Status/update $t\bar{t}W$ production in NNLO QCD

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LHC TOP WG — June 5^{th}- 7^{th} 2023

Universität Zürich[UZH]

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Introduction: why $t\bar{t}W$ production?

Motivations :

- the production of top-quark pairs in association with a W boson is among the **most massive SM signatures** at hadron colliders
- since the top quarks rapidly decay, the signature of the process is characterised by **two b-jets and three W bosons**

multi-lepton signature

relevant for BSM searches

irreducible source of same-sign dilepton pairs

- it represents a **relevant background** also for SM processes like $t\bar{t}H$ and $t\bar{t}t\bar{t}$ production

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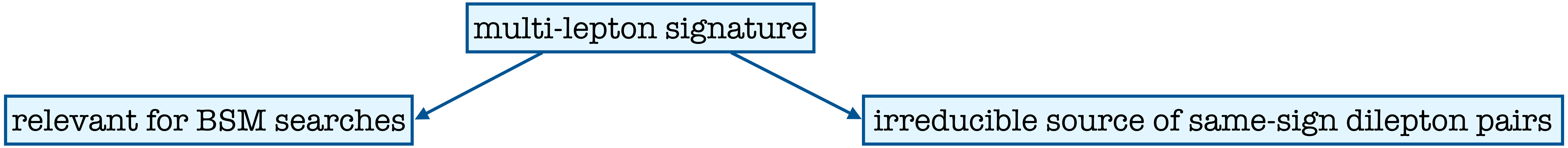

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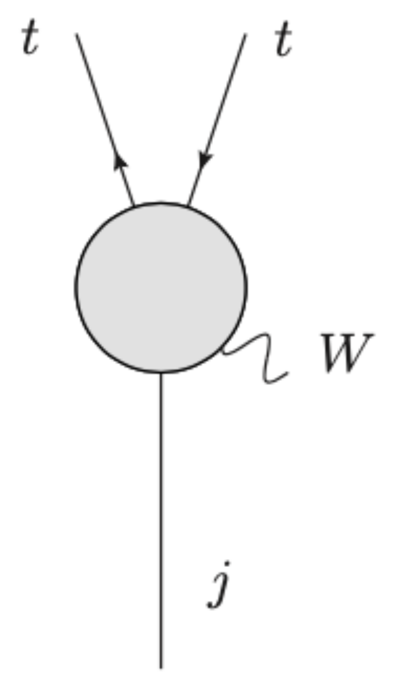
- different pattern of radiative corrections: both **QCD and EW corrections are relevant**

dominated by configurations where the $t\bar{t}$ pair recoils against hard QCD radiation, accompanied by a soft W boson

[Maltoni, Pagani, Tsinikos (2015)]



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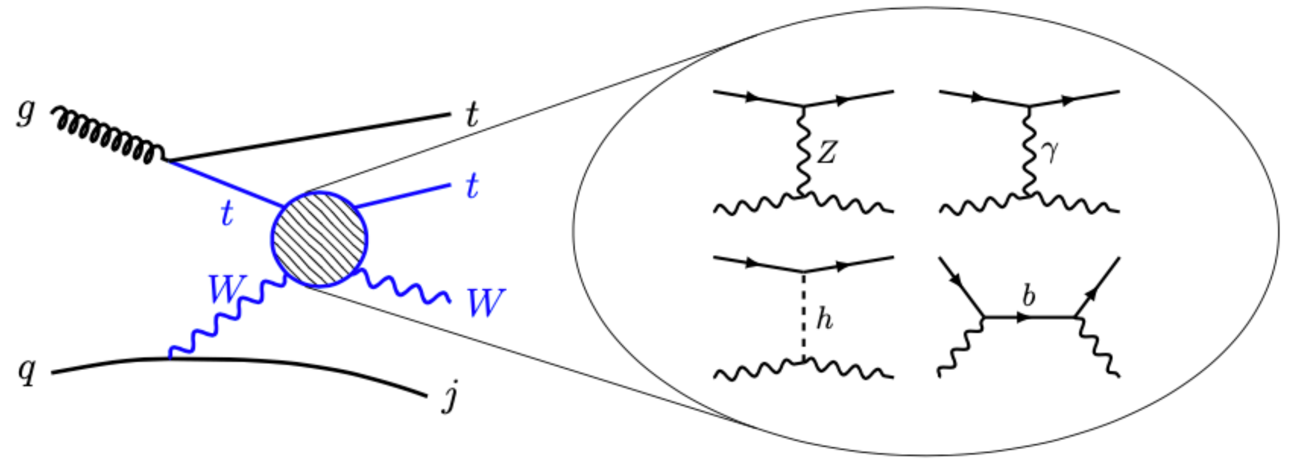
$\sim 10\,\%$ at the LHC, due to the opening of $tW \to tW$ scattering diagrams

[Frederix, Pagani, Zaro (2017)]

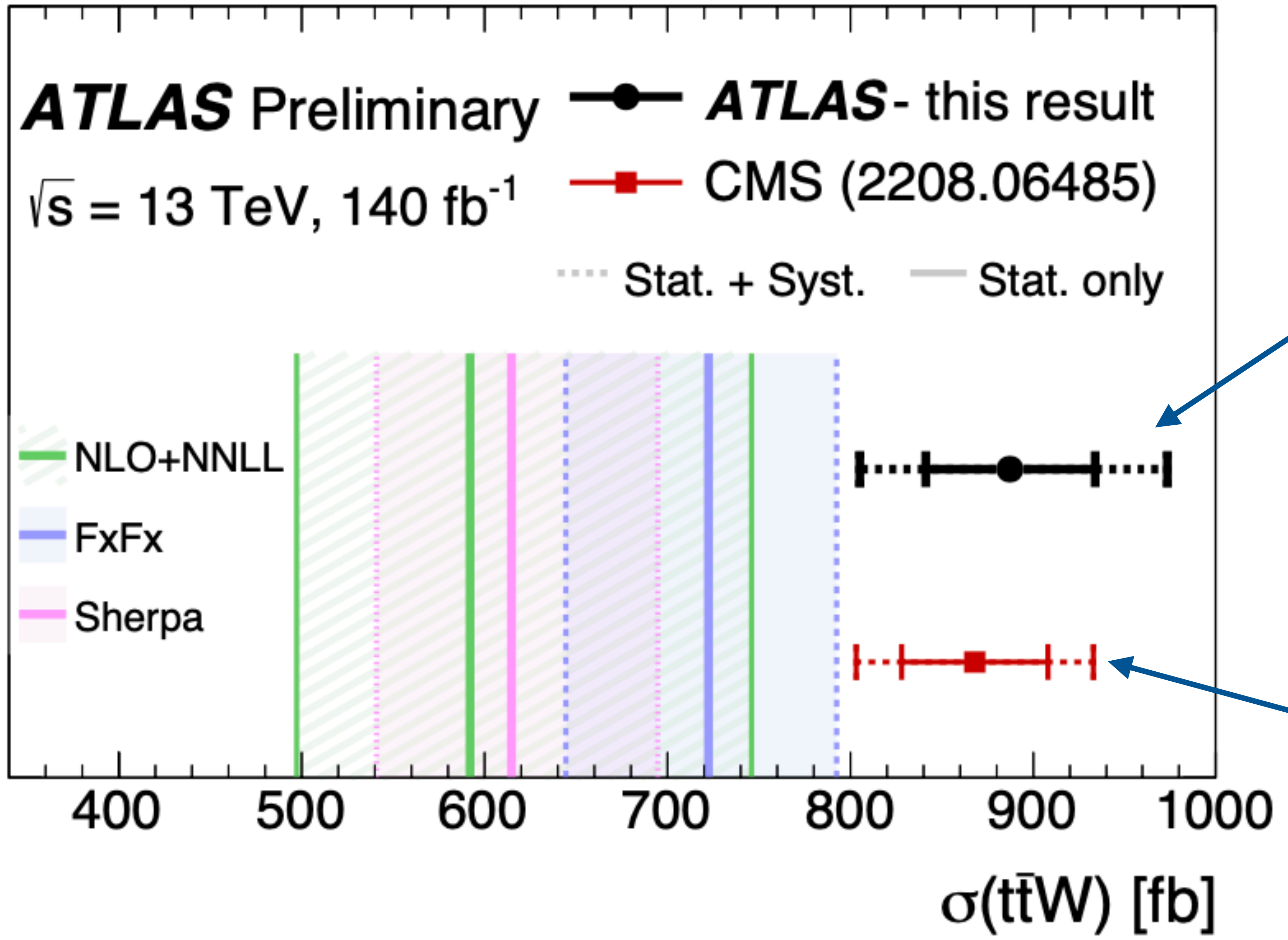


Introduction: $t\bar{t}W$ production

State of the art : experimental measurements

- measurements by ATLAS and CMS at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV → rates consistently higher compared to the SM prediction
- discrepancy confirmed also by indirect measurements of $t\bar{t}W$ in the context of $t\bar{t}H$ and $t\bar{t}t\bar{t}$ analyses
- most recent measurements, based on an integrated luminosity of 140 fb^{-1}, confirmed this picture

slight excess at 1-2 σ level



$$\sigma(t\bar{t}W^+) = 585\ ^{+35}_{-34}\ (\text{stat.})\ ^{+47}_{-44}\ (\text{syst.}) = 585\ ^{+58}_{-55}\ (\text{tot.})\ \text{fb}$$

$$\sigma(t\bar{t}W^-) = 301\ ^{+28}_{-27}\ (\text{stat.})\ ^{+35}_{-31}\ (\text{syst.}) = 301\ ^{+45}_{-41}\ (\text{tot.})\ \text{fb}$$

[ATLAS-CONF-2023-019]

$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb
$\sigma_{t\bar{t}W+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb
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[CMS: arXiv 2208.06485]

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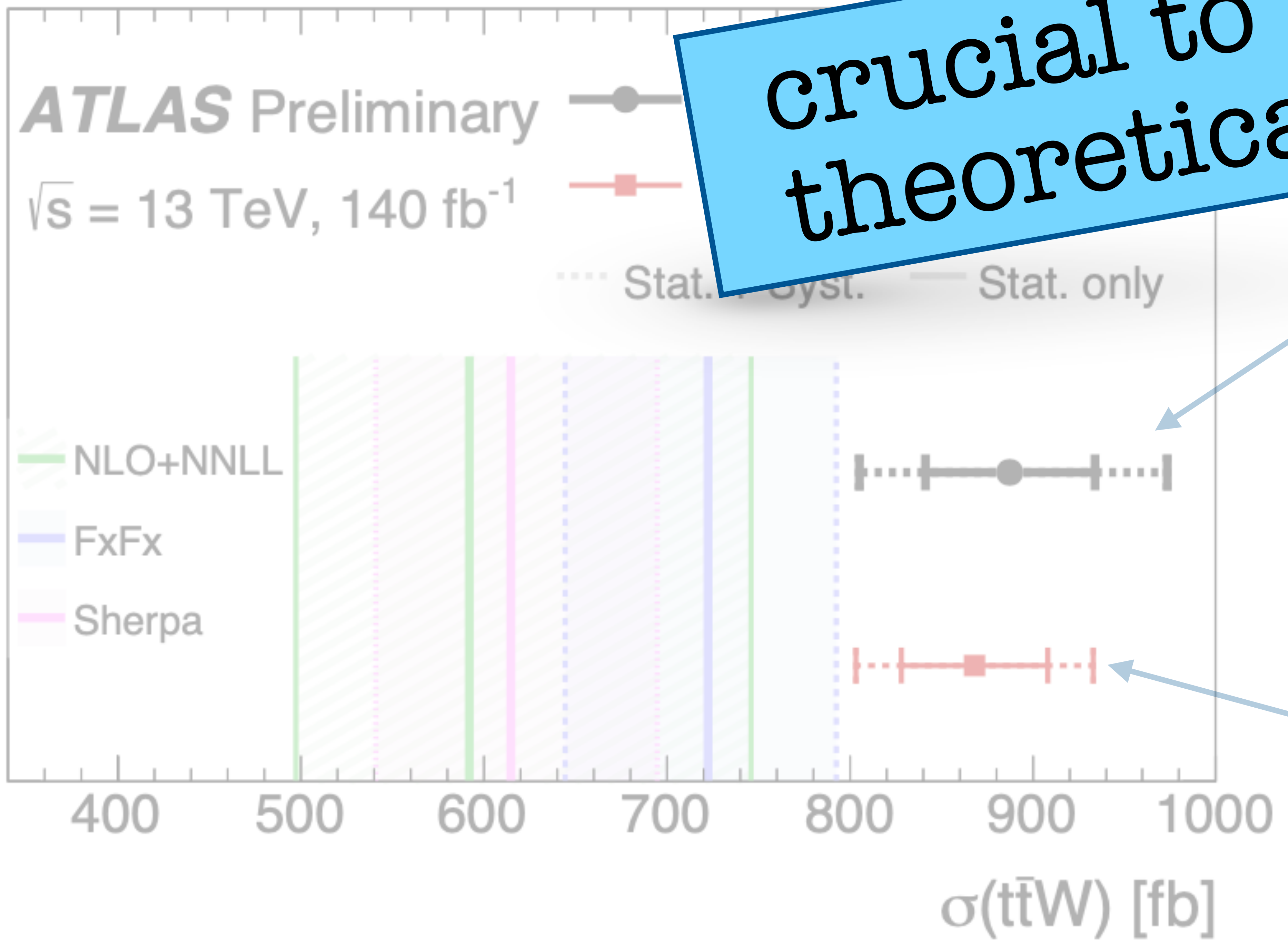
… ght excess at 1-2 σ level

crucial to rely on precise theoretical predictions!!



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State of the art : theoretical predictions

- ☑ **NLO QCD** corrections (*on-shell top quarks*) [Badger, Campbell, Ellis (2010-2012)]
- ☑ **NLO QCD + EW** corrections (*on-shell top quarks and W*) [Frixione, Hirschi, Pagani, Shao, Zaro (2015)]
- ☑ inclusion of **soft gluon resummation at NNLL** [Broggio et al. (2016)] [Kulesza et al. (2019)]
- ☑ **NLO QCD** corrections (*full off-shell process, three charged lepton signature*) [Bevilacqua et al. (2020)] [Denner, Pellicciolі (2020)]
- ☑ combined **NLO QCD + EW** corrections (*full off-shell process, three charged lepton signature)* [Denner, Pellicciolі (2021)]
- ☑ current experimental measurements are compared with **NLO QCD + EW** (*on-shell)* predictions supplemented with **multi-jet merging** [Frederix, Tsinikos (2021)]

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still affected by relatively large uncertainties

- **complete NNLO QCD + NLO EW** (*on-shell)* with approximated two-loop amplitudes in this talk!

The framework: q_T -subtraction

[Catani, Grazzini (2007)]

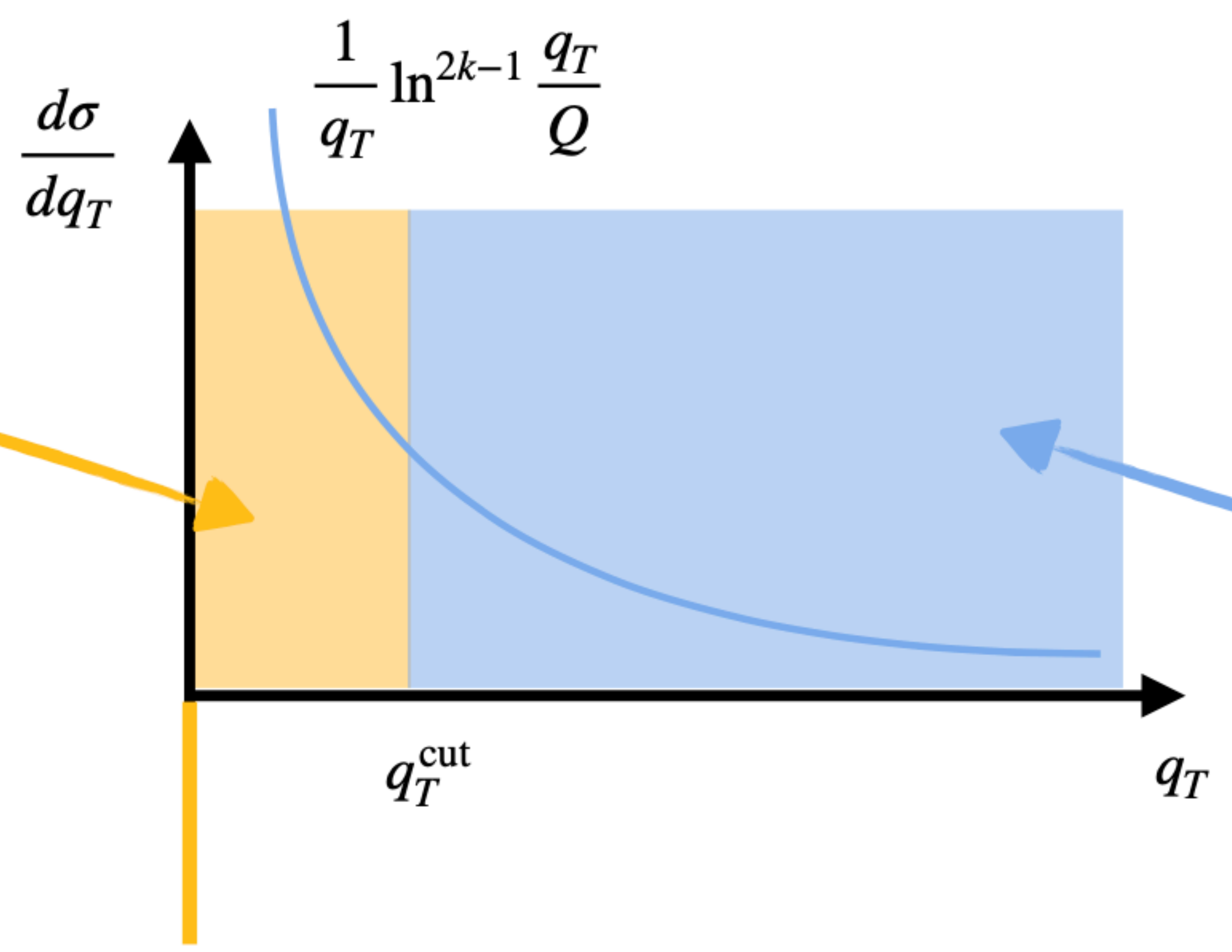
- cross section for the production of a triggered final state at N^kLO (in our case the triggered final state is $t\bar{t}W$)

crucial to keep the mass of the heavy quark

all emissions are unresolved

we can exploit the QCD factorisation of the matrix elements in the singular soft and/or collinear limits

ingredients from q_T - resummation



1 emission is always resolved

the complexity of the calculation is reduced by 1 order

logarithmic IR sensitivity to the cut

$$d\sigma_{N^kLO} = \mathcal{H}_{N^kLO} \otimes d\sigma_{LO} + [d\sigma^R_{N^{k-1}LO} - d\sigma^{CT}_{N^kLO}]_{q_t > q_t^{\rm cut}} + \mathcal{O}((q_t^{\rm cut})^p)$$

The framework: q_T -subtraction [Catani, Grazzini (2007)]

- master formula at NNLO

$$d\sigma_{NNLO} = \mathscr{H}_{NNLO} \otimes d\sigma_{LO} + [d\sigma^{R}_{NLO} - d\sigma^{CT}_{NNLO}]_{q_t > q_t^{\text{cut}}} + \mathcal{O}((q_t^{\text{cut}})^p)$$

- ☑ the required matrix elements can be computed with automated tools like `OpenLoops2`
- ☑ the remaining NLO-type singularities can be removed by applying a local subtraction method

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[Catani, Devoto, Grazzini, Mazzitelli (2023)]

- ☑ non trivial ingredient: **two-loop soft function** for an arbitrary kinematics of the heavy quarks [Devoto, Mazzitelli (in preparation)]
- ☑ all ingredients are known except for the **two-loop virtual amplitudes** contributing to the the hard-collinear coefficient

$$\mathscr{H}_{NNLO} = H^{(2)}\delta(1-z_1)\delta(1-z_2) + \delta\mathscr{H}^{(2)}(z_1, z_2)$$

where $$H^{(2)} = \left.\frac{2\Re(\mathscr{M}^{(2)}_{fin}(\mu_{IR}, \mu_R)\mathscr{M}^{(0)*})}{|\mathscr{M}^{(0)}|^2}\right|_{\mu_R=Q}$$

Remark: analogous definition for the hard-collinear coefficient at NLO $$H^{(1)} = \left.\frac{2\Re(\mathscr{M}^{(1)}_{fin}(\mu_{IR}, \mu_R)\mathscr{M}^{(0)*})}{|\mathscr{M}^{(0)}|^2}\right|_{\mu_R=Q}$$

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→ main bottleneck: $2 \to 3$ two-loop amplitudes with internal and external massive legs are currently out of reach!

The framework: q_T -subtraction

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crucial to find one (or more) reasonable approximation

Two-loop amplitudes: soft approximation

soft approximation in a nutshell:

bottleneck: the two-loop amplitudes are at the frontier of the current techniques

solution: development of a soft boson approximation

- for a **soft scalar Higgs** radiated off a heavy quark i, we have that

$$\lim_{k\to 0} \mathcal{M}(\{p_i\},k) = F(\alpha_s(\mu_R); m/\mu_R)\, J^{(0)}(k)\, \mathcal{M}(\{p_i\})$$

- overall normalisation, finite, gauge-independent and perturbatively computable

- **effective coupling** accounting for effects due to the renormalisation of the heavy quark mass and wave function

$$J^{(0)}(k) = \sum_i \frac{m}{v} \frac{m}{p_i \cdot k}$$

renormalised mass of the heavy quark

we assume that all heavy quarks involved in the process have the same mass

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- for a **soft gauge W boson** radiated off a massless quark i, we have that

$$\lim_{k\to 0} \mathcal{M}(\{p_i\},k) = J^{(0)\mu}(k) \cdot \epsilon_\mu(k)\, \mathcal{M}(\{p_i\})$$

valid at all perturbative orders

$$J^{(0)\mu}(k) = \frac{g_W}{\sqrt{2}} \sum_i \left(\sigma_i \frac{p_i^\mu}{p_i \cdot k} \right) \frac{1-\gamma_5}{2}$$

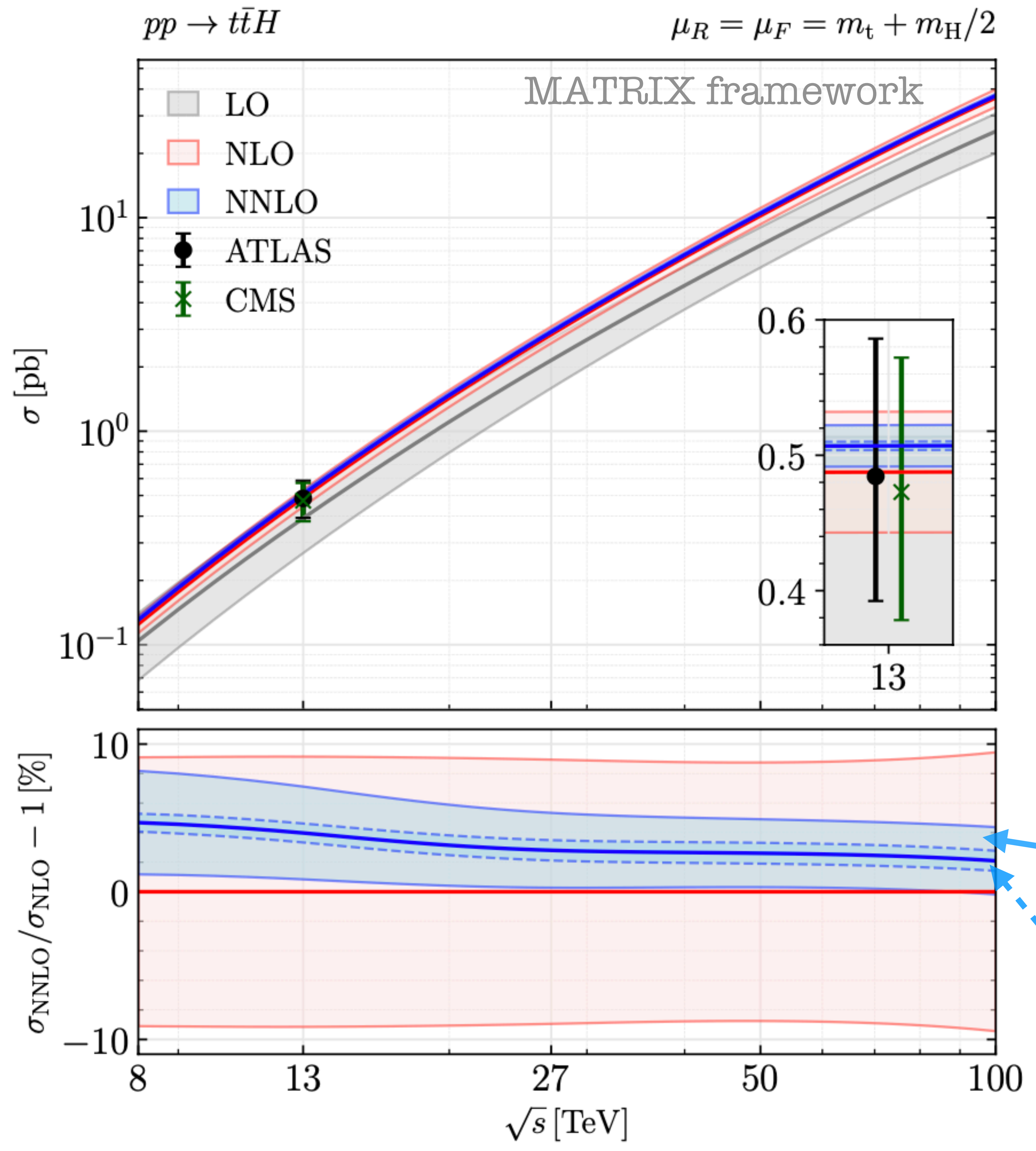
$$\sigma_i = \begin{cases} +1 & \text{incoming } \bar{q}\text{, outgoing } q \\ -1 & \text{incoming } q\text{, outgoing } \bar{q} \end{cases}$$

main differences between Higgs and W:
- scalar vs vectorial current
- massless vs massive emitters
- no renormalisation effects
- selection of the polarisation state of the emitter

Soft approximation in $t\bar{t}H$

[Catani et al. (2022)]

setup: NNLO NNPDF31, $m_H = 125GeV$, $m_t = 173.3GeV$, $\mu_R = \mu_F = (2m_t + m_H)/2$



- **all** NNLO ingredients are computed **exactly** except for the double virtual contribution
- at NNLO, the hard contribution is about **1%** of the LO cross section in gg and **2-3%** in $q\bar{q}$
- the observed deviation at NLO is used to estimate the uncertainty at NNLO
- it is clear that the quality of the final result depends on the size of the contribution we are approximating

FINAL UNCERTAINTY:

$\pm 0.6\,\%$ on σ_{NNLO} , $\pm 15\,\%$ on $\Delta\sigma_{NNLO}$

symmetrised 7-point scale variation

systematic + soft-approximation

Two-loop amplitudes: massification

massification in a nutshell:

bottleneck: the two-loop amplitudes are at the frontier of the current techniques
solution: exploit the massification of available massless two-loop 5-point amplitudes

- the idea is to exploit the leading-colour massless two-loop 5-point amplitudes for $q\bar{q}' \to WQ\bar{Q}$ production [Abreu at al. (2021)] [Badger at al. (2021)]
- we apply the **massification** technique [Moch, Mitov (2007)] [Becher, Melnikov (2007)] to reconstruct the corresponding massive amplitudes up to power corrections $m_Q/Q \ll 1$
- massification relies on the factorisation properties of QCD amplitudes (into jet, hard and soft functions)
- **basic idea**: the mass acts as a physical regulator of collinear singularities

$1/\epsilon$ poles are traded into $\log m_Q$

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- **master formula**:

$$\mathcal{M}^{(m_Q)}(\{p_i\};\mu,\epsilon) = Z_{[q]}^{(m_Q|0)}(\alpha_s(\mu), m_Q/\mu, \epsilon)\,\mathcal{M}^{(m_Q=0)}(\{p_i\};\mu,\epsilon) + \mathcal{O}(m_Q^2/Q^2)$$

- universal factor, perturbatively computable
- ratio between massive and massless quark form factors

Massification in $Wb\bar{b}$

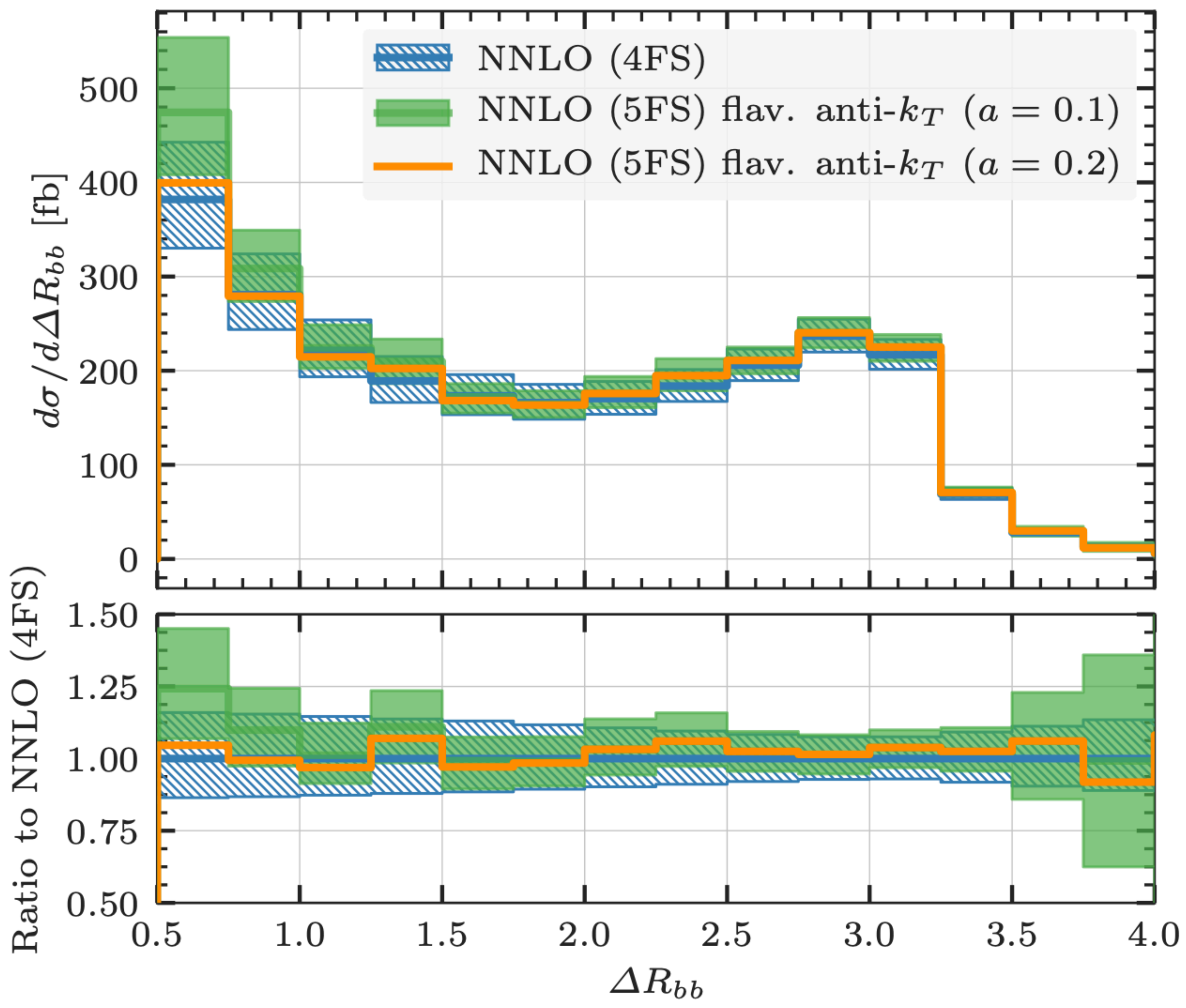
[Buonocore et al. (2022)]

[CMS: arXiv 1608.07561]

setup: NNLO NNPDF31 4F , $\sqrt{s} = 8\,TeV$, $\mu_R = \mu_F = E_T(l\nu) + p_T(b_1) + p_T(b_2)$

$p_{T,l} > 30\,GeV \;\; |\eta_l| < 2.1$, $p_{T,b} > 25\,GeV \;\; |\eta_l| < 2.4$, $p_{T,j} > 25\,GeV \;\; |\eta_l| < 2.4$

- **all** NNLO ingredients are computed **exactly** except for the double virtual contribution
- comparison against the 5F massless computation [Poncelet et al. (2022)]
  - overall **good agreement** within the scale uncertainties
  - the uncertainties due to variation of $m_b \in [4.2, 4.92]\,GeV$ are at **2%** level (smaller than the ones due to the variation of a)
- **reliability** of the procedure: the discrepancy between the exact and massified virtual contribution @NLO is only **3%** of the NLO correction



How to deal with $Wt\bar{t}$?

- good news! we have two rather different and complementary approximations of the exact two-loop virtual amplitudes
- **soft approximation**:
  - it works nicely in the case of $t\bar{t}H$, mainly due to the smallness of the approximated $H^{(2)}$ contribution
  - formally it is valid in the limit $E_W \to 0,\ m_W \ll m_t$ (which is not true for a physical W boson …)

$$\mathcal{M}_{Wt\bar{t}}(\{p_i\}, p_W; \mu, \epsilon) = J^{(0)\mu}(p_W) \cdot \epsilon_\mu(p_W)\, \mathcal{M}_{t\bar{t}}(\{p_i\}; \mu, \epsilon) + \mathcal{O}(m_W/m_t, E_W/Q_{t\bar{t}})$$

[Bärnreuther, Czakon, Fiedler (2013)]

- **massification**:
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[Abreu at al. (2021)]

how do these approximations perform for $Wt\bar{t}$?

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$$\mathcal{M}_{Wt\bar{t}}(\{p_i\}, p_W; \mu, \epsilon) = J^{(0)} \ldots (m_W/m_t, E_W/Q_{t\bar{t}})$$

… (2013)]

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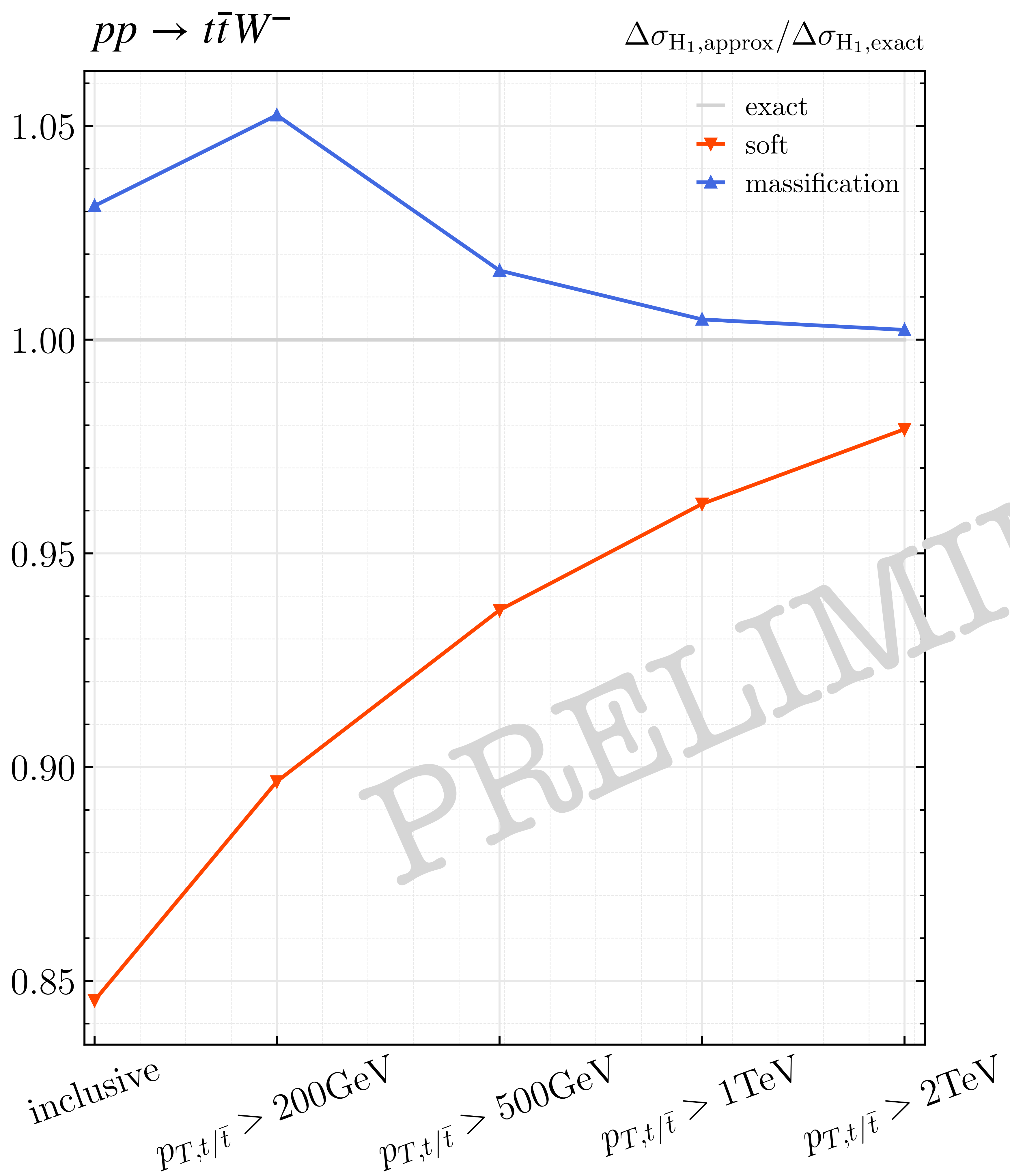
[Abreu at al. (2021)]

how do these approximations perform for $Wt\bar{t}$?

we will try to answer this question in the following !!

Preliminary results: validation @NLO

setup: NNLO LUXPDF4LHC15, $\sqrt{s} = 13\,TeV$, $m_W = 80.385 GeV$, $m_t = 173.2 GeV$, $\mu_R = \mu_F = (2m_t + m_W)/2$

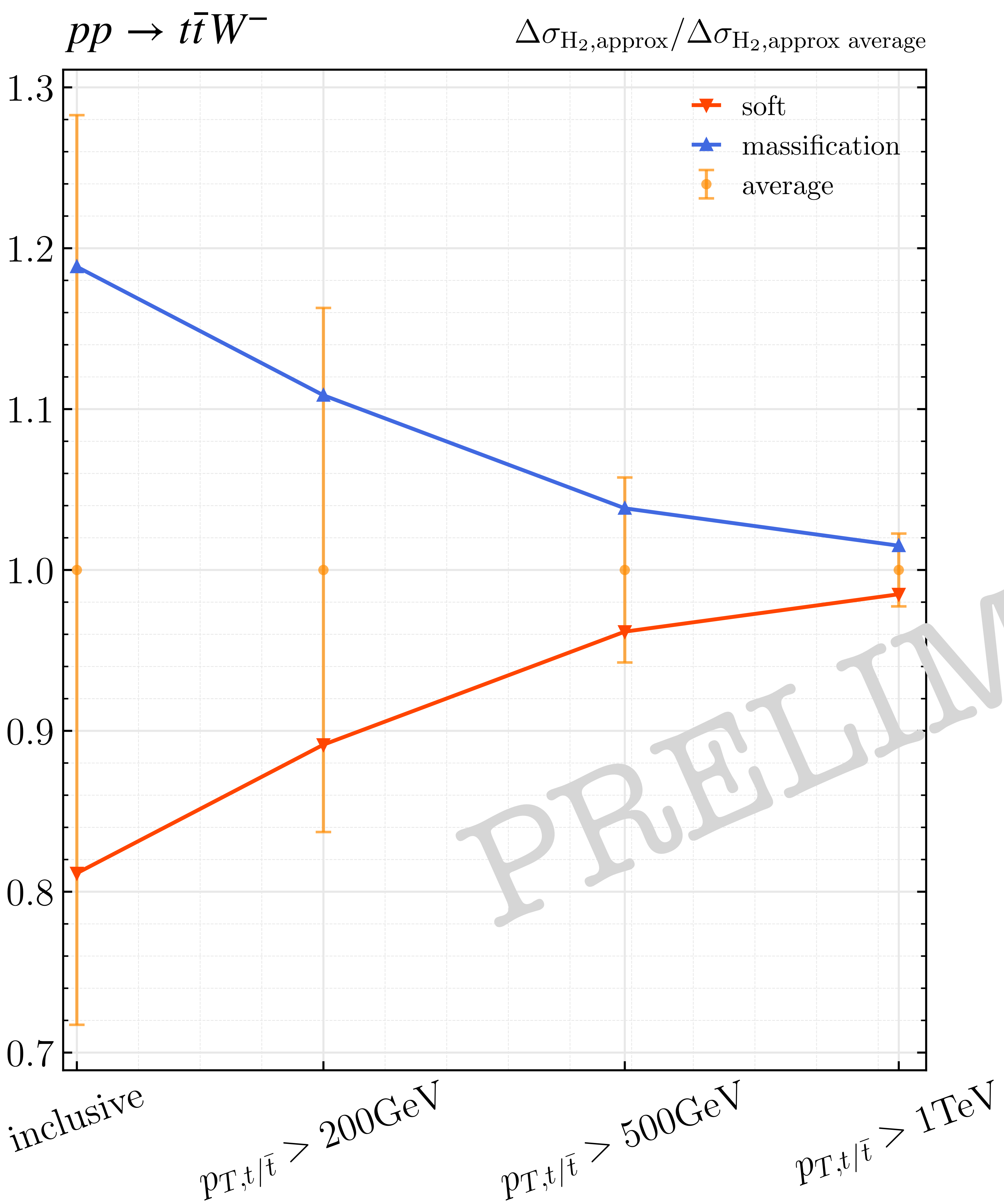


$\Delta\sigma^{H_1}_{\mathrm{NLO}}$ [fb]	exact	soft	massification
inclusive	52.6	$44.47^{+3.5}_{-3.5}$	$54.25^{+4.3}_{-4.4}$
$p_T > 200$ GeV	14.745	$13.22^{+0.74}_{-0.73}$	$15.519^{+0.12}_{-0.13}$
$p_T > 500$ GeV	1.5162	$1.42^{+0.04}_{-0.04}$	$1.541^{+0.0008}_{-0.0008}$
$p_T > 1000$ GeV	0.0823	$0.0792^{+0.08}_{-0.01}$	$0.0826^{+0.00002}_{-0.00006}$

- both approaches provide a **good quantitative approximation** of the exact virtual coefficient (discrepancy of 5-15%)
- the soft approximation tends to **undershoot** the exact result while the massification **overshoots** it
- clear **asymptotic behaviour** towards the exact result for high $p_{T,t}$ where both approximations are expected to perform better (faster convergence of the massification)

Preliminary results: performance @NNLO

setup: NNLO LUXPDF4LHC15, $\sqrt{s} = 13\,TeV$, $m_W = 80.385GeV$, $m_t = 173.2GeV$, $\mu_R = \mu_F = (2m_t + m_W)/2$



$\Delta\sigma^{H_2}_{NNLO}$ [fb]	soft	massification
inclusive	15.5 ± 4.8	22.7 ± 4.9
$p_T > 200$ GeV	4.72 ± 0.97	5.87 ± 0.89
$p_T > 500$ GeV	0.577 ± 0.073	0.623 ± 0.055
$p_T > 1000$ GeV	0.0359 ± 0.0028	0.037 ± 0.0016

- similar behaviour as @NLO: massified two-loop result systematically higher than the one from soft approximation
- **our best prediction**: average of the two approximated results
- **conservative uncertainty**: semi-difference multiplied by a tolerance factor 1.5
- the two-loop contribution turns out to be **6-7%** of the NNLO cross section (both for $t\bar{t}W^+$ and $t\bar{t}W^-$)

much better control than in $t\bar{t}H$

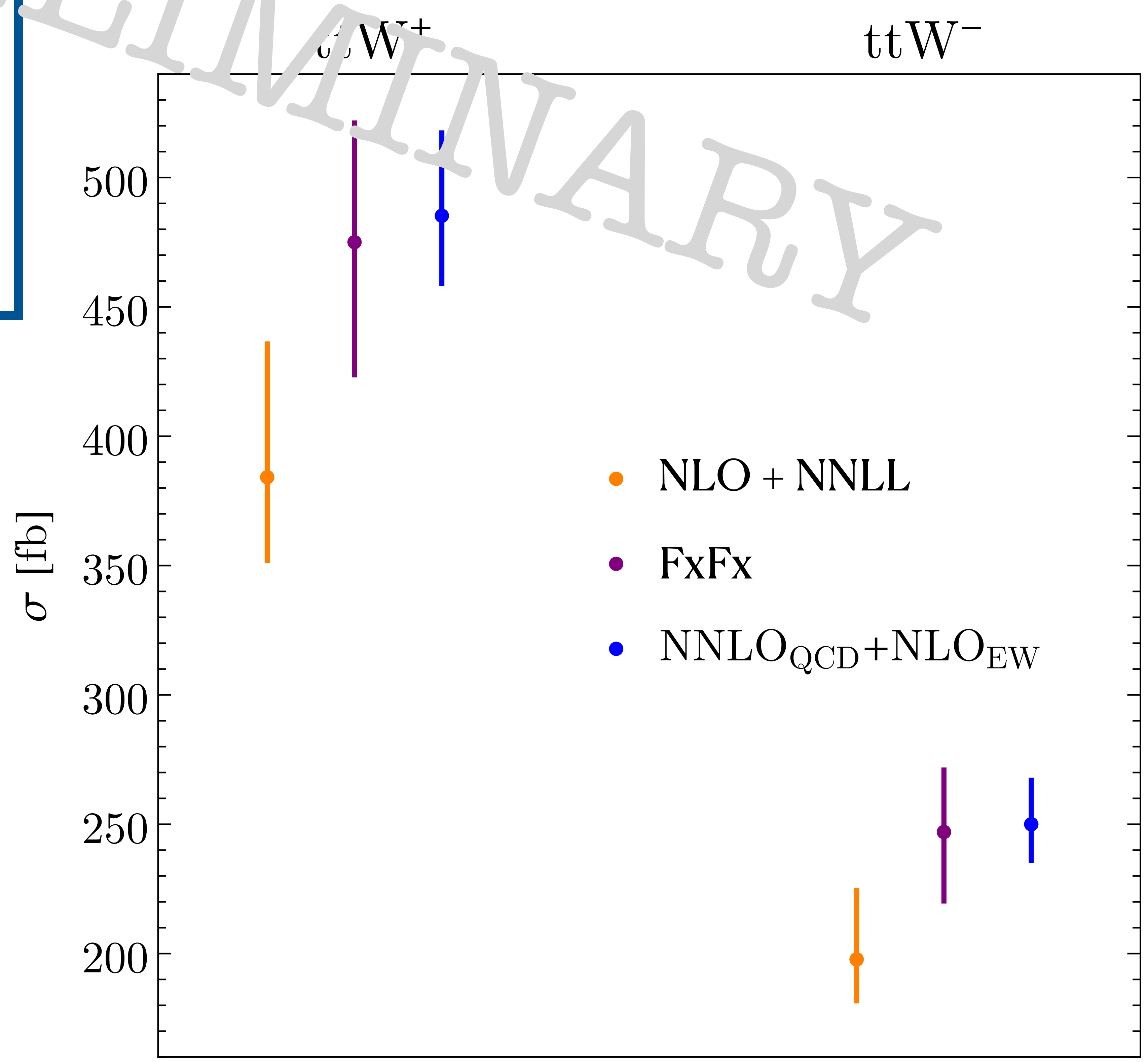
Preliminary results: total XS

setup: NNLO LUXPDF4LHC15, $\sqrt{s} = 13\,TeV$, $m_W = 80.385GeV$, $m_t = 173.2GeV$, $\mu_R = \mu_F = (2m_t + m_W)/2$

order	$\sigma_{t\bar{t}W^+}$ [fb]	$\sigma_{t\bar{t}W^-}$ [fb]	ratio
$\mathrm{LO_{QCD}}$	$272.4^{+25.1\%}_{-18.7\%}$	$136.5^{+25.0\%}_{-18.7\%}$	1.996
$\mathrm{NLO_{QCD}}$	$404.4^{+12.8\%}_{-11.5\%}$	$206.0^{+13.4\%}_{-11.8\%}$	1.963
$\mathrm{NNLO_{QCD}}$	$462.2^{+6.2\%}_{-4.8\%} \pm 2.3\%$	$237.0^{+6.7\%}_{-5.1\%} \pm 2.5\%$	1.950
$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$485.2^{+6.6\%}_{-5.4\%} \pm 2.2\%$	$250.0^{+6.8\%}_{-5.6\%} \pm 2.4\%$	1.941

systematic uncertainty due to the approximation

- @NLO QCD: large corrections (**+50%**)
- @NNLO QCD: moderate corrections (**+15%**)
- inclusion of **all subdominant LO and NLO** contributions ($\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha^4)$) labelled as NLO EW
- the ratio $\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$ is slightly reduced (very stable perturbative behaviour)



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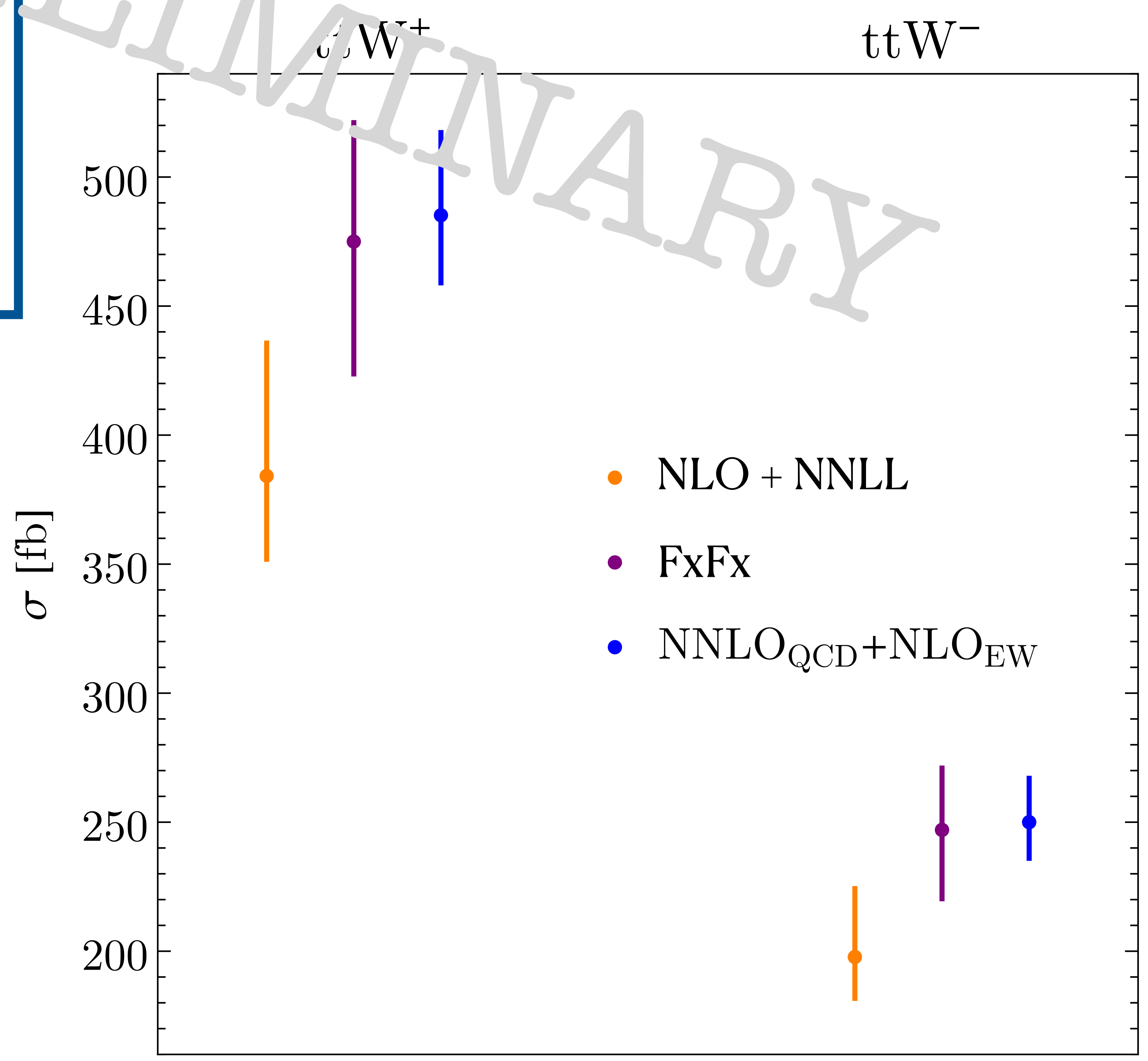

our result is fully compatible with FxFx with smaller perturbative uncertainties !!

Preliminary results: comparison with data

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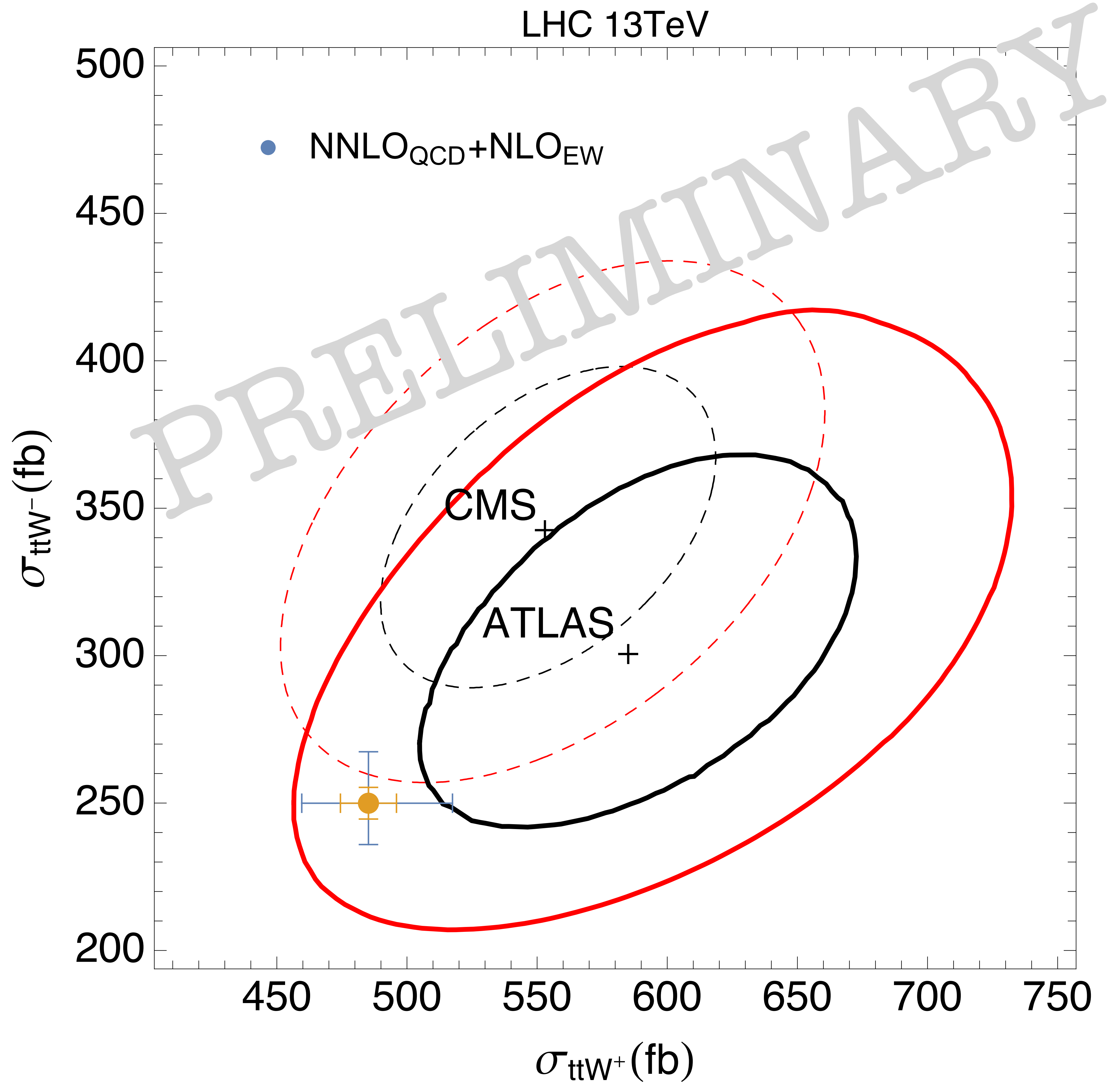

[ATLAS-CONF-2023-019]
[CMS: arXiv 2208.06485]

- comparison against the most recent ATLAS and CMS data:
  - the **agreement is at the** 1σ **and** 2σ **level** respectively
  - reduction of the perturbative scale uncertainties
  - systematic uncertainties due the two-loop approximation are under control and much smaller than the scale uncertainties

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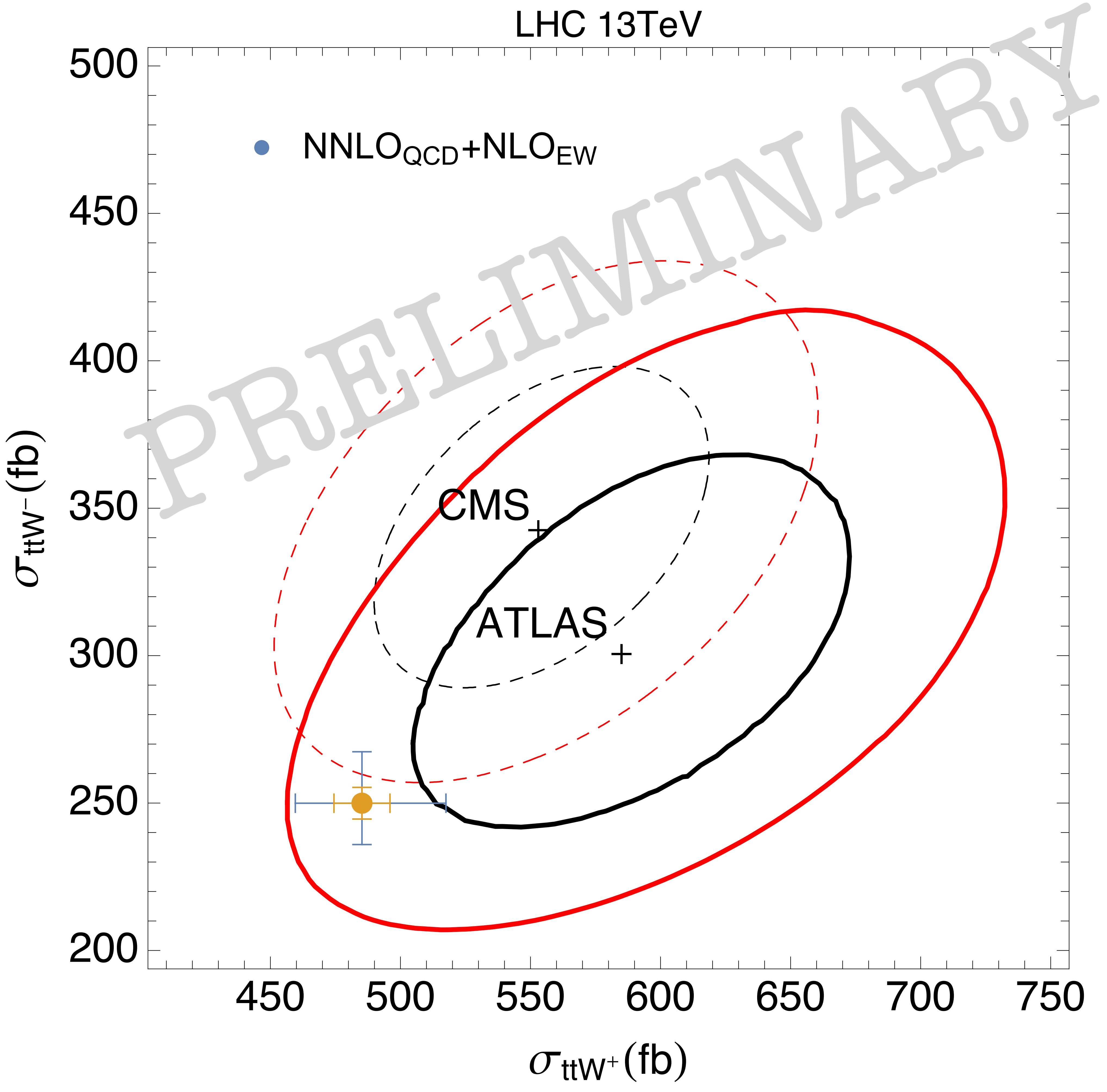

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take-home message:
two completely different approximations which lead to compatible results for the missing two-loop virtual contribution!!

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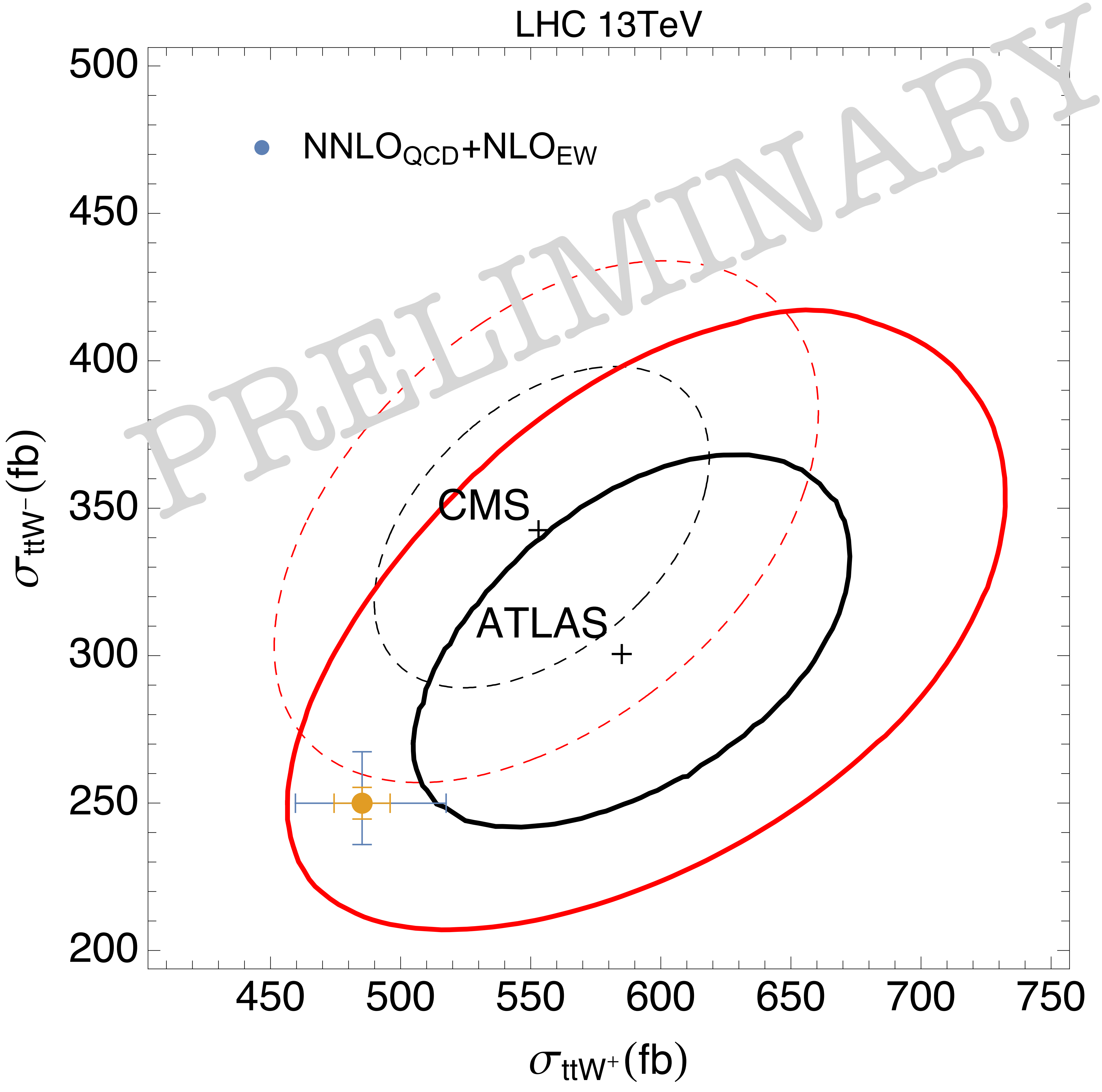

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STAY TUNED FOR UPDATES in the following weeks !!