Precision Predictions for Top-quark Width

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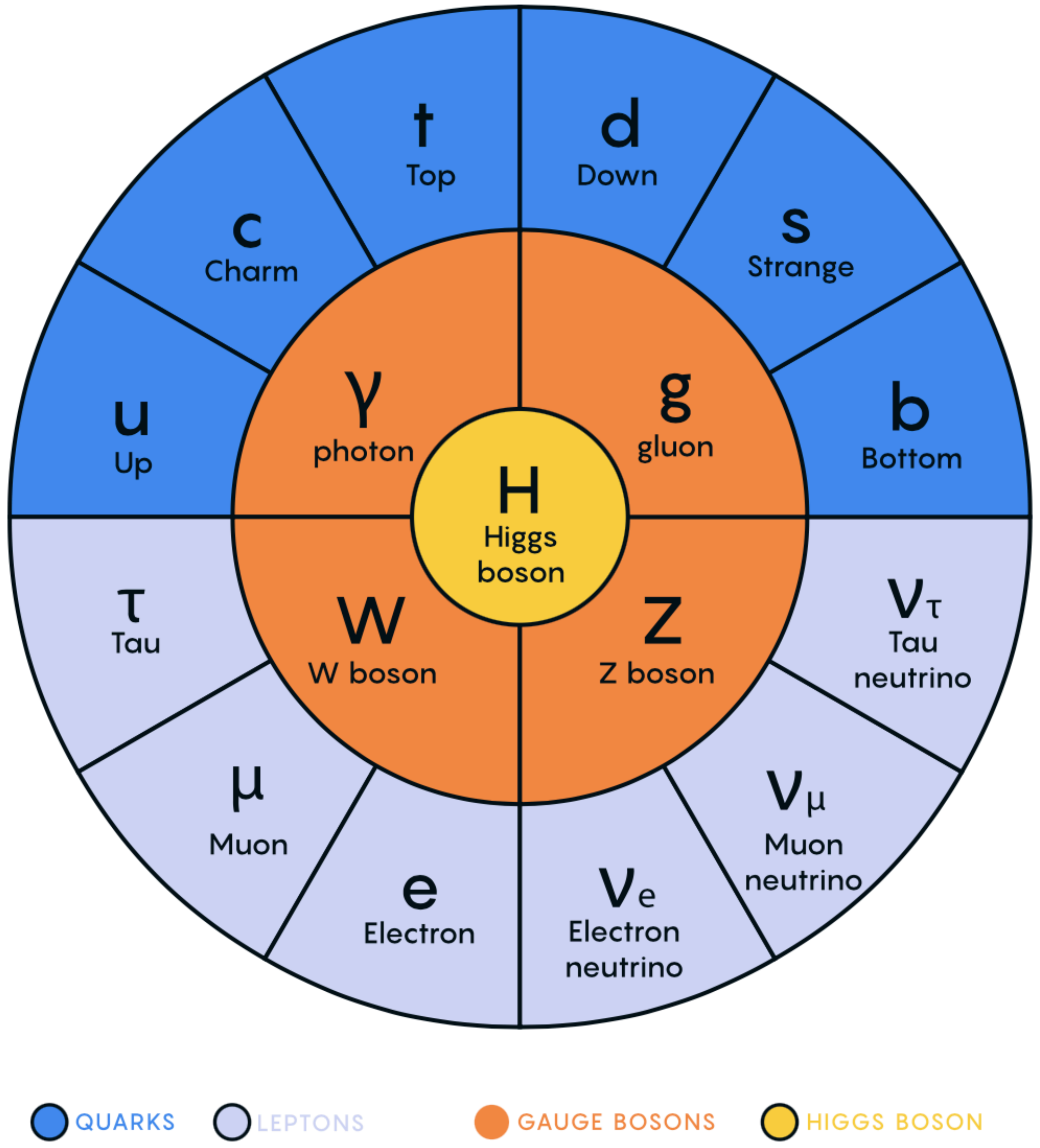
arXiv:2212.06341

华中师范大学，粒子物理小型工作会议

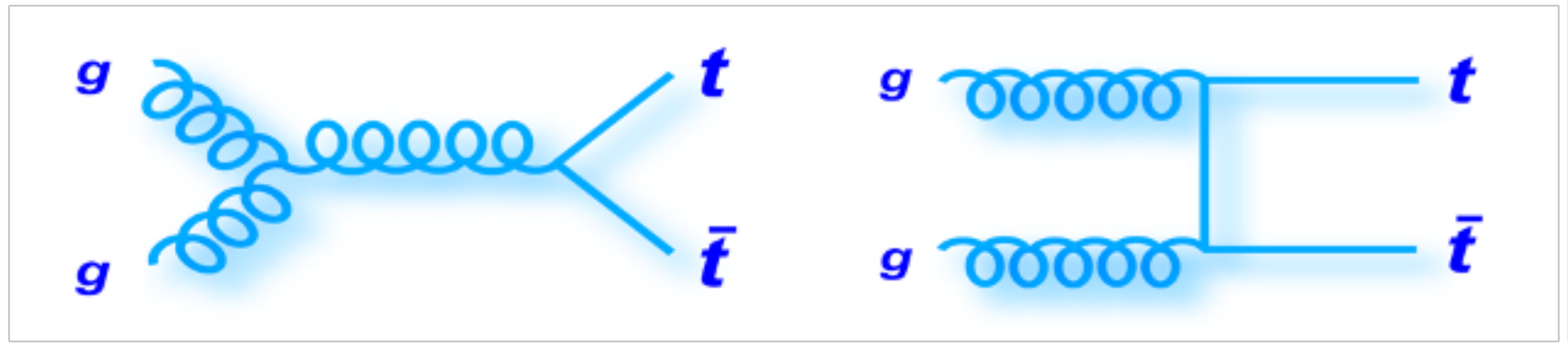
2023-04-24

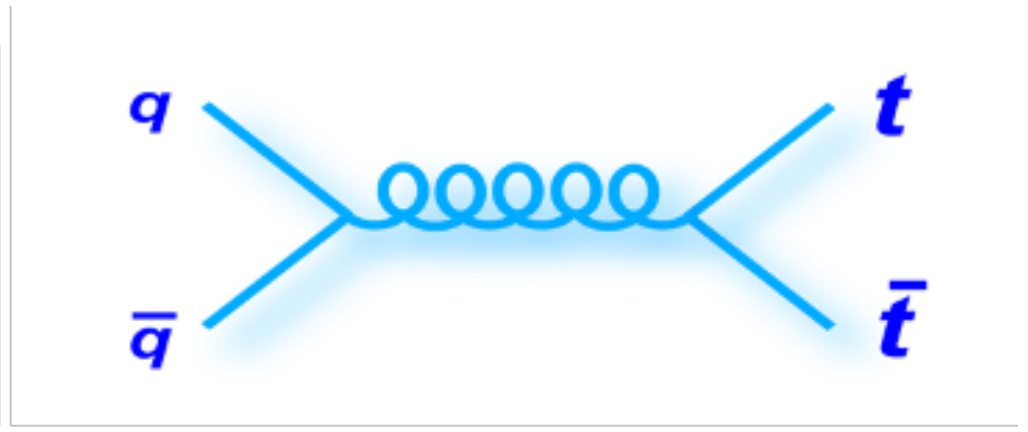
Introduction



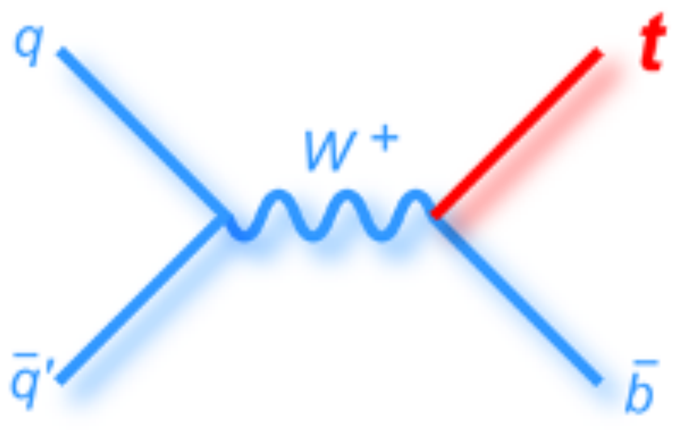
- ☑ Top quark is the heaviest elementary particle in the Standard Model.
- ☑ Top quark might play a role of electroweak symmetry breaking
- ☑ The measurements at the LHC offer the ultimate precision in top quark physics
- ☑ Top quark is a good probe of new physics

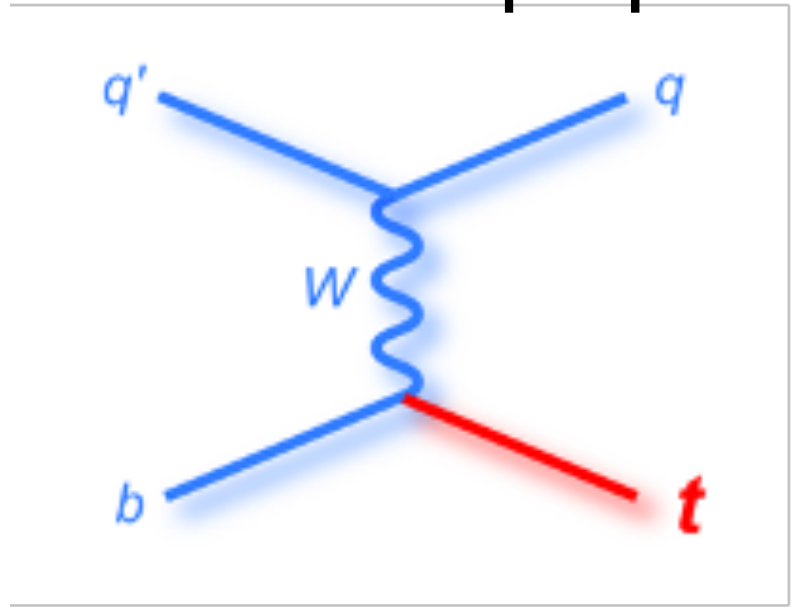
Introduction

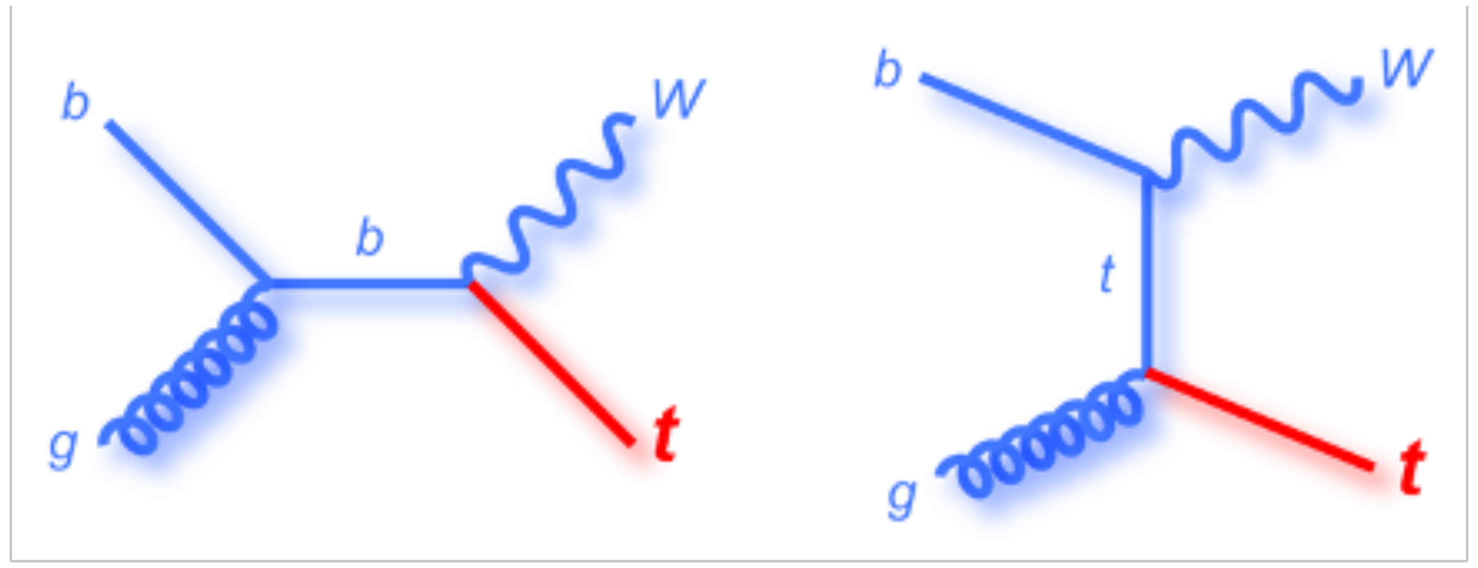




- It has high precision of the experimental measurements of total and differential cross sections
- It is used to study many properties of the top quark



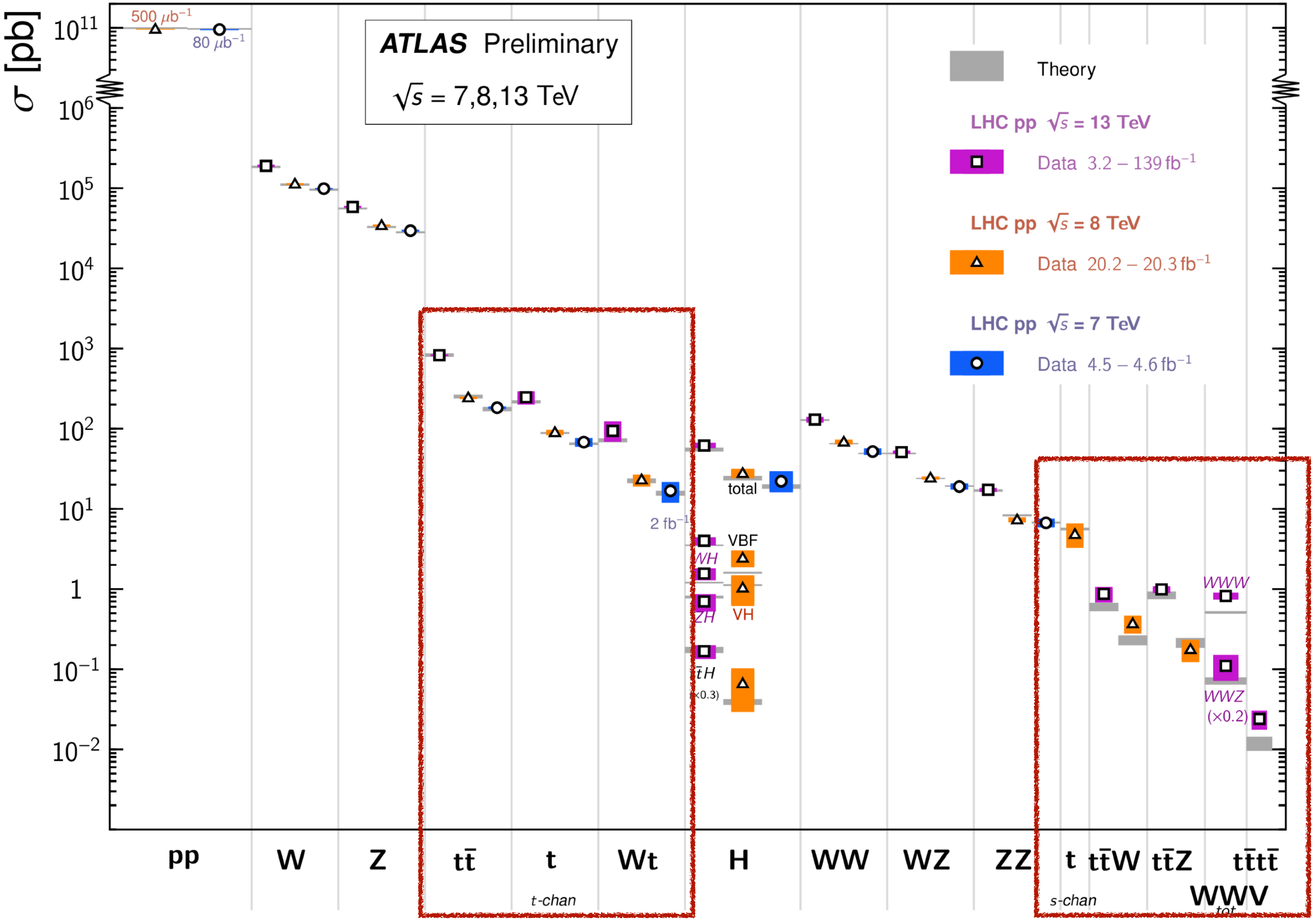




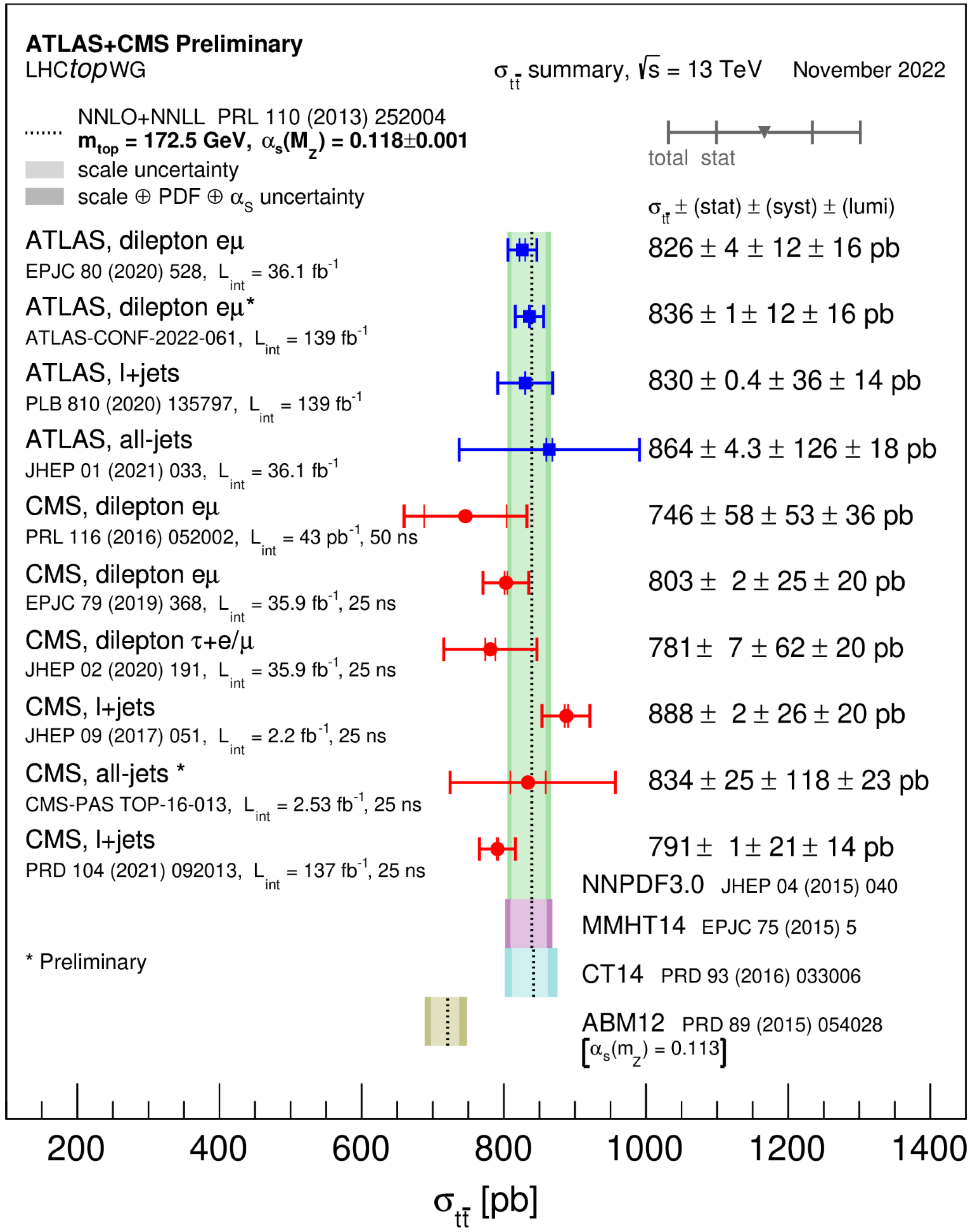
- it allows measurement of V_{tb} per channel
- It is easier to check the chiral structure of Wtb vertex than $t\bar{t}$ production
- it-channel can be used to measurement the b quark density

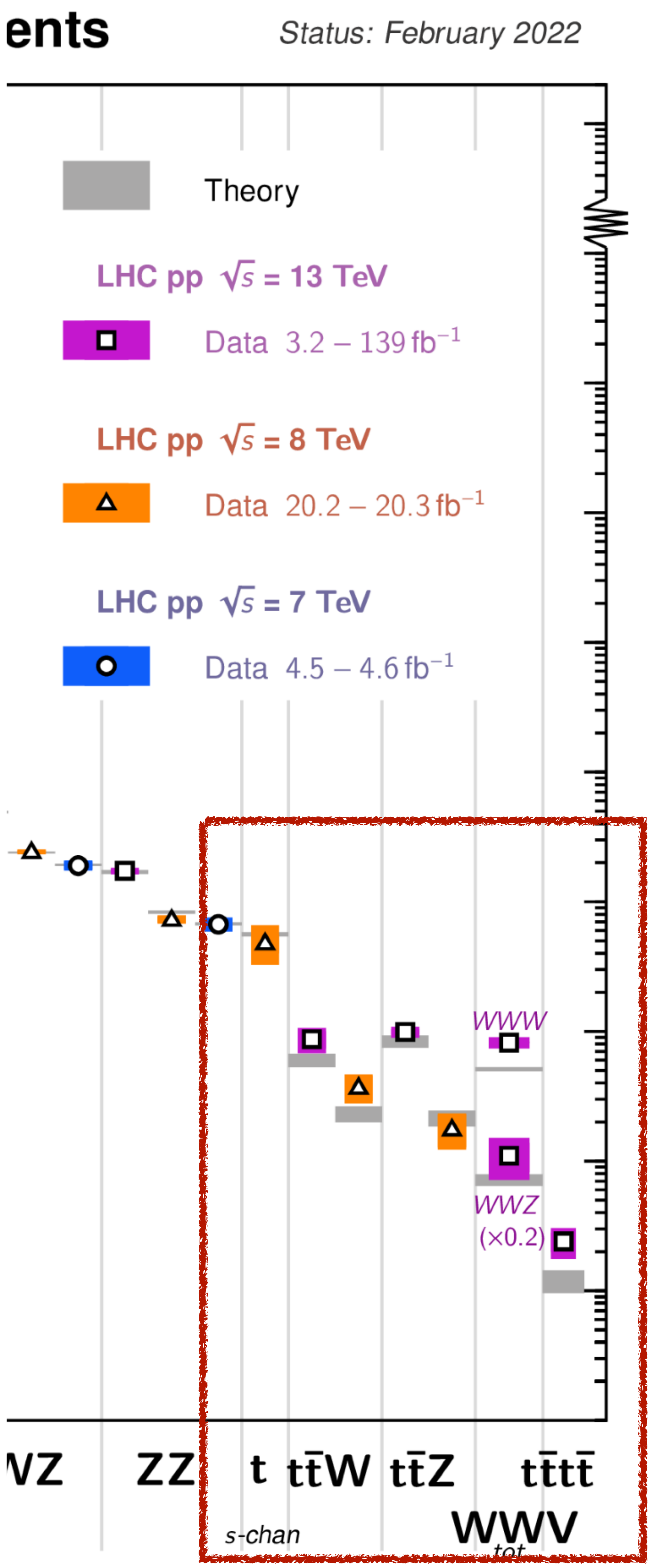
Standard Model Total Production Cross Section Measurements

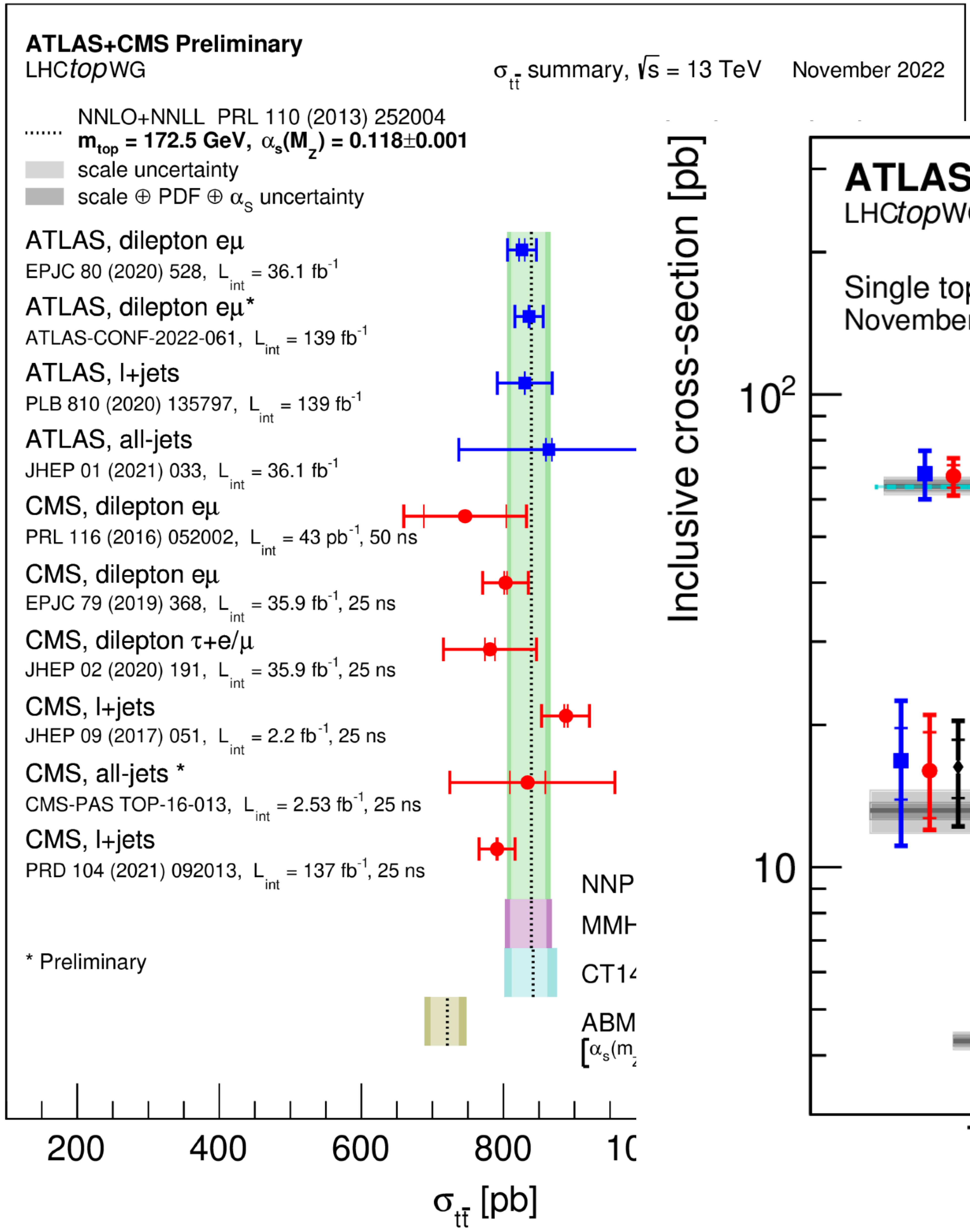
Status: February 2022




σ [pb]
s


ATLAS+CMS Preliminary
LHCtopWG
σ_tt̄ summary, √s = 13 TeV
November 2022
NNLO+NNLL PRL 110 (2013) 252004
m_top = 172.5 GeV, α_s(M_Z) = 0.118±0.001
scale uncertainty
scale ⊕ PDF ⊕ α_S uncertainty
total stat
σ_tt̄ ± (stat) ± (syst) ± (lumi)
ATLAS, dilepton eμ
EPJC 80 (2020) 528, L_int = 36.1 fb-1
826 ± 4 ± 12 ± 16 pb
ATLAS, dilepton eμ*
ATLAS-CONF-2022-061, L_int = 139 fb-1
836 ± 1± 12 ± 16 pb
ATLAS, l+jets
PLB 810 (2020) 135797, L_int = 139 fb-1
830 ± 0.4 ± 36 ± 14 pb
ATLAS, all-jets
JHEP 01 (2021) 033, L_int = 36.1 fb-1
864 ± 4.3 ± 126 ± 18 pb
CMS, dilepton eμ
PRL 116 (2016) 052002, L_int = 43 pb-1, 50 ns
746 ± 58 ± 53 ± 36 pb
CMS, dilepton eμ
EPJC 79 (2019) 368, L_int = 35.9 fb-1, 25 ns
803 ± 2 ± 25 ± 20 pb
CMS, dilepton τ+e/μ
JHEP 02 (2020) 191, L_int = 35.9 fb-1, 25 ns
781 ± 7 ± 62 ± 20 pb
CMS, l+jets
JHEP 09 (2017) 051, L_int = 2.2 fb-1, 25 ns
888 ± 2 ± 26 ± 20 pb
CMS, all-jets *
CMS-PAS TOP-16-013, L_int = 2.53 fb-1, 25 ns
834 ± 25 ± 118 ± 23 pb
CMS, l+jets
PRD 104 (2021) 092013, L_int = 137 fb-1, 25 ns
791 ± 1 ± 21 ± 14 pb
NNPDF3.0 JHEP 04 (2015) 040
MMHT14 EPJC 75 (2015) 5
CT14 PRD 93 (2016) 033006
ABM12 PRD 89 (2015) 054028
[α_s(m_Z) = 0.113]
* Preliminary
200
400
600
800
1000
1200
1400
σ_tt̄ [pb]


ents
Status: February 2022
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb−1
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb−1
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb−1
WWW
WWZ
(×0.2)
VZ
ZZ
t
tt̄W
tt̄Z
tt̄tt̄
s-chan
WWV
tot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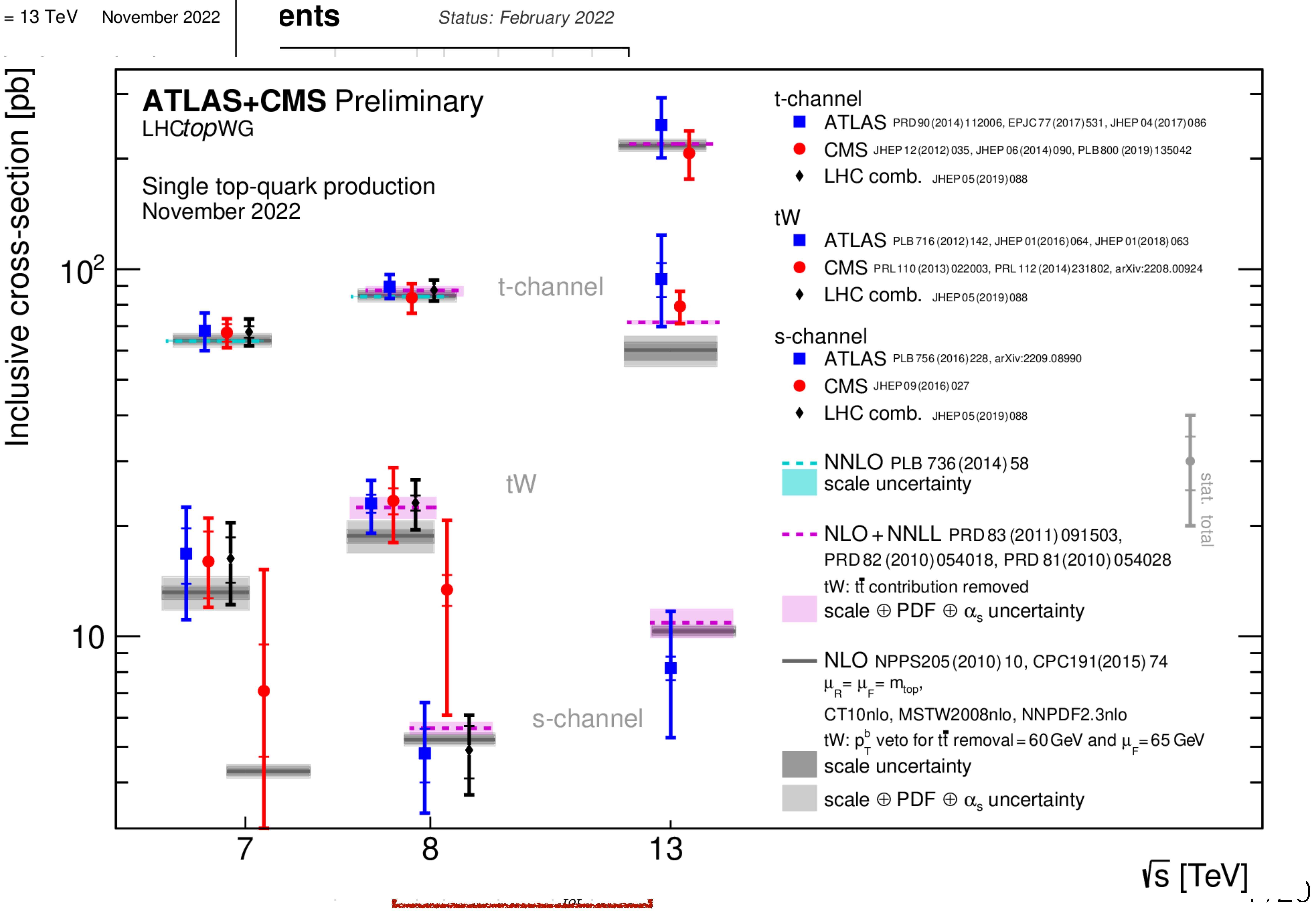
* Preliminary
200
400
600
800
σ_tt̄ [pb]


ents
Status: February 2022
ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
November 2022
Inclusive cross-section [pb]
10^2
10
t-channel
tW
s-channel
7
8
13
√s [TeV]
t-channel
ATLAS PRD 90 (2014) 112006, EPJC 77 (2017) 531, JHEP 04 (2017) 086
CMS JHEP 12 (2012) 035, JHEP 06 (2014) 090, PLB 800 (2019) 135042
LHC comb. JHEP 05 (2019) 088
tW
ATLAS PLB 716 (2012) 142, JHEP 01 (2016) 064, JHEP 01 (2018) 063
CMS PRL 110 (2013) 022003, PRL 112 (2014) 231802, arXiv:2208.00924
LHC comb. JHEP 05 (2019) 088
s-channel
ATLAS PLB 756 (2016) 228, arXiv:2209.08990
CMS JHEP 09 (2016) 027
LHC comb. JHEP 05 (2019) 088
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503,
PRD 82 (2010) 054018, PRD 81 (2010) 054028
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ α_s uncertainty
NLO NPPS205 (2010) 10, CPC191 (2015) 74
μ_R = μ_F = m_top,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: p_T^b veto for tt̄ removal = 60 GeV and μ_F = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty
stat. total

Introduction

$$\sigma = \boxed{\int_{t_{\text{cut}}}^{t_{\max}} \frac{d\sigma}{dt_N}} + \boxed{\int_0^{t_{\text{cut}}} \frac{d\sigma}{dt_N}} \longrightarrow \frac{d\sigma}{dt_N} \propto \int H \otimes B_1 \otimes B_2 \otimes \boxed{S} \otimes \left(\prod_{n=1}^{N} J_n \right)$$

Standard NLO

HTL, Wang, 1611.02749,1804.06358

Amplitude reads $\mathscr{M} = \boxed{\mathscr{M}_0} + \boxed{\frac{\alpha_s}{4\pi}\mathscr{M}_1} + \boxed{\left(\frac{\alpha_s}{4\pi}\right)^2 \mathscr{M}_2}$

Tree 1-loop 2-loop

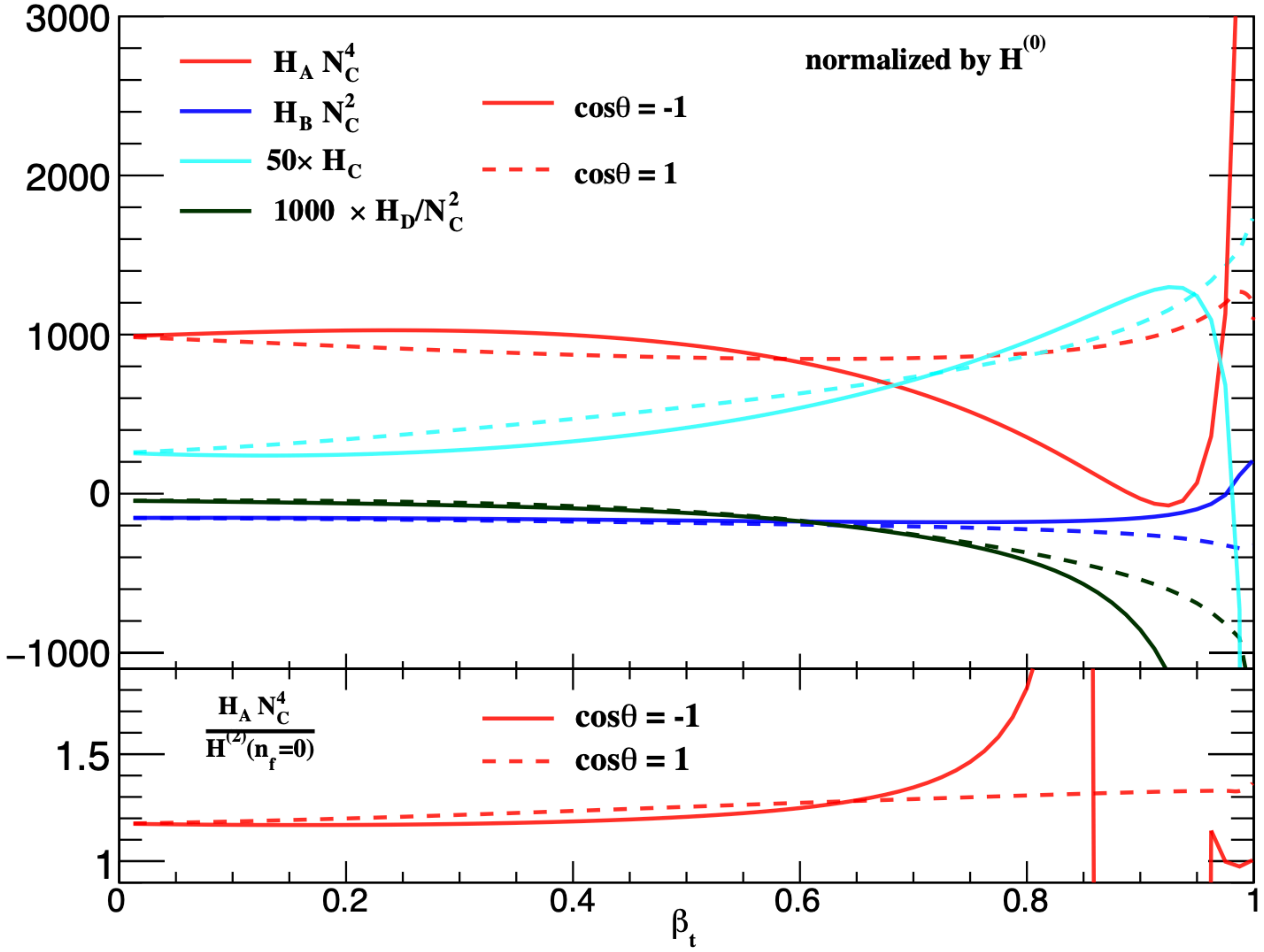
One-loop amplitude square arXiv:2204.13500

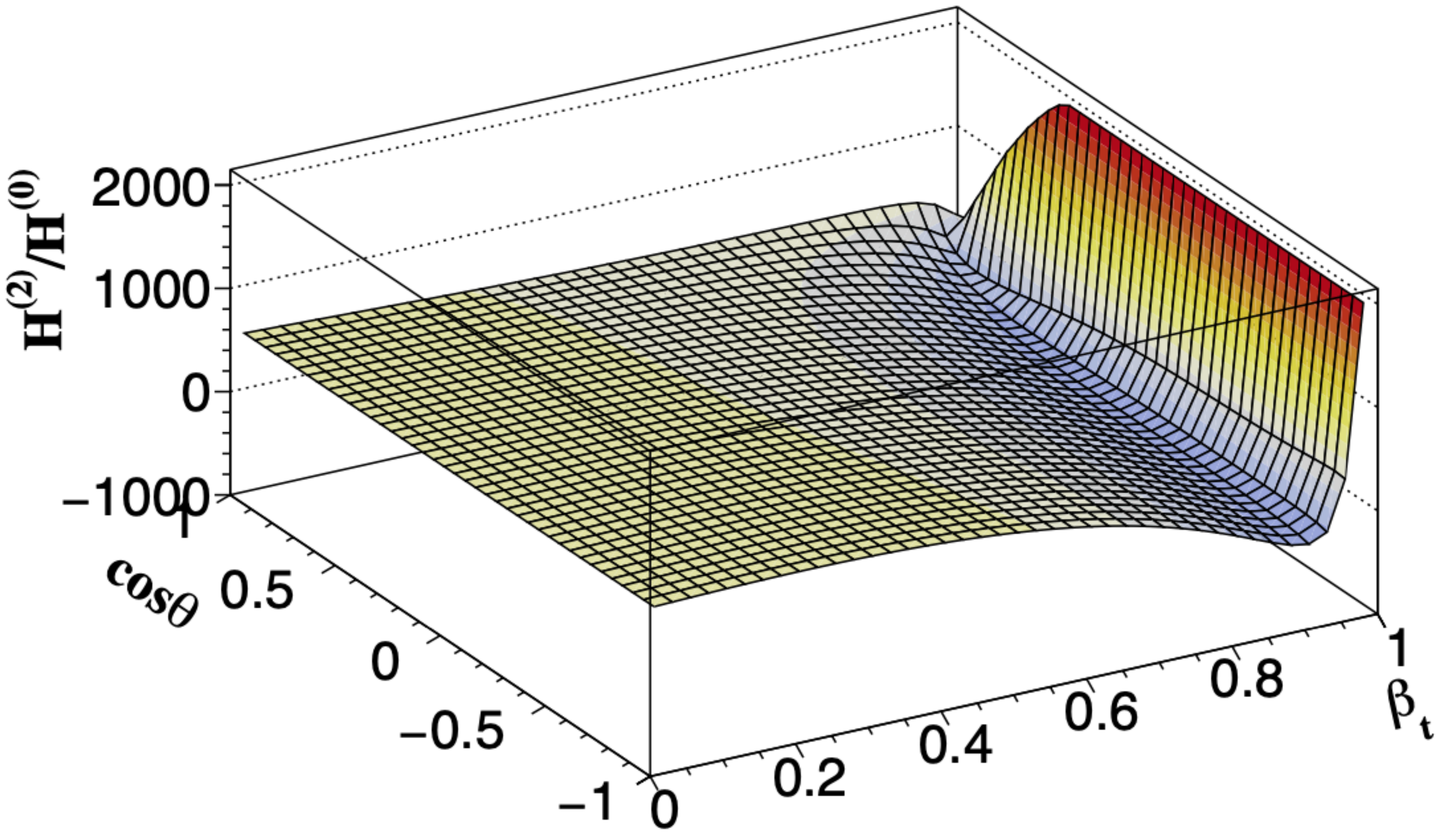
Two-loop analytical amplitude in LC approximation arXiv:2208.08786

Two-loop numerical amplitude in full color arXiv:2212.07190 by Chen, Dong, HTL, Li, Wang, Wang

Introduction

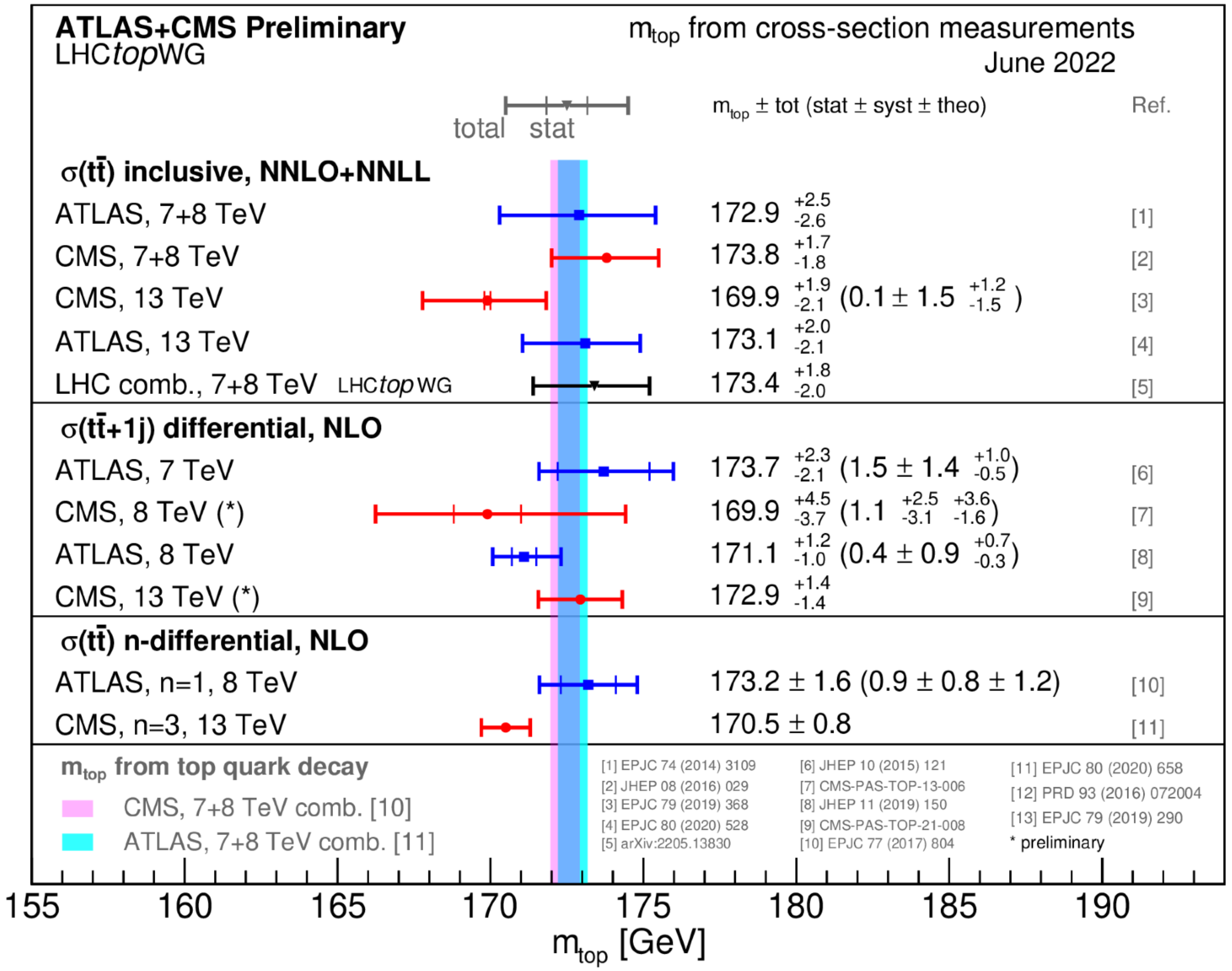
$$H^{(2)} = N_C^4 H_A + N_C^2 H_B + H_C + \frac{1}{N_C^2} H_D + n_l H_{nl} + n_h H_{nh}$$

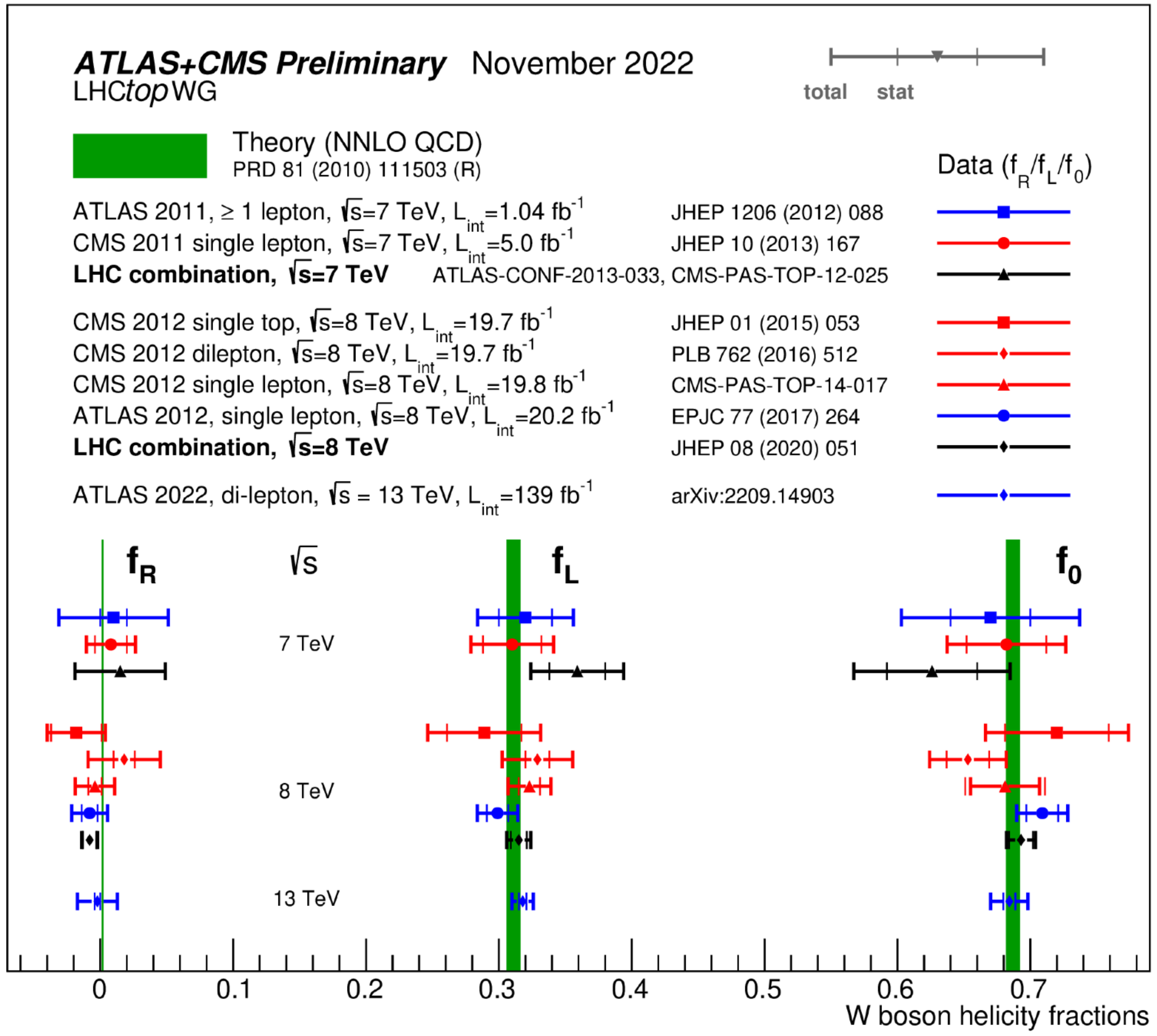




Introduction

Top quark intrinsic properties, Mass, Width, Spin 1/2, e-charge 2/3





Introduction

The top-quark decays almost exclusively to Wb, ie $\Gamma_t = \Gamma(t \to Wb)$.

At LHC, indirect techniques are precise but model dependent.

The most precise measurement is $\Gamma = 1.36 \pm 0.2^{+0.14}_{-11}$ GeV

$$\mathcal{R} = \frac{\mathcal{B}(\mathrm{t} \to \mathrm{Wb})}{\mathcal{B}(\mathrm{t} \to \mathrm{Wq})} = \mathcal{B}(\mathrm{t} \to \mathrm{Wb})$$

Measuring $\mathcal{R}$ with top pair event

$$\Gamma_{\mathrm{t}} = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(\mathrm{t} \to \mathrm{Wb})} \cdot \frac{\Gamma(\mathrm{t} \to \mathrm{Wb})}{\sigma^{\mathrm{theor.}}_{t\text{-ch.}}}$$

CMS, 2014

Direct techniques are less precise but model independent.

Direct result by ATLAS is $\Gamma_t = 1.9 \pm 0.5$ GeV **ATLAS, 2019**

Using events away from the resonance peak $\Gamma_t = 1.28 \pm 0.3$ GeV **Baskakov, Boos, Dudko, 2018** **Herwig, Jazo, Nachman, 2019**

In the future e^+e^- collider, Γ_t can be measured with an uncertainty of 30 MeV **Martinez, Miquel 2003**

Introduction

NLO QCD corrections

Bigi, Dokshitzer, Khoze, Kuhn,Zerwas, 1986

Jezabek, Kuhn 1989, Czarnecki 1990, Li, Oakes, Yuan 1991

NLO EW corrections

Denner, Sack 1991, Eilam, Mendel, Migneron, Soni 1991

Asymptotic expansions of NNLO QCD corrections near $m_W \to 0$ and $m_W \to m_t$

Czarnecki, Melnikov 1999, Chetyrkin, Harlander, Seidensticker, Steinhauser 1999,
Blokland, Czarnecki, Slusarczyk, Tkachov 2004, 2005

Numerical results of full NNLO QCD corrections Gao, Li, Zhu 2013, Brucherseifer, Caola, Melnikov 2013

Polarized top decay up to NNLO QCD Czarnecki, Groote, Körner and Piclum, 2018

PMC scale settings up to NNLO QCD Meng, Wang, Sun, Luo, Shen, Wu, 2022

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Analytical results of NNLO QCD corrections — Chen, HTL, Wang, Wang, 2022

Optical Theory

Unitarity implies the S-matrix

$$S^\dagger S = 1, \text{ with } S = 1 + iT$$

T is the transfer matrix

$$-i(T - T^\dagger) = TT^\dagger$$

Take the matrix element of this equation

$$\langle f | T | i \rangle = (2\pi)^4 \delta^{(4)}\left(p_i - p_f\right) \mathscr{M}(i \to f)$$

$$\left\langle \mathbf{p}_1 \mathbf{p}_2 \left| T^\dagger T \right| \mathbf{k}_1 \mathbf{k}_2 \right\rangle = \sum_n \int d\Phi_n \left\langle \mathbf{p}_1 \mathbf{p}_2 \left| T^\dagger \right| \{\mathbf{q}_n\} \right\rangle \left\langle \{\mathbf{q}_n\} | T | \mathbf{k}_1 \mathbf{k}_2 \right\rangle$$

The generalized optical theorem is

$$-i\left(\mathscr{M}(i \to f) - \mathscr{M}^*(i \to f)\right) = \sum_X \int d\Phi_X \mathscr{M}(i \to X) \mathscr{M}^*(f \to X)$$

For top quark decay width $|i\rangle = |f\rangle = |A\rangle$

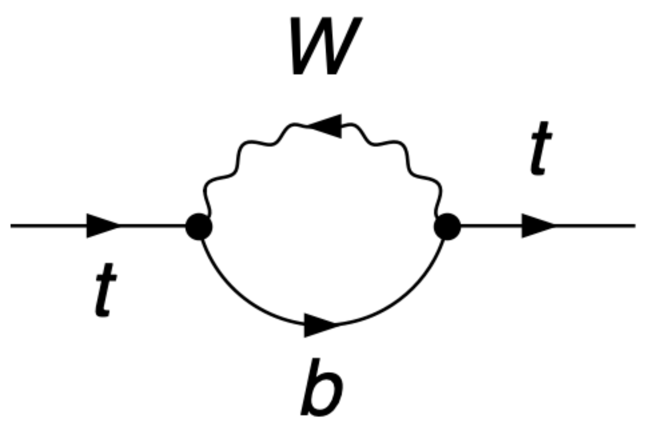
$$\operatorname{Im} \mathscr{M}(A \to A) = m_A \sum_X \Gamma(A \to X) = m_A \Gamma_{\text{tot}}$$

Optical Theory

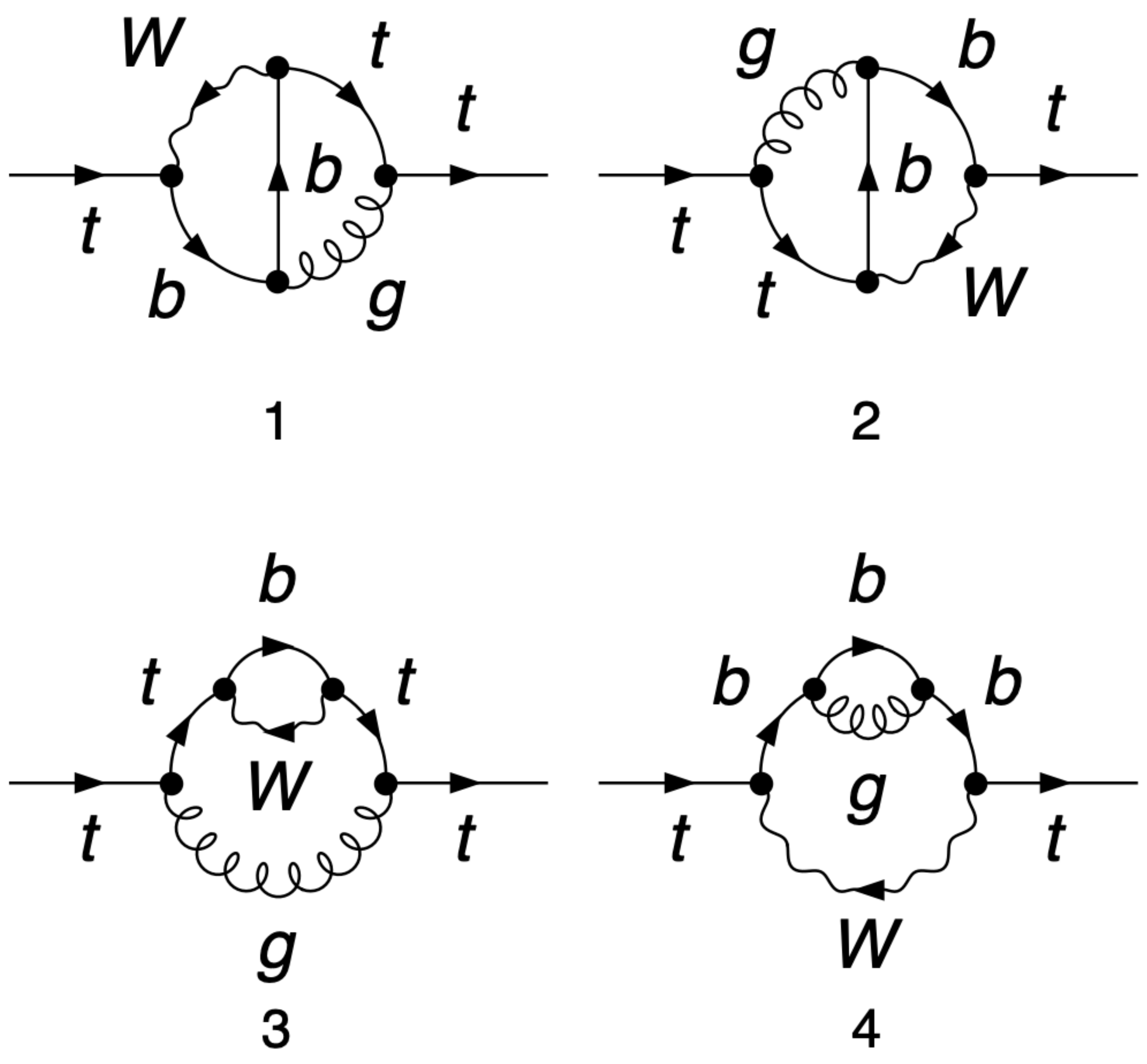
Top decaying into massless b quark and on-shell W boson

$$\Gamma_t = \frac{\mathrm{Im}\Sigma}{m_t}$$

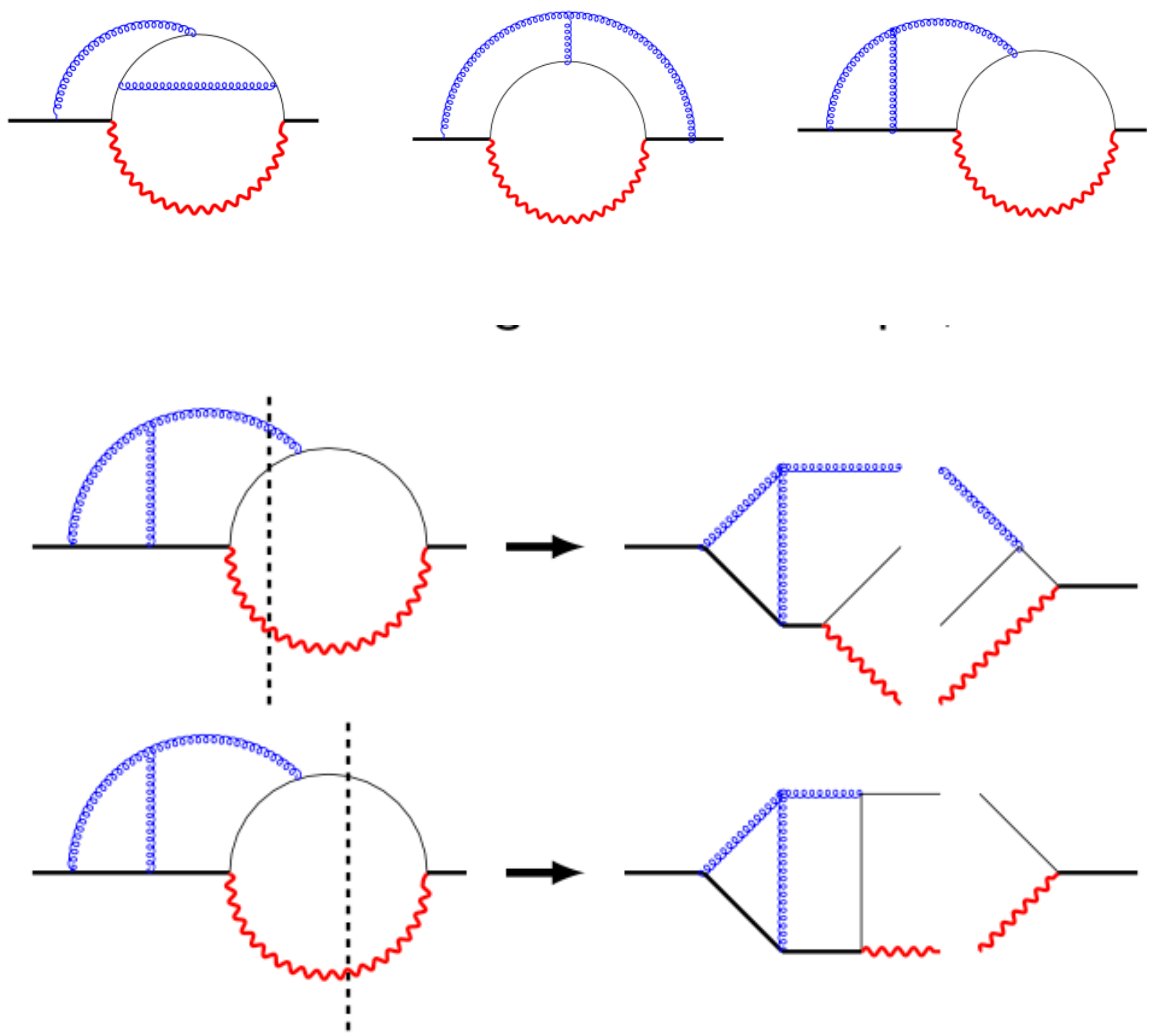
LO



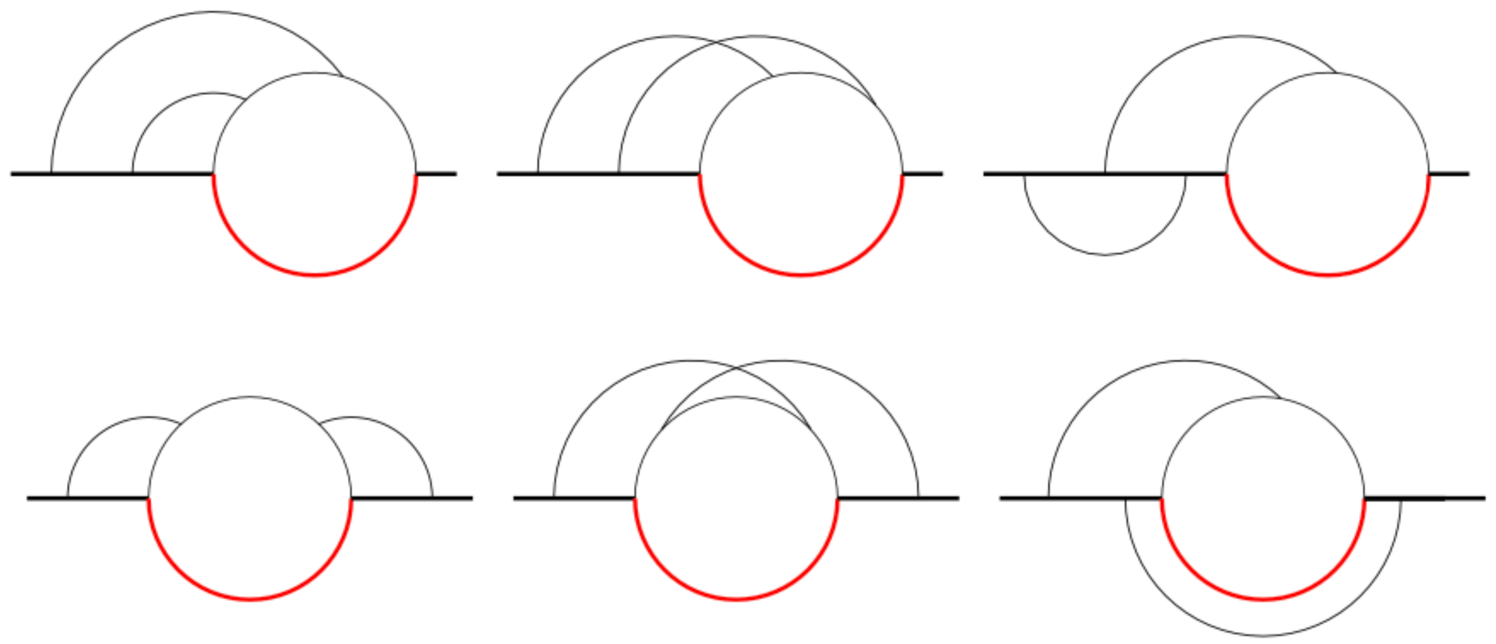
NLO



NNLO



Amplitude and Master integrals



The amplitudes generated by FeynArts and FeynCalc

Scalar integrals reduced to master integrals using FIRE 6

Canonical differential equations constructed for the cut MIs by choosing a proper basis **I**(w, ε) Henn, 2013

$$\mathrm{d}\,\mathrm{I}(w,\epsilon) = \epsilon\,\mathrm{d}\left[\sum_{i=1}^{4} \mathrm{R}_i \log(l_i)\right] \mathrm{I}(w,\epsilon)$$

Boundary conditions: $w = \frac{m_W^2}{m_t^2} = 0$

The analytical results of some master integrals in $w = 0$ can be found in literatures Blokland, Czarnecki, Slusarczyk, Tkachov 2005, Ritbergen, Stuart 2000.

Others reconstructed by PSLQ algorithm with AMFlow Liu, Ma 2022

Top decay width

Top decaying into massless b quark and on-shell W boson

$$\Gamma(t \to Wb) = \Gamma_0 \left[X_0 + \frac{\alpha_s}{\pi} X_1 + \left(\frac{\alpha_s}{\pi} \right)^2 X_2 \right],$$

$$X_2 = C_F(T_R n_l X_l + T_R n_h X_h + C_F X_F + C_A X_A)$$

NNLO contributions written as HPLs

$$X_l = -\frac{X_0}{3} \left[H_{0,1,0}(w) - H_{0,0,1}(w) - 2H_{0,1,1}(w) + 2H_{1,1,0}(w) - \pi^2 H_1(w) - 3\zeta(3) \right] + \cdots$$

$$X_F = \frac{1}{12} X_0 \left[-6 \left(2H_{0,1,0,1}(w) + 6H_{1,0,0,1}(w) - 3H_{1,0,1,0}(w) - 12\zeta(3) H_1(w) \right) - \pi^2 H_{1,0}(w) \right] + \left(X_0 + 4w \right) \left(-\frac{1}{6} \pi^2 H_{0,-1}(w) - 2H_{0,-1,0,1}(w) \right) + \cdots]$$

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$$X_2 = C_F(T_R n_l X_l + T_R n_h X_h + C_F X_F + C_A X_A)$$

NNLO contributions written as HPLs

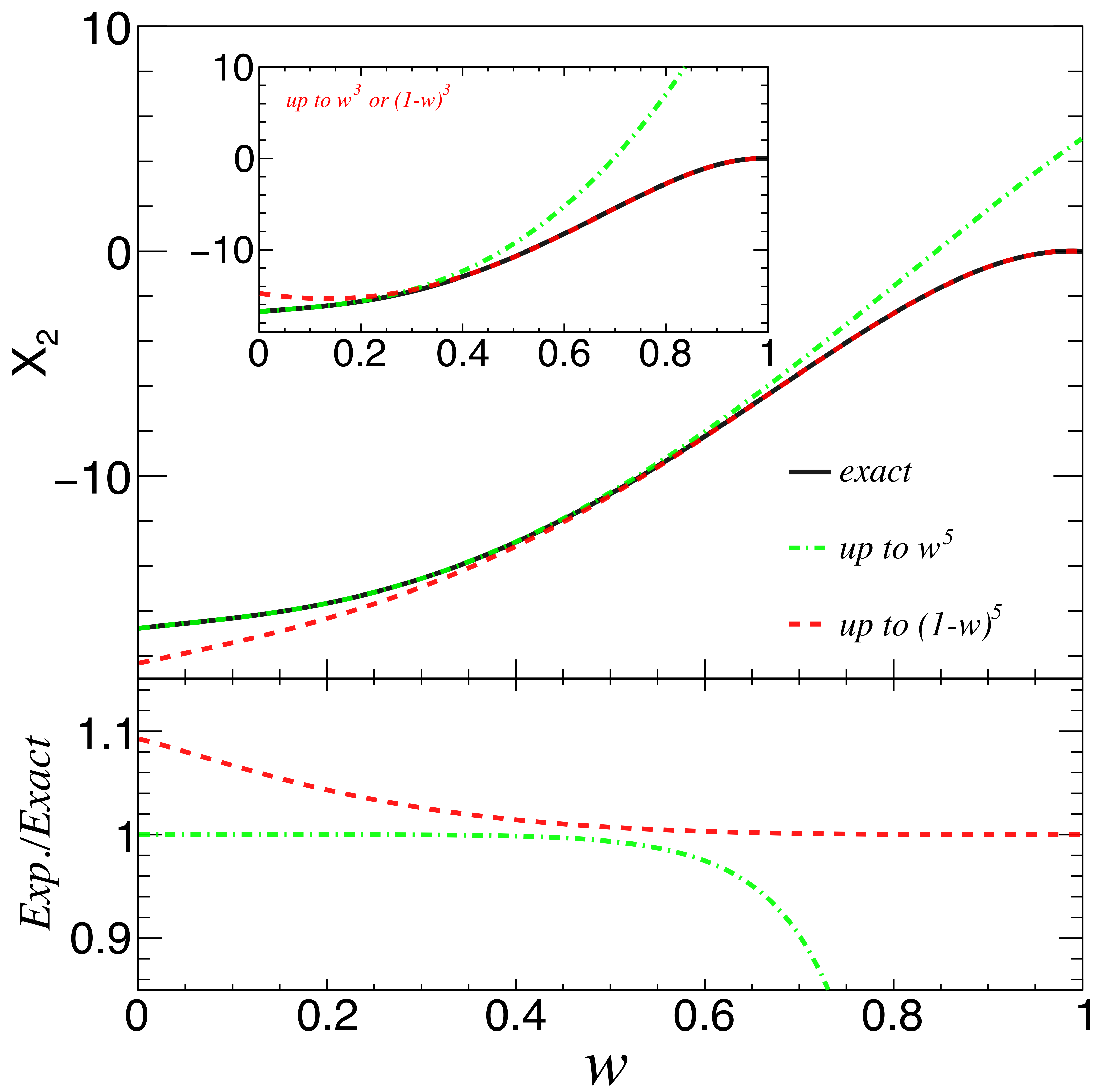
	width (GeV)	delta/LO width
LO	1.48642	—
NLO	1.35897	-8.58%
NNLO	1.32825	-2.07%

$$X_l = -\frac{X_0}{3}\left[H_{0,1,0}(w) - H_{0,0,1}(w) - 2H_{0,1,1}(w) + 2H_{1,1,0}(w) - \pi^2 H_1(w) - 3\zeta(3)\right] + \cdots$$

Consistent with Gao, Li, Zhu 2013

$$X_F = \frac{1}{12}X_0\Big[-6\left(2H_{0,1,0,1}(w) + 6H_{1,0,0,1}(w) - 3H_{1,0,1,0}(w) - 12\zeta(3)H_1(w)\right) - \pi^2 H_{1,0}(w)\Big] + \left(X_0 + 4w\right)\left(-\frac{1}{6}\pi^2 H_{0,-1}(w) - 2H_{0,-1,0,1}(w)\right) + \cdots]$$

Top decay width



Though the decay width at w=0 and w=1 is finite, it exhibits logarithmic structures at these two boundaries

$$X_l = \ln(w)\Big(-\frac{1}{3}(2w+1)(w-1)^2(H_{0,1}(w)+2H_{1,1}(w)) - \frac{1}{18}\left(38w^3-93w^2+18w+37\right)H_1(w) + \frac{1}{36}w\left(-106w^2+25w+86\right)\Big) + \cdots,$$

$$X_h = \frac{1}{54}\ln(1-w)\Big(-18\left(2w^3-3w^2-12w+1\right)H_{0,0}(w) + \frac{6\left(19w^4+32w^3-18w^2-8w+23\right)H_0(w)}{w-1} - 265w^3 - 168w^2 + 498w - \frac{9}{w} - 344\Big) + \cdots,$$

All the coefficients can be expanded in series of w or $1-w$

The result expanded in $w = 0$ and $w = 1$ coincides with

Blokland, Czarnecki, Slusarczyk, Tkachov 2004 2005

Top decay width

Corrections by keeping b quark mass

$$\Gamma_0 = \frac{G_F m_t^3}{8\sqrt{2}\pi} |V_{tb}|^2 \lambda^{1/2} \left[1, \frac{m_b}{m_t}, \frac{m_W}{m_t}\right] \times \left[\left[1 - \frac{m_b^2}{m_t^2}\right]^2 + \left[1 + \frac{m_b^2}{m_t^2}\right] \frac{m_W^2}{m_t^2} - 2\frac{m_W^4}{m_t^4} \right].$$

0.27% decrease compare to LO width

same order with $\frac{m_b^2}{m_t^2}$

Top decay width

Corrections by keeping b quark mass

$$\Gamma_0 = \frac{G_F m_t^3}{8\sqrt{2}\pi}|V_{tb}|^2 \lambda^{1/2}\left[1, \frac{m_b}{m_t}, \frac{m_W}{m_t}\right] \times \left[\left[1-\frac{m_b^2}{m_t^2}\right]^2 + \left[1+\frac{m_b^2}{m_t^2}\right]\frac{m_W^2}{m_t^2} - 2\frac{m_W^4}{m_t^4}\right].$$

0.27% decrease compare to LO width

same order with $\frac{m_b^2}{m_t^2}$

$$\Gamma = \Gamma_0 \left\{1 + \frac{C_F \alpha_s}{2\pi}\left[2\left[\frac{(1-\beta_W^2)(2\beta_W^2-1)(\beta_W^2-2)}{\beta_W^4(3-2\beta_W^2)}\right]\ln(1-\beta_W^2) - \frac{9-4\beta_W^2}{3-2\beta_W^2}\ln\beta_W^2 + 2\mathrm{Li}_2\beta_W^2 - 2\mathrm{Li}_2(1-\beta_W^2) - \frac{6\beta_W^4-3\beta_W^2-8}{2\beta_W^2(3-2\beta_W^2)} - \pi^2\right]\right\}.$$

0.126% increase compared to LO width

Li, Oakes, Yuan, 1991

Top decay width

For off-shell W effects, we could integrate over the

$$\Gamma(t \to W^* b) = \frac{1}{\pi}\int_0^{m^2} dq^2 \frac{m_W \Gamma_W}{(q^2 - m_W^2)^2 + m_W^2 \Gamma_W^2} \left(\Gamma_t \Big|_{m_W^2 \to q^2} \right)$$

Taking the limits $\Gamma_W \to 0$, $\frac{m_W \Gamma_W}{(q^2 - m_W^2)^2 + m_W^2 \Gamma_W^2} \to \pi \delta(q^2 - m_W^2)$

$$\Gamma(t \to W^* b) = \Gamma_0 \left(\tilde{X}_0 + \frac{\alpha_s}{\pi} \tilde{X}_1 + \left(\frac{\alpha_s}{\pi} \right)^2 \tilde{X}_2 \right),$$

X_i is expressed in terms of GPLs

For example $\tilde{X}_0 = 2rw(2w-1) - \frac{1}{2}\left[(2(r-i)w - i)((r-i)w + i)^2 G_{w+irw}(1) + (2(r+i)w + i)((r+i)w - i)^2 G_{w-irw}(1)\right]$

this effect can be included independently with QCD corrections

Top decay width

For off-shell W effects, we could integrate over the

$$\Gamma(t \to W^* b) = \frac{1}{\pi}\int_0^{m^2} dq^2 \frac{m_W \Gamma_W}{(q^2 - m_W^2)^2 + m_W^2 \Gamma_W^2}\left(\Gamma_t\Big|_{m_W^2 \to q^2}\right)$$

Taking the limits $\Gamma_W \to 0,\ \dfrac{m_W \Gamma_W}{(q^2 - m_W^2)^2 + m_W^2 \Gamma_W^2} \to \pi\delta(q^2 - m_W^2)$

$$\Gamma(t \to W^* b) = \Gamma_0 \left(\tilde{X}_0 + \frac{\alpha_s}{\pi}\tilde{X}_1 + \left(\frac{\alpha_s}{\pi}\right)^2 \tilde{X}_2\right),$$

X_i is expressed in terms of GPLs

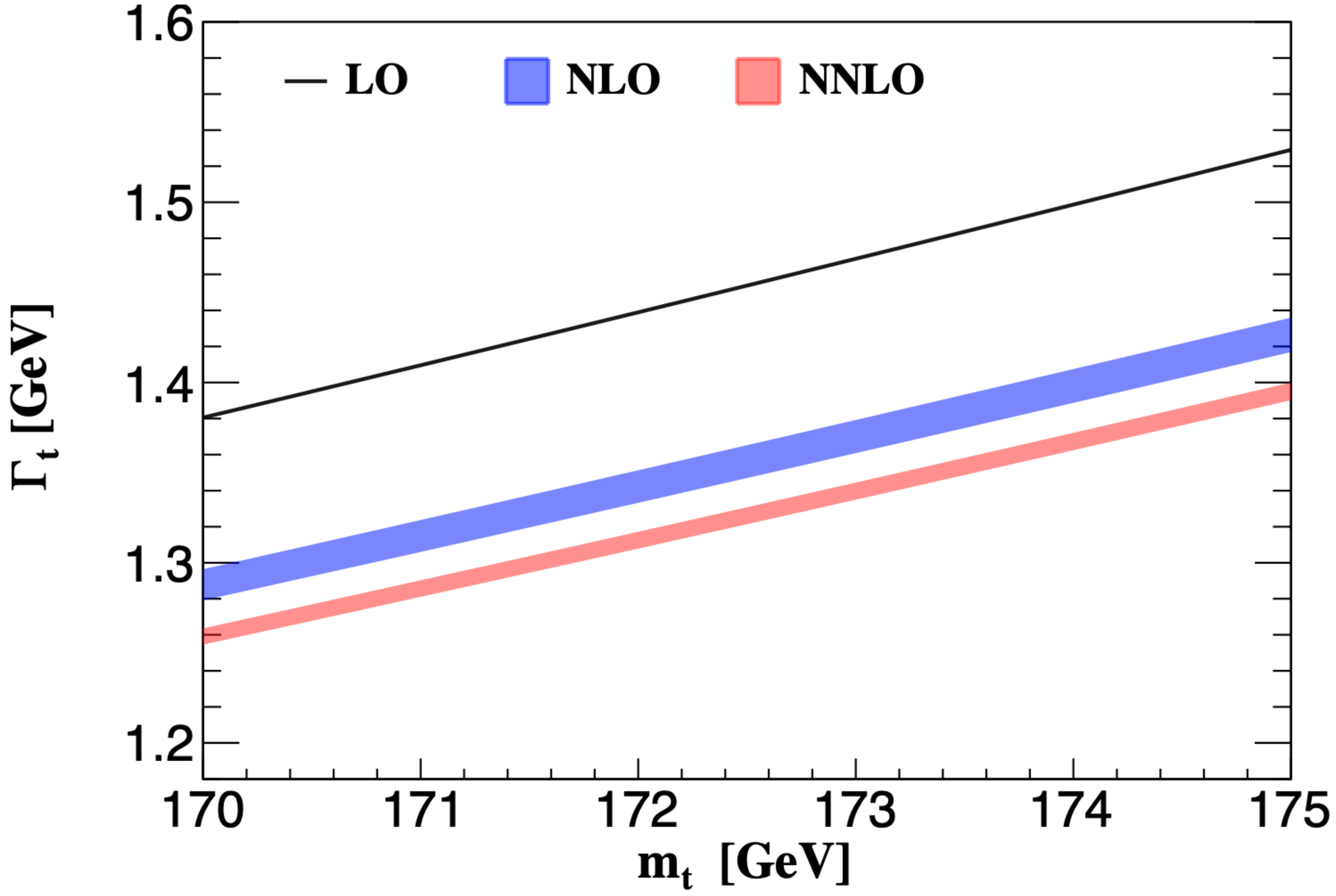
For example $\tilde{X}_0 = 2rw(2w-1) - \frac{1}{2}\left[(2(r-i)w - i)((r-i)w+i)^2 G_{w+irw}(1) + (2(r+i)w+i)((r+i)w-i)^2 G_{w-irw}(1)\right]$

this effect can be included independently with QCD corrections

	LO	NLO	NNLO
delta/LO width	-1.54%	0.13%	0.03%

Top decay width

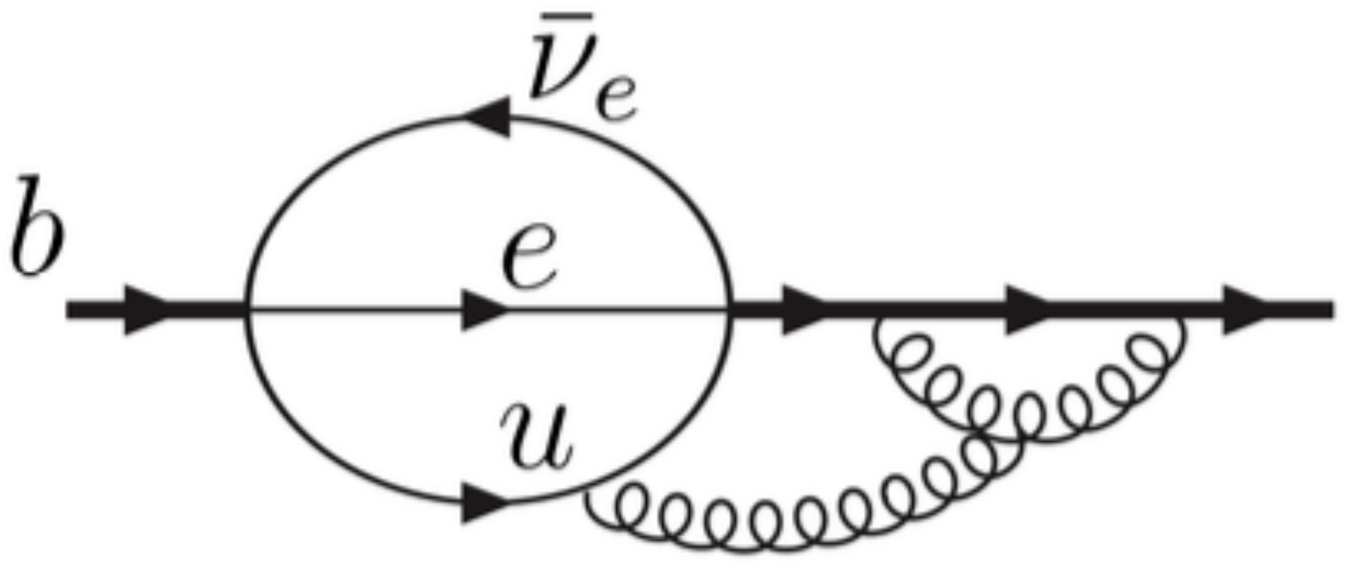
QCD renormalization scale $\mu \in [m_t/2, 2m_t]$, the variation is about ±0.8% and ±0.4% at NLO and NNLO.

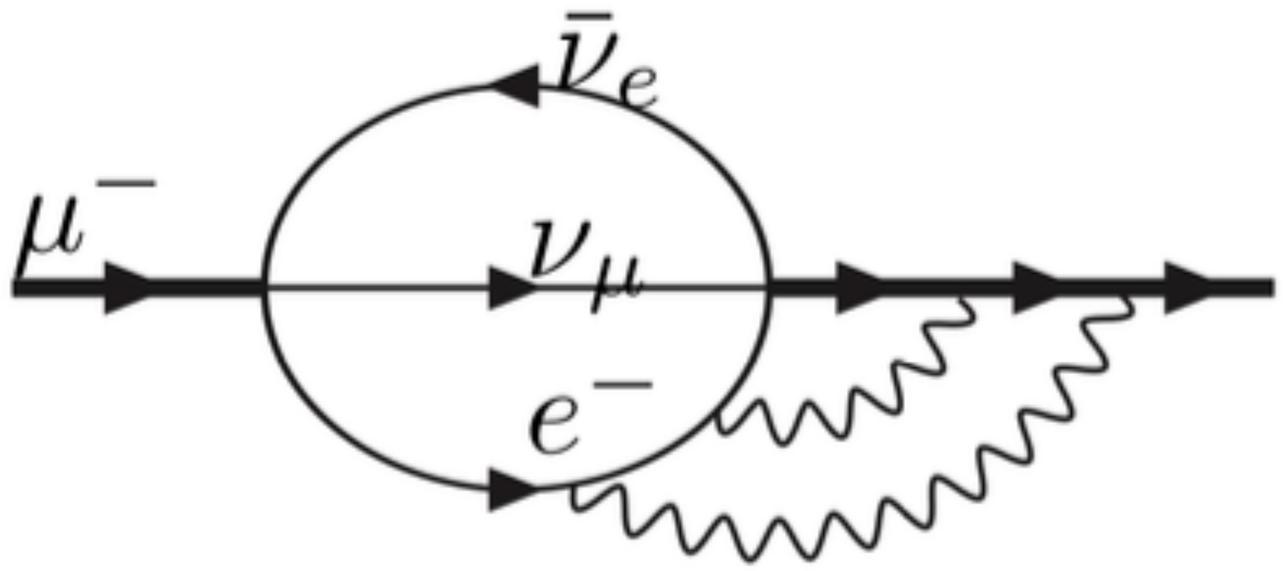


- On-shell renormalization scheme adopted
- This scale uncertainty has been reduced dramatically after including NNLO QCD corrections.
- MSbar scheme, $\Gamma_t^{\rm NLO} = 1.309$ GeV, $\Gamma_t^{\rm NNLO} = 1.332$ GeV. QCD corrections are –3.79% and 0.09% at NLO and NNLO.
- Assuming power like growth for QCD corrections, NNNLO corrections would be of around 0.4%

Top decay width

Cross-check and other applications





w can be understood as q^2/m^2

with q^2 the invariant mass of lepton sector, m^2 the mass of the parent particle

Integrating over w from 0 to 1, we reproduce NNLO QCD corrections in semileptonic decay $\Gamma(b \to Xe\bar{\nu})$

Ritbergen 1999

Integrating X_F over w, we obtain the analytic two-loop QED correction to the muon lifetime $\Gamma(\mu^- \to \nu_\mu e^- \bar{\nu}_e)$.

Ritbergen, Stuart 1999

Mathematica Package

https://github.com/haitaoli1/TopWidth

main · 1 branch · 0 tags | Go to file | Add file | Code

haitaoli1 typo corrected — ce94fe8 on Feb 10 — 30 commits

LICENSE.md	license added	4 months ago
README.md	typo corrected	2 months ago
TopWidth.m	arXiv information added	4 months ago
example.nb	typo corrected	2 months ago

README.md

TopWidth

Mathematica Package to calculate the top decay width with NNLO corrections in QCD and NLO corrections in EW.

Requirement

The HPL package is required to generate the numerics of the harmonic polylogarithm, which can be downloaded from https://krone.physik.uzh.ch/data/HPL/ .

HPL is supposed to be initialized through "<<HPL`". If not please set the path "$HPLPath="the:\path\of\the\installation".

Download

Download the package through

git clone https://github.com/haitaoli1/TopWidth.git

go to the directory "TopWidth", run the example notebook "example.nb".

About

Mathematica Package to calculate the top decay width with NNLO corrections in QCD and NLO corrections in EW.

Readme
LGPL-3.0 license
1 star
1 watching
0 forks

Releases

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Languages

Mathematica 100.0%

```
<< TopWidth`

(****** TopWidth-1.0 ******)
Authors: Long-Bin Chen, Hai Tao Li, Jian Wang, YeFan Wang
TopWidth[QCDorder, mbCorr, WwidthCorr,
EWcorr, mu] is provided for top width calculations
Please cite the paper for reference: arXiv:2212.06341

*-*-*-*-*-*-* HPL 2.0 *-*-*-*-*-*-*

Author: Daniel Maitre, University of Zurich
Rules for minimal set loaded for weights: 2, 3, 4, 5, 6.
Rules for minimal set for + - weights loaded for weights: 2, 3, 4, 5, 6.
Table of MZVs loaded up to weight 6
Table of values at I loaded up to weight 6
$HPLFunctions gives a list of the functions of the package.
$HPLOptions gives a list of the options of the package.
More info in hep-ph/0507152, hep-ph/0703052 and at
 http://krone.physik.unizh.ch/~maitreda/HPL/
```

In[5]:= SetParameters$\left[\frac{17269}{100}, \frac{478}{100}, 80377/1000, 2085/1000, 911876/10000, 11663788\times 10^{-12}\right]$

In[6]:= TopWidth$\left[2, 1\ (\ast\ \text{with mb effects}\ \ast), 1\ (\ast\ \text{with}\ \Gamma\text{w effects}\ \ast), 1\ (\ast\ \text{with NLO EW effects}\ \ast), \frac{17269}{100}\ (\ast\text{scale}\ast)\right]$

Out[6]= 1.33051

Summary

- ☑ We provide the full analytical result of top-quark width at NNLO.
- ☑ The b mass effect is included up to NLO
- ☑ The off-shell W boson contribution is calculated analytically up to NNLO.
- ☑ The analytical result can be used to perform both fast and exact evaluations.
- ☑ The missing contributions is supposed to be less than 1%.

	$\delta_b^{(i)}$	$\delta_W^{(i)}$	$\delta_{\rm EW}^{(i)}$	$\delta_{\rm QCD}^{(i)}$	Γ_t [GeV]
LO	-0.273	-1.544	–	–	1.459
NLO	0.126	0.132	1.683	-8.575	1.361
NNLO	$*$	0.030	$*$	-2.070	1.331

谢谢！