Dilepton Production in Transport Models

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The Agenda

- general intro
  - what's so interesting about dileptons?
  - vector mesons in medium
- the current state of things
  - what has been done in general
  - some important results
- what we can (and have to) do in a transport approach
- electromagnetic Δ transition form factor
  - 2-component model (Ramalho et al)
  - transport treatment: "2-step VMD"
- dileptons with Smash
  - treatment of resonances
  - what it means for dileptons
  - in particular: focus on ω meson

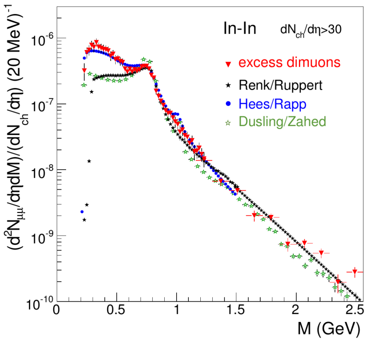
Intro & Motivation

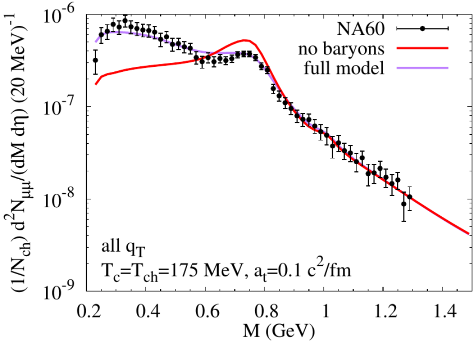
- dileptons (e^+e^-, $\mu^+\mu^-$) are an important probe of physics at high densities and temperatures
- only em. interaction, traverse hadronic medium
- "electromagnetic probe for studying QCD physics"

- vector mesons carry quantum numbers of a 'heavy photon', can directly convert into a lepton pair
- important application of dileptons: observe in-medium spectral function of vector mesons
- naive expectations: broadening or shift of spectral functions at finite density/temperature

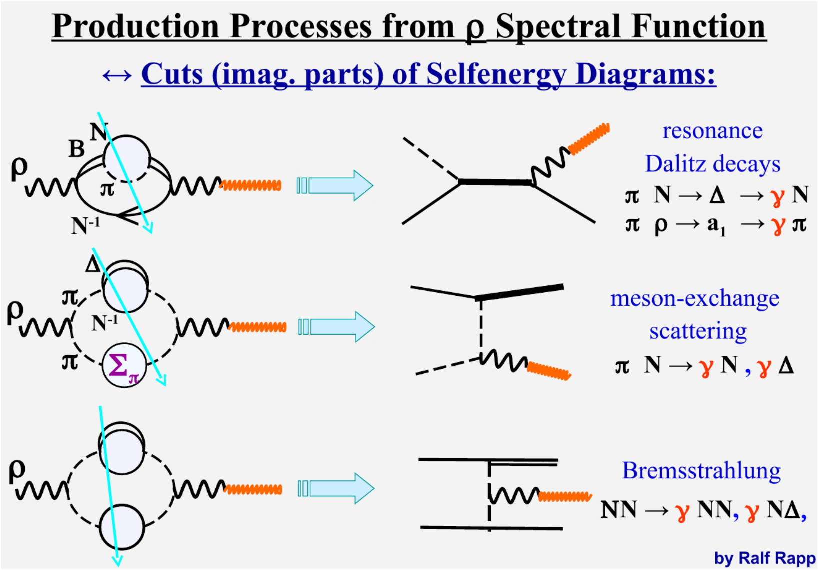
NA60

- important dimuon experiment at CERN-SPS, $\sqrt{s} \approx 17\,\mathrm{GeV}$
- NA60 data showed: ρ^0 spectral function substantially broadened in medium (but essentially no mass shift)
- shown by Rapp/Hees: mainly driven by baryonic effects (coupling to N^* resonances)



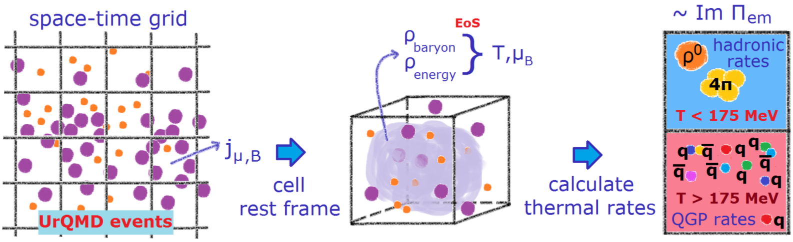


Rapp/Wambach spectral function

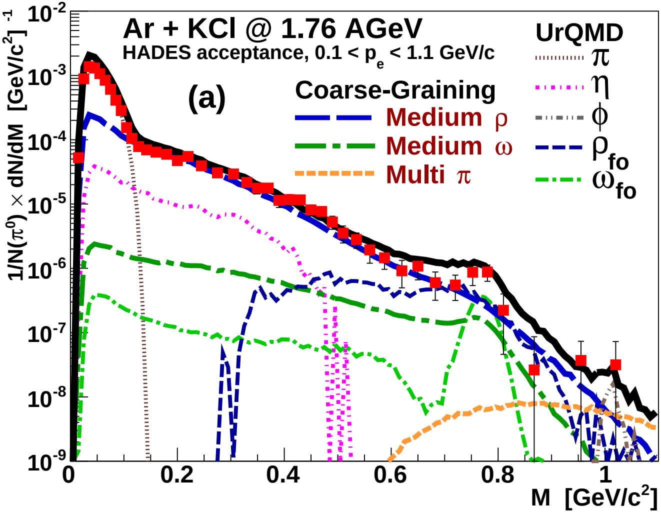


"Coarse Graining"

- PhD project of Stephan 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)



CG: HADES



S. Endres et al., Phys. Rev. C 92, 014911 (2015)

- a "standard model" for dilepton production has emerged ...
- Rapp/Wambach spectral function can explain dilepton data over a large range of energies (HADES, NA60, STAR, ...)
- most important ingredients: couplings of ρ meson to baryonic resonances (N^*, Δ^*)
- many transport models also contain these ingredients (e.g. UrQMD, GiBUU, ..)

- **question**: how far can we get with a transport* description of dilepton production? (* microscopical, off-equilibrium)

DILEPTONS IN TRANSPORT

- basic problem: how to deal with dynamic (i.e. density-dependent) spectral functions

- 'traditional' ansatz: use some externally-provided spectral function (pick your favorite model)
- plug it into the transport model via 'off-shell transport'

- $\Rightarrow$ test-particle masses (representing spectral function) change dynamically with density (even without collisions) off-shell EOM for test particles:

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

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

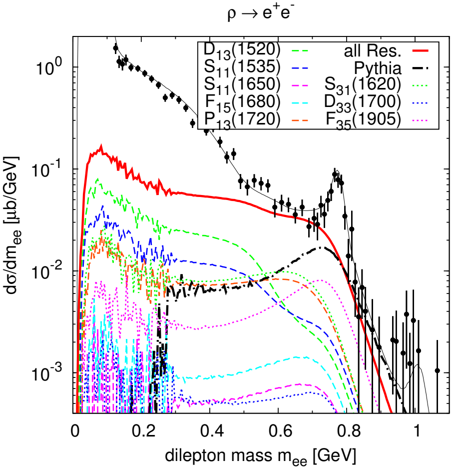
- needed to incorporate density-dependent spectral functions (self energy Σ_i, width $\Gamma_i \sim Im(\Sigma_i)$)
- test particles dynamically change their masses
- but: some approximations required
  - neglecting momentum dependence
  - only works 'close to mass shell'

SHIFTING THE PARADIGM

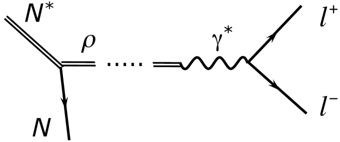
- problem: off-shell transport can only handle 'simple' spectral modifications
- was tried by different people (with different codes):
  M. Effenberger, E. Bratkovskaya, G. Wolf, J.W., ...
- to my knowledge, this approach never actually produced any convincing results

- the alternative: focus more on things that can be intrinsically provided by transport, instead of putting in things from the outside
- transport itself can generate many of the relevant effects
- "collisional broadening" via explicit collisions
- 'off-shell transport' may not even be required:
  with sufficient amount of collisions, SF changes dynamically anyway

- Dalitz decays of baryonic resonances (N^*, Δ^*) give important contributions to dil. spectrum



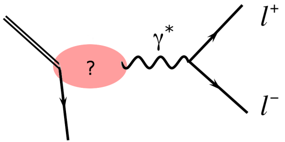
GiBUU simulation of pp@3.5GeV, compared to HADES data



Weil, Hees, Mosel, EPJA 48 (2012) 111

ELECTROMAGNETIC FORM FACTORS

- in general any em. Dalitz decay includes a transition FF



- FF of most mesonic Dalitz decays fixed by data (NA60)
- $\pi^0, \eta \rightarrow e^+e^-\gamma$ (Landsberg):

$$F(m) = \left(1 - \frac{m^2}{\Lambda^2}\right)^{-1}$$

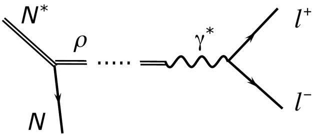
- $\omega \rightarrow e^+e^-\pi^0$ (Bratkovskaya):

$$F(m) = \frac{\Lambda^4}{(\Lambda^2 - m^2)^2 + \Lambda^2\Gamma^2}$$

- parameters Λ, Γ are fitted to data

BARYONIC FORM FACTORS & VMD

- em. FFs of the baryons are harder to grasp experimentally
- there are many N^* and Δ^* states, their contributions are hard to disentangle
- it is almost impossible to separate them out of a given data sample
- our ansatz of using $N^* \rightarrow \rho N \rightarrow e^+ e^- N$ practically corresponds to a vector-meson dominance (VMD) hypothesis
- VMD: "all hadrons couple to the em. sector primarily via vector mesons"
- the two-step procedure does not only provide a mass-dependence, but a full kinematic model of this coupling



Δ em. transition FF

- what about the $\Delta(1232)$?
- Δ em. transition FF measured in spacelike region (electron scattering) and at the real-photon point
- we need a model to extend the FF into the time-like region
- Δ Dalitz decay width (Krivoruchenko et al.):

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q} = \frac{2\alpha}{3\pi q} \frac{\alpha}{16} \frac{(W+m_N)^2}{W^3 m_N^2} \sqrt{(W+m_N)^2 - q^2} \left[(W-m_N)^2 - q^2\right]^{3/2} |F(q^2,W)|^2$$

- q = dilepton mass, $W = \Delta$ mass
- in principle there are three FFs (G_E, G_M, G_C), but G_M dominates strongly for the Δ

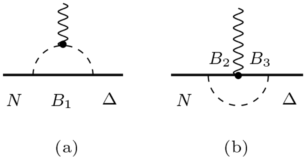
- we will try different approches for the form factor:
  - 'QED' (constant FF, fixed at photon point)
  - two-component model (Ramalho et al)
  - "2-step VMD" (as for N^*)

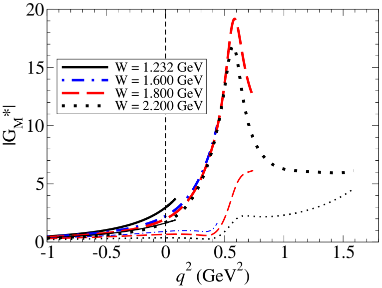
Ramalho/Peña model

- "covariant spectator quark model"
- phenomenological model: bare quark core + meson cloud

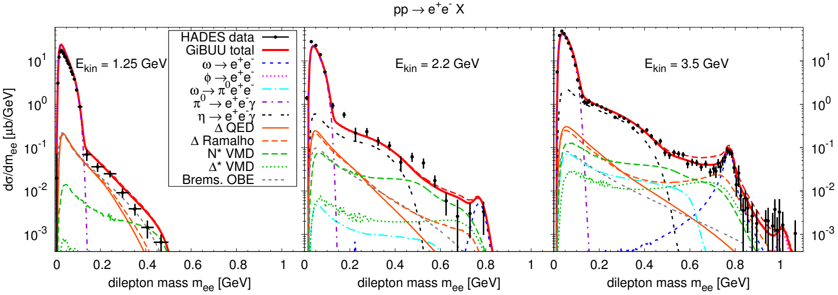
$$G(q^2, W) = G^b(q^2, W) + G^\pi(q^2)$$

- bare quark contribution calibrated with lattice QCD data
- pion-cloud contribution relies on measured pion form factor
- W dependence in pion cloud neglected
- Ramalho et al., arXiv:1512.03764 (accepted for Phys. Rev. D)





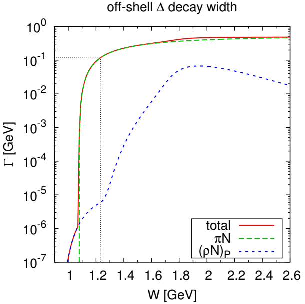
RESULTS WITH RAMALHO FF

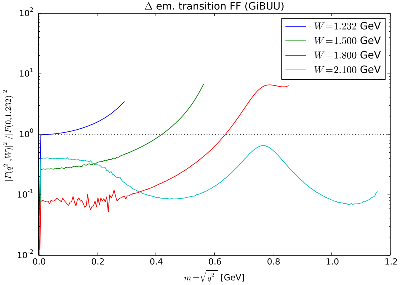


- at low energies FF has only minor influence
- at higher energies it enhances the yield by more than an order of magnitude
- slightly conflicting with HADES data when added to other channels (N^*, Δ^*)

2-step VMD: ρ-Δ coupling

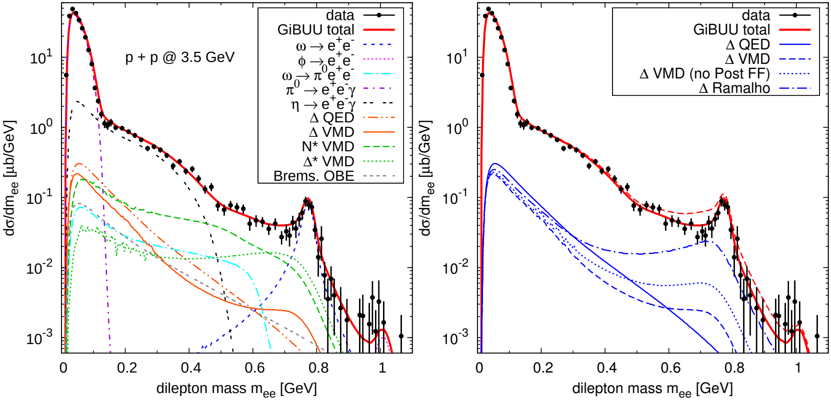
- $\Delta \to \rho N$ coupling can not be directly inferred from PWA of $\pi N \to 2\pi N$ data
- Δ is too light to decay into ρN (on the mass shell)
- but: off-shell Δ can decay into off-shell ρ
- this coupling can be important for dilepton spectra
- we introduce a p-wave decay with an (on-shell) BR of $5 \cdot 10^{-5}$
- $\to$ consistent 2-step VMD approach for all baryons



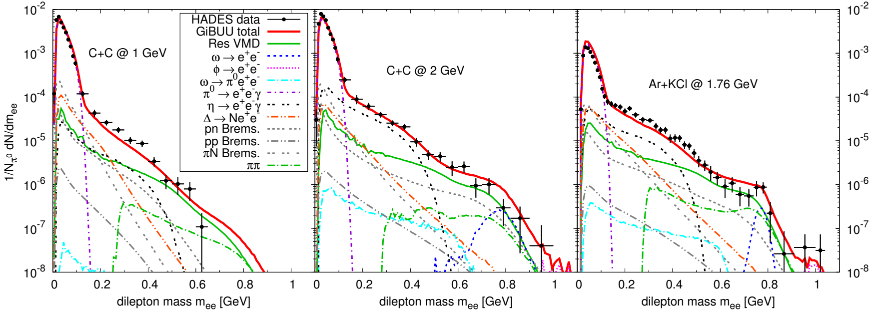


RESULTS WITH 2-STEP VMD APPROACH

- VMD vs Ramalho model
- result: very similar dependence on q^2 (i.e. dilepton mass)
- but: different W dependence (apparently important!)



HEAVY IONS WITH GiBUU



- once the elementary p+p collisions are all properly described, also A+A comes out rather well (but not perfect)
- not much room for additional modifications left (a la off-shell transport), but maybe a bit

INTERMEDIATE CONCLUSION

- 2-step VMD treatment is a reasonable ansatz for baryons
- probably the best we can do in a transport approach for now
- seems compatible with basically all the dilepton data measured by HADES
- some details yet to be clarified (coupling constants for particular resonances, etc)

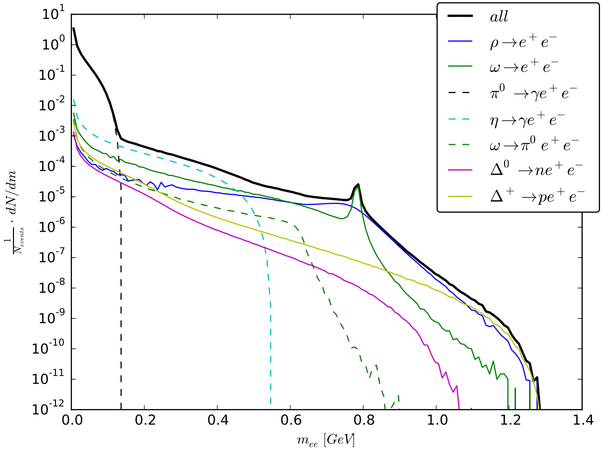
Dileptons with Smash

- SMASH: new hadronic transport model developed in group of Hannah Petersen
- still "in the making" (currently v0.9), but already yields some interesting results
- results shown here: so far only qualitative, need to be worked out further (no detector acceptance yet, etc)
- dilepton implementation started by Jan Staudenmaier (as BSc project)

SMASH: RESONANCE IMPLEMENTATION

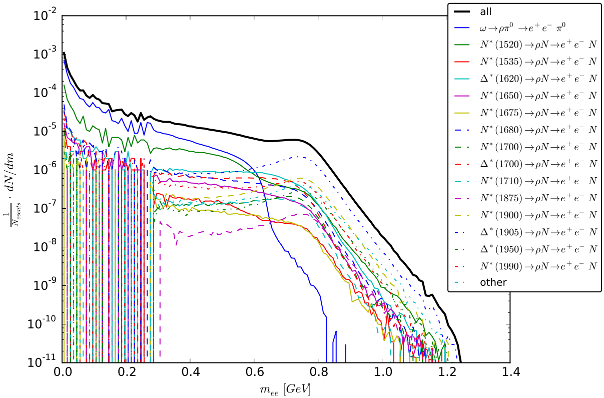
- primary particle production mechanisms in few-GeV regime:
  - $NN \rightarrow B_1 B_2$
  - $\pi N \rightarrow B$
- with baryons $B = N, N^*, \Delta, \Delta^*$
- essentially all mesons ($m = \pi, \eta, \rho, \omega, \ldots$) produced via B^* decays, $B^* \rightarrow mN$ etc
- model currently only contains $1 \leftrightarrow 2$ and $2 \leftrightarrow 2$ processes (in order to strictly fulfill detailed balance)
- no string fragmentation yet
- ω meson:
  - dominantly decays into 3π ($\sim 90\%$)
  - $\omega \rightarrow 3\pi$ emulated by decay chain $\omega \rightarrow \rho\pi \rightarrow 3\pi$ in Smash

EXAMPLE SPECTRUM: P+P @ 3.5 GEV



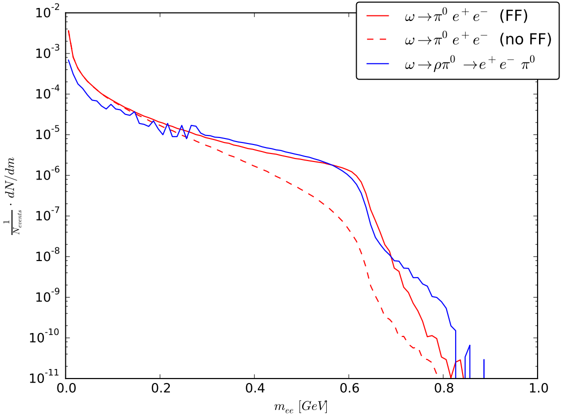
- most channels as expected (std Dalitz decays etc)
- ρ includes Dalitz-like contributions from N^* decays
- most surprising: ω

ρ-like contributions (B^* Dalitz decays)



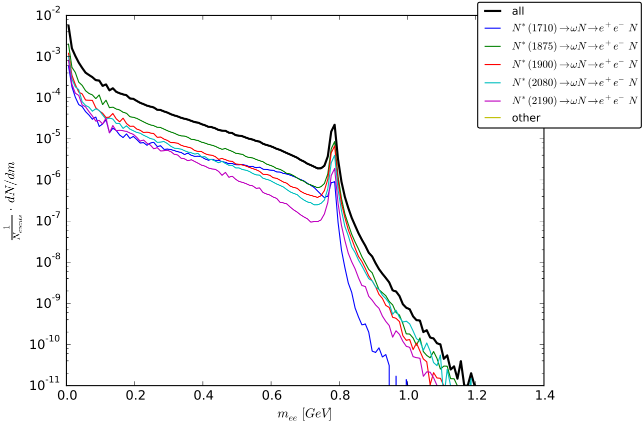
- whole cocktail of N^* and Δ^* decays
- different shapes (mostly determined by res. mass)
- plus: "feed-down" from ω (aka ω Dalitz decay)

ω Dalitz decay



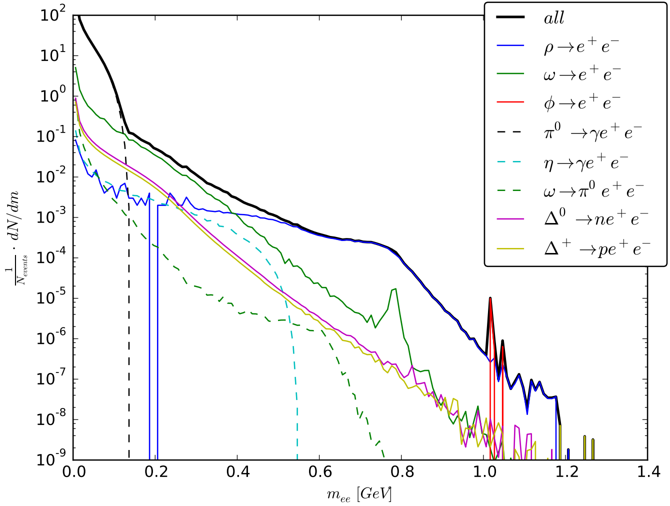
- red: Dalitz decay with FF (FF: fit to data by E. Bratkovskaya)
- blue: 2-step decay via ρ
- both are reasonably similar, but do not agree fully
- to do: compare to NA60 data for ω FF

ω-like contributions (N^* Dalitz decays)



- again: contributions from several N^* resonances
- structure: peak at ω pole mass, plus Dalitz-like tail

Outlook: Au+Au @ 1.25 GeV



- fully dominated by baryonic Dalitz decays via ρ and ω
- preliminary! further checks required ...

Summary / Conclusions / Outlook

- 2-step VMD approach shows good results for ω Dalitz FF
- also seems like a reasonable ansatz for the Δ (as well as N^*, Δ^*)
- em. Dalitz decays of N^* resonances not only through ρ, but also through ω meson

- to do for Smash:
  - apply detector acceptance
  - compare to pp data
  - possibly adjust some res. properties (branching ratios etc)
  - look at heavy-ion data
  - cross-check with pion beam