Coherent parton energy loss in pA collisions[1,2]

Greg Jackson

INT, University of Washington

– Heavy Flavour Workshop • Seattle • October 2022 –

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

[2] supported by the DOE under grant No. DE-FG02-00ER41132

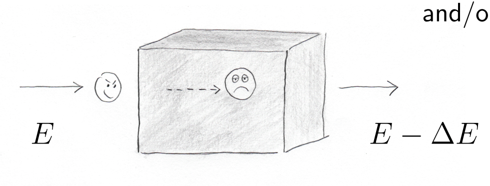
Parton energy loss

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 $t \approx 0$...

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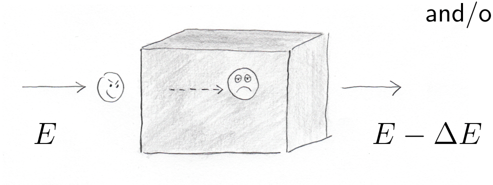

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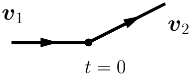
Main message: fully coherent energy loss (FCEL) dominates for large-E:

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

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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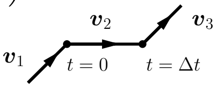

'formation time' $\quad t_f \equiv \dfrac{1}{\omega(1-\boldsymbol{n}\cdot\boldsymbol{v}_2)}$

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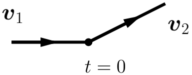

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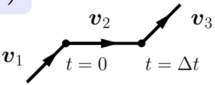

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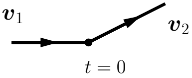

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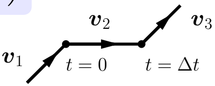
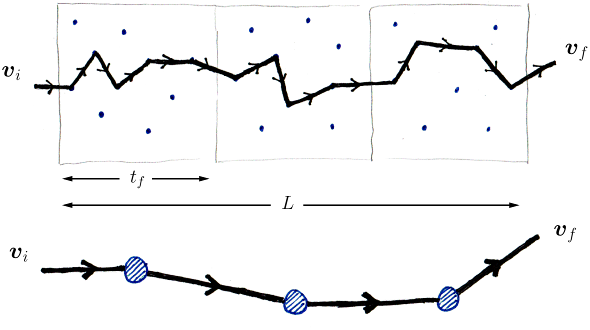


'formation time' $t_f \equiv \dfrac{1}{\omega(1-\boldsymbol{n}\cdot\boldsymbol{v}_2)} \approx \dfrac{1}{\omega\,\theta^2} \approx \dfrac{\omega}{k_\perp^2}$ as $\theta \to 0$

$t_f \gg$ 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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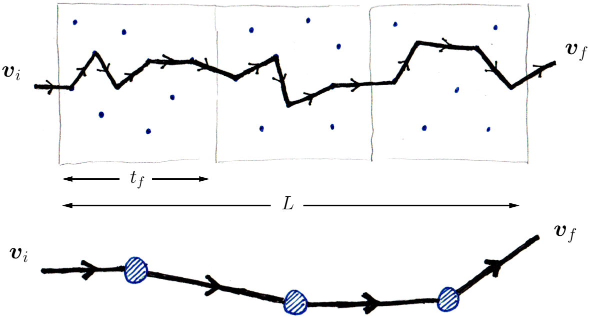

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$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_L \sim \frac{L}{t_f} \times \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_1 \sim \alpha_s L \sqrt{\frac{\hat{q}}{\omega}}$$

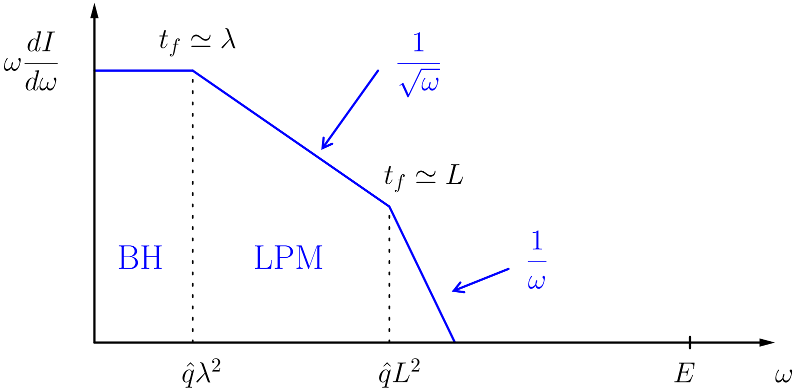
QED: [LPM (1953-6)]
QCD: [BDMPS-Z (1996)]

Regimes of radiation

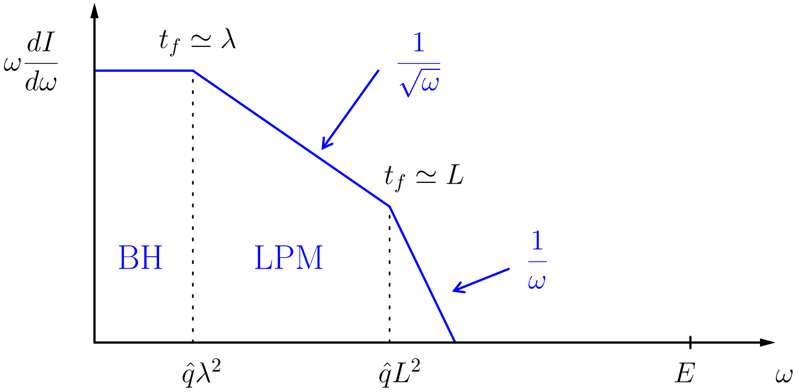
$$\mathrm{d}I \equiv \frac{\mathrm{d}\sigma_{\mathrm{rad}}}{\sigma_{\mathrm{el}}} = \left(\frac{\sum |\mathcal{M}_{\mathrm{rad}}|^2}{\sum |\mathcal{M}_{\mathrm{el}}|}\right) \frac{\mathrm{d}k^+ \mathrm{d}^2 \boldsymbol{k}_\perp}{2k^+ (2\pi)^3}$$

- **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

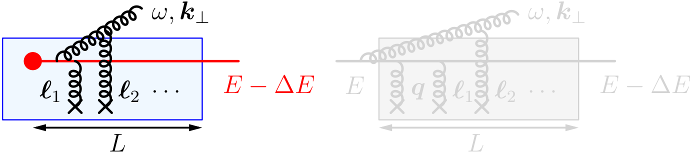
... but which one is most important??



*Modified fig from Jasmine's talk (week 1)



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



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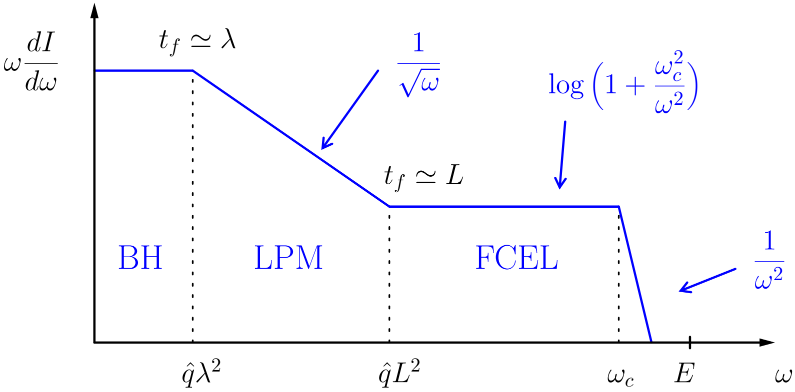

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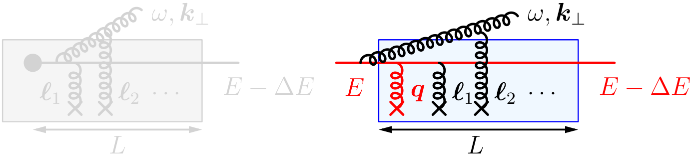

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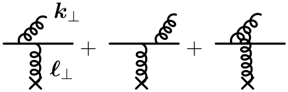
The fully coherent regime

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



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

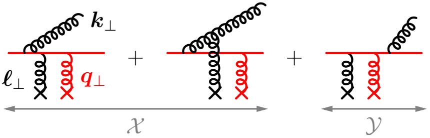
[Gunion, Bertsch (1982)]

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

The fully coherent regime

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

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



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

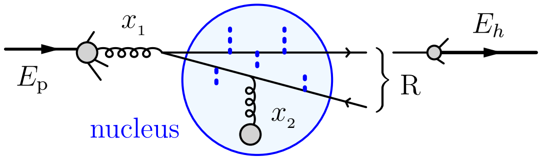
- $|\mathcal{X}|^2$ and $|\mathcal{Y}|^2$ cancel out in the induced spectrum $\mathrm{d}I/\mathrm{d}\omega$
- Interference terms, $\mathrm{Re}(\mathcal{X}\mathcal{Y}^\star)$, do not cancel in the induced spectrum!
- Gluon spectrum computed rigorously in several formalisms:

Peigné, Arleo, Kolevatov [1402.1671]

Liou, Mueller [1402.1647]

Munier, Peigné, Petreska [1603.01028]

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



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

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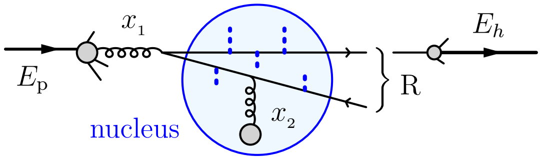

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Leading-log accuracy: *Pointlike dijet approx. (PDA)*

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

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

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

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

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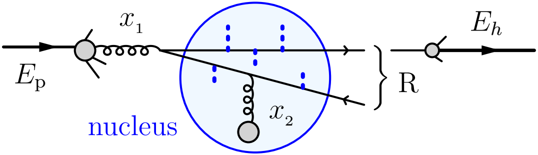

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Colour prefactor stems from *interference* between initial state and final state radiation:

$$2\,T^a_{{\rm R}_1}\,T^a_{\rm R} = (T^a_{{\rm R}_1})^2 + (T^a_{\rm R})^2 - (T^a_{\rm R} - T^a_{{\rm R}_1})^2$$
$$= C_1 + C_{\rm R} - C_2\,,$$

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

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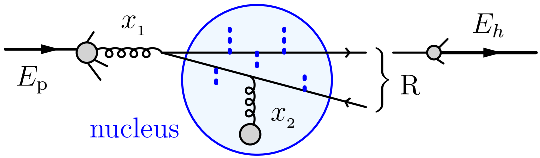

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Also applies for $2 \to 1$ type processes, where R is the colour rep. of the outgoing parton:

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

$$q\bar{q} \to g \quad : \quad F_c = C_{\rm F} + N_c - C_{\rm F} = N_c$$

$$qg \to q \quad : \quad F_c = C_{\rm F} + C_{\rm F} - N_c = -1/N_c \quad (< 0\,!)$$

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

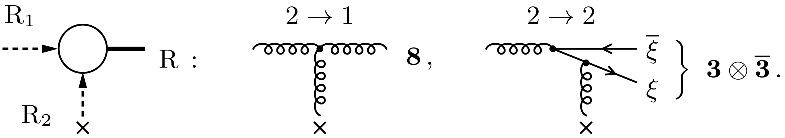
FCEL for hadron production

Average ΔE is not sufficient!

... need probability distribution, **Quenching weight** $\hat{\mathcal{P}}(x = \frac{\varepsilon}{E})$

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

- Dijet in colour state R
- energy fraction ξ



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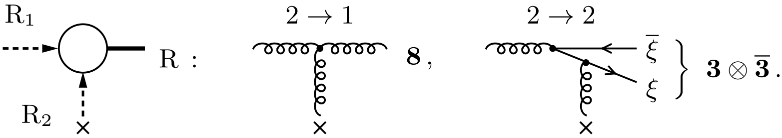

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$$\hat{\mathcal{P}}_{\mathrm{R}}(x,\xi) \leftarrow \left.\frac{\mathrm{d}I}{\mathrm{d}\varepsilon}\right|_{\mathrm{R}} \exp\left\{-\int_{\varepsilon}^{\infty} \mathrm{d}\omega\, \left.\frac{\mathrm{d}I}{\mathrm{d}\omega}\right|_{\mathrm{R}}\right\}$$

- Dijet in colour state R
- energy fraction ξ

Colour probabilities

Need to sum over available states R: $$\frac{d\sigma_{pA}}{dy} = \sum_R \int_0^1 d\xi\, \rho_R(\xi) \frac{d\sigma_{pA}^R}{dy\, d\xi}$$

$$\rho_R \equiv \frac{|\mathcal{M} \cdot \mathbb{P}_R|^2}{|\mathcal{M}|^2}$$

depends on pair's combined colour ...

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\end{aligned}$$

Exercise: for $gg \to Q\bar{Q}$, what's the probability to end in the octet?

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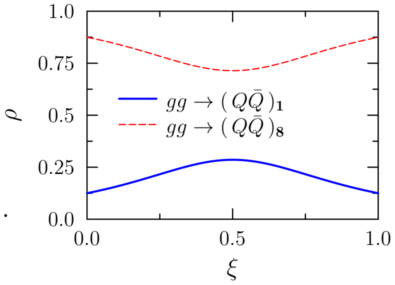

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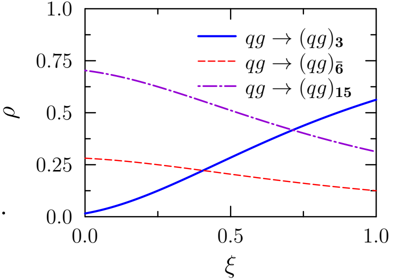

Exercise: for $qg \to qg$, what's the probability to end as a 15-plet?

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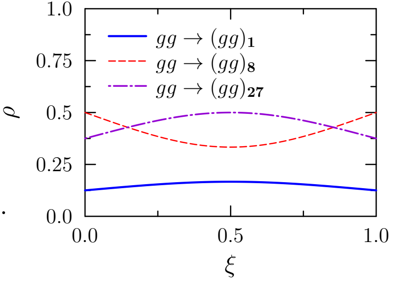
\mathbf{8} \otimes \mathbf{8} &= \mathbf{0} \oplus \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}\,.
\end{aligned}$$



Exercise: for $gg \to gg$, what's the probability to end as a 27-plet?

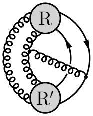
Colour probabilities

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

$$\rho_{\mathrm{R}} \equiv \frac{|\mathcal{M} \cdot \mathbb{P}_{\mathrm{R}}|^2}{|\mathcal{M}|^2}$$ depends on pair's combined colour ...

... beyond the PDA (leading-log),

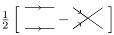
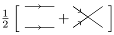
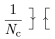
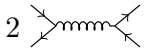
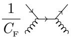
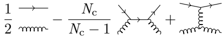
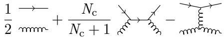
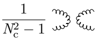
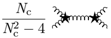
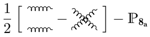
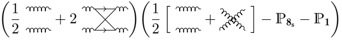
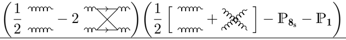
radiation can probe individual colour charges!



$$= \begin{pmatrix} 0 & 0 & \sqrt{2} \\ 0 & \frac{N_c}{2} & \frac{1}{2}\sqrt{N_c^2 - 4} \\ \sqrt{2} & \frac{1}{2}\sqrt{N_c^2 - 4} & \frac{N_c}{2} \end{pmatrix}$$

Need colour **transition matrices**! $(\mathrm{R} \to \mathrm{R}')$

[work in progress w/ Peigné, Watanabe]

system	irreps α	projectors $\mathbb{P}_\alpha$	dimensions K_α	Casimirs C_α
$\mathbf{3} \otimes \mathbf{3}$	$\bar{\mathbf{3}}$		$\frac{1}{2} N_c(N_c - 1)$	$2\,C_F - \frac{N_c + 1}{N_c}$
	$\mathbf{6}$		$\frac{1}{2} N_c(N_c + 1)$	$2\,C_F + \frac{N_c - 1}{N_c}$
$\mathbf{3} \otimes \bar{\mathbf{3}}$	$\mathbf{1}$		1	0
	$\mathbf{8}$		$N_c^2 - 1$	N_c
$\mathbf{3} \otimes \mathbf{8}$	$\mathbf{3}$		N_c	C_F
	$\bar{\mathbf{6}}$		$\frac{1}{2} N_c(N_c + 1)(N_c - 2)$	$C_F + N_c - 1$
	$\mathbf{15}$		$\frac{1}{2} N_c(N_c - 1)(N_c + 2)$	$C_F + N_c + 1$
$\mathbf{8} \otimes \mathbf{8}$	$\mathbf{1}$		1	0
	$\mathbf{8_a}$		$N_c^2 - 1$	N_c
	$\mathbf{8_s}$		$N_c^2 - 1$	N_c
	$\mathbf{10} \oplus \overline{\mathbf{10}}$		$\frac{1}{2}(N_c^2 - 1)(N_c^2 - 4)$	$2N_c$
	$\mathbf{27}$		$\frac{1}{4} N_c^2(N_c - 1)(N_c + 3)$	$2(N_c + 1)$
	$\mathbf{0}$		$\frac{1}{4} N_c^2(N_c + 1)(N_c - 3)$	$2(N_c - 1)$

Hadron production in pA collisions sensitive to 2 nuclear effects:

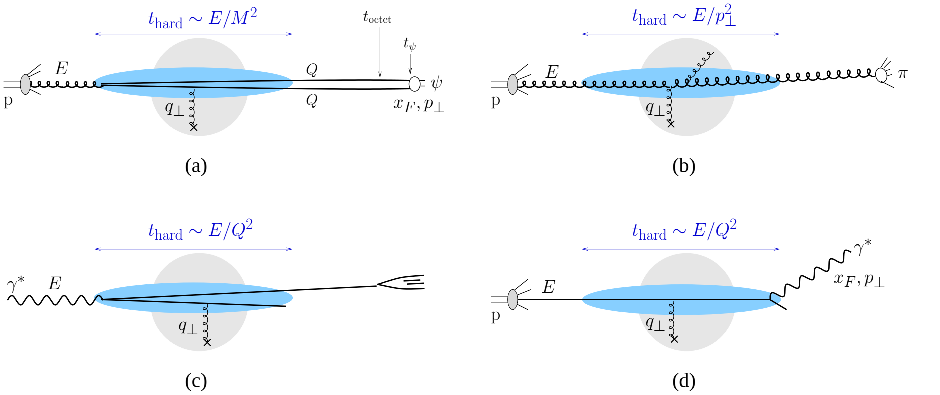
- **Nuclear parton distribution functions (nPDFs):**
  $\Rightarrow$ not directly calculable, extracted from fits

  see talk by Aleksander (week 1)

- **Fully coherent energy loss (FCEL)**
  $\Rightarrow$ predicted from first principles in pQCD

  see current talk...

Strength of FCEL/nPDF effects depend on x_{F}, Q, $\sqrt{s}$, ...



$2 \to 2$ *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 $x_2 = \dfrac{m_\perp\, e^{-y}}{\bar{\xi}\sqrt{s}}$

Phenomenology:

What is the impact of FCEL *alone*?

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 $\equiv$ model w/ minimal assumptions

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Goal ☞ FCEL baseline ≡ model w/ minimal assumptions

- model pp cross section from data, e. g. $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathsf{F}}} \sim \frac{(1-x_{\mathsf{F}})^n}{x_{\mathsf{F}}}$; $x_{\mathsf{F}} \equiv \frac{E_h}{E_{\mathrm{p}}}$
- transport coeff. $\hat{q}(x_2) \simeq \hat{q}_0 \left(\frac{10^{-2}}{x_2}\right)^{0.3}$; $\hat{q}_0 = 0.07\ \mathrm{GeV}^2/\mathrm{fm}$
- path length L estimated from Glauber model

Phenomenology:

What is the impact of FCEL *alone*?

Applied to a variety of processes in pA collisions

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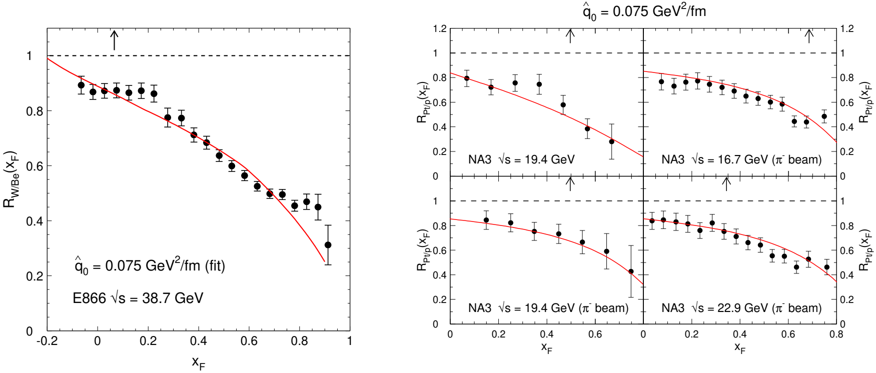
Goal ☞ **FCEL baseline ≡ model w/ minimal assumptions**

- model pp cross section from data, e. g. $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\dots}} \sim (1 \dots)^n$ [illegible] ; $x_{\mathsf{F}} \equiv \frac{E_h}{E_{\mathrm{p}}}$
- transport coeff. $\hat{q}(x_2) \simeq \hat{q}_0 \left(\frac{10^{-2}}{\dots} \right)$ [illegible] ; $\hat{q}_0 = 0.07\ \mathrm{GeV}^2/\mathrm{fm}$
- path length L e[illegible] from Glauber model

No nPDF effects included

Results!

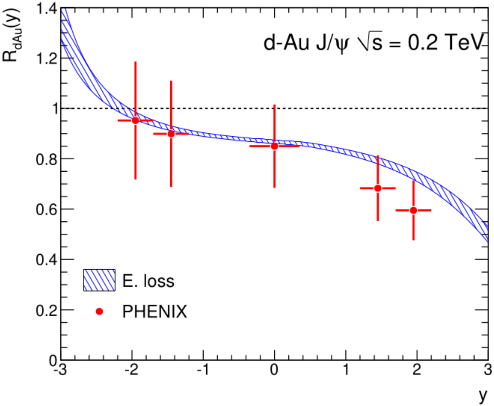
J/ψ suppression, low energy pA



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

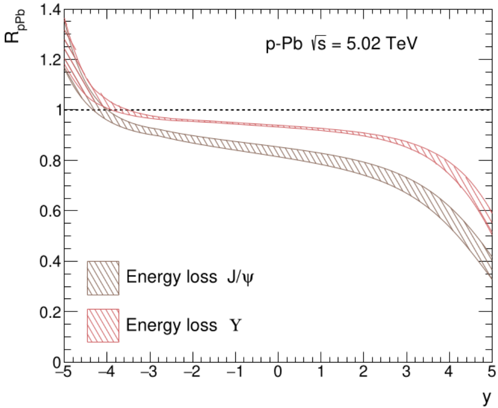
Arleo, Peigné [1212.0434]

J/ψ suppression @ RHIC



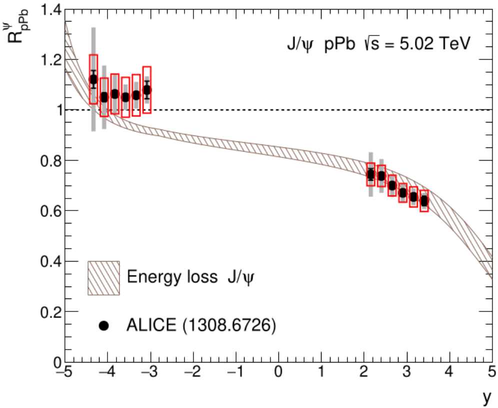
- nuclear modification, R_{pA}, reproduced within errors
- small uncertainty from varying model parameters

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

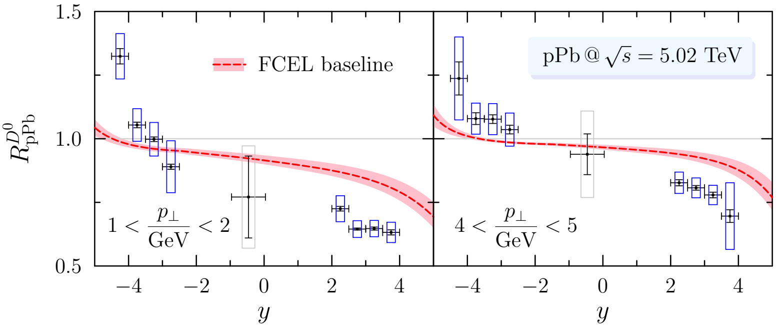


- very good agreement
- idea to disentangle FCEL from shadowing?

Arleo, Peigné [1512.01794]

D-meson production at LHCb

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



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

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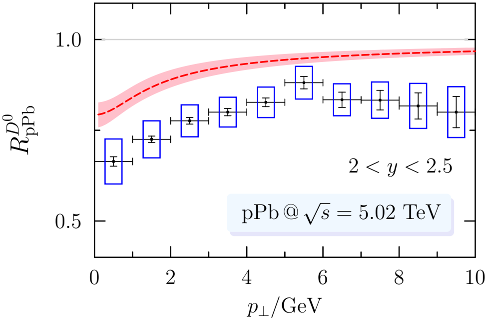

- Accounts for $\approx$ half of the observed suppression
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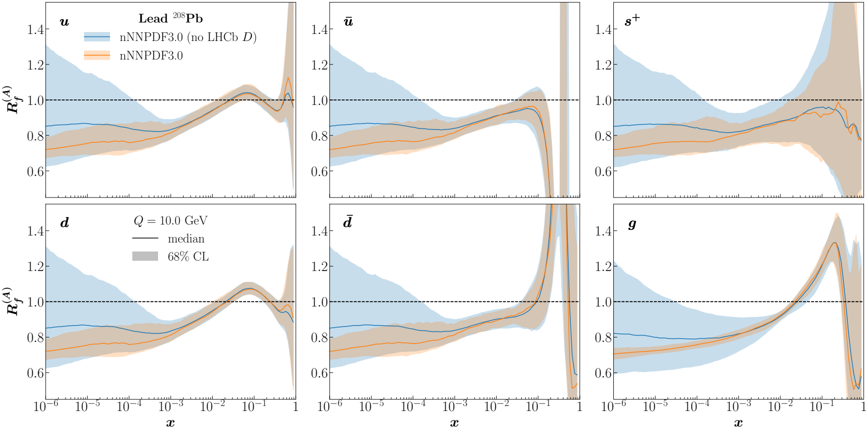
nPDFs w/ and w/o LHCb D-meson data

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

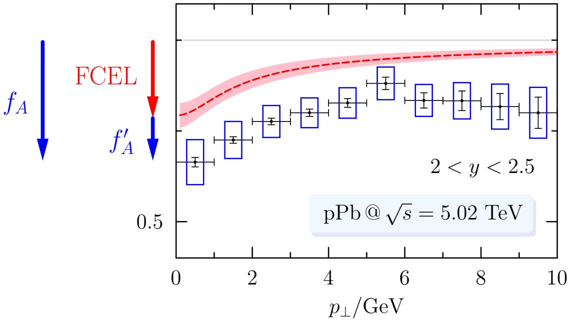


- Huge uncertainty on gluon shadowing
- Strong constraints given by forward D-meson data

nNNPDF3.0 (2022)

D-meson production at LHCb

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



$f_A \neq f'_A$

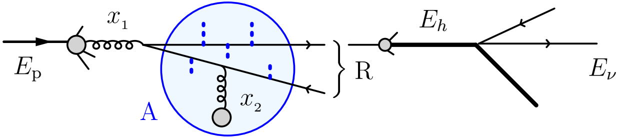
- $\chi^2\left(f'_A \,\middle|\, \text{FCEL} \cap \text{LHCb data}\right)$ vs. $\chi^2\left(f_A \,\middle|\, \text{no FCEL} \cap \text{LHCb data}\right)$
- Given new info (data/theory), nPDFs can be **reweighted**

[work in progress w/ Arleo, Peigné, 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)]



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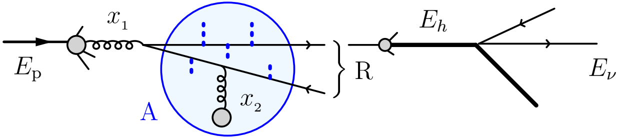

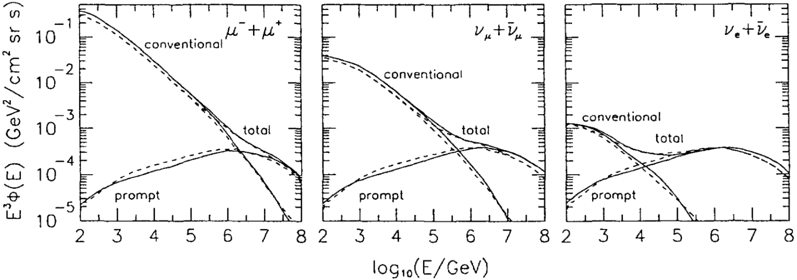

Fig. 3. The E^3-weighted vertical flux of muons, muon–neutrinos and electron–neutrinos from conventional (π, K decays) and prompt (charm decays) sources and their sum ('total'). The solid lines are from the cascade simulation (Section 3) and the dashed lines are from the analytic Z-moment method (Section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

Atmospheric neutrinos at IceCube

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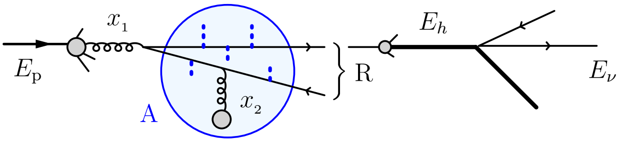
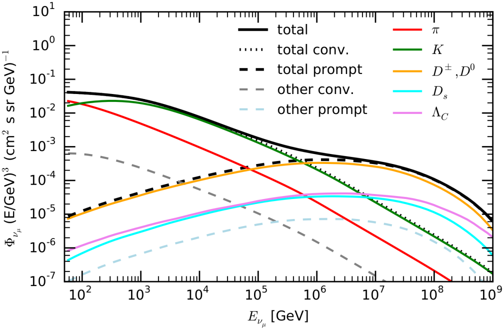
Feydynitch, *et al.* [1806.04140]





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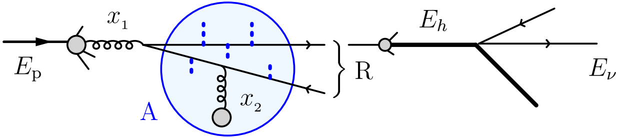
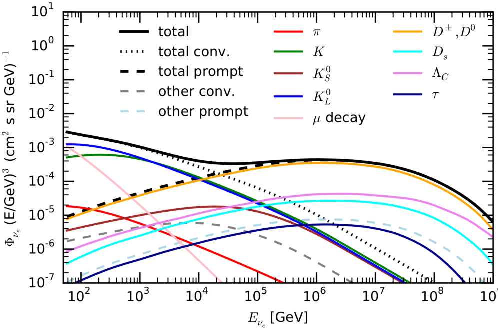
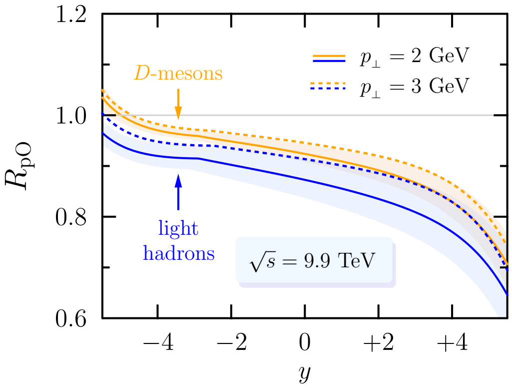




OO and pO @ LHC?

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: $$\Phi_\nu(E_\nu) = \frac{\Phi_p(E_\nu)}{1 - Z_{pp}} \sum_h \frac{Z_{ph}\, Z_{h\nu}}{1 + B_h E_\nu \cos\theta / \varepsilon_h}$$

- Proton regeneration Z_{pp}
- Hadron generation Z_{ph}
- Semi-leptonic decay $Z_{h\nu}$

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 $Z_{\mathrm{p}h}(E) \propto \int_0^1 \frac{\mathrm{d}x_\mathsf{F}}{x_\mathsf{F}}\, \Phi_\mathrm{p}\left(\frac{E}{x_\mathsf{F}}\right) \frac{\mathrm{d}\sigma^c_\mathrm{pA}}{\mathrm{d}x_\mathsf{F}}\left(x_\mathsf{F}; \frac{E}{x_\mathsf{F}}\right)$
- Semi-leptonic decay $Z_{h\nu}$

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

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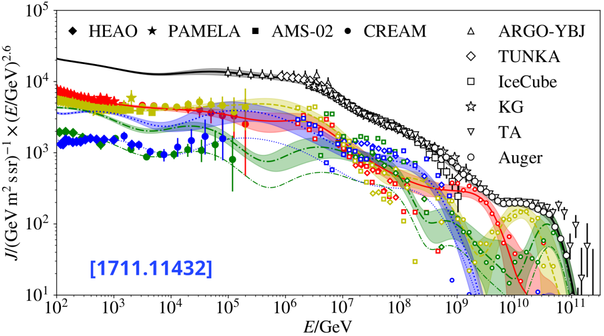


Depletion of neutrinos by FCEL

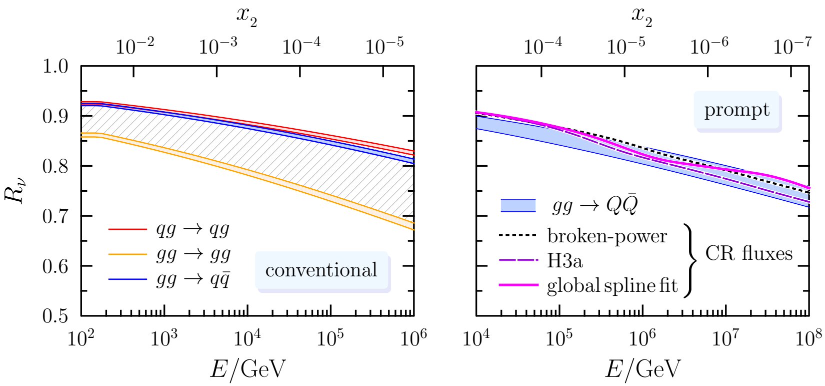
Modification factor: $R_\nu \equiv \dfrac{Z_{\mathrm{p}h}^{\mathrm{FCEL}}}{Z_{\mathrm{p}h}} \approx \int_0^1 \mathrm{d}z\, z^\gamma\, \mathcal{P}(z) \qquad z = \dfrac{E}{E+\varepsilon}$

Arleo, GJ, Peigné [2112.10791]

Depletion of neutrinos by FCEL

Modification factor: $R_\nu \equiv \frac{Z_{ph}^{\rm FCEL}}{Z_{\rm ph}} \approx \int_0^1 {\rm d}z\, z^\gamma\, \mathcal{P}(z) \qquad z = \frac{E}{E+\varepsilon}$

Arleo, GJ, Peigné [2112.10791]



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

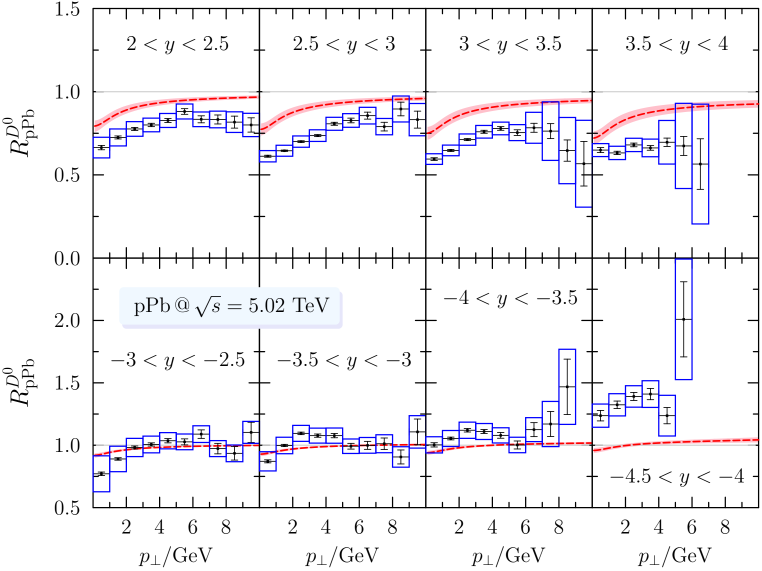
Prompt: $h = \{D^\pm, D^0, D_s, \Lambda_c\}$

Summary

Arxiv: 1212.0434
2003.06337
2107.05871
2112.10791

- FCEL at leading-log accuracy
  $\Rightarrow$ predicted from first principles, small uncertainty
- hadron production @ RHIC and LHC
  $\Rightarrow$ both FCEL and nPDF needed to reproduce data!
- background atmospheric ν flux
  $\Rightarrow$ suppressed by $\sim$10...25% in IceCube energy ranges

FCEL comparison with LHCb data



Parametrize pp cross section

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

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.