Angular correlations of HF+jet in heavy-ion collisions

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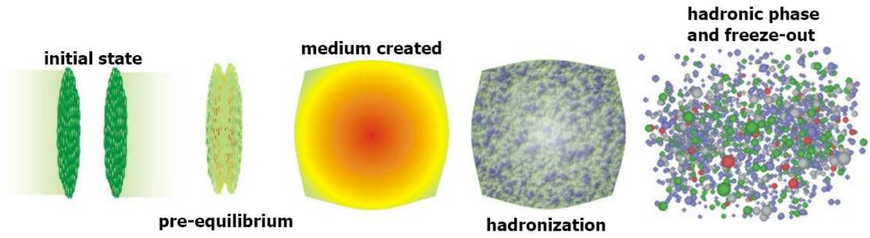
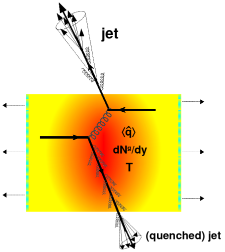
    - Radial distribution of D^0 in jets in HICs
    - B+jet angular correlations in HICs
4. Angular correlations of γ+HF in HICs
5. Summary

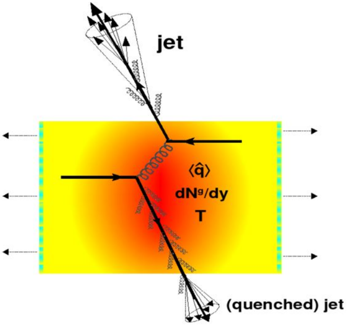
Introduction : QGP and jet quenching



- De-confined quark-gluon plasma (QGP) created at extreme hot and dense condition (lifetime$\sim 10 fm/c$).
- Provides an arena to test the Quantum Chromodynamics (QCD) and help us understand the early cosmic evolution ($\sim 10^{-6} s$).
- Jet quenching: Strong interactions between high p_T parton and medium, useful hard probe.



Jet quenching in HICs



Energy loss : $\frac{dE}{dt}$

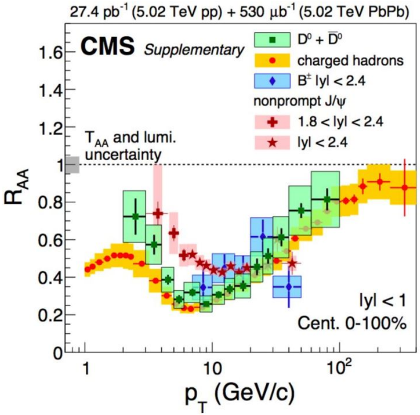
p_T-broadening : $\frac{dp_\perp}{dt}$

Jet transport coefficient : $\hat{q} = \frac{d\langle p_\perp^2 \rangle}{dt}$

- During the propagation and evolution in the QGP, the jet not only loses energy and momentum, but also accumulates transverse momentum through medium-induced radiation and scattering .

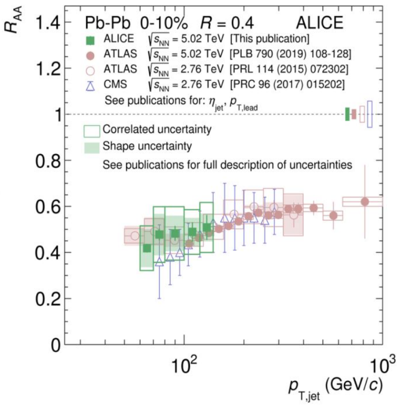
Jet in-medium energy loss

Hadron R_{AA}



CMS Collaboration, JHEP 04 (2017) 039
CMS Collaboration, Phys. Rev. Lett. 119 (2017) 152301
CMS Collaboration, Phys. Lett. B782 (2018) 474

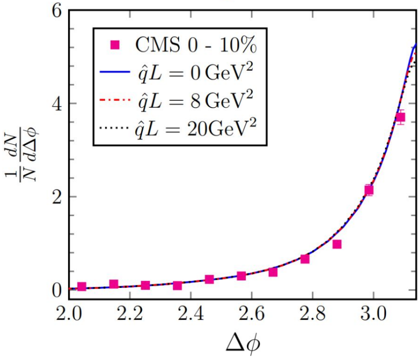
Jet R_{AA}



ATLAS Collaboration, PLB 790 (2019) 108-128
ATLAS Collaboration, PRL 114 (2015) 072302
CMS Collaboration, PRC 96(2017) 015202

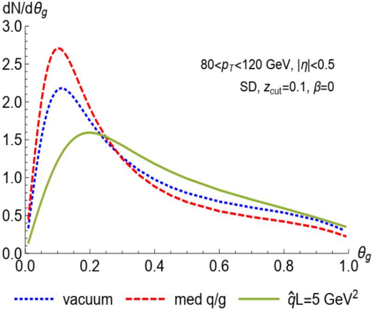
Jet in-medium P_T-broadening

Dijet



A. H. Mueller, Bin Wu, Bo-Wen Xiao, and Feng Yuan
Phys.Lett. B, 1604.04250

Subjets

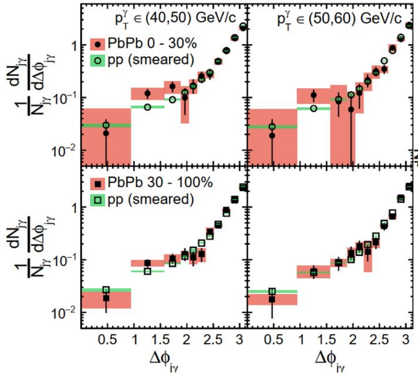


Felix Ringer, Bo-Wen Xiao, and Feng Yuan
Phys.Lett. B, 1907.12541

- Use jet angular de-correlations to capture the in-medium $\mathrm{P_T}$-broadening effects.

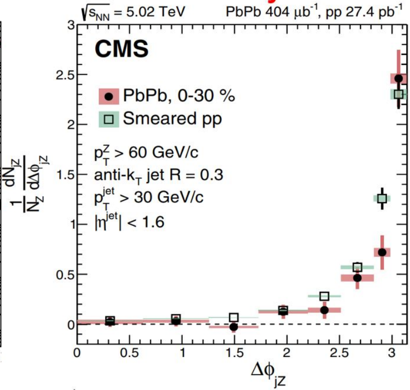
Jet in-medium P_T-broadening

photon+jet



CMS Collaboration, PLB, 1711.09738
CMS Collaboration, PLB, 1205.0206
T. Luo S. Cao, Y. He and X.N. Wang PLB, 1803.06785

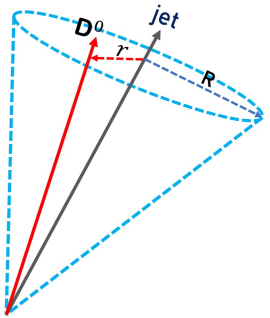
Z^0+jet



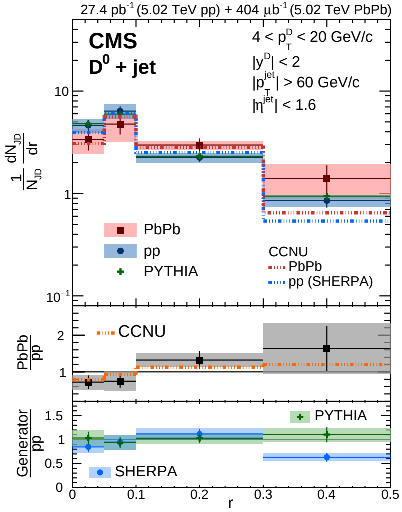
CMS Collaboration, PRL, 1702.01060
S.L Zhang, T. Luo B.W Zhang, and X.N. Wang, PRC, 1804.11041

- No evident angular broadening observed in the measurements on γ+jet and Z^0+jet.
- New observables are needed to capture the in-medium P_T−broadening effects.

Measurement : D^0 radial distribution in jets

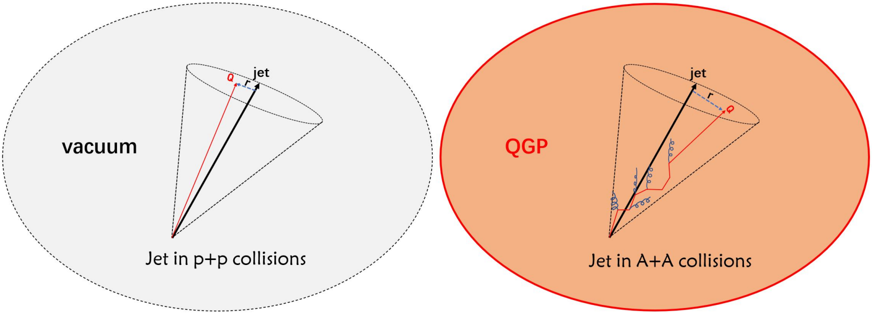


PRL.125(2020)10,102001



- $r = \sqrt{(\phi_D - \phi_{\text{jet}})^2 + (\eta_D - \eta_{\text{jet}})^2}$
- Angular distance of HQ to jet axis.
- Complementary to R_{AA} and v_2 of HF hadron.

Motivation : radial distribution of heavy quarks in jets



- The high p_T jets were viewed as references to probe the radial diffusion of lower p_T charm quark in A+A collisions.
- Provides a new perspective to study the dynamical details of the heavy quarks in-medium interactions.

Framework for the in-medium evolution of heavy flavor jet

Heavy quark jet transport in QGP

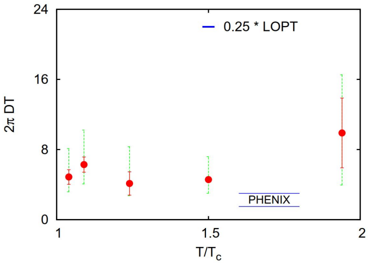
G.D. Moore and D. Teaney PRC 71 (2005) 064904; S. Cao, G.Y. Qin and S.A. Bass Phys.Rev. C88 (2013) 044907

- For heavy quark, $m_Q \gg T_{QGP}$, the modified discrete Langevin transport equations are used to describe the propagating of heavy quarks in the QGP.

$$\Delta\vec{x}(t+\Delta t) = \frac{\vec{p}(t)}{E}\Delta t \quad (1)$$

$$\Delta\vec{p}(t+\Delta t) = -\Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g \quad (2)$$

The fluctuation-dissipation relation: $\kappa = 2ET\Gamma = \frac{2T^2}{D_s}$
Based on the LQCD calculation , D_s is fixed at $(2\pi T)D_s = 4$
Debasish Banerjee et al. Phys.Rev.D 85 (2012) 014510
A. Francis, et al. Phys.Rev.D 92 (2015) 11, 116003



The stochastic term $\xi(t)$ obeys Gaussian distribution :

$$W(\vec{\xi}(t)) = N \cdot \exp\left(\frac{\vec{\xi}^2(t)}{2\kappa}\right) \quad (3)$$

which leads to

$$\langle \xi_i(t) \rangle = 0 \quad (4)$$

$$\langle \xi_i(t)\xi_j(t') \rangle = \kappa\delta_{ij}(t-t') \quad (5)$$

- For light parton, the collisional energy loss is described by the calculation at Hard Thermal Loop (HTL) approximation:

R.B. Neufeld, Phys.Rev. D83 (2011) 065012; J. Huang, Z.B. Kang and I. Vitev, Phys.Lett. B726 (2013) 251-256

$$\frac{dE}{dz} = -\frac{\alpha_s C_i m_D^2}{2} ln\frac{\sqrt{ET}}{m_D} \quad (6)$$

- Evolution of the bulk medium is produced by the iEBE-VISHNU hydro model.

C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput.Phys.Commun. 199 (2016) 61-85

Medium-induced gluon radiation

- For both heavy and light parton, the medium-induced gluon radiation is implemented based on the higher-twist approach.

X.f. Guo and X.N. Wang, Phys.Rev.Lett. 85 (2000) 3591-3594 ; B.W. Zhang, E. Wang and X. N. Wang, Phys.Rev.Lett. 93 (2004) 072301; A. Majumder, Phys.Rev. D85 (2012) 014023

$$\frac{dN_g}{dxdk_\perp^2\,dt} = \frac{2\alpha_s C_A P(x)\hat{q}}{\pi k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2M^2}\right)^4 \qquad (7)$$

$P(x)$ is the QCD splitting function in vacuum :
W. T. Deng and X. N. Wang, Phys. Rev. C 81 (2010) 024902

$$P_{q\to qg}(x) = \frac{(1+(1-x)^2)(1-x)}{x} \qquad (8)$$

$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)} \qquad (9)$$

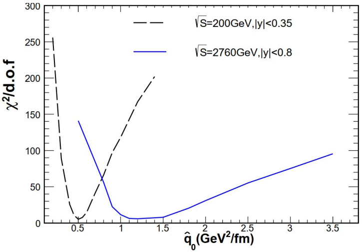
τ_f the gluon formation time :

$$\tau_f = \frac{2xE(1-x)}{k_\perp^2 + x^2M^2} \qquad (10)$$

- $\hat{q}$ is the jet transport coefficient.

X. F. Chen, C. Greiner, E. Wang, X.N. Wang and Z. Xu, Phys.Rev. C81 (2010) 064908

$$\hat{q} = \hat{q}_0\left(\frac{T}{T_0}\right)^3 \frac{p^\mu u_\mu}{p^0} \qquad (11)$$



G.Y. Ma, W. Dai, B.W. Zhang and E.K. Wang, Eur.Phys.J. C79 (2019) no.6, 518

$\hat{q}_0 \sim 0.5\ \mathrm{GeV}^2$/fm in Au+Au 200 GeV
$\hat{q}_0 \sim 1.2\ \mathrm{GeV}^2$/fm in Pb+Pb 2760 GeV

p+p baseline and model setup

Initial momentum sampling: SHERPA (NLO+PS)

JHEP0902(2009)007

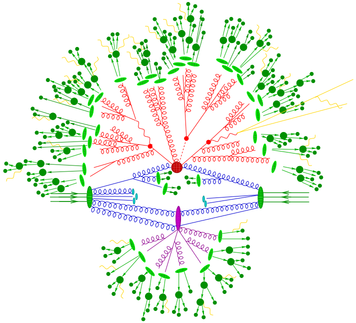
- Initial state parton shower (QCD)
- Underlying event
- Signal process
- Final state parton shower (QCD)
- Fragmentation
- Hadron decay
- QED radiation
- NNPDF3.0 NLO (proton) JHEP1504(2015)040
- nNNPDF1.0 NLO (nucleus) EPJC79(2019)no.6,471

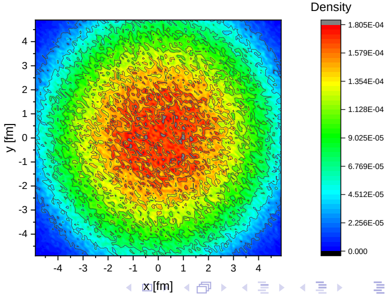
Initial position sampling

- Monte Carlo Glauber model EPJC72(2012)1896

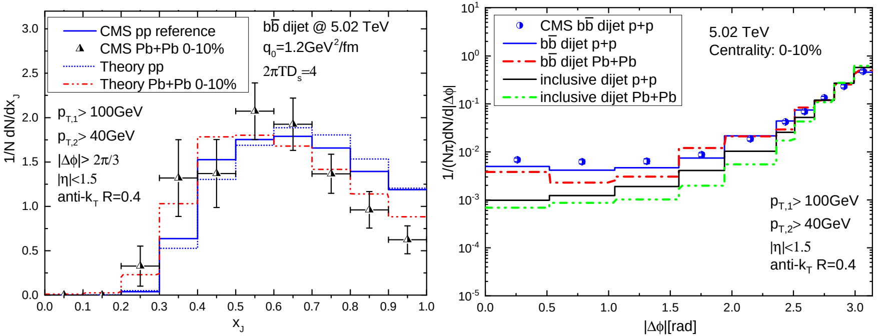
Jet reconstruction

- Fastjet3.0 EPJC72(2012)1896





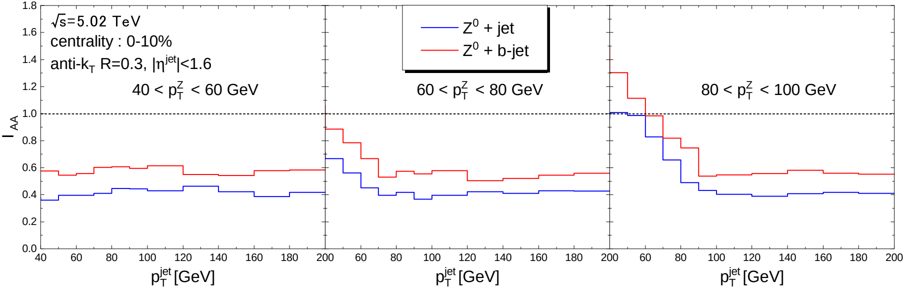
$b\bar{b}$ dijet production in nucleus-nucleus collisions



- $x_J = p_{T2}/p_{T1}$ shifts towards smaller values due to in-medium jet energy loss.
- No significant angular broadening observed both for inclusive dijet and $b\bar{b}$ dijet.

W. Dai, S. Wang, B. W. Zhang and E. Wang, Chin.Phys.C 44 (2020) 104105

$Z^0 +$ b-jet production in nucleus-nucleus collisions



- $I_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{\frac{dN^{AA}}{dp_T^{\rm jet}}|_{p_T^{\rm min}<p_T^Z<p_T^{\rm max}}}{\frac{dN^{pp}}{dp_T^{\rm jet}}|_{p_T^{\rm min}<p_T^Z<p_T^{\rm max}}}$
- By comparing the I_{AA} of $Z^0 +$ jet and $Z^0 +$ b-jet, we predict stronger yield suppression for light-quark jet compared to that of b-jet.

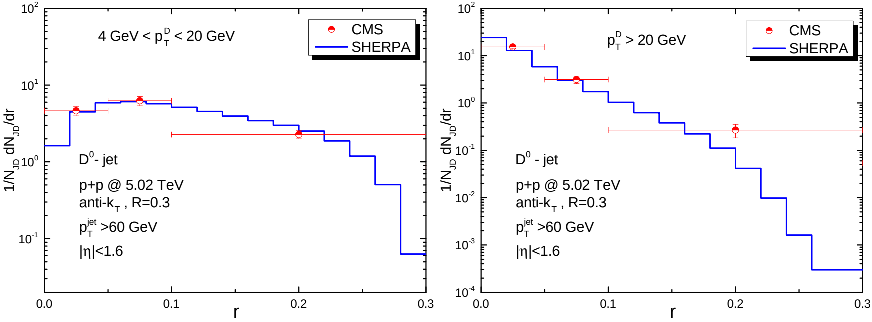
S. Wang, W. Dai, B. W. Zhang and E. Wang, arXiv:2005.07018

Angular correlations of HF+jet in HICs

S. Wang, W. Dai, B. W. Zhang and E. Wang, EPJC(2019), arXiv:1906.01499[nucl-th];

S. Wang, W. Dai, B. W. Zhang and E. Wang, CPC(2021), arXiv:2012.13935[nucl-th];

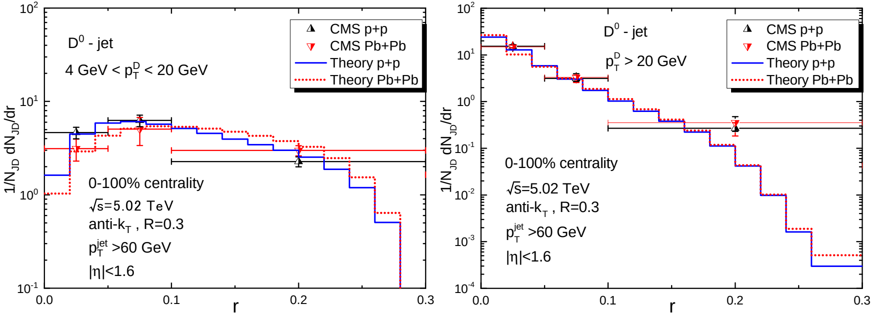
D^0 radial distribution in jets in p+p collisions



- The radial distribution of D^0 respect to the jet axis is sensitive to the heavy quark production mechanisms.
- At lower p_T^D, a broad distribution versus r, gluon splitting during parton shower.
- At higher p_T^D, spectra fall rapidly as a function of r, charm-initiated jet.

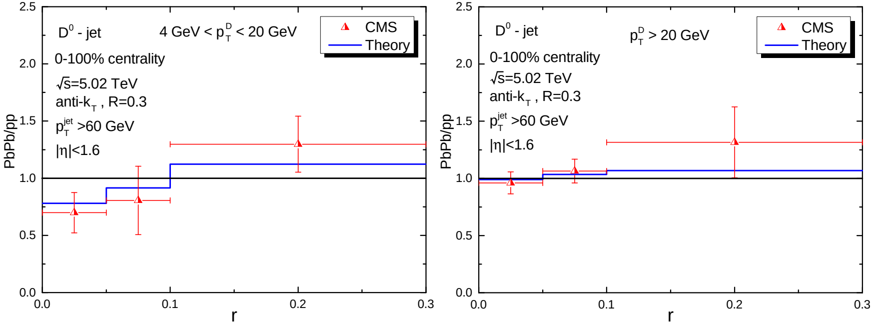
S. Wang, W. Dai., B. W. Zhang and E. Wang, Eur.Phys.J.C79(2019)9,789

D^0 radial distribution in jets in p+p and Pb+Pb collisions



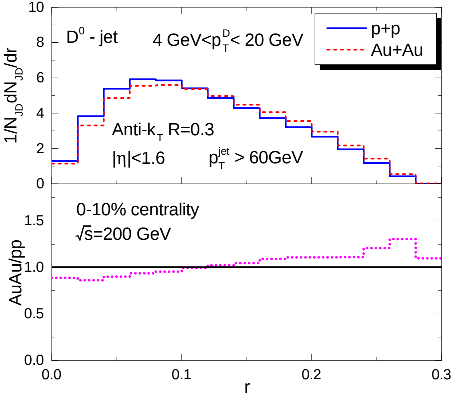
- At lower D^0 meson p_T $(4 - 20$ GeV), a visible shift towards large r is found in the normalized distribution.
- At higher D^0 meson p_T $(> 20$ GeV), no significant modification observed.

D^0 radial distribution in jets in p+p and Pb+Pb collisions



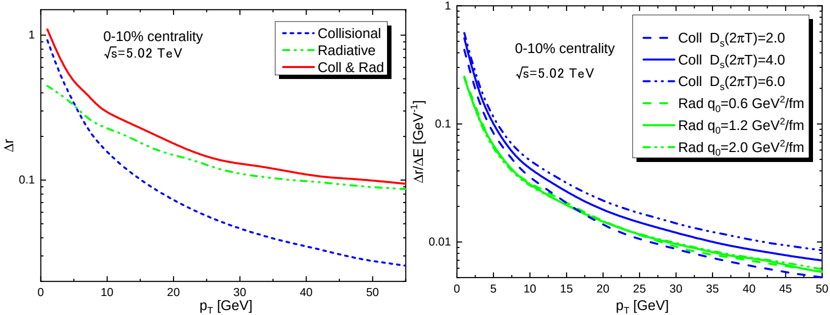
- At lower D^0 meson p_T $(4 - 20$ GeV$)$, a visible shift towards large r is found in the normalized distribution.
- At higher D^0 meson p_T $(> 20$ GeV$)$, no significant modification observed.

Radial profile of charm in jet at RHIC



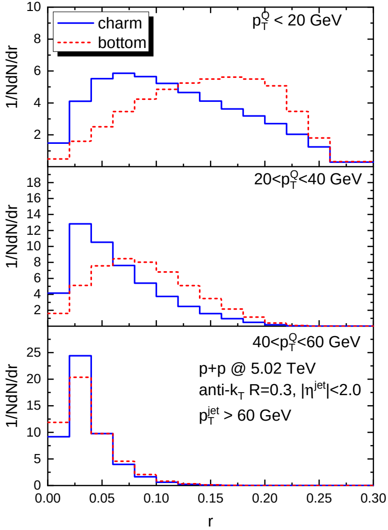
- Weaker modification compared to LHC, due to lower temperature of QGP at the RHIC energy.

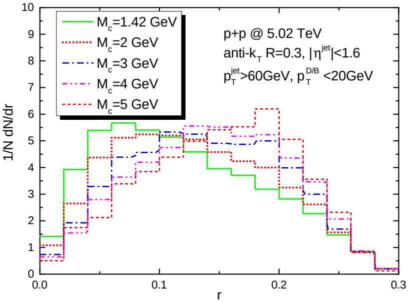
Parameter sensitivity



- $\Delta r = \sqrt{(\phi_c - \phi_c^0)^2 + (\eta_c - \eta_c^0)^2}$
- Elastic and inelastic scattering dominates the lower p_T^D and higher p_T^D region respectively.
- $\Delta r/\Delta E$ addresses the broadening strength per unit energy loss of charm quark, sensitive to D_s but not to $\hat{q}$

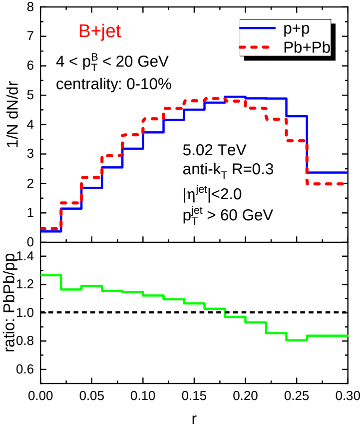
Mass effect reflected in the jet radial distribution





- At lower p_T, bottom quarks are farther apart from the jet axis than charm quarks.
- At higher p_T, distributions shift to near the jet axis, distinctions between charm and bottom trend to disappear.

Angular correlation of bottom+jets in HICs

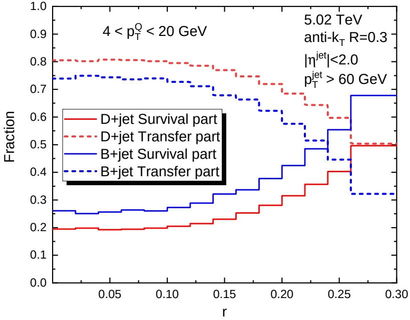


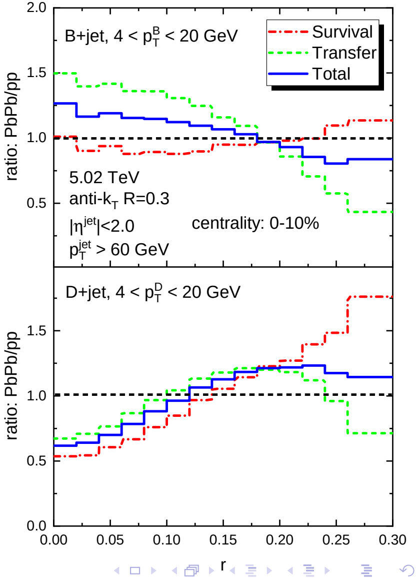
- Different modification patterns shown on the radial profiles: charm quarks shift towards lager radius while bottom quarks seems shift closer to the jet axis.

S. Wang, W. Dai, B. W. Zhang and E. Wang, Chin.Phys.C 45(2021)6,064105

HF+jet events in A+A collisions

	p+p	A+A
Total(p+p)	p_T^Q: 4–20	
Total(A+A)		p_T^Q: 4–20
Survival in A+A	p_T^Q: 4–20	p_T^Q: 4–20
Transfer in A+A	p_T^Q >20	p_T^Q: 4–20

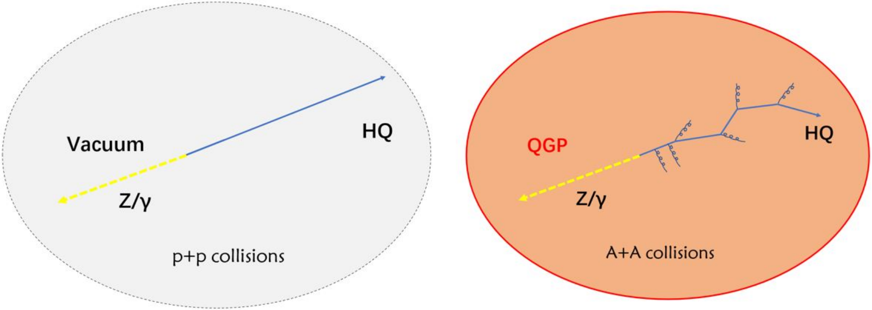




Angular de-correlations of γ+HF in HICs

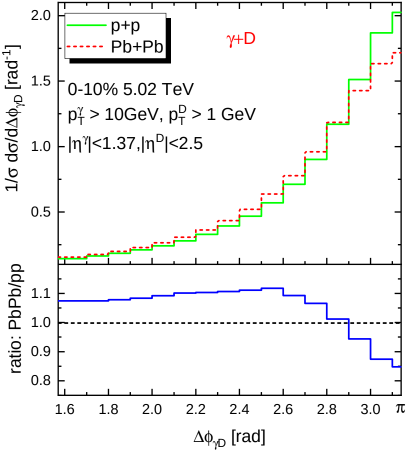
S. Wang, J. Kang, B.-W. Zhang and E. Wang, arXiv:2107.12000[nucl-th];

Probing the P_T-broadening by γ+HF correlations



- Vector bosons are good references to probe the changes of heavy quark momentum.
- Vector bosons constrain the initial kinematics of HQ in A+A, consistent with that of p+p.
- HQ excludes the impacts from the medium response effects.

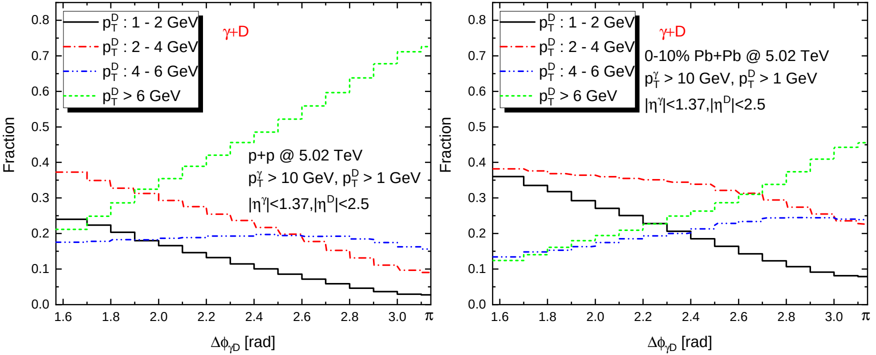
Angular de-correlations of γ+D in HICs



- In Pb+Pb collisions, distinct reduction of γ+D events at the back-to-back region compared to p+p, where $\Delta\phi_{\gamma D} = |\phi_\gamma - \phi_D|$.
- It indicates the angular de-correlations between γ and charm quarks in QGP.
- Evident signal of in-medium $\mathrm{P_T}$-broadening effect.

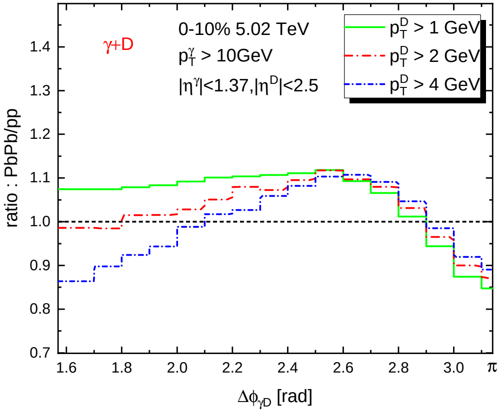
S. Wang, J. Kang, B.-W. Zhang and E. Wang, arXiv:2107.12000[nucl-th];

Angular de-correlations of γ+D in HICs



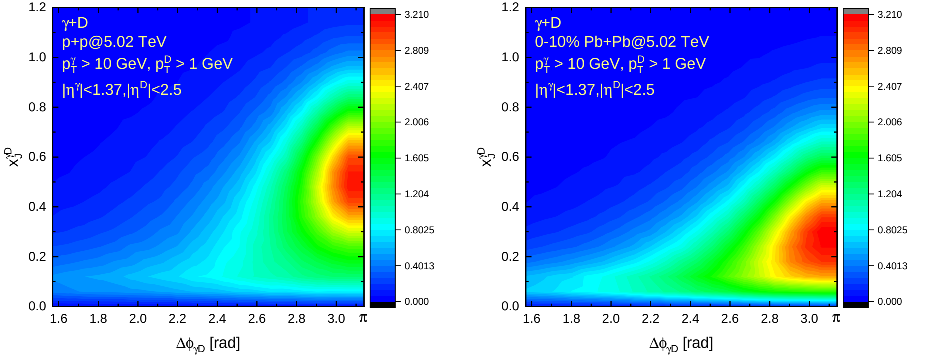
- In p+p collisions, higher p_T D mesons dominate the back-to-back $\Delta\phi_{\gamma D}$ region.
- In Pb+Pb collisions, higher P_T D mesons are significantly reduced at due to the energy loss of charm quarks. Lower p_T D mesons become the dominant contribution at smaller $\Delta\phi_{\gamma D}$ region.

Angular de-correlations of γ+D in HICs



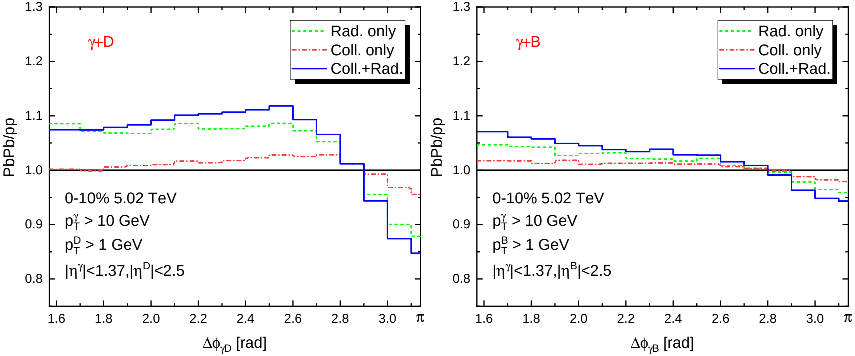
- The modification patterns of $\Delta\phi_{\gamma D}$ distribution are sensitive to the selection cut for D mesons.
- As selection cut increases, the enhancement at $\Delta\phi_{\gamma D} < 2.0$ gradually disappears and turns into suppression.
- The higher p_T^D cut excludes the contribution of lower p_T D meson.

Correlation diagram of $(x_J^{\gamma D}, \phi_{\gamma D})$



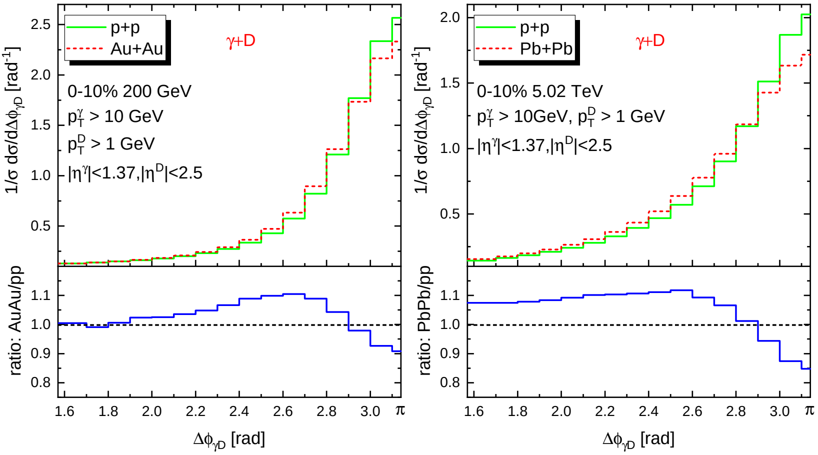
- The shifting of $x_J^{\gamma D} = p_T^D / p_T^\gamma$ from lager to smaller value is due to the energy loss of charm quarks during their traversing in QGP.
- The shifting of $\Delta\phi_{\gamma D} = |\phi_\gamma - \phi_D|$ is a clear signal of the P_T-broadening effect due to the in-medium interactions of charm quark.

Probing the mass effect of P_T-broadening at the LHC



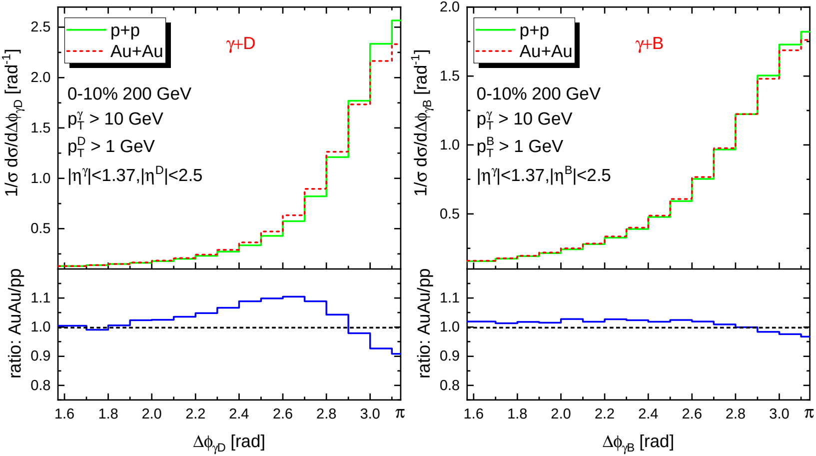
- The total modification of γ+B angular correlations is visibly smaller than that of γ+D.
- Angular de-correlations can serve as useful tool to test the mass effect of jet quenching.
- Inelastic scattering (radiation) is the dominant mechanism responsible for the angular de-correlations of γ+HF.

Angular de-correlations of γ+D at LHC Vs. RHIC



- The $\Delta\phi_{\gamma D}$ spectra in p+p collisions at RHIC energy is steeper than that at LHC.
- Visible modification of $\Delta\phi_{\gamma D}$ distributions in central Au+Au collisions.

Angular de-correlations of γ+D Vs. γ+B at RHIC



- No visible azimuthal angular de-correlations of γ+B in RHIC energy.

Summary I

- We present systematic studies on the radial profile of heavy quarks in jets in heavy-ion collisions.
- We observe considerable diffusion of charm quarks in jets at 5 TeV, may be an indication of the in-medium P_T-broadening effects.
- At RHIC energy, the diffusion effect of charm quarks is weaker than that at LHC.
- We predict different modification patterns: jet quenching effects narrow the jet radial profile of B mesons in jets while broaden that of D mesons in jets.
- The diffusion nature of heavy quark in-medium interactions broadens the radial profile, while energy loss narrows the distribution. These two effects consequently compete and offset with each other.

Summary II

- We present the first theoretical study of the azimuthal angular correlations of γ+HF in HICs as a new probe of the in-medium P_T-broadening effect.
- We observe angular de-correlations of photon and D meson, which can be used to probe the in-medium P_T-broadening.
- We construct the 2D correlations diagrams between $x_J^{\gamma D}$ and $\Delta\phi_{\gamma D}$ to show the energy loss and P_T-broadening effect simultaneously.
- We observe much weaker medium modification of azimuthal angular correlation of γ+B compared to that of γ+D in Pb+Pb collisions at the LHC. We demonstrate that the difference mainly results from the medium-induced gluon radiation.
- We predict an visible modification on the $\Delta\phi_{\gamma D}$ distributions in central Au+Au collisions.

Thanks for your attention !

Parameter sensitivity

$$\vec{x}(t+\Delta t) = \vec{x}(t) + \frac{\vec{p}(t)}{E}\Delta t$$

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g$$

$$\kappa = 2ET\Gamma = \frac{2T^2}{D_s}$$

$$\langle \xi_i(t) \rangle = 0$$

$$\langle \xi_i(t)\xi_j(t') \rangle = \kappa\delta_{ij}(t-t')$$

Radiative:

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

$$\frac{\Delta r}{\Delta E} \propto \frac{\int \frac{k_\perp}{E}\frac{dN}{dx dk_\perp^2 dt} dx dk_\perp^2 dt}{\int xE \frac{dN}{dx dk_\perp^2 dt} dx dk_\perp^2 dt}$$

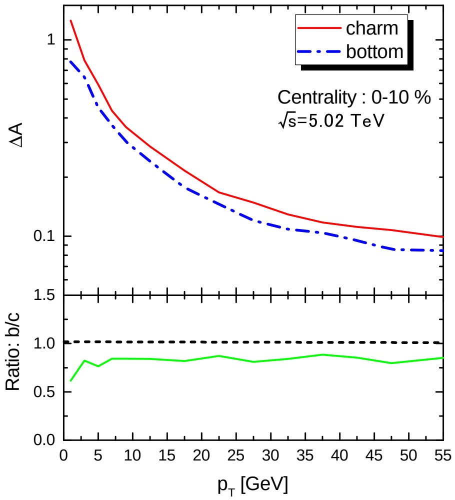
Collisional:

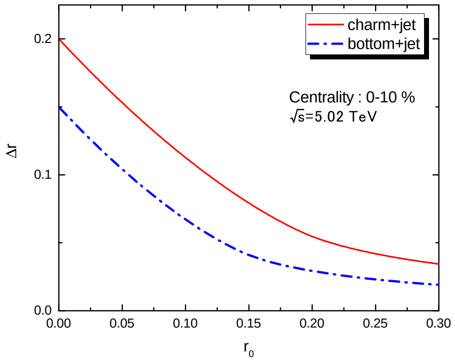
$$\Delta r \propto \int \frac{|\vec{\xi}(t)|}{E} dt \propto \int \frac{\sqrt{\kappa}}{E} dt \propto \int \frac{T}{E\sqrt{D_s}} dt$$

$$\Delta E \sim \int E\Gamma dt = \int \frac{T}{D_s} dt$$

$$\longrightarrow \quad \frac{\Delta r}{\Delta E} \propto \sqrt{D_s}$$

Angular deviation of HQ as traversing the QGP





- $\Delta A = \sqrt{(\phi_Q - \phi_Q^0)^2 + (\eta_Q - \eta_Q^0)^2}$
- $\Delta r = \sqrt{(\phi_Q - \phi_{\text{jet}})^2 + (\eta_Q - \eta_{\text{jet}})^2}$

- Charm quarks have slightly stronger angular diffusion effects than bottom quarks.
- Due to the different initial angular distance to jet axis, charm quarks show significant larger shift farther away from the jet axis than that of bottom quarks.