Coherent gluon radiation beyond the leading-log[1,2]

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[1] based on collaboration w/ F. Arleo, S. Peigné and K. Watanabe

[2] supported by the ANR under grant No. 22-CE31-0018

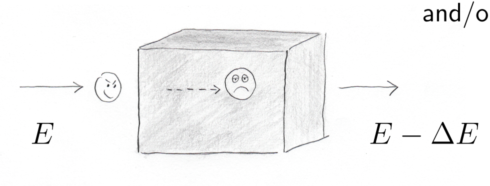
Parton energy loss

When passing through a medium (*hot* QGP, *cold* nucleus, ...),

a parton can lose energy due to collisions [Bjorken (1982)]

and/or via induced gluon radiation.

[Gyulassy, Wang (1993)]



Consider parton 'prepared' at $t = -\infty$ and scattered by a small angle after passing through the target at $t \approx 0 \ldots$

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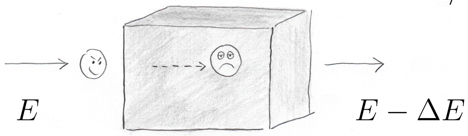


Consider parton 'prepared' at $t = -\infty$ and scattered by a small angle after passing through the target at $t \approx 0$...

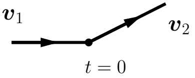
Main message: fully coherent energy loss (FCEL) dominates for large-E:

$$\Delta E_{\text{FCEL}} \propto \alpha_s \frac{\Delta p_\perp}{M_\perp} E$$

Reminder:

EM radiation spectrum from moving charges,

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega\,\mathrm{d}\Omega} = \frac{e^2}{4\pi}\left|\frac{\boldsymbol{n}\times\boldsymbol{v}_1}{1-\boldsymbol{n}\cdot\boldsymbol{v}_1} - \frac{\boldsymbol{n}\times\boldsymbol{v}_2}{1-\boldsymbol{n}\cdot\boldsymbol{v}_2}\right|^2$$



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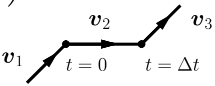

'formation time' $t_f \equiv \dfrac{1}{\omega(1-\boldsymbol{n}\cdot\boldsymbol{v}_2)}$

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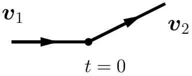

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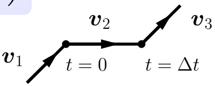

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(suppression of radiation)

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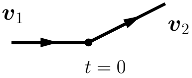

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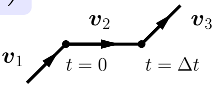
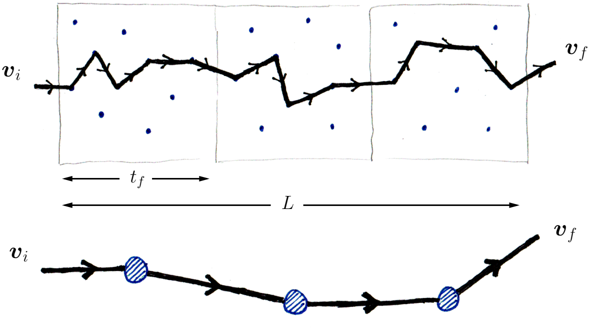


'formation time' $t_f \equiv \dfrac{1}{\omega(1-\boldsymbol{n}\cdot\boldsymbol{v}_2)} \approx \dfrac{1}{\omega\,\theta^2} \approx \dfrac{\omega}{k_\perp^2}$ as $\theta \to 0$

$t_f \gg$ dist. between scatterings $\Rightarrow$ *destructive interference* **(suppression of radiation)**

Momentum **broadening**: $\langle k_\perp^2 \rangle \sim \hat{q}\, t_f$ where $\hat{q} =$ 'diffusion' coefficient



kicks occasionally induce gluon radiation

... which cannot be resolved instantaneously!

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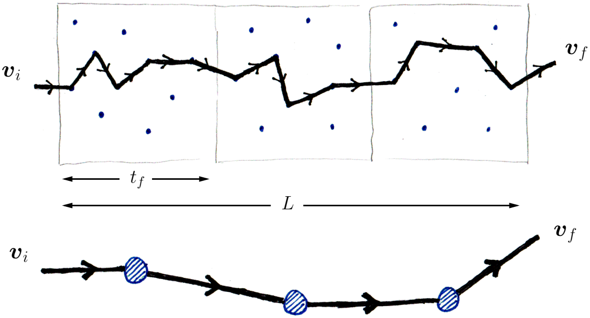

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$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_L \sim \frac{L}{t_f} \times \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_1 \sim \alpha_s L \sqrt{\frac{\hat{q}}{\omega}}$$

QED: [LPM (1953-6)]

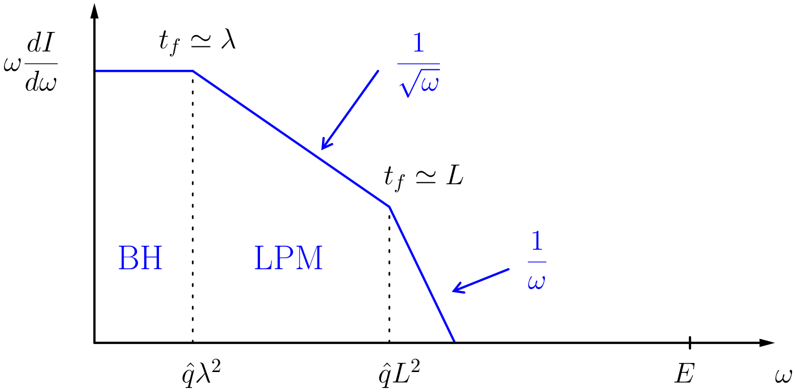
QCD: [BDMPS-Z (1996)]

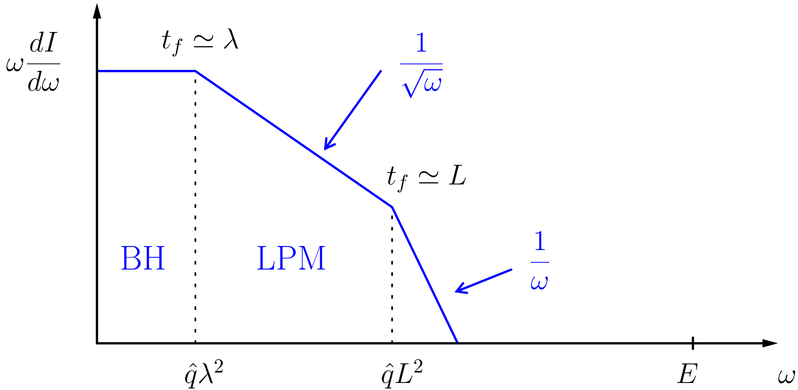
Regimes of radiation

$$\mathrm{d}I \equiv \frac{\mathrm{d}\sigma_{\mathrm{rad}}}{\sigma_{\mathrm{el}}} = \left(\frac{\sum |\mathcal{M}_{\mathrm{rad}}|^2}{\sum |\mathcal{M}_{\mathrm{el}}|^2}\right) \frac{\mathrm{d}k^+ \mathrm{d}^2\boldsymbol{k}_\perp}{2k^+(2\pi)^3}$$

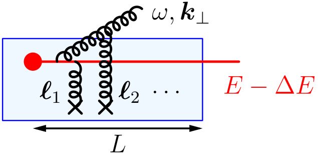
- **Bethe-Heitler (BH):** $t_f \ll \lambda$
  $\Rightarrow$ each scattering centre acts as an indep. source
- **Landau-Pomeranchuk-Migdal (LPM):** $\lambda \ll t_f \ll L$
  $\Rightarrow$ group of t_f/λ scattering centres acts as single radiator
- **Fully coherent energy loss (FCEL):** $t_f \gg L$
  $\Rightarrow$ *all* scattering centres in the medium act coherently

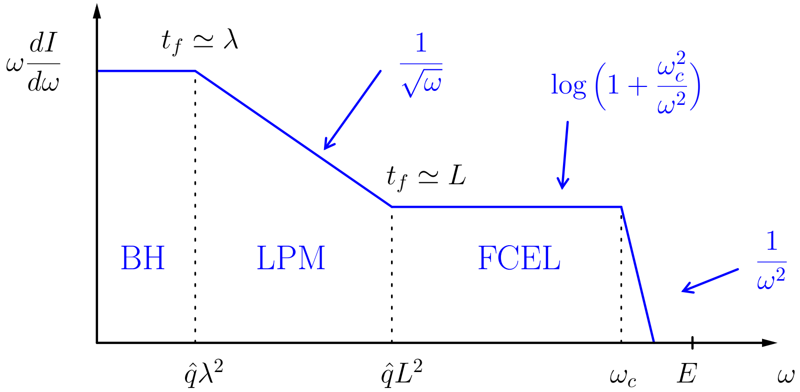
... but which one is most important??


$\omega \frac{dI}{d\omega}$
$t_f \simeq \lambda$
$\frac{1}{\sqrt{\omega}}$
$t_f \simeq L$
BH
LPM
$\frac{1}{\omega}$
$\hat{q}\lambda^2$
$\hat{q}L^2$
E
ω



Need to distinguish two physical situations: Arleo, Peigné, Sami [1006.0818]





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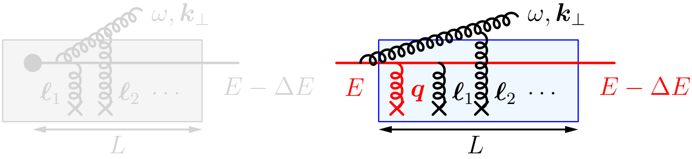
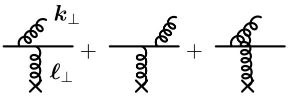


The fully coherent regime

$t_f \gg L \;\Rightarrow\;$ entire medium acts as effective scatterer:



$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega\, \mathrm{d}^2\boldsymbol{k}_\perp} = N_c \frac{\alpha_s}{\pi^2} \frac{\ell_\perp^2}{k_\perp^2 (\boldsymbol{k}_\perp - \boldsymbol{\ell}_\perp)^2}$$

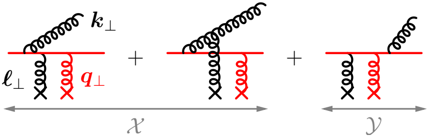
[Gunion, Bertsch (1982)]

$$\Rightarrow\; \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \;\sim\; \alpha_s \int_{Q_1}^{Q_2} \frac{\mathrm{d}k_\perp}{k_\perp} \;=\; \alpha_s \log \frac{Q_2}{Q_1}$$

The fully coherent regime

Incoming parton, undergoes hard process ($\boldsymbol{q}_\perp$)

and *multiple* soft scatterings ($\boldsymbol{\ell}_\perp \sim \sqrt{\hat{q}L} \ll \boldsymbol{q}_\perp$)



$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \log\left(\frac{\hat{q}L\, E^2}{\omega^2 M^2}\right)$$

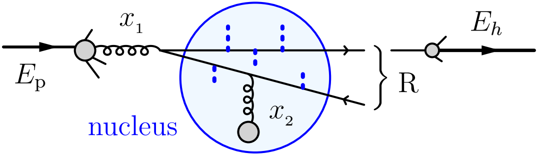
- $|\mathcal{X}|^2$ and $|\mathcal{Y}|^2$ cancel out in the induced spectrum $\mathrm{d}I/\mathrm{d}\omega$
- Interference terms, $\mathrm{Re}(\mathcal{X}\mathcal{Y}^\star)$, do not cancel in the induced spectrum!
- Gluon spectrum computed rigorously in several formalisms:

Peigné, Arleo, Kolevatov [1402.1671]

Liou, Mueller [1402.1647]

Munier, Peigné, Petreska [1603.01028]

E.g. heavy flavour from underlying process $gg \to (Q\bar{Q})_{\rm R}$



$$\omega \frac{{\rm d}I}{{\rm d}\omega}\bigg|_{\rm R} = (C_1 + C_{\rm R} - C_2)\frac{\alpha_s}{\pi}\left[\log\left(1+\frac{\hat{q}L_{\rm A}\, E^2}{\omega^2 M^2}\right) - {\rm pp}\right]$$

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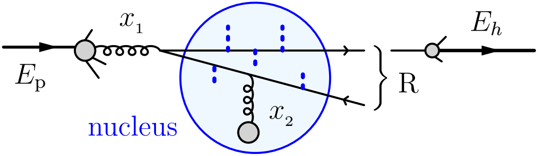

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Leading-log accuracy: *Pointlike dijet approx. (PDA)*

$$Q_1 = \quad xM \ll k_\perp \ll \sqrt{\hat{q}L} \quad = Q_2$$

Radiation cannot probe $Q\bar{Q}$ dijet constituents

$x \equiv \frac{\omega}{E}$; $M^2 = x_1 x_2 s$

Wavelength *can* resolve medium-induced sep. from broadening: $\ell_\perp^2 = \hat{q}L$

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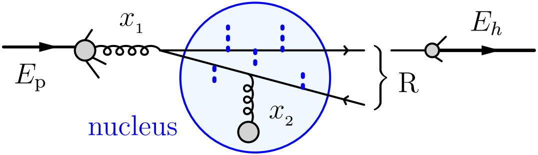

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Colour prefactor stems from *interference* between initial state and final state radiation:

$$\begin{aligned} 2\,T^a_{\mathrm{R}_1}\,T^a_{\mathrm{R}} &= (T^a_{\mathrm{R}_1})^2 + (T^a_{\mathrm{R}})^2 - (T^a_{\mathrm{R}} - T^a_{\mathrm{R}_1})^2 \\ &= C_1 + C_{\mathrm{R}} - C_2\,, \end{aligned}$$

where the T^a are Hermitian generators of SU(3).

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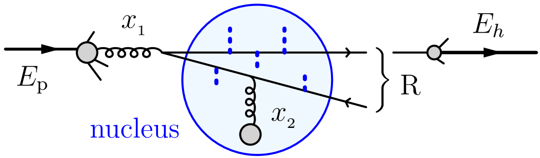

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Also applies for $2 \to 1$ type processes, where R is the colour rep. of the outgoing parton:

$$gg \to g \quad : \quad F_c \;=\; N_c + N_c - N_c \;=\; N_c$$

$$q\bar{q} \to g \quad : \quad F_c \;=\; C_F + N_c - C_F \;=\; N_c$$

$$qg \to q \quad : \quad F_c \;=\; C_F + C_F - N_c \;=\; -1/N_c \quad (< 0\,!)$$

Parametric dependence

☞ LPM energy loss (small formation time $t_f \lesssim L$)

$$\Delta E_{\text{LPM}} \;\propto\; \alpha_s \; \hat{q} \; L^2$$

- hadron production in nuclear DIS
- parton suddenly accelerated (e.g. jet in QGP)

☞ Coherent energy loss (large formation time $t_f \gg L$)

$$\Delta E_{\text{FCEL}} \;\propto\; \alpha_s \; F_c \; \frac{\sqrt{\hat{q}L}}{M_\perp} \; E$$

- needs colour in both initial & final state (otherwise $F_c = 0$)
- important at all energies, in particular large rapidity
- hadron production in pA collisions

Average ΔE is not sufficient!

... need probability distribution, **Quenching weight** $\mathcal{P}(\varepsilon)$

$$\frac{1}{A}\,\frac{\mathrm{d}\sigma^h_{\mathrm{pA}}}{\mathrm{d}E}\big(E,\sqrt{s}\big) = \int_0^{\varepsilon_{\max}} \mathrm{d}\varepsilon\; \mathcal{P}(\varepsilon, E)\; \frac{\mathrm{d}\sigma^h_{\mathrm{pp}}}{\mathrm{d}E}\big(E+\varepsilon,\sqrt{s}\big)$$

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$$\mathcal{P}(\varepsilon, E) \leftarrow \frac{\mathrm{d}I}{\mathrm{d}\varepsilon}\exp\left\{-\int_\varepsilon^\infty \mathrm{d}\omega\,\frac{\mathrm{d}I}{\mathrm{d}\omega}\right\}$$

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Phenomenology:

Applied to a variety of processes in pA collisions

- quarkonia — Arleo, Peigné [1212.0434]
- light hadrons — Arleo, Cougoulic, Peigné [2003.06337]
- open heavy-flavour — Arleo, GJ, Peigné [2107.05871]
- neutrinos from D decays — Arleo, GJ, Peigné [2112.10791]

Goal ☞ FCEL baseline ≡ model w/ minimal assumptions

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significant QCD effect!

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Colour probabilities

Need to sum over available states R: $$\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y} = \sum_{\mathrm{R}} \int_0^1 \mathrm{d}\xi \, \rho_{\mathrm{R}}(\xi) \frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\mathrm{R}}}{\mathrm{d}y \, \mathrm{d}\xi}$$

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depends on pair's combined colour ...

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depends on pair's combined colour ...

$$
\begin{aligned}
\mathbf{3} \otimes \bar{\mathbf{3}} &= \mathbf{1} \oplus \mathbf{8} \\
\mathbf{3} \otimes \mathbf{3} &= \bar{\mathbf{3}} \oplus \mathbf{6} \qquad \bar{\mathbf{3}} \otimes \bar{\mathbf{3}} = \mathbf{3} \oplus \bar{\mathbf{6}} \\
\mathbf{3} \otimes \mathbf{8} &= \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15} \\
\mathbf{8} \otimes \mathbf{8} &= \mathbf{0} \oplus \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}
\end{aligned}
$$

Exercise: for $qg \to qg$, what's the probability to end as a 15-plet?

(expressions for $\mathcal{M}$ and $\mathbb{P}_R$ can be found in backup slides)

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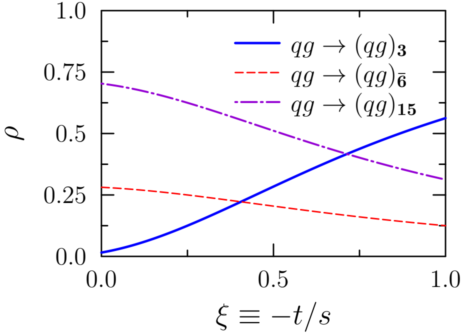
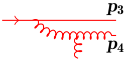
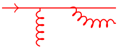


Beyond leading-log accuracy

☞ final parton pair no longer 'pointlike,' irrep *not* preserved

Consider the underlying hard process to be $q\,g \to q\,g$:

$$\mathcal{M}^{\mathrm{vac}}_{qg\to qg} \equiv \mathcal{M} =$$ 

$+$  $+$ 

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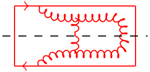
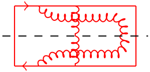
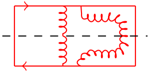
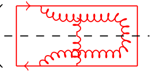
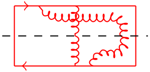
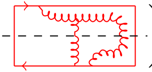
$|\mathcal{M}|^2 =$  $+$  $+$ 

$+\ 2\Big($  $+$  $+$  $\Big)$

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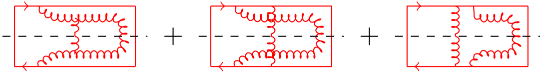
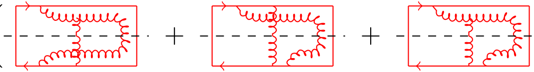


$+\ 2\,\Big($

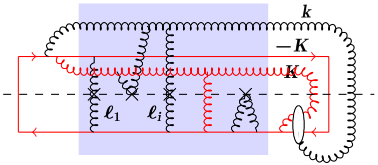


$\Big)$

induced spectrum $\mathrm{d}I = \sum_n \mathrm{d}I^{(n)}$ ... ($n =$ number of soft rescatterings)

$$x\,\frac{\mathrm{d}I^{(n)}}{\mathrm{d}x} = \frac{\alpha_s}{\pi}\int\frac{\mathrm{d}^2\boldsymbol{k}}{\pi}\left[\prod_{i=1}^{n}\int\frac{\mathrm{d}z_i}{N_\mathrm{c}\lambda_g}\int\mathrm{d}^2\boldsymbol{\ell}_i\ V(\boldsymbol{\ell}_i)\right]\ C_n(\boldsymbol{k},\boldsymbol{K})\ ,$$

$$C_n(\boldsymbol{k},\boldsymbol{K}) = \frac{2}{|\mathcal{M}|^2}\left\{\right.$$



$$\left. + \quad \ldots \right\}$$

... it can be done, for any $2 \to 2$ process: GJ, Peigné, Watanabe [2312.11650]

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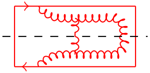
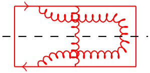
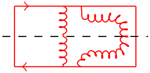
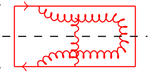
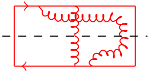
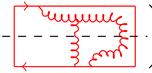
$|\mathcal{M}|^2 =$  $+$  $+$ 

$+\,2\Big($  $+$  $+$  $\Big)$

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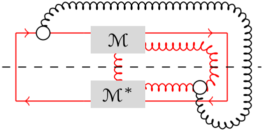
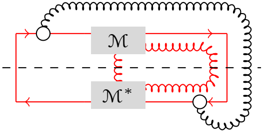
$$x\frac{\mathrm{d}I}{\mathrm{d}x} = \frac{\alpha_s}{\pi}\,\frac{2}{|\mathcal{M}|^2}\Bigg\{\ \mathcal{L}\left(\xi\,;\,\frac{\sqrt{\hat{q}L_\mathrm{A}}}{xM}\right)$$



$$+\,\mathcal{L}\left(1-\xi\,;\,\frac{\sqrt{\hat{q}L_\mathrm{A}}}{xM}\right)$$



$$\Bigg\}$$

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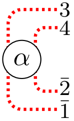
$$\frac{\mathrm{d}I}{\mathrm{d}x} = \Phi_{\alpha\beta}\, S(x)_{\beta\alpha} = \mathrm{Tr}\left\{\Phi \cdot S(x)\right\}$$

colour decompose the hard amplitude: (red dots can be any parton)

colour indices only

$$\mathcal{M}_{12\to 34} = \sum_\alpha \nu_\alpha \langle\alpha| \,, \quad \text{where } \langle\alpha| \equiv \frac{1}{\sqrt{d_\alpha}}$$



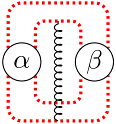
kinematics, spin, flavour

colour density matrix

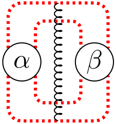
$$\Phi_{\alpha\beta} = \frac{\mathrm{tr_d}(\nu_\alpha \nu^*_\beta)}{\mathrm{tr_c}\,\mathrm{tr_d}\,|\mathcal{M}|^2}$$

soft radiation matrix

$$S(x)_{\alpha\beta} = \frac{\alpha_s}{\pi\, x}\frac{2}{\sqrt{d_\alpha d_\beta}} \Bigg(\mathcal{L}(\xi)$$



$$+\, \mathcal{L}(\bar{\xi})$$



$$\Bigg)$$

Reminder: $\mathcal{L}(\xi) \simeq \log\left(1 + \xi^2 \frac{\hat{q} L_\mathrm{A}}{x^2 m_\perp^2}\right) - \log\left(1 + \xi^2 \frac{\hat{q} L_\mathrm{p}}{x^2 m_\perp^2}\right)$

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Leading-log: $\xi = \bar{\xi} = \frac{1}{2}$ or $\mathcal{L}(\xi) \simeq \mathcal{L}(\bar{\xi}) \gg 1$:

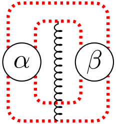
final parton pair is 'pointlike' $\Rightarrow$ soft radiation conserves pair irrep.

$(T_1 + T_2 = T_\alpha = T_3 + T_4)$

$$\langle\alpha|\, 2\, T_1\, T_\alpha\, |\beta\rangle = \langle\alpha|\, T_1^2 + T_\alpha^2 - T_2^2\, |\beta\rangle = (C_1 + C_\alpha - C_2)\delta_{\alpha\beta}$$

$$\left.\frac{\mathrm{d}I}{\mathrm{d}x}\right|_{\xi=\frac{1}{2}} = \sum_\alpha \Phi_{\alpha\alpha}(C_1 + C_\alpha - C_2)\frac{\alpha_s}{\pi\, x}\mathcal{L}(\tfrac{1}{2})$$

$\equiv \rho_\alpha$ (probability to be in α)

$$S(x)_{\alpha\beta} = \frac{\alpha_s}{\pi\, x}\frac{2}{\sqrt{d_\alpha d_\beta}}\Bigg(\mathcal{L}(\xi)$$


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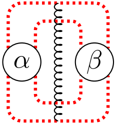

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$\equiv \rho_\alpha$ (probability to be in α)

Beyond leading-log, or $\xi \neq \frac{1}{2}$:

soft gluon can change parton pair irreps, "colour transitions"

(without probing its spatial size $\rightarrow$ *non-Abelian feature*)

E.g. underlying LO process $q\,g \to q\,g$: $\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$

$$\Phi(\xi) = \frac{1}{C_F\xi^2 + N_c\bar{\xi}} \begin{pmatrix} C_F\left(\bar{\xi} + \frac{1}{d_A}\right)^2 & \frac{U_1 D_2}{2\sqrt{2}}\left(\bar{\xi} + \frac{1}{d_A}\right) & -\frac{U_2 D_1}{2\sqrt{2}}\left(\bar{\xi} + \frac{1}{d_A}\right) \\ \frac{U_1 D_2}{2\sqrt{2}}\left(\bar{\xi} + \frac{1}{d_A}\right) & \frac{N_c(N_c - 2)}{4(N_c - 1)} & -\frac{N_c}{4}\frac{U_2 D_2}{U_1 D_1} \\ -\frac{U_2 D_1}{2\sqrt{2}}\left(\bar{\xi} + \frac{1}{d_A}\right) & -\frac{N_c}{4}\frac{U_2 D_2}{U_1 D_1} & \frac{N_c(N_c + 2)}{4(N_c + 1)} \end{pmatrix}$$

$$\langle\alpha|\, 2\,T_1\,T_4\,|\beta\rangle = \frac{1}{2}\begin{pmatrix} \frac{N_c(N_c^2 - 3)}{N_c^2 - 1} & -\frac{\sqrt{2}N_c\,U_1\,D_2}{d_A} & -\frac{\sqrt{2}N_c\,D_1\,U_2}{d_A} \\ -\frac{\sqrt{2}N_c\,U_1\,D_2}{d_A} & \frac{3N_c^2 - 5N_c + 3}{(N_c - 1)^2} & -\frac{N_c\,U_2\,D_2}{U_1\,D_1} \\ -\frac{\sqrt{2}N_c\,D_1\,U_2}{d_A} & -\frac{N_c\,U_2\,D_2}{U_1\,D_1} & \frac{3N_c^2 + 5N_c + 3}{(N_c + 1)^2} \end{pmatrix}$$

where $\bar{\xi} = 1 - \xi\,,\; d_A = N_c^2 - 1\,,\; U_k \equiv \sqrt{N_c + k}$ and $D_k \equiv \sqrt{N_c - k}$

(general `qgraf` and `FORM` code provided) GJ, Peigné, Watanabe [2312.11650]

Basis to diagonalize $S(x)$

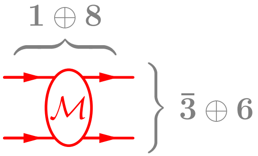
$$\left.\frac{\mathrm{d}I}{\mathrm{d}x}\right|_{\xi=\frac{1}{2}} = \sum_{\alpha} \rho_\alpha \left(C_1 + C_\alpha - C_2\right) \frac{\alpha_s}{\pi\, x} \mathcal{L}(\tfrac{1}{2})$$

$$\left.\frac{\mathrm{d}I}{\mathrm{d}x}\right|_{\xi\to 0} = \sum_{\alpha^t} \rho^t_{\alpha^t} \left(C_1 + C_3 - C_{\alpha^t}\right) \frac{\alpha_s}{\pi\, x} \mathcal{L}(1)$$

$$\left.\frac{\mathrm{d}I}{\mathrm{d}x}\right|_{\xi\to 1} = \sum_{\alpha^u} \rho^u_{\alpha^u} \left(C_1 + C_4 - C_{\alpha^u}\right) \frac{\alpha_s}{\pi\, x} \mathcal{L}(1)$$

E.g. $\xi \to \frac{1}{2}$ best viewed in 's-channel basis'

$\xi \to 0$ . . . 't-channel basis'



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$$\left.\frac{\mathrm{d}I}{\mathrm{d}x}\right|_{\xi\to 0} = \left[\,\rho^t_{\mathbf{1}}(2\,C_F) + \rho^t_{\mathbf{8}}\,(2\,C_F - N_c)\,\right]\frac{\alpha_s}{\pi\,x}\,\mathcal{L}(1)$$

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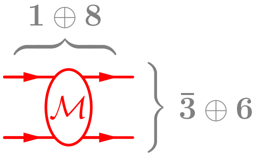

An unusual effect: *fully coherent energy gain* (FCEG)

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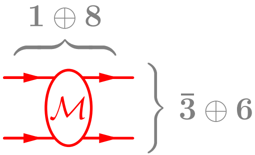

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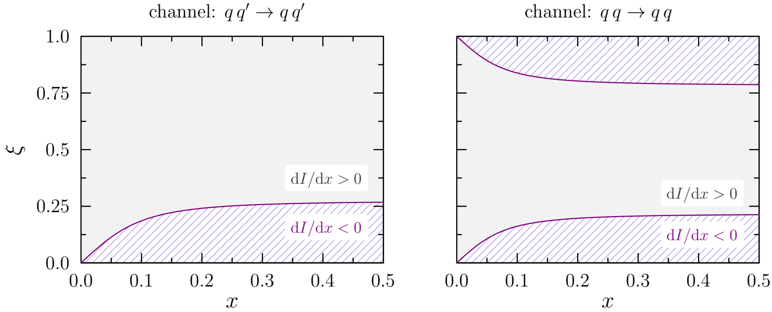

Summary

Arxiv: 2003.06337
2107.05871
2112.10791
2312.11650

- coherent E-loss predicted from QCD

  ⇒ important at all energies, from colliders to cosmic rays!

- FCEL(G) beyond leading-log accuracy

  ⇒ *colour transitions*, spectrum can be negative

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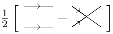
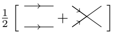
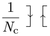
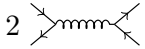
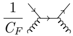
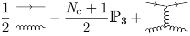
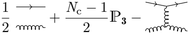
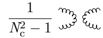
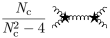
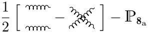
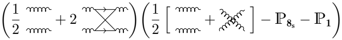
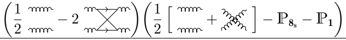
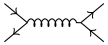
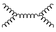
- coherent E-loss predicted from QCD
  $\Rightarrow$ important at all energies, from colliders to cosmic rays!
- FCEL(G) beyond leading-log accuracy
  $\Rightarrow$ *colour transitions*, spectrum can be negative

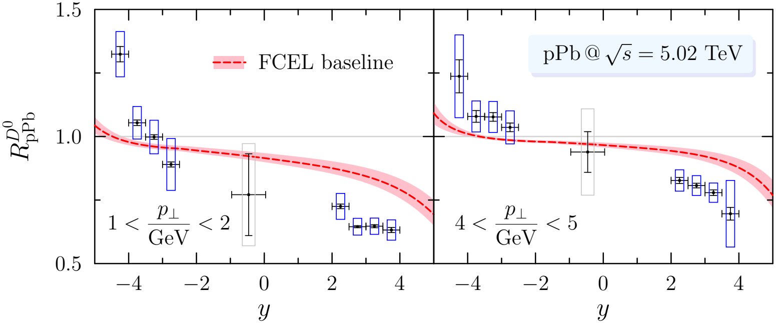
challenge: derive a quenching weight $\mathcal{P}(x)$ valid for any ξ

system	irreps α	projectors $\mathbb{P}_\alpha$	dimensions d_α	Casimirs C_α
$\mathbf{3}\otimes\mathbf{3}$	$\bar{\mathbf{3}}$		$\frac{1}{2}N_\mathrm{c}(N_\mathrm{c}-1)$	$2C_F-\dfrac{N_\mathrm{c}+1}{N_\mathrm{c}}$
	$\mathbf{6}$		$\frac{1}{2}N_\mathrm{c}(N_\mathrm{c}+1)$	$2C_F+\dfrac{N_\mathrm{c}-1}{N_\mathrm{c}}$
$\mathbf{3}\otimes\bar{\mathbf{3}}$	$\mathbf{1}$		1	0
	$\mathbf{8}$		N_c^2-1	N_c
$\mathbf{3}\otimes\mathbf{8}$	$\mathbf{3}$		N_c	C_F
	$\bar{\mathbf{6}}$		$\frac{1}{2}N_\mathrm{c}(N_\mathrm{c}+1)(N_\mathrm{c}-2)$	$C_F+N_\mathrm{c}-1$
	$\mathbf{15}$		$\frac{1}{2}N_\mathrm{c}(N_\mathrm{c}-1)(N_\mathrm{c}+2)$	$C_F+N_\mathrm{c}+1$
$\mathbf{8}\otimes\mathbf{8}$	$\mathbf{1}$		1	0
	$\mathbf{8}_\mathrm{a}$		N_c^2-1	N_c
	$\mathbf{8}_\mathrm{s}$		N_c^2-1	N_c
	$\mathbf{10}\oplus\overline{\mathbf{10}}$		$\frac{1}{2}(N_\mathrm{c}^2-1)(N_\mathrm{c}^2-4)$	$2N_\mathrm{c}$
	$\mathbf{27}$		$\frac{1}{4}N_\mathrm{c}^2(N_\mathrm{c}-1)(N_\mathrm{c}+3)$	$2(N_\mathrm{c}+1)$
	$\mathbf{0}$		$\frac{1}{4}N_\mathrm{c}^2(N_\mathrm{c}+1)(N_\mathrm{c}-3)$	$2(N_\mathrm{c}-1)$

channel	$\mathcal{M}$	$\dfrac{\mathrm{tr_d}\,\mathrm{tr_c}\lvert\mathcal{M}\rvert^2}{4g^4(N^2-1)}$	α	$\dfrac{\nu_\alpha}{\sqrt{d_\alpha}}$
$qq' \to qq'$	$\mathcal{A}$ 	$\dfrac{1+\bar\xi^2}{2\xi^2}$	$\bar{\mathbf{3}}$	$\mathcal{A}\,\frac{N_c+1}{2N_c}$
			$\mathbf{6}$	$-\mathcal{A}\,\frac{N_c-1}{2N_c}$
$qq \to qq$	$\mathcal{B}_t$  $+\,\mathcal{B}_u$ 	$\dfrac{1+\xi^2}{2\bar\xi^2}+\dfrac{1+\bar\xi^2}{2\xi^2}-\dfrac{1}{N_c\xi\bar\xi}$	$\bar{\mathbf{3}}$	$\frac{N_c+1}{4N_c}\,(\mathcal{B}_t-\mathcal{B}_u)$
			$\mathbf{6}$	$-\frac{N_c-1}{4N_c}\,(\mathcal{B}_t+\mathcal{B}_u)$
$q\bar q' \to q\bar q'$	$\mathcal{C}$ 	$\dfrac{1+\bar\xi^2}{2\xi^2}$	$\mathbf{1}$	$C_F\,\mathcal{C}$
			$\mathbf{8}$	$-\frac{1}{2N_c}\,\mathcal{C}$
$q\bar q \to q'\bar q'$	$\mathcal{D}$ 	$\dfrac{\xi^2+\bar\xi^2}{2}$	$\mathbf{1}$	0
			$\mathbf{8}$	$\frac{1}{2}\,\mathcal{D}$
$q\bar q \to q\bar q$	$\mathcal{E}_s$  $+\,\mathcal{E}_t$ 	$\dfrac{\xi^2+\bar\xi^2}{2}+\dfrac{1+\bar\xi^2}{2\xi^2}+\dfrac{\bar\xi^2}{N_c\xi}$	$\mathbf{1}$	$C_F\,\mathcal{E}_t$
			$\mathbf{8}$	$\frac{1}{2}\big(\mathcal{E}_s-\frac{1}{N_c}\mathcal{E}_t\big)$
$qg \to qg$	$\mathcal{F}\,\Big[$  $-\,\xi$  $\Big]$	$(1+\bar\xi^2)\Big(\dfrac{N_c}{\xi^2}+\dfrac{C_F}{\bar\xi}\Big)$	$\mathbf{3}$	$\Big(\frac{1}{2N_c}+\bar\xi C_F\Big)\,\mathcal{F}$
			$\bar{\mathbf{6}}$	$\frac{1}{2}\,\mathcal{F}$
			$\mathbf{15}$	$-\frac{1}{2}\,\mathcal{F}$
$gg \to gg$	$\mathcal{G}\,\Big[$  $-\,\xi$  $\Big]$	$4N_c^2\dfrac{(1-\xi\bar\xi)^3}{\xi^2\bar\xi^2}$	$\mathbf{8}_\mathrm{a}$	$\frac{N_c}{2}(\bar\xi-\xi)\,\mathcal{G}$
			$\mathbf{10}\oplus\overline{\mathbf{10}}$	0
			$\mathbf{1}$	$N_c\,\mathcal{G}$
			$\mathbf{8}_\mathrm{s}$	$\frac{N_c}{2}\,\mathcal{G}$
			$\mathbf{27}$	$-\mathcal{G}$
			$\mathbf{0}$	$\mathcal{G}$
$gg \to q\bar q$	$\mathcal{H}\,\Big[$  $-\,\xi$  $\Big]$	$(\xi^2+\bar\xi^2)\Big(\dfrac{C_F}{\xi\bar\xi}-N_c\Big)$	$\mathbf{1}$	$\frac{\sqrt{N_c^2-1}}{2\sqrt{N_c}}\,\mathcal{H}$
			$\mathbf{8}_\mathrm{a}$	$\frac{1}{2}\,(\bar\xi-\xi)\,\frac{\sqrt{N_c}}{\sqrt{2}}\,\mathcal{H}$
			$\mathbf{8}_\mathrm{s}$	$\frac{\sqrt{N_c^2-4}}{2\sqrt{2N_c}}\,\mathcal{H}$

D-meson production at LHCb

Nuclear modification @ LHC: (assuming dominance of $gg \to Q\bar{Q}$)



- Accounts for $\approx$ half of the observed suppression
- Small relative uncertainties ($\lesssim 10\%$) Arleo, GJ, Peigné [2107.05871]

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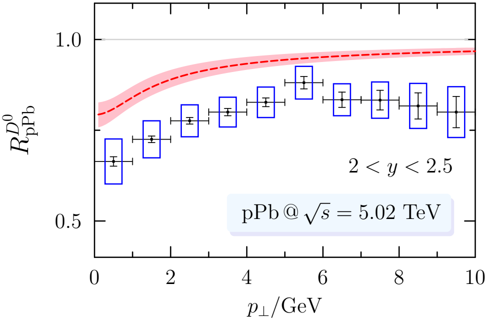

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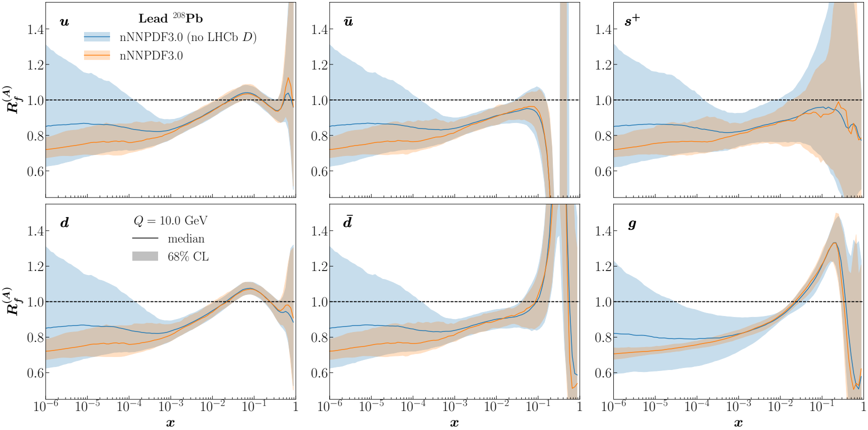
- Small relative uncertainties ($\lesssim 10\%$) Arleo, GJ, Peigné [2107.05871]

nPDFs w/ and w/o LHCb D-meson data

$$f_i^{\mathrm{A}} = Z\, R_i^{\mathrm{p/A}} f_i^{\,\mathrm{p}} + (A - Z)\, R_i^{\mathrm{n/A}} f_i^{\,\mathrm{n}}$$



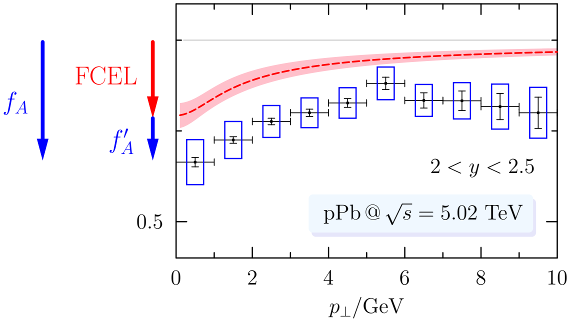
- Huge uncertainty on gluon shadowing

nNNPDF3.0 [2201.12363]

- Strong constraints given by forward D-meson data

D-meson production at LHCb

Nuclear modification @ LHC: $R^h_{\rm pA}\left(y,\, p_\perp; \sqrt{s}\right) = \frac{1}{A}\, \frac{{\rm d}\sigma^h_{\rm pA}}{{\rm d}y\,{\rm d}p_\perp} \Big/ \frac{{\rm d}\sigma^h_{\rm pp}}{{\rm d}y\,{\rm d}p_\perp}$



$f_A \neq f'_A$

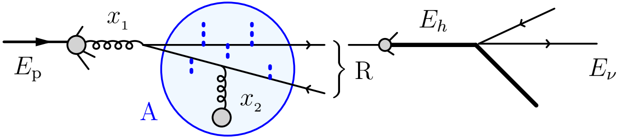
- $\chi^2\left(f'_A \,\middle|\, \text{FCEL} \cap \text{LHCb data}\right)$ vs. $\chi^2\left(f_A \,\middle|\, \text{no FCEL} \cap \text{LHCb data}\right)$
- Given new info (data/theory), nPDFs can be **reweighted**

[work in progress w/ Arleo, Watanabe]

Atmospheric neutrinos at IceCube

High-E cosmic rays (protons) impinge on $\langle A \rangle \simeq 14.5 \;\Rightarrow$ air shower

[Gondolo, Ingelman, Thunman (1996)]



Event generators for extensive air showers, e.g. SYBILL [1806.04140]

atm. neutrinos = main background to astrophysical ν's

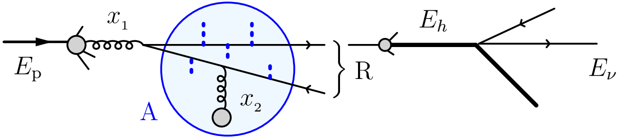
Reminder: $\Delta E_{\text{FCEL}} \;\propto\; \alpha_s \; F_c \; \dfrac{\sqrt{\hat{q}L}}{M_\perp} \; E \;\; \sim A^{1/6}$

$\Rightarrow$ FCEL should also be significant for light ions!

Atmospheric neutrinos at IceCube

High-E cosmic rays (protons) impinge on $\langle A \rangle \simeq 14.5 \;\; \Rightarrow$ air shower

[Gondolo, Ingelman, Thunman (1996)]



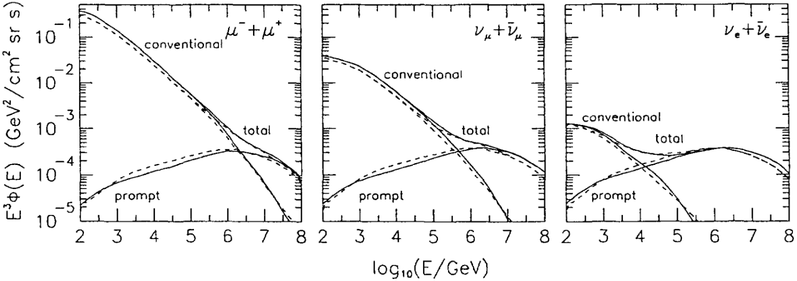


Fig. 3. The E^3-weighted vertical flux of muons, muon–neutrinos and electron–neutrinos from conventional (π, K decays) and prompt (charm decays) sources and their sum ('total'). The solid lines are from the cascade simulation (Section 3) and the dashed lines are from the analytic Z-moment method (Section 4).

Atmospheric neutrinos at IceCube

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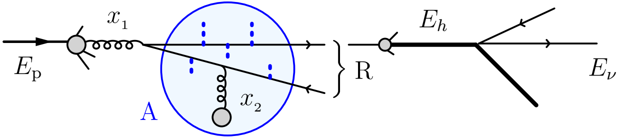
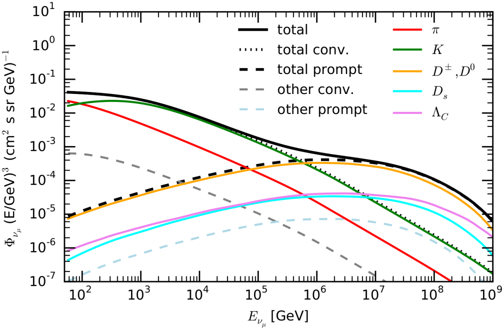
Feydynitch, *et al.* [1806.04140]





Atmospheric neutrinos at IceCube

High-E cosmic rays (protons) impinge on $\langle A \rangle \simeq 14.5$ $\Rightarrow$ air shower

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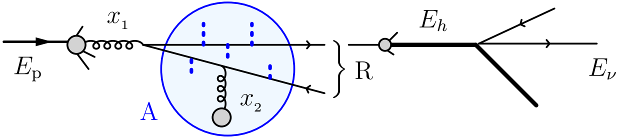
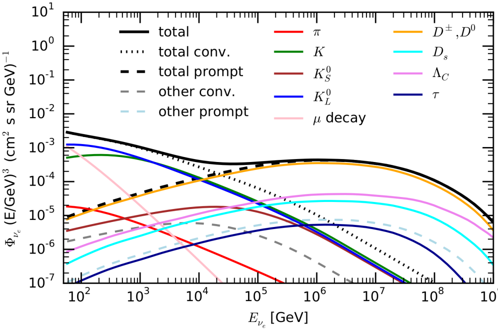
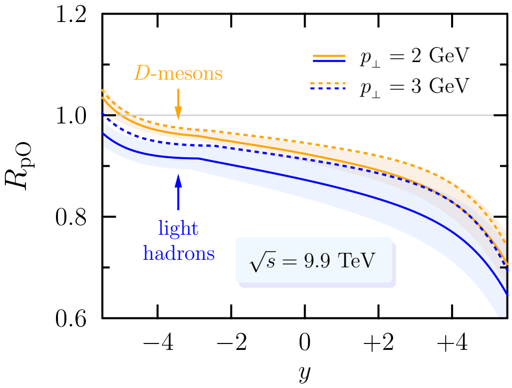




OO and pO @ LHC?

Possible opportunity at the LHC? Foreseen collision energy, $\sqrt{s} = 9.9$ TeV
$\Rightarrow$ CR proton energy $E_p = 5.2 \times 10^7$ GeV in the oxygen rest frame.

CERN workshop [2103.01939]



physics of air showers is related to particle prod. at *forward* rapidities!

Method of Z-moments: $$\Phi_\nu(E_\nu) = \frac{\Phi_\mathrm{p}(E_\nu)}{1 - Z_\mathrm{pp}} \sum_h \frac{Z_{\mathrm{p}h}\, Z_{h\nu}}{1 + B_h E_\nu \cos\theta/\varepsilon_h}$$

- Proton regeneration Z_pp
- Hadron generation $Z_{\mathrm{p}h}$
- Semi-leptonic decay $Z_{h\nu}$

Method of Z-moments: $$\Phi_\nu(E_\nu) = \frac{\Phi_{\rm p}(E_\nu)}{1 - Z_{\rm pp}} \sum_h \frac{Z_{{\rm p}h}\, Z_{h\nu}}{1 + B_h E_\nu \cos\theta / \varepsilon_h}$$

- Proton regeneration $Z_{\rm pp}$
- Hadron generation $Z_{{\rm p}h}(E) \propto \int_0^1 \frac{{\rm d}x_{\sf F}}{x_{\sf F}} \Phi_{\rm p}\left(\frac{E}{x_{\sf F}}\right) \frac{{\rm d}\sigma^h_{\rm pA}}{{\rm d}x_{\sf F}}\left(x_{\sf F}; \frac{E}{x_{\sf F}}\right)$
- Semi-leptonic decay $Z_{h\nu}$

where $\Phi_{\rm p} \sim E_{\rm p}^{-\gamma}$

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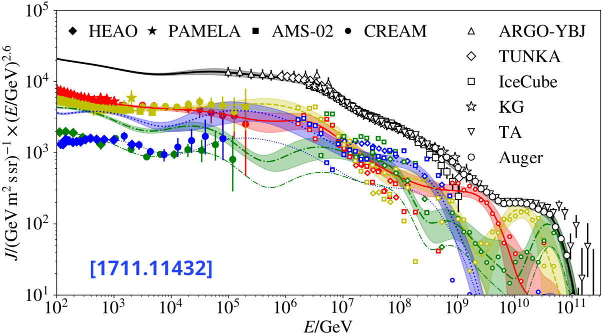
- Semi-leptonic decay $Z_{h\nu}$ where $\Phi_{\rm p} \sim E_{\rm p}^{-\gamma}$



Depletion of neutrinos by FCEL

Modification factor: Arleo, GJ, Peigné [2112.10791]

... focus on promt ν's: (h=charm)

$$Z_{\mathrm{p}c}(E) \;\propto\; \int_0^1 \frac{\mathrm{d}x_F}{x_F} \Phi_{\mathrm{p}}\left(\frac{E}{x_F}\right) \frac{\mathrm{d}\sigma^c_{\mathrm{pA}}}{\mathrm{d}x_F}\left(x_F, \frac{E}{x_F}\right) \equiv \Omega(E)$$

FCEL rescales $x_F \to x_F/z$ with prob. $\mathcal{F}(z)$ $\quad \left(x = \frac{1}{1+x}\right)$

$$\Rightarrow R_\nu(E) \;\equiv\; \frac{\Omega^{\mathrm{FCEL}}(E)}{\Omega(E)} \;=\; \int_0^1 \mathrm{d}z\, \mathcal{F}(z) \frac{\Omega(E/z)}{\Omega(E)} \;<\; 1$$

Ideal case: $\Phi_{\mathrm{p}}(E) \propto E^{-\gamma}$ and $\mathrm{d}\sigma^c_{\mathrm{pp}}/\mathrm{d}x_F$ fnc. of x_F only

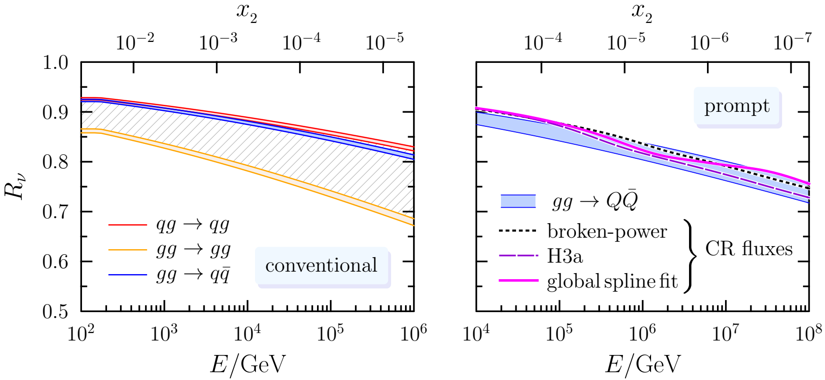
$$\Rightarrow R_\nu = \int_0^1 \mathrm{d}z\, z^\gamma\, \mathcal{F}(z)$$

depends on E via $\hat{q}(x_2)$ w/ $x_2 \sim \frac{M^2_{c\bar{c}}}{4m_{\mathrm{p}}E}$

Depletion of neutrinos by FCEL

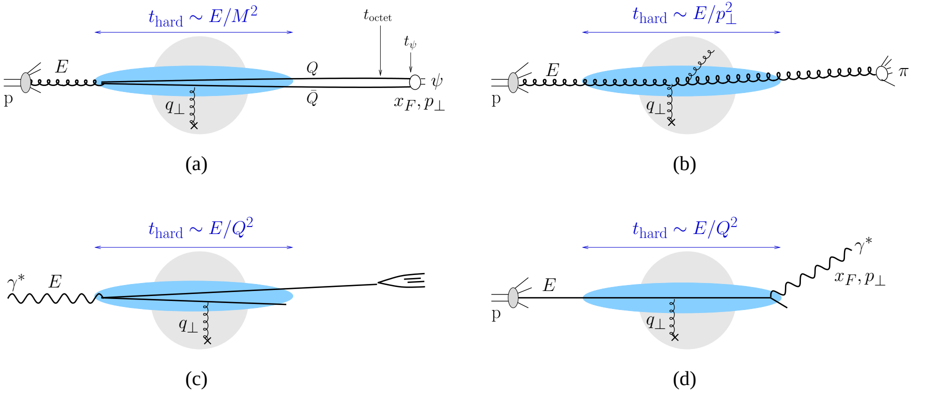
Modification factor: $R_\nu \approx \int_0^1 \mathrm{d}z\, z^\gamma\, \mathcal{F}(z)$ Arleo, GJ, Peigné [2112.10791]

$\gamma \in [2.7, 3.6]$ encompasses more realistic Φ_p and $\mathrm{d}\sigma^c_\mathrm{pp}$!



Conv: $h = \{\pi^\pm, K^\pm, K^0_L\}$

Prompt: $h = \{D^\pm, D^0, D_s, \Lambda_c\}$

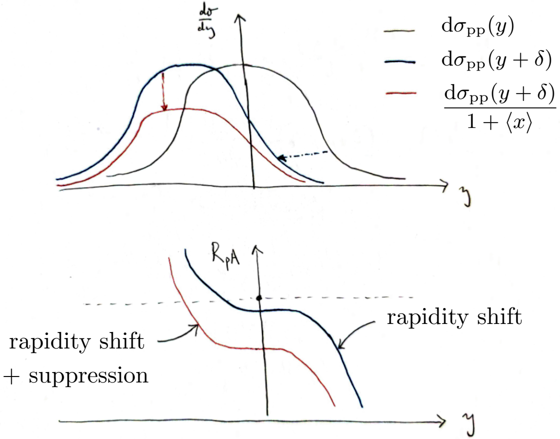


$2 \to 2$ *kinematics in nucleus rest frame:*

parton pair invariant mass reads $M^2 = \dfrac{m_\perp^2}{\xi(1-\xi)}$ with $m_\perp^2 \equiv K_\perp^2 + m^2$

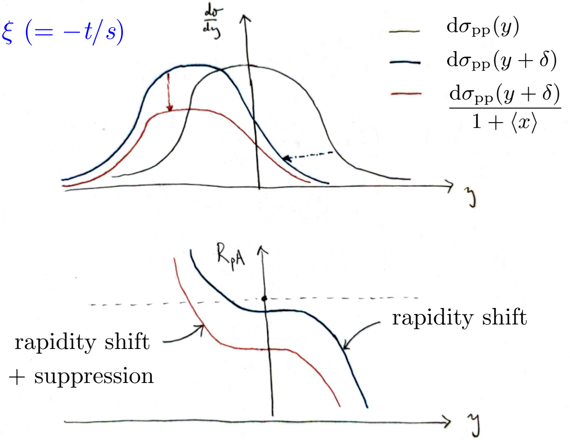
momentum fractions of incoming partons: $x_1 = \dfrac{m_\perp\, e^{y}}{\xi\sqrt{s}}$ and $x_2 = \dfrac{m_\perp\, e^{-y}}{\bar{\xi}\sqrt{s}}$

$$\frac{1}{A}\,\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \frac{\mathrm{d}x}{1+x}\;\hat{\mathcal{P}}(x)\;\frac{\mathrm{d}\sigma_{\mathrm{pp}}(y+\delta)}{\mathrm{d}y}\;; \qquad \delta \equiv \log(1+x)$$

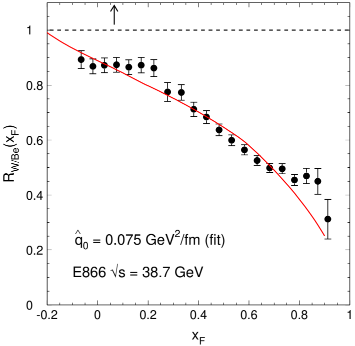


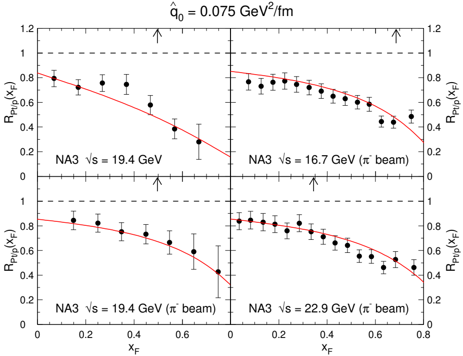
$$\frac{1}{A}\frac{\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{pA}}(y)}{\mathrm{d}y\,\mathrm{d}\xi} = \int_0^{x_{\max}} \frac{\mathrm{d}x}{1+x}\,\hat{\mathcal{P}}_{\mathrm{R}}(x,\xi)\,\frac{\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{pp}}(y+\delta)}{\mathrm{d}y\,\mathrm{d}\xi}\,; \quad \delta \equiv \log(1+x)$$

- Dijet in colour state R
- energy fraction ξ $(= -t/s)$



J/ψ suppression, low energy pA

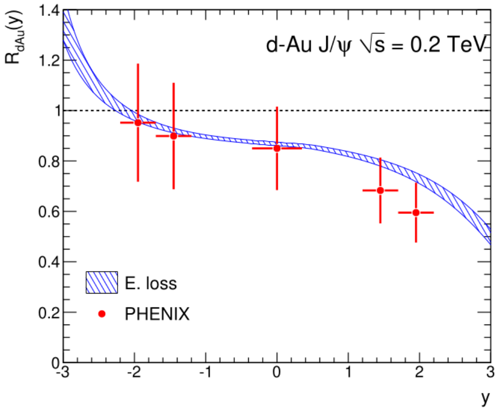




- good agreement w/ E866, NA3, NA60, ...
- no global nPDF fit can explain all these data!

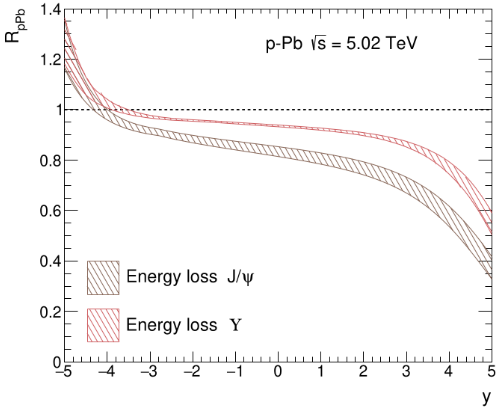
Arleo, Peigné [1212.0434]

J/ψ suppression @ RHIC



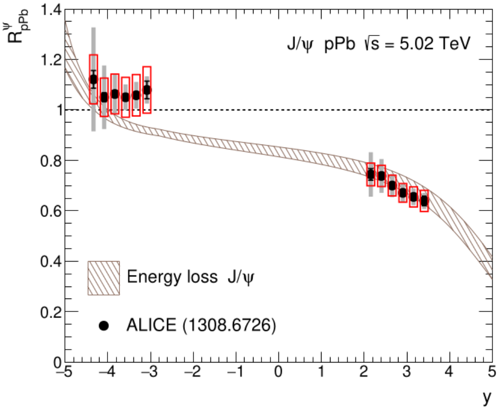
- nuclear modification, R_{pA}, reproduced within errors
- small uncertainty from varying model parameters

J/ψ suppression @ LHC



- moderate effects ($\sim 20\%$) at mid-rapidity, smaller at $y < 0$
- large influence above $y \gtrsim 2...3$
- smaller suppression expected in the Υ channel

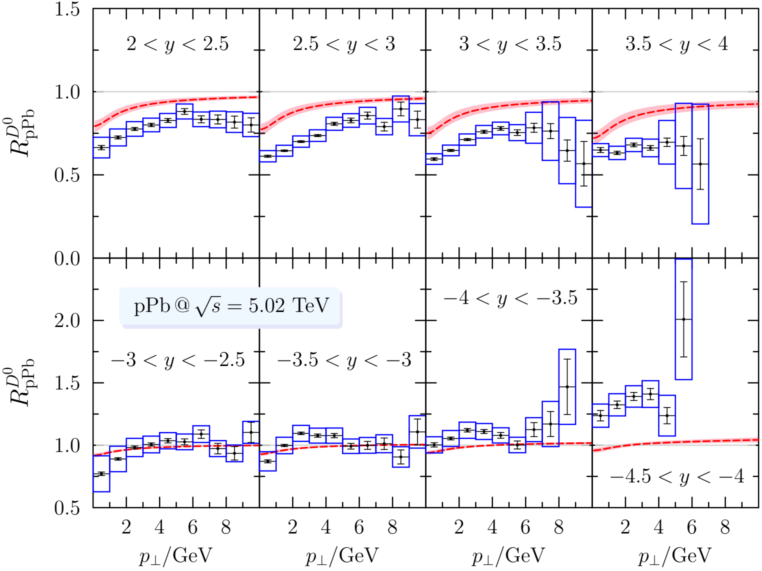
J/ψ suppression @ LHC



- very good agreement
- idea to disentangle FCEL from shadowing?

Arleo, Peigné [1512.01794]

FCEL comparison with LHCb data



Parametrize pp cross section

$$\frac{\mathrm{d}\sigma^H_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}p_\perp} = \mathcal{N}(p_\perp)\left[\left(1-\chi\right)\left(1-\sqrt{\chi}\,\right)\right]^n, \quad \chi \equiv 4\left(\frac{p_\perp^2+\mu_H^2}{s}\right)^{\frac{1}{2}}\cosh y\,.$$

for both charm and bottom production, with parameters $\mu_D = 1.8$ GeV and $n = 4 \pm 1$, and $\mu_B = 5.3$ GeV and $n = 2.0 \pm 0.5$, respectively.