Standard Model theory for the LHC: the present and the future

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Menu

- Highest perturbative orders
- Applications in Higgs-boson physics
- Applications in top-quark physics

Les Houches 2021: Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

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Abstract

Les Houches activities in 2021 were truncated due to the lack of an in-person component. However, given the rapid progress in the field, and the restart of the LHC, we wanted to continue the bi-yearly tradition of updating the standard model precision wishlist. If nothing else, this will keep us from having even more work to do at Les Houches 2023.

Current wishlist

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO^{(t)}_{QCD}}$ $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO^{(b,c)}_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg \to HZ}$	
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH + 2j$	$\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^{\pm}W^+W^-$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$

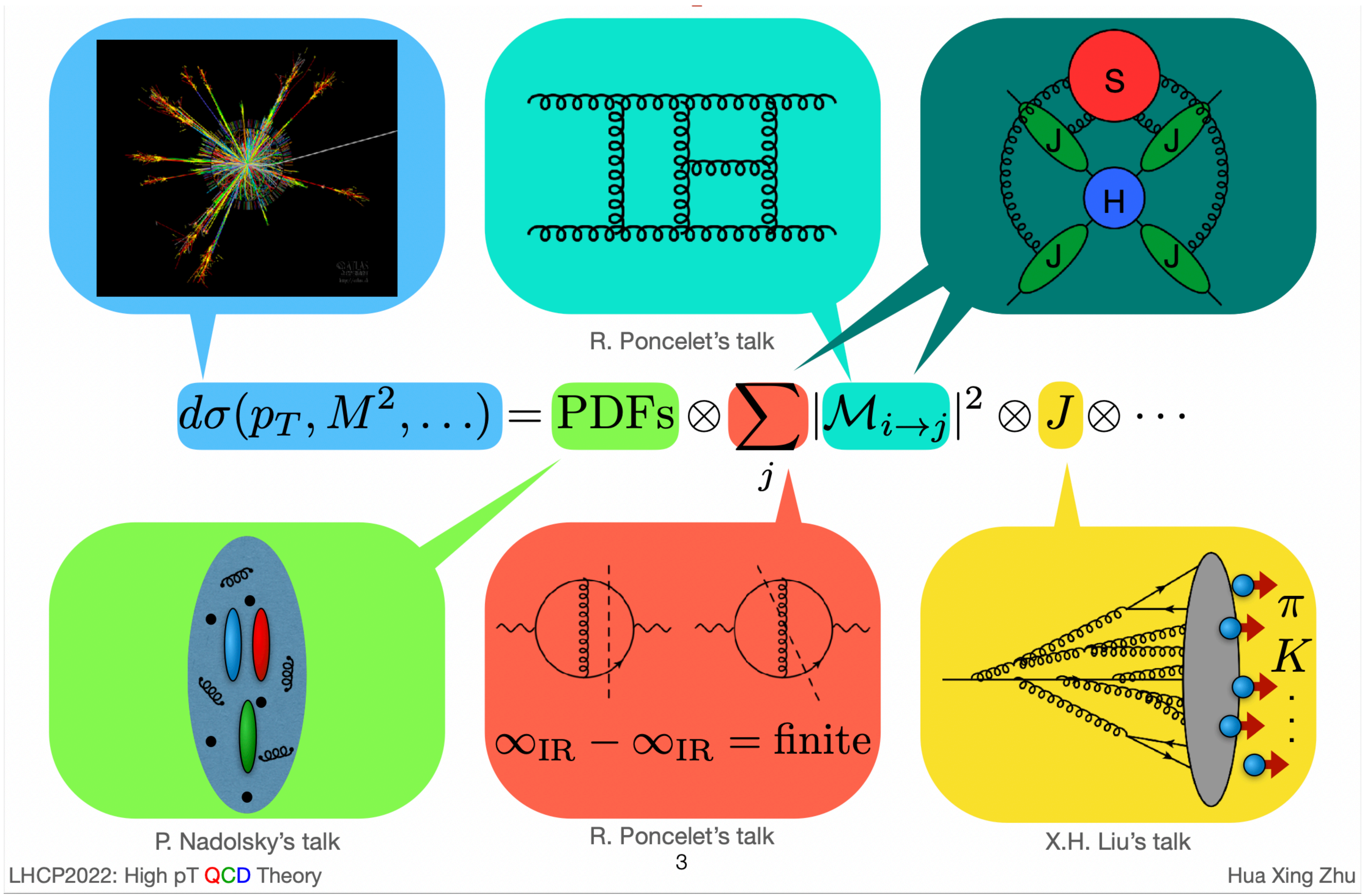
Current wishlist

process	known	desired
$pp \to t\bar{t}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell effects) $\mathrm{NNLO_{QCD}}$ (w/ decays)	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t} + j$	$\mathrm{NLO_{QCD}}$ (off-shell effects) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + 2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + V'$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + \gamma$	$\mathrm{NLO_{QCD}}$ (off-shell effects)	
$pp \to t\bar{t} + Z$	$\mathrm{NLO_{QCD}}$ (off-shell effects)	
$pp \to t\bar{t} + W$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell effects)	
$pp \to t/\bar{t}$	$\mathrm{NNLO_{QCD}}$*(w/ decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to tZj$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)
$pp \to t\bar{t}t\bar{t}$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell effects) $\mathrm{NNLO_{QCD}}$

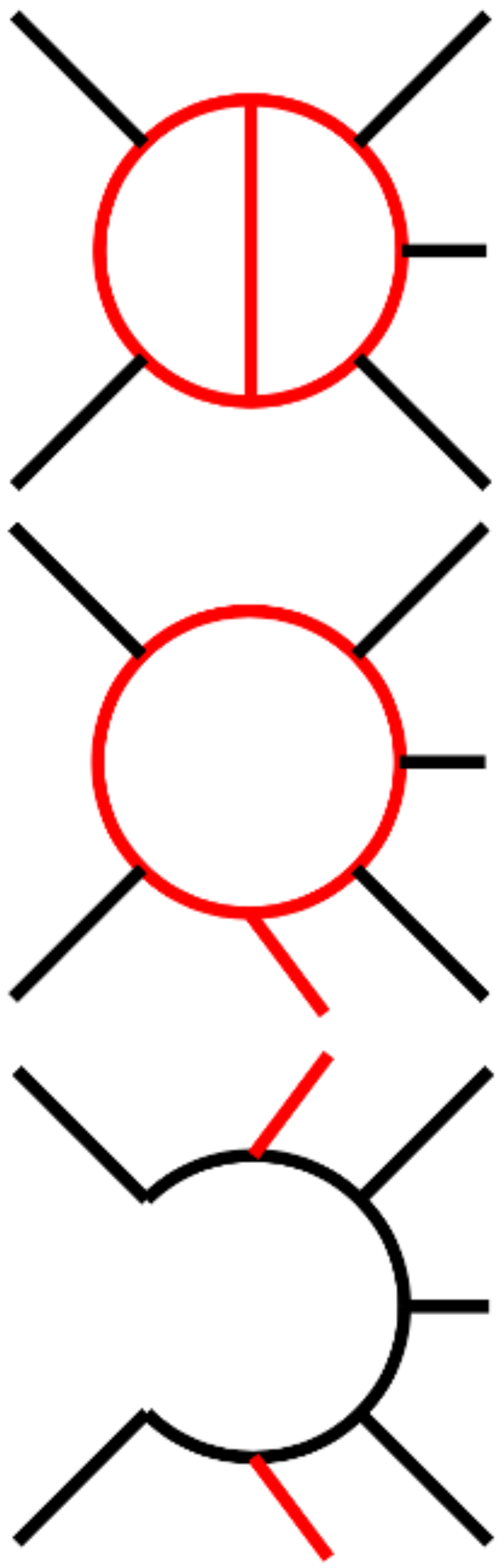
process	known	desired
$pp \to 2\,\mathrm{jets}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 3\,\mathrm{jets}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	

Precision frontier

Cross section from the theory POV



What you need for $2 \to 3$ at NNLO



2 → 3 Two-loop amplitudes:

- (Non-) planar 5 point massless 'pheno ready'
  [Chawdry'19'20'21,Abreu'20'21,Agarwal'21,Badger'21]
  fast progress in the last half year
  → triggered by efficient MI representation [Chicherin'20]
- 5 point with one external mass [Abreu'20,Syrrakos'20,Canko'20,Badger'21]

Many leg, IR stable one-loop amplitudes → OpenLoops [Buccioni'19]

Cross sections → Combination with real radiation

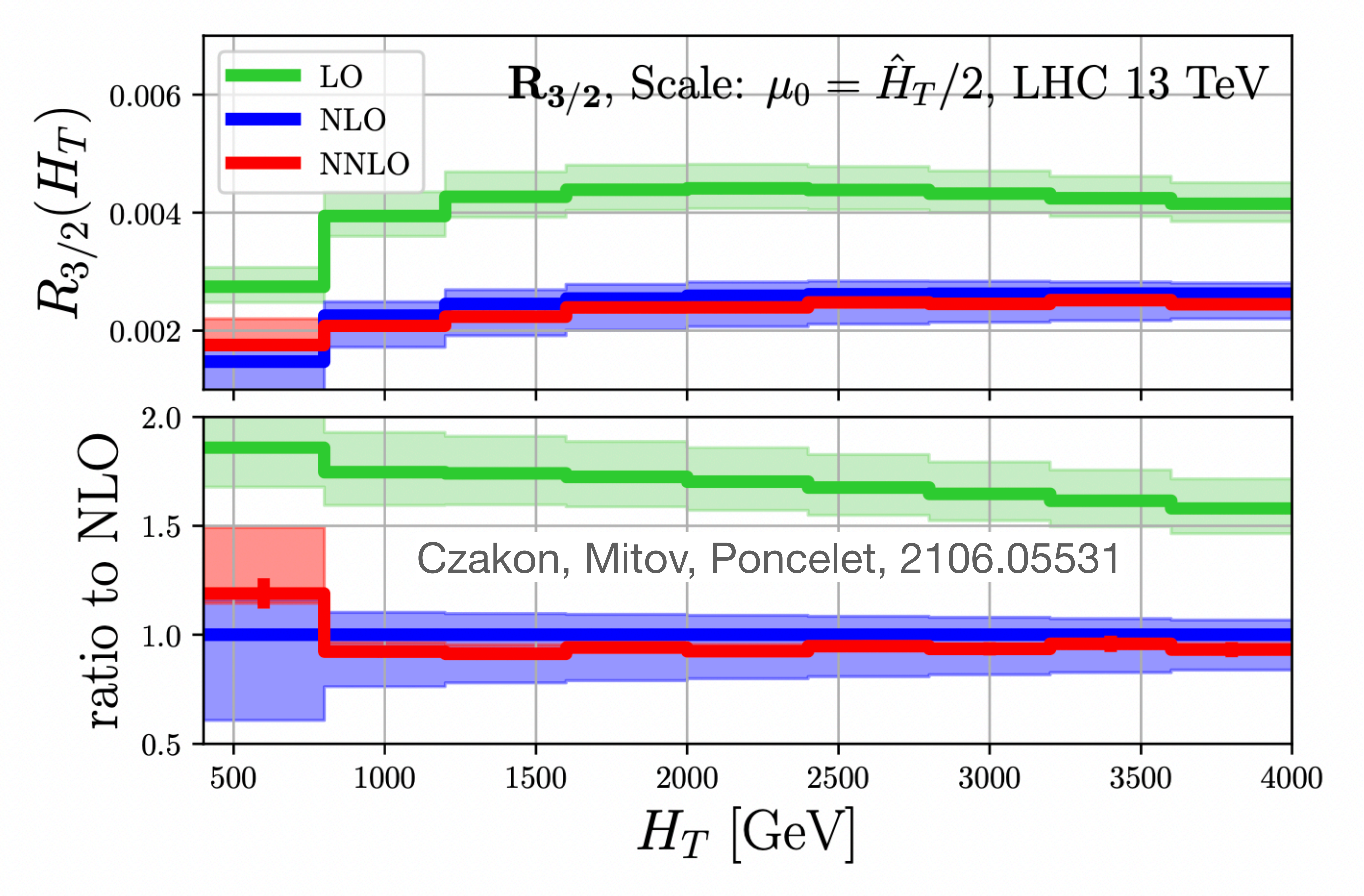
- Various NNLO subtraction schemes are available:
  qT-slicing [Catain'07], N-jettiness slicing [Gaunt'15/Boughezal'15], Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15], Projection [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Sector-improved residue subtraction [Czakon'10-'14,'19]

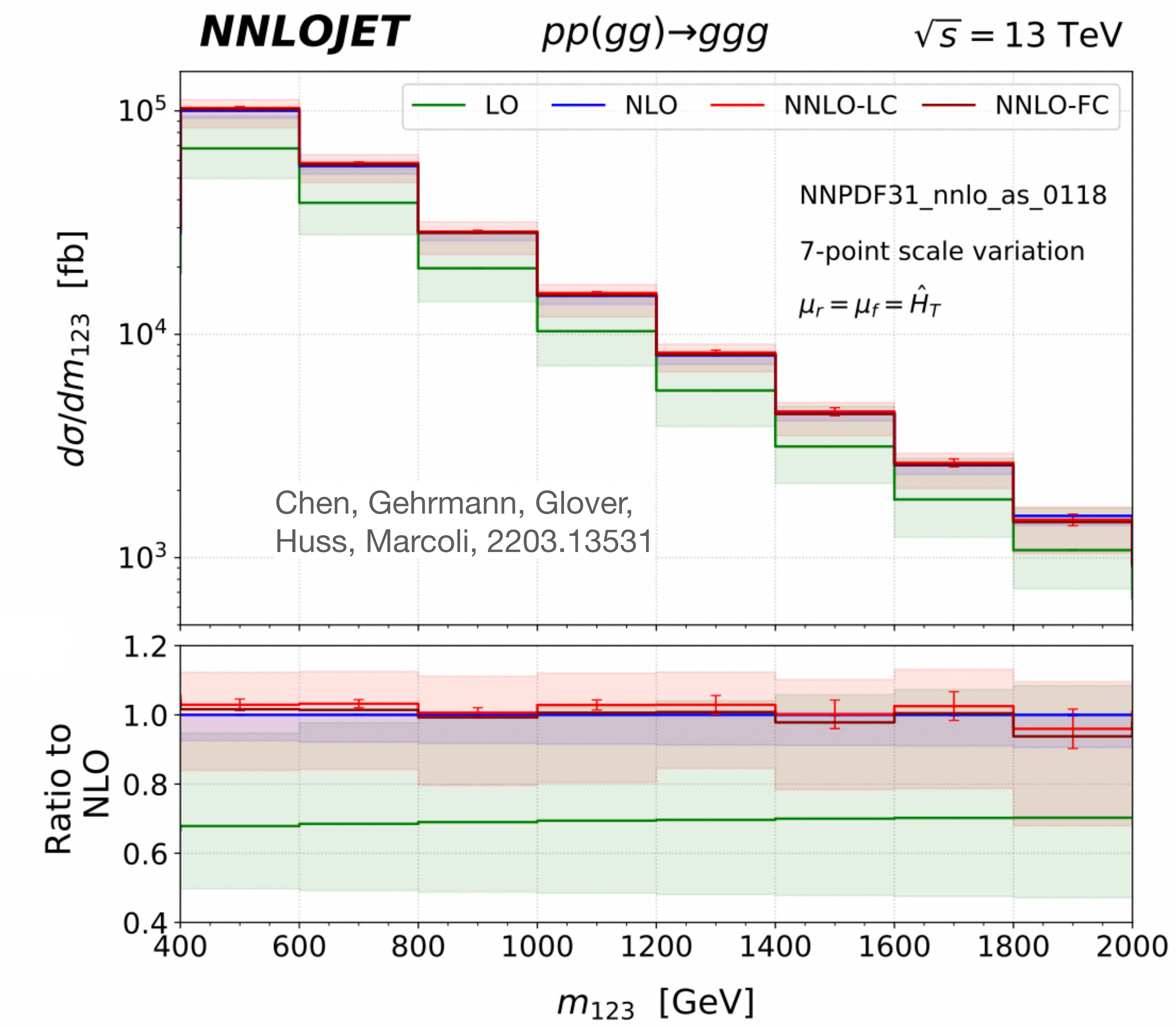
High-multiplicity processes at NNLO

- An impressive number of 2 to 3 processes calculated at NNLO in the past few years:
  - $pp \to 3$ jets   Czakon, Mitov, Poncelet; Chen, Gehrmann, Glover, Huss, Marcoli
  - $pp \to \gamma\gamma +$ jet   Chawdry, Czakon, Mitov, Poncelet; Badger, Gehrmann, Marcoli, Moddie
  - $pp \to \gamma\gamma\gamma$ Chawdry, Czakon, Mitov, Poncelet; Kallweit, Sotnikov, Wiesemann
  - $pp \to Wb\bar{b}$ Hartanto, Poncelet, Popescu, Zoia
- Remarkable progress in the past few years thanks to break-through calculations of two-loop five point amplitudes: master integral calculation (analytic or numerical) and efficient integral reduction. Very impressive community efforts!

Abreu, Agawal, Badger, Bern, Bohm, Bonetti, Bonnum-Hansen, Buccioni, Canko, Chawdry, Chicherin, Czakon, de Laurentis, Dixon, Dormans, Duhr, Febres Cordero, Gehrmann, Georgoudis, Georgoudis, Gluza, Guan, Hartanto, Heinrich, Heller, Henn, Hermann, Hidding, Ita, Jones, Kadja, Kardos, Klinkert, Kosher, Kraus, Kreer, Krys, Larsen, Liu, Lo Presti, Ma, Maitre, Marcoli, Mitov, Moddie, Moriello, Page, Panzer, Papadopoulos, Pascual, Peraro, Poncelet, Ruf, Schabinger, Schulze, Smirnov, Sotnikov, Syrrakos, Tancredi, Tommasini, Tschernow, von Manteuffel, Wang, Wasser, Weinzierl, Wever, Zeng, Zhang, Zoia, ...

Three-jet production at leading color





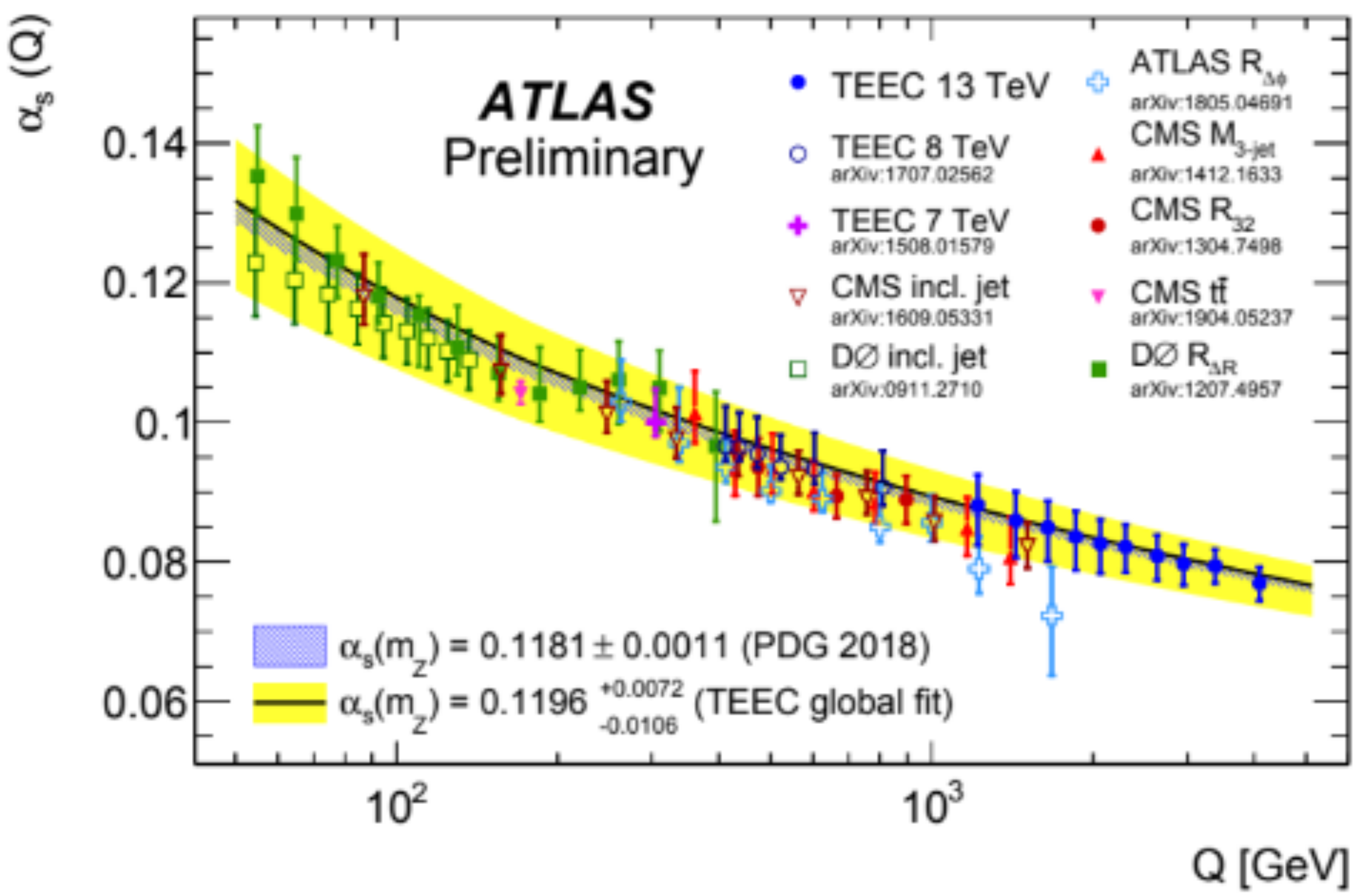
- Different subtraction schemes:
  sector-improved residue subtraction (left) v.s. antenna (right)
- Main bottleneck to full color is virtual two-loop amplitudes
- 3/2 jet ratio is important for α_s measurement
- NNLO stabilizes the ratio and smaller scale uncertainties
  How to better estimate scale uncertainties?
- Small corrections to triple jet invariant mass at NNLO

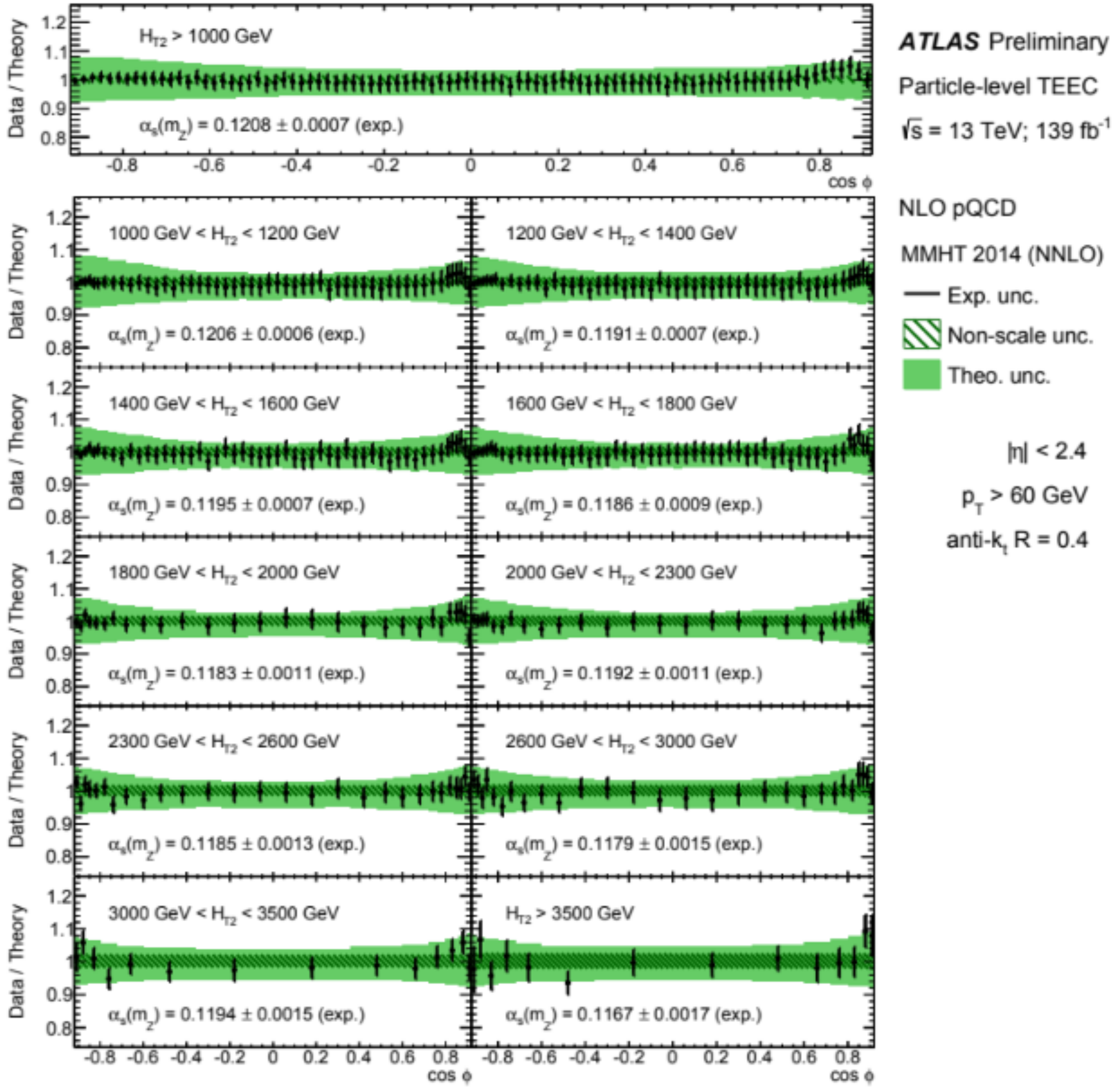
Three-jet production at leading color

Strong coupling measurements from event-shapes:
→ three jet is leading contribution
→ normalization through dijet rates

TEEC: Transverse Energy-Energy Correlation

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\perp,i}E^A_{\perp,j}}{\left(\sum_k E^A_{T,k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

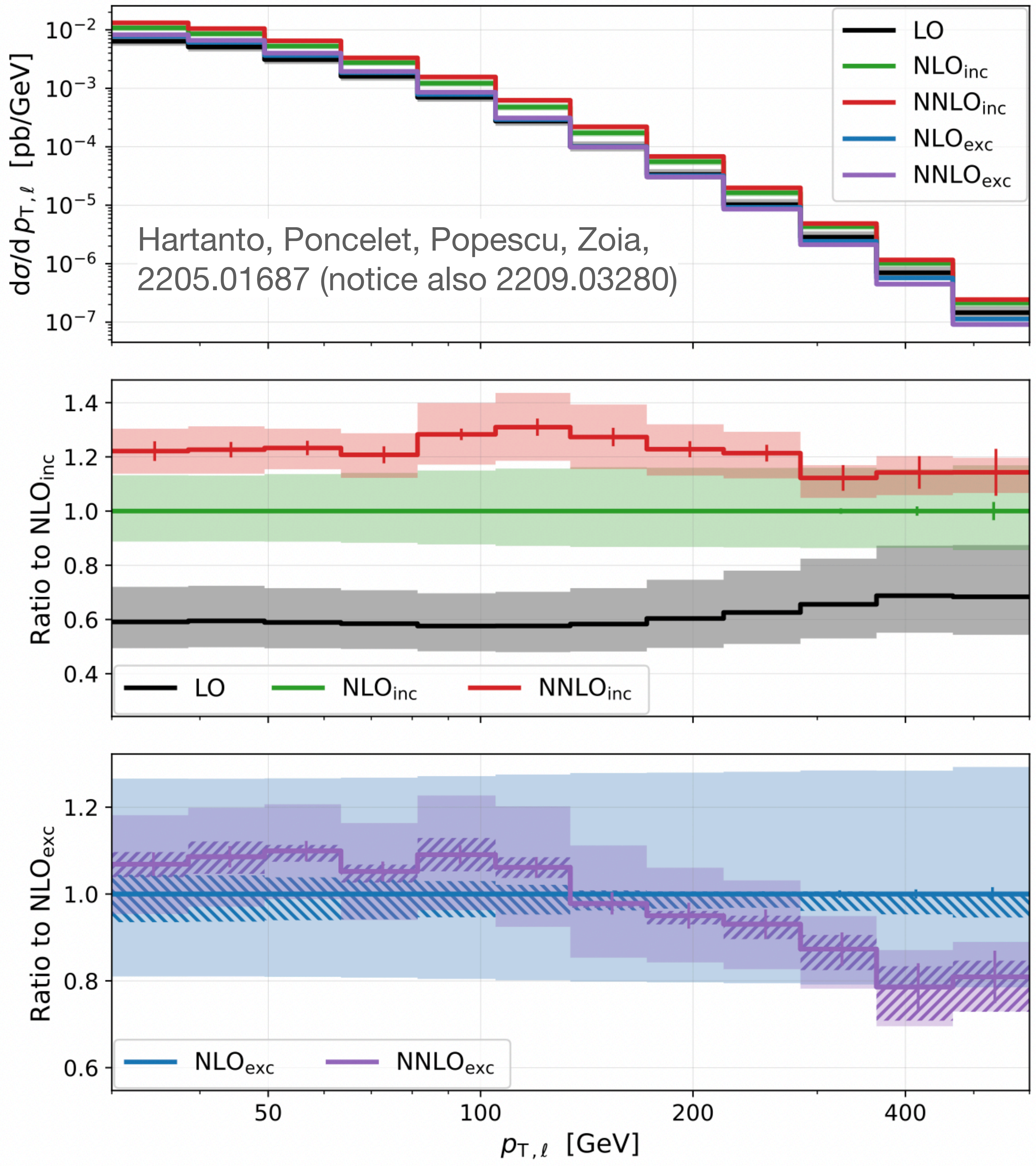




[ATLAS-CONF-2020-025]

$Wb\bar{b}$ production at leading color

- First NNLO corrections for a 1-mass 5 particle process
- Irreducible background to $pp \to WH$ and $pp \to bt$
- Test ground for b-quark scheme.
- Substantial contributions from two- loop virtual corrections: 5%(incl.) v.s. 10%(excl.)



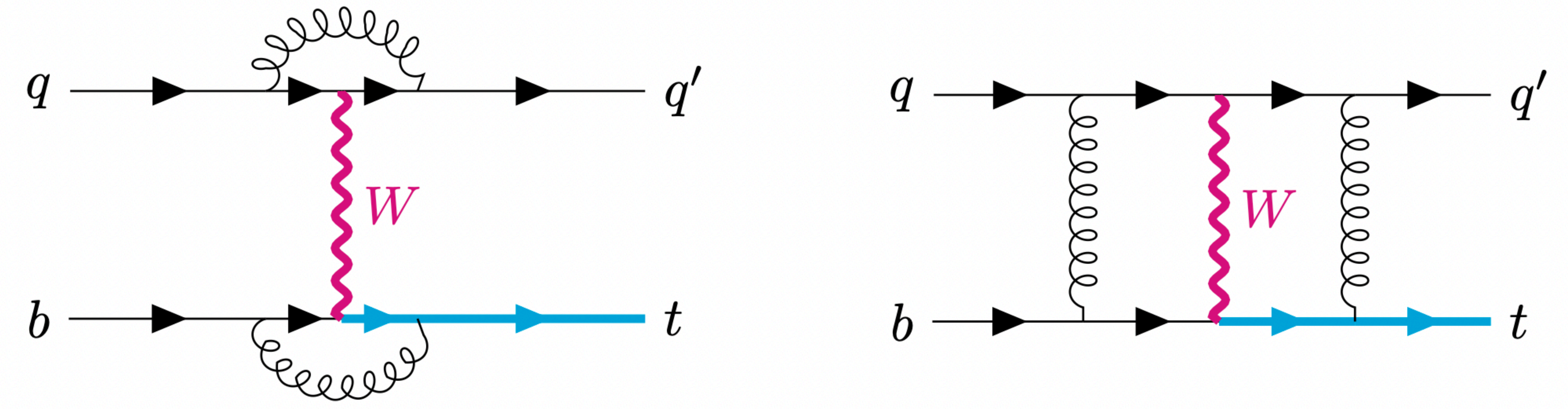
	at least 2 b-jet		exactly 2 b-jet	
	inclusive [fb]	$\mathcal{K}_{\mathrm{inc}}$	exclusive [fb]	$\mathcal{K}_{\mathrm{exc}}$
σ_{LO}	$213.2(1)^{+21.4\%}_{-16.1\%}$	-	$213.2(1)^{+21.4\%}_{-16.1\%}$	-
σ_{NLO}	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.7	$249.8(4)^{+3.9(+27)\%}_{-6.0(-19)\%}$	1.17
σ_{NNLO}	$445(5)^{+6.7\%}_{-7.0\%}$	1.23	$267(3)^{+1.8(+11)\%}_{-2.5(-11)\%}$	1.067

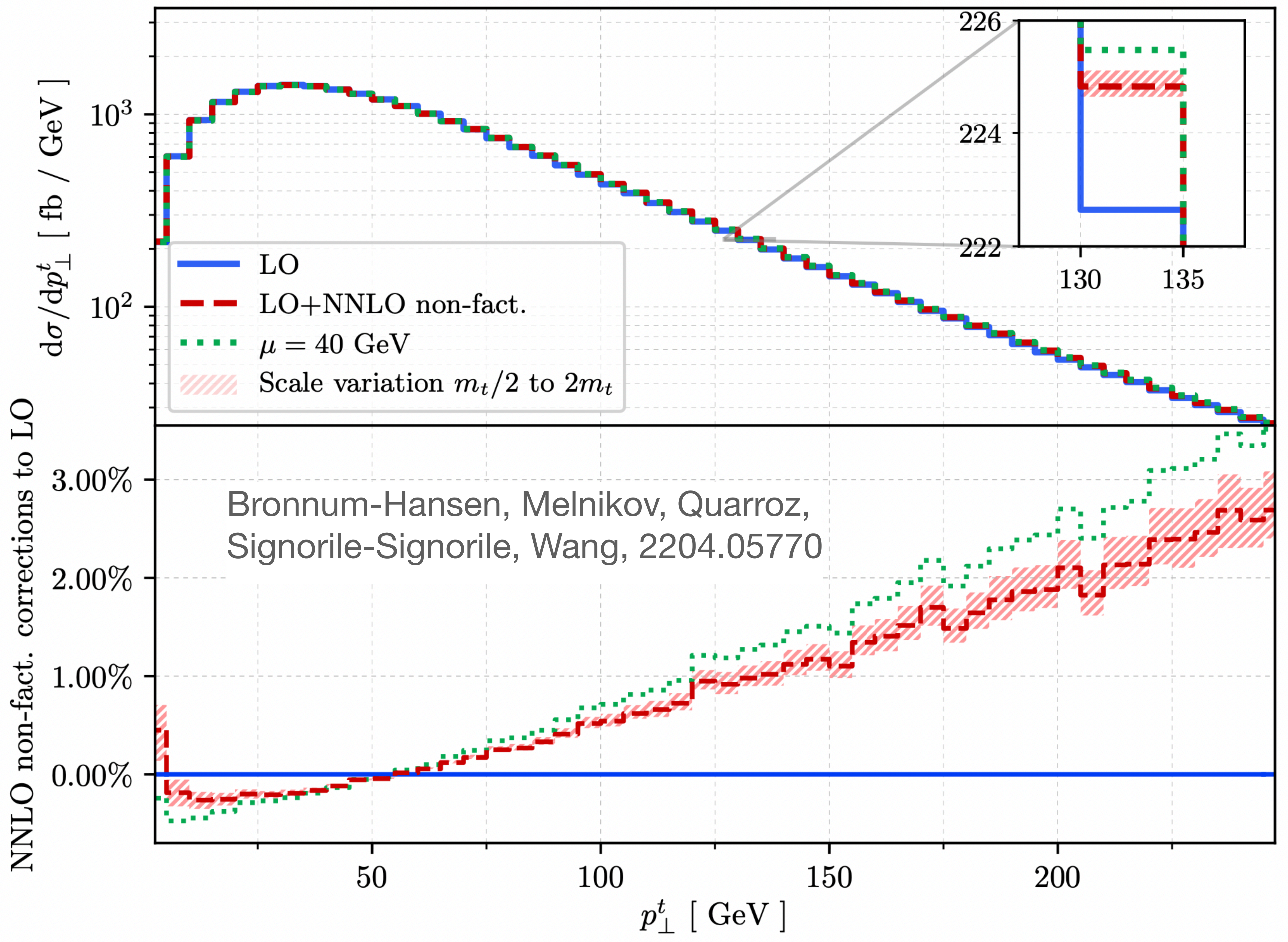
(uncorrelated scale variation

Stewart, Tackmann, 1107.2117)

More scales: non-factorizable single top production

- Large rate for single-top at the LHC can be used to measure properties of top quark and CKM.
- Previously NNLO corrections for factorisable only
  Brucherseifer, Caola, Melnikov
  Berger, Gao, Yuan, Zhu
  Campbell, Neumann, Sullvian
- Main bottleneck two-loop non-factorizable diagrams
  Bronnum-Hansen, Melnikov, Quarroz, Wang
  using auxiliary mass flow method
  Liu, Ma, Wang
- Only slightly smaller than factorisable corrections:
  0.4% for inclusive Xsec
  O(1-2)% for kinematical corrections
  Need to be taken into account in future percent-level measurements.





N3LO frontier

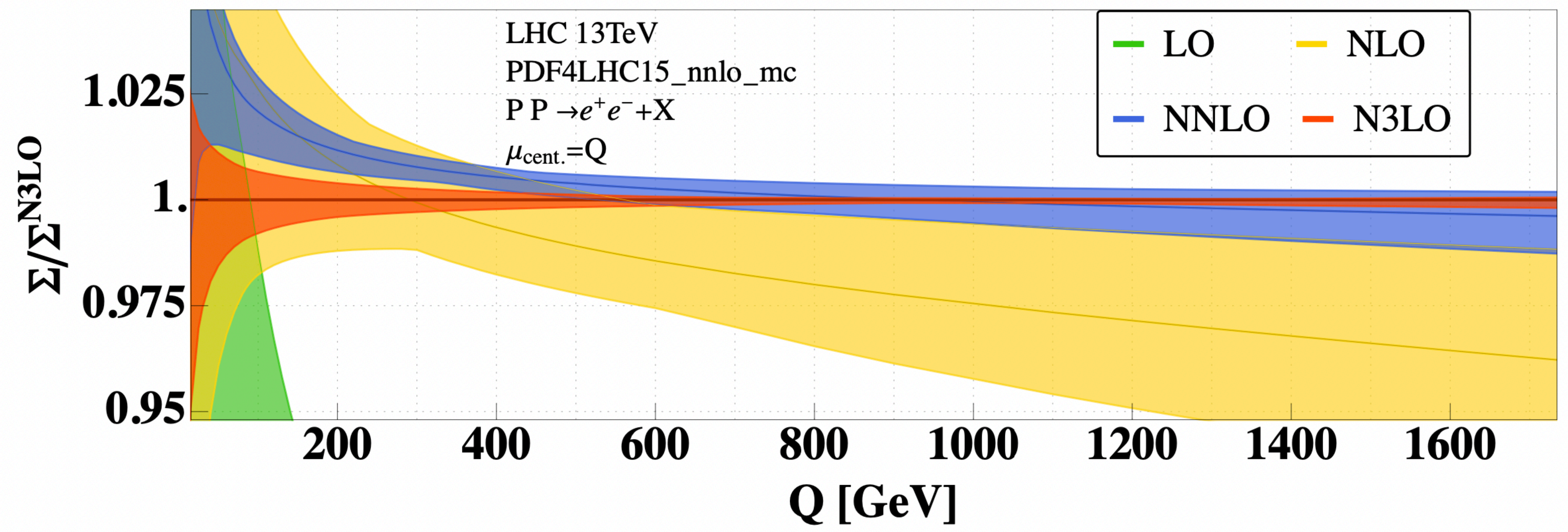
- Rapid progress in N3LO calculations in the past few years
  - $gg \to H$: Anastasiou, Duhr, Dulat, Herzog, Mistlberger; Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni; Mistlberger; Dulat, Mistlberger, Pelloni; Cieri, Chen, Gehrmann, Glover, Huss; Billis, Dehnadi, Ebert, Michel, Tackmann
  - $b\bar{b} \to H$: Duhr, Dulat, Mistlberger; Duhr, Dulat, Hirschi, Mistlberger
  - $pp \to H + 2$ jets: Dreyer, Karlberg
  - DIS jet production: Currie, Gehrmann, Glover, Huss, Niehues, Vogt; Gehrmann, Huss, Niehues, Vogt, Walker
  - $gg \to HH$: Chen, Li, Shao, Wang
  - Neutral-current Drell-Yan: Duhr, Dulat, Mistlberger; Chen, Gehrmann, Glover, Huss, Yang, Zhu; Duhr, Mistlberger; Chen, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli
  - Charged-current Drell-Yan: Duhr, Dulat, Mistlberger
- Three methods for infrared singularities:
  analytic phase space integration
  qT subtraction, Projection-to-Born (slicing methods)

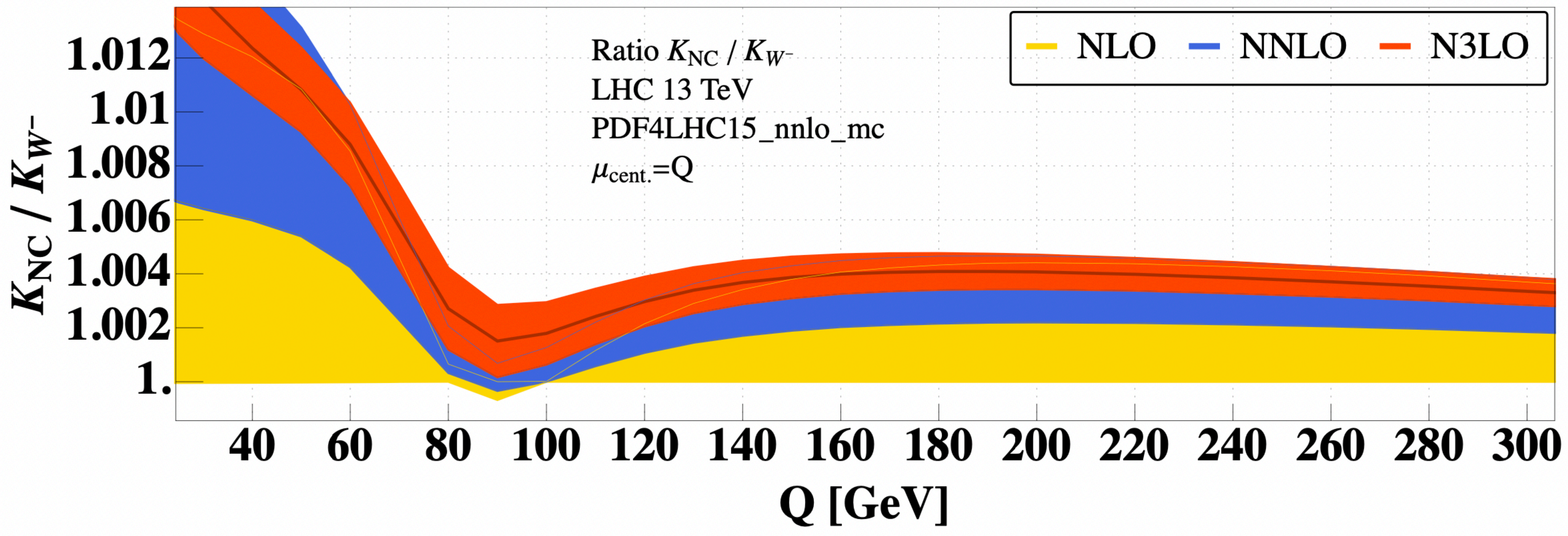
Z/γ^* at N3LO

- The last missing contribution to neutral-current DY
  Duhr, Mistlberger
- New ingredient: singlet axial-current contribution
  Three-loop virtual amplitudes
  Ahmed, Chen, Czakon
  Chen, Czakon, Niggetiedt
  Gehrmann, Primo
- The size of corrections and scale dependence similar to γ^* or W production (evaluated earlier)
- Scale variation band does not overlap from NNLO to N3LO
- The ratio of NC-DY and W production shows a few percent difference in K factor
- Careful with precision estimates
  for W production based on neutral current DY

Q [GeV]	$\Sigma^{\rm N3LO}$ [pb]	$K^{\rm N^3LO}$	$\delta(\text{PDF-}\alpha_S)$	δ(PDF-TH)
30	$531.7^{+1.53\%}_{-2.54\%}$	0.952	$^{+3.7\%}_{-3.8\%}$	2.8%
60	$112.636^{+0.97\%}_{-1.29\%}$	0.97	$^{+2.8\%}_{-2.5\%}$	2.5%
91.1876	$21756.4^{+0.7\%}_{-0.86\%}$	0.977	$^{+2.2\%}_{-2.1\%}$	2.5%
100	$458.473^{+0.66\%}_{-0.79\%}$	0.979	$^{+2.0\%}_{-1.8\%}$	2.5%
300	$1.24661^{+0.26\%}_{-0.29\%}$	0.992	$^{+1.9\%}_{-1.6\%}$	1.7%

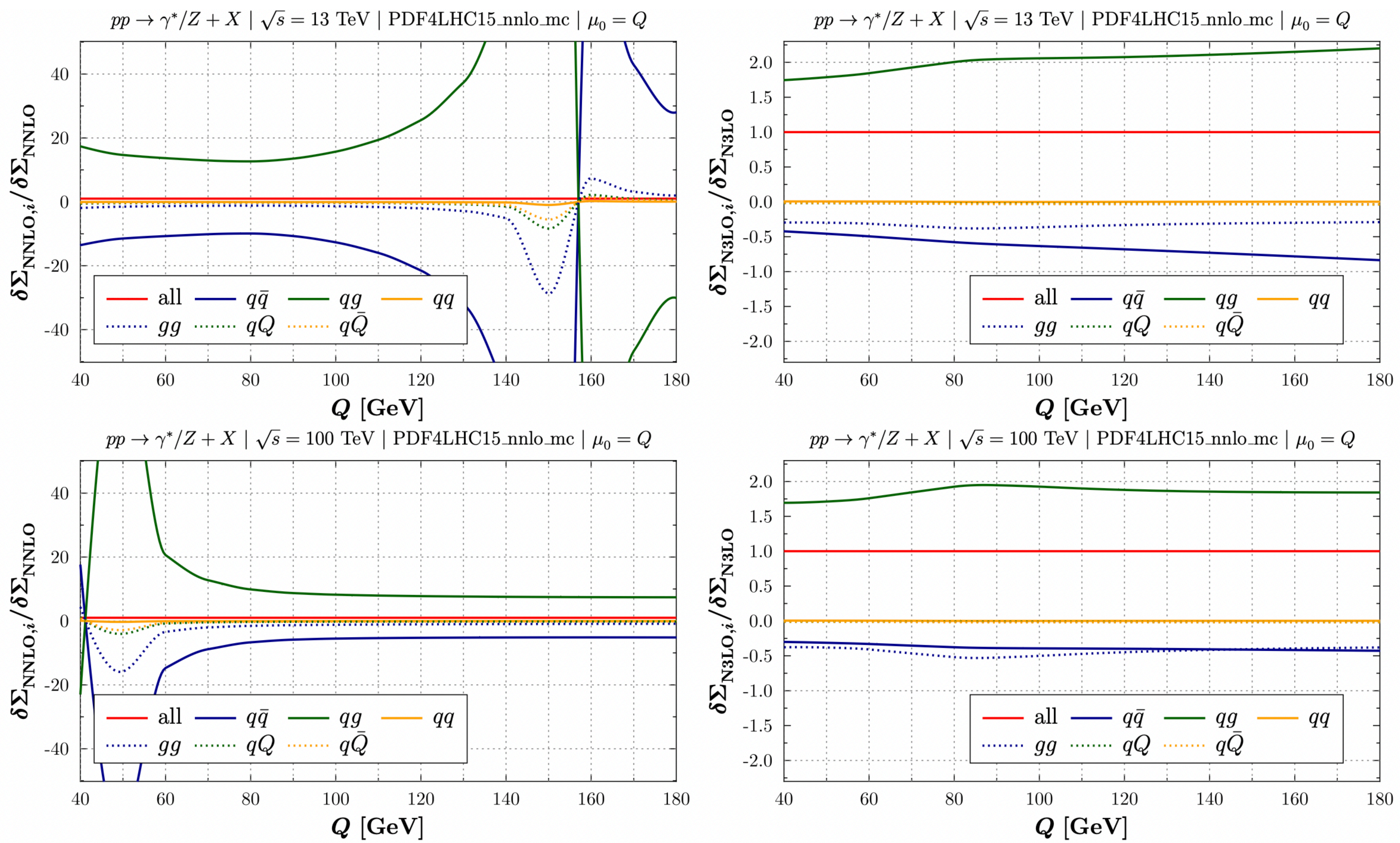
Duhr, Mistlberger, 2111.10379





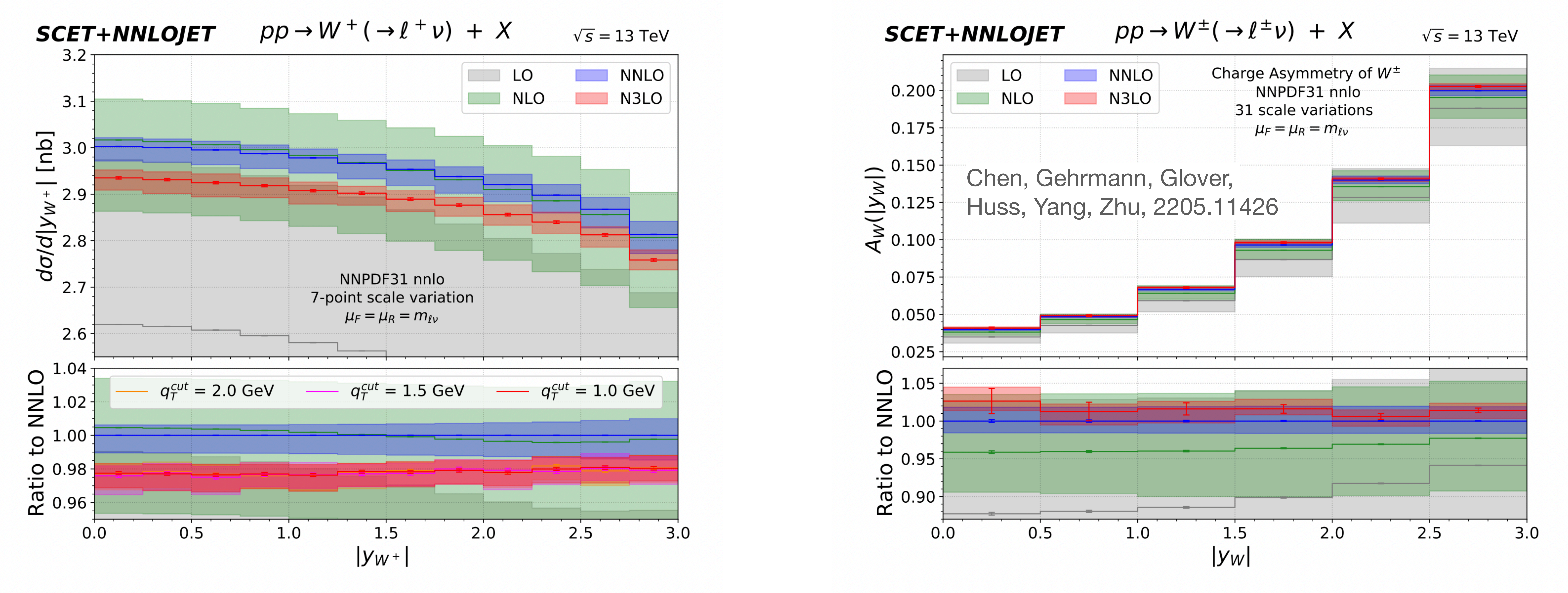
Z/γ* at N3LO

- Scale variation band does not overlap from NNLO to N3LO : an effect of PDFs ?



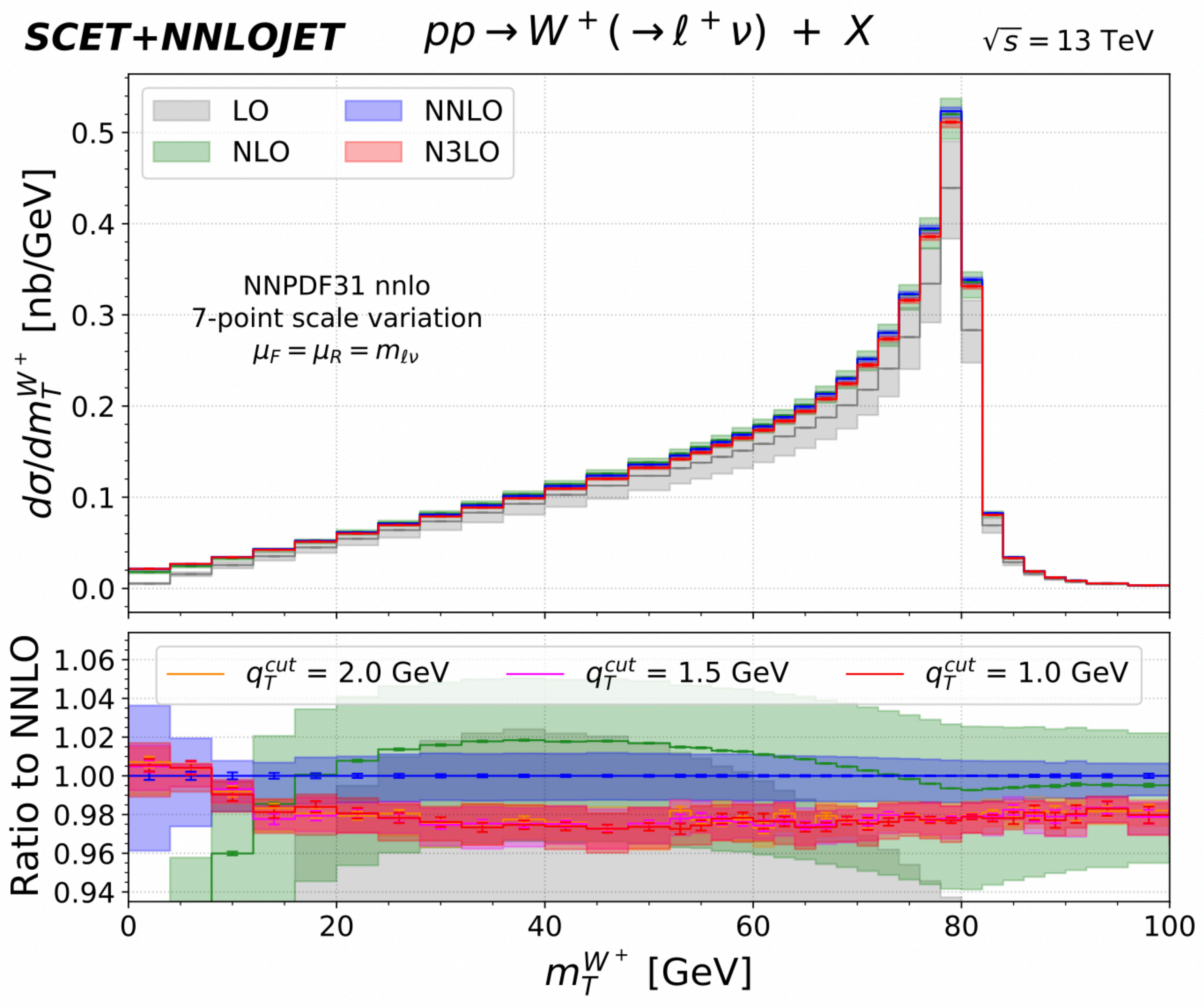
Baglio, Duhr, Mistlberger, Szafron, 2209.06138

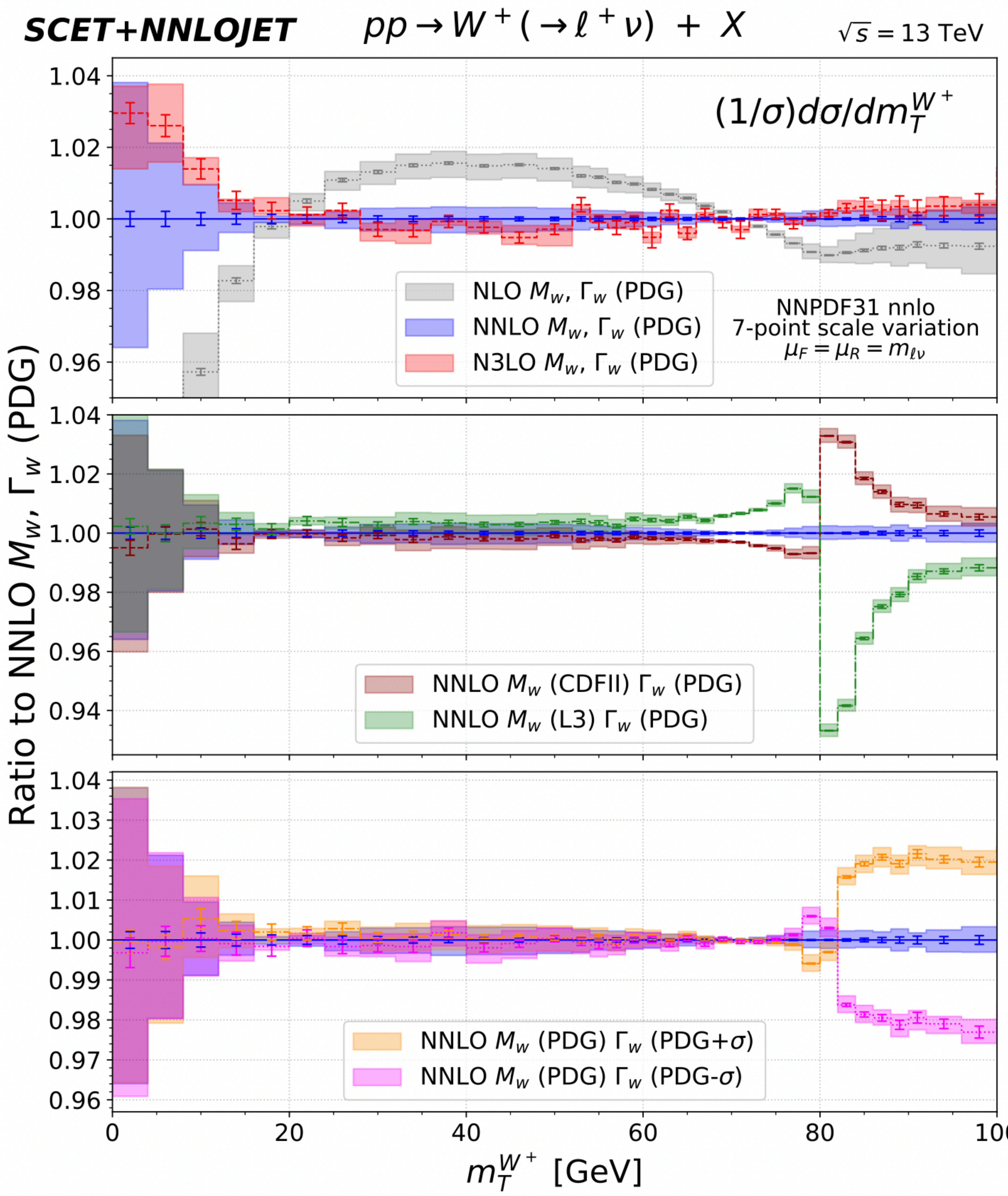
W boson rapidity at N3LO



- Relatively flat N3LO corrections in function of rapidity (-2.5%)
  - As for inclusive cross section, rapidity distribution with non-overlapping scale variation band from NNLO to N3LO
- Charge asymmetry sensitive to PDFs
  - Scale uncertainties varying independently in the numerator and denominator
    N3LO corrections depends on rapidity
    Scale variation bands overlap for charge asymmetry

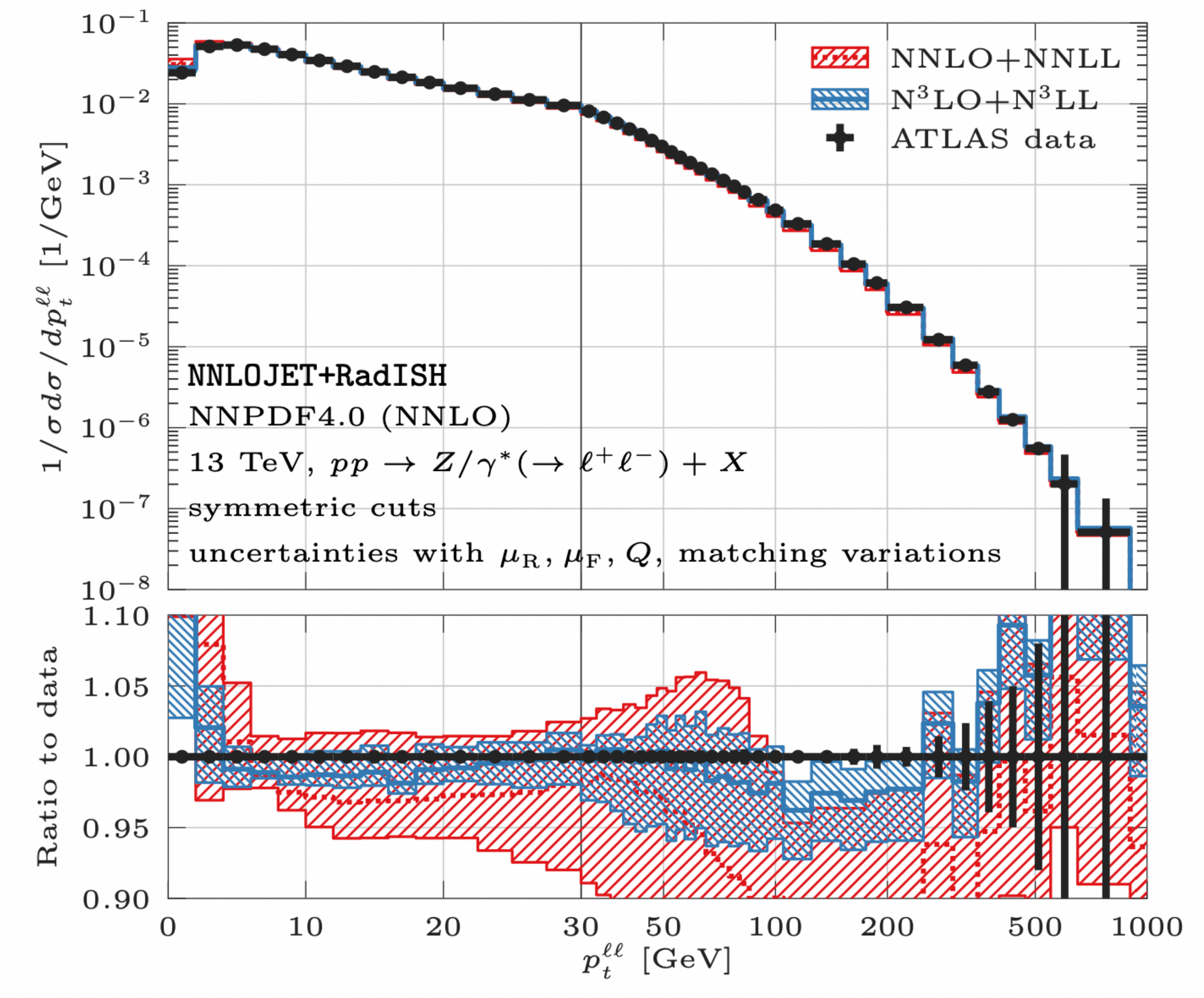
W transverse mass at N3LO



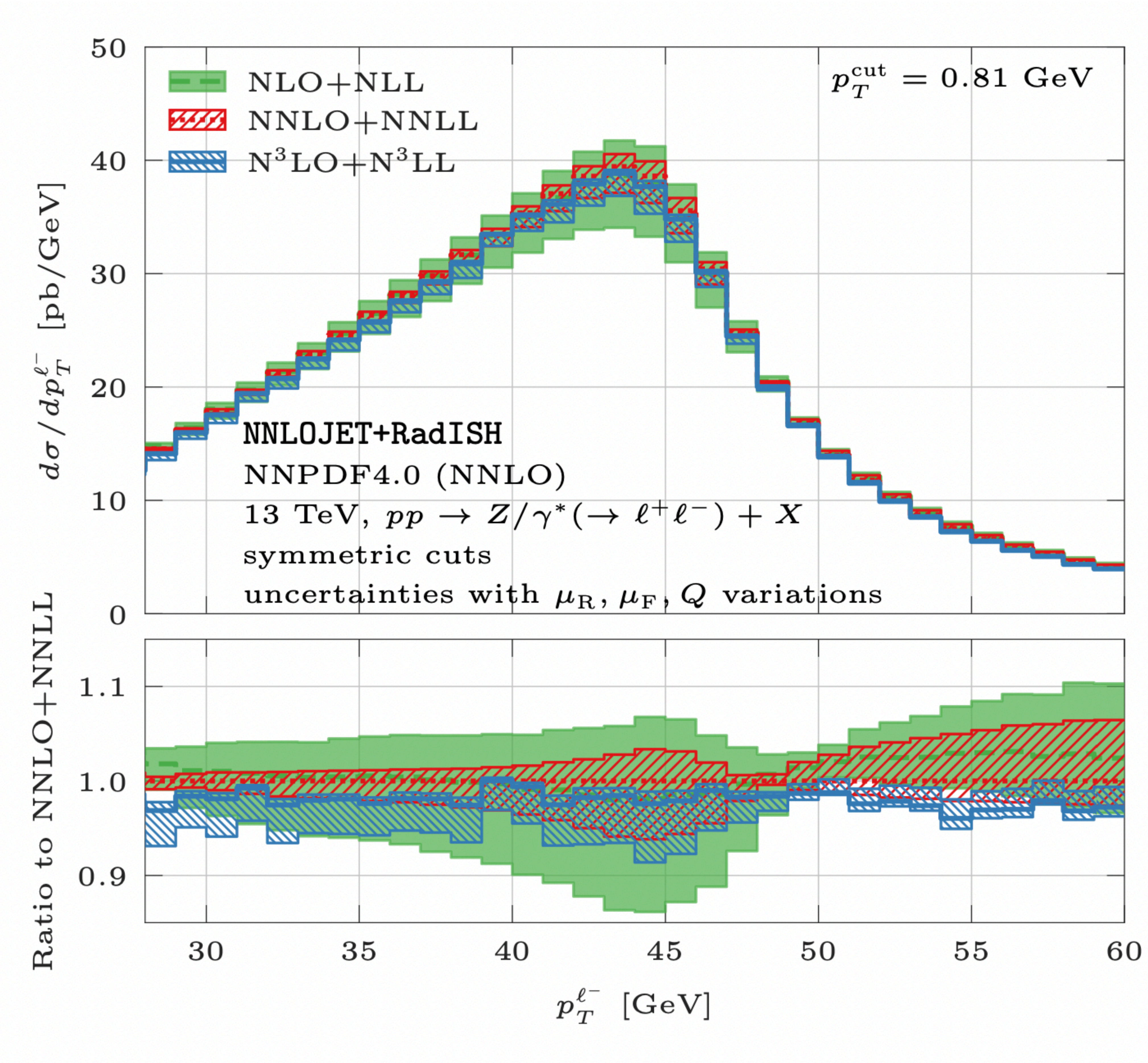


- W boson transverse mass distribution plays significant role in recent CDFII W mass determination
- Normalised distribution shows convergence of perturbation series at N3LO (less than 1% in the peak region) in contrast to large corrections from NLO to NNLO.
- Sensitivity to EW parameters can be reliably estimated using NNLO
- Variation of EW parameters M_W and Γ_W modifies normalised distributions by 2-6%.

pT resummation: state-of-the-art



Chen, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli, 2203.01565



- N3LL'+N3LO standard for DY and Higgs pT distributions
- Less than 5% theory uncertainties for DY for pT<50 GeV
- Excellent agreement with ATLAS for pT spectrum
  More efforts required to bring down theory uncertainties to compete with experimental ones
- Lepton pT important for W mass measurement
  Good perturbative convergence with N3LL resummation. Inclusion of EW corrections?

Higgs physics

Higgs production in gluon fusion

δ(scale)	δ(~~trunc~~)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

improved: approximate N4LO corrections
Das, Moch, Vogt '20

removed
B. Mistlberger '18

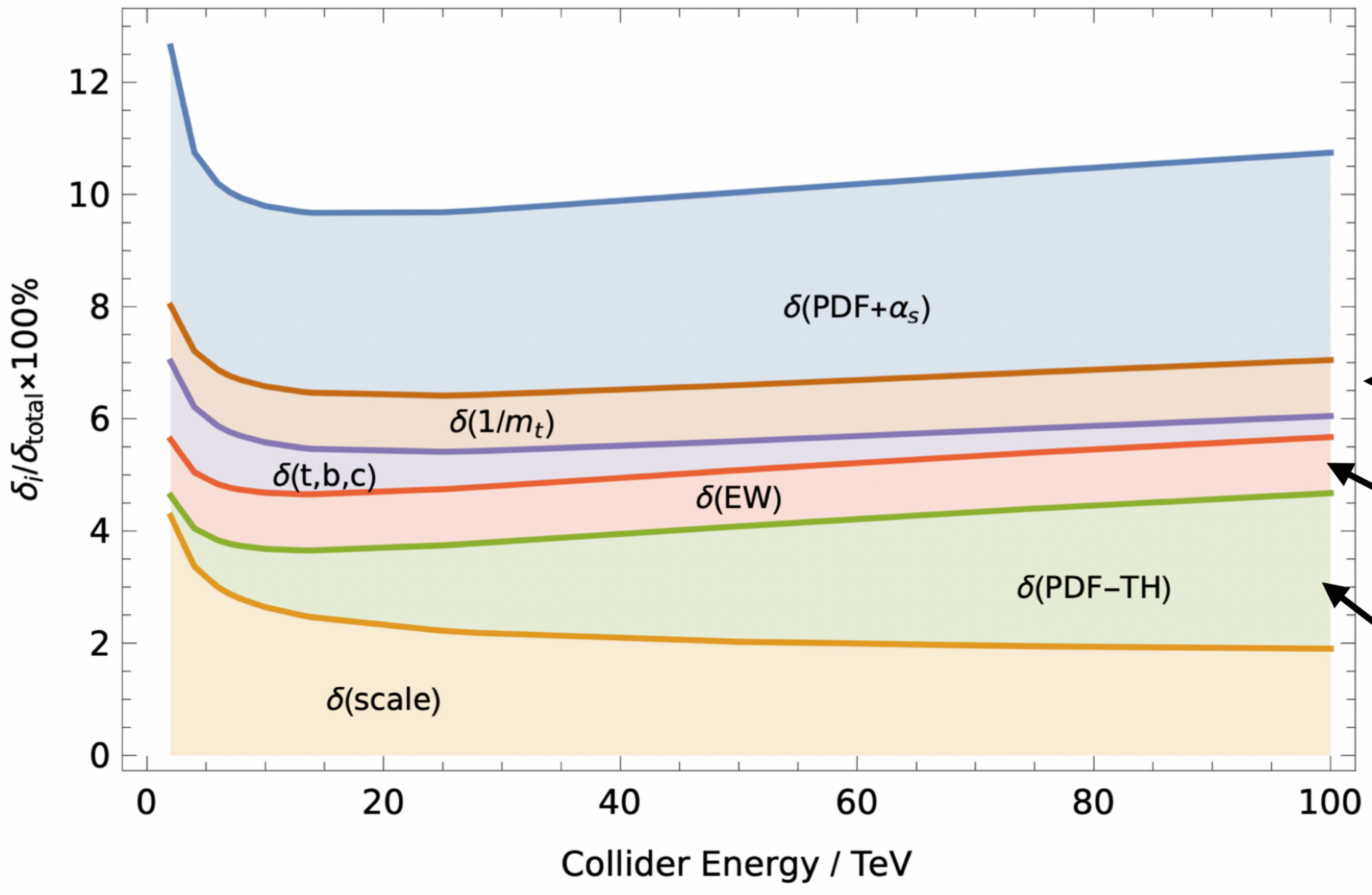
missing N3LO PDFS

reduced to ~0.6%
Bechetti et al '20, '21, Bonetti et al '18, '20, '22

light quark and mass scheme effects

reduced, -0.26%
Czakon, Harlander, Klappert, Niggetiedt '20

uncertainty budget Dulat, Lazopoulos, Mistlberger '18



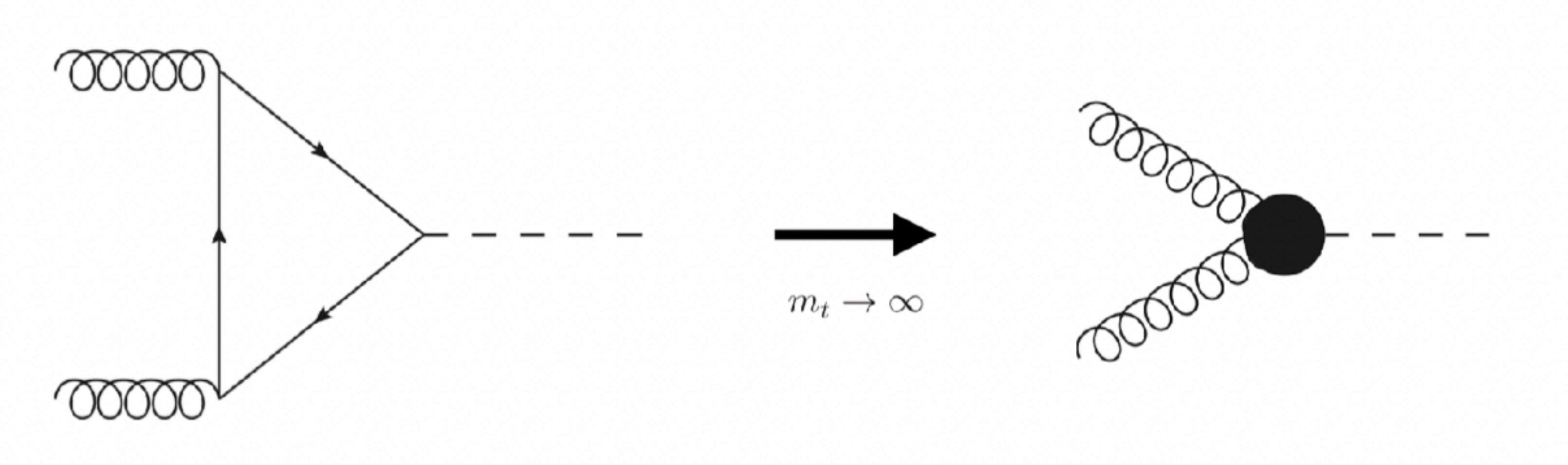
basically removed recently
Czakon, Harlander, Klappert, Niggetiedt '20

reduced substantially
Bechetti et al '20, '21, Bonetti et al '18, '20, '22

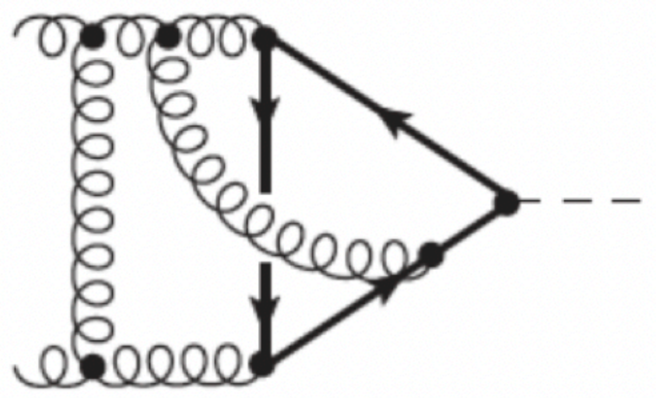
mismatch between PDF (NNLO) and ME (N3LO)

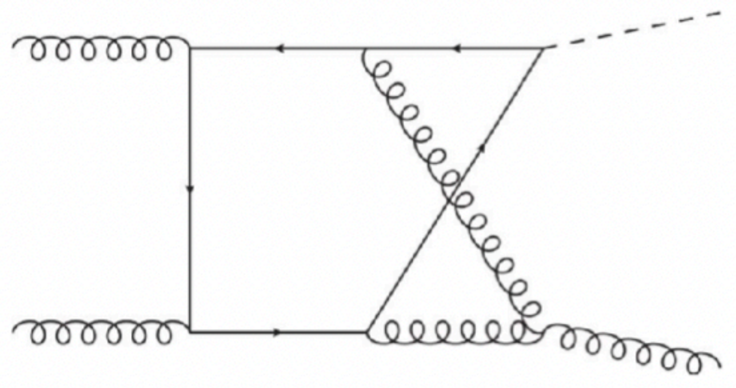
$gg \to H$: top quark mass effects

- N3LO results have been obtained in heavy top limit (HTL)



- Full top mass effects at NNLO:
  Czakon, Harlander, Klappert, Niggetiedt '20
  -0.26% @13TeV relative to HTL



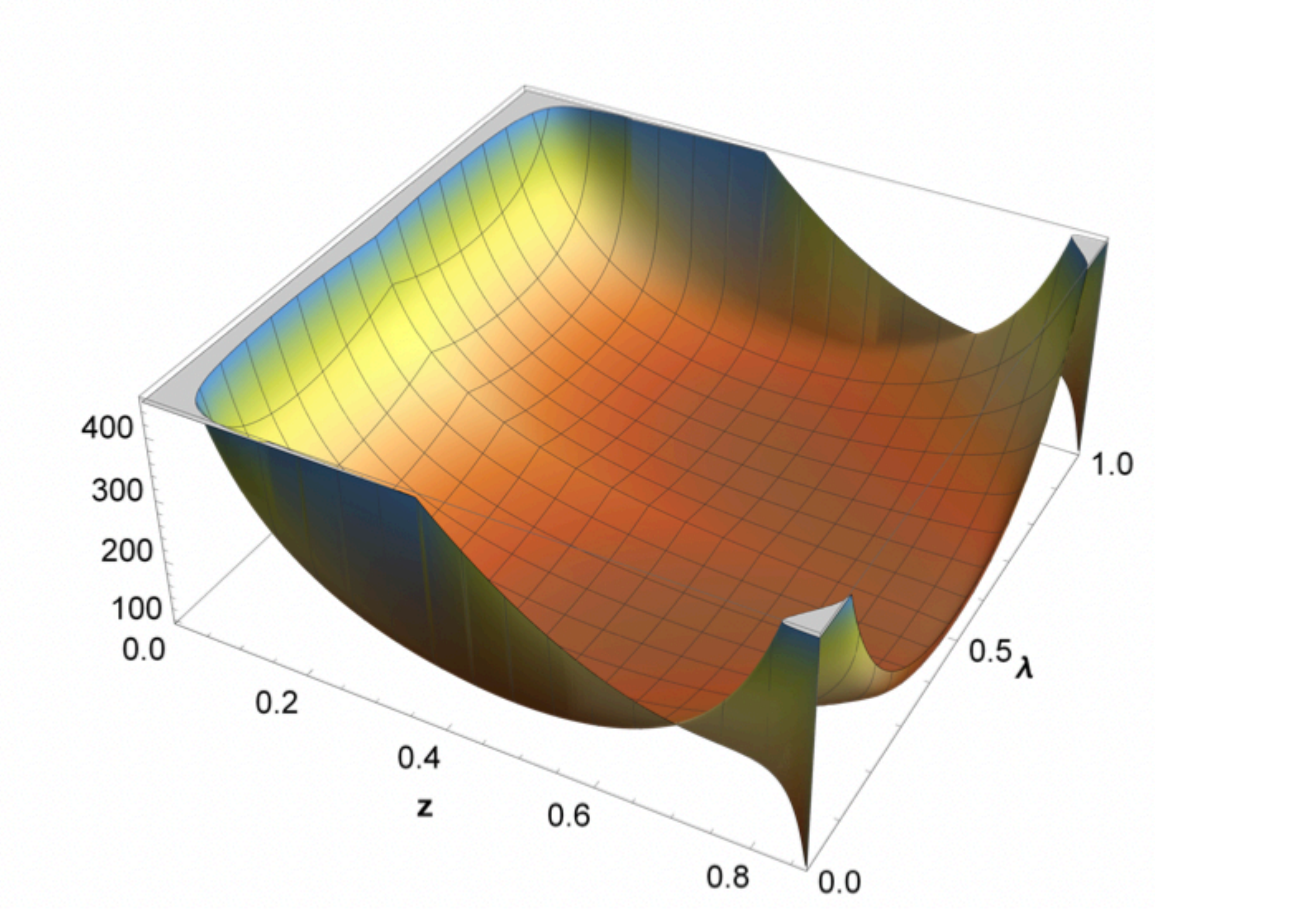


virtual 3-loop

Davies, Gröber, Maier, Rauh '19; Czakon, Niggetiedt '20

real-virtual

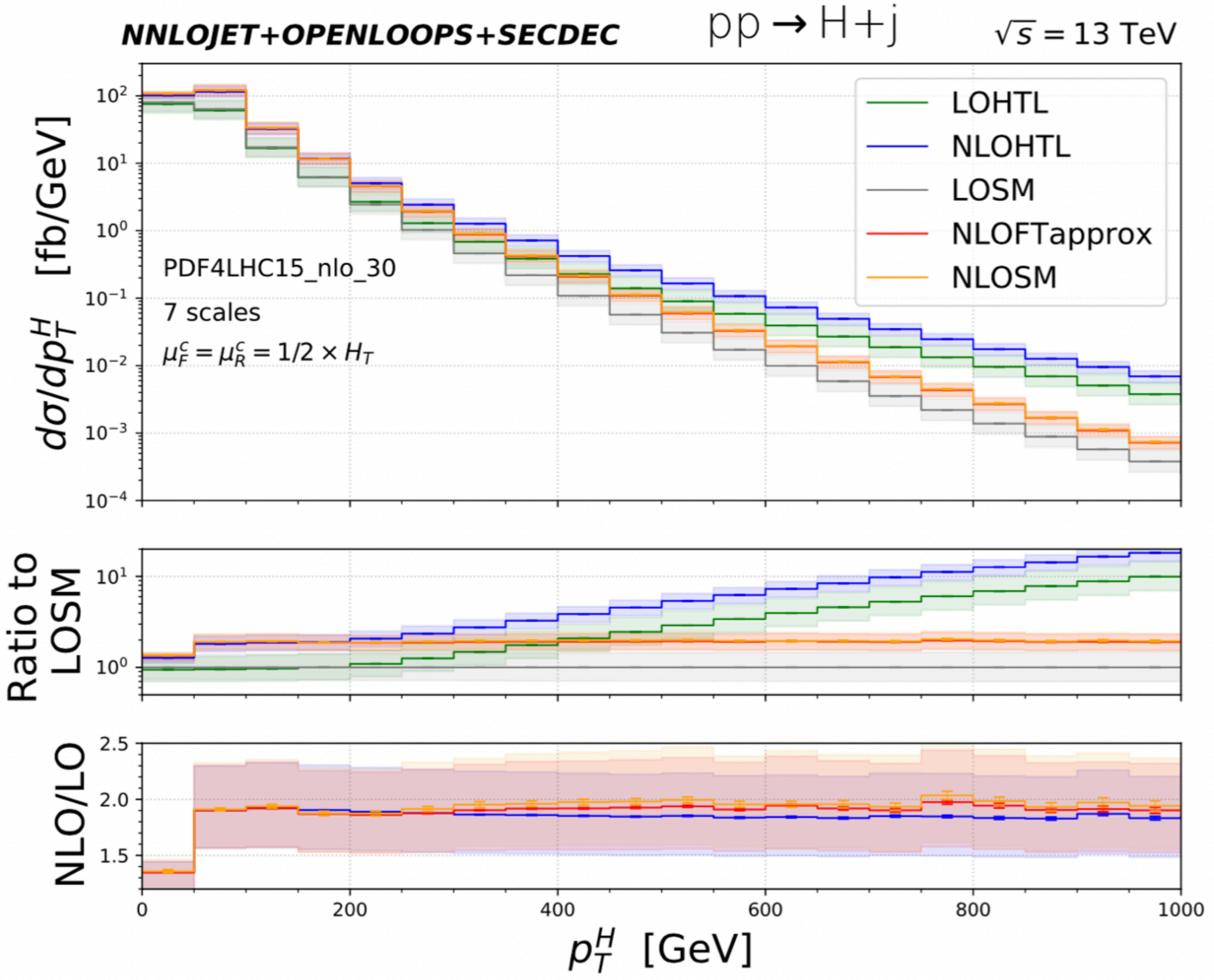
recalculated by Czakon et al
see also
Jones, Kerner, Luisoni '18; Frellesvig, Hidding et al '19



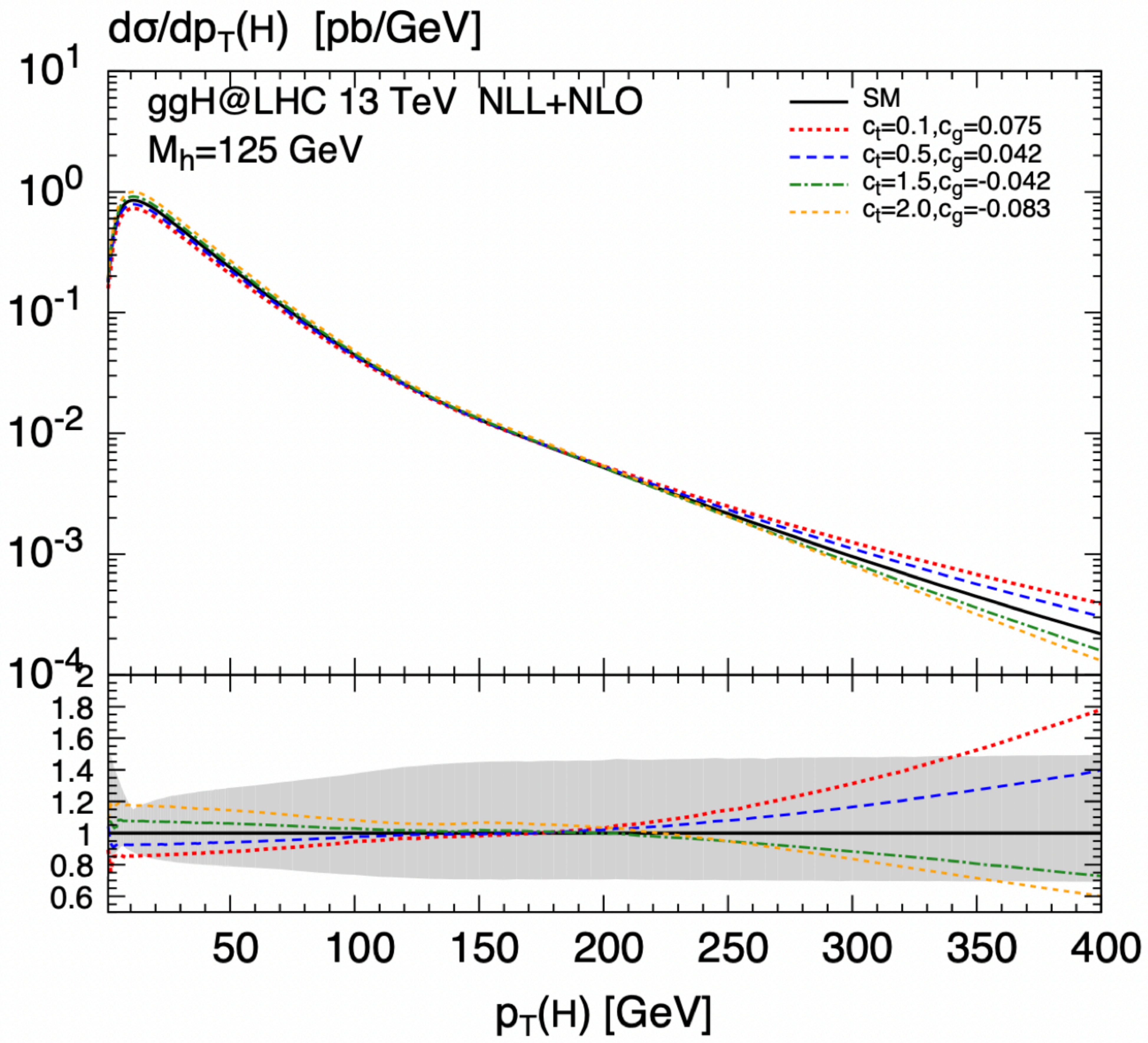
channel	$\sigma^{\mathrm{NNLO}}_{\mathrm{HEFT}}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\mathrm{NNLO}}_{\mathrm{exact}} - \sigma^{\mathrm{NNLO}}_{\mathrm{HEFT}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\mathrm{NNLO}}_{\mathrm{exact}}/\sigma^{\mathrm{NNLO}}_{\mathrm{HEFT}} - 1)$ [%]
		$\sqrt{s} = 8\,\mathrm{TeV}$		
gg	$7.39 + 8.58 + 3.88$	$+0.0353$	$+0.0879 \pm 0.0005$	$+0.62$
qg	$0.55 + 0.26$	-0.1397	-0.0021 ± 0.0005	-18
qq	$0.01 + 0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39 + 9.15 + 4.18$	-0.0873	$+0.0667 \pm 0.0007$	-0.10
		$\sqrt{s} = 13\,\mathrm{TeV}$		
gg	$16.30 + 19.64 + 8.76$	$+0.0345$	$+0.2431 \pm 0.0020$	$+0.62$
qg	$1.49 + 0.84$	-0.3696	-0.0115 ± 0.0010	-16
qq	$0.02 + 0.10$	$+0.0322$	-0.0501 ± 0.0006	-15
total	$16.30 + 21.15 + 9.79$	-0.3029	$+0.1815 \pm 0.0023$	-0.26

Higgs+jet with mass effects

Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21



Grazzini, Ilnicka, Spira, Wiesemann '16

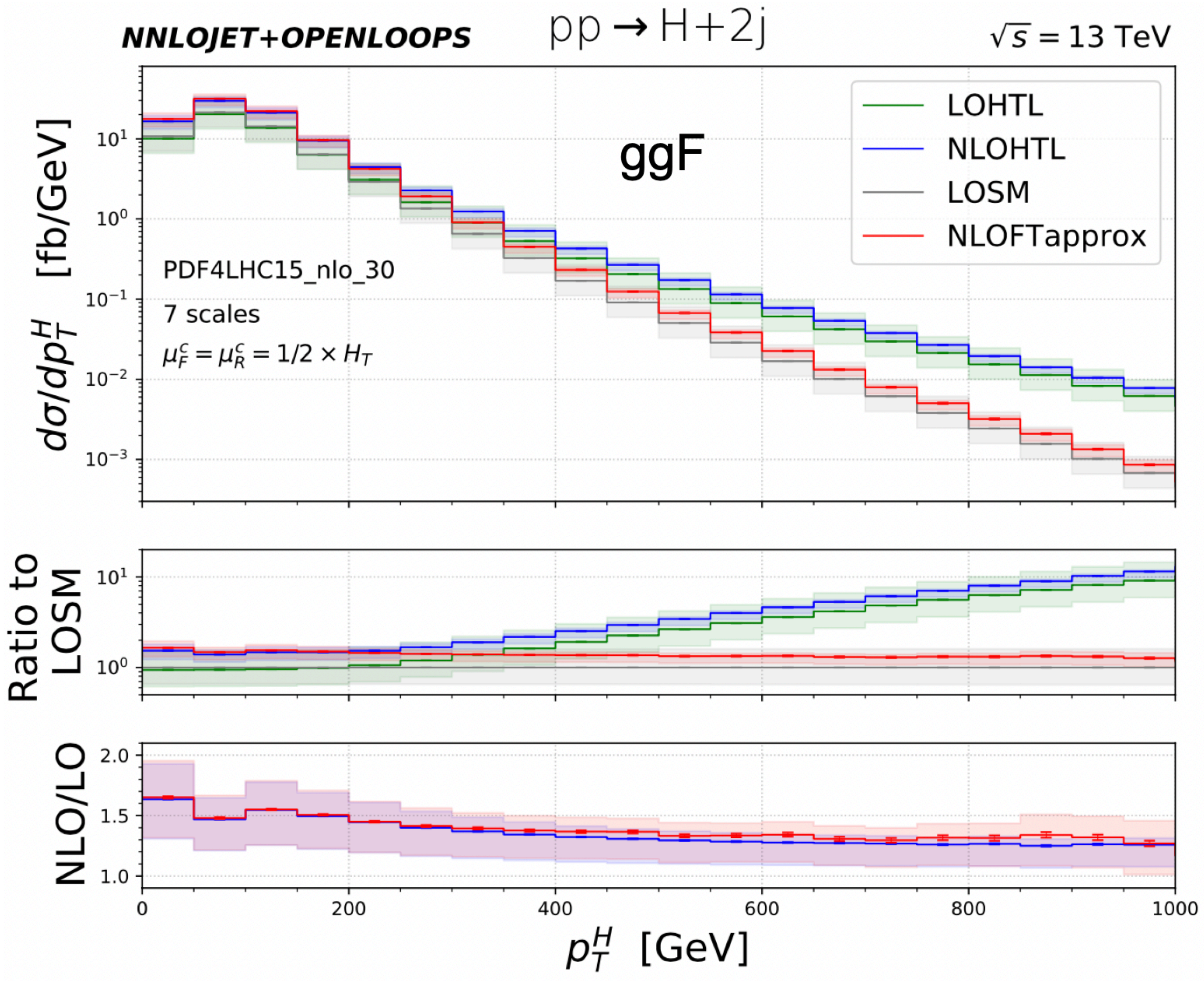


HTL: wrong scaling in the tail, FTapprox: within 5% of full

NLO scale (and mass scheme) uncertainties $\mathcal{O}(20\%)$

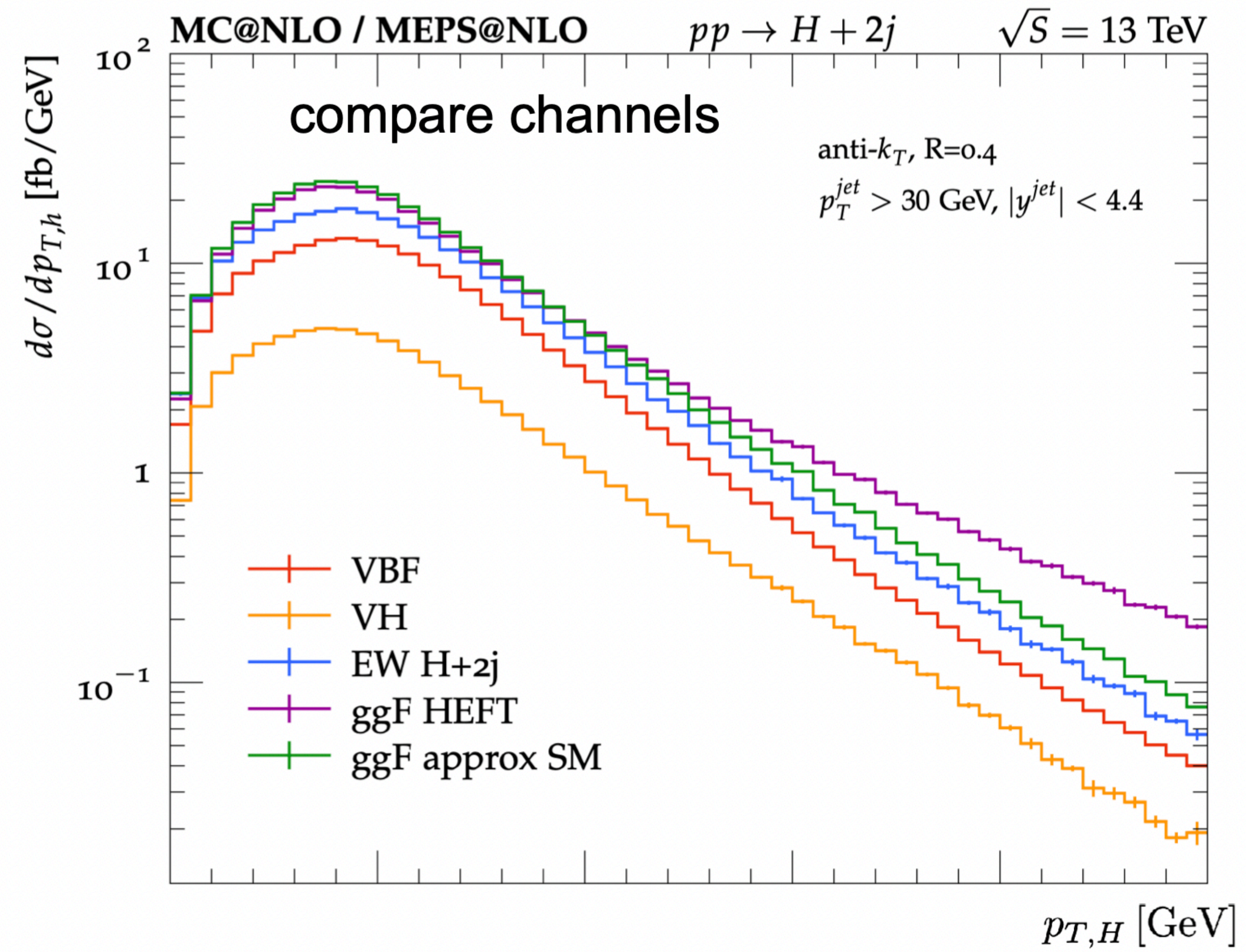
pT-tail important for effects of anomalous couplings

Higgs+2 jets: ggF and VBF with mass effects



Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21

full NLO not available,
FTapprox QCD corrections ~60% at small pT



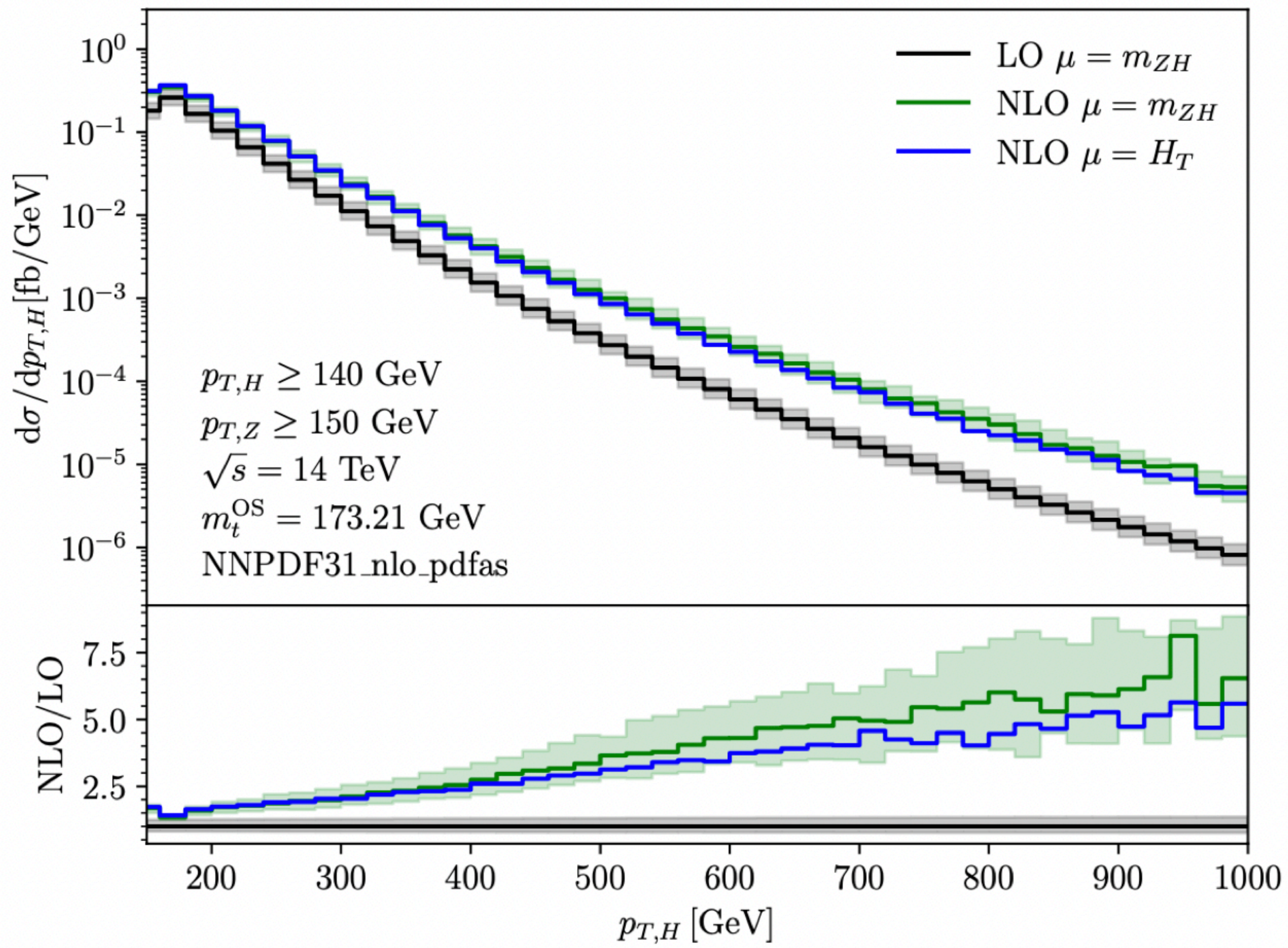
comprehensive study of fiducial cuts,
EW corrections, different tools

Buckley, Chen, Cruz-Martinez, Ferrario-Ravasio et al. '21

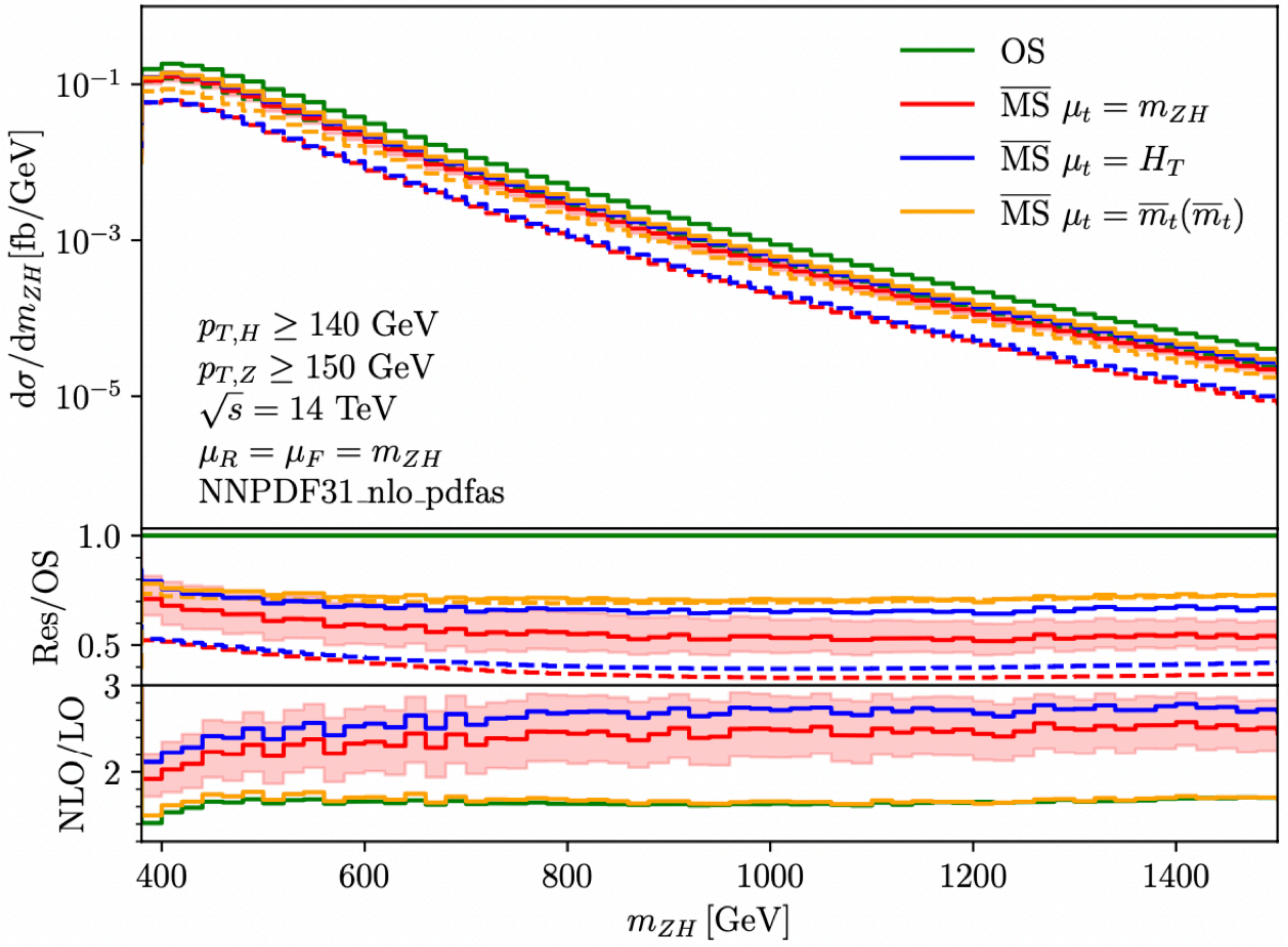
$gg \to H + Z$@**NLO**

Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser '22

2204.05225

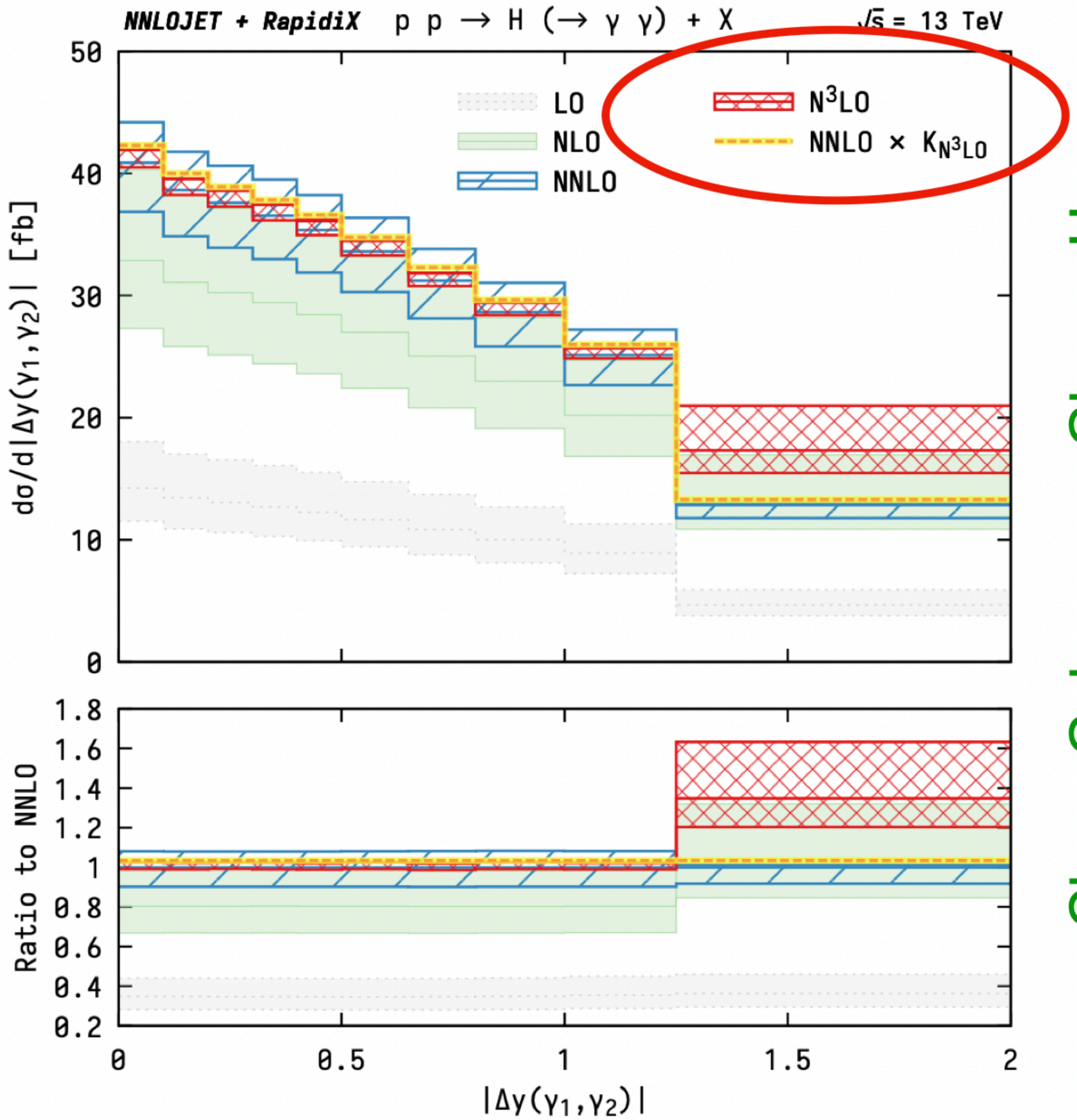


very large K-factor in pT,H tail



mass scheme uncertainty: difference between on-shell (OS) and $\overline{\mathrm{MS}}(\mu_t = m_{ZH})$?

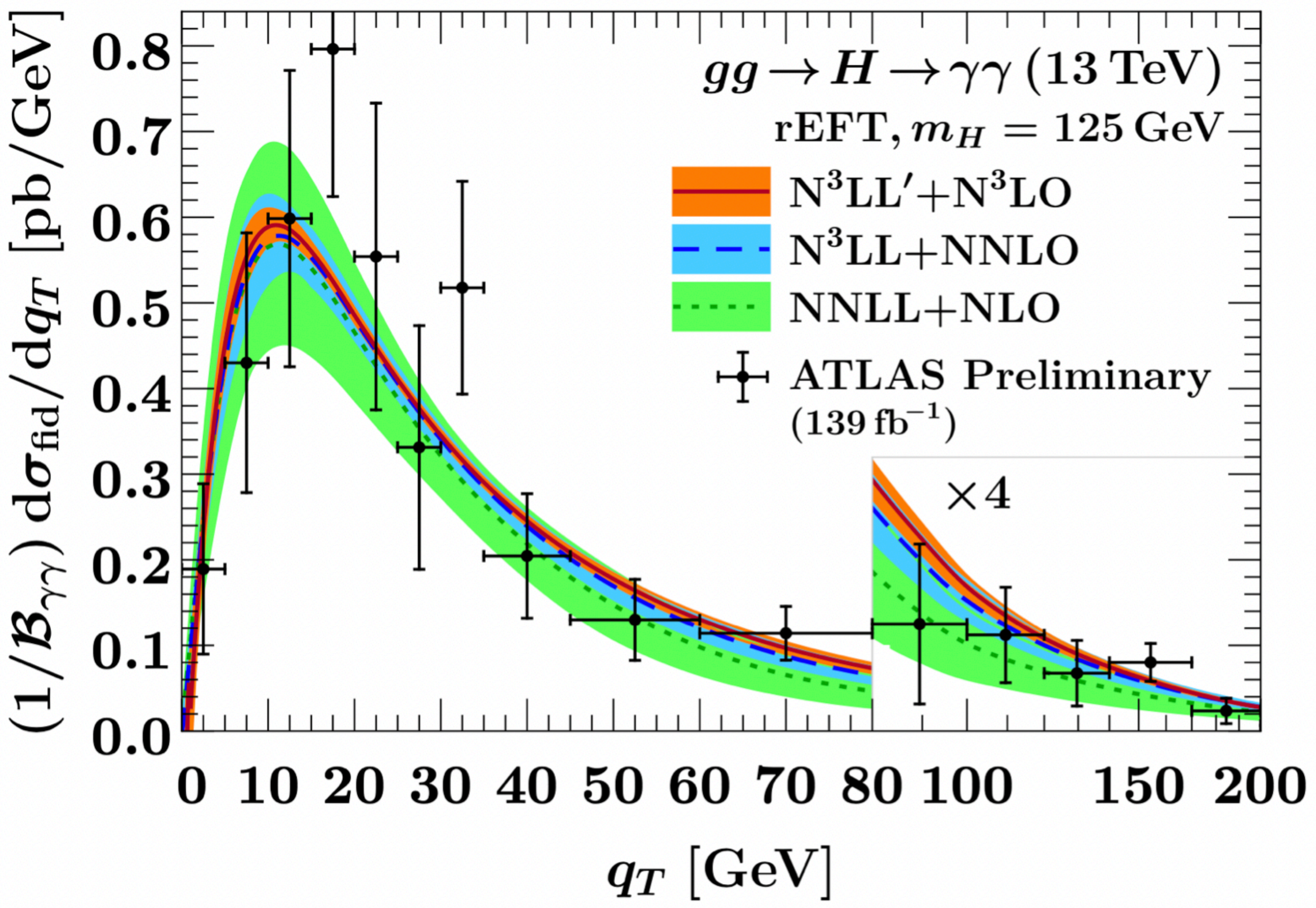
$gg \to H$: highest orders fiducial



Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607

differential information important

$pp \to H \to \gamma\gamma$

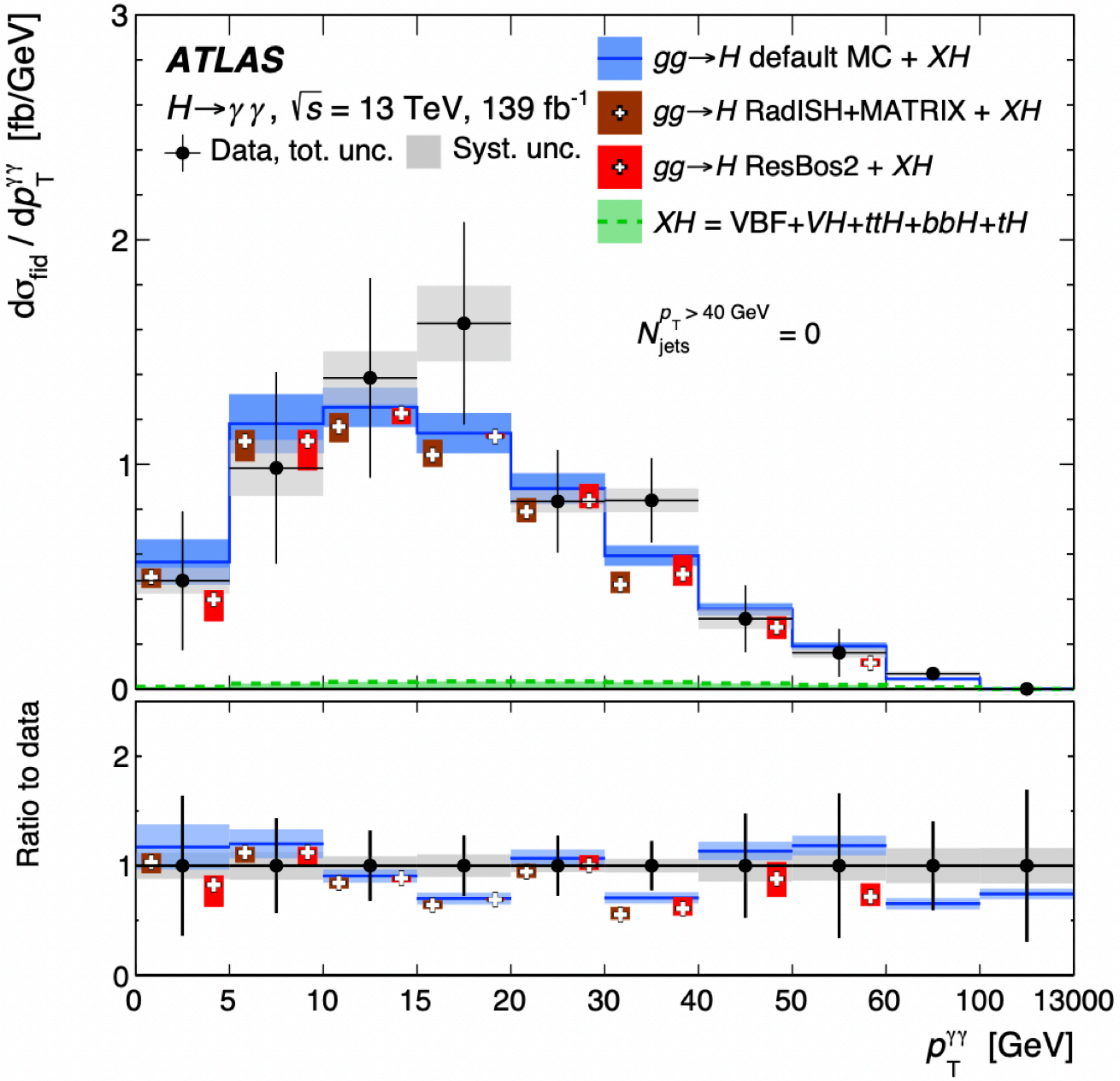


Billis, Dehnadi, Ebert, Michel, Tackmann, 2102.08039

scale uncertainties not the dominant uncertainties anymore

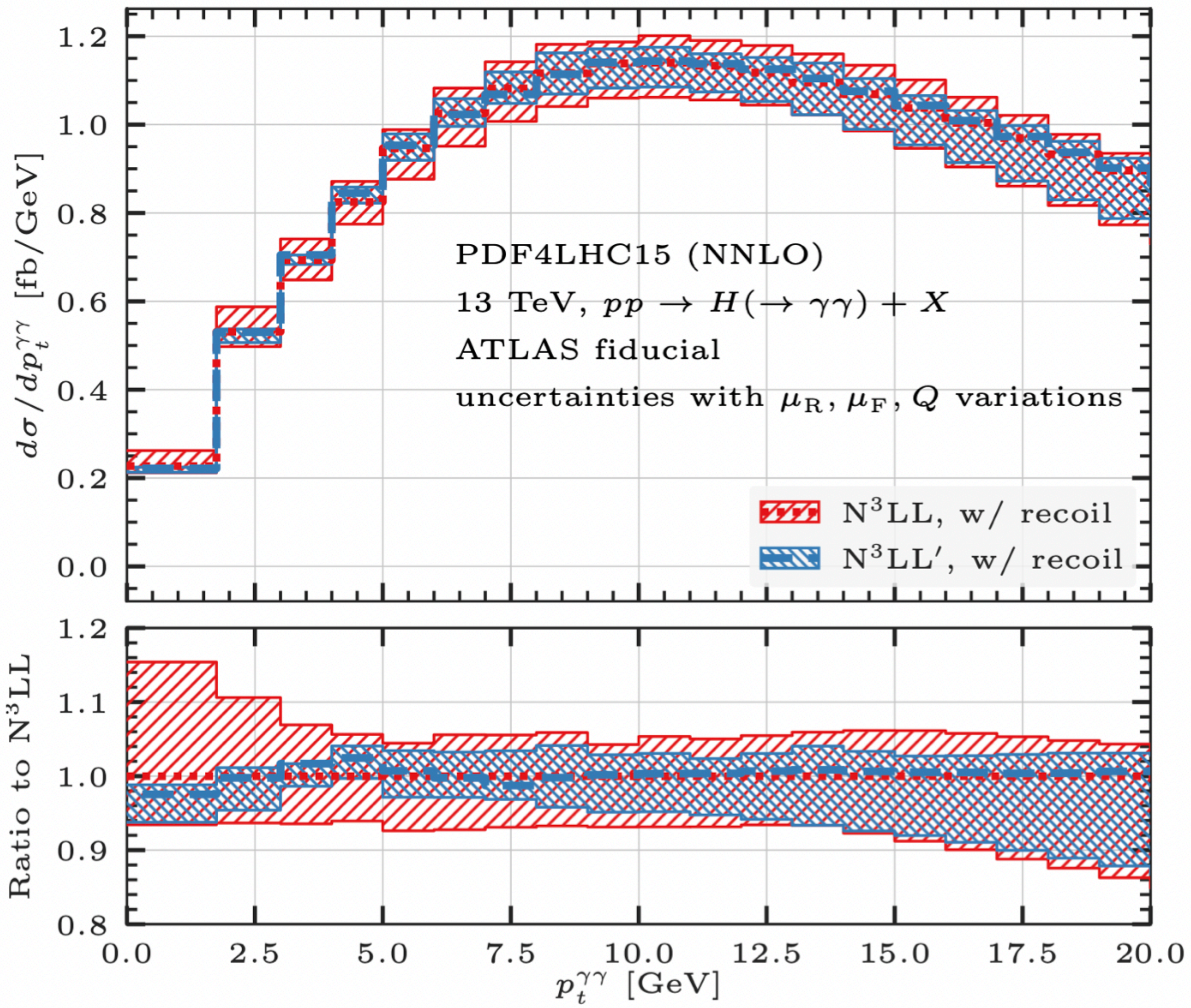
$gg \to H$: high orders + resummation

ATLAS 2202.00487



resum logarithms of type $\ln(p_T^{\gamma\gamma}/m_H)$ to control region of small $p_T^{\gamma\gamma}$

(important region e.g. for light quark Yukawa couplings)

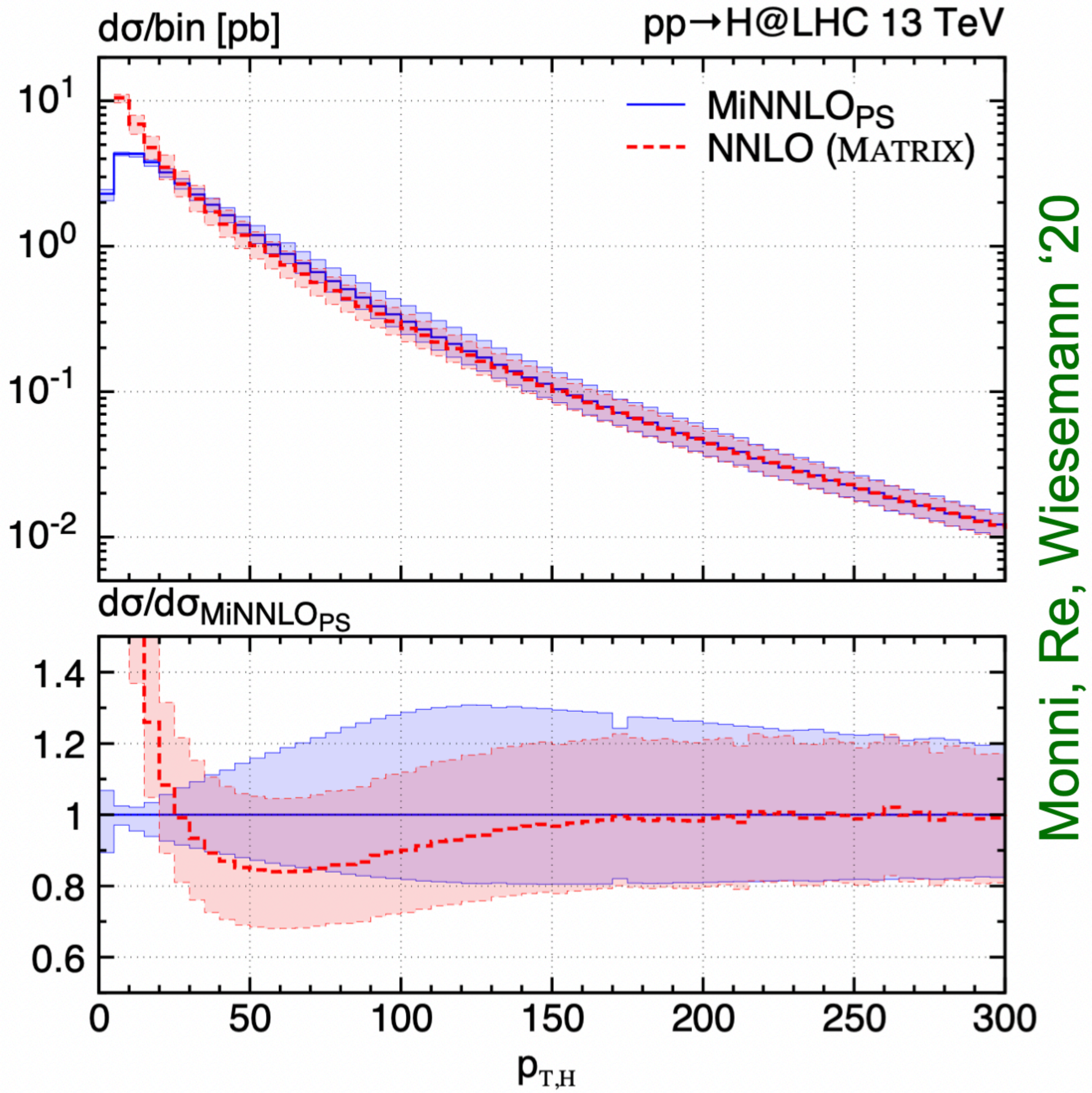


Re, Rotttoli, Torrielli '21 (RadISH)

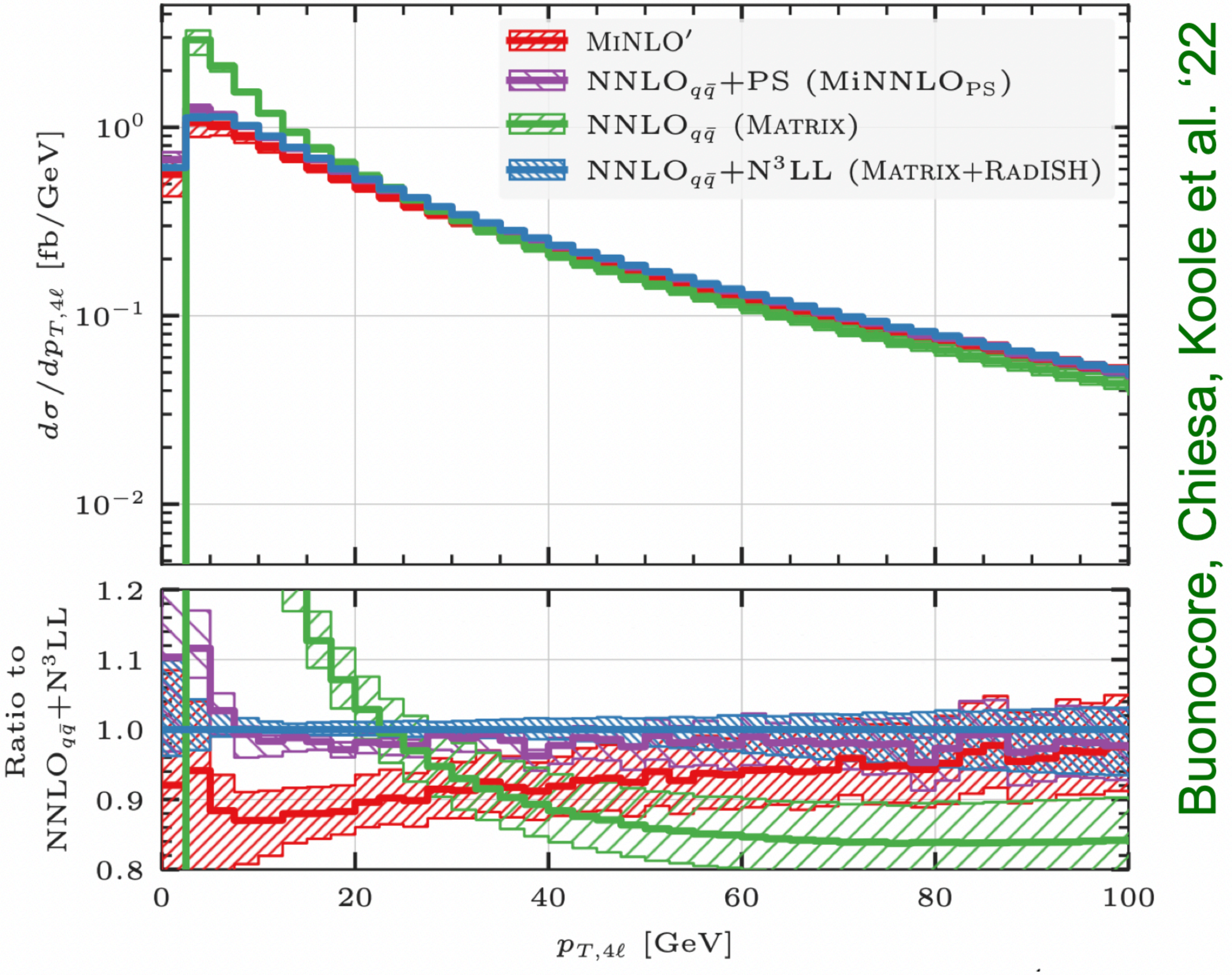
N3LL': include all constant terms up to $\mathcal{O}(\alpha_s^3)$

(e.g. 3-loop hard-virtual coefficient)

NNLO + parton shower



importance of resummation at low pT



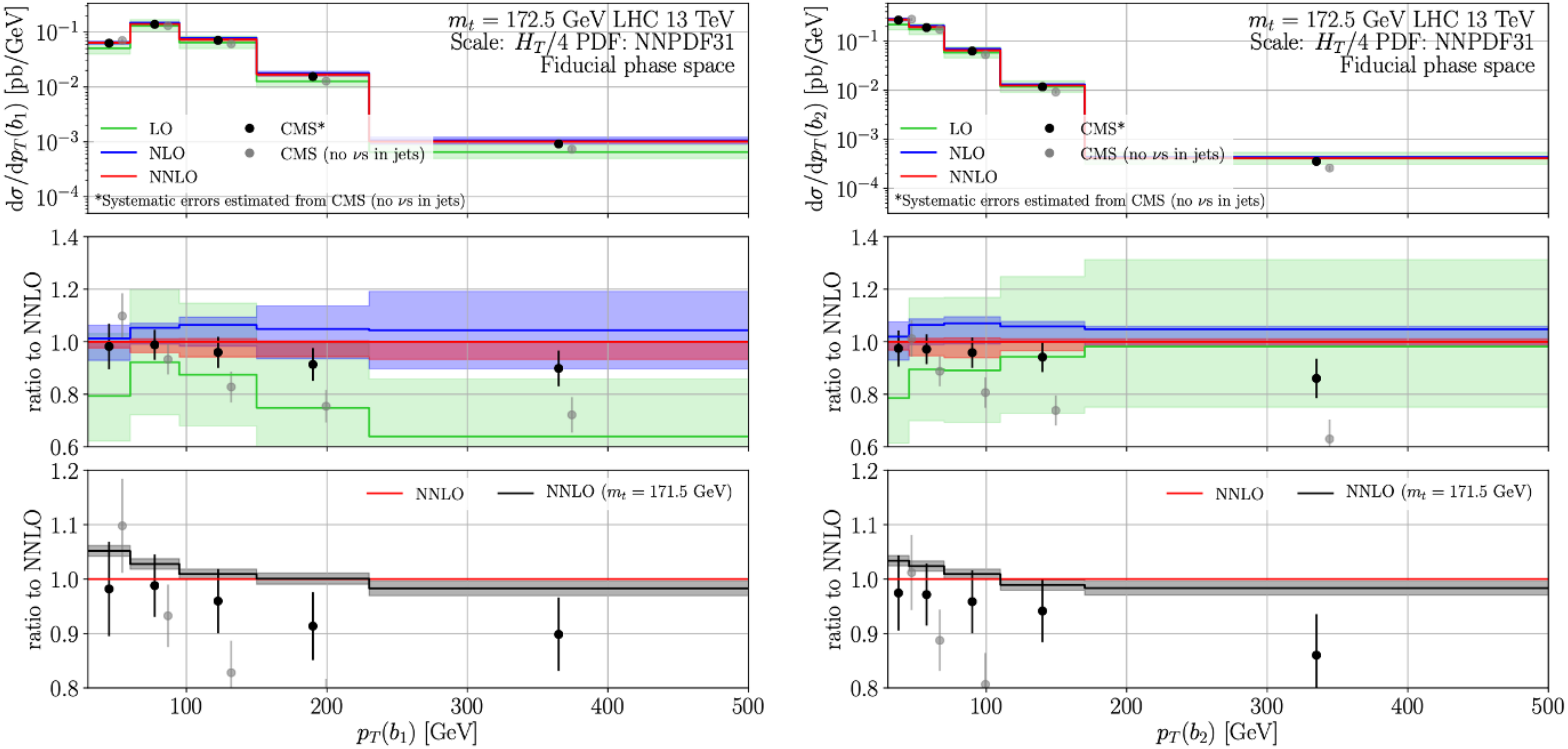
ZZ production (background to $H \to 4l$)

Top-quark physics

Best description of $t\bar{t}$ in the di-lepton channel

- NLO QCD/EW full off-shell:
  - NLO QCD corrections to WWbb production at hadron colliders Denner, Dittmaier, Kallweit, Pozzorini, 1012.3975
  - Complete off-shell effects in top quark pair hadroproduction with leptonic decay at next-to-leading order
    Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek, 1012.4230
  - NLO electroweak corrections to off-shell top-antitop production with leptonic decays at the LHC Denner, Pellen, 1607.05571
- NWA @ NNLO
  - Higher order corrections to spin correlations in top quark pair production at the LHC
    Behring, Czakon, Mitov, Papanastasiou, Poncelet, 1901.05407
  - NNLO QCD corrections to leptonic observables in top-quark pair production and decay Czakon, Mitov, Poncelet, 2008.11133
- b-quark fragmentation:
  - B-hadron production in QCD: application to LHC ttbar events with leptonic decays
    Czakon, Generet, Mitov and Poncelet, 2102.08267
- NNLO + PS:
  - Next-to-Next-to-Leading Order Event Generation for Top-Quark Pair Production
    Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, 2012.14267
  - Top-pair production at the LHC with MiNNLO_PS Mazzitelli, Monni, Nason, Re, Wiesemann and Zanderighi, 2112.12135

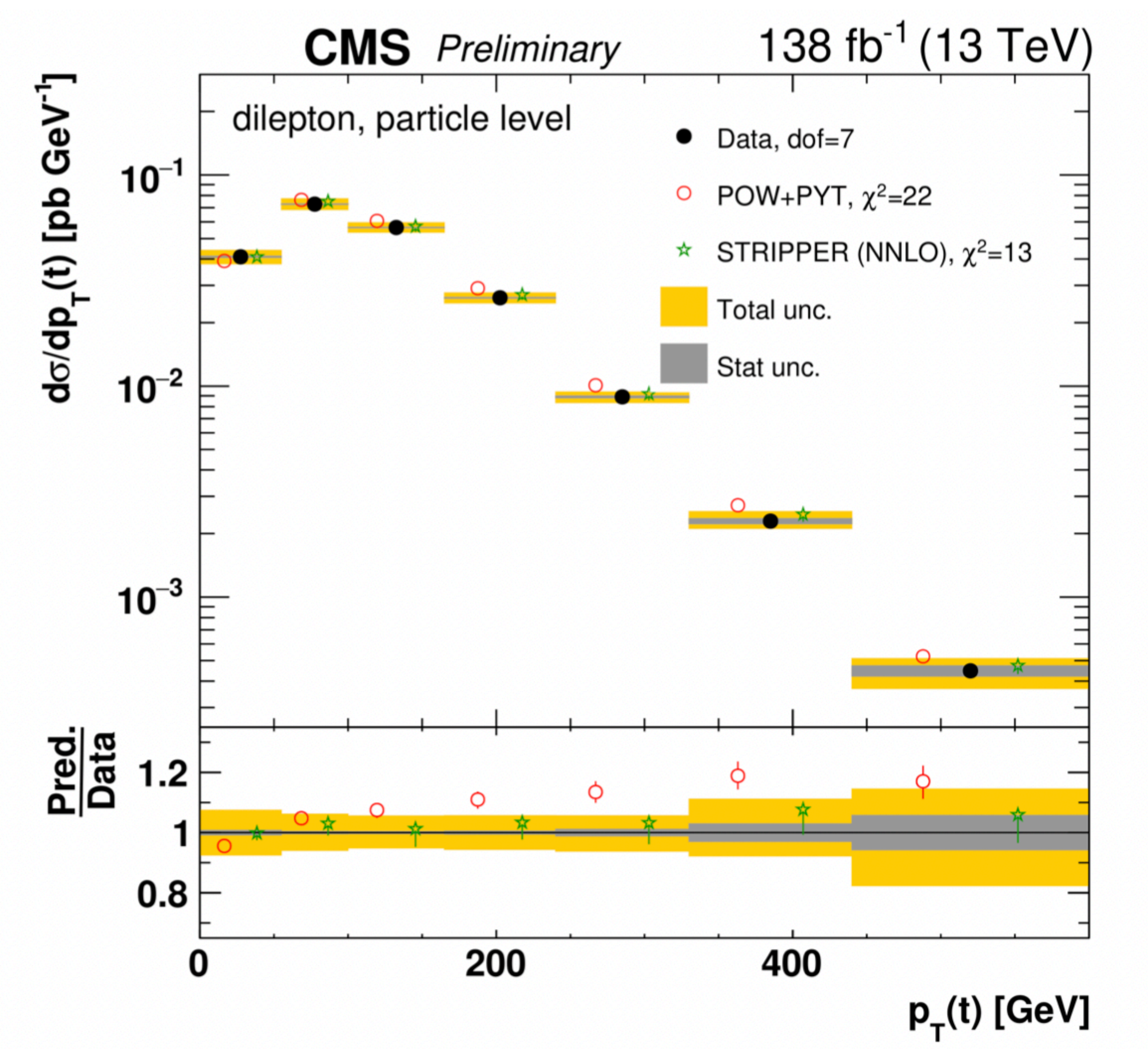
Careful definitions needed



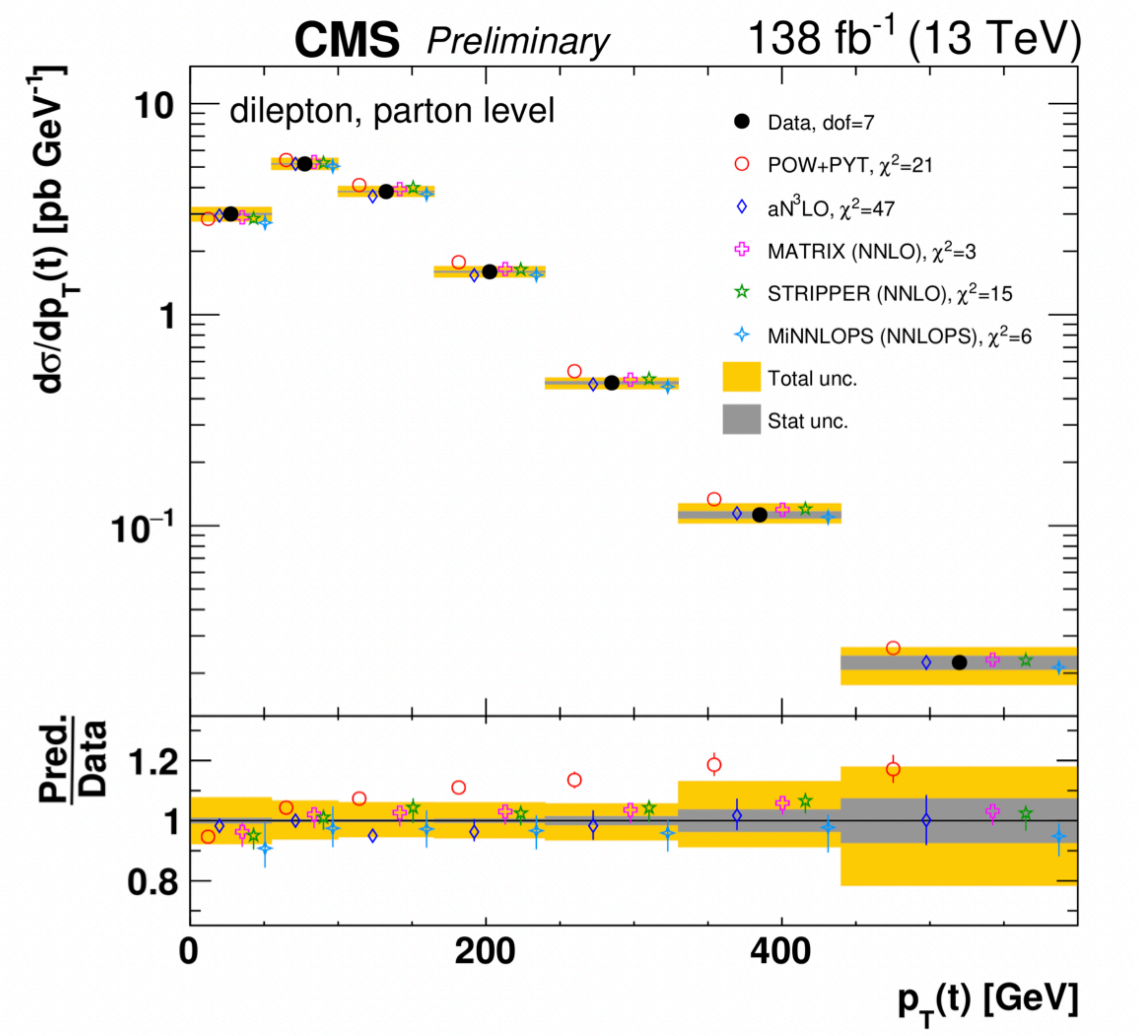
Czakon, Mitov, Poncelet, 2008.11133

Multitude of tools at parton level

Reconstructed top-quark pT with applied fiducial cuts



Extrapolated top-quark pT

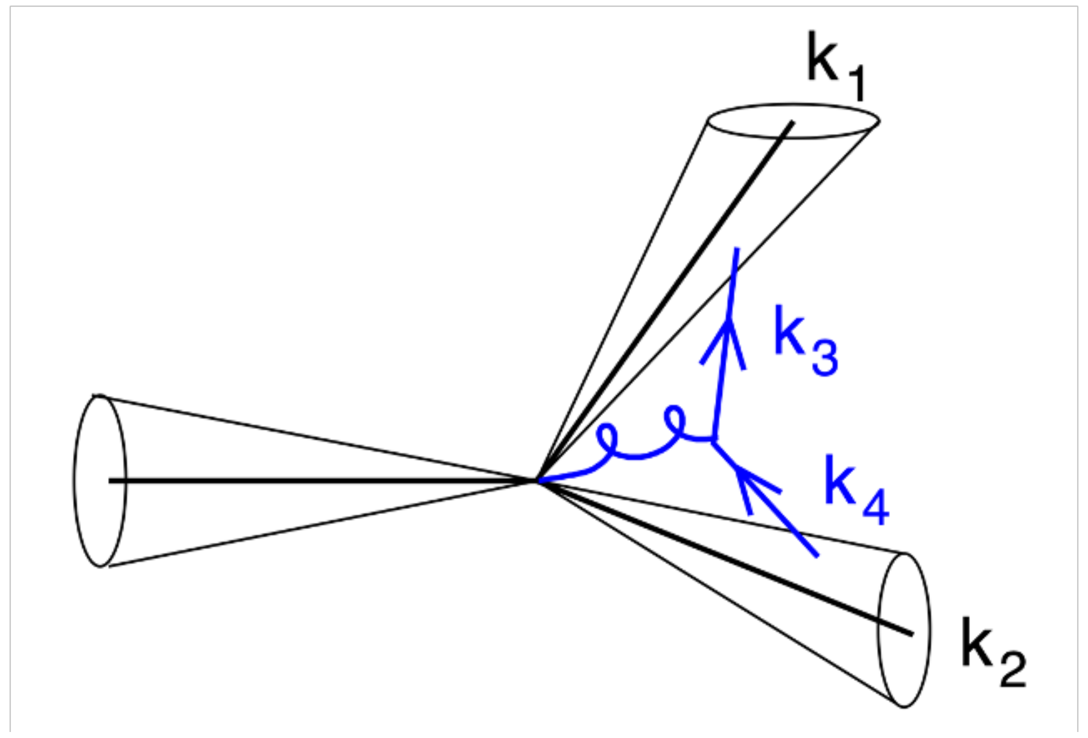


CMS-PAS-TOP-20-006

Clearly improved description through NNLO QCD corrections → translates to the extrapolation
Reason: NNLO K-factors are similar for fiducial & inclusive spectrum in this case

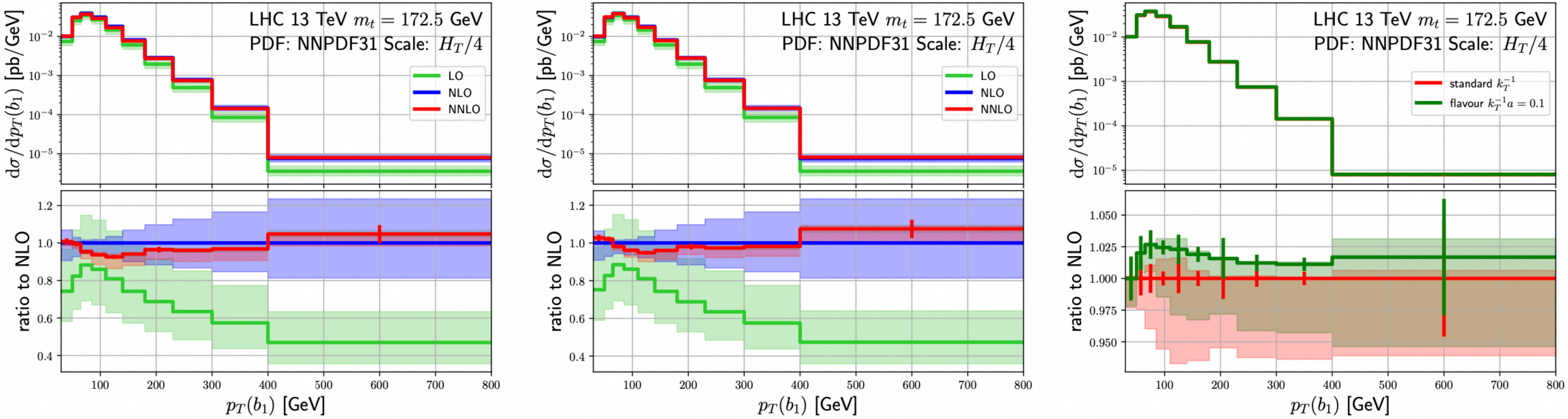
Flavour anti-kT algorithm

- Flavor-sensitive jet algorithms are needed due to this type of configurations



- Originally problem solved with the flavour kT algorithm of Banfi, Salam, Zanderighi `06
- A flavour anti-kT algorithm has been proposed in Czakon, Mitov, Poncelet, 2205.11879

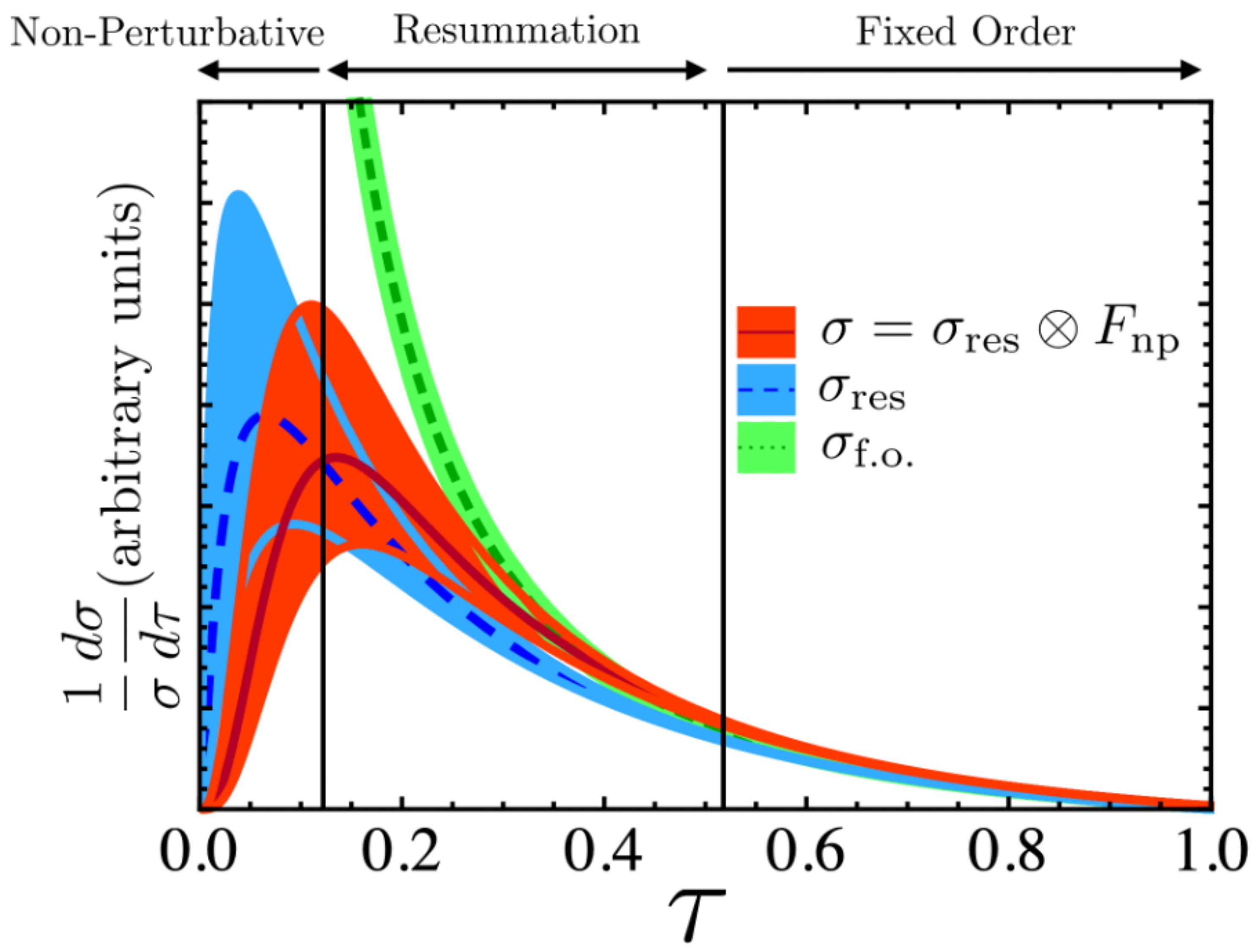
$pp \to t\bar{t} \to l\bar{l}\nu\bar{\nu} + 2b$-jets



Czakon, Mitov, Poncelet, 2205.11879

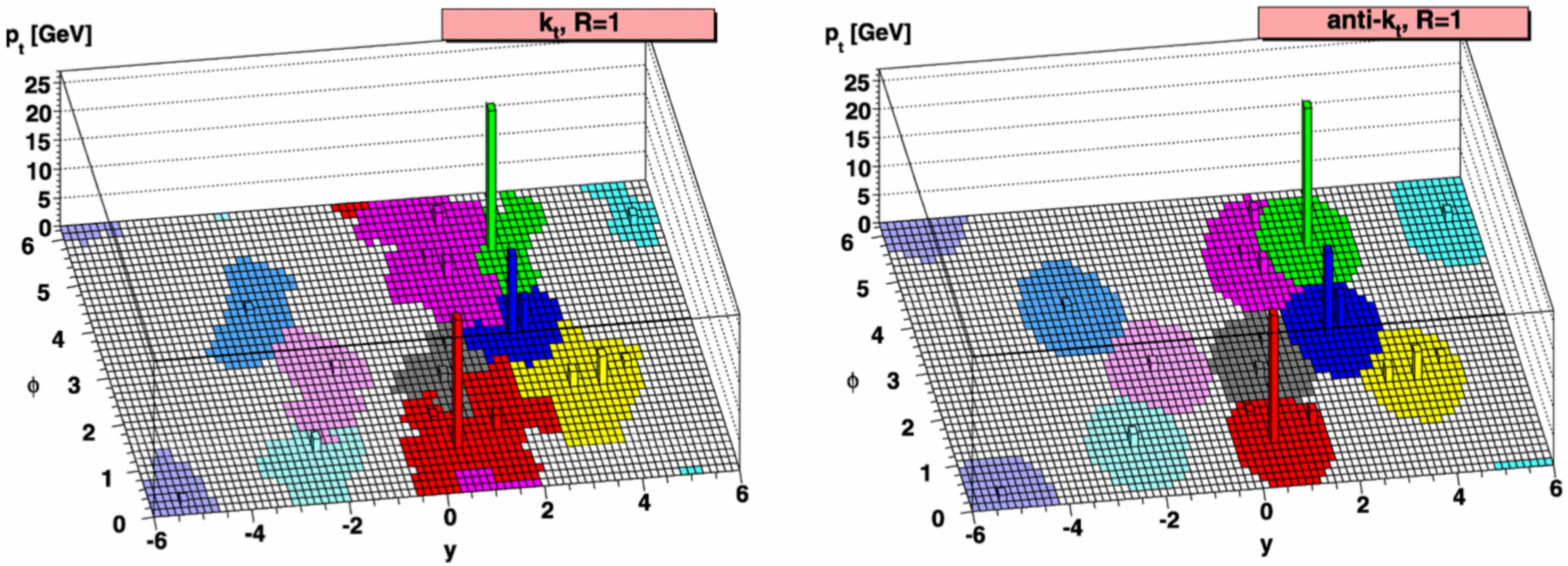
Jet algorithms

Relevance of infrared safety



Reproduced from Larkoski, Moult, Nachman, '17

Classic summary in Salam, '09



Sequential recombination according to a distance measure

Final state

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Initial state

$$d_{iB} = p_{ti}^{2p}$$

Flavoured jet algorithms

- Flavor k_T algorithm Banfi, Salam, Zanderighi, '06

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^\alpha & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

$0 < \alpha \leq 2$ typically $\alpha = 2$

$$d_{i\overset{(-)}{B}} = \begin{cases} \max(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^\alpha \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^{2-\alpha} & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^\alpha & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

$$k_{tB}(y) = \sum_i k_{ti} \left(\Theta(y_i - y) + \Theta(y - y_i)\, e^{y_i - y}\right)$$

$$k_{t\bar{B}}(y) = \sum k_{ti} \left(\Theta(y - y_i) + \Theta(y_i - y)\, e^{y - y_i}\right)$$

jet flavor = net flavor or net flavor modulo 2, with flavor of relevant quarks +1 or -1

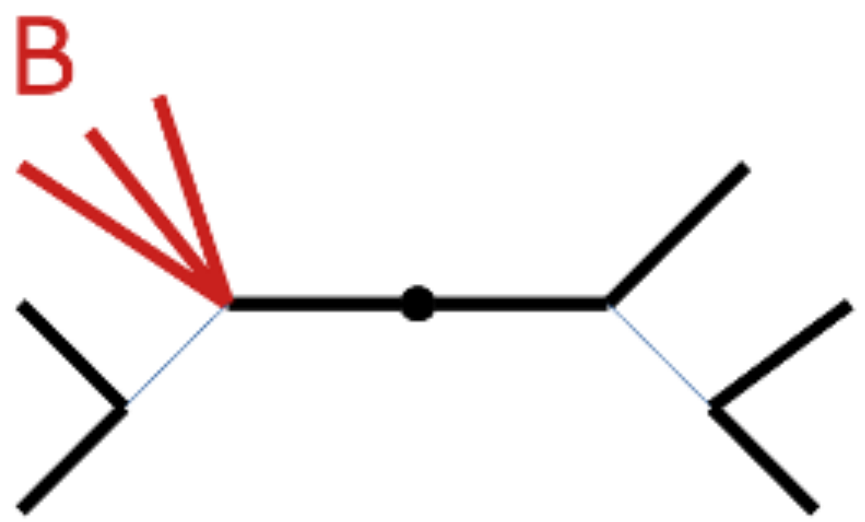
- Flavor anti-k_T algorithm proposal **MC**, A. Mitov, R. Poncelet

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{if } i, j \text{ is a flavoured pair} \\ 1 & \text{else} \end{cases}$$

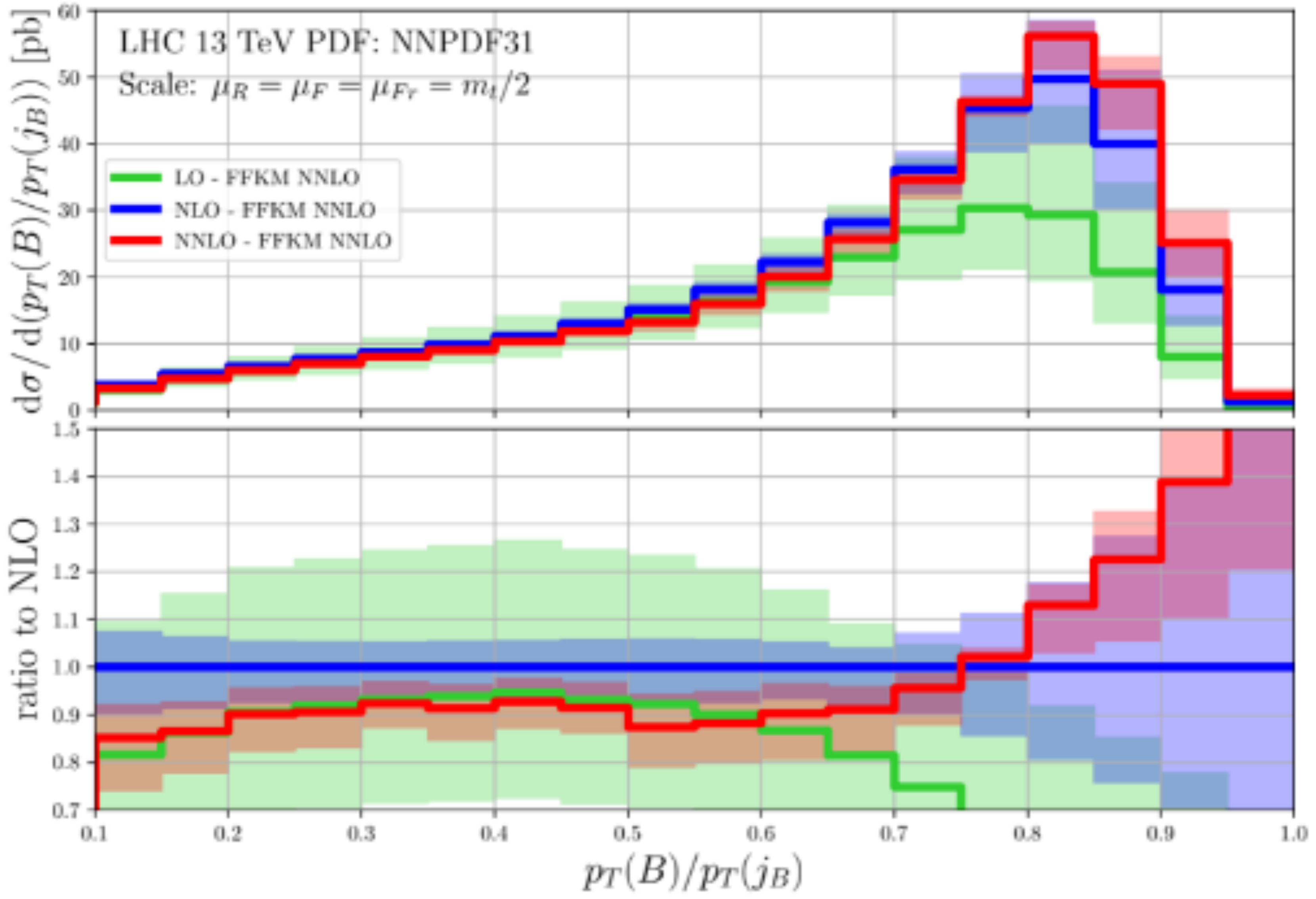
$$\mathcal{S}_{q\bar{q}}^a = 1 - \theta\,(1 - x) \cos\left(\frac{\pi}{2} x\right) \quad \text{with} \quad x = \frac{k_T(q)^2 + k_T(\bar{q})^2}{a 2 k_{T,\max}^2}$$

B-hadron observables through fragmentation

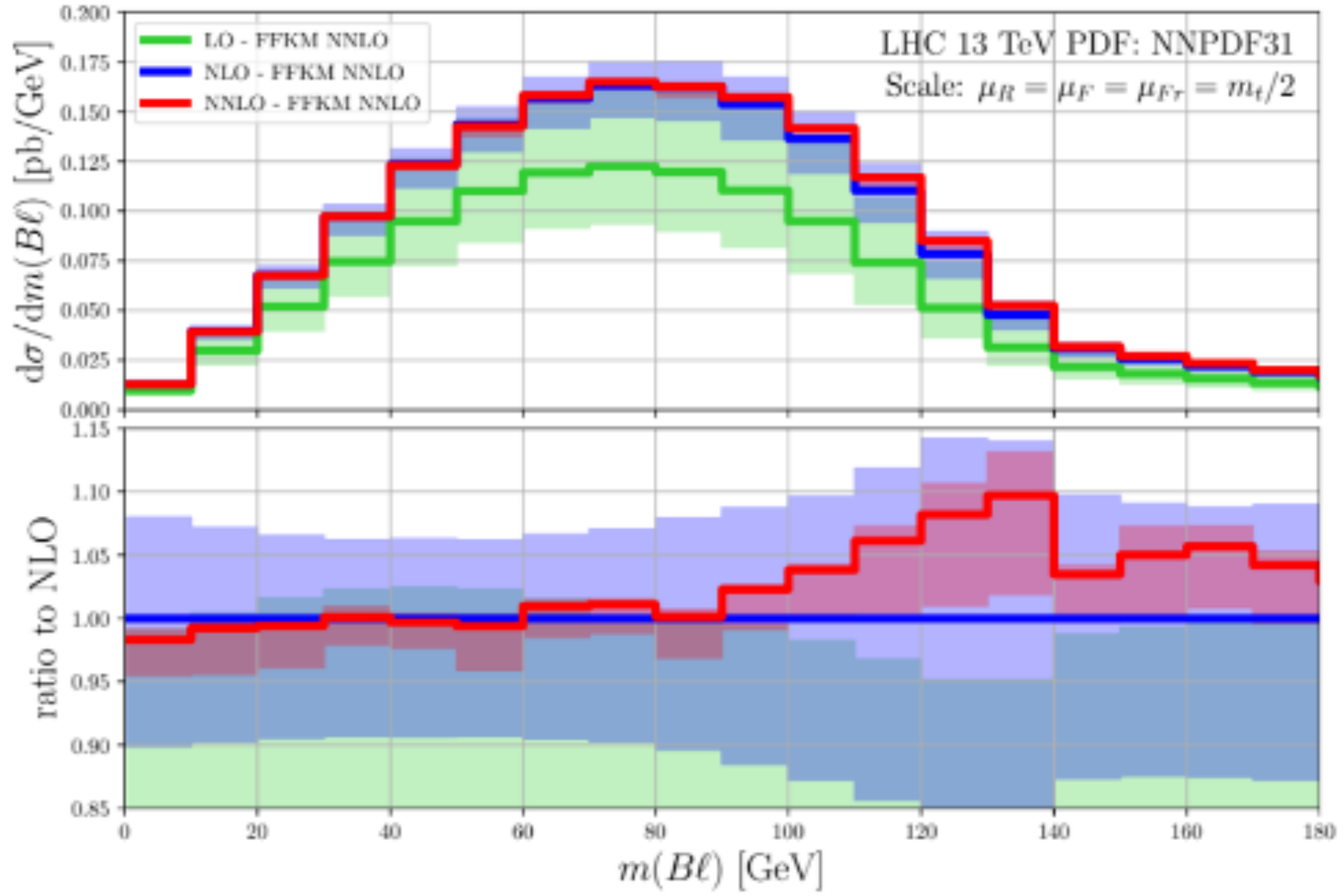
$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}b + X$$

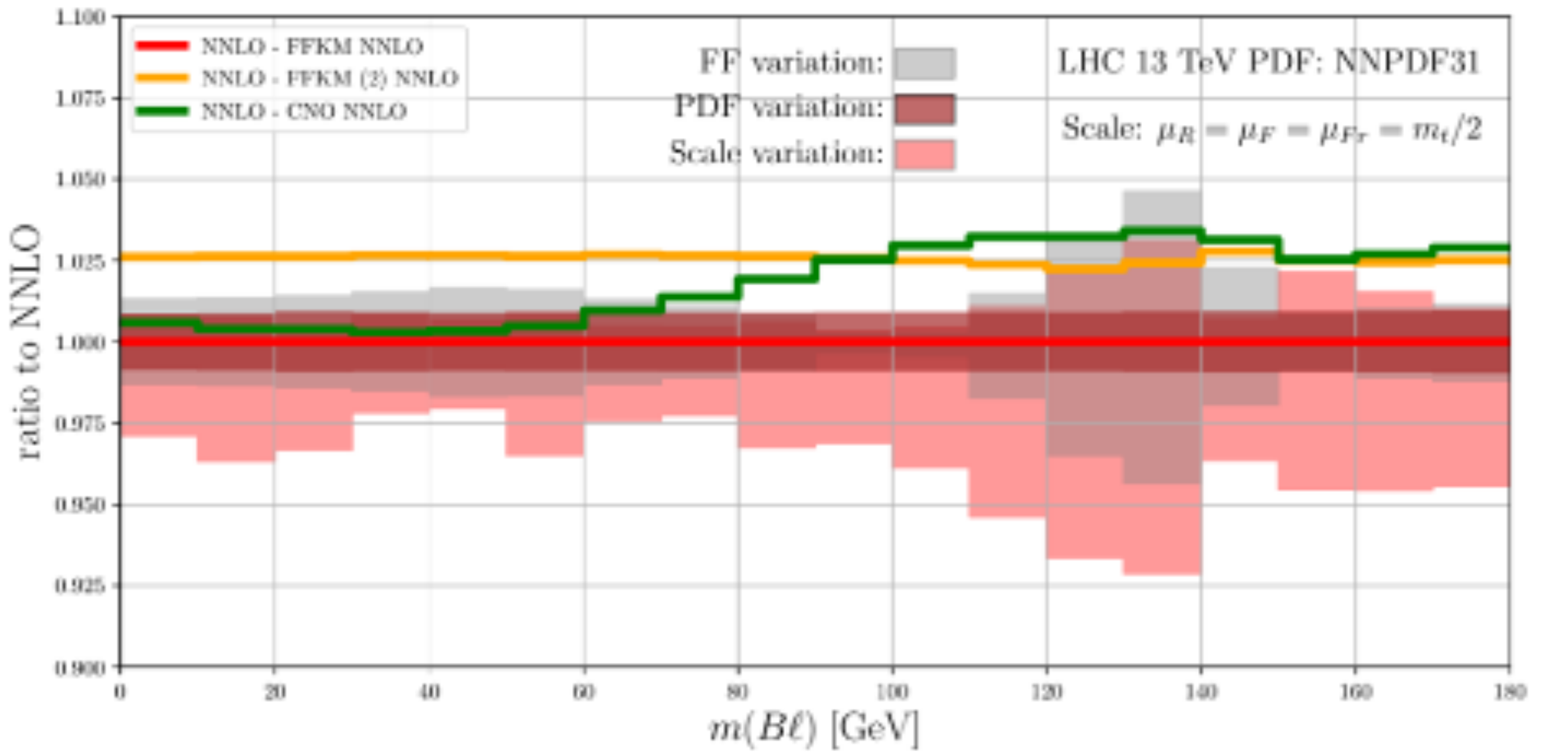


pT(B)/pT(jB): sensitive to B-hadron fraction x



m(lB): sensitive to top-quark mass

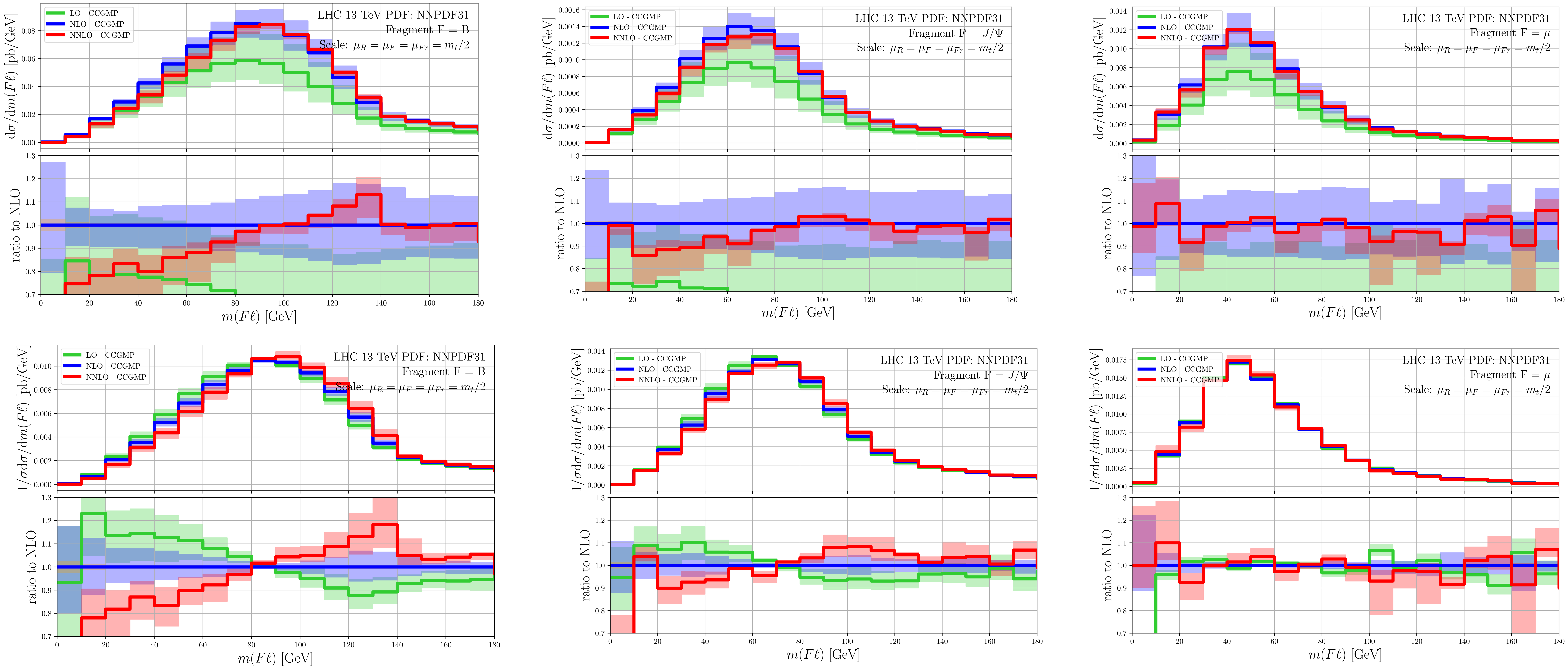




Czakon, Generet, Mitov and Poncelet, 2210.06078

B-hadron observables through fragmentation

A step further and we can also describe B-hadron decays

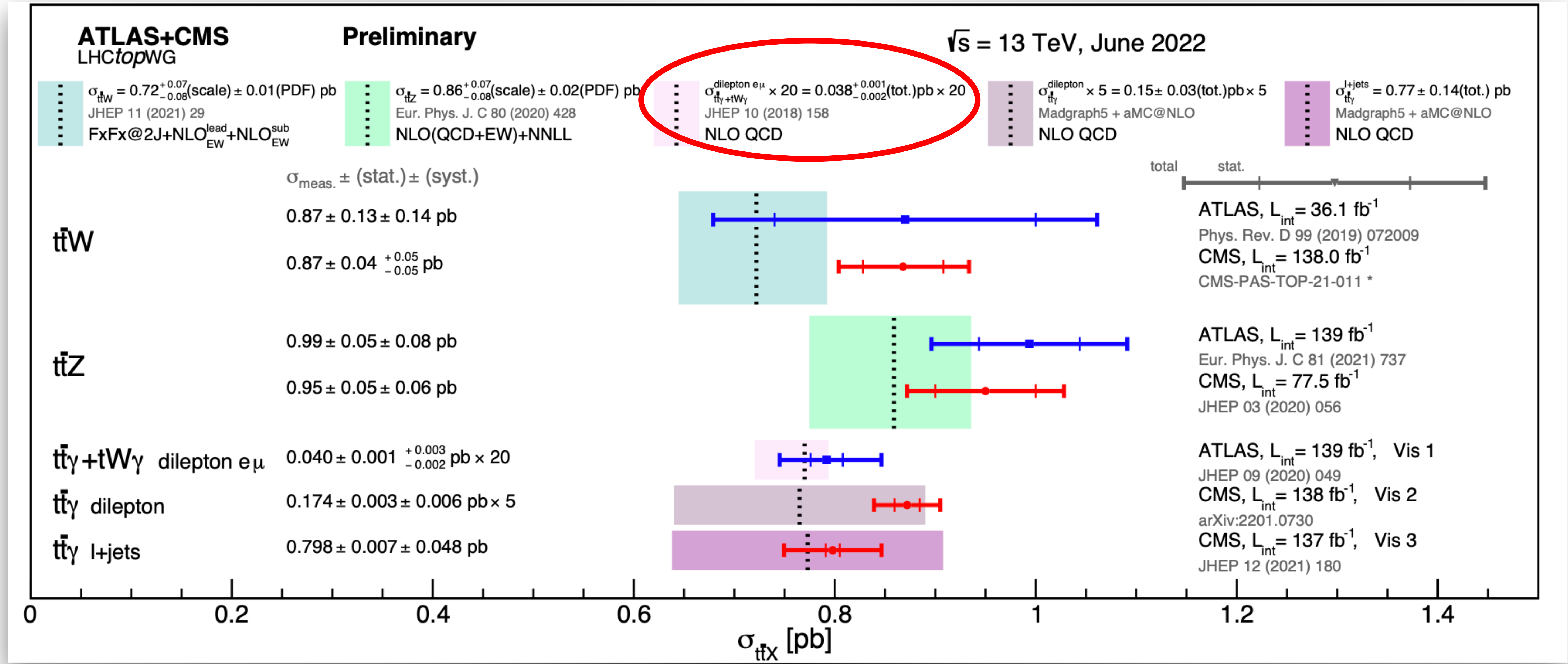


Czakon, Generet, Mitov and Poncelet, 2210.06078

Associated $t\bar{t}$ Production

- More exclusive final states are produced @ LHC

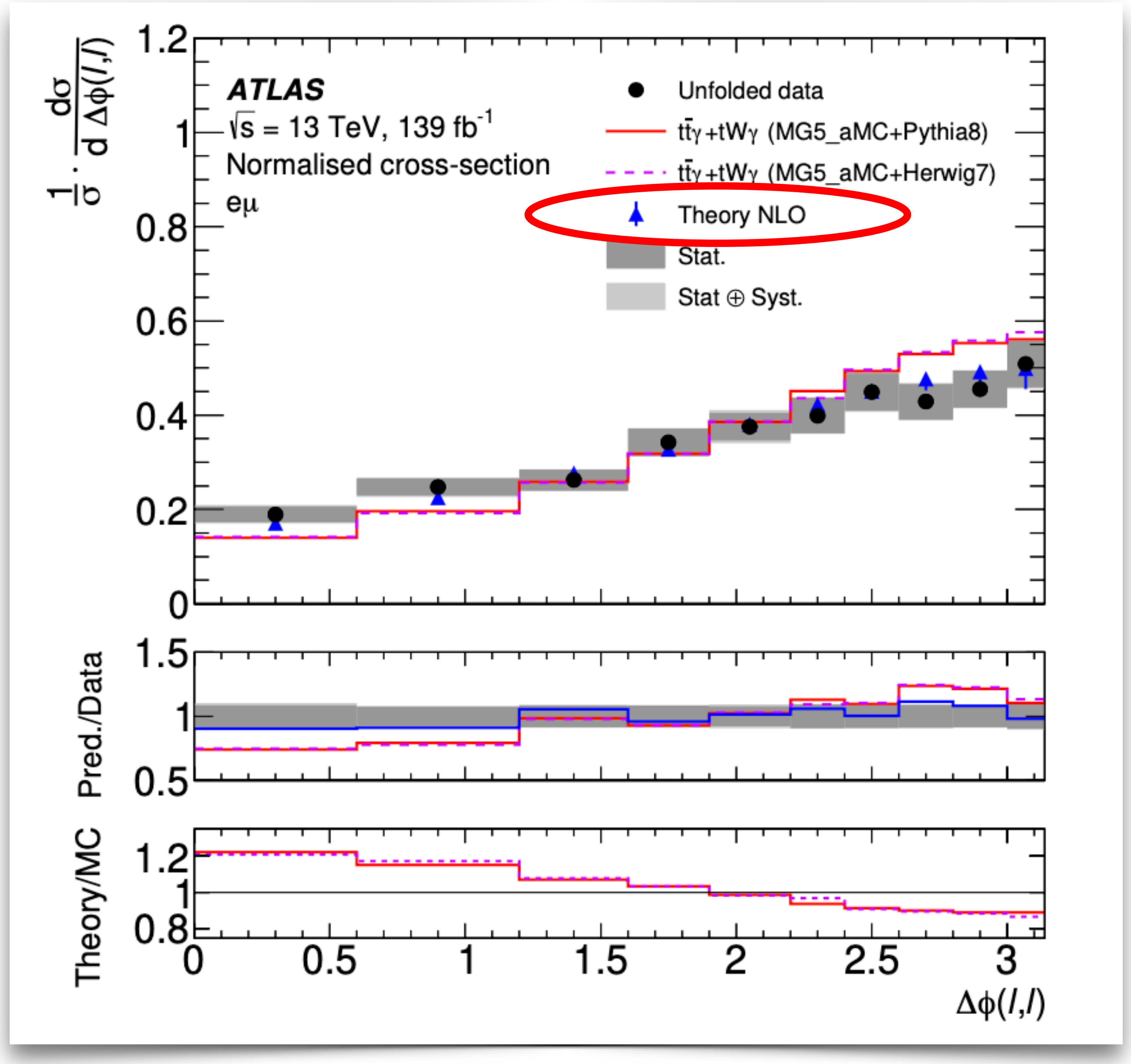
$$pp \to t\bar{t} + X, X = \gamma, W^{\pm}, Z$$



Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	$\lvert\eta(\gamma)\rvert$ p-value	$\Delta R(\gamma,\ell)_{\min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{\min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	$\lvert\Delta\eta(\ell,\ell)\rvert$ p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

χ^2/ndf and p-values between measured normalised cross sections and various predictions from MC simulations and NLO calculation

$$pp \to \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b\bar{b}\gamma$$



- NLO QCD full off-shell predictions for $t\bar{t}\gamma$
  - Di-lepton channel

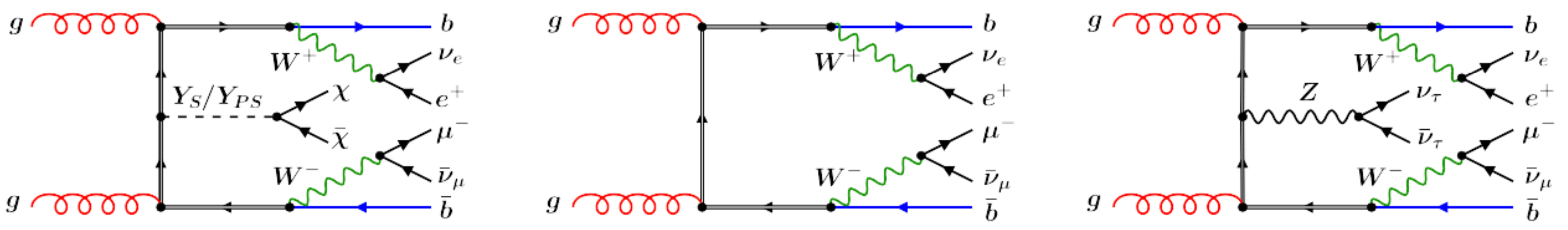
Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20
ATLAS Collaboration '20

Application: BSM Exclusion Limits

NLO ttZ

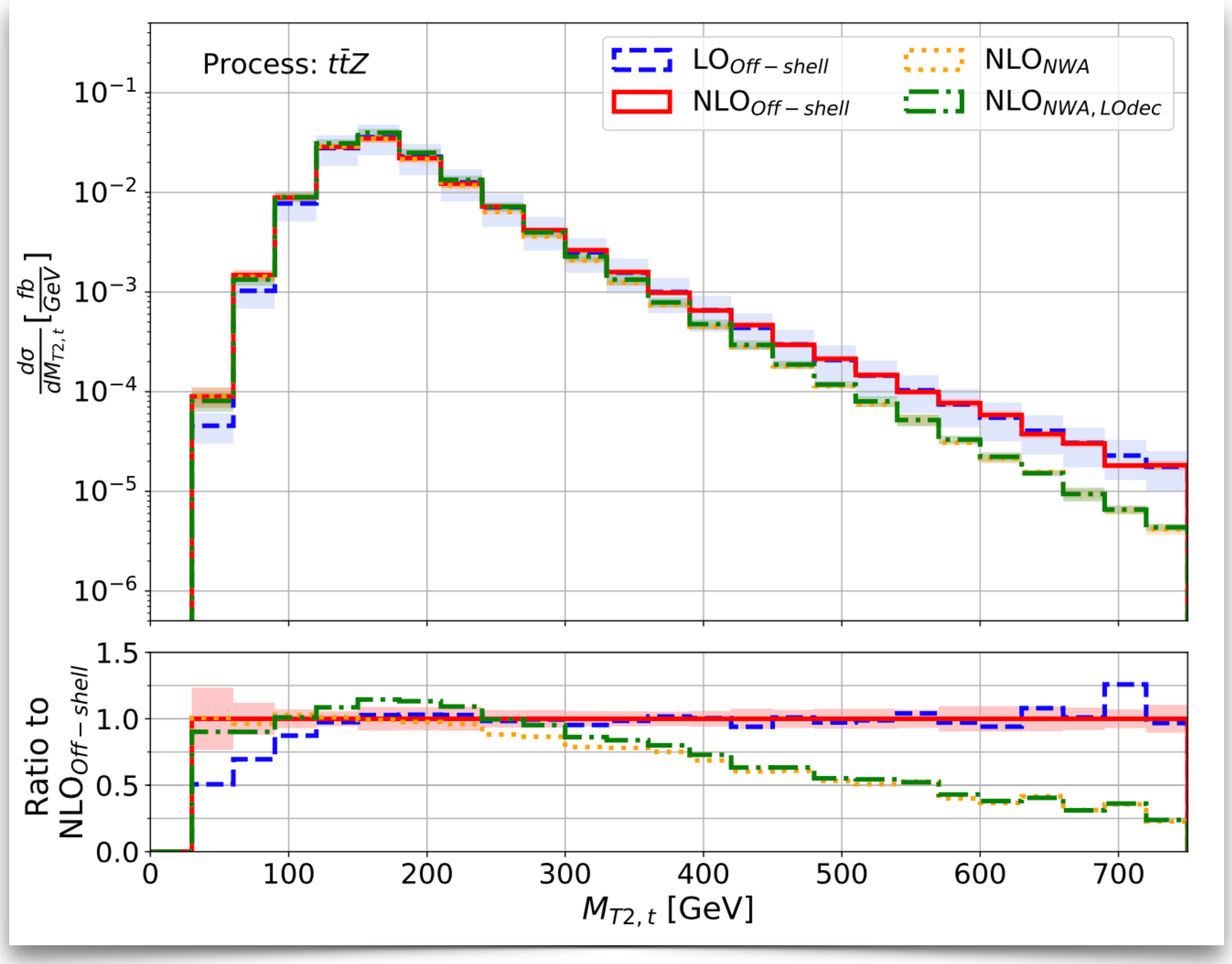
- BSM ➪ Kinematical edges & high p_T regions
- $t\bar{t} + DM$ ➪ Top quark backgrounds: $t\bar{t}$ & $t\bar{t}Z$
- Observable ➪ $M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}

$$pp \to t\bar{t} + Y_{S/PS} \to W^+W^-b\bar{b} + Y_{S/PS} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b} + \chi\chi$$



Before & after applying additional cuts

Process	Order	Scale	σ_{uncut} [fb]	σ_{cut} [fb]	$\sigma_{\text{cut}}/\sigma_{\text{uncut}}$	Events for $L = 300$ fb^{-1}
$t\bar{t}$ NWA	LO	$H_T/4$	1061	0	0.0%	0
	LO	$E_T/4$	984	0	0.0%	0
	LO	m_t	854	0	0.0%	0
	NLO	$H_T/4$	1097	0	0.0%	0
	NLO, LO dec	$H_T/4$	1271	0	0.0%	0
$t\bar{t}Z$ NWA	LO	$H_T/3$	0.1223	0.0130	11%	47
	LO	$E_T/3$	0.1052	0.0116	11%	42
	LO	$m_t + m_Z/2$	0.1094	0.0134	12%	48
	NLO	$H_T/3$	0.1226	0.0130	11%	47
	NLO, LO dec	$H_T/3$	0.1364	0.0140	10%	50
$t\bar{t}$ Off-shell	LO	$H_T/4$	1067	0.0144	0.0013%	17
	LO	$E_T/4$	989	0.0131	0.0013%	16
	LO	m_t	861	0.0150	0.0017%	18
	NLO	$H_T/4$	1101	0.0156	0.0014%	19
$t\bar{t}Z$ Off-shell	LO	$H_T/3$	0.1262	0.0135	11%	49
	LO	$E_T/3$	0.1042	0.0115	11%	41
	LO	$m_t + m_Z/2$	0.1135	0.0140	12%	50
	NLO	$H_T/3$	0.1269	0.0134	11%	48



- After cuts 25% of events come from $t\bar{t}$
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

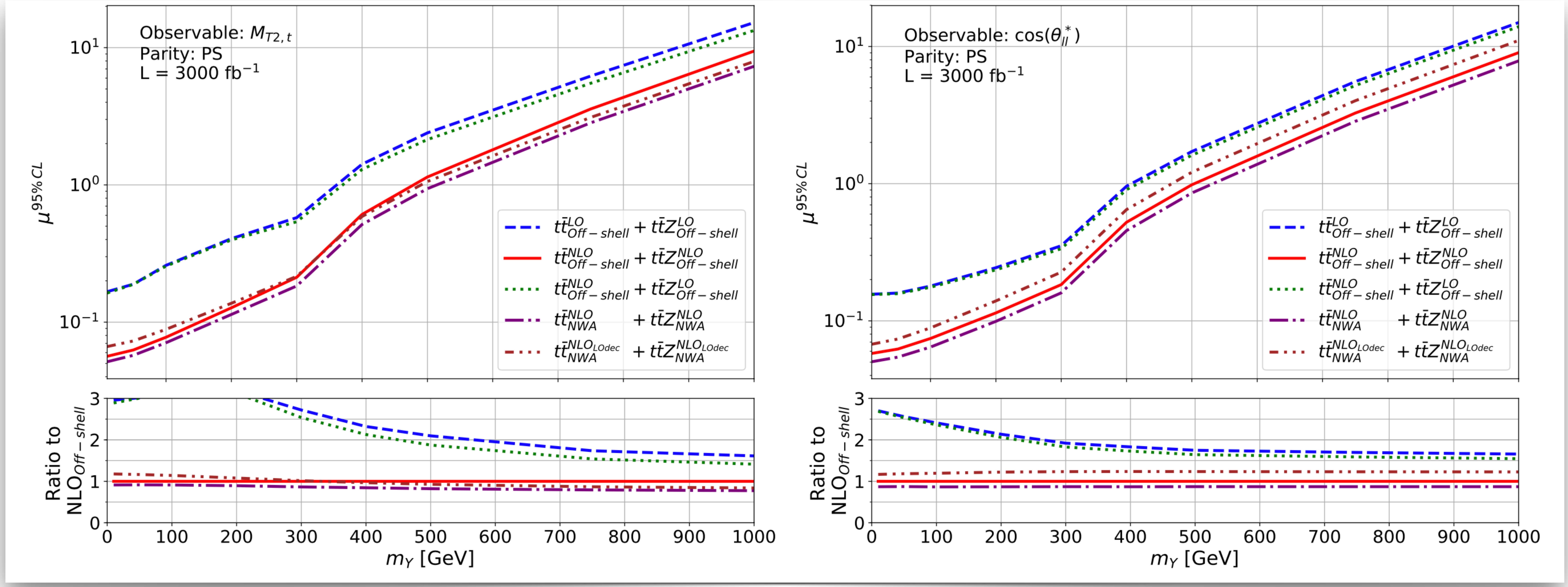
Hermann, Worek '21

Application: BSM Exclusion Limits

NLO ttZ

Comparison of signal strength exclusion limits

Hermann, Worek '21



$$M_{T2,t}^2 = \min_{\substack{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2} \\ =\mathbf{p}_{T,\mathrm{miss}}}} [\max\{M_T^2\left(\mathbf{p}_T^{(lb)_1}, \mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{(lb)_2}, \mathbf{p}_T^{\nu_2}\right)\}]$$

$$\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$$

$$M_T^2\left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i}\right) = M_{(lb)_i}^2 + 2\left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i} \cdot \mathbf{p}_T^{\nu_i}\right)$$

Conclusions

Future directions

- Higher-order calculations:
  1. Higher multiplicity at NNLO (four final states) and N3LO (two final states)
  2. Several mass scales on internal and external lines (top quark and EW bosons)
  3. Combination with electroweak corrections
  4. Inclusion of decays in the Narrow Width Approximation
  5. Direct evaluation of cross sections for the actual final state (off-shell, interferences, ...)

- Resummation:
  1. Analytic resummation for selected processes
  2. Parton-shower matching and merging at NNLO
  3. NLO parton showers