Precision top-quark physics

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Universität Zürich[UZH]

FNSNF
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Outline

- Introduction
- Top-quark pair production
  - NNLO and beyond
  - tt, Wt and bb4l
- ttH
- Summary

Many more interesting results presented in the Top Physics session

Introduction

The top quark has a very special place in the Standard Model

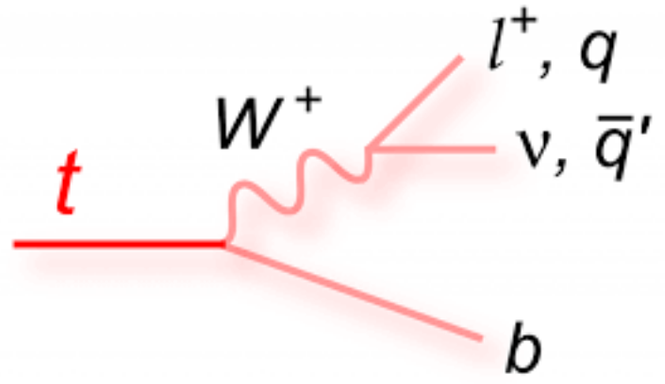
- It is the heaviest elementary particle $m_t \sim 173\,\text{GeV}$ ➡ $y_t \sim 1$

- It couples strongly to the Higgs boson $m_t = y_t v/\sqrt{2} \sim 173\,\text{GeV}$

- It decays through EW interaction before hadronizing

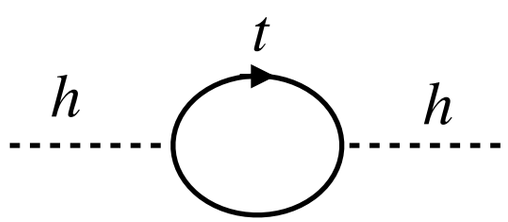
  - $\tau_{\text{had}} \sim 1/\Lambda_{QCD} \sim 10^{-23}\,s$

  - $\tau_t = 1/\Gamma_t \sim \left(G_F m_t^3 |V_{tb}|^2\right)^{-1} \sim 5 \cdot 10^{-25}\,s$



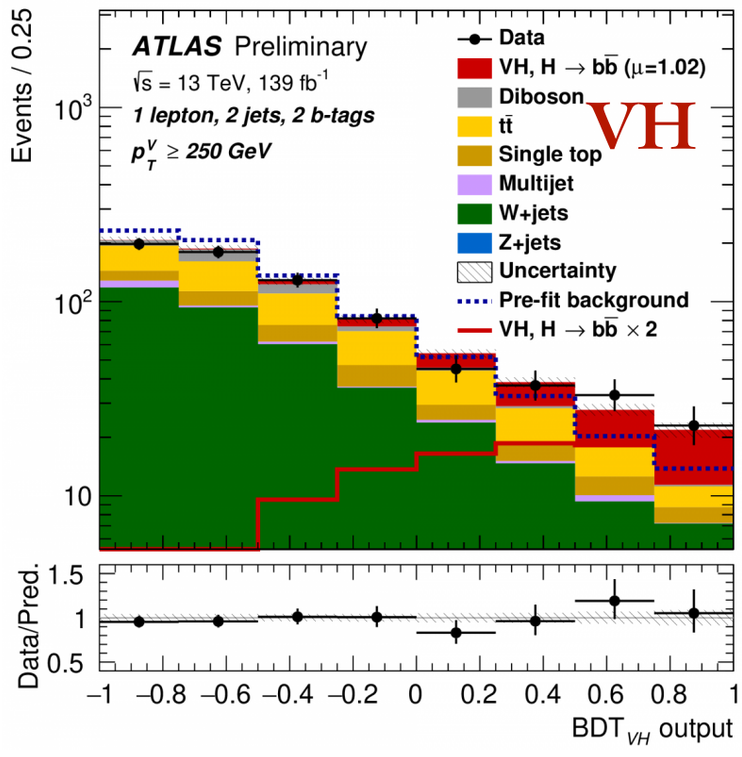
Introduction

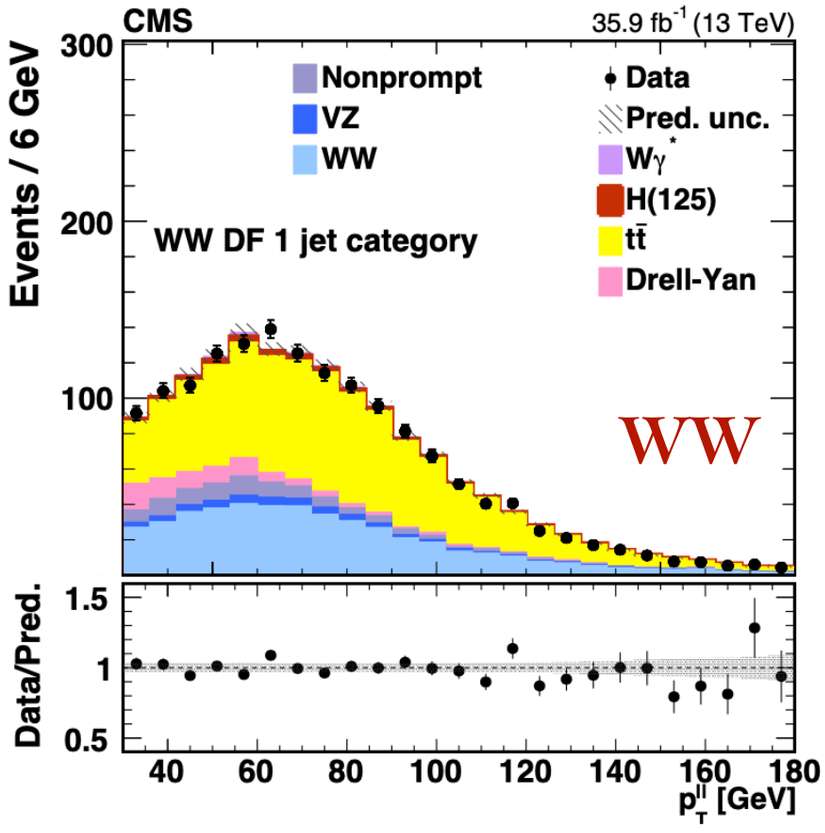
- Possible window on new physics



$$\sim \frac{y_t^2}{8\pi^2}\Lambda_{UV}^2$$

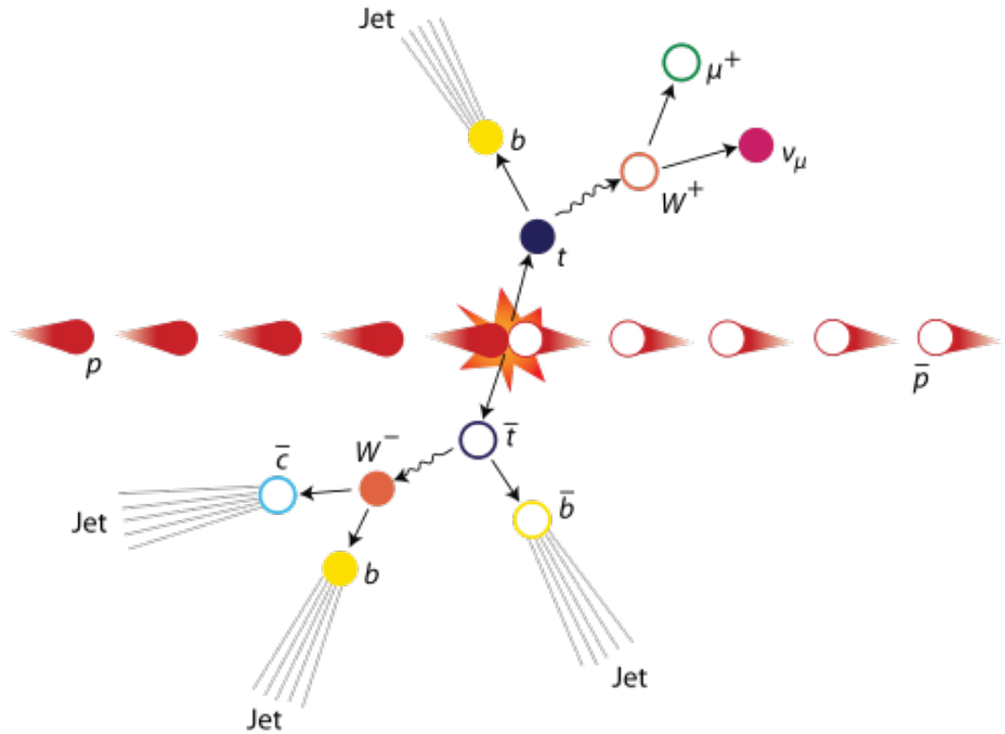
- Events with top quarks provide an ubiquitous background to SM, Higgs measurements and new physics searches



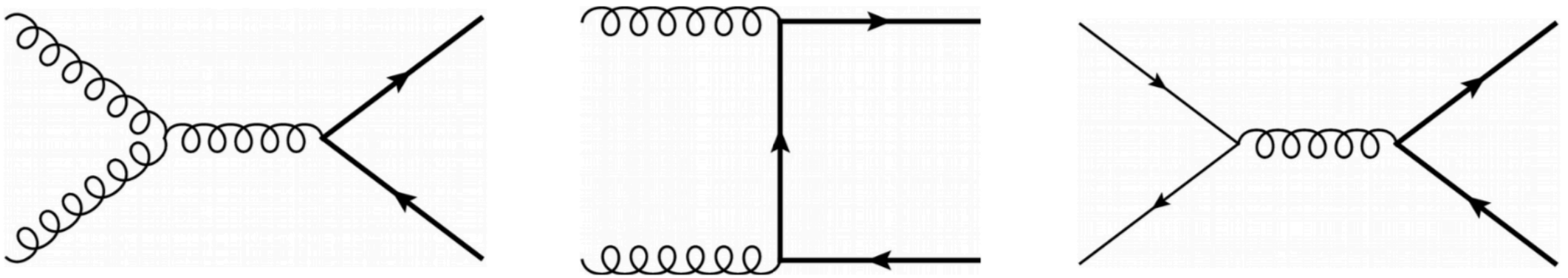


Introduction

Main source of top-quark events at hadron colliders is $t\bar{t}$ production

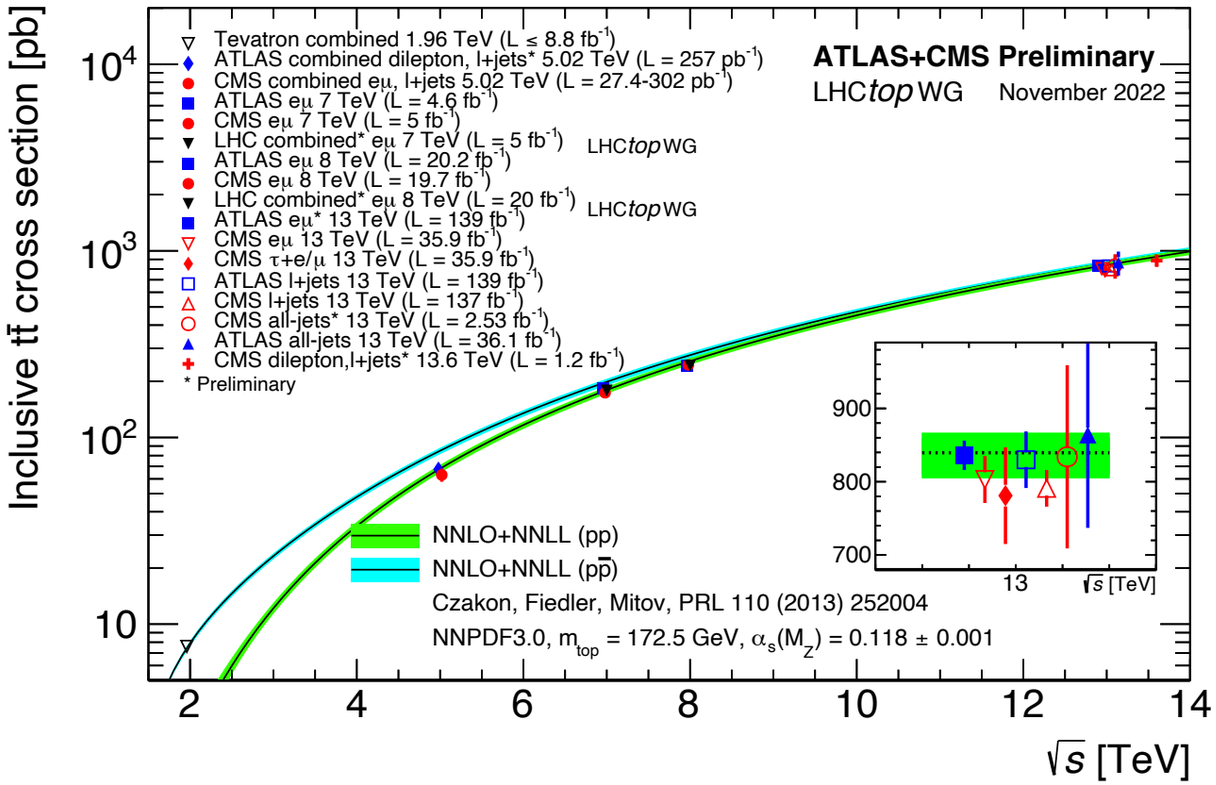


About 15 $t\bar{t}$ events per second at the LHC !



gg contribution dominant
at the LHC (85% at LO)

Theoretical status



Inclusive cross section known at NNLO+NNLL in QCD

Bärnreuther, Czakon, Mitov (2012)
Czakon, Mitov (2012)
Czakon, Fiedler, Mitov (2013)
Czakon, Fiedler, Heymes, Mitov (2015,2016)

NNLO calculation independently* completed by our group

*The only common ingredient are the two-loop gg and $q\bar{q}$ virtual amplitudes

Bärnreuther et al (2013)

For the $q\bar{q}$ channel recently confirmed by fully analytical calculation

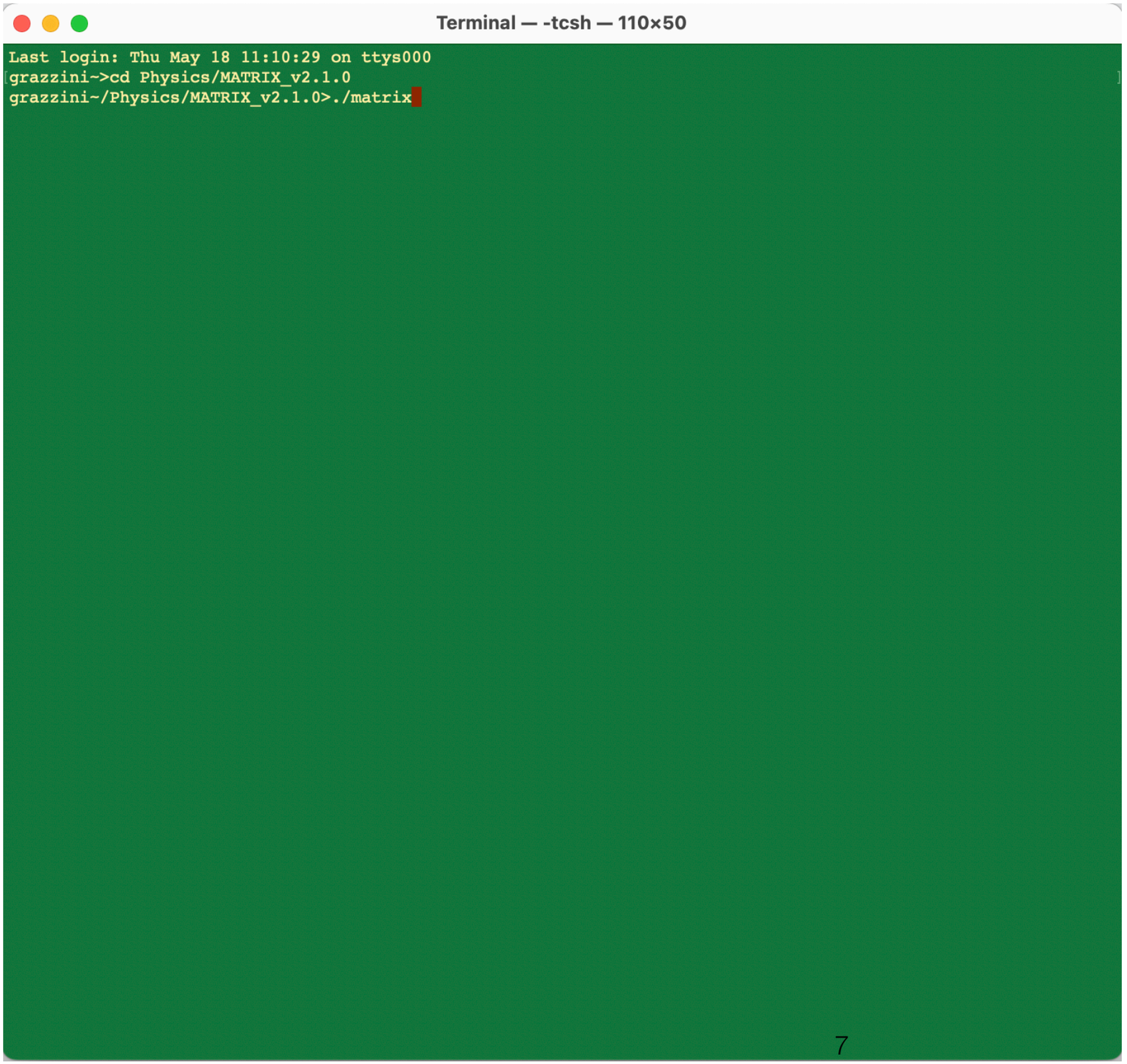
Mastrolia et al (2022)

σ_{NNLO} [pb]	MATRIX	TOP++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$794.0(8)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$
100 TeV	$35215(74)^{+2.8\%}_{-4.7\%}$	$35216^{+2.9\%}_{-4.8\%}$

Excellent agreement with Top++ !

Catani, Devoto, Kallweit, Mazzitelli, Sargsyan , MG(2019)

MATRIXv2.1

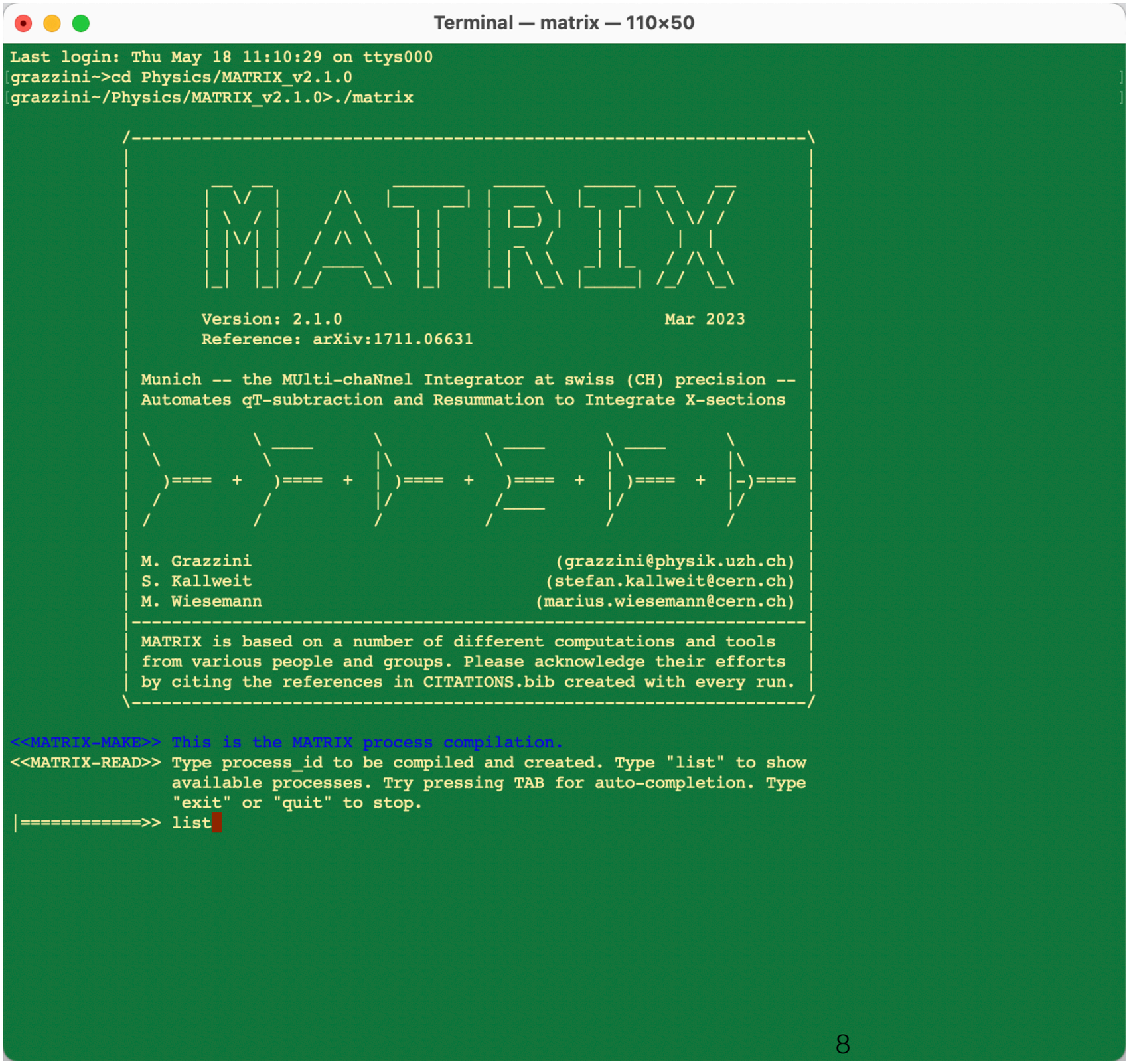


MATRIX allows the user to evaluate fully differential cross sections for a wide class of processes at hadron colliders in NNLO QCD, NLO EW and NLO QCD for the loop-induced contribution

Publicly available here

http://matrix.hepforge.org

MATRIXv2.1



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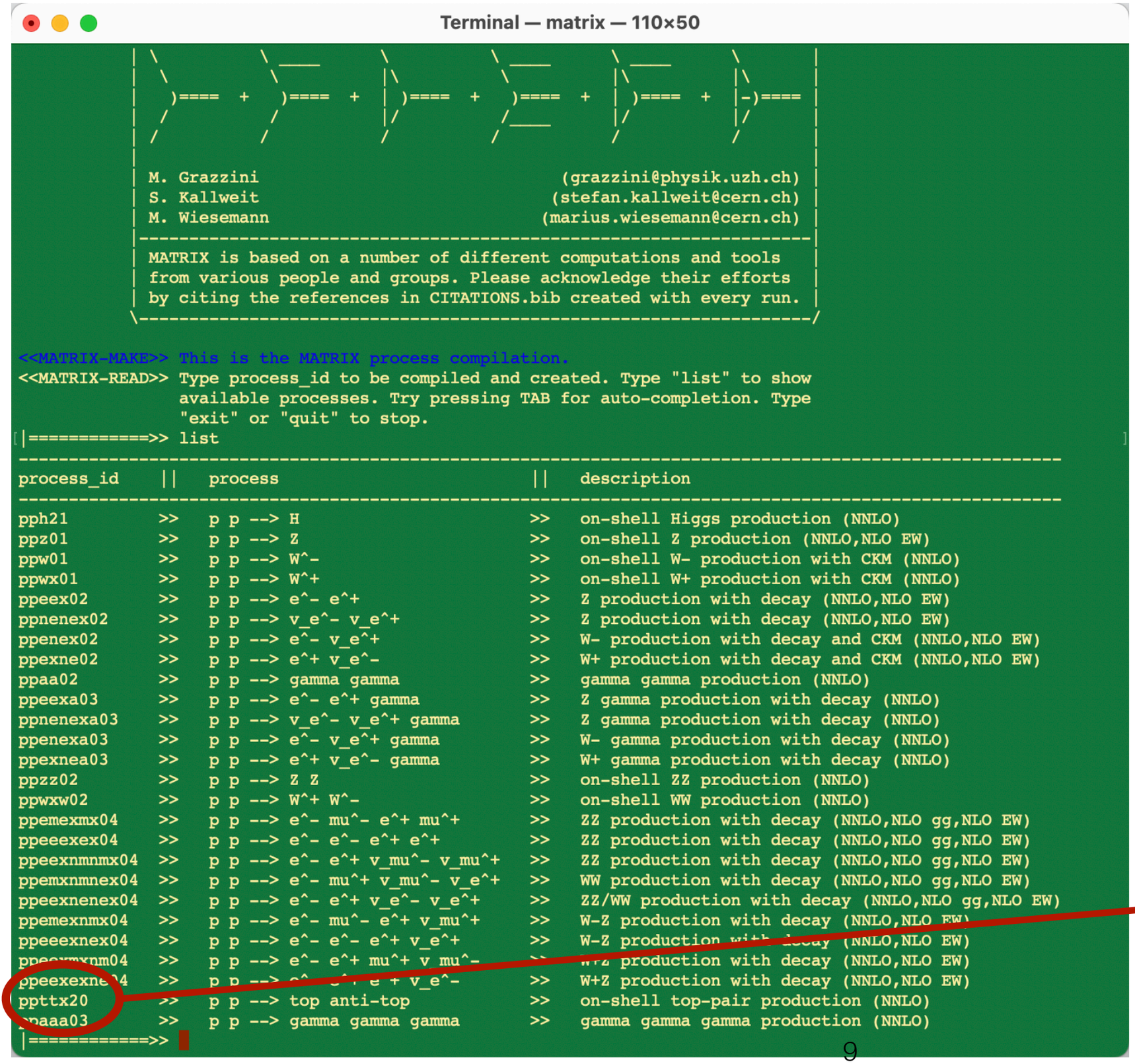

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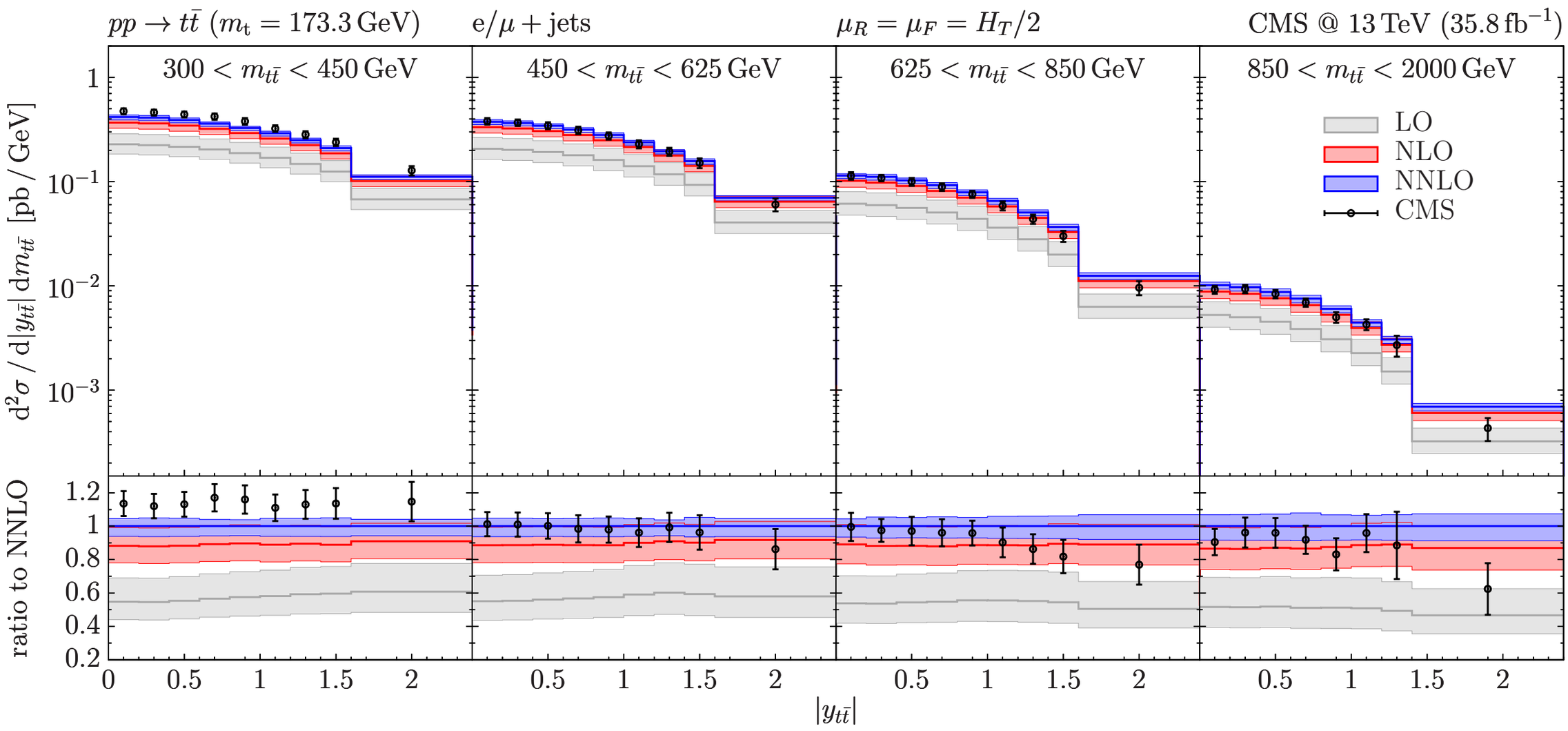
Version 2.1 includes top-pair production

MATRIXv2.1

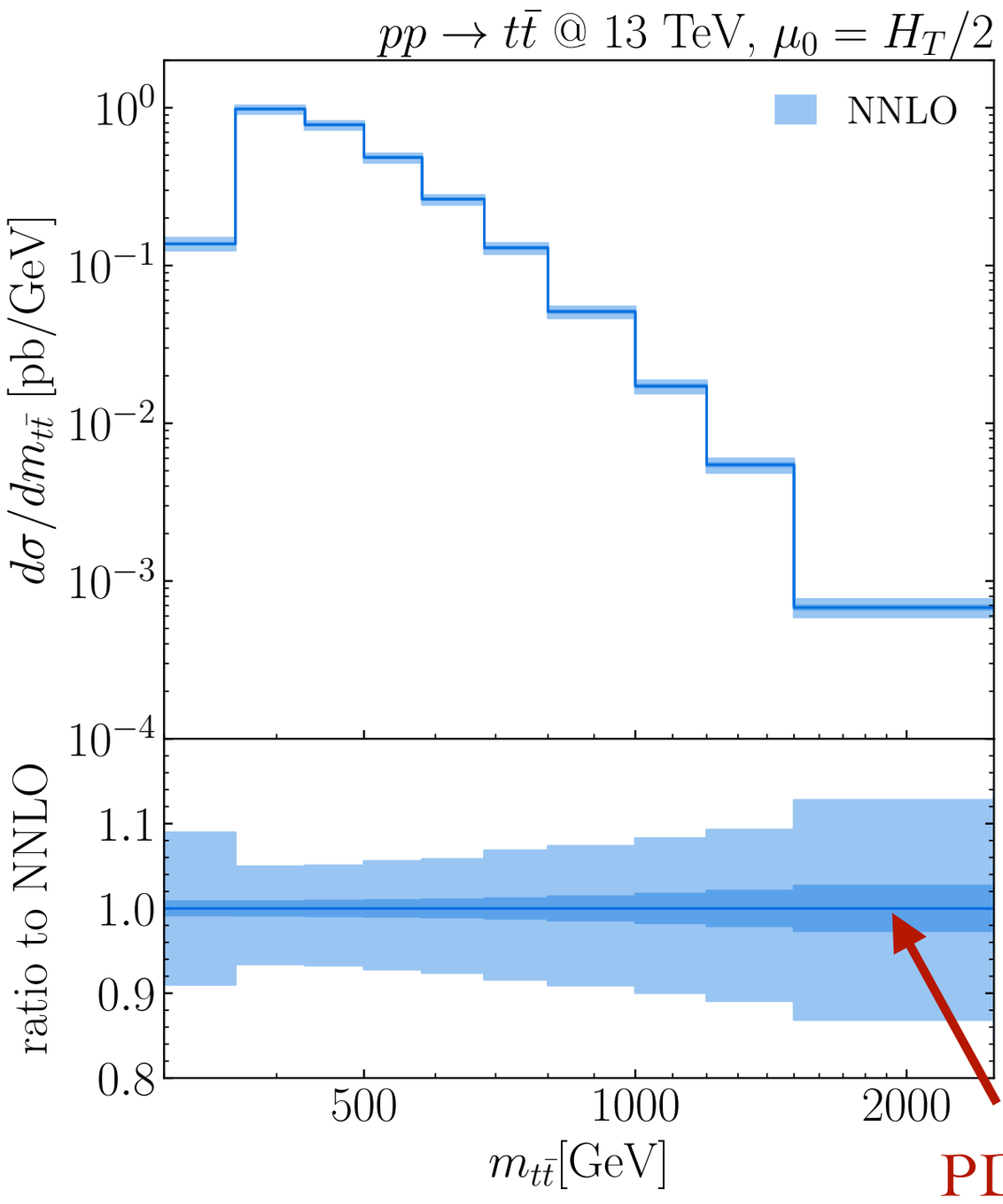
Multidifferential distributions

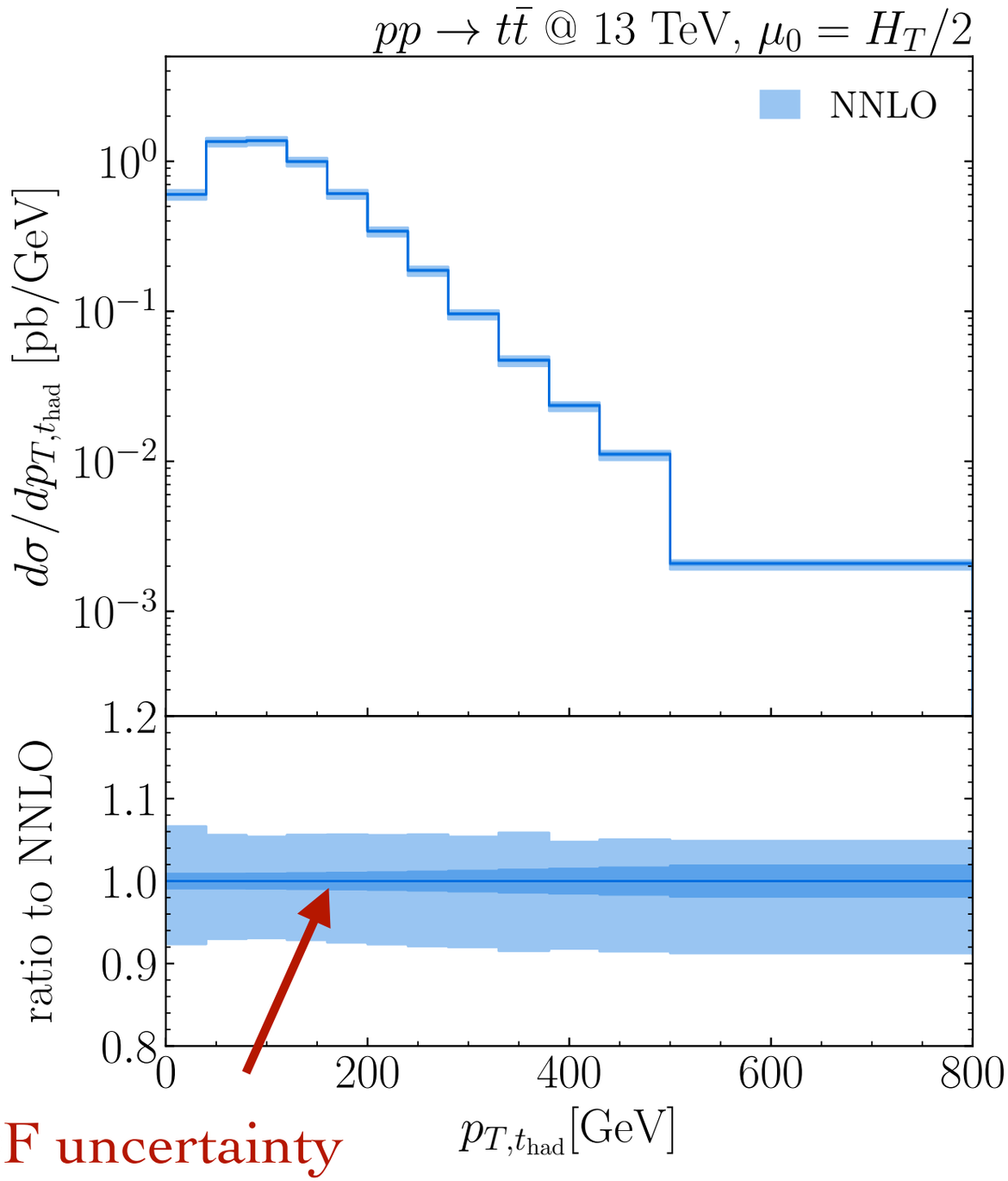


NNLO corrections significantly improve the agreement with the data

NEW: PDF uncertainties: MATRIX+PineAPPL interface

Devoto, Jezo, Kallweit, Schwan (in preparation)





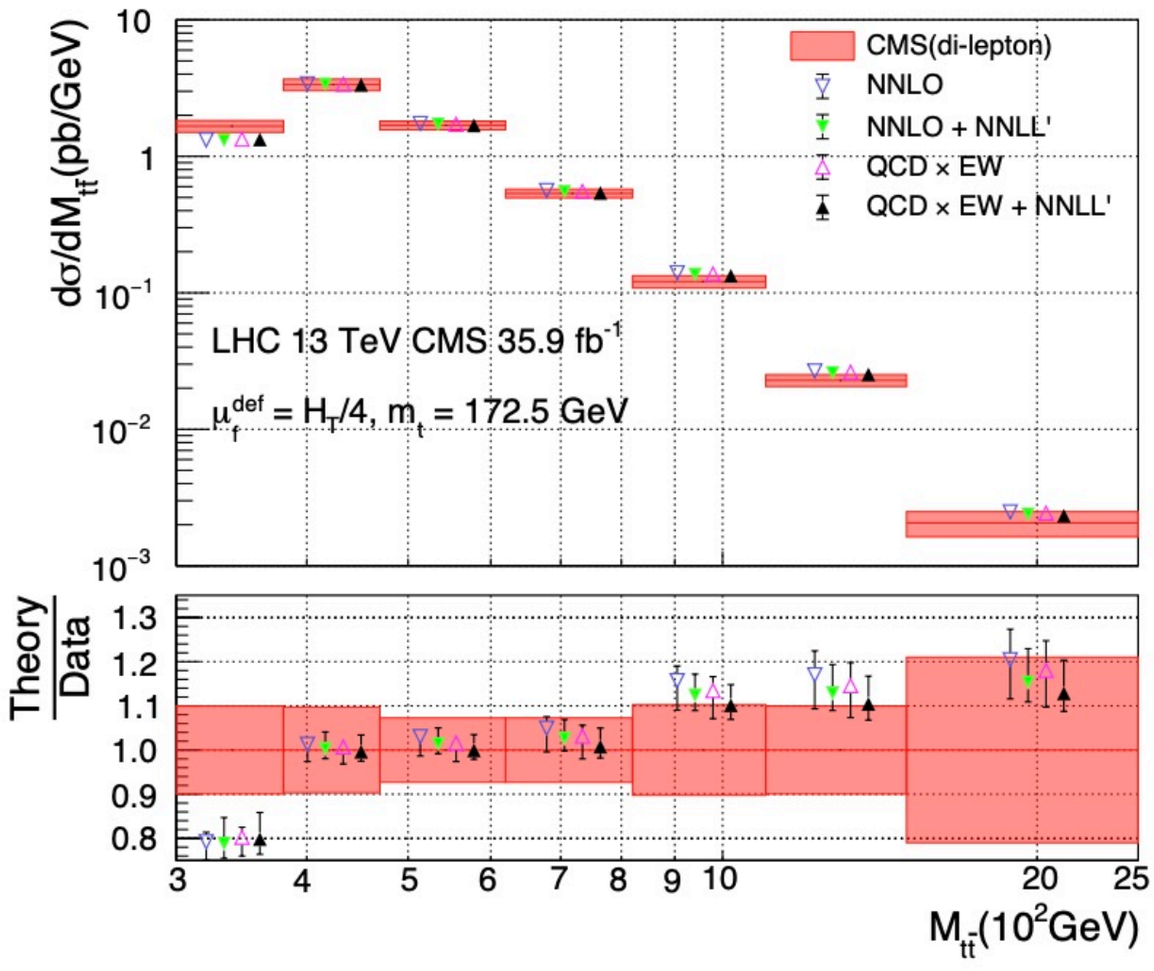
PDF uncertainty

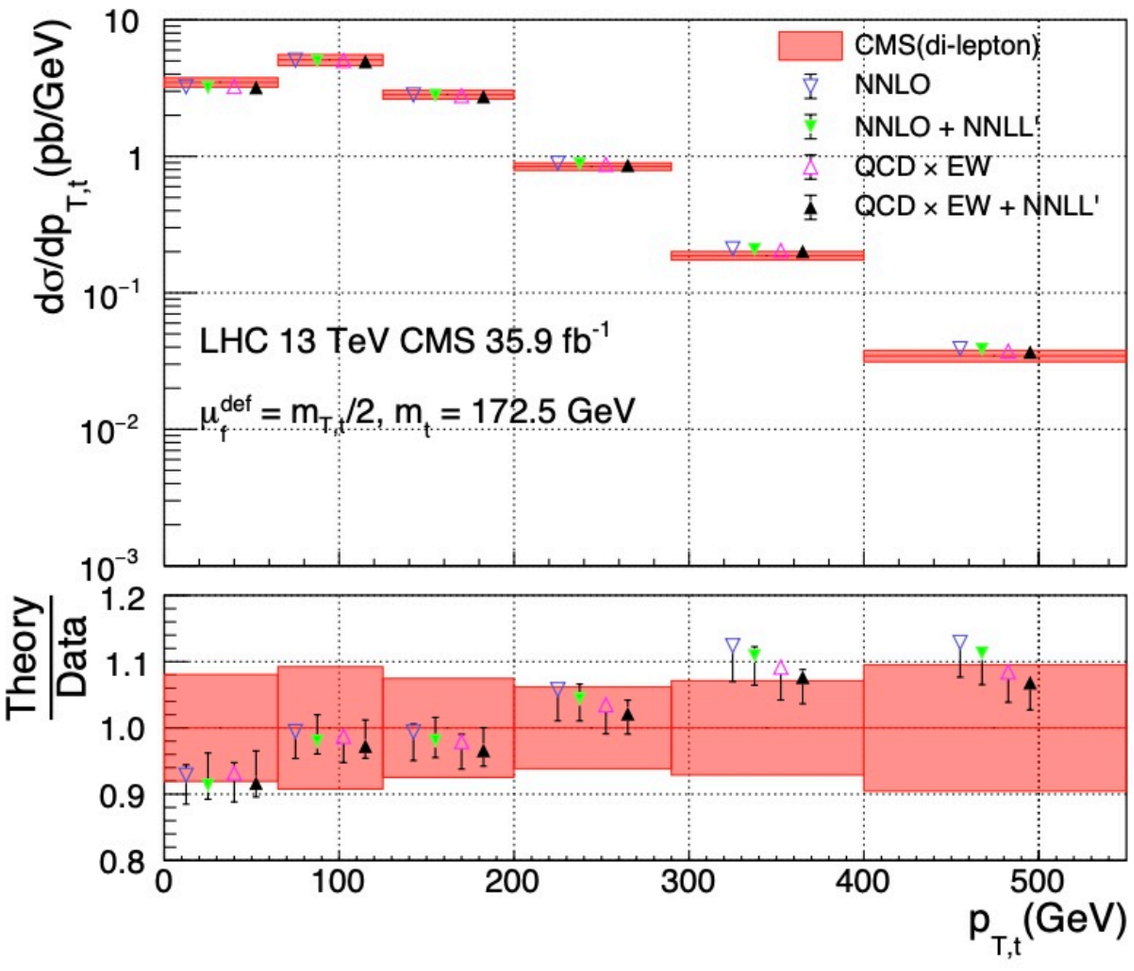
Plots: courtesy S. Devoto

Beyond NNLO effects

Further effects that can/should be included are EW corrections and soft-gluon resummations at small and large invariant masses Zaro et al (2019)

Relatively small impact but slightly improves the agreement with the data





Still threshold region not properly described

Resummation of Coulomb effects partially improves the situation L. L. Yang et al (2019)

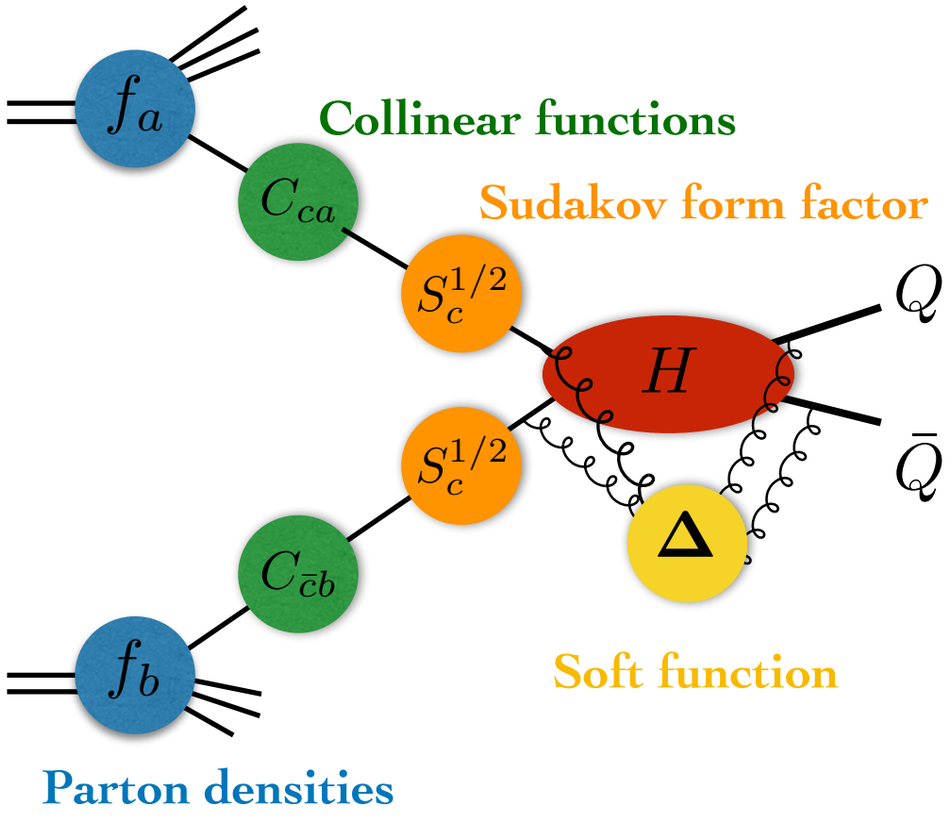
NNLOPS

Event generators keeping formal NNLO accuracy for inclusive observables

Recently achieved for $t\bar{t}$ with the MiNNLOPS method

Mazzitelli et al (2020,2021)

Exploit available knowledge of transverse-momentum resummation



Catani, Torre, MG (2014)

Catani, Devoto, Mazzitelli, MG (2023)

NNLO matching for colourless production well established

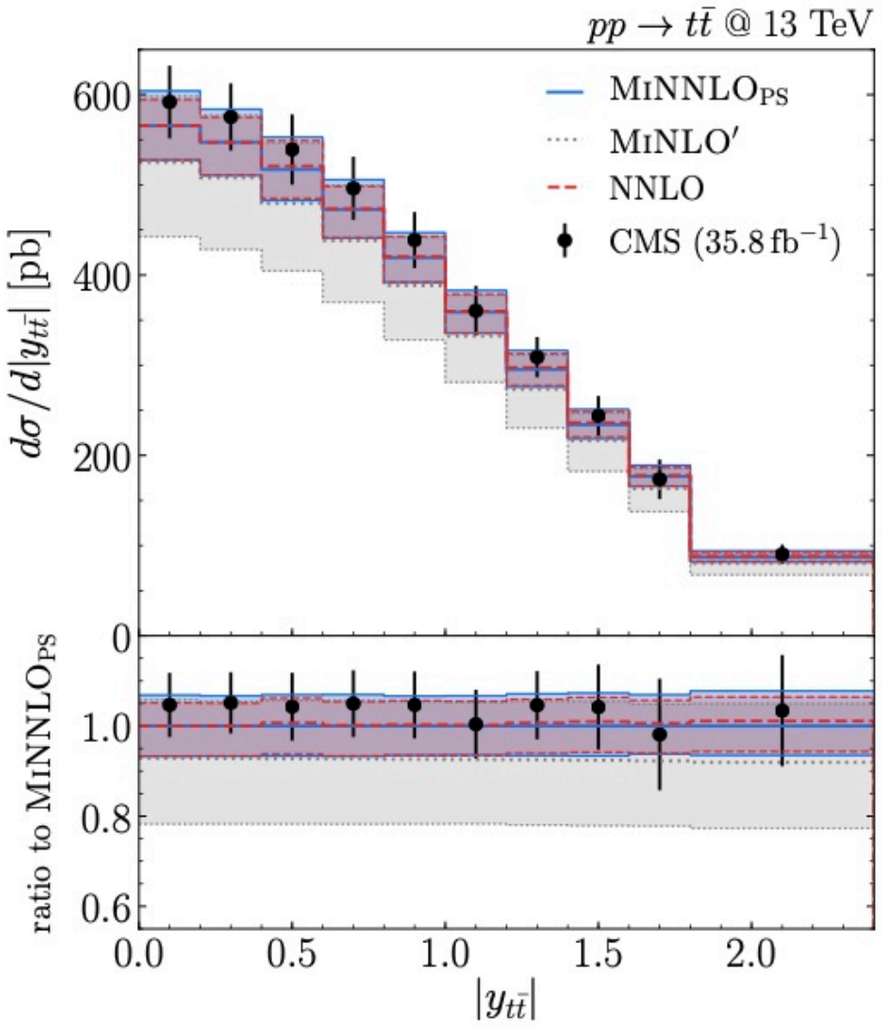
See talk by Silvia Zanoli

$t\bar{t}$ production first example of coloured final state with non trivial soft-radiation pattern

Allows to directly deploy NNLO precision into $t\bar{t}$ experimental analyses

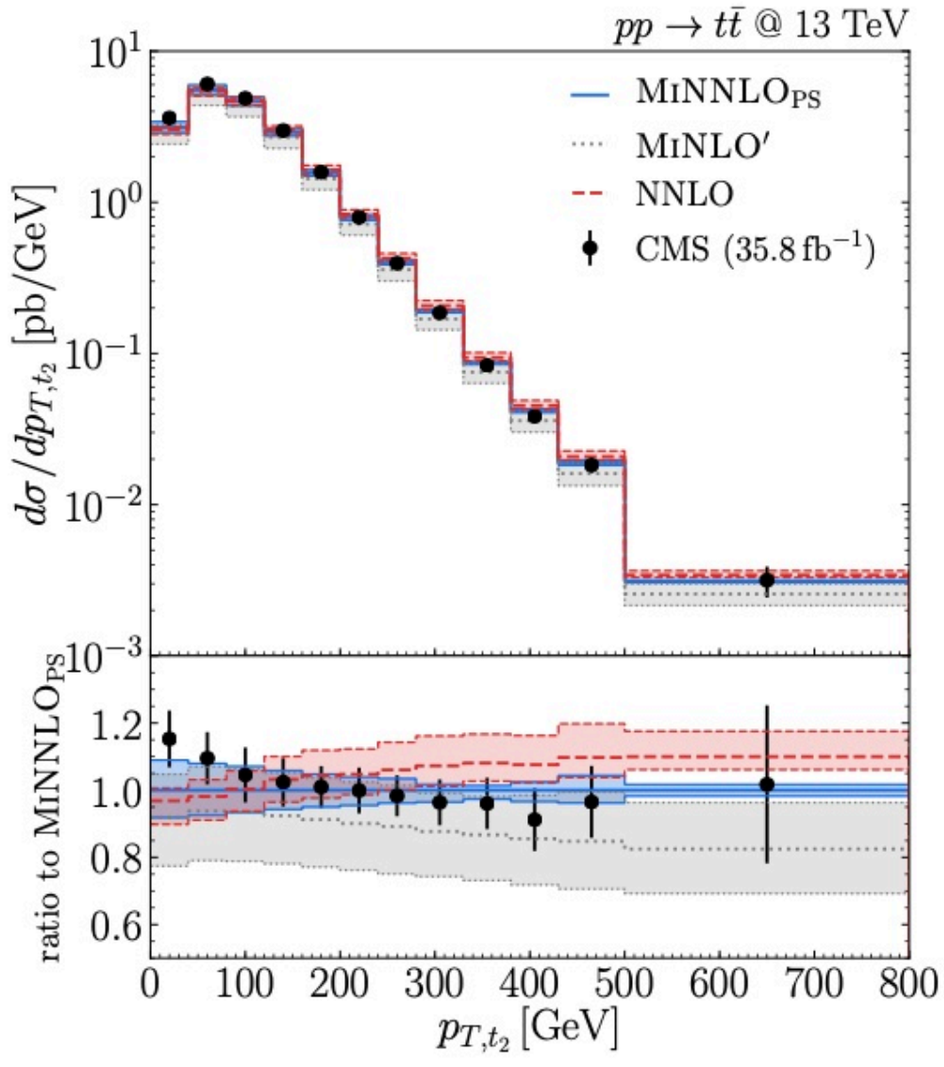
NNLOPS

Mazzitelli et al (2020,2021)



Excellent agreement with NNLO prediction, with differences only at the permille level

Excellent description of the data

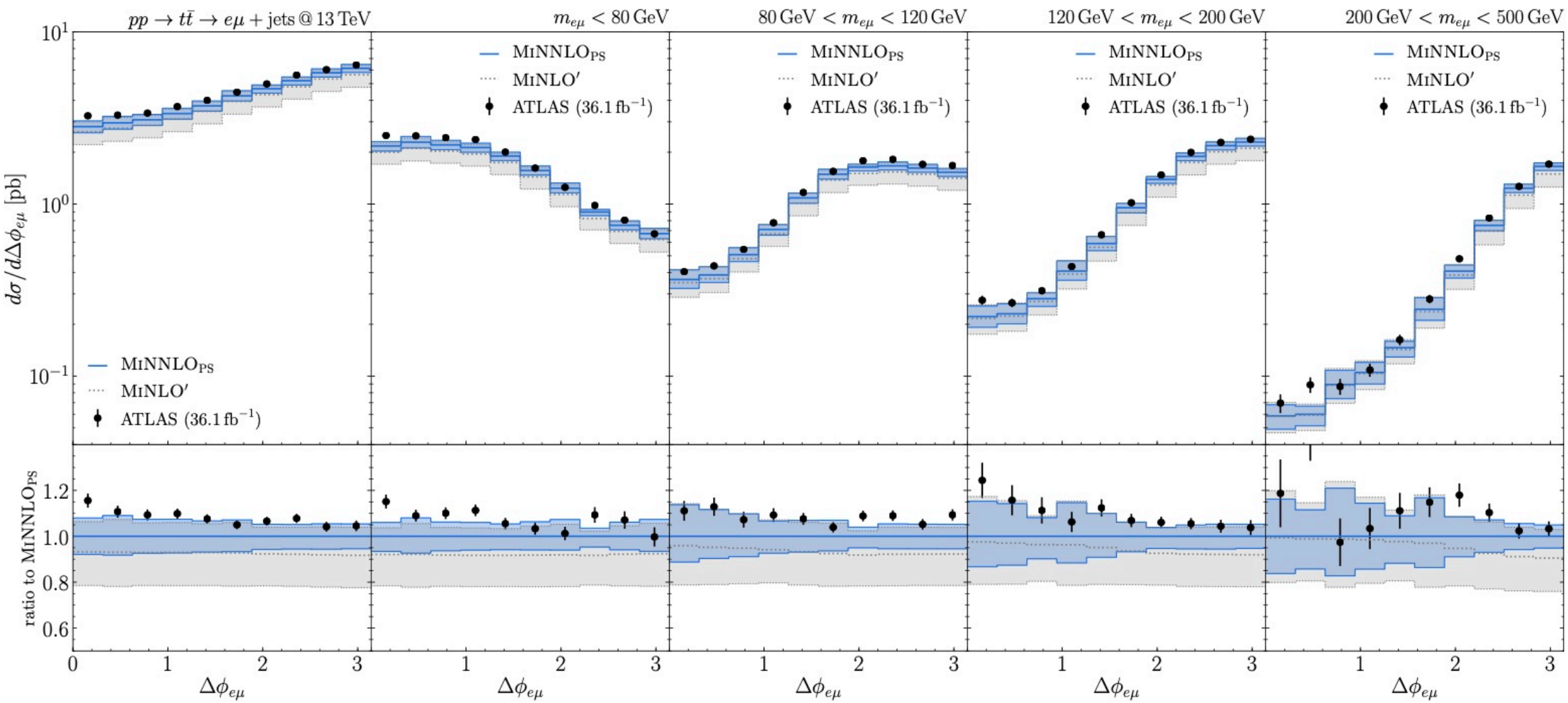


Improves where fixed order NNLO has problems (like p_T of softer top quark)

NNLOPS

Mazzitelli et al (2020,2021)

Top decay and spin correlations included at LO only



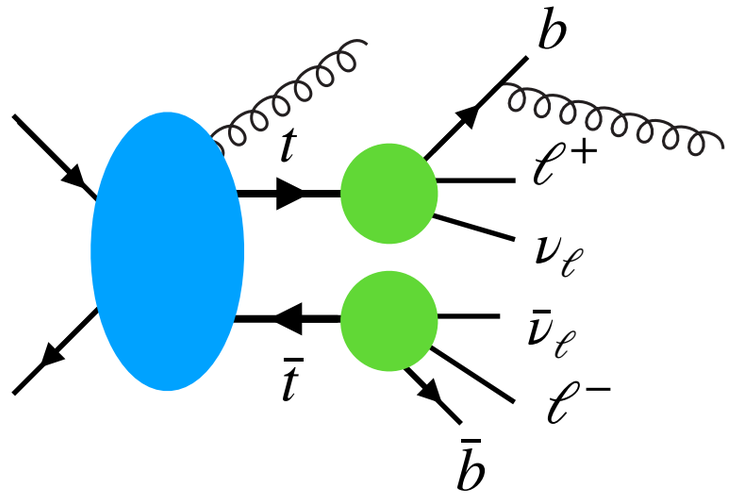
Still good description of the data

Top decay

- Narrow width approximation (NWA)

  - based on the limit $\Gamma_t/m_t \to 0$

  - considerable simplifications from the factorisation of production and decay



  - treatment of spin-correlations possible

Melnikov, Schulze (2009)

- Off-shell calculations

  - consider the complete process, say $pp \to b\bar{b}l\nu l\nu + X$

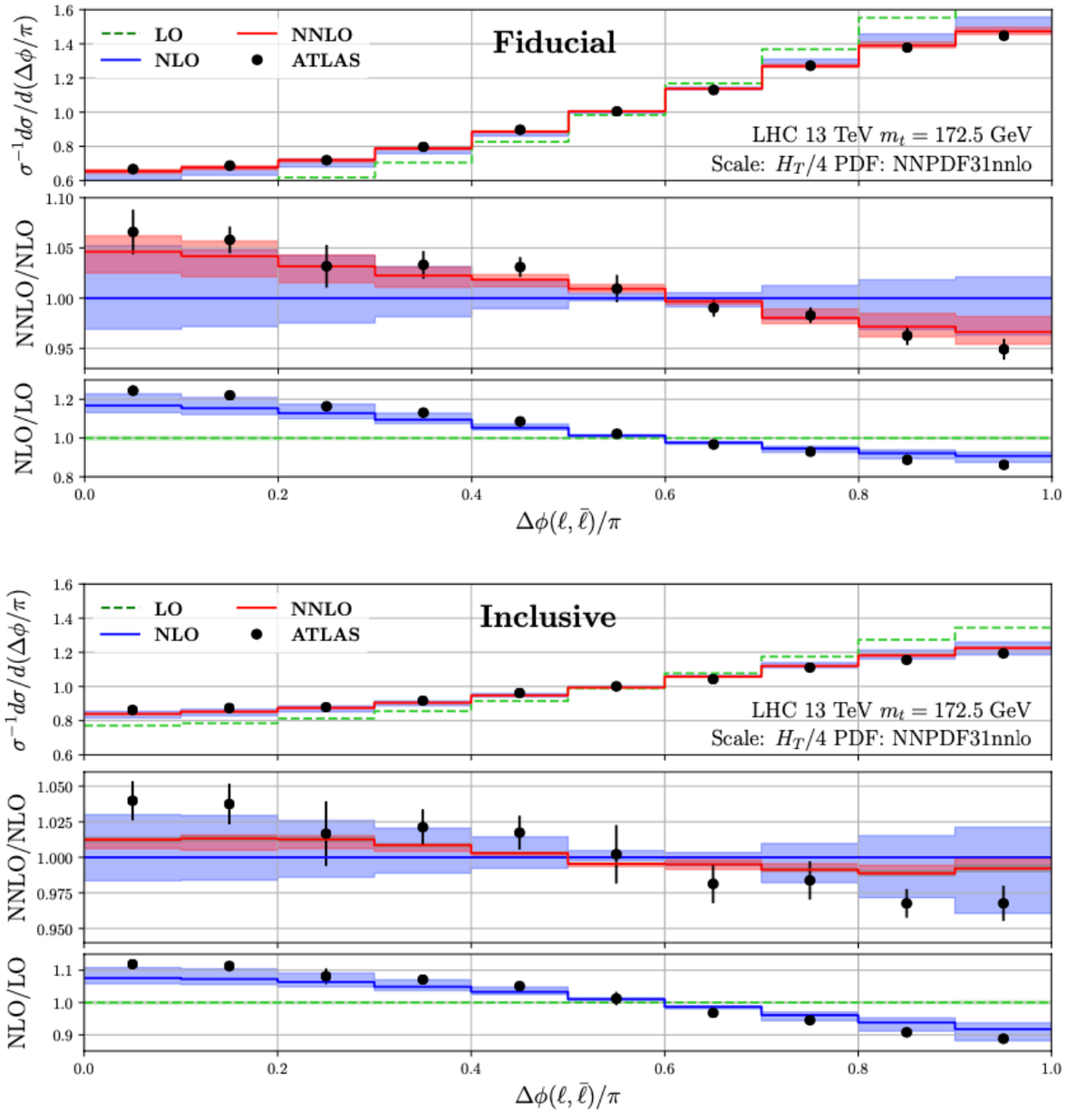
  - challenges come from high-multiplicity phase space and interferences between production and decay

More on on-shell effects in the talk by Giovanni Pelliccioli

Full NNLO in NWA

NNLO production and NNLO decay combined in NWA

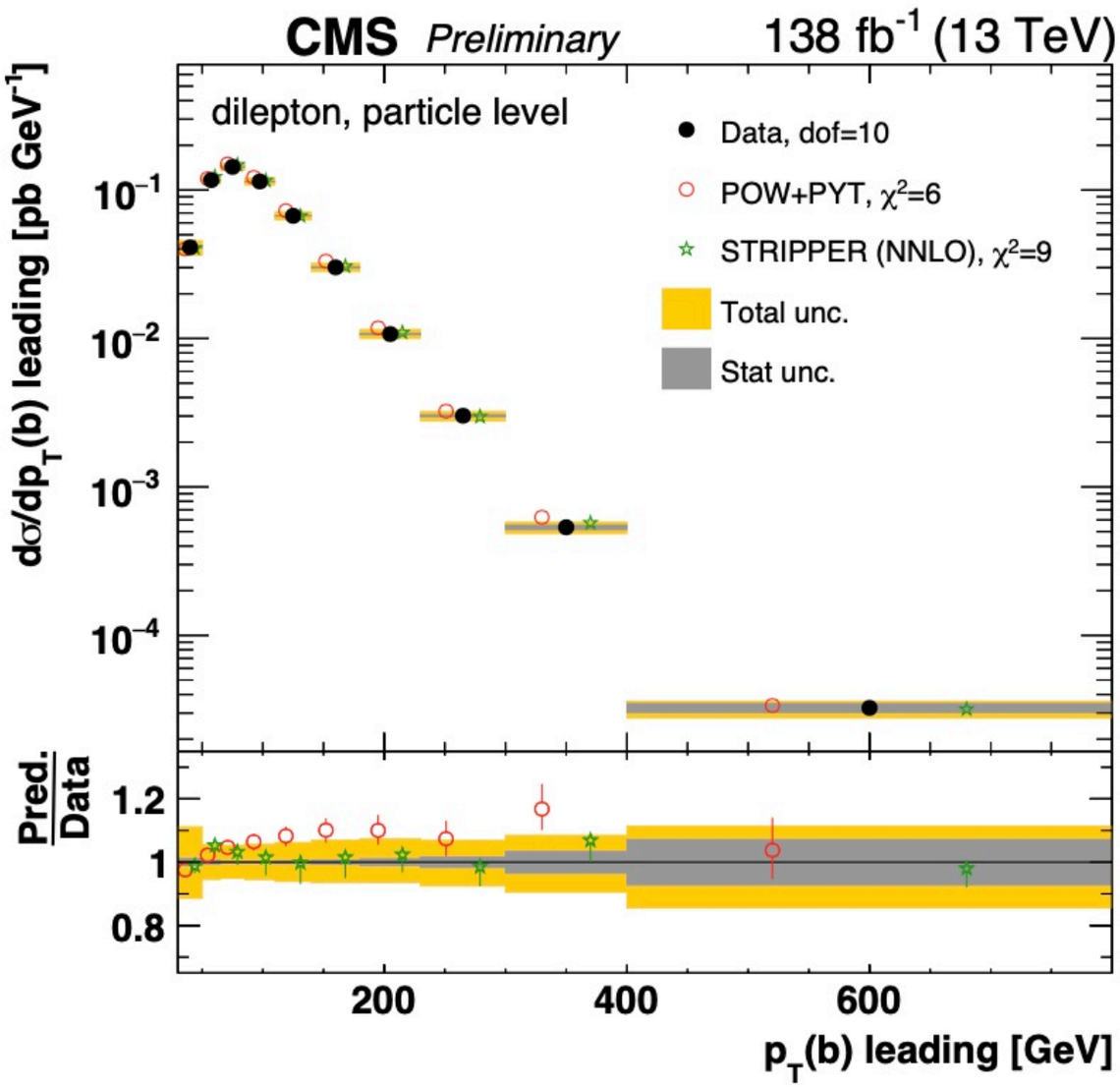
Czakon et al (2019,2020)

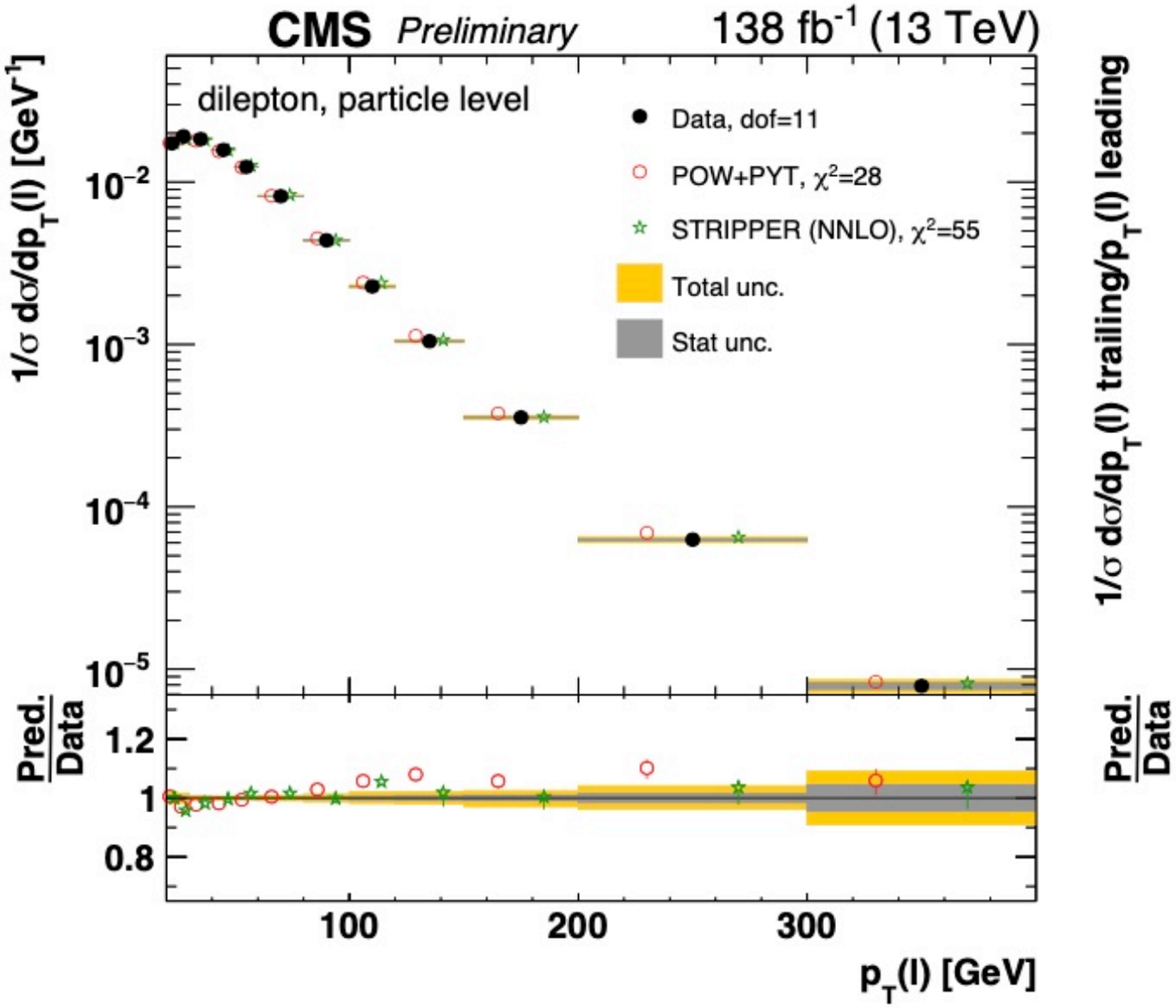


NNLO predictions describe the $\Delta\phi(\ell\bar{\ell})$ well in the fiducial region while some tension exists when the comparison is done in the inclusive phase space

Effect of extrapolation relevant at this level of precision

Full NNLO in NWA

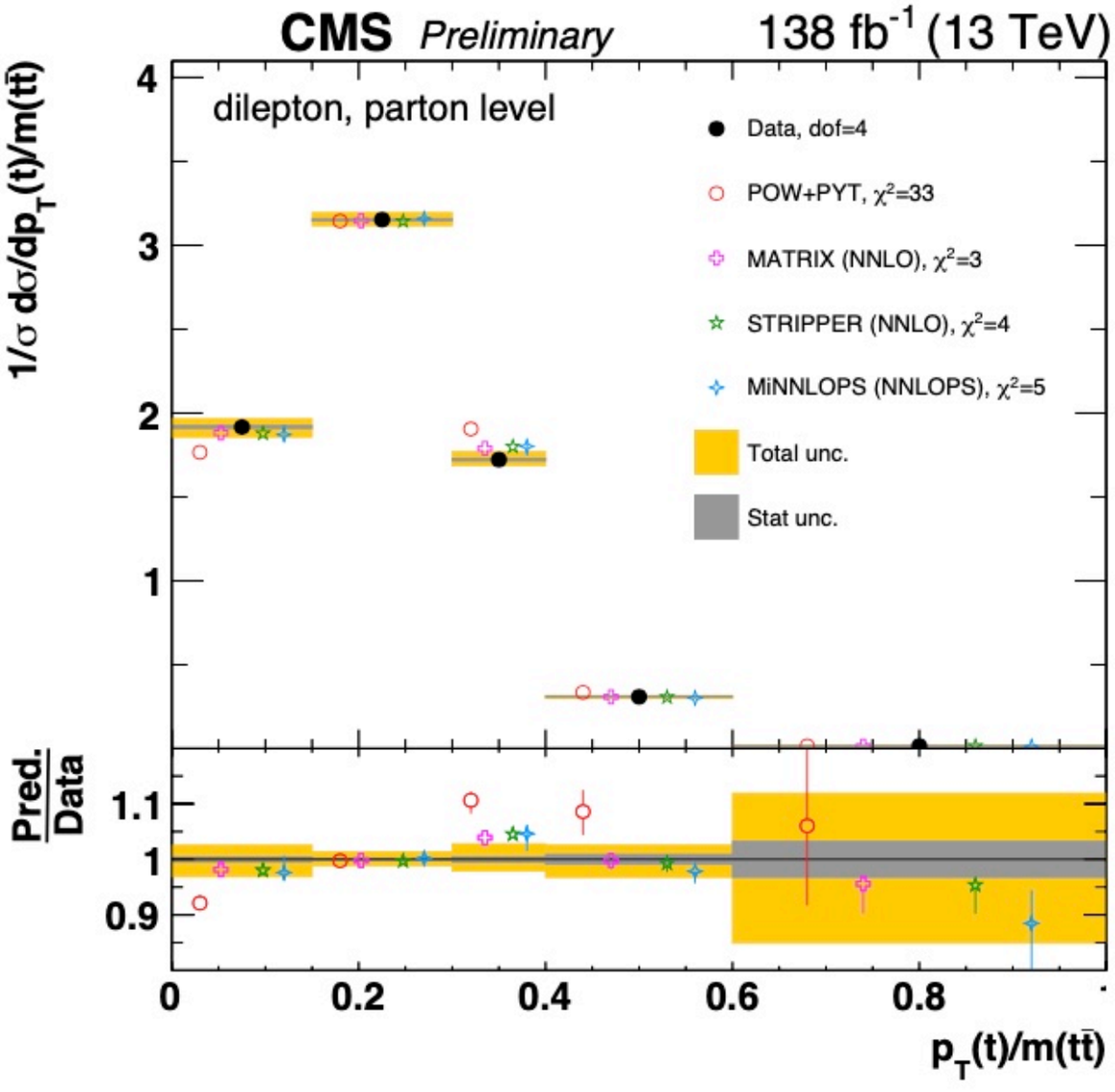


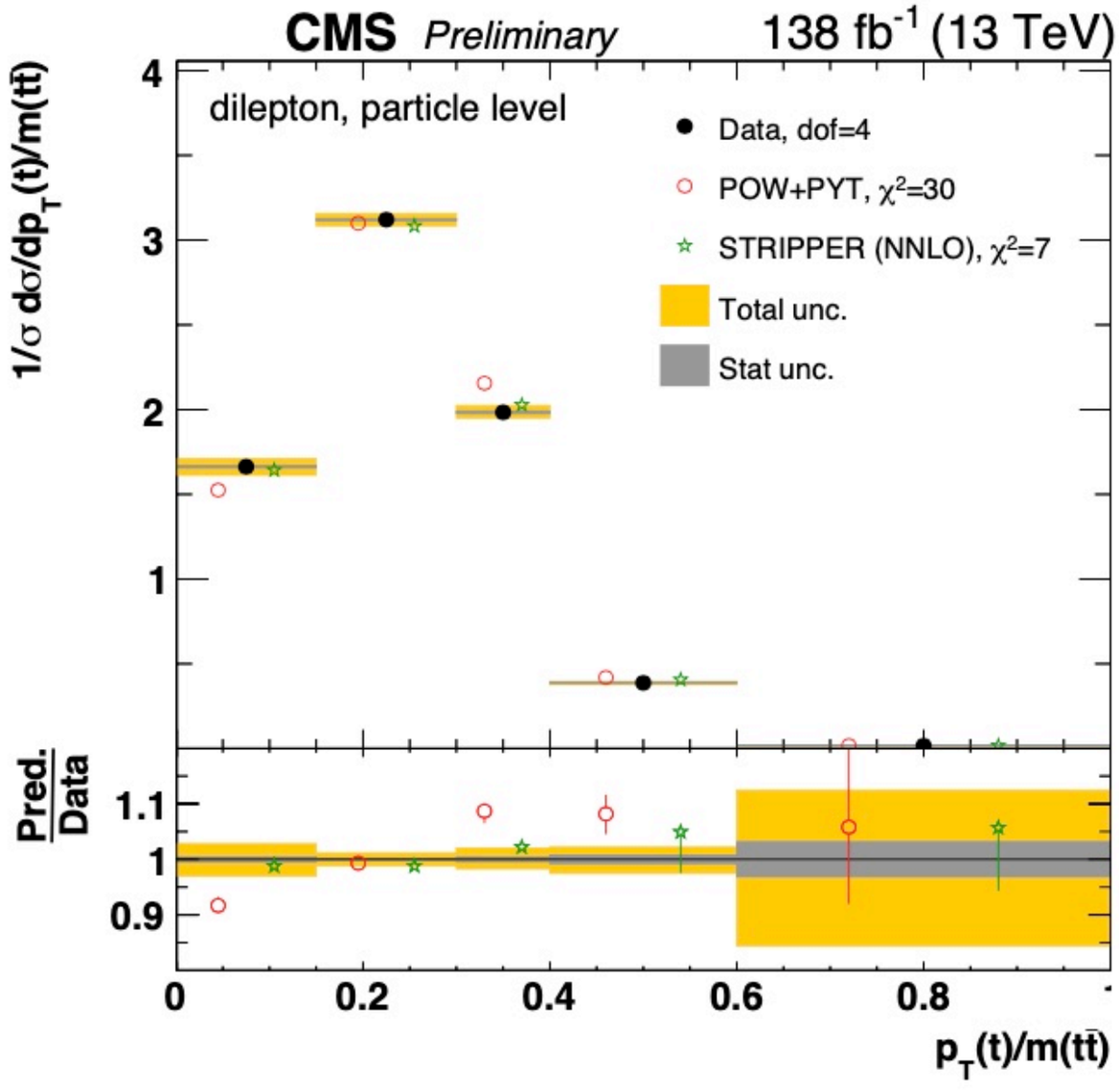


Excellent description of the data both in shape and normalisation

Full NNLO in NWA

Reconstructed top p_T normalised to $m_{t\bar{t}}$: extrapolated vs fiducial





Full NLO QCD and EW calculations

- Off-shell effects through complete process $pp \to b\bar{b}l\nu l\nu + X$ in NLO QCD

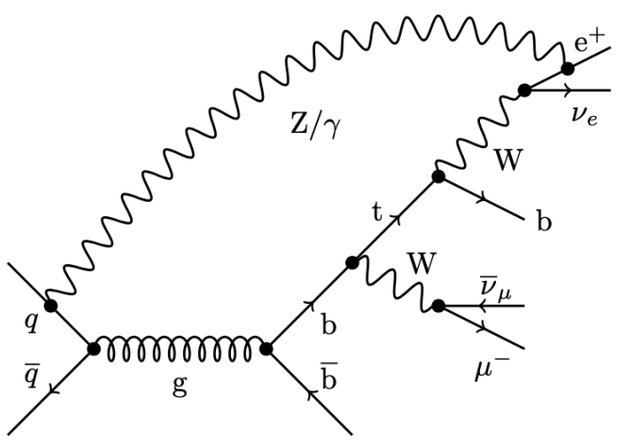
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2010)
Denner, Dittmaier, Kallweit, Pozzorini (2012)
Heinrich et al (2013)

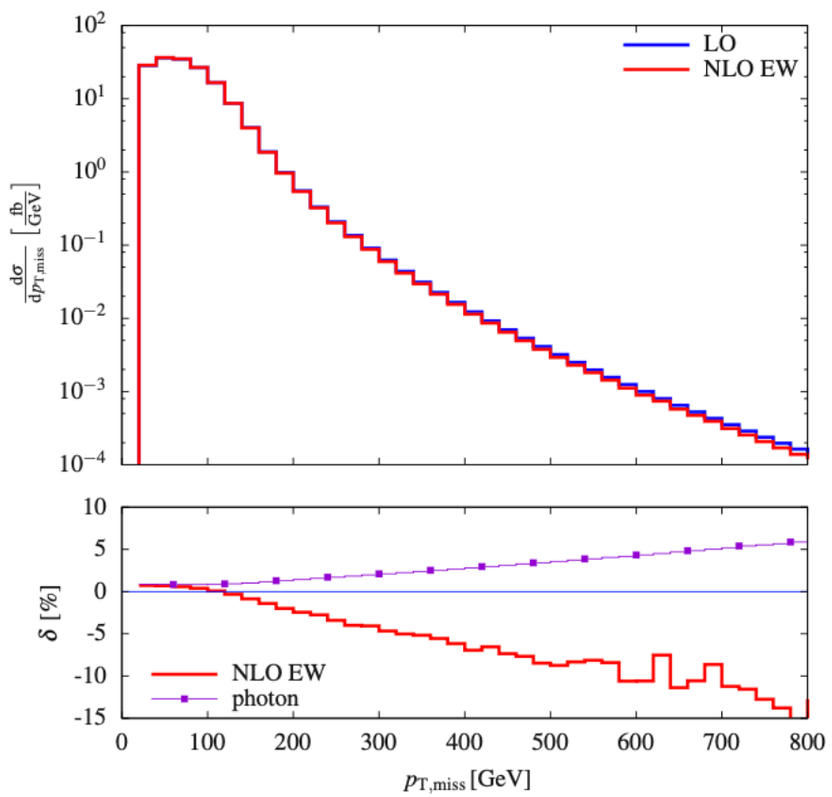
- Unified $t\bar{t}$ and Wt with massive b-quarks

Cascioli, Kallweit, Maierhöfer, Pozzorini (2013)
Frederix (2013)

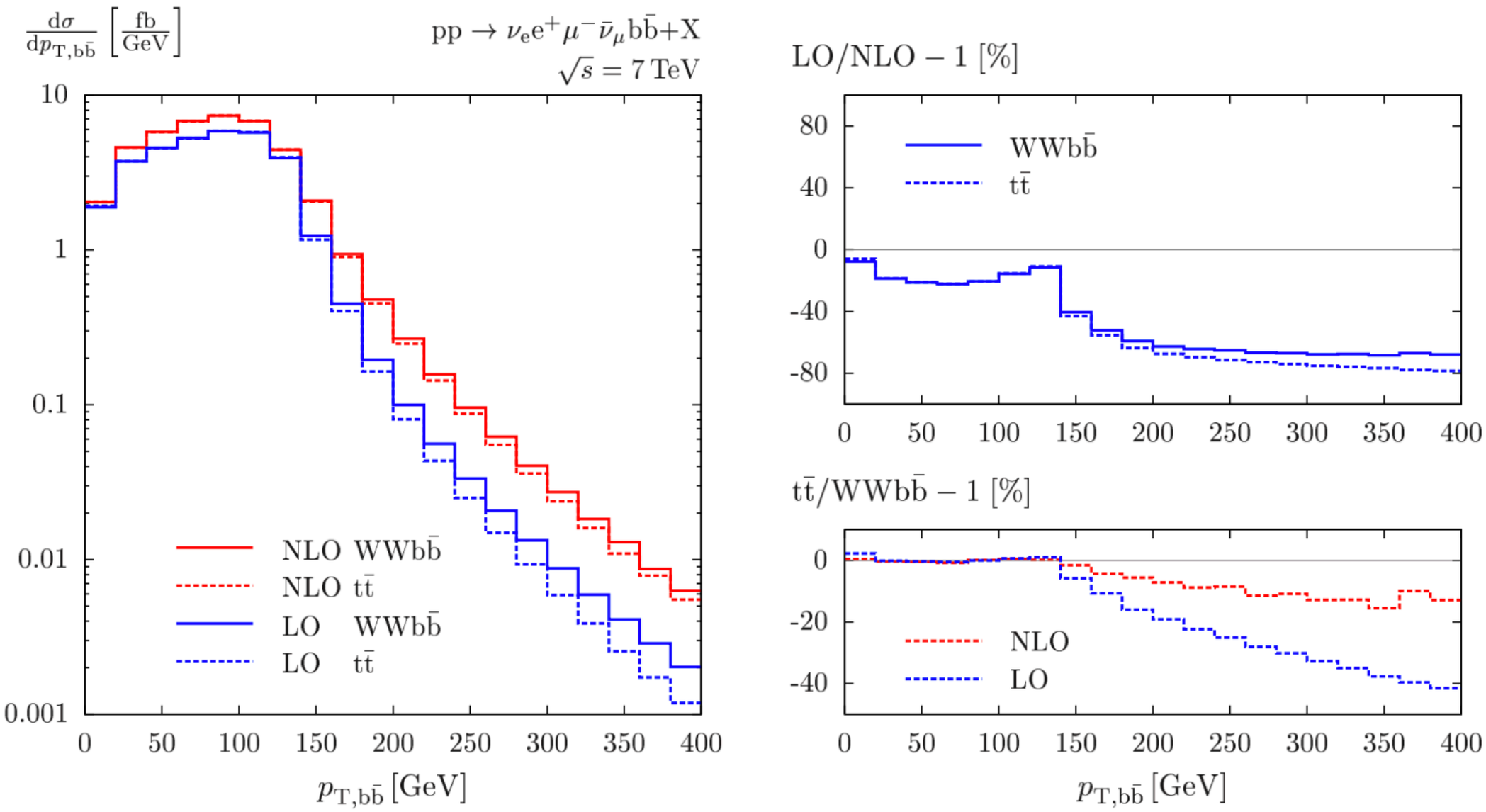
- NLO EW corrections to full $b\bar{b}l\nu l\nu$

Denner and Pellen (2016)





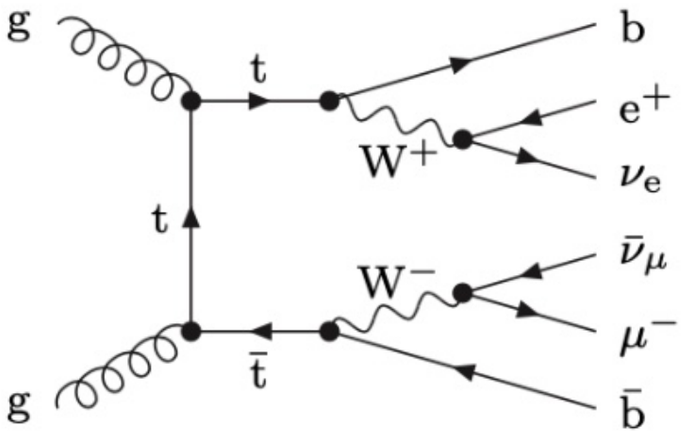
Finite-width effects

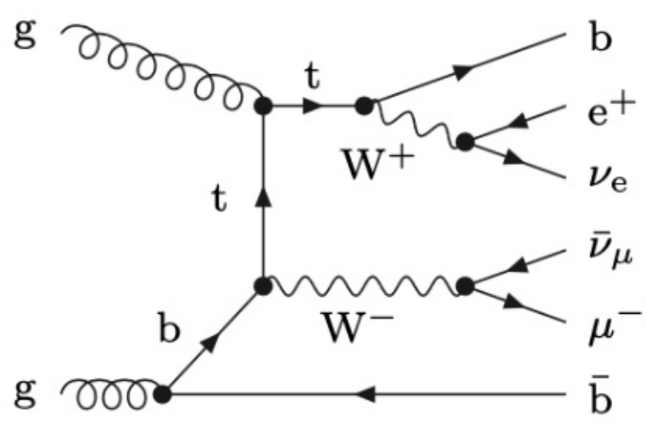


Pozzorini et al. (2012)

Finite-width effects of the top quark are typically small but more important than those of the W

Isolating Wt





NLO Wt simulations typically based on either

Frixione et al (2008)

- Diagram Removal (DR): removing doubly resonant diagrams
- Diagram Subtraction (DS): cancelling doubly resonant contributions in a gauge invariant way

These methods are a significant source of uncertainty for many BSM searches

Unified tt and Wt description

Experimental studies have shown the limitations of simulations based on subtraction of Wt contribution

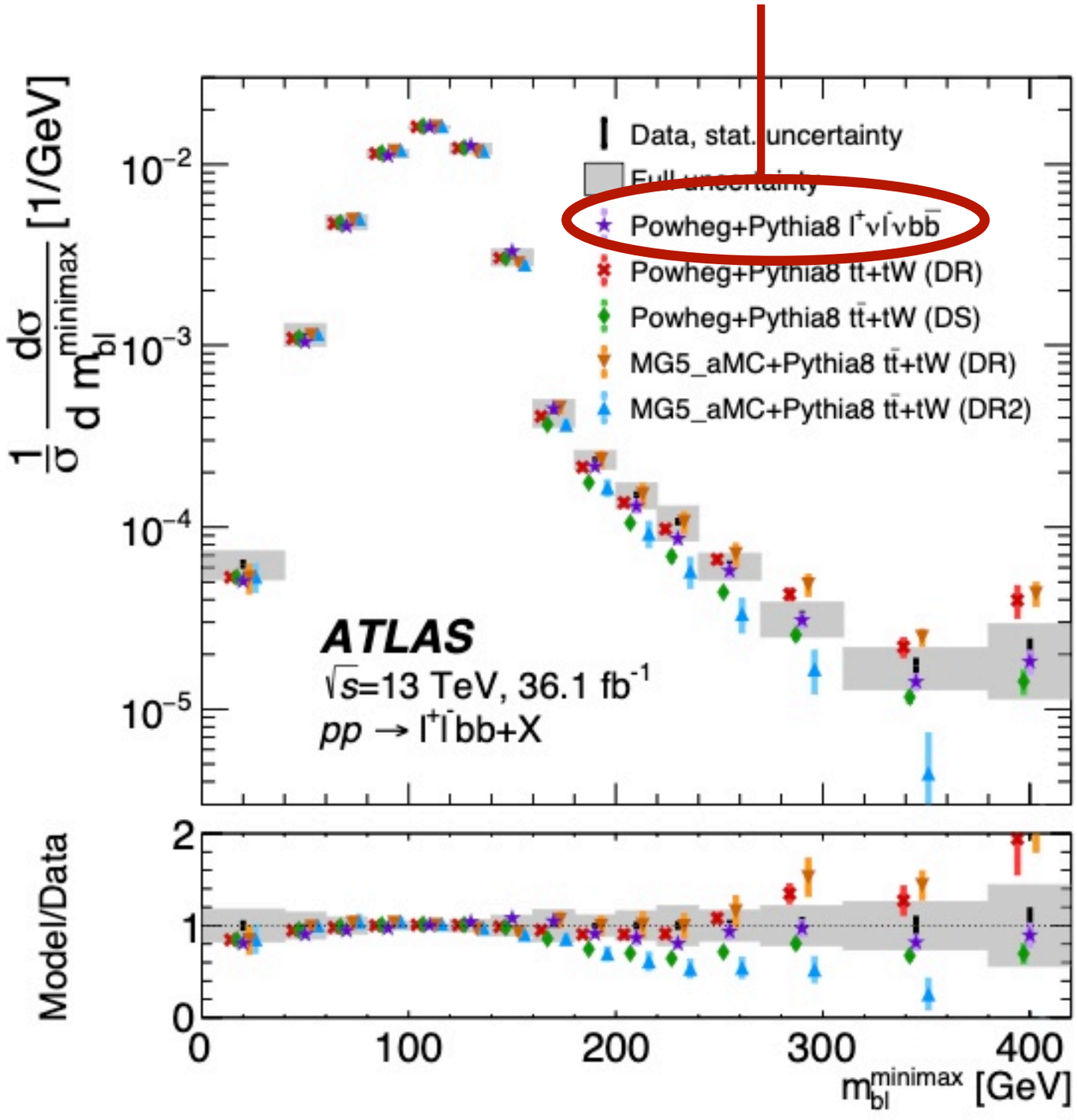
$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

Low m_{bl}^{minimax} region dominated by doubly resonant topologies

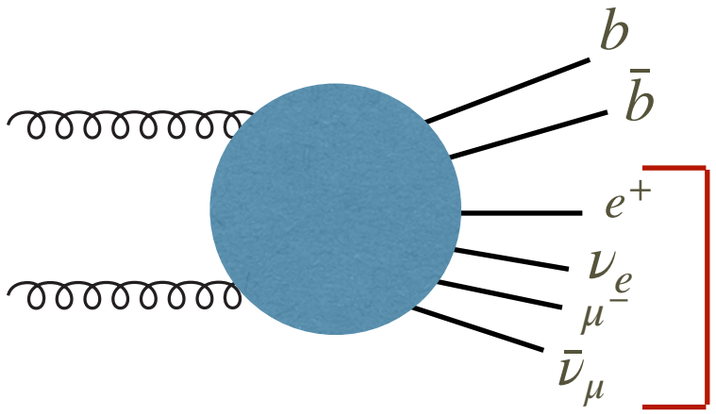
High m_{bl}^{minimax} region properly modelled by full tt+Wt simulation

Full tt+Wt prediction

Jezo, Lindert, Nason, Oleari, Pozzorini (2016)



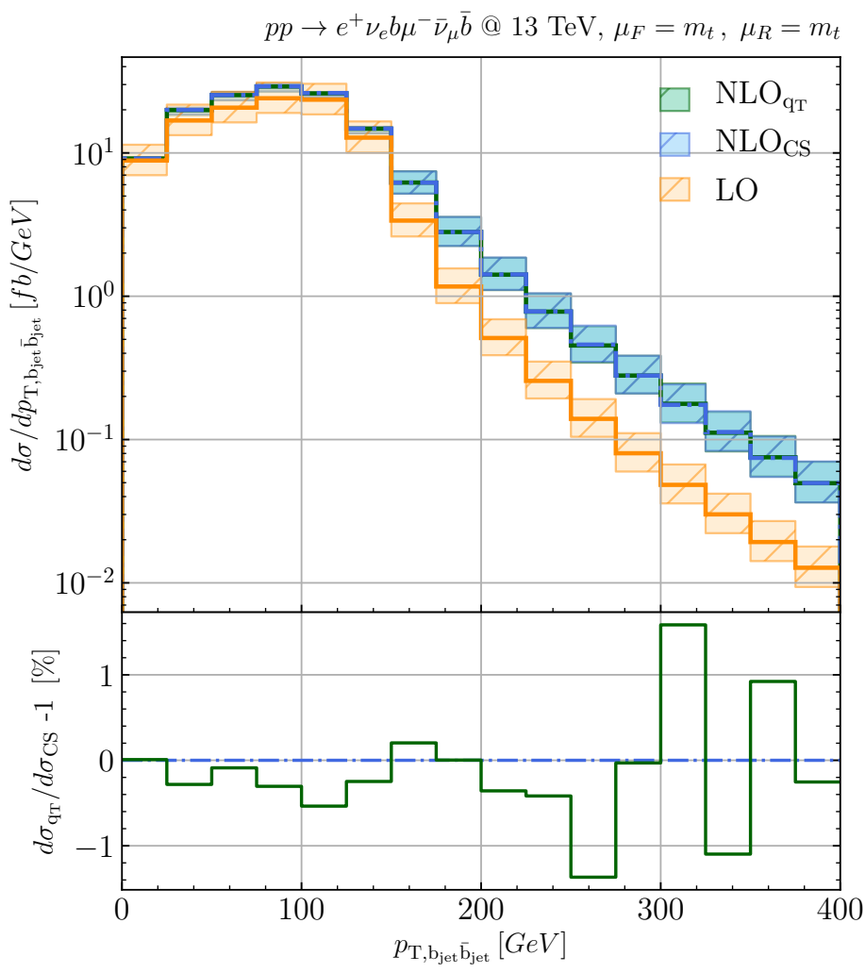
NNLO ?

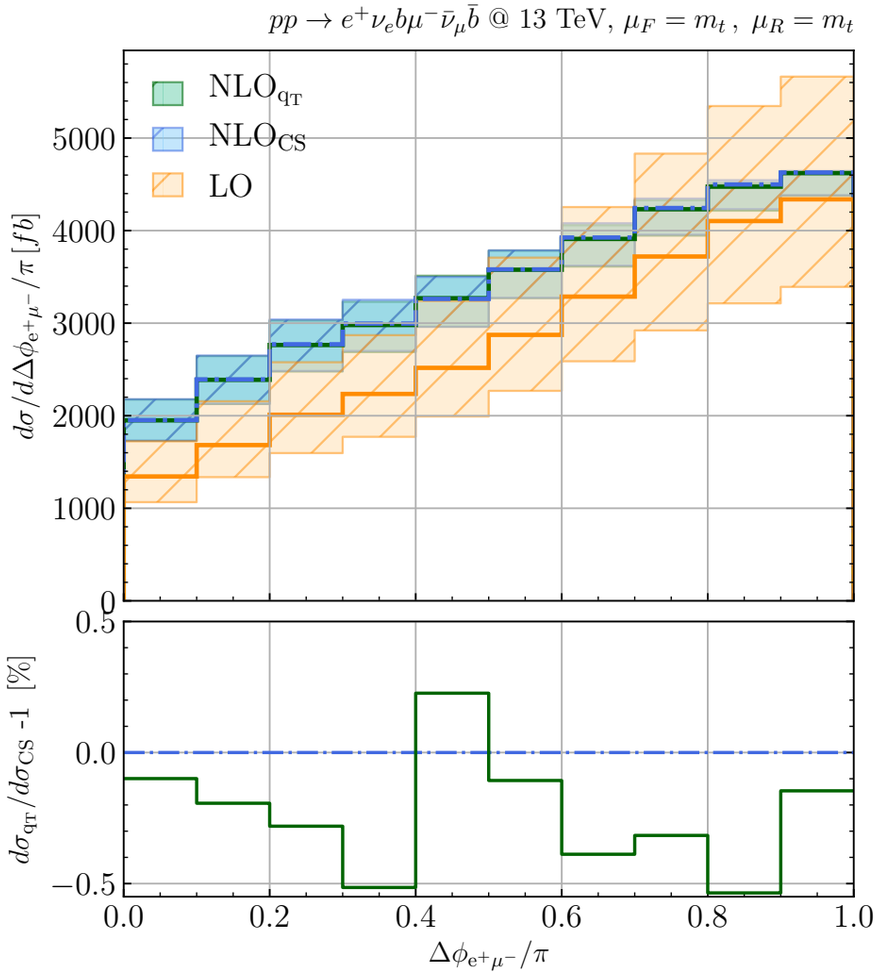


colourless

Required two-loop amplitudes are beyond current possibilities

Appropriate approximations needed





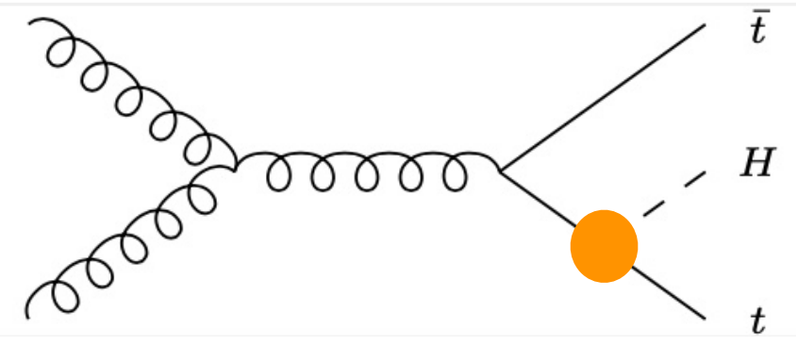
Fully validated at NLO

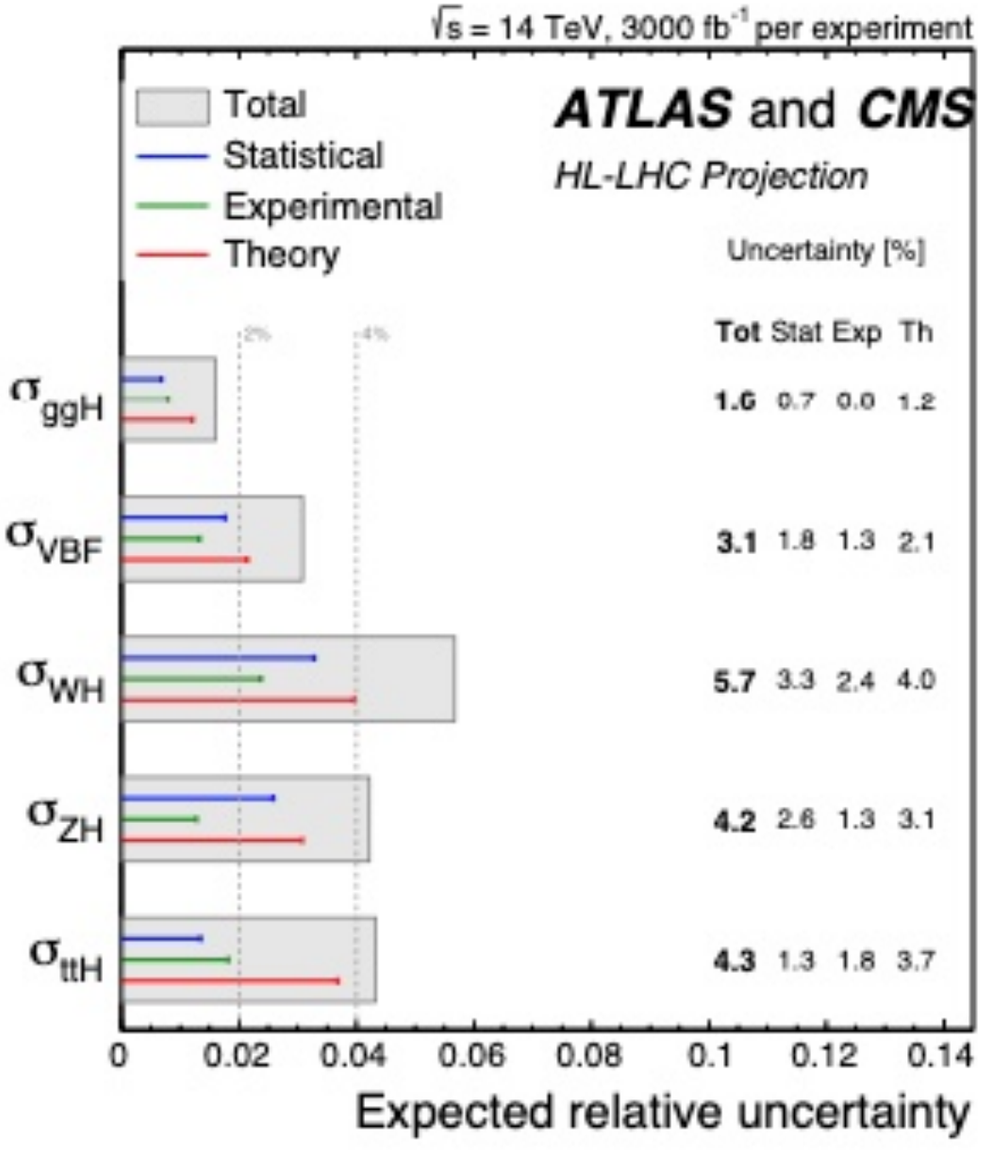
work in progress with Buonocore, Lindert, Devoto, Mazzitelli, Kallweit, Savoini

ttH

The associated production of the Higgs boson with a top-quark pair is a crucial process at the LHC

It allows a direct extraction of the top Yukawa





Experimental uncertainties are now at the $\mathcal{O}(20\%)$ level but expected to go down to the 2% level at the end of the HL-LHC

Current predictions based on NLO QCD+EW (+ resummations) affected by $\mathcal{O}(10\%)$ uncertainty

Missing ingredients for NNLO are the two-loop $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ amplitudes

ttH

The idea: use an approximation for the missing two-loop amplitude (similar in spirit to recent $2 \to 3$ NNLO calculations where leading colour approximation for the 2-loop is used)

See talk by Javier Mazzitelli

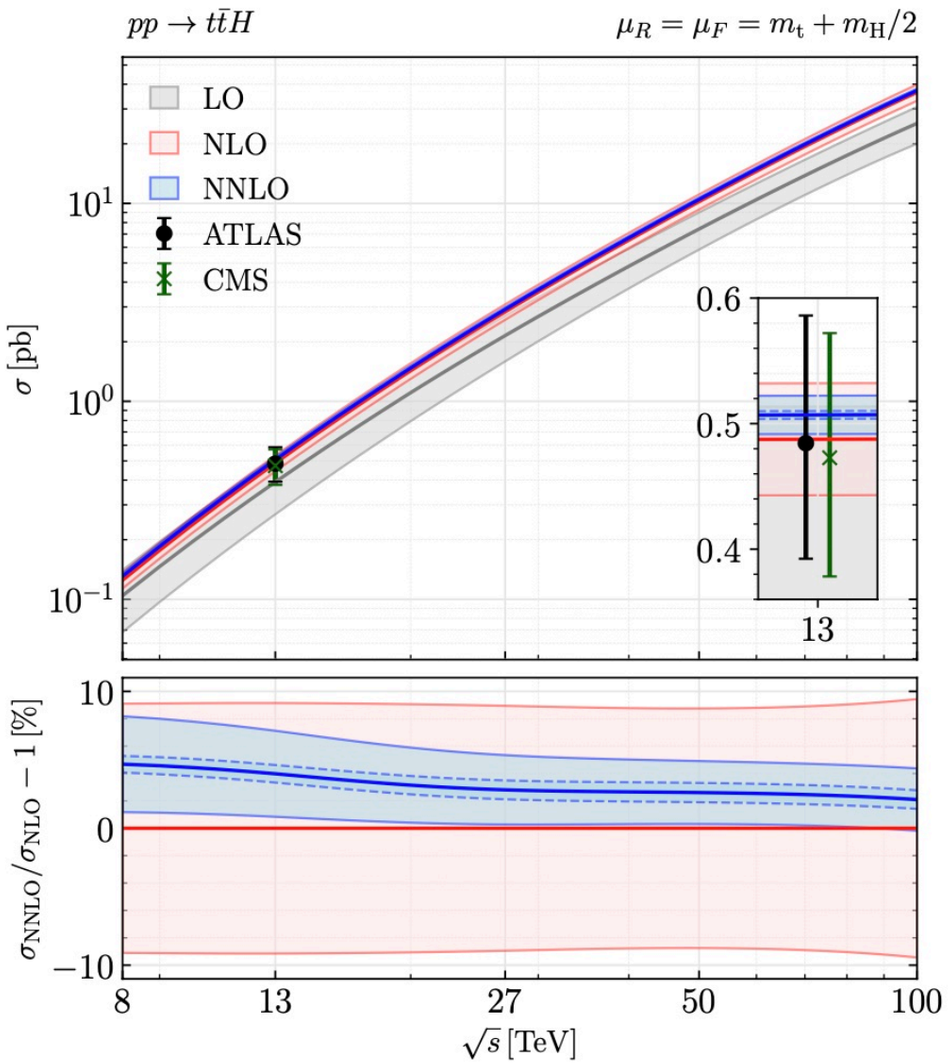
$$\mathscr{M}(\{p_i\}, k) \simeq F(\alpha_S(\mu_R); m/\mu_R)\, J(k)\mathscr{M}(\{p_i\})$$

Soft limit of the scalar heavy-quark form factor

Bernreuther et al (2005); Blümlein et al (2017)
Fael, Lange, Schönwald, Steinhauser (2022)

Approximated term has very small impact

σ [pb]	$\sqrt{s} = 13\,\text{TeV}$	$\sqrt{s} = 100\,\text{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)\,^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$



NNLO effect is about +4 % at 13 TeV and +2 % at 100 TeV

Catani, Devoto, Mazzitelli, Kallweit, Savoini, MG (2022)

Summary

- Top quarks are ubiquitous at the LHC
- Precise control of top production is fundamental to tame backgrounds in most of BSM searches and to fully exploit the LHC potential
- Theoretical predictions in good shape with NNLO+NLO EW becoming the standard
- NNLO precision starts to be deployed in MC generators
- Further progress is expected/needed to include off-shell effects beyond NLO
- First NNLO results for ttH