CMS Experiment at the LHC, CERN

Discussion and Summary

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EMMI Workshop: Probing the Early Stages with Jets

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Discussion

Ismail Soudi:
Glasma as a virtuality filter of the early shower

Conclusions

Takeaways

- Off-shell radiation introduces a new hard scale M^2 in the shockwave calculation.
- The glasma resolves transverse sizes $u \approx 1/Q_s$:

$$M^2 \ll Q_s^2 \;\Rightarrow\; \text{on-shell limit}, \quad M^2 \gg Q_s^2 \;\Rightarrow\; \text{color transparency}. \quad (54)$$

- The glasma selects part of early shower with virtuality of order $\sim Q_s^2$.

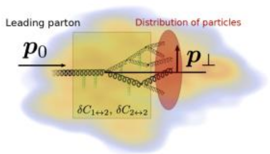
Outlook

- Compute the medium-induced spectrum $\frac{dN}{dy d^2k}$ and compare to on-shell results.
- Understand interference term $2\,\mathrm{Re}\langle \mathcal{A}_{\mathrm{vac}} \mathcal{A}^{\dagger}_{\mathrm{med}} \rangle$.

Ismail Soudi Energy Loss from Off-shell Quark in Gluon Fields 31 / 34

Summary

Minijets as linear perturbations



Transport coefficients:

- cutoff $\Lambda_{\min}$ exhibits effects of the medium

Equilibration:

- universal evolution by scaling with $\hat{q}$ and $\sqrt{E}$
- $t_{\mathrm{therm}} \sim 16\,\mathrm{fm}$ for a jet of $15\,\mathrm{GeV}$ (weakly coupled picture)
- jet perturbation becomes part of the hydrodynamical background

Outlook:

- non-equilibrium $\hat{q}_{ij}(\tau)$ Lindenbauer et al., PLB 2303.12595, PRD, 2312.0044

Fabian Zhou:
Kinetic theory bridge microscopic jet scatterings with the eventual conversion of a minijet into hydrodynamic medium response.

Summary

- Local LPM suppression has been embedded consistently into the off-shell DQPM $2 \to 3$kernel
- Coherence effects increase with jet energy and affect dE/dx more strongly than $\hat{q}$.
- The standard massive setup gives moderate suppression; the massless-emission and gluon-jet cases are much more sensitive.
- The method is BDMPS-Z-inspired but remains less dynamical than the SUBA-Jet phase-accumulation approach
- $D_s(T)$ for heavy quarks is not sensitive to inelastic reactions
- Antenna interference is substantial and motivates a future unified treatment in thermal transport and PHSD

Olga Soloveva:
same nonperturbative quasiparticles can describe both the medium and its hard probes, but realistic jet energy loss requires quantum coherence

Conclusions and Outlook

Conclusions

- $Q\bar{Q}$ suppression signal of deconfinement and QGP formation
- incredibly complicated system: with **OQS** and **EFT**
  - $Q\bar{Q}$ as multiscale probe of strongly coupled medium
  - non-equilibrium, quantum evolution
  - systematically derive QCD master equation
    $\implies$ get observables
- numerically solve master equation

Outlook: Early Stages

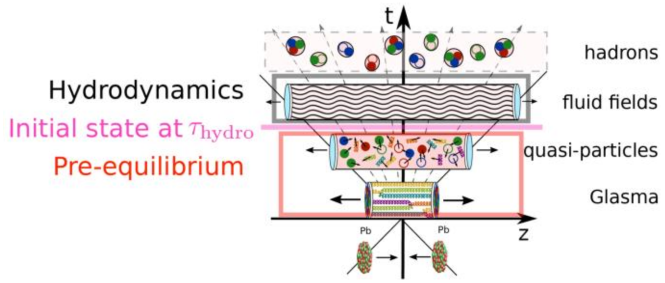
- **OQS** and **EFT** ((p)NRQCD, SCET) for jet evolution
- **smaller systems** perhaps more sensitive to early stages
- other $Q\bar{Q}$ observables (**energy correlators**) may be sensitive

Peter Vander Griend:
quarkonium suppression is a non-equilibrium quantum-transport problem governed by singlet-octet transitions and medium correlators. Inclusive suppression is likely too integrated to isolate the earliest stage.

How do we separate the filtering effect from Glasma and QGP?
How does this impact the extraction of transport properties of QGP?
Which observable is more likely to isolate the early stages from Quarkonia?

Consensus from the Workshop

- Early-time jet physics should be treated as a continuous, multi-stage problem
    - Glasma / classical field: roughly $0 < \tau < O(0.1)$ fm/c
    - Kinetic pre-equilibrium: roughly $0.1 < \tau \leq O(0.4-1)$ fm/c
    - Hydrodynamic QGP: roughly $\tau > O(0.4-1)$ fm/c
    - However, exact boundary is not agreed on



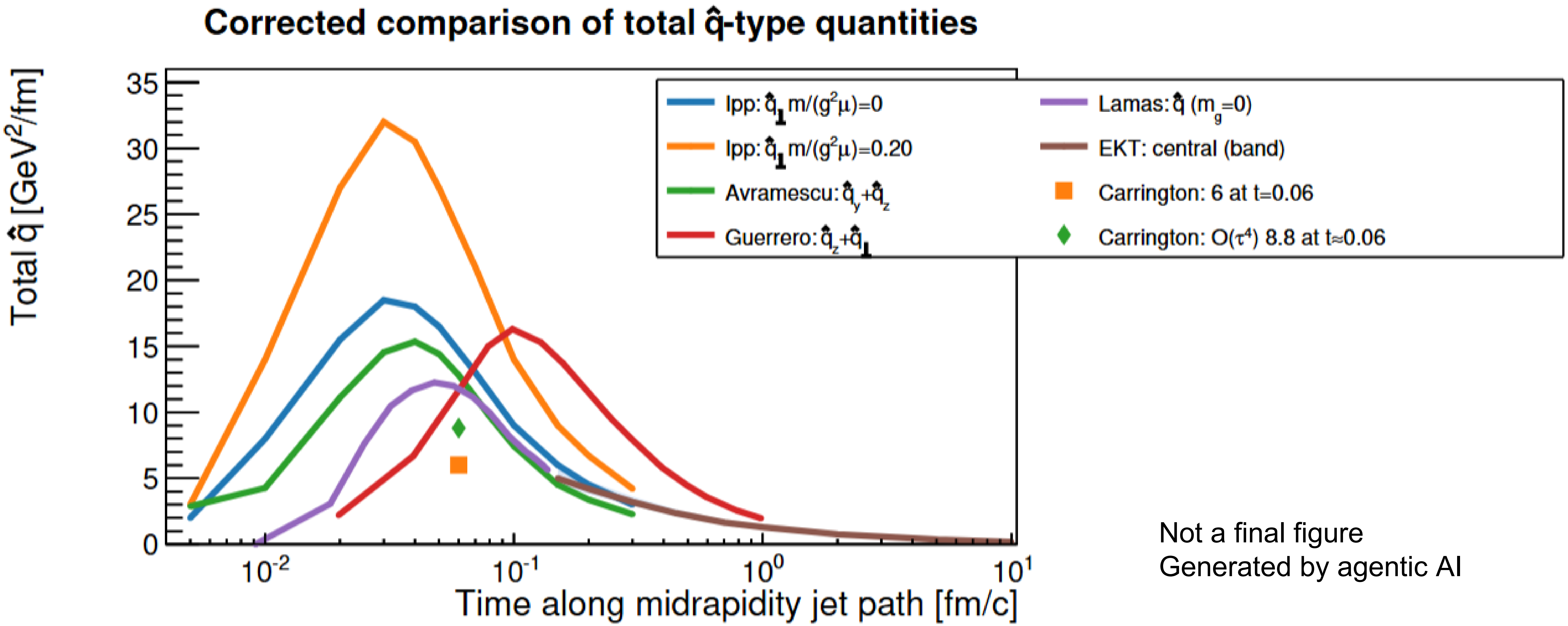
- Large early $\hat{q}$ doesn't necessarily mean dominant energy loss
    - Short stage, formation-time and interference effect matter
    - The early field may resolve the shower by virtuality scale
    - Boson-jet data disfavor extremely large net random transverse kick
    - However, exact fraction of the total jet energy loss from early stages is not yet established
- We need more than a scalar, time-independent $\hat{q}$
    - Broadening depends on direction, shear stress, gradients, velocity fields and the jet orientation
    - However, the size of the effects are not agreed on

Consensus from the Workshop

- Experimental challenge: Inclusive R_{AA} is not sufficient to identify the mechanism
  - Many distinct effects, like energy loss, coherence breaking, altered shower formation, selection bias, quark/gluon composition changes, out-of-cone transport, medium response and initial-state correlations
  - Experimental control includes:
    - Photon- and Z-tagged
    - WTA for recoil-free direction tagging
    - Study prompt vs. non-prompt
    - Selection on splitting or formation time
    - Beam-direction vs azimuthal-direction observable
    - Systematic scans of system size and lifetime: light vs heavy ions
- Medium response is part of the signal in various observables and has been observed experimentally
  - A realistic calculation should conserve 4-momentum and describe both surviving shower and the excited medium
- Baseline control is as important as medium modeling
  - Precise pp, ee references and modern high-accuracy vacuum showers

What was not yet Agreed

- Magnitude of pre-hydrodynamic energy loss and $\hat{q}$



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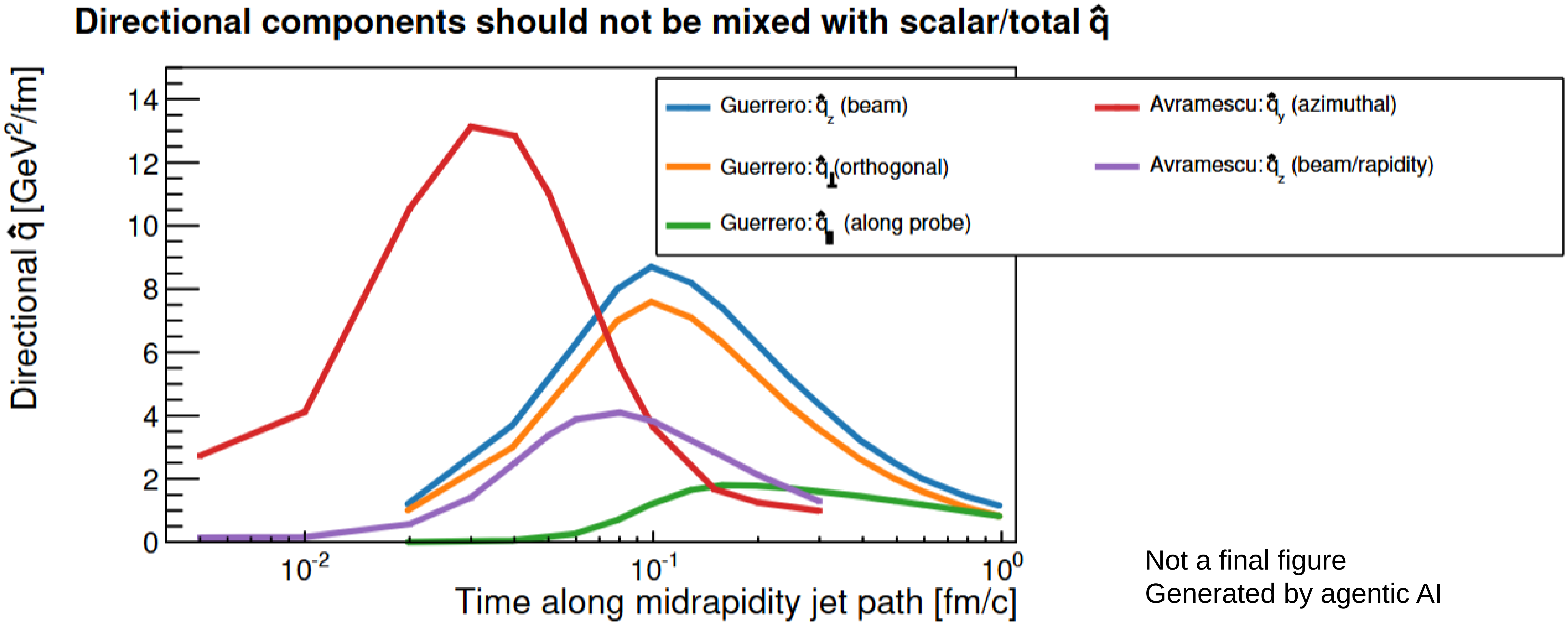
What was not yet Agreed

- Magnitude of pre-hydrodynamic $\hat{q}$ in different directions



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What was not yet Agreed

- Microscopic nature of the medium
  - Discrete/quasiparticle scattering vs. excitation of a continuous strongly interacting medium
  - Existence, Classical versus quantum treatment of the Glasma

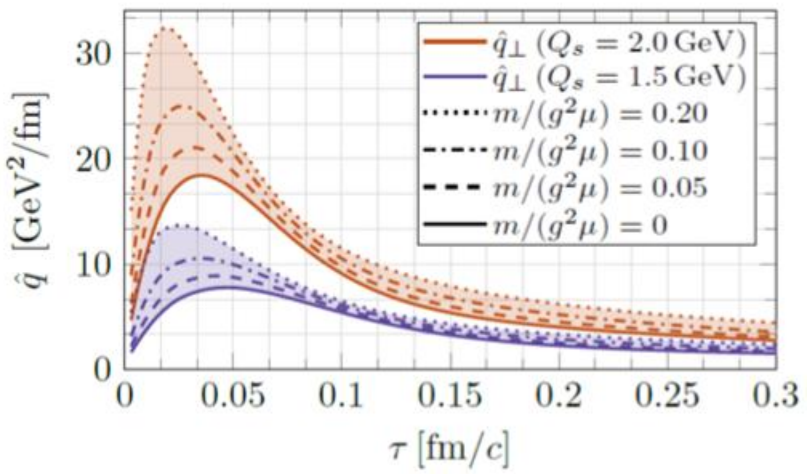
- A single “Golden Observable” and additional collision system
  - Is pO, pPb, OO, XeXe and PbPb at the RHIC/LHC already good enough?
  - If we can't find a silver bullet observable, **precise quantification** is needed

Follow-up for the Future Workshop / RRTF

- **Benchmark early-time transport**: agree on a common presentation of the variable $\hat{q}(t)$, $\hat{q}_{ij}(t)$, $\Delta p_\perp^2$ and radiation kernels.
- Detailed **comparison among different approaches** to reduce the theoretical uncertainty on broadening, start and end time of different phases.
- Run an "**early-stage observable challenge**" with identical cuts and backgrounds.
- Prioritize tagged/timed handles: γ/Z+jet, heavy flavor, formation-time substructure and **extension** of EECs / C_{ij} idea.
- Answer what would be the best way to **vary the relative contributions** from initial stages and hydro phase.
- Implication to the extraction of the QGP transport properties

Backup slides

Probing the Early Stages with Jets



Timeline:

- Glasma / classical field: roughly $0 < \tau < 0.1$ fm/c
- Kinetic pre-equilibrium: roughly $0.1 < \tau \leq 0.4$ fm/c
- Hydrodynamic QGP: roughly $\tau > 0.4$ fm/c

Experimental Control:

- **Direction**: beam axis vs. azimuthal angle
- **Production time**: prompt versus delayed probes
- **Shower time**: splitting formation time
- **System lifetime**: OO vs PbPb

What Have We Learned from Experimental Data?

- Existing jet-hadron and dihadron broadening is striking. However, selection bias, flow and medium response prevent a unique Glasma interpretation

- Experimental controls become possible:
  - beam versus azimuth, prompt versus delayed probes, before versus after splitting and OO vs. PbPb

- Current boson-jet data **disfavor extremely large net random kicks**, but still allow a short-lived early broadening stage