Open bottom production at hadron colliders at NNLO+NNLL

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The Ninth International Workshop on
High Precision for Hard Processes at the LHC (HP^2 2024)
Turin, Italy, 12 September 2024

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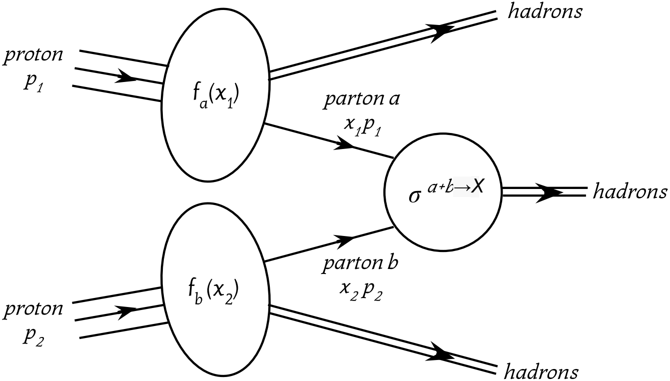
The goal

- Want to describe the process $pp \to b/\overline{b} + X$ with high precision
- At high energies, the b-quark is effectively almost massless
- $\Rightarrow$ Quasi-collinear singularities ($b \to b\,g$, $g \to b\,\overline{b}$, etc.)
- These introduce large logarithms $\sim \ln p_{T,b}/m_b$
- So: want to perform resummation (through NNLL)
- Many details already covered by Matteo Cacciari on Tuesday!
- Note: also logs from initial state and UV
- Those already resummed by PDF collaboration (4-flavour vs. 5-flavour PDF$+\alpha_s$ sets)

Reminder:

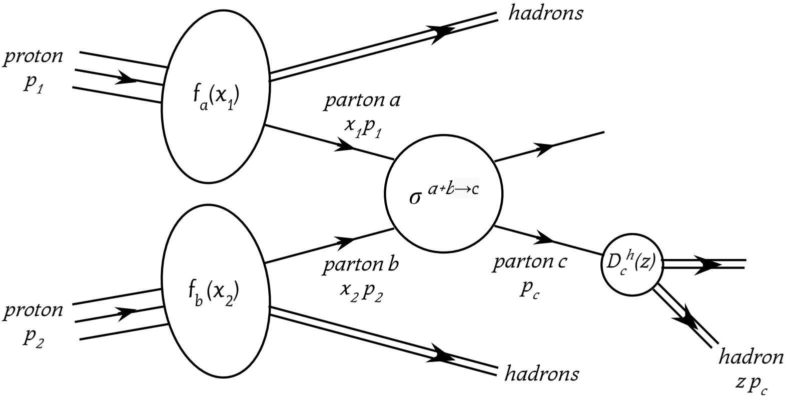
fragmentation functions

Standard QCD collinear factorisation



$$\sigma^{pp\to X}(p_1,p_2) = \sum_{a,b} \iint_0^1 f_a(x_1) f_b(x_2)$$
$$\sigma^{a+b\to X}(p_a = x_1 p_1,\, p_b = x_2 p_2)\, dx_1\, dx_2 + \mathcal{O}(m_p^n/Q^n)$$

Final-state factorisation



$$\sigma^{pp\to h+X}(p_1,p_2,p_h) = \sum_{a,b,c} \iiint_0^1 f_a(x_1) f_b(x_2) D^{\mathrm{NP}}_{c\to h}(z)\delta(p_h - zp_c)$$

$$\sigma^{a+b\to c}(p_a = x_1 p_1, p_b = x_2 p_2, p_c)\, dx_1\, dx_2\, dz + \mathcal{O}(m_p^n/Q^n, m_h^m/E_h^m)$$

Perturbative fragmentation functions

- So far FFs of non-perturbative nature (parton→hadron)
- Can also define perturbative FFs as follows: *Mele, Nason (1991)*

$$\sigma_b(m_b) = \sum_i \sigma_i(m_b = 0) \otimes D_{i\to b} + \mathcal{O}(m_b^n/E_b^n)$$

- Convolution with $D_{i\to b}$ restores correct behaviour of mass-independent and log-enhanced terms $(\ln^m p_{T,b}/m_b)$
- Works for any massive particle, multiple masses, multiple particles, etc.
- As long as $m_b \gg \Lambda_{\text{QCD}}$: perturbatively calculable!

Perturbative fragmentation functions

$$\sigma_b(m_b) = \sum_i \sigma_i(m_b = 0) \otimes D_{i \to b} + \mathcal{O}(m_b^n / E_b^n)$$

- The $\sigma_i(m_b = 0)$ contain additional collinear singularities w.r.t. $\sigma_b(m_b)$
- $\Rightarrow$ The PFF must contain collinear poles which cancel these
- $\Rightarrow$ Predictable poles, which can be renormalised away
- Introduces new and arbitrary factorisation scale
  + corresponding RGEs (time-like DGLAP equations)
- Plan for resummation:
  1. Evaluate PFF at $\mu \sim m_b$ (no large log of m_b)
  2. Evolve to $\mu \sim Q$ (hard scale of process)
  3. Combine with massless cross sections evaluated at $\mu \sim Q$

Soft-gluon resummation

- PFF contains large threshold logs $\Rightarrow$ soft-gluon resummation
- Discussed in detail in Matteo Cacciari's talk
- We perform soft-gluon resummation with NNLL accuracy
- But: care must be taken at very large x (see Andrea Ghira's talk)
- Fortunately not a problem here (large x not probed)
- Note: partonic cross section also contains threshold logarithms
- Those are not resummed here

The final resummation formula

- Factorising the mass dependence into FFs allows resummation
- But only accurate up to power corrections $\mathcal{O}(m_b/E_b)$ (leading-power, LP)
- At low p_{T}, resummation not needed
- $\Rightarrow$ Can use fixed-order result with full mass dependence
- 'Best prediction' across full spectrum: combine the two!
- Naïve matching:

$$\text{Best prediction} = (\text{FO massive}) + (\text{resummed LP}) - \underbrace{(\text{FO LP})}_{\text{double counting}}$$

The final resummation formula

- Resummation of PFF performed in previous work

  Czakon, TG, Mitov, Poncelet (2022)

- 'Double counting' is FO expansion of resummed calculation

- Combination of partonic cross sections with
  1. NNLO perturbative fragmentation functions

     Melnikov, Mitov (2004, 2005)
  2. NNLO PDF threshold matching conditions

     Buza, Matiounine, Smith, Migneron, van Neerven (1996)
  3. NNLO α_s threshold matching condition

     Bernreuther, Wetzel (1982/1983)

- These extra contributions now also implemented in STRIPPER

- STRIPPER: fully general NNLO subtraction scheme code

The final resummation formula

- Naïve matching:

  Best prediction = (FO massive) + (resummed LP) – (FO LP)

- But: LP cross sections blow up at low p_T
- Solution: change $E_T(m_b = 0) \longrightarrow E_T(m_b) \Leftrightarrow p_T^2 \longrightarrow p_T^2 - m_b^2$ for LP
- In practice still not enough: large resummation effects at low p_T
- Artificially suppress resummation effects at low p_T
- FONLL approach: Cacciari, Greco, Nason (1998)

$$\text{FONLL} = (\text{FO massive}) + G(p_{T,b}) \cdot \left[(\text{resummed LP}) - (\text{FO LP})\right]$$

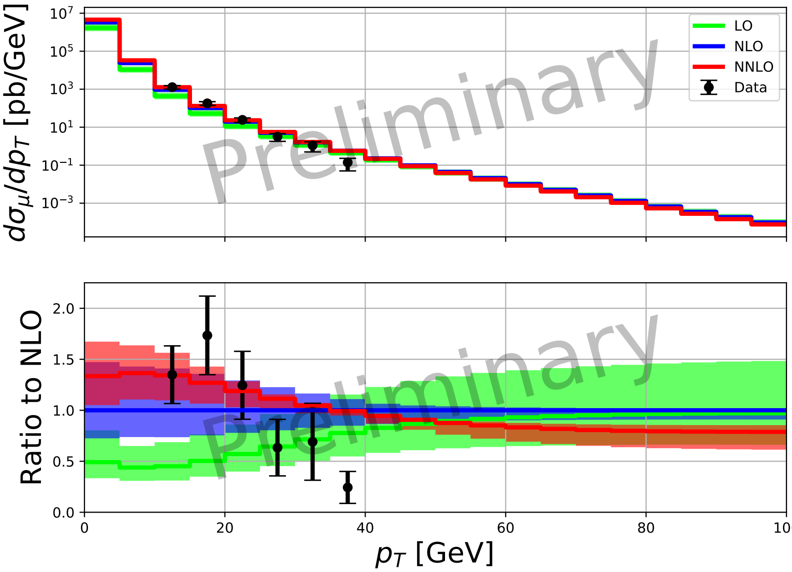
$$G(p_T) = \frac{p_T^2}{p_T^2 + c^2 m_b^2}, \text{ with } c = 5$$

Preliminary results at NNLO+NNLL

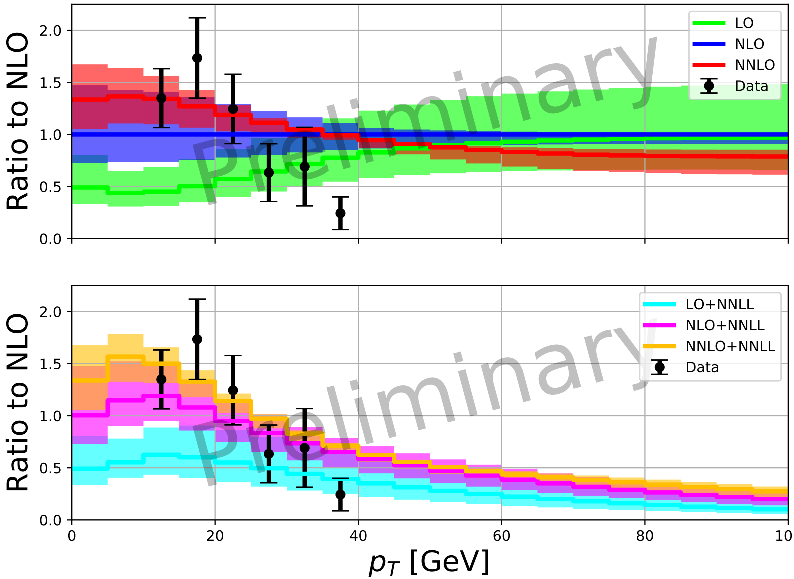
The muon p_T spectrum through NNLO+NNLL

- Study muons from B-hadron decays at 630 GeV S$p\bar{p}$S
  Phys.Lett.B 256 (1991) 121
- From b to B: standard (non-perturbative) fragmentation
  $\Rightarrow$ nothing new
- From B to μ: data-driven implementation
- Data probes muons up to 40 GeV $\leftrightarrow$ b-quarks up to $\sim$ 80 GeV
- $\Rightarrow \ln(p_{T,b}^2/m_b^2) \sim 6$
- Resummation effects expected to be large

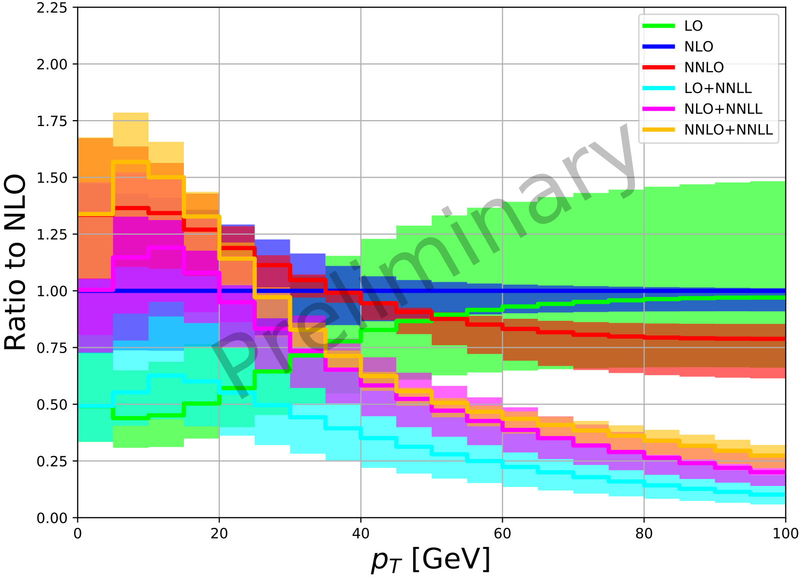
The muon p_T spectrum through NNLO+NNLL



The muon p_T spectrum through NNLO+NNLL



The muon p_T spectrum through NNLO+NNLL



Conclusion & outlook

- First NNLO+NNLL calculation of open bottom at hadron colliders
- Resummed $\ln(p_{T,b}/m_b)$ + some soft-gluon resummation
- Including full mass dependence at FO
- Straightforward extension of FONLL to higher order
- Improved precision and agreement with data w.r.t. NLO+NLL
- Prediction shown just an illustrative example
- Also have predictions for LHC & Tevatron
- Stay tuned for the publication!