Dilepton anisotropic flow in hadronic transport

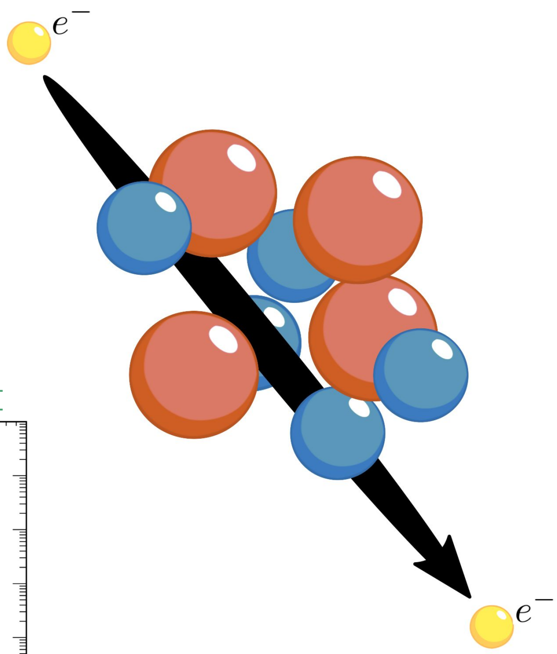
Renan Hirayama and **Hannah Elfner**

October 2nd, 2023

HFHF Retreat + STRONG 2020, Giardini Naxos, Sicily

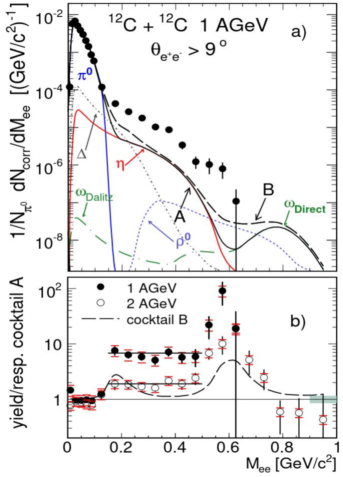
1. Dilepton as probes

Pairs of single-origin, opposite charge leptons



- No strong interaction ⇨ leave the medium undisturbed
- Multi-messenger: *spectrometer, chronometer, barometer, thermometer, ...*
- Experimental difficulties:
  - rare probes $\mathrm{BR}(h \to l^+ l^-) \sim 10^{-5}$
  - combinatorial background

HADES



[PLB 663, 43 (2008)]

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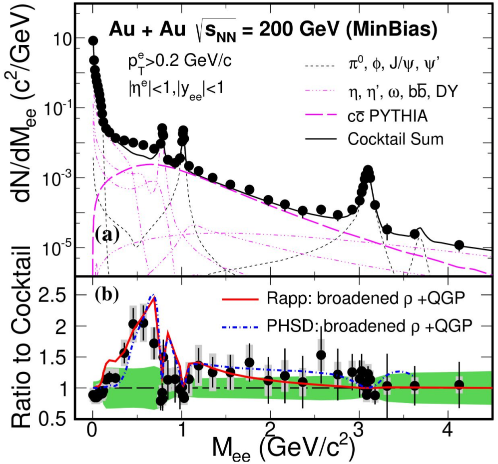
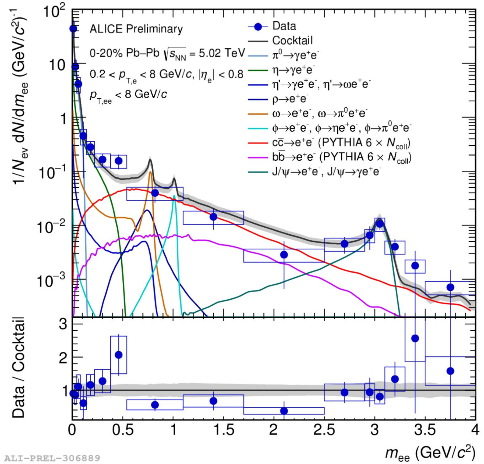


[PRL. 113, 022301 (2014)]

ALICE



[J.Phys.Conf. 1602, 012016 (2020)]

2 "dilepton" talks + few mentions!

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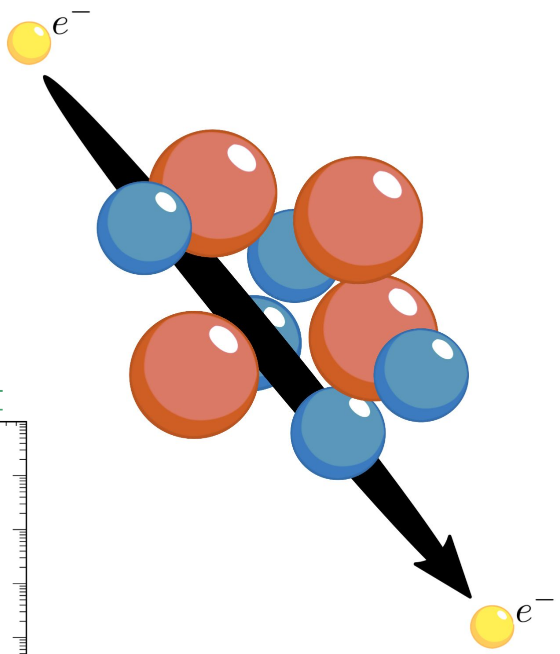
This work: Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV, 0-40%



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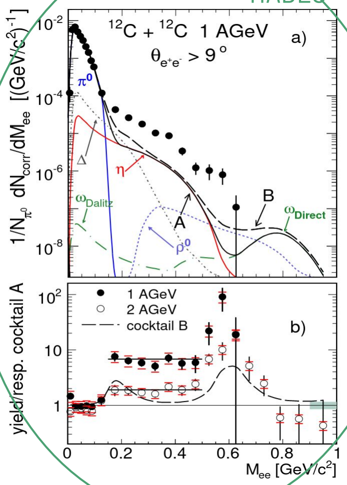

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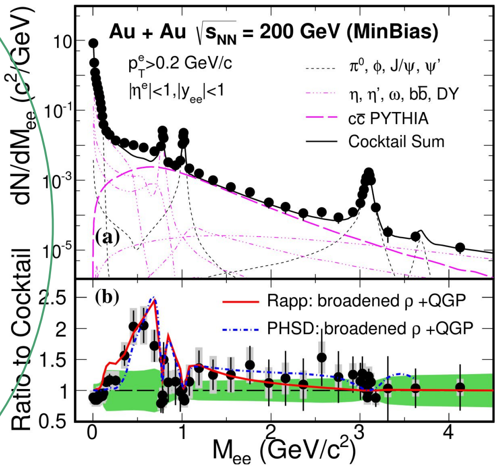

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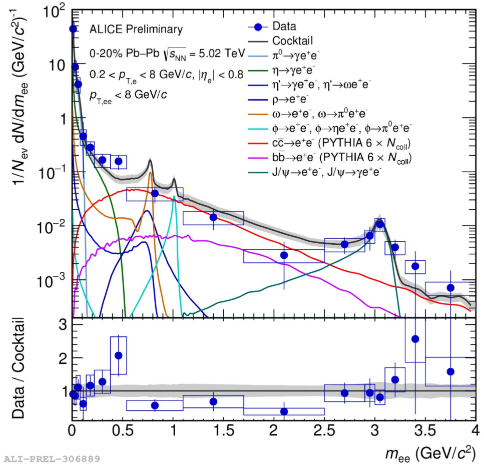


[J.Phys.Conf. 1602, 012016 (2020)]

2 "dilepton" talks + few mentions!

2. the SMASH approach

Simulating Many Strongly-interacting Hadrons

smash

https://smash-transport.github.io/

Hadrons

- Hadrons evolved with the relativistic Boltzmann equation (BUU)

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial_\alpha^p f_i(x,p) = C^i_{\text{coll}}$$

- Scatterings determined geometrically from "bottom-up" cross sections

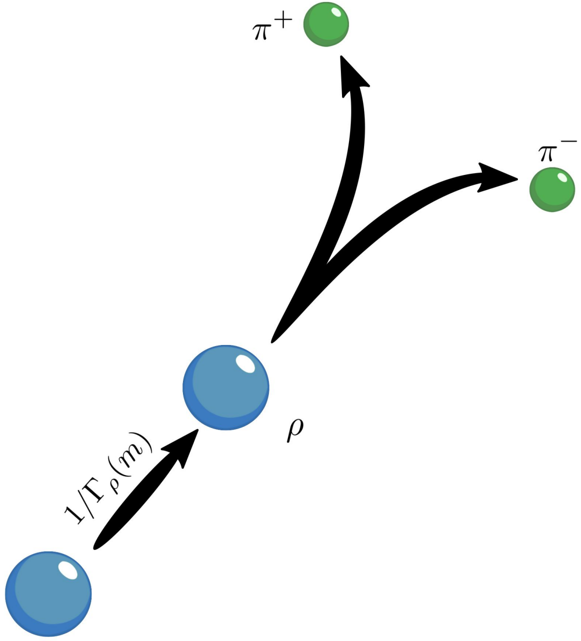
$$\pi d^2_{\text{trans}}(a,b) < \sigma_{\text{tot}}(a,b) = \sum_R \sigma_{ab\to R} + \sum_{cd} \sigma_{ab\to cd}$$

- Mass-dependent width for hadronic decays

$$\frac{\text{Prob}(R \text{ decays in } \Delta t)}{\Delta t} = \Gamma_R^{\text{vac}}(m) = \sum_{ab} \Gamma_{R\to ab}(m)$$

Vacuum properties a priori

[J. Weil et al, PRC 94 (2016) 5, 054905]



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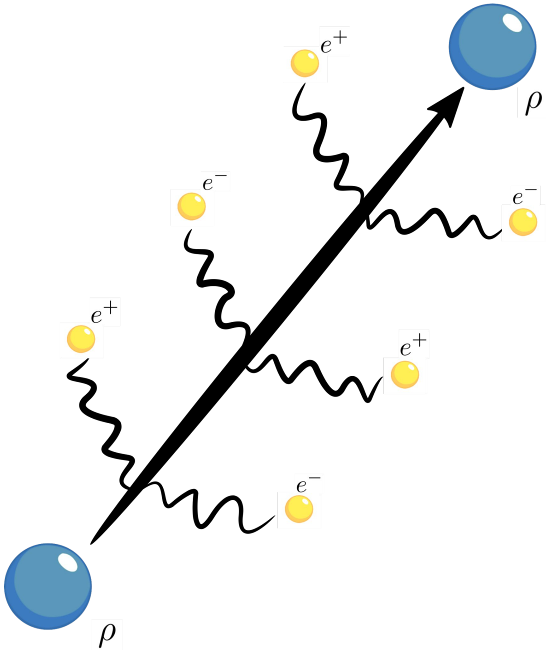
- Electromagnetic coupling is much smaller than strong coupling
- Stable hadrons decay at the end
- Time-integration: perturbative treatment for dilepton emission

$$w_{R\to l^+l^-}(\tau) = \int_{t_0}^{\tau - t_0} \frac{\text{d}t}{\gamma} \Gamma_{R\to l^+l^-}(m_R)$$

[U. Heinz and K. S. Lee, Nucl. Phys. A 544, 503 (1992)]
[G.-Q. Li and C. M. Ko, Nucl. Phys. A 582, 731 (1995)]

- At every time step the particle radiates a lepton pair, carrying *the shining* weight



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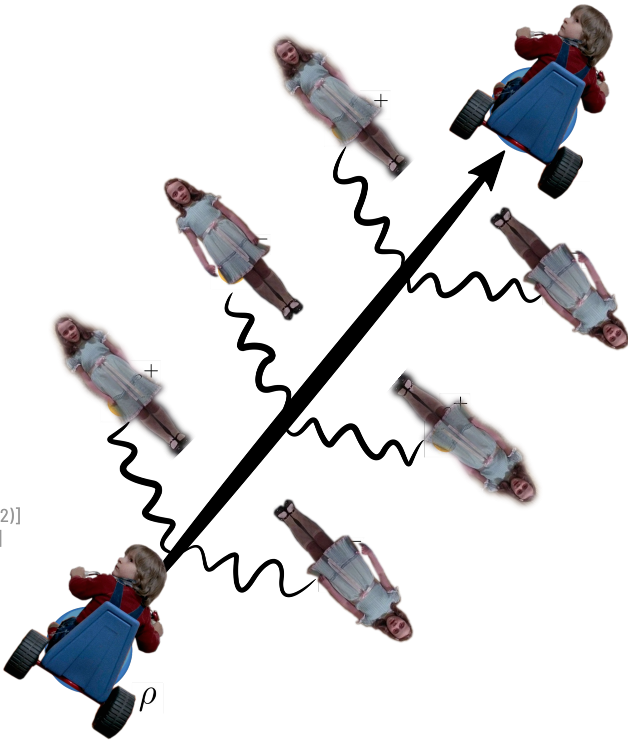

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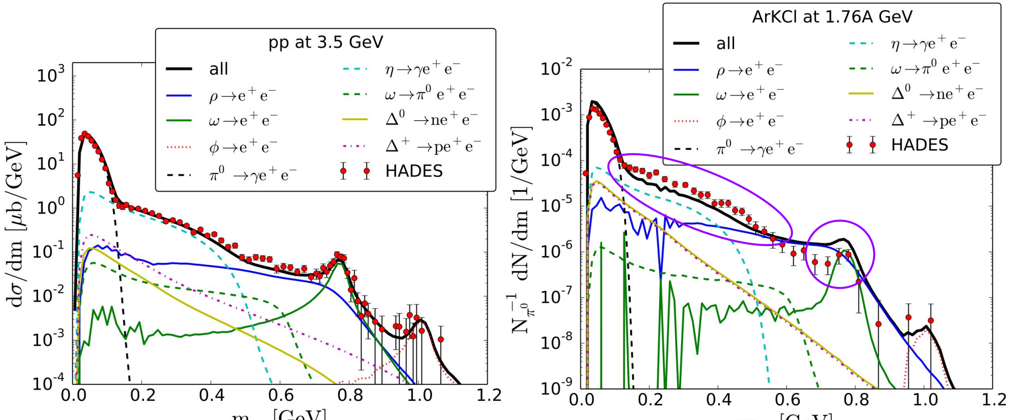
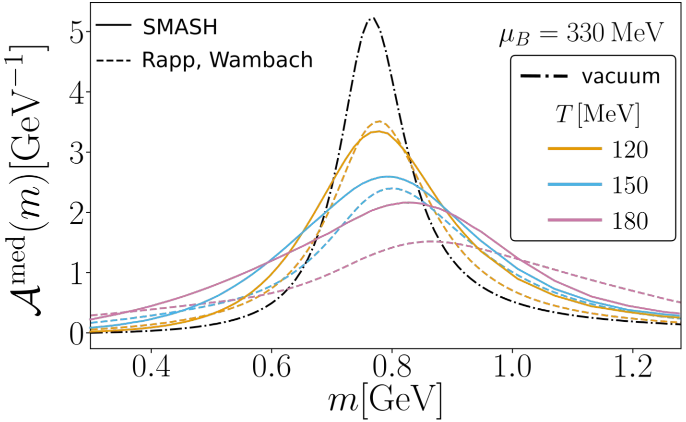


[J. Staudenmaier, H. Elfner, PRC 98 (2018) 3, 054908]

Caveat

Medium modifications are not fully reproduced by collisional broadening from vacuum interactions



[R. Rapp, J. Wambach, Eur.Phys.J.A 6 (1999) 415-420]
[H. van Hees, R. Rapp, Nucl.Phys.A 806 (2008) 339-387]
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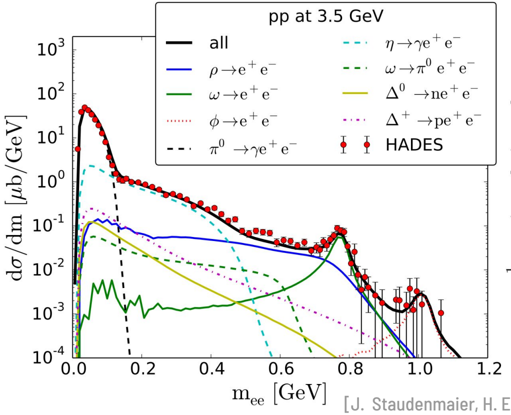

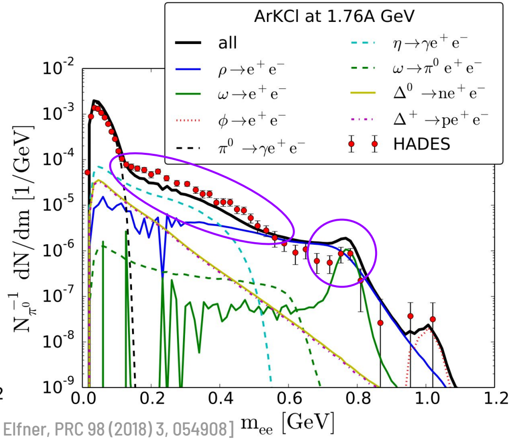

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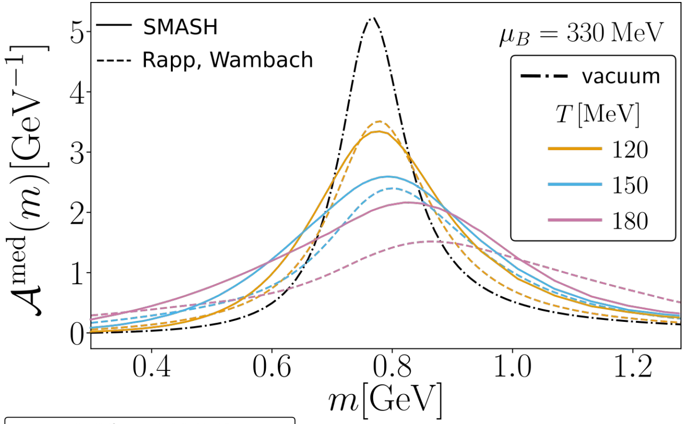

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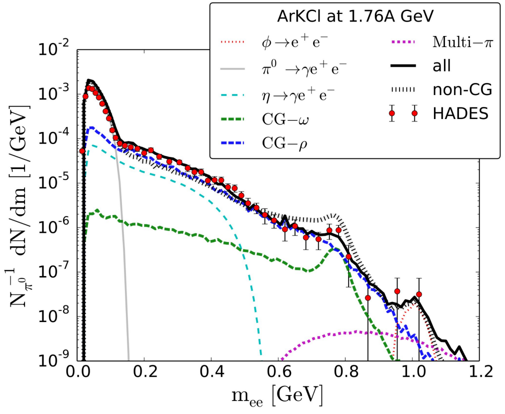
[**RH**, J. Staudenmaier, H. Elfner, PRC 107 (2022) 2, 025208]

Alternative: Coarse-graining

- Local average of $T^{\mu\nu}$ and j_B^μ over several collisions
- Use EoS to determine ensemble thermodynamics
- Extract yields from in-medium spectral function of Rapp et al. [S. Endres et al., PRC 91 (2015) 5, 054911] [S. Endres et al., PRC 94 (2016) 2, 024912]



Assumption here:
Flow is independent of these modifications

[see Tom Reichert's talk]

4. Anisotropic flow 101

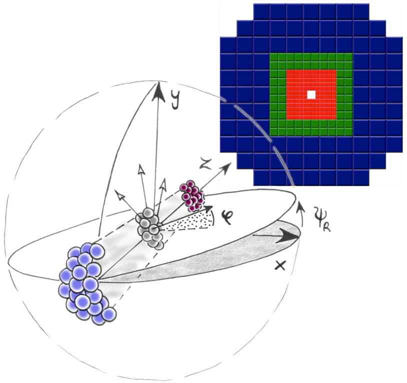
Azimuthal Fourier decomposition of yields:

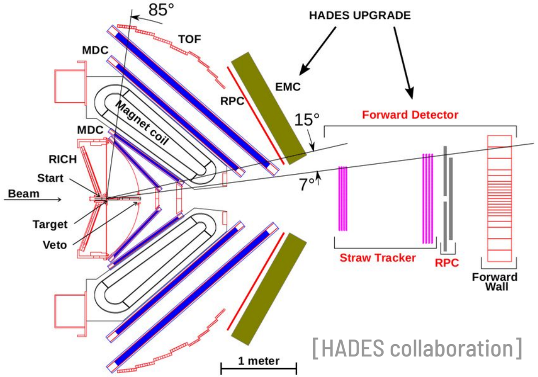
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_R)\right]$$

Anisotropic flow coefficient

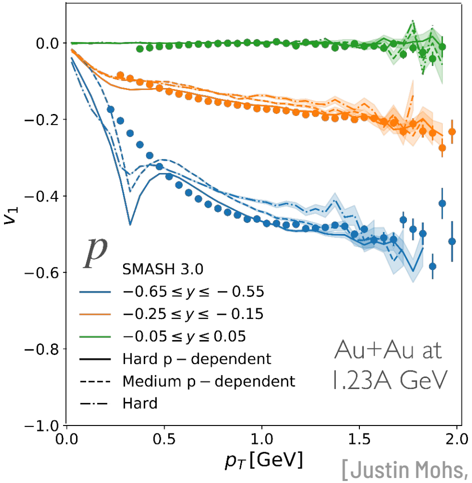
$$v_n \approx v_n\{\mathrm{RP}\} = \langle \cos[n(\phi - \Psi_R)] \rangle$$

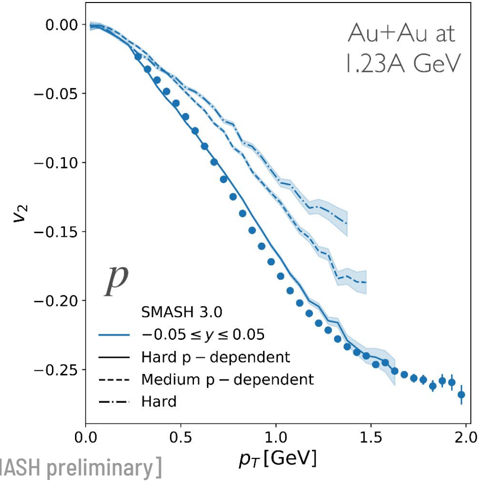
Reaction plane Ψ_R : spanned by beam axis and impact parameter



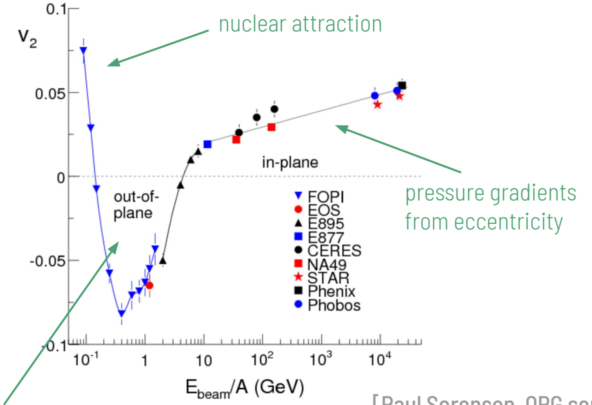


[HADES collaboration]





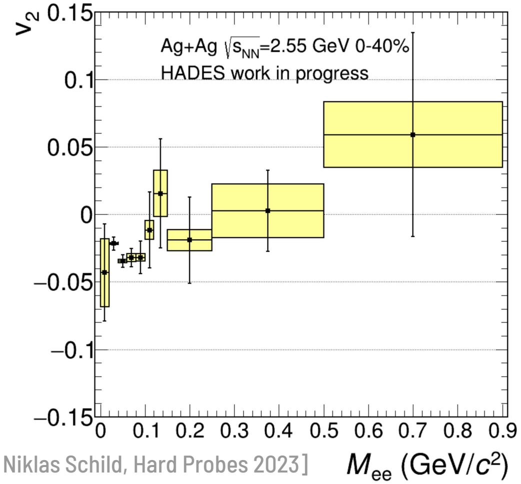
[Justin Mohs, SMASH preliminary]
[B. Kardan Nucl. Phys. A 967 (2017)]



[Paul Sorensen, QPG series]

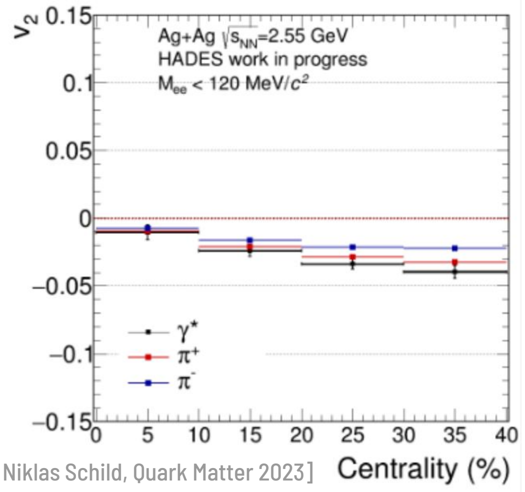
In particular: v_2 follows from initial geometry

5. Comparisons to HADES (preliminary)

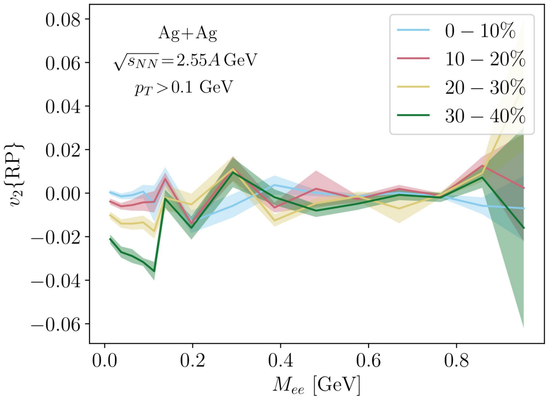


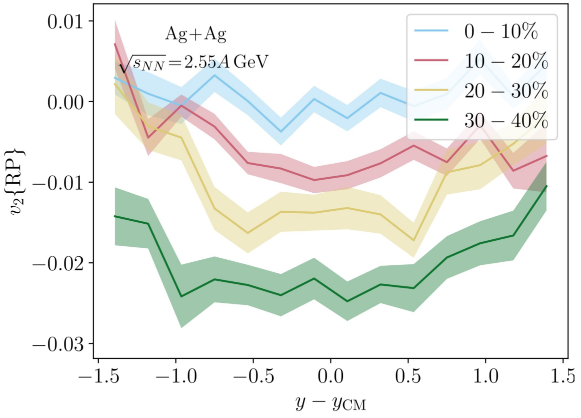
[Niklas Schild, Hard Probes 2023]

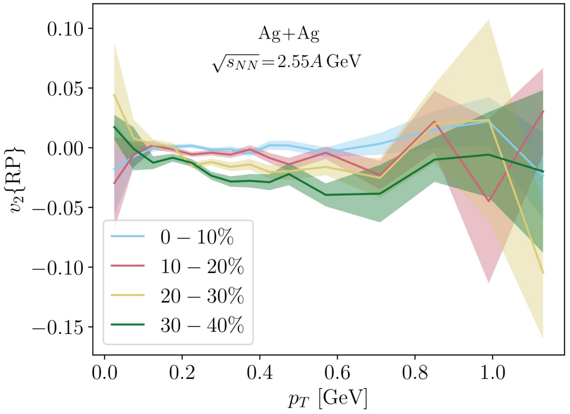
- Out-of-plane flow in Dalitz π^0 region
- Overall consistency to experiment
- "Zero" flow for $M_{ee} > m_{\pi^0}$
- Error bars (both experimental and from SMASH) are still very large!
- Centrality dependence follows expected trend (less central, more flow)



[Niklas Schild, Quark Matter 2023]







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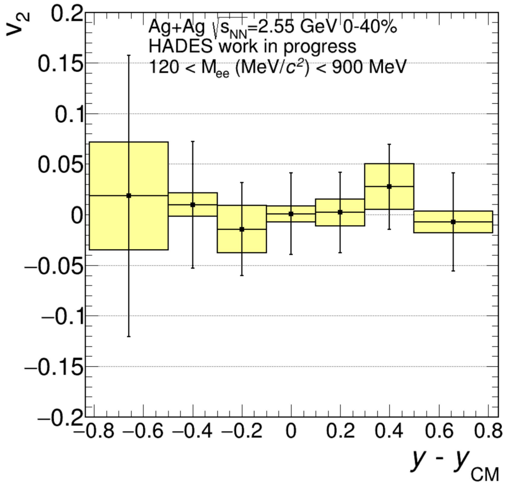
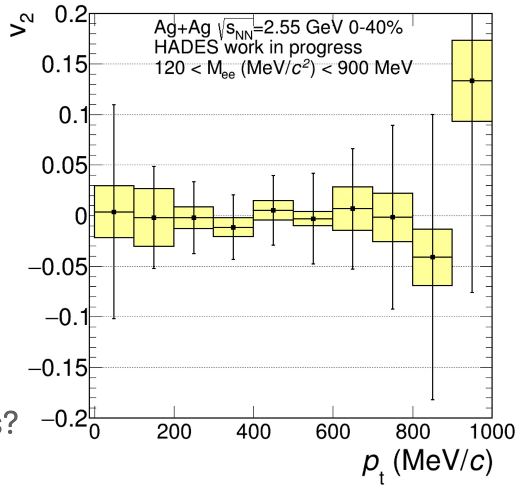
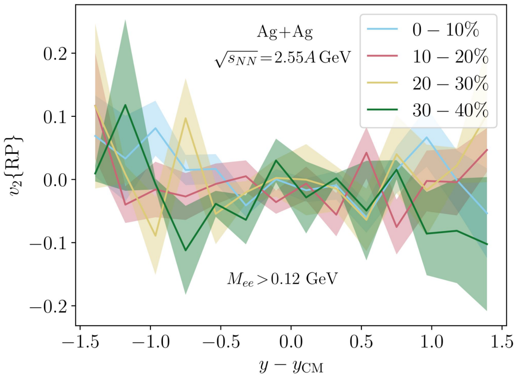
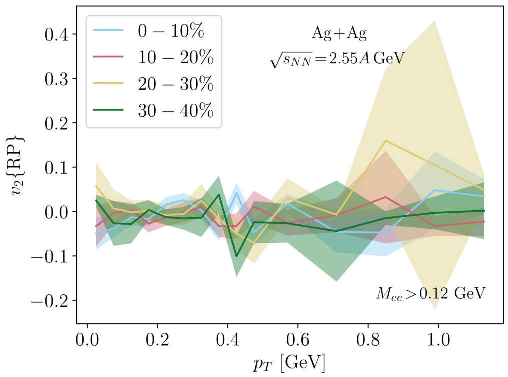


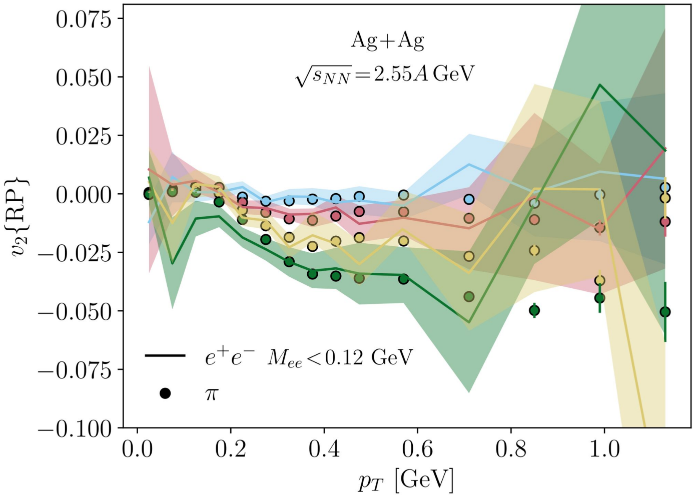


"Zero" flow in resonance region:
signal of dileptons as penetrating probes?





6. Checks within SMASH



- Self-consistency: low-mass SMASH dileptons follow charged pion flow

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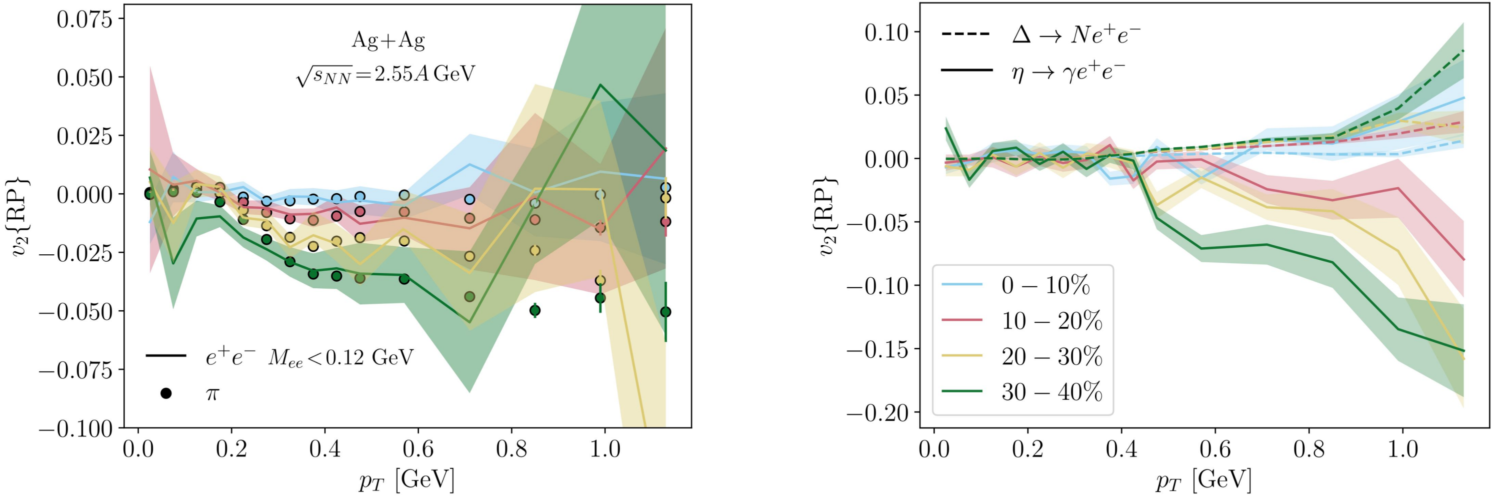

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- Cancellations lead to “zero” flow in higher masses: in-plane flow of Δ vs. out-of-plane flow of η

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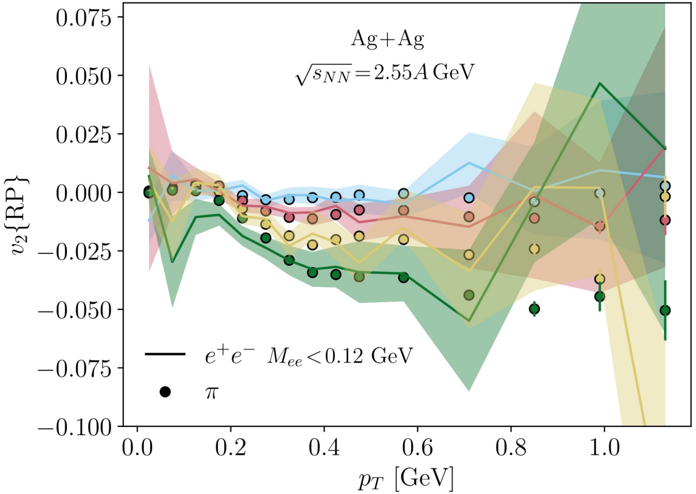

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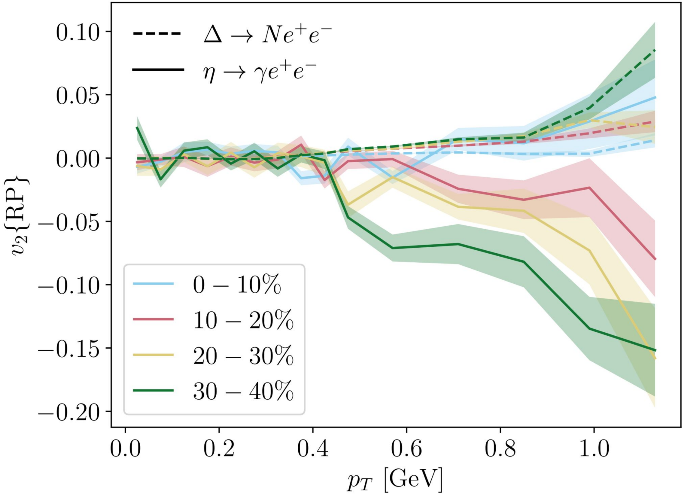


- Dilepton from resonances have flow!
- Cancellations lead to “zero” flow in higher masses: in-plane flow of Δ vs. out-of-plane flow of η

Still: error bars are very large

7. Can we improve this?

Scalar product method: correlate global hadron flow with differential dilepton flow

$$\mathrm{Cov}(\mathbf{q}^h, \mathbf{q}^{ll}(X)) = \langle \mathbf{q}^h \mathbf{q}^{ll}(X)^* \rangle - \langle \mathbf{q}^h \rangle \langle \mathbf{q}^{ll}(X)^* \rangle$$

O(?)

Event flow vectors

$$\mathbf{q}_n^h = \frac{1}{N^h} \int \mathrm{d}^3 p \frac{dN^h}{d^3 p} e^{in\phi_j} \xrightarrow{\text{SMASH}} \frac{1}{N^h} \sum_j^{N^h} e^{in\phi_j}$$

final state

$$\mathbf{q}_n^{ll}(\mathrm{bin}) = \frac{1}{N^{ll}} \int_{\mathrm{bin}} \mathrm{d}t \mathrm{d}y p_T \mathrm{d}p_T \int_0^{2\pi} \mathrm{d}\phi \frac{dN^{ll}}{d^4 p} e^{in\phi_j} \xrightarrow{\text{SMASH}} \frac{1}{\sum w_j} \sum_{j \in \mathrm{bin}}^{N^{ll}} w_j e^{in\phi_j}$$

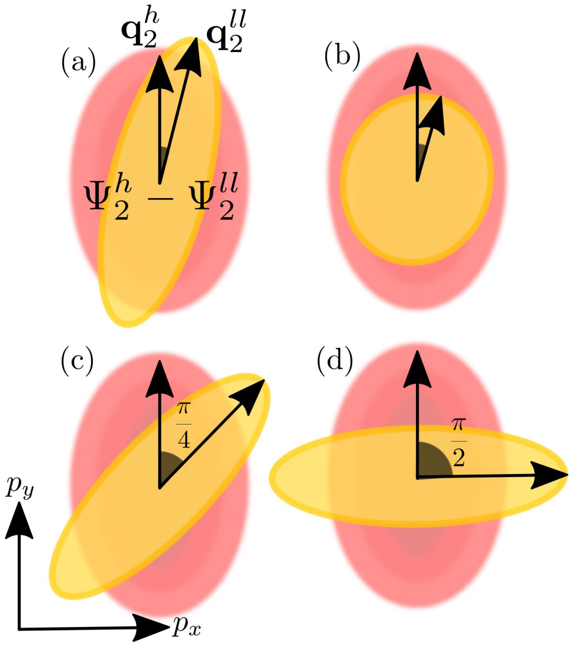
full evolution

$$v_2^{ll}(X) = \frac{\langle |\mathbf{q}_n^h| |\mathbf{q}_n^{ll}(X)| \cos[n(\Psi_n^h - \Psi_n^{ll})] \rangle_{\mathrm{ev}}}{\sqrt{\langle |\mathbf{q}_n^h|^2 \rangle_{\mathrm{ev}}}}$$

low resolution

Proposed for LHC energies:

[Jean-François Paquet et al. PRC 93, 044906 (2016)]
[Gojko Vujanovic et al. PRC 101, 044904 (2020)]

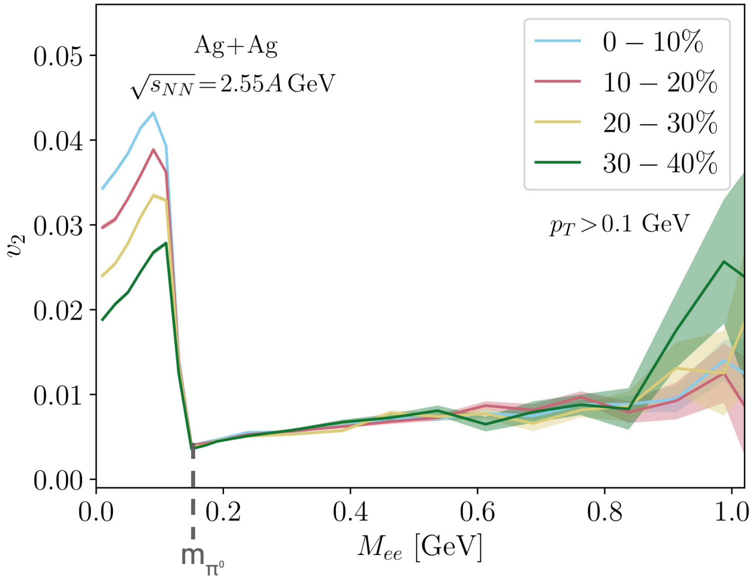


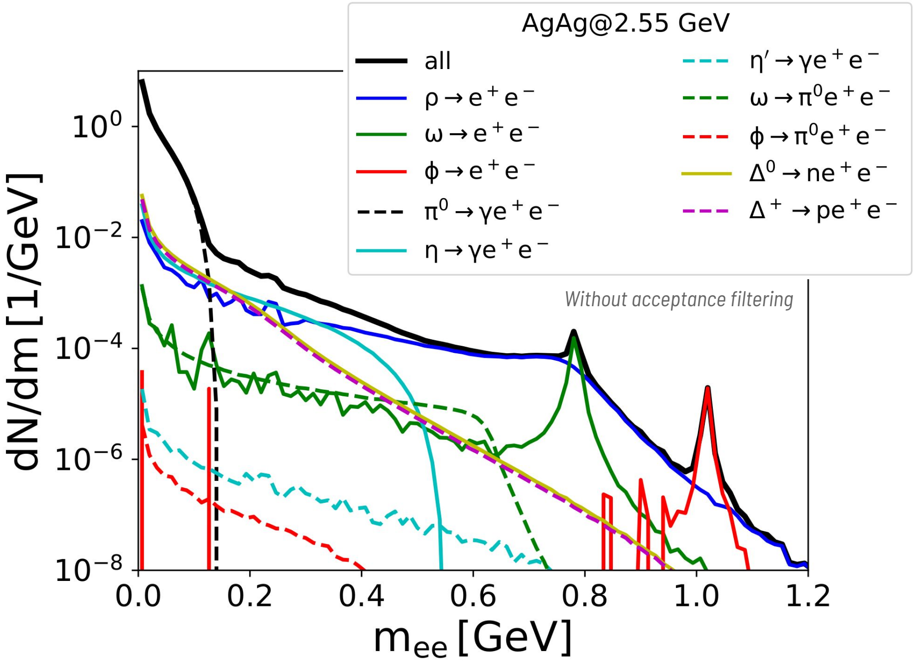
$$v_2(\mathrm{a}) > v_2(\mathrm{b}) > 0$$

$$v_2(\mathrm{c}) = 0 \quad v_2(\mathrm{d}) < 0$$

Usual **geometric interpretation** is lost!

8. Invariant mass

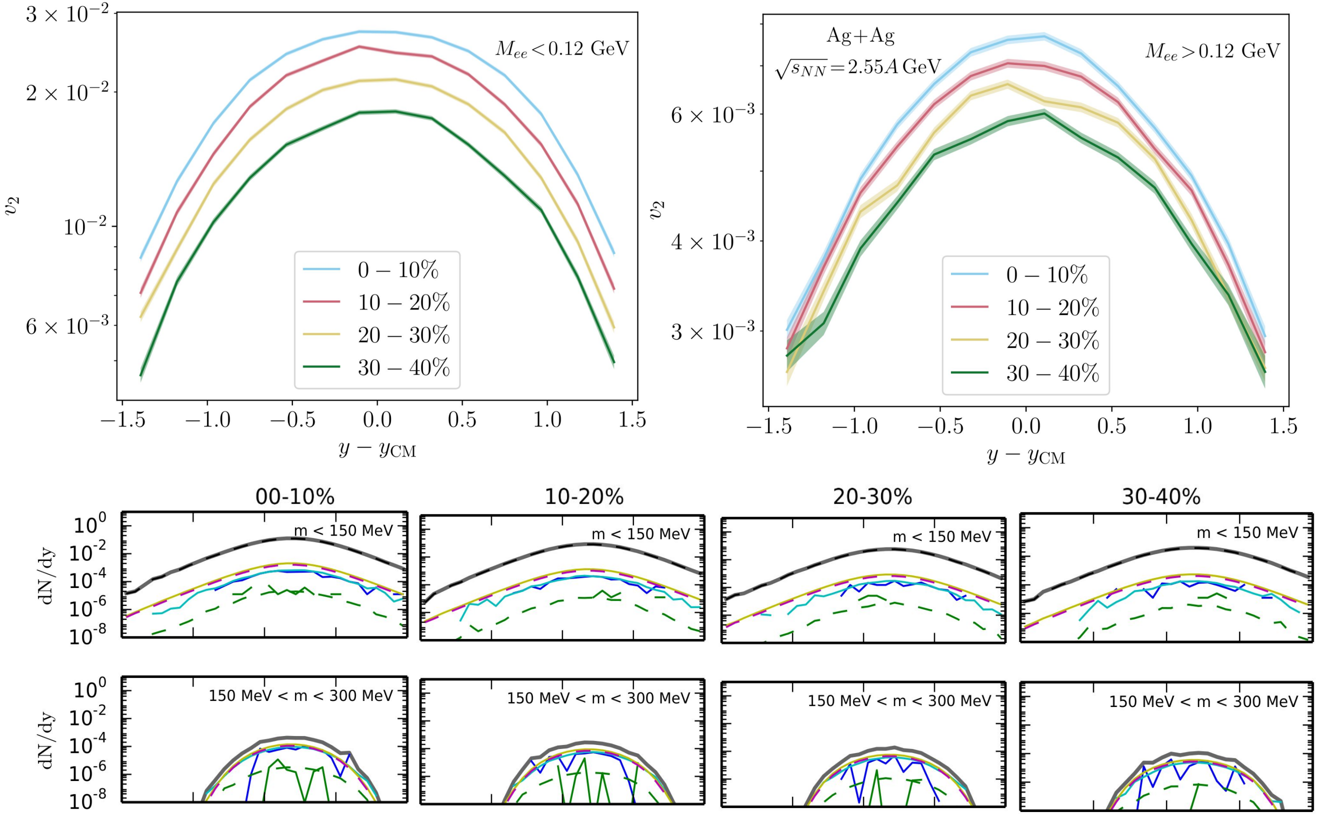




- Peak from Dalitz decay of $\pi^0 \to \gamma e^+ e^-$
- Small *non-zero* signal in resonance region

👎 Reverse centrality dependence!

9. Rapidity

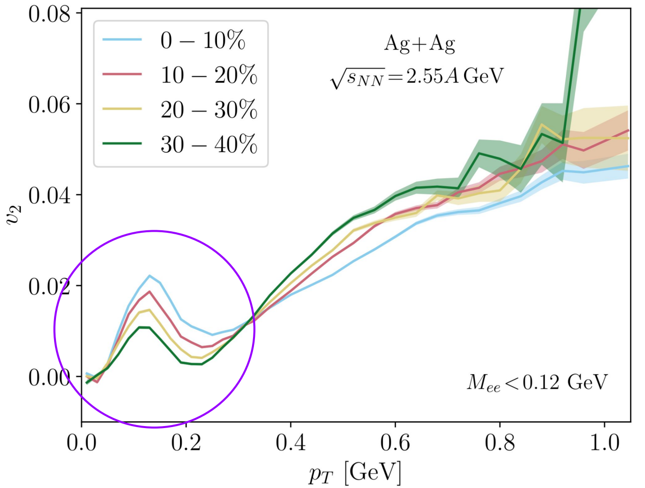


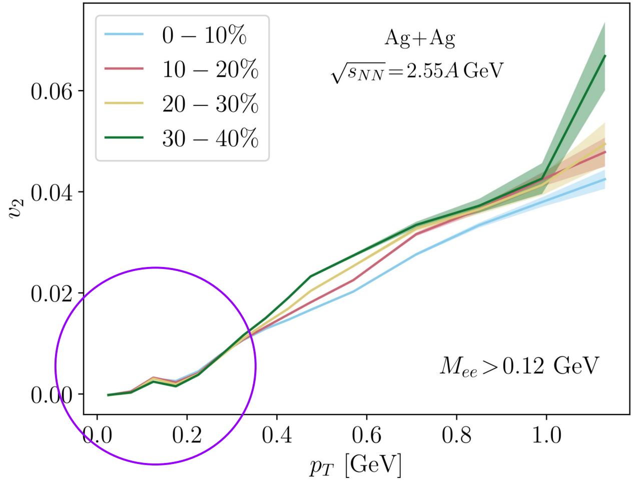
[Jan Staudenmaier, PhD thesis]

- 👎 $v_2(y)$ behavior seems to mimic multiplicity
- $v_2\{SP\}$ is a correlation between time-integrated dileptons with final-state hadrons
- *Guess*: central events have larger contributions of π^0/Δ

10. Transverse momentum

- 👎 Low mass, low p_T: bump structure with opposite centrality dependence
  - At p_T~0.3 GeV: switch to intuitive behavior
- 👍 Resonance region: no unexpected structures





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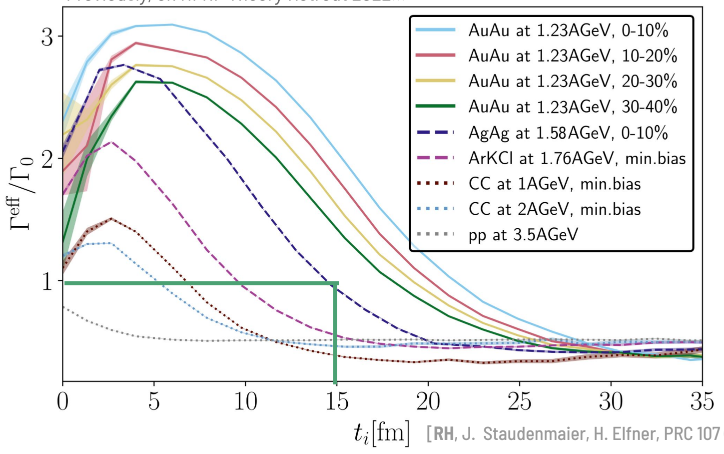
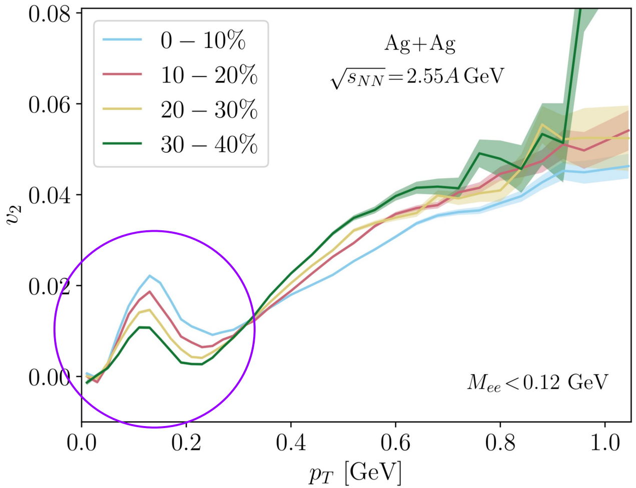
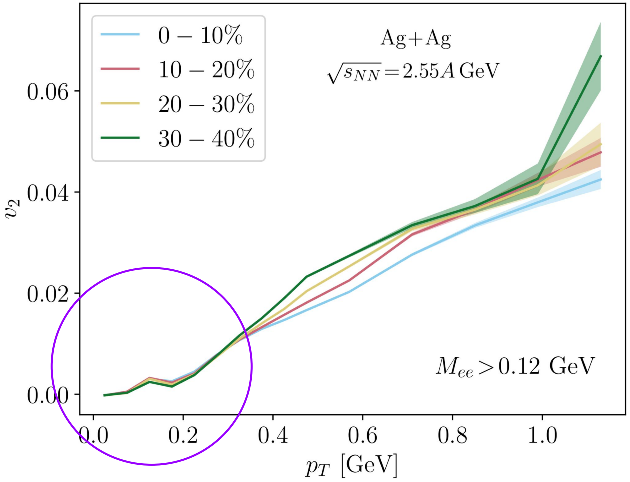
Previously, on HFHF Theory Retreat 2022...



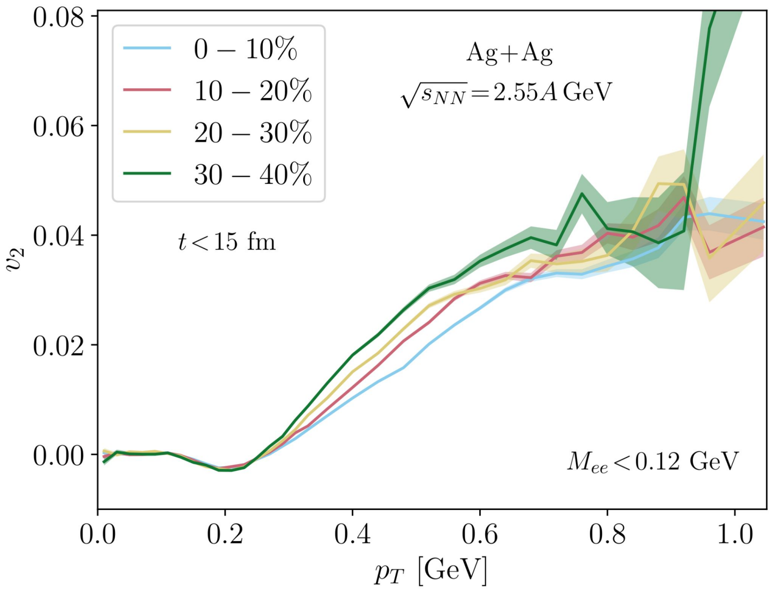
[RH, J. Staudenmaier, H. Elfner, PRC 107 (2022) 2, 025208]

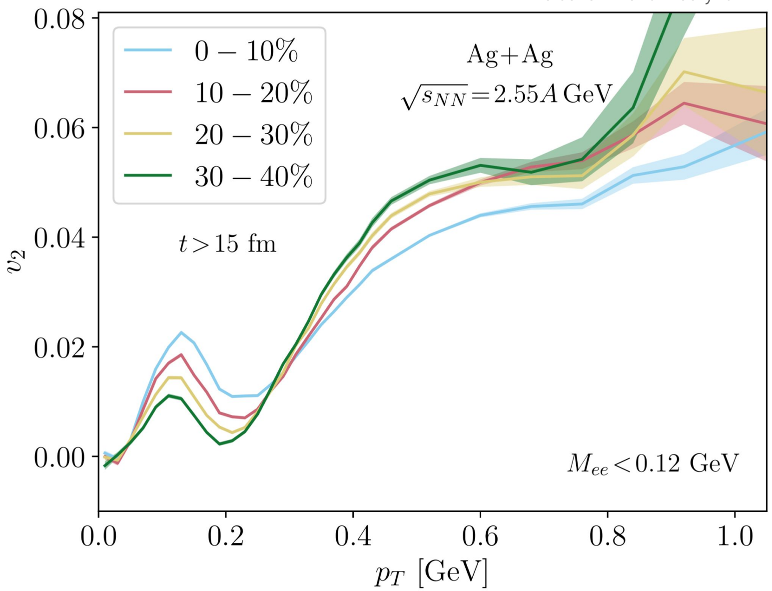




11. Time dependence

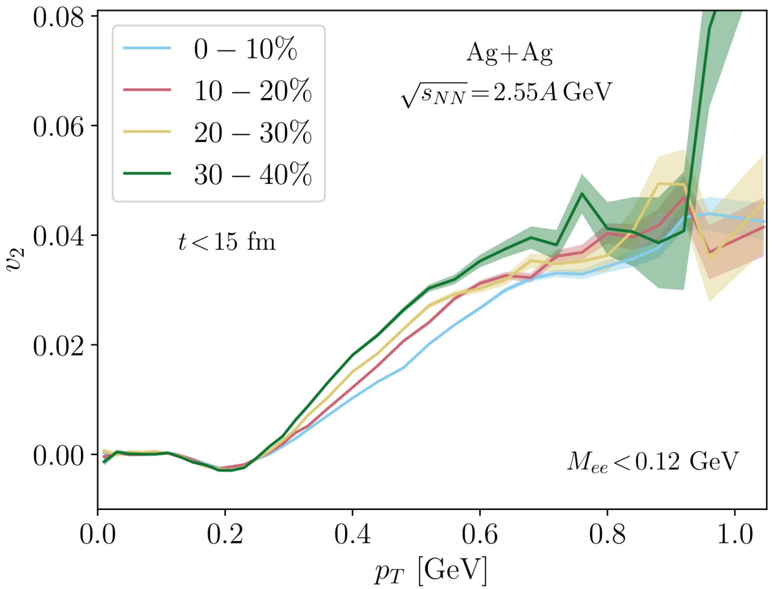
The benefits of a theory talk!

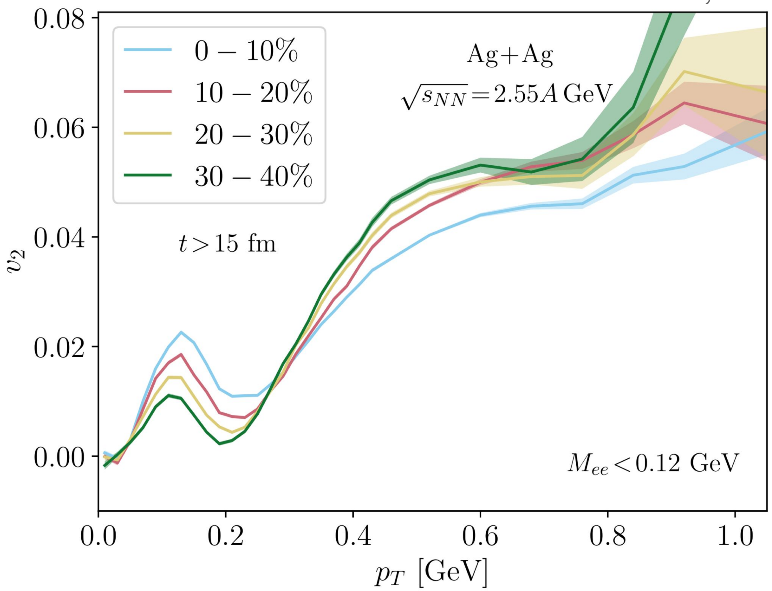




11. Time dependence

The benefits of a theory talk!

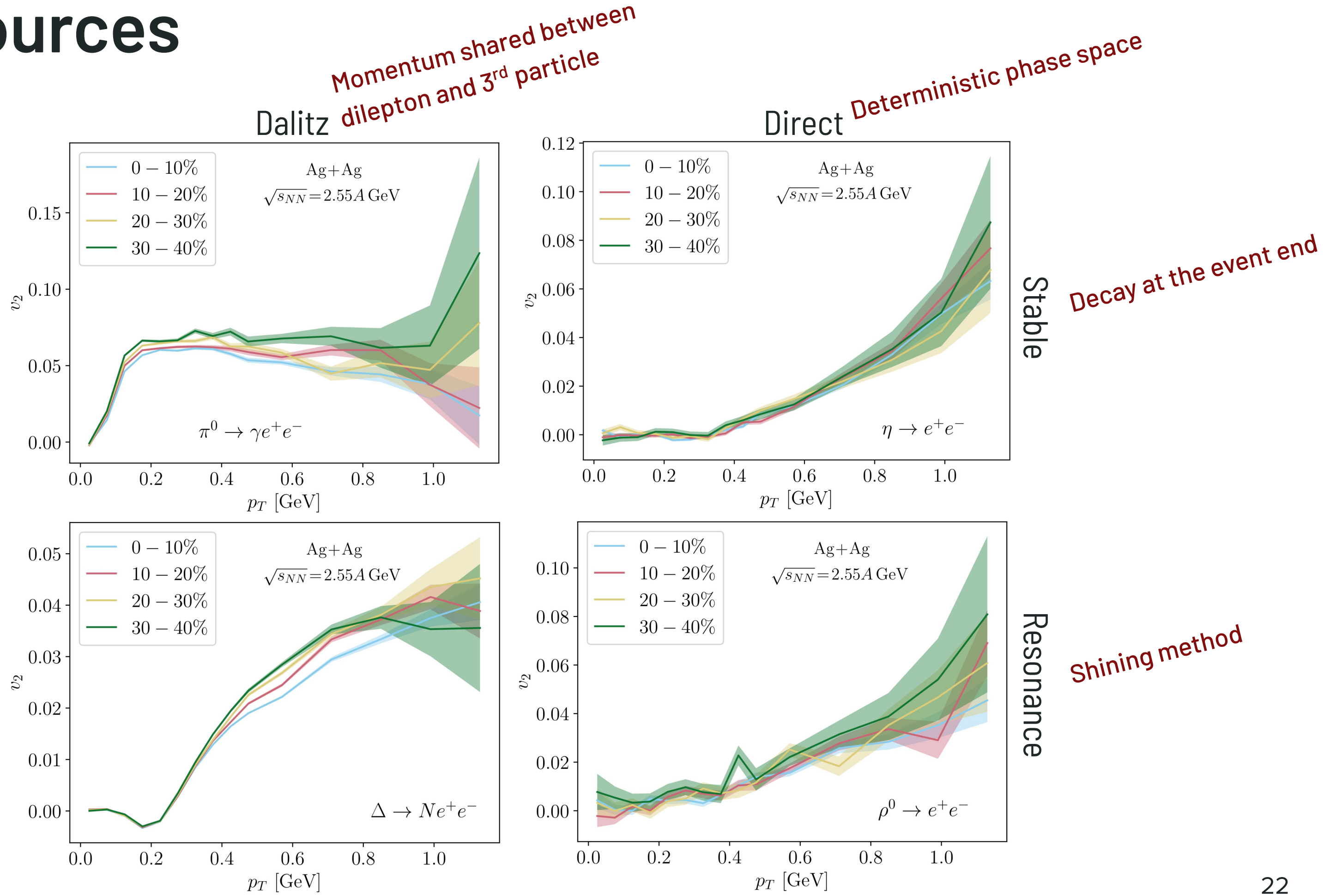




- Bump appears only in the low mass region, and when the system is dilute
- Non-flow: resonances survive the medium but decay into π^0

→ They inherit the flow, but have a smaller p_T

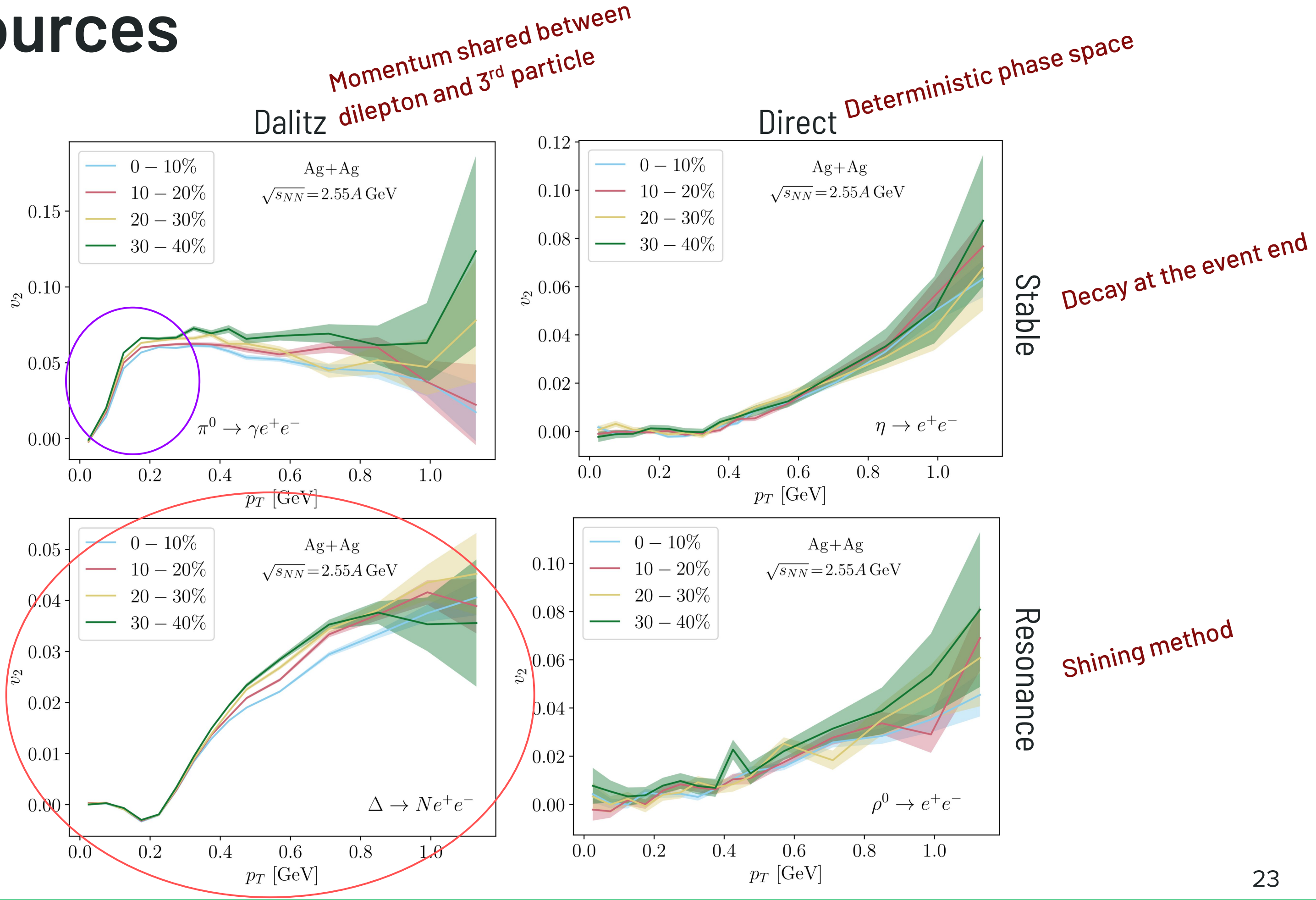
12. Flow of sources



12. Flow of sources

Only flow at low p_T is indeed coming from π^0

Looks similar to $v_2(pT)$ in resonance region and dilute stage. Coincidence?

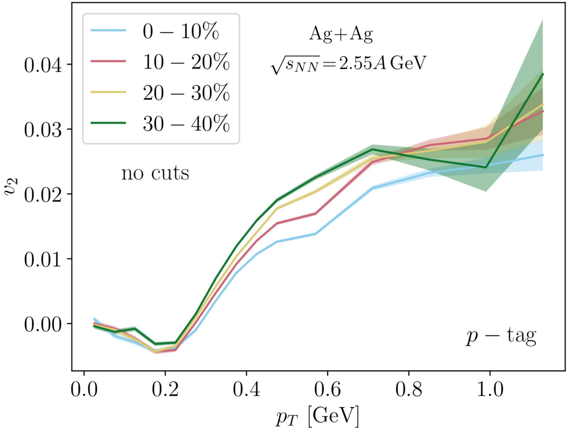


13. Dilepton "tagging"

$$v_2^{ll}(X) = \frac{\langle |\mathbf{q}_n^h||\mathbf{q}_n^{ll}(X)| \cos[n(\Psi_n^h - \Psi_n^{ll})] \rangle_{\mathrm{ev}}}{\sqrt{\langle |\mathbf{q}_n^h|^2 \rangle_{\mathrm{ev}}}}$$

We can choose which hadrons are correlated to dileptons!

13. Dilepton "tagging"



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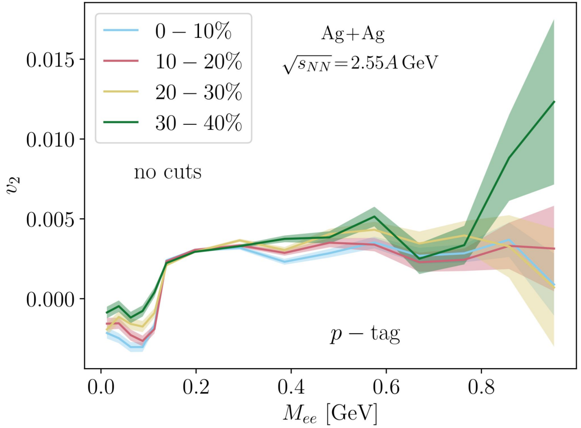
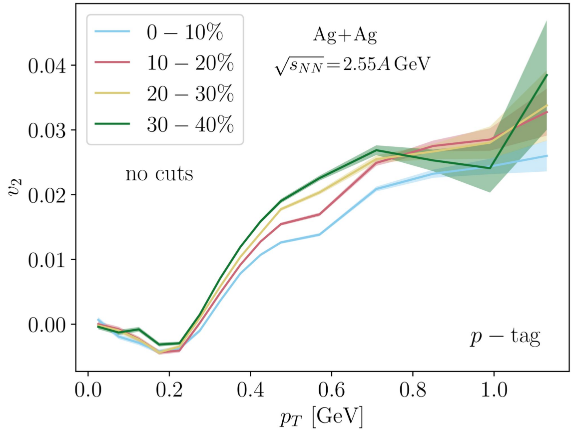
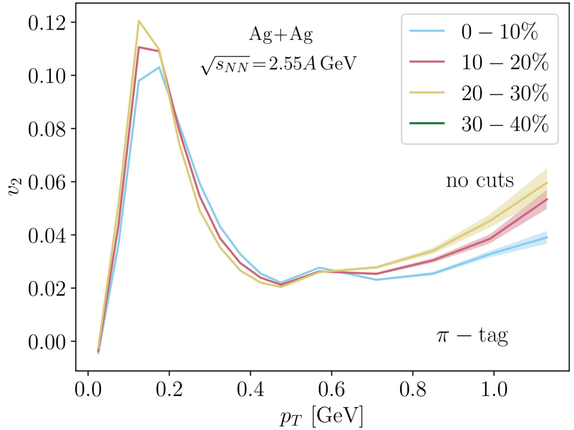
We can choose which hadrons are correlated to dileptons!

- When a Δ decays into dileptons, it also produces a nucleon
- 👍 Protons are then a natural probe for $\Delta \rightarrow Ne^+e^-$ processes



13. Dilepton "tagging"





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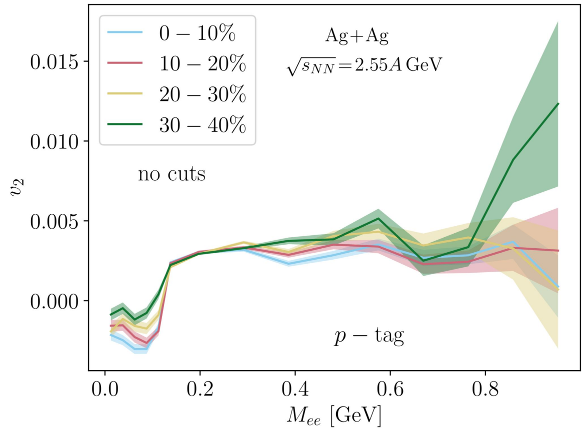
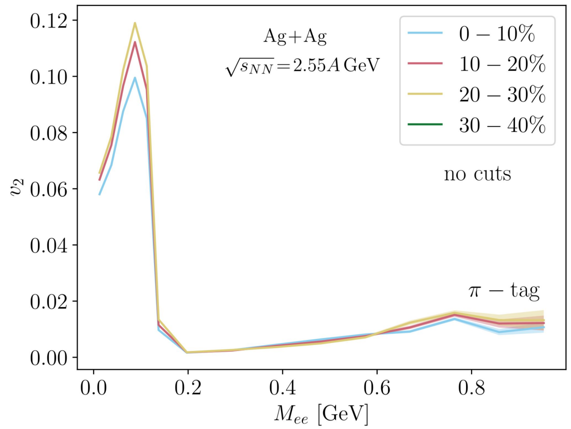
We can choose which hadrons are correlated to dileptons!

- When a Δ decays into dileptons, it also produces a nucleon
- 👍 Protons are then a natural probe for $\Delta \to Ne^+e^-$ processes
- 👍 Charged pions ~ neutral pion. Using them isolates the low mass region and the bump
- 👍 Intuitive centrality dependence restored!



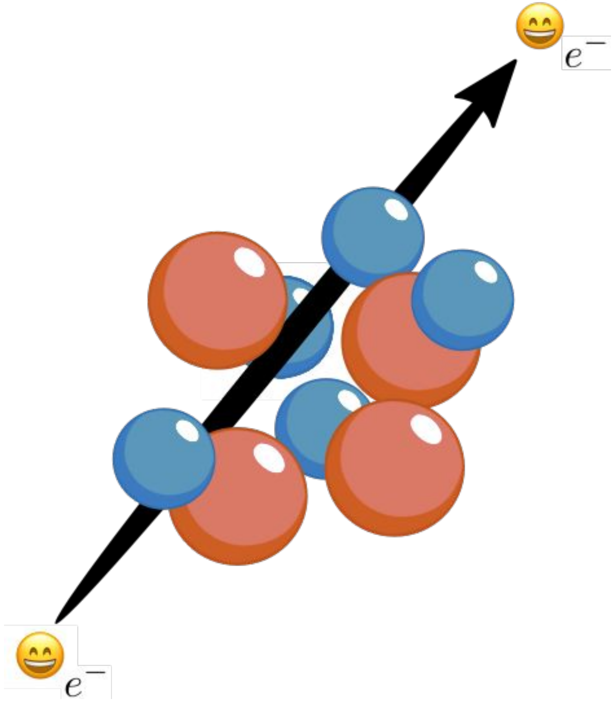


Conclusions

- Scalar Product method has smaller fluctuations than reaction plane, currently used by HADES
- Geometric interpretation of flow is lost and replaced with correlations, which don't always have a clear origin
- Hadronic transport allows for demystification of this signal
- Different tags are accessible in experiment and can distinguish sources of correlations!

Outlook

- Include nuclear potentials for realistic calculation
- Compare to coarse-grained signal and to the new dynamic initialization of our hybrid model



Thank you for the attention!