Jet and hadron nuclear modification factors

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Phys.Rev.C 103 (2021) [2007.13754, 2007.13758]

M. Attems, J. Brewer, G.M. Innocenti, AM, S. Park, W. van der Schee, U. Wiedemann [2203.11241]

CERN

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DFG Deutsche
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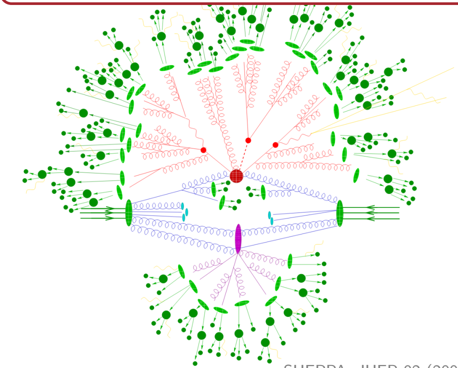
2022-2028, Heidelberg

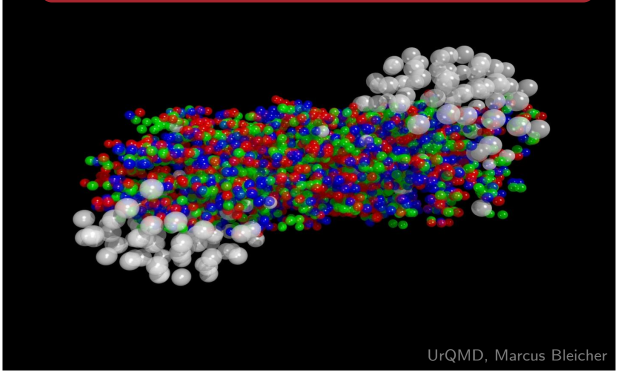
High-energy (HEP) and heavy-ion (HIP) physics paradigms of hadron collisions

(HEP) free-streaming final state in pp



SHERPA, JHEP 02 (2009)

(HIP) abundant parton re-scatterings in AA

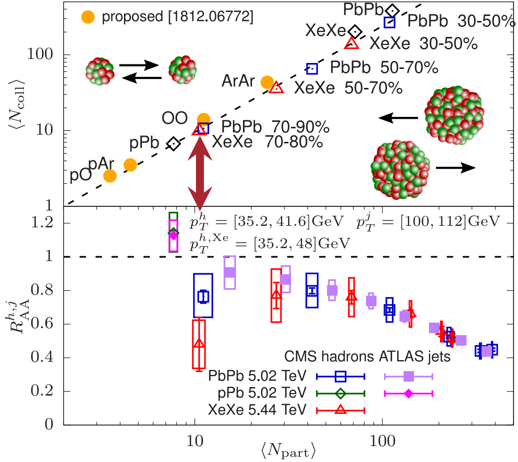


UrQMD, Marcus Bleicher

Core hypothesis: partonic rescattering $\Leftrightarrow$ HIP phenomena.

Many medium signals have been observed in small systems, but not energy loss.

System size scan with light ions at the LHC and RHIC



$\sqrt{s_{NN}} \sim 7$ TeV OO at LHC in 2024

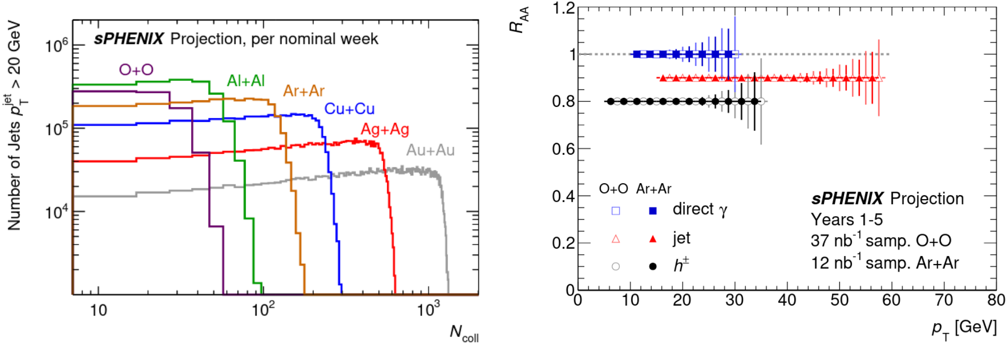
STAR collected $\mathcal{L}_{\rm OO} = 32\,\mathrm{nb}^{-1}$ at $\sqrt{s_{NN}} = 200$ GeV

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2026	$p^\uparrow p^\uparrow$	200	28	15.5	1.0 pb^{-1} [10 kHz] 80 pb^{-1} [100%-*str*]	80 pb^{-1}
–	O+O	200	–	2	18 nb^{-1} 37 nb^{-1} [100%-*str*]	37 nb^{-1}
–	Ar+Ar	200	–	2	6 nb^{-1} 12 nb^{-1} [100%-*str*]	12 nb^{-1}
2027	Au+Au	200	28	24.5	30 nb^{-1} [100%-*str*/DeMux]	30 nb^{-1}

Potential sPHENIX Beam Use Proposal 2026–2027

- Measurements with peripheral AA and pA collisions are inconclusive.
- *Minimum bias oxygen-oxygen collisions probe the relevant size regime!*

sPHENIX reach with light ions



Potential sPHENIX Beam Use Proposal 2026–2027

- OO and ArAr corresponds to $\langle N_{\text{part}} \rangle \sim 10$ and $\langle N_{\text{part}} \rangle \sim 25$
- Jet reach up to $p_T \sim 50\,\text{GeV}$

Hadron (jet) nuclear modification factor R_{AA}

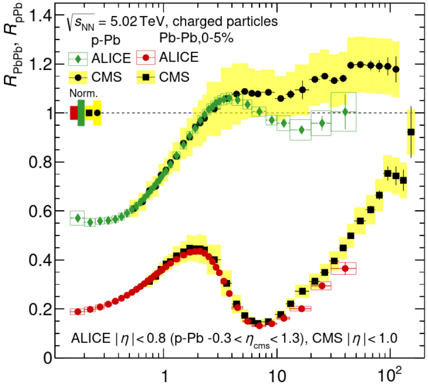
Ratio of spectrum in AA to an *equivalent number* N_{coll} of pp collisions.

$$R_{\mathsf{AA}}(p_T) = \underbrace{\frac{1}{\langle N_{\mathrm{coll}}\rangle/\sigma_{nn}^{\mathsf{inel}}}}_{\langle T_{\mathsf{AA}}\rangle} \frac{1/N_{\mathsf{ev}}^{AA} dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

R_{AA} can deviate from unity because:

- nPDF effects (different quark/gluon abundances).
- Parton rescattering (medium-induced energy loss).
- Geometry and event selection bias. Loizides, Morsch (2017) [1]
- Extrapolation of pp reference spectrum. ATLAS (2016) [2]

$\langle T_{\mathsf{AA}}\rangle$ – model dependent quantity.



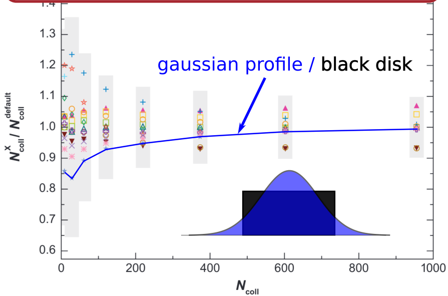
ALICE JHEP 11 (2018)

Soft physics assumptions in R_{AA} normalization

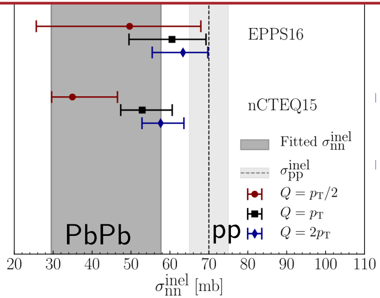
Nuclear overlap function $\langle T_{\mathrm{AA}} \rangle = \frac{\langle N_{\mathrm{coll}} \rangle}{\sigma_{\mathrm{nn}}^{\mathrm{inel}}}$ is the ratio of *model-dependent quantities*

number of binary collisions $\langle N_{\mathrm{coll}} \rangle$

inelastic nucleon-nucleon cross-section $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$



Miller, Reygers, Sanders, Steinberg (2007) [3]



Eskola, Helenius, Kuha, Paukkunen (2020)[4], see also Jonas, Loizides (2021) [5]

This way nominally high-p_T observable R_{AA} depends on soft physics assumptions.

Inclusive hadron (jet) nuclear modification factor R_{AA}

$\langle T_{\mathrm{AA}} \rangle$ can be replaced with *experimentally measurable* beam luminosity.

$$R^{h,j}_{\mathrm{AA,\ min\ bias}}(p_T) = \frac{1}{A^2} \frac{d\sigma^{h,j}_{\mathrm{AA}}/dp_T}{d\sigma^{h,j}_{pp}/dp_T}, \quad A \text{ – the nucleon number}$$

- Only applicable to minimum bias AA measurements[1].
- *Requires van der Meer scan to determine absolute AA luminosity.*
- System size (multiplicity) controlled by nuclei species and collision energy.
- Light nuclei collisions $\Longrightarrow$ precision studies of system size dependence.

Unique opportunity of complementary measurements of $^{16}_{8}$O at the LHC and RHIC.

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[1] Theoretically can do pA, but worse cancellation of experimental uncertainties due to shifted rapidities in pp and pA.

The null hypothesis—no medium-induced energy loss

The null baseline of R_{AA} can be computed with HEP precision techniques

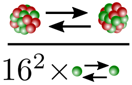
- Factorization of jet cross-section in perturbative QCD:

$$\sigma({}^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \to j + X) = \underbrace{\mathrm{nPDF}({}^{16}_{8}\mathrm{O})}_{\text{parton distribution functions}} \otimes \underbrace{\hat{\sigma}^{j}_{ab}}_{\text{hard partonic cross section}}$$

- (n)PDF – process-independent, non-perturbative, fixed by data.
- $\hat{\sigma}_{ab}$ – universal, perturbative and systematically improvable (LO, NLO, . . .).

We will calculate jet and hadron no-energy-loss baseline at next-to-leading order

$$R^{h,j}_{\text{AA, min bias}}(p_T) = \frac{1}{A^2}\frac{d\sigma^{h,j}_{\text{AA}}/dp_T}{d\sigma^{h,j}_{pp}/dp_T} =$$

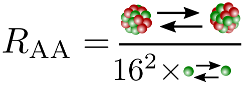


Deviation from the baseline $\Longrightarrow$ medium induced energy loss.

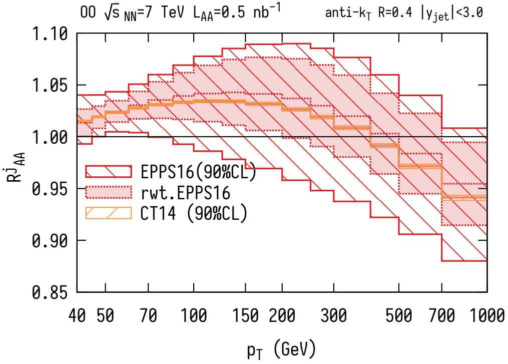
Minimum-bias jet R^j_{AA} (no energy loss) in OO at $\sqrt{s_{\mathrm{NN}}} = 7\,\mathrm{TeV}$

We calculated partonic jet cross-sections with `NNLOJET` code. HKMPSW (2020) [6, 7]

$\mathcal{O}(5\%)$ baseline deviation from unity.



- Cancelation of scale, hadronization and proton PDF uncertainties.
- $\mathcal{O}(2\text{–}7\%)$ oxygen nPDF uncertainties
- Additional pPb di-jet data reduces nPDF uncertainties Eskola et al. (2019) [8].



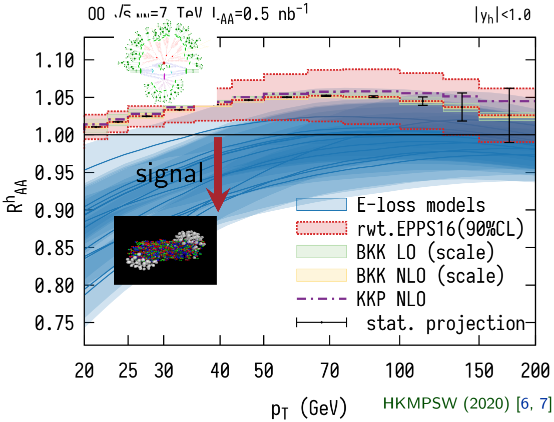
We achieved $\mathcal{O}(1\text{–}4\%)$ accuracy in the no-energy-loss jet baseline.

We also performed NLO calculations of inclusive hadron R_{AA} with `INCNLO` code.

Minimum-bias hadron R^h_{AA} in OO at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV and $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

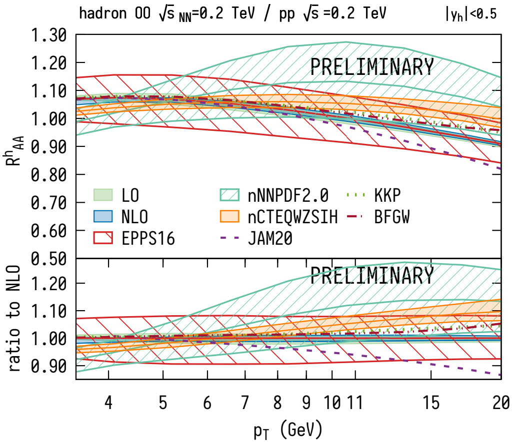
We constructed plausible energy loss signal from 12 models fitted to AA data.

LHC baseline and predictions



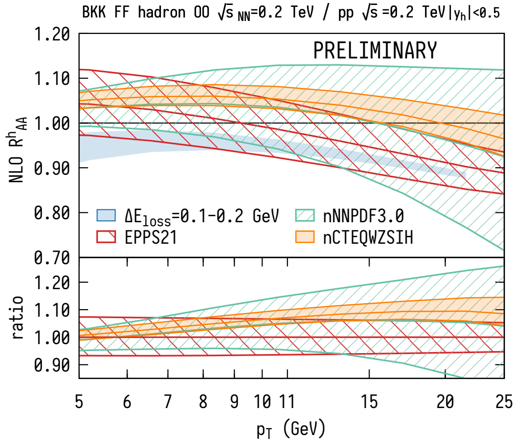
HKMPSW (2020) [6, 7]

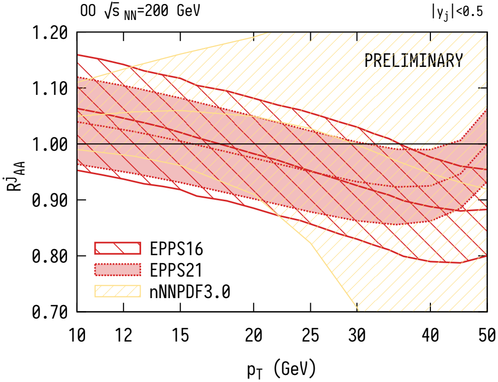
RHIC baseline



Measurable energy loss signal in 10 GeV $< p_T < 50$ GeV region at the LHC.

Hadron and nuclear modification factors at $\sqrt{s_{NN}} = 200$ GeV



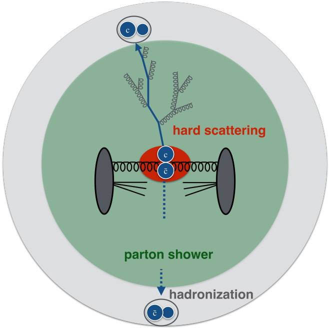


- For hadron R_{AA} preferred range $5\,\mathrm{GeV} < p_T^h < 15\,\mathrm{GeV}$
- For jet R_{AA} preferred range $p_T^j < 25\,\mathrm{GeV}$

Physics opportunities with high-statistics ion runs

Heavy quark production and energy loss in high-energy collisions

- Heavy quarks $m_{c,b} \gg \Lambda_{QCD}$
  $\Longrightarrow$ *short-distance perturbative production.*
- Scattering with Quark Gluon Plasma
  $\Longrightarrow$ *long-distance gluon radiation* $c \to cg$
- Observed modification of p_T spectra
  $\Longrightarrow$ *heavy flavour quenching*



New effect: interaction with the medium modifies $g \to c\bar{c}$ splitting rate!

gluon radiation

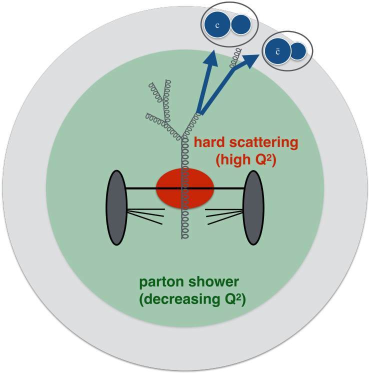
$c\bar{c}$ radiation

Colinear splitting $g \to c\bar{c}$ in parton shower

- Factorization in the colinear limit

$$\sigma^{gg\to c\bar{c}X} = \underbrace{\sigma^{gg\to gg}}_{\text{hard gluons}} \otimes \frac{\alpha_s}{2\pi}\frac{1}{Q^2} \quad \underbrace{P_{g\to c\bar{c}}}_{\text{splitting function}}$$

- Formation time $t_{\text{form}} \sim \frac{2E_g}{Q^2}$
  $\Longrightarrow$ *boosted pairs are produced late*
- Interaction with the medium changes *the number of charmed hadrons*.

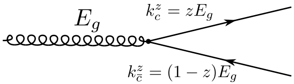


Modification of $\frac{1}{Q^2}P_{g\to c\bar{c}}$ calculable in the perturbative BDMPS-Z framework.

See arXiv:2203.11241 (*v2 next week*)

$g \to c\bar{c}$ splitting function: $P_{g\to c\bar{c}}$

- In vacuum



$$\left(\frac{1}{Q^2}\,P_{g\to c\,\bar{c}}\right)^{\text{vac}} = \frac{1}{Q^4 2z(1-z)}(m_c^2+\boldsymbol{\kappa}^2[z^2+(1-z)^2])$$

where $\boldsymbol{\kappa} = \frac{1}{2}(\mathbf{k}_c - \mathbf{k}_{\bar{c}})$

- In medium $P_{g\to c\bar{c}}$ is modified (correct up to $\mathcal{O}(\frac{1}{N_c^2})$)

see arXiv:2203.11241

$$\left(\frac{1}{Q^2}\,P_{g\to c\,\bar{c}}\right)^{\text{tot}} = \mathfrak{Re}\,\frac{1}{4\,E_g^2 z(1-z)}\int_{t_{\text{init}}}^{t_\infty} dt \int_t^{t_\infty} d\bar{t}\, e^{i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t})}\int d\mathbf{r}_{\text{out}}$$

$$\times\, e^{-\frac{1}{2}\int_{\bar{t}}^{\infty} d\xi\, n(\xi)\,\sigma_3(\mathbf{r}_{\text{out}},z)}\, e^{-i\,\boldsymbol{\kappa}\cdot\mathbf{r}_{\text{out}}}\left[m_c^2 + \underbrace{\frac{\partial}{\partial\mathbf{r}_{\text{in}}}\cdot\frac{\partial}{\partial\mathbf{r}_{\text{out}}}}_{\text{momentum at the vertex}}[z^2+(1-z)^2]\right]\underbrace{\mathcal{K}\left[\mathbf{r}_{\text{in}}, t; \mathbf{r}_{\text{out}}, \bar{t}\right]}_{\text{path integral of HO}}$$

- In the multiple soft scattering approximation

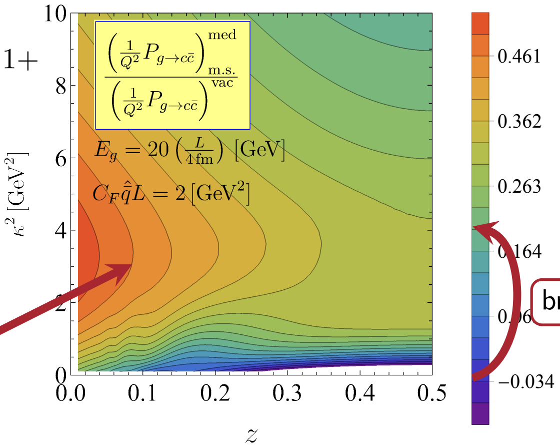
$$n(\xi)\sigma_3(\boldsymbol{r}_{\text{out}}, z) = \frac{1}{2}C_F\hat{\bar{q}}(1-\frac{9}{4}z(1-z))\boldsymbol{r}_{\text{out}}^2$$

Broadening and enhancement of $c\bar{c}$ pairs

We observe enhancement of the splitting function over wide phase-space.

$$\frac{\left(\frac{1}{Q^2}\,P_{g\to c\,\bar{c}}\right)^{\text{tot}}}{\left(\frac{1}{Q^2}\,P_{g\to c\,\bar{c}}\right)^{\text{vac}}} = 1+$$

weight



enhancement

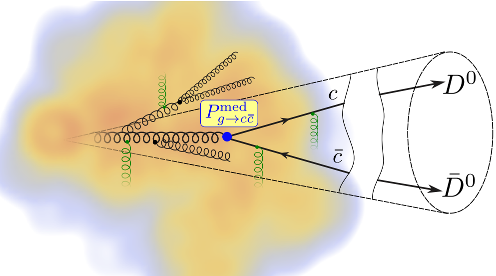
broadening

$\Longrightarrow$ reweight vacuum shower

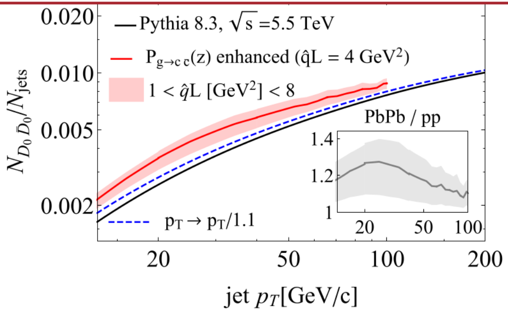
Medium-induced charm meson production inside jets

- Consider the fraction of jets with $D^0, \bar{D}^0$ pairs ⇒ *contains $g \to c\bar{c}$ splitting.*
- Reweight each $g \to c\bar{c}$ splitting ⇒ *explore range of $\hat{q}$ values for for PbPb*.

$$1\,\text{GeV}^2 \lesssim C_F\hat{q}L \lesssim 8\,\text{GeV}^2, L = 4\,\text{fm}$$



Fraction of $D^0\bar{D}^0$ tagged jets w/out modification

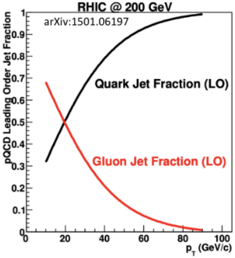


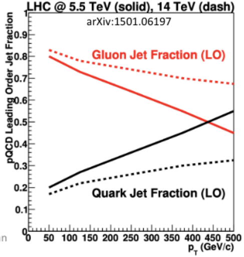
10-40% enhancement of $D^0\bar{D}^0$ tagged jets ⇒ novel test of BDMPS-Z picture.

Medium-induced charm meson production inside jets

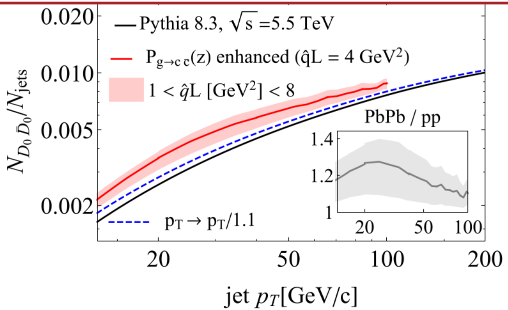
- Consider the fraction of jets with $D^0, \bar{D}^0$ pairs $\Rightarrow$ *contains $g \to c\bar{c}$ splitting.*
- Reweight each $g \to c\bar{c}$ splitting $\Rightarrow$ *explore range of $\hat{q}$ values for for PbPb*.

$$1\,\mathrm{GeV}^2 \lesssim C_F \hat{q} L \lesssim 8\,\mathrm{GeV}^2, L = 4\,\mathrm{fm}$$





Fraction of $D^0 \bar{D}^0$ tagged jets w/out modification



10-40% enhancement of $D^0 \bar{D}^0$ tagged jets $\Rightarrow$ novel test of BDMPS-Z picture.

Conclusions

Summary:

- Oxygen collisions at LHC and RHIC provide unique discovery opportunities.
- nPDF uncertainties $\Longrightarrow$ dominant source of theory uncertainties.
- Medium modification enhances $g \to c\bar{c}$ splitting.

Open questions

- Will sPHENIX measure absolute luminosity for light ions?
- How can sPHENIX contribute to constraining nPDF uncertainties (pO, pAr)?
- Is there feasibility to measure double heavy-flavour tagged jets?

If observed in OO, jet quenching will be clear signal of high-p_T partonic rescattering affecting high momentum observables in a system just a few times larger than pp.

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