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

H.F.R.I.
Hellenic Foundation for Research & Innovation

Top quark pair production and decay with jet activity at the LHC

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Theory Seminar

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

Based on: *JHEP 08 (2021) 008* *Phys.Rev.D 107 (2023) 11, 014028* *Phys.Rev.D 107 (2023) 11, 114027*

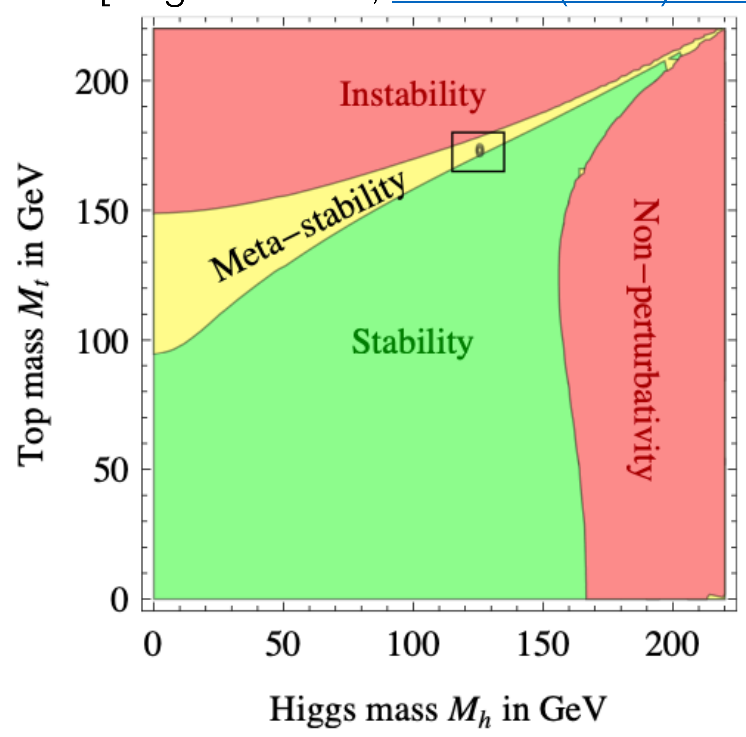
Fundamentals of top quark physics

Why is top quark physics interesting?

$$y_t = \sqrt{2}\,\frac{m_t}{v} \approx 1$$

- The top quark is the heaviest particle of the Standard Model
  - ↪ • Substantial Yukawa coupling: sensitive to EWSB mechanism
  - • Top mass is a free parameter: need precise measurements

[Degrassi et al., JHEP 08 (2012) 098]

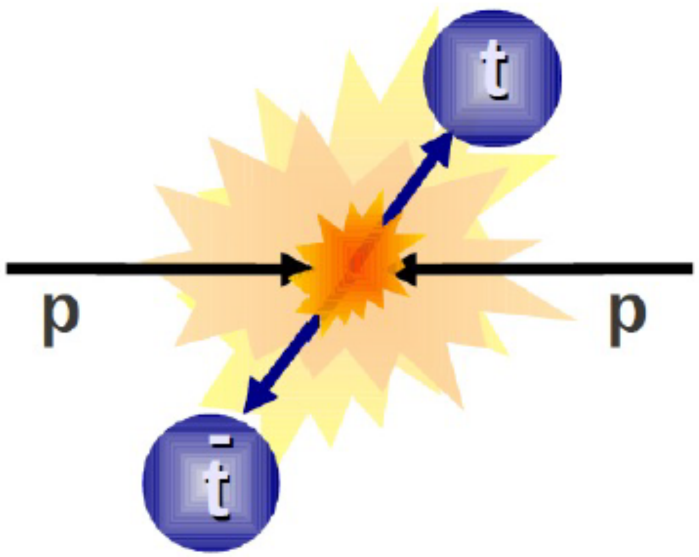


- Extremely short-lived $\sim 5 \cdot 10^{-25}\,\mathrm{s} \ll \Lambda_{QCD}^{-1}$
  - ↪ • Decays before bound states can be formed
  - • $\mathrm{BR}(t \to Wb) \approx 100\,\%$: unique experimental signature
  - • Direct handle of top quark properties from decay products

Production	**Decays**	**Intrinsic properties**
• Inclusive rates • Differential distributions • New production mechanisms • …	• Decay channels (SM & BSM) • Couplings to SM particles • Spin correlations • …	• Mass • Charge • Lifetime • Width • …

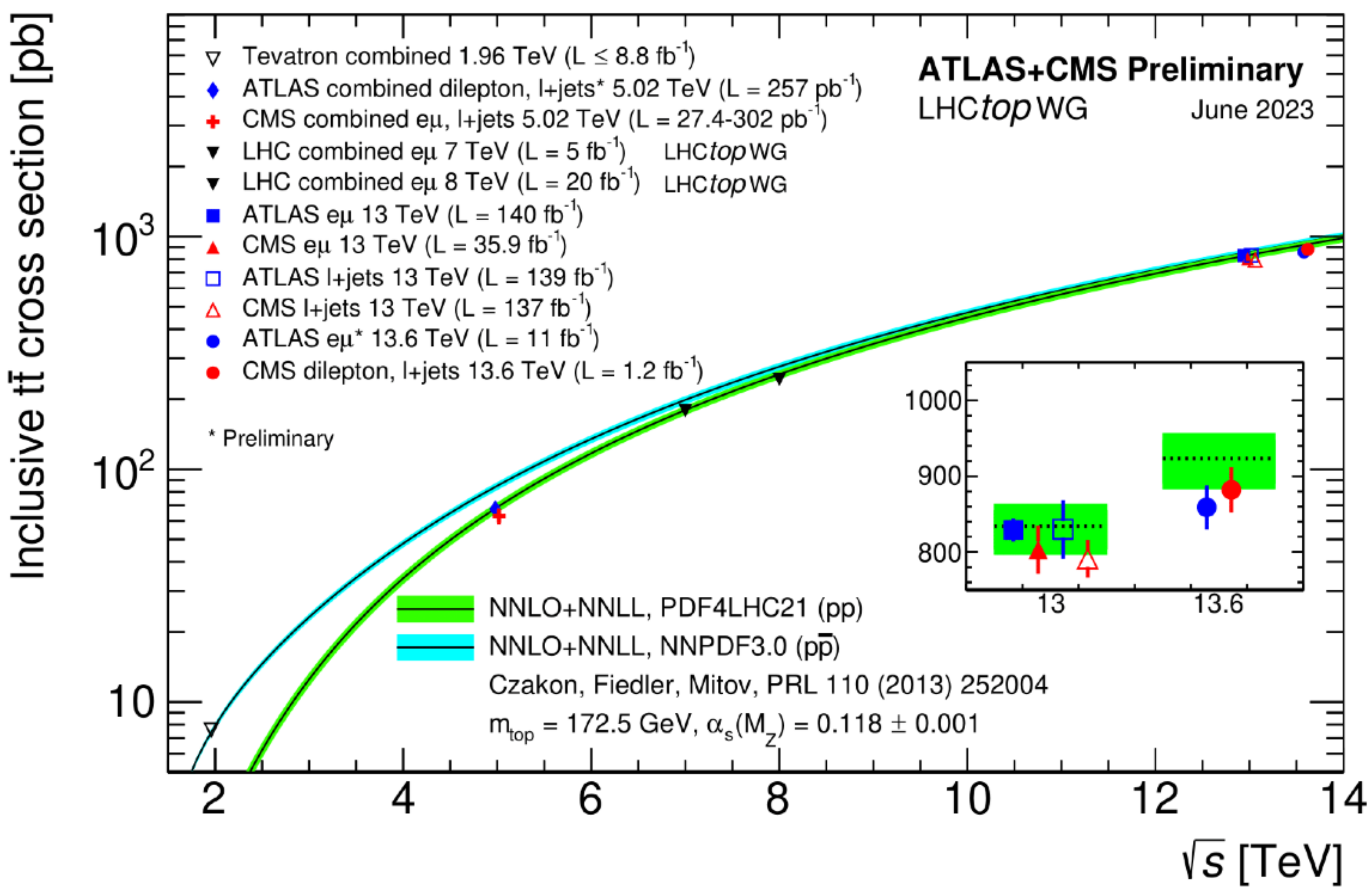
$t\bar{t}$ production at the LHC

- Dominant mode of top quark production at the LHC
- Can be selected with high purity (dilepton, but also ℓ+jets)
- $\mathcal{O}(100\,\mathrm{M})$ $t\bar{t}$ events in Run 2
- "Standard candle" for precisions tests of SM



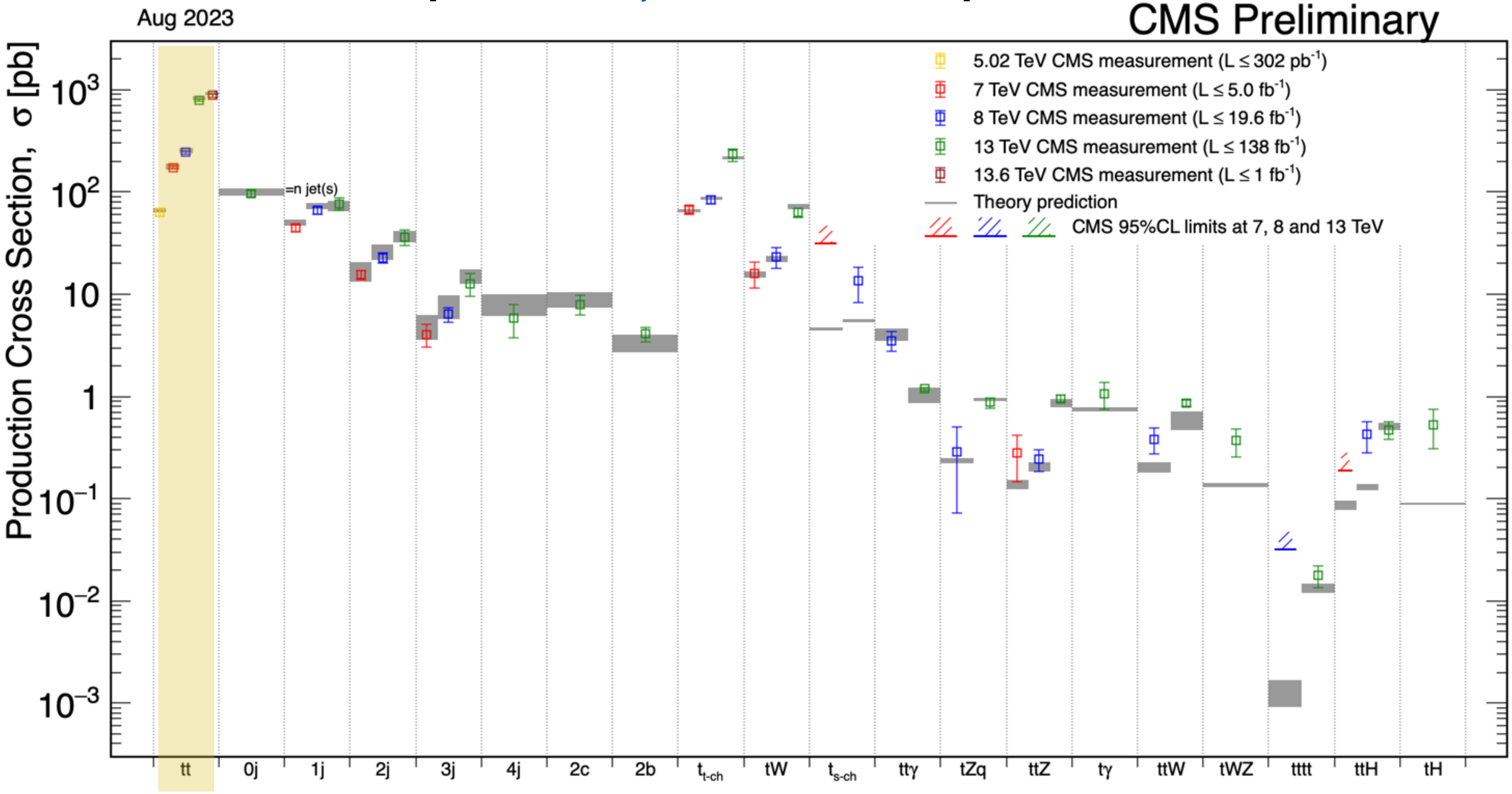
[LHCPhysics/TtbarNNLO]

7 TeV			
Central value	Scale uncert.	PDF+alpha$_S$ uncert.	Mass uncert. up / down
179.6	+4.8 -6.2	± 6.1	-5.26 +5.44
8 TeV			
Central value	Scale uncert.	PDF+alpha$_S$ uncert.	Mass uncert. up / down
256.0	+6.7 -8.9	± 8.0	-7.33 +7.58
13 TeV			
Central value	Scale uncert.	PDF+alpha$_S$ uncert.	Mass uncert. up / down
833.9	+20.5 -30.0	± 21.0	-22.5 +23.2
13.6 TeV			
Central value	Scale uncert.	PDF+alpha$_S$ uncert.	Mass uncert. up / down
923.6	+22.6 -33.4	± 22.8	-24.6 +25.4



Top quark production cross sections

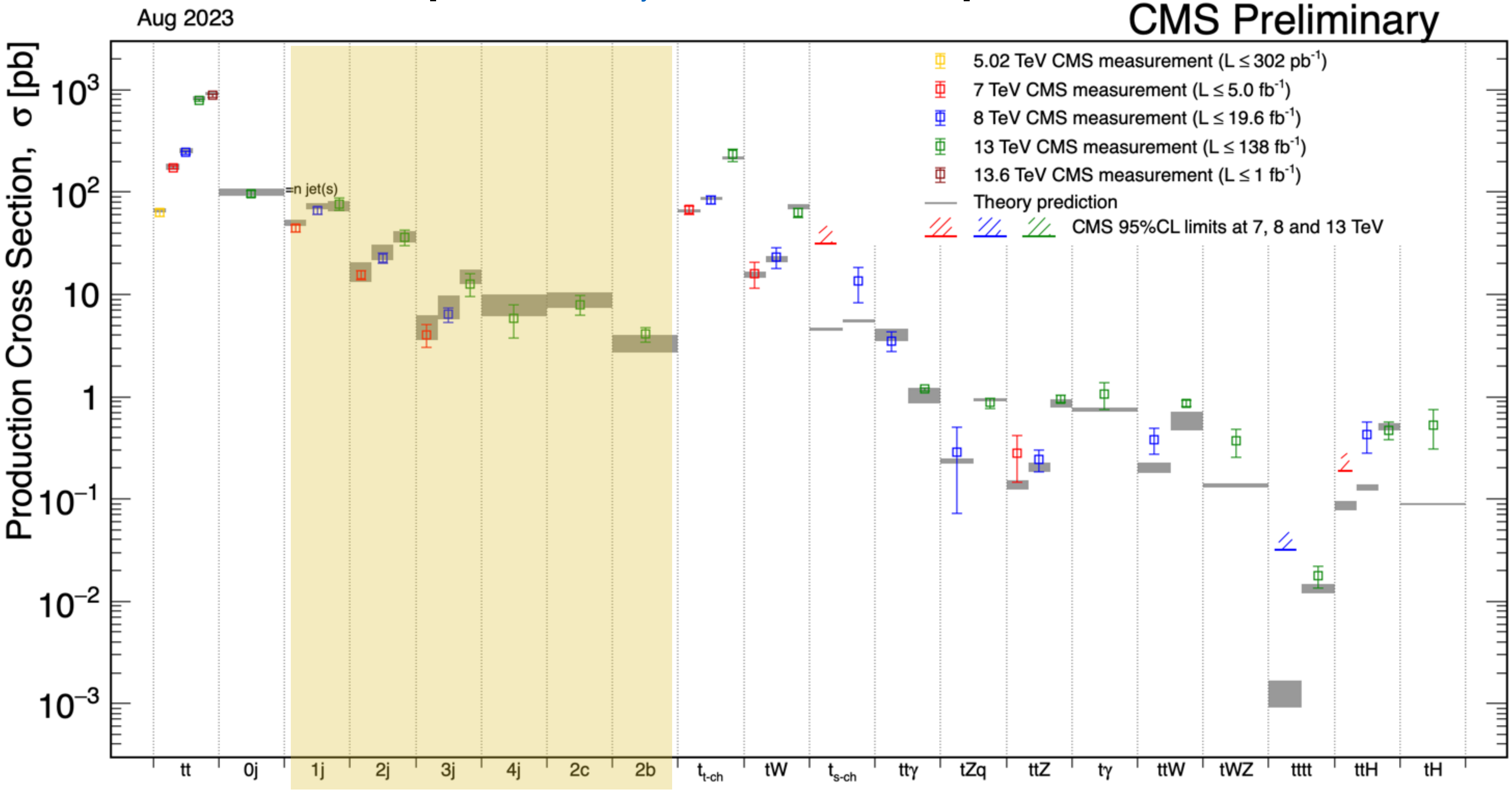
[CMSPublic/PhysicsResultsCombined]



Inclusive $t\bar{t}$ sample

Top quark production cross sections

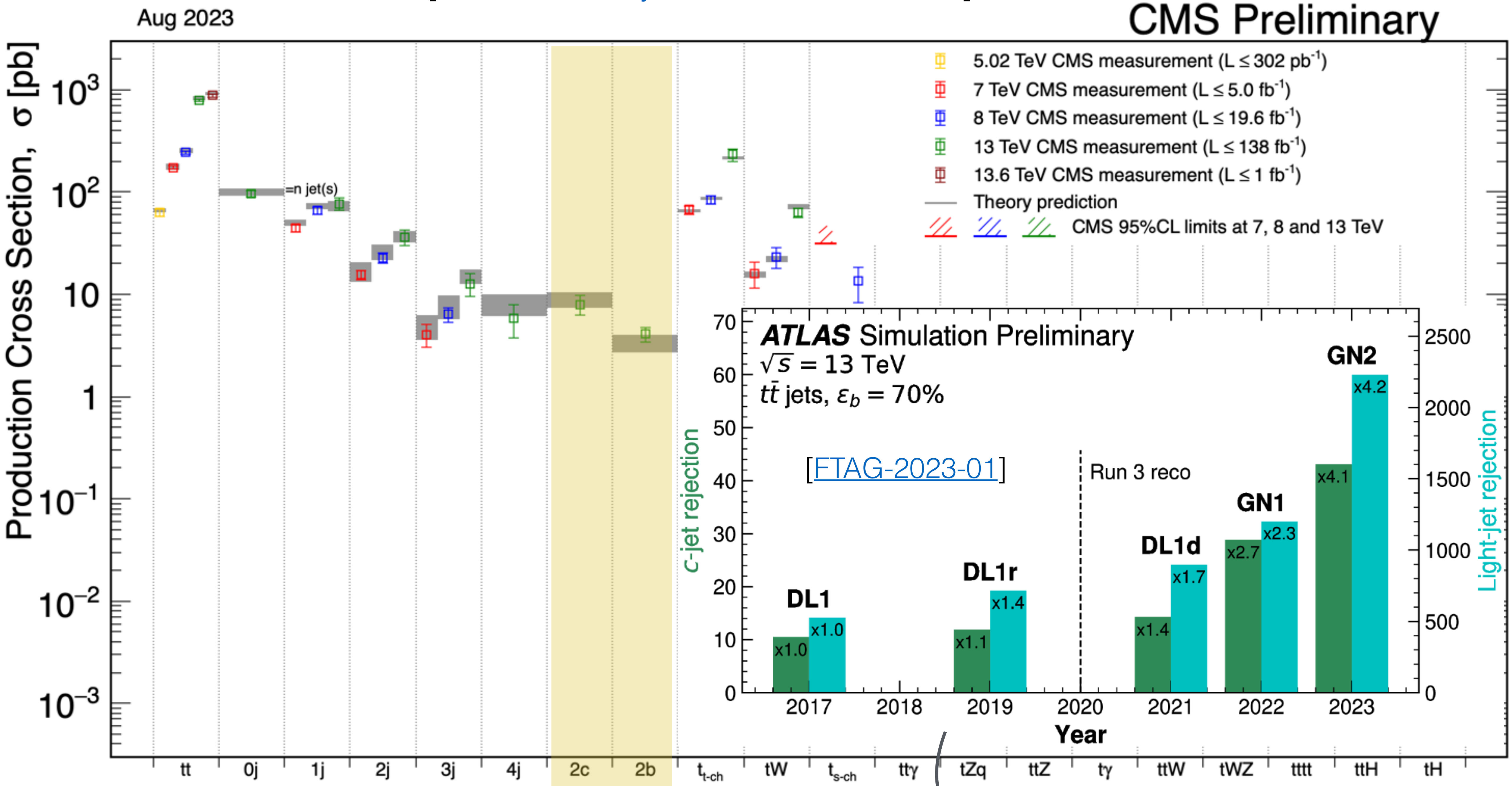
[CMSPublic/PhysicsResultsCombined]



Hadronic jet activity in $t\bar{t}$ events

Top quark production cross sections

[CMSPublic/PhysicsResultsCombined]

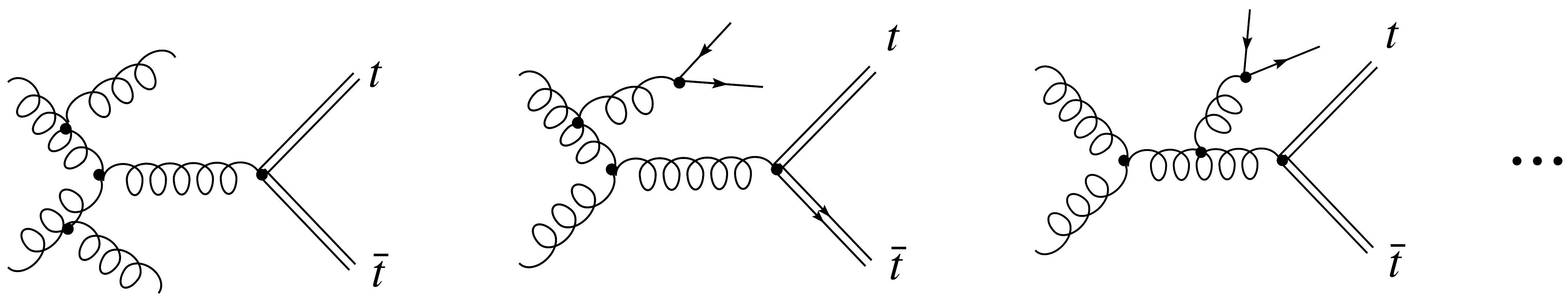


$t\bar{t}$ + HF

b- and c-tagging algorithms are constantly improving

$t\bar{t}$+jets as a signal

- A significant fraction of the inclusive $t\bar{t}$ sample is accompanied by additional hard jet(s) arising from QCD radiation



- Genuine *multiscale* process with characteristic scales typically separated by one order of magnitude $\rightarrow$ test of perturbative QCD

- Several $t\bar{t}$ observables are sensitive to extra-jet radiation

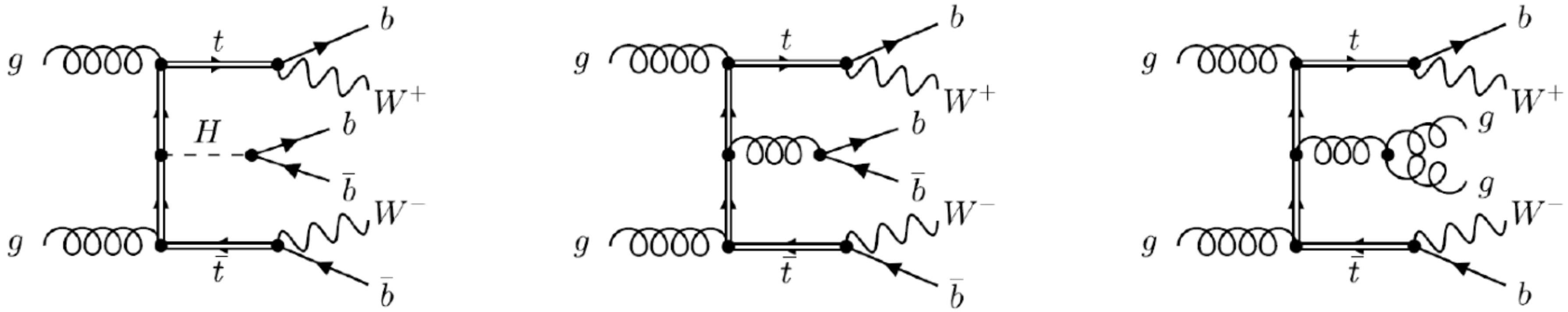
- $t\bar{t} + 1\,\mathrm{jet}$ provides one method to extract top quark mass at the LHC

Alioli, Fuster, Irles, Moch and Uwer '13

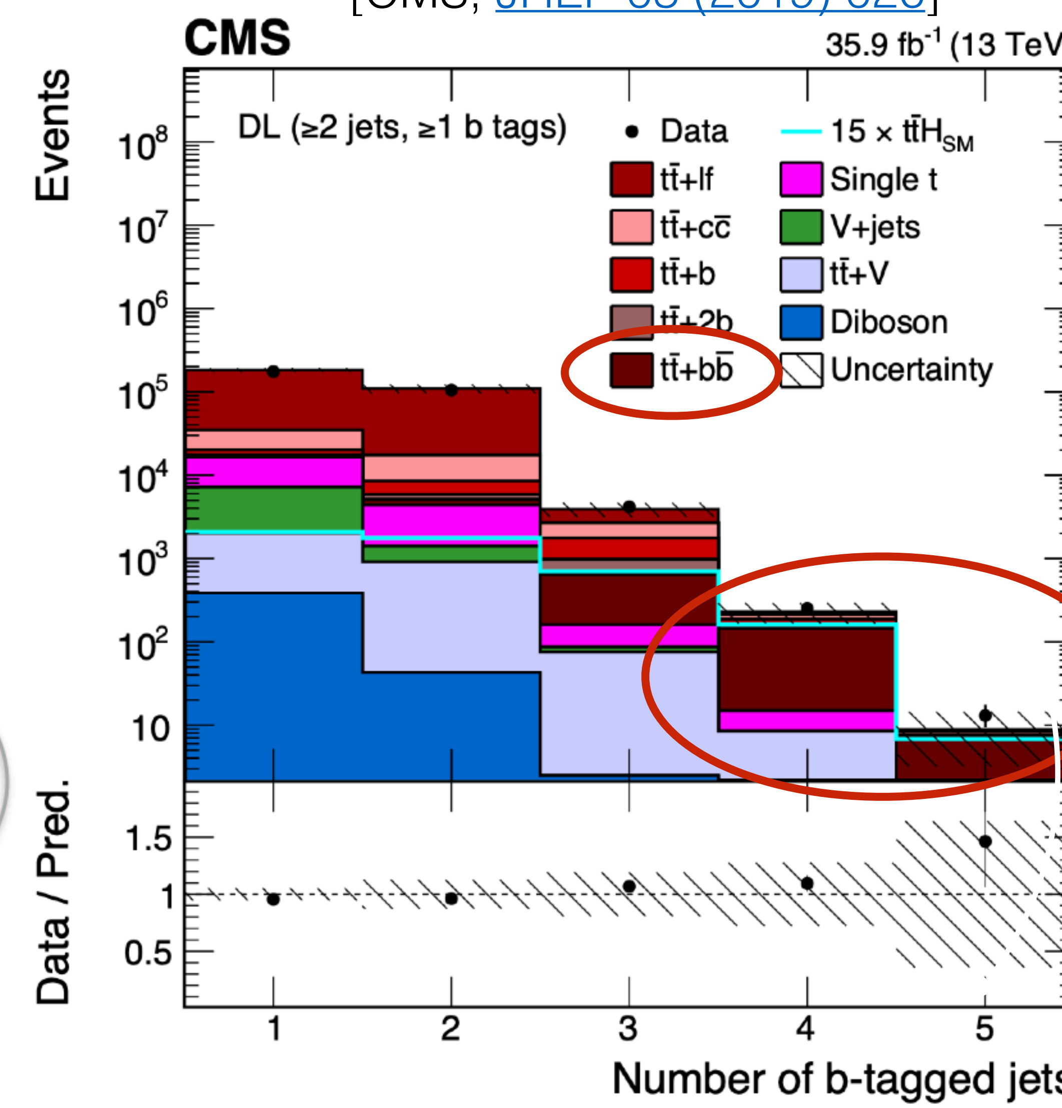
Alioli, Fuster, Garzelli, Gavardi, Irles, Melini, Moch, Uwer and Voss '22

$t\bar{t}+$jets as a background

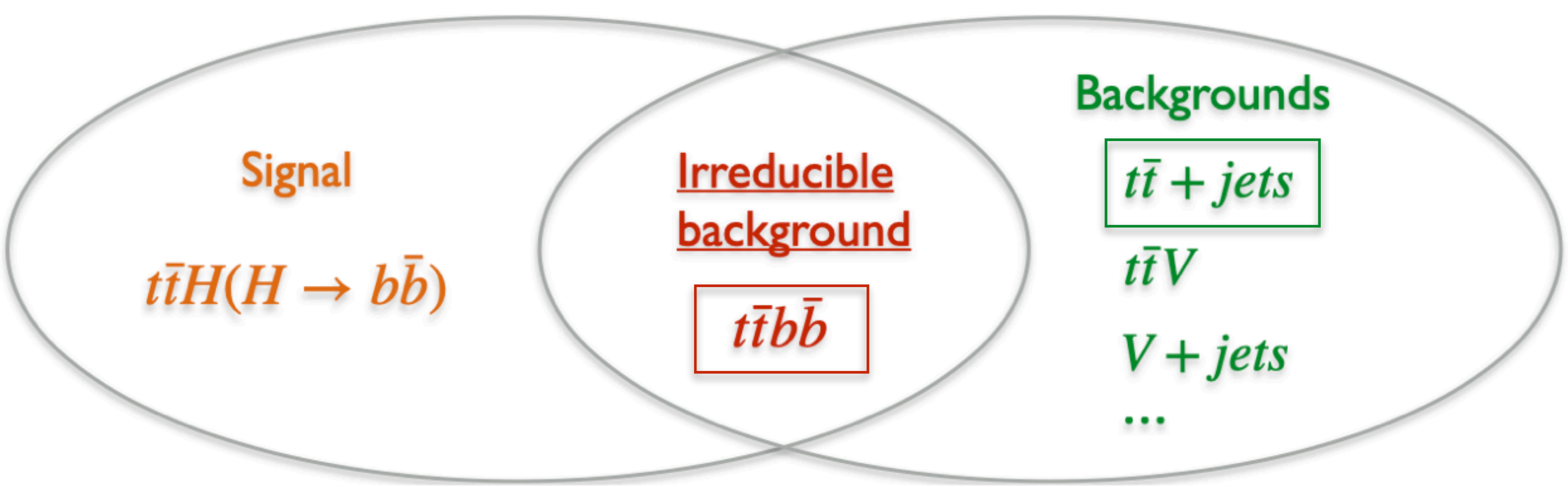
- Background to $t\bar{t}H(H \to b\bar{b})$ production (and to many BSM searches)



[CMS, JHEP 03 (2019) 026]



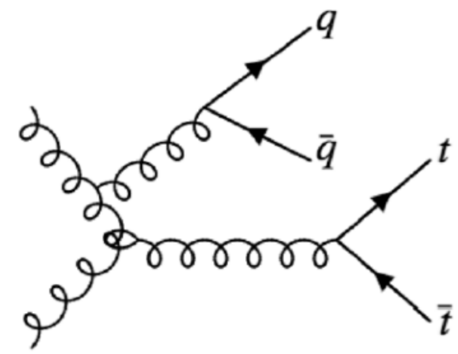
- $pp \to t\bar{t}H$: direct sensitivity to top Yukawa coupling
- $H \to b\bar{b}$: largest BR ($\sim 58\,\%$)
- $t\bar{t}H(H \to b\bar{b})$ is a tiny signal in a huge background



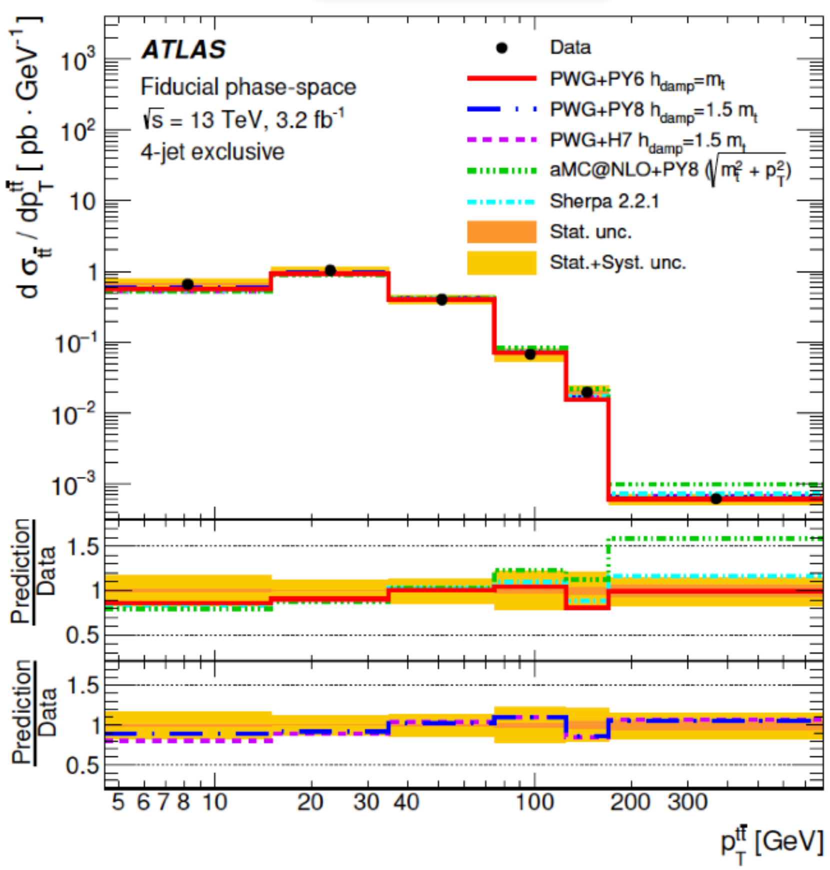
$t\bar{t}$ differential measurements (I)

[ATLAS, JHEP 10 (2018) 159]

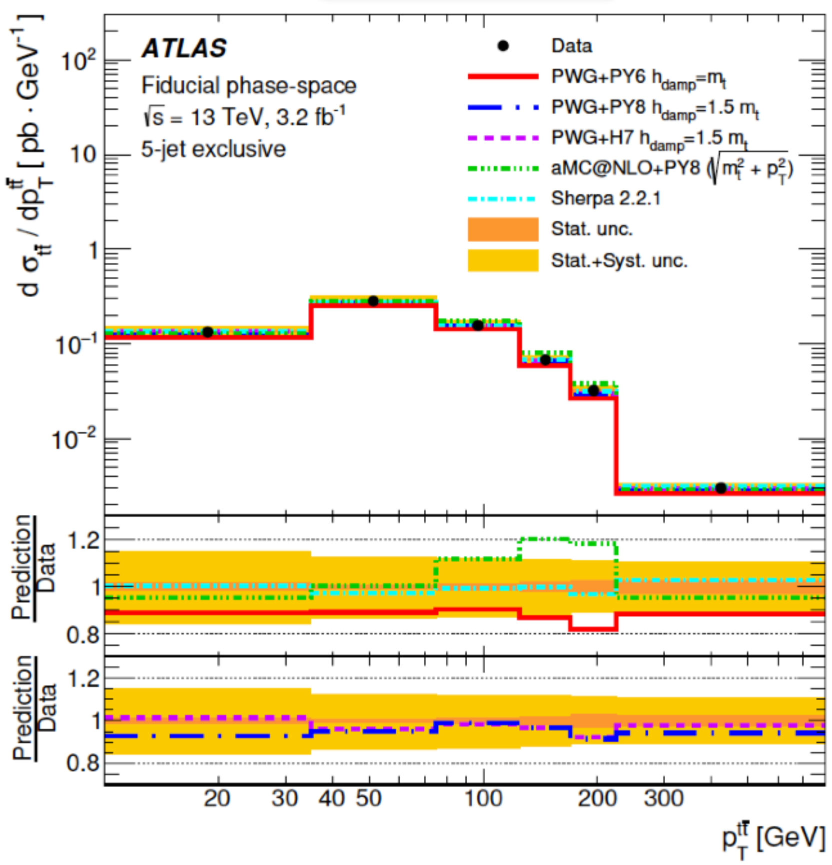
- Reconstruction of $t\bar{t}$ kinematics in ℓ+jets channel
- $t\bar{t}$ kinematics measured for different additional jet multiplicities: $N_{\mathrm{j,add}}$
- Some observables sensitive to extra-jet radiation, e.g. $p_T(t\bar{t})$:



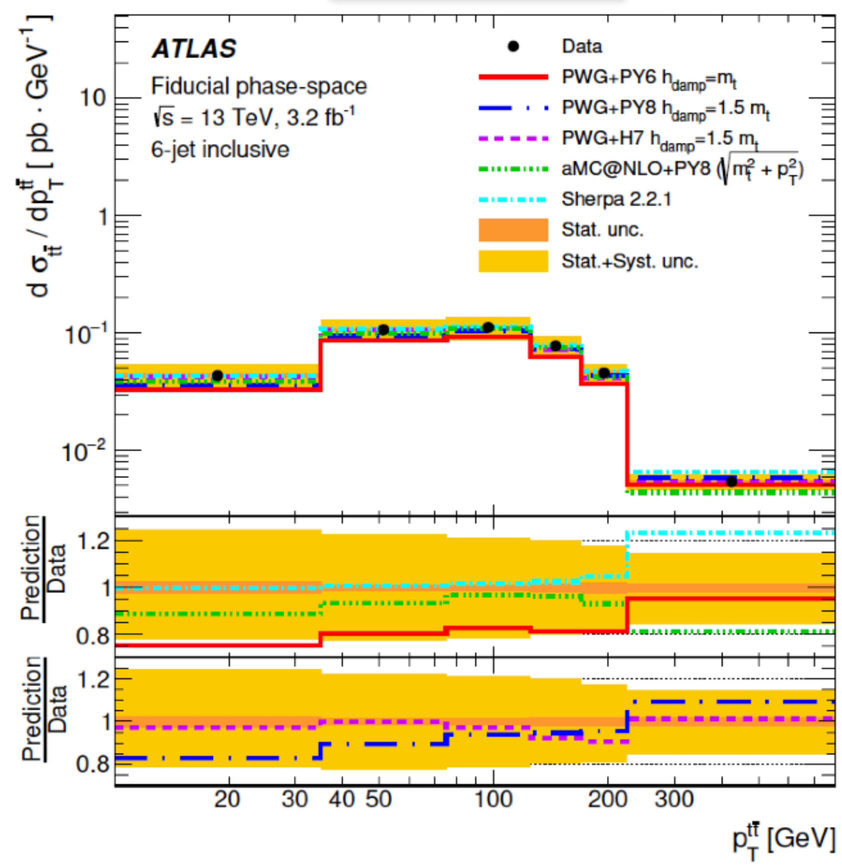
$N_{\mathrm{j,add}} = 0$



$N_{\mathrm{j,add}} = 1$



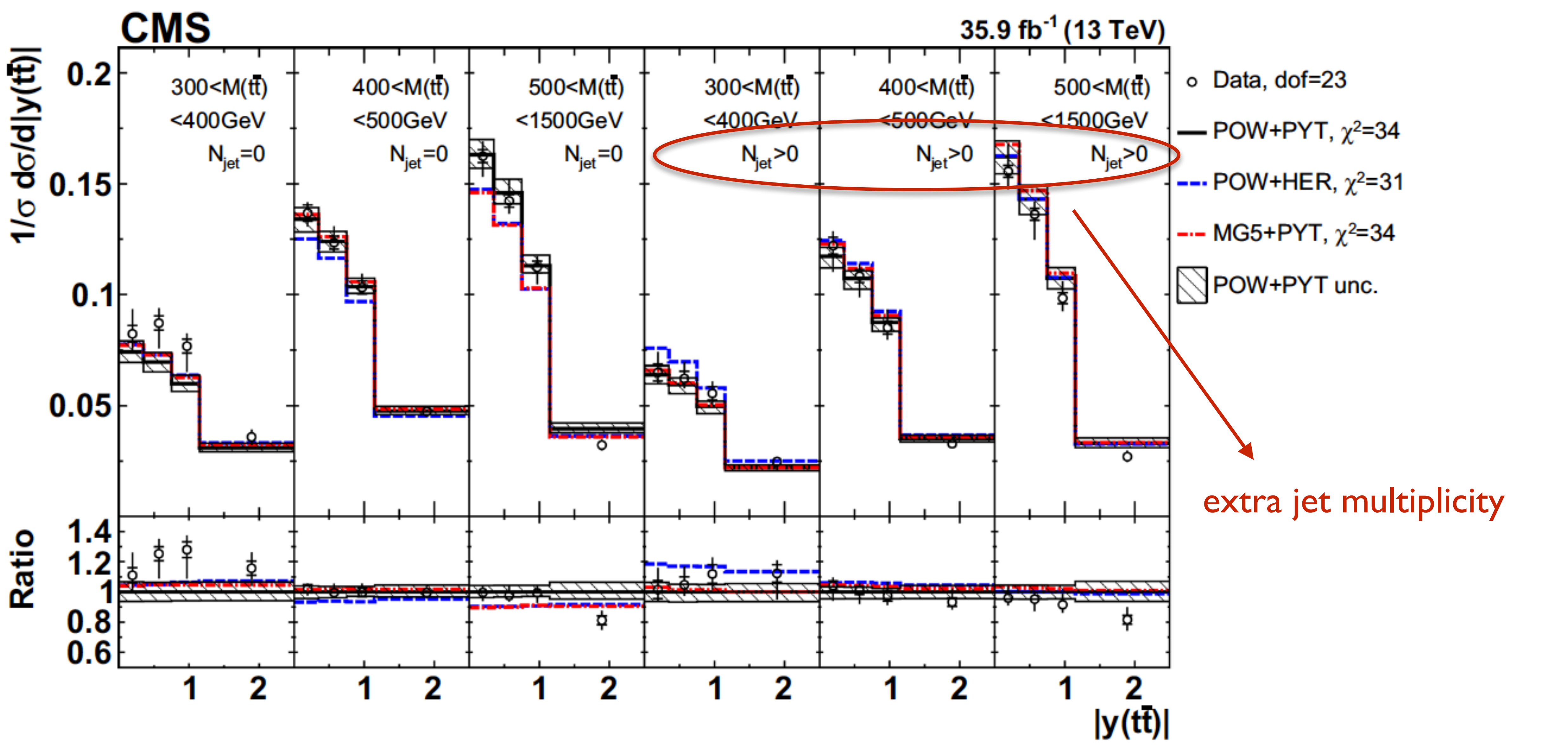
$N_{\mathrm{j,add}} \geq 2$



$t\bar{t}$ differential measurements (II)

[CMS, EPJ C80 (2020) 658]

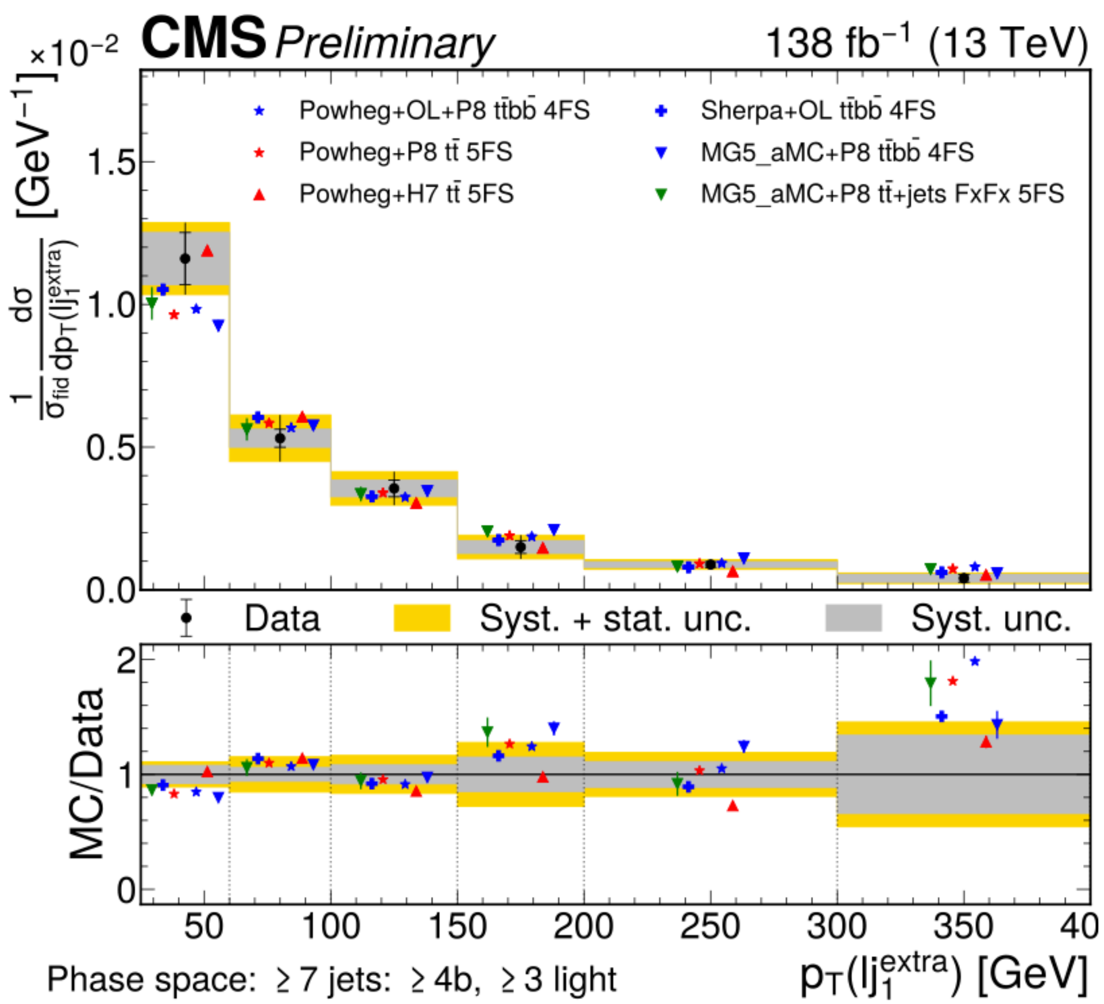
- Dilepton channel (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\pm$)
- At least two jets in the final state; at least one of them b-tagged
- Triple-differential measurements → simultaneous extraction of α_s , m_t , PDFs

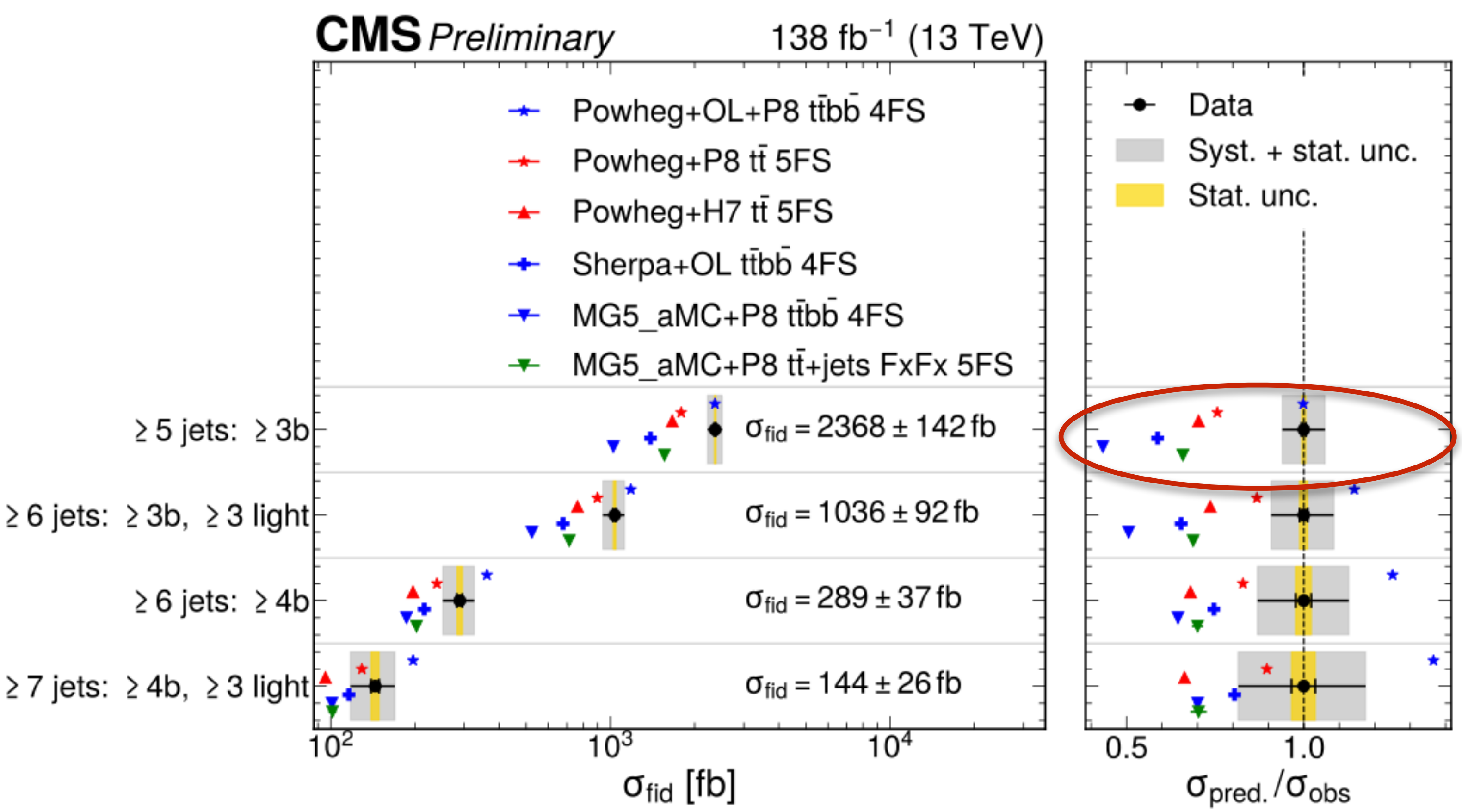


Measurements of $t\bar{t}b\bar{b}$ production

[CMS-PAS-TOP-22-009]

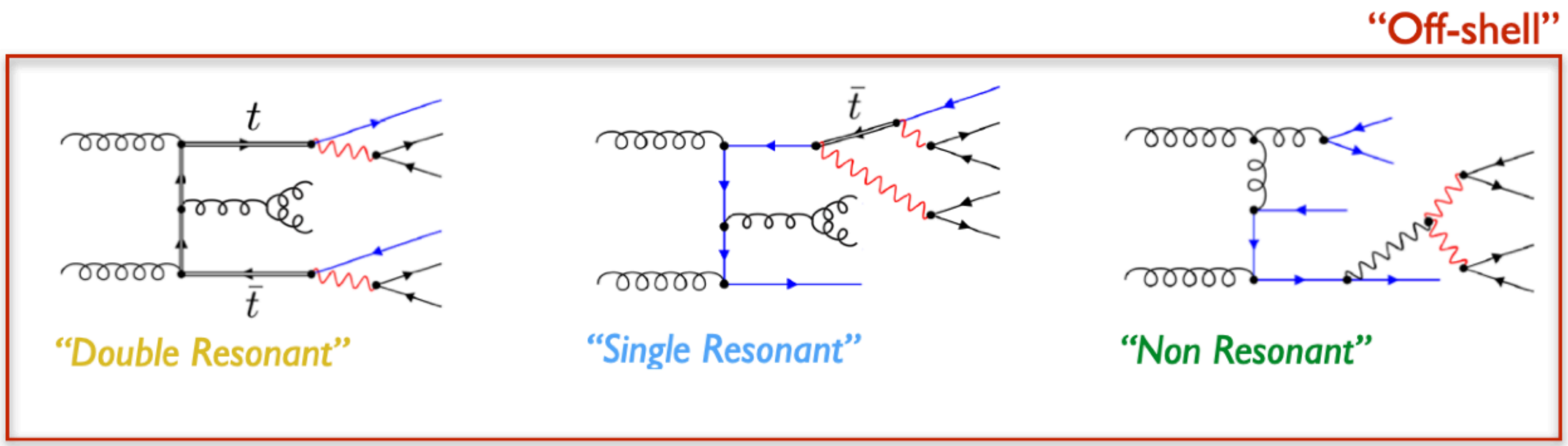
- ℓ+jets channel
- Inclusive and differential measurements $\rightarrow$ 4 fiducial regions: $5j3b$, $6j4b$, $6j3b3\ell$, $7j4b3\ell$
- Inclusive σ higher than theory predictions (consistent with previous measurements)





$t\bar{t}$ + multijets at LHC: theory challenges

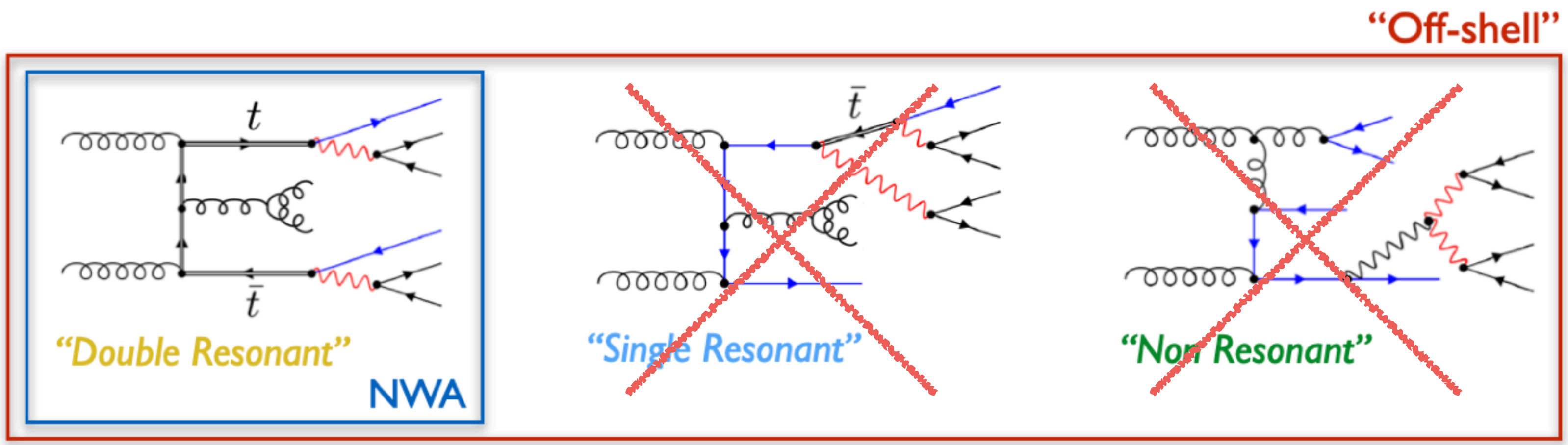
- ME calculations for fully decayed final states are often challenging



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

$t\bar{t}$ + multijets at LHC: theory challenges

- ME calculations for fully decayed final states are often challenging → use NWA



$$\Gamma_t/m_t \to 0$$
$$\Gamma_W/m_W \to 0$$

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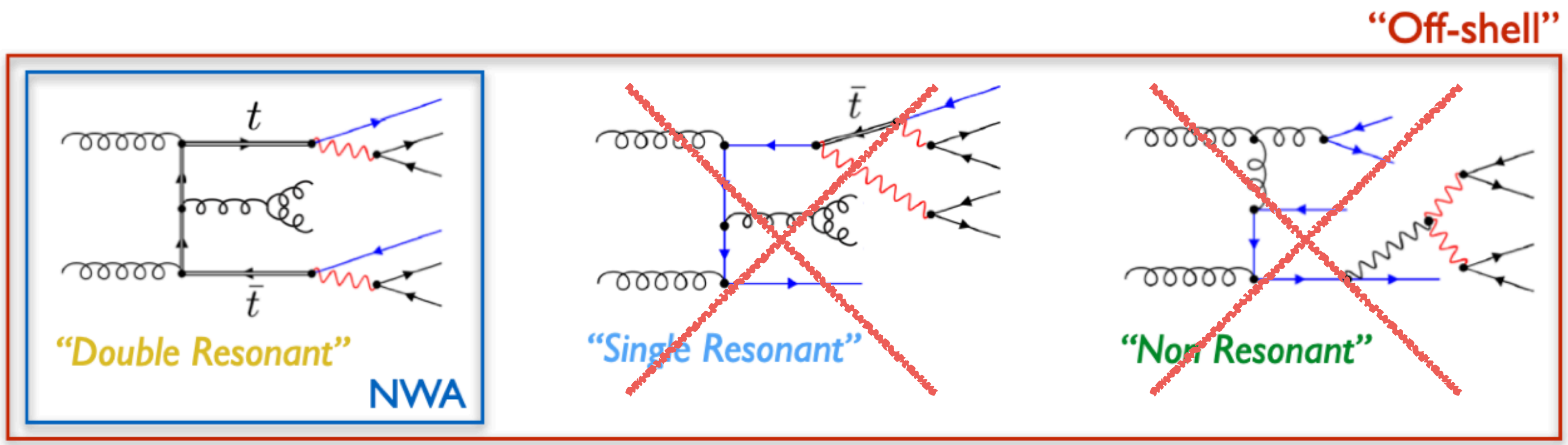


$\Gamma_t/m_t \rightarrow 0$

$\Gamma_W/m_W \rightarrow 0$

$$\Gamma_t/m_t \rightarrow 0 \quad \Rightarrow \quad \boxed{\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} \overset{\Gamma_t\to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\,\delta(p_t^2-m^2)+\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)}$$

- Off-shell effects are suppressed by powers of $\Gamma_t/m_t = \mathcal{O}(1\%)$ for *sufficiently inclusive* observables

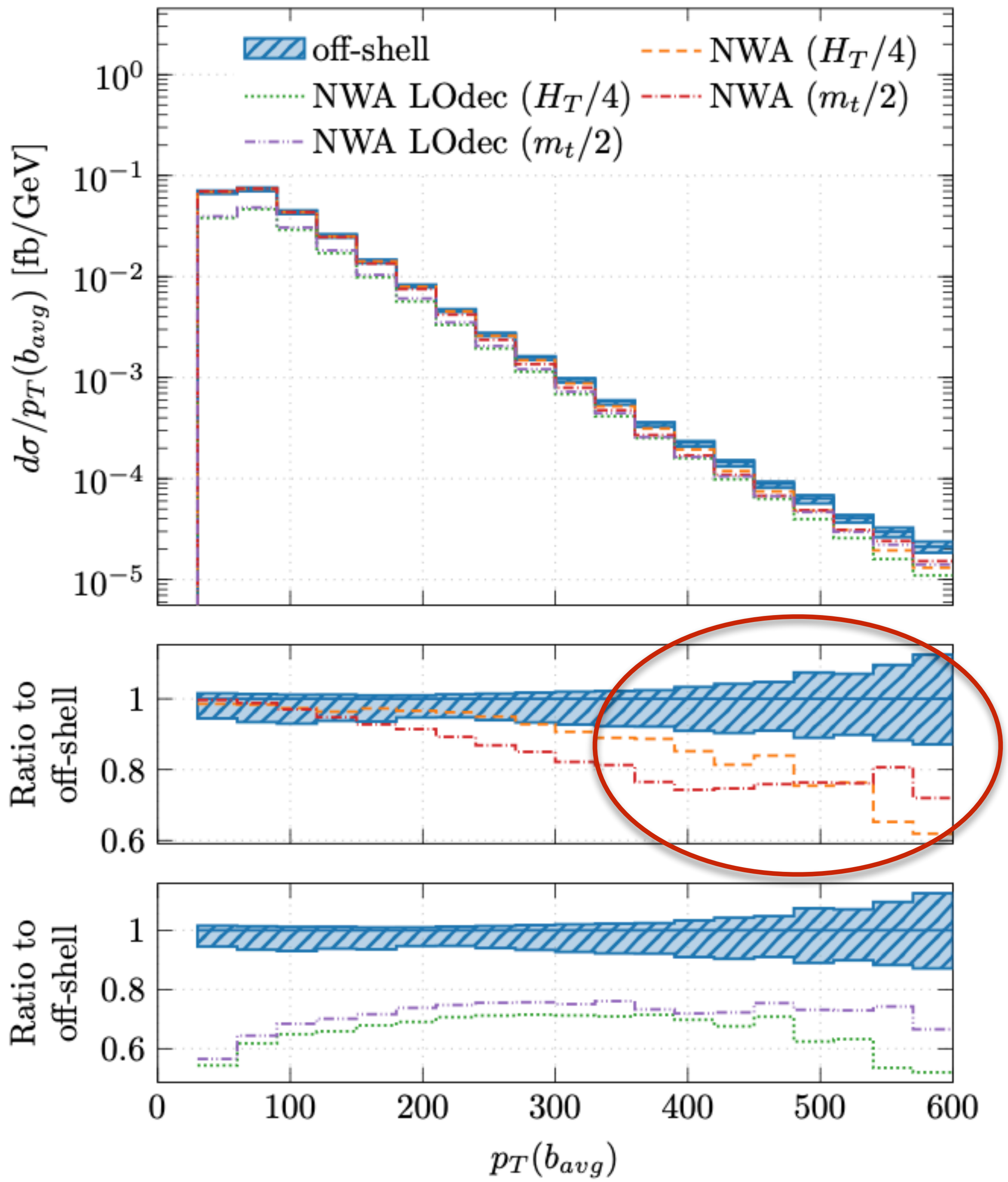
[Fadin, Khoze and Martin, Phys.Lett.B 320 (1994) 141-144]

Note: in general, this is not true at differential level

$t\bar{t}$ + multijets at LHC: theory challenges

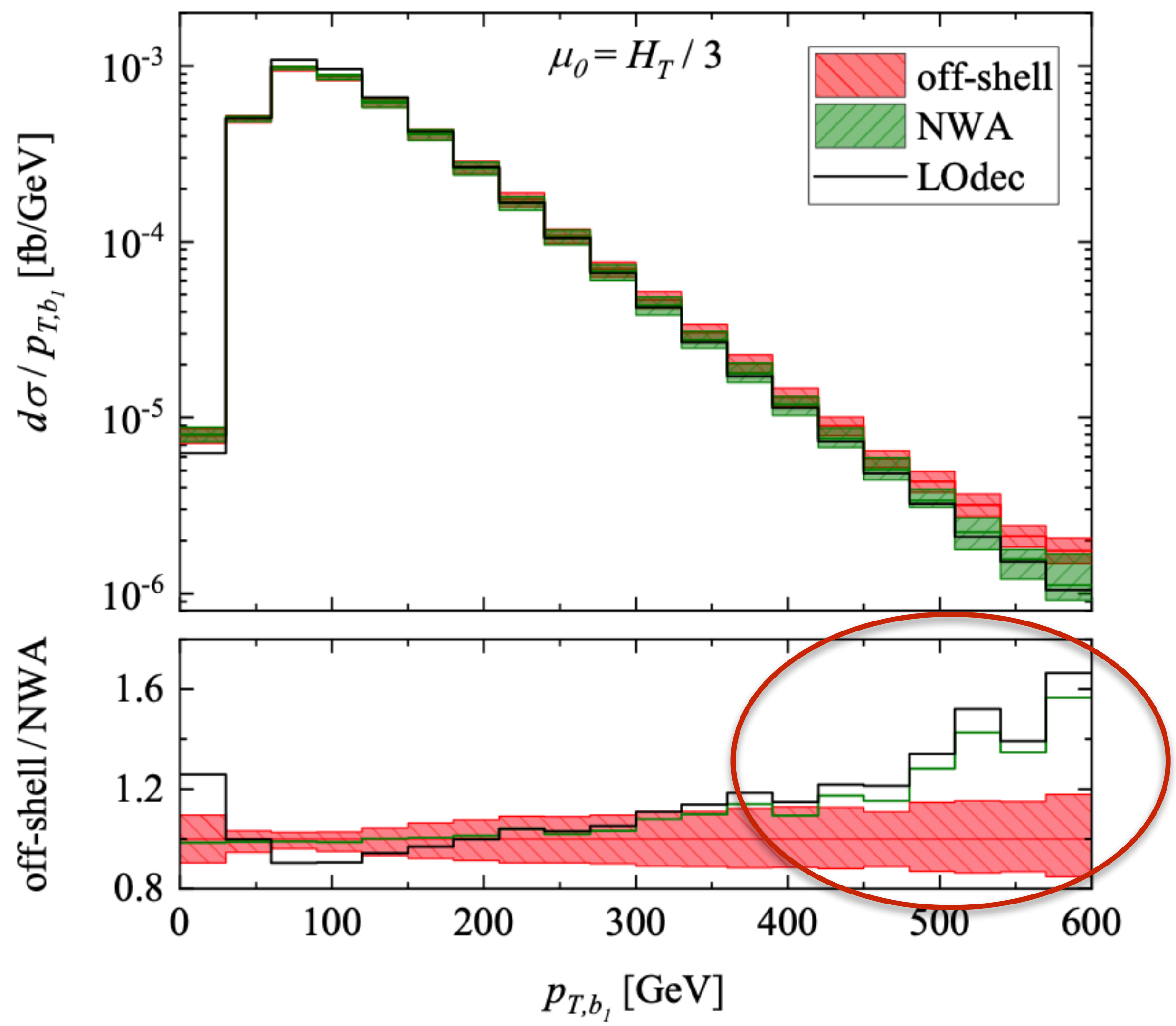
$pp \to t\bar{t}\gamma$ (dilepton)

GB, Hartanto, Kraus, Weber and Worek, JHEP 03 (2020) 154



$pp \to t\bar{t}W^{\pm}$ (dilepton)

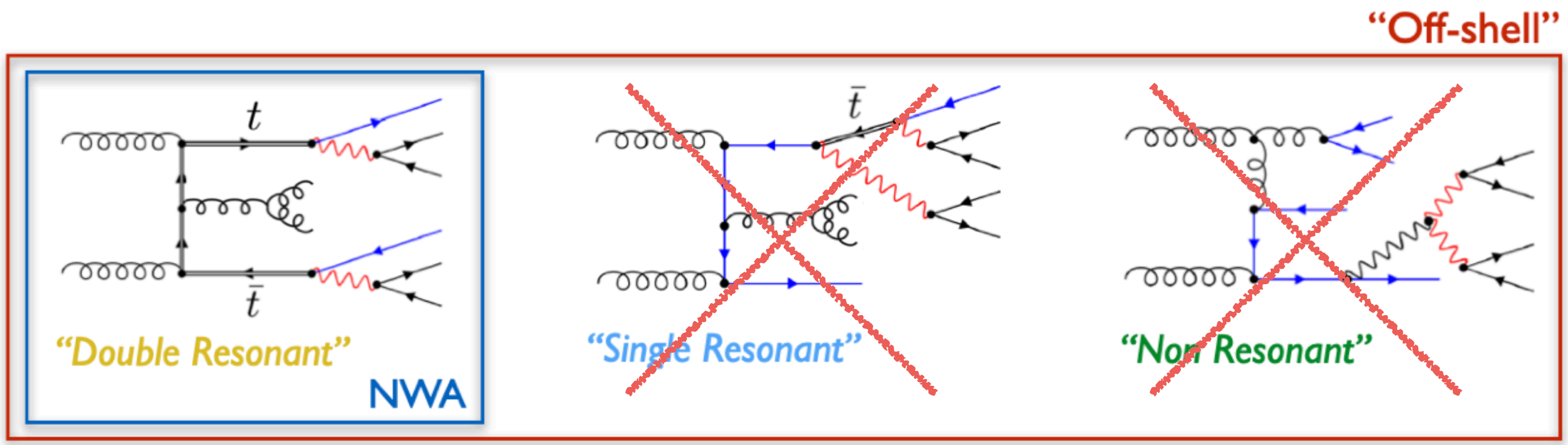
GB, Bi, Hartanto, Kraus and Worek, JHEP 08 (2020) 043



- Off-shell effects can reach $\mathcal{O}(50\%)$ and more differentially!

$t\bar{t}$ + multijets at LHC: theory challenges

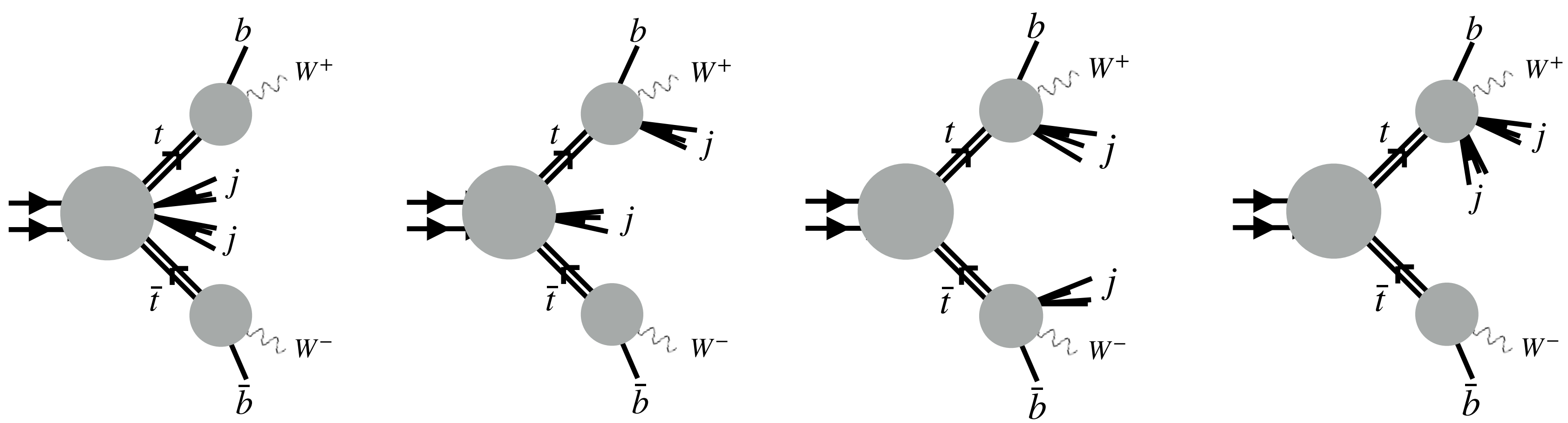
- ME calculations for fully decayed final states are often challenging $\rightarrow$ use NWA



$$\Gamma_t/m_t \to 0$$
$$\Gamma_W/m_W \to 0$$

- The number of resonant structures entering the $t\bar{t} + n\,\mathrm{jets}$ cross section in NWA increases rapidly with n

e.g. : $n = 2$



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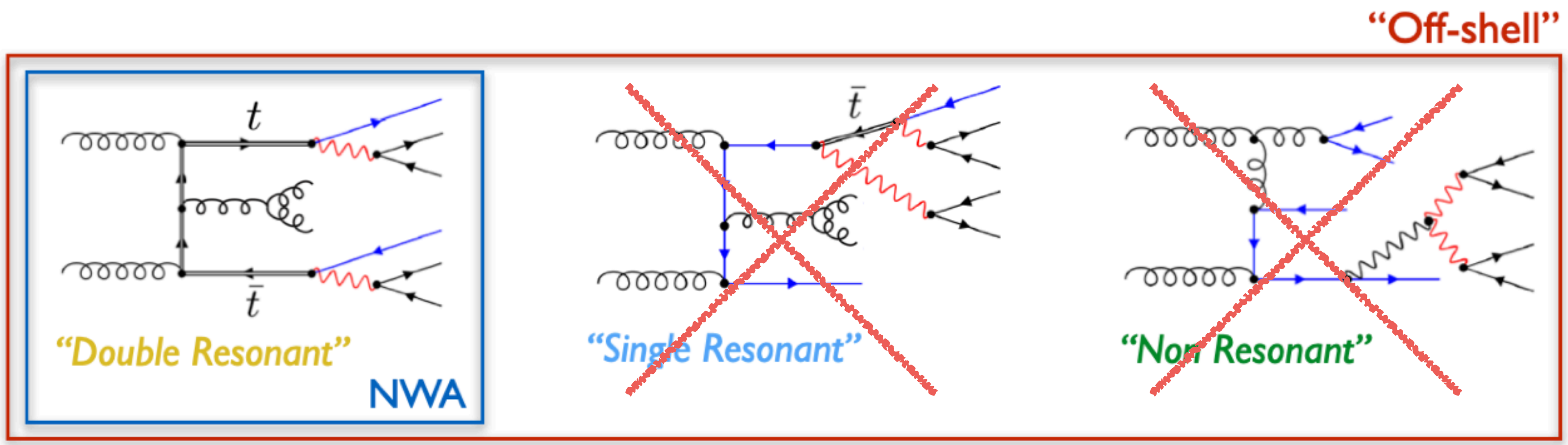

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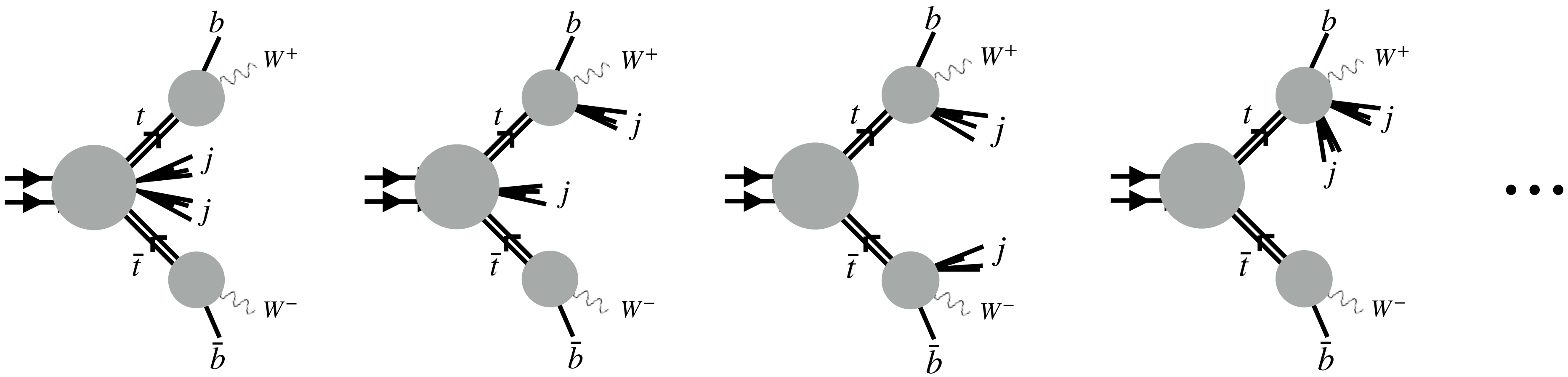

- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

$t\bar{t}$ + multijets at LHC: theory challenges

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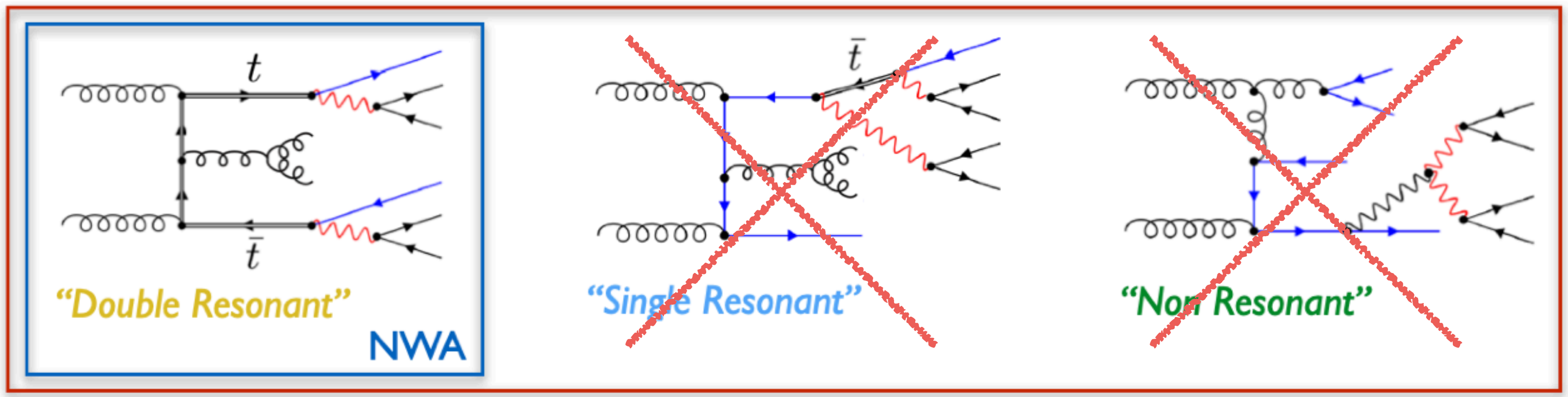

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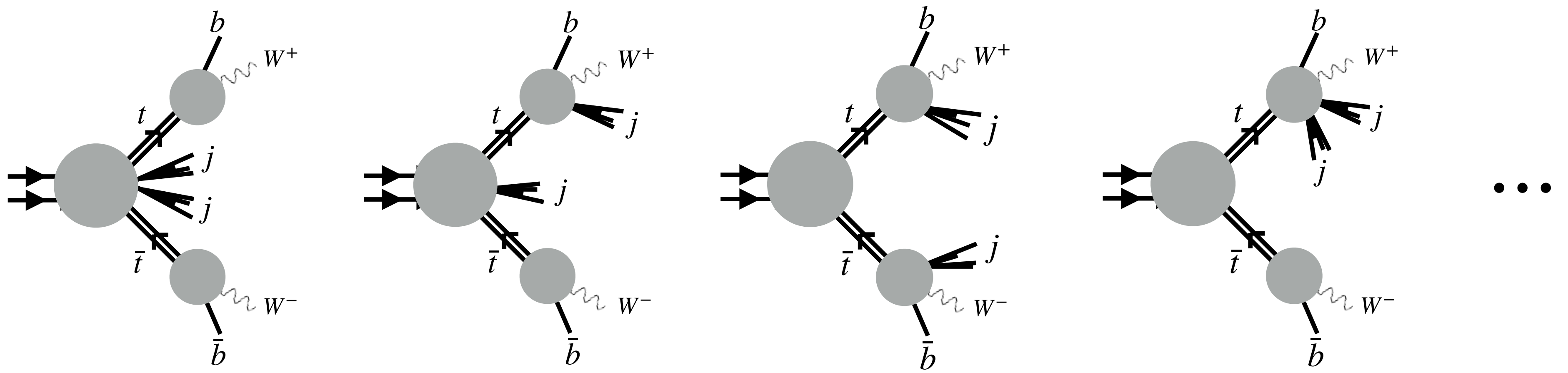


- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

We'll focus on the case of $t\bar{t} + 2\,\mathrm{jets}$

Stable top quarks

- $\boxed{pp \to t\bar{t} + 2\,\text{jets}}$ [GB, Czakon, Papadopoulos and Worek '10,'11]

  ↪ NLO QCD: fixed-order

- $\boxed{pp \to t\bar{t} + 0{,}1{,}2{,}3\,\text{jets}}$ [Höche, Maierhöfer, Moretti, Pozzorini and Siegert '17]

  ↪ NLO QCD: NLO vs MiNLO

Exclusive final states

- $\boxed{pp \to t\bar{t} + 0{,}1{,}2\,\text{jets}}$ [Höche, Krauss, Maierhöfer, Pozzorini, Schönherr and Siegert '15]

  ↪ NLO QCD: MEPS@NLO multi-jet merging

- $\boxed{pp \to t\bar{t} + 0{,}1{,}2{,}3{,}4\,\text{jets}}$ [Gütschow, Lindert and Schönherr '18]

  ↪ NLO QCD+EW ($n \leq 1$ jet) & LO QCD+EW ($n > 1$): MEPS@NLO multi-jet merging

$t\bar{t}bb$: theory status

Fixed order

- $\boxed{pp \to t\bar{t}b\bar{b}}$ $\to$ stable tops

[Bredenstein, Denner, Dittmaier and Pozzorini '09]
[GB, Czakon, Papadopoulos, Pittau and Worek '09]

- $\boxed{pp \to t\bar{t}b\bar{b}j}$ $\to$ stable tops

[Buccioni, Kallweit, Pozzorini and Zoller '19]

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

$\hookrightarrow$ Full off-shell

[Denner, Lang and Pellen '21]
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek ''21]

Matched to PS

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

$\hookrightarrow$ POWHEG matching

[Garzelli, Kardos and Trocsanyi '14] *5FS*
[GB, Garzelli and Kardos '17] 4F*S*
[Jezo, Lindert, Moretti and Pozzorini '18] 4F*S*

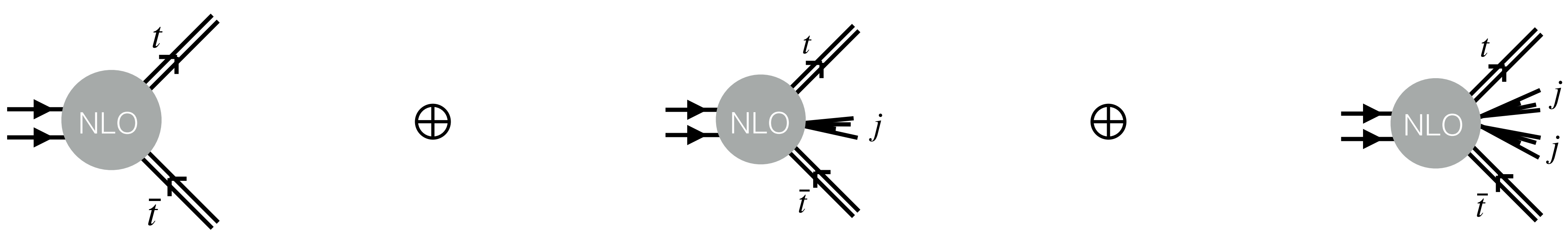
- $\boxed{pp \to t\bar{t}b\bar{b}}$

$\hookrightarrow$ MC@NLO matching

[Cascioli, Maierhöfer, Moretti, Pozzorini and Siegert '14] *4FS*

$t\bar{t}jj$: state-of-the-art in a nutshell

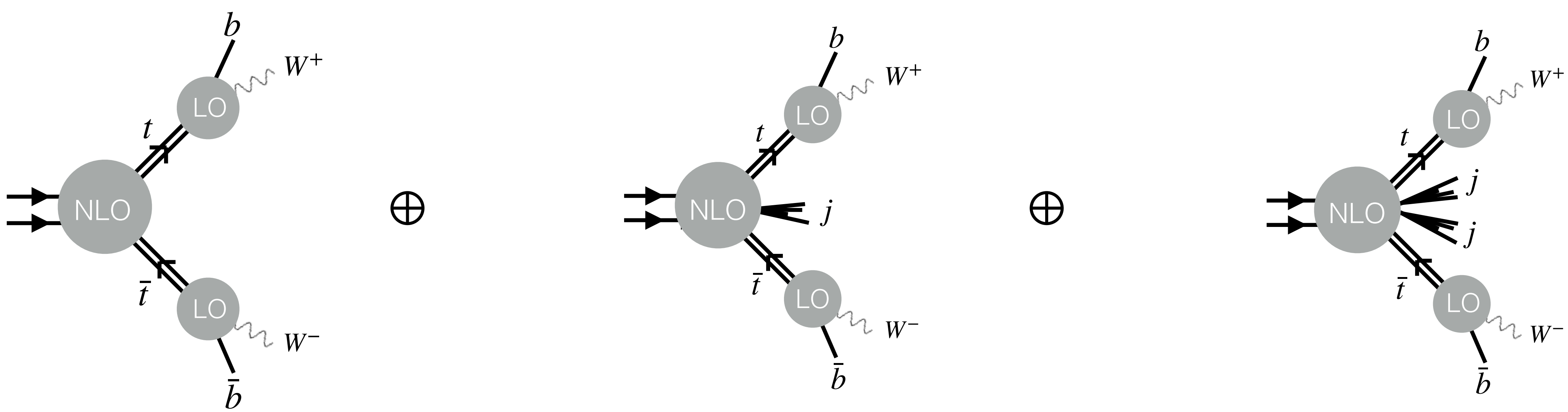
- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)



$pp \to t\bar{t} + 0\,\text{jet}$ $\quad$ $pp \to t\bar{t} + 1\,\text{jet}$ $\quad$ $pp \to t\bar{t} + 2\,\text{jets}$

- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)

- Top quarks produced on-shell and decayed at LO with spin correlations

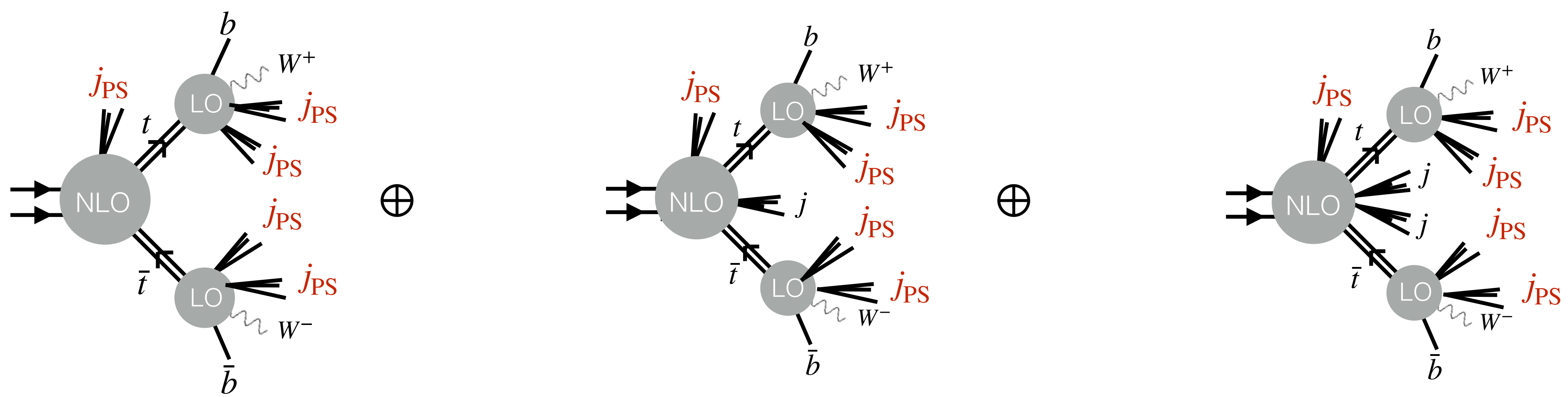


$t\bar{t}jj$: state-of-the-art in a nutshell

- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)

- Top quarks produced on-shell and decayed at LO with spin correlations

- Parton Shower evolution (ISR/FSR) accounts for additional jet activity

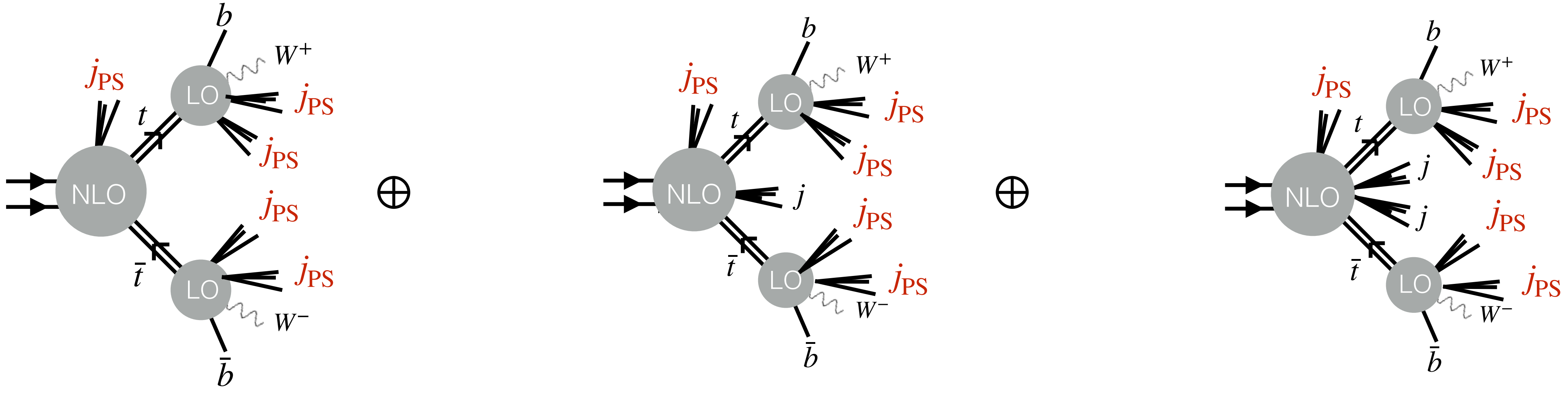


Some interesting questions

I. To what extent do QCD corrections to decays impact fiducial cross sections?
$\rightarrow$ normalisation

II. Which phase space regions are more sensitive to radiation off decays?
$\rightarrow$ shapes

III. What's the impact of full off-shell effects? $\rightarrow$ shapes, normalisation



Outline

- NLO QCD analysis of $pp \to t\bar{t}jj$ (dilepton) — *NWA*

  - Anatomy of resonant contributions at NLO QCD
  - Effects of hard radiation off top quark decays

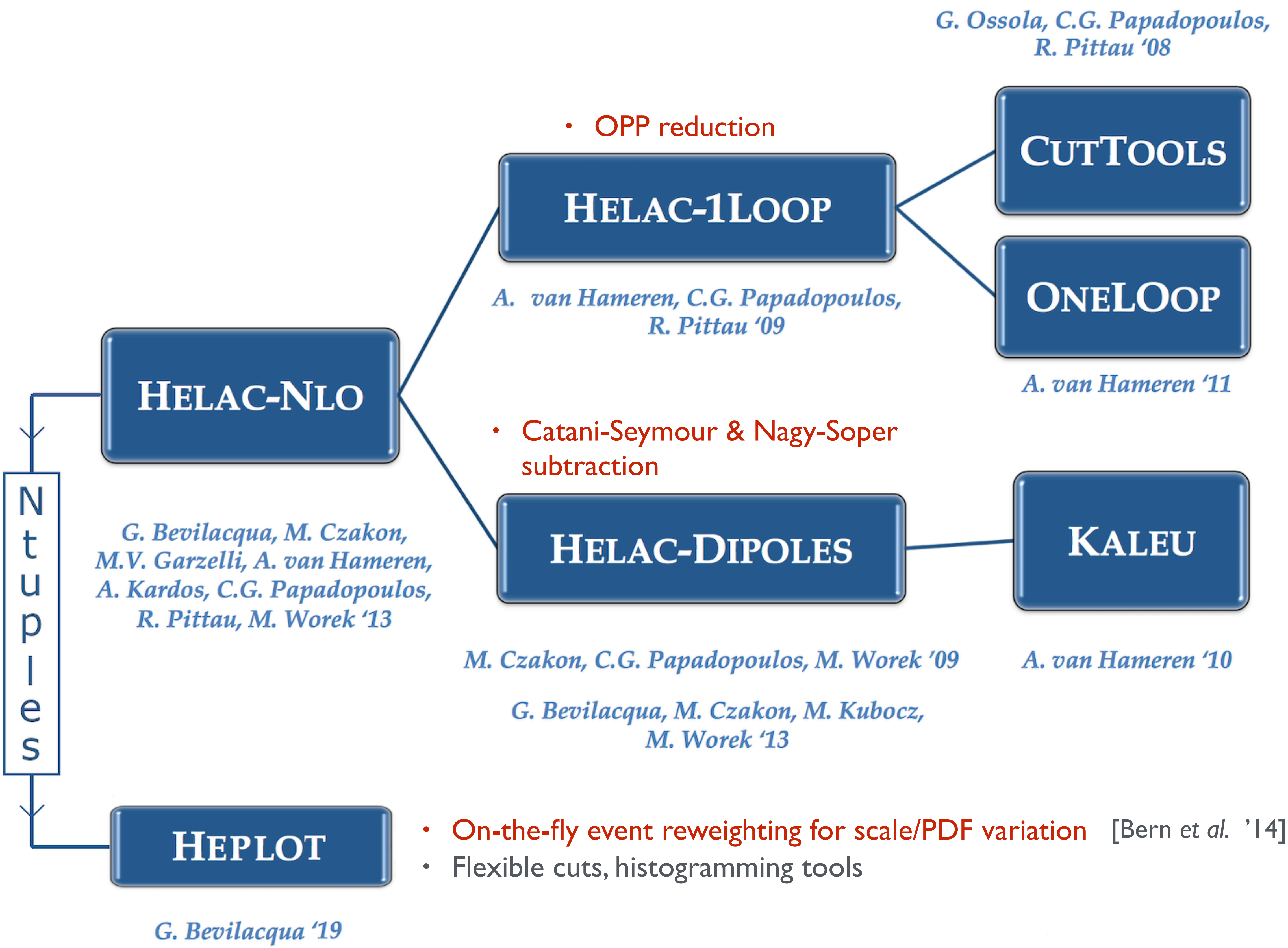
- NLO QCD analysis of $pp \to t\bar{t}b\bar{b}$ (dilepton) — *full off-shell*

  - Impact of genuine off-shell effects
  - Categorization of prompt b-jets

Results obtained with the HELAC-NLO framework

[GB, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau and Worek '13]

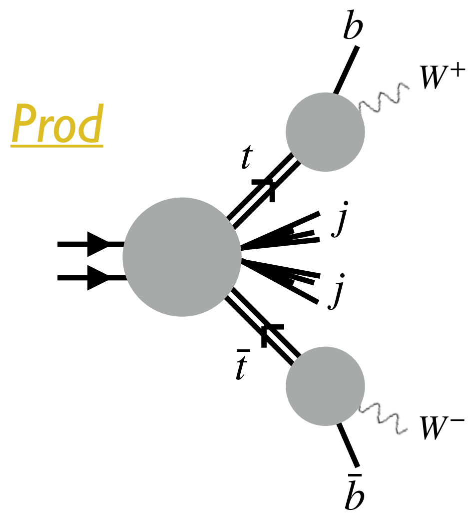
Computational framework

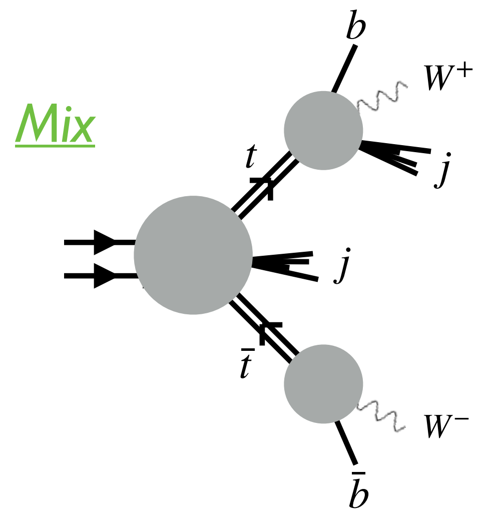


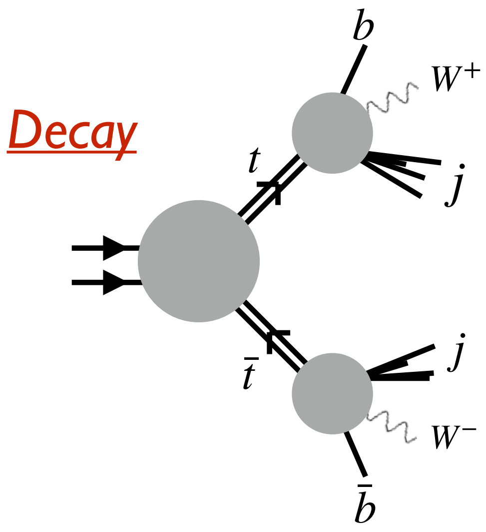
I. A study of jet activity in $t\bar{t}jj$ at the LHC

Resonant contributions to $t\bar{t}jj$ in NWA: **LO**

$$d\sigma^{\rm LO}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(\underbrace{d\sigma^{\rm LO}_{t\bar{t}jj}\, d\Gamma^{\rm LO}_{t\bar{t}}}_{\boxed{\text{Prod.}}} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j}}_{\boxed{\text{Mix}}} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}jj}}_{\boxed{\text{Decay}}}\Big)$$

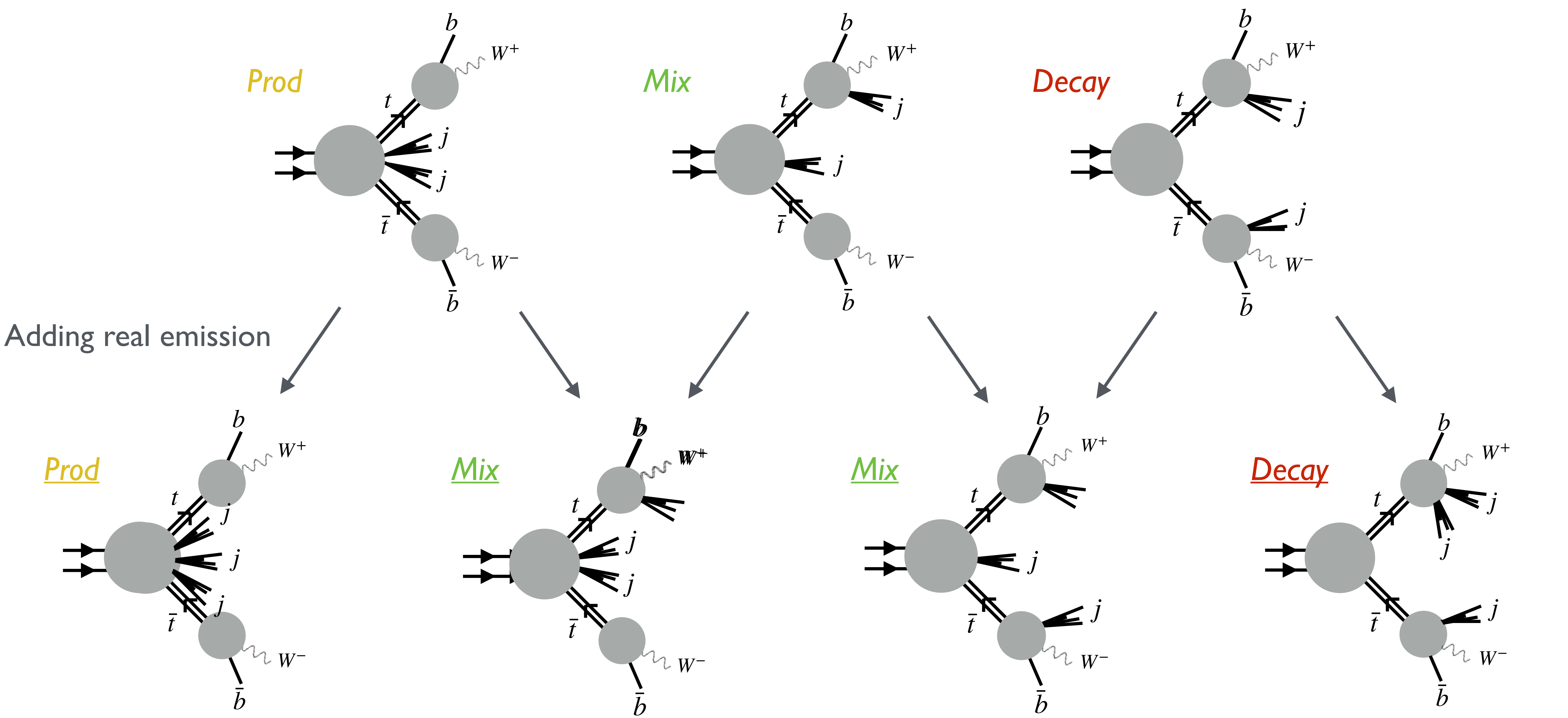






Resonant contributions to $t\bar{t}jj$ in NWA: **NLO**

$$
\begin{aligned}
d\sigma^{\rm NLO}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(& \overbrace{\left(d\sigma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}jj} + d\sigma^{\rm real}_{t\bar{t}jjj}\right) d\Gamma^{\rm LO}_{t\bar{t}}}^{\boxed{\text{Prod.}}} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}} \left(d\Gamma^{\rm LO}_{t\bar{t}jj} + d\Gamma^{\rm virt}_{t\bar{t}jj} + d\Gamma^{\rm real}_{t\bar{t}jjj}\right)}^{\boxed{\text{Decay}}} \\
& \underbrace{+\, d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}jj}\, d\Gamma^{\rm virt}_{t\bar{t}} + d\sigma^{\rm virt}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm virt}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}jj}\, d\Gamma^{\rm real}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}j}\, d\Gamma^{\rm real}_{t\bar{t}jj}}_{\boxed{\text{Mix}}}\Big)
\end{aligned}
$$



$t\bar{t}jj$: fiducial cross sections

Integrated fiducial cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
$\rm NWA_{full}$	$868.8(2)^{+60\%}_{-35\%}$	$1225(1)^{+1\%}_{-14\%}$	1.00	1.00
Prod	$843.2(2)^{+60\%}_{-35\%}$	$1462(1)^{+12\%}_{-19\%}$	0.97	1.19
Mix	25.465(5)	−236(1)	0.029	−0.19
Decay	0.2099(1)	0.1840(8)	0.0002	0.0002
$\rm NWA_{full,exp}$	–	$1173(1)^{+7\%}_{-16\%}$	–	0.96
$\rm NWA_{LOdec}$	–	$1222(1)^{+12\%}_{-19\%}$	–	0.998

$\mu_0 = H_T/2$ NNPDF3.1 PDF

$\Delta R(jb) > 0.8$

Fiducial cuts:

$p_{T,\ell} > 20$ GeV ,
$p_{T,b} > 30$ GeV ,
$p_{T,j} > 40$ GeV ,
$\Delta R_{bl} > 0.4$,
$\Delta R_{\ell\ell} > 0.4$,
$\Delta R_{jj} > 0.4$,
$|y_\ell| < 2.4$,
$|y_b| < 2.4$,
$|y_j| < 2.4$,
$\Delta R_{jl} > 0.4$,
$\Delta R_{bb} > 0.4$,
$\Delta R_{jb} > 0.8\ (0.4)$

- Moderate QCD corrections: $+41\ \%$
- NLO uncertainties — Scale: $\mathcal{O}(15\%)$ PDF: $\mathcal{O}(2\% - 3\%)$

Integrated fiducial cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Modelling	σ^{LO} [fb]	σ^{NLO} [fb]	$\frac{\sigma_i^{\mathrm{LO}}}{\sigma_{\mathrm{NWA}}^{\mathrm{LO}}}$	$\frac{\sigma_i^{\mathrm{NLO}}}{\sigma_{\mathrm{NWA_{full}}}^{\mathrm{NLO}}}$
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$$\Delta R_{bl} > 0.4,\quad \Delta R_{\ell\ell} > 0.4,\quad \Delta R_{jj} > 0.4,$$
$$|y_\ell| < 2.4,\quad |y_b| < 2.4,\quad |y_j| < 2.4,$$
$$\Delta R_{jl} > 0.4,\quad \Delta R_{bb} > 0.4,\quad \Delta R_{jb} > 0.8\ (0.4)$$

- At LO: *Prod* is dominant, *Mix* and *Decay* are negligible (and all positive)
- At NLO: non-negligible and *negative* contribution from *Mix*: $-19\,\%$

Integrated fiducial cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
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$\mu_0 = H_T/2$ NNPDF3.1 PDF

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$|y_\ell| < 2.4$,
$|y_b| < 2.4$,
$|y_j| < 2.4$,
$\Delta R_{jl} > 0.4$,
$\Delta R_{bb} > 0.4$,
$\Delta R_{jb} > 0.8$ (0.4)

- $\rm NWA_{full}$ vs $\rm NWA_{LOdec}$: permille level difference

How stable are these conclusions under different kinematical cuts ?

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

$\Delta R(jb) > 0.8$

Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
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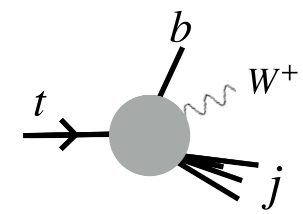
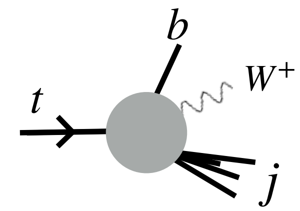
$\rm NWA_{LOdec}$	–	$1222(1)^{+12\%}_{-19\%}$	–	0.998

"more  suppressing"

"less  suppressing"

$\Delta R(jb) > 0.4$

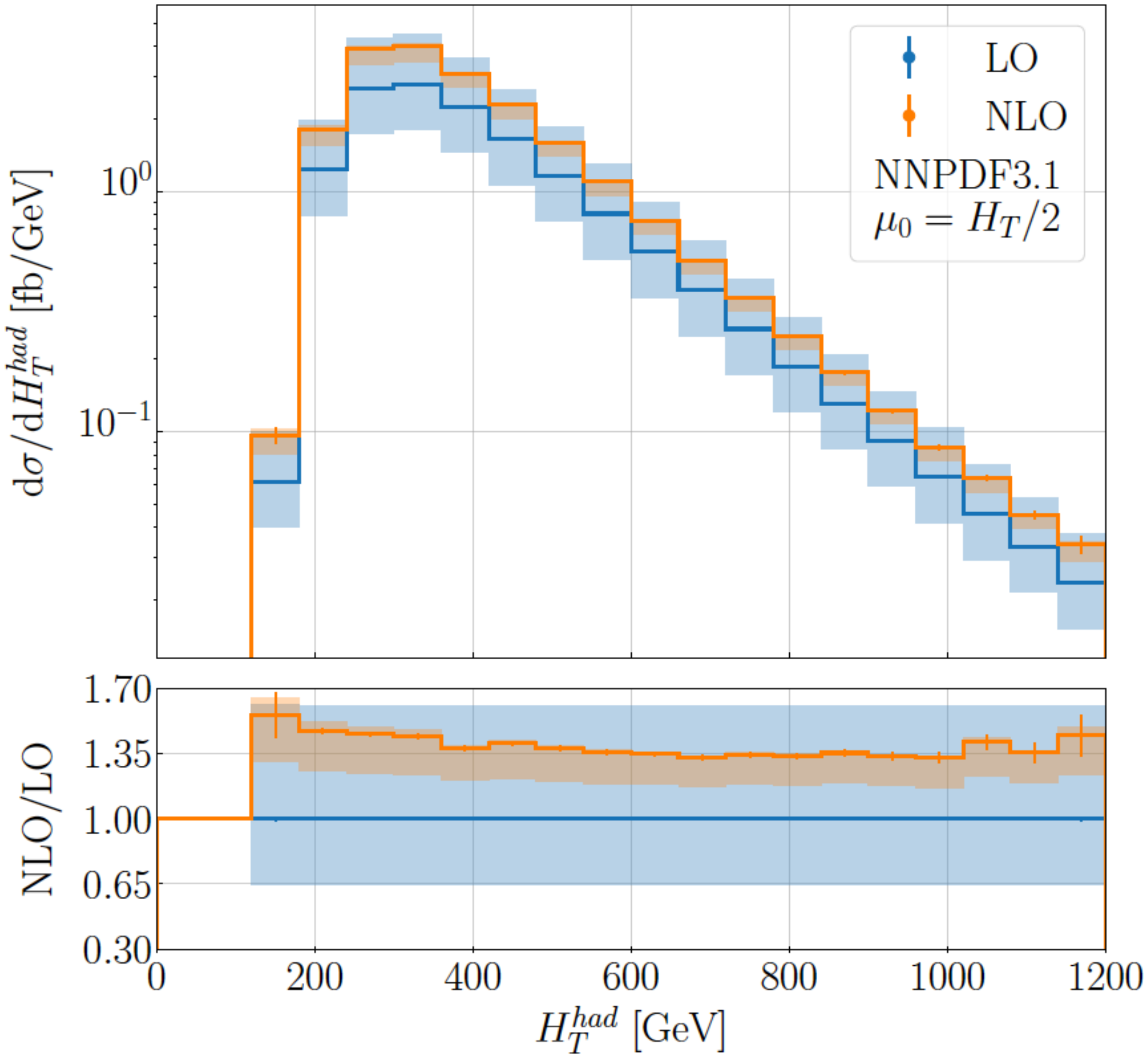
Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
$\rm NWA_{full}$	$1074.5(3)^{+60\%}_{-35\%}$	$1460(1)^{+1\%}_{-13\%}$	1.00	1.00
Prod	$983.1(3)^{+60\%}_{-35\%}$	$1662(1)^{+11\%}_{-18\%}$	0.91	1.14
Mix	89.42(3)	−205(1)	0.083	−0.14
Decay	1.909(1)	2.436(6)	0.002	0.002
$\rm NWA_{LOdec}$	–	$1390(2)^{+11\%}_{-18\%}$	–	0.95

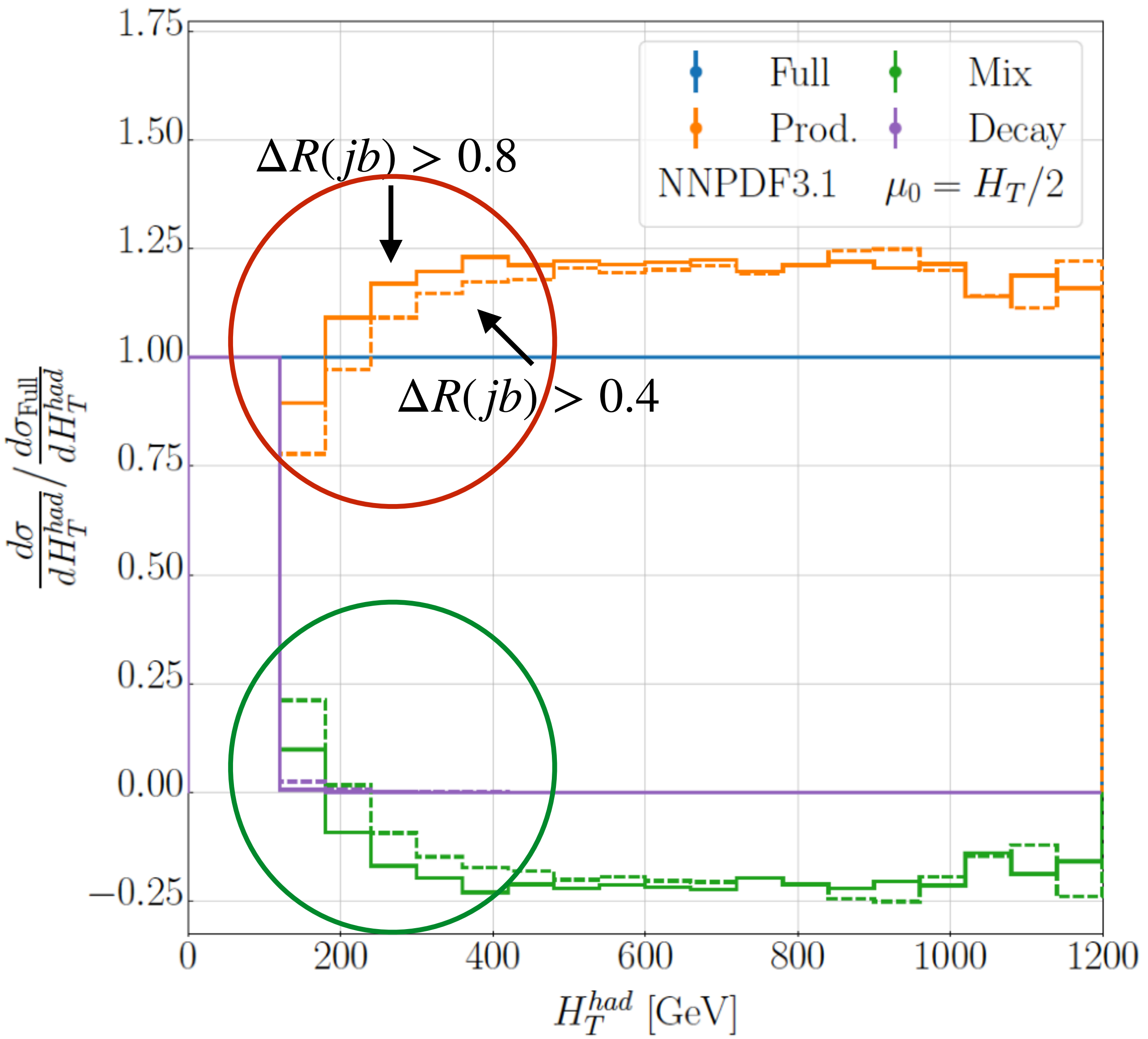
- *Prod-Mix* interplay varies when jet radiation off top quarks is less suppressed
- $|\mathrm{NWA_{full}} - \mathrm{NWA_{LOdec}}| \sim 5\,\%$ for $\Delta R(jb) > 0.4$

$t\bar{t}jj$: differential cross sections

$$H_T^{had} = \sum_{i=1}^{2} p_{T j_i} + \sum_{i=1}^{2} p_{T b_i}$$

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

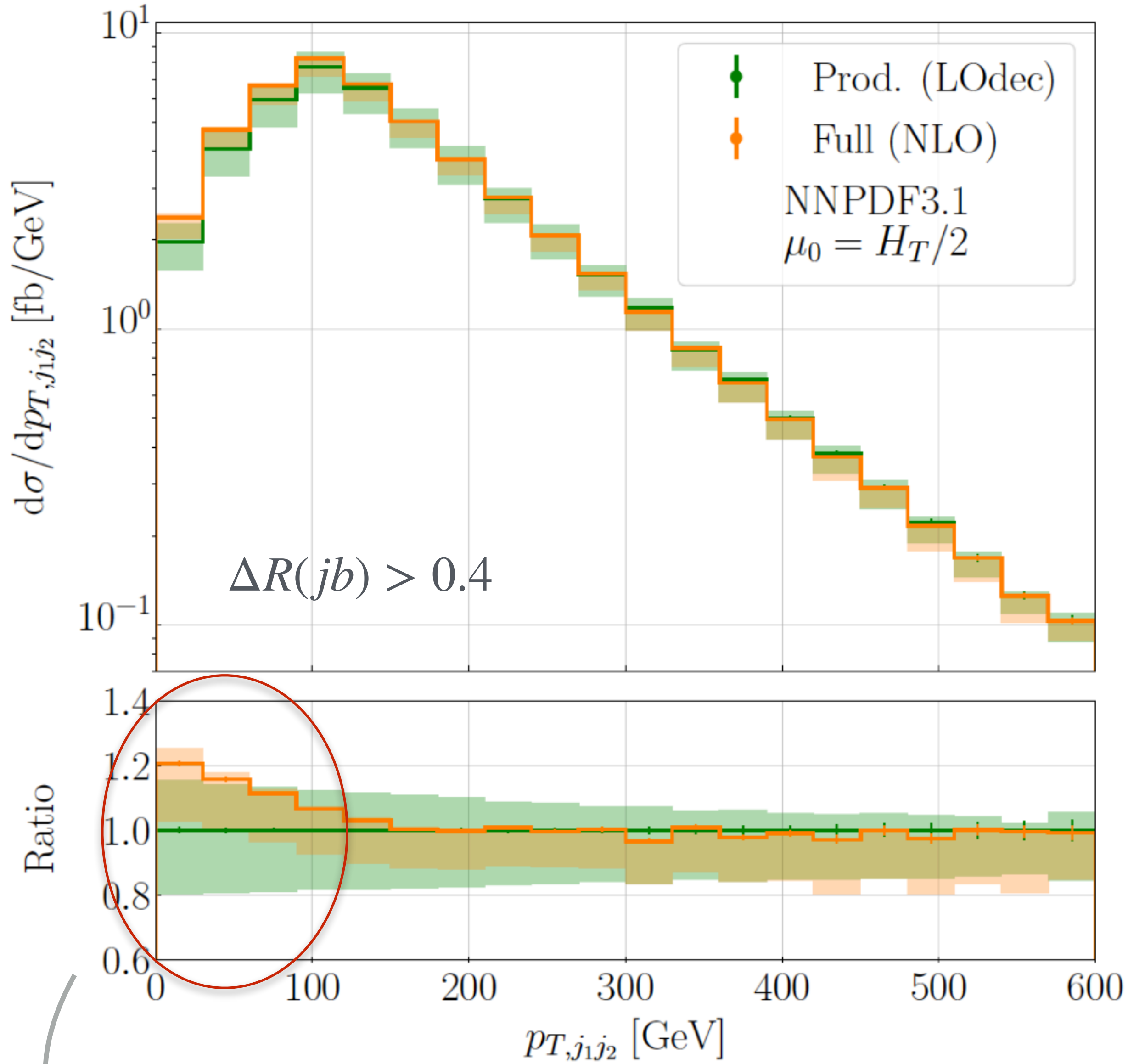


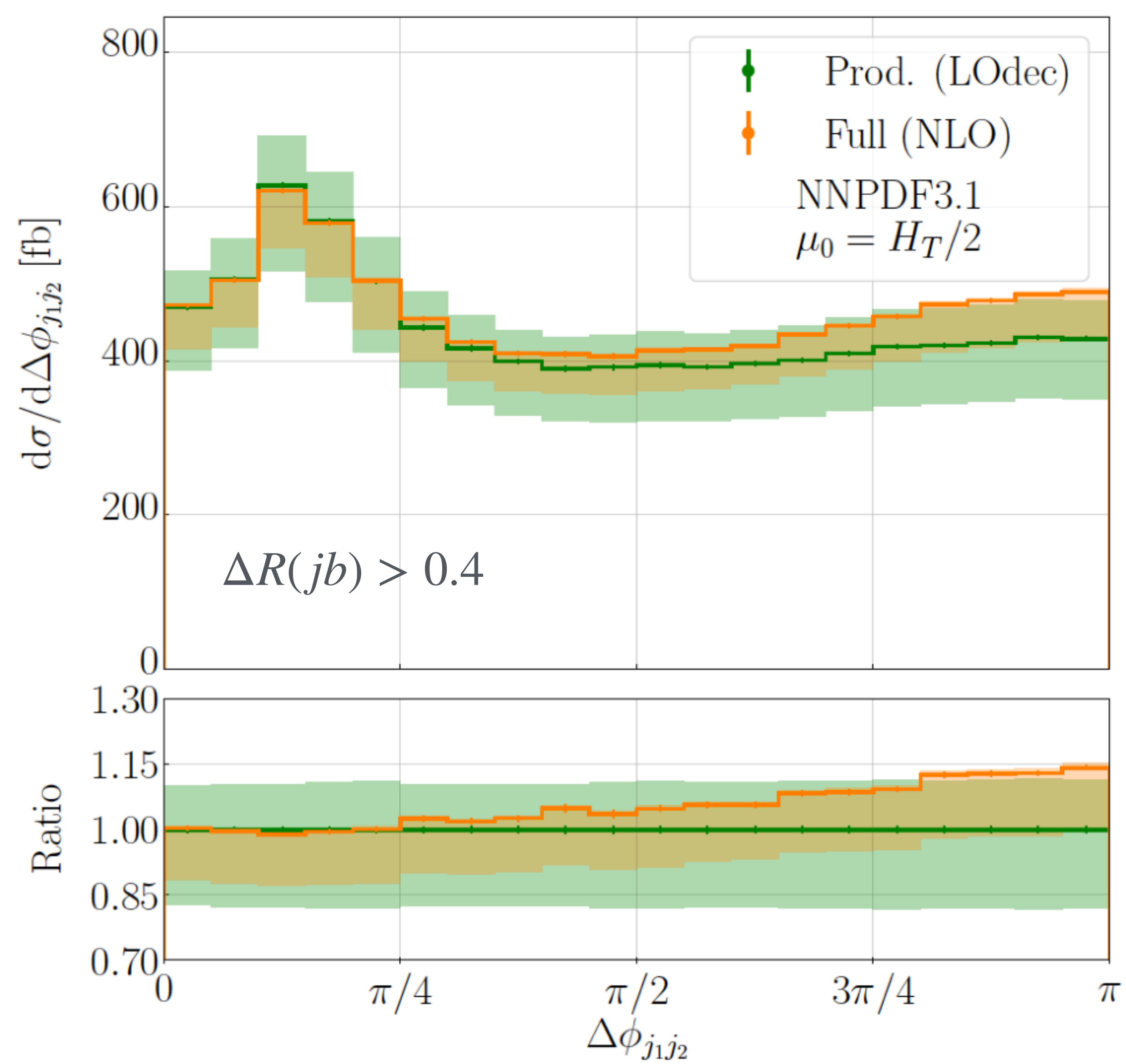


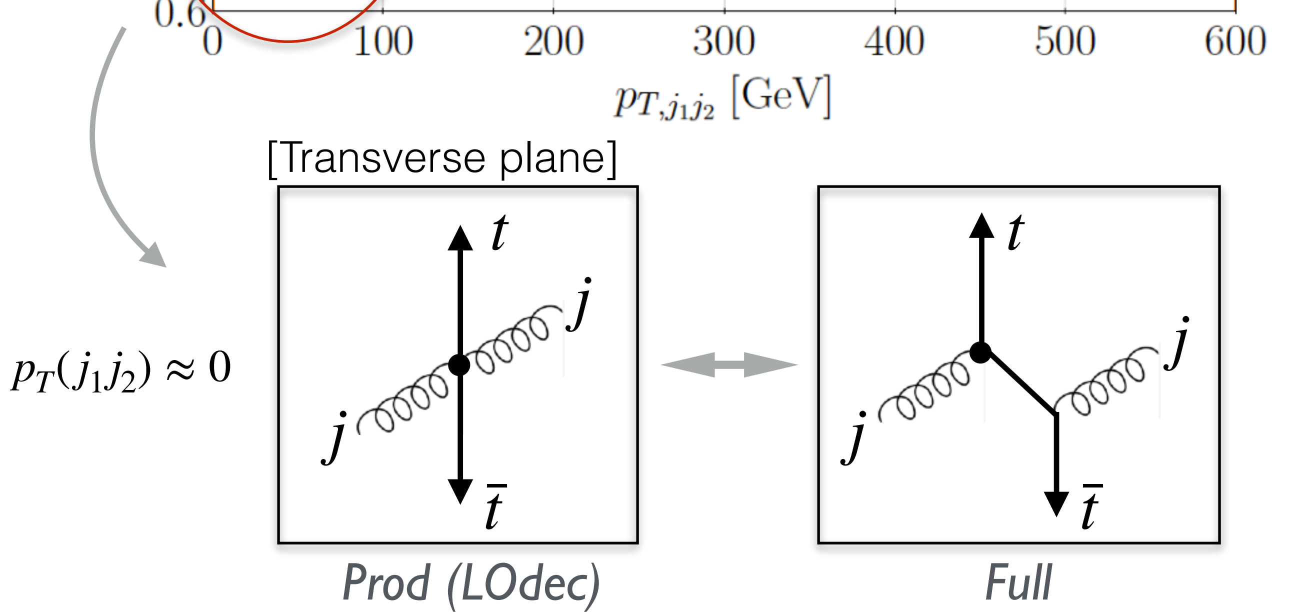
- Sensitivity to different $\Delta R(jb)$ cuts enhanced around the bulk

$t\bar{t}jj$: differential cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]







- Shape distortions up to 15% - 20 % in both dimensionful and dimensionless observables

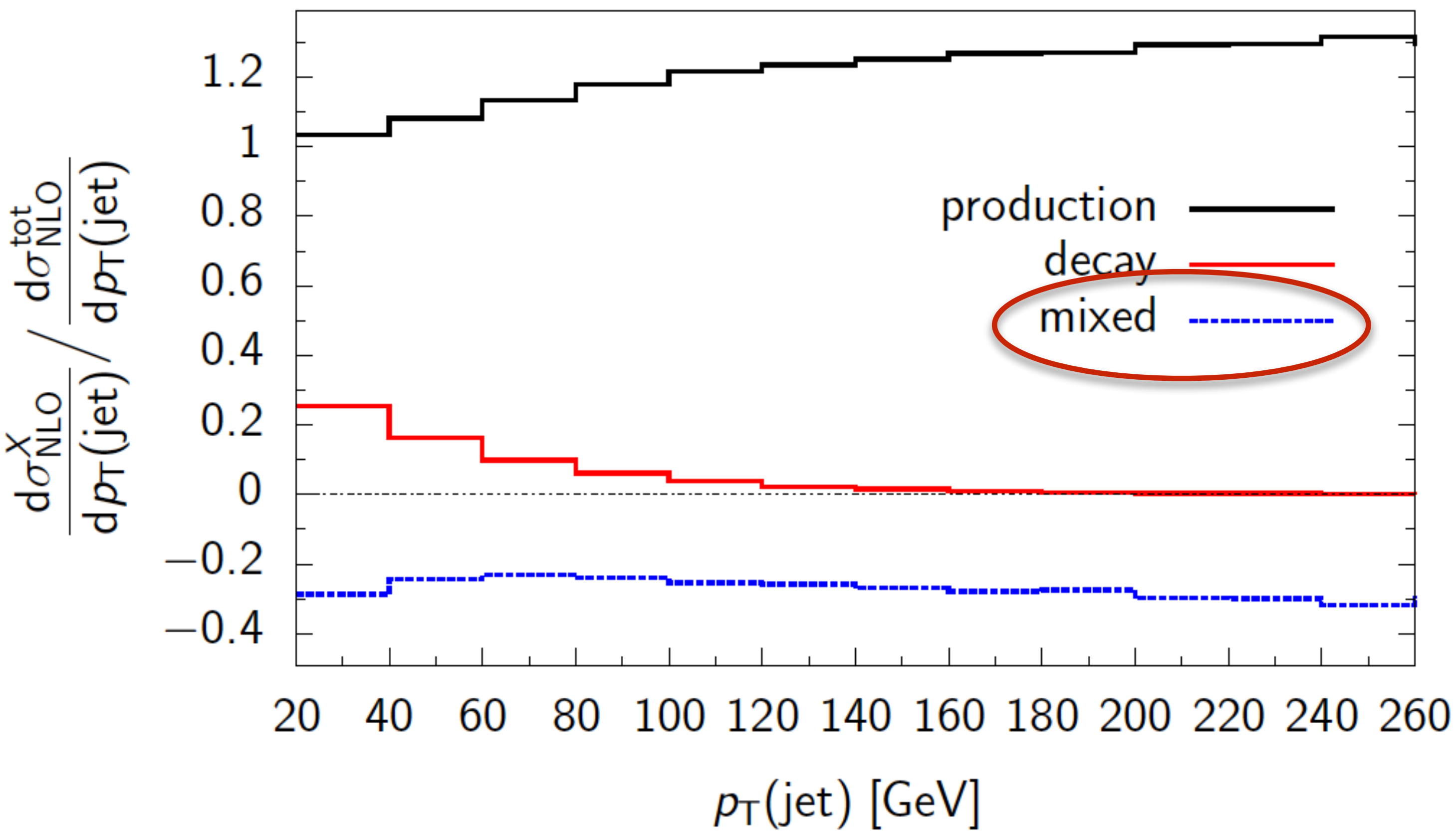
[Melnikov, Scharf and Schulze, Phys.Rev.D 85 (2012) 054002]

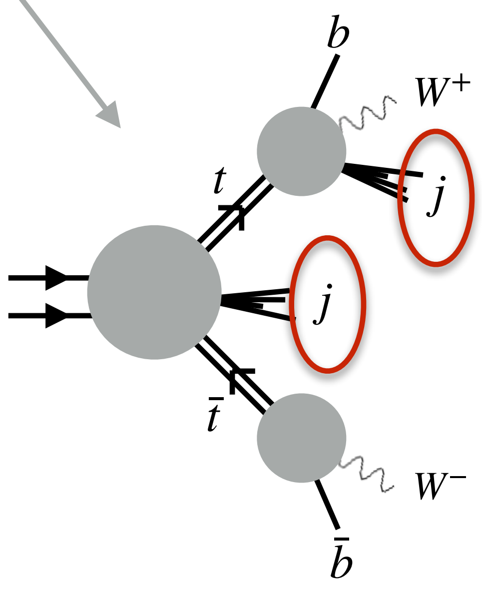
$$\boxed{pp \to t\bar{t}j \to b\bar{b}\,\ell\nu_\ell\, jjj} \qquad \sqrt{s} = 7\,\text{TeV}$$

$$\sigma_{\rm LO} = 316.9\ (\text{Pr}) + 33.4\ (\text{Dec}) = 350.3\ \text{fb},$$

$$\sigma_{\rm NLO} = 323\ (\text{Pr}) + 40.5\ (\text{Dec}) - 75.5\ (\text{Mix}) = 288\ \text{fb}.$$

-25% of $\sigma_{\rm NLO}$



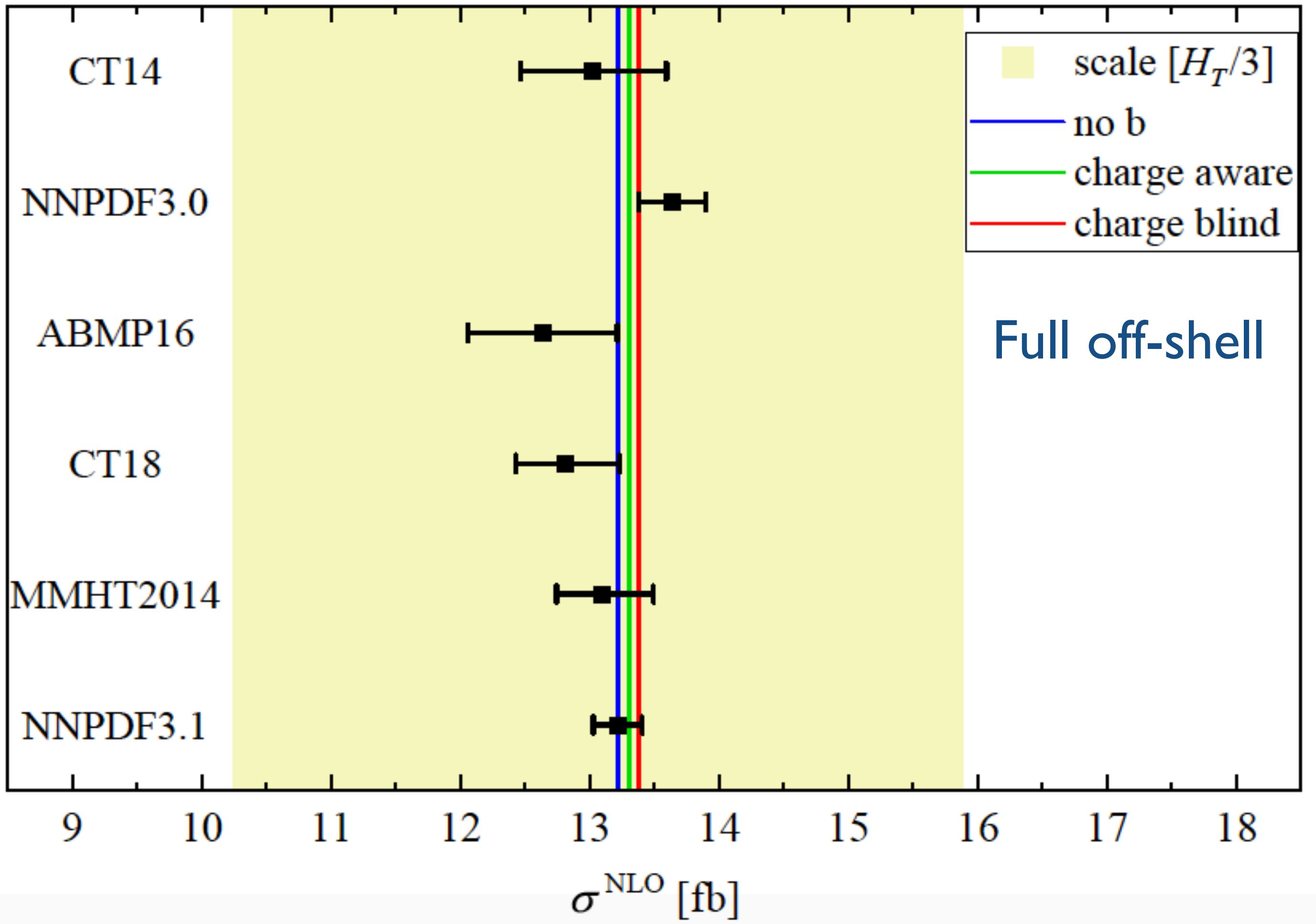


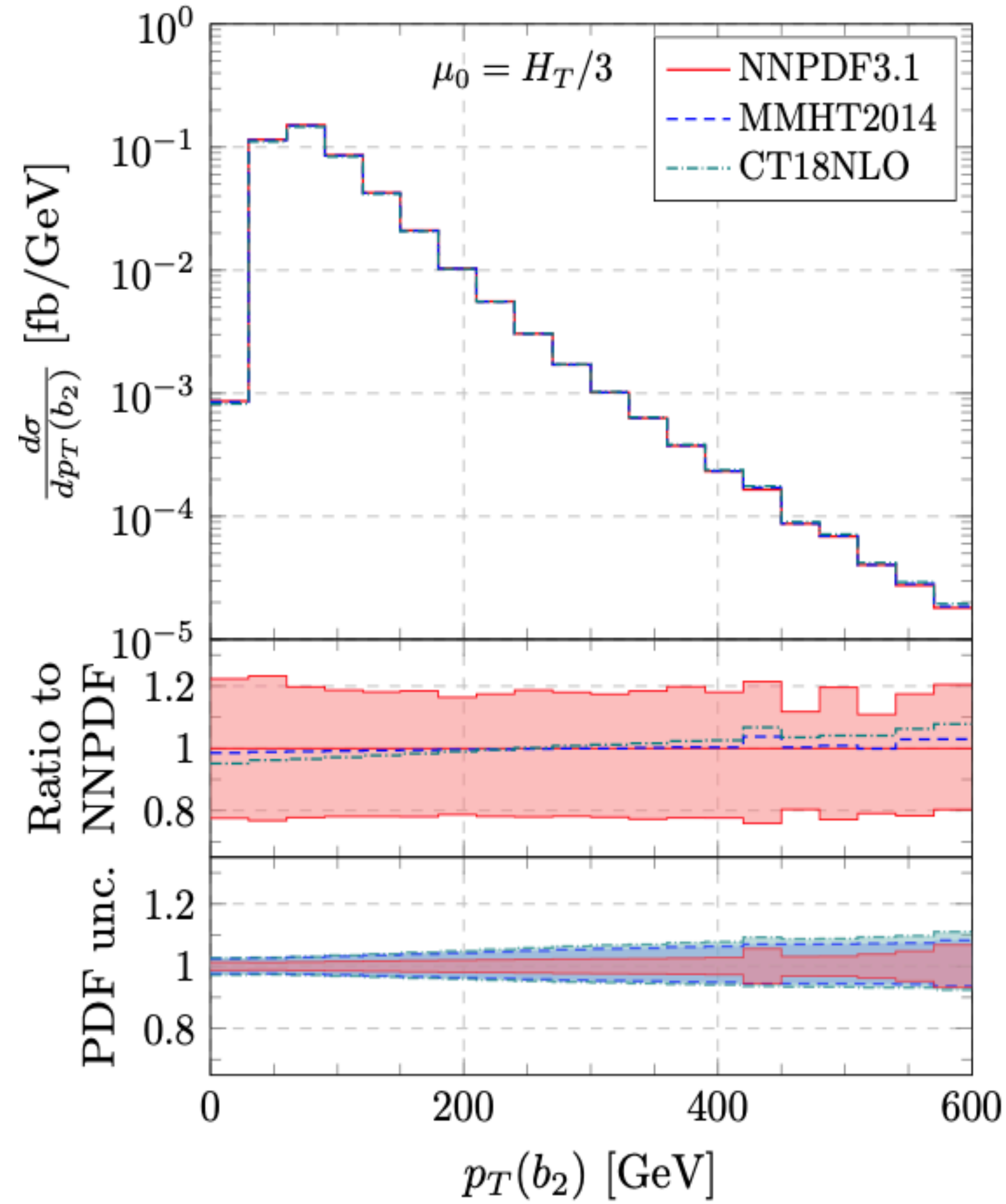
II. $t\bar{t}b\bar{b}$: off-shell effects and prompt b-jet categorisation

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

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

- $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}b\bar{b}$ 13 TeV





NLO theory uncertainties

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

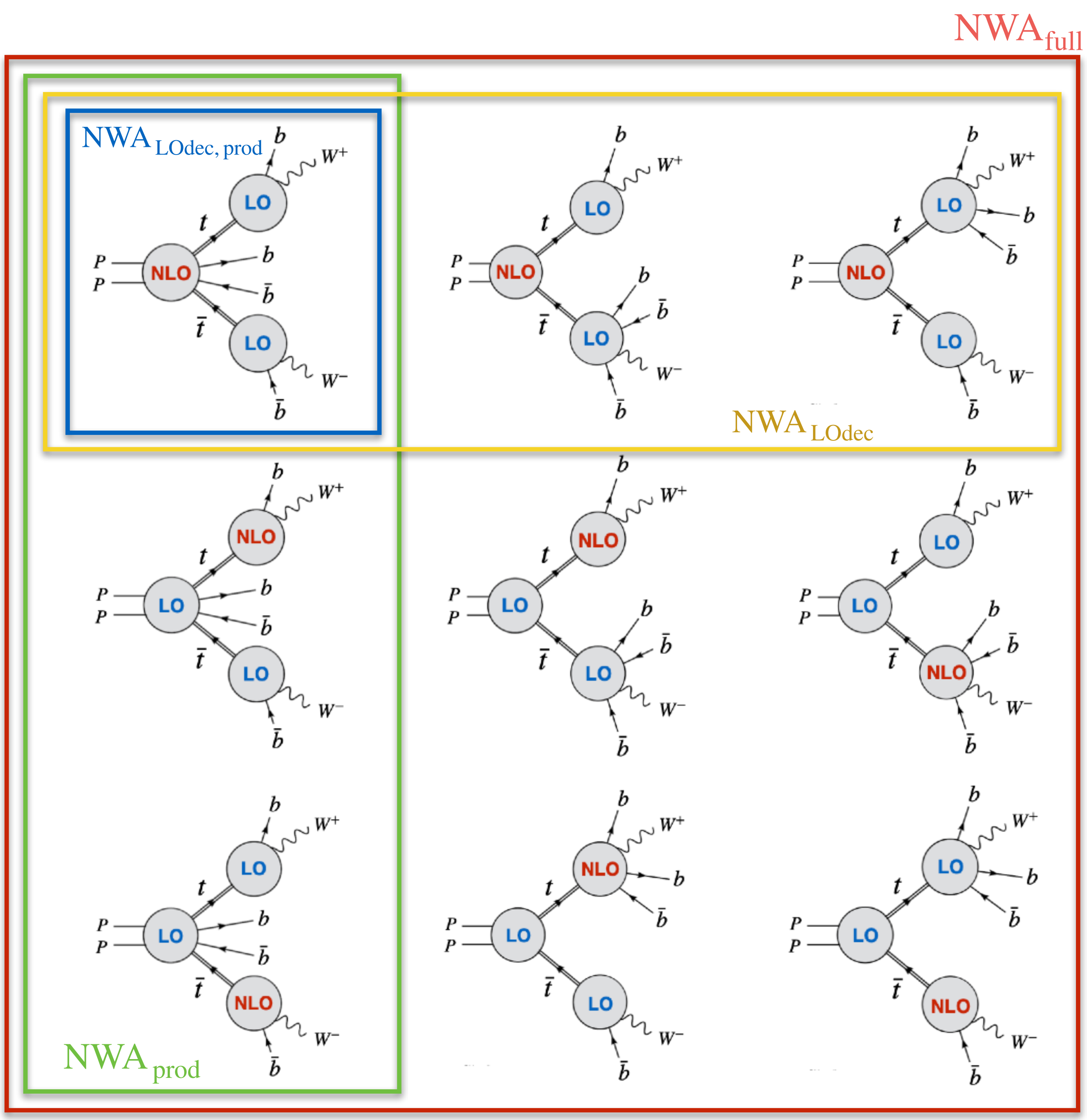
↪ Relative sizes vary at high-energy tails

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

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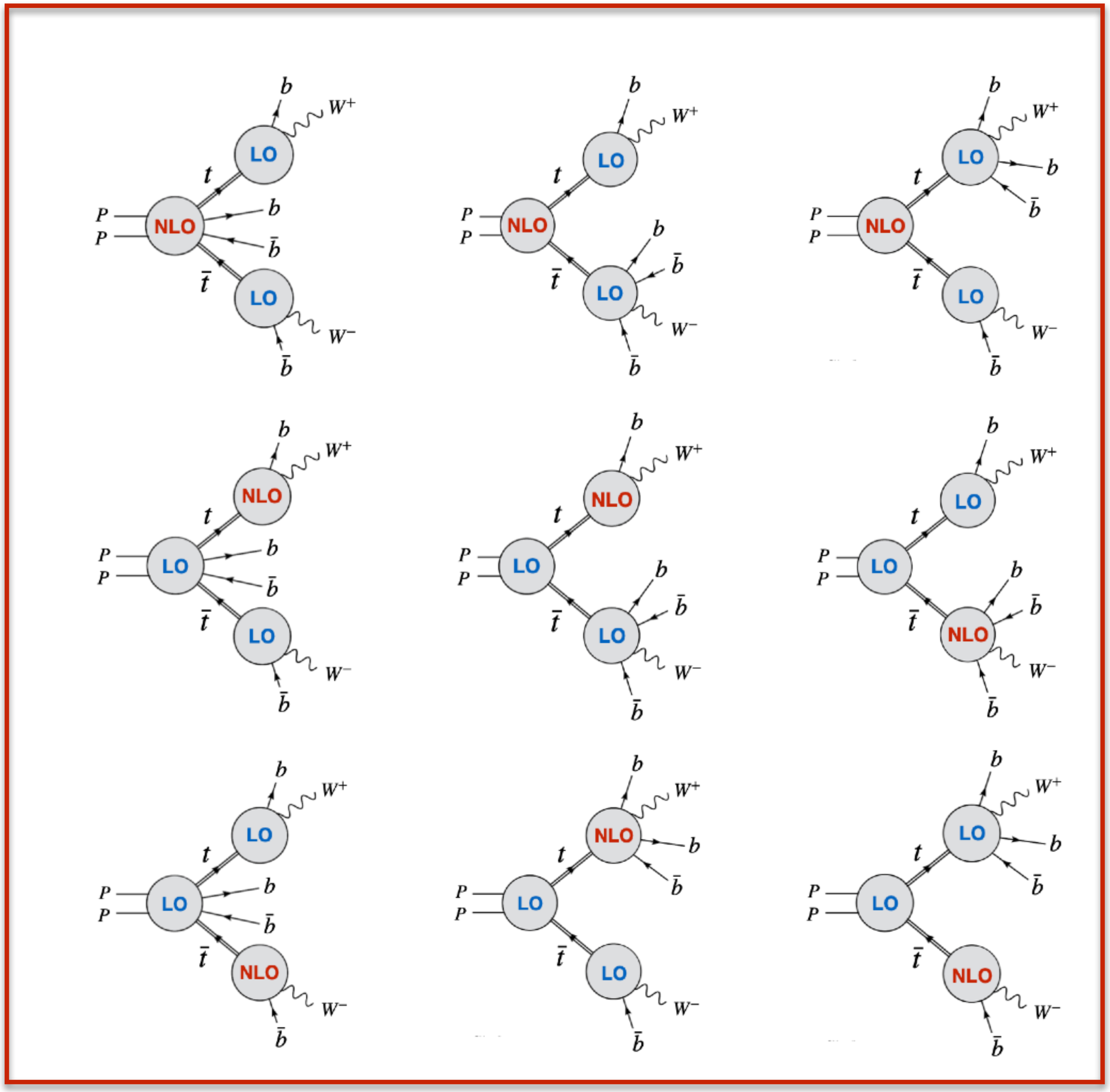
$\rm NWA_{full}$



- 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]

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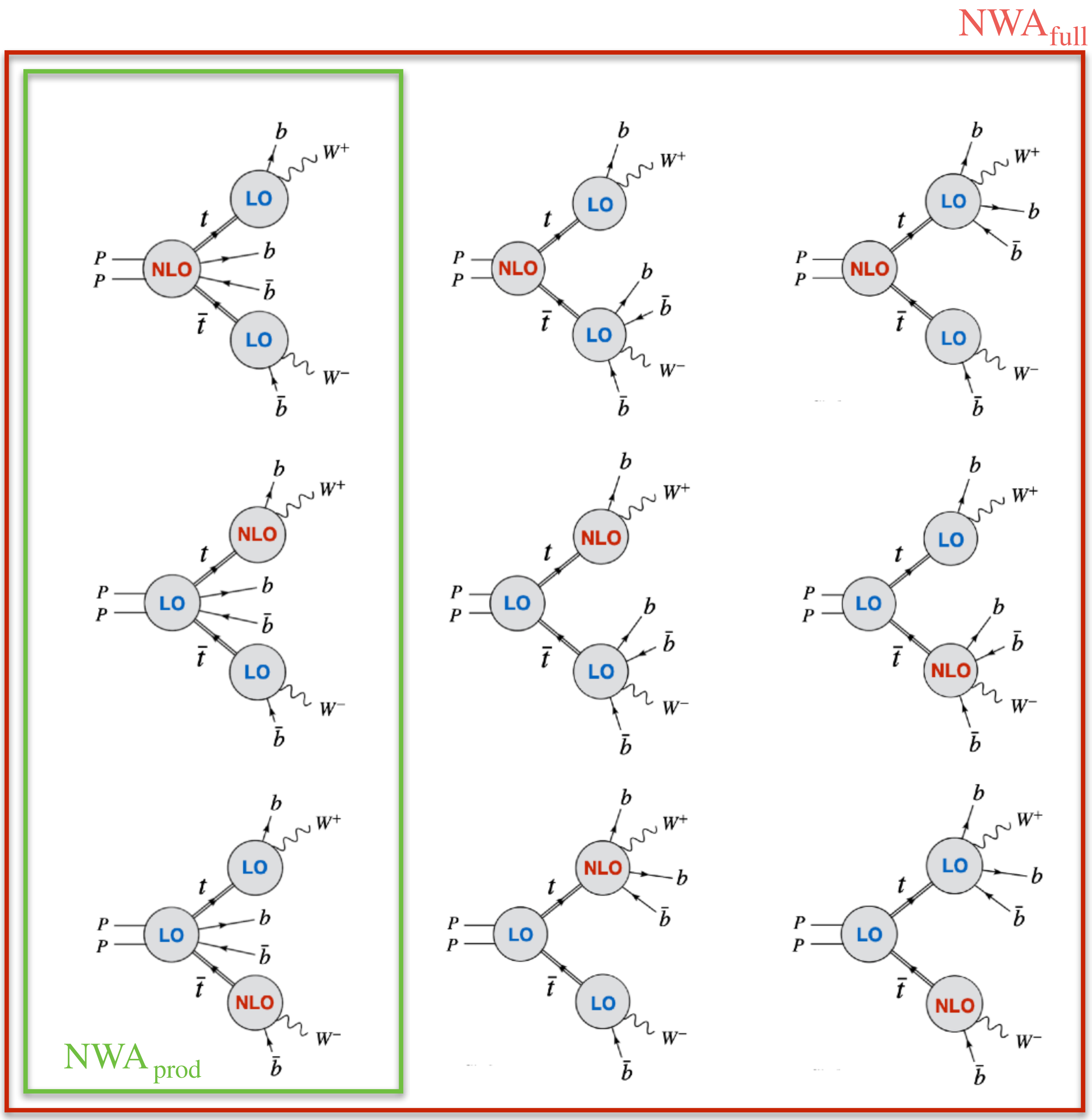

- $\rm NWA_{full}$ vs $\rm NWA_{prod}$:

↪ 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]

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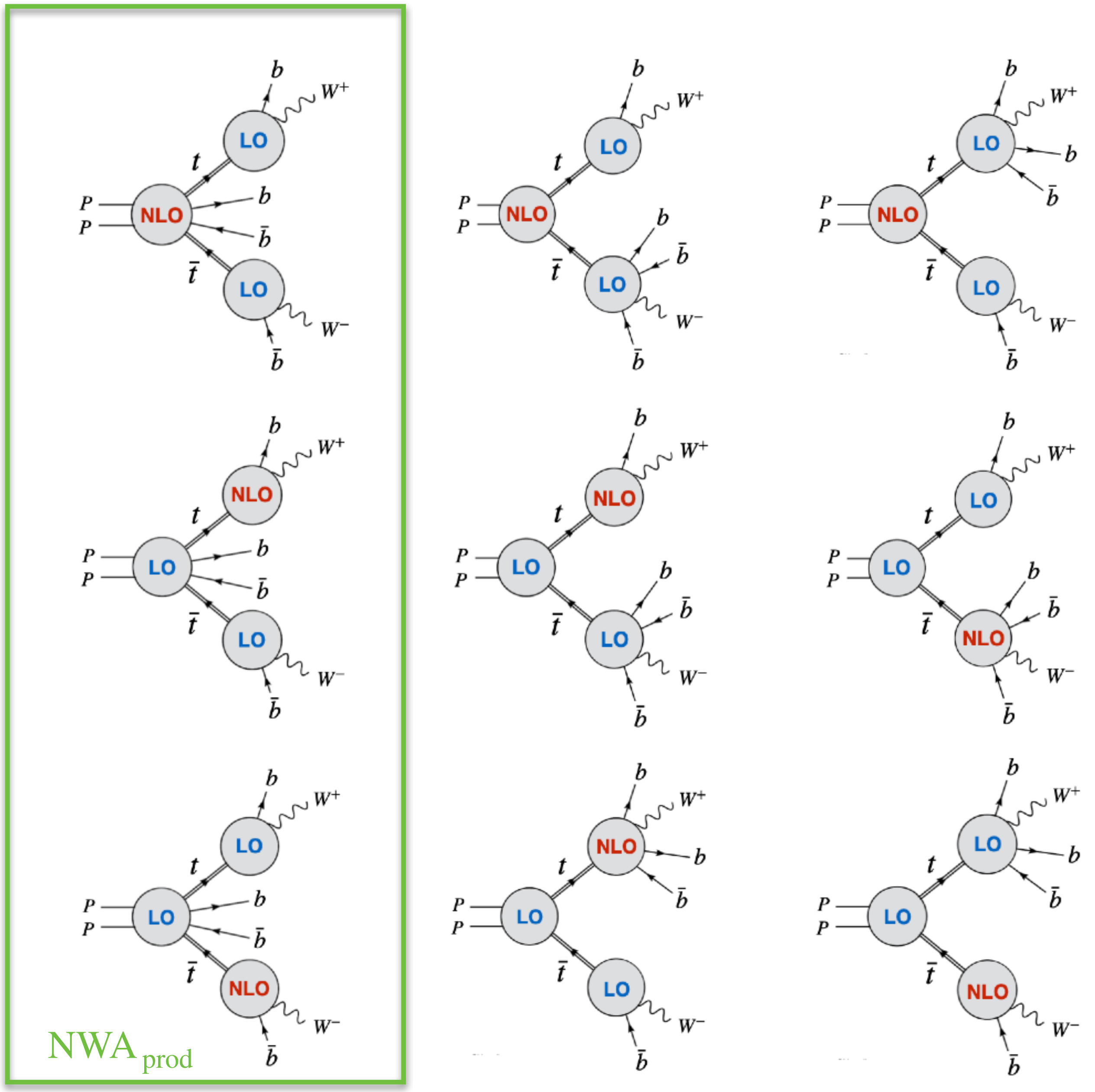

- $\rm NWA_{prod}$ vs $\rm NWA_{prod,exp}$:

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

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

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

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

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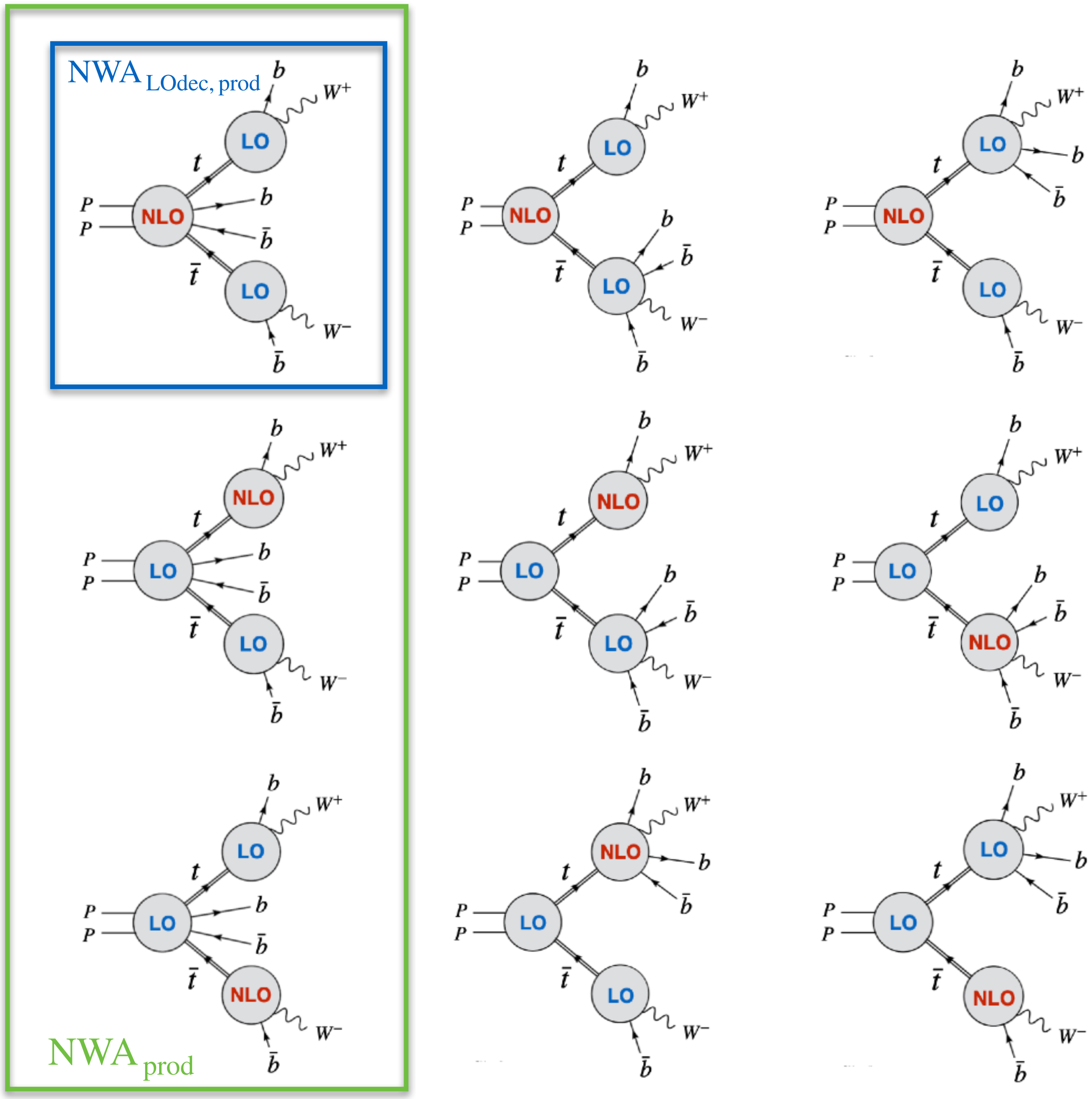
- $\rm NWA_{prod,exp}$ vs $\rm NWA_{prod,LOdec}$:

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

Accidental cancellations with $\mathcal{O}(\alpha_s^2)$ effects

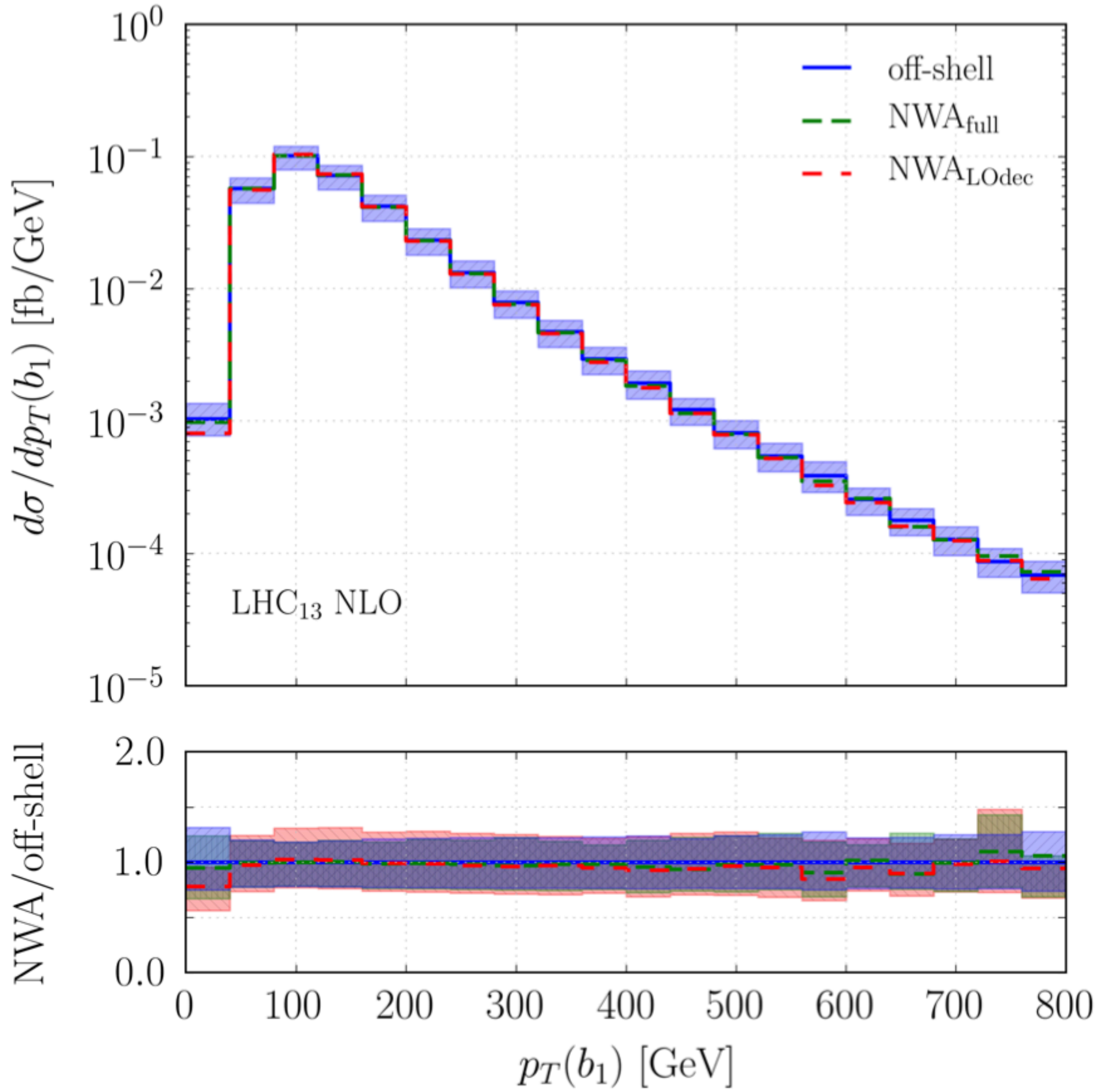


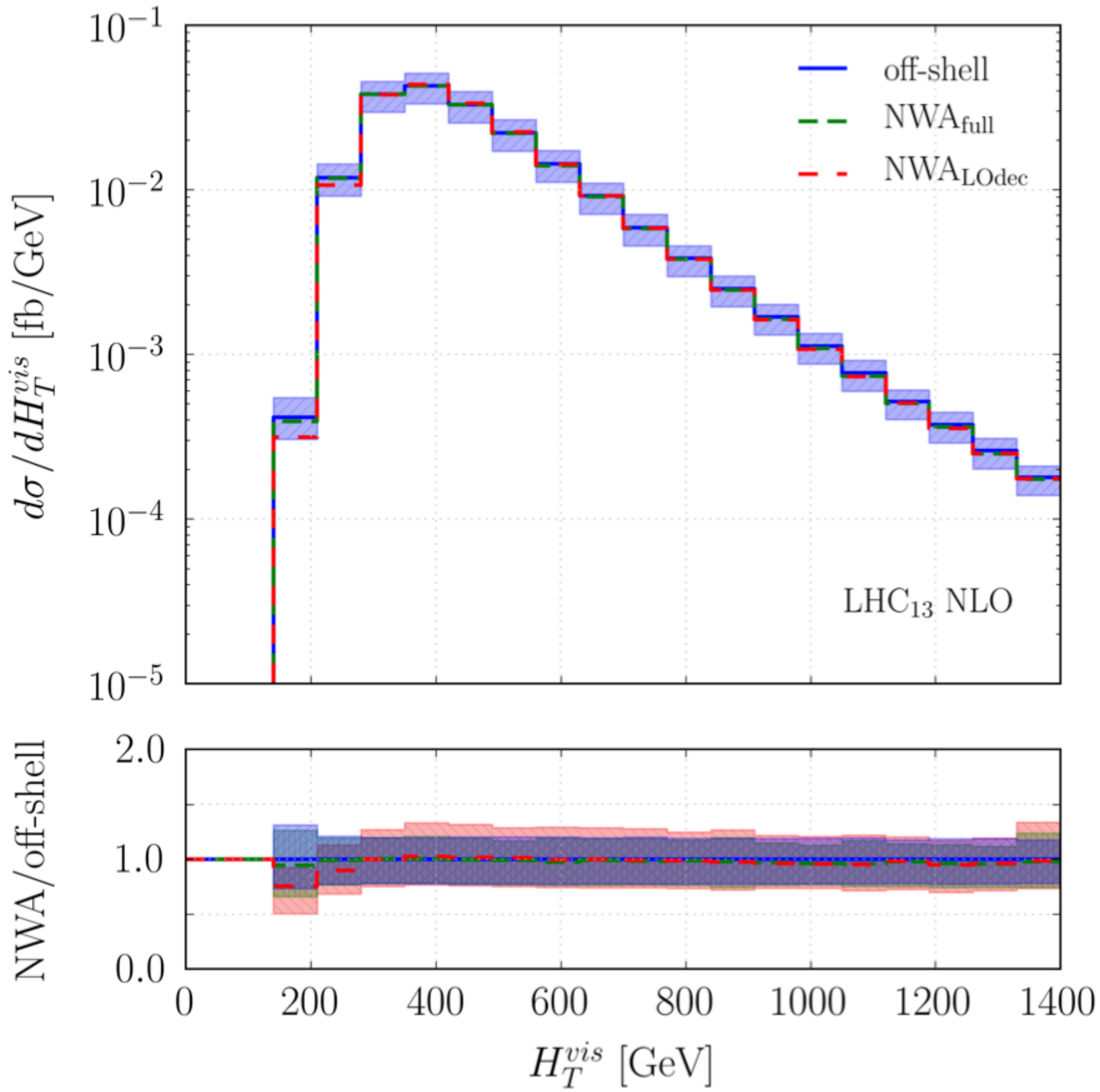
$t\bar{t}b\bar{b}$: impact of off-shell effects at differential level

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

- Off-shell effects amount to few permille for most observables used in SM analyses

    ↪ Examples:



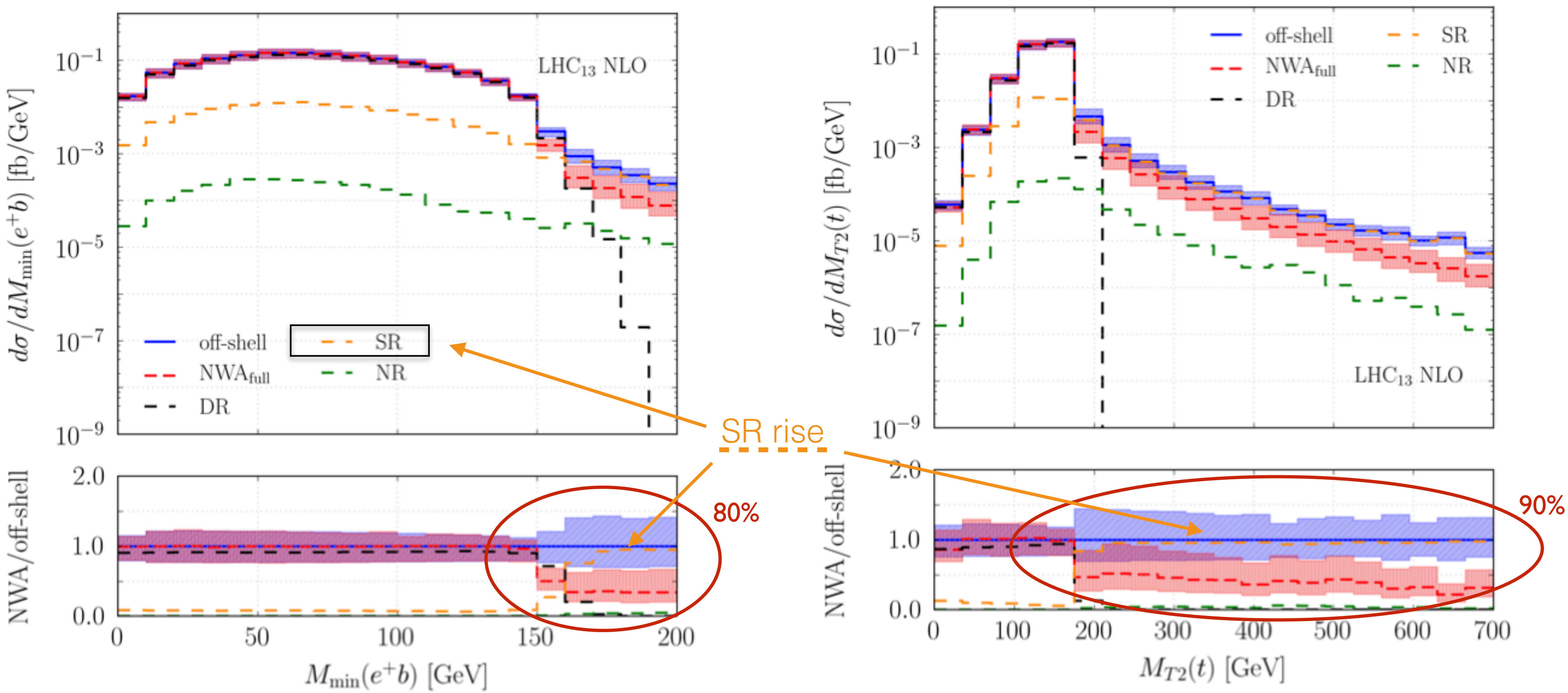


$$H_T^{vis} = \sum_{i=1}^{4} p_T(b_i) + p_T(e^+) + p_T(\mu^-)$$

$t\bar{t}b\bar{b}$: anatomy of full off-shell effects at differential level

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

- Threshold observables (mainly used in BSM studies) are more sensitive:



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

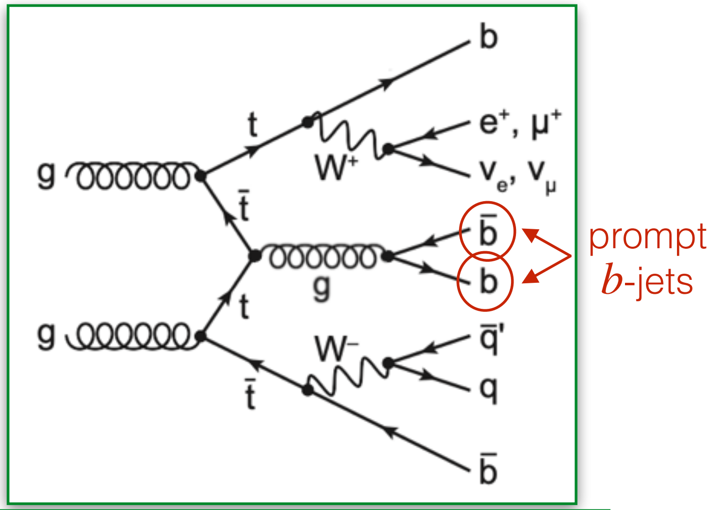
$$M_{T2}(t) = \min_{\sum p_T^{\nu_i} = p_T^{miss}} \left[\max\{M_T^2(p_T(e^+X_t), p_T(\nu_1)), M_T^2(p_T(\mu^-X_{\bar{t}}), p_T(\nu_2))\}\right]$$

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

- 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)

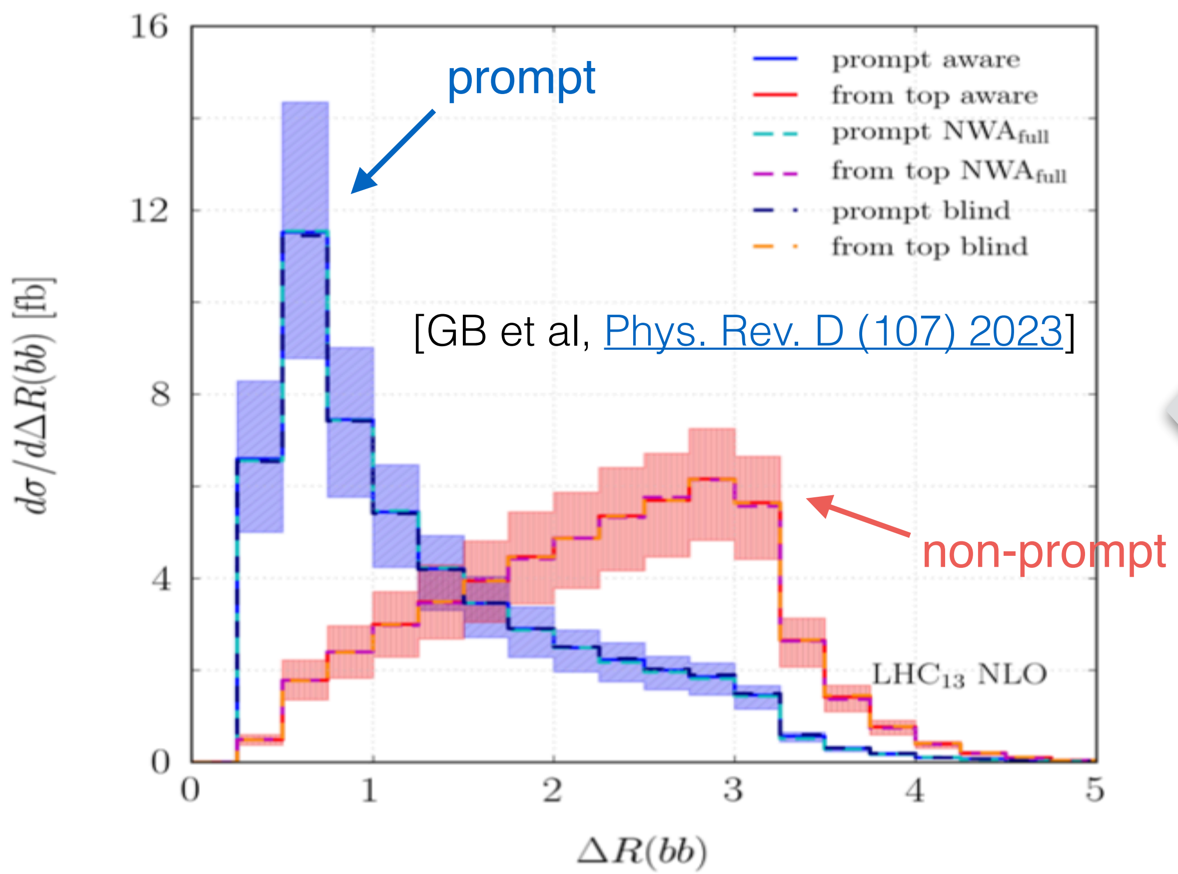
- Kinematic-based prescription: determine prompt b-jets according to a minimum principle for Q:

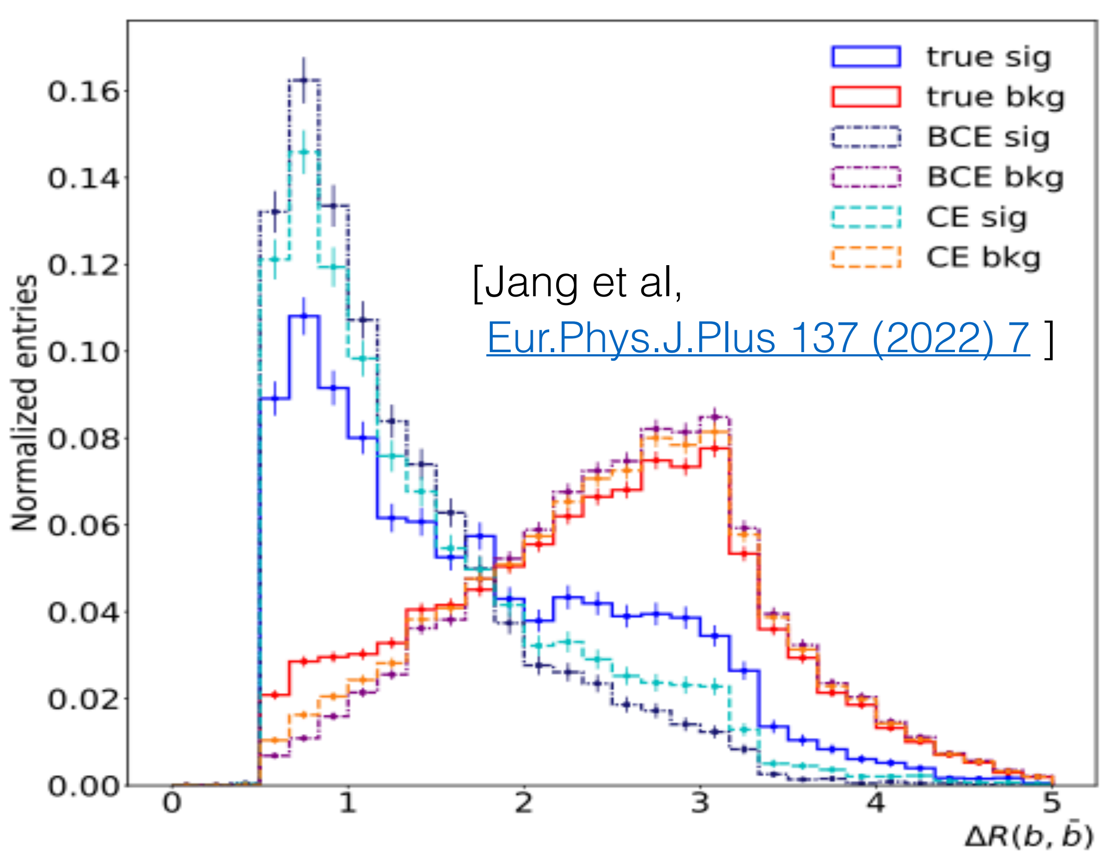
$$\boxed{\mathcal{Q} = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times |M^{\text{prompt}}(bb)|}$$



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

- Results consistent with DNN-based studies:





Conclusions

- We have examined some recent developments concerning matrix element description of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ @ NLO QCD

$t\bar{t}jj$ dilepton

- Jet radiation included in production and decays
- "*Mix*" contribution impacts NLO normalisation

$$\boxed{\Delta R(jb) > 0.8} \quad \to \quad \sigma_{\rm NLO} \; = \; 1462\,(\text{Prod}) \; - 236\,(\text{Mix}) \; + 0.2\,(\text{Dec}) \; = \; 1225 \;\; \text{fb}$$

-19% of $\sigma_{\rm NLO}$

$$\boxed{\Delta R(jb) > 0.4} \quad \to \quad \sigma_{\rm NLO} \; = \; 1662\,(\text{Prod}) \; - 205\,(\text{Mix}) \; + 2.4\,(\text{Dec}) \; = \; 1460 \;\; \text{fb}$$

-14% of $\sigma_{\rm NLO}$

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

- 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)

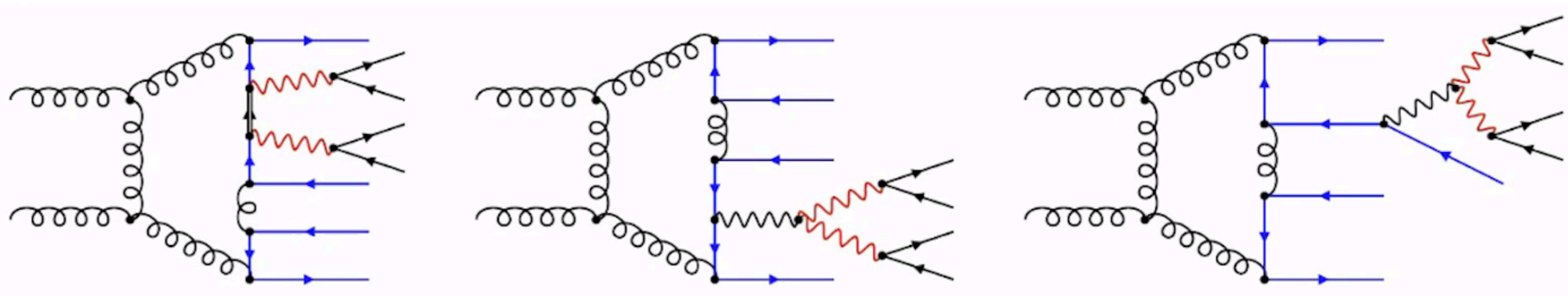
Backup slides

Full off-shell calculations for multi-leg processes can be very challenging

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

<u>Example</u>: $gg \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}$

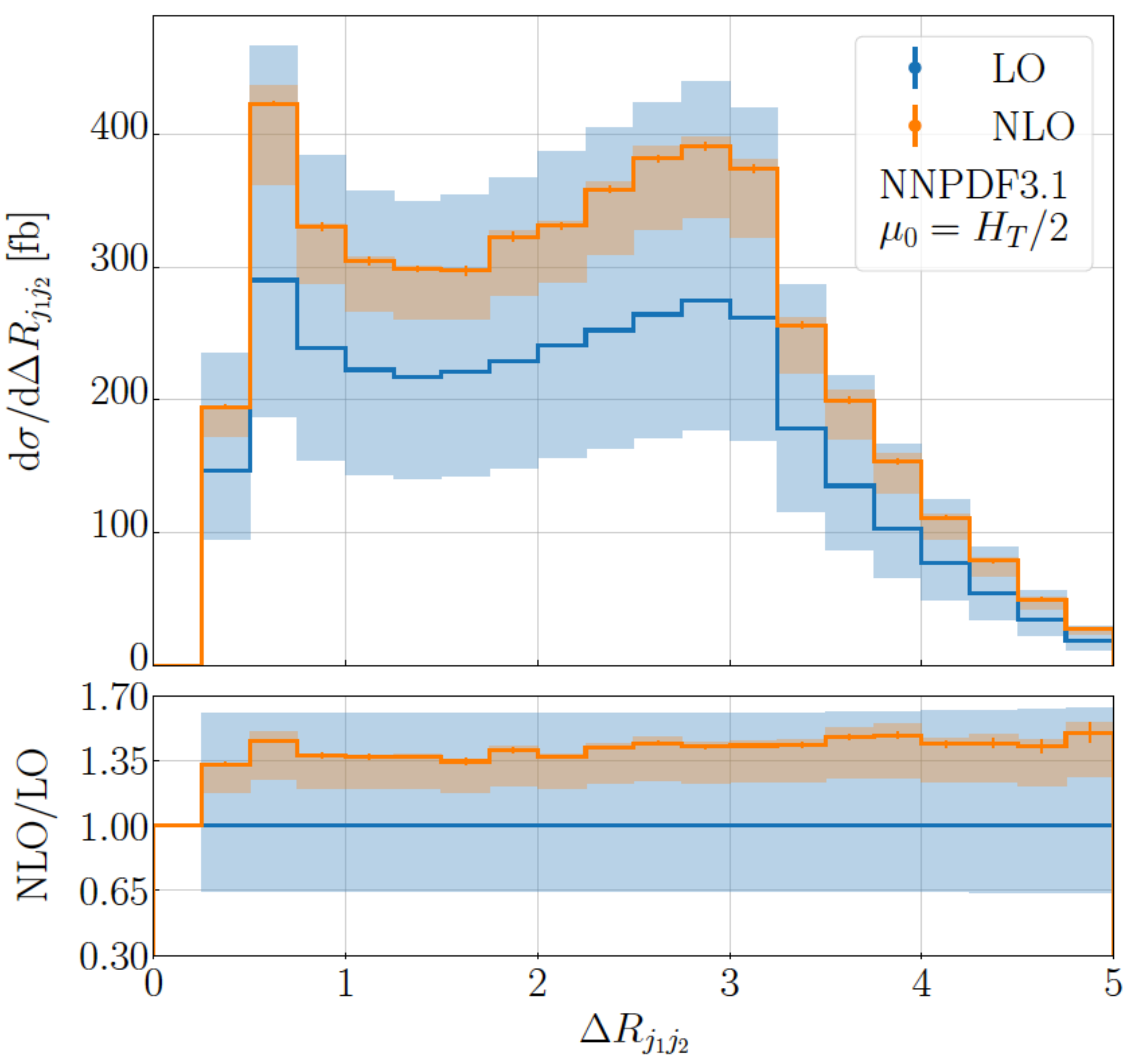
Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$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

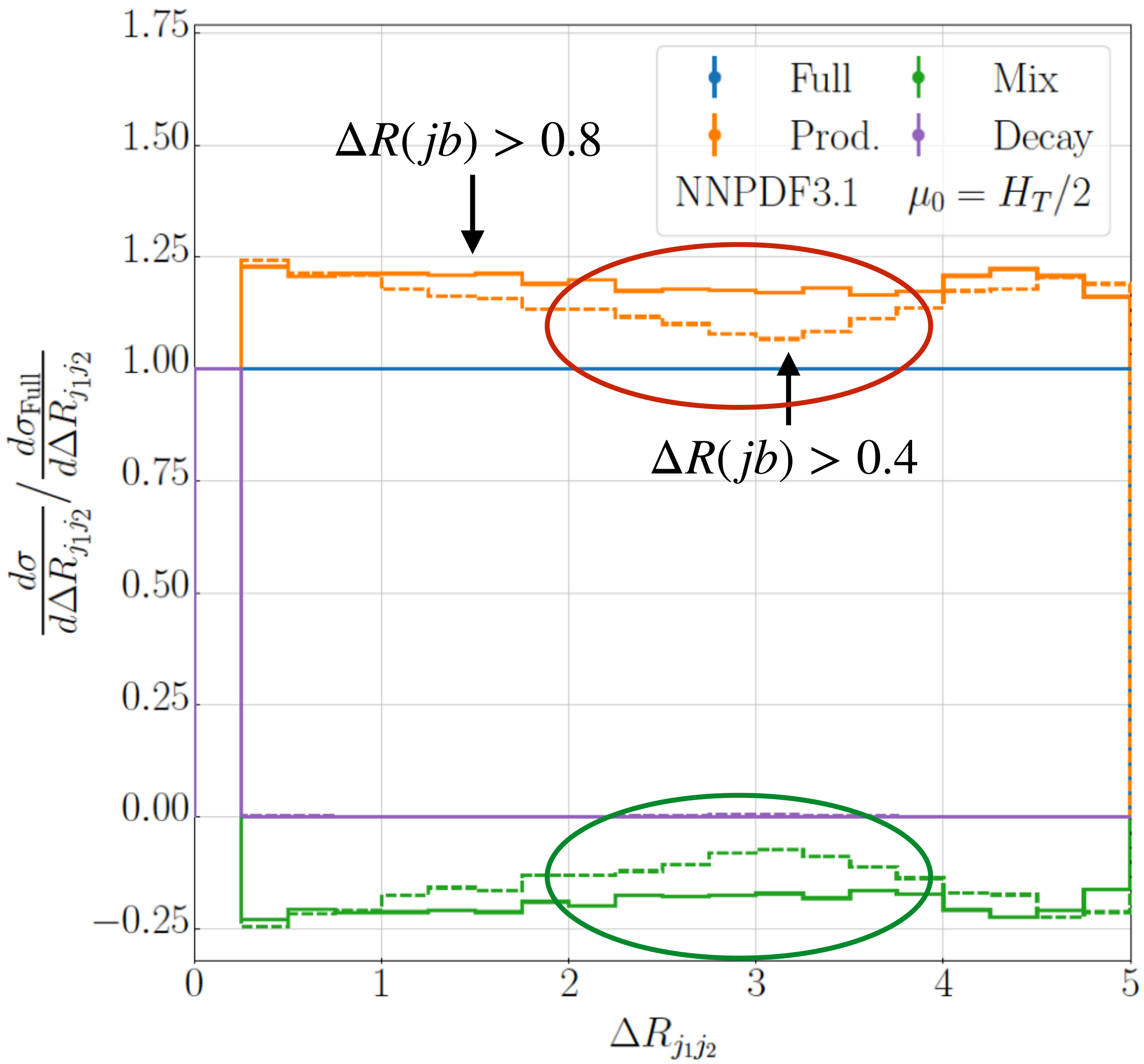


$t\bar{t}jj$: differential cross sections

$\Delta R_{j_1 j_2}$

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]





- Sensitivity to $\Delta R(jb)$ cuts enhanced around $\Delta R(j_1 j_2) = 3$

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Fiducial cross section ratios

$\Delta R(jb) > 0.8$

$\mathcal{R}_n$	$\mathcal{R}^{\mathrm{LO}}$	$\mathcal{R}^{\mathrm{NLO}}$	$\mathcal{R}^{\mathrm{NLO}}_{\mathrm{exp}}$
$\mathcal{R}_1 = \sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$	$0.3686\,^{+12\%}_{-10\%}$	$0.3546\,^{+0\%}_{-5\%}$	$0.3522\,^{+0\%}_{-3\%}$
$\mathcal{R}_2 = \sigma_{t\bar{t}jj}/\sigma_{t\bar{t}j}$	$0.2539\,^{+11\%}_{-9\%}$	$0.2660\,^{+0\%}_{-5\%}$	$0.2675\,^{+0\%}_{-2\%}$

$$\mathcal{R}^{\mathrm{NLO}}_{\mathrm{exp}} = \frac{\sigma^0_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}(j)}}\left(1 + \frac{\sigma^1_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}j(j)}} - \frac{\sigma^1_{t\bar{t}(j)}}{\sigma^0_{t\bar{t}(j)}}\right)$$

- NLO QCD corrections: $\mathscr{R}_1 \to -4\,\%$ $\mathscr{R}_2 \to +4\,\%$
- NLO uncertainties: Scale $\to \mathcal{O}(5\%)$ PDF $\to \mathcal{O}(0.5\%)$

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

- **Integrated fiducial cross sections**

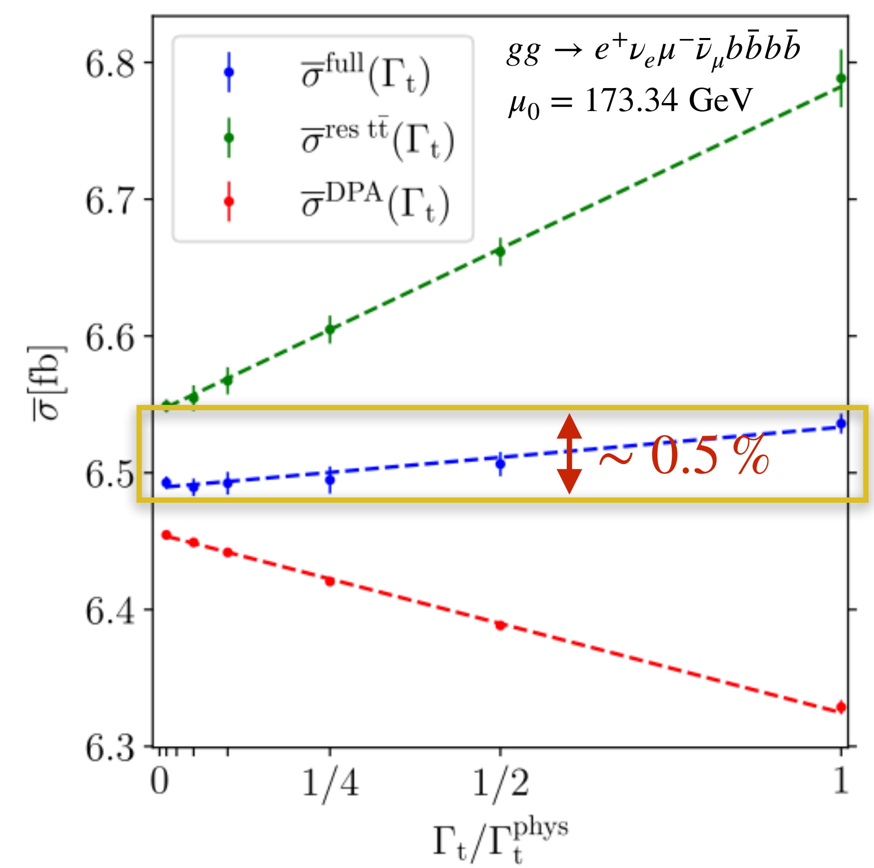
$\sqrt{s} = 13$ TeV

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: $\mathcal{O}(80\%)$

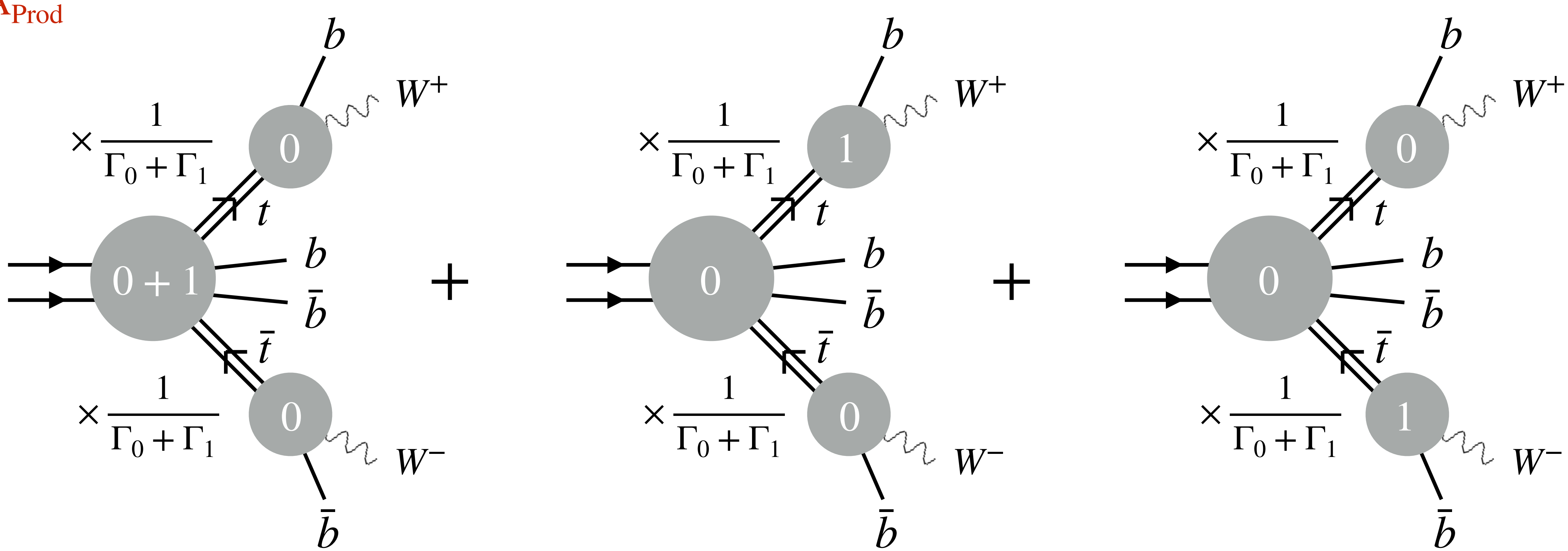
Effects of Γ_t expansion in NWA

- "Unexpanded" cross section in NWA:

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

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

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



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

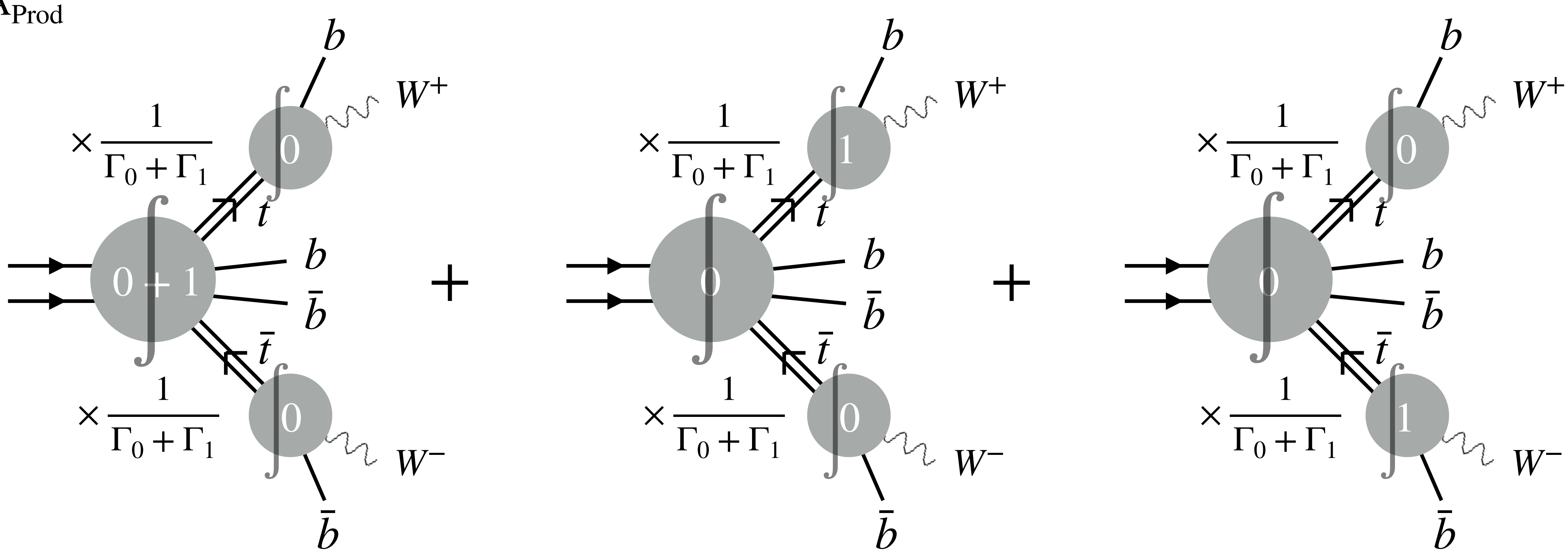
- Most suitable setup to assess the impact of genuine off-shell effects

Effects of Γ_t expansion in NWA

- "Unexpanded" cross section in NWA:

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

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



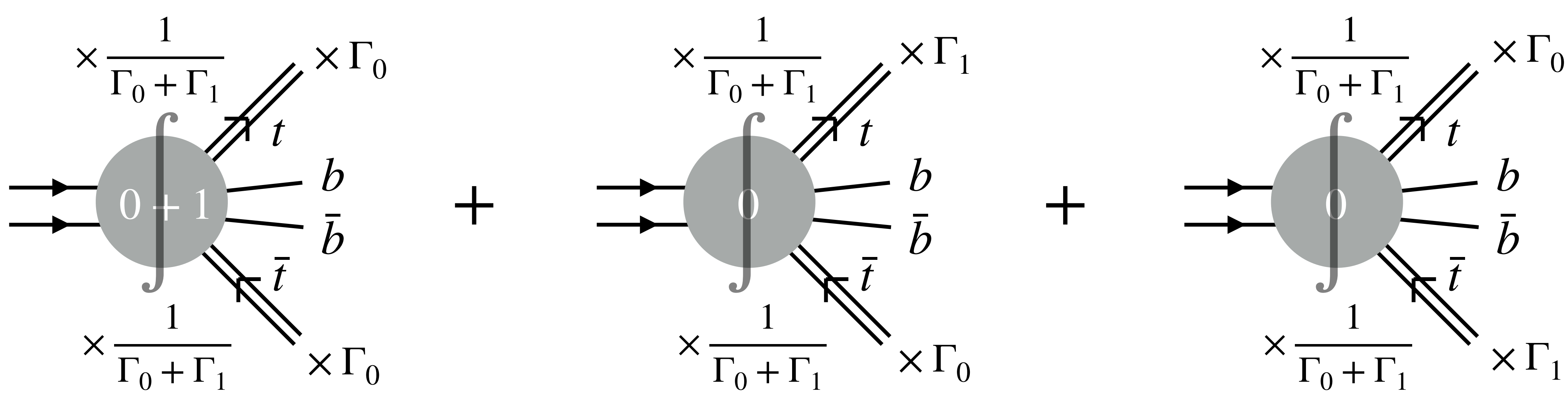
Effects of Γ_t expansion in NWA

- "Unexpanded" cross section in NWA:

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

$\Gamma_0 \rightarrow \mathcal{O}(\alpha_s^0)$, $\Gamma_1 \rightarrow \mathcal{O}(\alpha_s)$

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



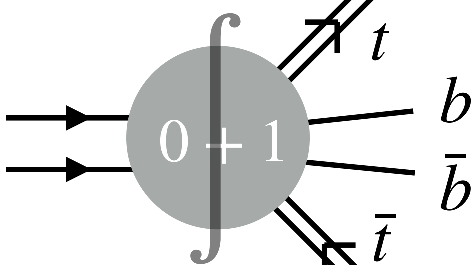
- "Unexpanded" cross section in NWA:

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

${\color{blue}\mathcal{O}(\alpha_s^0)}$ ${\color{red}\mathcal{O}(\alpha_s)}$

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

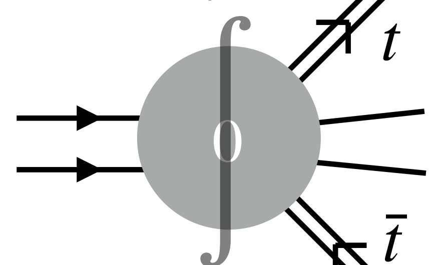
$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_0$



$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_0$

$+$

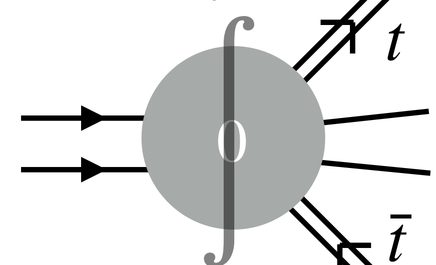
$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_1$



$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_0$

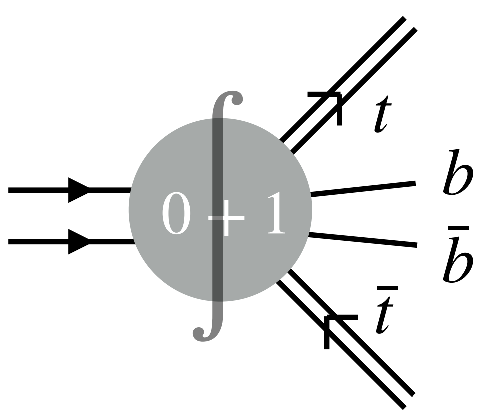
$+$

$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_0$



$\times \frac{1}{\Gamma_0+\Gamma_1}$ $\times \Gamma_1$

$=$



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

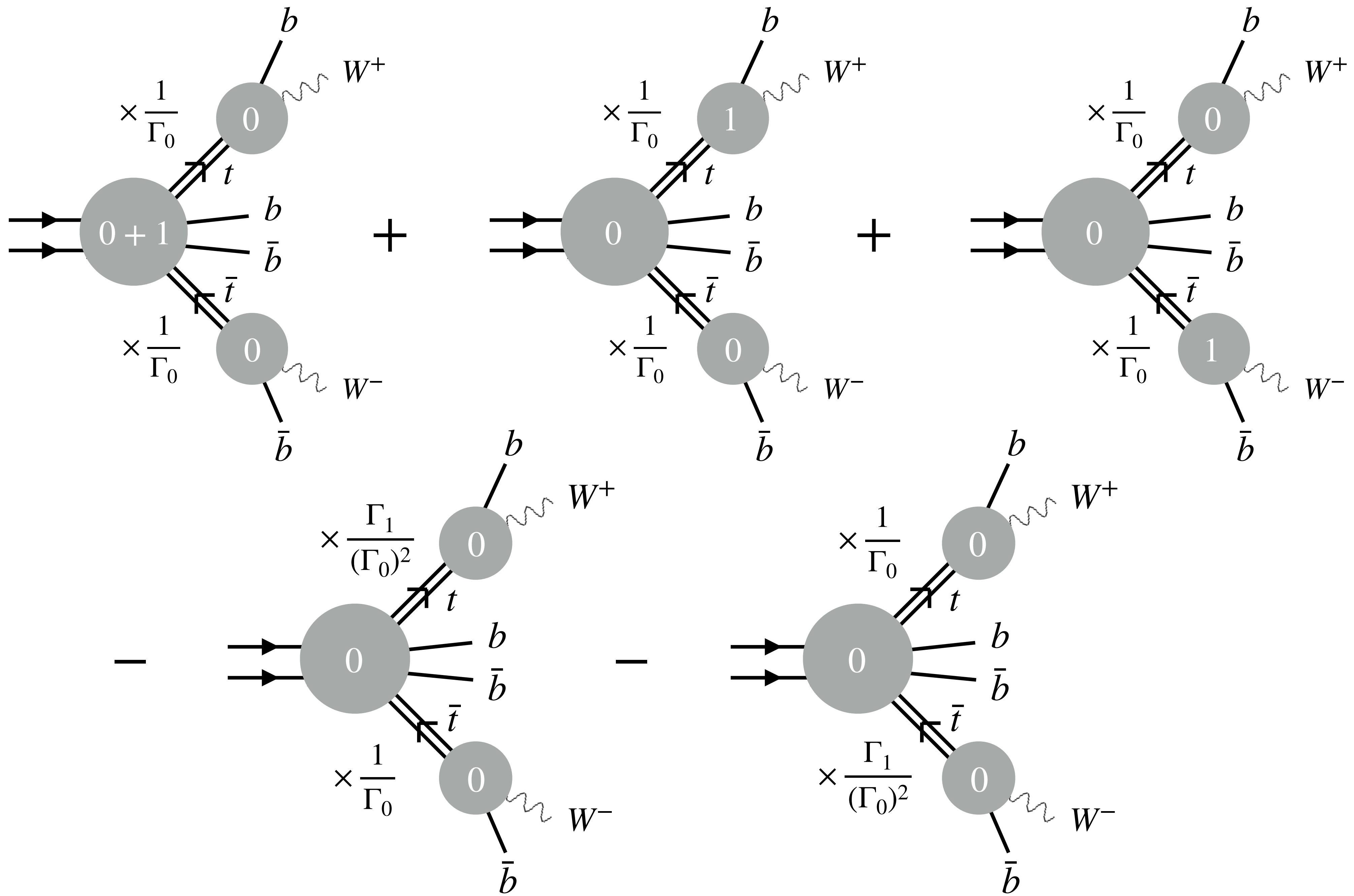
- Rigorous factorization at NLO spoiled by *formally suppressed $\mathcal{O}(\alpha_s^2)$ terms*.

Effects of Γ_t expansion in NWA

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

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

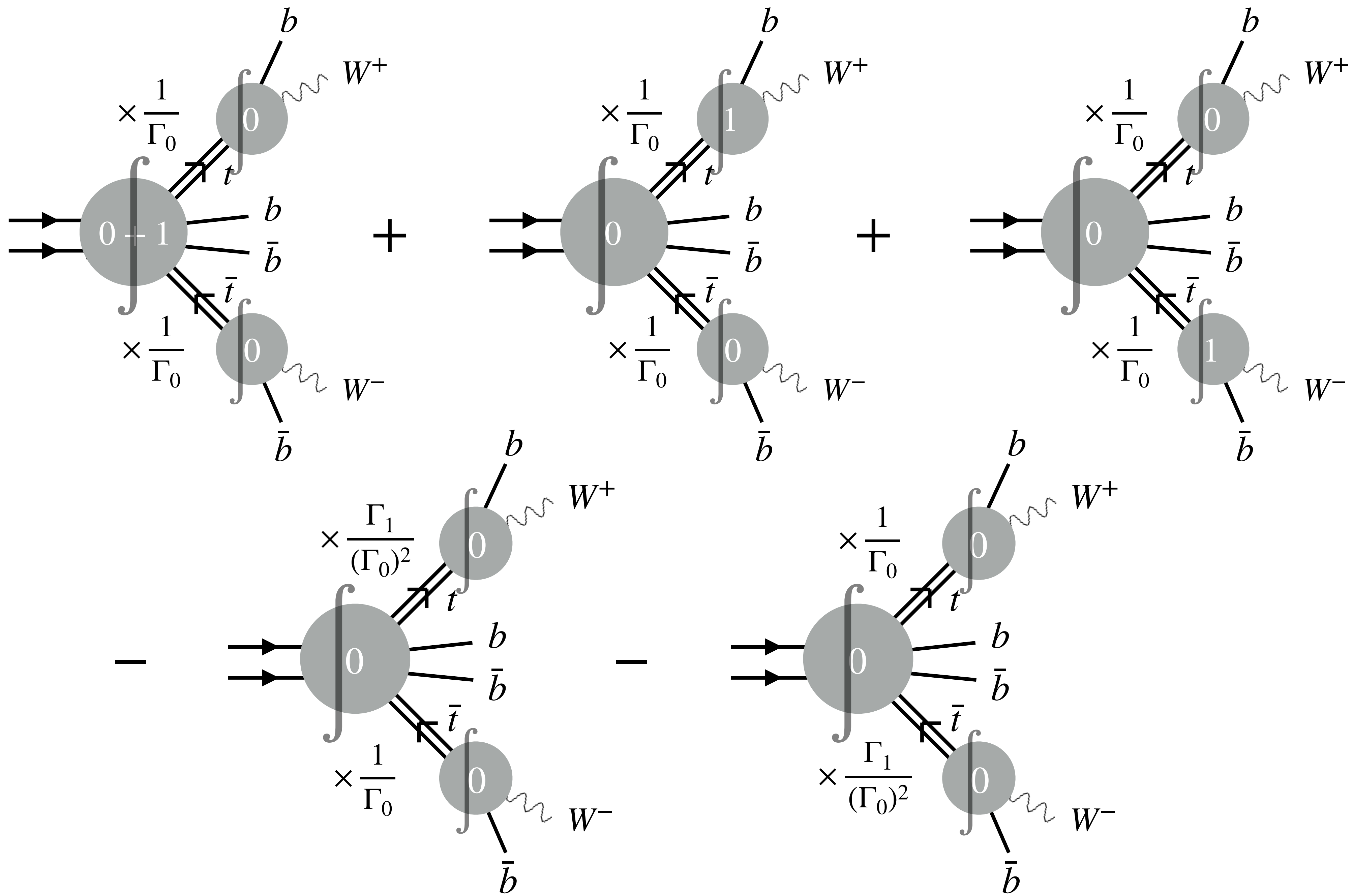
$$d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,\,exp}}} \equiv$$



- "Expanded" cross section in NWA:

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

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

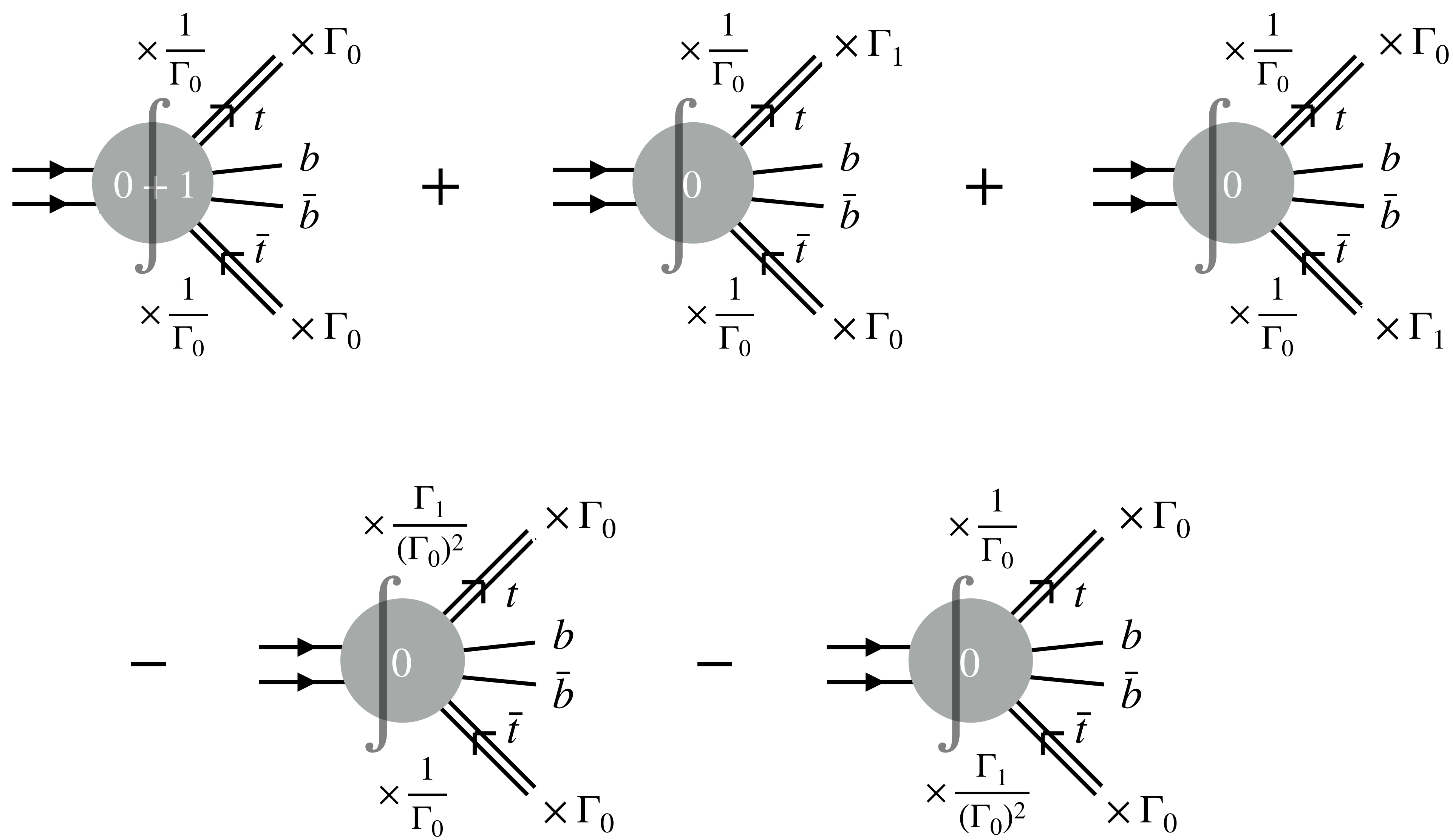


Effects of Γ_t expansion in NWA

- ”Expanded” cross section in NWA:

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

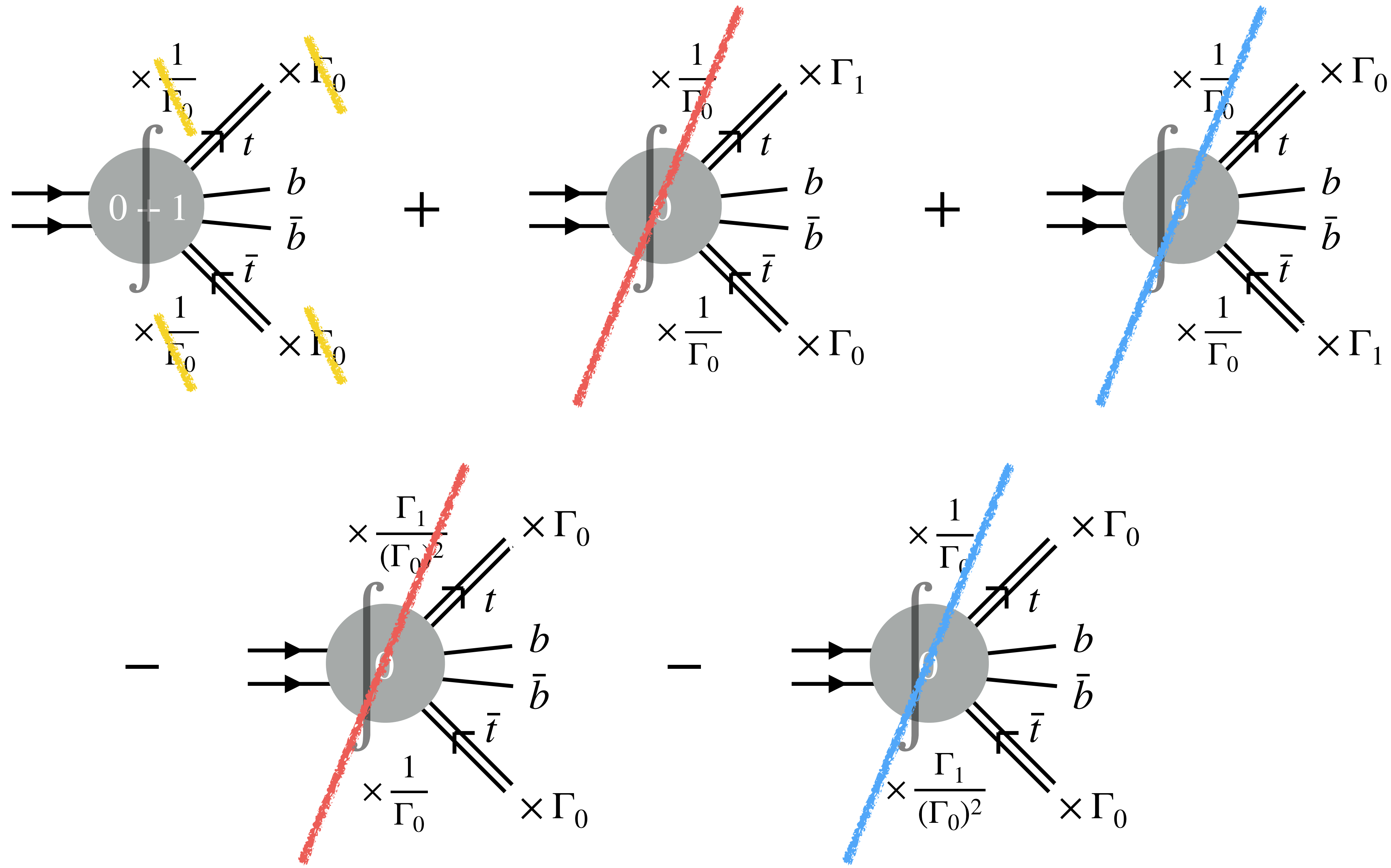
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



- "Expanded" cross section in NWA:

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

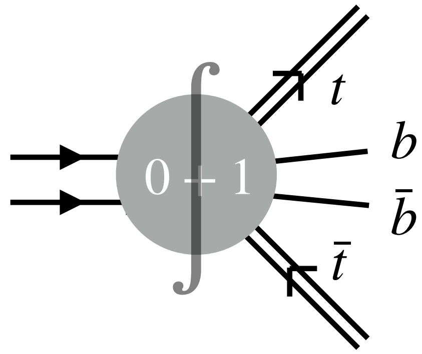
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



Effects of Γ_t expansion in NWA

- 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, $\mathcal{O}(20\%)$