NATIONAL CENTRE FOR
SCIENTIFIC RESEARCH "DEMOKRITOS"
INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

H.F.R.I.
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Research & Innovation

Modelling uncertainties and prompt b-jet identification in $\mathrm{t\bar{t}b\bar{b}}$ with dilepton signatures at the LHC

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RADCOR 2023

Crieff, Scotland
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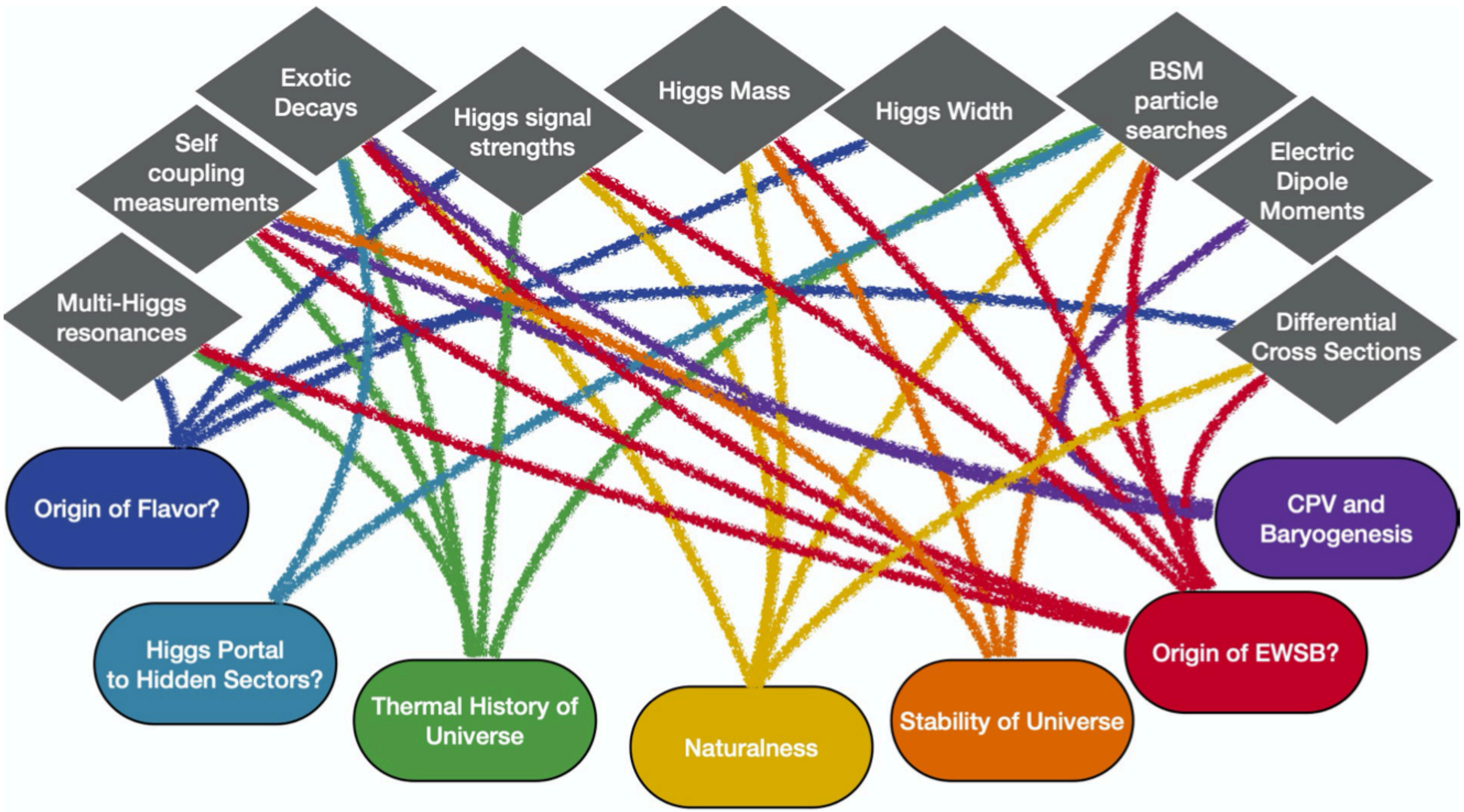
Work in collaboration with H.Y. Bi, H.B. Hartanto, M.Kraus, M.Lupattelli and M.Worek

Based on: JHEP 08 (2021) 008 Phys. Rev. D 107 (2023) 1

Motivation

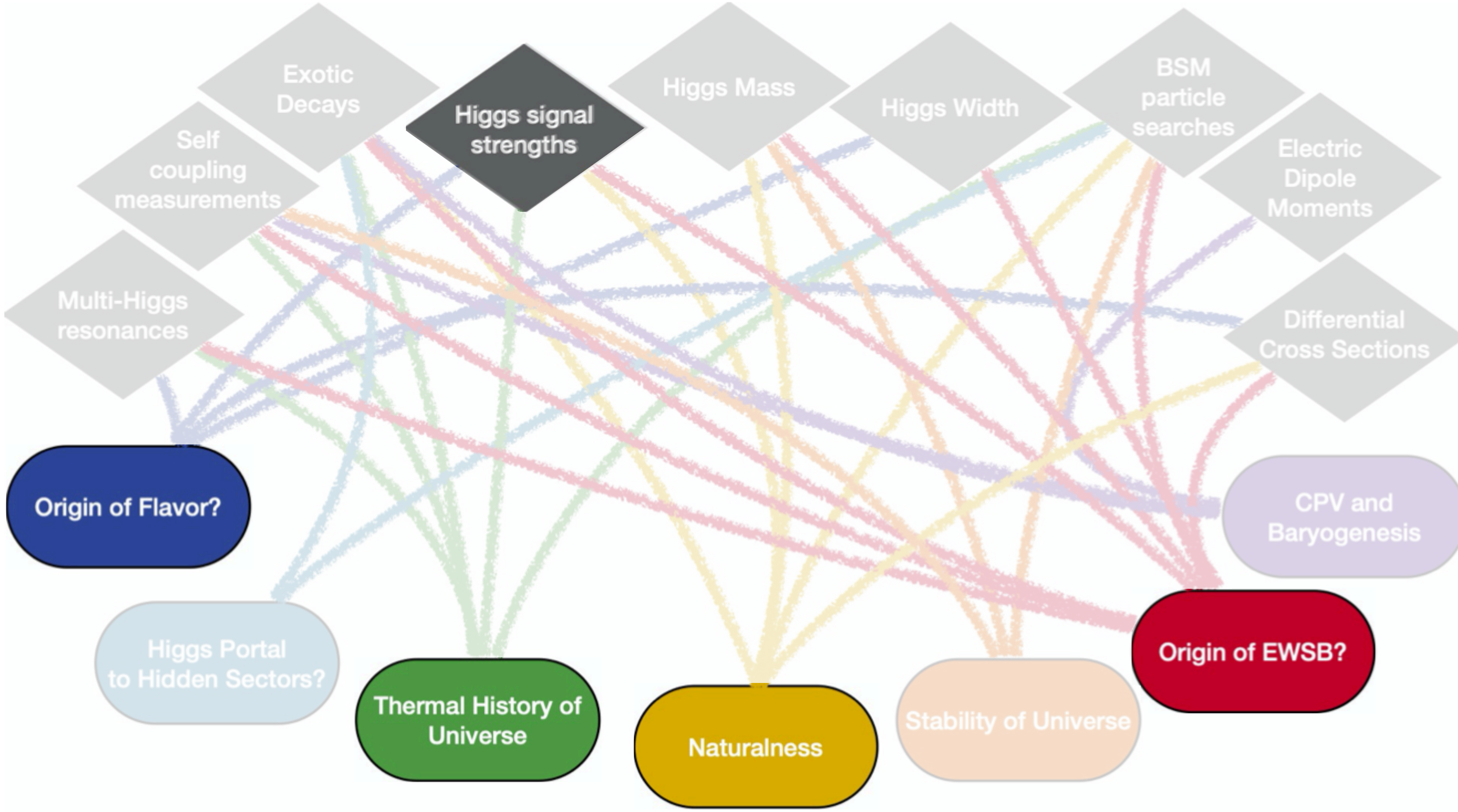
- Understanding the properties of the SM Higgs boson is central to the physics program of the LHC (and of future colliders as well)



2209.07510 [hep-ph]

- Measurements of Higgs signal strengths can provide stringent tests of the SM
- BSM physics can manifest through coupling modifiers (κ) with effects up to few %

↪ Talk by Sinead Farrington

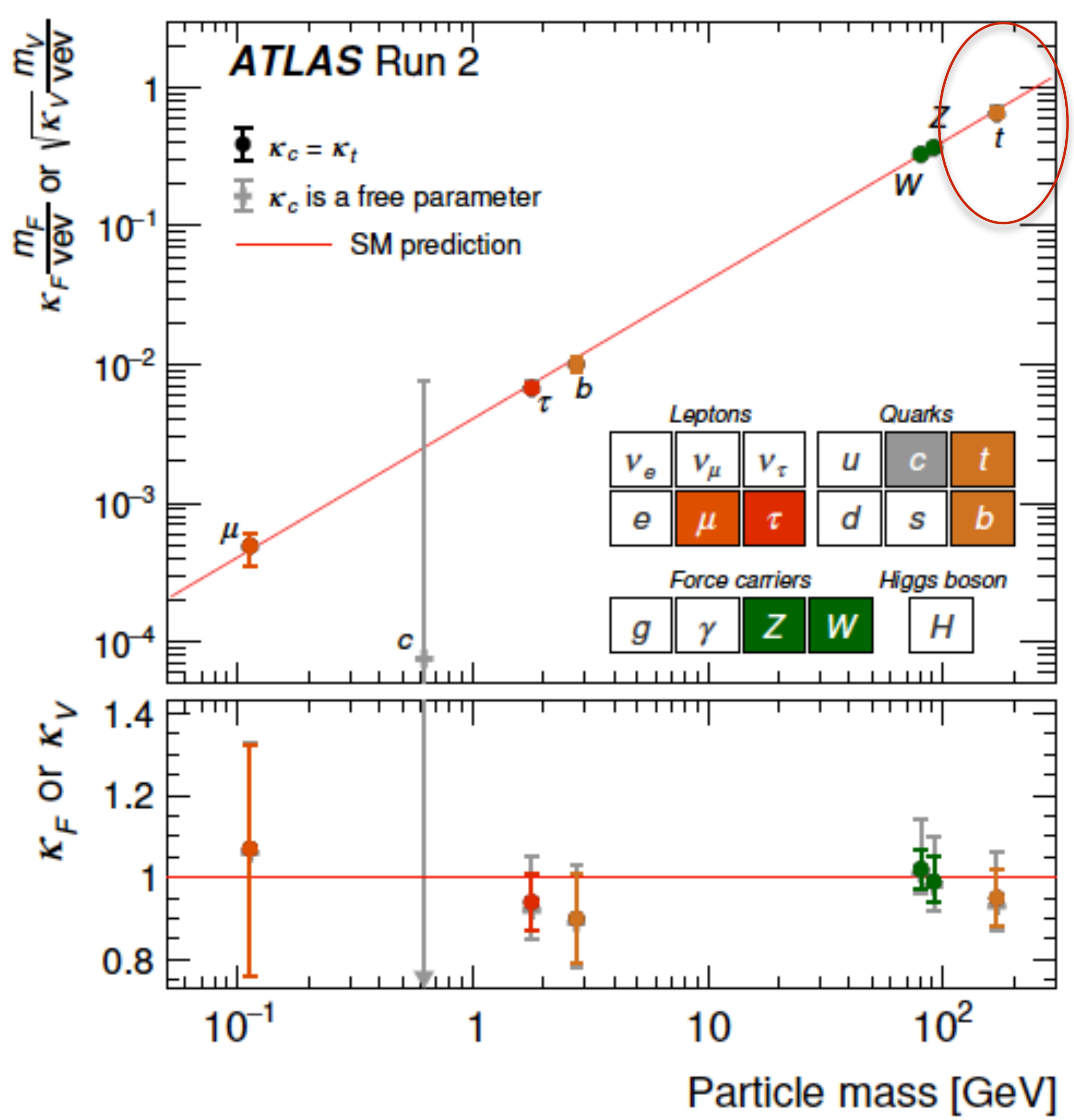


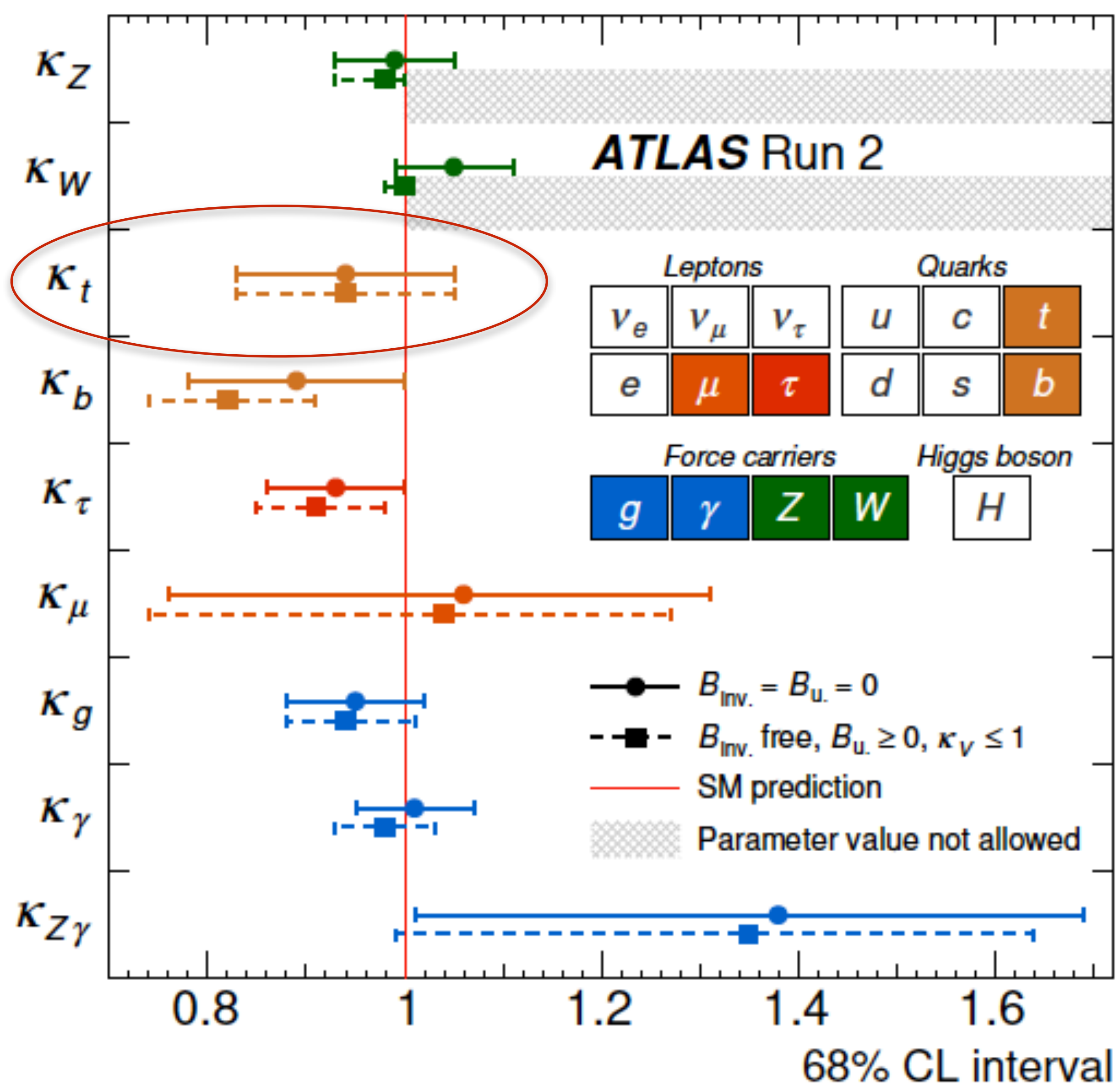
2209.07510 [hep-ph]

Higgs coupling measurements

- Legacy results from the LHC Run 2

[ATLAS, Nature 607 (2022) 7917, 52-59]



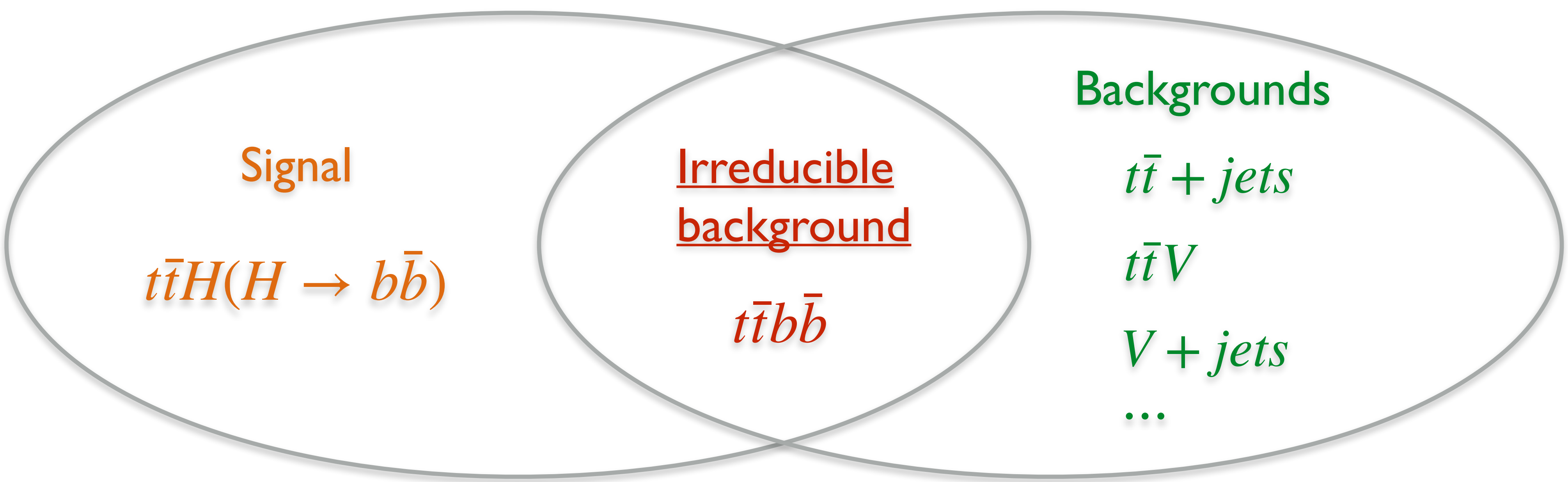


Why $ttH(H \to b\bar{b})$?

- Top-quark Yukawa coupling is the largest among SM particles
- $pp \to t\bar{t}H$ has direct sensitivity to top-quark Yukawa coupling at LHC

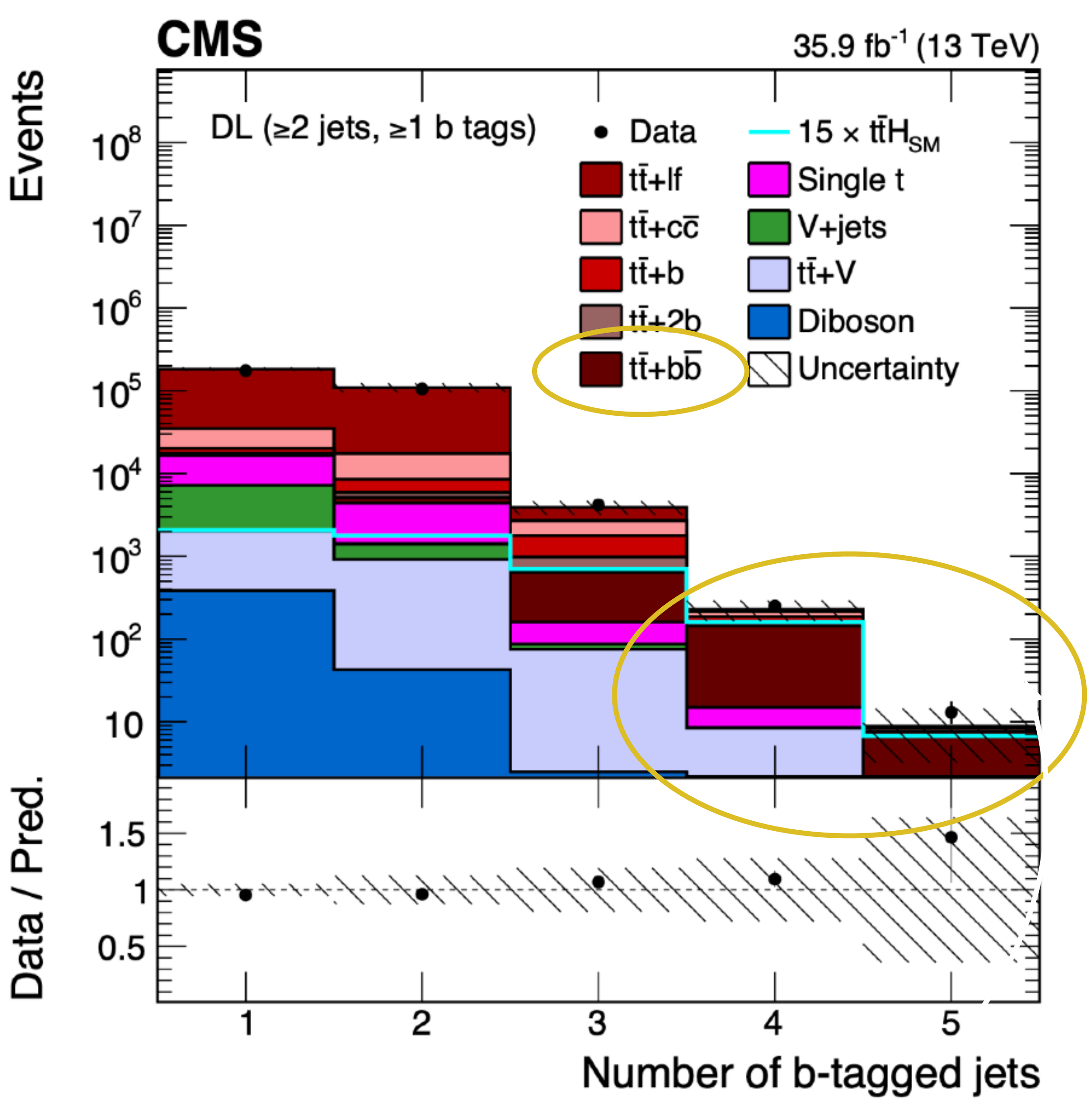
  ↪ Talk by Chiara Savoini
- $H \to b\bar{b}$ is the decay channel with the largest Branching Ratio ($\sim 58\%$)

However $pp \to t\bar{t}H(H \to b\bar{b})$ is a tiny signal in a huge QCD background



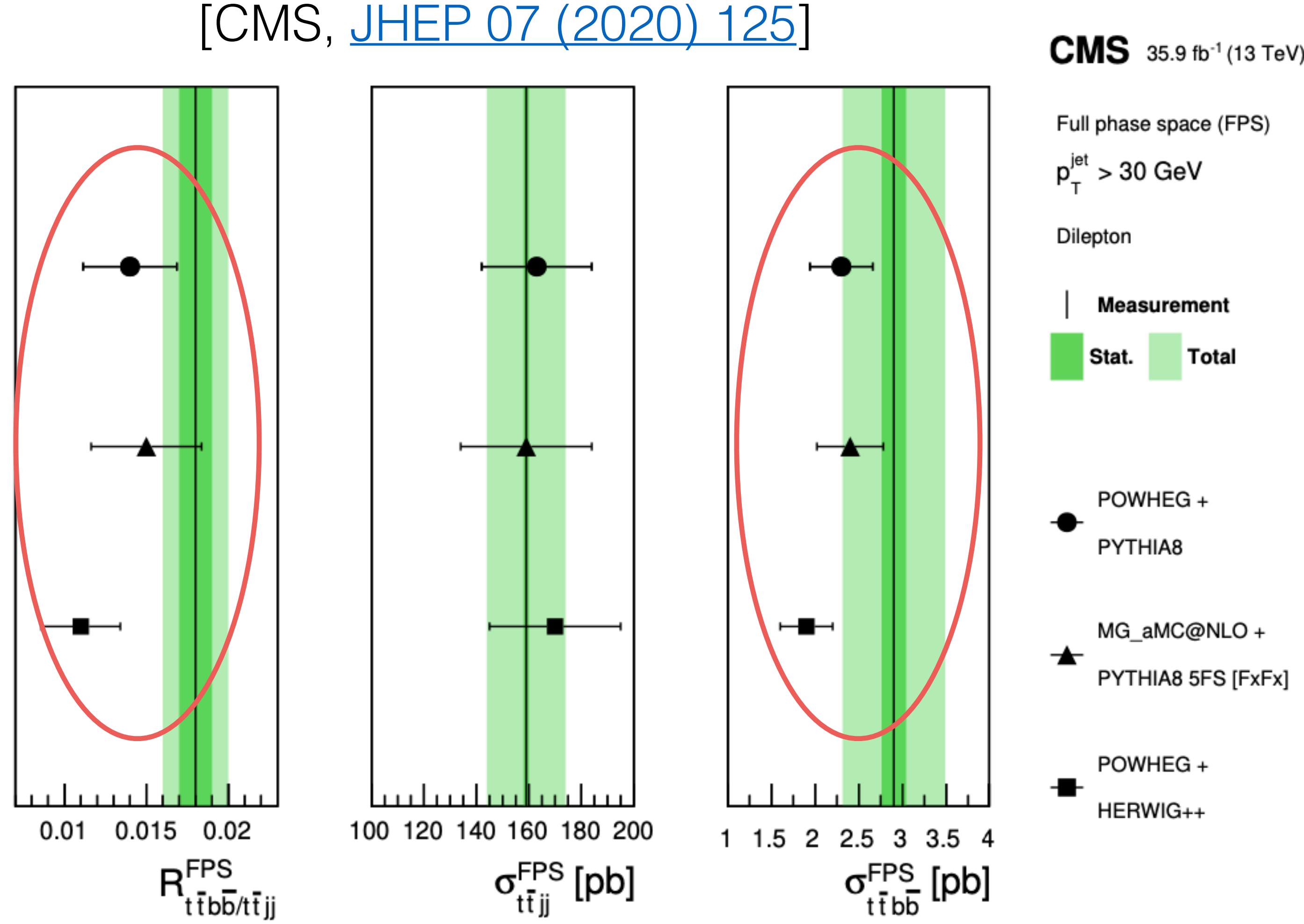
$t\bar{t}b\bar{b}$: theoretical challenges

[CMS, JHEP 03 (2019) 026]



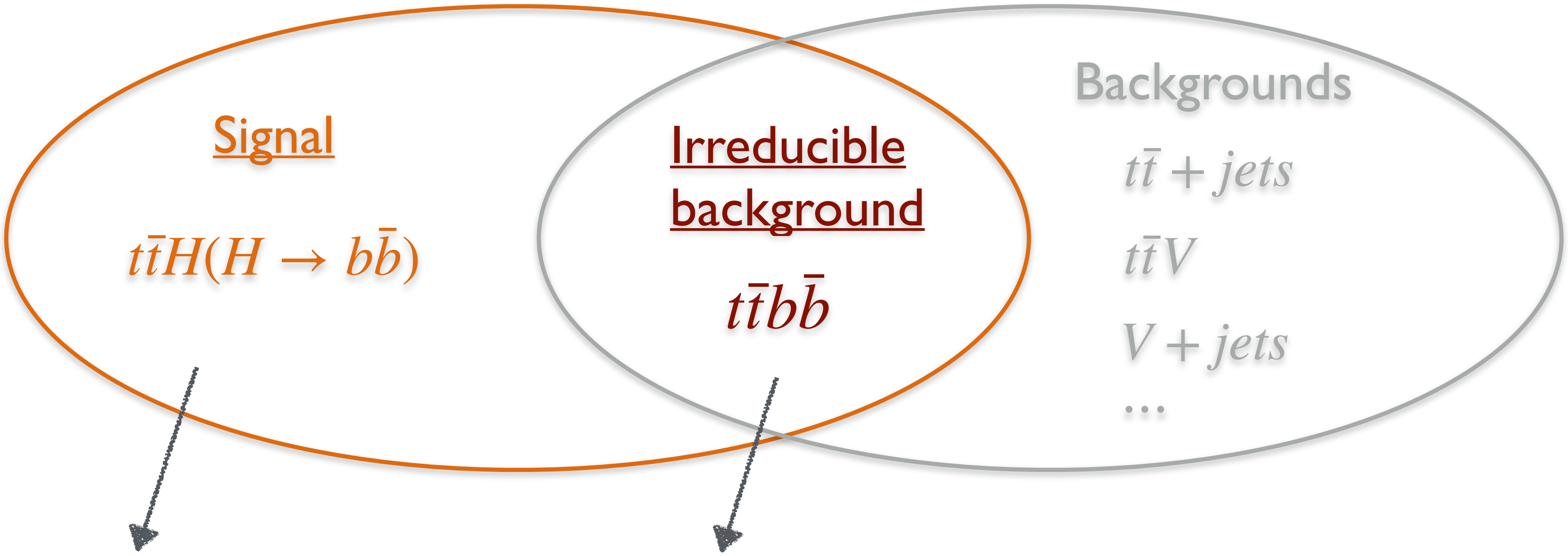
- Slight tension with data reported in $\sigma(t\bar{t}b\bar{b})$ and in $\mathscr{R} = \dfrac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$

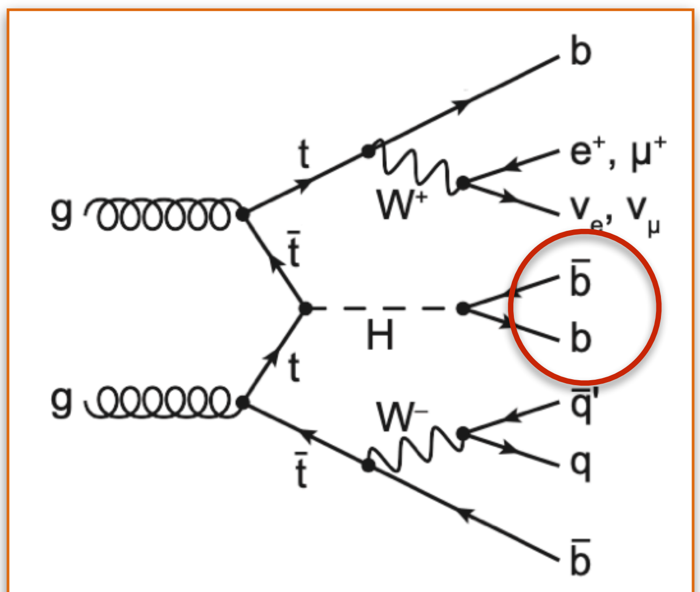
[CMS, JHEP 07 (2020) 125]



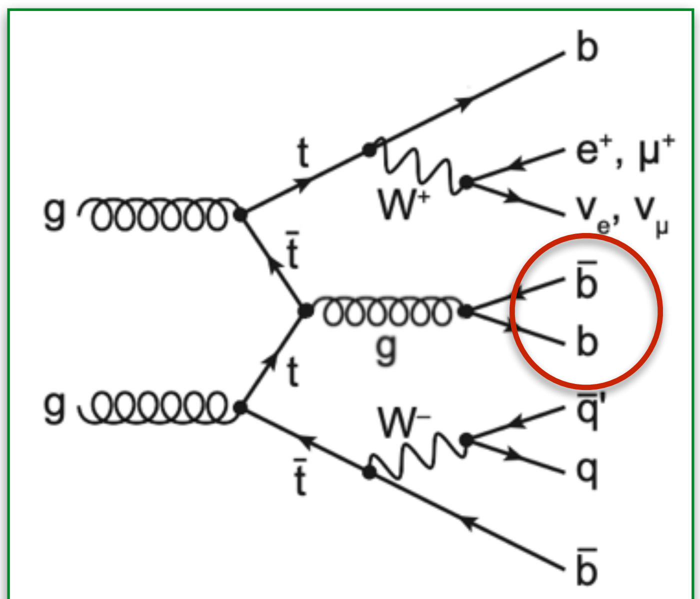
- $t\bar{t}b\bar{b}$: main background to $t\bar{t}H(H \to b\bar{b})$ for $N_{bjets} \geq 4$

$t\bar{t}b\bar{b}$: prompt b-jet identification





$t \to W^+ b \quad \bar{t} \to W^- \bar{b} \quad H \to b\bar{b}$

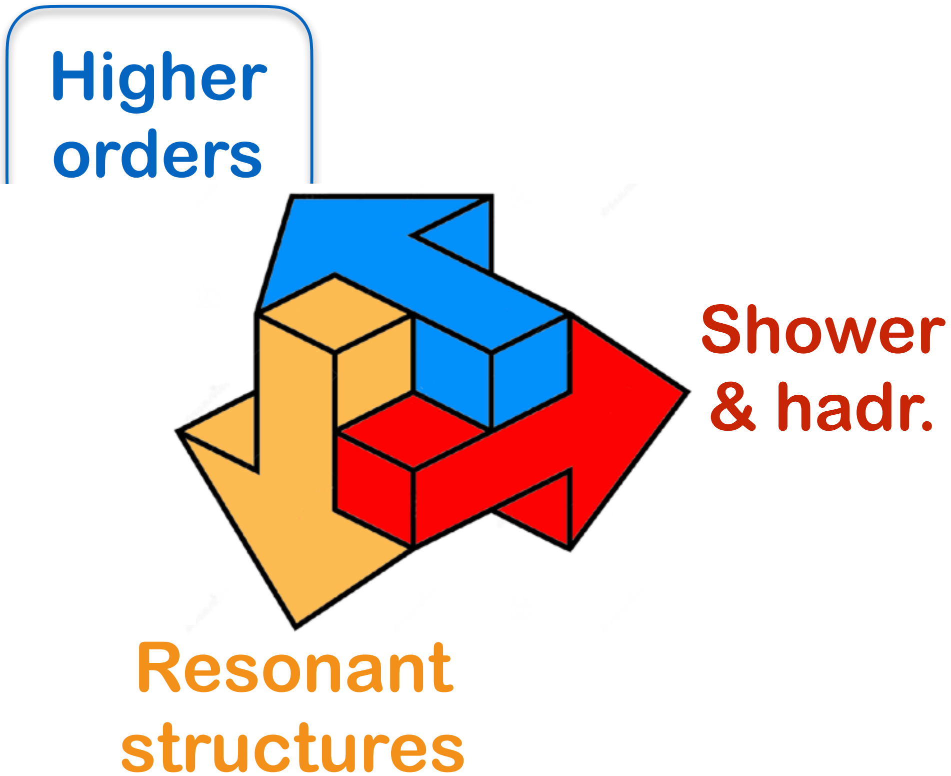


$t \to W^+ b \quad \bar{t} \to W^- \bar{b} \quad g \to b\bar{b}$

Combinatorial background:

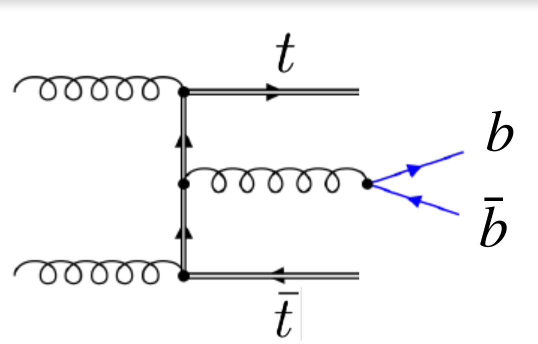
- challenges in top reconstruction & "prompt b-jet" identification
- smearing of Higgs peak in $M(b\bar{b})$ distribution

Avenues to precision



- Accurate predictions for *inclusive production rates*
- General idea on the impact of QCD corrections to $t\bar{t}b\bar{b}$ production
- Global view on the size of dominant theory uncertainties

State of the art: NLO QCD



Inclusive top production

$pp \to t\bar{t}b\bar{b}$

Bredenstein, Denner, Dittmaier, Pozzorini '08 '09

GB, Czakon, Papadopoulos, Pittau, Worek '09

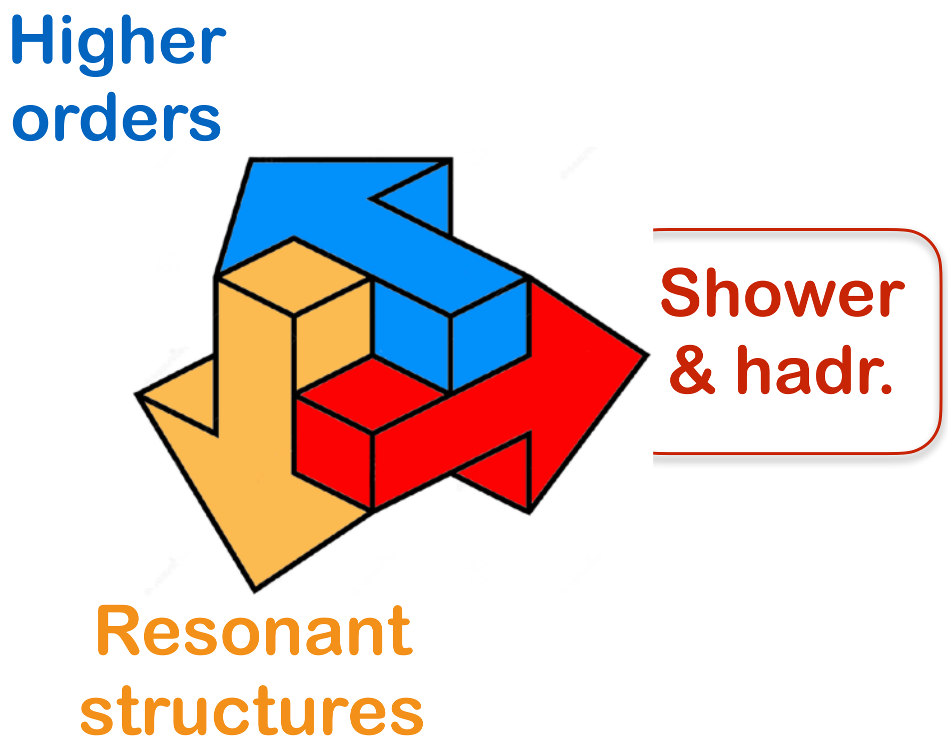
Denner, Dittmaier, Kallweit, Pozzorini '10

Worek '12

$pp \to t\bar{t}b\bar{b}j$

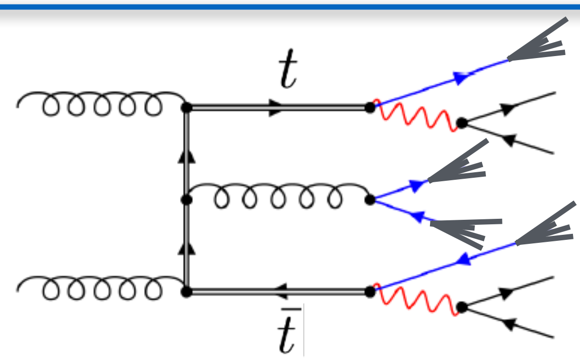
Buccioni, Kallweit, Pozzorini, Zoller '19

Avenues to precision



- Most realistic description of *hadronic observables*
- Based on Narrow Width Approximation for t and W decays (with spin correlations)
- Decay matrix elements computed with LO accuracy (radiative effects approximated by PS)

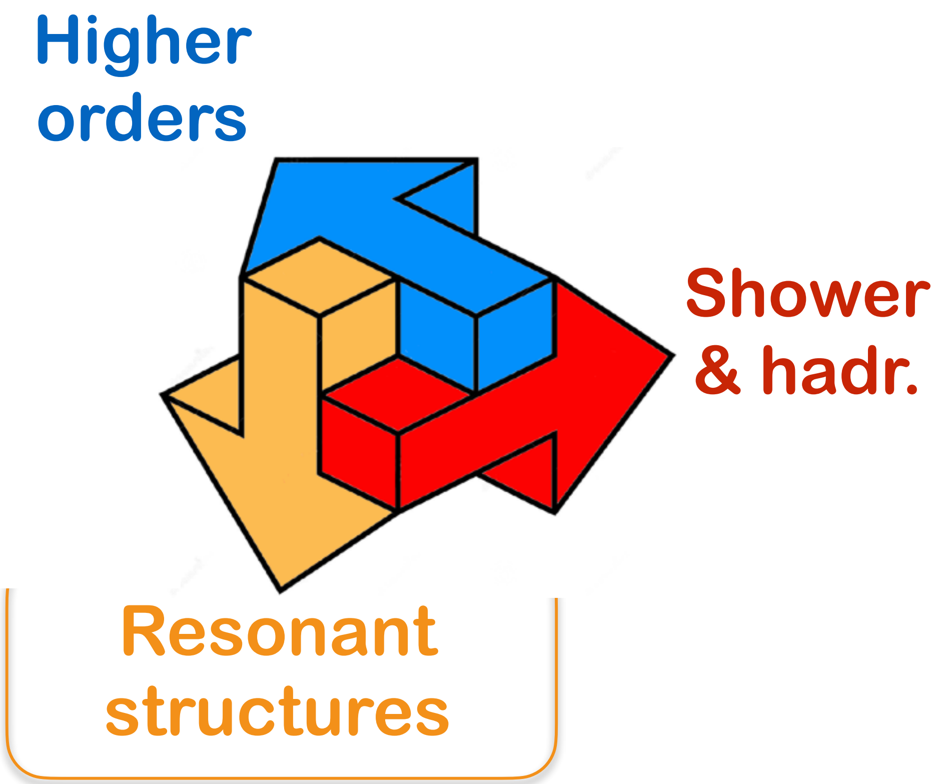
State of the art: NLO QCD



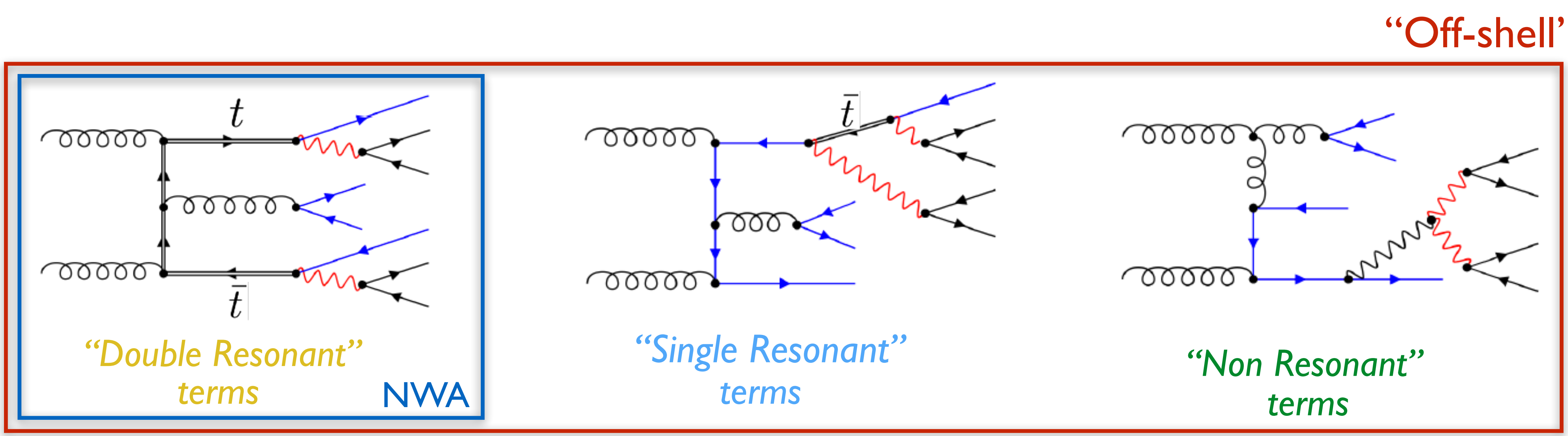
"Double Resonant" production x decay

- **POWHEG** matching
  - Garzelli, Kardos, Trocsanyi '14 '15 [5FS]
  - GB, Garzelli, Kardos '17 [4FS]
  - Jezo, Lindert, Moretti, Pozzorini '18 [4FS]
- **MC@NLO** matching
  - Cascioli, Maierhofer, Moretti, Pozzorini, Siegert '14 [4FS]
- Dedicated comparison of $t\bar{t}b\bar{b}$ MC's (**LHC HXSWG)**
  - Pozzorini, Buccioni, Siegert, Garzelli, GB, Jezo, Krause, Kardos, Lindert, Podskubka, Reuschle and Zaro '21 [4FS]

Avenues to precision



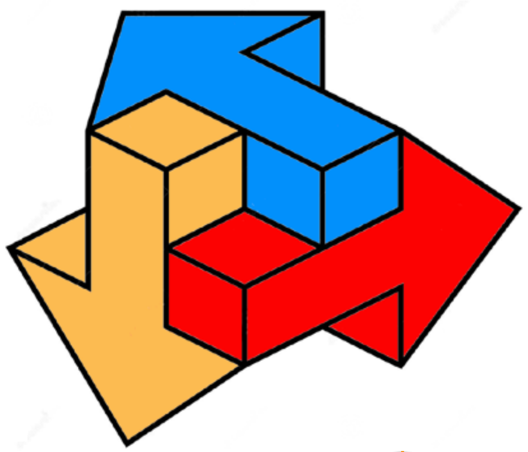
- Most realistic description of *resonant structures* over phase space
- Drops the limits $\Gamma_t/m_t \to 0,\ \Gamma_W/m_W \to 0$
- Complete calculation of fully decayed process at *fixed order*



"Off-shell" = DR + SR + NR + interferences

Avenues to precision

Higher orders



Shower & hadr.

Resonant structures

- Most realistic description of *resonant structures* over phase space
- Drops the limits $\Gamma_t/m_t \to 0,\ \Gamma_W/m_W \to 0$
- Complete calculation of fully decayed process at *fixed order*

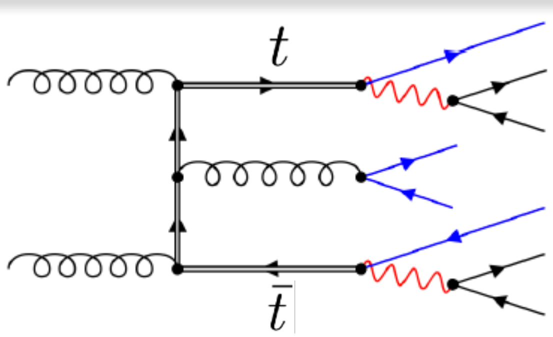
Focus of this talk

$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}b\bar{b}$$

Denner, Lang, Pellen '21

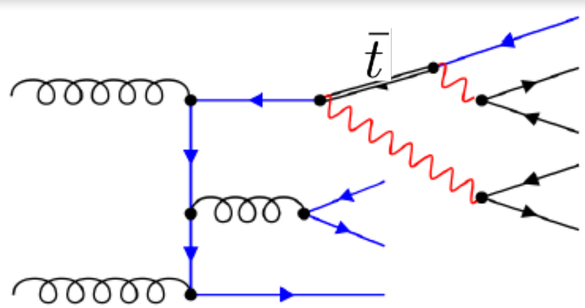
GB, Bi, Hartanto, Kraus, Lupattelli, Worek '21 '23

"Off-shell"

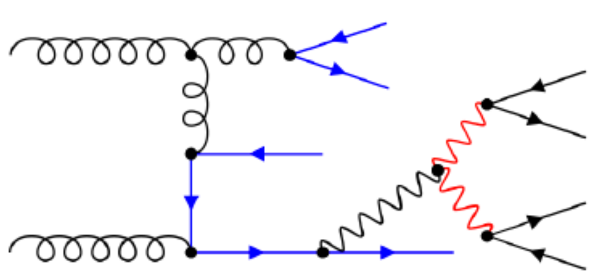


"Double Resonant" terms

NWA



"Single Resonant" terms



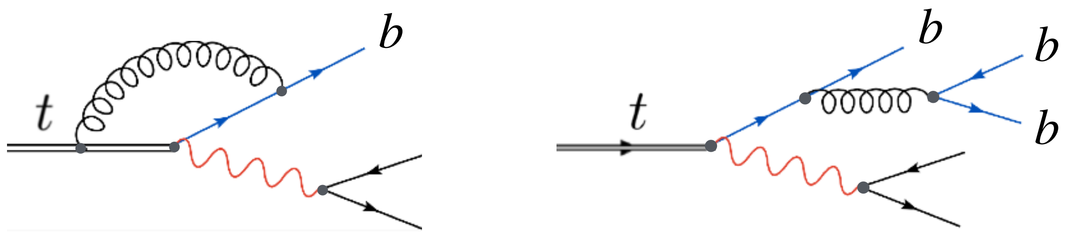
"Non Resonant" terms

"Off-shell" = DR + SR + NR + interferences

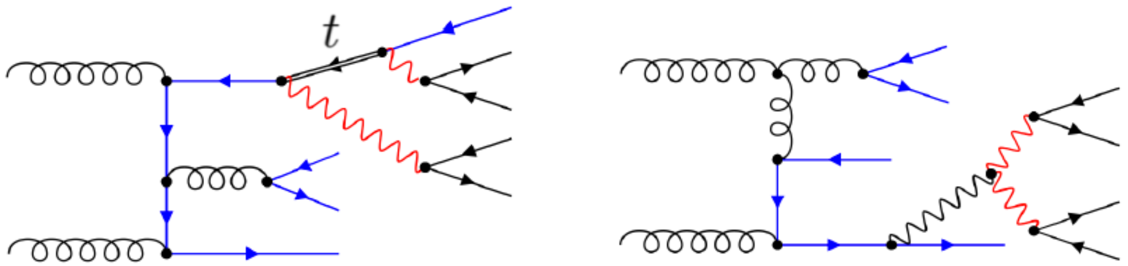
Topics covered in this talk

- Dominant theory uncertainties in $t\bar{t}b\bar{b}$ with *dilepton* signatures

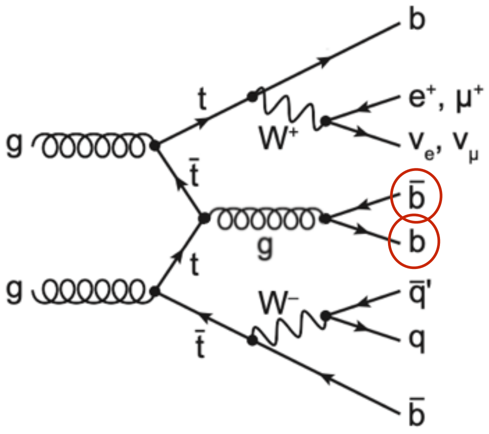
- Impact of top-quark decay modelling accuracy
  - QCD corrections to top decays
  - Multi b-jet top decays



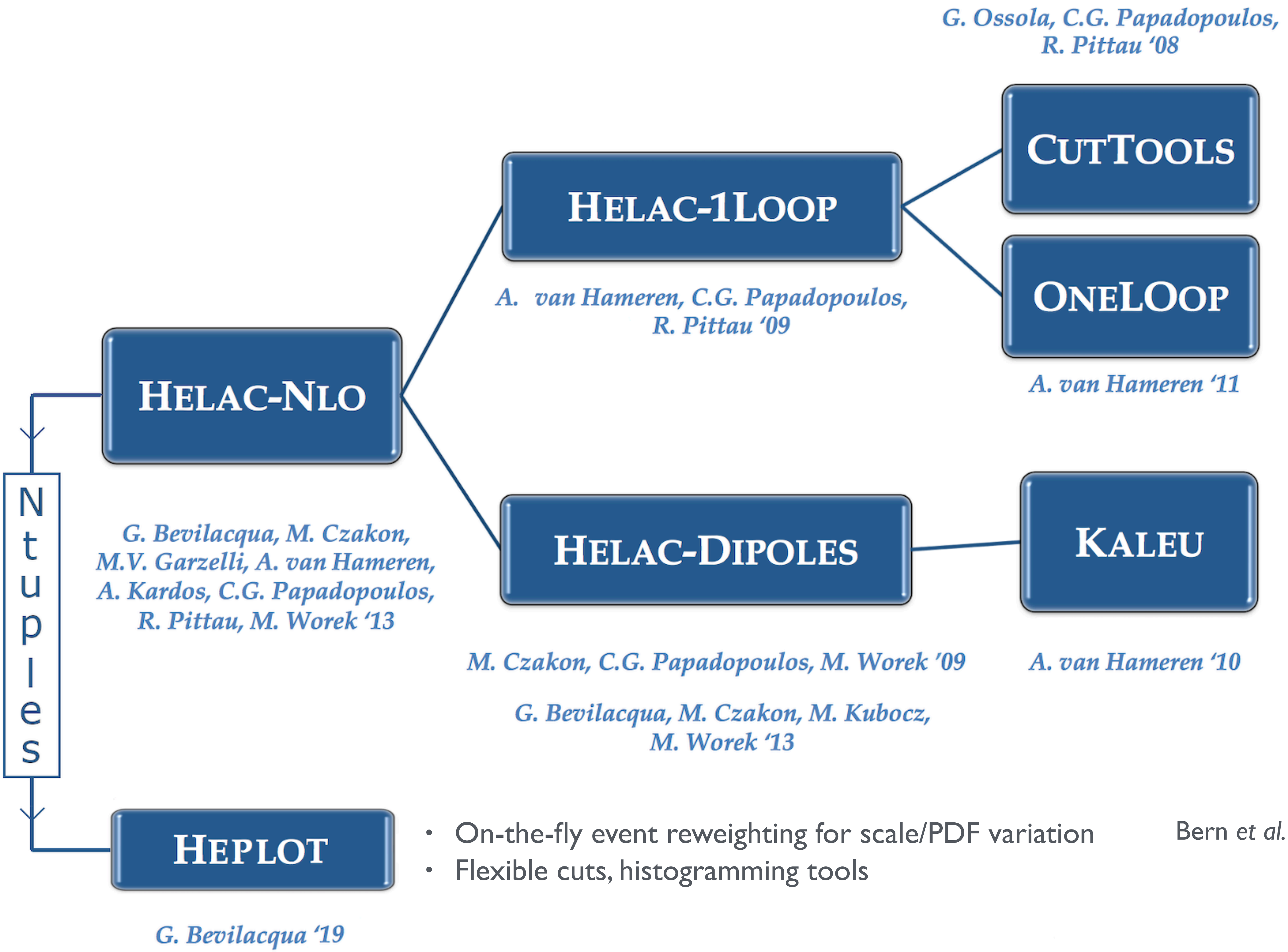
- Impact of full off-shell effects for t and W decays



- b-jet labelling and identification of prompt b-jets



Computational framework



- On-the-fly event reweighting for scale/PDF variation
- Flexible cuts, histogramming tools

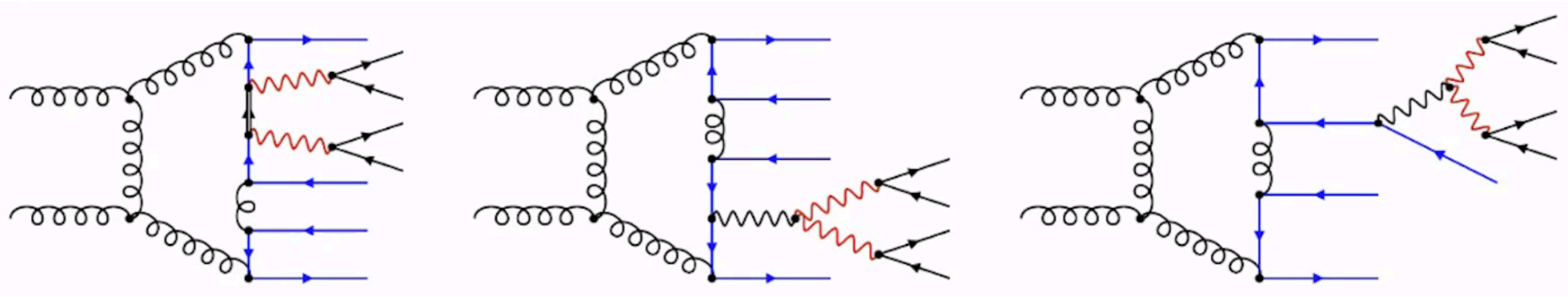
Bern *et al.* '14

Technical aspects of off-shell $t\bar{t}b\bar{b}$ at NLO

One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number [gg channel]	271528

$$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\,b\bar{b}$$

Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$	9576	50	10
$g\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,\bar{q}$	9576	50	10



I. Size of QCD corrections and dominant theory uncertainties at NLO

$t\bar{t}b\bar{b}$ with dilepton signatures: full off-shell predictions

- **Integrated fiducial cross sections**

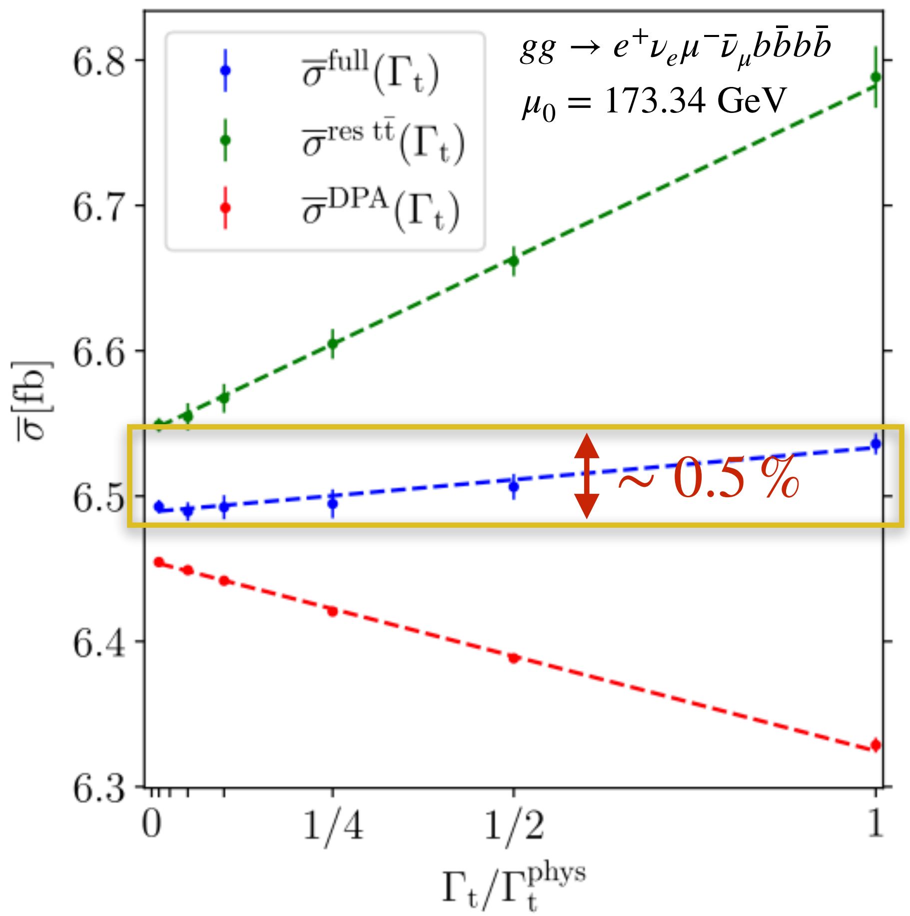
$\sqrt{s} = 13$ TeV

Analysis cuts: $p_T(\ell) > 20$ GeV , $p_T(b) > 25$ GeV , $|y(\ell)| < 2.5$, $|y(b)| < 2.5$

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
		$\mu_R = \mu_F = \mu_0 = H_T/3$	[NNPDF 3.1]			
25	6.813	$^{+4.338\ (64\%)}_{-2.481\ (36\%)}$	13.22	$^{+2.66\ (20\%)}_{-2.95\ (22\%)}$	$^{+0.19\ (1\%)}_{-0.19\ (1\%)}$	1.94
30	4.809	$^{+3.062\ (64\%)}_{-1.756\ (37\%)}$	9.09	$^{+1.66\ (18\%)}_{-1.98\ (22\%)}$	$^{+0.16\ (2\%)}_{-0.16\ (2\%)}$	1.89
35	3.431	$^{+2.191\ (64\%)}_{-1.256\ (37\%)}$	6.37	$^{+1.07\ (17\%)}_{-1.36\ (21\%)}$	$^{+0.11\ (2\%)}_{-0.11\ (2\%)}$	1.86
40	2.464	$^{+1.582\ (64\%)}_{-0.901\ (37\%)}$	4.51	$^{+0.72\ (16\%)}_{-0.95\ (21\%)}$	$^{+0.09\ (2\%)}_{-0.09\ (2\%)}$	1.83

[Denner, Lang, Pellen, Phys. Rev. D 104 (2021), 056018]



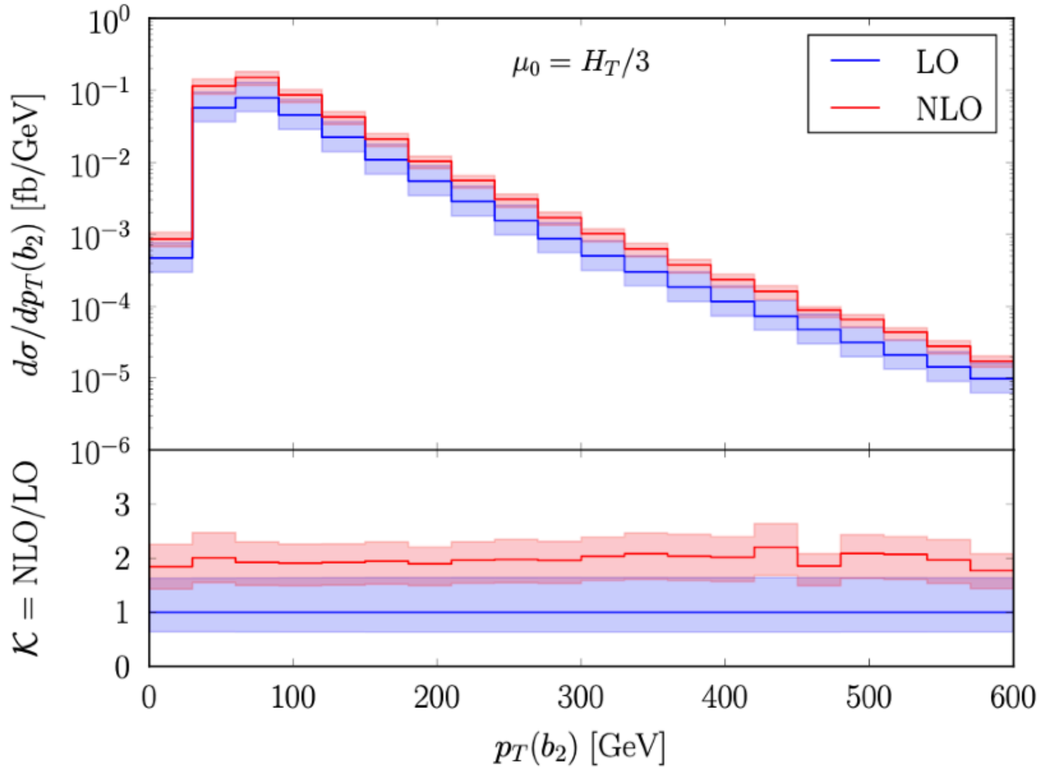
- QCD corrections are large
- Impact of jet veto:

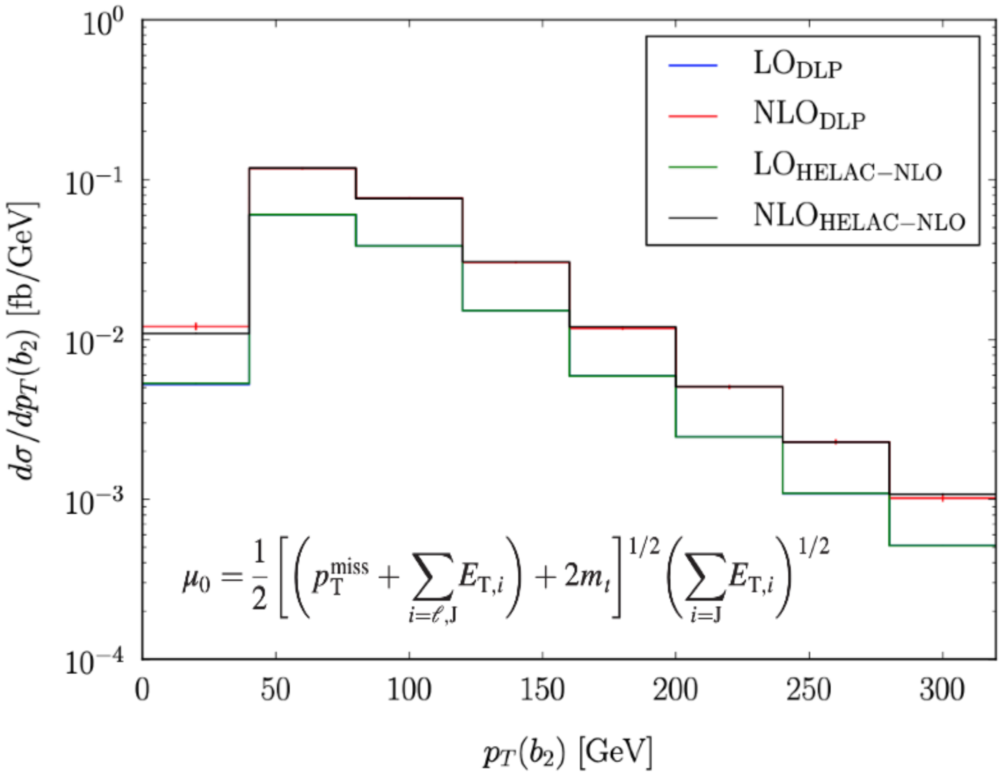
$$p_T^{\rm veto}(j) = 100 \text{ GeV} \;\rightarrow\; \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.58$$
$$p_T^{\rm veto}(j) = 50 \text{ GeV} \;\rightarrow\; \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.23$$

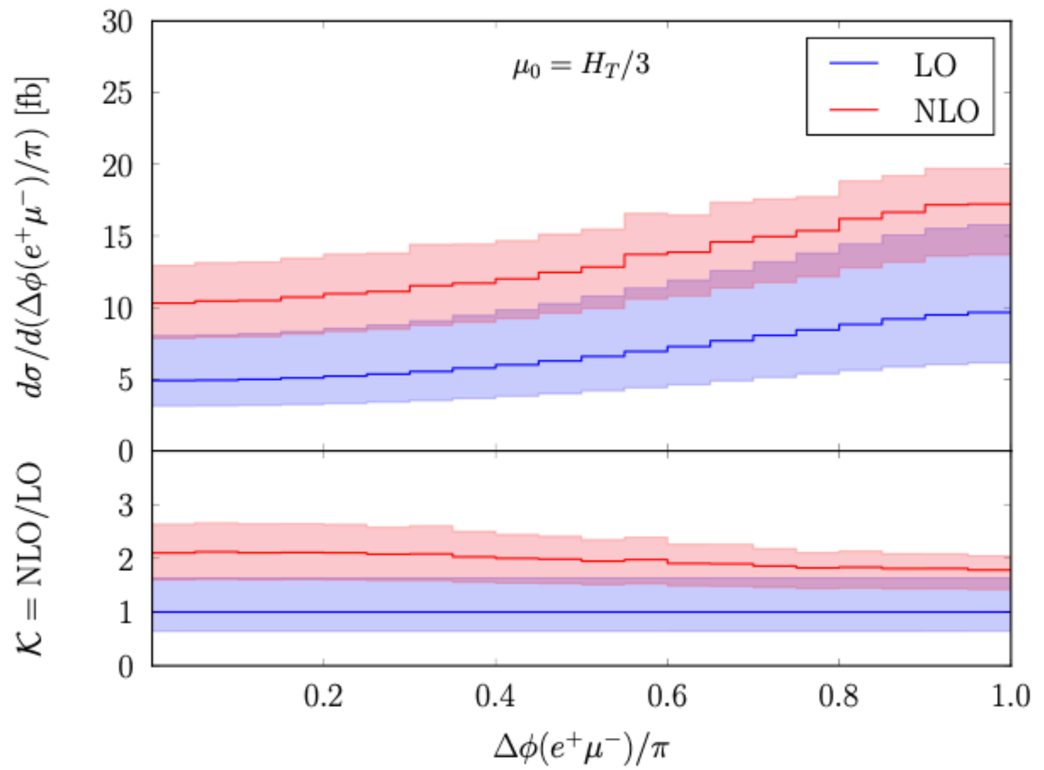
Off-shell $t\bar{t}b\bar{b}$: differential cross sections

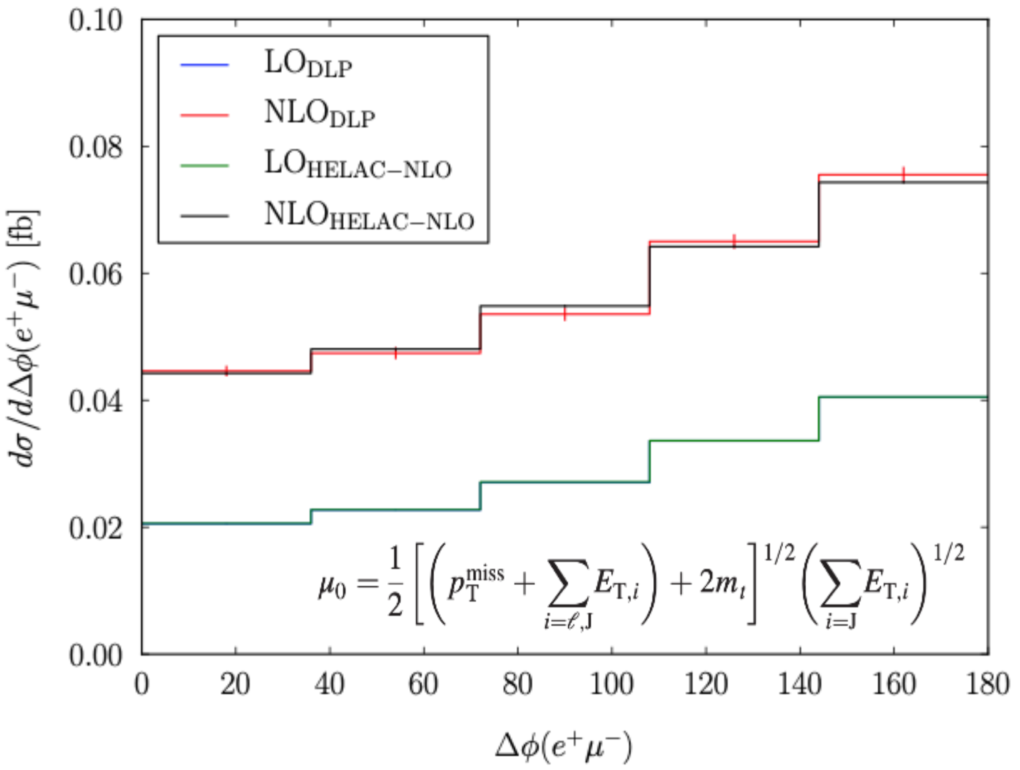
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

Comparison with Denner, Lang and Pellen, [Phys. Rev. D 104 (2021), 056018]









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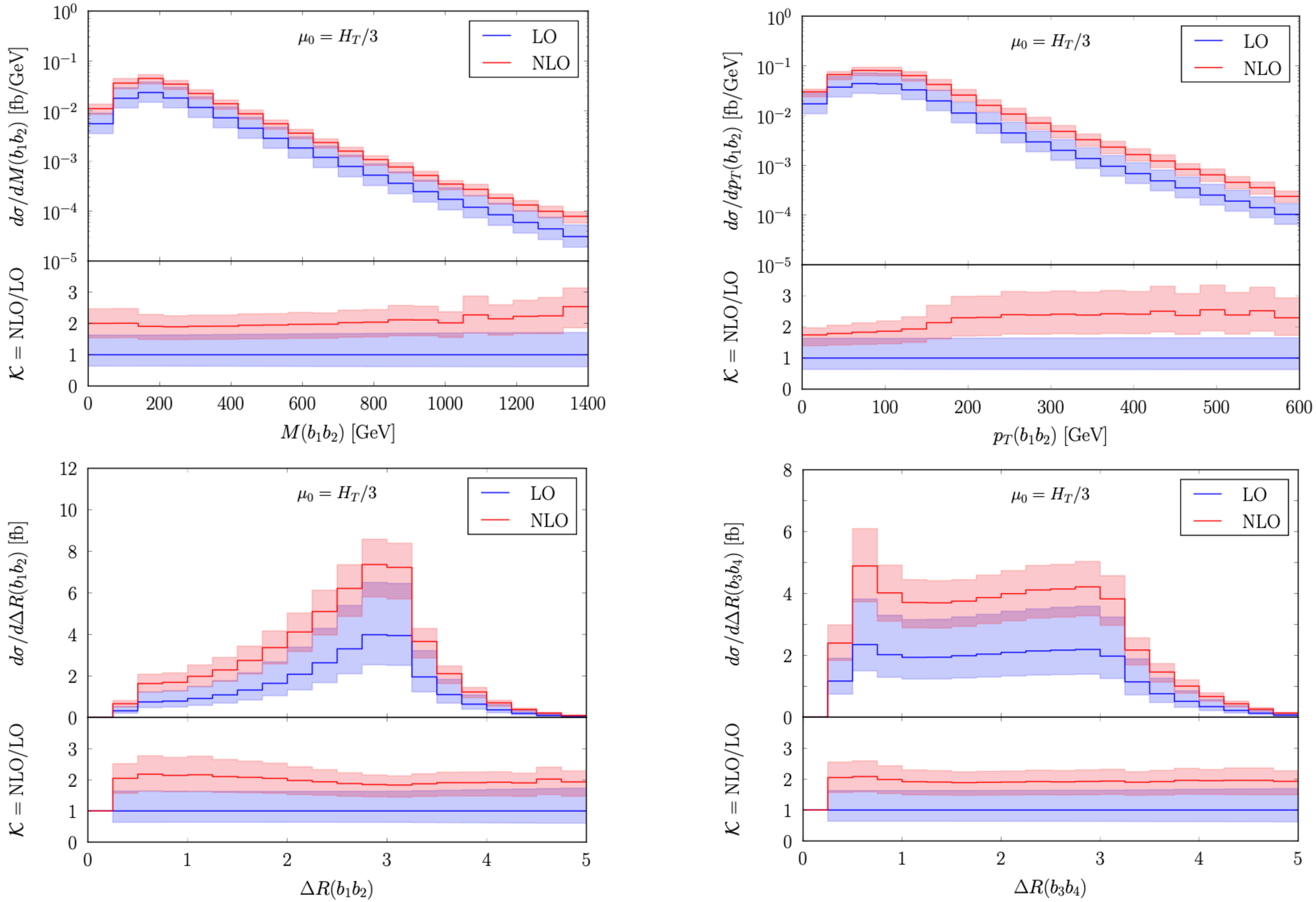
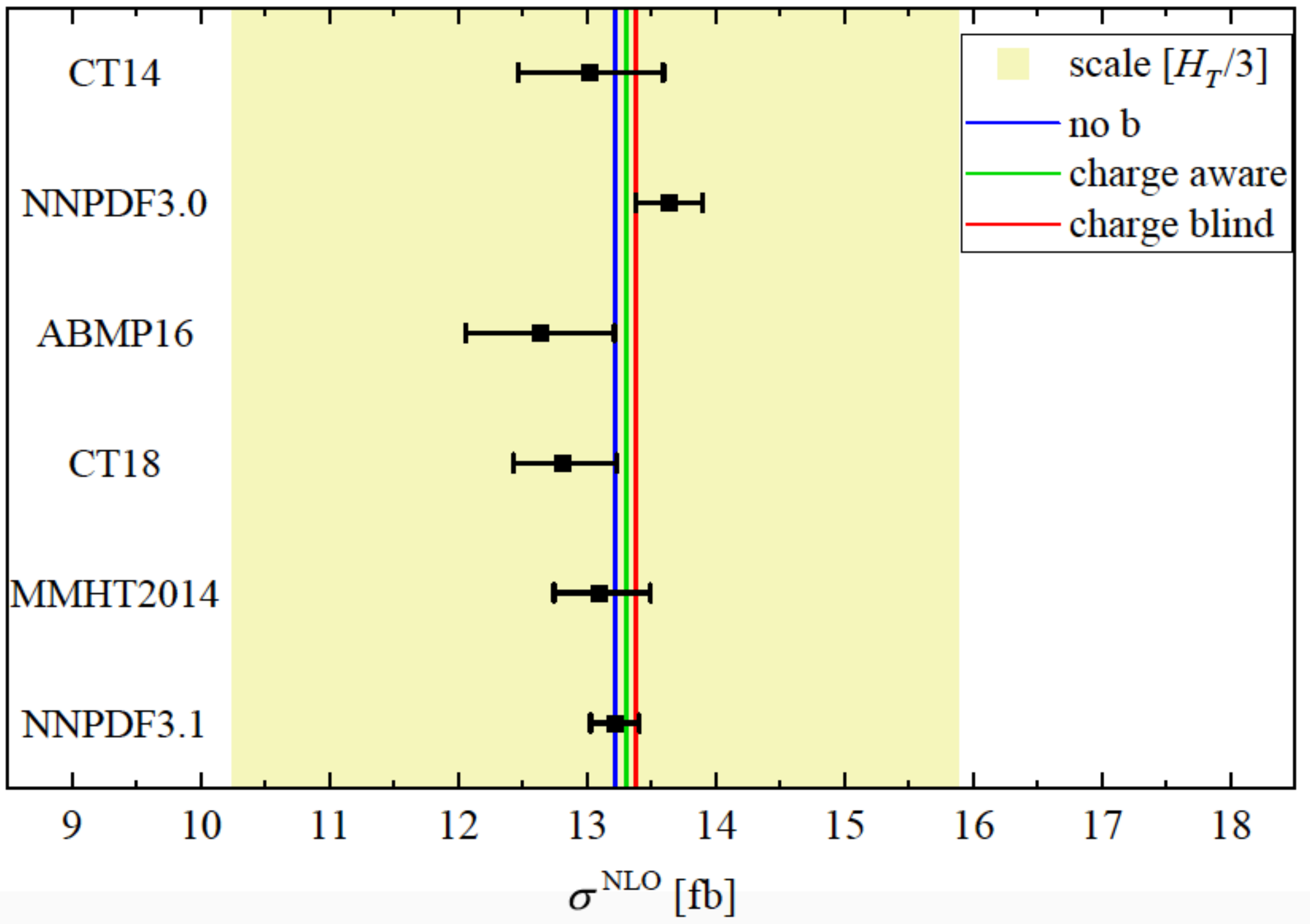
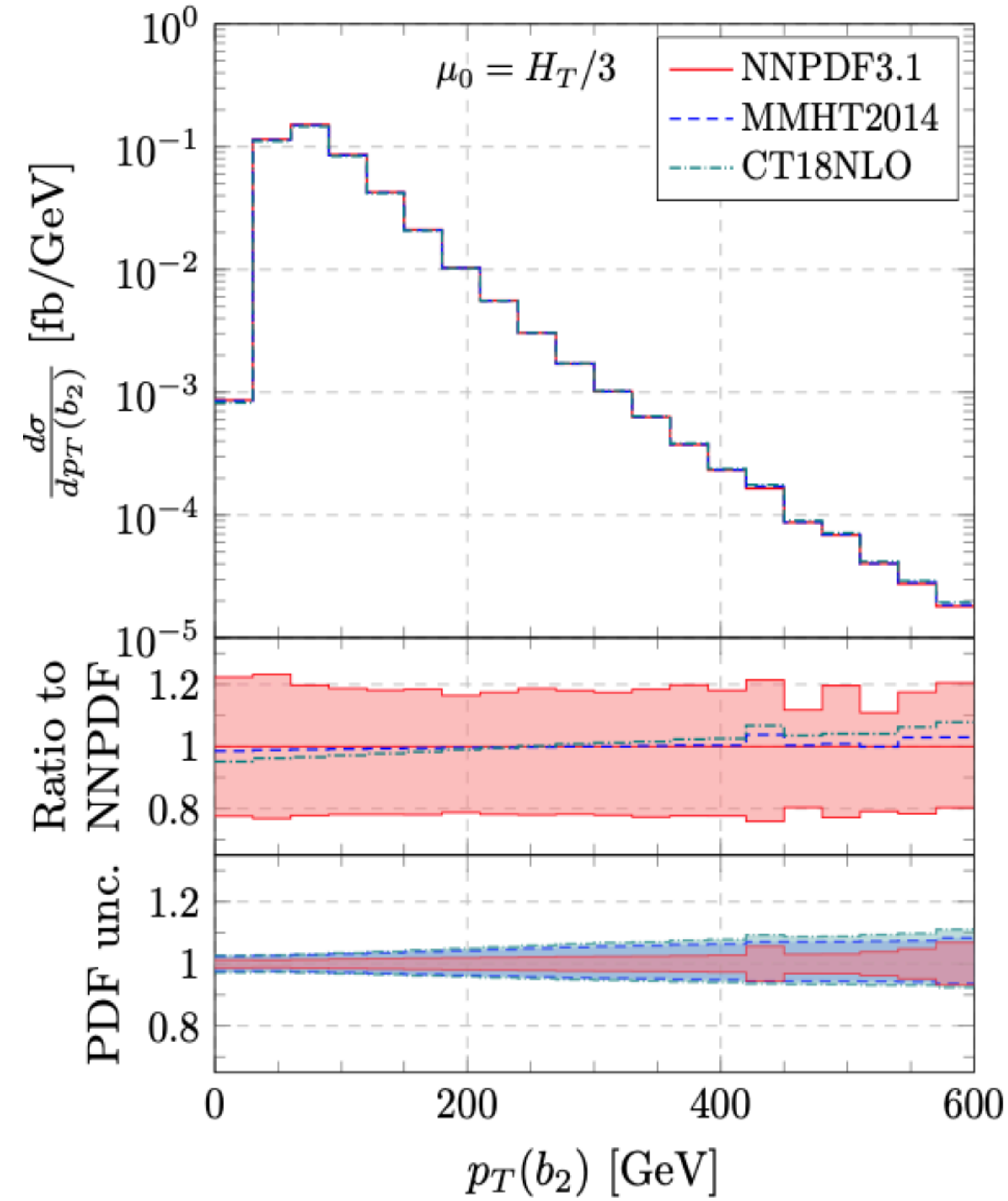


Off-shell $t\bar{t}b\bar{b}$: theoretical uncertainties at NLO

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]





NLO theory uncertainties

- Scale : $\mathcal{O}(20\%)$ - PDF : $\mathcal{O}(1\% - 3\%)$

↪ Relative sizes vary at high-energy tails

II. Accuracy of NWA and off-shell effects

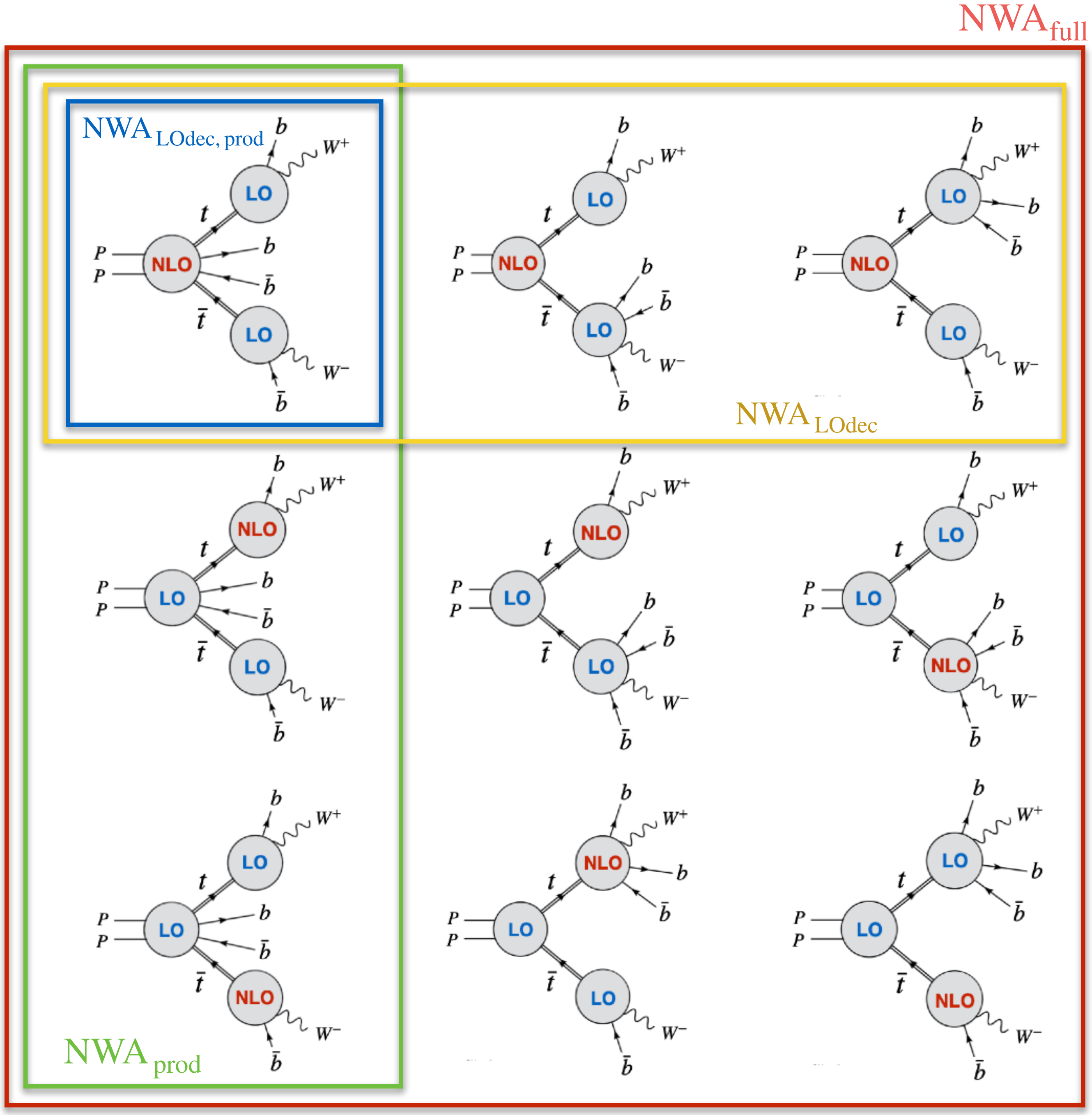
$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- NWA cross sections based on different levels of accuracy in top decay modelling



$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

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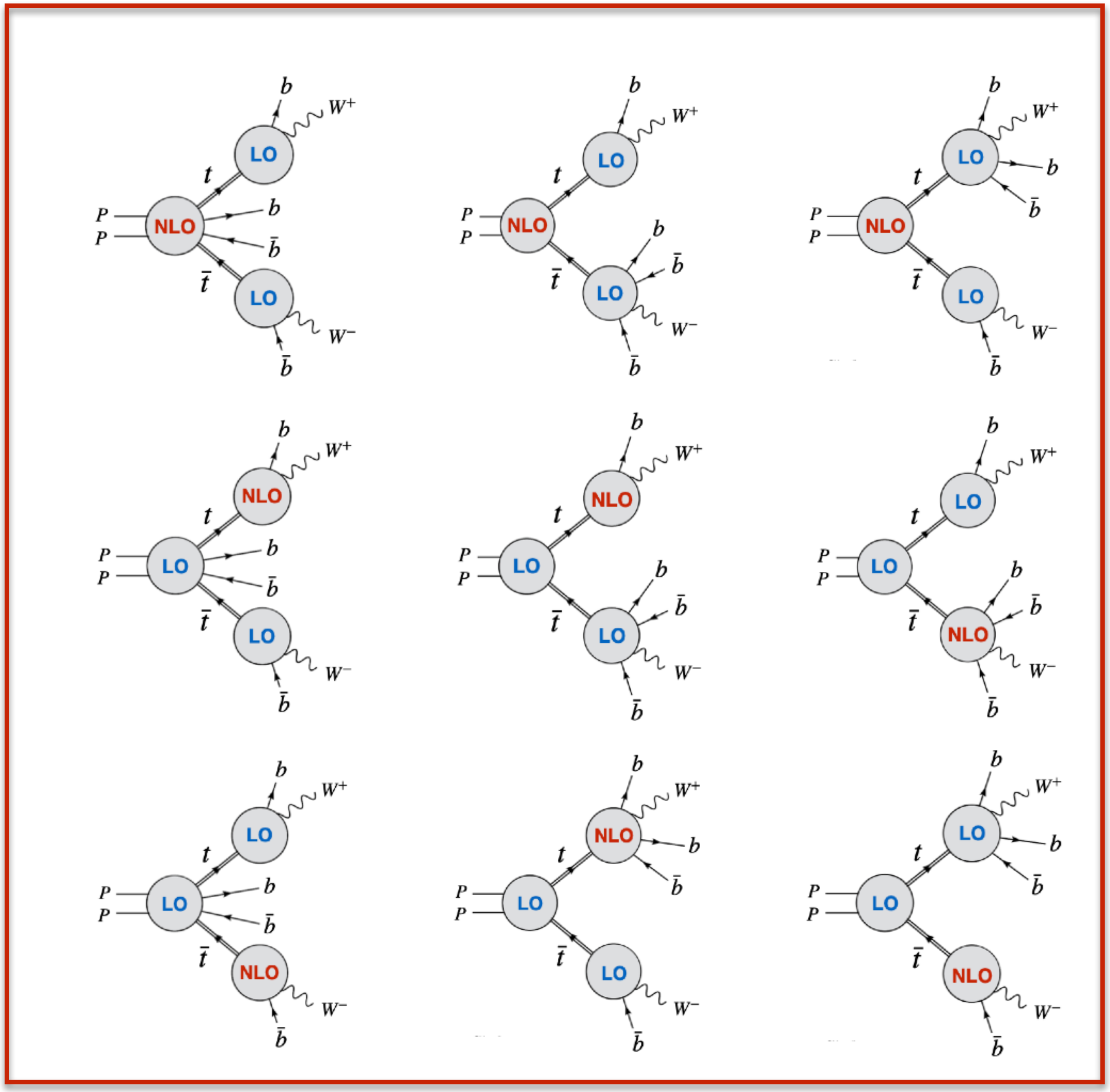
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

$\rm NWA_{full}$



- Off-shell vs $\rm NWA_{full}$:

↪ Off-shell effects: $+0.5\ \%$

$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
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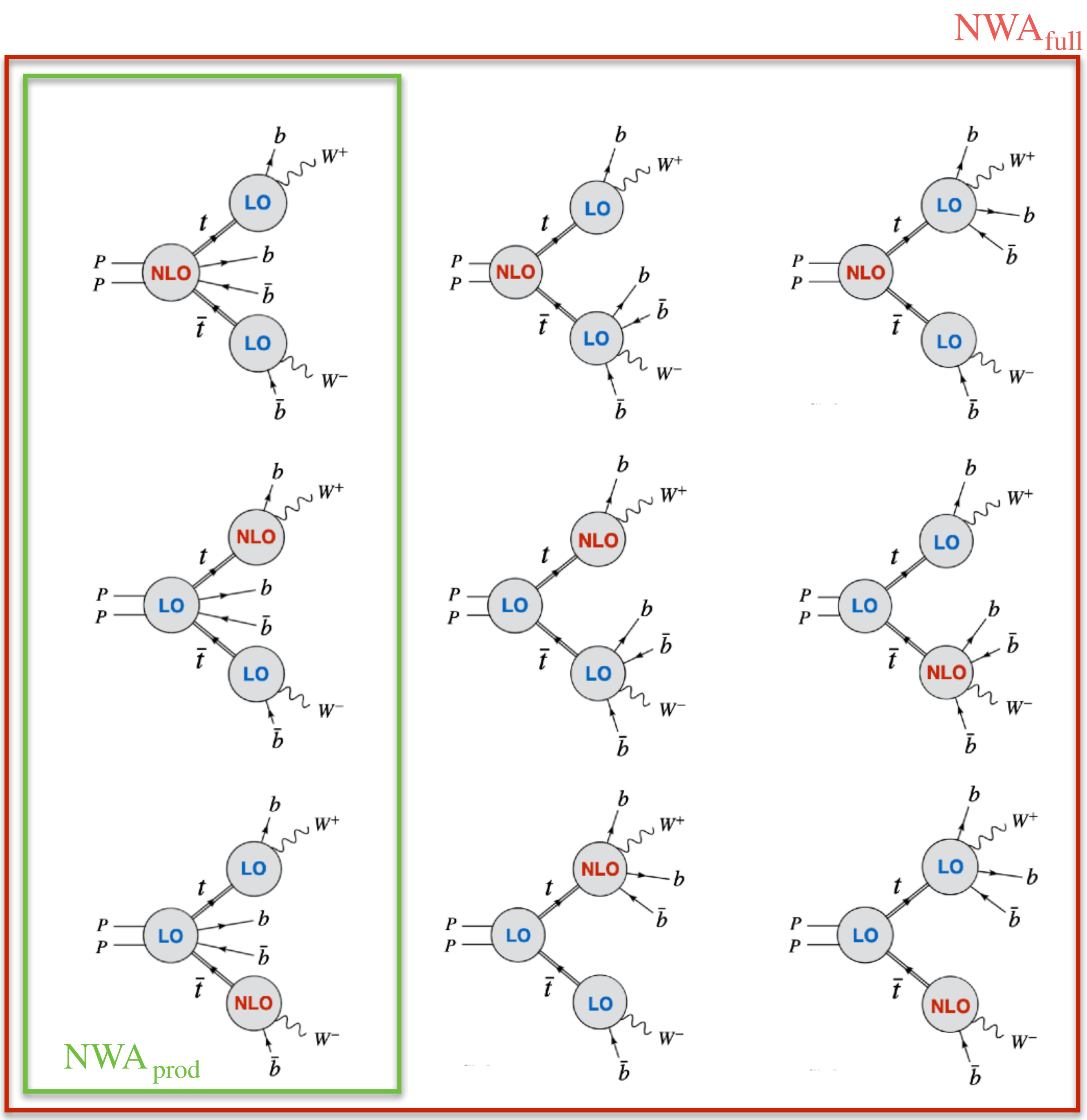
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- $\rm NWA_{full}$ vs $\rm NWA_{prod}$:

↪ Impact of $t \to Wbb\bar{b}$ decays: $+1\ \%$



$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
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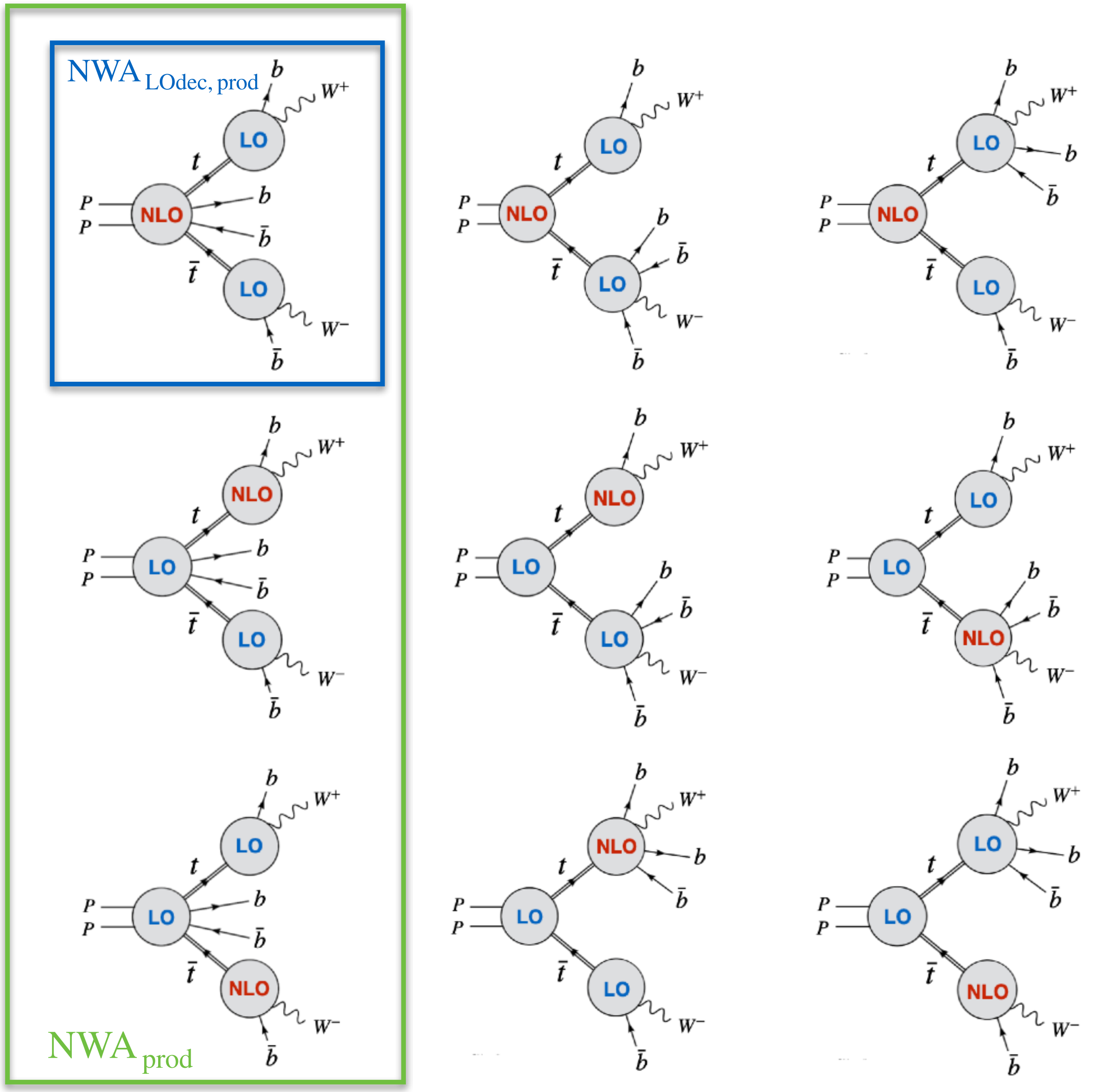
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- $\rm NWA_{prod}$ vs $\rm NWA_{prod,LOdec}$:

↪ Tiny difference: 0.8 %

How shall this be interpreted?



$t\bar{t}b\bar{b}$: comparing modelling approaches

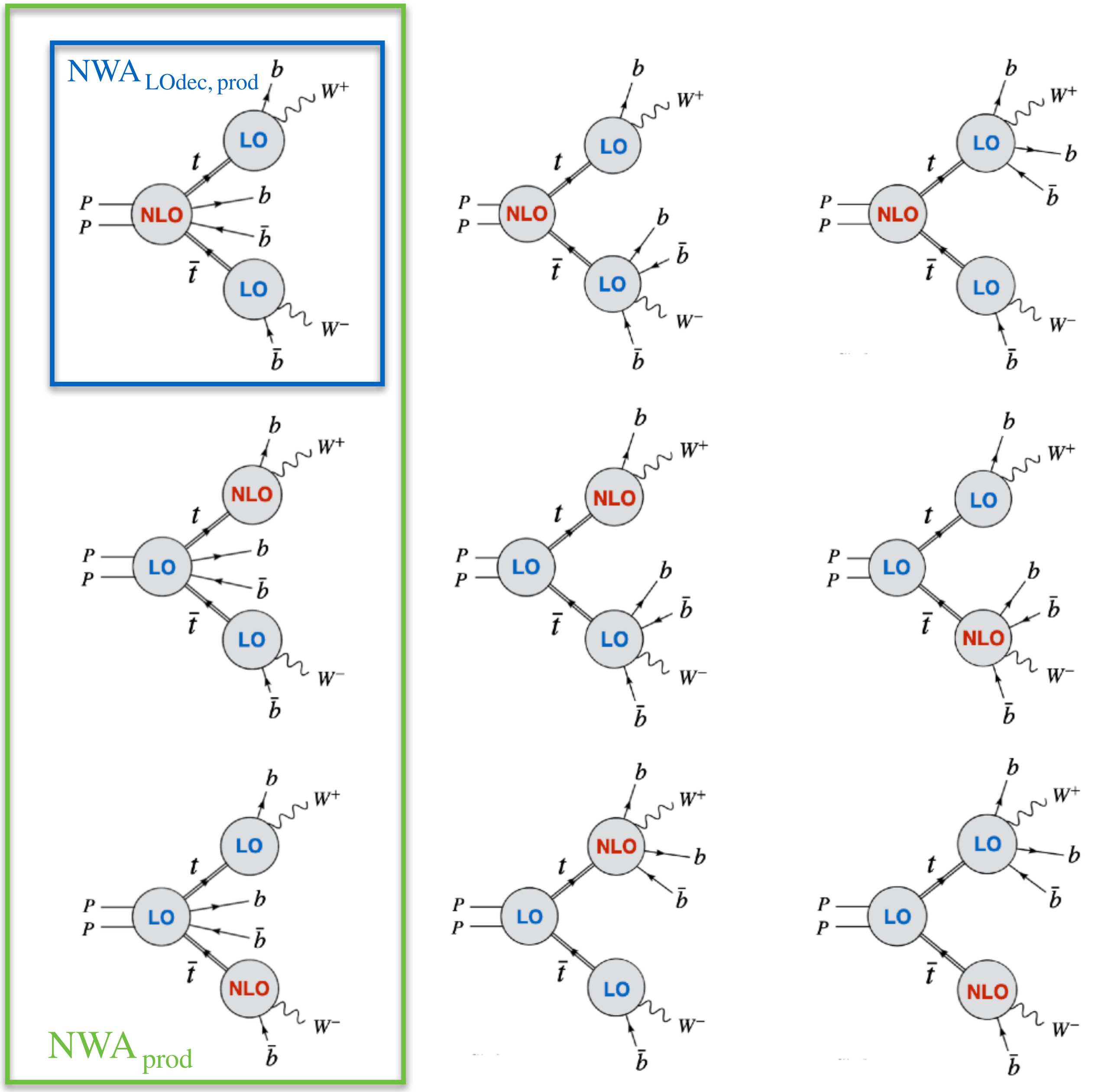
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	σ^{NLO} [fb]	δ_{scale} [fb]	$\frac{\sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{NLO}}_{\mathrm{NWA_{full}}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\mathrm{NWA_{full}}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\mathrm{NWA_{LOdec}}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\mathrm{NWA_{prod}}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\mathrm{NWA_{prod,\,exp}}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\mathrm{NWA_{prod,\,LOdec}}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- $\mathrm{NWA_{prod,exp}}$ vs $\mathrm{NWA_{prod,LOdec}}$:

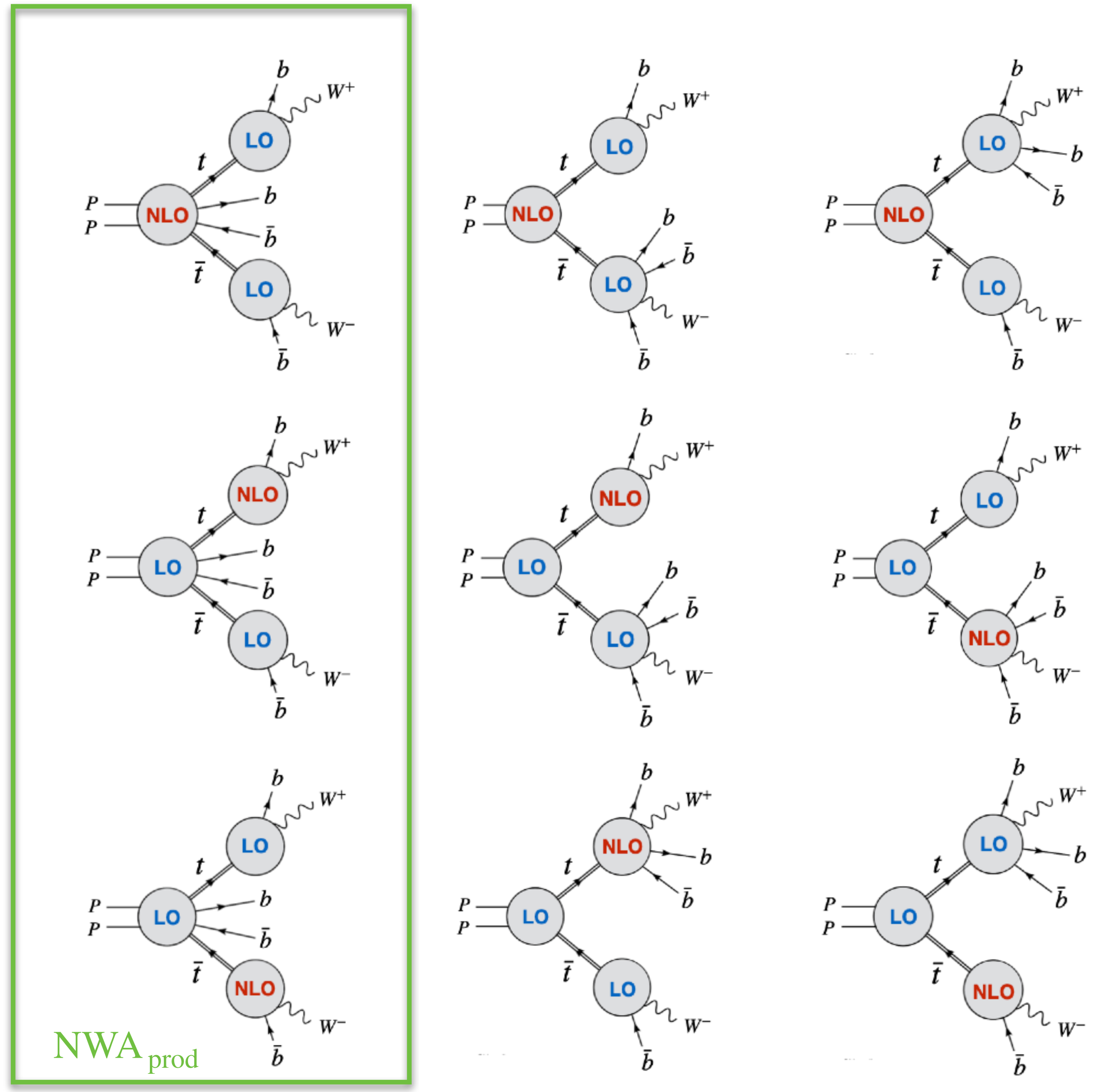
↪ Genuine QCD corrections to top decays: $-7\,\%$



[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%



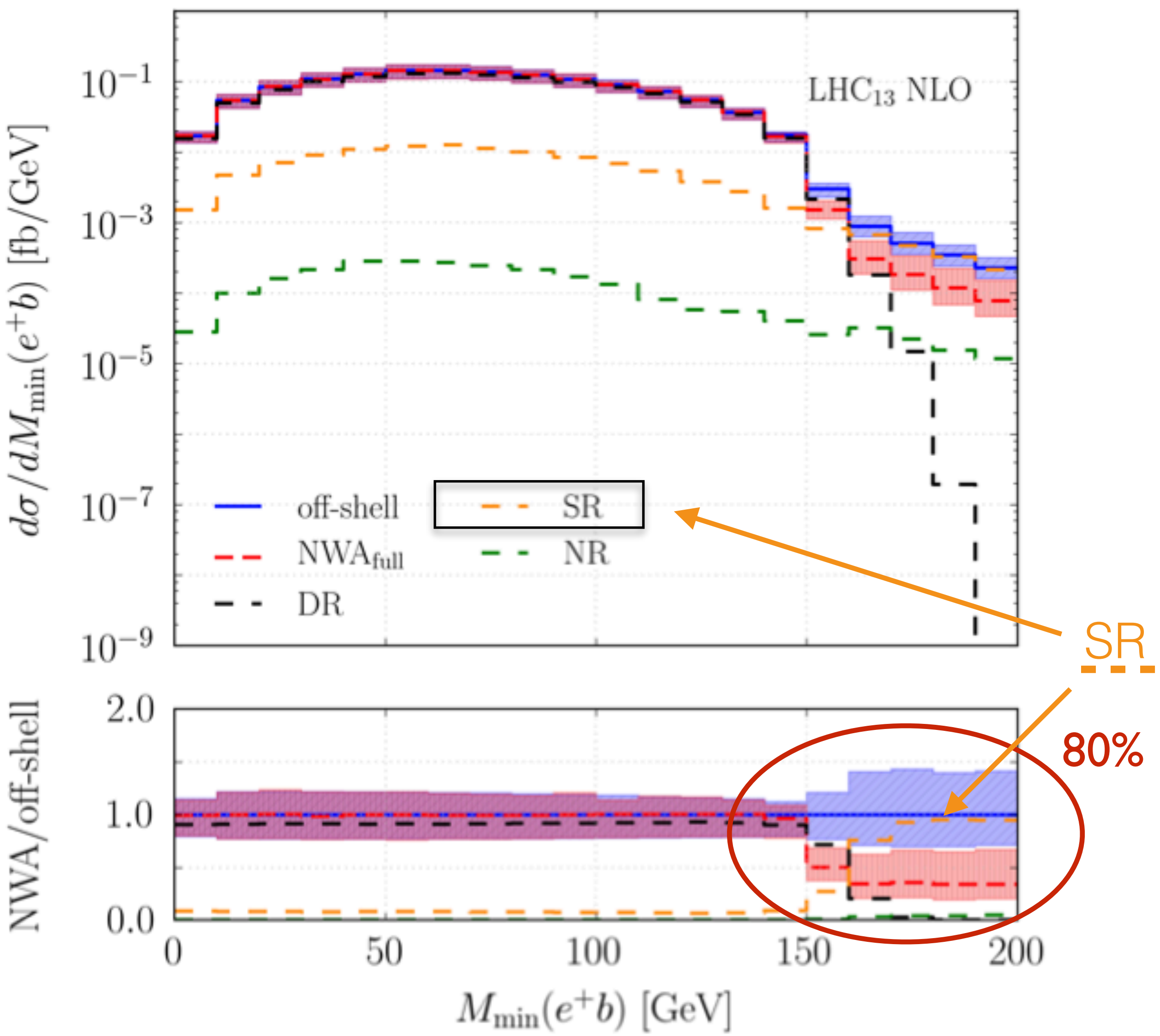
- $\rm NWA_{prod}$ vs $\rm NWA_{prod,exp}$:

$\hookrightarrow$ Impact of Γ_t^{NLO} expansion: $+6\,\%$

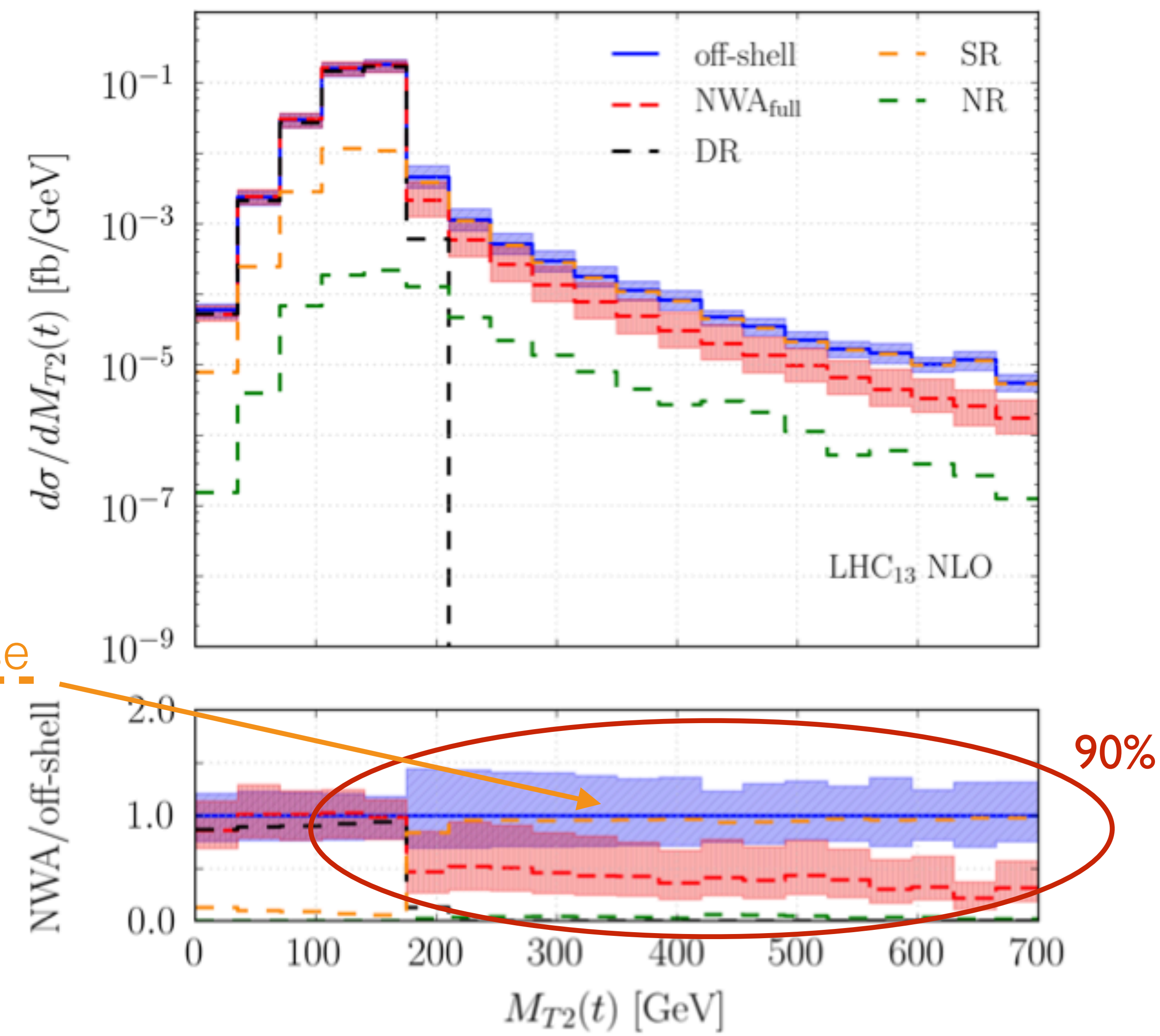
$\mathcal{O}(\alpha_s^2)$ effects (within NLO scale uncertainty)

- Off-shell effects amount to few permille for most observables used in SM analyses
- Threshold observables used in BSM studies are naturally more sensitive:

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]



SR rise



$$\mathrm{LO_{NWA}} \rightarrow M_{min}(e^+b) < \sqrt{m_t^2 - m_W^2} \approx 153\ \mathrm{GeV}$$

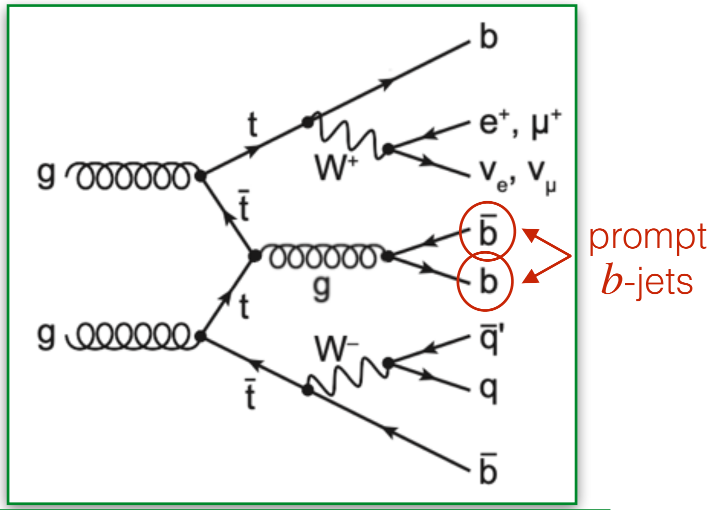
$$M_{T2}(t) = \min_{\sum p_T^{\nu_i} = p_T^{miss}} \left[\max\{M_T^2(p_T(e^+X_t), p_T(\nu_1)), M_T^2(p_T(\mu^- X_{\bar{t}}), p_T(\nu_2))\}\right]$$

III. Identification of prompt b-jets

- Labelling prompt b-jets in $t\bar{t}b\bar{b}$ is not free of ambiguities in a full calculation (due to combinatorial background and quantum interference)

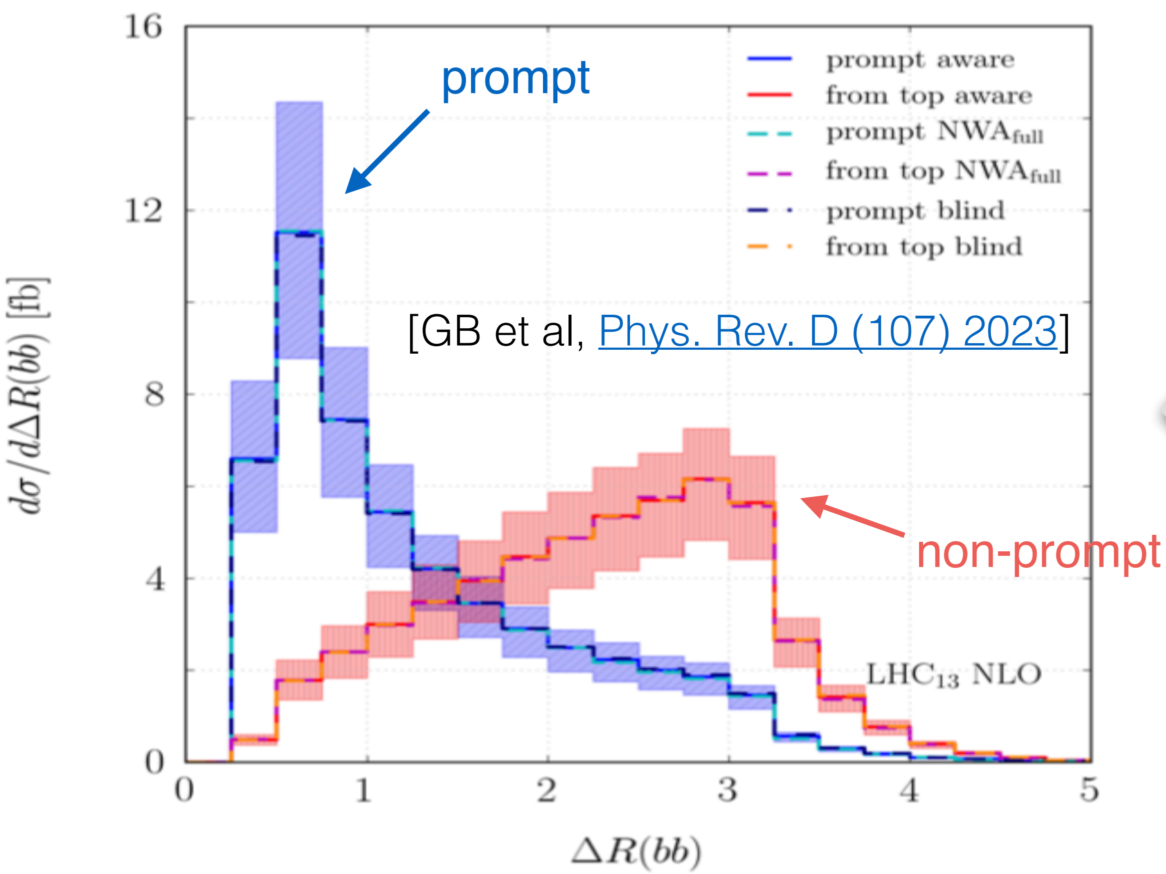
- Kinematic-based prescription: determine prompt b-jets according to a minimum principle for Q:

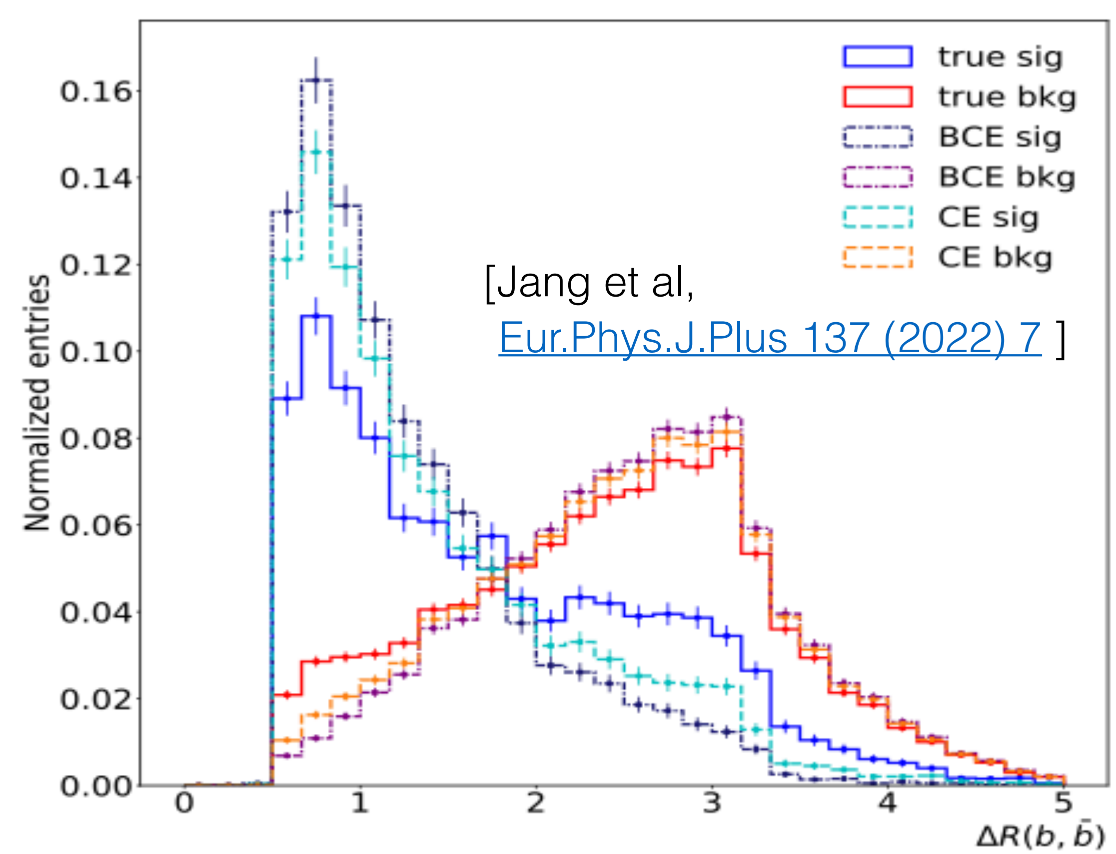
$$\boxed{Q = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times |M^{\text{prompt}}(bb)|}$$



$t \to W^+ b \quad \bar{t} \to W^- \bar{b} \quad g \to b\bar{b}$

- Results consistent with DNN-based studies:

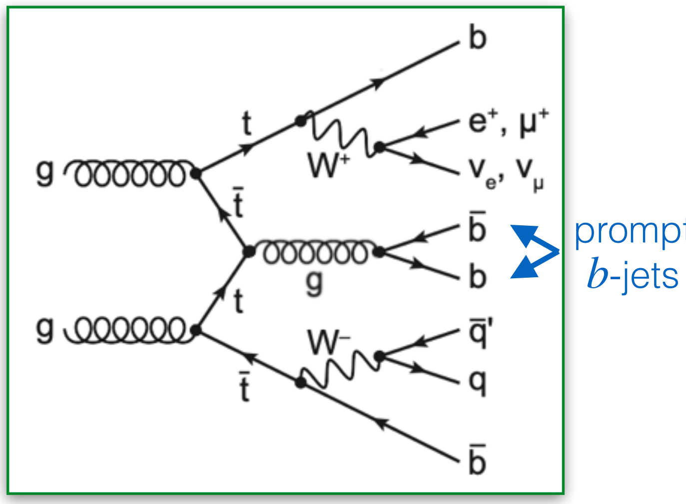


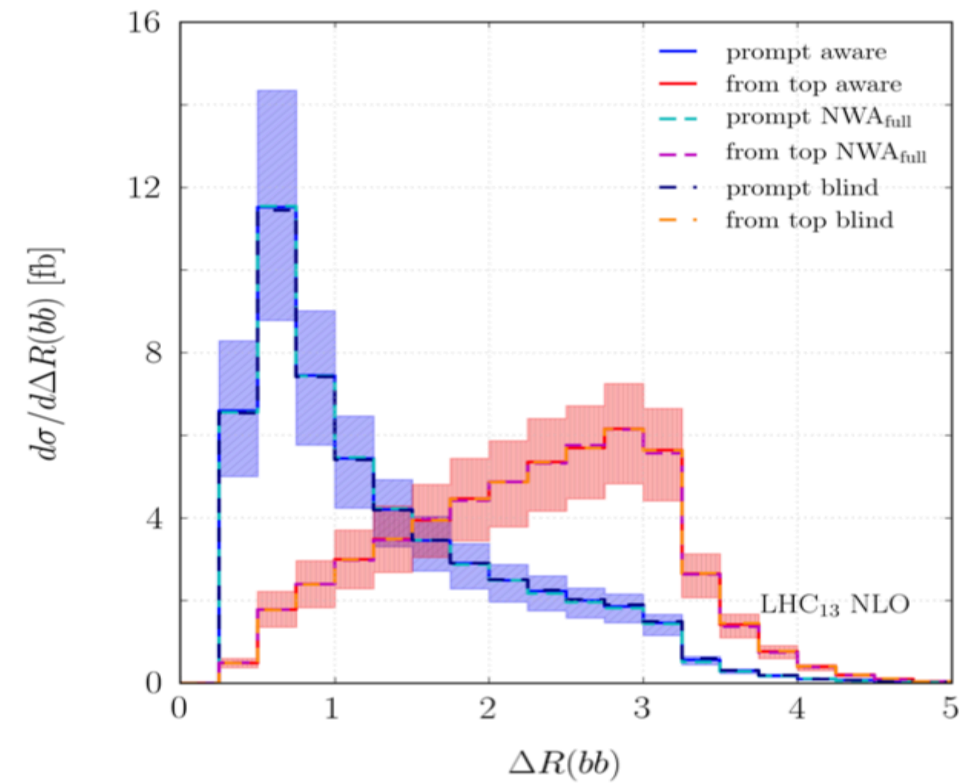


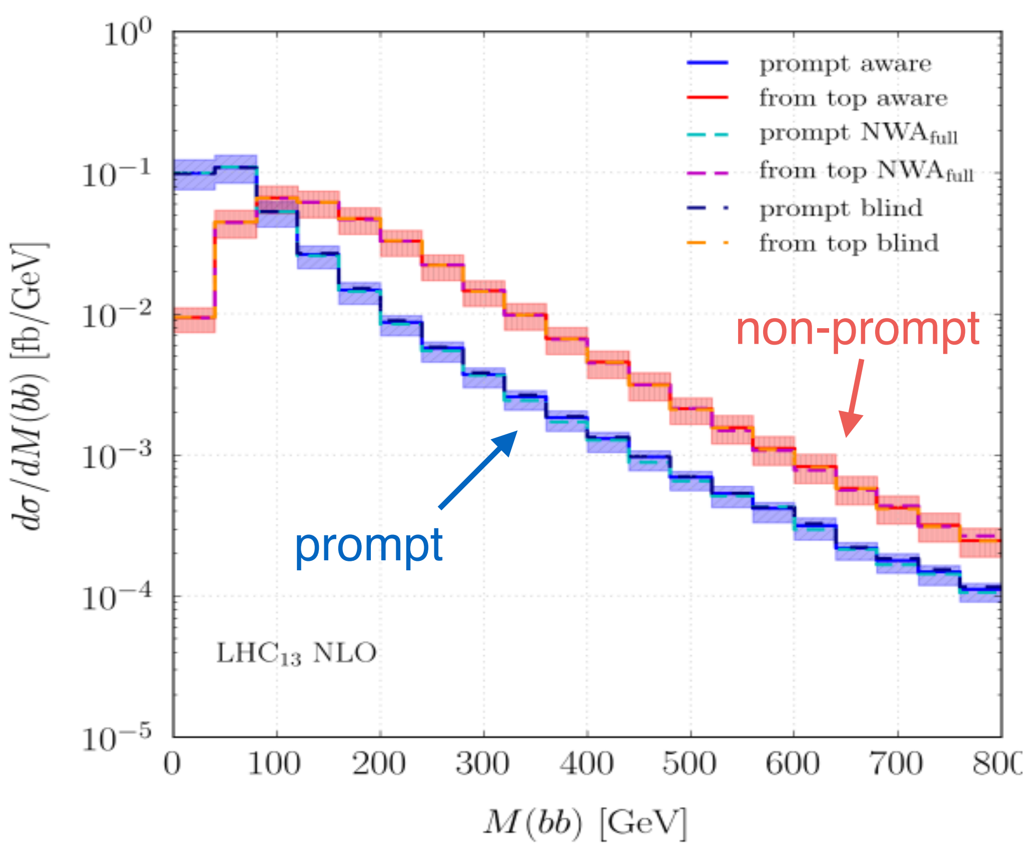
$t\bar{t}b\bar{b}$: prompt b-jet identification

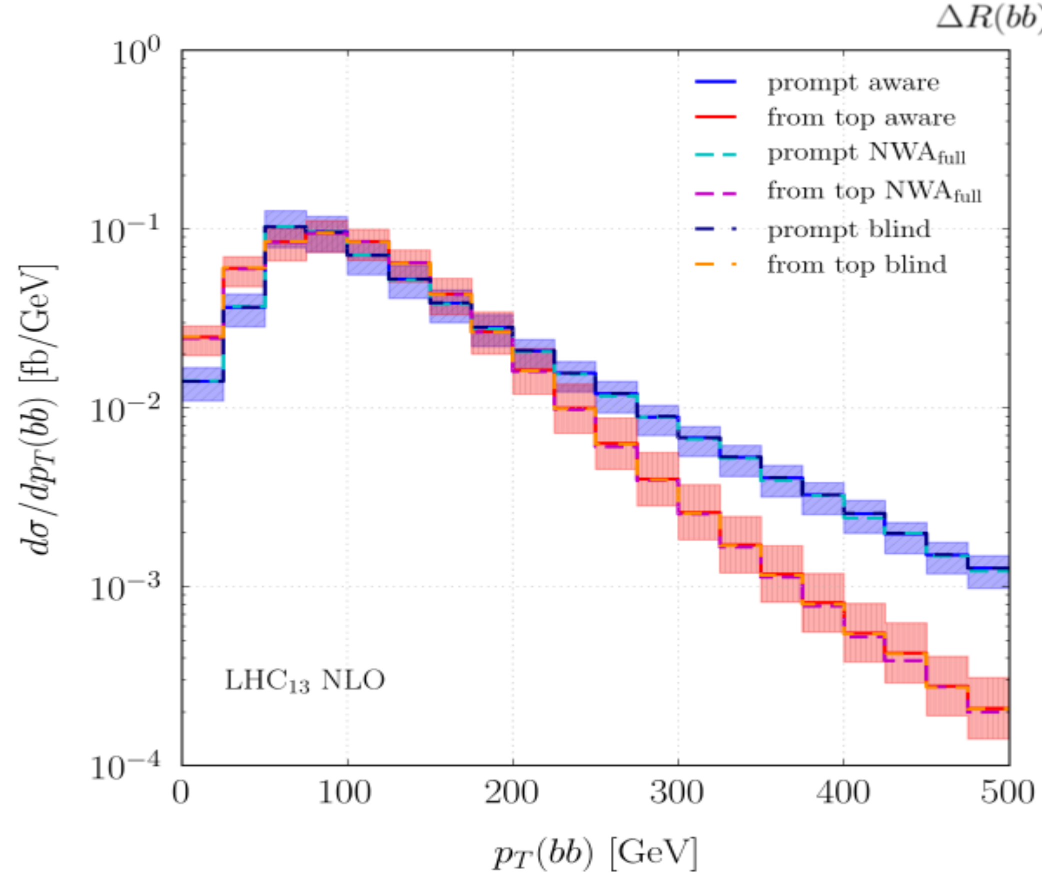
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- Kinematical differences between $b\bar{b}$ pairs belonging to prompt and non-prompt categories









Conclusions

Summary

- Fixed-order analysis of based on *off-shell* $pp \to t\bar{t}b\bar{b}$ (dilepton signatures)
  - QCD corrections are large
  - Dominant uncertainties at NLO: $\mathcal{O}(20\%)$ [scale]

- Systematic comparison with NWA at different levels of accuracy
  - Off-shell effects small for most distributions used in SM analyses: $\mathcal{O}(0.5\%)$
  - Impact of QCD corrections to top quark decays: $-7\,\%$
  - Impact of $\mathcal{O}(\alpha_s^2)$ effects in $\sigma^{\rm NLO}_{\rm NWA}$ and $\sigma^{\rm NLO}_{\rm off-shell}$: $6\,\%$ (within the scale uncertainties)

- Kinematic-based method for prompt b-jet labelling and top-quark reconstruction

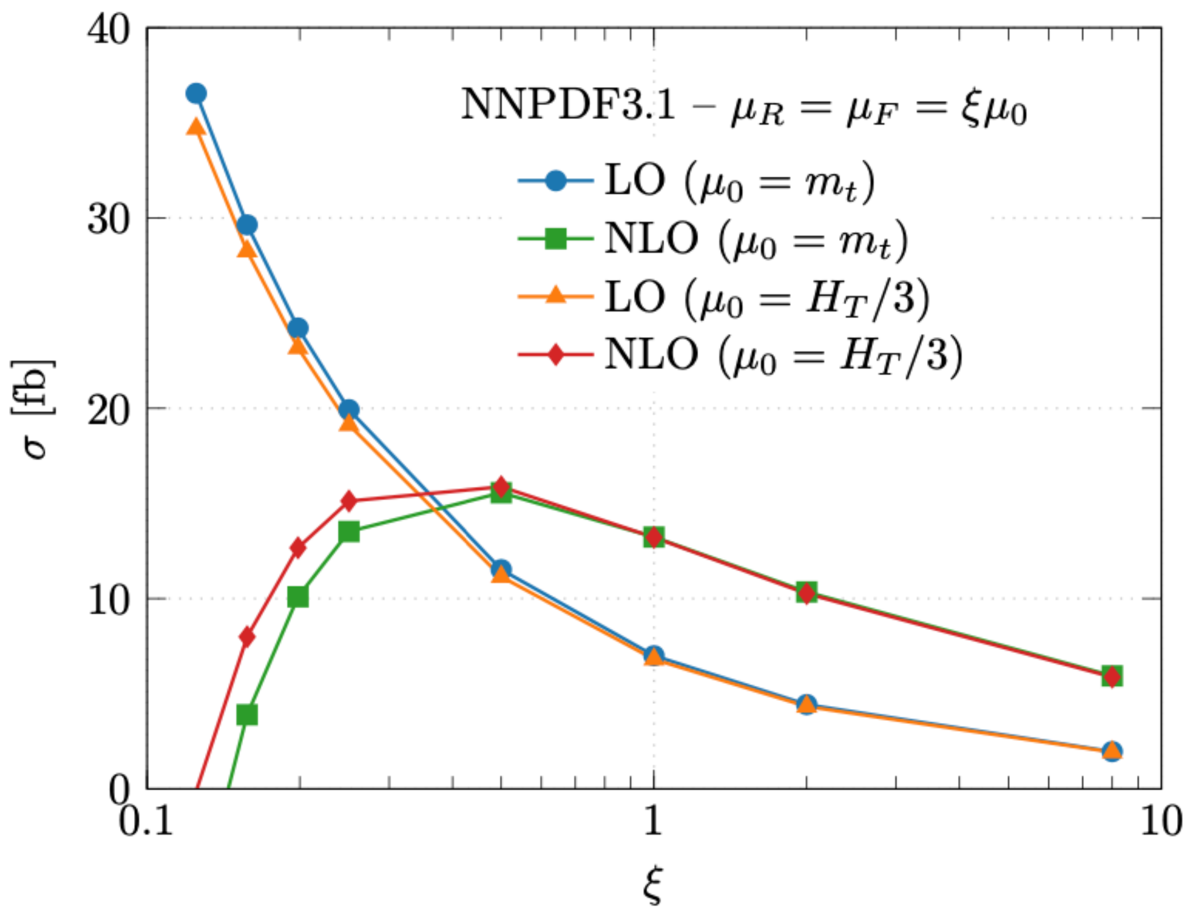
Outlook

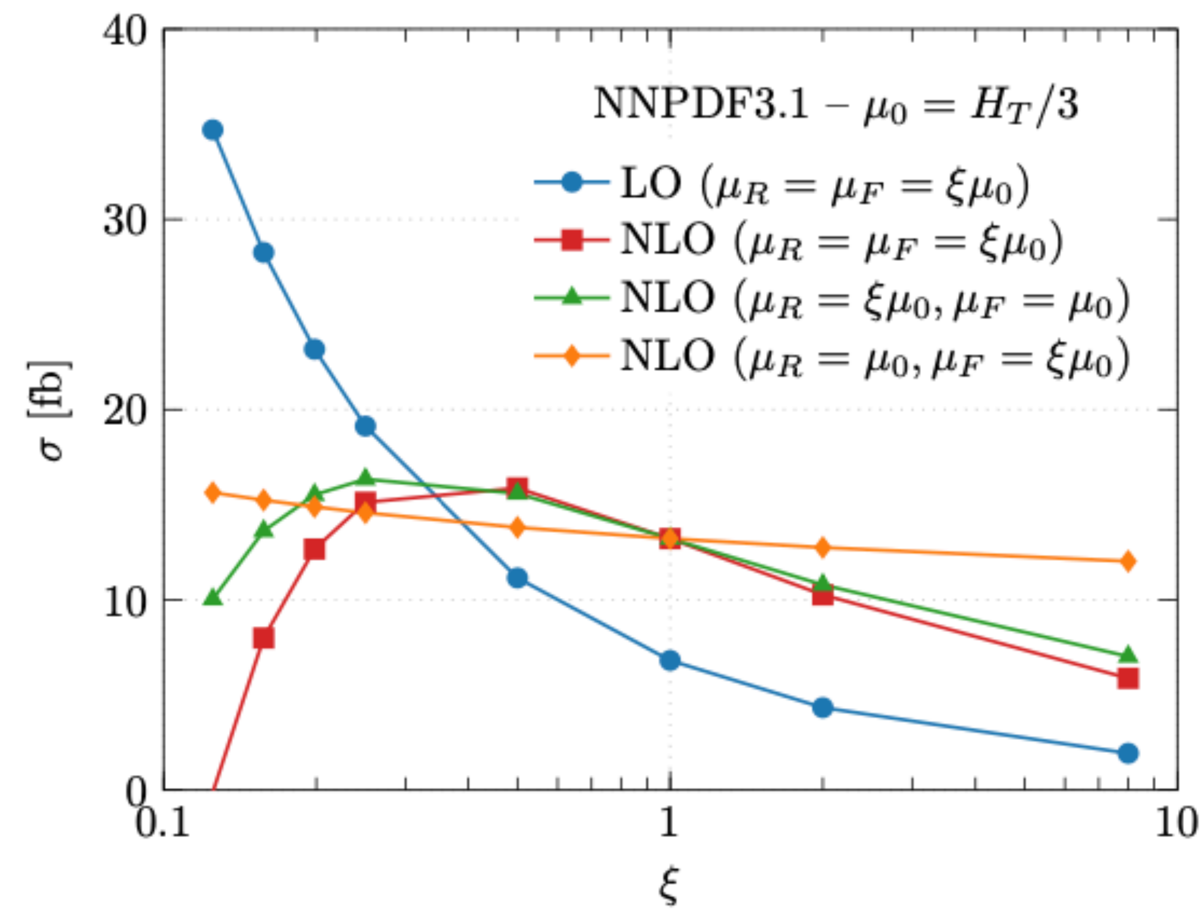
- Comparison with LHC data at differential level based on off-shell predictions

Backup slides

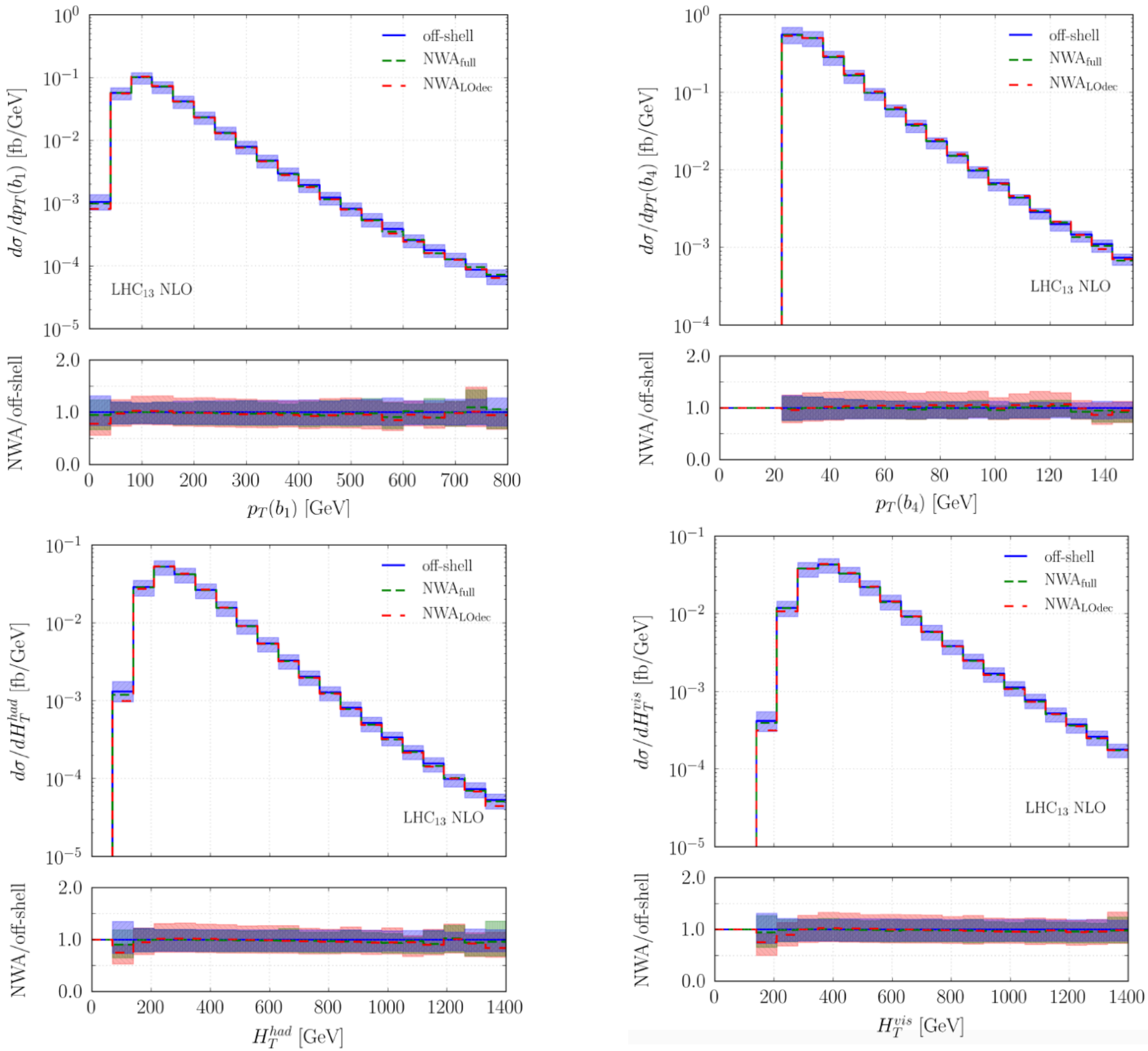
$t\bar{t}b\bar{b}$: scale dependence of the integrated cross section

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]





[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]



$$H_T^{had} = \sum_{i=1}^{4} p_T(b_i)$$

$$H_T^{vis} = H_T^{had} + \sum_{i=1}^{2} p_T(\ell_i)$$

$t\bar{t}b\bar{b}$: impact of initial-state b quark contributions

- Contributions induced by initial state b-quarks are suppressed by PDFs

- How good is the approximation of neglecting b-initiated contributions ?

Born

$$b\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}$$
$$bb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,bb$$
$$\bar{b}\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\bar{b}\bar{b}$$

Real

$$gb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,b \qquad bb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,bb\,g$$
$$g\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,\bar{b} \qquad \bar{b}\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\bar{b}\bar{b}\,g$$
$$b\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$$

- Comparing two different approaches of identifying b-jets:

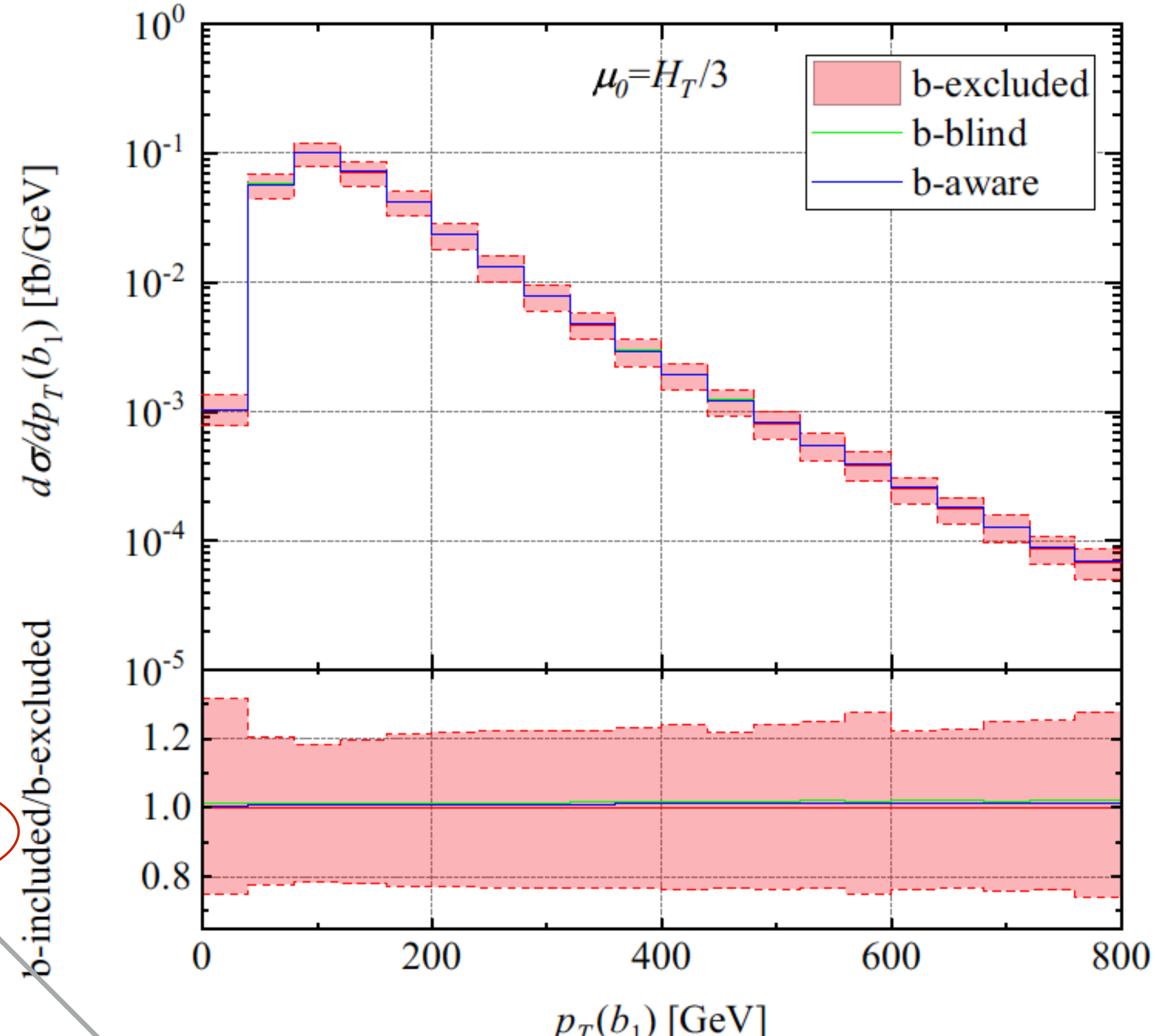
"Charge blind" vs "Charge aware" [see *e.g.* ATLAS-CONF-2018-022]

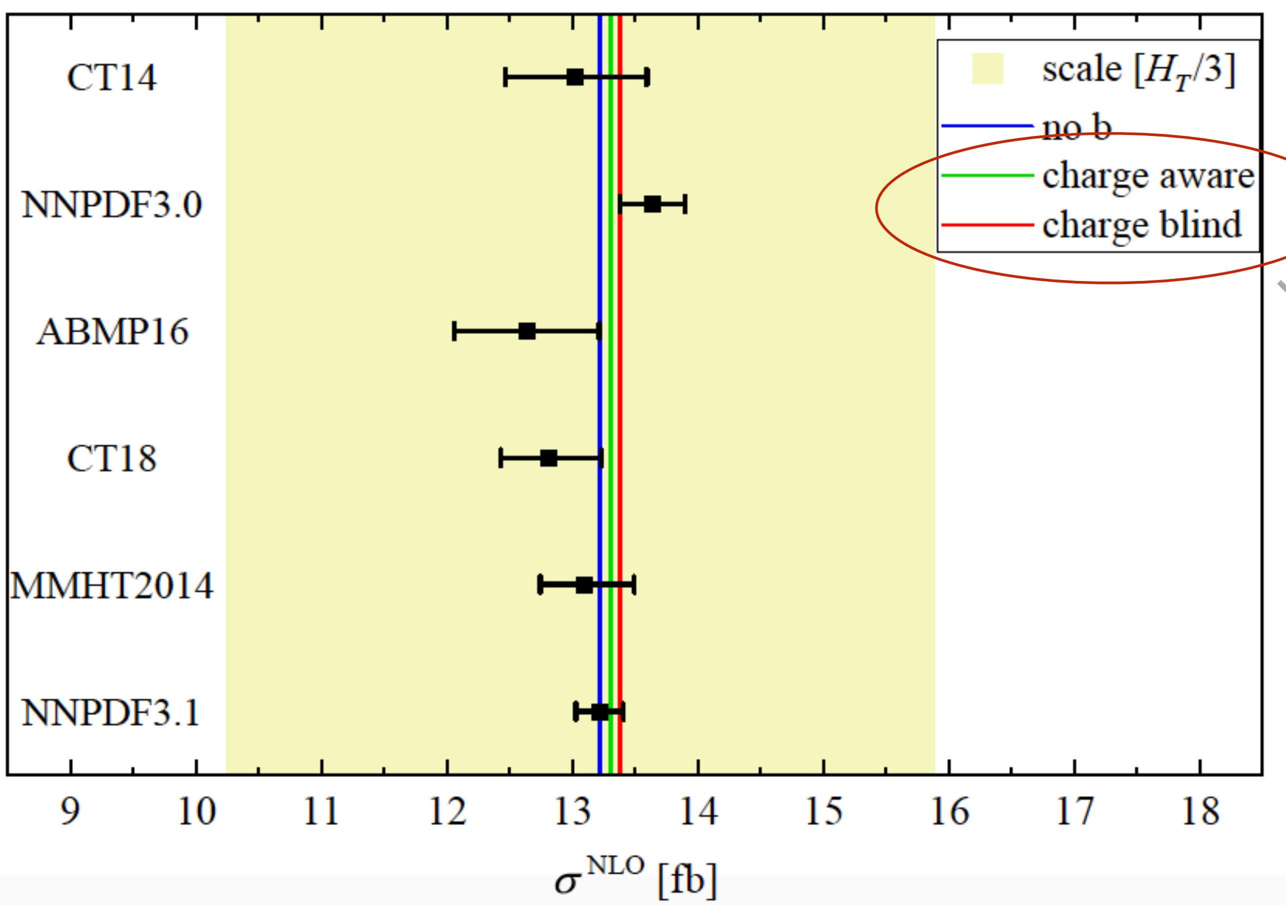
Cannot distinguish b- from $\bar{b}$-jets

Can distinguish b- from $\bar{b}$-jets

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

LO	NLO
$\sigma^{\mathrm{LO}}_{\text{no b}} = 6.813(3)$ fb	$\sigma^{\mathrm{NLO}}_{\text{no b}} = 13.22(3)$ fb
$\sigma^{\mathrm{LO}}_{\text{aware}} = 6.822(3)$ fb	$\sigma^{\mathrm{NLO}}_{\text{aware}} = 13.31(3)$ fb
$\sigma^{\mathrm{LO}}_{\text{blind}} = 6.828(3)$ fb	$\sigma^{\mathrm{NLO}}_{\text{blind}} = 13.38(3)$ fb
impact: ~0.2%	impact: ~1%





"Charge blind" vs "Charge aware"

"Charge blind": *Cannot* distinguish b- from $\bar{b}$-jets

"Charge aware": *Can* distinguish b- from $\bar{b}$-jets

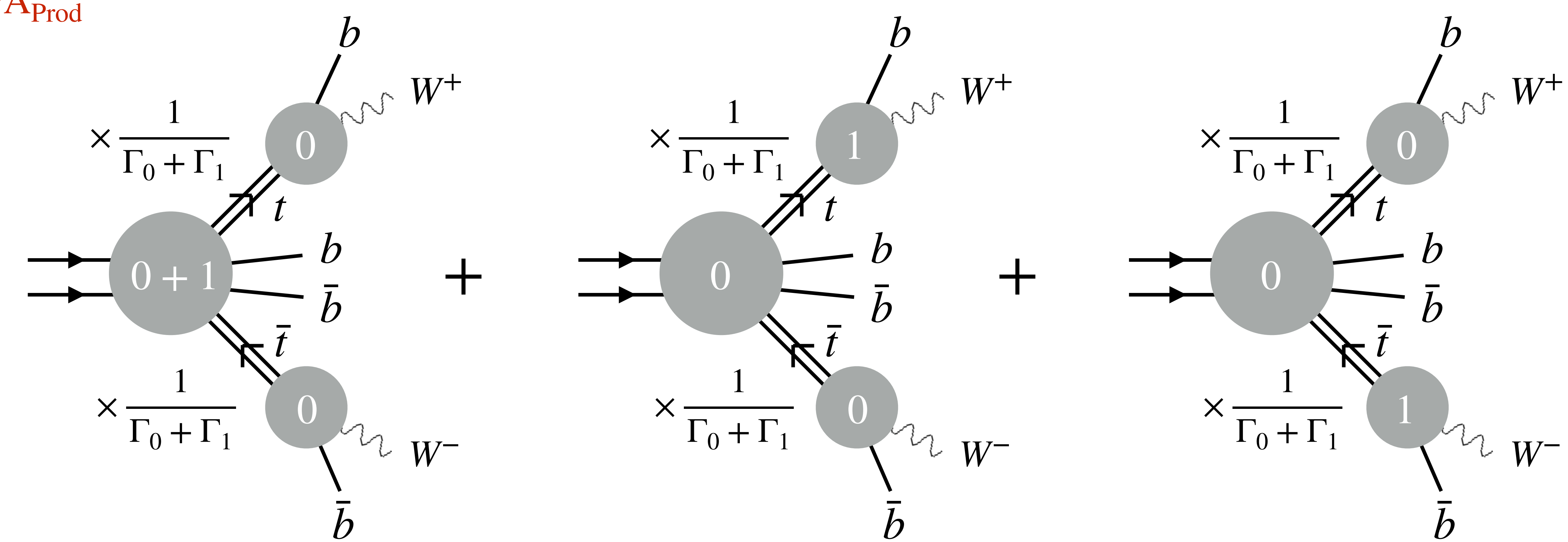
Effects of Γ_t expansion in NWA

- **"Unexpanded"** cross section in NWA:

$$\boxed{\Gamma_t^{NLO} = \Gamma_0 + \Gamma_1}$$

$\mathcal{O}(\alpha_s^0)$ $\mathcal{O}(\alpha_s)$

$d\sigma^{NLO}_{\mathrm{NWA_{Prod}}} \equiv$



- $d\sigma^{NLO}_{\mathrm{NWA_{Prod}}}$ yields the same Γ_t^{NLO} factors that are present in the full off-shell calculation

- Most suitable setup to assess the impact of genuine off-shell effects

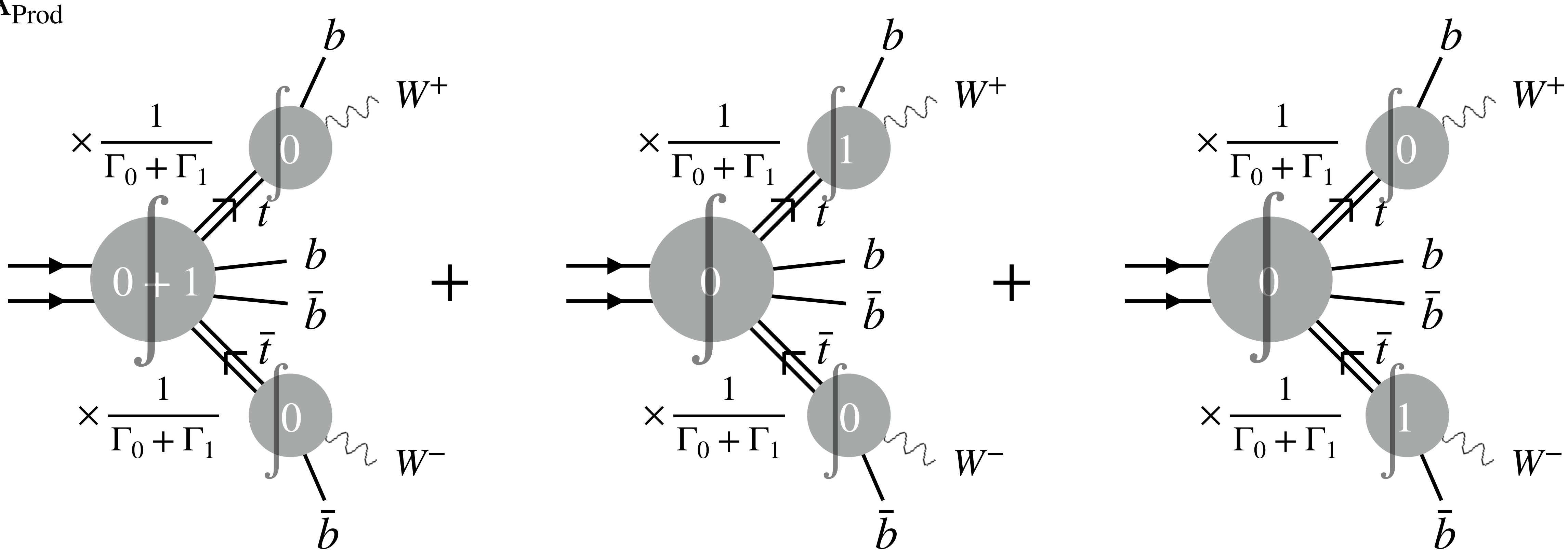
Effects of Γ_t expansion in NWA

- "Unexpanded" cross section in NWA:

$$\Gamma_t^{NLO} = \Gamma_0 + \Gamma_1$$

Γ_0: $\mathcal{O}(\alpha_s^0)$ Γ_1: $\mathcal{O}(\alpha_s)$

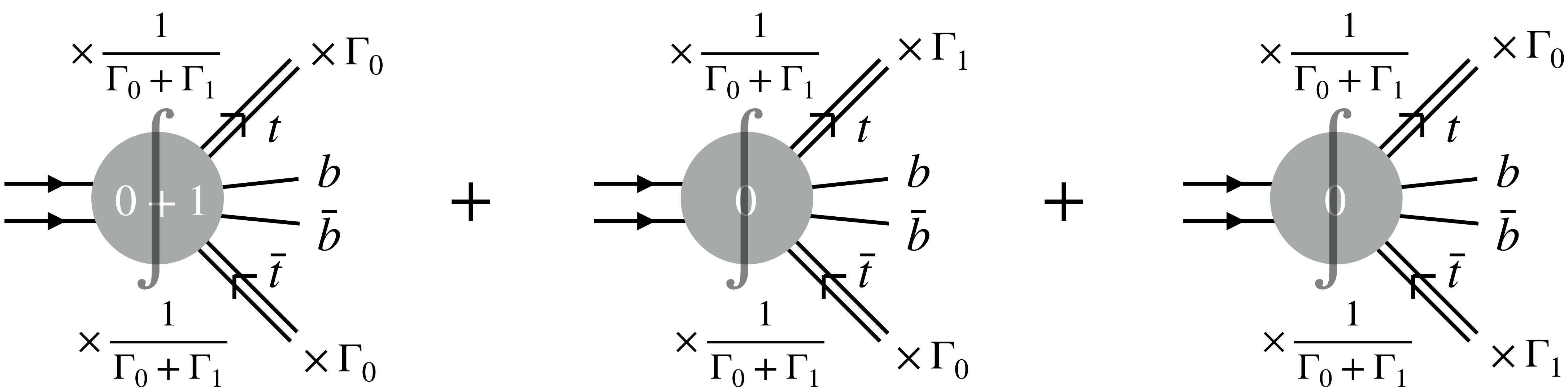
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod}}} =$$



- "Unexpanded" cross section in NWA:

$$\Gamma_t^{NLO} = \underbrace{\Gamma_0}_{\mathcal{O}(\alpha_s^0)} + \underbrace{\Gamma_1}_{\mathcal{O}(\alpha_s)}$$

$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod}}} =$$



Effects of Γ_t expansion in NWA

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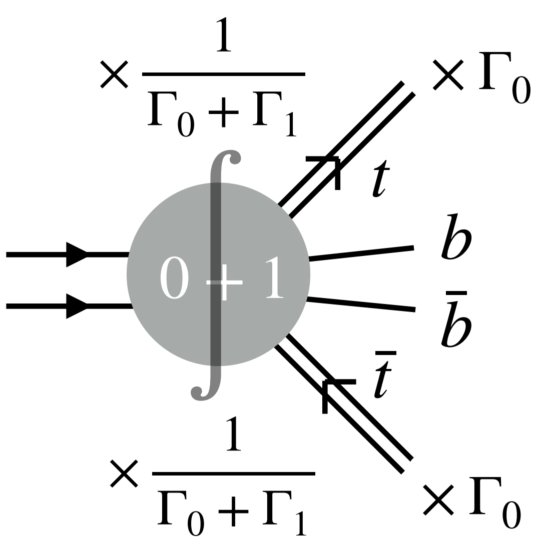

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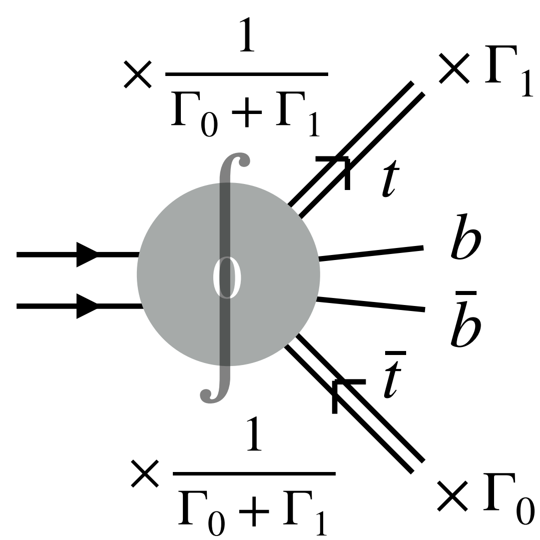

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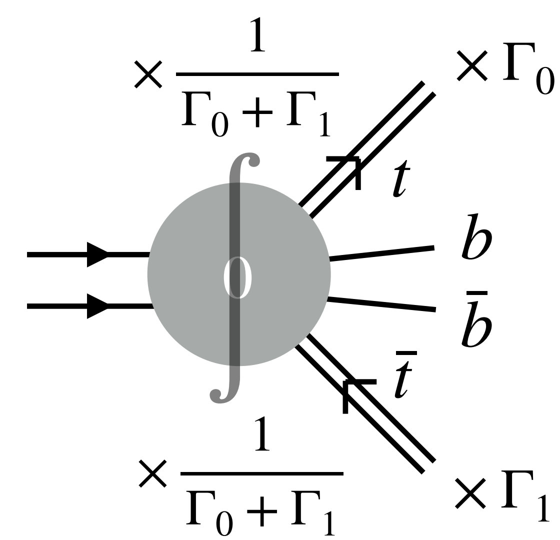

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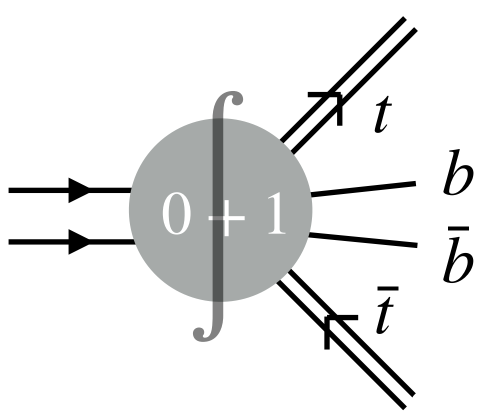


$$+ \ \mathcal{O}(\alpha_s^2) \quad = \quad \sigma^{NLO}_{t\bar{t}b\bar{b},\, incl.} + \ \mathcal{O}(\alpha_s^2)$$

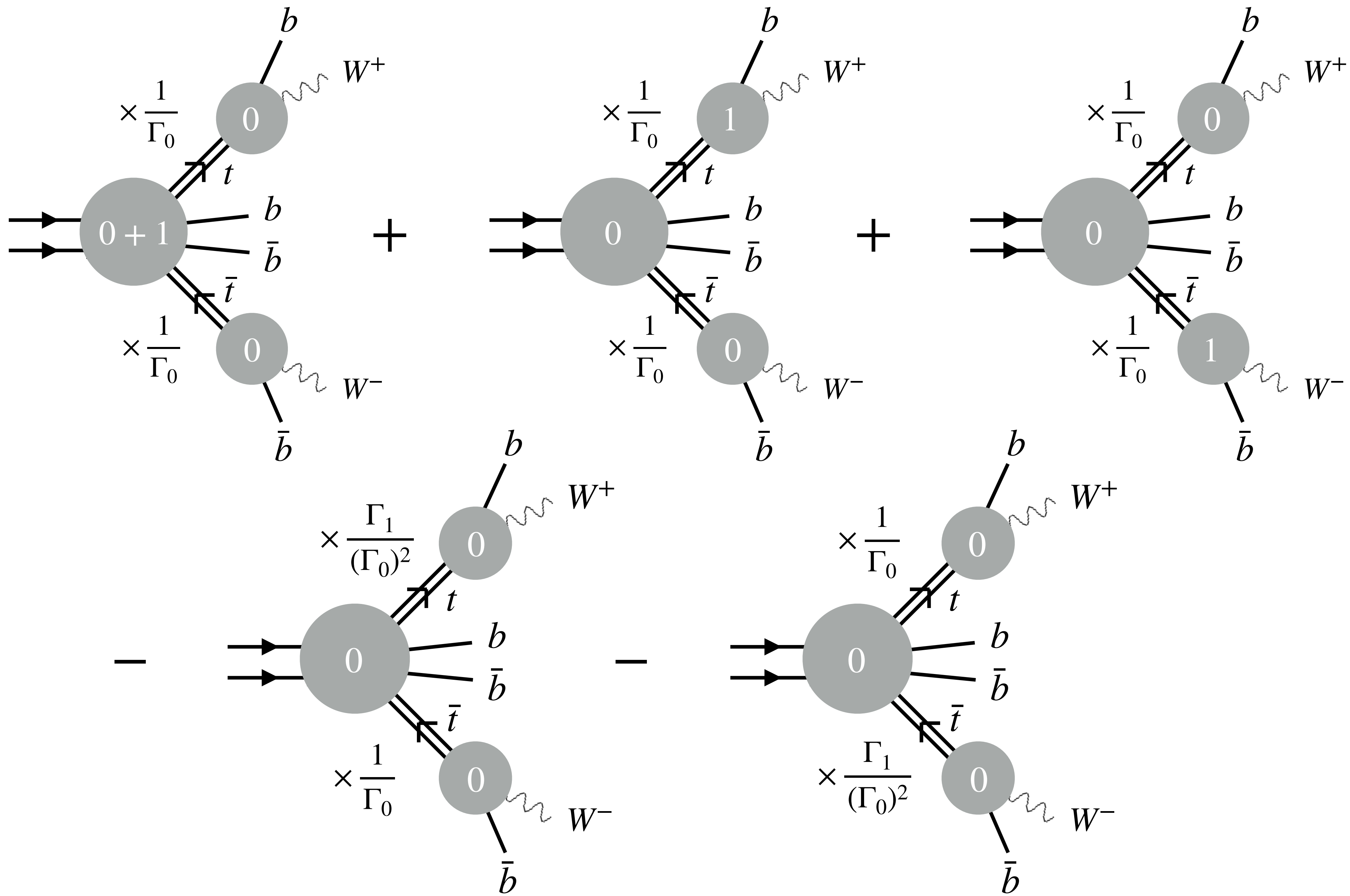
- Rigorous factorization at NLO spoiled by *formally suppressed $\mathcal{O}(\alpha_s^2)$ terms*.

Effects of Γ_t expansion in NWA

- ”**Expanded**” cross section in NWA:

$$\frac{1}{\Gamma_0 + \Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)$$

$$d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,\,exp}}} \equiv$$

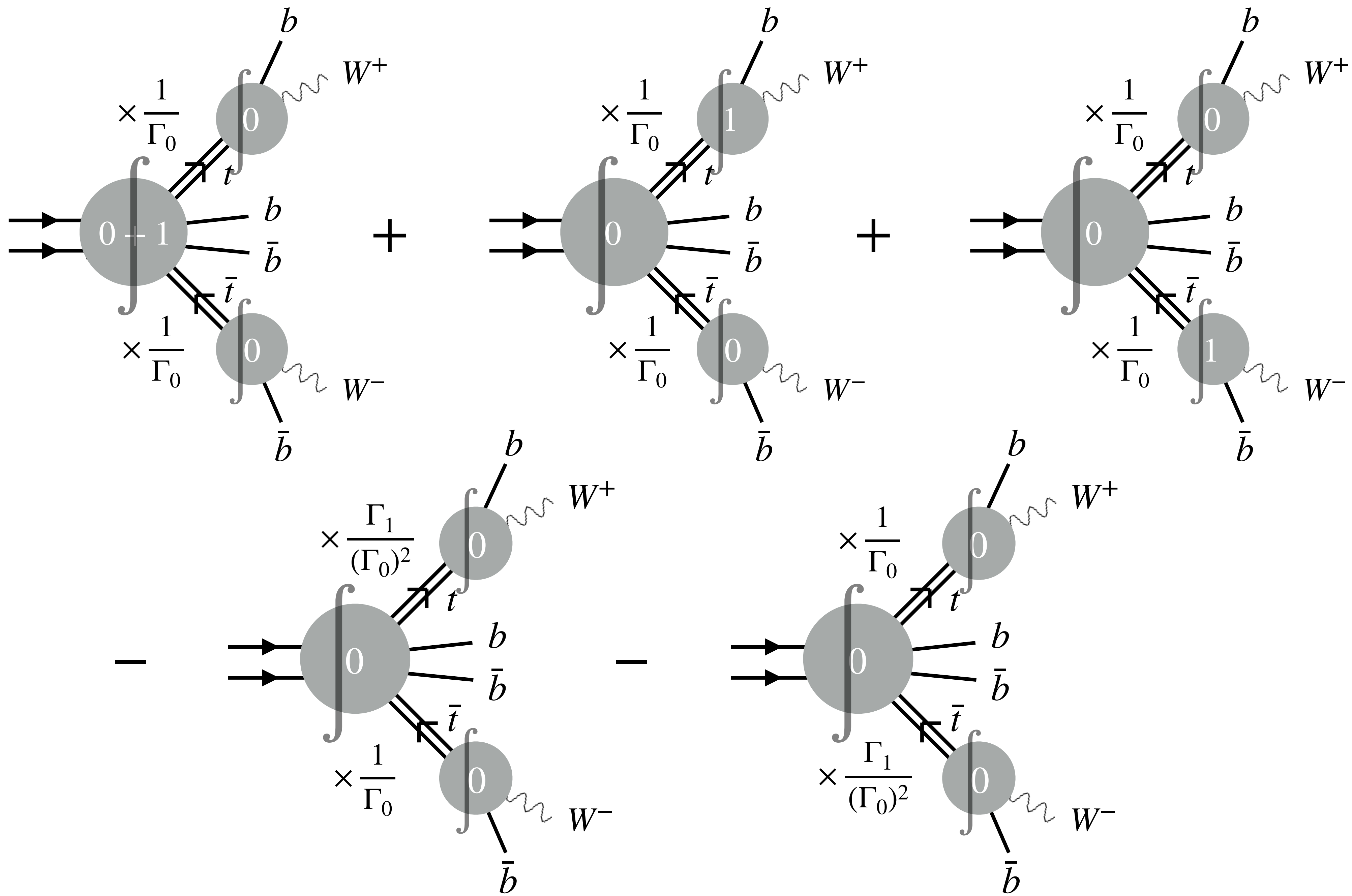


Effects of Γ_t expansion in NWA

- "Expanded" cross section in NWA:

$$\boxed{\frac{1}{\Gamma_0 + \Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)}$$

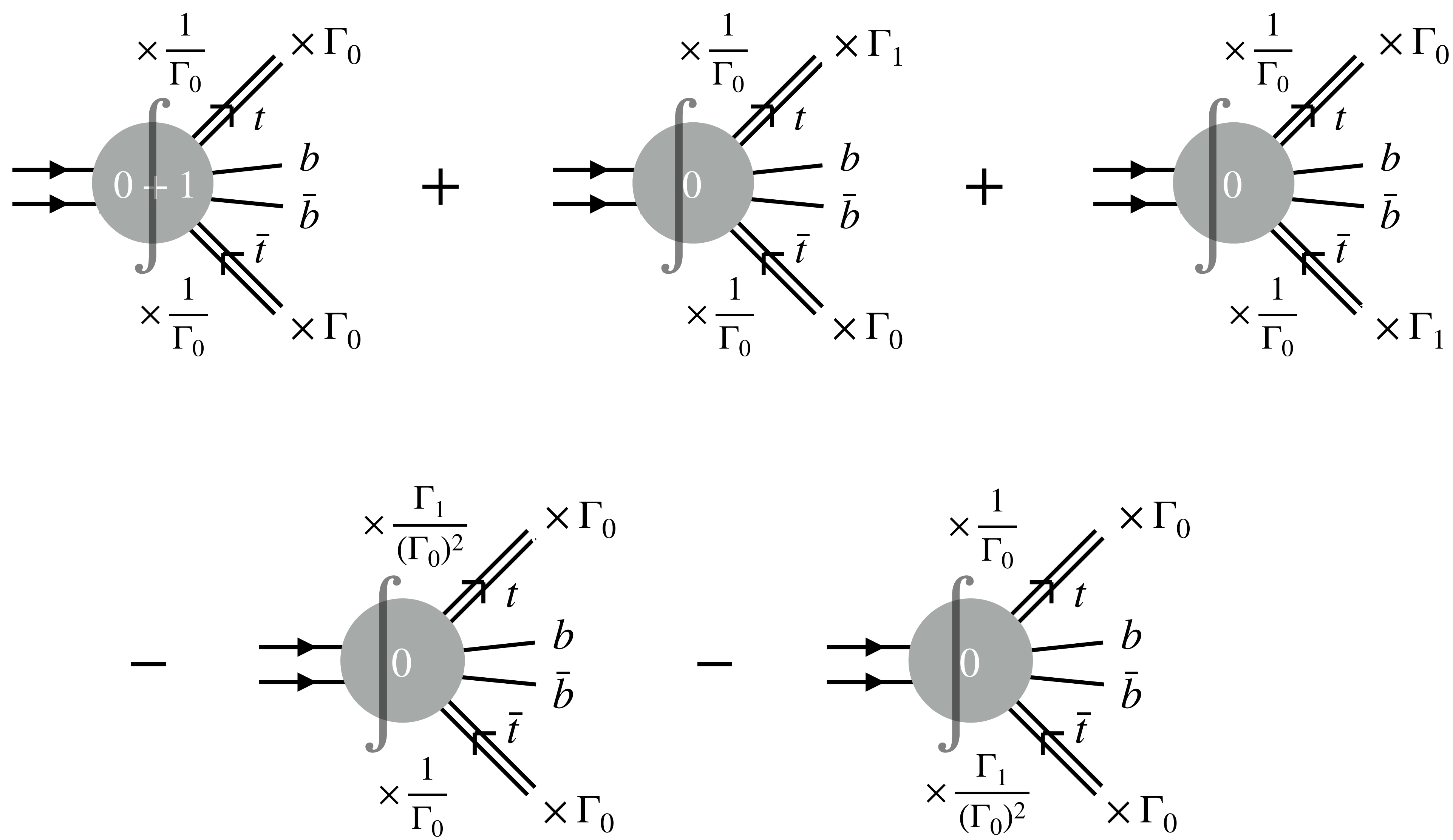
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



- "Expanded" cross section in NWA:

$$\boxed{\frac{1}{\Gamma_0+\Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)}$$

$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$

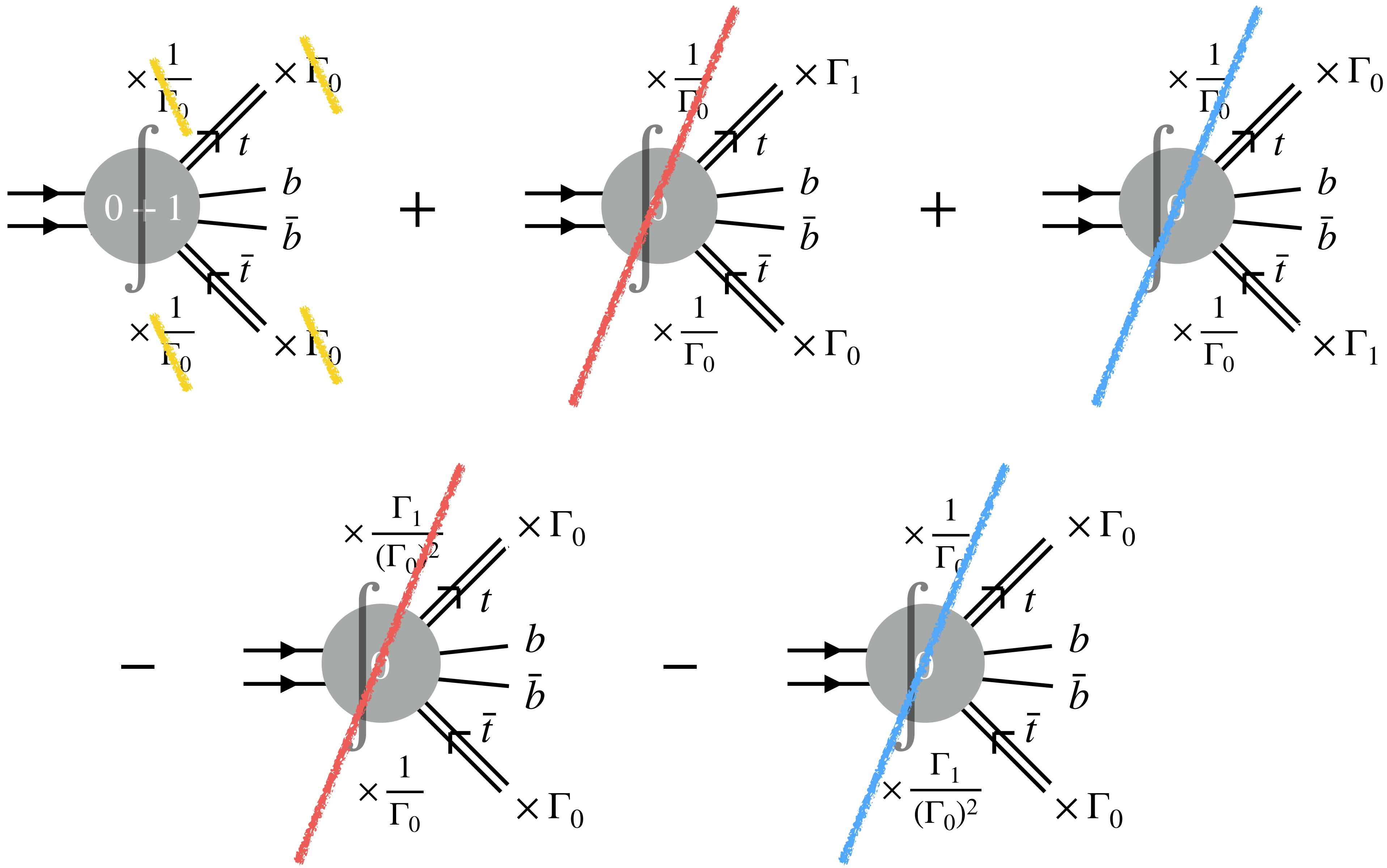


Effects of Γ_t expansion in NWA

- "Expanded" cross section in NWA:

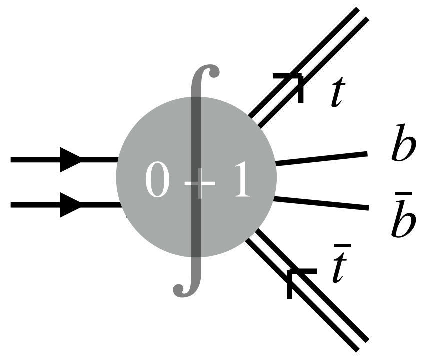
$$\boxed{\frac{1}{\Gamma_0 + \Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)}$$

$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod\,,exp}}} =$$



- Rigorous expansion of Γ_t^{NLO} in NWA gets rid of "spurious" $\mathcal{O}(\alpha_s^2)$ contributions
- Note: the same procedure does not apply straightforwardly to the off-shell calculation

$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



$$\equiv \quad \sigma^{\mathrm{NLO}}_{t\bar{t}b\bar{b},\,\mathrm{incl.}}$$

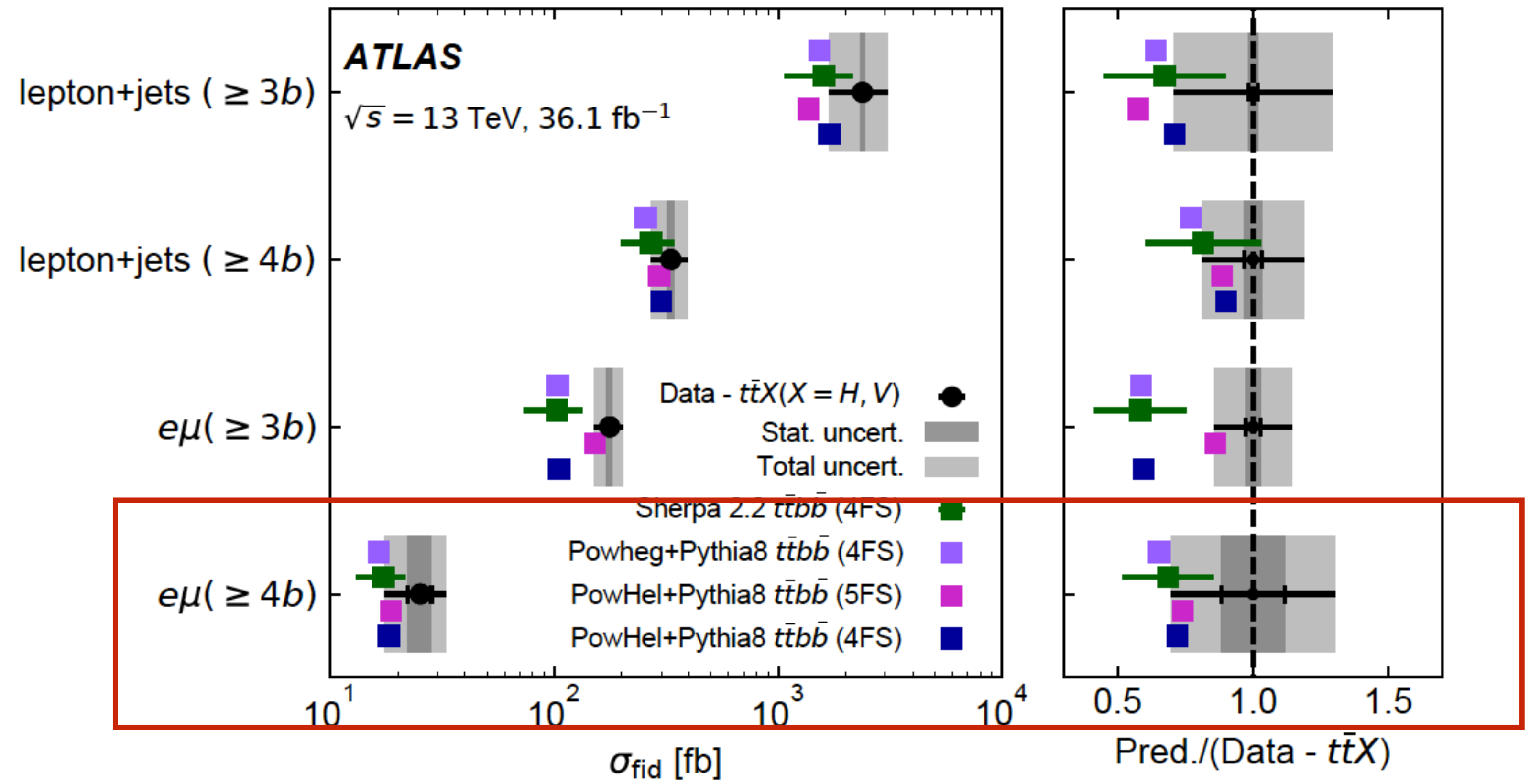
- The unusually large size of $\mathcal{O}(\alpha_s^2)$ effects, $\mathcal{O}(6\%)$, relates to the large size of QCD corrections to $t\bar{t}b\bar{b}$ production cross section

- These effects are well within the NLO scale uncertainties, $\mathcal{O}(20\%)$

$t\bar{t}b\bar{b}$: comparison with ATLAS analysis JHEP 04 (2019) 046

ATLAS cuts:

$$p_T(\ell) > 25 \text{ GeV}\,, \quad p_T(b) > 25 \text{ GeV}\,,$$
$$|y(\ell)| < 2.5\,, \quad |y(b)| < 2.5\,,$$
$$\Delta R(bb) > 0.4\,, \quad \Delta R(\ell b) > 0.4\,,$$



[ATLAS, JHEP 04 (2019) 046]

Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
SHERPA+OPENLOOPS (4FS)	17.2 ± 4.2
POWHEG-BOX+PYTHIA 8 (4FS)	16.5
POWHEL+PYTHIA 8 (5FS)	18.7
POWHEL+PYTHIA 8 (4FS)	18.2
Experimental result (ATLAS)	25 ± 6.5

[GB et al, JHEP 08 (2021) 008]

HELAC-NLO (5FS): 20.0 ± 4.3 fb