Effective field theory approach to open heavy flavor production in heavy-ion collisions

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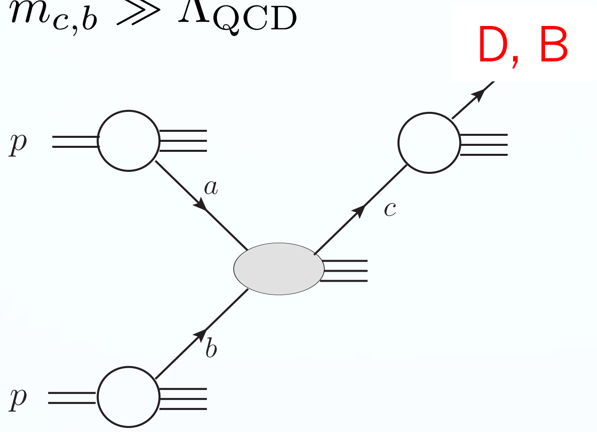
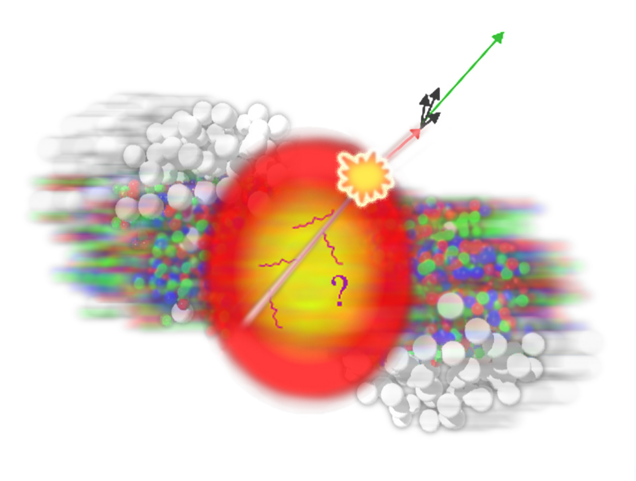
Kang, Ringer, Vitev, arXiv: 1610.02043, JHEP 1703 (2017) 146

Why heavy flavor (D, B)?

- pp: precision tests of our understanding of QCD, in particular, of quark mass effects

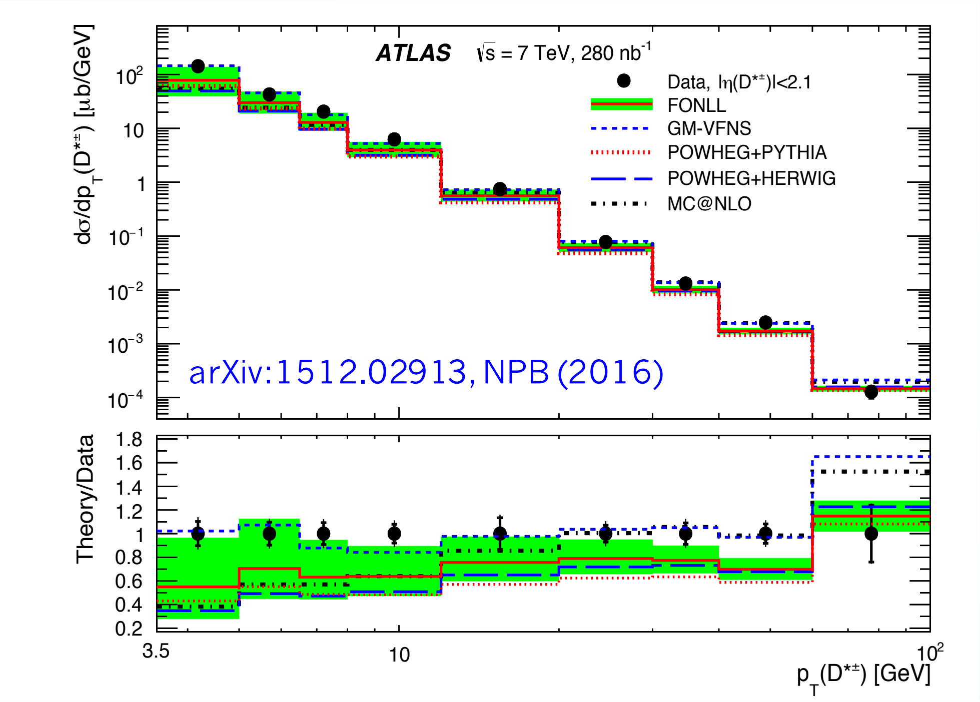
$m_{c,b} \gg \Lambda_{\rm QCD}$

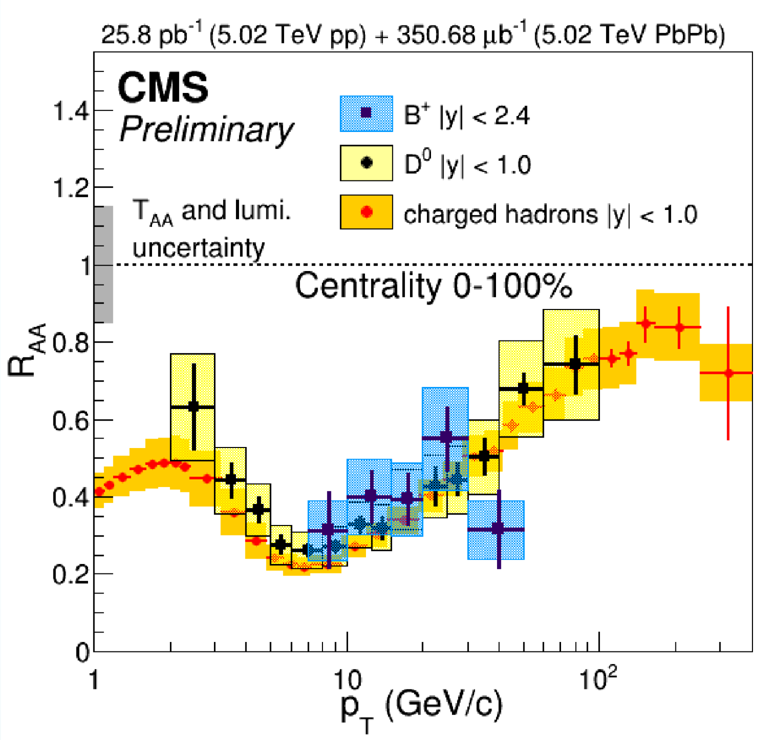




- AA: produced in the early stage of the collisions, provide information of the hot and dense medium

Precision data at LHC





PP

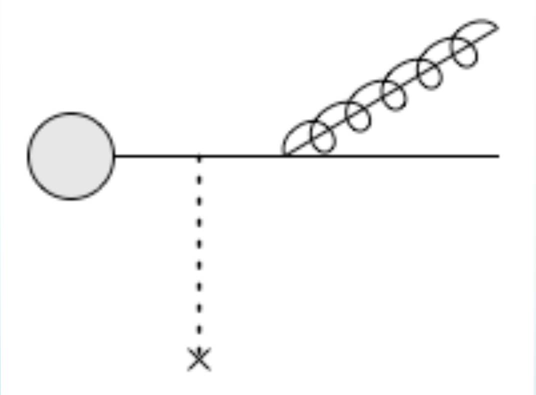
AA

Goal of our work

- Put open heavy flavor production in pp and AA collisions at the same precision, i.e., consistent full NLO calculation
- Understand the heavy flavor mass puzzle
  - Radiative E-loss in heavy quarks < E-loss for light quarks, and thus should be less suppressed? (Dead-cone effect)

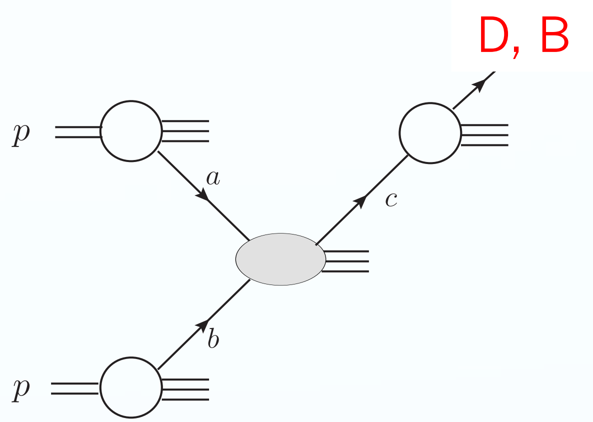
$$R_B < R_D < R_h$$

- Go beyond the traditional energy loss paradigm, where the radiated gluon is assumed to be soft (small-x limit)



Heavy flavor meson production in pp

- Zero-Mass Variable Flavor Number Scheme (ZM-VFNS): works when $p_T >> m_{c,b}$



$$pp \to HX$$

$$\frac{d\sigma_{pp}^{H}}{dp_T d\eta} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^{1} \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^{1} \frac{dx_b}{x_b} f_b(x_b,\mu) \int_{z_c^{\min}}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dv dz} D_c^H(z_c,\mu)$$

- Next-to-leading order in QCD: hard function massless

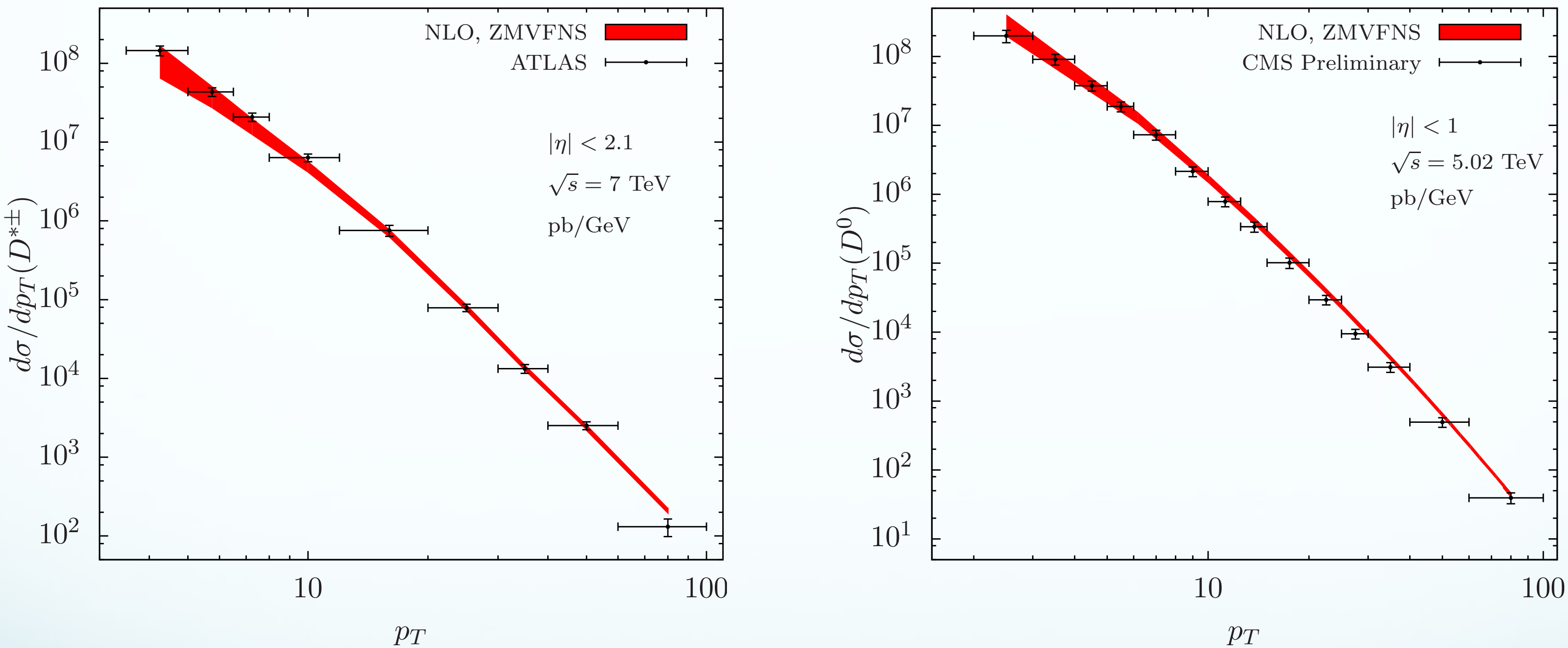
Jager, Stratmann, Vogelsange, 02

- Heavy meson fragmentation function: fitted from $e^+e^- \to HX$

Kneesch, Kniehl, Kramer, Schienbien, 08

D meson at the LHC

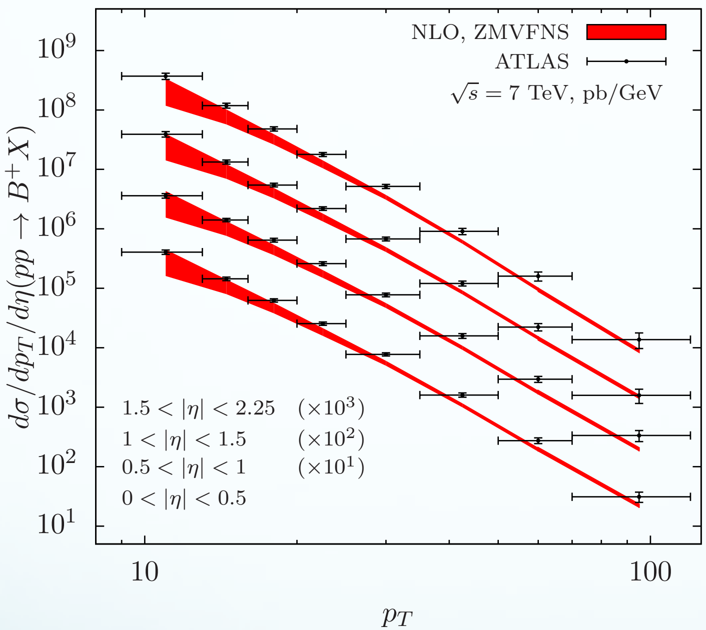
- ATLAS and CMS at 7 or 5 TeV: work well

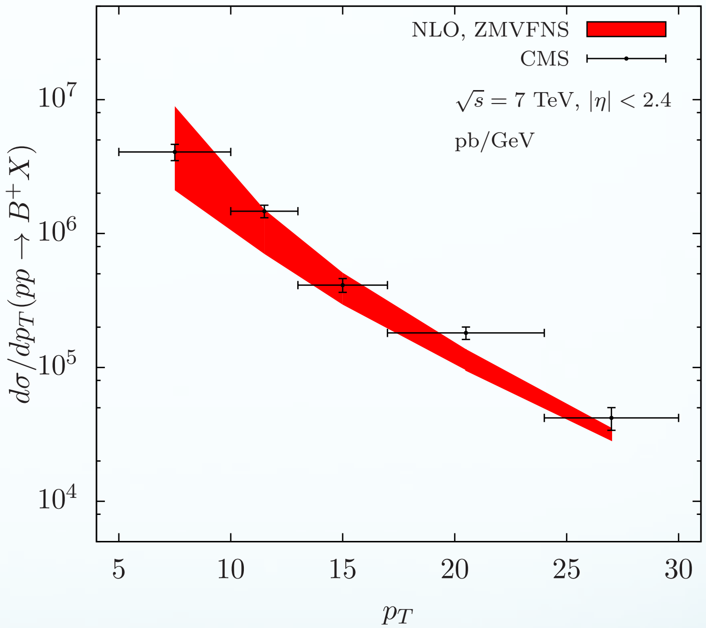


$$\mu_{R,F} = m_T = \sqrt{p_T^2 + m_c^2}$$

B meson at the LHC

- ATLAS and CMS at 7 TeV

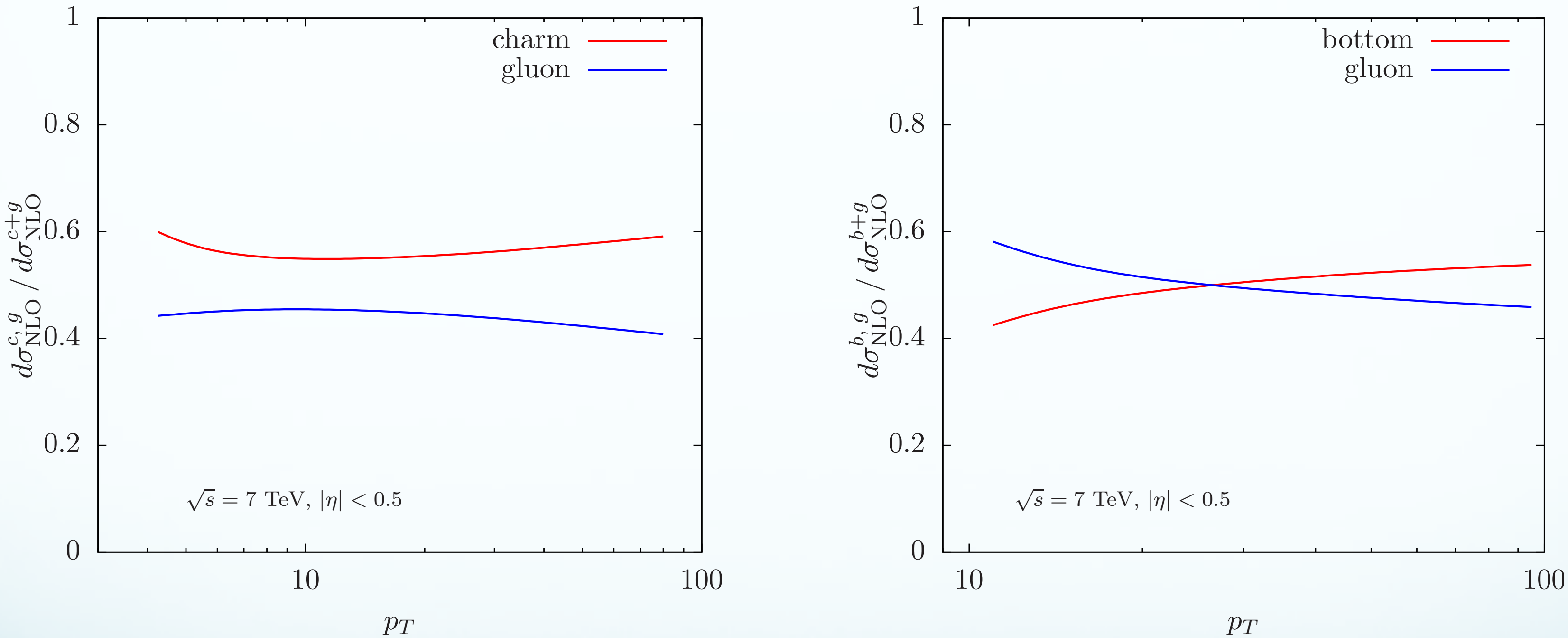




$$\mu_{R,F} = m_T = \sqrt{p_T^2 + m_b^2}$$

Heavy-quark and gluon fragmentation contributions

- In such a NLO framework, check the relative contributions of heavy quark, and gluons



- **Gluons play a very important role:** important consequence for D/B meson production in heavy ion collisions?!

Soft-Collinear Effective Theory (SCET)

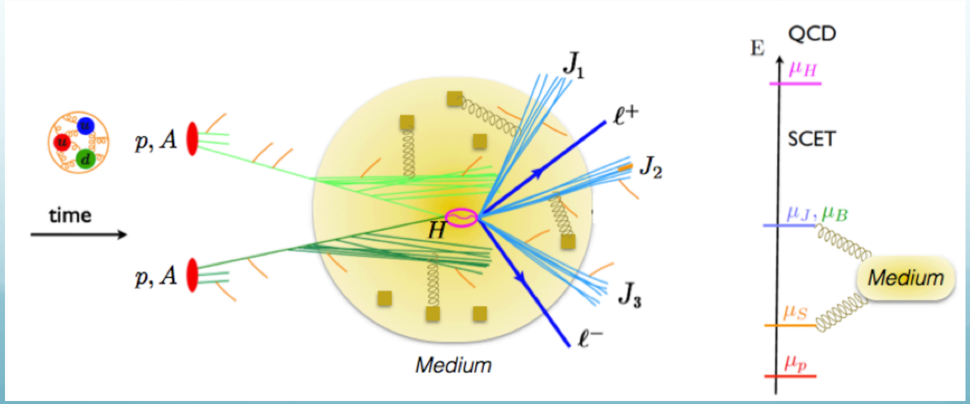
- SCET: an effective field theory of QCD — Bauer et al. 01, Pirjol et al. 04
  - Suitable for processes where there are energetic, nearly light-like (collinear) degrees of freedom interacting with one another via soft radiation

- Modes in SCET

Collinear quarks, antiquarks	$\xi_n,\ \bar{\xi}_n$
Collinear gluons, soft gluons	$A_n,\ A_s$

modes	$p^\mu = (+, -, \perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

- High precision QCD phenomenology, especially for multi-scale problems

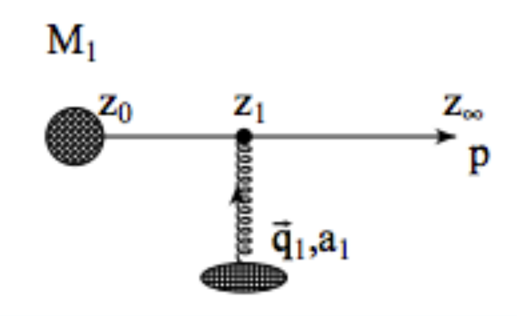


Medium: Glauber gluons are important

- To describe the propagation of an highly energetic jet (q/g) in the medium
  - t-channel dominance (forward scattering): transverse momentum transfer is the most important degree of freedom

Glauber: $k \sim Q\left[\lambda^2, \lambda^2, \lambda\right]$

Idilbi, Majumder 08, D'Dramo, Liu, Rajgopal 10, Ovanesyan, Vitev 11, 12



- SCET_G = SCET with Glauber gluons

$$\mathcal{L}_{\text{SCET}_\text{G}}(\xi_n, A_n, A_\text{G}) = \mathcal{L}_\text{SCET} + \mathcal{L}_\text{G}$$

Ovanesyan, Vitev 11, 12

$$\mathcal{L}_\text{G}(\xi_n, A_n, A_\text{G}) = g\left(\bar{\xi}_{n,p'} T^a \frac{\bar{\not{n}}}{2} \xi_{n,p} - i f^{abc} A^{\lambda c}_{n,p'} A^{\nu,b}_{n,p} g^\perp_{\nu\lambda} \bar{n}\cdot p\right) n \cdot A^a_\text{G}$$

SCET$_{\mathrm{M,G}}$

- To study the propagation of heavy quark in the medium
  - Understand the interaction between heavy quark and the Glauber gluons

$$\mathcal{L}_{\mathrm{SCET_{M,G}}}(\xi_n, A_n, A_{\mathrm{G}}) = \mathcal{L}_{\mathrm{SCET_M}} + \mathcal{L}_{\mathrm{G}}$$

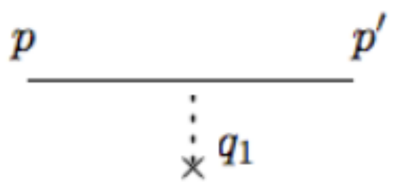
  - Standard SCET with mass effects

$$\mathcal{L}_{\mathrm{SCET_M}} = \bar{\xi}_{n,p'}\left[in\cdot D + (\slashed{\mathcal{P}}_\perp + g\slashed{A}^\perp_{n,q}) W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger (\slashed{\mathcal{P}}_\perp + g\slashed{A}^\perp_{n,q'})\right] \frac{\slashed{\bar{n}}}{2}\xi_{n,p} + m\,\bar{\xi}_{n,p'}\left[(\slashed{\mathcal{P}}_\perp + g\slashed{A}^\perp_{n,q}), W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \right] \frac{\slashed{\bar{n}}}{2}\xi_{n,p} - m^2\,\bar{\xi}_{n,p'} W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \frac{\slashed{\bar{n}}}{2}\xi_{n,p}$$

Leibovich, Ligeti, Wise 03, Rothstein 03

  - We find that: Feynman rules for interaction with the medium do not depend on the mass to leading power

Kang, Ringer, Vitev, 16

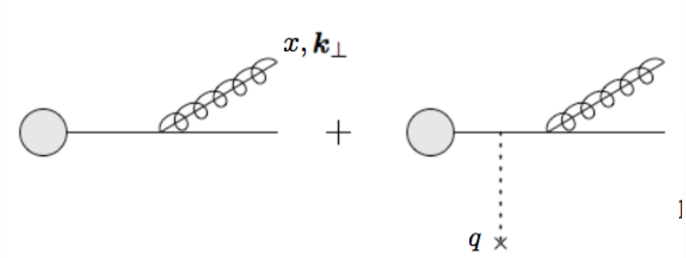


$$= i\,v(q_{1\perp})\,(b_1)_R\,(b_1)_{T_i}\,\frac{\slashed{\bar{n}}}{2}$$

Derive parton splitting kernels: $\mathrm{SCET}_{\mathrm{M,G}}$

- Two situations

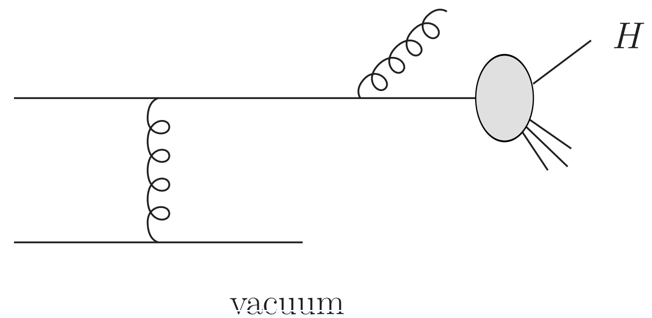
- For the first case, in the medium

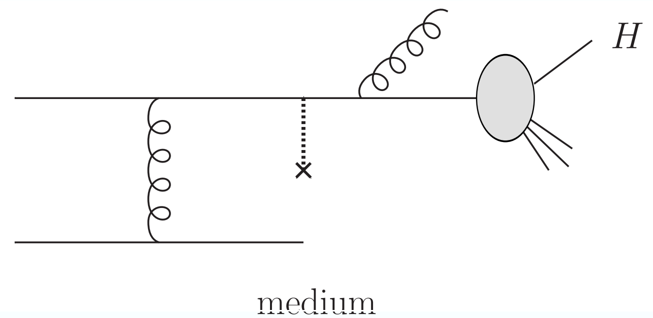


$$
\begin{aligned}
\left(\frac{dN^{\mathrm{med}}}{dx\,d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = {} & \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\mathrm{med}}}{d^2\boldsymbol{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right.\right. \\
& \times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \cdot \left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \right. \\
& \left. - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} (1-\cos[(\Omega_2-\Omega_3)\Delta z]) \\
& + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \right) (1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} (1-\cos[\Omega_5\Delta z]) \\
& \left. + \frac{1}{N_c^2} \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) \right] \\
& \left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots \right] \right\}
\end{aligned}
$$

Application of in-medium splitting functions

- Parton splitting at NLO





$$\sum_j \hat{\sigma}_i^{(0)} \otimes P_{ji} \otimes D_j^H$$

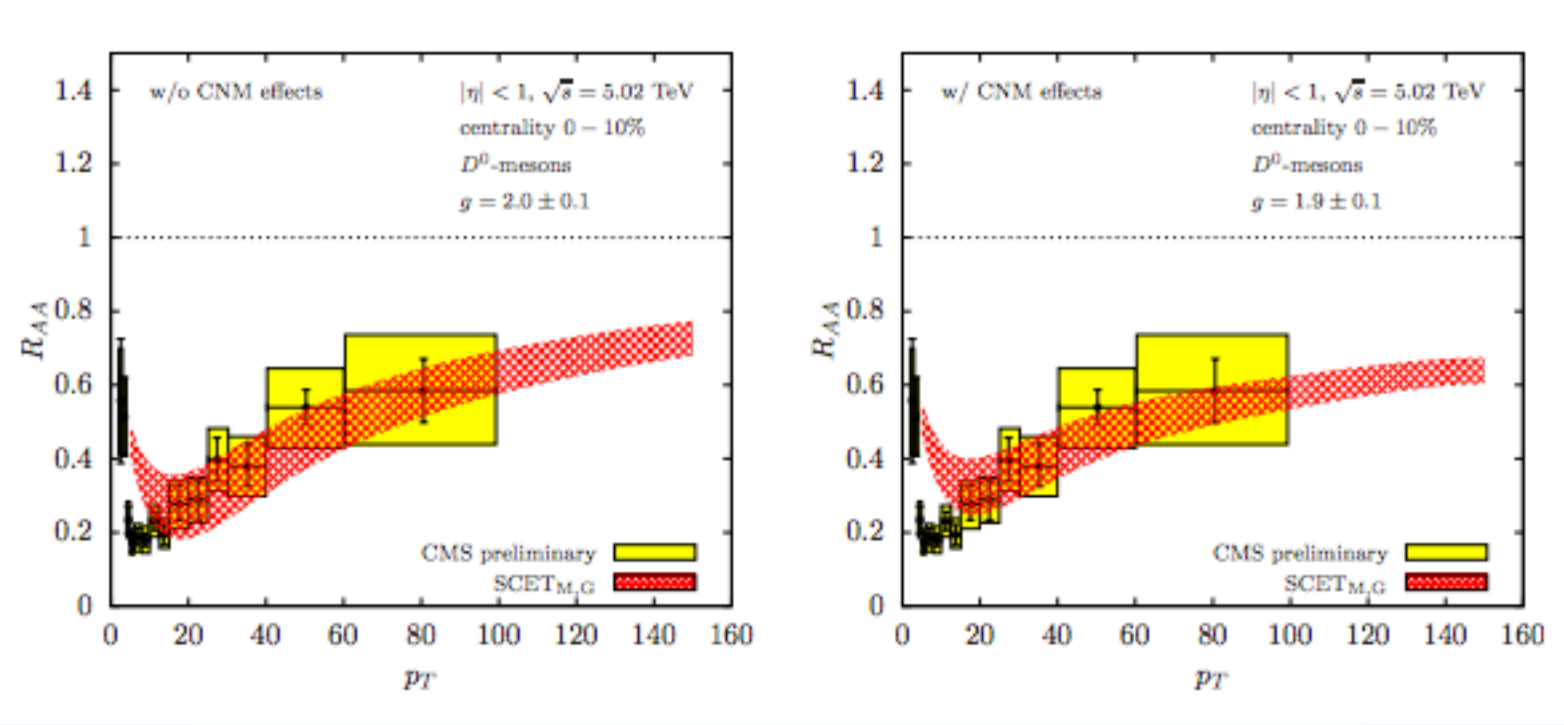
$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}^{\mathrm{med}}_{i\to jk} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,\mathrm{med}}$$

- At NLO, consistently we should have

$$d\sigma^H_{\mathrm{PbPb}} = d\sigma^{H,\mathrm{NLO}}_{pp} + d\sigma^{H,\mathrm{med}}_{\mathrm{PbPb}}$$

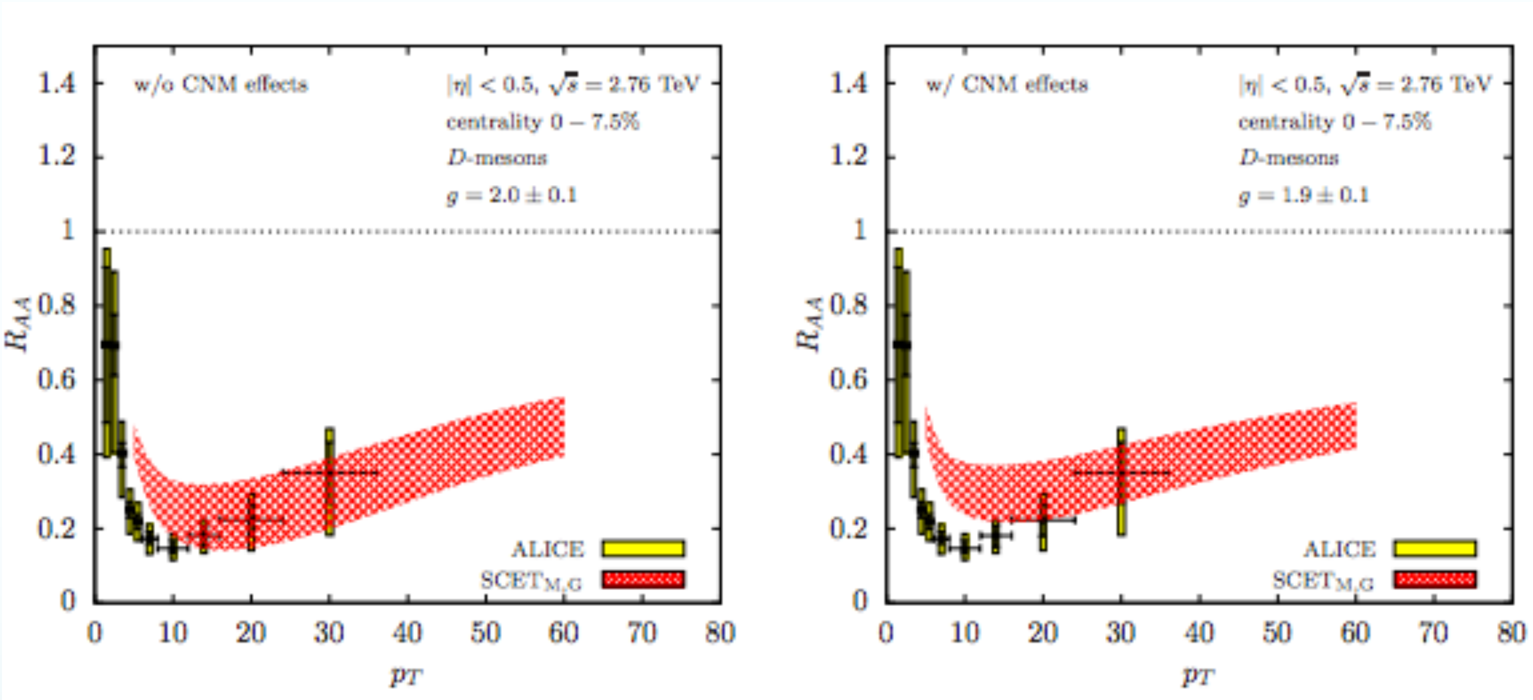
Comparison with the LHC data: D meson

- CMS data



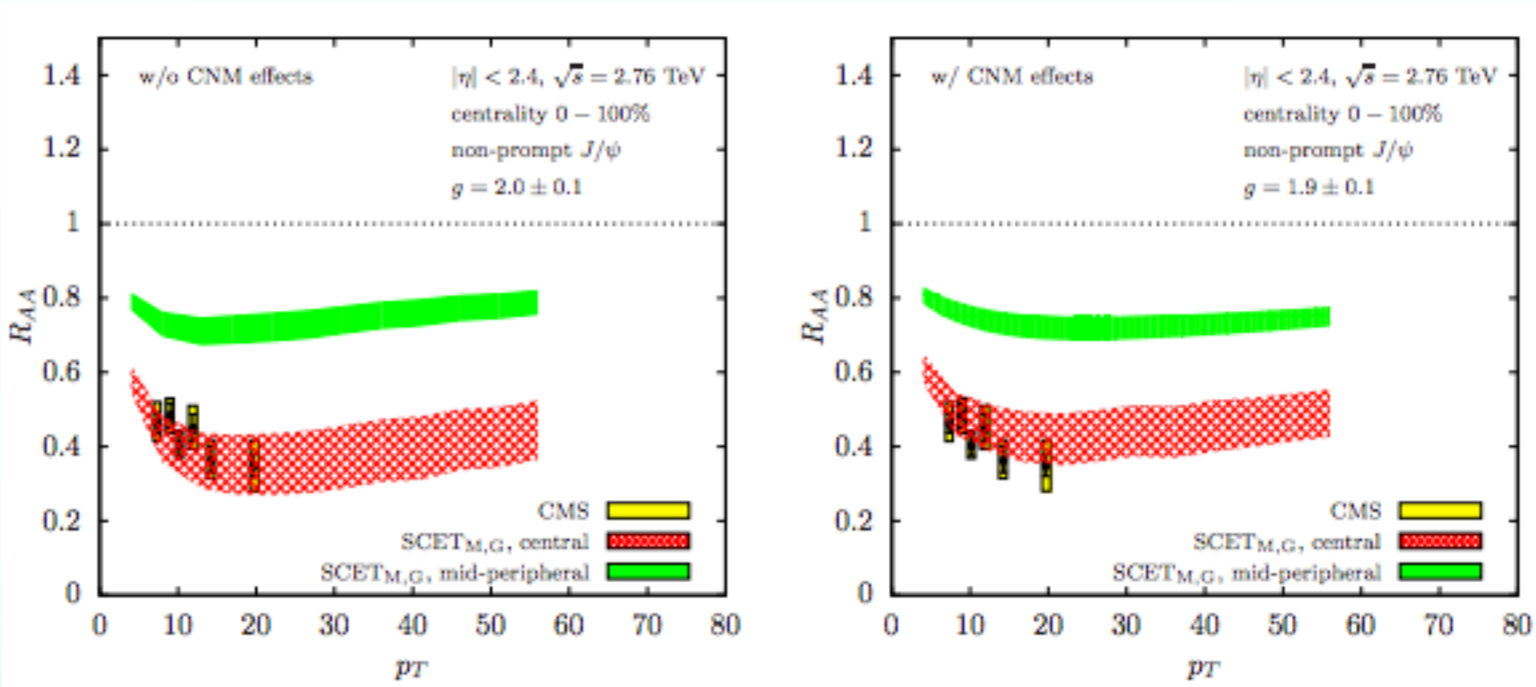
Comparison with LHC data: D meson

- ALICE data



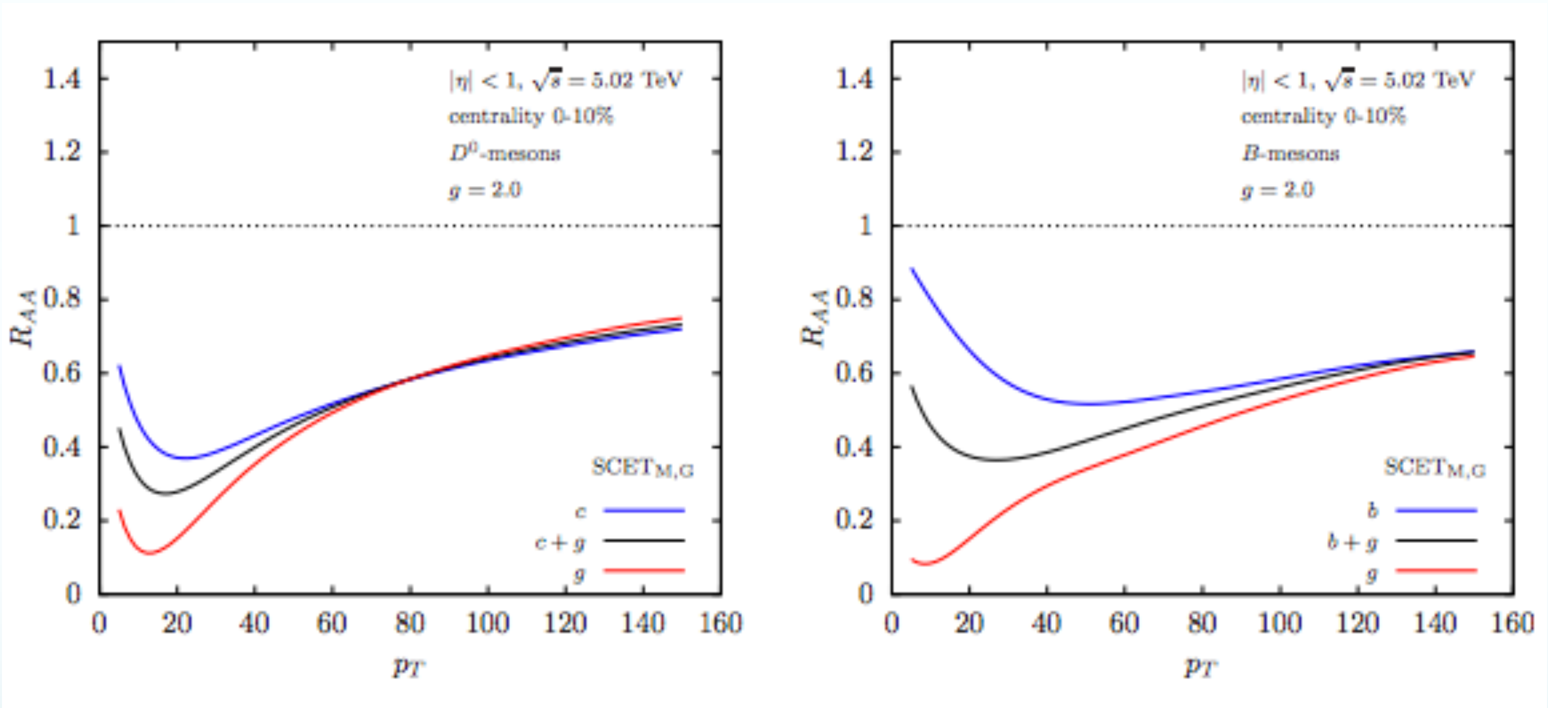
Comparison with LHC data: B meson

- CMS data: non-prompt J/psi (B meson)



Gluon fragmentation

- Gluon fragmentation contribution plays a very important role



Conclusions

- SCET is a very useful tool to make reliable/precise predictions and computations for hard particle production at both p+p and A+A collisions
  - Inclusion of Glauber gluons through $\mathrm{SCET}_{M,G}$
- With that we derived new massive in-medium splitting functions
- With these functions in hand, we provide a pQCD framework for pp and AA, both at NLO accuracy
- Such a treatment leads to good description of D and B meson nuclear modification in medium
  - Gluon plays a very important role in such a description

Thank you!