重离子碰撞中的喷注
Jets in Heavy-Ion Collisions

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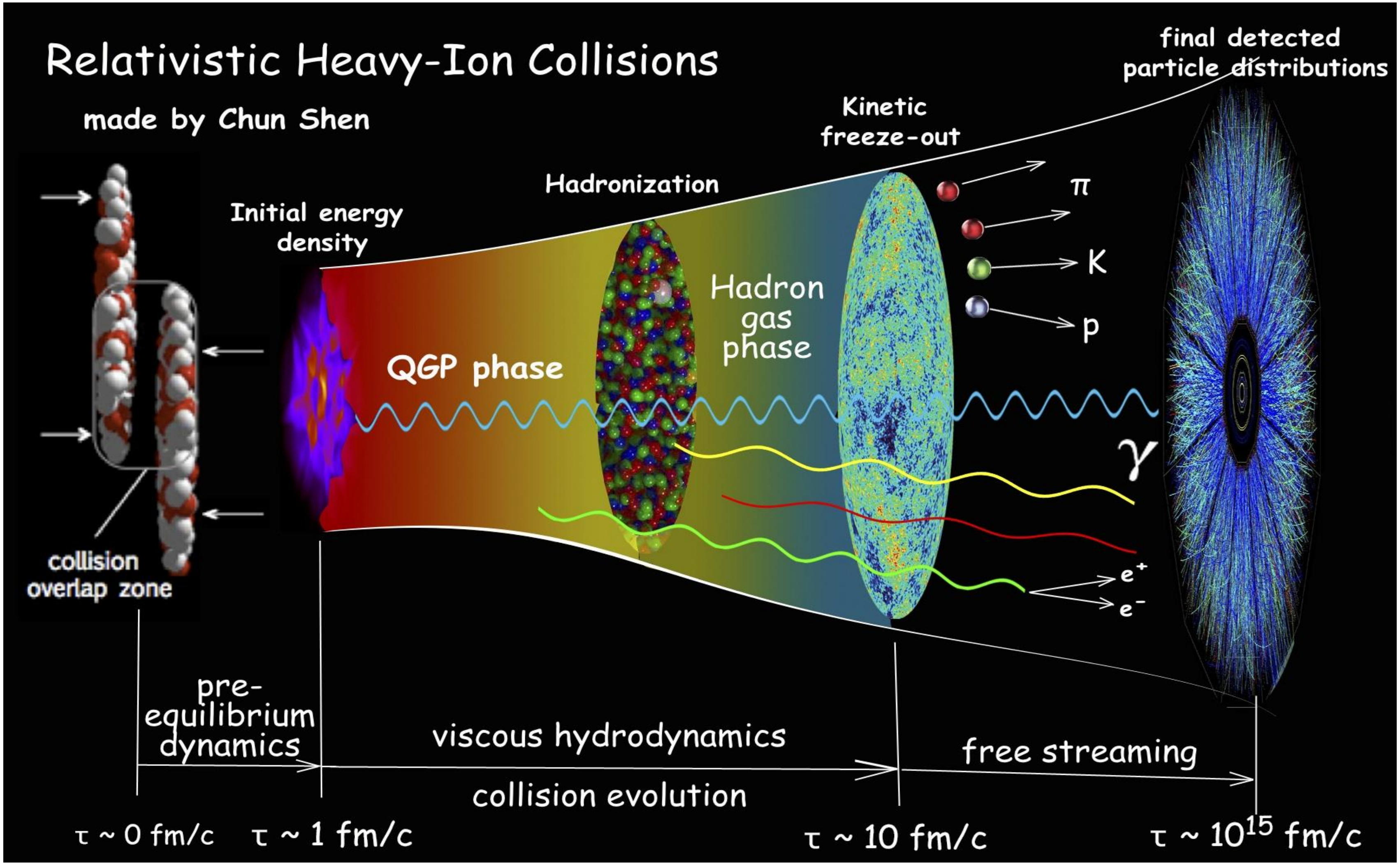
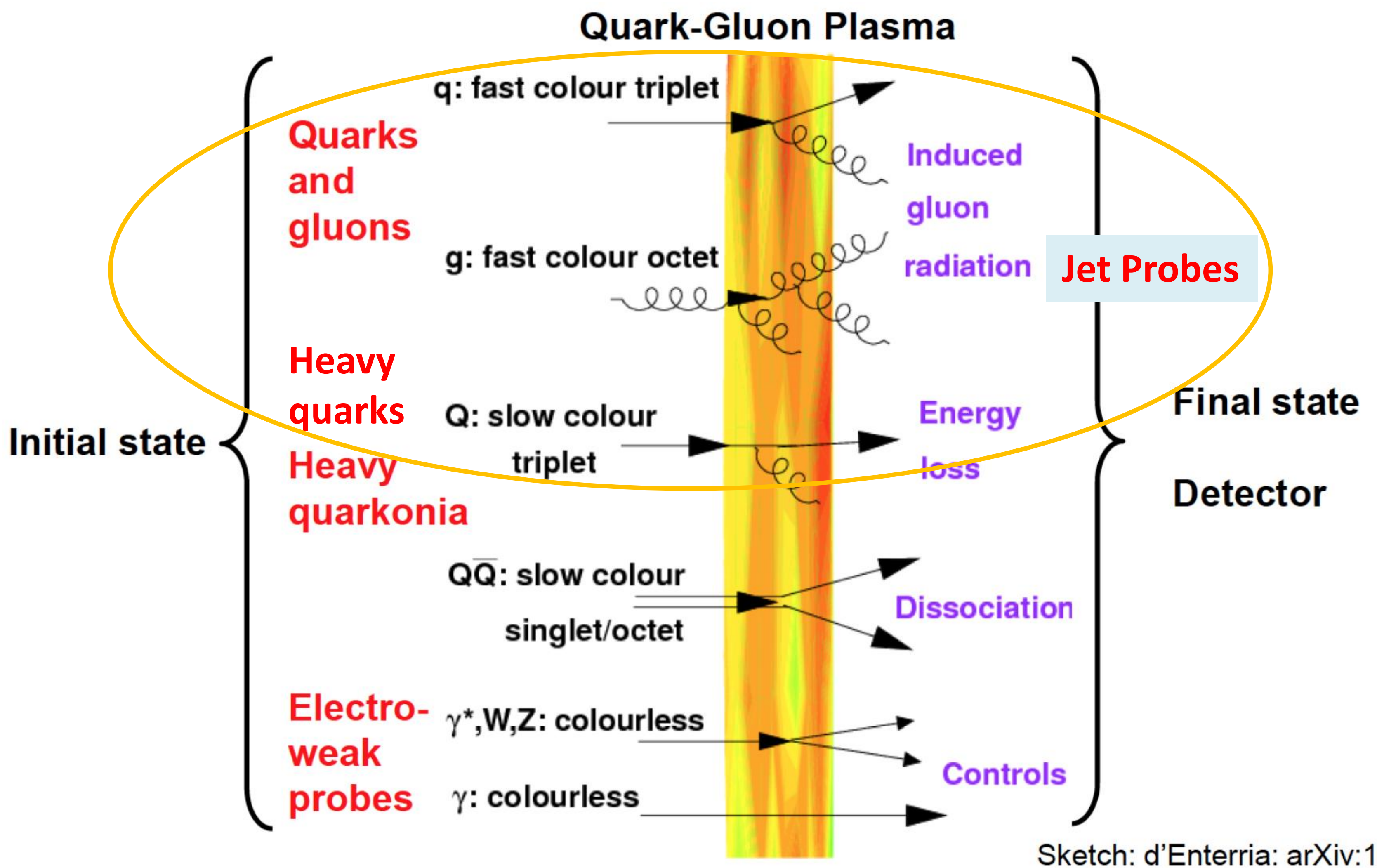
Outline

- Lecture 1
  - Introduction to heavy-ion collisions and quark-gluon plasma
- Lecture 2
  - Jet probes (of QGP in HIC), jet quenching and energy loss (some simple discussion)
- Lecture 3
  - Jet probes of QGP in HIC: flavor dependence of parton energy loss and jet quenching
- Lecture 4
  - Jet probes of QGP in HIC: full jets, jet energy loss, medium response, jet (sub)structure

"Standard Model" of RHIC & LHC heavy-ion collisions



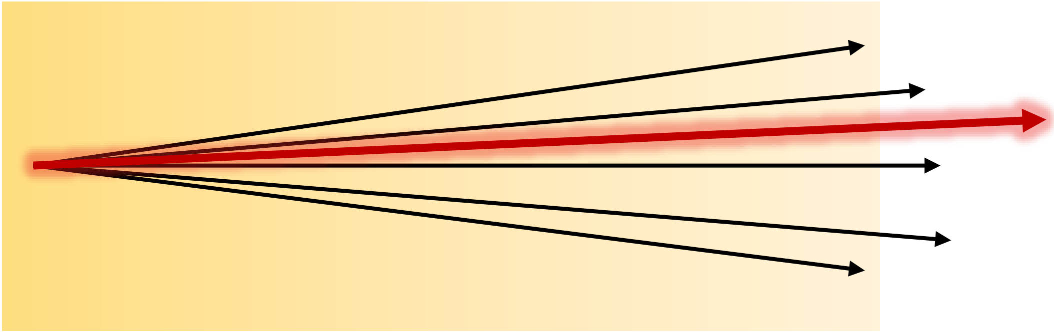
Penetrating probes of QGP



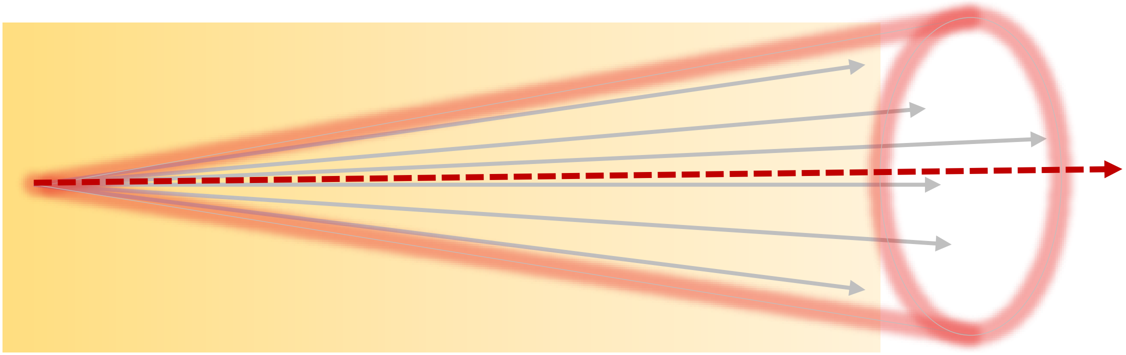
Sketch: d'Enterria: arXiv:1207.4362

Jet observables (measurements)

- 1st type of observables: leading (high momentum) hadron as a proxy for a jet

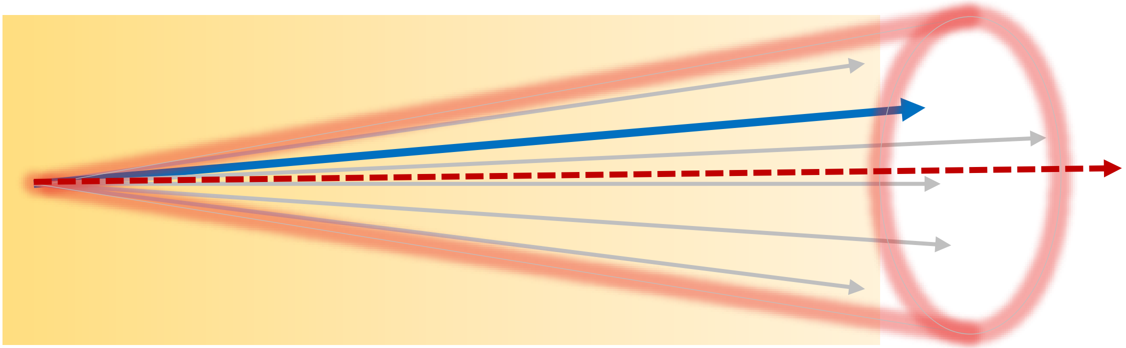


- 2nd type of observables: fully-reconstructed jet as a proxy for hard-scattered high-energy parton

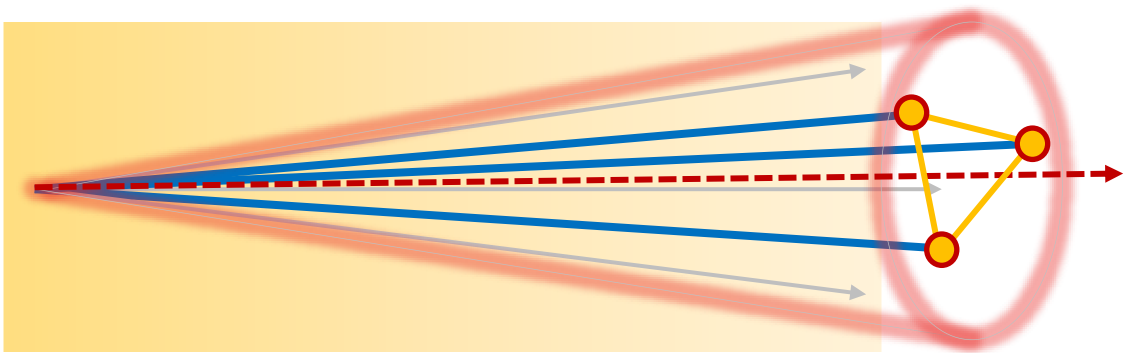


Jet observables (measurements)

- 3rd type of observables: looking at particle distribution inside the jet, such as jet shape and fragmentation function,



- 4th type of observables: looking at particle correlations inside the jet, such as jet splitting function, splitting angle, EEC

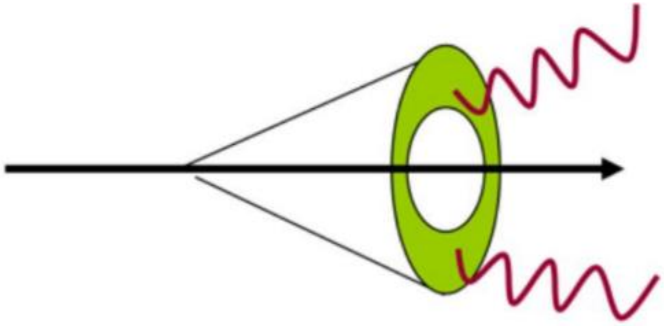


Jet quenching without jets: leading hadrons flavor dependence

Flavor dependence of parton energy loss

Color charge: Energy loss in gluons > Energy loss in quarks

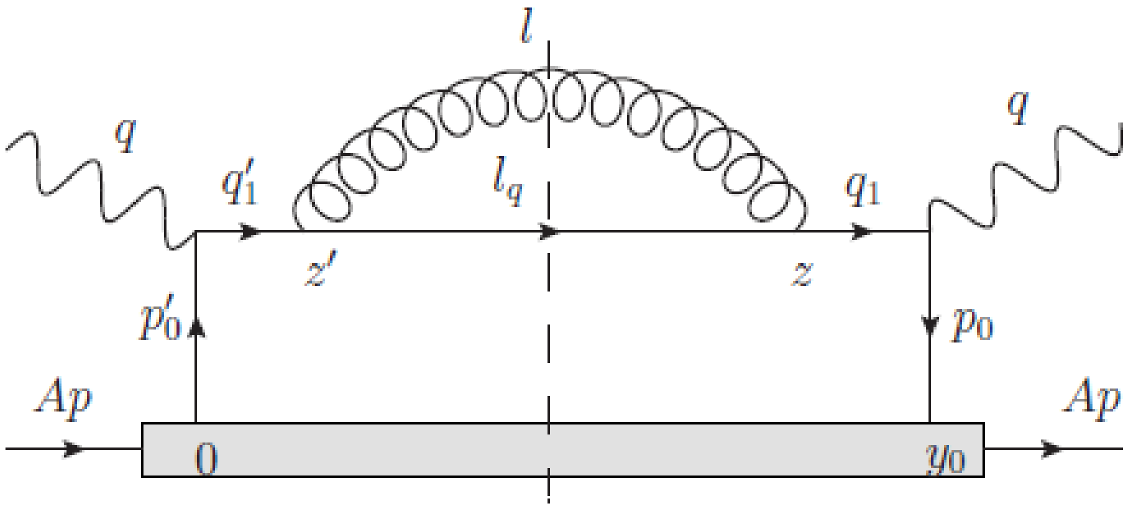
Due to finite masses of heavy quarks, the forward radiation with the angle θ< M/E is suppressed due to kinematics, which is usually called **dead cone effect**.



Low momentum
Energy loss in QGP:
gluons > light quarks > heavy quarks
M/E is large, dead cone effect

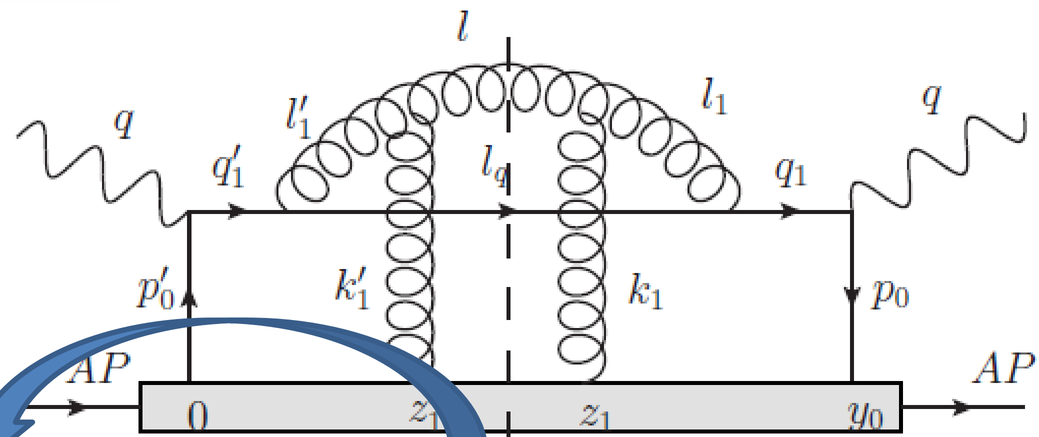
High momentum
Energy loss in QGP:
gluons > light quarks ~ heavy quarks
M/E is small, no dead cone effect

Gluon emission in vacuum



$$\frac{dN_g^{\text{vac}}}{dy\, d^2 l_\perp} = C_F \frac{\alpha_s}{2\pi^2} P(y) \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{(l_\perp^2 + y^2 M^2)^2}.$$

Gluon emission in medium



Zhang, Hou, GYQ, PRC 2018
& PRC 2019;
Zhang, GYQ, Wang, PRD 2019.

+ other 20 diagrams

$$\frac{dN_g^{med}}{dy\, d^2 l_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int \frac{dk^- d^2 k_{1\perp}}{(2\pi)^3} \mathcal{D}(k_1^-, k_{1\perp})$$

$$\times \left\{ \left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)(1+\lambda_1^- - y)} \frac{(l_\perp - k_{1\perp})^2 + (y-\lambda_1^-)^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}^-_{\rm form}} \right) \right] \right.$$

$$C_A \left[\frac{1+(1+\lambda_1^- - y)^2}{1+(1-y)^2} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right)^2 \frac{(l_\perp - k_{1\perp})^2 + \frac{(y-\lambda_1^-)^4 M^2}{1+(1+\lambda_1^- - y)^2}}{[(l_\perp - k_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]^2} \right.$$

$$- \frac{1+(1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{l_\perp \cdot (l_\perp - k_{1\perp}) + \frac{y^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)} M^2}{[l_\perp^2 + y^2 M^2]\,[(l_\perp - k_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]}$$

$$\left. \left. - \frac{1+(1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{(l_\perp - k_{1\perp}) \cdot \left(l_\perp - \frac{y}{1+\lambda_1^-} k_{1\perp} \right) + \frac{\left(\frac{y}{1+\lambda_1^-}\right)^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})} M^2}{\left[\left(l_\perp - \frac{y}{1+\lambda_1^-} k_{1\perp} \right)^2 + (\frac{y}{1+\lambda_1^-})^2 M^2 \right] [(l_\perp - k_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]} \right] + \ldots\ldots \right\}$$

$$\mathcal{D}(k_1^-, k_{1\perp}) = (2\pi)^3 \frac{dP_{\rm el}}{dk_1^- d^2 k_{1\perp} dZ_1^-}$$

The medium-induced gluon emission spectrum is controlled by the full differential elastic scattering rates

Medium-induced gluon emission **beyond collinear expansion & soft gluon emission limit** with transverse & longitudinal scatterings for massive quarks

Only transverse scatterings

- Modeling the traversed nuclear medium by heavy static scattering centers (only transverse scatterings)

$$
\begin{aligned}
\frac{dN_g^{\text{med}}}{dy\,d^2\mathbf{l}_\perp} &= \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int d^2\mathbf{k}_{1\perp}\frac{dP_{\text{el}}}{d^2\mathbf{k}_{1\perp}dZ_1^-} \\
&\times\Bigg\{C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}^-_{\text{form}}}\right)\right]\times\left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}\right. \\
&- \frac{1}{2}\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{1}{2}\left.\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\right] \\
&+\left(\frac{C_A}{2}-C_F\right)\left[2-2\cos\left(\frac{Z_1^-}{\tilde{\tau}^-_{\text{form}}}\right)\right]\left[\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right] \\
&+C_F\left[\frac{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right]\Bigg\}.
\end{aligned}
$$

Soft gluon emission approximation

- Further taking soft gluon emission approximation $y^2 M \ll yM \sim l_\perp \sim k_{1\perp}$

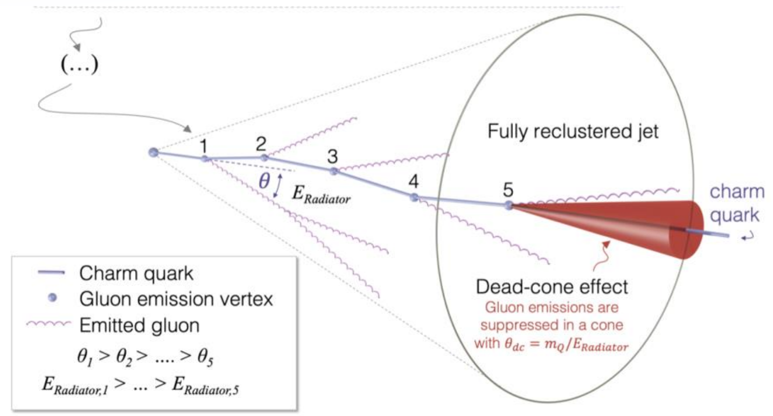
$$\frac{dN_g^{\rm med}}{dy d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int d^2\mathbf{k}_{1\perp} \frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp} dZ_1^-} \times C_A \left[2 - 2\cos\left(\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2}{l_\perp^2 + y^2M^2} \frac{Z_1^-}{\tilde{\tau}_{\rm form}^-} \right) \right] \\ \times \left[\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2\right]^2} - \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp})}{[l_\perp^2 + y^2M^2]\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2\right]} \right].$$

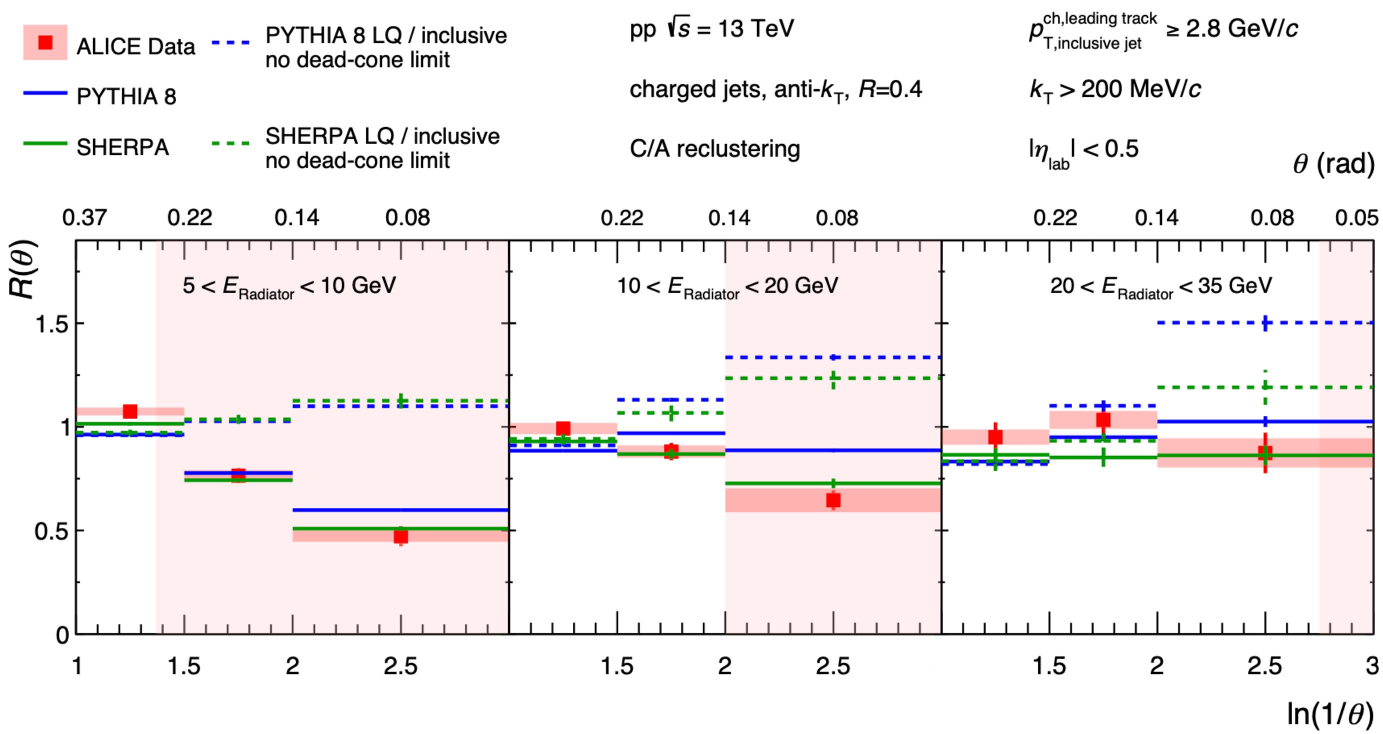
- This agrees with the DGLV first-order-in-opacity formula.

- Jet transport parameter is related to the differential elastic scattering rate as follows:

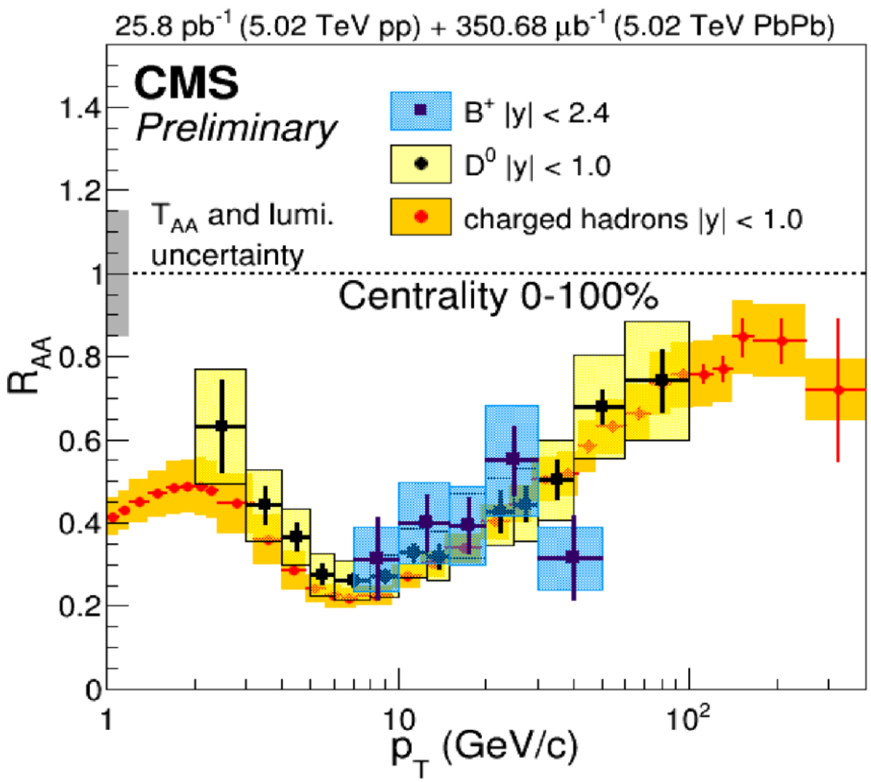
$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2 \rangle}{dL^-} = \int \frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathbf{k}_{1\perp}^2 \mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = \int \frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2} \mathbf{k}_{1\perp}^2 \mathcal{D}_\perp(\mathbf{k}_{1\perp}) = \int d^2\mathbf{k}_{1\perp} \mathbf{k}_{1\perp}^2 \rho^- \frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}.$$

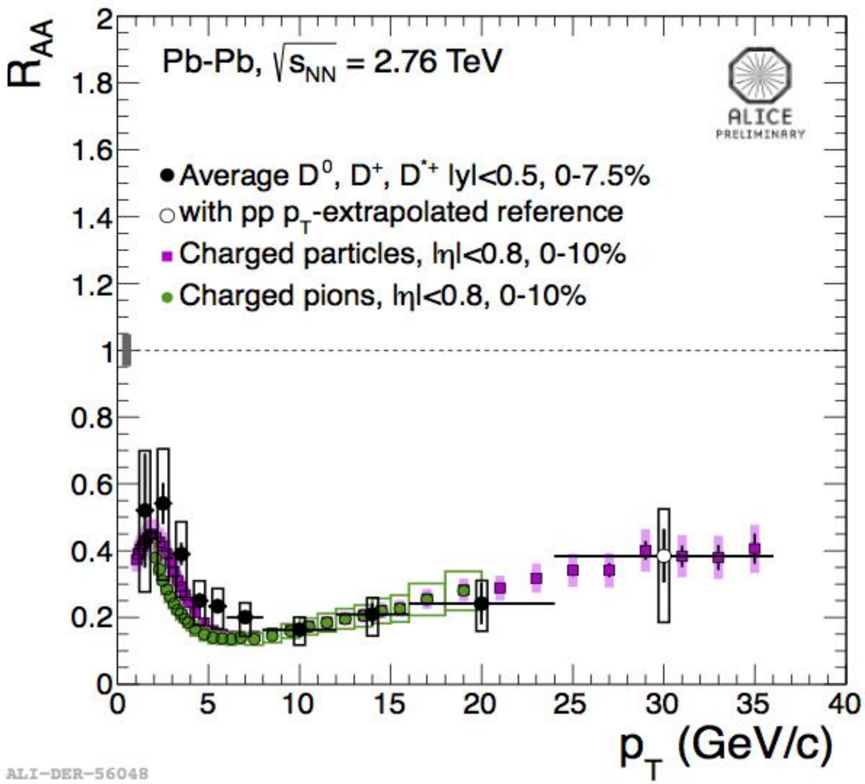
Dead cone effect





Flavor dependence of jet quenching



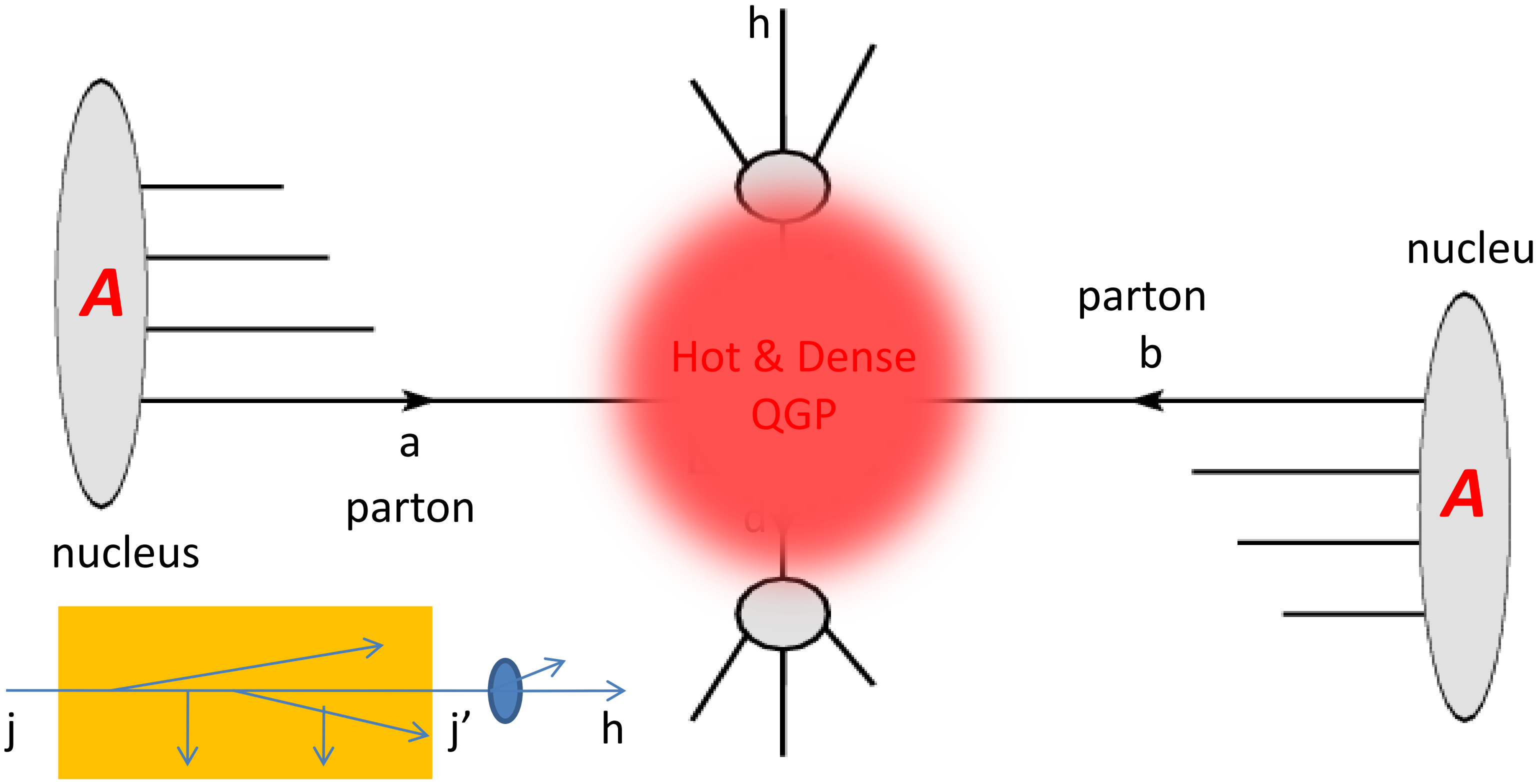


$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

$\boldsymbol{R_{AA}(D) \approx R_{AA}(h)}$ at high p_T

Where is the dead cone effect?

General framework for jet quenching study

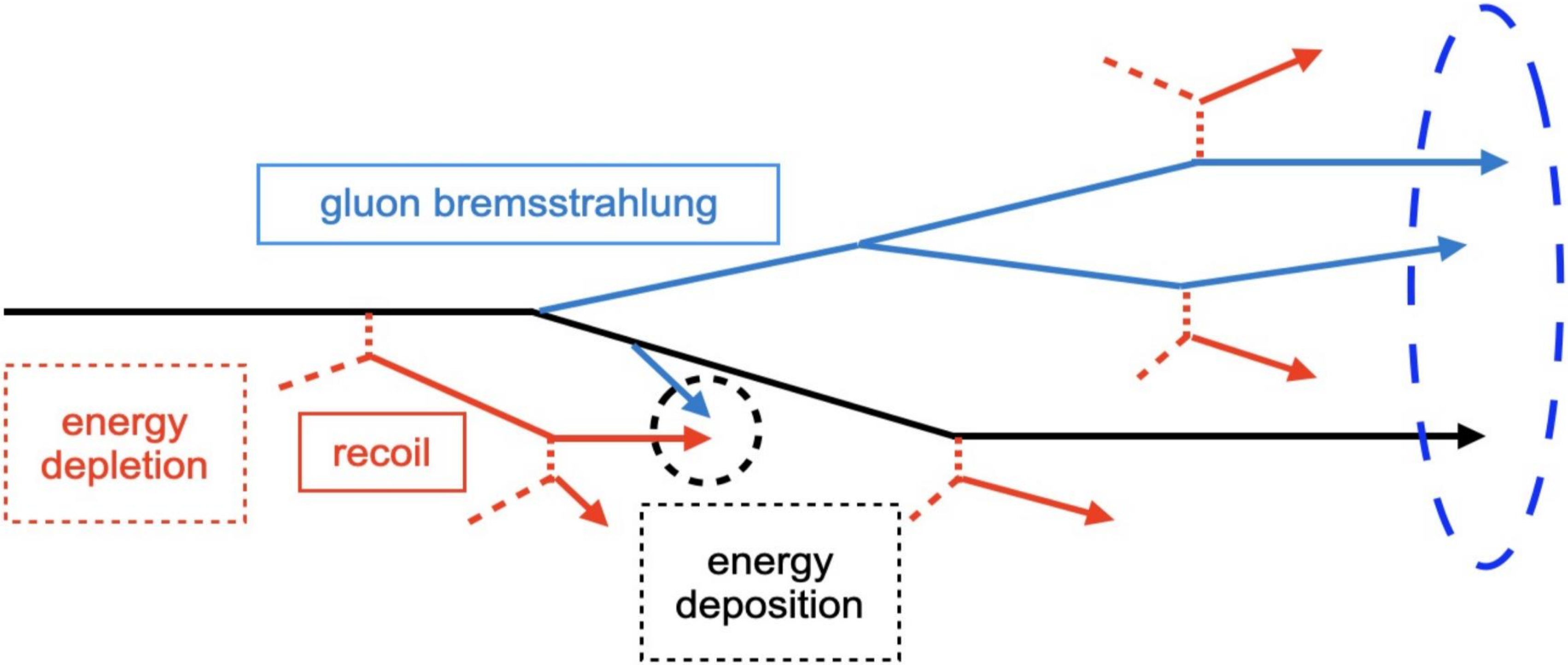


$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'} f_a \otimes f_b \otimes d\sigma_{ab\to jX} \otimes P_{j\to j'} \otimes D_{h/j'}$$

Linear Boltzmann Transport (LBT) Model

$$p \cdot \partial f_a(x,p) = E(\mathcal{C}_{\text{el}} + \mathcal{C}_{\text{inel}})$$



He, Luo, Wang, Zhu, Phys.Rev.C 91 (2015) 054908; Luo, He, Cao, Wang, Phys.Rev.C 109 (2024) 3, 034919; Cao, Luo, GYQ, Wang, Phys.Rev.C 94 (2016) 1, 014909; Phys.Lett.B 777 (2018) 255-259.

Monte-Carlo approaches of jet quenching

- **JEWEL** (*Jet Evolution With Energy Loss*): K. Zapp , G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann, Eur.Phys.J.C 60 (2009) 617-632; JHEP 03 (2013) 080.
- **Q-Pythia** (A medium-modified implementation of final state radiation): N. Armesto, L. Cunqueiro and C. A. Salgado, Eur.Phys.J.C 63 (2009) 679-690.
- **MARTINI** (*Modular Algorithm for Relativistic Treatment of heavy IoN Interactions*): B. Schenke, C. Gale, S. Jeon, Phys.Rev.C 80 (2009) 054913
- **LBT** (*Linear Boltzmann Transport Model*): Y. He, T. Luo, X. N. Wang, Y. Zhu, Phys.Rev.C 91 (2015) 054908; T. Luo, Y. He, S. Cao, X. N. Wang, Phys.Rev.C 109 (2024) 3, 034919; S. Cao, T. Luo, GYQ, X. N. Wang, Phys.Rev.C 94 (2016) 1, 014909; Phys.Lett.B 777 (2018) 255-259.
- **Hybrid** (*A Hybrid Strong/Weak Coupling Approach to Jet Quenching*): J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos, K. Rajagopal, JHEP 10 (2014) 019
- **MATTER** (*Modular-All-Twist-Transverse-and-Elastic-scattering-induced-Radiation*): A. Majumder, Phys.Rev.C 88 (2013) 014909.
- **LIDD**: W. Ke, Y. Xu, S. A. Bass, Phys.Rev.C 98 (2018) 6, 064901.
- **CoLBT-Hydro**: W. Chei, T. Luo, S. Cao, L.G. Pang, X. N. Wang, Phys.Lett.B 777 (2018) 86-90.
- **JETSCAPE** (*Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope*): 1903.07706 [nucl-th].

Different model implementations

- Keep vacuum splitting function and modify parton kinematics from Pythia
  - Hybrid: $\frac{1}{E_i}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$, where $x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{1/3}}{T^{4/3}}$
- Modify splitting function in Pythia
  - Q-Pythia: $P_{tot}(z) = (1 + f_{med})P_{vac}(z)$
  - MATTER: $P_{tot}(z) = P_{vac}(z) + P_{med}(z)$, where $P_{med}(z)$ from HT
- Implement the BDMPS-Z limit of LPM effect based on formation time constraint
  - JEWEL: Radiated gluon can scatter with medium within τ_f; Each scattering medium increases transverse momentum, thus dynamically updates τ_f.
- Solve transport equations for the time evolution of jet particles
  - MARTINI: Rate equation with AMY
  - **LBT: Boltzmann equation with HT**
- Multi-stage evolution
  - LIDO: Combine Boltzmann and Langevin equations
  - JETSCAPE: Combine MATTER and LBT

Elastic scattering in LBT: rates

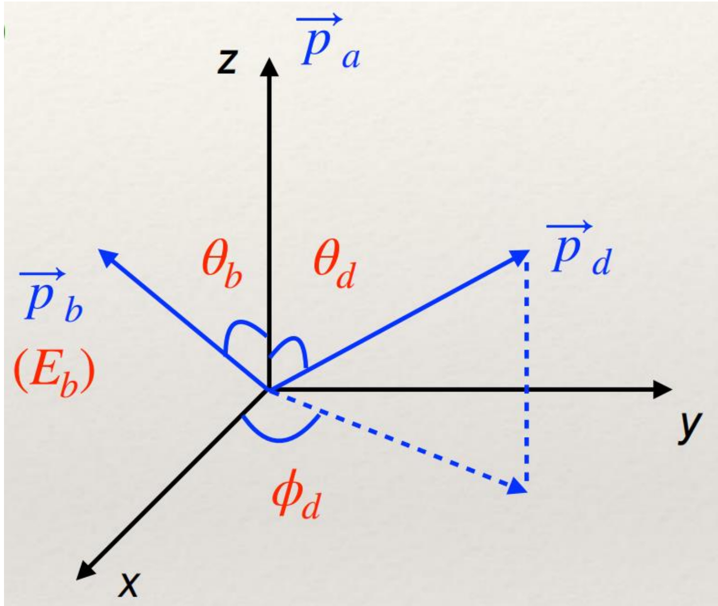
$$\Gamma_{12\to34}(\vec{p}_1) = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\,[1\pm f_3(\vec{p}_3)]\,[1\pm f_4(\vec{p}_4)]\,S_2(s,t,u)$$
$$\times (2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to34}|^2,$$

$$S_2(s,t,u) = \theta(s\geq 2\mu_{\rm D}^2)\theta(-s+\mu_{\rm D}^2\leq t\leq -\mu_{\rm D}^2)$$

$$\Gamma_{12\to34}(\vec{p}_1,T) = \frac{\gamma_2}{16E_1(2\pi)^4}\int dE_2 d\theta_2 d\theta_4 d\phi_4$$
$$\times f_2(E_2,T)\,[1\pm f_4(E_4,T)]\,S_2(s,t,u)|\mathcal{M}_{12\to34}|^2$$
$$\times \frac{E_2E_4\sin\theta_2\sin\theta_4}{E_1-|\vec{p}_1|\cos\theta_4+E_2-E_2\cos\theta_{24}},$$

$$\cos\theta_{24} = \sin\theta_2\sin\theta_4\cos\phi_4+\cos\theta_2\cos\theta_4,$$

$$E_4 = \frac{E_1E_2-p_1E_2\cos\theta_2}{E_1-p_1\cos\theta_4+E_2-E_2\cos\theta_{24}}.$$



In high-energy & eikonal approximations and only t-channel:

$$\Gamma \sim \frac{\alpha_s^2 T^3}{\mu_D^2}$$

$$\hat{q} \sim \alpha_s^2 T^3 \ln\frac{ET}{\mu_D^2}, \qquad \frac{dE}{dt} \sim \alpha_s^2 T^2 \ln\frac{ET}{\mu_D^2}$$

Elastic scattering in LBT: channels

$$\Gamma_{12\to34}(\vec{p}_1) = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2)\,[1\pm f_3(\vec{p}_3)]\,[1\pm f_4(\vec{p}_4)]\,S_2(s,t,u) \times (2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to34}|^2,$$

$$\Gamma_a^{el} = \sum_{b,(cd)} \Gamma_{ab\to cd}\,,\; P_a^{el} = 1 - e^{\Gamma_a^{el}\Delta t}$$

$ij \to kl$	$\lvert M\rvert^2_{ij\to kl}$
$gg \to gg$	$\frac{9}{2}g_s^4\left(3-\frac{ut}{s^2}-\frac{us}{t^2}-\frac{st}{u^2}\right)$
$gg \to q\bar{q}$	$\frac{3}{8}g_s^4\left(\frac{4}{9}\frac{t^2+u^2}{tu}-\frac{t^2+u^2}{s^2}\right)$
$gq \to gq$ $g\bar{q} \to g\bar{q}$	$g_s^4\left(\frac{s^2+u^2}{t^2}-\frac{4}{9}\frac{s^2+u^2}{su}\right)$
$q_iq_j \to q_iq_j$ $q_i\bar{q}_j \to q_i\bar{q}_j$ $\bar{q}_iq_j \to \bar{q}_iq_j$ $\bar{q}_i\bar{q}_j \to \bar{q}_i\bar{q}_j$	$\frac{4}{9}g_s^4\frac{s^2+u^2}{t^2}, \quad i\neq j$
$q_iq_i \to q_iq_i$ $\bar{q}_i\bar{q}_i \to \bar{q}_i\bar{q}_i$	$\frac{4}{9}g_s^4\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}-\frac{2}{3}\frac{s^2}{tu}\right)$
$q_i\bar{q}_i \to q_j\bar{q}_j$	$\frac{4}{9}g_s^4\frac{t^2+u^2}{s^2}$
$q_i\bar{q}_i \to q_i\bar{q}_i$	$\frac{4}{9}g_s^4\left(\frac{s^2+u^2}{t^2}+\frac{t^2+u^2}{s^2}-\frac{2}{3}\frac{u^2}{st}\right)$
$q\bar{q} \to gg$	$\frac{8}{3}g_s^4\left(\frac{4}{9}\frac{t^2+u^2}{tu}-\frac{t^2+u^2}{s^2}\right)$

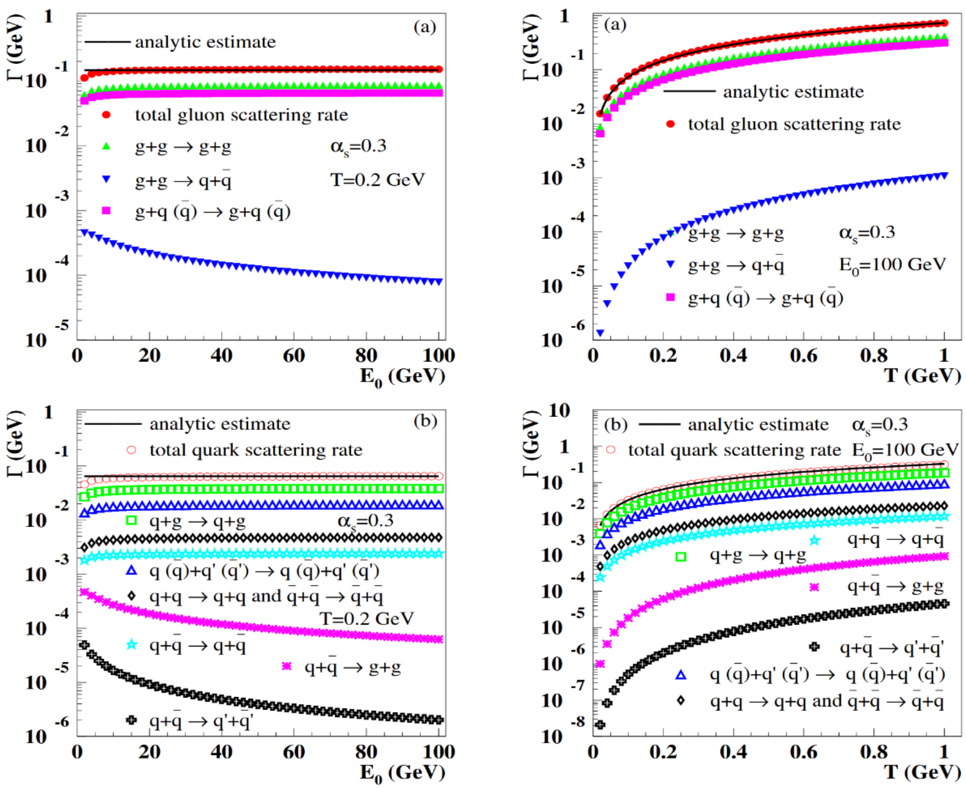
$$\Sigma|\mathcal{M}_{qQ\to qQ}|^2 = \frac{64}{9}\pi^2\alpha_s^2(M_\mathrm{T})\frac{(M^2-u)^2+(s-M^2)^2+2M^2t}{t^2},$$

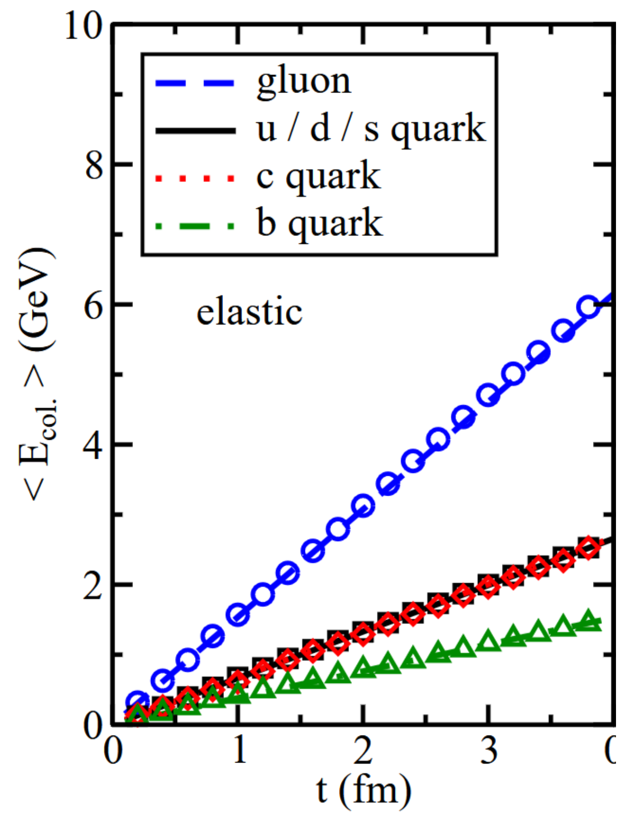
$$\begin{aligned}\Sigma|\mathcal{M}_{gQ\to gQ}|^2 = \pi^2\alpha_s^2(M_\mathrm{T})\Bigg[&\frac{32}{t^2}(s-M^2)(M^2-u)\\ &+\frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2}\\ &+\frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(M^2+u)}{(M^2-u)^2}\\ &+\frac{16}{9}\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)}\\ &+16\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t(s-M^2)}\\ &-16\frac{(s-M^2)(M^2-u)-M^2(s-u))}{t(M^2-u)}\Bigg],\end{aligned}$$

Elastic scattering in LBT

$$\Gamma_{12\to34}(\vec{p}_1) = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2)\,[1\pm f_3(\vec{p}_3)]\,[1\pm f_4(\vec{p}_4)]\,S_2(s,t,u) \times (2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to34}|^2,$$

$$\Gamma_a^{el} = \sum_{b,(cd)} \Gamma_{ab\to cd}\,,\; P_a^{el} = 1 - e^{\Gamma_a^{el}\Delta t}$$



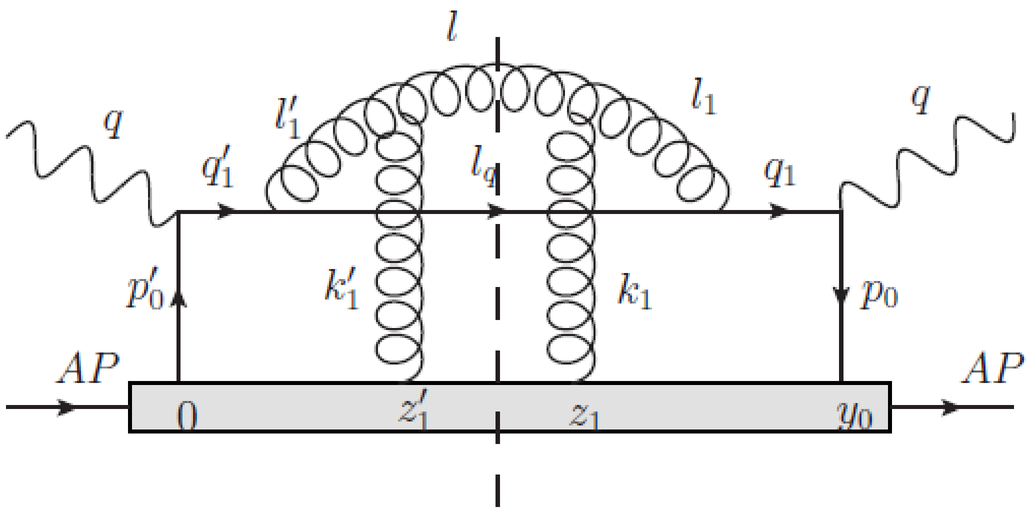


Our Monte-Carlo simulation of elastic collisions agrees with semi-analytical result.

He, Luo, Wang, Zhu, Phys.Rev.C 91 (2015) 054908

Medium-induced radiation in LBT (HT)

- In higher twist formalism, the gluon radiation is calculated in the framework of DIS off a large nucleus



+ other 20 diagrams

- The medium-induced gluon radiation spectrum (after collinear expansion)

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4 \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

- Guo, Wang, PRL 2000, Majumder, PRC 2012; Zhang, Wang, Wang, PRL 2004

Implementation of inelastic radiation in LBT

- Calculate $\langle N_g \rangle$ & $P_{inel} = 1 - e^{-\langle N_g \rangle}$

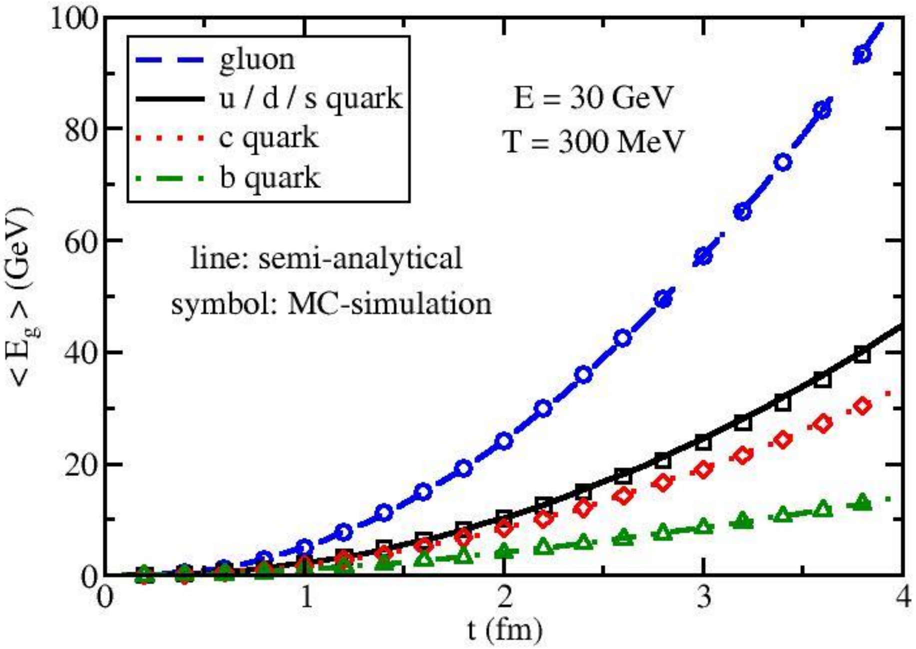
$$\langle N_g \rangle (E, T, t, \Delta t) = \Gamma_g \Delta t = \Delta t \int dx\, dk_\perp^2 \frac{dN_g}{dx\, dk_\perp^2 dt}$$

- If gluon radiation happens, sample *n* gluons from Poisson distribution

$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

- Sample *E* & *p* of radiatied gluons using the differential radiation spectrum

- First do $2 \to 2$ process, then adjust *E* & *p* of $2 + n$ final partons to guarantee *E* & *p* conservation for $2 \to 2 + n$ process



$\langle E_g \rangle$ from our MC simulation agrees with the semi-analytical result.

Combine elastic & inelastic

- Total probability:

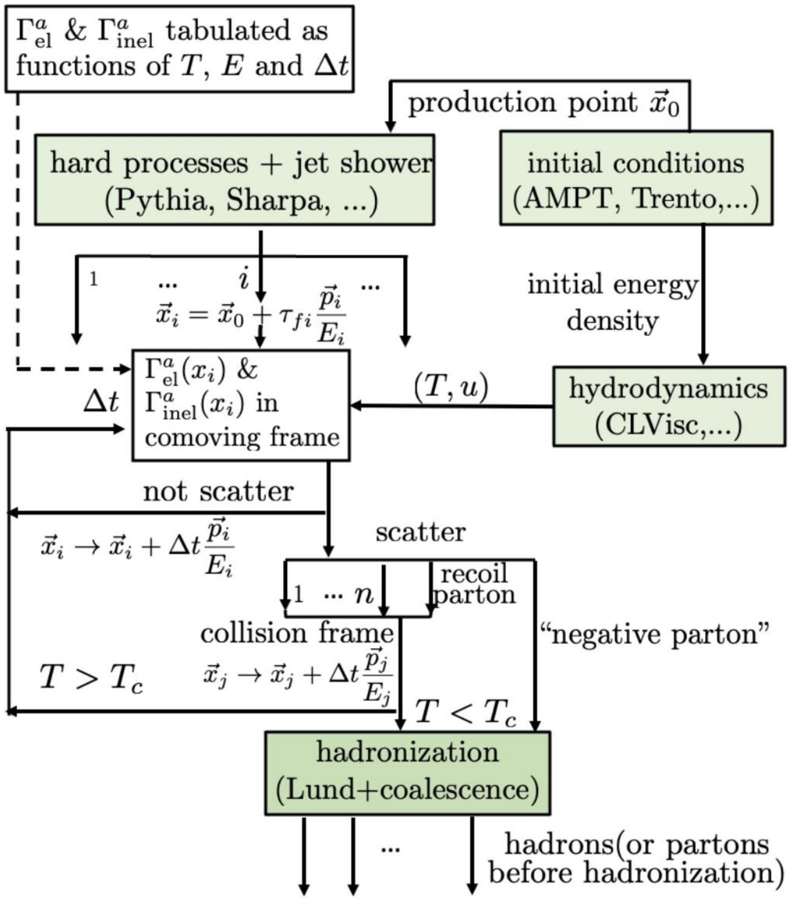
$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

  - Pure elastic scattering without gluon radiation: $P_{el}(1 - P_{inel})$
  - Inelastic scattering: P_{inel}

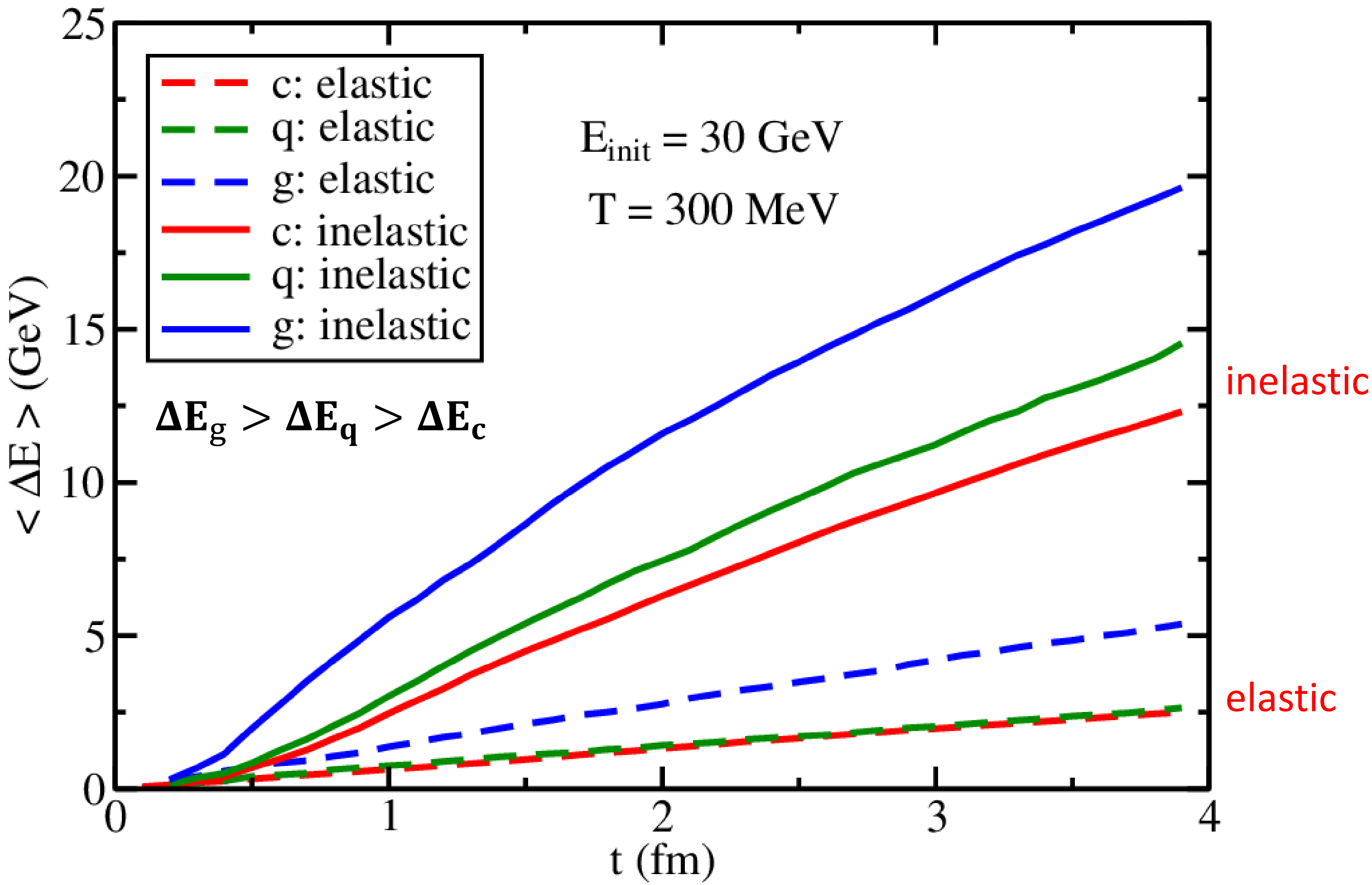
- Use P_{tot} to determine whether jet parton interact with thermal medium

- If jet-medium interaction happens, then determine whether it is pure elastic or inelastic

- Then simulate $2 \to 2$ or $2 \to 2 + n$ process

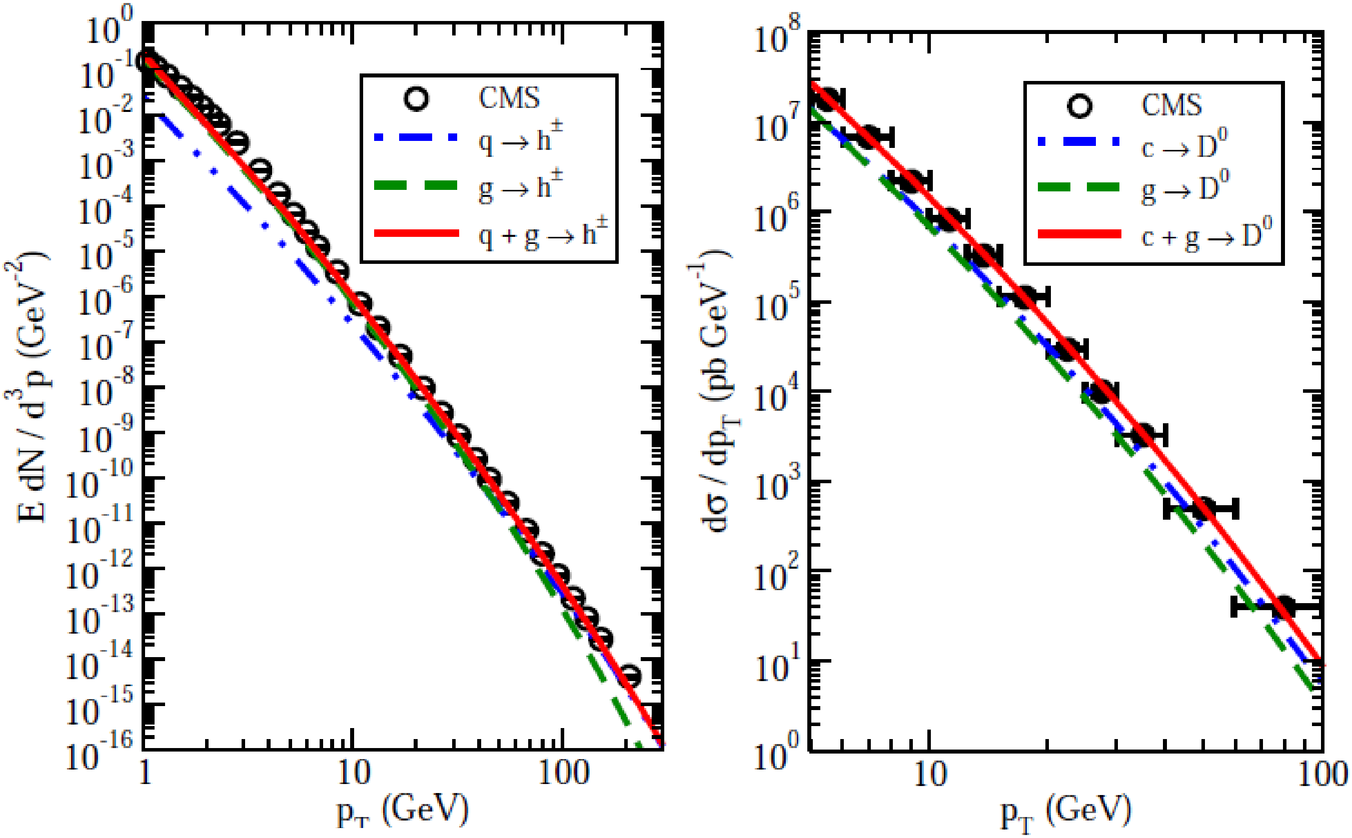


Flavor hierachy of parton energy loss



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016 ; PLB 2018; etc.

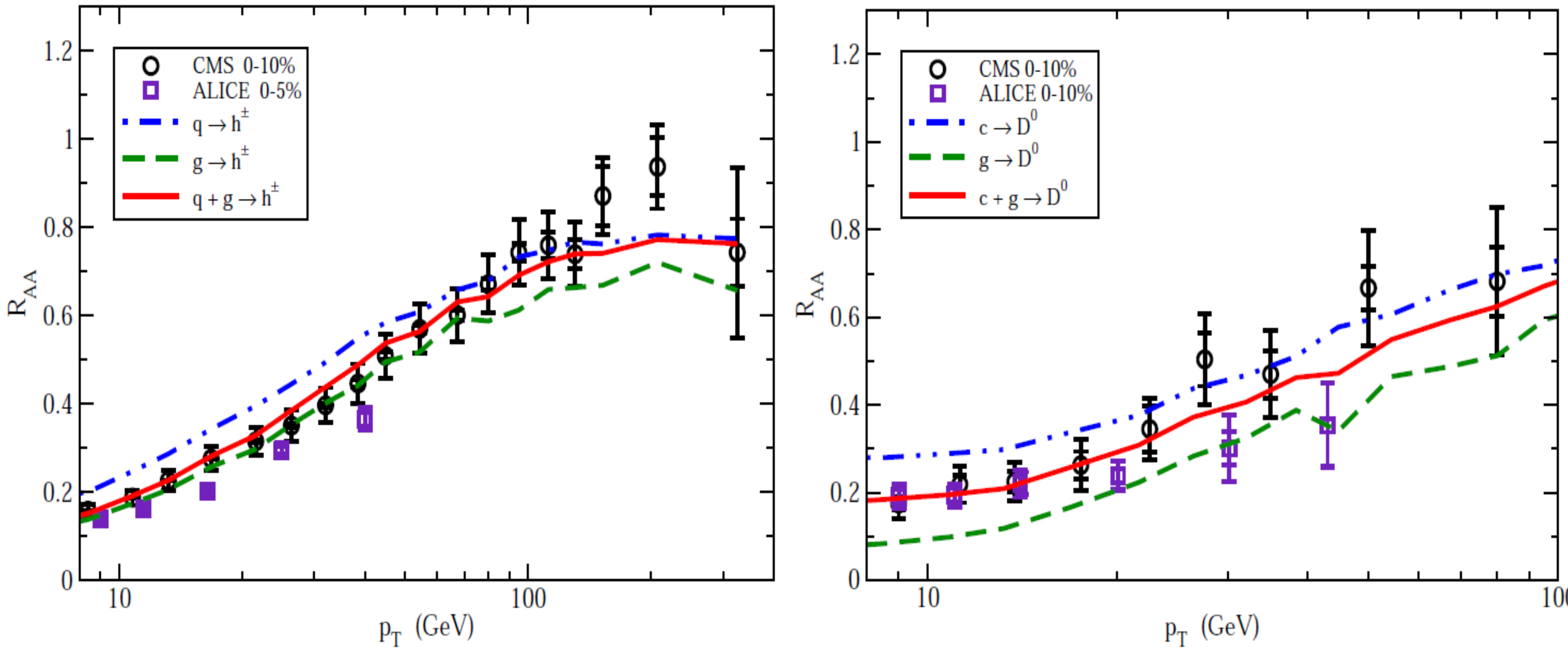
Baseline: hadron productions in pp @ NLO



$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

Based on B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B327, 105 (1989).

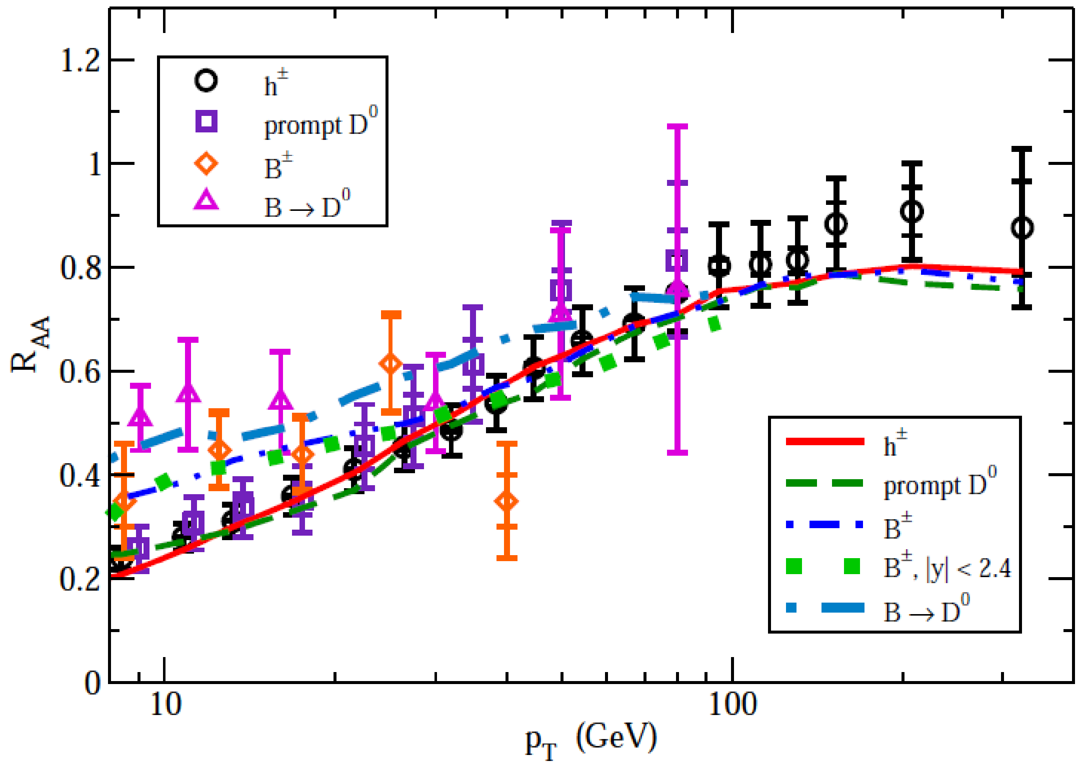
Flavor hierarchy of jet quenching



Build a state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.
Combining both quark and gluon contributions, we obtain a nice description of charged hadron & D meson R_{AA} over a wide range of p_T.

Xing, Cao, GYQ, Xing, PLB 2020

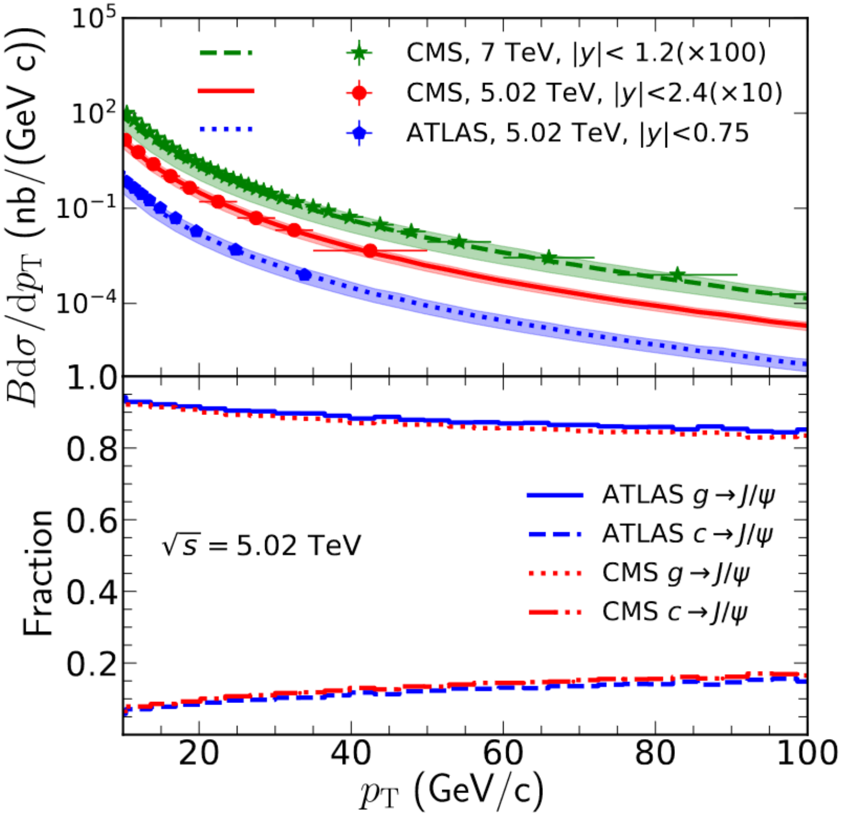
Flavor hierarchy of jet quenching



A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
At p_T > 30-40 GeV, B mesons will also exhibit similar suppression effects to charged hadrons and D mesons, which can be tested by future measurements.

Xing, Cao, GYQ, Xing, PLB 2020

Gluons dominate high p_T J/Ψ production



Leading power (p_T^2/m_c^2) NRQCD:

$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$$D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

Gluon fragmentation-improved PYTHIA (GFIP)

MadGraph for hard parton creation

PYTHIA8 for parton shower

Short-distance coefficients from 1311.7078, 1208.5301

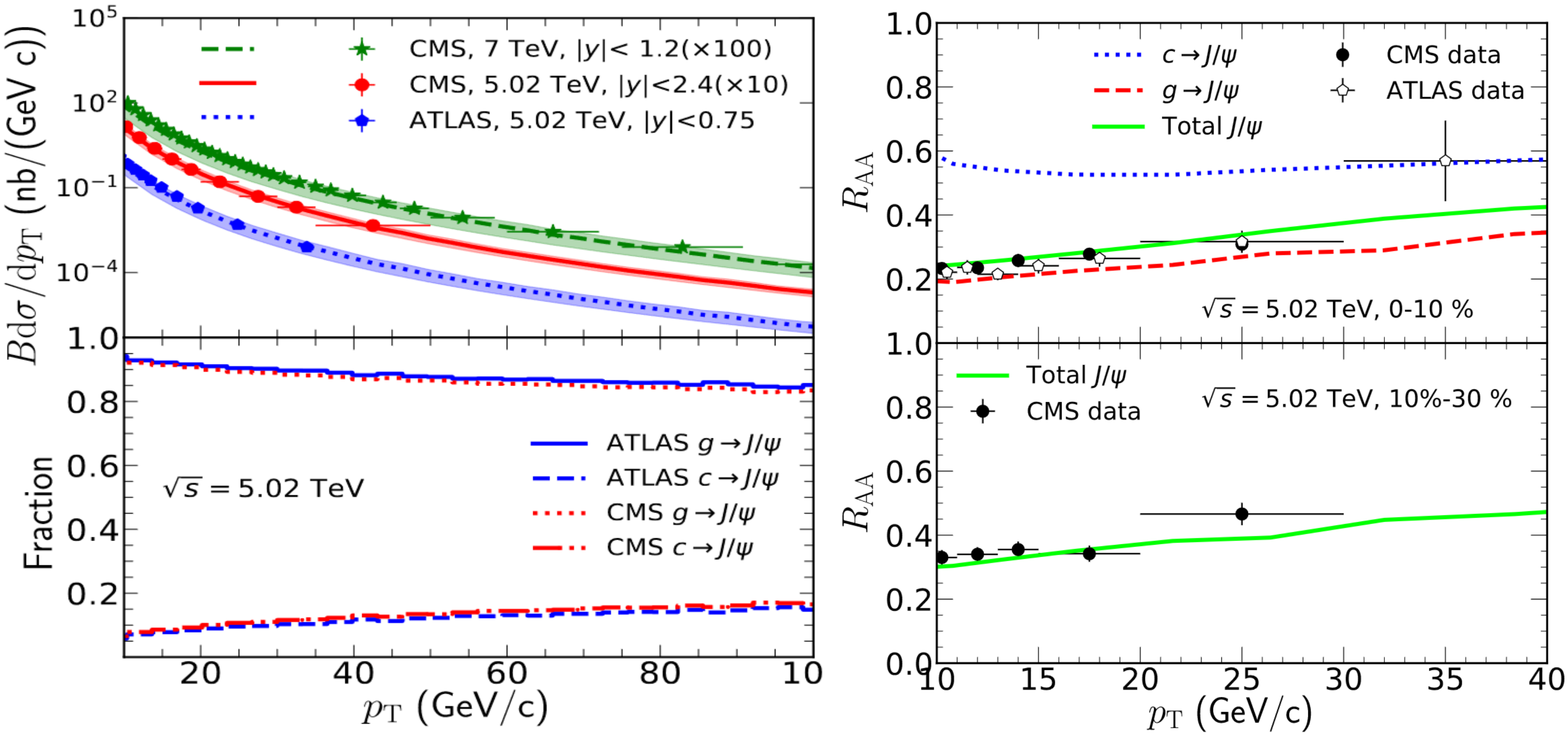
Long-distance matrix element from 1403.3612.

Within the framework of leading power NRQCD, gluons dominate high p_T J/Ψ production.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

Gluons dominate high p_T J/Ψ suppression



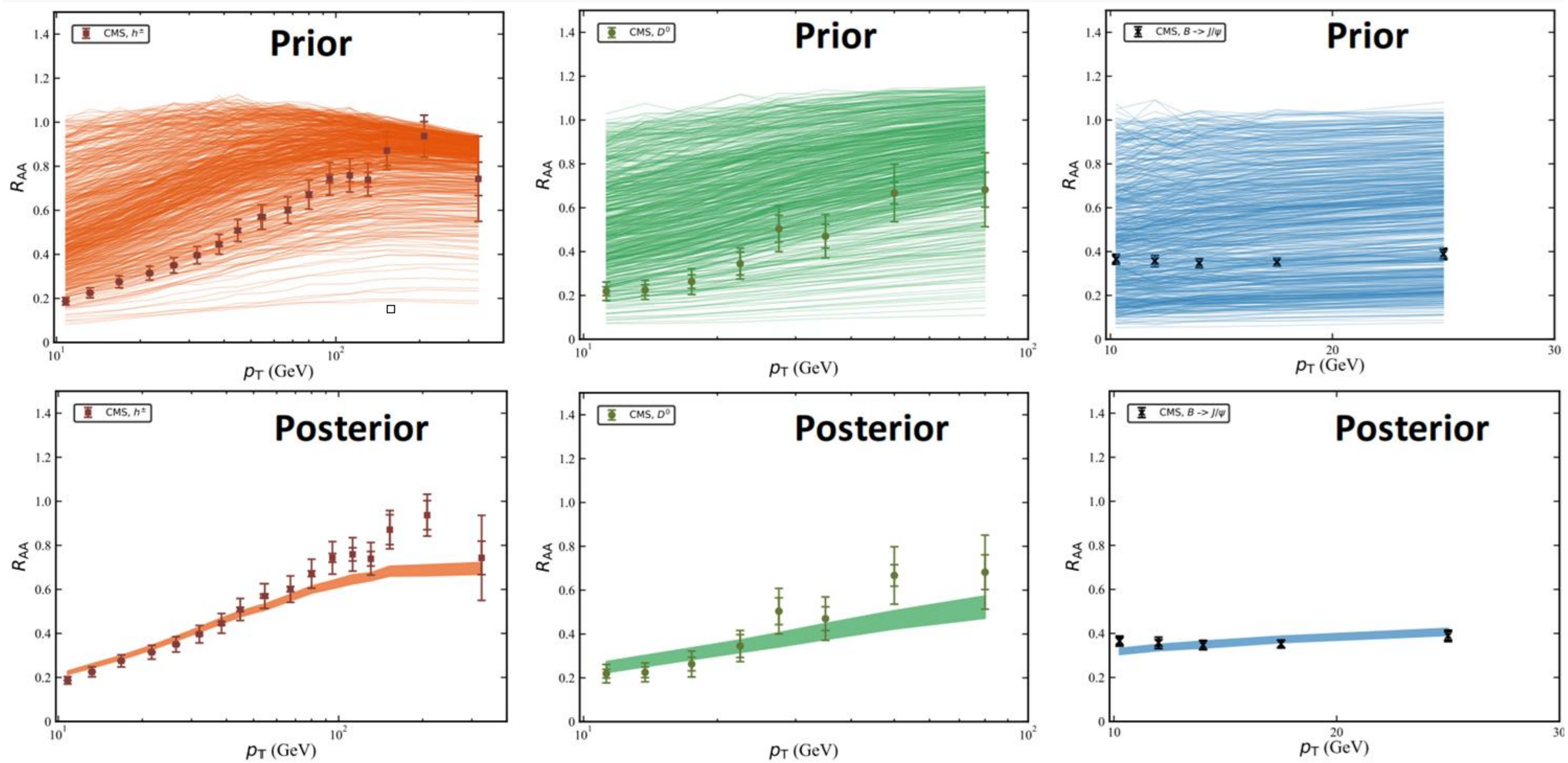
$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi} \quad D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

The gluon jet quenching is the driving force for high p_T J/Ψ suppression.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, Sci.Bull. 68 (2023) 2003-2009

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

Bayesian analysis of high p_T hadron R_{AA}

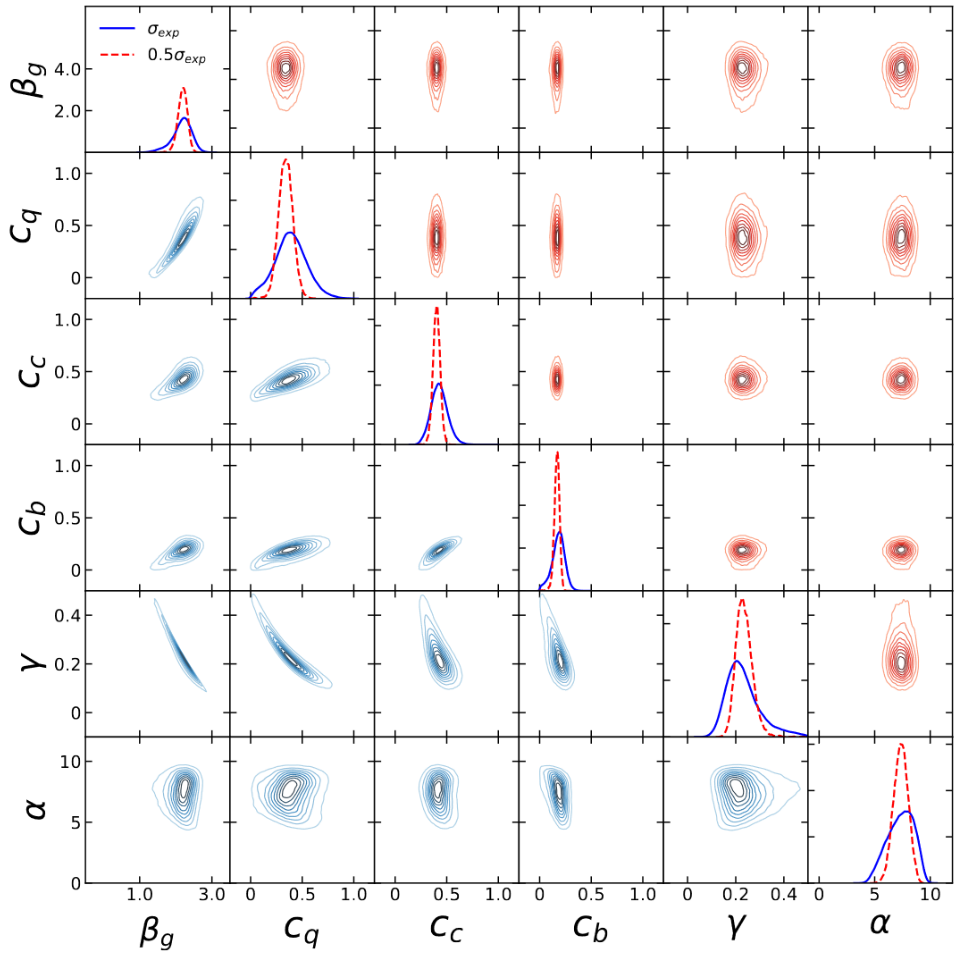


$$\frac{1}{\langle N_{\rm coll}\rangle}\frac{d\sigma_{\rm AA\to hX}}{dp_{\rm T}^{h}} = \sum_j \int dp_{\rm T}^{j} dx dz \frac{d\hat{\sigma}_{\rm p'p'\to jX}}{dp_{\rm T}^{j}}(p_{\rm T}^{j})\; W_{\rm AA}(x) D_{j\to h}(z)\delta\left(p_{\rm T}^{h} - z(p_{\rm T}^{j} - x\langle\Delta p_{\rm T}^{j}\rangle)\right)$$

$$\left\langle \Delta p_{\rm T}^{j}\right\rangle = C_j \beta_g p_{\rm T}^{\gamma} \log(p_{\rm T}) \qquad W_{\rm AA}(x) = \frac{\alpha^{\alpha} x^{\alpha-1} e^{-\alpha x}}{\Gamma(\alpha)}$$

W. J. Xing, S. Cao, GYQ, Phys.Lett.B 850 (2024) 138523

Posterior distributions of parameters

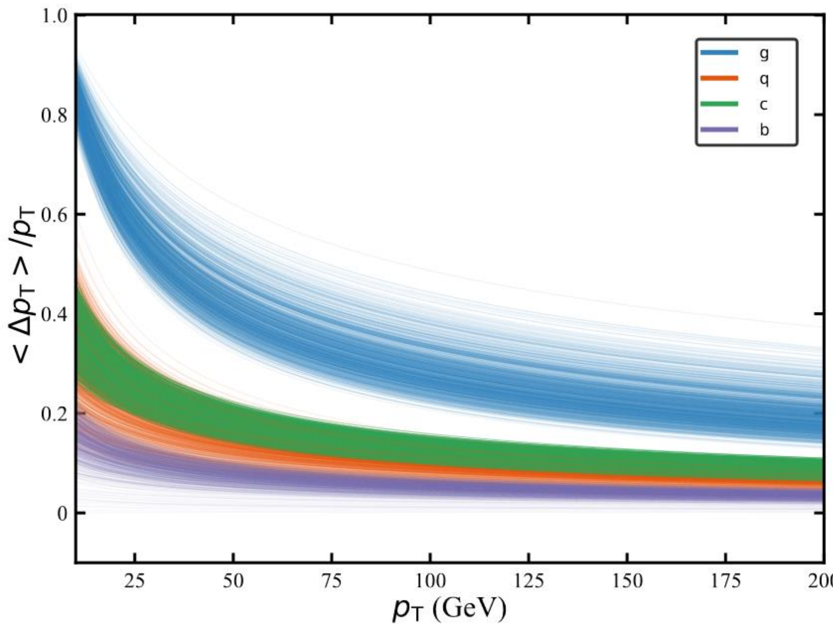


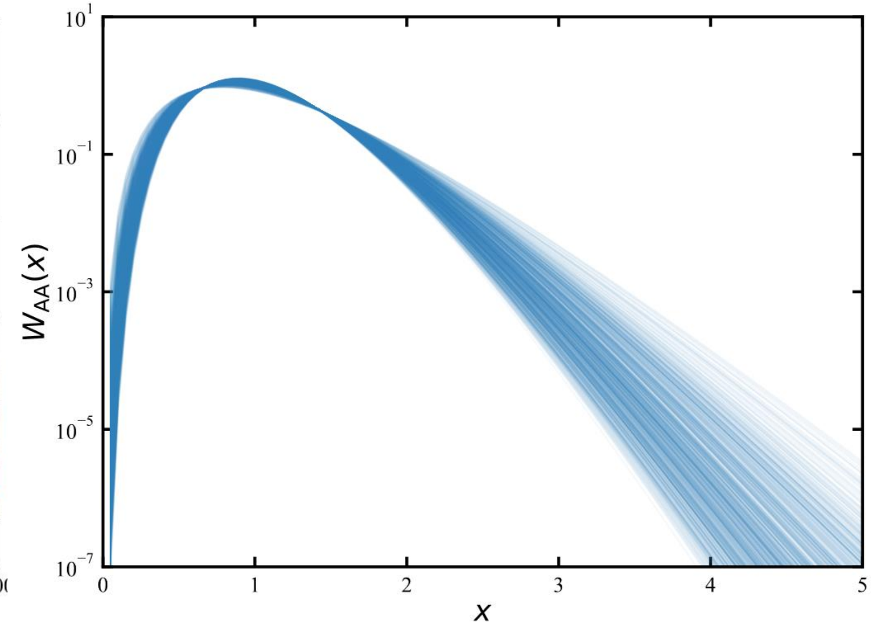
	with σ_{exp}	with $0.5\sigma_{\text{exp}}$
β_g	(1.646, 2.56)	(1.96, 2.39)
C_q	(0.129, 0.65)	(0.226, 0.454)
C_c	(0.3, 0.567)	(0.344, 0.459)
C_b	(0.065, 0.277)	(0.124, 0.207)
γ	(0.137, 0.378)	(0.184, 0.295)
α	(5.287, 9.061)	(6.266, 8.401)

The energy loss parameters for jet-medium interaction can be well constrained by the Bayesian analysis.

Reducing experimental data error bars can improve the precision of the extracted parameters.

Flavor hierarchy of parton energy loss





$$\frac{1}{\langle N_{\rm coll}\rangle}\frac{d\sigma_{\rm AA\to hX}}{dp_{\rm T}^h} = \sum_j \int dp_{\rm T}^j dx dz \frac{d\hat{\sigma}_{\rm p'p'\to jX}}{dp_{\rm T}^j}(p_{\rm T}^j)\; W_{\rm AA}(x) D_{j\to h}(z)\delta\left(p_{\rm T}^h - z(p_{\rm T}^j - x\langle\Delta p_{\rm T}^j\rangle)\right)$$

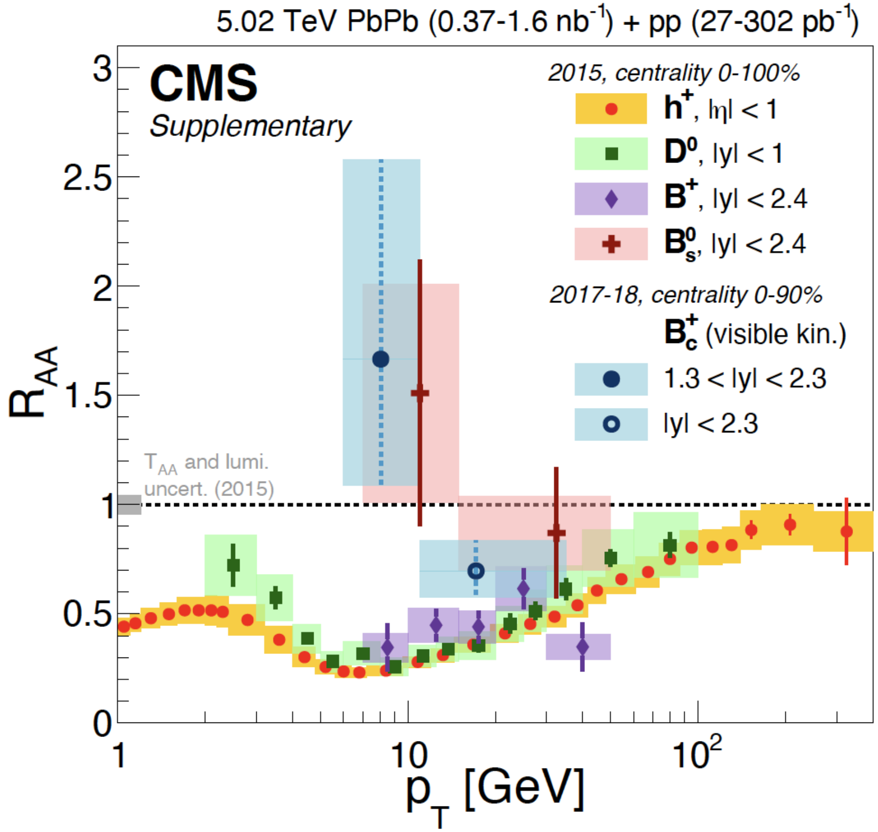
$$\langle\Delta E_g\rangle > \langle\Delta E_q\rangle \sim \langle\Delta E_c\rangle > \langle\Delta E_b\rangle$$

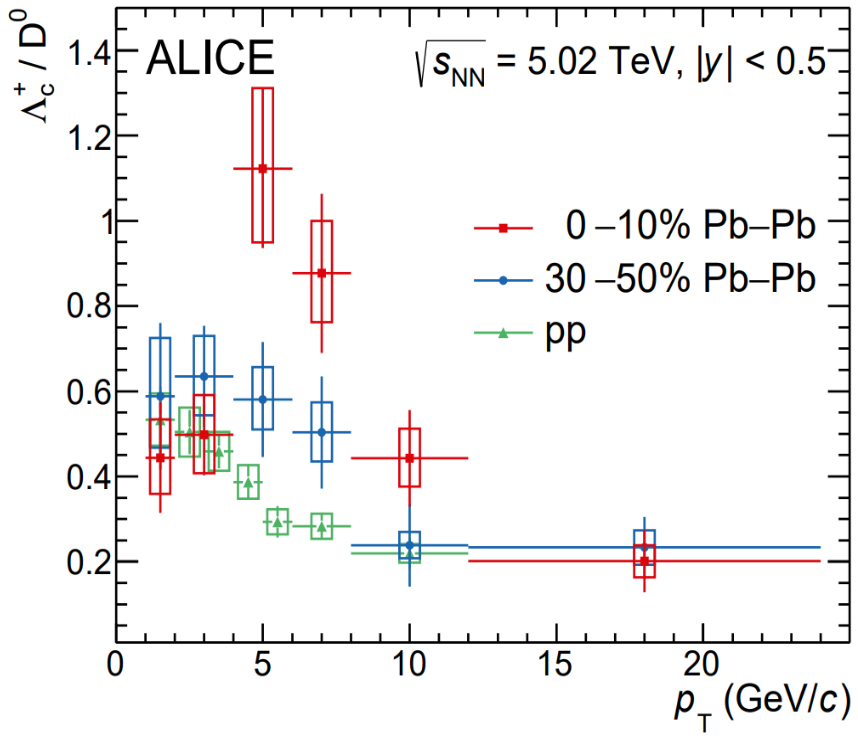
Direct extraction of the flavor dependence of parton energy loss in QGP from data.

Provides a stringent test of pQCD calculation of parton-medium interaction.

W. J. Xing, S. Cao, GYQ, PLB 2024

Heavy quarks: quenching & hadronization



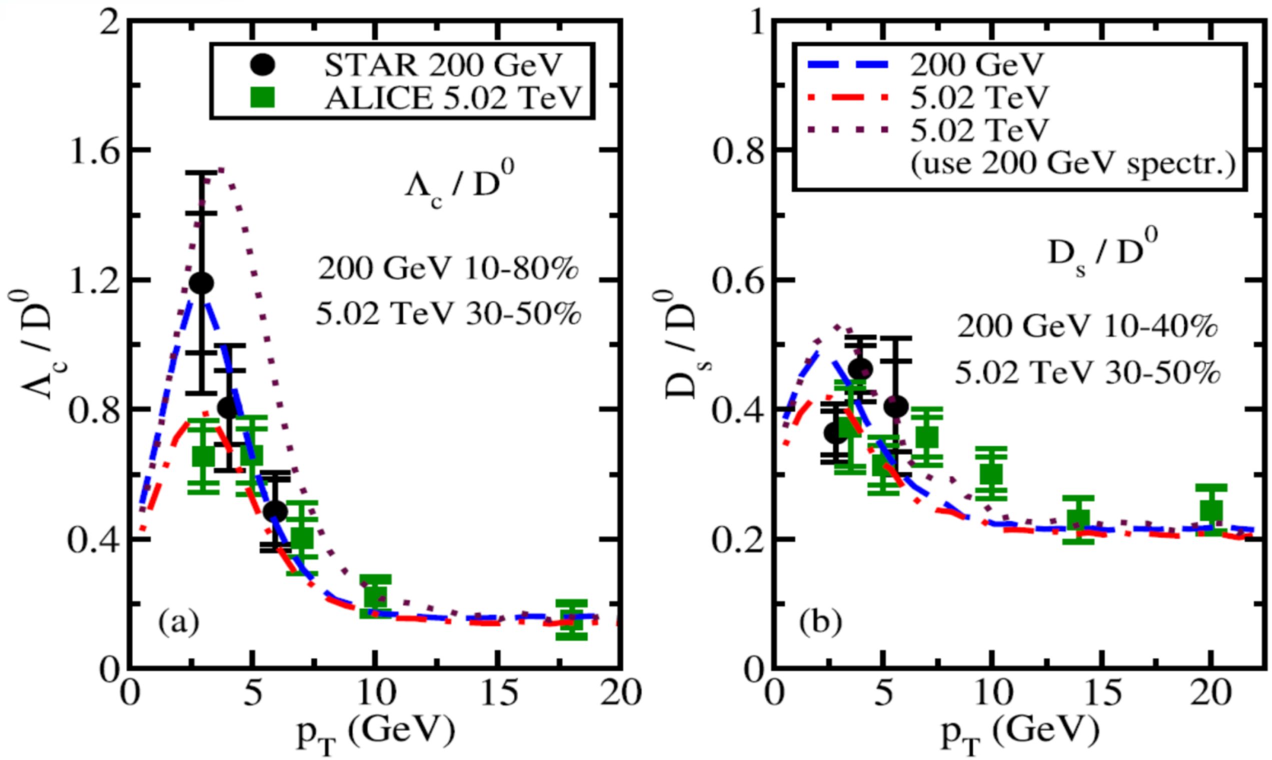


High-energy heavy quarks can probe the flavor dependence of parton energy loss and jet quenching.

Heavy flavor hadron chemistry can be used to probe the hadronization mechanisms.

Enhancement of B/M ratios in AA relative to pp can be explained by quark coalescence.

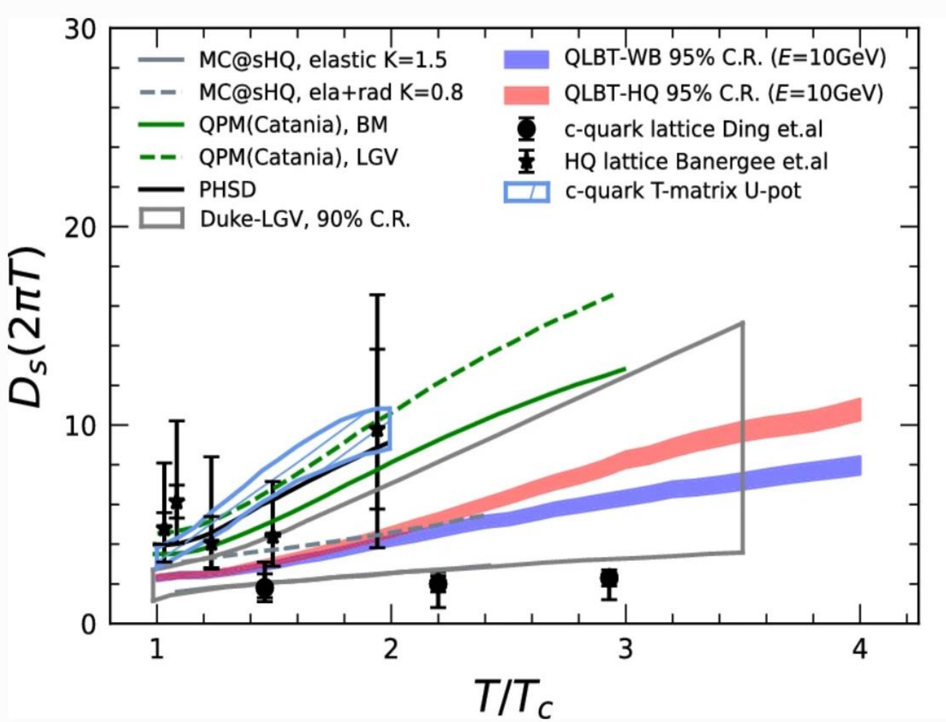
Baryon/meson & strangeness enhancement

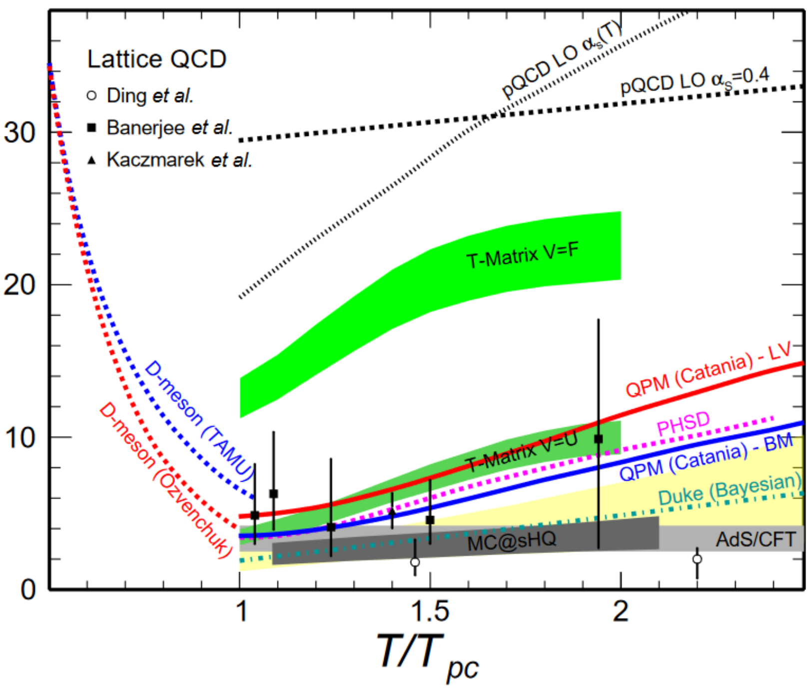


B/M & strangeness enhancement can be explained by **coalescence** mechanism.
Smaller B/M and strange/non-strange ratios at the LHC than at RHIC can be explained by the interplay between the QGP flow and charm quark p_T spectrum.
The harder charm quark p_T spectrum at the LHC suppresses the QGP flow effect, yielding a smaller B/M and strange/non-strange ratios.

S. Cao, K.-J. Sun, S.-Q. Li, S. Liu, W.-J. Xing, GYQ, C.M. Ko, PLB 2020

Heavy quark diffusion in QGP

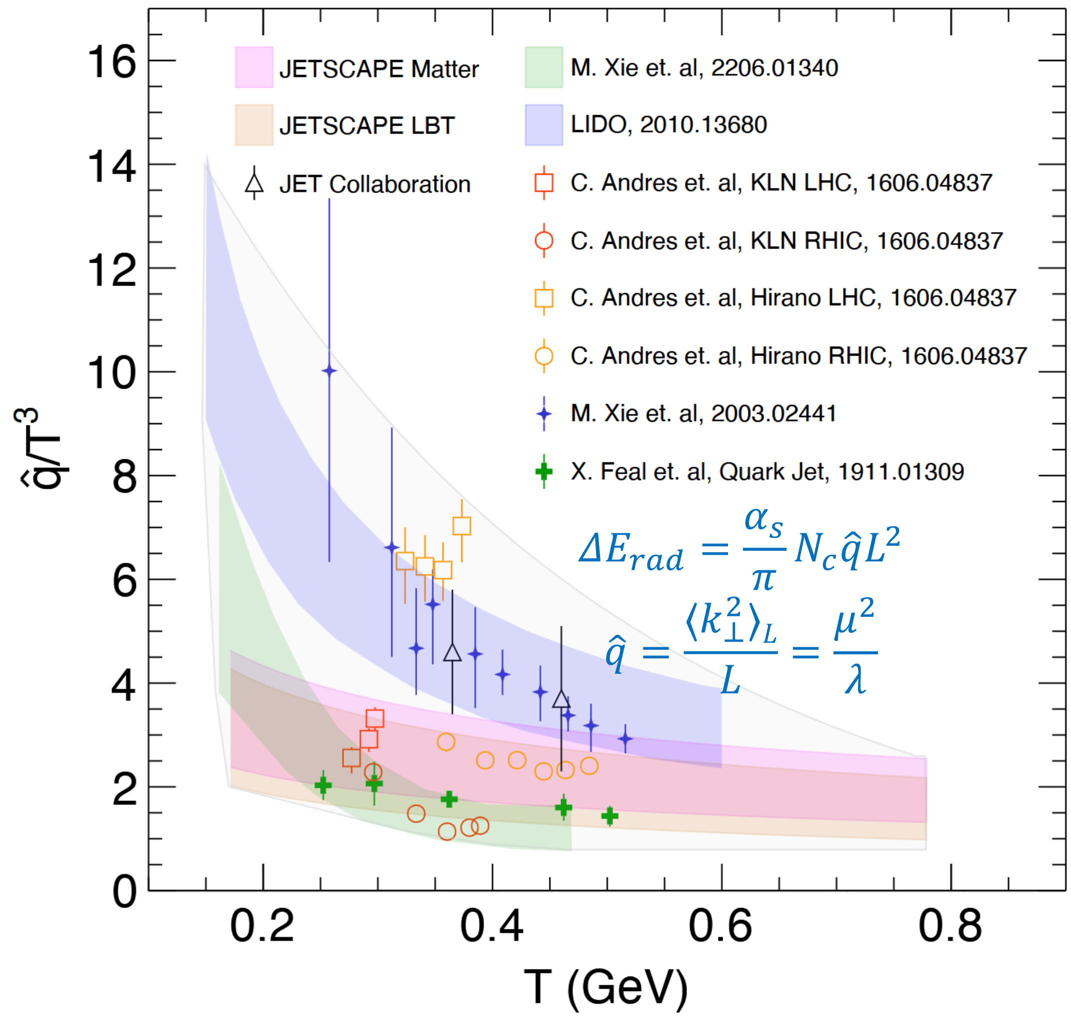




Brown motion: $\langle(\Delta x)^2\rangle = 2D_s\Delta t$

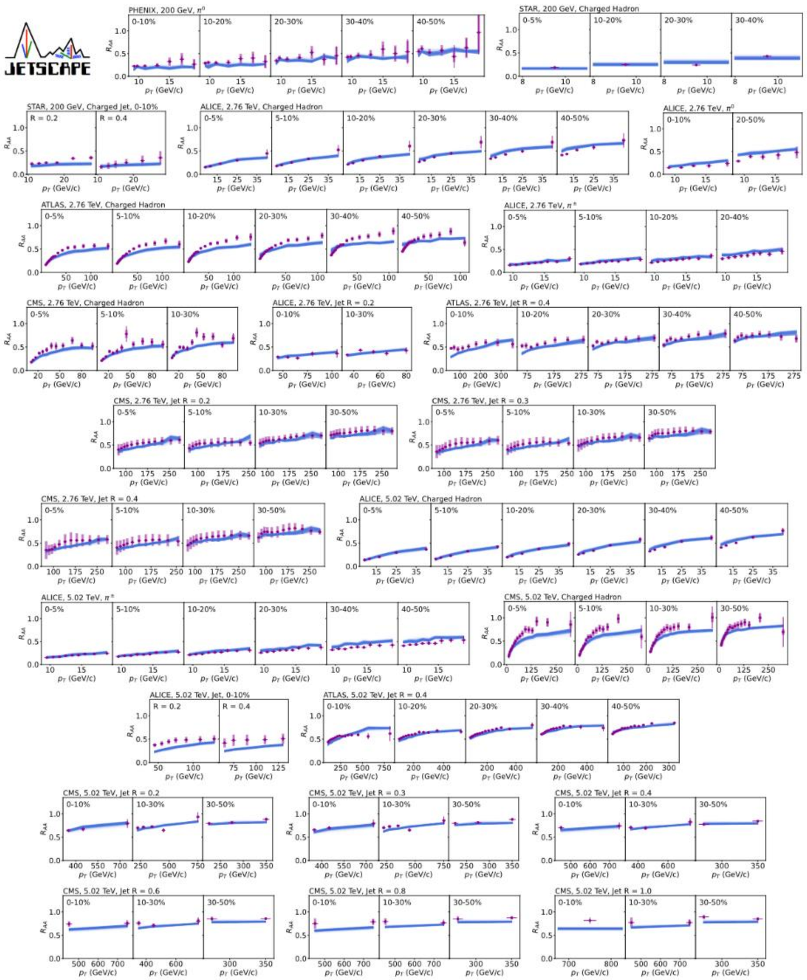
F.-L. Liu, W.-J. Xing, X.-Y. Wu, GYQ, S. Cao, X.-N. Wang, EPJC 2022
X. Dong, Y.-J. Lee, R. Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

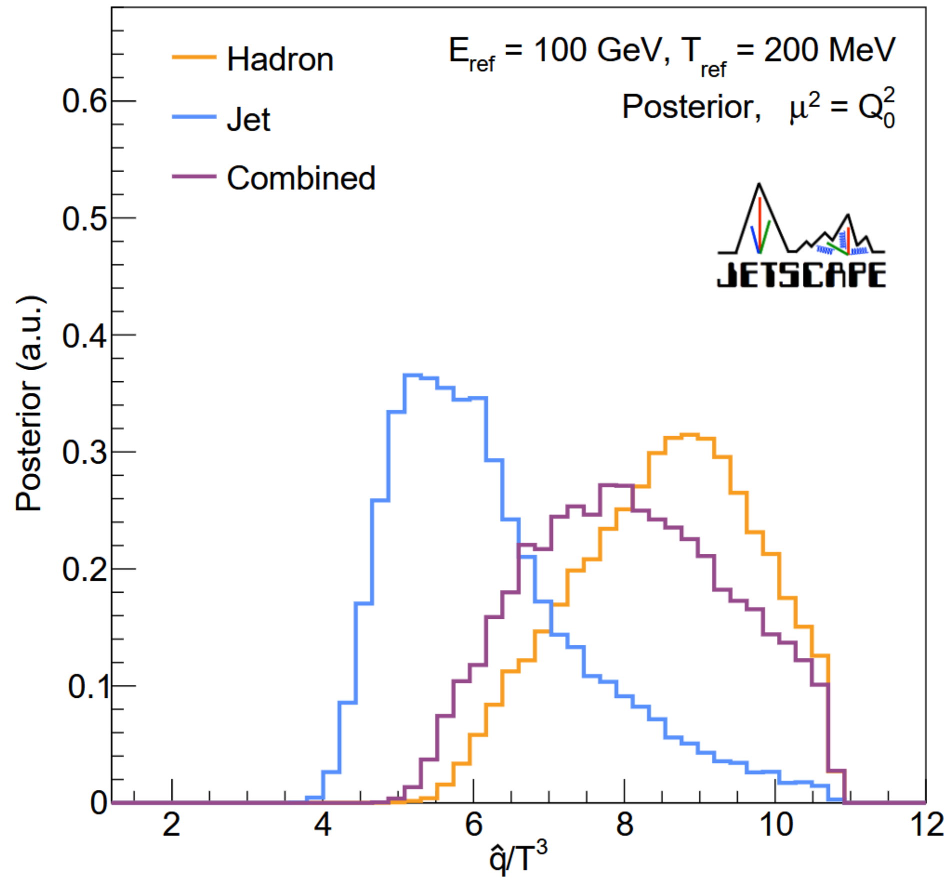
Global extraction of $\hat{q}$



L. Apolinario, Y.-J. Lee, M. Winn, Prog.Part. Nucl. Phys. 127 (2022) 103990

Extraction of $\hat{q}$ by JETSCAPE





JETSCAPE, 2408.08247 [hep-ph]

Summary for Lecture III

- Perturbative QCD based parton energy loss model can explain the flavor hierarchy of jet quenching.
- Difference between charged hadron and D/B R_{AA} disappears at high p_T
- Heavy quarks are versatile probes: both parton energy loss and hadronization.
- Jets and heavy flavors provide important tools to extract the transport properties of QGP
- The interpretation of final jet quenching via parton energy loss is complicated by modification of hadronization process, which calls for full jet observables (see next lecture)
- Need consistent understanding of both leading hadrons and full jets

重离子碰撞中的喷注
Jets in Heavy-Ion Collisions

秦广友（Guang-You Qin）
华中师范大学（Central China Normal University）

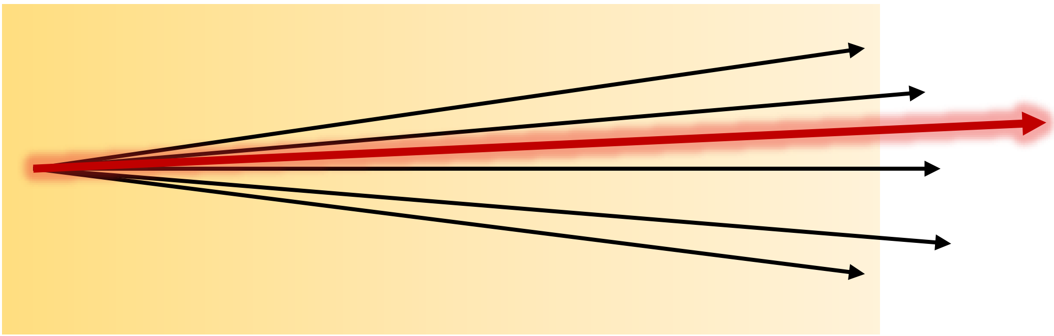
“微扰量子场论及其应用”前沿讲习班暨前沿研讨会
山东济南
2025 年7月6日-7月21日

Outline

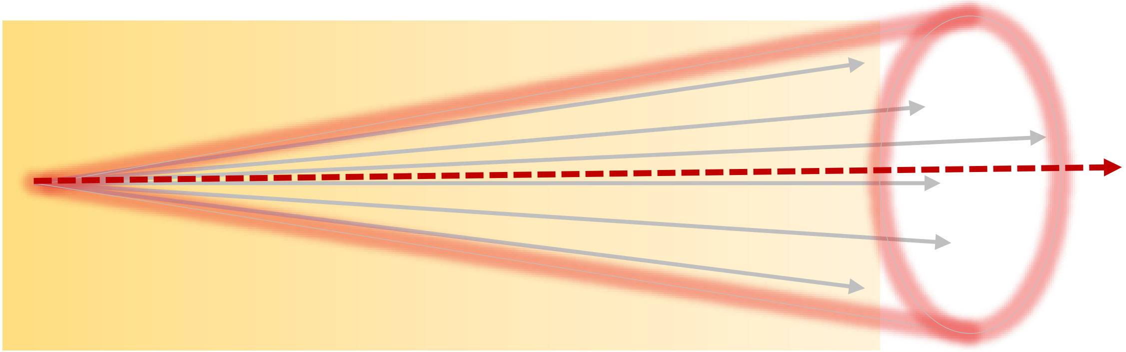
- Lecture 1
  - Introduction to heavy-ion collisions and quark-gluon plasma
- Lecture 2
  - Jet probes (of QGP in HIC), jet quenching and energy loss (some simple discussion)
- Lecture 3
  - Jet probes of QGP in HIC: flavor dependence of parton energy loss and jet quenching
- Lecture 4
  - Jet probes of QGP in HIC: full jets, jet energy loss, medium response, jet (sub)structure

Why full jets?

- Leading hadron is sensitive to the leading parton (fragment) of the jet, therefore, the interpretation of jet quenching via parton energy loss is complicated by modification of hadronization process.

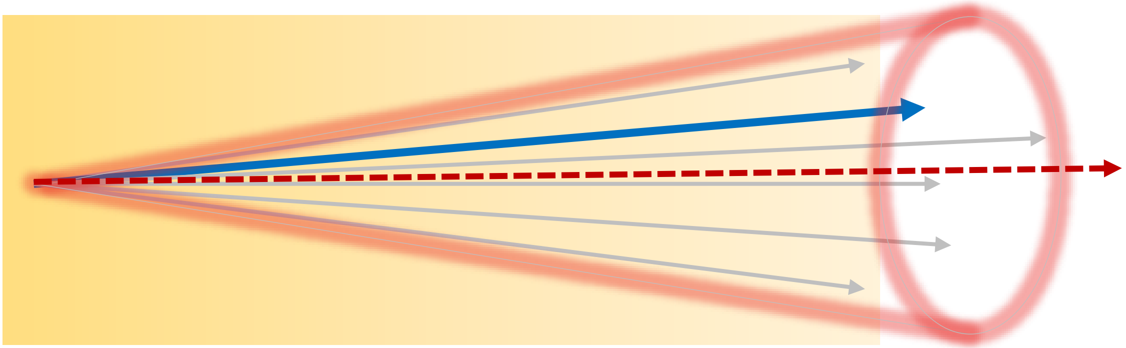


- Ideally, one would like to study the initial hard-scattered high-energy parton, which can be approximated by the fully-reconstructed jet.

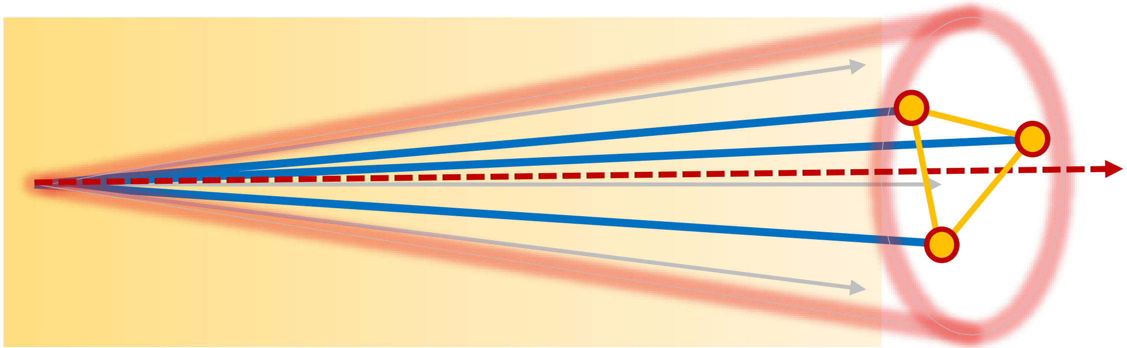


Why full jets?

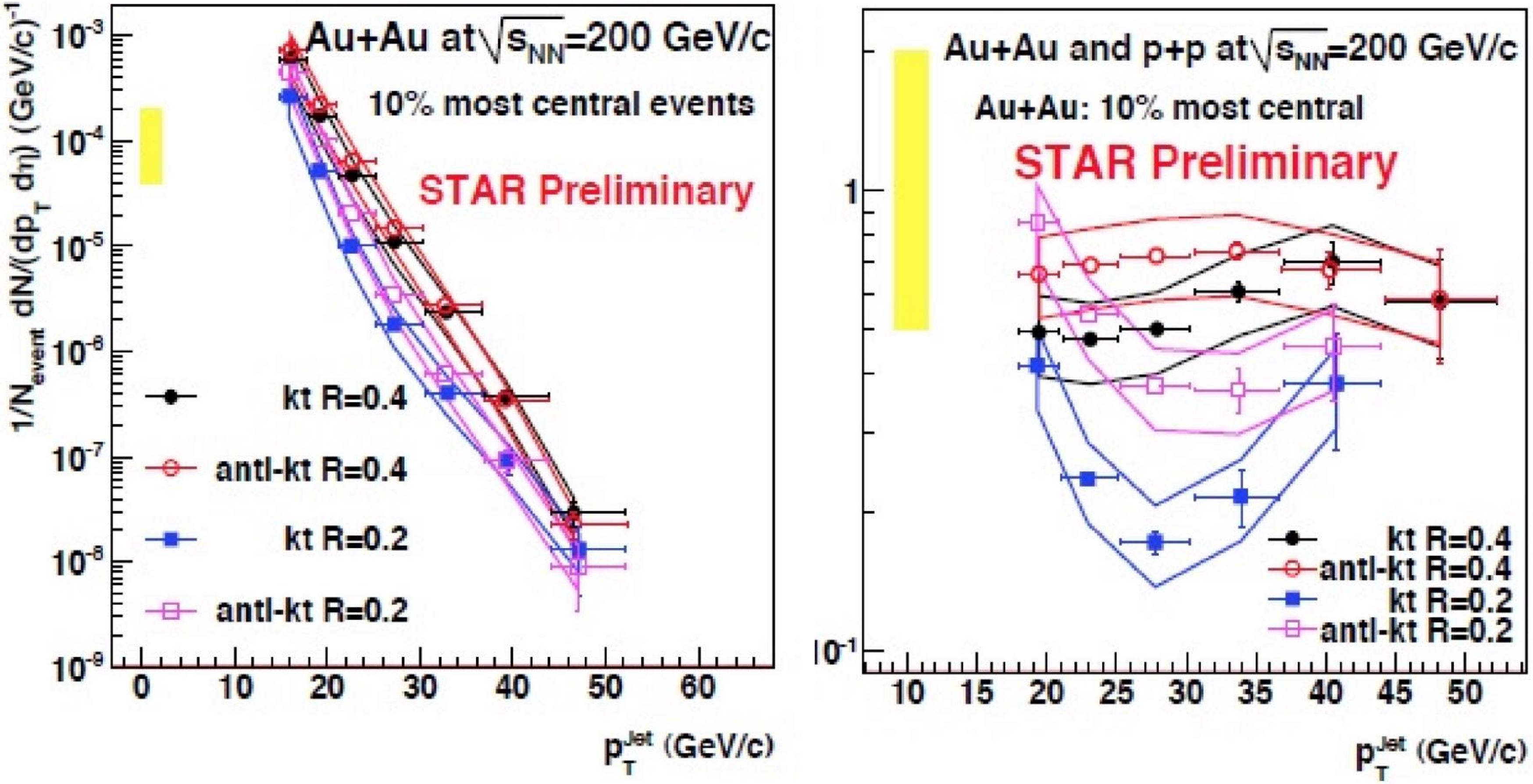
- For fully-reconstructed jets, one can also look at particle distribution inside the jet, such as jet shape, fragmentation function, etc.



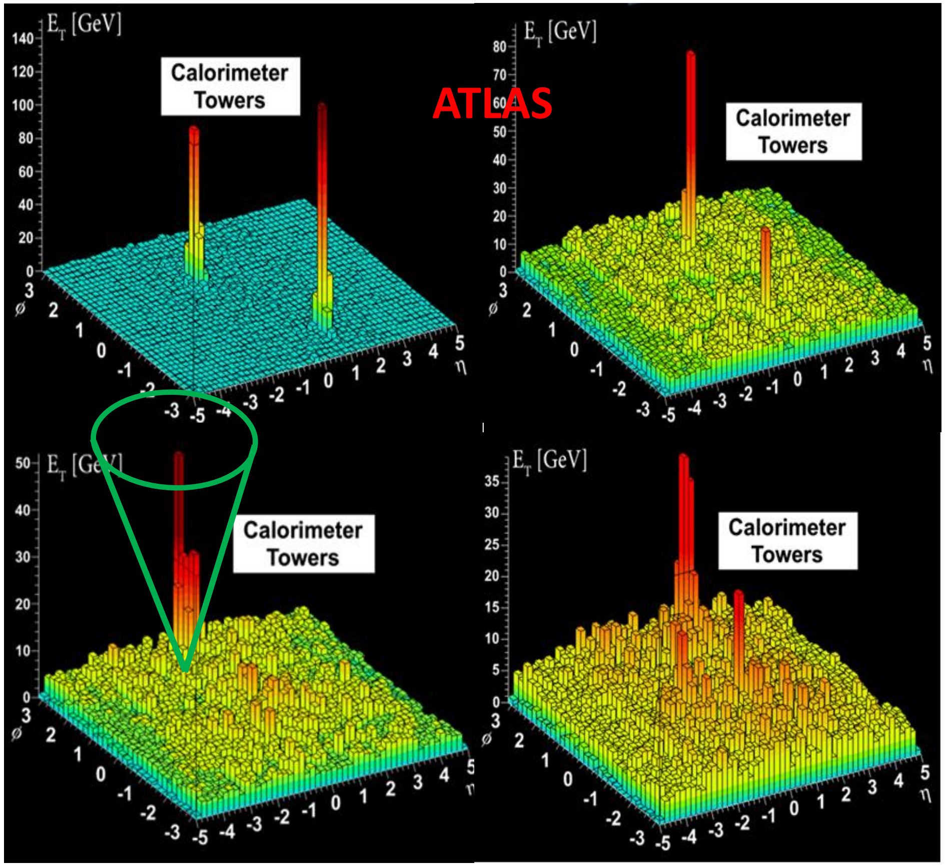
- One can also look at subjet and particle correlations inside the jet, such as jet splitting function, splitting angle, EEC, etc.

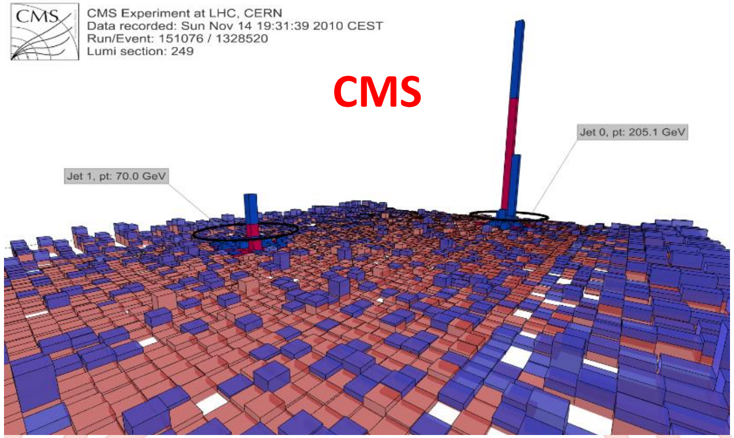


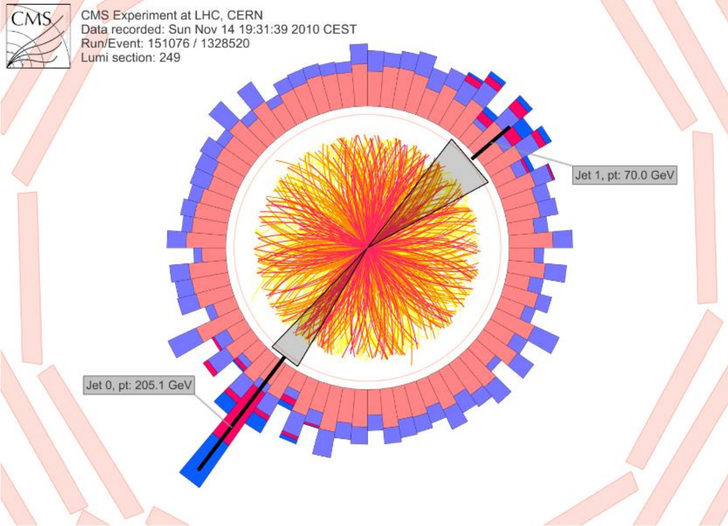
Earlier full jet measurement at RHIC



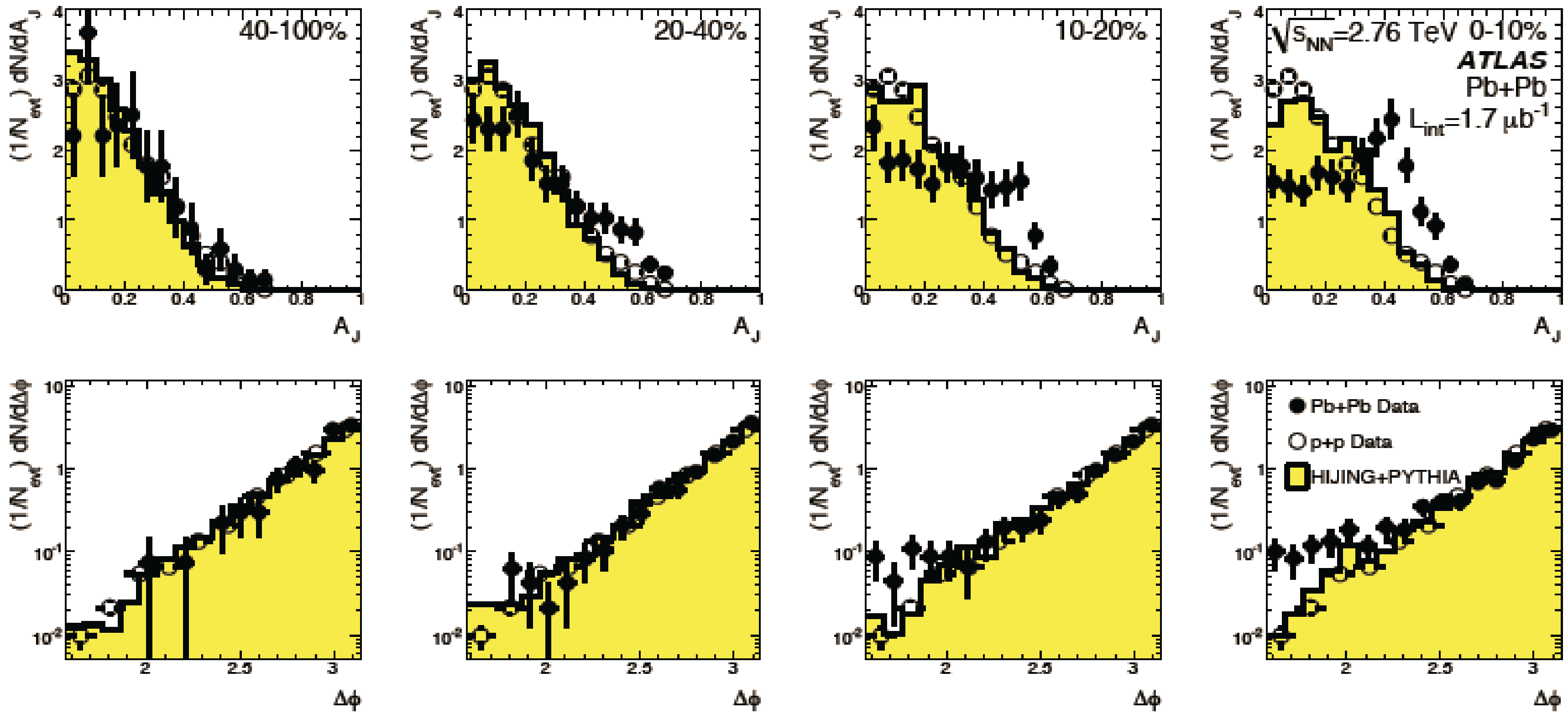
First full jet measurements in AA at LHC







Dijet asymmetry and angular correlations



$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$$\Delta\phi = |\phi_1 - \phi_2|$$

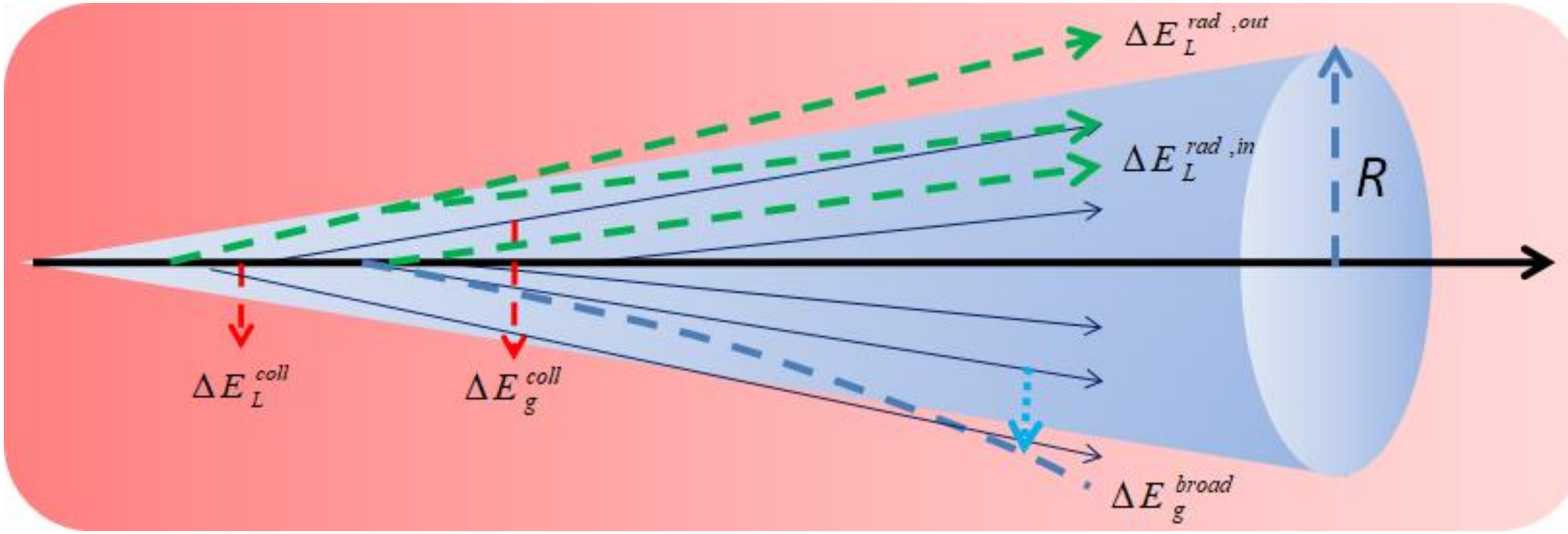
Strong modification of momentum imbalance distribution

=> Significant energy loss experienced by the subleading jets

Largely-unchanged angular distribution

=> medium-induced broadening effect is quite modest (here)

Full jet evolution & energy loss in QGP



$$E_{jet} = E_{in} + E_{lost} = E_{in} + E_{rad,out} + E_{kick,out} + (E_{th} - E_{th,in})$$

Vitev, Zhang, PRL 2010; GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.

A model for full jet evolution in QGP

- Solve the following equation for the distribution of radiated gluons:

$$\frac{\partial f_g(\omega, k_\perp, t)}{\partial t} = -\hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla^2_{k_\perp} f_g + \frac{dN_g^{\rm rad}}{d\omega dk_\perp^2 dt}$$

- The total energy of radiated gluons inside the jet cone:

$$E_g(t_f, R) = \int_R d\omega dk_\perp^2 \omega f_g(\omega, k_\perp^2, t_f)$$

- The final energy of the leading parton:

$$E_L(t_f) = E_L(t_i) - \int dt \hat{e}_L(t) - \int dt d\omega dk_\perp^2 \omega \frac{dN_g^{\rm rad}}{d\omega dk_\perp^2 dt}$$

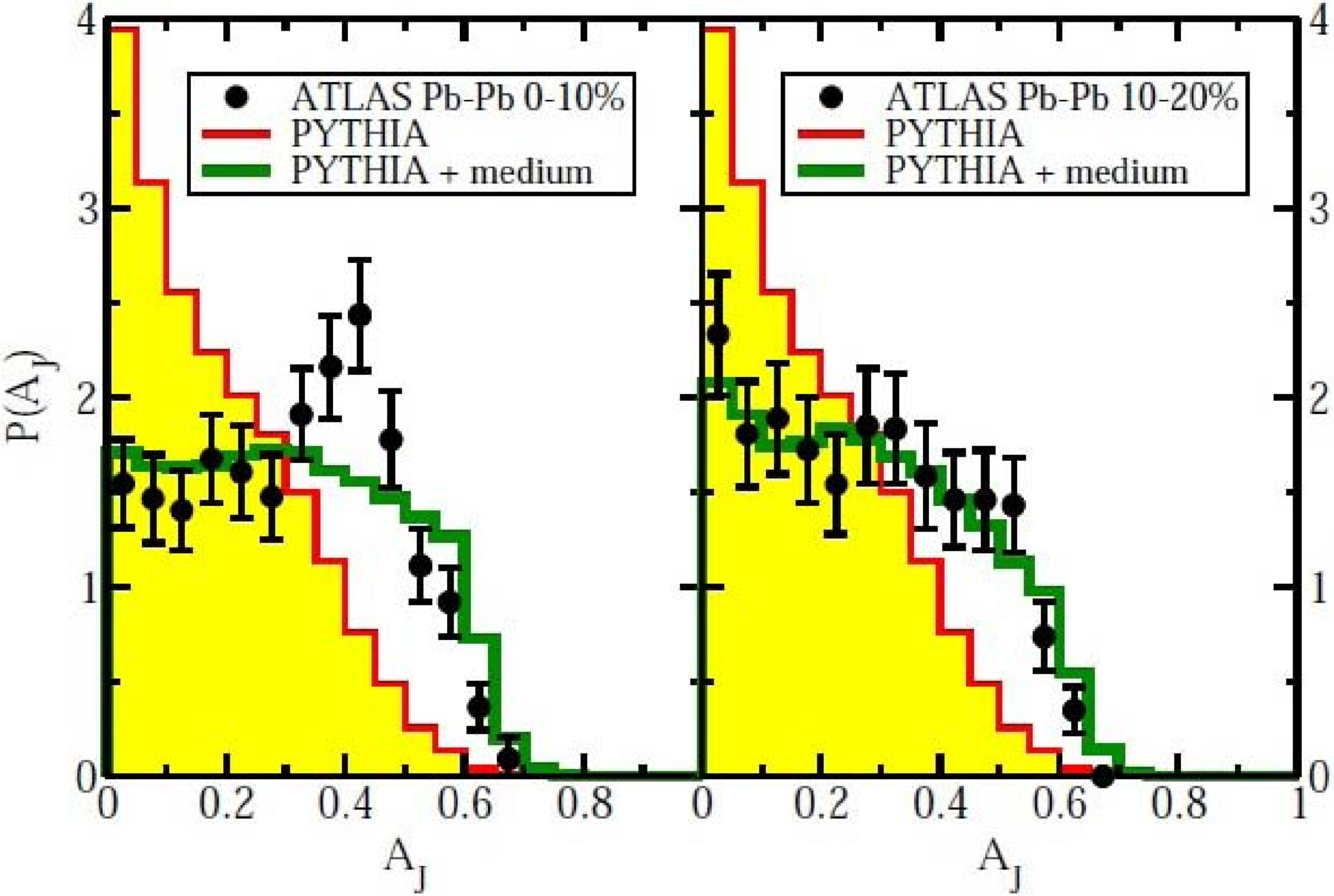
- The total energy and energy loss of the jet

$$E_{\rm jet}(t_f, R) = E_L(t_f) + E_g(t_f, R)$$

$$\Delta E_{\rm jet}(t_f, R) = E_{\rm jet}(t_i, R) - E_{\rm jet}(t_f, R)$$

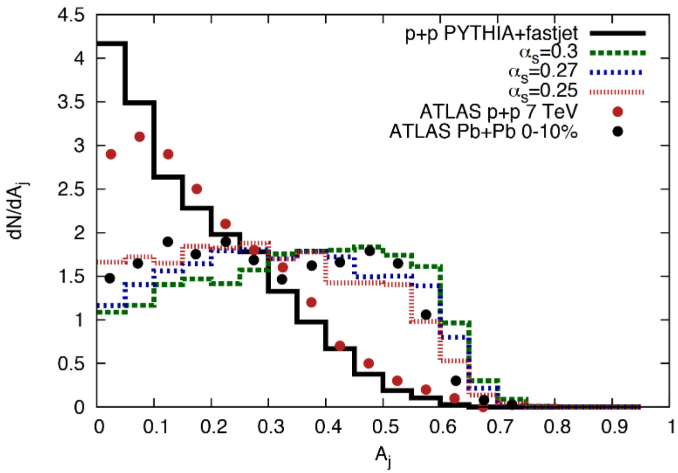
GYQ, Muller, PRL, 2011

Explanation of dijet asymmetry

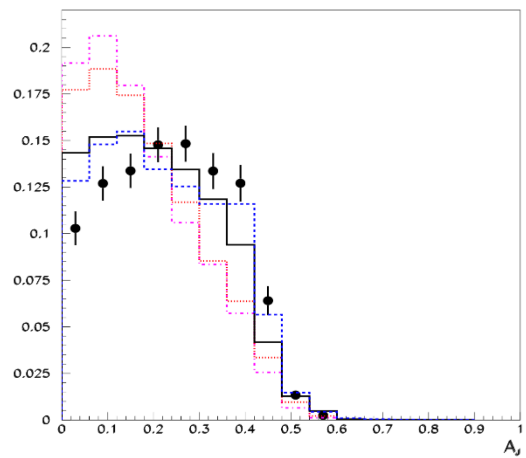


GYQ, Muller, PRL, 2011

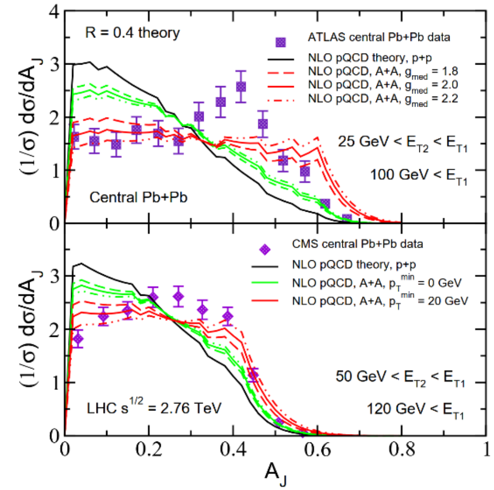
Dijet asymmetry from different models



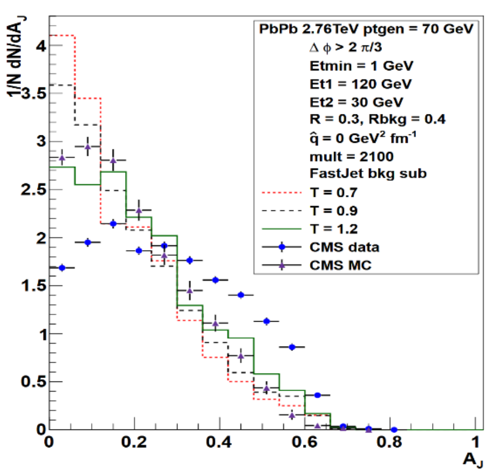
Phys.Rev.C 84 (2011) 024907



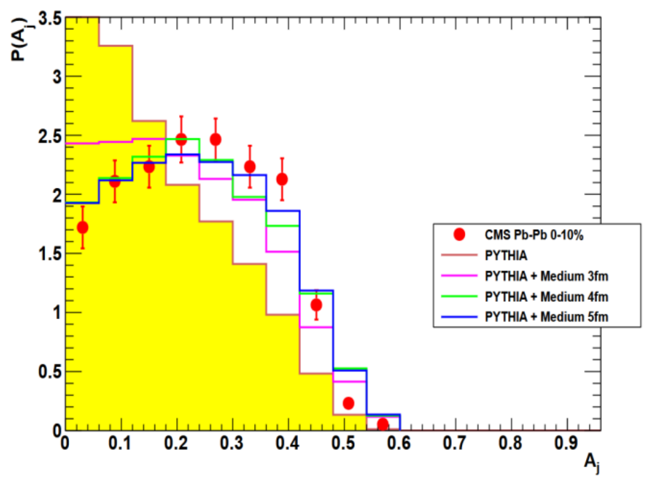
Eur.Phys.J.C 71 (2011) 1650



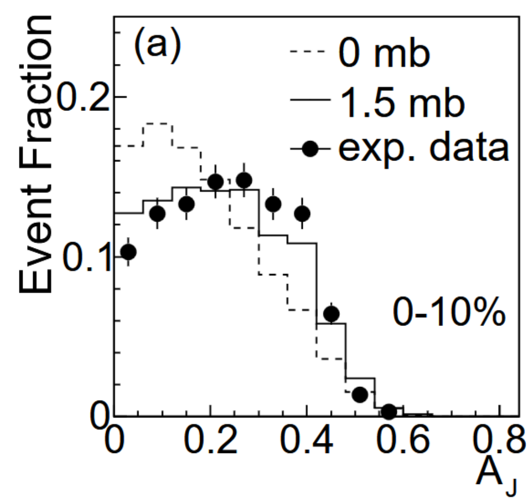
Phys.Lett.B 713 (2012) 224-232



JHEP 02 (2013) 022

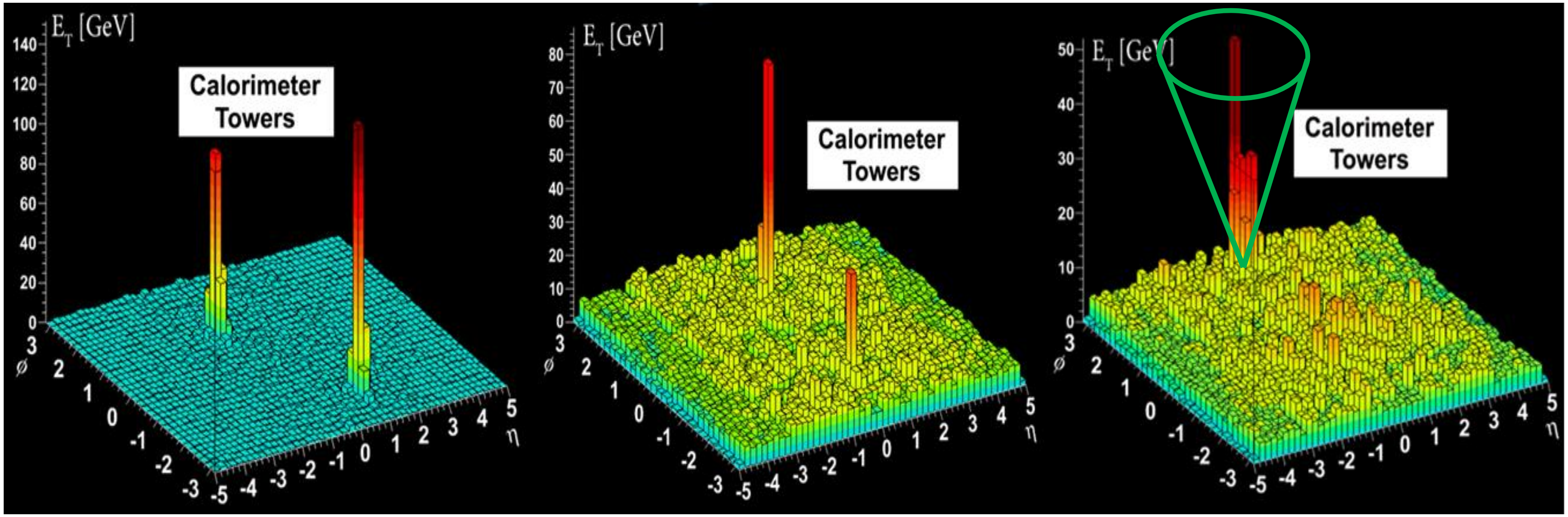


Phys.Rev.C 86 (2012) 054901



Phys.Rev.C 87 (2013) 6, 064901

Where does the lost energy go?



A significant energy is lost from the jet and deposited into medium.

How does the medium respond to the lost/deposited energy?

How does the lost energy redistribute and manifest in final state?

Where to search for the signal of medium response?

How to use jet-induced medium response to probe the medium properties?

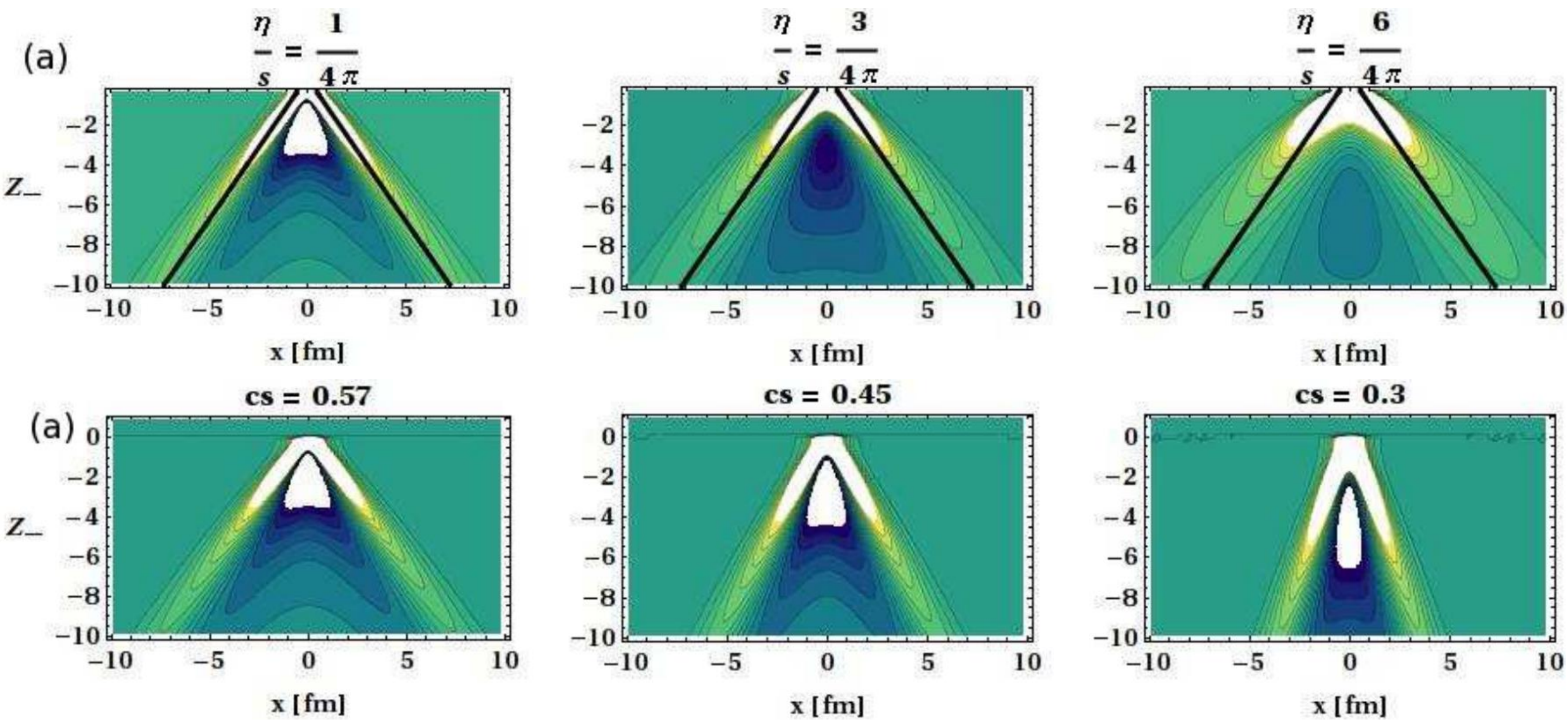
Earlier works on medium response

$$T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$$

$$\delta T^{00} \equiv \delta\epsilon, \qquad \delta T^{0i} \equiv g^i,$$

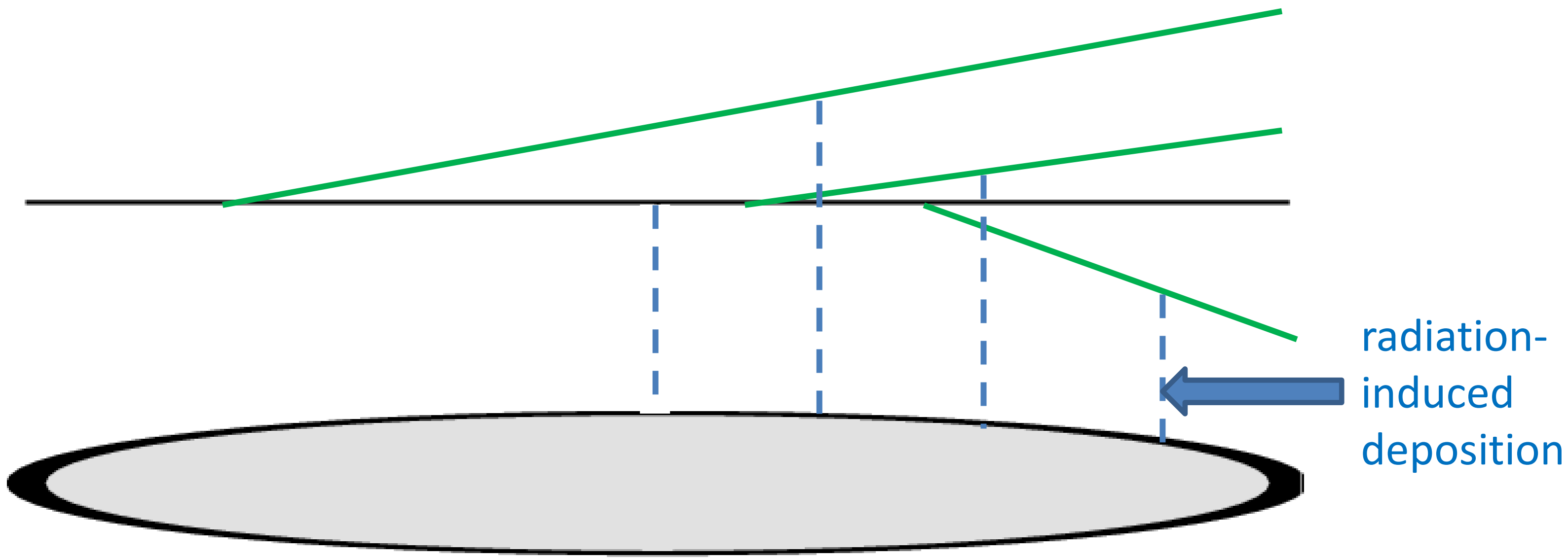
$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s(\partial^i g^j + \partial^j g^i - \tfrac{2}{3}\delta_{ij}\nabla \cdot \vec{g}).$$

Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315; Stoecker, nucl-th/0406018; Ruppert, Muller, PLB 2005; ...



Neufeld, PRC 2009

Energy deposition by jet shower



Jet loses/deposits energy and momentum via elastic collisions/absorptions.

Jet loses energy also by radiations.

The radiations serve as additional sources for the energy deposition.
This will lead to *stronger length dependence for* the energy deposition rate.

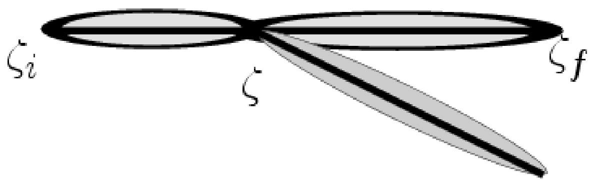
GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009

Energy deposition by jet shower

- Consider at some low scale μ, the collisional energy deposition by the jet is given:

$$\Delta E(\mu^2)|_{\zeta_i}^{\zeta_f} = \int_{\zeta_i}^{\zeta_f} d\zeta \frac{dE}{dL}(\zeta) \quad =$$

- This contains the contribution to energy deposition from all emissions up to μ
- Now increase the virtuality, then the jet tends to drop virtuality by radiation

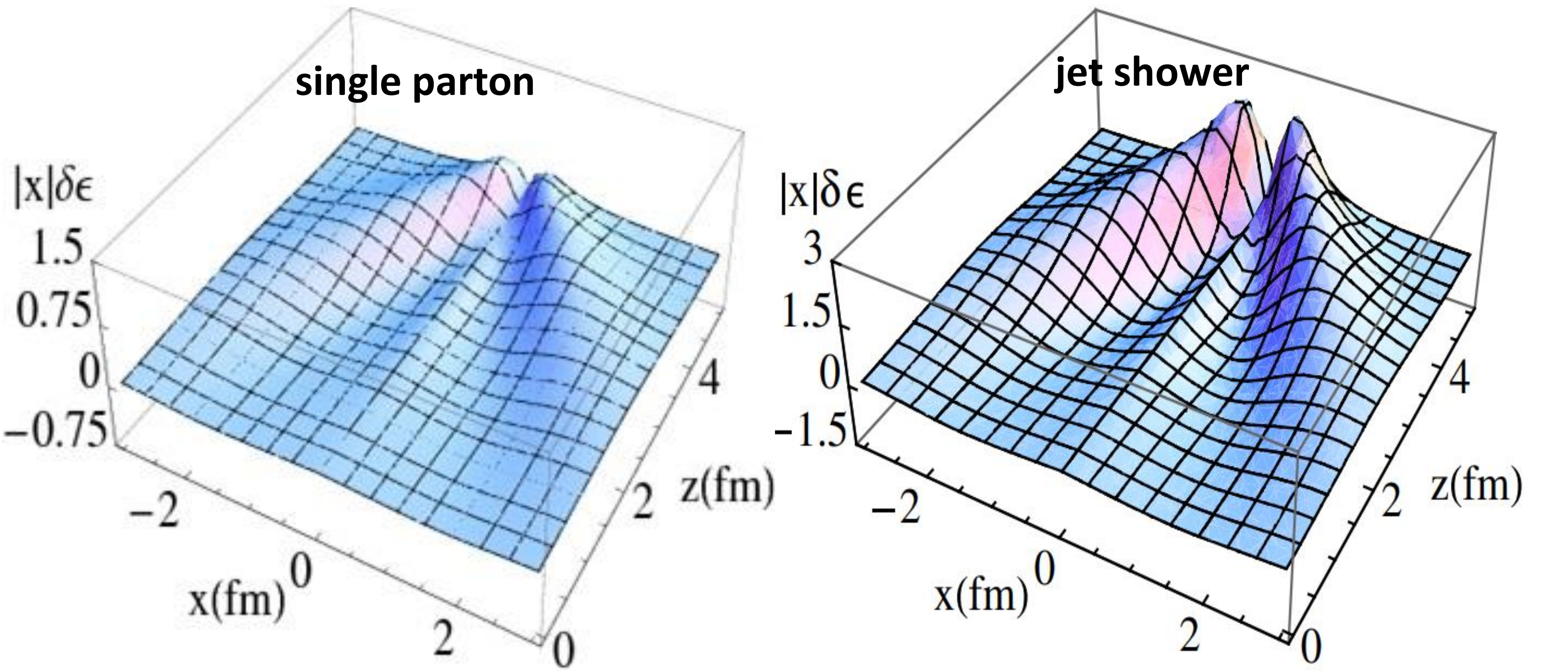


- The total energy deposition would be from the parent parton from z_i to z, and two daughter partons from z to z_f
- One may solve the following evolution equation for energy deposition by the jet

$$\frac{d\Delta E_q(E,Q^2)_{\zeta_i}^{\zeta_f}}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int dy \int_{\zeta_i}^{\zeta_f} d\zeta P_{q\to qg}(y,\zeta,Q^2,E)$$
$$\left[\Delta E_q(E,Q^2)_{\zeta_i}^{\zeta} + \Delta E_q(yE,Q^2)_{\zeta}^{\zeta_f} + \Delta E_g((1-y)E,Q^2)_{\zeta}^{\zeta_f}\right]$$

GYQ, Majumder, Song, Heinz, PRL 2009

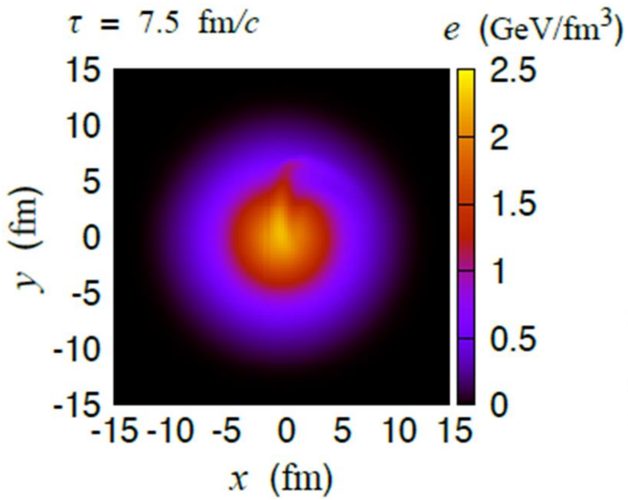
Medium response to jet shower

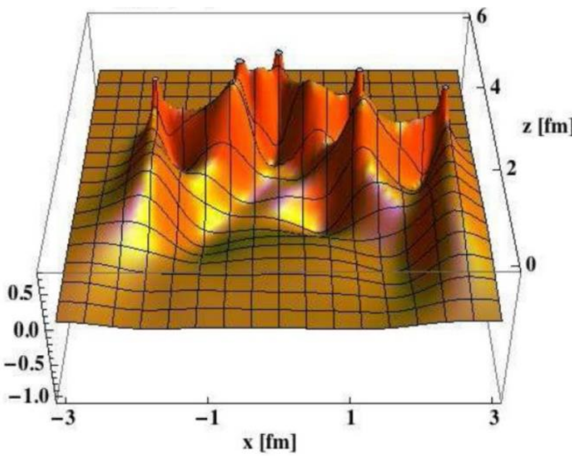


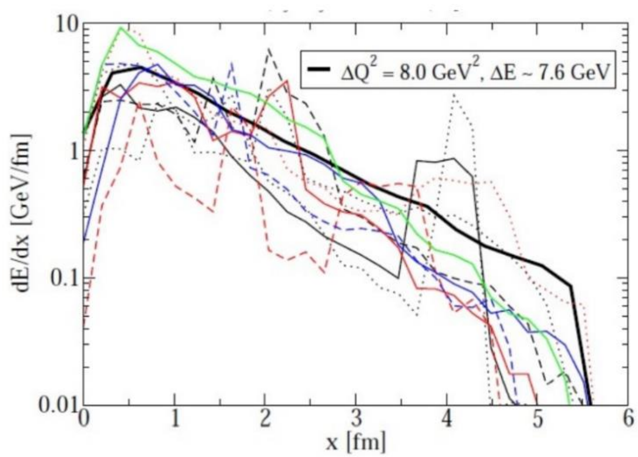
The radiations serve as additional sources for the energy deposition, which leads to much stronger energy deposition and medium response.

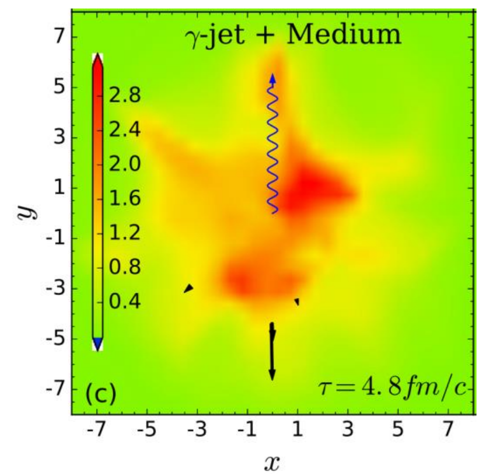
GYQ, Majumder, Song, Heinz, PRL 2009

Complications in medium response









The flow of the expanding medium can distort the conic structure

Detailed distributions of the energy and momentum deposition profiles

Even-by-event fluctuations of jet shower evolution and energy loss

Large and event-by-event fluctuating background medium

Neufeld, Vitev, PRC 2012; Renk, PRC 2013; Tachibana, Chang, GYQ, PRC 2017; Chen, Cao, Luo, Pang, Wang, PLB 2018

Market for selling medium response

- **Jet + recoil**
  - **LBT** (He, Luo, Cao, Zhu, Wang, Xing, GYQ, et al, 1503.03313; 1803.06785, 2409.12843)
  - JEWEL (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)
  - MARTINI (Park, Jeon, Gale, 1807.06550)

- **Jet + hydrodynamics**
  - **Coupled Jet-Fluid** (Tachibana, Chang, GYQ: 1701.07951; 1906.09562)
  - **CoLBT-Hydro** (Chen, Yang, Luo, He, Cao, Ke, Pang, Wang, et al, 1704.03648; 2005.09678; 2101.05422; 2203.03683)
  - JETSCAPE (2002.12250)
  - Minijet+Hydro (Pablos, Singh, Jeon and Gale, 2202.03414)
  - Hybrid Model (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842)

- **Full Boltzmann**
  - **AMPT** (Gao, Luo, Ma, Mao, GYQ, Wang, Zhang, 1612.02548; 2107.11751; 2109.14314)
  - BAMPS (Bouras, Betz, Xu, Greiner, 1201.5005; 1401.3019)

- **See Cao, GYQ, 2211.16821 [nucl-th] for a recent review:** https://doi.org/10.1146/annurev-nucl-112822-031317

Coupled jet-fluid model

$$p^\mu \partial_\mu f = C_{coll}[f] + C_{broad}[f] + C_{rad}[f]\,, \qquad \partial_\mu T^{\mu\nu}_{QGP} = J^\nu = -\partial_\mu T^{\mu\nu}_{jet} = -\frac{dP^\nu_{jet}}{dt d^3x}$$

$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\rm jet}(x) = -\frac{dP^\nu_{\rm jet}}{dt d^3x} = -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

$$= -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\hat{e},\hat{q}}\right] + \sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\rm rad.}\right]$$

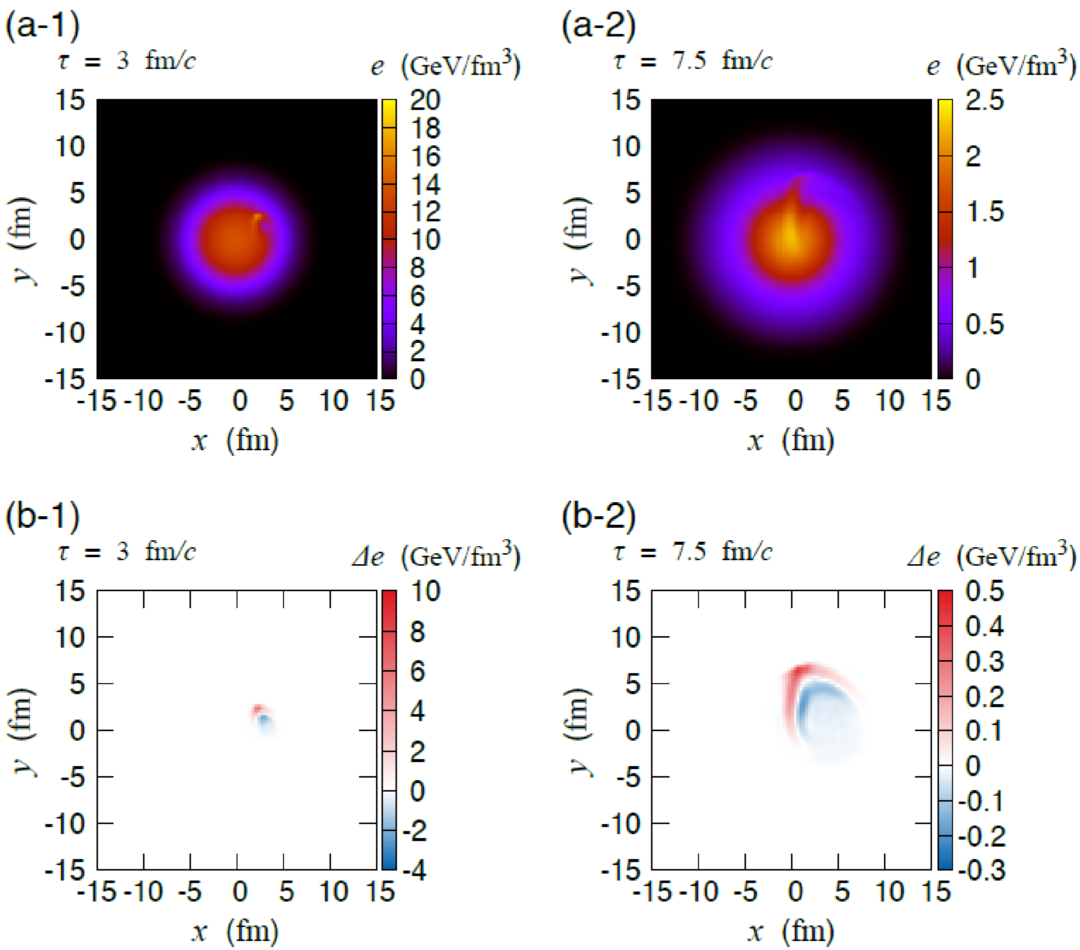
$$= -\sum_j \int d^3k_j k_j^\nu \left.\frac{df_j(\boldsymbol{k}_j,t)}{dt}\right|_{\rm col.} \delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_0^{\rm jet} - \frac{\boldsymbol{k}_j}{\omega_j} t\right)$$

$$J^\nu(x) \approx -\frac{1}{2\pi r t^3}(x^\nu - x^\nu_{\rm jet,0}) \left.\frac{dE^{\rm jet}}{dt dr}\right|_{\rm col.} \delta\left(|\boldsymbol{x} - \boldsymbol{x}_0^{\rm jet}| - t\right)$$

$$\left.\frac{dE^{\rm jet}}{dt dr}\right|_{\rm col.} = \sum_j \int d\omega dk_{j\perp}^2 \omega_j \left.\frac{df_j\left(\omega_j, k_{j\perp}^2, t\right)}{dt}\right|_{\rm col.} \delta\left(r - \frac{k_{j\perp}}{\omega_j}\right)$$

$$J^{\bar{\nu}}(\tau, x, y, \eta_s) = -\frac{dP^{\bar{\nu}}_{\rm jet}}{\tau d\tau dx dy d\eta_s} = \Lambda^{\bar{\nu}}_\mu J^\mu(x) = -\Lambda^{\bar{\nu}}_\mu \frac{dP^\mu_{\rm jet}}{dt d^3x}$$

Jet energy loss & medium response



Jet-fluid model:

$$p^{\mu}\partial_{\mu}f = C[f], \partial_{\mu}T^{\mu\nu} = J^{\nu}$$

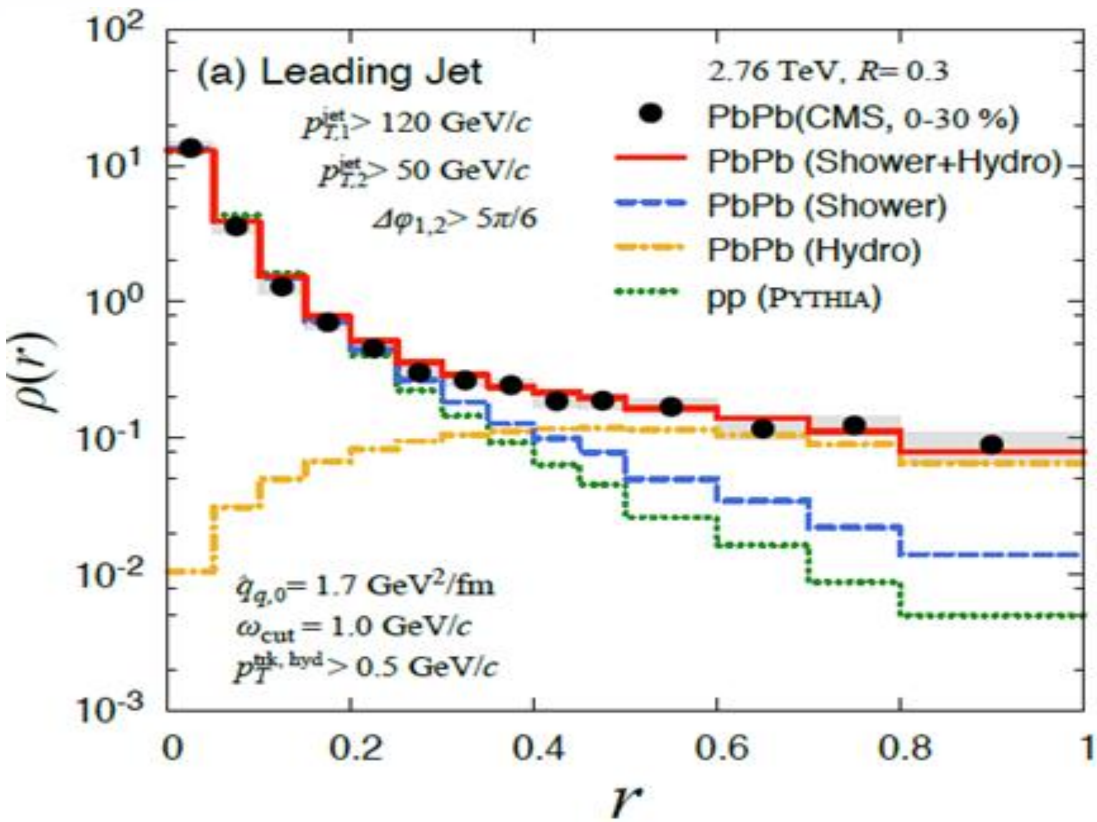
Jet deposits energy and momentum into medium, and induces V-shaped wave fronts

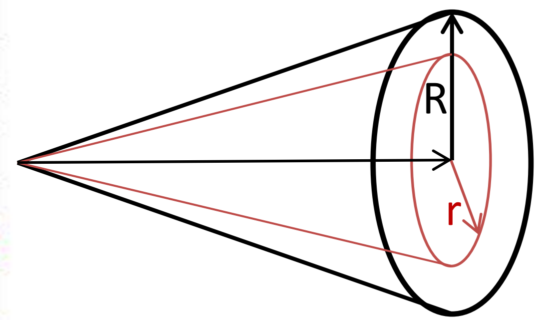
The wave fronts carry energy and momentum, propagates forward and outward, and depletes the energy behind the jet **(diffusion wake)**

Jet-induced flow and the radial flow of medium are pushed and distorted by each other

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Signal of jet-induced medium response



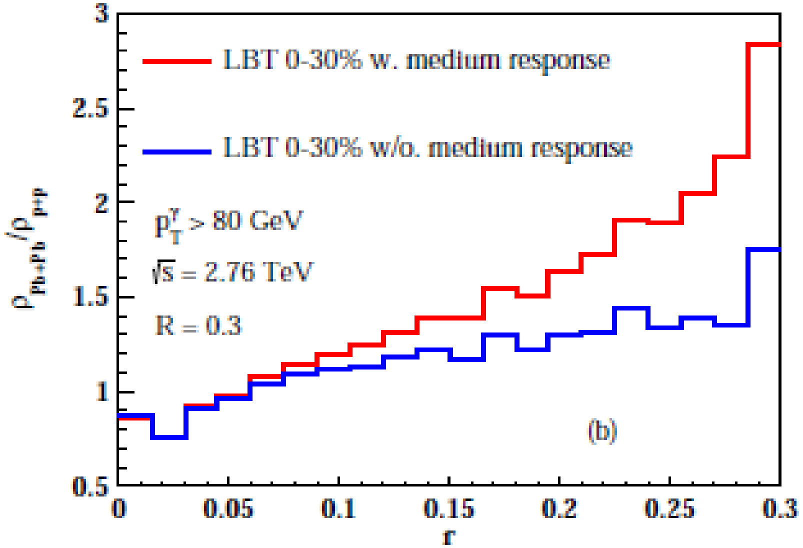


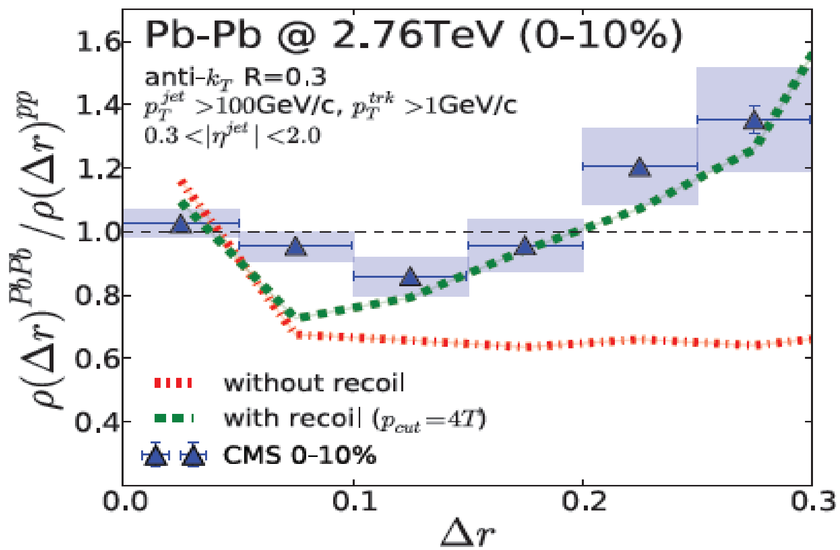
The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

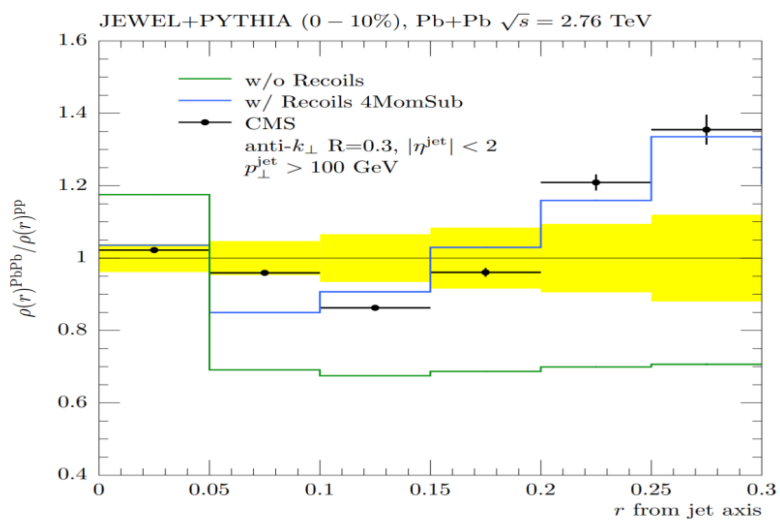
Signal of medium response in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Signal of jet-induced medium response







Luo, Cao, He, Wang, PLB 2018;
C. Park, S. Jeon, C. Gale, 2018;
Elayavalli, Zapp, JHEP 2017;

The inclusion of medium response can naturally explains the enhancement of jet shape at larger r.

CoLBT-Hydro model

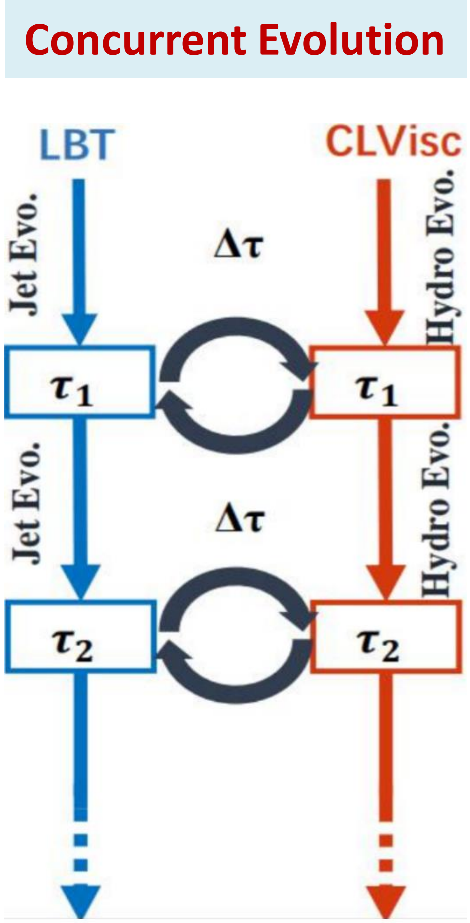
- **Linear Boltzmann Transport (LBT)** model for hard parton (jet shower and recoil) evolution
- **Hydrodynamics (CLVisc)** model for the bulk evolution
- Sort jet and recoil partons according to a cut-off parameter
  - Hard partons (**LBT**): $\boldsymbol{p \cdot \partial f(x,p) = C[f]}$ for $p \cdot u > p^0_{cut}$
  - Soft partons (**source**):

$$J^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

- Update medium information by solving the hydrodynamics equation with source term (**CLVisc**)

$$\boldsymbol{\partial_\mu T^{\mu\nu}(x) = J^\nu(x)}$$

- Final hadron spectra:
  - Hadronization of hard partons
  - Jet-induced medium response via Cooper-Frye freeze-out

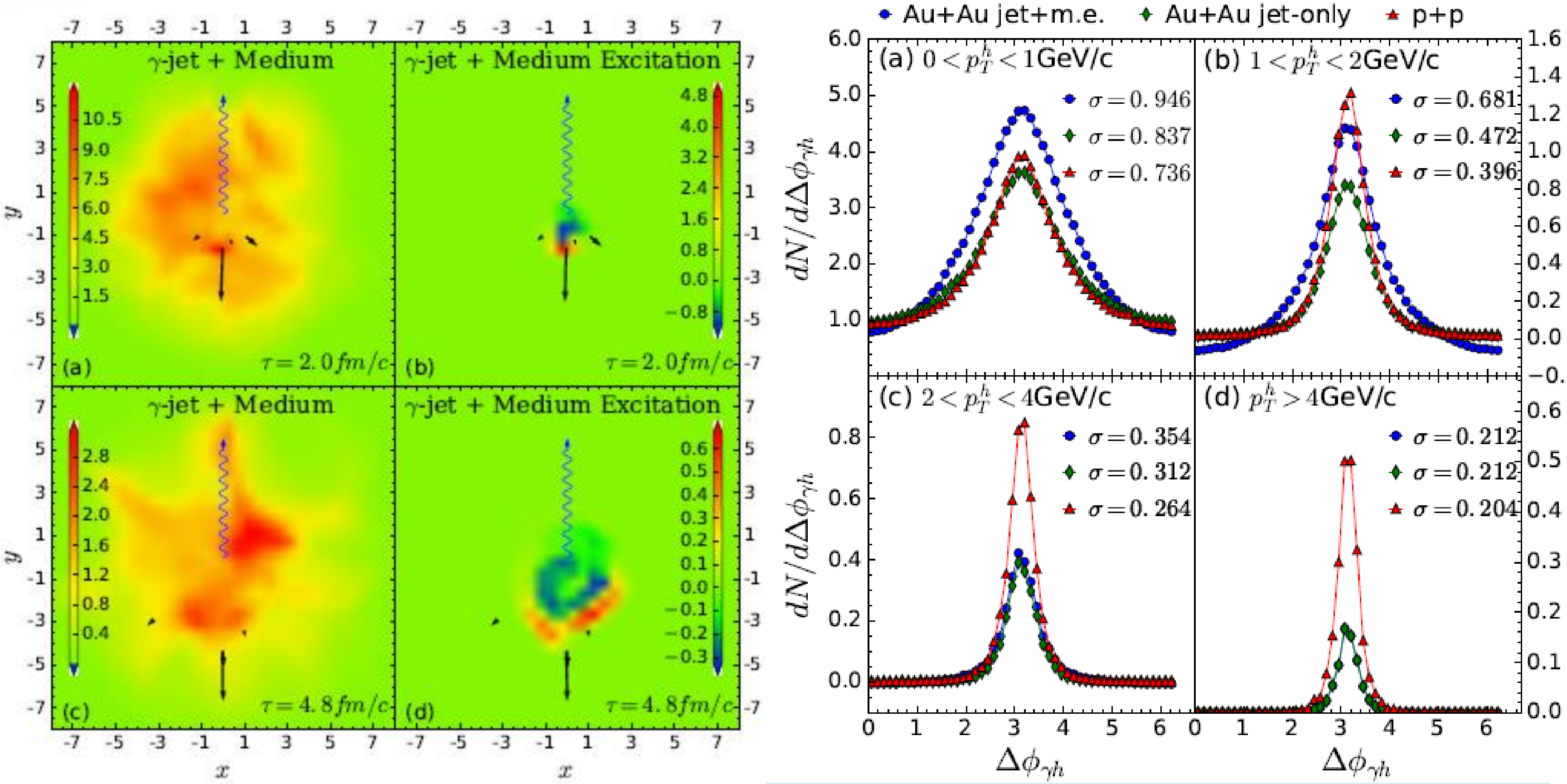


LBT: He, Luo, Wang, Zhu, Cao, GYQ, etc., 1503.03313, 1605.06447, 1703.00822, 2306.13742.

CLVisc: Pang, Wang, Wang, Petersen, Wu, GYQ, 1205.5019, 1802.04449, 2107.04949.

CoLBT: W. Chei, T. Luo, S. Cao, L.G. Pang, X. N. Wang, Phys.Lett.B 777 (2018) 86-90.

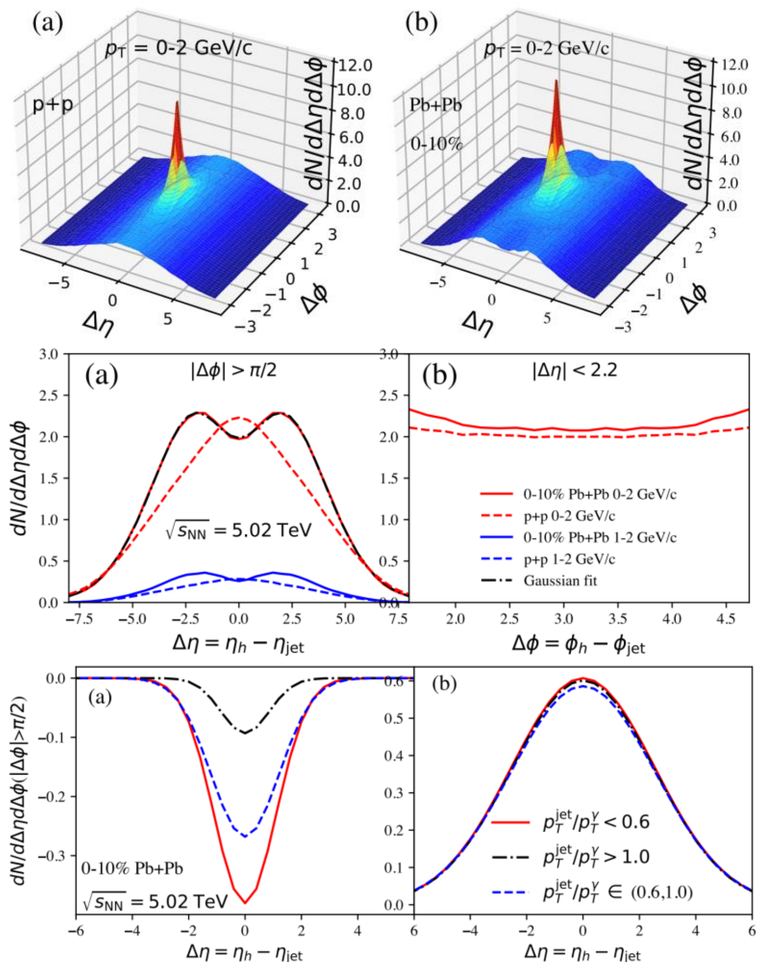
γ-hadron correlations from CoLBT-Hydro



Soft hadrons in jet direction are enhanced due to jet-induced medium excitation and has significantly broadened azimuthal distribution relative to jet direction.
Soft hadrons in γ direction are depleted due to a **diffusion wake** behind the jet.
Hard hadrons in γ direction are suppressed due to parton energy loss.

Chen, Cao, Luo, Pang, Wang, PLB 2018, arXiv:1704.03648

Diffusion wake: 3D structure



Signal: the double-peak structure in the γ-hadron correlations as a function of rapidity and azimuthal angle.

Such double-peak structure is a combined effect of a valley structure caused by the diffusion wake and a ridge from MPI effect.

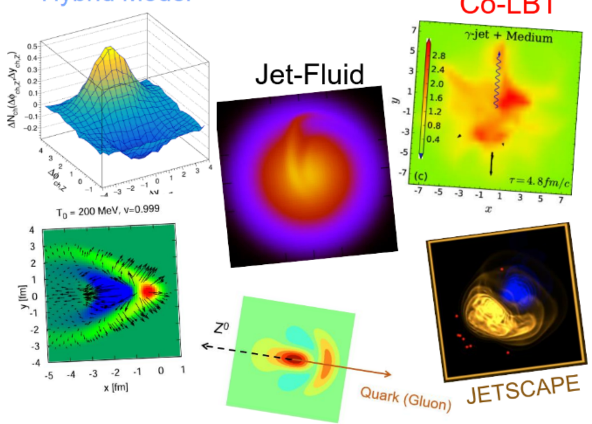
The depth of the diffusion wake valley increases with increasing jet energy loss as characterized by γ-jet asymmetry.

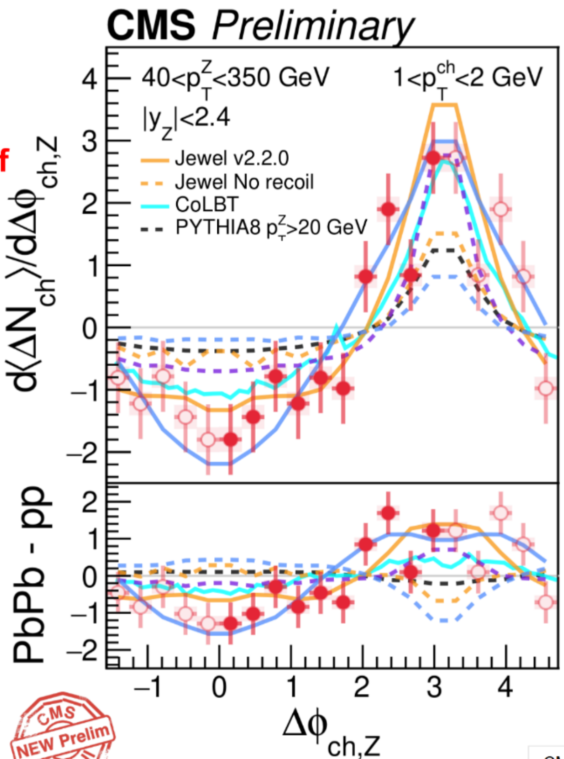
Future data on the diffusion wake together with other observables will provide combined constraints on the EoS and transport properties of QGP.

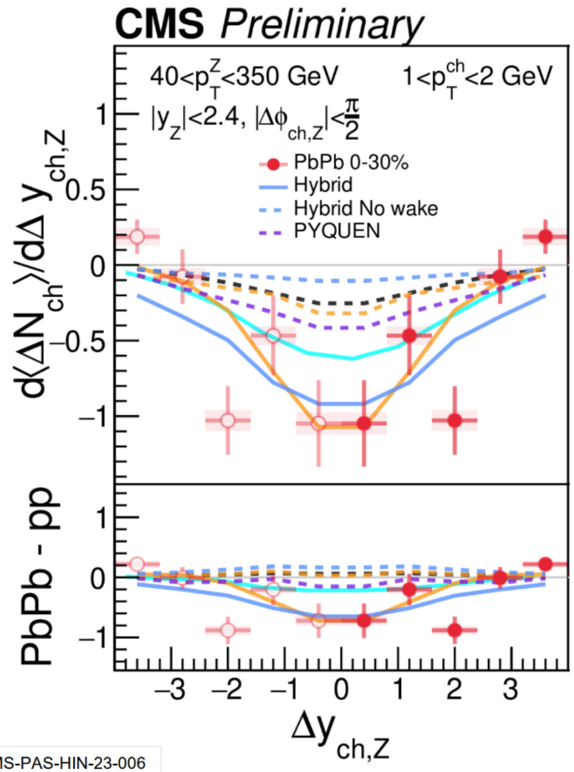
Z. Yang, T. Luo, W. Chen, L.G. Pang , X. N. Wang, Phys. Rev. Lett. 130, 052301 (2023)

Evidence of diffusion wake from CMS

- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future



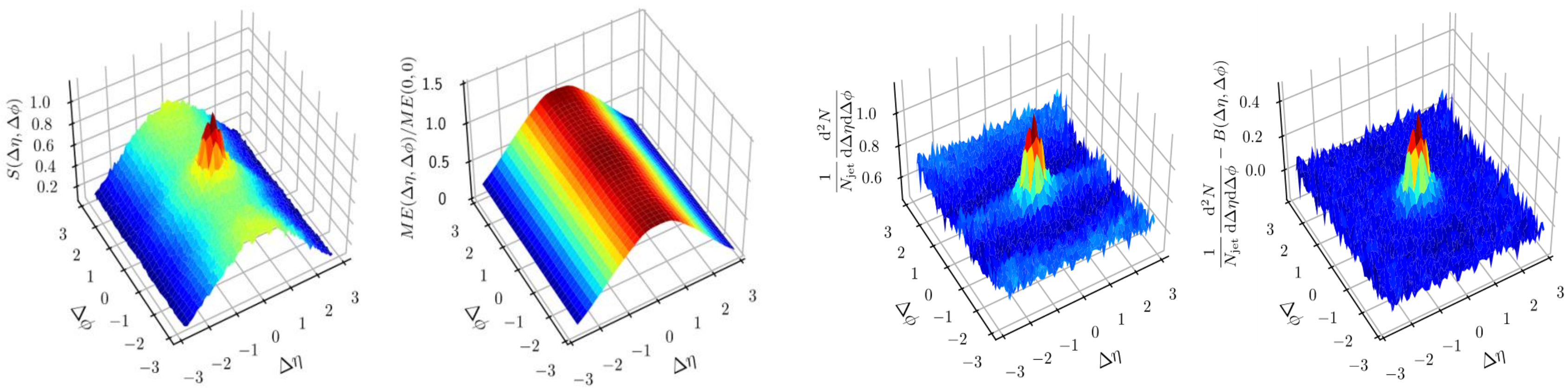




CMS NEW Prelim 24'Fall

CMS-PAS-HIN-23-006

Hadron chemistry around quenched jets



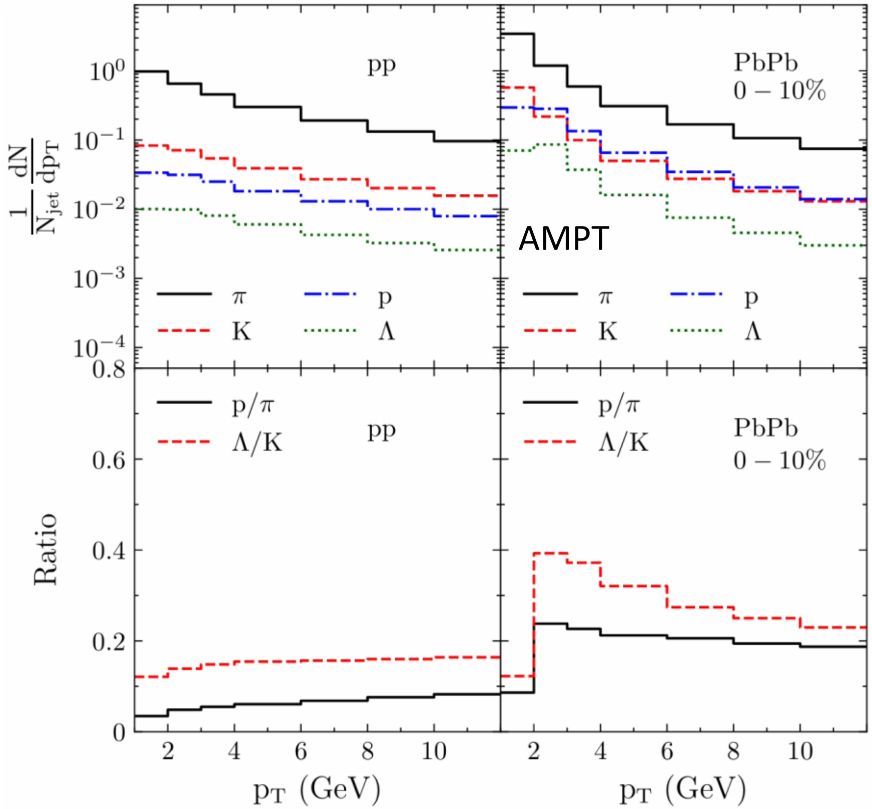
$$\frac{1}{N_{\rm jet}} \frac{d^2N}{d\Delta\eta d\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta, \Delta\phi)} S(\Delta\eta, \Delta\phi) \Longrightarrow \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$$

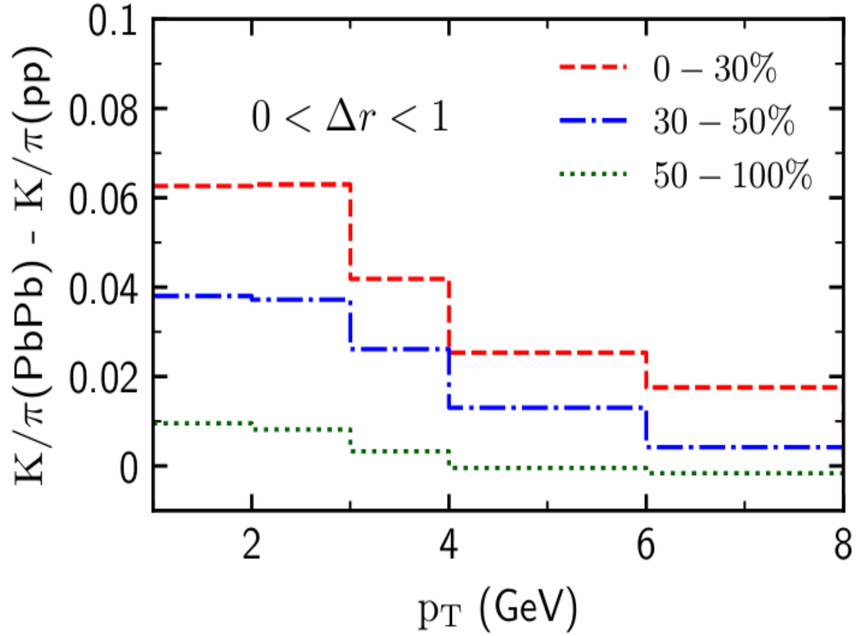
$$\frac{dN}{dp_T} = \int d\Delta\phi \int d\Delta\eta \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\bigg|_{\Delta r<1}$$

$$\frac{dN}{d\Delta r} = \int d\Delta\phi \int d\Delta\eta \int dp_T \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta} \delta(\Delta r - \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Luo, Mao, GYQ, Wang, Zhang, Phys.Lett.B 837 (2023) 137638

B/M & strangeness enhancement around jets

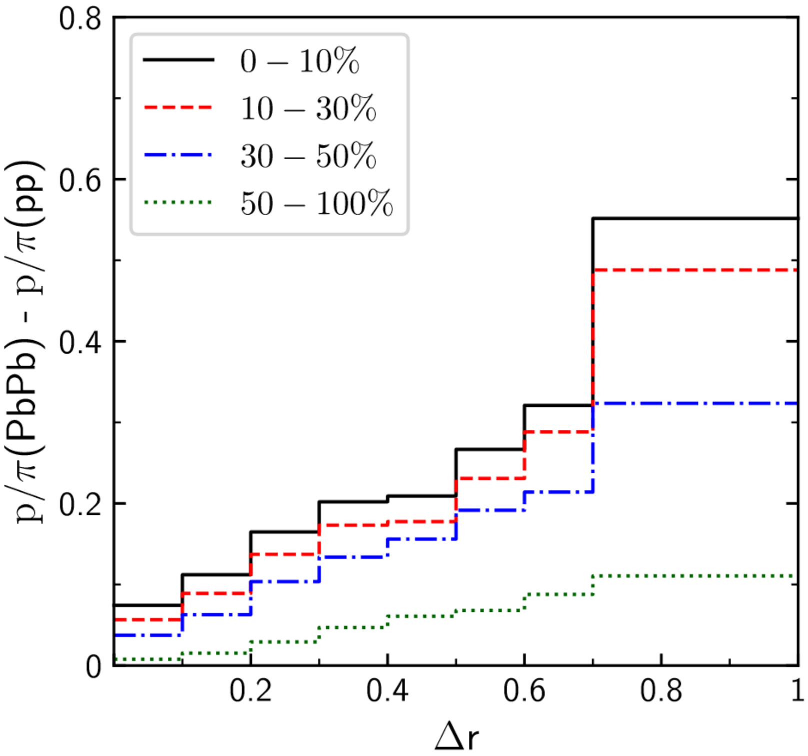


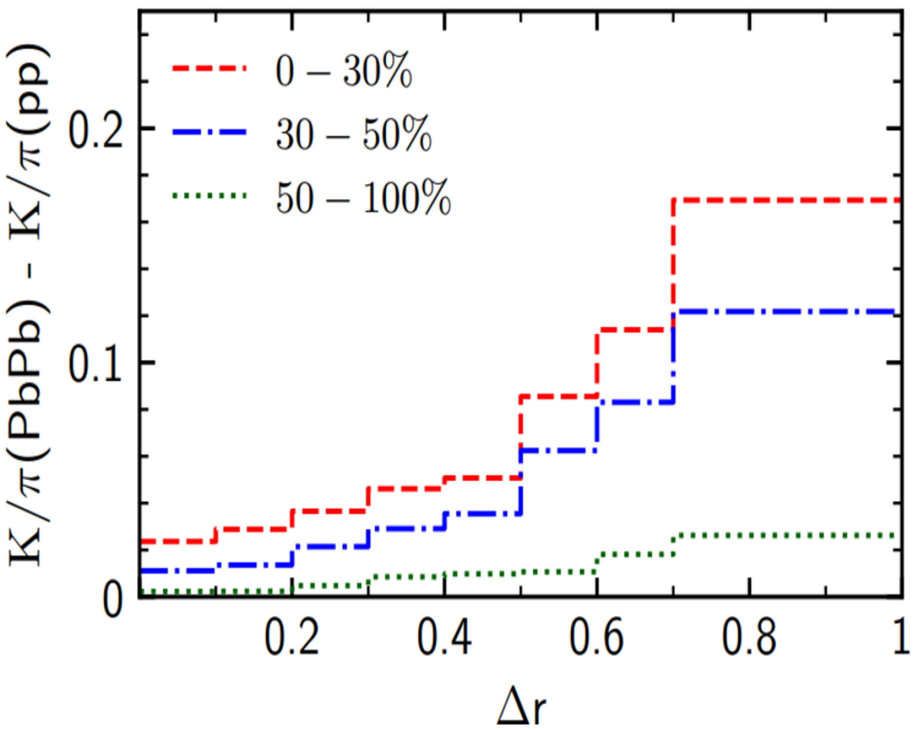


We find strong enhancement of baryons/mesons and strangeness/non-strangeness particles around the quenched jets.

Luo, Mao, GYQ, Wang, Zhang, Phys.Lett.B 837 (2023) 137638; Luo, Cao, GYQ, e-Print: 2412.19283

B/M & strangeness enhancement around jets

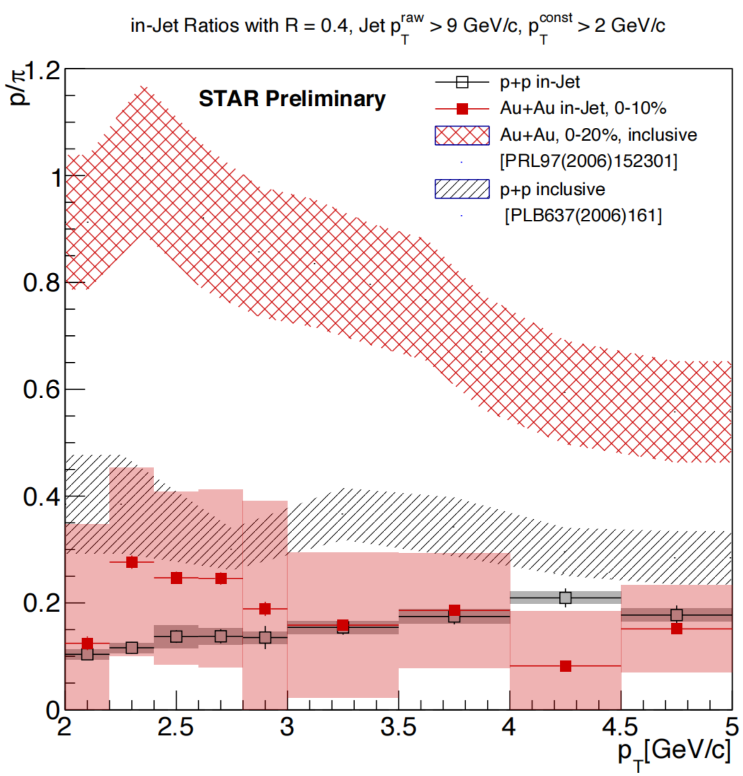


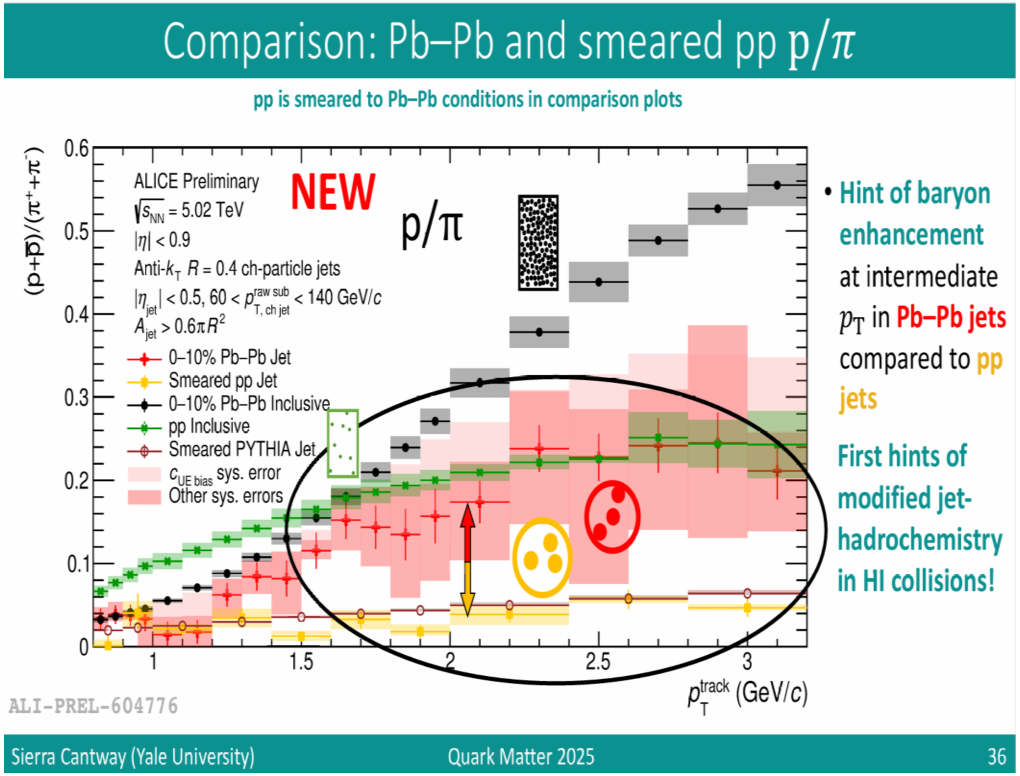


For intermediate p_T (2-4GeV) regime, the enhancement of jet-induced B/M & strange/non-strange is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

Luo, Mao, GYQ, Wang, Zhang, Phys.Lett.B 837 (2023) 137638; Luo, Cao, GYQ, e-Print: 2412.19283

Experimental result on in-jet B/M & strangeness

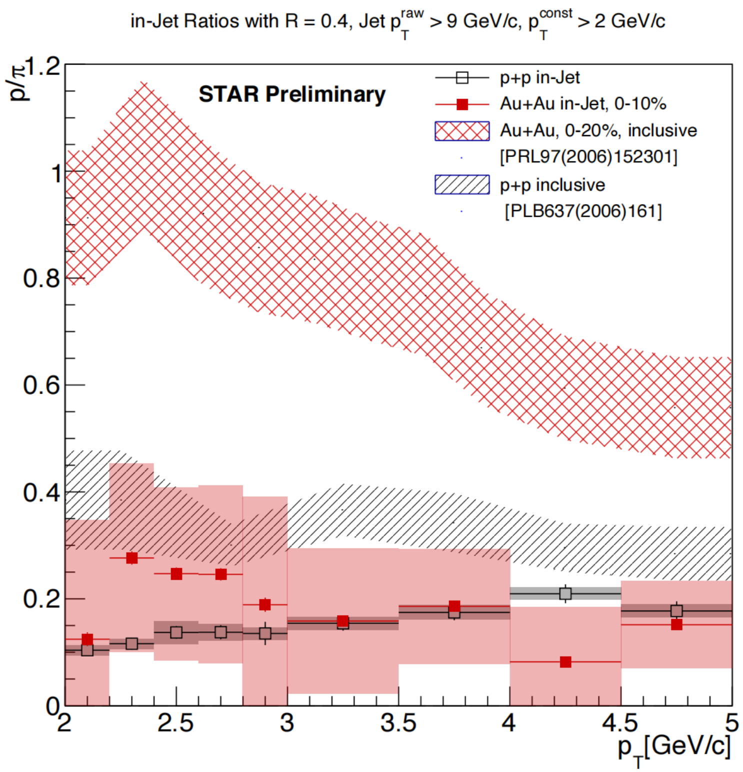


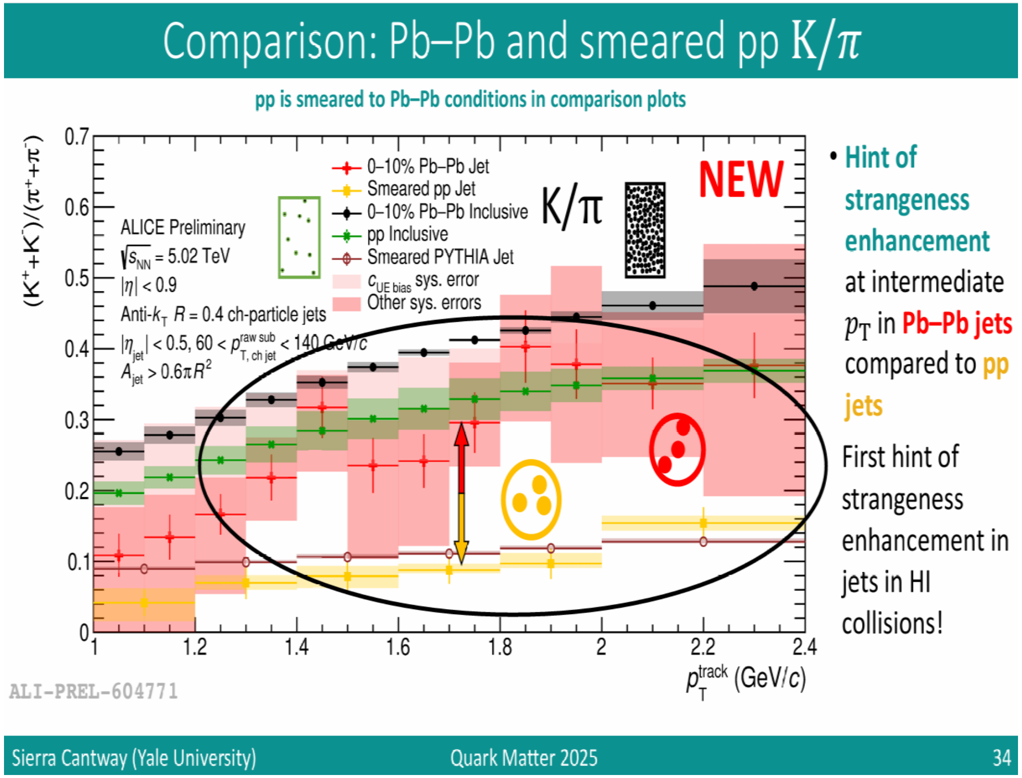


Can we also measure hadron chemistry around (outside) the quenched jets?

Gabriel Dale-Gau (for STAR) & Sierra Cantway (for ALICE), talks at HP2024/QM2025

Experimental result on in-jet B/M & strangeness

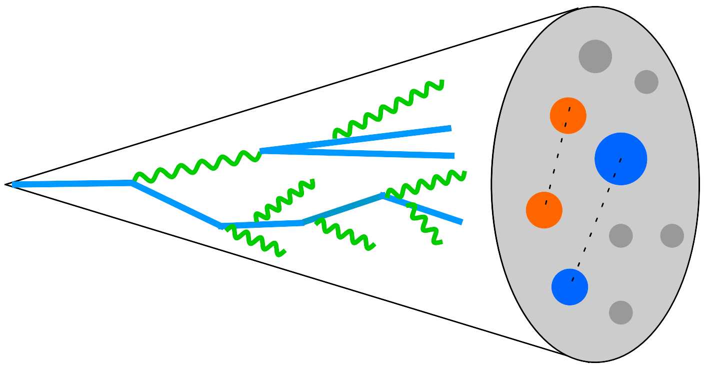




Can we also measure hadron chemistry around (outside) the quenched jets?

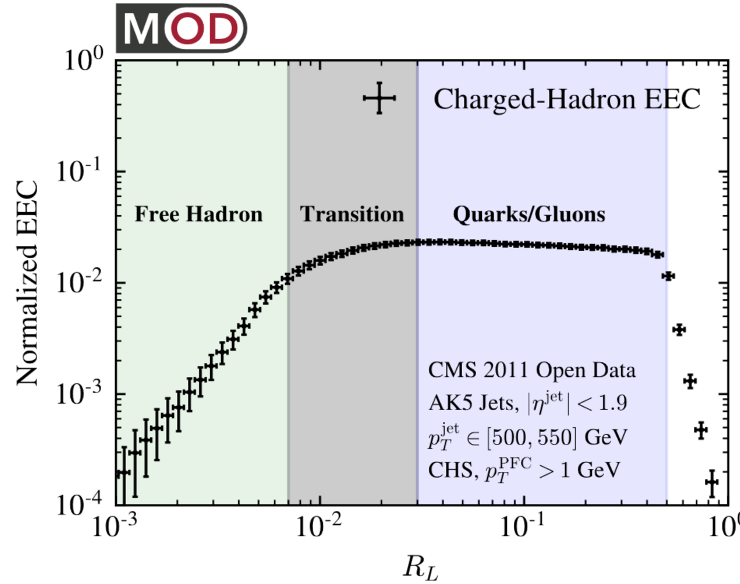
Gabriel Dale-Gau (for STAR) & Sierra Cantway (for ALICE), talks at HP2024/QM2025

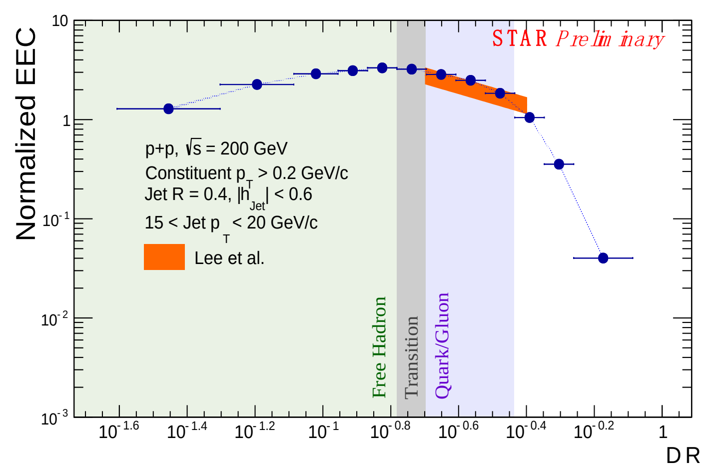
Jet energy-energy correlator (EEC)



$$\frac{d\sigma_{\mathrm{EEC}}}{dR_L} = \int d\sigma(\Delta R_{ij}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}} \delta(\Delta R_{ij} - R_L)$$

$$\Delta R_{ij} = \sqrt{\Delta\phi^2_{ij} + \Delta\eta^2_{ij}}$$

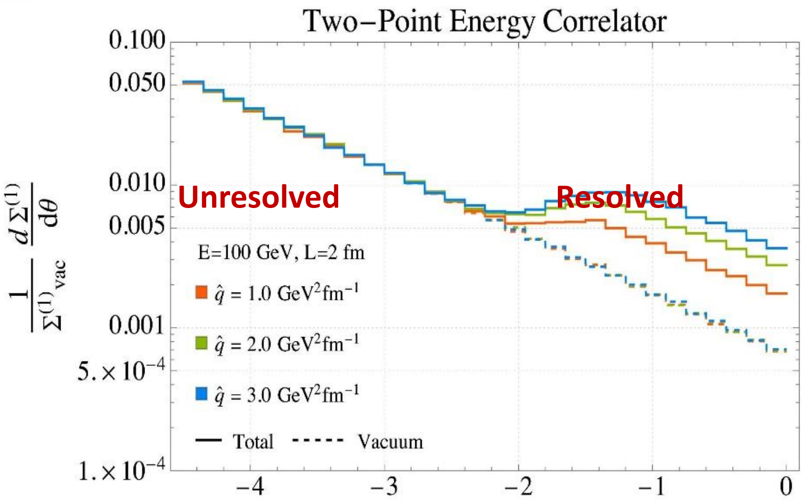


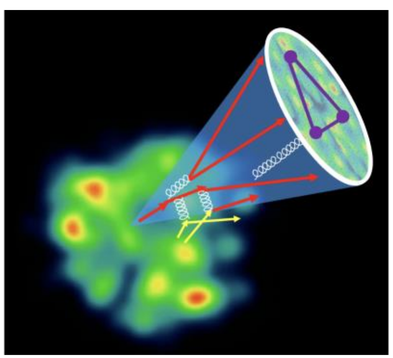


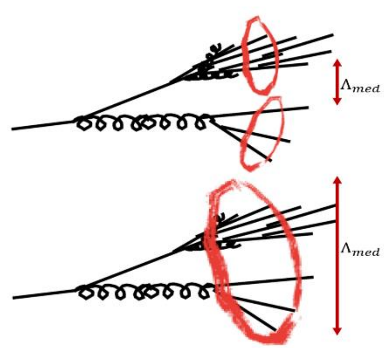
Jet energy correlators are sensitive to various intrinsic or emergent scales.
Jet EEC presents a clear transition between perturbative and non-perturbative regions.

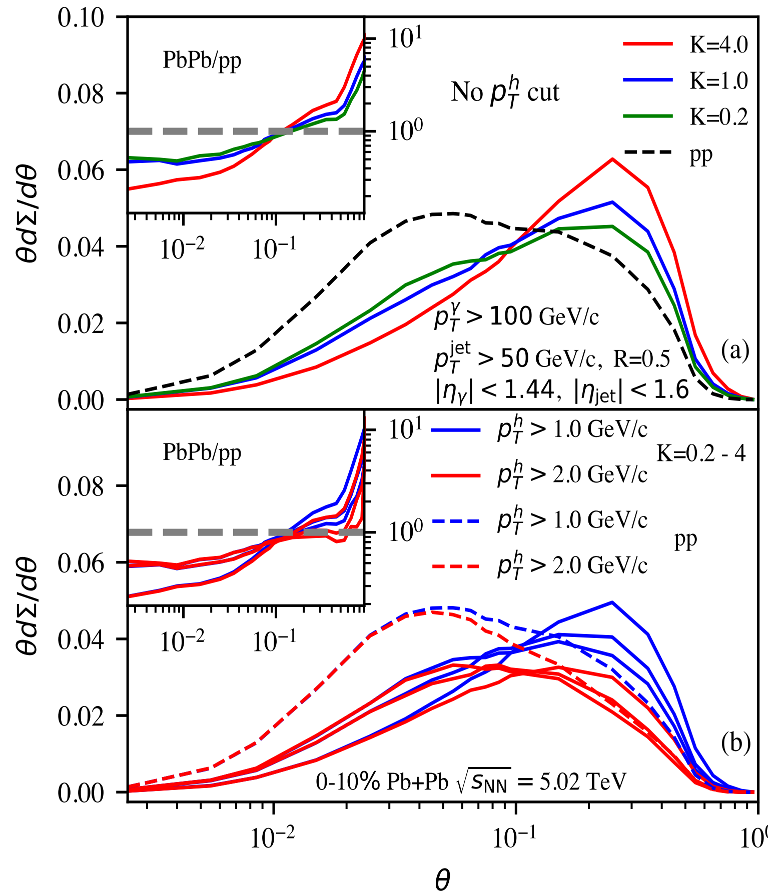
Komiske, IMoult, Thaler, Zhu, PRL 130, 051901 (2023)
Liu, Zhu, PRL 130, 091901 (2023)
Liu, Liu, Pan, Yuan, Zhu, PRL 130, 181901 (2023)

Jet EEC in QGP





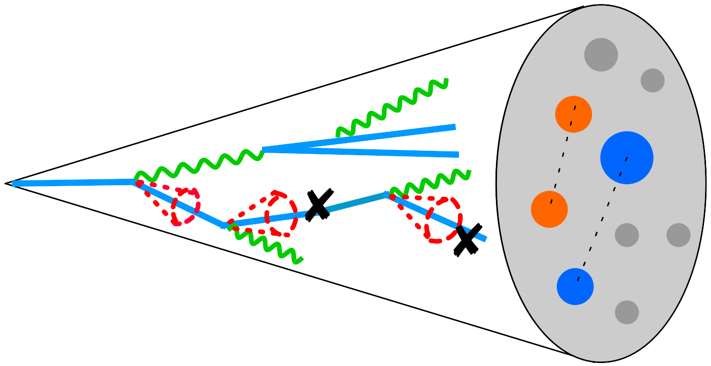


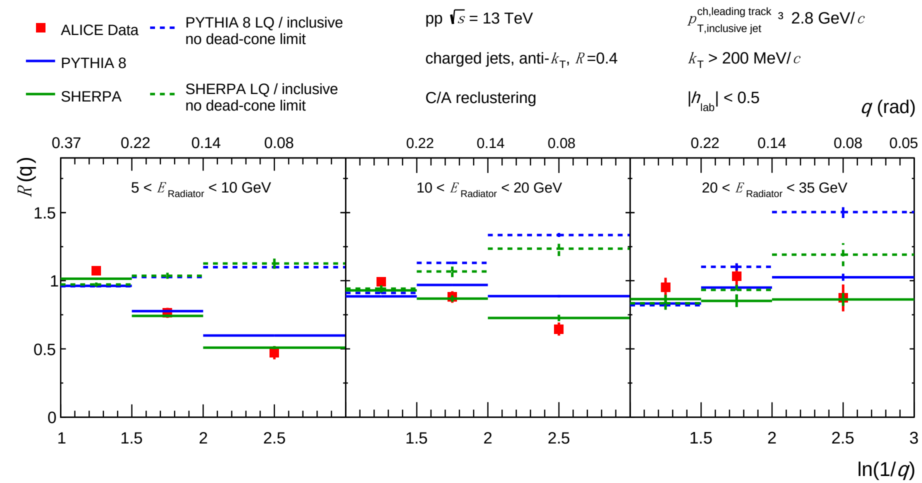


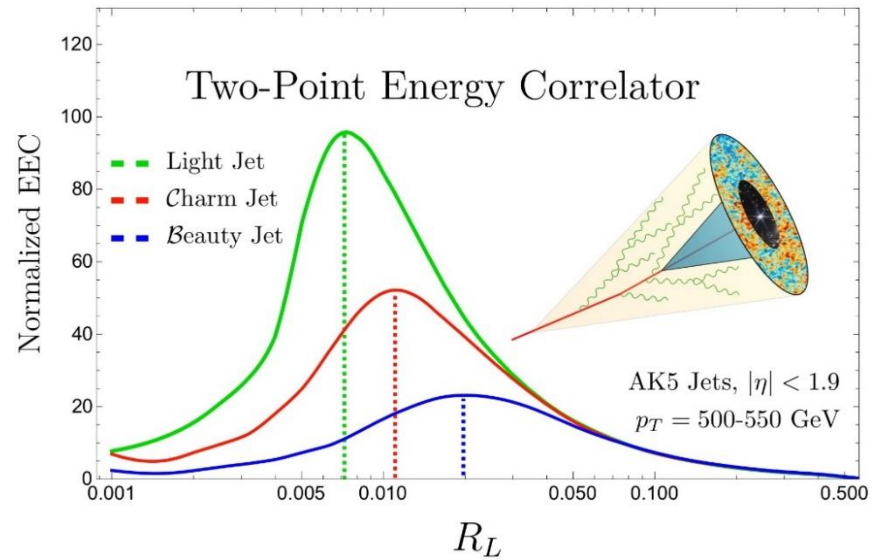
Medium-modified jet EEC provides unique opportunity to probe jet-medium interaction mechanisms and QGP properties.

Andres, Dominguez, Elayavalli, Holguin, Marquet, PRL 130 (2023) 26, 262301;
Yang, He, Moult, Wang, PRL 132 (2024) 1, 1

Heavy flavor jets in vacuum







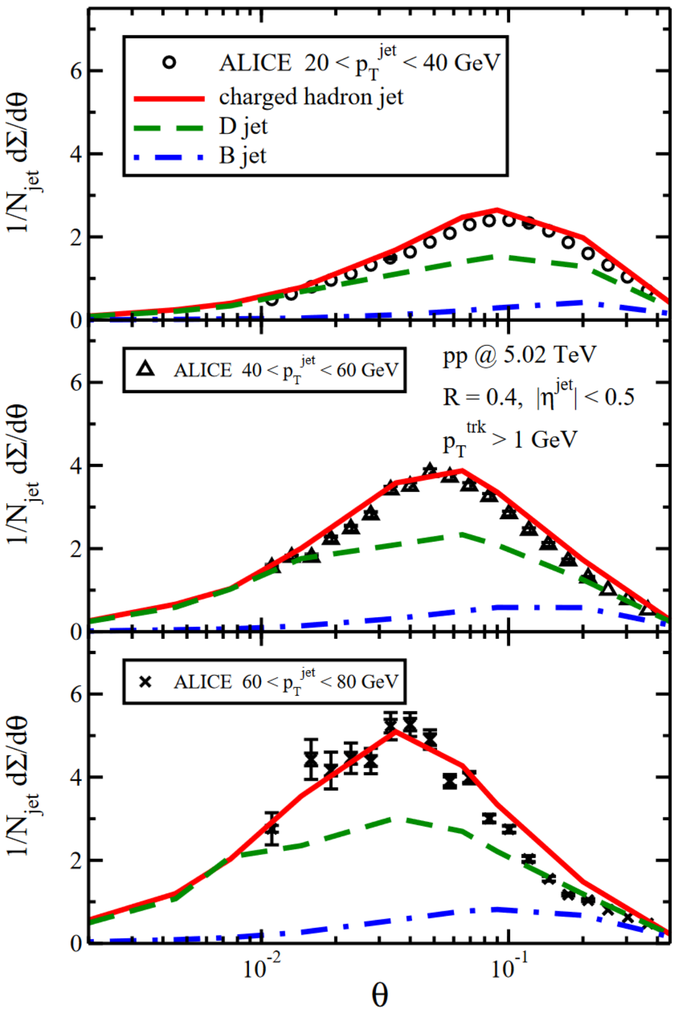
E. Craft, Lee, Mecaj, Moult, arXiv:2210.09311

Heavy flavor jets provide a direct access to the mass effect on jet substructure.

Dead-cone effect in QCD: gluon emissions from massive quark are suppressed within a cone of $\theta_0 \sim m_Q/E$.

Heavy flavor jet EEC can probe the mass effect on parton splitting.

Flavor hierarch of jet EEC in vaccum



$\langle\theta\rangle$	Charged jet	*D* jet	*B* jet
$20 < p_T^{jet} < 40$ GeV	0.207	0.214	0.263
$40 < p_T^{jet} < 60$ GeV	0.167	0.18	0.233
$60 < p_T^{jet} < 80$ GeV	0.144	0.162	0.214

Flavor (mass) dependence:

$\Sigma(\text{ch. jet}) > \Sigma(\text{D jet}) > \Sigma(\text{B jet})$

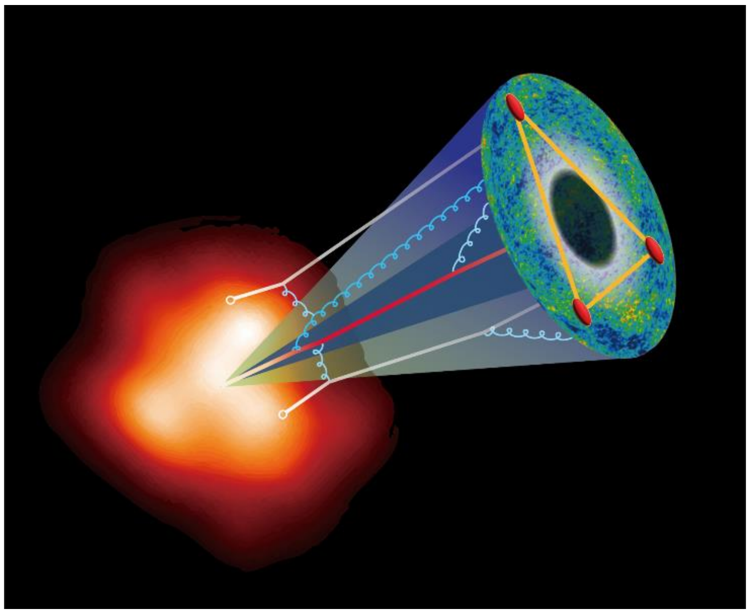
$\theta^{\text{peak}}(\text{ch. jet}) < \theta^{\text{peak}}(\text{D jet}) < \theta^{\text{peak}}(\text{B jet})$

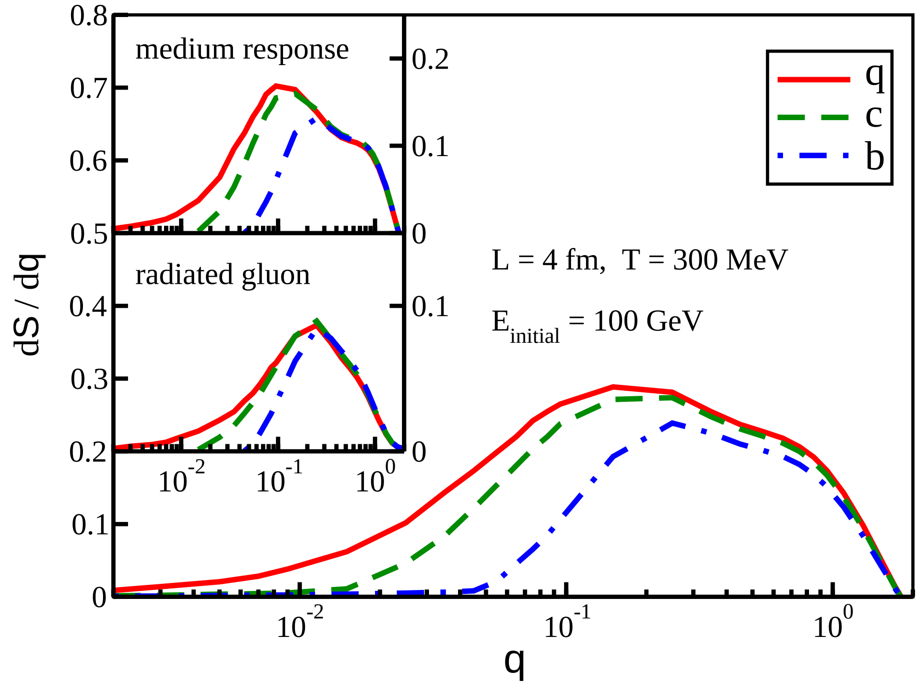
Jet energy dependence:

Higher p_T jets peaks at smaller angles.

Xing , Cao, GYQ, Wang, Phys. Rev. Lett. 134, 052301 (2025)

Medium effect on jet EEC





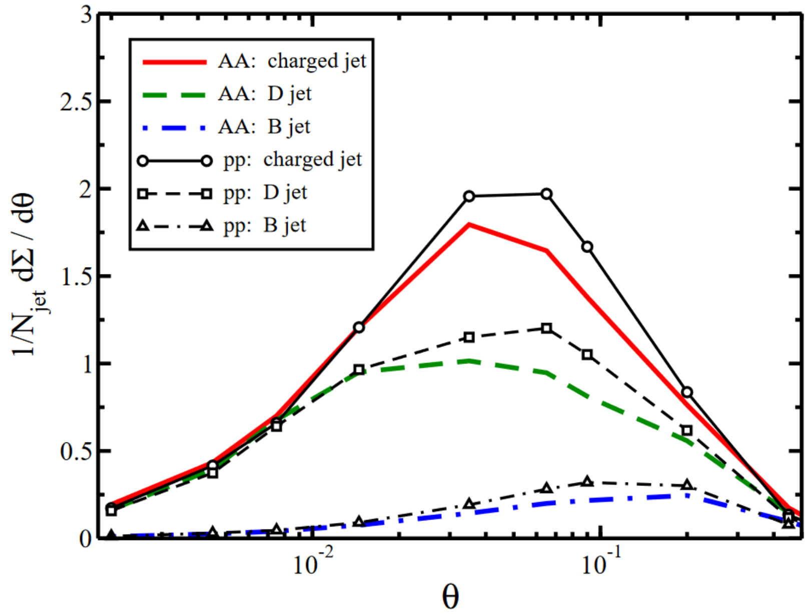
Flavor (mass) hierarchy in quark-jet EEC:

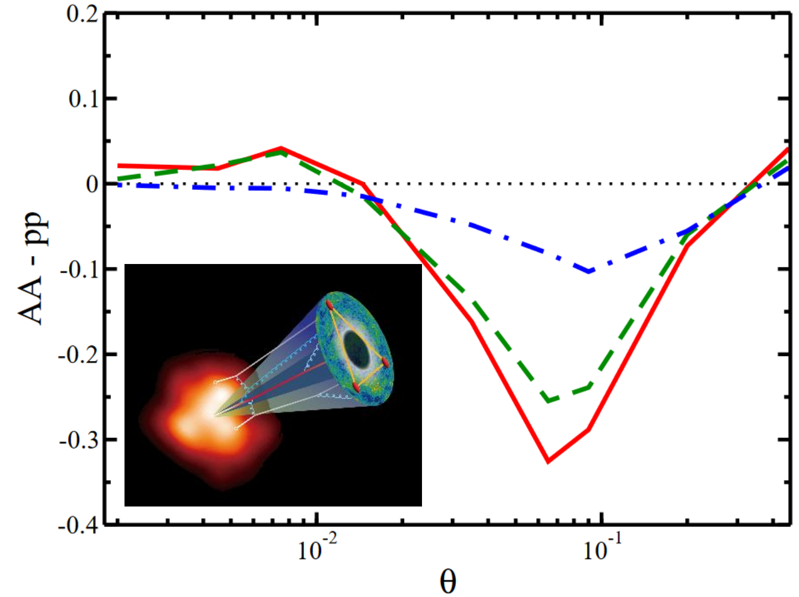
$\boldsymbol{\Sigma(q\ jet) > \Sigma(c\ jet) > \Sigma(b\ jet),\ \ \theta^{peak}(q\ \ jet) < \theta^{peak}(c\ jet) < \theta^{peak}(b\ jet).}$

The above flavor hierarchy maintains in the contribution from medium response and medium-induced radiation.

Xing , Cao, GYQ, Wang, Phys. Rev. Lett. 134, 052301 (2025)

Flavor hierarchy of jet EEC in QGP





Flavor (mass) hierarchy in the nuclear modification of jet EEC in HIC:

- For charged jets , the EEC spectra gets a strong suppression at intermediate angle (due to energy loss), and gets enhanced at small and large angles.
- For heavy-meson-tagged jets, both suppression and enhancement become weaker.

Xing , Cao, GYQ, Wang, Phys. Rev. Lett. 134, 052301 (2025)

Summary

- Relativistic heavy-ion collisions at RHIC and the LHC have created the hottest, most perfect, most vortical and highly opaque fluid on Earth

- Jets are versatile probes of strongly-interacting quark-gluon plasma in relativistic heavy-ion collisions

- Leading hadrons
  - Parton energy loss leads to leading hadron suppression in heavy-ion collisions
  - PQCD based energy loss models can explain the flavor hierarchy of jet quenching
  - Jet quenching provides important tool to extract the transport property of QGP
  - Baysian analysis can help extract flavor-dependent parton energy loss from data

- Full jets
  - The interaction of full jets and medium involves various mechanisms and effects
  - Jet-induced medium response can affect hadron yield and chemistry around jets
  - Jet substructure (such as EEC) can probe jet-medium interaction at different scales

- Towards consistent understanding of leading hadrons and full jets