Full off-shell predictions for $t\bar{t}b\bar{b}$ at NLO in QCD

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Modelling of the ttbb process at the LHC in light of ttH measurements
The LHC Higgs XS WG (ttH/tH)

Online meeting
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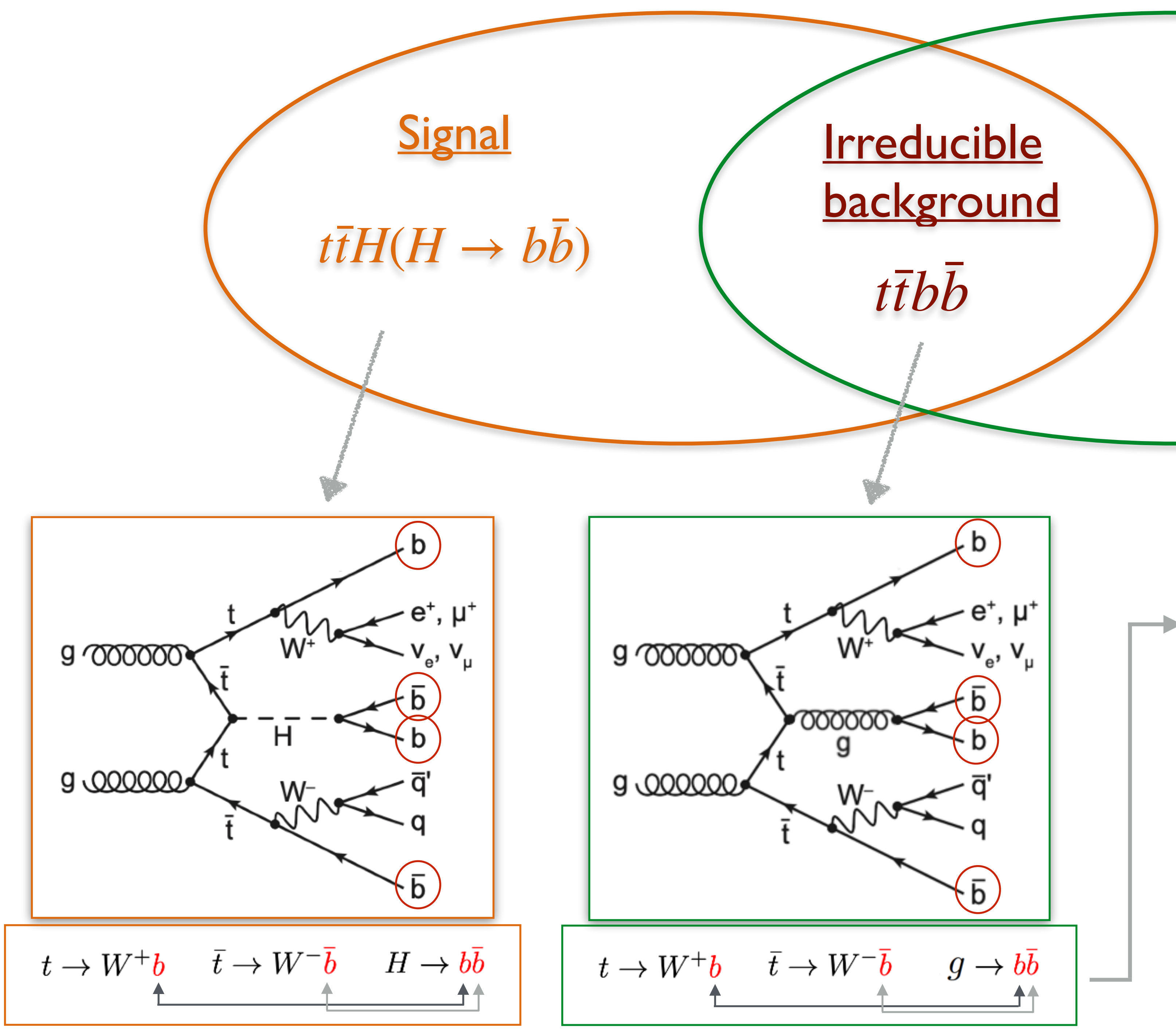
Based on:

JHEP 08 (2021) 008 - *Phys. Rev. D 104 (2021) 5, 056018* - *JHEP 02 (2022) 196* - *2202.11186 [hep-ph]*

Motivation: $t\bar{t}H(H \to b\bar{b})$ at the LHC

- $pp \to t\bar{t}H$: probes top Yukawa coupling at tree level; $H \to b\bar{b}$: largest BR ($\sim 58\%$)
- Experimental and theoretical challenges

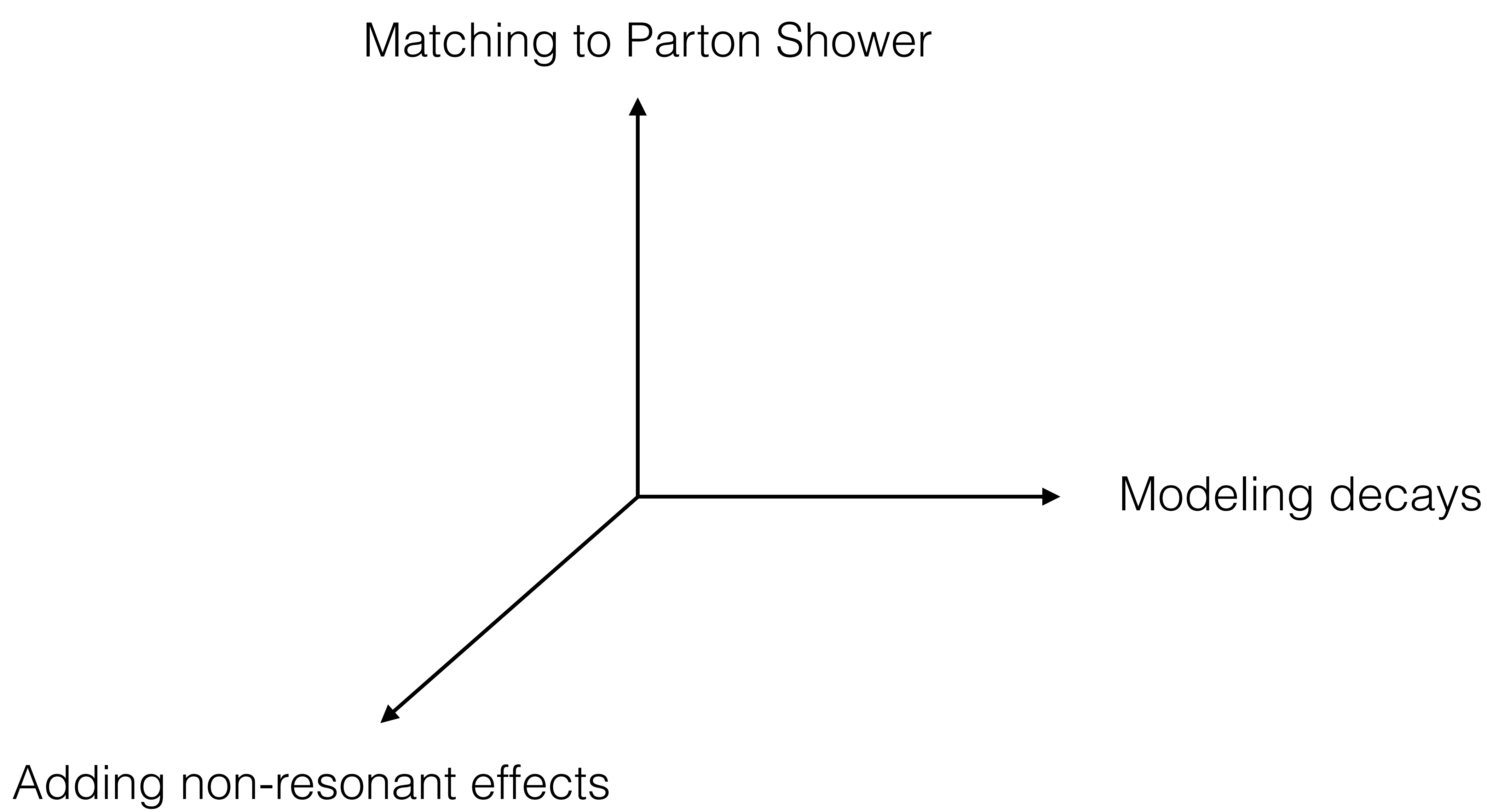


Combinatorial background:

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

Paths to precision

- Realistic **final states** => incorporate decays and Parton Shower
- Realistic **resonant structures** => incorporate "off-shell" contributions into ME



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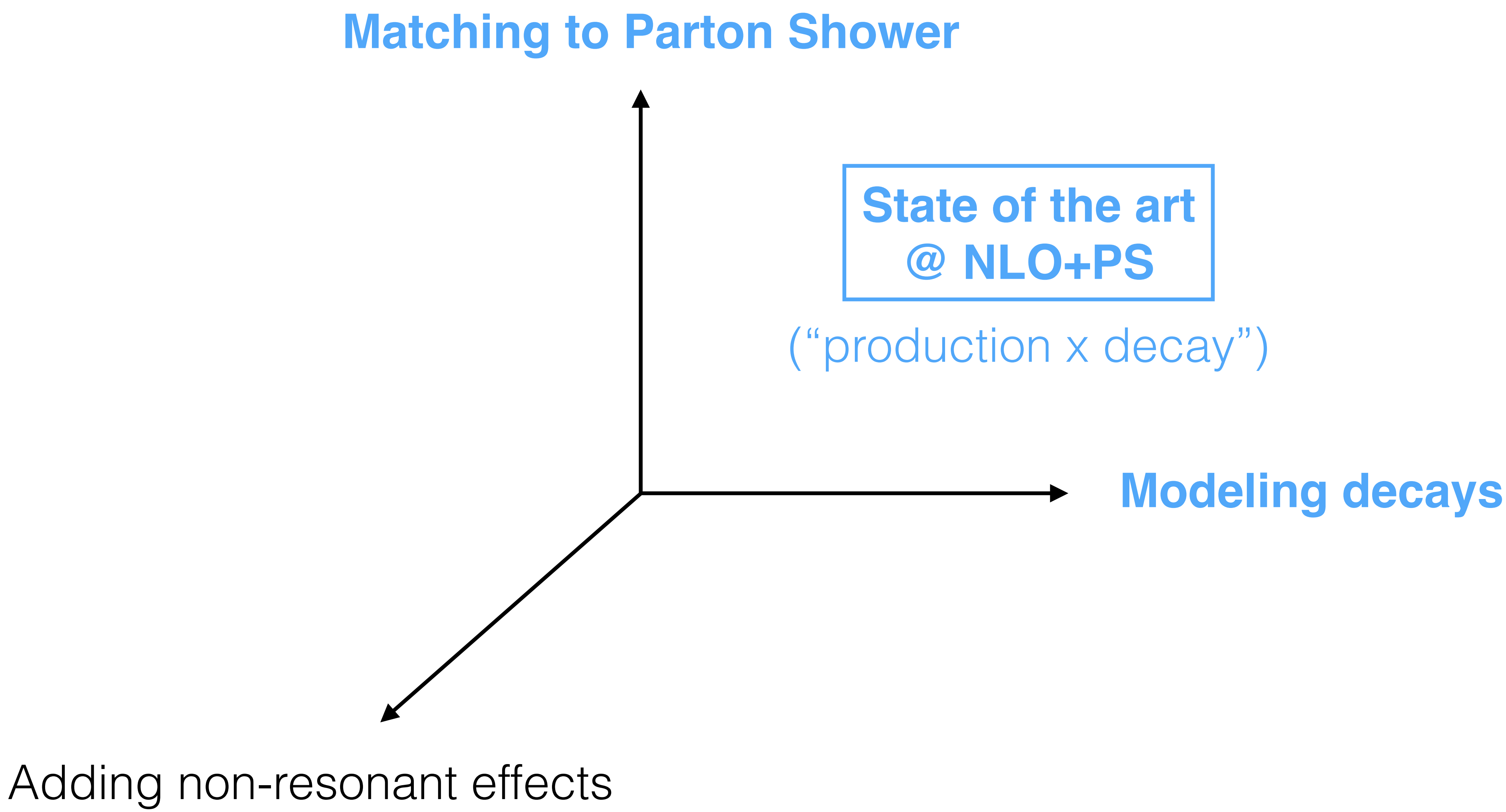

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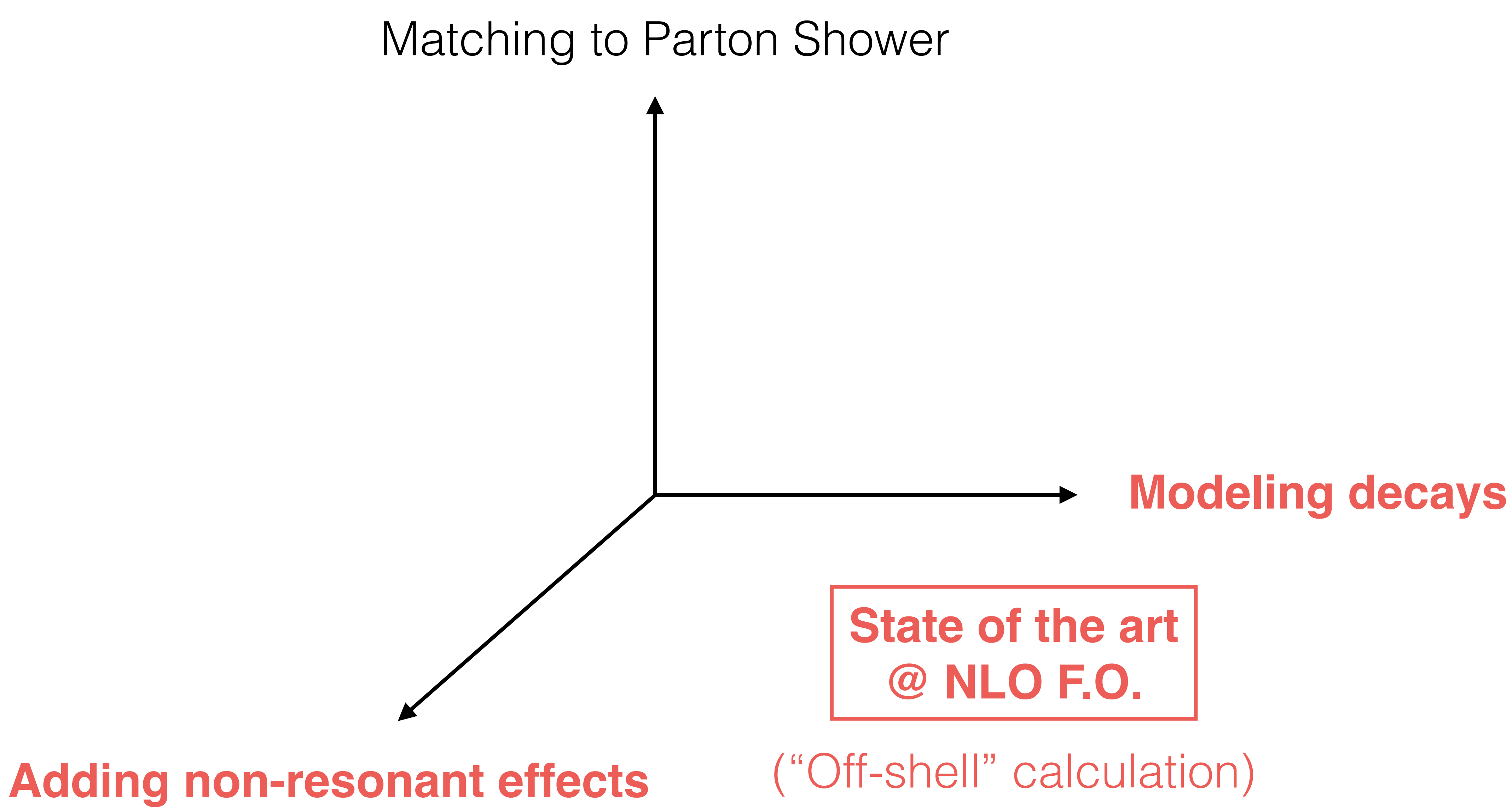

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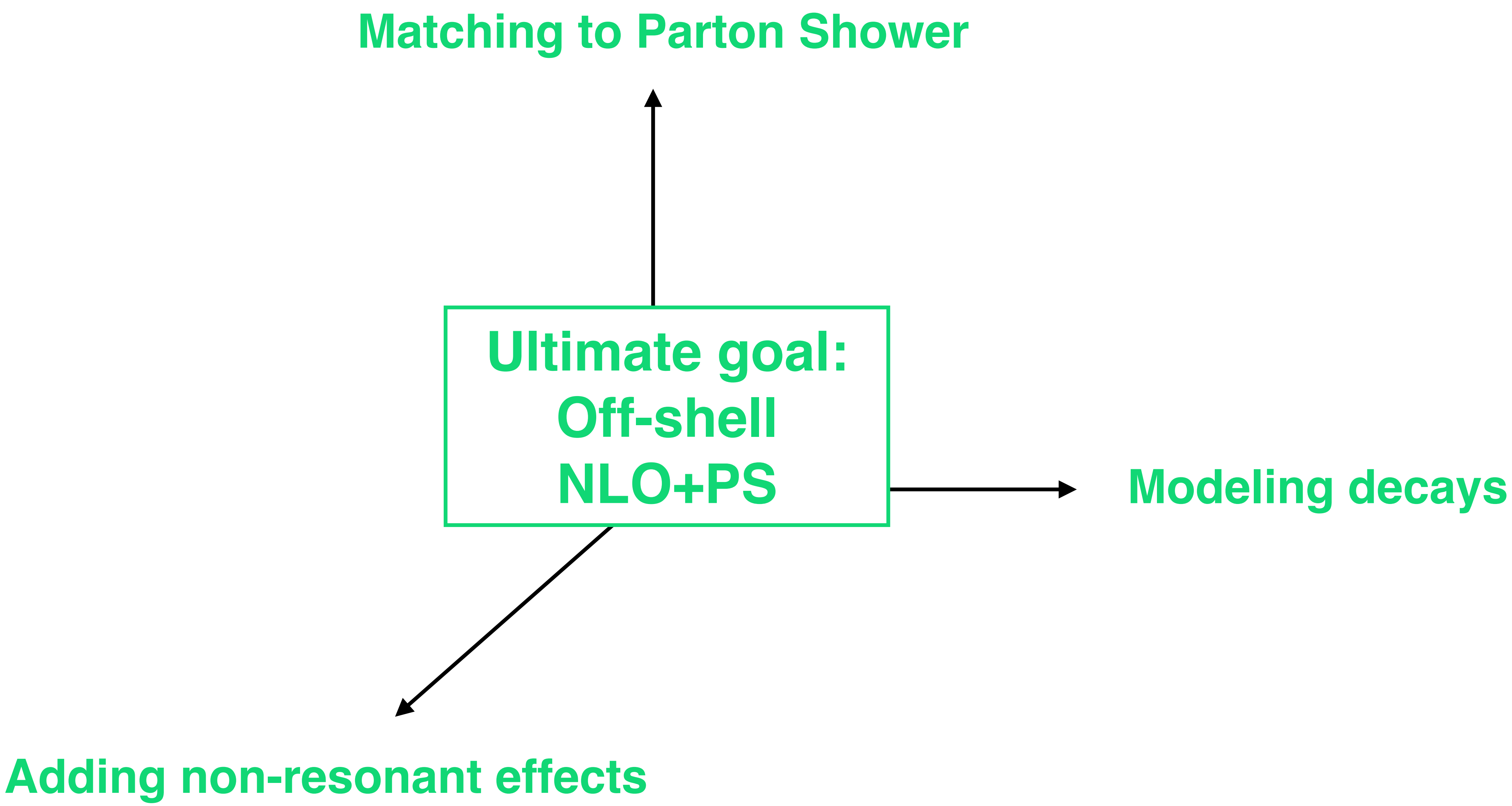

Theory status of $t\bar{t}H$ & $t\bar{t}b\bar{b}$

$t\bar{t}H$

State of the art: NLO (QCD + EW) + NNLL

[*first steps towards NNLO QCD: $gq/qq/qq'/q\bar{q}' \to t\bar{t}H$ [Catani et al. '21]]

Parton level

- $pp \to t\bar{t}H$ — Beenakker et al. '01'02; Reina, Dawson '01; Dawson et al. '02 '03; Martin, Moch, Saibel '21; Frixione et al. '14 '15; Zhang et al. '14; Frederix et al. '18; Kulesza et al. '15 '17 '20; Broggio et al. '15 '16 '19
- $pp \to e^+\nu_e\,\mu^-\nu_\mu\,b\bar{b}\,H$ — Denner, Feger '15; Denner, Lang, Pellen, Uccirati '17
- $pp \to e^+\nu_e\,\mu^-\nu_\mu\,b\bar{b}\,H\ (H \to X)$, $X = \{b\bar{b},\ \gamma\gamma,\ \tau^+\tau^-,\ e^+e^-e^+e^-\}$ — Stremmer, Worek '21; Hermann, Stremmer, Worek '22

Particle level

- POWHEG matching $pp \to t\bar{t}H$ — Garzelli, Kardos, Papadopoulos, Trocsanyi '11; Hartanto, Jäger, Reina, Wackeroth '15
- MC@NLO matching $pp \to t\bar{t}H$ — Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli '11; Maltoni, Pagani, Tsinikos '15

$t\bar{t}b\bar{b}$

State of the art: NLO QCD

Parton level

- $pp \to t\bar{t}b\bar{b}$ — Bredenstein, Denner, Dittmaier, Pozzorini '08 '09 '10; GB, Czakon, Papadopoulos, Pittau, Worek '09
- $pp \to t\bar{t}b\bar{b}j$ — Buccioni, Kallweit, Pozzorini, Zoller '19
- $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ — Denner, Lang, Pellen '20; GB, Bi, Hartanto, Kraus, Lupattelli, Worek '21 '22

Particle level

- 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]

Theory status of $t\bar{t}H$ & $t\bar{t}b\bar{b}$

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- MC@NLO matching — Cascioli, Maierhofer, Moretti, Pozzorini, Siegert '14 [4FS]

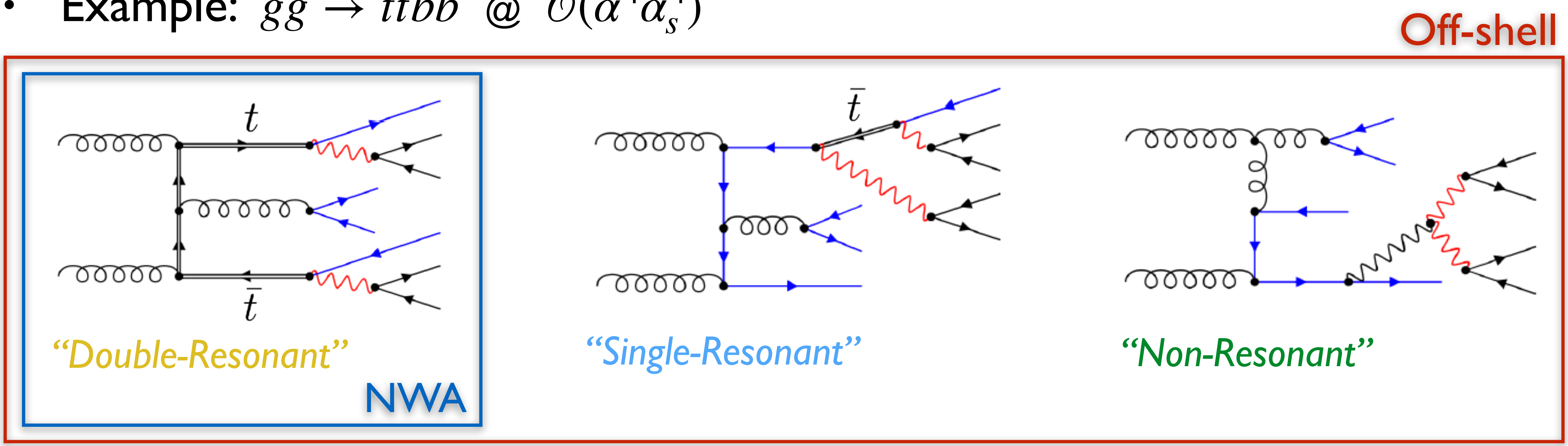
Focus: recent developments on off-shell calculations

- Complete matrix elements at fixed perturbative order:

  ↪ - release limit $\Gamma_t / m_t \to 0$ [Narrow Width Approximation]

  - include non-factorizable contributions

- Example: $gg \to t\bar{t}b\bar{b}$ @ $\mathcal{O}(\alpha^4 \alpha_s^4)$



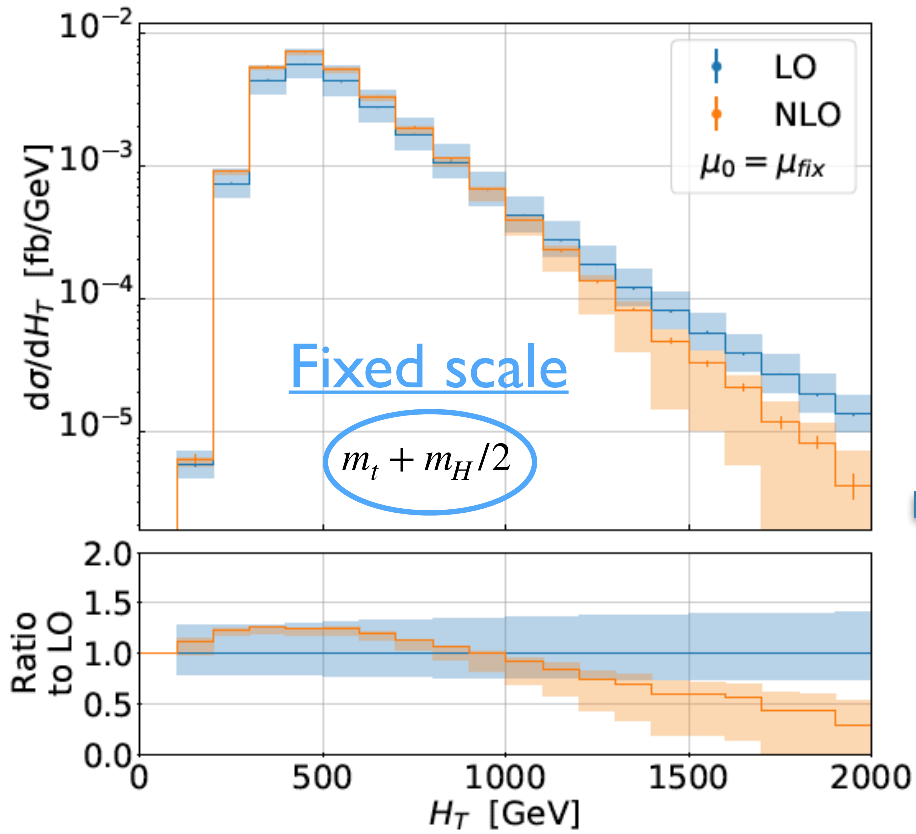
"Off-shell" = DR + SR + NR + interferences + Breit-Wigner effects

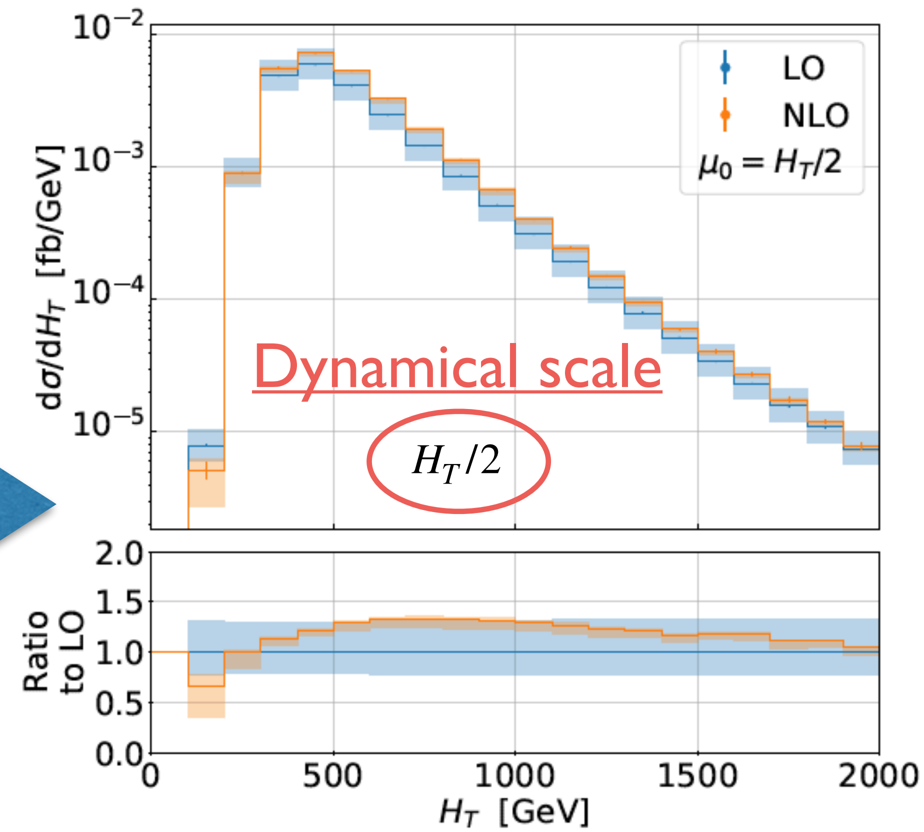
- Genuine *multiscale* process

I. Production of Higgs boson in association with $t\bar{t}$

[Stremmer and Worek, JHEP 02 (2022) 196]

- Impact of scale choice and theory uncertainties





$$p_{T,b} > 25\,\text{GeV}\,, \quad |y_b| < 2.5\,,$$
$$p_{T,\ell} > 20\,\text{GeV}\,, \quad |y_\ell| < 2.5\,,$$
$$p_{T,\text{miss}} > 20\,\text{GeV}$$

$$H_T = p_{T,b_1} + p_{T,b_2} + p_{T,e^+} + p_{T,\mu^-} + p_{T,\text{miss}} + p_{T,H}$$

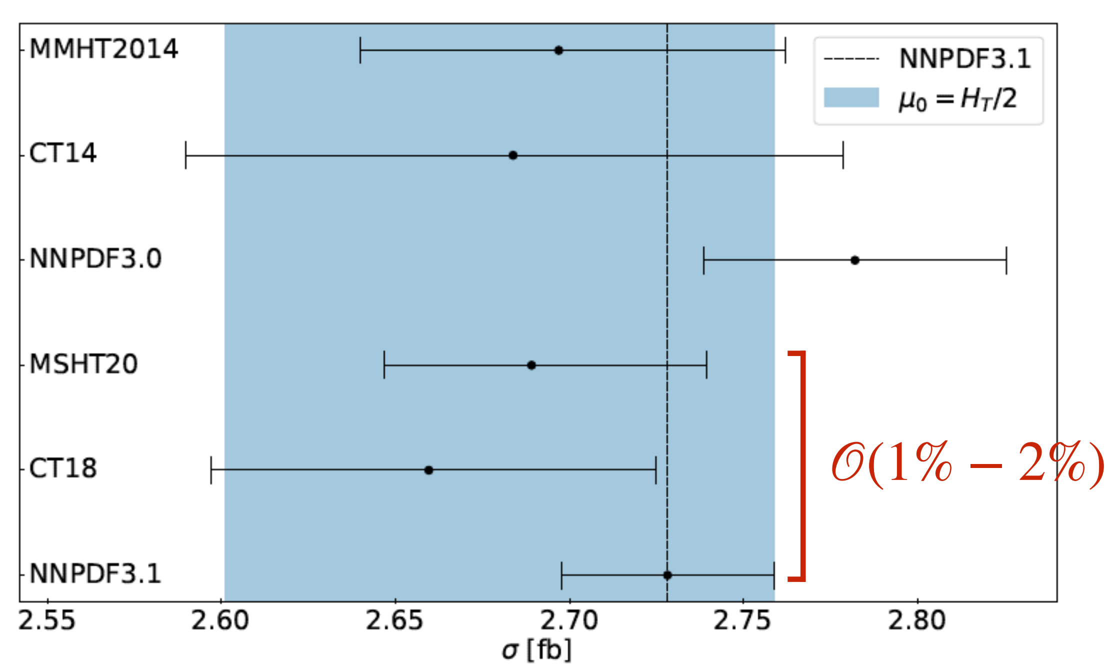
Fiducial cross sections

μ_0 [NNPDF3.1]	σ_{LO} [fb]	σ_{NLO} [fb]
$H_T/2$	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$
μ_{fix}	$2.3005(2)^{+30.8\%}_{-21.9\%}$	$2.731(2)^{+0.6\%}_{-5.4\%}$

scale uncertainties

- $H_T/2 \to$ K-factor = 1.23

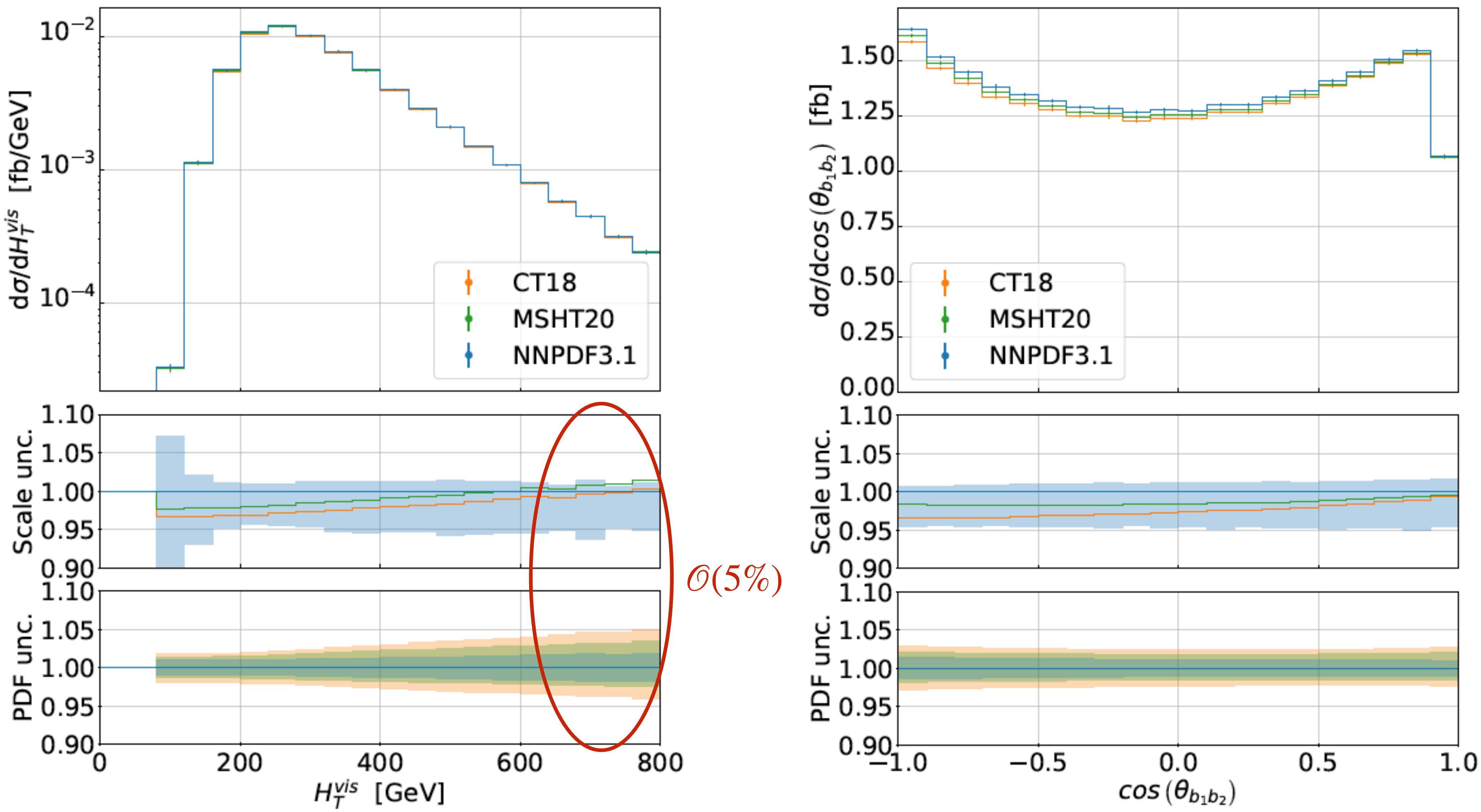
Scale vs PDF uncertainties



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

[Stremmer and Worek, JHEP 02 (2022) 196]

- Scale vs PDF uncertainties at differential level



- PDF uncertainties smaller than scale dependence at the bulk, but comparable in high-energy tails of dimensionful observables

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

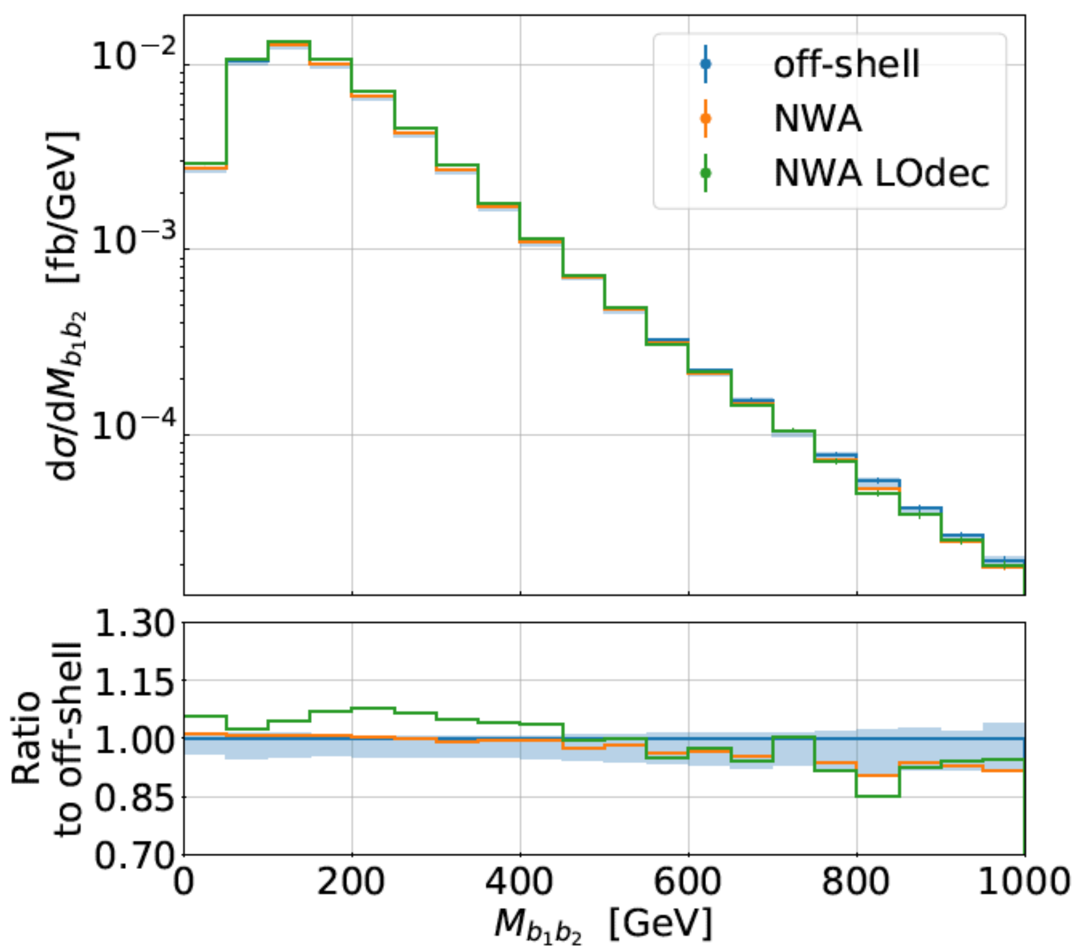
[Stremmer and Worek, JHEP 02 (2022) 196]

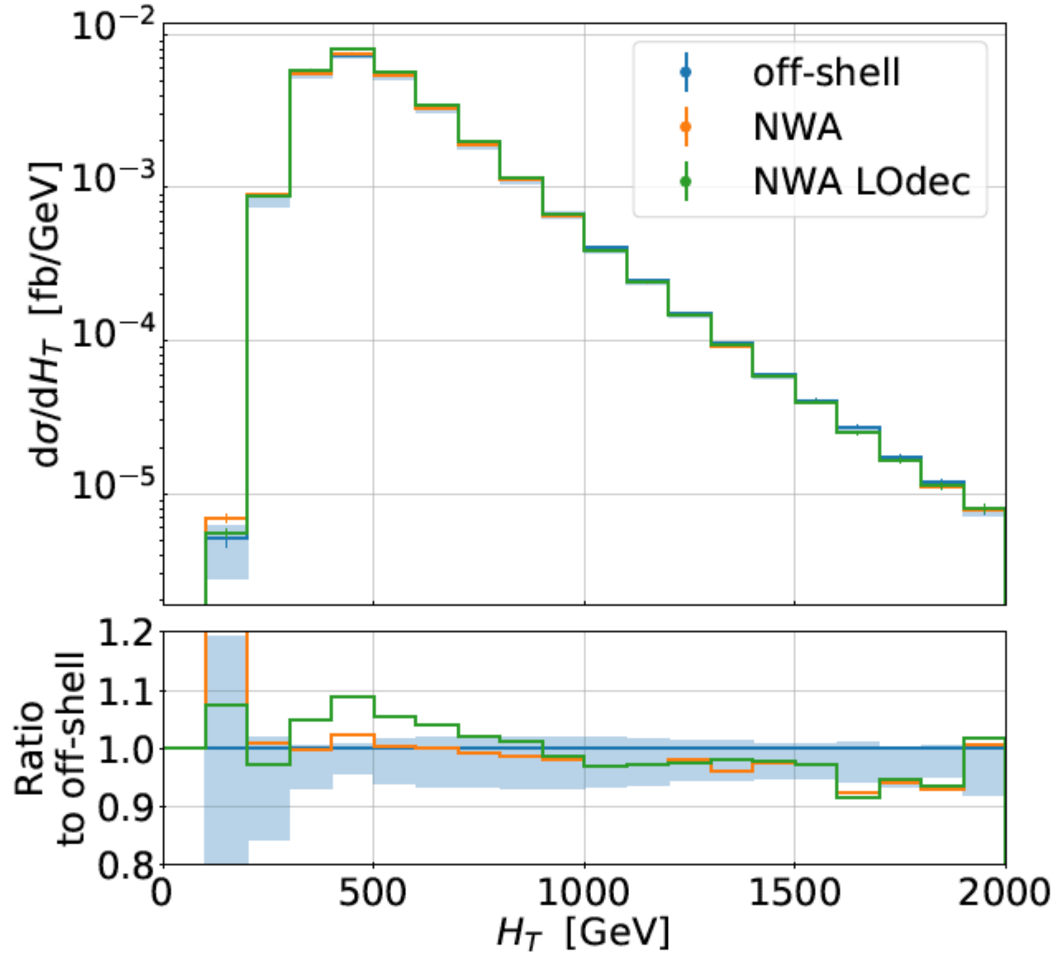
- Off-shell effects for top-quark and W decays

Modelling	μ_0	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]
full off-shell	$H_T/2$	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$
NWA	$H_T/2$	$2.2235(2)^{+30.1\%}_{-21.6\%}$	$2.738(1)^{-3.0\%}_{-4.7\%}$
$\rm NWA_{LOdec}$	$H_T/2$	—	$2.862(1)^{+6.3\%}_{-9.4\%}$

scale uncertainties

- Off-shell effects:
  - → $-0.5\,\%$ globally
  - → up to $+10\,\%$ differentially
- $\rm NWA_{LOdec}$ → larger scale uncertainties

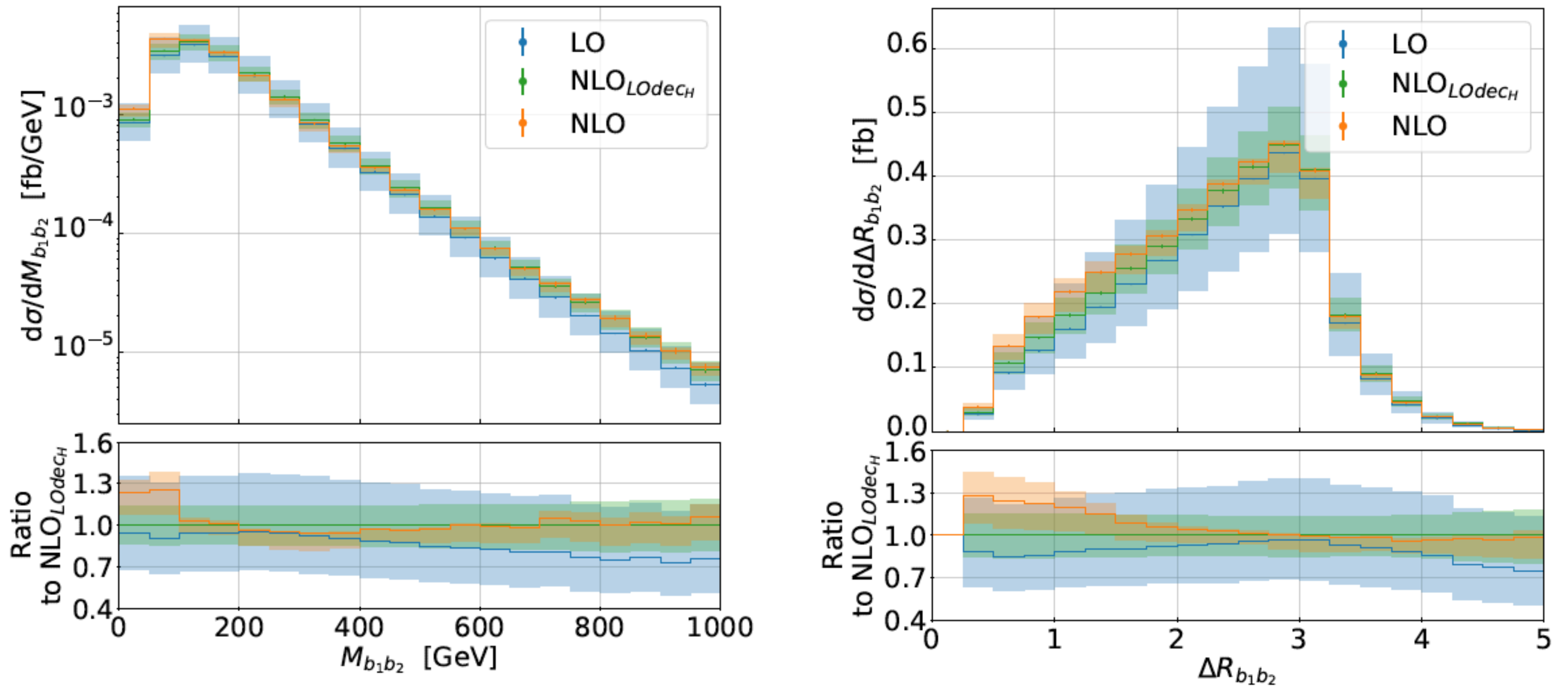




Predictions for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} H (H \to b\bar{b})$

[Stremmer and Worek, JHEP 02 (2022) 196]

- Impact of QCD corrections to $H \to b\bar{b}$ decay



- NLO QCD modelling of $H \to b\bar{b}$ influences scale uncertainties

  $\hookrightarrow$ $\Delta R_{b_1b_2} \approx 3$: 45 % (LO) $\to$ 15 % (NLO$_{\mathrm{LOdec_H}}$) $\to$ 10 % (NLO)

- Enhancements up to 30 % for small $M_{b_1b_2}$ and $\Delta R_{b_1b_2}$

II. Irreducible QCD background to $t\bar{t}H(H \to b\bar{b})$

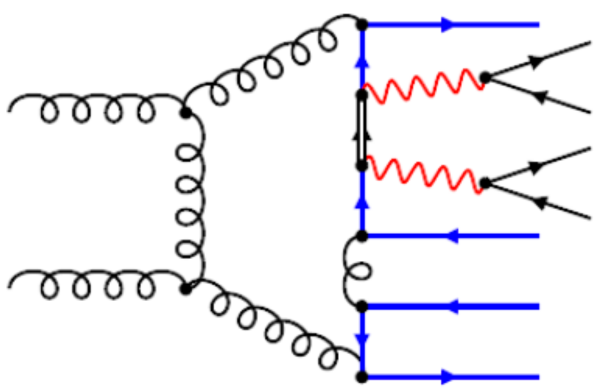
Off-shell $t\bar{t}b\bar{b}$: a glimpse at the complexity

- "2 —> 6" complexity (from QCD viewpoint)

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

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

Computationally demanding!
$\mathcal{O}(10^5)$ CPU hours



Two independent off-shell $t\bar{t}b\bar{b}$ calculations:

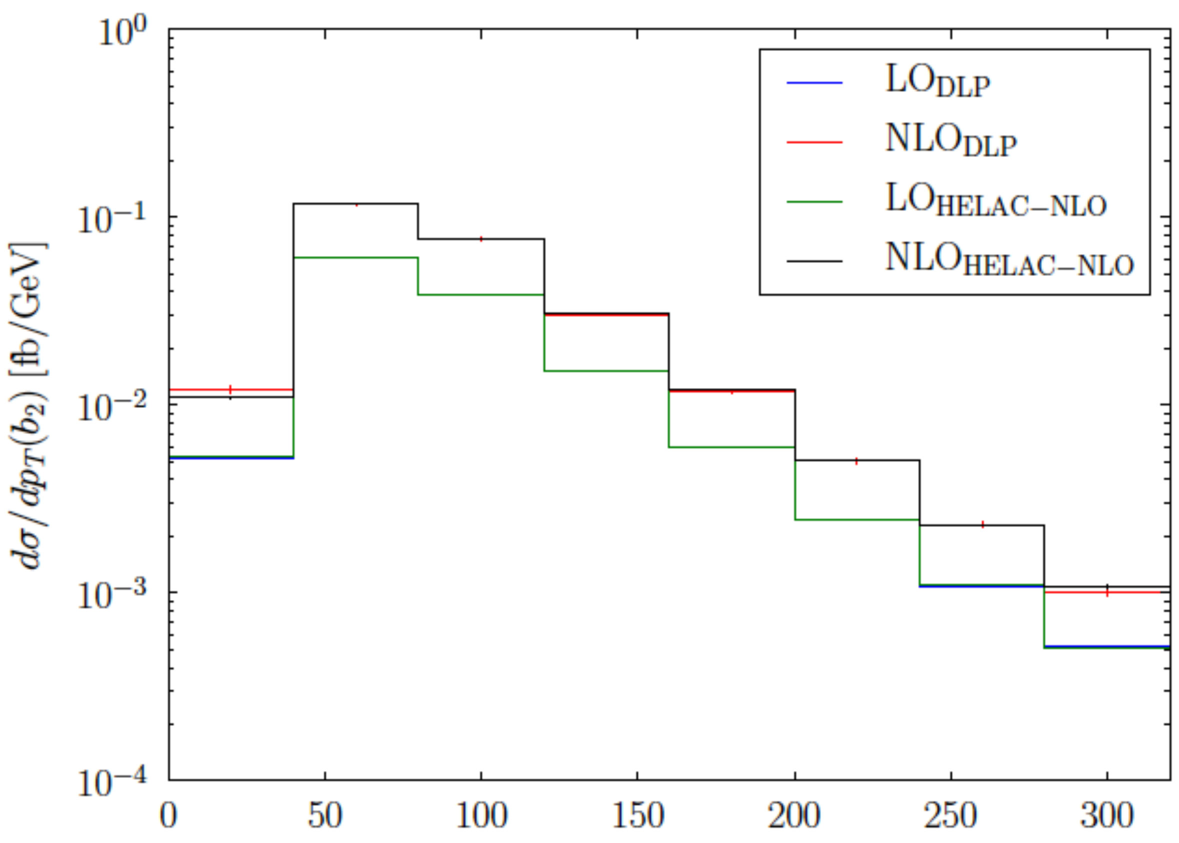
- Denner, Lang and Pellen, Phys.Rev.D 104 (2021) 5, 056018
- G.B., Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008

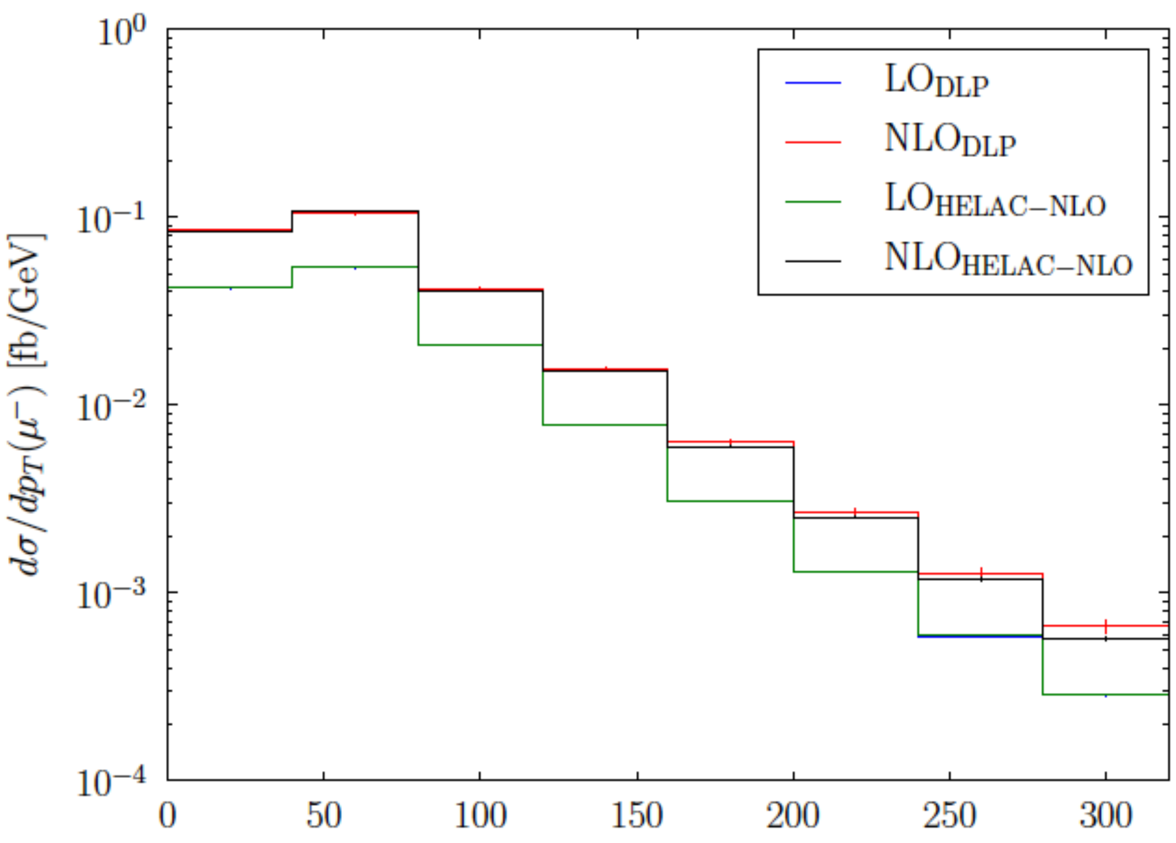
Cross checks between independent calculations

- **Comparison with** Denner, Lang and Pellen, [Phys.Rev.D 104 (2021) 5, 056018]

$$\sigma^{\text{NLO}}_{\text{HELAC}} = 10.28(1)^{+18\%}_{-21\%} \text{ fb} \qquad \sigma^{\text{NLO}}_{\text{DLP}} = 10.28(8)^{+18\%}_{-21\%} \text{ fb}$$

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





Agreement at permille level

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

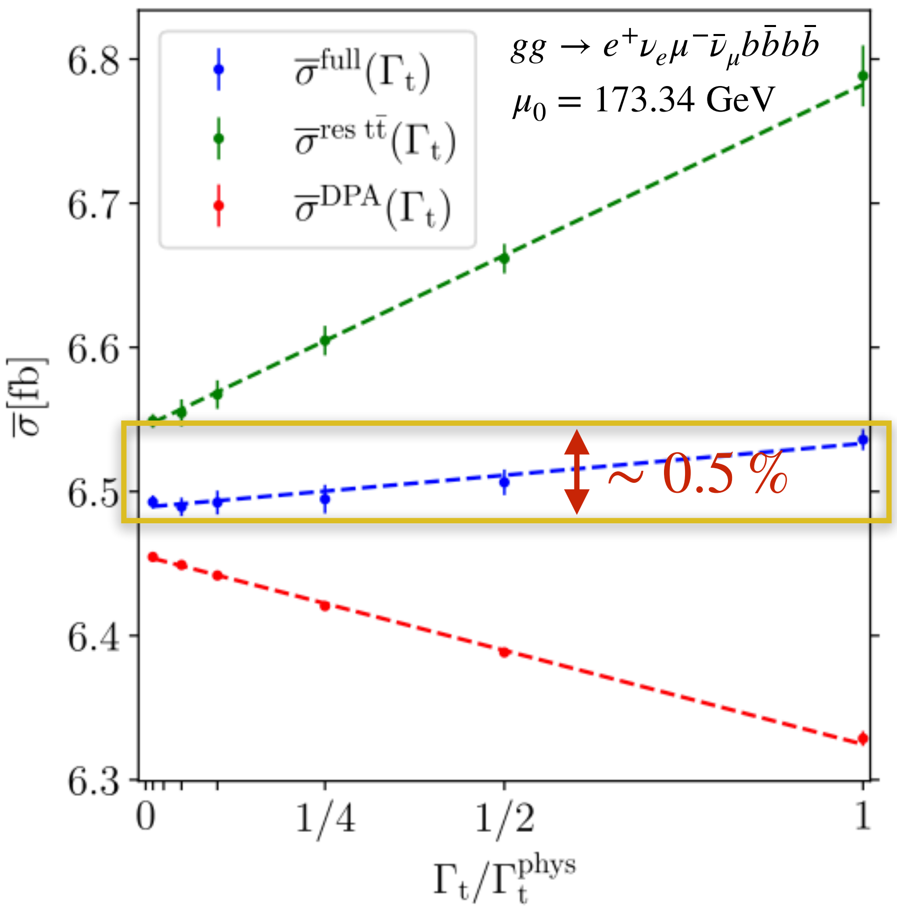
- **Fiducial cross sections** $\sqrt{s} = 13$ TeV

$$p_T(\ell) > 20 \text{ GeV}, \quad p_T(b) > 25 \text{ GeV}, \quad |y(\ell)| < 2.5, \quad |y(b)| < 2.5$$

[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]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
			$\mu_R = \mu_F = \mu_0 = m_t$ [NNPDF 3.1]			
25	6.998	+4.525 (65%) −2.569 (37%)	13.24	+2.33 (18%) −2.89 (22%)	+0.19 (1%) −0.19 (1%)	1.89
30	5.113	+3.343 (65%) −1.889 (37%)	9.25	+1.32 (14%) −1.93 (21%)	+0.14 (2%) −0.14 (2%)	1.81
35	3.775	+2.498 (66%) −1.401 (37%)	6.57	+0.79 (12%) −1.32 (20%)	+0.10 (2%) −0.10 (2%)	1.74
40	2.805	+1.867 (67%) −1.051 (37%)	4.70	+0.46 (10%) −0.91 (19%)	+0.08 (2%) −0.08 (2%)	1.68
			$\mu_R = \mu_F = \mu_0 = H_T/3$ [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]

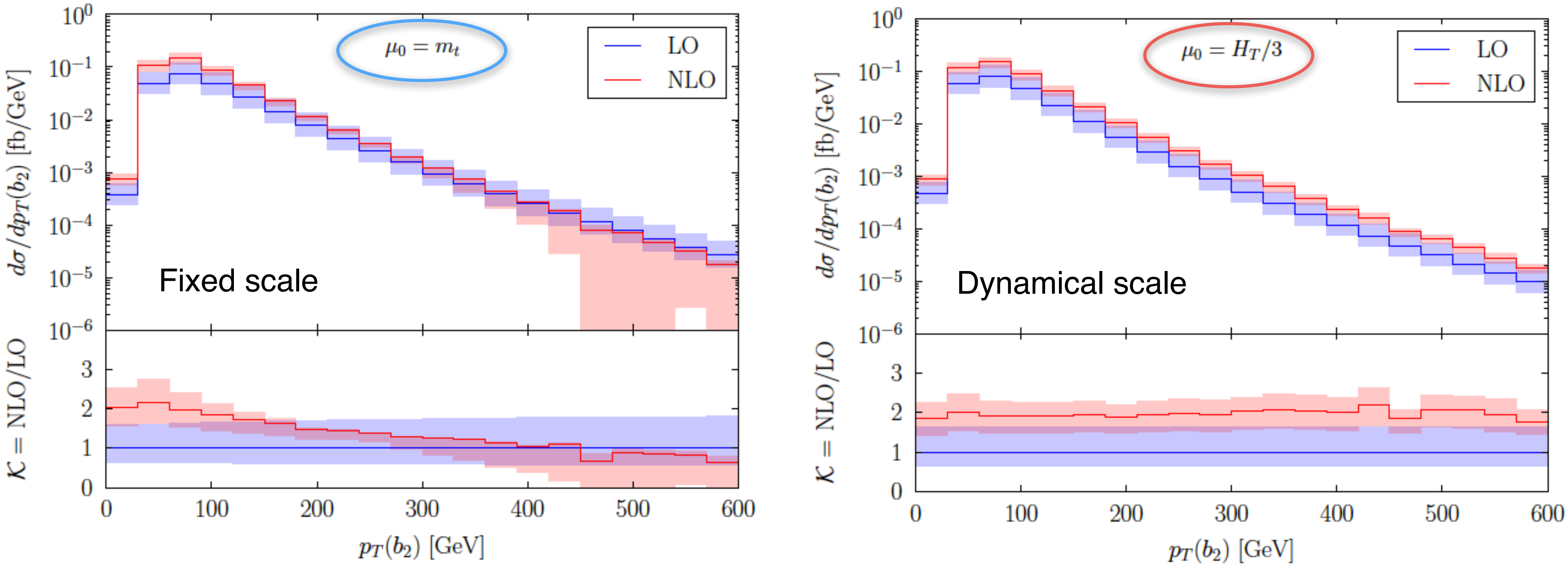


Theory uncertainties:

- **Scale** : $\mathcal{O}(20\%)$
- **PDF** : $\mathcal{O}(1\% - 2\%)$

$t\bar{t}b\bar{b}$: impact of scale choice (I)

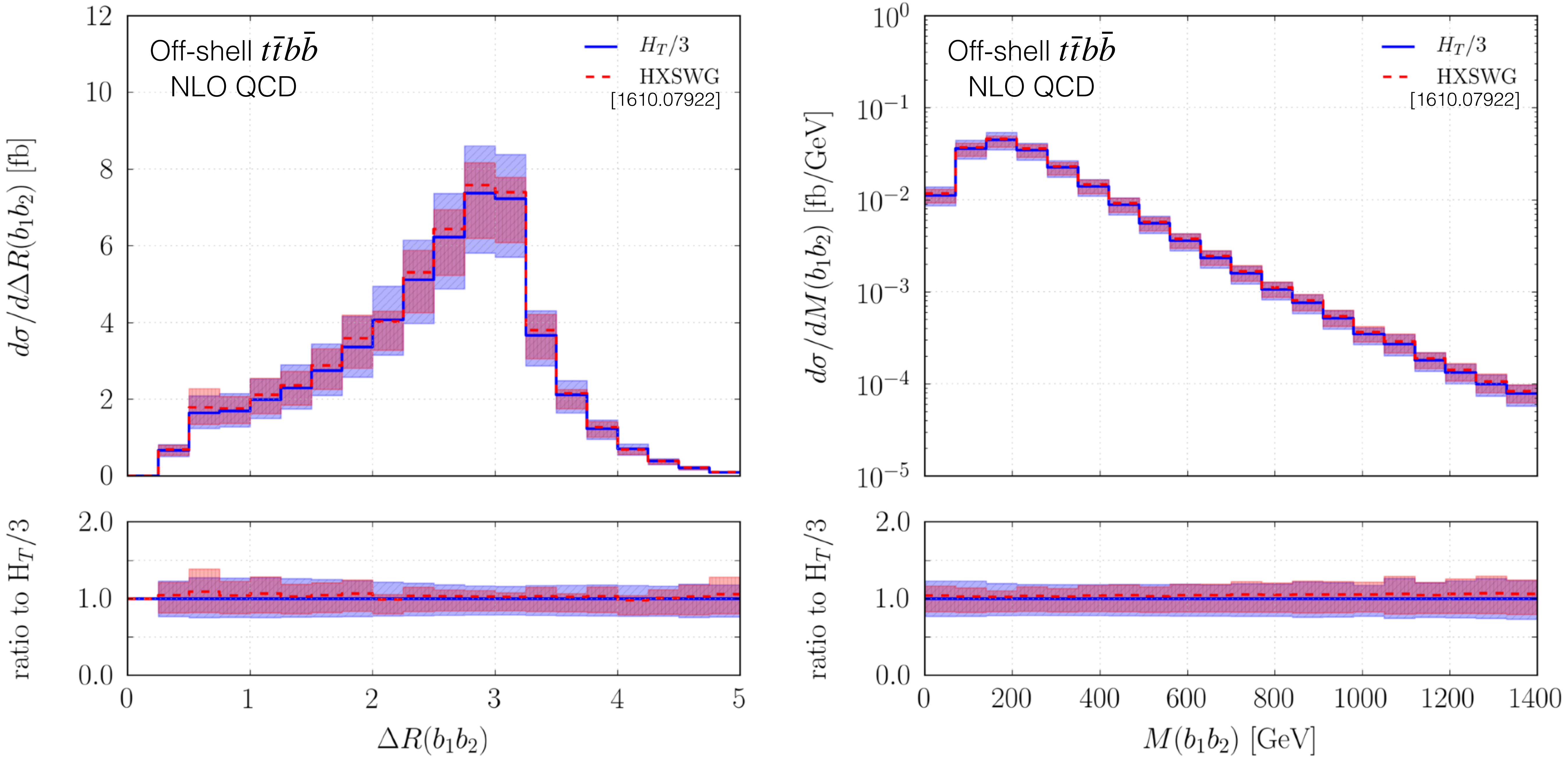
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]



- Dynamical scales help to flatten K-factors
- QCD corrections still large, improved perturbative stability

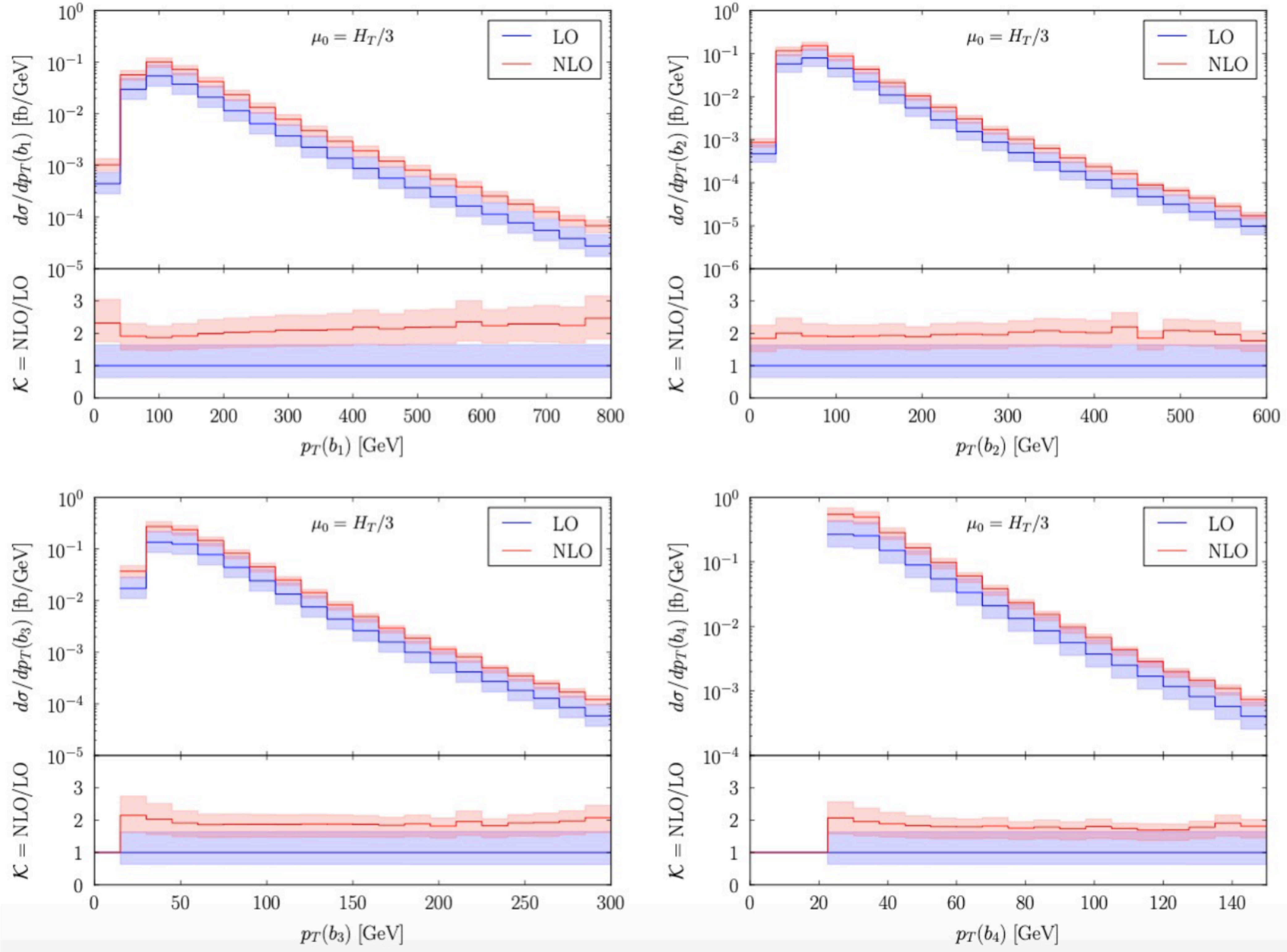
- Comparison with scales recommended within the HXSWG (arXiv:1610.07922)

HXSWG (1610.07922) → $\mu_{R,0} = \left(\prod_{i=t,\bar{t},b,\bar{b}} E_{T,i} \right)^{1/4}, \quad \mu_{F,0} = \frac{H_T}{2} = \frac{1}{2} \sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}$



$t\bar{t}b\bar{b}$: impact of QCD corrections

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

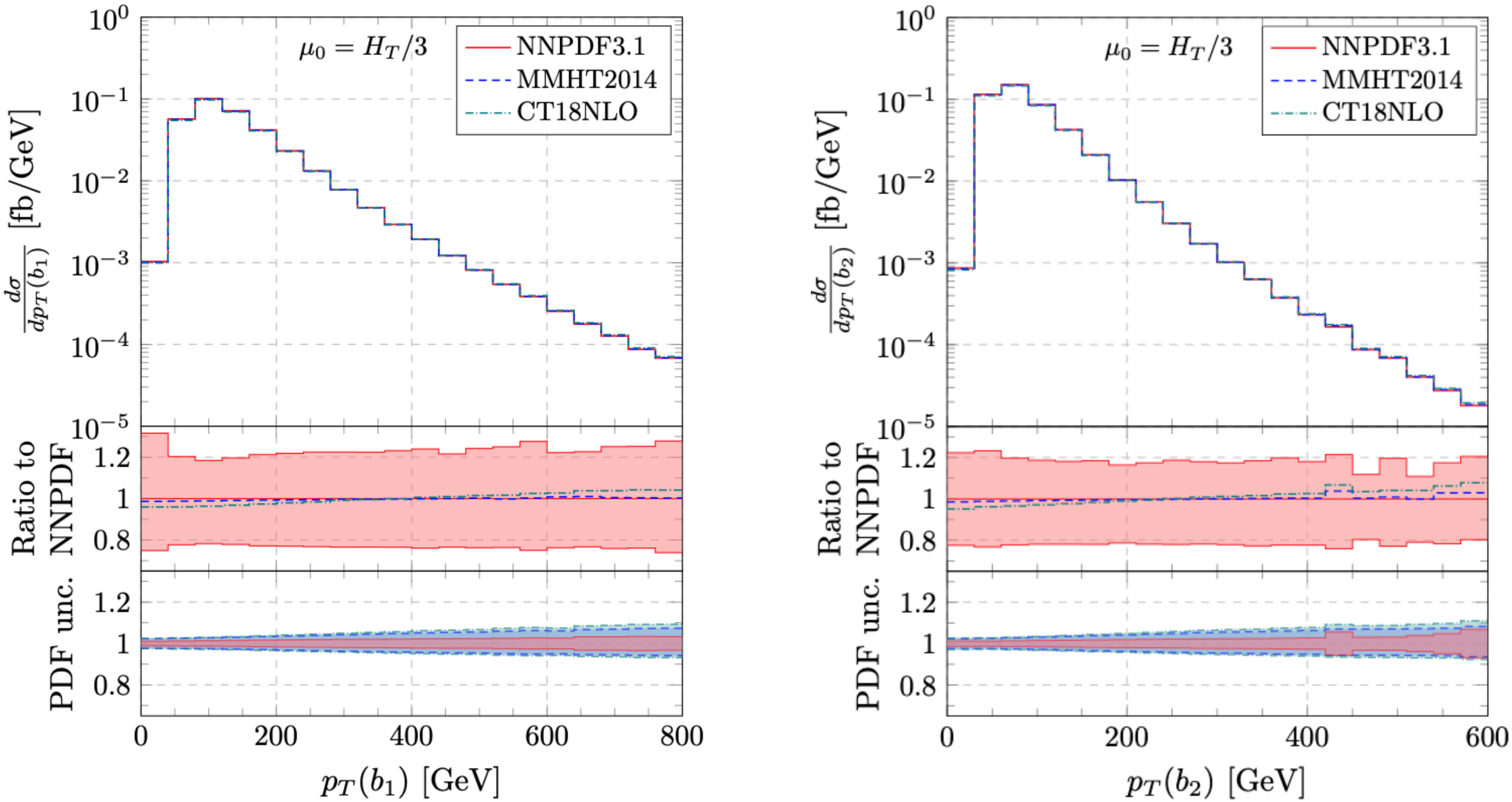


Large but rather stable QCD corrections at differential level

$t\bar{t}b\bar{b}$: impact of scale and PDF uncertainties (I)

- Theory uncertainties at differential level

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

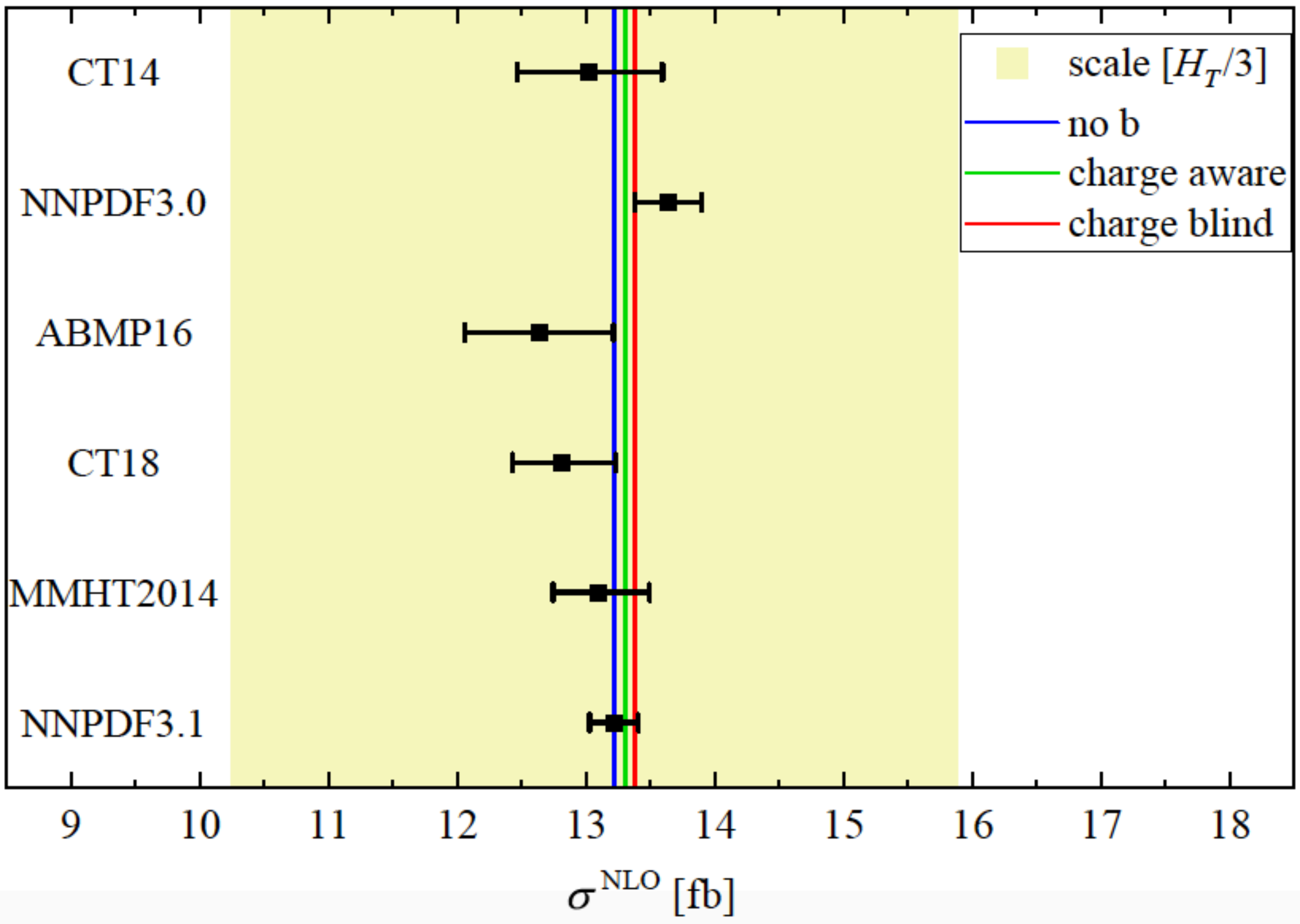


PDF uncertainties systematically smaller than scale (but can reach 10% in tails)

$t\bar{t}b\bar{b}$: impact of scale and PDF uncertainties (II)

- Integrated cross section for different choices of PDF sets

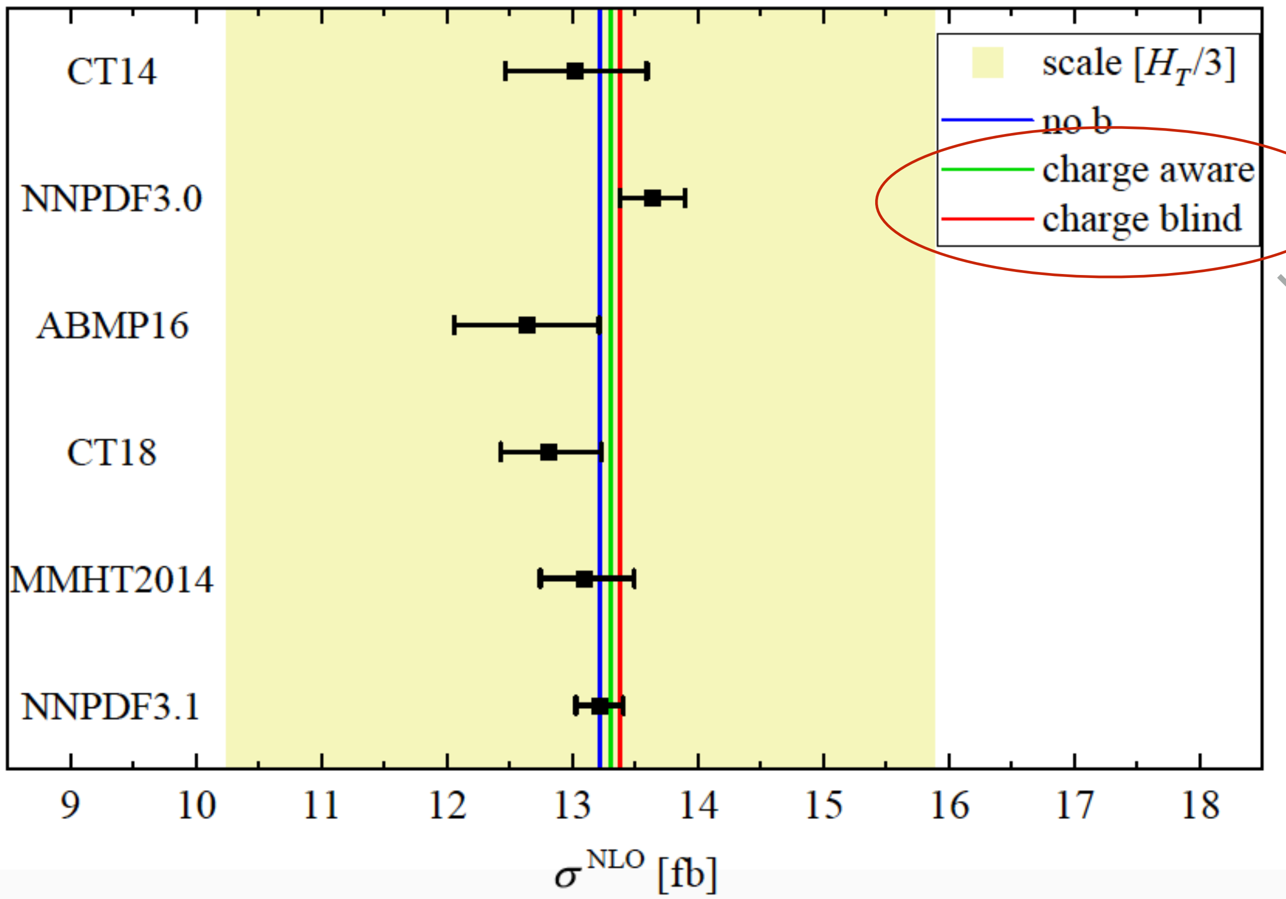
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

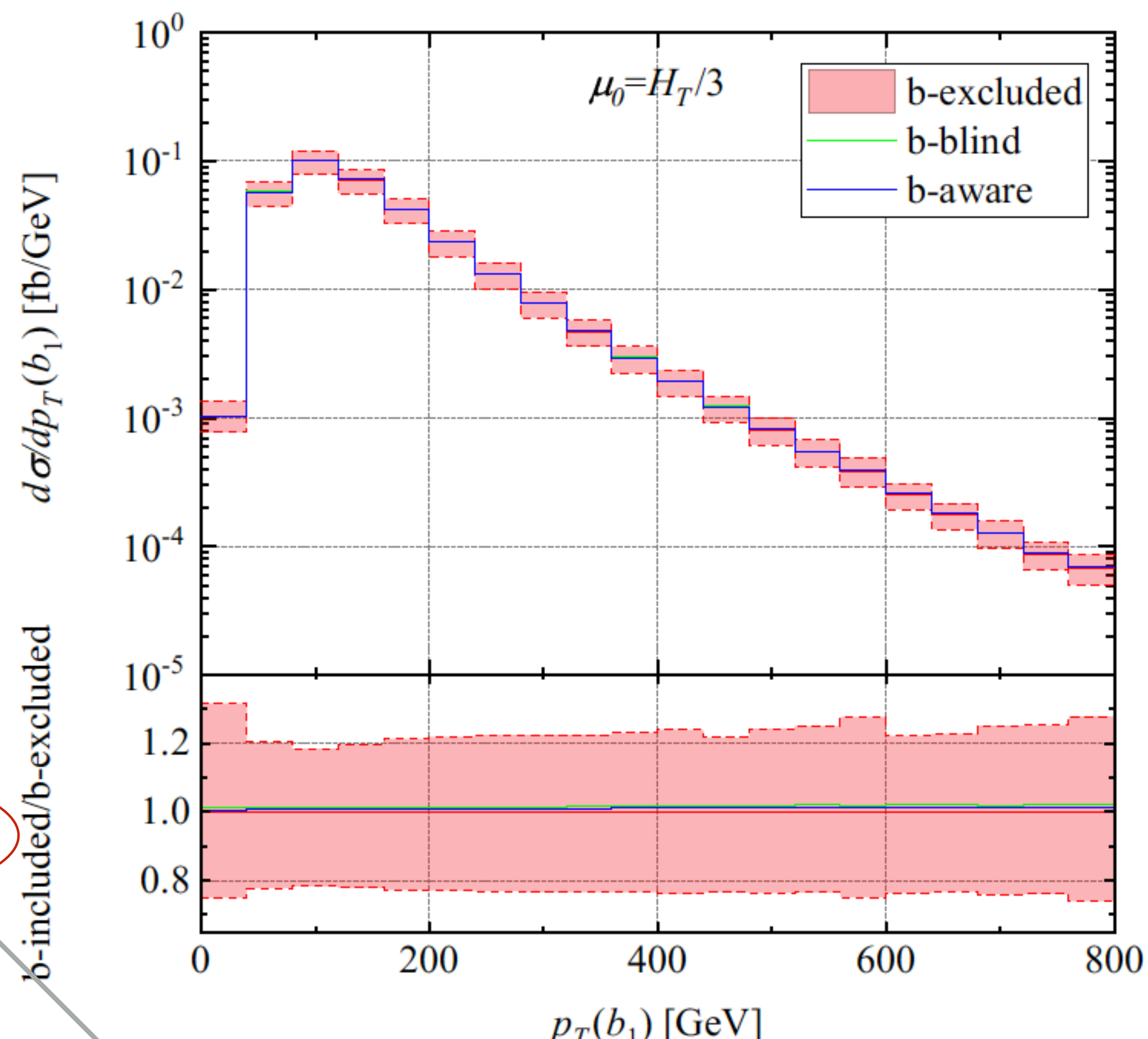


$t\bar{t}b\bar{b}$: impact of initial-state b quark contributions

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

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





"Charge blind" vs "Charge aware"

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

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

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

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, 2202.11186 [hep-ph]]

- Impact of off-shell effects and decay accuracy

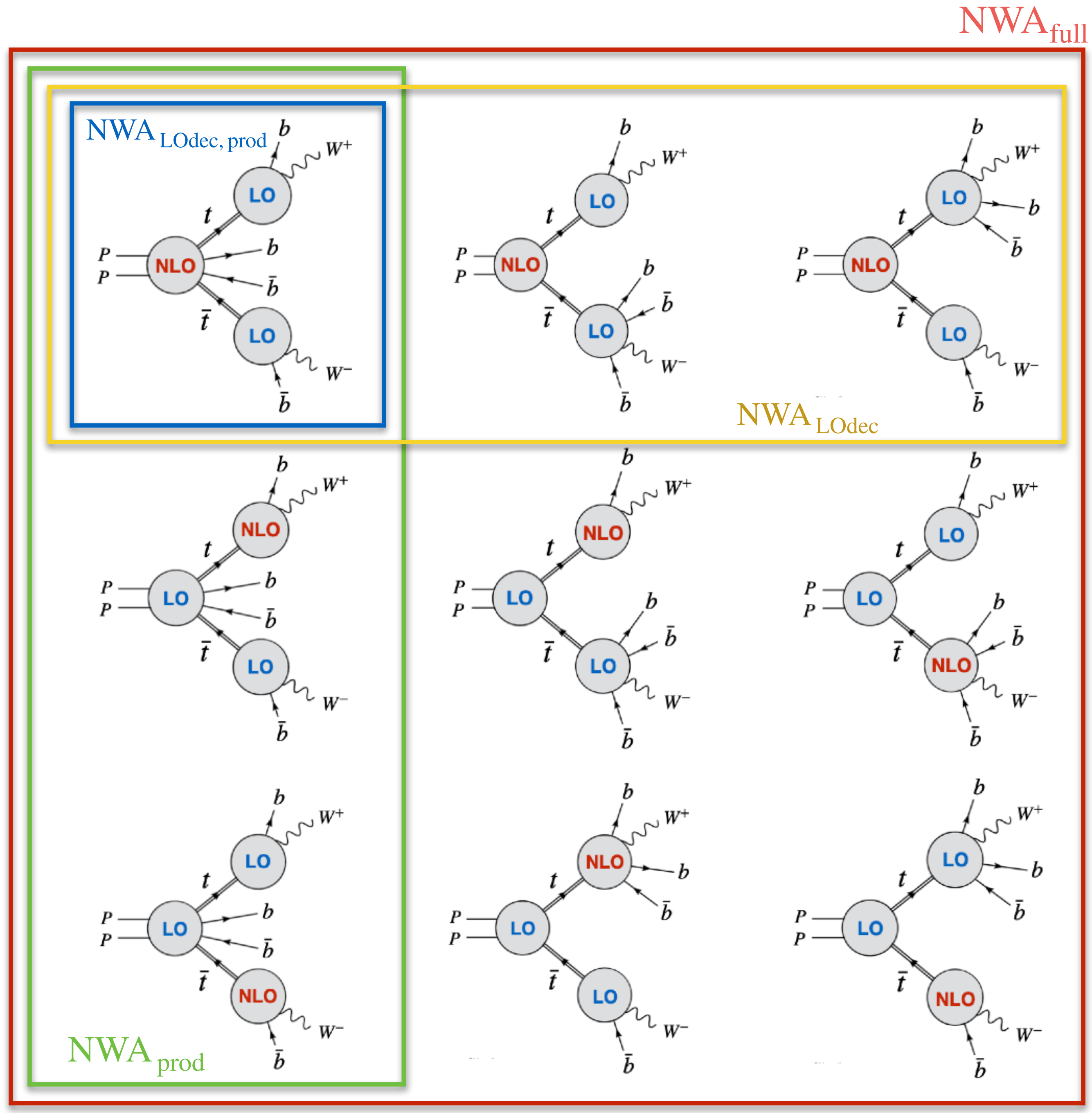
Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\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

Performing full expansion in strong coupling:

$$\mathrm{NWA}_{\rm full,\,exp} = 12.38(1)\ ^{+2.91(24\%)}_{-2.89(23\%)}\ \mathrm{fb}$$

$$\mathrm{NWA}_{\rm prod,\,exp} = 12.25(1)\ ^{+2.87(23\%)}_{-2.86(23\%)}\ \mathrm{fb}$$

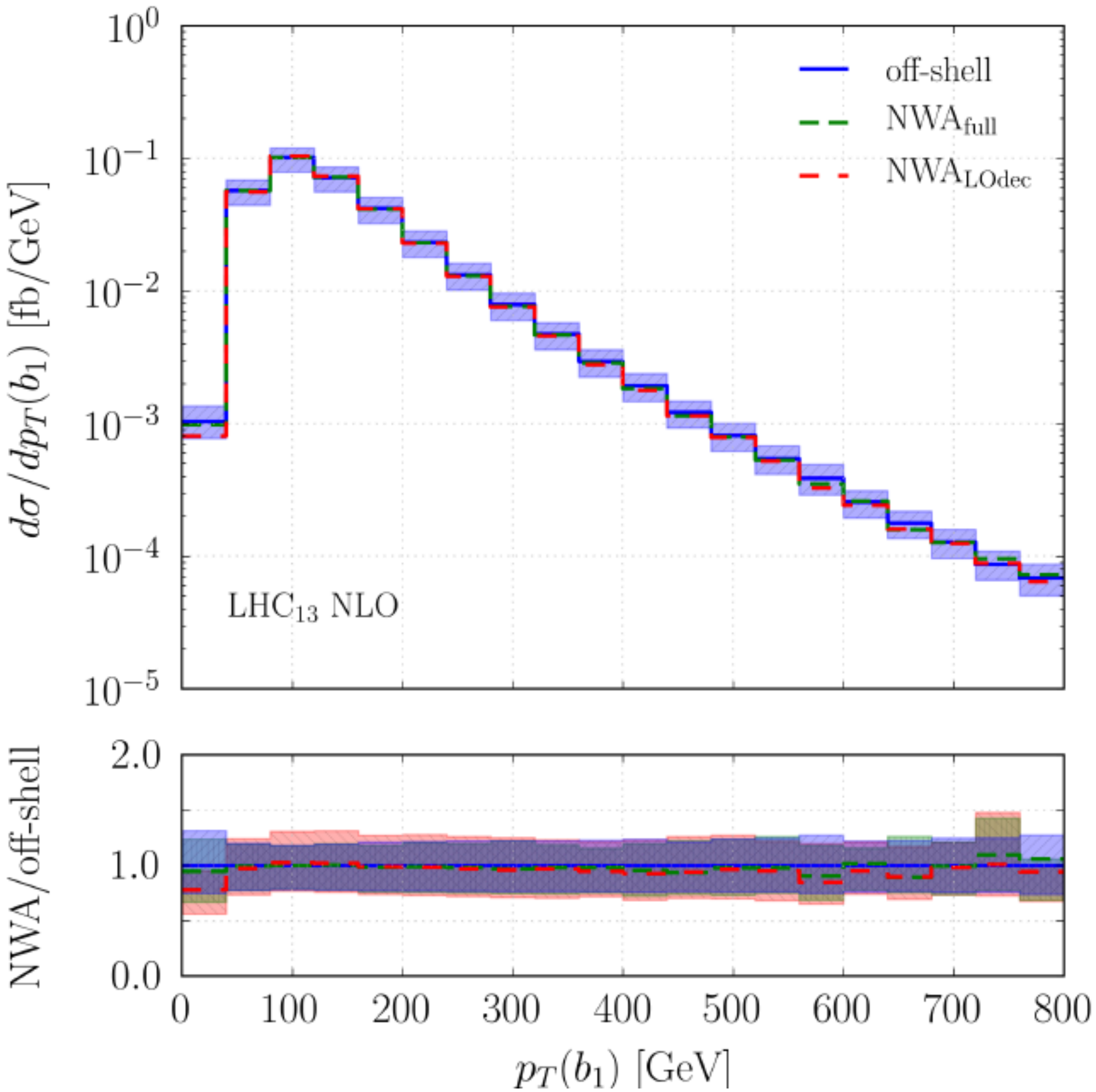
$$d\sigma^{\rm NLO}_{\rm NWA_{exp}} = d\sigma^{\rm NLO}_{\rm NWA_{full}} \left(\frac{\Gamma^{\rm NLO}_{t,\rm NWA}}{\Gamma^{\rm LO}_{t,\rm NWA}}\right)^2 - d\sigma^{\rm LO}_{\rm NWA_{full}} \frac{2(\Gamma^{\rm NLO}_{t,\rm NWA} - \Gamma^{\rm LO}_{t,\rm NWA})}{\Gamma^{\rm LO}_{t,\rm NWA}}$$

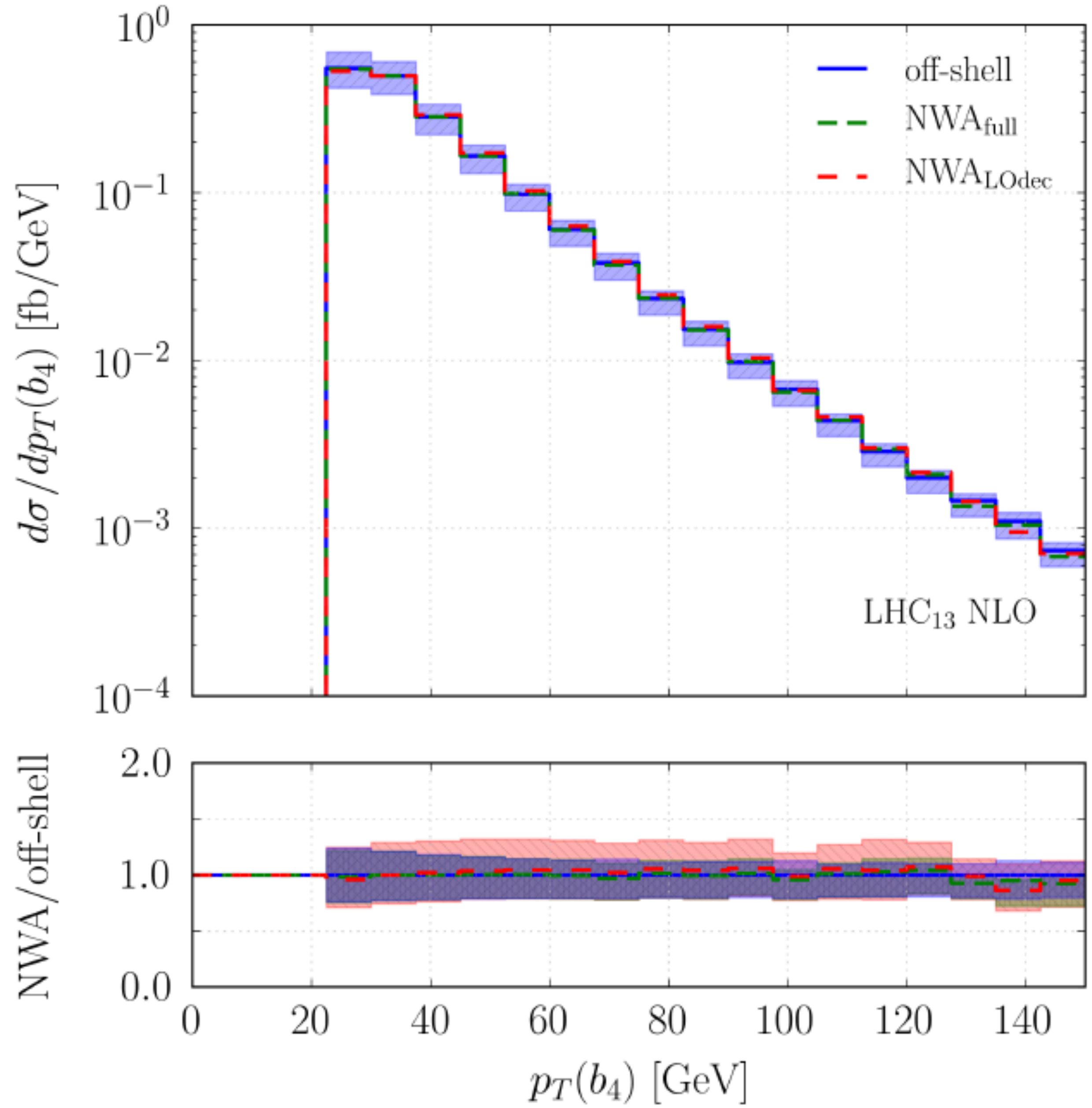


$t\bar{t}b\bar{b}$: impact of off-shell effects

- For most observables, off-shell effects are very small also *differentially*

1. Transverse momentum of the 1st- and 4th-hardest b jet:





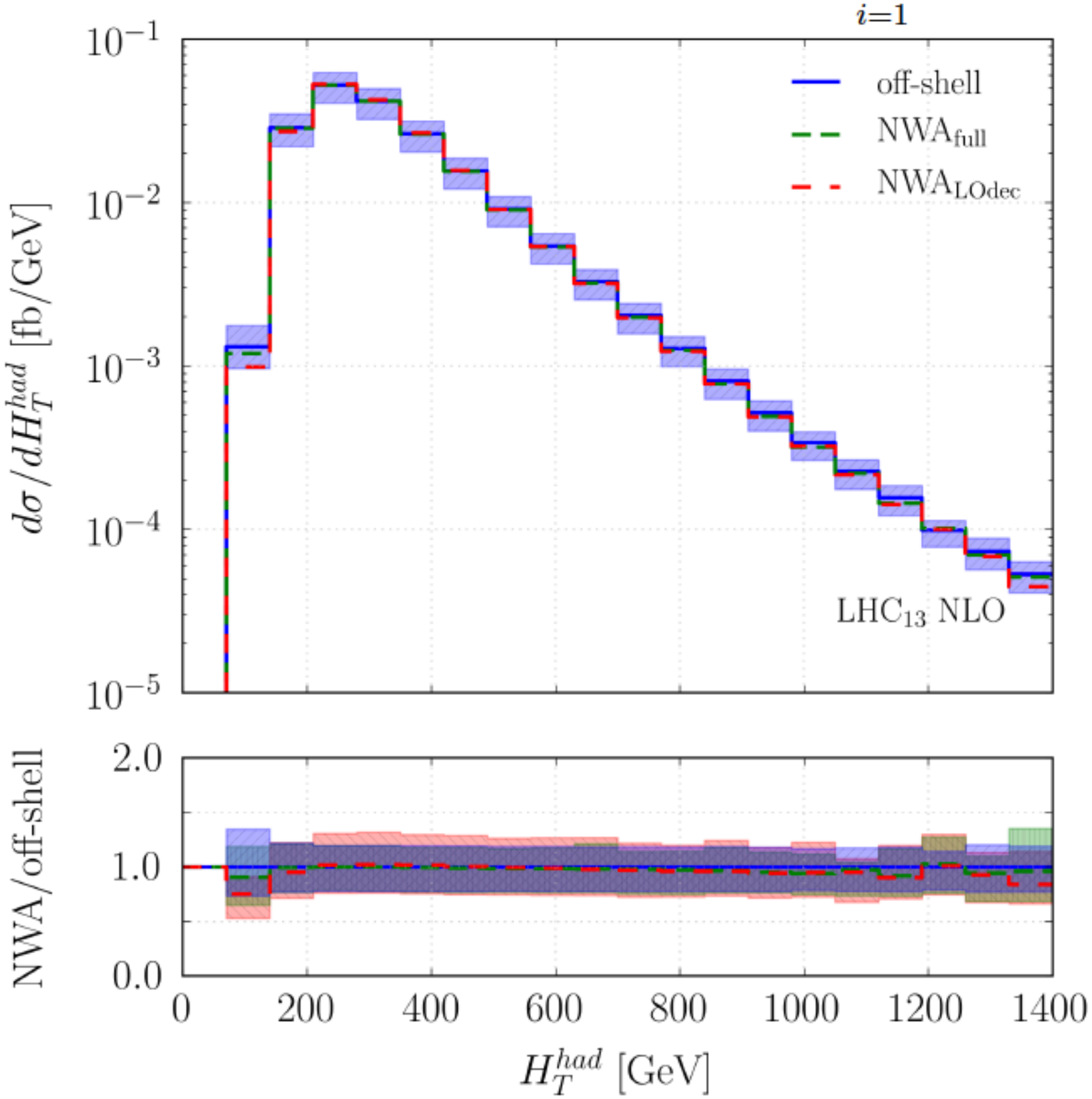
[GB et al, 2202.11186 [hep-ph]]

$t\bar{t}b\bar{b}$: impact of off-shell effects

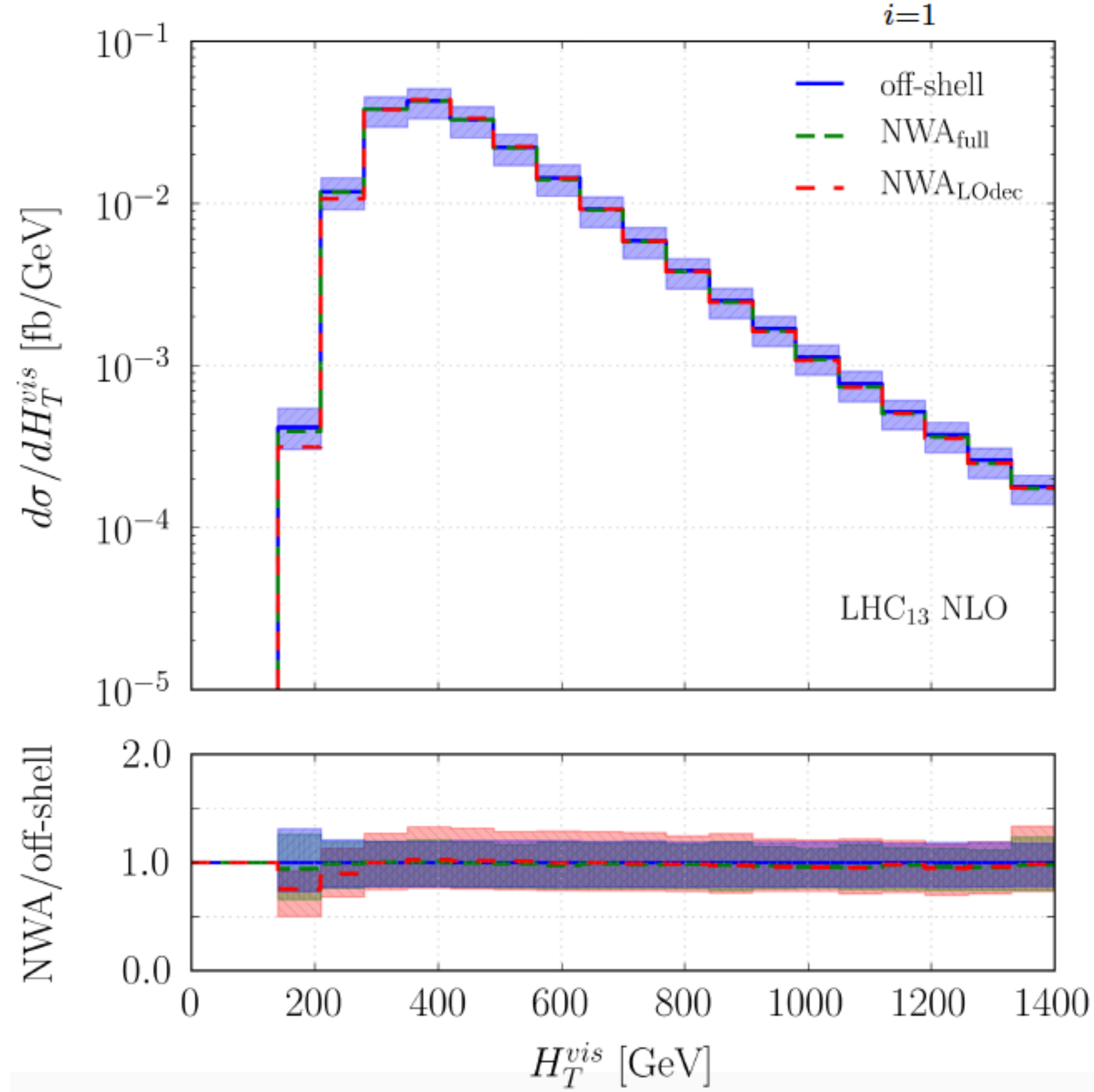
- For most observables, off-shell effects are very small also *differentially*

2. H_T^{had} and H_T^{vis}:

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



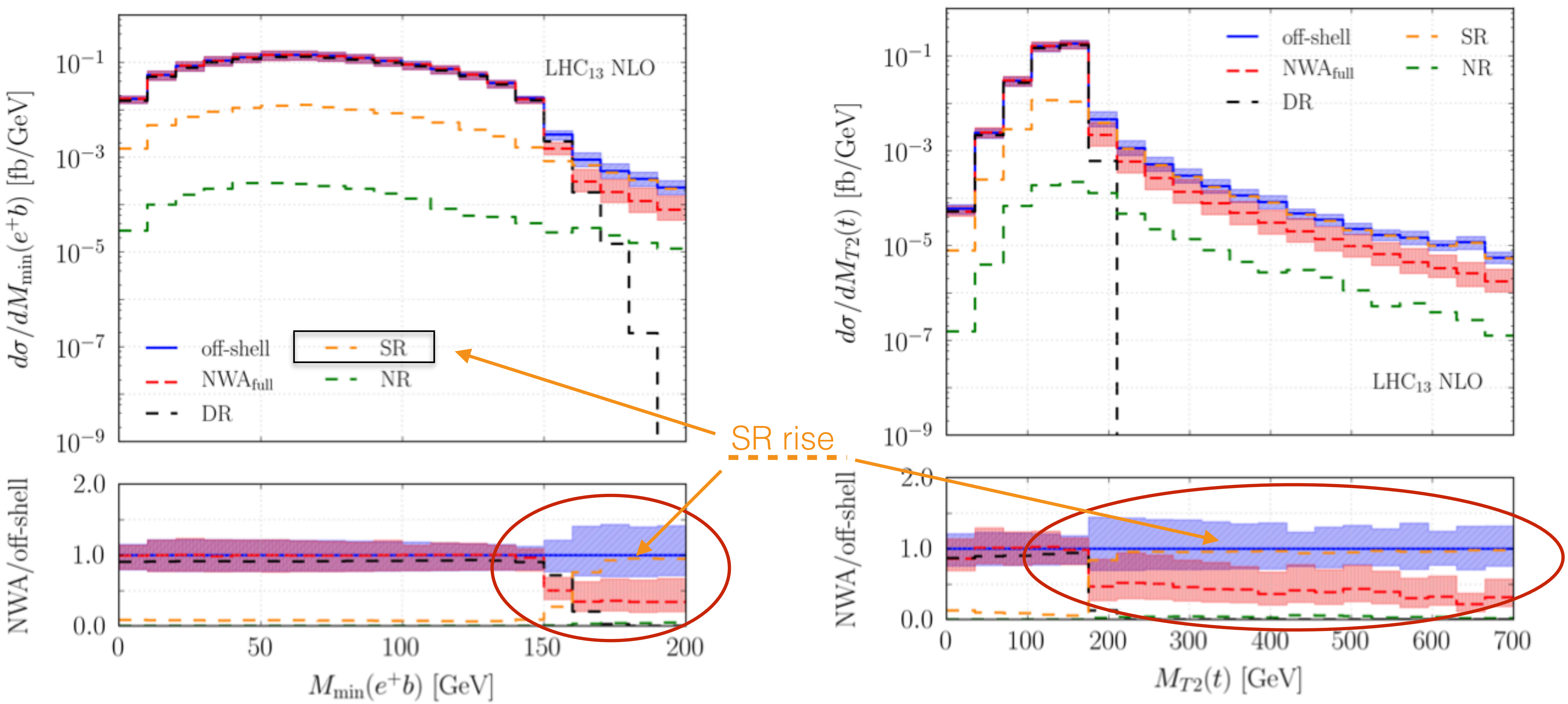
$$H_T^{vis} = H_T^{had} + \sum_{i=1}^{2} p_T(\ell_i)$$



[GB et al, 2202.11186 [hep-ph]]

- *Threshold observables* are naturally more sensitive to off-shell effects:

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, 2202.11186 [hep-ph]]



$$\text{LO}_{\text{NWA}} \rightarrow \quad M_{min}(e^+b) < \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

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

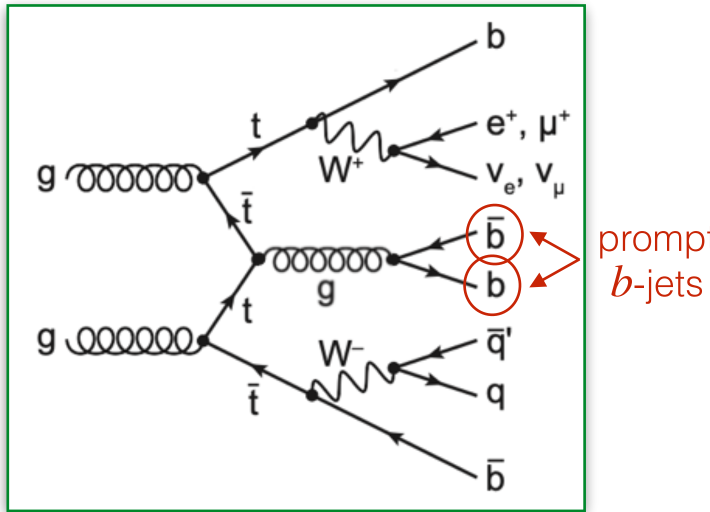
$t\bar{t}b\bar{b}$: prompt b-jet identification

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, 2202.11186 [hep-ph]]

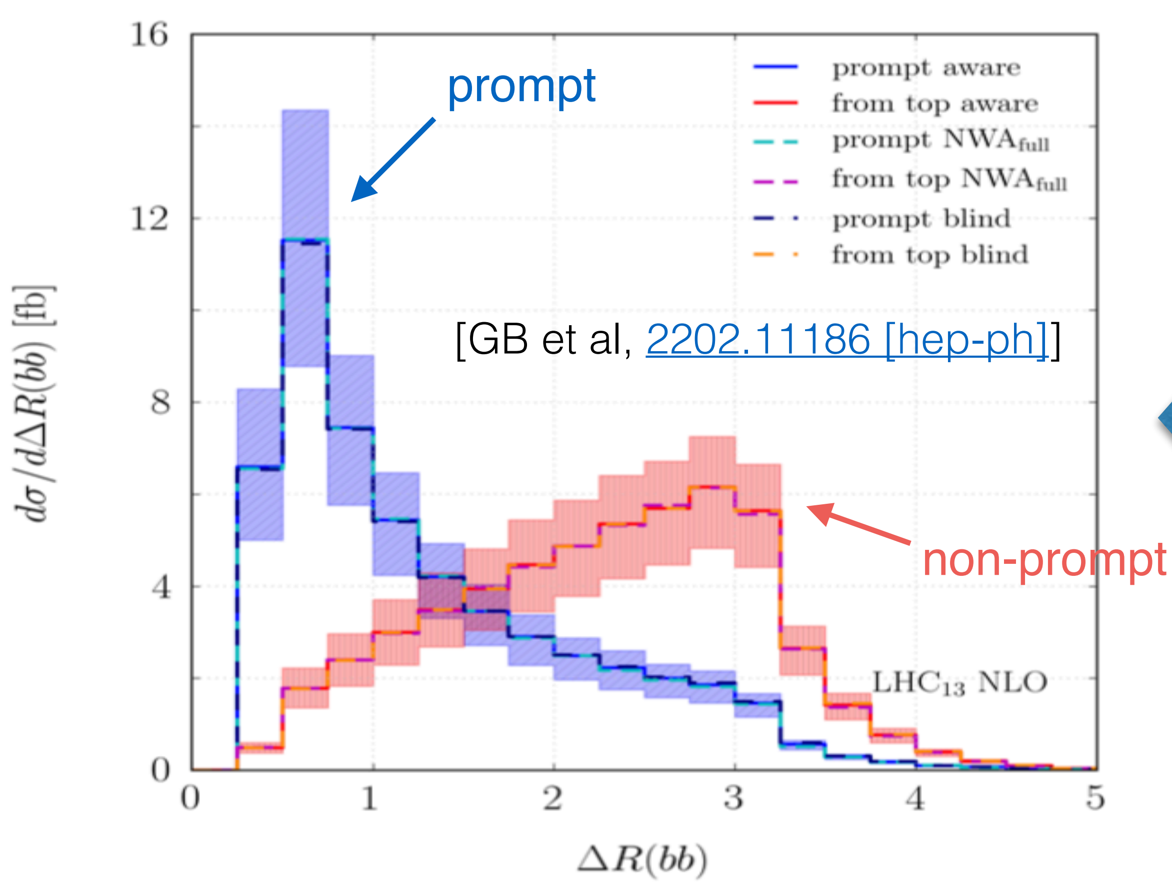
- Labelling prompt b-jets in $t\bar{t}b\bar{b}$ is not free of ambiguities in a full calculation (combinatorial background, interferences…)
- Kinematic-based prescription: reconstruct top quarks and prompt b's according to minimum principle for Q:

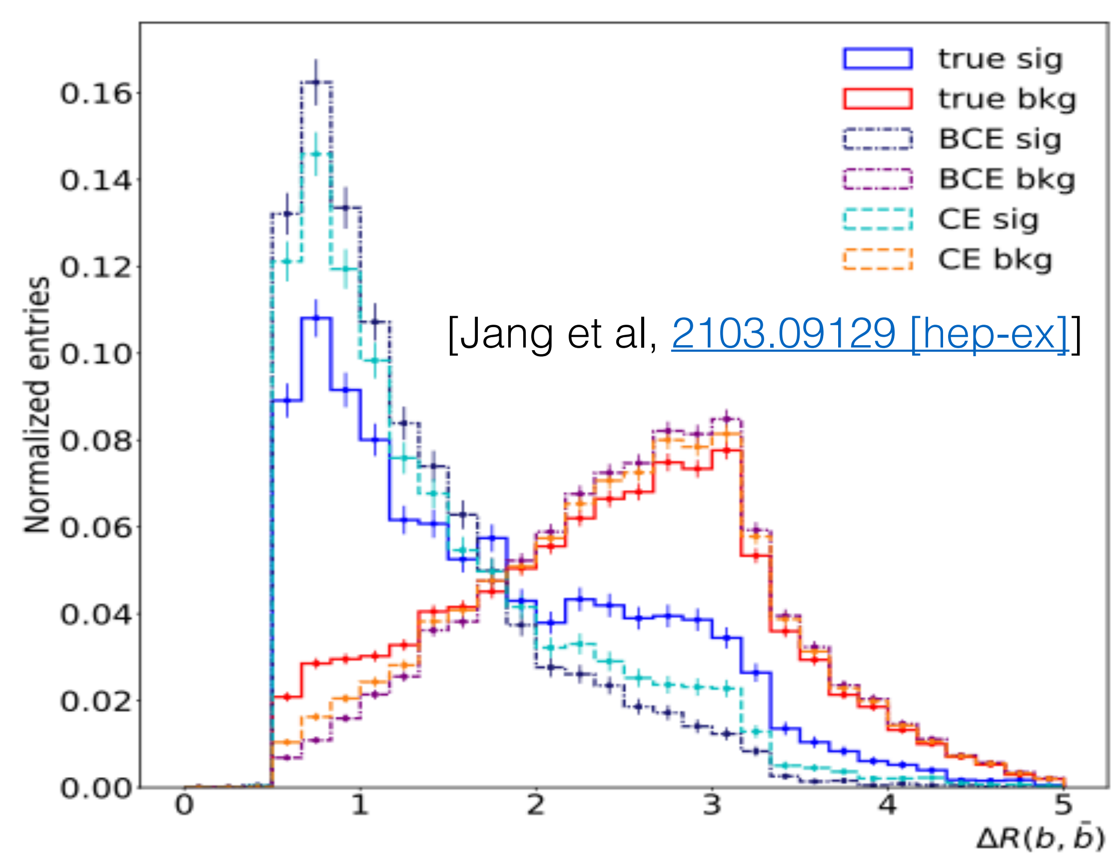
$$\mathcal{Q} = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times |M^{\text{prompt}}(bb)|$$

- Results consistent with expectations from DNN studies



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

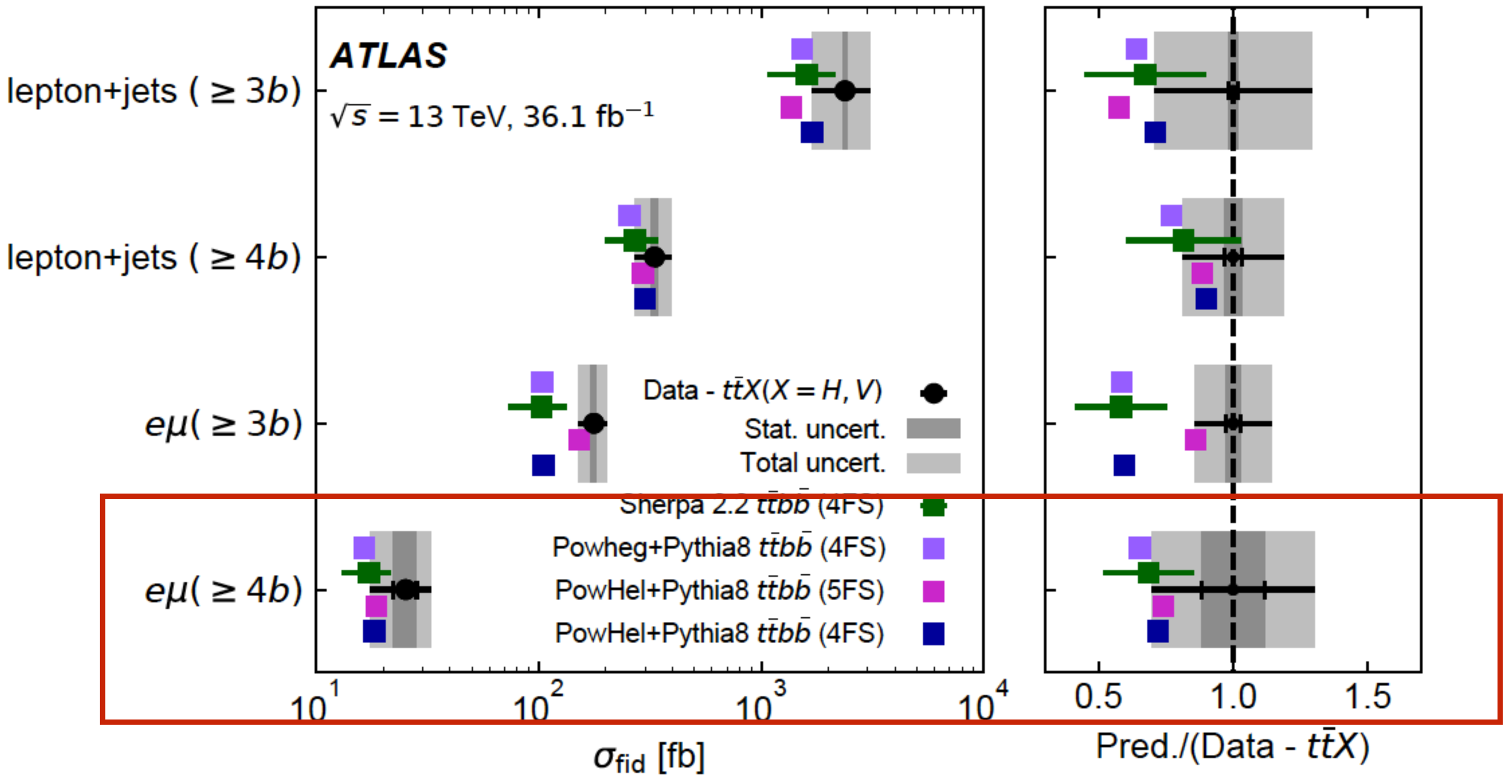




$t\bar{t}b\bar{b}$: comparison with ATLAS results

- 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, $H_T/3$): 20.0 ± 4.3 fb

- Very good agreement with the experimental result
- All predictions are compatible within theoretical uncertainties

Summary

- Remarkable progress in off-shell $t\bar{t}+X$ calculations in past years
- We have examined some recent developments concerning $t\bar{t}H(H\to b\bar{b})$ and $t\bar{t}b\bar{b}$ (dilepton channel)

$t\bar{t}H(H\to b\bar{b})$

- Scale and PDF uncertainties become comparable in high-energy tails
- Off-shell effects for t and W can reach $\mathcal{O}(10\%)$ differentially
- NLO QCD modelling of $H\to b\bar{b}$ decay impacts M_{bb}, ΔR_{bb} distributions

$t\bar{t}b\bar{b}$

- Good agreement with ATLAS results
- NWA is doing fine for most distributions of interest (but not for threshold obs.)
- Kinematics-based prescription can help to categorise prompt b-jets

- Next step: combine $t\bar{t}H(H\to b\bar{b})$ and $t\bar{t}b\bar{b}$ into state-of-the-art pheno study

Outlook

What can be done with complete fixed-order calculations?

- Compare directly against LHC data in fiducial phase-space regions

  Examples:

  - $t\bar{t}$ @ NNLO QCD (NWA) $\longrightarrow$ 2008.11133 [hep-ph] | CMS-PAS-TOP-20-006
  - $t\bar{t}\gamma + tW\gamma$ @ NLO QCD (off-shell) $\longrightarrow$ 2007.06946 [hep-ex]

- Approximately incorporate off-shell effects into NLO+PS simulations

  Example:

  - $t\bar{t}W^{\pm}$ @ NLO QCD $\longrightarrow$ 2109.15181 [hep-ph]

- Match to PS programs using methods that allow for consistent treatment of resonances

  Example:

  - $t\bar{t} + tW$ @ NLO QCD $\longrightarrow$ 1607.04538 [hep-ph]

Backup slides

$t\bar{t}b\bar{b}$: 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]

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

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

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

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, 2202.11186 [hep-ph]]

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