Top quark physics and Top-Higgs interplay

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Peking University

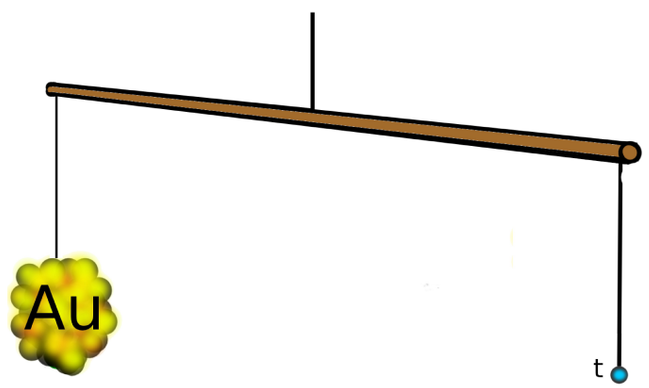
14th Workshop on TeV Physics
at Nanjing Normal University

Outline

* Introduction
* Top quark pair production
* Top-Higgs interplay
  * Higgs production associated with a top quark pair
  * Top quarks inside loops for Higgs physics
* Single top quark production

Basic facts about the top quark

Large mass $m_t \approx 173$ GeV



Strong Yukawa coupling $y_t \sim 1$

Fermion mass origin

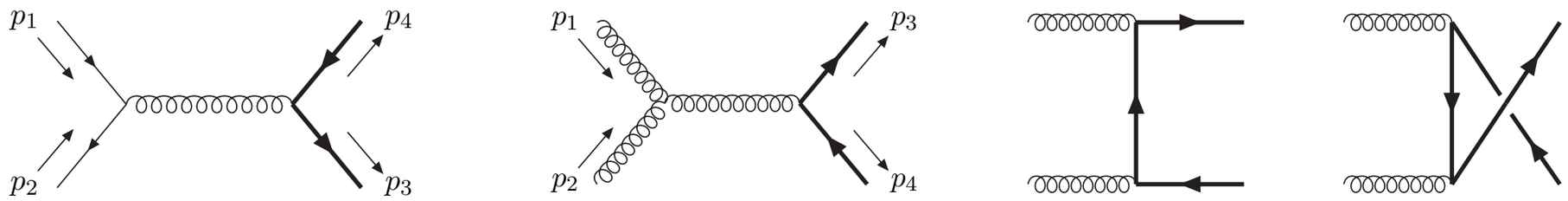
Hierarchy problem

Vacuum stability

Short lifetime $\tau \sim 5 \times 10^{-25}$ s

Decays before hadronization: pQCD dominates!

Top quark pair production



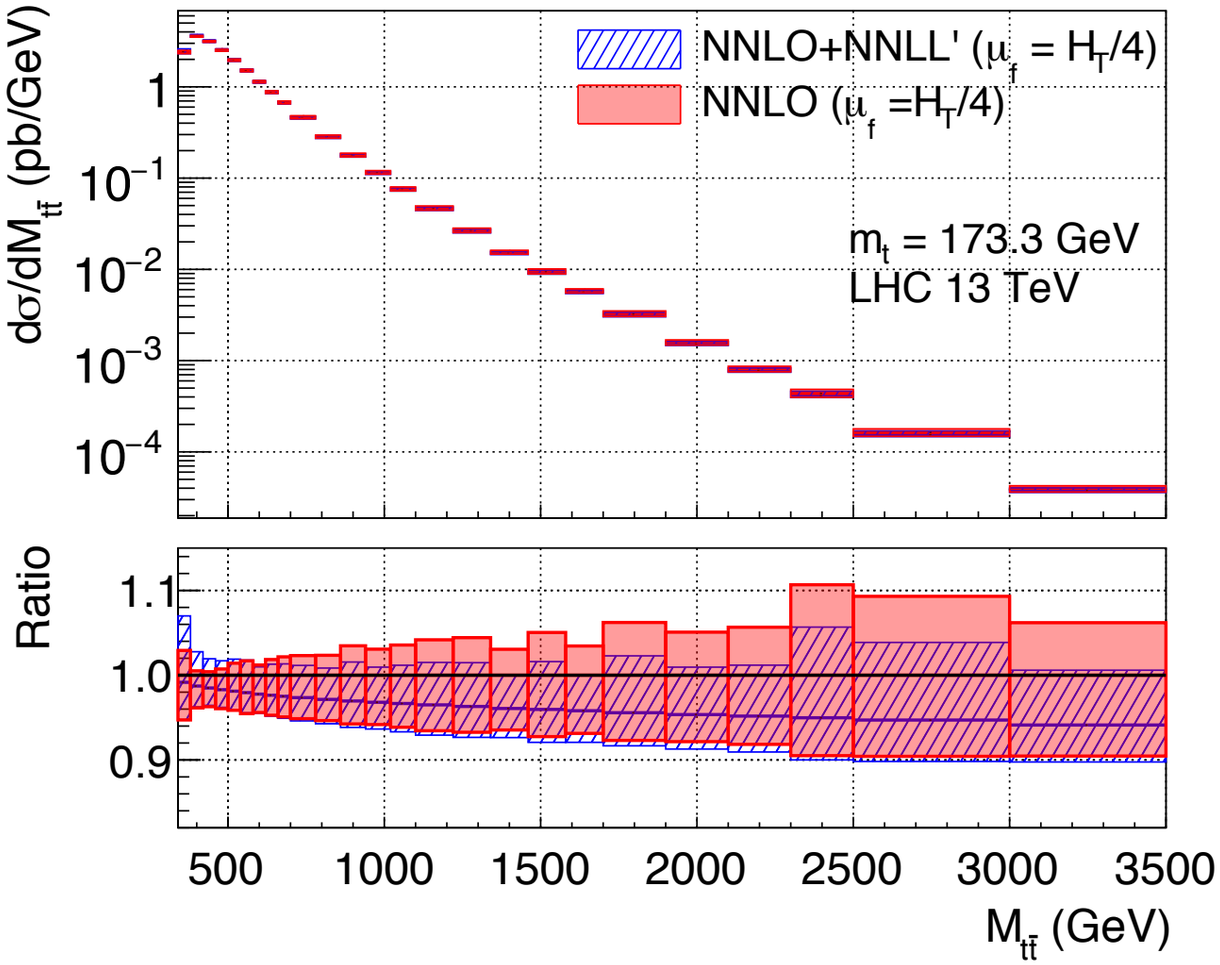
A standard candle for the LHC and future colliders

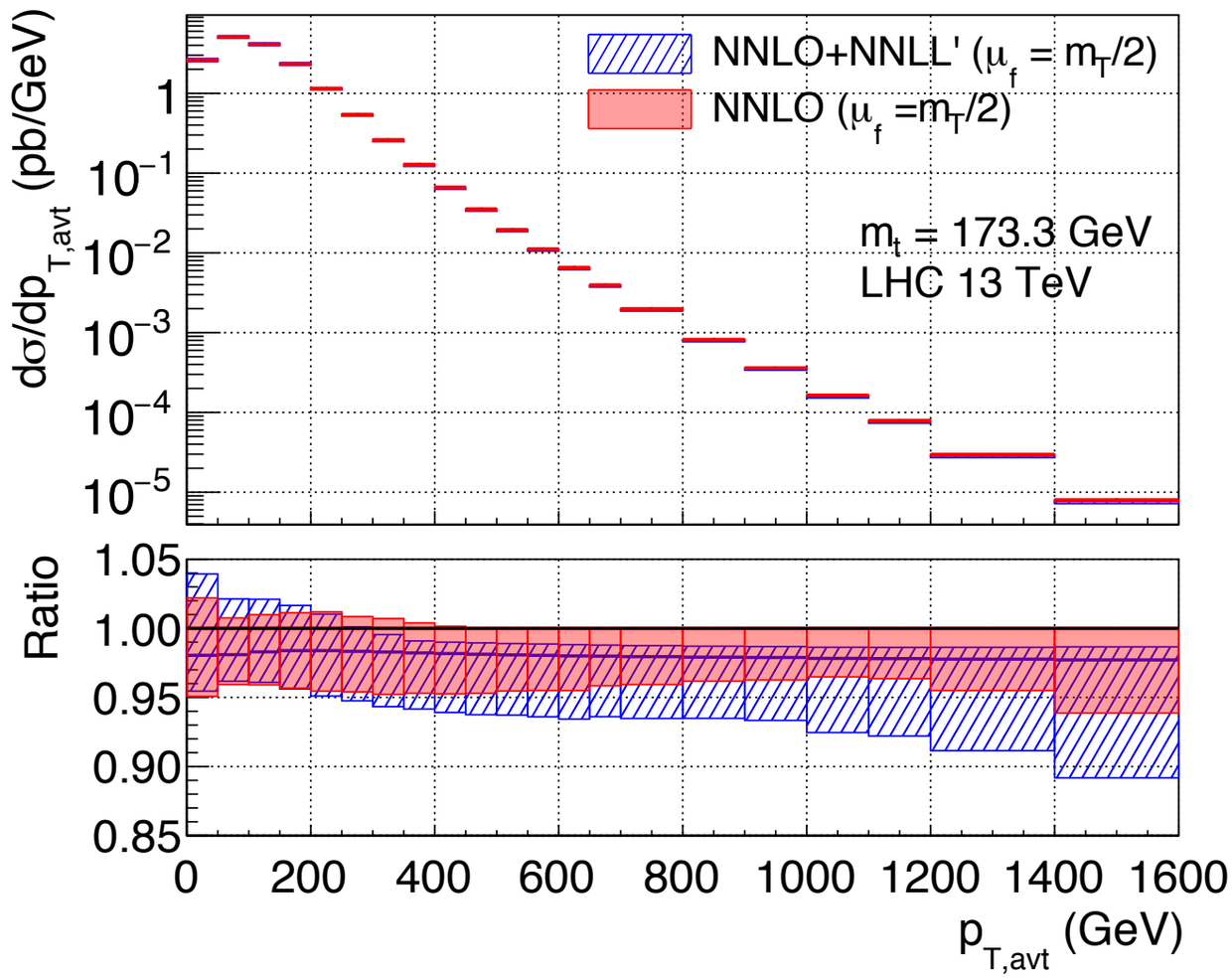
* Main production mechanism for top quarks
* Test of the Standard Model at the energy frontier
* Possible signals of new physics
* Major background to many searches

State-of-the-art predictions

NNLO+NNLL′ in QCD

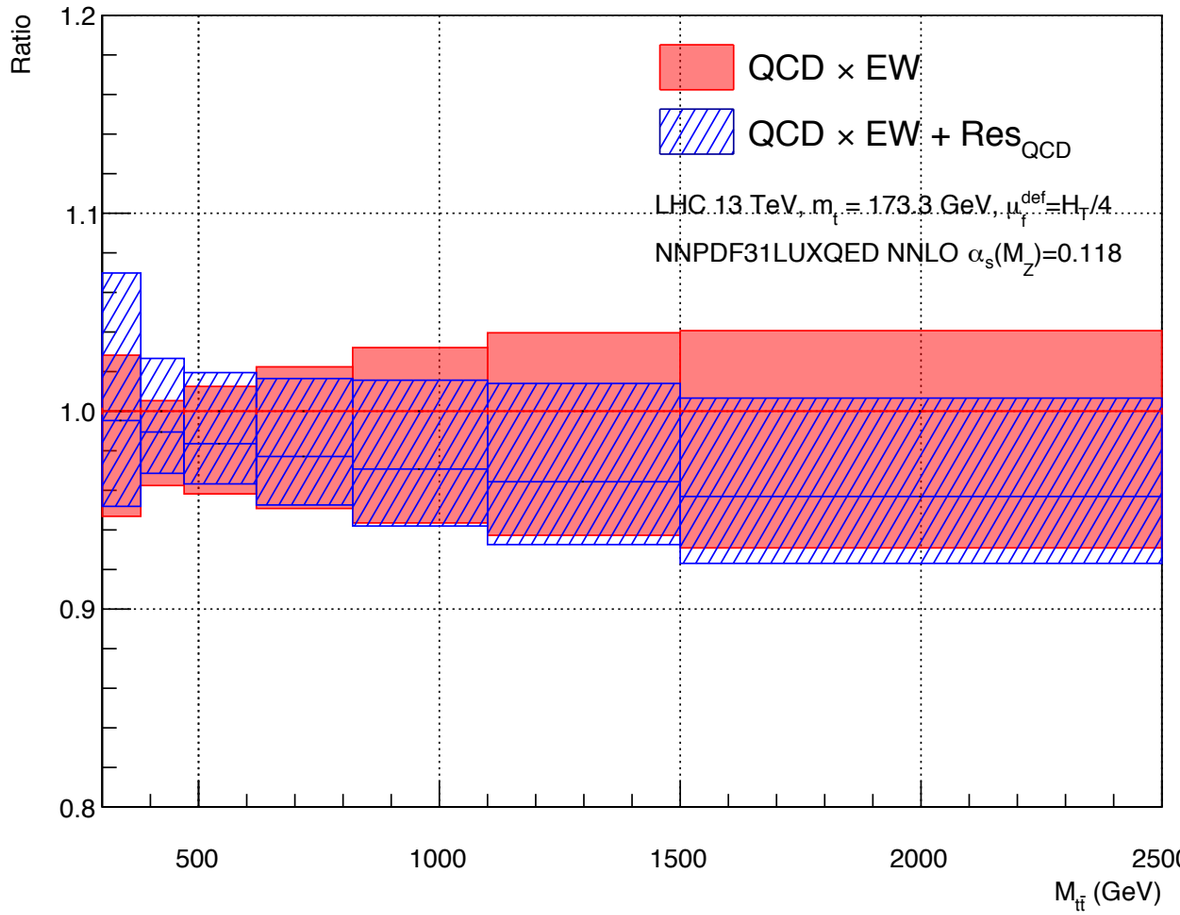
Pecjak, Scott, Wang, **LLY**: 1601.07020
Czakon, Heymes, Mitov: 1606.03350
Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, **LLY**: 1803.07623
Pecjak, Scott, Wang, **LLY**: 1811.10527

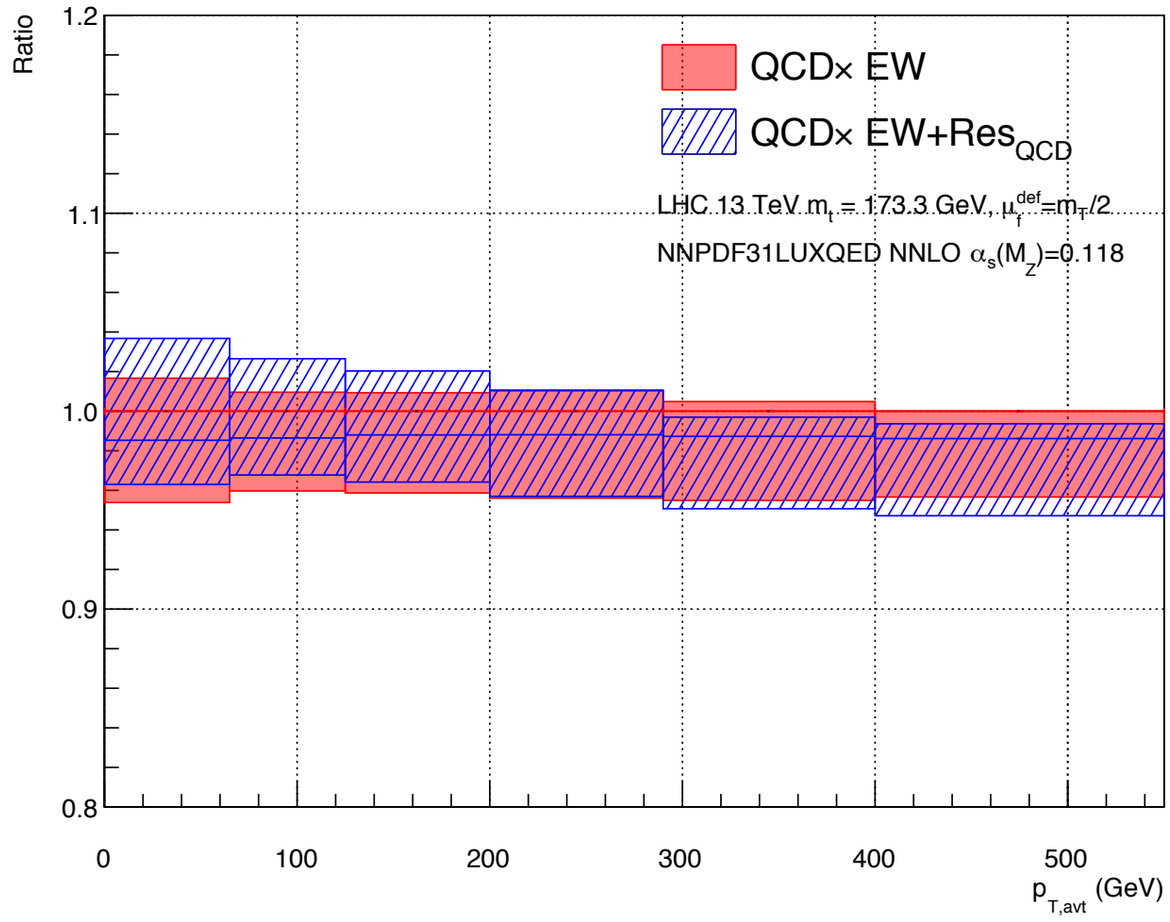




State-of-the-art predictions

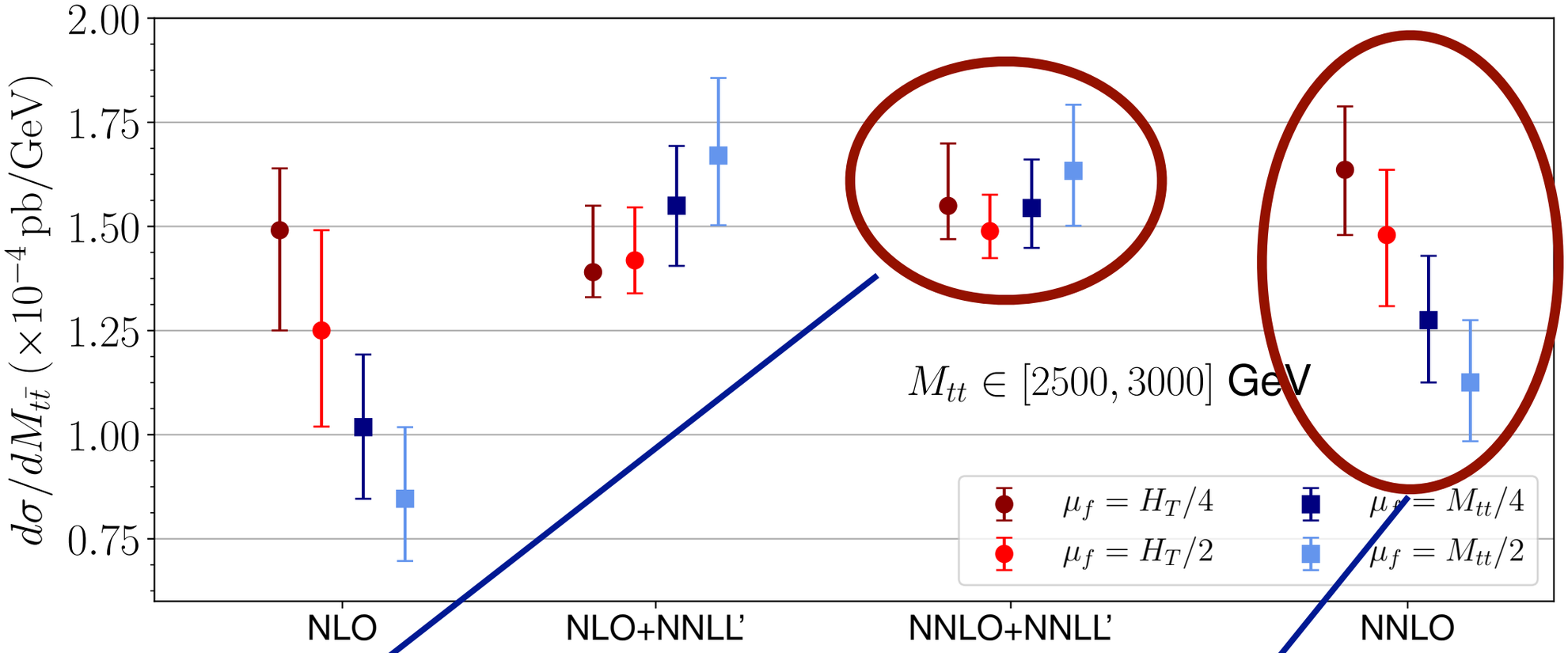
Combined with NLO electroweak corrections





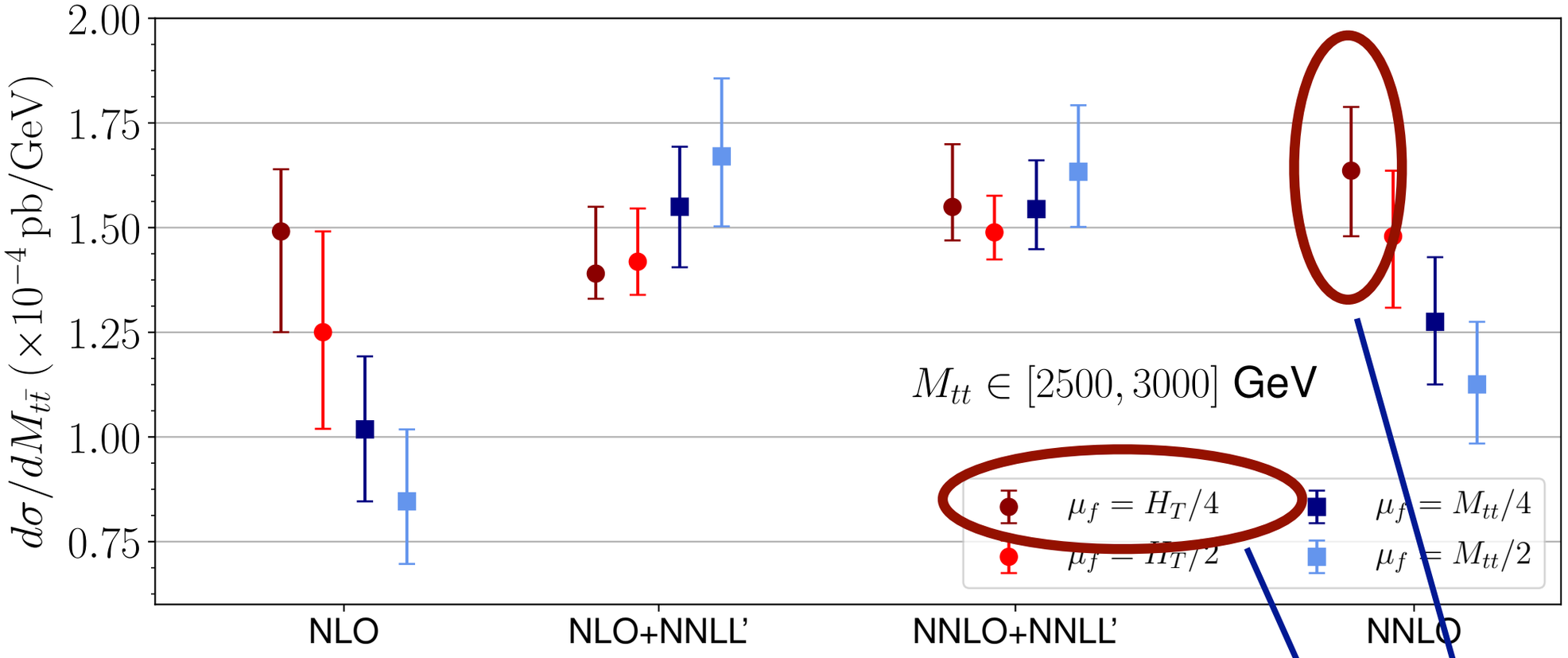
Czakon, Ferroglia, Mitov, Pagani, Papanastasiou, Pecjak, Scott, Tsinikos, Wang, **LLY**, Zaro: 1901.08281

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, **LLY**: 1803.07623



NNLL′ resummation stabilizes scale ambiguity compared to NNLO

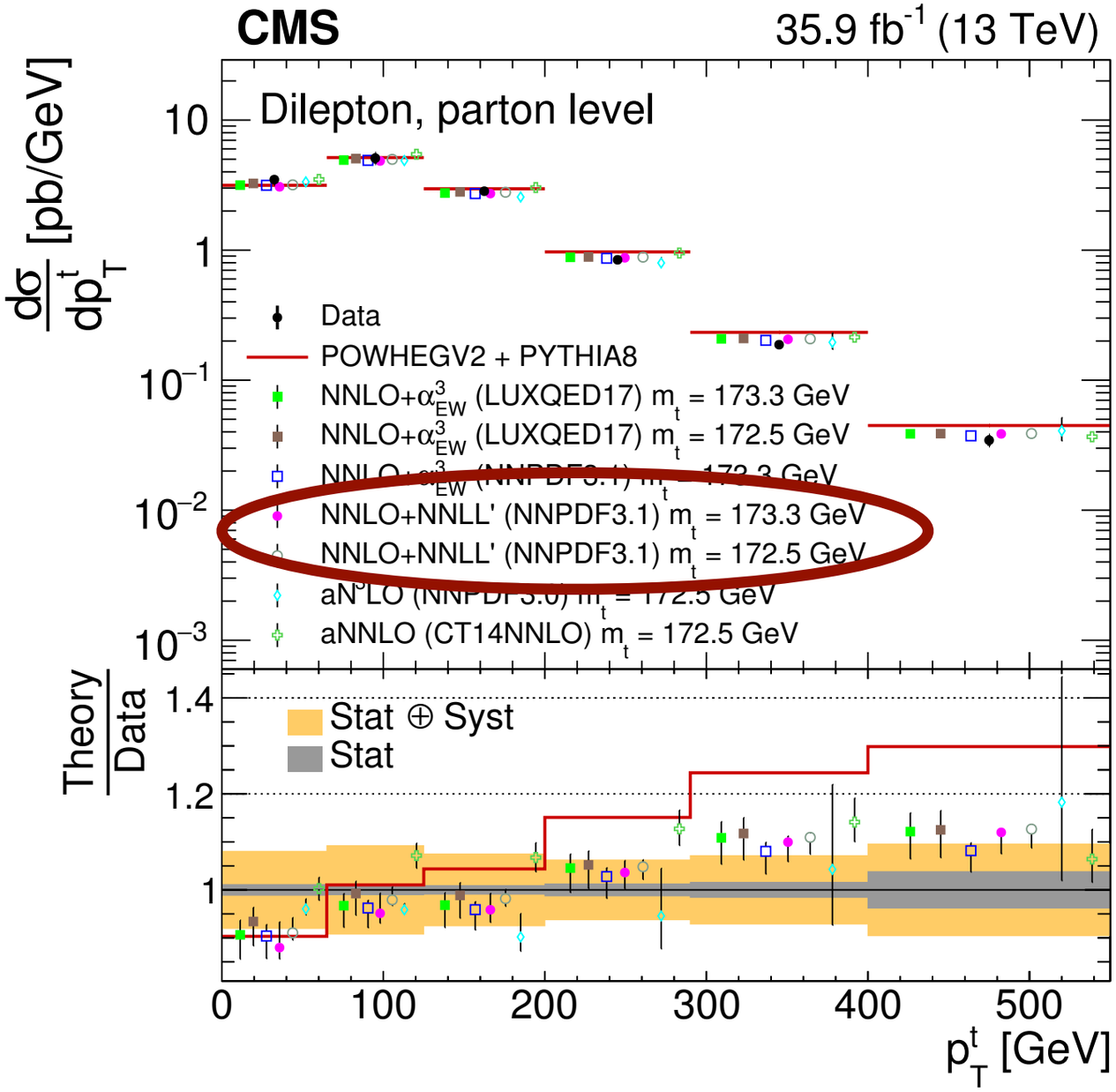
Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, **LLY**: 1803.07623



And confirms optimal scale choice for fixed order simulations

Theory confronting data

CMS collaboration: 1811.06625



Transverse momentum

Theory confronting data

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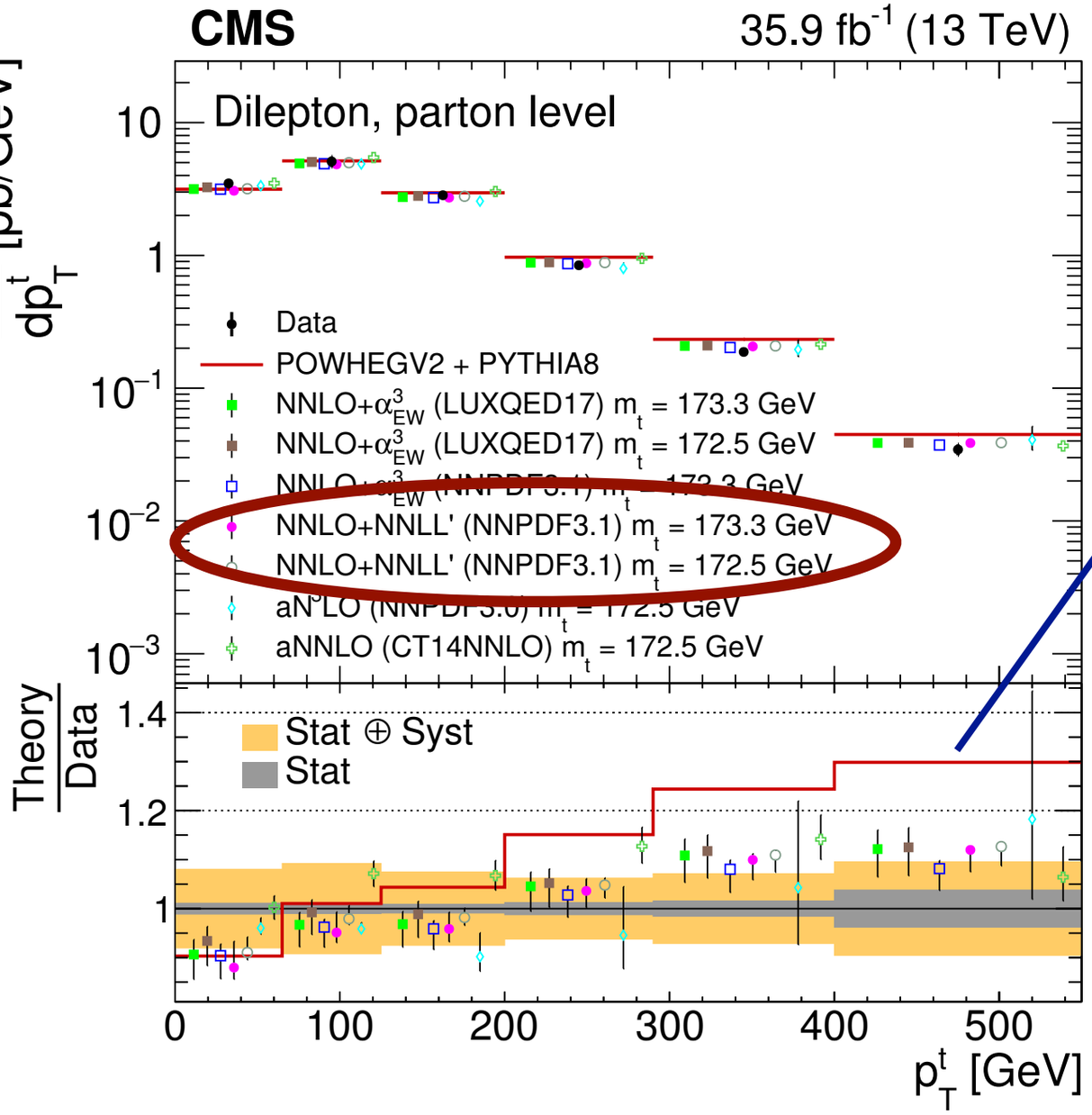

Transverse momentum

NLO + parton shower cannot describe the shape!

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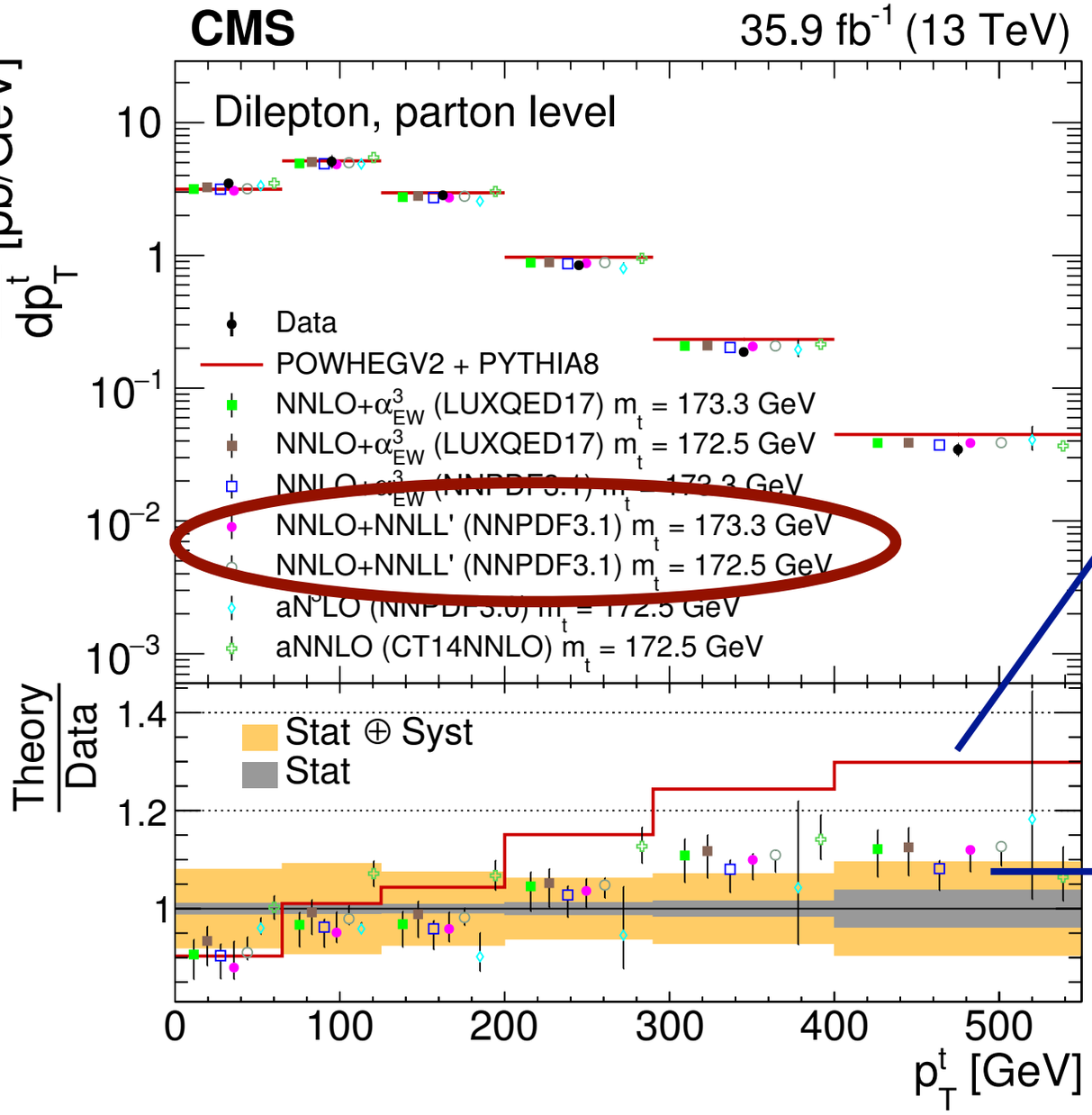


Transverse momentum

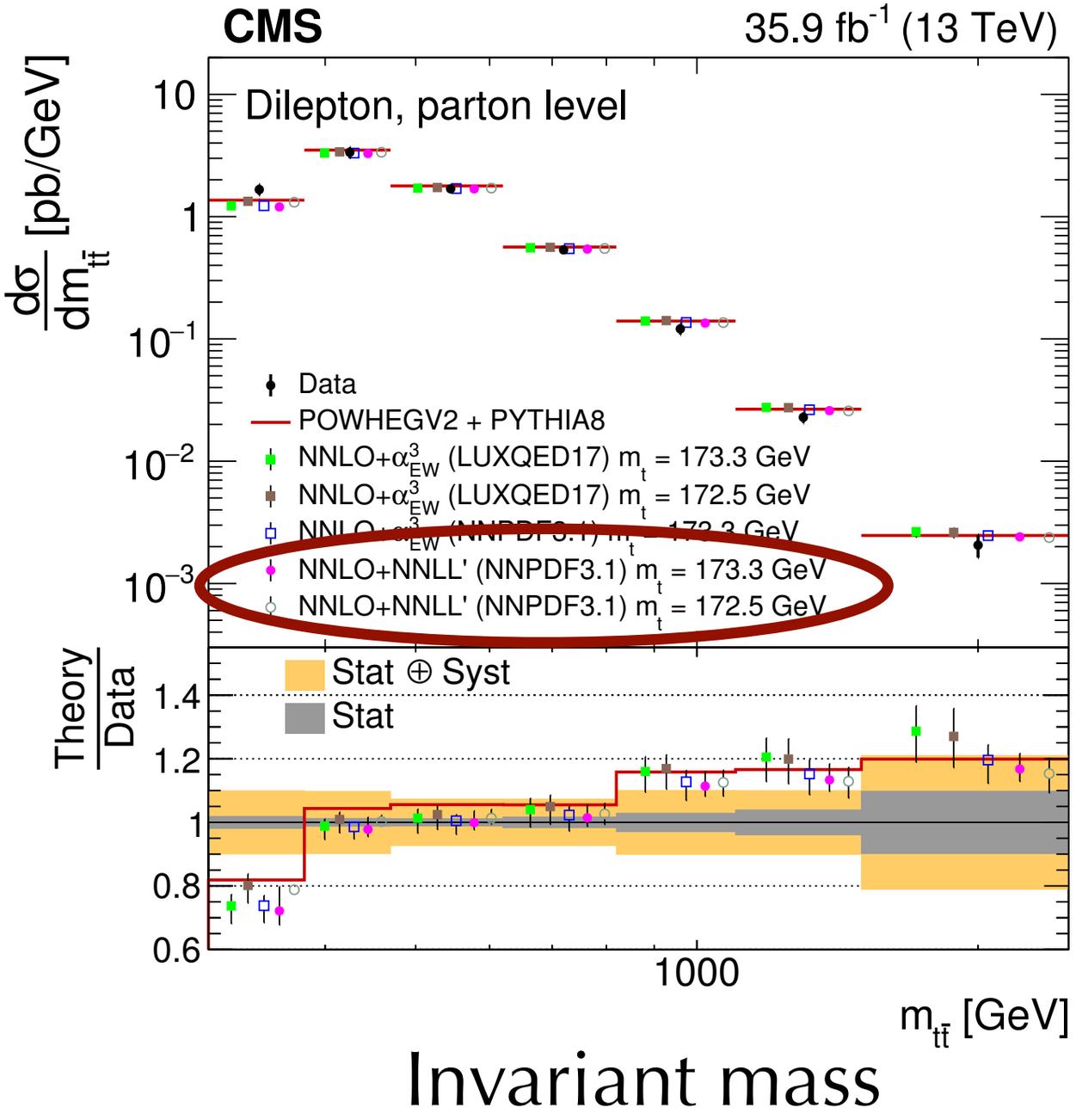
NLO + parton shower cannot describe the shape!

Higher order calculations bring together theory and experiment

Theory confronting data

CMS collaboration: 1811.06625

Overall good agreement



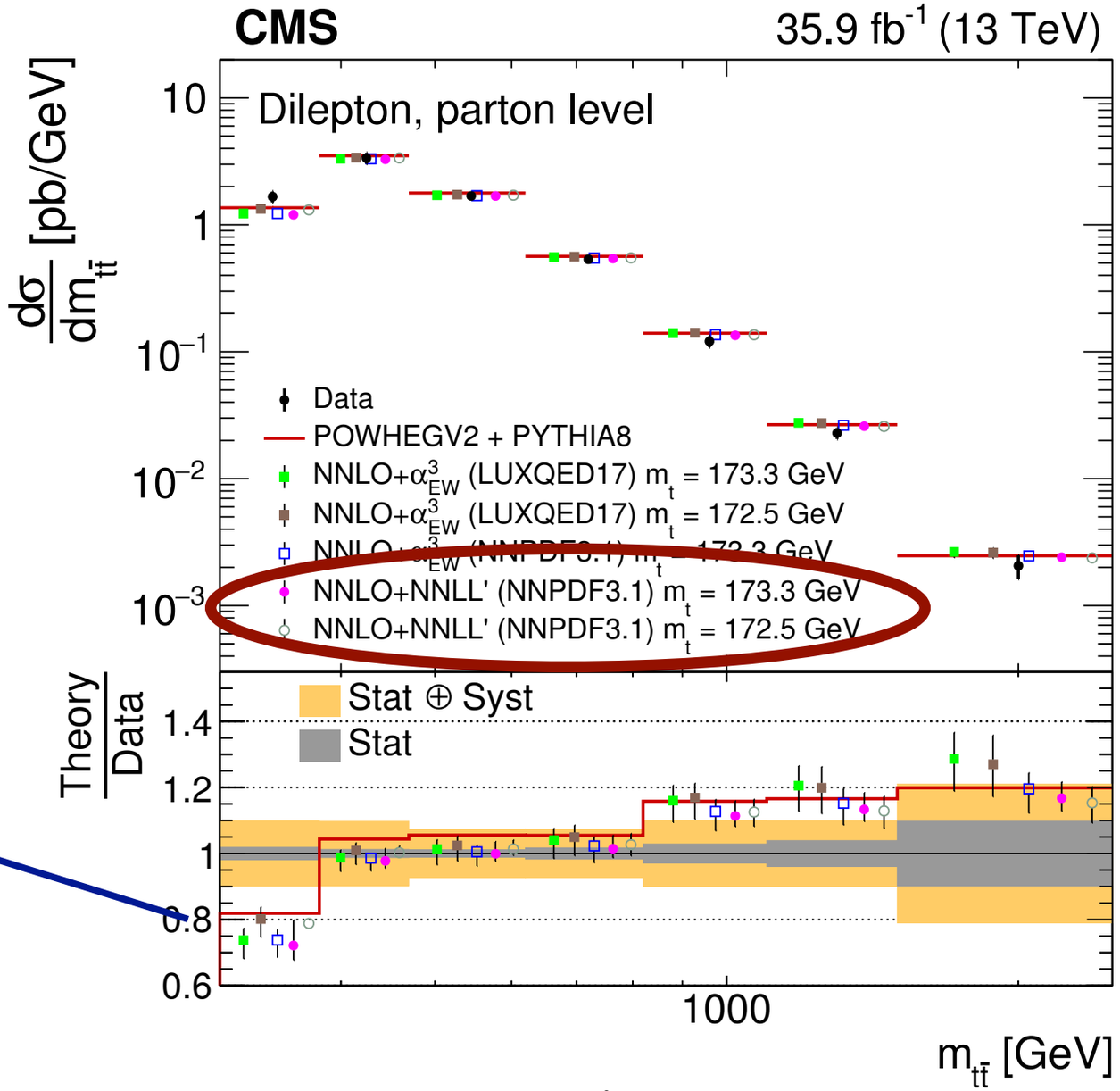
Invariant mass

Theory confronting data

CMS collaboration: 1811.06625

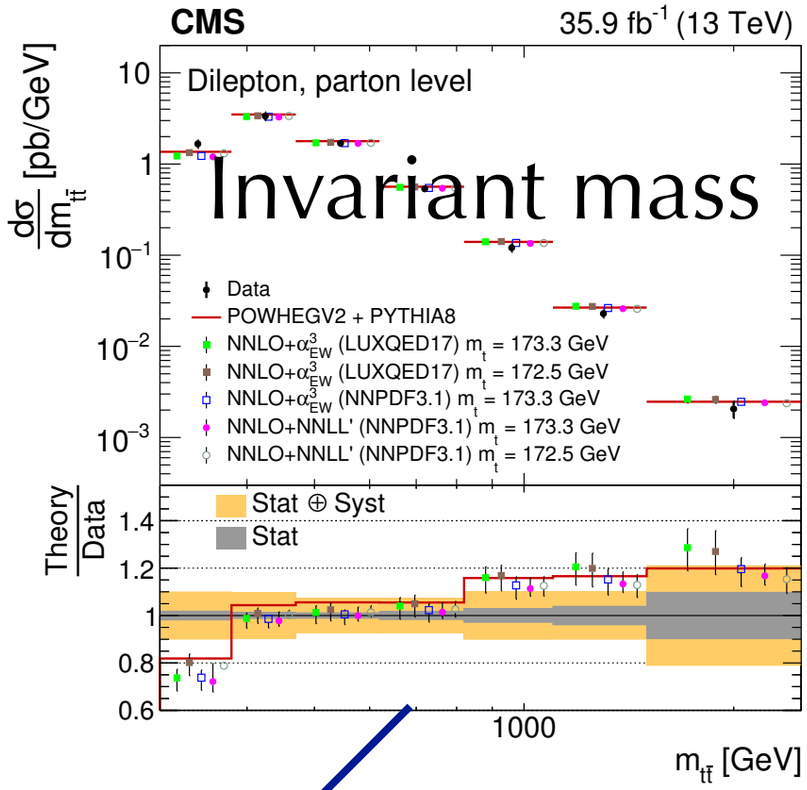
Overall good agreement

Except the first bin



Invariant mass

Inside the calculations



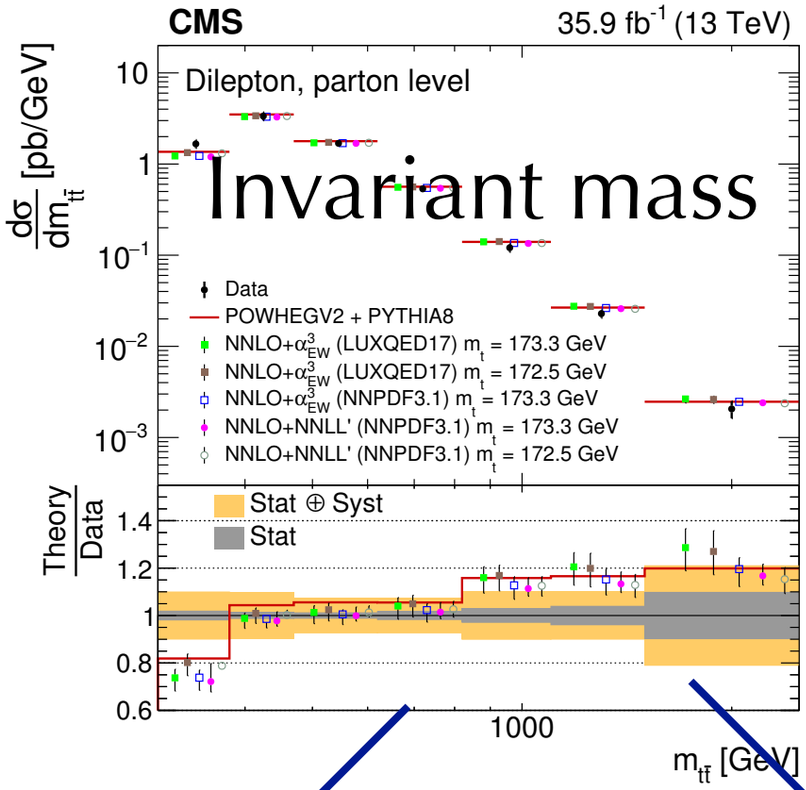
Whole region

soft emissions to all orders

Ahrens, Ferroglia, Neubert, Pecjak, **LLY**: 1003.5827

$$\ln \frac{\hat{s} - M_{t\bar{t}}^2}{M_{t\bar{t}}^2}$$

Inside the calculations



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Boosted region

soft+quasi-collinear emissions to all orders

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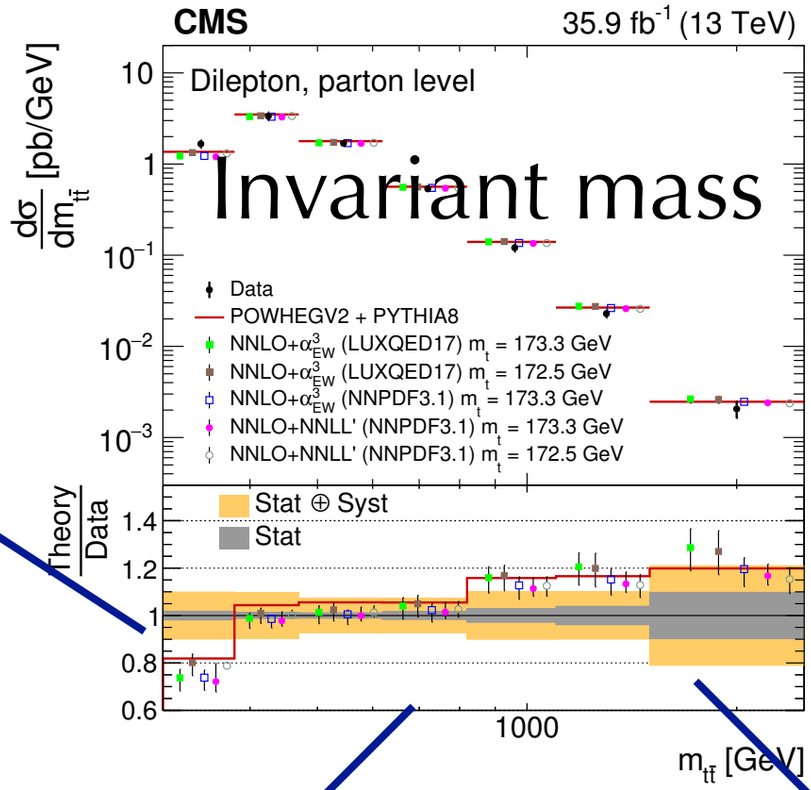
Inside the calculations

Threshold region
soft+Coulomb?



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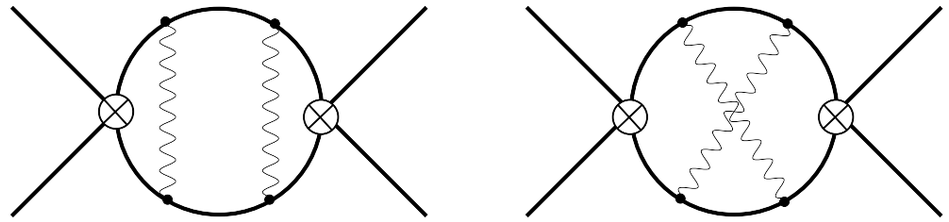
Coulomb corrections for total cross section

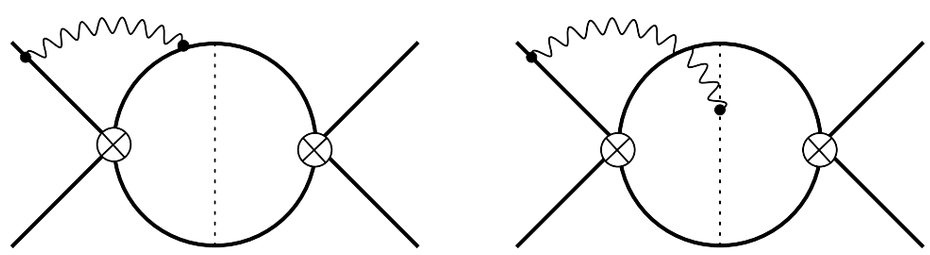
Coulomb corrections for total cross section have been considered in, e.g.:

Beneke, Czakon, Falgari, Mitov, Schwinn: 0911.5166
Beneke, Falgari, Schwinn: 1007.5414

Threshold limit: $\sqrt{\hat{s}} \to 2m_t$



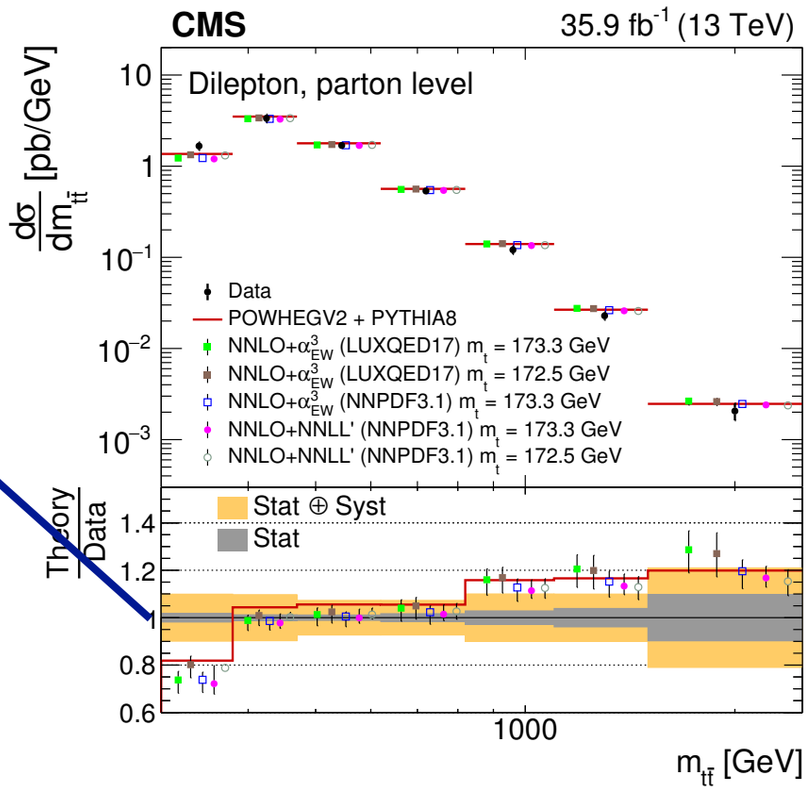
SCET+NRQCD



Remark: top quark physics is a good place to study NRQCD since mv^2 is (very often) a perturbative scale

Coulomb corrections for invariant mass distribution

$\sqrt{\hat{s}} \to 2m_t$ is not the same as $M_{t\bar{t}} \to 2m_t$



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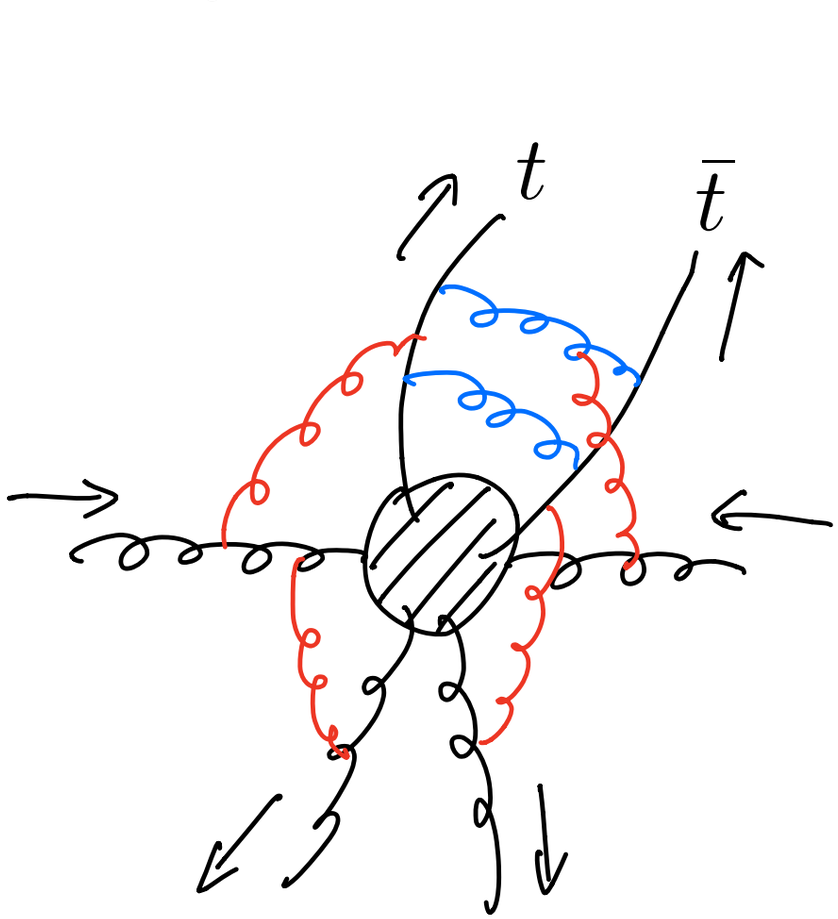

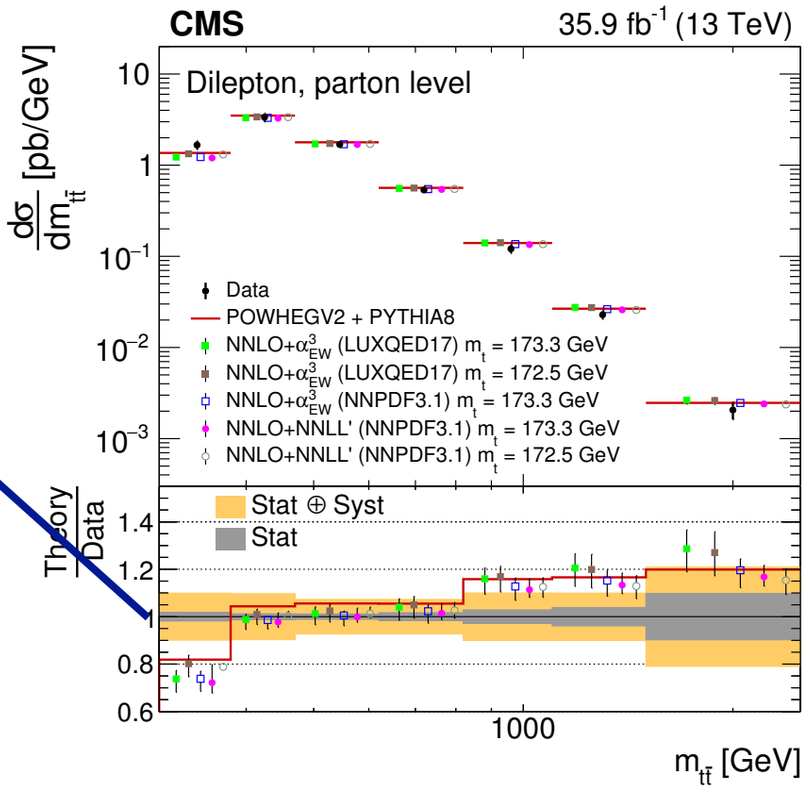

The top quark pair can be recoiled by extra emissions

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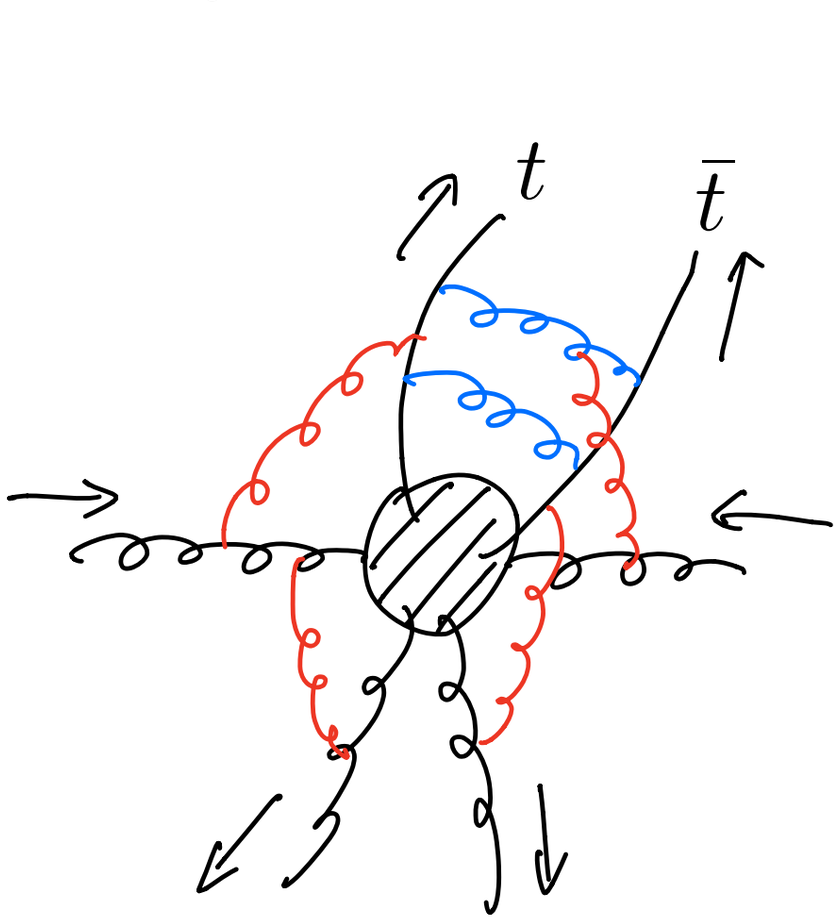
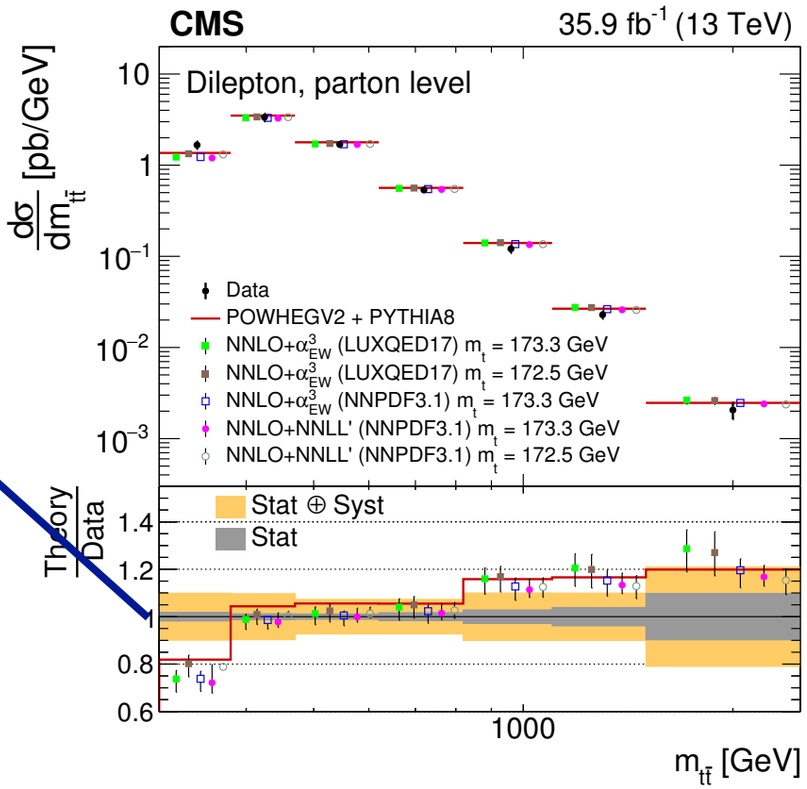




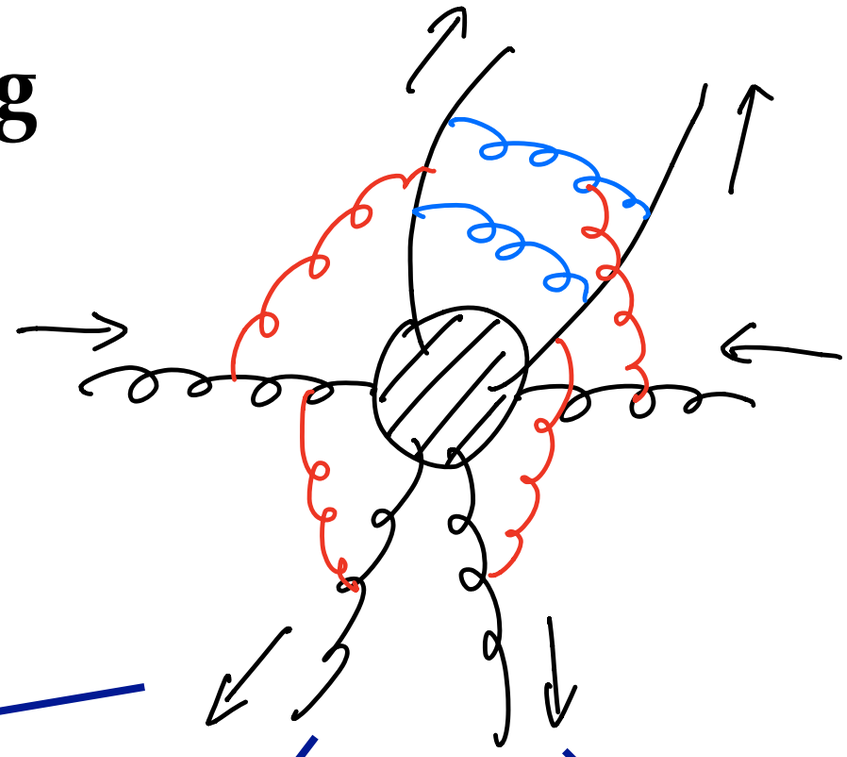
More complicated interplay among collinear, soft and Coulomb gluons

Ju, Wang, Xu, **LLY**: in progress

The top quark pair can be recoiled by extra emissions

The resummation framework depends on the power-counting of extra emissions!

$E \sim$ binding energy of top quark pair



$E_g \sim E$

ultrasoft

Same as $\sqrt{\hat{s}} \to 2m_t$

$E_g \sim \sqrt{m_t E}$

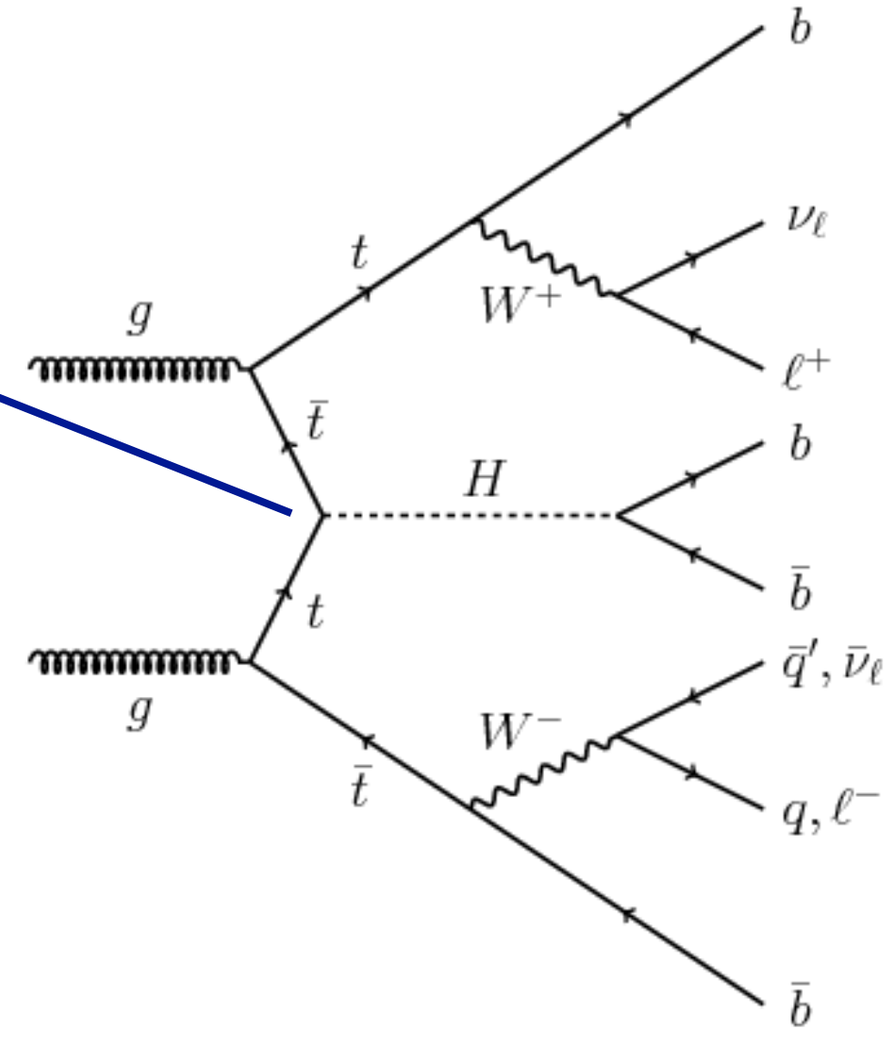
soft

$E_g \sim m_t$

hard

A warm-up: tTH production

Probing the Yukawa coupling of the top quark (origin of large mass)



Just observed at the LHC

CMS collaboration: 1804.02610
ATLAS collaboration: 1806.00425

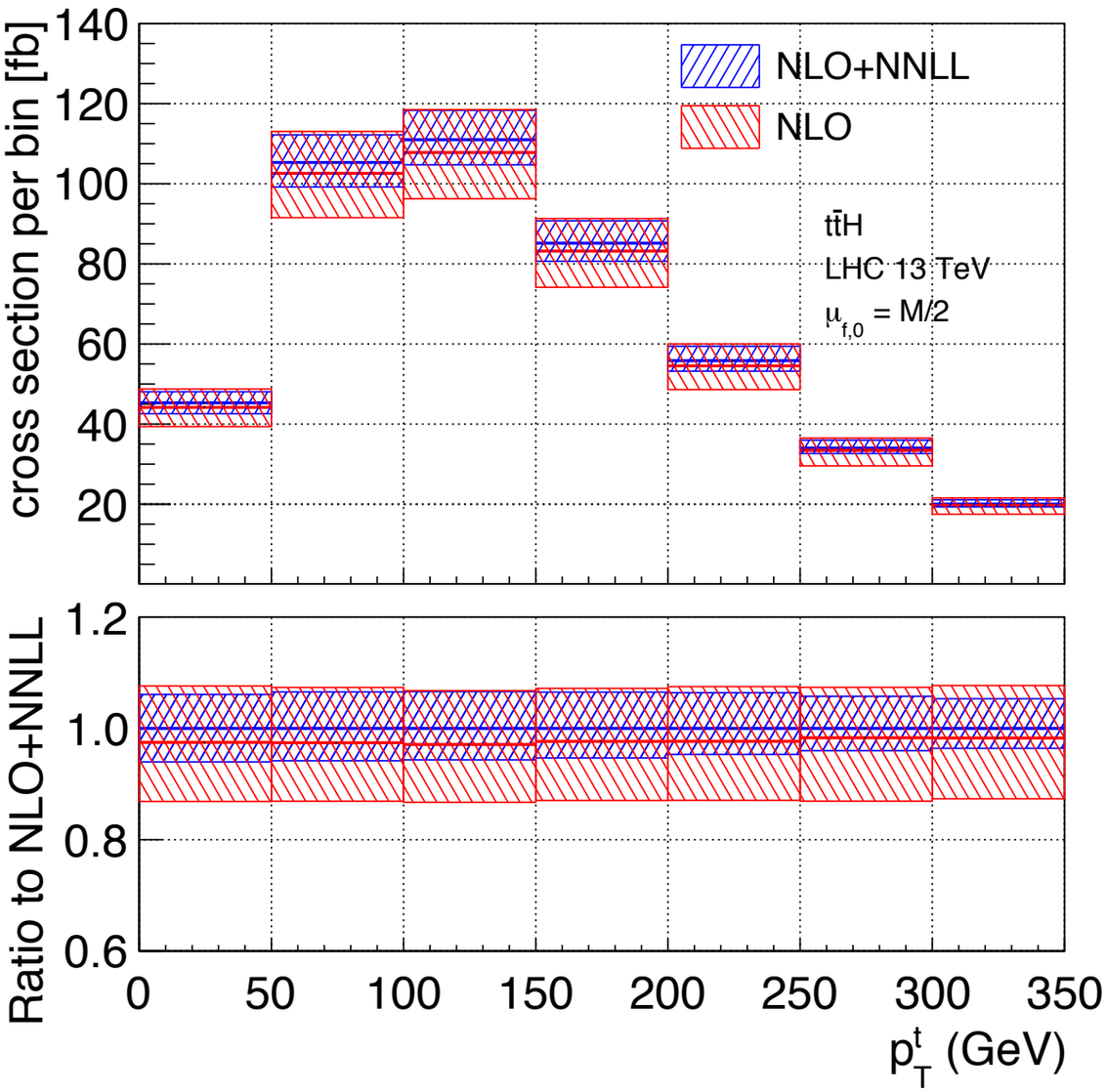
Also sensitive to possible CP violation in top quark sector

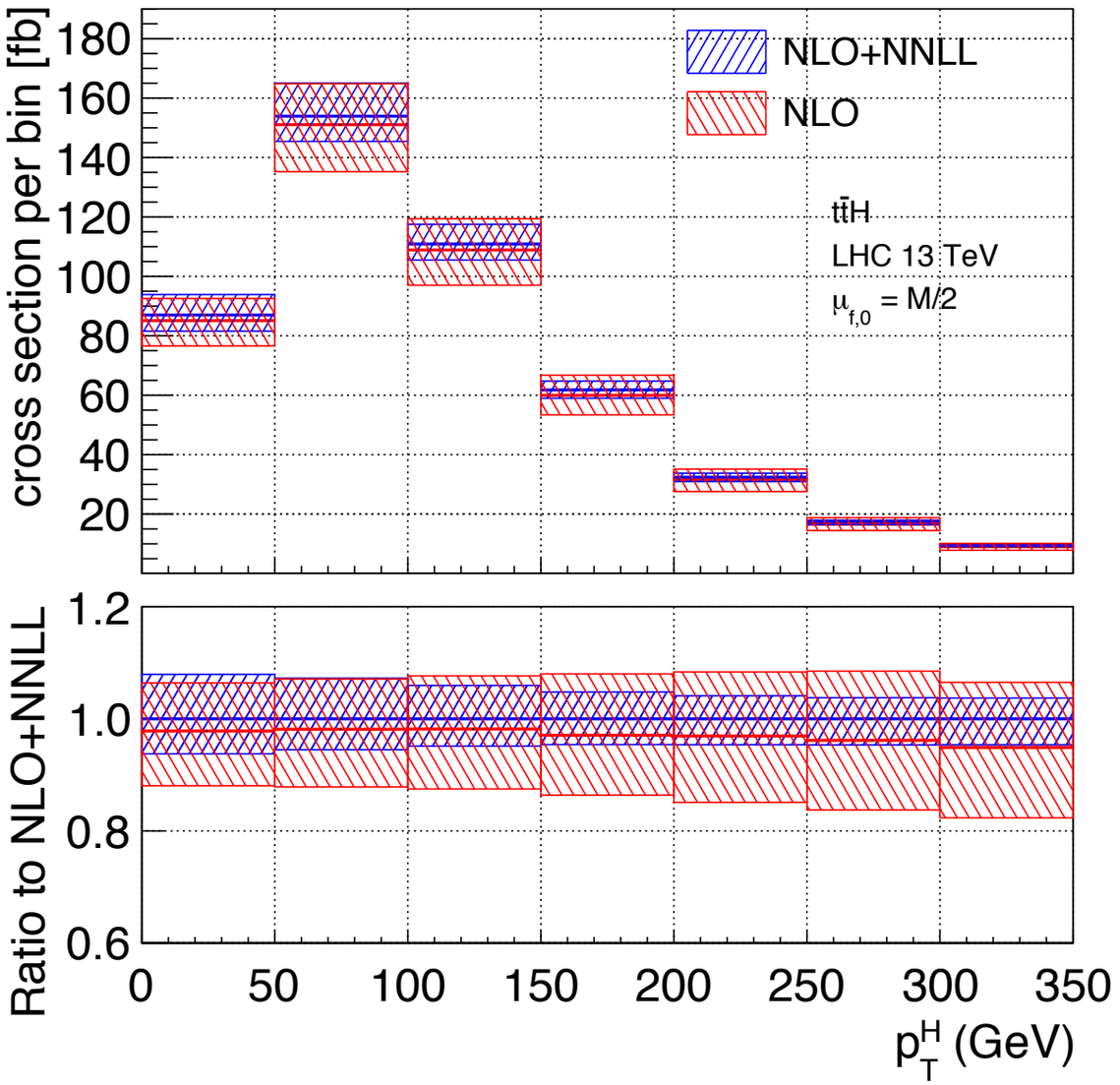
See talk by Prof. Qing-Hong Cao

Differential cross sections

Broggio, Ferroglia, Pecjak, **LLY**: 1611.00049
Kulesza, Motyka, Stebel, Theeuwes: 1704.03363

Soft gluon resummation for $\sqrt{\hat{s}} \to M_{t\bar{t}H}$





State-of-the-art QCD calculation

Total cross section at threshold

Ju, **LLY**: 1904.08744
See also Kulesza et al.: 1509.02780

Threshold limit for total cross section

$$\sqrt{\hat{s}} \to 2m_t + m_H \qquad \beta = \sqrt{1 - \frac{(2m_t + m_H)^2}{s}} \to 0$$

Typical 3-velocity of final-state particles

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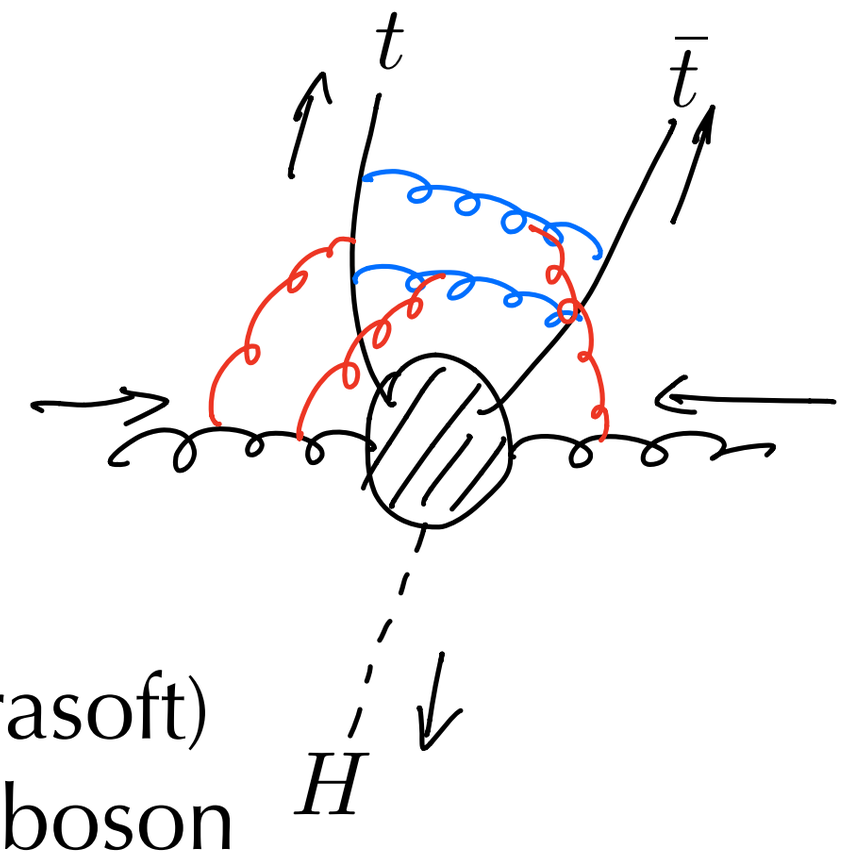
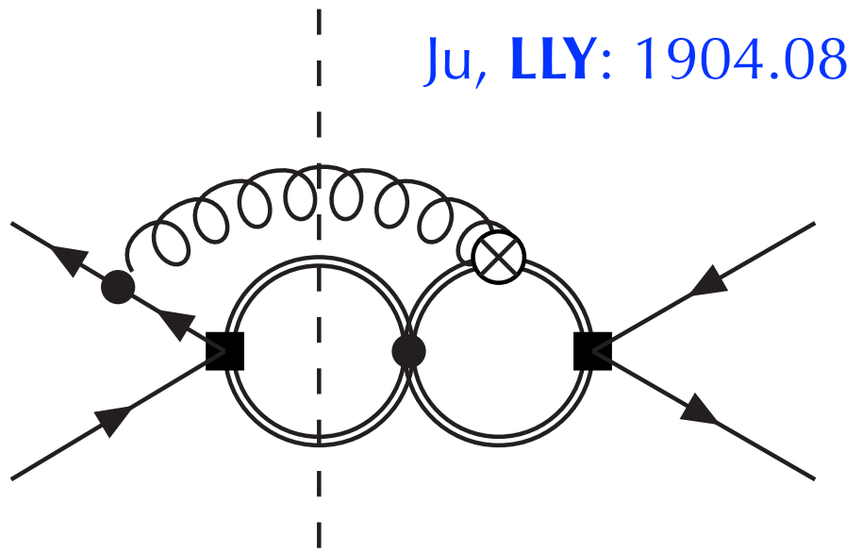


Recoiled by soft (NOT ultrasoft) 3-momentum of the Higgs boson

Factorization near threshold

Non-trivial cancellation
of ultrasoft interactions at
next-to-leading power

Ju, **LLY**: 1904.08744



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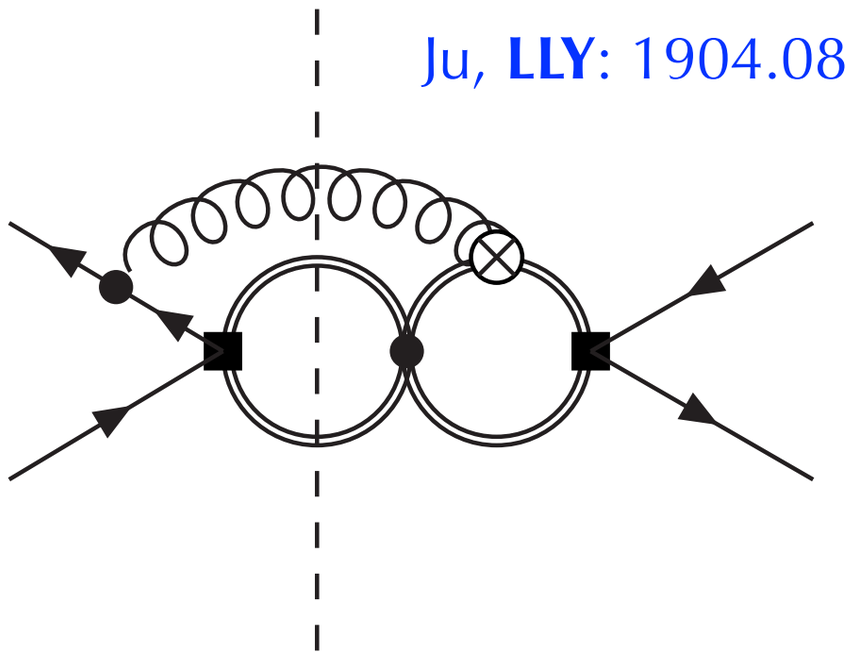

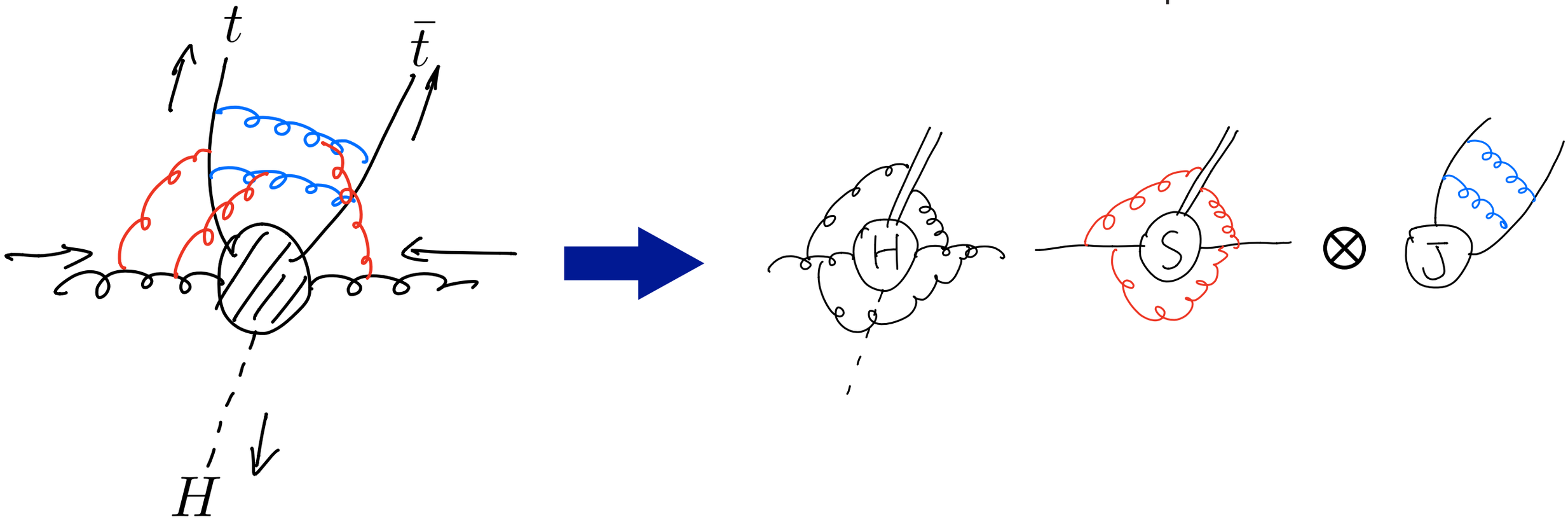

Resummation of soft and Coulomb corrections

Ju, **LLY**: 1904.08744

	13 TeV LHC (pb)
NLO	$0.493^{+5.8\%}_{-9.2\%}$
NLL′+NLO	$0.521^{+1.9\%}_{-2.6\%}$
K-factor	1.06

6% effect

Big reduction of scale dependence

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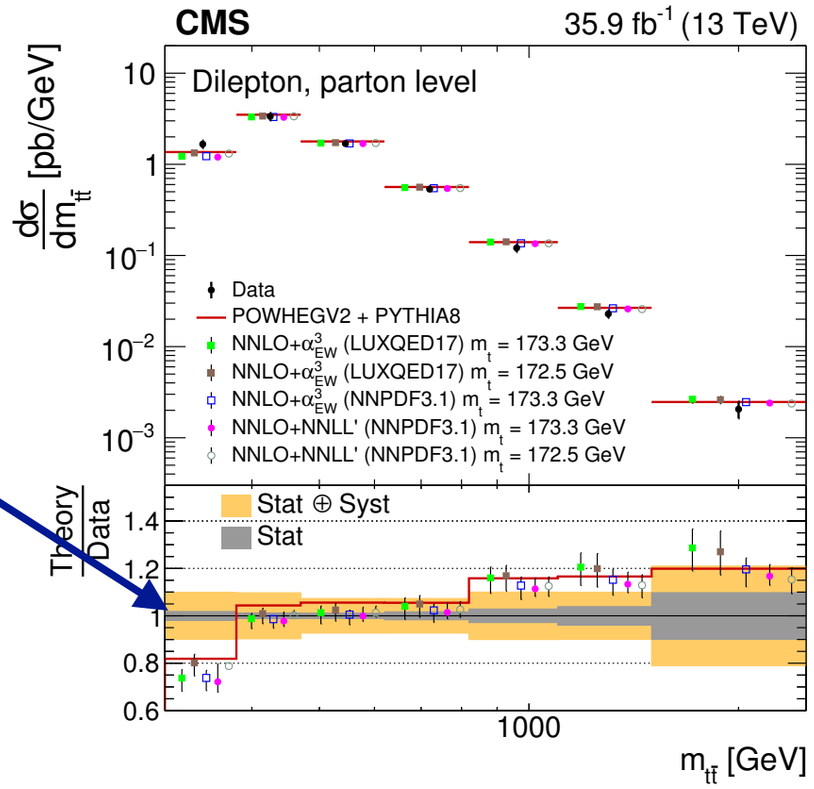
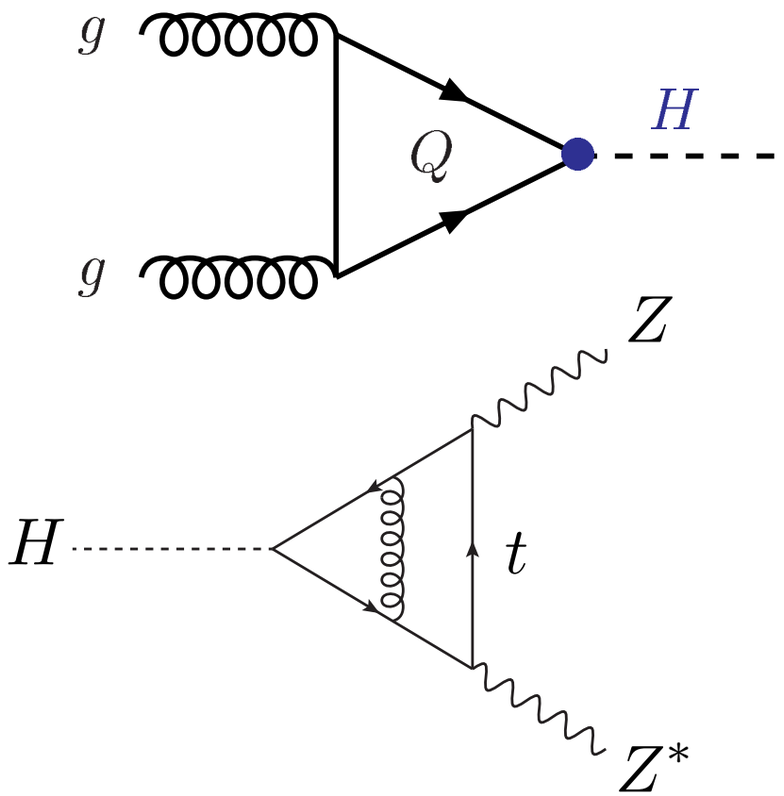
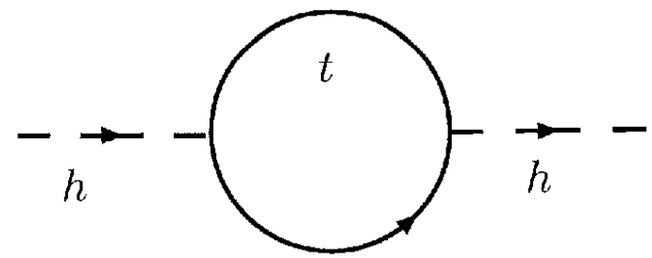
May be generalized to

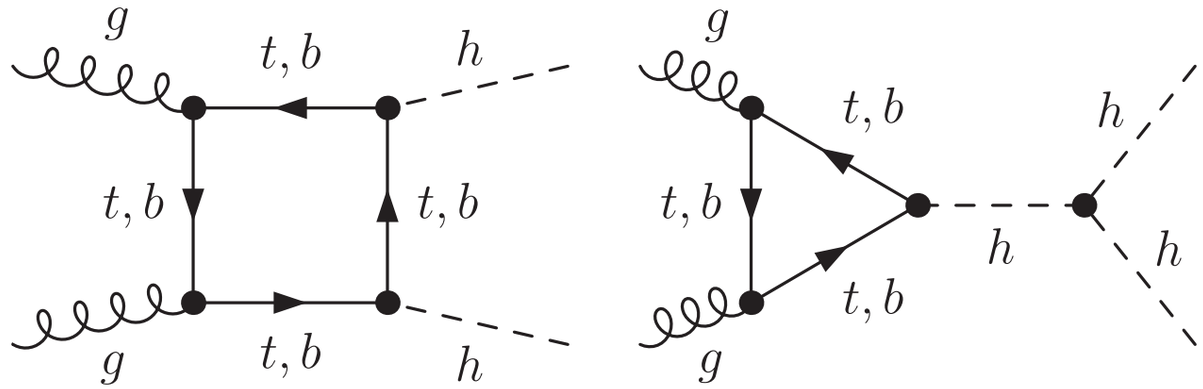


Top quarks in loops (for Higgs)

Virtual top quarks are everywhere in Higgs physics
(due to the large Yukawa coupling)







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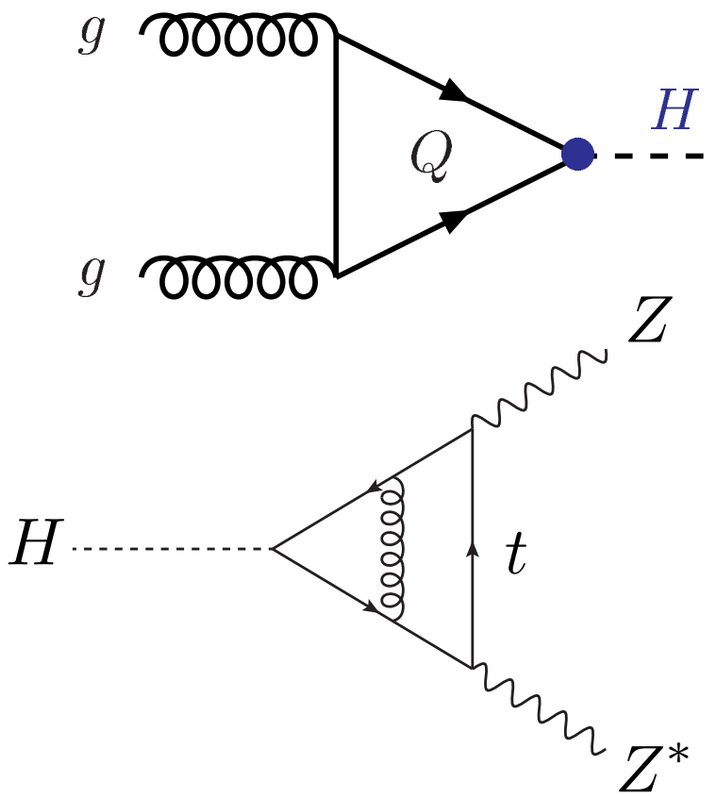
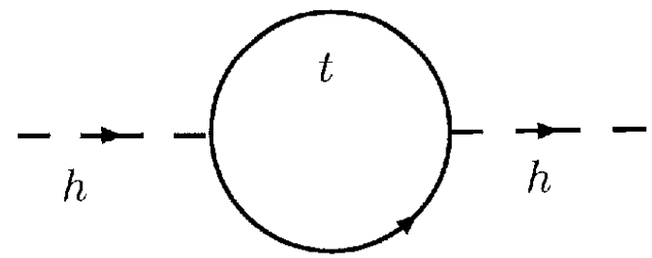
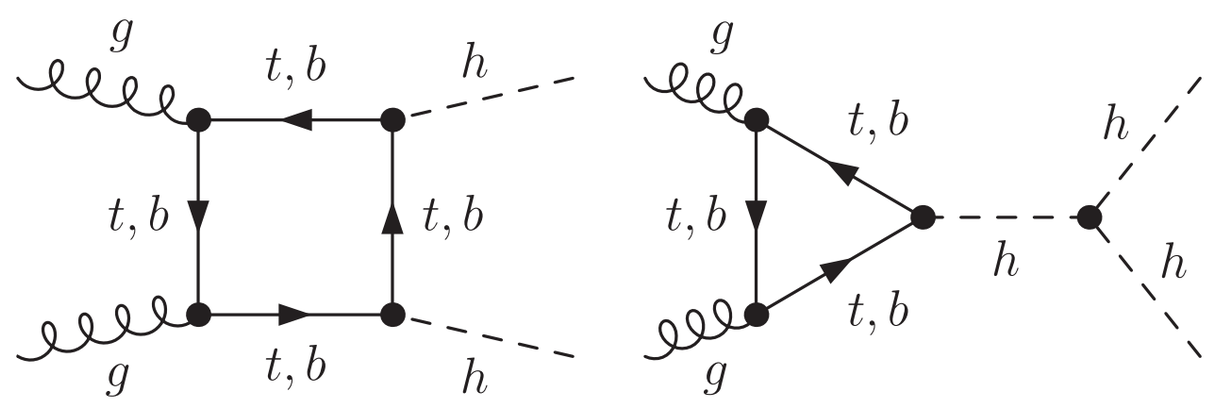






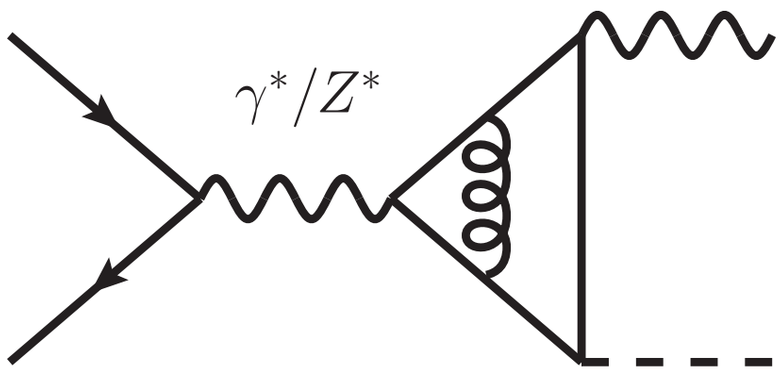
Knowledge of these top loops crucial for extracting interesting information

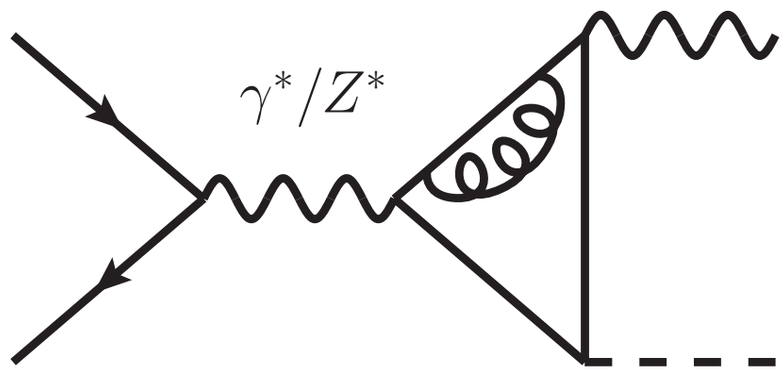
e.g., anomalous Hgg, HZZ, HHH couplings

ZH production at CEPC

Gong, Li, Xu, **LLY**, Zhao: 1609.03955
Sun, Feng, Jia, Sang: 1609.03995
See also talk by Prof. Yu Jia

NNLO mixed QCD-EW corrections





Two-loop integrals with 4 scales

Purely numeric evaluation (sector decomposition)
highly resource-demanding!

Large top mass expansion

Gong, Li, Xu, **LLY**, Zhao: 1609.03955

Taylor series in $\dfrac{s, m_H^2, m_Z^2}{m_t^2}$

$$\sigma^{\alpha\alpha_s}(\sqrt{s}, m_H, m_Z, m_t) = m_t^2\, c_2(\sqrt{s}, m_H, m_Z)$$
$$+ m_t^0\, c_0(\sqrt{s}, m_H, m_Z)$$
$$+ m_t^{-2}\, c_{-2}(\sqrt{s}, m_H, m_Z)$$
$$+ \cdots$$

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$$+ \cdots$$

Simple analytic expressions!

Blazingly fast numeric evaluation

Easy to be implemented in an event generator

Convergence of the expansion

Gong, Li, Xu, **LLY**, Zhao: 1609.03955

Good convergence for optimal energies of Higgs factories!

$\sqrt{s}$ (GeV)	$\mathcal{O}(m_t^2)$	$\mathcal{O}(m_t^0)$	$\mathcal{O}(m_t^{-2})$	$\mathcal{O}(m_t^{-4})$
240	81.8%	16.2%	1.4%	0.4%
250	81.7%	16.1%	1.5%	0.5%

$$\frac{m_t^2\, c_2}{\sigma^{\alpha\alpha_s}}$$

Convergence of the expansion

Gong, Li, Xu, **LLY**, Zhao: 1609.03955

Good convergence for optimal energies of Higgs factories!

$\sqrt{s}$ (GeV)	$\mathcal{O}(m_t^2)$	$\mathcal{O}(m_t^0)$	$\mathcal{O}(m_t^{-2})$	$\mathcal{O}(m_t^{-4})$
240	81.8%	16.2%	1.4%	0.4%
250	81.7%	16.1%	1.5%	0.5%

$$\frac{m_t^2\, c_2}{\sigma^{\alpha\alpha_s}}$$

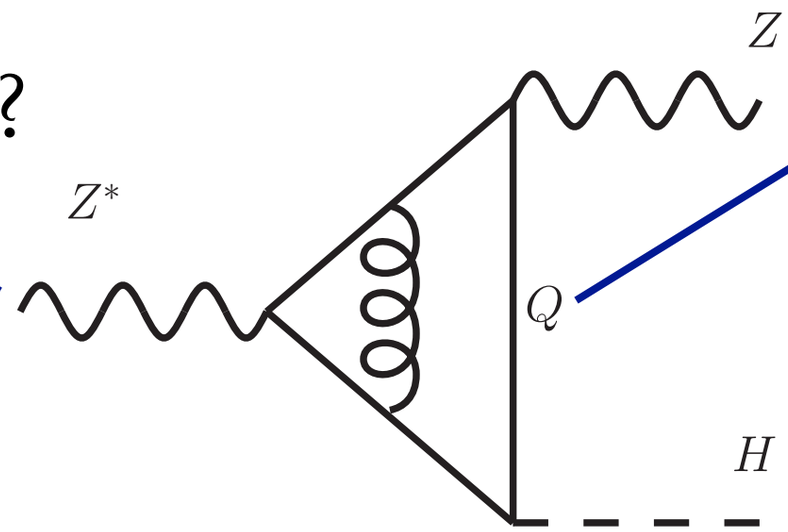
$\sqrt{s}$ (GeV)	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm NNLO}^{\rm exp.}$ (fb)
240	252.0	228.6	231.5	231.5
250	252.0	227.9	230.8	230.8

No difference between exact and expanded results (4 digits)

Exact analytic solution

Wang, Xu, **LLY**: 1904.xxxxx

What if energy above 346 GeV?



What if bottom quarks are included?

Exact analytic solution

Wang, Xu, **LLY**: 1904.xxxxx

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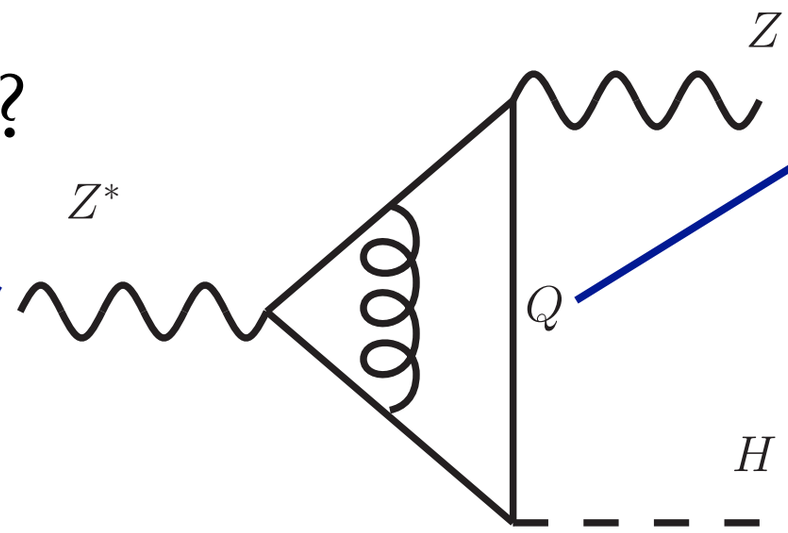

What if bottom quarks are included?

Large mass expansion doesn't work!

Exact analytic solution

Wang, Xu, **LLY**: 1904.xxxxx

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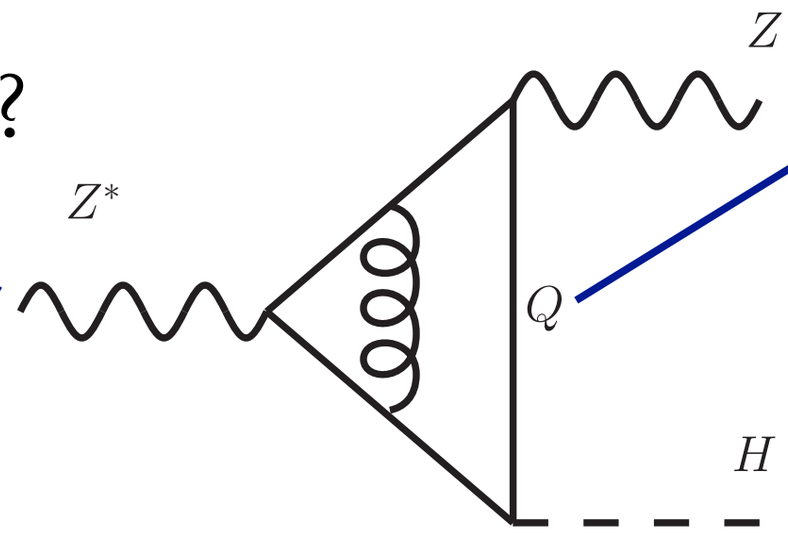

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Sector decomposition very slow!

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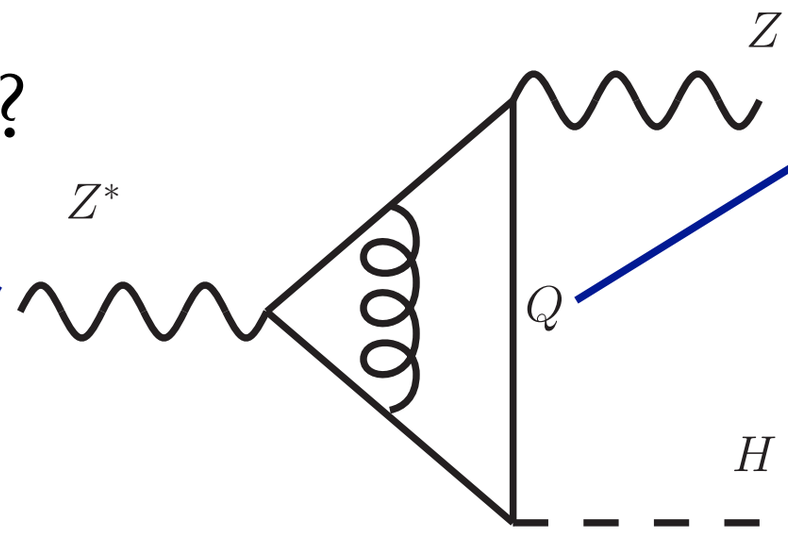

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Wang, Xu, **LLY**: 1904.xxxxx

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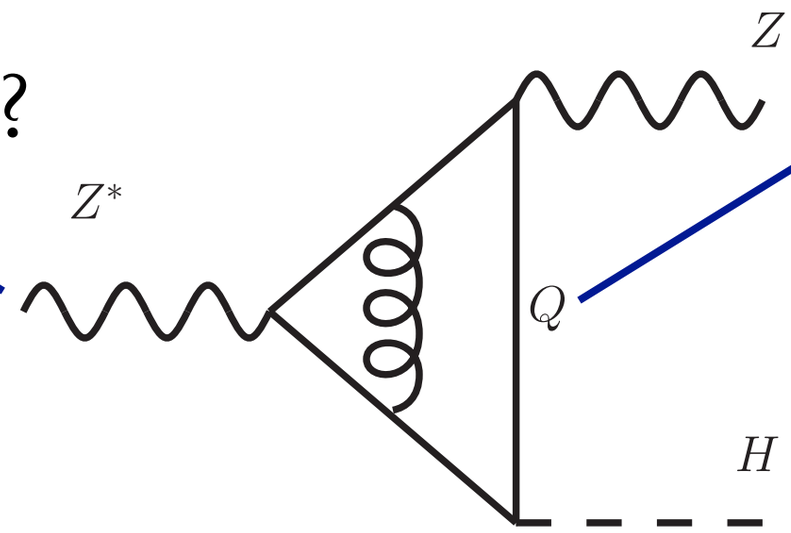


What if bottom quarks are included?

Large mass expansion doesn't work!

Sector decomposition very slow!

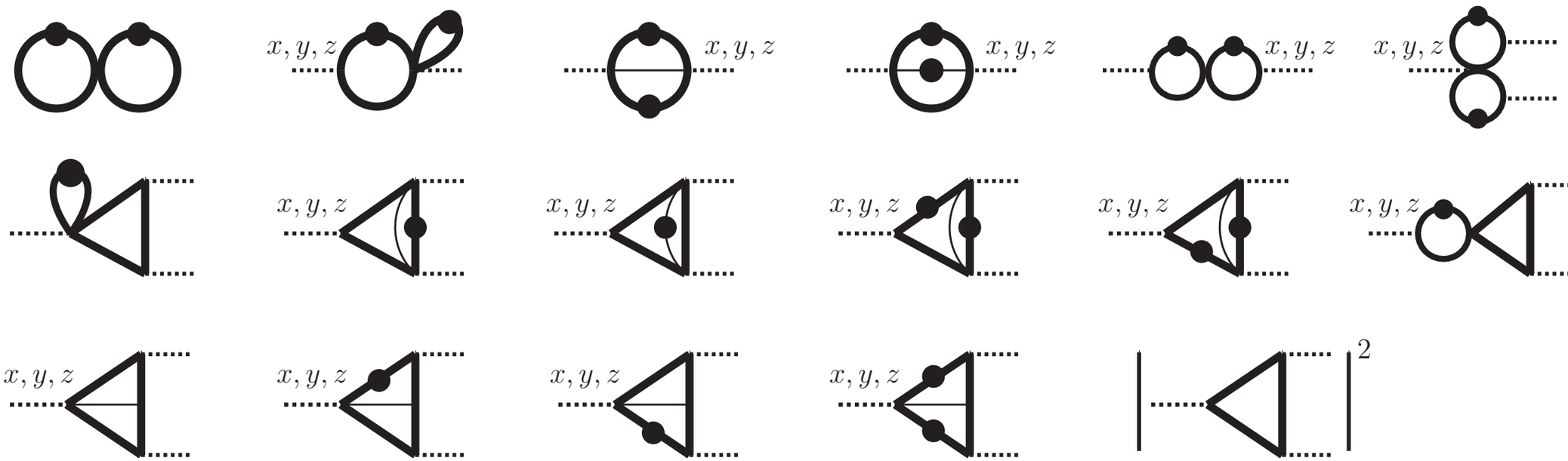
Exact analytic solution needed…

Also theoretically interesting: few massive two-loop multiple-scale integrals are known analytically

Exact analytic solution

Wang, Xu, **LLY**: 1904.xxxxx

Solve 41 master integrals using differential equations and symbol techniques

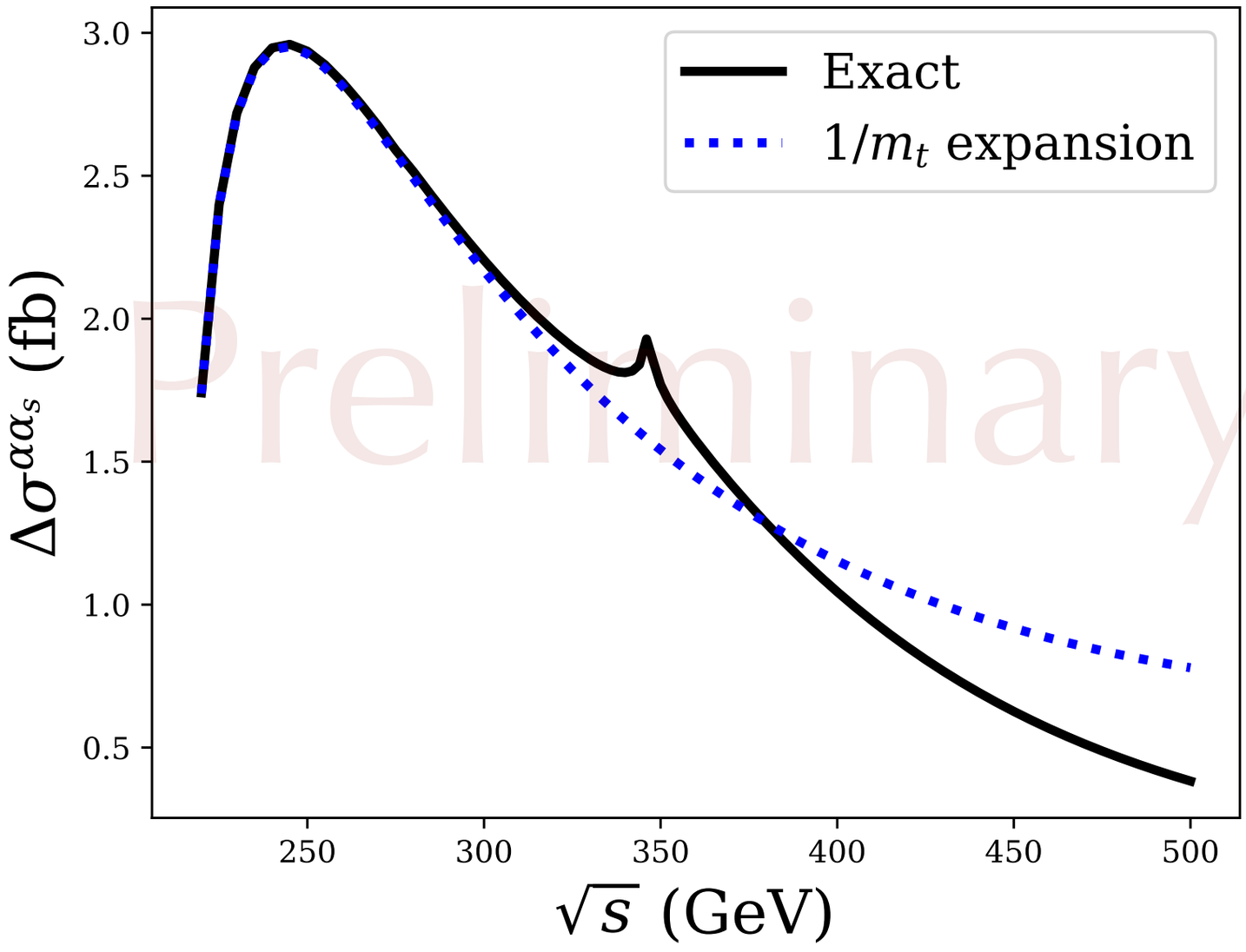


Functions of 3 dimensionless variables

$$x = -\frac{q^2}{4m_Q^2}\,, \quad y = -\frac{p_Z^2}{4m_Q^2}\,, \quad z = -\frac{p_H^2}{4m_Q^2}$$

The analytic solution allows us to perform numeric studies efficiently

Wang, Xu, **LLY**: 1904.xxxxx



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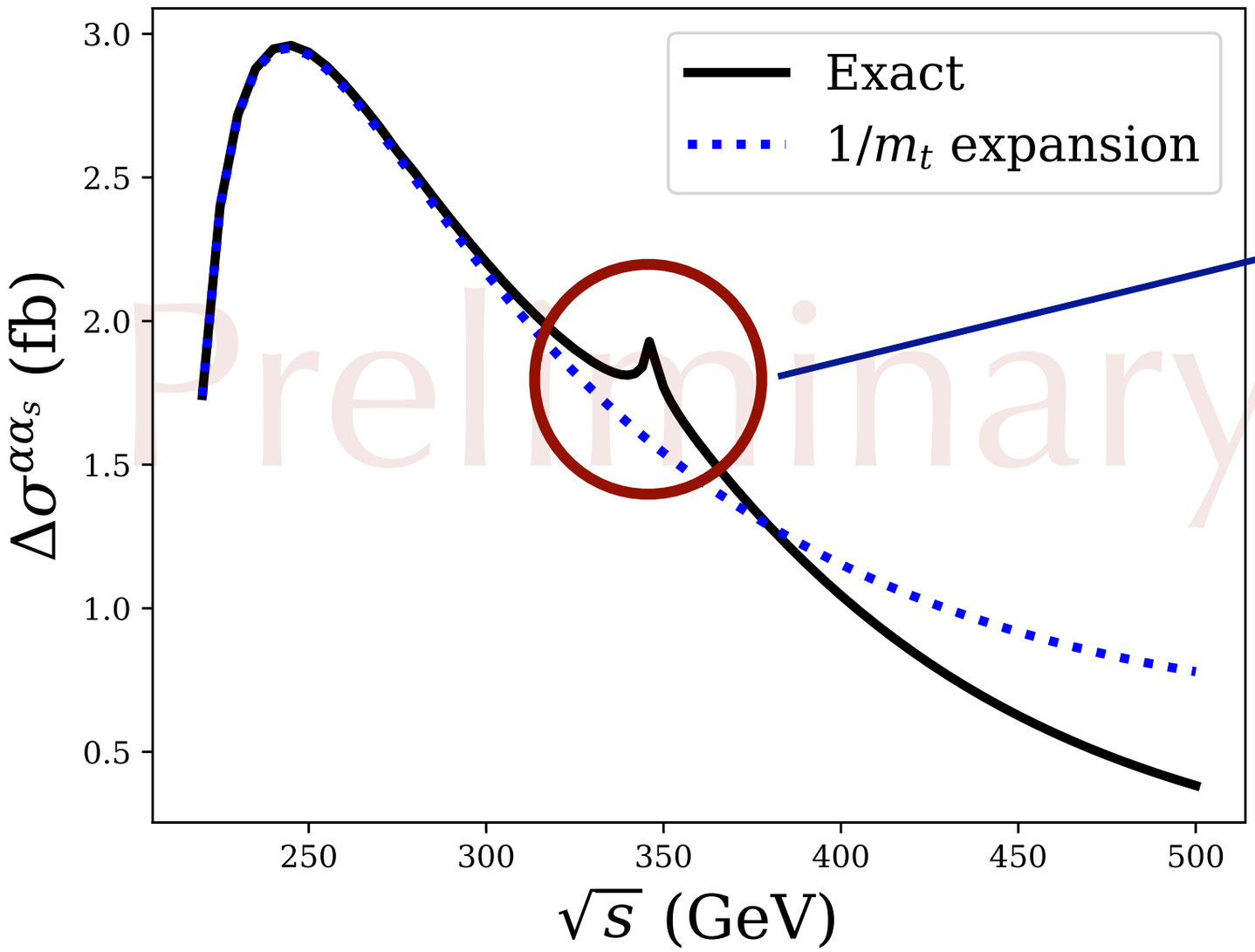
Wang, Xu, **LLY**: 1904.xxxxx

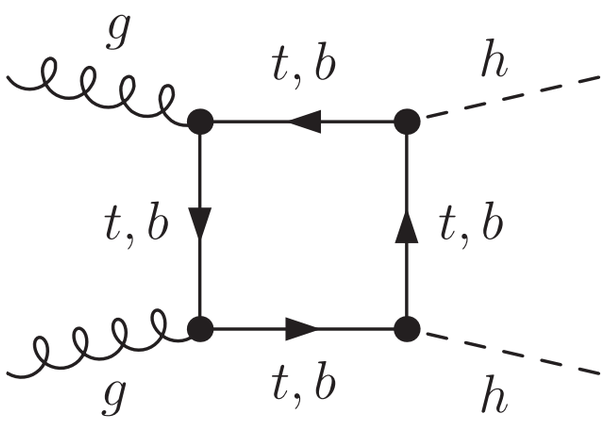


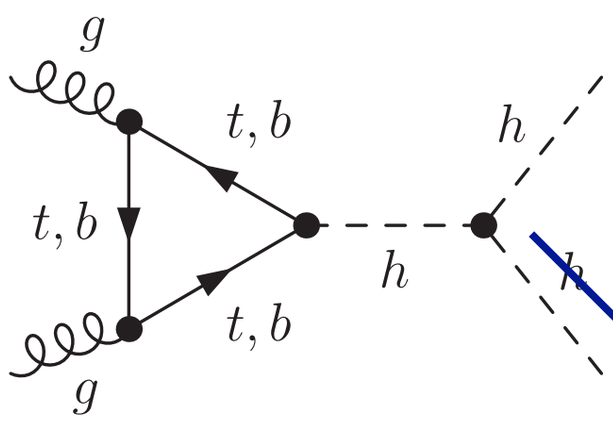
$t\bar{t}$ threshold

Difficult for sector decomposition

Easy with analytic solution

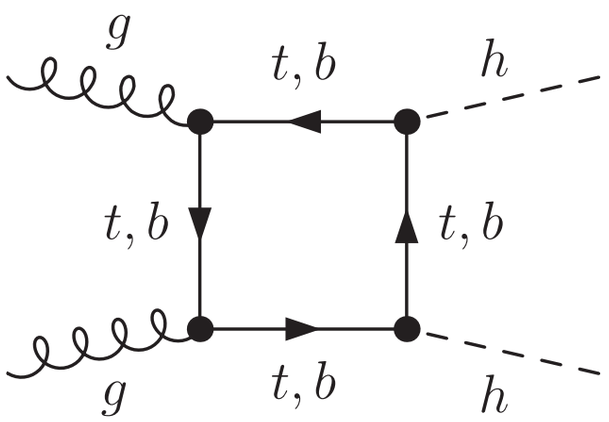
A more complicated case

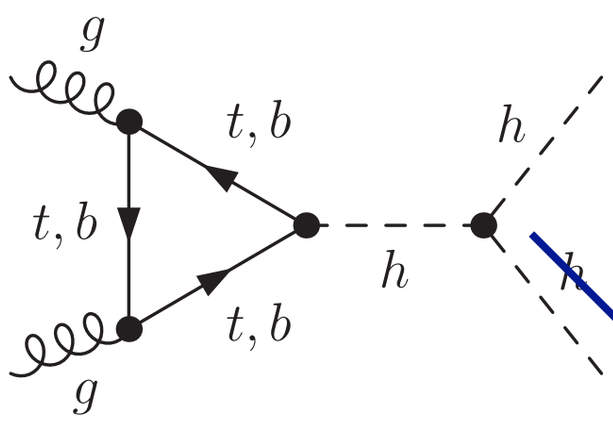




Probe Higgs self-coupling

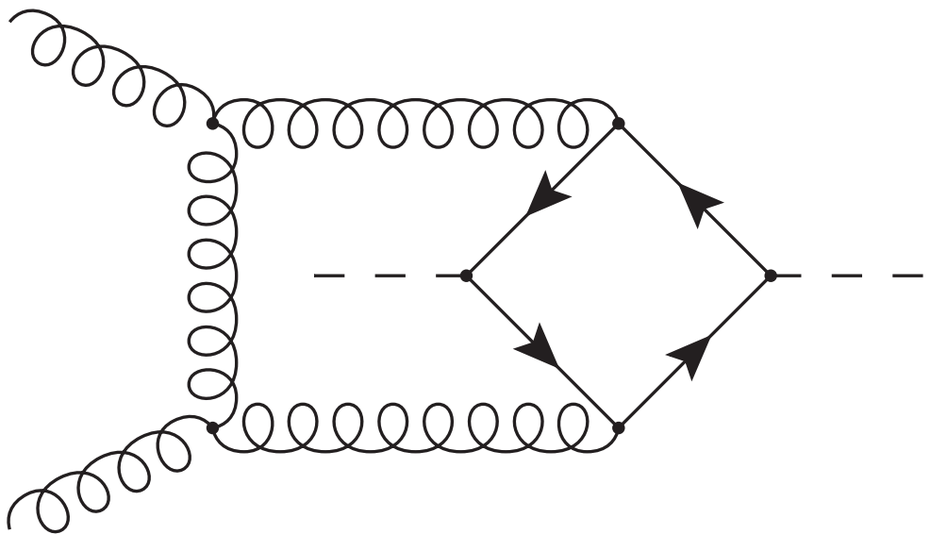
A more complicated case





Probe Higgs self-coupling

Loop induced, NLO QCD already difficult two-loop integrals involving massive top quark propagators



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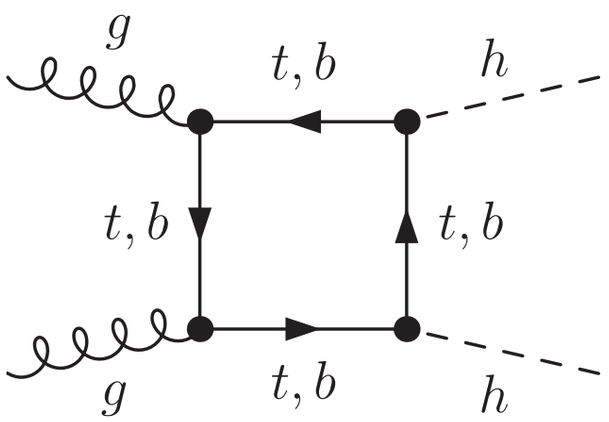

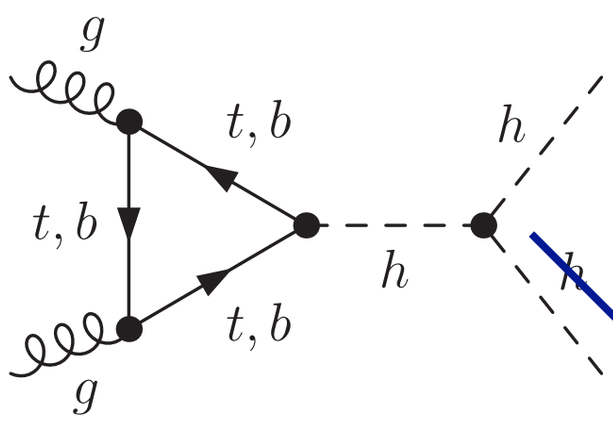

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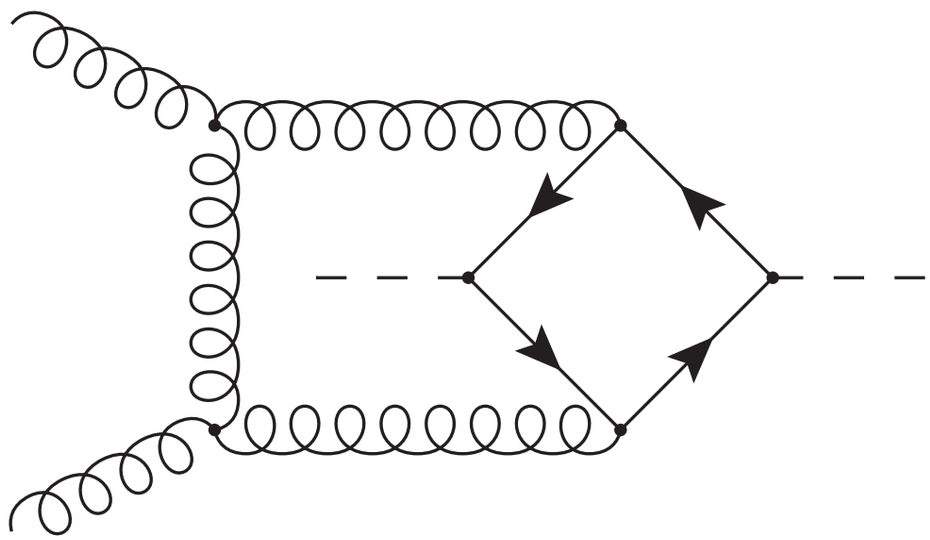

Extremely resource-demanding using conventional methods

A new approximation method

Xu, **LLY**: 1810.12002

Taylor expansion in the $m_h \to 0$ limit

$$I(s,t,m_t^2,m_h^2,\epsilon) = \sum_{n=0}^{\infty} \frac{m_h^{2n}}{n!} I^{(n)}(s,t,m_t^2,\epsilon)$$

A new approximation method

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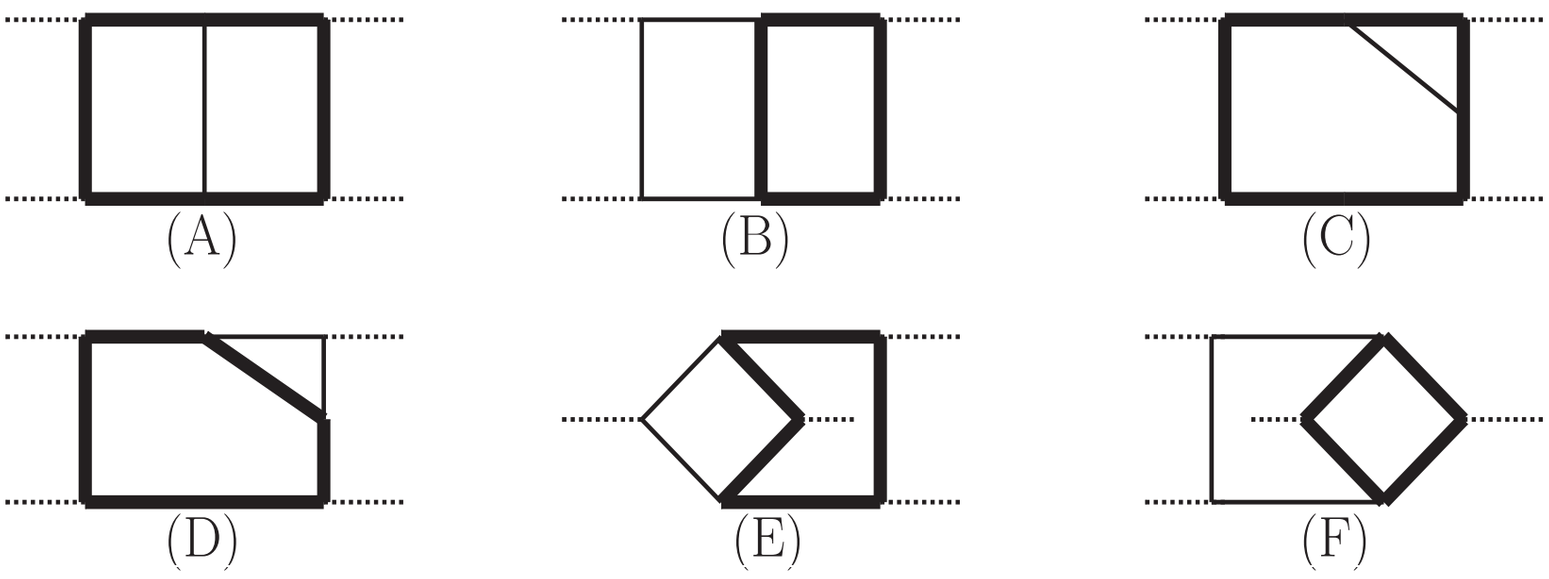
$$I(s,t,m_t^2,m_h^2,\epsilon) = \sum_{n=0}^{\infty} \frac{m_h^{2n}}{n!} I^{(n)}(s,t,m_t^2,\epsilon)$$

Still complicated integrals



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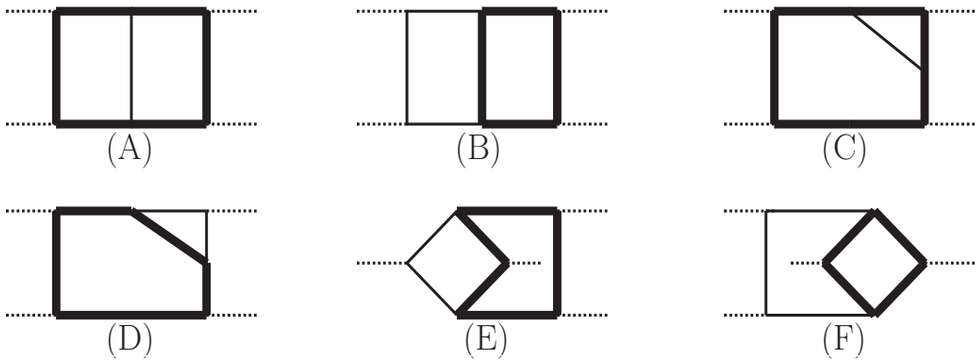
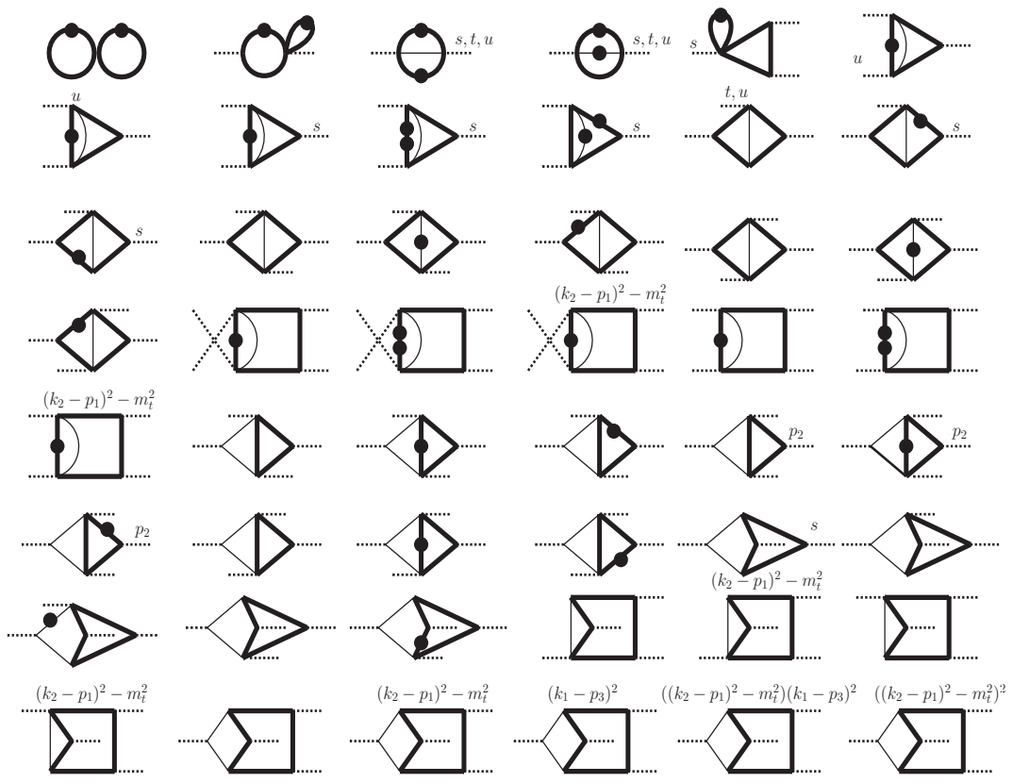


Xu, **LLY**: 1810.12002

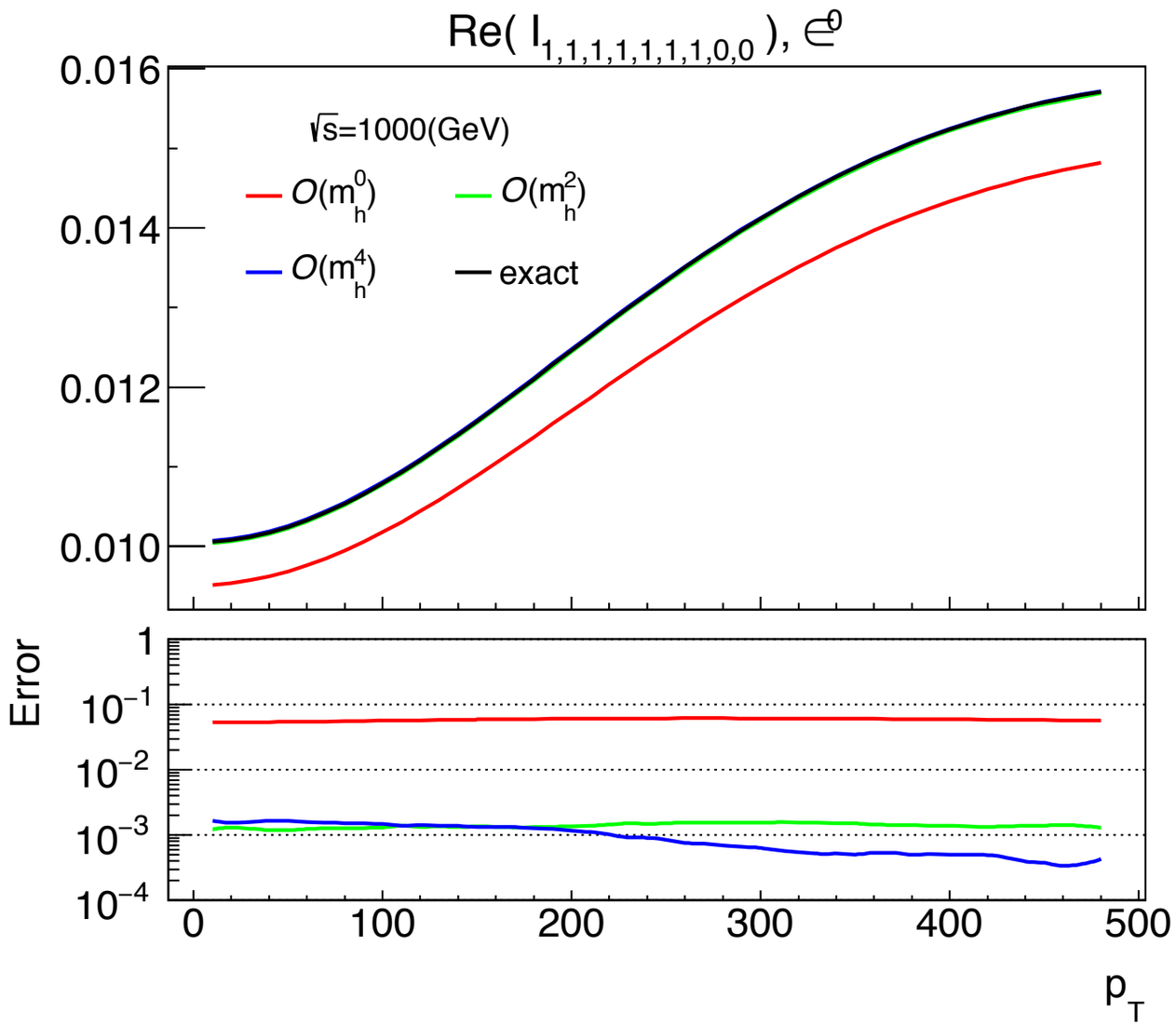
Solve 54 master integrals in topology E using differential equations



A new approximation method

Good convergence for master integrals

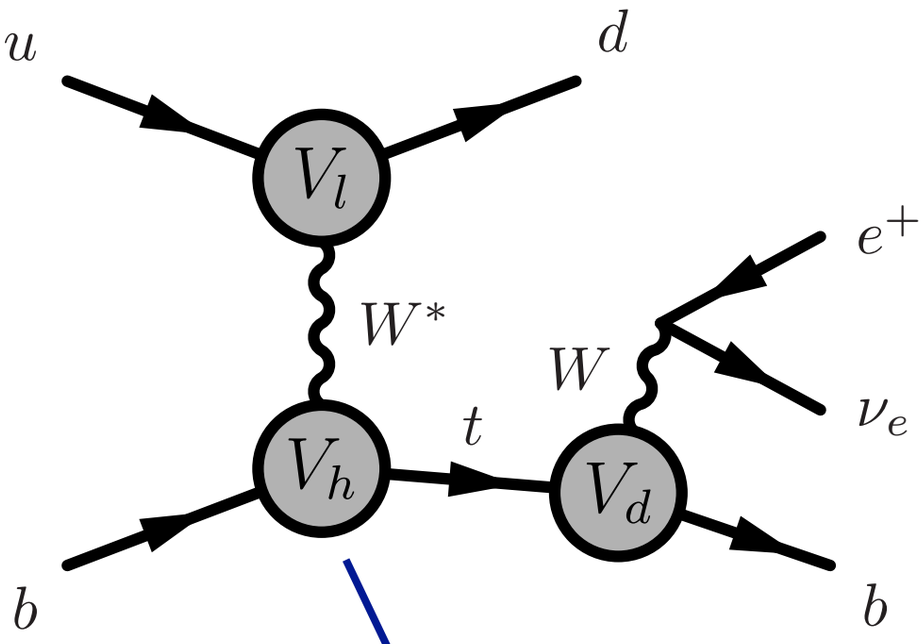
Xu, **LLY**: 1810.12002

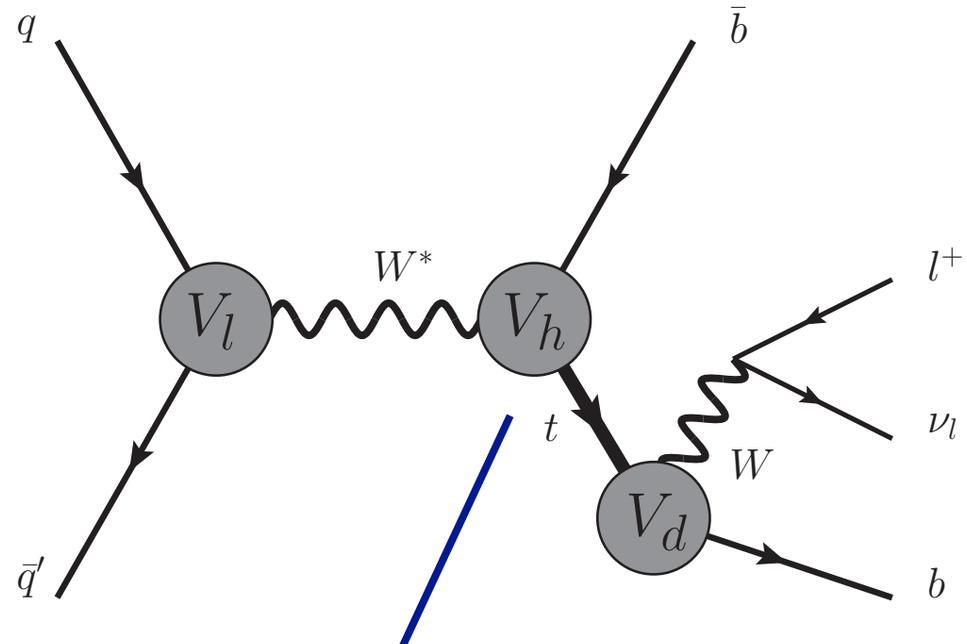


Towards the full amplitude

Wang, Xu, **LLY**: in preparation

Single top quark production



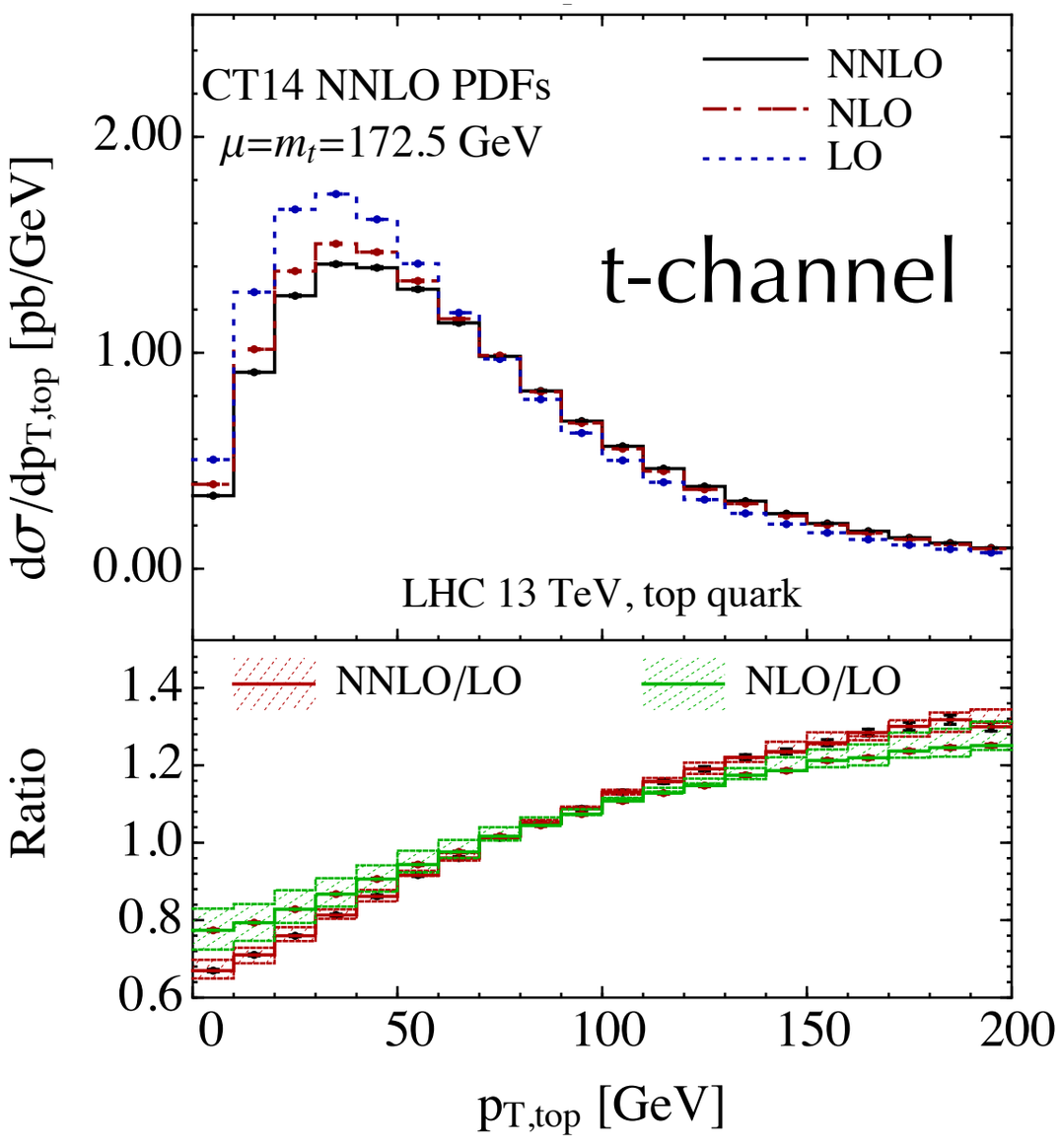


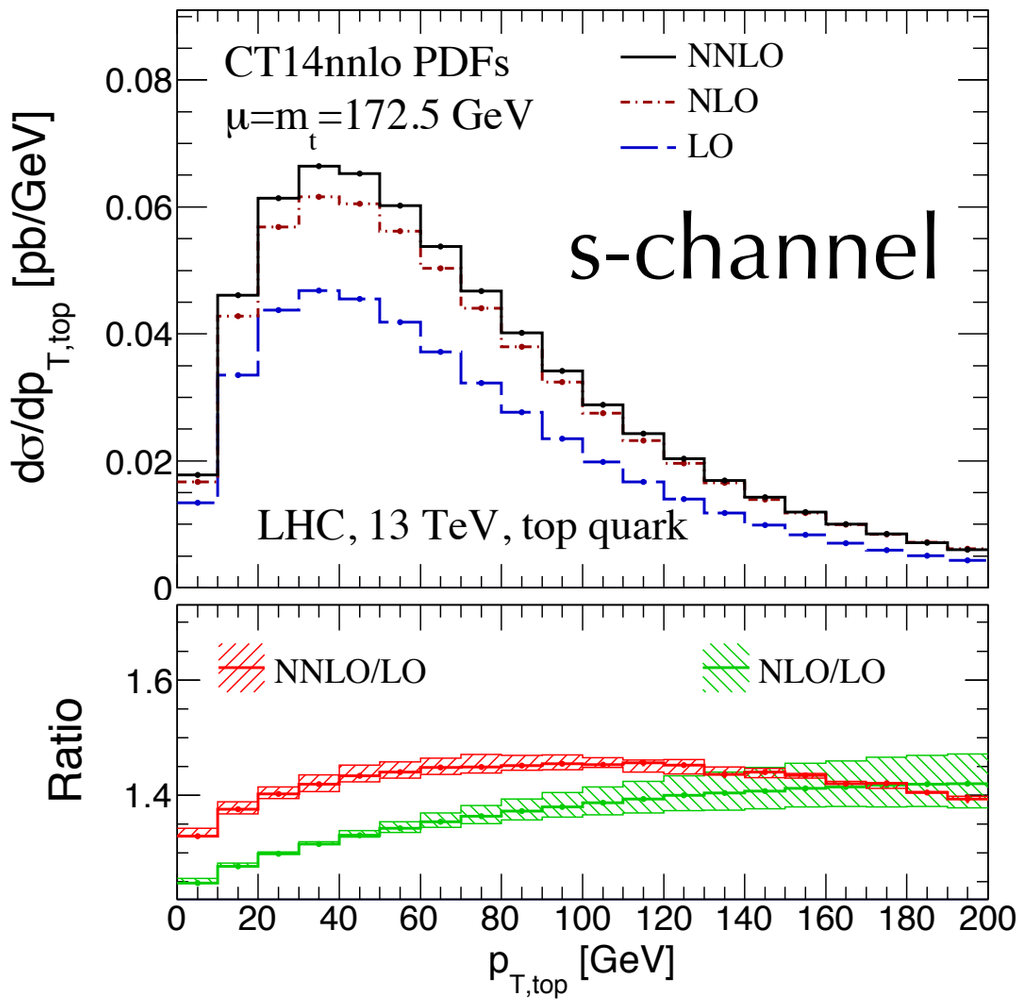
Probe weak interactions of the top quark

In particular, the CKM matrix element V_{tb}

Single top production and decay at NNLO

Berger, Gao, Yuan, Zhu: 1606.08463
Berger, Gao, Zhu: 1708.09405
Liu, Gao: 1807.03835





Shape change in distributions

TOP2019 Workshop

Hosted at IHEP in Beijing this September

12th International Workshop on Top Quark Physics (TOP2019)

22-27 September 2019
Beijing
Asia/Shanghai timezone

https://indico.cern.ch/e/top2019

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Welcome to the 12th International Workshop on Top Quark Physics (TOP2019)

The 12th International Workshop on Top Quark Physics (TOP 2019) will be held at **Institute of High Energy Physics (IHEP), Beijing, China**, from **September 22nd to 27th**.

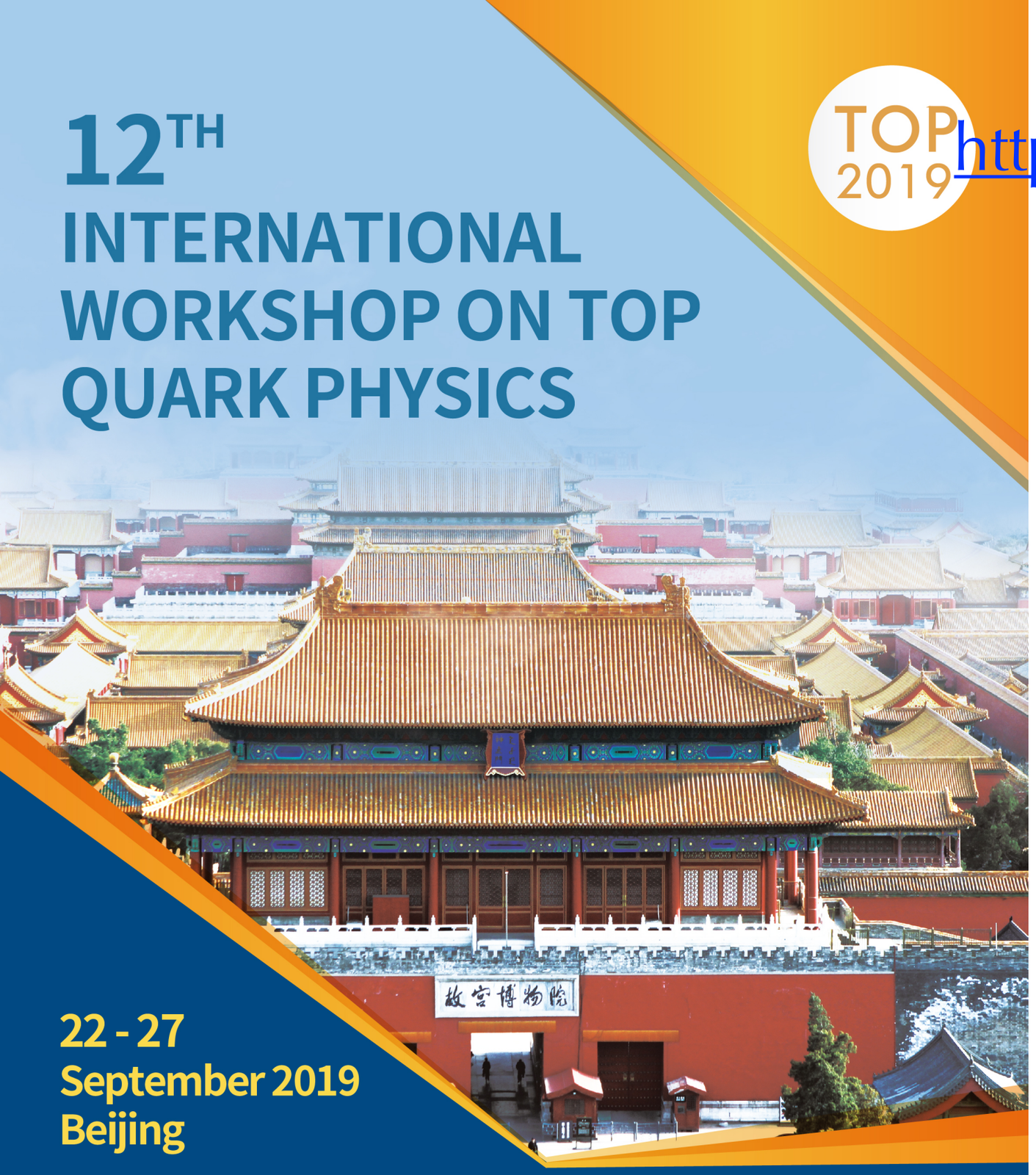
Following the long tradition of the workshop series, the 2019 edition will be dedicated to an overview of the most up-to-date experimental measurements at the Large Hadron Collider (LHC) and latest theoretical developments on top quark physics. Special focus on theoretical developments related to physics beyond the standard model will be given in a Mini-Workshop with the name “Top Meets New Physics” that will take place on Thursday, September 26th. There will also be a session on top quark physics at future facilities such as the High Luminosity LHC and CEPC/SppC.

We are looking forward to meeting you in Beijing this coming September.

12TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS

TOP 2019

https://indico.cern.ch/e/top2019



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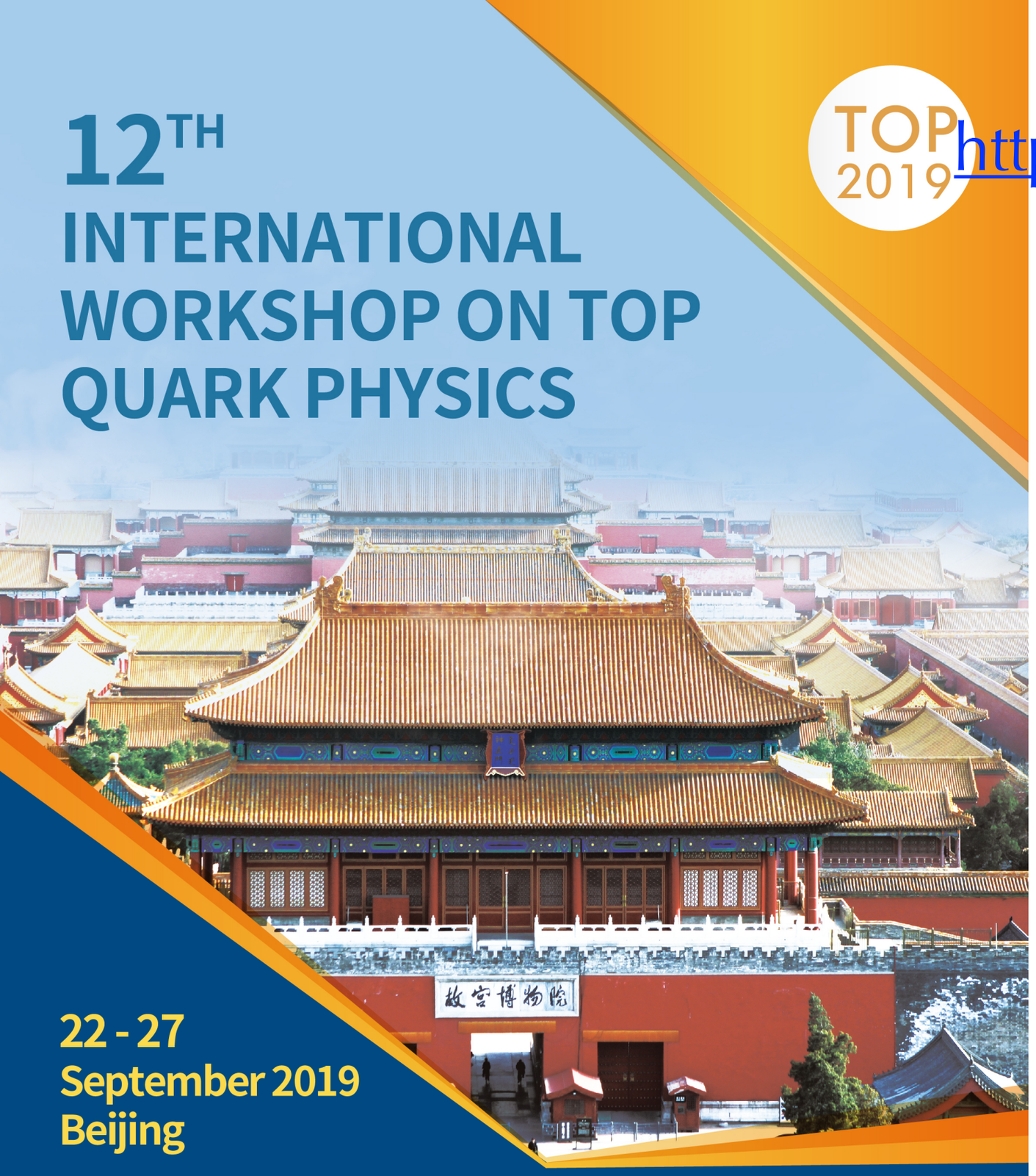

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Thank you!