Funded by Deutsche Forschungsgemeinschaft German Research Foundation

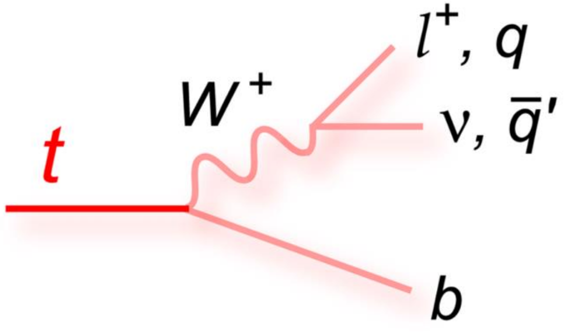
Research Training Group Physics of the Heaviest Particles at the LHC

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

SPONSORED BY THE Federal Ministry of Education and Research

Problems & Challenges in Modelling PP → TT + X @ LHC



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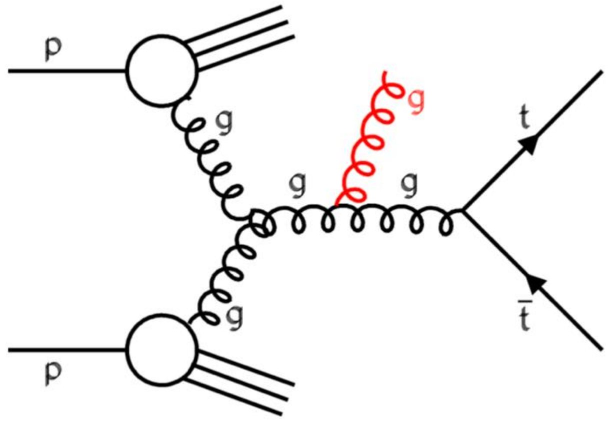


Outline of the Talk

1. Introduction
2. Part I – Fixed-order predictions: NLO QCD
3. Part II – Fixed-order predictions: Complete NLO
4. Part III – Parton-shower based predictions: NLO + PS

Introduction

Large Hadron Collider

- Current status: LHC Run 3 @ 13.6 TeV
- HL-LHC planned from 2030 to 2041

Integrated Luminosity $\mathcal{L}_{\text{int}} = \int_0^T \mathcal{L}(t')dt'$

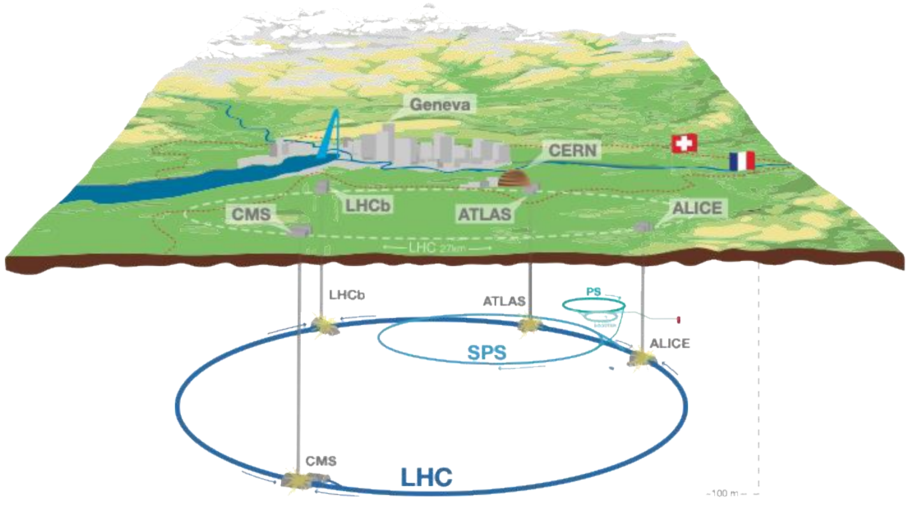
Run 1	Run 2	Run 3	HL-LHC
30 fb^{-1}	190 fb^{-1}	500 fb^{-1}	3000 - 4000 fb^{-1}

$$\mathcal{L}_{\text{int}} \cdot \sigma_p = \text{number of events of interest}$$

LHC/HL-LHC Plan (last update January 2025)

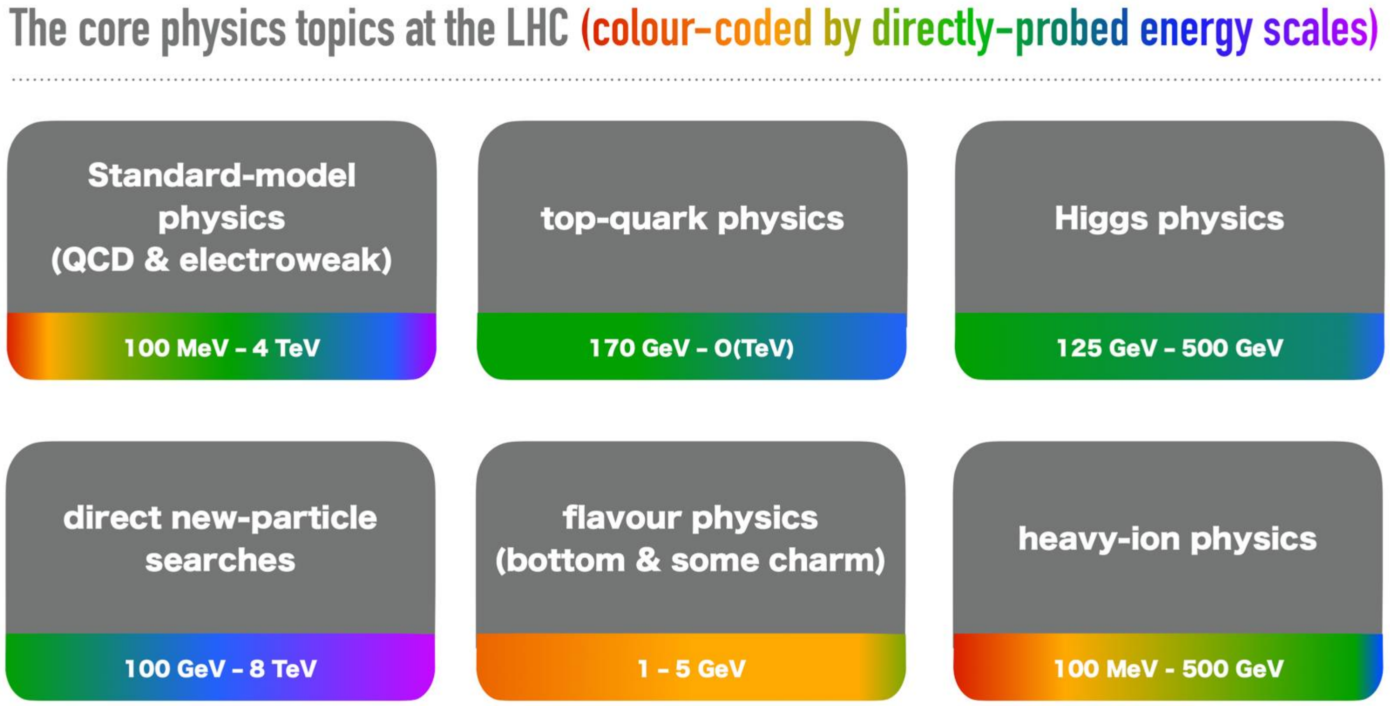
WE ARE HERE !

Overall view of the LHC



OPEN-PHO-CHART-2014-006

Key Physics Goals



Graphic borrowed from Gavin Salam - Amplitudes 2020

- Understand better Standard Model
- Establish structure of Higgs sector
- Search for signs of new physics BSM
- **Direct searches**
  - Many proposals for New Physics
  - No model of NP really stands out
  - No obvious candidates to look for
- **Indirect searches**
  - New Physics as small corrections to SM reactions
- **Precision SM measurements**
  - High Luminosity LHC
- **High Precision Theoretical Predictions**
  - Top Quark & Higgs boson

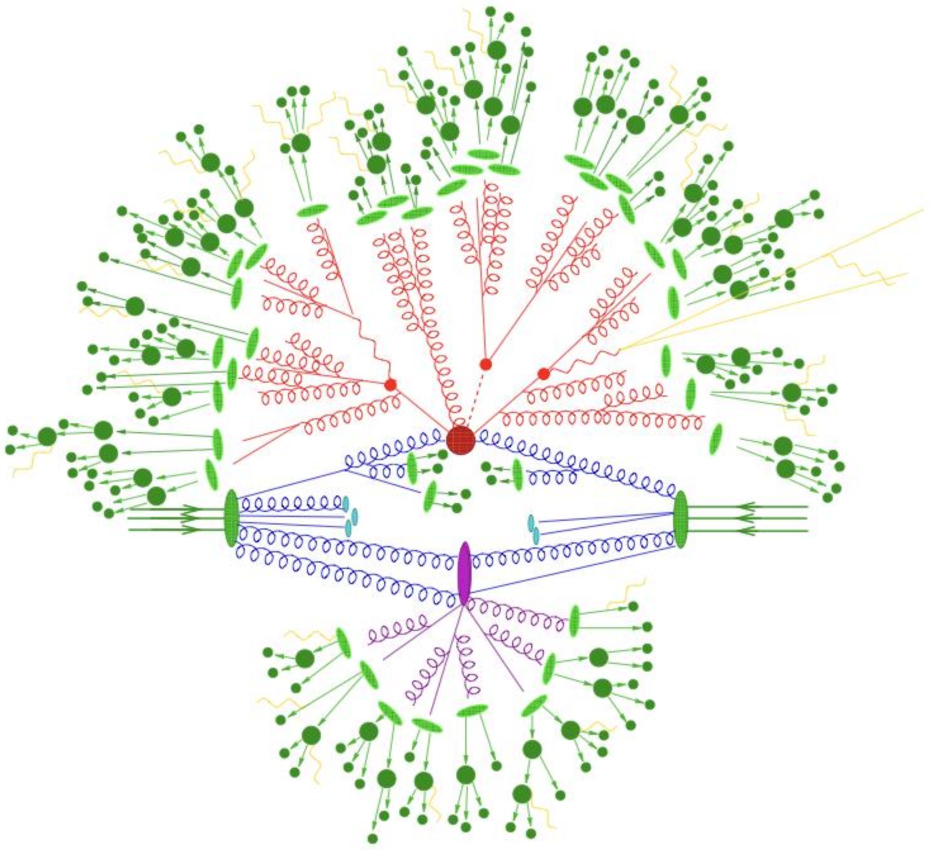
Complementary

Key Physics Goals

- A synergy between theory & experiment is key to foster discoveries at the HL-LHC
- Shed more light on Higgs-boson sector
- On theory side, path to precision runs through several directions:
  - Perturbative accuracy of amplitude calculations
  - Numerical stability of integration & subtraction of IR divergencies
  - Robust assessment of theoretical uncertainties
- Modelling of realistic final states in fiducial phase-space regions
  - Multi-particle final states, resonant structures, …
- Precision & Accuracy $\rightarrow$ Identify which effects are important & should be taken into account

Pictorial representation of a $pp \rightarrow ttH$ event as produced by an event generator

SHERPA, JHEP 02 (2009) 007

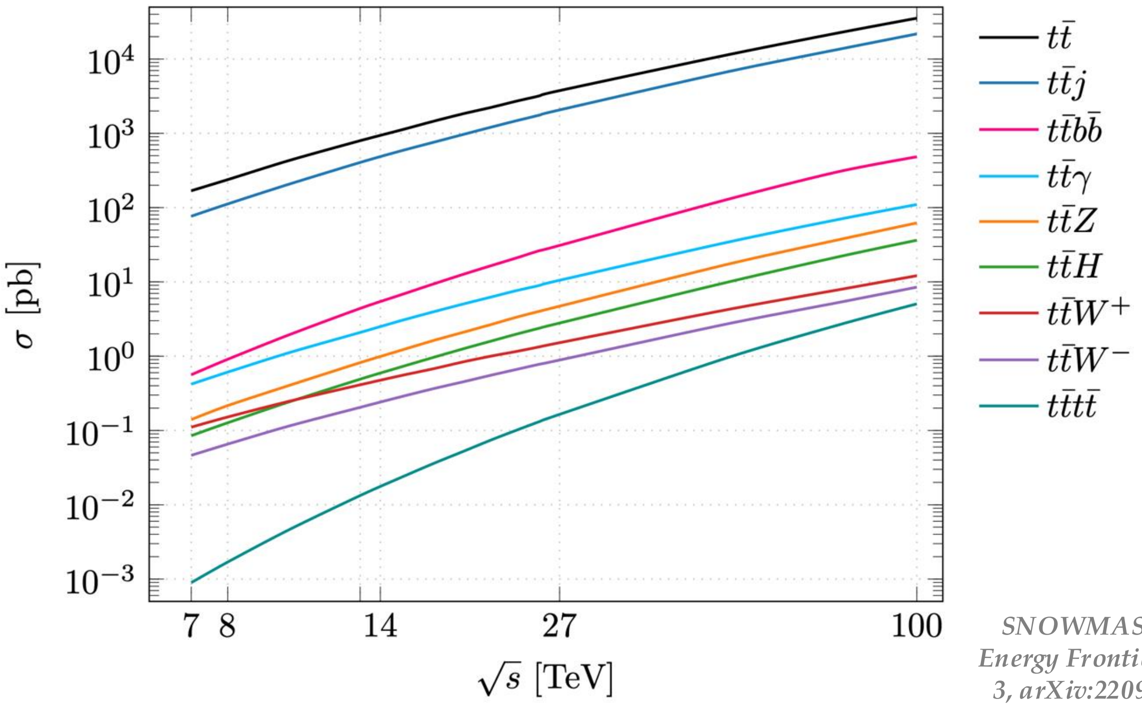


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

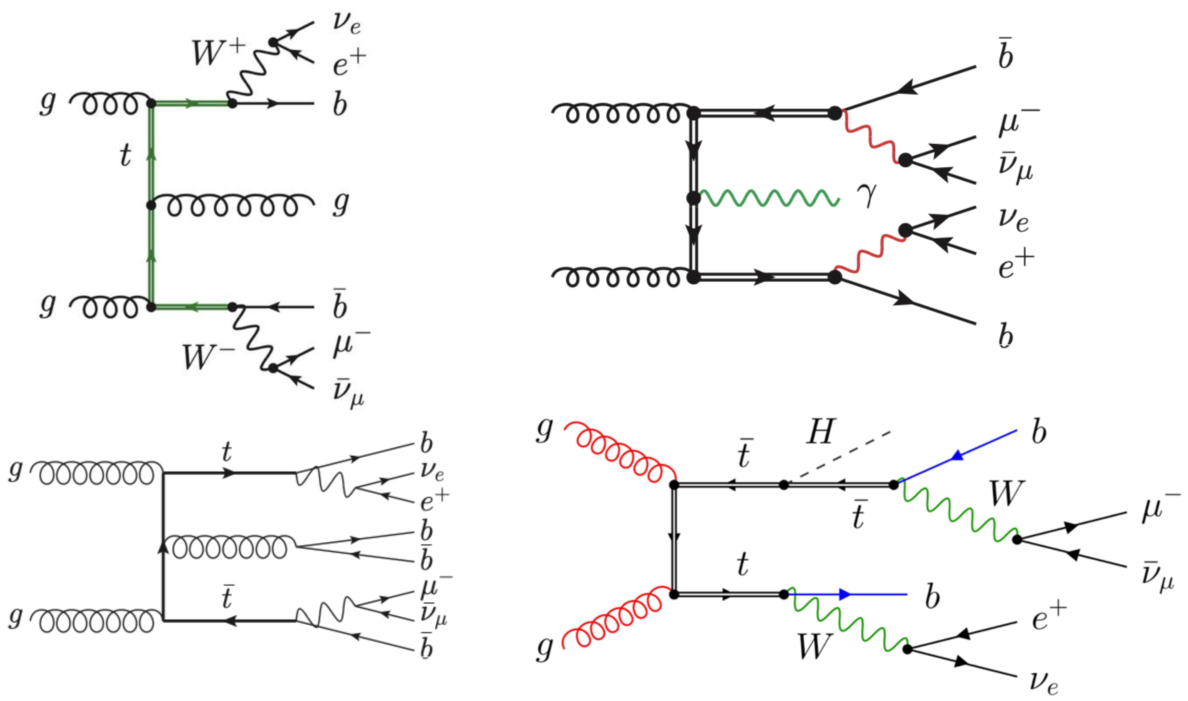
Top-Quark Pair Production +X @ LHC

State of the art: NLO

- More exclusive final states are produced @ LHC
- Interactions between top quarks and other SM particles



SNOWMASS 21, Report of Energy Frontier Topical Group 3, arXiv:2209.11267 [hep-ph]



- Only selected results for $pp \to tt + X$ will be discussed in following slides
- Helac-Nlo group delivered results for all these processes & more

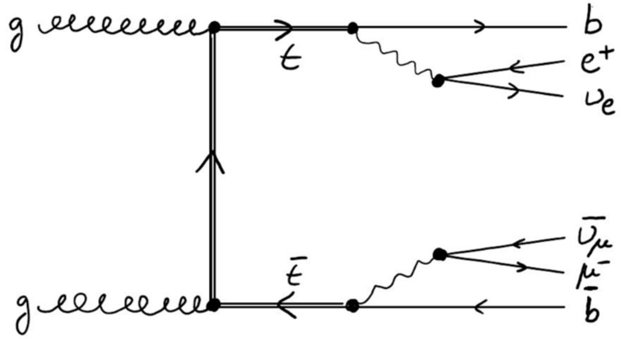
Main Focus:

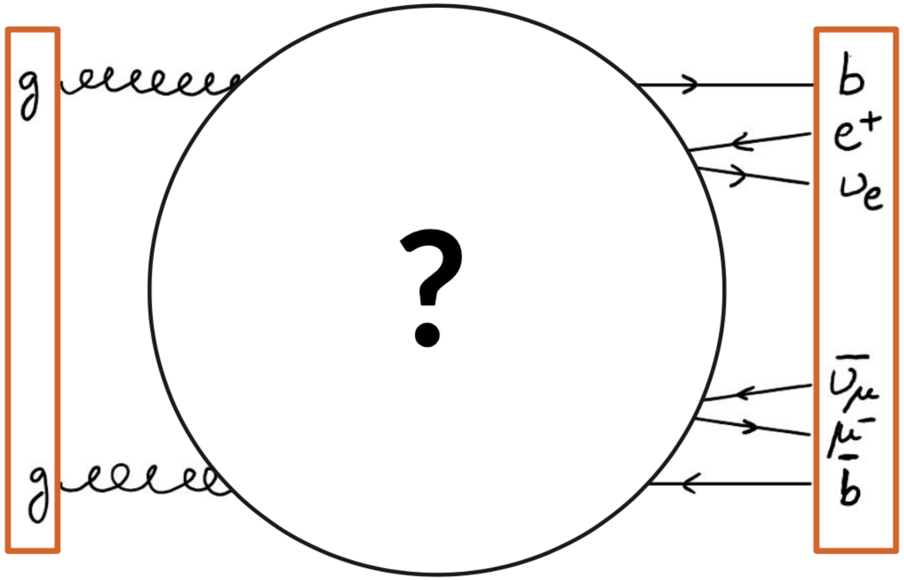
- Modelling of realistic final states in fiducial phase-space regions

TT Production with Realistic Final States

- Modelling of unstable particles

$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$

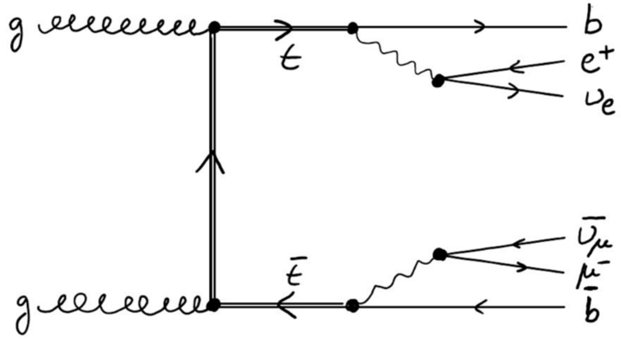




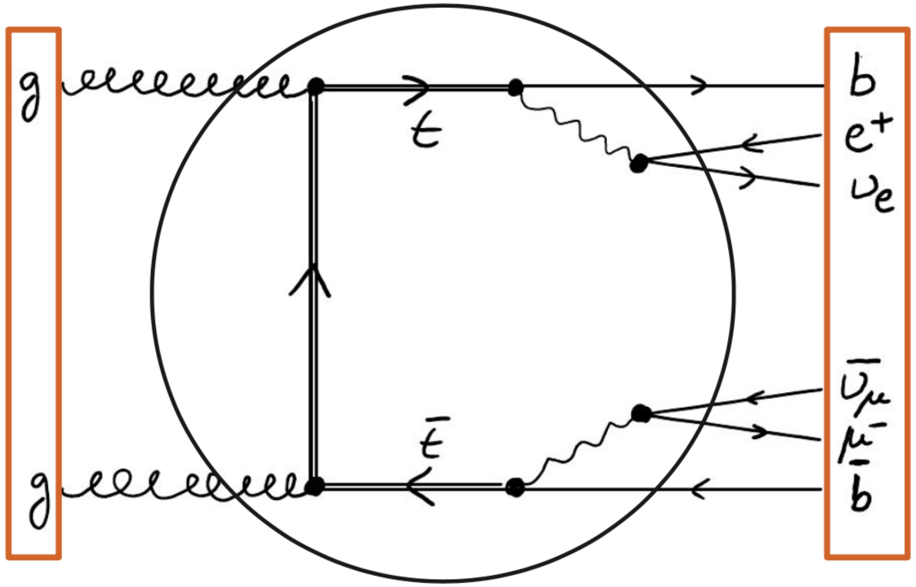
TT Production with Realistic Final States

- Modelling of unstable particles

$$pp \to b\bar{b}e^{+}\mu^{-}\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$



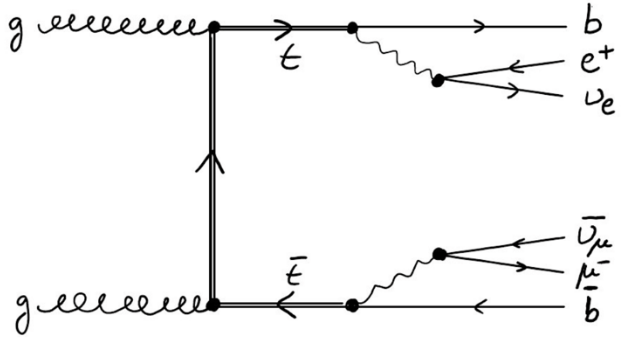
Double-resonant diagram



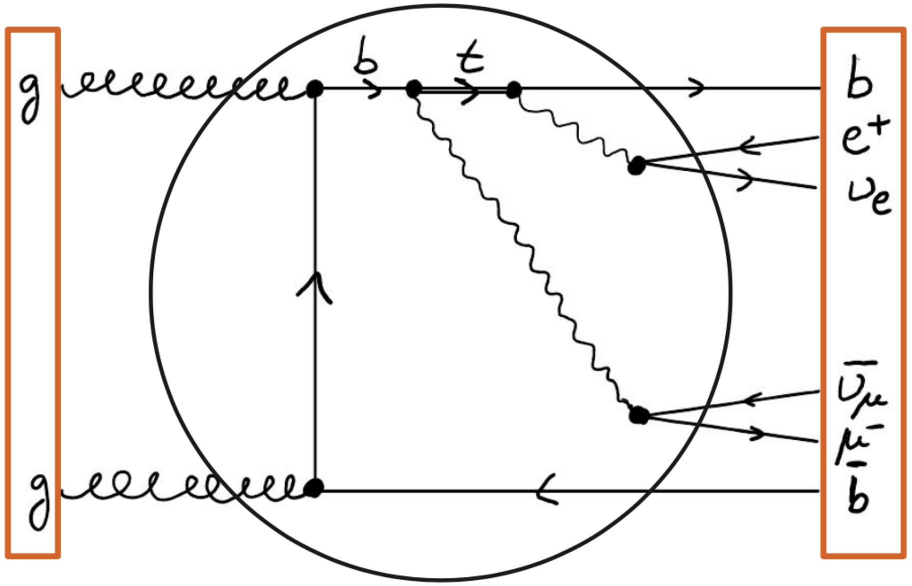
TT Production with Realistic Final States

- Modelling of unstable particles

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$



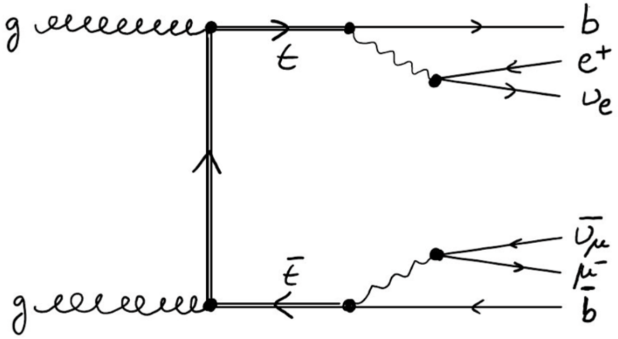
Single-resonant diagram



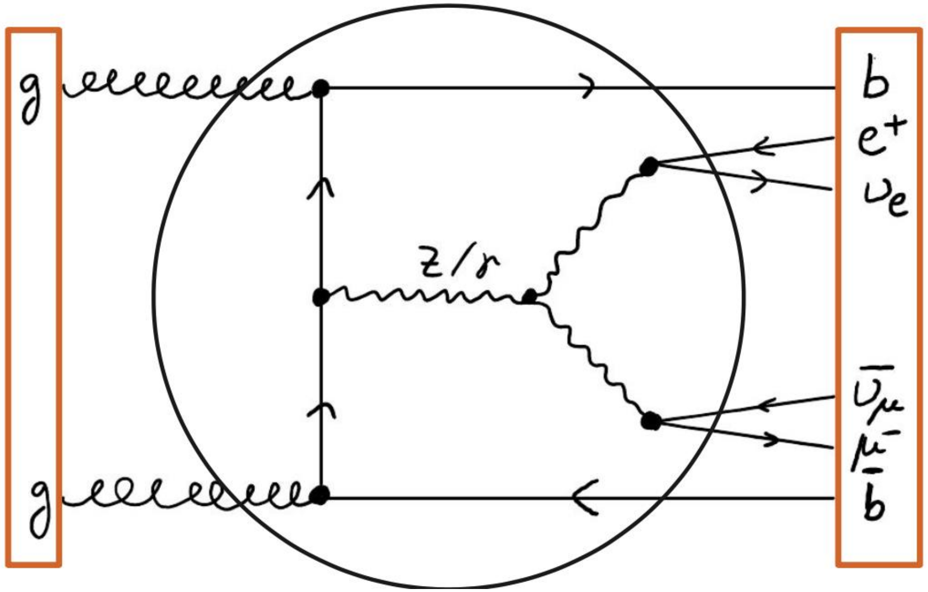
TT Production with Realistic Final States

- Modelling of unstable particles

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

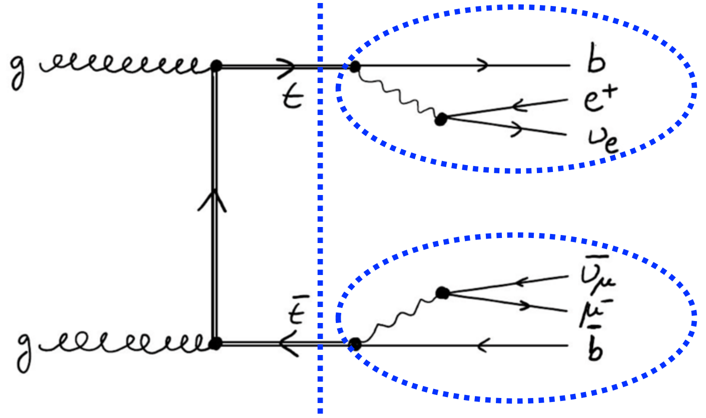


Non-resonant diagram



TT Production with Realistic Final States

- Modelling of unstable particles

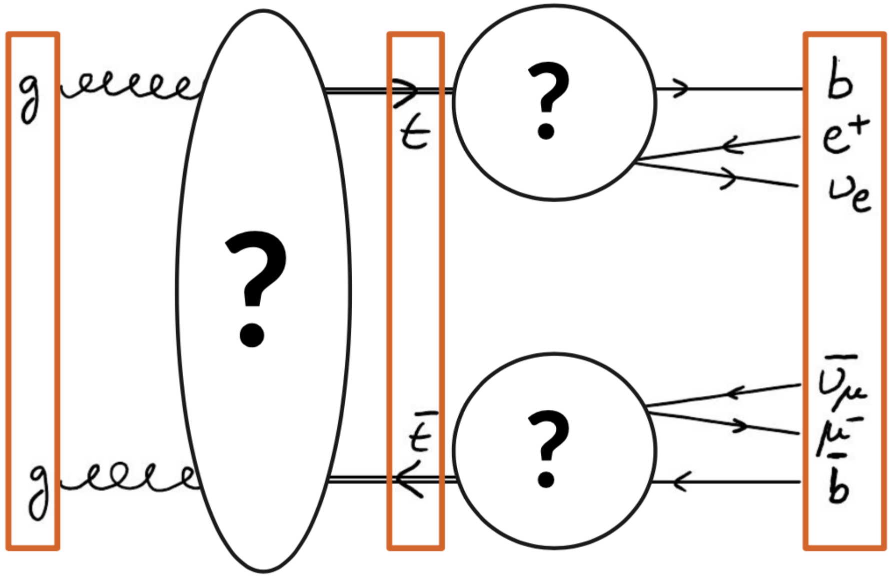


$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$

$$\frac{\Gamma_W}{m_W} > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H}\,,$$
$$2.6\% > 0.8\% \gg 0.003\%\,.$$

Narrow-width approximation (NWA)
→ Fix intermediate state to be on-shell

$$\frac{\Gamma}{m} \to 0$$

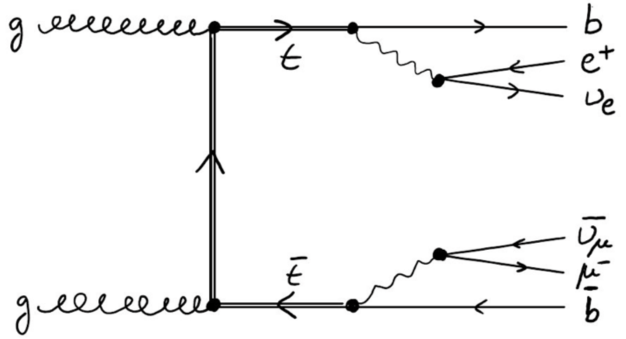


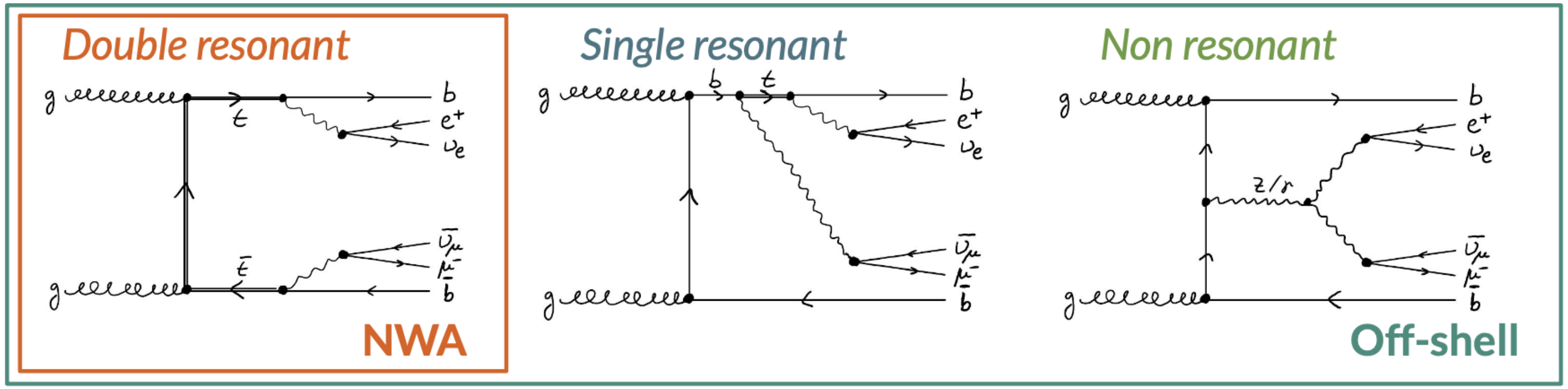
- NLO QCD correction separately to production & decays
- Nonfactorizable NLO corrections are missing
- No cross-talk between production & decays
- NLO spin correlations

TT Production with Realistic Final States

- Modelling of unstable particles

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$





- Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators
- NWA = DR contributions & unstable *t & W* restricted to on-shell states

TT Production with Realistic Final States

- NLO QCD corrections to stable $pp \to tt+X$ matched to parton-showers
  - *Decays via parton shower without any spin correlations*
  - *LO decays with approximate spin correlations*
  - Double resonant contributions only
  - Breit-Wigner propagators for ***t & W***
  - Single & non-resonant contributions still missing as well as their interference effects
  - Scale settings & theoretical uncertainties based on production stage only

Powheg-Box MG5_aMC@NLO
Powheg-Box + LO Decays MG5_aMC@NLO + MadSpin

- Dominant contributions resumed
  - Collinear parton splitting or soft gluon emission
- Connection to non-perturbative aspects
  - Hadronic final states

$$\boxed{pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)}$$

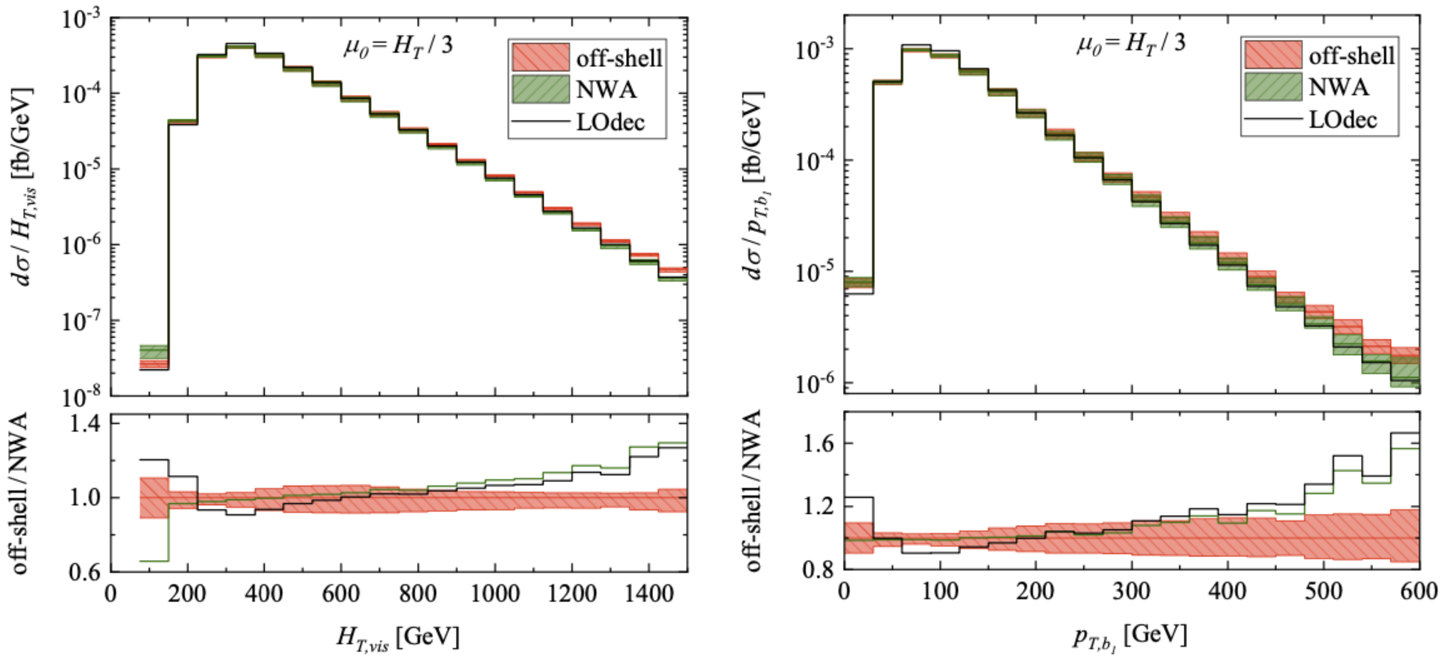
Part I – Fixed-order predictions: NLO QCD

How Good is NWA

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

Bevilacqua, Bi, Hartanto, Kraus, Worek, JHEP 08 (2020) 043

Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
NWA ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$



Integrated level

- Full off-shell effects ***0.2%***
- NLO QCD corrections to decays ***3%-5%***

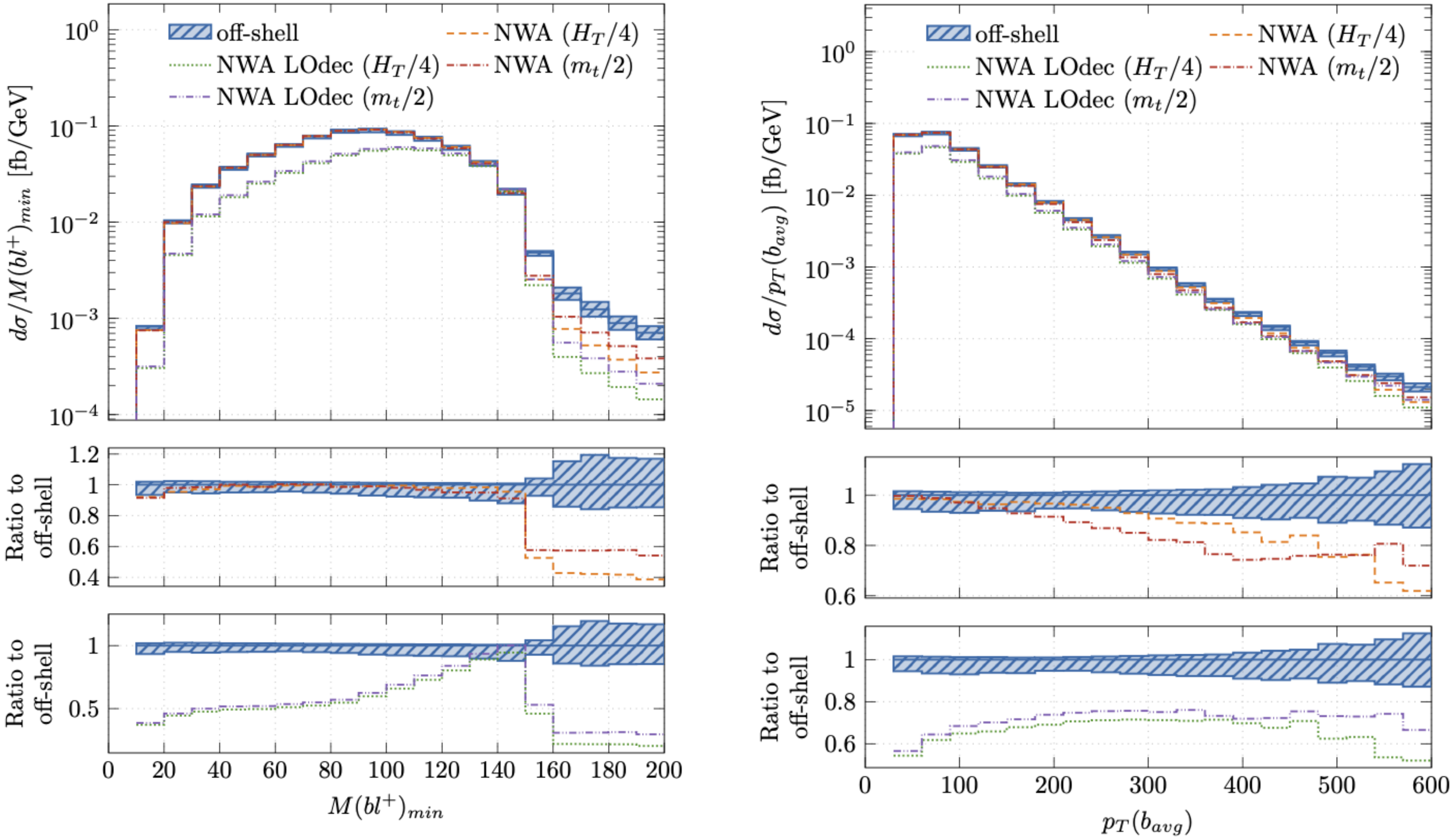
Differential level

- Off-shell effects up to ***60% - 70%***
- Substantial differences between NWA & $\rm NWA_{LODECAY}$

How Good is NWA

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154

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



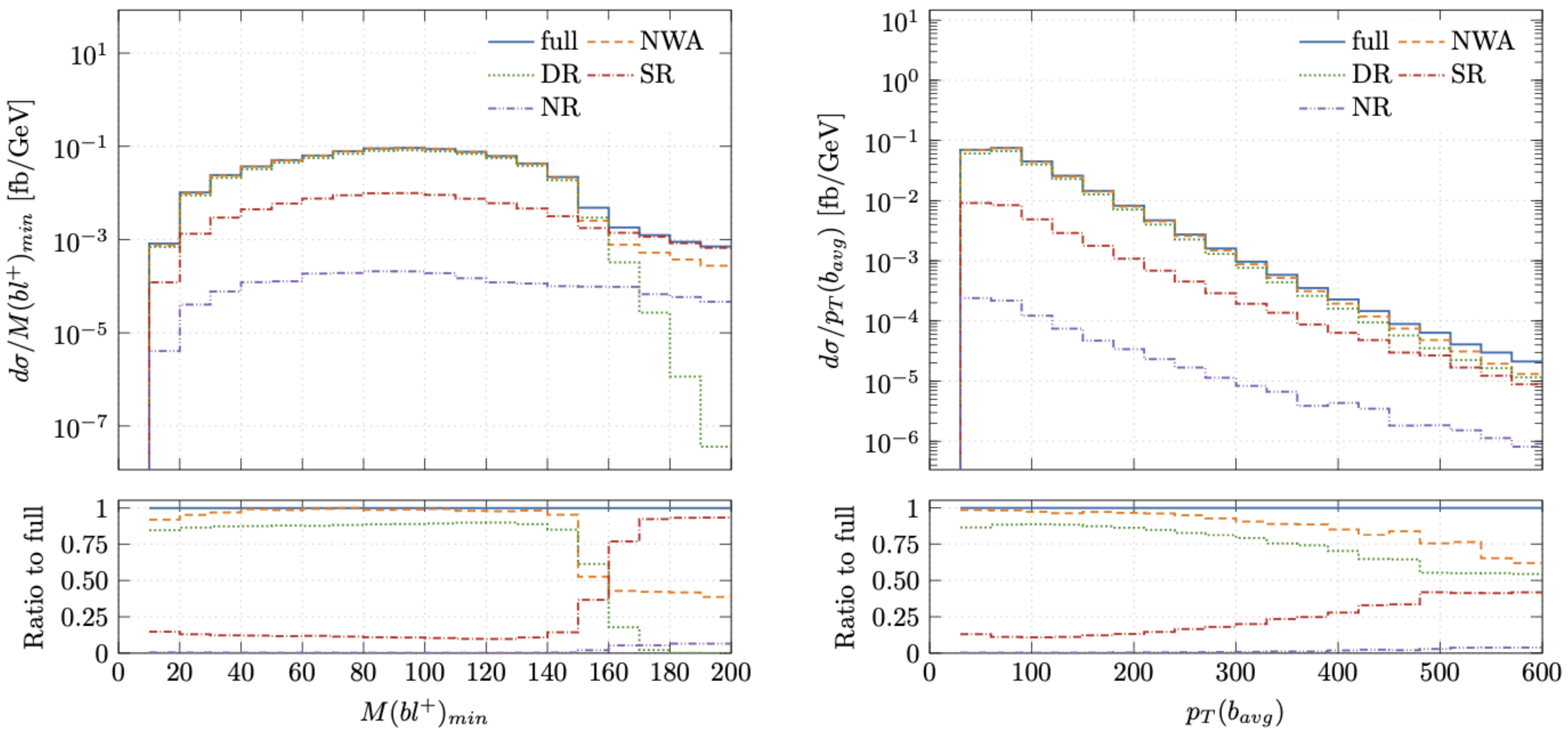
Dimensionful observables

- Substantial differences between NWA & NWA$_{\text{LODECAY}}$ when γ only in production stage
- NLO + PS not suitable to describe $pp \to tt\gamma$ process
- Off-shell effects up to ***50% − 60%***
- Specific phase space regions
  - *Kinematical edges*
  - *High p_T regions*

Various Phase-Space Regions

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

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154



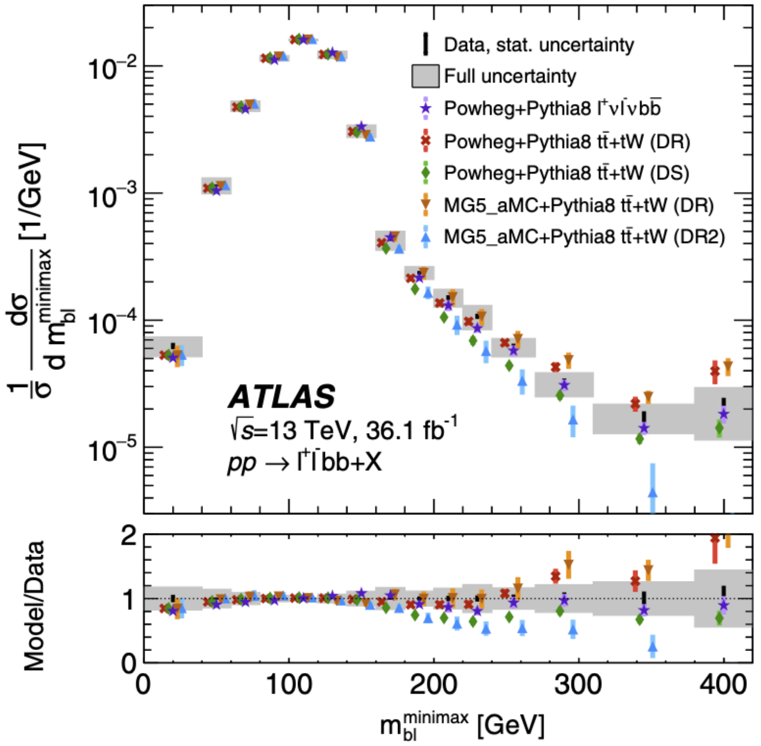
Dimensionful observables

- Sensitive to non-factorizable top quark corrections
- Effects up to ***50% − 60%***
- Specific phase space regions
  - ***Kinematical edges***
  - ***High p_T regions***

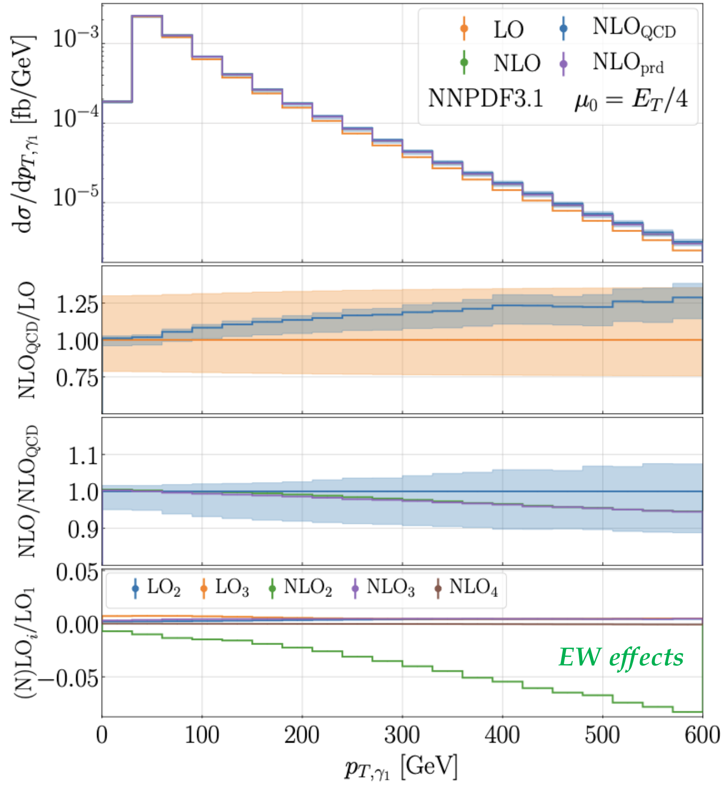
Competing Effects

$pp \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell b\bar{b}(\gamma)$

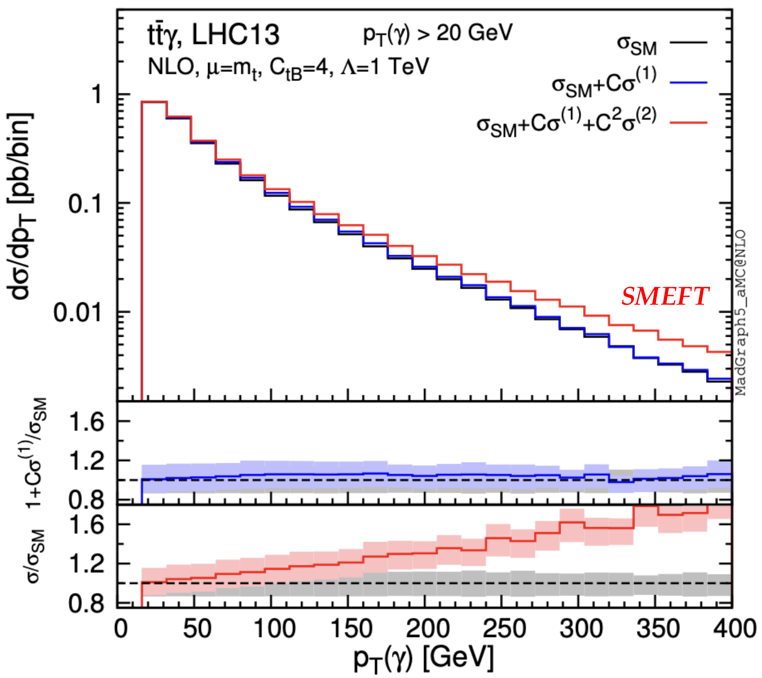
ATLAS, Phys. Rev. Lett. 121 (2018) 15, 152002



Stremmer, Worek, JHEP 07 (2024) 091



Bylund, Maltoni, Tsinikos, Vryonidou, Zhang, JHEP 05 (2016) 052



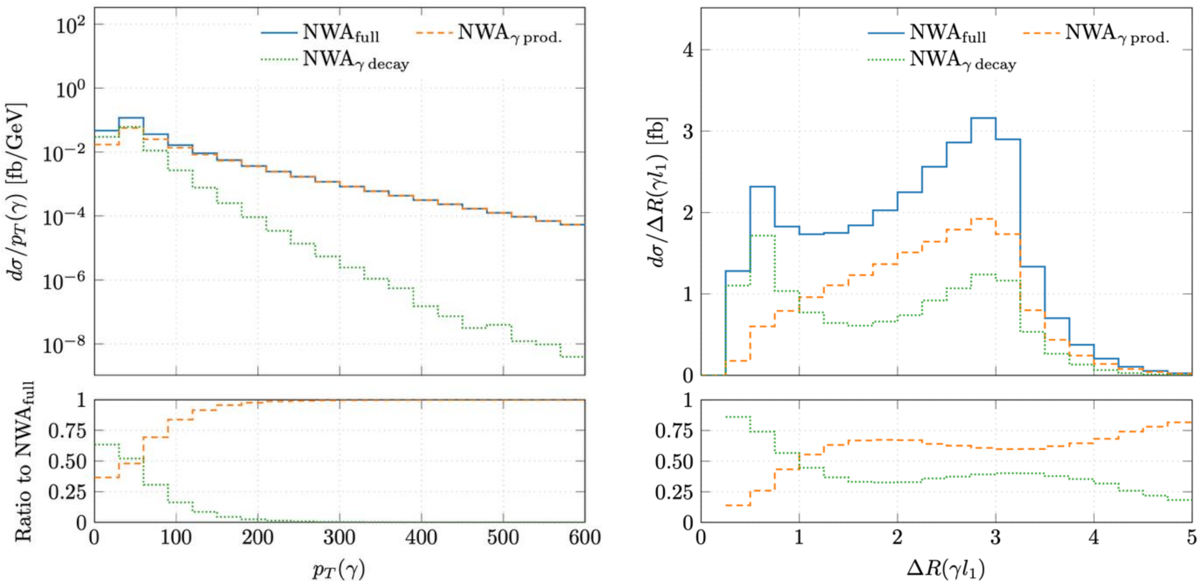
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_iC_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

- ***Full off-shell effects relevant in high p_T tails & for kinematical edges***
- Other relevant effects in the same phase-space regions $\rightarrow$ EW Sudakov logarithms $\rightarrow$ SMEFT contributions

Photon in Production & Decays

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

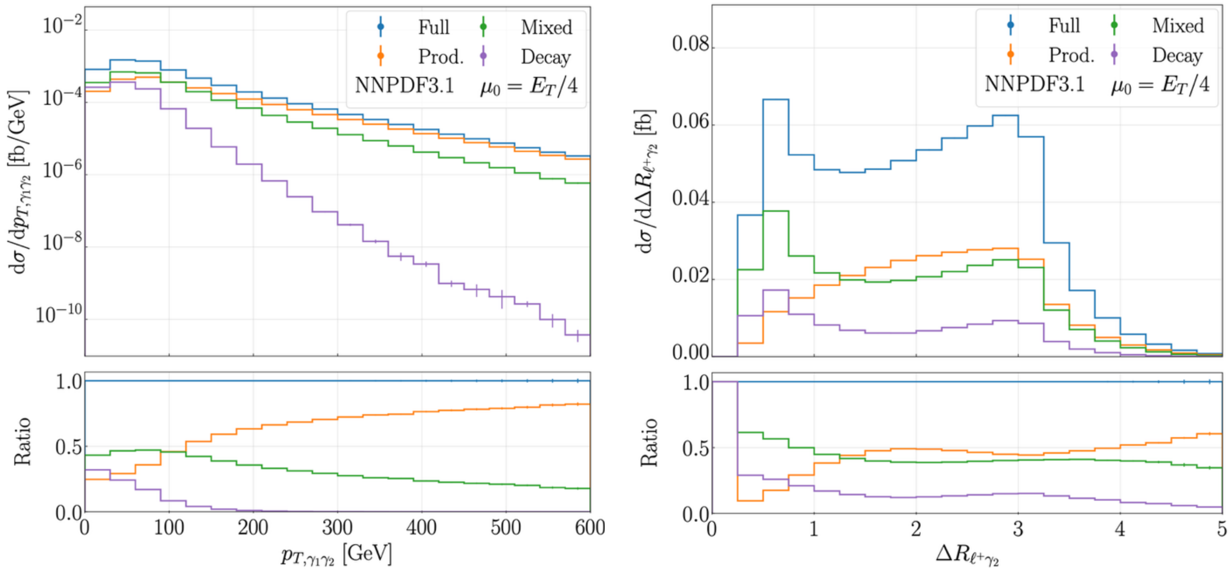
- Integrated level for $p_{T,b} > 40$ GeV & $p_{T,\gamma} > 25$ GeV:
  - ***Prod. Contribution*** at the level of ***57%***
  - ***Decay contribution*** at the level of ***43%***



Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154
Stremmer, Worek, JHEP 08 (2023) 179

$pp \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell b\bar{b}\gamma\gamma$

- Integrated level for $p_{T,b} > 25$ GeV & $p_{T,\gamma} > 25$ GeV:
  - ***Mixed contribution*** at the level of ***44%***
  - ***Prod. contribution*** at the level of ***40%***
  - ***Decay contribution*** is about half the size ***16%***

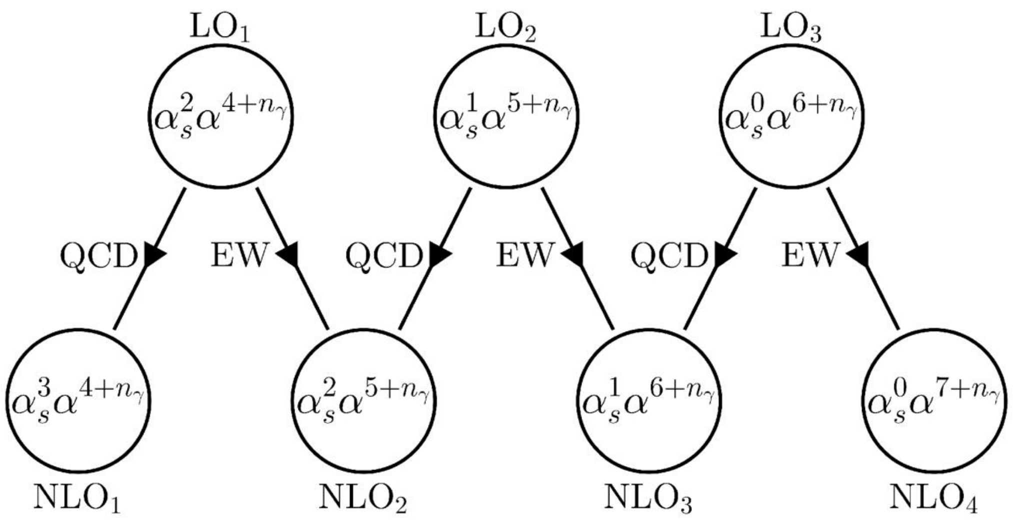


- Different phase-space regions with various effects
- $pp \to tt\gamma(\gamma)$ process cannot be described correctly by standard NLO+PS predictions

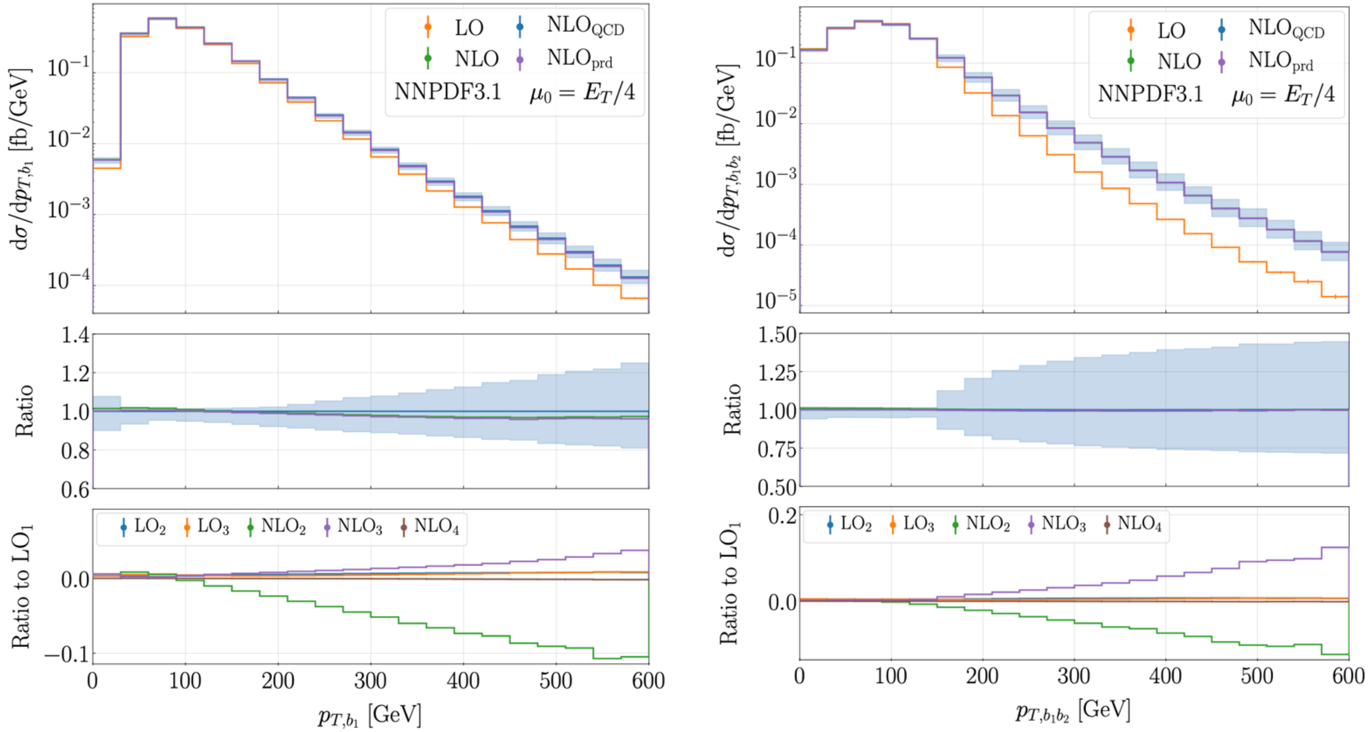
Part II – Fixed-order predictions: Complete NLO

Complete NLO Corrections

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



		σ_i [fb]	Ratio to LO$_1$
LO$_1$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$55.604(8)^{+31.4\%}_{-22.3\%}$	1.00
LO$_2$	$\mathcal{O}(\alpha_s^1\alpha^6)$	$0.18775(5)^{+20.1\%}_{-15.4\%}$	+0.34%
LO$_3$	$\mathcal{O}(\alpha_s^0\alpha^7)$	$0.26970(4)^{+14.3\%}_{-16.9\%}$	+0.49%
NLO$_1$	$\mathcal{O}(\alpha_s^3\alpha^5)$	+3.44(5)	+6.19%
NLO$_2$	$\mathcal{O}(\alpha_s^2\alpha^6)$	−0.1553(9)	−0.28%
NLO$_3$	$\mathcal{O}(\alpha_s^1\alpha^7)$	+0.2339(3)	+0.42%
NLO$_4$	$\mathcal{O}(\alpha_s^0\alpha^8)$	+0.001595(8)	+0.003%
LO		$56.061(8)^{+31.2\%}_{-22.1\%}$	1.0082
NLO$_{\rm QCD}$		$59.05(5)^{+1.6\%}_{-5.9\%}$	1.0620
NLO$_{\rm prd}$		$59.08(5)^{+1.5\%}_{-5.9\%}$	1.0626
NLO		$59.59(5)^{+1.6\%}_{-5.9\%}$	1.0717



Stremmer, Worek, JHEP 07 (2024) 091

- EW Sudakov logarithms in **NLO$_2$** leads to reduction in tails of up to ***10%*** compared to **NLO$_{\rm QCD}$** result
- Accidental cancellations between **NLO$_2$ & NLO$_3$** → Should be considered together
- **NLO$_{\rm prd}$** approximation models complete **NLO** result very well

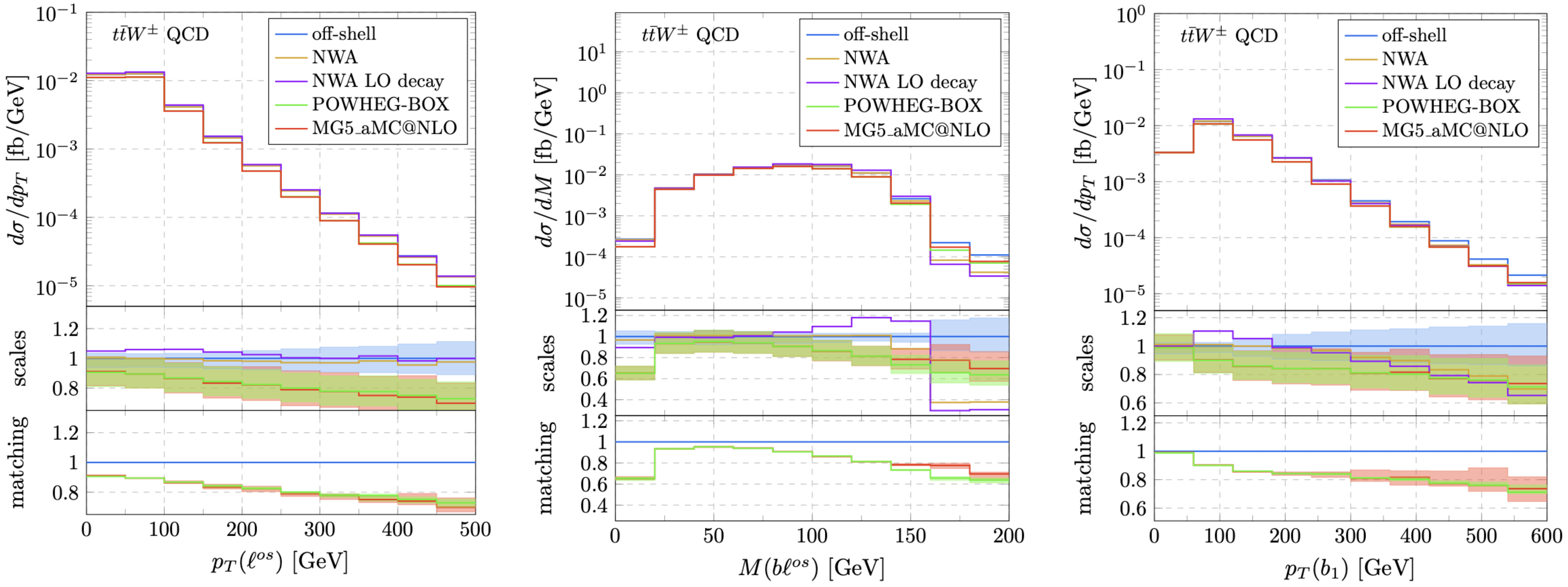
$$\text{NLO}_{\rm prd} = \text{LO}_1 + \text{LO}_2 + \text{LO}_3 + \text{NLO}_1 + \text{NLO}_{2,\rm prd} + \text{NLO}_{3,\rm prd} + \text{NLO}_{4,\rm prd}$$

Part III – Parton-shower based predictions: NLO + PS

Parton-Shower Based Predictions

- Transverse momentum of opposite-sign lepton

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



Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek
Phys. Rev. D 105 (2022) 1, 014018

Various Theoretical Predictions

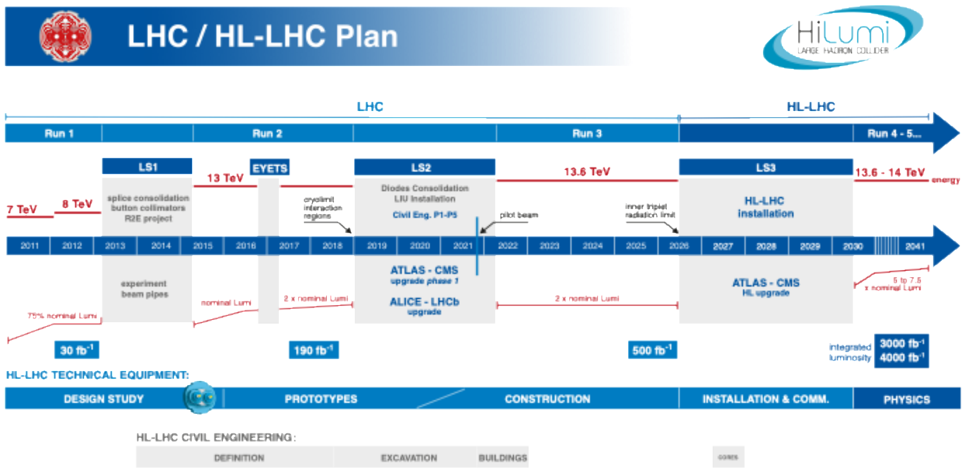
- ***Full $pp \to tt$+X versus $pp \to tt$+X + $pp \to tWb$+X $\to$ Coherent sum versus incoherent sum $\to$ Comparison of various approaches important:***

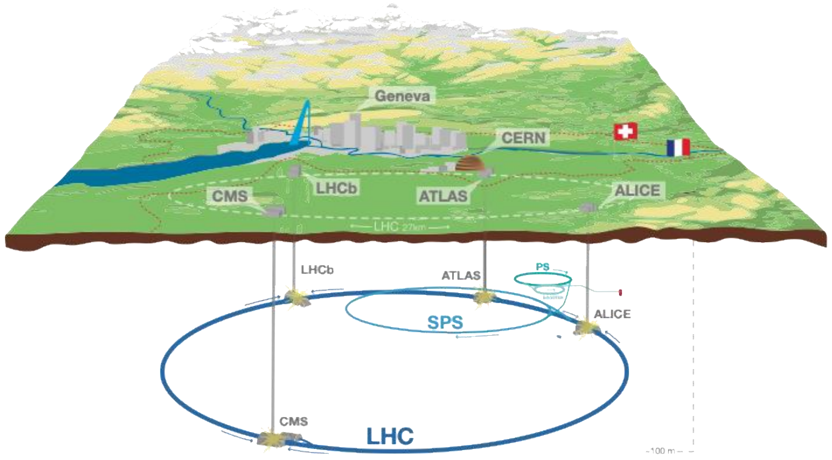
    - Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators
    - NWA = DR restricts unstable t & W to on-shell states
    - Parton-shower based predictions = $pp \to tt$+X production @ NLO + decays within parton shower or decays @ LO + approximate spin correlations
        - ✓ *Spin correlations important to probe new physics scenarios*

- ***Understand various theoretical approaches important as they can impact:***

    - IR-safe (integrated) cross sections: Normalisation
    - IR-safe (differential) cross section distributions: Shape of distributions
    - SM parameter extraction: m_t & Γ_t
    - SM observables: Top Charge Asymmetry
    - BSM exclusion limits: $pp \to tt$ + *Dark Matter* with backgrounds $pp \to tt$ & $pp \to ttZ$ ($Z \to \nu\nu$)
    - New Physics Modelling: $pp \to ttH$ with anomalous couplings $\to$ $pp \to ttH$ in SMEFT
    - Systematic uncertainties: Subtraction of $pp \to tWb$ from $pp \to tt$
    - Matching to parton showers: Resonant aware matching when NLO decays are included

Summary





- **Proper Modelling of Top-Quark Production & Decay Essential**
  - Already now in presence of inclusive cuts

- **NLO QCD** corrections to $pp \to t\bar{t}$ & $t\bar{t} + X$
  - ***Full-off-shell predictions:***
    - ✓ $X = H, \gamma, W^{\pm}, Z(\to \nu_\ell \bar{\nu}_\ell), Z(\to \ell\ell), j, b\bar{b}, W^{\pm}j$
  - ***NWA Results***: $X = jj, \gamma\gamma, tt$

- **Important**
  - Corrections to production & decays important
  - Complete off-shell effects important
    - ✓ *kinematical edges & high p_T*
  - Same phase-space regions are also sensitive to
    - ✓ Subleading higher-order corrections
    - ✓ New Physics effects
  - Photon emissions must be properly included at all stages
  - *Matching to parton showers → To be used in addition to accurate matrix-element predictions, not instead of them*

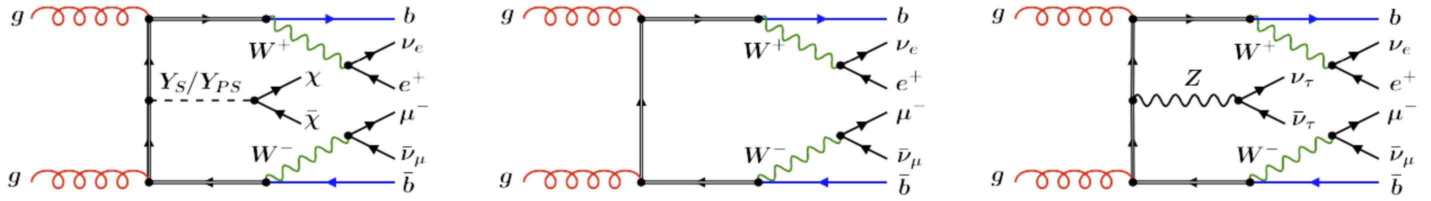
- **Even More Important for**
  - Exclusive cuts & HL-LHC
  - New Physics searches & Exclusion limits
  - SM parameter extraction
  - SM observables

Backup

Application I: BSM Exclusion Limits

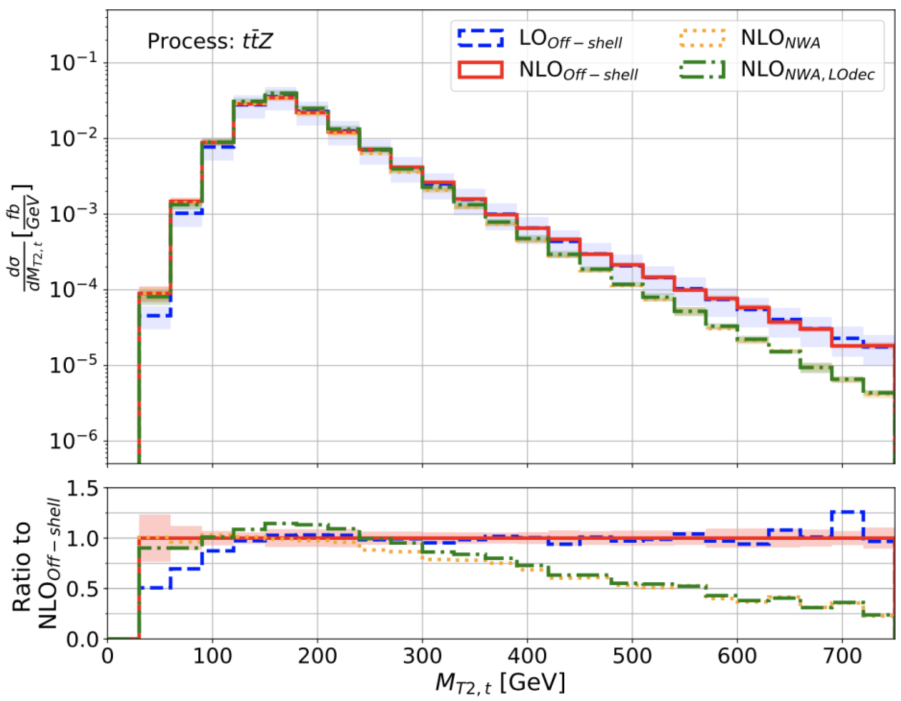
- BSM $\rightarrow$ Kinematical edges & high p_T regions
- $t\bar{t} + DM$ $\rightarrow$ Top quark backgrounds: $t\bar{t}$ & $t\bar{t}Z$
- Observable $\rightarrow$ $M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}

$$pp \rightarrow t\bar{t} + Y_{S/PS} \rightarrow W^+W^-b\bar{b} + Y_{S/PS} \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + \chi\chi$$



Before & after applying additional cuts

Process	Order	Scale	σ_{uncut} [fb]	σ_{cut} [fb]	$\sigma_{\text{cut}}/\sigma_{\text{uncut}}$	Events for $L = 300$ fb^{-1}
$t\bar{t}$ NWA	LO	$H_T/4$	1061	0	0.0%	0
	LO	$E_T/4$	984	0	0.0%	0
	LO	m_t	854	0	0.0%	0
	NLO	$H_T/4$	1097	0	0.0%	0
	NLO, LO dec	$H_T/4$	1271	0	0.0%	0
$t\bar{t}Z$ NWA	LO	$H_T/3$	0.1223	0.0130	11%	47
	LO	$E_T/3$	0.1052	0.0116	11%	42
	LO	$m_t + m_Z/2$	0.1094	0.0134	12%	48
	NLO	$H_T/3$	0.1226	0.0130	11%	47
	NLO, LO dec	$H_T/3$	0.1364	0.0140	10%	50
$t\bar{t}$ Off-shell	LO	$H_T/4$	1067	0.0144	0.0013%	17
	LO	$E_T/4$	989	0.0131	0.0013%	16
	LO	m_t	861	0.0150	0.0017%	18
	NLO	$H_T/4$	1101	0.0156	0.0014%	19
$t\bar{t}Z$ Off-shell	LO	$H_T/3$	0.1262	0.0135	11%	49
	LO	$E_T/3$	0.1042	0.0115	11%	41
	LO	$m_t + m_Z/2$	0.1135	0.0140	12%	50
	NLO	$H_T/3$	0.1269	0.0134	11%	48



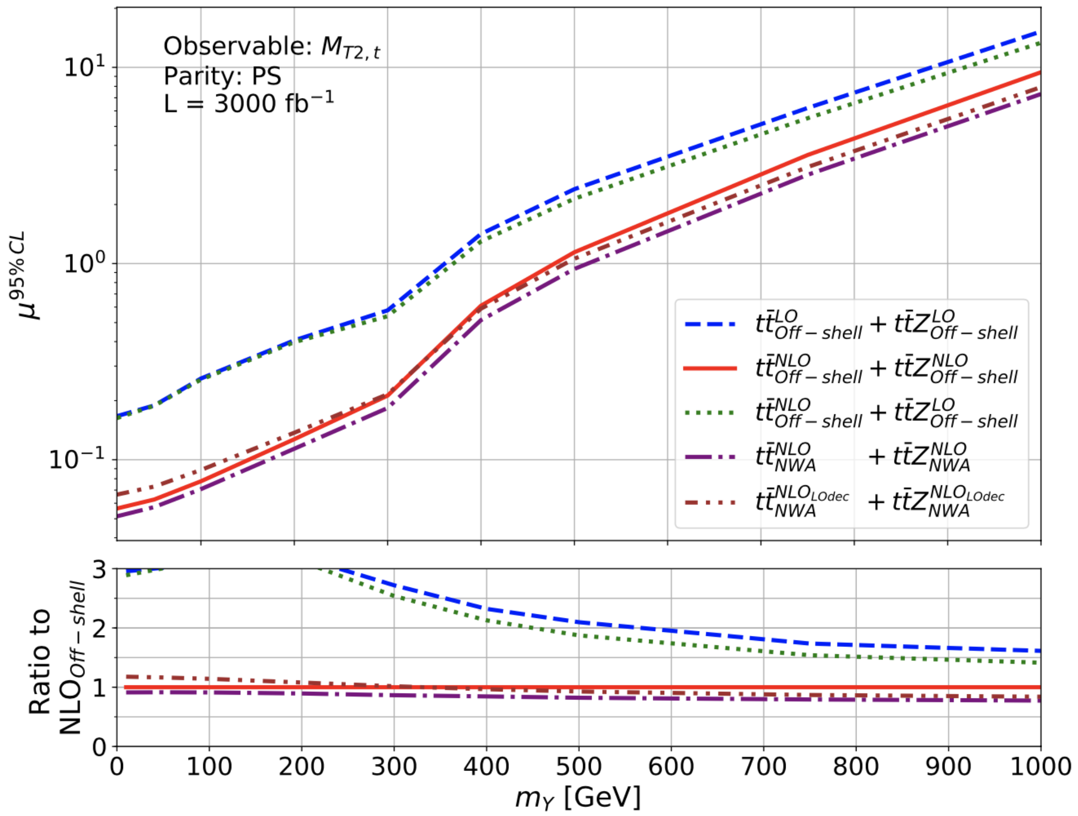
Hermann, Worek, Eur. Phys. J. C 81 (2021) 11, 1029

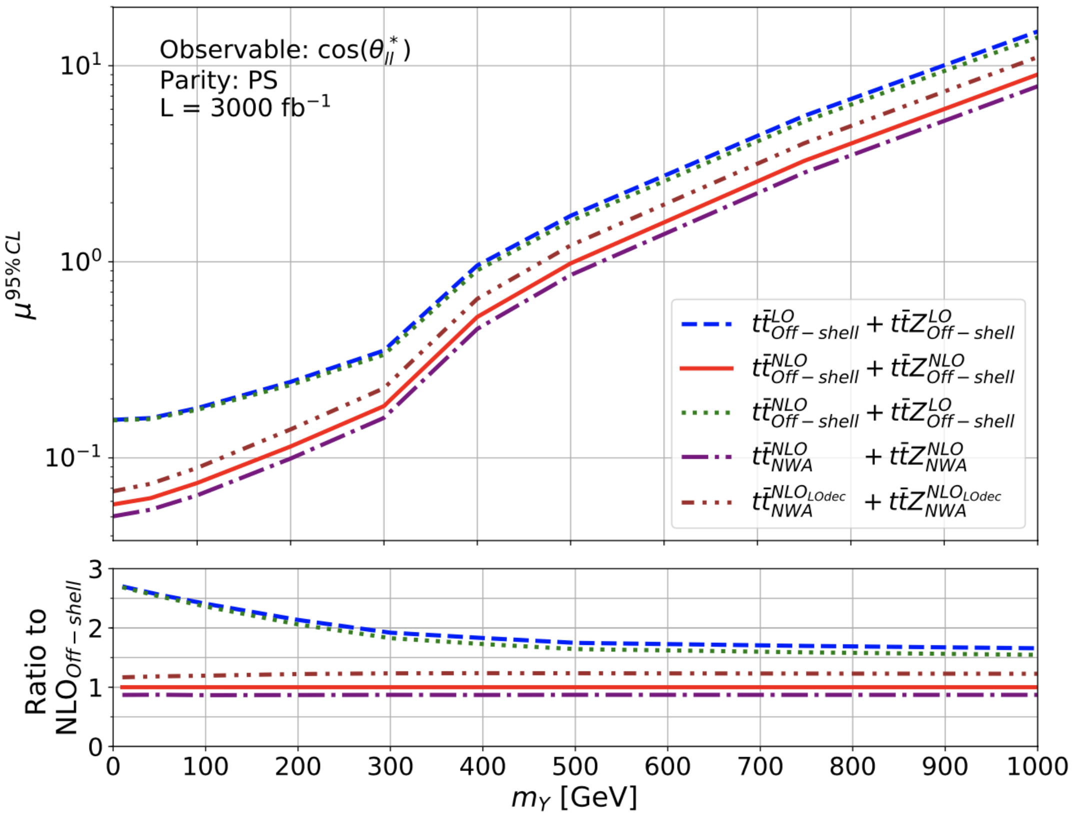
- After cuts 25% of events come from $t\bar{t}$
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

Application I: BSM Exclusion Limits

- Comparison of signal strength exclusion limits

Hermann, Worek, Eur. Phys. J. C 81 (2021) 11, 1029





$$M^2_{T2,t} = \min_{\substack{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2} \\ =\mathbf{p}_{T,\mathrm{miss}}}} [\max\{M_T^2\left(\mathbf{p}_T^{(lb)_1}, \mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{(lb)_2}, \mathbf{p}_T^{\nu_2}\right)\}]$$

$$\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$$

$$M_T^2\left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i}\right) = M^2_{(lb)_i} + 2\left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i} \cdot \mathbf{p}_T^{\nu_i}\right)$$

Application II: Yukawa Coupling

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

$\alpha_{\rm CP}$		Off-shell	NWA	Off-shell effects
	$\sigma_{\rm LO}$ [fb]	$2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$	$2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$	-0.37%
0 (SM)	$\sigma_{\rm NLO}$ [fb]	$2.466(2)^{+0.027\,(1.1\%)}_{-0.112\,(4.5\%)}$	$2.475(1)^{+0.027\,(1.1\%)}_{-0.113\,(4.6\%)}$	-0.36%
CP-even	$\sigma_{\rm NLO_{LOdec}}$ [fb]	—	$2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.21	1.21 (LOdec: 1.27)	
	$\sigma_{\rm LO}$ [fb]	$1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$	$1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$	0.66%
$\pi/4$	$\sigma_{\rm NLO}$ [fb]	$1.465(2)^{+0.016\,(1.1\%)}_{-0.071\,(4.8\%)}$	$1.452(1)^{+0.015\,(1.0\%)}_{-0.069\,(4.8\%)}$	0.89%
CP-mixed	$\sigma_{\rm NLO_{LOdec}}$ [fb]	—	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.23	1.23 (LOdec: 1.28)	
	$\sigma_{\rm LO}$ [fb]	$0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$	$0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$	13.4%
$\pi/2$	$\sigma_{\rm NLO}$ [fb]	$0.5018(3)^{+0.0083\,(1.2\%)}_{-0.0337\,(6.7\%)}$	$0.4301(2)^{+0.0035\,(0.8\%)}_{-0.0264\,(6.1\%)}$	14.3%
CP-odd	$\sigma_{\rm NLO_{LOdec}}$ [fb]	—	$0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.31	1.30 (LOdec: 1.34)	

- Off-shell effects @ integrated fiducial level:
  - Small for *CP-even* and *CP-mixed* Higgs boson
  - Large effects for *CP-odd* Higgs boson

Hermann, Stremmer, Worek, JHEP 09 (2022) 138

- Higgs characterisation framework

Mixing angle

$$\mathcal{L}_{t\bar{t}H} = -\bar{\psi}_t \frac{Y_t}{\sqrt{2}} \left(\kappa_{Ht\bar{t}} \cos(\alpha_{\rm CP}) + i\kappa_{At\bar{t}} \sin(\alpha_{\rm CP})\gamma_5 \right) \psi_t \, H,$$

CP-even *CP-odd*

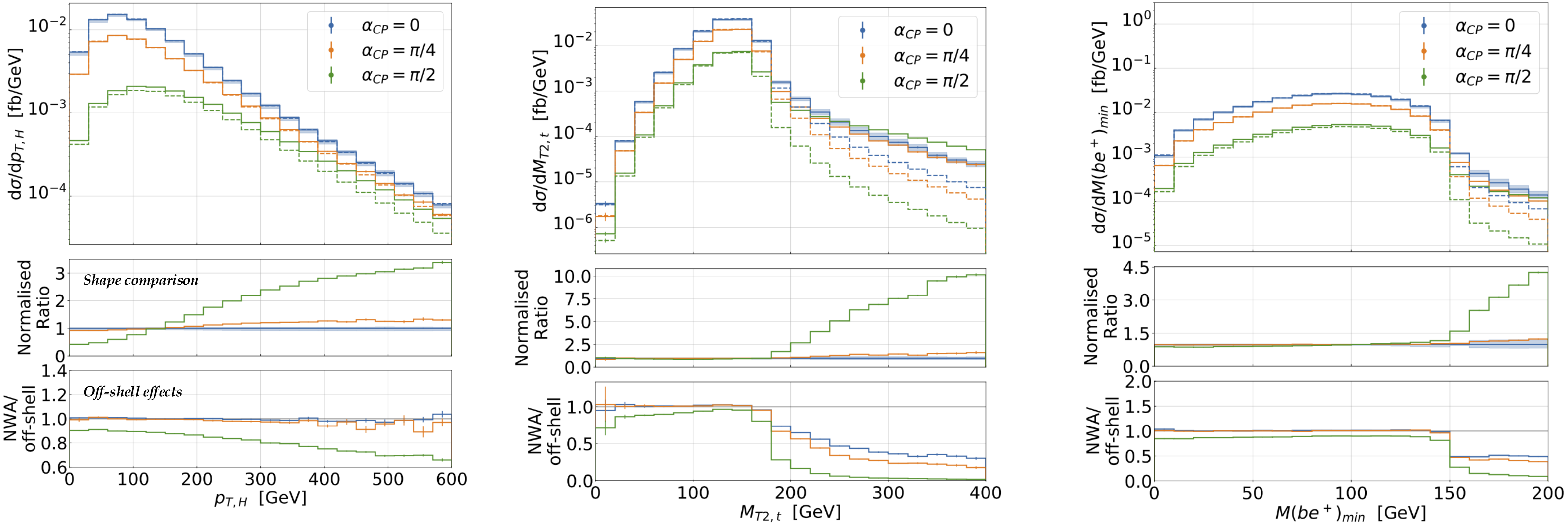
$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right) H,$$

Coupling choices: $\kappa_{At\bar{t}} = 2/3$ & $\kappa_{Ht\bar{t}} = 1$ & $\kappa_{HVV} = 1$
Ensure consistency with current experimental bounds (ggF, VBF)

Artoisenet et al., JHEP 11 (2013) 043
Maltoni et al., Eur. Phys. J. C 74 (2014) 1, 2710
Demartin et al., Eur. Phys. J. C 74 (2014) 9, 3065
Demartin et al., Eur. Phys. J. C 75 (2015) 6, 267

Application II: Yukawa Coupling

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



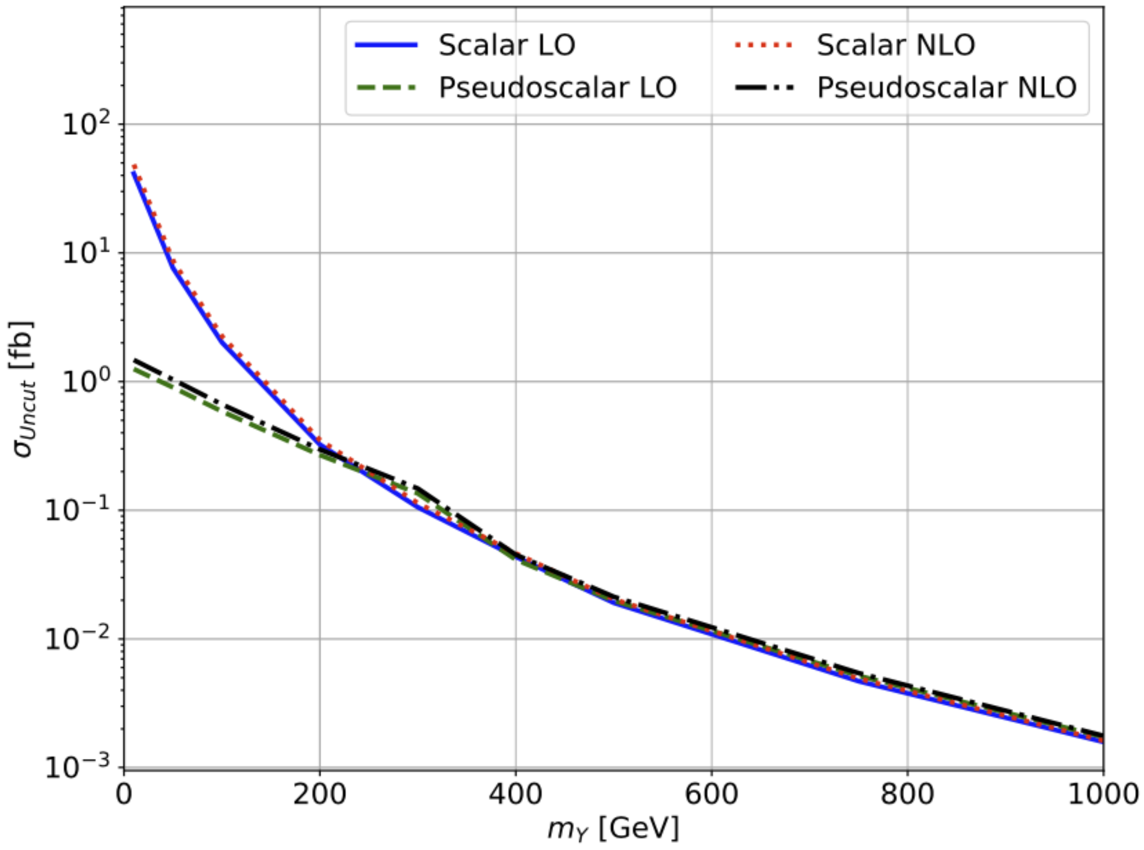
- *CP-even*
- *CP-mixed*
- *CP-odd*

Hermann, Worek, Eur. Phys. J. C 81 (2021) 11, 1029

- Off-shell effects @ differential fiducial level:
  - Large effects on size and shape for CP-odd Higgs boson
  - Only small effects for CP-even and CP-mixed
  - *Reason: SR contributions ~ tWHb production*

Application II: Yukawa Coupling

Hermann, Worek, Eur. Phys. J. C 81 (2021) 11, 1029



- Cross section for $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu\chi\bar{\chi}$ with scalar & pseudoscalar mediators depending on the mass m_Y

- Production of pseudoscalar in association with top quarks is suppressed compared to scalar for masses below ~ 200 GeV if the two couplings $\kappa_{Ht\bar{t}} = \kappa_{At\bar{t}} = 1$

Haisch, Pani, Polesello, JHEP 02 (2017) 131

- This difference can be understood when looking at $t \to t + H/A$ fragmentation functions

$$f_{t\to t+H}(x) = \frac{\kappa_{Ht\bar{t}}^2}{(4\pi)^2}\left[\frac{4(1-x)}{x} + x\ln\left(\frac{s}{m_t^2}\right)\right]$$

$$f_{t\to t+A}(x) = \frac{\kappa_{At\bar{t}}^2}{(4\pi)^2}\left[x\ln\left(\frac{s}{m_t^2}\right)\right],$$

Dawson, Reina, Phys. Rev. D 57 (1998) 5851

- x momentum fraction that Higgs boson carries
- Scalar fragmentation function has additional $1/x$
- Enhanced production of soft scalar compared to pseudoscalars

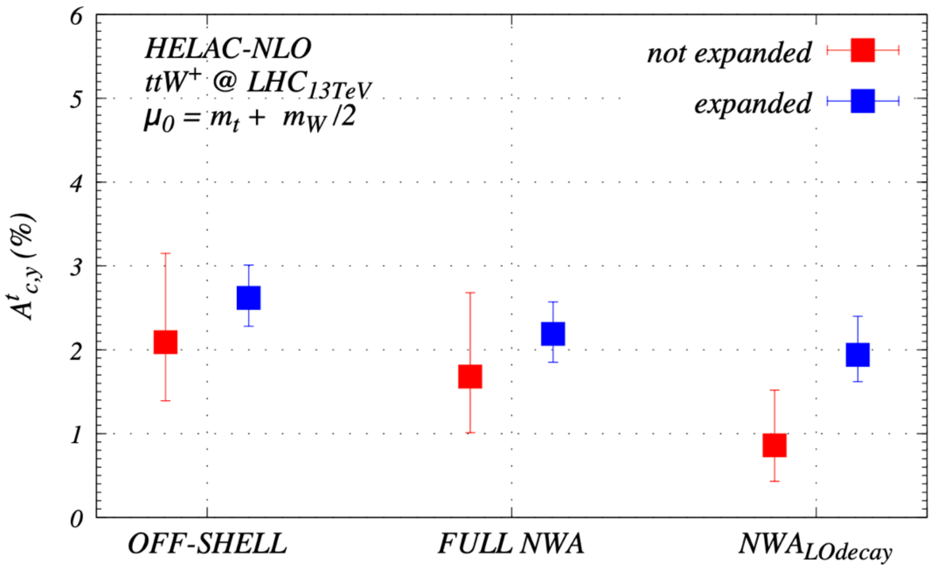
Application III: Top Charge Asymmetry

Searching for more precise observables

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek, Eur. Phys. J. C 81 (2021) 7, 675

$$A_c^t = \frac{\sigma^+_{\rm bin} - \sigma^-_{\rm bin}}{\sigma^+_{\rm bin} + \sigma^-_{\rm bin}}, \qquad \sigma^\pm_{\rm bin} = \int \theta(\pm\Delta|y|)\,\theta_{\rm bin}\,d\sigma$$

$$\Delta|y| = |y_t| - |y_{\bar t}|$$



- A_c^t charge asymmetry @ NLO for $pp \to t\bar{t}W^+$

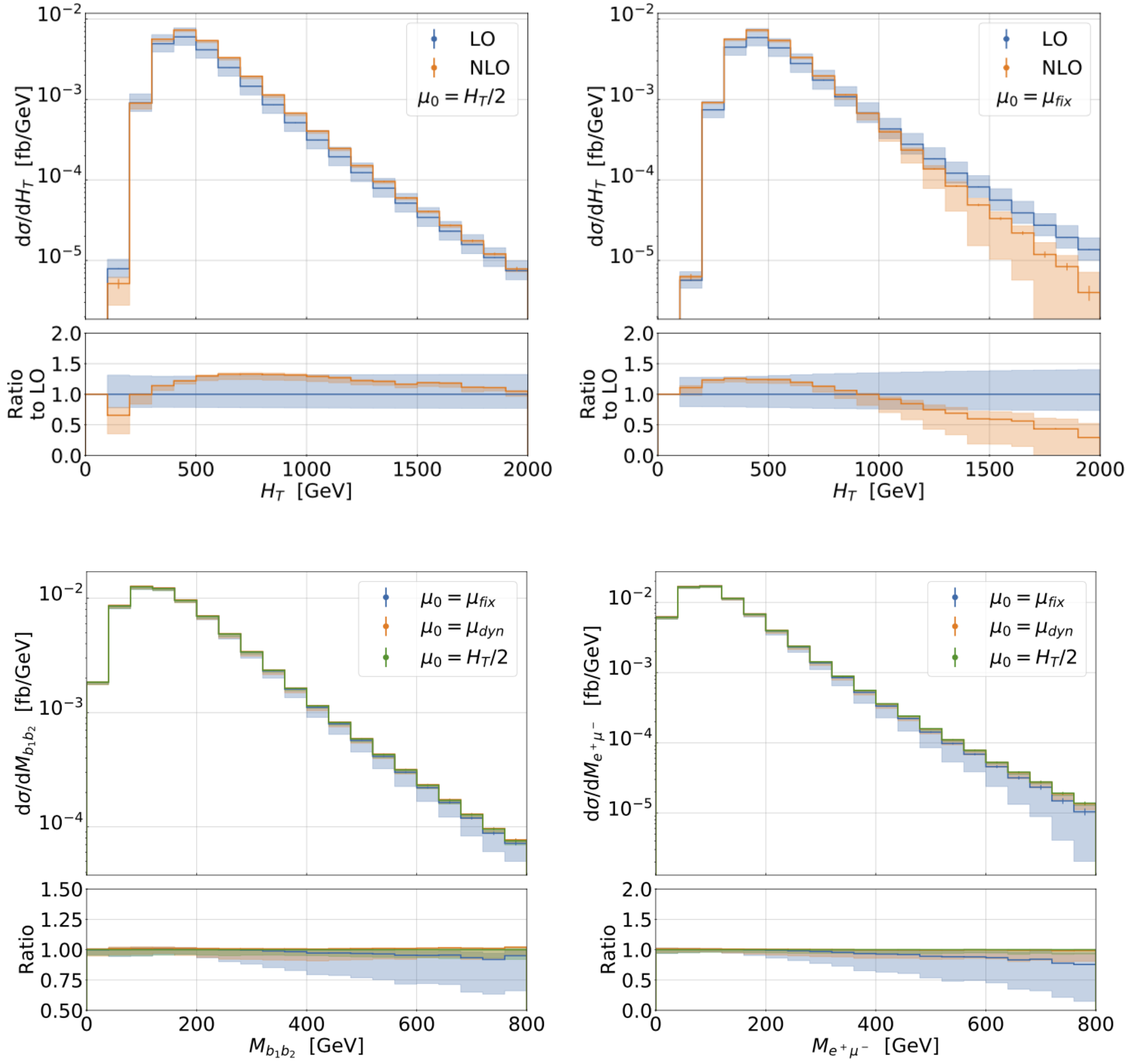
- Asymmetry larger than for $pp \to t\bar{t}$
- Top quark momenta must be reconstructed
- Scale setting not important $\rightarrow$ Fixed & dynamical scale choice gives similar results
- Top-quark modelling important

$t\bar{t}W^+$, $\mu_0 = H_T/3$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.36(8)^{+1.19\,(50\%)}_{-0.77\,(33\%)}$	$1.93(5)^{+1.23\,(64\%)}_{-0.72\,(37\%)}$	$1.11(3)^{+0.55\,(49\%)}_{-0.53\,(48\%)}$
$A^t_{c,exp,y}$ [%]	$2.66(10)^{+0.38\,(14\%)}_{-0.34\,(13\%)}$	$2.20(5)^{+0.45(20\%)}_{-0.31(14\%)}$	$2.08(5)^{+0.24\,(11\%)}_{-0.40\,(19\%)}$

$t\bar{t}W^+$, $\mu_0 = m_t + m_W/2$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.09(8)^{+1.06\,(51\%)}_{-0.70\,(33\%)}$	$1.68(4)^{+1.00(60\%)}_{-0.67(40\%)}$	$0.86(3)^{+0.66\,(77\%)}_{-0.43\,(50\%)}$
$A^t_{c,exp,y}$ [%]	$2.62(10)^{+0.39\,(15\%)}_{-0.34\,(13\%)}$	$2.19(4)^{+0.38(17\%)}_{-0.34(16\%)}$	$1.94(5)^{+0.46\,(24\%)}_{-0.32\,(16\%)}$

NLO QCD Corrections & Scale Setting

Stremmer, Worek, JHEP 02 (2022) 196



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

- **Fixed scale choice**
  - Perturbative instabilities in ~ TeV regions
  - LO & NLO uncertainties band do not overlap
  - Scale uncertainties @ NLO larger than @ LO
  - For some scale choices NLO results negative
- **Dynamical scale choice**
  - Stabilizes tails
  - NLO uncertainties bands within LO ones

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

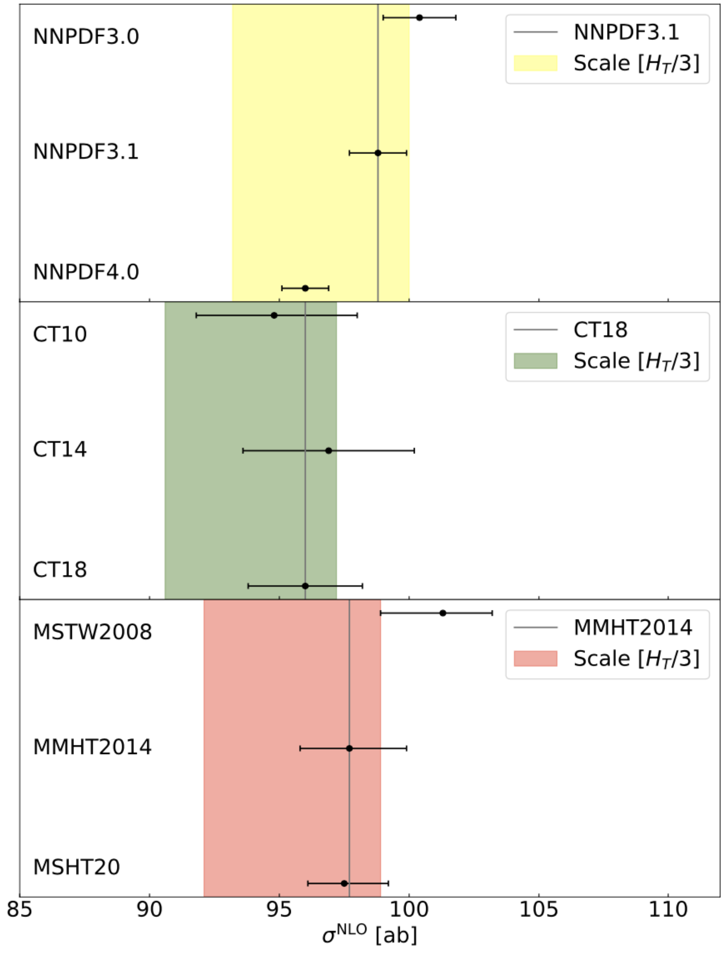
$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad m_T = \sqrt{m^2 + p_T^2}.$$

$$\mu_{fix} = m_t + \frac{m_H}{2} = 236 \text{ GeV}$$

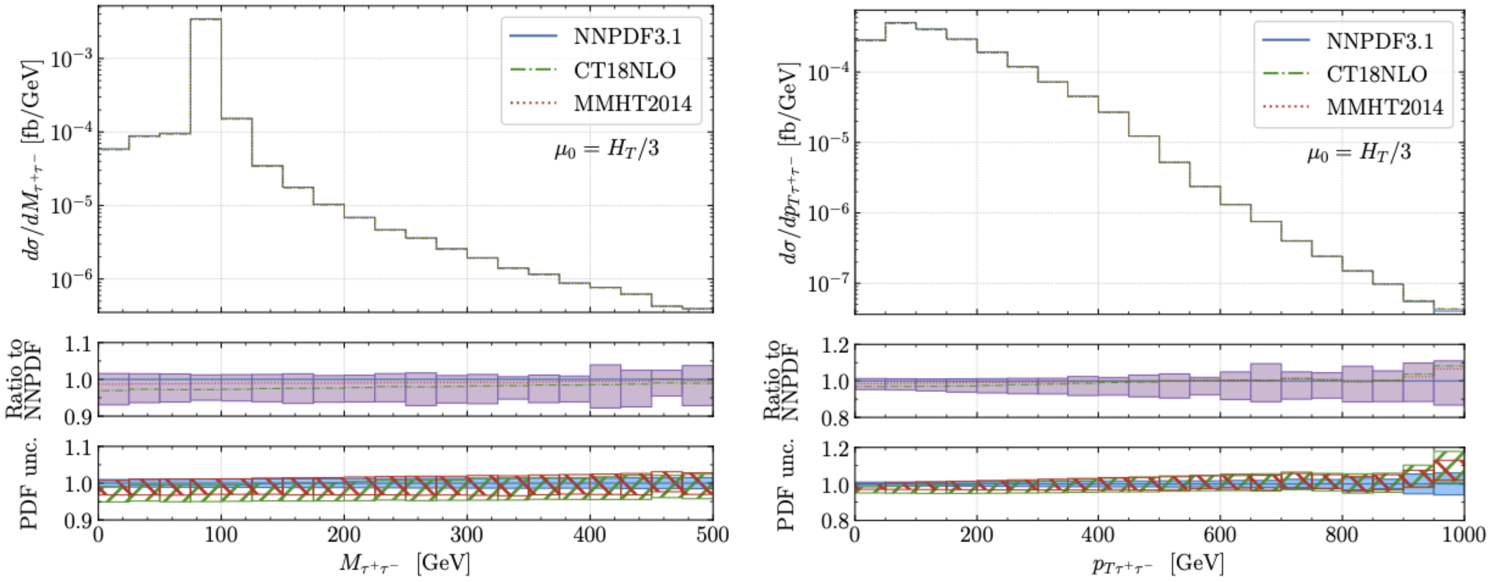
PDF Uncertainties

Bevilacqua, Hartanto, Kraus, Nasufi, Worek, JHEP 08 (2022) 060

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



Integrated level



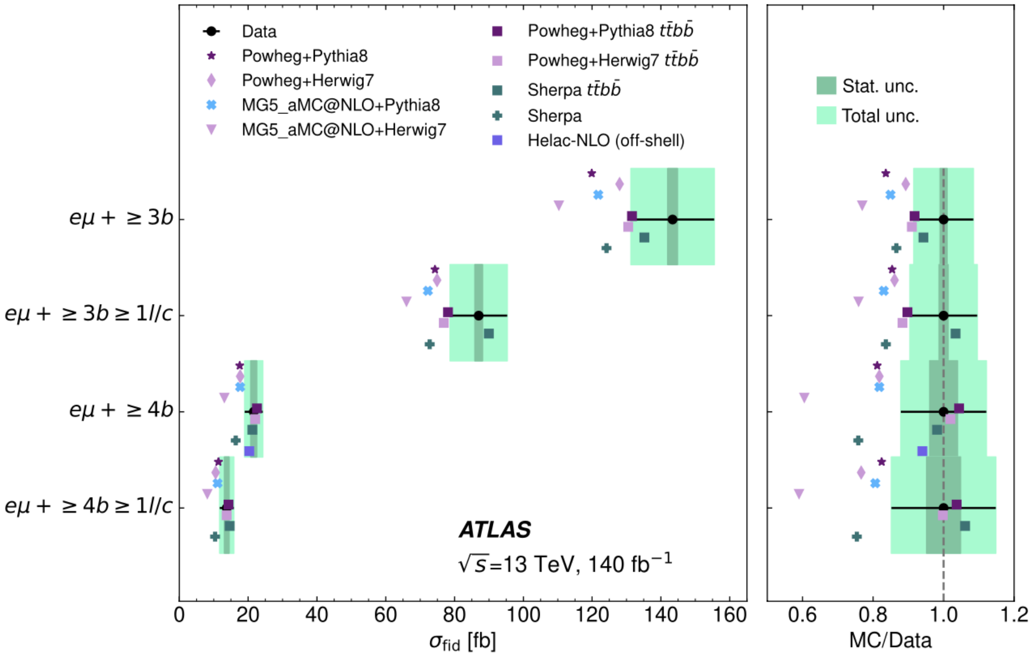
Differential level

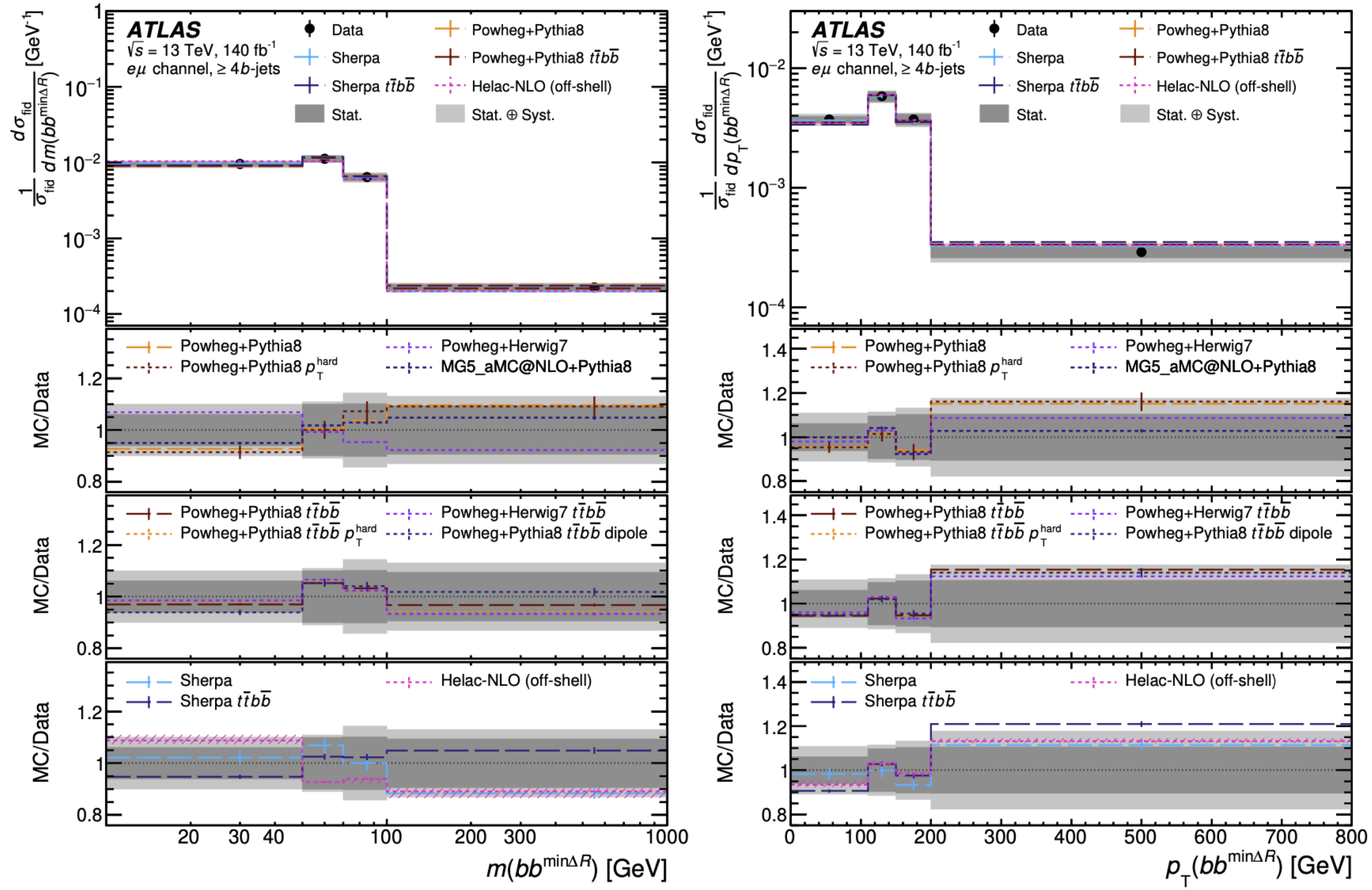
- PDF uncertainties for CT18 & MMHT14 similar
- Factor of 2 larger than PDF uncertainties for NNPDF3.1
- *PDF uncertainties smaller than scale variation → But are not constant over the phase space and can reach 10% for large p_T*

Comparisons with LHC Data

HELAC-NLO

$$pp \to \ell^+ \nu_\ell \ell^- \overline{\nu}_\ell b\bar{b}b\bar{b}$$



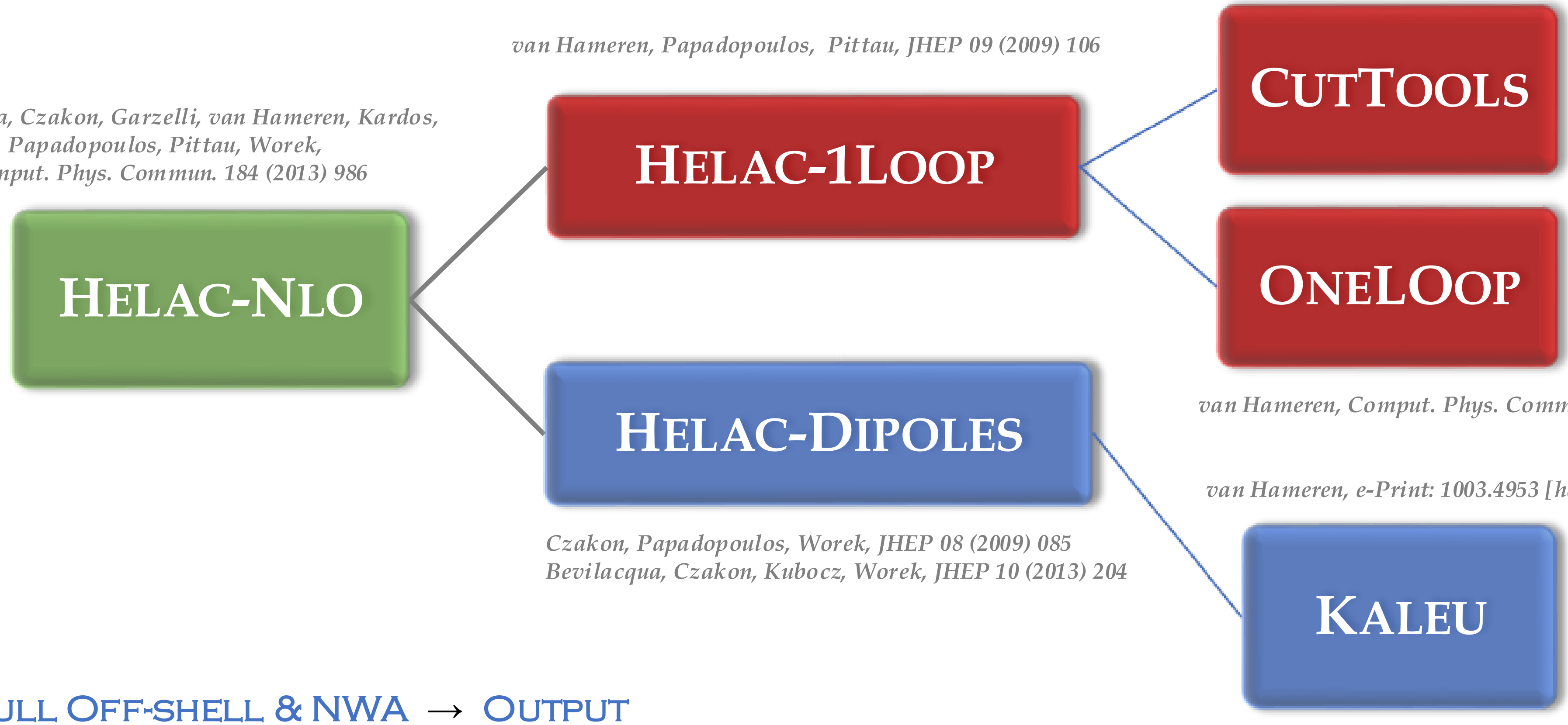


- NLO QCD full off-shell predictions for $t\bar{t}b\bar{b}$ → Di-Lepton Channel

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008 & Phys.Rev.D 107 (2023) 1, 014028

ATLAS Collaboration, JHEP 01 (2025) 068

HELAC-NLO



- BOTH FULL OFF-SHELL & NWA → OUTPUT
  - Predictions stored as partially unweighted "events" → *ROOT-Ntuples Files* & *Les Houches Files*
  - Each "event" provided with supplementary matrix element & PDF information
  - Results for different scale settings & PDF choices by can be obtained by reweighting
  - Different observables and/or binning can be provided + more exclusive cuts → With caveat

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Comput. Phys. Commun. 185 (2014) 1443

Various Phase – Space Regions

- 3 different resonance histories ⇨ Resolved jet at NLO gives 9 in total

$$\begin{array}{llcl}
\text{(i)} & t = W^+(\to e^+\nu_e)\,b & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\,, \\
\text{(ii)} & t = W^+(\to e^+\nu_e)\,b\gamma & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\,, \\
\text{(iii)} & t = W^+(\to e^+\nu_e)\,b & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\gamma
\end{array}$$

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

Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154

- Compute for each history Q and pick one that minimises Q

$$Q = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

- Double-resonant (DR)

$$|M(t) - m_t| < n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| < n\,\Gamma_t$$

- Two single-resonant regions (SR)

$$|M(t) - m_t| < n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

$$|M(t) - m_t| > n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| < n\,\Gamma_t$$

- Non-resonant region (NR)

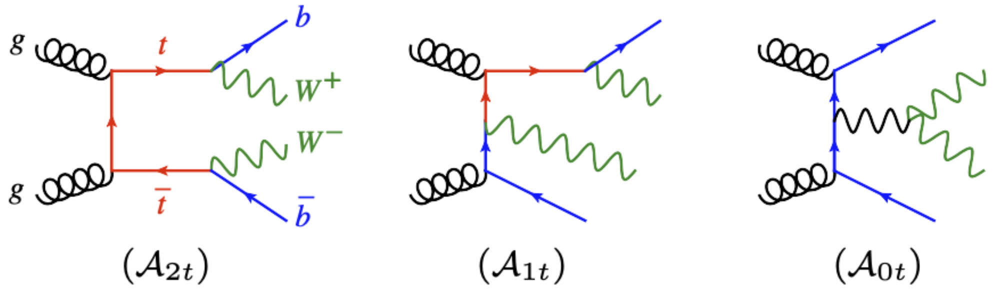
$$|M(t) - m_t| > n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

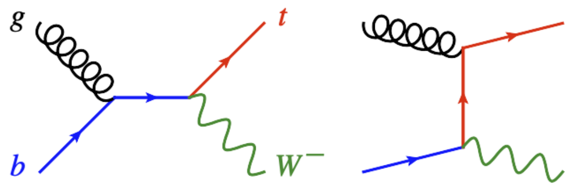
- Boundary parameter
  - Determines size of resonant region for each reconstructed top quark
  - *n = 5, 10, 15*
  - For n = 15

$$M(t) \in (152.9, 193.5)\ \text{GeV}$$

TWB

Demartin, Maier, Maltoni, Mawatari, Zaro, Eur. Phys. J. C 77 (2017) 1, 34





- Squared matrix element for producing $tW^-\bar{b}$

$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$
$$= |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*) + |\mathcal{A}_{2t}|^2,$$

- *DS (diagram subtraction):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t},$$

- Local subtraction term C_{2t} by definition must cancel exactly the resonant matrix element $|\mathcal{A}_{2t}|^2$ when the kinematics is exactly on top of the resonant pole
- Be gauge invariant
- Decrease quickly away from the resonant region

- *DR1 (without interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR1}} = |\mathcal{A}_{1t}|^2.$$

- *DR2 (with interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR2}} = |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*).$$

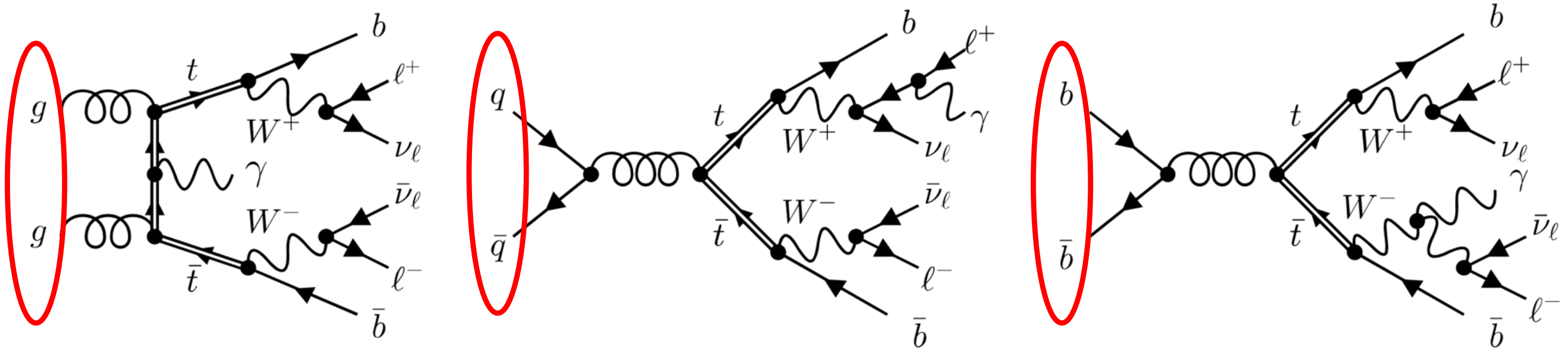
- DR schemes based on removing contributions all over the phase space

- They are not gauge invariant

Definition of LO$_1$

$pp \to e^+\nu_e\mu^-\overline{\nu}_\mu b\overline{b}\gamma$

- **LO$_1$:** Dominant contributions at $\mathcal{O}(\alpha_s^2\alpha^{4+n_\gamma})$ where n_γ is number of photons appearing in Born-level process



- Typical QCD production of top-quark pair with photons, which leads to the following partonic subprocesses

$$gg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$$

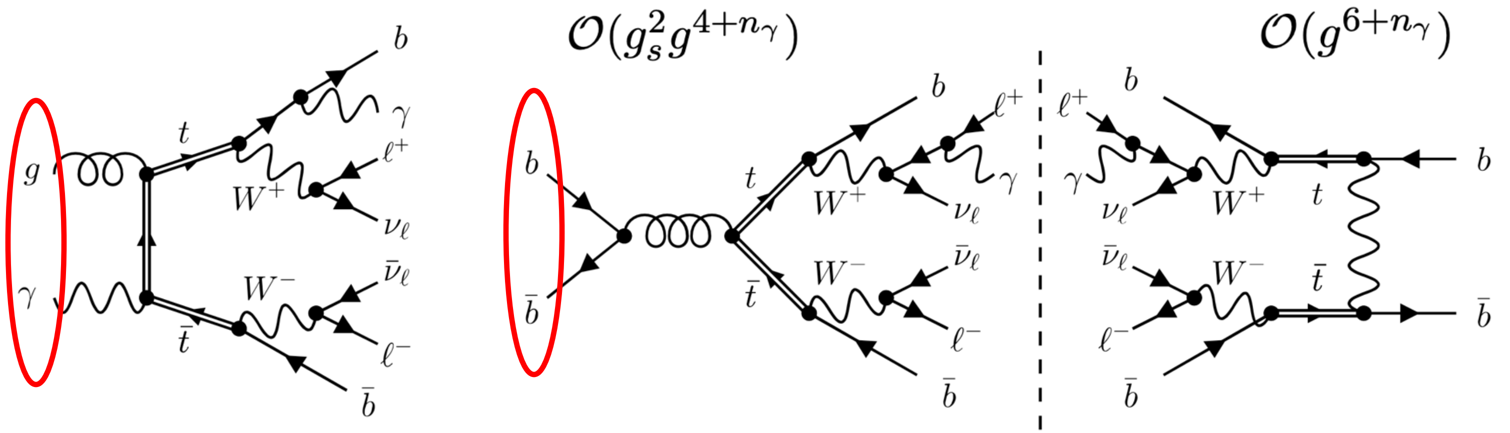
$$q\bar{q}/\bar{q}q \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,, \qquad b\bar{b}/\bar{b}b \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$$

Stremmer, Worek, JHEP 07 (2024) 091

Definition of LO_2 & LO_3

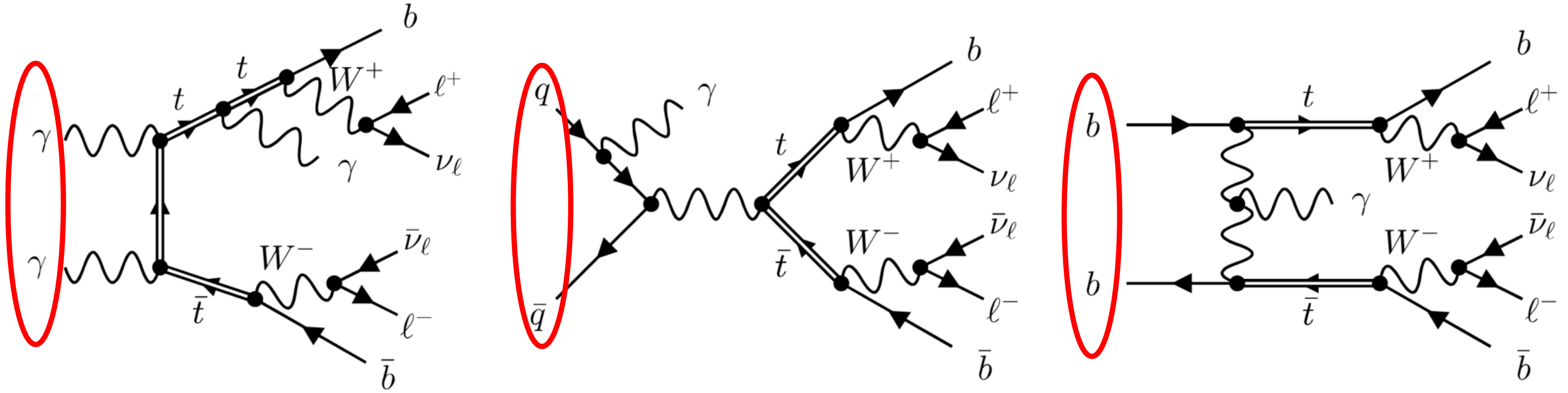
$pp \to e^+\nu_e\mu^-\overline{\nu}_\mu b\bar{b}\gamma$

- **LO_2:** Contributions at $\mathcal{O}(\alpha_s^1\alpha^{5+n_\gamma})$



- Interference between gluon mediated diagrams with Z/γ mediated ones vanishes due to colour for qq initial state
- Interference does not vanish for bb due to t-channel diagrams with intermediate W boson
- When CKM matrix is not diagonal these contributions for qq initial state can also be non-zero but are CKM-suppressed

- **LO_3:** Purely EW induced production of top-quark pair at $\mathcal{O}(\alpha^{6+n_\gamma})$
  - Suppressed by power coupling & without gluon PDFs



$$\mathrm{LO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3$$