Loop corrections to tW production

李海涛

山东大学物理学院
SCHOOL OF PHYSICS, SHANDONG UNIVERSITY

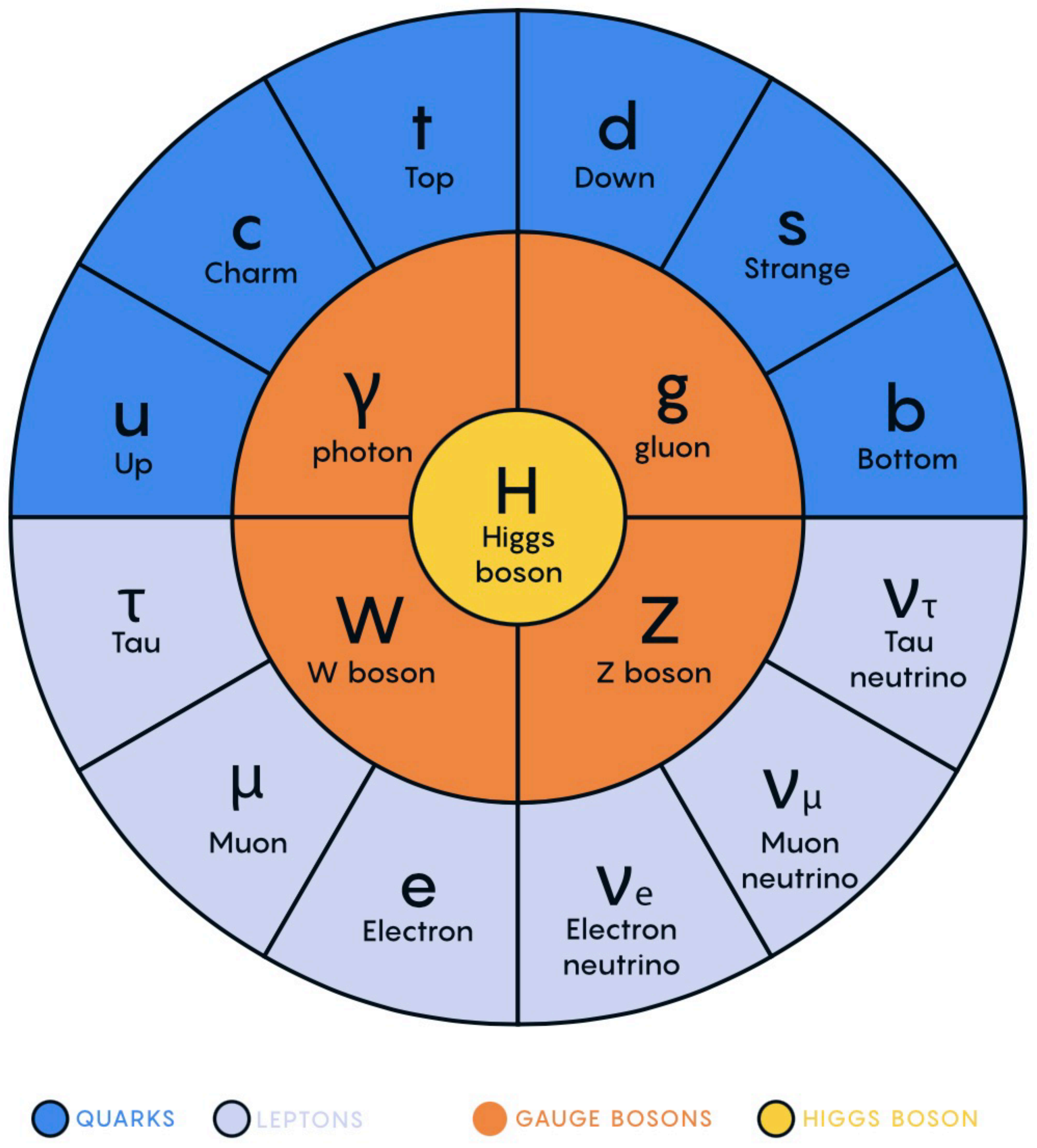
In cooperation with L.-B. Chen, J.L Ding, L. Dong, Z. Li, J. Wang, Y.F. Wang

arXiv:2204.13500, arXiv:2208.08786, arXiv:2212.07190,
arXiv:2411.07455, arXiv:2502.18648

2025 粒子物理标准模型及新物理精细计算研讨会

河北大学，保定，2025-03-30

Introduction



- ☑ Top quark is the heaviest elementary particle in the Standard Model.
- ☑ Top quark provides the strongest coupling to the SM Higgs boson and opens doors to new physics.
- ☑ 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

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".

```
In[1]:= (* Note that the mathematica package  HPL is used for numerical evaluations for HPL functions  *)
        (* HPL is loaded through "<<HPL`"*)
        (* Set directory where TopWidht.m is  *)
        SetDirectory[NotebookDirectory[]];
        << TopWidth`
```

(****** TopWidth-2.0 ******)

Authors: Long-Bin Chen, Hai Tao Li, Zhao Li, Jian Wang, YeFan Wang, QuanFeng Wu

TopWidth[QCDorder, mbCorr, WwidthCorr, EWcorr, mu] is provided for top width calculations

Please cite the paper for reference: arXiv:2212.06341 and arXiv:2309.00762

--*-*-*-* 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[mt,mb,mw,Wwidth, GF] *)
        (* If the parameters are not set by the users the code will use the default ones *)
```

$$\text{SetParameters}\left[\frac{17\,269}{100}, \frac{478}{100}, 80\,377/1000, 2085/1000, 911\,876/10\,000, 11\,663\,788\times 10^{-12}\right]$$

```
        (* NNNLO decay width *)
```

$$\text{TopWidth}\left[3, 0\ (\text{* with mb effects *}), 0\ (\text{* with }\Gamma\text{w effects*}), 0\ (\text{* with NLO EW effects *}), \frac{17\,269}{100}\right]$$

Out[6]= 1.31833

First fully analytical NNLO QCD corrections

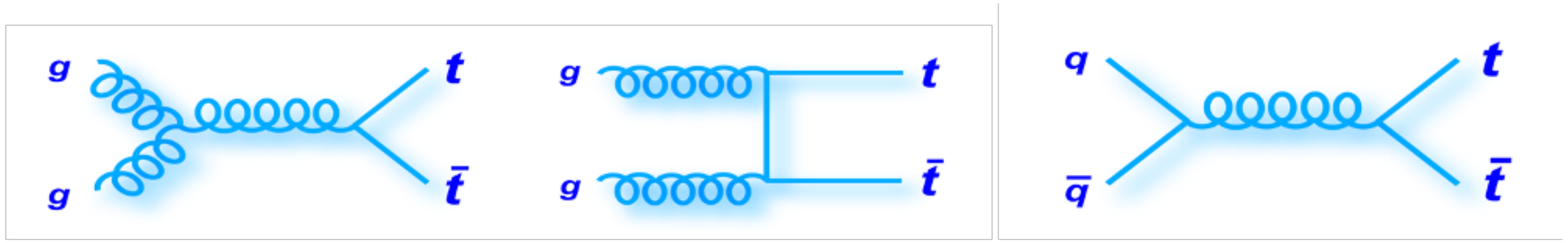
First analytical leading color N3LO QCD corrections

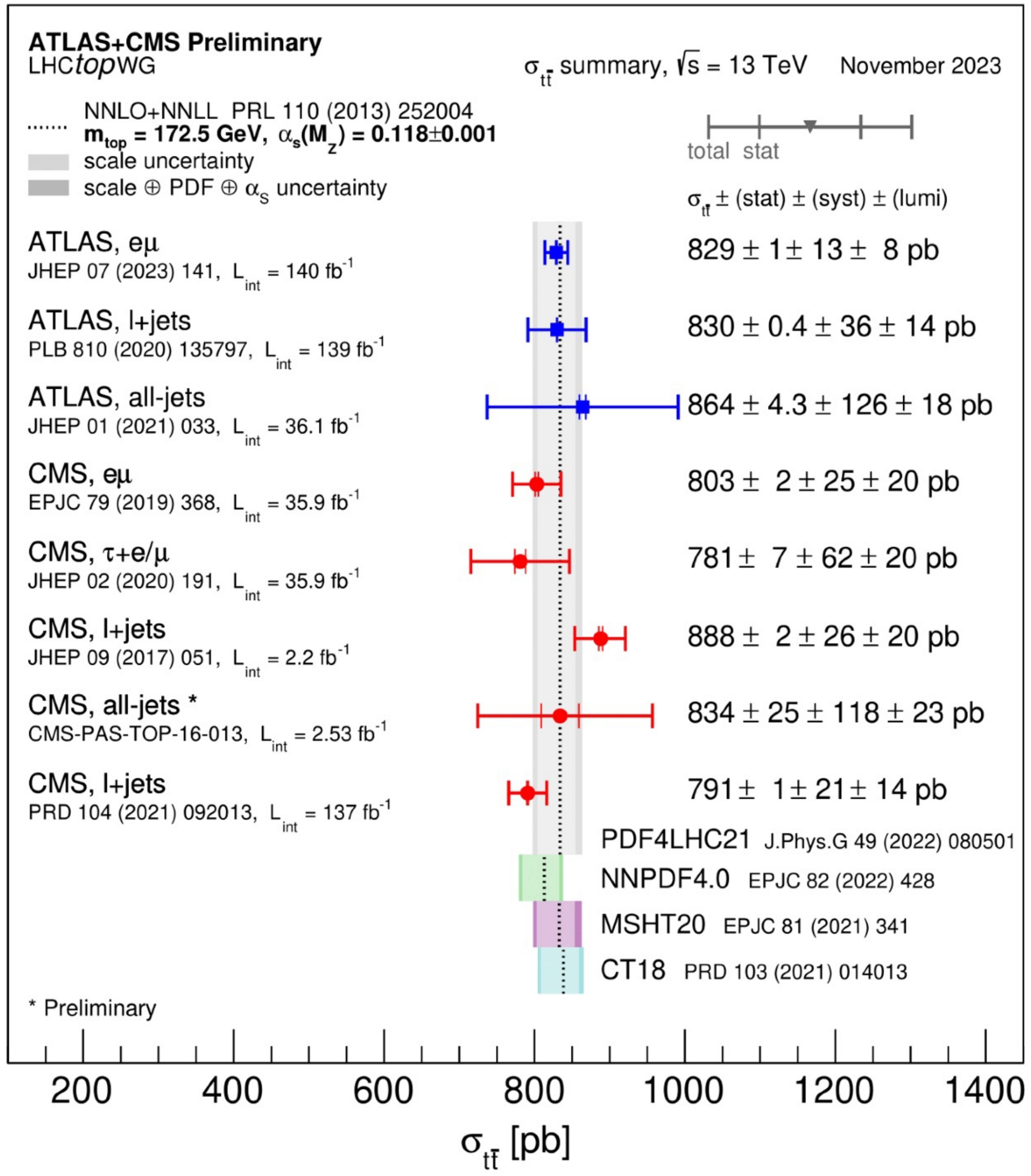
L.B.Chen, HTL, Wang, Wang, arXiv:2212.06341

L.B.Chen, HTL, Li, Wang, Wang, Wu, arXiv:2309.00762

also see Chen Long's talk yesterday for the result from another group

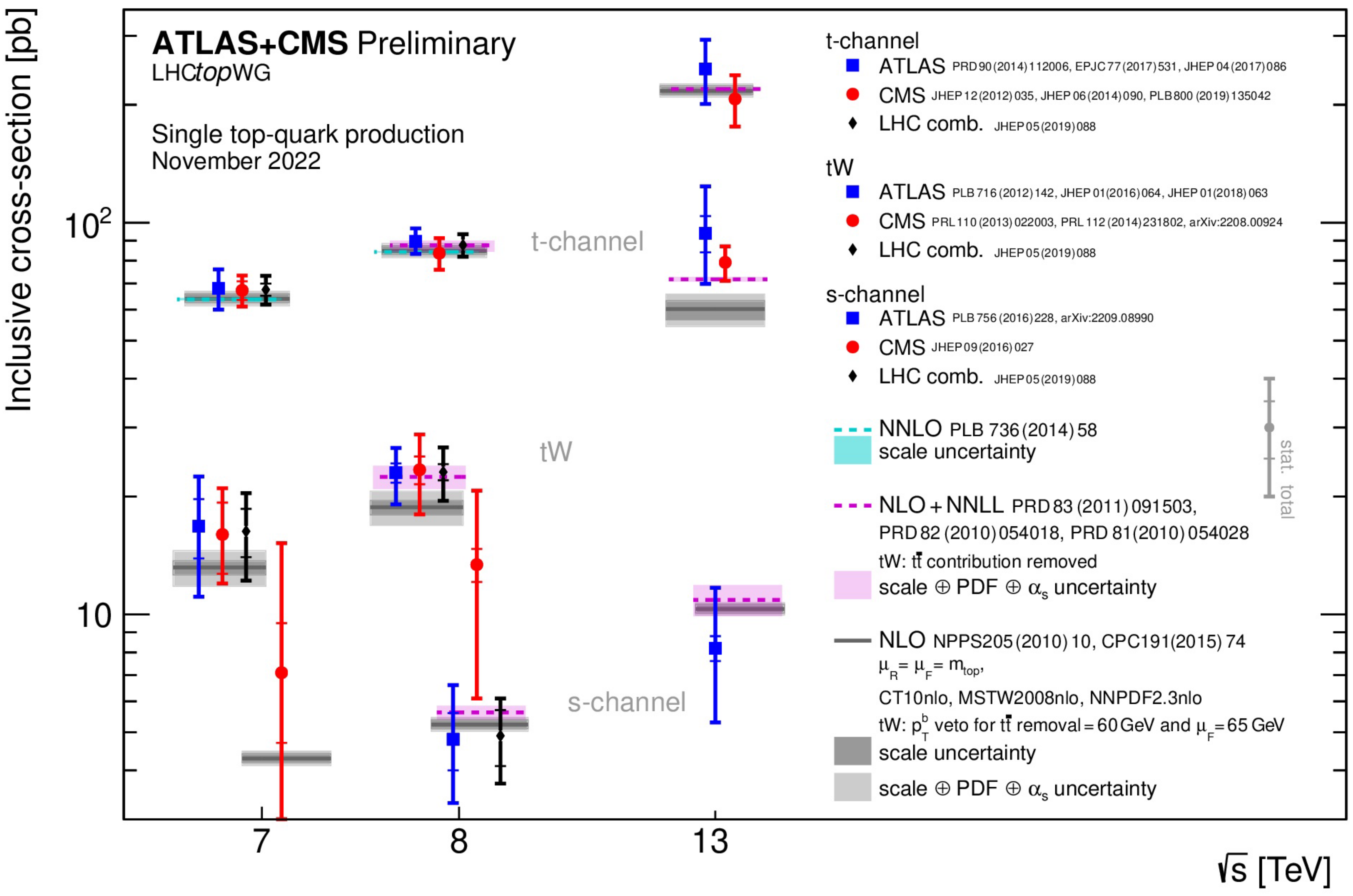
Introduction

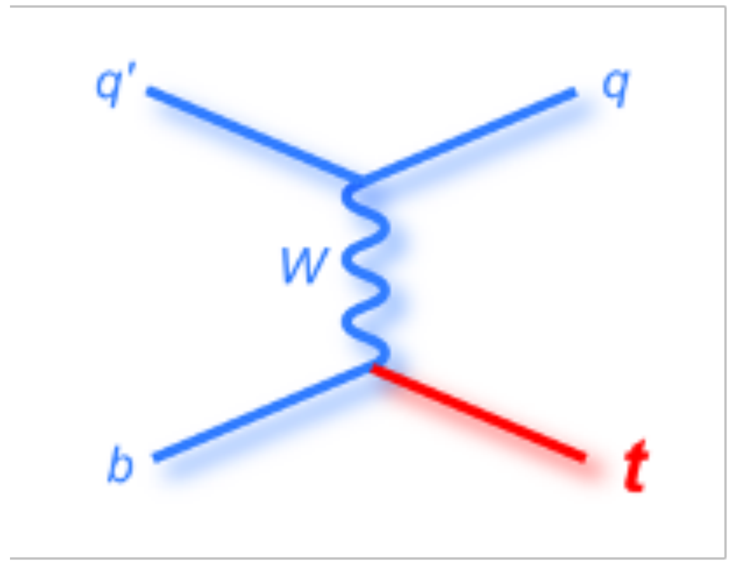


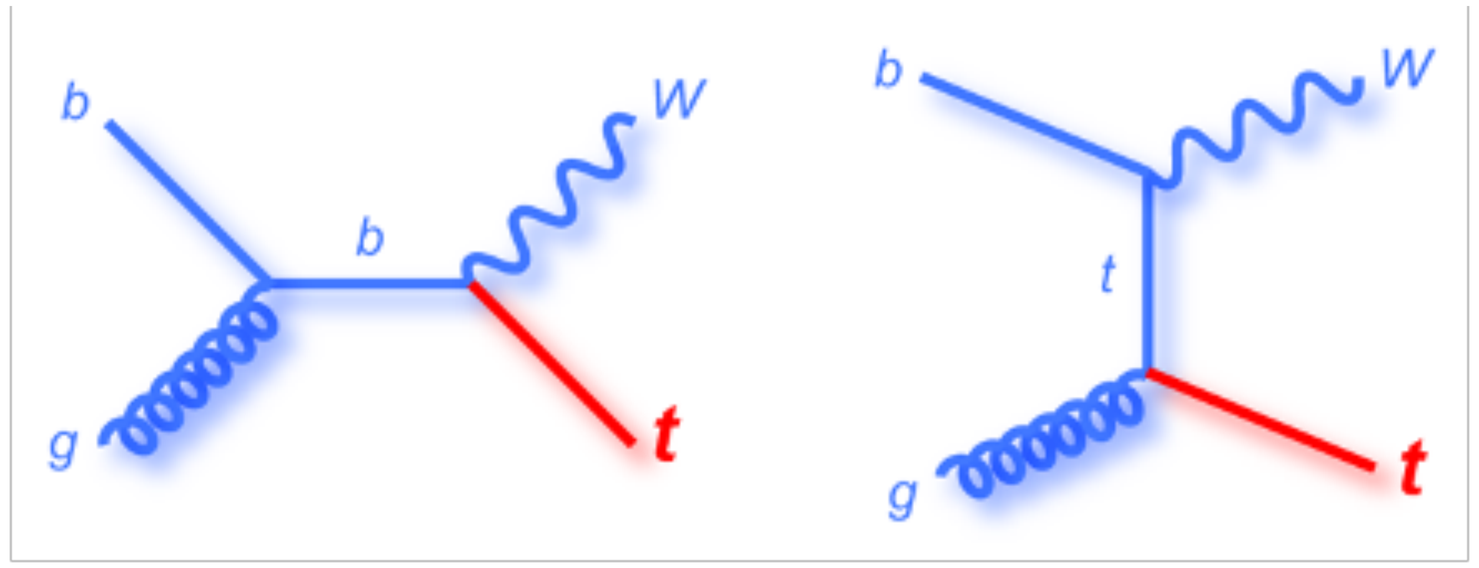


- ➢ It has high precision of the experimental measurements of total and differential cross sections
- ➢ It is used to study many properties of the top quark

Introduction

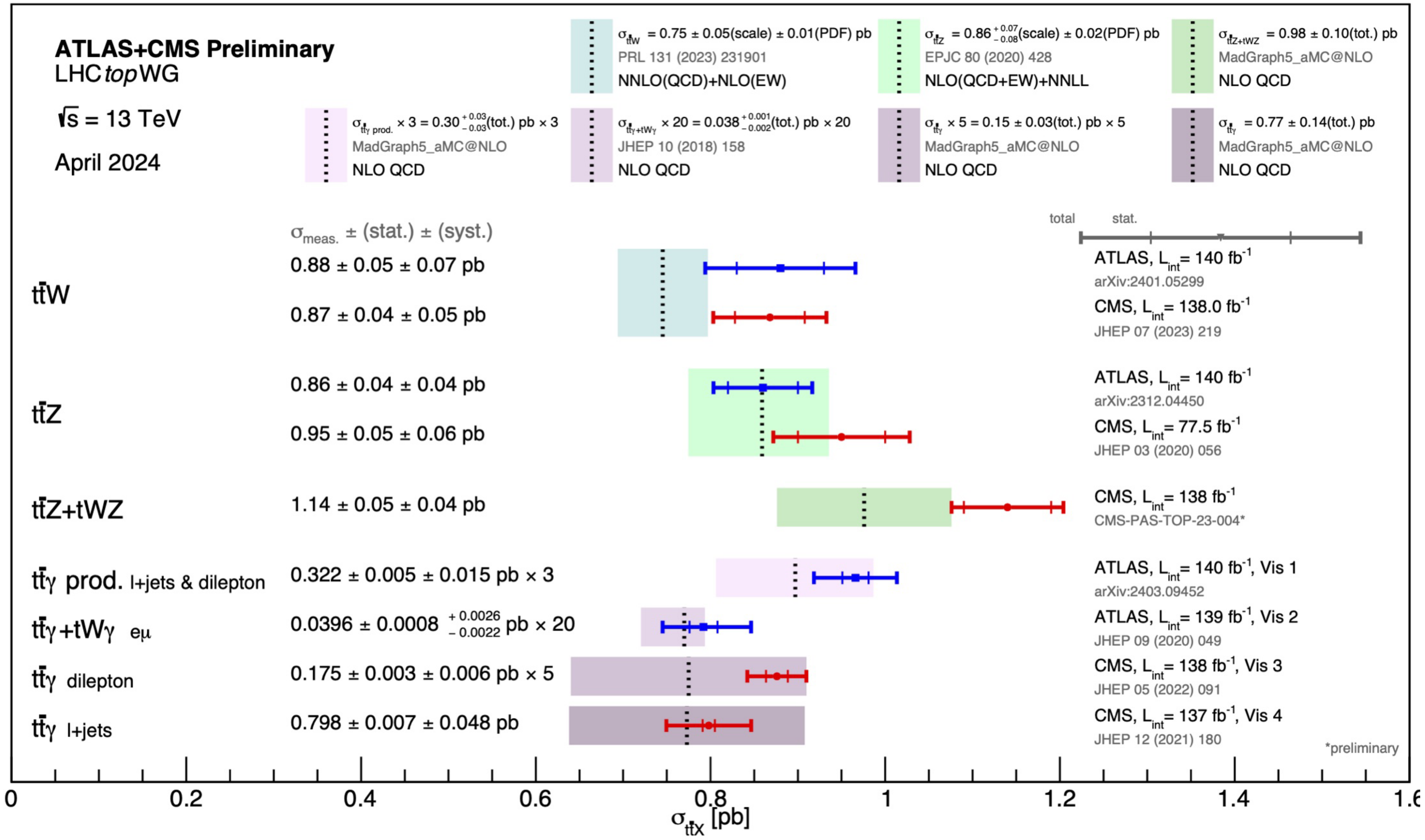


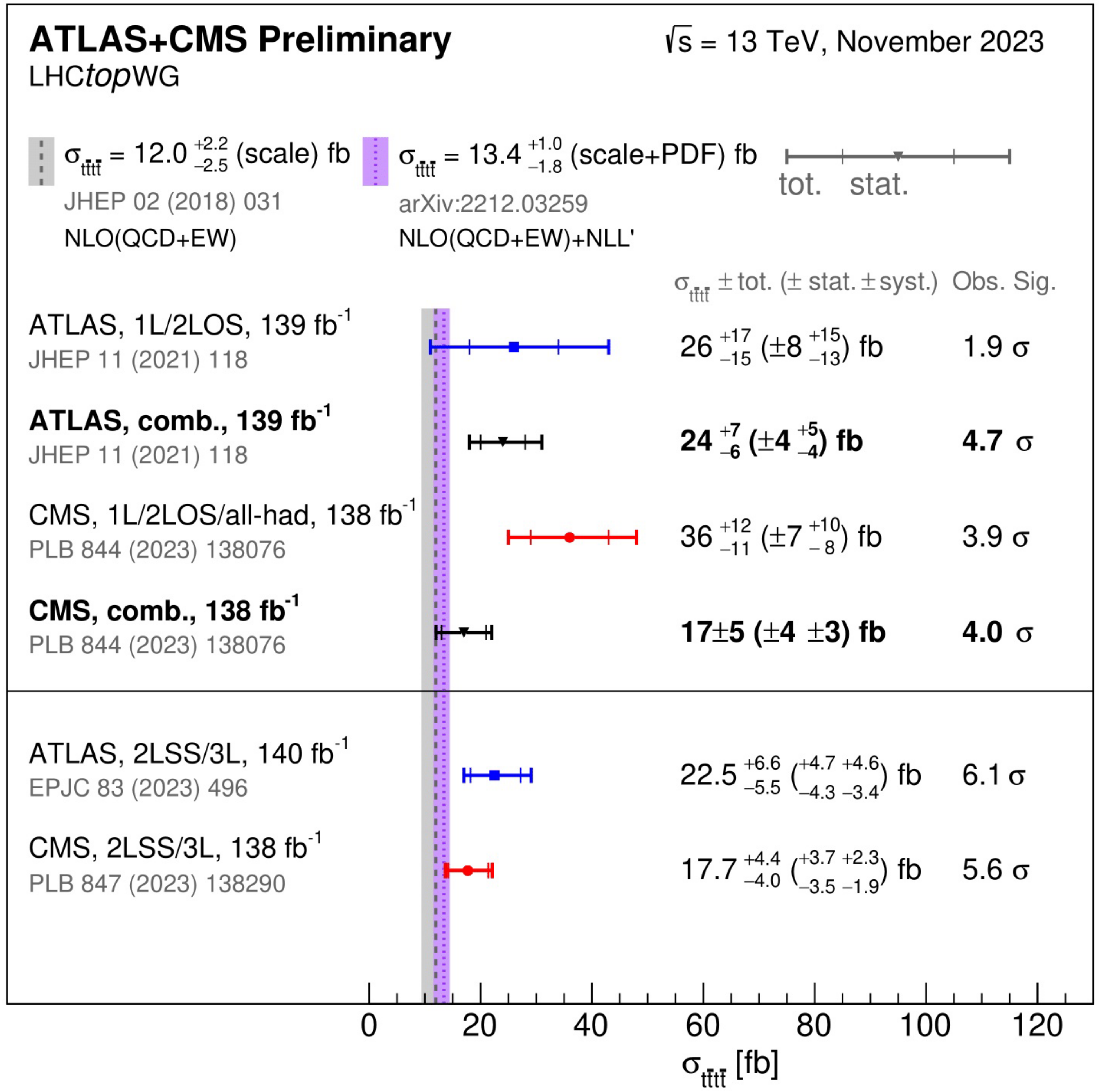




- ➢allows measurement of V_{tb}
- ➢ check the chiral structure of Wtb vertex than top pair production
- ➢ t-channel can be used to measurement the b quark density
- ➢ sensitive to FCNC (t-channel), or W' resonances (s-channel)

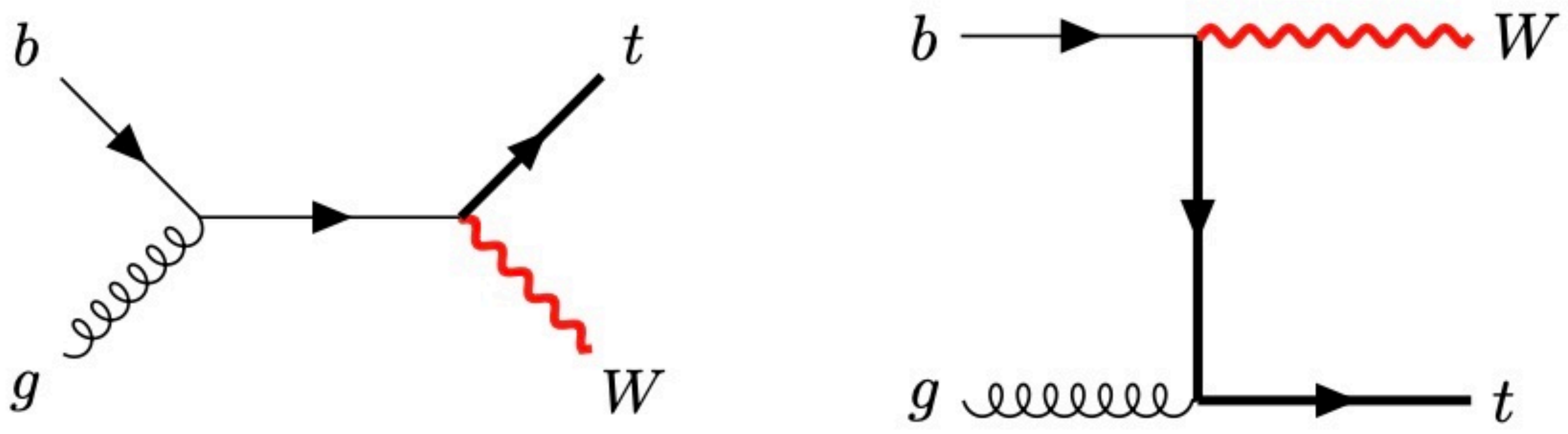
Introduction



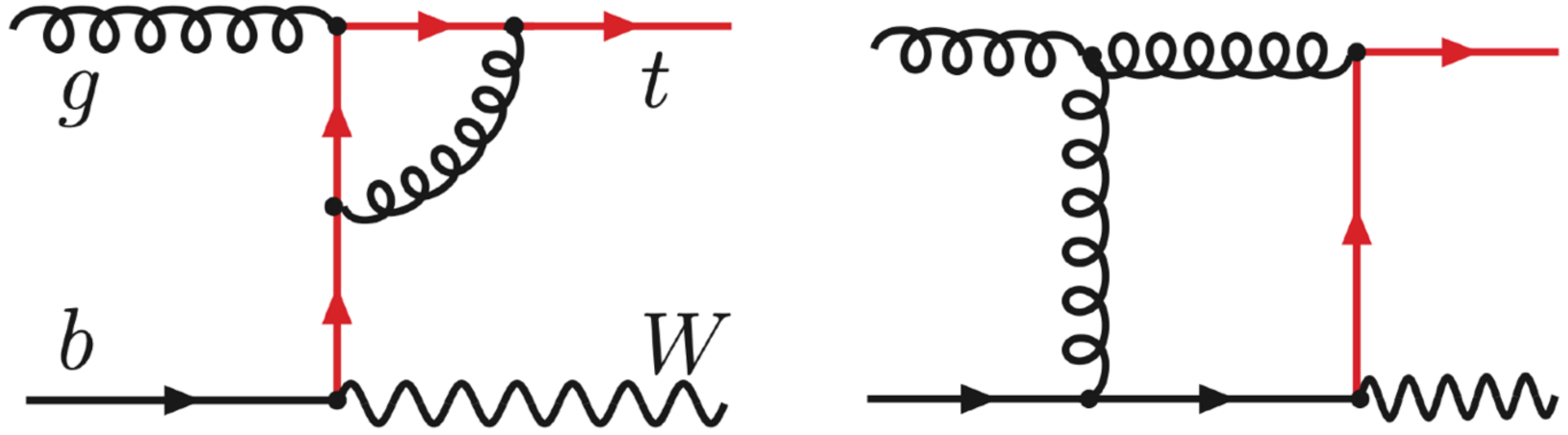


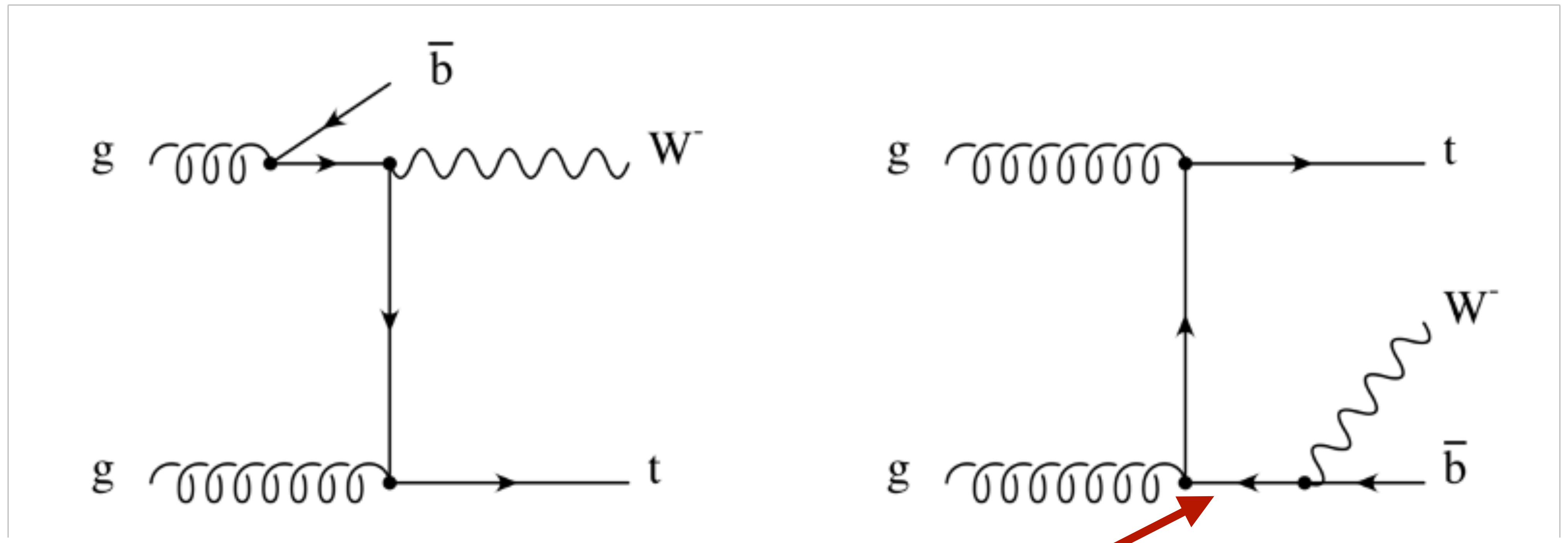
tW production

LO



NLO





Real corrections to tW production

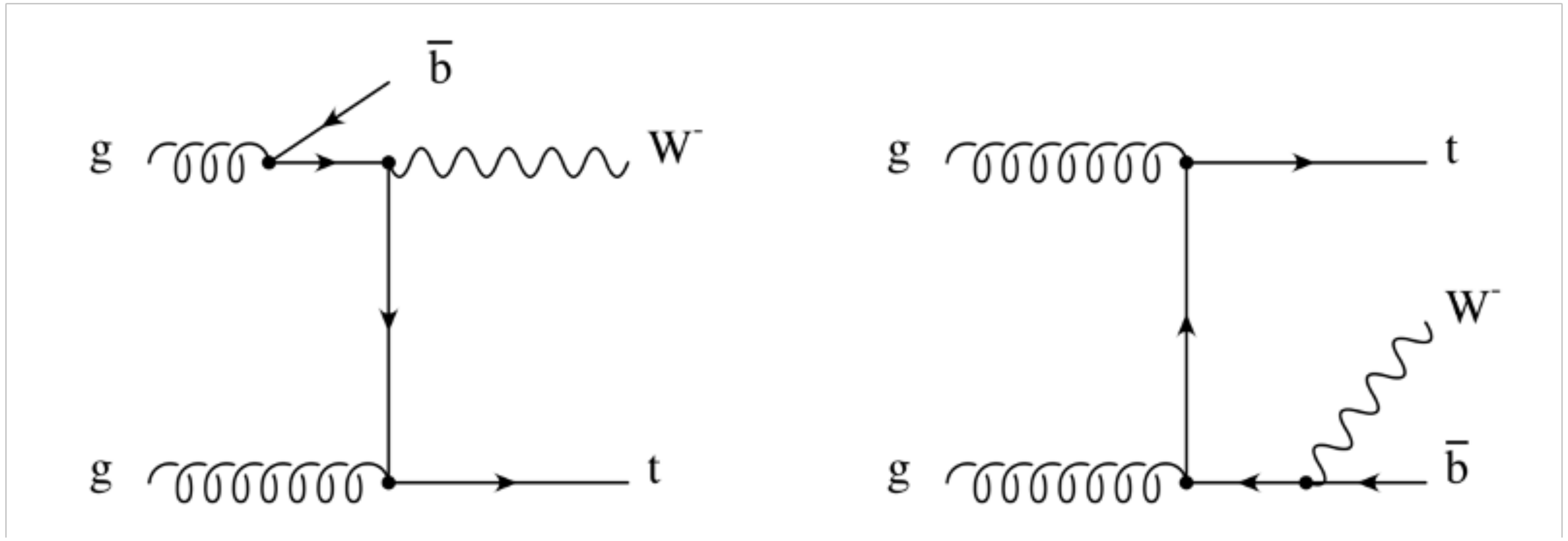
Giele, arXiv:hep-ph/9511449
Zhu, arXiv:hep-ph/0109269
Campbell, Tramontano, arXiv:hep-ph/0606289
Cao, arXiv:0801.1539
Kant et al arXiv:1406.4403

onshell and offshell anti-top propagator

Frixione et al 2008
Hollik et al 2012
Campbell et al 2005

tW production

NLO



Real corrections to tW production | top quark pair production

- diagram removal (DR), remove the diagrams for top quark pair production; not gauge invariant
- diagram subtraction (DS), using a local subtraction term to cancel the matrix element square in the resonance region
- b-jet veto, together with a careful choice of the factorization scale

Campbell, Tramontano, arXiv:hep-ph/0506289
Frixione et al, arXiv:0805.3067
Hollik ,Lindert ,Pagani, arXiv:1207.1071

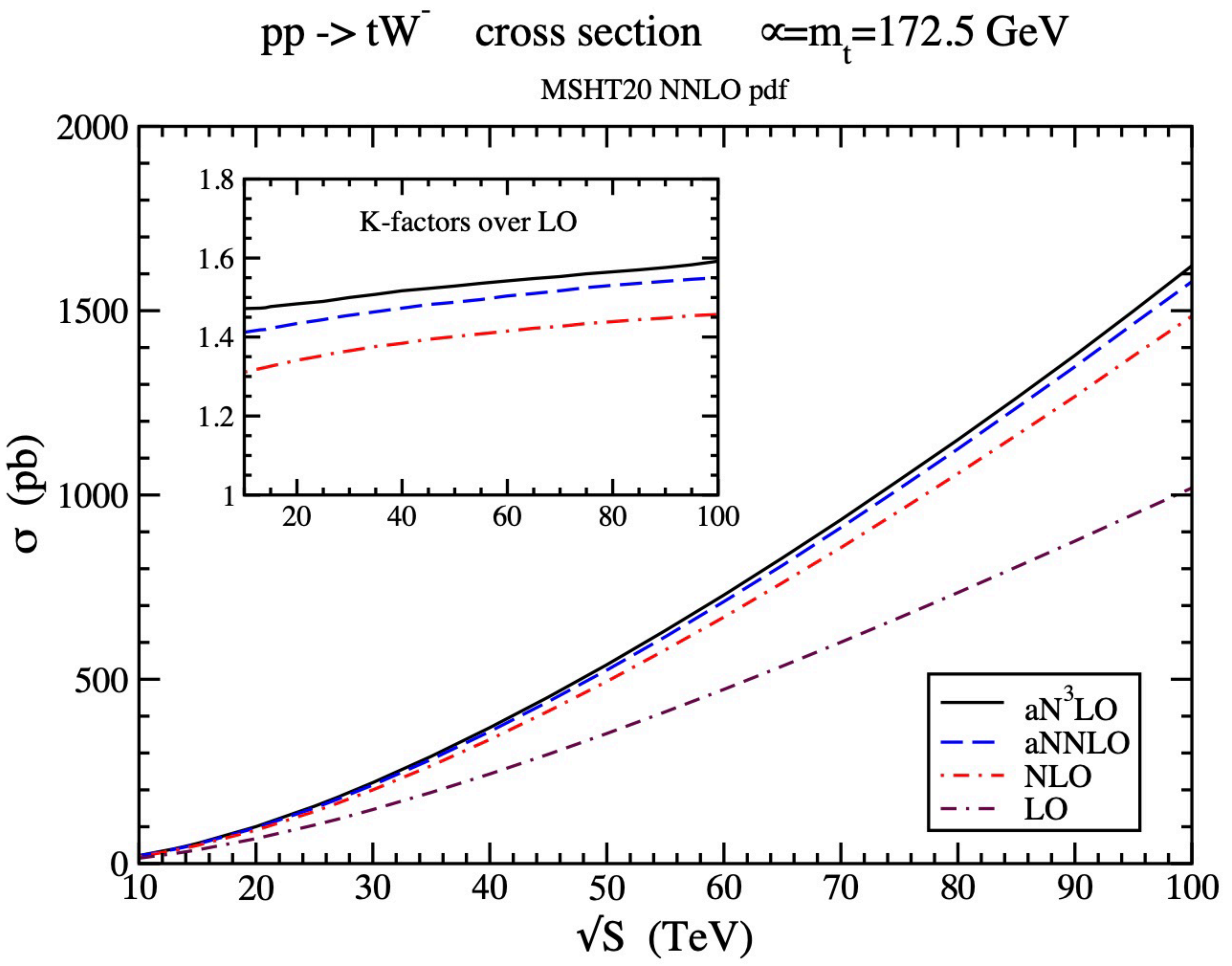
tW production

Beyond NLO

$$\frac{d^2\sigma^{\rm PIM}}{dM^2\, d\cos\theta} = \frac{\lambda^{1/2}}{32\pi s M^2}\sum_{ij}\int_\tau^1 \frac{dz}{z}\int_z^1 \frac{dx}{x} f_{i/p}(x,\mu_f)\, f_{j/p}(z/x,\mu_f)\, H(\mu_h)\, U_{\rm PIM}(\mu_h,\mu_s,\mu_f)$$
$$\times \frac{z^{-\eta}}{(1-z)^{1-2\eta}}\, \tilde{s}_{\rm PIM}\left(\ln\frac{M^2(1-z)^2}{z\mu_s^2}+\partial_\eta,\mu_s\right)\frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)}\Bigg|_{\eta=(C_A+C_F)a_{\gamma^{\rm cusp}}(\mu_s,\mu_f)}$$

[pb]	PIM		1PI	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$7.0^{+5\%}_{-6\%}$	$22.4^{+5\%}_{-2\%}$	$7.2^{+5\%}_{-4\%}$	$22.9^{+3\%}_{-1\%}$
NLO	$9.92^{+2\%}_{-2\%}$	$32.8^{+1\%}_{-1\%}$	$10.0^{+1\%}_{-2\%}$	$33.0^{+1\%}_{-1\%}$
aNNLO	$11.6^{+4\%}_{-5\%}$	$37.1^{+5\%}_{-5\%}$	$11.2^{+6\%}_{-6\%}$	$35.9^{+7\%}_{-6\%}$
NLO+NNLL	$11.4^{+7\%}_{-7\%}$	$36.7^{+7\%}_{-7\%}$	$11.7^{+12\%}_{-17\%}$	$37.3^{+16\%}_{-21\%}$
aNNLO/NLO	1.16	1.13	1.12	1.09
(NLO+NNLL)/NLO	1.15	1.12	1.17	1.13

Li, HTL, Shao, Wang, arXiv:1903.01646



For soft gluon contribution in threshold region, see Ding JiaLe's talk yersterday

Kidonakis, Yamanaka, arXiv: 2102.11300

tW production

Toward NNLO

Many methods has already developed at NNLO level

$$\sigma = \left(\int_0^{\tau_{\rm cut}} d\tau + \int_{\tau_{\rm cut}}^{\tau_{\rm max}} d\tau \right) \frac{d\sigma}{d\tau}$$

tW production

Toward NNLO

Many methods has already developed at NNLO level

$$\sigma = \left(\int_0^{\tau_{\rm cut}} d\tau + \int_{\tau_{\rm cut}}^{\tau_{\rm max}} d\tau \right) \frac{d\sigma}{d\tau}$$

SCET $H \otimes B_1 \otimes B_2 \otimes S$

standard NLO corrections to tW+j

tW production

Toward NNLO

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standard NLO corrections to tW+j

N-Jettiness soft function *HTL, Wang, arXiv:1611.02749 and 1804.06358*

TMD soft function *can be extracted from the soft function for top quark pair production*

NNLO beam function is universal which have been available

Hard function can be extracted from virtual-virtual contributions

tW production

Toward NNLO

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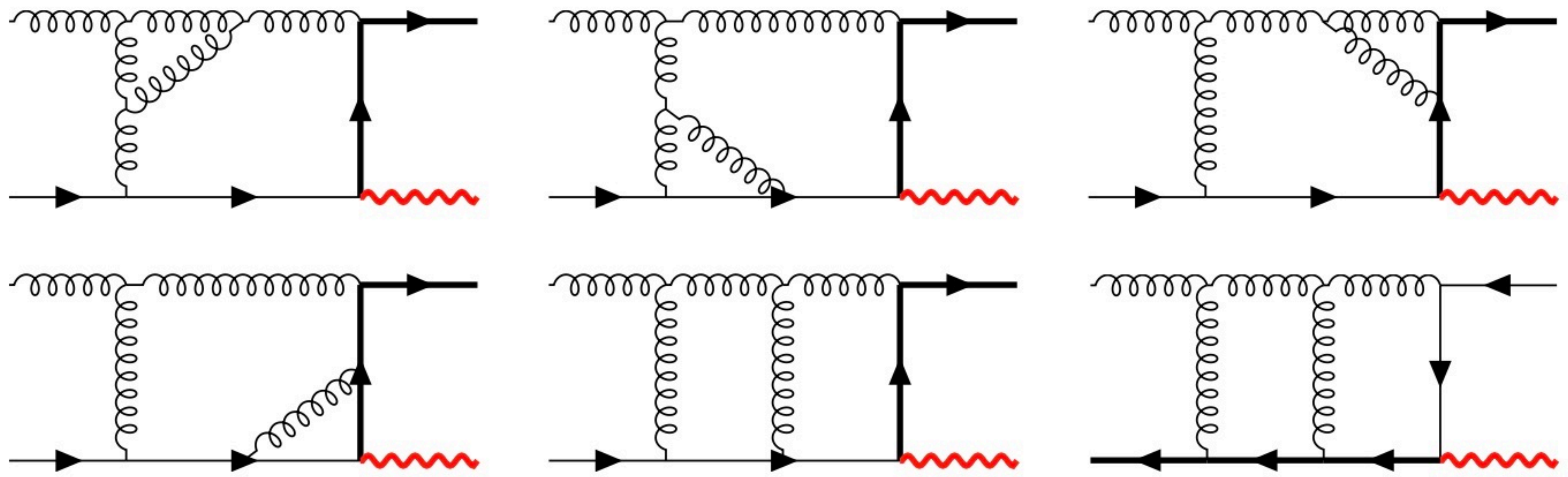
Hard function can be extracted from virtual-virtual contributions

we have to deal with the resonance divergence for tW+j production $\begin{cases} \text{real} - \text{virtual} \\ \text{real} - \text{real} \end{cases}$

`

Toward NNLO

1. double virtual



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

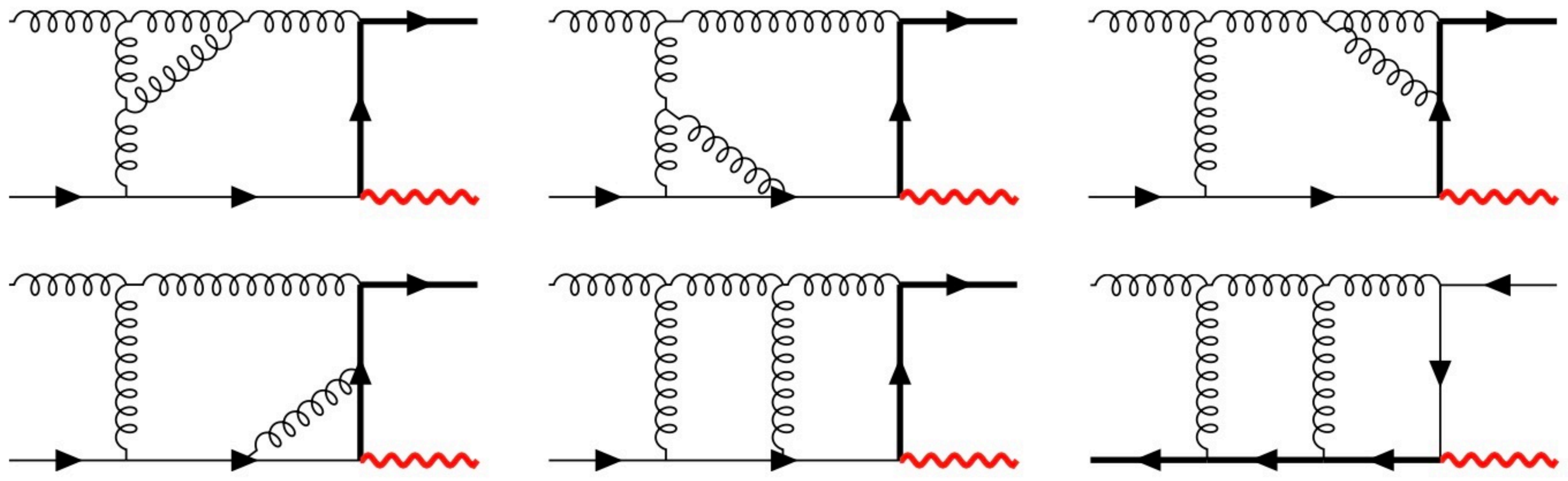
Tree   1-loop   2-loop

$$\left(\frac{\alpha_s}{4\pi}\right)^2 \left(|\mathscr{M}_1^{\rm ren}|^2 + \mathscr{M}_2^{\rm ren}\mathscr{M}_{0*}^{\rm ren} + \mathscr{M}_0^{\rm ren} * \mathscr{M}_{2*}^{\rm ren}\right)$$

1-loop square   2-loop × tree

Toward NNLO

1. double virtual



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

Tree   1-loop   2-loop

$$\left(\frac{\alpha_s}{4\pi}\right)^2 (|\mathscr{M}_1^{\text{ren}}|^2 + \mathscr{M}_2^{\text{ren}}\mathscr{M}_{0*}^{\text{ren}} + \mathscr{M}_0^{\text{ren}} * \mathscr{M}_{2*}^{\text{ren}})$$

1-loop square   2-loop × tree

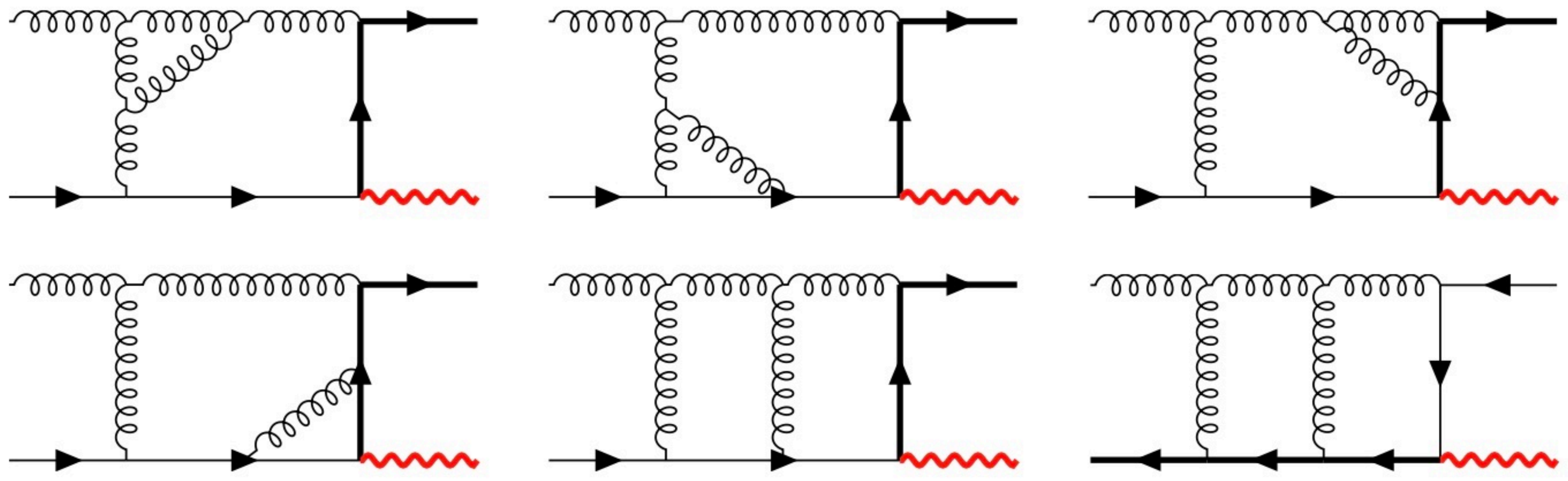
analytical result 1-loop square *Chen, Dong, HTL, Li, Wang, Wang, arXiv:2204.13500*

Toward NNLO

1. double virtual

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

Tree 1-loop 2-loop



$$\left(\frac{\alpha_s}{4\pi}\right)^2 \left(|\mathcal{M}_1^{\text{ren}}|^2 + \mathcal{M}_2^{\text{ren}}\mathcal{M}_{0*}^{\text{ren}} + \mathcal{M}_0^{\text{ren}} * \mathcal{M}_{2*}^{\text{ren}}\right)$$

1-loop square 2-loop × tree

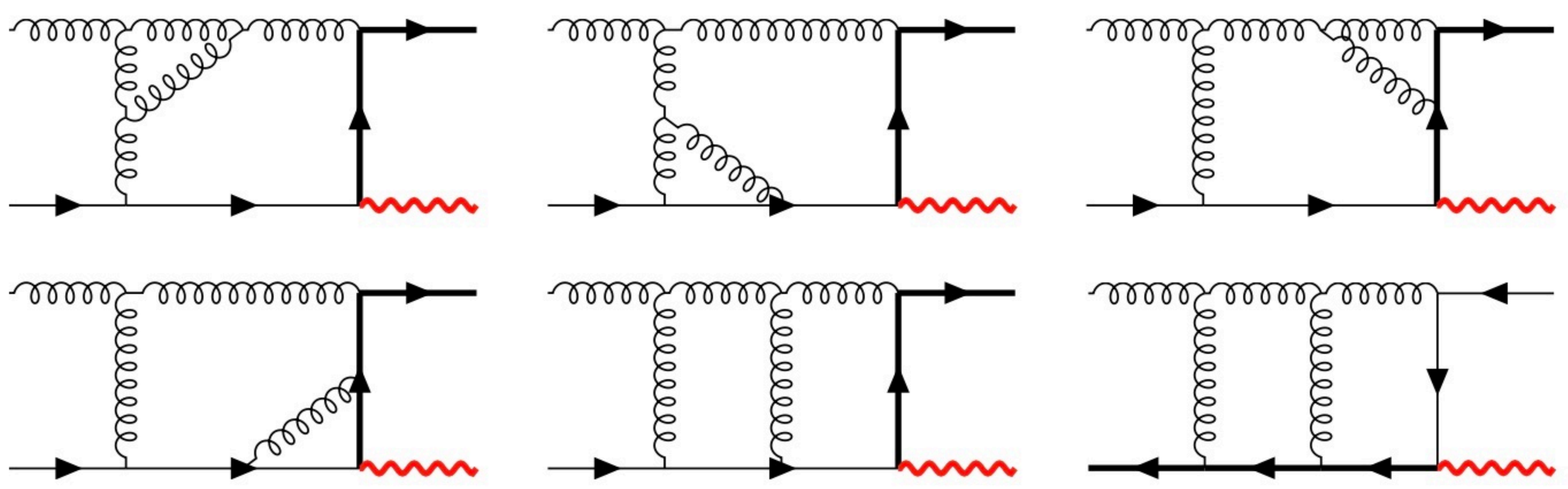
analytical result 1-loop square *Chen, Dong, HTL, Li, Wang, Wang, arXiv:2204.13500*

$$2\,\mathrm{Re}\sum_{s,c}\mathcal{M}^{(0)*}\mathcal{M}^{(2)} = N_C^4 A + N_C^2 B + C + \frac{1}{N_C^2}D + n_l\left(N_C^3 E_l + N_C F_l + \frac{1}{N_C}G_l\right) + n_h\left(N_C^3 E_h + N_C F_h + \frac{1}{N_C}G_h\right)$$

`

Toward NNLO

1. double virtual



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

Tree 1-loop 2-loop

$$\left(\frac{\alpha_s}{4\pi}\right)^2 \left(|\mathscr{M}_1^{\text{ren}}|^2 + \mathscr{M}_2^{\text{ren}}\mathscr{M}_{0*}^{\text{ren}} + \mathscr{M}_0^{\text{ren}} * \mathscr{M}_{2*}^{\text{ren}}\right)$$

1-loop square 2-loop × tree

analytical result 1-loop square *Chen, Dong, HTL, Li, Wang, Wang, arXiv:2204.13500*

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analytical LC 2-loop amplitude *Chen, Dong, HTL, Li, Wang, Wang, arXiv:2208.08786*

numerical full 2-loop amplitude *Chen, Dong, HTL, Li, Wang, Wang, arXiv:2212.07190*

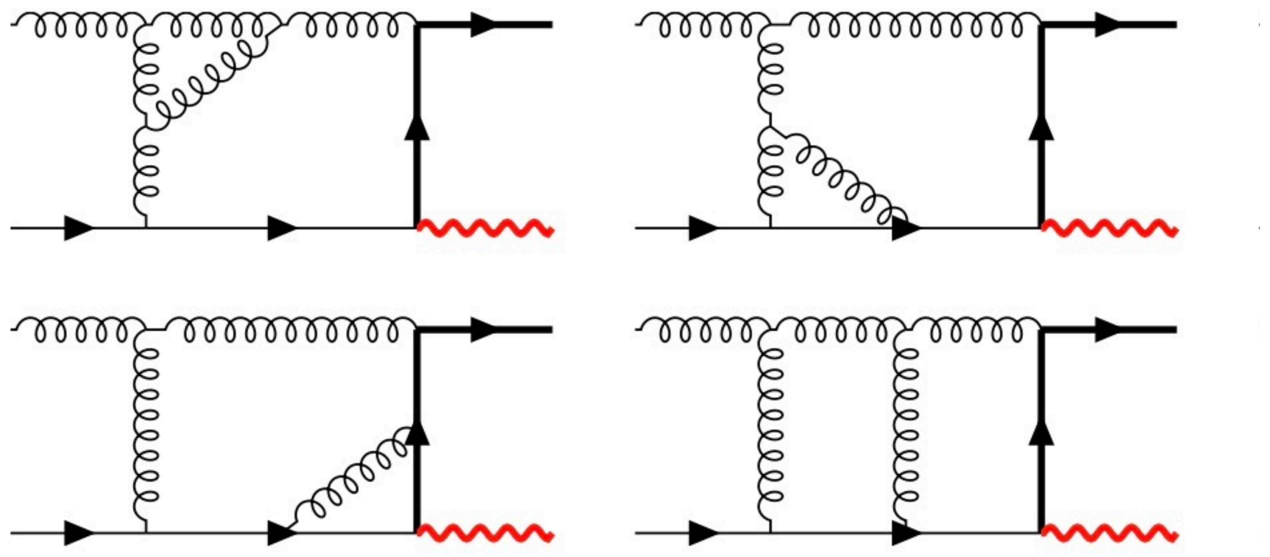
Toward NNLO

1. double virtual

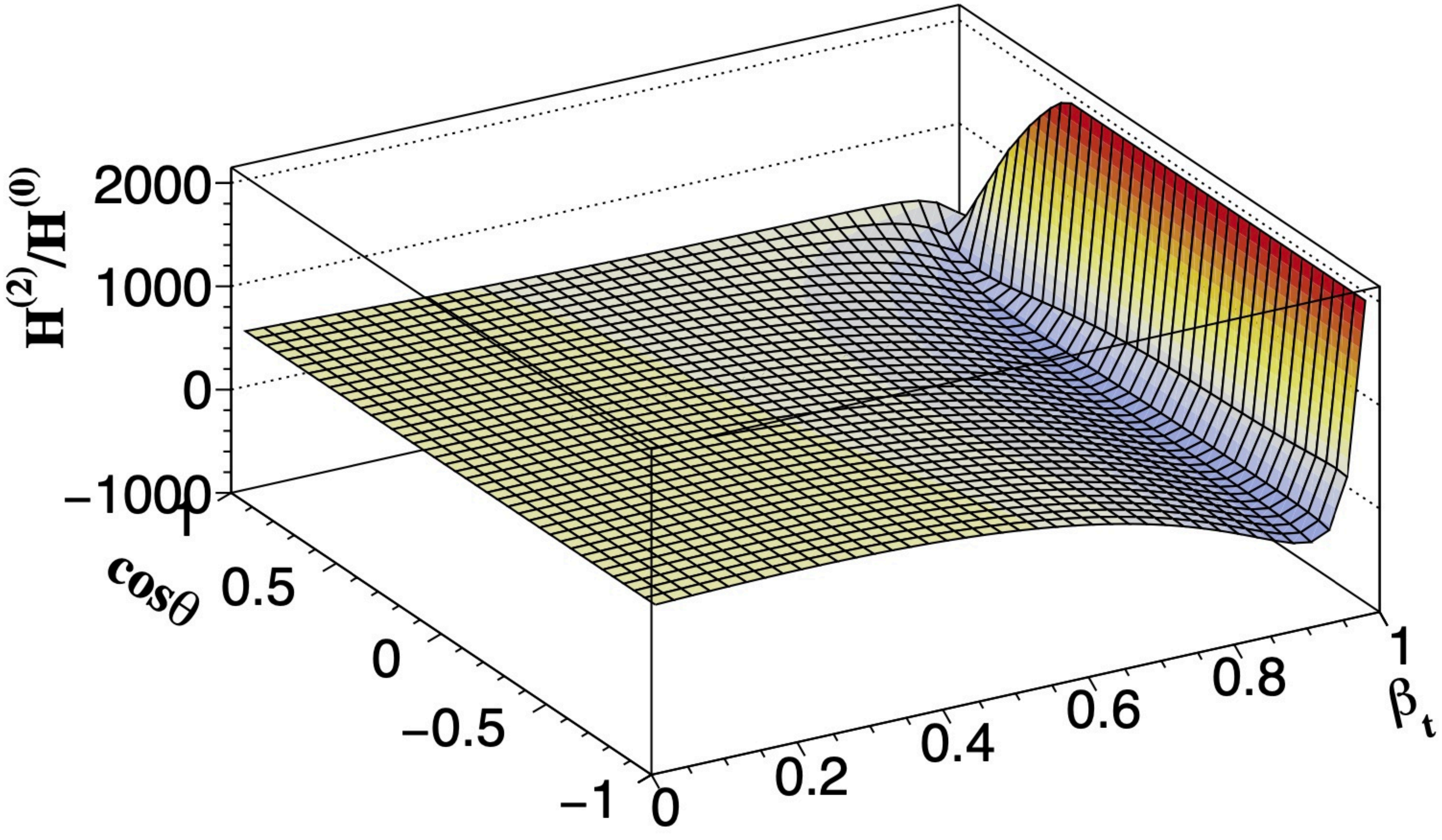
Amplitude reads $\mathscr{M} = \mathscr{M}_0 + \frac{\alpha_s}{4\pi}\mathscr{M}_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \mathscr{M}_2$

2-loop

$* \mathscr{M}^{\rm ren}_{2*})$



analytical result 1-loop square



$$2\,{\rm Re}\sum_{s,c}\mathscr{M}^{(0)*}\mathscr{M}^{(2)} = N_C^4 A + \quad \ldots \quad N_C F_h + \frac{1}{N_C} G_h \Big)$$

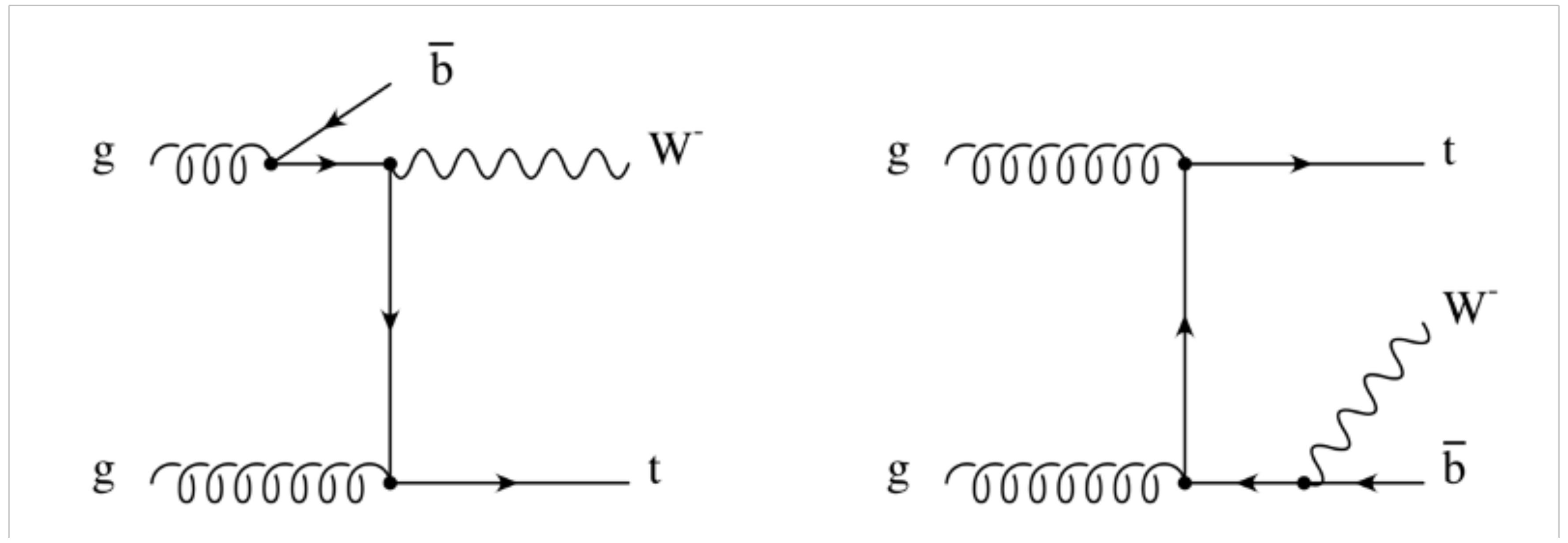
analytical LC 2

numerical full 2-loop amplitude

tW production

Toward NNLO

2. real-virtual

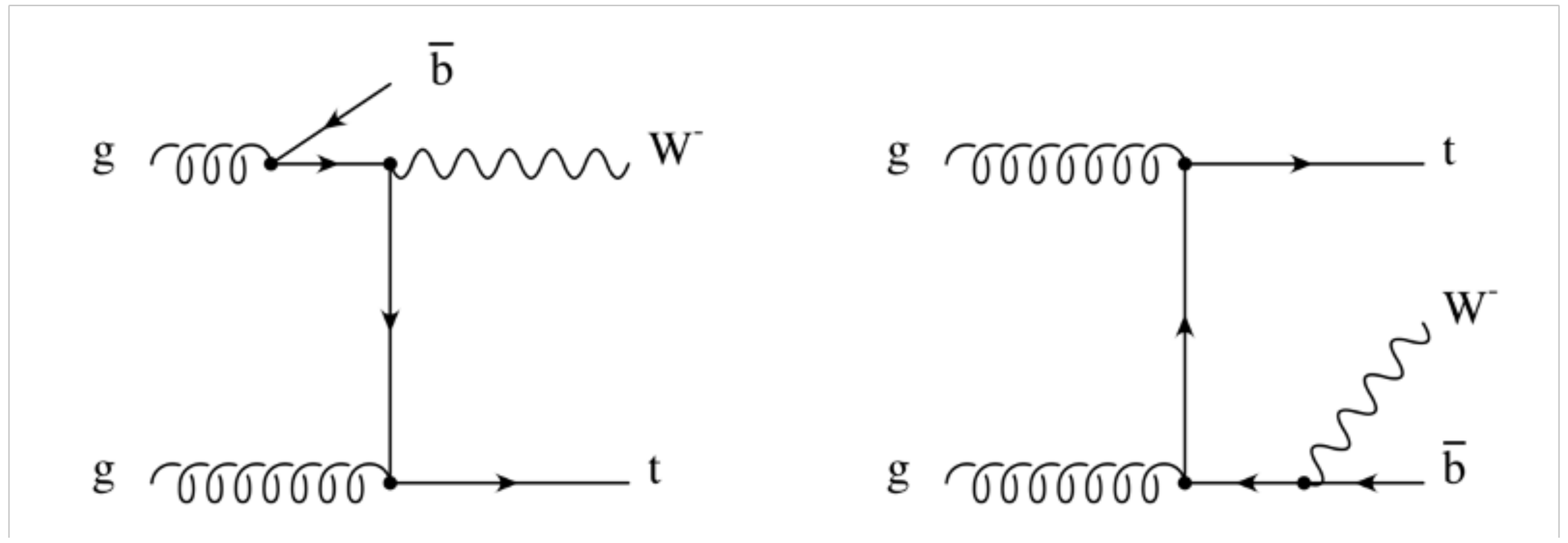


- diagram removal (DR), remove the diagrams for top quark pair production; not gauge invariant
- diagram subtraction (DS), using a local subtraction term to cancel the matrix element square in the resonance region
- b-jet veto, together with a careful choice of the factorization scale

tW production

Toward NNLO

2. real-virtual



- diagram removal (DR), remove the diagrams for top quark pair production; not gauge invariant
- diagram subtraction (DS), using a local subtraction term to cancel the matrix element square in the resonance region
- b-jet veto, together with a careful choice of the factorization scale

$\Delta = s_{Wb} - m_t^2$ In $\Delta \to 0$ limit, the amplitude square is $\left| \mathscr{M}_{tW\bar{b}} \right|^2_{\text{LO}} = \frac{B^{(2)}}{\Delta^2} + \frac{B^{(1)}}{\Delta} + B^{(0)} + \cdots$

The leading singular contribution can be subtracted by

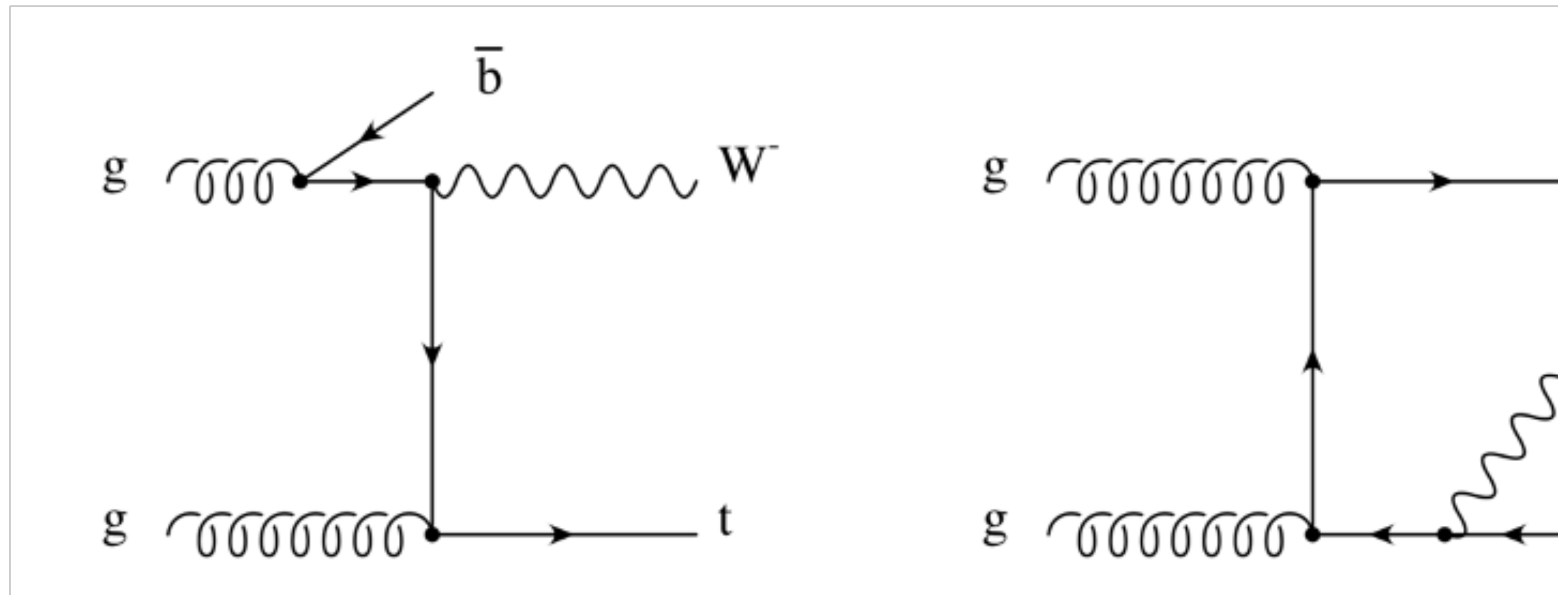
Dong, HTL, Wang, arXiv:2411.07455

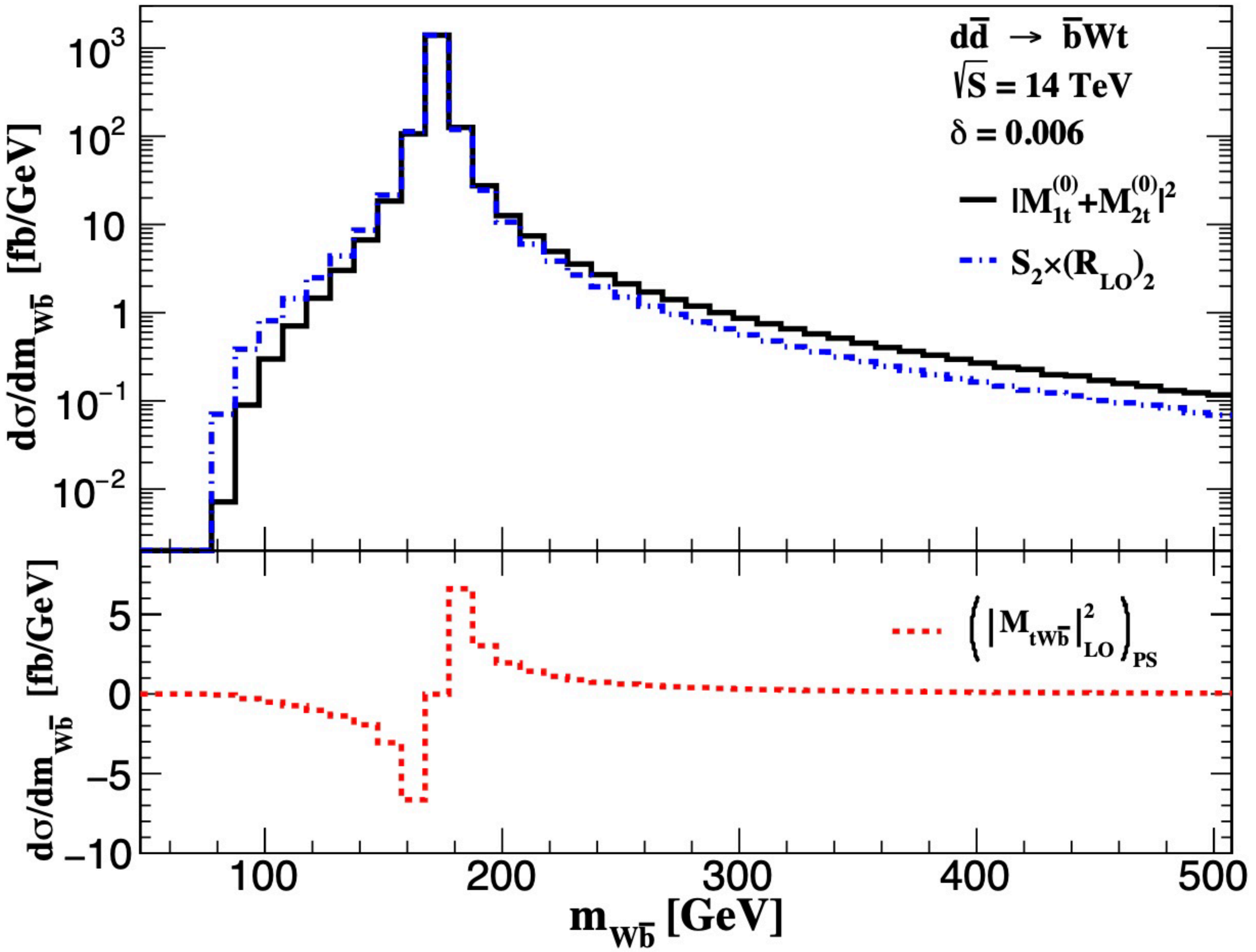
$$\left(\left| \mathscr{M}_{tW\bar{b}} \right|^2_{\text{LO}} \right)_{\text{PS}} = \left| \mathscr{M}^{(0)}_{1t} + \mathscr{M}^{(0)}_{2t} \right|^2 - S_2 \cdot \left(R_{\text{LO}} \right)_2 = \left| \mathscr{M}^{(0)}_{1t} + \mathscr{M}^{(0)}_{2t} \right|^2 - \frac{\widetilde{B^{(2)}}}{\Delta^2}$$

tW production

Toward NNLO

2. real-virtual





top quark pair

ion term to cancel
on

factorization scale

$\Delta = s_{Wb} - m_t^2$ In $\Delta \rightarrow 0$ limit

The leading singular contribution can be

$- \frac{\widetilde{B^{(2)}}}{\Delta^2}$

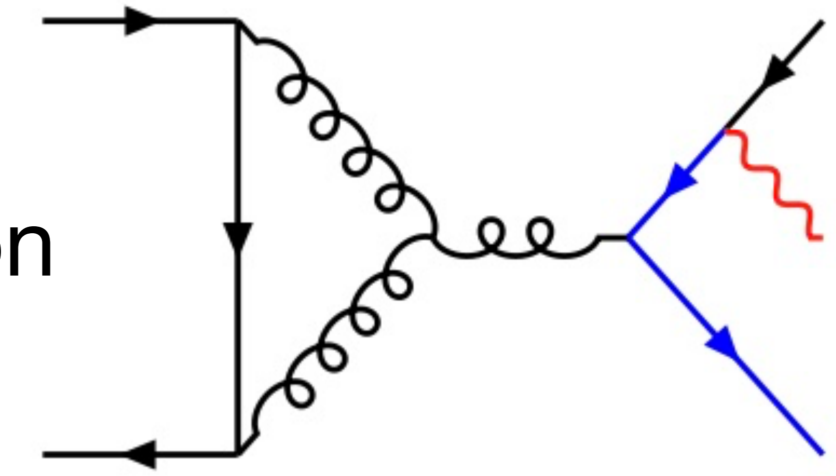
Dong, HTL, Wang, arXiv:2411.07455

tW production

Toward NNLO

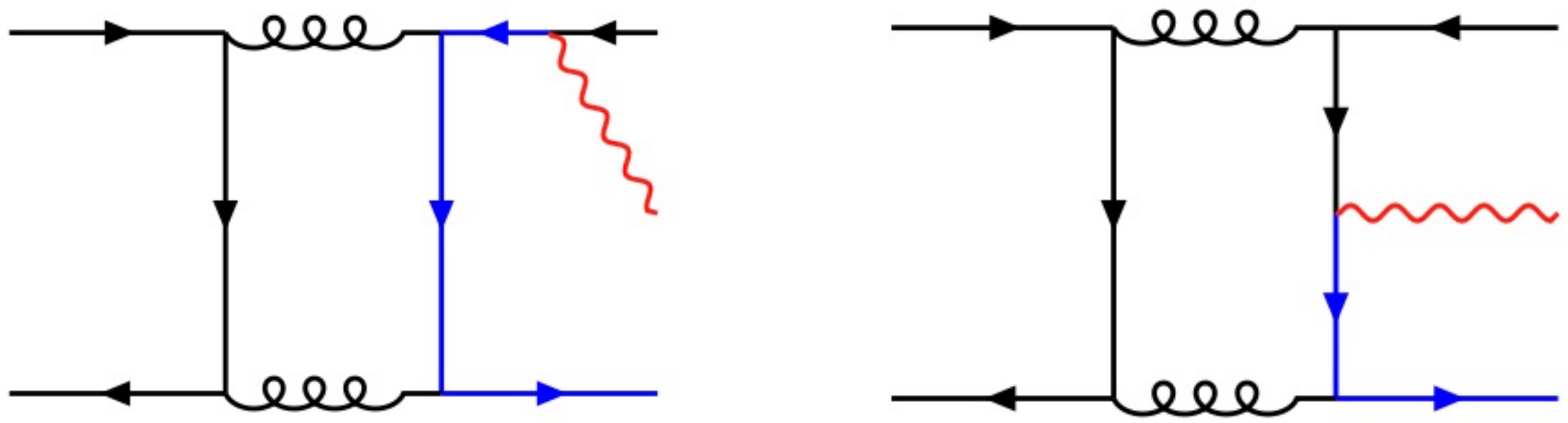
2. real-virtual

Possible diagrams with resonance contribution



factorizable

Loop corrections to top quark pair production and decay



loop with top propagators

generate nested IR or $\ln\Delta$ structure

factorizable + soft gluon contribution

$$RV_{\text{Ren}} \equiv 2\,\mathbf{Re}\left[\mathscr{M}^{(0)*}\mathscr{M}^{(1)}_{\text{Ren}}\right] = \frac{C^{(2)}}{\Delta^2} + \frac{C^{(1)}}{\Delta} + C^{(0)} + \cdots$$

All the coefficients contain IR poles

IR poles for 1-loop amplitude is well studied

Dong, HTL, Wang, arXiv:2411.07455

$$\begin{aligned}C^{(2)} = \frac{\alpha_s}{2\pi}B^{(2)}\Bigg\{ & -\frac{3C_F}{\epsilon^2} + \frac{1}{\epsilon}\Bigg[\left(C_A - 2C_F\right)\log\left(\frac{\mu^2}{s_{12}}\right) - 2\left(C_A - 2C_F\right)\log\left(\frac{\mu^2}{-s_{13}}\right) \\ & + \left(C_A - 4C_F\right)\log\left(\frac{\mu^2}{-s_{23}}\right) + \left(C_A - 4C_F\right)\log\left(\frac{m_t\mu}{-s_{15} + m_t^2}\right) \\ & - 2\left(C_A - 2C_F\right)\log\left(\frac{m_t\mu}{-s_{25} + m_t^2}\right) + \left(C_A - 2C_F\right)\log\left(\frac{m_t\mu}{s_{35} - m_t^2}\right) - \frac{11}{2}C_F\Bigg]\Bigg\} \\ & + \cdots\end{aligned}$$

tW production

Toward NNLO

2. real-virtual

IR poles introduce additional $\ln \Delta$ terms

$$2\log\left(\frac{m_t\mu}{|\Delta|}\right)\cdot\frac{\alpha_s}{2\pi}B^{(2)}\Bigg[(C_A-2C_F)\left(\log\left(\frac{m_t^2}{s_{35}-m_t^2}\right)-\frac{1+\beta_t^2}{2\beta_t}\log\left(\frac{1-\beta_t}{1+\beta_t}\right)\right)$$
$$-2(C_A-2C_F)\left(\log\left(\frac{m_t^2}{-s_{13}}\right)-\log\left(\frac{m_t^2}{2p_1\cdot p_{\bar{t}}}\right)\right)$$
$$+(C_A-4C_F)\left(\log\left(\frac{m_t^2}{-s_{23}}\right)-\log\left(\frac{m_t^2}{2p_2\cdot p_{\bar{t}}}\right)\right)+2C_F\log\left(\frac{m_t^2}{2p_{\bar{t}}\cdot p_3}\right)+2C_F\Bigg]$$

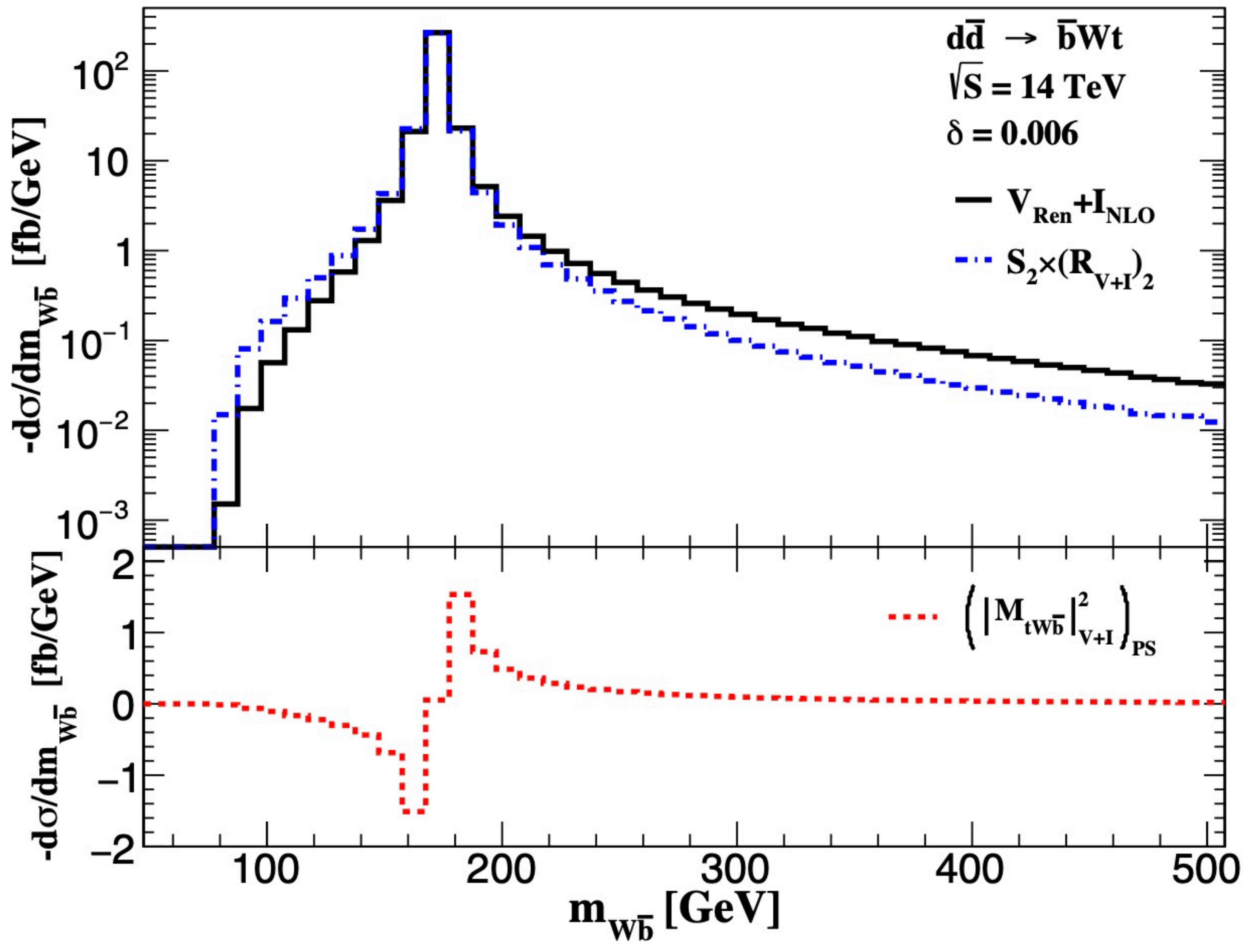
$$I^{\rm div}_{d\bar{d}\to\bar{b}Wt}=\frac{d_2}{\epsilon^2}+\frac{d_1}{\epsilon}+\frac{d_s}{\epsilon}\left(\frac{-\Delta-i0}{\mu m_t}\right)^{-2\epsilon}=\frac{d_2}{\epsilon^2}+\frac{d_1+d_s}{\epsilon}-2d_s\log\left(\frac{-\Delta-i0}{\mu m_t}\right)$$

Proportional to the difference between the infra-red divergences of the matrix elements for $d\bar{d}\to\bar{b}Wt$ and $d\bar{d}\to t\bar{t}$ with on-shell $\bar{t}\to\bar{b}W$

Subtracted RV contribution

$$\left(\left|\mathcal{M}_{tW\bar{b}}\right|^2_{\rm V+I}\right)_{\rm PS}=V_{\rm Ren}+\mathcal{I}_{\rm NLO}-S_2\cdot\left(R_{\rm V+I}\right)_2=V_{\rm Ren}+\mathcal{I}_{\rm NLO}-\frac{\widetilde{C^{(2)}}+\widetilde{I^{(2)}}}{\Delta^2}$$

Dong, HTL, Wang, arXiv:2411.07455



tW production

Toward NNLO

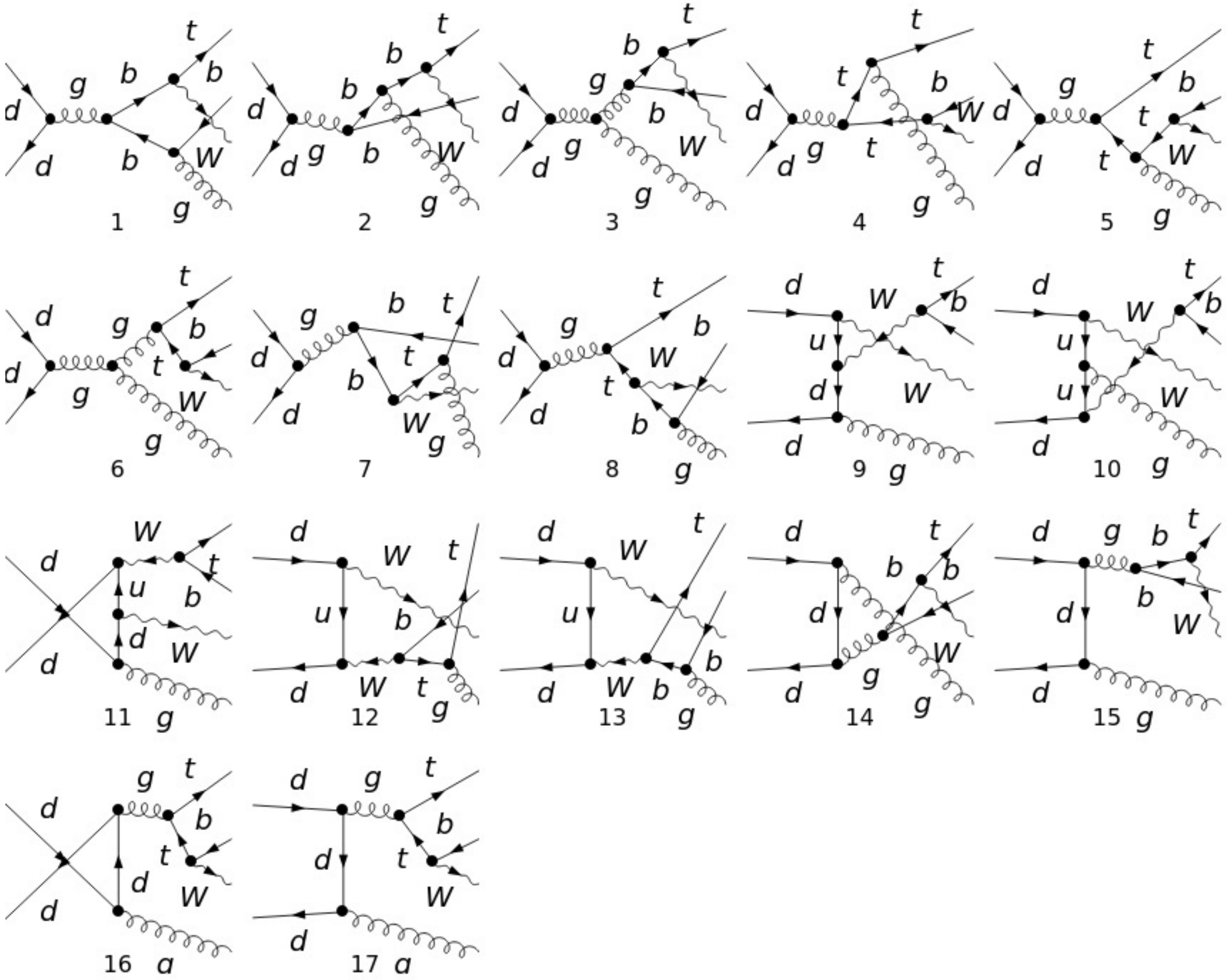
3. real-real

IR cancelled by NLO subtraction method

Resonance singularities cancelled by Power Expansions

factorizable + soft gluon contribution

Dong, HTL, Li, Wang, work in progress



Summary

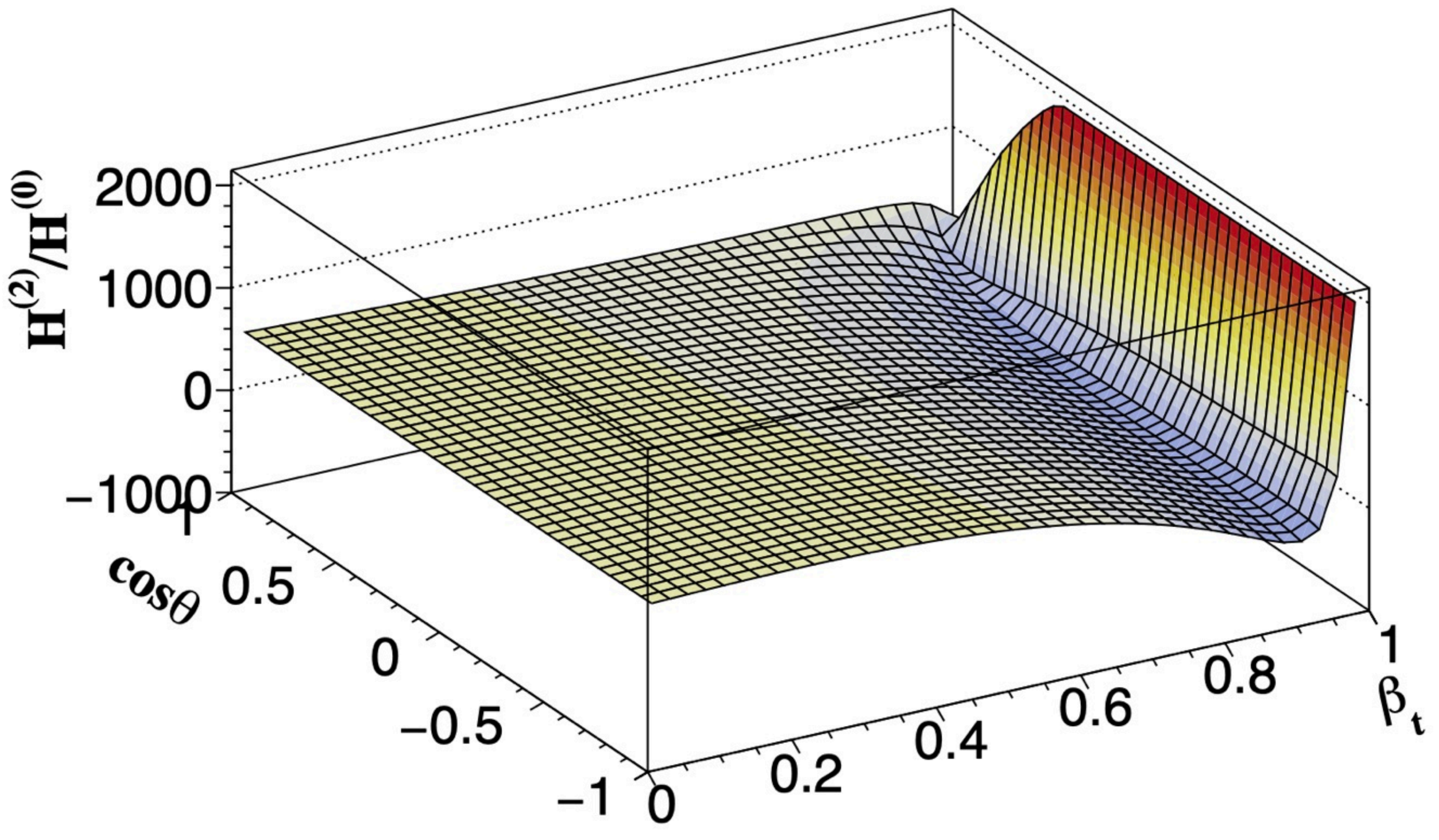
- Single top-quark production: a direct measurement of the CKM matrix element V_{tb} and new physics

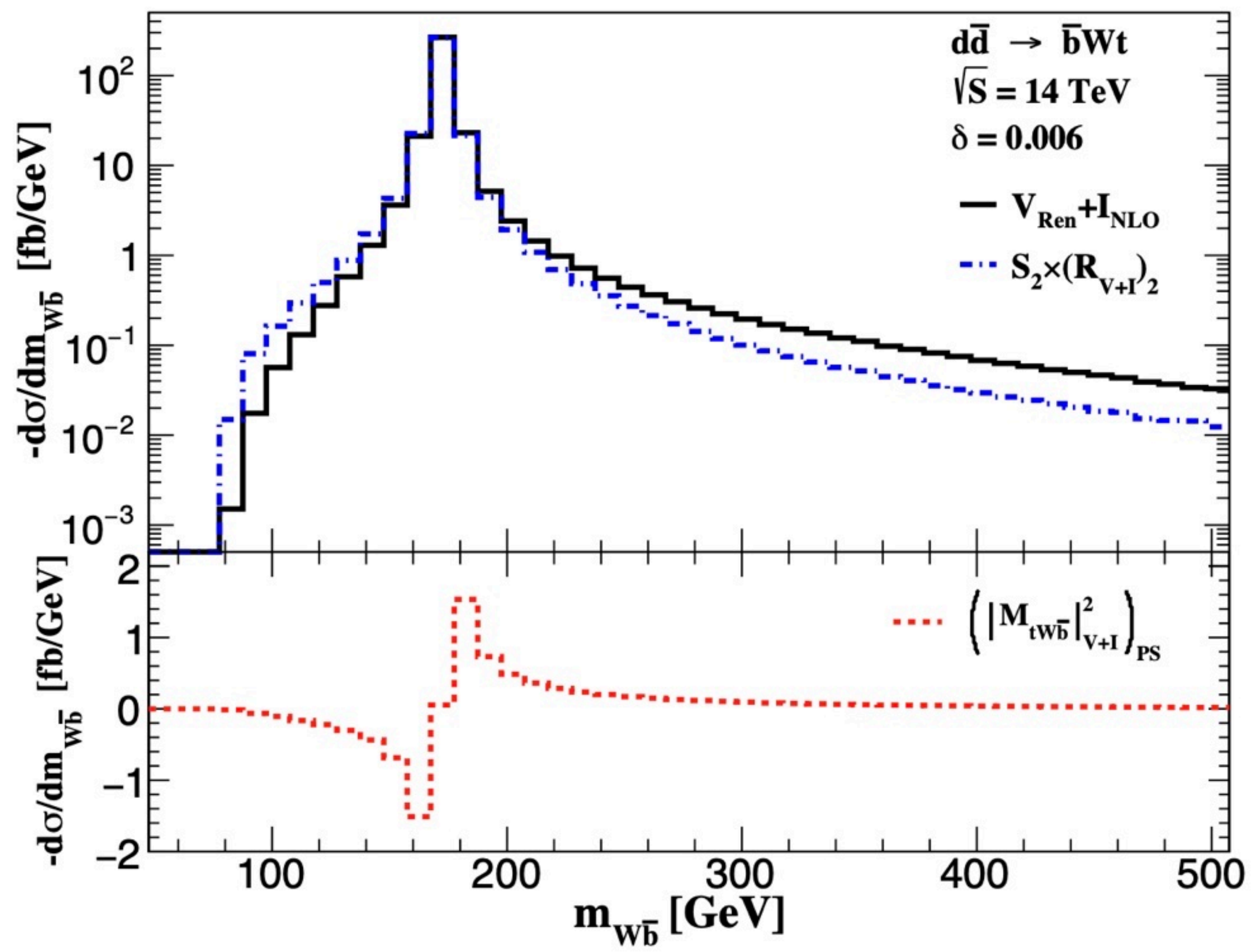
- Toward NNLO QCD corrections to tW production

- Present the two-loop matrix element for tW production

- Resonance singularity in the tree and loop amplitude has to be subtracted

- Real-Virtual and Double real can be dealt with power expansion method





微扰量子场论及其应用前沿讲习班

Jul 6 – 20, 2025
Asia/Shanghai timezone

Enter your search term

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Contact

haitao.li@email.sdu.edu...
jian.wang@email.sdu.ed...

为帮助研究生系统了解粒子物理科研现状、前沿方向、未来发展等专业知识，"微扰量子场论及其应用"前沿讲习活动将于2025年7月6日至20日在山东大学中心校区举办。7月6日报到，7月20日离会。

讲习活动以"微扰量子场论和对撞机物理"为主要内容，由电弱规范理论、量子色动力学理论、对撞机唯象学、微扰量子场论方法、有效场论思想及应用、新物理研究方法等内容组成，同时暑期学校计划安排粒子物理宇宙学、引力波探测、高能宇宙射线等方向的专题讲座。

本次讲习活动主要面向研究生，不收取注册费。**请申请学员认真填写注册表格，并安排导师写一封推荐信，发给会务组，注册截止时间为4月30日。**申请截止后，暑期学校将根据申请人的学术背景和研究兴趣来确定最终名单。**为了保证教学效果，暑期学校限定学员总数为50人，要求全程参加，不接受请假。**

会务组为学员提供餐食，住宿和交通费用自理。如学员需要资助，可联系会务组，择优资助部分费用。

本次讲习活动由国家自然科学基金委理论物理专项、国家自然科学基金委创新群体项目资助。本次学术活动由山东大学主办。

会务组：陈龙，陈暄，蒋军，李海涛，李世渊，刘言锐，路鹏程，司宗国，王健，王耀光，吴群。

讲习班主页：https://indico.ihep.ac.cn/event/25318/

泉城-济南

https://indico.ihep.ac.cn/event/25318/

Thank You !!