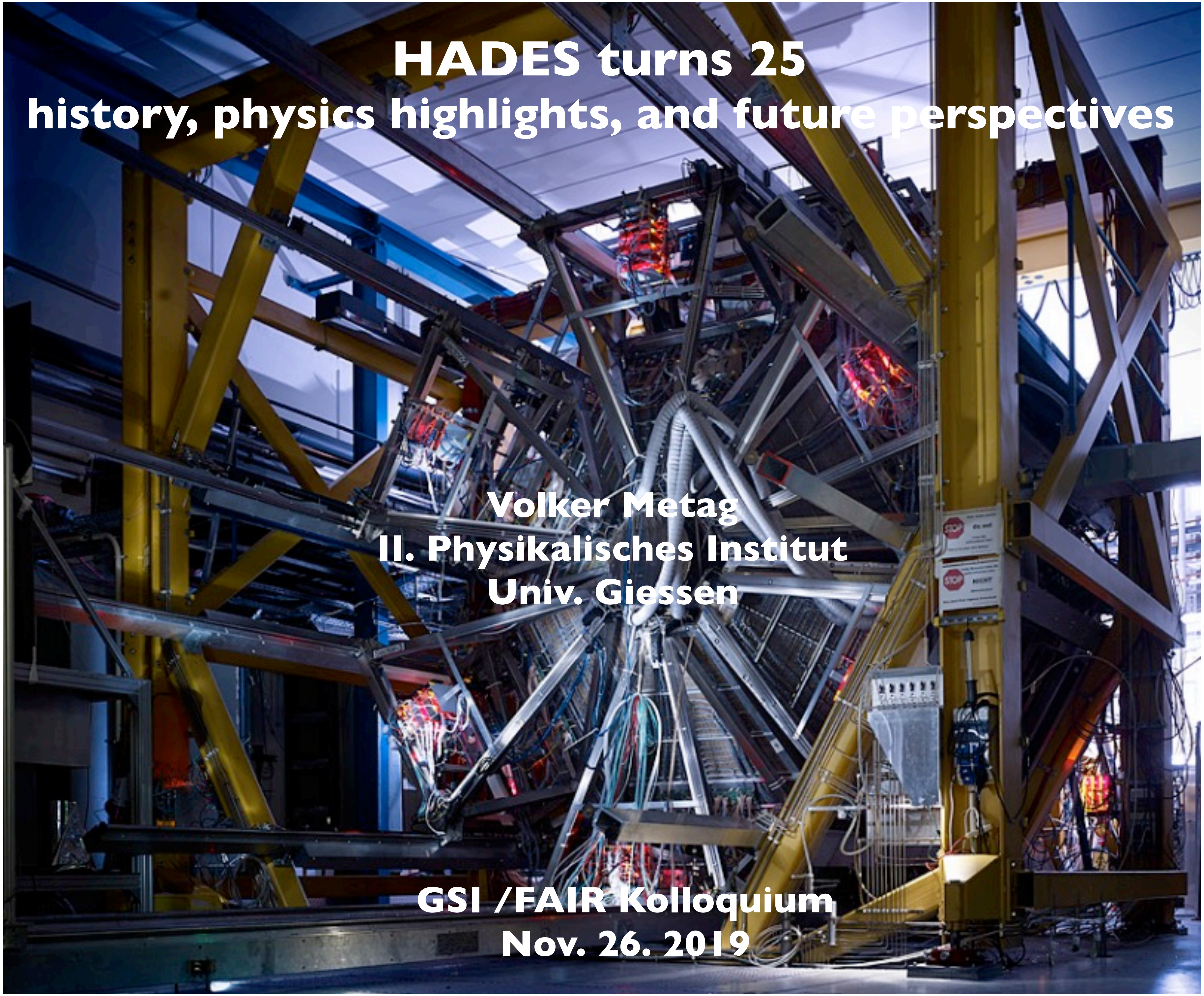


HADES turns 25
history, physics highlights, and future perspectives

Volker Metag
II. Physikalisches Institut
Univ. Giessen

GSI /FAIR Kolloquium
Nov. 26. 2019

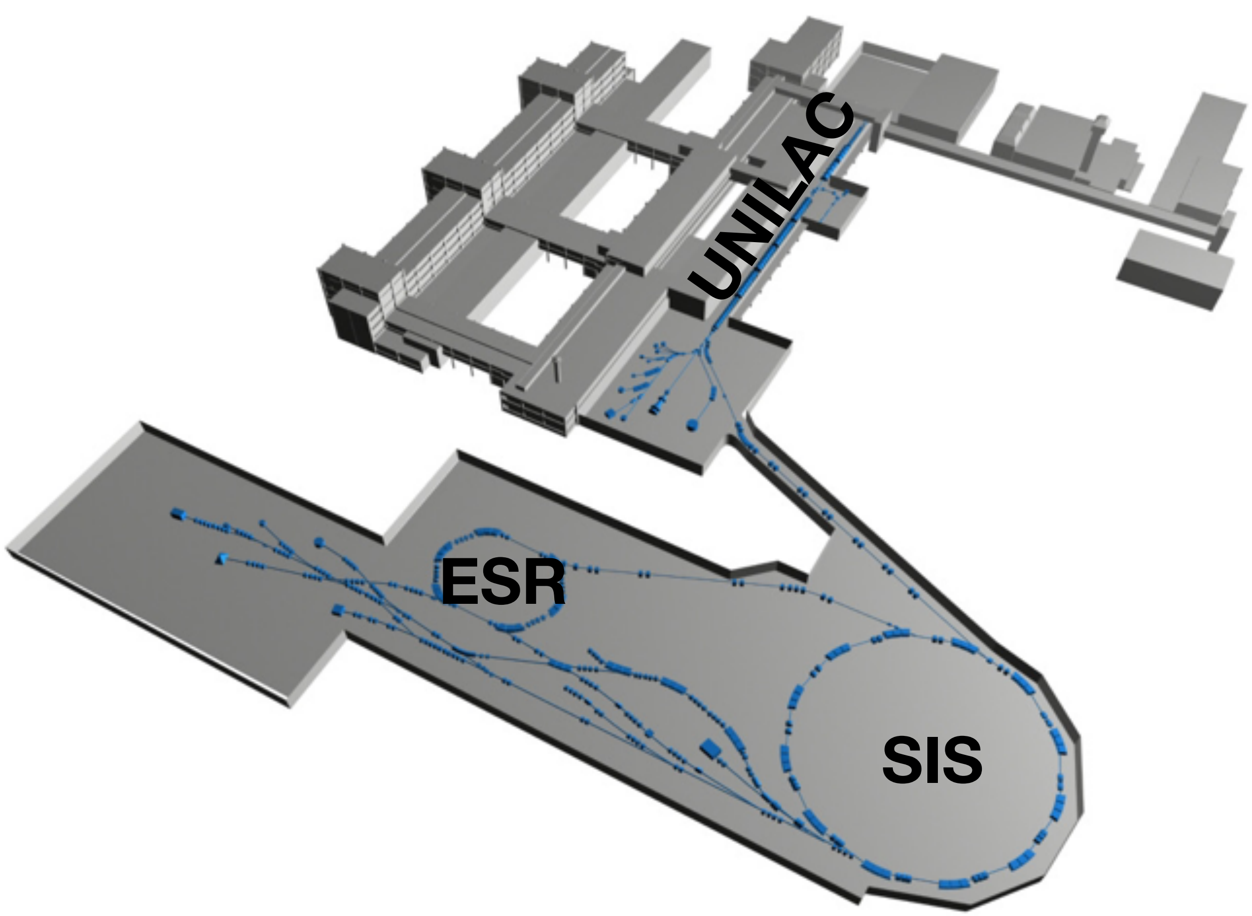
GSI in the 1980's

1985, April 17 approval of SIS/ESR project by Federal Ministry (Dr. Riesenhuber)

1986, Nov 3 start of construction

1987, April 2 discussion of detector systems and experimental proposals

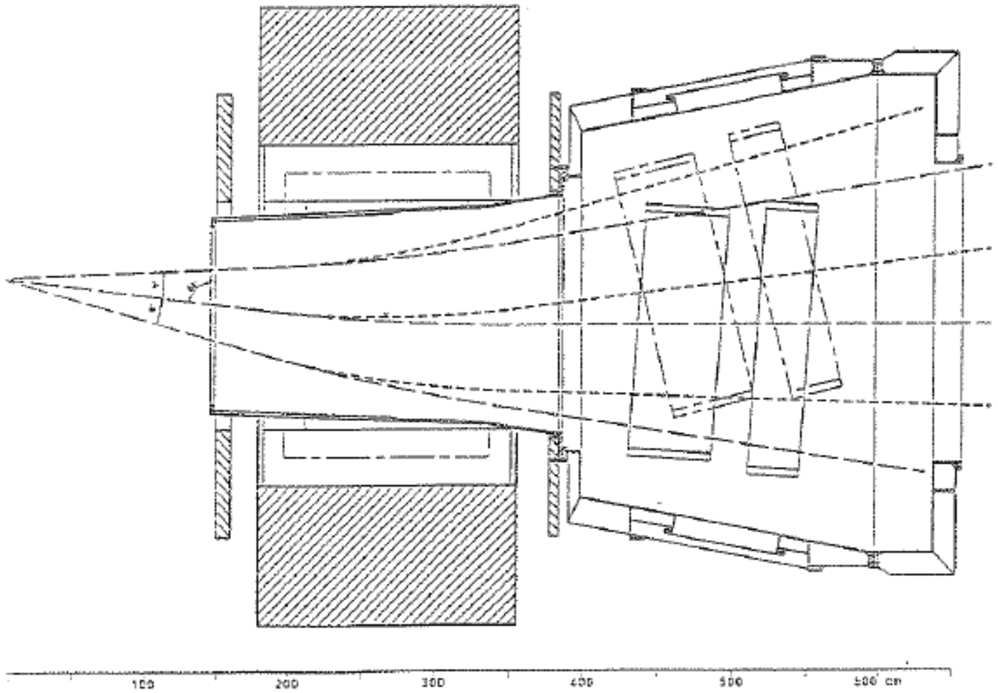
1990, April 23 inauguration of SIS/ESR



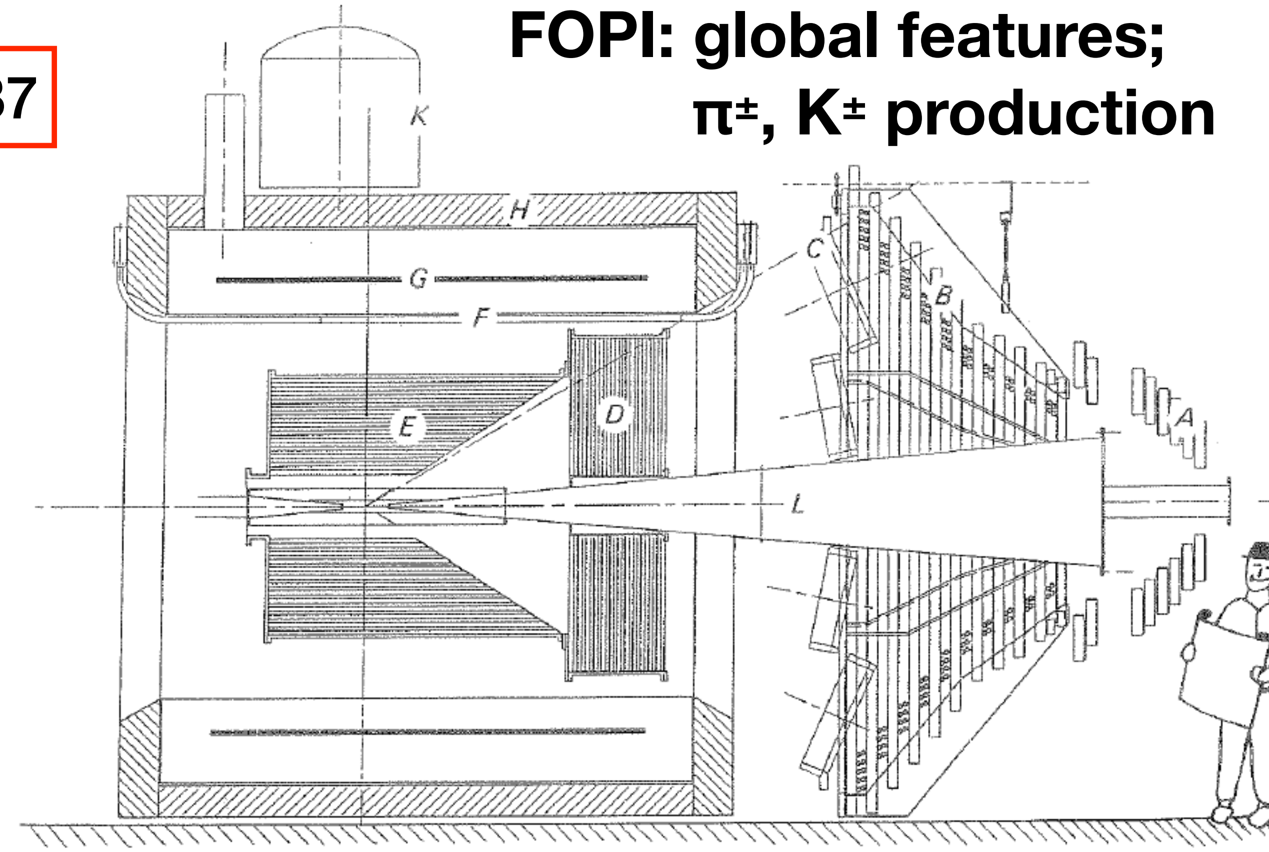
detector systems nuclear reactions at SIS

ALADIN: multifragmentation

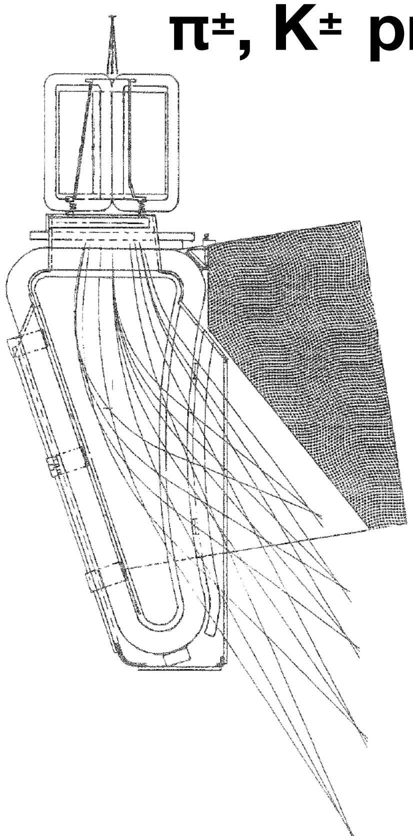
1987



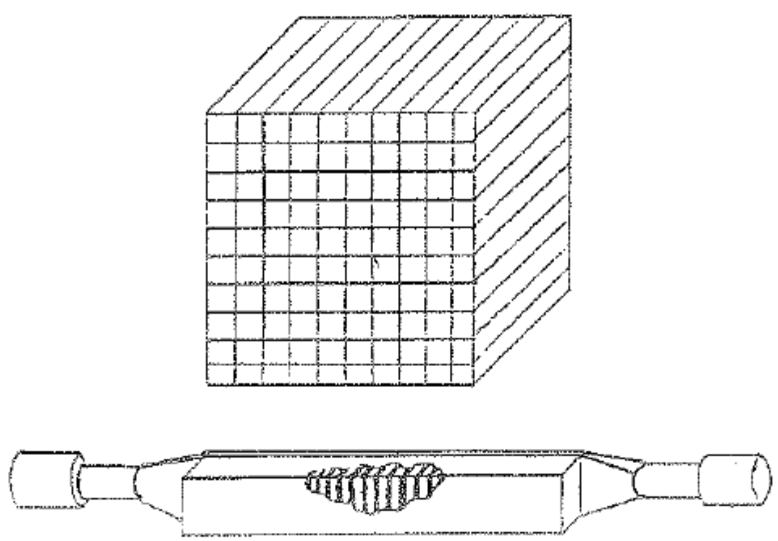
FOPI: global features; $\pi^{\pm}$, $K^{\pm}$ production



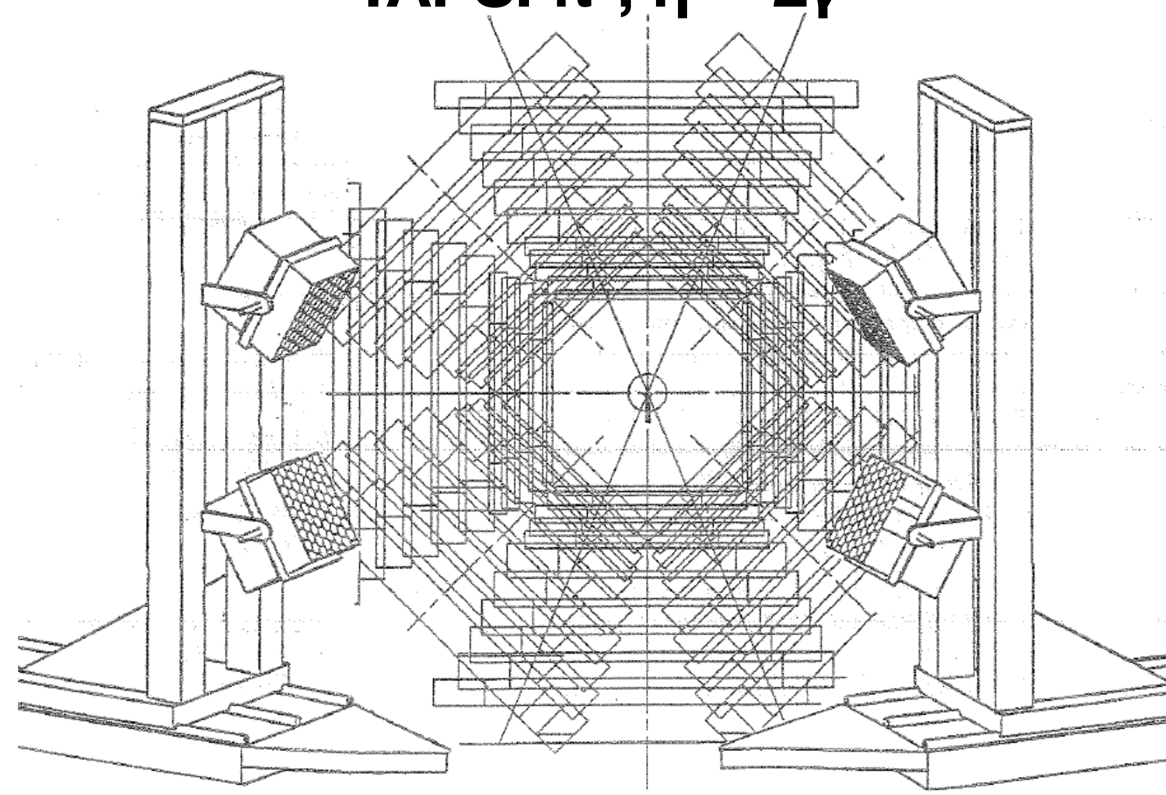
KaoS - spectrometer: $\pi^{\pm}$, $K^{\pm}$ production



LAND: neutrons



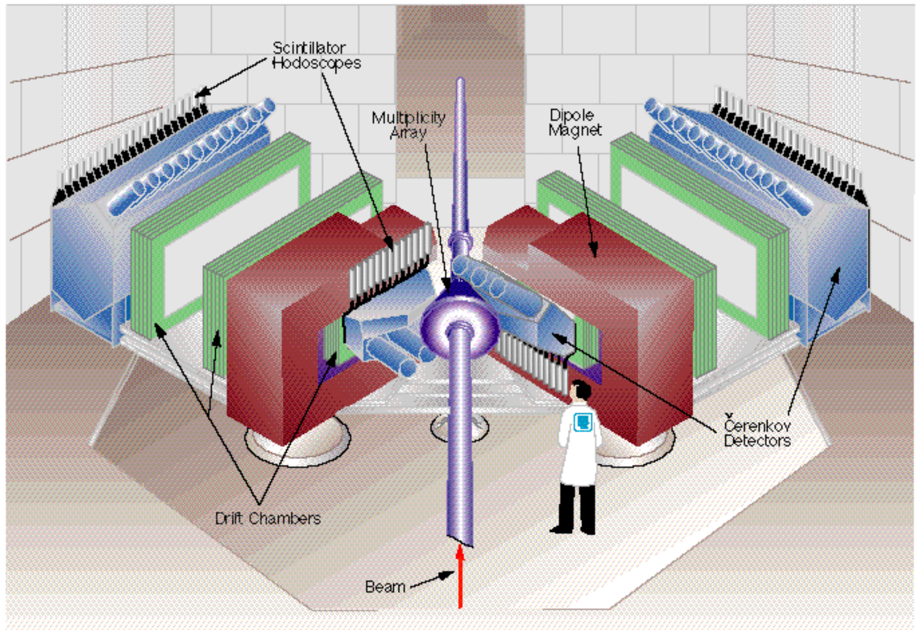
TAPS: π^0, $\eta \rightarrow 2\gamma$



Dilepton detector systems

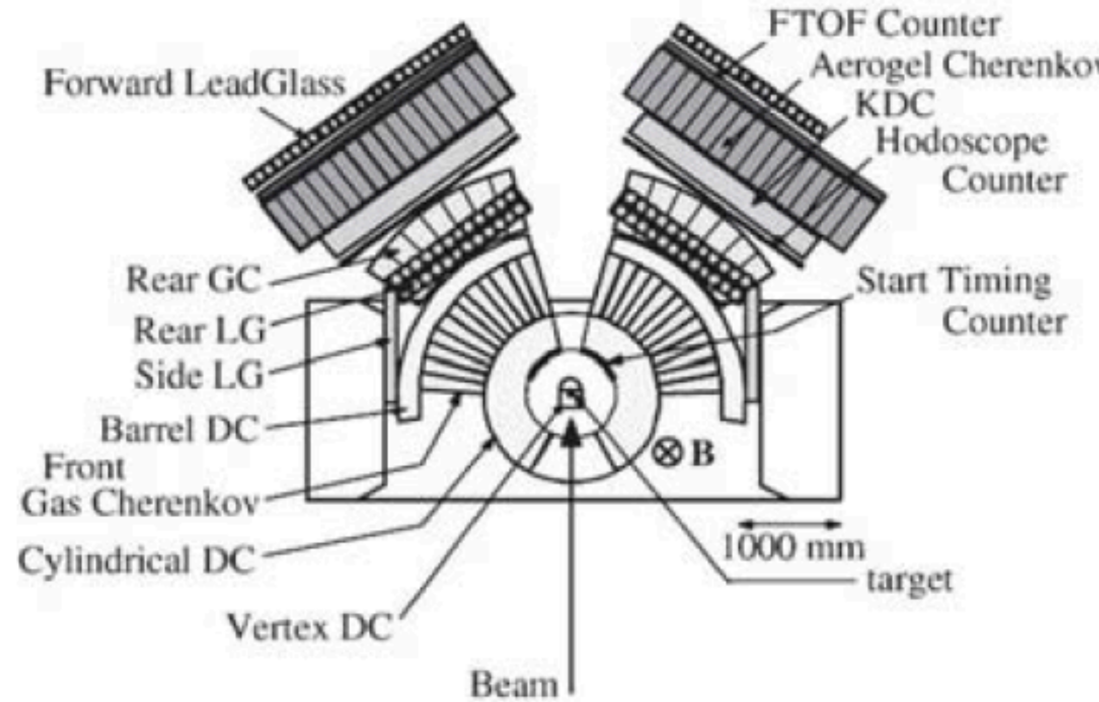
dileptons from relativistic heavy-ion collisions

DiLepton Spectrometer



DLS @ LBL Berkeley

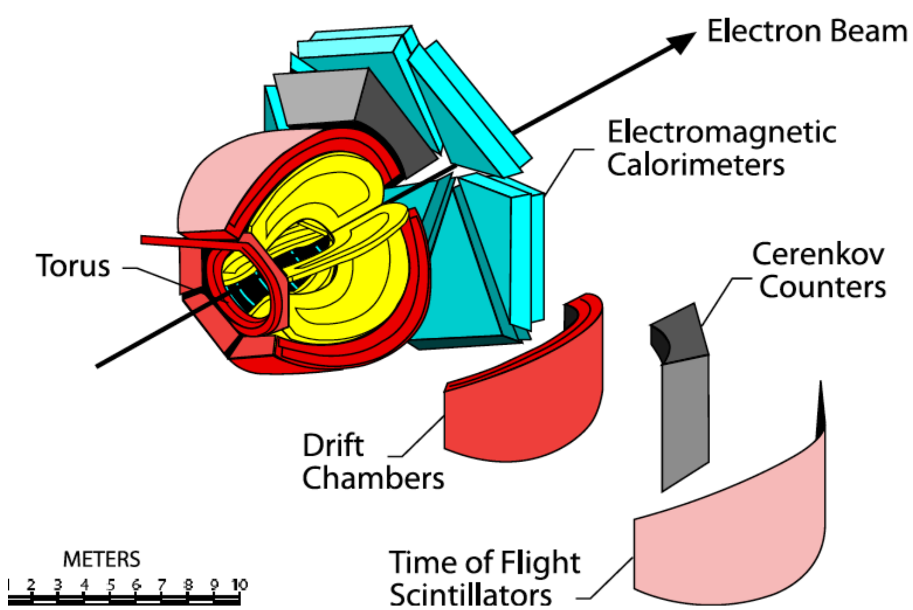
dileptons from proton induced nuclear reactions



KEK E325

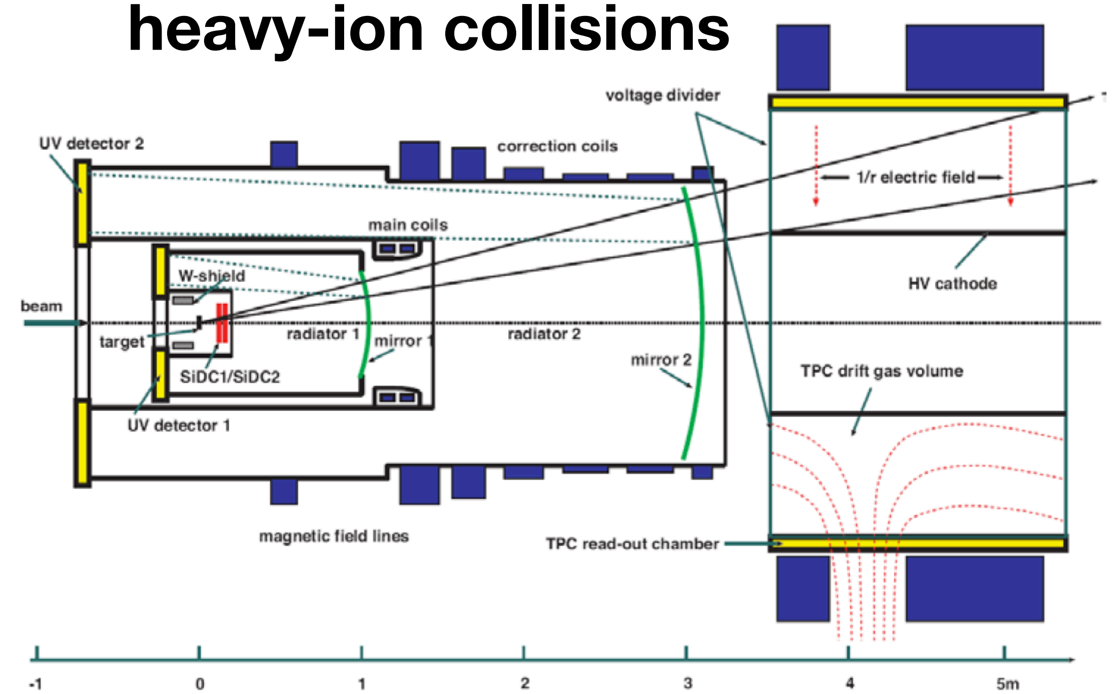
dileptons from photonuclear reactions

Large Acceptance Spectrometer



CLAS@Jlab

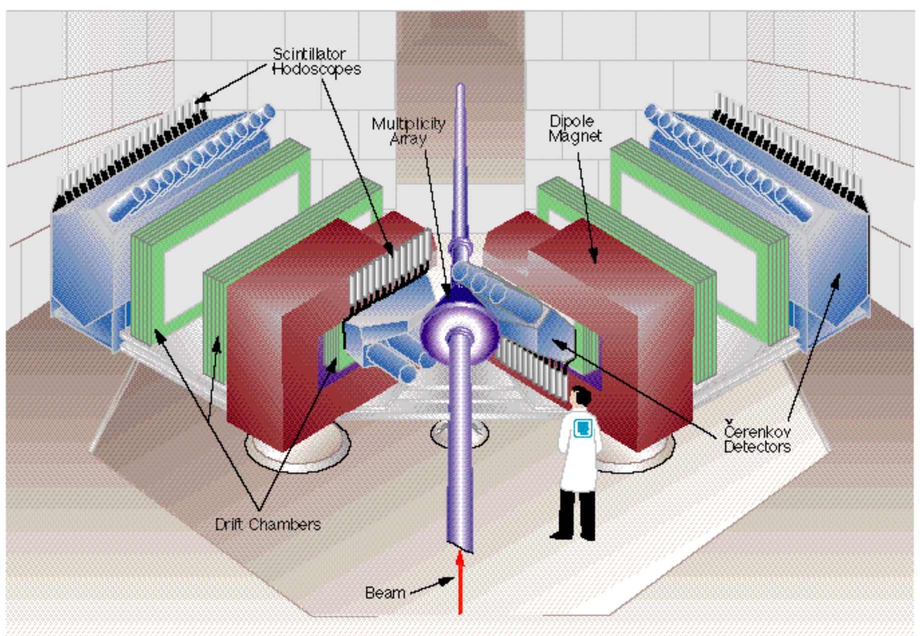
dileptons from ultra-relativistic heavy-ion collisions



CERES@CERN SPS

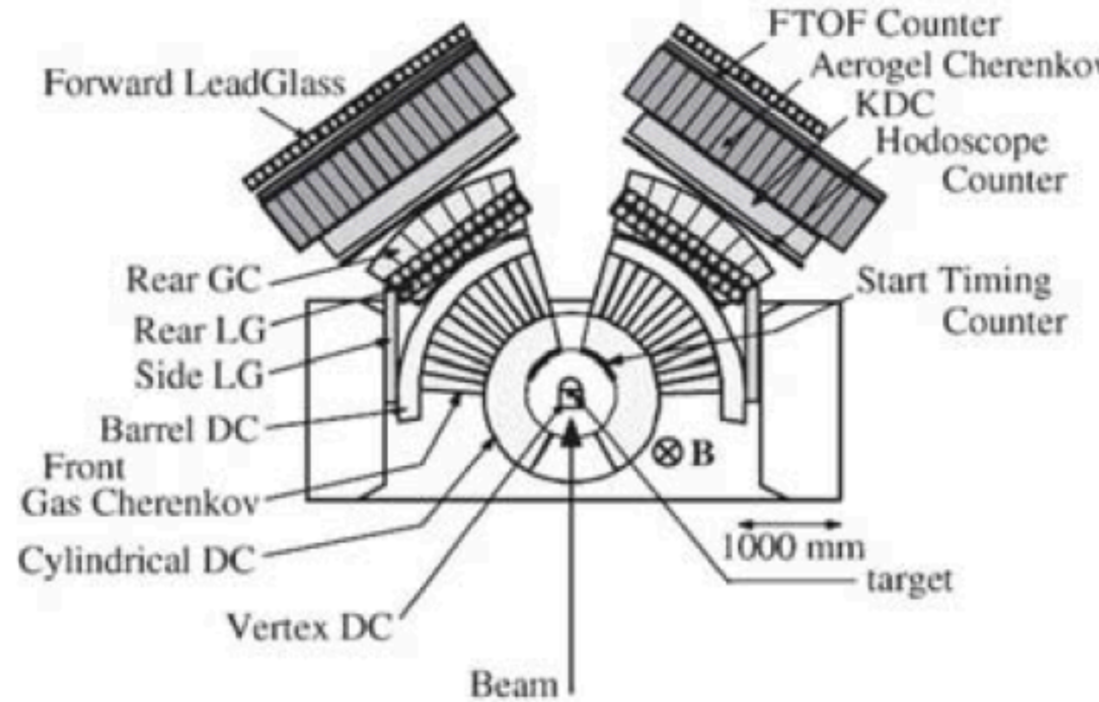
Dilepton detector systems

dileptons from relativistic heavy-ion collisions



DLS @ LBL Berkeley

dileptons from proton induced nuclear reactions

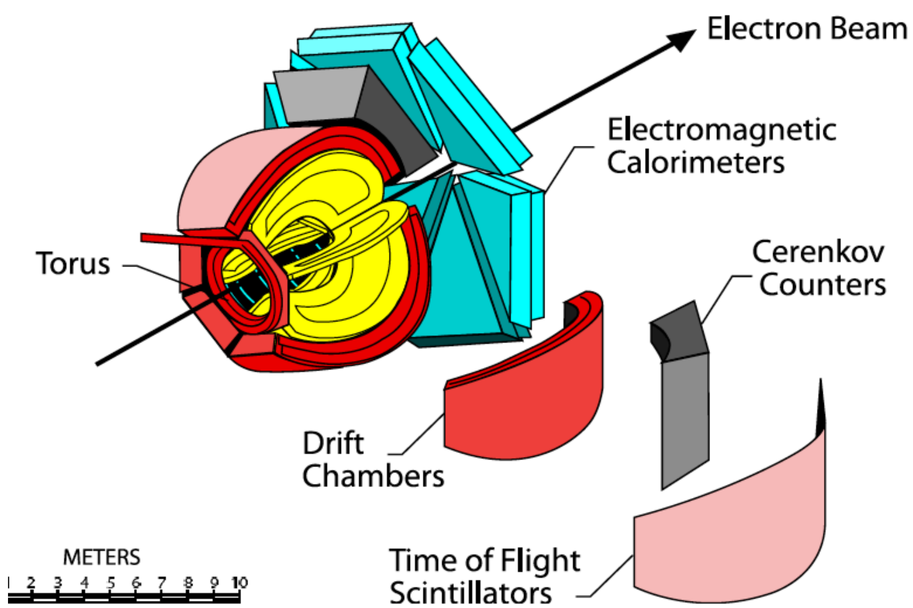


KEK E325

e+e-: penetrating probes !!

dileptons from photonuclear reactions

Large Acceptance Spectrometer



CLAS@Jlab

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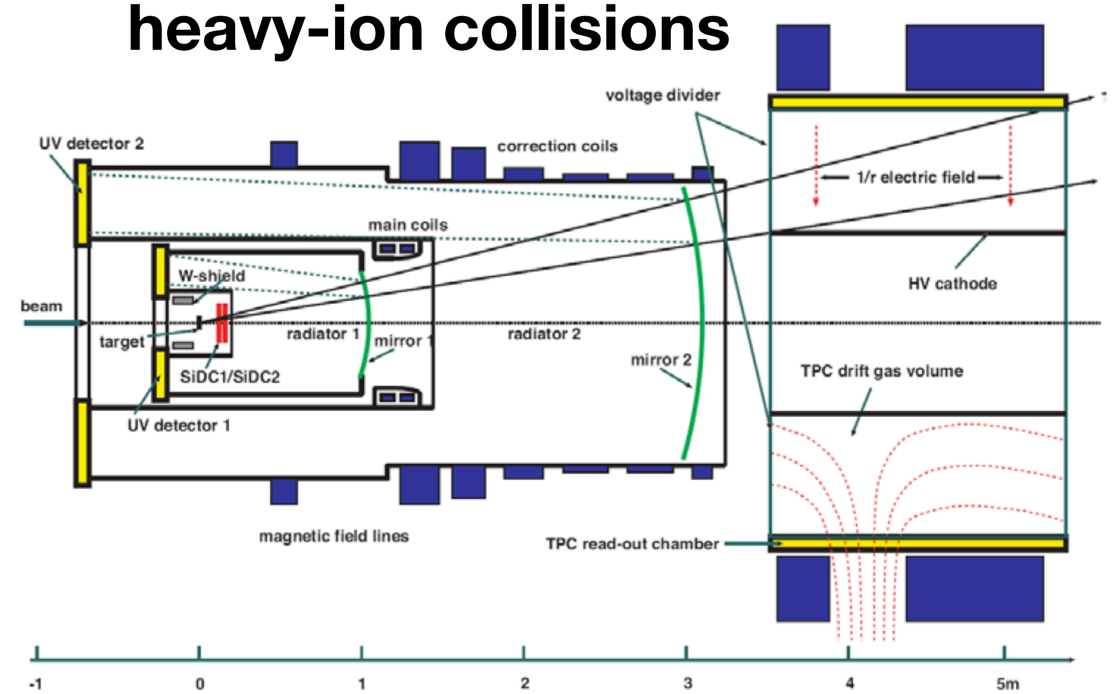

CERES@CERN SPS

On the way to the HADES project I

Formulation of the physics case

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(Berkeley) *G. Roche: First results on dilepton production at the BEVALAC*

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1991: Nov.21./22. (Rauischholzhausen) — 3rd. workshop on a real photon/dilepton program for SIS

3rd. workshop on a real photon/dilepton program for SIS

Rauischholzhausen castle
21./22. Nov. 1991

3rd. workshop on a real photon/dilepton program for SIS

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Hans Specht:

Electron Pair Spectrometer at SIS

1) design requirements

- acceptance $\varepsilon \approx 0.5$
  (factor 100 - 1000 to DLS)
- mass resolution $\delta m/m \sim 1\%$
  (factor 10 to DLS)

2) guide lines for design

- 0 material in acceptance
- 0 size
- 0 costs

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2) guide lines for design

- 0 material in acceptance
- 0 size
- 0 costs

1992: Jan.10 (GSI) formation of the HADES collaboration; spokesperson W. Kühn
(High **A**cceptance **D**i-**E**lectron **S**pectrometer)

On the way to the HADES project II

from the letter-of-intent to the accepted physics & technical proposal

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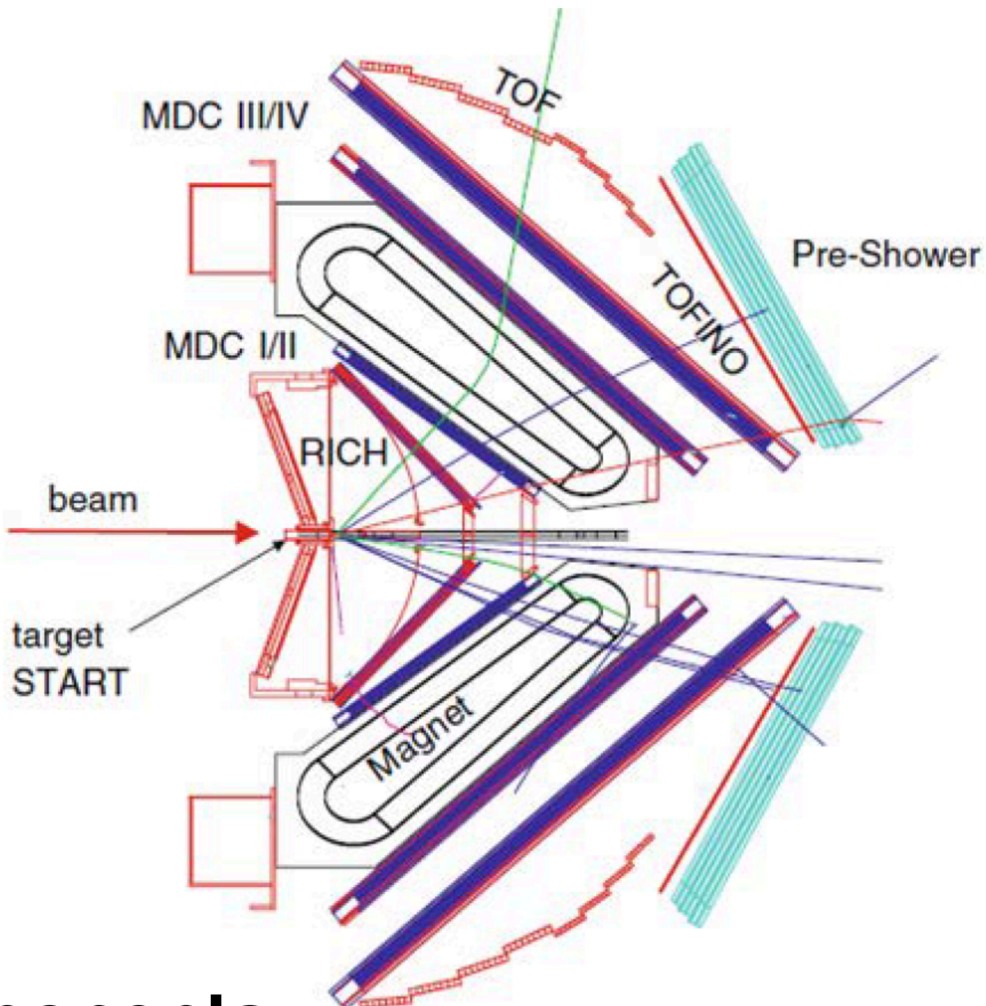
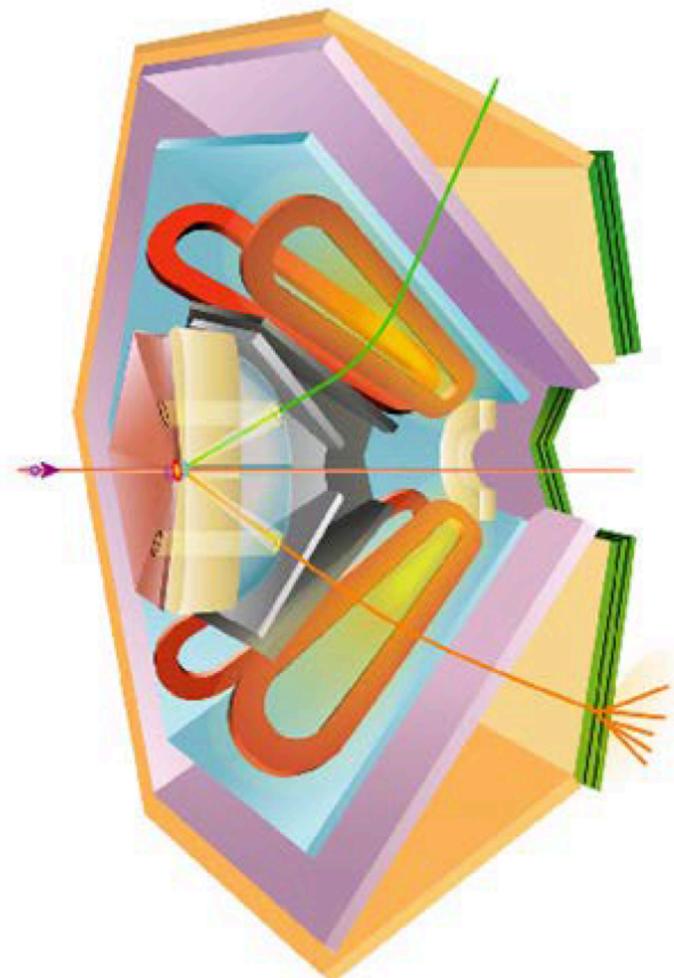
1994: 8.June decision by GSI directorate: HADES is part of GSI scientific program

the proposed and approved HADES detector setup





detector system for lepton and charged particle detection with momentum $\Delta m/m = 2\%$

components:

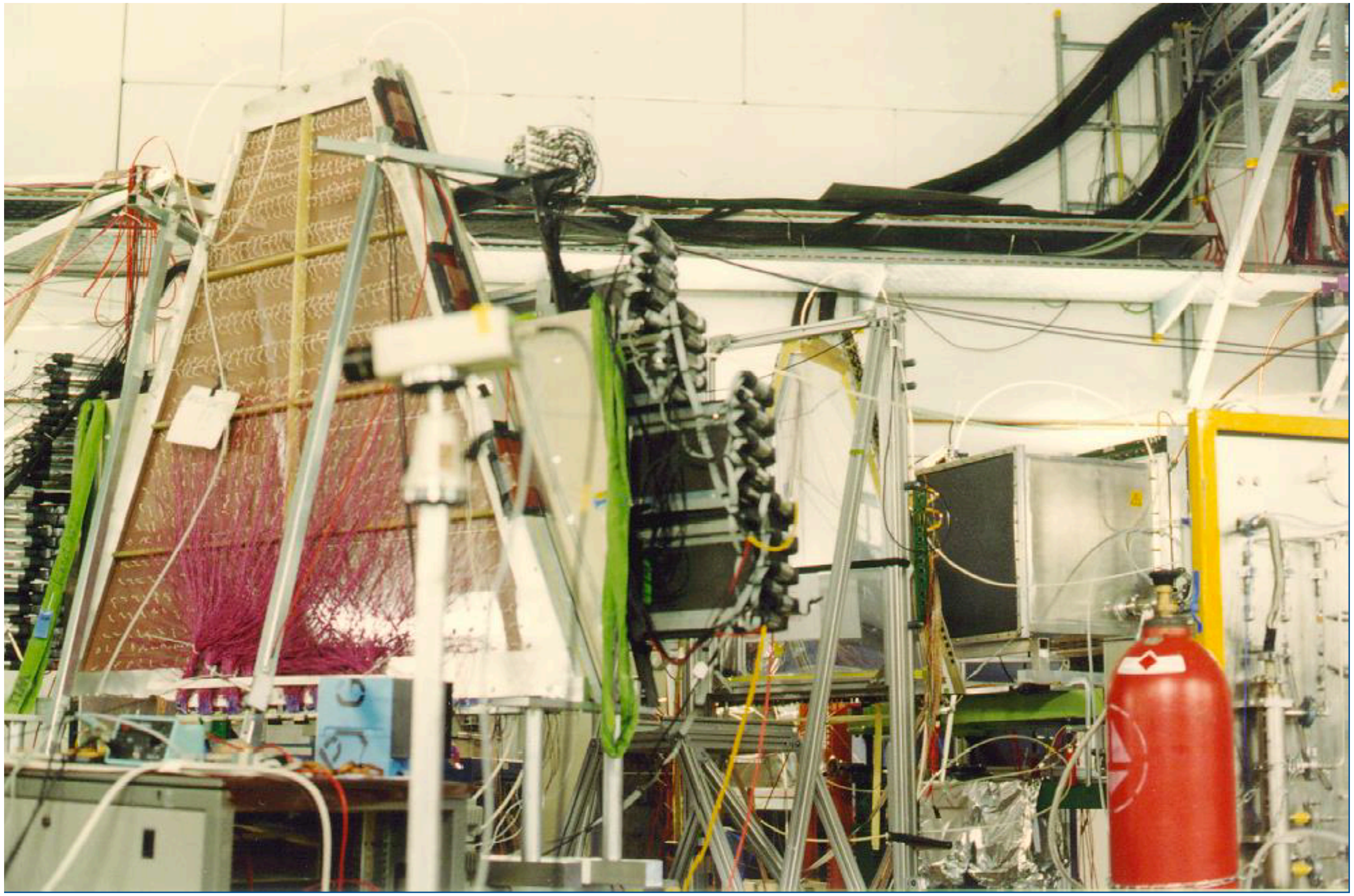
- gas ring imaging Cherenkov detector (RICH) for e^+ e^- identification
- a toroidal magnetic field produced by superconducting coils; field free target area
- tracking chambers before (MDC I, II) and behind (MDC III, IV) the magnetic field
- time-of-flight (TOF) and multiplicity array for impact parameter selection

→ broad physics program: π^- + p, p + p, d + p, π^- + A, p + A, A + A

On the way to the HADES project III

1994-1998 construction of HADES cave, beam line and installation of detector

1997: July successful test with CsI-RICH, MDC, and TOF prototypes in U+Pb @1 AGev



1998: installation of a pion beam

Detector installation 1988/1989

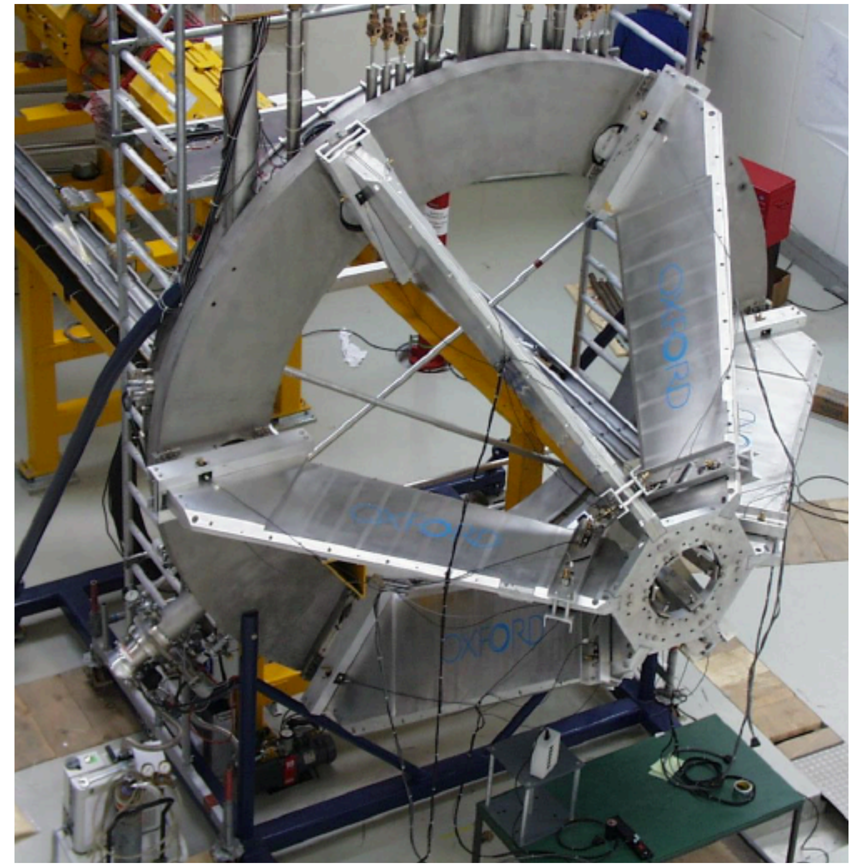
Feb. 1998

empty cave

Detector installation 1988/1989

Feb. 1998

empty cave



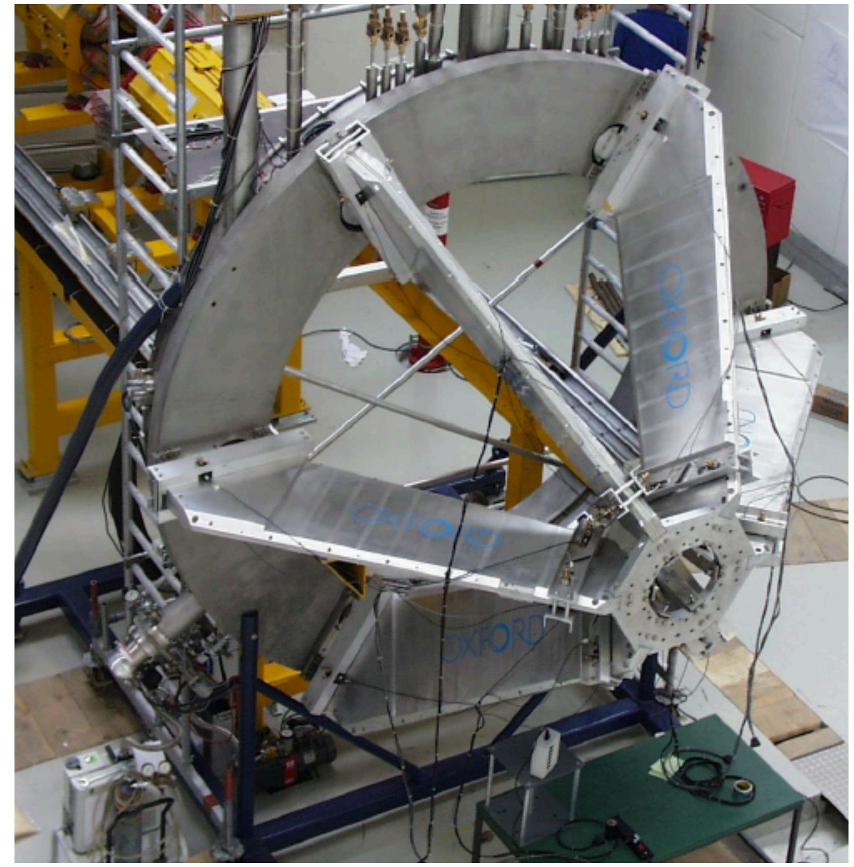
May 1998

magnet installed

Detector installation 1988/1989

Feb. 1998

empty cave

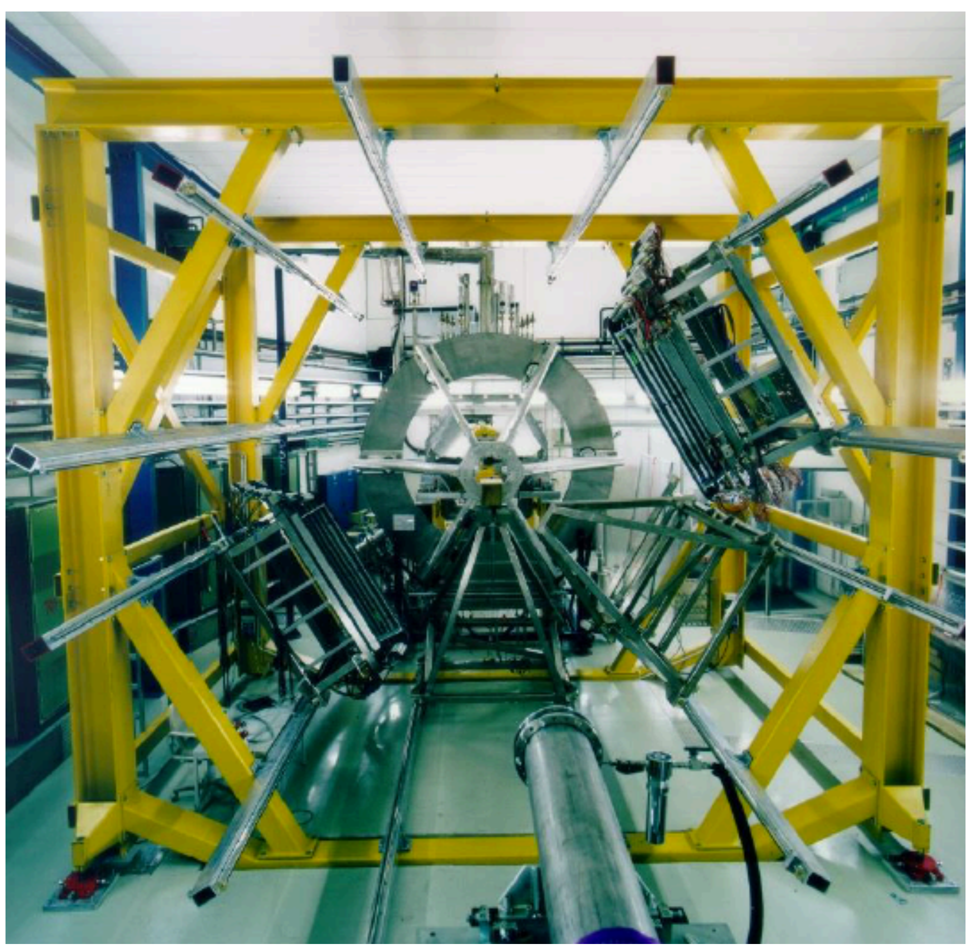


May 1998

magnet installed

June 1998

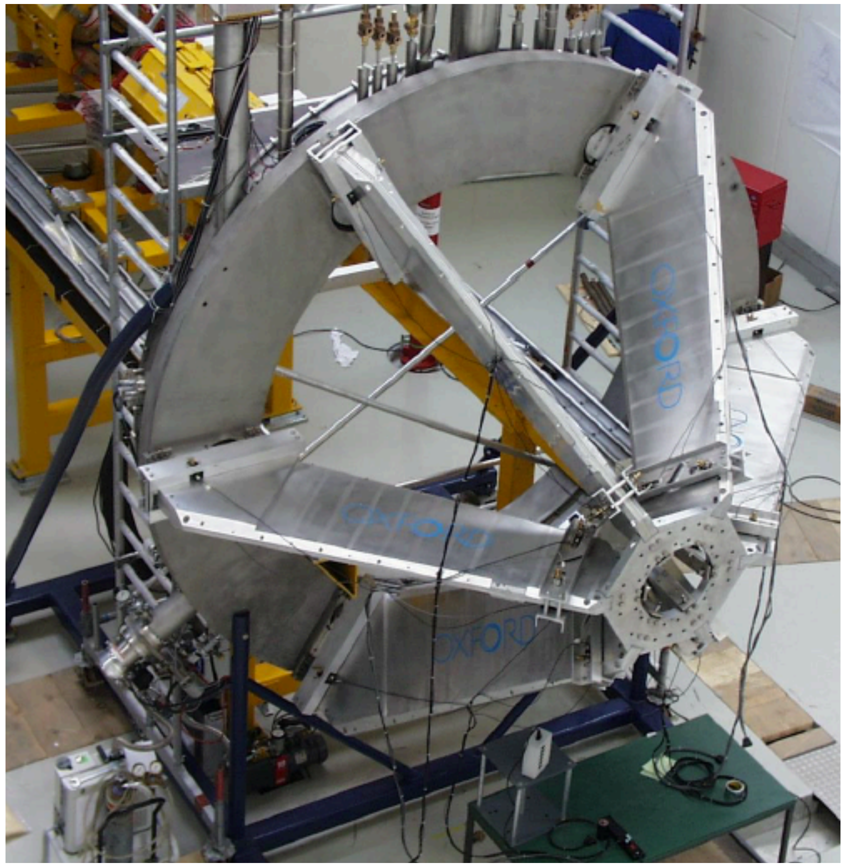
two sector setup



Detector installation 1988/1989

Feb. 1998

empty cave



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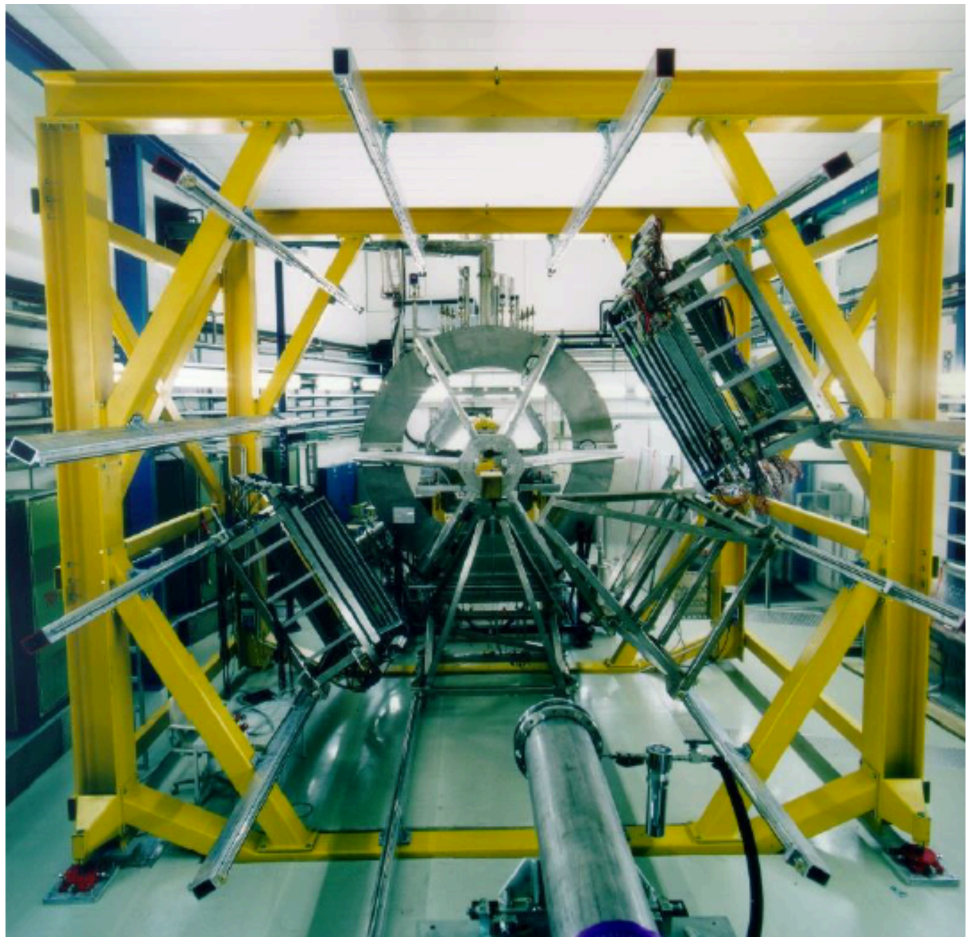

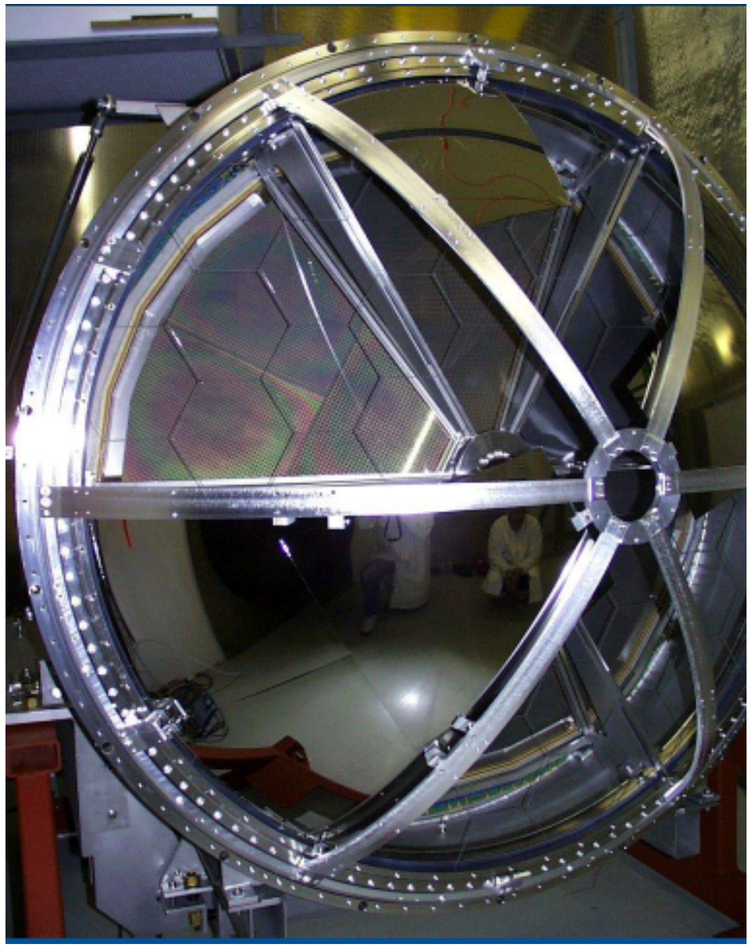

Aug. 1999

RICH detector installed

On the way to the HADES project IV

from the installation of the detector to first physics results

On the way to the HADES project IV

from the installation of the detector to first physics results

1999-2001 HADES commissioning

2001: Nov test experiment: $^{12}C + {}^{12}C$ @1.0 AGeV w/o MDCIII/IV; $\Delta m/m \approx$ 10%

2002: Nov first production run: $^{12}C + {}^{12}C$ @ 2.0 AGeV with MDCIII/IV(4 sectors)

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2006: Dez all MDC planes complete; $\Delta m/m \approx$ 2%
HADES detector completed in configuration proposed in 1994

On the way to the HADES project IV

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2002 - now active physics program: π^- +p , p+p, d+p, π^- +A, p+A, A+A
≈ 60 PhDs, > 40 papers in refereed journals

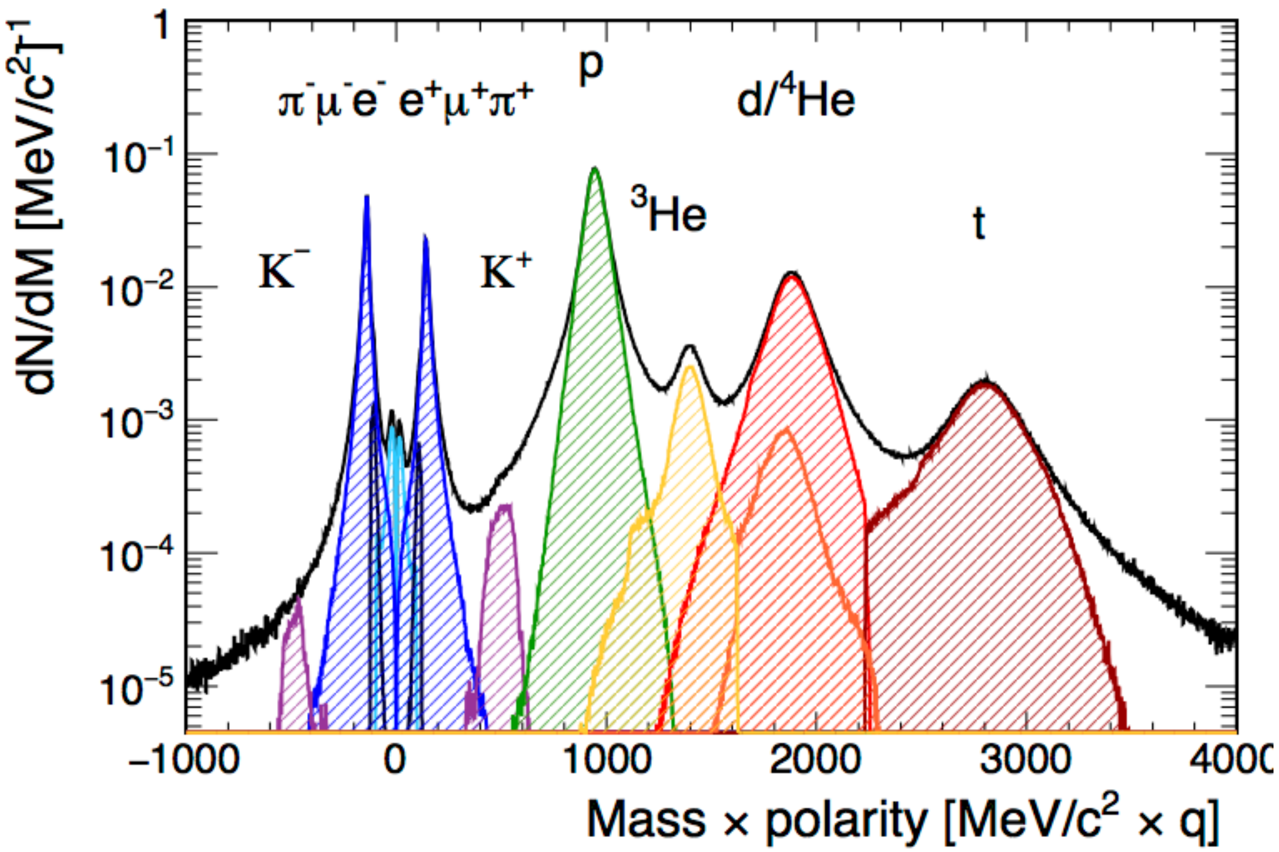
2012: April Au + Au @1.23 AGeV → Nature Physics 15 (2019) 1040

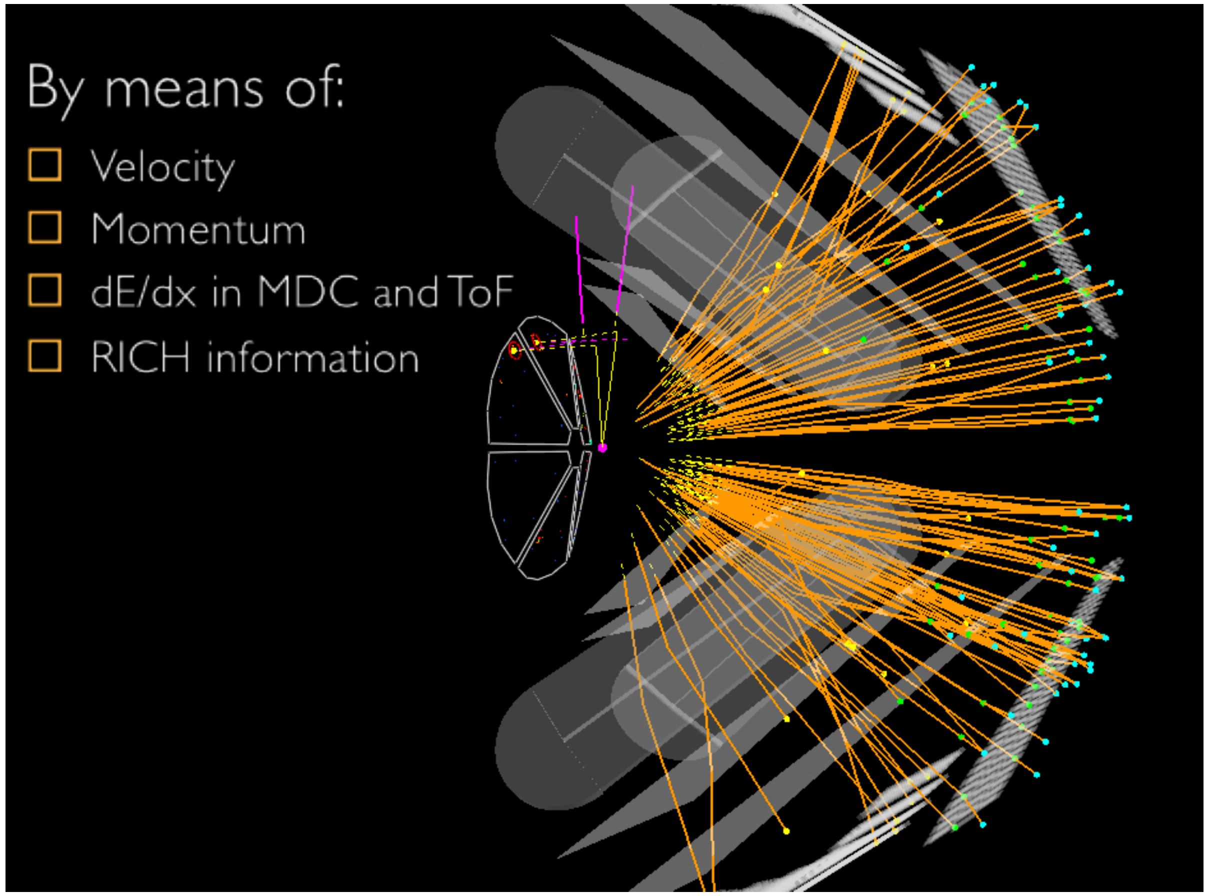
only few highlights of the broad physics program will be discussed

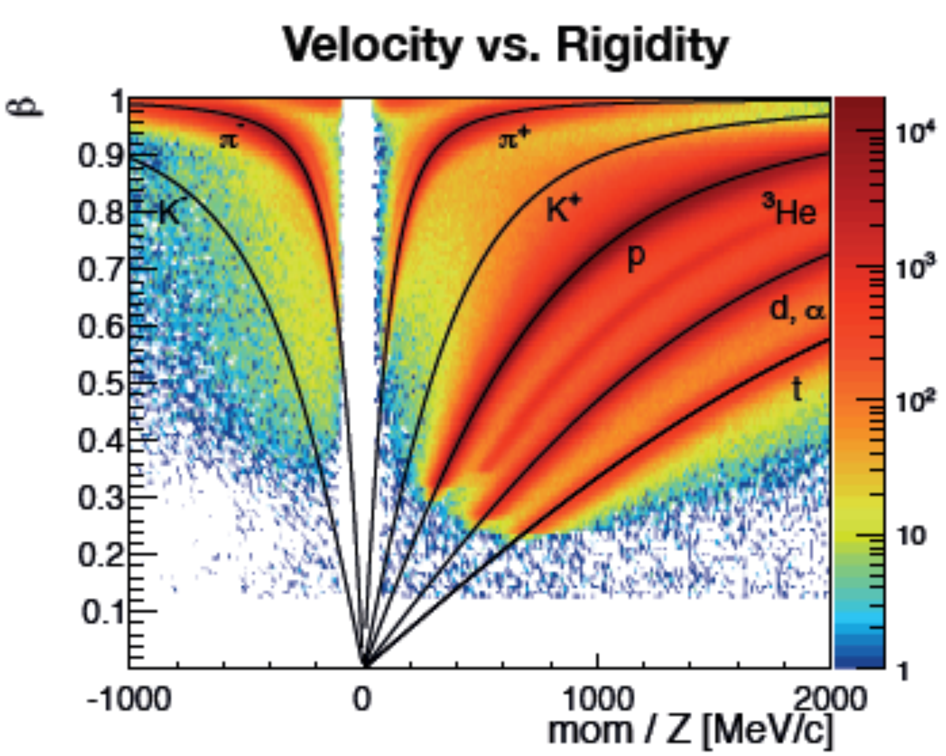
HADES detector performance

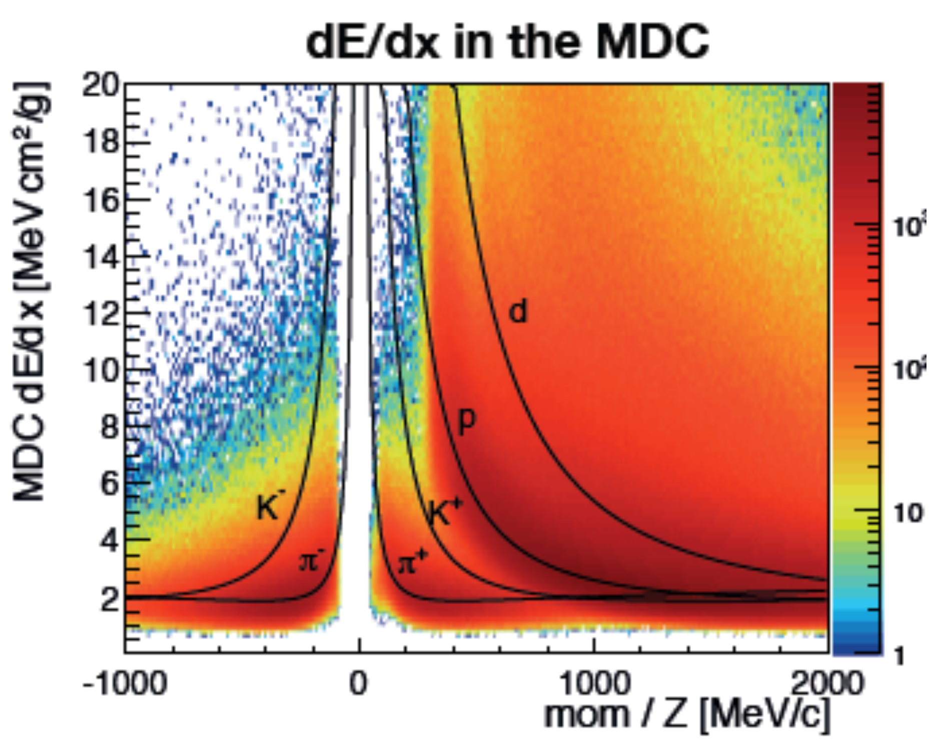
particle identification by energy loss and time-of-flight

Au+Au @ 1.23 AGeV



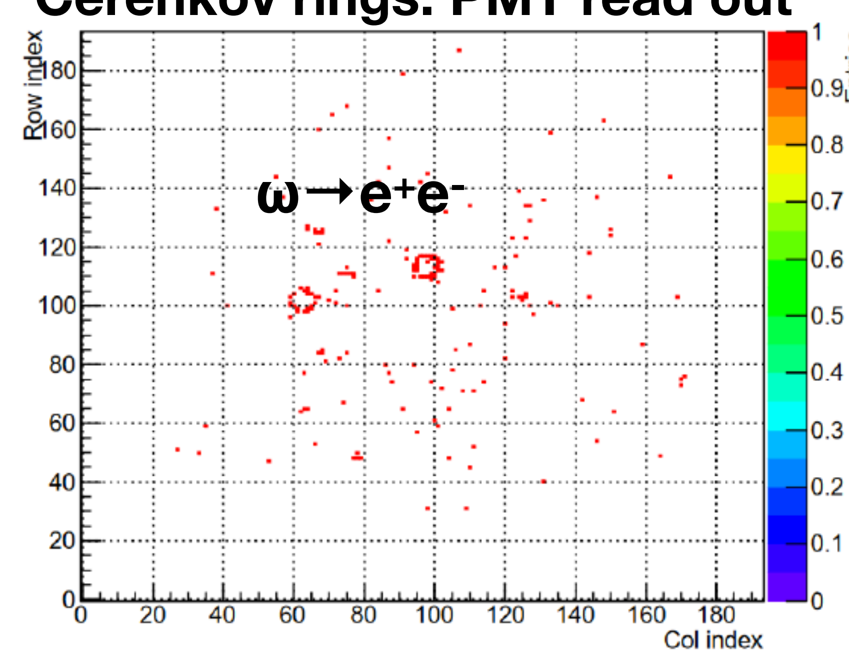






(Ag + Ag @1.23 AGeV)

Cerenkov rings: PMT read out



Physics highlights

I: virtual photon emission

nucleon-nucleon bremsstrahlung and
electromagnetic properties of baryon resonances

dileptons from p + A reactions
in-medium modification of vector mesons

dileptons from relativistic heavy-ion reactions
in-medium modification of vector mesons

II: strangeness production

strange baryon production and structure
in-medium properties of strange hadrons

III: bulk properties of compressed nuclear matter

collective phenomena: particle flow patterns

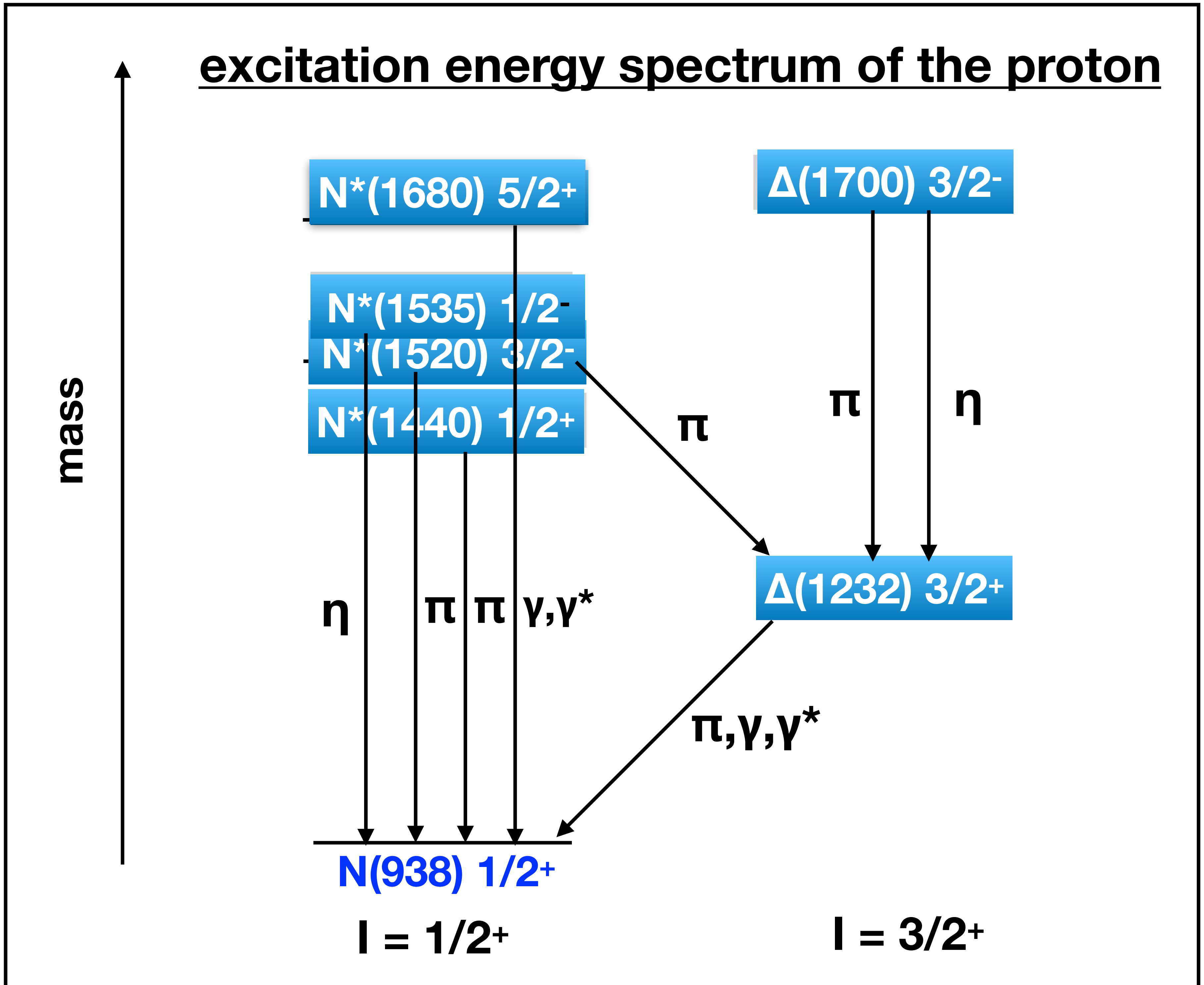
IV: future perspectives

hyperon spectroscopy
χ-symmetery restoration

Baryon resonances

baryons = composite particles with an internal structure of quarks and gluons

the excitation energy spectrum reflects the interactions among the constituents

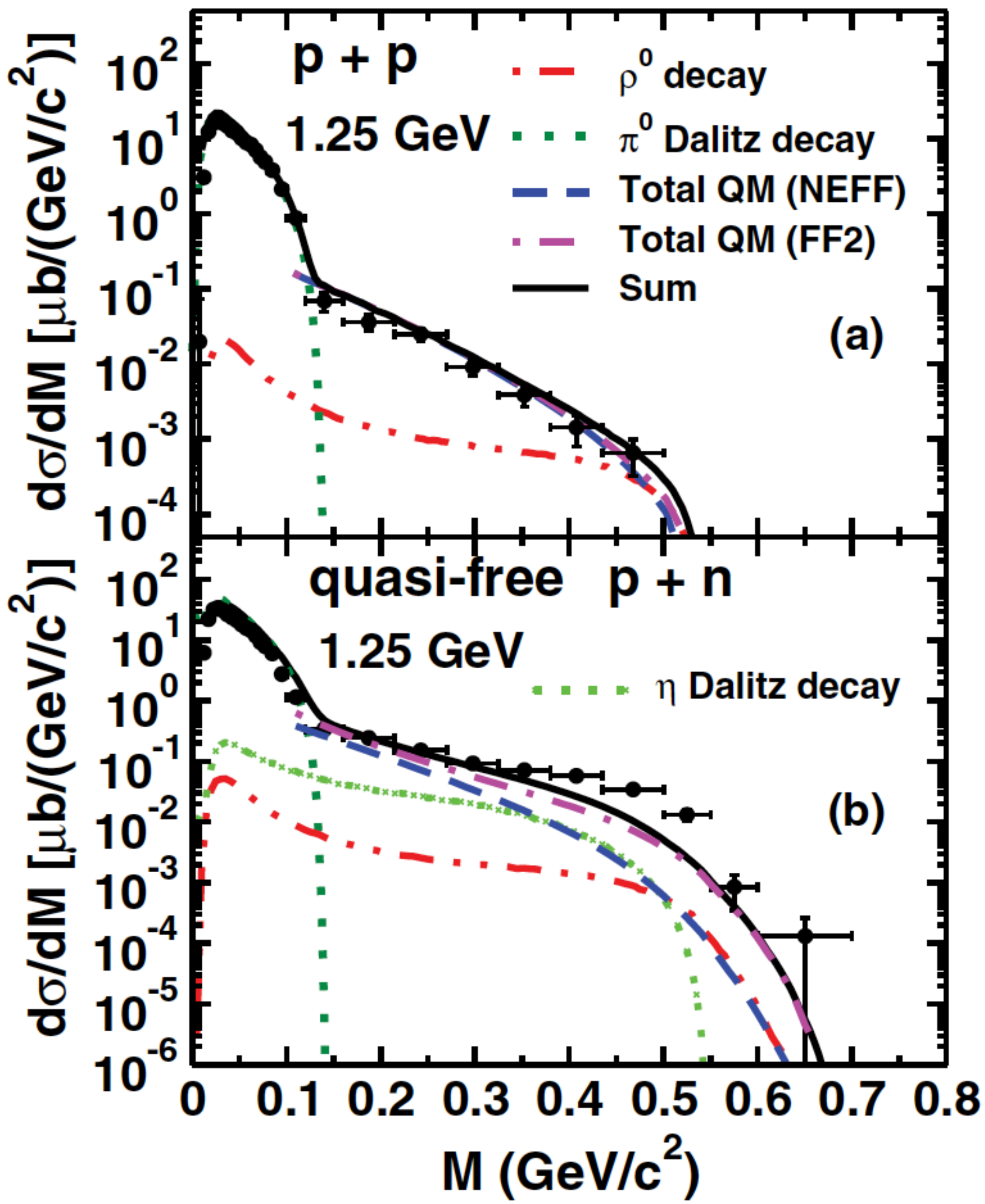


decay of baryon resonances via meson and γ, γ* emission

nucleon - nucleon bremsstrahlung

comparison of p + p and p + n bremsstrahlung @ $\sqrt{s_{NN}}$ = 2.4 GeV

HADES data: PLB 690 (2010) 118
EPJA 7 (2017) 149

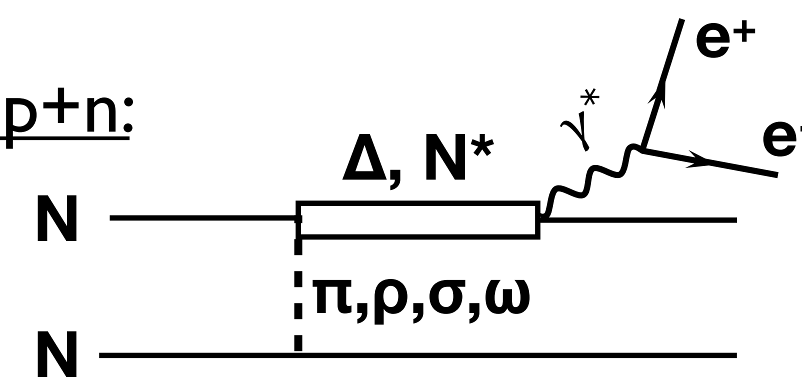


dilepton yield in p+n about an order of magnitude larger than in p+p

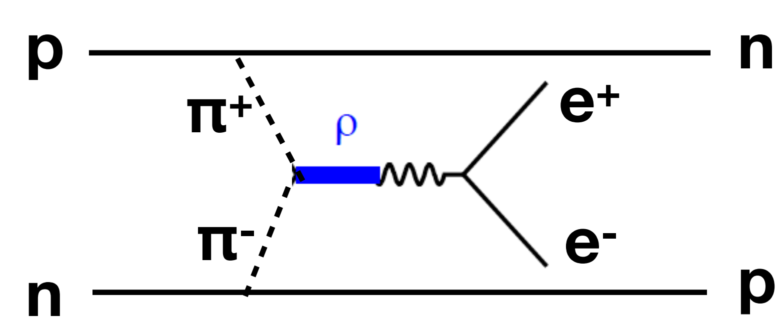
quasi-elastic p-n bremsstrahlung
difficult theoretical problem
discussed since 1980's

L.P. Kaplan, B. Kämpfer NPA 764 (2006) 338
R. Shyam, U.Mosel PRC 82 (2010) 062201

- <u>for p+p and p+n:</u>



- <u>additional diagram for p+n:</u>
(involving pion em. formfactor)



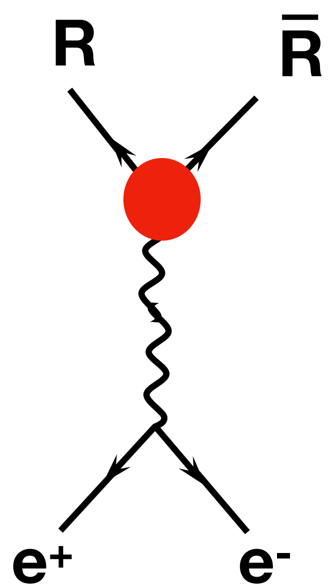
M. Bashkanov, H. Clement EPJA 50 (2014) 107

$p+n \rightarrow d^* \rightarrow \Delta^+\Delta^0 \rightarrow np\pi^+\pi^-$

electromagnetic structure of baryon resonances

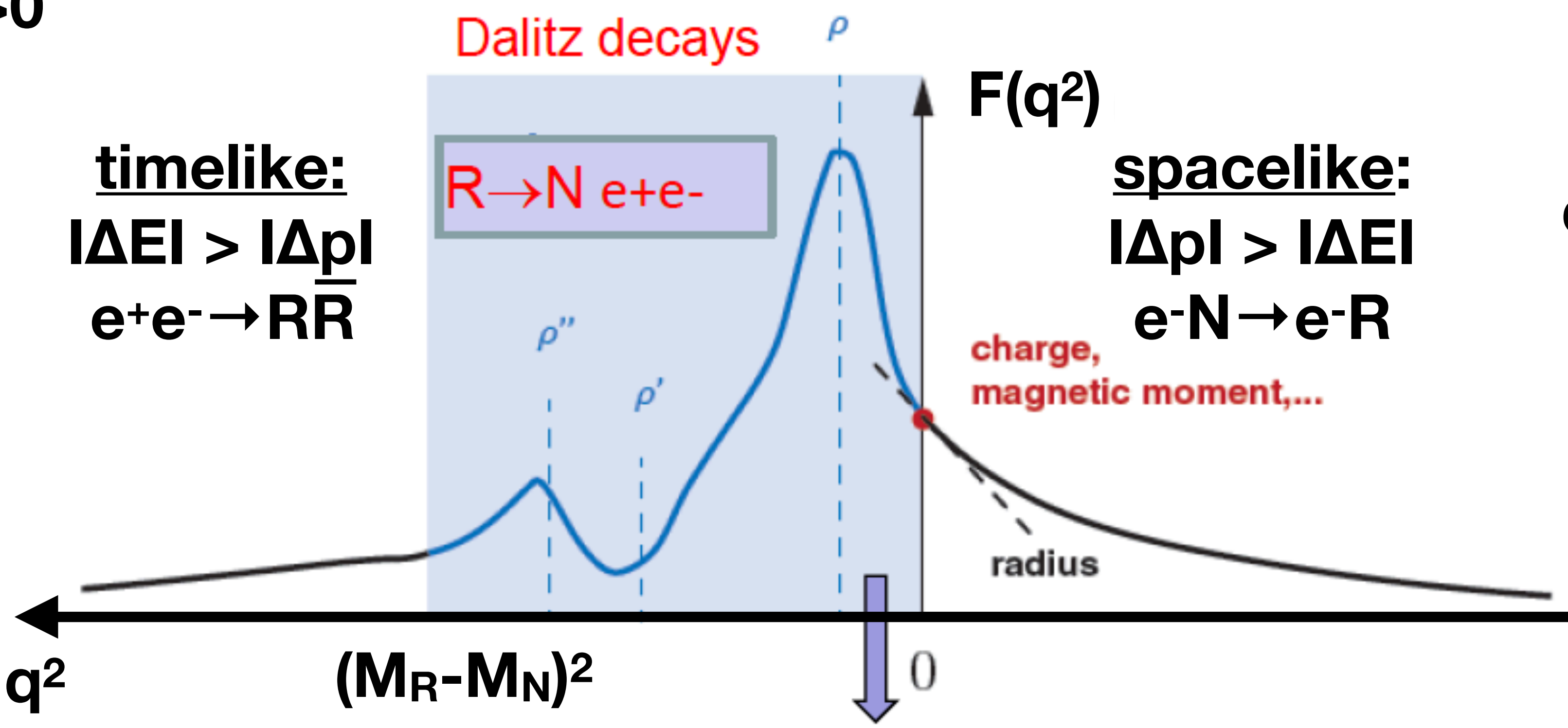
access to internal structure by measurement of form factors $F(q^2)$
deviation from QED expectations for point-like particles

e.g. BABAR, Belle, BESS, CLEO
$q^2 = \Delta E^2 - \Delta p^2 > 0$



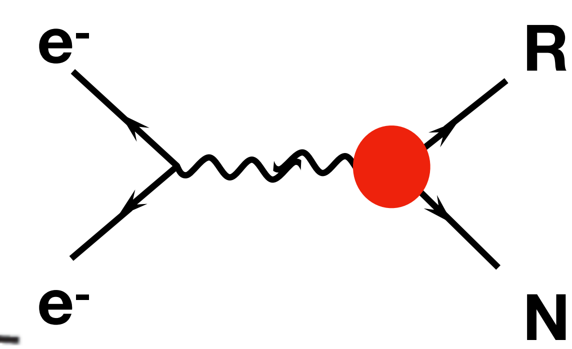
timelike:
$|\Delta E| > |\Delta p|$
$e^+e^- \to R\bar{R}$

HADES

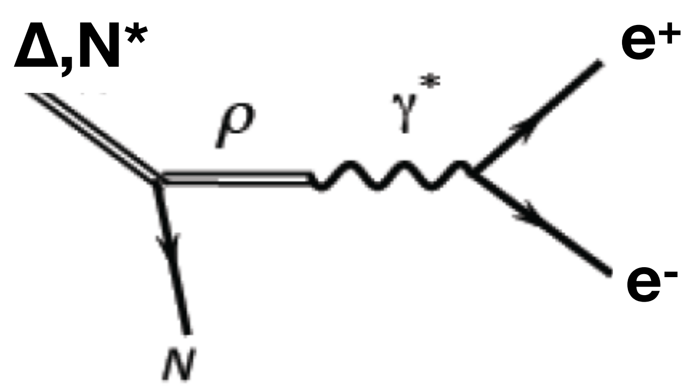


spacelike:
$|\Delta p| > |\Delta E|$
$e^-N \to e^-R$

e.g. CLAS
$q^2 = \Delta E^2 - \Delta p^2 < 0$



transition formfactor
only access for $0 < q^2 < 4M_{ee}^2$



vector meson dominance model:
hadrons couple to e^+e^- via ρ
$R \to N\rho \to N e^+e^-$

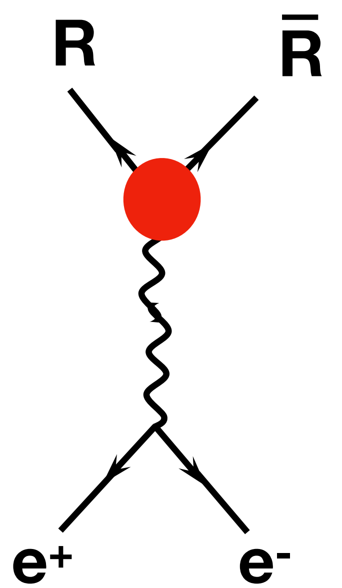
electromagnetic structure of baryon resonances

access to internal structure by measurement of form factors $F(q^2)$

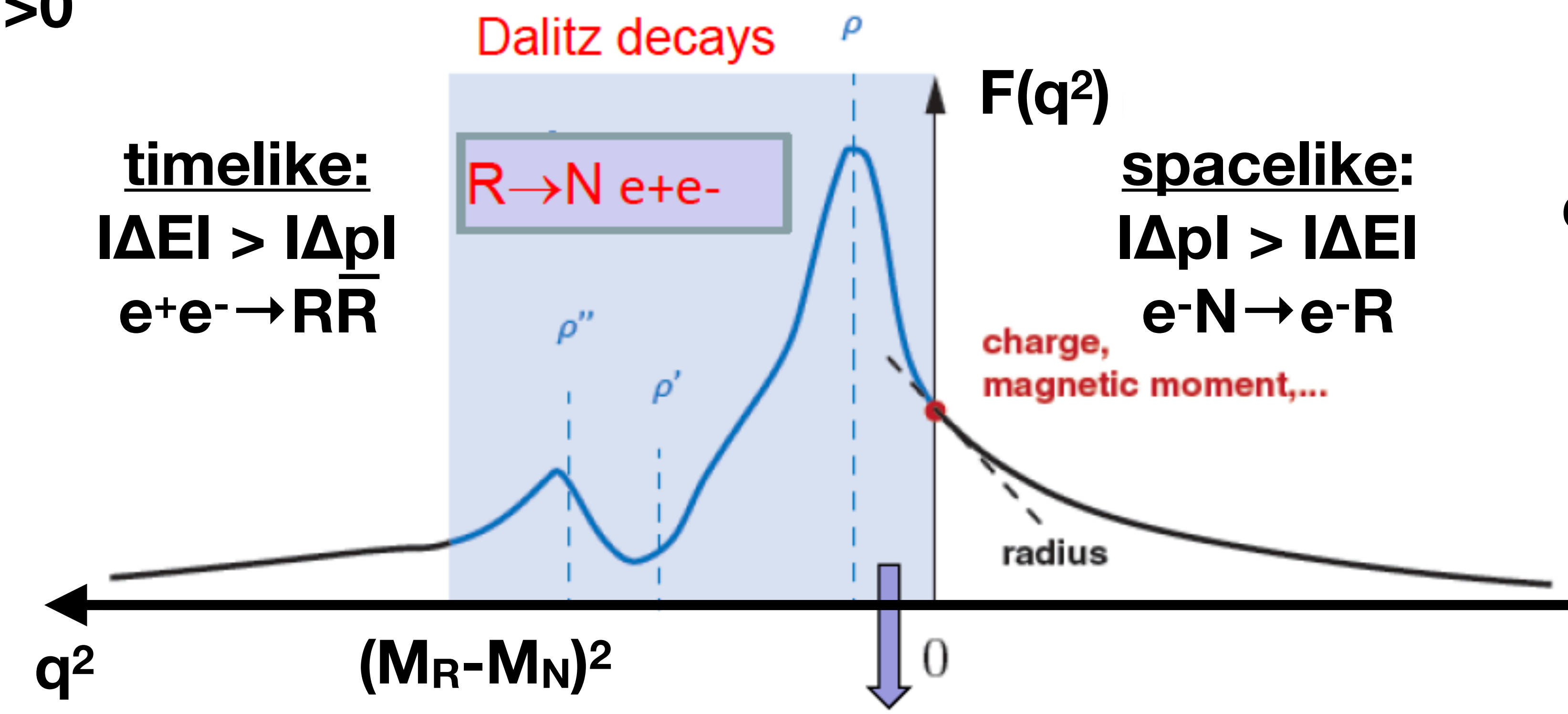
deviation from QED expectations for point-like particles

e.g. BABAR, Belle, BESS, CLEO

$q^2 = \Delta E^2 - \Delta p^2 > 0$

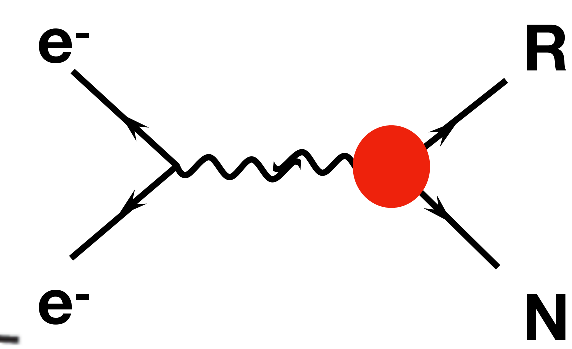


HADES



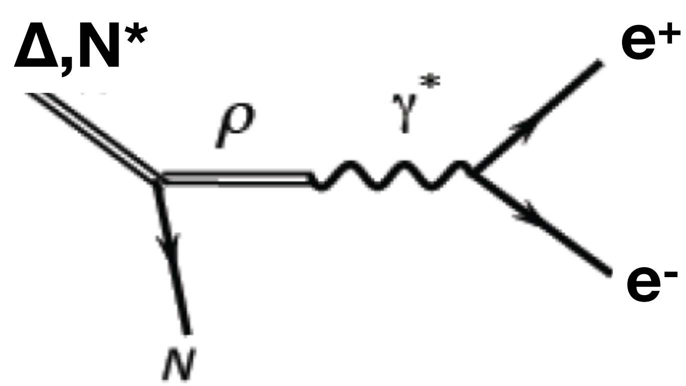
e.g. CLAS

$q^2 = \Delta E^2 - \Delta p^2 < 0$



transition formfactor

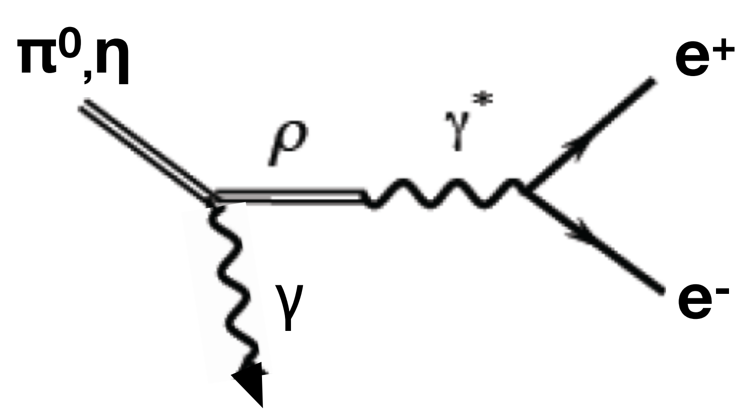
only access for $0 < q^2 < 4M_{ee}^2$



vector meson dominance model:

hadrons couple to e^+e^- via ρ

$R \rightarrow N\,\rho \rightarrow N\,e^+e^-$



for neutral mesons

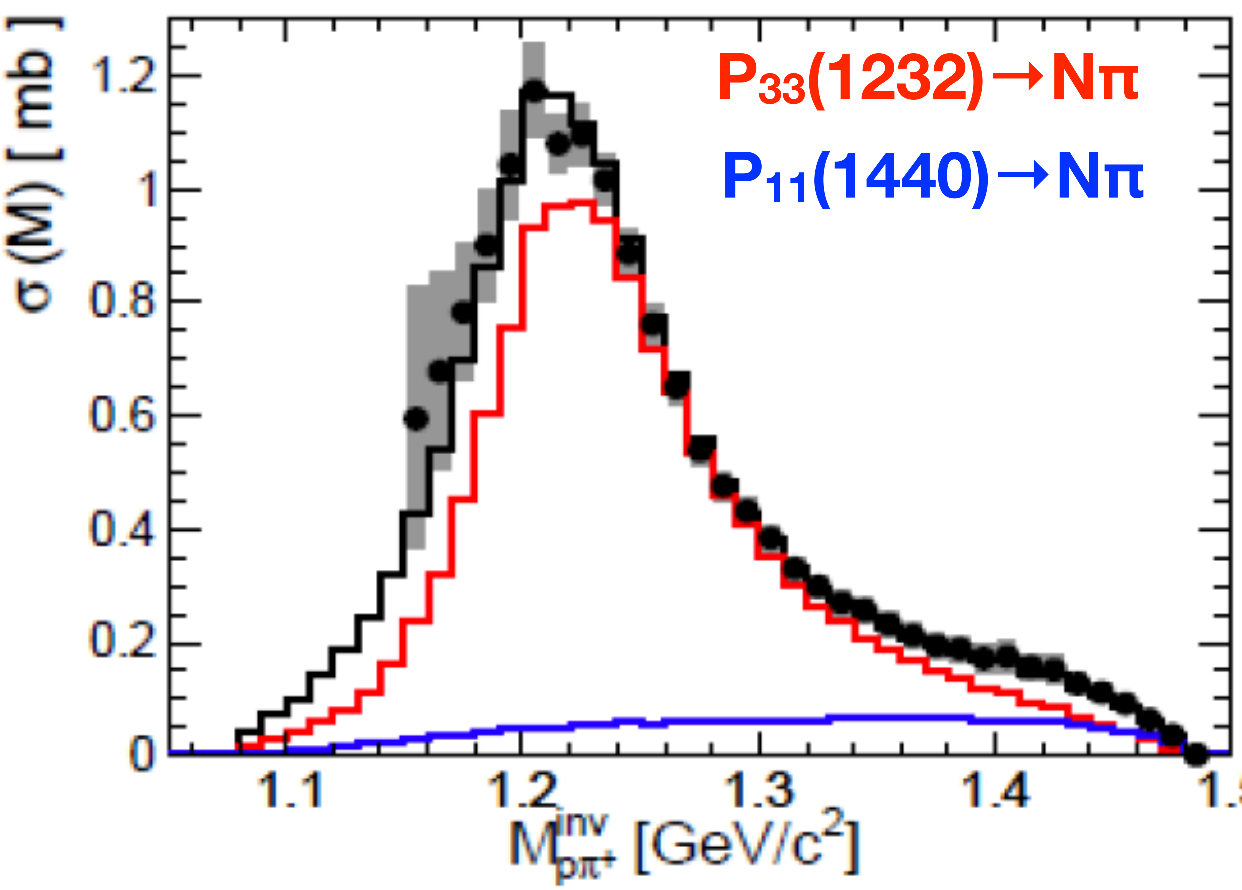
$\pi^0,\eta \rightarrow \gamma\,\rho \rightarrow \gamma\,e^+e^-$

Δ (1232) excitation in p + p @ √s = 2.42 GeV

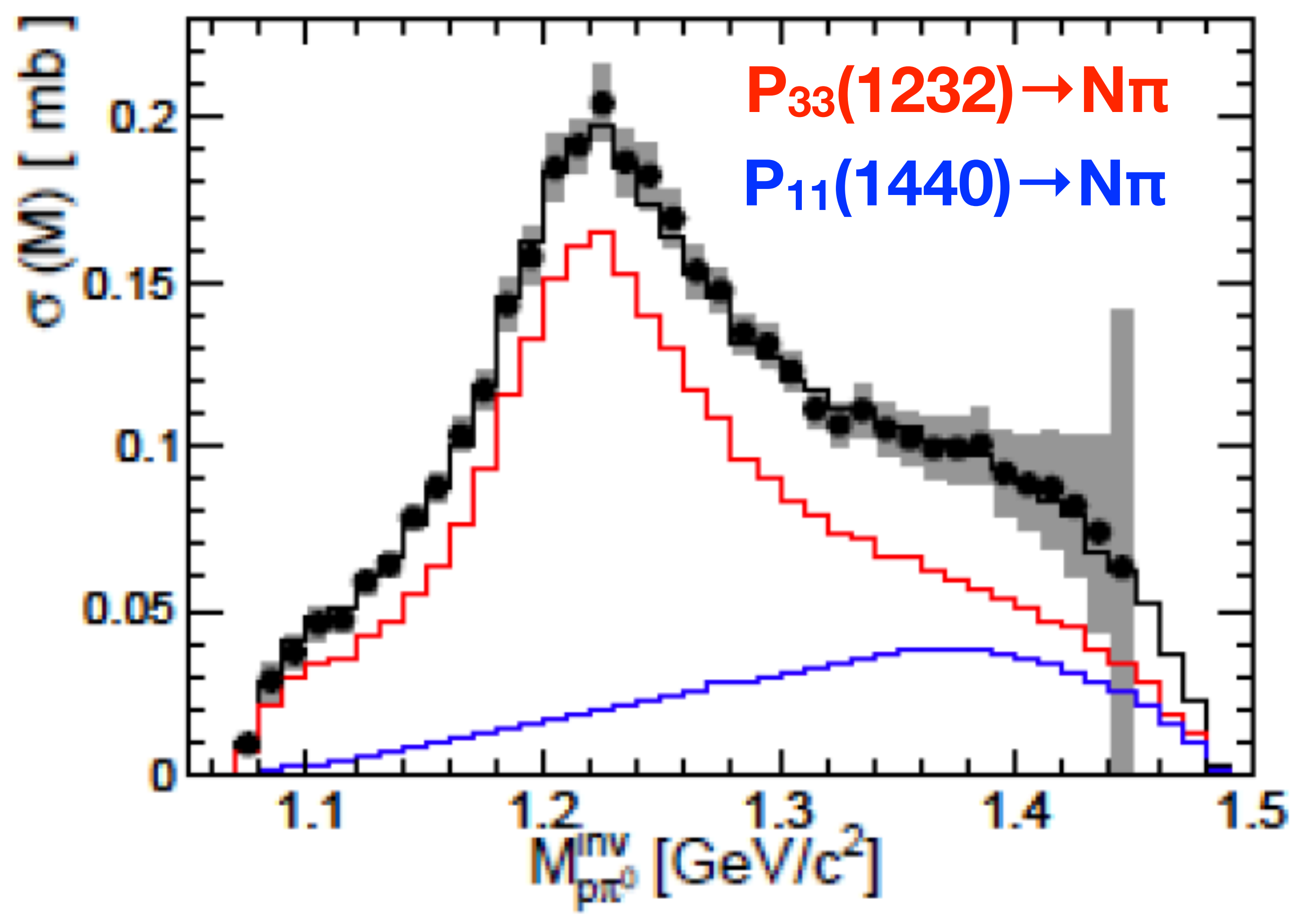
HADES data: EPJA 51 (2015) 137

information from hadronic final states

$p + p \rightarrow \Delta^{++}(1232)\, n \rightarrow p\, \pi^+\, n$



$p + p \rightarrow \Delta^{+}(1232)\, p \rightarrow p\, \pi^0\, p$



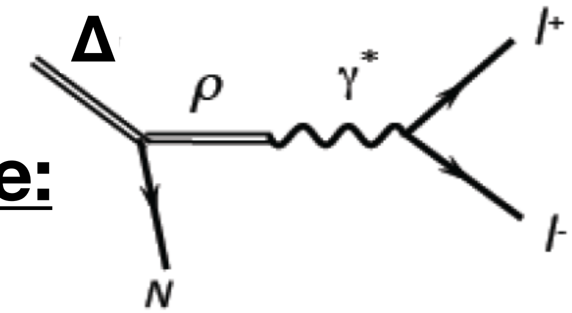
comparison to Bonn - Gatchina partial wave analysis:

Δ (1232) dominantly populated in p + p @ √s = 2.42 GeV

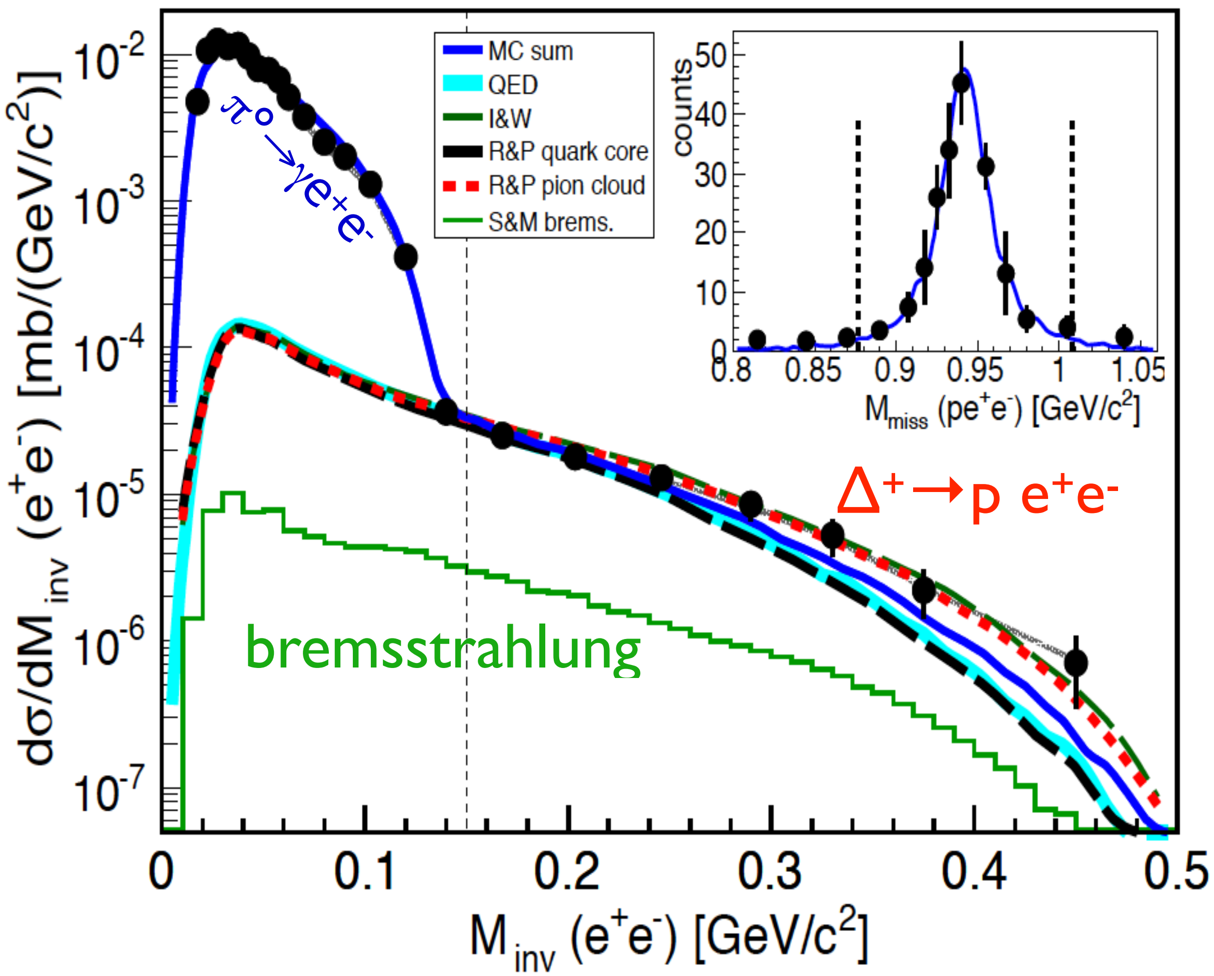
p + p → p p e⁺ e⁻ @ $\sqrt{s}$ = 2.42 GeV

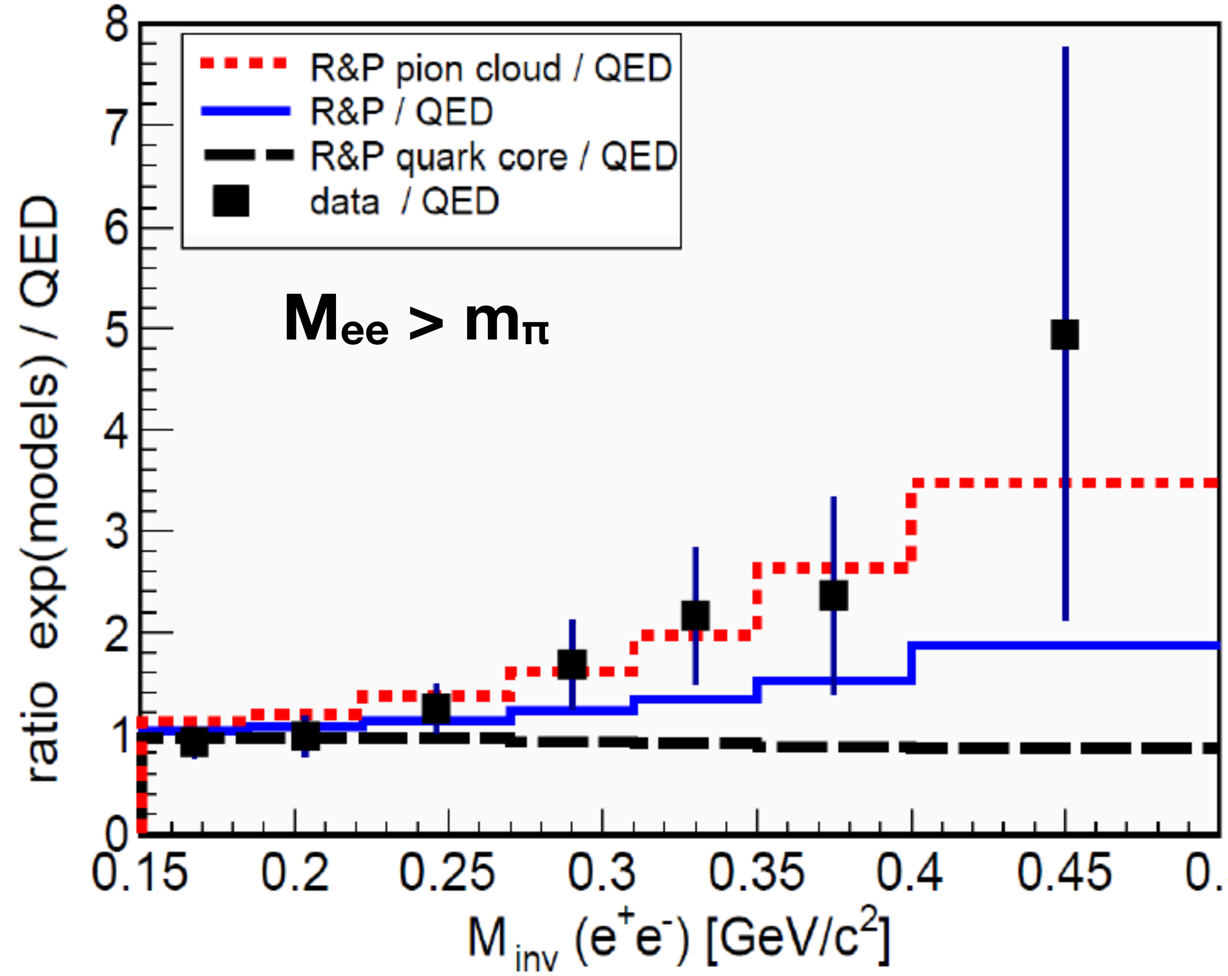
information from dileptons

exclusive channel !! **vector meson dominance:**



HADES data: PRC 95 (2017) 065205





first measurement of Δ Dalitz decay:

$\Delta^+ \rightarrow p\, e^+e^-$

Br = (4.19±0.34(stat)±0.46 (syst))*10^{-5}

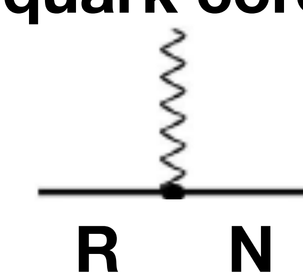
→ PDG entry 2018

- **evidence for VDM in baryonic transitions**

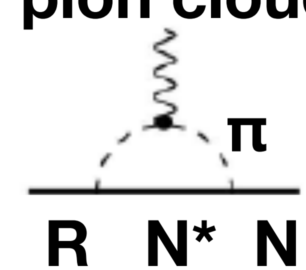
importance of pion cloud effect

G. Ramalho and M. T. Pena, PRD95 (2017) 014003

quark core



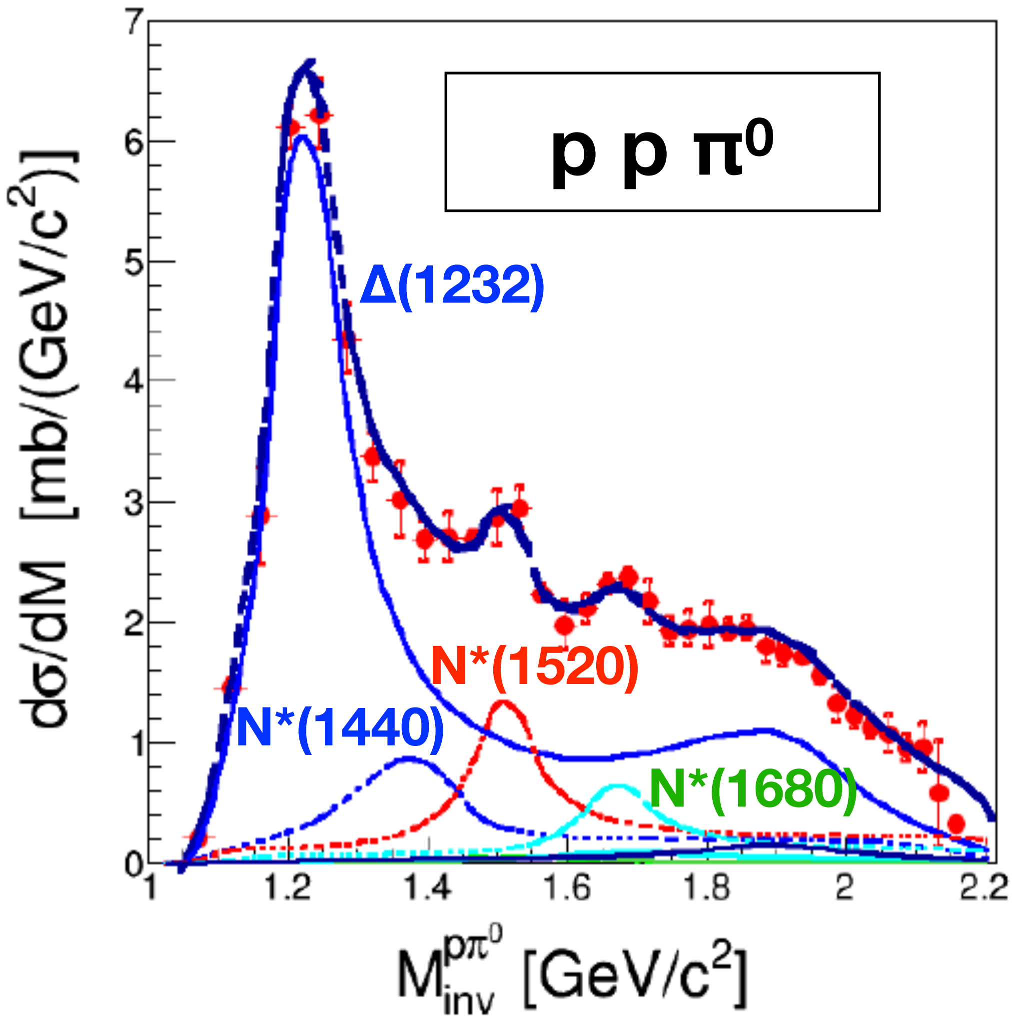
pion cloud



excitation of higher lying nucleon resonances

p + p @ √s = 3.18 GeV

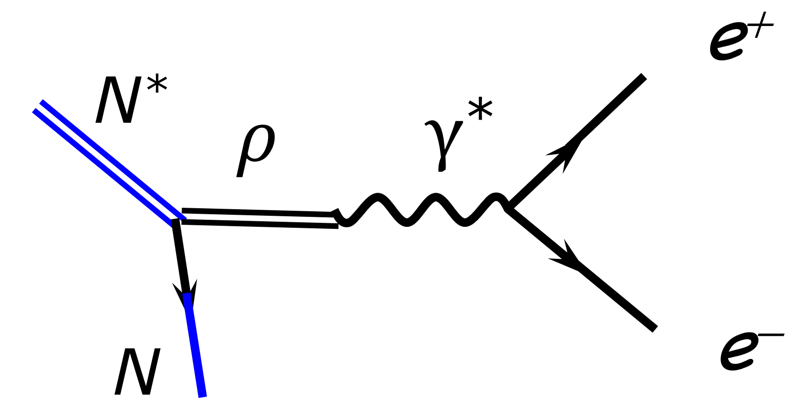
HADES data: EPJA 50 (2014) 82



invariant mass spectrum decomposed into contributions from various baryon resonances by comparison with resonance model:

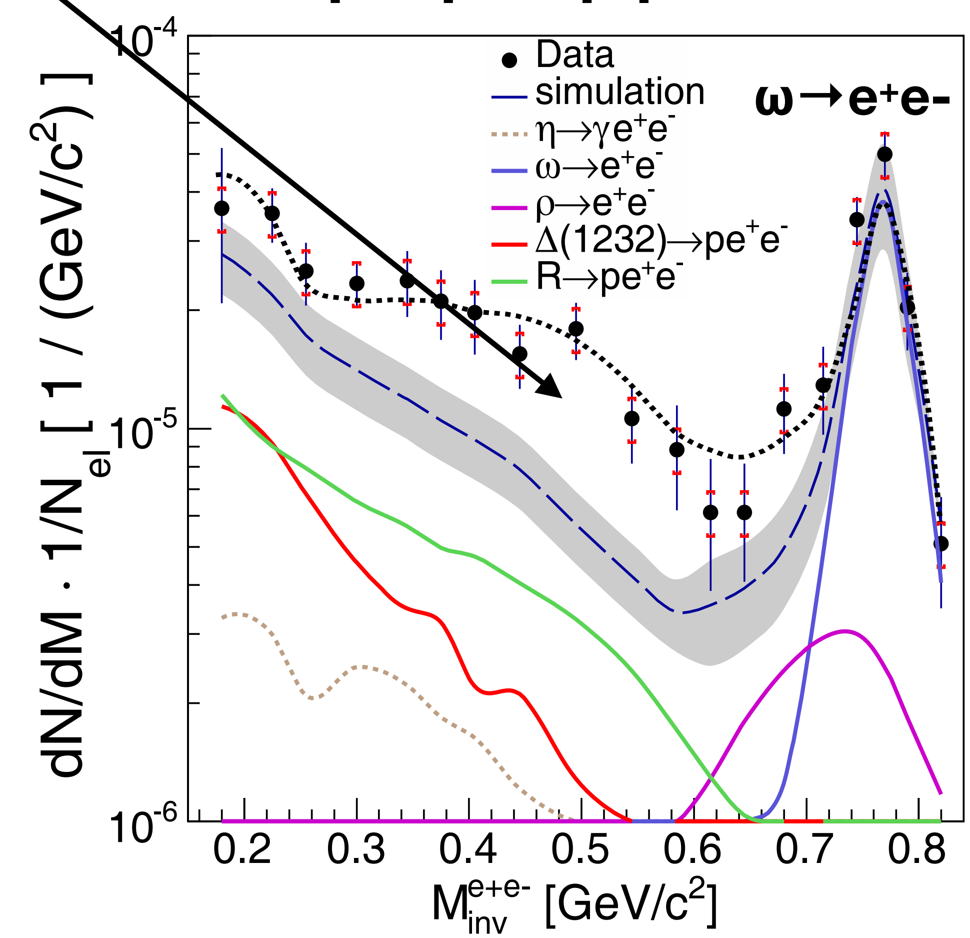
Z. Teis et al., Z. Phys. A 356 (1997) 421
J. Weil et al., EPJA 48 (2012) 111

vector meson dominance



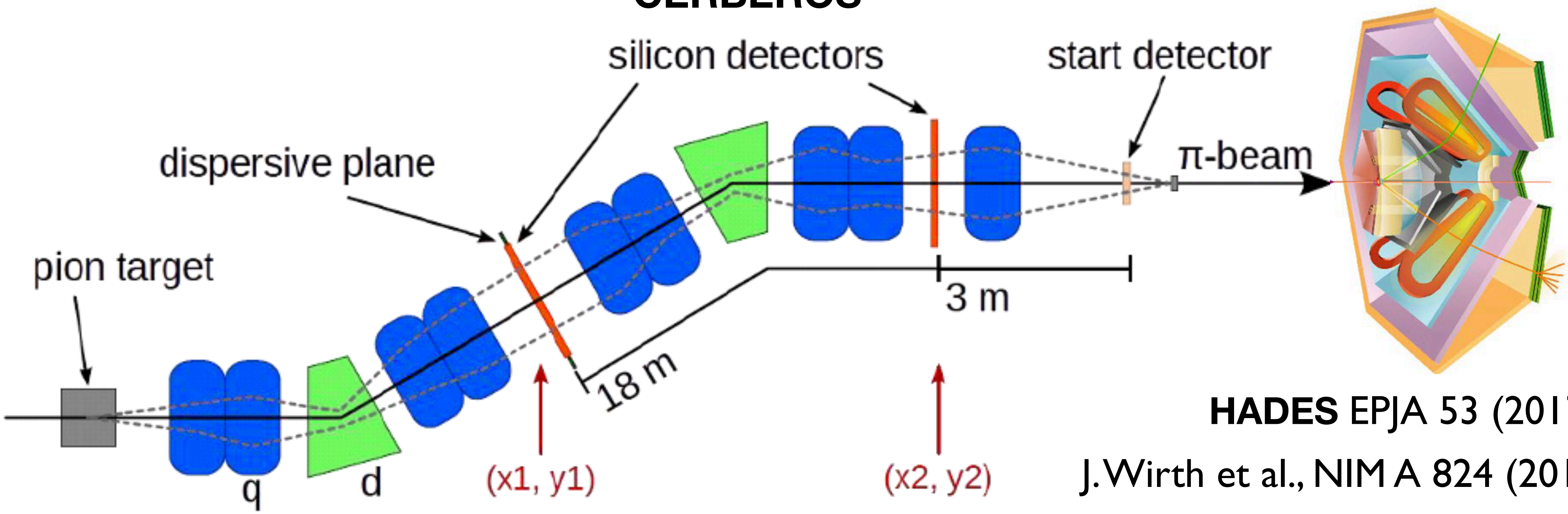
e⁺e⁻ excess above QED cocktail due to sub-threshold coupling of R→Nρ→Ne+e-

p + p → p p e⁺e⁻



- exploiting the combined analysis of hadronic final states and dilepton emission provides unprecedented access to electromagnetic structure of baryon resonances

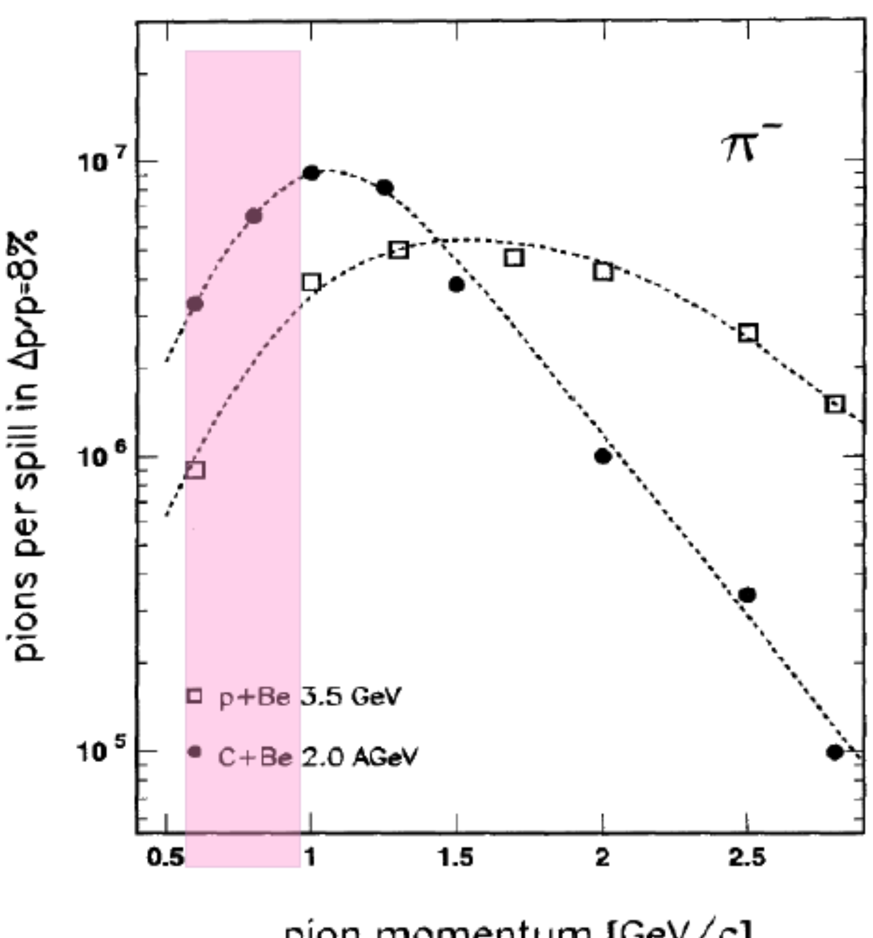
pion beam @ GSI



33.5 m from π-target

HADES EPJA 53 (2017) 188

J.Wirth et al., NIM A 824 (2016) 243



- π^- beam produced in N_2 + Be with 8-10*10^{10} N_2 ions/(spill (3s)
- secondary π^- intensity 2-3 * 10^5 /s
  momentum range $0.5 < p_{\pi-} < 2.0$ GeV/c
  momentum resolution $\Delta p/p \approx 1\%$
- unique facility world wide in combination with a di-electron spectrometer

J. Diaz et al., NIM A 478 (2002) 511

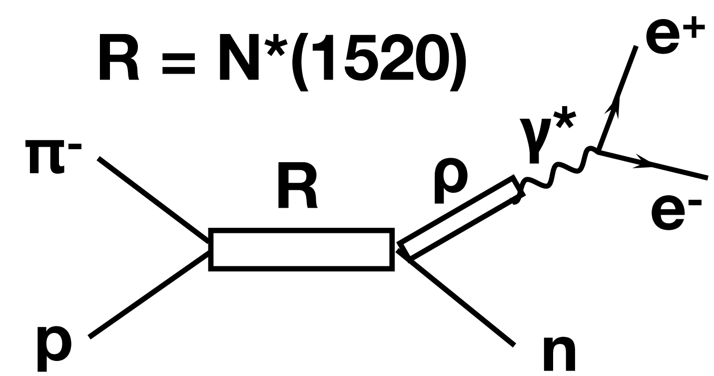
$\pi^- + \text{'p'} \rightarrow n\ e^+\ e^-$

exploiting the information from the hadronic final state

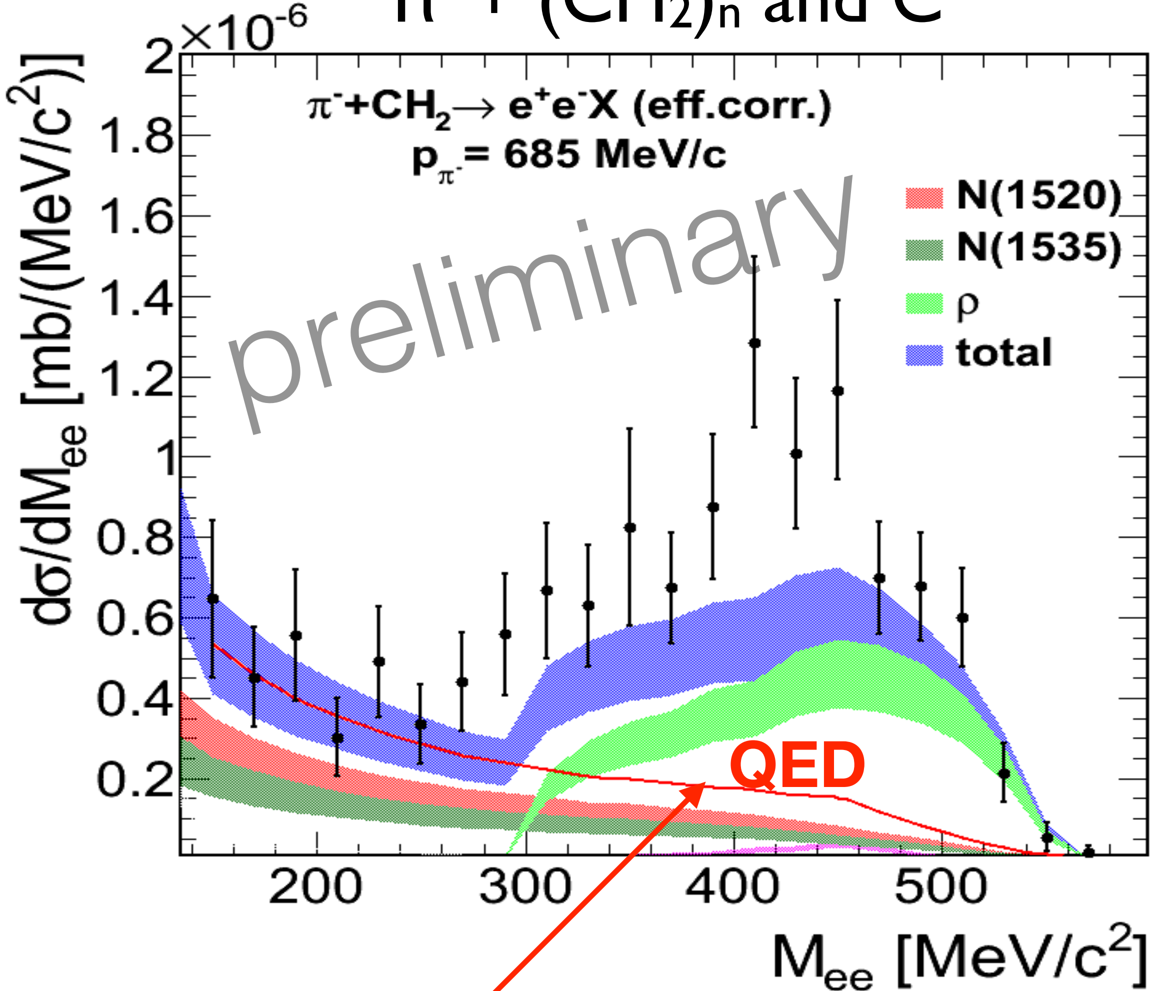
$\pi^- + p \rightarrow R \rightarrow n\ \pi^+\ \pi^-$ @ $\sqrt{s} = 1.49$ GeV

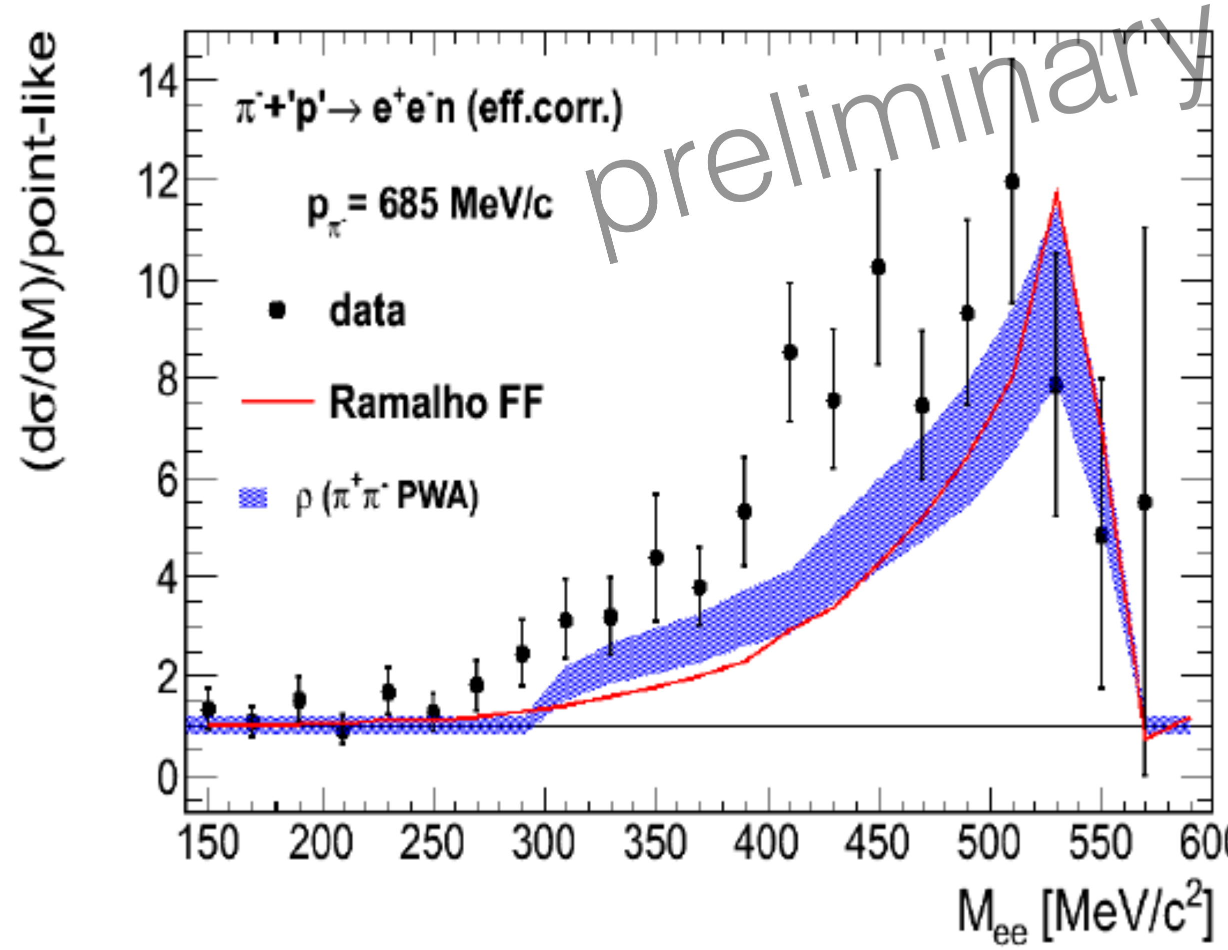
the dilepton spectrum can be calculated

$d\sigma/dM_{ee} = d\sigma/dM_{\pi\pi} * M_\rho / M_{ee}^3 * BR(\rho \rightarrow e^+e^-)$



π- + (CH2)n and C





QED (pointlike) contribution

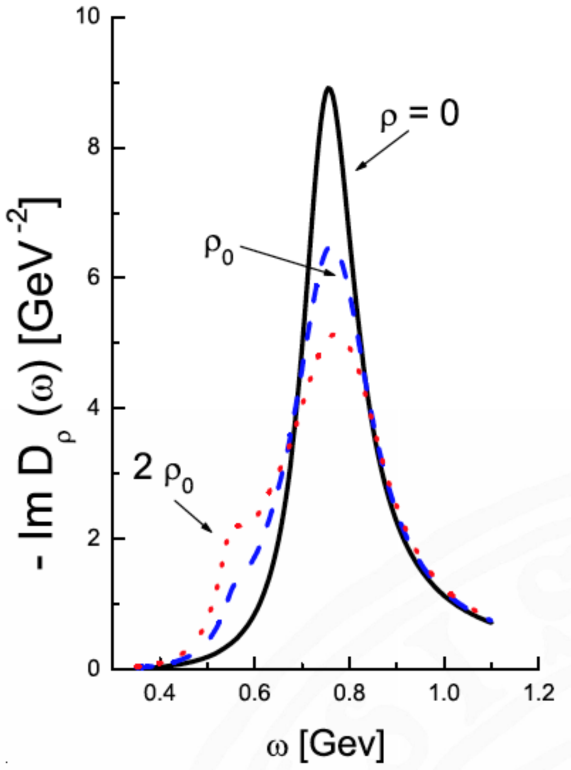
$D_{13}(1520)$ (≈ 60%)
$S_{11}(1535)$ (≈20%)

- increase with mass → signature of VDM
- e^+e^- yield consistent with ρ contribution from $\pi^+\pi^-$ channel (BnGA PWA)
- consistent with 2 component model of $D_{13}(1520) \rightarrow n\ e^+e^-$ (Ramahlo & Pena)

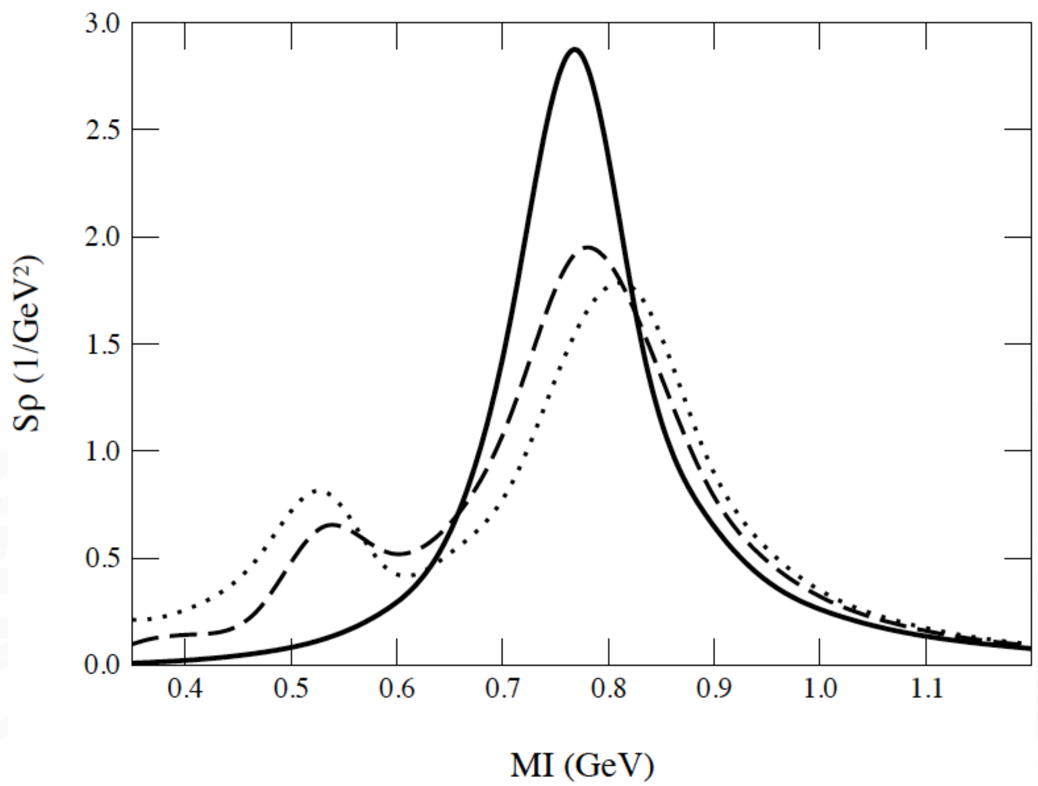
dileptons from p + A reactions
in-medium modification of vector mesons

model predictions for in-medium mass of ρ meson

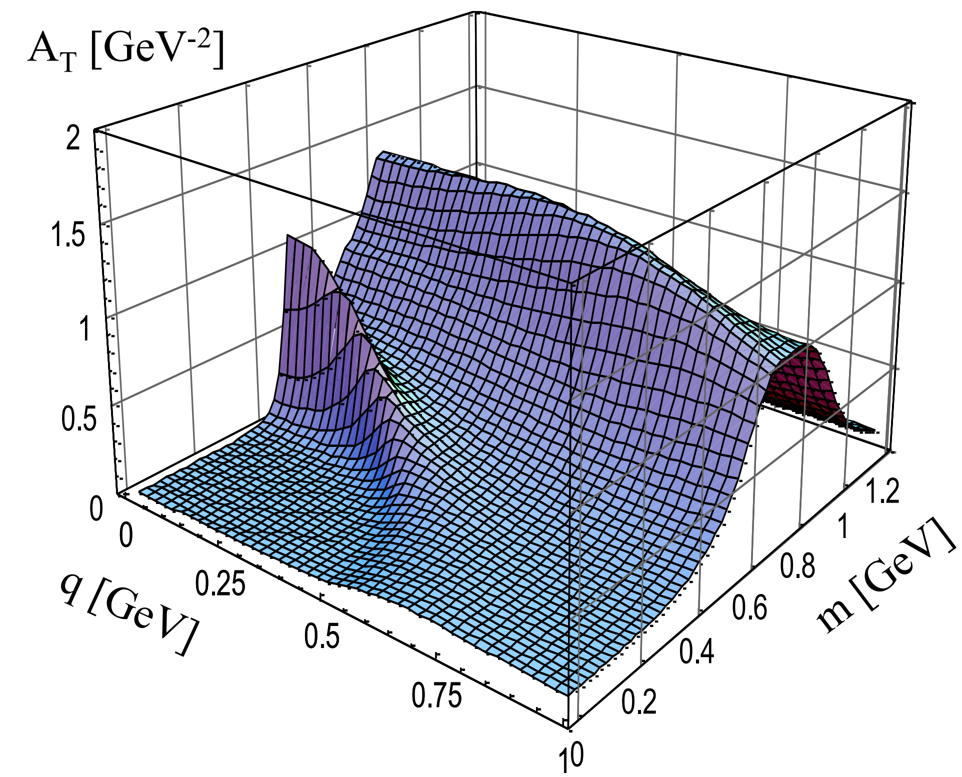
M. Lutz. G. Wolf, B. Friman
NPA 706 (2002) 431



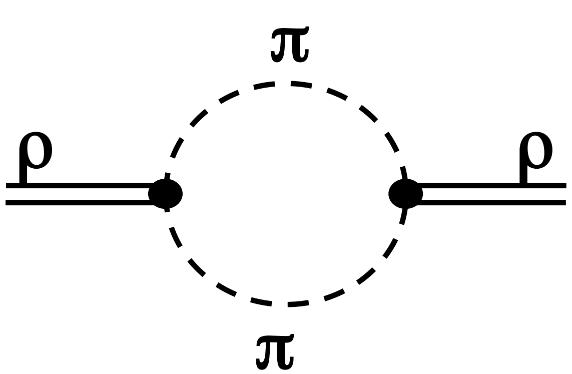
Cabrera, E. Oset, Vicente Vacas
NPA 705 (2002) 90



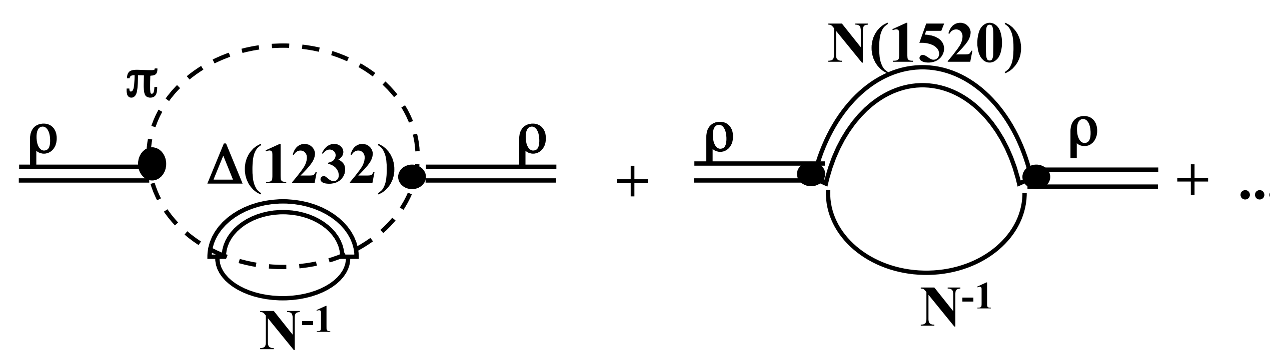
M. Post, S. Leupold, U. Mosel
NPA 741(2004) 84



<u>in vacuum:</u>



<u>in medium</u>



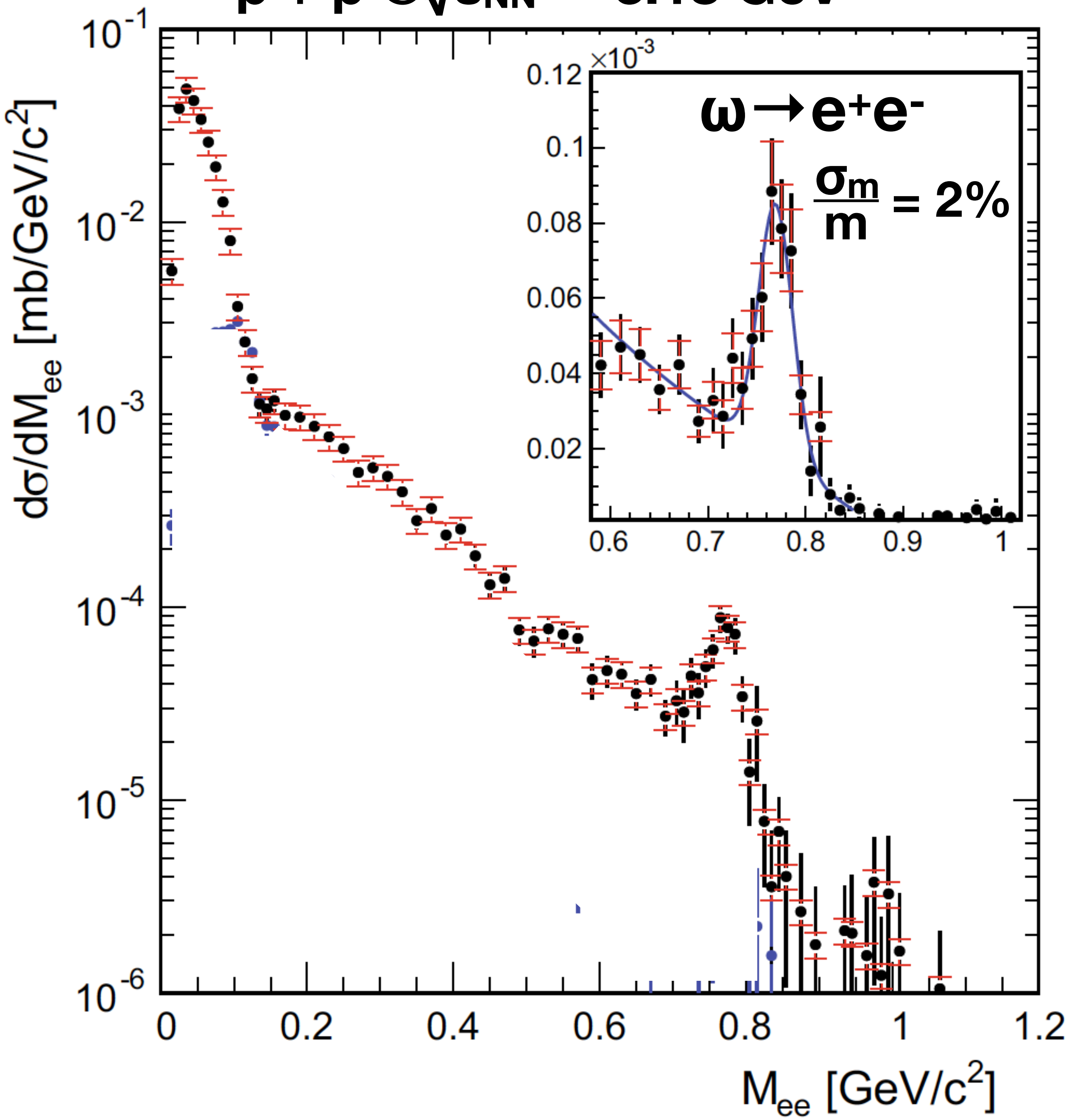
in-medium vector meson spectral function modified due to coupling to resonance - holes states (modifications confined to small momenta)

→ **collisional broadening** (known from atomic physics)

e^+e^- from p + p and p + Nb @ $\sqrt{s_{NN}}$ = 3.18 GeV

HADES data: EPJA 48 (2012) 64

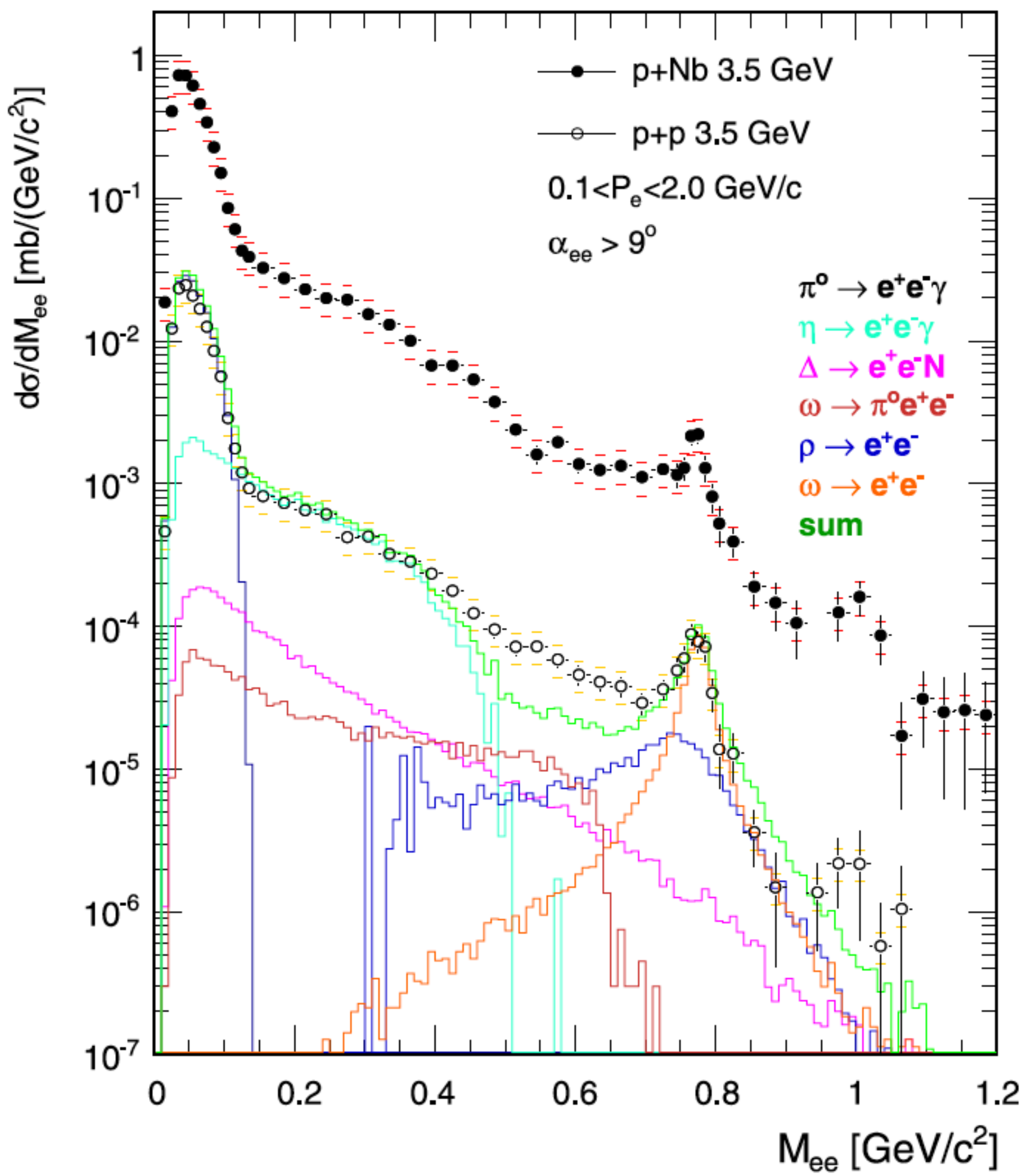
p + p @$\sqrt{s_{NN}}$ = 3.18 GeV



e^+e^- from p + p and p + Nb @ $\sqrt{s_{NN}}$ = 3.18 GeV

e^+e^- from p + p and p + Nb @ $\sqrt{s_{NN}}$ = 3.18 GeV

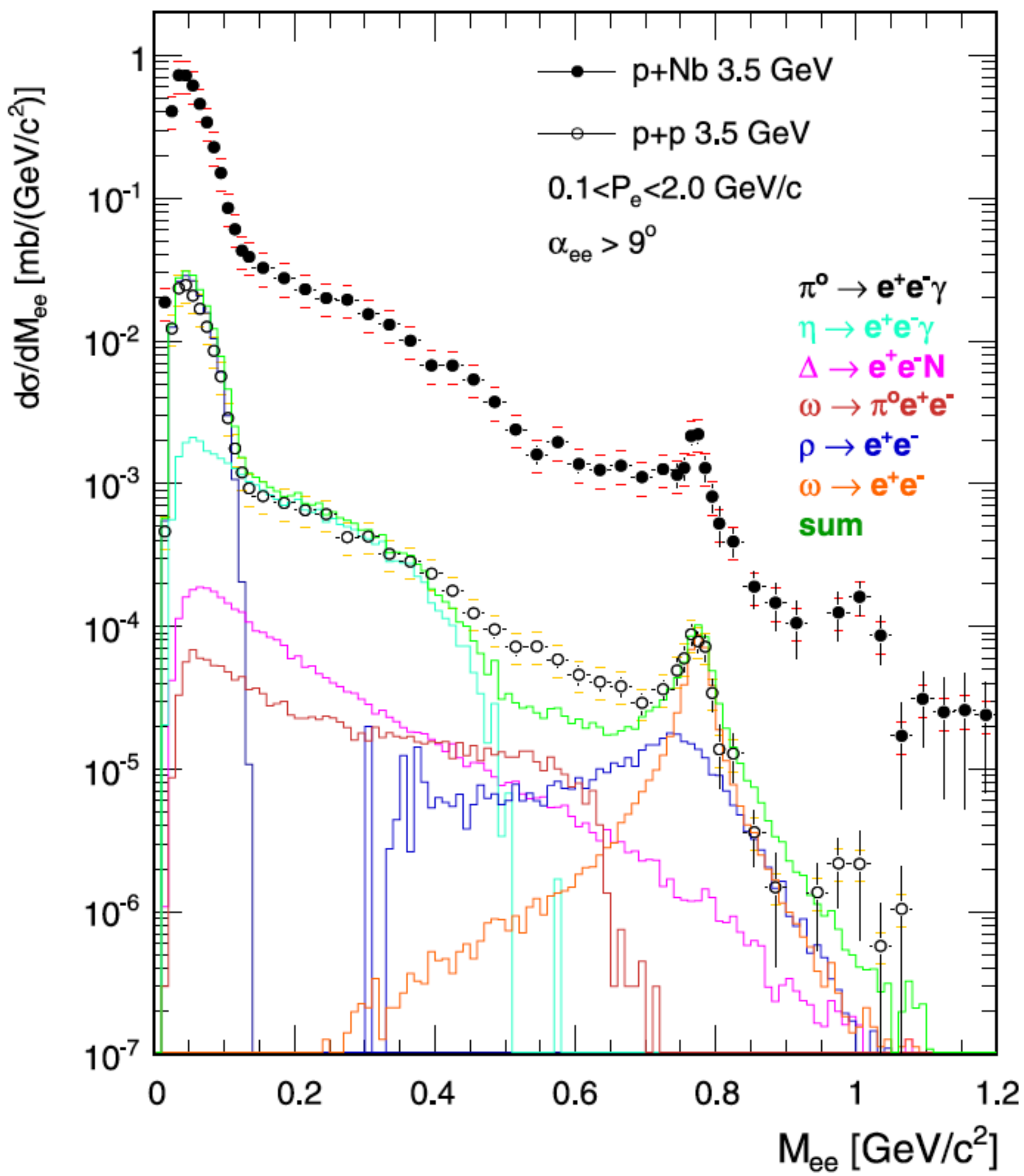
HADES data: PLB 715 (2012) 304



p+p cocktail: based on known sources:
π, η, ω, Φ, Δ, p+p bremsstrahlung

e^+e^- from p + p and p + Nb @ $\sqrt{s_{NN}}$ = 3.18 GeV

HADES data: PLB 715 (2012) 304



p+p cocktail: based on known sources:
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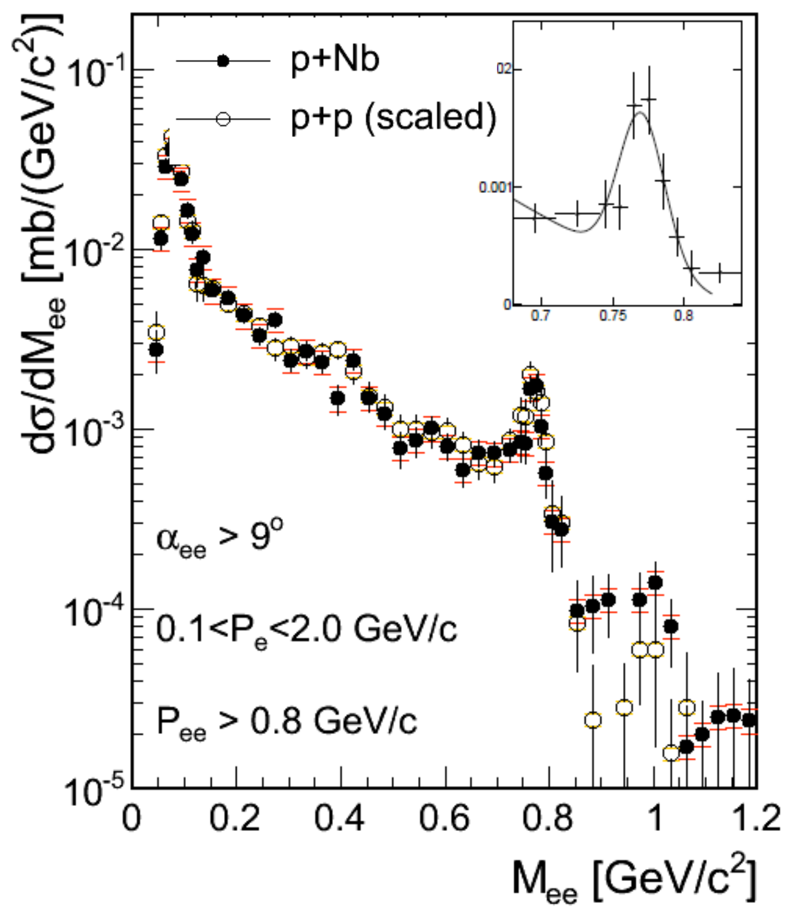
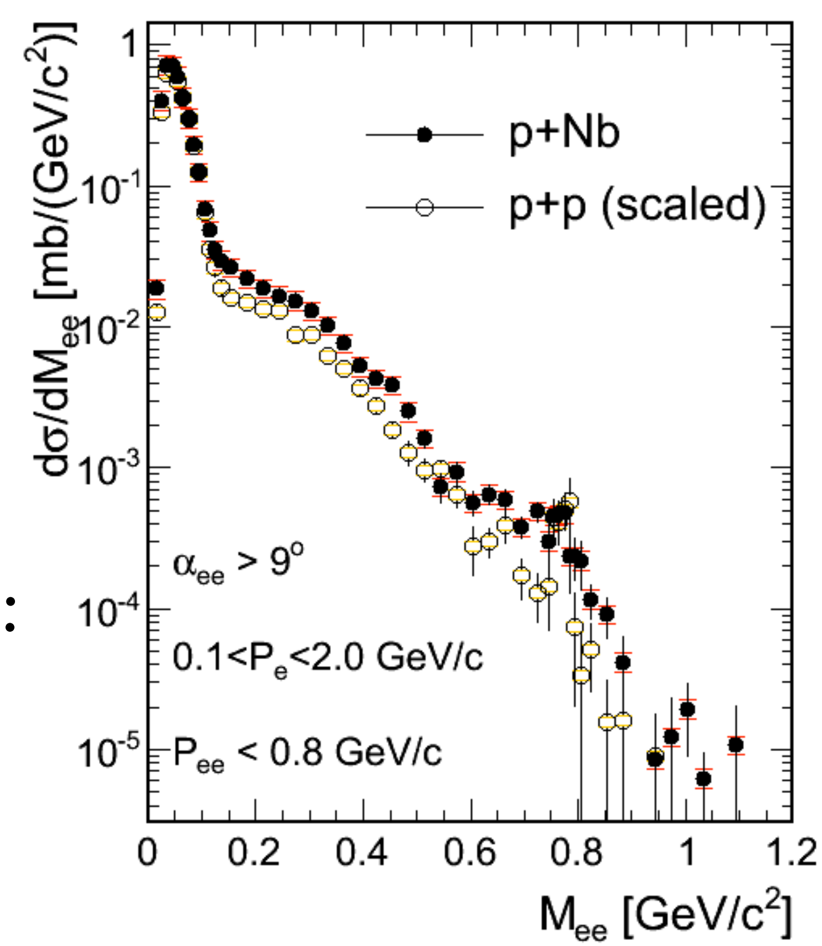


p_{ee} > 800 MeV/c:

shape of m_{ee} spectrum in p+Nb identical to reference spectrum in p+p

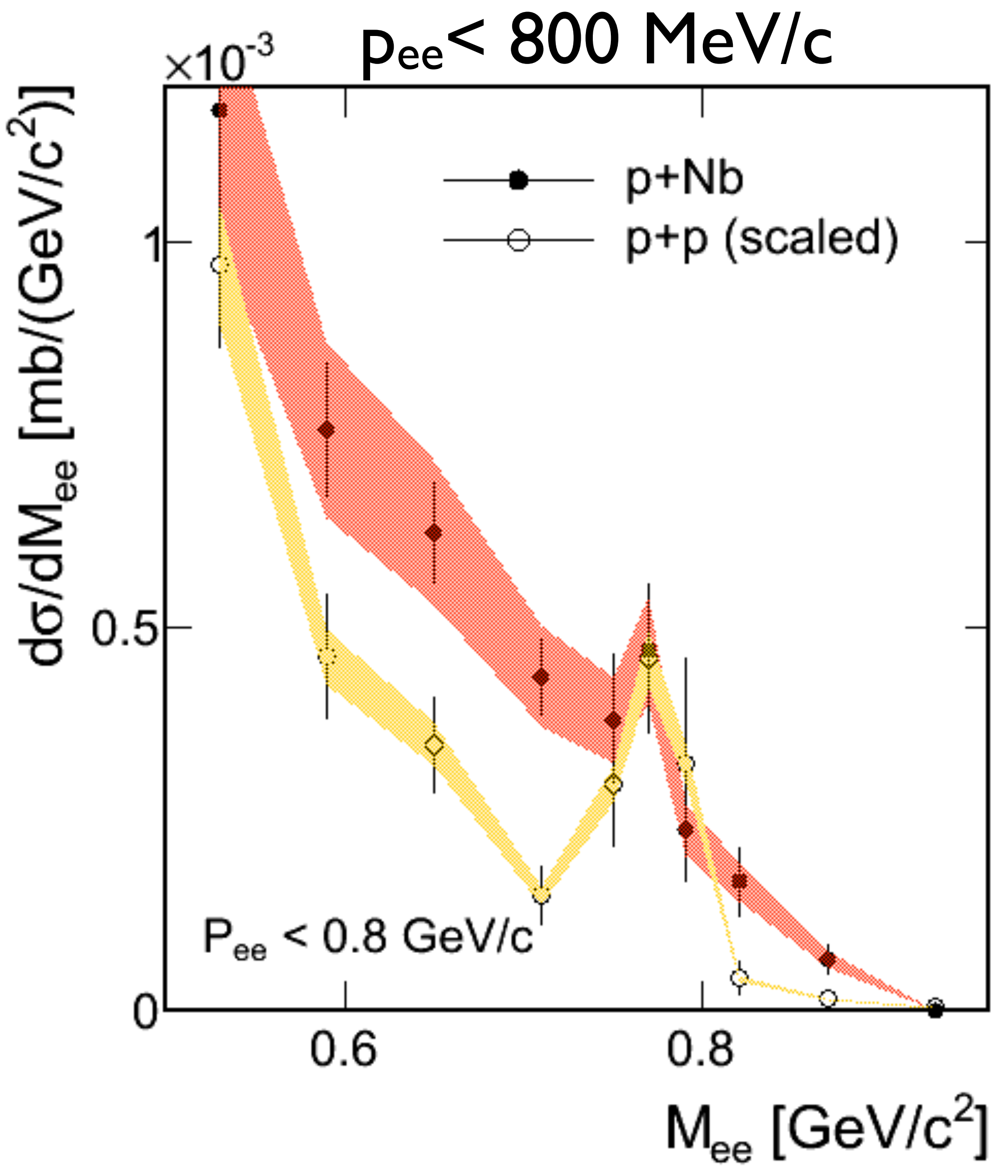


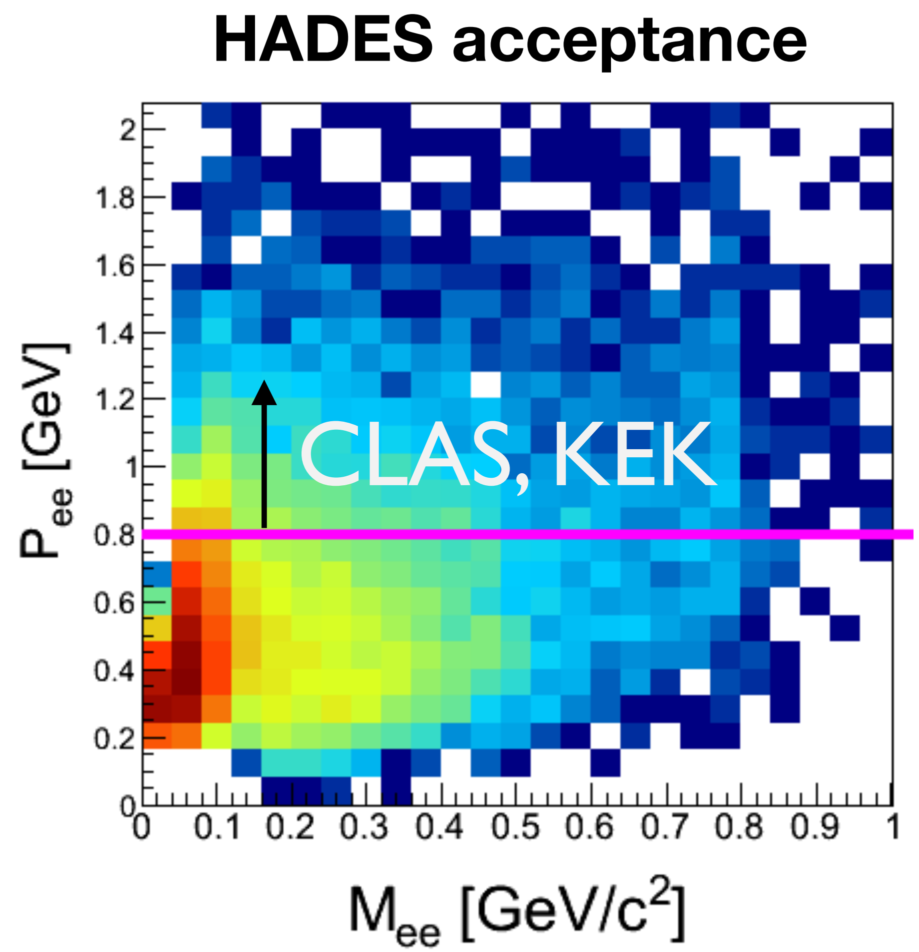
p_{ee}< 800 MeV/c:

strong e^+e^- excess yield below ω peak

dilepton signals from cold nuclear matter

p + Nb @ $\sqrt{s_{NN}}$ = 2.42 GeV





first measurement of vector meson decays in relevant momentum range

CLAS, KEK E325 acc. only for p_{ee} > 0.8 GeV/c

remarkable difference between p+p and p+Nb:

- reduction of ω yield (absorption)
- broadening of ρ

→ manifestation of in-medium modifications of vector mesons at low momenta

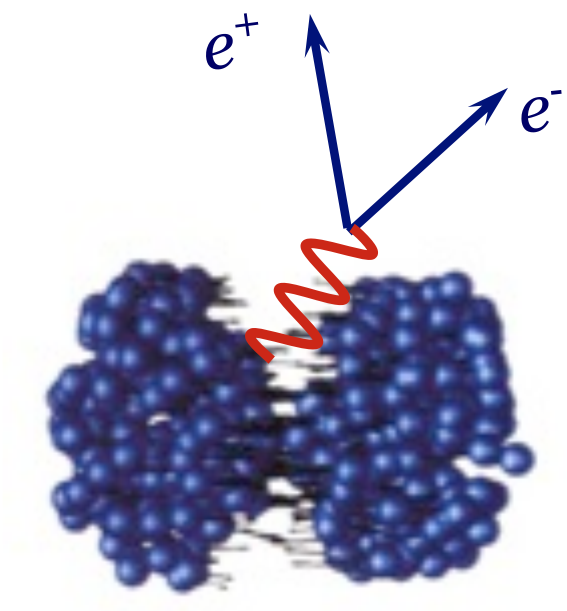
dileptons from relativistic heavy-ion reactions
in-medium modification of vector mesons

dileptons from A + A reactions

collective kinetic energy is dissipated into intrinsic degrees of freedom

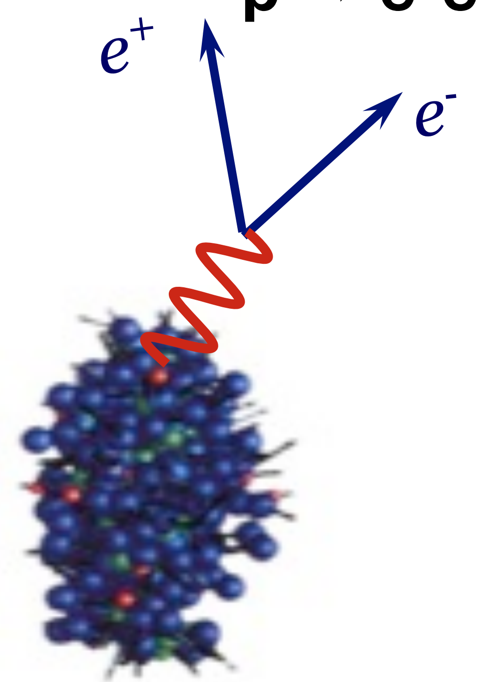
penetrating probes: e^+e^- pairs, emitted over the full space-time evolution of the collision

different dilepton sources have be disentangled in the data analysis



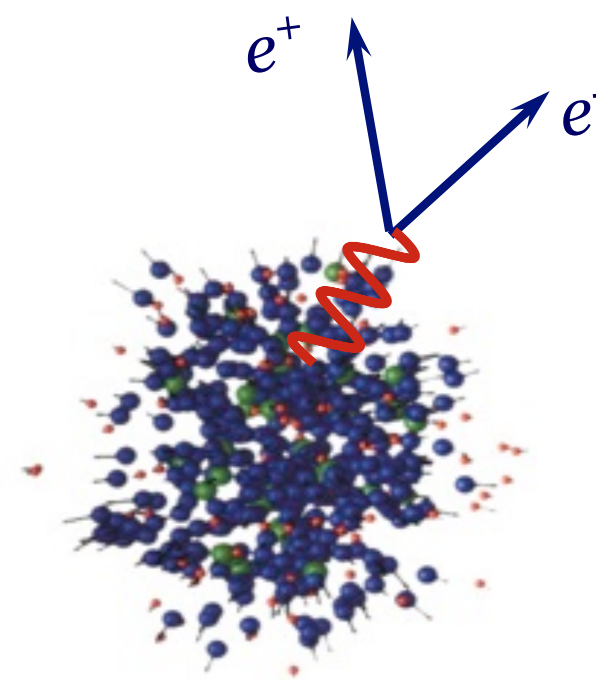
first chance collisions, bremsstrahlung

$\rho \rightarrow e^+e^-$



hot and dense collision zone

probing the interior of the fireball



freeze out

final state hadrons

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

$\omega, \phi \rightarrow e^+e^-$

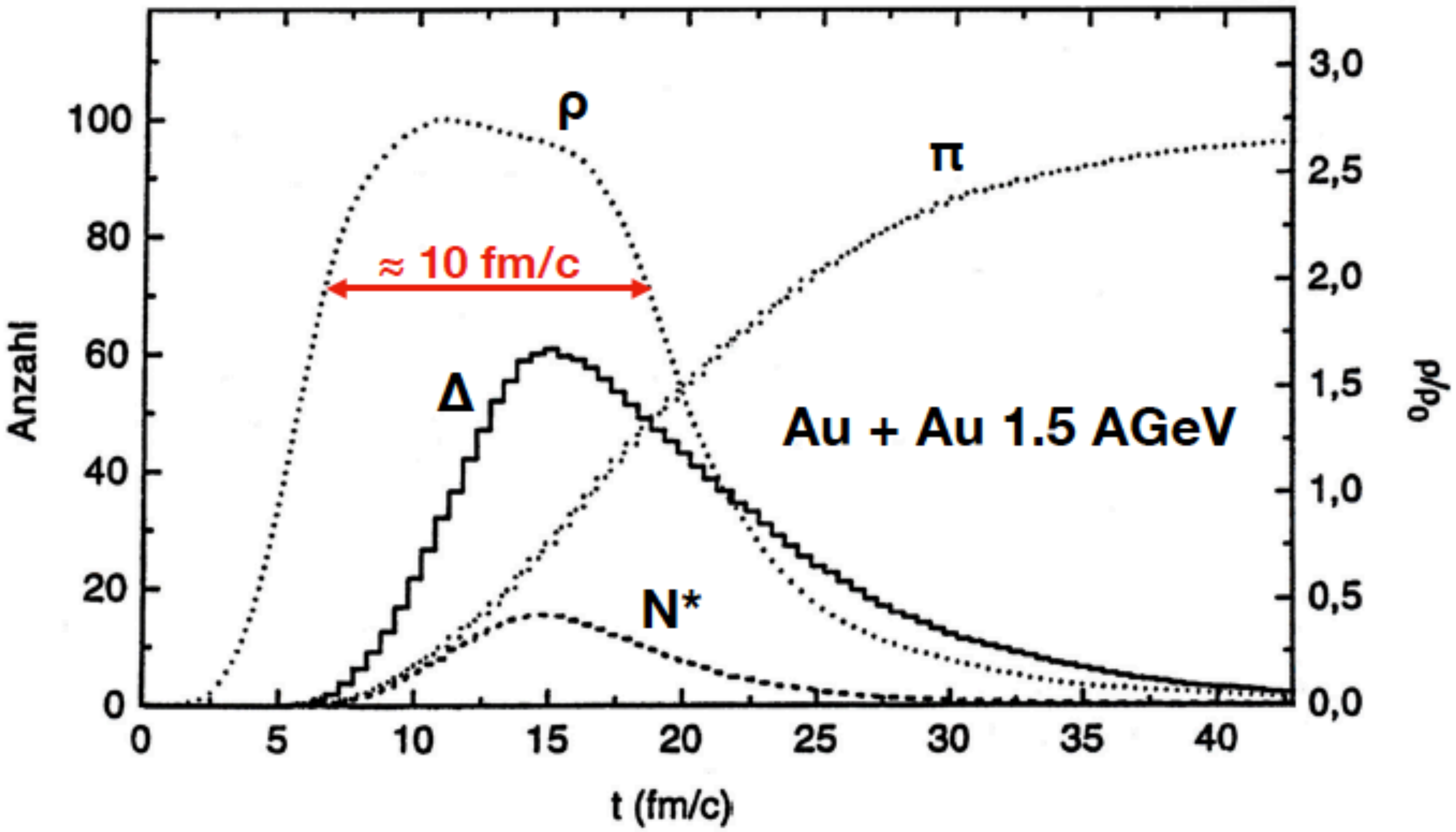
$\pi^\pm, K^\pm, \Lambda, \Sigma, \Xi$

different dilepton sources have to be disentangled in the data analysis

t

transport calculations: GiBUU, UrQMD, IQMD, HSD

S. Teis et al., Z. Phys. A 359 (1997) 297

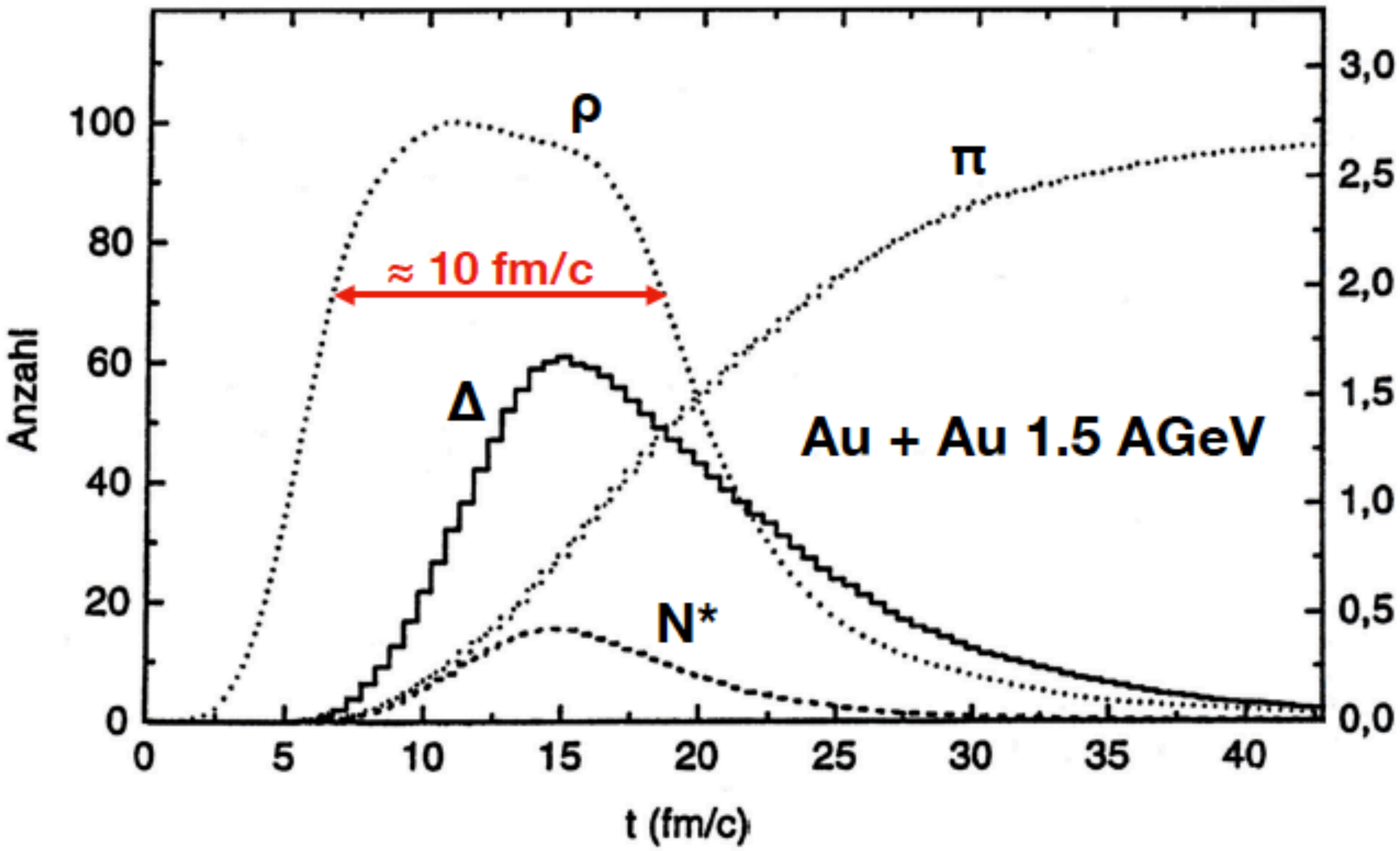


$\rho_N \approx 2.5\ \rho_0$

resonance matter

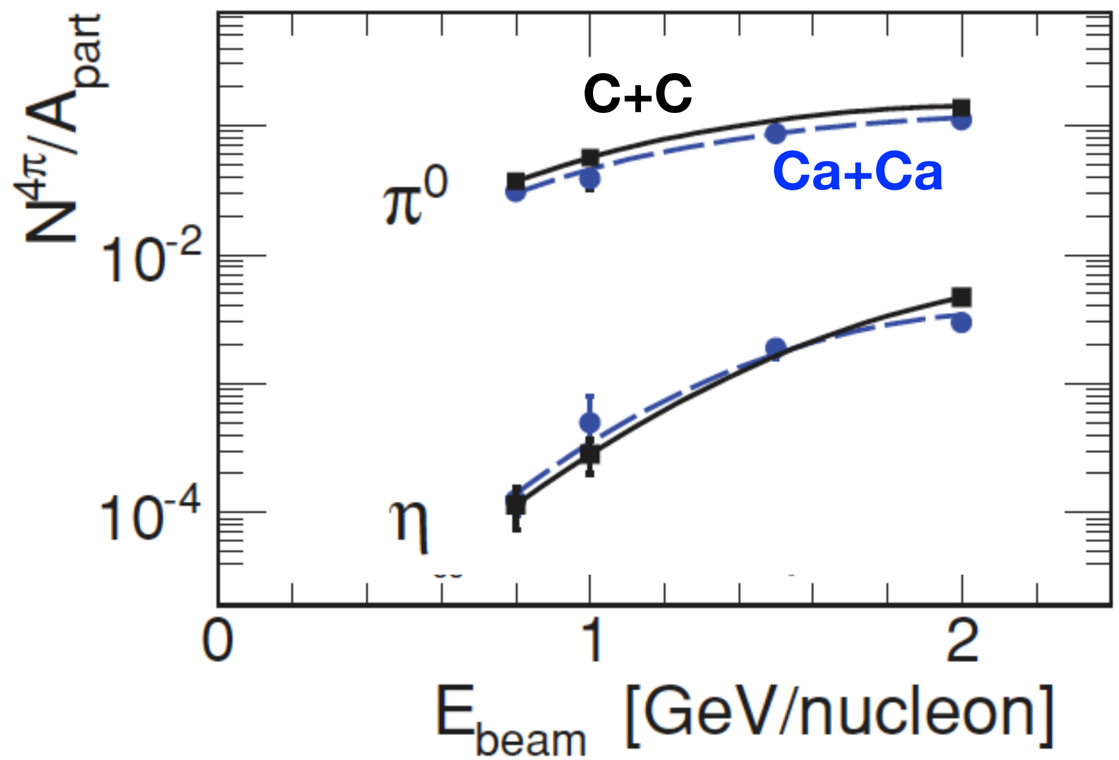
transport calculations: GiBUU, UrQMD, IQMD, HSD

S.Teis et al.,Z. Phys.A 359 (1997) 297



TAPS data:

R. Holzmann et al. PRC56 (1997) R2920



$N_{\pi 0} = 1/2 \bullet (N_{\pi+}+N_{\pi-}) = 0.147\pm0.01$

HADES data: EPJA 40 (2009) 45

$\Sigma\, N_{\pi\pm,\pi 0} = 3\bullet\, N_{\pi 0}$

$\rho_{\Delta,N*} = 0.45\ \rho_N$

$\rho_N \approx 2.5\ \rho_0$

$\rho_{\Delta,N*} = 0.45\ \rho_N = 0.45 \bullet 2.5\ \rho_0 \approx 1.1\ \rho_0$

density of baryon resonances reaches nucleon density ρ_0 in normal nuclear matter

baryon resonances start interacting among each other: **resonance matter**

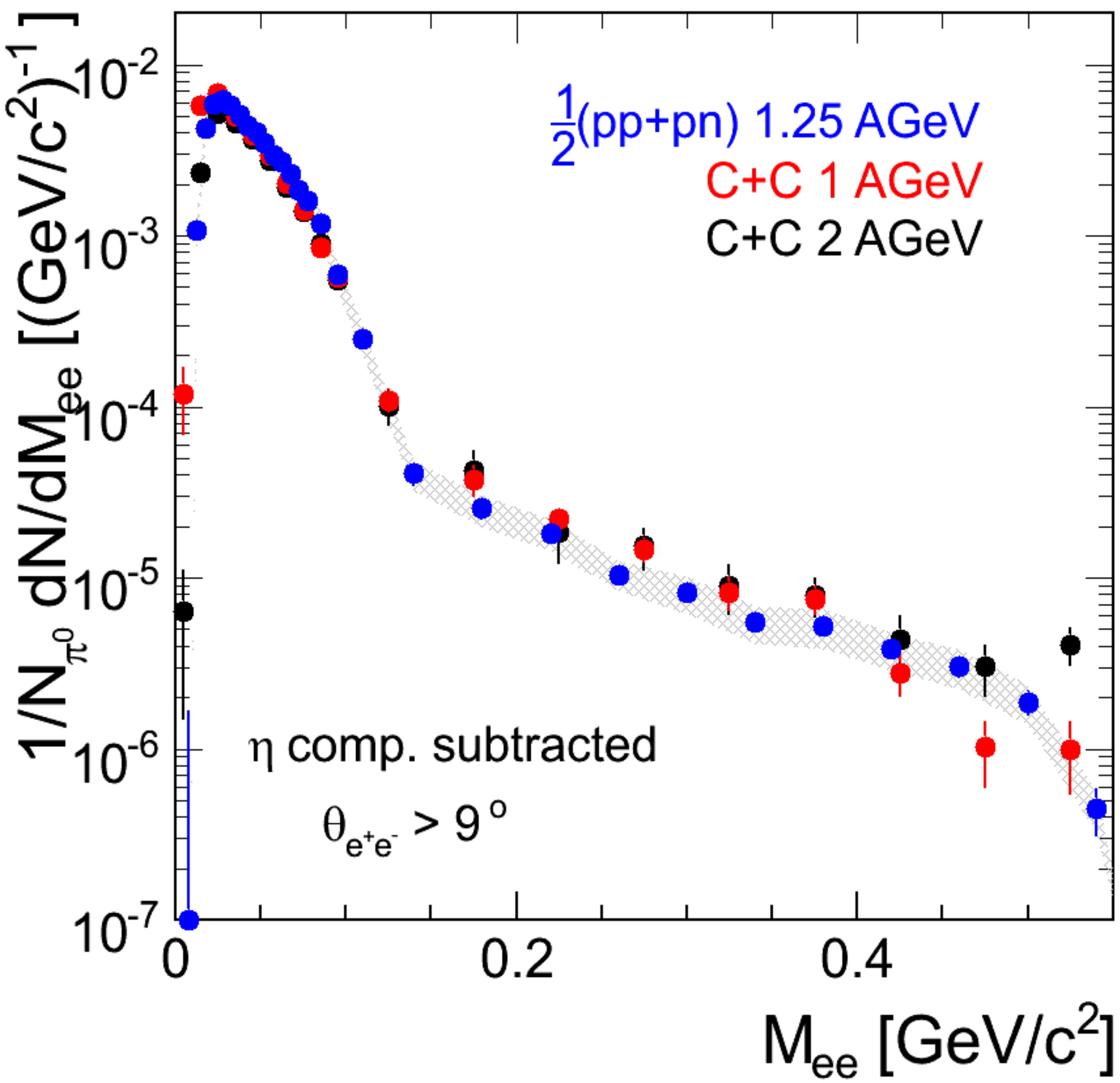
U. Mosel, V. Metag , Nucl. Phys. News 3 (1993) 25; Phys. Bl. 49 (1993) 426

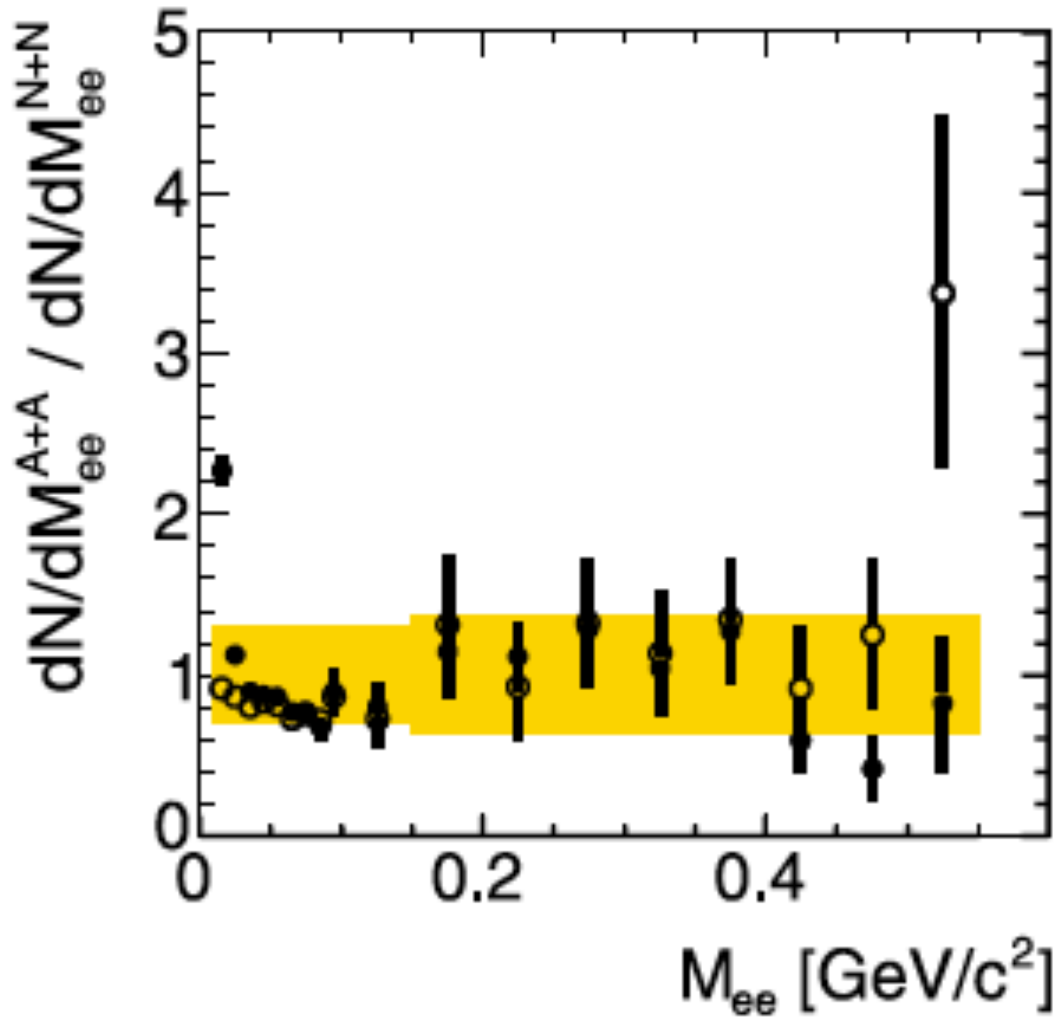
impact on particle production in relativistic heavy-ion collisions

dileptons from A + A collisions I

$^{12}C + ^{12}C$ @ 1.0 and 2.0 AGeV

HADES data: PLB 690 (2010) 118





dilepton spectrum in C + C compatible with superposition of elementary n + p and p + p collisions;

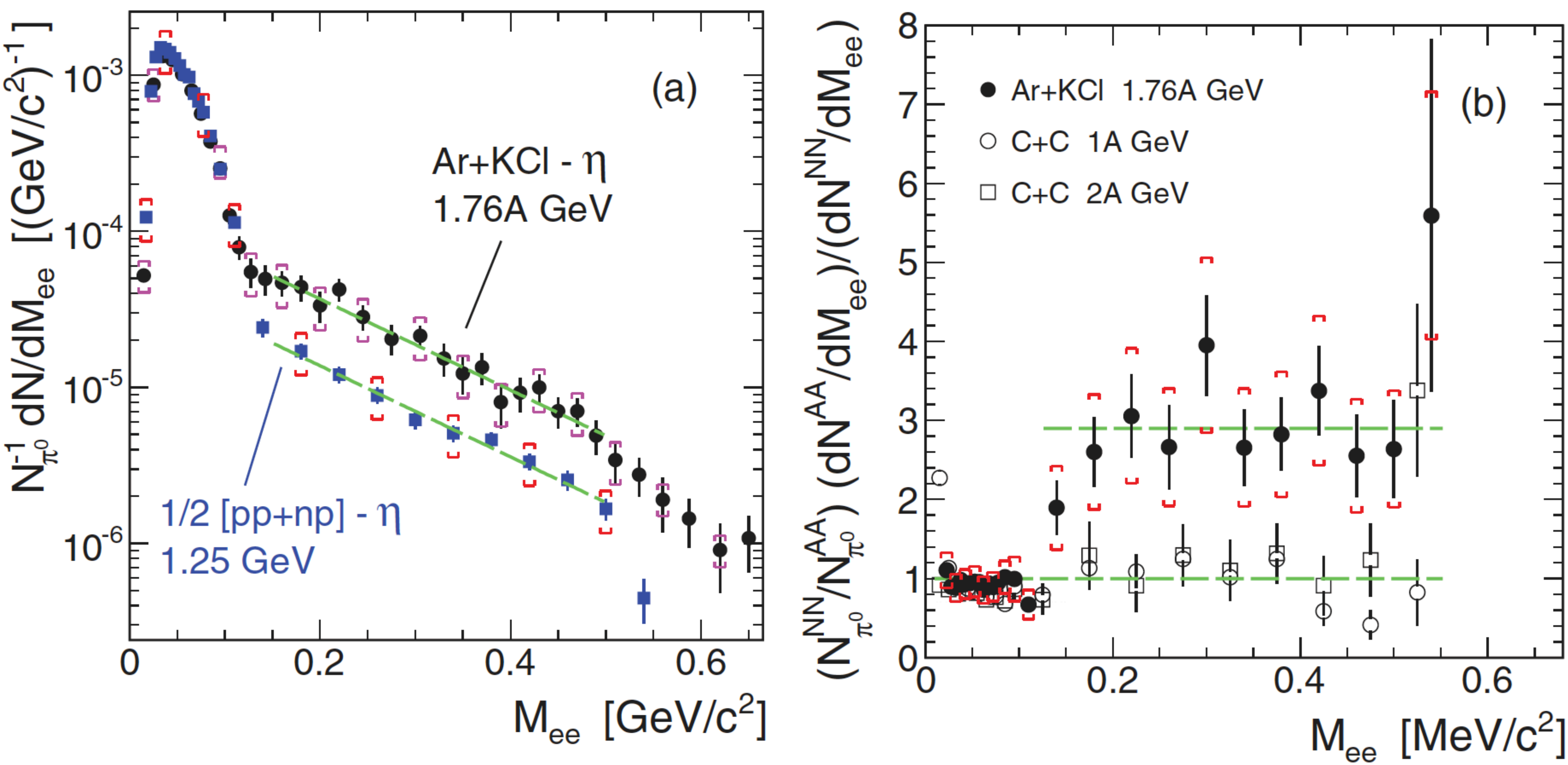
N + N reference spectrum: $\sigma_{NN}(M_{e+e-}) = 1/2\ (\sigma_{pp}(M_{e+e-}) + \sigma_{pn}(M_{e+e-}))$

no radiation beyond binary nucleon-nucleon collisions in this light system !!

dileptons from A + A collisions II

^{40}Ar + KCl @ 1.76 AGeV

HADES data: PRC 84 (2011) 014902



dilepton excess yield compared to N+N reference spectrum and ^{12}C + ^{12}C

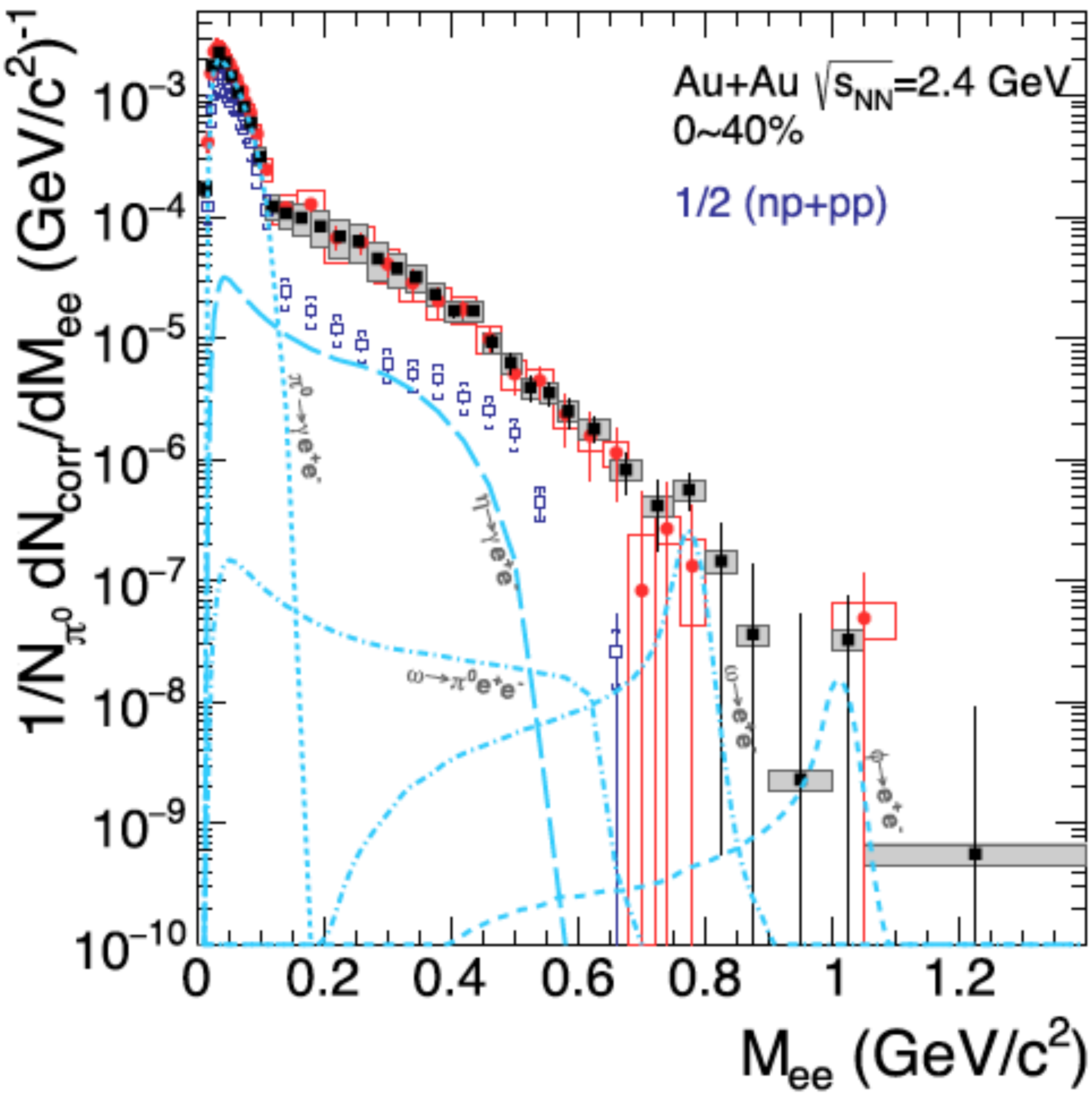
regeneration of baryonic resonances in the fireball

- **onset of fireball radiation**

dileptons from A + A collisions III

Au + Au @ 1.23 AGeV ($\sqrt{s_{NN}}$ = 2.42 GeV)

HADES data: Nature Physics 15 (2019) 1040



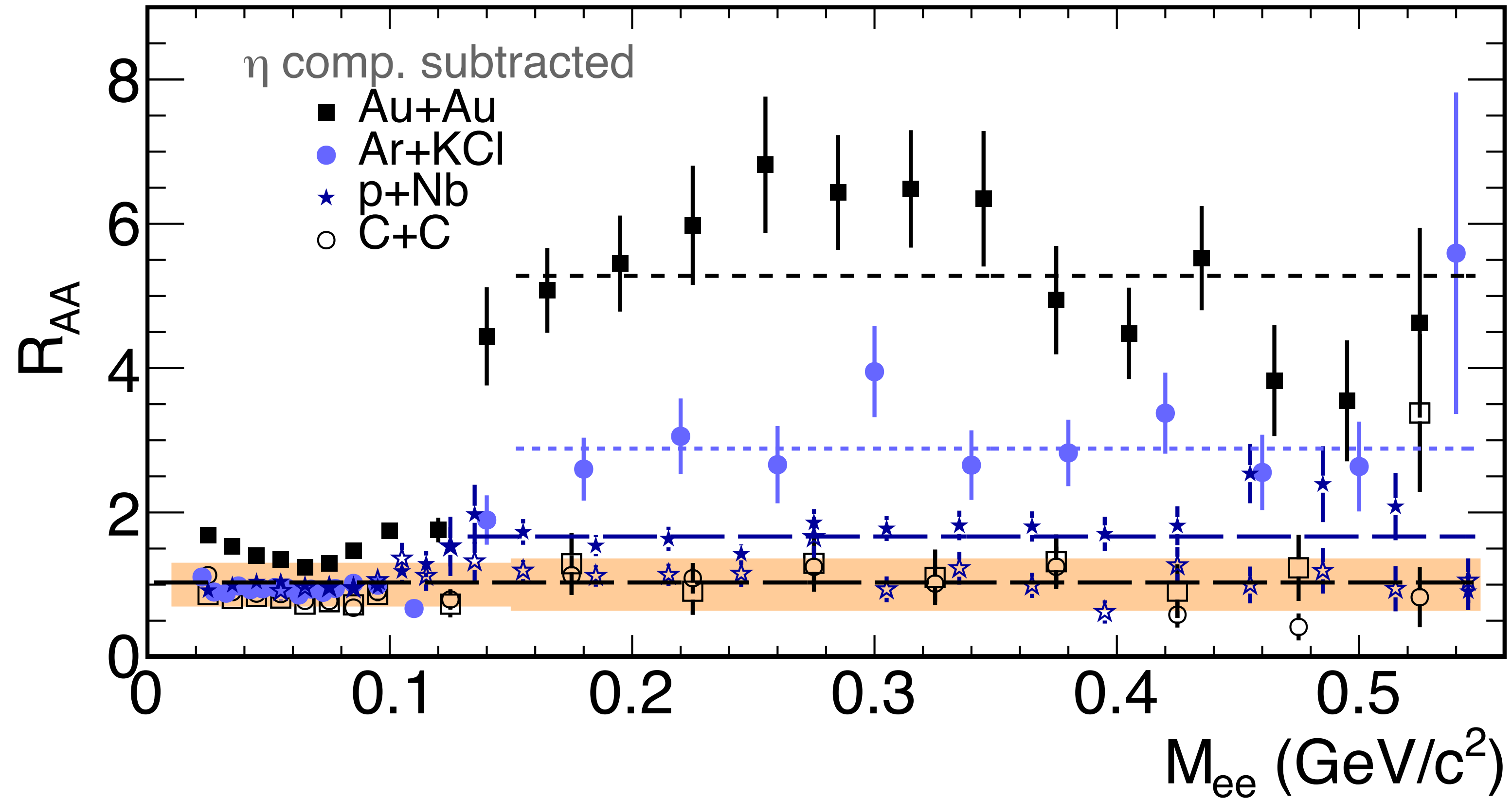
for M_{e+e-} > 0.15 GeV clear dilepton excess yield above **mesonic** (η,ω,Φ) and **baryonic** sources (NN bremsstrahlung + $\Delta \to$ N e^+e^-)

NN reactions scaled by A_{part} (number of pions)

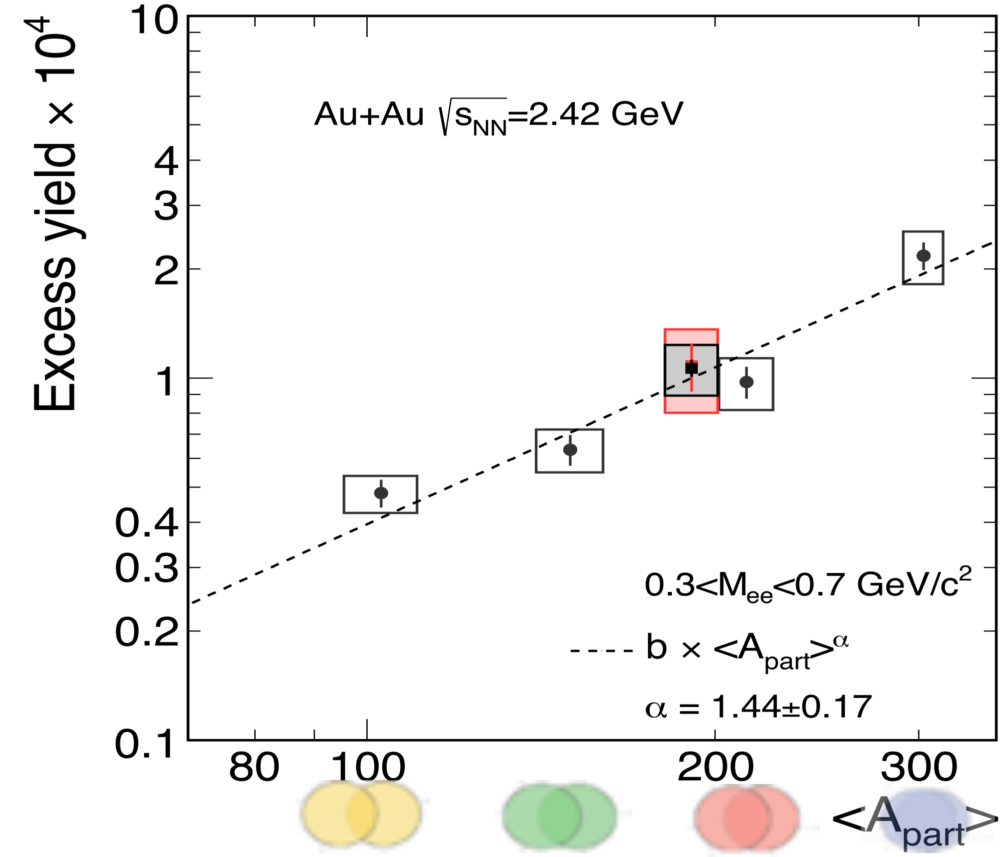
The onset of the excess radiation

HADES data: Nature Physics 15 (2019) 1040

system size dependence



centrality dependence



$$R_{AA} = \frac{1}{\langle A_{\rm part}^{\rm AA}\rangle}\frac{dN^{\rm AA}}{dM_{ee}}\left(\frac{dN^{\rm NN}}{dM_{ee}}\right)^{-1}$$

excess yield ~$\langle A_{part}\rangle^{\alpha}$

α = 1.44±0.17

- for Au + Au the number of e^+e^- pairs per participant nucleon is ≈ 6 times higher than in a free N+N collision;

  6 generations of baryon resonances with τ ≈ 1.5 fm/c → fireball lifetime of ≈10 fm/c

- dilepton radiation from the hot and dense collision zone increases with system size and centrality of the collision

fireball = thermal source??

statistical hadronization models: THERMUS

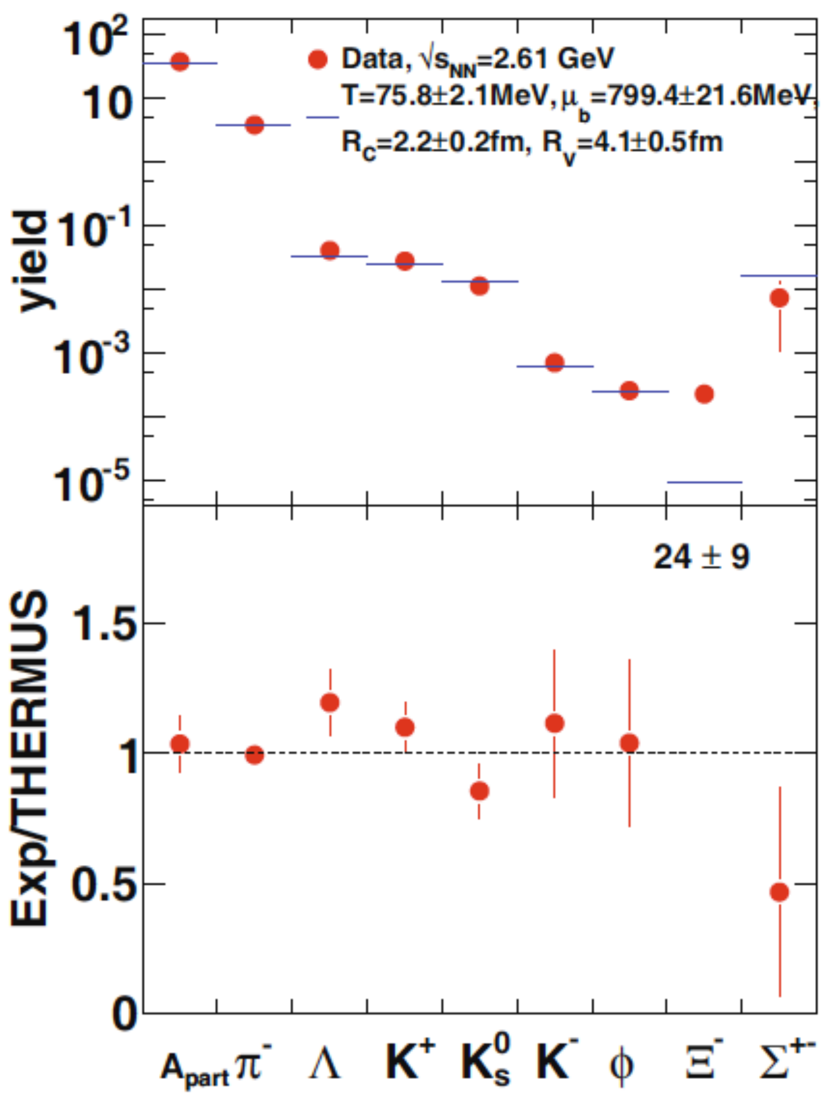
S. Wheaton, J. Cleymans, Comp. Phys. Comm. 180 (2009) 84S

particle yields at freeze out determined by T, μ_B

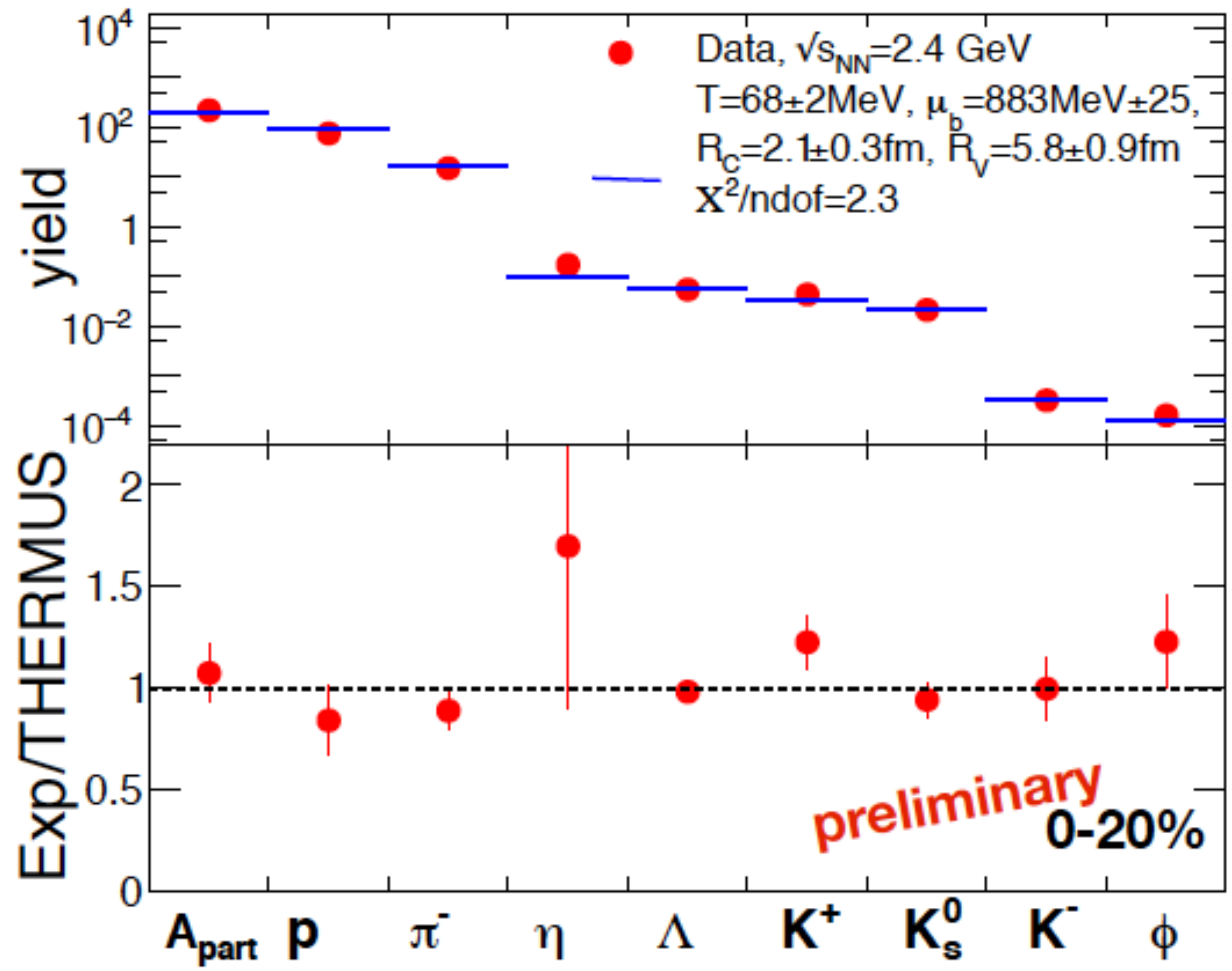
$$\rho(\mu_B, T) = \frac{g}{(2\pi\hbar)^3} \int 4\pi p^2 f(pR) dp \int \frac{A(m)dm}{\exp[(E - \mu_B B)/T] \pm 1}$$

HADES data: EPJA 47 (2011) 21

Ar + KCl @ 1.76 AGeV



Au+Au @ 1.23 AGeV

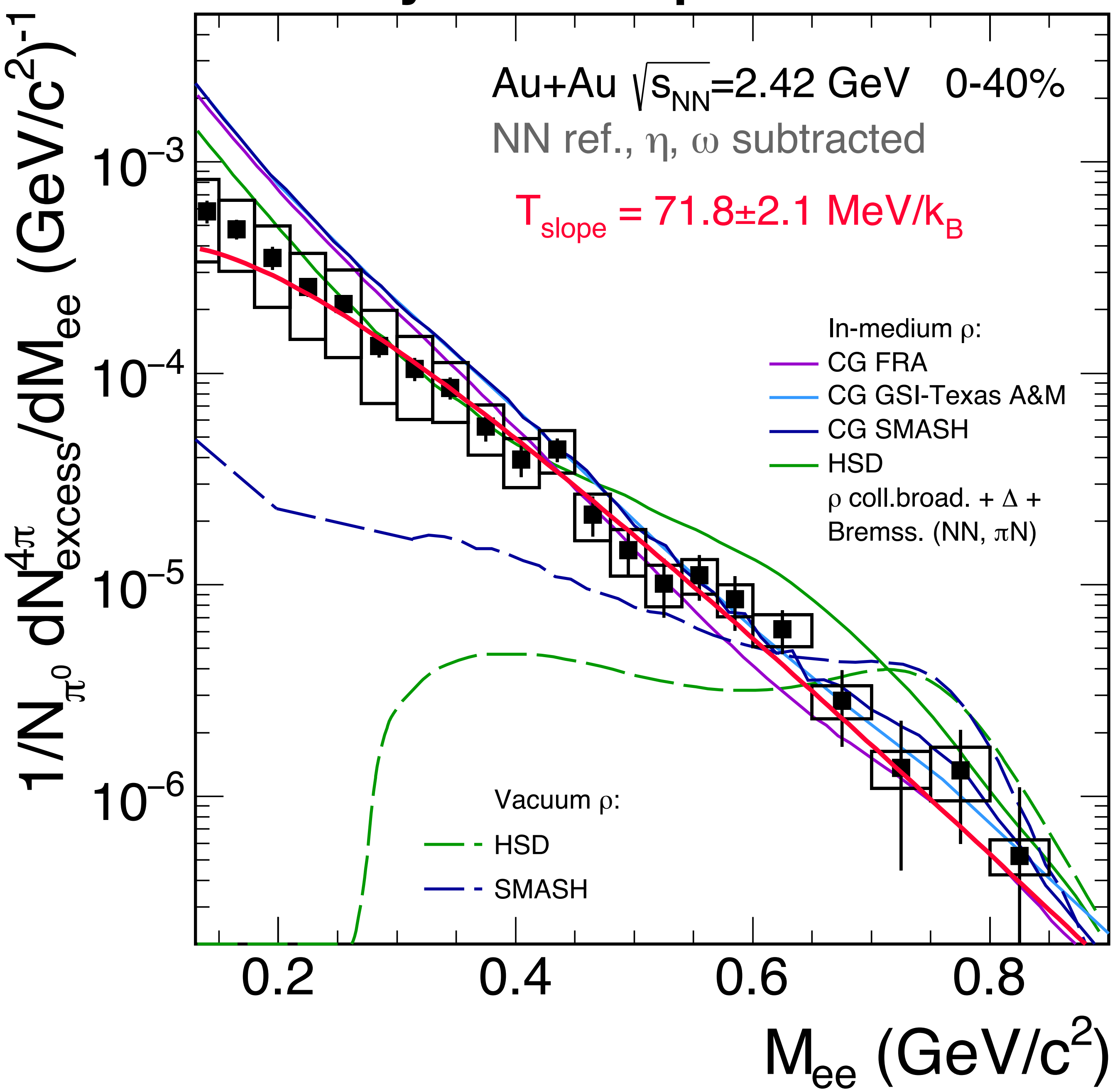


excellent description of particle yields also in SIS energy regime (except for Ξ^-)

virtual photon radiation from the fireball

contributions from early NN collisions and final state particle decays subtracted

efficiency and acceptance corrected



M_{ee} = invariant quantity; not affected by blue shift due to the expanding fireball

HADES data: Nature Physics 15 (2019) 1040

strong ρ broadening in the medium !!

interpretation:

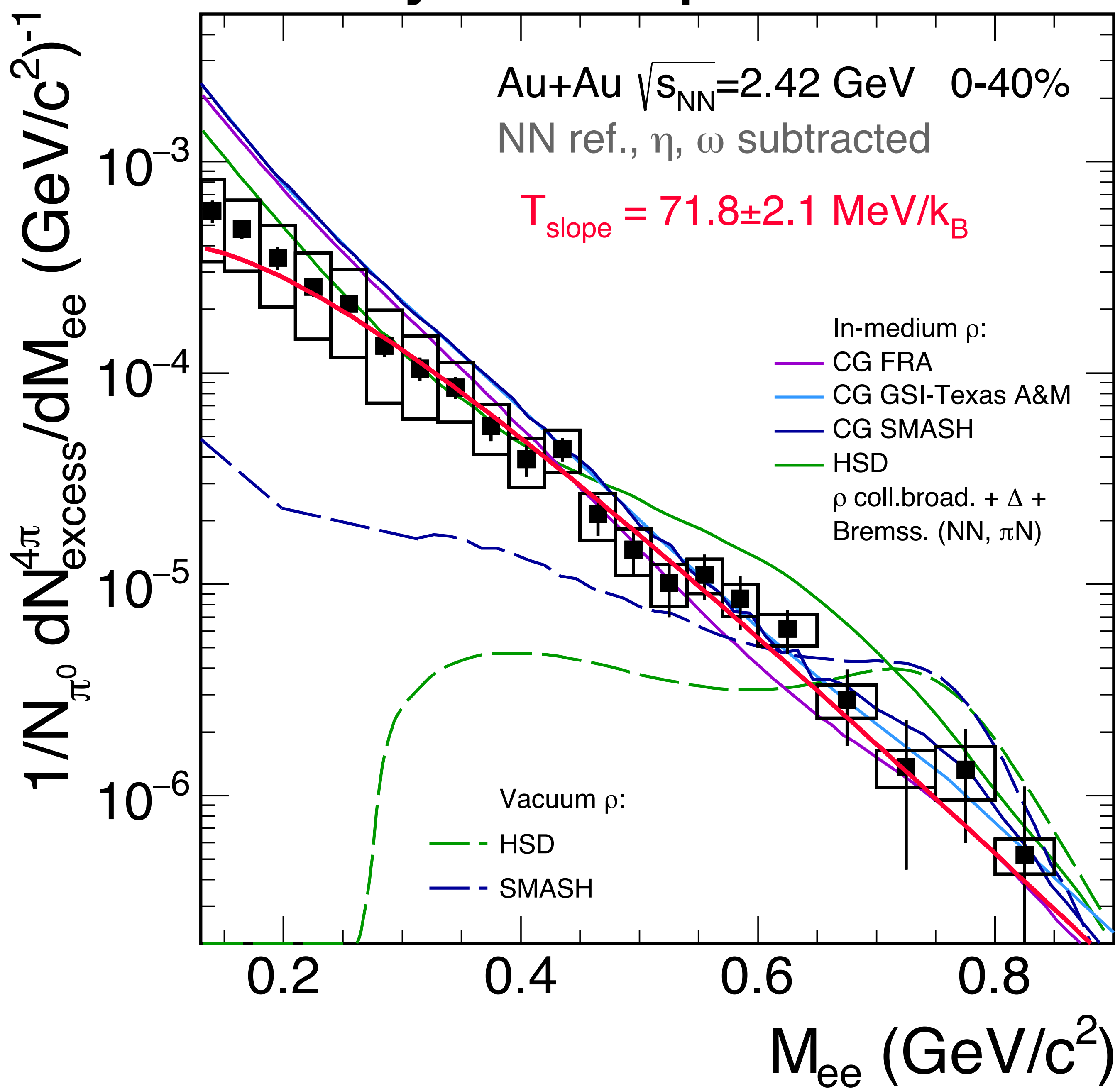
a.) hadronic many-body effects

b.) partial chiral symmetry retoration

virtual photon radiation from the fireball

contributions from early NN collisions and final state particle decays subtracted

efficiency and acceptance corrected



M_{ee} = invariant quantity; not affected by blue shift due to the expanding fireball

HADES data: Nature Physics 15 (2019) 1040

strong ρ broadening in the medium !!

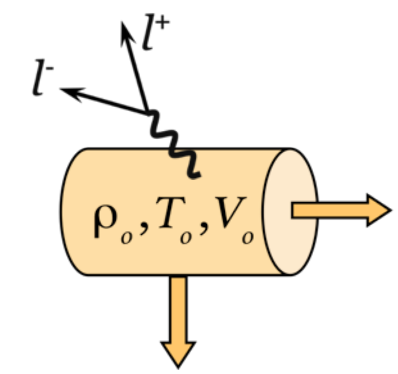
interpretation:

a.) hadronic many-body effects

b.) partial chiral symmetry retoration

thermal radiation

dileptons as thermometer



emessivity:

$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

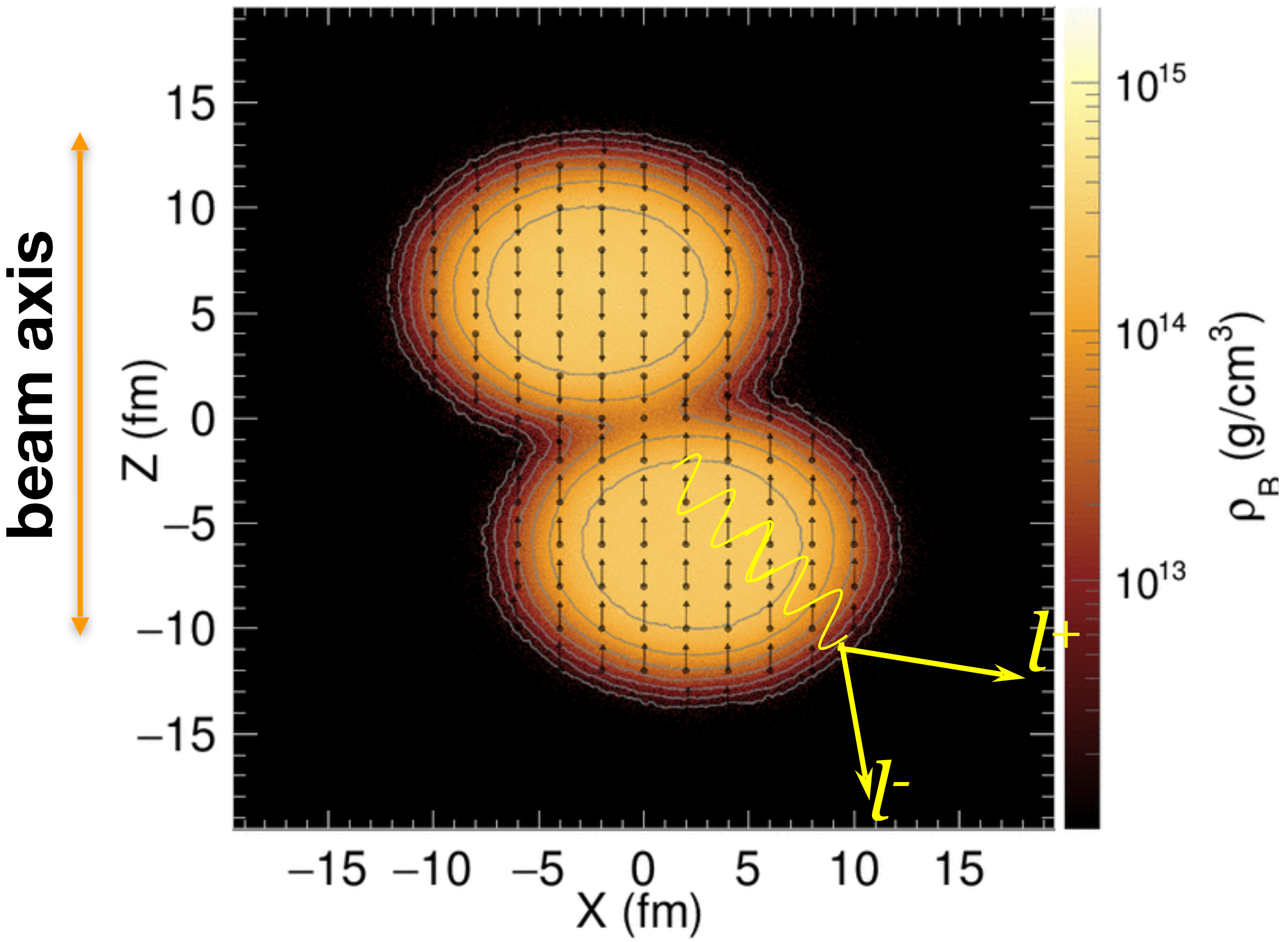
successful approach with coarse graining (T. Galatyuk et al., EPLA 52 (2016) 131); assuming thermalisation in cells of the collision zone

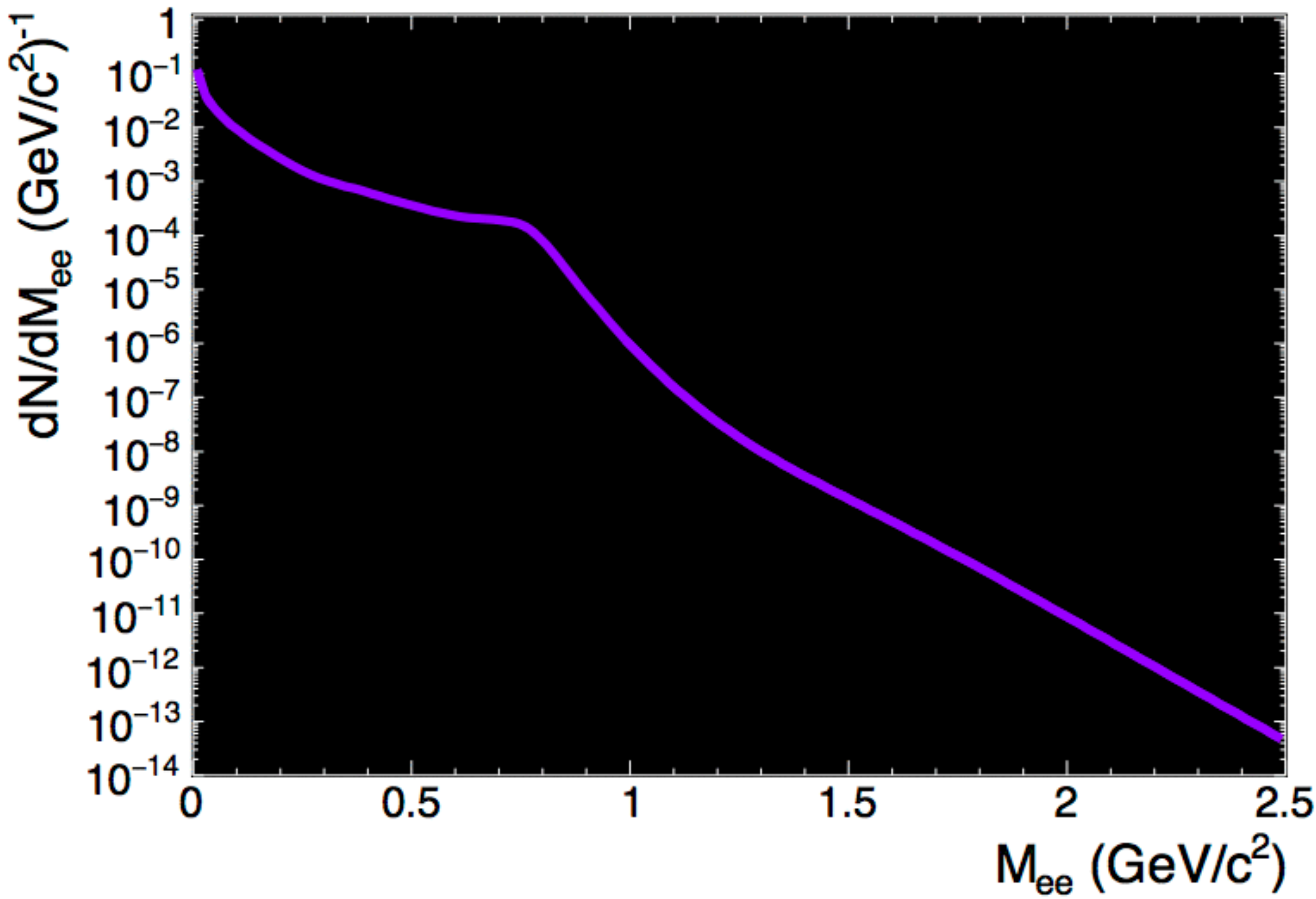
$$\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$$

T = (71.8 ± 2.1) MeV

Space time evolution of dilepton radiation

T. Galatyuk, F. Seck: simulation of space-time resolved dilepton emission

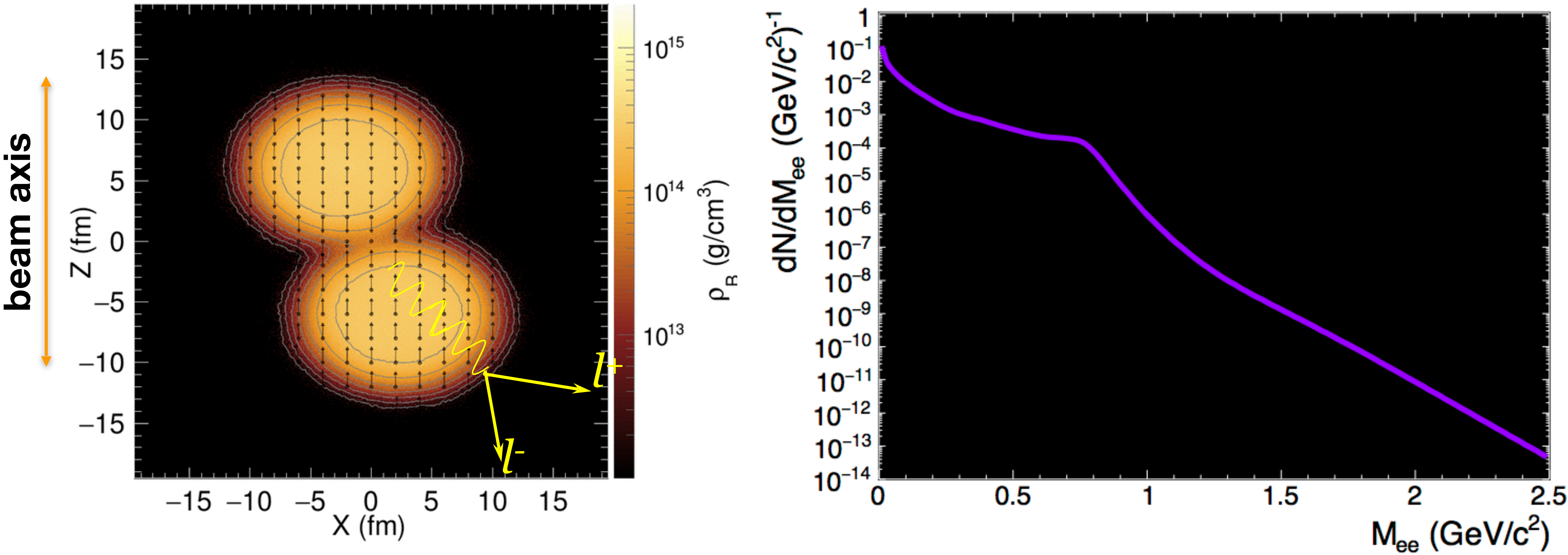




starting from a spectral function with a ρ pole one
ends up with a structure less invariant mass spectrum

Space time evolution of dilepton radiation

T. Galatyuk, F. Seck: simulation of space-time resolved dilepton emission

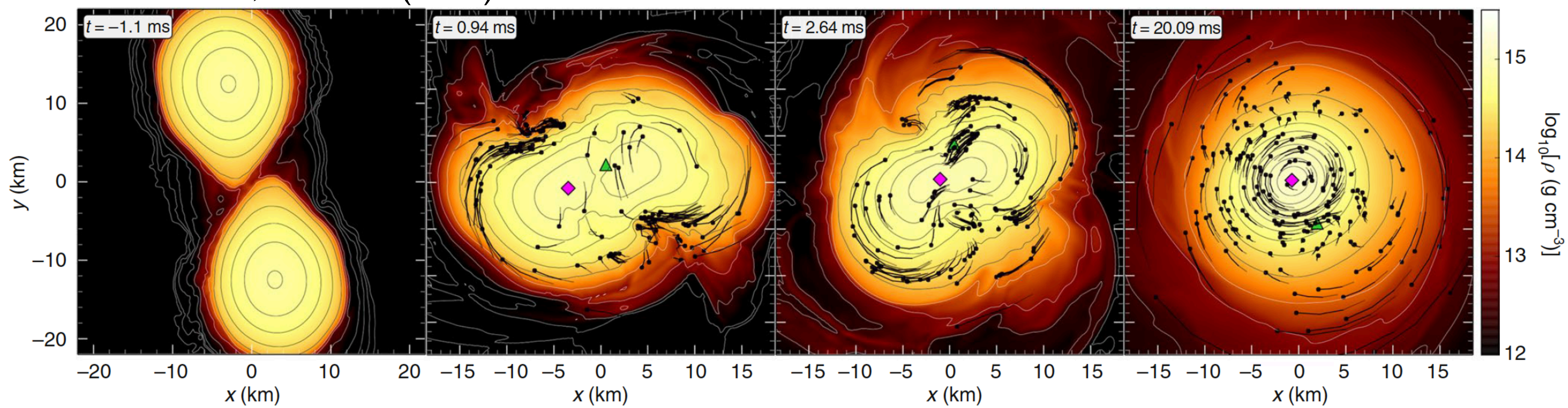


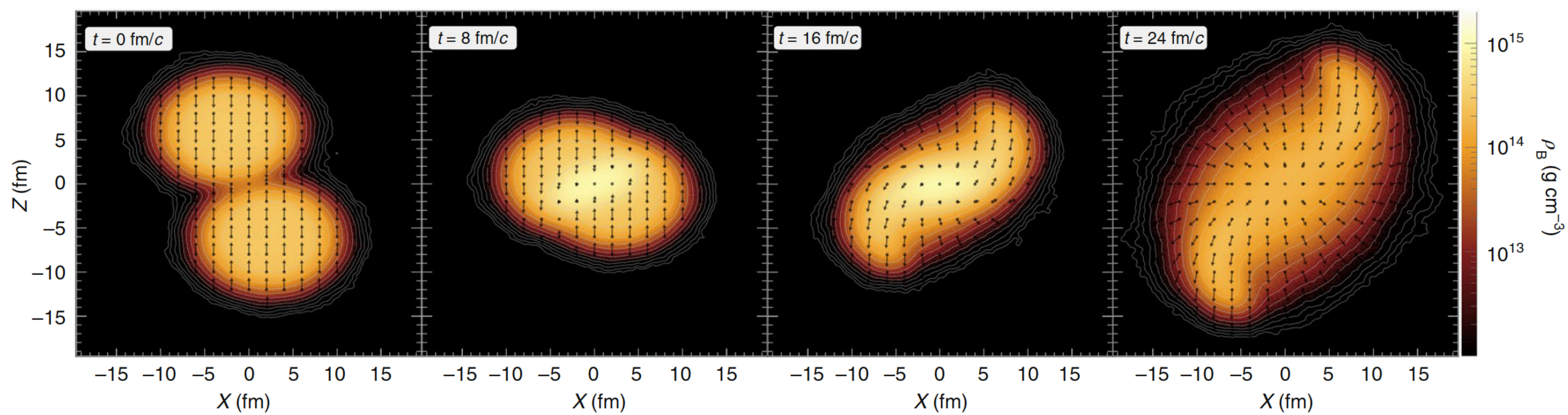
starting from a spectral function with a ρ pole one
ends up with a structure less invariant mass spectrum

link to astrophysics: neutron star mergers

heated shell around dense remnant core in postmerger neutron star configurations may reach T ≈ 50-80 MeV and $\rho \approx 2\rho_0$

E. Most et al., PRL 122 (2019) 061101





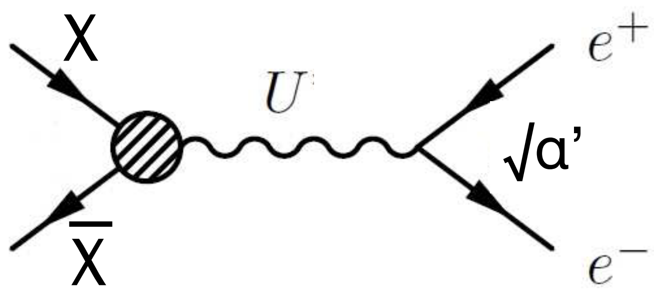
S.Bass et al., PPNP 41 (1998) 255

similar matter densities and temperatures reached as in neutron star mergers although space and timescales differ by typically 20 orders of magnitude

link to astrophysics: dark photon search

annihilation of dark matter particles may explain observed positron excess (e.g. AMS)

annihilation mediated by dark photon U, linking dark matter to the visible world

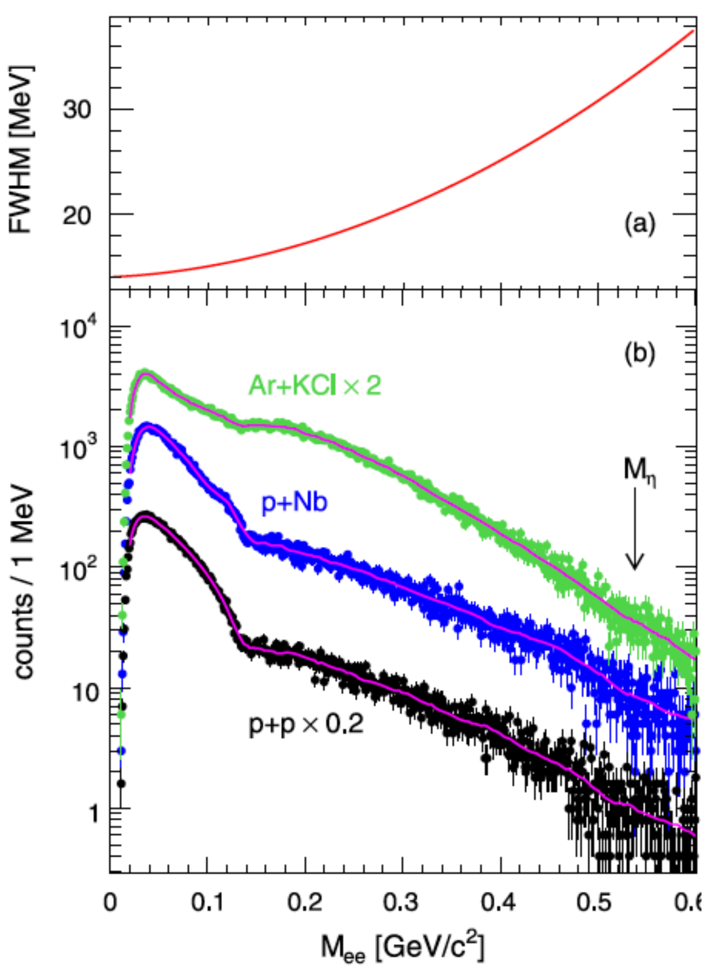


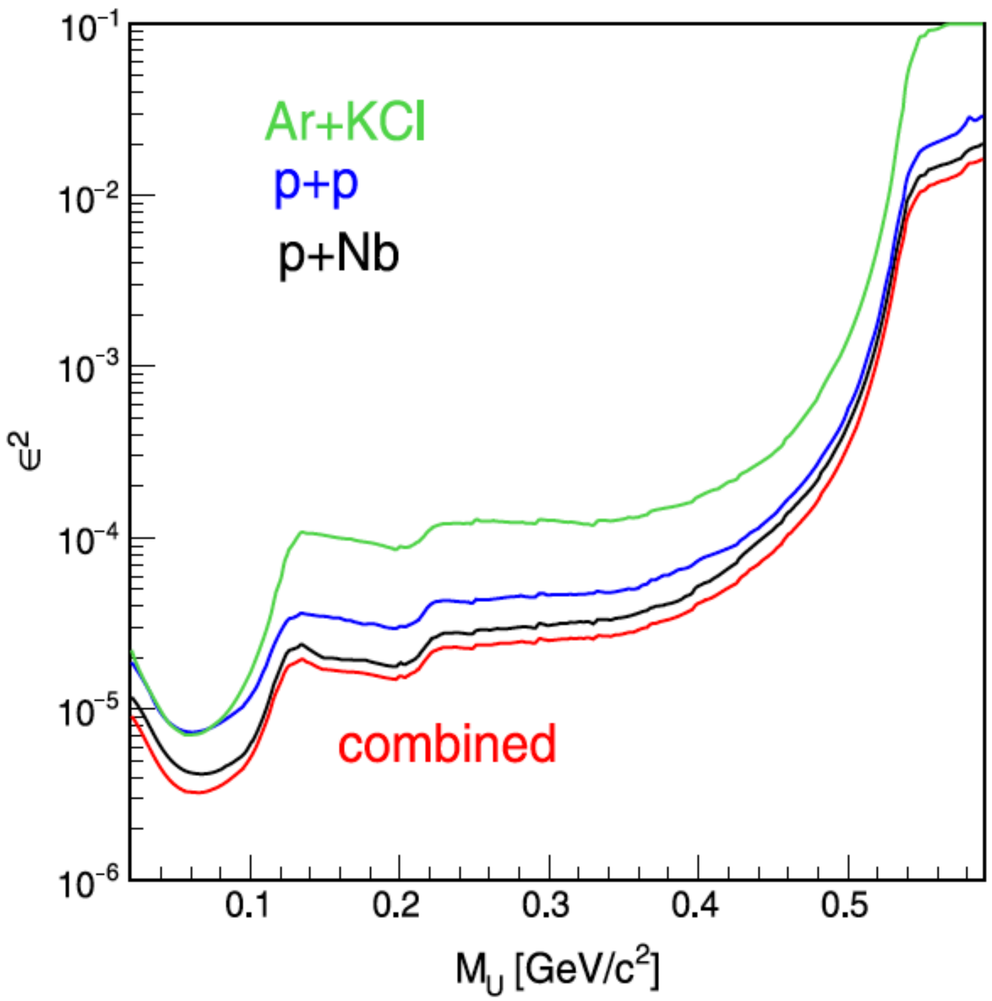
$\varepsilon^2 = \alpha'/\alpha$

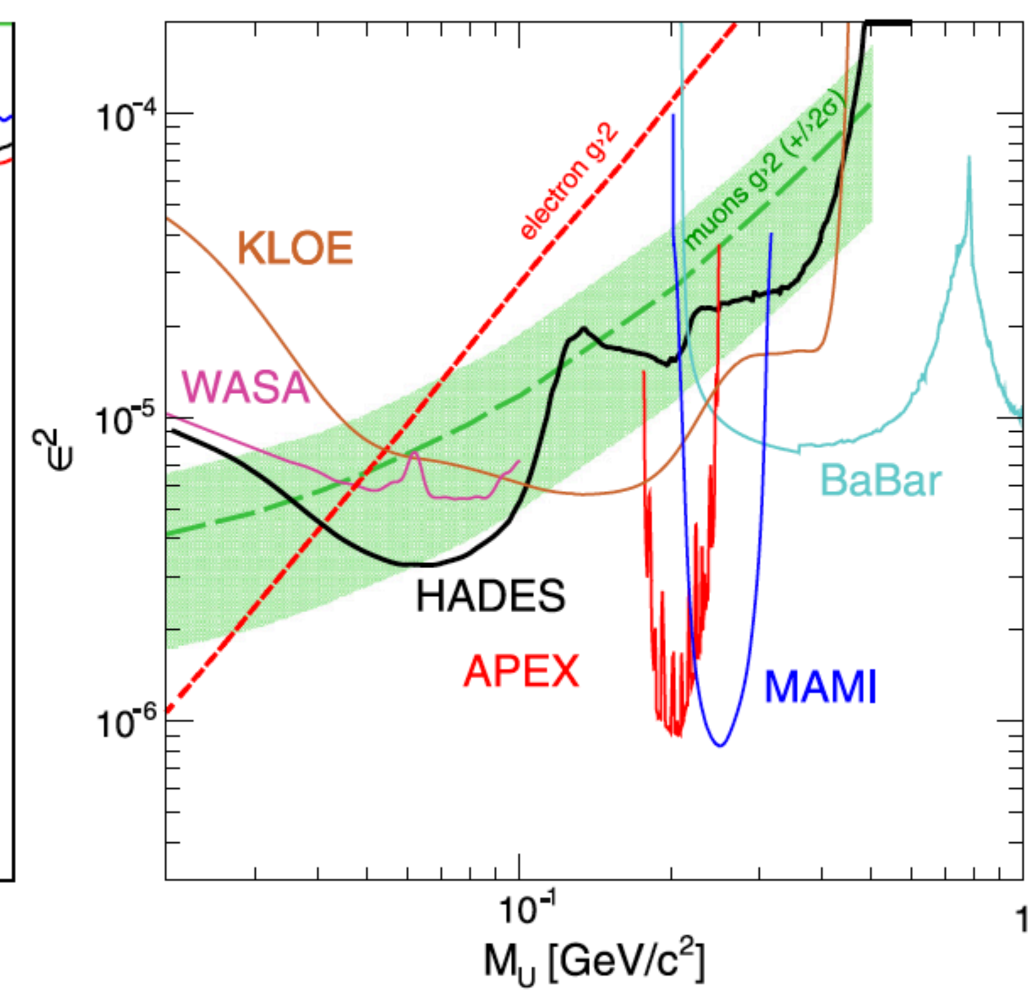
search for a peak structure on top of a smoothly varying continuum

$$\left.\begin{array}{l}\eta \to \gamma\, U \\ \pi^0 \to \gamma\, U\end{array}\right\} U \to e^+e^-$$

HADES data: PLB 731 (2014) 265 (cited > 150 times)







Br ($\eta \to e^+e^-$) < 2.3* 10^{-6} (90% CL); PDG entry 2016

Near-threshold strangeness production

The two pole structure of Λ(1405)

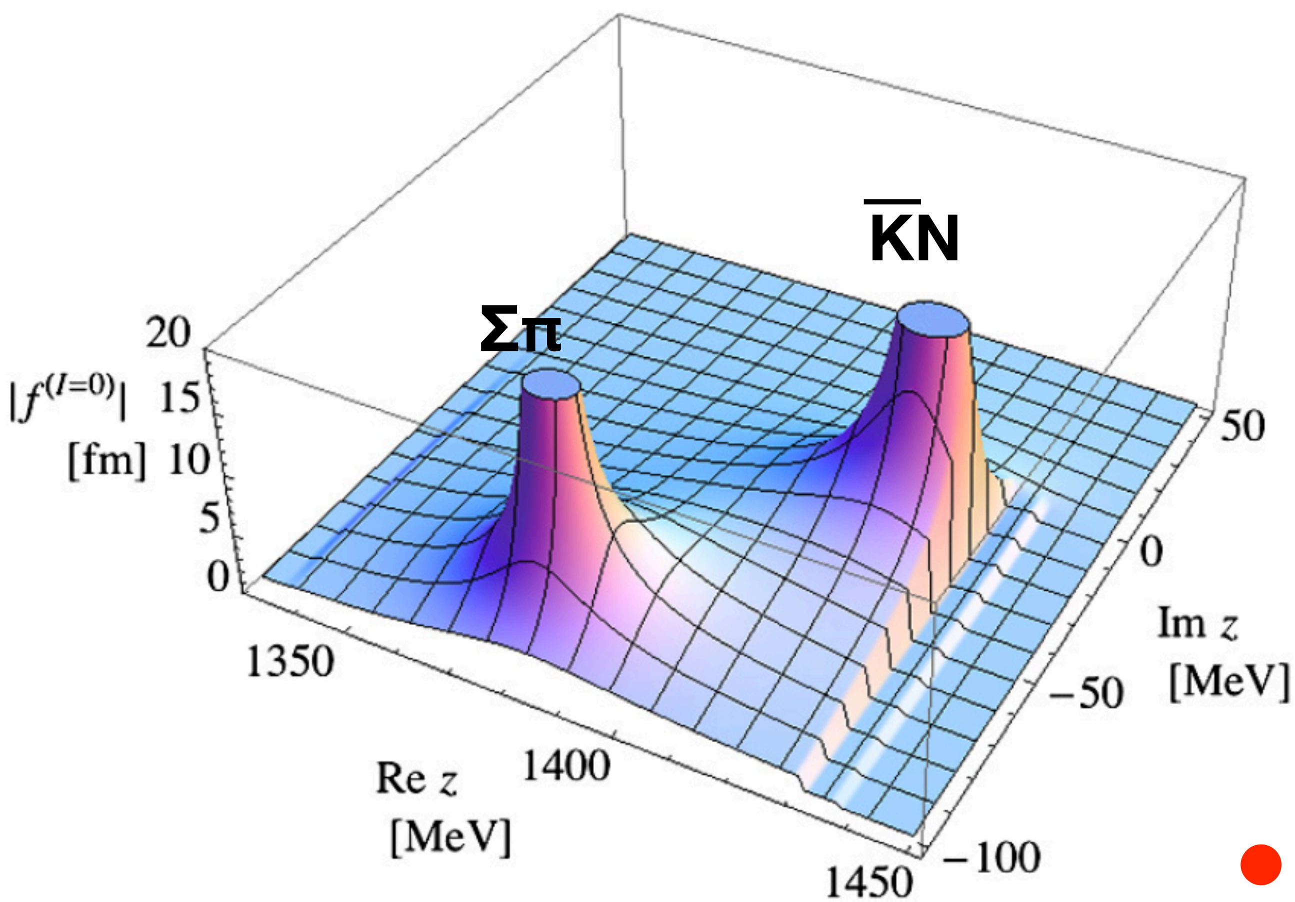
- Λ(1405)1/2$^-$ = nucleon resonance near the $\bar{K}$N threshold at 1432 MeV
- important for understanding $\bar{K}$N interaction
- dynamically generated resonance: superposition of $\bar{K}$N and Σπ molecular states

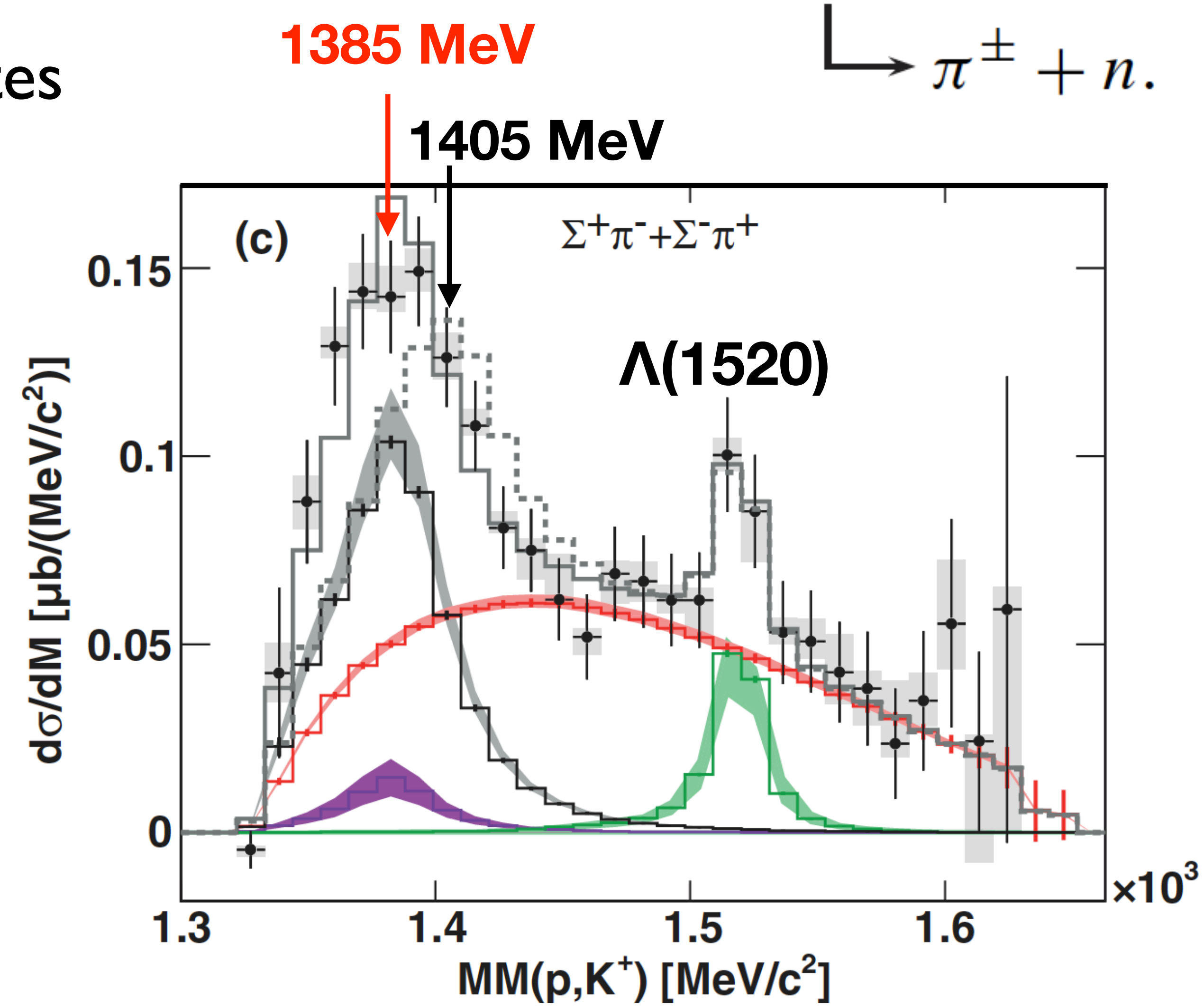
HADES data: PRC87 (2013) 025201

$$p + p \xrightarrow{3.5\text{ GeV}} \Lambda(1405) + K^+ + p$$
$$\hookrightarrow \Sigma^\pm + \pi^\mp$$
$$\hookrightarrow \pi^\pm + n.$$

two pole structure:

Kamiya et al.,NPA 954 (2016) 41

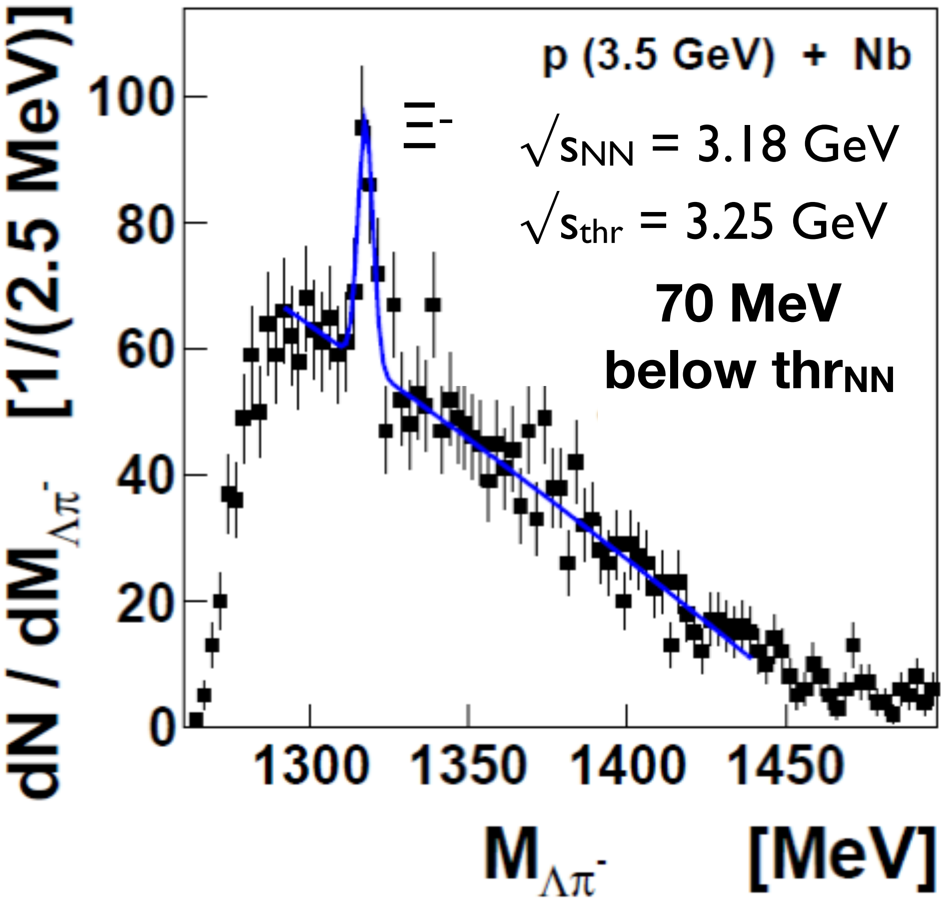




- **first confirmation of Σπ pole at 1385 MeV in p + p reaction at 3.5 GeV**

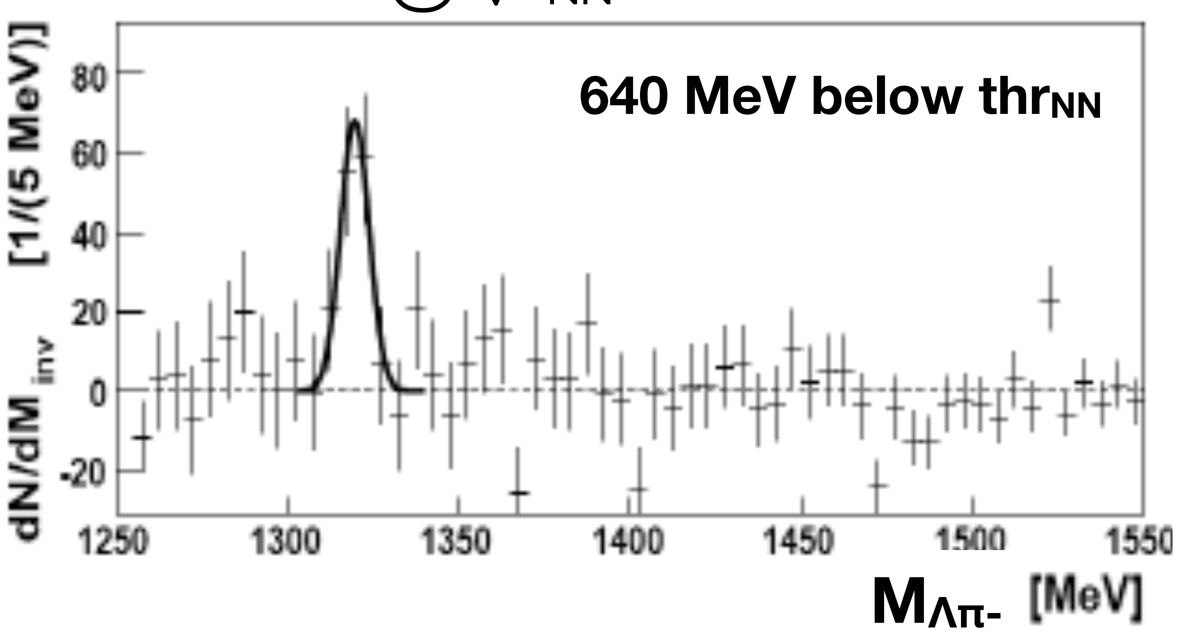
Enhanced Ξ⁻ (dss) production

HADES data: PRL 114 (2015) 212301



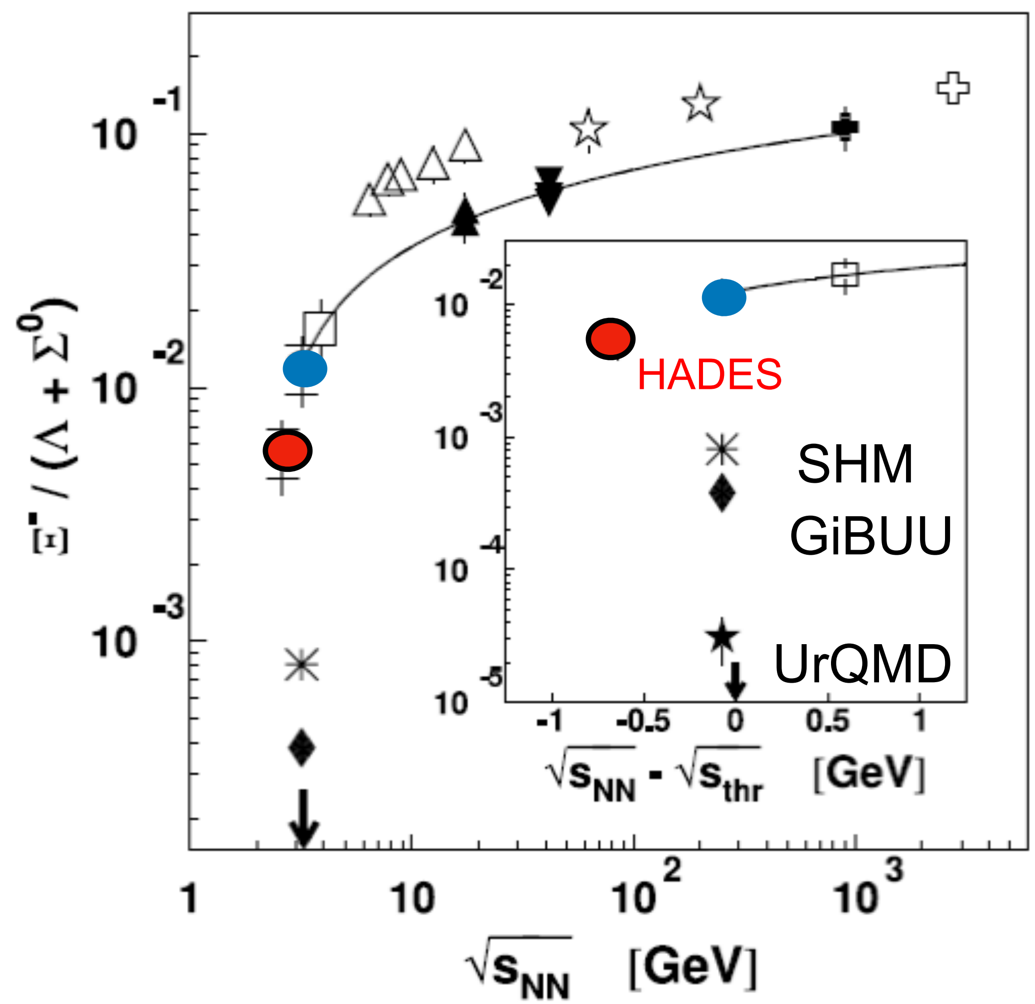
HADES data: PRL 103 (2009) 132301

Ar+KCl @ $\sqrt{s_{NN}}$ = 2.61 GeV



first observation of Ξ⁻ in p + A reaction

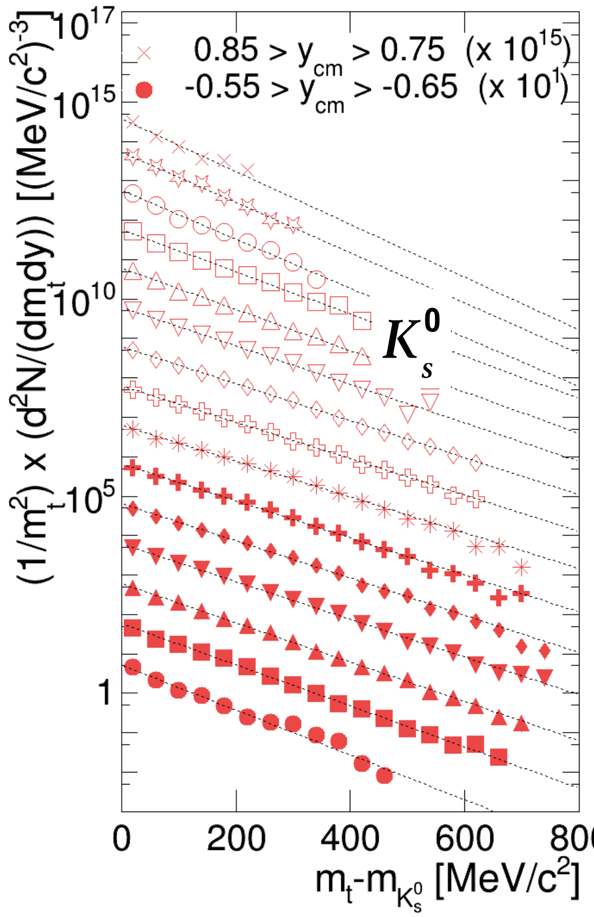
$$\Xi^- (1321) \rightarrow \Lambda + \pi^-$$
$$\hookrightarrow \Lambda \rightarrow p + \pi^-$$

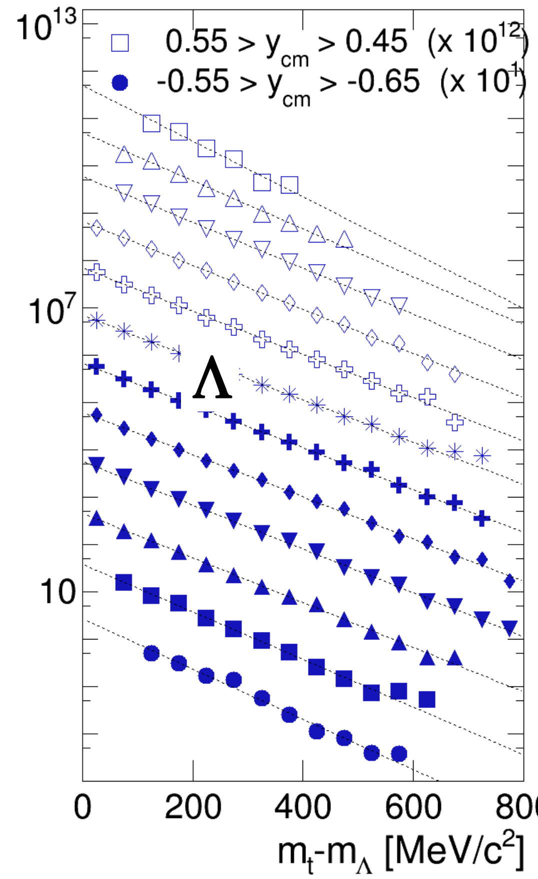


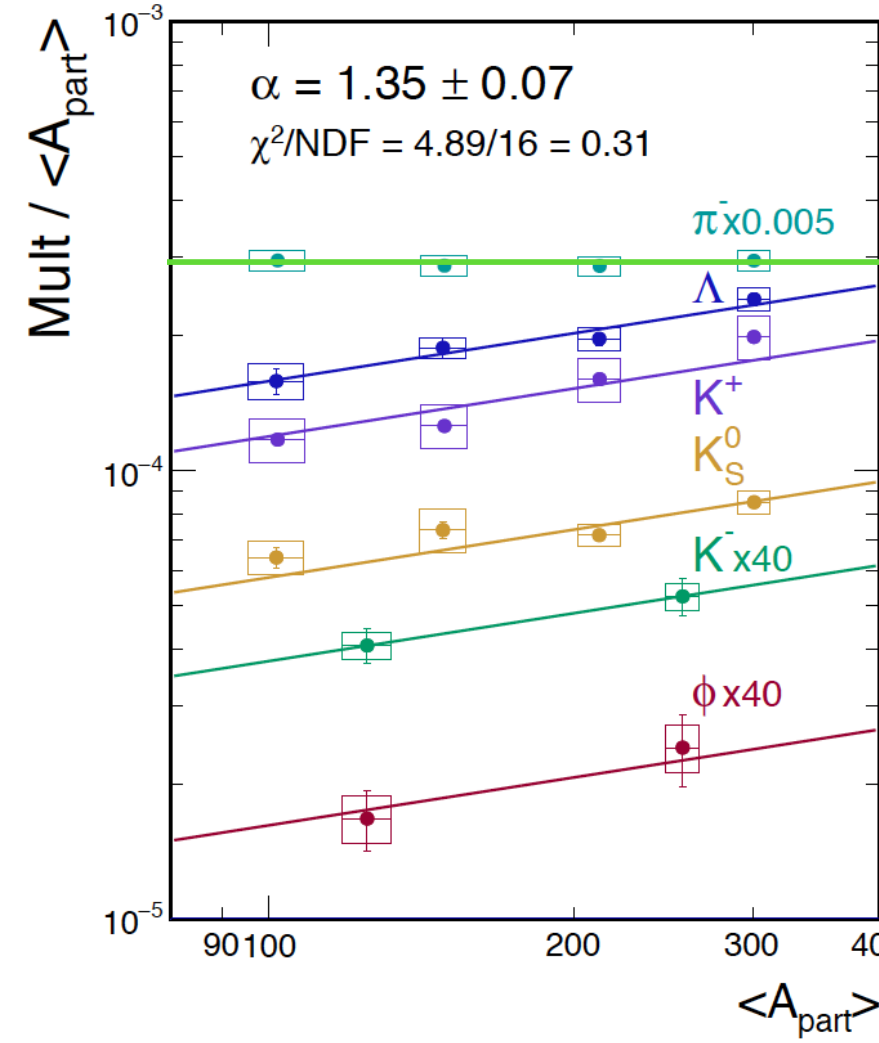
- strong enhancement above SHM, UrQMD, GiBUU
- strangeness production requires deep off-shell production or multi-step or multi-particle processes (production off correlated nucleons?)

Strangeness production: Au+Au @$\sqrt{s}$=2.4 GeV

HADES data: PLB 793 (2019) 457





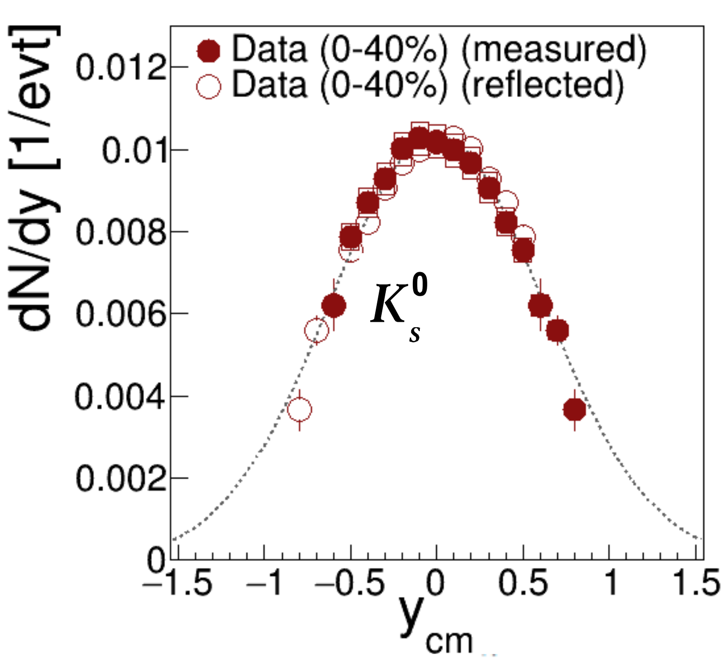


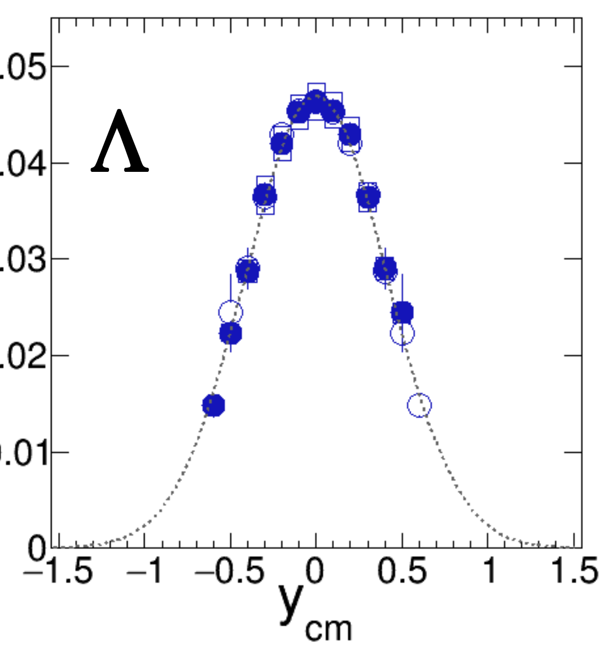
T_{eff} = (93±1±4) MeV

T_{eff} = (98±1±4) MeV

Mult/<A_{part}> ~ A_{part}^{α}

α = 1.35 ± 0.07





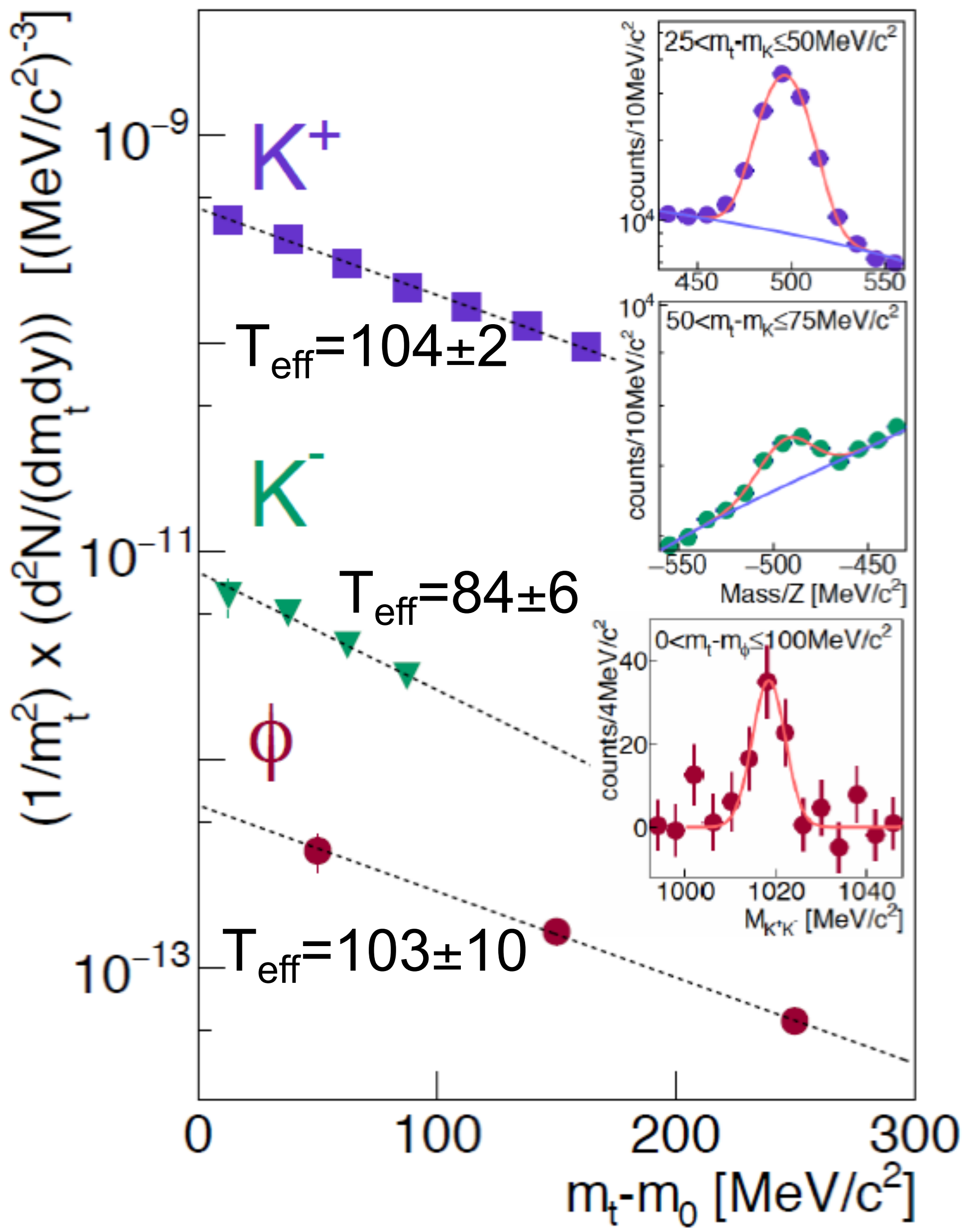
$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$$

- universal non-linear scaling with A_{part} for all particles with strangeness irrespective of the different production thresholds in NN collisions
- for pions linear increase with A_{part} !!

ϕ production at subthreshold energies: important source of K⁻

HADES data: PLB778 (2018) 403

Au+Au @$\sqrt{s_{NN}}$ = 2.4 GeV



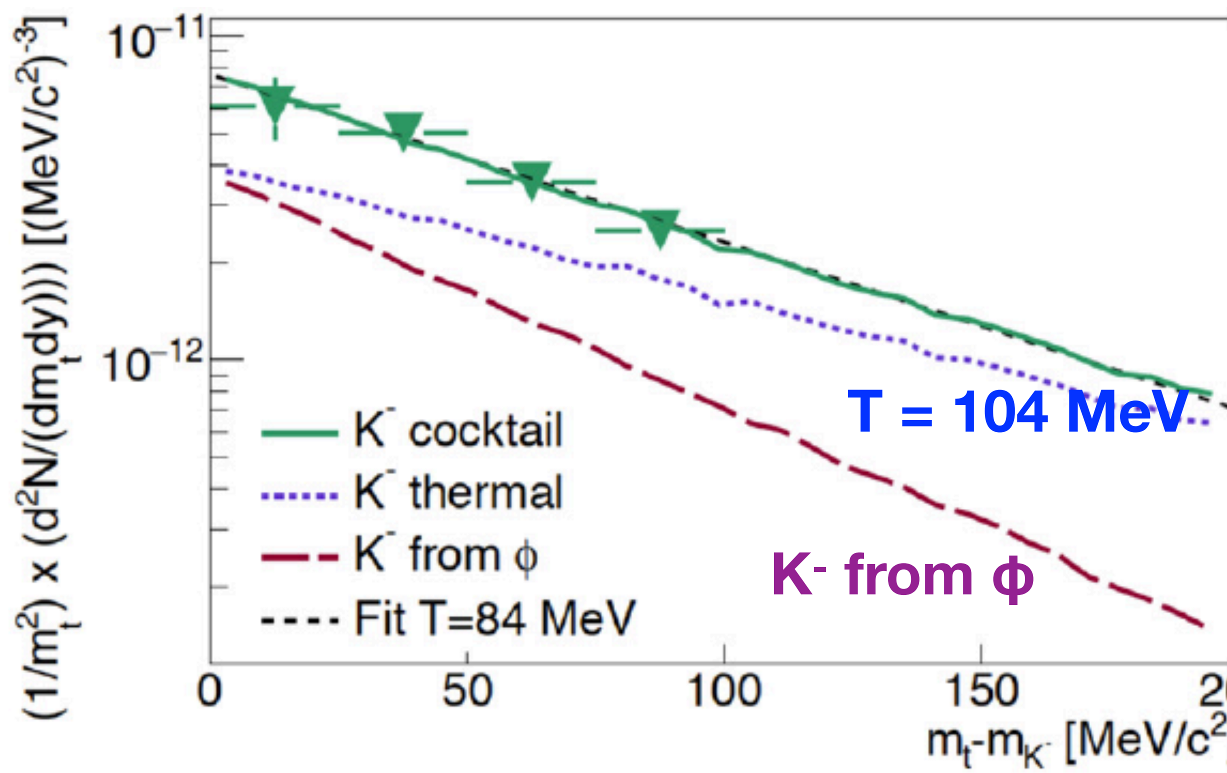
different slopes of K^+ and K^- spectra explained so far by later freeze-out of K^-

A. Förster et al. (**KaoS**) PRL91 (2003) 152301

sizeable contribution to low momentum K^- from $\Phi \rightarrow K^+ K^-$ decays to be taken into account !

Φ/K^- = 0.34±0.06 in Al+Al; Ni+Ni (**FOPI**)

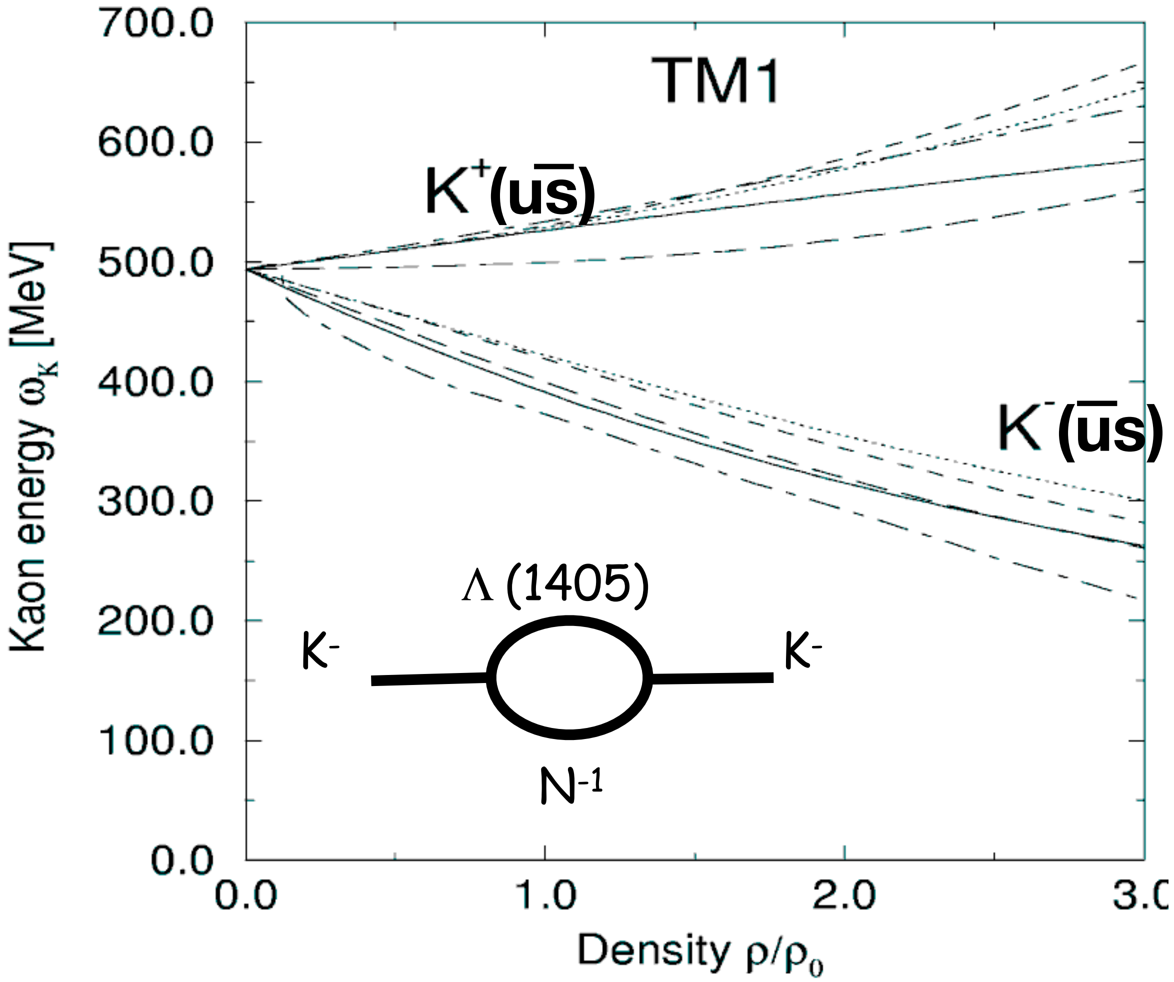
Φ/K^- = 0.52±0.16 in Au+Au (**HADES**)



- assuming $T_{therm}(K^-) = T(K^+)$, 26% contribution from Φ-decay reproduces experimental spectrum, → no difference in freeze out times for K^+ and K^-

in-medium effects in the strangeness sector

J. Schaffner-Bielich et al., NPA625 (1997) 325



exp. evidence for repulsive K^0, K^+ - nucleus potential and attractive K^- - nucleus potential by analysing meson momentum spectra

ANKE: EPJA 22 (2004) 301
FOPI: PRL 102 (2009)182501
KaoS: PRL96 (2006) 072301

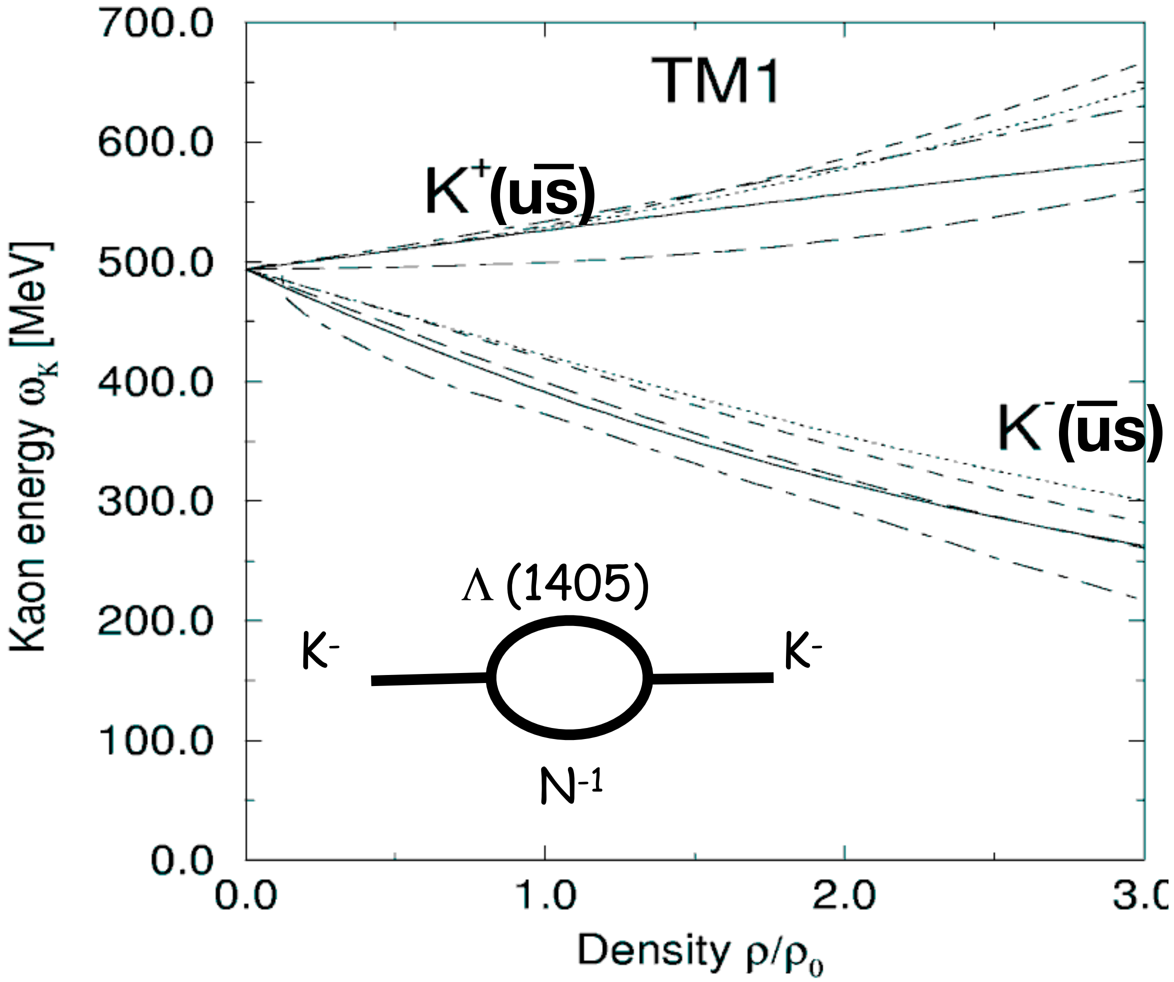
} V_{K+A} **= 15-25 MeV repulsive**

KaoS: PRL96 (2006) 072301

V_{K-A} **= - 80 MeV attractive**

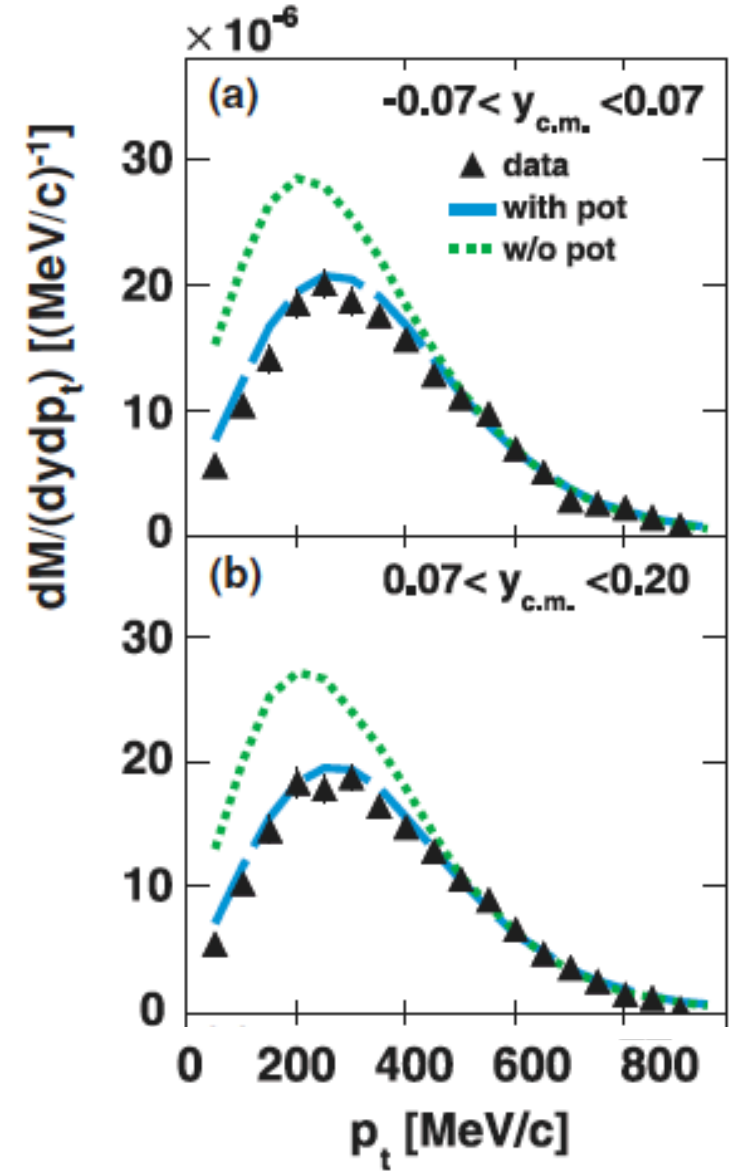
in-medium effects in the strangeness sector

J. Schaffner-Bielich et al., NPA625 (1997) 325



HADES data: PRC 82 (2010) 044907

Ar+KCl @ 1.76 AGeV



$K^0(d\bar{s})$

exp. evidence for repulsive K^0, K^+ - nucleus potential and attractive K^- - nucleus potential by analysing meson momentum spectra

ANKE: EPJA 22 (2004) 301
FOPI: PRL 102 (2009)182501
KaoS: PRL96 (2006) 072301

} **V_{K+A} = 15-25 MeV repulsive**

KaoS: PRL96 (2006) 072301 — **V_{K-A} = - 80 MeV attractive**

$V_{K0A} \approx$ 40 MeV • ρ/ρ_0

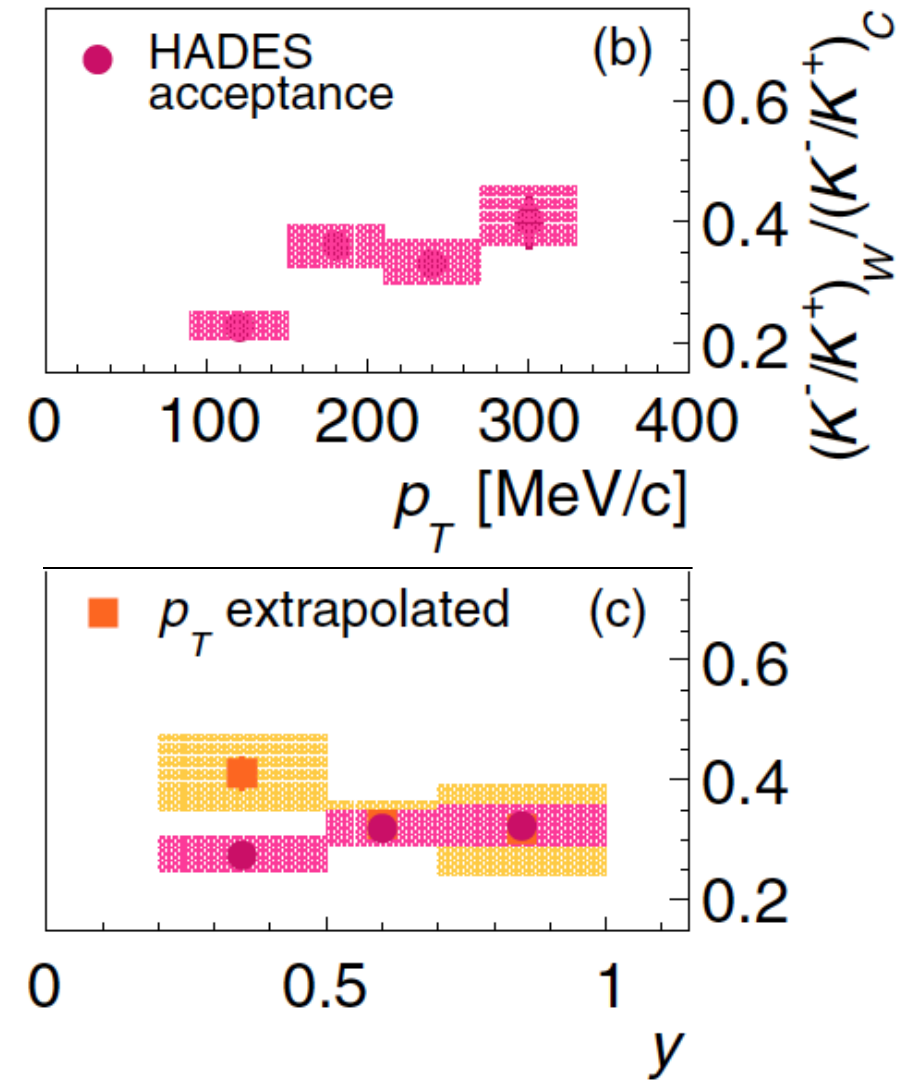
confirmed for p+Nb in
HADES: PRC 90 (2014) 054906

K^- and ϕ absorption

K^+: very low absorption in nuclei

K^- atoms:

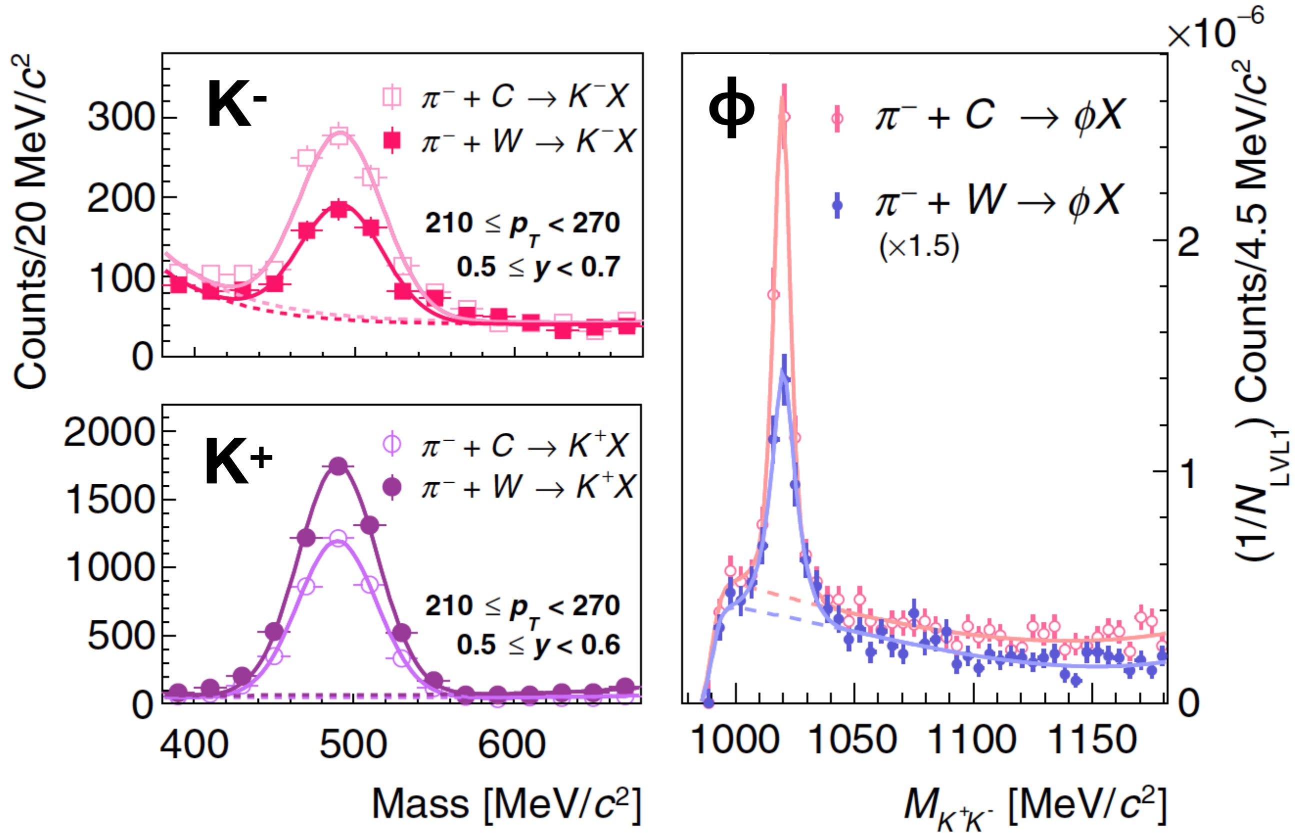
kaonic hydrogen (SIDDHARTA) } K^- strongly absorbed in nuclear matter



HADES data: PRL 123 (2019) 022002

π^- + C,W 1.7 GeV/c

simultaneous measurement of K^+, K^-, and Φ



$(K^-/K^+)_W/(K^-/K^+)_c = 0.319 \pm 0.009$(stat) compared to 0.93 without absorption

→ sizeable K^- absorption in nuclei

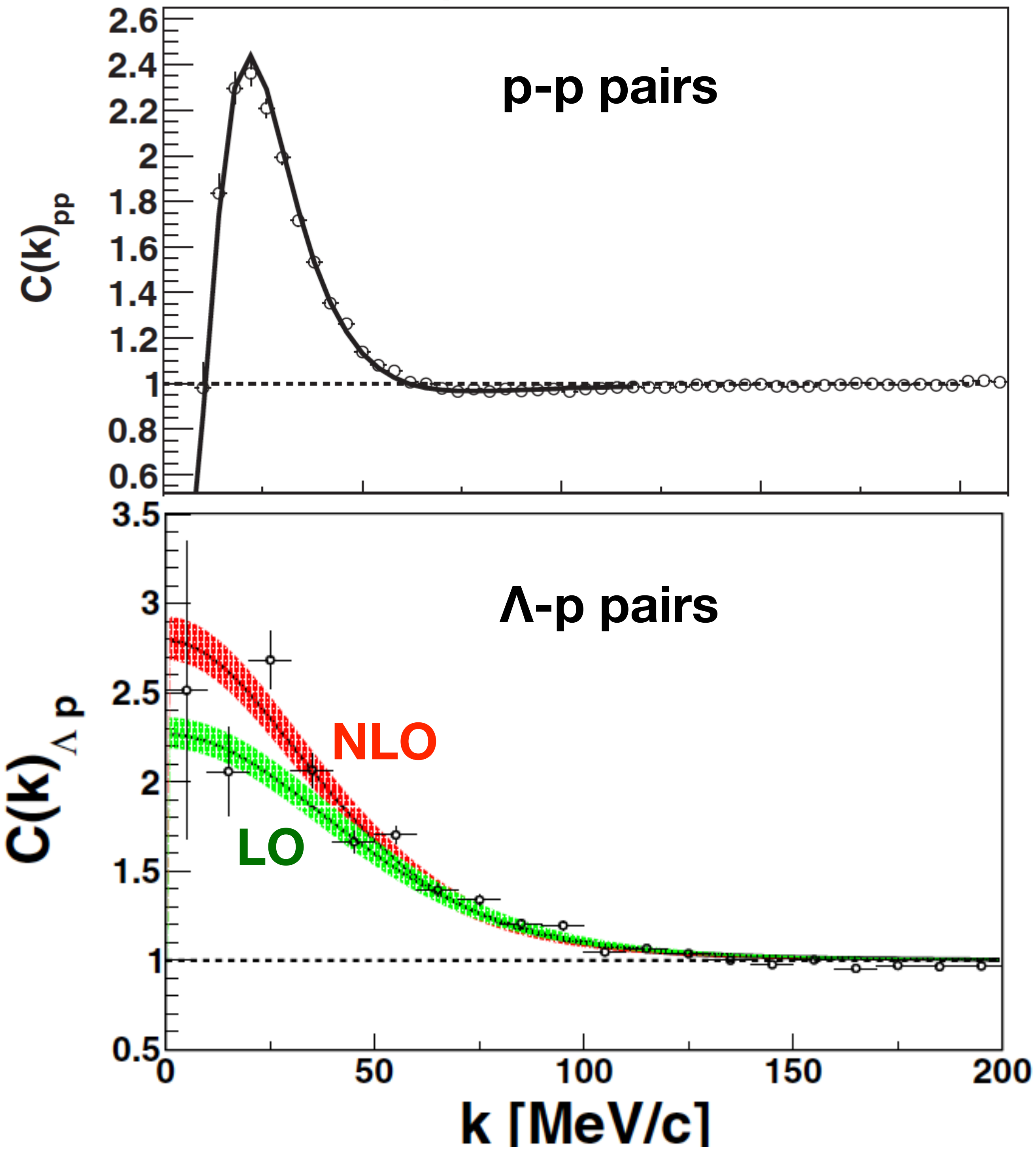
$(\Phi/K^-)_w = 0.63 \pm 0.11$(stat) $\approx (\Phi/K^-)_c = 0.55 \pm 0.04$(stat) → sizeable Φ absorption in nuclei

Femtoscopy: two body particle correlations

two particle correlation function

HADES data: PRC 94 (2016) 025201

p+Nb @$\sqrt{s_{NN}}$ = 3.18 GeV



short range correlations:

- insight into short range part of the nucleon-nucleon interaction
- Λ-p scattering parameters

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1)P(\mathbf{p}_2)}$$

size of particle emitting source:

source size of p-p pairs:

r_{pp}=(2.02±0.01(stat)±0.12(sys)) fm

source size of Λ-p pairs:

$r_{p\Lambda}$=1.62±0.02(stat)±0.19(sys) fm

information on Λ-p interaction:

comparison of Λ-p correlation function with χEFT calculations for different scattering parameters

collective phenomena in heavy-ion collisions:

Particle flow patterns

particle flow patterns

collective expansion of the fireball produces correlated emission of particles;

access to nuclear equation-of-state (EOS)

in perfectly central collisions isotropic expansion: radial flow

less central collisions: azimuthal anisotropy;

Fourier decomposition of transverse momentum / rapidity spectra

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\{1 + \sum_n 2v_n cos\left[n(\phi - \Psi_{RP})\right]\}$$

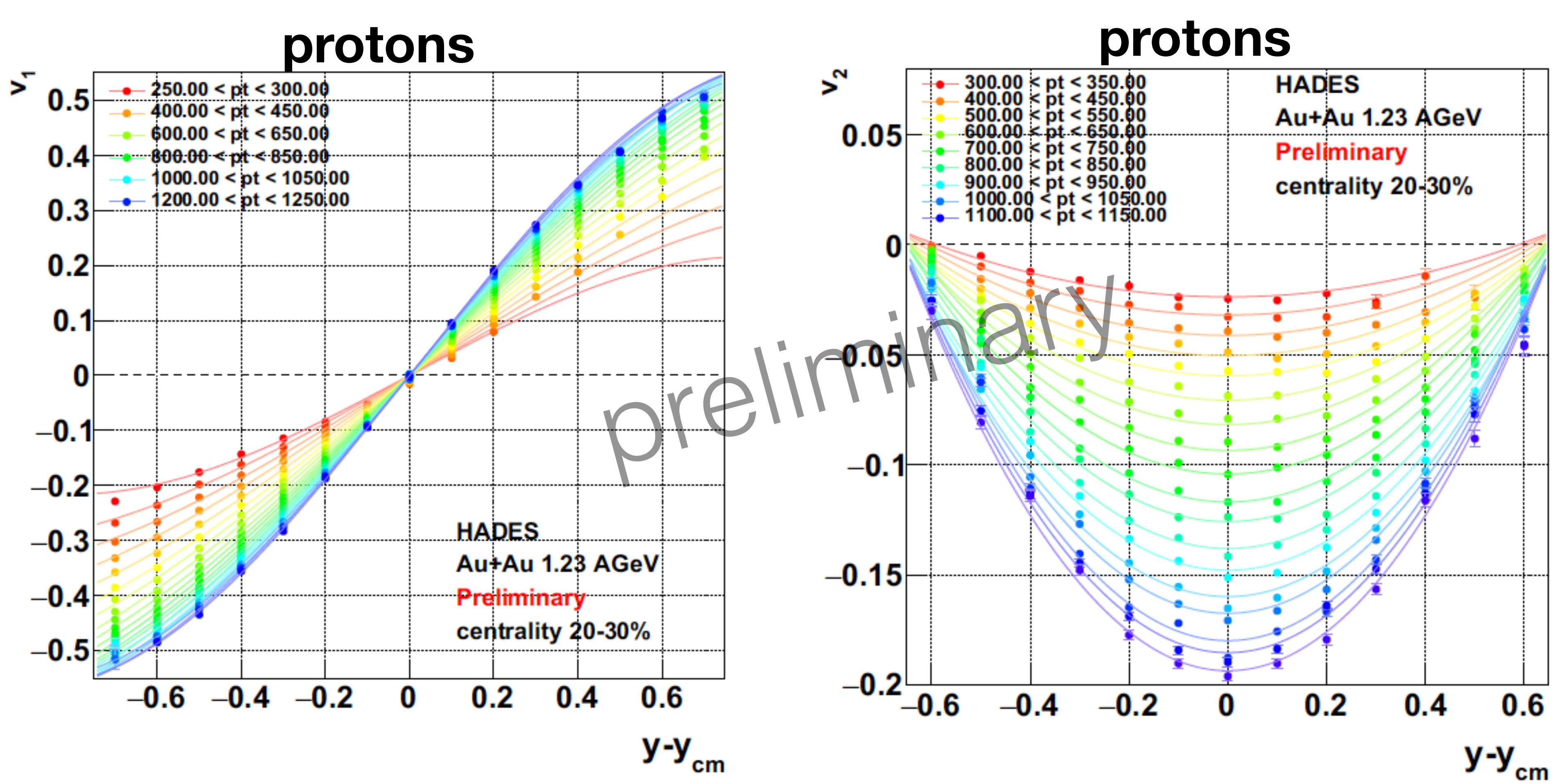
v_1 directed flow

v_2: elliptic flow

v_3: triangular flow

Au+Au 1.23 AGeV; semi central collisions: 20-30%, b = 6.6 - 8.8 fm

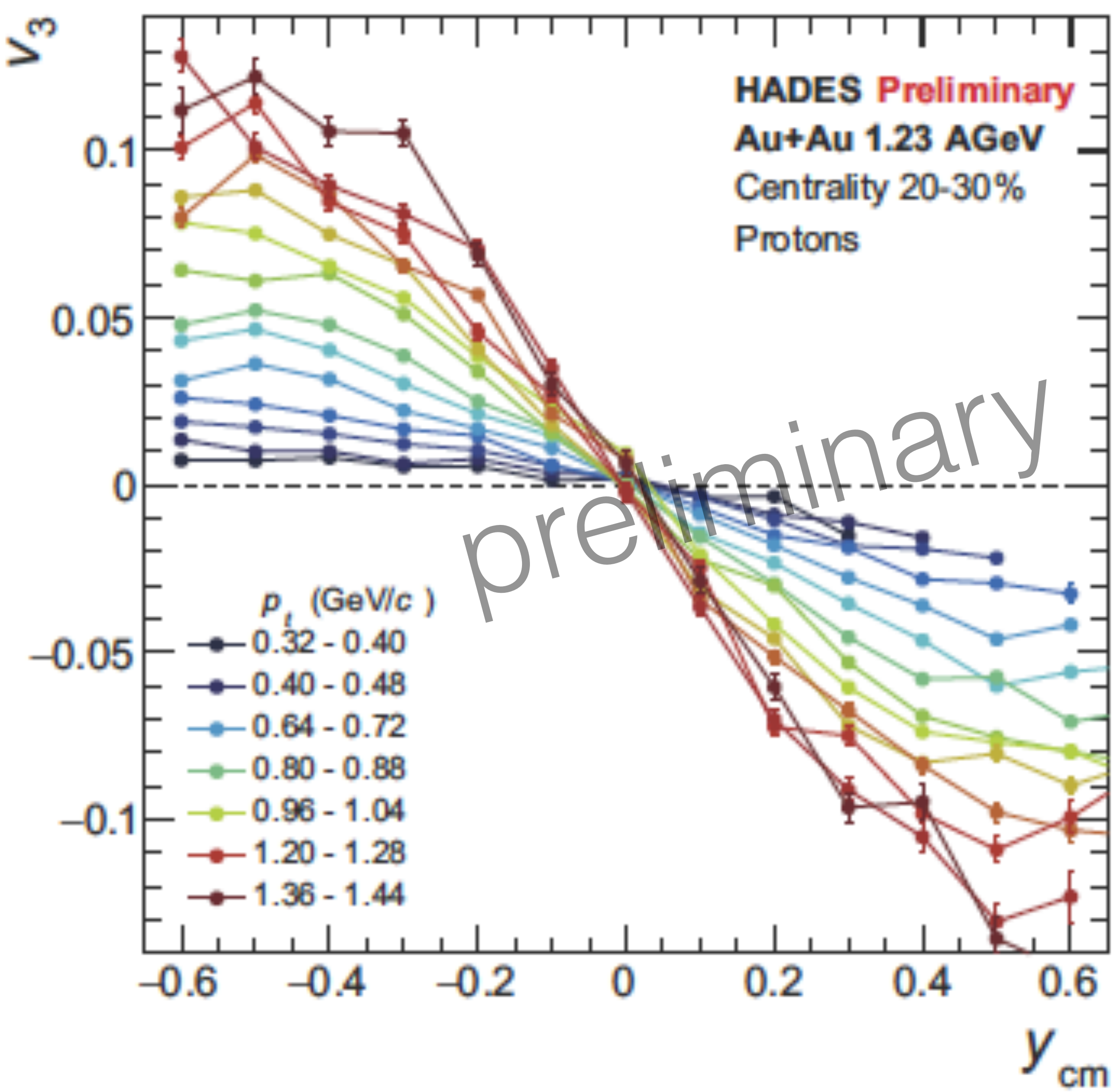
HADES data: B. Kardan NPA 967 (2017) 812



particle flow patterns

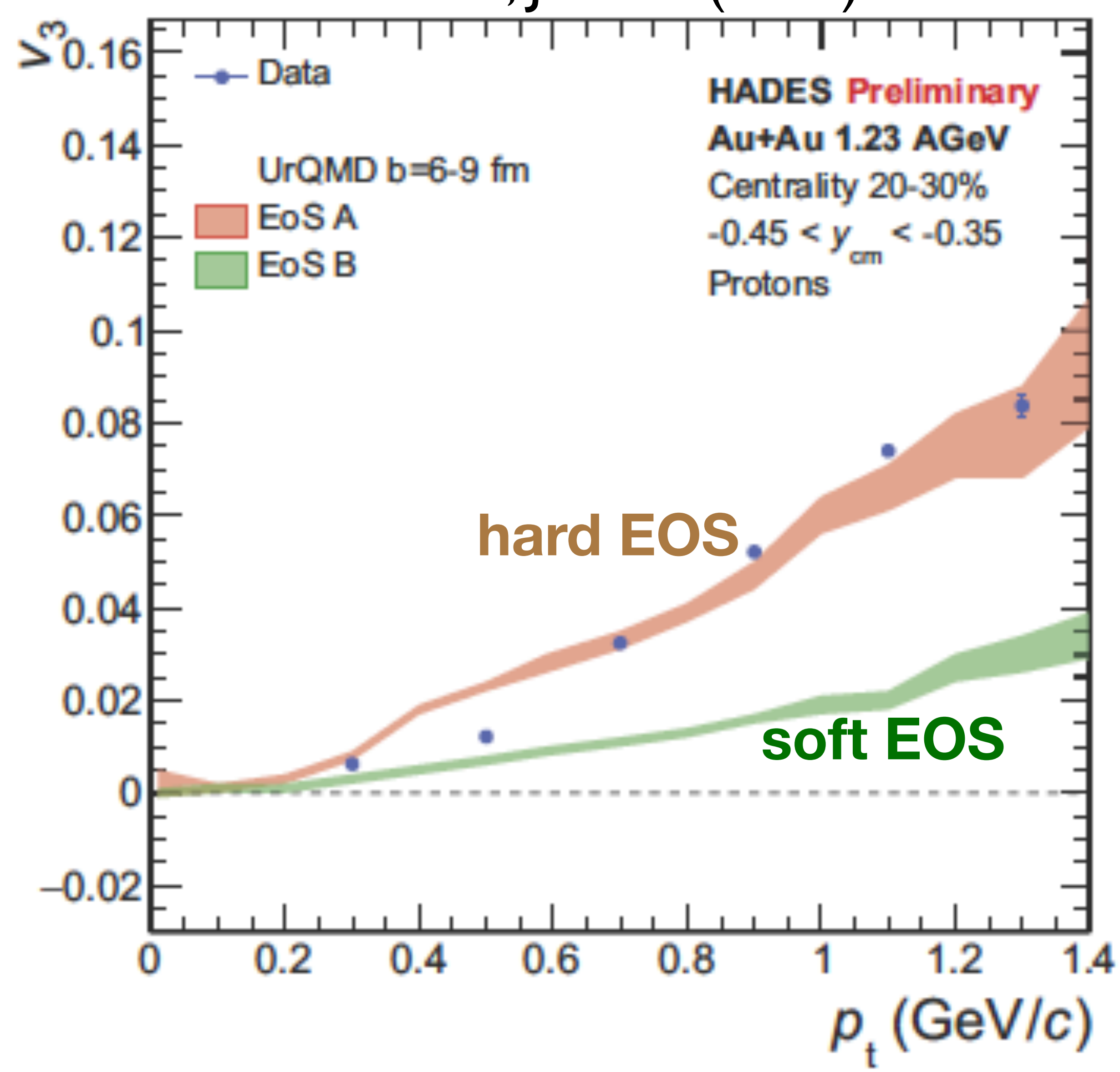
HADES data: B. Kardan NPA 982 (2019) 431

triangular flow $v_3(y_{cm})$ for protons



triangular flow $v_3(p_t)$ for protons

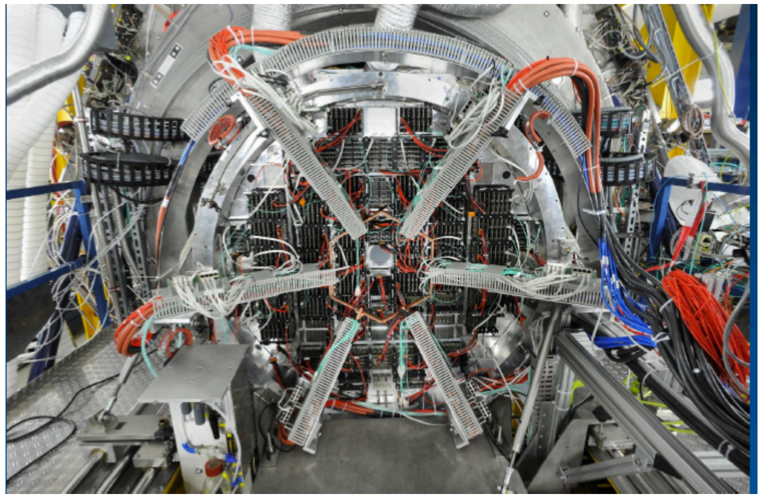
Hillmann et al., JPG 45 (2018) 085101



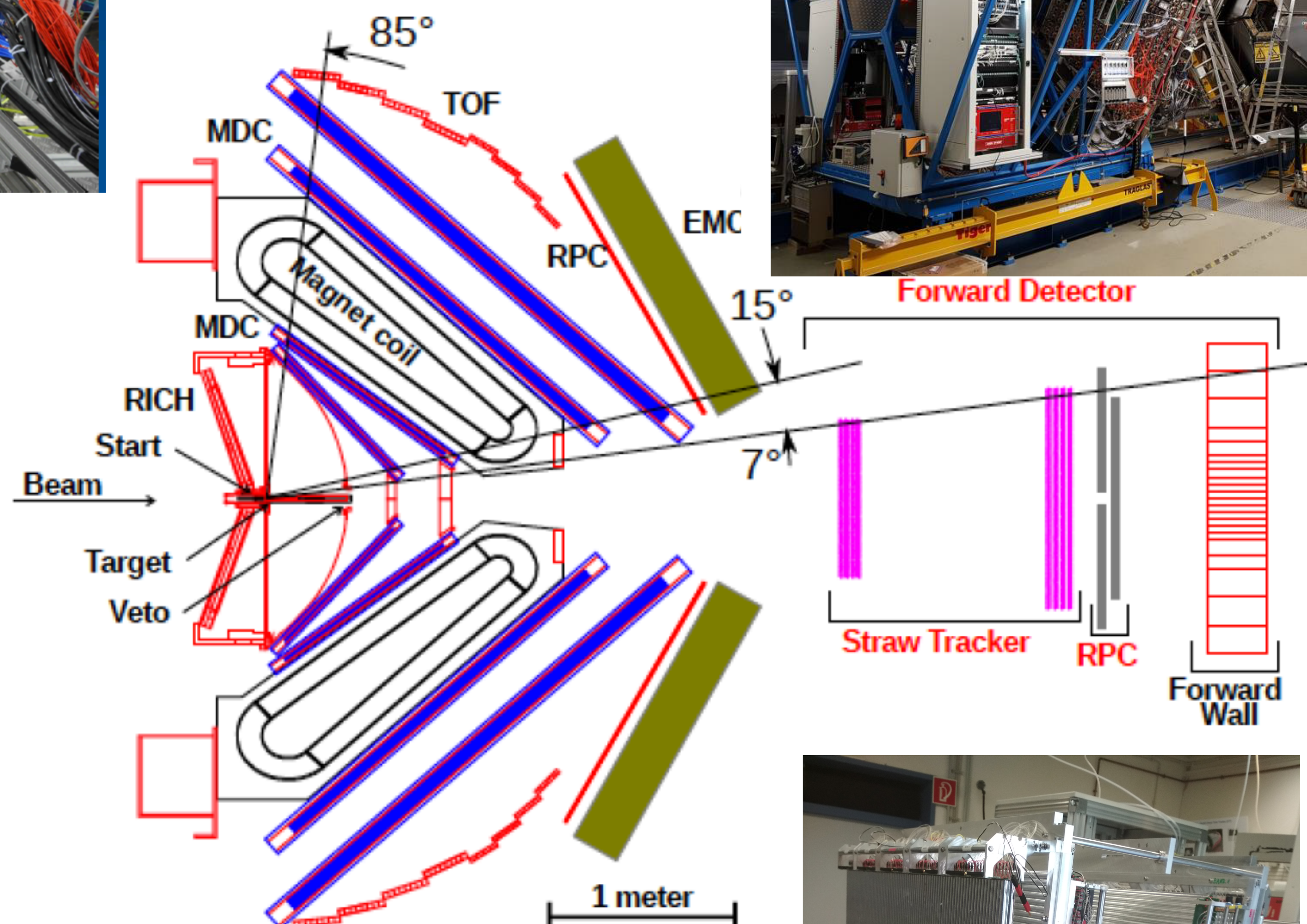
high precision data on particle flow will further constrain nuclear equation of state

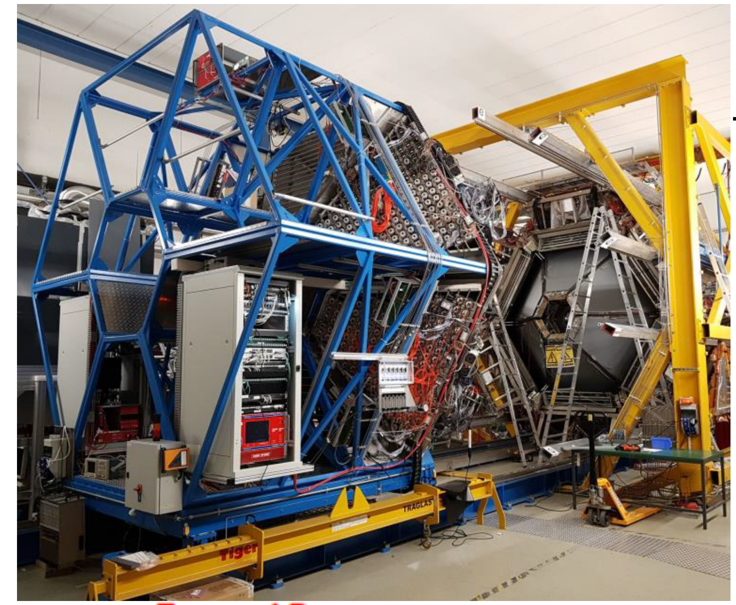
future perspectives

HADES upgrade



RICH PMT readout
gain x5 in e± eff.
coll. with CBM@FAIR
used in Ag + Ag 2019





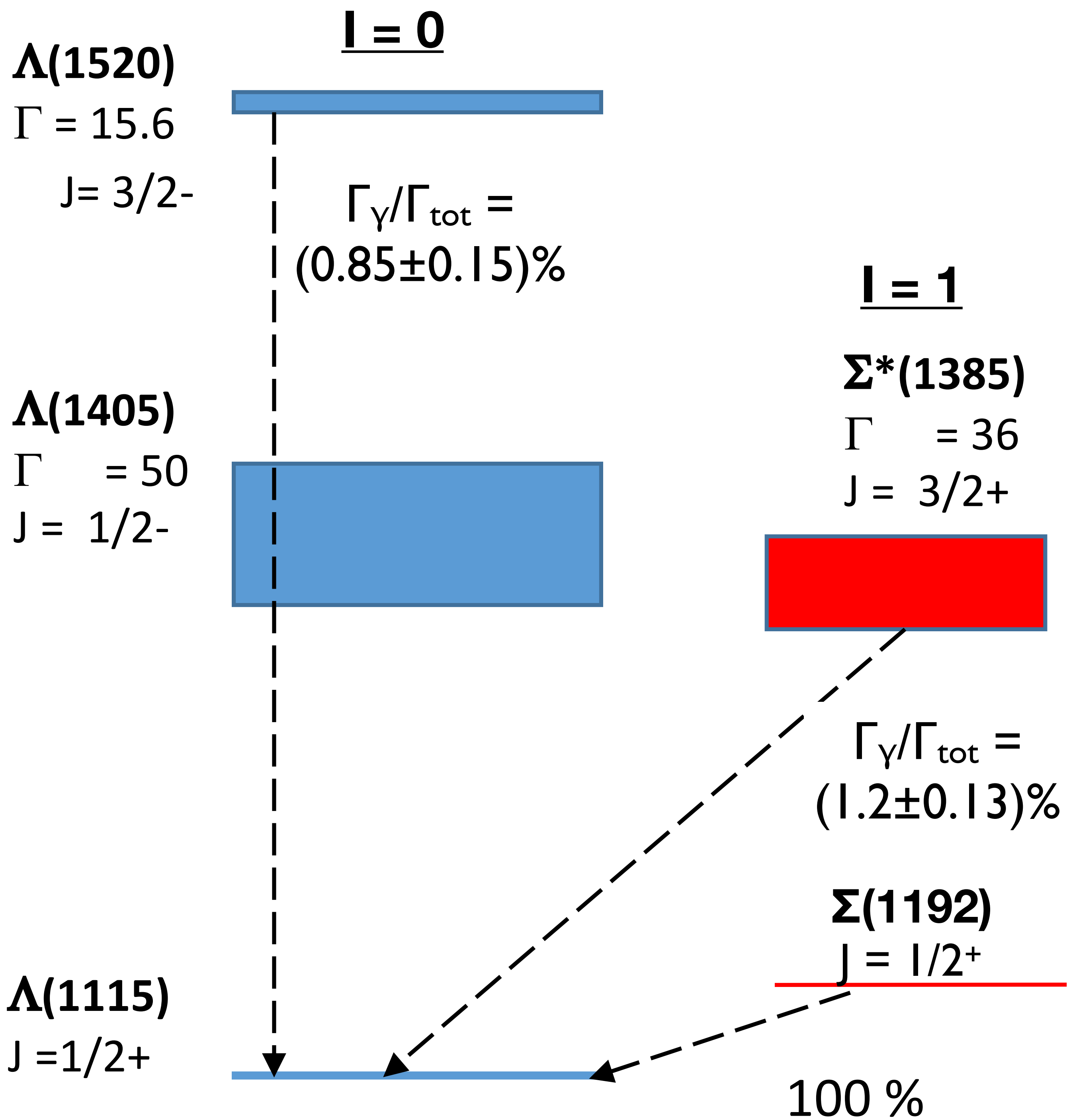
ECAL (Pb glass)
for γ, e±
ΔE/E≈5%
used in
Ag + Ag 2019

Forward detector
straws + RPC TOF
0.5^0 - 6.5^0
collab. with
PANDA@FAIR
σ(x) ≈150 μm
σ(TOF) ≈ 70 ps
to be installed 2020

data acquisition
upgrade to 200 kHz data rate

Hyperon radiative and Dalitz decays

FAIR phase-0 program



using additional information from **forward detector** and the **electromagnetic calorimeter** to reconstruct hyperon decays

$p + p = \Lambda(1520) + p + K^{+}$ @4.5 GeV

↓

$\Lambda(1115) + \gamma\ (e^{+}e^{-})$

↓

$p\ \pi^{-}$

- extend measurements of electromagnetic form factors to strange baryon resonances

- study reaction mechanism for Ξ production

$p + p \rightarrow \Xi^{-} K^{+} K^{+} p \rightarrow \Lambda\ \pi^{-} K^{+} K^{+} p$ @ 4.5 GeV

Signatures for chiral symmetry restoration

χ- partners: $\rho(770)$ (vector $J^{\pi}=1^{-}$) and $a_1(1260)$ (axial-vector $J^{\pi}=1^{+}$)

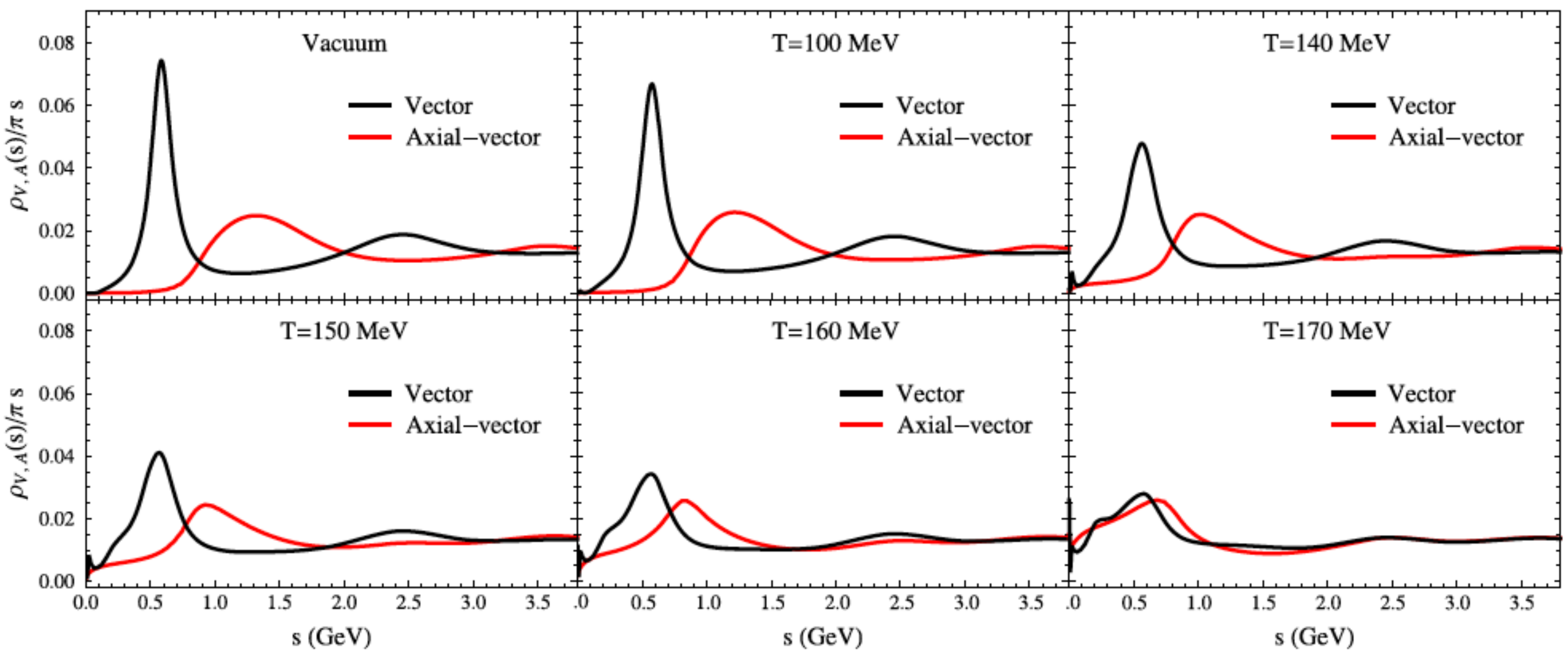
χ- symmetry restoration: spectral functions of chiral partners become degenerate:

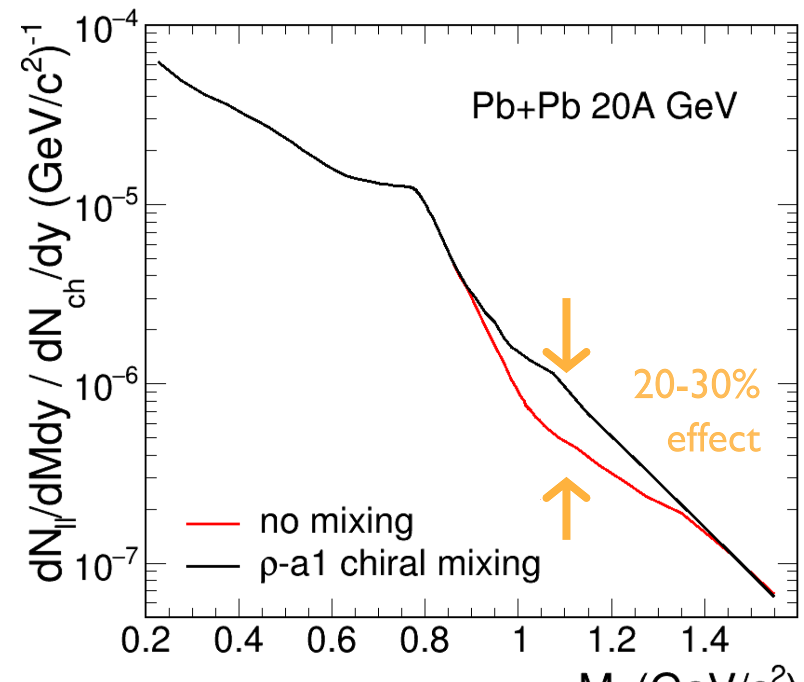
Weinberg sum rule: $\int ds(\rho_v - \rho_a) = - m_q \langle \bar{q}q \rangle$

ρ mass stays almost constant while a_1 shows significant mass shift towards the ρ accompanied with melting of the resonances when approaching χ symmetry restoration

C. Jung et al., PRD 95 (2017) 036020

P. M. Hohler and R. Rapp PLB 731 (2014) 103

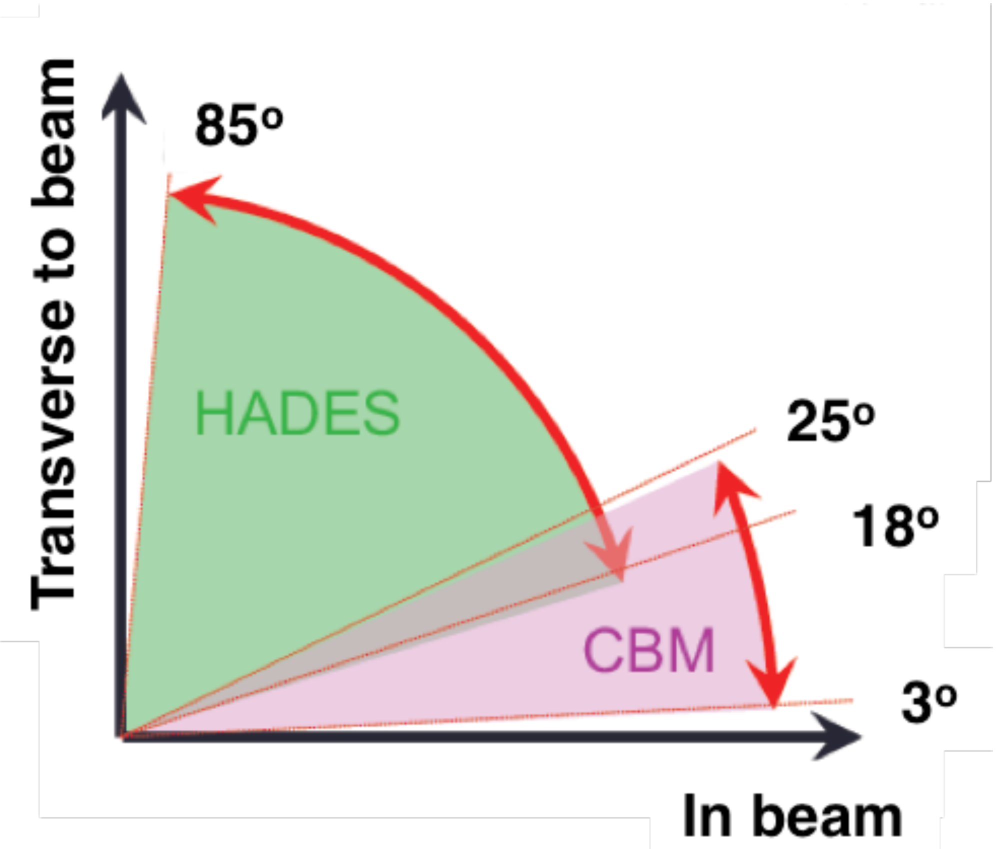


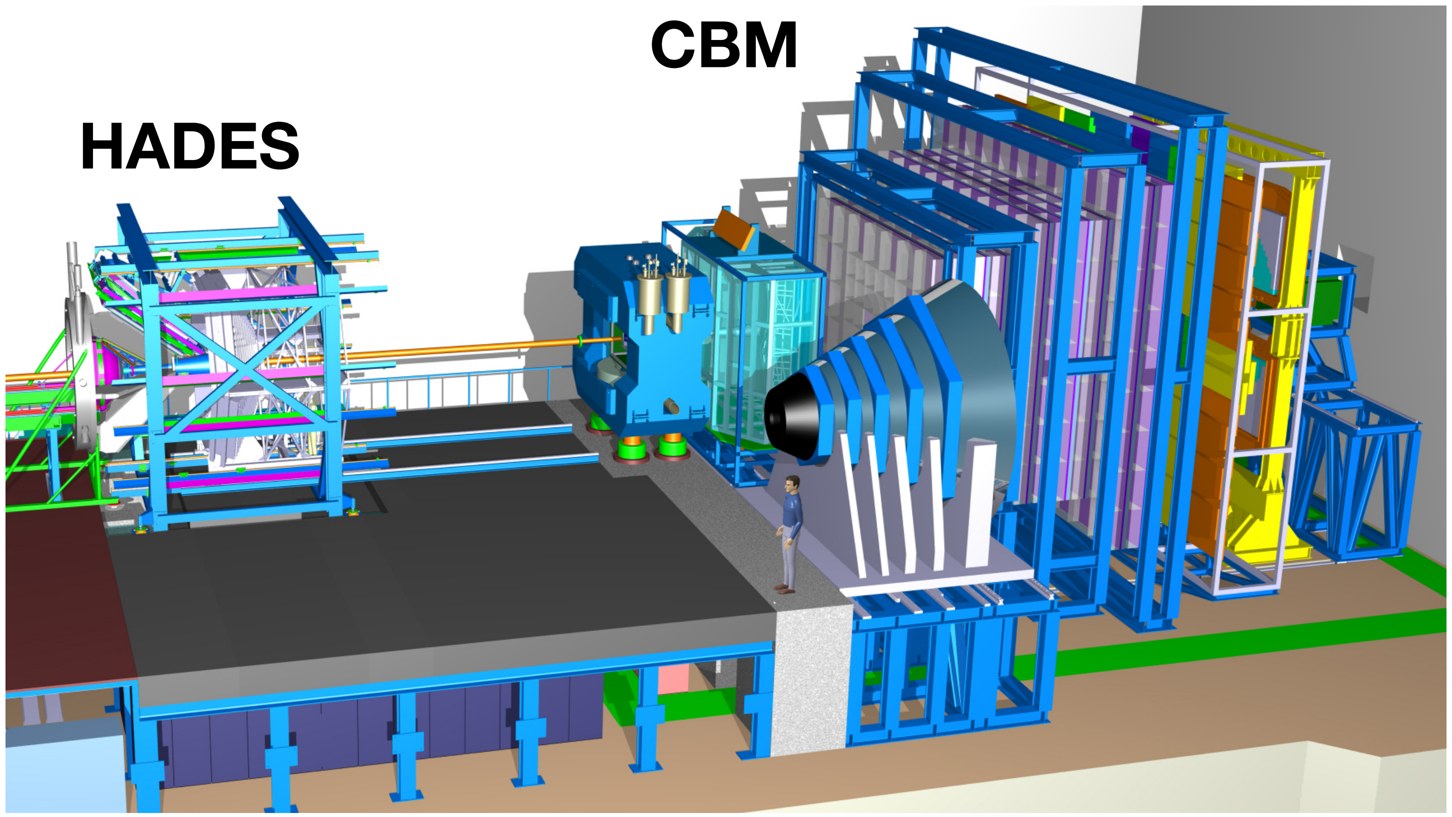


Calculations R. Rapp

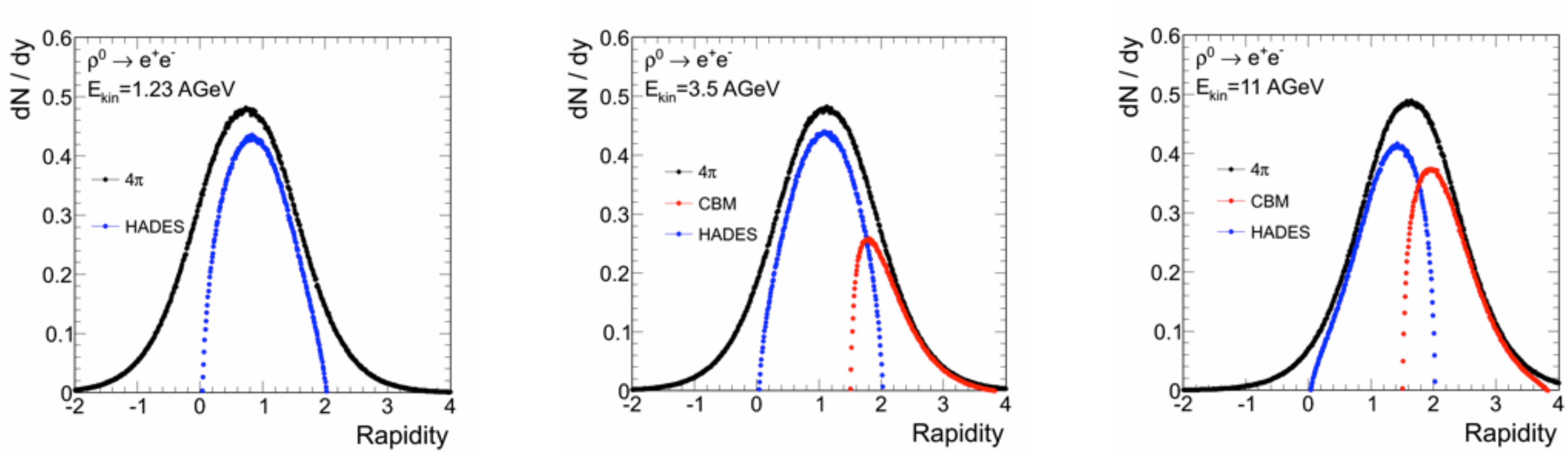
degeneration of ρ and a_1 spectral functions leads to an observable modification of the M_{ee} invariant mass spectrum near 1.1 GeV

HADES in combination with CBM





good rapidity coverage for $\rho \rightarrow e^+ e^-$ over full incident energy range



Summary: highlights

broad physics program with elementary reactions and heavy-ion collisons

dileptons:

- electromagnetic form factors of baryon resonances and hyperons; evidence for vector meson dominance in baryonic transitions
- in-medium modifications of vector mesons in cold nuclear matter at low momenta
- melting of ρ meson in hot and compressed matter in SIS energy regime; evidence for thermal radiation from fireball

hadronic final states:

- 2-pole structure of Λ(1405)
- exceptionally high yield of Ξ^- in p+A and A+A
- particle yields consistent with statistical hadron models
- strange hadron nucleus interaction
- particle flow in A+A: $v_1, v_2, v_3 \rightarrow$ equation-of-state of nuclear matter

The HADES team

XXXVII collaboration meeting , Cracow, Sept. 23-27, 2019

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Joachim Stroth

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