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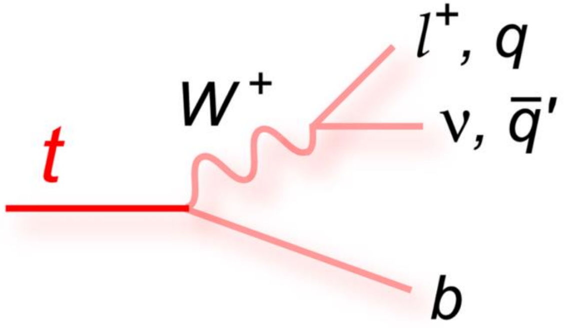
Research Training Group
Physics of the Heaviest
Particles at the LHC

RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257
P3H
Particle Physics Phenomenology after the Higgs Discovery

With funding from the:
Federal Ministry
of Research, Technology
and Space

Problems & Challenges in Modelling
$pp \to tt + X$ @ NLO



Malgorzata Worek

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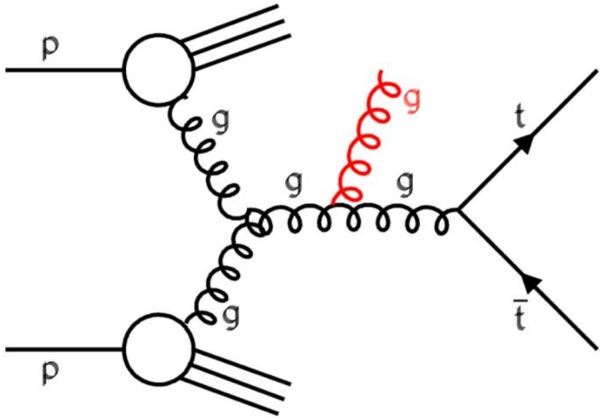


Outline of the Talk

1. Introduction
2. Part I – Fixed-order predictions: full off-shell NLO QCD predictions
3. Part II – Fixed-order predictions: Complete NLO predictions
4. Part III – Parton-shower based predictions: NLO + PS predictions
5. Summary
6. Open Questions & Problems

Introduction

Large Hadron Collider

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

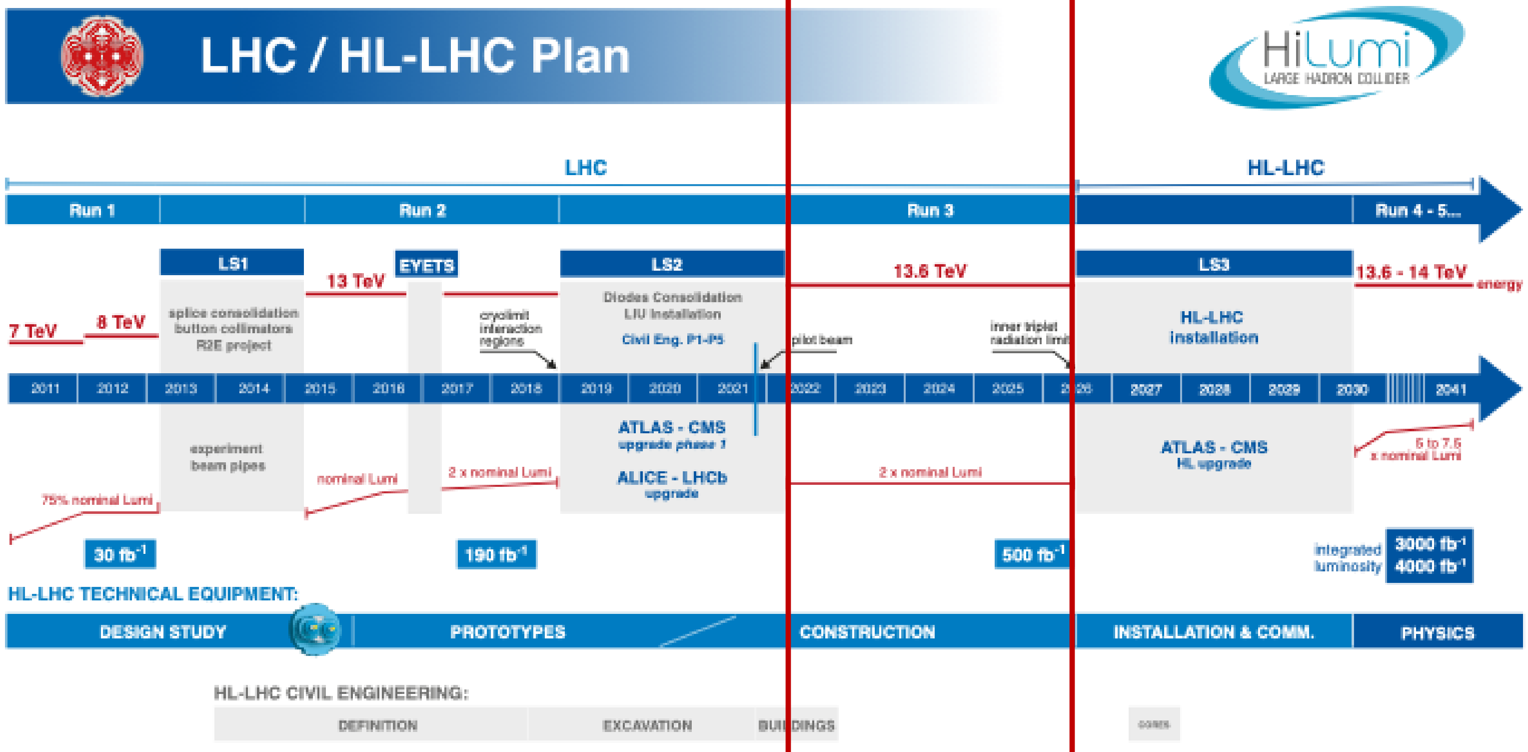
Integrated Luminosity $\mathcal{L}_{\text{int}} = \int_0^T \mathcal{L}(t')dt'$

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

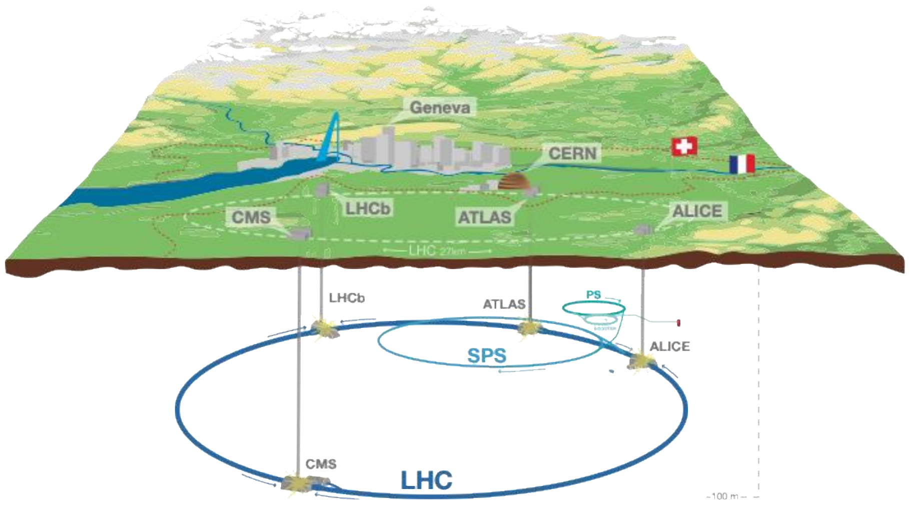
$$\mathcal{L}_{\text{int}} \cdot \sigma_p = \text{number of events of interest}$$

WE ARE HERE !

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



Overall view of the LHC



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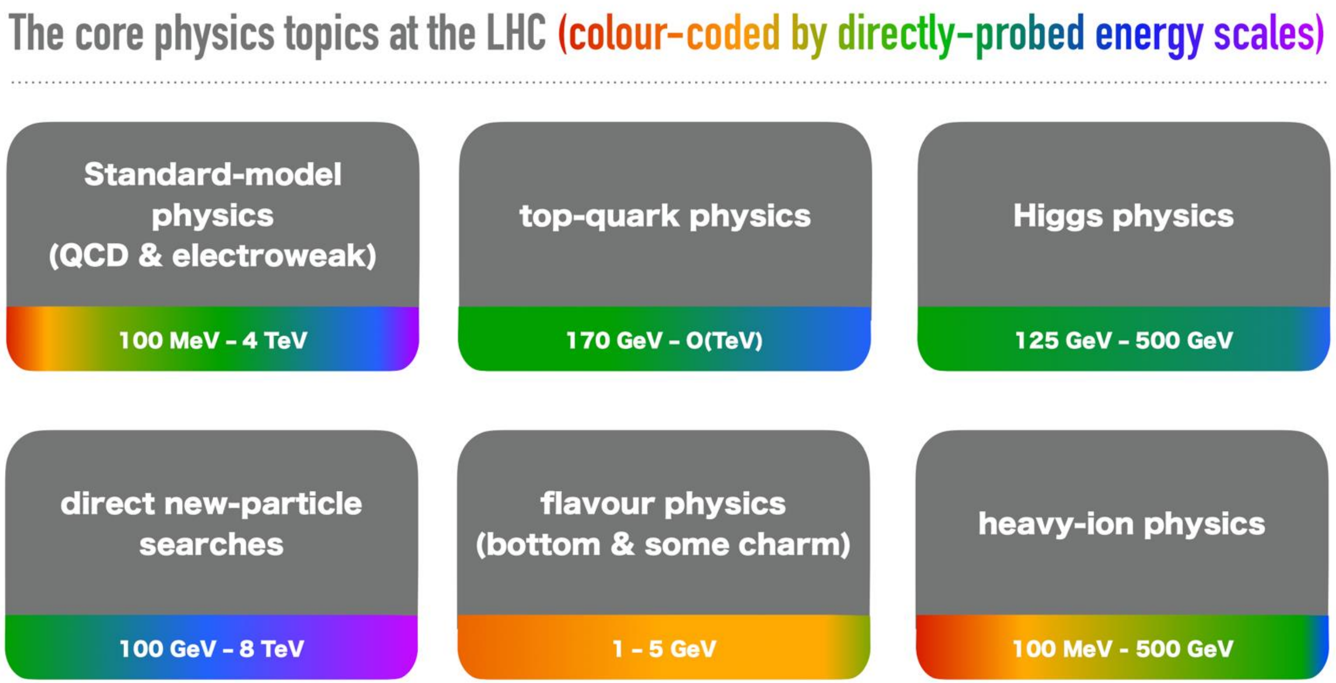
KEY PHYSICS GOALS

1) Understand Standard Model better, not only what particles we have, but also how they interact with each other

2) Establish structure of Higgs boson sector

3) Search for signs of new physics BSM



Graphic borrowed from Gavin Salam - Amplitudes 2020

- **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

- Carefully examine top-quark sector for deviations from SM

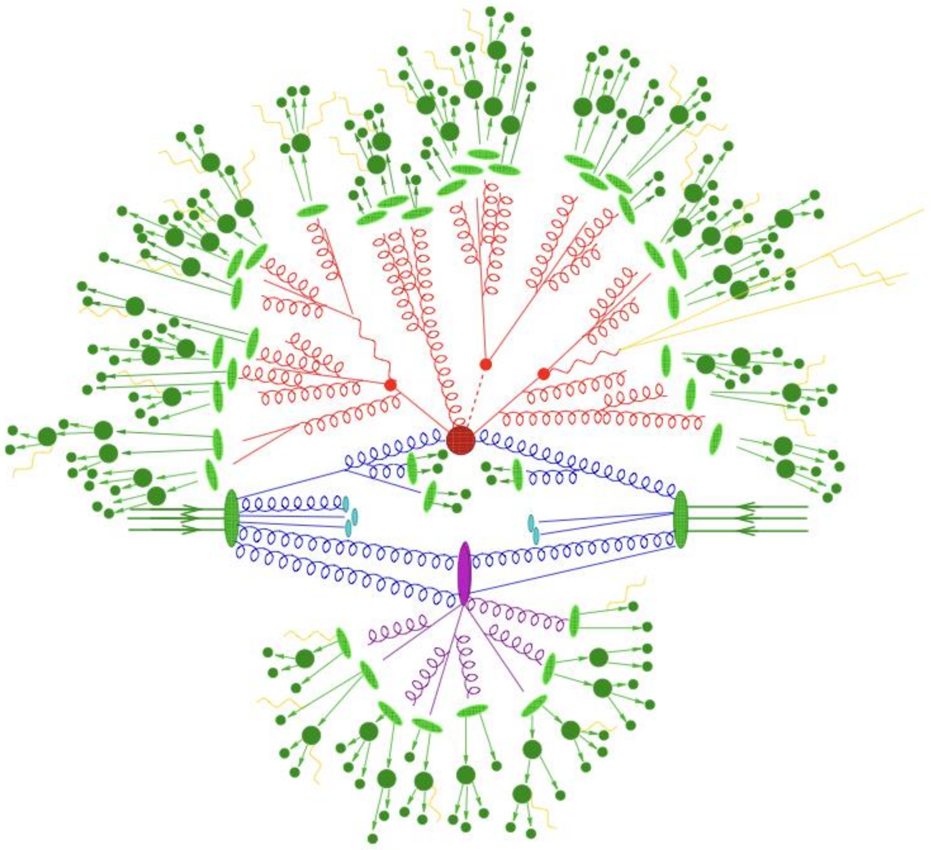
- On theory side, path to precision runs through several directions:

  - Perturbative accuracy of amplitude calculations
  - Numerical stability of integration & subtraction of IR divergencies
  - Robust assessment of theoretical uncertainties
  - Modelling realistic final states in fiducial phase-space regions
  - Modelling resonant particles
  - Parton shower effects
  - Non perturbative aspects

- **Precision & Accuracy** $\rightarrow$ Determine which effects are important & have to be included

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

SHERPA, JHEP 02 (2009) 007

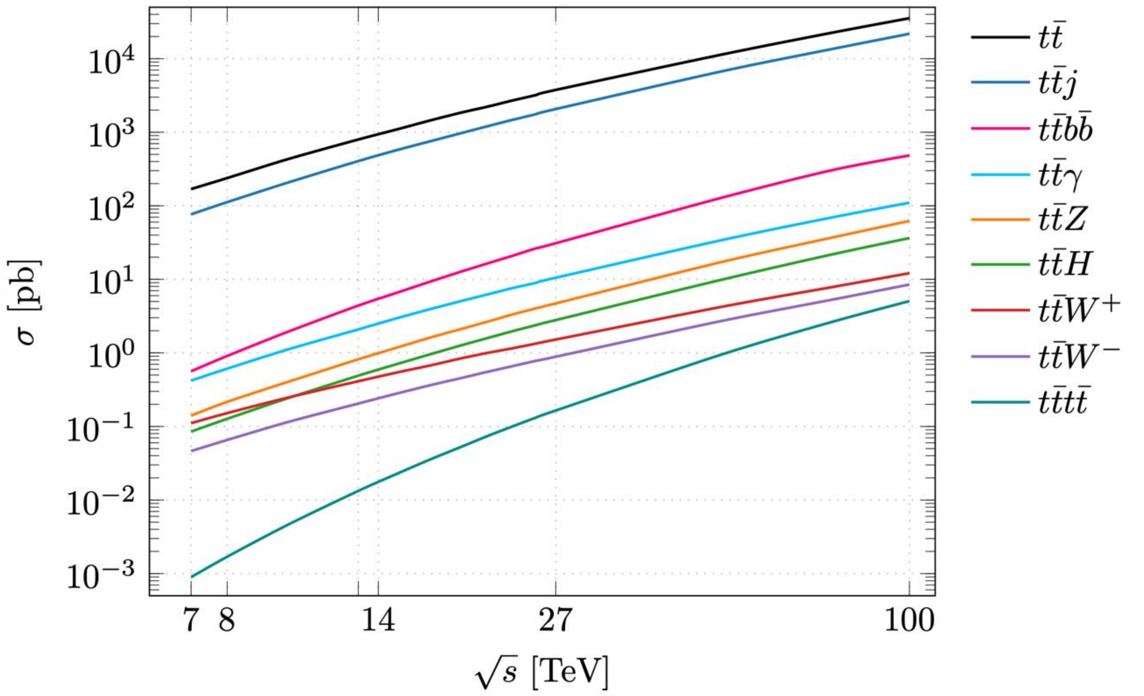


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

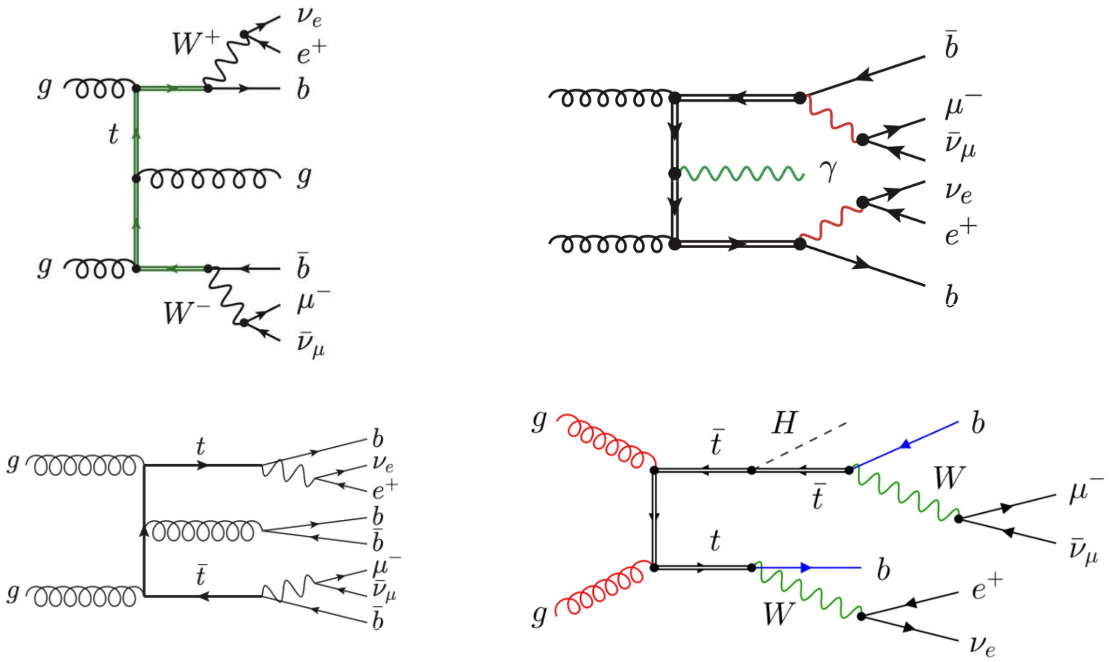
Top-Quark Pair Production +X @ LHC

State of the art: NLO

- More exclusive final states are produced @ LHC



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



- Only selected results for $pp \to tt + X$ to illustrate some issues
- **Helac-Nlo:** Results for all these processes & more:
  - $pp \to ttjj$, $pp \to tt\gamma\gamma$ & $pp \to ttWj$
- See also results by *Ansgar Denner & collaborators*

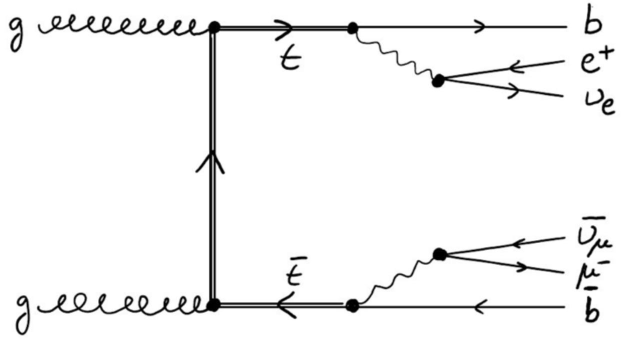
Main Focus:

Precise & accurate modelling of realistic final states in fiducial phase-space regions

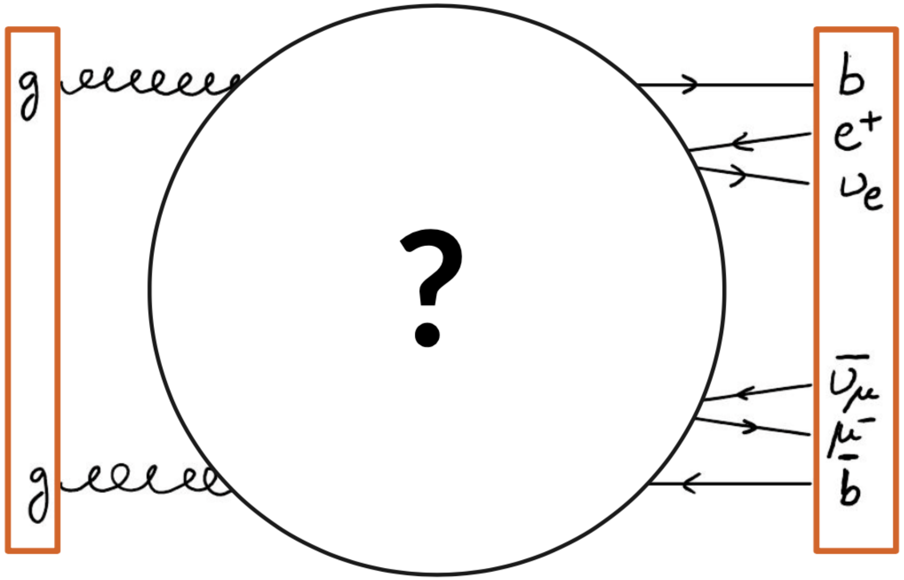
TT Production with Realistic Final States

- Modelling of unstable particles

tt in di-lepton decay channel



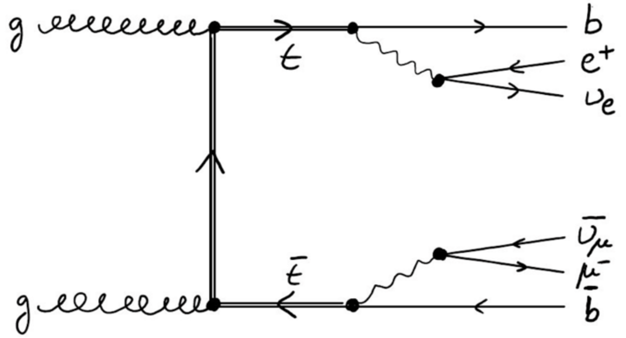
$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$



TT Production with Realistic Final States

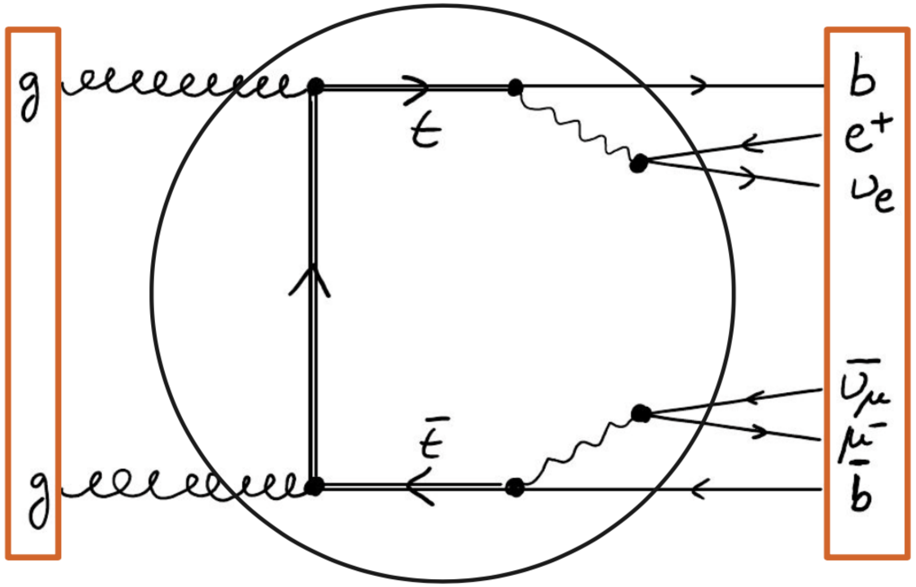
- Modelling of unstable particles

tt in di-lepton decay channel



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

Double-resonant diagram

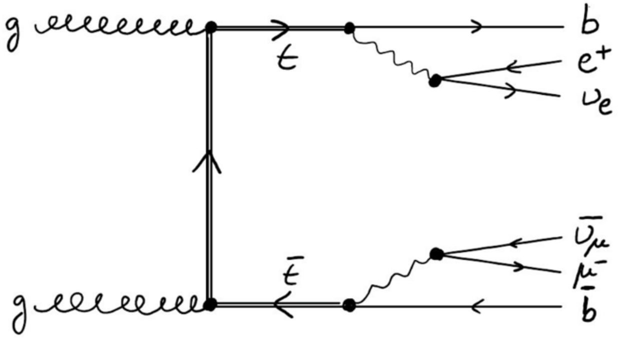


TT Production with Realistic Final States

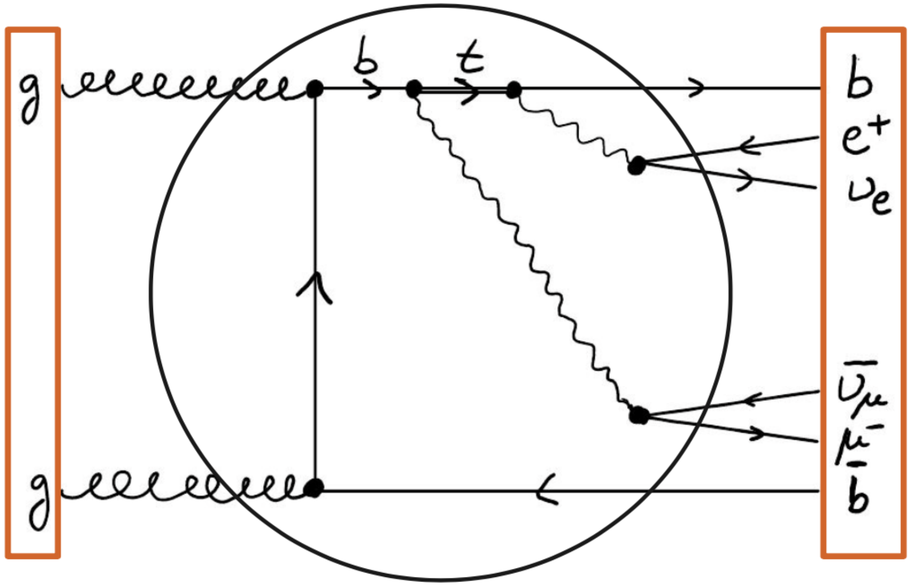
- Modelling of unstable particles

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

tt in di-lepton decay channel



Single-resonant diagram

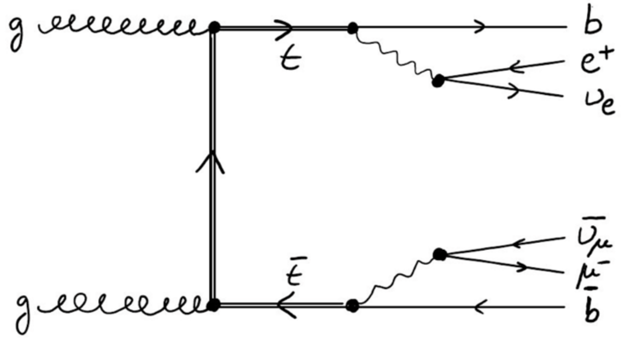


TT Production with Realistic Final States

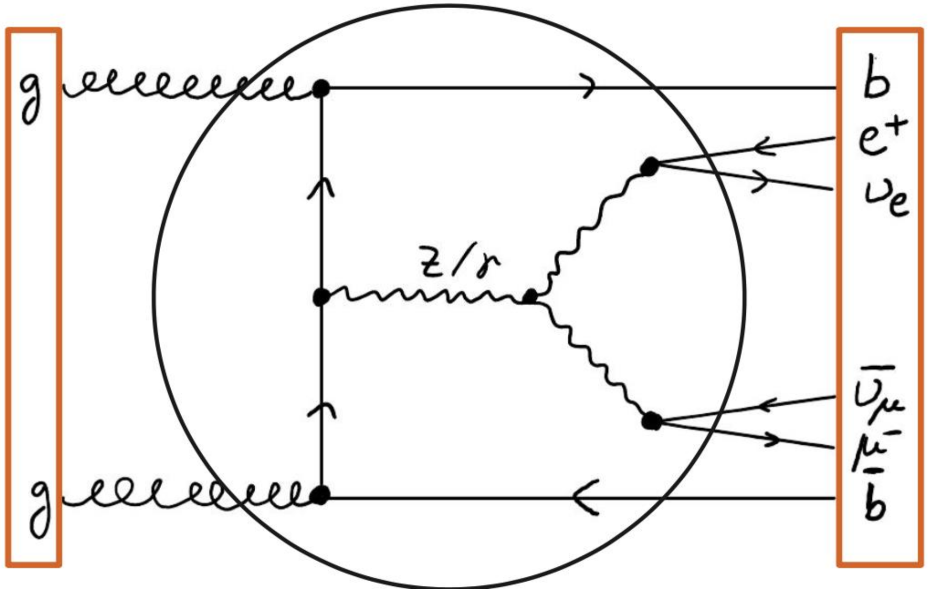
- Modelling of unstable particles

tt in di-lepton decay channel

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



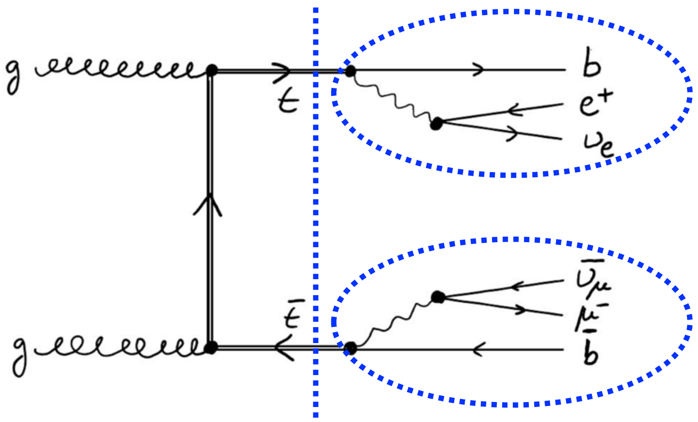
Non-resonant diagram



TT Production in NWA

tt in di-lepton decay channel

- Modelling of unstable particles

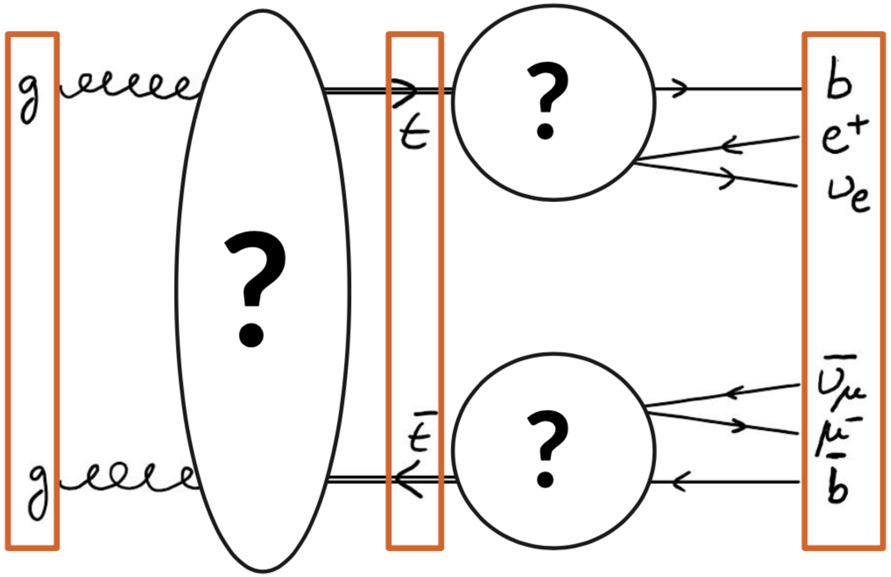


$$pp \rightarrow b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$

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

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

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



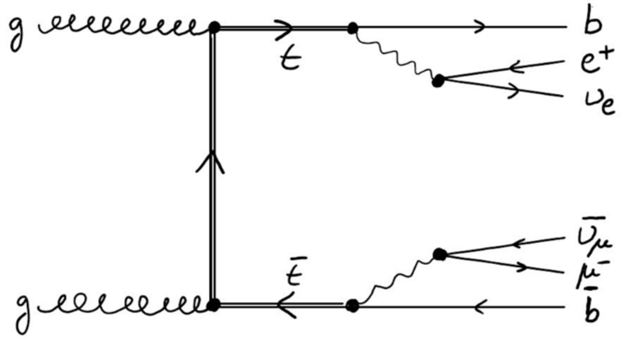
- NLO QCD correction separately to production & decays
- Nonfactorizable NLO corrections are missing
- No cross-talk between production & both decays
- NLO spin correlations

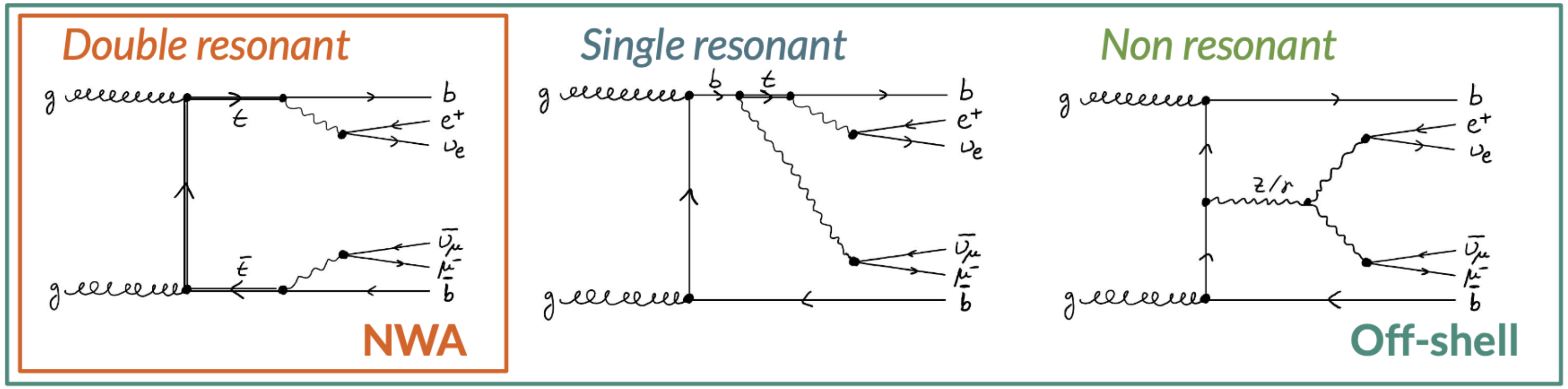
TT Production

- Modelling of unstable particles

tt in di-lepton decay channel

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





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

TT Production with Parton Showers

- NLO QCD corrections to stable $pp \to tt + X$ matched to parton-showers: Powheg & MC@NLO
  - *NLO QCD for production only*
  - *Decays of top quarks included with LO spin correlations*
  - Double resonant contributions only
  - Single & non-resonant contributions still missing as well as their interference effects
  - Scale settings & theoretical uncertainties based on production stage only
- Another approach for *tt* production is ***bb4l-dl & bb4l-sl MC generators***
  - Full off-shell predictions at NLO QCD in ***di-lepton & l+j*** channels matched to (semi-classical) PS using a resonance-aware matching

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
- Assess if parton showers can reproduce all contributions required at NLO QCD
- Identify regions of phase space & specific observables which are sensitive to parton shower effects

Ježo, Lindert, Nason, Oleari, Pozzorini, Eur. Phys. J. C 76 (2016) 12, 691
Ježo, Lindert, Pozzorini, JHEP 10 (2023) 008

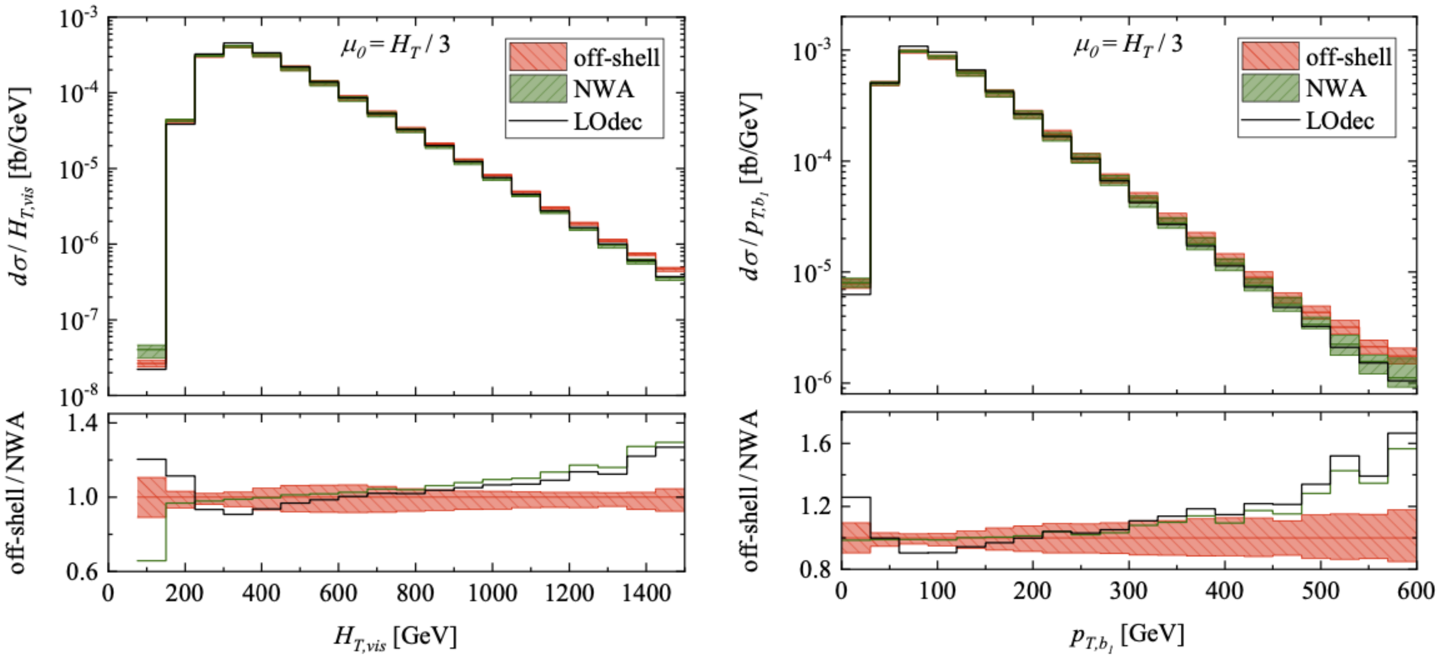
Part I – Fixed-Order Predictions: Full Off-Shell NLO QCD

When Do We Need Full Off-Shell Predictions

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 ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

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



Integrated level

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

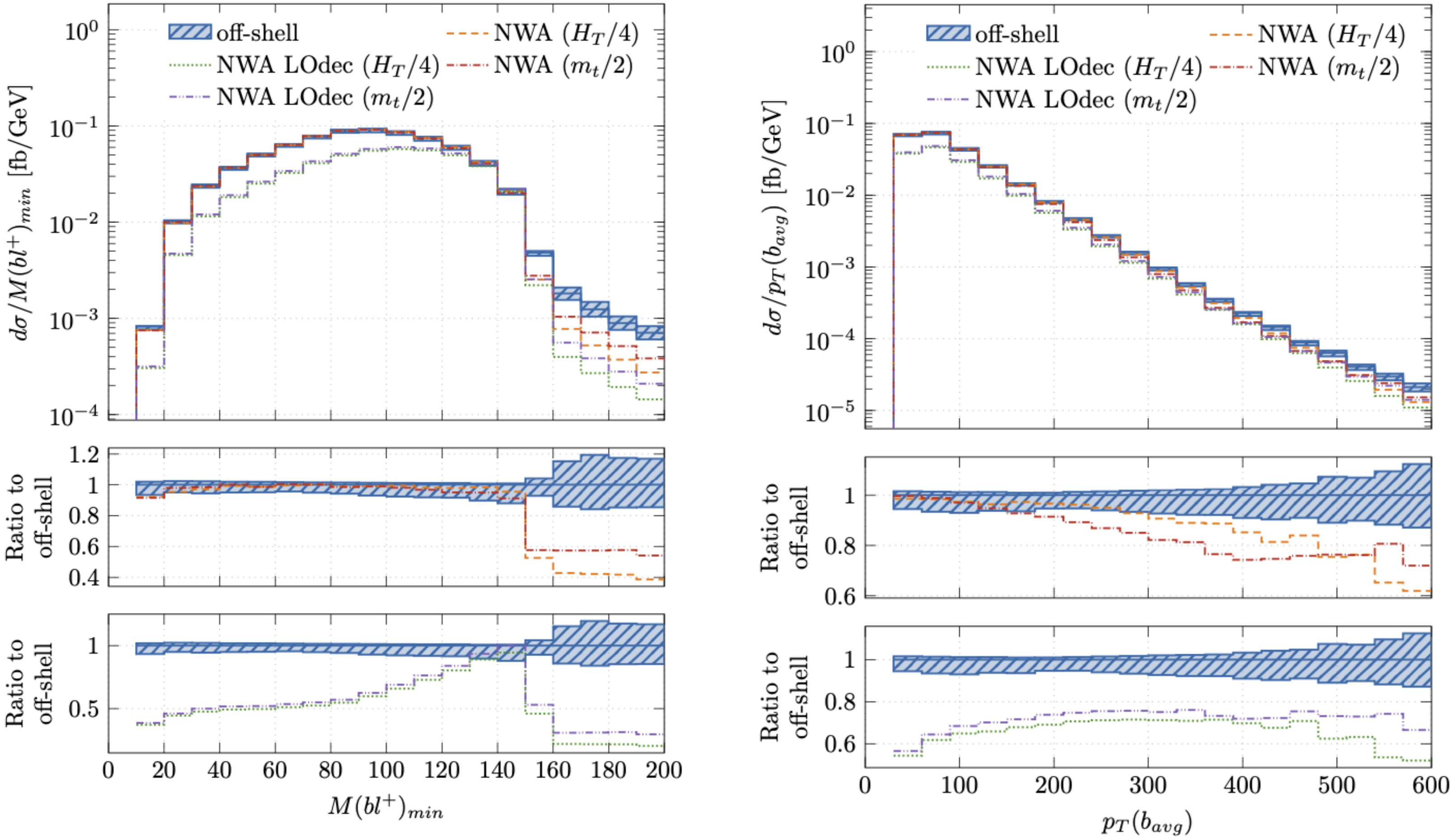
Differential level

- 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

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



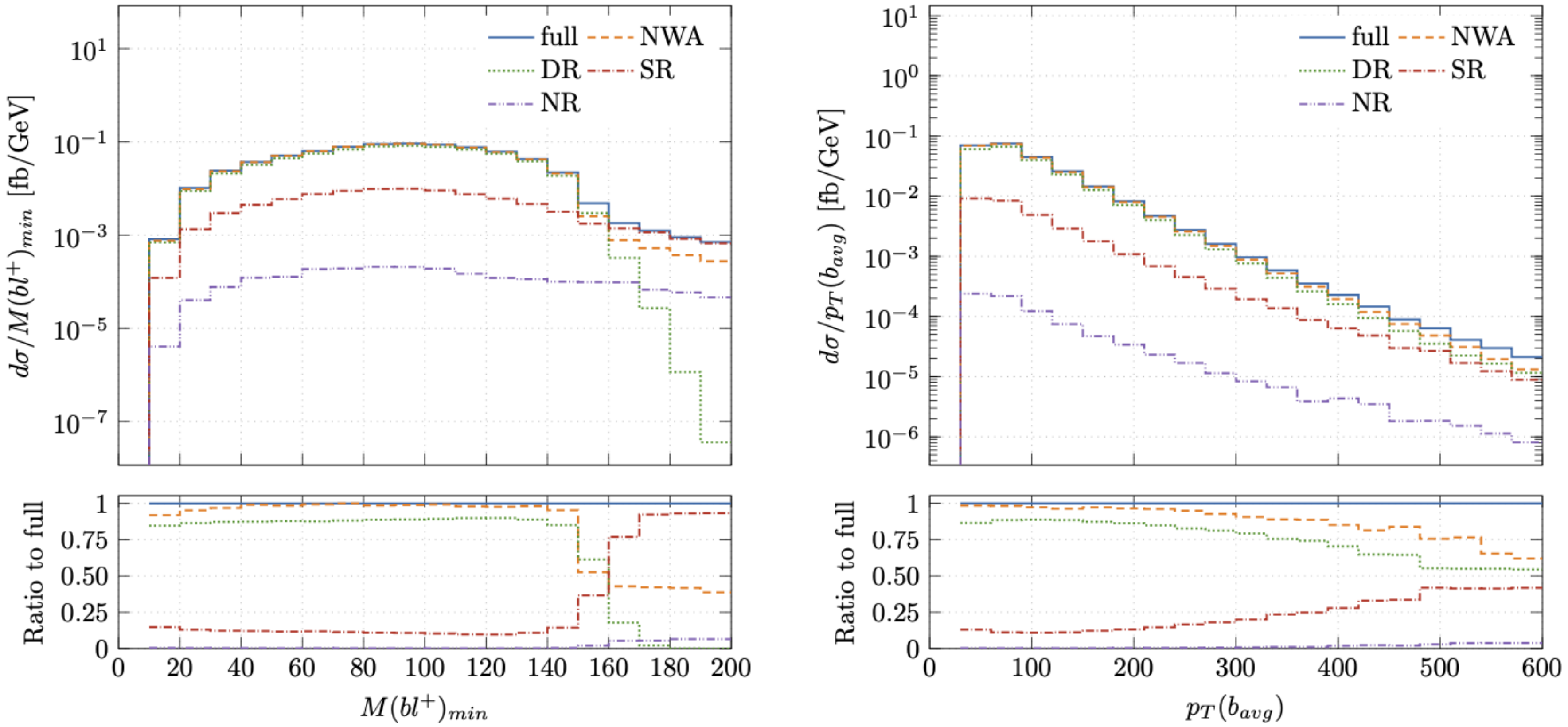
Dimensionful observables

- 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



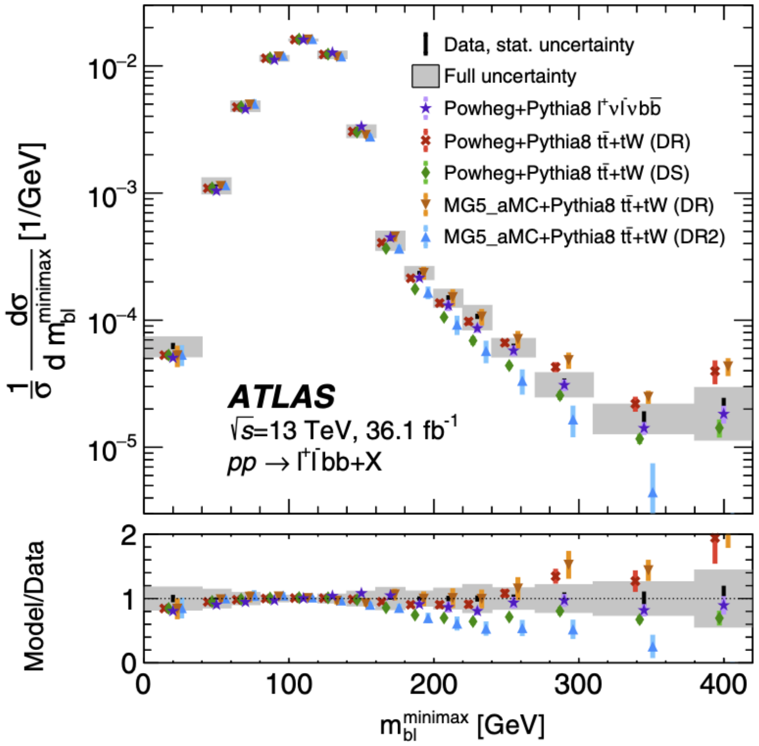
Dimensionful observables

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

Competing Effects

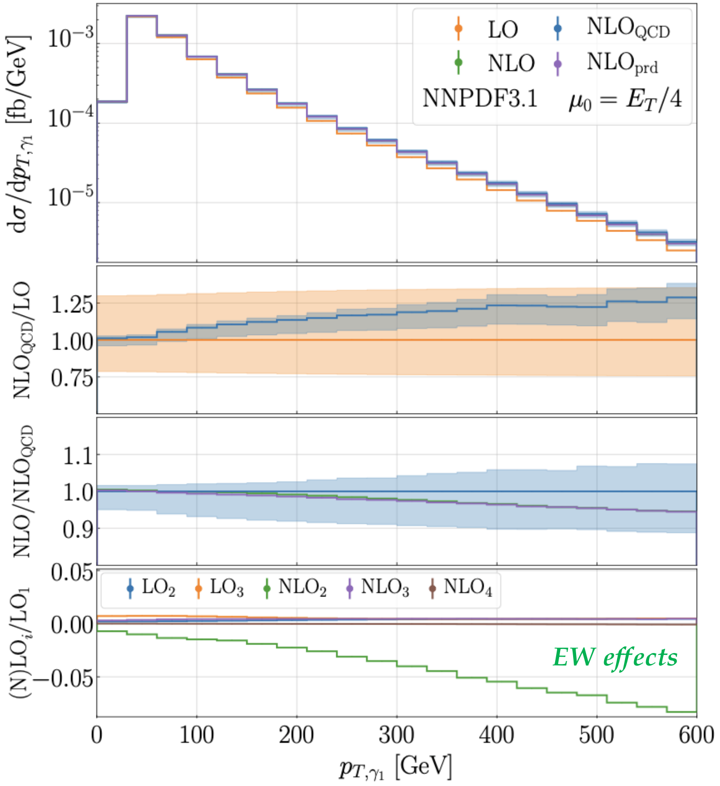
$pp \to \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b \bar{b}(\gamma)$

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

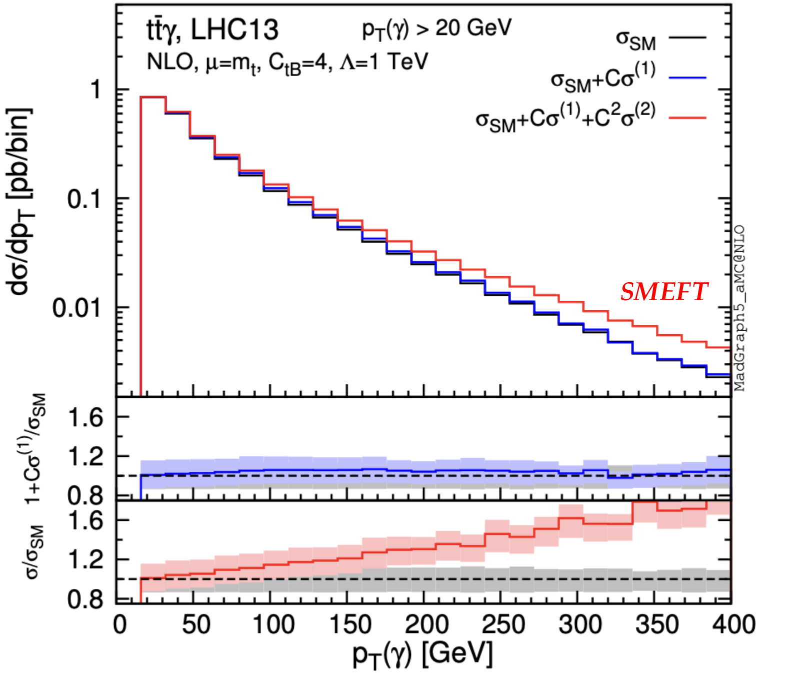


bb4l versus standard MC

Stremmer, Worek, JHEP 07 (2024) 091



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



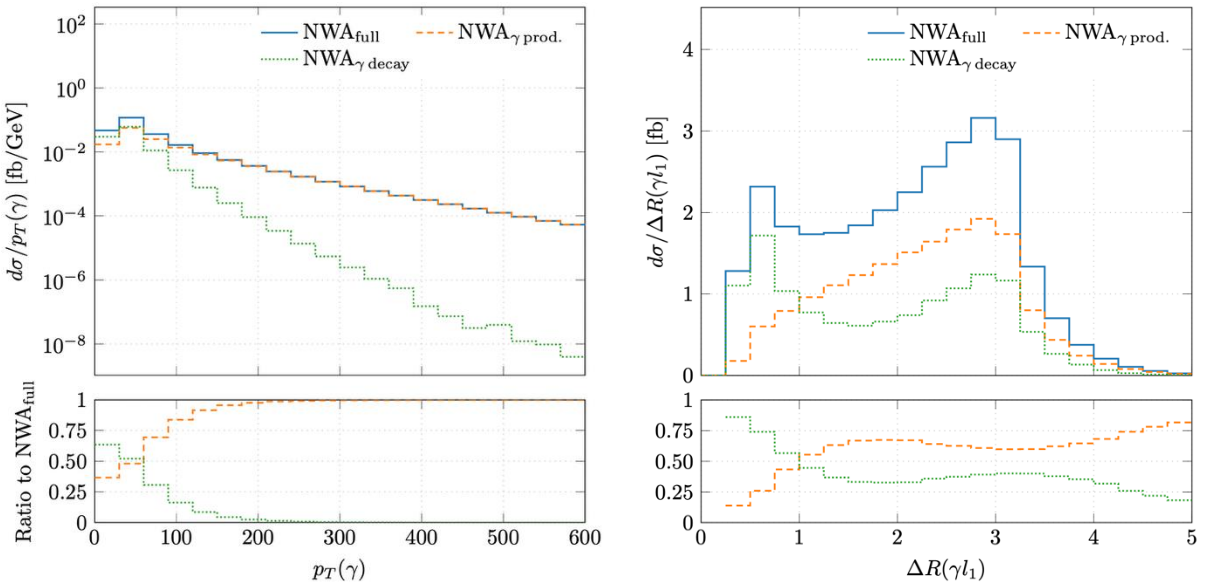
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

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

Photon in Production & Decays

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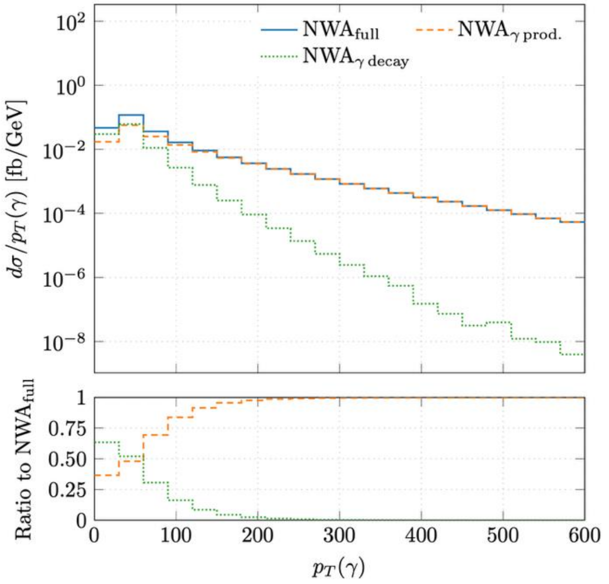
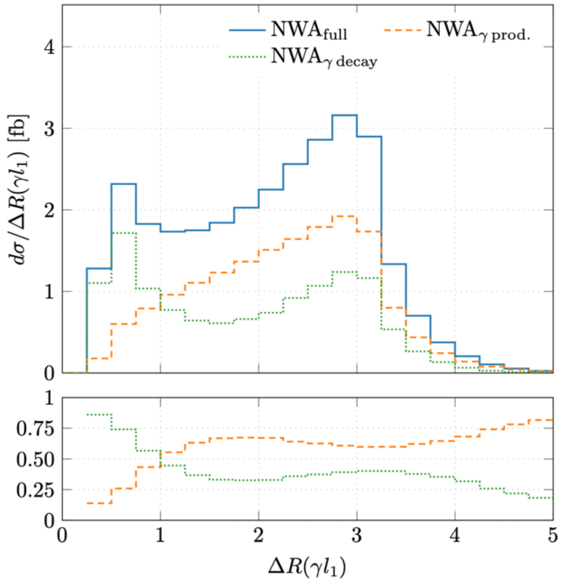
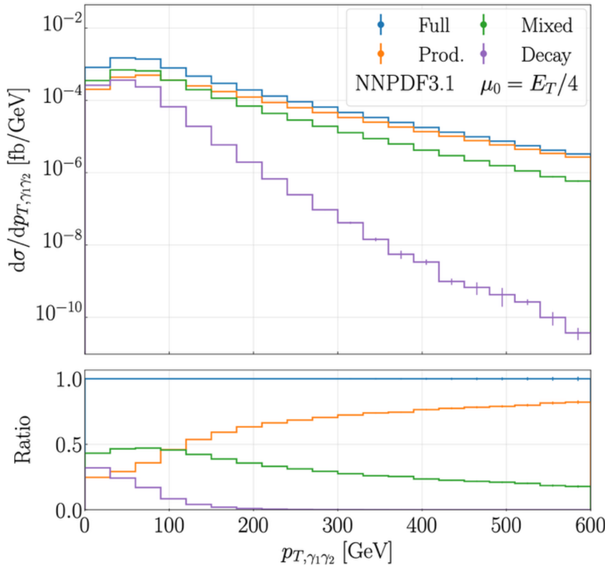


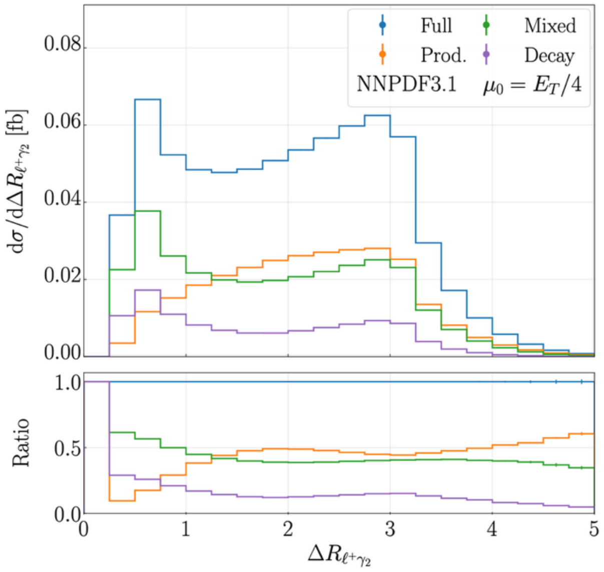


Bevilacqua, Hartanto, Kraus, Weber, Worek, JHEP 03 (2020) 154
Stremmer, Worek, JHEP 08 (2023) 179

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

- 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

Application: 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 cross-section 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*

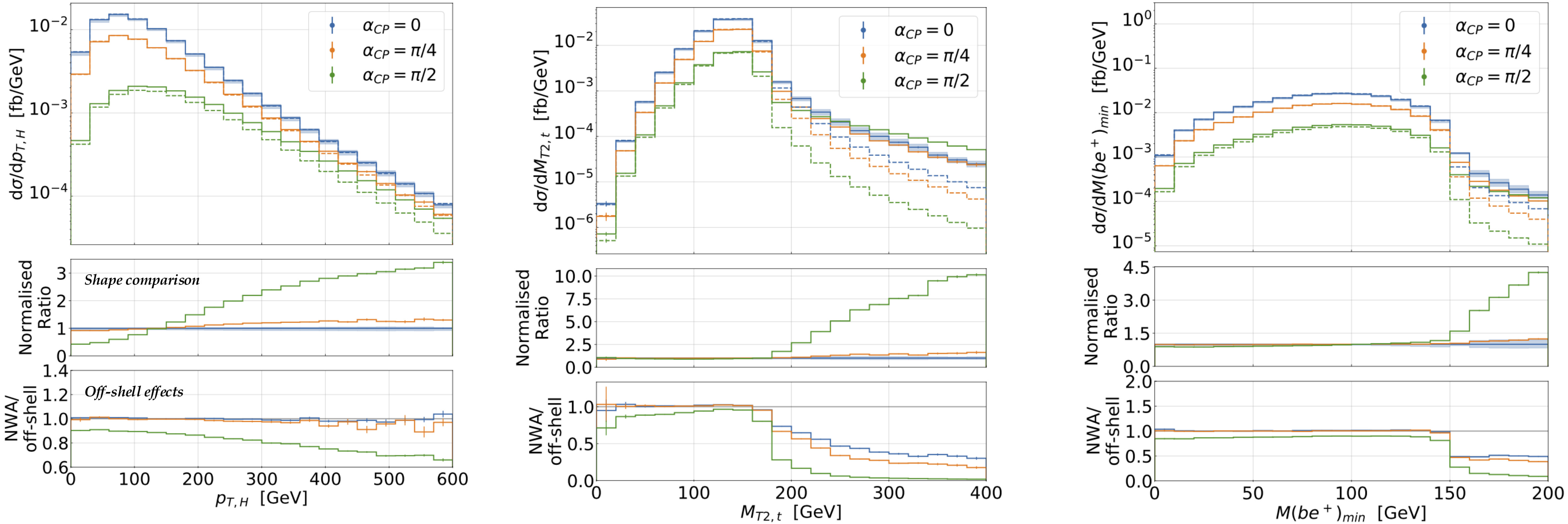
$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right) H,$$

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: Yukawa Coupling

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



- *CP-even*
- *CP-mixed*
- *CP-odd*
- Solid line full off-shell results, dashed line NWA

- Off-shell effects @ differential fiducial cross-section 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*

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

Application: Top Quark Mass

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

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: JHEP

CERN-EP-2025-135
4th July 2025

arXiv:2507.02632v1 [hep-ex] 3 Jul 2025

Measurement of the top-quark pole mass in dileptonic $t\bar{t}$ + 1-jet events at $\sqrt{s}$ = 13 TeV with the ATLAS experiment

The ATLAS Collaboration

A measurement of the top-quark pole mass m_t^{pole} is presented in $t\bar{t}$ events with an additional jet, $t\bar{t}$ + 1-jet, produced in pp collisions at $\sqrt{s}$ = 13 TeV. The data sample, recorded with the ATLAS experiment during Run 2 of the LHC, corresponds to an integrated luminosity of 140 fb^{-1}. Events with one electron and one muon of opposite electric charge in the final state are selected to measure the $t\bar{t}$ + 1-jet differential cross-section as a function of the inverse of the invariant mass of the $t\bar{t}$ + 1-jet system. Iterative Bayesian Unfolding is used to correct the data to enable comparison with fixed-order calculations at next-to-leading-order accuracy in the strong coupling. The process $pp \to t\bar{t}j$ ($2 \to 3$), where top quarks are taken as stable particles, and the process $pp \to b\bar{b}l^+\nu l^-\bar{\nu}j$ ($2 \to 7$), which includes top-quark decays to the dilepton final state and off-shell effects, are considered. The top-quark mass is extracted using a χ^2 fit of the unfolded normalized differential cross-section distribution. The results obtained with the $2 \to 3$ and $2 \to 7$ calculations are compatible within theoretical uncertainties, providing an important consistency check. The more precise determination is obtained for the $2 \to 3$ measurement: $m_t^{\text{pole}} = 170.7 \pm 0.3$ (stat.) $\pm$ 1.4 (syst.) $\pm$ 0.3 (scale) $\pm$ 0.2 (PDF $\oplus\, \alpha_s$) GeV, which is in good agreement with other top-quark mass results.

Bevilacqua, Hartanto, Kraus, Worek, Phys. Rev. Lett. 116 (2016) 5, 052003
Bevilacqua, Hartanto, Kraus, Worek, JHEP 11 (2016) 098
Bevilacqua, Hartanto, Kraus, Schulze, Worek, JHEP 03 (2018) 169

$$\mathcal{R}(\rho_s; m_t^{\text{pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}, \text{ with } \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

- *$2 \to 3$:*

$$m_t^{\text{pole}} = 170.73 \pm 0.33\ (\text{stat.}) \pm 1.36\ (\text{syst.})\ ^{+0.34}_{-0.28}\ (\text{scale}) \pm 0.24\ (\text{PDF} \oplus \alpha_s)\ \text{GeV}.$$

- *$2 \to 7$:*

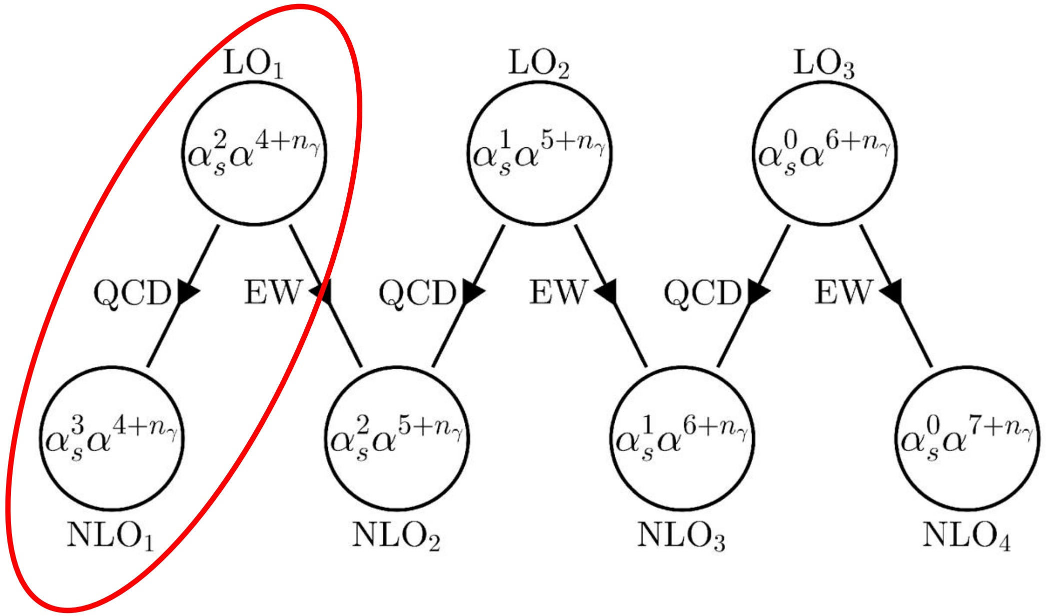
$$m_t^{\text{pole}} = 171.69 \pm 0.41\ (\text{stat.}) \pm 1.68 (\text{syst.})\ ^{+0.66}_{-1.34}\ (\text{scale})\ ^{+0.49}_{-0.46}\ (\text{PDF} \oplus \alpha_s)\ \text{GeV}.$$

- *Central value of $2 \to 7$ result is approximately 1 GeV higher than for $2 \to 3$ case*
- Difference is covered by scale uncertainties of theoretical prediction
- *Theoretical error grows from 0.3 − 0.4 GeV in $2 \to 3$ to 1 GeV in $2 \to 7$*

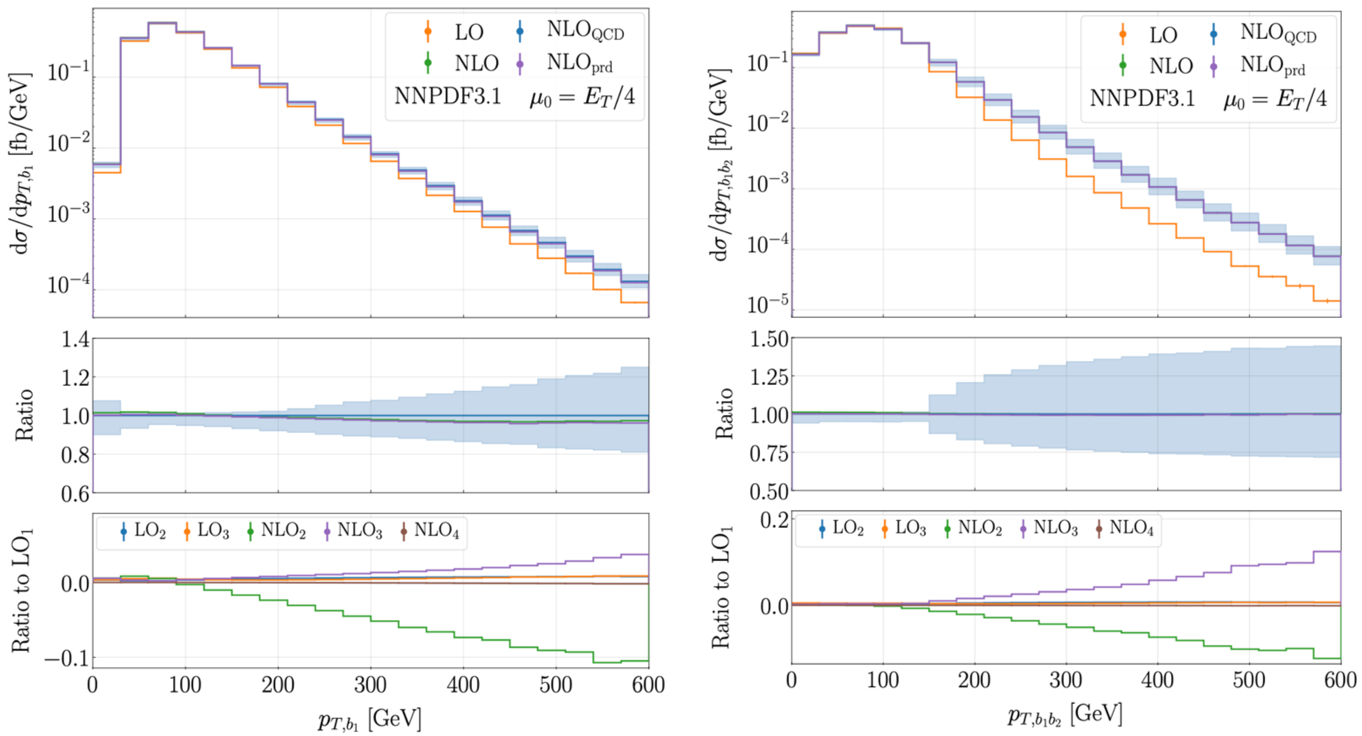
Part II – Fixed-Order Predictions: Complete NLO

Complete NLO Corrections

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



		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



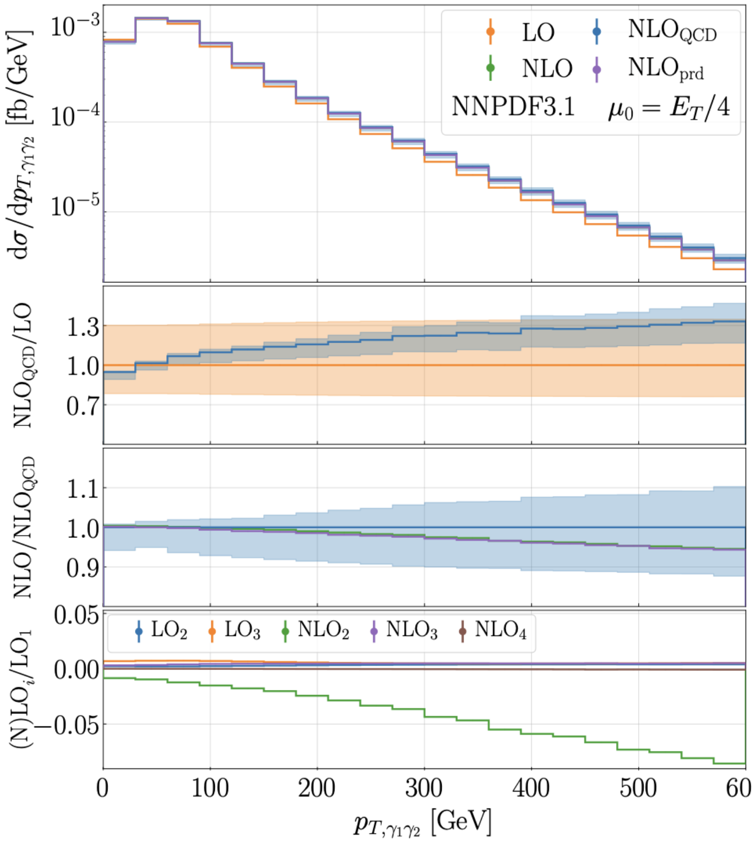
Stremmer, Worek, JHEP 07 (2024) 091

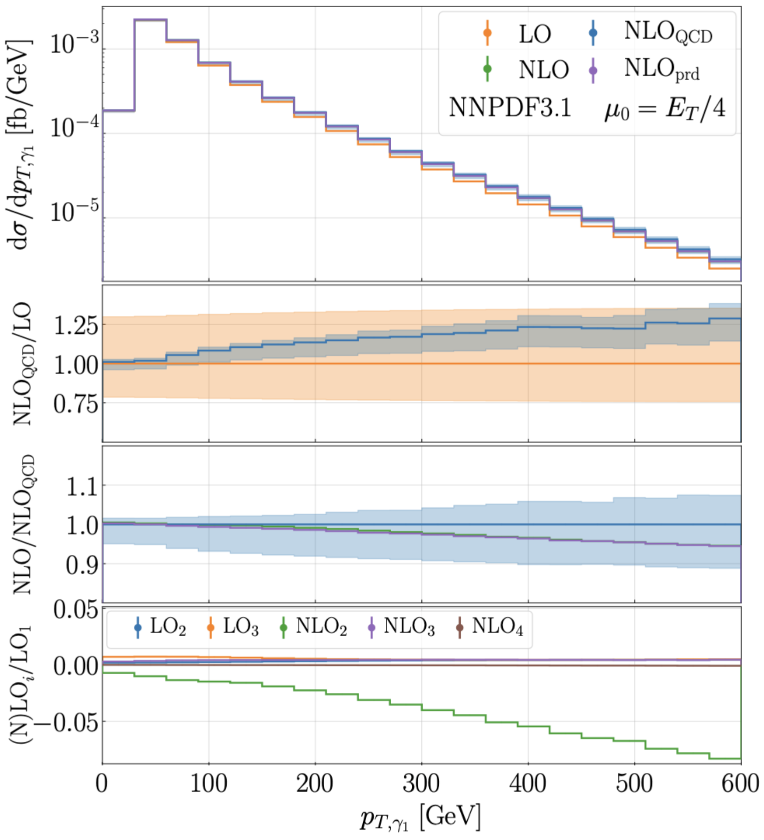
- EW Sudakov logarithms in **NLO$_2$** leads to reduction in tails of up to ***10%*** compared to **NLO$_{\rm QCD}$** result
- Accidental cancellations between **NLO$_2$ & NLO$_3$** → Should be considered together
- **NLO$_{\rm prd}$** approximation models complete **NLO** result very well

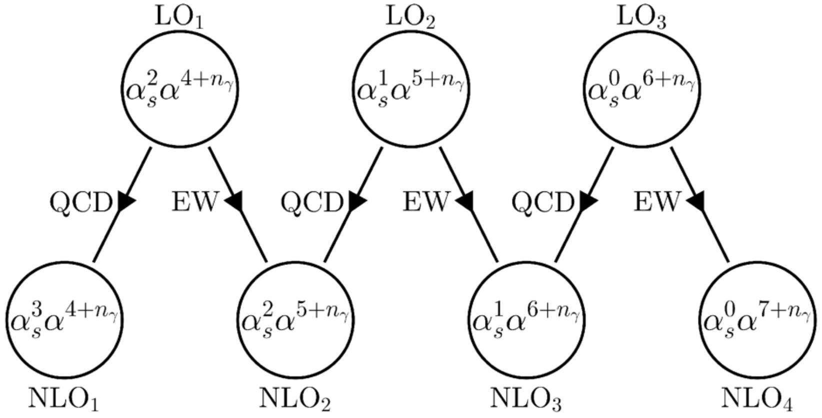
$$\text{NLO}_{\rm prd} = \text{LO}_1 + \text{LO}_2 + \text{LO}_3 + \text{NLO}_1 + \text{NLO}_{2,\rm prd} + \text{NLO}_{3,\rm prd} + \text{NLO}_{4,\rm prd}$$

Complete NLO Corrections

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







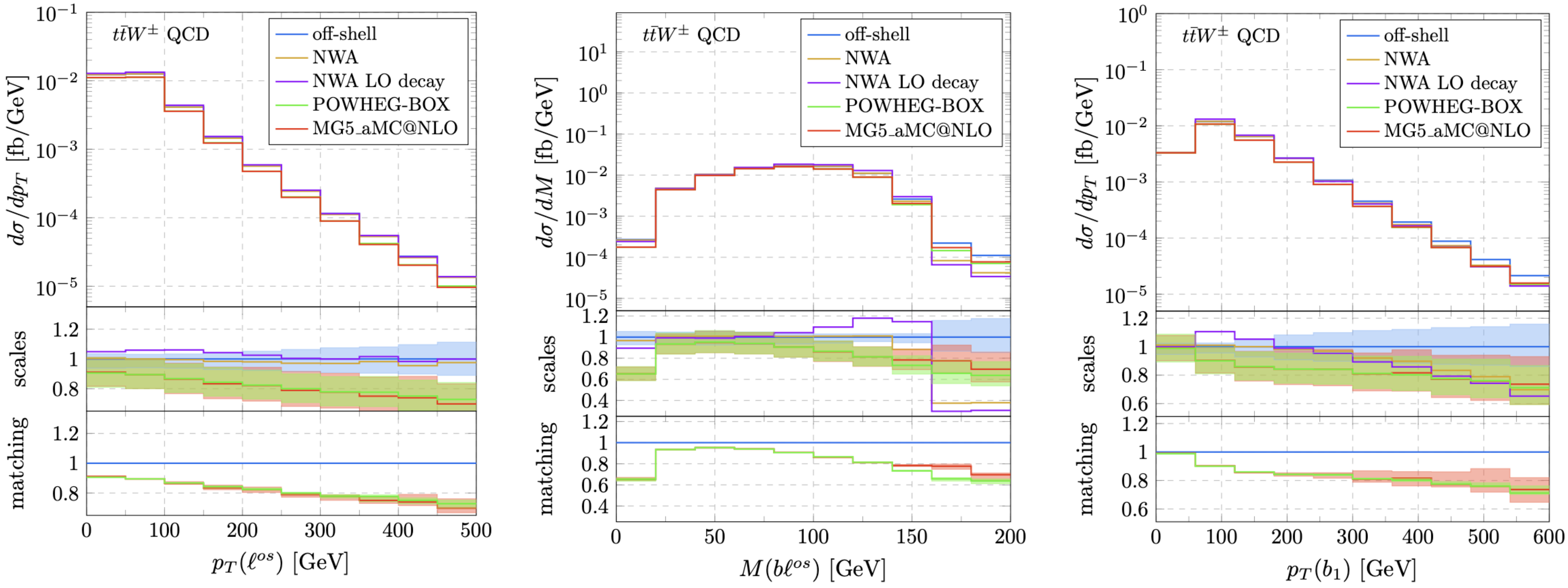
Stremmer, Worek, JHEP 07 (2024) 091

Part III – Parton-Shower Based Predictions: NLO QCD + PS

Fixed Order versus Parton-Shower

- l^{os} → Opposite-Sign lepton

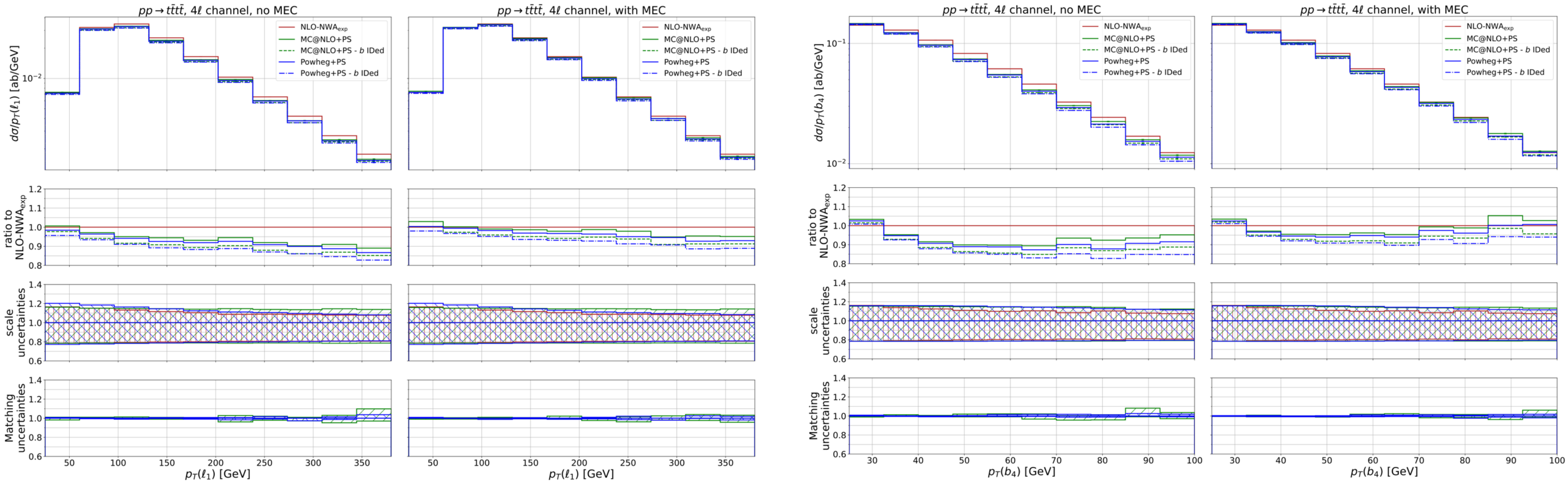
$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$



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

Fixed Order versus Parton-Shower with MEC

$$pp \to l^+\nu_l l^-\bar{\nu}_l l^+\nu_l\, l^-\bar{\nu}_l b\bar{b}b\bar{b}$$



- Emission in $t \to bW$ decay is corrected by means of $t \to bWg$ tree-level matrix element

Alsairafi, Dimitrakopoulos, Worek, e-Print: 2507.04849 [hep-ph]

Various Theoretical Predictions

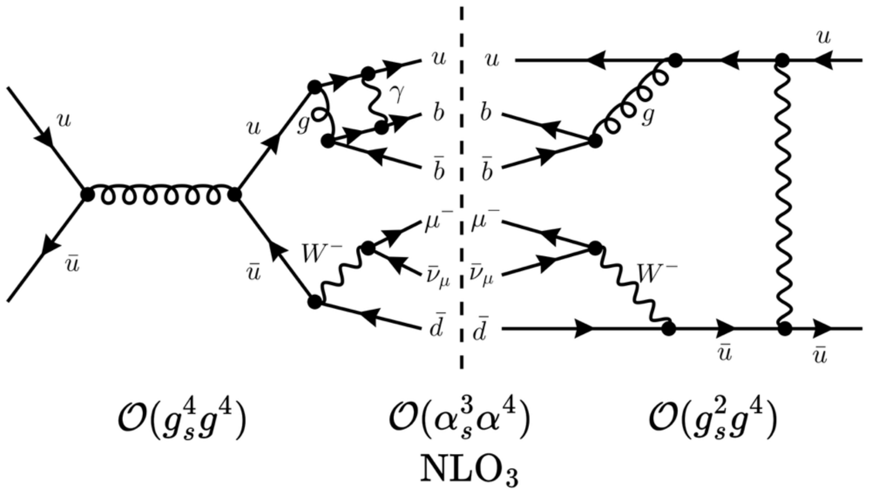
- **Full Off-Shell $pp \to tt$+X versus On-Shell $pp \to tt$+X + $pp \to tWb$+X**
  - Coherent sum versus incoherent sum
  - Comparison of various approaches important
  - Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators
  - NWA = DR restricts unstable *t & W* to on-shell states
  - Parton-shower based predictions = *$pp \to tt$ + X* production @ NLO + LO decays with spin correlations
    - ✓ *Spin correlations important to probe new physics scenarios*

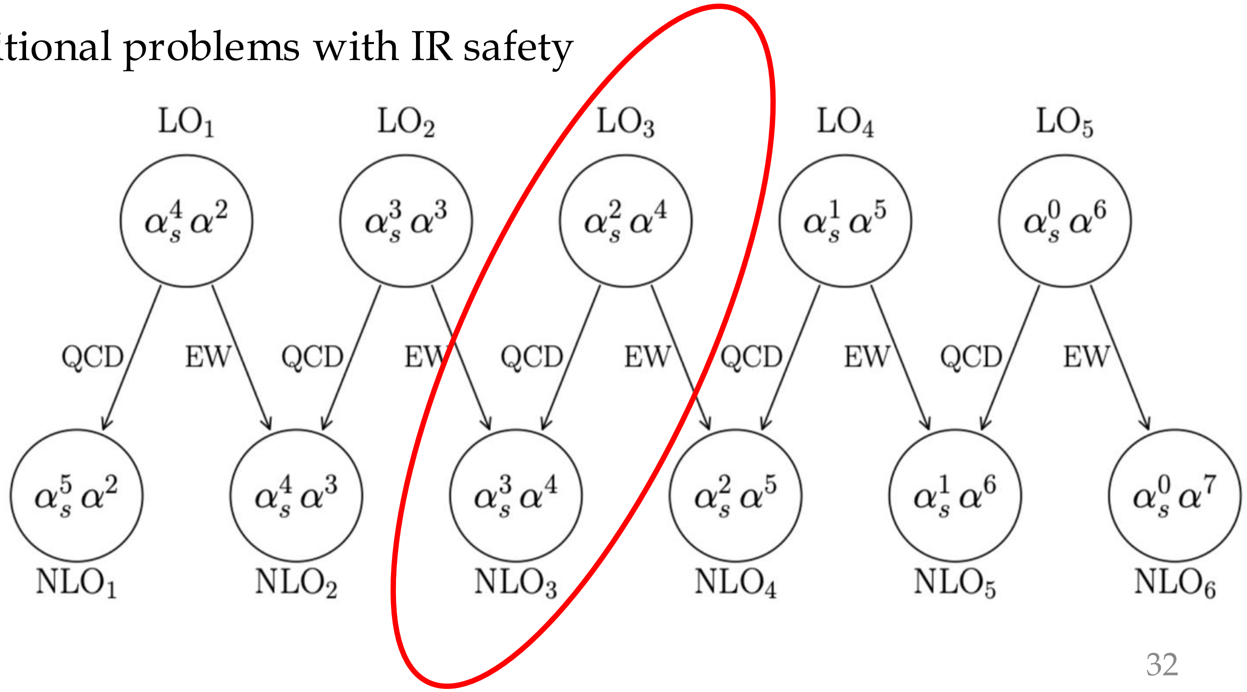
- **Understand various theoretical approaches is important as they can impact:**
  - IR-safe (integrated) cross sections: Normalisation
  - IR-safe (differential) cross section distributions: Shape of distributions
  - SM parameter extraction: m_t & Γ_t
  - SM observables: Top Charge Asymmetry
  - BSM 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 → *$pp \to ttH$* 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

Open Questions & Problems

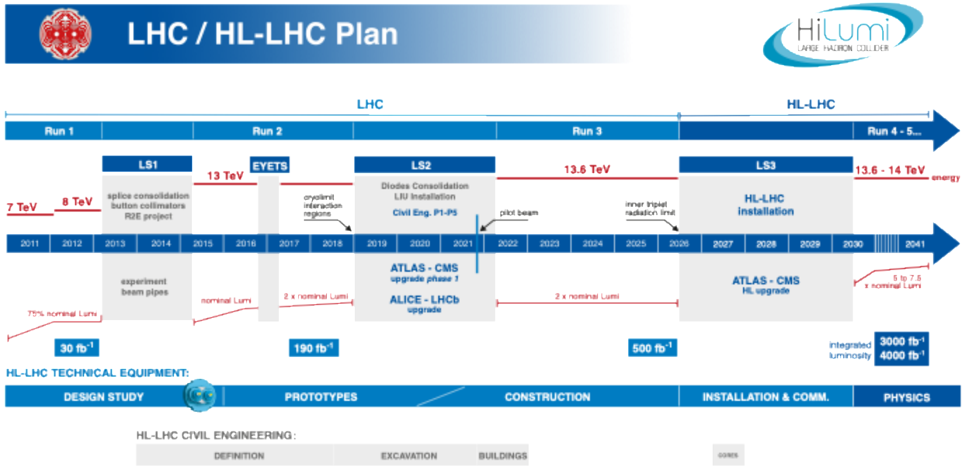
- Full Off-Shell Predictions: $pp \to t\bar{t}$ & $t\bar{t} + X,\ X = H, \gamma, W^{\pm}(\to \ell\nu_\ell), Z(\to \nu_\ell\bar{\nu}_\ell), Z(\to \ell\ell), j, b\bar{b}, W^{\pm}j$
  - *Multilepton final states only*
  - Combined NLO EW & NLO QCD results as well as complete NLO predictions only for a few selected cases
  - Matching to PS for *tt* production only → *bb4l* & only with Powheg
  - Time-consuming computations requiring large computer resources & storage
  - *l+j top-quark decay channel only for tt (?)* → Additional problems with IR safety
  - *Fully hadronic final states are completely missing*

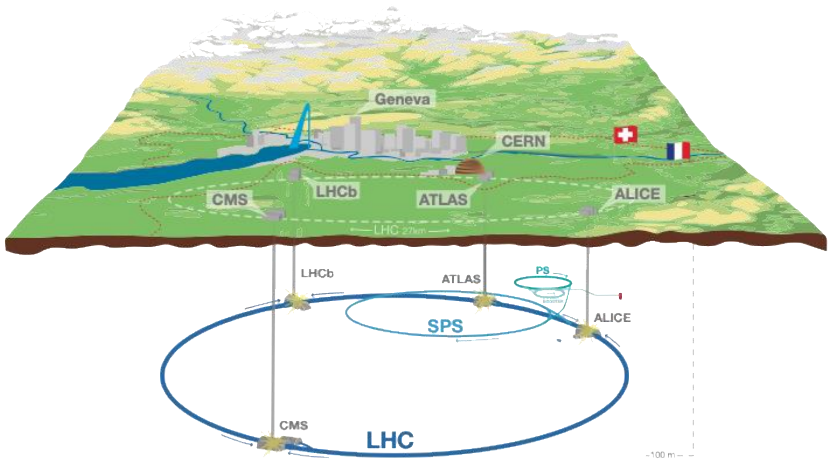
$pp \to \mu^-\bar{\nu}_\mu\, jj\, b\bar{b}$





Summary





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

- 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
    - ✓ EW higher-order corrections
    - ✓ Subleading contributions
    - ✓ 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*

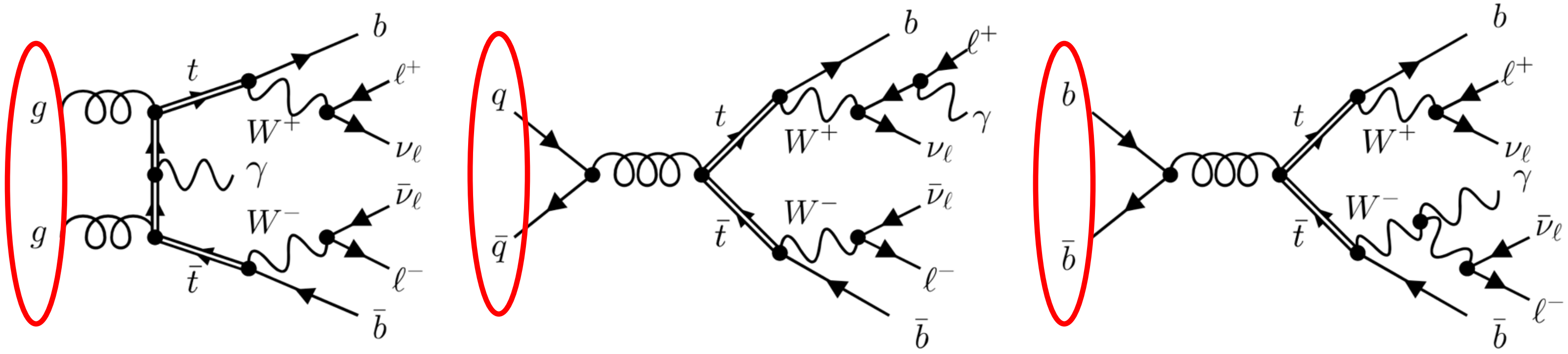
- **Even More Important for**
  - Exclusive phase-space regions & HL-LHC
  - New Physics searches & Exclusion limits
  - SM parameter extraction & Various observables

Backup

Definition of LO$_1$

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

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



- Typical QCD production of top-quark pair with photons with following partonic subprocesses

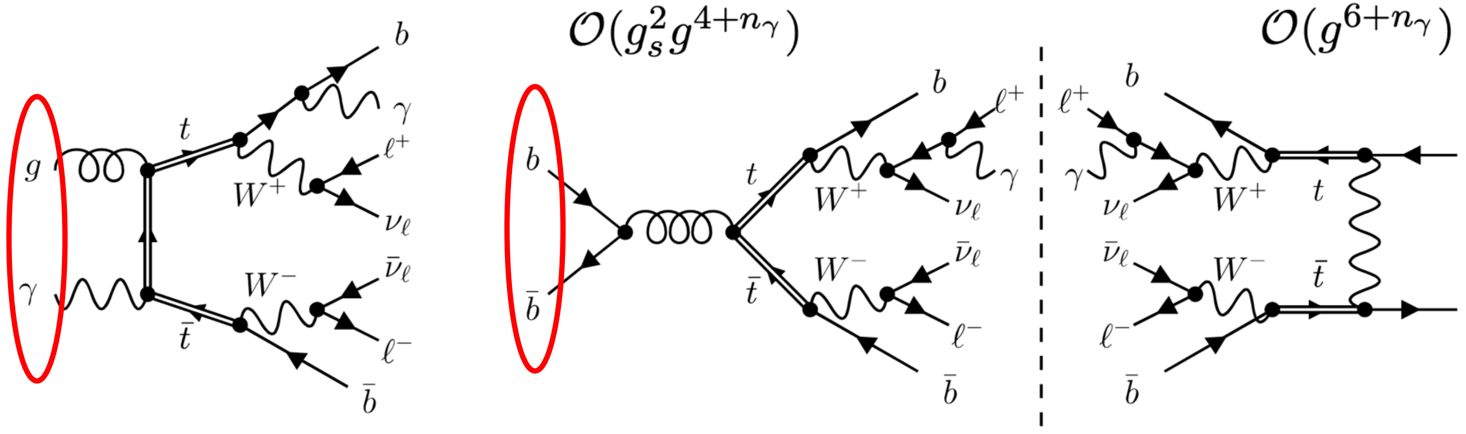
$gg \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$
$q\bar{q}/\bar{q}q \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,\qquad b\bar{b}/\bar{b}b \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,\gamma(\gamma)\,,$

Stremmer, Worek, JHEP 07 (2024) 091

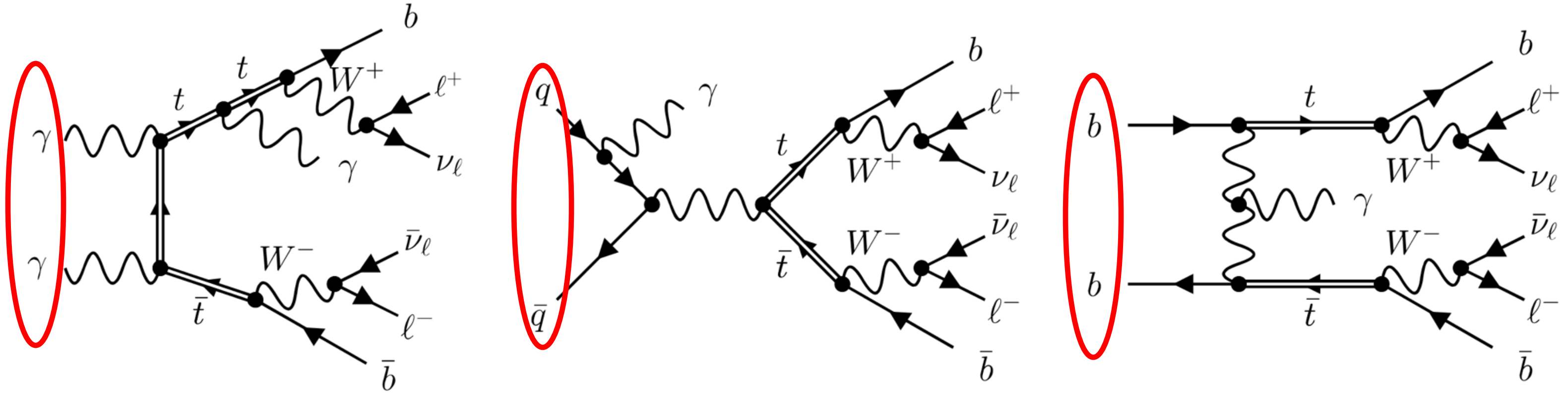
Definition of LO_2 & LO_3

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

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



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



- 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

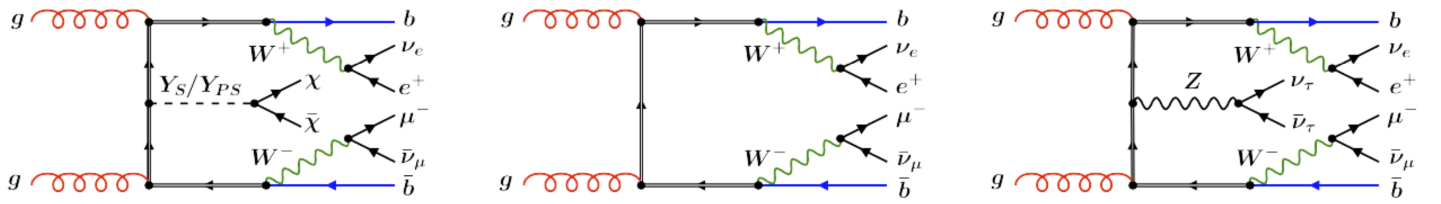
$$\mathrm{LO} = \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3$$

Application: BSM Exclusion Limits

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

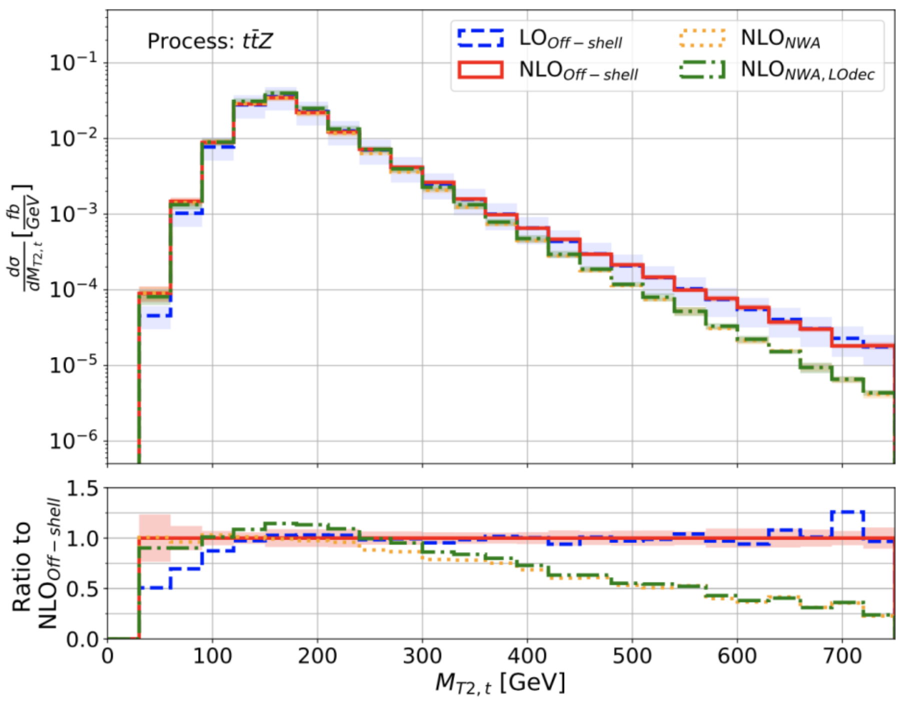
- BSM $\to$ Kinematical edges & high p_T regions
- $t\bar{t} + DM$ $\to$ Top quark backgrounds: $t\bar{t}$ & $t\bar{t}Z$
- Observable $\to$ $M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}

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



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

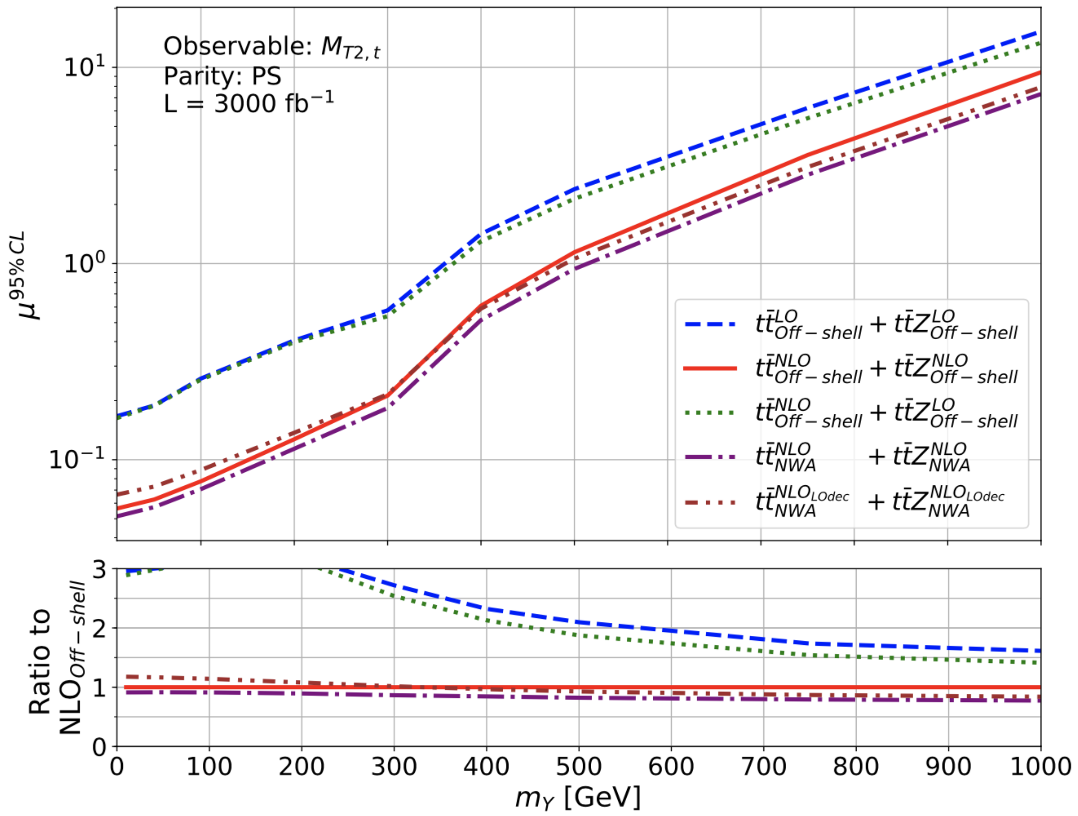
- After cuts 25% of events come from $t\bar{t}$
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

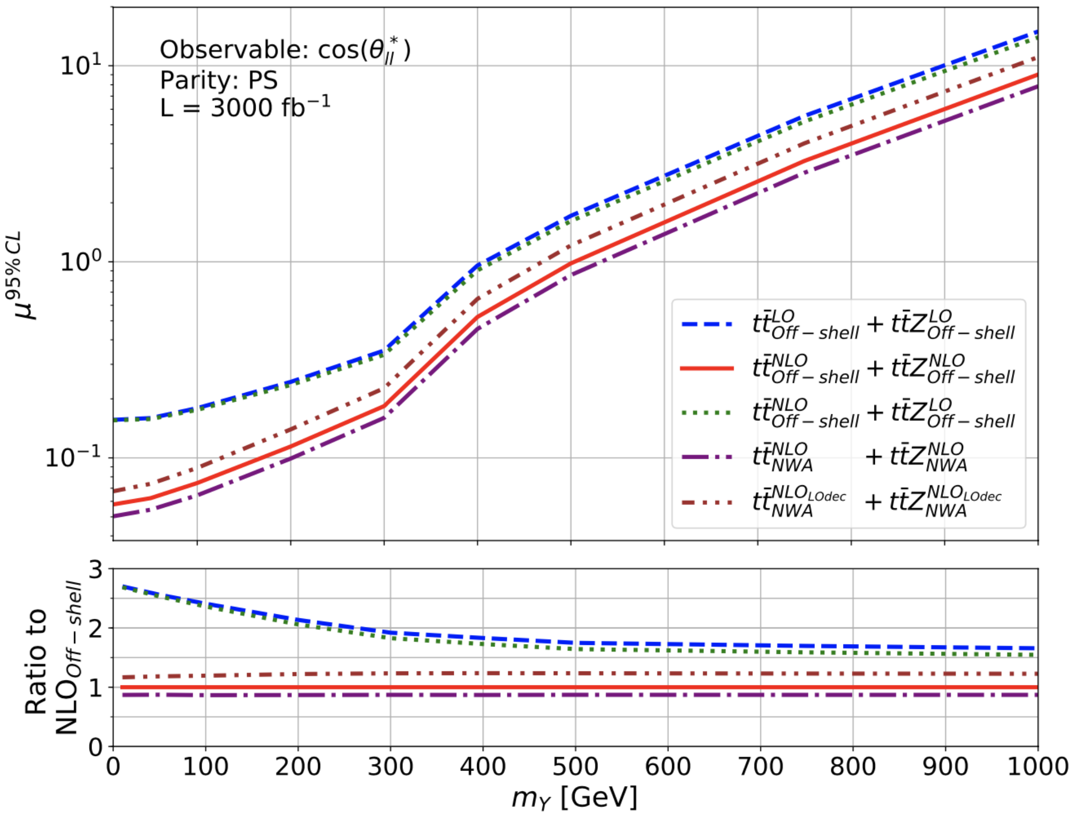
Application: BSM Exclusion Limits

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

- Comparison of signal strength exclusion limits

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





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

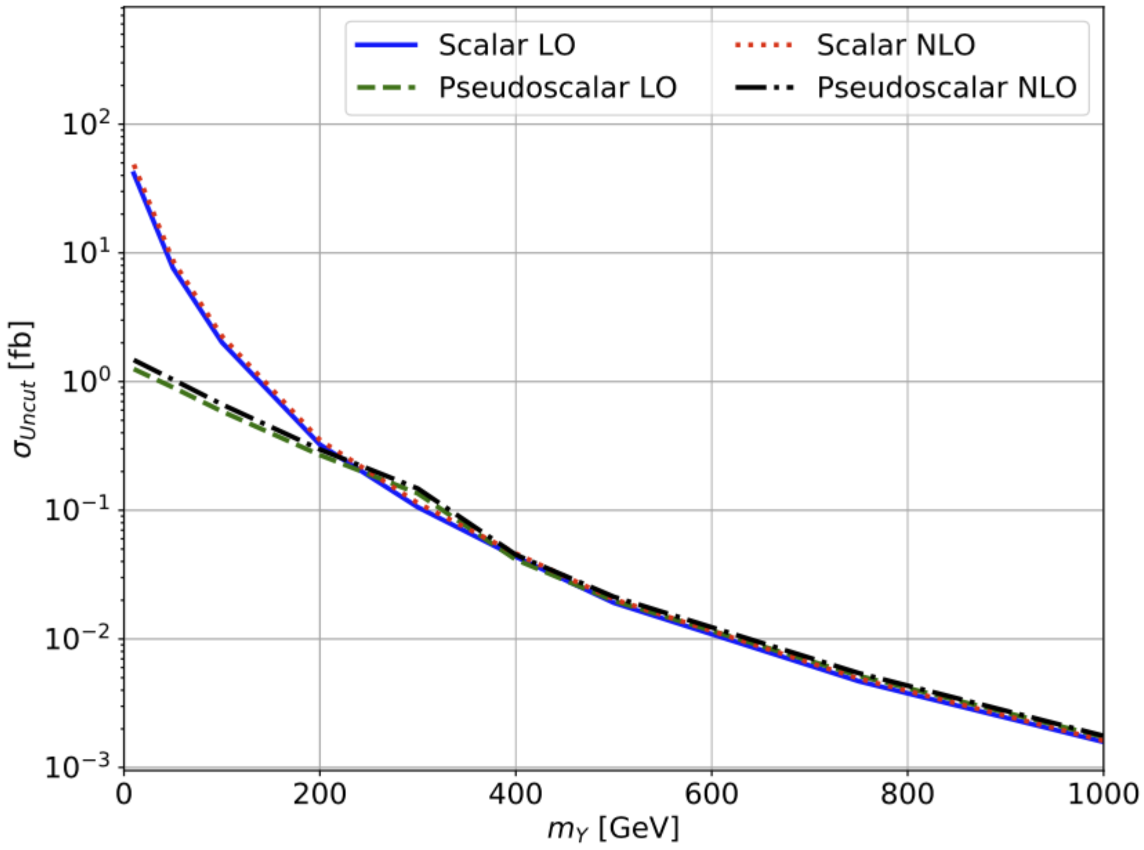
$$\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$$

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

Application: Yukawa Coupling

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

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

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

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

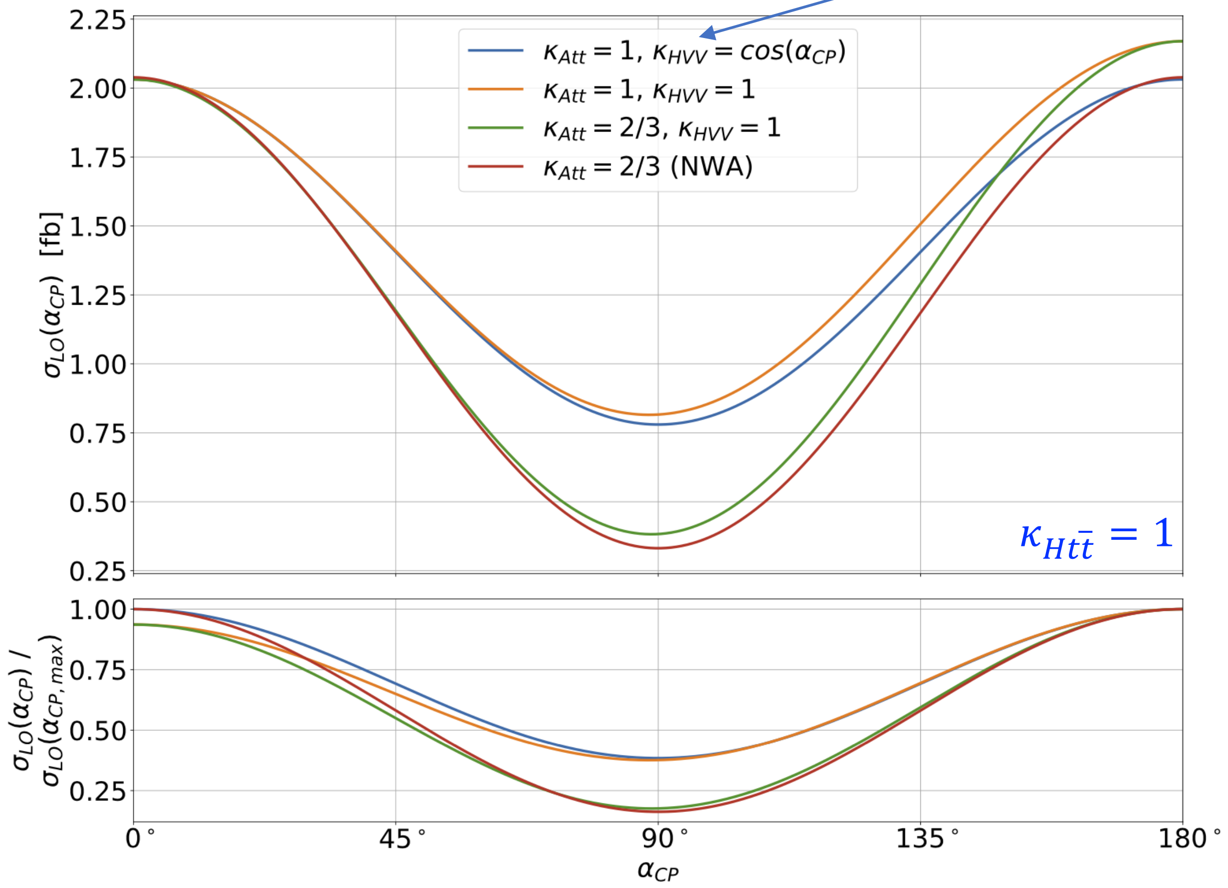
Dawson, Reina, Phys. Rev. D 57 (1998) 5851

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

Application: Yukawa Coupling

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

CP-conserving 2HDM



- Cross sections in NWA symmetric with respect to $\alpha_{CP} \to \pi - \alpha_{CP}$
- Equivalent to changing sign of Y_t
- In full off-shell case symmetry is present if we set $\kappa_{HVV}(\alpha_{CP}) = \cos(\alpha_{CP})$
- Symmetry is broken if we take $\kappa_{HVV} = 1$
- *Interference:* Higgs boson radiated off *W/Z* ⇨ *SR & NR* ⇨ Higgs boson emitted top quarks ⇨ *DR & SR*

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

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

Application: Top Quark Charge Asymmetry

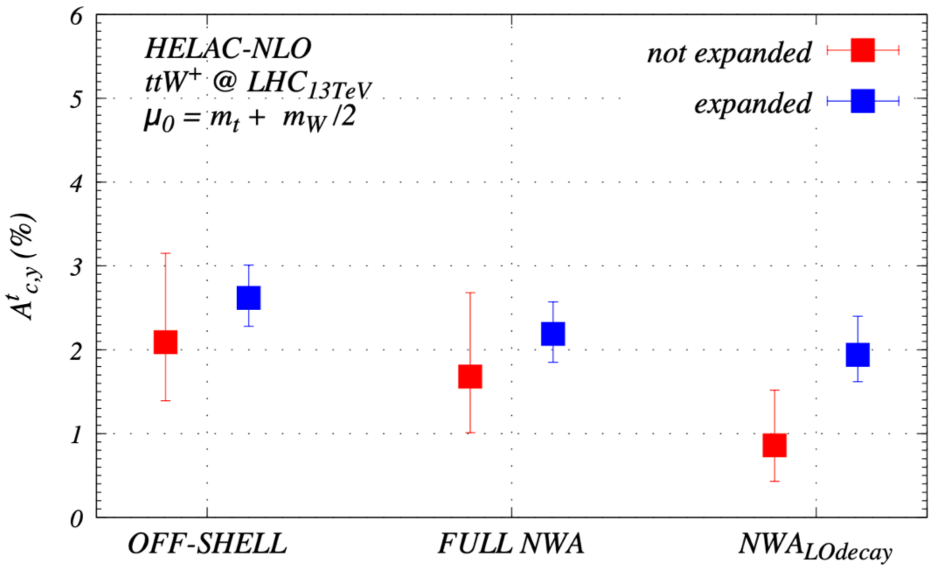
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$

Searching for more precise observables

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

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

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



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

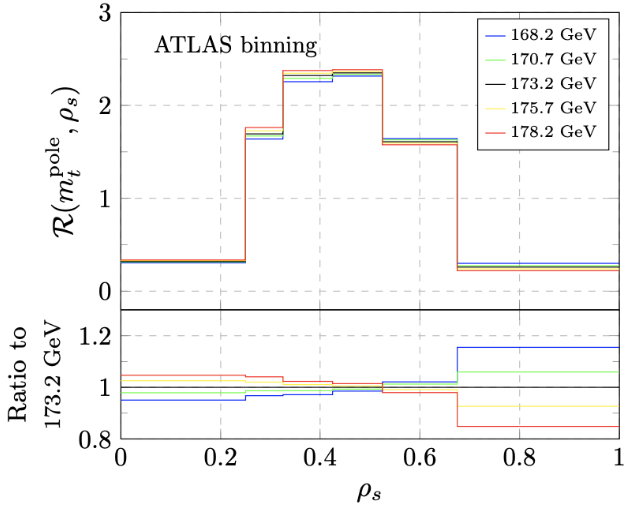
$t\bar{t}W^+$ $\mu_0 = H_T/3$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.36(8)^{+1.19\,(50\%)}_{-0.77\,(33\%)}$	$1.93(5)^{+1.23\,(64\%)}_{-0.72\,(37\%)}$	$1.11(3)^{+0.55\,(49\%)}_{-0.53\,(48\%)}$
$A^t_{c,exp,y}$ [%]	$2.66(10)^{+0.38\,(14\%)}_{-0.34\,(13\%)}$	$2.20(5)^{+0.45(20\%)}_{-0.31(14\%)}$	$2.08(5)^{+0.24\,(11\%)}_{-0.40\,(19\%)}$
$t\bar{t}W^+$ $\mu_0 = m_t + m_W/2$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.09(8)^{+1.06\,(51\%)}_{-0.70\,(33\%)}$	$1.68(4)^{+1.00(60\%)}_{-0.67(40\%)}$	$0.86(3)^{+0.66\,(77\%)}_{-0.43\,(50\%)}$
$A^t_{c,exp,y}$ [%]	$2.62(10)^{+0.39\,(15\%)}_{-0.34\,(13\%)}$	$2.19(4)^{+0.38(17\%)}_{-0.34(16\%)}$	$1.94(5)^{+0.46\,(24\%)}_{-0.32\,(16\%)}$

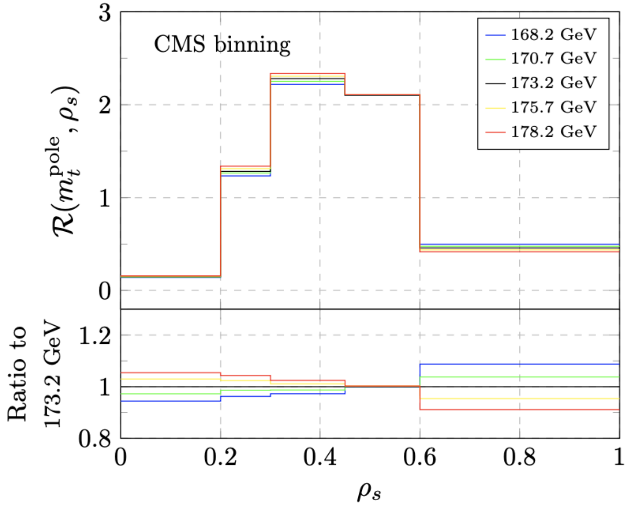
- A_c^t charge asymmetry @ NLO for $pp \to t\bar{t}W^+$

Application: Top Quark Mass

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

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{pole}, \rho_s), \qquad \text{with} \qquad \rho_s = \frac{2m_0}{M_{t\bar{t}j}}$$





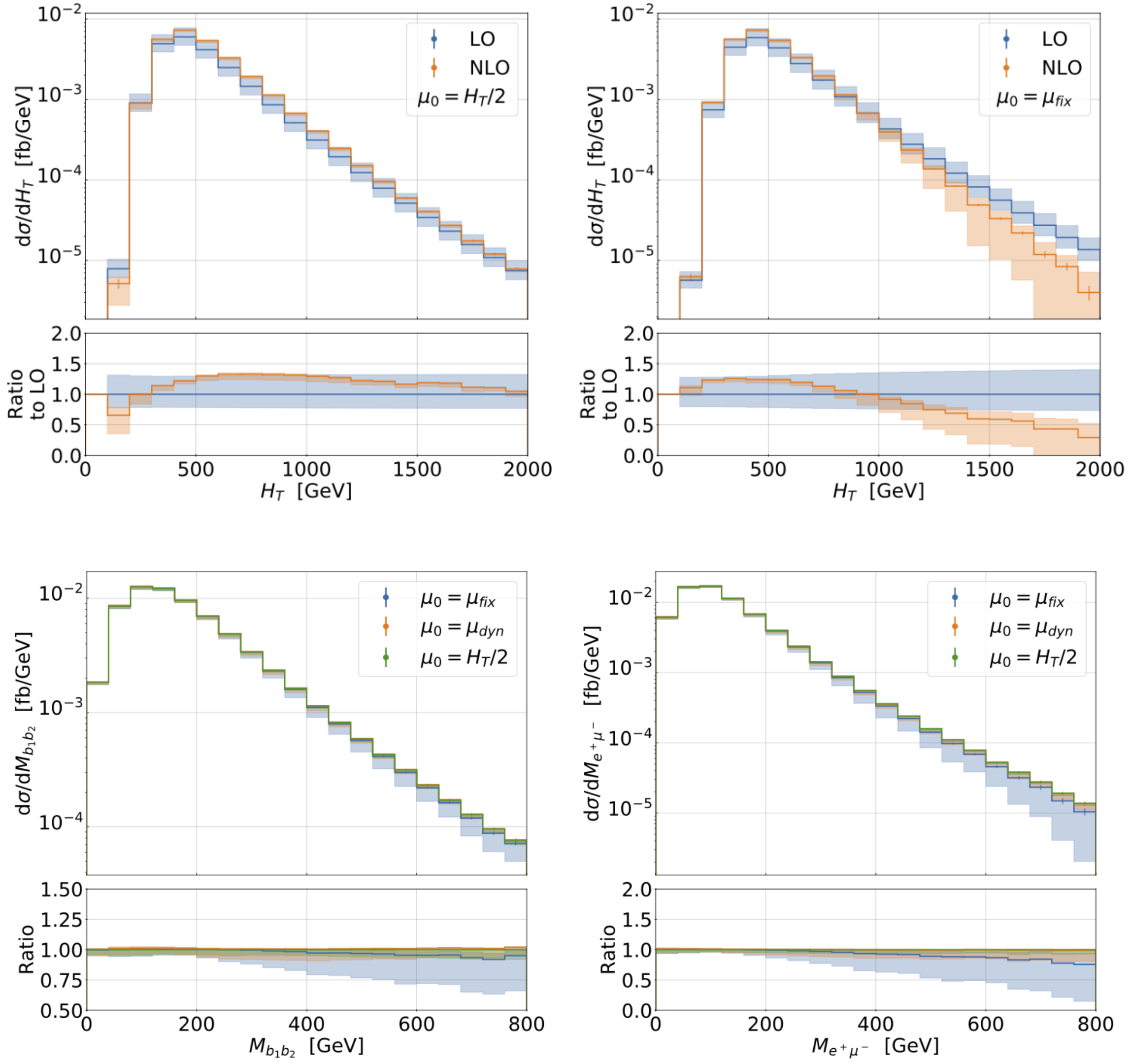
Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	173.76 ± 0.40	1.87	0.003 (3.0σ)	−0.56
NWA, $\mu_0 = m_t$	175.65 ± 0.31	2.99	$7 \cdot 10^{-8}$ (5.4σ)	−2.45
$NWA_{Prod.}$, $\mu_0 = m_t$	169.59 ± 0.30	3.10	$2 \cdot 10^{-8}$ (5.6σ)	+3.61
5 bins				
Full, $\mu_0 = H_T/2$	173.08 ± 0.40	0.94	0.44 (0.8σ)	+0.12
Full, $\mu_0 = E_T/2$	172.48 ± 0.38	1.58	0.18 (1.3σ)	+0.72
Full, $\mu_0 = m_t$	173.75 ± 0.40	6.76	$2 \cdot 10^{-5}$ (4.3σ)	−0.55
NWA, $\mu_0 = m_t$	175.49 ± 0.30	5.31	$2 \cdot 10^{-4}$ (3.7σ)	−2.29
$NWA_{Prod.}$, $\mu_0 = m_t$	169.39 ± 0.47	3.42	$8 \cdot 10^{-3}$ (2.6σ)	+3.81
ATLAS binning				
Full, $\mu_0 = H_T/2$	173.06 ± 0.44	0.97	0.44 (0.8σ)	+0.14
Full, $\mu_0 = E_T/2$	172.36 ± 0.44	1.38	0.23 (1.2σ)	+0.84
Full, $\mu_0 = m_t$	173.84 ± 0.42	5.12	$1 \cdot 10^{-4}$ (3.9σ)	−0.64
NWA, $\mu_0 = m_t$	175.23 ± 0.37	5.28	$7 \cdot 10^{-5}$ (4.0σ)	−2.03
$NWA_{Prod.}$, $\mu_0 = m_t$	169.43 ± 0.50	2.61	0.02 (2.3σ)	+3.77
CMS binning				
Full, $\mu_0 = H_T/2$	173.09 ± 0.50	0.96	0.43 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.22 ± 0.48	1.32	0.26 (1.1σ)	+0.98
Full, $\mu_0 = m_t$	174.02 ± 0.46	6.57	$3 \cdot 10^{-5}$ (4.2σ)	−0.82
NWA, $\mu_0 = m_t$	175.74 ± 0.34	6.00	$8 \cdot 10^{-5}$ (3.9σ)	−2.54
$NWA_{Prod.}$, $\mu_0 = m_t$	170.22 ± 0.53	2.19	0.07 (1.8σ)	+2.98

- Sensitivity to scale setting & top quark modelling

Bevilacqua, Hartanto, Kraus, Schulze, Worek, JHEP 03 (2018) 169

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

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

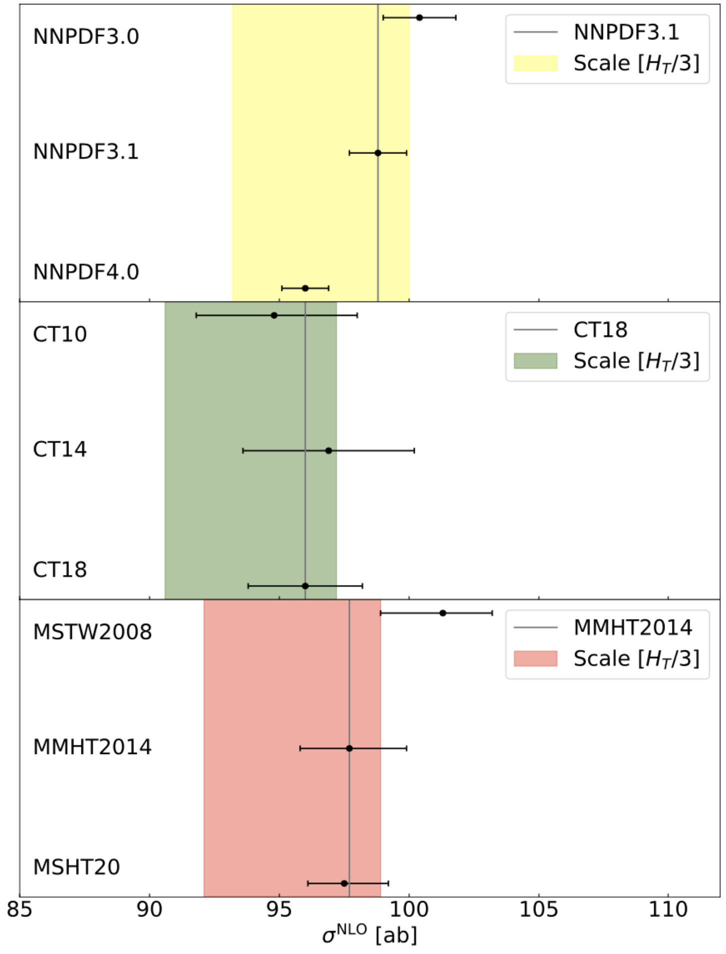
$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad m_T = \sqrt{m^2 + p_T^2}.$$

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

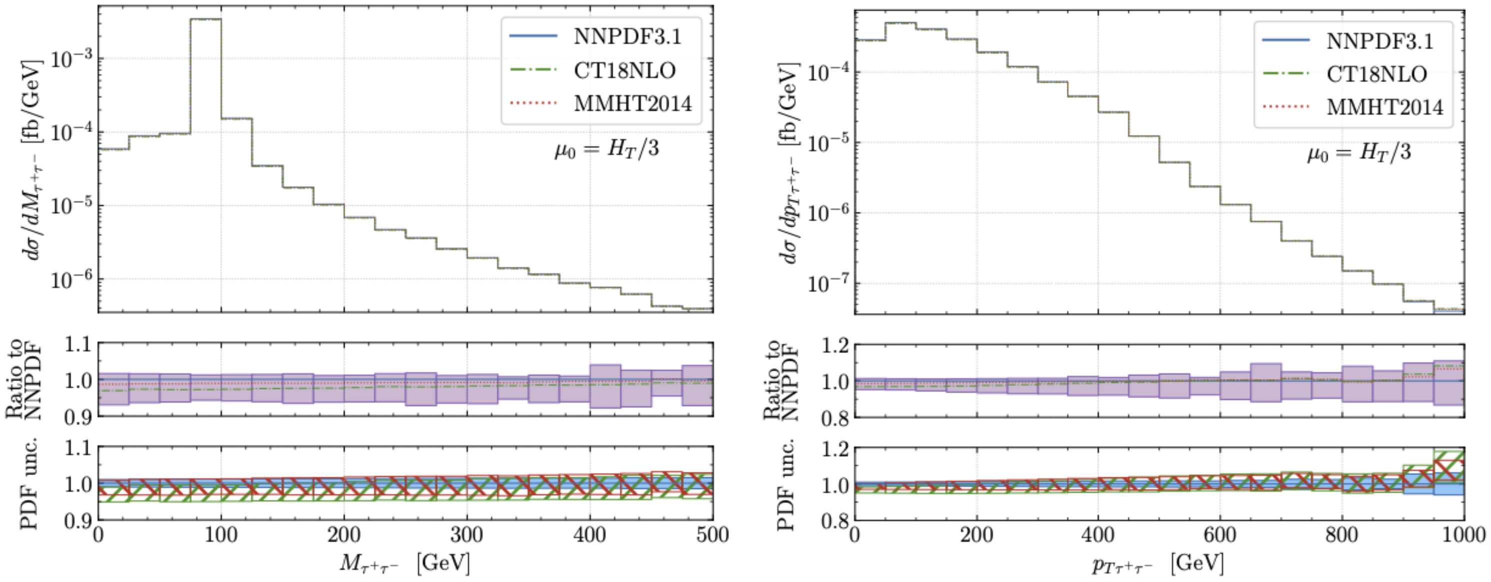
PDF Uncertainties

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

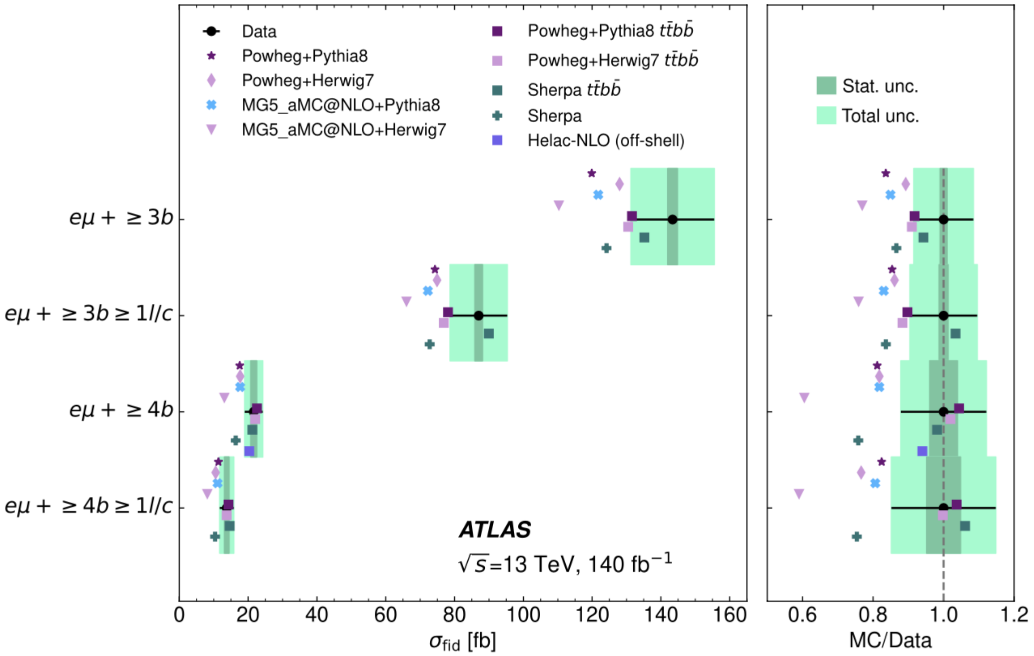


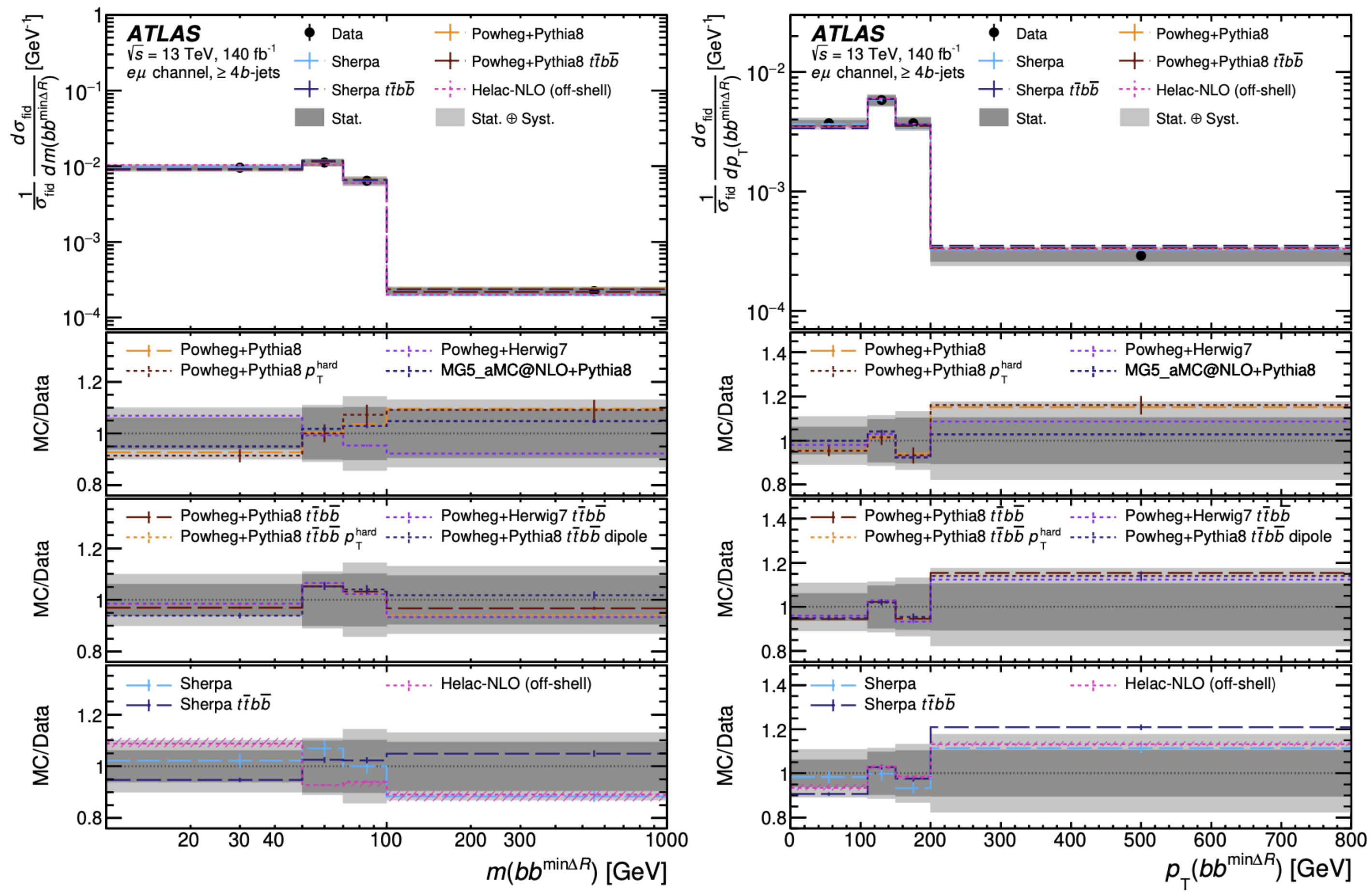
Differential level

- 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

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





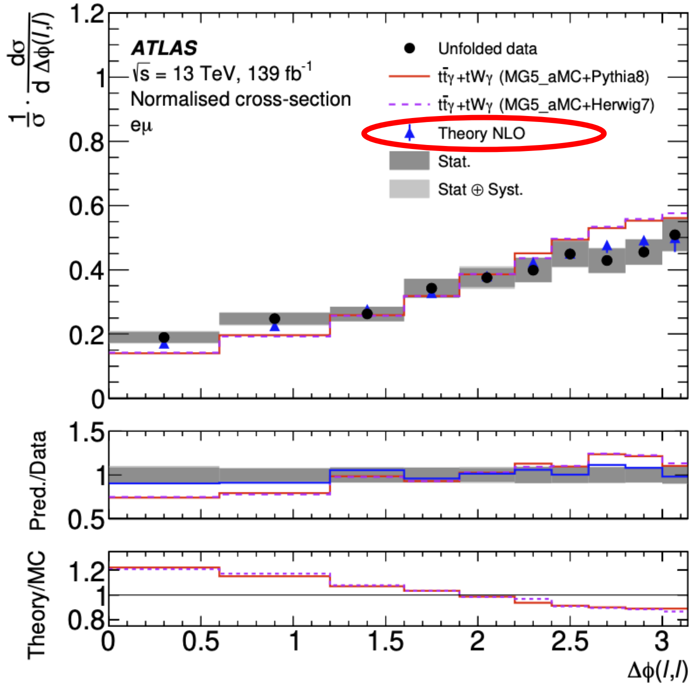
- NLO QCD full off-shell predictions for $t\bar{t}b\bar{b}$ → Di-Lepton Channel

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

ATLAS Collaboration, JHEP 01 (2025) 068

Comparisons with LHC Data

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

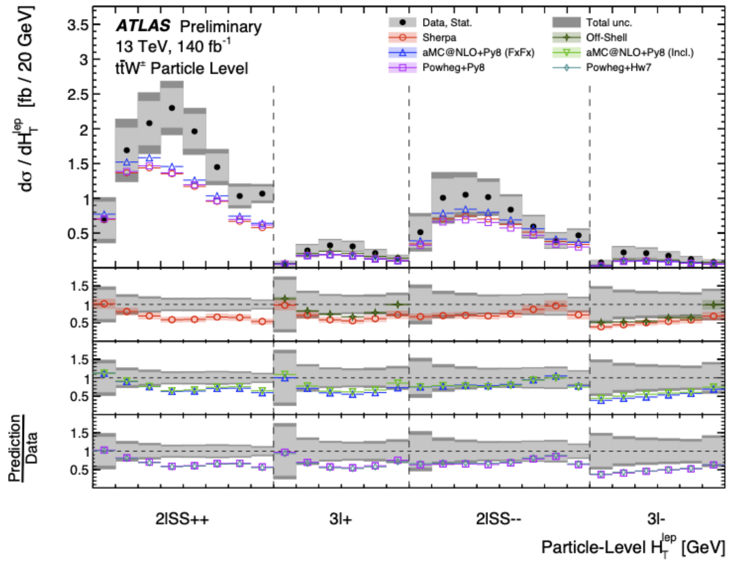


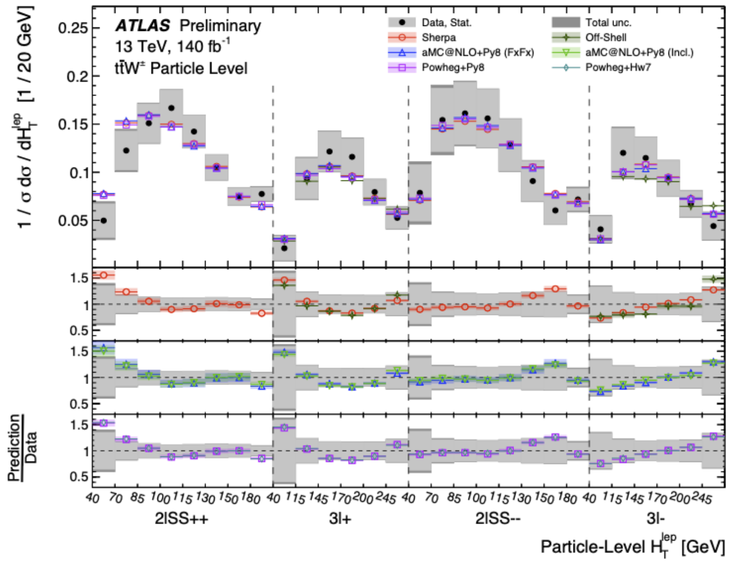
- NLO QCD full off-shell predictions for $t\bar{t}\gamma \to$ Di-Lepton Channel

Bevilacqua, Hartanto, Kraus, Weber, Worek
JHEP 10 (2018) 158 & JHEP 01 (2019) 188 & JHEP 03 (2020) 154

ATLAS Collaboration, JHEP 09 (2020) 049

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





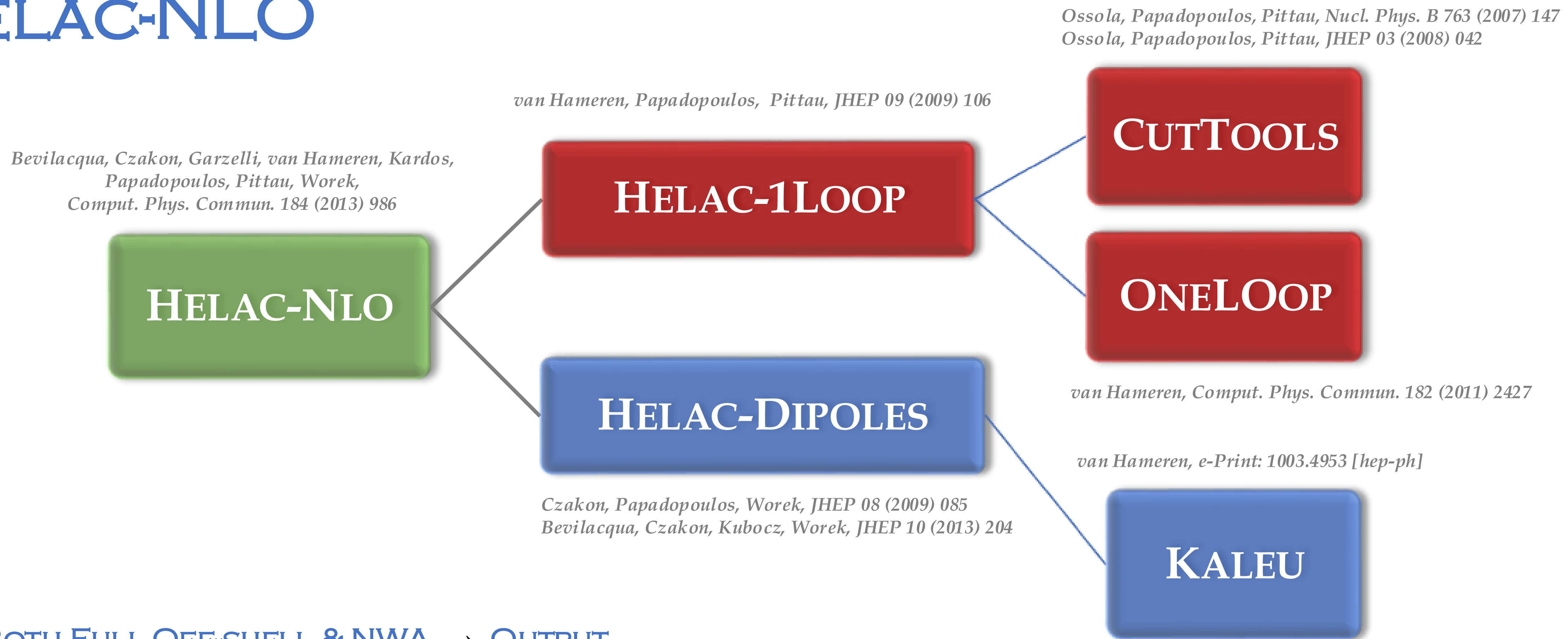
$$H_T^{lep} = p_T^{\ell^+} + p_T^{\ell^-} + p_T^{\ell^\pm}$$

- NLO QCD full off-shell predictions for $t\bar{t}W \to$ Multi-Lepton Channel

Bevilacqua, Bi, Hartanto, Kraus, Worek, JHEP 08 (2020) 043
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek, Eur. Phys. J. C 81 (2021) 7, 675
Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek, Phys. Rev. D 105 (2022) 1, 014018

ATLAS Collaboration, JHEP 05 (2024) 131

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

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

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

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

- Compute for each history Q and pick one that minimizes 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)

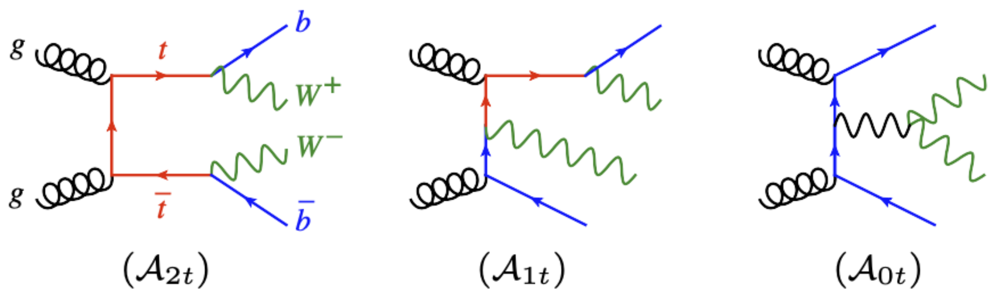
$$|M(t) - m_t| > n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

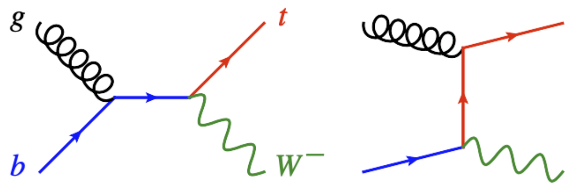
- Boundary parameter
  - Determines size of resonant region for each reconstructed top quark
  - ***n = 5, 10, 15***
  - For n = 15

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

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