Off-shell $t\bar{t}b\bar{b}$ at the LHC:
on the size of corrections and b-jet definitions

Giuseppe Bevilacqua

ELKH-DE Particle Physics Research Group, Debrecen

XLIV International Conference of Theoretical Physics
"Matter To The Deepest"

Online edition
September 16, 2021

G.B., H.Y. Bi, H. B. Hartanto, M. Kraus, M. Lupattelli and M. Worek,
JHEP 08 (2021) 008 [arXiv:2105.08404 [hep-ph]]

Outline

- Introduction
  - Motivations for ttbb at the LHC
  - State of the art
  - The need for precision
- Off-shell ttbb at NLO QCD
  - Comparisons with literature
  - Dominant theory uncertainties
  - Size of QCD corrections
  - Impact of b-initiated subprocesses
- Summary and outlook

Motivations for ttbb at the LHC

Measurements of $pp \to t\bar{t}H \; (H \to b\bar{b})$ are challenging!

- **Signal:**

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

- **Reducible background:**

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

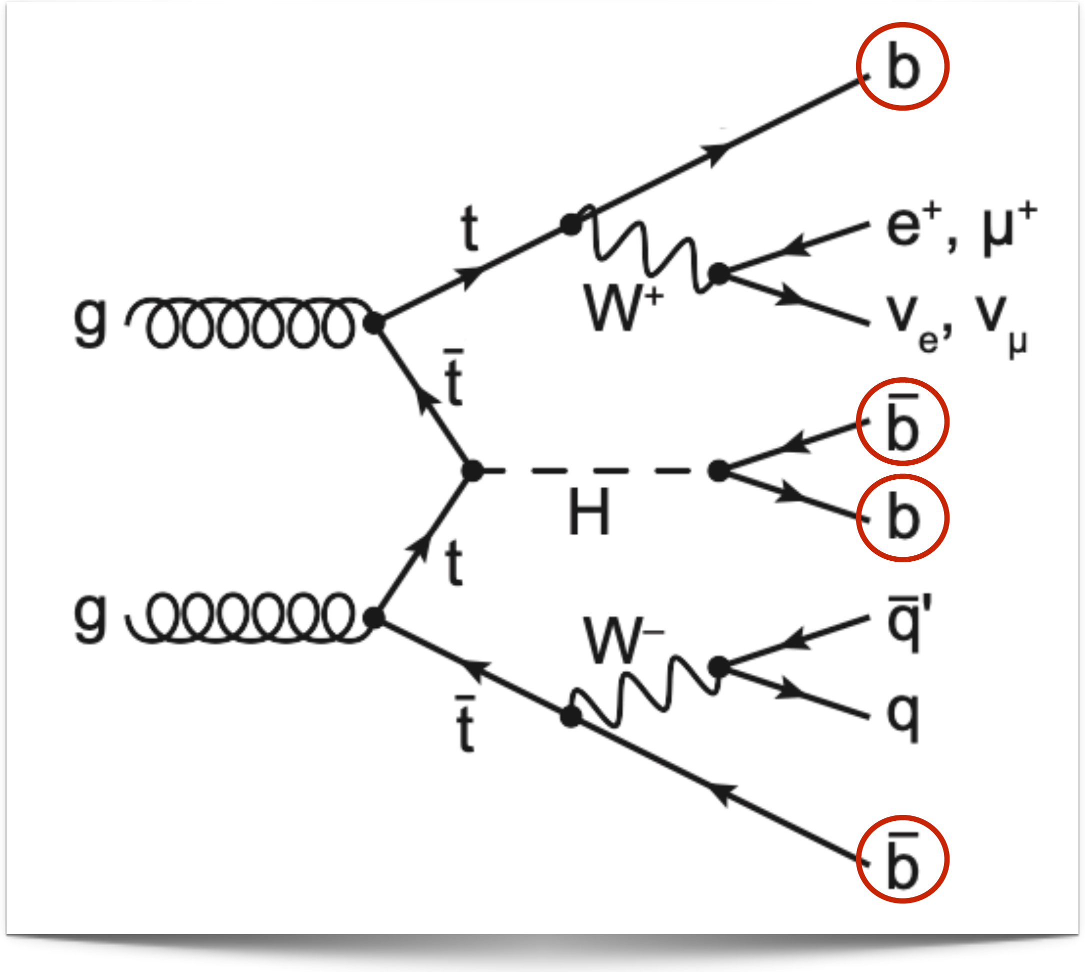
- **Irreducible background:**

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

- **Combinatorial background:**

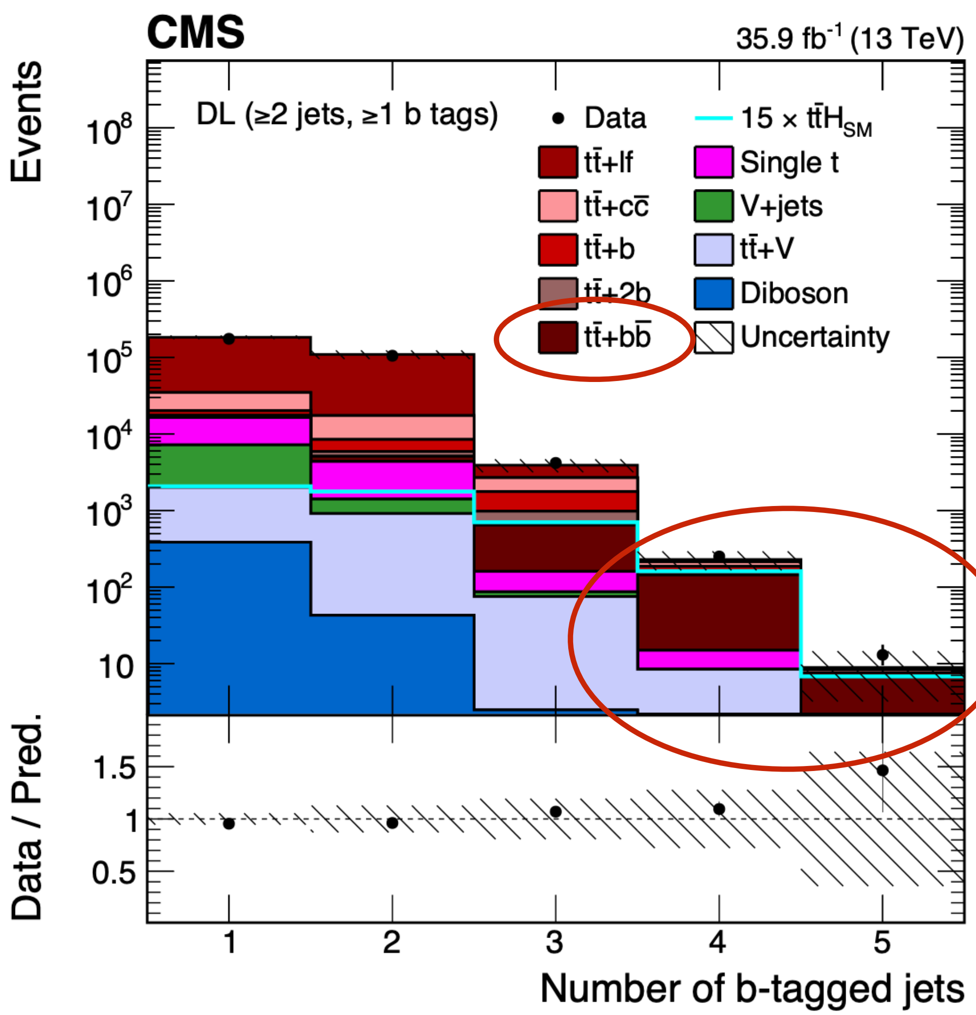
  $t \to W^+ b \qquad \bar{t} \to W^- \bar{b} \qquad H \to b\bar{b}$

  → smearing of Higgs peak in $M(b\bar{b})$, challenges in top reconstruction

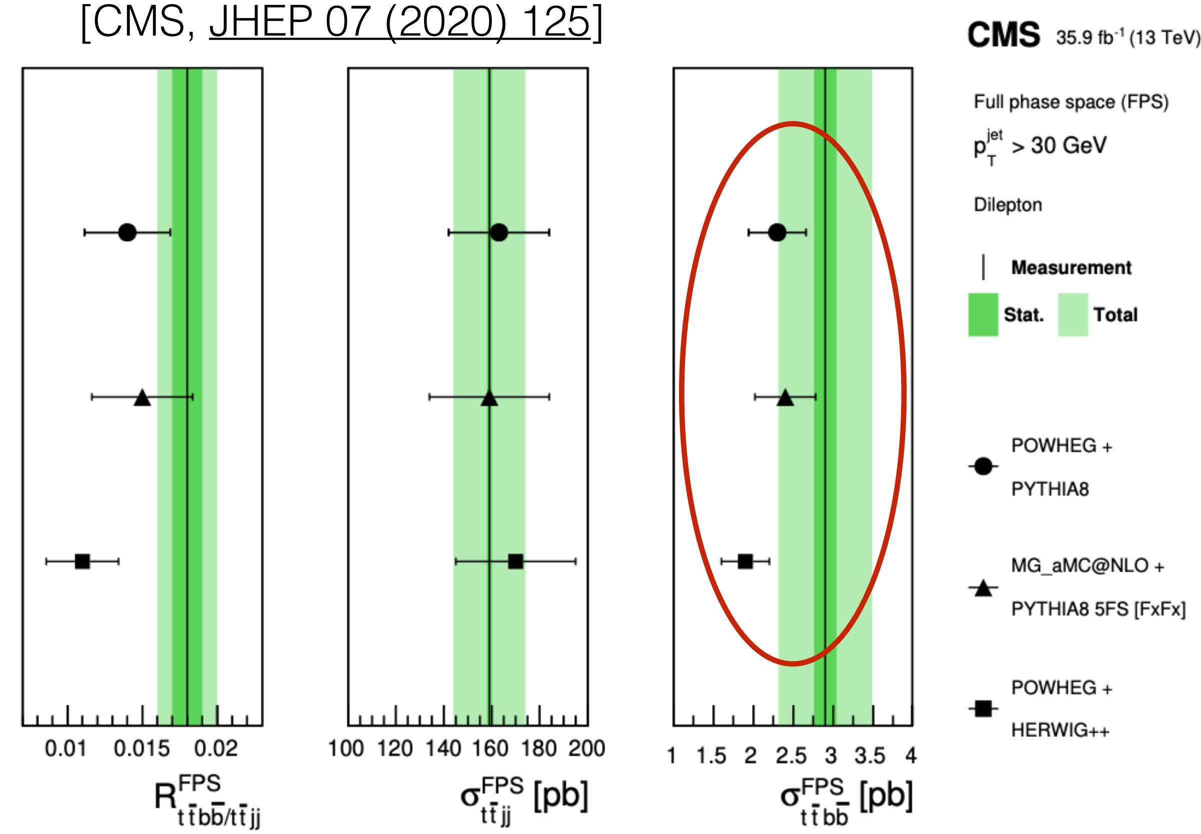


Motivations for ttbb at the LHC

[CMS, JHEP 03 (2019) 026]



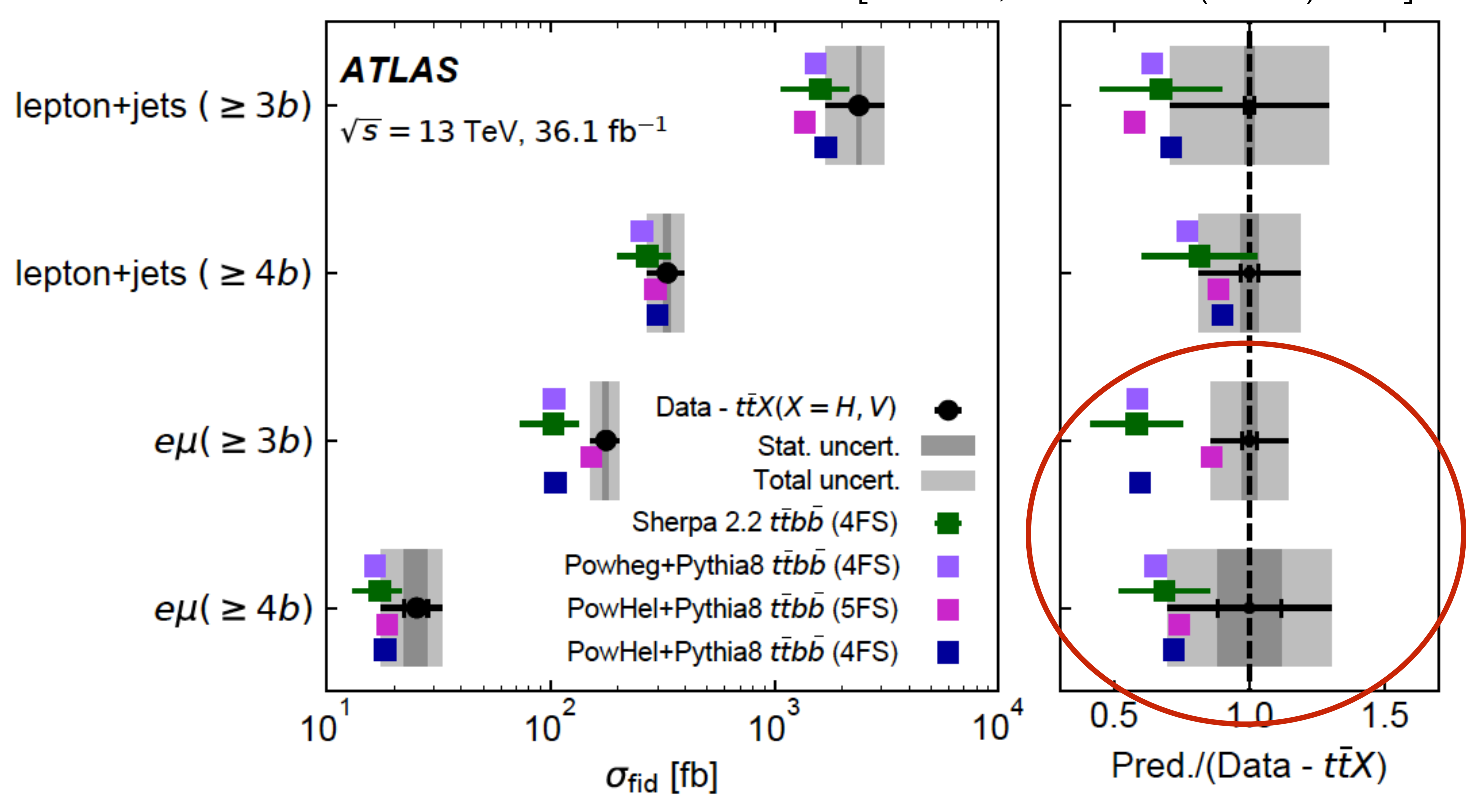
[CMS, JHEP 07 (2020) 125]



- $pp \to t\bar{t}b\bar{b}$: main background for $N_{b\,jets} \geq 4$

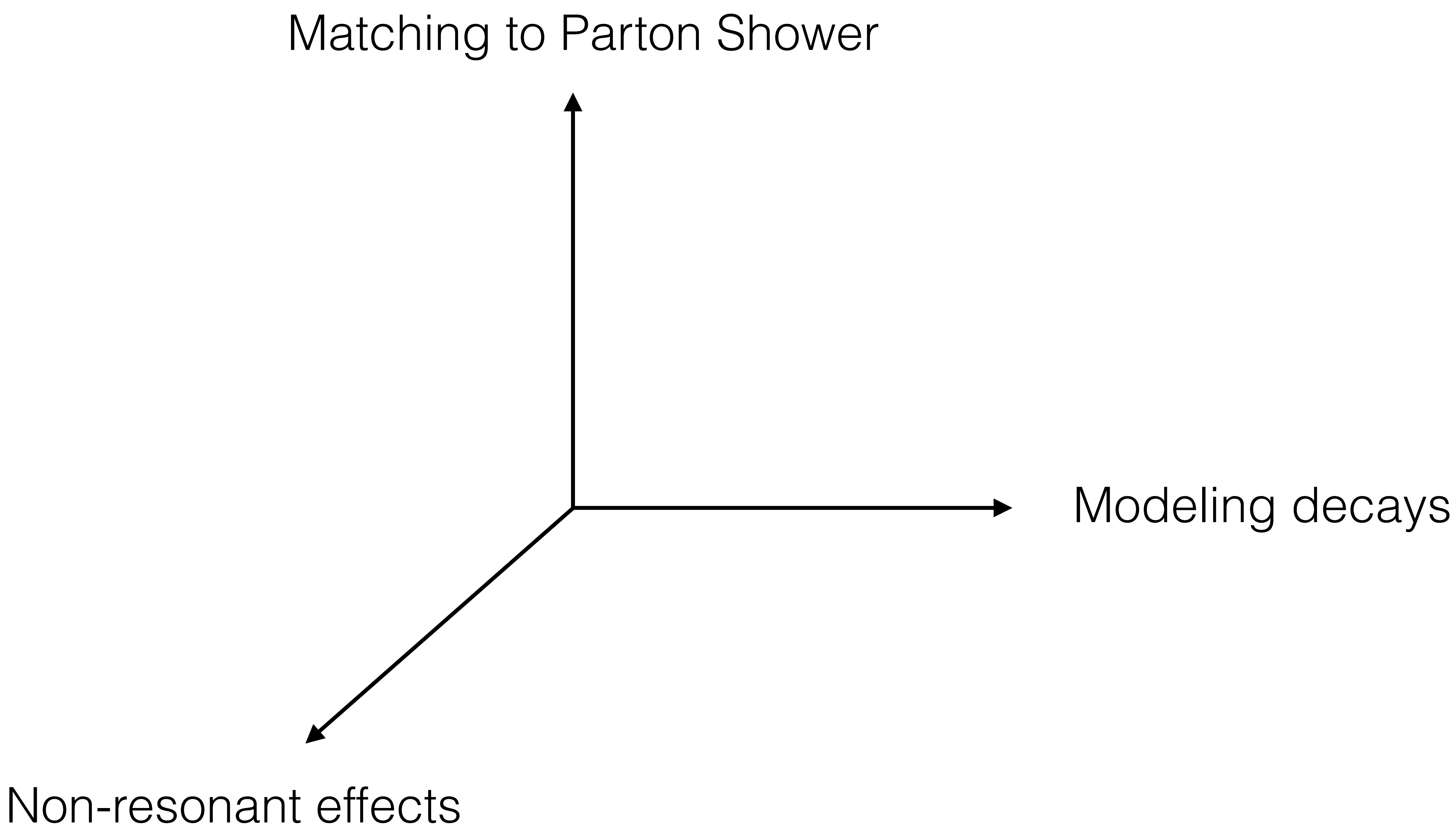
- Current ttbb predictions are systematically below data

[ATLAS, JHEP 04 (2019) 046]



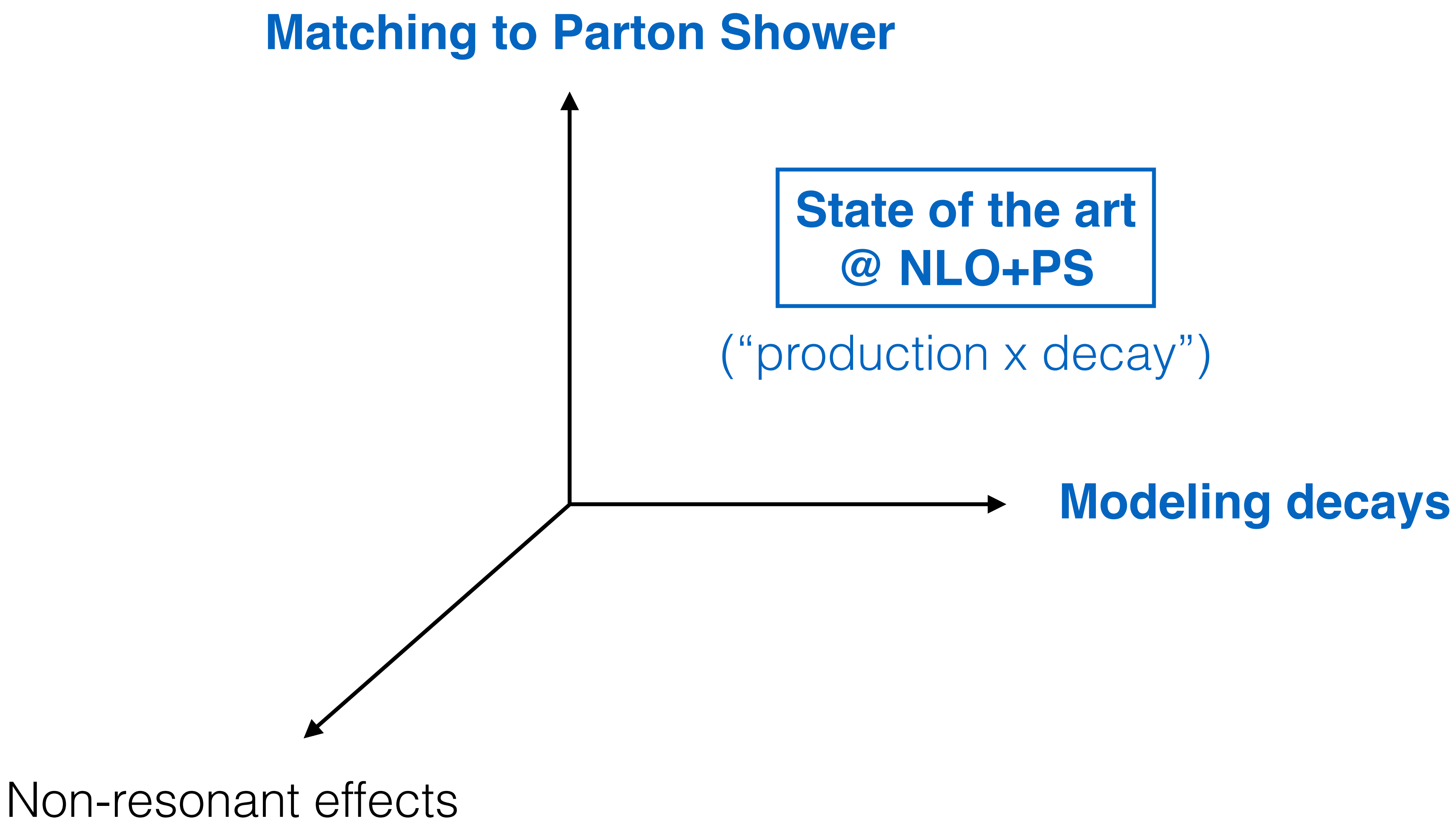
Paths to precision

- Realistic **final states** —> incorporate decays and Parton Shower
- Realistic **resonant structures** —> incorporate “off-shell” contributions into ME



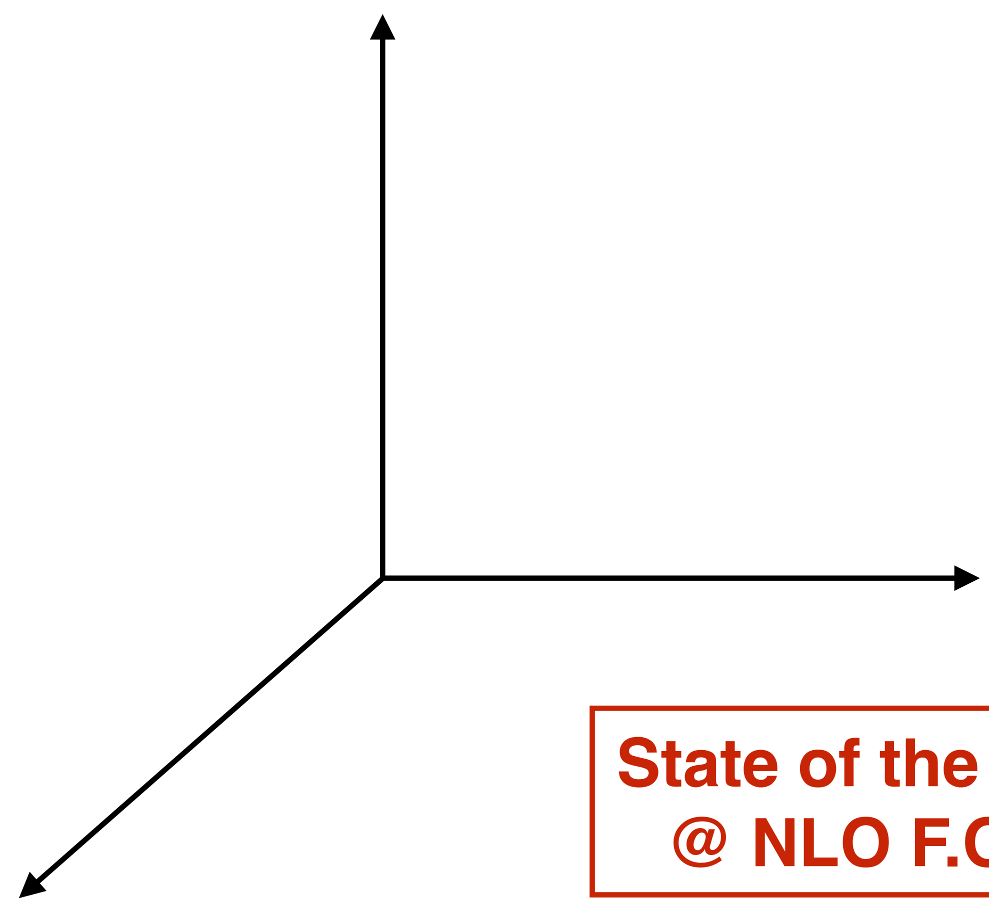
Paths to precision

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



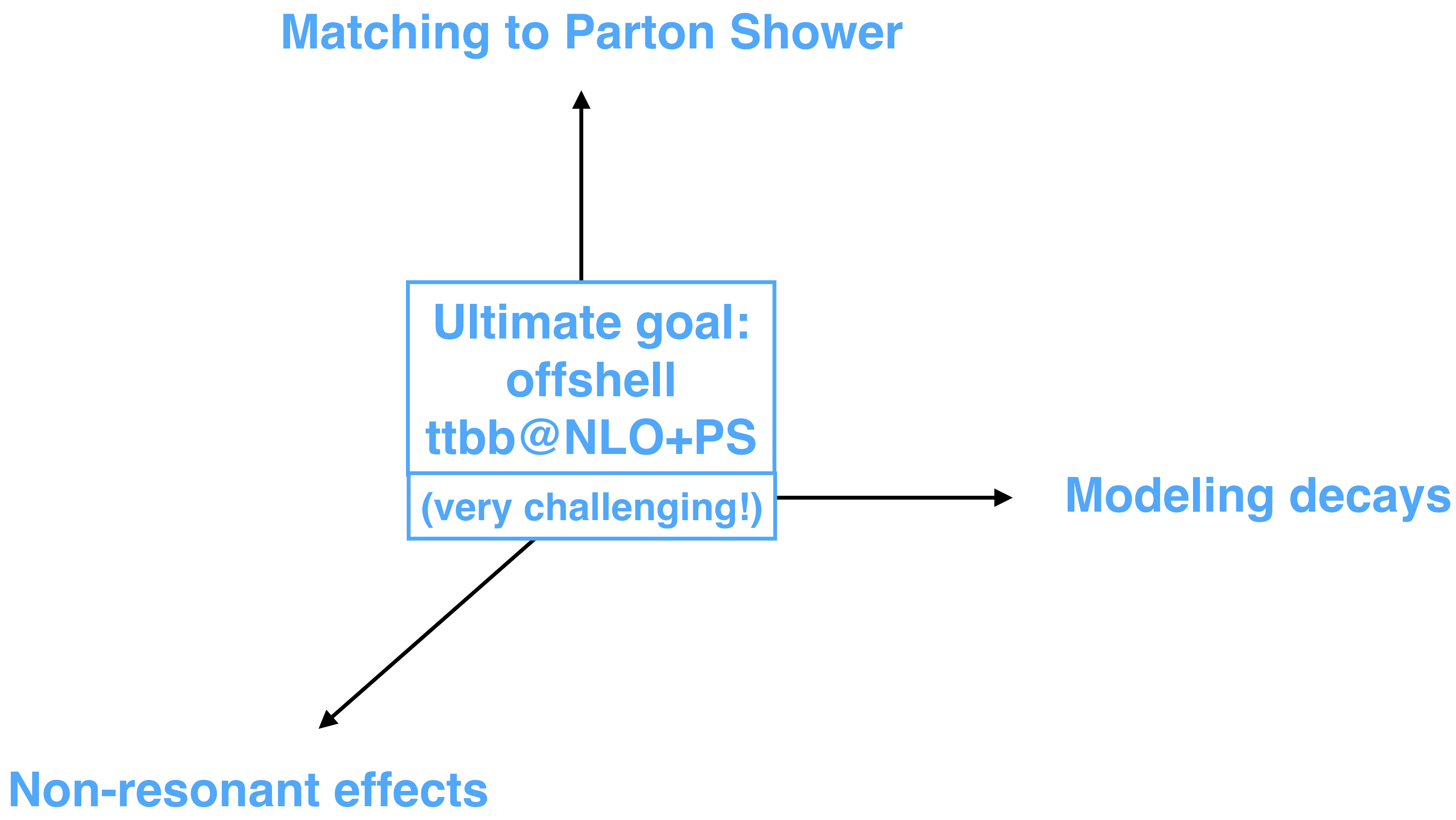
Paths to precision

- Realistic **final states** —> incorporate decays and Parton Shower
- Realistic **resonant structures** —> incorporate “off-shell” contributions into ME



Paths to precision

- Realistic **final states** —> incorporate decays and Parton Shower
- Realistic **resonant structures** —> incorporate “off-shell” contributions into ME



Theory status of ttbb

State of the art: NLO QCD

Fixed Order

- $pp \to t\bar{t}b\bar{b}$ — 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

Matched to Parton Shower

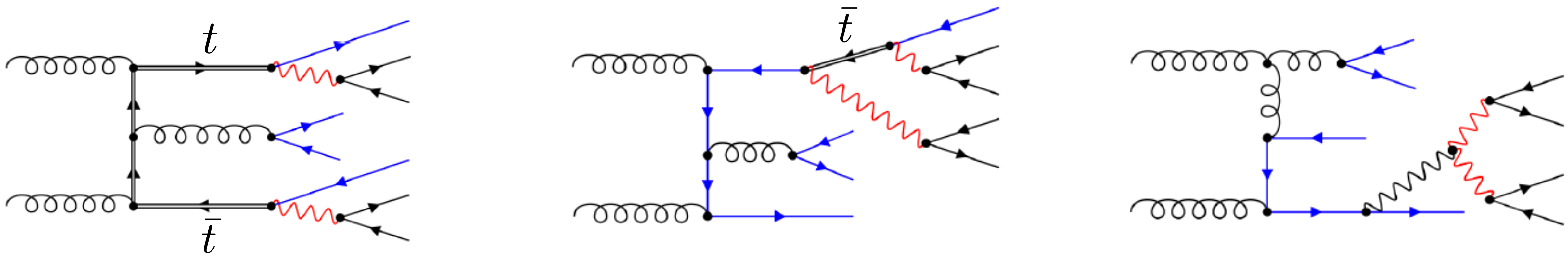
- POWHEG matching
  - Garzelli, Kardos and Trocsanyi '14 '15 [5FS]
  - GB, Garzelli, Kardos '17 [4FS]
  - Jezo, Lindert, Moretti, Pozzorini '18 [4FS]
- MC@NLO matching
  - Cascioli, Maierhofer, Moretti, Pozzorini, Siegert '14 [4FS]

Computational setup

- NLO QCD corrections to $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu b\bar{b}b\bar{b}$ $\longrightarrow$ $\mathcal{O}(\alpha_s^5 \alpha^4)$

  [5-Flavor Scheme]

- *Complete* calculation at fixed order —> no on-shell approximation



Double Resonant | Single Resonant | Non Resonant

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

- Genuine *multiscale* process —> m_t not necessarily the "most natural" scale

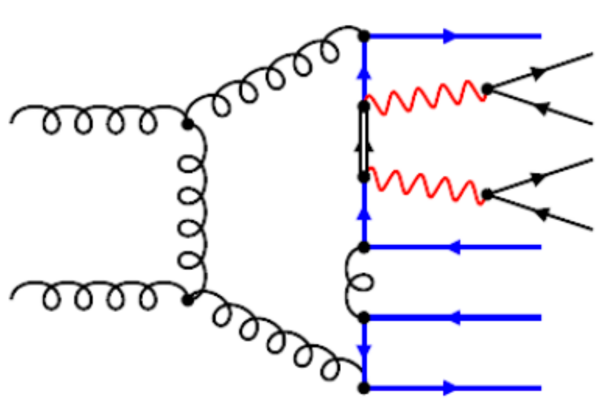
A glimpse at the complexity

- First NLO computation of “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



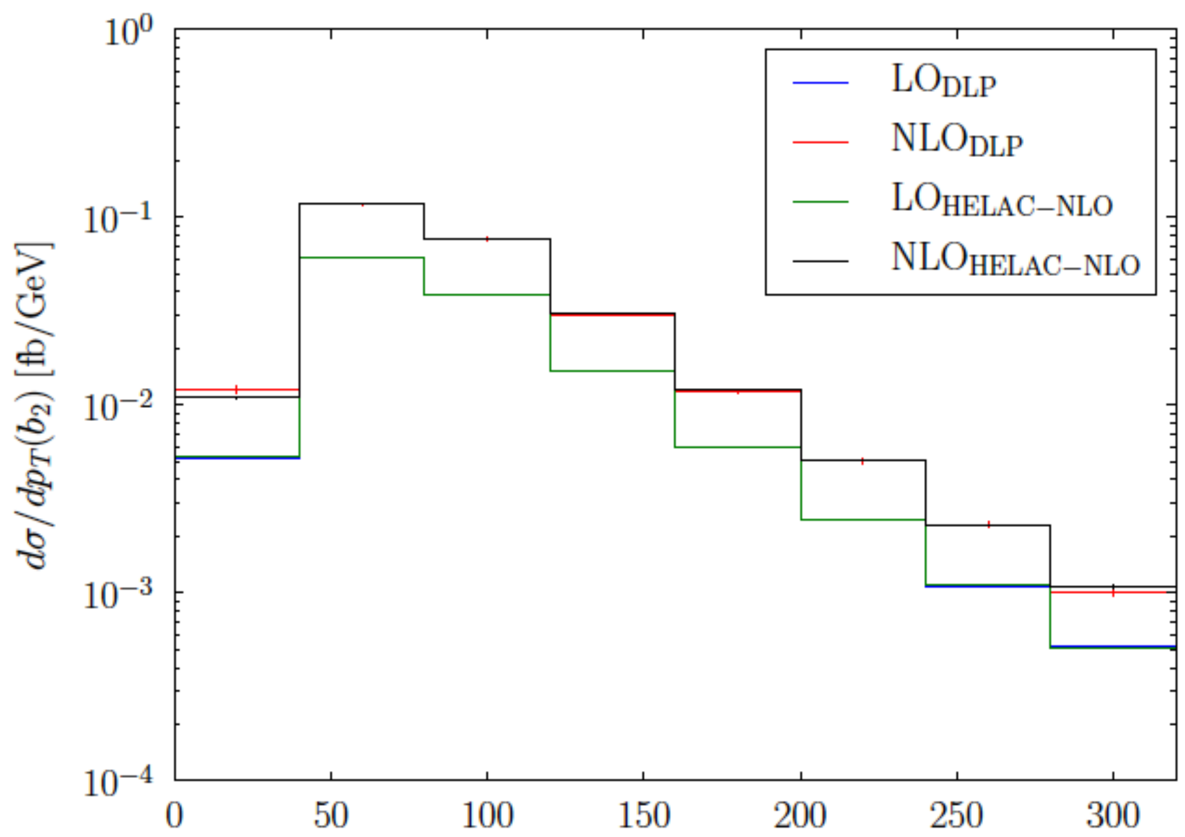
Computation performed with **HELAC-NLO**

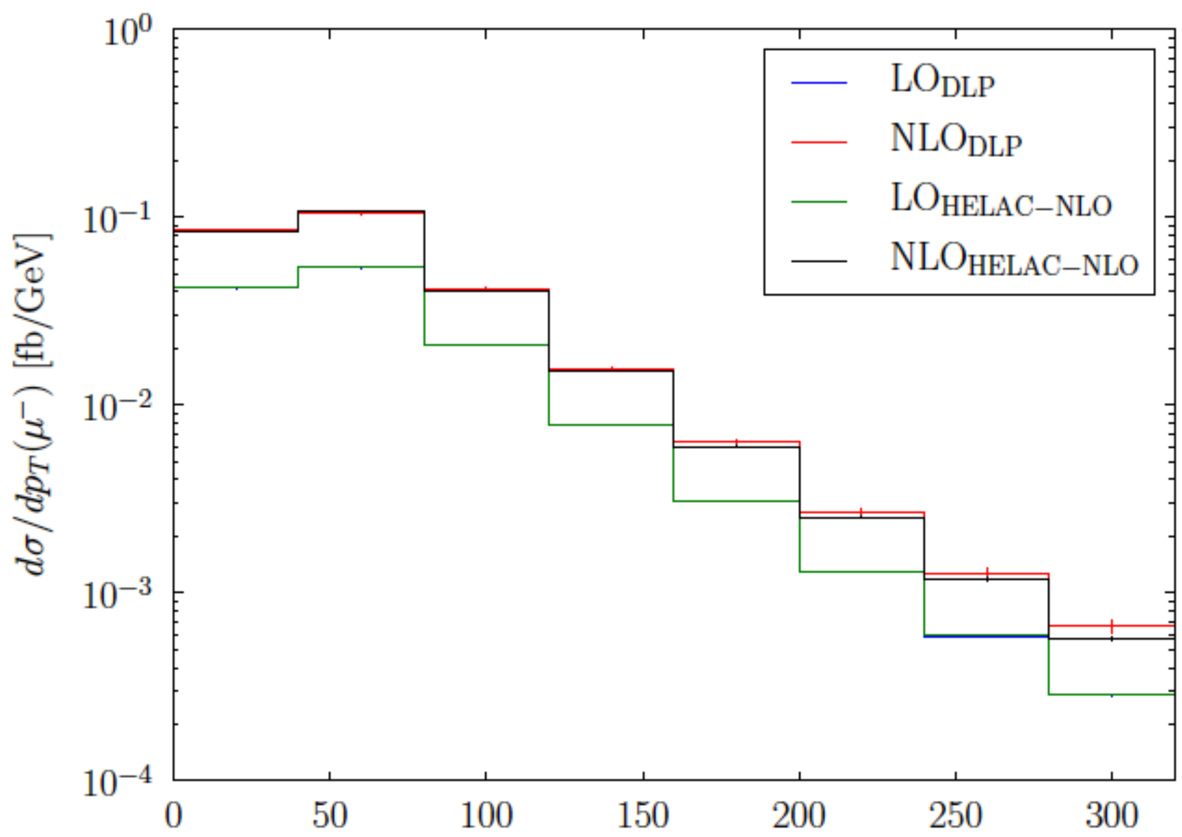
Comparison with literature

- **Comparison with previous results:** Denner, Lang and Pellen, 2008.00918 [hep-ph]

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

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





Excellent agreement

Fiducial cross sections

- **Event selection:** $p_T(\ell) > 20$ GeV , $p_T(b) > 25$ GeV , $|y(\ell)| < 2.5$, $|y(b)| < 2.5$

$p_T(b)$	$\sigma^{\rm LO}$ [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

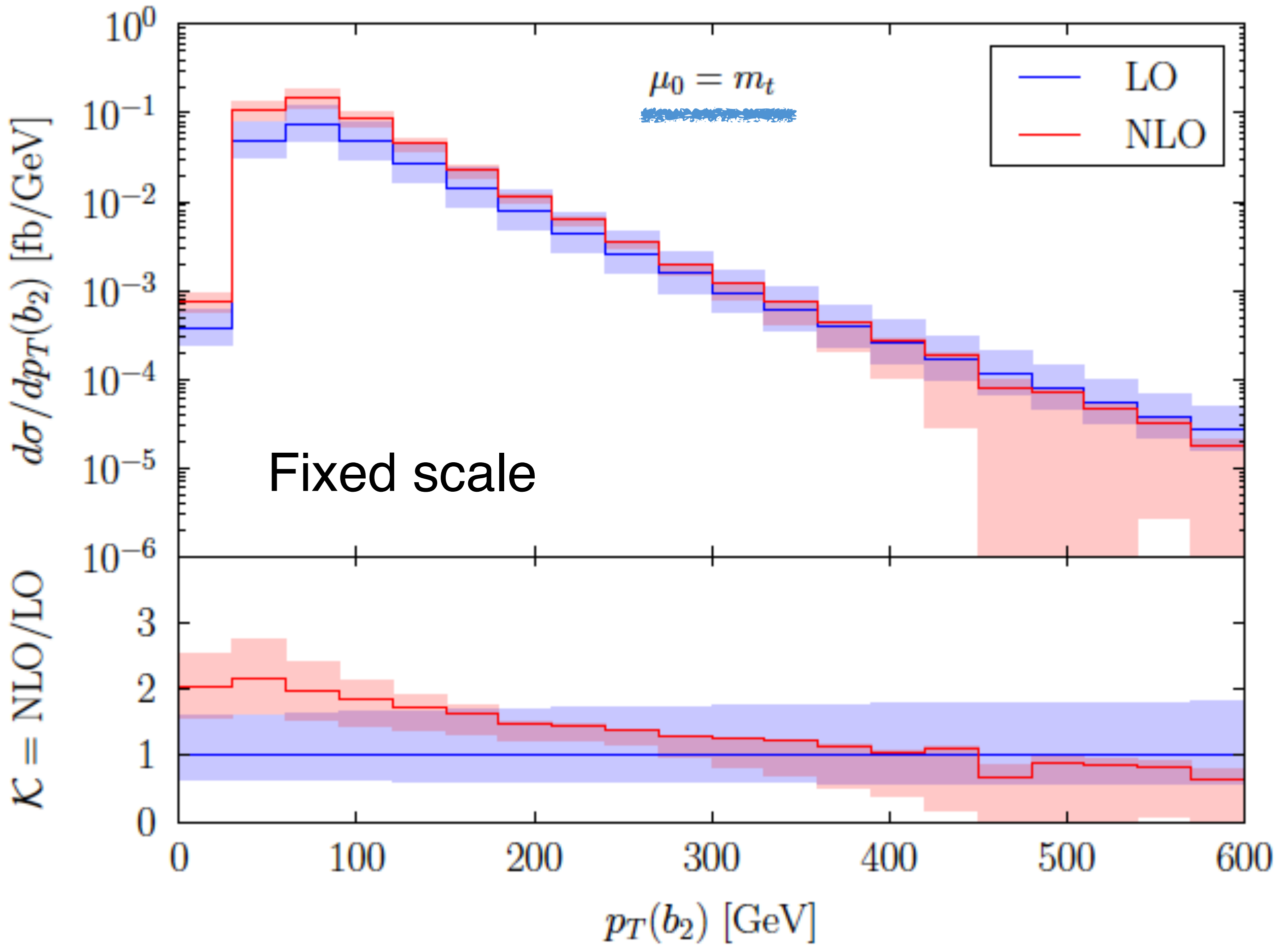
- Large QCD corrections
- Dominated by real radiation
- Applying jet veto:
  $p_T^{\rm veto}(j) = 50$ GeV
  $\Rightarrow \mathcal{K} = 1.11$ for $\mu = m_t$
  $\mathcal{K} = 1.23$ for $\mu = H_T/3$

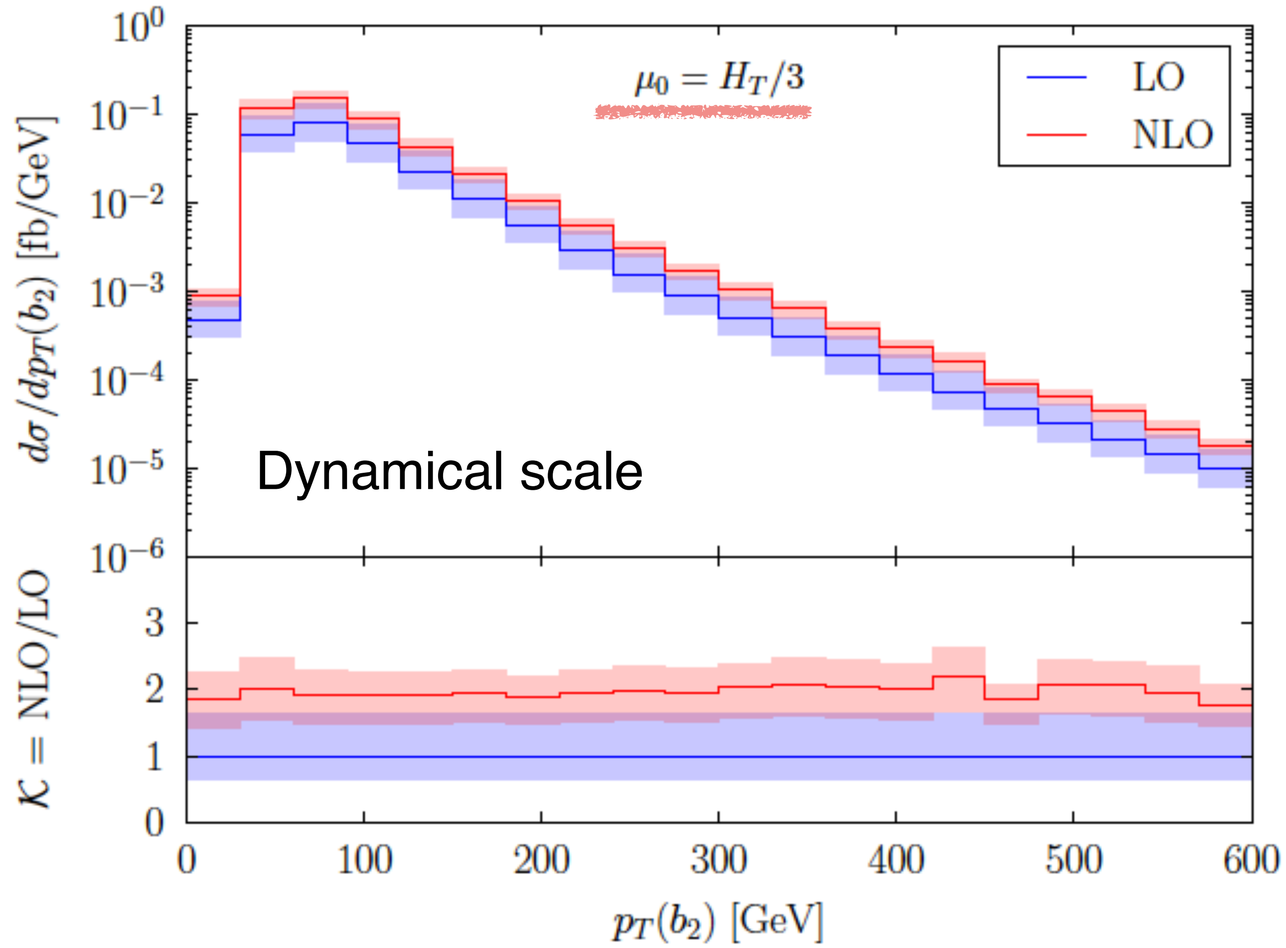
Theory uncertainties:
- Scale : $\mathcal{O}(20\%)$
- PDF : $\mathcal{O}(2\%)$

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

Differential cross sections — impact of scale choice

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

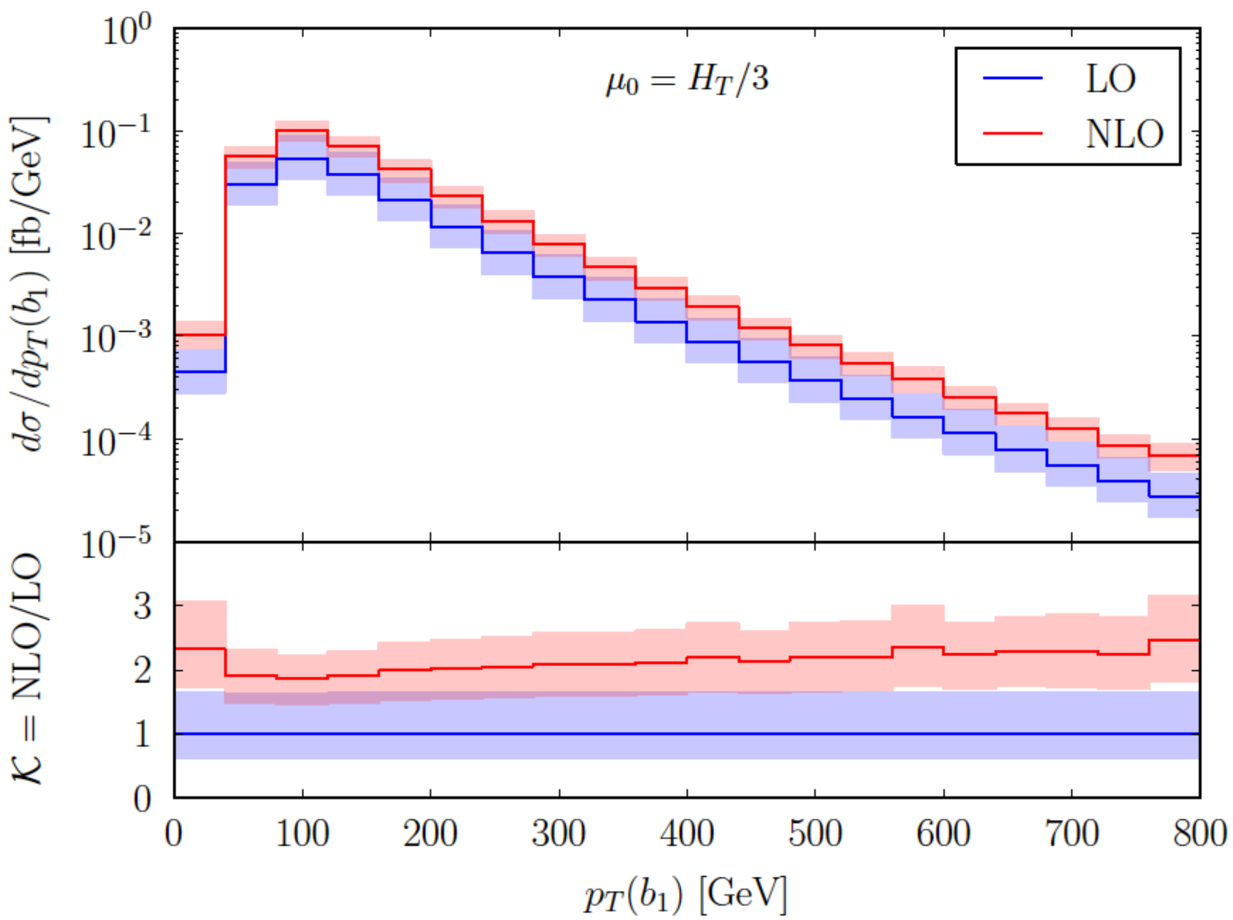


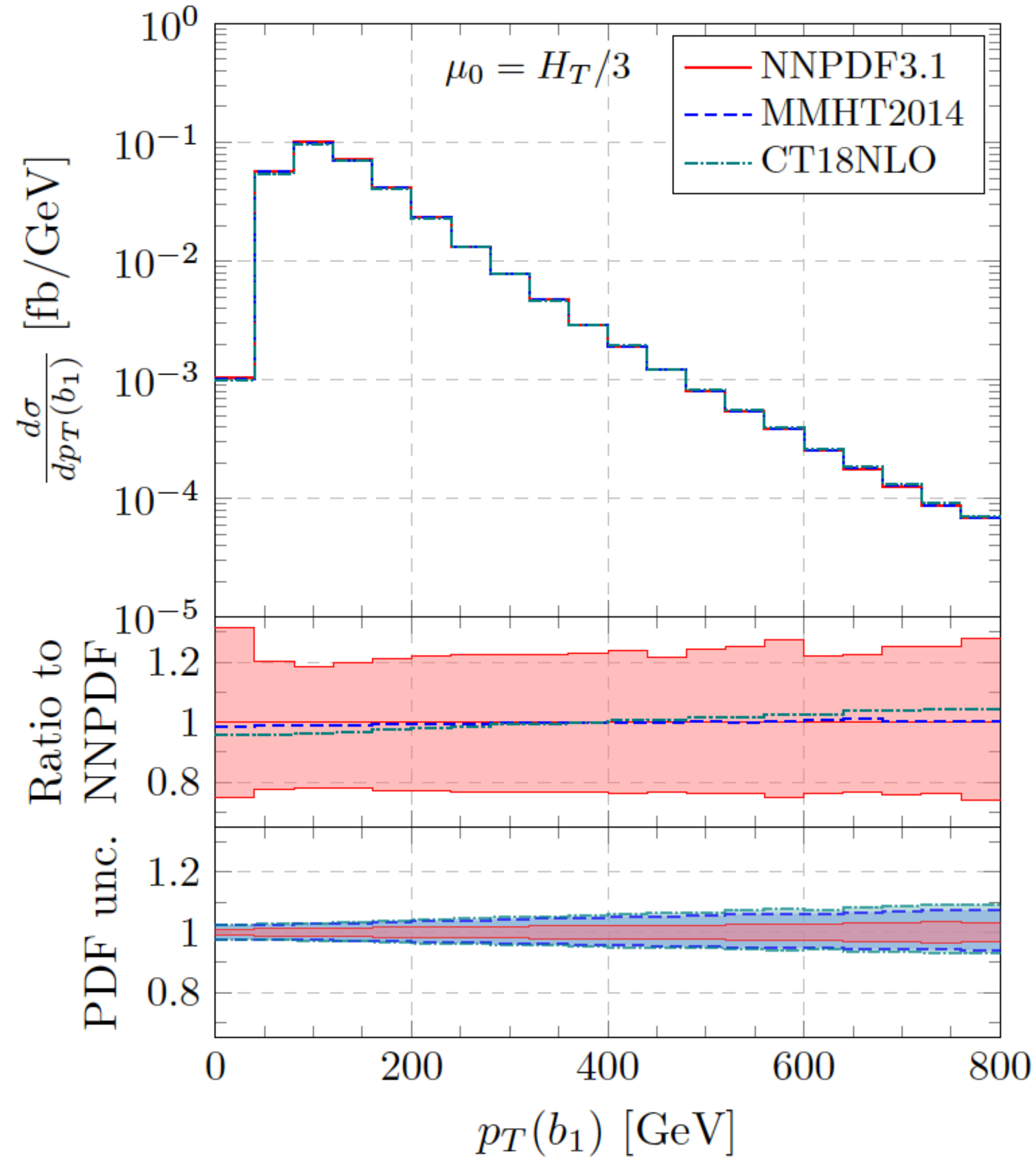


- Dynamical scales flatten K-factors (but shape distortions are still there)
- QCD corrections still large, but more stable

Differential cross sections — theory uncertainties

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



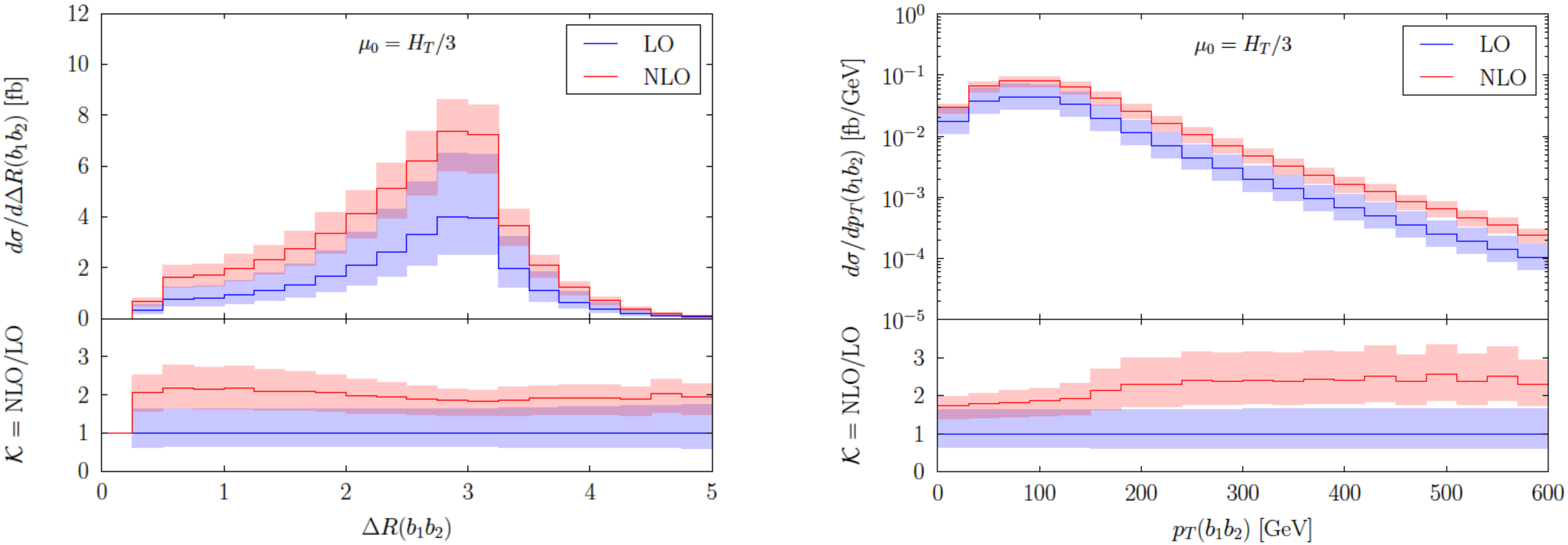


- Scale uncertainties dominate everywhere (from 20 to 30%)

- PDF uncertainties are smaller (but can reach 10% in tails)

Differential cross sections

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



- $\Delta R(b_1 b_2)$ —> Hardest b-jets mainly produced back-to-back
- $p_T(b_1 b_2)$ —> Large K factor up to ~2.5 in tails: effect of real radiation

Large QCD corrections found also in leptonic observables

Impact of initial state b-quarks in ttbb

- Contributions induced by initial state b-quarks are suppressed by PDFs
  Let's *quantify* this statement in the context of a full NLO calculation.

- 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 radiation

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

- We consider two different approaches for tagging b-jets:

"Charge blind" vs "Charge aware"

[see *e.g.* ATLAS-CONF-2018-022]

Charge-blind vs charge-aware b-tagging

"Charge blind" b-tagging

- Sensitive to the *absolute flavor* of the b-jet
- Cannot distinguish between b and $\bar{b}$ jets
- Recombination rules:

$$bg \to b\,, \quad \bar{b}g \to \bar{b}\,, \quad bb \to g\,,$$
$$b\bar{b} \to g\,, \quad \bar{b}\bar{b} \to g$$

"Charge aware" b-tagging

- Sensitive to the *charge* of the b-jet
- Can distinguish between b and $\bar{b}$ jets
- Recombination rules:

$$bg \to b\,, \quad \bar{b}g \to \bar{b}\,, \quad b\bar{b} \to g\,,$$
$$bb \to b\,, \quad \bar{b}\bar{b} \to \bar{b}$$

- Jets are clustered using the anti-kT algorithm with R = 0.4
- The two b-tagging variants are IR-safe at NLO.
  Beyond NLO —> *flavor kT* [Banfi, Salam, Zanderighi '06], *flavor anti-kT* [Czakon et al. '21]

Impact of initial state b-quarks

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

LO

$\sigma^{\rm LO}_{\rm no\,b} = 6.813(3)$ fb

$\sigma^{\rm LO}_{\rm aware} = 6.822(3)$ fb

$\sigma^{\rm LO}_{\rm blind} = 6.828(3)$ fb

impact: ~0.2%

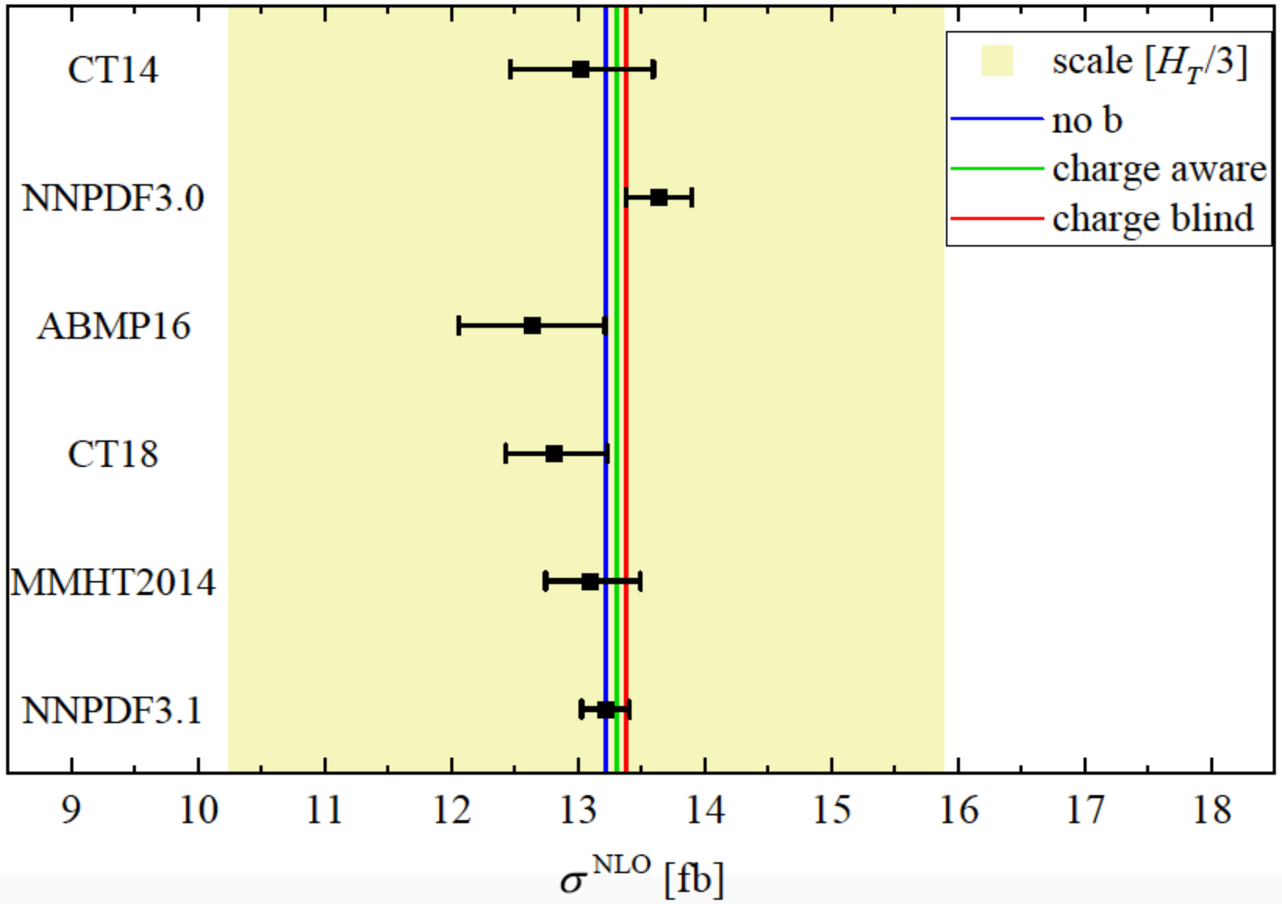
NLO

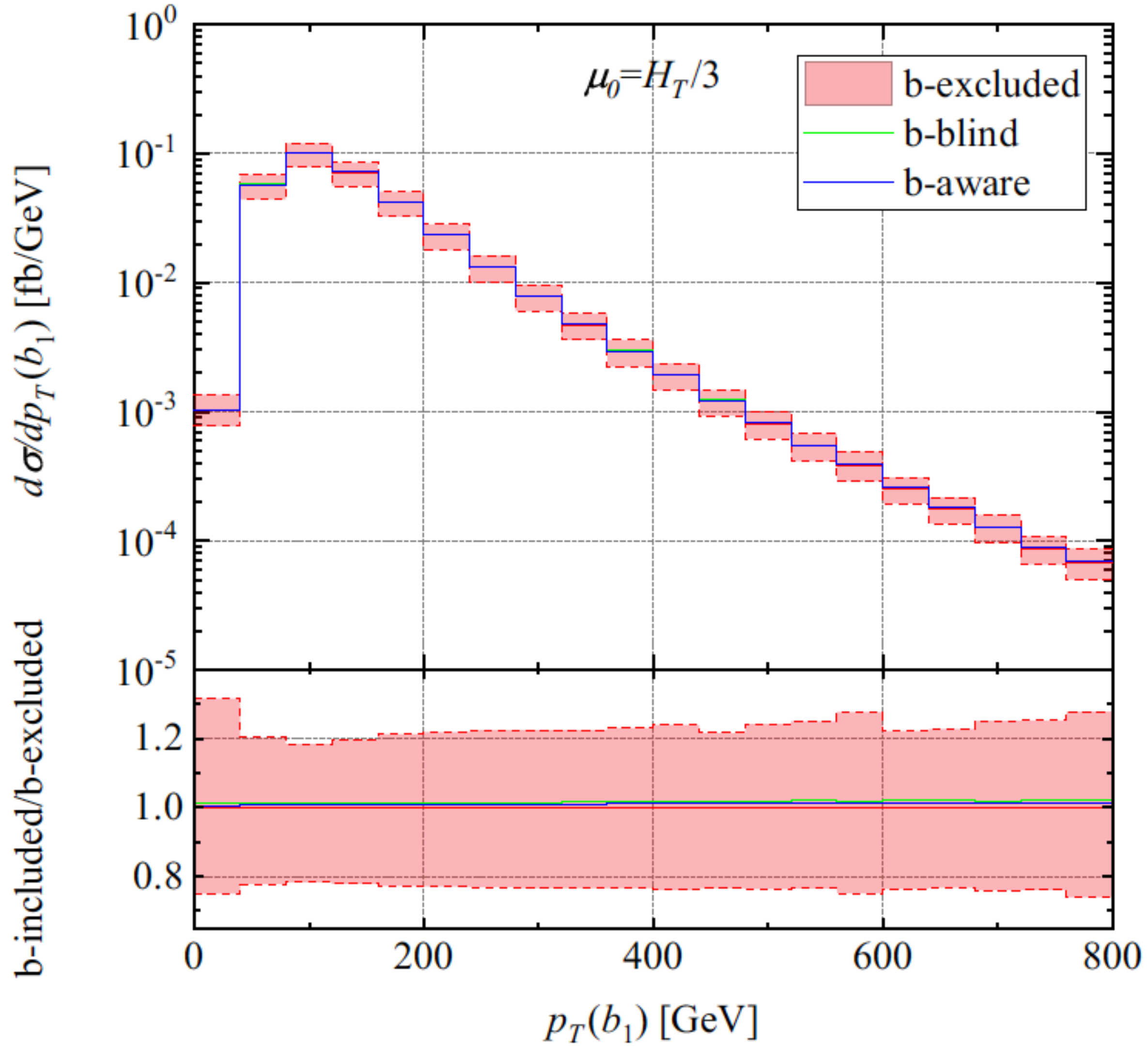
$\sigma^{\rm NLO}_{\rm no\,b} = 13.22(3)$ fb

$\sigma^{\rm NLO}_{\rm aware} = 13.31(3)$ fb

$\sigma^{\rm NLO}_{\rm blind} = 13.38(3)$ fb

impact: ~1%



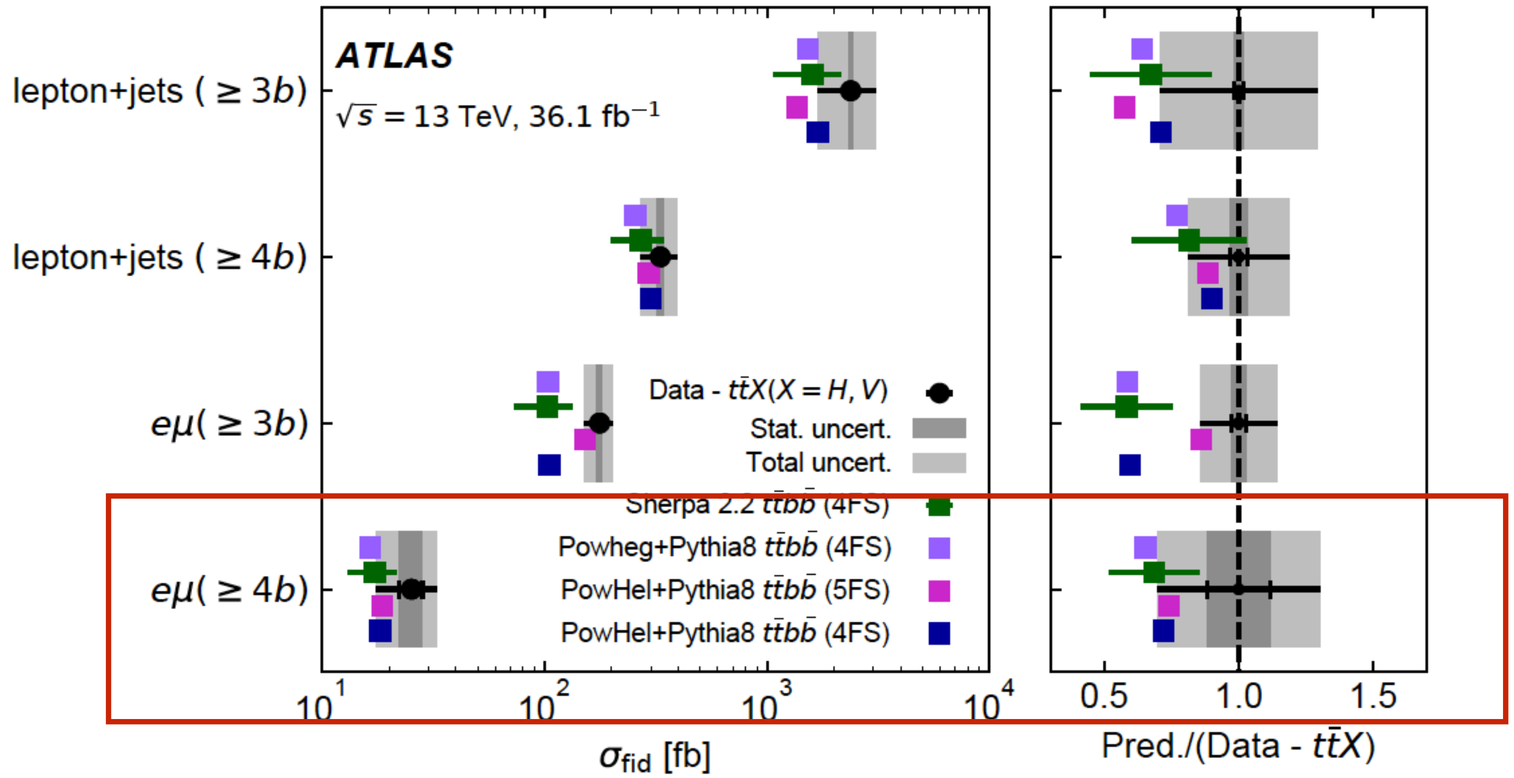


Contributions induced by initial state can be safely neglected even in extreme phase space regions

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): 20.0 ± 4.3 **fb**

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

Summary & outlook

Summary

- Two independent calculations of off-shell ttbb (dilepton channel) @NLO QCD in excellent agreement
- The size of QCD corrections is large: $\mathcal{O}(90\%)$
- Theoretical uncertainties dominated by scale variation: $\mathcal{O}(20\%)$
- Impact of contributions induced by initial state b-quarks: $\mathcal{O}(1\%)$
- Very good agreement with ATLAS results

Outlook

- Quantifying off-shell effects: comparison with Narrow Width Approximation
- How well can we distinguish b's from top decays vs prompt b's?