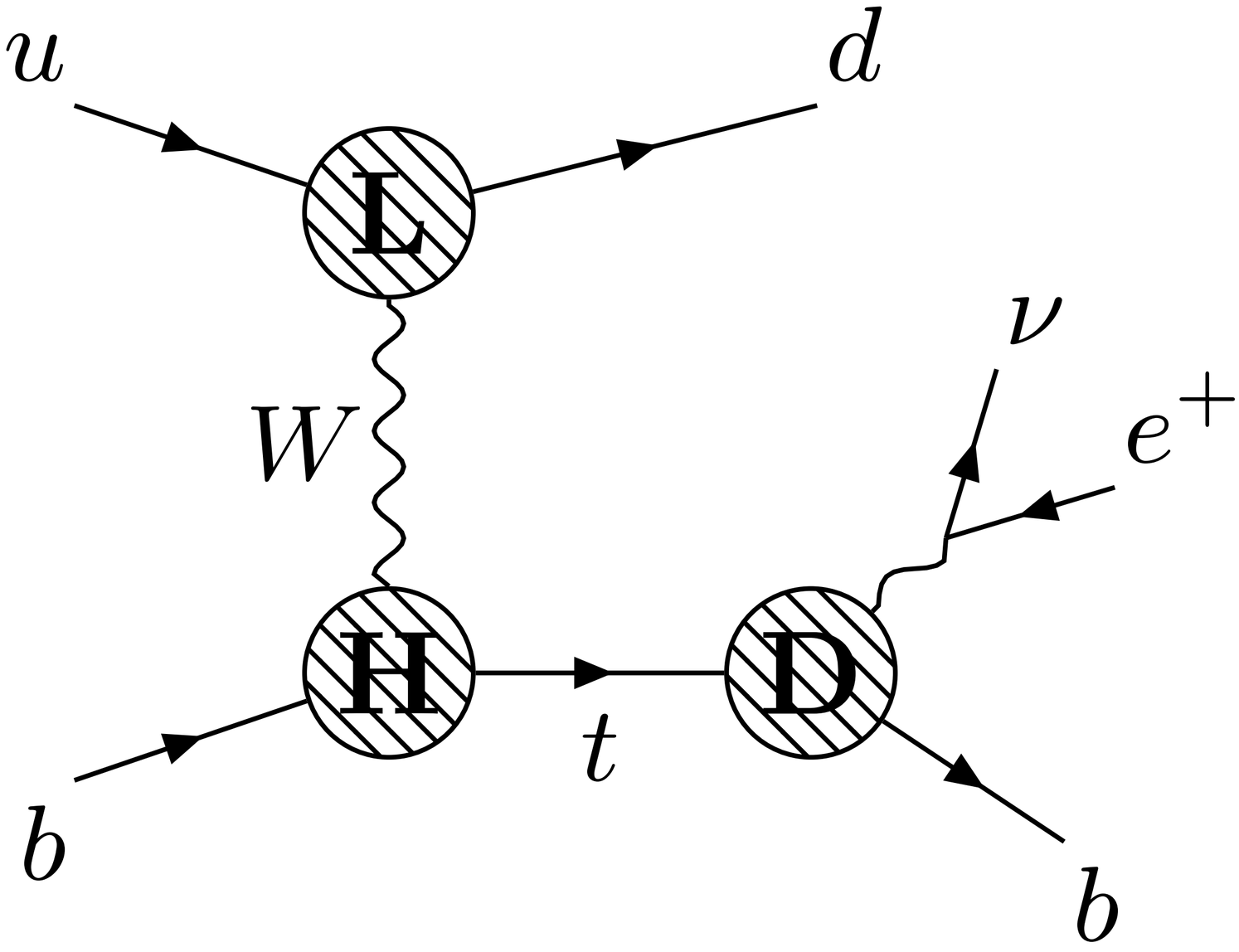
# Single-top-quark production (and decay) in the t-channel at NNLO

**Tobias Neumann, BNL**

**with John Campbell, Fermilab and Zack Sullivan, Illinois Tech**

**arXiv:2012.01574 / JHEP 02 (2021) 040**

**May 17th, 2021**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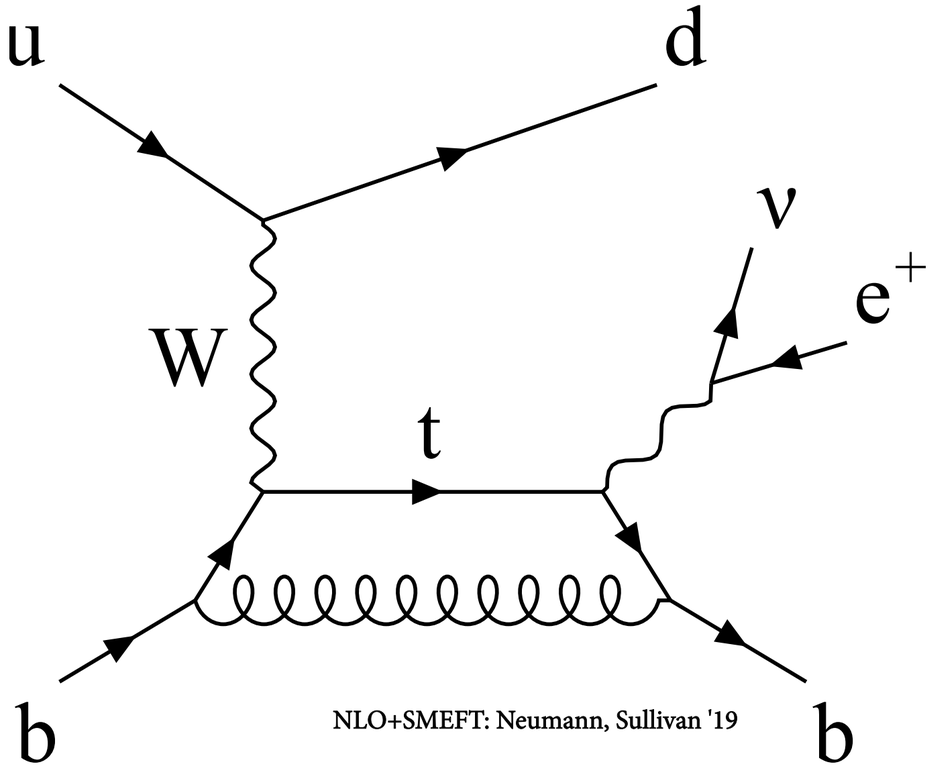
# Off-shell contributions




NLO+SMEFT: Neumann, Sullivan '19

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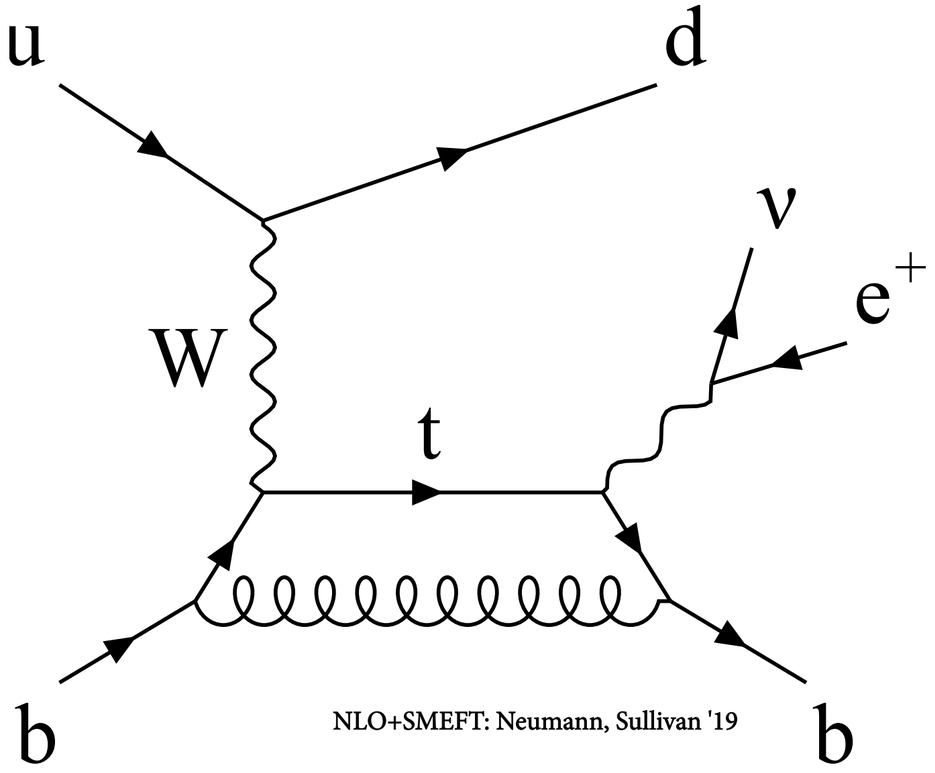
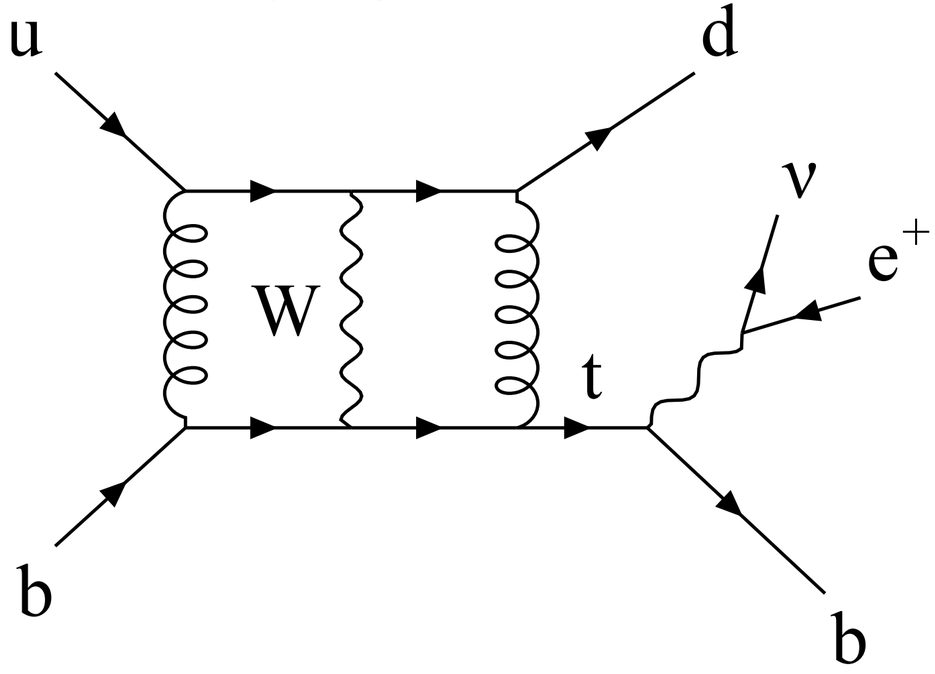
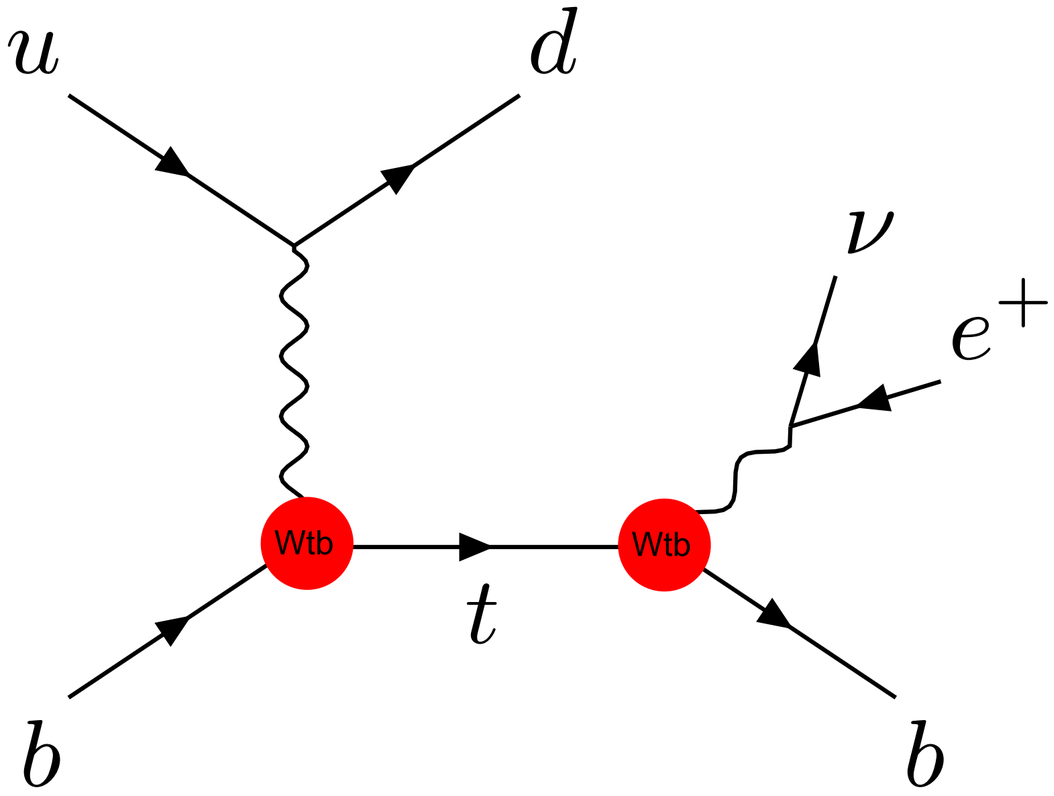



NLO+SMEFT: Neumann, Sullivan '19

# Heavy-light interference






Prime process to test V-A structure $\gamma^\mu P_L$

Access to $V_{tb}$: $\propto |V_{tb}|^2$

Top-quark mass: $m_{bl}$ lineshape

As background with signature $W$, $b$ + light jets

# 1. non-decaying top, needs decay

*(Brucherseifer, Caola, Melnikov '14)*

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(NNLO corrections are ~1-2%)

> *We found a difference of ~1% on the NNLO cross sections. [...] It has not been possible to further pin down the differences*
>
> *— Berger, Gao, Zhu '17*

$$\sigma_{i,j} = \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{f_i}(\mathrm{x_i}, \mu_\mathrm{F}) \mathrm{f_j}(\mathrm{x_j}, \mu_\mathrm{F}) \cdot \sigma^H_{i,j}(\mu_R, \mu_F, \vec{p})$$

# DIS

$$\mathbf{f_i}\left(\mathbf{x_i}, \boldsymbol{\mu_F}\right)$$

$$\mathcal{O} = \int dx\, f_q^{LO}(x) \quad q \text{ —— } (LO) \text{ —— } q' \;(+\,W) \;=\; \boxed{\text{physics}}$$

$$\mathcal{O} = \int dx\, f_q^{NLO}(x) \quad q \text{ —— } (NLO) \text{ —— } q' \;(+\,W) \;=\; \boxed{\text{physics}}$$

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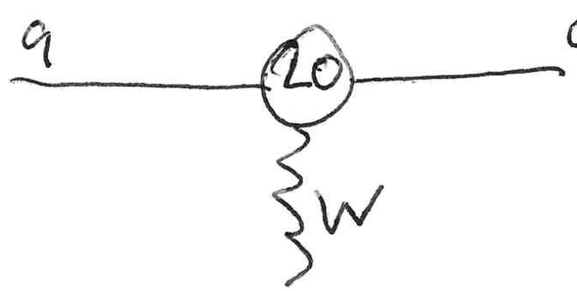
$$\mathcal{O} = \int dx\, f_q^{LO}(x)$$ 

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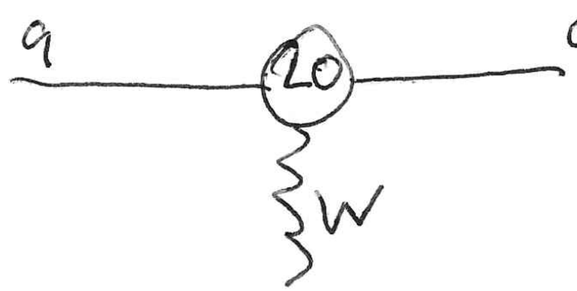
$$\mathcal{O} = \int dx\, f_q^{LO}(x)$$ 

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= physics

||

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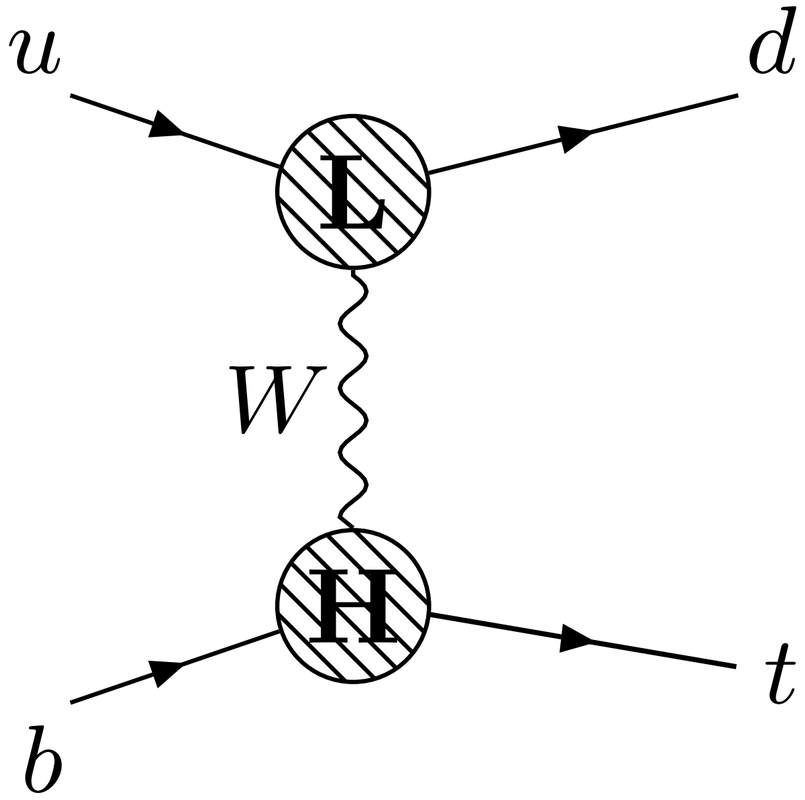
= physics

# Double DIS = DDIS




DDIS contraint at NLO: "Are PDFs still consistent with Tevatron data?"

*(Sullivan '17)*

**1. non-decaying top, needs decay**

***(Brucherseifer, Caola, Melnikov '14)***

**2. full calculation, *same scale everywhere***

**"found discrepancy of ~1%"**

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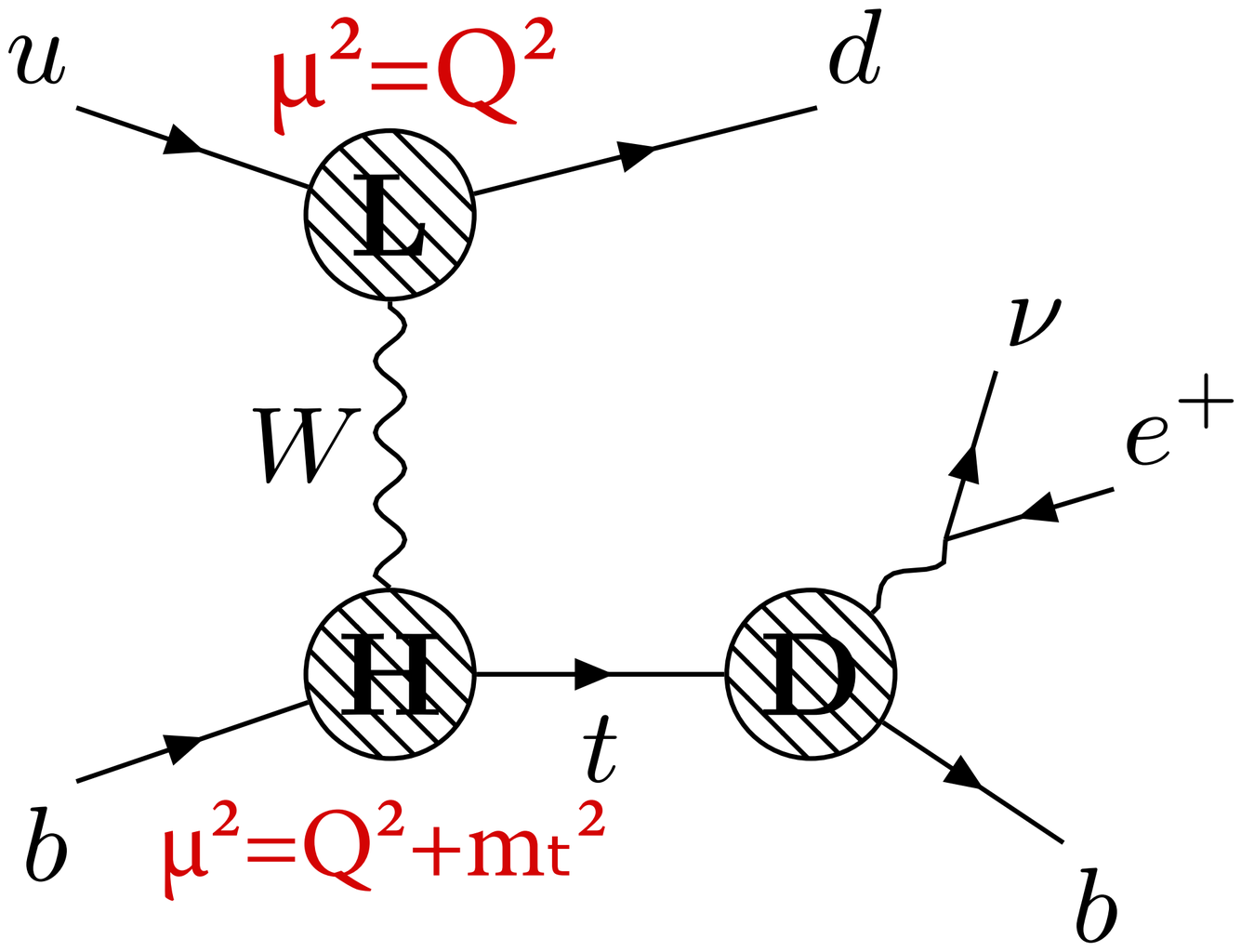
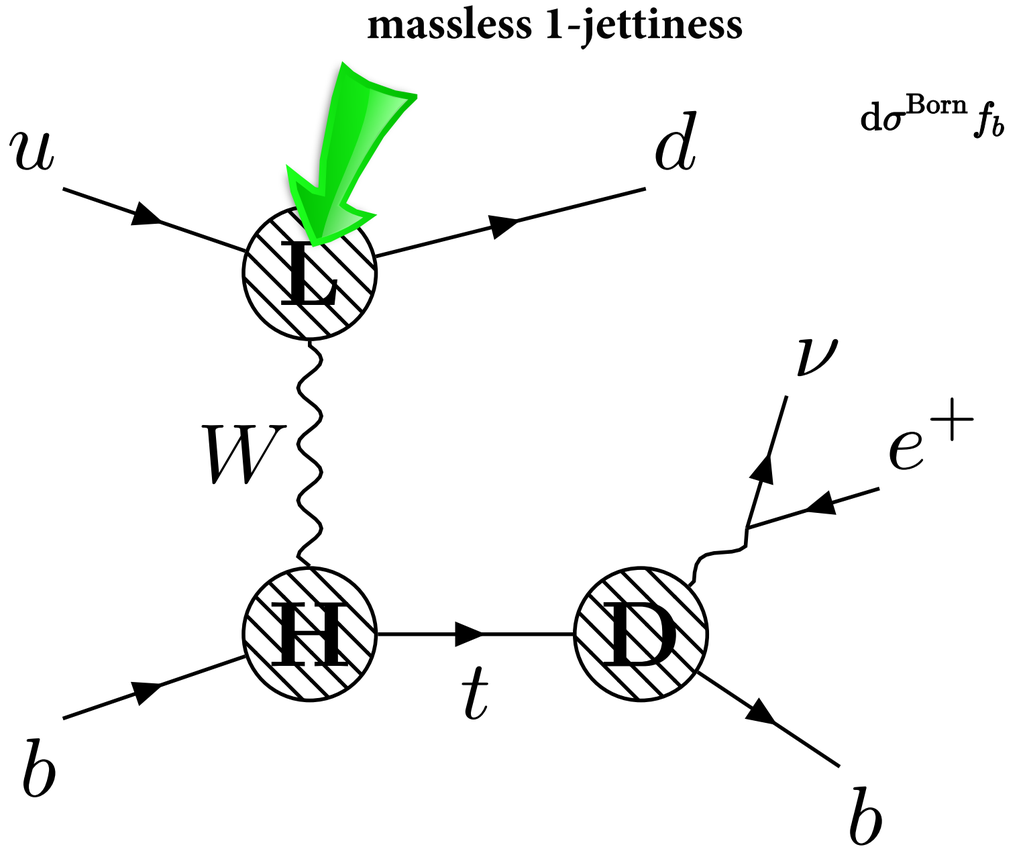
**Why is the same scale everywhere a problem?**

# Double DIS



# Three NNLO calculations




$$\mathrm{d}\sigma^{\mathrm{Born}} f_b(x_b,\mu) \int_0^{\tau^{\mathrm{cut}}} \mathrm{d}\tau\, B(x_u,\mu) \otimes J(\mu) \otimes S(\mu) \otimes H(\mu) + \mathcal{O}(\tau^{\mathrm{cut}} \log(\tau^{\mathrm{cut}}))$$

Gaunt, Stahlhofen, Tackmann, Walsh '15; Boughezal, Focke, Liu, Petriello '15

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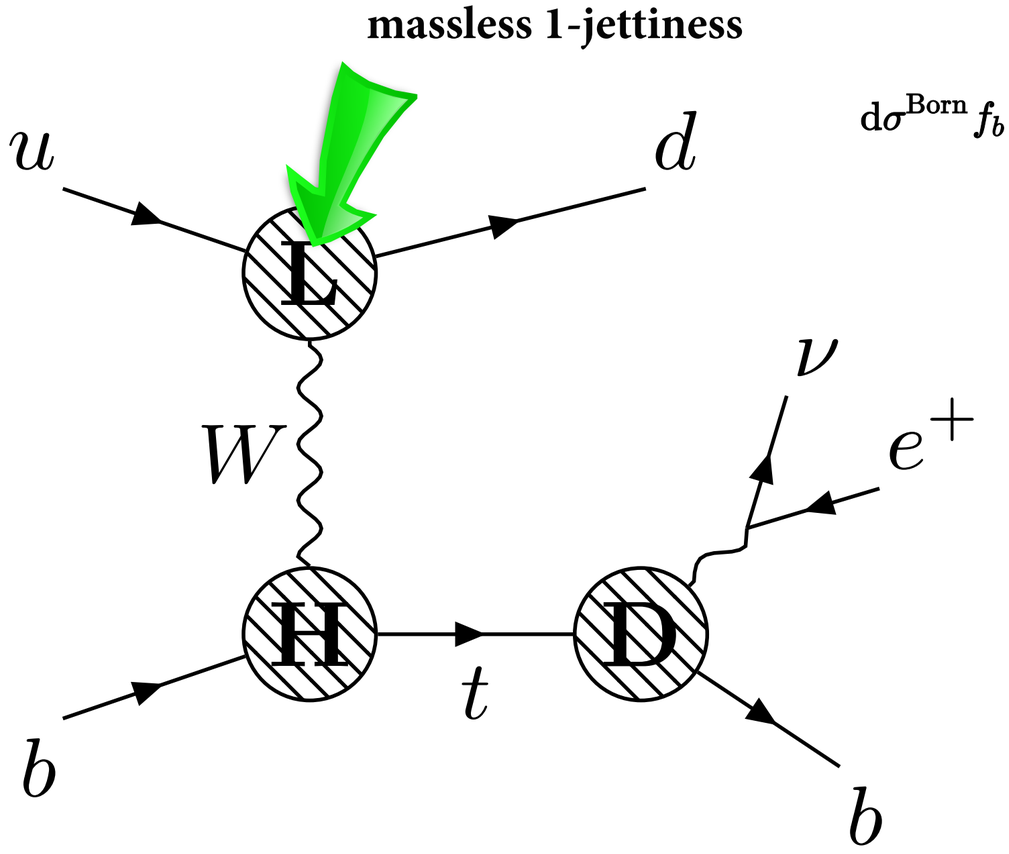


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NNLO H: crossed qqV form factor: Gehrmann, Huber, Maitre '05

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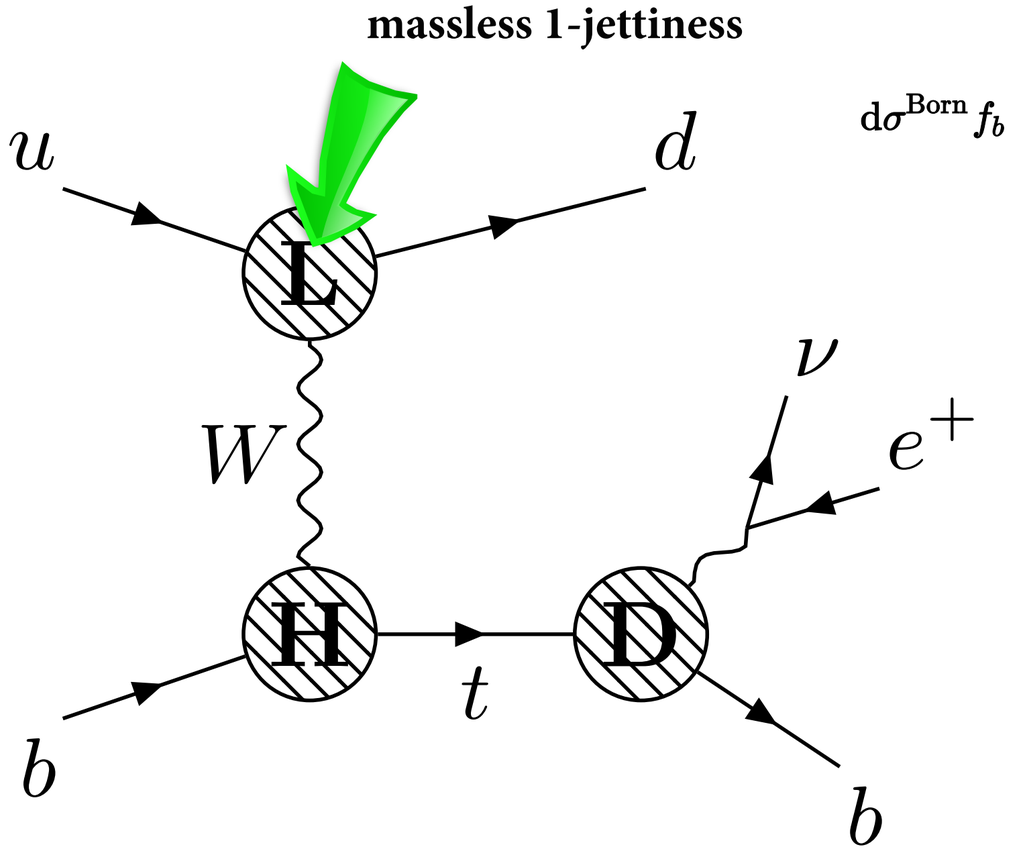


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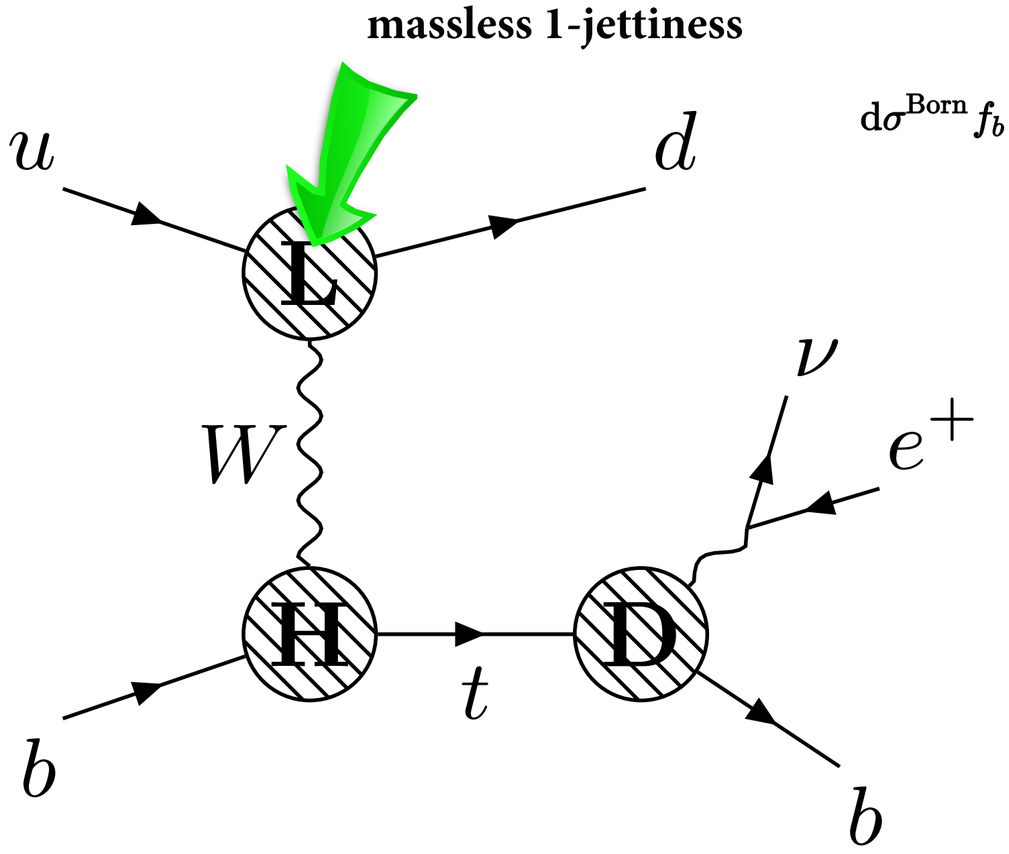


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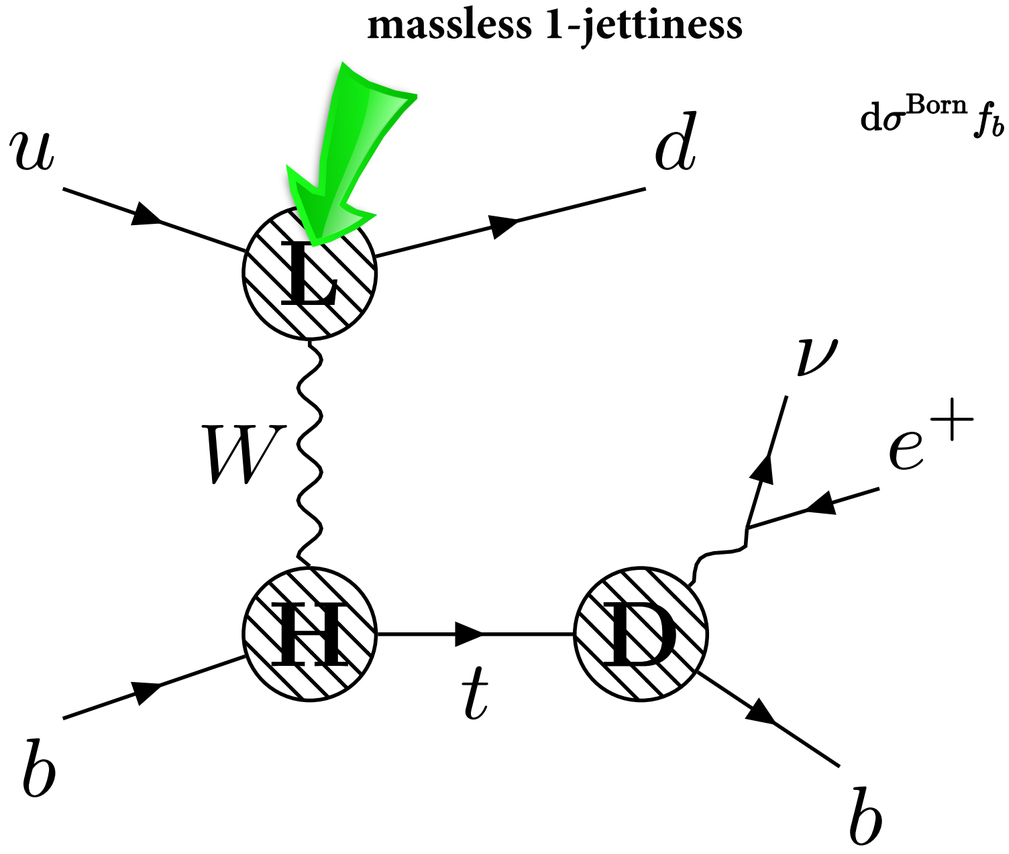


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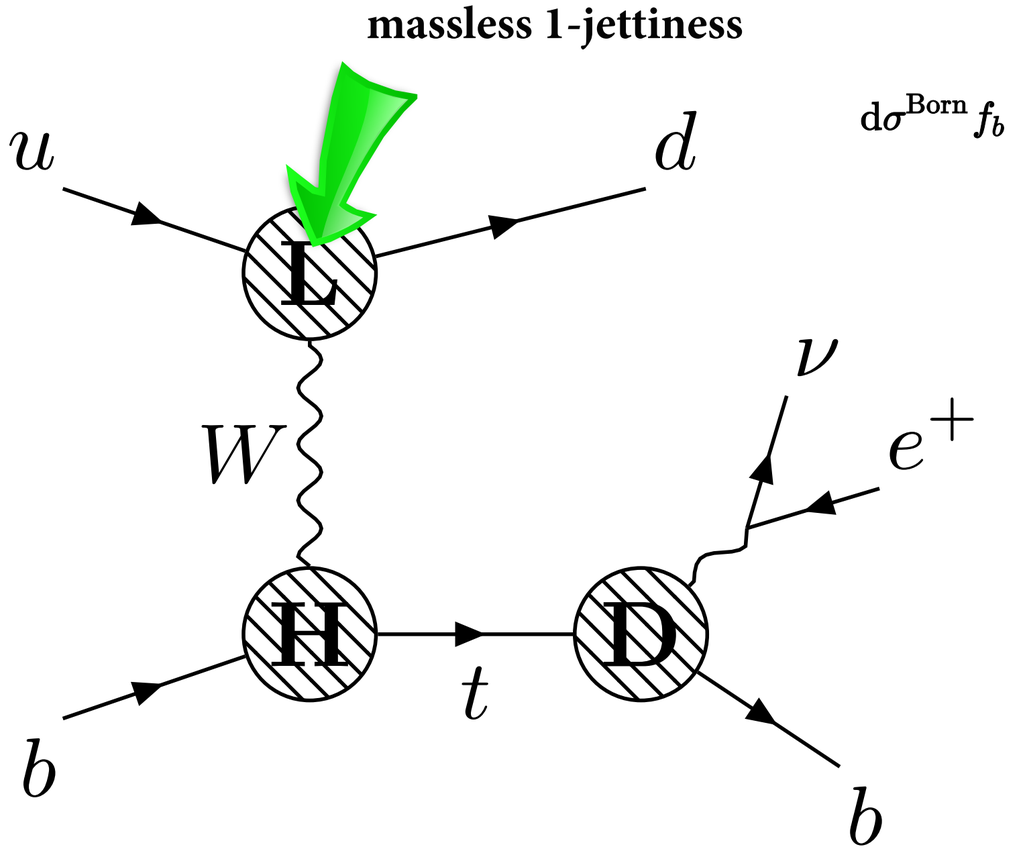


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$\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{blob+jet}}\theta(\tau > \tau^{\mathrm{cut}})$ above cut: crossed NLO W+jet

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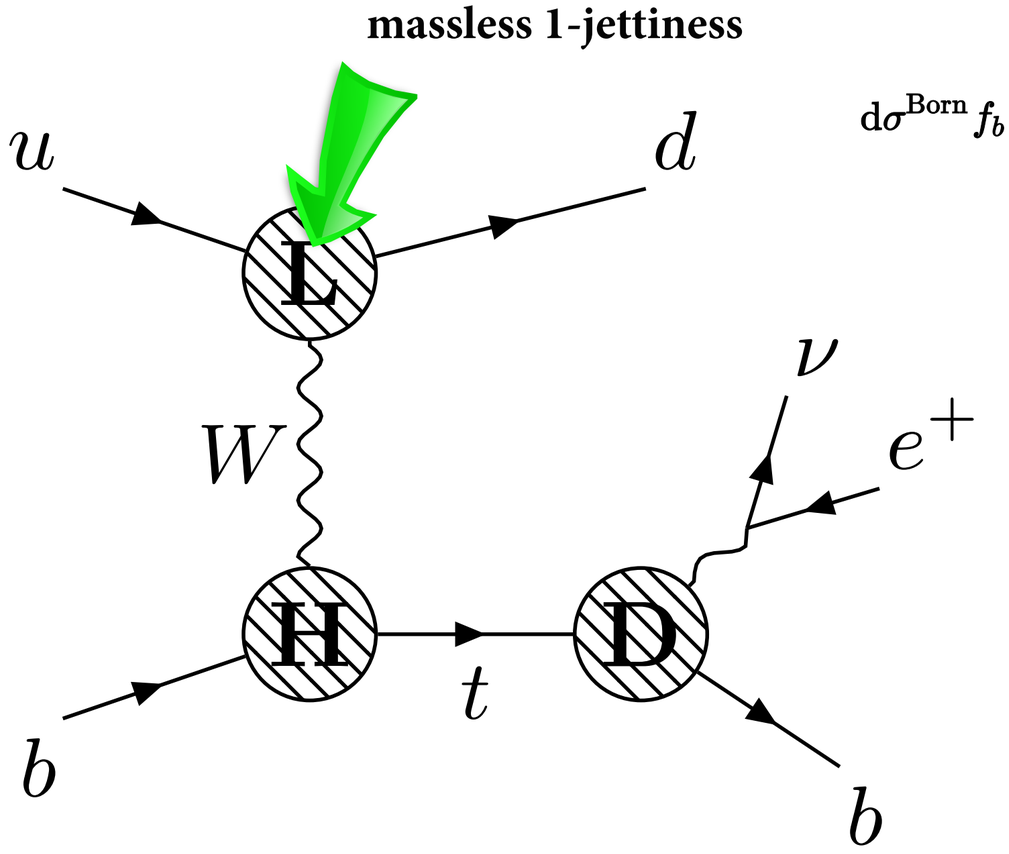


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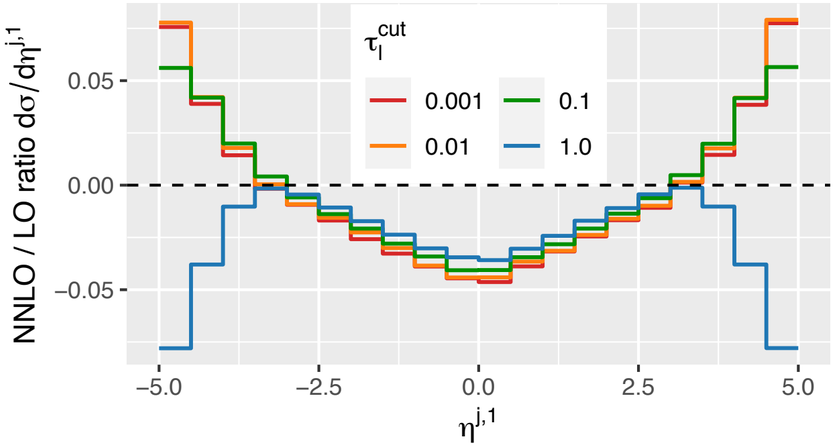

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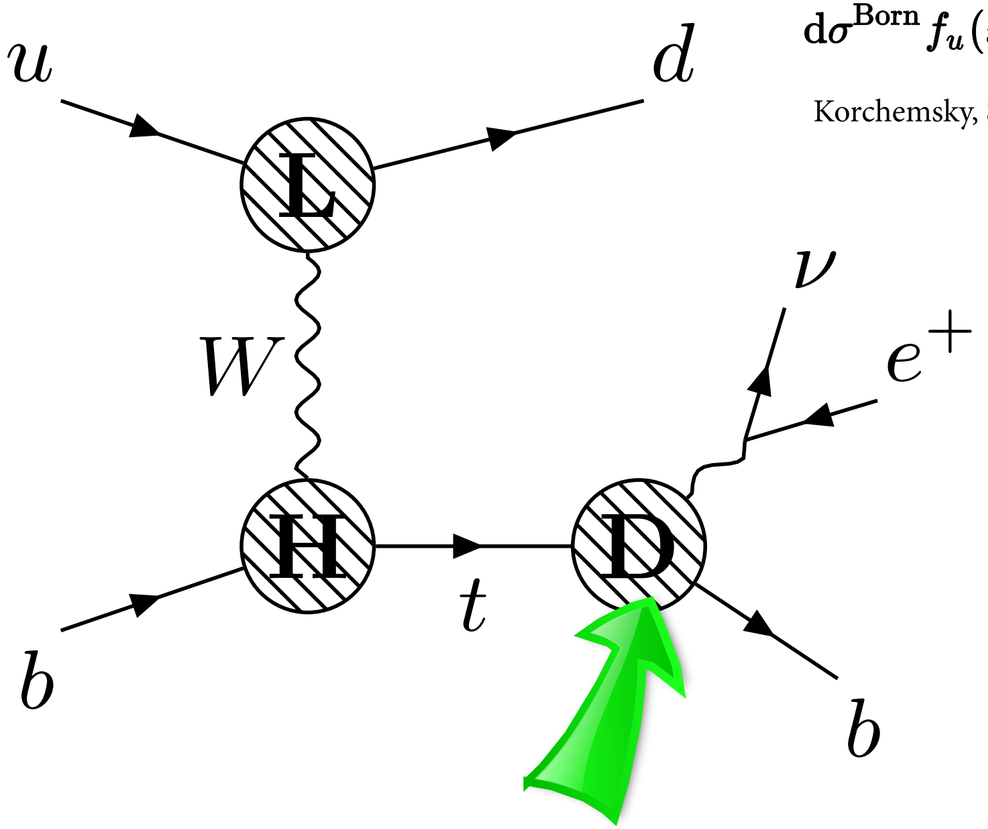


"massive" jettiness

$$\mathrm{d}\sigma^{\mathrm{Born}} f_u(x_u,\mu) f_b(x_b,\mu) \int_0^{\tau_d^{\mathrm{cut}}} \mathrm{d}\tau_d \, H(\mu) \otimes J(\mu) \otimes S(\mu) + \mathcal{O}(\tau_d^{\mathrm{cut}} \log(\tau_d^{\mathrm{cut}}))$$

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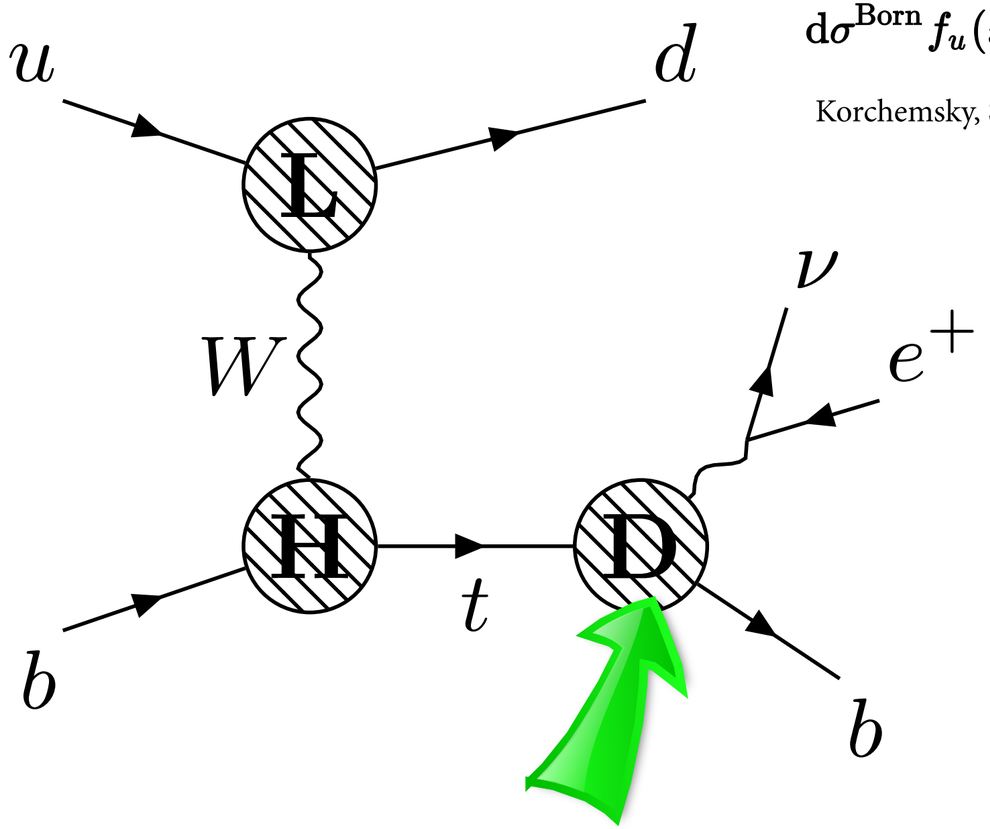


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NNLO J: Becher, Neubert '06
NNLO S: Becher, Neubert '05
NNLO H: Bonciani, Ferroglia '08; Asatrian Greub, Pecjak '08;
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above cut: crossed from Wt production at NLO (Campbell, Tramontano '05);
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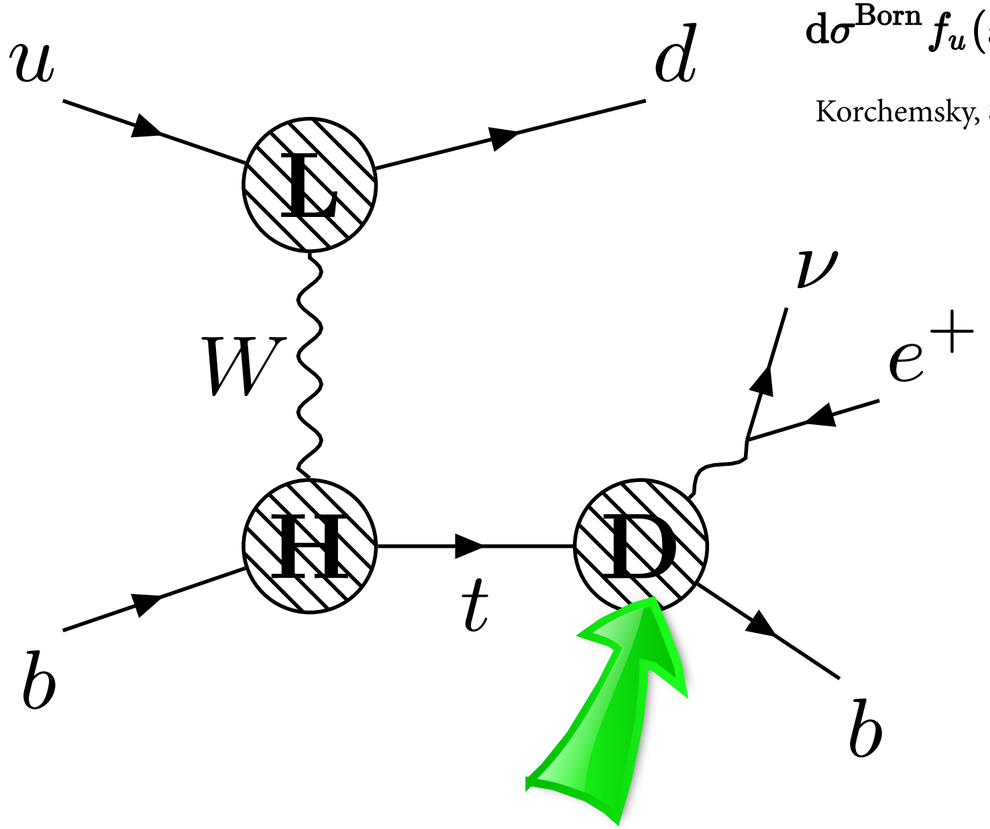


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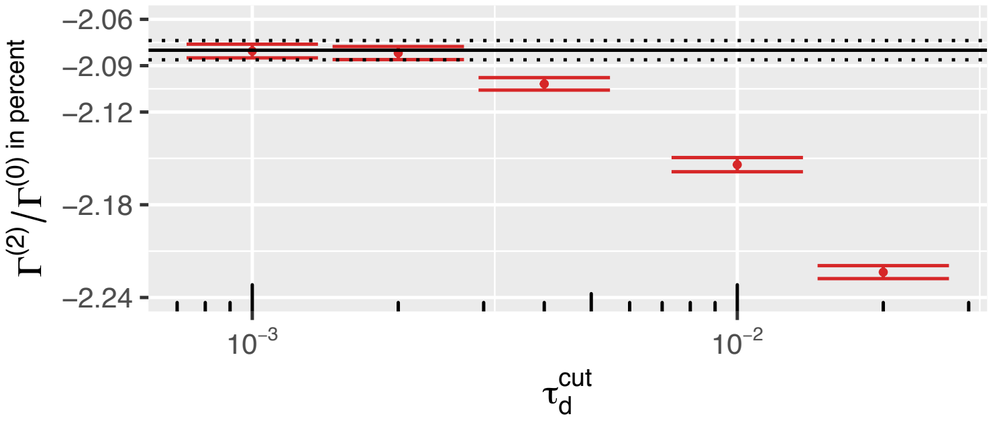

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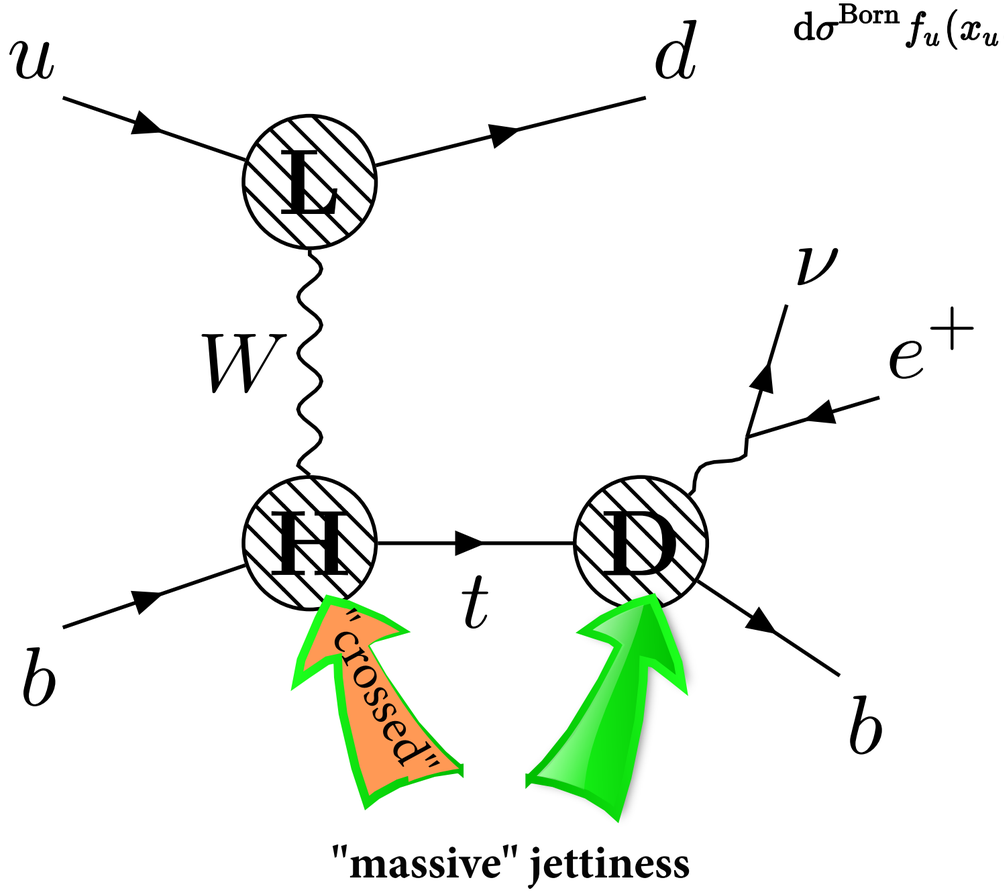


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Berger, Gao, Li, Liu, Zhu '16

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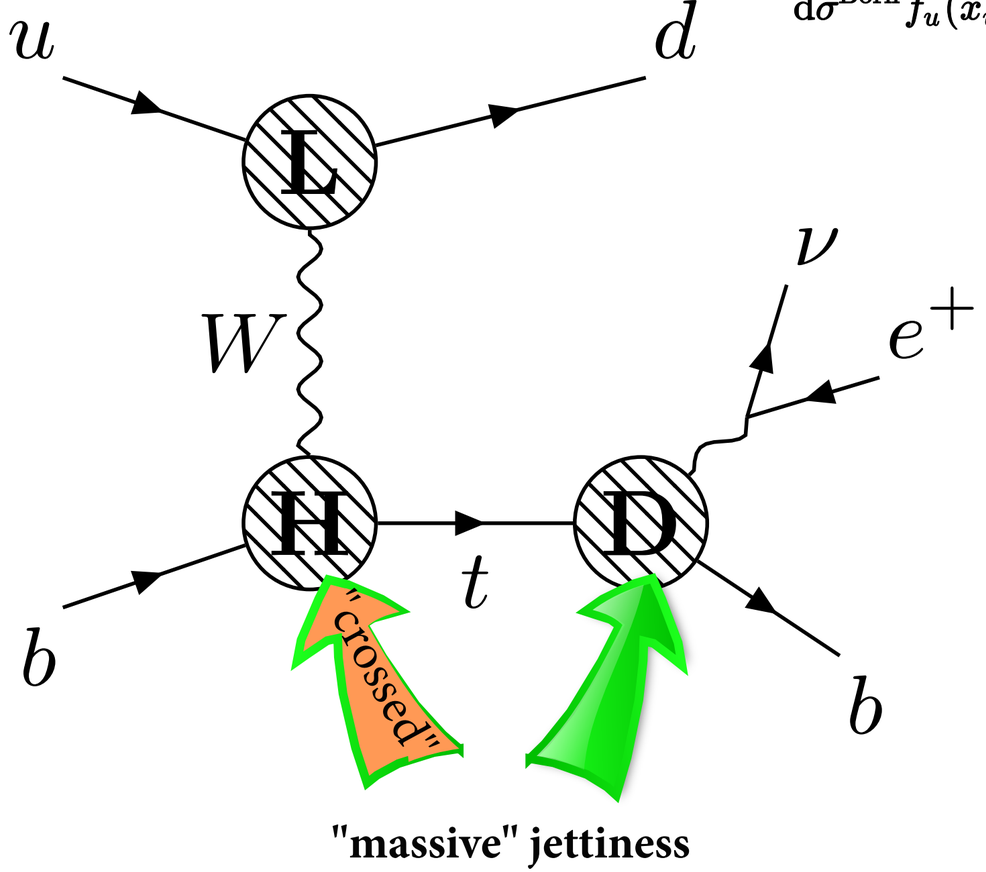


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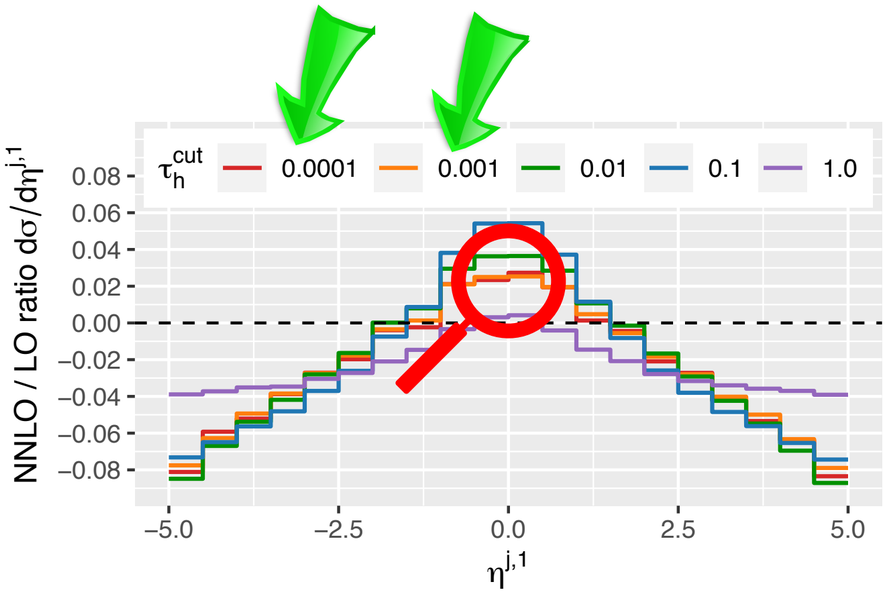
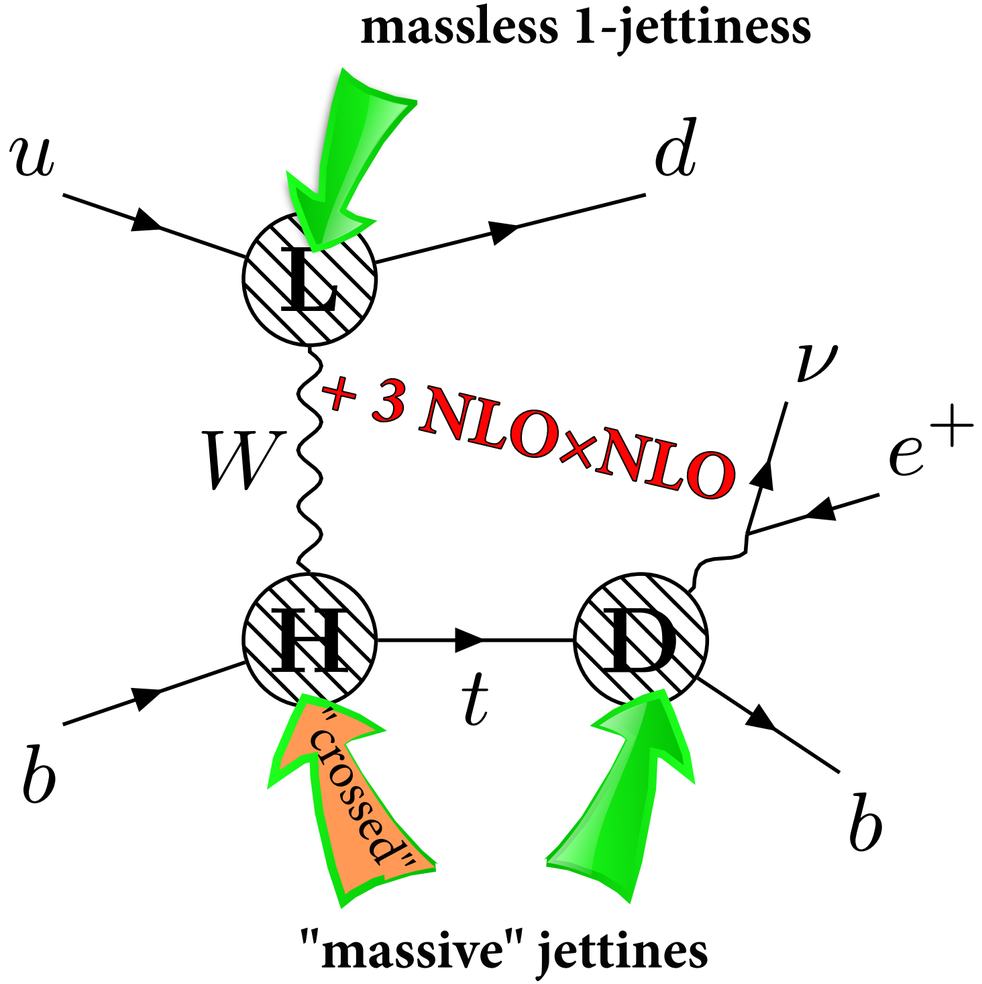


# Three NNLO calculations + three NLOxNLO calculations




$$L \times H$$

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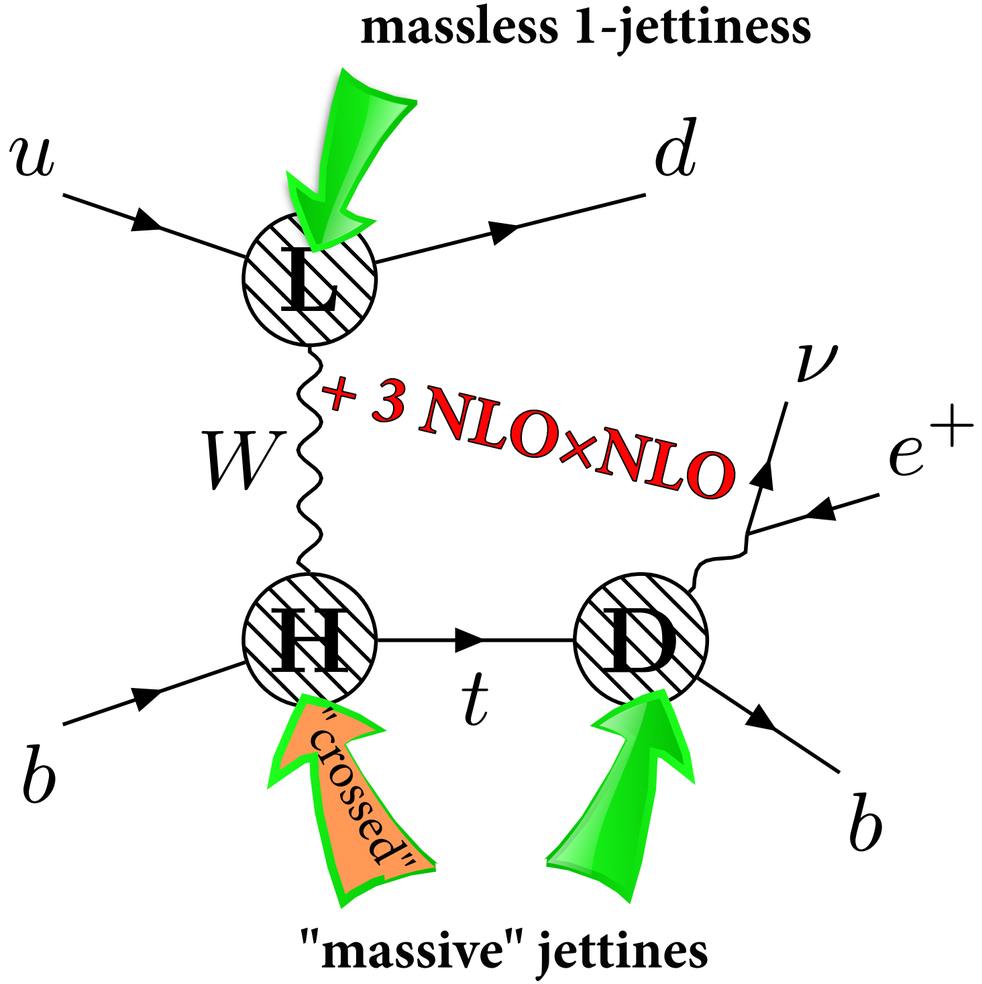


$$L \times H$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

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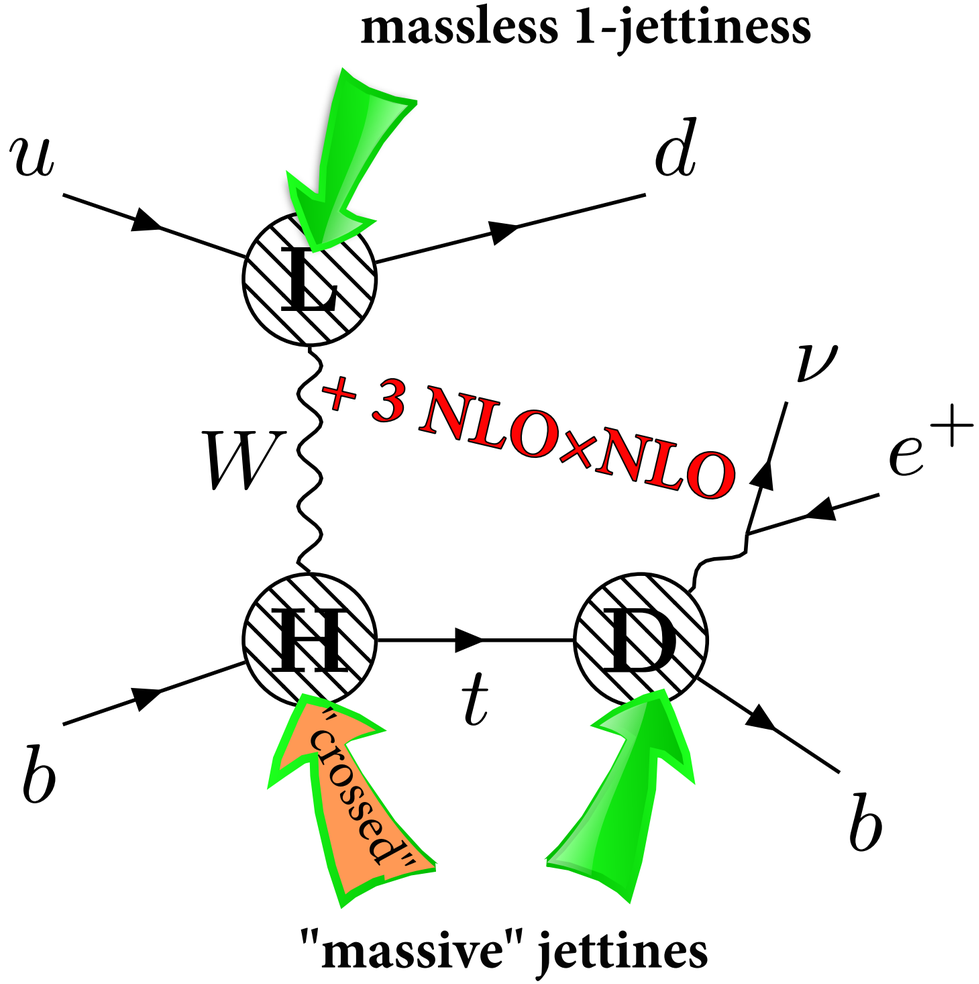


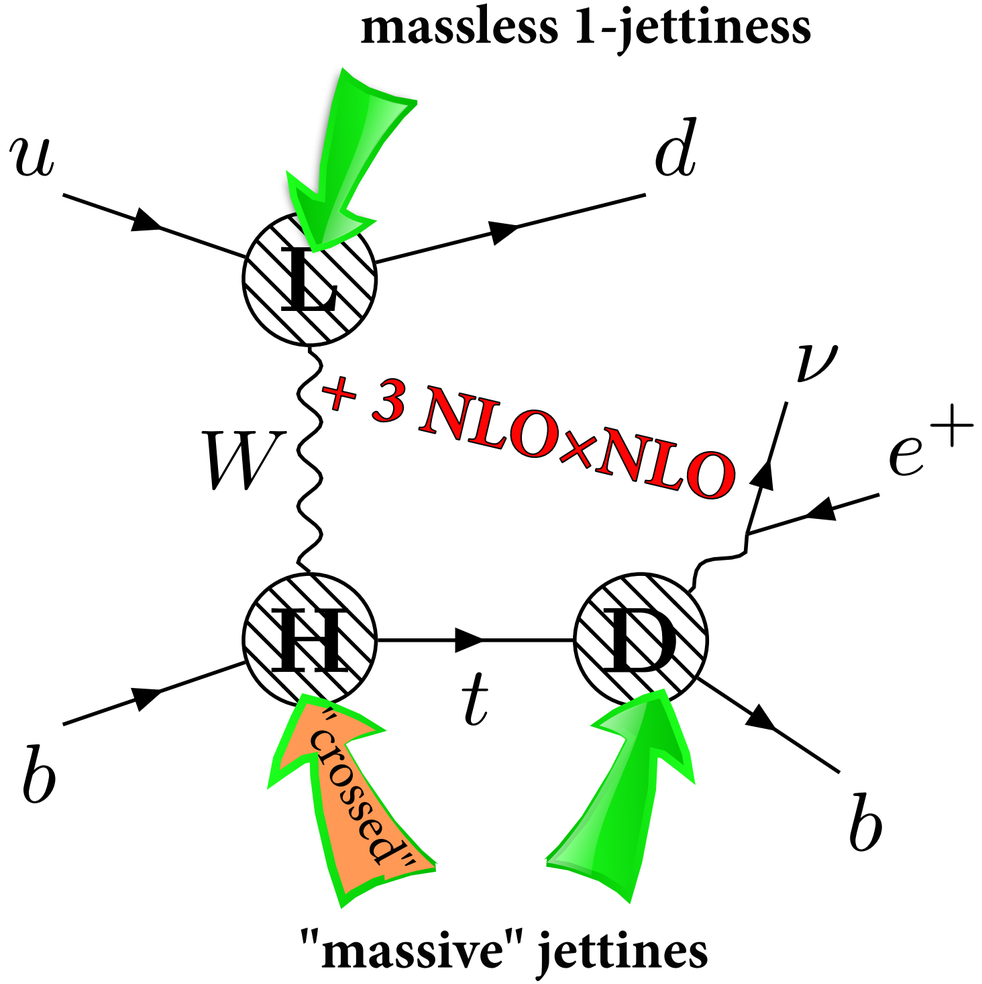

$$L \times H$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

$$L \times D$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

# Three NNLO calculations + three NLOxNLO calculations




$$L \times H$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

$$L \times D$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

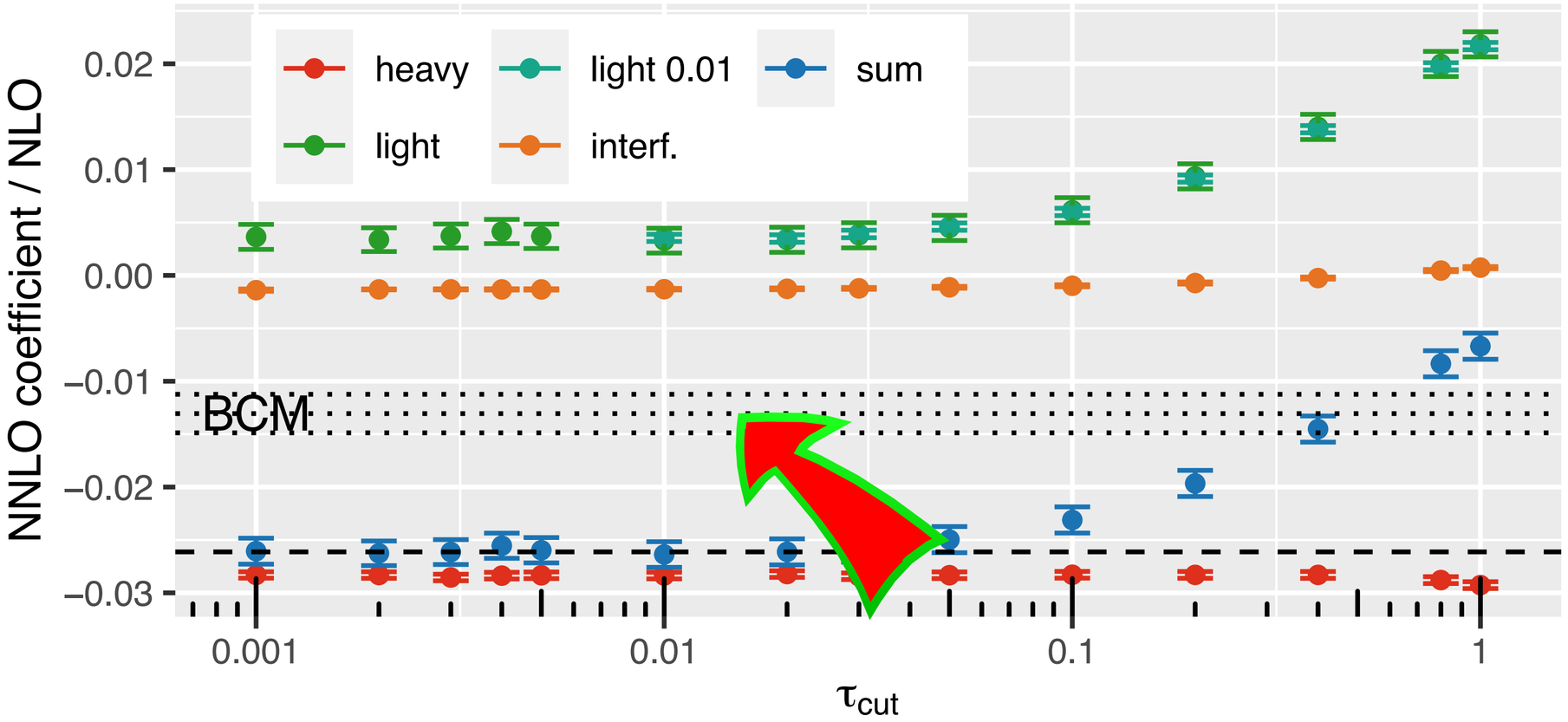
$$H \times D$$

real ⊗ real, real ⊗ virtual, virtual ⊗ real, virtual ⊗ virtual

**After all of this...**

**full agreement with Berger, Gao, Zhu in extensive comparisons!**

# Identify discrepancy with Brucherseifer, Caola, Melnikov (BCM):



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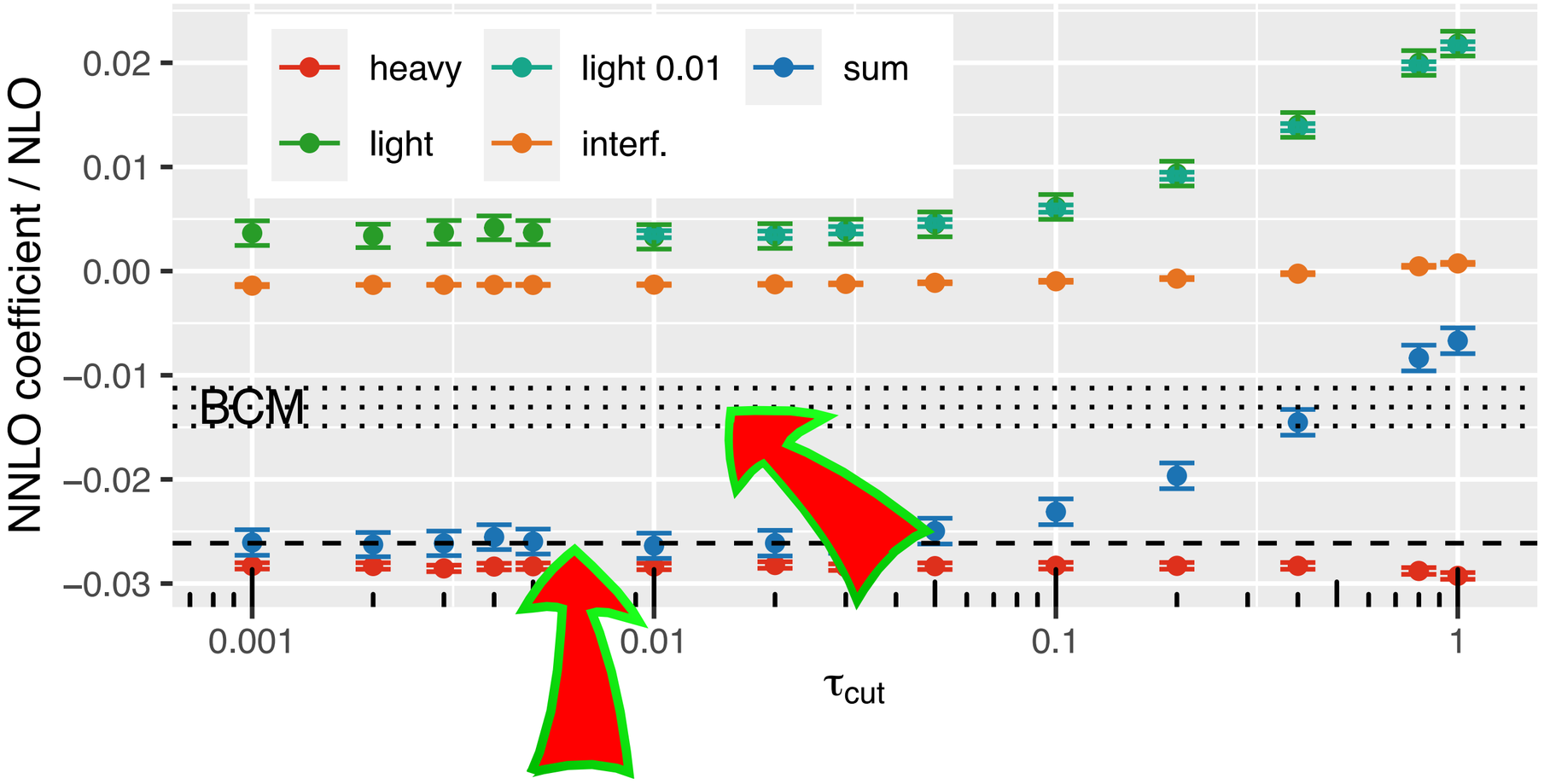
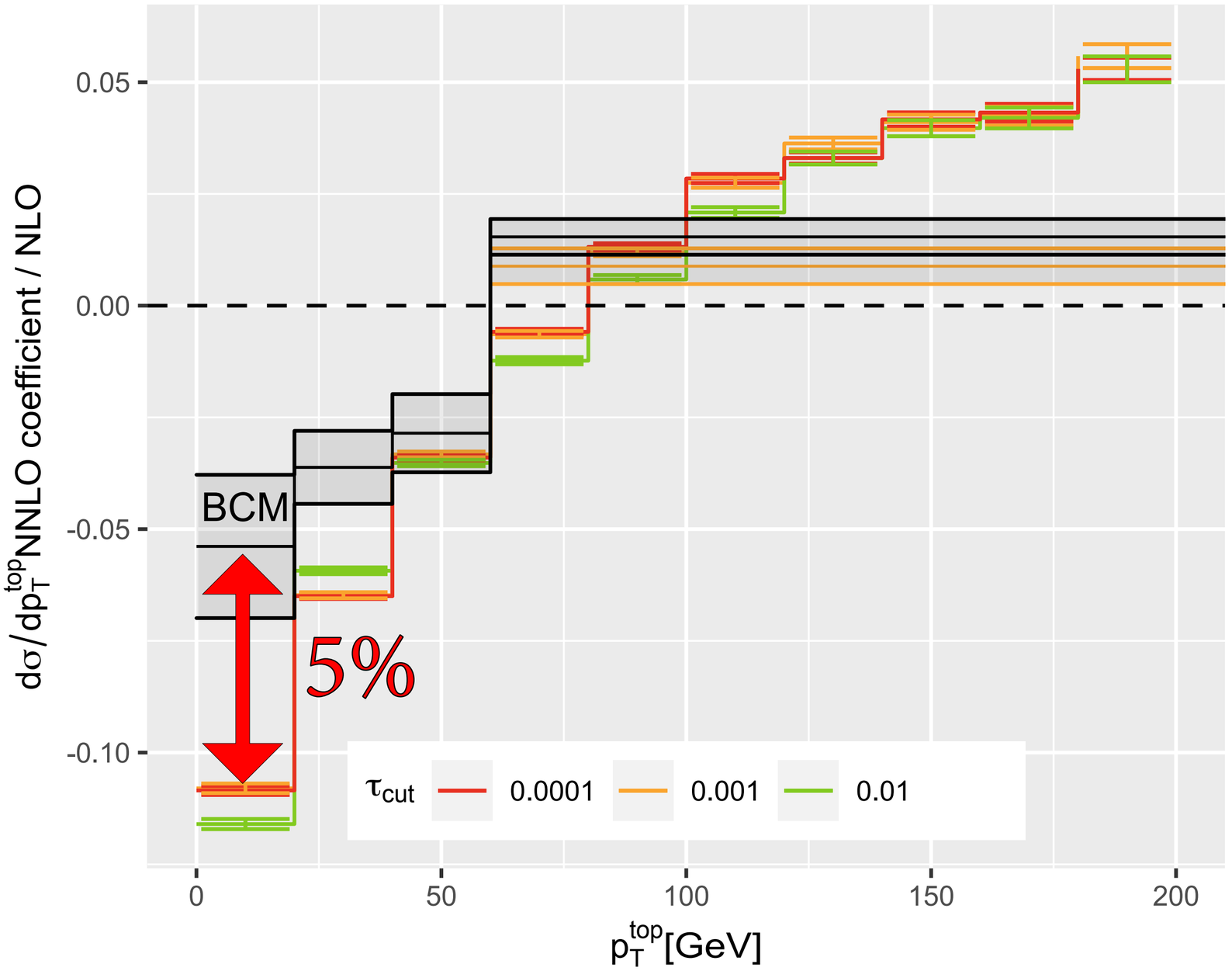
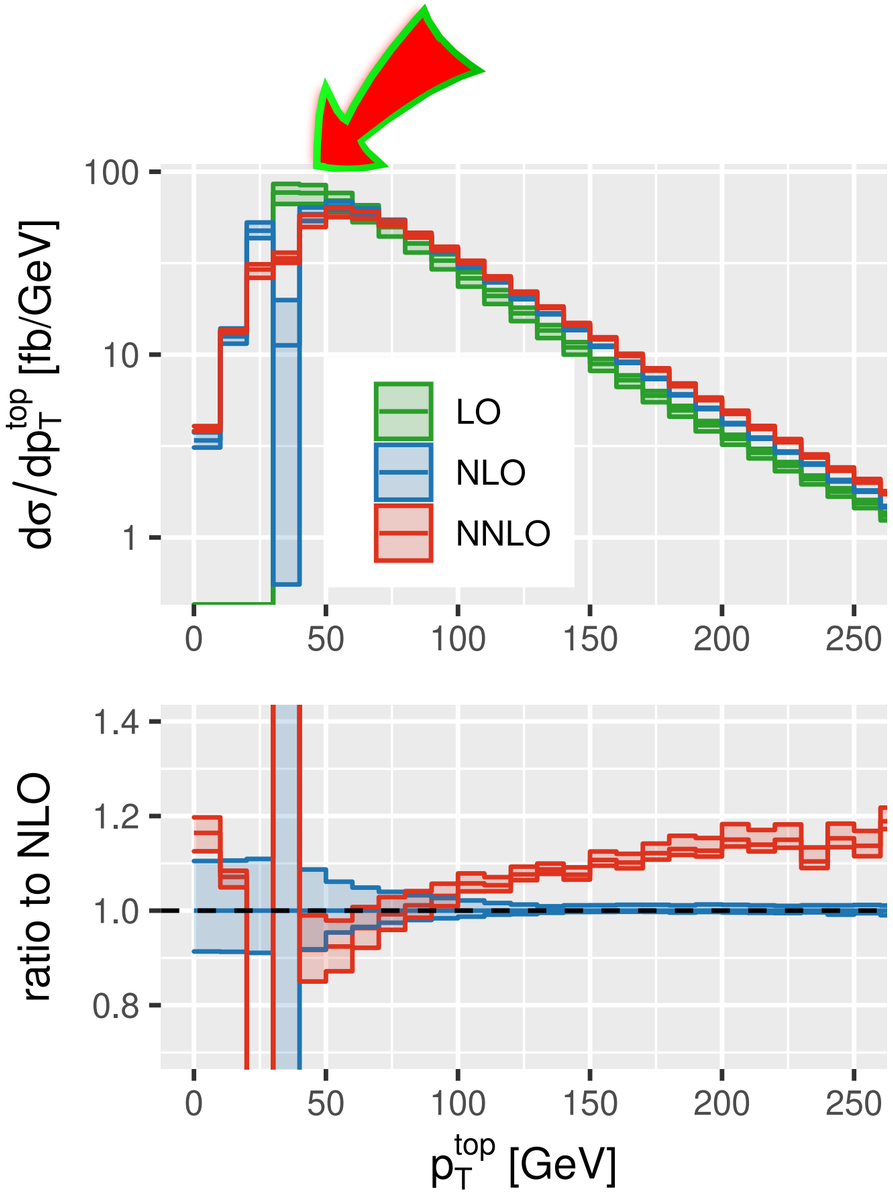
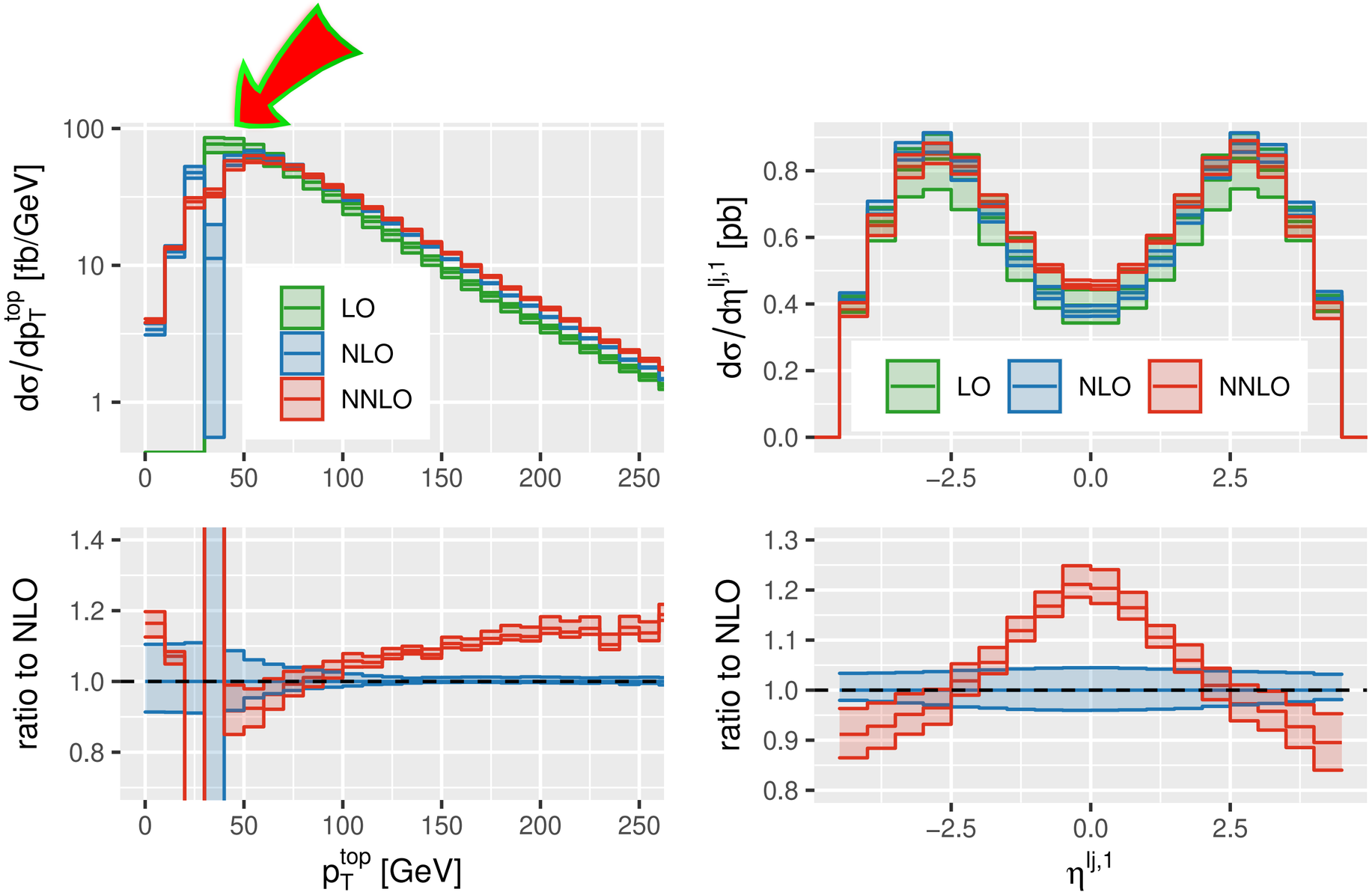



0.05
0.00
-0.05
-0.10
0
50
100
150
200
$d\sigma/dp_T^{top}$NNLO coefficient / NLO
$p_T^{top}$[GeV]
BCM
5%
$\tau_{cut}$
0.0001
0.001
0.01

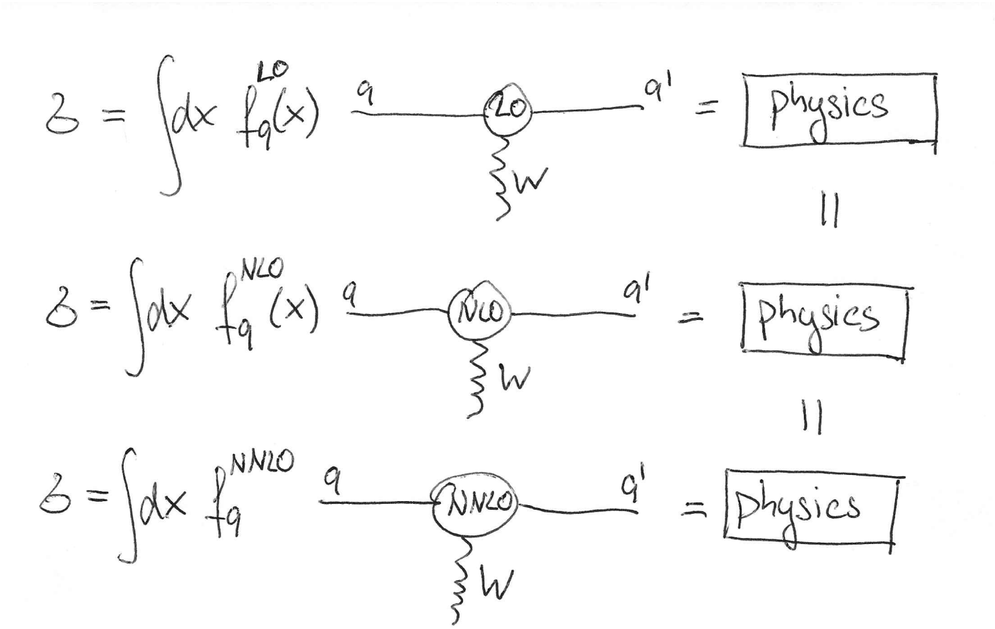



(LHC, typical fiducial cuts, DDIS scales)

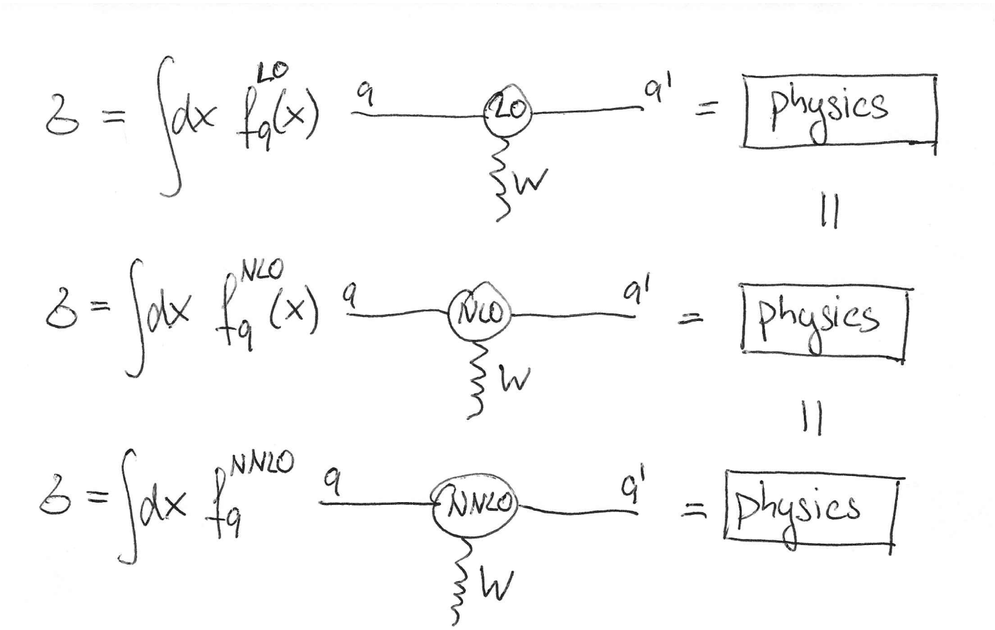



(LHC, typical fiducial cuts, DDIS scales)

# Study of PDF consistency with DDIS in upcoming study!

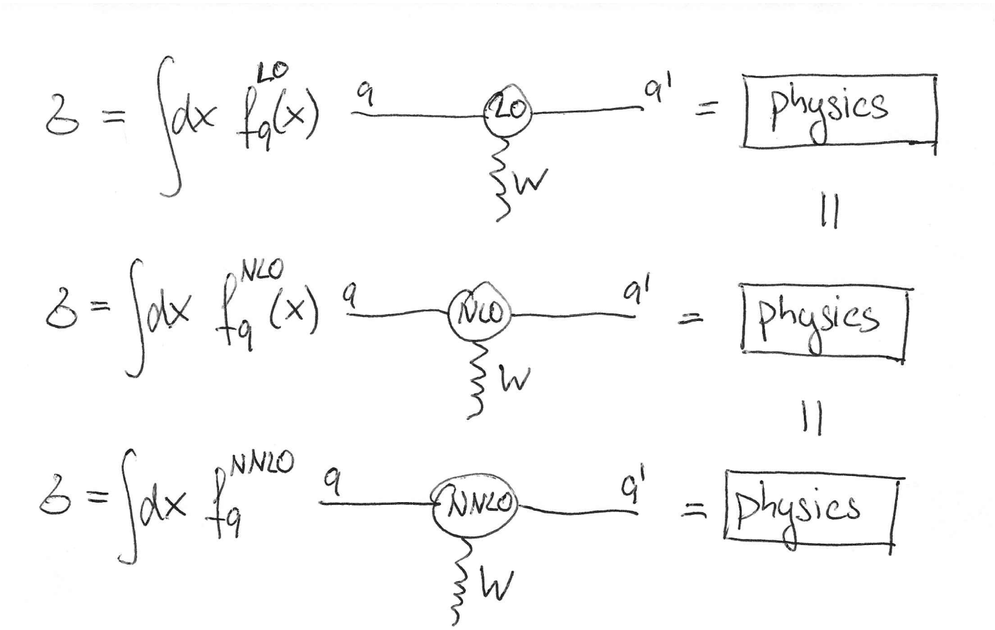


# Study of PDF consistency with DDIS in upcoming study!




NNPDF30 NLO and NNLO consistent ✔

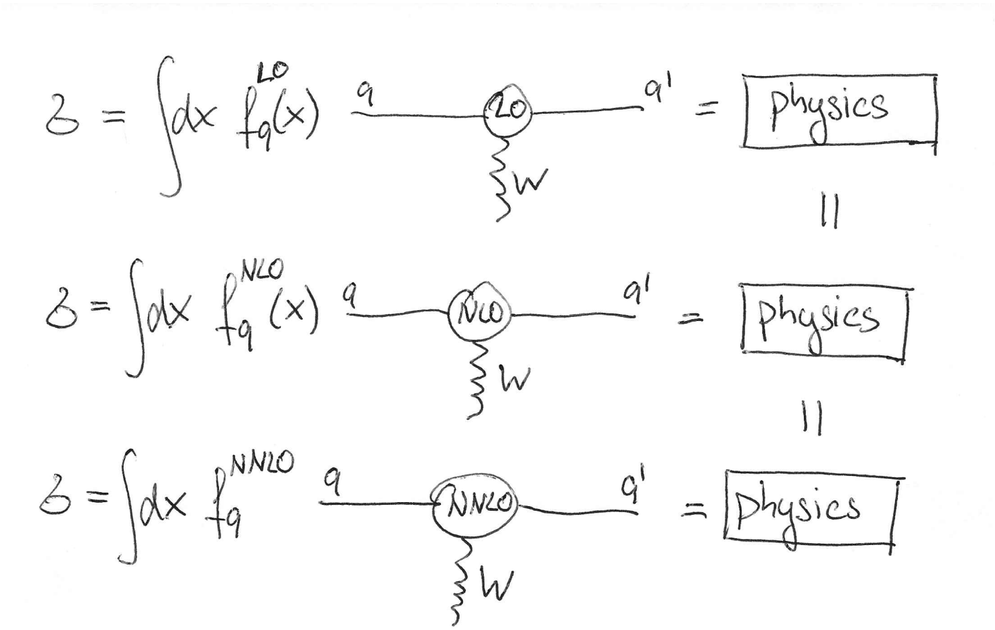
# Study of PDF consistency with DDIS in upcoming study!




NNPDF30 NLO and NNLO consistent ✔

NNPDF31 NLO and NNLO consistent ✔

# Study of PDF consistency with DDIS in upcoming study!

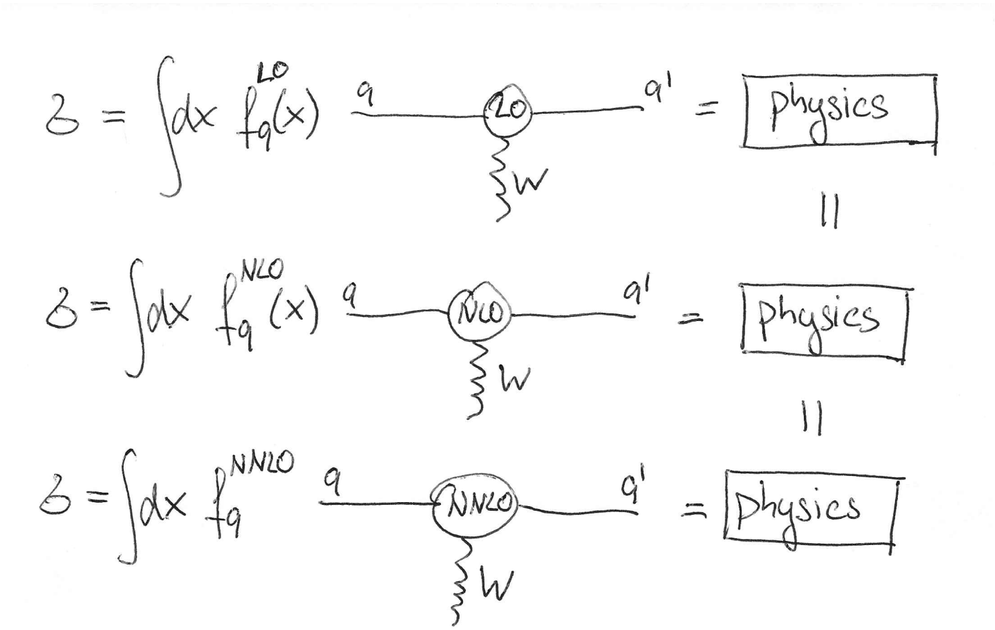



NNPDF30 NLO and NNLO consistent ✔

NNPDF31 NLO and NNLO consistent ✔

NNPDF30 and NNPDF31 differ by 12% (2% PDF uncertainty) ✖

# Study of PDFs discrepancies with DDIS in upcoming study!




NNPDF30 NLO and NNLO consistent ✔

NNPDF31 NLO and NNLO consistent ✔

NNPDF30 and NNPDF31 differ by 12% (2% PDF uncertainty) ✖

HERAPDF20 NLO and NNLO differ by 14% (2% PDF uncertainty) ✖

# Contributions

**Calculation of t-channel single-top-quark production and decay at NNLO**

Resolved discrepancies between previous two calculations

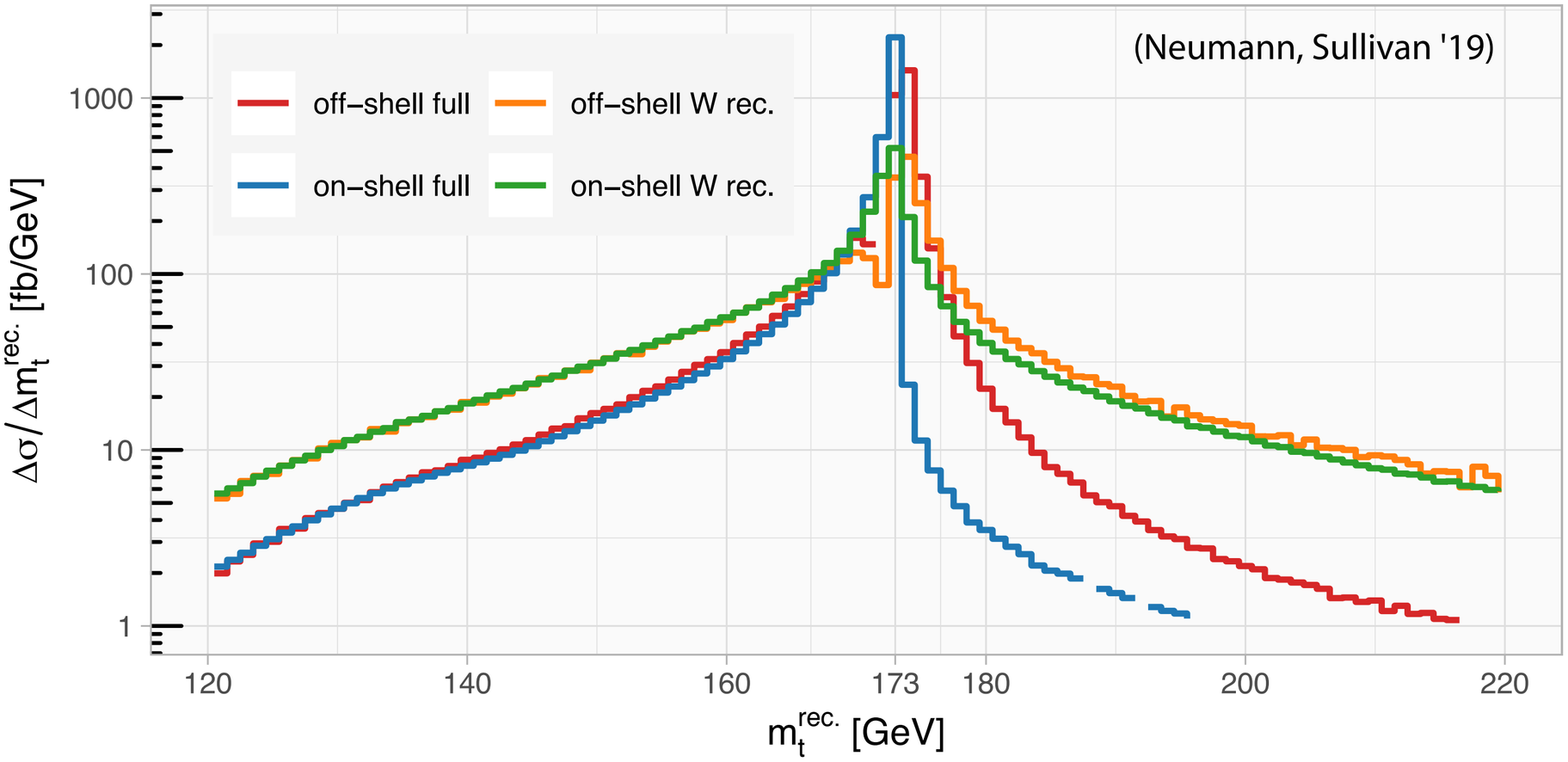
Large fiducial corrections make NNLO important

Double-DIS scales allow for unique PDF constraint

MCFM as top precision framework: NLO 4 flavor-scheme; NLO 5-flavor scheme off-shell + SMEFT (Neumann, Sullivan '19); NNLO 5-flavor scheme

# Backup/Details

# Inclusively: Off-shell effects $\mathcal{O}(\Gamma_t/m_t)$



# NLO effects in the SMEFT are crucial