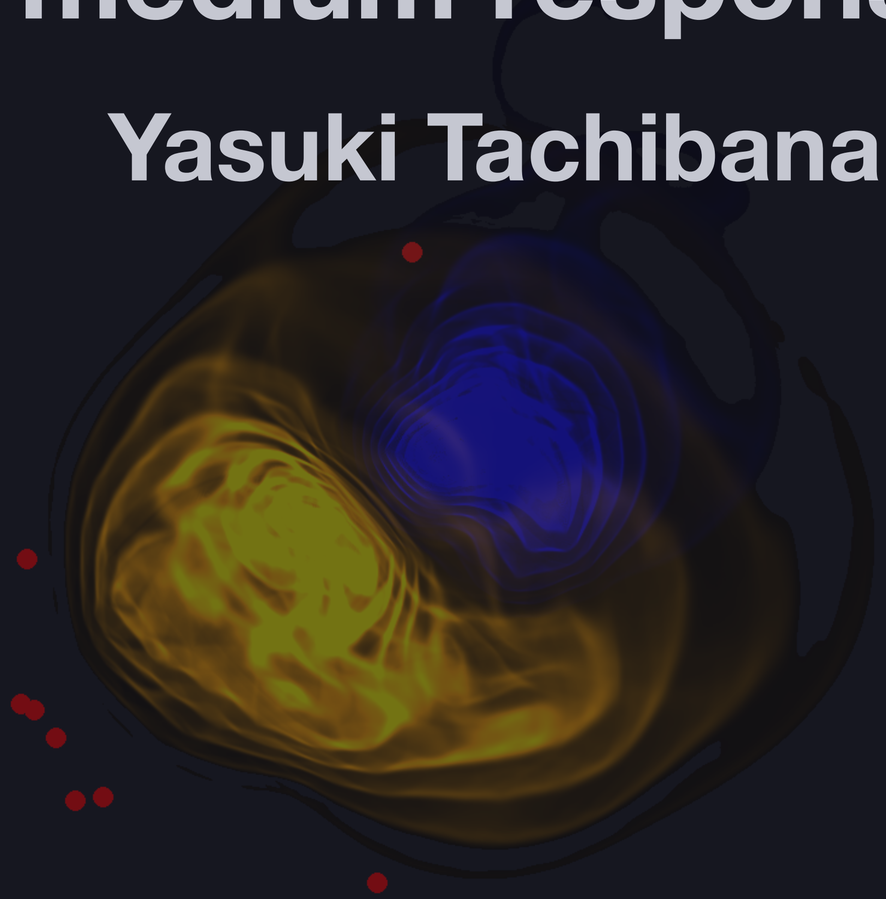
公立大学法人
国際教養大学
Akita International University

JETSCAPE

THIC2023

Jets and medium response (Theory)

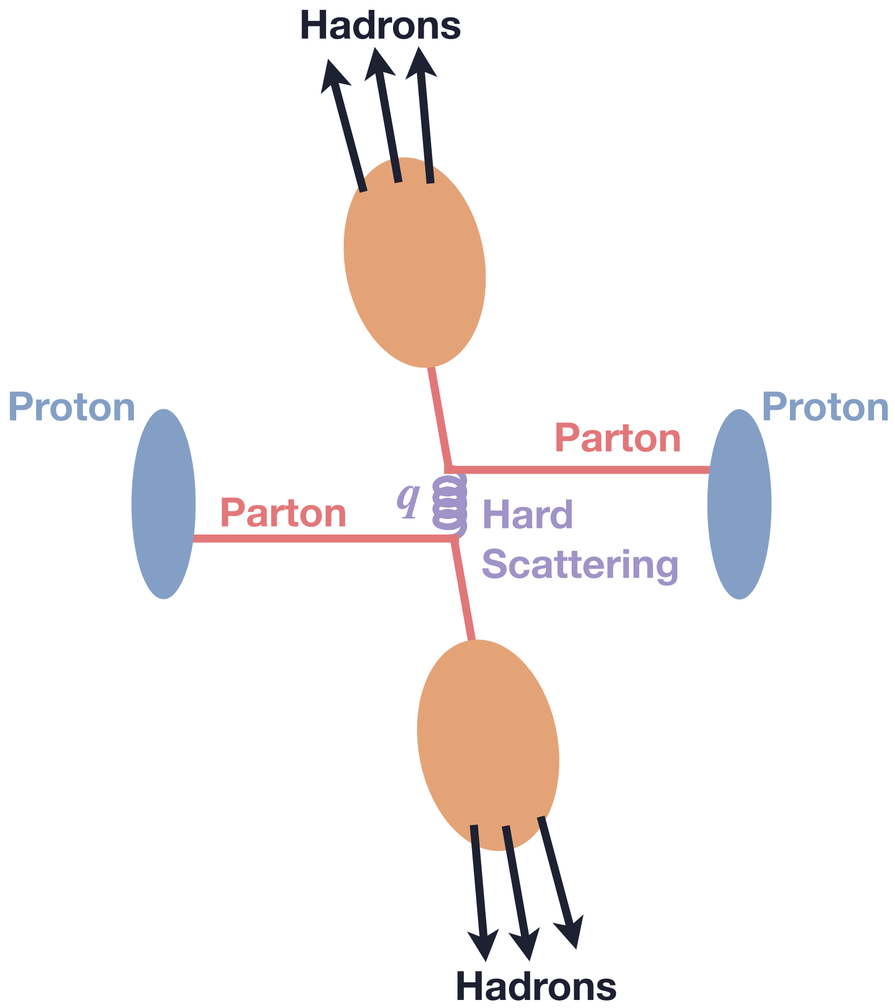
Yasuki Tachibana



Introduction

Jet

- **Jet in proton-proton (pp) collisions**



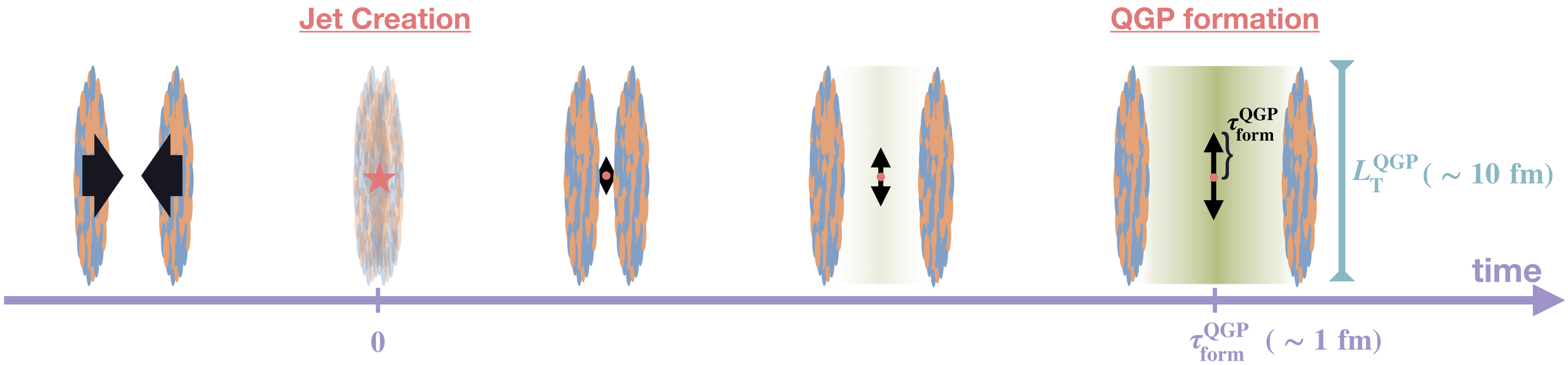
- Results in concentration of high-p_{T} hadrons in a small angle
- Originate from a hard (large-momentum transfer $-q^2$) scattering
- *Relatively* well-established formulation for the cross-section (pQCD+universal input from exp.)

Good baseline with clear signal

Development of further accurate in-vacuum parton shower models [e.g. PanScales Dasgupta et al. PRL125, 052002 (2020)]

Jet propagation in heavy-ion collisions

Bjorken, FERMILAB-PUB-82-059-THY (1982)



- Rapid formation of large QGP medium ($\tau_{\rm form}^{\rm QGP} < L_{\rm T}^{\rm QGP}$)

Jet propagation through QGP medium

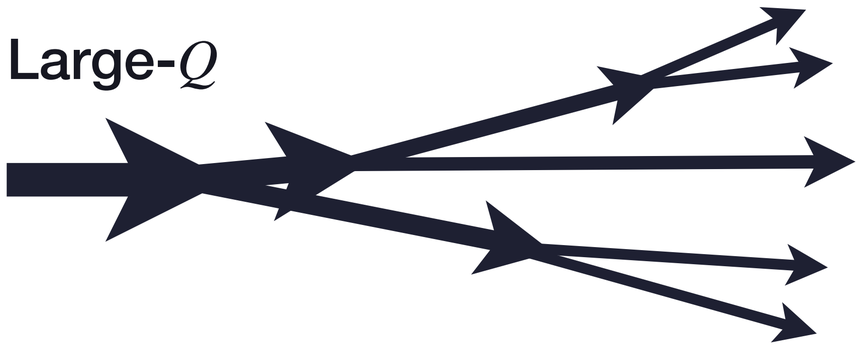
Parton shower evolution in QGP medium

In-vacuum

- **In-vacuum parton shower**
  - Virtuality-driven parton splittings

Small-Q

Large-Q



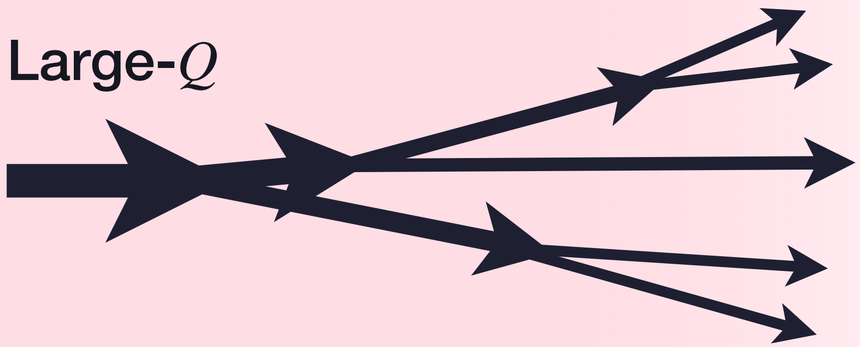
$\boldsymbol{Q^2 = p^\mu p_\mu - m^2}$**: virtuality (off-shellness)**

Parton shower evolution in QGP medium

In-medium

Small-Q

Large-Q



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- **In-medium parton shower**

Parton shower evolution in QGP medium

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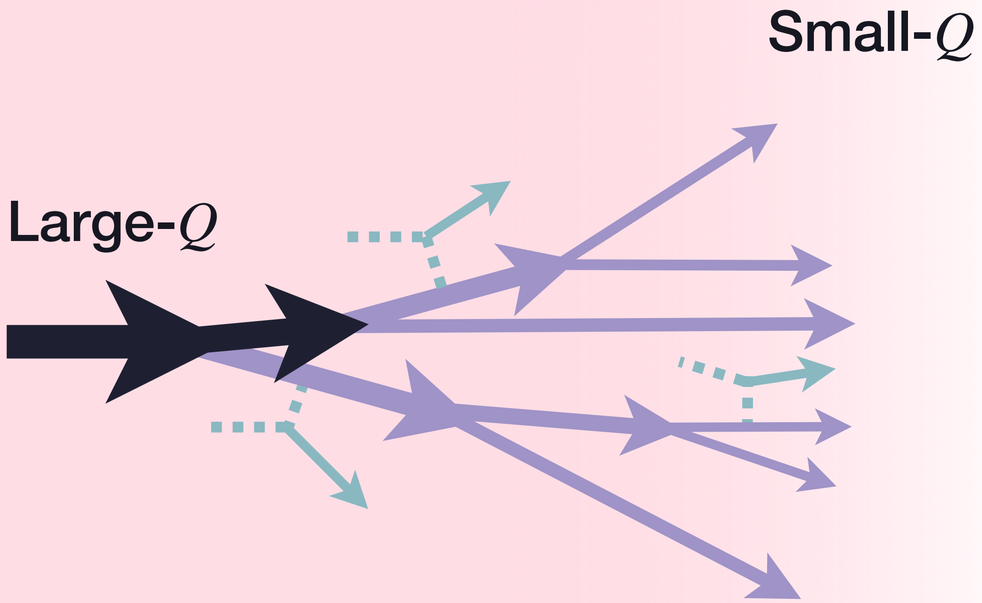

- **In-vacuum parton shower**
  - Virtuality-driven parton splittings
- **In-medium parton shower**
  - Jet parton-medium interactions
  - Large-Q: Medium effect on top of vacuum-like splitting

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Parton shower evolution in QGP medium

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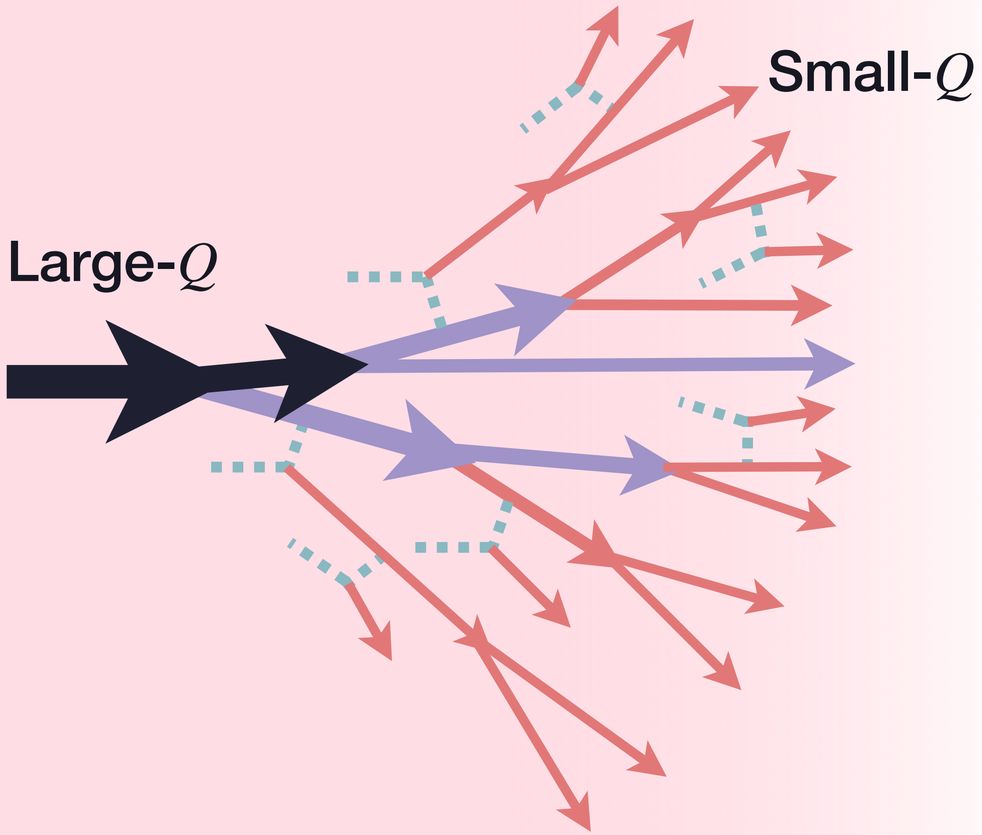

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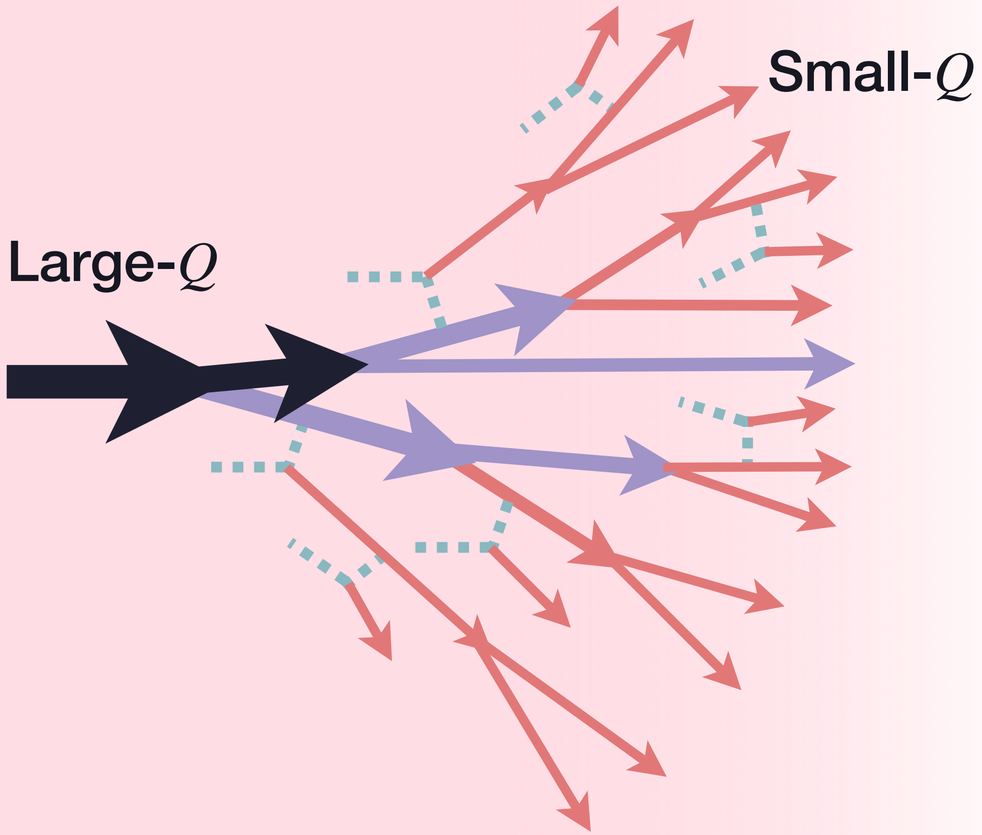

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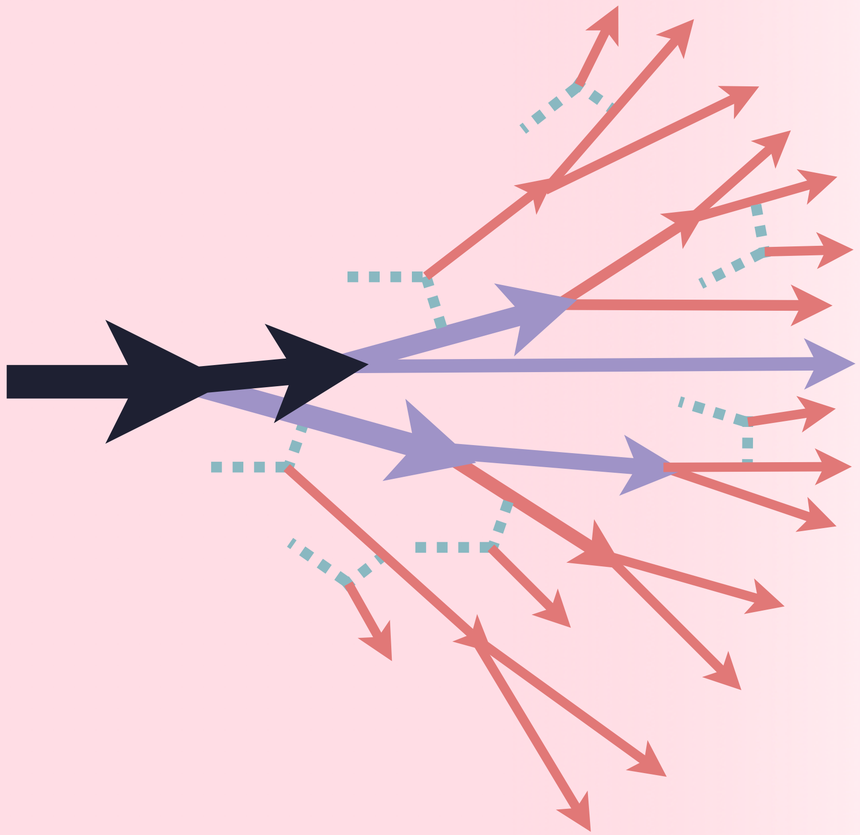
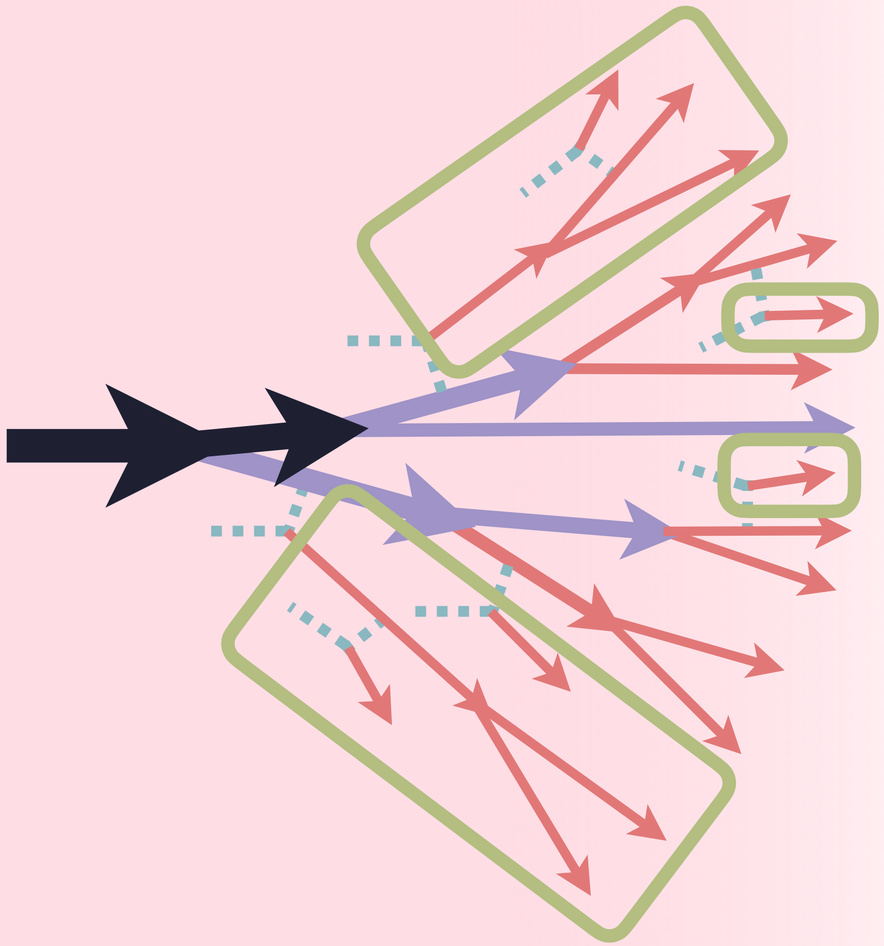
Modification of showering pattern

Medium response to jet propagation in QGP



- **Recoils**
  - Medium constituents struck by jet partons
  - Propagate as a parton in jet shower
  - Harder than the typical scale of the medium constituents
- **Hydrodynamic medium response**
  - In-medium thermalization of jets
  - Transition to hydrodynamic transport: jet-induced flow
  - Evolve as part of bulk medium fluid
- **Hadrons from medium repsonse**
  - Generally soft and spread out from jet
  - Jet-correlated, cannot/should not be subtracted
  - Affect structures inside/around jet

Medium response to jet propagation in QGP



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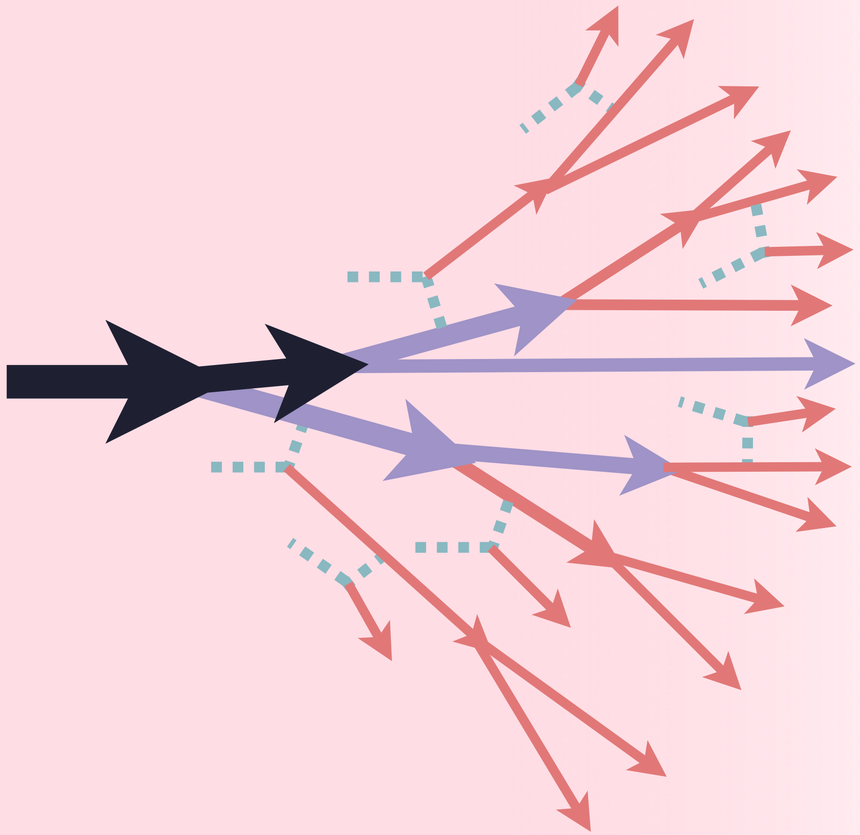

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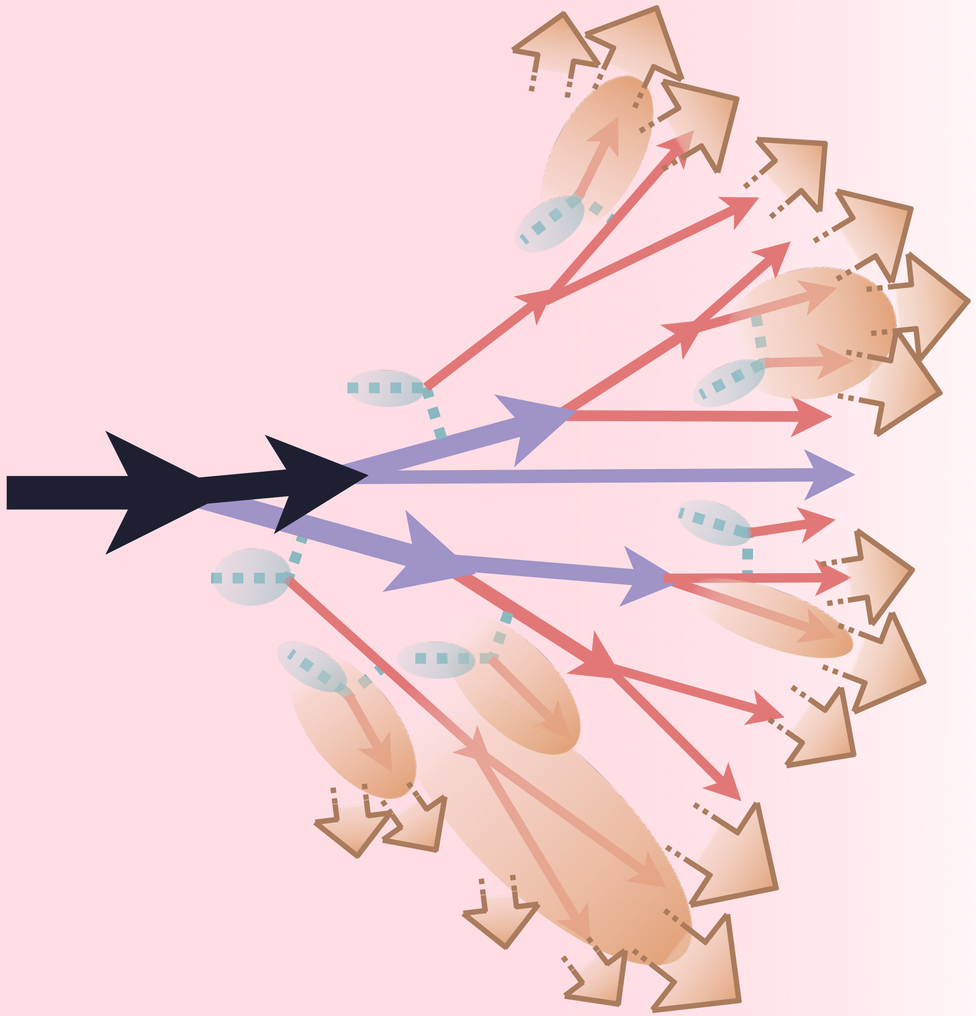

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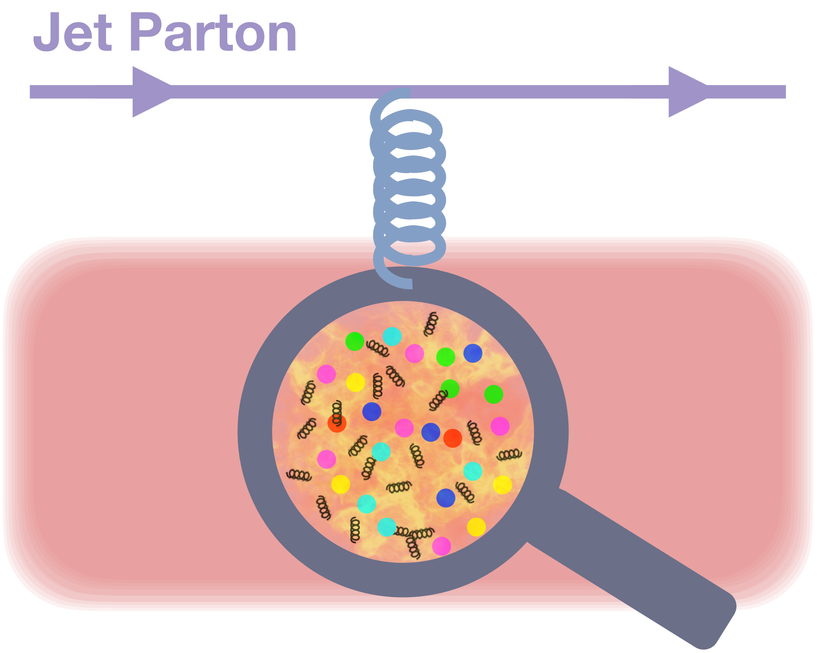
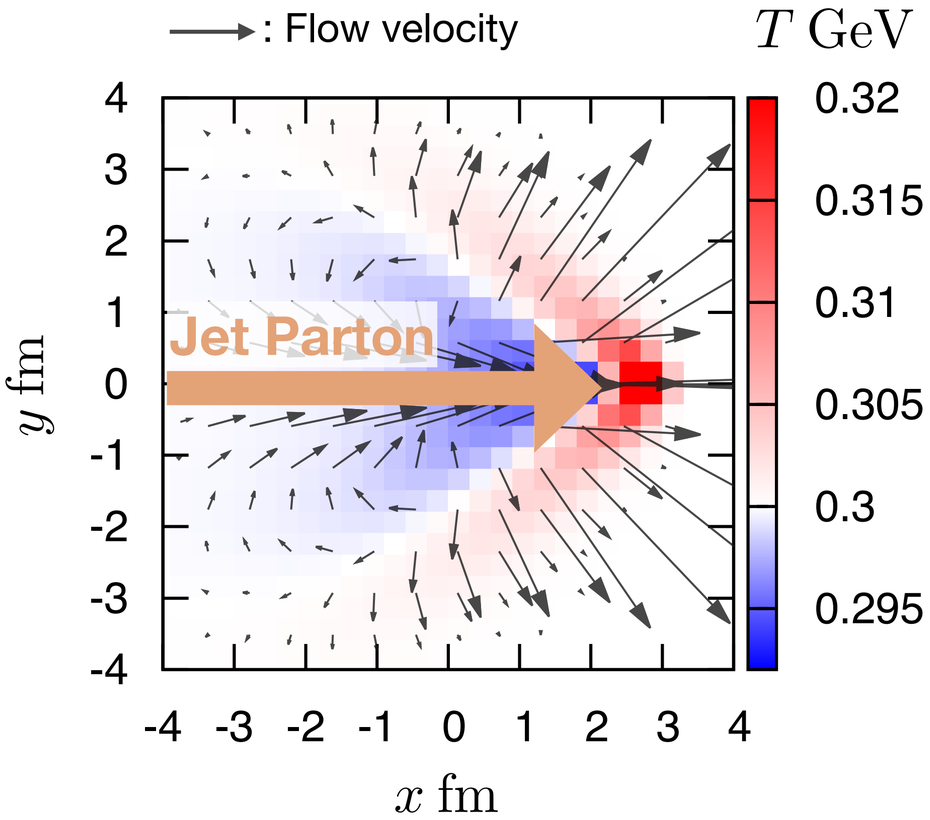
Motivations of jet studies in QGP

- **Hard interaction with QGP**
  - Structures inside QGP



- **Collective reaction of QGP**
  - In-medium thermalization process
  - Bulk property of QGP medium



Recent progress in jet phenomenology

Medium effects at high virtuality

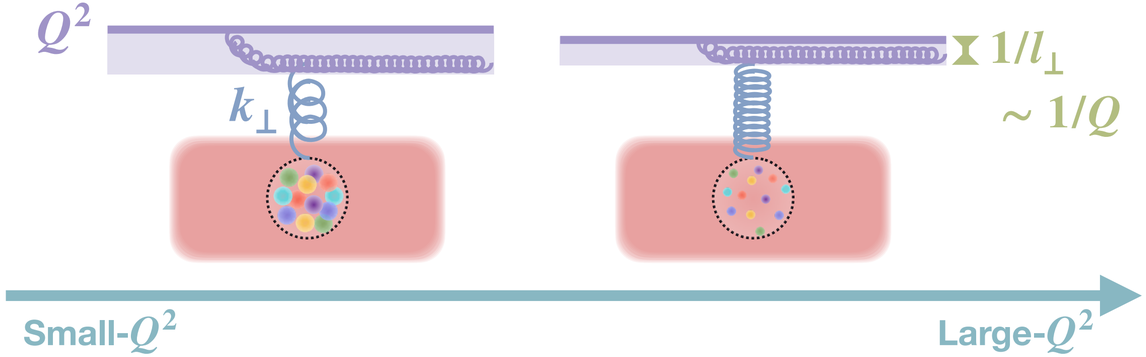
- **Reduction of medium effect at large-Q^2**
  - Scale evolution of QGP constituent distribution
    Kumar, Majumder, Shen, PRC101, 034908 (2020)
  - Less interaction for large-Q^2 parton
  - Implementation by parametrized modulation factor
    Kumar et al (JETSCAPE), PRC107, 034911 (2023)

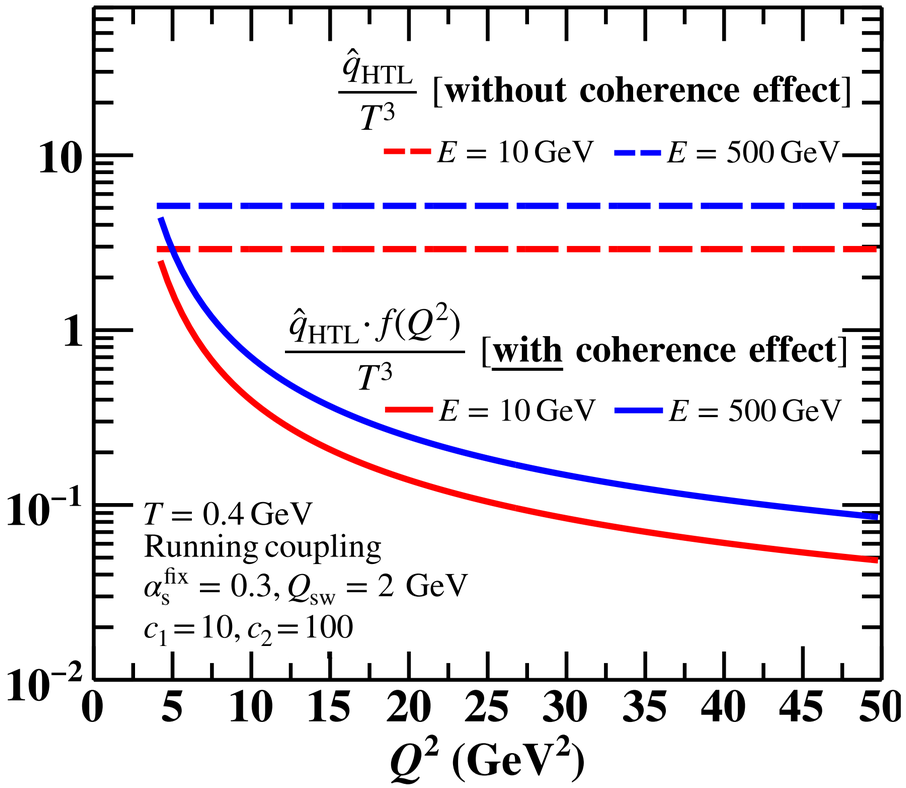
Effective jet-quenching strength

$$\hat{q}_{\mathrm{HTL}} \cdot f(Q^2)$$

$$f(Q^2) = \frac{1 + c_1 \ln^2(Q_{\mathrm{sw}}^2) + c_2 \ln^4(Q_{\mathrm{sw}}^2)}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$

$$\hat{q}_{\mathrm{HTL}} = C_a \frac{42\zeta(3)}{\pi} \alpha_{\mathrm{s}}^{\mathrm{run}} \alpha_{\mathrm{s}}^{\mathrm{fix}} T^3 \ln\left[\frac{2ET}{6\pi T^2 \alpha_{\mathrm{s}}^{\mathrm{fix}}}\right]$$

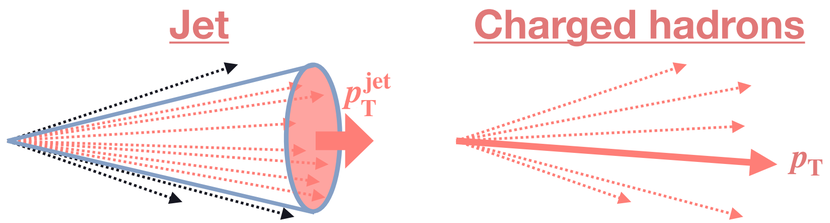




Medium effects at high virtuality

- **Reduction of medium effect at large-Q^2**

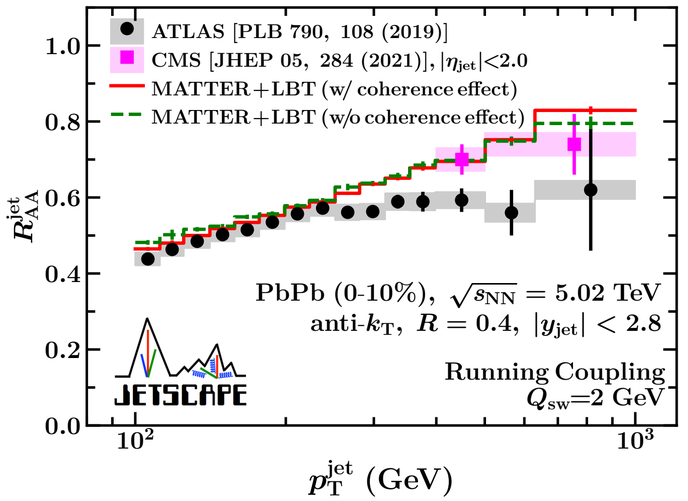
  - Needed for simultaneous description of jet and single hadron

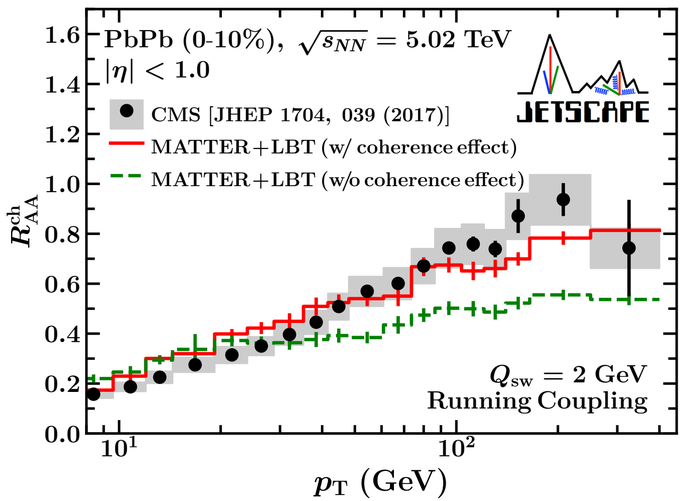


  - Very strong sensitivity of hadrons at high-p_{T}

MATTER+LBT

Kumar et al (JETSCAPE), PRC107, 034911 (2023)

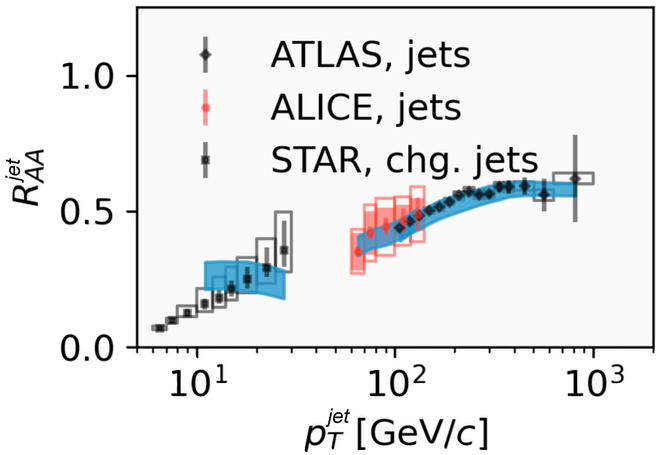


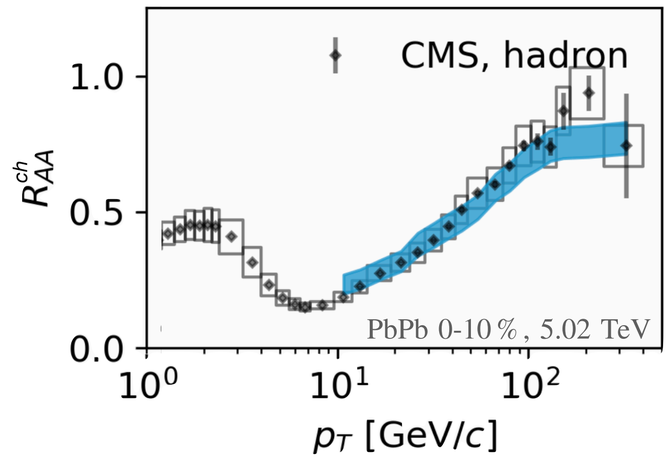


LIDO

Ke, Wang, JHEP05, 041(2021)

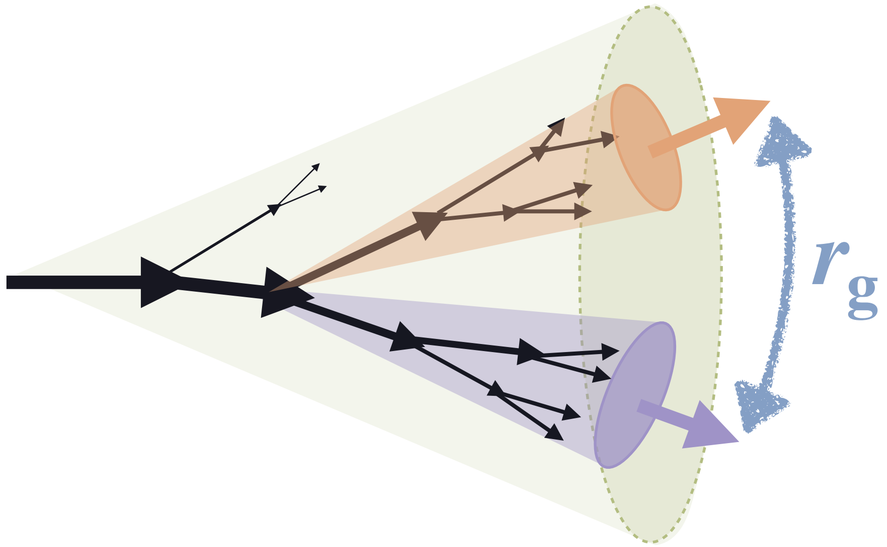
Medium effect OFF at high virtuality





Medium effects at high virtuality

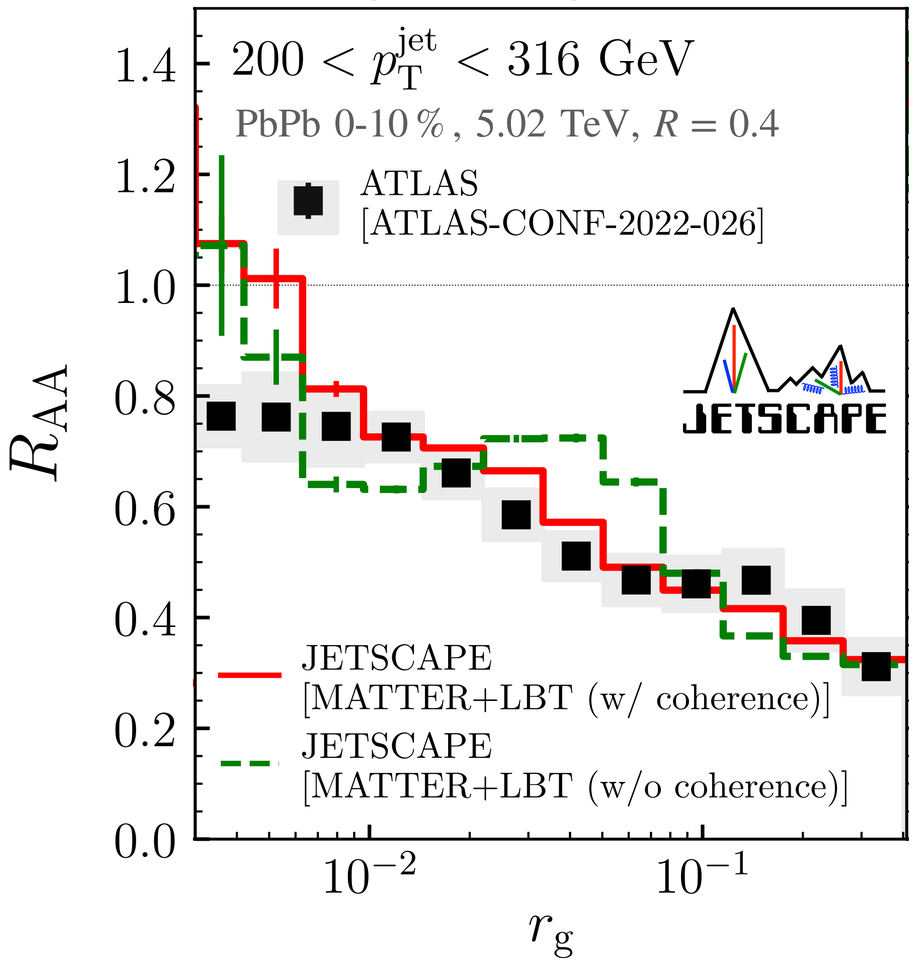
- **Modification of splitting at high virtuality**



- Hard splitting at high virtuality identified by SoftDrop
- Splitting radial distance r_g dependence in energy loss
- Suppression of broadening (bump disappearance)

MATTER+LBT

YT et al (JETSCAPE), arXiv:2301.02485



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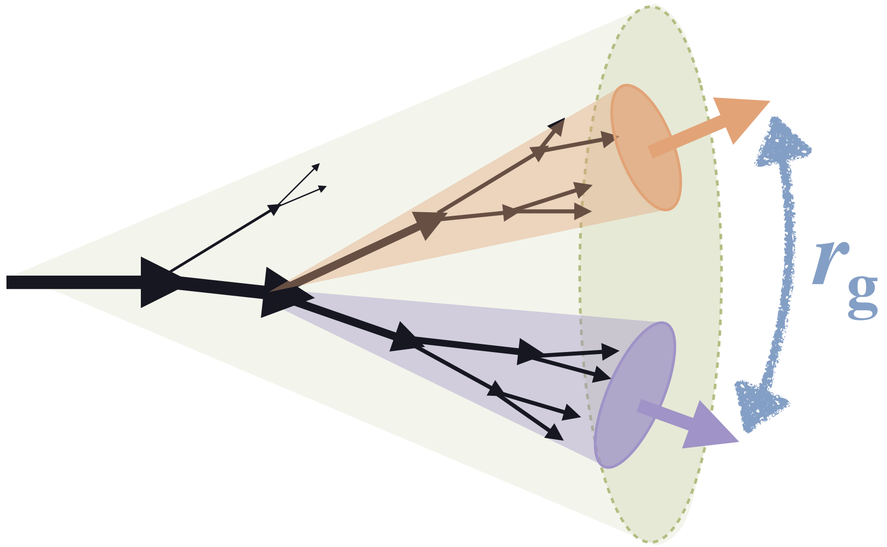

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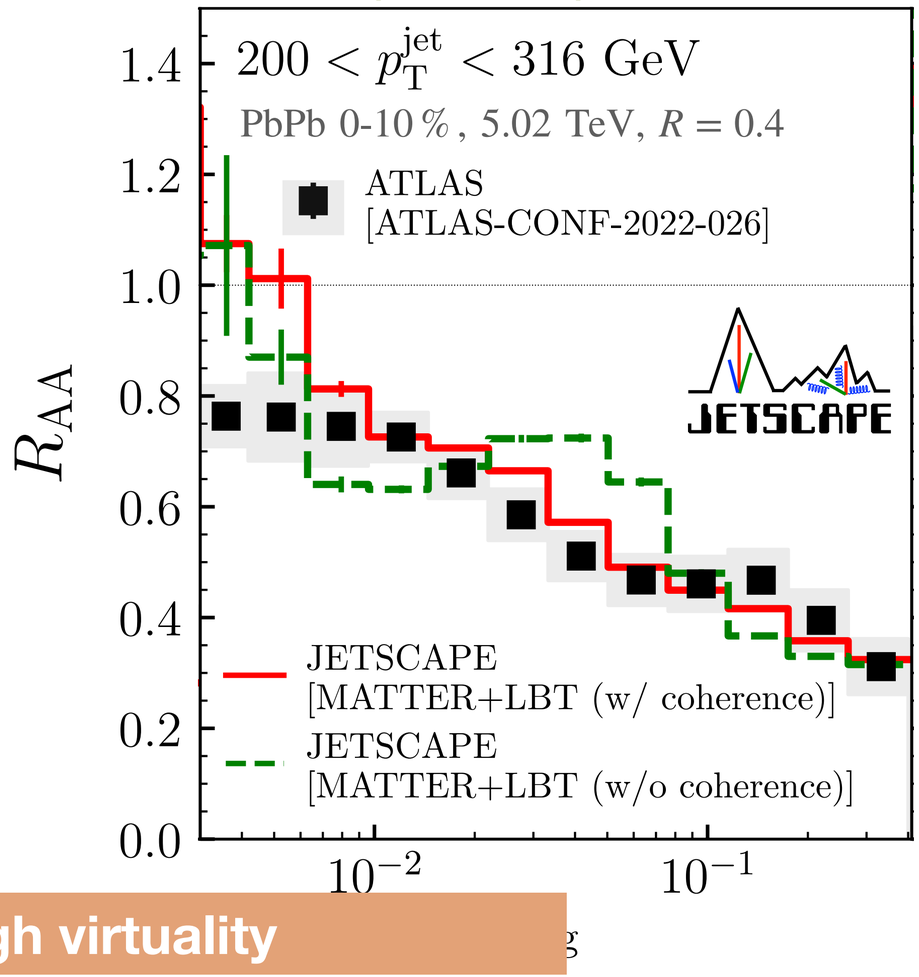


Medium effect reduction at high virtuality

Medium effect at low virtuality

- **Comparison between models for small-Q^2** Shi, Yazdi, Gale, Jeon, arXiv:2212.05944

- MATTER (w/o coherence) for large-Q^2
- CUJET or MARTINI for small-Q^2

CUJET Shi, Xu, Liao, Gyulassy

DGLV formalism, Recoil ON

Gyulassy, Levai, Vitev (00,01), Djordjevic, Gyulassy (04)

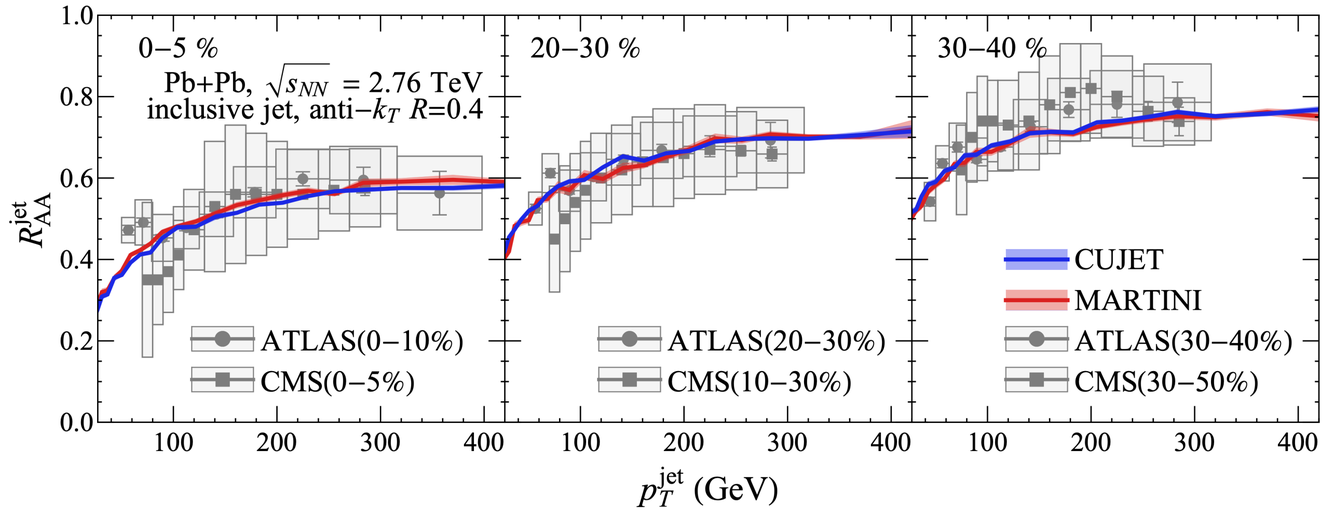
MARTINI Schenke, Gale, Jeon, Park, Yazdi

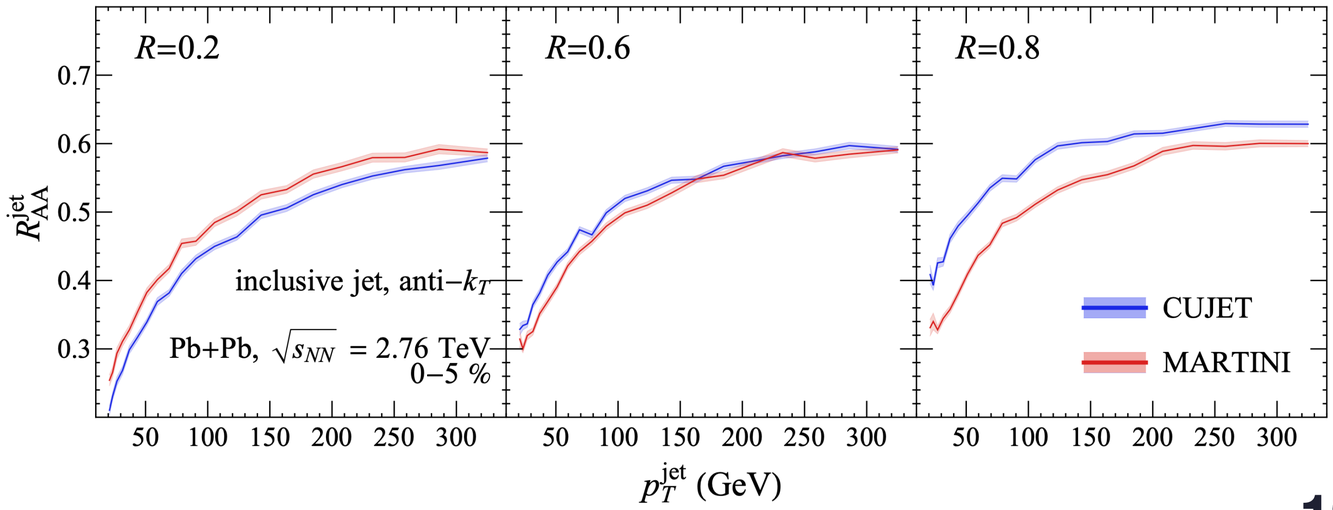
AMY formalism, Recoil ON

Arnold, Moore, Yaffe(01,02,03), Jeon, Moore(05), Turbide, Gale, Jeon, Moore(05)

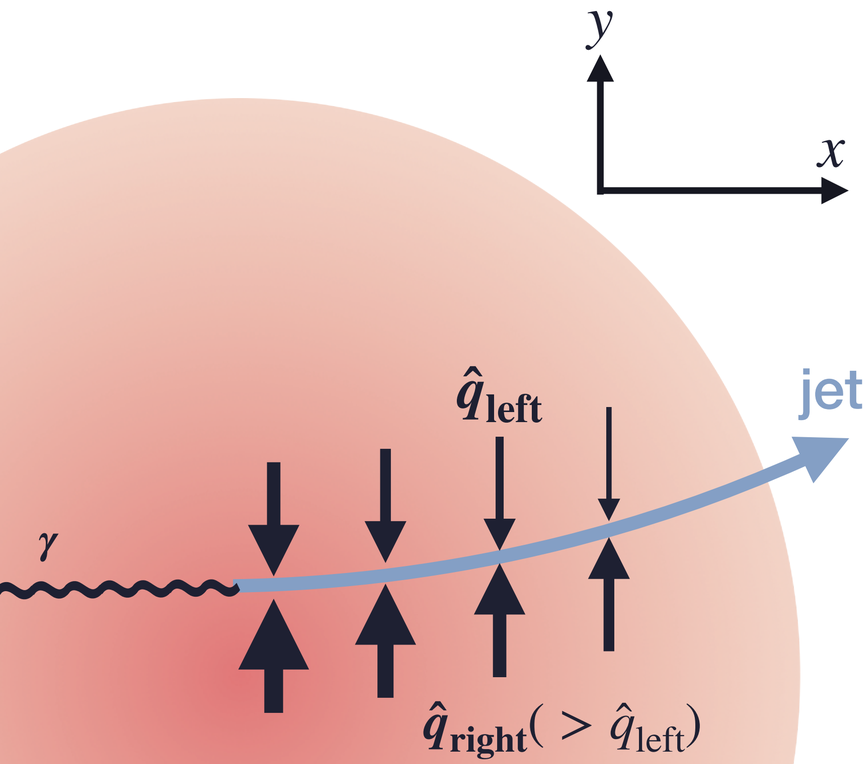
MARTINI jet radiates more soft gluons with tuned parameters

- Both similarly describe jet energy loss
- Internal structure shows the difference





Gradient Tomography



- **Jet deflection due to $\hat{q}$ gradient**

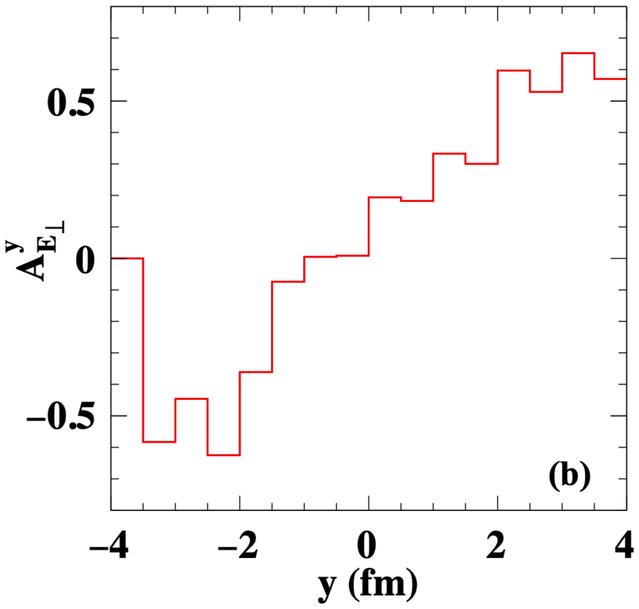
Talk by Y. He (Mon)

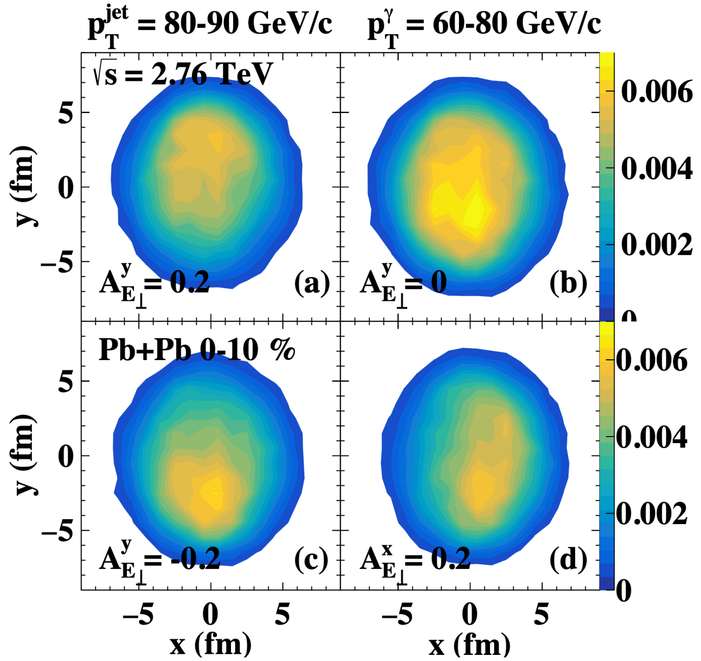
He, Pang, Wang, PRL 125, 122301 (2020)

- Transverse energy asymmetry

$$A_{E_\perp}^{\vec{n}} = \frac{\int d^3r d^3k\ (\vec{n}\cdot\vec{k})\ f(\vec{k},\vec{r})}{\int d^3r d^3k\,|\vec{n}\cdot\vec{k}|\ f(\vec{k},\vec{r})}$$

- Simulation by LBT Wang, Zhu(13), Luo, et al.(15,18), Cao, et al.(16,17), He, et al.(18)
- Localize the jet production point by limiting $A_{E_\perp}^{\vec{n}}$





Various effects in jet quenching

- **Heavy quark jet substructure**
  - Langevin+gluon radiation with dead-cone effect (SHELL model)

    Zhang, Xu, Dai, Zhang, Wang

    Talk by Q. Zhang (Wed)

- **$\hat{q}$ behavior near T_c in spatial anisotropic strongly-coupled plasma**
  - AdS/CFT calculation with anisotropy and velocity (mass) dependence

    Zhou, Zhang, arXiv:211.14792

    Talk by Q. Zhou (Wed)

- **Transverse momentum broadening evolution with BDMPS-Z**
  - Solution using MINCAS Markov-Chain Monte-Carlo (MCMC) program

    Adhya, Kutak, Płaczek, Rohrmoser, Tywoniuk, arXiv:2211.15803

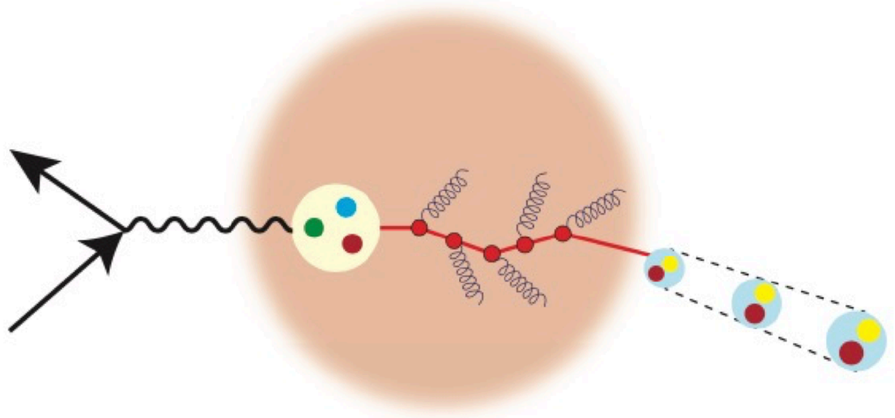
    Talk by S. P. Adhya (Wed)

Jet production in various systems

- **Cold nuclear matter (CNM) effect in eA collisions**
  - Momentum broadening due to multiple partonic scattering inside the nuclear target

    Ru, Kang, Wang, Xing, Zhang, arXiv:2302.02329

    Talk by P. Ru (Wed)



- **Forward quak dijet production mechanism in pA collisions**
  - Comparison of improved-TMD and CGC frameworks Talk by H. Fujii (Wed)

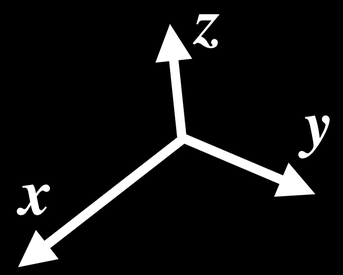
    Fujii, Marquet, Watanabe JHEP 12, 181 (2020)

Medium response to jet propagation

Structure arising as medium response

MATTER + LBT + Causal Diff. + Ideal Hydro [Static Brick, $T_{\mathrm{brick}} = 250\ \mathrm{MeV}$]
YT, C. Shen, A. Majumder, PRC 106, L021902 (2022)

- Jet-Induced flow induced by a parton shower propagating in the x direction



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Blue: Region with $T < 250\ \mathrm{MeV}$

Red: Energetic Partons

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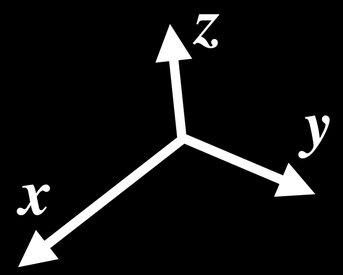

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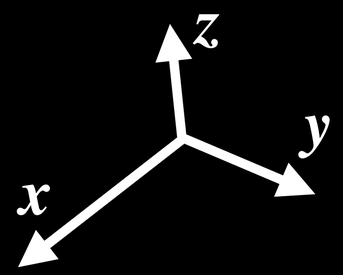

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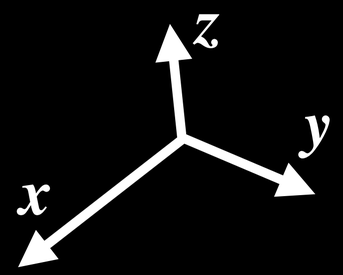

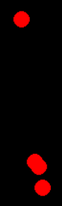

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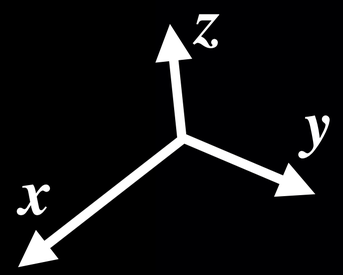

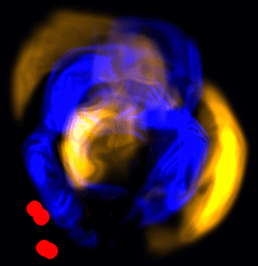

Orange: Region with $T > 250\ \mathrm{MeV}$

Blue: Region with $T < 250\ \mathrm{MeV}$

Red: Energetic Partons

Structure arising as medium response

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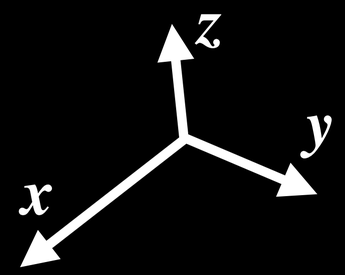

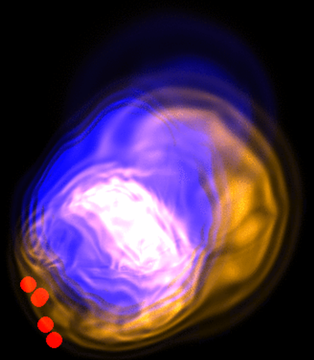

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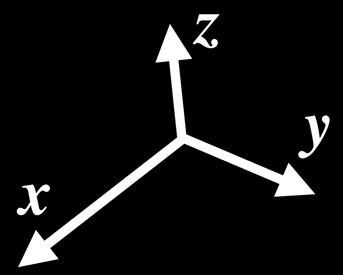

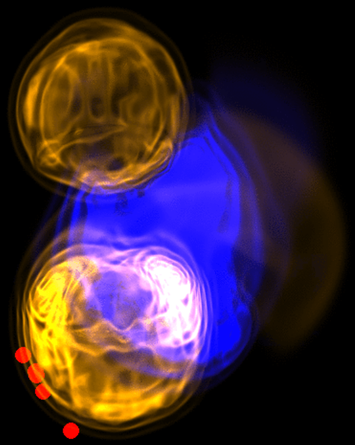

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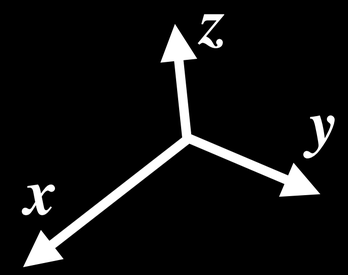

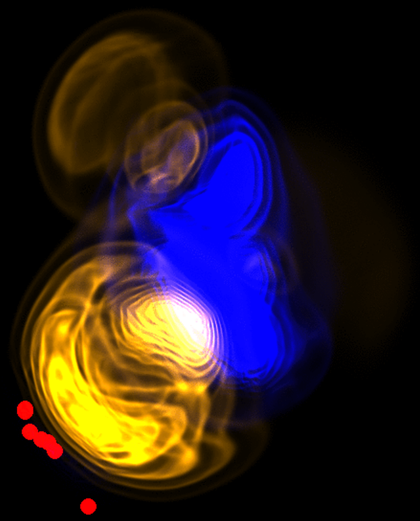

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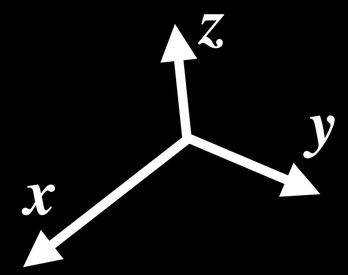

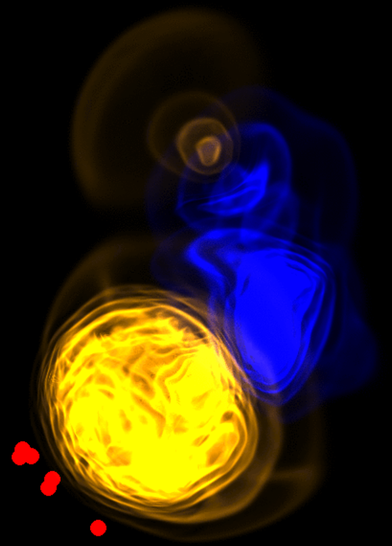

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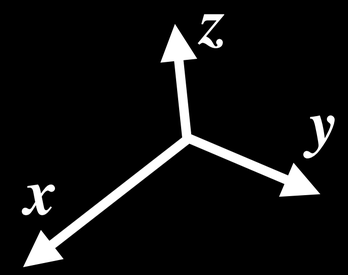

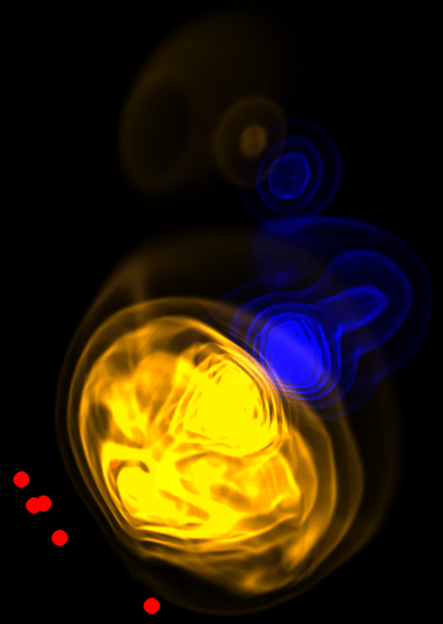

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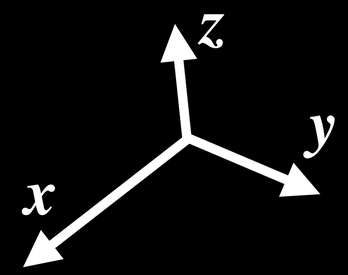

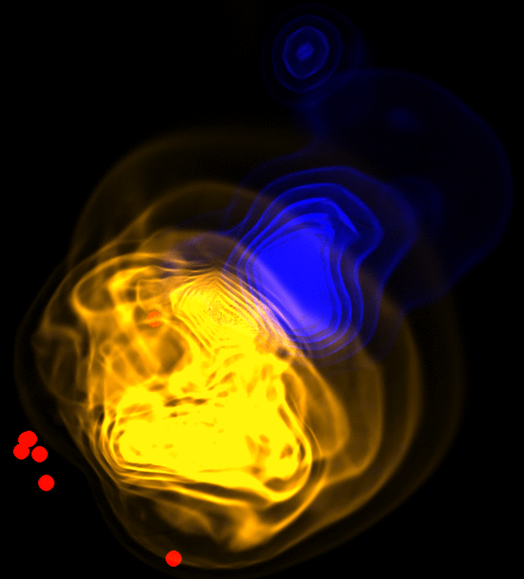

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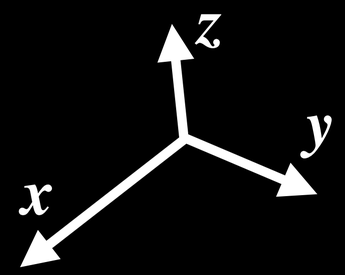

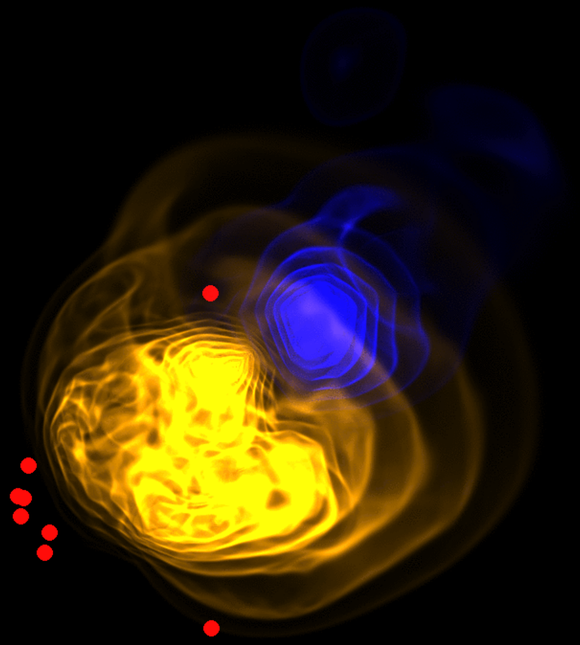

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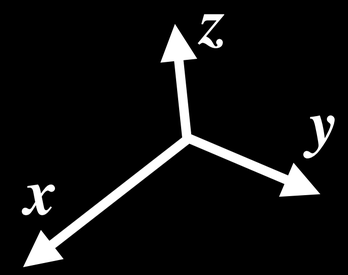

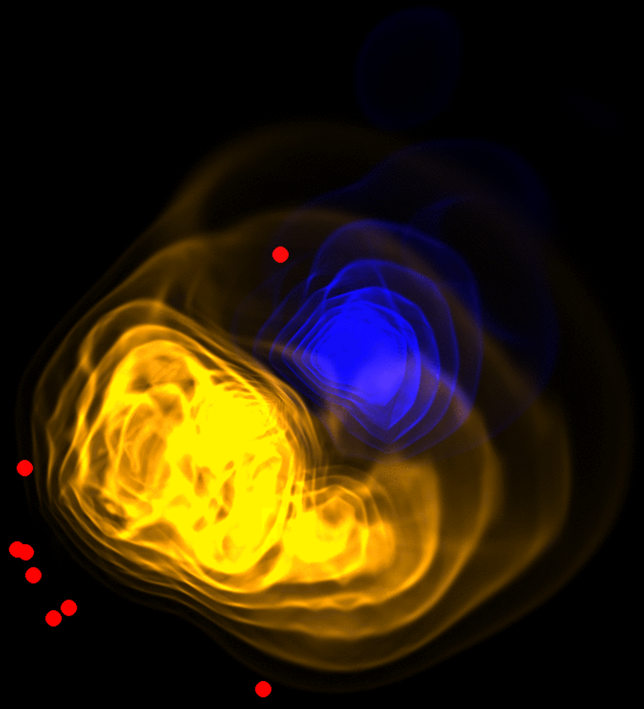

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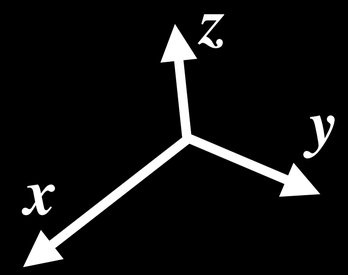

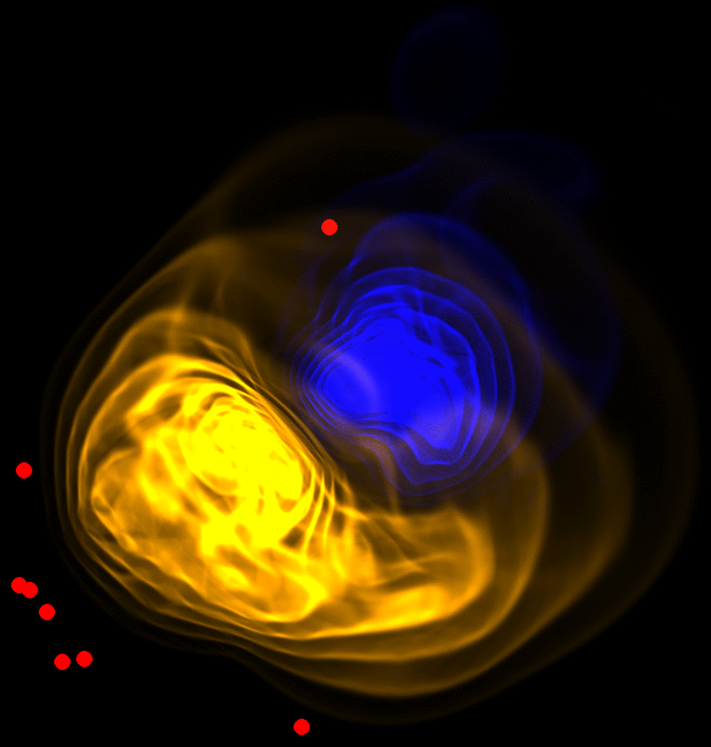

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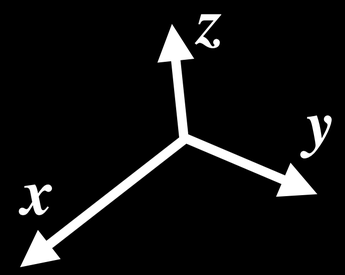

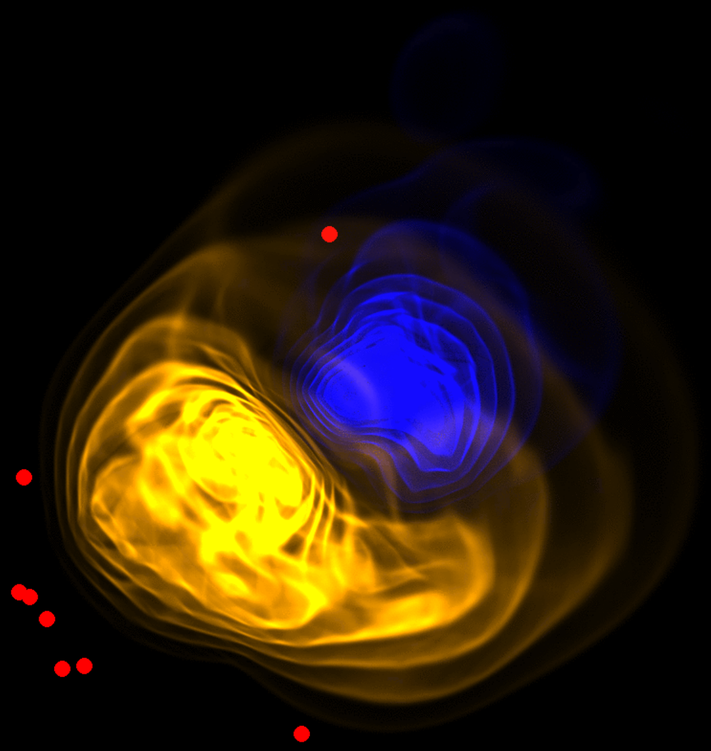

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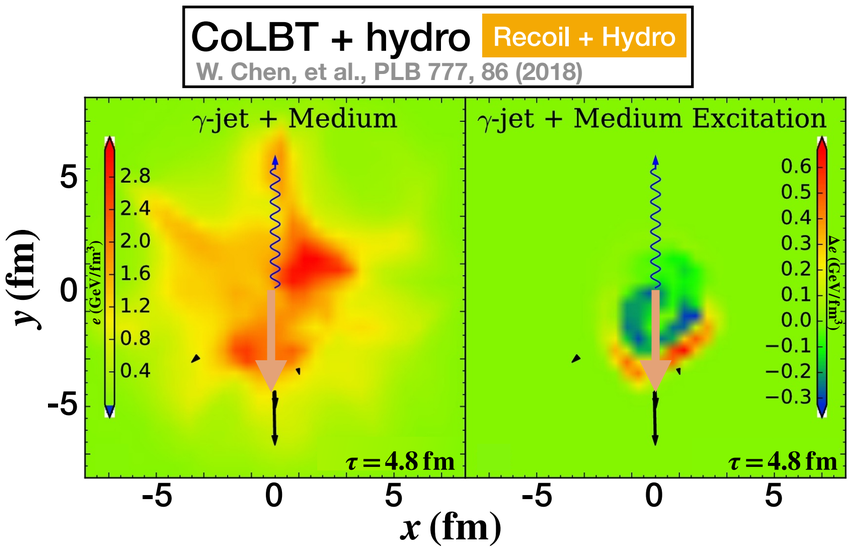
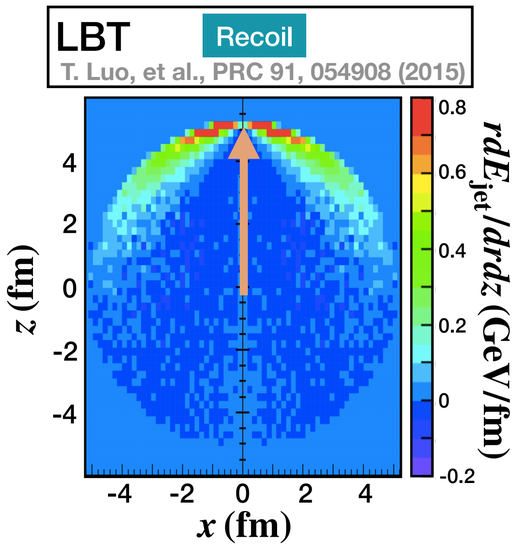
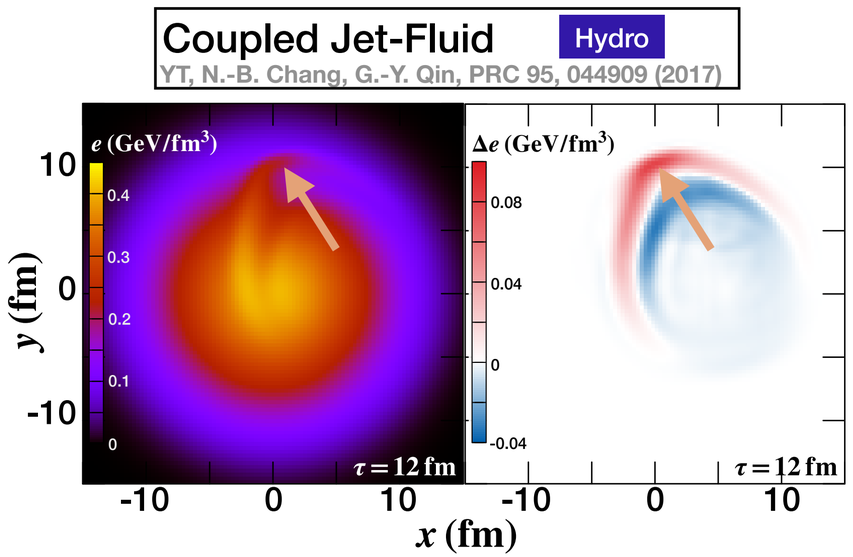
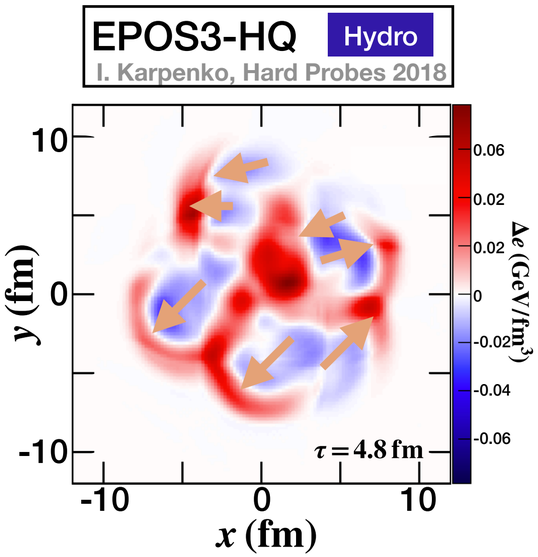








- **Mach cone**
  - Conical shockwave
  - Transporting energy and momentum away from jet

Large angle broadening

- **Diffusion wake**
  - Strong flow following jet
  - Push medium and cause depletion

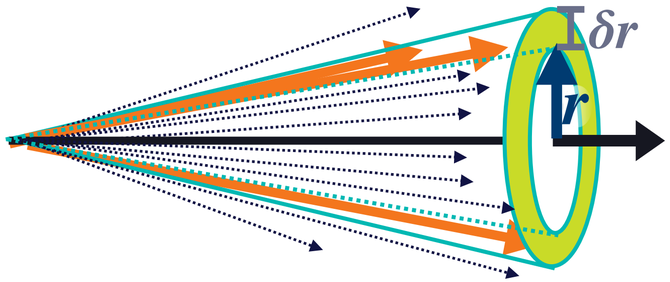
Prevent backward particle emission

Angular structures inside jets

- **Jet shape function**

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{i \in (r-\delta r/2,\, r+\delta r/2)} p_{\mathrm{T}}^{i}}{\sum_{i \in (0,R)} p_{\mathrm{T}}^{i}}$$

$$\left(r = \sqrt{(\eta_p - \eta^{\mathrm{jet}})^2 + (\phi_p - \phi^{\mathrm{jet}})^2} \right)$$



Enhancement at large angles

Couple jet-fluid: YT, Chang, Qin, PRC 95, 044909 (2017)
MARTINI: Park, Jeon, Gale, NPA 982, 643 (2019)
Hybrid: Pablos et al, JHEP 03, 135 (2017)

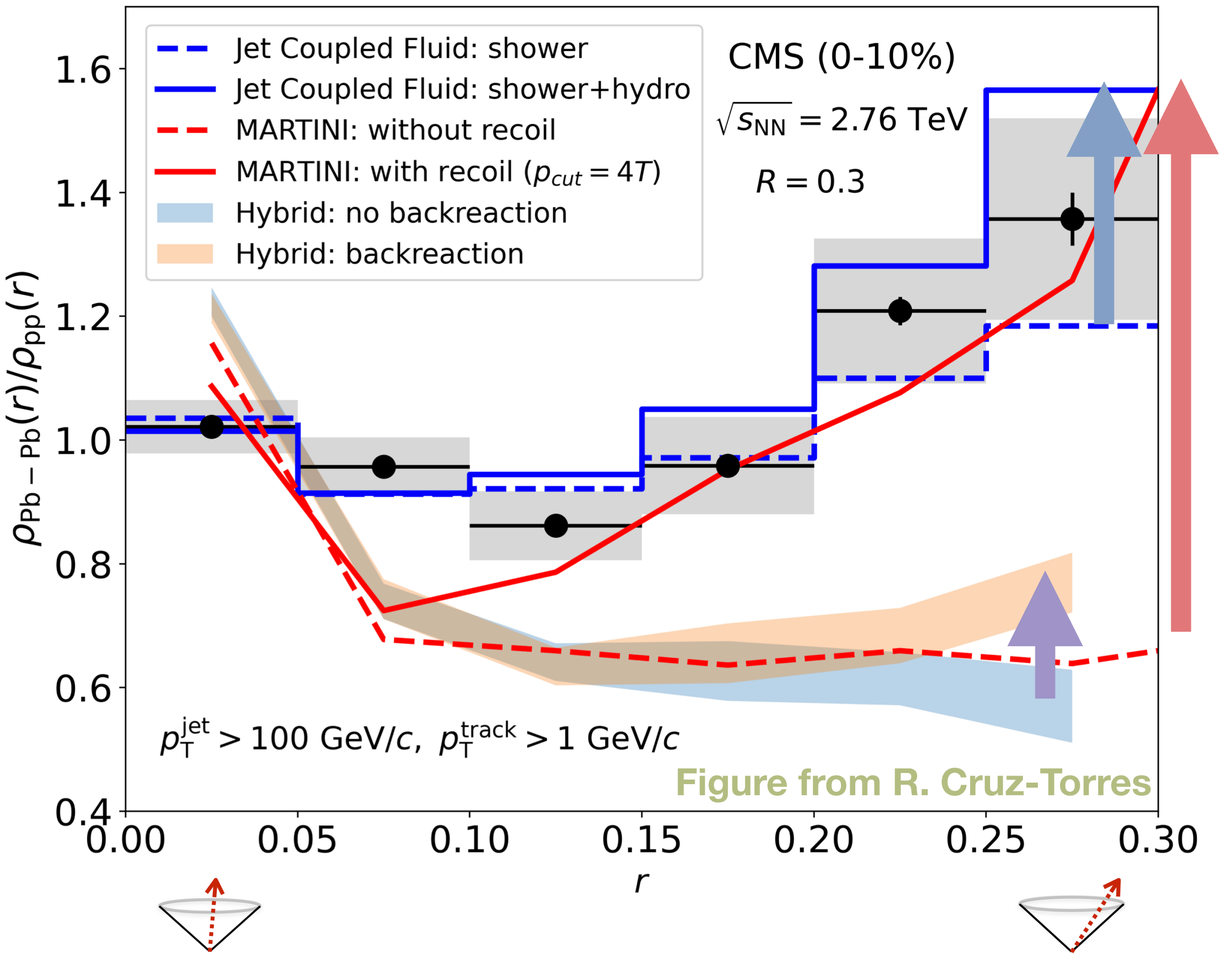


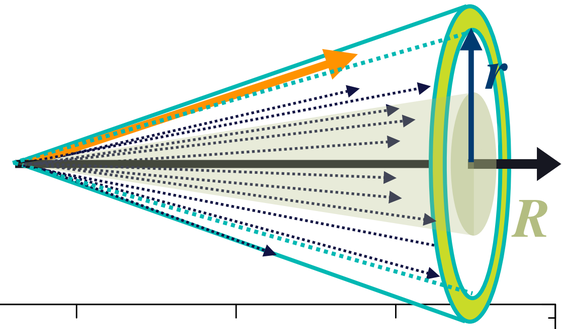
Figure from R. Cruz-Torres

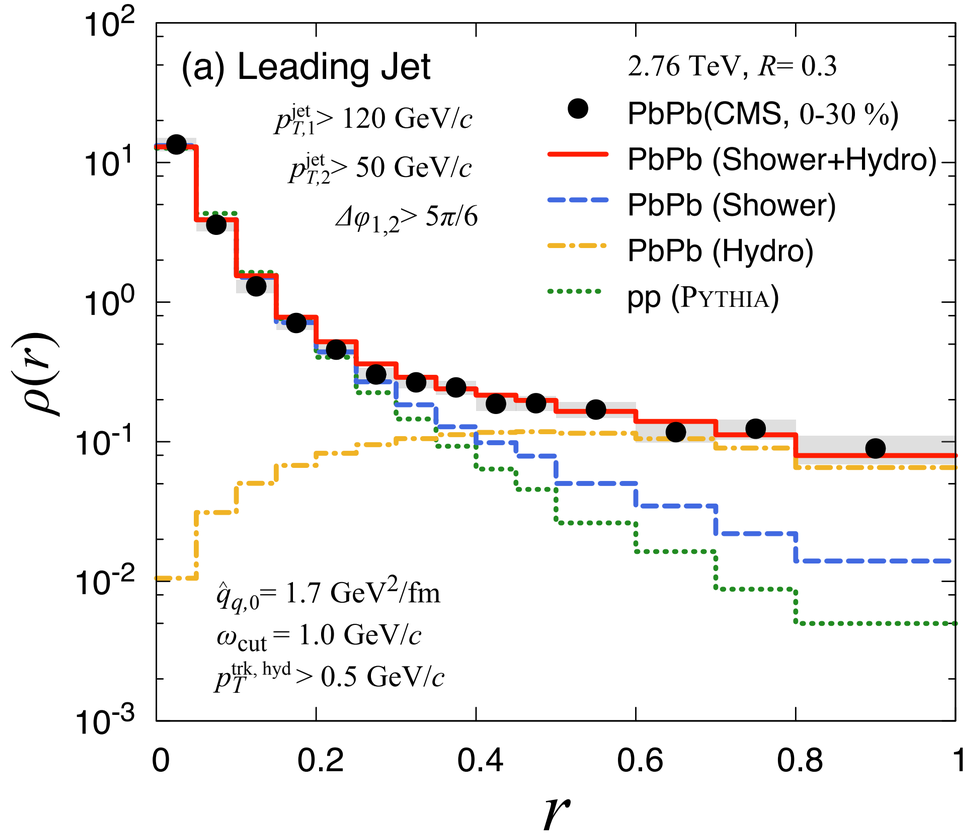
The same trend seen in other model calculations:
JEWEL [Kunnawalkam Elayavalli, Zapp, JHEP 1707, 141 (2017)],
LBT [Luo et al, PLB782, 707-716(2018)], etc.

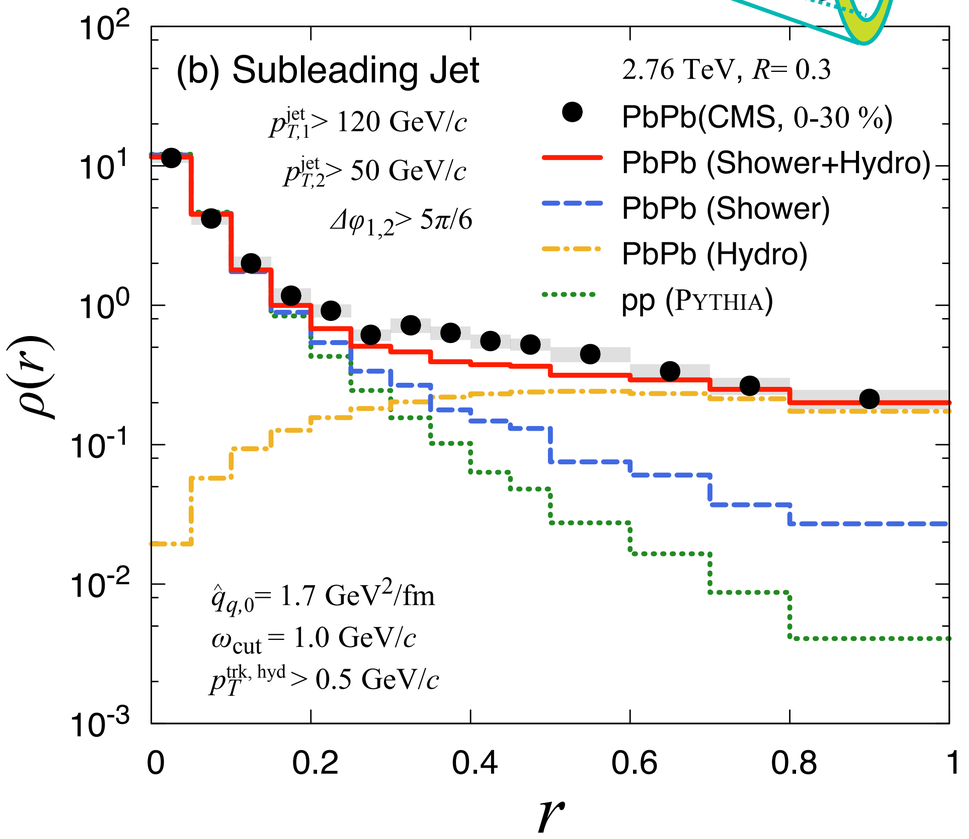
Angular structures outside jets

Couple jet-fluid: YT, Chang, Qin, PRC 95, 044909 (2017)

- **Jet shape function**
  - Extended to out-cone region
  - Dijet Event $p_{T,1}^{\rm jet} \geq 120\,{\rm GeV}/c,\ p_{T,2}^{\rm jet} \geq 50\,{\rm GeV}/c$







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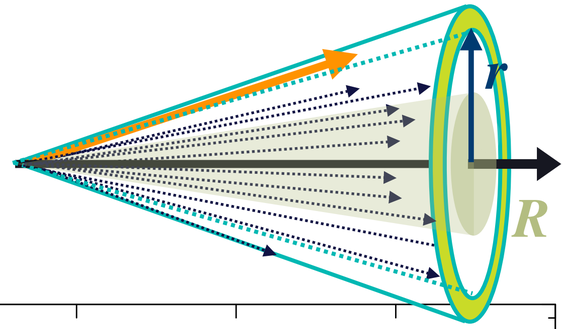
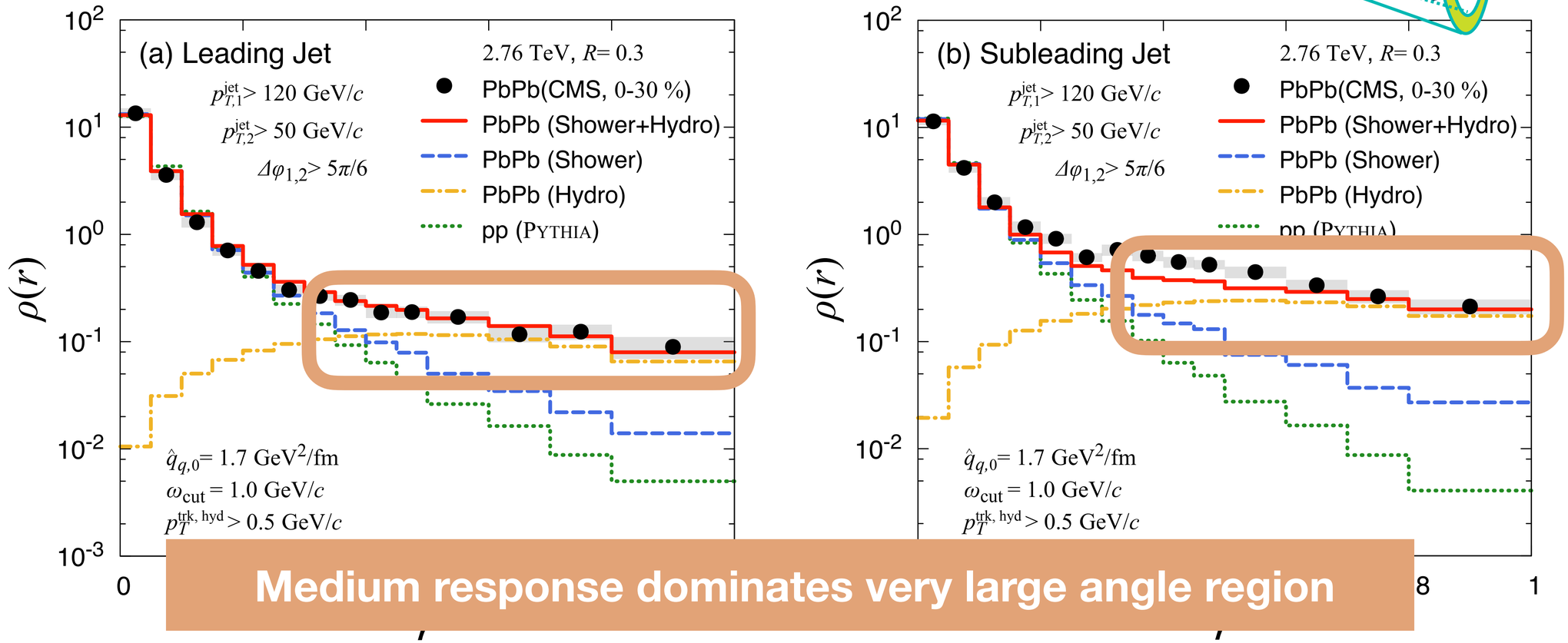




Medium response dominates very large angle region

Medium response as probes for flow

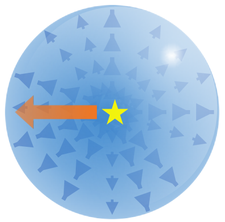
- **Effect from the background medium flow**

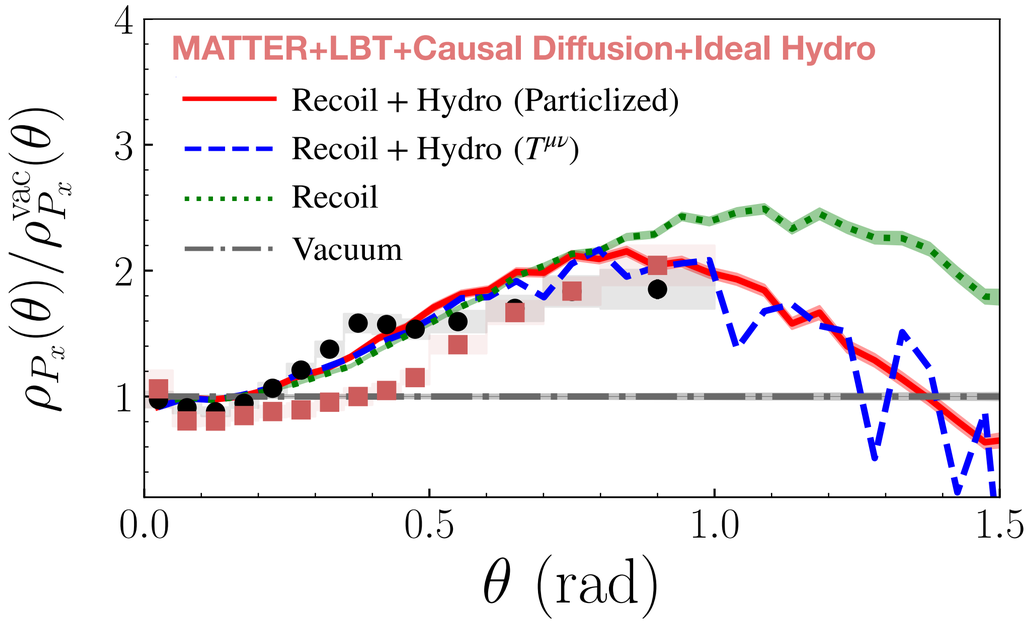
  YT, Shen, Majumder, PRC 106, L021902 (2022)

$$\rho_{P_x}(\theta) = \frac{1}{P_x(\theta=1)} \frac{dP_x}{d\theta}$$

  - Propagation of jet with medium response in an expanding fluid

Tailwind





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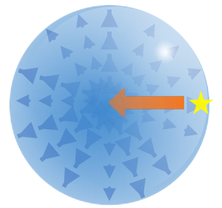

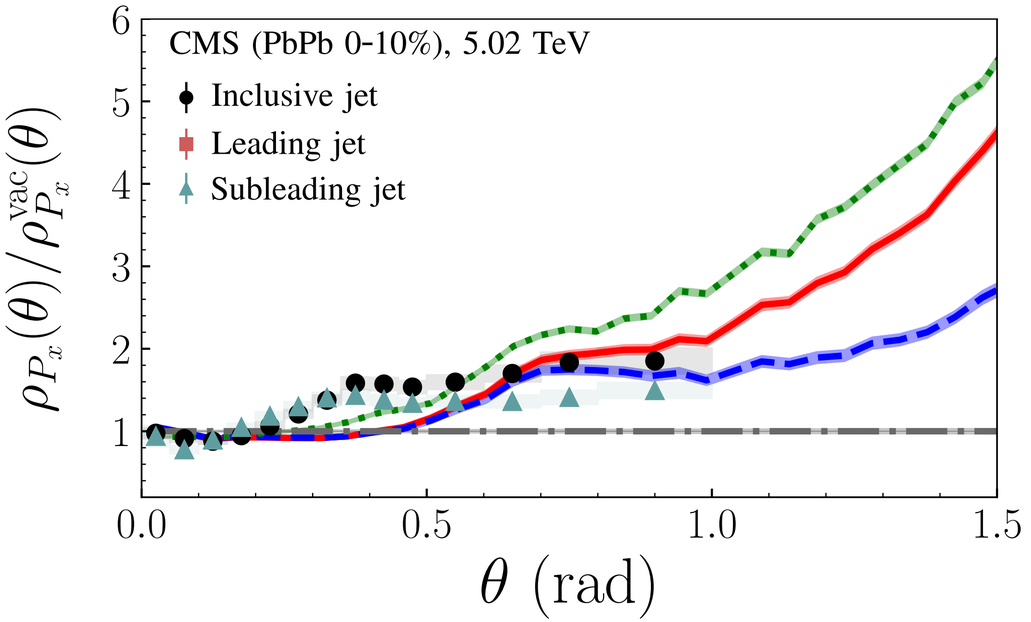

Clear dependence on models/flows at very large angles

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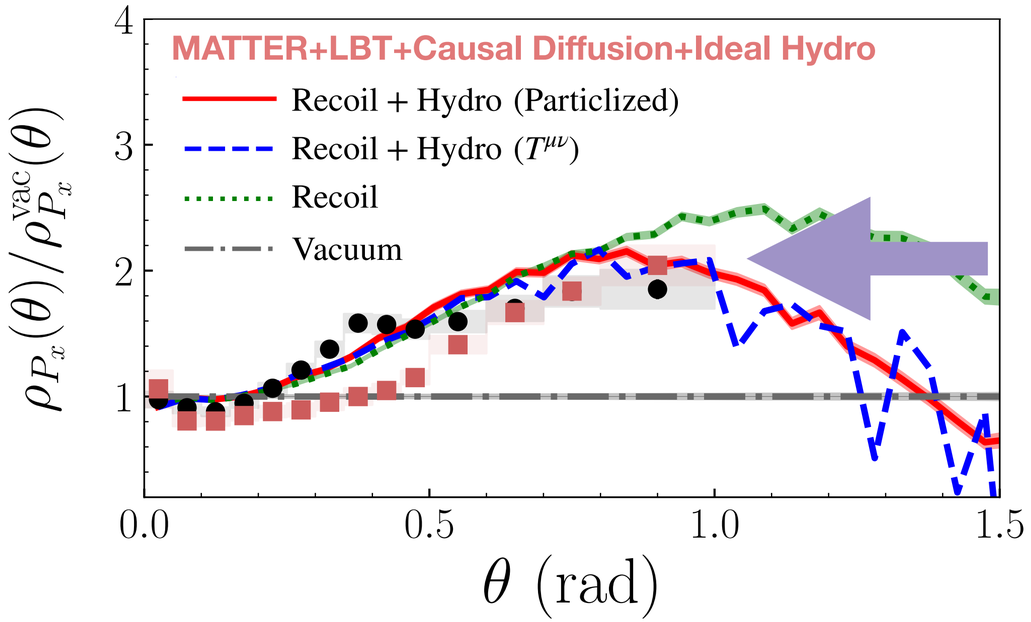

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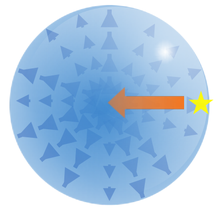
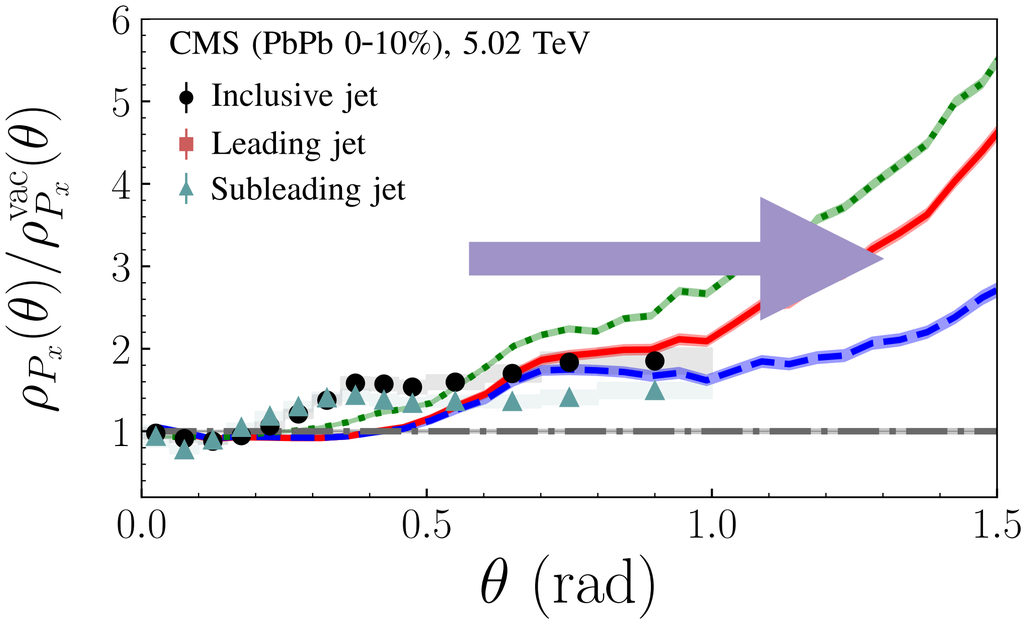
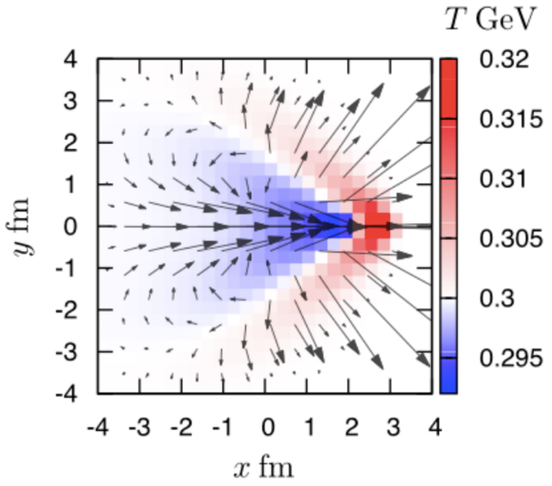




Clear dependence on models/flows at very large angles

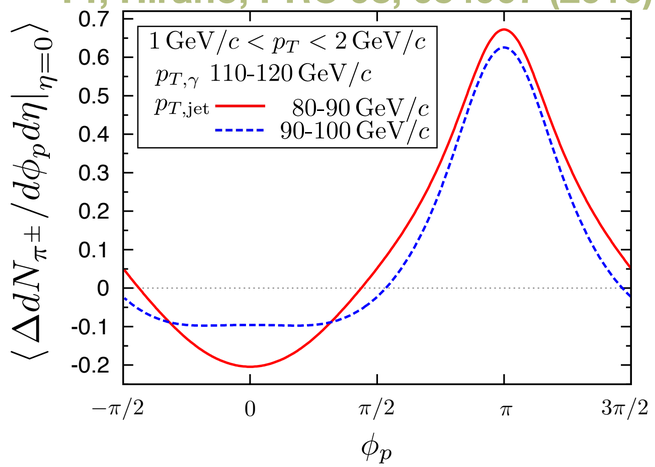
Signal of jet-induced flow: Diffusion wake

- **Backward dip due to diffusion wake**



  - Jet-hadron correlation in γ-jet events

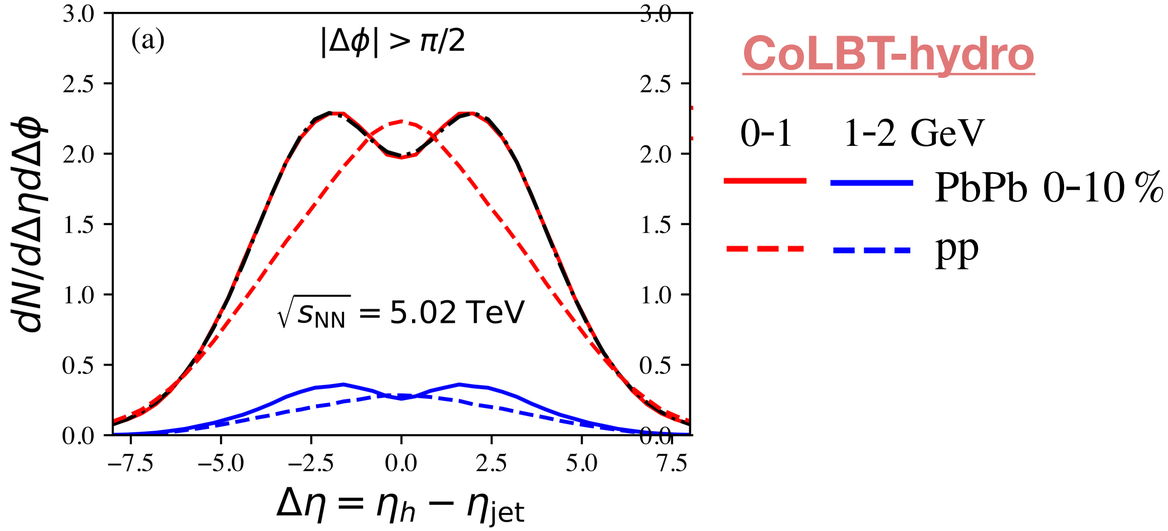
YT, Hirano, PRC 93, 054907 (2016)



- **Longitudinal structure: *Diffusion valley***

Yang, Luo, Chen, Pang, Wang, PRL 130, 052301 (2023)

Talk by Z. Yang (Mon)



  - Show dependence on viscosity and EoS in width and depth

- **Effect on backward jet structure**

  - Modify $p_{\mathrm{T}}^{\mathrm{jet}}$ of jet with large-R

Pablos, PRL 124, 052301 (2020)

Signal of jet-induced flow: Diffusion wake

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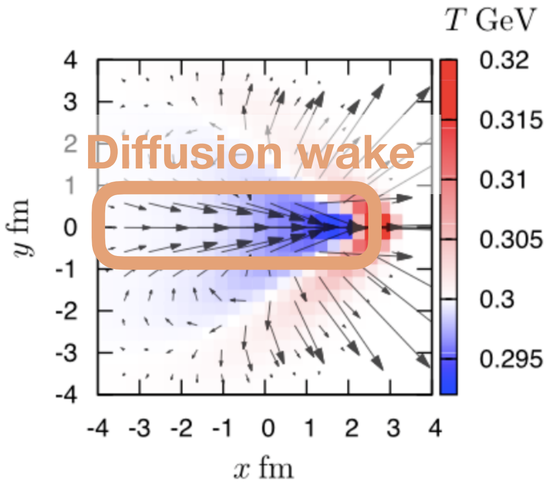

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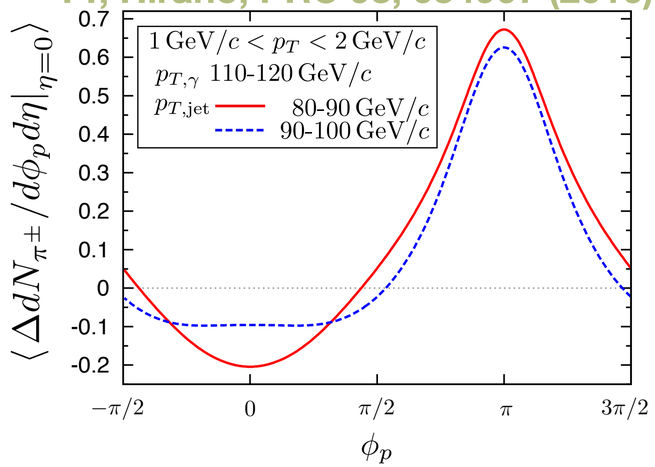
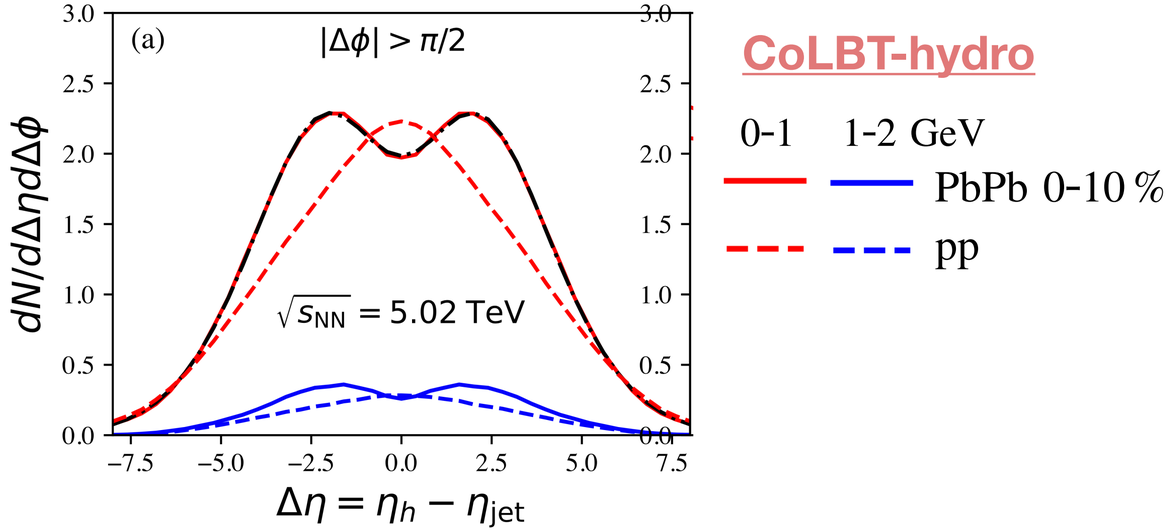


- **Longitudinal structure: *Diffusion valley***

Yang, Luo, Chen, Pang, Wang, PRL 130, 052301 (2023)

Talk by Z. Yang (Mon)



  - Show dependence on viscosity and EoS in width and depth

- **Effect on backward jet structure**
  - Modify $p_{\mathrm{T}}^{\mathrm{jet}}$ of jet with large-R

Pablos, PRL 124, 052301 (2020)

Signal of jet-induced flow: Diffusion wake

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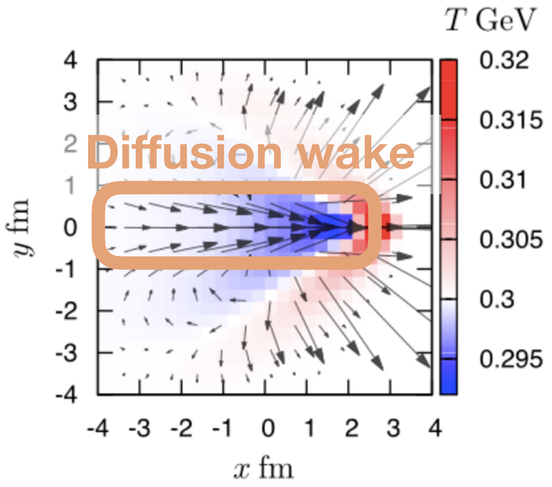

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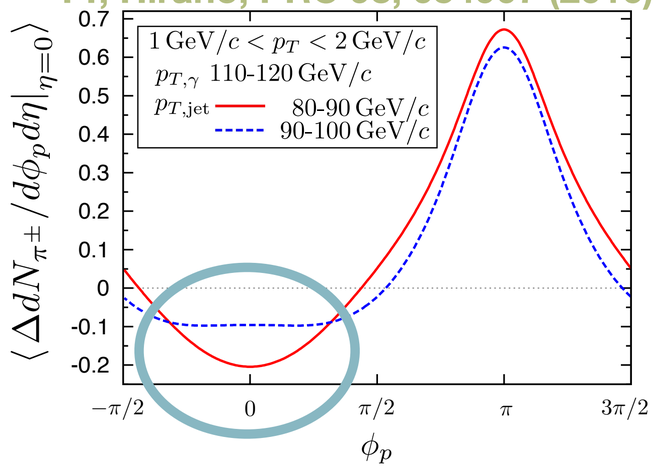

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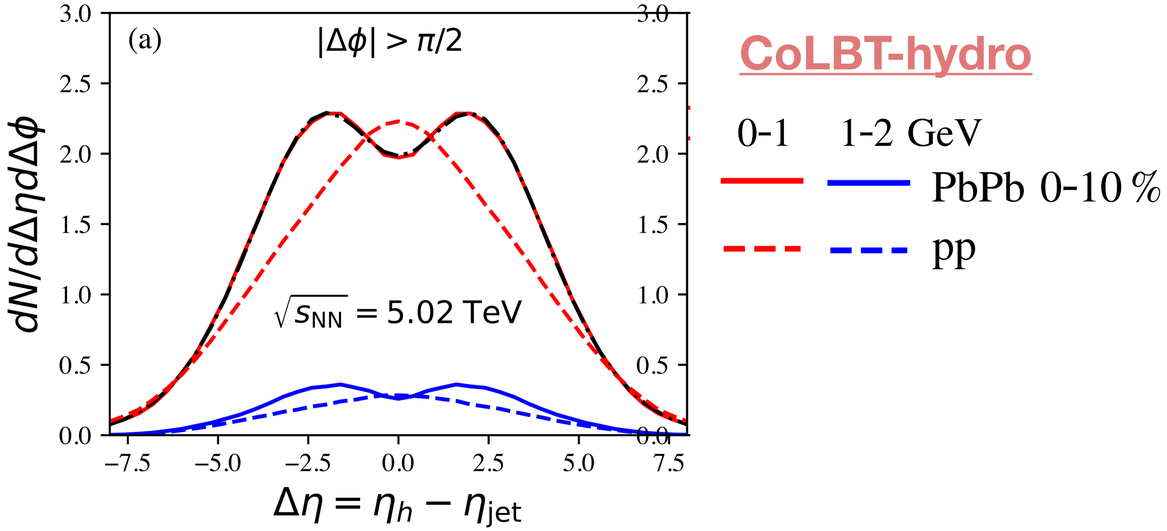

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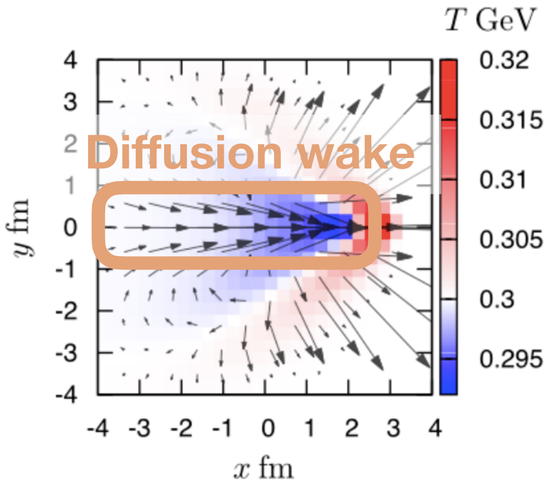

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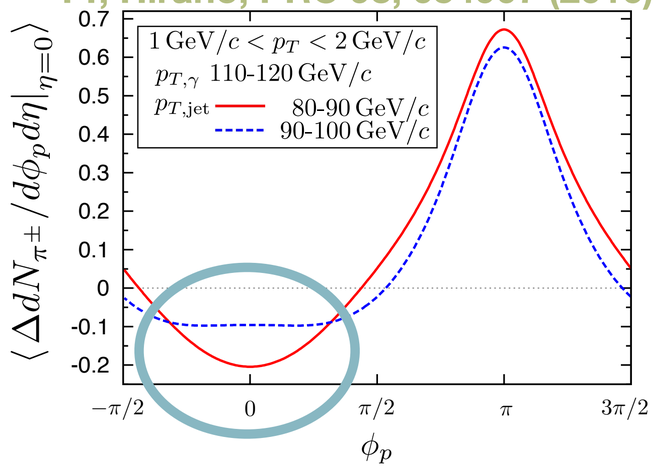

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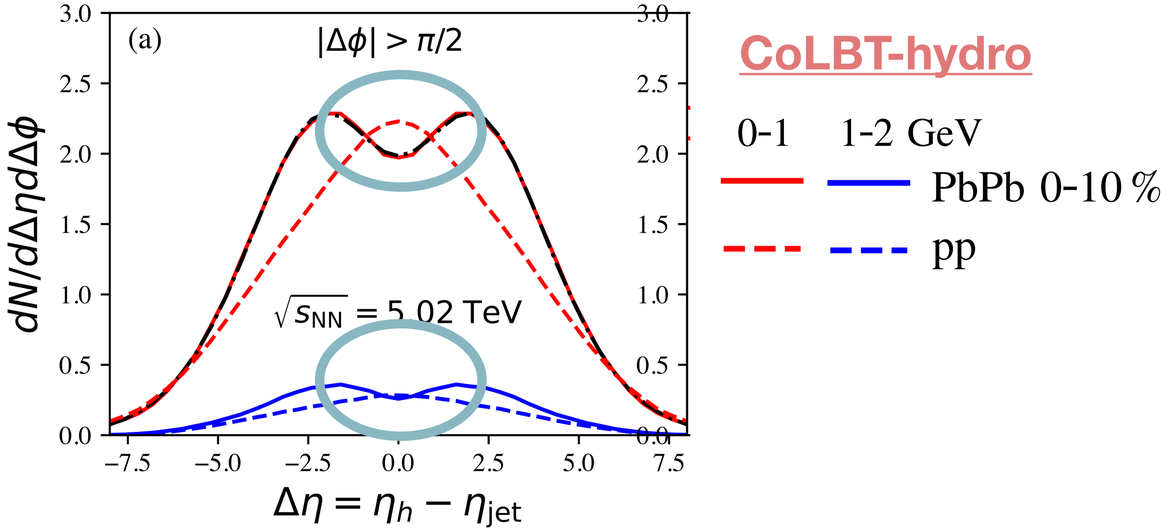

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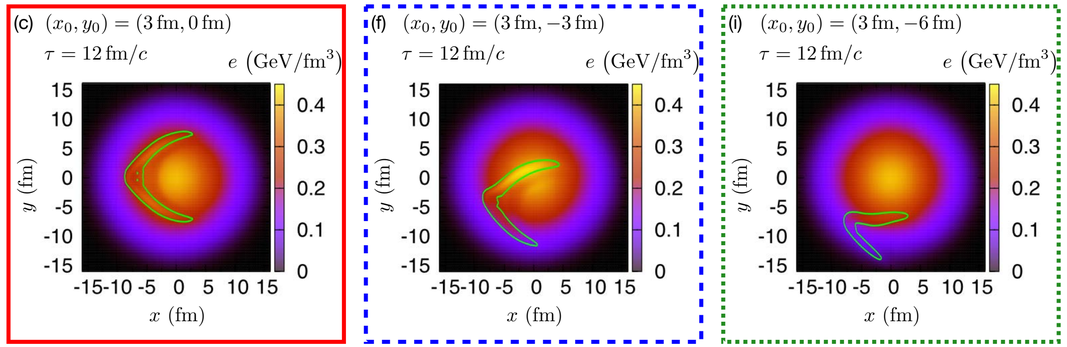
Pablos, PRL 124, 052301 (2020)

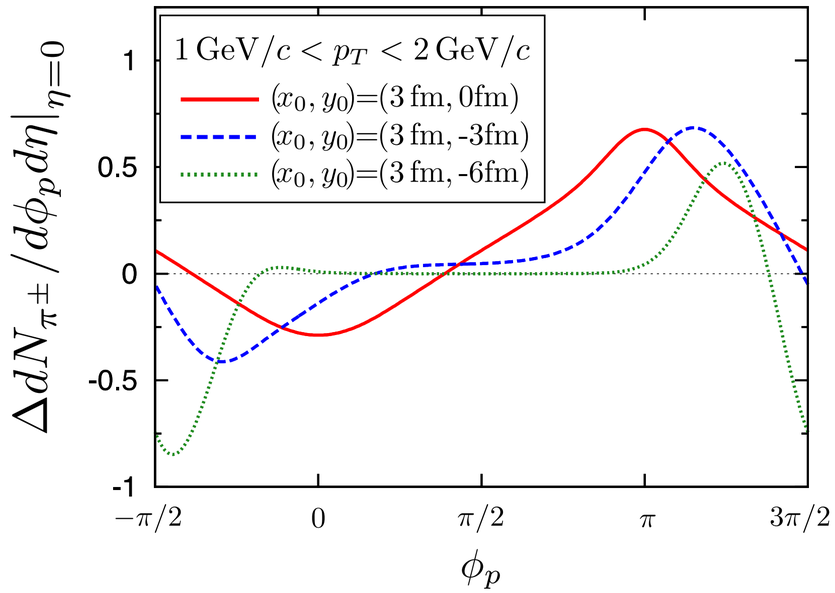
Distorted Mach cone signature

- **Interplay with medium expansion**

  YT, Hirano, PRC 93, 054907 (2016)

  - Correlation with jet production point

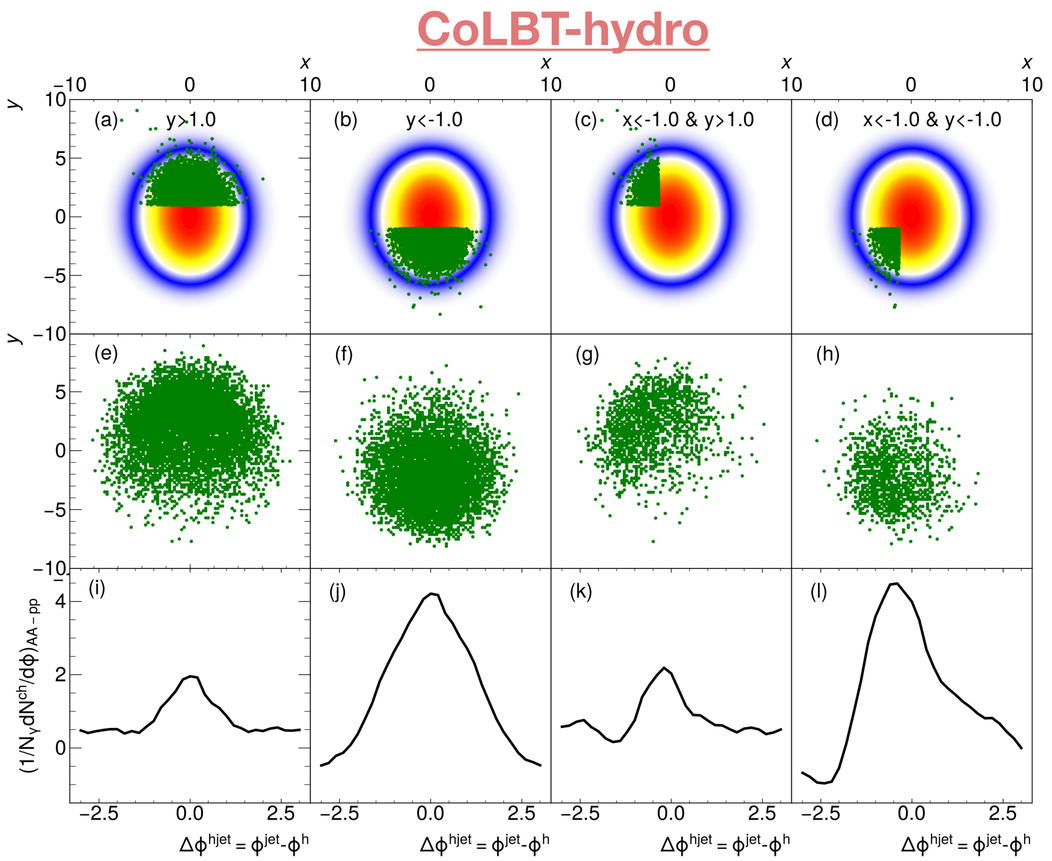




- **Deep Learning tomography**

  Yang, He, Chen, Ke, Pang, Wang, arXiv:2206.02393

  Talk by L. Pang (Mon)

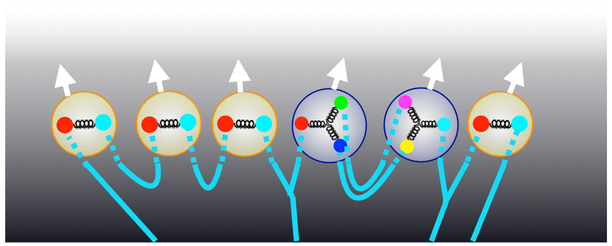


  - New technique to reveal Mach cone signals

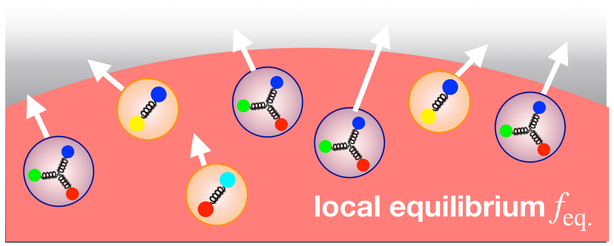
Signal of jet-induced flow: Jet hadrochemistry

- **Baryon-meson ration enhancement in jets**
  - Hadronization in jet and thermal medium

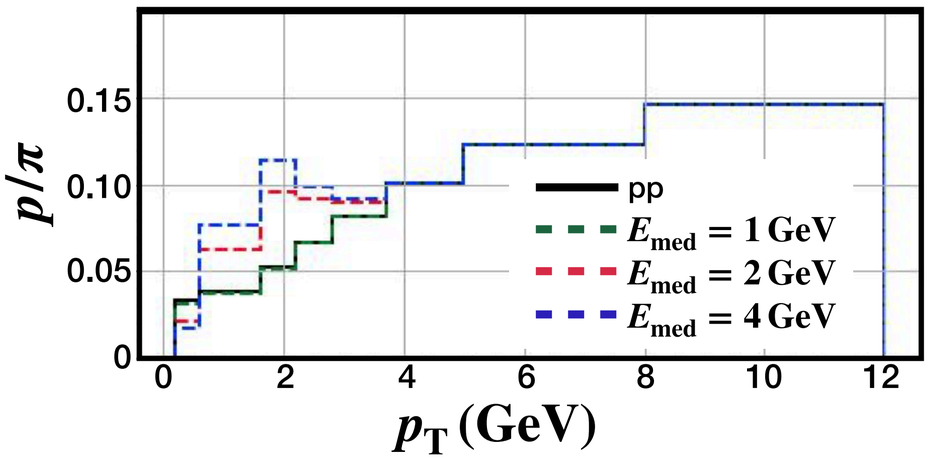
jet fragmentation



in-medium hadronization



CoLBT-hydro Wei et al.

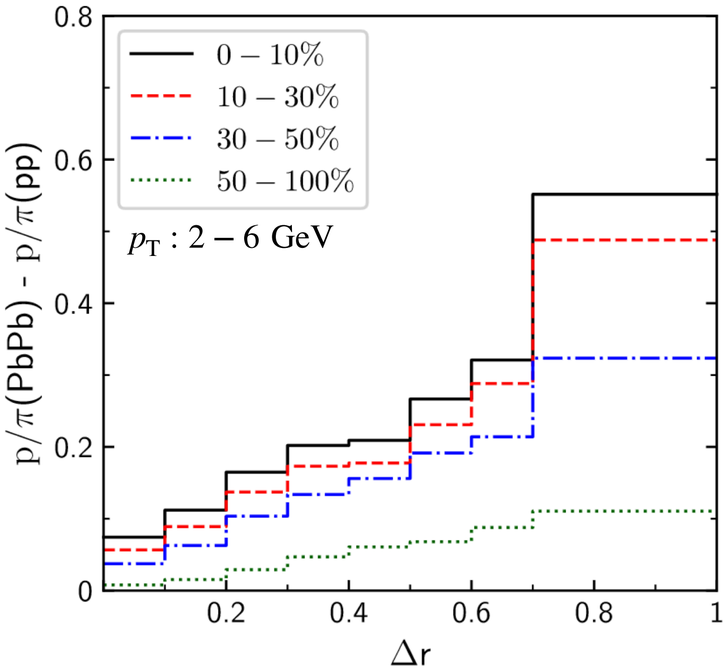


  - Angular distribution around jet

Luo, Mao, Qin, Wang, Zhang, PLB 837 137638 (2023)

Talk by G. Y. Qin (canceled)

AMPT



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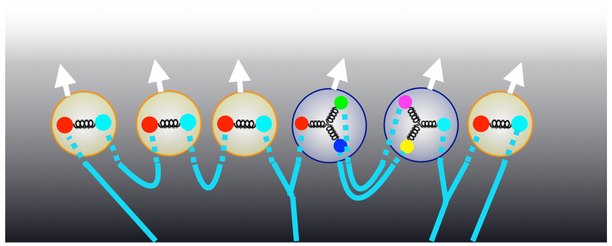

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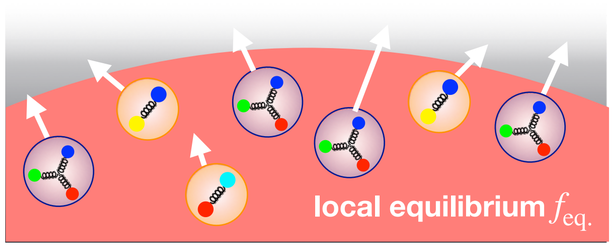

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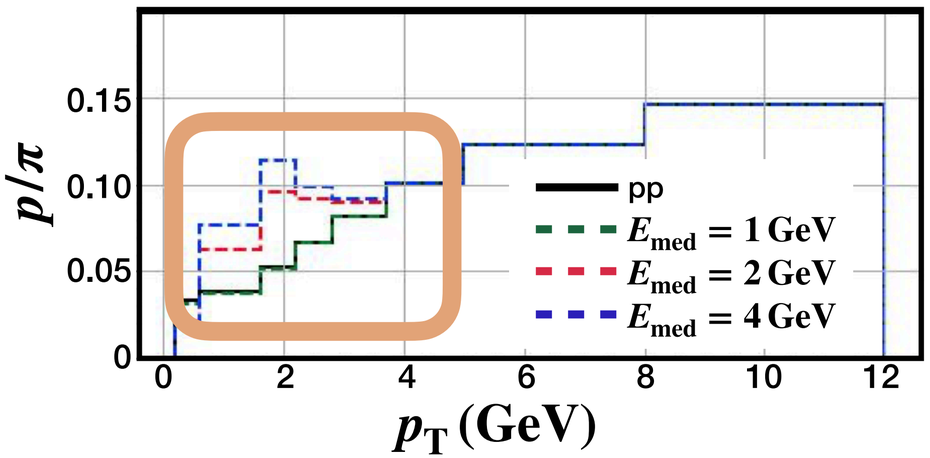

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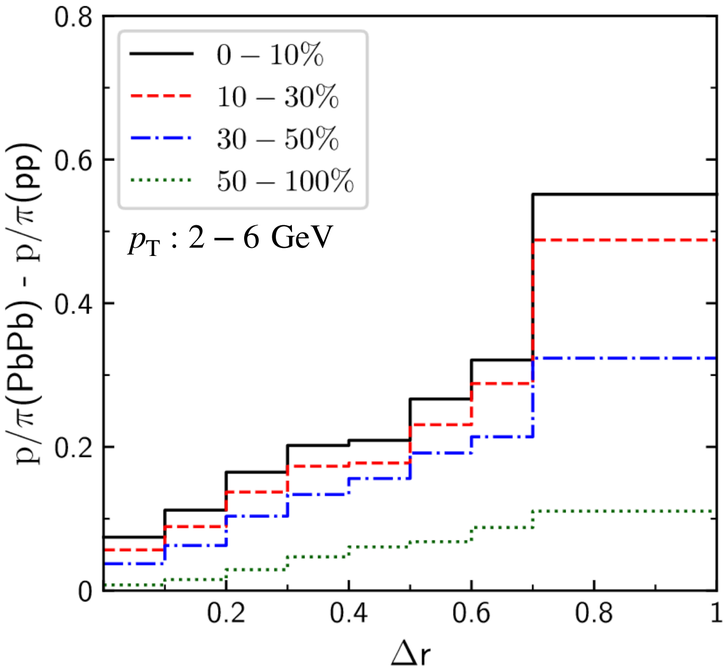

Summary

- **Jet propagation in heavy-ion collisions**
  - Interaction with jet parton and QGP medium constituents
  - Modify parton splitting patterns and cause medium reponse
- **Jet quenching phenomenology**
  - Medium effect reduction at high virtuality for the simultaneous description of jet and single particle
  - Details of energy loss mechanisms can be exploreed in jet substructures
  - Tomography of medium gradient profile
- **Medium response to jet propagation**
  - Contribute to jets observed in heavy ion collisions
  - Possible unique signals characterizing the QGP medium properties

Coherence effects at high virtuality

- **Spectrum of induced gluons (Higher-Twist)**

Kumar, Majumder, Shen, PRC101, 034908 (2020)

$$\frac{dN_g}{dy dl_\perp^2} = \frac{\alpha_s}{2\pi^2} P(y) \int \frac{d^2k_\perp}{(2\pi)^2} H(k_\perp, l_\perp, q^-, y)$$

$$\times \int d\delta\zeta^- d^2\zeta_\perp e^{-i\frac{k_\perp^2}{2q^-}\delta\zeta^- + i\vec{k}_\perp\cdot\vec{\zeta}_\perp} \langle p_B \mid A^{a+\alpha}(\delta\zeta^-, \vec{\zeta}_\perp)\, A^{a+}_{\alpha}(0,0_\perp) \mid p_B \rangle$$

$$H(k_\perp, l_\perp, q^-, y) = \int_0^{\tau^-} d\zeta^- \frac{2 - 2\cos\left\{\frac{(l_\perp - k_\perp)^2 \zeta^-}{2q^- y(1-y)}\right\}}{(l_\perp - k_\perp)^4}$$