Vector mesons in medium in transport-based approaches

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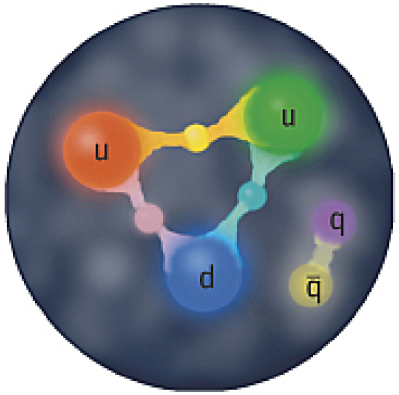
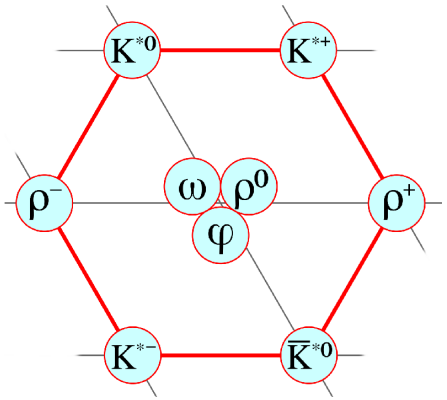
Outline

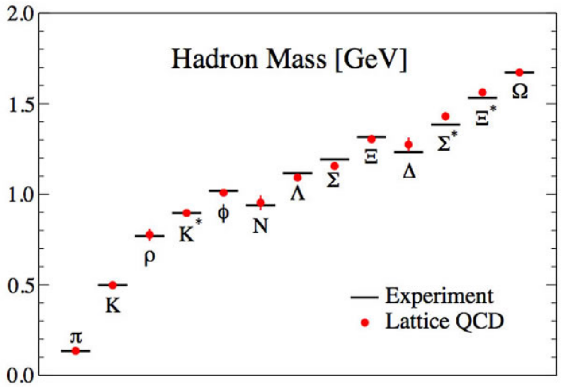
- vector mesons in medium: motivation & basic ideas
- theoretical models & simulation techniques:
  - hadronic transport models (example: GiBUU)
  - coarse graining (with UrQMD)
- results: light VM in medium
  - ω meson in γA (CB/TAPS)
  - ρ meson in AA collisions (NA60, HADES)
  - ϕ meson in pA (KEK-E325 at 12 GeV)
- predictions for J-PARC E16 (pPb @ 30 GeV)

Hadron masses

- $m_{had.} \gg \sum m_q$
- m_q ($\sim$ MeV) generated by Higgs mech.
- most of $m_{had.}$ ($\sim$ GeV) dynamically generated by QCD



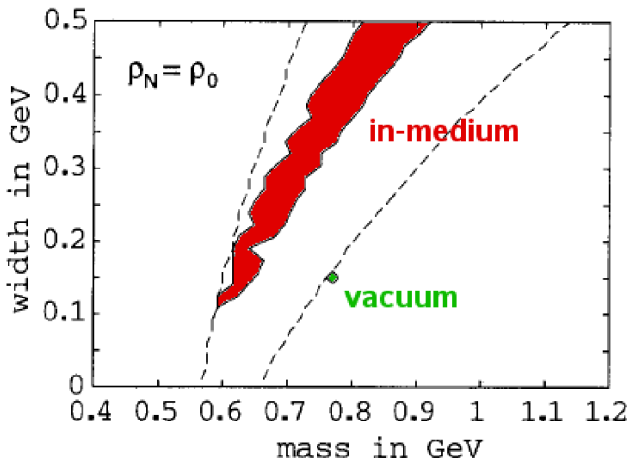


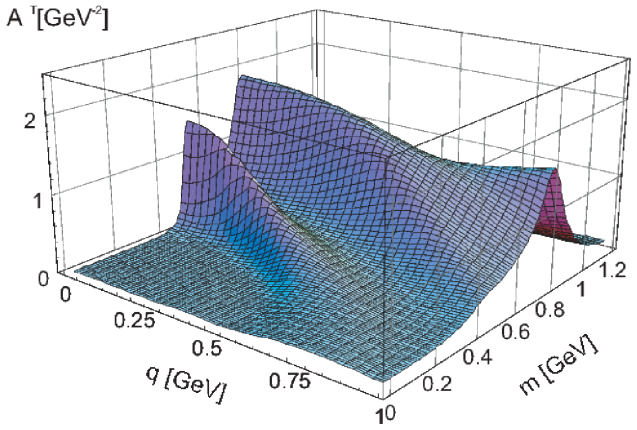


- How do the hadronic masses come about?
  (rather well understood by lattice QCD)
- How to they change at large densities & high temperatures,
  i.e. in a hadronic 'medium'? (can be studied in nuclear react.)

Hadrons in Medium

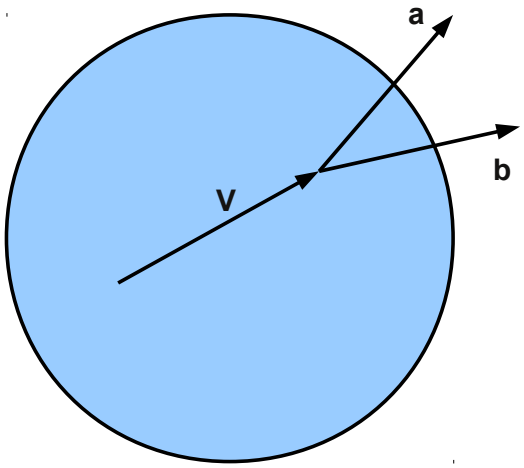
- how do vector mesons change their properties inside a hadronic medium?
- Brown/Rho, Hatsuda/Lee:
  mass shift (restoration of chiral sym.)
  $m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0)$,
  $\alpha \approx 0.16 \pm 0.06$
- collisional broadening (LDA):
  $\Gamma_{coll} = \rho < v_{rel}\sigma_{VN} >$
- QCD sum rules (Leupold, NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (Post, 2003)





How to study in-medium properties?

- basic idea: observe decays $V \to ab$ inside the medium
- reconstruct in-medium mass from invariant mass of decay products: $m_V^* = \sqrt{(p_a + p_b)^2}$



we need:

- reasonably large medium:
  - either: 'cold' nucleus (e.g. γA, pA: $\rho \approx \rho_0$, $T \approx 0$)
  - or: 'fireball' from heavy-ion collision ($\rho >> \rho_0$, $T >> 0$)
- short meson lifetime and/or low momentum
- FSI of decay products should be small (ideal: $V \to e^+e^-$)

The GiBUU transport model

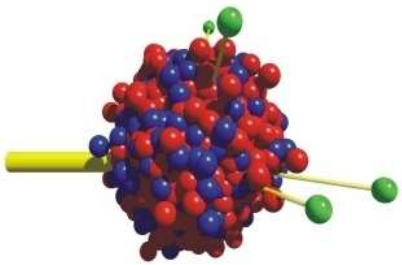
- GiBUU: "The Giessen BUU transport model"
- coupled-channel hadronic transport model, based on the Boltzmann-Uehling-Uhlenbeck equation (BUU)
- microscopic, non-equilibrium description of nuclear reactions
- unified framework for various types of reactions
  - electroweak: γA, eA, νA
  - hadronic: pA, πA, KA
  - heavy-ion collisions: AA
- wide energy range: $\sqrt{s} \approx 100$ MeV to 100 GeV
- implementation: large Fortran code ($\sim$ 100k lines of code)
- publicly available releases (open source)
- website: http://gibuu.hepforge.org
- contributors: Mosel, Gallmeister, Gaitanos, Larionov, J.W., ...
- similar models: UrQMD, HSD, JAM, ...

The BUU equation

- BUU equ.: space-time evolution of phase-space density F (from gradient expansion of Kadanoff-Baym eq.)

$$\frac{\partial(p_0-H)}{\partial p_\mu}\frac{\partial F(x,p)}{\partial x^\mu} - \frac{\partial(p_0-H)}{\partial x_\mu}\frac{\partial F(x,p)}{\partial p^\mu} = C(x,p)$$

- Hamiltonian H:
  - hadronic mean fields, Coulomb, "off-shell potential"
- collision term $C(x,p)$:
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model, high energy: string fragment.
- test-particle method: $F = \sum_i \delta(\vec{r} - \vec{r_i})\delta(p - p_i)$
- review paper: O. Buss et al., Phys. Rep. 512 (2012)



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

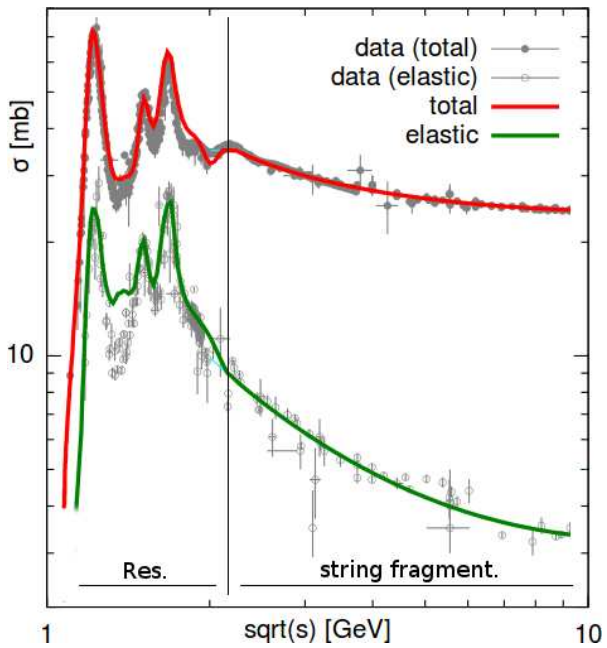
Degrees of Freedom

- included hadronic states:
  - 61 baryons
    - non-strange: N, Δ, 16 N^*, 13 Δ^* states
    - single-strange: Λ, Σ, 12 Λ^*, 7 Σ^* states
    - multi-strange/charmed: Ξ, Ω, Λ_c, Σ_c, Ξ_c, Ω_c
  - 22 mesons
    - non-strange pseudo-scalars: π, σ, f_2, η, η', η_c
    - non-strange vectors: ρ, ω, ϕ, J/Ψ
    - strange: K, K^*
    - charmed: D, D^*, D_s, D_s^*
- each of those is an isospin multiplet (we assume isospin symmetry)
- plus antiparticles

COLLISION TERM

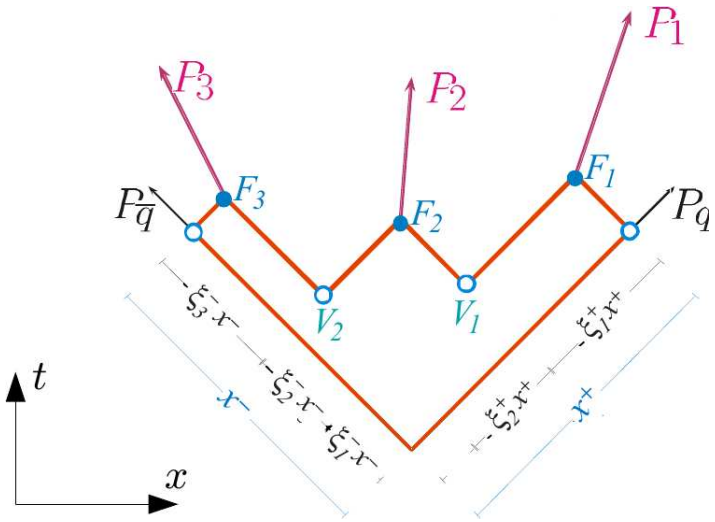
low energies: resonance model

- $\sqrt{s} \lesssim 3GeV$
- assumption: cross sections dominated by resonance formation
- all res. parameters taken from Manley/Saleski PWA (Phys.Rev.D45,1992)



high energies: Lund string model

- PYTHIA 6.4 (Lund string model)
- hard pQCD interactions plus string fragmentation



Dilepton decays

- $V \to e^+e^-$ (with $V = \rho, \omega, \phi$) via strict VMD: $\Gamma(\mu) \propto \mu^{-3}$
- $P \to \gamma e^+e^-$ (with $P = \pi^0, \eta, \eta'$) [Landsberg, Phys.Rep.128, 1985]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{4\alpha}{3\pi} \frac{\Gamma_{P\to\gamma\gamma}}{\mu} \left(1 - \frac{\mu^2}{m_P^2}\right)^3 |F_P(\mu)|^2,$$

- $\omega \to \pi^0 e^+e^-$ [Landsberg]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{2\alpha}{3\pi} \frac{\Gamma_{\omega\to\pi^0\gamma}}{\mu} \left[\left(1 + \frac{\mu^2}{\mu_\omega^2 - m_\pi^2}\right)^2 - \frac{4\mu_\omega^2\mu^2}{(\mu_\omega^2 - m_\pi^2)^2}\right]^{3/2} |F_\omega(\mu)|^2$$

- $\Delta \to N e^+e^-$ [Krivoruchenko, Phys.Rev.D65, 2002]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{2\alpha}{3\pi\mu} \frac{\alpha}{16} \frac{(m_\Delta + m_N)^2}{m_\Delta^3 m_N^2} \sqrt{(m_\Delta + m_N)^2 - \mu^2} \left[(m_\Delta - m_N)^2 - \mu^2\right]^{3/2} |F_\Delta(\mu)|^2$$

- important: form factors well restricted for π^0, η and ω, but completely unknown for Δ! (often neglected)
- NN Bremsstrahlung in soft-photon approximation

POTENTIALS & PROPAGATION

- hadronic mean fields:
  - usually: Skyrme-like potentials

$$U_0(x,\vec{p}) = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma} + \frac{2C}{\rho_0}\sum_{i=p,n}\int \frac{gd^3p'}{(2\pi)^3}\frac{f_i(x,\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2} + d_{symm}\frac{\rho_p(x)-\rho_n(x)}{\rho_0}\tau_i$$

  - or: relativistic mean fields (RMF)
- Coulomb potential
- "off-shell potential" (for density-dependent spectral functions)
- mean-field propagation with dynamical density evolution (according to test particle distribution)

Off-Shell Transport

off-shell EOM for test particles:

[Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

$$
\begin{aligned}
\dot{\vec{r}}_i &= \frac{1}{1-C_i}\frac{1}{2E_i}\left[2\vec{p}_i + \frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i}\right], \\
\dot{\vec{p}}_i &= -\frac{1}{1-C_i}\frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{r}_i}\right], \\
C_i &= \frac{1}{2E_i}\left[\frac{\partial}{\partial E_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial E_i}\right], \\
\chi_i &= \frac{m_i^2 - M^2}{\Gamma_i}, \quad \frac{d\chi_i}{dt} = 0
\end{aligned}
$$

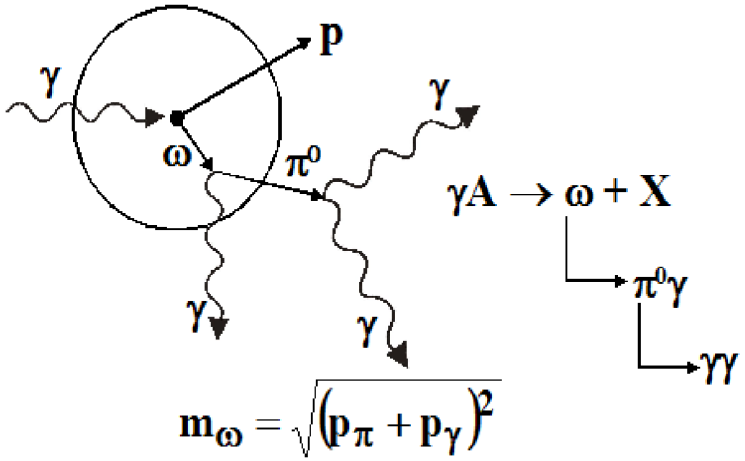
- needed to incorporate density-dependent spectral functions (self energy Σ_i, width $\Gamma_i \sim Im(\Sigma_i)$)
- test particles dynamically change their masses
- but: some approximations required
  - neglecting momentum dependence
  - only works 'close to mass shell'

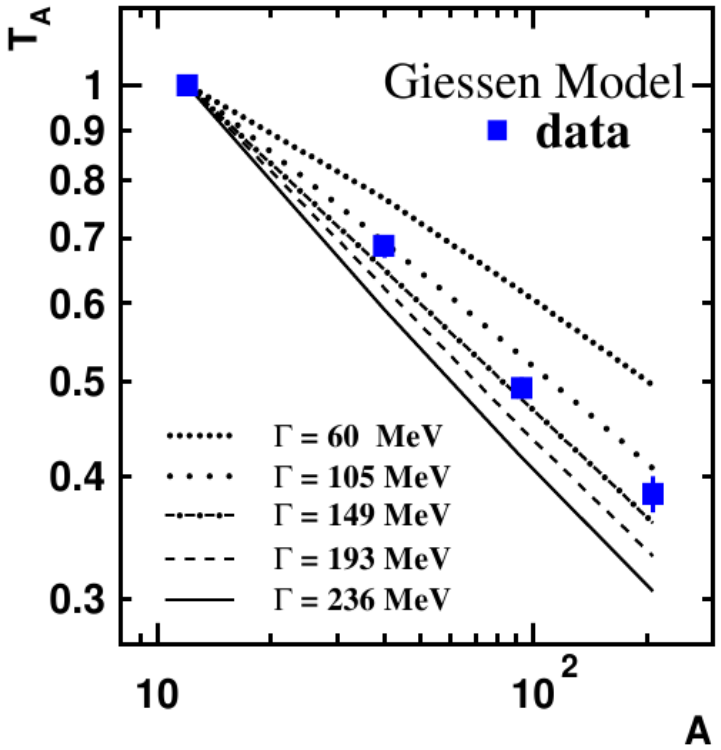
Results I:
ω in medium

(with U. Mosel, V. Metag, M. Nanova, S. Friedrich)

CB/TAPS: $\gamma A \to \omega X$

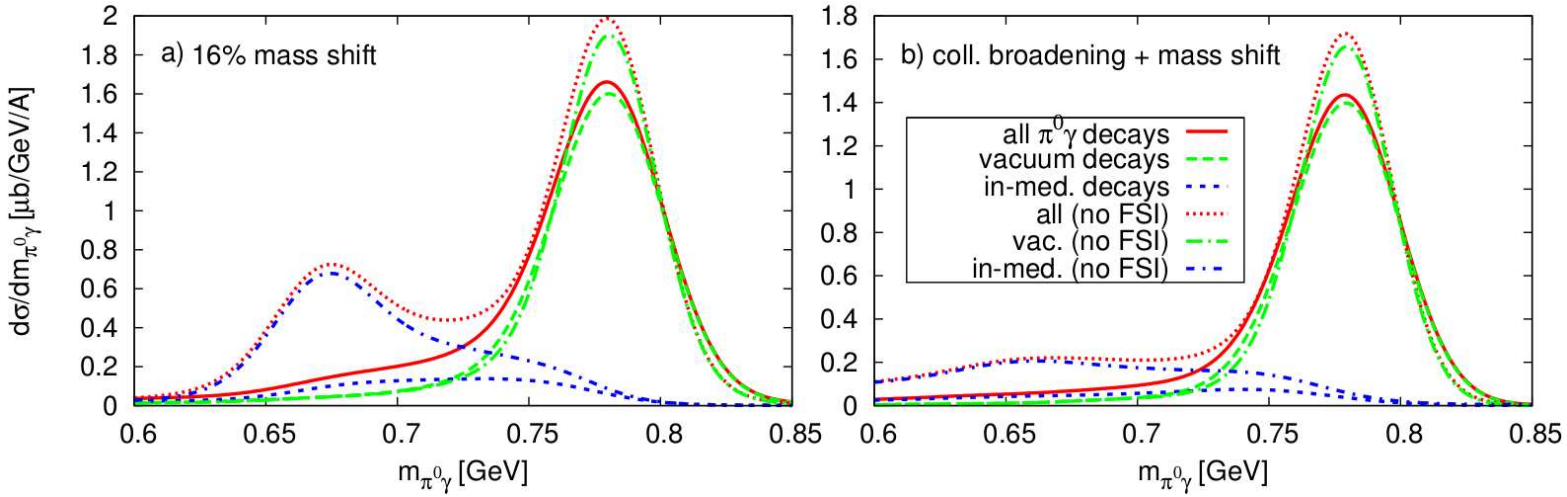
- $\gamma A \to \omega X \to \pi^0 \gamma X \to 3\gamma X$
- measure photon triples
  $\to$ demand that two make up a π^0
  $\to$ reconstruct ω mass
- mass resolution $\sim 25 MeV$
- transparency-ratio measurement (Kotulla et al., PRL 100, 2008)
- $T_A = \frac{12 \cdot \sigma(\gamma A \to \omega X)}{A \cdot \sigma(\gamma^{12} C \to \omega X)}$
- revealed strong broadening/absorption $\Gamma_{coll.} = 130 - 150\,\mathrm{MeV}$





CB/TAPS: mass spectrum

- GiBUU simulations showed: CB/TAPS has insufficient sensitivity to spectral modifications of the ω
- reasons: FSI of π^0 and strong broadening of ω (and limited statistics)
- conclusion: CB/TAPS detector can make no statement about ω mass shift, but has established strong broadening

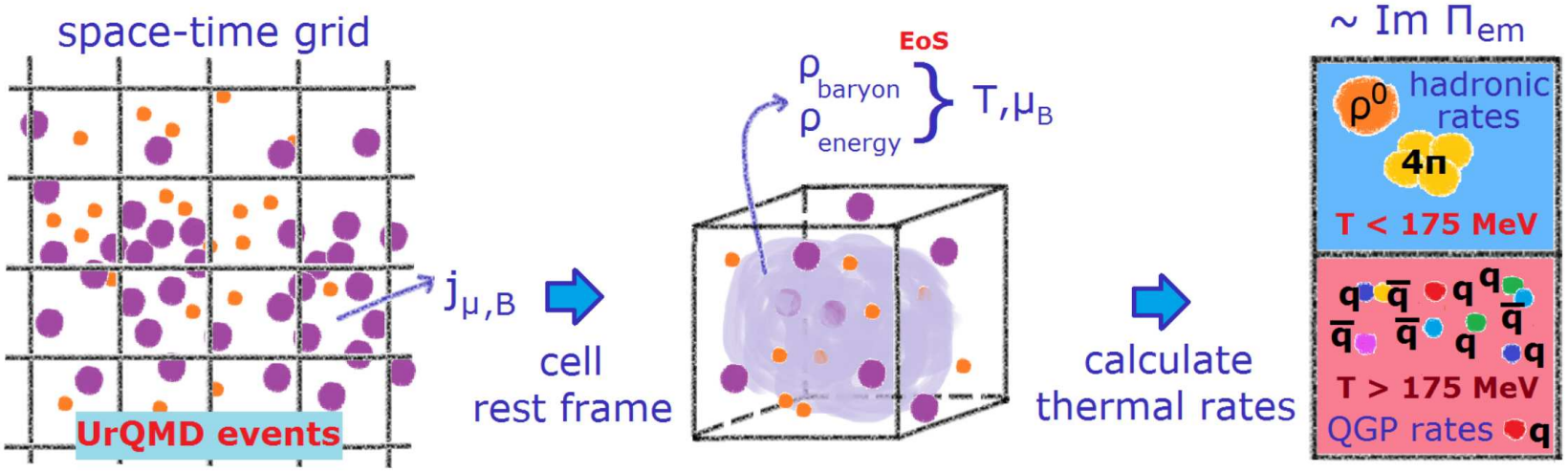


Results II:
ρ in medium

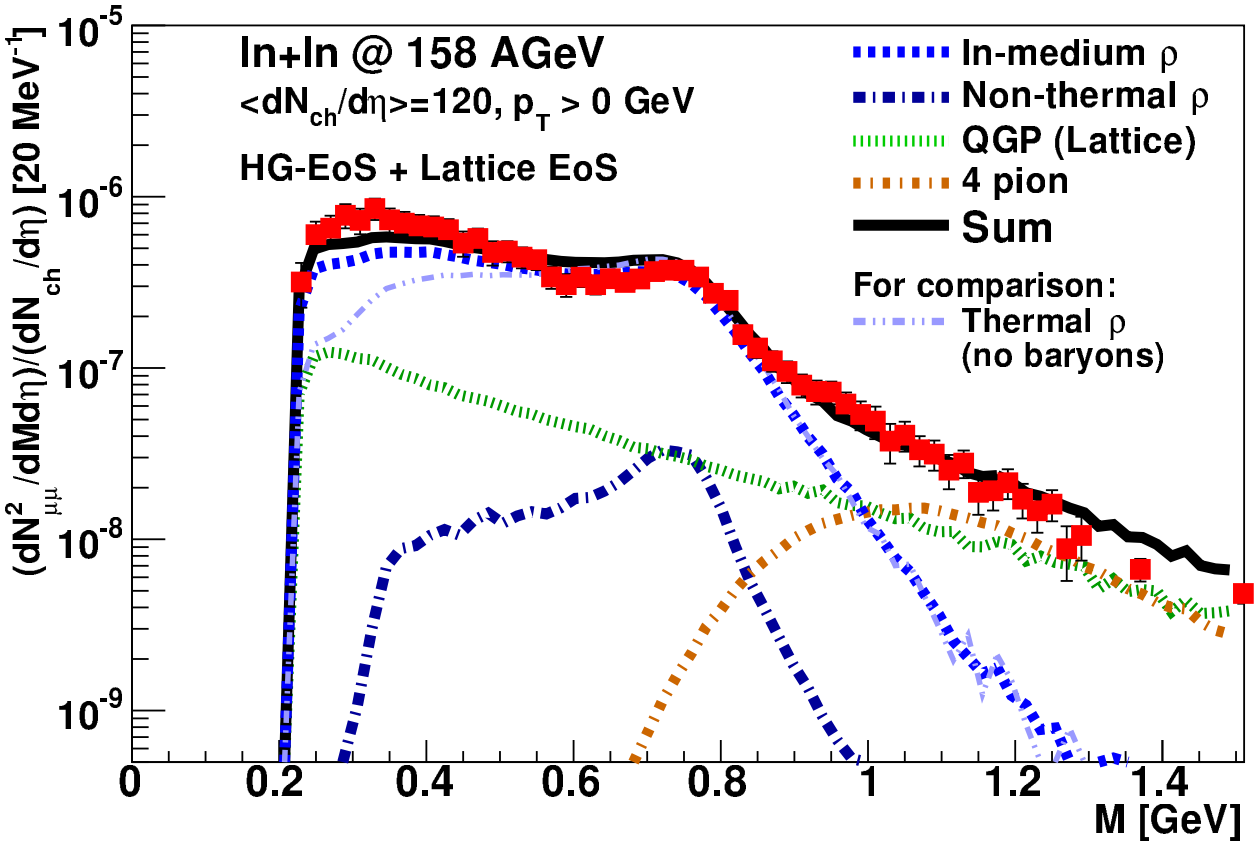
(with S. Endres, H. van Hees, M. Bleicher, U. Mosel)

Heavy-Ion Collisions: "Coarse Graining"

- PhD project of S. Endres
- put UrQMD simulation onto space-time grid
- for each cell, determine baryon and energy density
- use equation of state to calculate local temperature and baryo-chemical potential
- calculate thermal dilepton rates using Rapp-Wambach spectral function (Rapp 1997, NPA 617)

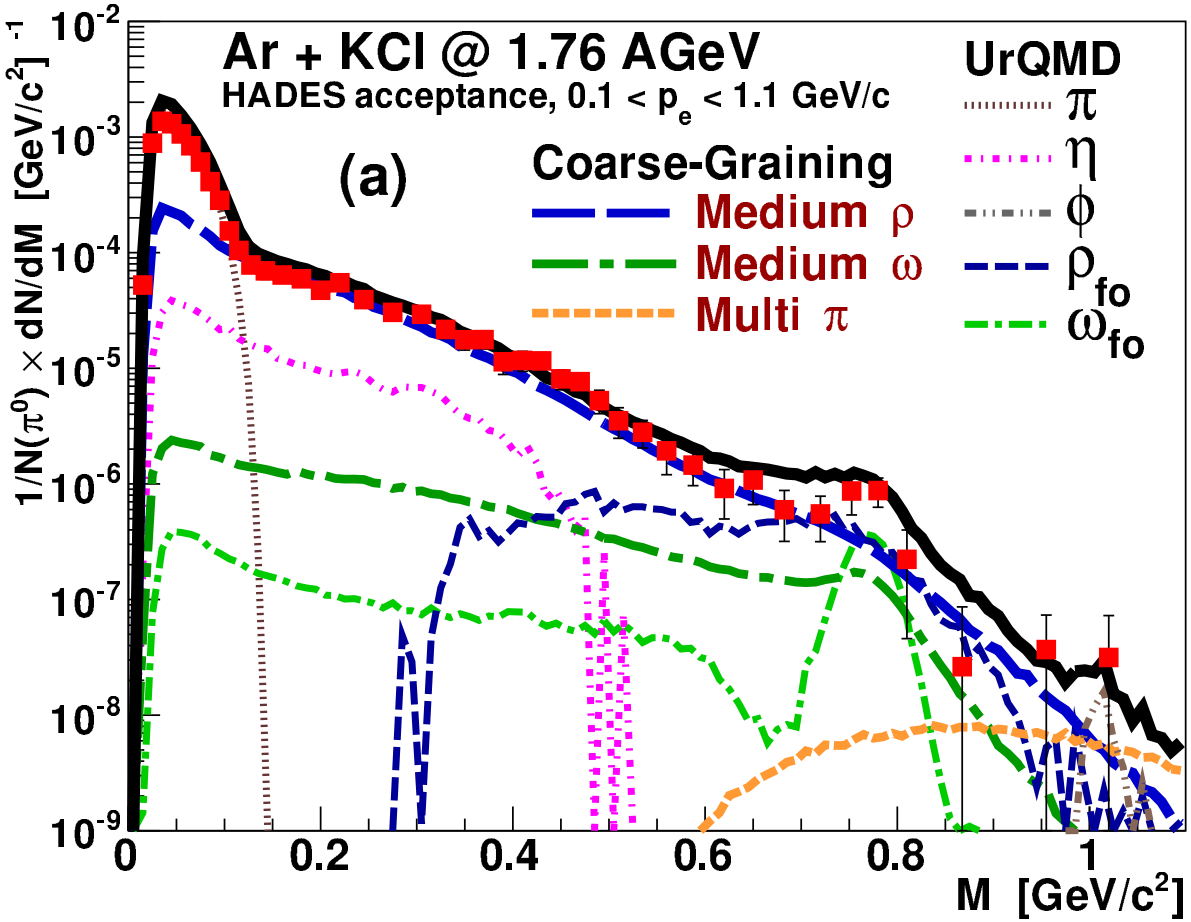


NA60 $\mu^+\mu^-$ spectrum



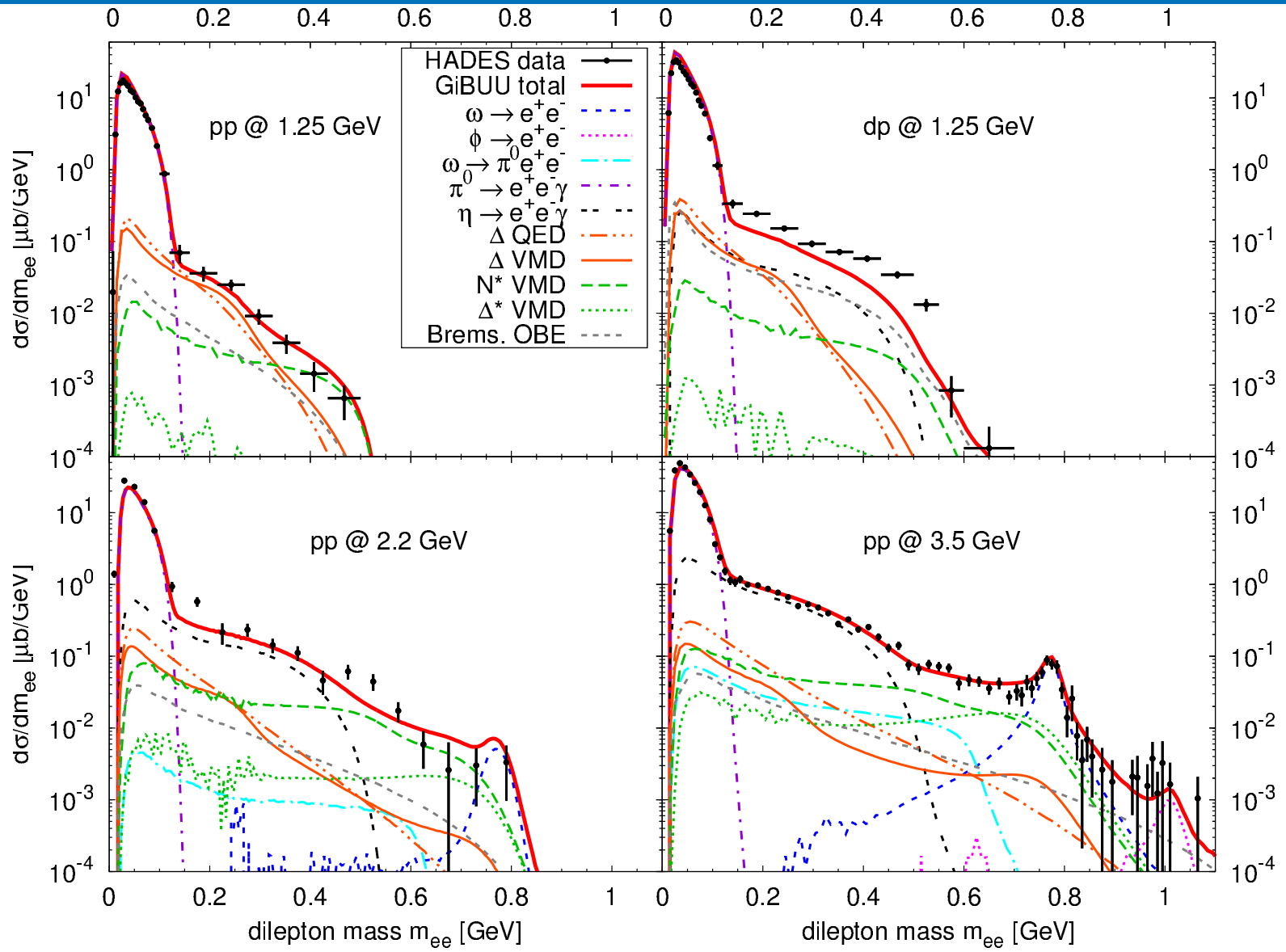
- good agreement with NA60 data, essentially reproducing earlier results by Rapp/Hees (in a simple fireball model)
- benchmark/proof of principle
- plus: more realistic description of collision dynamics

HADES: Ar+KCl at 1.76 GeV



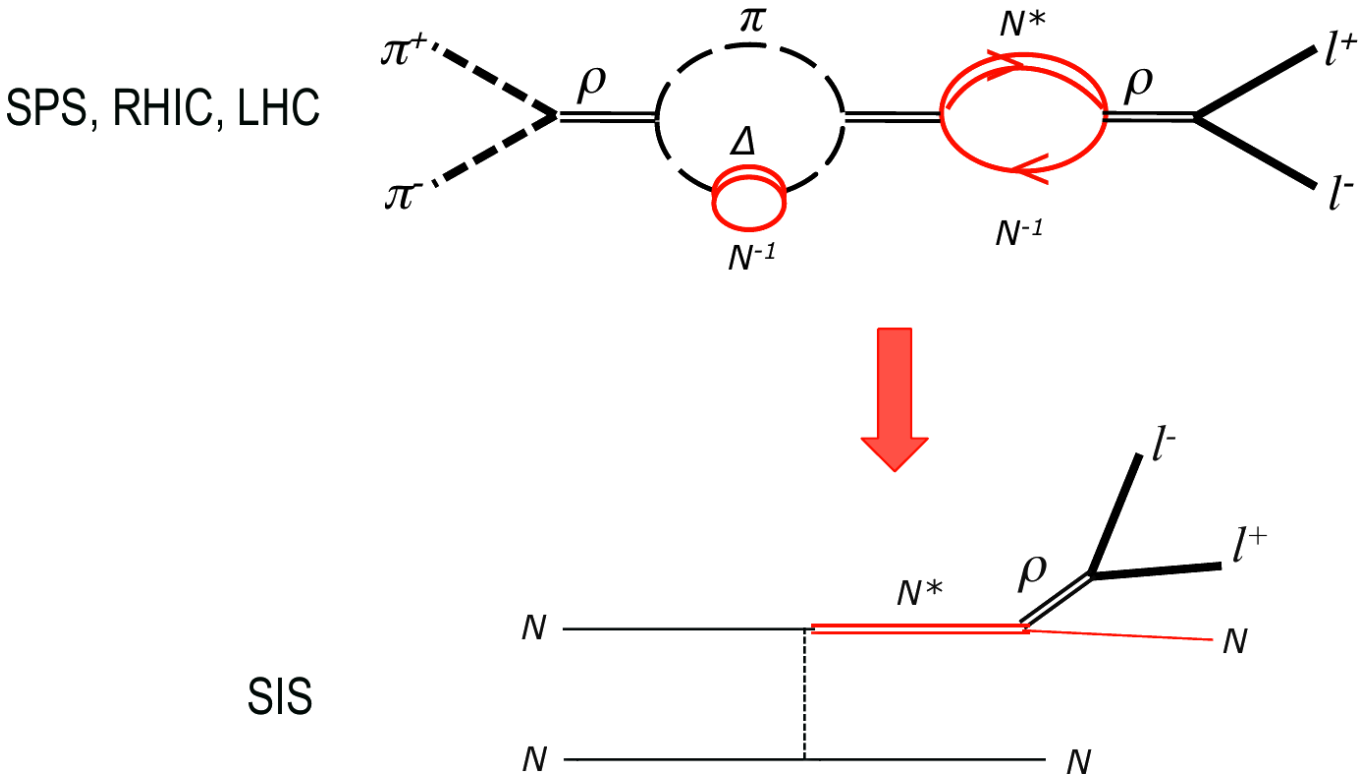
- very good agreement
- dominant ρ in-medium contribution
- baryonic effects are crucial

HADES: pp



ρ shape already nontrivial in pp collision due to production

ρ IN MEDIUM

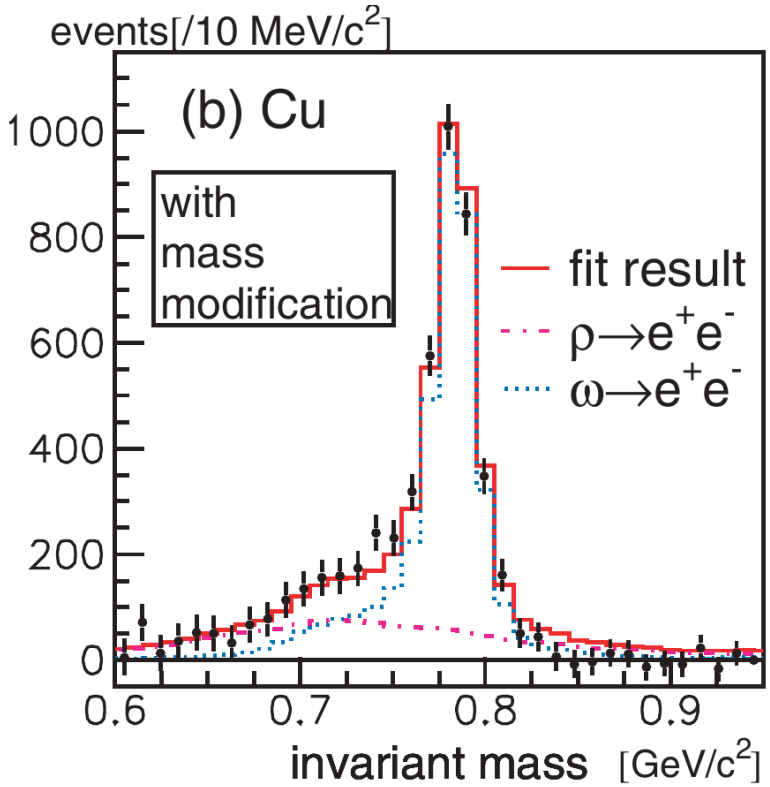


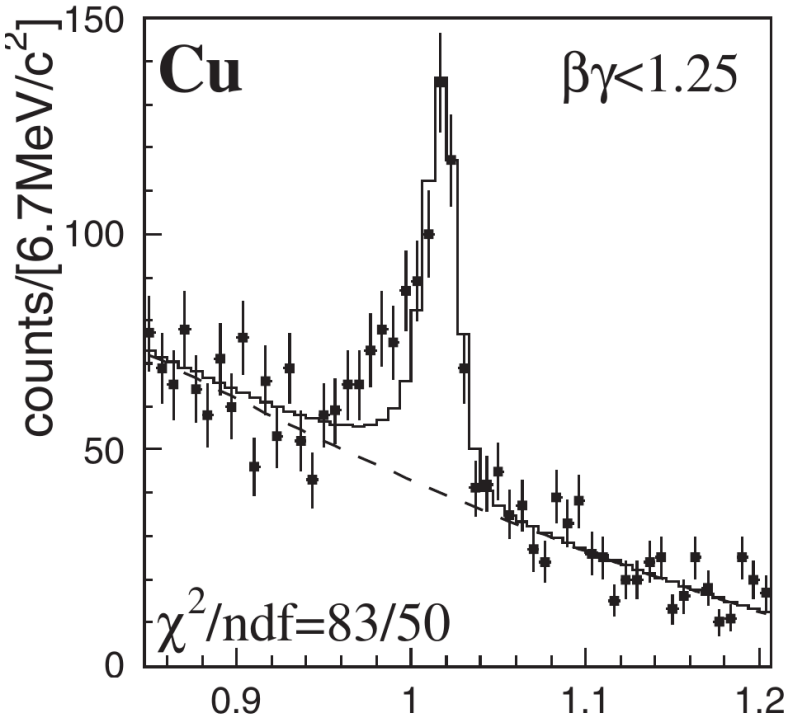
- in-medium properties of ρ dominated by coupling to N^* resonances (coll. broadening!)
- in-medium physics at SPS connected to vacuum physics at SIS

Results III: ϕ in medium

(KEK E325, J-PARC E16)

KEK E325: $p + Cu$ at 12 GeV

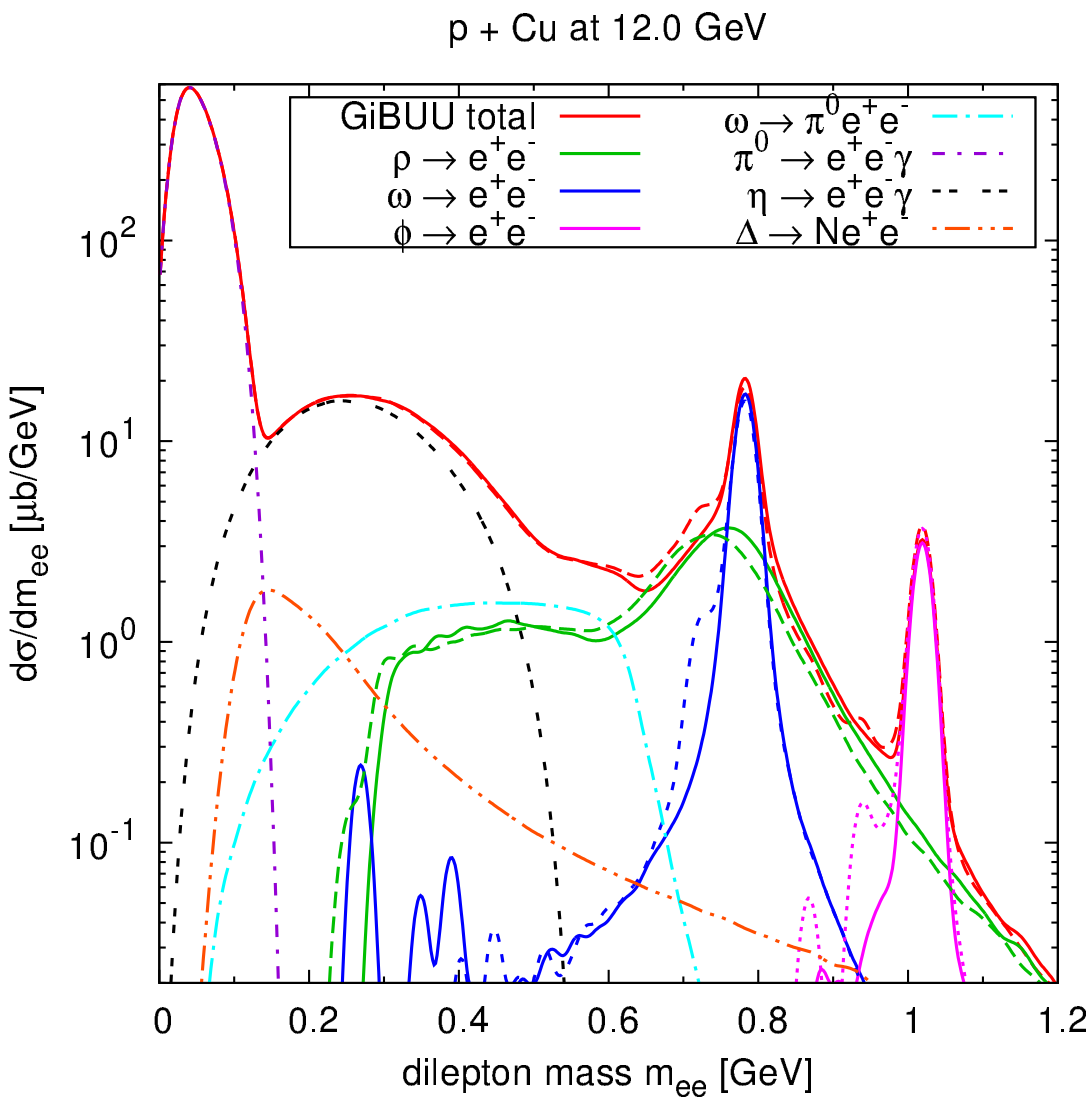




- ρ/ω: 9% mass shift, no broadening [Naruki et al, PRL96, 2006]
- in conflict with NA60 and CB/TAPS!
- ϕ: 3.4% mass shift, broadening factor 3.6 [Muto et al, PRL98, 2007]
- one of the few experiments claiming mass shifts of the vector mesons, heavily debated in the community

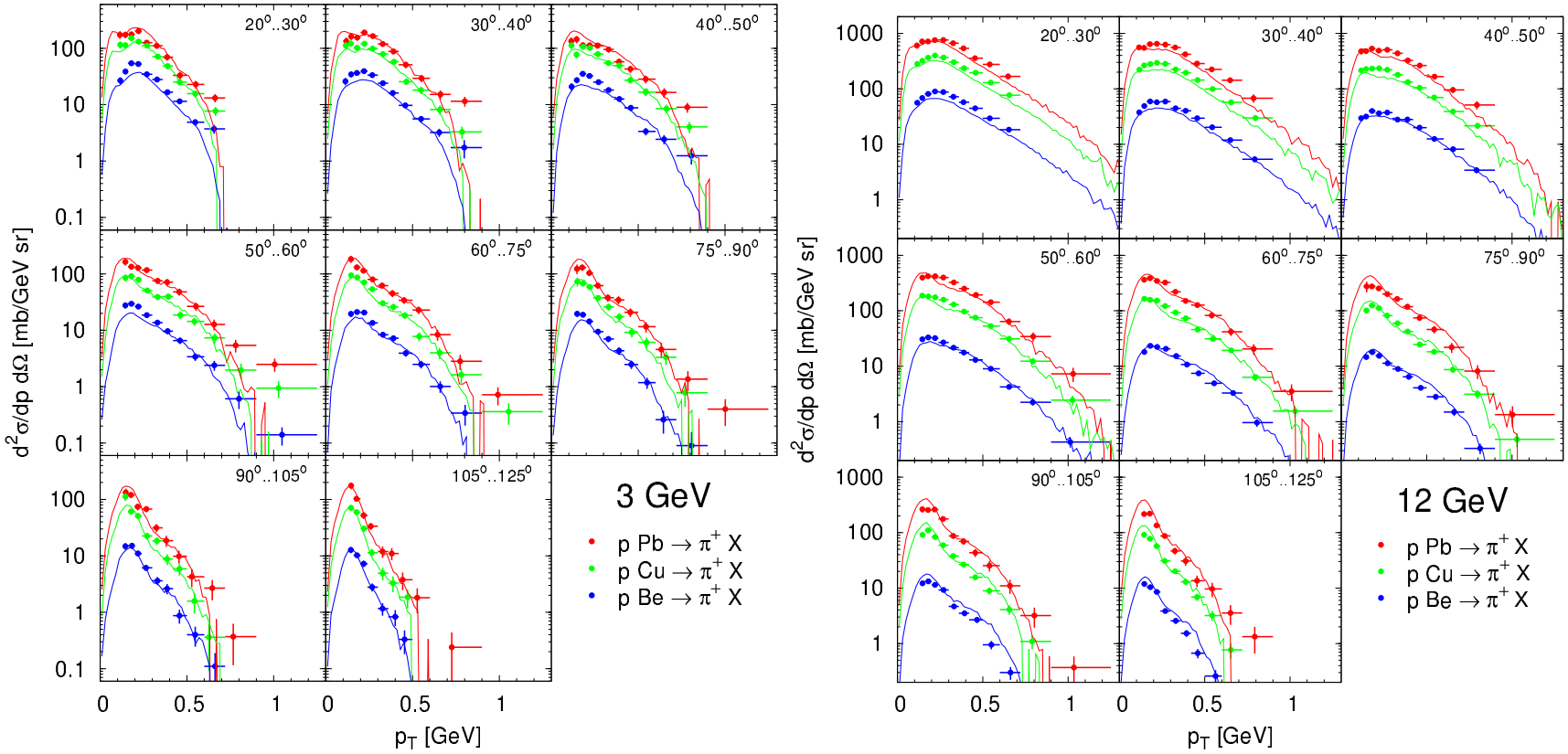
KEK E325: GiBUU simulation (preliminary)

- solid: vacuum SF
- dashed: 9% mass shift, no broadening
- cuts:
  - $0.6 < y < 2.2$
  - $p_T < 1.5\,\mathrm{GeV}$
  - $50^\circ < \theta_{ee} < 150^\circ$
  - $\beta\gamma < 1.25$
- mass resolution: 11 MeV
- todo:
  - do various checks
  - take care of detector acceptance
  - compare with data



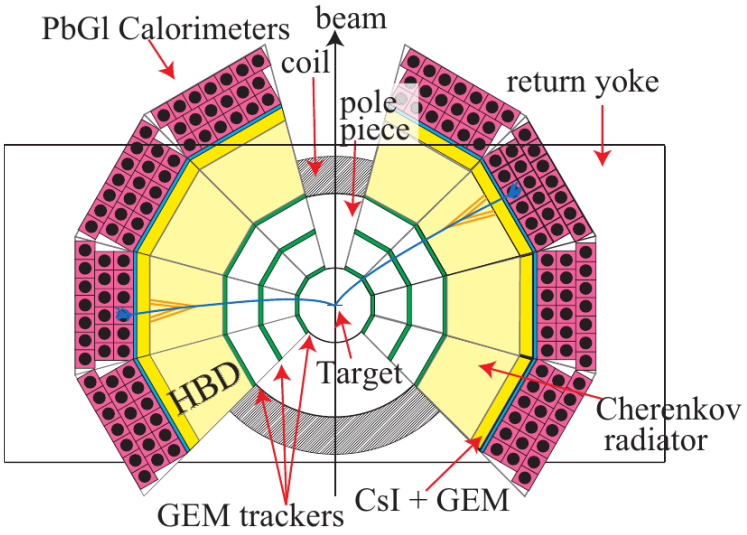
Benchmark: $pA \to \pi X$ (HARP)

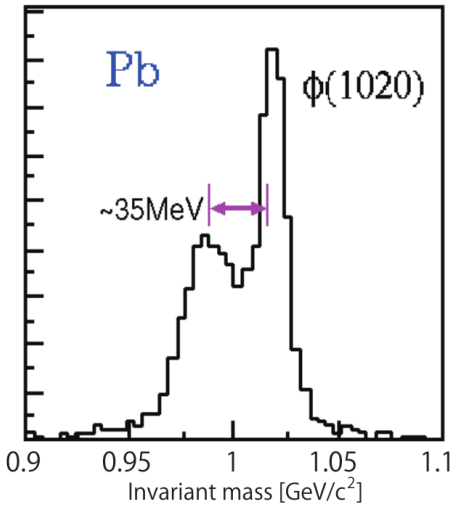
- GiBUU nicely describes inclusive pion production data by the HARP collaboration (Gallmeister et al., NPA 826, 2009)



J-PARC E16: $p + Pb$ at 30 GeV

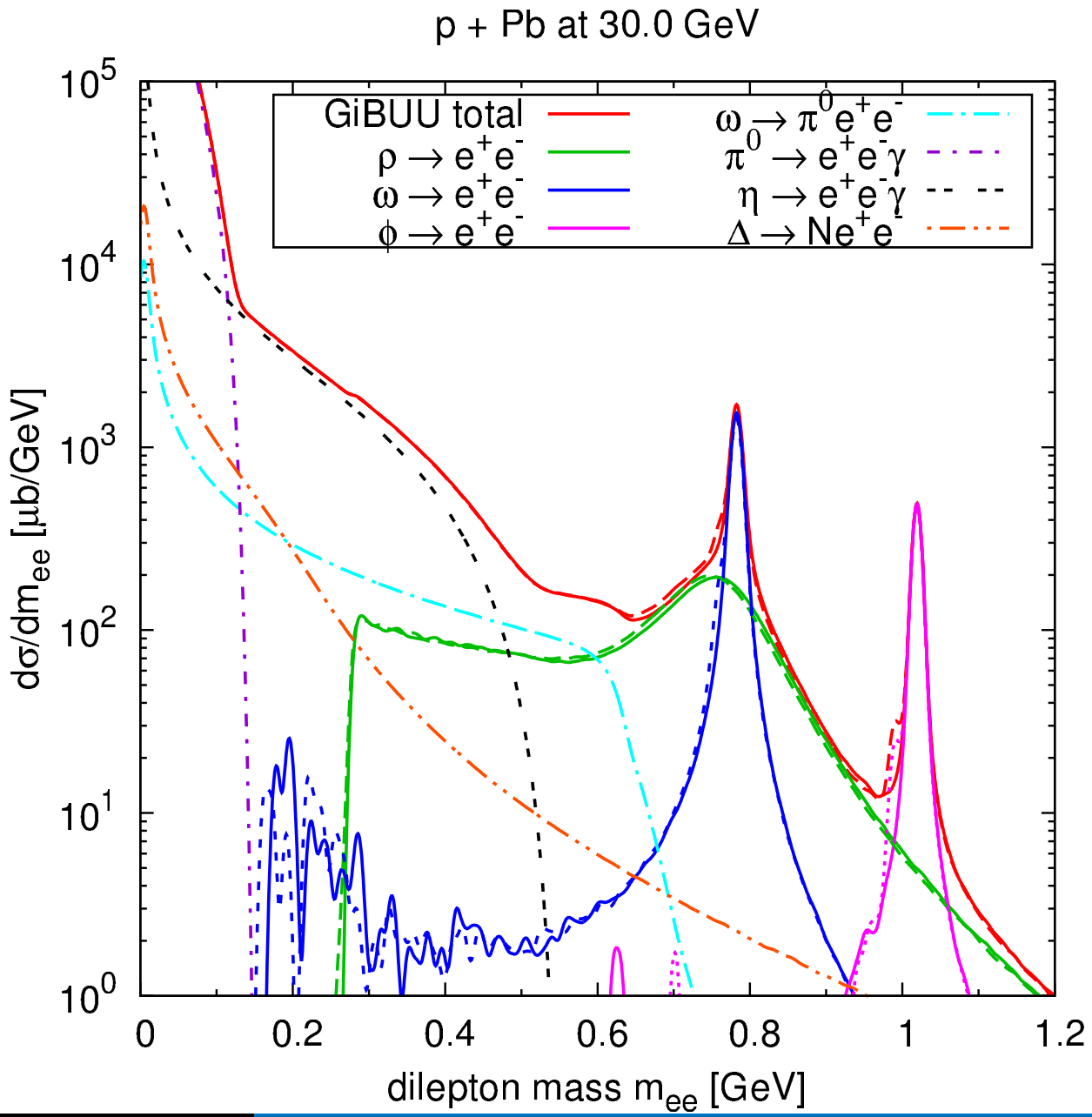
- planned experiment at the high-momentum beamline of J-PARC
- will expand on E325 results, confirm or reject them
- mainly aims for the ϕ (could measure also ρ/ω region?)





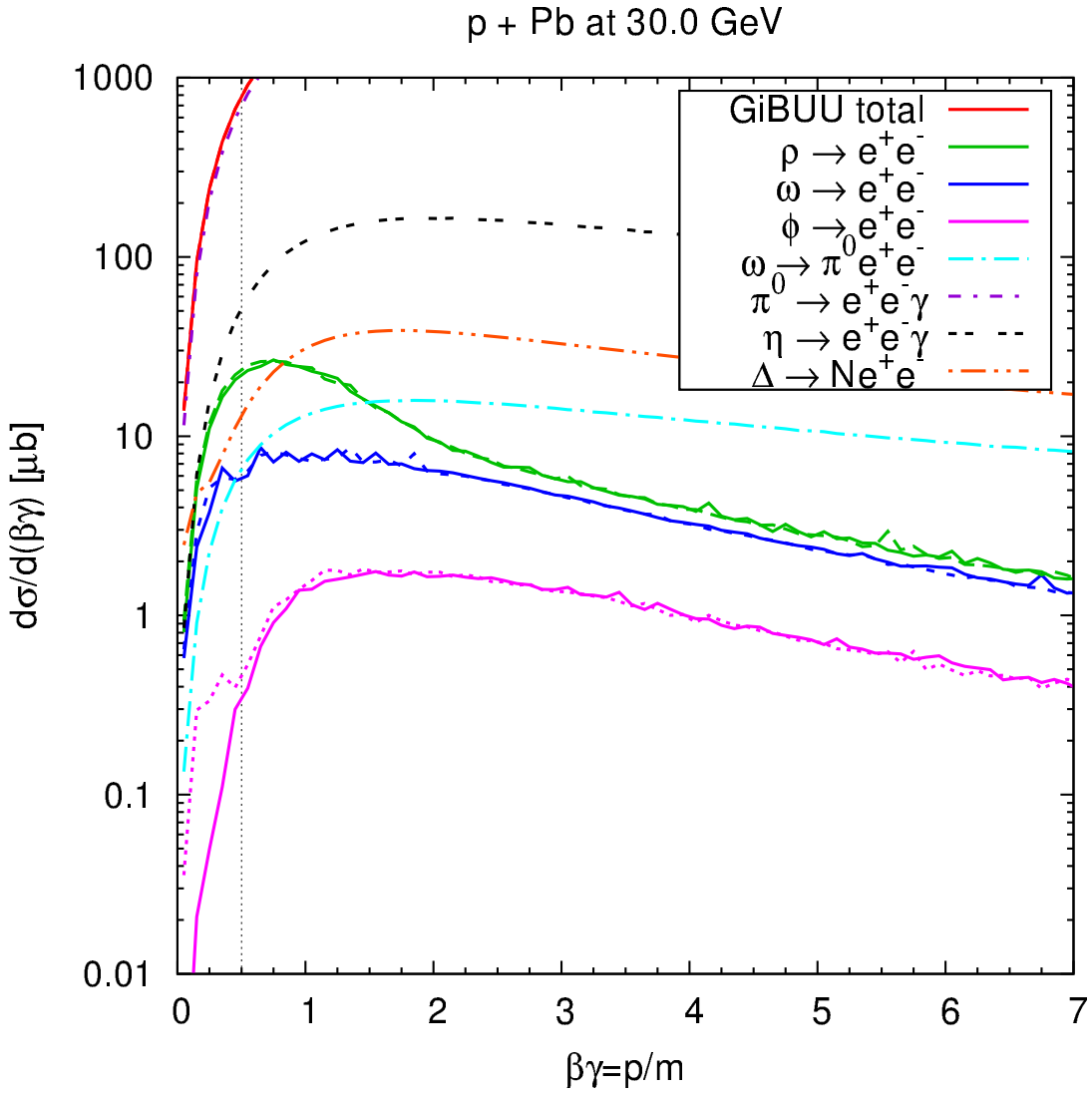
$p + Pb$ at 30 GeV: simulation

- "first shot"
- no cuts
- resolution: 5 MeV
- 3.4% mass shift
- moderate effects visible



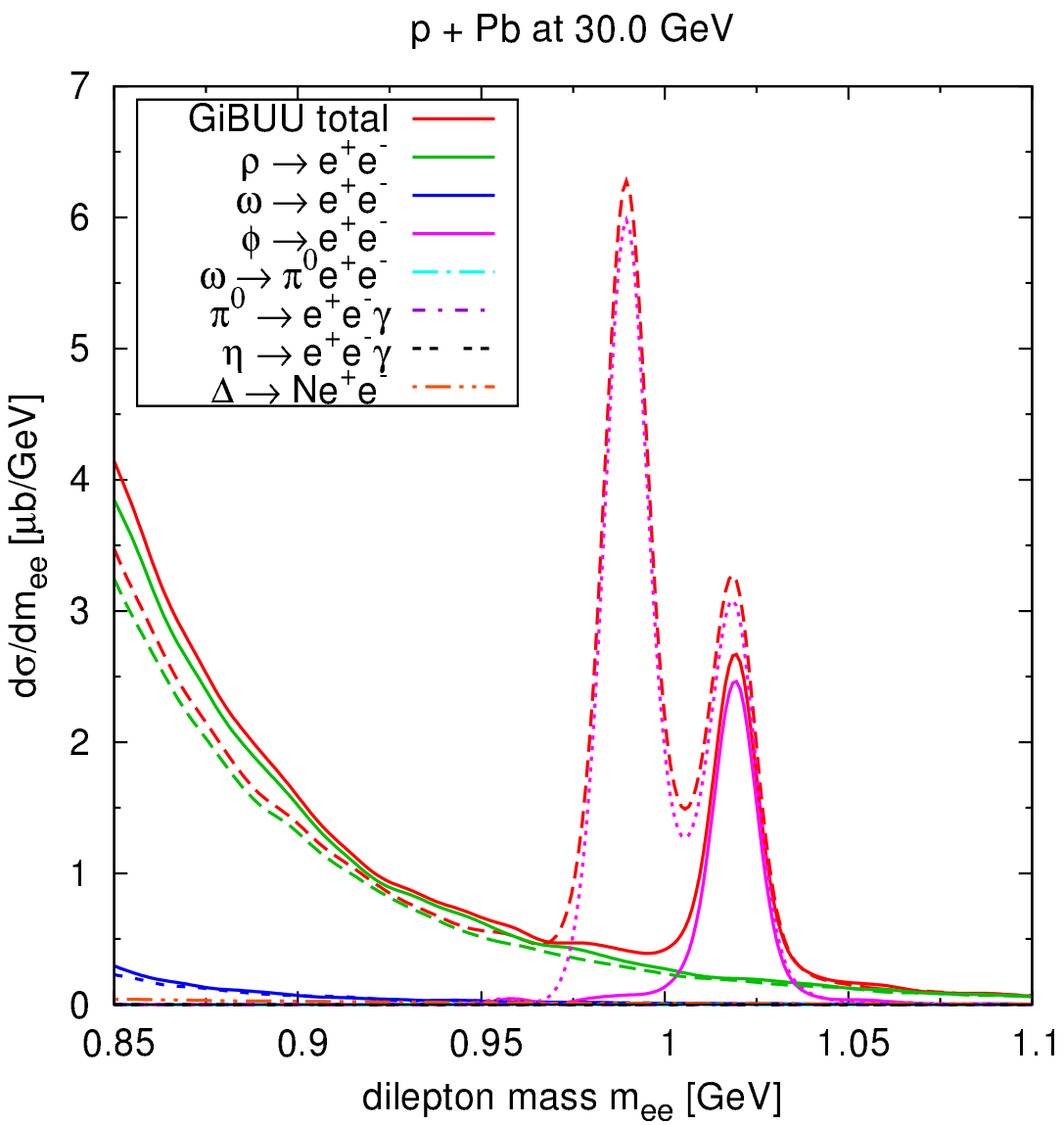
$\beta\gamma$ SPECTRUM

- $\beta\gamma = p/m$
- proposed: cut on small $\beta\gamma$ selects low-momentum ϕ mesons
- larger prob. to decay inside the nucleus
- add. effect: enhanced production of low momenta for shifted ϕ
- cut on $\beta\gamma < 0.5$
- selects a very small fraction of all produced ϕ mesons



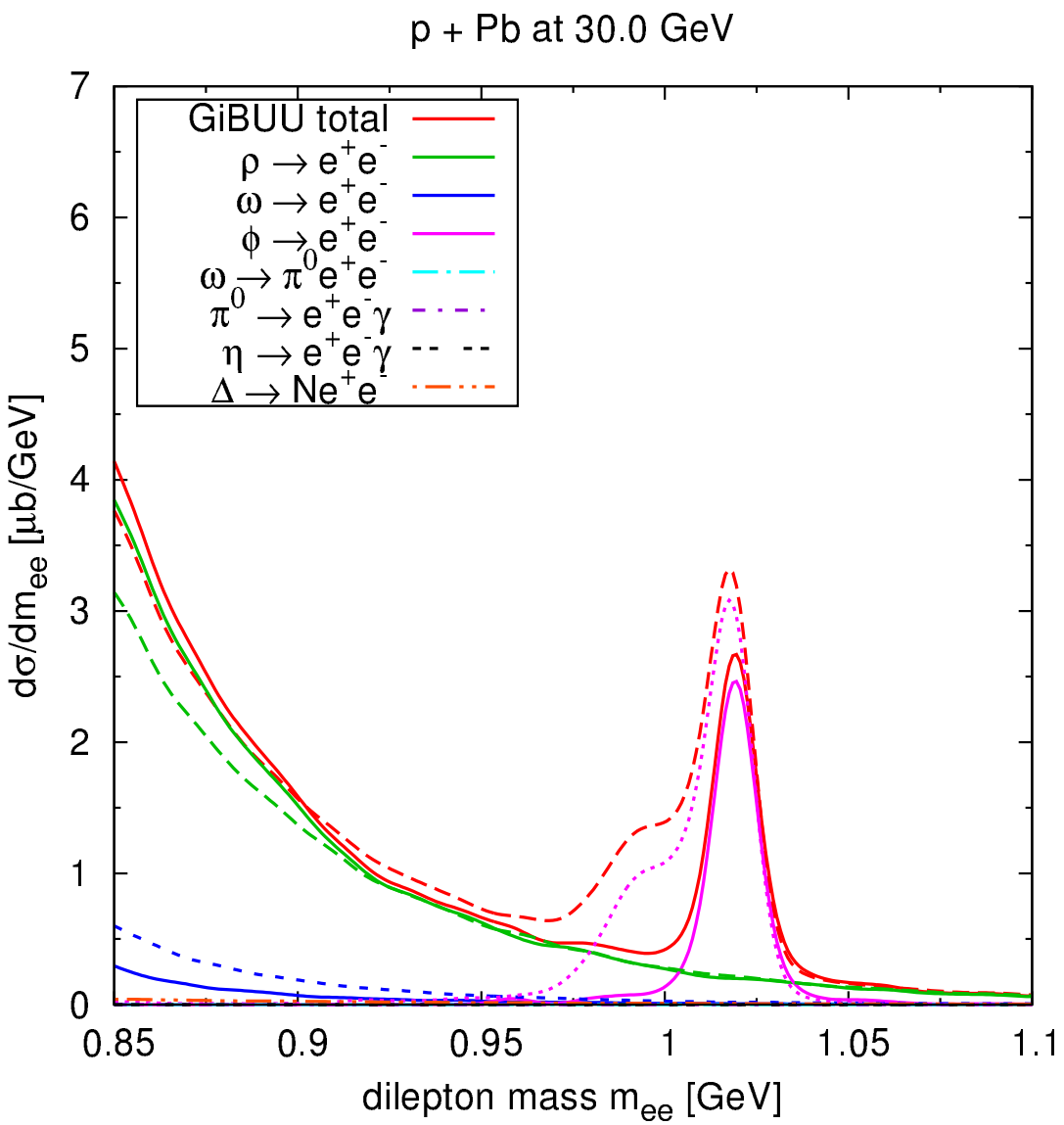
MASS SPECTRUM WITH $\beta\gamma$ CUT

- mass shift of 3.4%
- no broadening
- huge effect
- in-medium peak is stronger than vacuum peak



MASS SPECTRUM WITH $\beta\gamma$ CUT

- mass shift + broadening (factor 3.6)
- much smaller effect
- phase-space enhancement of low momenta not so strong in this scenario



Summary / Conclusions

- exp. situation of VM in-medium properties is still confusing
  - NA60 sees broadening of ρ in AA collisions
  - CB/TAPS established strong broadening of the ω meson in γA
  - KEK-E325 claims to see mass shifts of all light VMs
- transport models are an important tool to understand and interpret exp. results
- J-PARC E16 will hopefully help to clarify the situation
- has good chance to verify or exclude mass shift of the ϕ
- provided it collects enough statistics to make hard cuts