Exploration of hadron properties and production mechanisms in p+p and p+A collisions at SIS100 energies

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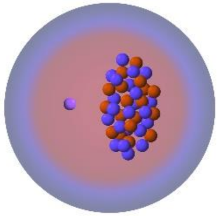


"Physics opportunities with proton beams at SIS100"
Wuppertal University
6-9 February 2024

Elementary *p+p, p+n(d)* reactions – where we are now?

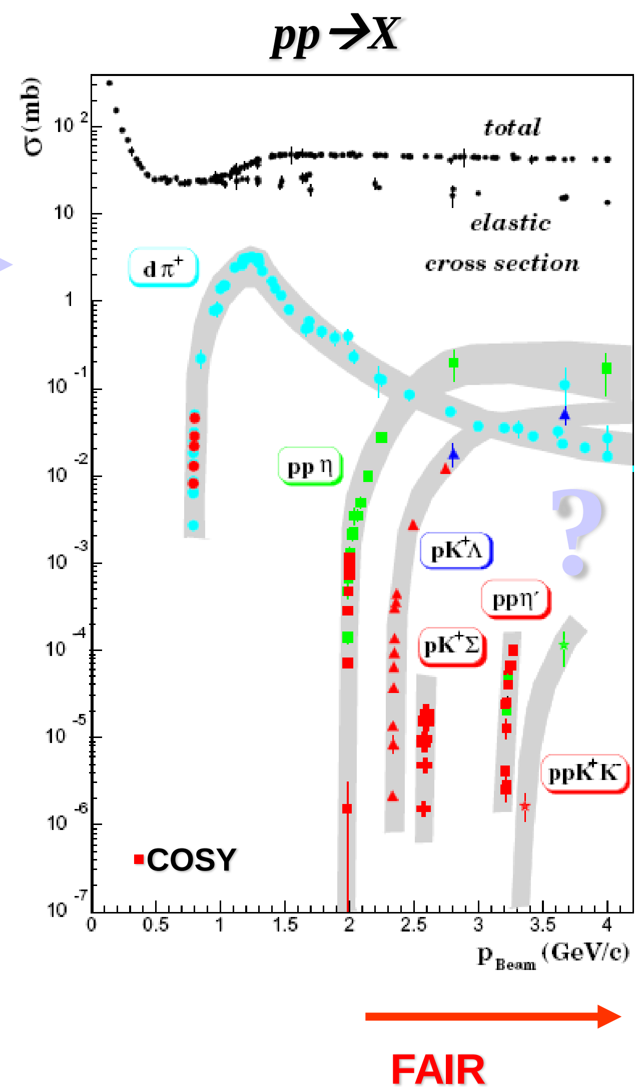
❑ Present experimental situation at the FAIR energy range:

- poor data on (light and strange) hadron multiplicities in pp reactions
- practically NO data on hadron production in pn reactions !
- little information on differential spectra, correlations etc.

❑ Present theoretical situation at the FAIR energy range:

complicated region for theoretical descriptions:

- transition from resonance production mechanisms (2→2, 2→3) to multiparticle production (2→n)
- description by resonance models (3d phase space) or via string formation and decay (longitudinal phase space)?



Elementary reactions: mandatory for HIC physics

- **A good knowledge of elementary reactions is mandatory:**
- **for the proper interpretation of experimental data as ‚reference spectra' in order to pin down nuclear effects (e.g. nuclear modification factor *R(AA/NN),* slope parameter etc.)**
- **for the ‚input' (hadron production cross sections, momentum distributions) in theoretical models in order to obtain robost conclusions on in-medium dynamics in heavy-ion collisions**
- **for study of polarization phenomena**

➔ HADES and CBM experiments
can provide the missing experimental information on light and (multi-) strange hadron production in elementary p+p and p+n(d) reactions in a wide energy range

Proton induced *p+A* reactions

- **Study of isospin effects on hadron production by proton collisions with light nuclei *(Be, C)* :
  provide an independent constraint on *p+n* and *n+n* reactions and baryonic (Δ, N*) resonance excitations**

- **Study of ‚cold' nuclear matter (at about normal nuclear density ρ_0) by proton collisions with heavy nuclei *(Au, Pb, U)* :**

- **in-medium effects up to ρ_0**
- **role of re-scattering and baryon absorption mechanisms**
- **cumulative particle production with large momentum**
- **substhreshold (below s_{NN}) particle prodution –** cf. talk by M. Bleicher
- **NN potential**
- **cluster production in p+A**

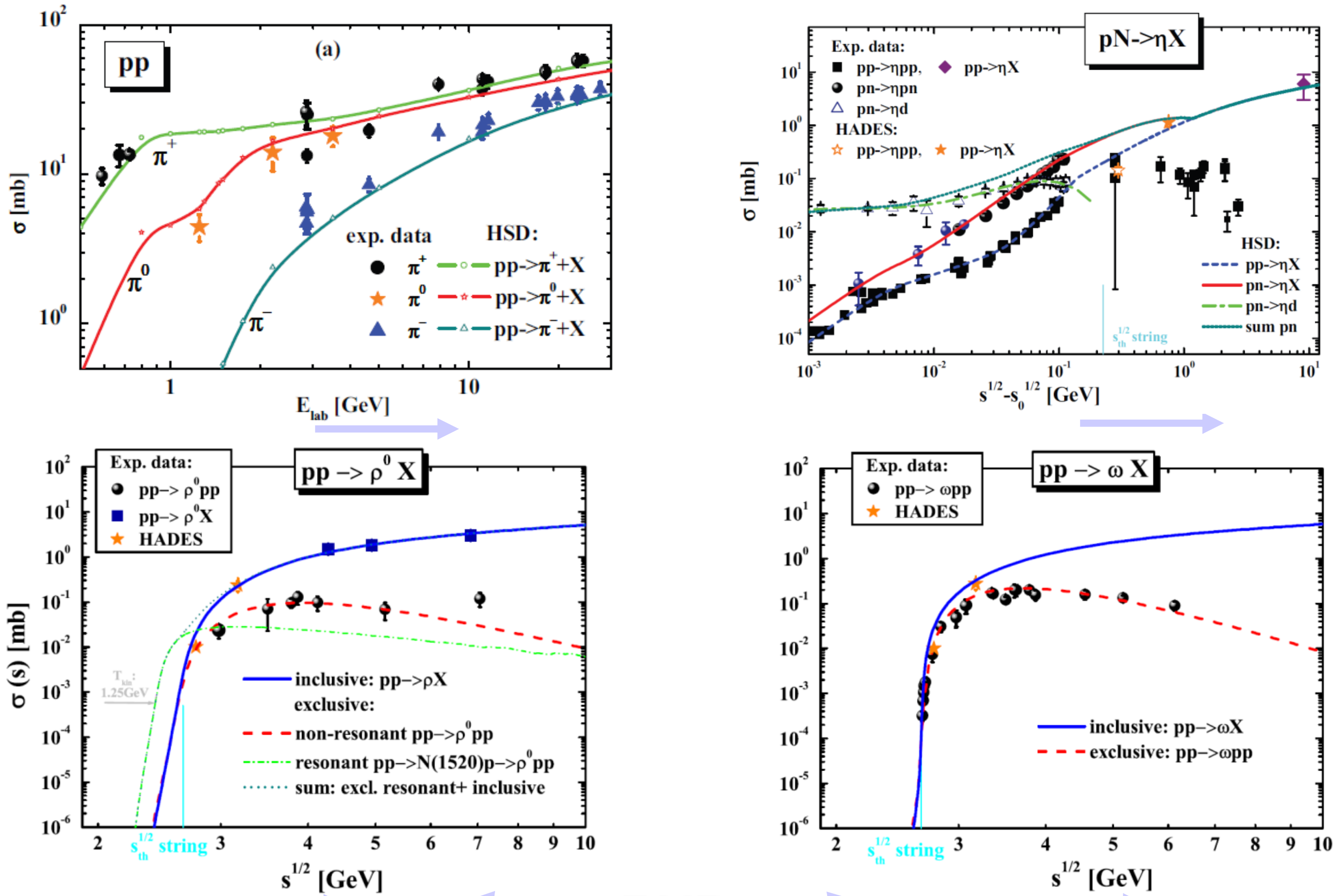
➔ **HADES and CBM experiments can explore this physics!**

Inclusive / exclusive cross sections for p+p, p+n, n+n reactions

Exitation functions of hadron multiplicities in p+p vs. A+A

Elementary reactions p+p, p+n(d)

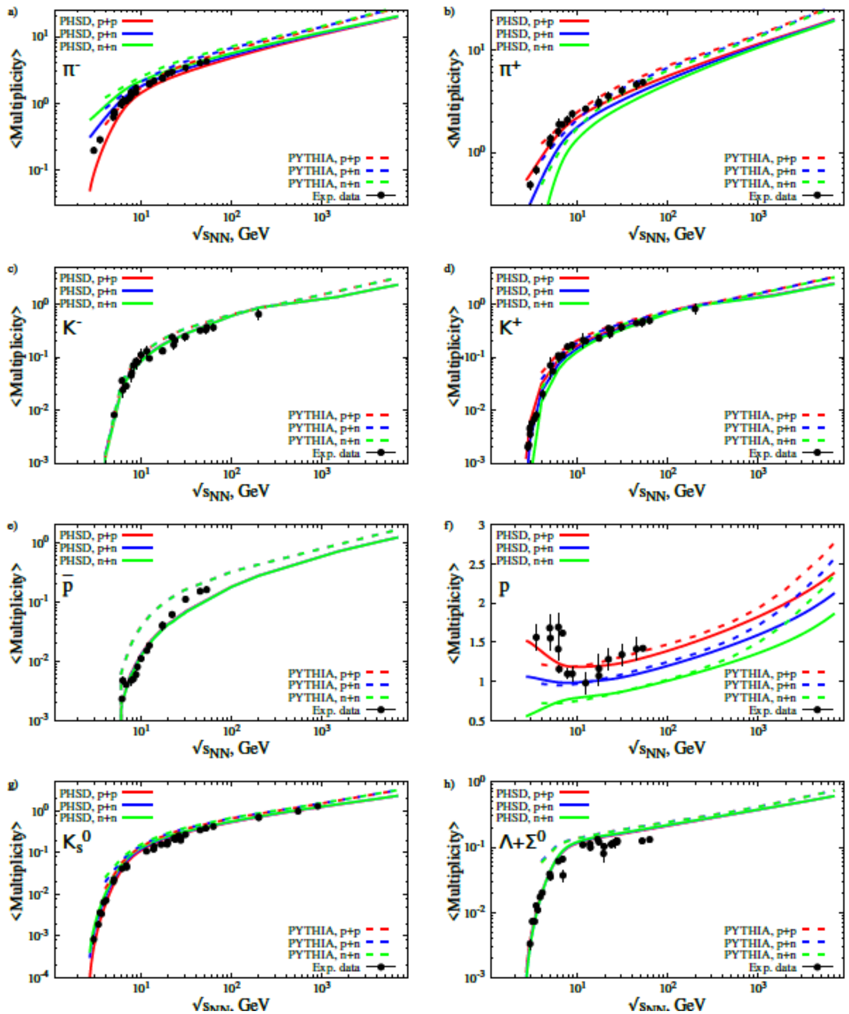
- It is important to know the elementary cross sections of pions, η and vector meson (ρ,ω,ϕ) for an understanding of the in-medium effects in nuclear matter observed via dilepton production in A+A

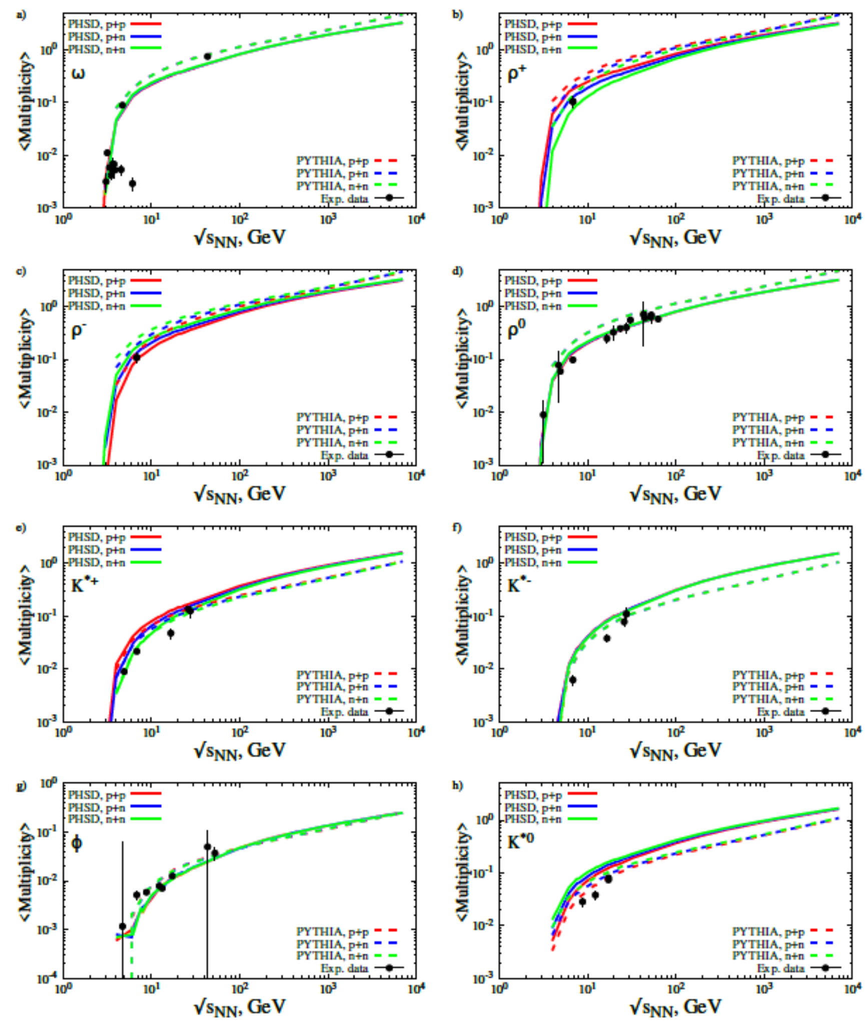


FAIR

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

Elementary reactions p+p, p+n, n+n

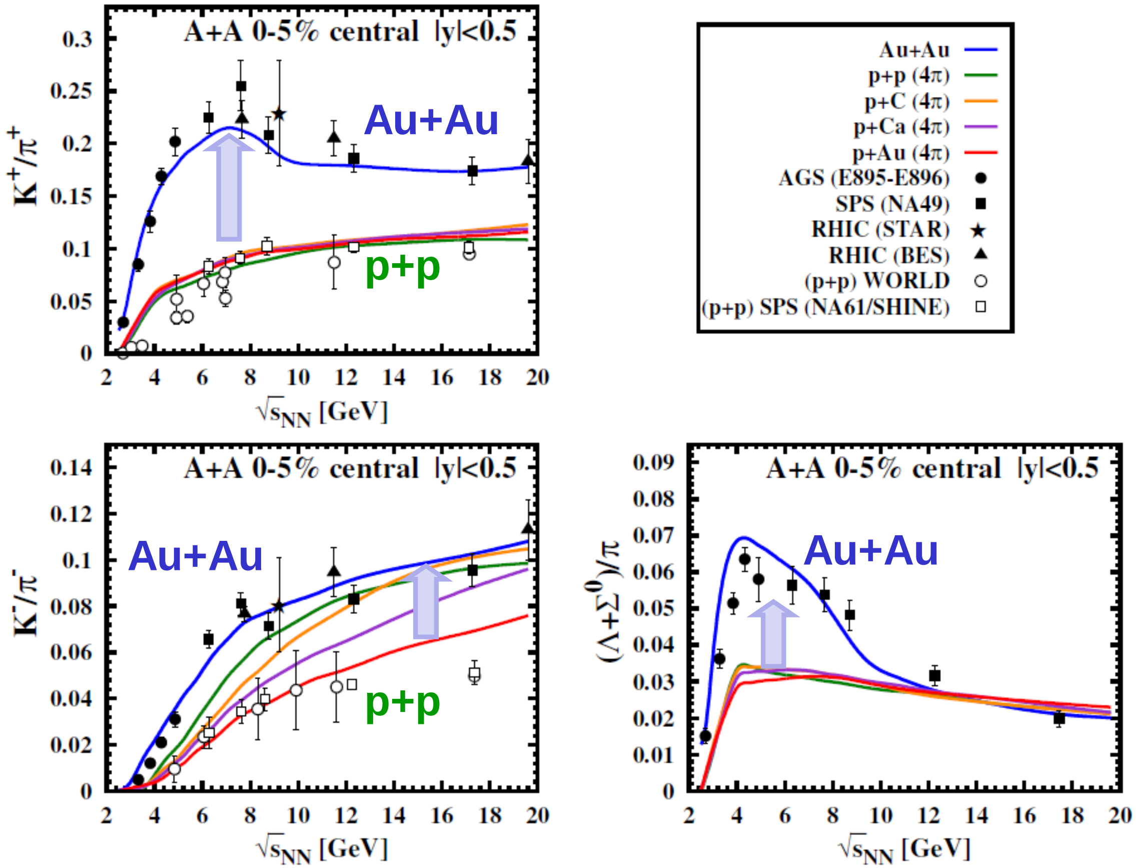




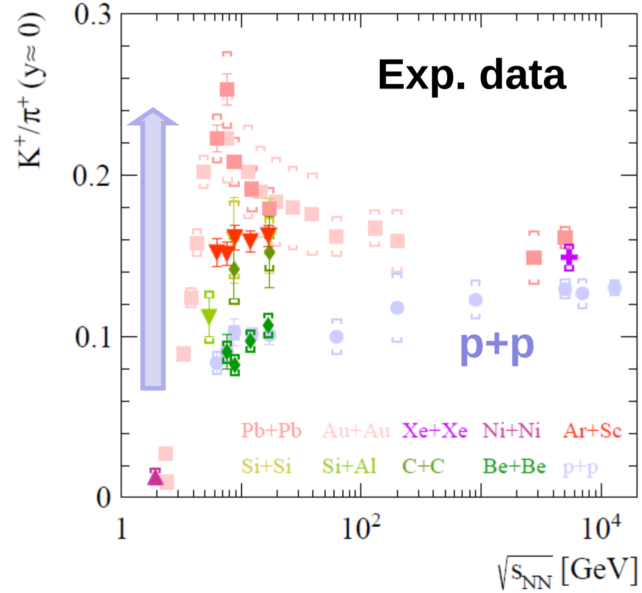
- **Existing experimental data on p+p are poor**
  Practically NO data on p+n reactions
- **Poor data on resonance production**

V. Kireyeu et al., Eur.Phys.J.A 56 (2020) 223

Sensitivity to the system size: p+p, p+A, A+A



- Excitation function of hadron yields is **very different** in p+p and A+A



- p+p, p+A: monotonic increase with energy
- A+A: „horn“ structure is due to the interplay between chiral symmetry restoration and deconfinement (QGP) - within the PHSD

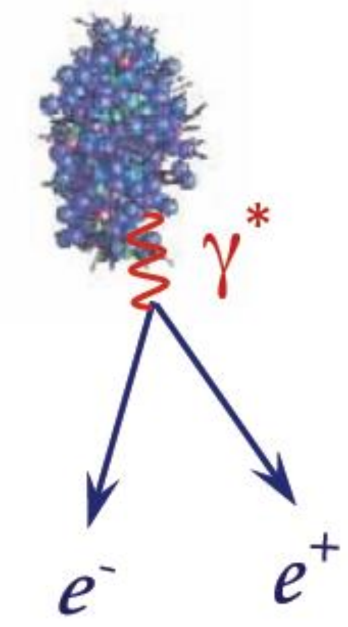
A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073

Outlook-I:
exitation functions of hadrons in p+p, p+A

Measurement of inclusive and exclusive cross sections and exitation functions of hadrons in p+p, p+n(d), p+A provide information on

- **mechanisms for hadron production in p+p, p+n(d)**
- **isospin effects in p+p and p+n(A)**
- **resonance production and their properties**
- **rescattering**
- **modification of in-medium hadron properties up to ρ_0**
- **substhreshold (below s_{NN}) particle prodution**

Electromagnetic probes: dileptons from N+N to A+A

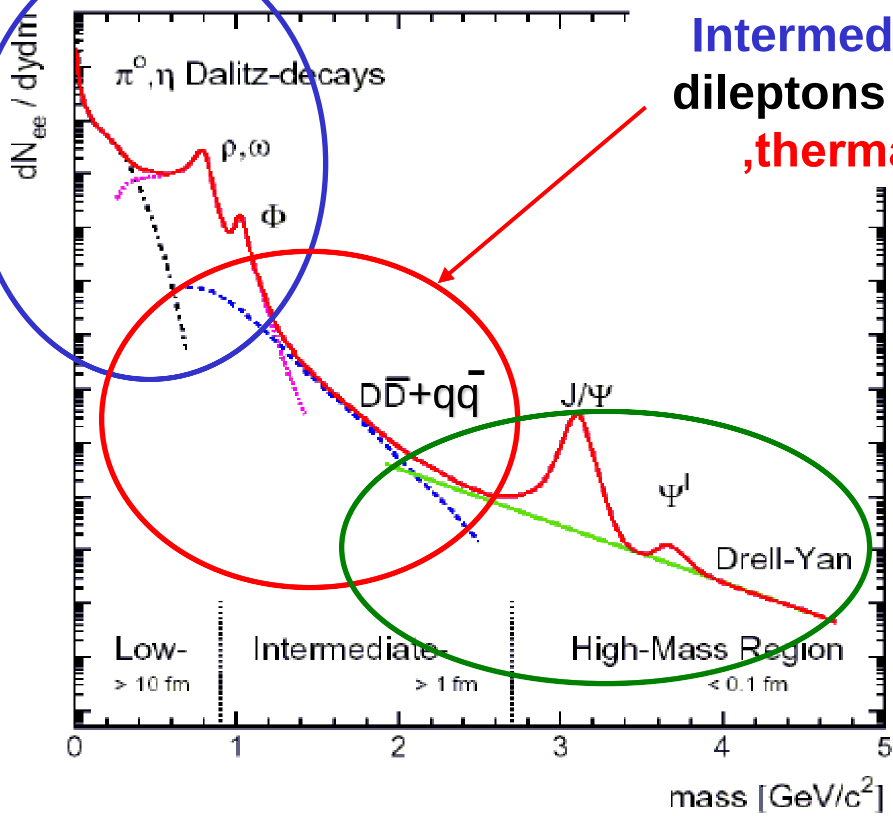


Physics with dileptons

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

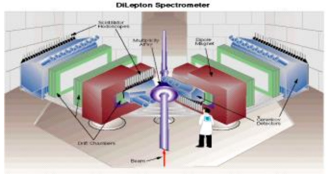
Advantage of dileptons vs. photons:
additional „degree of freedom“ (*M*) allows to disentangle various sources

FAIR

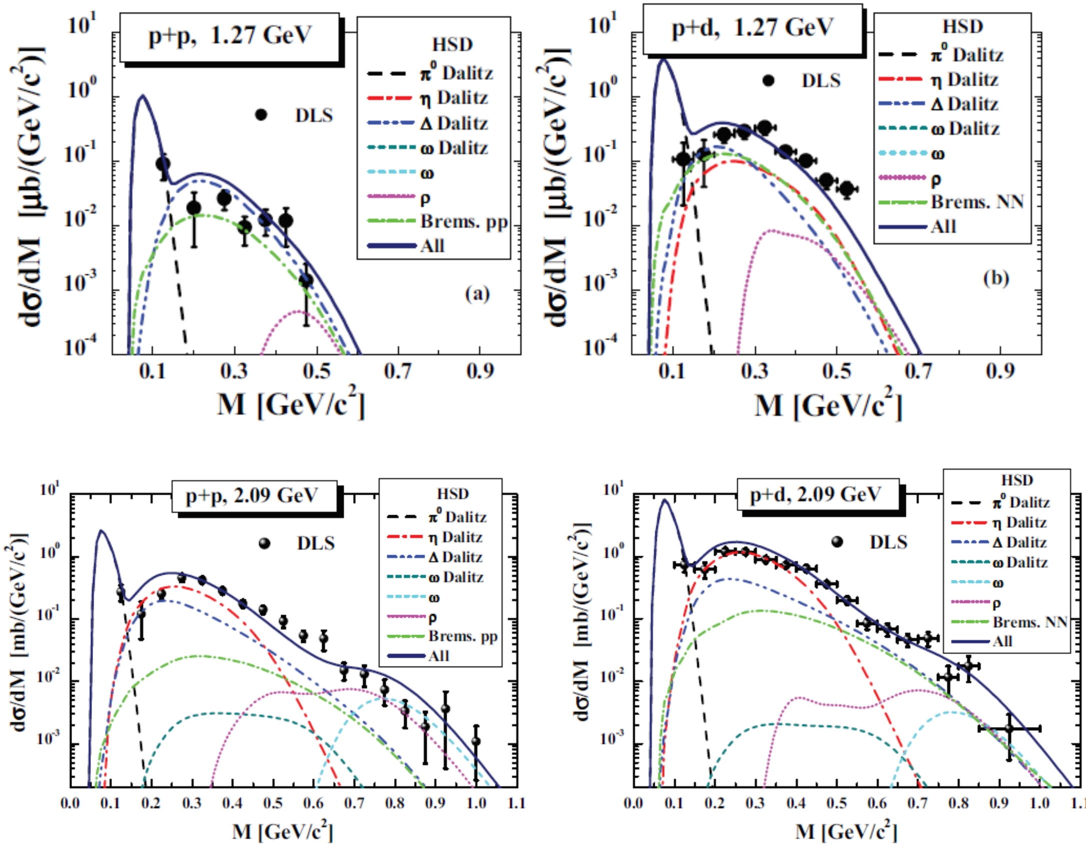


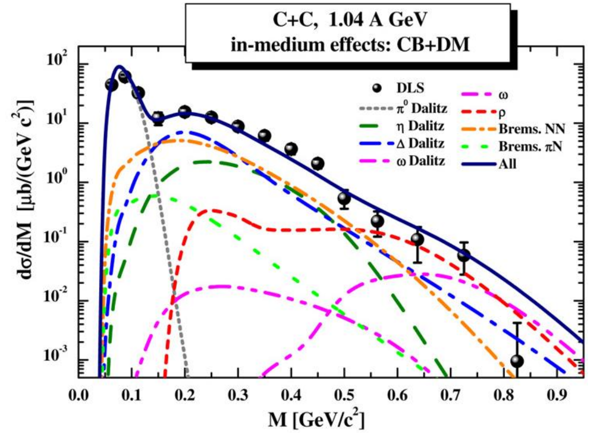
Intermediate mass dileptons – probe of ‚thermal QGP‘

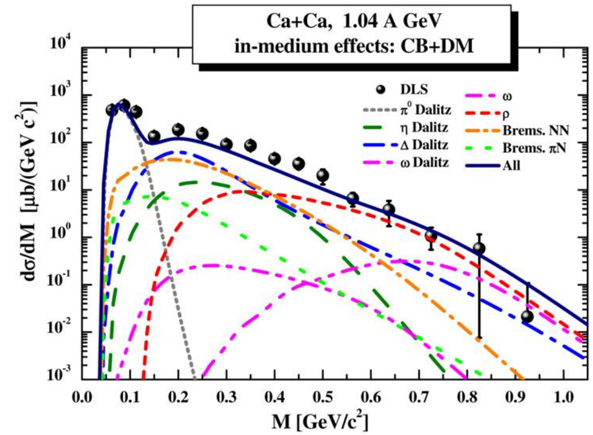
High-mass dileptons – probe of pQCD and hard probes
(early time emission)



DLS: Dileptons from p+p, p+d, A+A



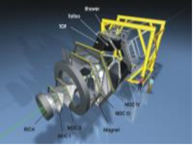




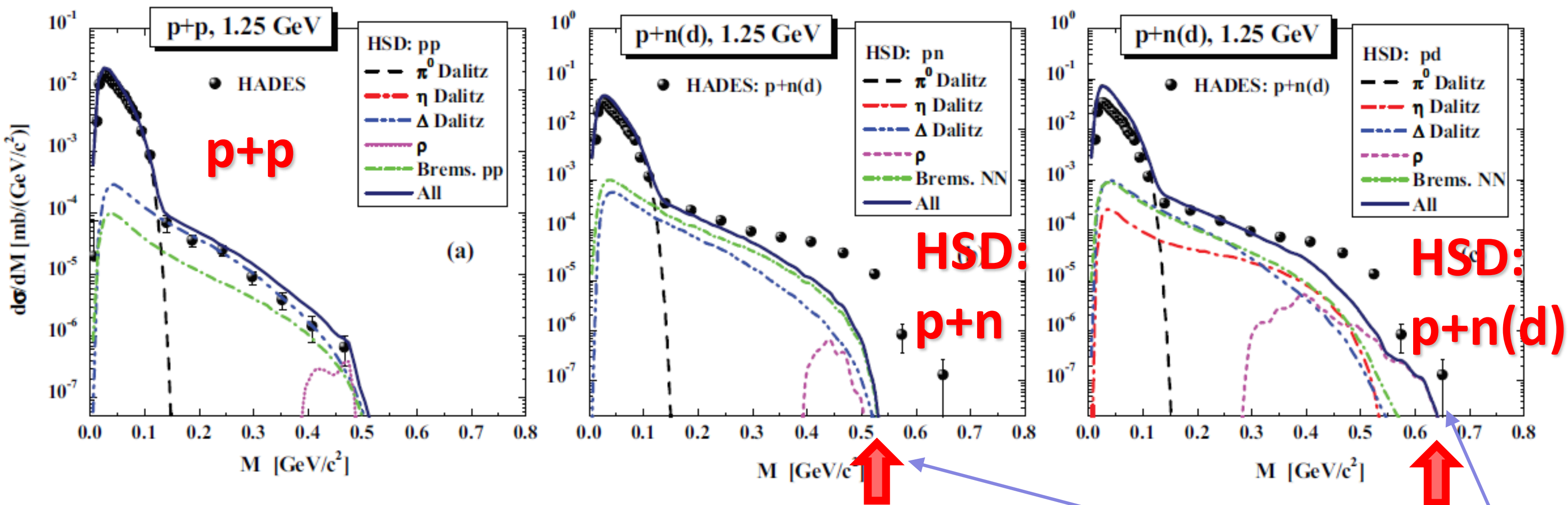
- **bremsstrahlung*** and **Δ-Dalitz decay** are the dominant contributions in low energy p+p, p+d and A+A collisions for 0.15 < M < 0.55 GeV ➔ solution of the **„DLS puzzle“**
- **in-medium ρ width** for A+A
- **off-shell dynamics** in HSD derived from Kadanoff-Baym many-body theory

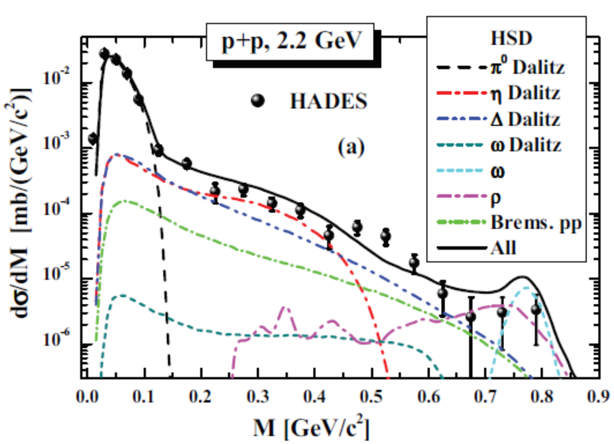
* OBE model: L. Kaptari, B. Kämpfer, NPA 764 (2006) 338

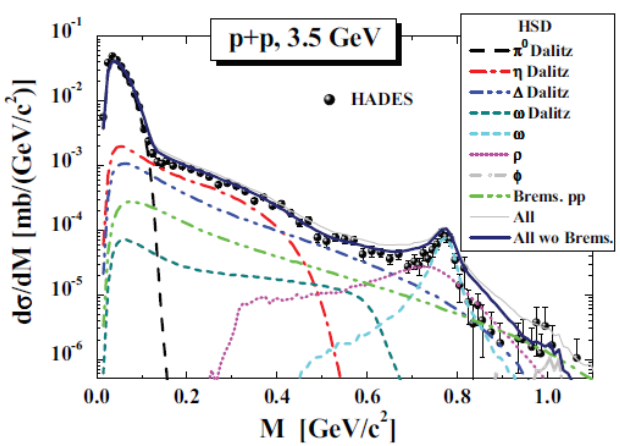
DLS: W.K. Wilson et al., Phys. Rev. C 57 (1998) 1865
HSD: E.B., W. Cassing, Nucl.Phys.A 807 (2008) 214



HADES: Dileptons from p+p, p+n and p+d





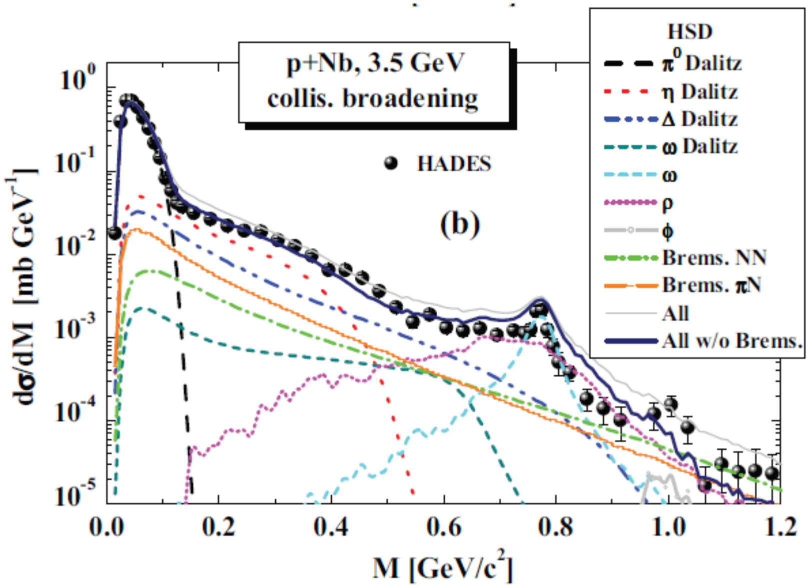


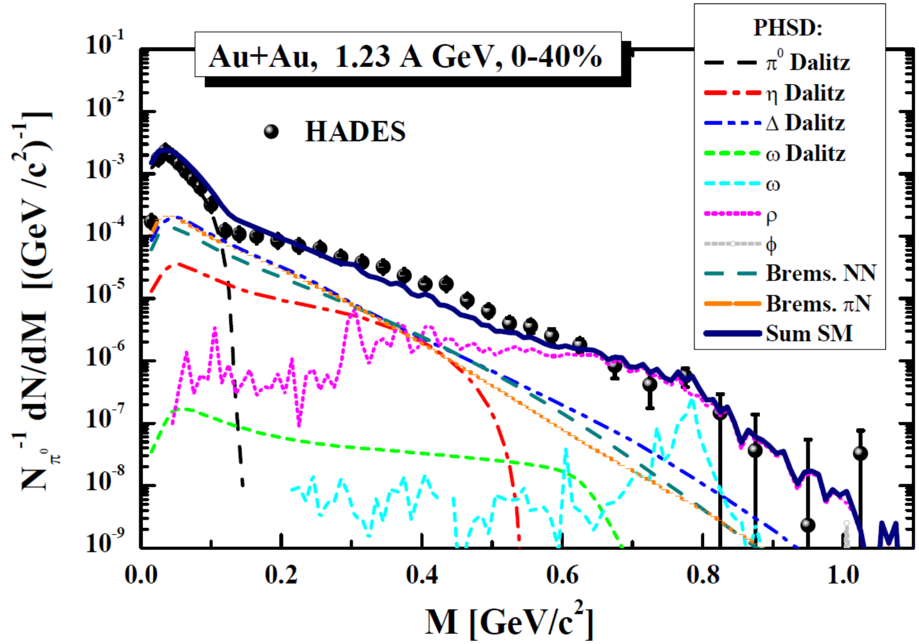
- Strong influence of the Fermi-motion in p+n(d)
- Strong isospin dependence of dN/dM in p+p vs p+n!

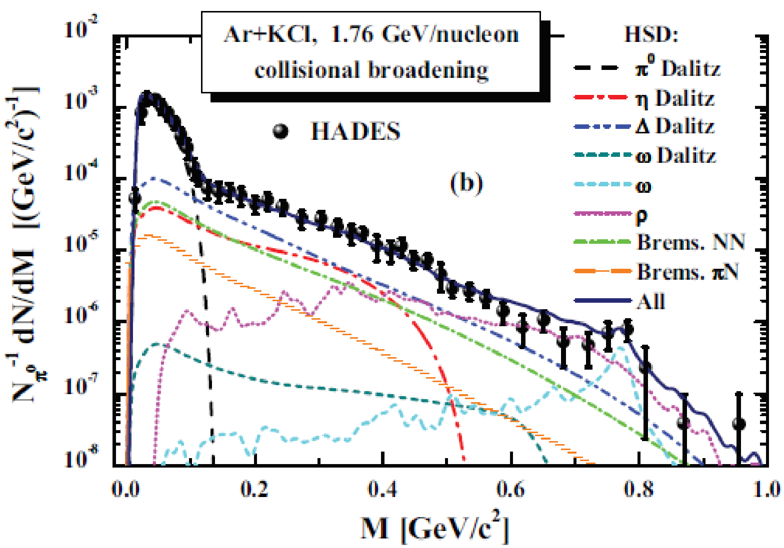
- New exp. data on p+n / p+d are needed! → HADES, CBM

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

HADES: Dileptons from p+A and A+A at SIS energies







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

- **In-medium effects are visible in p+A collisions,**
- **In-medium effects are stronger for large systems (Au+Au)**

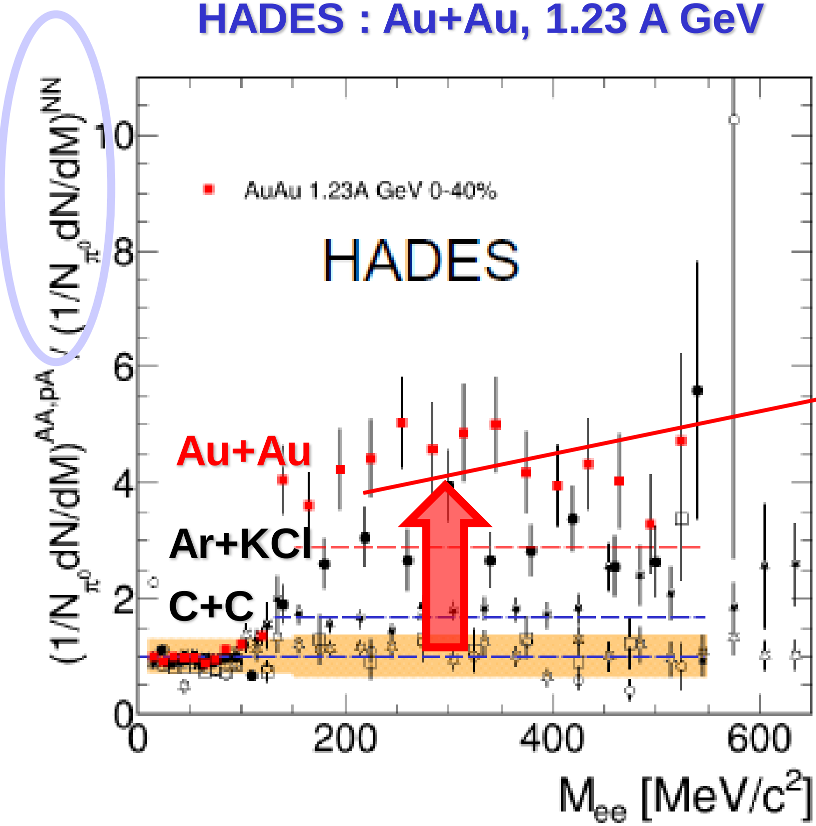
HADES: J. Adamczewski-Musch et al., Nat. Phys. 15 (2019), 1040.
PHSD: I. Schmidt, E.B., M. Gumberidze, R. Holzmann, PRD 104 (2021), 015008

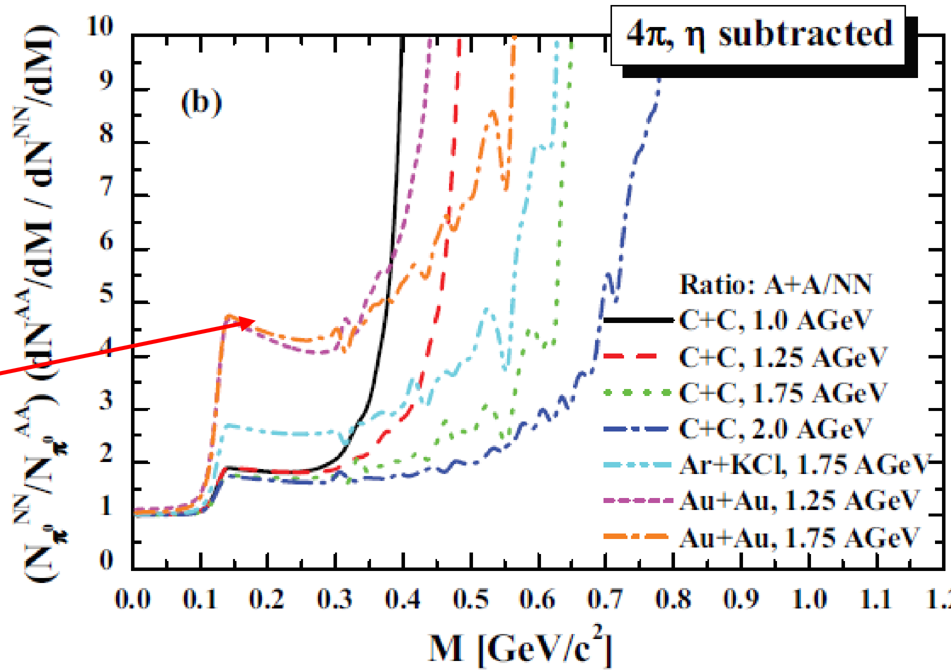
Dileptons at SIS (HADES): Au+Au

HADES, Nature Phys.15 (2019) 1040

▪ HSD predictions (2013)

HADES : Au+Au, 1.23 A GeV





❑ **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN

❑ **Increases with the system size!**

1) **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) **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

Polarization phenomena with dileptons

Polarization: Dilepton anisotropy coefficients

E.B., O.V. Teryaev, V. D. Toneev, Phys. Lett. B 348 (1995) 283;
E.B., M. Schäfer, W. Cassing, U. Mosel, O.V. Teryaev, V. D. Toneev, B 348 (1995) 325; B 362 (1995) 17, B 376 (1996) 12; Z. Phys. C75 (1997)197

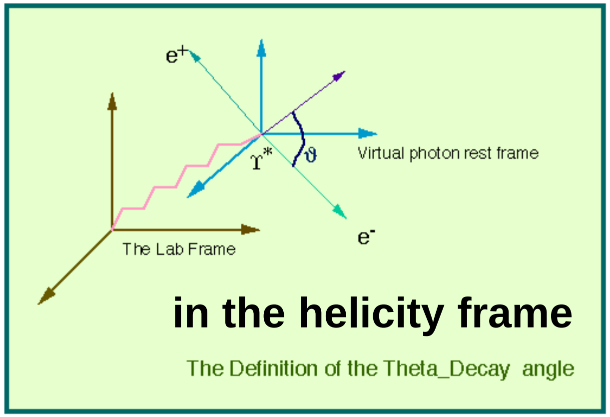
Angular distribution → density matrix elements :

$$W(\theta,\varphi)=\frac{3}{8\pi}\Big[\rho_{11}(1+\cos^2\theta)+(1-2\rho_{11})\sin^2\theta+\rho_{1-1}\sin^2\theta\cos^2 2\varphi +\sqrt{2}\mathrm{Re}\rho_{10}\sin 2\theta\cos\varphi\Big],$$

$W(\theta,\phi)=d\sigma/d(\cos\theta) \sim 1 + B\cos^2\theta$

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

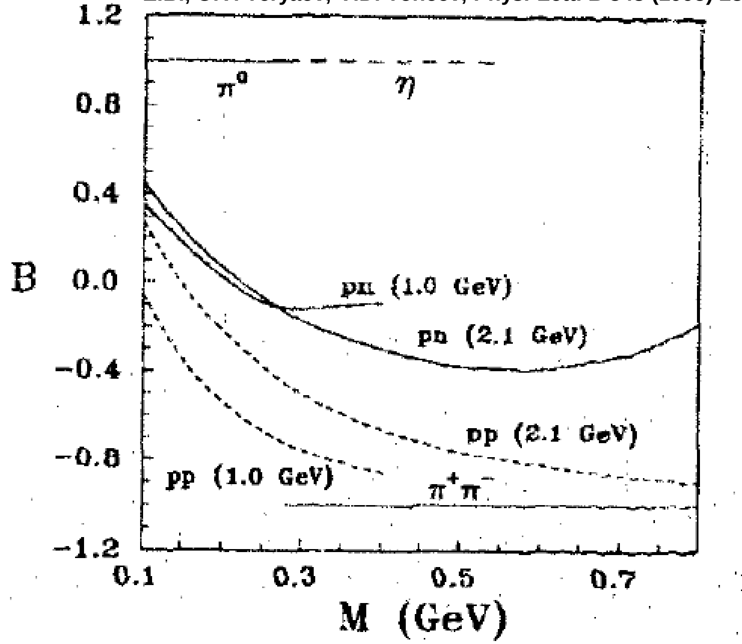
$$\rho_{00}+2\rho_{11}=1$$



Anisotropy coefficient B for elementary channels:

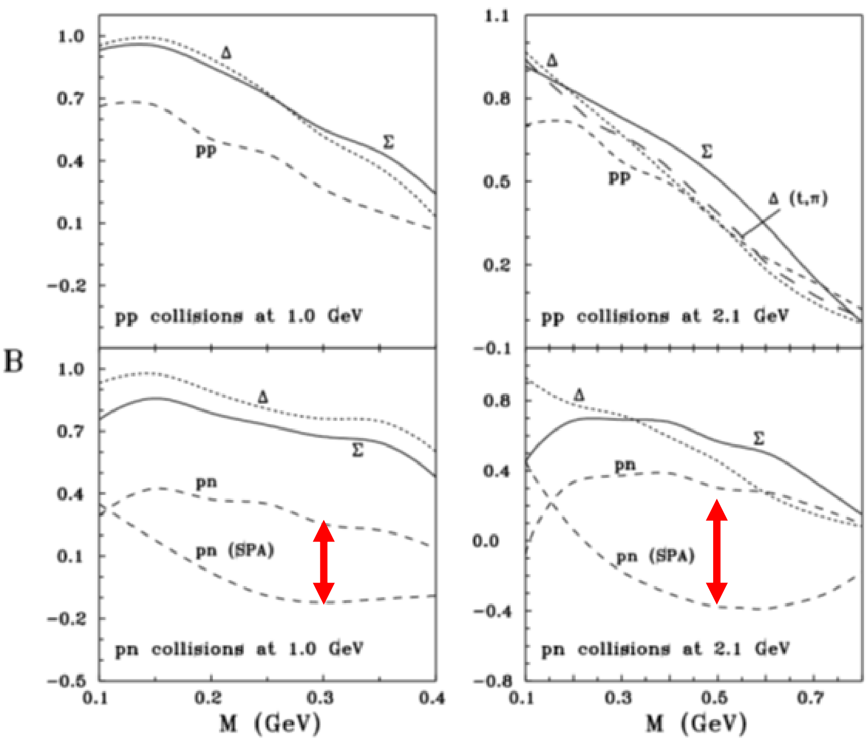
- **pseudoscalar mesons** (e.g. π^0 and η):
  B = +1
- **vector mesons** (e,g, ρ, ω and ϕ) from NN→VX:
  if no preferred spin orientation of VM
  B → 0
- **π π annihilation**: $\pi^+\pi^-\to\rho\to e^+e^-$: **B = -1**
  p wave (L=1 ⊥ to π π scattering plane)
- **Δ and N* decays**: **B(M)**
- NN and πN **bremsstrahlung**: **B(M)**

E.B., O.V. Teryaev, V.D. Toneev, Phys. Lett. B 348 (1995) 283

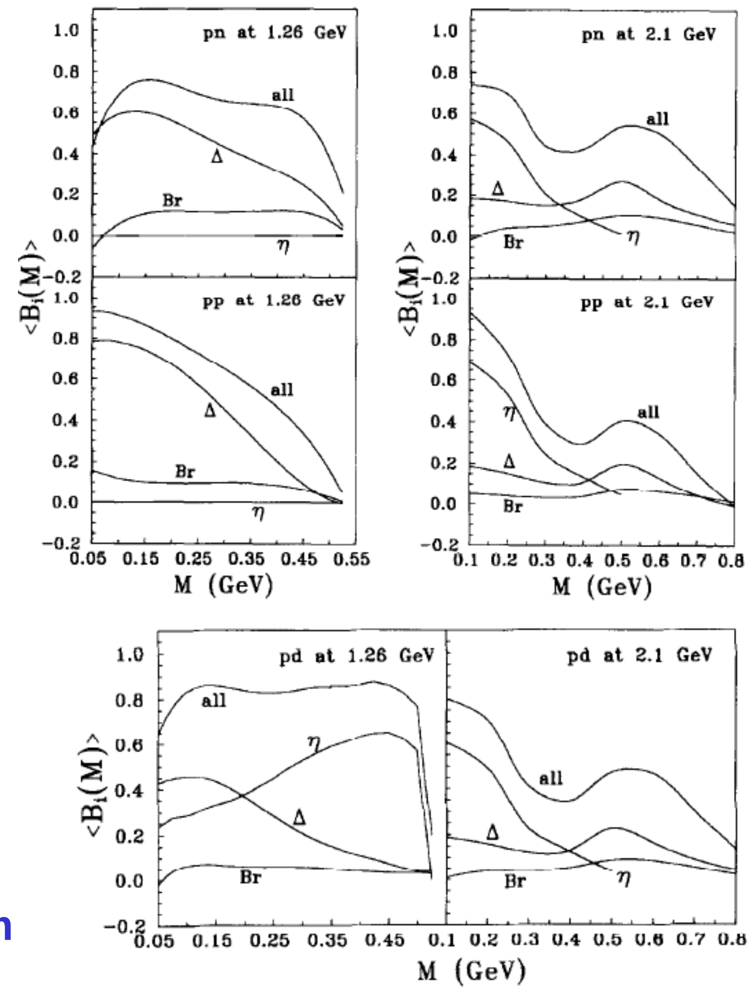


Dilepton anisotropy coefficients in p+p, p+n, p+d

B **from Δ-decay and Bremsstrahlung**
("pn" on plots):
sensitive to the model details:
B **from SPA <** ***B*** **from OBE model**



The "weighted" anisotropy coefficients for p+p, p+n and p+d collisions



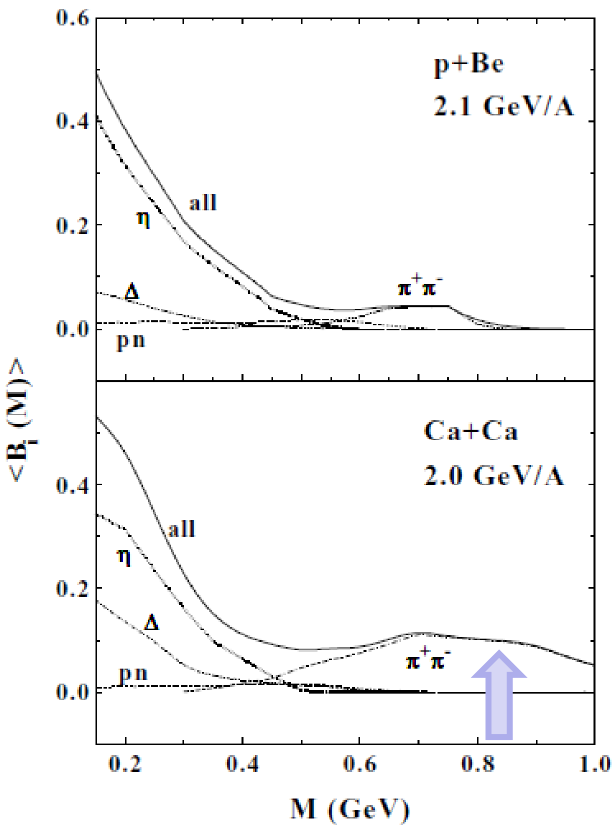
➔ <B> is sensitive to the production mechanism and model description of polarization

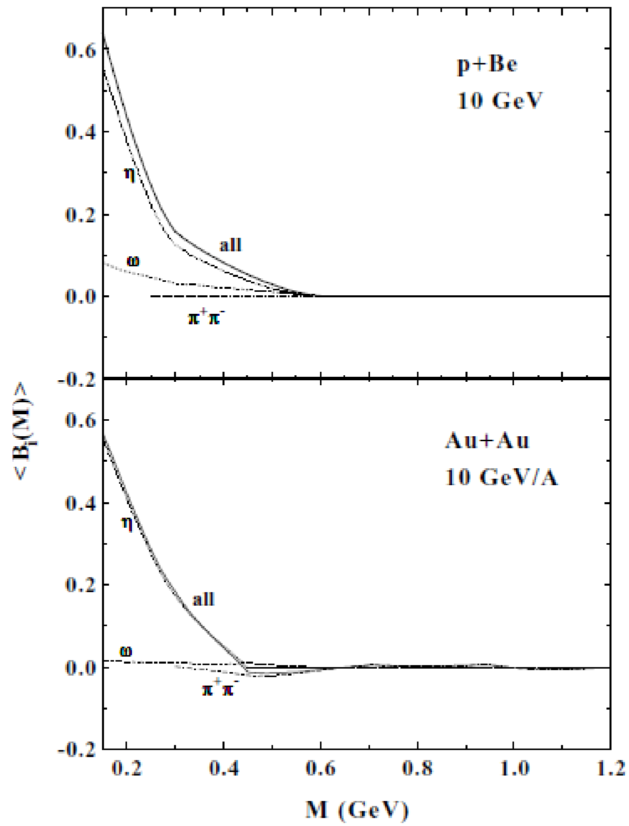
E.B., M. Schäfer, W. Cassing, U. Mosel, O.V. Teryaev, V. D. Toneev, Phys. Lett. B 348 (1995) 325; B 362 (1995) 17, B376 (1996) 12

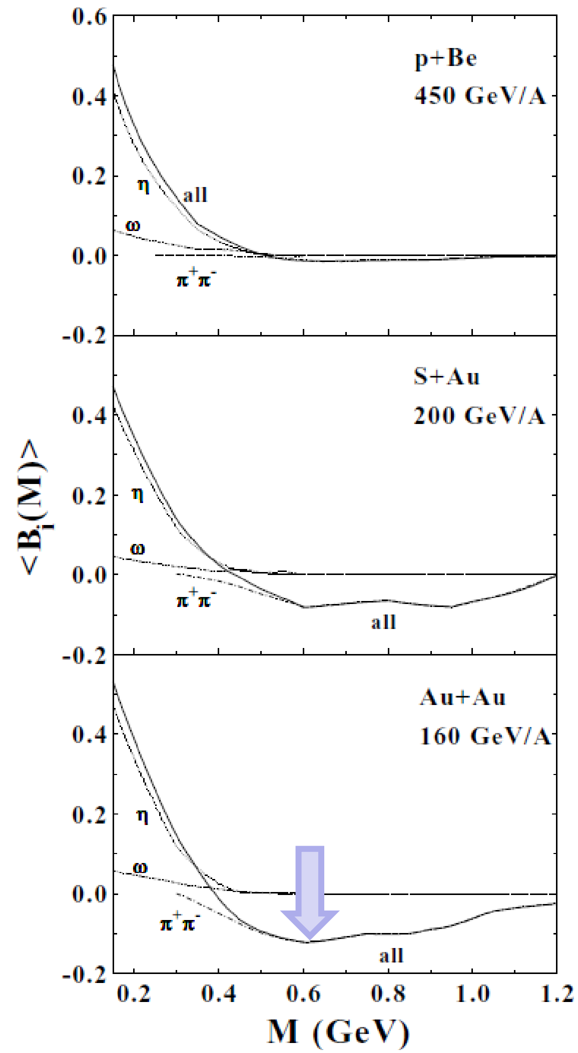
Dilepton anisotropy coefficients in p+A, A+A

The **"weighted" anisotropy coefficients** for p+Be and A+A collisions

Z. Phys. C75 (1997)197







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

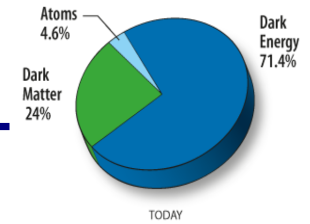
➔ **Information on ρ polarization (depends on ρ production mechanism)!**

➔ **Opportunities for the FAIR dilepton program!**

Physics beyond the standard model: search for dark matter with dileptons

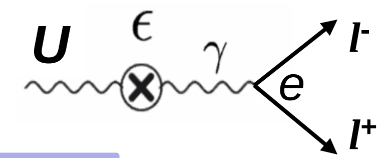
DM ‚candidate‘

Light dark photons searches with p+p, p+A



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

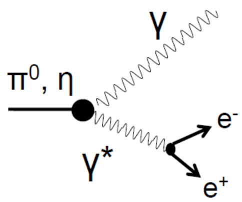
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$



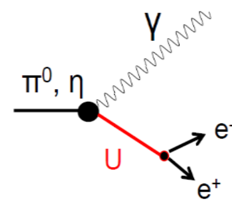
Notation for 'dark photon': A' or U- boson

Unknown: kinetic mixing parameter ϵ and mass M_U

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

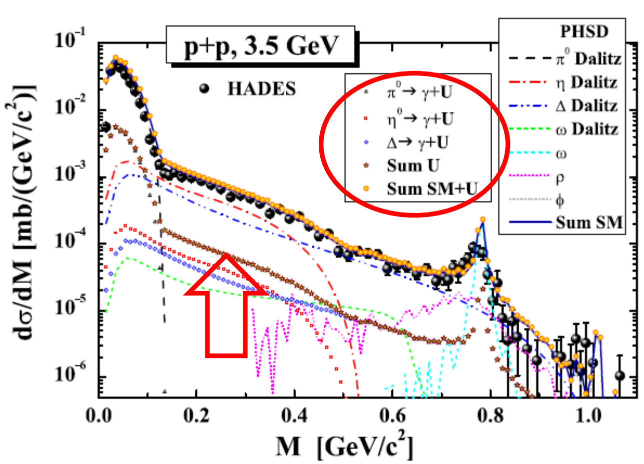


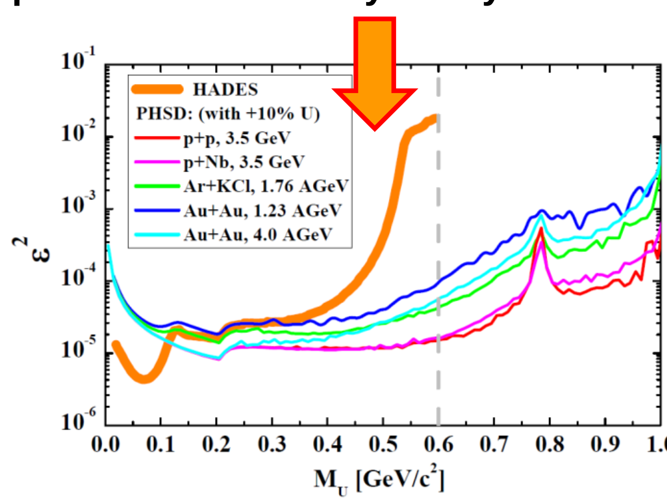
U(1)-U(1)′ kinetic mixing

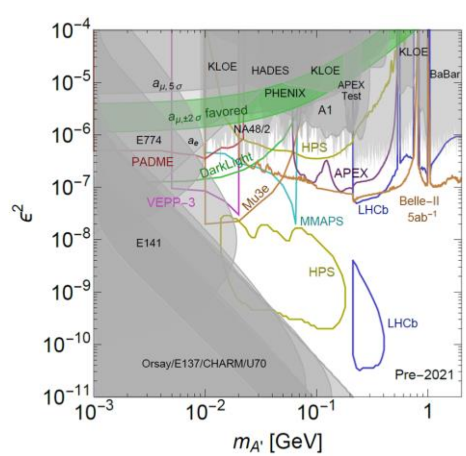


$\pi^0 \rightarrow \gamma + U$,
$\eta \rightarrow \gamma + U$, $U \rightarrow e^+e^-$
$\Delta \rightarrow N + U$

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:







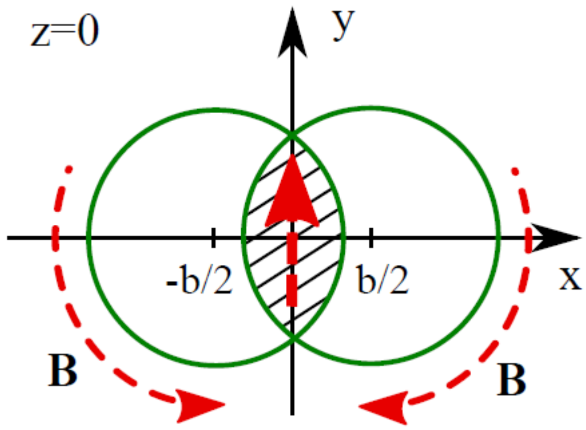
Ida Schmidt, E.B., Malgorzata Gumberidze, Romain Holzmann, Phys.Rev.D 104 (2021) 015008

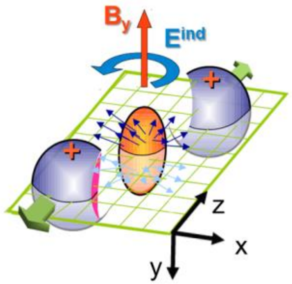
Outlook-II: possibilities with dileptons in p+p, p+A:

- Study of different elementary production channels in p+p, p+n(d)
- Study of isospin effects in p+p and p+n(A)
- Study of mesonic and baryonic resonance production and their properties
- Study of in-medium effects with vector mesons (ρ,ω,ϕ) in p+A at normal nuclear density
- Observation of the polarization phenomena with dileptons – dilepton anisotropies
  + an additional information on production mechanisms

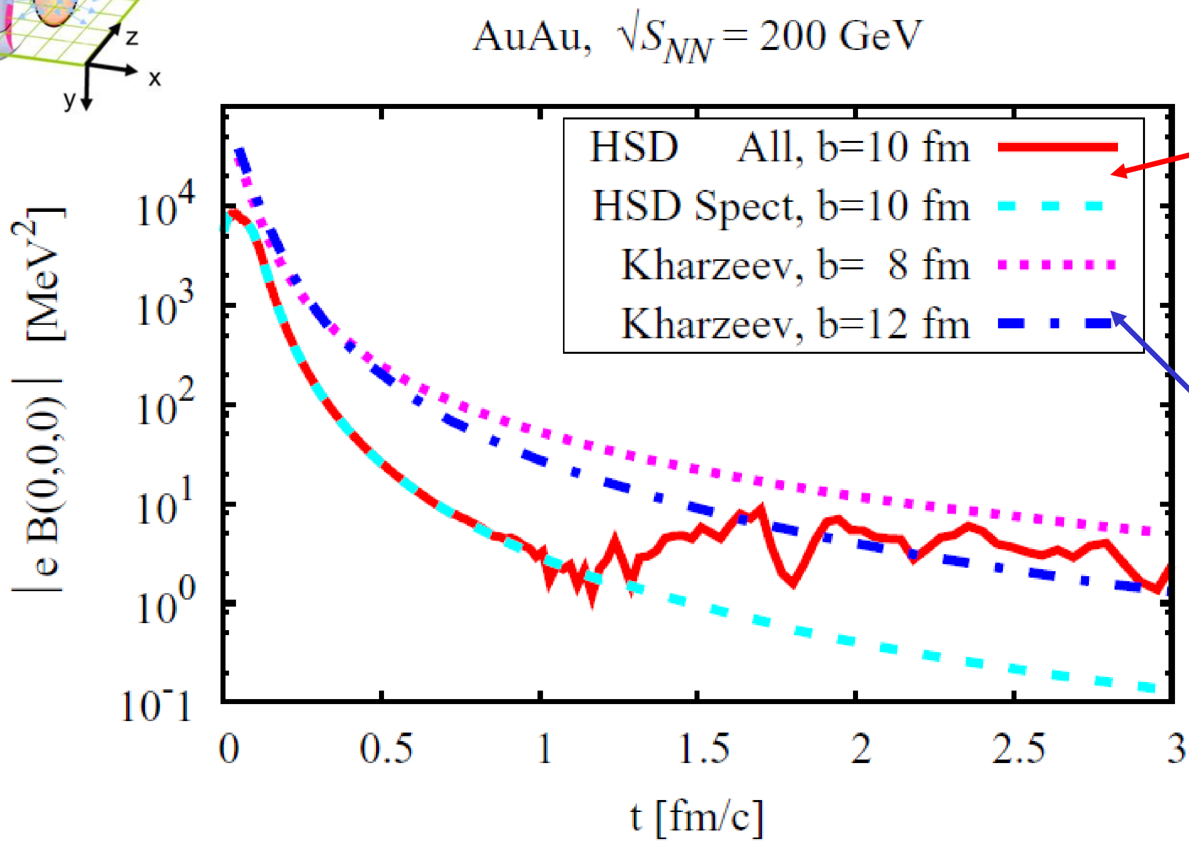
- Possibility to search for dark photons with dileptons

Influence of the electromagnetic fields on p+A and A+A dynamics





Time dependence of eB_y



First microscopic calculations of **dynamically generated EM fields**

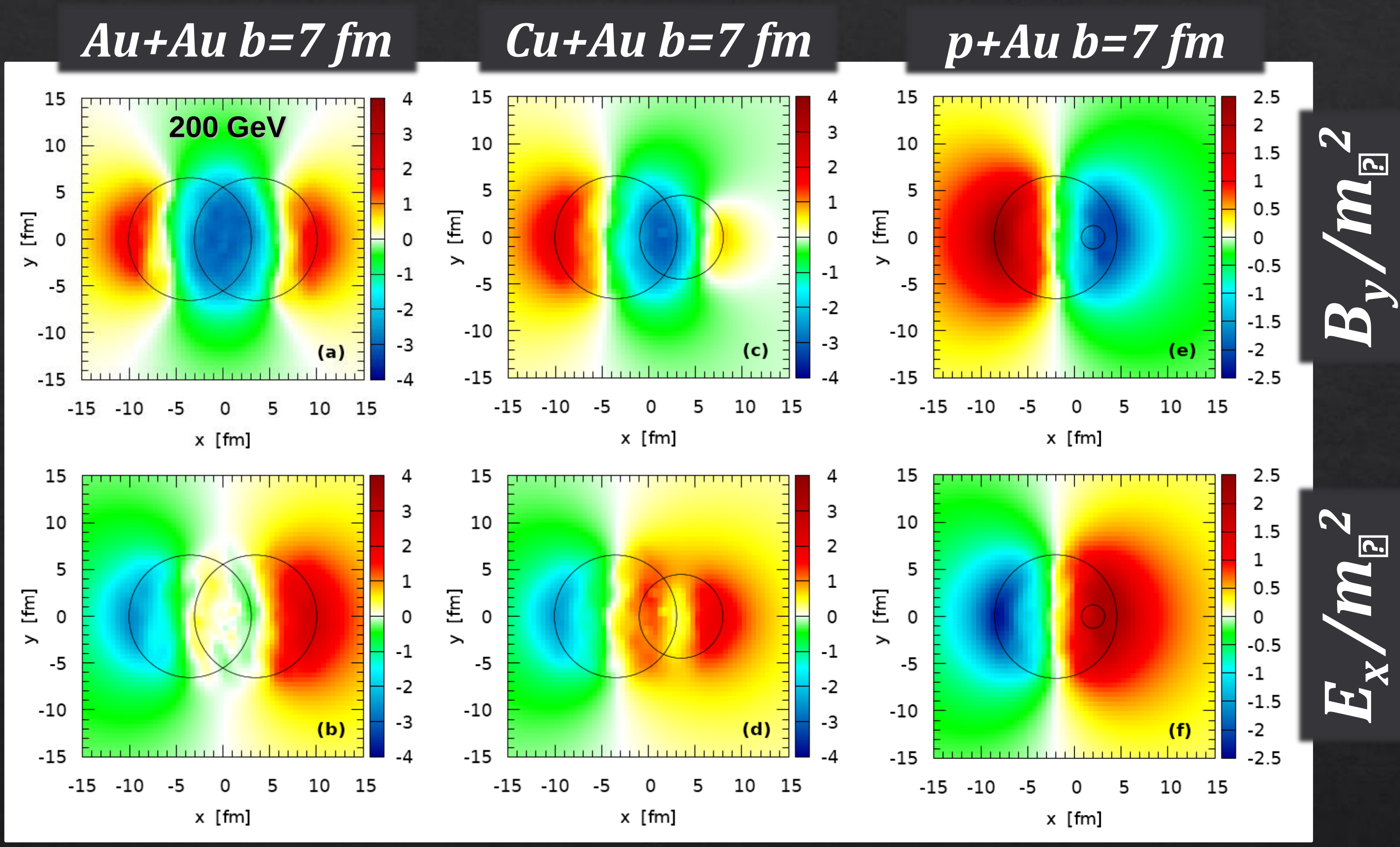
HSD: V.Voronyuk, et al., PRC83 (2011) 054911

Collision of two infinitely thin layers (pancake-like)
D.E. Kharzeev et al., NPA803, 227 (2008)

- **Until t~1 fm/c the induced magnetic field is defined by spectators only**
- **Maximal magnetic field is reached during nuclear overlap time Δt~0.2 fm/c, then the field drops exponentially**

V. Voronyuk, V.D. Toneev et al., Phys.Rev. C83 (2011) 054911

Electromagnetic fields: A+A vs p+A



initial transvese profiles at RHIC 200 GeV

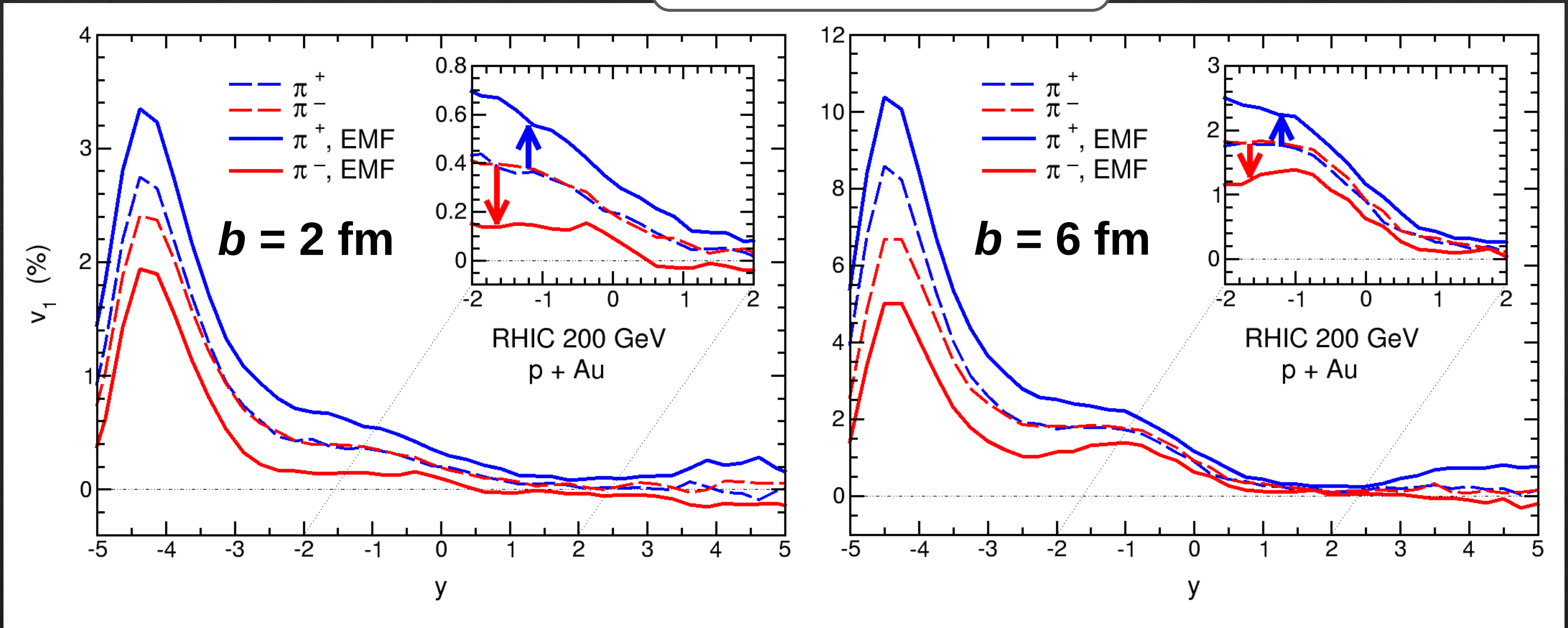
intense electric fields directed from the heavy nuclei to light one in the overlap region of asymmetric colliding systems due to the different number of protons in the two nuclei

Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014)
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

EMF and directed flow in p+A

rapidity dependence of the DIRECTED FLOW OF PIONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



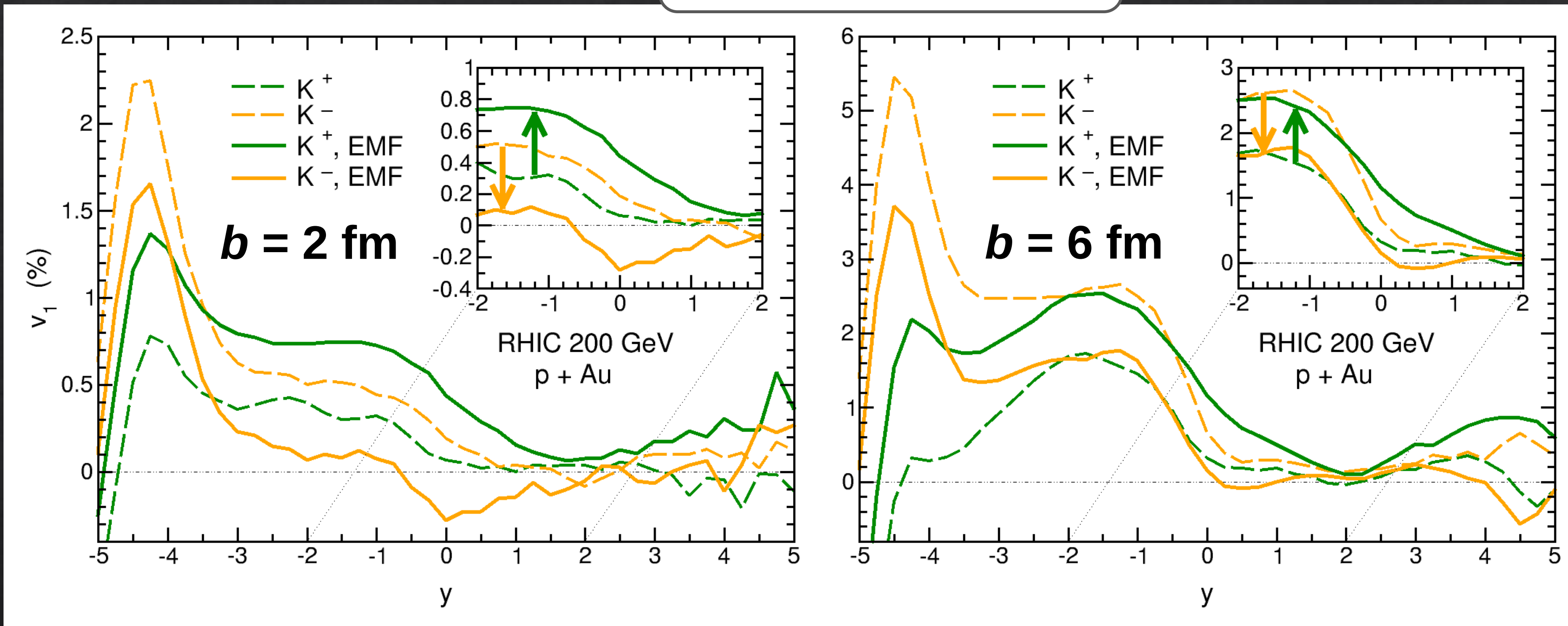
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Splitting of π^+ and π^- induced by the electromagnetic field

EMF and directed flow in p+A

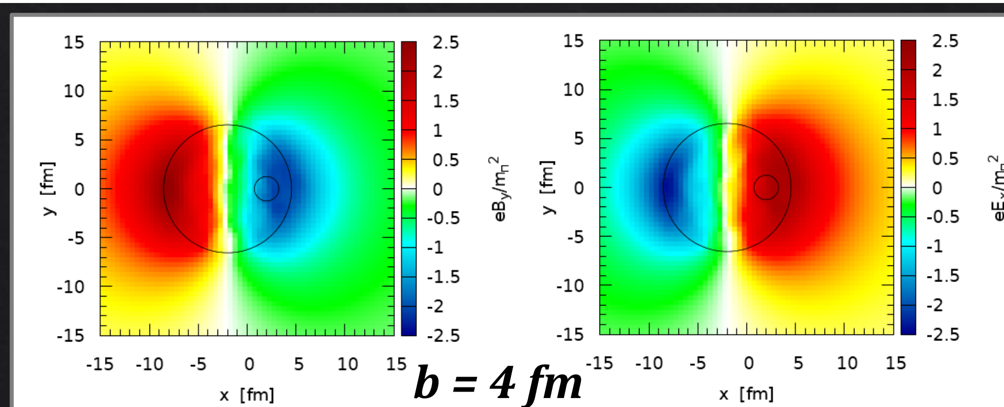
rapidity dependence of the DIRECTED FLOW OF KAONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Splitting of K^+ and K^- induced by the electromagnetic field



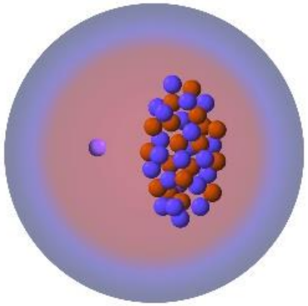
Outlook-III: EM fields in p+A reactions

Generation of strong electromagnetic fields in p+A reactions

➔ **study of the influance of the electromagnetic fields on particle dynamics in p+A reactions**

Observables:

Splitting of v_1 (y) of mesons: π^+ / π^- and K^+ / K^- induced by the electromagnetic field



Thank you for your attention !

Thanks to the Organizers !

HFHF Helmholtz Forschungsakademie Hessen für FAIR