Institut für
Theoretische Physik I

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Dilepton production within GiBUU microscopic transport model

Alexei Larionov, Ulrich Mosel, Lorenz von Smekal

Institut für Theoretische Physik, Universität Gießen, D-35392 Gießen, Germany

Physics programme for the first stage of the NICA SPD experiment, 5-6.10.2020

Plan:

- Motivation: dileptons as a probe of hadron modifications in nuclear matter.

- Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model:
  relativistic mean field, collision term, dilepton (e^+e^-) production channels.

- Spectral function of ρ-meson in nuclear matter. Collisional broadening.

- Heavy ion collísions at SIS18 energies (1-2 A GeV): comparison with HADES data
  on e^+e^- production. Deuteron puzzle.

- Opportunities at NICA-SPD: dilepton production, proton and pion production,
  hadron formation effect.

- Conclusions.

Based on **AL, U. Mosel, L. von Smekal, arXiv:2009.11702**

Motivation

- Vector mesons (ρ,ω,φ) may experience spectral changes in nuclear matter: mass lowering due to disappearance of the scalar $\bar{q}q$ condensate with nuclear density (G.E. Brown, M. Rho, PRL 66, 2720 (1991); T. Hatsuda, S.H. Lee, PRC 46, R34 (1992)), and collisional broadening.

- Direct decays to dileptons $V \rightarrow l^+l^-$ allow to study the spectral function of vector mesons in hadronic medium. Lepton momentum is almost undistorted by interactions with hadrons.

- Heavy-ion collision (HIC) experiments at CERN/SPS (cf. D. Adamova et al., PRL 91, 042301 (2003); G. Agakishiev et al., EPJC 41, 475 (2005)) did not allow to make a clear distinction between in-medium mass shift and collisional broadening of ρ. Why ? Educated guess: too quickly evolving system. No time for mesons to change their spectral properties.

- HADES experiment at SIS18 (see P. Salabura and J. Stroth, 2020, arXiv:2005.14589 for the most recent overview) is designed to study e^+e^- signals from HIC at moderate energies of 1-2 A GeV. Here the evolution is relatively slow and in-medium modifications are more probable.

GiBUU model

- solves the coupled system of kinetic equations for the baryons (N,N*,Δ,Λ,Σ,…), corresponding antibaryons ($\overline{N}$,$\overline{N^*}$,$\overline{\Delta}$,$\overline{\Lambda}$,$\overline{\Sigma}$,…), and mesons (π,K,...)

- initializations for the lepton-, photon-, hadron-, and heavy-ion-induced reactions on nuclei

Open source code in Fortran 2003 downloadable from:

https://gibuu.hepforge.org/trac/wiki

Details of GiBUU: ***O. Buss et al., Phys. Rep. 512, 1 (2012).***

Kinetic equation with relativistic mean fields

Distribution function in phase space (***r***,***p****)

Number of sort "j" particles = $\int \frac{g_s^j d^3r d^3p^*}{(2\pi)^3} f_j^*(x, \mathbf{p}^*)$

$$(p_0^*)^{-1}\left[p_\mu^* \partial^\mu + (p_\mu^* \mathcal{F}_j^{\alpha\mu} + m_j^* \partial^\alpha m_j^*)\frac{\partial}{\partial p^{*\alpha}}\right] f_j^*(x, \mathbf{p}^*) = \underbrace{I_j[\{f^*\}]}_{\text{Collision term}} , \qquad (*)$$

$\mu = 0,1,2,3, \quad \alpha = 1,2,3, \quad j = N, \bar{N}, \Delta, \bar{\Delta}, \Lambda, \bar{\Lambda}, \pi, K, \ldots \qquad x \equiv (t, \mathbf{r})$

$m_j^* = m_j + S_j$ - effective mass, $S_j = g_{\sigma j}\sigma$ - scalar field,

$p^{*\mu} = p^\mu - V_j^\mu$ - kinetic four-momentum with effective mass shell constraint $p^{*\mu}p_\mu^* = m_j^{*2}$,

$V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau_j^3 \rho^{3\mu} + q_j A^\mu$ - vector field, $\qquad \tau_j^3 = +(-)1 \text{ for } j = p, \bar{n}\ (\bar{p}, n)$,

$\mathcal{F}_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$ - field tensor.

- For momentum-independent fields Eq.(*) is equivalent to the BUU equation

$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon_j \nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon_j \nabla_{\mathbf{p}}) f_j(x, \mathbf{p}) = I_j[\{f\}]$$

$$\varepsilon_j(x, \mathbf{p}) = V_j^0 + \sqrt{m_j^{*2} + \mathbf{p}_j^{*2}} , \quad f_j(x, \mathbf{p}) = f_j^*(x, \mathbf{p}^*) .$$

Direct derivations of relativistic kinetic equation: ***Yu.B. Ivanov, NPA 474, 669 (1987); B. Blättel, V. Koch, U. Mosel, Rept. Prog. Phys. 56, 1 (1993).***

Used non-linear Walecka model version NL2 from ***A. Lang et al., NPA 541, 507 (1992)***

Collision term of the GiBUU model

- Includes 2$\rightarrow$2, 2$\leftrightarrow$3, 2$\rightarrow$4, and 3$\rightarrow$3 transitions at low energies, and 2$\rightarrow$N transitions at high energies (via PYTHIA and FRITIOF models) and for baryon-antibaryon annihilation (via statistical annihilation model);

- Pauli blocking for the outgoing nucleons;

- Cross sections of the time-reversed processes (e.g. ΛK$\rightarrow$Nπ) – by the detailed balance relation:

$$\sigma_{cd\to ab} = \sigma_{ab\to cd} \left(\frac{q_{ab}}{q_{cd}}\right)^2 \frac{(2J_a+1)(2J_b+1)}{(2J_c+1)(2J_d+1)} \frac{\mathcal{S}_{ab}}{\mathcal{S}_{cd}} \ ,$$

$q_{ab},\ q_{cd}$ - c.m. momenta,

$J_a,\ J_b$ - spins,

$$\mathcal{S}_{ab} = \begin{cases} 1 & \text{if a,b not identical} \\ \frac{1}{2} & \text{if a,b identical} \ . \end{cases}$$

Baryon-baryon collisions:

For $\sqrt{s} < 4$ GeV: $BB \to BB$ (elastic & inelastic), $NN \to NNM$ $(M = \pi,\ \omega,\ \phi)$,
$np \to d\eta$ (via $np\eta$ final state) , $BB \to BYK$, $BB \to NNK\bar{K}$ $(B = N,\ R)$.

For $\sqrt{s} > 4$ GeV: $BB \to X$ (PYTHIA 6).

Meson-baryon collisions:

For $\sqrt{s} < 2.2$ GeV: $\pi N \to R,\ MN\ (M = \pi, \omega, \phi, \rho, \sigma, \eta),\ M\Delta\ (M = \pi, \eta, \rho),$
$\pi N^*(1440),\ K\Lambda,\ K\Sigma,\ \omega\pi N,\ \phi\pi N,\ K\bar{K}N,\ \Lambda K\pi,\ \Sigma K\pi,\ \pi\pi N,\ \pi\pi\pi N;$
$\omega N \to R,\ \pi N,\ \omega N,\ \pi\pi N,\ \Lambda K,\ \Sigma K;$
$\rho N \to R,\ \pi N,\ \Lambda K,\ \Sigma K;$
$\sigma N \to R,\ \pi N,\ \sigma N;$
$\eta N \to R,\ \pi N,\ \Lambda K,\ \Sigma K;$
$\phi N \to \phi N,\ \pi N,\ \pi\pi N;$
$KN \to KN,\ KN\pi;$
$\bar{K}N \to Y^*,\ \bar{K}N,\ Y\pi,\ Y^*\pi,\ \Xi K,\ \Xi K\pi;$
$J/\psi N \to J/\psi N,\ \Lambda_c\bar{D},\ \Lambda_c\bar{D}^*,\ ND\bar{D};$
$\pi\Delta \to R,\ K\Lambda,\ \Sigma\Lambda;$
$\rho\Delta \to R;$
$\eta\Delta \to \pi N;$
$\pi N^*(1440) \to R;$
$\pi Y(Y^*) \to Y^*,\ \bar{K}N;$
$\eta\Lambda \to \Lambda^*;$
$K\Lambda \to R,\ \pi N,\ \pi\Delta;$

For $\sqrt{s} > 2.2$ GeV: $MB \to X$ (PYTHIA 6 and JETSET)

Meson-meson collisions:
$MM \to R,\ K\bar{K},\ K^*\bar{K},\ K\bar{K}^*\ (M = \pi, \eta, \eta', \sigma, \rho, \omega)$.

Baryon-antibaryon collisions:
$\bar{B}B \to$ mesons by statistical annihilation model
E.S. Golubeva et al., NPA 537, 393 (1992);
I.A. Pshenichnov, PhD thesis, INR Moscow (1998)
or by string model (if $|Z_{\rm tot}| > 1$ or total charm$\neq 0$ or total strangeness$\neq 0$),
$\bar{B}B \to \bar{B}B$ (EL and CEX), $\bar{N}N \leftrightarrow \bar{\Delta}N(\bar{N}\Delta)$ (for $\sqrt{s} < 2.38$ GeV)
or $\bar{B}B \to \bar{B}B +$ mesons by FRITIOF (for $\sqrt{s} > 2.38$ GeV),
$\bar{N}N \to \bar{\Lambda}\Lambda$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Lambda}\Sigma(\bar{\Sigma}\Lambda)$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Xi}\Xi$, $\bar{N}N \to \bar{\Omega}\Omega$,
$\bar{N}N \to J/\psi$.

$3 \to 2$ collisions: $NN\pi \to NN$.

$3 \to 3$ collisions: $NN\Delta \to NNN$.

$3 \to N$ collisions: optional.

Dilepton production channels

Direct decays of vector mesons, $V \to e^+e^-$, with $V = \rho, \omega, \phi$,
partial widths are calculated based on the vector dominance model (VDM)
Y. Nambu, J.J. Sakurai, PRL 8, 79 (1962); O. Dumbrajs et al., NPB 216, 277 (1983)

$$\Gamma_{V\to e^+e^-}(m) = C_V \frac{m_V^4}{m^3}(1 + 2m_e^2/m^2)\sqrt{1 - 4m_e^2/m^2} \ ,$$

with $C_V = 4\pi\alpha^2/3f_V^2$ chosen to reproduce empirical $V \to e^+e^-$ width at pole mass,
m – off-shell mass of decaying hadron.

Direct $\eta \to e^+e^-$ **decay**:

$$\Gamma_{\eta\to e^+e^-} = \Gamma_\eta^{\rm tot}\,{\rm BR}_{\eta\to e^+e^-}, \quad \Gamma_\eta^{\rm tot} = 1.3 \ {\rm keV}, \quad {\rm BR}_{\eta\to e^+e^-} = 7\cdot 10^{-7}$$

upper limit from
M. Tanabashi et al. (PDG), PRD 98, 030001 (2018)

Dalitz decays $A \to B e^+ e^-$:

$$\frac{d\Gamma_{A\to Be^+e^-}}{dm^2} = \Gamma_{A\to B\gamma^*} \frac{\alpha}{3\pi m^2}(1+2m_e^2/m^2)\sqrt{1-4m_e^2/m^2} \ ,$$

Meson Dalitz decays: $P \to \gamma e^+ e^-$, $P = \pi^0, \eta, \eta'$; $\omega \to \pi^0 e^+ e^-$

$$\Gamma_{A\to B\gamma^*}(m^2) = \eta_{\rm sym}\Gamma_{A\to B\gamma}\left(\frac{q_{B\gamma^*}(m^2)}{q_{B\gamma^*}(0)}\right)^3 |F_{AB}(m^2)|^2 \ ,$$

$\eta_{\rm sym} = 2$ for $P \to \gamma\gamma^*$; $\eta_{\rm sym} = 1$ for $\omega \to \pi^0\gamma^*$

Eff. Lagrangian description:
R.H. Dalitz, Proc. Phys. Soc. A 64, 667 (1951); A. Faessler et al., PRC 61, 035206 (2000)

$$q_{B\gamma^*}(m^2) = \frac{m_A^2 - m_B^2}{2m_A}\left[\left(1+\frac{m^2}{m_A^2-m_B^2}\right)^2 - \frac{4m_A^2 m^2}{(m_A^2-m_B^2)^2}\right]^{1/2}$$

– c.m. momentum of B and γ^*.

Form factors:

$F_{\pi^0\gamma}(m^2) = 1 + b_\pi m^2$, $b_\pi = 5.5\ \mathrm{GeV}^{-2}$ **L.G. Landsberg, Phys. Rept. 128, 301 (1985)**

$F_{\eta\gamma}(m^2) = (1-m^2/\Lambda_\eta^2)^{-1}$, $\Lambda_\eta^{-2} = 1.95\ \mathrm{GeV}^{-2}$ **R. Arnaldi et al. (NA60), PLB 677, 260 (2009)**

$F_{\eta'\gamma}(m^2) = 1$

$$F_{\omega\pi^0}(m^2) = \frac{\Lambda_\omega^2}{[(\Lambda_\omega^2 - m^2)^2 + \Lambda_\omega^2\Gamma_\omega^2]^{1/2}} \ , \quad \Lambda_\omega = 0.65\ \mathrm{GeV} \ , \quad \Gamma_\omega = 75\ \mathrm{MeV}$$

E.L. Bratkovskaya, W. Cassing, NPA 619, 413 (1997)

Δ **Dalitz decay**: $\Delta(1232) \to N e^+ e^-$ **M.I. Krivoruchenko, A. Faessler, PRD 65, 017502 (2002)**

$$\Gamma_{\Delta \to N\gamma^*}(m^2) = \frac{\alpha}{16} \frac{(m_\Delta + m_N)^2}{m_\Delta^3 m_N^2} [(m_\Delta + m_N)^2 - m^2]^{1/2} [(m_\Delta - m_N)^2 - m^2]^{3/2} |F_{\Delta N}(m^2)|^2 \ ,$$

$F_{\Delta N}(m^2) \equiv F_{\Delta N}(0) = 3.029$, from the real photon decay width $\Gamma_{\Delta \to N\gamma^*}(0) = 0.66$ MeV.

$N^*(1520)$ **Dalitz decay**: effectively included via the two-step decay $N^* \to \rho N$, $\rho \to e^+ e^-$.

Bremsstrahlung $pn \to pne^+e^-$**,** $pp \to ppe^+e^-$:

boson exchange model , including radiation from internal pion line

R. Shyam, U. Mosel, PRC 82, 062201 (2010)

Charged pion bremsstrahlung $\pi^\pm N \to \pi^\pm N e^+ e^-$: soft-photon approximation (SPA)

C. Gale, J.I. Kapusta, PRC 35, 2107 (1987); G. Wolf et al., NPA 517, 615 (1990)

ρ-meson spectral function

In vacuum:

$$\mathcal{A}(m^2) = \frac{m\,\Gamma_{\rm dec}(m)/\pi}{(m^2 - m_\rho^2)^2 + m^2\Gamma_{\rm dec}^2(m)} \;, \qquad \int\limits_{4m_e^2}^{\infty} dm^2\,\mathcal{A}(m^2) = 1 \;.$$

$$\Gamma_{\rm dec}(m) = \Gamma_{\rho\to\pi\pi}(m) + \Gamma_{\rho\to e^+e^-}(m)$$

$$\Gamma_{\rho\to\pi\pi}(m) = \Gamma^0_{\rho\to\pi\pi}\left(\frac{q_{\rm cm}(m)}{q_{\rm cm}(m_\rho)}\right)^3 \frac{m_\rho}{m}\,\frac{1+(q_{\rm cm}(m_\rho)R)^2}{1+(q_{\rm cm}(m)R)^2} \;, \qquad q_{\rm cm}(m) = \sqrt{m^2/4 - m_\pi^2}$$

$$m_\rho = 775.5~\mathrm{MeV},\ \Gamma^0_{\rho\to\pi\pi} = 149.1~\mathrm{MeV},\ R = 1~\mathrm{fm}$$

D.M. Manley, E.M. Saleski, PRD 45, 4002 (1992)

In nuclear matter: $\Gamma_{\rm dec} \to \Gamma_{\rm dec} + \Gamma_{\rm coll}\;,\quad \Gamma_{\rm coll} = \gamma_{\rm Lor}\langle v_{\rho N}\sigma_{\rho N}\rangle \rho_N \;,$

$$\rho_N = \rho_n + \rho_p,\ \sigma_{\rho N} = (\sigma_{\rho n} + \sigma_{\rho p})/2,\ \ v_{\rho N} = \sqrt{(qp_N)^2 - m^2 m_N^2}/q^0 p_N^0,\ \gamma_{\rm Lor} = q^0/m$$

q and p_N – four momenta of ρ and nucleon, resp., $q^2 = m^2$, $p_N^2 = m_N^2$,

$\langle \ldots \rangle$ – averaging over nucleon Fermi motion.

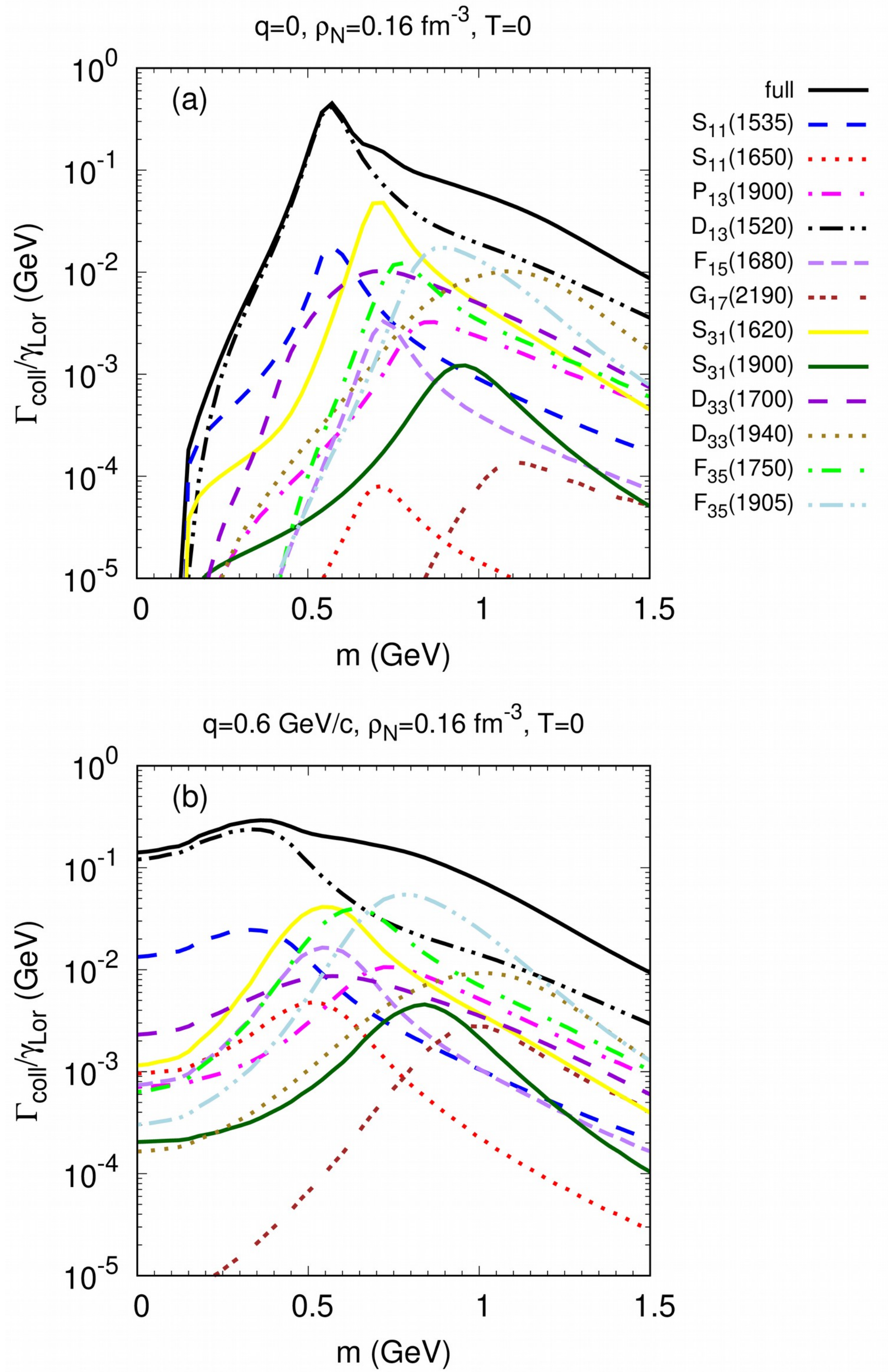
Collisional width of ρ-meson
in the nuclear matter rest frame

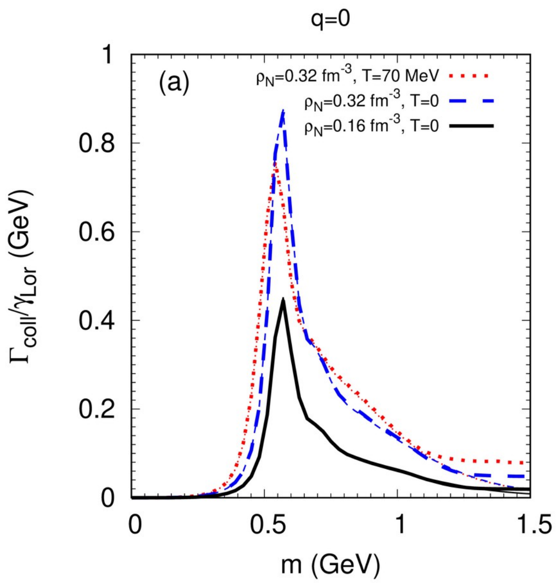
- Significant effect, comparable to vacuum ρ decay width (149 MeV).

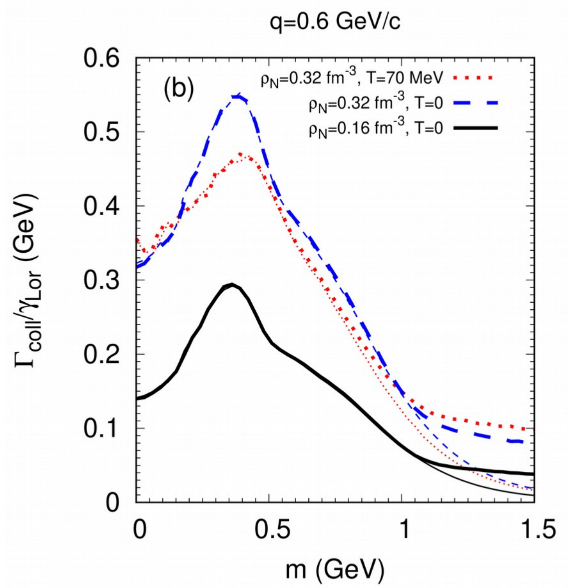
- Dominant contribution:

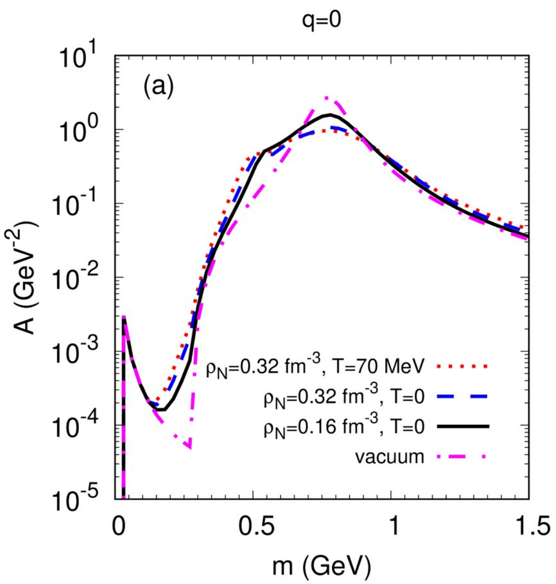
$$\rho + N \to D_{13}(1520)$$

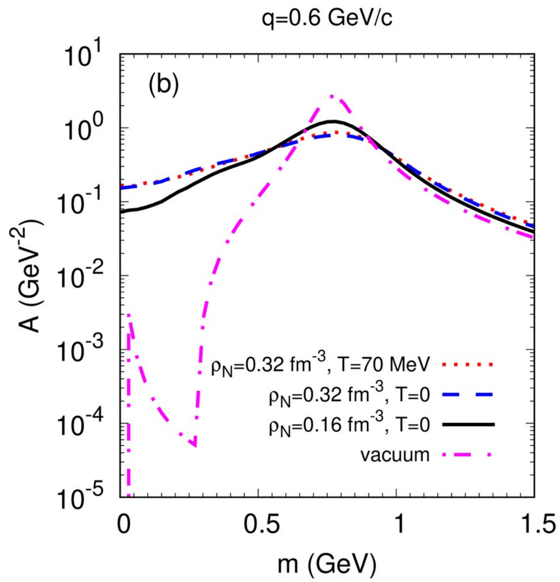
- At finite momentum, ρ becomes broad even at very low inv. mass.





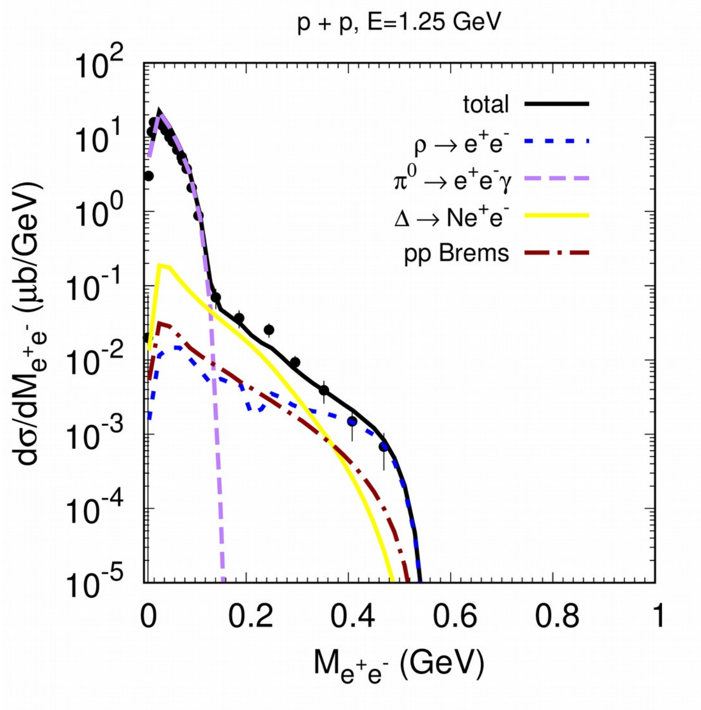


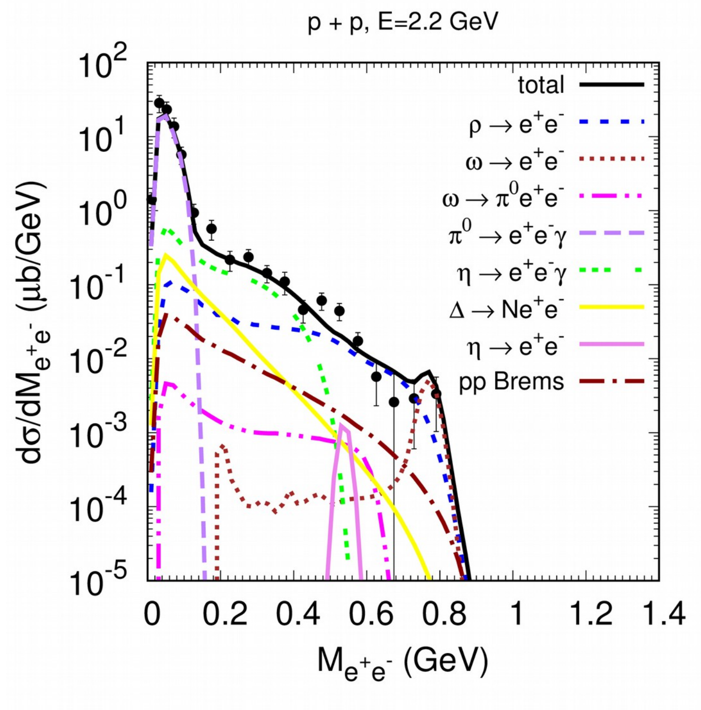




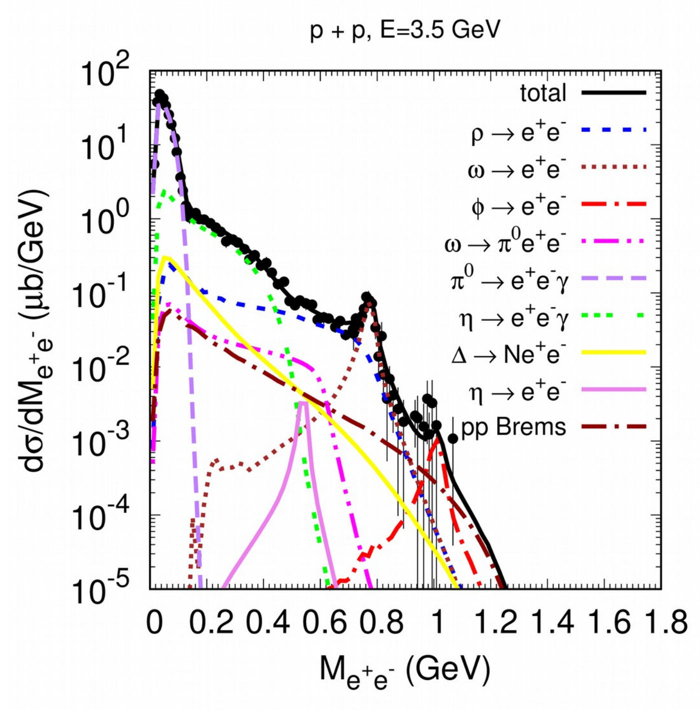
- Big effect of collisional width at finite momenta of ρ !

pp collisions



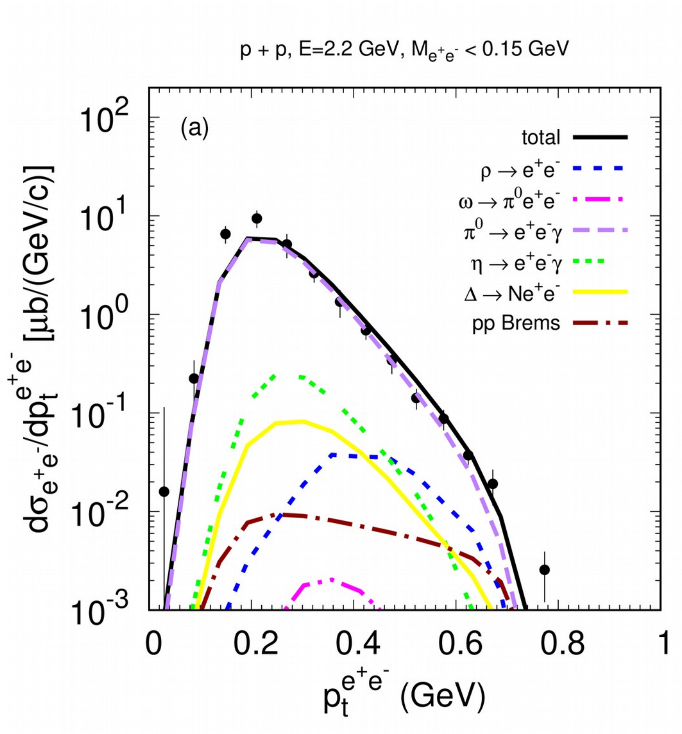


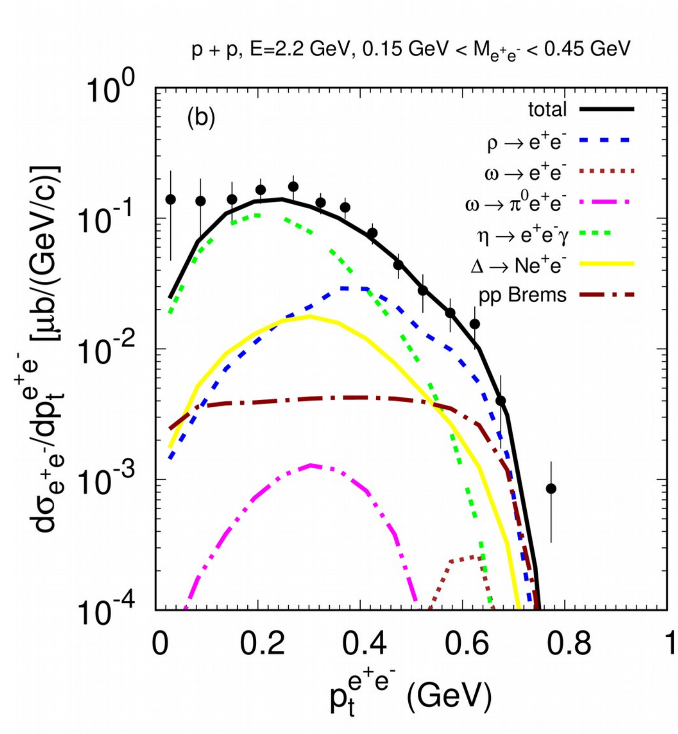
Data: ***G. Agakishiev et al. (HADES), PLB 690 (2010) 118; PRC 85 (2012) 054005; EPJA 48 (2012) 64.***



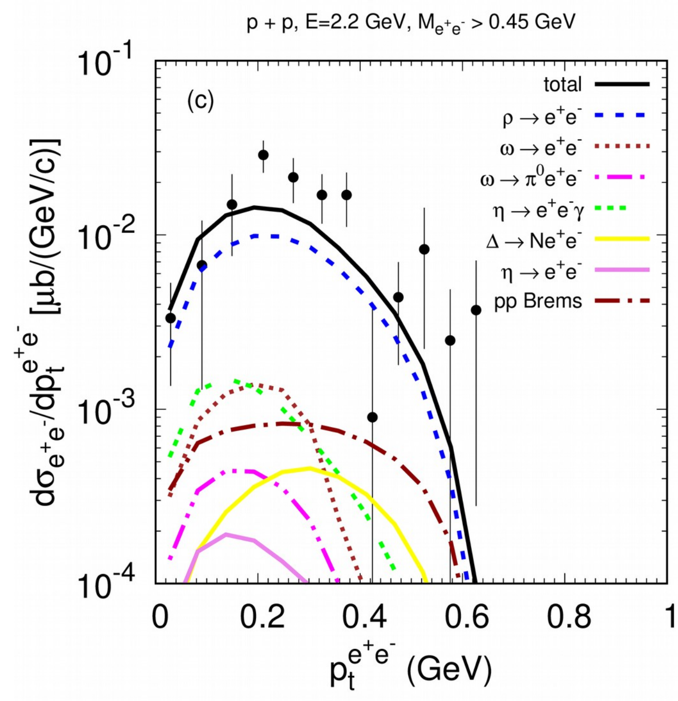
HADES acceptance filter and cuts on lepton's momenta and opening angle $(\Theta_{e^+e^-} > 9^\circ)$ applied.

Good agreement in the entire M_{e+e-} range.





Data: ***G. Agakishiev et al. (HADES), PRC 85 (2012) 054005***



dp collisions

In the r.f. of deuteron: $$\sigma_{pd\to e^+e^-p_{\rm spec}X} \simeq \int d^3p_n|\phi(p_n)|^2\sigma_{pn\to e^+e^-X}(\sqrt{s}_{pn})$$

Deuteron wave function of full Bonn model R. Machleidt et al., Phys. Rept. 149, 1 (1987)

- η Dalitz component is due to neutron Fermi motion:
  $E_{\rm thr} = 1.256$ GeV

- Default calculation underpredicts dilepton yield with inv. mass above ≈0.2 GeV.

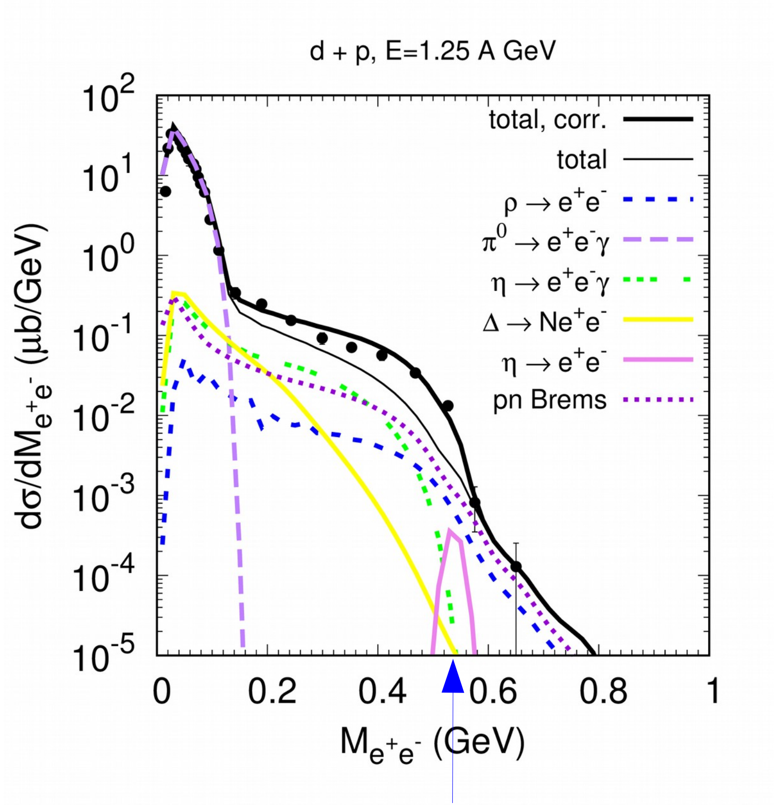
- Many possible reasons: insufficient brems., insufficient η, LC corrections to the DWF ...

- Educated guess:
  brems. need to be corrected
  by dil. mass dependent factor

$$f(M) = C\frac{1+wM^2/b^2}{(\exp[(a-M)/d]+1)(\exp[(M-b)/d]+1)} + 1\ ,$$

with dilepton invariant mass M in GeV,
$C = 1.5$, $d = 0.01$, $a = 0.10$, $b = 0.55$, and $w = 3.0$.

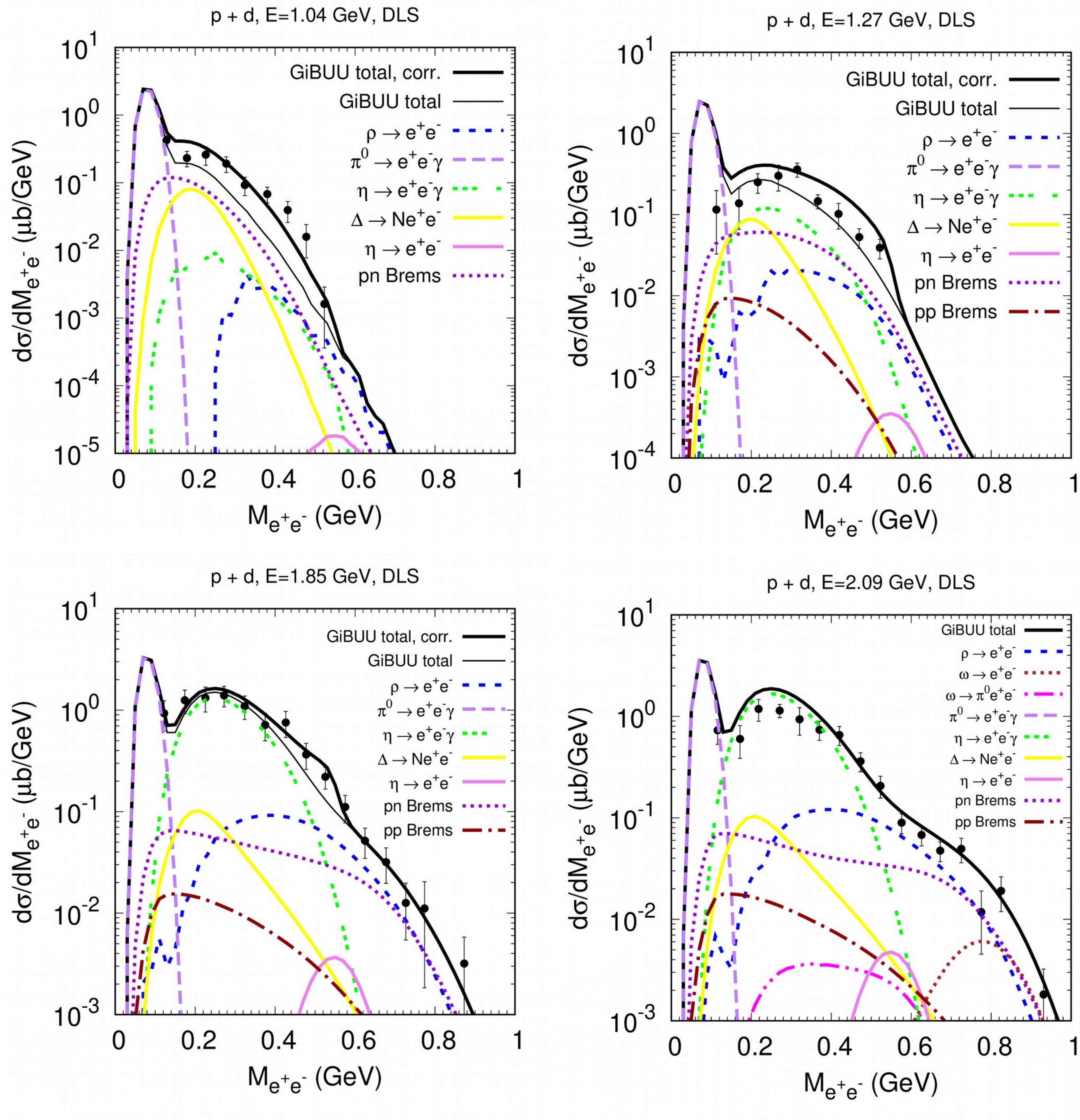
- Parameters determined by fit to the data



kin. limit for free np

$$M^{\rm max}_{e^+e^-} = \sqrt{s_{NN}} - 2m_N = 0.545 \text{ GeV}$$

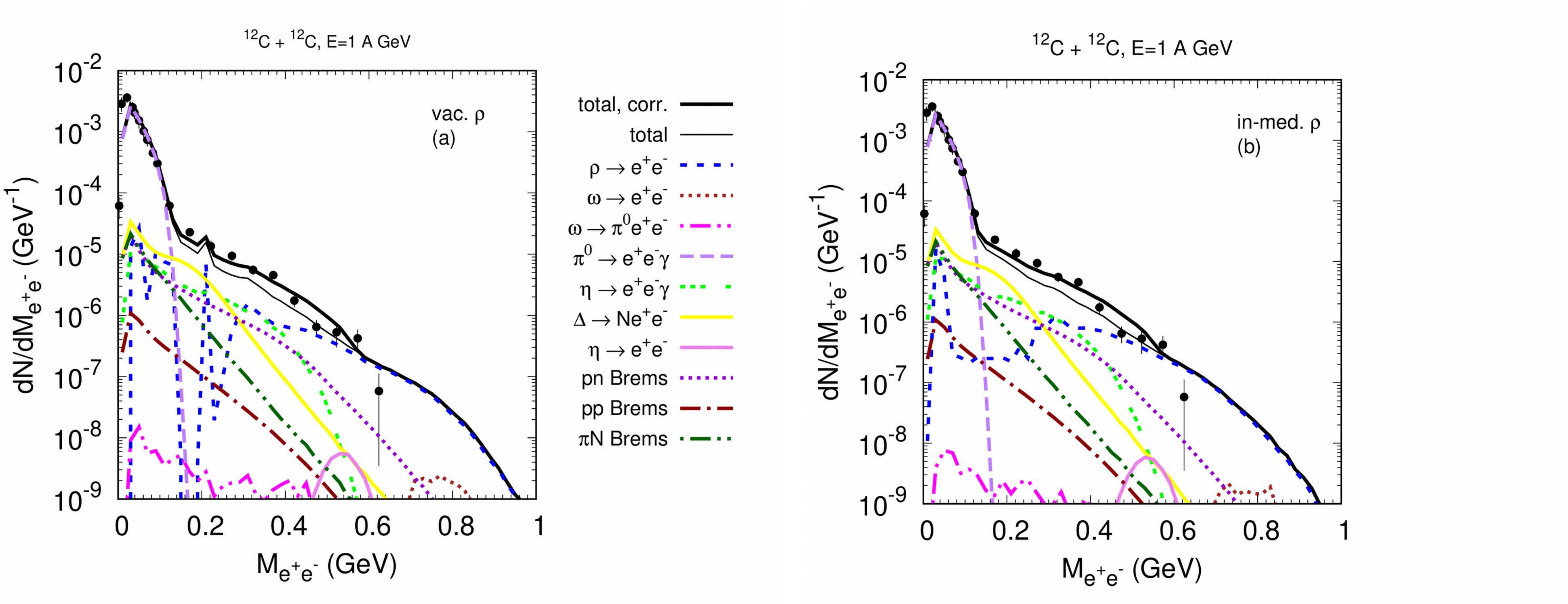
Data: ***G. Agakishiev et al. (HADES), PLB 690 (2010) 118***



Data: ***W.K. Wilson et al. (DLS), PRC 57, 1865 (1998)***

- At beam energies above ≈2 GeV correction of pn brems. is not needed.

Heavy ion collisions at SIS18 energies (1-2 A GeV)

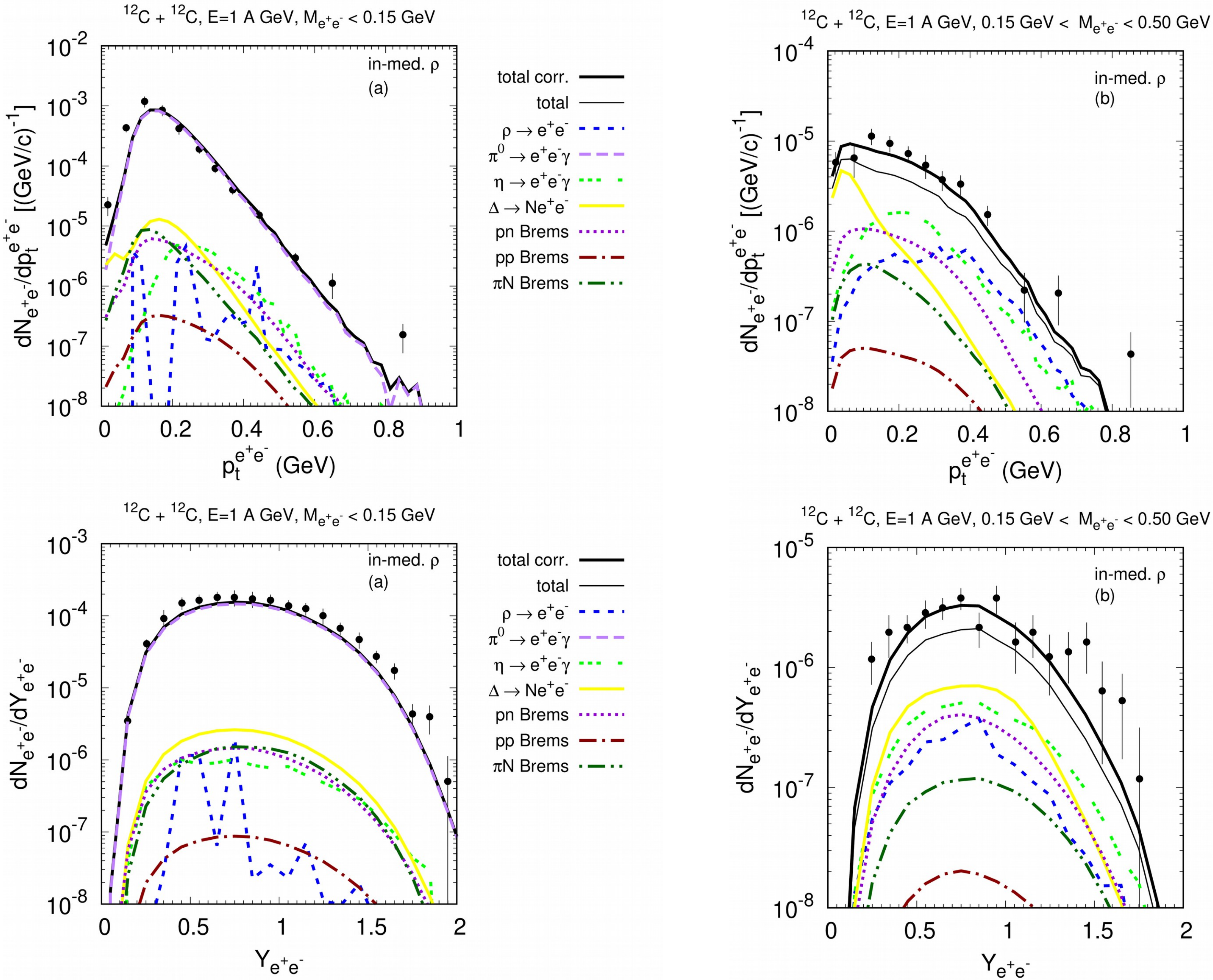


Data: ***G. Agakishiev et al. (HADES), PLB 663 (2008) 43***

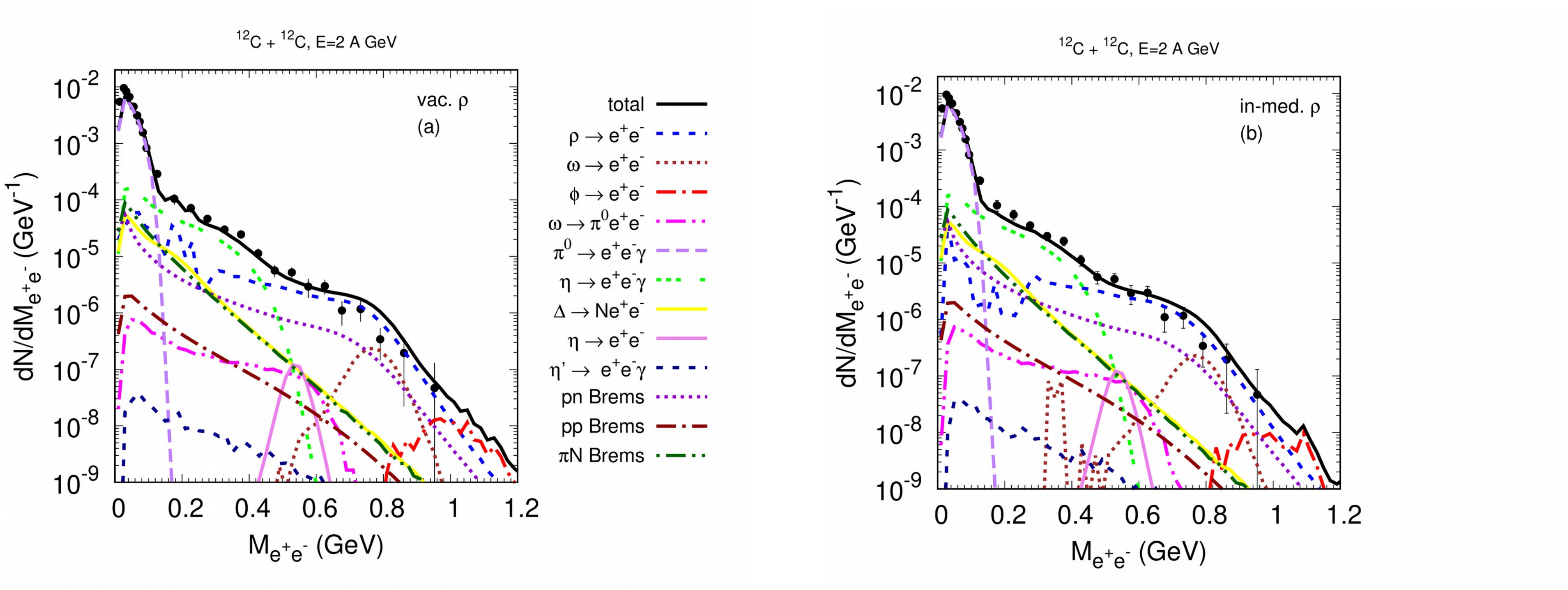
- Several comparable contribs. in the interm. inv. mass region 0.2-0.4 GeV.

- Corrected pn brems. improves agreement at E_{beam} = 1 A GeV.

- Collisional broadening of ρ: marginal effect for a light C+C system (reduced stat. fluctuations in $\rho \rightarrow e^+e^-$ component below 2π threshold).



Data: ***Y. Pachmayer (HADES), PhD thesis, Frankfurt U. (2008).***

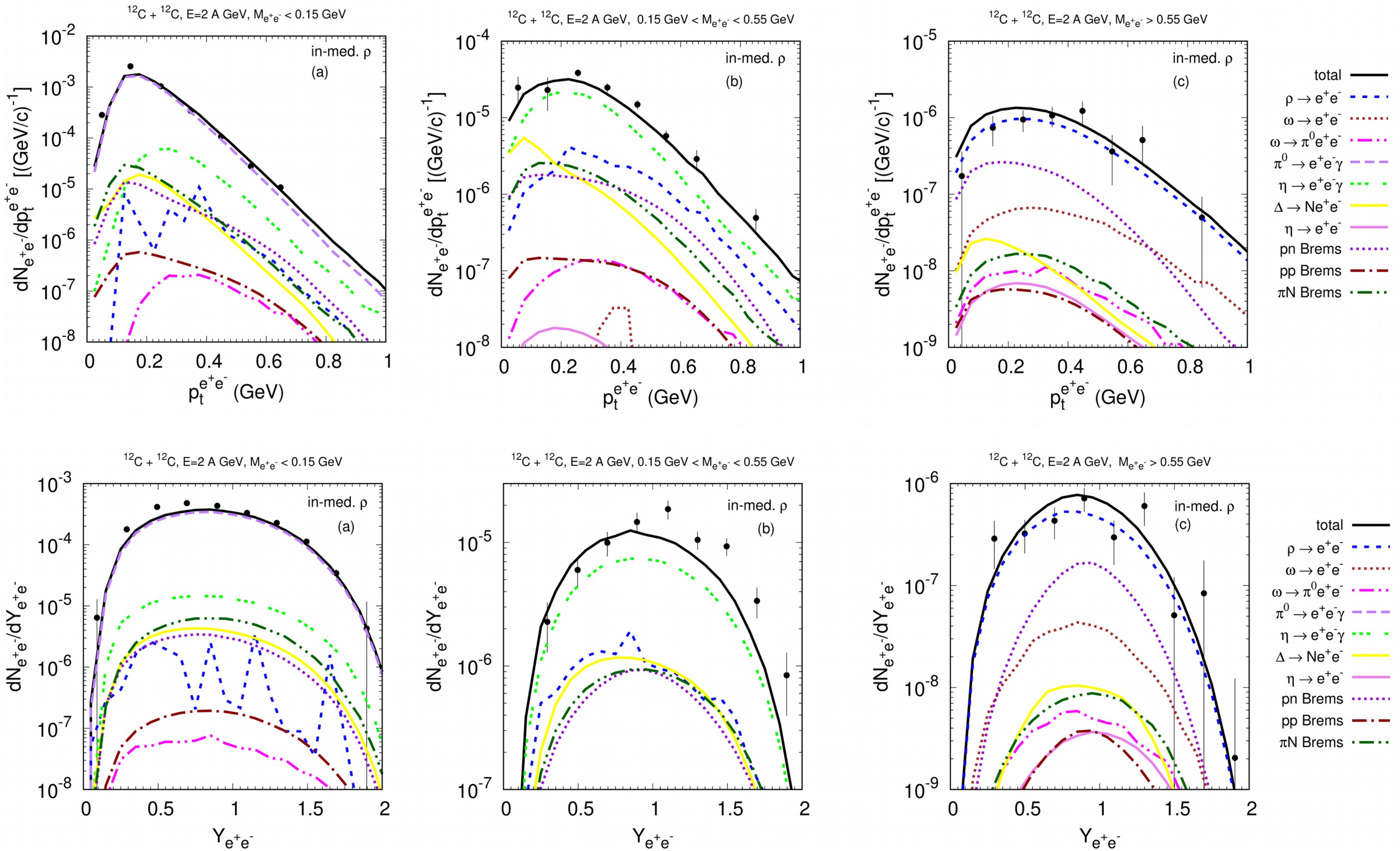


Data: ***G. Agakishiev et al. (HADES), PRL 98 (2007) 052302***

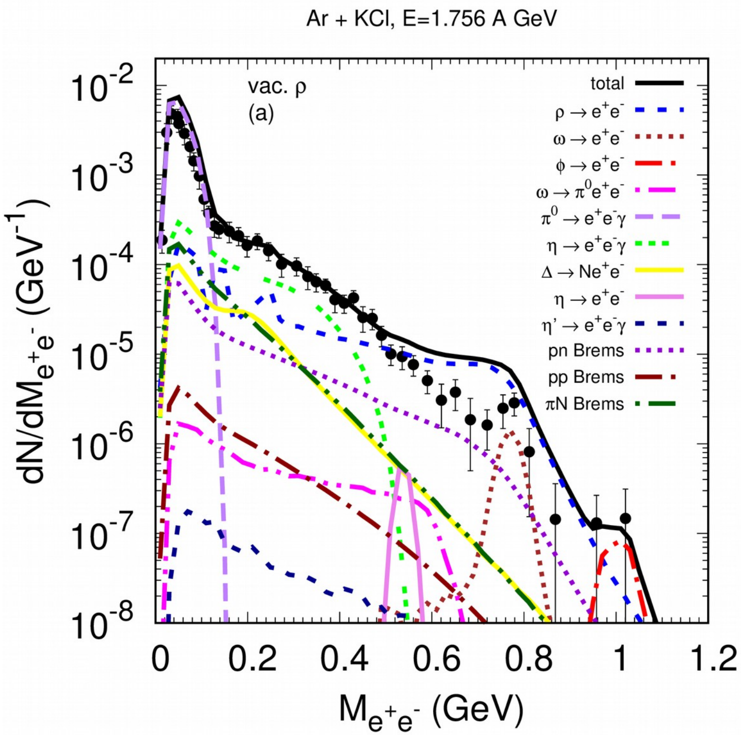
- η Dalitz contrib. dominates in the interm. inv. mass range 0.2-0.4 GeV.

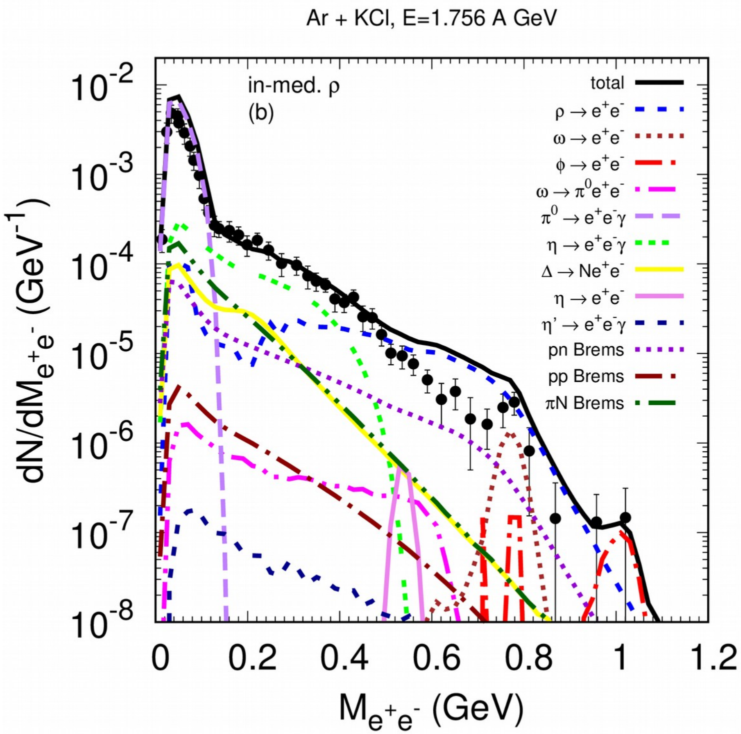
- very good agreement with data, no need to correct pn brems.

- ρ coll. broadening: again marginal effect (small system).



Data: ***M. Sudol (HADES), PhD thesis, Frankfurt U. (2007).***



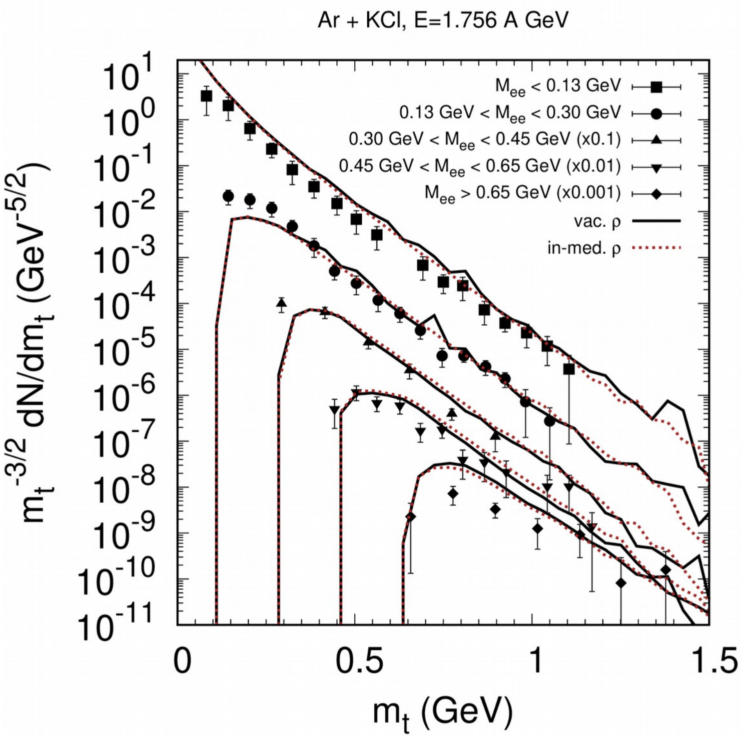


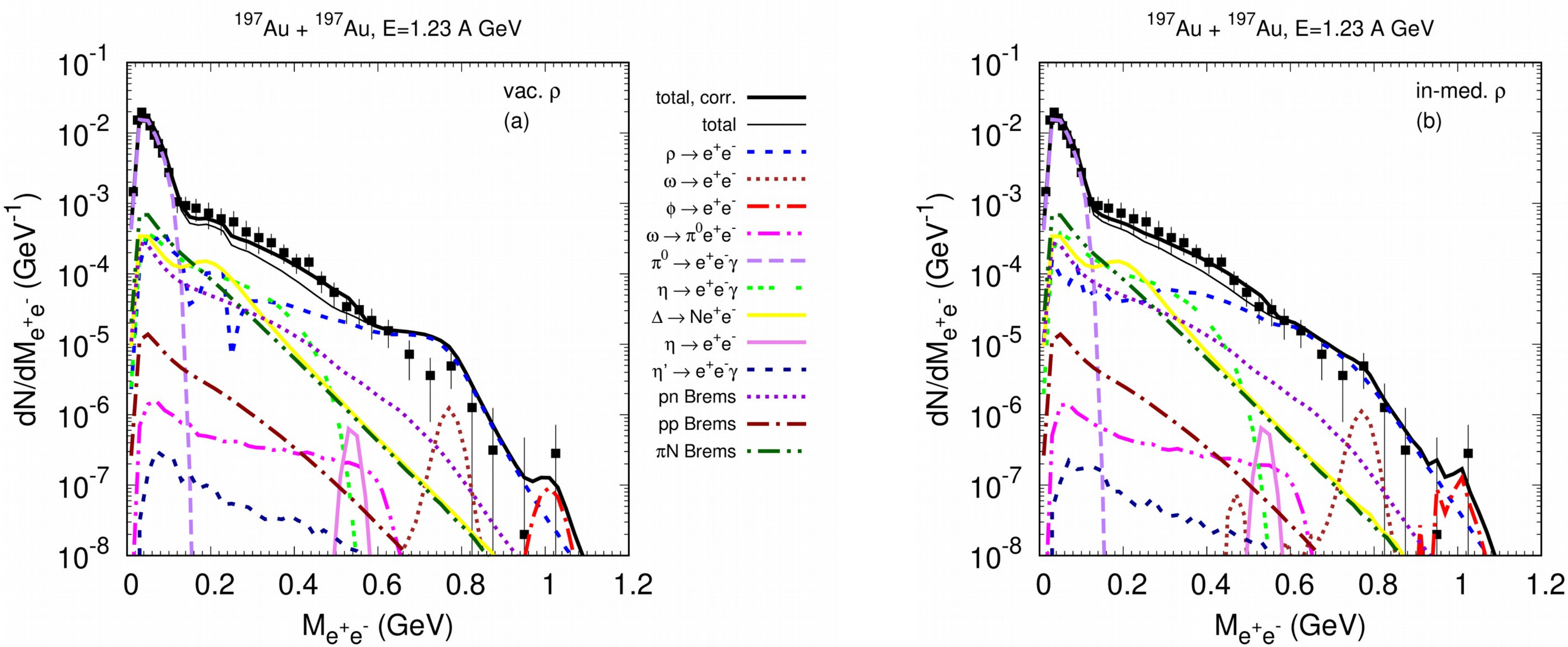
Data: ***G. Agakishiev et al. (HADES), PRC 84 (2011) 014902***

- Overestimation at ρ on-shell mass.

- Collisional broadening of ρ improves agreement with data, but not enough.

- m_t-slopes well described.





Data: ***J. Adamczewski-Musch et al. (HADES), Nature Physics 15 (2019) 1040***

- Significant effect of ρ collisional broadening for the heavy Au+Au system. Improvement near the on-shell ρ mass.

- In the interm. inv. mass region 0.2-0.4 GeV corrected pn brems. needed.

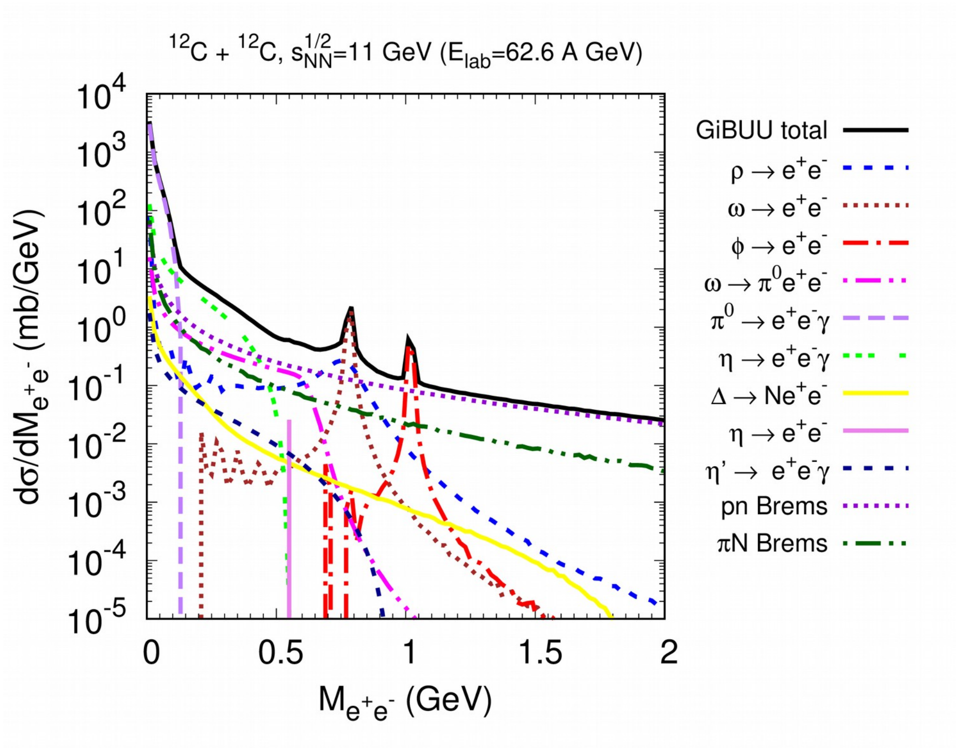
Opportunities at NICA-SPD

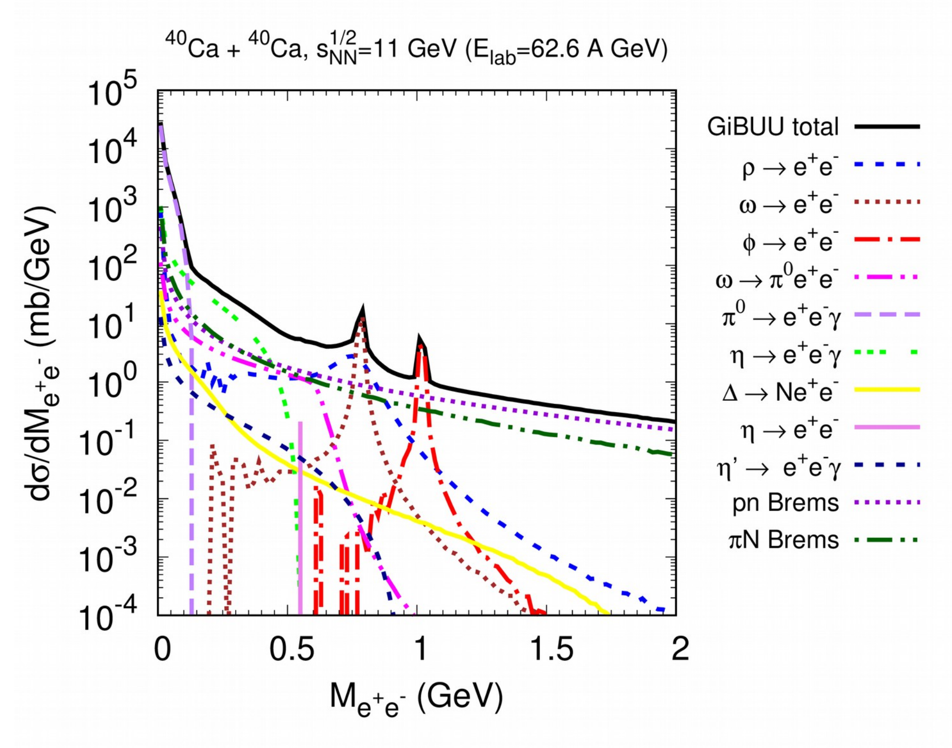
- Higher energies: $\sqrt{s}_{NN} = 3.35 - 14$ GeV (C+C, Ca+Ca) $\leftrightarrow$ $E_{\mathrm{lab}} = 4 - 103$ A GeV for fixed target.

- PYTHIA is activated (at least in primary NN collisions).

- Hadronic formation effects.

- Mean field potentials turned-off: cascade simulation
  (with ‘frozen’ nuclei to avoid spurious particle emission).





- pn brems. dominates at M_{e+e-} > 0.5 GeV (calculated using SPA).

- pronounced ω and φ peaks.

Hadron formation

- Hadrons created in a hard binary ***exclusive*** process emerge, first, as “prehadrons” that have a reduced transverse size, so-called point-like color singlet $q\bar{q}$ and qqq configurations (PLCs):

$$r_\perp \sim 1/Q$$

Color dipole – proton cross section in the pQCD limit $(r_\perp \to 0)$:

$$\sigma_{q\bar{q}} \propto r_\perp^2 \sim 1/Q^2$$

Color transparency (CT) – today's afternoon talk by ***Mark Strikman***.

- In ***inclusive*** 2 $\rightarrow$X processes CT is not proved theoretically.
However, on phenomenological basis, most transport models include it.

Hadron formation length:

$$l_h \simeq \frac{2p_h}{|M_h^2 - M_{h'}^2|} \sim 0.4 - 0.6(\mathrm{fm}/\mathrm{GeV}) \cdot p_h[\mathrm{GeV}]$$

Typically, h' is the 1st radially excited state of h.

Models (prescriptions) for the prehadron-nucleon interaction cross section:

(I) Based on JETSET-production-formation points (GiBUU default):

K. Gallmeister, T. Falter, PLB 630, 40 (2005)

$$\sigma_{\mathrm{eff}}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{t - t_{\mathrm{prod}}}{t_{\mathrm{form}} - t_{\mathrm{prod}}} \ ,$$

$$X_0 = r_{\mathrm{lead}} a/Q^2, \ a = 1 \ \mathrm{GeV}^2,$$

r_{lead} - the ratio (#of leading quarks)/(total # of quarks) in the prehadron,

Favored by the simultaneous analysis of HERMES and EMC data on fast forward production in DIS within GiBUU **K. Gallmeister, U. Mosel, NPA 801, 68 (2008).**

(II) Quantum diffusion model (QDM): **G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988)**

$$\sigma_{\mathrm{eff}}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{c(t - t_{\mathrm{hard}})}{l_h} \ ,$$

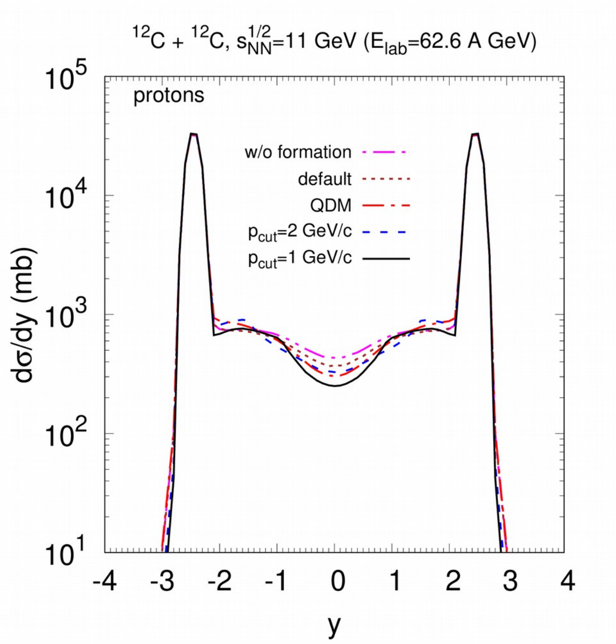
(No direct way to derive X_0 in inclusive processes. Here we set X_0=0 for simplicity.)

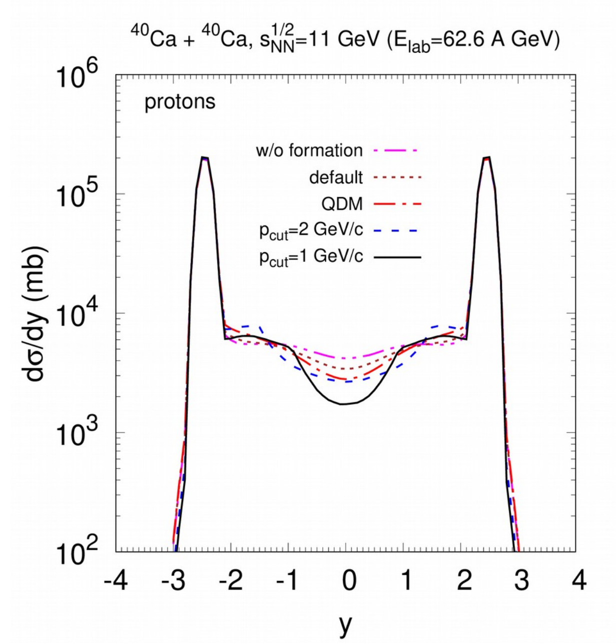
Favored by analysis of pion electroproduction at JLab ***A. Larson, G. Miller, M. Strikman, PRC 74, 018201 (2006); AL, M. Strikman, M. Bleicher, PRC 93, 034618 (2016).***

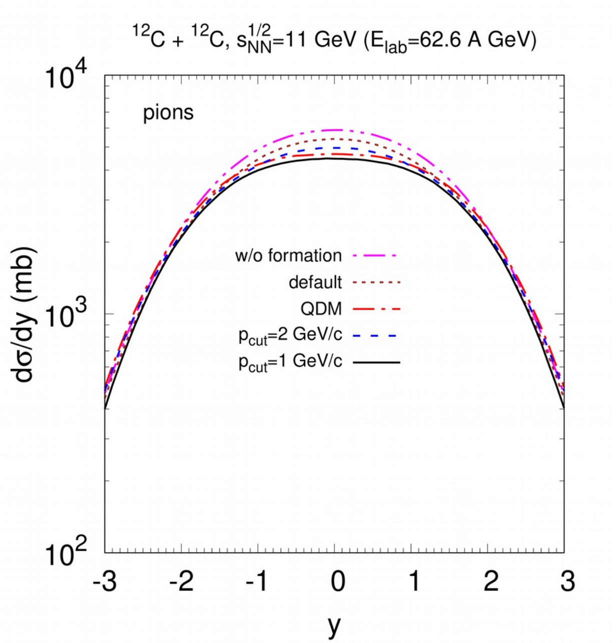
(III) Cutoff: $\sigma_{\mathrm{eff}}/\sigma_0 = \Theta(p_{\mathrm{cut}} - p) \ , \quad p_{\mathrm{cut}} \sim 1 - 2 \ \mathrm{GeV/c}.$

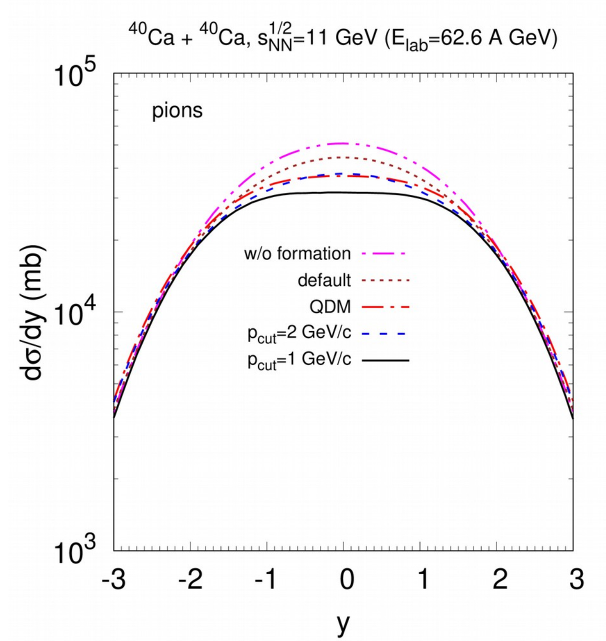
Favored by analysis of low-energy (E < 10 MeV) neutron production in μ^- DIS at 470 GeV on Pb (E665 experiment at Fermilab) ***M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999); AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231.***

Proton and pion rapidity spectra



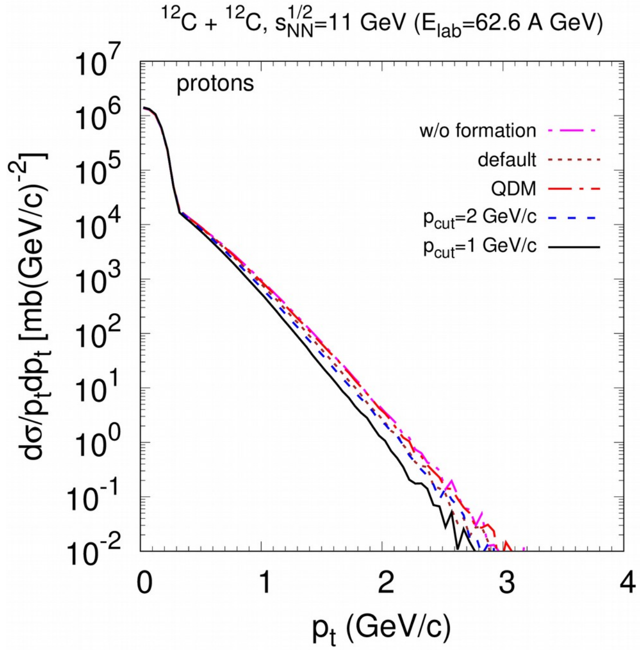


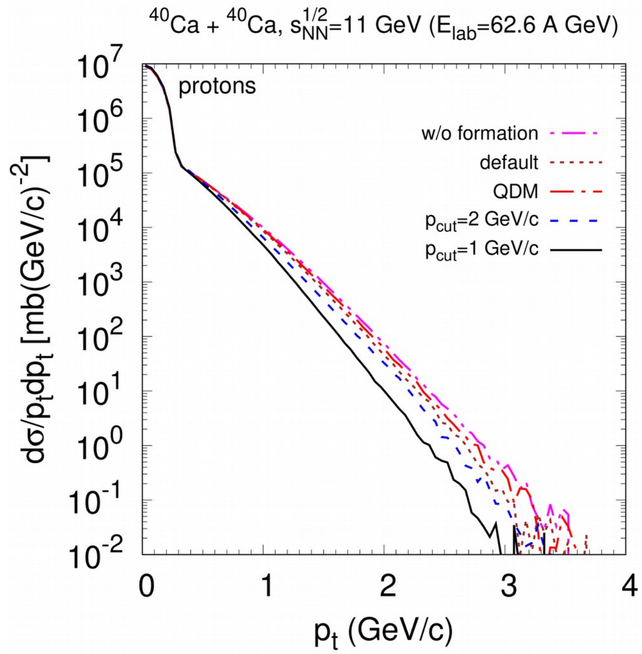


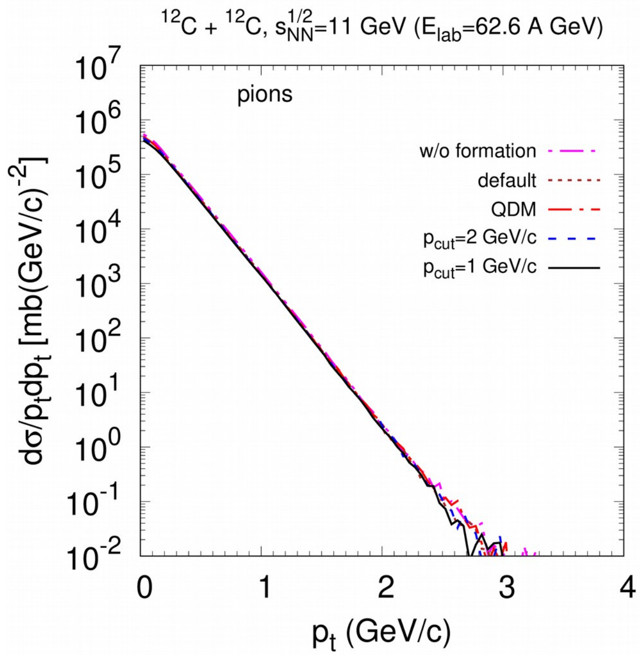


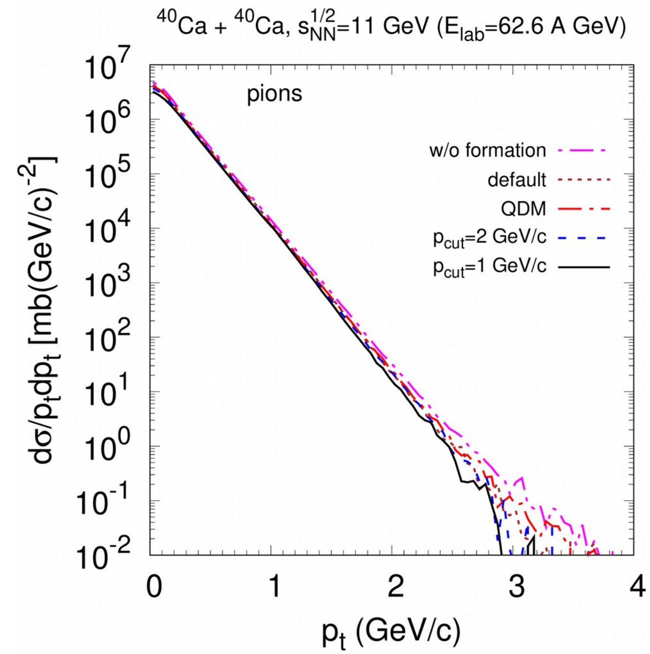
- less proton stopping and less pion production for more restrictive FSI (p_{cut}=1 GeV/c)

Proton and pion transverse momentum spectra









- less proton rescattering → softer proton p_t spectra for restrictive FSI (p_{cut}=1 GeV/c)

Conclusions

- GiBUU successfully describes dilepton production in pp,dp, and AA at beam energies 1-2 A GeV. Collisional broadening of ρ improves agreement with HADES data for heavy colliding systems (Ar+KCl at 1.76 A GeV and Au+Au at 1.23 A GeV). Remaining underprediction in the intermediate inv. masses of e^+e^- (0.2-0.4 GeV) for d+p at 1.25 A GeV, C+C at 1 A GeV and Au+Au at 1.23 GeV is removed by correcting pn brems. component (same correction for all three systems).

- The reason for underprediction of e^+e^- yield at inv. mass above 0.2 GeV in d+p collisions at 1.25 A GeV remains unclear. At higher beam energies the discrepancy seems to disappear (DLS data). Good to have d+p data on e^+e^- production at NICA-SPD test the np channel.

- Dilepton inv. mass spectra from systems C+C and Ca+Ca at $\sqrt{s_{NN}}$=11 GeV show up sharp peaks at ω and φ on-shell masses on the smooth background (mostly due to pn brems.). Sharp peak of J/ψ is also expected (to be calculated).

- NICA-SPD energies are well suited to study hadron formation. Sensitive observables are rapidity- and p_t-spectra of protons and pions.

Backup

Lagrangian density:

$$\mathcal{L} = \sum_{j=N,\bar{N}} \bar{\psi}_j[\gamma_\mu(i\partial^\mu - g_{\omega j}\omega^\mu - g_{\rho j}\boldsymbol{\tau}\boldsymbol{\rho}^\mu - \frac{e}{2}(B_j+\tau^3)A^\mu) - m_N - g_{\sigma j}\sigma]\psi_j$$

$$+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\boldsymbol{R}_{\mu\nu}\boldsymbol{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^2 - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} \ ,$$

$$B_N = 1,\ B_{\bar{N}} = -1, \quad \Omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \ , \ \boldsymbol{R}_{\mu\nu} = \partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu \ , \ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \ ,$$

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 \ .$$

G-parity (Walecka model): $g_{\sigma\bar{N}} = g_{\sigma N}, \quad g_{\omega\bar{N}} = -g_{\omega N}, \quad g_{\rho\bar{N}} = g_{\rho N}$.

Phenomenological couplings: $g_{\sigma\bar{N}} = \xi g_{\sigma N}, \quad g_{\omega\bar{N}} = -\xi g_{\omega N}, \quad g_{\rho\bar{N}} = \xi g_{\rho N}, \quad 0 < \xi \le 1.$

Lagrange equations of motion for meson fields:

$$\left\{ \begin{aligned} &(\partial_\mu\partial^\mu + m_\sigma^2)\sigma(x) + g_2\sigma^2 + g_3\sigma^3 = -\sum_{j=N,\bar{N}} g_{\sigma j}\,\rho_{Sj}(x) \ , \\ &(\partial_\nu\partial^\nu + m_\omega^2)\,\omega^\mu(x) = \sum_{j=N,\bar{N}} g_{\omega j}\,J^\mu_{Bj}(x) \ , \\ &(\partial_\nu\partial^\nu + m_\rho^2)\,\rho^{3\,\mu}(x) = \sum_{j=N,\bar{N}} g_{\rho j}\,J^\mu_{Ij}(x) \ , \\ &\partial_\nu\partial^\nu A^\mu(x) = 4\pi \sum_{j=N,\bar{N}} J^\mu_{Qj}(x) \ . \end{aligned} \right.$$

$$\rho_{Sj}(x) =< \bar{\psi}_j(x)\psi_j(x) >= \frac{2}{(2\pi)^3}\int \frac{d^3p^*}{p^{*0}} m_j^* f_j(x,\boldsymbol{p}^*) \ ,$$

$$J^\mu_{aj}(x) =< \bar{\psi}_j(x)\gamma^\mu O_a\psi_j(x) >= \frac{2}{(2\pi)^3}\int \frac{d^3p^*}{p^{*0}} p^{*\mu} O_a f_j(x,\boldsymbol{p}^*) \ , \quad O_B = 1, \ \ O_I = \tau^3, \ \ O_Q = \frac{e}{2}(B_j+\tau^3) \equiv q_j \ .$$

Particles propagated by GiBUU

By default, all resonances are propagated
while for cross sections are used all resonances except those with I=1/2 one-star.

Nonstrange baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
N	1	0.938	0.000	0.5	****	0.5	0	0	0	0.700
Δ	2	1.232	0.118	1.5	****	1.5	0	0	3	1.076
$P_{11}(1440)$	3	1.462	0.391	0.5	****	0.5	0	0	3	1.076
$S_{11}(1535)$	4	1.534	0.151	0.5	***	0.5	0	0	3	1.076
$S_{11}(1650)$	5	1.659	0.173	0.5	****	0.5	0	0	3	1.076
$S_{11}(2090)$	6	1.928	0.414	0.5	*	0.5	0	0	3	1.076
$D_{13}(1520)$	7	1.524	0.124	1.5	****	0.5	0	0	3	1.076
$D_{13}(1700)$	8	1.737	0.249	1.5	*	0.5	0	0	3	1.076
$D_{13}(2080)$	9	1.804	0.447	1.5	*	0.5	0	0	3	1.076
$D_{15}(1675)$	10	1.676	0.159	2.5	****	0.5	0	0	3	1.076
$G_{17}(2190)$	11	2.127	0.547	3.5	****	0.5	0	0	3	1.076
$P_{11}(1710)$	12	1.717	0.478	0.5	*	0.5	0	0	3	1.076
$P_{11}(2100)$	13	1.885	0.113	0.5	*	0.5	0	0	3	1.076
$P_{13}(1720)$	14	1.717	0.383	1.5	*	0.5	0	0	3	1.076
$P_{13}(1900)$	15	1.879	0.498	1.5	***	0.5	0	0	3	1.076
$F_{15}(1680)$	16	1.684	0.139	2.5	****	0.5	0	0	3	1.076
$F_{15}(2000)$	17	1.903	0.494	2.5	*	0.5	0	0	3	1.076
$F_{17}(1990)$	18	2.086	0.535	3.5	**	0.5	0	0	3	1.076
$S_{31}(1620)$	19	1.672	0.154	0.5	**	1.5	0	0	3	1.076
$S_{31}(1900)$	20	1.920	0.263	0.5	***	1.5	0	0	3	1.076
$D_{33}(1700)$	21	1.762	0.599	1.5	*	1.5	0	0	3	1.076
$D_{33}(1940)$	22	2.057	0.460	1.5	*	1.5	0	0	3	1.076
$D_{35}(1930)$	23	1.956	0.526	2.5	**	1.5	0	0	3	1.076
$D_{35}(2350)$	24	2.171	0.264	2.5	**	1.5	0	0	3	1.076
$P_{31}(1750)$	25	1.744	0.299	0.5	*	1.5	0	0	3	1.076
$P_{31}(1910)$	26	1.882	0.239	0.5	****	1.5	0	0	3	1.076
$P_{33}(1600)$	27	1.706	0.430	1.5	***	1.5	0	0	3	1.076
$P_{33}(1920)$	28	2.014	0.152	1.5	*	1.5	0	0	3	1.076
$F_{35}(1750)$	29	1.752	0.251	2.5	*	1.5	0	0	3	1.076
$F_{35}(1905)$	30	1.881	0.327	2.5	***	1.5	0	0	3	1.076
$F_{37}(1950)$	31	1.945	0.300	3.5	****	1.5	0	0	3	1.076

Strange baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
Λ	32	1.116	0.000	0.5	****	0.0	-1	0	0	1.076
Σ	33	1.189	0.000	0.5	****	1.0	-1	0	0	1.076
$\Sigma(1385)$	34	1.385	0.036	1.5	****	1.0	-1	0	3	1.254
$\Lambda(1405)$	35	1.405	0.050	0.5	****	0.0	-1	0	3	1.254
$\Lambda(1520)$	36	1.520	0.016	1.5	****	0.0	-1	0	3	1.254
$\Lambda(1600)$	37	1.600	0.150	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1670)$	38	1.670	0.035	0.5	****	0.0	-1	0	3	1.254
$\Lambda(1690)$	39	1.690	0.060	1.5	****	0.0	-1	0	3	1.254
$\Lambda(1810)$	40	1.810	0.150	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1820)$	41	1.820	0.080	2.5	****	0.0	-1	0	3	1.254
$\Lambda(1830)$	42	1.830	0.095	2.5	****	0.0	-1	0	3	1.254
$\Sigma(1670)$	43	1.670	0.060	1.5	****	1.0	-1	0	3	1.254
$\Sigma(1775)$	44	1.775	0.120	2.5	****	1.0	-1	0	3	1.254
$\Sigma(2030)$	45	2.030	0.180	3.5	****	1.0	-1	0	3	1.254
$\Lambda(1800)$	46	1.800	0.300	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1890)$	47	1.890	0.100	1.5	****	0.0	-1	0	3	1.254
$\Lambda(2100)$	48	2.100	0.200	3.5	****	0.0	-1	0	3	1.254
$\Lambda(2110)$	49	2.110	0.200	2.5	***	0.0	-1	0	3	1.254
$\Sigma(1660)$	50	1.660	0.100	0.5	***	1.0	-1	0	3	1.254
$\Sigma(1750)$	51	1.750	0.090	0.5	***	1.0	-1	0	3	1.254
$\Sigma(1915)$	52	1.915	0.120	2.5	****	1.0	-1	0	3	1.254
Ξ	53	1.315	0.000	0.5	****	0.5	-2	0	0	1.254
Ξ^*	54	1.530	0.009	1.5	****	0.5	-2	0	3	1.254
Ω	55	1.672	0.000	1.5	****	0.0	-3	0	0	1.254

Charmed baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
Λ_c	56	2.285	0.000	0.5	****	0.0	0	1	0	1.076
Σ_c	57	2.452	0.000	0.5	****	1.0	0	1	0	1.076
Σ_c^*	58	2.520	0.015	1.5	****	1.0	0	1	3	2.423
Ξ_c	59	2.466	0.000	0.5	***	0.5	-1	1	0	2.423
Ξ_c^*	60	2.645	0.004	1.5	***	0.5	-1	1	3	2.423
Ω_c	61	2.697	0.000	0.5	***	0.0	-2	1	0	2.423

Mesons

Name	ID	Mass	Width	Spin	Isospin	Strange	Charm	Stability	min.Mass
π	101	0.1380	0.0000	0.0	1.0	0	0	0	0.000
η	102	0.5478	0.0000	0.0	0.0	0	0	3	0.000
ρ	103	0.7755	0.1491	1.0	1.0	0	0	3	0.276
σ	104	0.8000	0.5000	0.0	0.0	0	0	3	0.276
ω	105	0.7826	0.0085	1.0	0.0	0	0	3	0.138
η'	106	0.9578	0.0002	0.0	0.0	0	0	3	0.000
ϕ	107	1.0194	0.0043	1.0	0.0	0	0	3	0.414
η_c	108	2.9800	0.0280	0.0	0.0	0	0	3	0.000
J/ψ	109	3.0969	0.0000	1.0	0.0	0	0	0	0.000
K	110	0.4960	0.0000	0.0	0.5	1	0	0	0.496
$\overline{K}$	111	0.4960	0.0000	0.0	0.5	-1	0	0	0.496
K^*	112	0.8920	0.0500	1.0	0.5	1	0	3	0.634
$\overline{K}^*$	113	0.8920	0.0500	1.0	0.5	-1	0	3	0.634
D	114	1.8670	0.0000	0.0	0.5	0	1	0	1.500
$\overline{D}$	115	1.8670	0.0000	0.0	0.5	0	-1	0	1.500
D^*	116	2.0070	0.0020	1.0	0.5	0	1	3	1.500
$\overline{D}^*$	117	2.0070	0.0020	1.0	0.5	0	-1	3	1.500
D_s^+	118	1.9690	0.0000	0.0	0.0	1	1	0	1.500
D_s^-	119	1.9690	0.0000	0.0	0.0	-1	-1	0	1.500
D_s^{*+}	120	2.1120	0.0010	1.0	0.0	1	1	3	1.500
D_s^{*-}	121	2.1120	0.0010	1.0	0.0	-1	-1	3	1.500
$f_2(1270)$	122	1.2754	0.1852	2.0	0.0	0	0	3	0.276

Off-shell particle propagation: off-shell potential (OSP) ansatz

M. Effenberger, U. Mosel, PRC 60, 051901 (1999); O. Buss et al, Phys. Rept. 512, 1 (2012)

- generalized distribution function in (x,p) space:

$$F(x,p) = \frac{(2\pi)^4}{N} \sum_{n=1}^{N_{\rm phys}N} \delta(\boldsymbol{r} - \boldsymbol{r}_n(t))\delta(\boldsymbol{p} - \boldsymbol{p}_n(t))\delta(p^0 - \varepsilon_n(t)) \ .$$

- centroids satisfy:

$$\left.\begin{aligned} \dot{\boldsymbol{r}}_n &= \left(1 - \frac{\partial H_n}{\partial \varepsilon_n}\right)^{-1} \frac{\partial H_n}{\partial \boldsymbol{p}_n} \ , \\ \dot{\boldsymbol{p}}_n &= -\left(1 - \frac{\partial H_n}{\partial \varepsilon_n}\right)^{-1} \frac{\partial H_n}{\partial \boldsymbol{r}_n} \ , \\ \dot{\varepsilon}_n &= \left(1 - \frac{\partial H_n}{\partial \varepsilon_n}\right)^{-1} \frac{\partial H_n}{\partial t} \ . \end{aligned}\right\} \Longleftrightarrow \left\{\begin{aligned} \dot{\boldsymbol{r}}_n &= \frac{\partial \varepsilon_n}{\partial \boldsymbol{p}_n} \ , \\ \dot{\boldsymbol{p}}_n &= -\frac{\partial \varepsilon_n}{\partial \boldsymbol{r}_n} \ , \\ \varepsilon_n &= H_n(\varepsilon_n, \boldsymbol{p}_n, t, \boldsymbol{r}_n) \ . \end{aligned}\right.$$

H_n - single-particle Hamilton function:

self-energy

total in-medium width

$$H_n = \sqrt{m_{\rm phys}^2 + {\rm Re}\,\Pi + \Delta m_n^2 + \boldsymbol{p}_n^2} \ , \quad \Delta m_n^2 = -\chi_n {\rm Im}\,\Pi \ , \quad {\rm Im}\Pi = -\sqrt{p_n^2}\,\Gamma_n \ , \quad p_n^2 = \varepsilon_n^2 - \boldsymbol{p}_n^2 \ .$$

Constant fixed at the particle production space-time point

- Particle's off-shellness scales with its total in-medium width. Equivalent to the test particle equations of motion derived from retarded Green's function formalism
W. Cassing, S. Juchem, NPA 672, 417 (2000).

Modeling dilepton emission by “shining” method:

- Dilepton production is simulated perturbatively, i.e. it does not change the state of the system.

- At every time step Δt every resonance emits a e^+e^- pair that contributes to the total dilepton spectrum with a weight

$$w = \gamma_{Lor} \Gamma_{R \to e^+ e^-} \Delta t$$

for direct decay (and similar for Dalitz decay).

- A resonance that survived until the end of time evolution emits a e^+e^- pair with a weight

$$w = \Gamma_{R \to e^+ e^-} / \Gamma_R^{tot}$$

- At every $\pi^{\pm}N$, pn, and pp collision a e^+e^- pair is emitted with a weight

$$w = \sigma_{brems} / \sigma_{tot}$$

Charged pion bremsstrahlung $\pi^{\pm}N \to \pi^{\pm}Ne^{+}e^{-}$: soft-photon approximation (SPA)

C. Gale, J.I. Kapusta, PRC 35, 2107 (1987); G. Wolf et al., NPA 517, 615 (1990)

$$E\,\frac{d\sigma_{e^+e^-}}{d^3p\,dm} = \frac{\alpha^2}{6\pi^3}\,\frac{\overline{\sigma}_{\rm el}(s)}{mE^2}\,\frac{R_2(s_2)}{R_2(s)}\ , \qquad \overline{\sigma}_{\rm el}(s) = \int\limits_{-|t|_{\rm max}}^{0} dt\,\frac{-t}{m_\pi^2}\,\frac{d\sigma_{\rm el}(s,t)}{dt} \simeq \frac{2q_{\rm cm}^2(s)}{m_\pi^2}\sigma_{\rm el}(s)\ ,$$

$(E,\boldsymbol{p})$ – four-momentum of the e^+e^- pair in the c.m. system of the colliding pion and nucleon,

$m^2 = E^2 - \boldsymbol{p}^2$,

$q_{\rm cm}(s) = [(s + m_\pi^2 - m_N^2)^2/4s - m_\pi^2]^{1/2}$,

$s_2 = s + m^2 - 2\sqrt{s}E\ ,$

$R_2(s) = 2q_{\rm cm}(s)/\sqrt{s}$ – two-body (πN) phase space.