Dilepton results in SMASH

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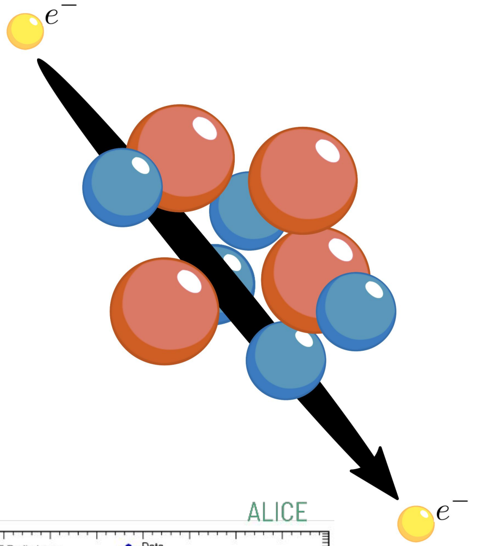
in collaboration with Hannah Elfner

November 11th, 2025

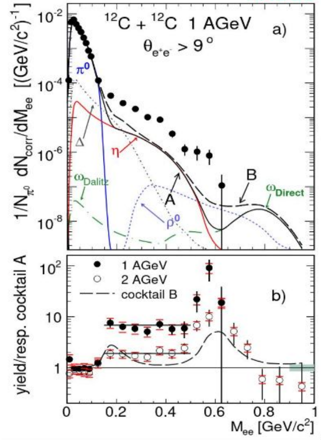
EMMI Workshop: Collective phenomena and the Equation-of-State of dense baryonic matter

Dileptons as probes



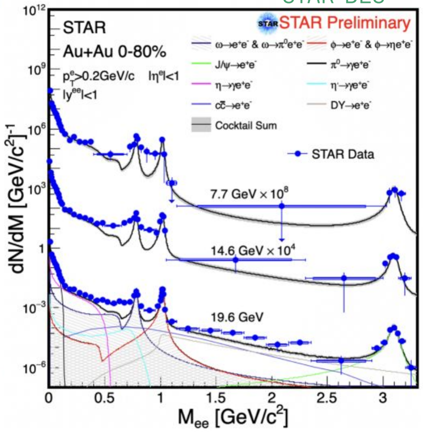
- No strong interaction ⇨ leave the medium undisturbed
- Multi-messenger: *spectrometer, chronometer, barometer, thermometer, ...*
- Experimental difficulties:
  - rare probes $\mathrm{BR}(h \to l^+l^-) \sim 10^{-5}$
  - combinatorial background

HADES



[PLB 663, 43 (2008)]

STAR-BES



[EPJ Web Conf. 296 (2024) 07004]

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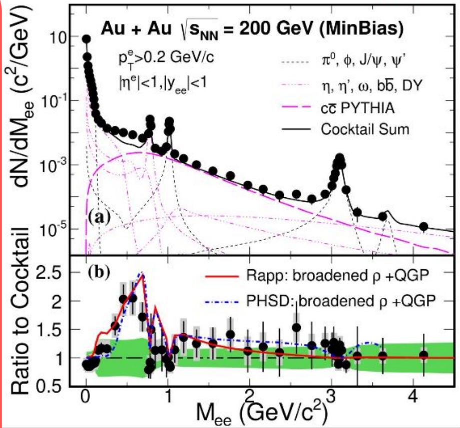
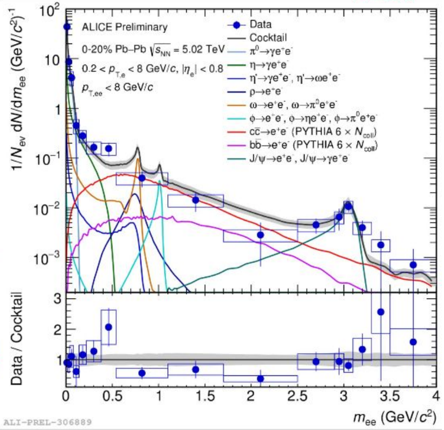


[PRL. 113, 022301 (2014)]

ALICE



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

The SMASH approach

smash

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

Hadrons

- Hadrons evolved with the relativistic Boltzmann equation (BUU)

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

- 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

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

Vacuum properties a priori

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

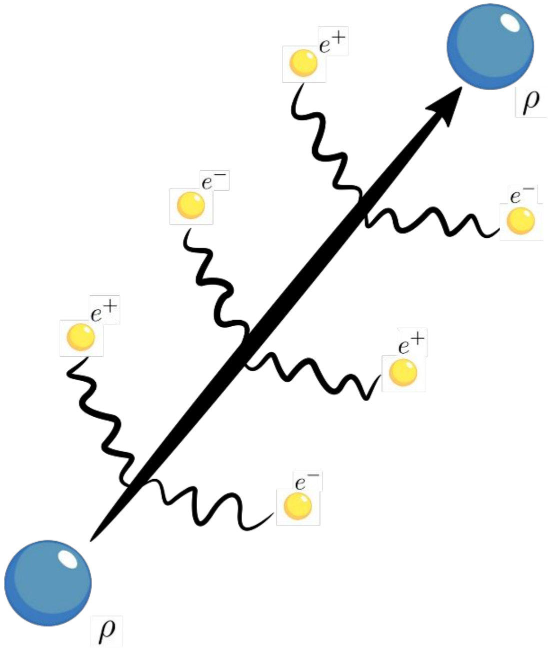
Dileptons

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

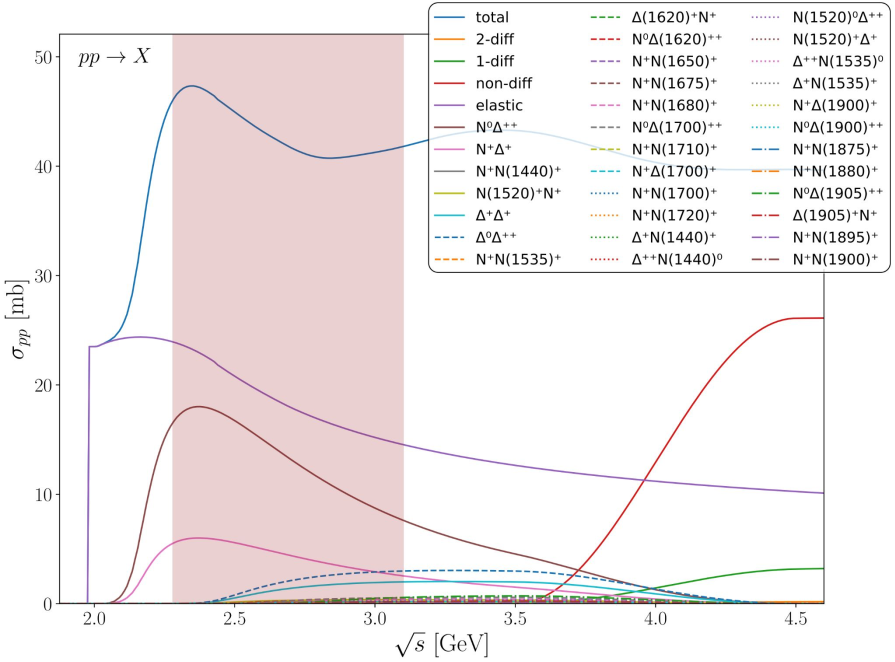
$$w_{R\to l^+l^-}(\tau) = \int_{t_0}^{\tau - t_0} \frac{\mathrm{d}t}{\gamma} \Gamma_{R\to l^+l^-}(m_R)$$

[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)]

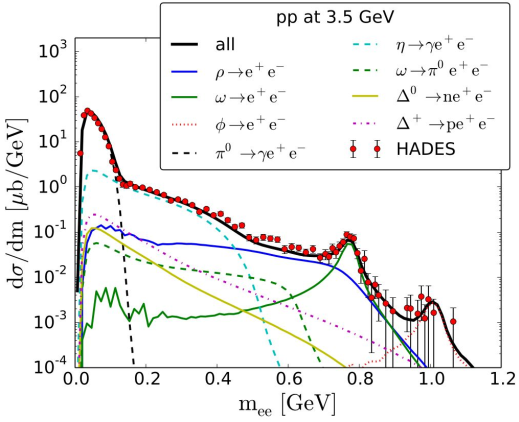
- At every time step the particle radiates a lepton pair, carrying *the shining* weight

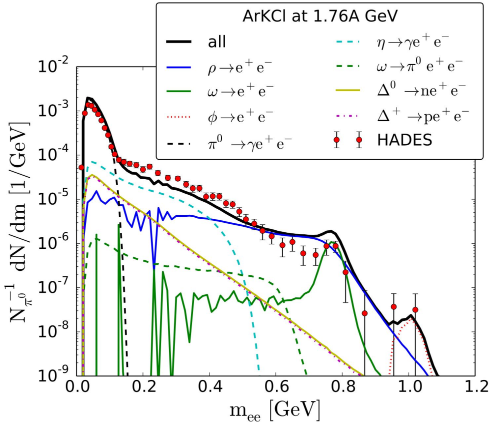


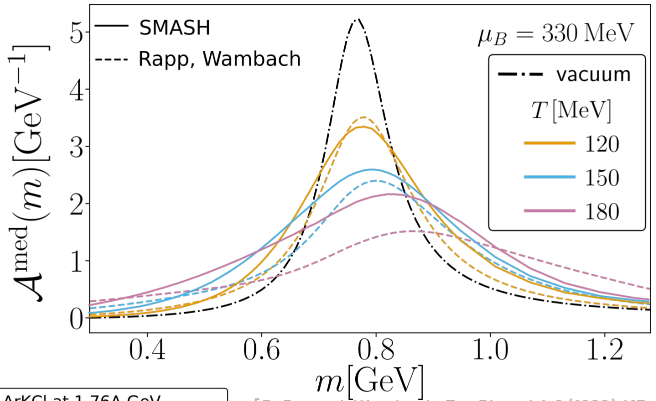
The SMASH approach - NN cross sections



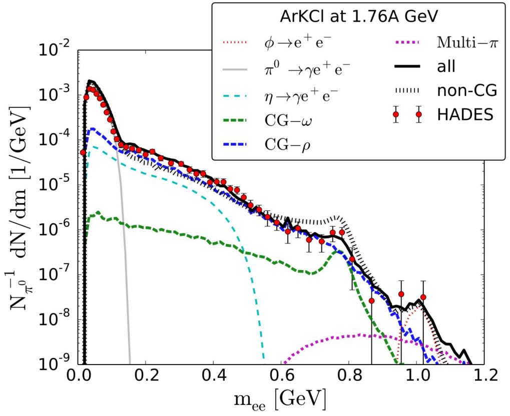
The SMASH approach - dilepton production







[R. Rapp, J. Wambach, Eur.Phys.J.A 6 (1999) 415-420]
[H. van Hees, R. Rapp, Nucl.Phys.A 806 (2008) 339-387]
[**RH**, J. Staudenmaier, H. Elfner, PRC 107 (2022) 2, 025208]



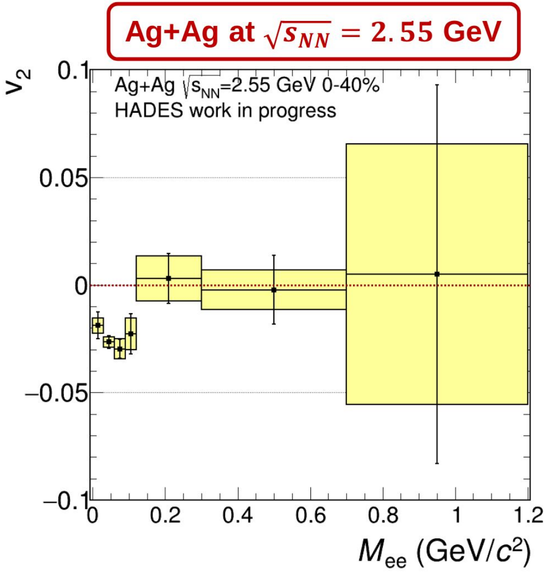
- Data well described in pp collisions, but not in ArKCl
- Missing in-medium modifications
- Alternative: coarse graining

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

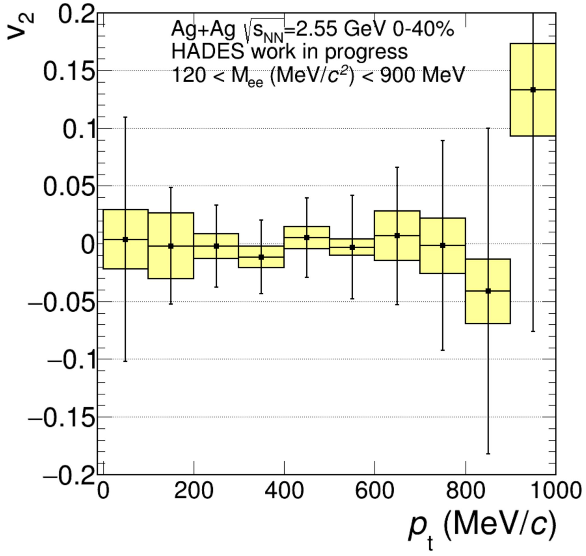
Elliptic flow and finding the Δ

Based on Phys.Rev.C 110 (2024) 6, 064903

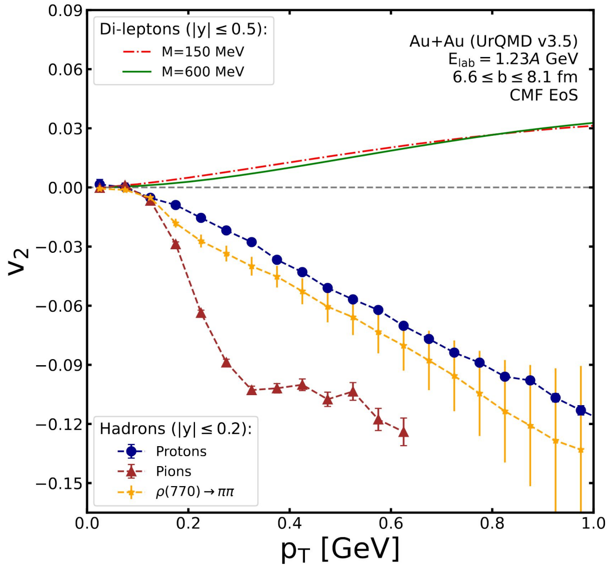
Tension?



[Niklas Schild, 15 minutes ago]



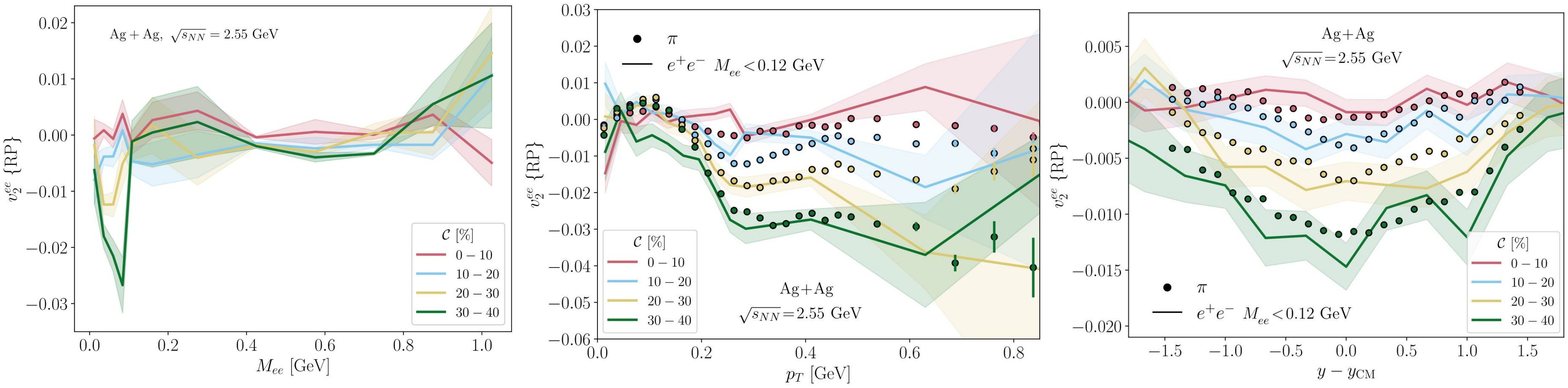
[Niklas Schild, PoS HardProbes2023 (2024) 072]



[Reichert et al. Phys.Lett.B 841 (2023) 137947]

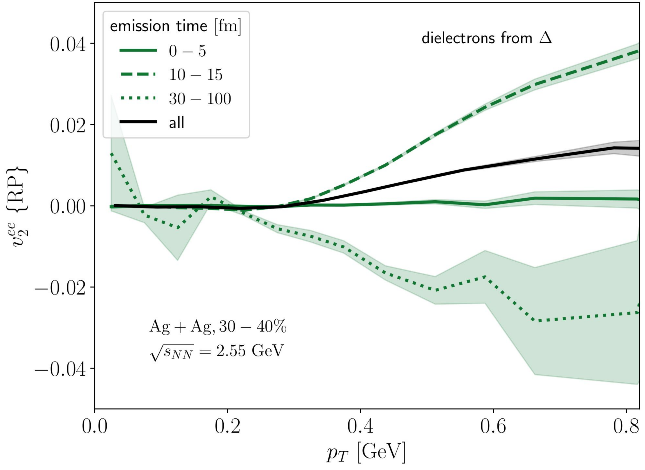
Reaction plane results

$$v_n\{\text{RP}\} = \langle\langle e^{in\phi}\rangle\rangle$$

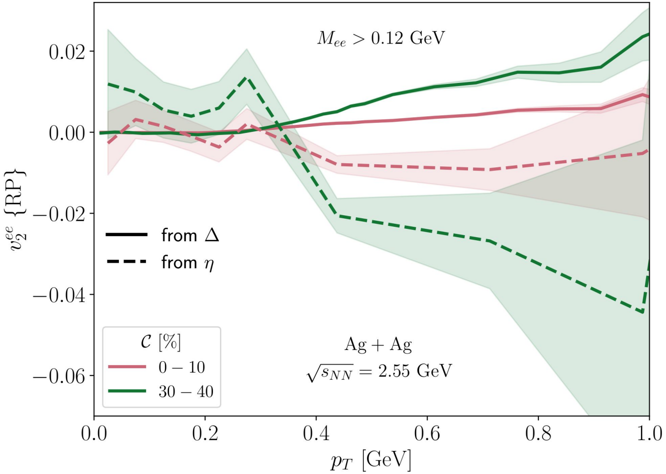


- Centrality dependence follows expected trend (less central, more flow)
- Self-consistency: low-mass SMASH dileptons follow own charged pion flow
- Overall consistency to HADES
- "Zero" flow for $M_{ee} > m_{\pi^0}$ ← Does this mean that resonances do not develop anisotropic flow?

Reaction plane results



No!



Cancellation effects: Zero flow is *only on average*

- Detected dileptons emitted throughout evolution, and flow of the medium changes direction
- Typical radiation of each source happens at different times

short-lived Δ vs. "final state" resonance η

Tagging the dileptons

$$\mathbf{q}_n^X(\Omega) = \frac{1}{N_X(\Omega)} \sum_{k\in\Omega}^{N_X} e^{in\phi_k}$$ Event flow vector

Measure

Tagged scalar product method

Measure differential flow of dileptons from global flow of a hadron species

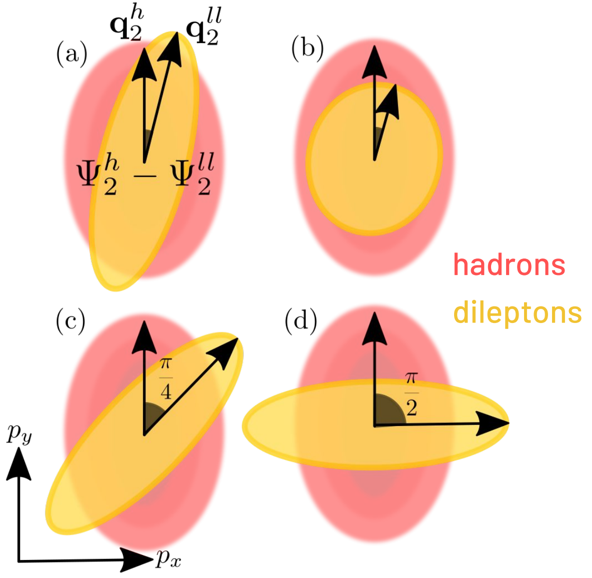
$$v_{ll}\{\mathrm{SP}|h\}(\Omega) \equiv \frac{\mathrm{Cov}\left[\mathbf{q}_{ll}(\Omega), \mathbf{q}_h\right]}{\sqrt{\langle |q_h|^2\rangle}}$$

$$\mathrm{Cov}(\mathbf{A},\mathbf{B}) = \langle \mathbf{A}\cdot\mathbf{B}^\dagger\rangle - \langle\mathbf{A}\rangle\cdot\langle\mathbf{B}\rangle$$

Usually very small

$$v_{ll}\{\mathrm{SP}|h\}(\Omega) = \frac{\langle q_{ll}(\Omega) q_h \cos n(\Psi_{ll} - \Psi_h)\rangle}{\sqrt{\langle |q_h|^2\rangle}} - \frac{v_{ll}\{\mathrm{RP}\}(\Omega) v_h\{\mathrm{RP}\}}{\sqrt{\langle |q_h|^2\rangle}}$$

"Free" measurement!



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

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

Usual geometric interpretation lost

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

Time evolution

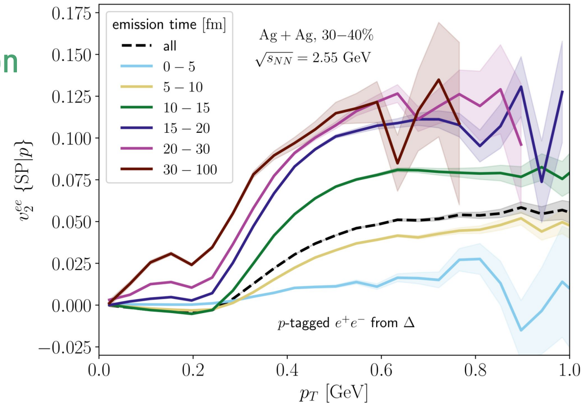
$\Delta \rightarrow Ne^{+}e^{-}$ and $\Delta \rightarrow N\pi$

- Δ contribution starts at 0 and increases as medium expands
- Expansion: Δ collides elastically with the medium, loses momentum
- Typical emission at ~10 fm
- Vector mesons not linked to the protons but decay directly into pions

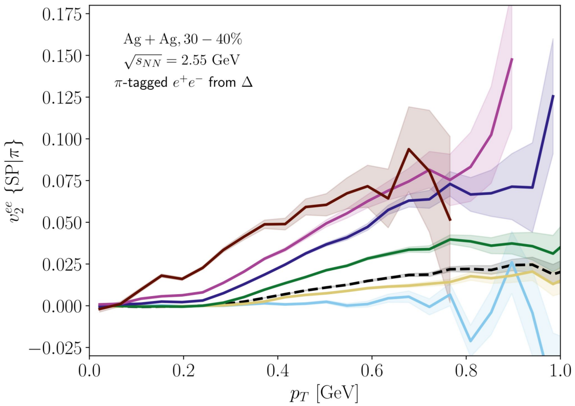
Tagging selects the relevant sources

Δ baryon

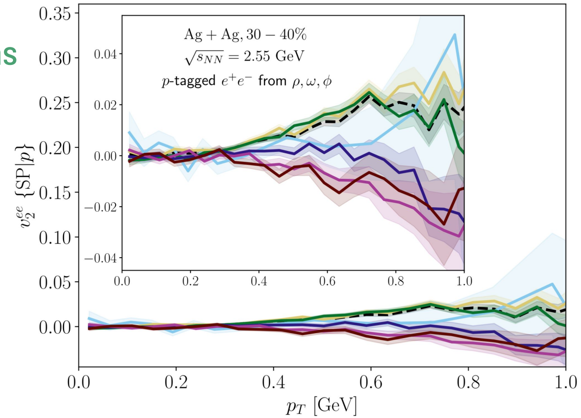
proton tag

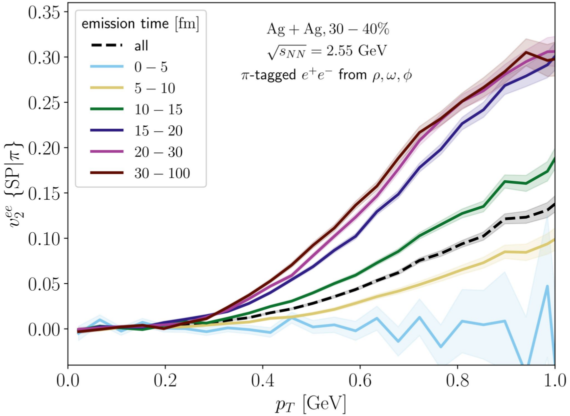


pion tag

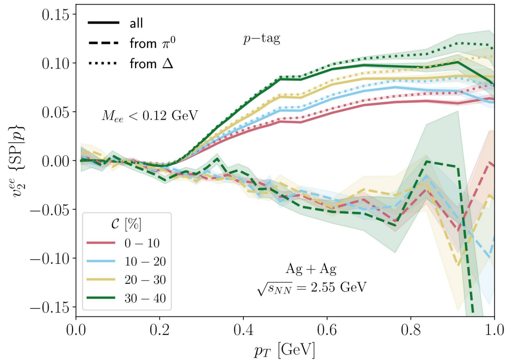


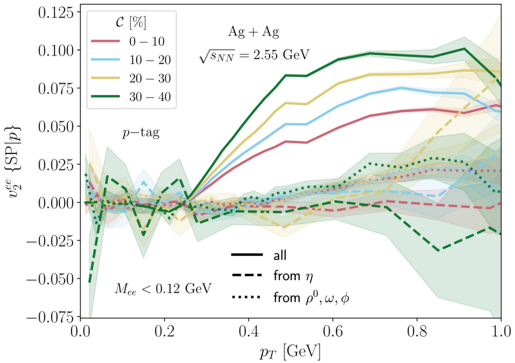
vector mesons

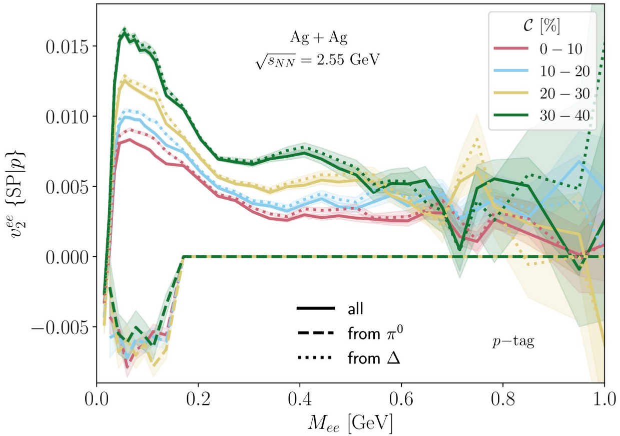




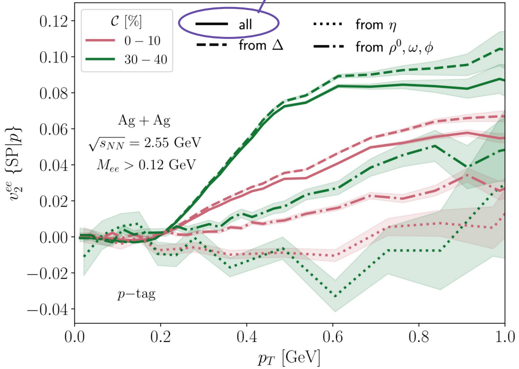
Momentum and mass dependence





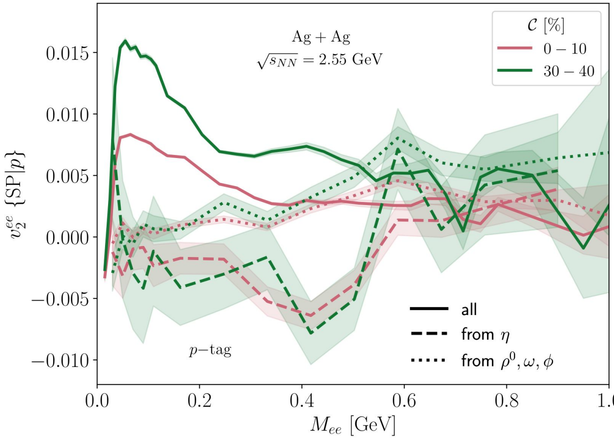


can be measured



Even though Δ is not the strongest dilepton production channel, it's more strongly correlated to the proton flow

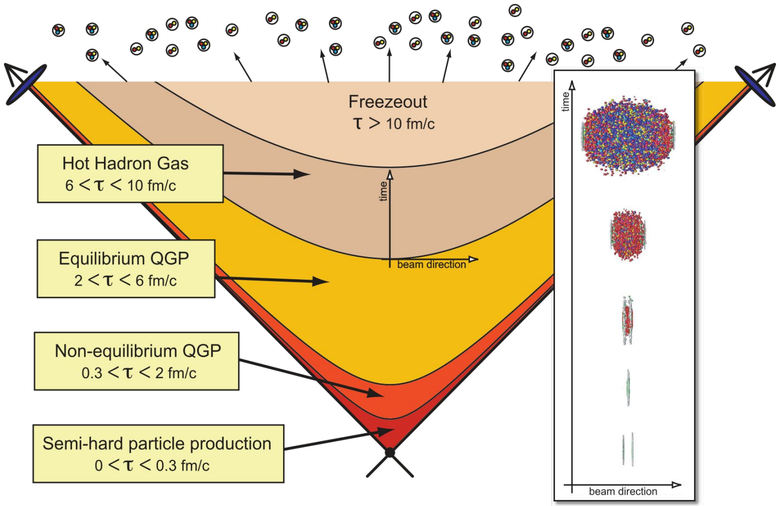
We can use the p-tag to track the Δ!



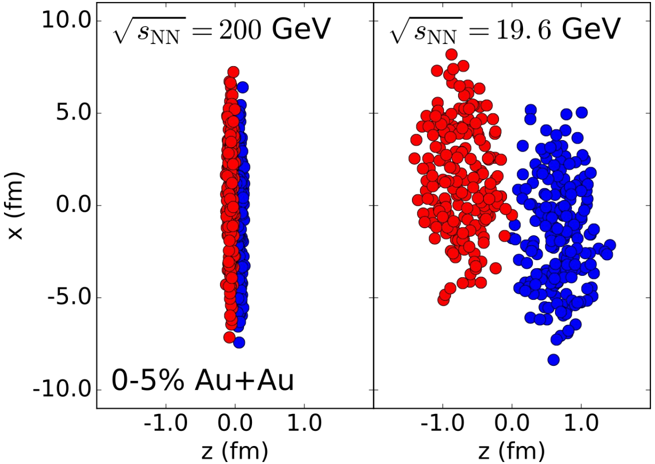
Dilepton production in a hybrid model

Based on 2507.19389 and 2510.02862

The standard HIC pictures



[M. Strickland, A Phys. Pol. B 45, 2355 (2014)]



[C. Shen & B. Schenke, Phys.Rev.C 97, 024907 (2018)]

High energy initial conditions: nuclear passing time $\tau_0 = \frac{2R/\gamma}{v_z} = 2R\left(\frac{s_{NN}}{4m_N^2} - 1\right)^{-1/2}$

$(20 \leq \sqrt{s_{NN}}/\mathrm{GeV} \leq 200)$

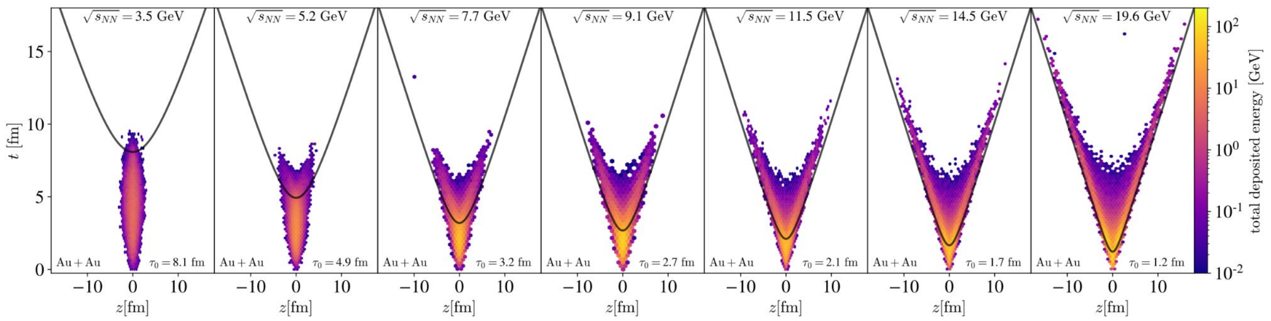
[I. Karpenko, P. Huovinen, & H. Elfner, Phys.Rev.C 91 (2015) 6, 064901]

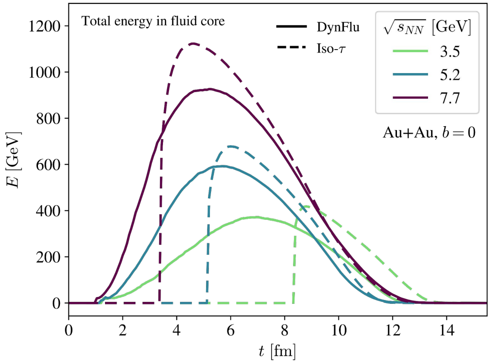
Low/intermediate beam energies: nuclei are not pancakes!

$(3 \leq \sqrt{s_{NN}}/\mathrm{GeV} \leq 20)$

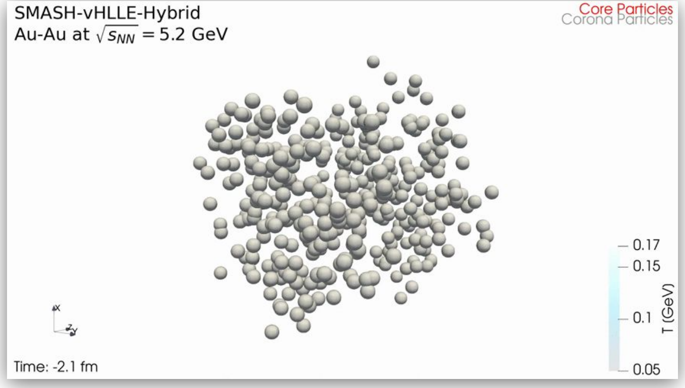
How do we start a hydro evolution in this case?

Dynamic fluidization





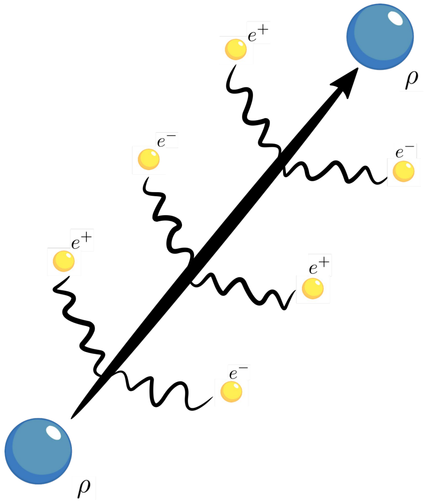
- SMASH Hadrons in regions of *enough* energy density become part of the "core" IC
- Given as sources for the fluid evolution in vHLLE Hydro
- After particlization, *core+corona* are merged for rescattering
  Sampler Afterburner



Dilepton emission

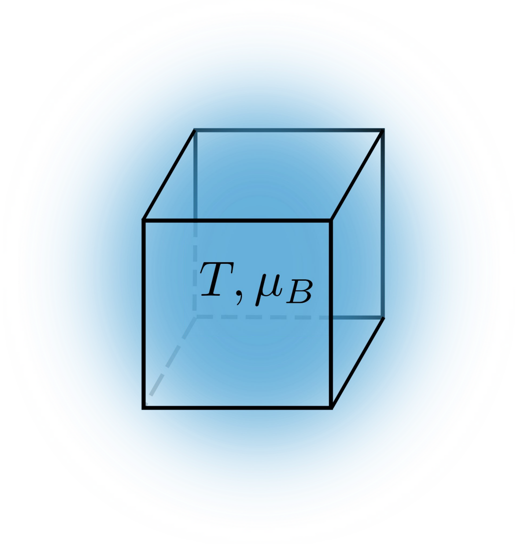
SMASH

Shining method: radiate weighted dileptons every time step



vHLLE

Thermal rates: generate dilepton for each source in each hydro cell



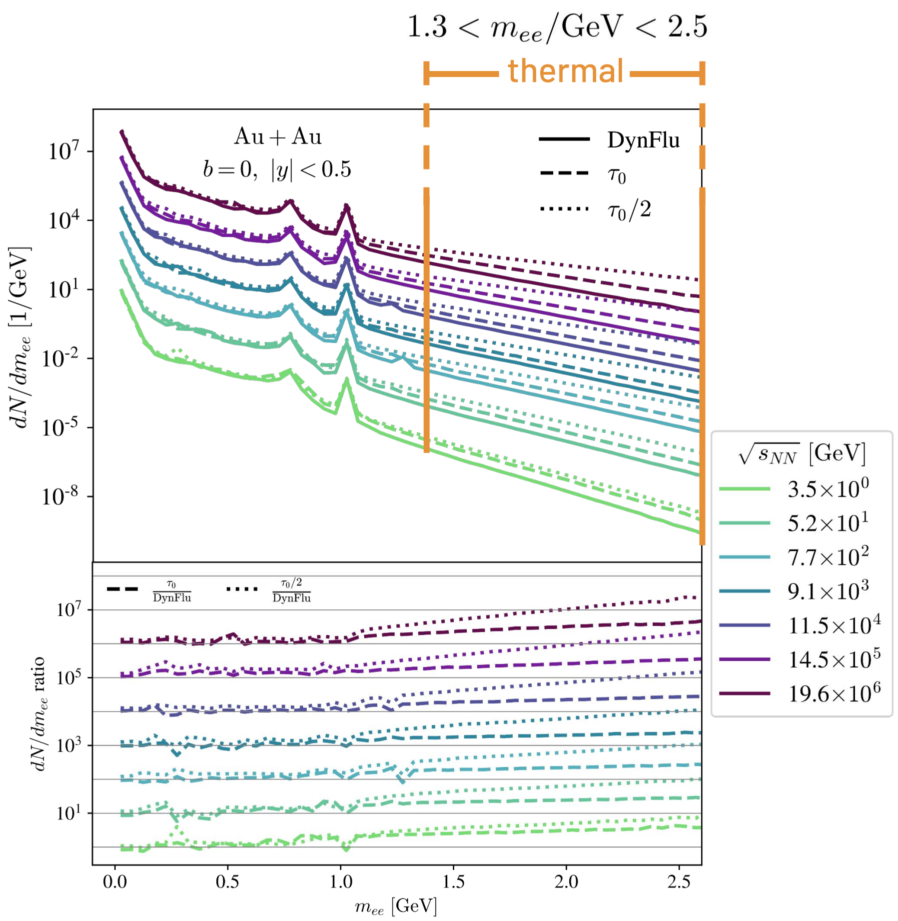
Invariant mass spectra

➔ LMR: little sensitivity to IC type

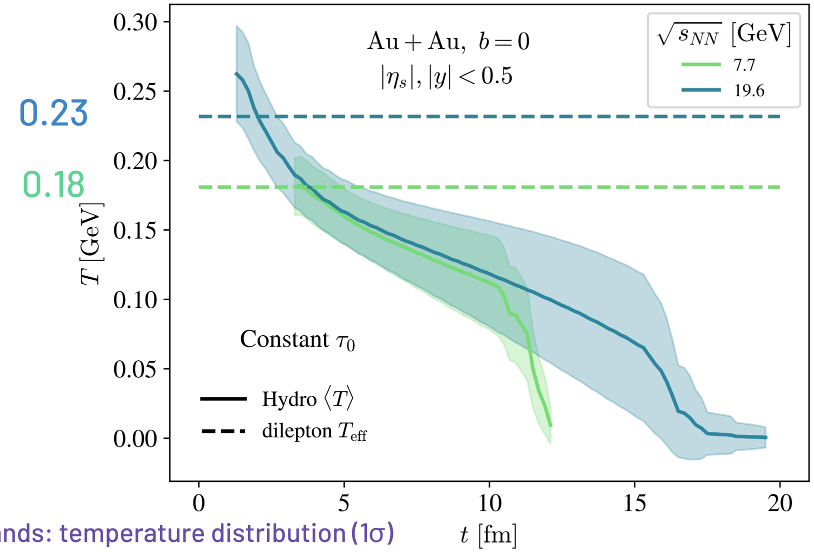
➔ IMR: both yield and angle are affected

$$\frac{\mathrm{d}N}{\mathrm{d}m} \propto m^{3/2} e^{-m/T}$$

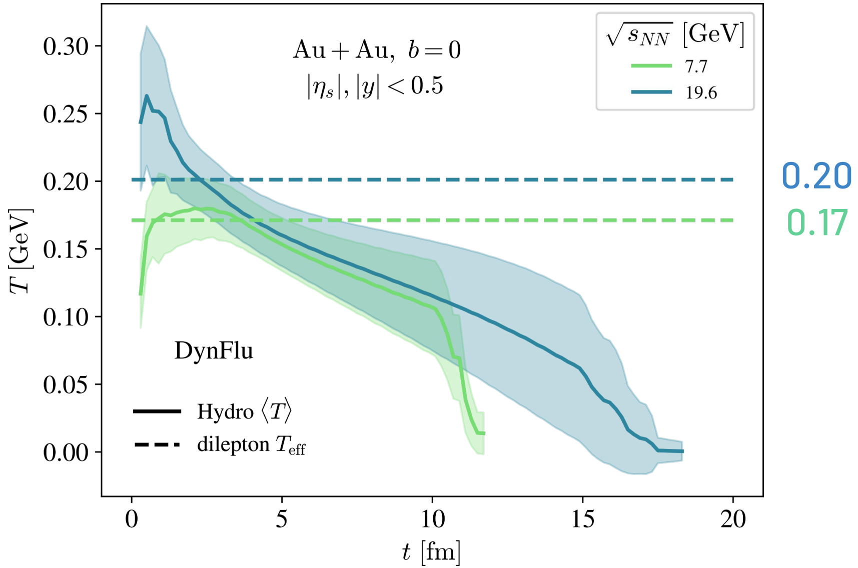
Hotter fluid ➔ harder dileptons



Dileptons as thermometers



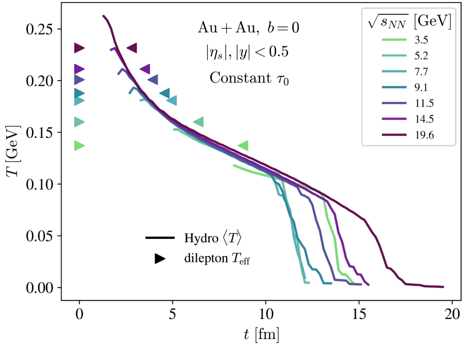
Bands: temperature distribution (1σ)

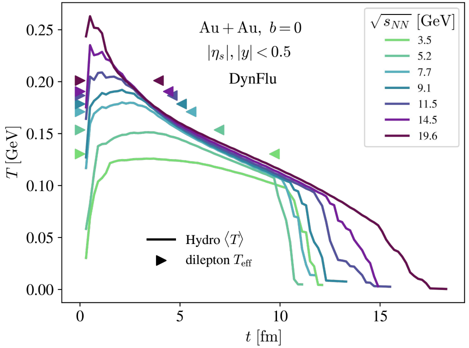


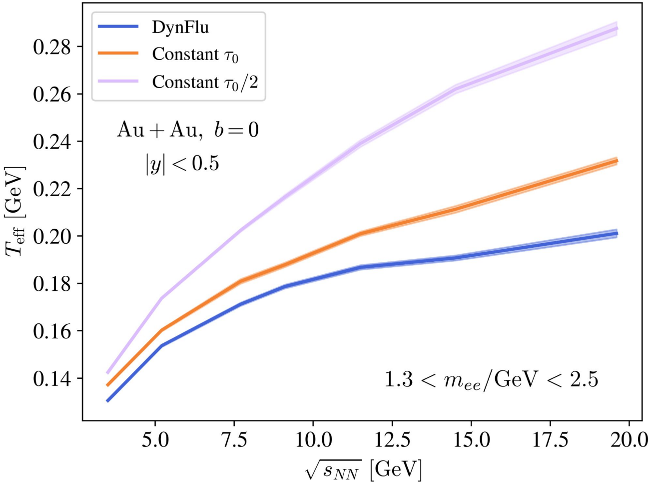
Hydro curves are similar, but smaller effective temperatures

fewer hot early hydro cells

Dileptons as thermometers

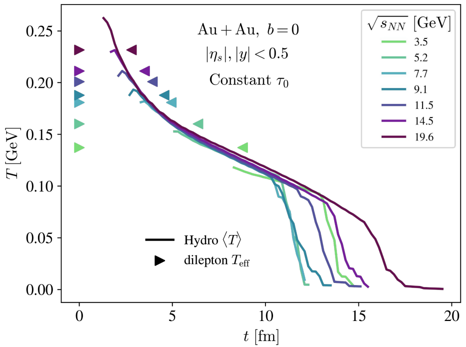


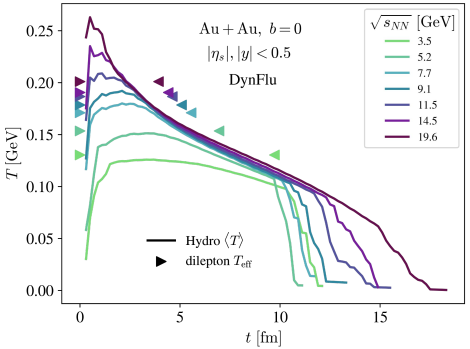


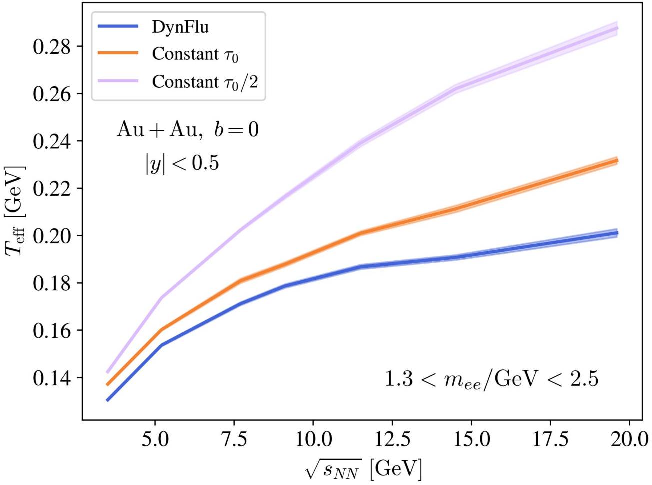


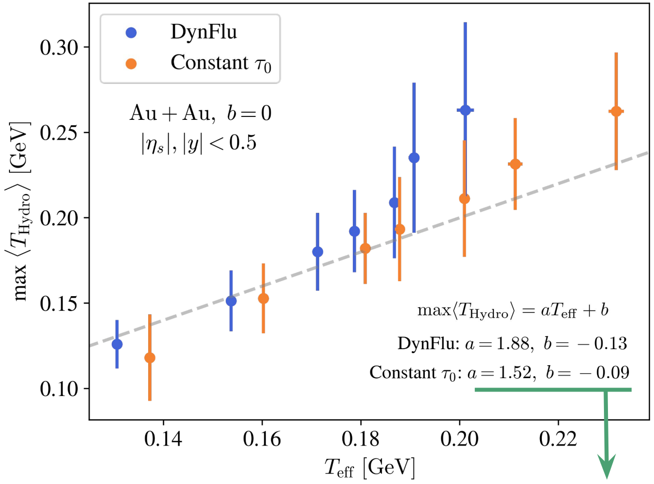
- ➔ IMR dileptons track early stages of hydro
- ➔ Low energies: extracted T_{eff} above $\langle T_{\mathrm{Hydro}} \rangle$
- ➔ Dynamic fluid is colder

Dileptons as thermometers

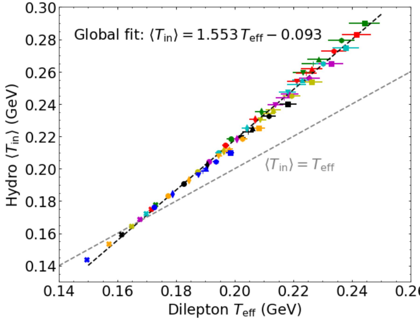








[J. Churchill et al. Phys. Rev. C 109, 044915]



➔ IMR dileptons track early stages of hydro

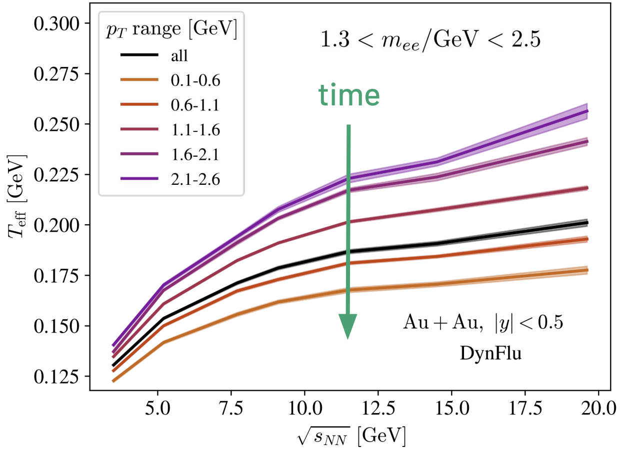
➔ Low energies: extracted T_{eff} above $\langle T_{\mathrm{Hydro}}\rangle$

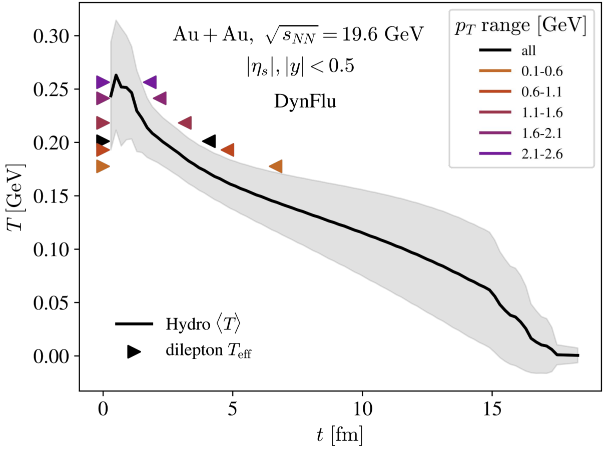
➔ Dynamic fluid is colder

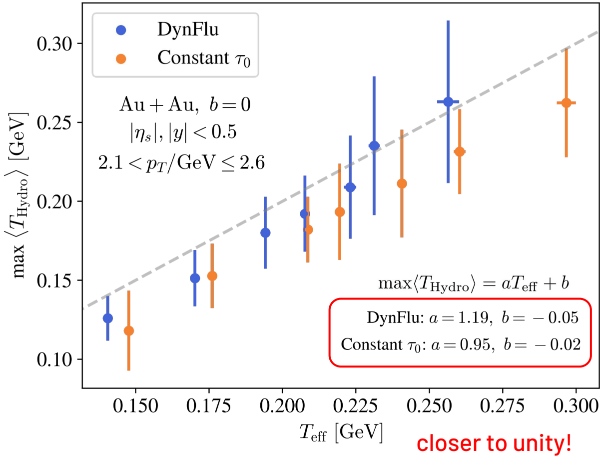
Different interpretations of measurement

Dileptons as thermoclocks

Early fluid → hotter cells → higher p_T dileptons







closer to unity!

Different p_T cuts probe different times!

Summary

Dilepton flow at HADES

- Cancellation between opposing sources may lead to “zero” flow
- Delta contribution can be tracked by correlating dilepton with protons

Production in hybrid

- Dilepton effective temperature highly dependent on initialisation
- Going to high p_T

Backup

Dynamic fluidization

Philosophy: *dense systems thermalize*

1. Energy momentum tensor for particles: $T^{\mu\nu}(\mathbf{x}) = \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} K(\mathbf{x} - \mathbf{x}_i)$ — Truncated gaussian smearing
2. Fluidization time of string fragmentation products: $f_t = 0.25 \text{ fm}$ (rest frame)
3. Hadron j becomes core if fluidization time has passed and $T^{00}(\mathbf{x}_j) > m_j K(0) + \epsilon_{\text{threshold}}$ — 0.5 GeV/fm^3
4. Core and corona particles only interact elastically