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

signal and irreducible background from the off-shell perspective

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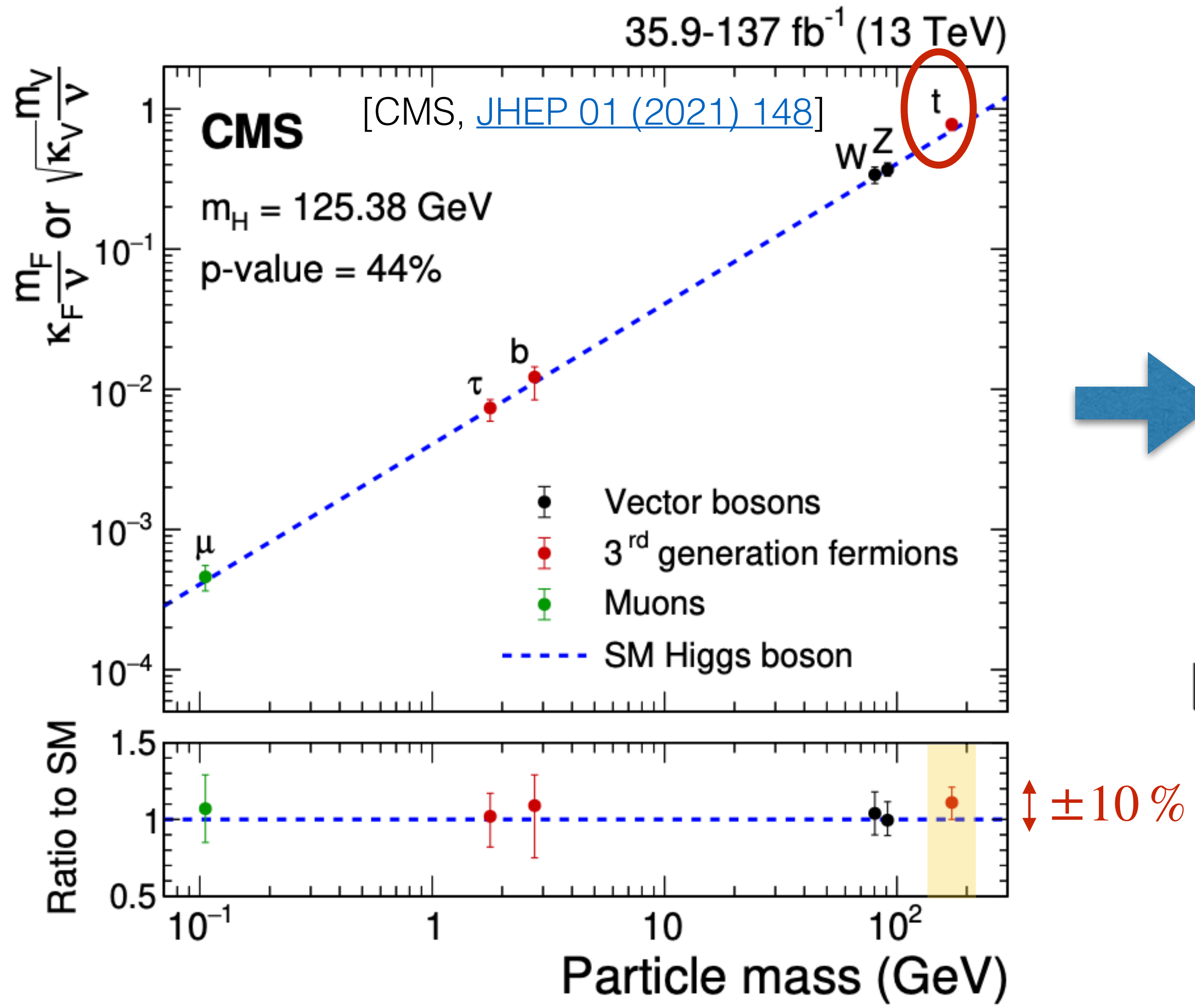
SM@LHC 2022

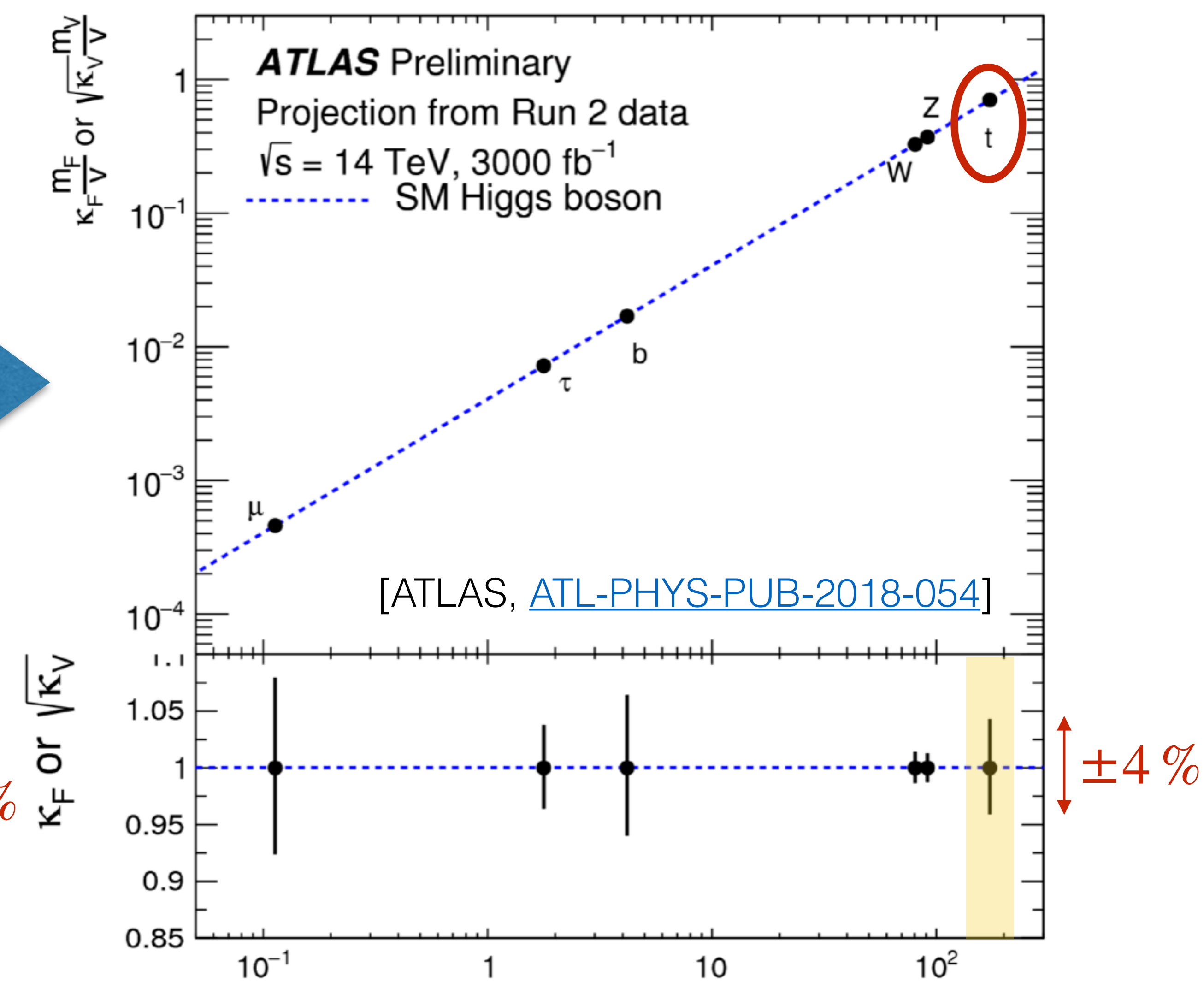
CERN
April 14, 2022

Based on:

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

- Higgs Boson measurements are stringent tests of the Standard Model



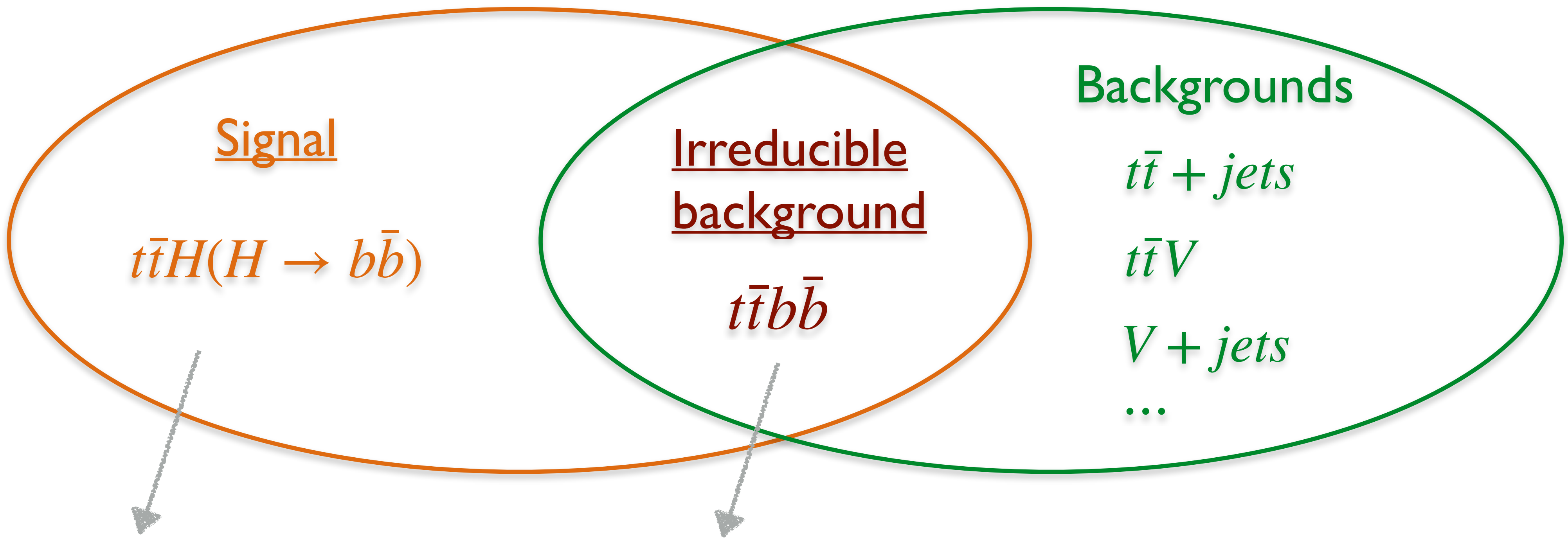


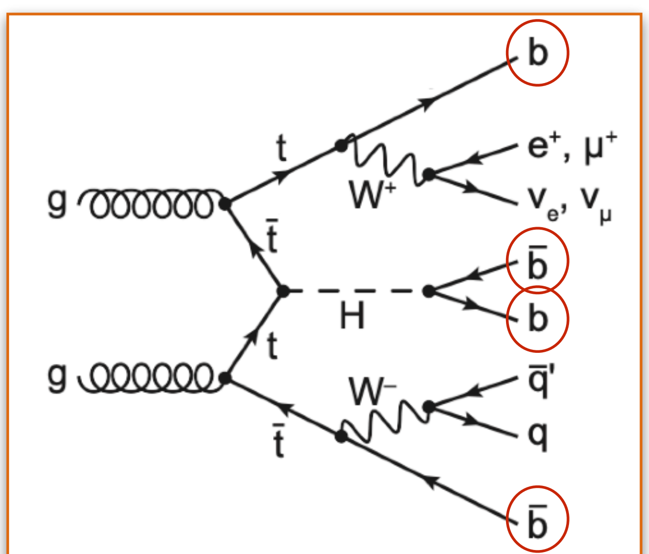
- BSM physics can manifest through Higgs coupling modifiers (κ) with effects up to few percents

see e.g. Peskin, 1207.2516 [hep-ph]

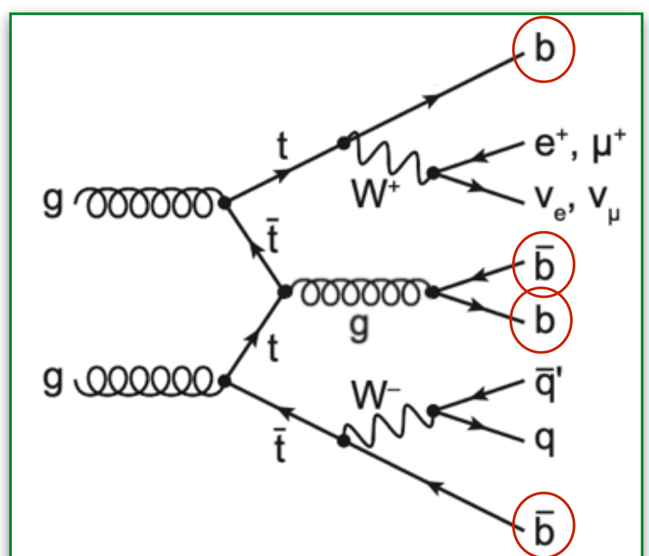
Why $ttH(H \to b\bar{b})$?

- $pp \to t\bar{t}H$: probes tH coupling at tree level; $H \to b\bar{b}$: largest BR ($\sim 58\%$)
- Challenging theoretically and experimentally:





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



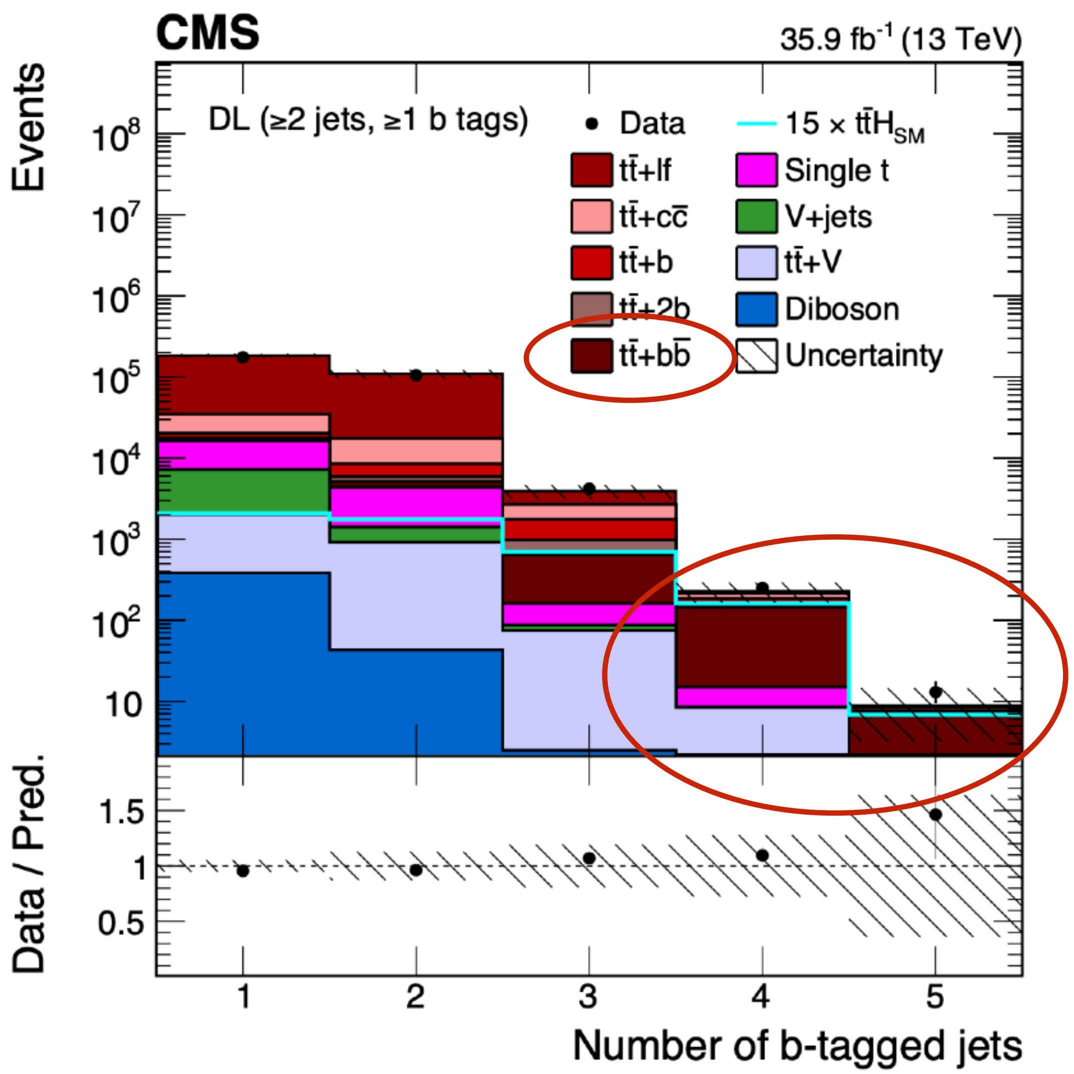
$t \to W^+ b$ $\bar{t} \to W^- \bar{b}$ $g \to b\bar{b}$

Combinatorial background:

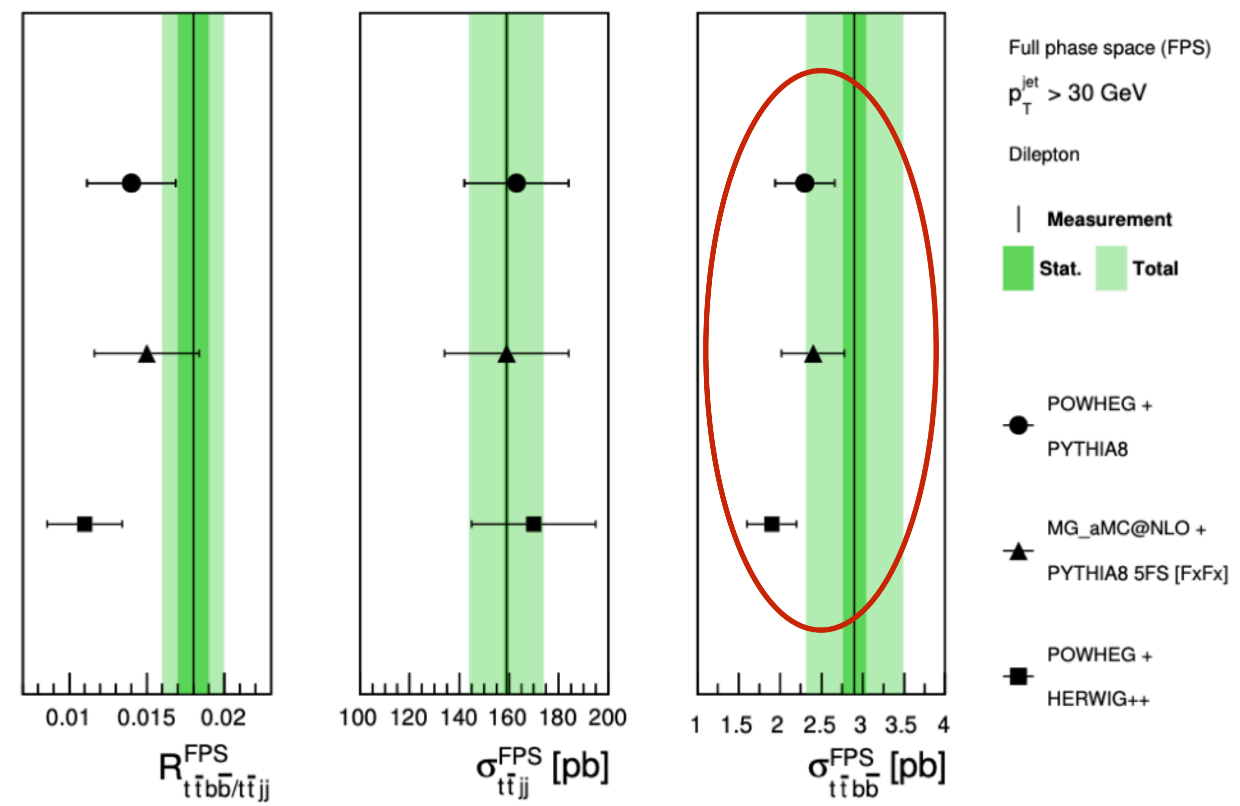
- smearing of Higgs peak in $M(b\bar{b})$ distribution
- challenges in top reconstruction & "prompt b-jet" identification

$tt\bar{b}$: theoretical challenges

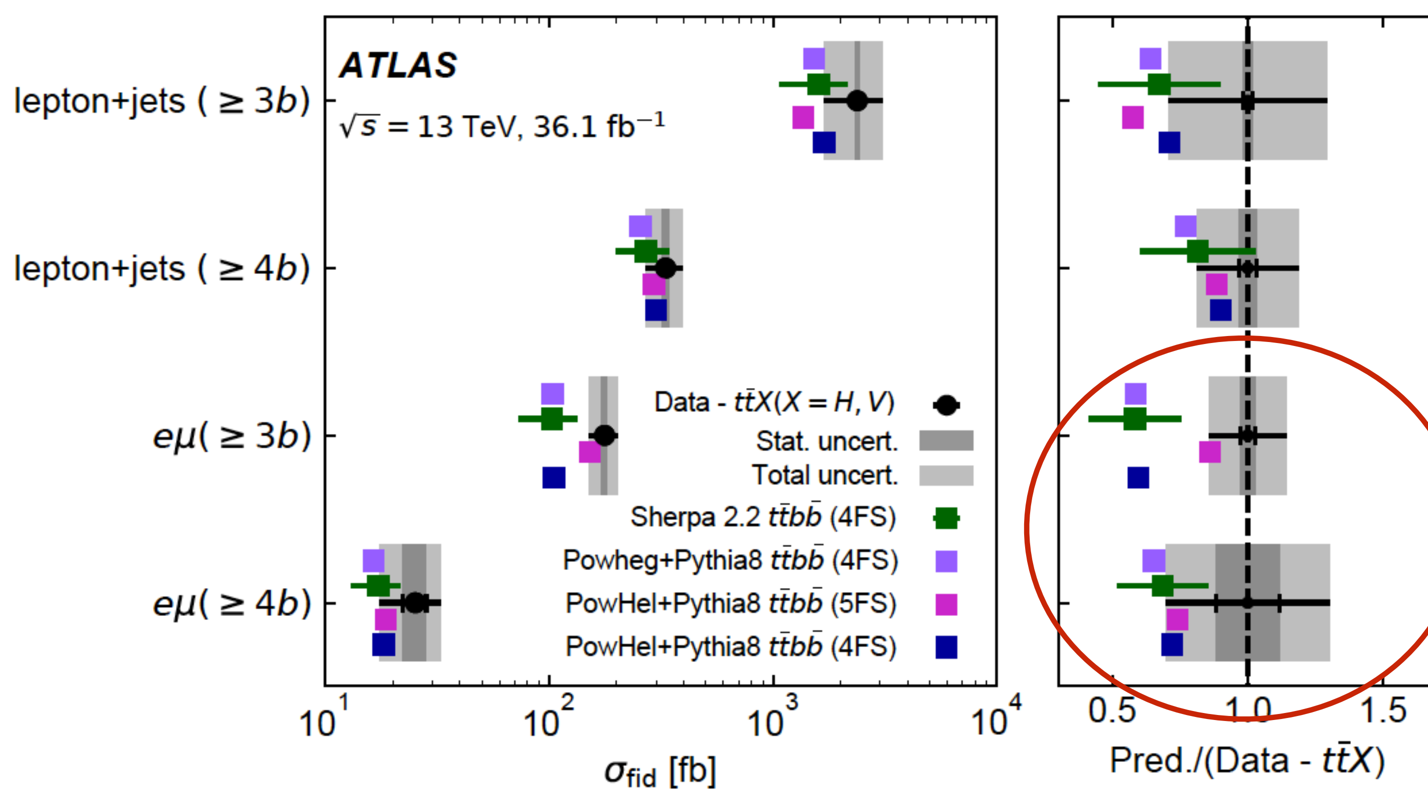
[CMS, JHEP 03 (2019) 026]



[CMS, JHEP 07 (2020) 125]



[ATLAS, JHEP 04 (2019) 046]



- $t\bar{t}b\bar{b}$: main background to $t\bar{t}H(H \to b\bar{b})$ for $N_{bjets} \geq 4$
- Tension with $t\bar{t}b\bar{b}$ measurements
  ↪ improve modelling

Theory status

$t\bar{t}H$

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

Matched to Parton Shower

- POWHEG matching — Garzelli, Kardos, Papadopoulos, Trocsanyi '11; Hartanto, Jäger, Reina, Wackeroth '15
- MC@NLO matching — 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

Matched to Parton Shower

- 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]

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

Focus: recent developments on off-shell calculations

The off-shell perspective

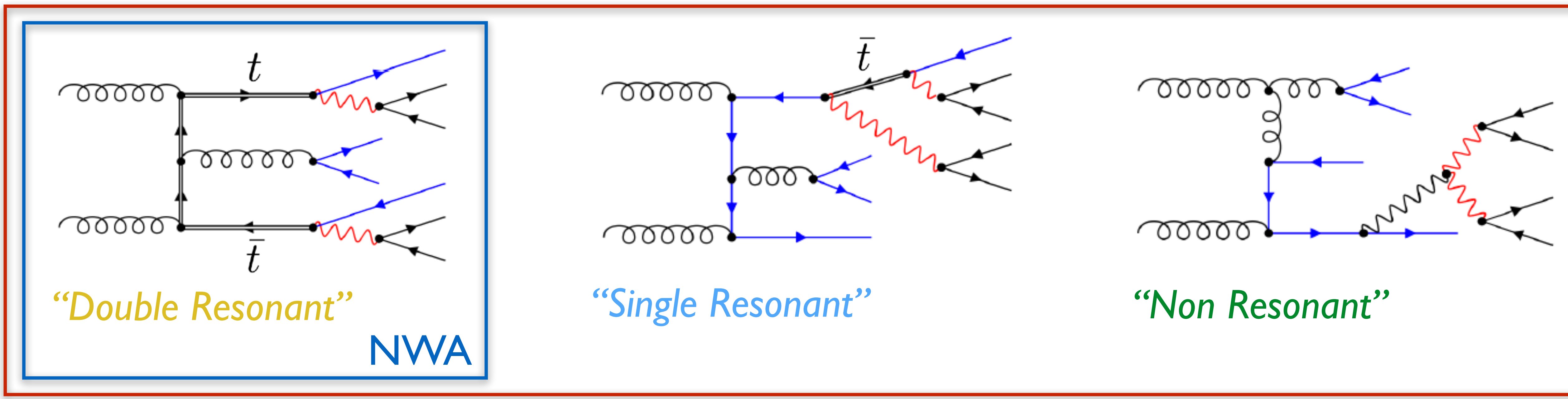
- Complete matrix elements at fixed perturbative order:

  ↪ - 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



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

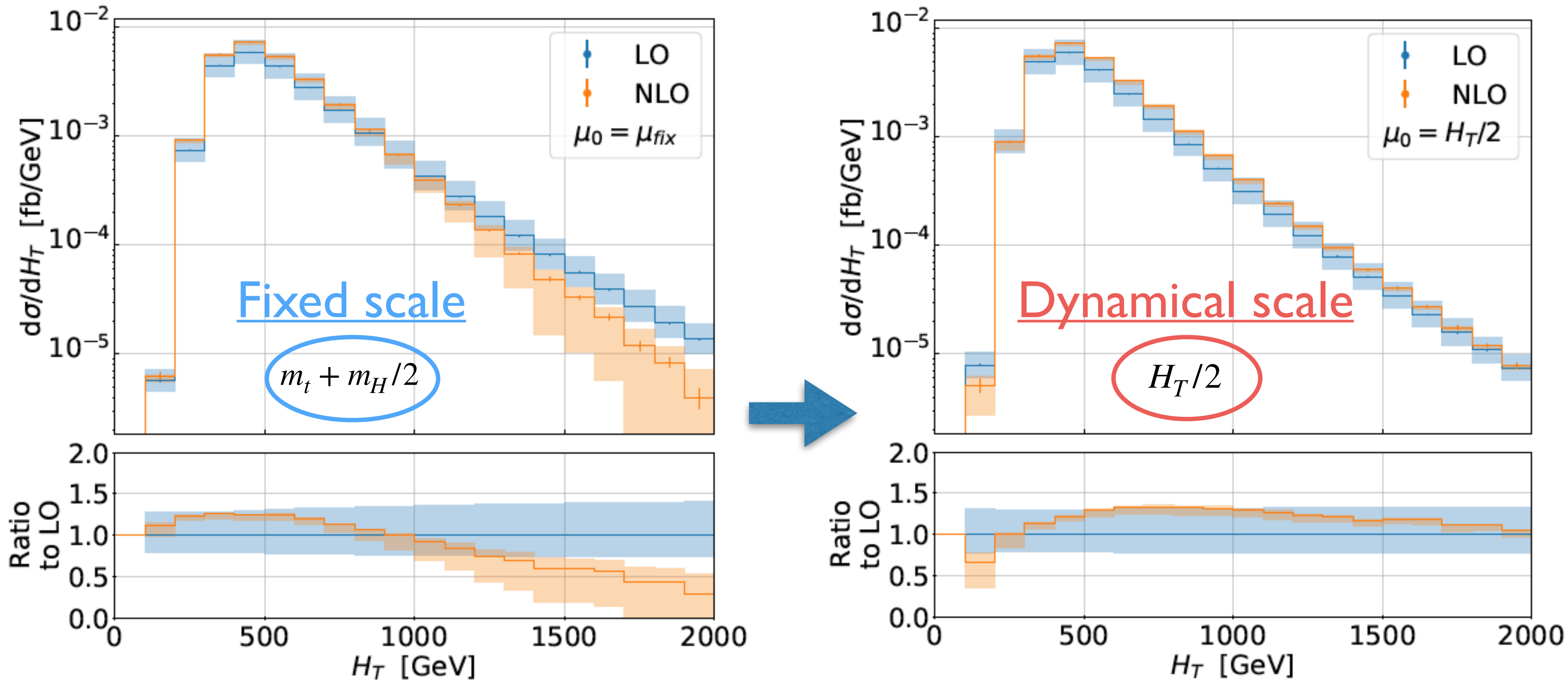
- Genuine *multiscale* process!

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

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

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

- Impact of scale choice and theory uncertainties



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

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

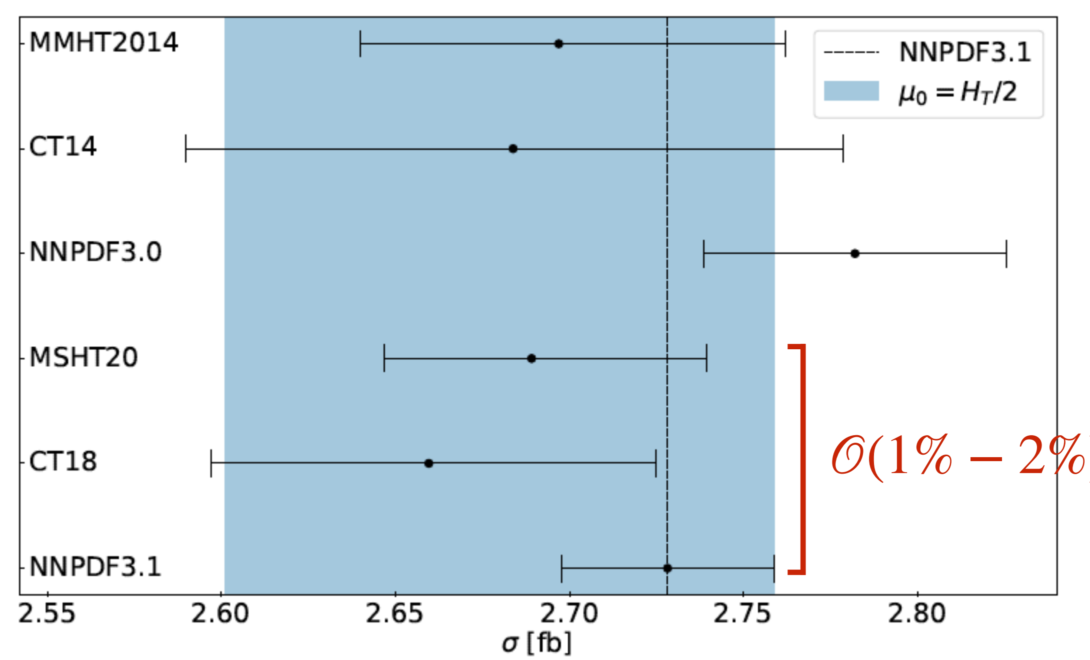
Fiducial cross sections

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

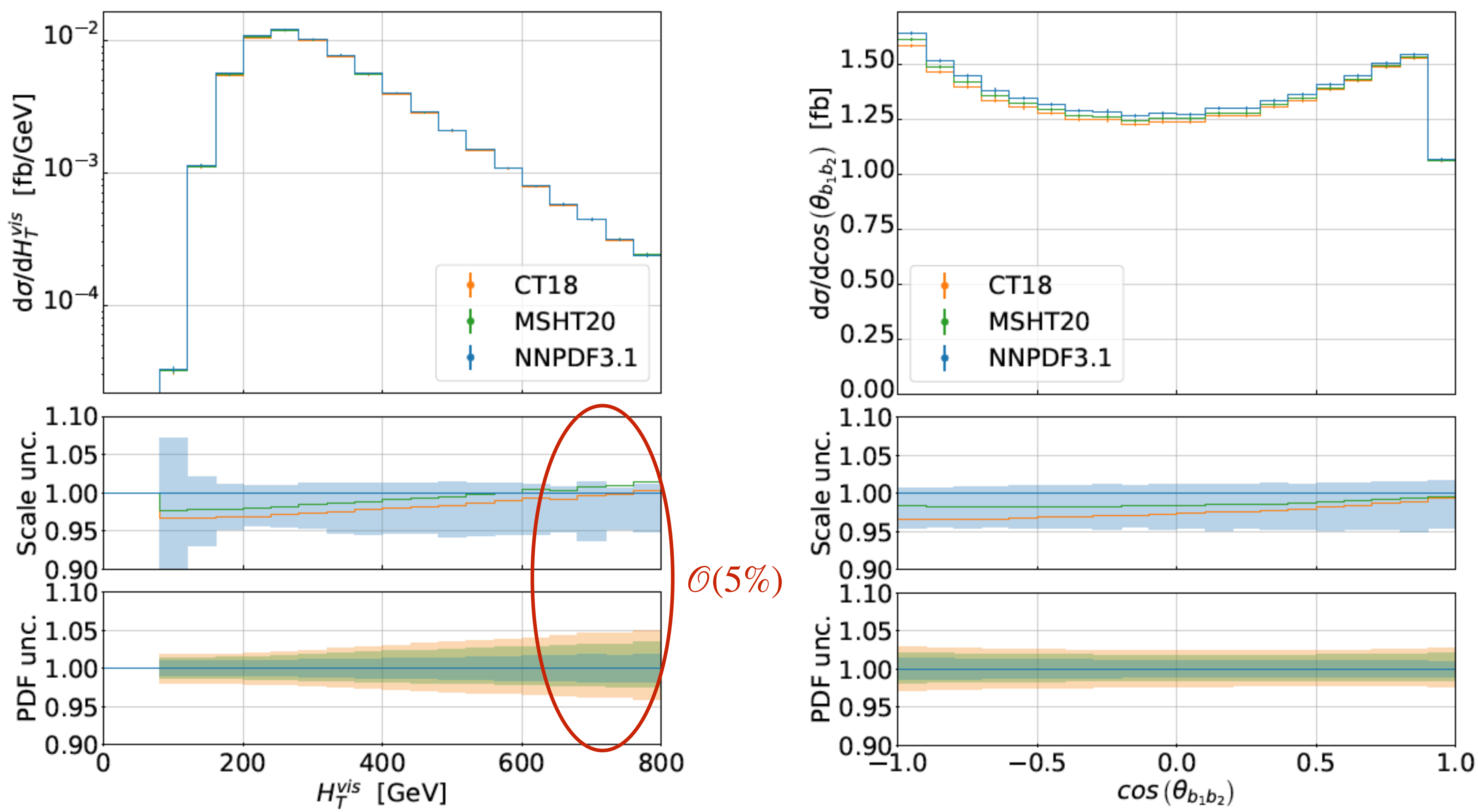
Scale vs PDF uncertainties



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

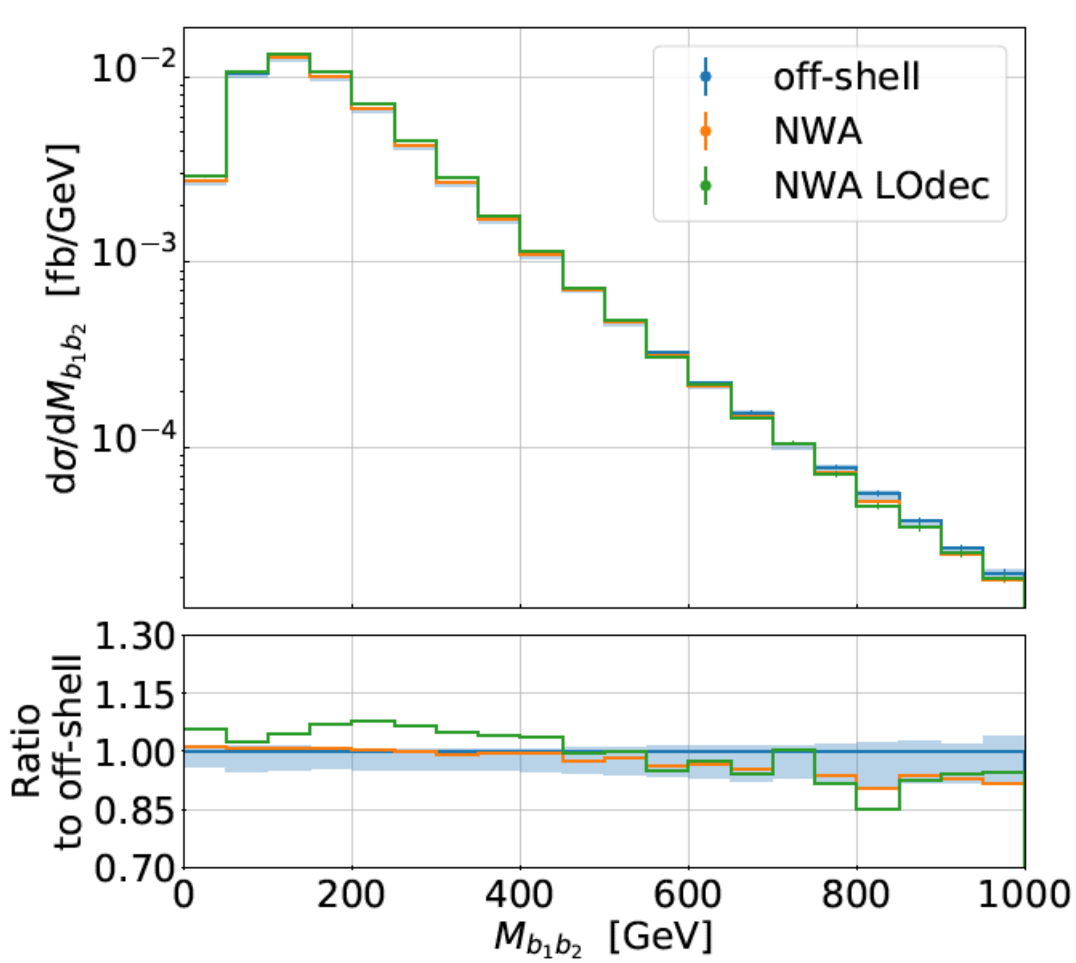
[Stremmer and Worek, JHEP 02 (2022) 196]

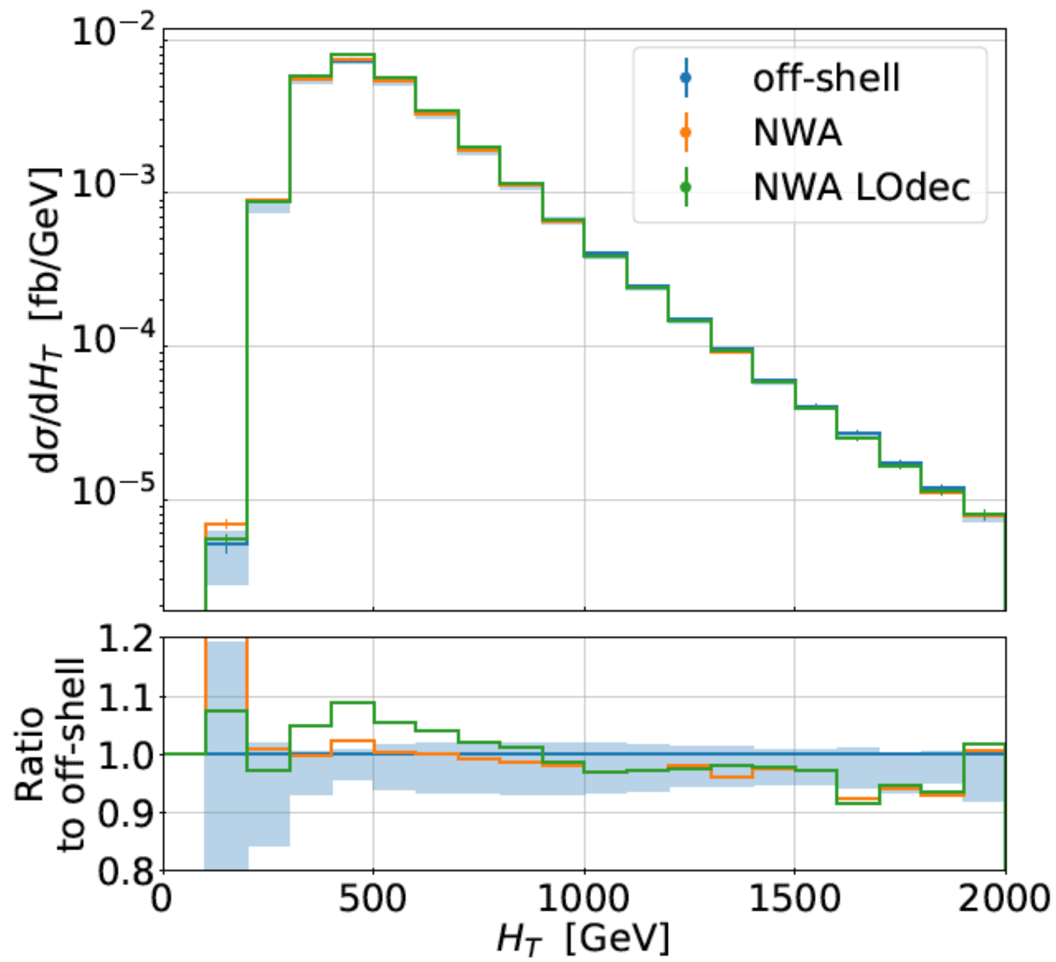
- Off-shell effects for top-quark and W decays

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

scale uncertainties

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

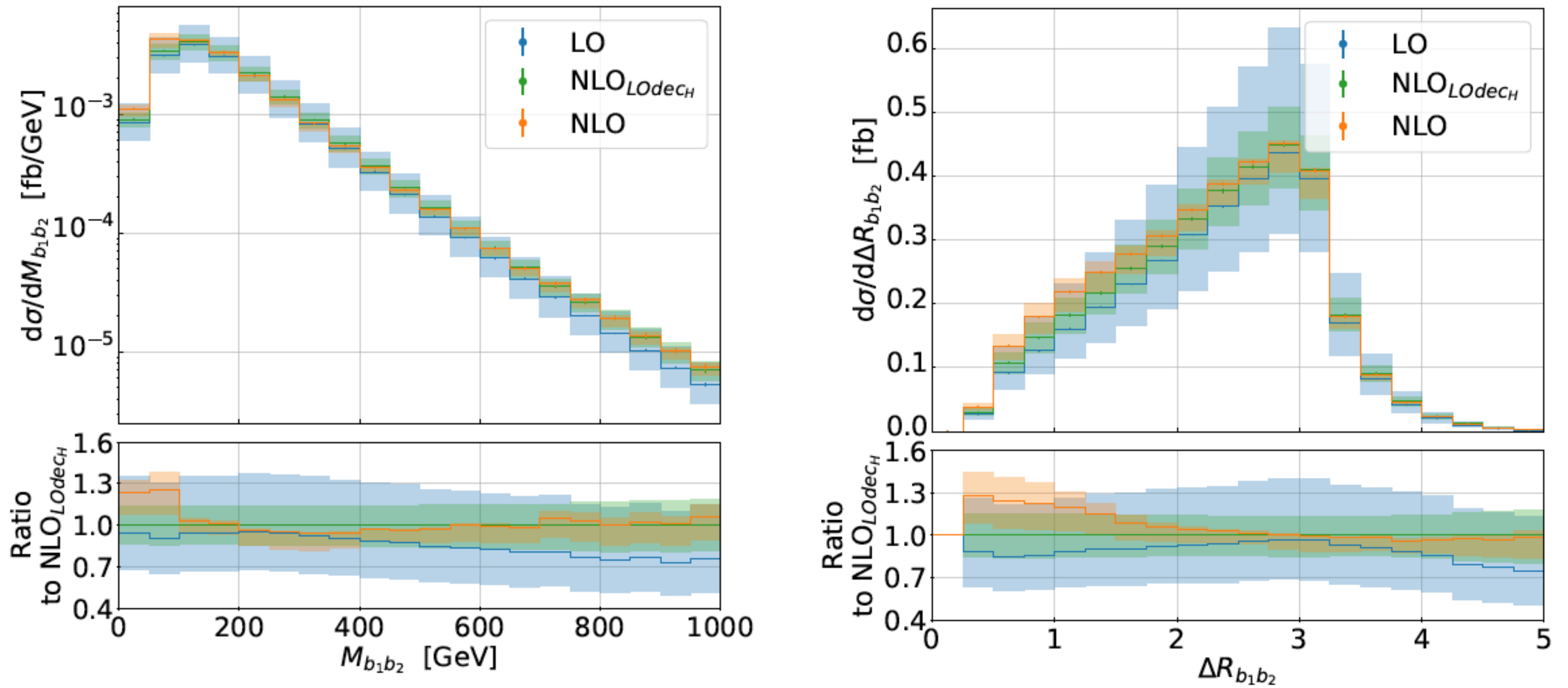




Predictions for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} H(H \to b\bar{b})$

[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

  $\hookrightarrow$ $\Delta R_{b_1 b_2} \approx 3$: 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 $t\bar{t}H(H \to b\bar{b})$

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

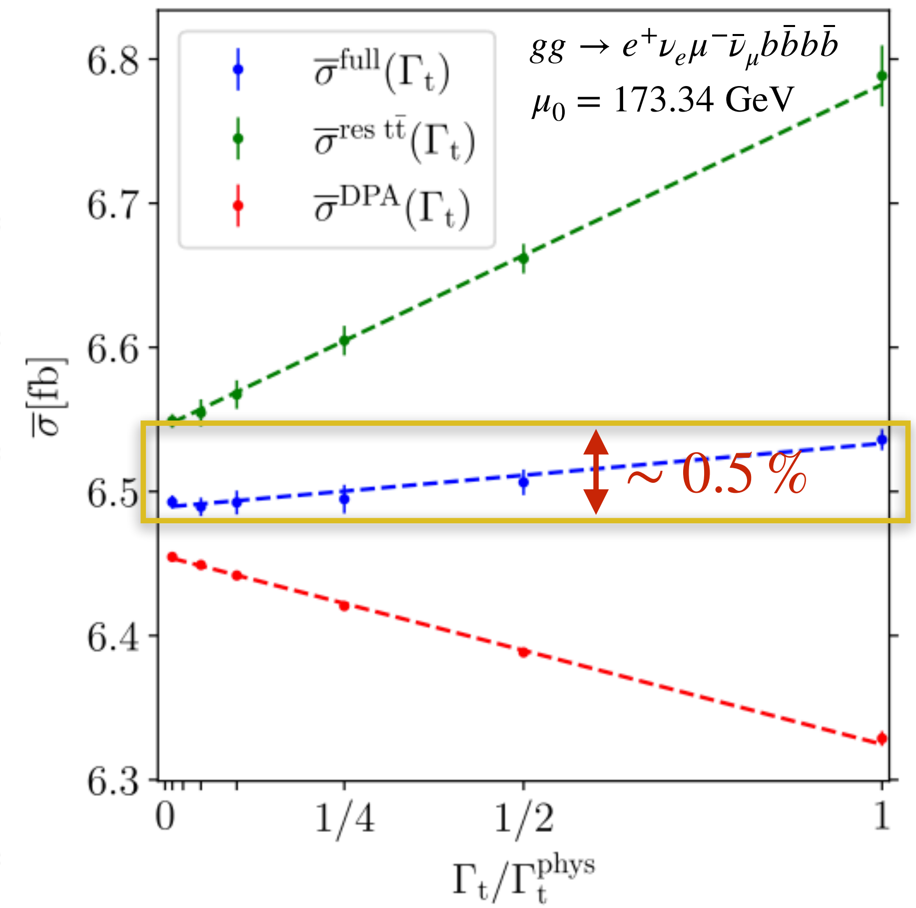
- **Fiducial cross sections** $\sqrt{s} = 13$ TeV

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

[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]

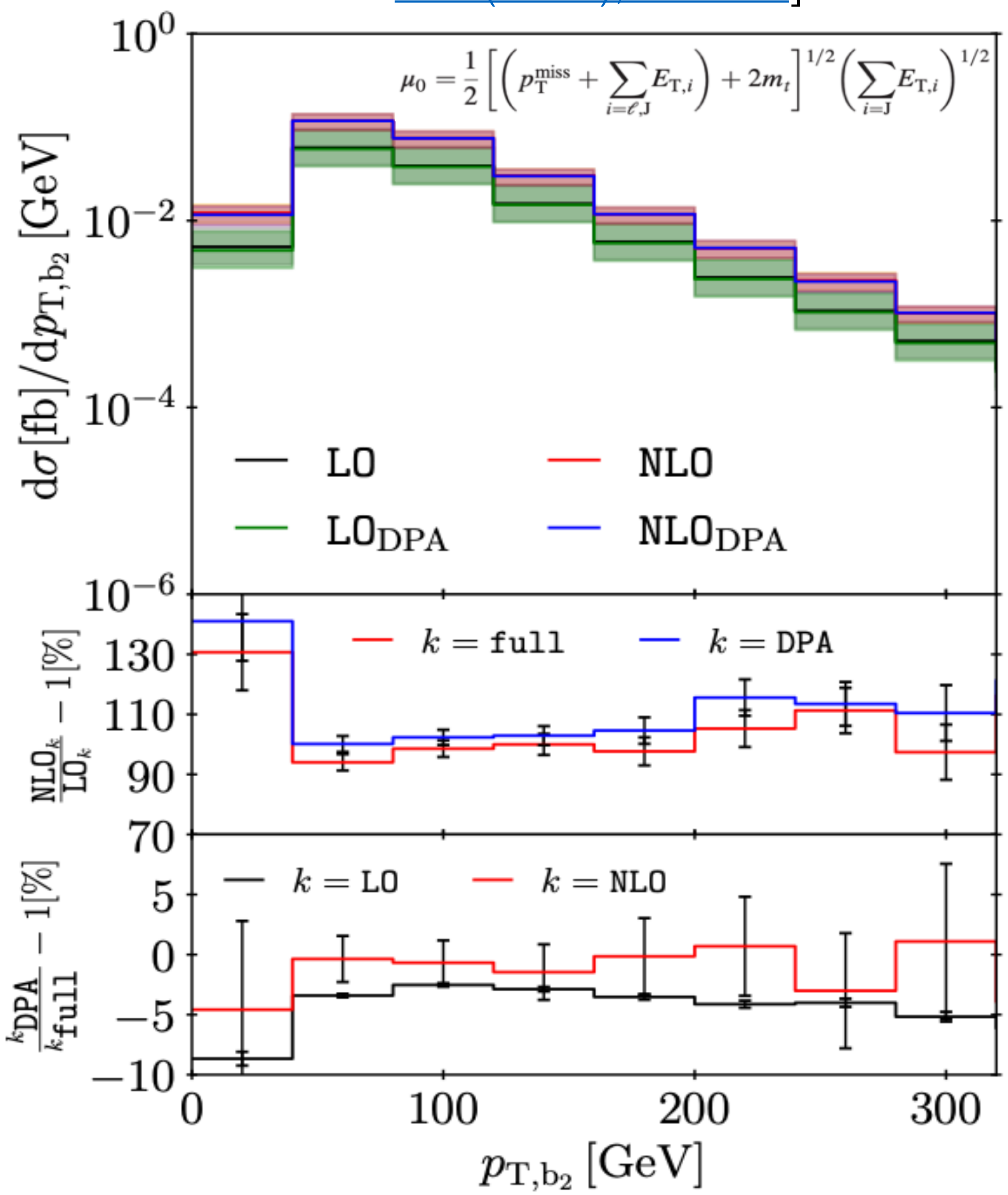


Theory uncertainties:

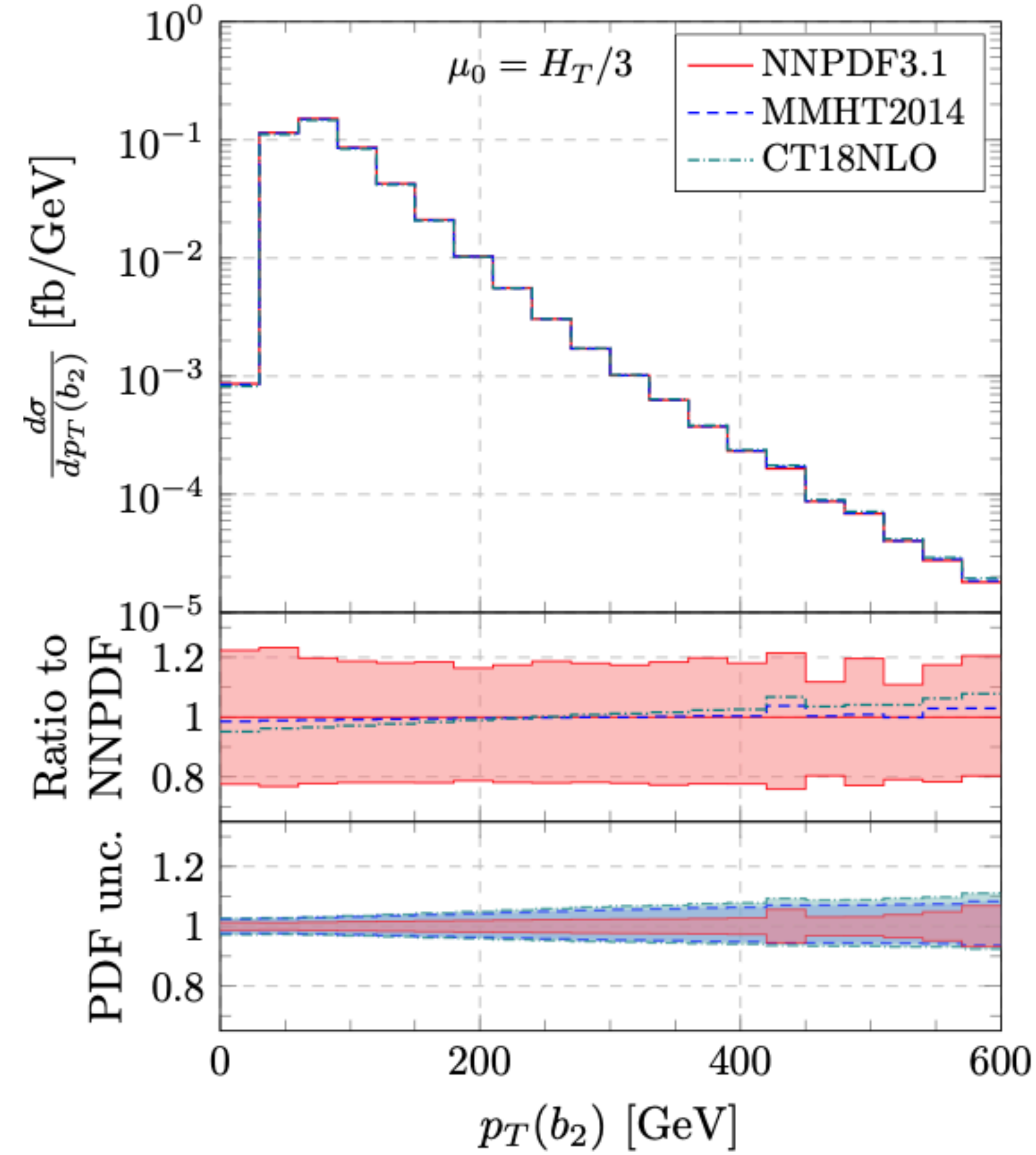
- Scale : $\mathcal{O}(20\%)$
- PDF : $\mathcal{O}(1\% - 2\%)$

- Theory uncertainties at differential level

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



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

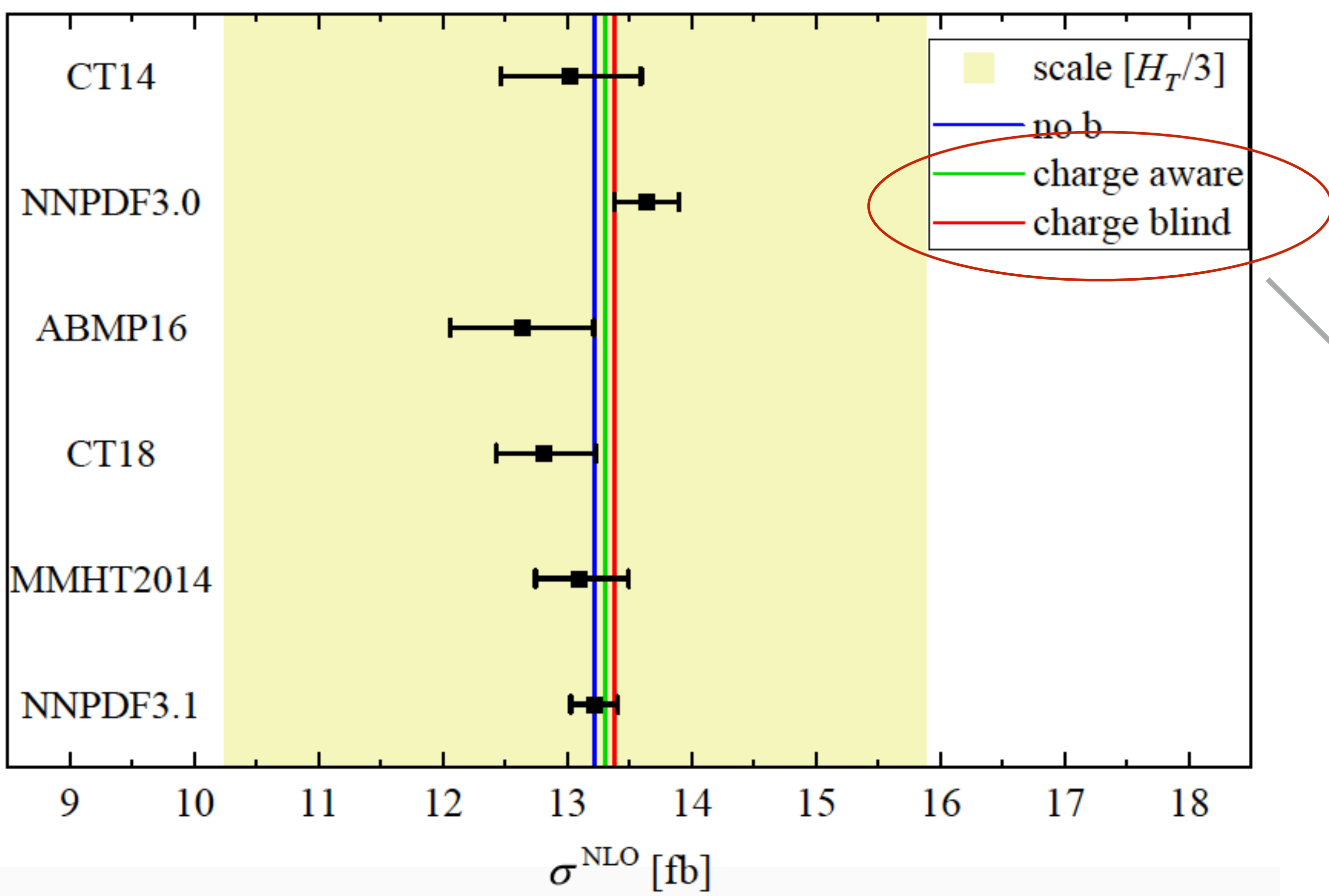


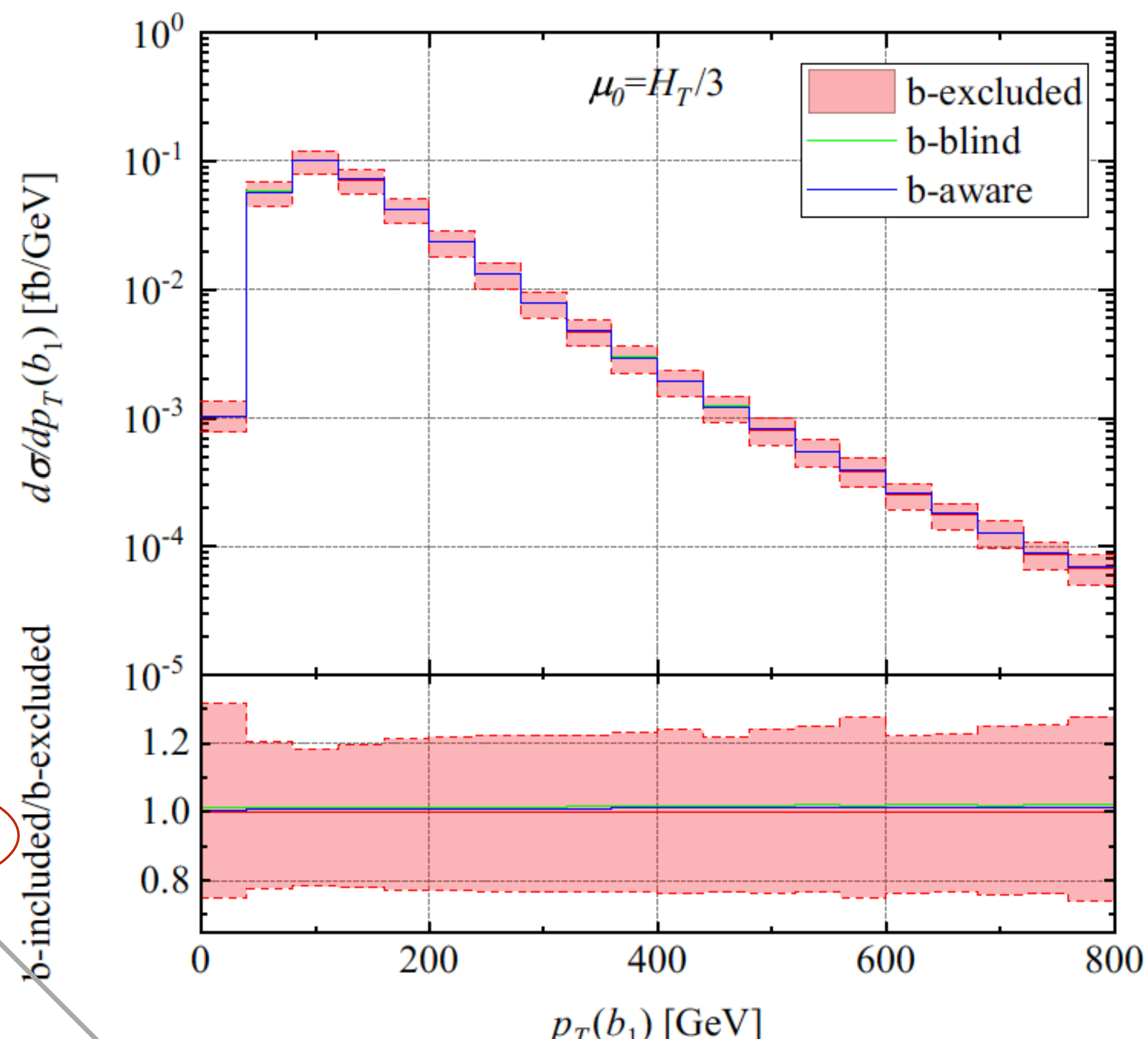
- PDF uncertainties systematically smaller than scale (but can reach 10% in tails)

$t\bar{t}b\bar{b}$: impact of 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"

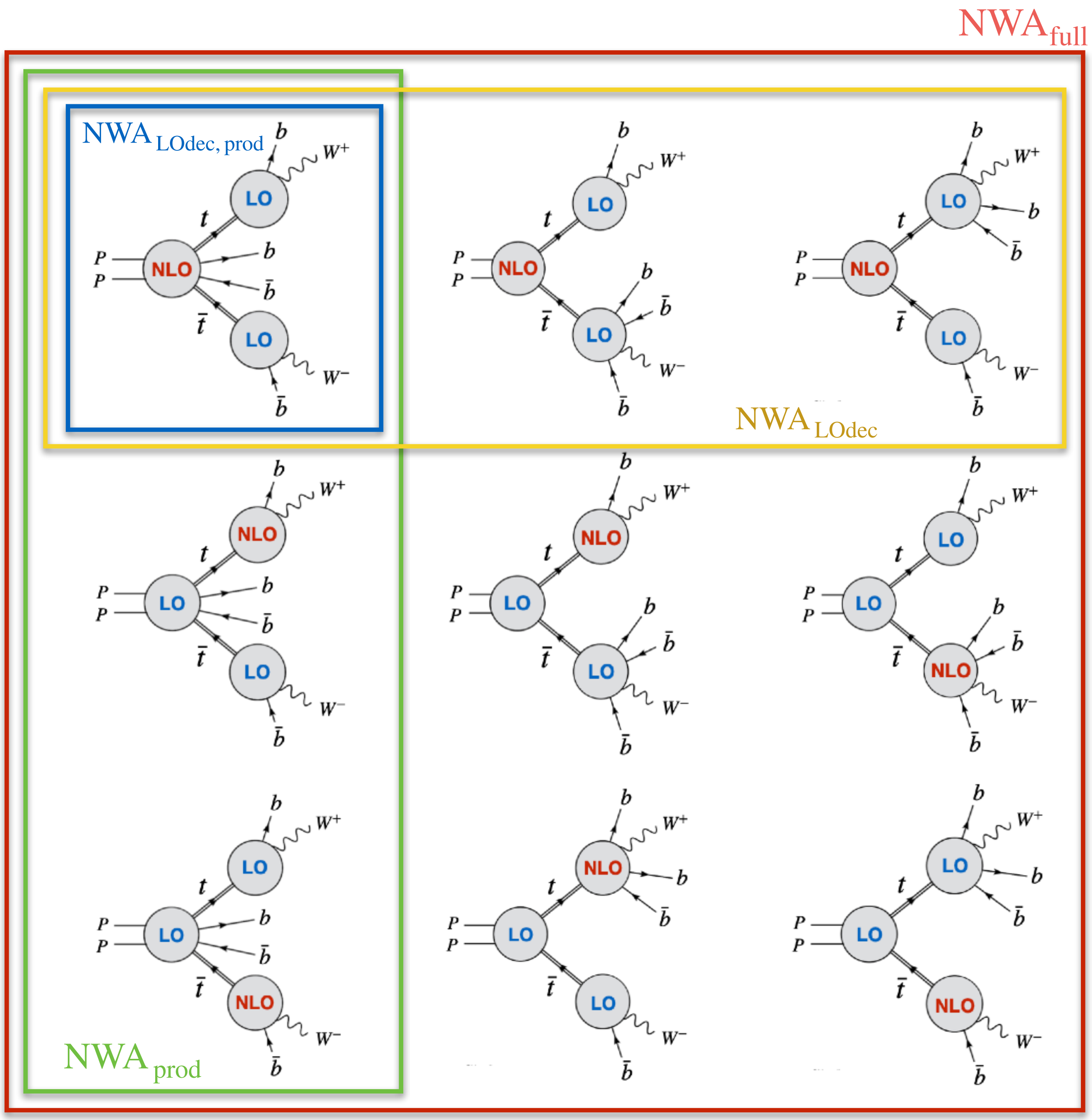
- "Charge blind" → *Cannot* distinguish b- from $\bar{b}$-jets
- "Charge aware" → *Can* distinguish b- from $\bar{b}$-jets

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

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

- Impact of off-shell effects and decay modelling accuracy

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



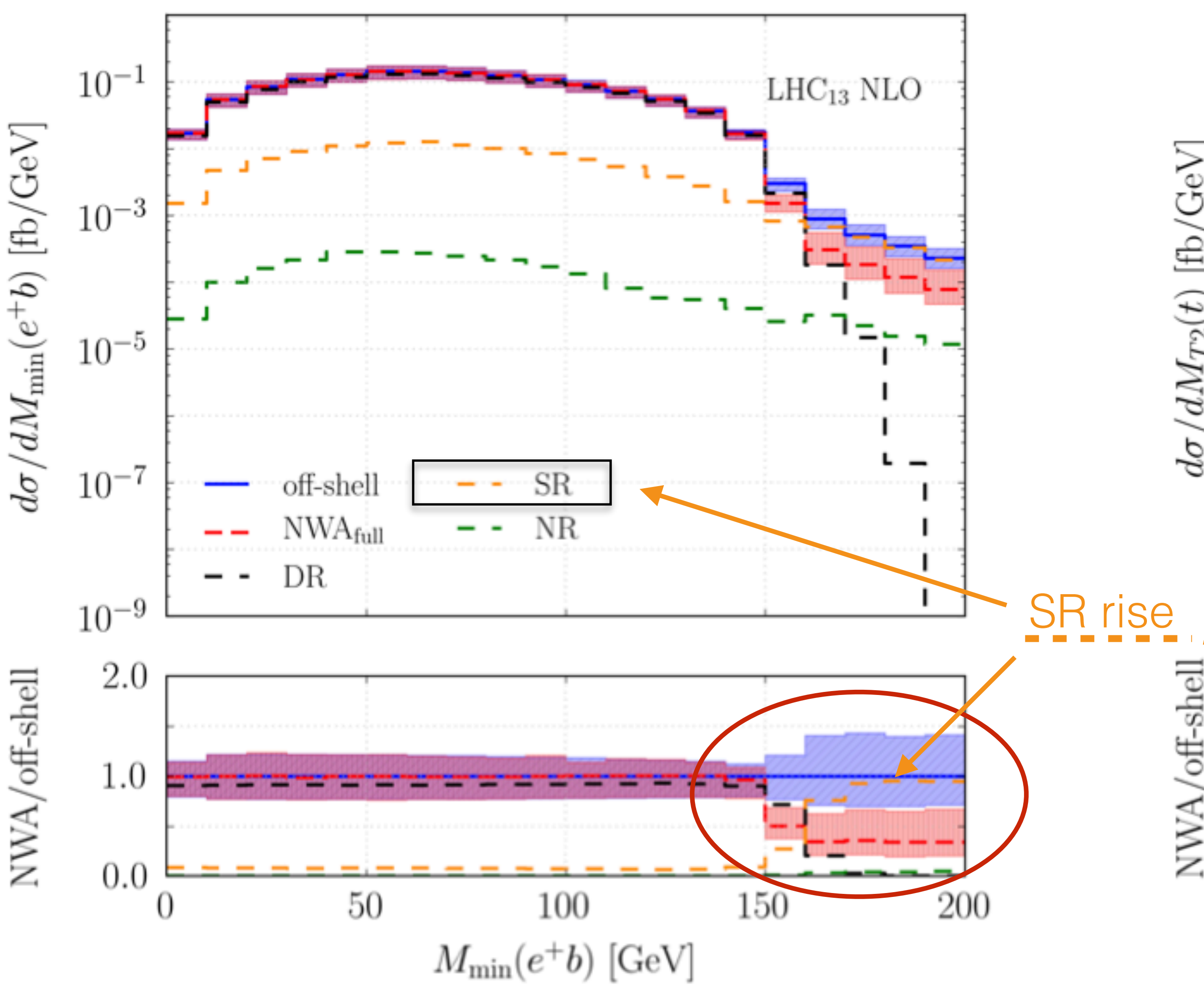
- Complete off-shell effects: $+0.5\ \%$
- $\mathrm{NWA_{LOdec}}$ agrees well with Off-shell [but scale uncertainties are larger]

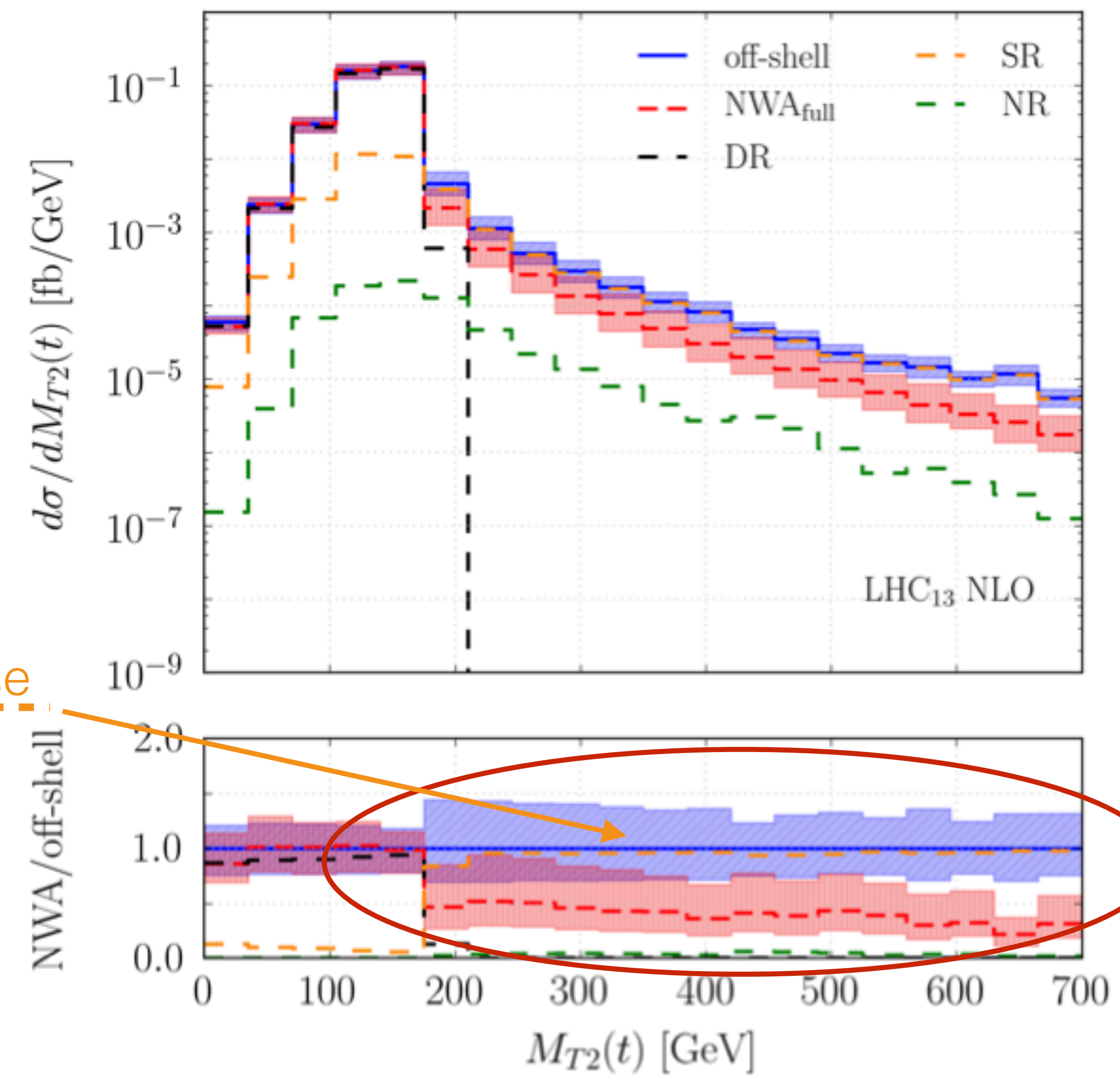
↪ Interplay among different resonant contributions to $\mathrm{NWA_{full}}$

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

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

- For most observables, off-shell effects are few permille also *differentially*
- *Threshold observables* are naturally more sensitive to off-shell effects:





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

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

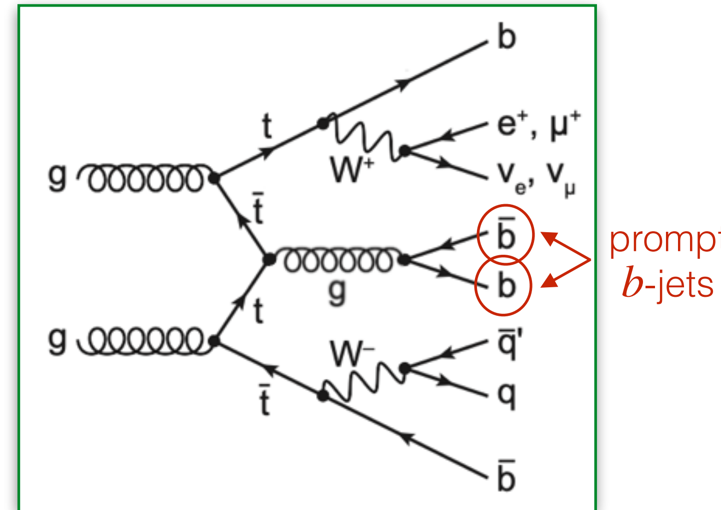
$t\bar{t}b\bar{b}$: prompt b-jet identification

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

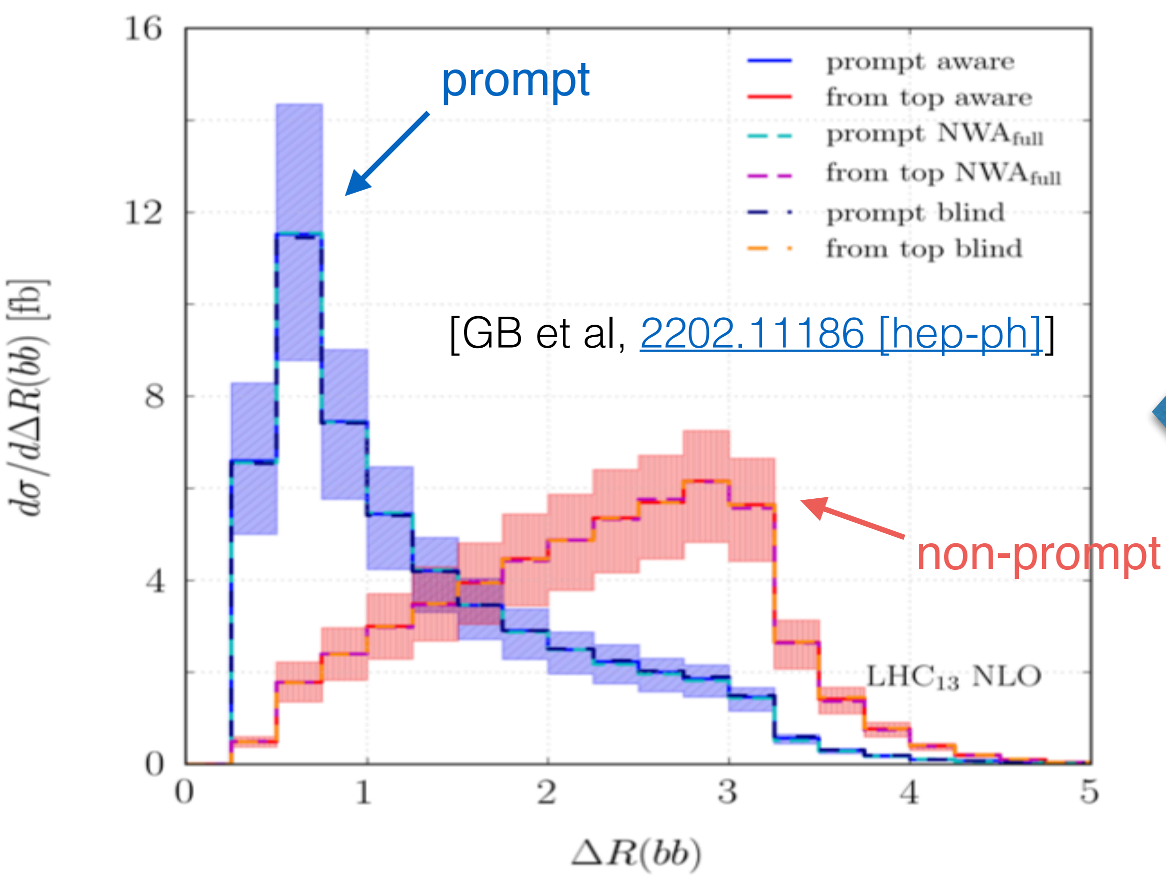
- Labelling prompt b-jets in $t\bar{t}b\bar{b}$ is not free of ambiguities in a full calculation (combinatorial background, interferences…)
- Kinematic-based prescription: reconstruct top quarks and prompt b's according to minimum principle for $\mathcal{Q}$:

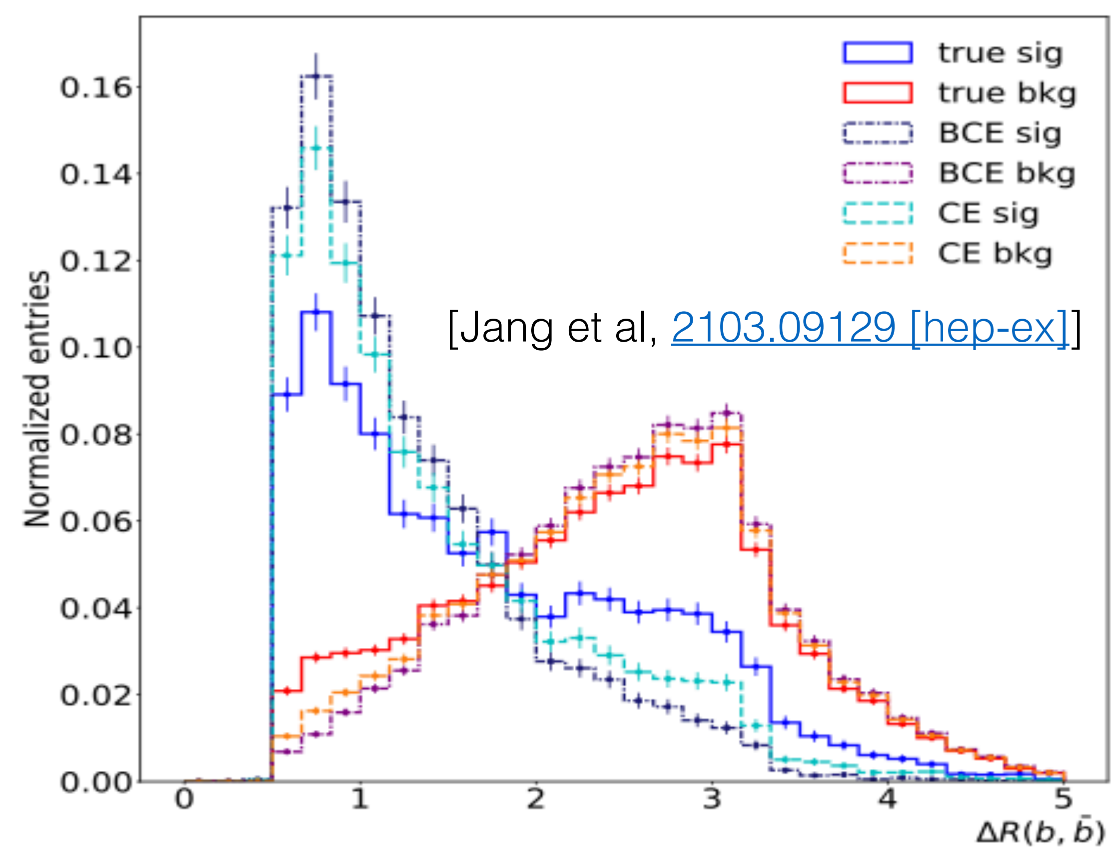
$$\mathcal{Q} = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times |M^{\text{prompt}}(bb)|$$

- Results consistent with expectations from NN studies



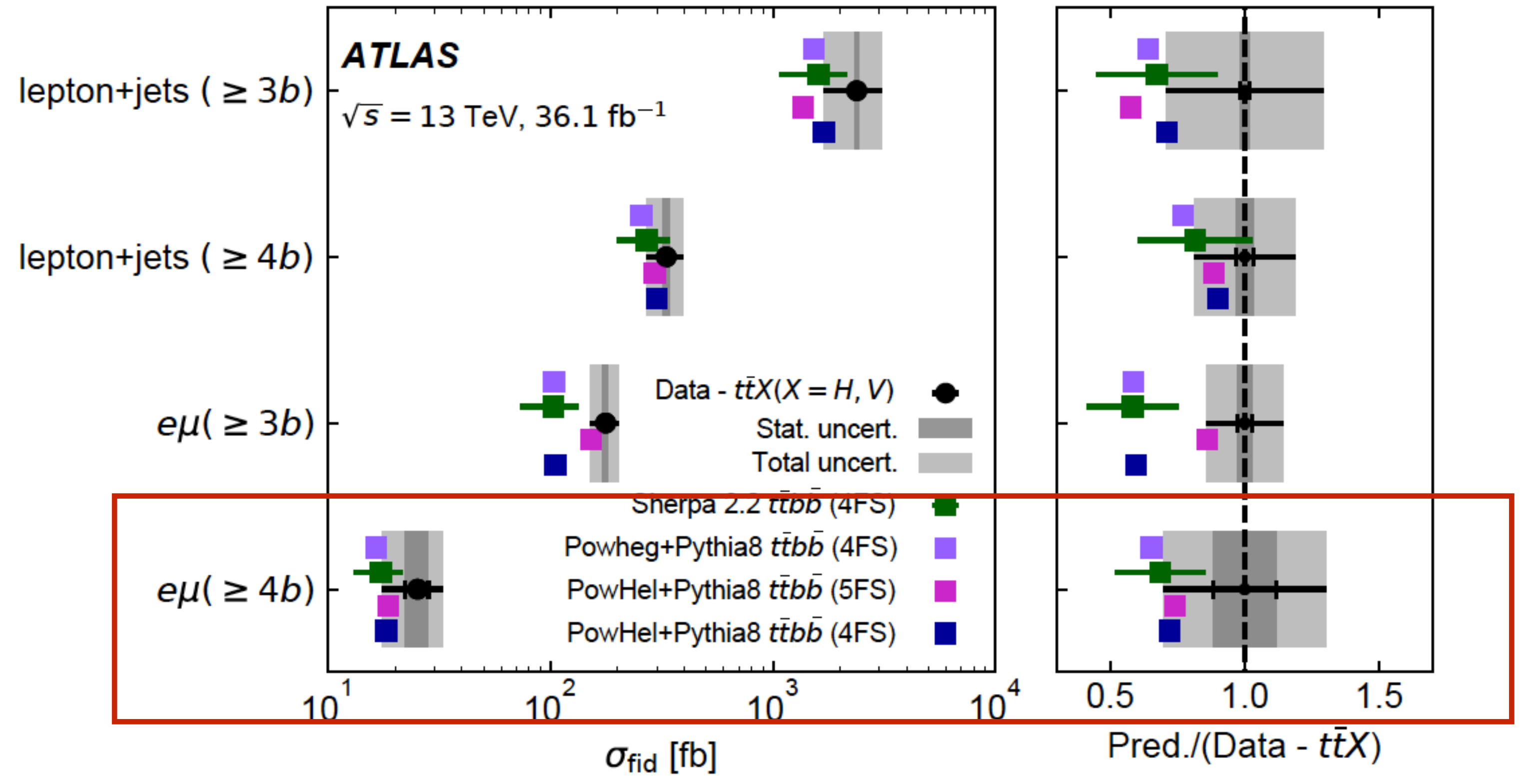
$$t \to W^+ b \qquad \bar{t} \to W^- \bar{b} \qquad g \to b\bar{b}$$





- 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

- 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

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:

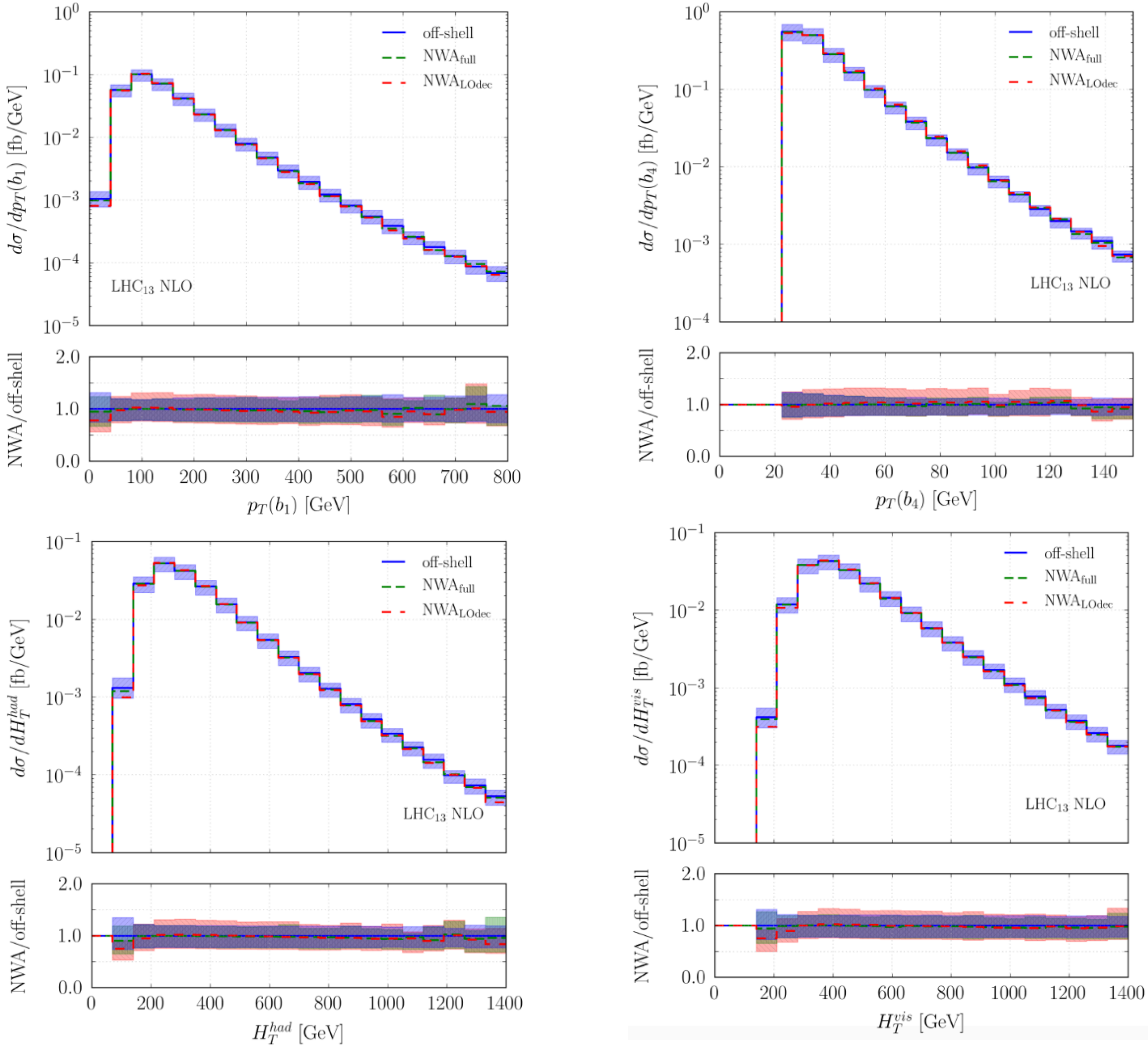
"Charge blind" vs "Charge aware" [see *e.g.* ATLAS-CONF-2018-022]

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

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

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

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



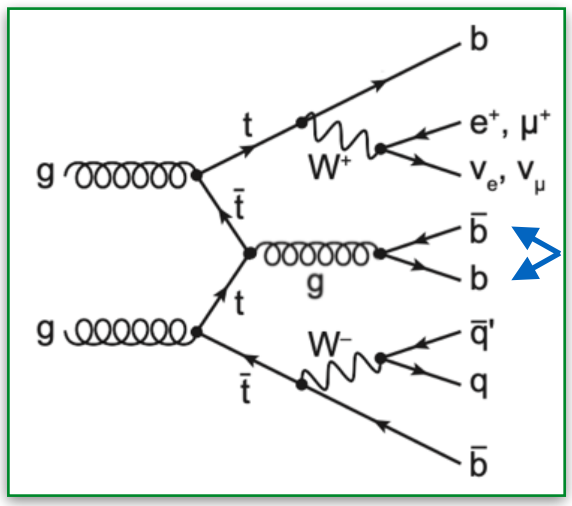
$$H_T^{had} = \sum_{i=1}^{4} p_T(b_i)$$

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

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



prompt b-jets