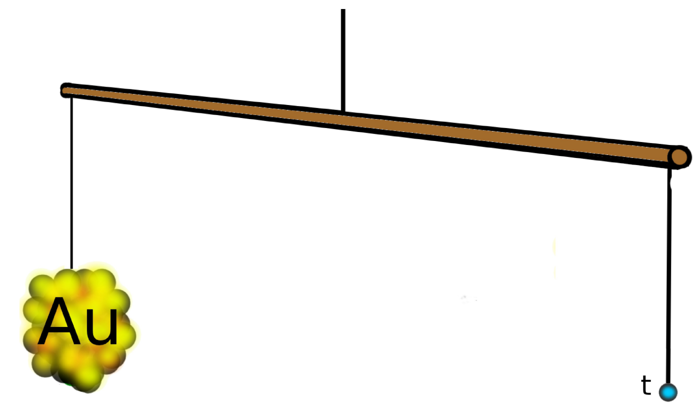
Top quark pair production w/ and w/o a Higgs boson

Li Lin Yang
Peking University

Basic facts about the top quark



Large mass $m_t \approx 173$ GeV

Fermion mass origin

Hierarchy problem

Vacuum stability

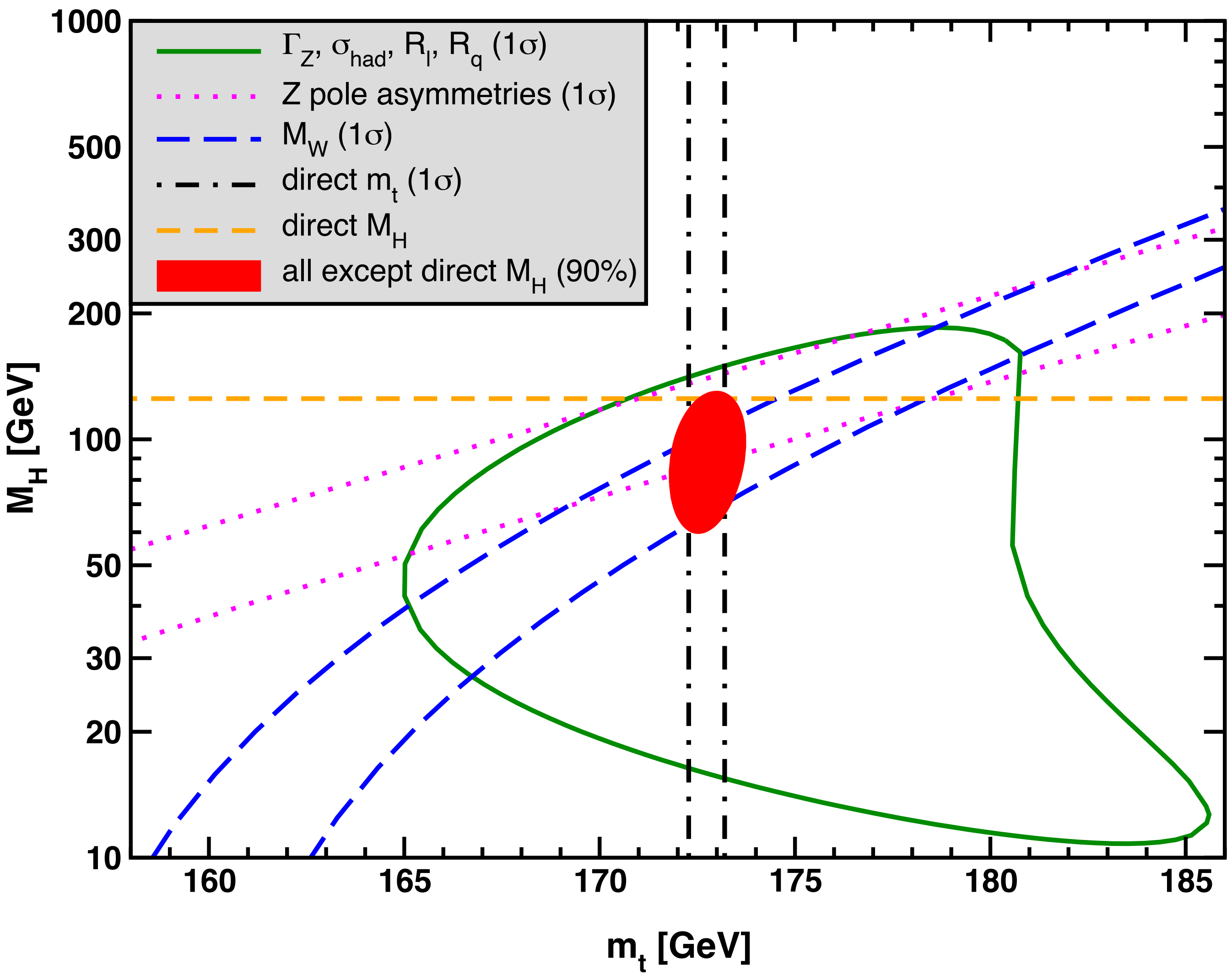
Strong Yukawa coupling $y_t \sim 1$

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

Decays before hadronization: pQCD dominates!

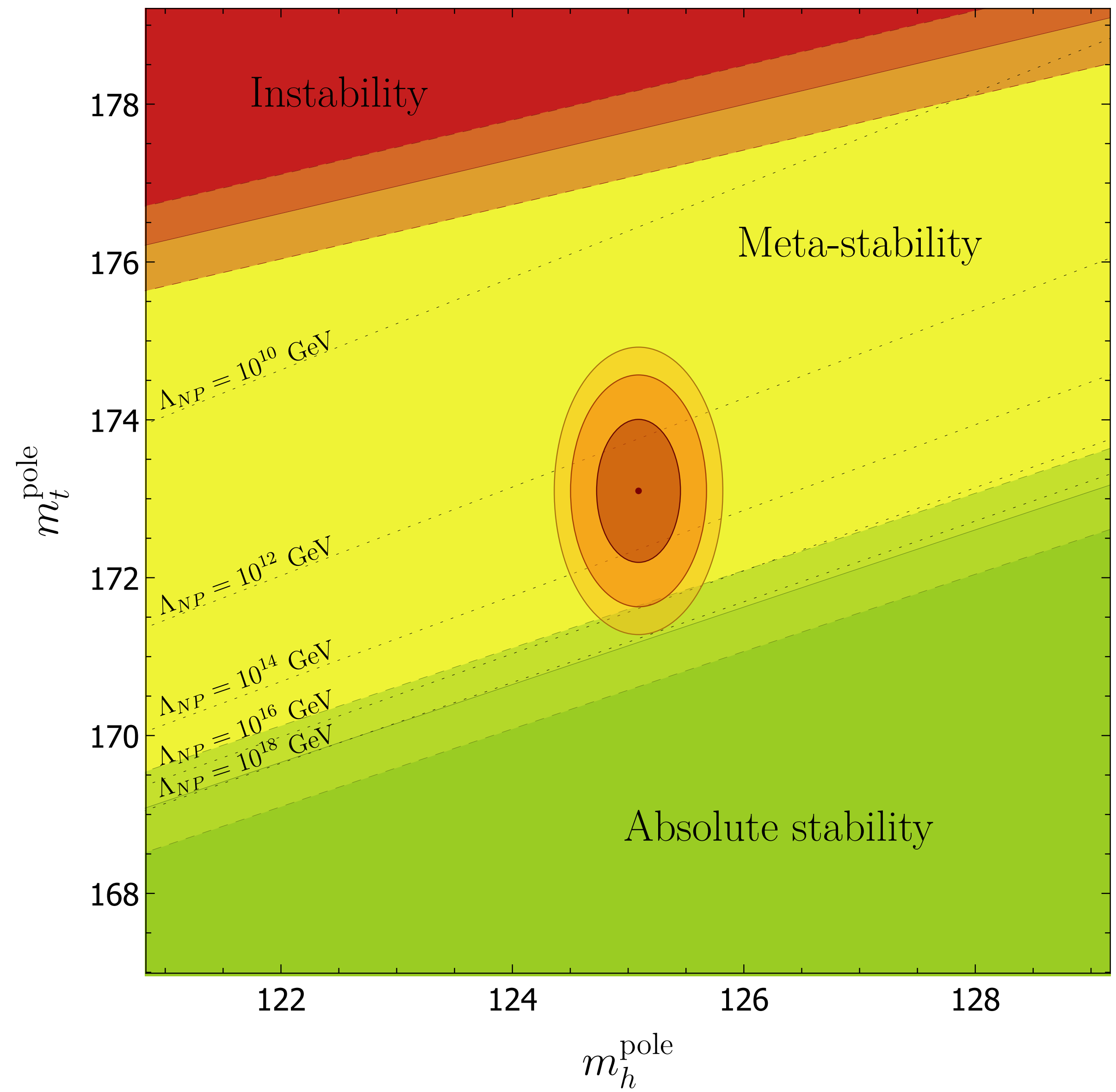
Implications of the top quark mass

Constraints on new physics



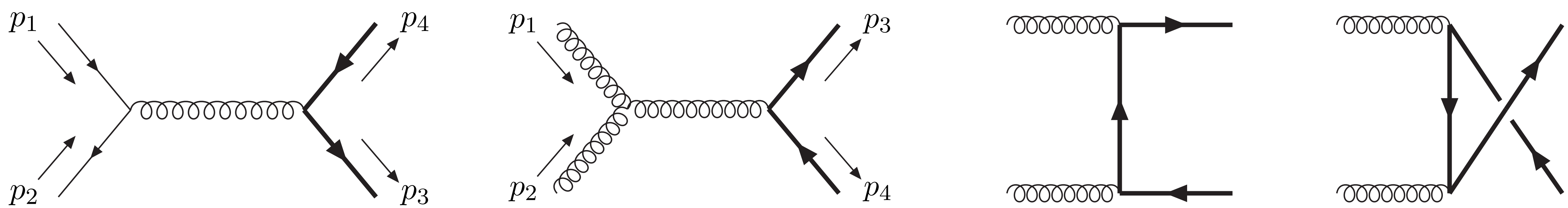
2018 Review of Particle Physics

The fate of our universe



A. Andreassen, W. Frost, M. D. Schwartz: 1707.08124

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
- Measurement of PDFs, strong coupling and top quark mass
- Possible signals of new physics
- Major background to many searches

State-of-the-art predictions

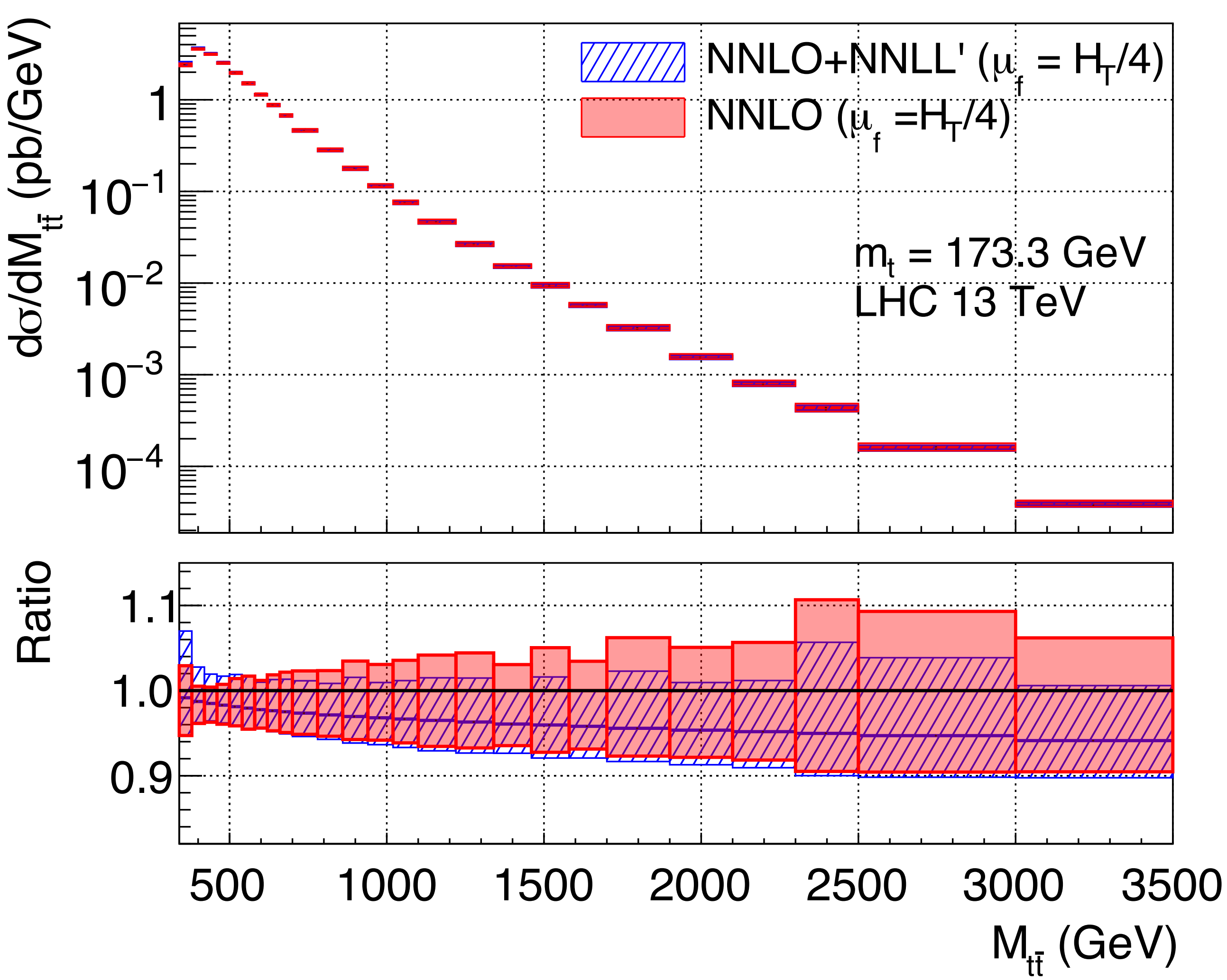
NNLO+NNLL' in QCD

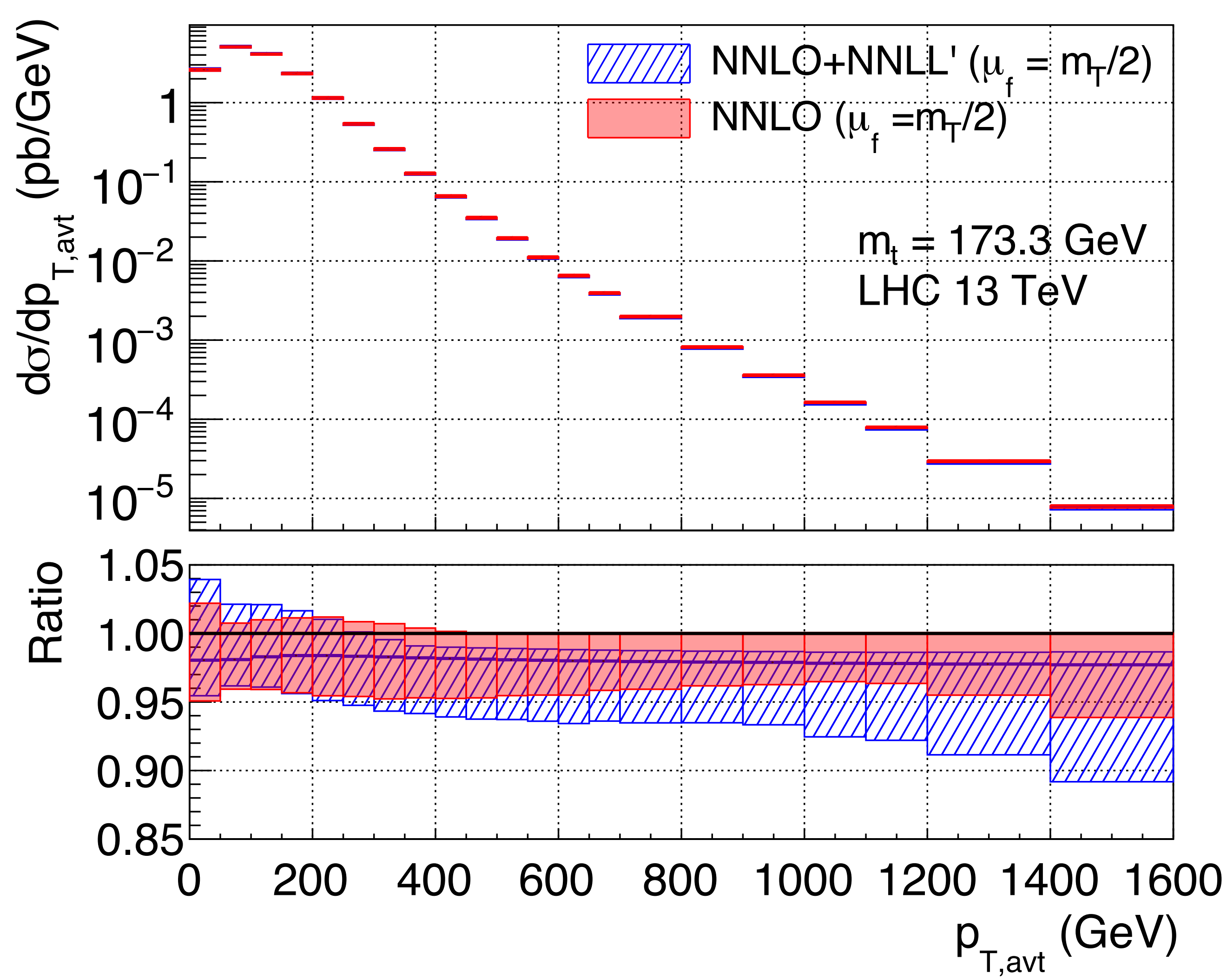
Pecjak, Scott, Wang, **LLY**: 1601.07020

Czakon, Heymes, Mitov: 1606.03350

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

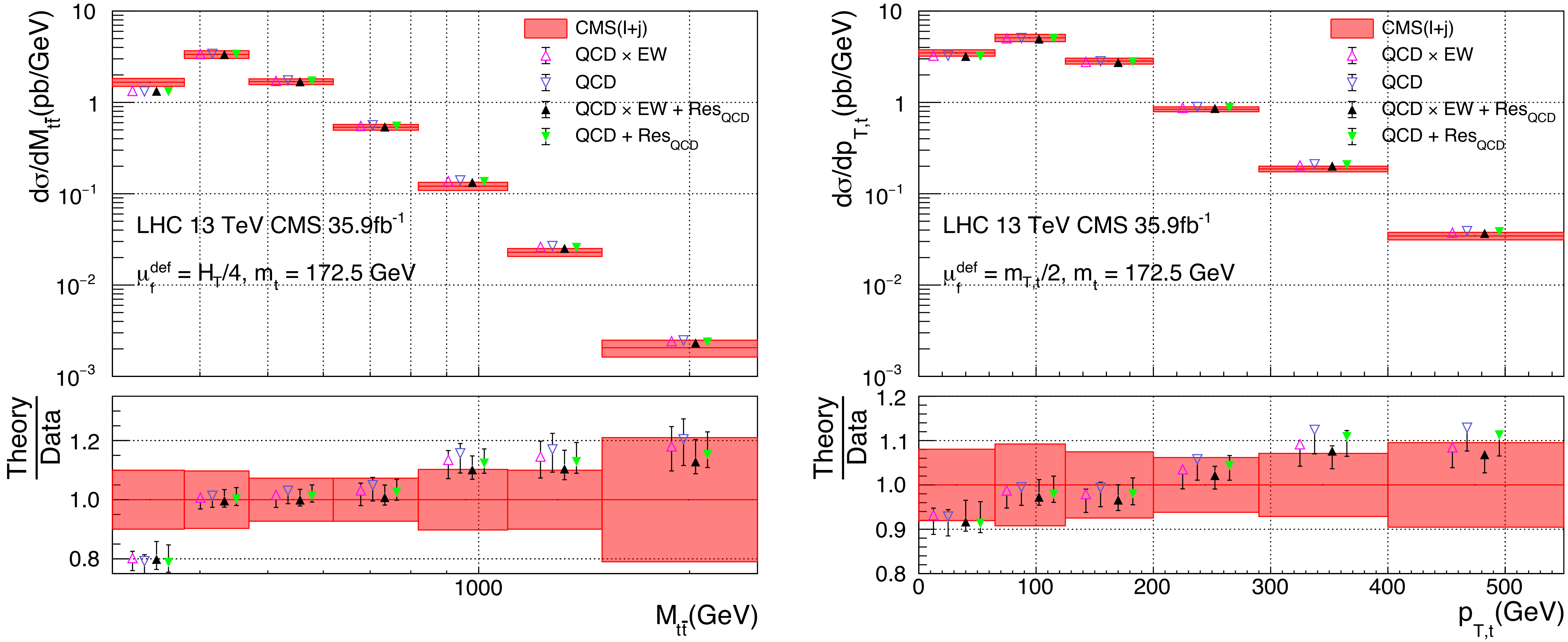
Pecjak, Scott, Wang, **LLY**: 1811.10527





State-of-the-art predictions

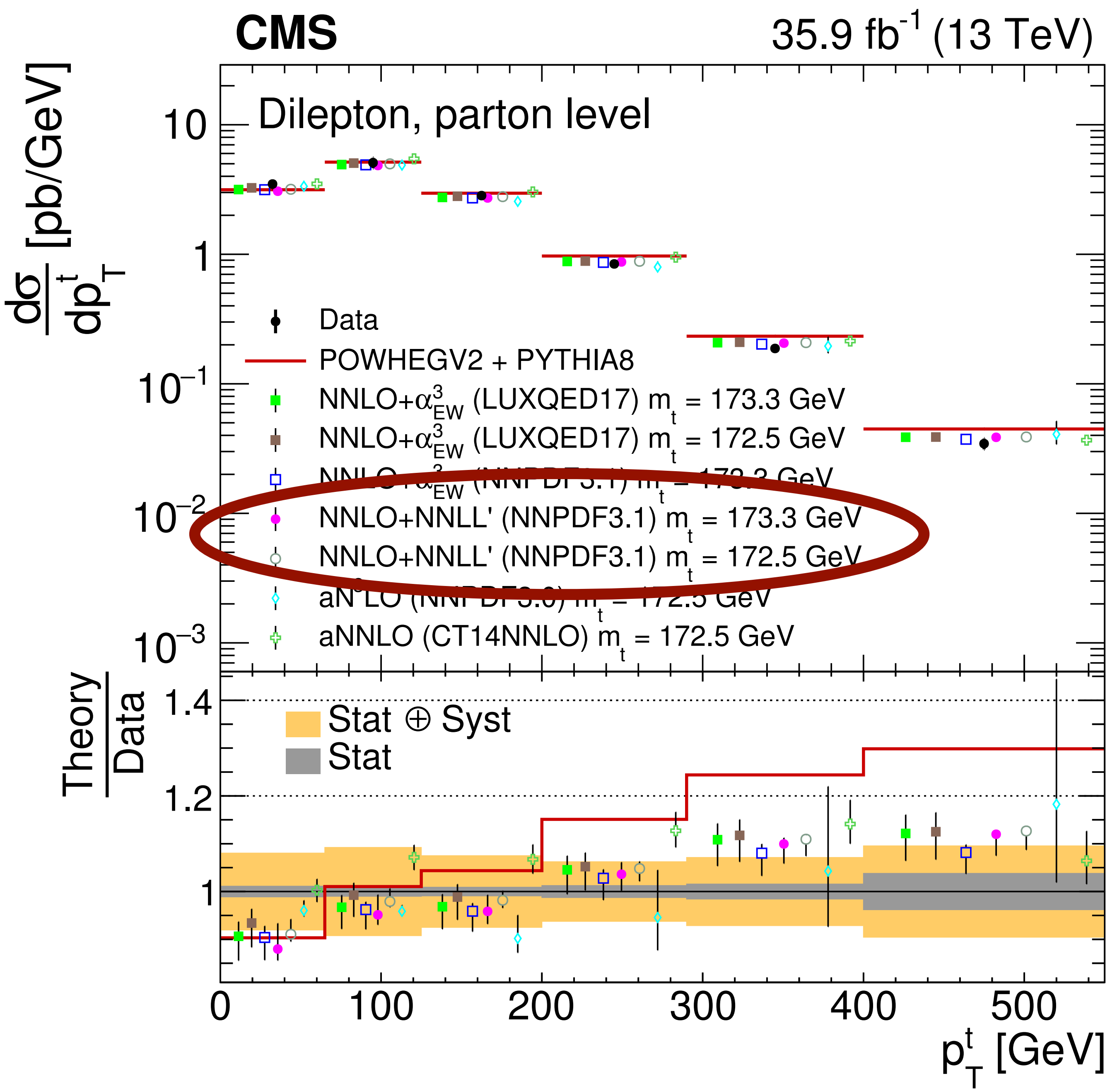
Combined with NLO electroweak corrections



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

Theory confronting data

CMS collaboration: 1811.06625



Transverse momentum

Theory confronting data

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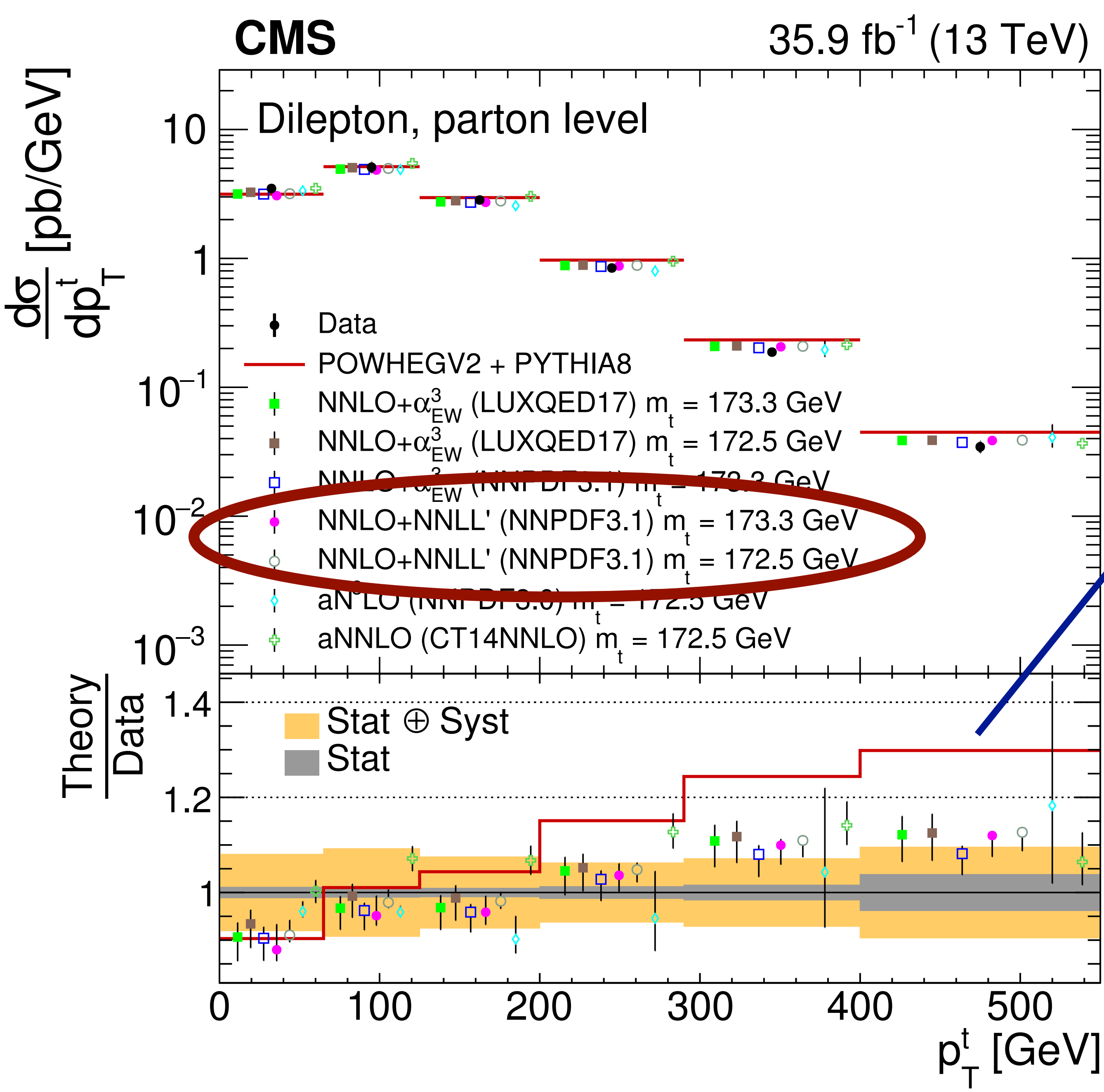
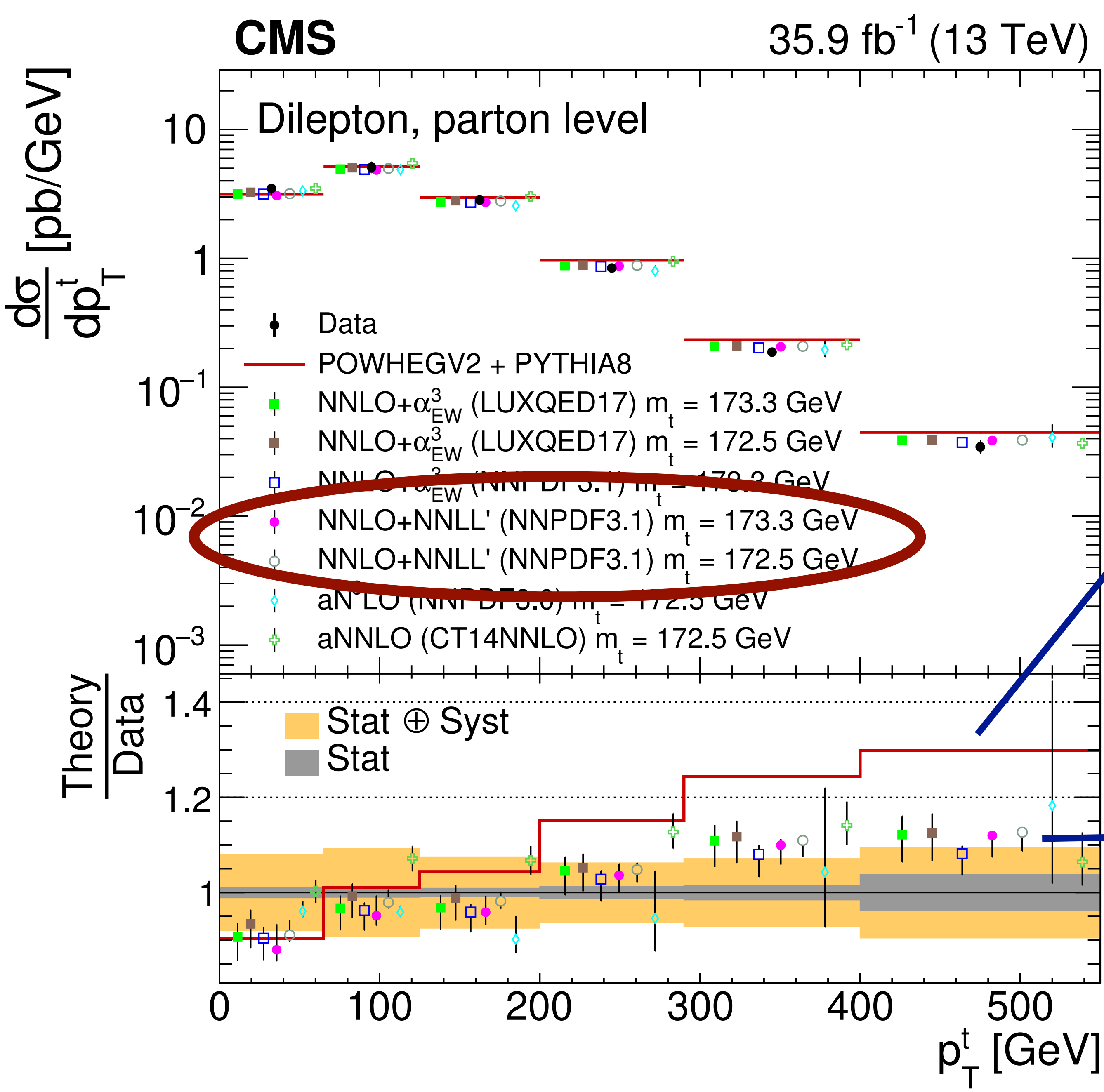


Transverse momentum

NLO + parton shower cannot describe the shape!

Theory confronting data

CMS collaboration: 1811.06625



Transverse momentum

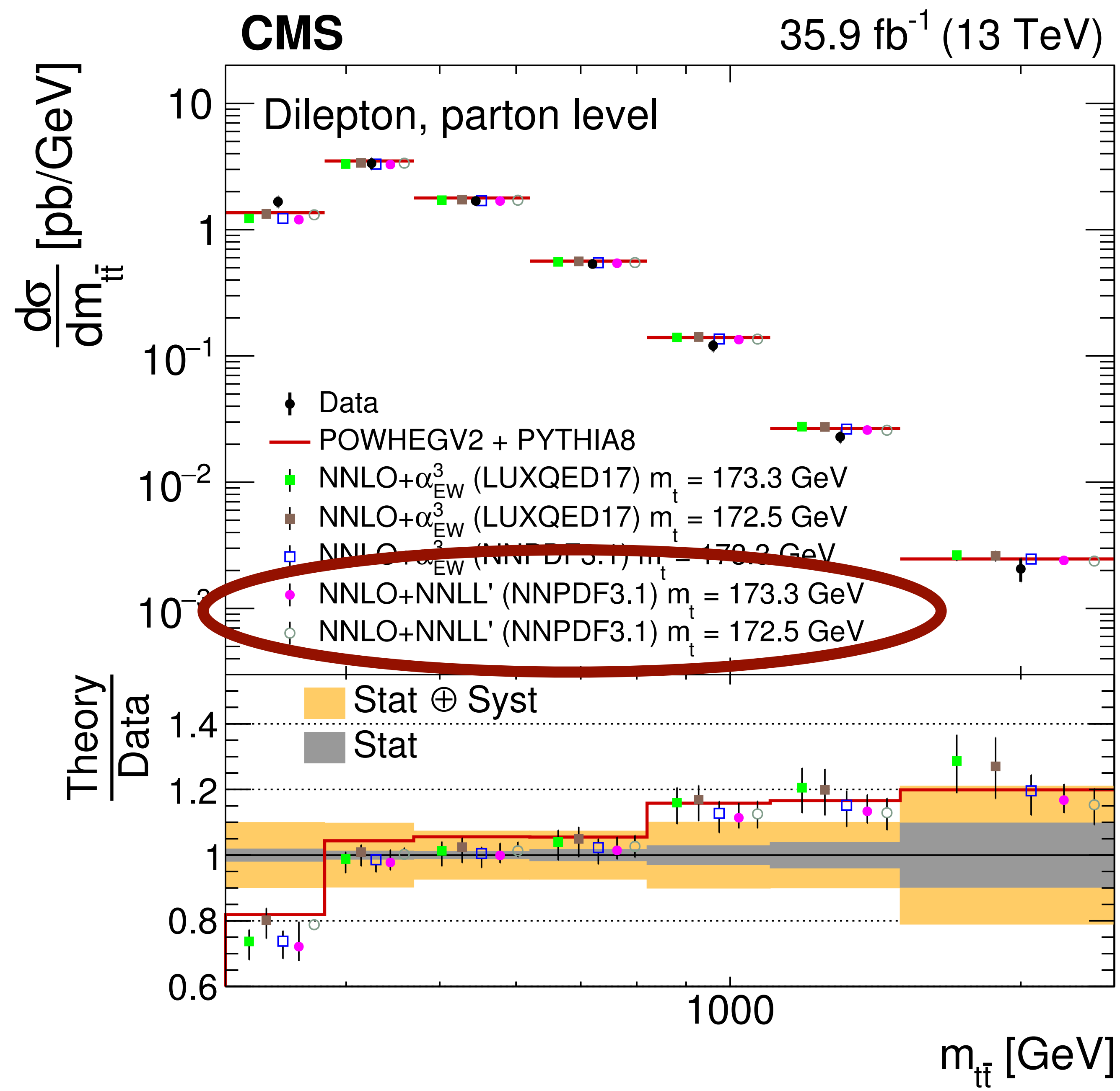
NLO + parton shower cannot describe the shape!

Higher order calculations bring together theory and experiment

Theory confronting data

CMS collaboration: 1811.06625

Overall good agreement



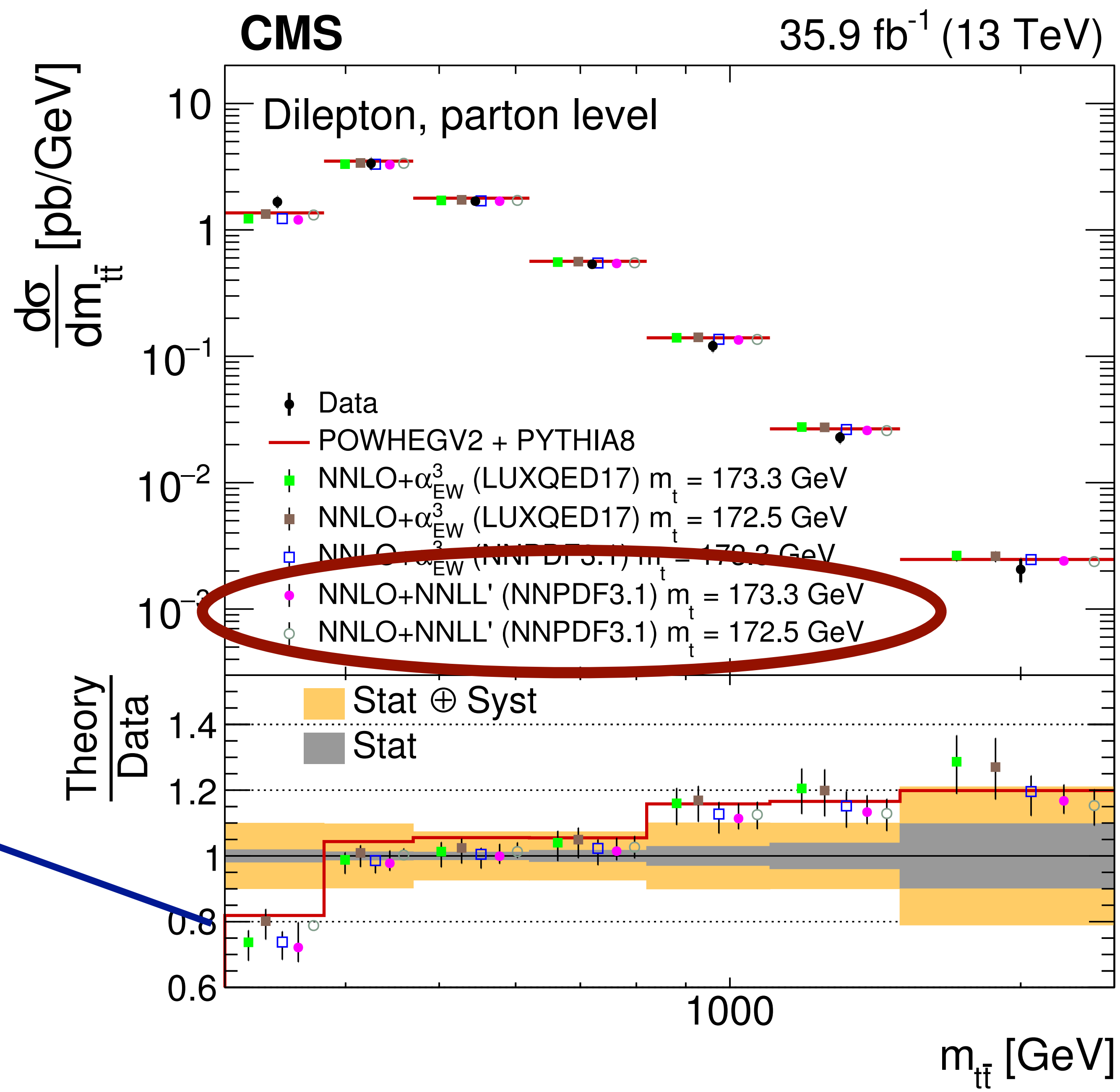
Invariant mass

Theory confronting data

CMS collaboration: 1811.06625

Overall good agreement

Except the first bin (threshold region)



Invariant mass

Threshold region and top quark mass

The differential cross sections in the threshold region are highly sensitive to the top quark mass

→ Can be used to fit m_t!

Threshold region and top quark mass

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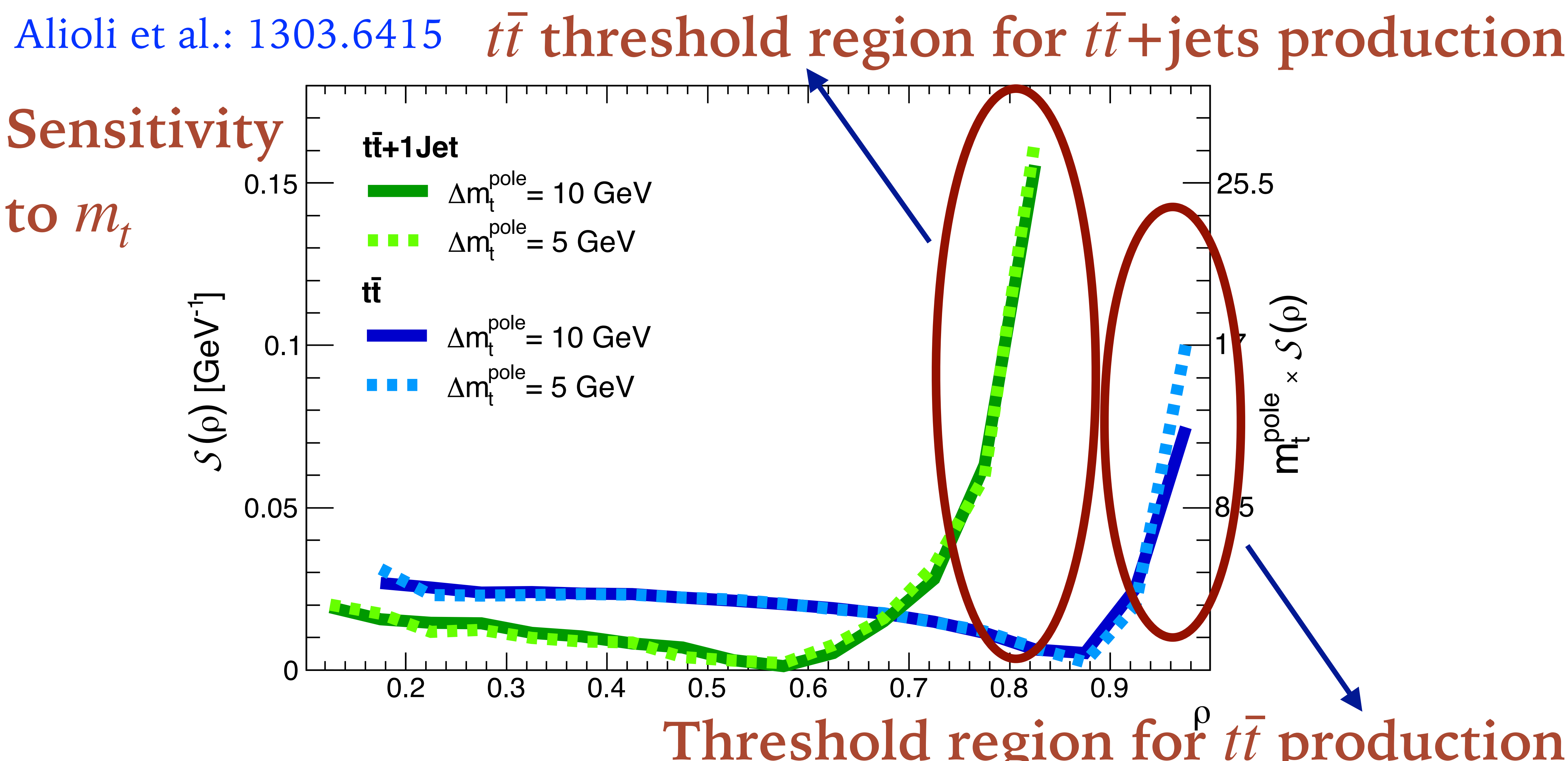
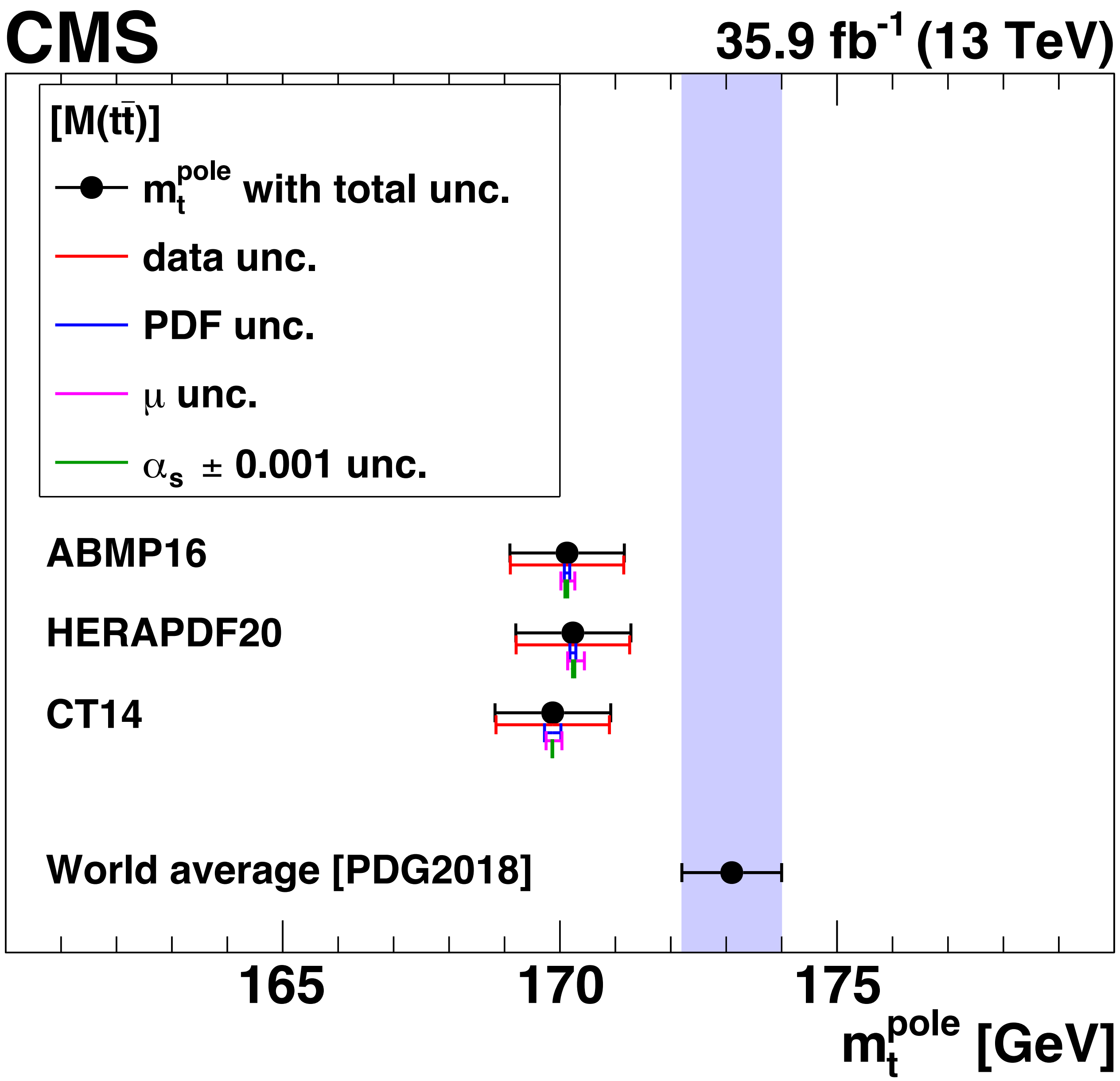
→ Can be used to fit m_t!

E.g., Alioli et al.: 1303.6415



Threshold region and top quark mass



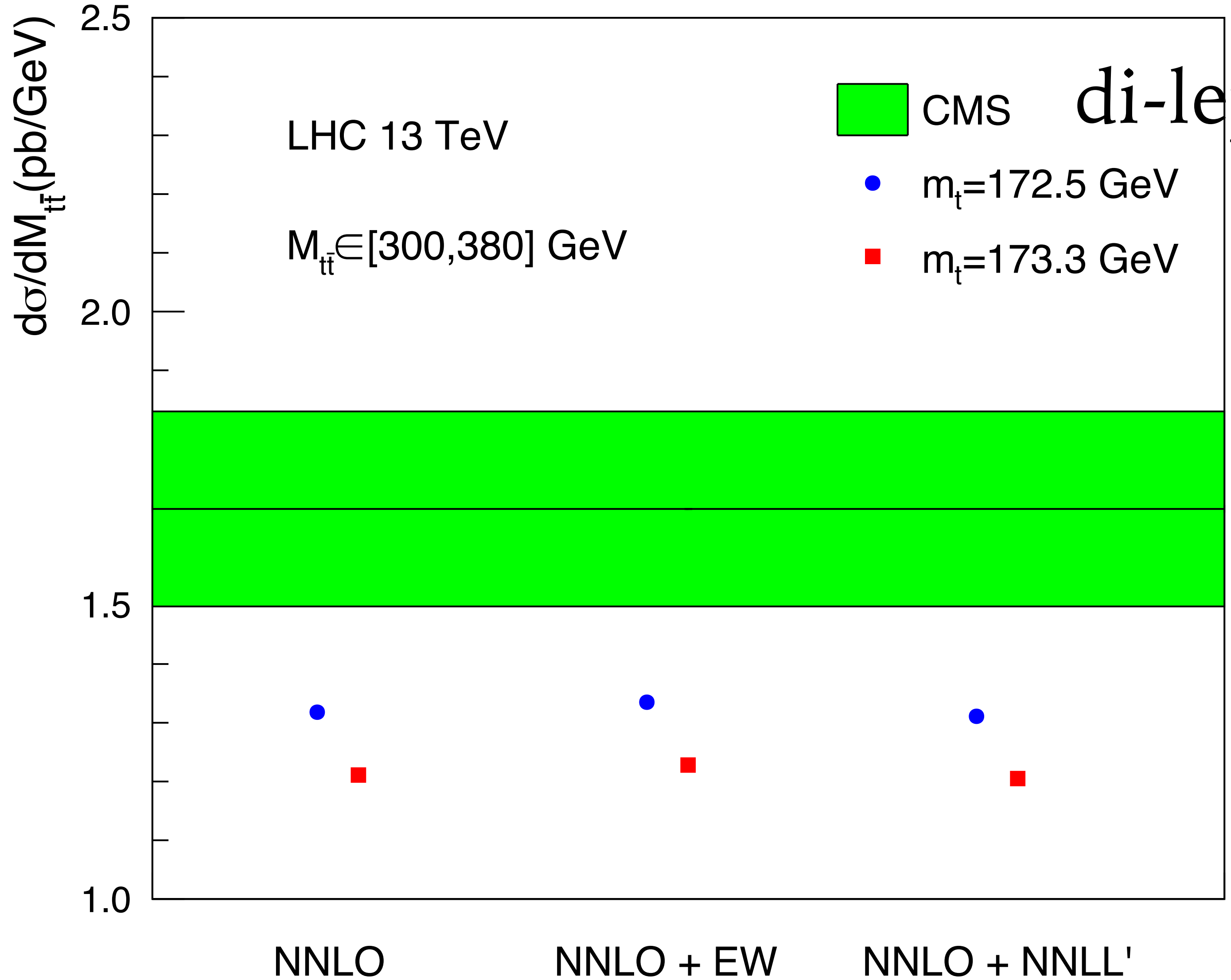
ATLAS collaboration: 1905.02302

CMS collaboration: 1904.05237

The fits favor much lower values of m_t than the world average!

Deserves a closer look…

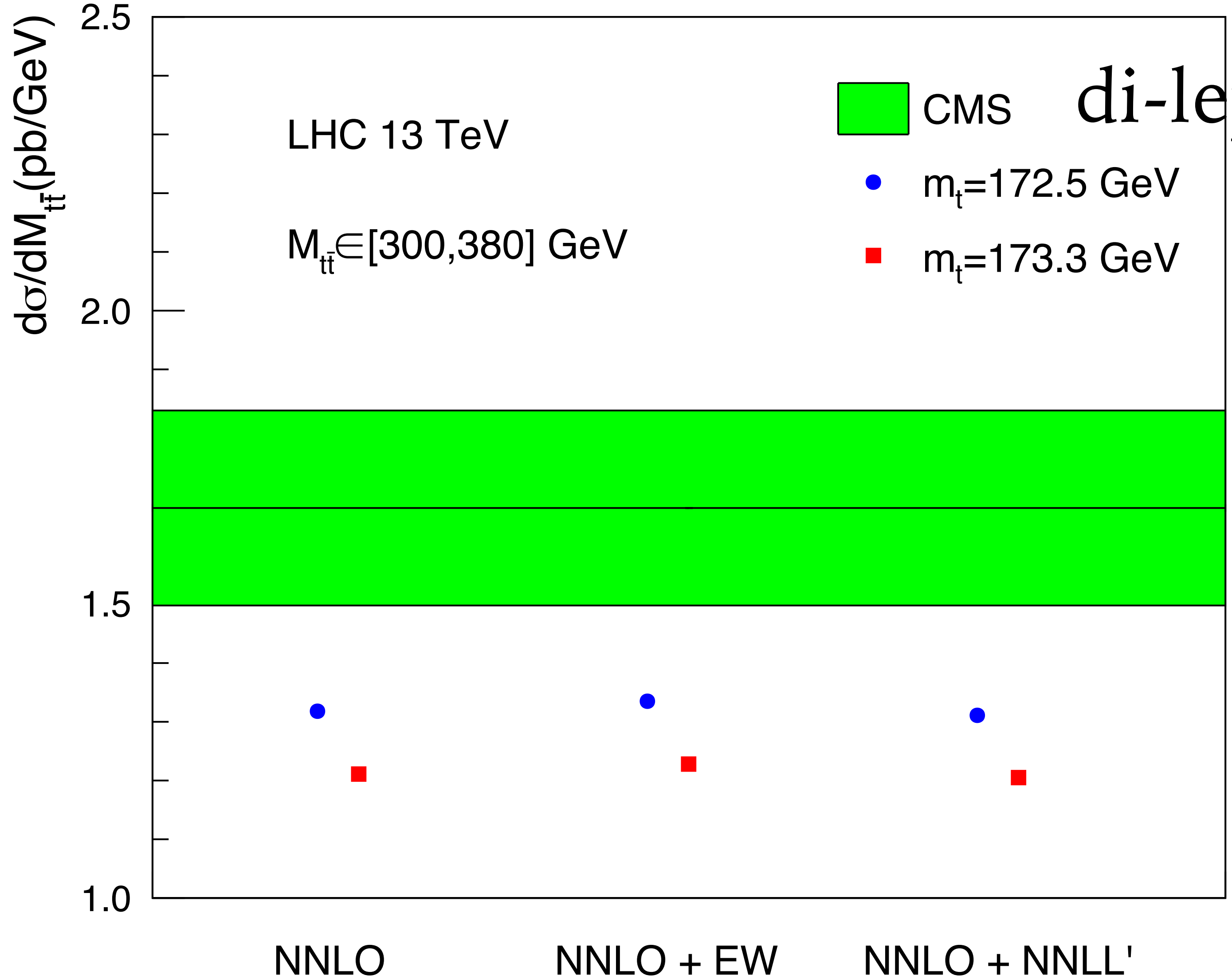
A closer look at the threshold region



di-lepton channel

Seems like a systematic deviation, affected by neither electroweak corrections nor soft gluon resummation

A closer look at the threshold region



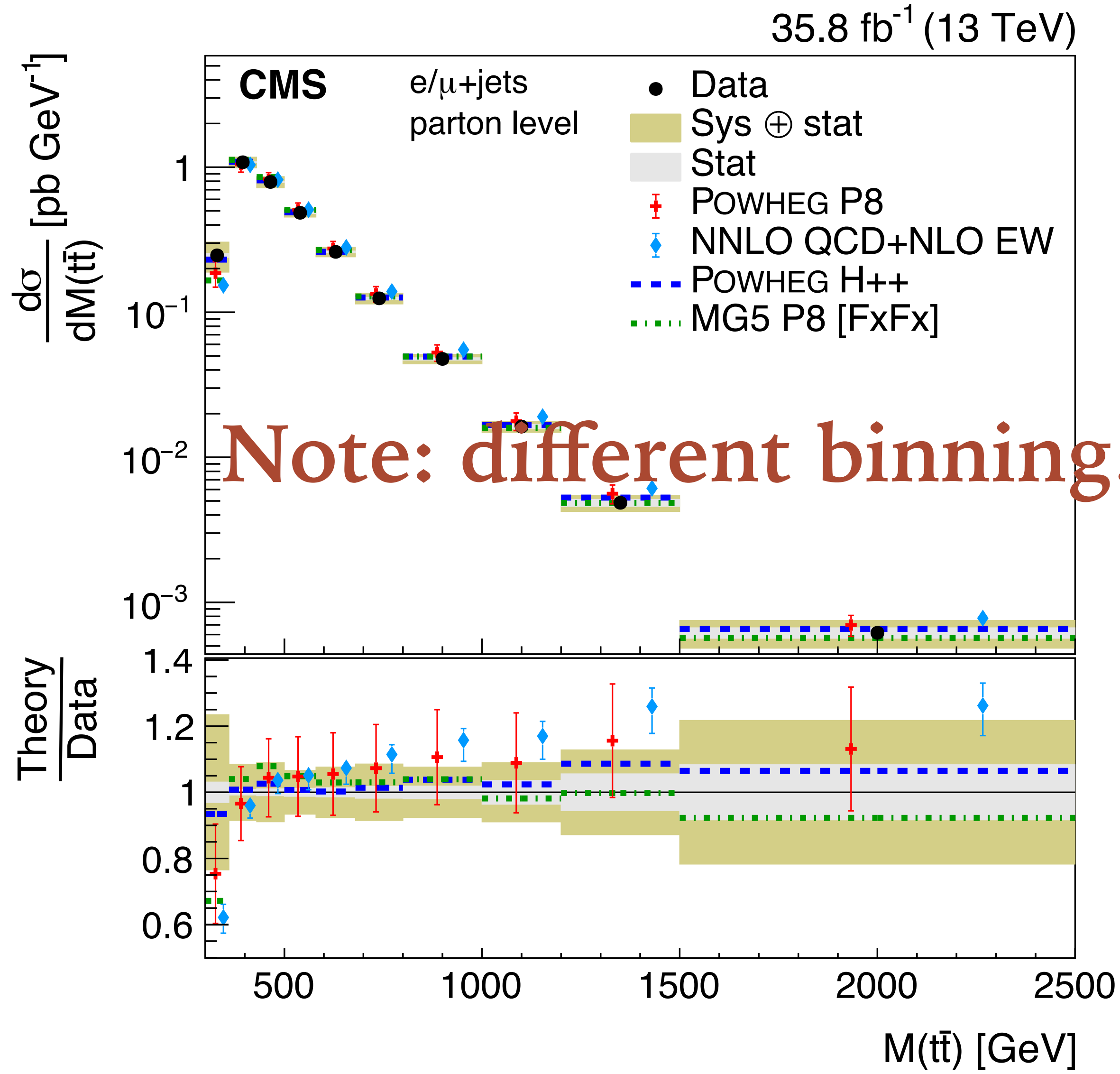
di-lepton channel

Seems like a systematic deviation, affected by neither electroweak corrections nor soft gluon resummation

Could it be an experimental issue?

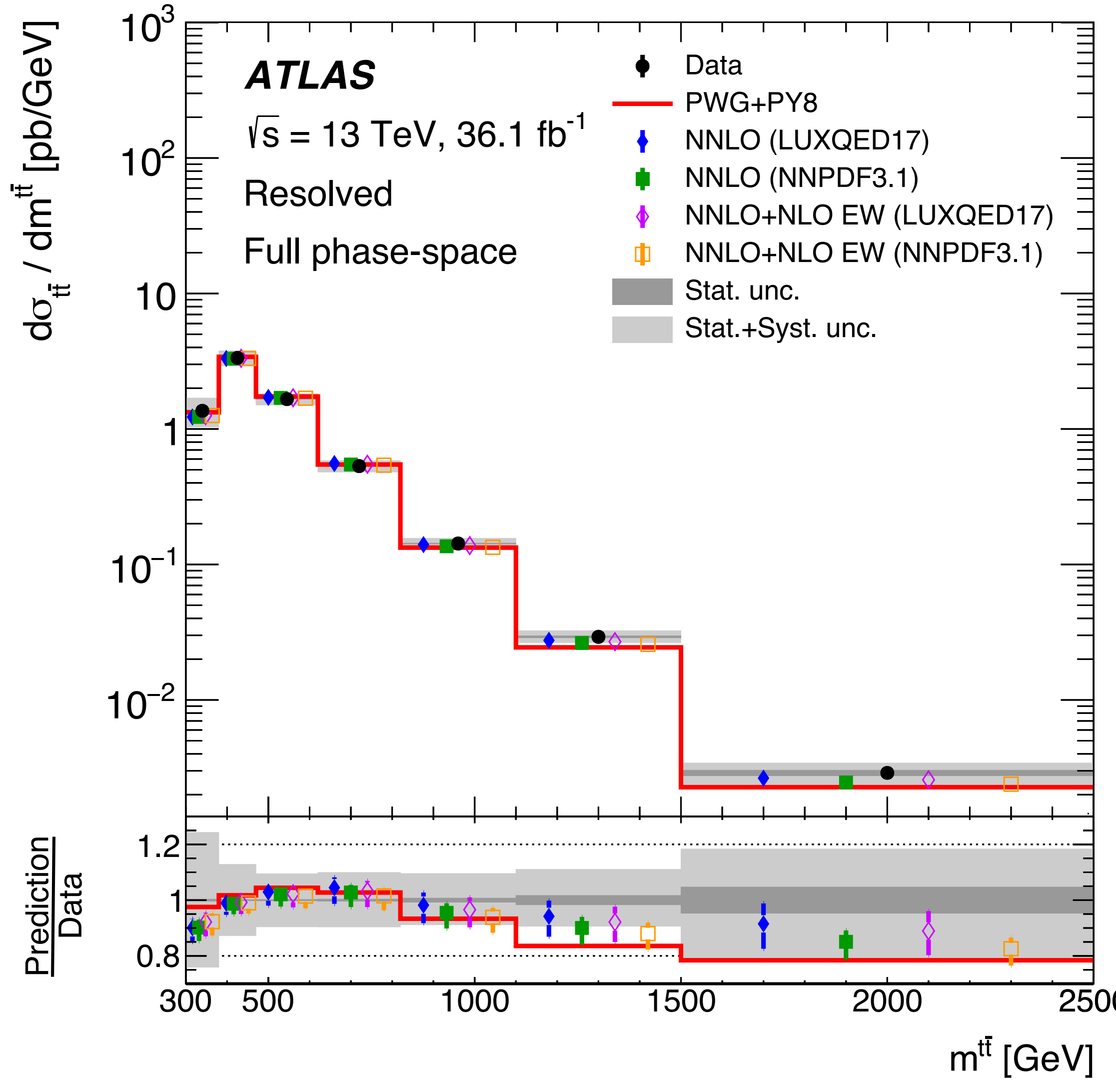
A closer look at the threshold region

CMS collaboration: 1803.08856



Note: different binning!

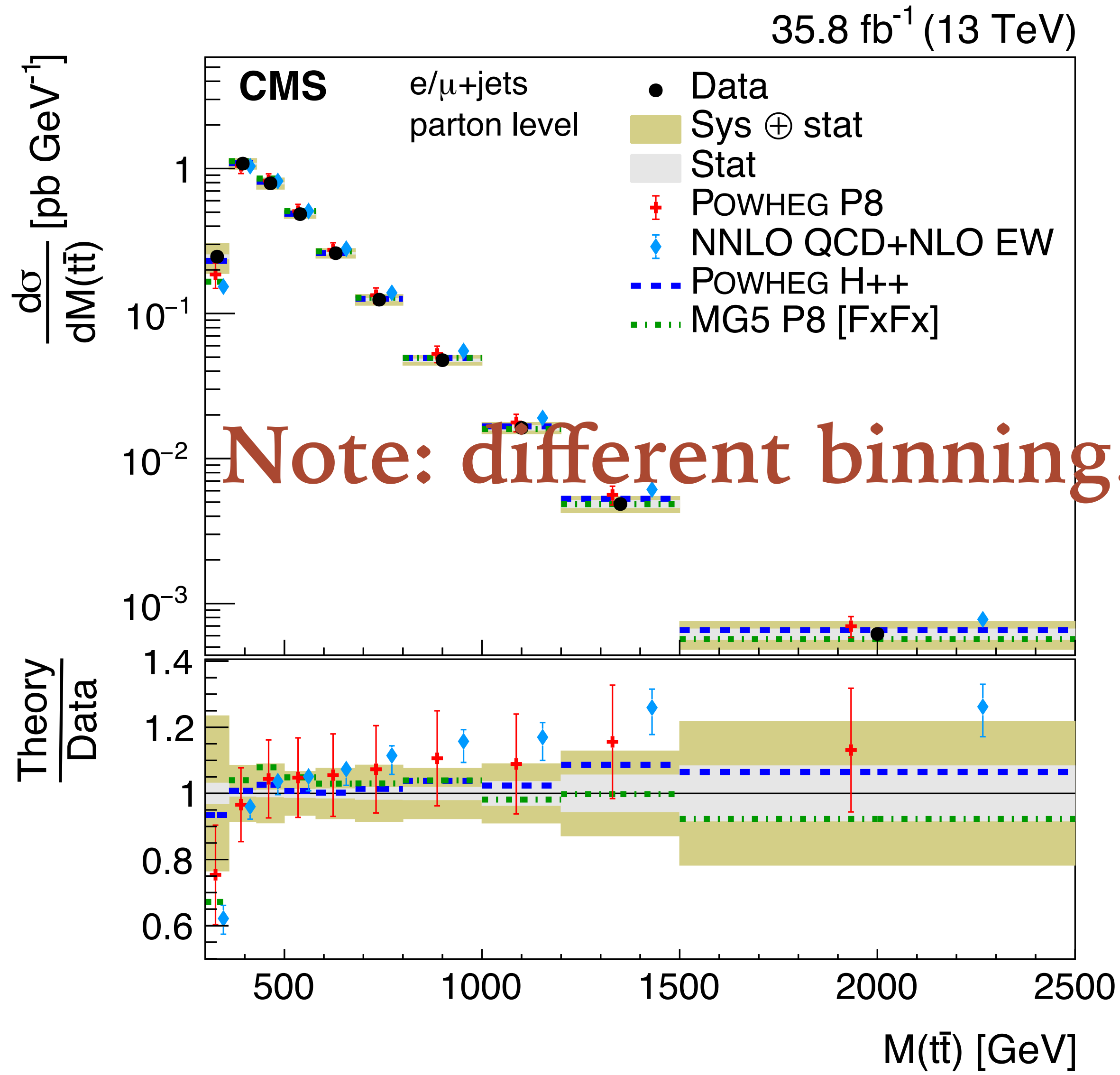
ATLAS collaboration: 1908.07305



Much larger uncertainties for the first bin in the lepton+jet channel reported by ATLAS&CMS: inconclusive

A closer look at the threshold region

CMS collaboration: 1803.08856



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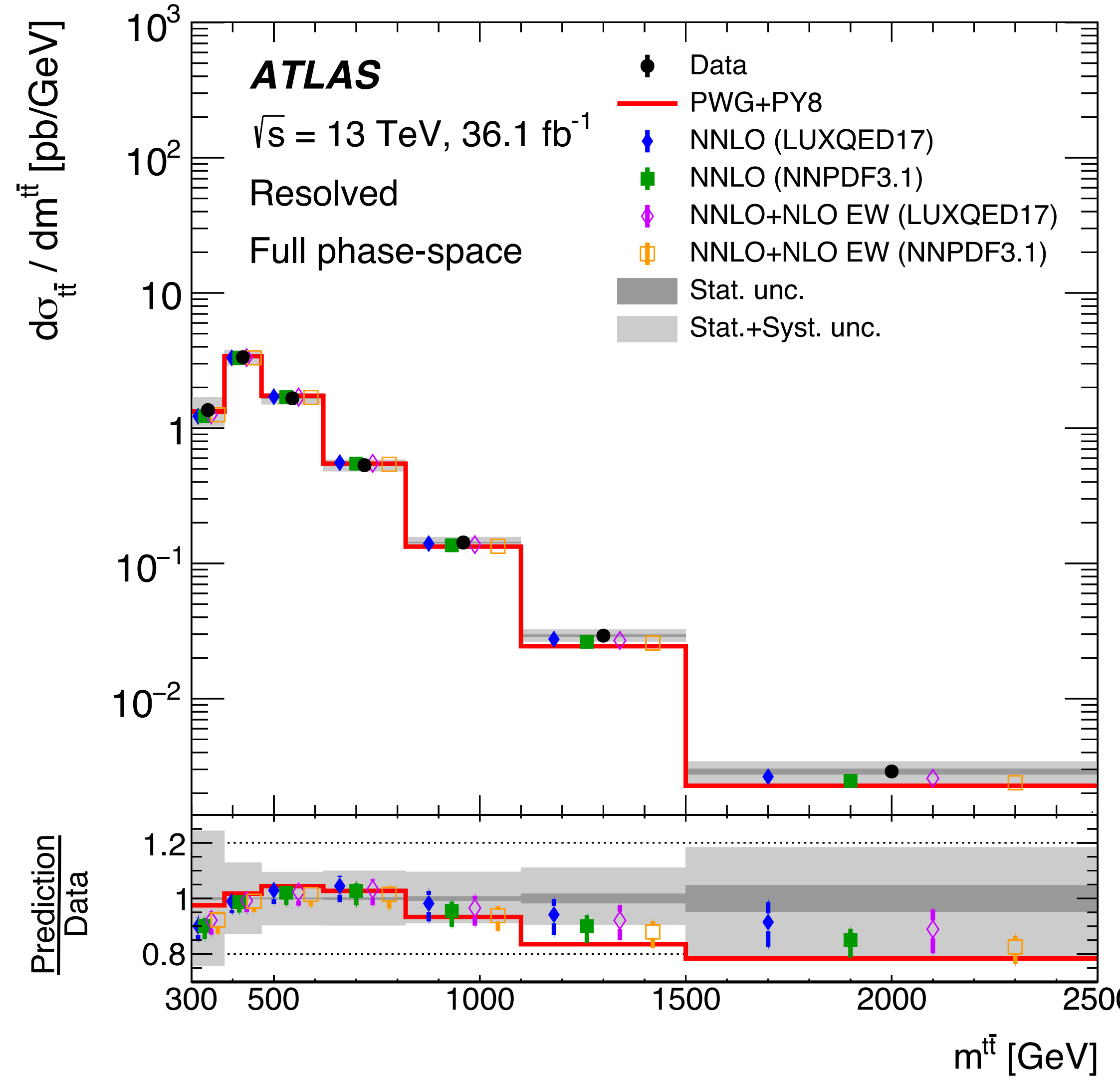
ATLAS collaboration: 1908.07305



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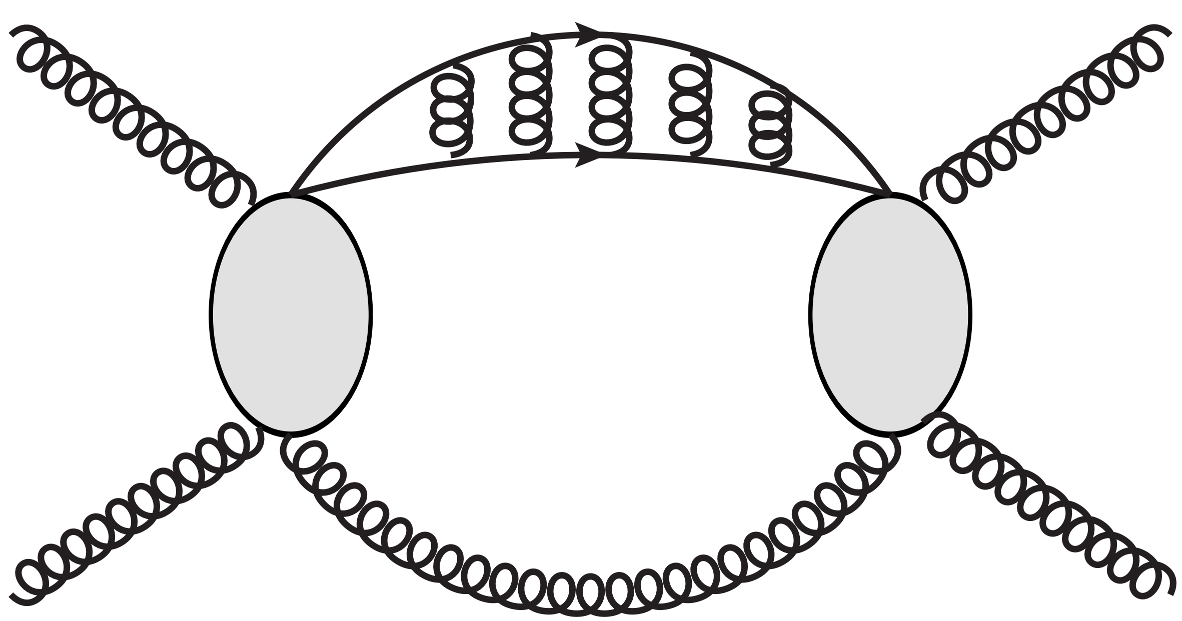
Let’s check what we might have missed on the theory side…

Non-relativistic Coulomb corrections

When the top and anti-top quarks move slowly with respect to each other, exchanges of gluons in between lead to "Coulomb corrections" or "Sommerfeld enhancement"

$$\frac{\alpha_s^n}{\beta^n}$$



$$\beta = \sqrt{1 - \frac{4m_t^2}{4M_{t\bar{t}}^2}} \to 0$$

Coulomb corrections for total cross section

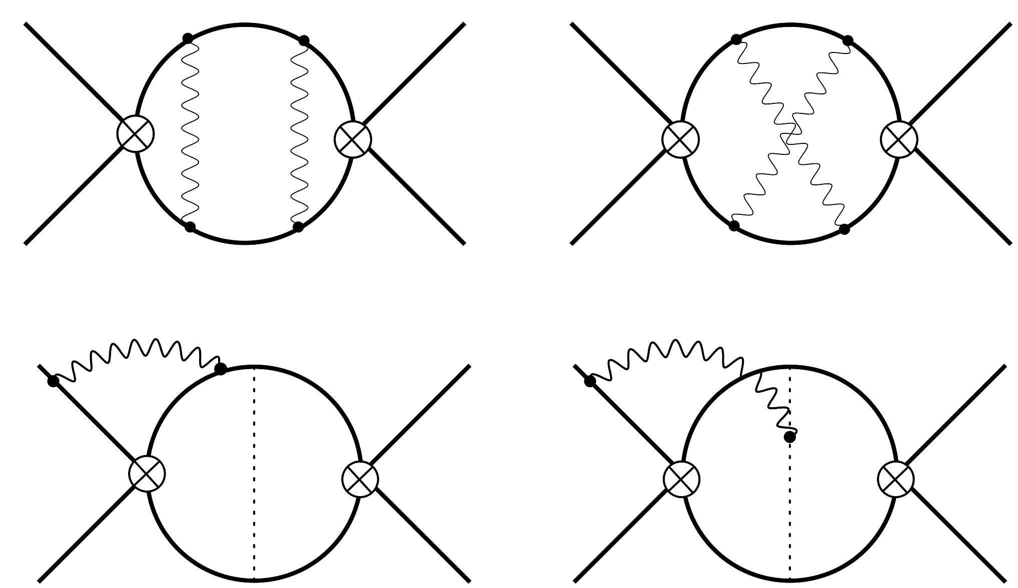
Coulomb corrections for total cross section
have been considered in, e.g.:

Beneke, Czakon, Falgari, Mitov, Schwinn: 0911.5166

Beneke, Falgari, Schwinn: 1007.5414

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

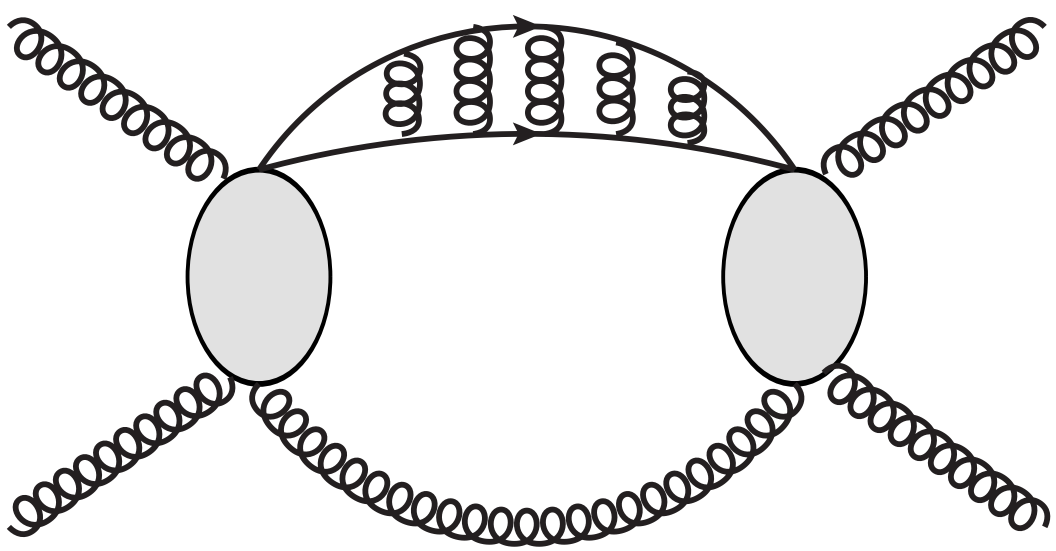
SCET+pNRQCD

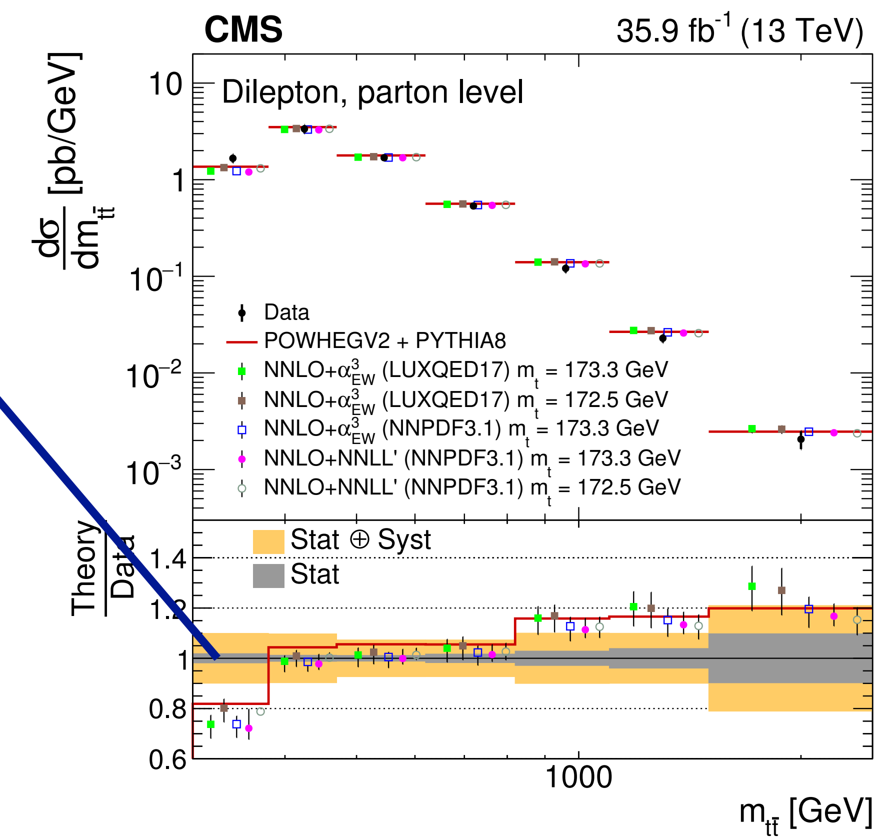


Remark: top quark physics is a good place to study NRQCD
since mv^2 is (very often) a perturbative scale

Coulomb corrections for invariant mass distribution

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





The top quark pair can be recoiled by extra hard emissions

See, .e.g., Kiyo et al.: 0812.0919

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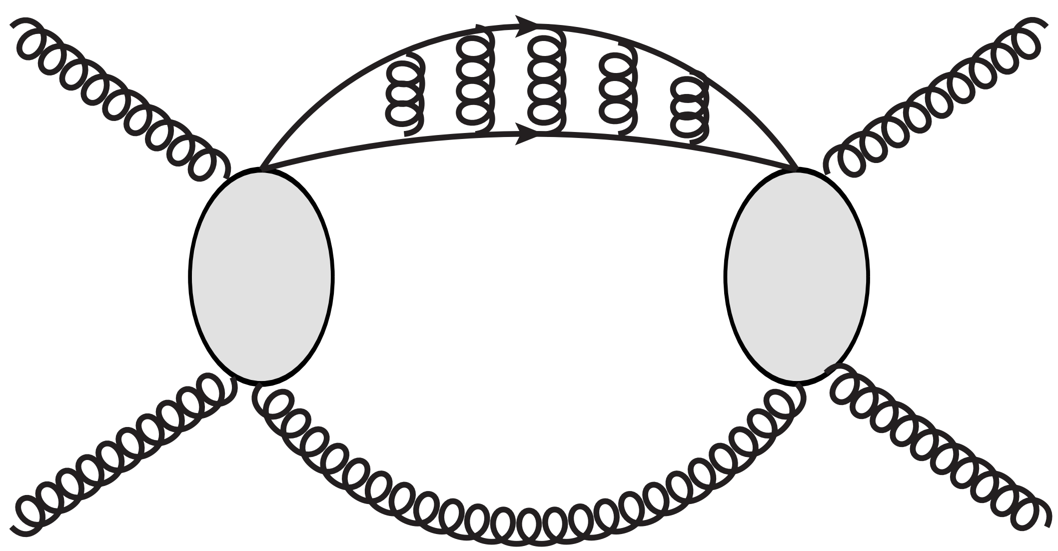

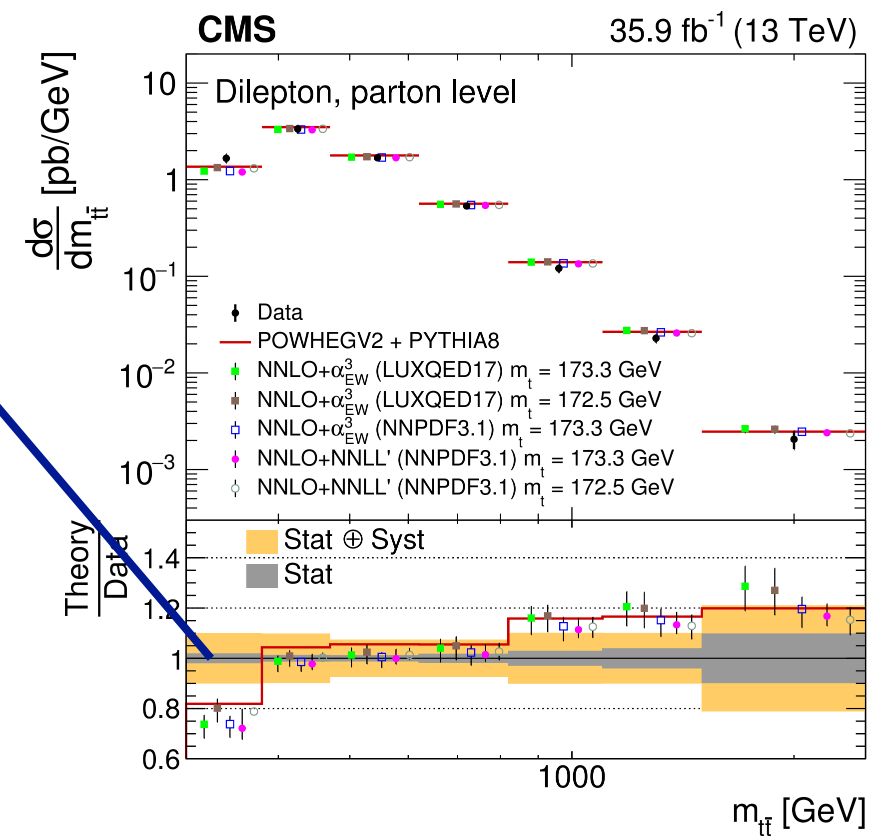

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Further complication: "dynamic scales"

$$H_T = \sqrt{p_{T,t}^2 + m_t^2} + \sqrt{p_{T,\bar{t}}^2 + m_t^2}$$

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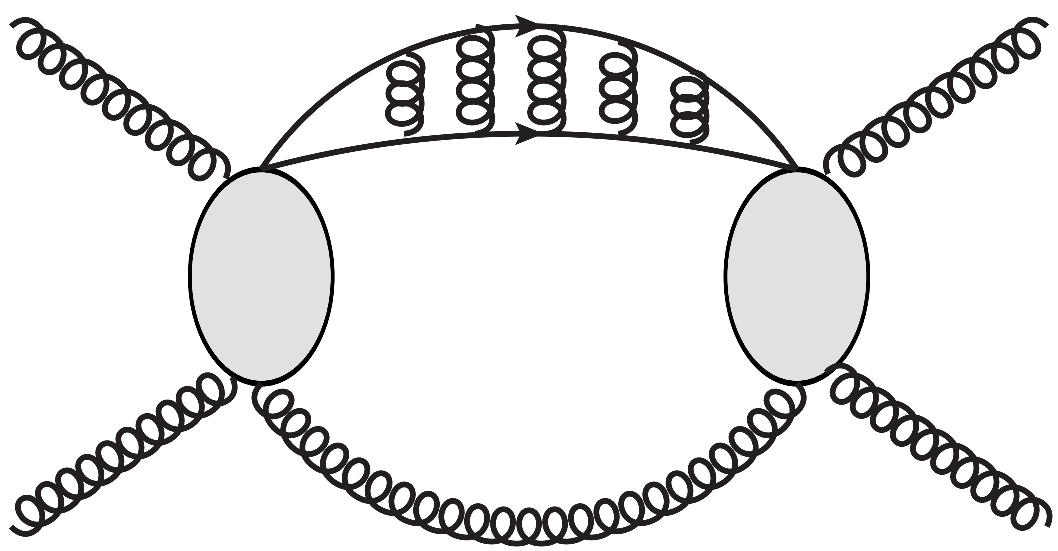

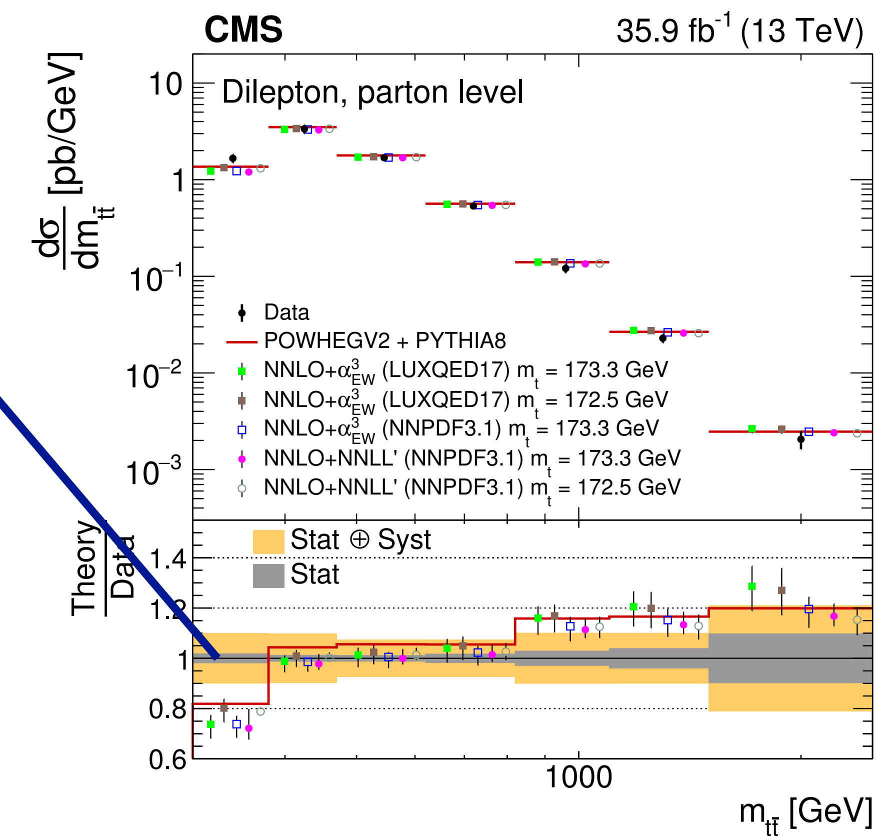

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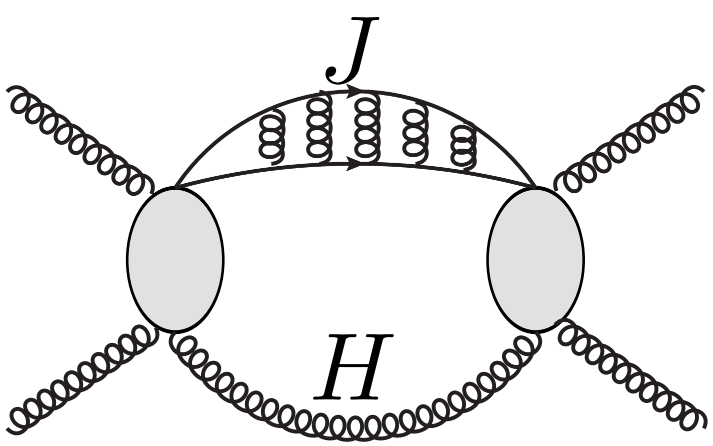
Further complication: "dynamic scales"

$$H_T = \sqrt{p_{T,t}^2 + m_t^2} + \sqrt{p_{T,\bar{t}}^2 + m_t^2}$$

Requires a new resummation formula (retaining kinematic information about the top and anti-top quarks)

Factorization and resummation

Ju, Wang, Wang, Xu, Xu, **LLY**: 1908.02179



Potential function

Parton luminosity

$$\frac{d\sigma}{dM_{t\bar{t}}} \sim \int H \times J \times ff$$

Kinematics-dependent hard function (different from known ones in literature)

We calculate it analytically to the next-to-leading order

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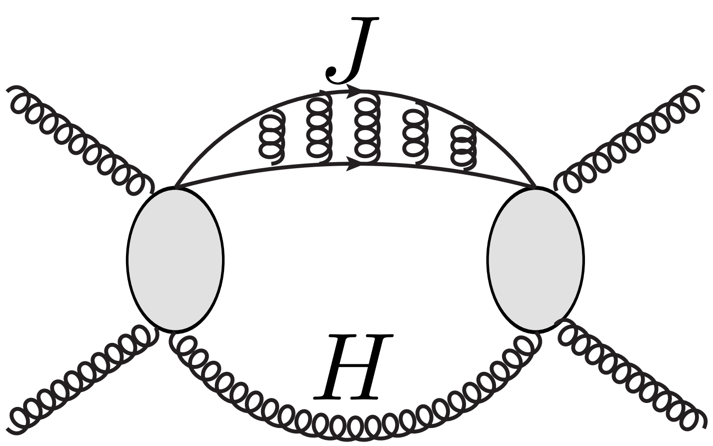

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Kinematics-dependent hard function (different from known ones in literature)

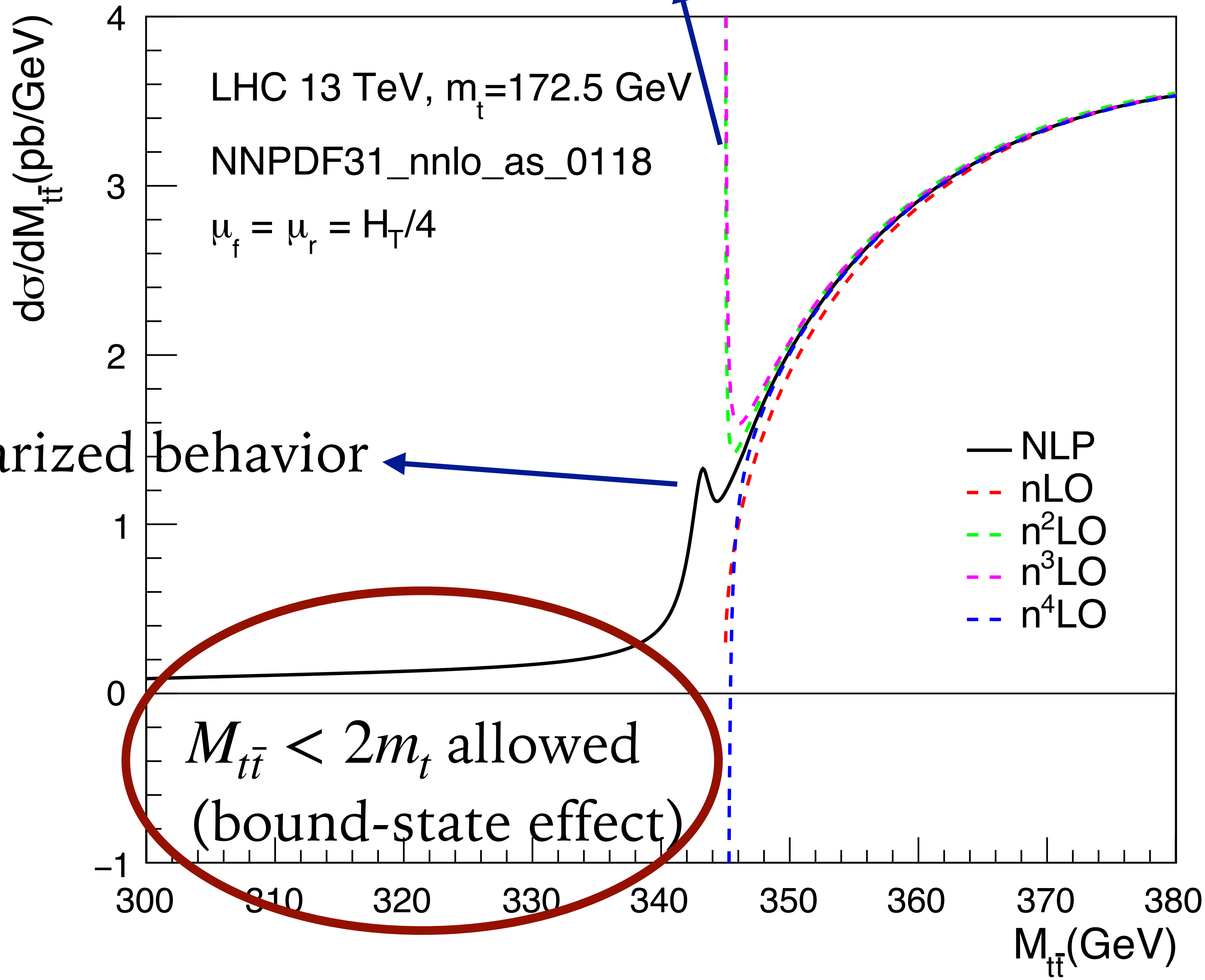
We calculate it analytically to the next-to-leading order

Note: no soft function at NLP! What about higher powers?

Perturbative behavior

Ju, Wang, Wang, Xu, Xu, **LLY**: 1908.02179

Fixed-order expansion divergent in the threshold limit

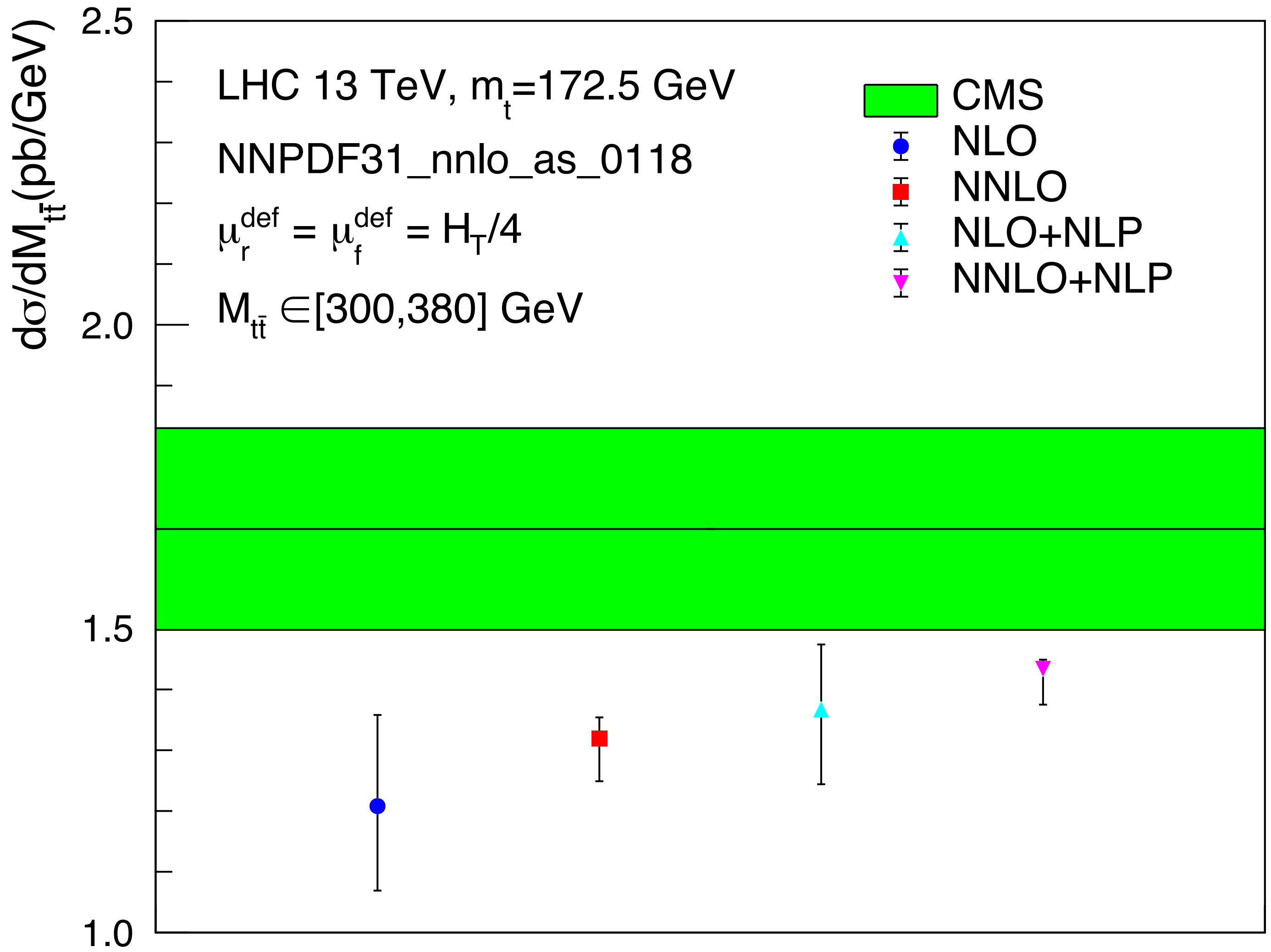


Regularized behavior

$M_{t\bar{t}} < 2m_t$ allowed
(bound-state effect)

Compare to data

Ju, Wang, Wang, Xu, Xu, **LLY**: 1908.02179



Enhance the differential cross section by 9%

(compared to NNLO)

Better compatibility with CMS di-lepton data

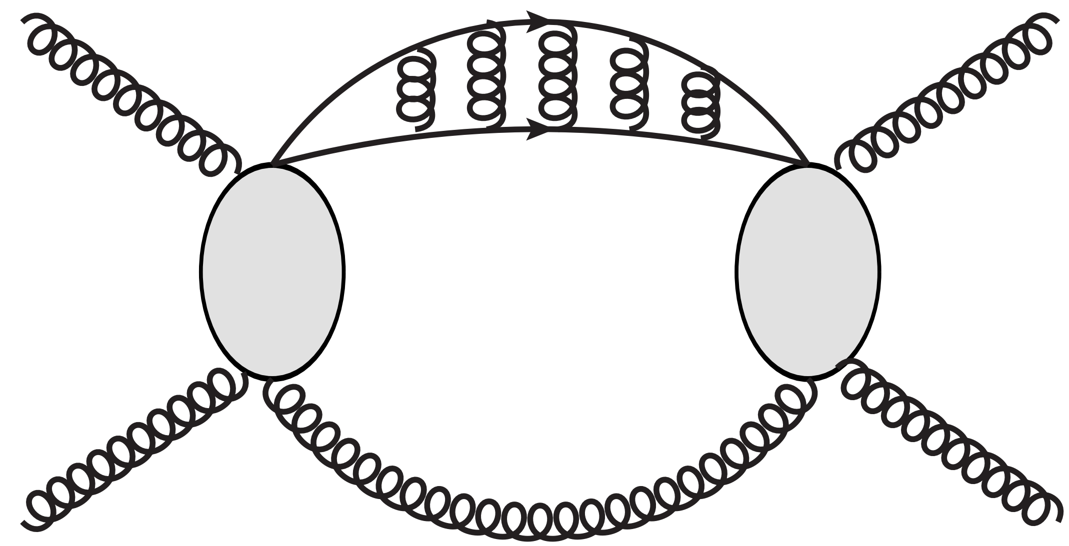
And also compatible with ATLAS&CMS l+j data

Will have implications in the fits of top quark mass!

Adding a hard jet

Work in progress…

May be applied to $t\bar{t}$+jets production



Phenomenologically interesting:
used to fit the top quark mass

Measurement of the top-quark mass in $t\bar{t}$ + 1-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s}$ = 8 TeV

1905.02302

The ATLAS Collaboration

Theoretically interesting: High p_T limit resembles J/ψ production

Polluted by non-perturbative effects for J/ψ

But should be perturbatively calculable for $t\bar{t}$

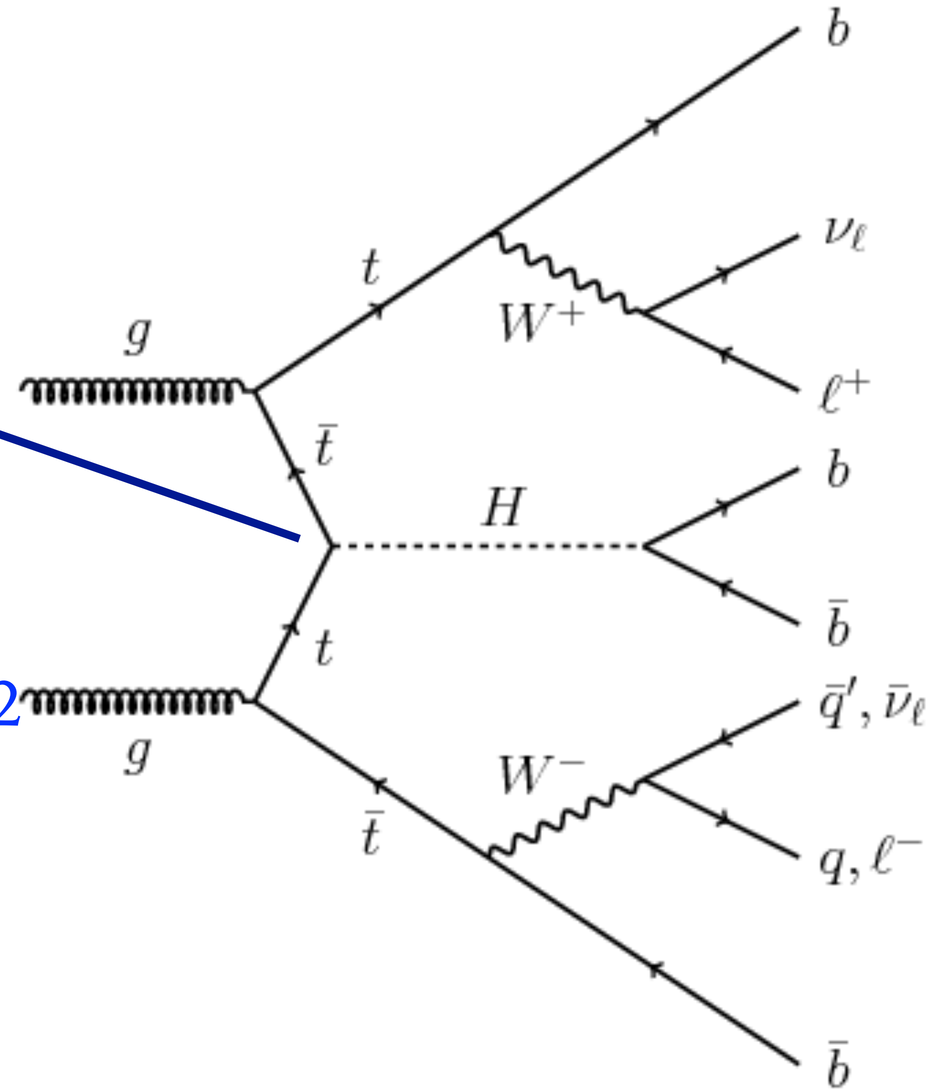
Adding a Higgs

The $t\bar{t}$ can also be recoiled by a Higgs boson

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

NLO QCD known since 2001

Beenakker et al.: hep-ph/0107081, hep-ph/0211352
Reina, Dawson: hep-ph/0107101
Reina, Dawson, Wackeroth: hep-ph/0109066



Observed at the LHC

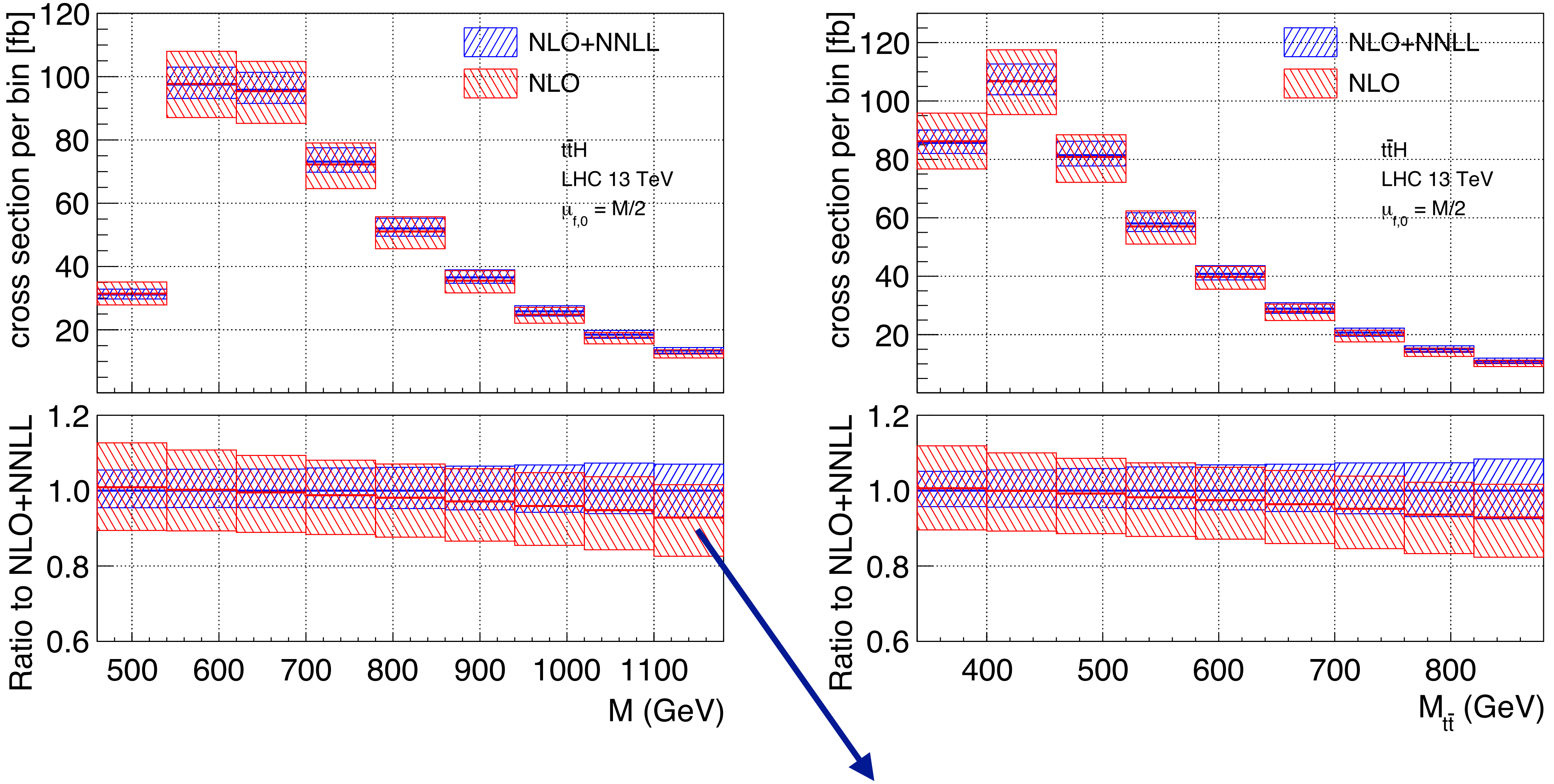
CMS collaboration: 1804.02610

ATLAS collaboration: 1806.00425

Beyond NLO for differential cross sections

Broggio, Ferroglia, Pecjak, **LLY**: 1611.00049

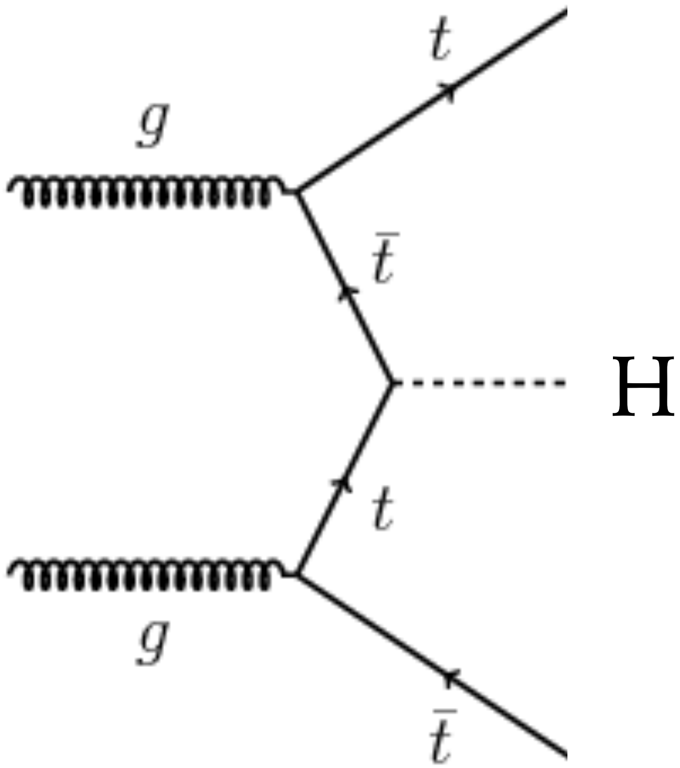
State-of-the-art QCD predictions for this process: NLO+NNLL



Higher order effect important at high energies

Coulomb corrections for total rate

Ju, **LLY**: 1904.08744



Consider the threshold region

$$\sqrt{\hat{s}} \to 2m_t + m_H$$

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

Sudakov and Sommerfeld corrections

Coulomb corrections for total rate

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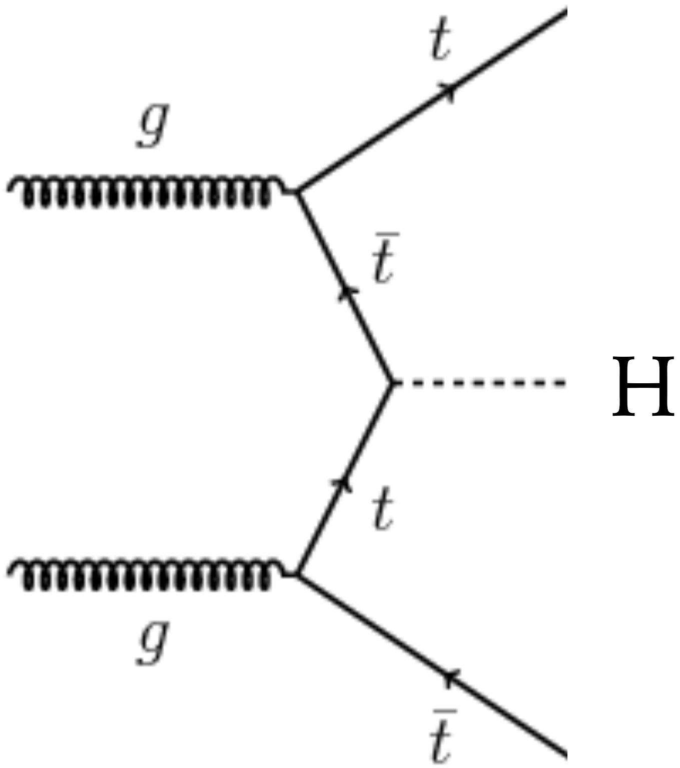

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Sudakov and Sommerfeld corrections

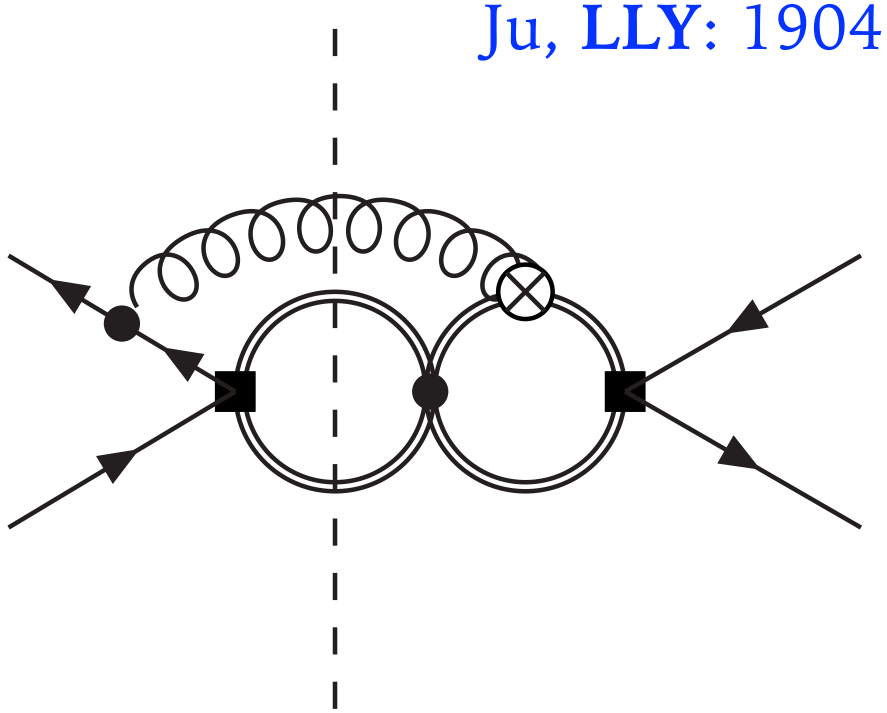
Combination of SCET and pNRQCD

$$\begin{aligned}
&\text{hard}: && k^\mu \sim \sqrt{\hat{s}}\,, \\
&\text{soft}: && k^\mu \sim \sqrt{\hat{s}}\,\beta\,, \\
&\text{potential}: && k^0 \sim \sqrt{\hat{s}}\,\beta^2\,, \quad \vec{k} \sim \sqrt{\hat{s}}\,\beta\,, \\
&\text{ultrasoft}: && k^\mu \sim \sqrt{\hat{s}}\,\beta^2\,, \\
&\text{collinear}: && (k_+, k_-, k_\perp) \sim \sqrt{\hat{s}}\,(1, \beta^2, \beta)\,, \\
&\text{anticollinear}: && (k_+, k_-, k_\perp) \sim \sqrt{\hat{s}}\,(\beta^2, 1, \beta)\,.
\end{aligned}$$

Factorization near threshold

Ju, **LLY**: 1904.08744

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



$$\hat{\sigma}_{ij} = \sum_{\alpha} \frac{1}{2\hat{s}} \int d\Phi_h d\omega \, H^{\alpha}_{ij}(\mu) \, J^{\alpha}\left(E_J - \frac{\omega}{2}, \vec{p}_J\right) S^{\alpha}_{ij}(\omega, \mu)$$

hard modes

potential modes
and soft modes

ultrasoft modes

Resummation

Ju, **LLY**: 1904.08744

Resummation at NLL' accuracy

$$\hat{\sigma}_{ij}^{\mathrm{NLL}'} \sim \alpha_s^0 \Big\{ 1, \beta \Big\} + \alpha_s \Big\{ \ln^2 \beta, \ln \beta, 1, \frac{1}{\beta}, \beta \ln^2 \beta, \beta \ln \beta \Big\}$$
$$+ \alpha_s^2 \Big\{ \ln^4 \beta, \ln^3 \beta, \ln^2 \beta, \frac{1}{\beta^2}, \frac{1}{\beta}, \frac{\ln^2 \beta}{\beta}, \frac{\ln \beta}{\beta}, \beta \ln^4 \beta, \beta \ln^3 \beta \Big\} + \cdots$$

	13 TeV LHC (pb)	14 TeV LHC (pb)
NLO	$0.493^{+5.8\%}_{-9.2\%}$	$0.597^{+6.1\%}_{-9.2\%}$
NLL′+NLO	$0.521^{+1.9\%}_{-2.6\%}$	$0.630^{+2.3\%}_{-2.6\%}$
K-factor	1.06	1.06

6% effect; big reduction of scale dependence

Extension to differential cross sections…

Summary

- Theoretical predictions for top quark pair differential cross sections have achieved remarkable precisions
  - Current state-of-the-art: NNLO+NNLL'+EW
- Still a small gap at low invariant mass near threshold
  - Use pNRQCD to derive a resummation formula for Coulomb corrections
  - Calculated relevant ingredients for NLP resummation
  - New result better compatible with data and has significant impact on top quark mass measurement
- Also studied Coulomb resummation for ttH production
- Many things to be done in the future: beyond NLP? $t\bar{t}$+jets? $t\bar{t}H$ distributions?

祝赵老师八十大寿生日快乐！

如月之恒
如日之升

如南山之寿
不骞不崩

如松柏之茂
无不尔或承