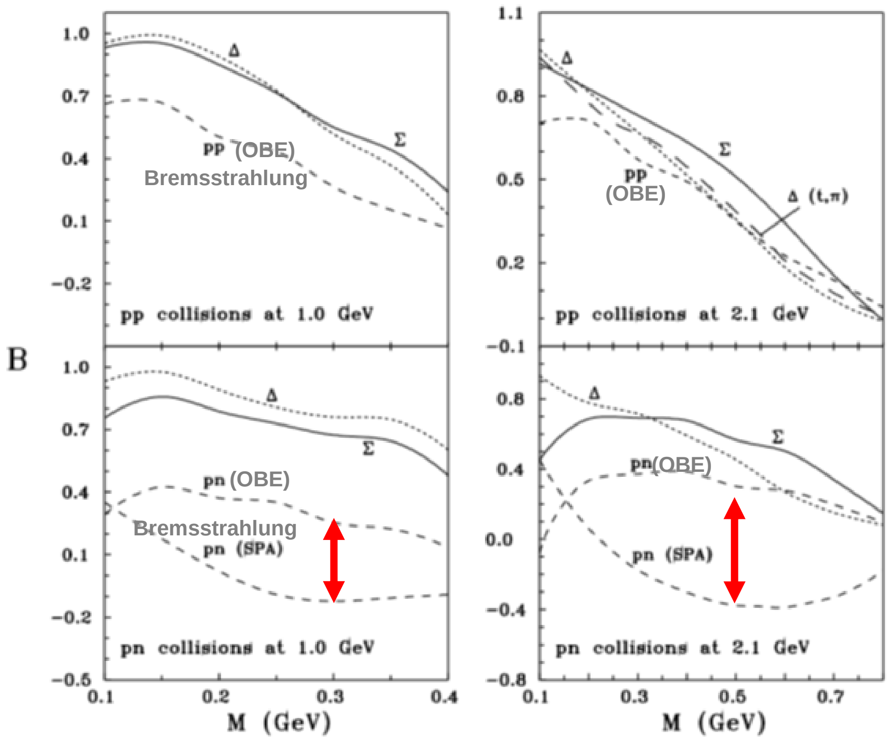
  B = -1

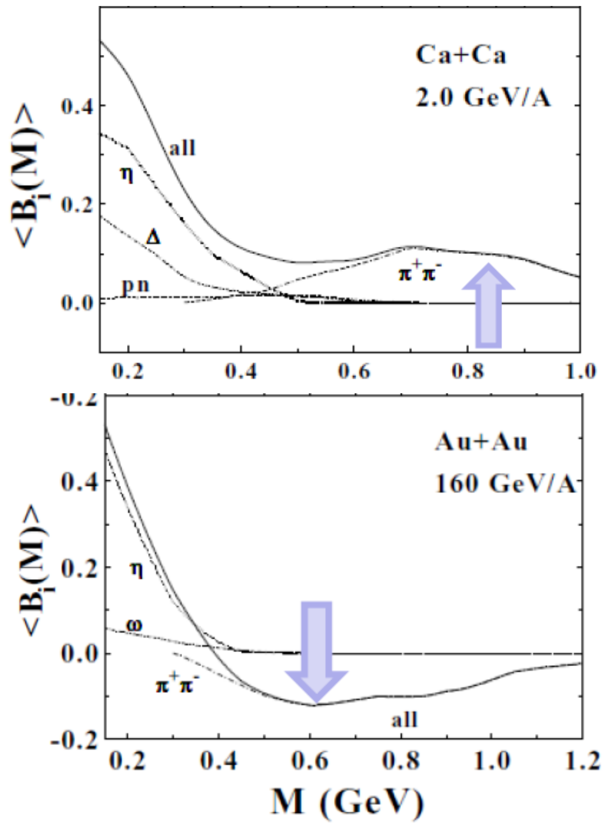
- **Δ and N* decays: B ≠ 0**

- **NN and πN bremsstrahlung: B ≠ 0**



Dilepton anisotropy coefficients in N+N, A+A





N+N collisions:

- ❑ ***B*** **from Δ-decay and Bremsstrahlung (pp, pn) sensitive to the model details:**
  B **from SPA <** ***B*** **from OBE model**
- ❑ **Strong isospin dependence of** ***B***

A+A collisions:

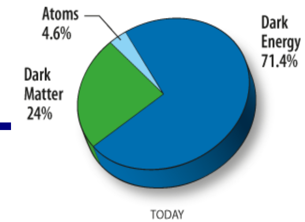
B **from $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ changes sign with increasing energy!**

➔ Information on ρ polarization (depends on ρ production mechanism)

➔ Opportunities for the HIC dilepton programs to study production mechanisms by polarizations!

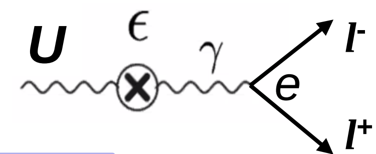
E.B., M. Schafer, W. Cassing, U. Mosel, O.V. Teryaev, V. D. Toneev, Phys. Lett. B 348 (1995) 325; B 362 (1995) 17, B376 (1996) 12

Light dark photons searches with heavy ions



The 'vector' portal : existence of a U(1)-U(1)′ gauge symmetry group mixing

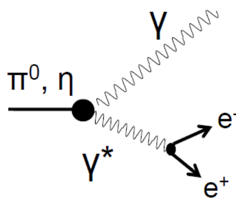
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \boxed{\frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu}} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$



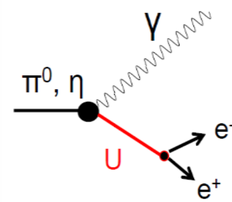
Notation for 'dark photon': A' or U- boson

Unknown: kinetic mixing parameter ϵ and mass M_U

B. Holdom, PL B 166, 196 (1986)
B. Batell et al., PRD 80, 095024 (2009)

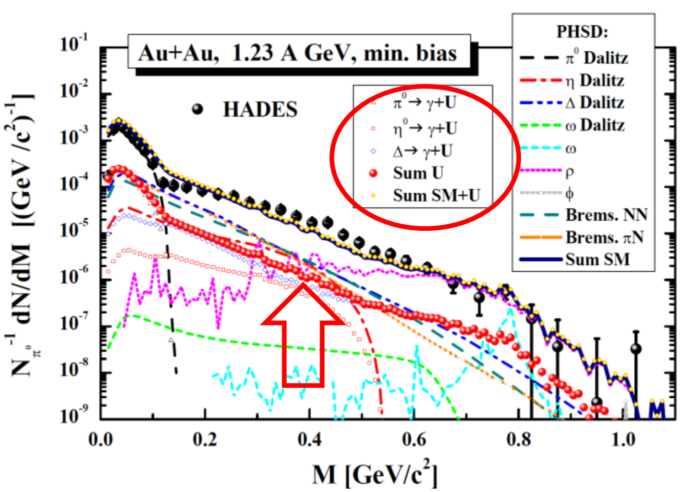


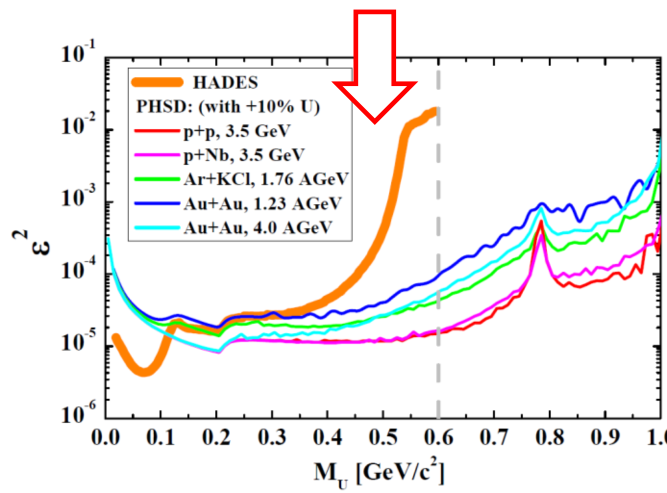
U(1)-U(1)′ kinetic mixing

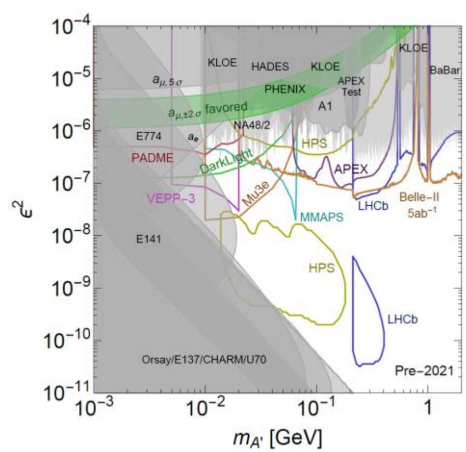


$\pi^0 \rightarrow \gamma + U$,
$\eta \rightarrow \gamma + U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N + U$

The upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$ of light dark photons extracted from the PHSD dilepton spectra - with 10% allowed surplus of the total SM yield by an additional DM yield at given M:







Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

Summary

I. SIS energies:

Strong in-medium enhancement of dilepton yield in Au+Au vs. NN (which increases with the system size) – due to the multiple Δ regeneration, pN bremsstrahlung and in-medium ρ-contribution

II. High energies:

- **Low dilepton masses:**
  Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening)

- **Intermediate dilepton masses M>1.2 GeV :**

  - Dominant sources : QGP (qbar-q) and correlated charm D/Dbar

  - Fraction of QGP grows with increasing energy; however, the relative contribution of QGP dileptons to dileptons from charm pairs increases with decreasing energy

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➔ **In-medium effects can be observed at all energies from SIS to LHC**

➔ **QGP contribution overshines charm with decreasing energy**
Good perspectives for FAIR / NICA / RHIC BES !

➔ **Study of polarization phenomena with dileptons**

➔ **Possibility to search for dark photons with dilepton heavy-ion experiments**