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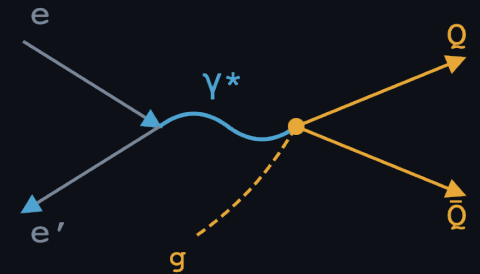
Heavy Quark Pair Production in DIS in POWHEG

Clara Del Pio

[arXiv:2606.21510](https://arxiv.org/abs/2606.21510)

in collaboration with S. Castro, A. Kardos, S. O. Moch, A. Spourdalakis

Precision QCD for ep physics at the EIC · 23 September 2026



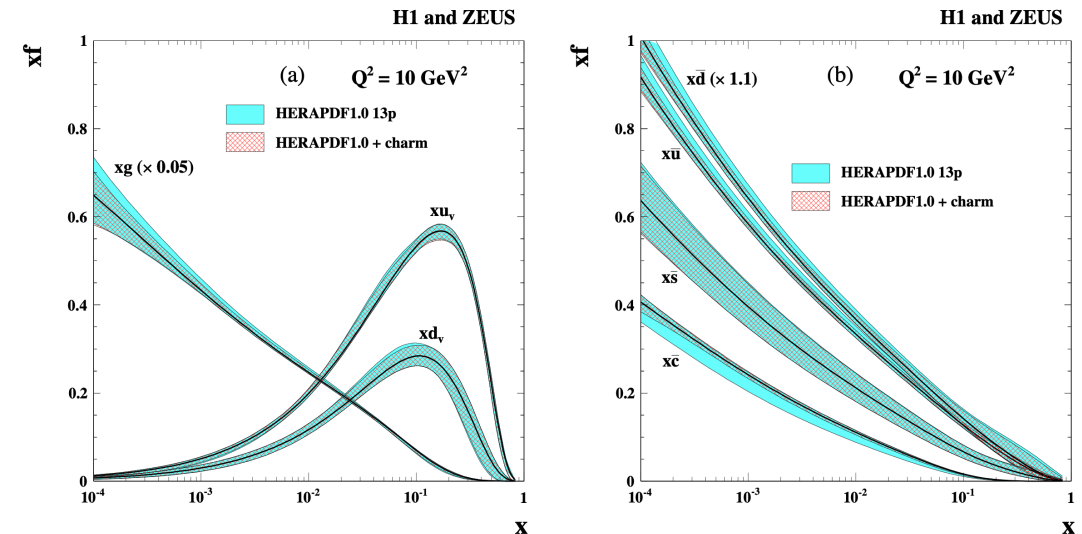
INTRODUCTION

Heavy quark production in DIS

The EIC will feature $\mathcal{L} = 10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with electron and proton polarization; excellent bottom/charm tagging

Heavy-quark production crucial for:

- probe of gluon and heavy-quark PDFs at medium/low x
- heavy quark mass as hard scale for perturbative QCD tests: mass effects, threshold behavior, higher-order corrections



INTRODUCTION

EIC reach

LHC $\sqrt{s} = 13 \text{ TeV}$

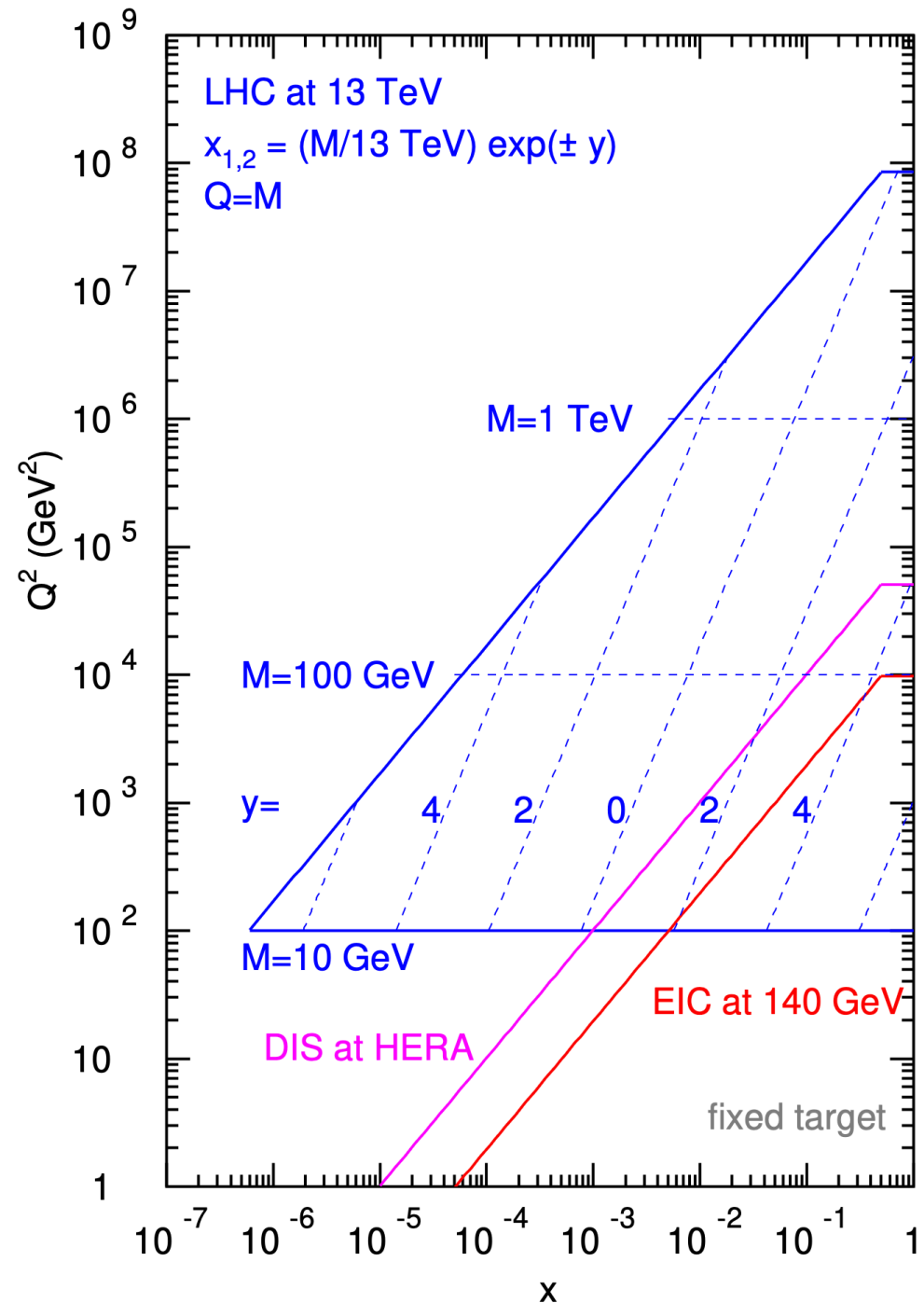
parton kinematics well covered by
HERA and fixed target experiments

forward rapidities sensitive to small x

EIC $\sqrt{s} = 140 \text{ GeV}$

collisions at EIC cover large part
of phase space relevant for LHC

overlap with HERA and fixed target
experiments



Heavy quark production in DIS

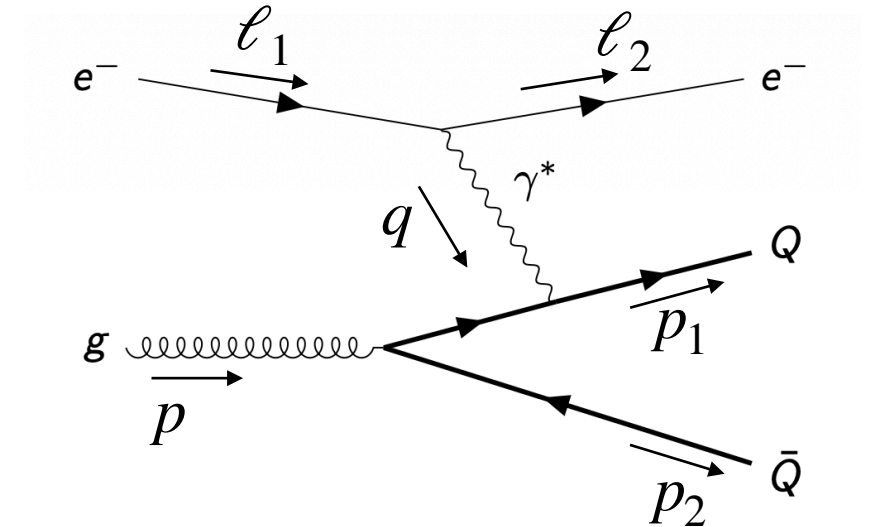
Riemersma, Smith, van Neerven, Phys. Lett. B347 (1995) 143–151

Neutral current exchange

$$\frac{d^2\sigma}{dxdy} = \frac{2\pi\alpha^2}{Q^4} S[\underbrace{\{1 + (1 - y)^2\}}_{\text{structure functions}} \underbrace{F_2(x, Q^2, m^2)}_{\text{structure functions}} - y^2 \underbrace{F_L(x, Q^2, m^2)}_{\text{structure functions}}]$$

structure functions

$$x = \frac{Q^2}{2p \cdot q} \quad (0 < x \leq 1) \quad y = \frac{p \cdot q}{p \cdot l_1} \quad -q^2 = Q^2 = xyS$$



Heavy quark production in DIS

Neutral current exchange $z^{\max} = 1/(1 + 4m^2/Q^2)$

$$F_k(x, Q^2, m^2) = \frac{\alpha_s e_h^2}{4\pi^2} \xi \sum_{i=q, \bar{q}, g} \int_x^{z^{\max}} \frac{dz}{z} f_i\left(\frac{x}{z}, \mu_f^2\right) c_{k,i}(\eta(z), \xi, \mu_f^2, \mu_r^2) \quad k = 2, L$$

$$\eta = \frac{s}{4m^2} - 1, \quad \xi = \frac{Q^2}{m^2}$$

$$c_{k,i}(\eta, \xi, \mu^2) = \sum_{j=0}^{\infty} (4\pi\alpha_s)^j c_{k,i}^{(j)}(\eta, \xi, \mu^2) = \sum_{j=0}^{\infty} (4\pi\alpha_s)^j \sum_{l=0}^j c_{k,i}^{(j,l)}(\eta, \xi) \ln^l \frac{\mu^2}{m^2}$$

NLO corrections $c_{k,i}^{1,0}, c_{k,i}^{1,1}$

Riemersma, Smith, van Neerven, Phys. Lett. B347 (1995) 143–151

Laenen, Riemersma, Smith, van Neerven, Nucl. Phys. B392 (1993) 162–228

Harris, Smith, Nucl. Phys. B452 (1995) 109–160

Heavy quark production in DIS

Neutral current exchange

$$c_{k,i}(\eta, \xi, \mu^2) = \sum_{j=0}^{\infty} (4\pi\alpha_s)^j c_{k,i}^{(j)}(\eta, \xi, \mu^2) = \sum_{j=0}^{\infty} (4\pi\alpha_s)^j \sum_{l=0}^j c_{k,i}^{(j,l)}(\eta, \xi) \ln^l \frac{\mu^2}{m^2}$$

NNLO corrections

current frontier of research

$$c_{k,i}^{2,1}, \quad c_{k,i}^{2,2}$$

$$c_{k,i}^{2,0}$$

$$c_{2,g}^{2,0}, \quad c_{2,q}^{2,0}$$

no complete results available

approx. with info from energy regions

$$s \simeq 4m^2, \quad s \gg 4m^2, \quad Q^2 \gg m^2$$

Laenen, Moch, Phys. Rev. D59 (1999) 034027

Behring et al., Eur. Phys. J. C74 (2014), no. 9 3033

Alekin, Moch, Phys. Lett. B699 (2011) 345–353

Mellin moments up to $N = 22$

Klann, Moch, Schönwald, 2602.04455

Kawamura et al., Nucl. Phys. B864 (2012) 399–468

Ablinger et al., Nucl. Phys. B890 (2014) 48–151

Ablinger et al., Nucl. Phys. B882 (2014) 263–288

Behring et al., Phys. Rev. D92 (2015), no. 11 114005

Heavy quark production in DIS

Change current exchange

$$F_k(x, Q^2, m^2) = \sum_{i=q, \bar{q}, g} \int_{\chi}^1 \frac{dz}{z} f_i\left(\frac{x}{z}, \mu_f^2\right) C_{k,i}(z, \xi, \mu_r^2, \mu_f^2)$$

$\chi = \left(1 + \frac{m^2}{Q^2}\right)x$

NLO corrections $C_{k,i}^1$

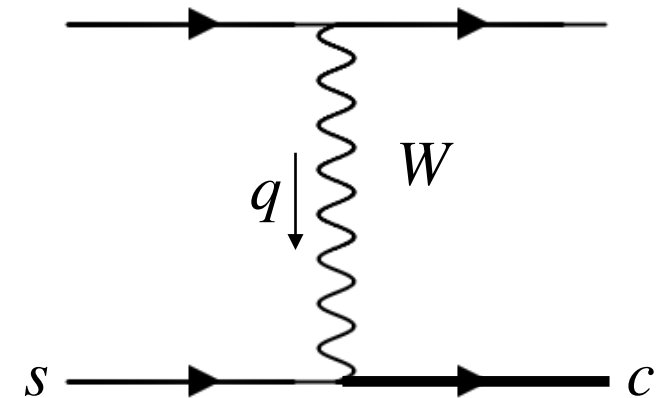
Gottschalk, Phys. Rev. D23 (1981) 56

Glück, Kretzer, Reya, Phys. Lett. B380 (1996) 171–176

Blümlein, et al., Phys. Lett. B700 (2011) 294–304

POWHEG implementation

Buonocore et al., JHEP 08 (2024) 083



Heavy quark production in DIS

Change current exchange

$$F_k(x, Q^2, m^2) = \sum_{i=q, \bar{q}, g} \int_{\chi}^1 \frac{dz}{z} f_i\left(\frac{x}{z}, \mu_f^2\right) C_{k,i}(z, \xi, \mu_r^2, \mu_f^2)$$

$\chi = \left(1 + \frac{m^2}{Q^2}\right)x$

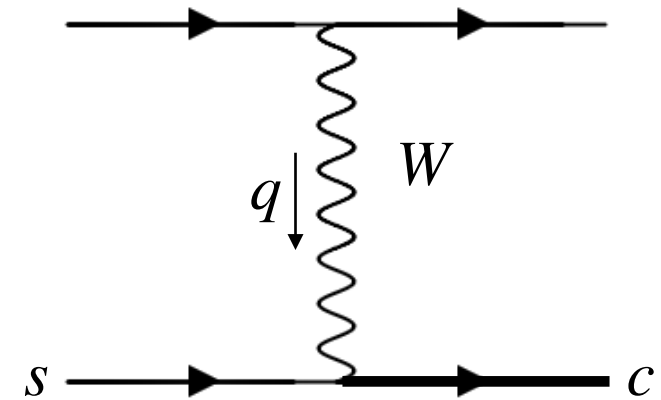
NNLO corrections $C_{k,i}^2$

Berger et al., Phys. Rev. Lett. 116 (2016), no. 21 212002

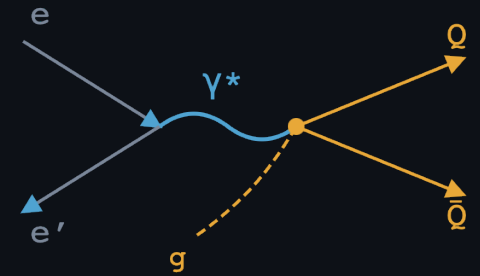
Caola, Gimbuti, Link, 2606.21702 [hep-ph]

QCD corrections small for scale choices $\mu = \sqrt{Q^2 + m^2}$

reduction of the theoretical uncertainties due to scale variations

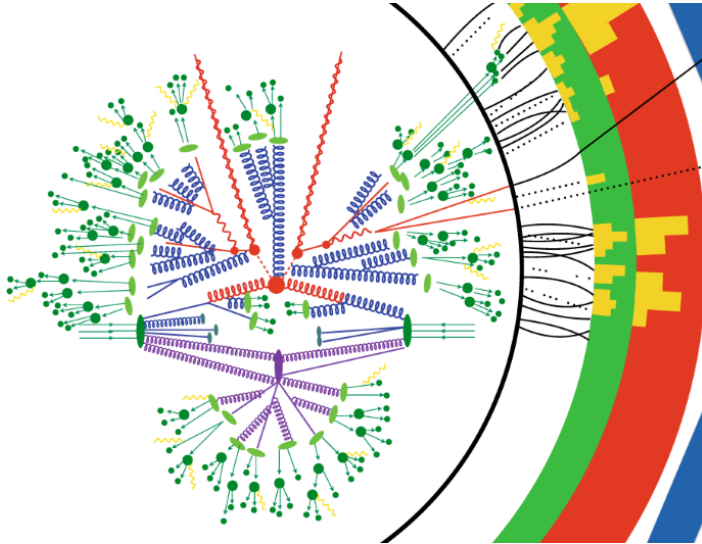


Numerical implementation at NLO



The POWHEG method

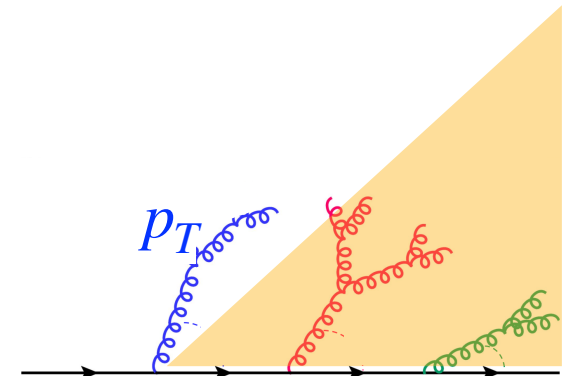
POsitive Weighted Hardest Emission Generator



- problem: interface parton-shower generators with NLO QCD computations without double counting
- MC@NLO: subtract from the NLO cross section its approximation as simulated in the shower → possible **negative weights**



POWHEG: hardest emission is generated first with the exact NLO matrix element



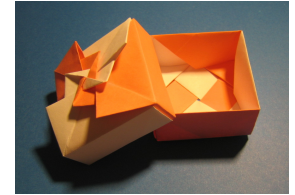
The POWHEG method

POsitive Weighted Hardest Emission Generator

Hardest emission generated with

POWHEG master formula

$$d\sigma = \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T(\Phi_{n+1})) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right\}_{\bar{\Phi}_n = \Phi_n}$$



$$\bar{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int d\Phi_{\text{rad}} R(\Phi_{\text{rad}}) \quad \text{Normalization}$$

The POWHEG method

POsitive Weighted Hardest Emission Generator

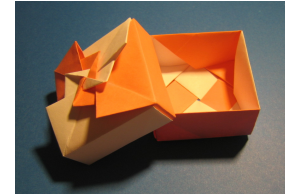
Hardest emission generated with

POWHEG master formula

probability of no emission above some minimum

$$d\sigma = \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T(\Phi_{n+1})) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right\}_{\bar{\Phi}_n = \Phi_n}$$

probability of exactly one emission at k_T



Sudakov form factor

$$\Delta(\Phi_n, p_T) = \exp \left\{ - \int \frac{[d\Phi_{\text{rad}} R(\Phi_{n+1}) \theta(k_T(\Phi_{n+1}) - p_T)]}{B(\Phi_n)} \right\}_{\bar{\Phi}_n = \Phi_n}$$

probability of no emission at $k_T > p_T$

Process implementation

- born & real matrix elements for $c\bar{c}$ and $b\bar{b}$ in spinor-helicity formalism

Britto, Cachazo, Feng, Witten, Phys. Rev. Lett. 94:181602, 2005

Ochirov, JHEP 1804 (2018) 089 Lazopoulos, Ochirov, Shi, JHEP 03 (2022) 009

- virtual: approximated with massification

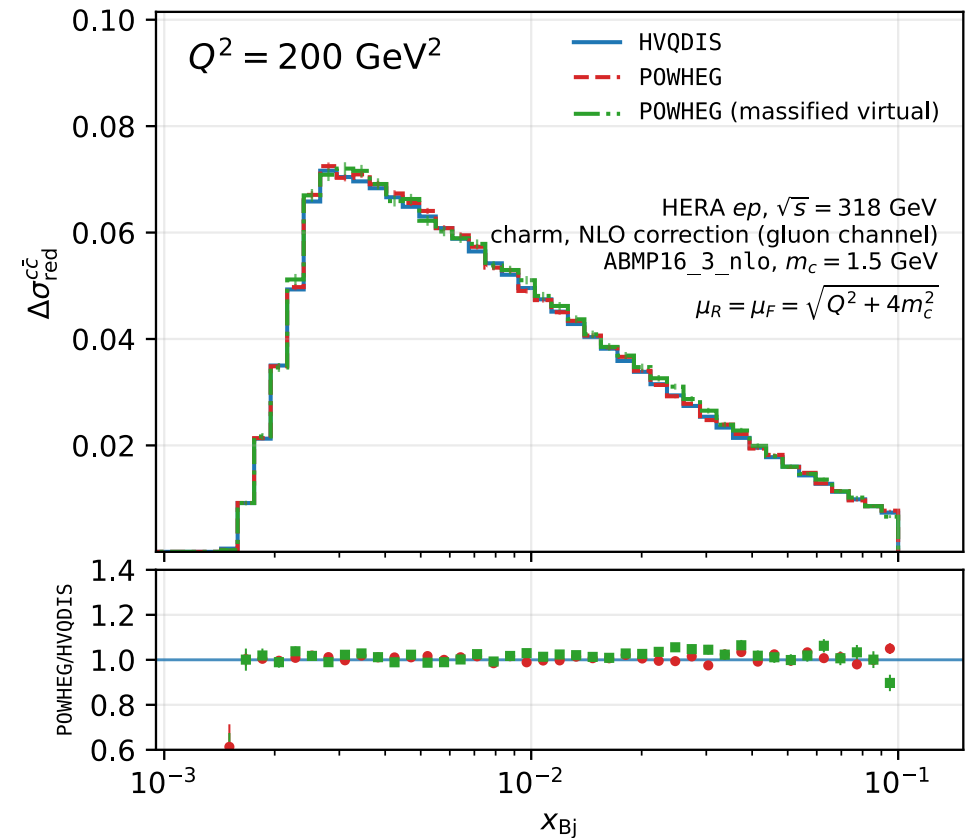
$$|\mathcal{M}_m^{(1)}\rangle = |\mathcal{M}_0^{(1)}\rangle + \mathbf{I}_m |\mathcal{M}_m^{(0)}\rangle - \mathbf{I}_0 |\mathcal{M}_0^{(0)}\rangle$$

Catani, Phys.Lett. B427 (1998) 161-171

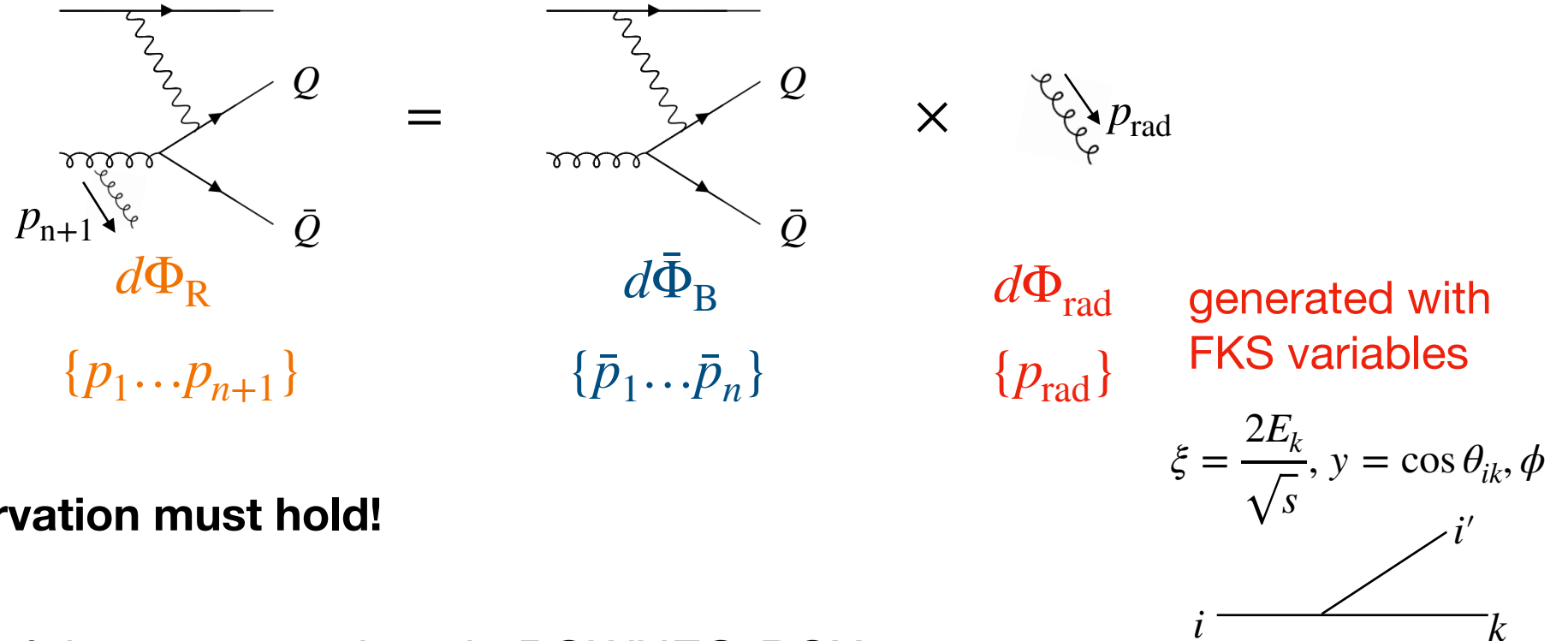
Catani, Dittmaier, Trocsanyi, Phys.Lett.B500:149-160,2001

exact calculation from HVQDIS

Riemersma, Smith, van Neerven, Phys. Lett. B347 (1995) 143-151



Phase space mapping



momentum conservation must hold!

- implementation of the real mappings in POWHEG-BOX
- crucial to construct subtraction terms in the Monte Carlo

Phase space mapping

$$d\Phi_R = d\bar{\Phi}_B \times \frac{\nu S}{(2\pi)^3} \xi \sqrt{\frac{x_{1,2}}{\Delta_x}} d\xi dy d\phi$$

$$\nu = (l_1 - l_2)P$$

$$x_{1,2} = x_{1,2}(\xi, y, \phi)$$

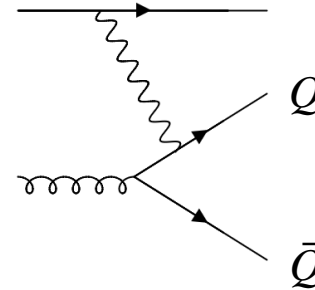
$$\Delta_x = \Delta_x(\xi, y, \phi)$$

- DIS mappings should preserve y (or Q^2) and the Bjorken x , i.e. it preserves the lepton momentum

Banfi et al., JHEP 02 (2024) 001

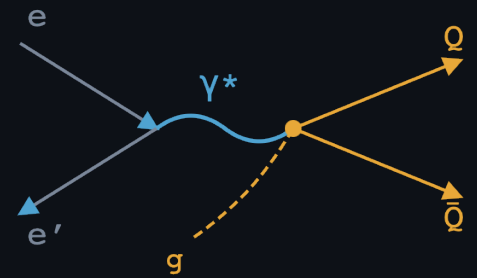
Buonocore et al., JHEP 08 (2024) 083

- in our case also $p_{Q\bar{Q}}^2$ preserved



- Checked against in-house fixed-order Monte Carlo code

Results



RESULTS

Heavy quark observables

DIS kinematics:

$$Q^2, \quad y, \quad x_{\text{Bj}} = \frac{Q^2}{s y}$$

$$\frac{d^2\sigma}{dx_{\text{Bj}} dQ^2} = \frac{2\pi\alpha^2(Q^2)}{x_{\text{Bj}} Q^4} \left[(1 + (1 - y)^2) F_2(x_{\text{Bj}}, Q^2, m^2) - y^2 F_L(x_{\text{Bj}}, Q^2, m^2) \right]$$

Reduced cross section: isolates the structure functions - genuine hadronic structure

$$\begin{aligned} \sigma_{\text{red}}^{Q\bar{Q}} &= \frac{d^2\sigma}{dx_{\text{Bj}} dQ^2} \cdot \frac{x_{\text{Bj}} Q^4}{2\pi\alpha^2(Q^2) (1 + (1 - y)^2)} \\ &= F_2(x_{\text{Bj}}, Q^2, m^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x_{\text{Bj}}, Q^2, m^2) \end{aligned}$$

RESULTS

Validation

H1+ZEUS

Eur.Phys.J.C 78 (2018) 6, 473

$$\sqrt{s} = 318 \text{ GeV}$$

$$2 < Q^2 < 2500 \text{ GeV}^2$$

Contribution

LO

NLO g

NLO q ($\gamma^* Q$)

NLO q ($\gamma^* q + \text{int.}$)

Cross section [pb]

34.3539(1)

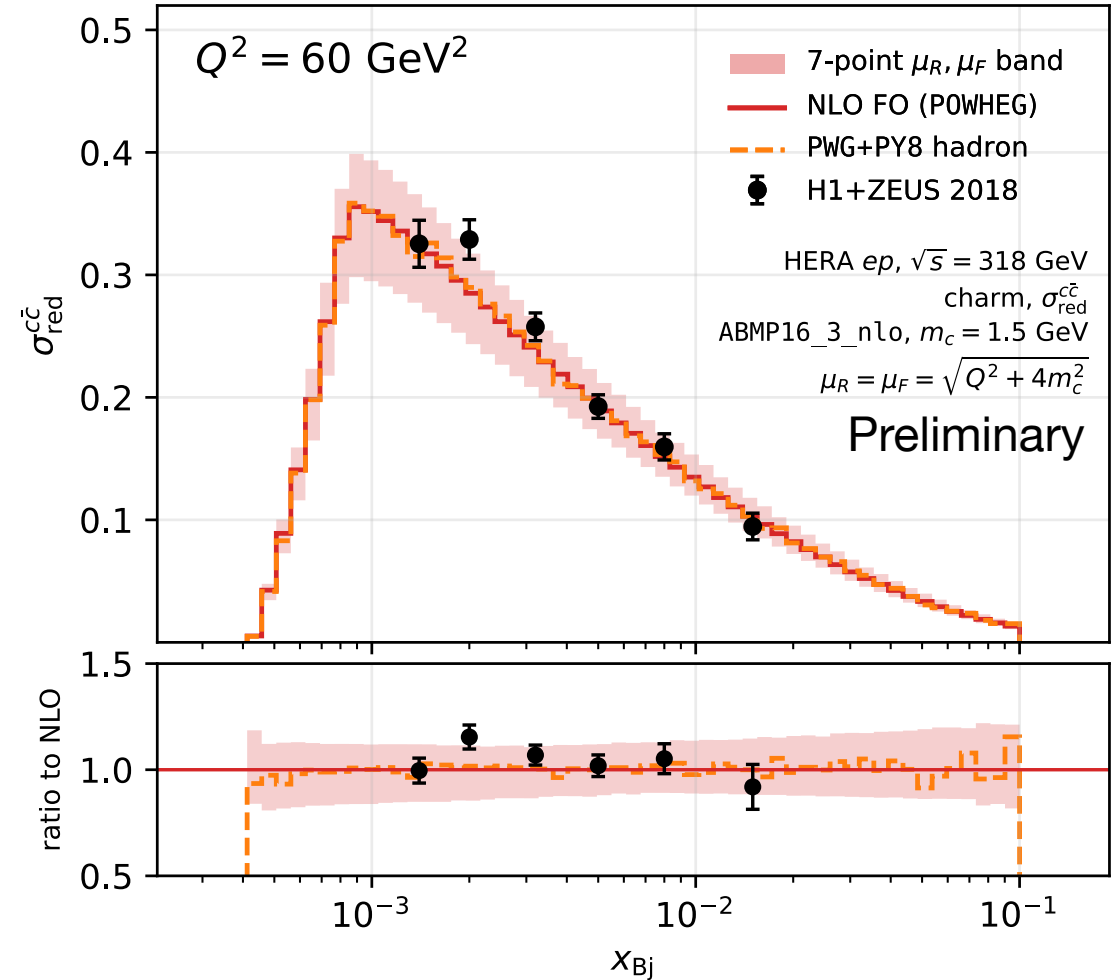
14.6432(6)

-1.8752(31)

0.1907(31)

$\gamma^* Q$: virtual photon coupled to the heavy-quark line

$\gamma^* q$: light-quark-coupled contribution and its interference with heavy-quark-coupled one



RESULTS

Loose vs. tight selection

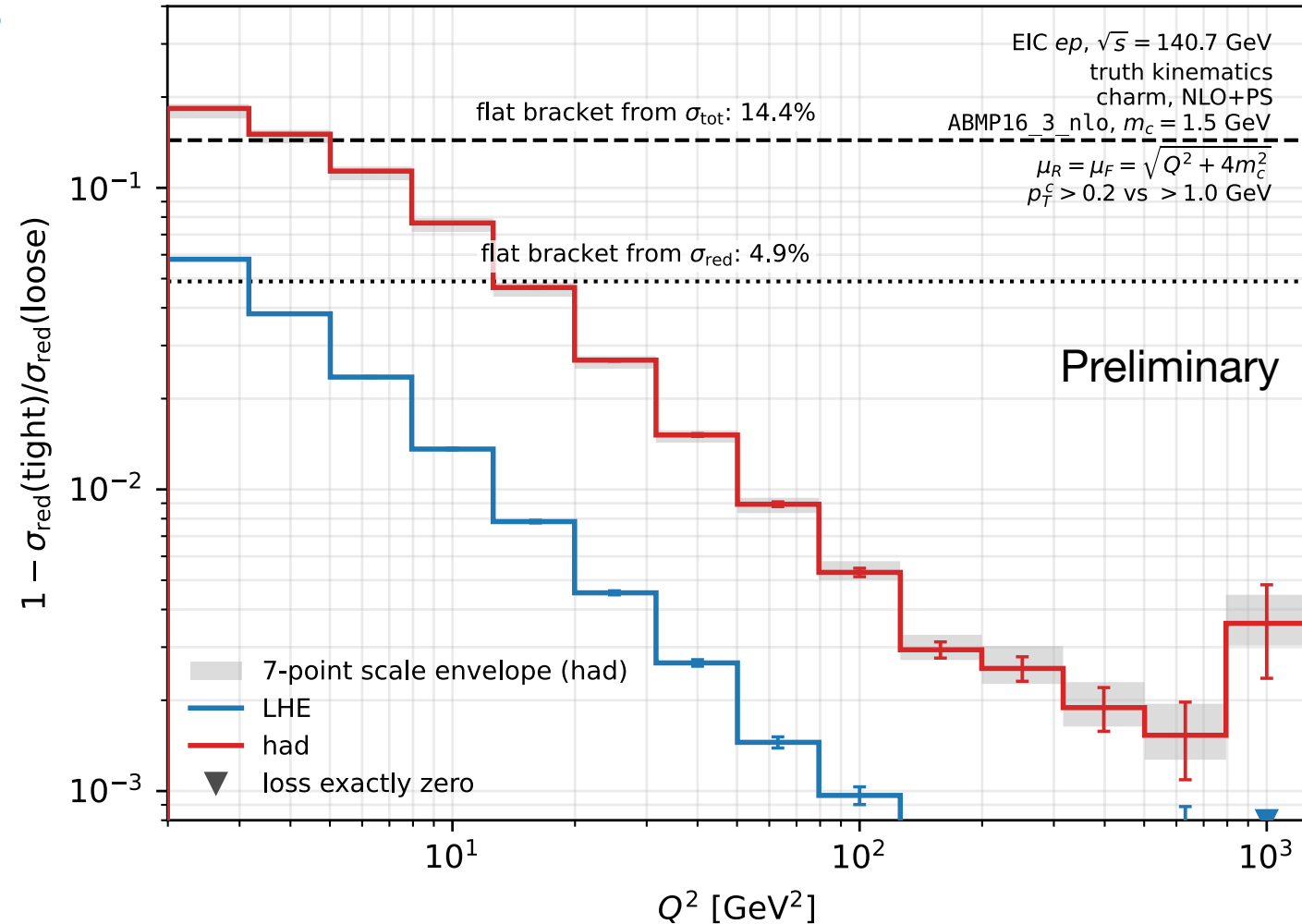
loose selection interesting for 2nd detector

Loss due to selection cuts

Hadronization smears
 p_T spectrum

At low Q^2 less events
with high p_T

In σ_{red} less effect
from low Q^2 bins



RESULTS

Kinematics reconstruction

DIS kinematics:

$$Q^2, \quad y, \quad x_{Bj} = \frac{Q^2}{s y}$$

MC truth

DIS variables directly from the hard process

Electron method

Energy and angle of the scattered electron

$$y_e = 1 - \frac{E'_e}{2E_e}(1 - \cos \theta_e), \quad Q_e^2 = 2E_e E'_e(1 + \cos \theta_e)$$

Jacquet-Blondel method

Energy and momentum of hadronic system

$$\Sigma = \sum_{i \in \text{hadrons}} (E_i - p_{z,i}), \quad y_{JB} = \frac{\Sigma}{2E_e}, \quad Q_{JB}^2 = \frac{p_{T,had}^2}{1 - y_{JB}}$$

Double angle method

Polar angles of electron and hadronic

$$Q_{DA}^2 = 4E_e^2 \frac{\sin \theta_h(1 + \cos \theta_e)}{\sin \theta_h + \sin \theta_e - \sin(\theta_h + \theta_e)}, \quad y_{DA} = \frac{\sin \theta_e(1 - \cos \theta_h)}{\sin \theta_h + \sin \theta_e - \sin(\theta_h + \theta_e)}$$

RESULTS

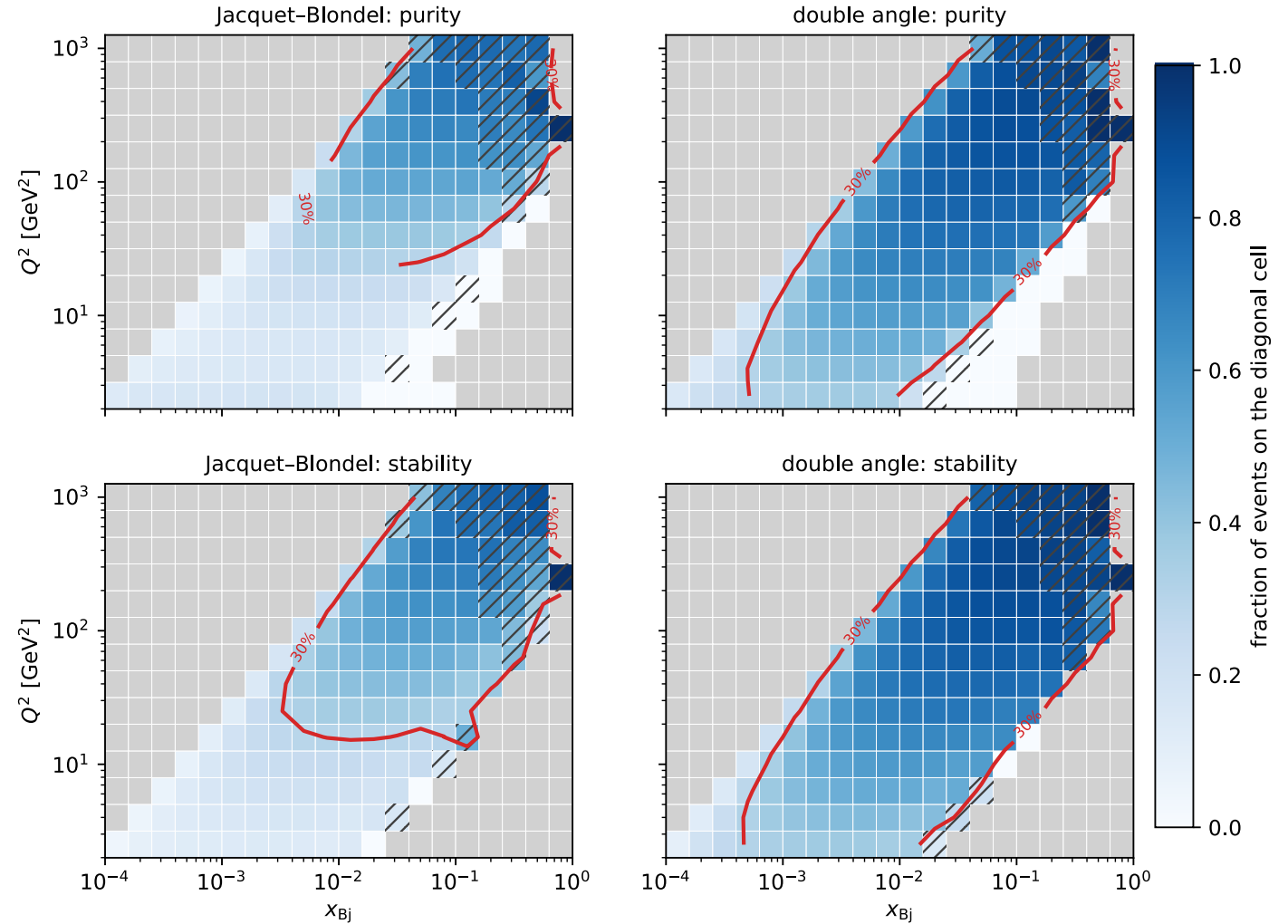
Kinematics reconstruction

Purity and stability: DA vs JB

purity: contamination from other cells

stability: migration from given cell to others

EIC ep , $\sqrt{s} = 140.7$ GeV | hadron level | charm, NLO+PS | ABMP16_3_nlo, $m_c = 1.5$ GeV | $\mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$ Preliminary



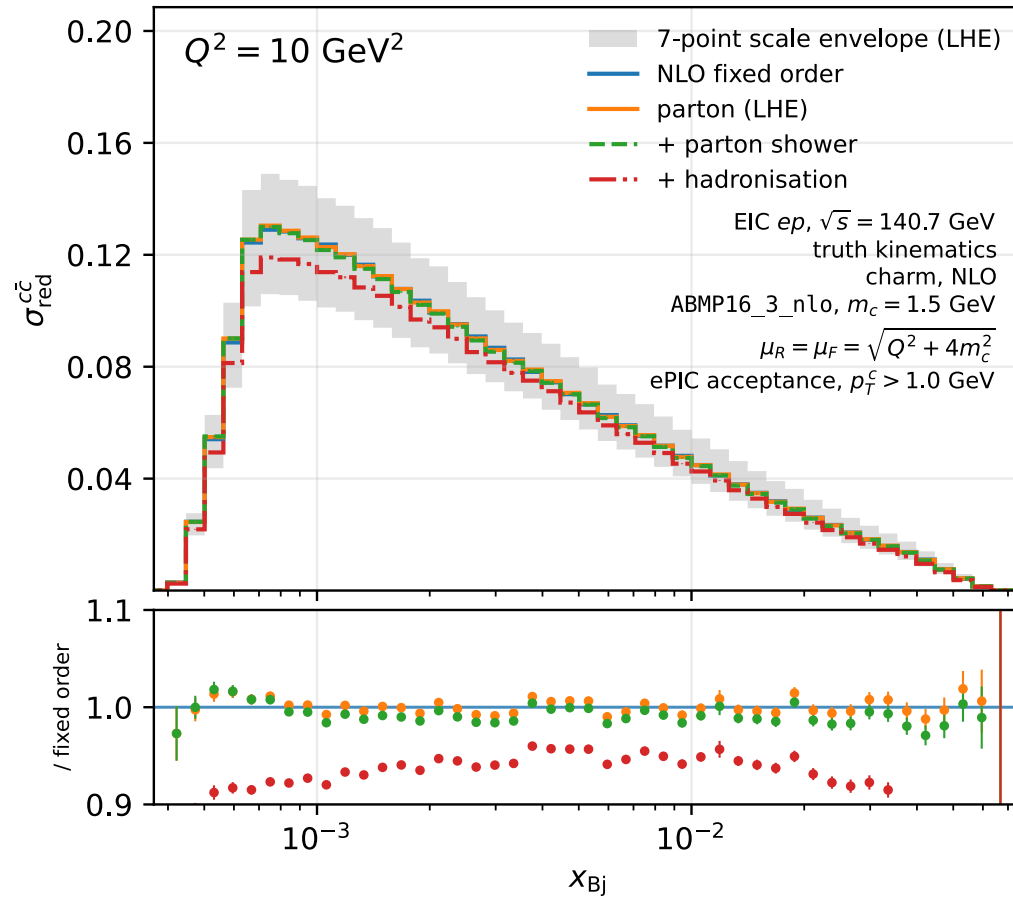
red contour: Yellow Report 30% benchmark | hatched: MC error > 5% | grey: no reconstructed events

RESULTS

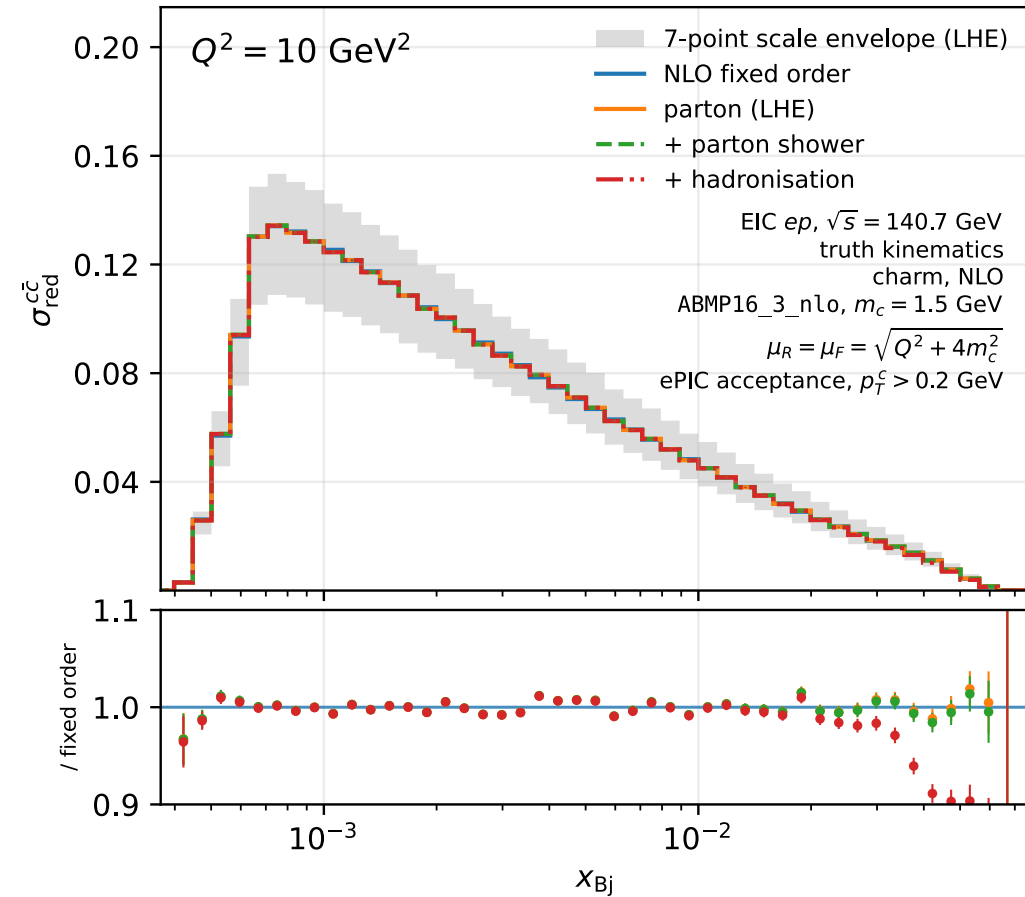
EIC predictions

Truth

Preliminary



Preliminary

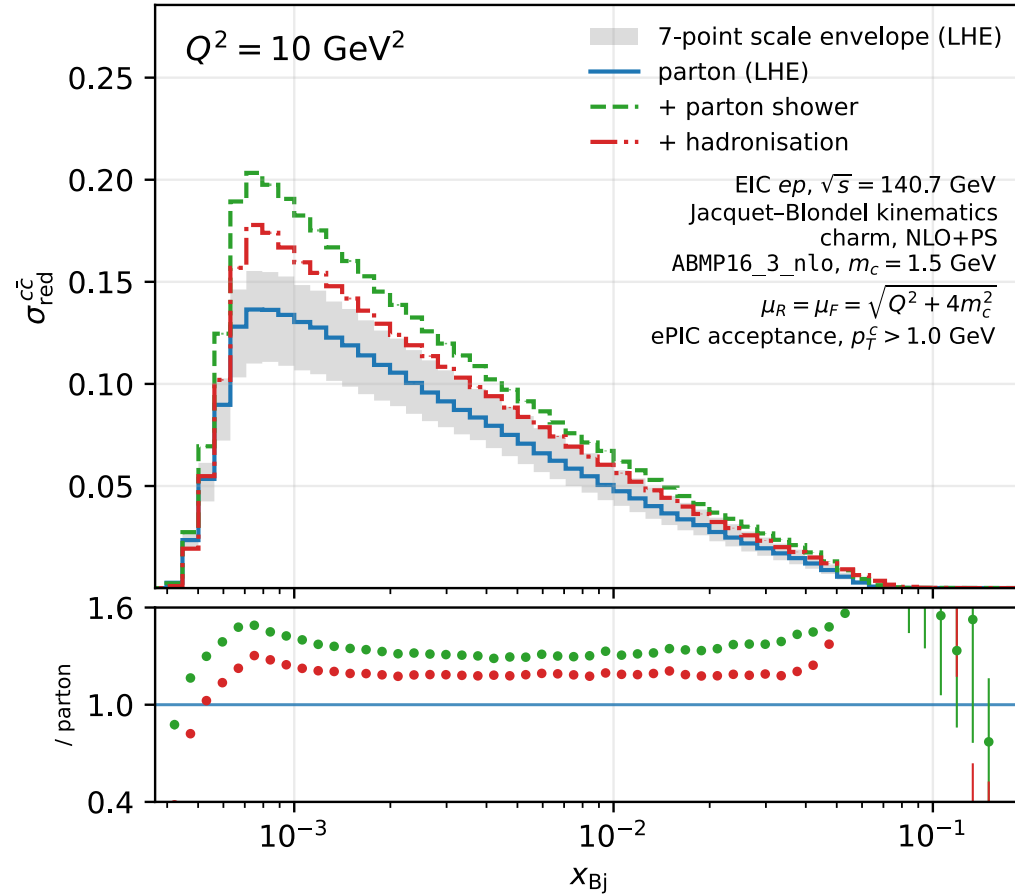


RESULTS

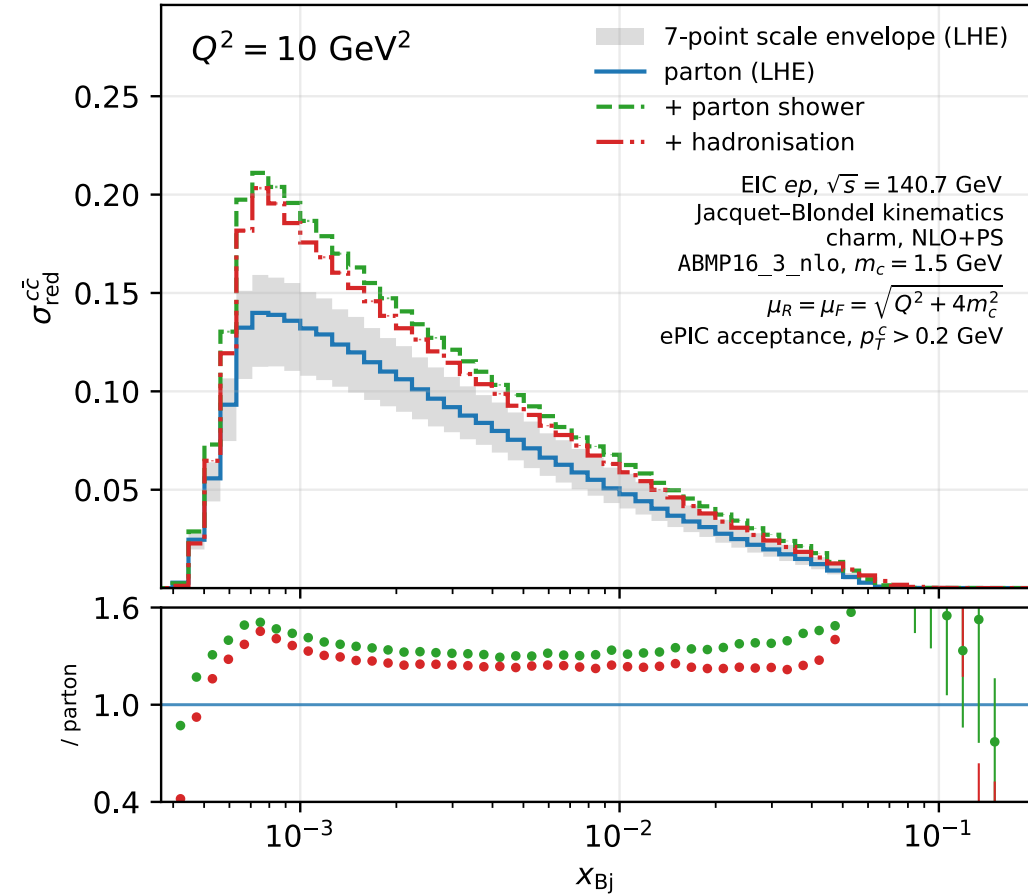
EIC predictions

Jacquet-Blondel

Preliminary

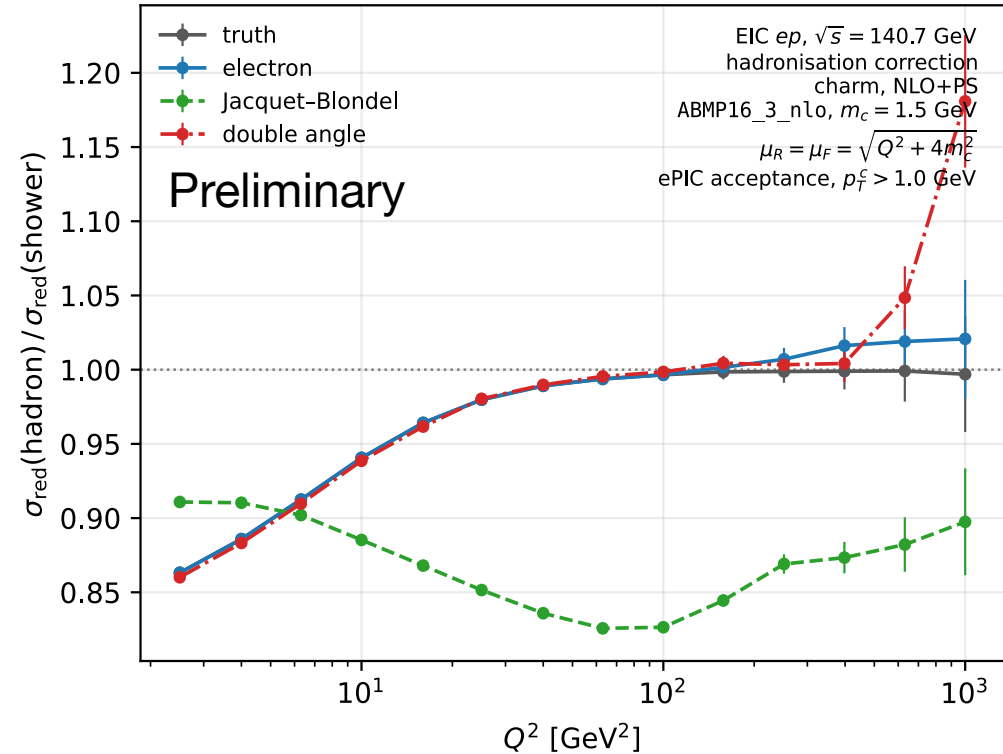
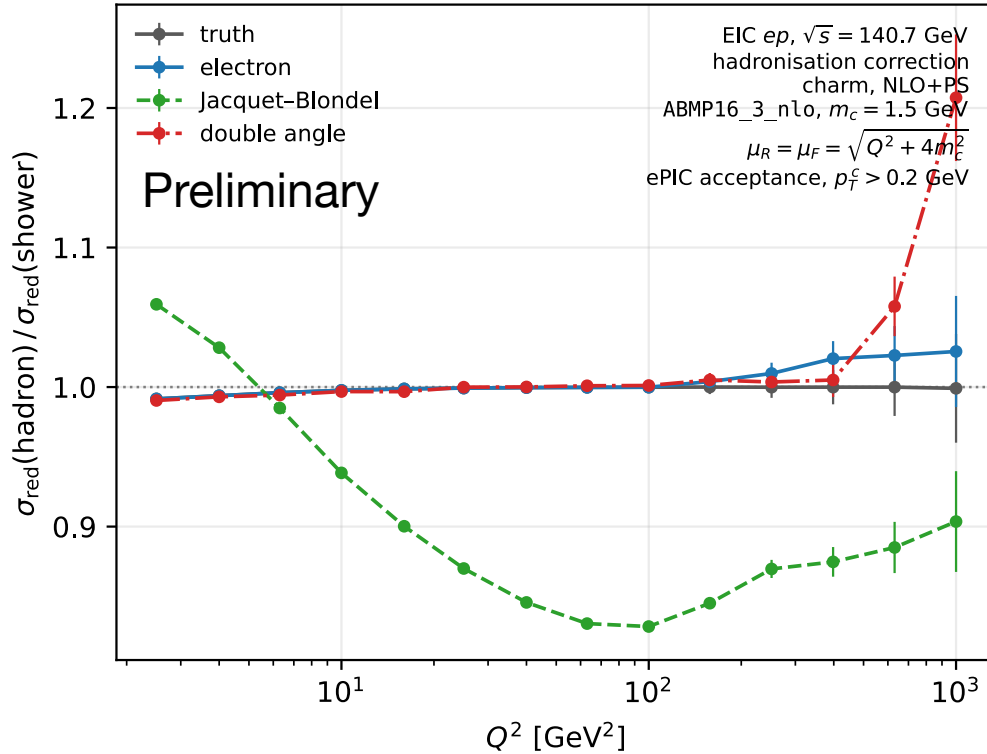


Preliminary



RESULTS

Hadronization effects



MC truth and electron: very small hadronization effects

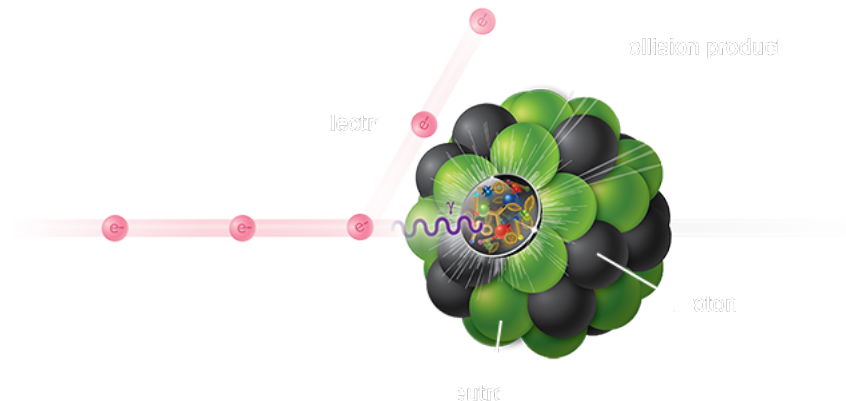
DA: at high Q^2 hadronic system is more boosted - sensitive to hadronization reshuffling of the final state

JB: most sensitive to hadronization - less effect at high Q^2

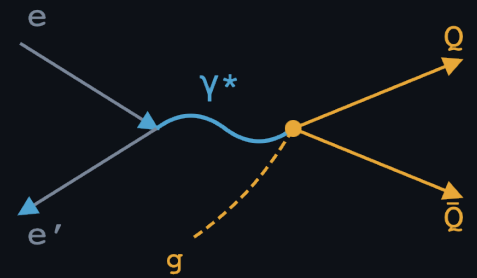
THANK YOU!

To conclude

- Neutral-current heavy quark production in DIS is a very interesting process at the EIC
- NLO QCD predictions matched to a parton shower with POWHEG. Shower and hadronisation effects strongly depend on the reconstruction method and phase-space cuts
- Electron reconstruction is nearly exact in the present setup; DA remains close to truth, while JB shows considerably larger migration



Back up

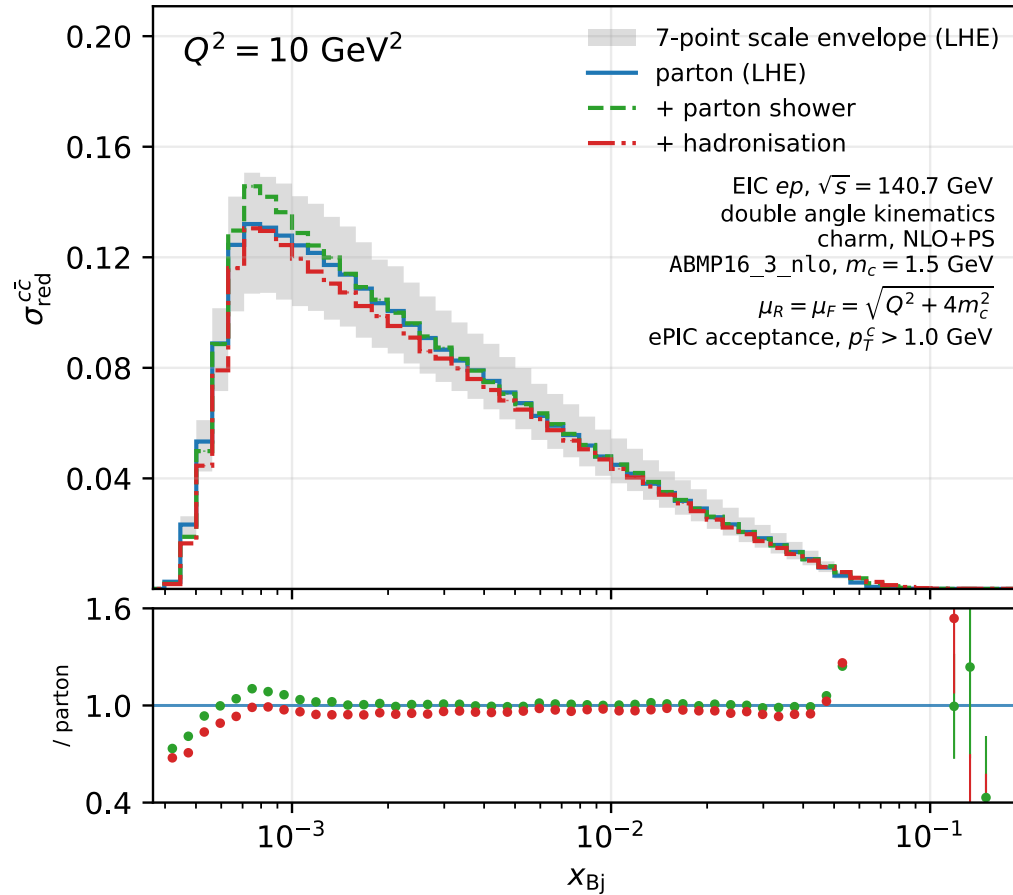


RESULTS

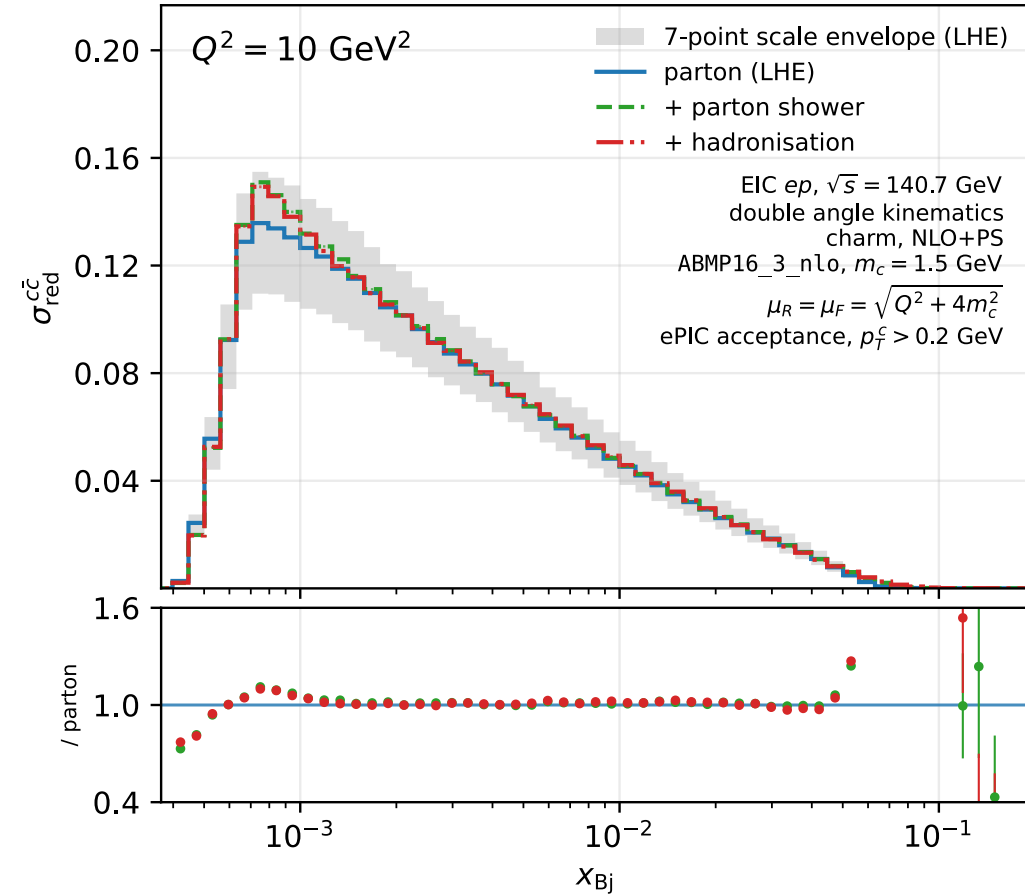
EIC predictions

Double angle

Preliminary



Preliminary



Massification breaks down

- virtual: approximated with massification

$$|\mathcal{M}_m^{(1)}\rangle = |\mathcal{M}_0^{(1)}\rangle + \mathbf{I}_m |\mathcal{M}_m^{(0)}\rangle - \mathbf{I}_0 |\mathcal{M}_0^{(0)}\rangle$$

Catani, Phys.Lett. B427 (1998) 161-171

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