⦿ Overview of Jet Physics and Energy Loss in QGP

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For the JETSCAPE Collaboration

JETSCAPE Summer School 2023

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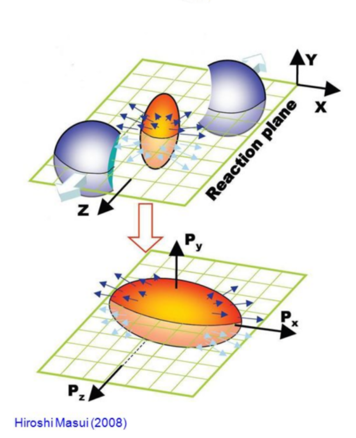
Introduction

Creation of QGP in HIC characterized by:

- Collective flow ⇒ see Lecture on last Wednesday
- Heavy flavor modification ⇒ see Lecture on next Monday
- Strangeness enhancement…
- Jet quenching



Hiroshi Masui (2008)

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[1] J. D. Bjorken, Fermilab-Pub-82/59-THY, Batavia (1982)

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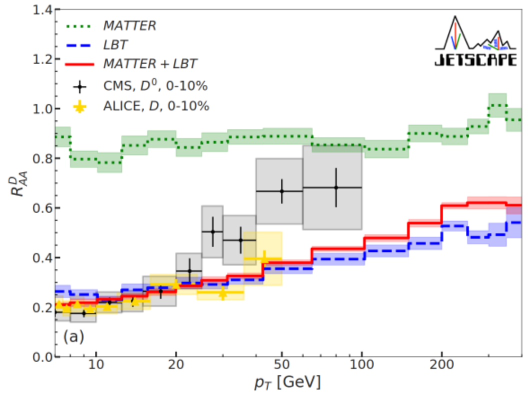

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⊙ Introduction

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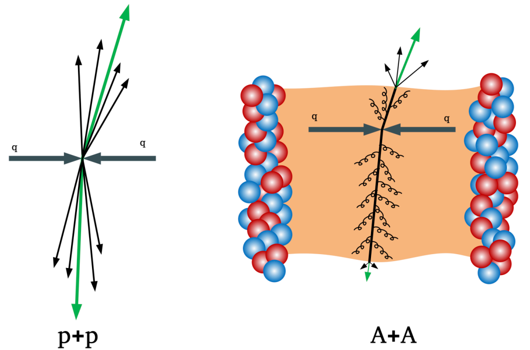

- In 80s, Bjorken predicted that QGP would "quench" these high p_T probes [1]

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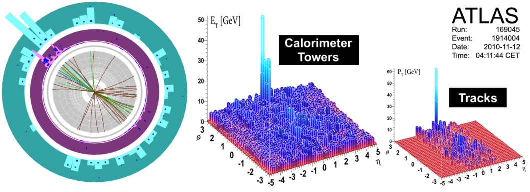
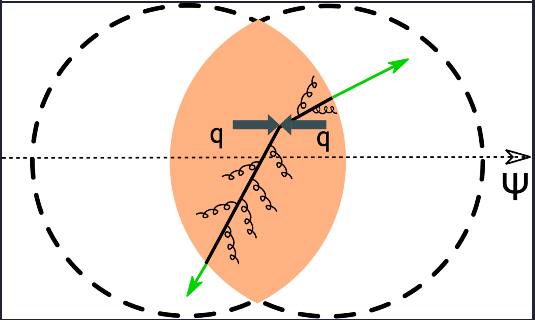
[1] J. D. Bjorken, Fermilab-Pub-82/59-THY, Batavia (1982)

Jet quenching?

- Hard probes created in early stages of HIC propagate through QGP before detection





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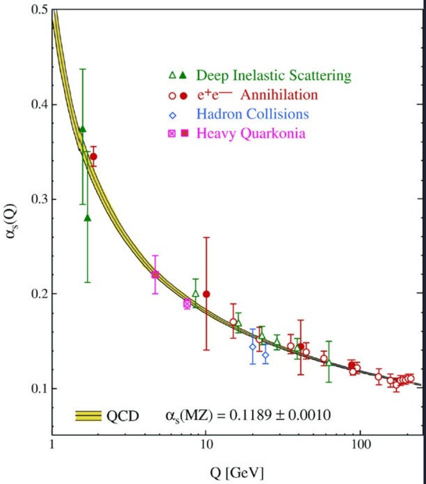
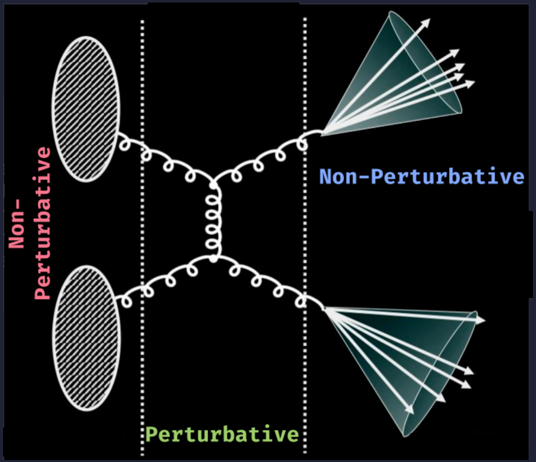
⊙ Factorization

- PDFs ⊗ Hard process ⊗ FFs



Factorization

- PDFs $\otimes$ Hard process $\otimes$ FFs
- Hard process timescale $t \sim 1/E \ll 1$
  $\Rightarrow$ Perturbative QCD



$$\frac{d\sigma^{AB\to H+X}}{d^2p_T dy} = \sum_{abcd} \int dx_a dx_b f_a^A(x_a, Q^2) f_b^B(x_b, Q^2) \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}} D_H^c(z_c, Q^2) \quad (1)$$

Factorization

- PDFs $\otimes$ Hard process $\otimes$ FFs
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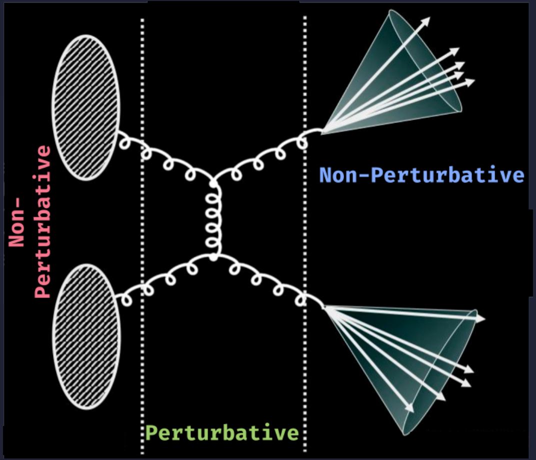
- PDFs and FFs non-perturbative $\Rightarrow$ Study variation with resolution scale Q^2 given by hard probes



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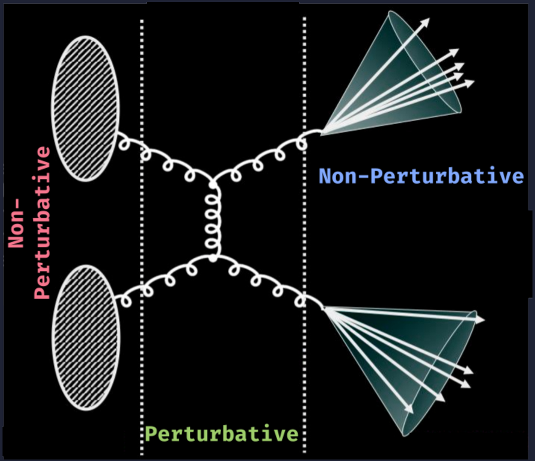
- PDF: Probability of finding parton a in hadron A with momentum fraction $x_a = \frac{p_a}{P_A}$



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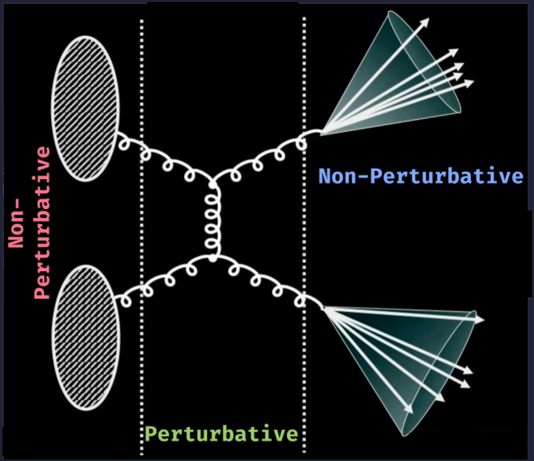

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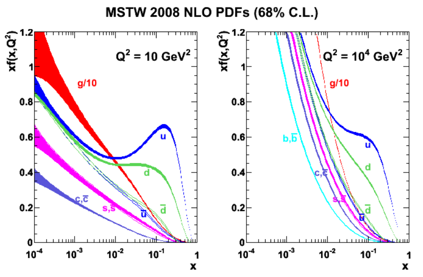
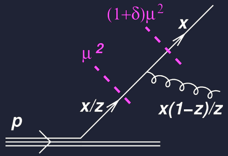
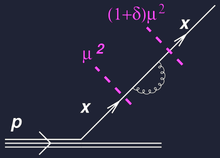
⊙ Parton distribution functions (PDFs)



- Universal ⇒ Extracted from DIS
- x: Momentum fraction of parton
- Q^2, μ^2, t: Momentum transfer
- DGLAP: scale evolution from $\mu^2 \to Q_0^2$
  ⇒ Resolve more and more sea quarks and gluons

$$\partial_{\ln \mu^2} D(x,\mu^2) = \underbrace{\int_x^1 \frac{dz}{z} P(z) D(x/z,\mu^2)}_{\text{Real}} - \underbrace{D(x,\mu^2)\int dz P(z)}_{\text{Virtual Diagram}}\,, \qquad (2)$$





Parton fragmentation

Using the Sudakov form factor:

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int_{z_0}^{1-\epsilon} dz\,\frac{\alpha_s(t')}{2\pi}\hat{P}_{a\to bc}(z)\right]. \tag{3}$$

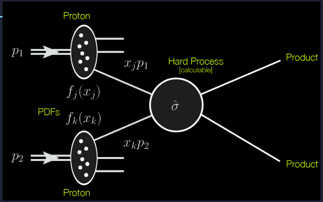
The DGLAP equation can be written as

$$D(z,t) = \Delta(t)D(z,t) + \int_{t_0}^{t}\frac{dt'}{t'}\frac{\Delta(t)}{\Delta(t')}\int\frac{dz}{z}\frac{\alpha_s}{2\pi}\hat{P}(z)D(z,t'). \tag{4}$$

- $\Delta(t)$: Probability of no branching between t_0 and t
- $\frac{\Delta(t)}{\Delta(t')}$: Probability of no branching between $t' \to t$
- $P(z)$: Probability distribution of the momentum fraction z of the branching
- Forward evolution in time from High virtual parton to lower virtualities

Initial State Radiation

- How to generate the fragmentation that happens before the scattering?



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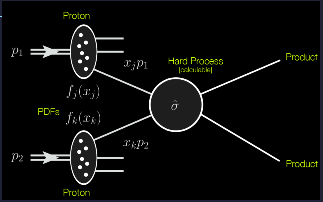

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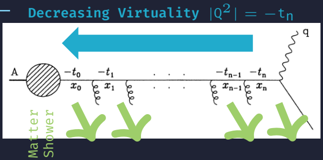

T. Sjostrand, Phys. Lett. B157 (1985) 321.
G. Marchesini and B.R. Webber, Nucl Phys. B310 (1988) 461.
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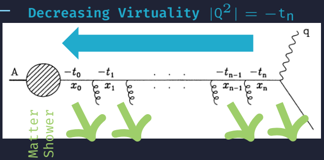
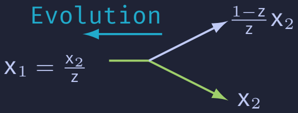
- The Sudakov is dependent on the PDF ⇒ limits the energy of earlier partons





Backward Sudakov

$$\Pi(t_1, t_2; x) = \frac{f(x,t_1)\Delta(t_2)}{f(x,t_2)\Delta(t_1)},$$

PDFs Sudakov

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Initial State Radiation

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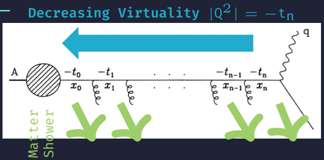
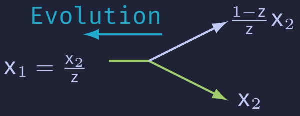
- The initial state radiation generated in backward shower, starting from 2 scattering partons
- The Sudakov is dependent on the PDF $\Rightarrow$ limits the energy of earlier partons
- Splitting probability also $\propto$ PDF





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$$\Pi(t_1, t_2; x) = \frac{f(x,t_1)\Delta(t_2)}{f(x,t_2)\Delta(t_1)} ,$$

PDFs Sudakov

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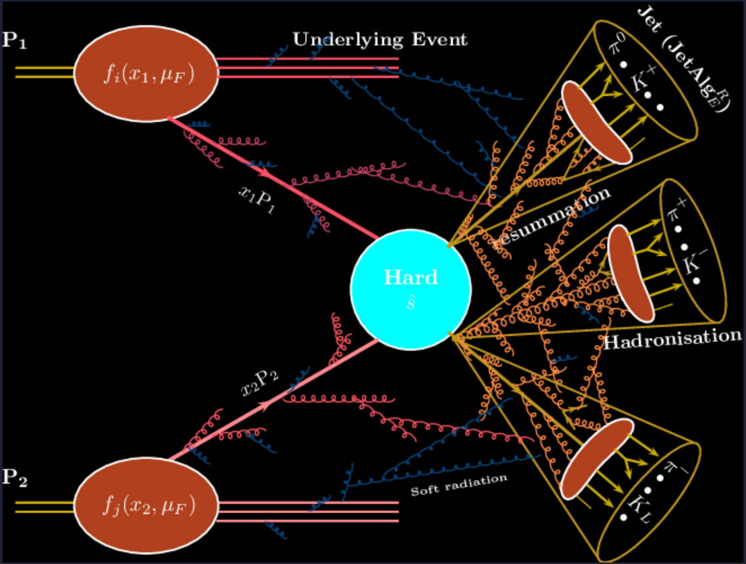
⊙ MonteCarlo Simulation: PYTHIA



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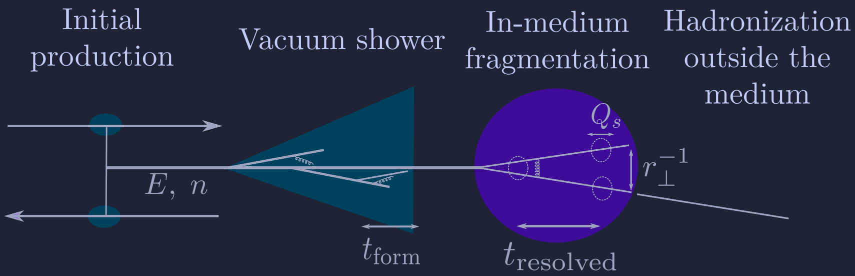
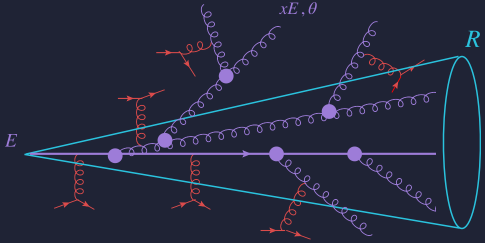
Jet-Medium Interactions

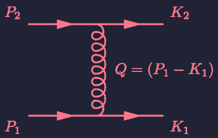


- HIC: hard partons cannot freely propagate to the detector.
- They must pass through the medium first.
- Hard process timescale t $\sim 1/E \ll 1$ not affected by medium
- Hard probes E $\gg$ T
  $\Rightarrow$ In-Medium Separation of scales

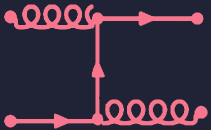


Jet-Medium Interactions

- Elastic Scattering:

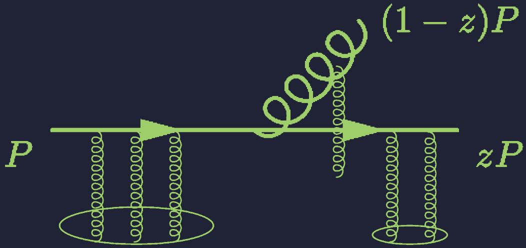


Diffusion/Drag



Conversion

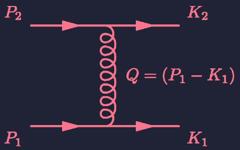
- Inelastic Scattering:



Elastic Scattering

Collision integral for elastic scattering

$$C_a^{2\leftrightarrow 2}[\{f_i\}] = \frac{1}{4|\boldsymbol{p}_1|\nu_a}\sum_{bcd}\int_{\boldsymbol{p}_2\boldsymbol{p}_3\boldsymbol{p}_4}\left|\mathcal{M}^{ab}_{cd}(\boldsymbol{p},\boldsymbol{p}_2;\boldsymbol{p}_3,\boldsymbol{p}_4)\right|^2(2\pi)^4\delta^{(4)}(P+P_2-P_3-P_4)$$
$$\times\left\{f_a(\boldsymbol{p})f_b(\boldsymbol{p}_2)(1\pm f_c(\boldsymbol{p}_3))(1\pm f_d(\boldsymbol{p}_4)) - f_c(\boldsymbol{p}_3)f_d(\boldsymbol{p}_4)(1\pm f_a(\boldsymbol{p}))(1\pm f_b(\boldsymbol{p}_2))\right\}\,,$$



⊙ Transport Coefficients

- Small Angle Approx. Boltzmann Eq. ⇒ Fokker-Planck Eq.

$$\boxed{C_a^{\mathrm{diff}}[\delta f] \equiv -\frac{\partial}{\partial p^i}\left[\eta_D(p) p^i \delta f^a(\boldsymbol{p})\right] - \frac{1}{2}\frac{\partial^2}{\partial p^i \partial p^j}\left[\left(\hat{p}^i\hat{p}^j \hat{q}_L(p) + \frac{1}{2}(\delta^{ij} - \hat{p}^i\hat{p}^j)\hat{q}(p)\right)\delta f^a(\boldsymbol{p})\right].}$$

- Longitudinal Drag: $\frac{dp_L}{dt} = -\int dq^z\, q^z \frac{d\Gamma(\boldsymbol{p}, \boldsymbol{p}-\boldsymbol{q})}{dq^z},$
- Longitudinal Diffusion: $\hat{q}_L(p) = \int dq^z\, (q^z)^2 \frac{d\Gamma(\boldsymbol{p}, \boldsymbol{p}+\boldsymbol{q})}{dq^z},$
- Transverse Diffusion: $\hat{q}(p) = \int d^2q_\perp\, q_\perp^2 \frac{d\Gamma(\boldsymbol{p}, \boldsymbol{p}+\boldsymbol{q})}{d^2q_\perp},$

$$\eta_D(p) = -\frac{1}{p_L}\frac{dp_L}{dt}, \qquad \hat{q}(p) \equiv \frac{d}{dt}\left\langle(\Delta p_\perp)^2\right\rangle, \qquad \hat{q}_L(p) \equiv \frac{d}{dt}\left\langle(\Delta p_L)^2\right\rangle,$$

⊙ In-Medium Parton Fragmentation I

- Medium scale governed by the transport coefficient

$$\hat{q} = \frac{1}{N_{\text{events}}} \sum_{i}^{N_{\text{events}}} \frac{(k_T^i)^2}{L_i} \,. \tag{5}$$

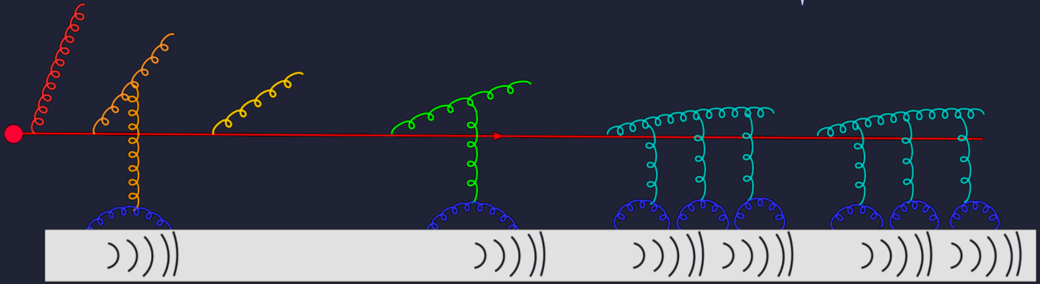
⇒ Typical momentum transfer per unit length

- Typical virtuality gained in the medium

$$Q^2_{\text{med}} \simeq \hat{q}\tau \,. \tag{6}$$

In-Medium Parton Fragmentation II

$$Q^2_{\text{med}} \simeq \hat{q}\tau\,, \quad \tau = \frac{2E}{Q^2}\,, \quad \Rightarrow Q^2_{\text{med}} \simeq \sqrt{2E\hat{q}}\,, \quad \tau_{\text{Transition}} \simeq \sqrt{\frac{2E}{\hat{q}}}\,. \qquad (7)$$



- Faster Vacuum formation $\tau \ll \sqrt{\frac{2E}{\hat{q}}}$ $\Rightarrow$ MATTER/PYTHIA-FSR phase $Q^2 \gg \sqrt{2E\hat{q}}$: Splitting dominated by the Medium modified virtuality-ordered shower
- Slower Vacuum formation $\tau \gg \sqrt{\frac{2E}{\hat{q}}}$ $\Rightarrow$ MARTINI/LBT $Q \ll \sqrt{2E\hat{q}}$: Jet-Medium interactions (vacuum splitting subdominant)

Coherence Effects

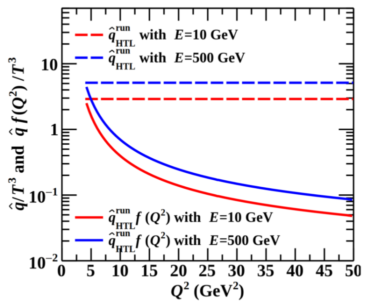
- How to bridge the gap between the two regimes?

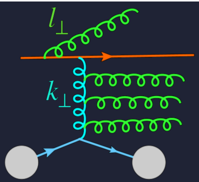
- $k_T^2 = \hat{q}L$ is not the full picture
- Medium may fluctuate to $k_T^2 \gg \hat{q}L$
- These fluctuations resolve smaller virtual dipoles
  $\Rightarrow$ Modification of the vacuum splitting
- Modifying[a] $\hat{q}$

$$\hat{q}(t) = \hat{q}_{\mathrm{fix}} f(Q)\,, \tag{8}$$

$$f(Q) = \begin{cases} \frac{1+10\ln^2(Q_{\mathrm{sw}}^2)+100\ln^4(Q_{\mathrm{sw}}^2)}{1+10\ln^2(Q^2)+100\ln^4(Q^2)} & Q < Q_{\mathrm{sw}} \\ 1 & Q > Q_{\mathrm{sw}} \end{cases}, \tag{9}$$

$Q_{\mathrm{sw}} \simeq 2\mathrm{GeV}$ is the switching scale





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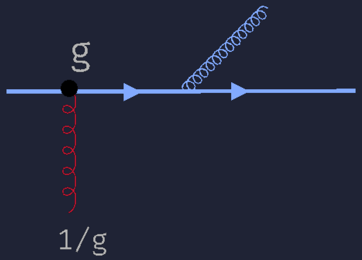
[a] A. Kumar, A.M., C. Shen, PRC 101 (2020) 034908

Medium-Induced Radiation

- For "on-shell" parton (virtuality $\ll \sqrt{\hat{q}E}$) Multiple scatterings with the medium can drive the parton slightly off-shell leading to radiation.
- Radiation enhanced in the collinear region



- Gluon propagator enhanced

$$D_{00}(\omega,\mathbf{q}) = \frac{-1}{q^2 + m_D^2 \Pi_{00}} \,, \quad D_{ij}(\omega,\mathbf{q}) = \frac{\delta_{ij} - \hat{\mathbf{q}}_i \hat{\mathbf{q}}_j}{q^2 + m_D^2 \Pi_T} \,, \quad \Rightarrow \frac{1}{m_D^2} \simeq \frac{1}{(gT)^2} \tag{10}$$

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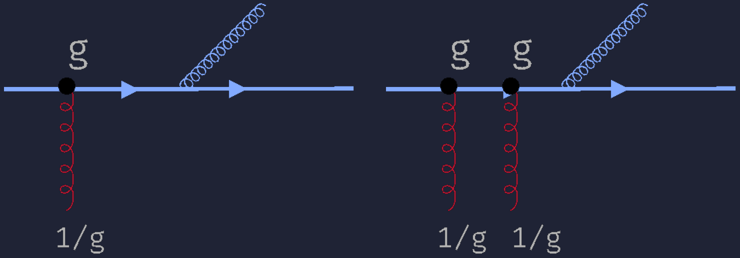

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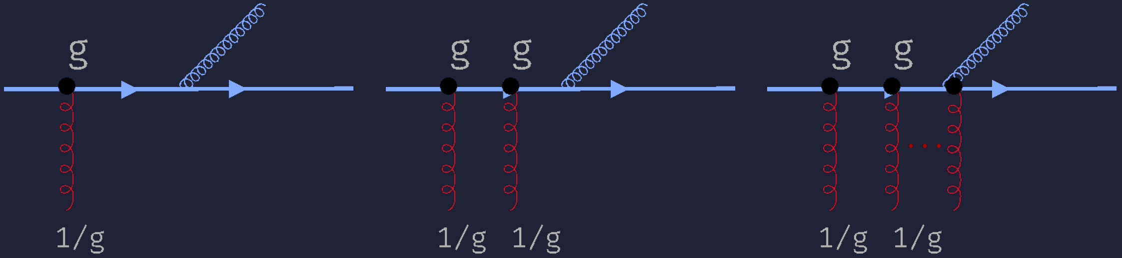

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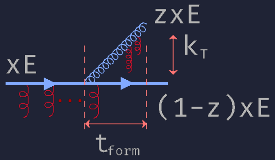
⊙ Medium-Induced Radiation

- >> Multiple scatterings
  ⇒ induced radiation

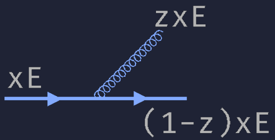


- >> Emission controlled by the formation time

$$t_{\text{form}} \sim \frac{z(1-z)xE}{k_T^2} \Rightarrow k_T^2 \sim \hat{q}\, t_{\text{form}} \qquad (11)$$

$$t_{\text{form}} \sim \sqrt{\frac{z(1-z)xE}{\hat{q}}} \Rightarrow \hat{q} \sim \frac{m_D^2}{\lambda_{\text{mfp}}} \qquad (12)$$

- >> Resummed into an effective $1 \leftrightarrow 2$



- >> $t_{\text{form}} \ll \lambda_{\text{mfp}}$: Medium cannot resolve the quanta until it is formed
- >> $t_{\text{form}} \gg \lambda_{\text{mfp}}$: Multiple scatterings act coherently

- >> Coherence effects lead to suppression of high energy radiation
  ⇒ LPM effect

---

[1] (Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Wiedemann, Arnold, Moore, Yaffe..)

⊙ Resummation of Medium-Induced Radiation

There are different approaches to resum the medium-induced radiation

- BDMPS-Z: Infinite medium ($L = \infty$) and medium interactions mediate by $\hat{q}$
  $\Rightarrow$ Harmonic oscillator | Analytic solution [2]

---

[2] R. Baier, Y. L. Dokshitzer, S. Peigne, and D. Schiff, Phys. Lett. B 345, 277 (1995), B. G. Zakharov, JETP Lett. 63, 952 (1996)

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[5] P. B. Arnold, G. D. Moore, and L. G. Yaffe, JHEP 01, 030 (2003)

[6] S. Caron-Huot and C. Gale, Phys. Rev. C 82, 064902 (2010)

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  $\Rightarrow$ Integro-Differential Equation[5]

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- (Improvement on HO and OE available) …

---

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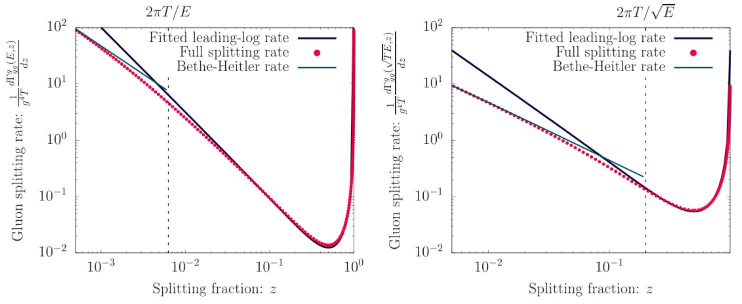
Different Regimes

- $\frac{d\Gamma}{dz}(P, z)$: Rate to radiate of a gluon with energy E to radiate a gluon zP after large time t in the medium

$E = \sqrt{1000}T$ Infinite Medium Rate $E = 1000T$



[7]

- BH (first Order Opacity Expansion): $t_{\text{form}} \ll \lambda_{\text{mfp}}$
- Single scattering is dominant

- Deep LPM: $t_{\text{form}} \gg \lambda_{\text{mfp}}$
- Multiple scatterings act coherently, $\hat{q}$ is enough to describe the medium

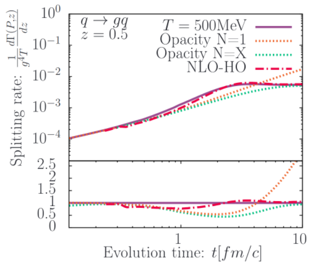
---

[7] JHEP 07 (2021), 077

⊙ Different Regimes

- $\frac{d\Gamma}{dz}(P, z)$: Rate to radiate of a quark with energy P to radiate a gluon zP after a time t in the medium

Finite Medium Rate



[7]

- Single Hard scattering dominate

---

[7] Phys.Rev.D 105 (2022) 7, 076002

Outline

- Introduction
- Factorization
- Jet Medium Interactions
- Multi-Stage Approach In Heavy-ion Collisions
- JETSCAPE Results
- Summary & Outlook

⊙ Multi-Stage Approach In Heavy-ion Collisions I

- Modular Framework for studying jets and bulk dynamics of HIC
- Latest version 3.5 available: github.com/JETSCAPE

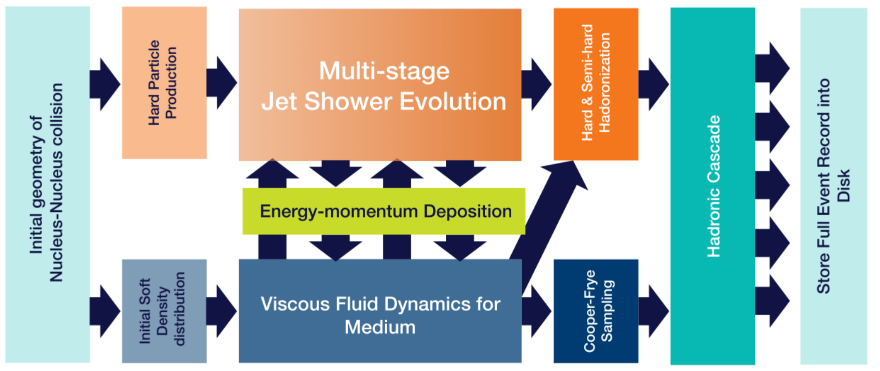


Diagram by
Y. Tachibana

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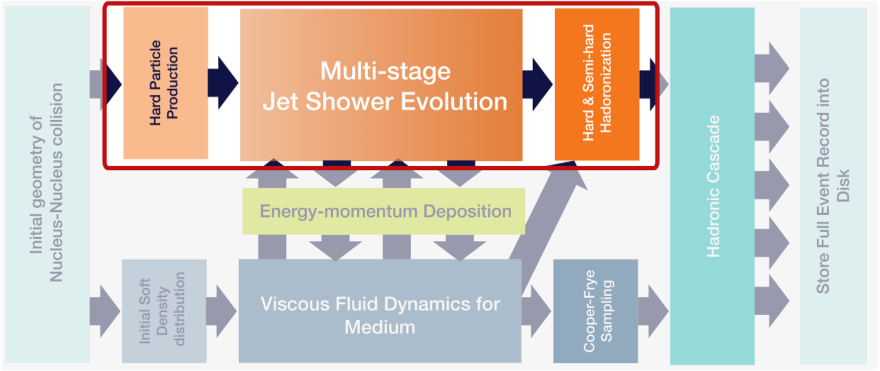

Diagram by
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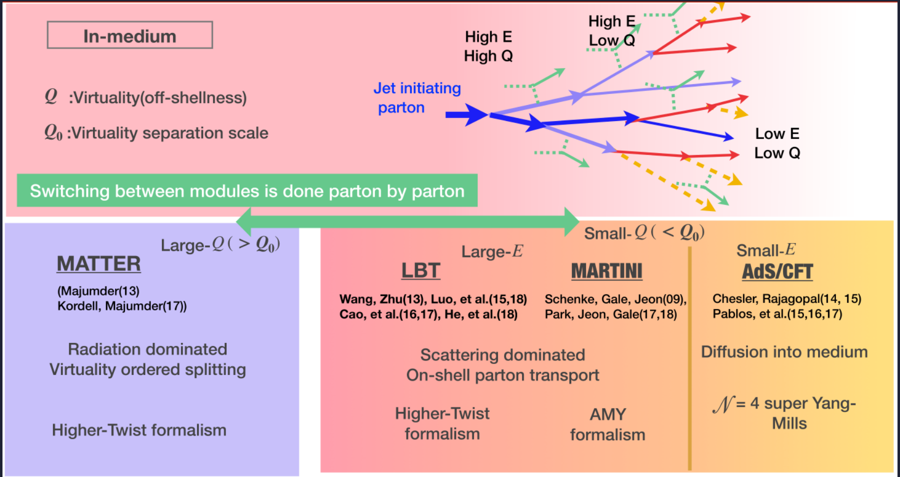
⊙ Multi-Stage Approach In Heavy-ion Collisions II



In-medium

Q :Virtuality(off-shellness)

Q_0 :Virtuality separation scale

Switching between modules is done parton by parton

Large-$Q\,(>Q_0)$

MATTER

(Majumder(13)
Kordell, Majumder(17))

Radiation dominated
Virtuality ordered splitting

Higher-Twist formalism

Small-$Q\,(<Q_0)$

Large-E

LBT

Wang, Zhu(13), Luo, et al.(15,18)
Cao, et al.(16,17), He, et al.(18)

MARTINI

Schenke, Gale, Jeon(09),
Park, Jeon, Gale(17,18)

Scattering dominated
On-shell parton transport

Higher-Twist formalism

AMY formalism

Small-E

AdS/CFT

Chesler, Rajagopal(14, 15)
Pablos, et al.(15,16,17)

Diffusion into medium

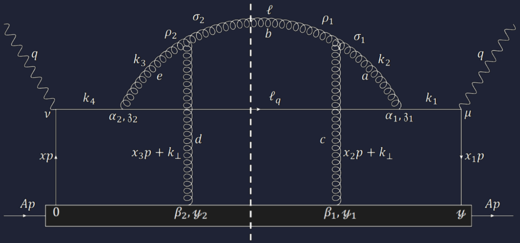
$\mathcal{N}=4$ super Yang-Mills

Diagram by
Y. Tachibana

⊙ MATTER

Modular All Twist Transverse-scattering Elastic-drag and Radiation (MATTER)[8]

- MonteCarlo simulation of medium modified DGLAP shower
- Jet-medium interactions governed by transport coefficient q̂



$$\frac{\partial D\left(z,Q^2,\zeta_i^-\right)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_z^1 \frac{dy}{y}\left[\underbrace{P_+(y)\,D\left(\frac{z}{y},Q^2,\zeta_i^-\right)}_{\text{Vacuum term}} + \underbrace{\left(\frac{P(y)}{y(1-y)}\right)_+ D\left(\frac{z}{y},Q^2,\zeta_i^-+\tau^-\right)\times\int_{\zeta_i^-}^{\zeta_i^-+\tau^-} d\zeta^- \frac{\hat{q}\left(\zeta^-\right)}{Q^2}\left\{2-2\cos\left(\frac{\zeta^- - \zeta_i^-}{\tau^-}\right)\right\}}_{\text{Medium term}}\right]$$

---

[8] Phys. Rev. C 88, 014909 (2013)
Phys. Rev. C 96, 024909 (2017)

⊙ LBT

Linear Boltzmann Transport (LBT)[9]

$$\partial_t f(x,\vec{p}) = C_{el}[f] + C_{inel}[f]\,. \tag{13}$$

- MonteCarlo simulation of jet-medium interactions
- Elastic LO $2 \leftrightarrow 2$ scattering
- Inelastic single gluon emission using Higher Twist ($\hat{q}$)

$$\frac{d\Gamma_a^{\rm inel}}{dzdk_\perp^2} = \frac{6\alpha_s P_a(z) k_\perp^4}{\pi(k_\perp^2 + z^2 m^2)^4}\frac{p\cdot u}{p_0}\hat{q}_a(x)\sin^2\frac{\tau-\tau_i}{2\tau_f},$$

- Multiple scatterings via Poisson distribution
- Medium-induced radiation probability

$$P^a_{\rm inel} = 1 - \exp[-\Delta\tau\Gamma_a^{\rm inel}(x)],\quad \Gamma_a^{\rm inel} = \frac{1}{1+\delta_g^a}\int dzdk_\perp^2\frac{d\Gamma_a^{\rm inel}}{dzdk_\perp^2}$$

---

[9] Phys. Rev. C 91, 054908 (2015)
Phys. Rev. C 94, 014909 (2016)

⊙ MARTINI

Modular Algorithm for Relativistic Treatment of heavy-IoN Interactions (MARTINI)[10]

$$\partial_t f(x, \vec{p}) = C_{el}[f] + C_{inel}[f]\,. \tag{14}$$

- MonteCarlo simulation of jet-medium interactions
- Elastic LO $2 \leftrightarrow 2$ scattering
- AMY infinite medium induced radiation

$$\frac{dP(p)}{dt} = \int_{-\infty}^{\infty} dk \left(P(p+k) \frac{d\Gamma(p+k,k)}{dk} - P(p) \frac{d\Gamma(p,k)}{dk} \right)$$

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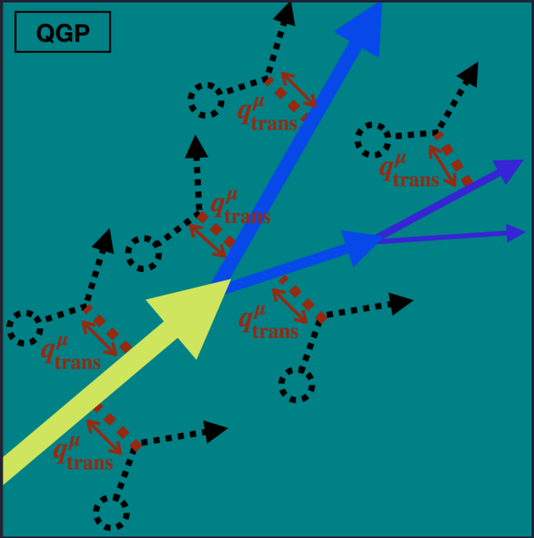
[10] JHEP 01, 030 (2003)
JHEP 06, 030 (2002)

⊙ Medium Response



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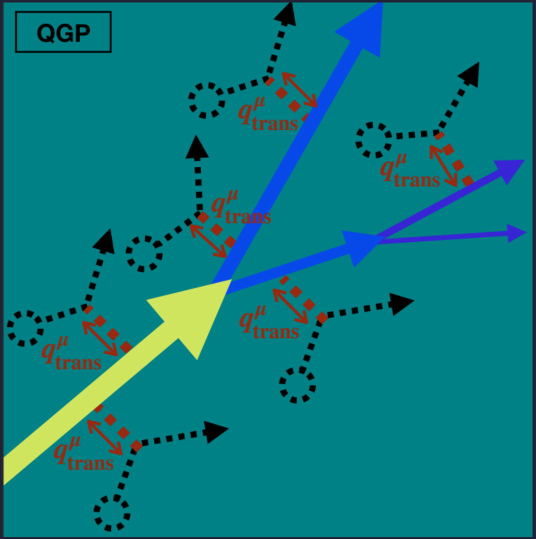

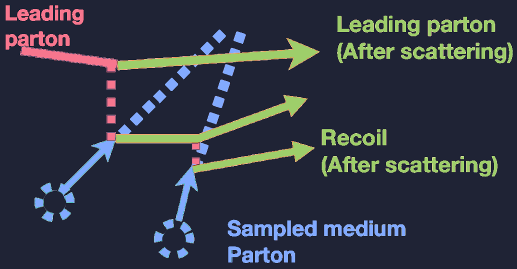

- Hard partons scatter off medium partons
- Partons sampled from medium ⇒ Hole (negative partons)
- Final state partons ⇒ Recoil (positive partons)
- Recoil − Hole = Medium Response

⊙ Outline

- ⊙ Introduction
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- ⊙ Multi-Stage Approach In Heavy-ion Collisions
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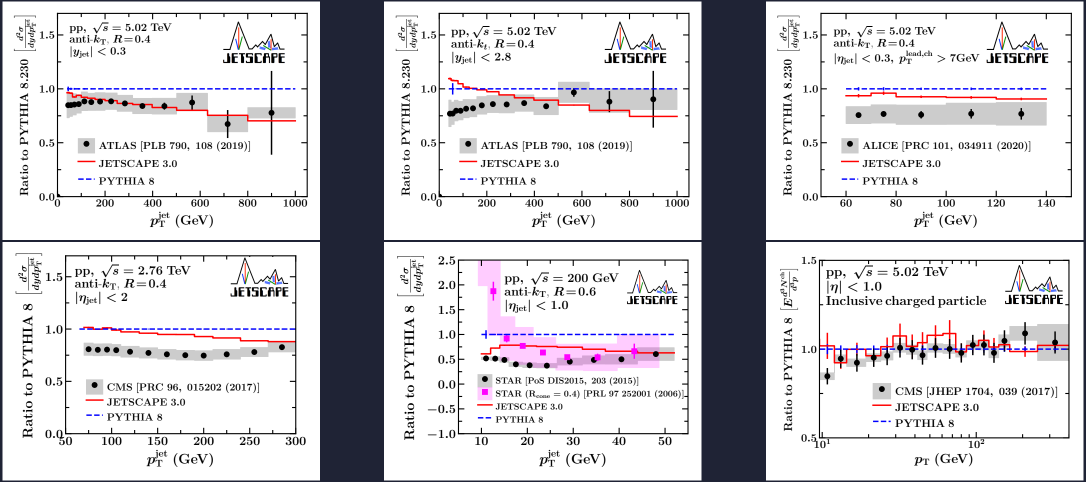
Reproduce pp Results



[11]

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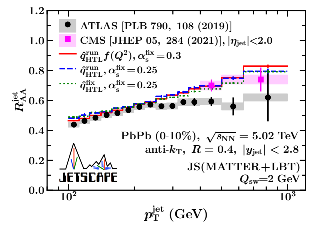
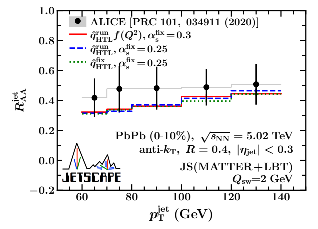
[11] Phys.Rev.C 107 (2023) 3, 034911

JETSCAPE R_{AA}

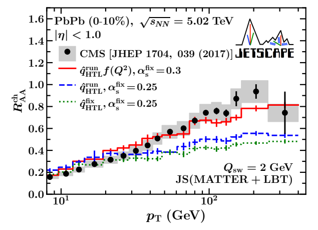
Jet ATLAS / CMS



Jet ALICE



Charged Hadron CMS



- Dashed blue: Fixed q̂
- Dotted green: Running q̂
- Solid red: Virtuality dependent $\hat{q} \cdot f(Q^2)$
    - $f(Q^2)$ is needed to describe both jet and hadron spectra

$$\hat{q} \cdot f = \hat{q}^{\rm fix}_{\rm HTL} = C_a \frac{50.484}{\pi} \alpha_s^{\rm fix} \alpha_s^{\rm fix} T^3 \ln\left[\frac{2ET}{m_D^2}\right],$$

$$\hat{q} \cdot f = \hat{q}^{\rm run}_{\rm HTL} = C_a \frac{50.484}{\pi} \alpha_s^{\rm run}(Q^2_{\rm max}) \alpha_s^{\rm fix} T^3 \ln\left[\frac{2ET}{m_D^2}\right],$$

where $Q^2_{\rm max} = 2ET$

$$\hat{q} \cdot f = \hat{q}^{\rm run}_{\rm HTL} f(Q^2)$$

$$f(Q^2) = \begin{cases} \frac{1+10\ln^2(Q^2_{\rm sw})+100\ln^4(Q^2_{\rm sw})}{1+10\ln^2(Q^2)+100\ln^4(Q^2)} & Q^2 > Q^2_{\rm sw} \\ 1 & Q^2 \leq Q^2_{\rm sw} \end{cases},$$

12

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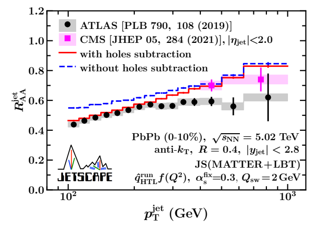
[12] Phys.Rev.C 107 (2023) 3, 034911

⊙ Medium Response

PbPb (0-10%)



13

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[13] Phys.Rev.C 107 (2023) 3, 034911

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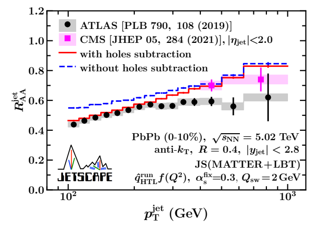
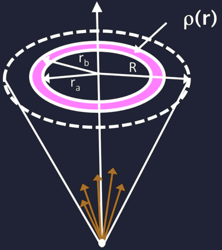
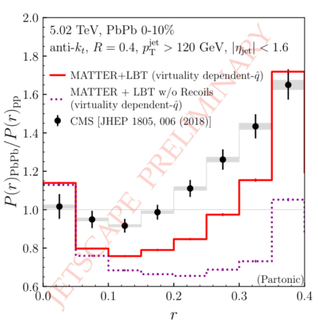




$$\rho(r) = \frac{1}{\delta r} \frac{\sum\limits_{r_{\rm a}<r_i<r_{\rm b}} p_{{\rm T},i}}{\sum\limits_{r_i<R} p_{{\rm T},i}},$$

Jet shape function:



/!\ Better description of Medium Response needed

⇒ 2-stage Hydro : Energy lost as source for Hydro

13

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[13] Phys.Rev.C 107 (2023) 3, 034911

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⊙ Summary & Outlook

- **Summary:**
  - Factorization allows a natural separation of scales
  - Multi-Stage approach employes the right model for the right scale
  - New approaches can bridge the gap between vacuum and medium
    ⇒ Important for the simultaneous description of jet and hadron observables

- **Coming up next:**
  - Today: Hands on tutorial to reproduce these results by Chathuranga Sirimanna
  - Monday: Lecture on Heavy flavor energy loss by Gojko Vujanovic

⊙ And thanks to all collaborators !

⊙ Outline

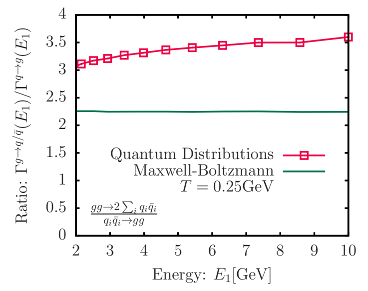
- ⊙ Backup Slides: Flavor Conversion

Flavor Conversion

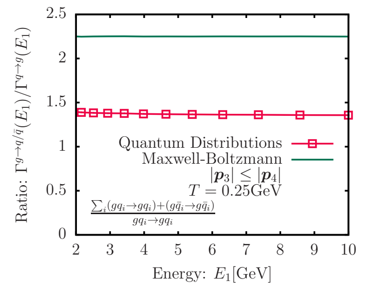
- >> Due to scatterings with the medium ⇒ Partons change flavor
- >> The rate of flavor conversion is determined by the d.o.f. of the medium

Ratio of the rate $\frac{\Gamma_{g\to q}}{\Gamma_{q\to g}}$

>> Annihilation $gg \to q\bar{q}$



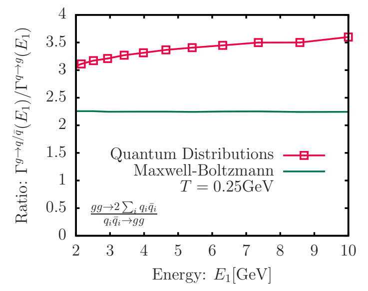
>> Scattering $gq_i \to gq_i$



Flavor Conversion

- Due to scatterings with the medium ⇒ Partons change flavor
- The rate of flavor conversion is determined by the d.o.f. of the medium
- Since gluon have a larger # partons to scatter of (quarks must scatter with other quarks of same flavor) ⇒ Gluons are converted to quarks at a higher rate than quarks to gluons

- Annihilation $gg \to q\bar{q}$



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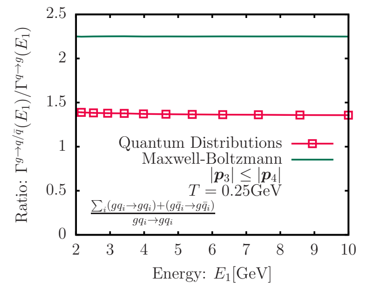
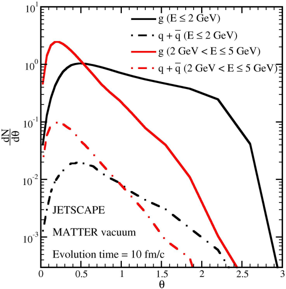
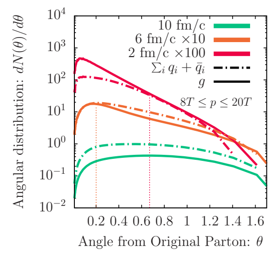
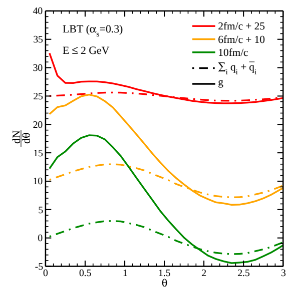


Flavor Composition Of The Shower

- >> Vacuum (MATTER)
- >> Kinetic evolution
- >> Vacuum + Energy loss (MATTER + LBT)







- >> Quark content of the in-medium shower is much more quark-like than in vacuum

⊙ Flavor Composition Of The Shower

- >> An order of magnitude increase in the fermion content of jets due to the medium.
- >> New transport coefficients needed to incorporate quark exchange in jet quenching discussion.
- >> Increase in fermion content affects conserved charge fluctuations, not energy profile of the jet.
- ⚠ Hadronization introduces own fluctuations and may introduce additional energy loss. (Work in progress)