Higher-order calculations and precision phenomenology

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FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Outline

- Introduction
- NLO calculations
- NNLO
  - jets
  - heavy-quarks
- Beyond NNLO
  - NNLO QCD + NLO EW for dibosons
  - N3LO
- Summary & Outlook

Disclaimer: a (personal) selection of recent fixed order QCD results !

QCD at hadron colliders

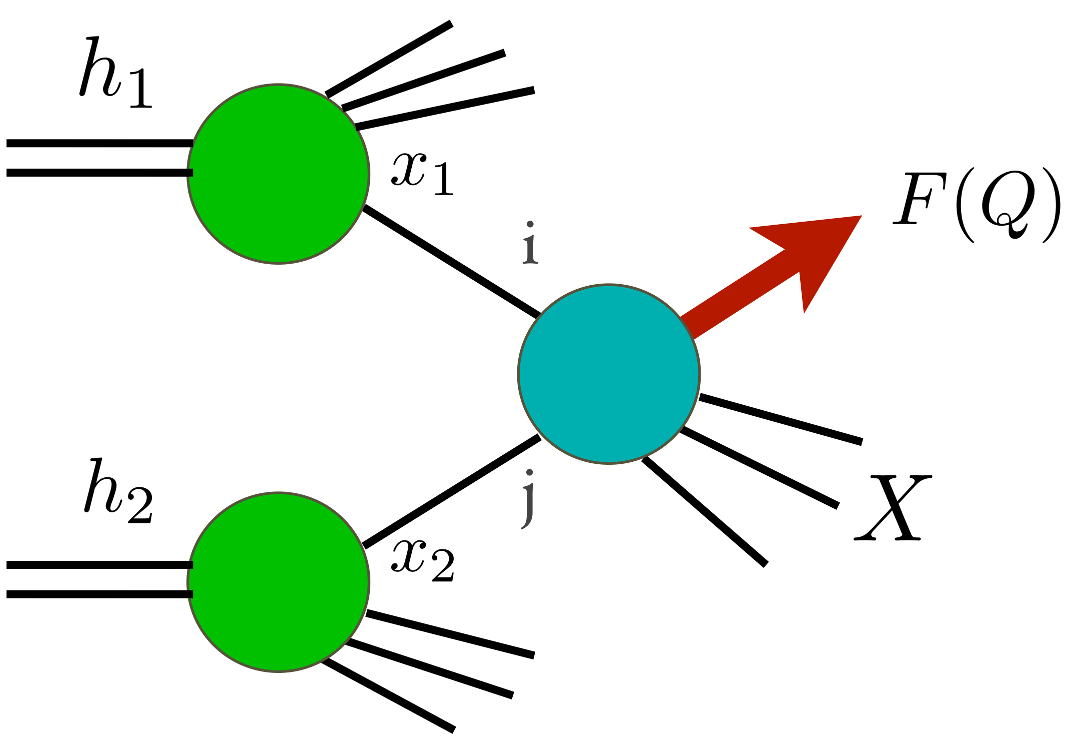
$$\sigma(P_1,P_2) = \sum_{i,j}\int dx_1 dx_2 f_{i/h_1}(x_1,\mu_F^2) f_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2;\mu_F^2,\mu_R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)$$

Parton distributions: universal but not perturbatively computable

Hard partonic cross section: process dependent but computable in perturbation theory

Power-suppressed contributions

Talks by Kassabov, Alekhin, Nadolsky...



The factorisation picture is systematically improvable (until the power-suppressed contributions become quantitative relevant...)

NLO

The NLO revolution has left us with flexible tools that make possible to carry out NLO QCD+EW computations

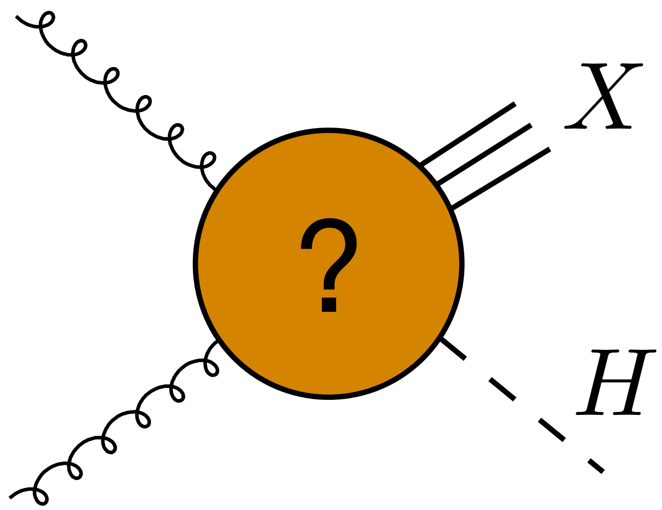
- Realistic final states with off-shell effects and interferences
- Merging to Parton Shower and full deployment into Monte Carlo tools used in experimental analyses

Treatment of QCD IR singularities based on well established CS and FKS methods

Focus is now on NNLO (and beyond) but….

….NLO for loop-induced processes require two-loop amplitudes !

NLO: Higgs at high p_T



Higgs production at high-p_T can be useful to test new physics scenarios

New Physics could change the high-p_T spectrum mildly affecting the inclusive rates

For example: current constraints on the charm Yukawa y_c are rather weak but if y_c is very different from its SM value → effect on Higgs p_T distribution

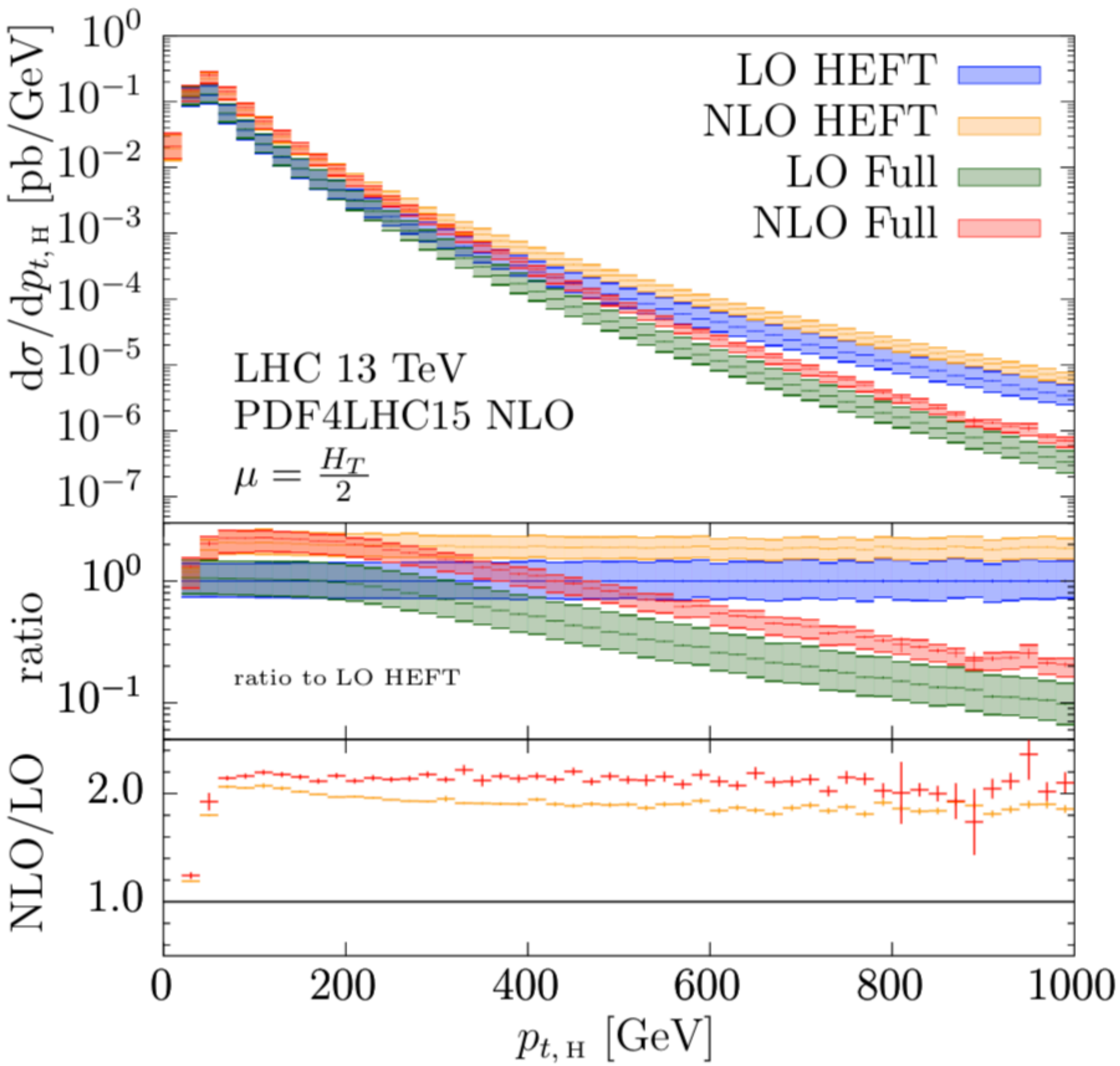
see e.g. Bishara, Haisch,Monni, Re (2016)

Up to very recently the theoretical predictions beyond LO only available in the large-m_t limit

De Florian, Kunszt, MG (1999)
Glosser, Schmidt (2002)
Ravindran, Smith , van Neerven (2002)

Exact NLO calculation requires 2-loop amplitudes with different mass scales: this is at the forefront of current technologies !

NLO: Higgs at high p_T



First exact NLO calculation recently completed numerically

Jones, Kerner, Luisoni (2018)

Trick used: $m_H^2/m_{top}^2 = 12/23$

→ eliminates one scale

K-factor similar to the one obtained in the large-m_{top} limit

Consistent with approximate result valid at large p_T

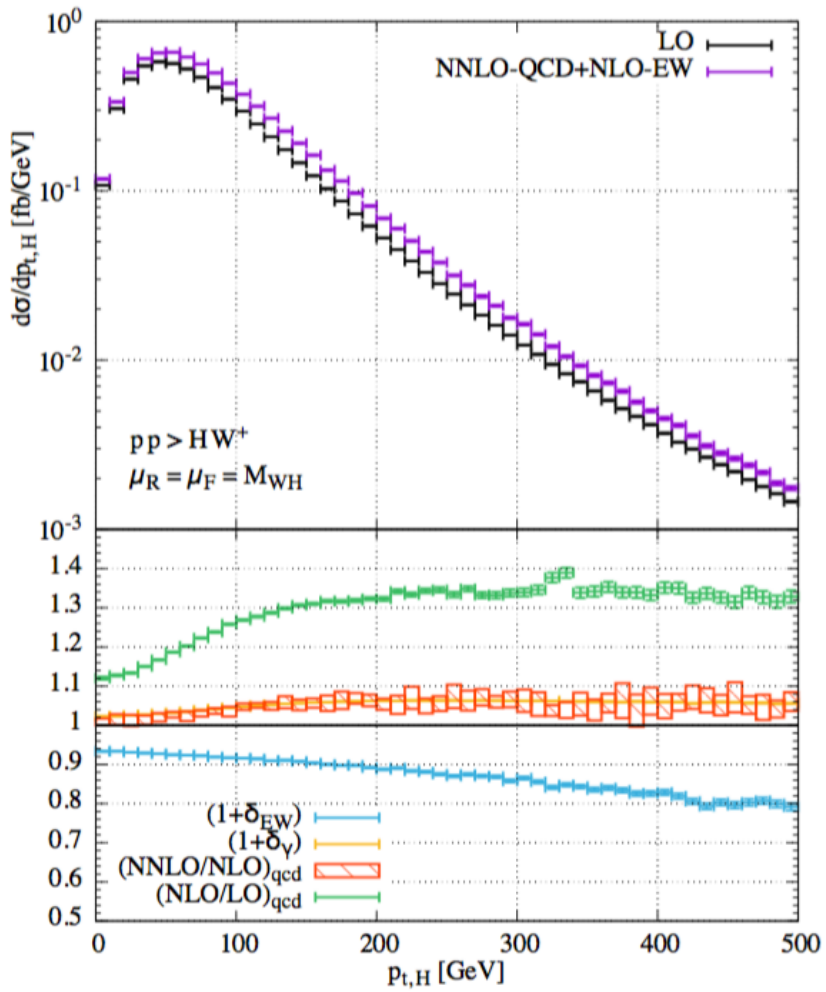
Lindert et al (2018)

$p_\perp^{cut}$	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	$\text{NNLO}^{\text{approximate}}_{\text{lin.unc.}}$ [fb]
400 GeV	$32.0^{+9.1\%}_{-11.6\%}$	$32.0^{+9.4\%}_{-11.9\%}$
430 GeV	$22.1^{+9\%}_{-11.4\%}$	$22.1^{+9.3\%}_{-11.8\%}$
450 GeV	$17.4^{+8.9\%}_{-11.5\%}$	$17.4^{+9.3\%}_{-11.9\%}$

HXSWG ggF subgroup, preliminary

Combined with NNLO in EFT leads to accurate reference predictions for boosted analyses

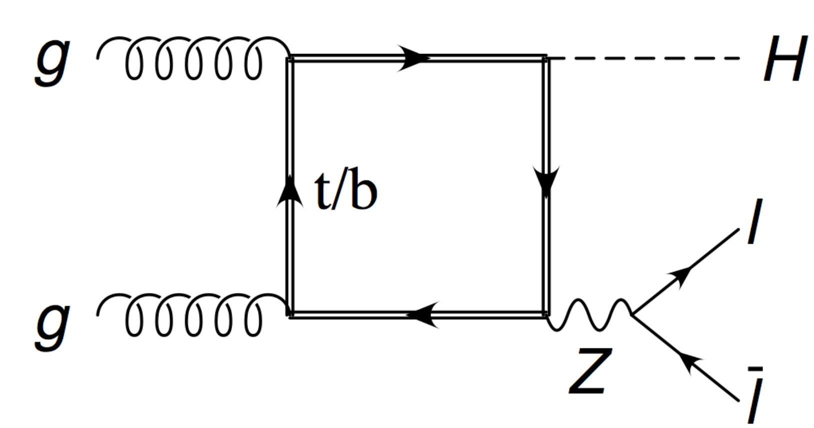
NLO: gg→ZH



S.Dittmaier et al. HXSWG YR4 (2016)

Despite highly accurate NNLO QCD+NLO-EW predictions still ZH not fully under control

gg induced loop contribution (first appears at NNLO and leads to large uncertainties !)



Impact of gg → ZH

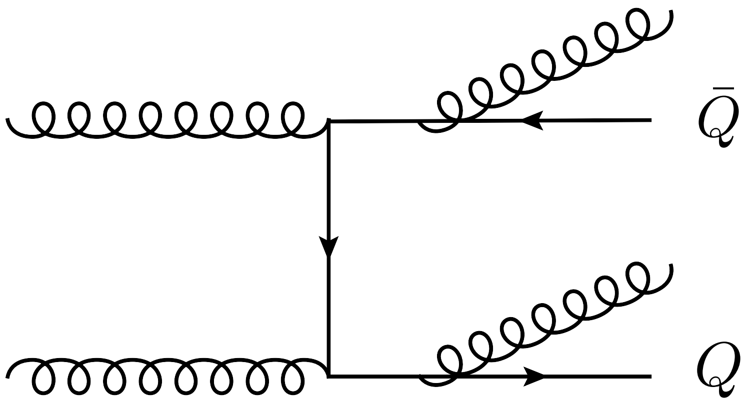
σ (fb)	NLO	NNLO (DY-like)	NNLO	
LHC8	$0.2820^{+2\%}_{-2\%}$	$0.2574^{+3\%}_{-4\%}$	$0.3112^{+3\%}_{-2\%}$	+21%
LHC14	$0.2130^{+10\%}_{-12\%}$	$0.1770^{+7\%}_{-6\%}$	$0.2496^{+5\%}_{-2\%}$	+41%

Very important in the boosted region

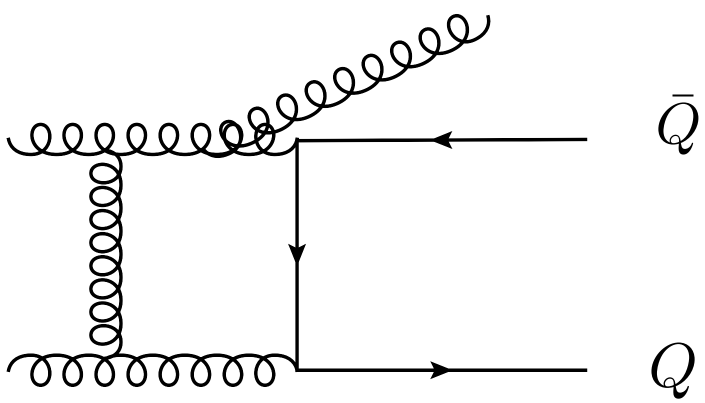
Altenkamp et al. (2012)

NLO corrections known only in large m_t limit (~100%)

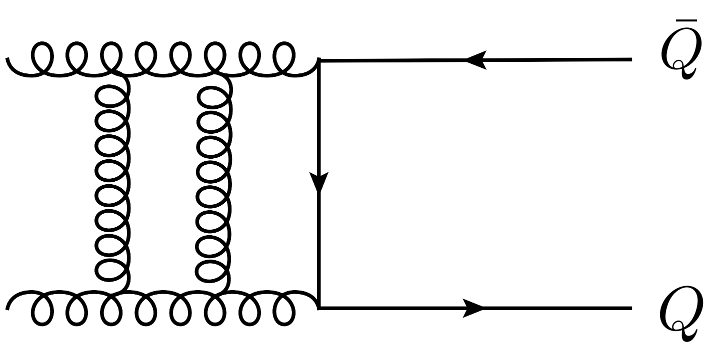
NNLO: building blocks



Tree-level amplitudes with two additional partons



One-loop amplitudes with one additional parton
(to be evaluated in unresolved regions where instabilities may arise)



Two-loop amplitudes → currently the major bottleneck (new class of functions, charting new territory…)

All the three contributions separately divergent !

Crucial to keep the calculation fully differential: corrections for fiducial and inclusive rates may be significantly different (H in VBF, WW…)

NNLO methods

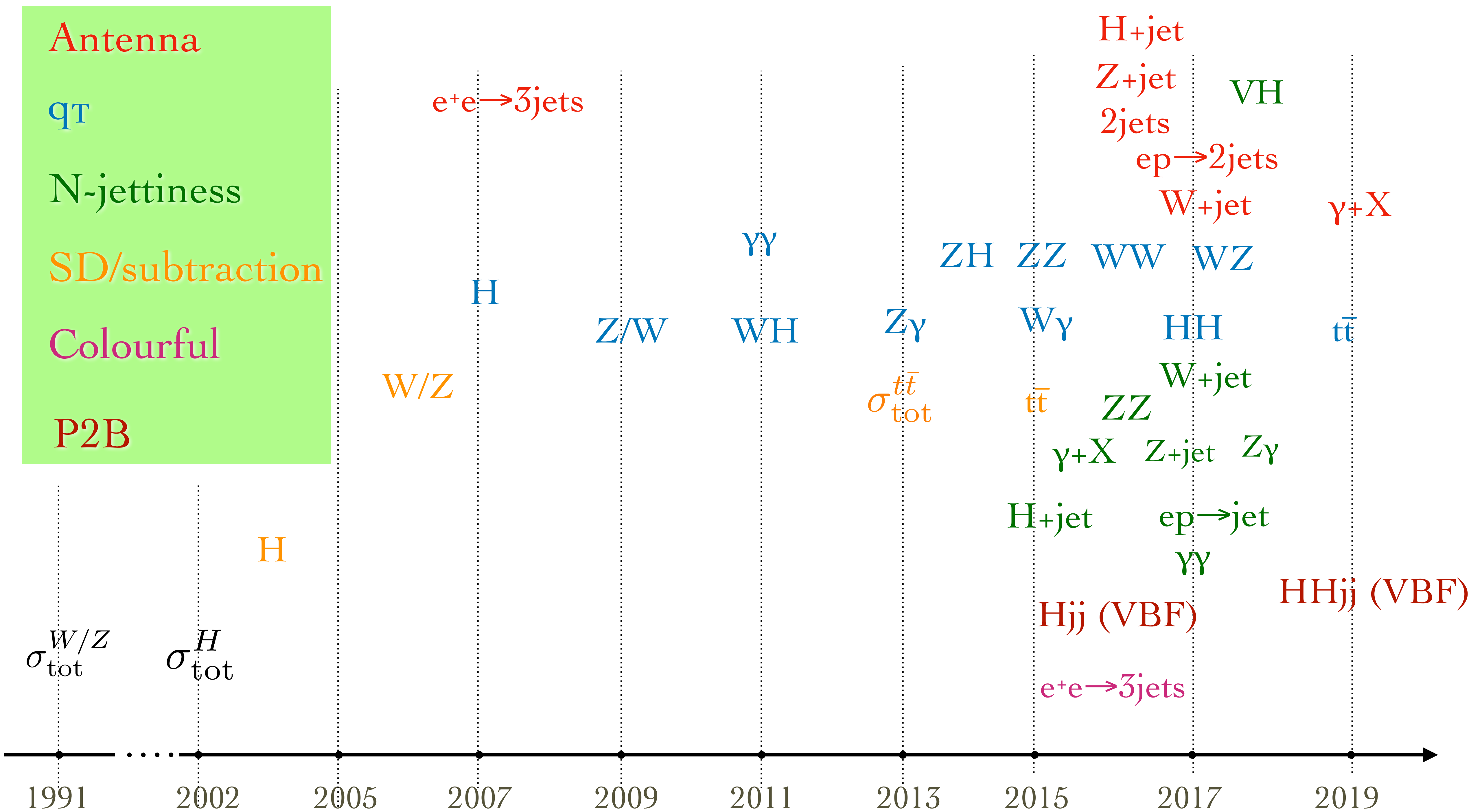
Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities
  - Sector Decomposition (SD) — Binoth, Heinrich (2000,2004); Anastasiou, Melnikov, Petriello (2004)
  - antenna subtraction — Gehrmann, Glover (2005)
  - colourful subtraction — Somogyi, Trocsanyi, Del Duca (2005, 2007)
  - subtraction+sector decomposition (stripper, nested subtractions…) — Czakon (2010,2011); Boughezal, Melnikov, Petriello (2011); Caola, Melnikov, Rontsch (2017)

- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process
  - q_T subtraction — Catani, MG (2007)
  - N-jettiness method — Boughezal, Focke,Liu, Petriello (2015); Tackmann et al. (2015)
  - born projection (P2B) method — Cacciari, Dreyer, Karlberg, Salam,Zanderighi (2015)

Search for an "ideal" subtraction method that can be applied as easily as CS or FKS at NLO is still subject of intense work

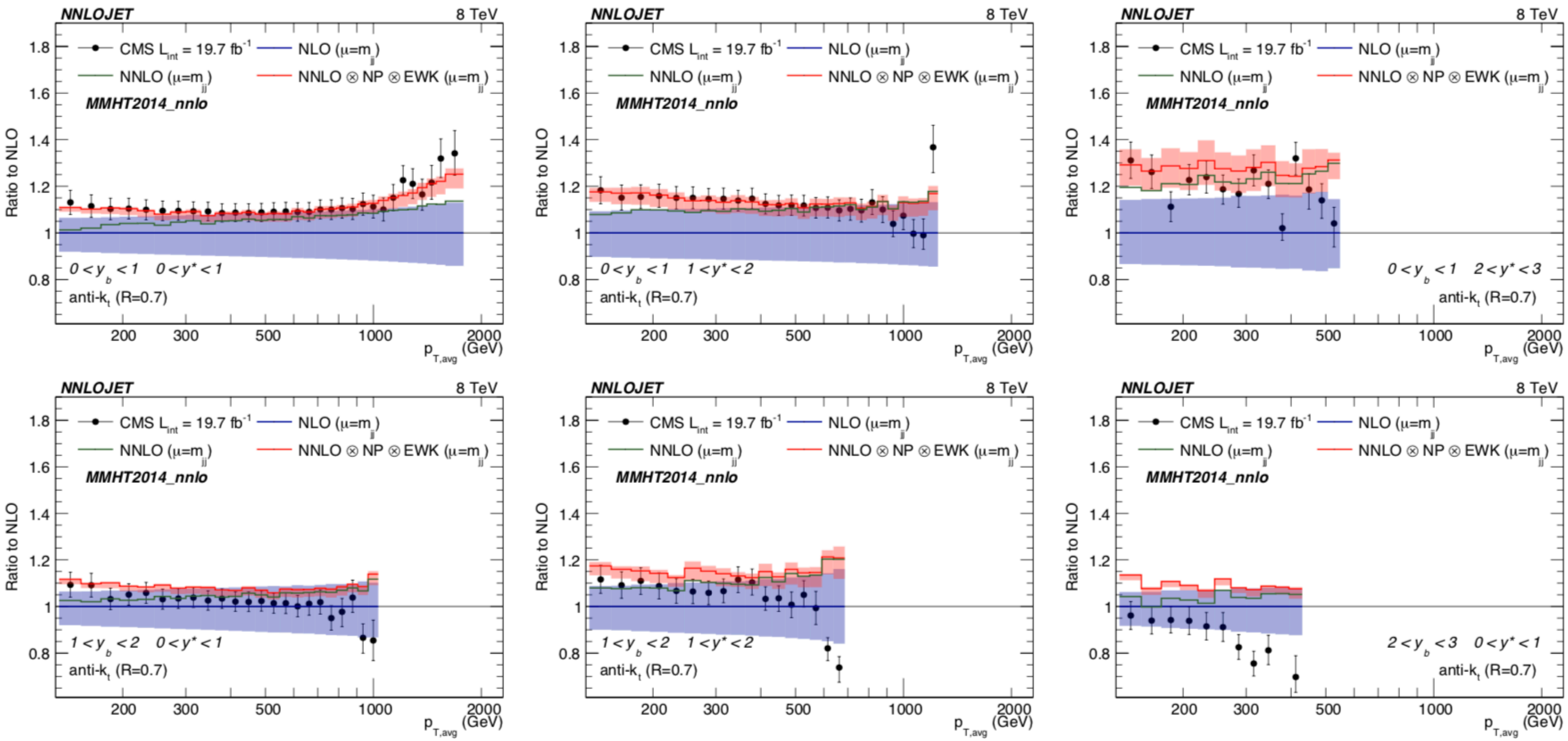
NNLO progress



NNLO results lead to much better description of the data

Jets

Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires (2019)



Triple differential di-jet cross section as a function of the average p_T of the leading jets $y^*=|y_1-y_2|/2$ and $y_b=|y_1+y_2|/2$

NNLO, NPxEW of the same order

EW correction included assuming factorisation

Heavy quarks

Catani, Devoto, Kallweit,Mazzitelli, Sargsyan, MG (2019)

Extension of q_T subtraction to heavy-quark production now completed

$$d\sigma^{t\bar{t}}_{(N)NLO} = \mathcal{H}^{t\bar{t}}_{(N)NLO} \otimes d\sigma^{t\bar{t}}_{LO} + \left[d\sigma^{t\bar{t}+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

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✅ Modified subtraction counterterm fully known

Additional perturbative ingredient: soft anomalous dimension $\boldsymbol{\Gamma}_t$ known at NNLO

Mitov, Sterman, Sung (2009)
Neubert et al (2009)

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✅ Additional soft contributions needed to evaluate $\mathcal{H}^{t\bar{t}}_{NNLO}$

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Inclusive cross section

σ_{NNLO} [pb]	Matrix	Top++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$794.0(8)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$
100 TeV	$35215(74)^{+2.8\%}_{-4.7\%}$	$35216^{+2.9\%}_{-4.8\%}$

statistical+systematic — scale uncertainties

Tree and loop amplitudes from Openloops 2 (cross check with Recola)

Two-loop amplitudes from Czakon et al. (0.1% effect at 13 TeV)

Heavy quarks

Catani, Devoto, Kallweit,Mazzitelli, MG (2019)

Fully differential results

LO, NLO and NNLO predictions obtained using NNPDF3.1 PDFs with $\alpha_S(m_Z)$=0.118 at the corresponding order

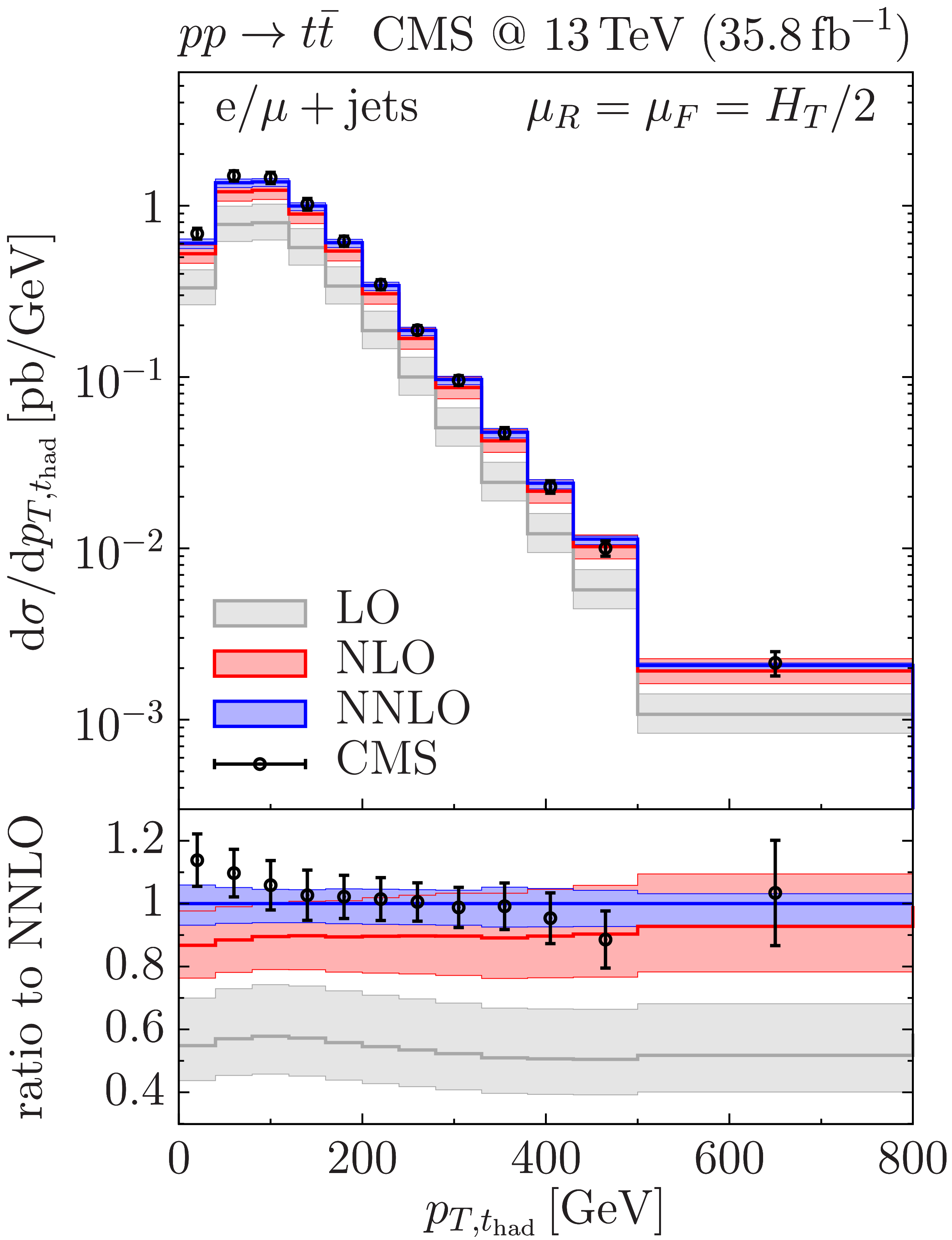
CMS data of CMS-TOP-17-002 in the lepton+jets channel

Extrapolation to parton level in the inclusive phase space

→ Our calculation is carried out without cuts

To compare with data we multiply our absolute predictions by 0.438 (semileptonic BR of the $t\bar{t}$ pair) times 2/3 (only electrons and muons)

Heavy quarks

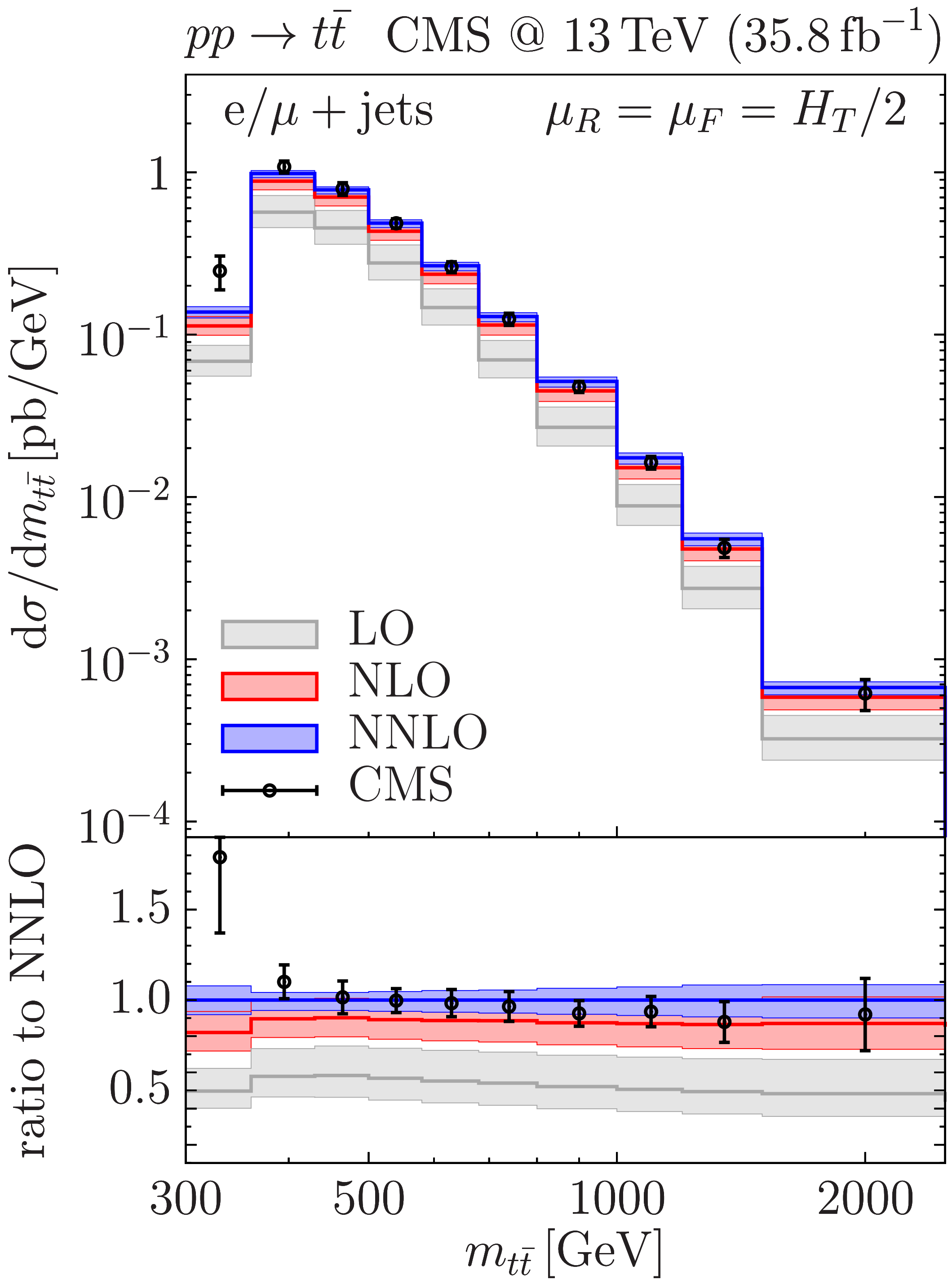


As noted in various previous analyses the measured p_T distribution is slightly softer than the NNLO prediction

Perturbative prediction relatively stable when going from NLO to NNLO

Data and theory are consistent within uncertainties

Heavy quarks



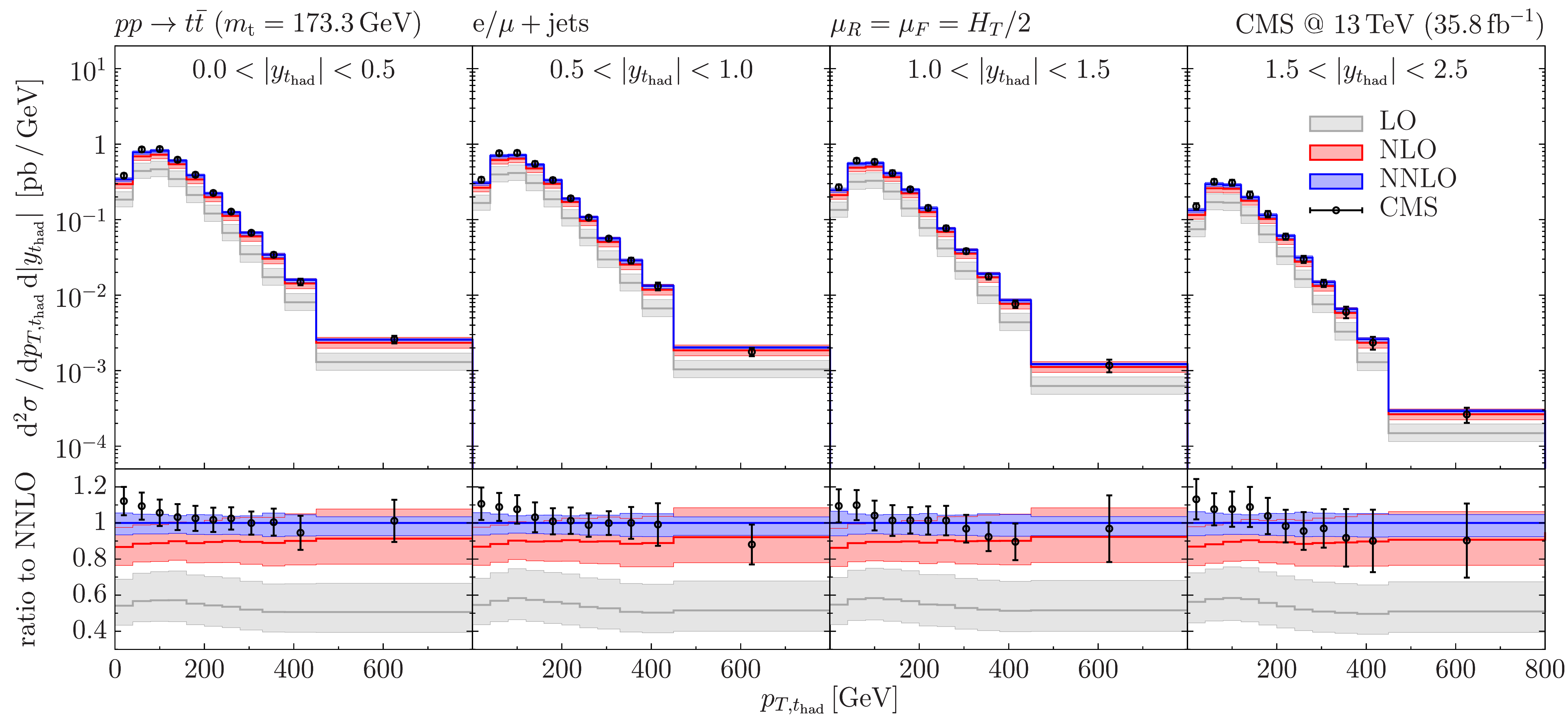
Good description of the data except in the first bin

Issues in extrapolation ? Smaller m_t ?

A smaller m_t (just by about 2 GeV) leads to a higher theoretical prediction in this bin and to small changes at higher m_{tt}

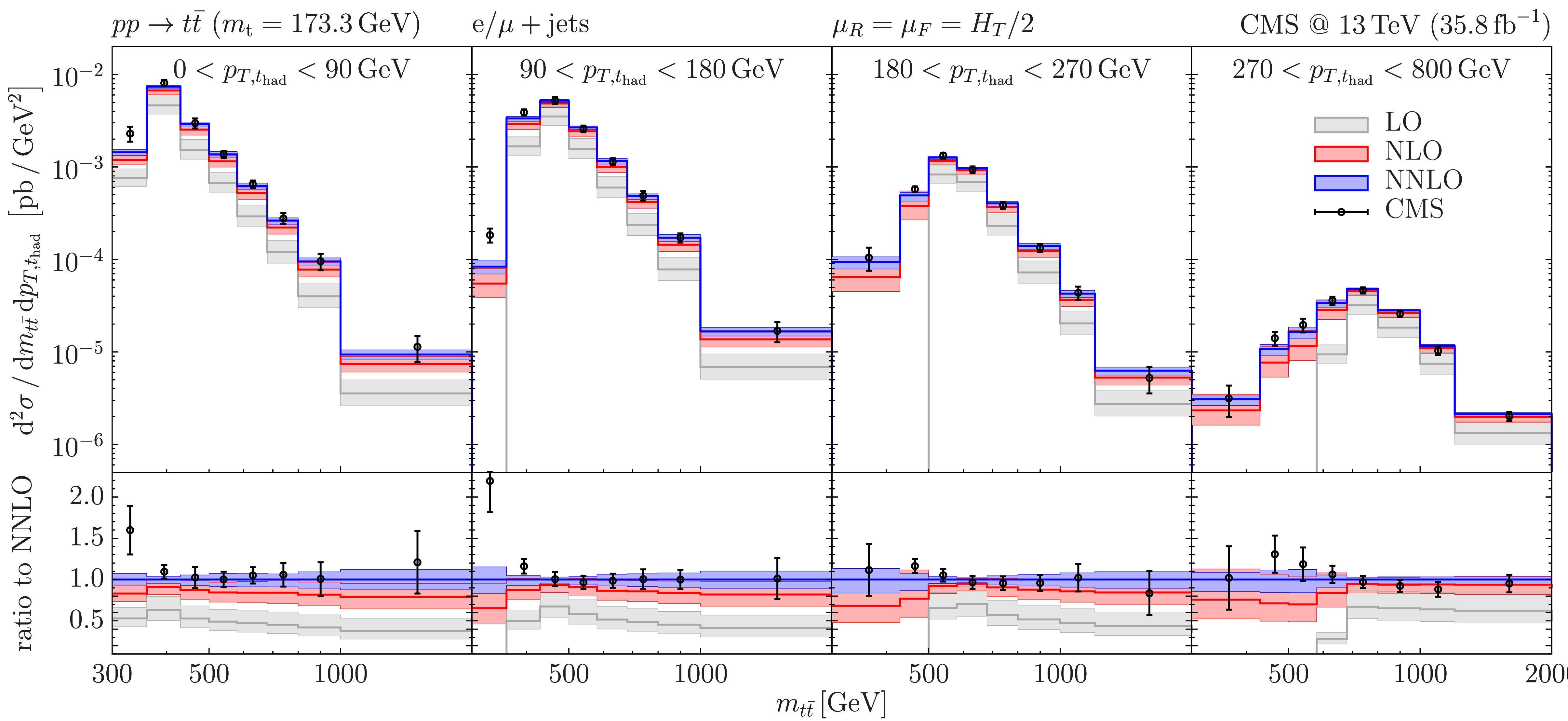
CMS-TOP-18-004: leptonic channel: a fit with the same PDFs leads to m_t=170.81 ± 0.68 GeV

Heavy quarks



As for the single-differential distribution the p_T distribution is softer than the NNLO prediction in all the rapidity intervals

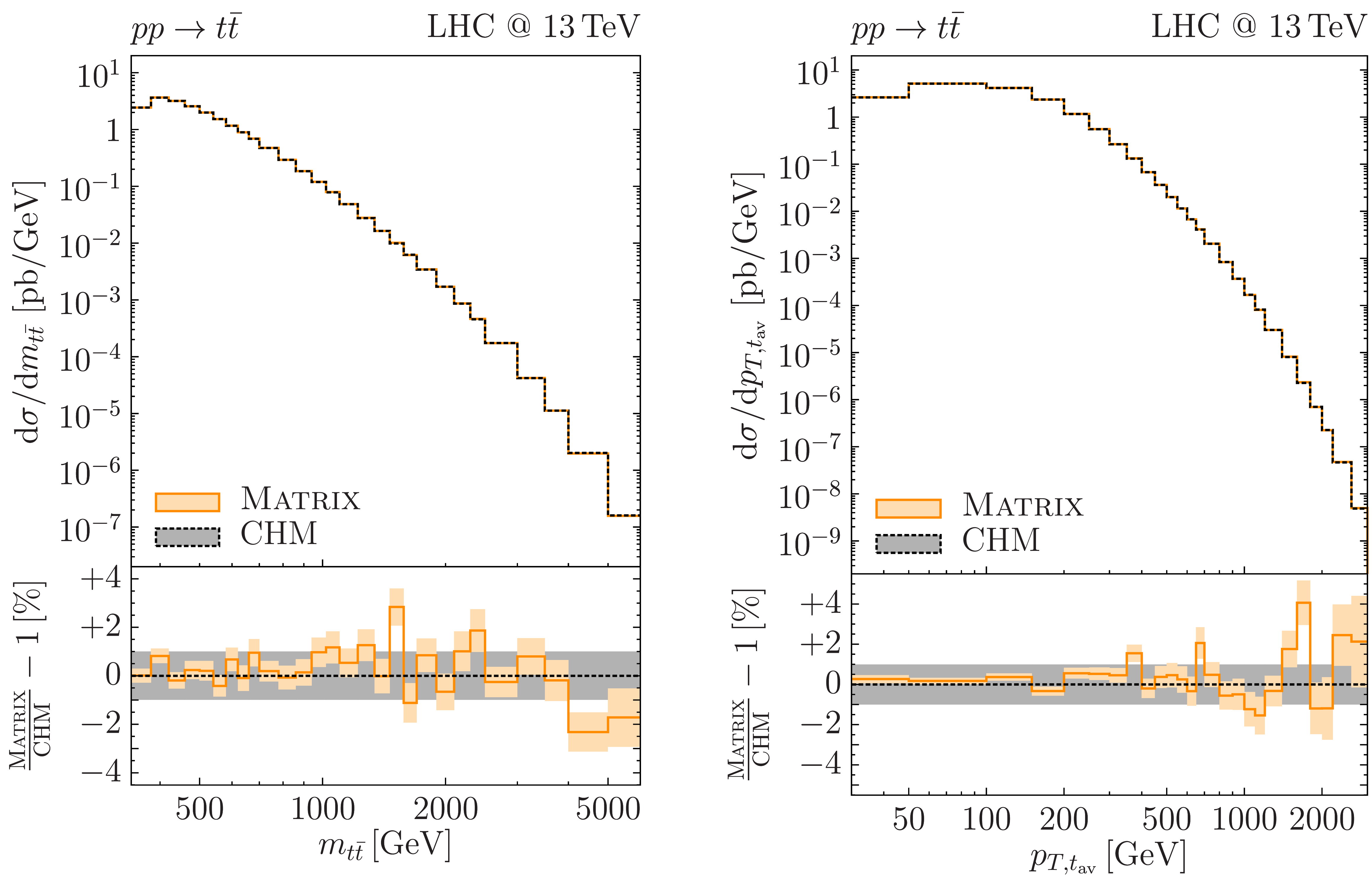
Heavy quarks



At LO there is a kinematical boundary $m_{tt} > 2m_{T\min}$ → Perturbative instabilities starting from NLO, smeared by the relatively large bin size

NNLO result nicely describes the data except in the first m_{tt} (first two panels)

Comparison with Czakon et al.

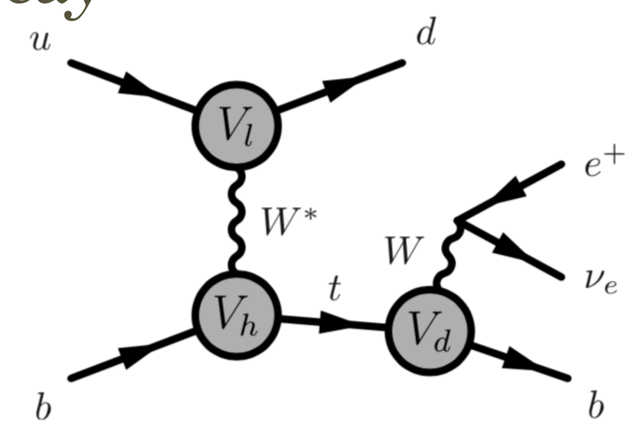


Excellent agreement even in extreme kinematical regions

More NNLO progress

We have now even NNLO computations for production + decay

- t-channel single top with t→Wb (N-jettiness + P2B)



Berger, Gao, Yuan, Zhu (2016)

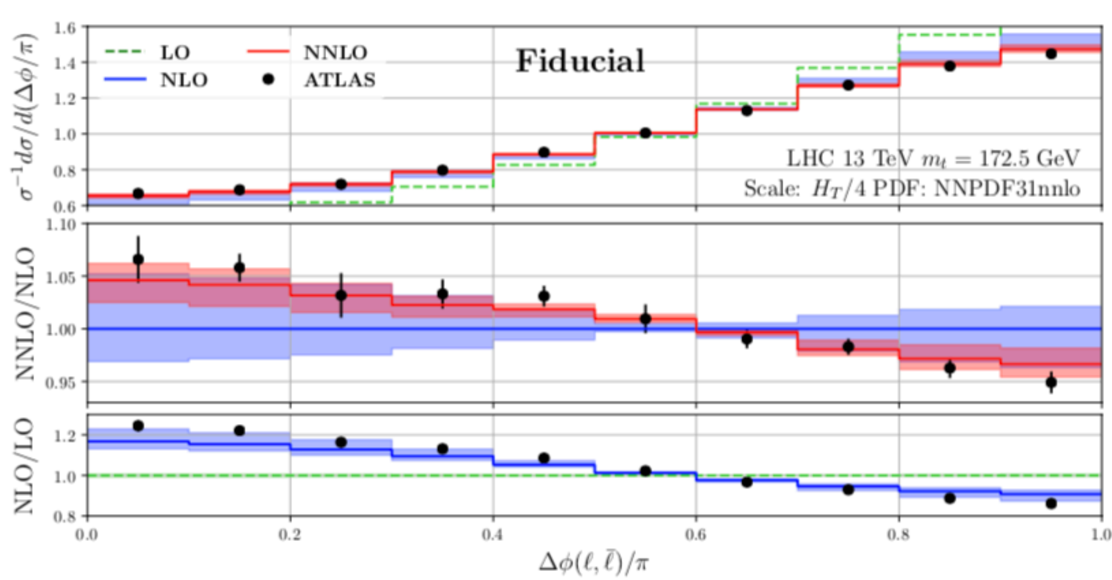
- VH with H→bb
  - q_T+colourful
  - nested subtractions
  - antenna

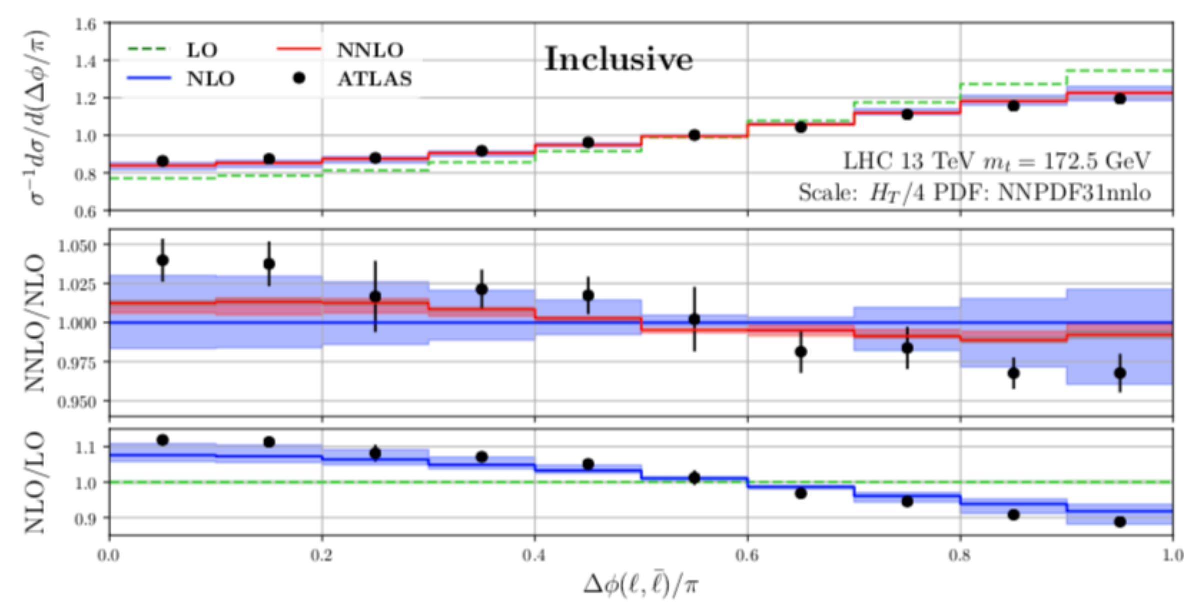
Ferrera, Somogyi, Tramontano (2017)
Caola, Luisoni, Melnikov, Röntsch (2017)
Gauld, Gehrmann De Ridder, Glover, Huss, Mayer (2019)

- $t\bar{t}$ with t→Wb (stripper)

→ Interesting issues with extrapolation

Czakon et al (2019)





NNLO: deployment of results

NNLO computations are generally rather expensive (may need up to $O(10^6)$ CPU hours for a production run): most results obtained through private codes

- Fast tool for total cross sections and repository for differential distributions
  - ➡ Top-quark pairs — Czakon et al.
- NTUPLES ➡ Viable at NNLO ? (LH17 estimate: 2jets should require O(100 TB))
- Applegrid (fast interpolation grids)
  - ➡ makes use in PDF fits possible

$$f(x) \simeq \sum_{i=0}^{N} f^{[i]}\ E_i(x)$$

nodes — Interpolation kernels

Talk by Rabbertz

- Public codes for limited sets of processes

Process specific: FEWZ, DYNNLO, HNNLO, 2γNNLO, proVBFH…

General purpose: MCFM, MATRIX

MCFM

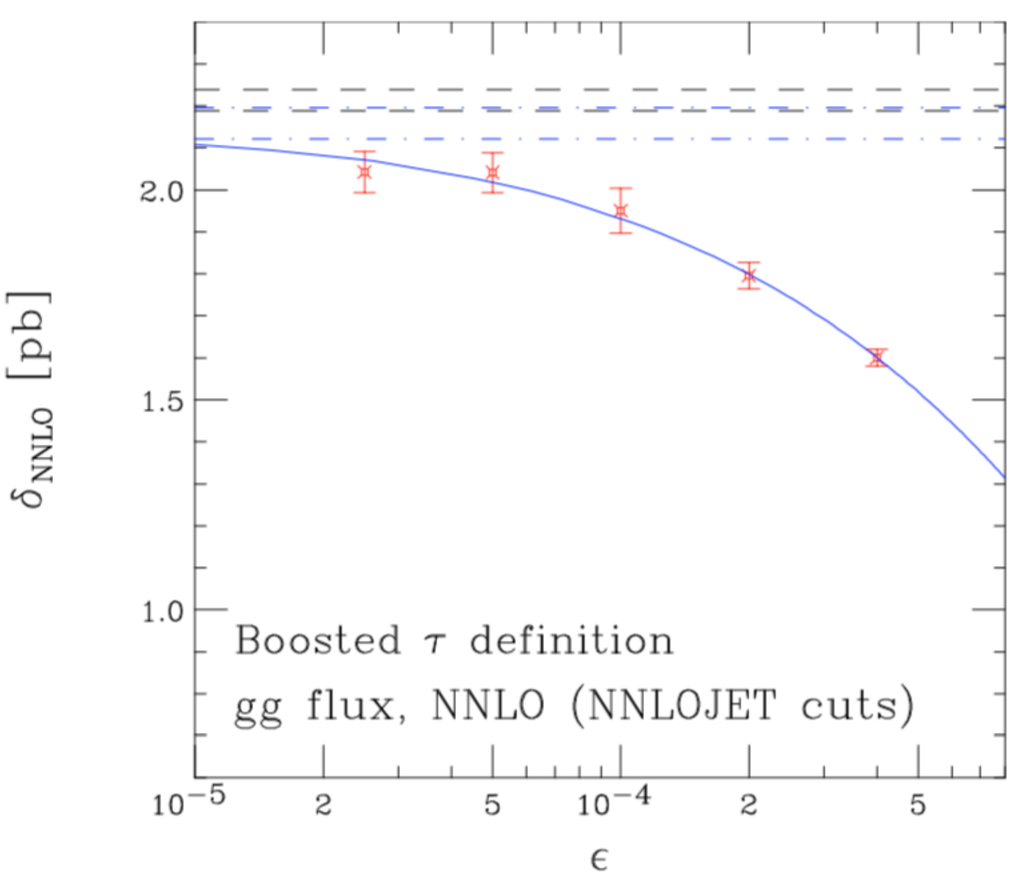
Campbell, Ellis, Neumann, Williams

MCFM has marked the Tevatron era as “the tool” for NLO computations

An increasing number of processes now implemented at NNLO accuracy by using N-jettiness

Process	`nproc`	$\sigma_{\rm NLO} \pm \delta\sigma^{\rm MC}_{\rm NLO}$	$\sigma_{\rm NNLO} \pm \delta\sigma^{\rm MC}_{\rm NNLO} \pm \delta\sigma^{\rm pc}_{\rm NNLO}$
W^+	1	4.220 ± 0.002 nb	$4.19 \pm 0.02 \pm 0.043$ nb
W^-	6	3.315 ± 0.001 nb	$3.23 \pm 0.01 \pm 0.033$ nb
Z	31	885.2 ± 0.3 pb	$878 \pm 3 \pm 9$ pb
H	112	1.395 ± 0.001 pb	$1.865 \pm 0.004 \pm 0.019$ pb
$\gamma\gamma$	285	27.94 ± 0.01 pb	$43.60 \pm 0.06 \pm 0.44$ pb
W^+H	91	2.208 ± 0.002 fb	$2.268 \pm 0.007 \pm 0.023$ fb
W^-H	96	1.494 ± 0.001 fb	$1.519 \pm 0.004 \pm 0.015$ fb
ZH	110	0.7535 ± 0.0004 fb	$0.846 \pm 0.001 \pm 0.0085$ fb
$Z\gamma$	300	959 ± 8 fb	1268 ± 22 fb

Talk by T. Neumann

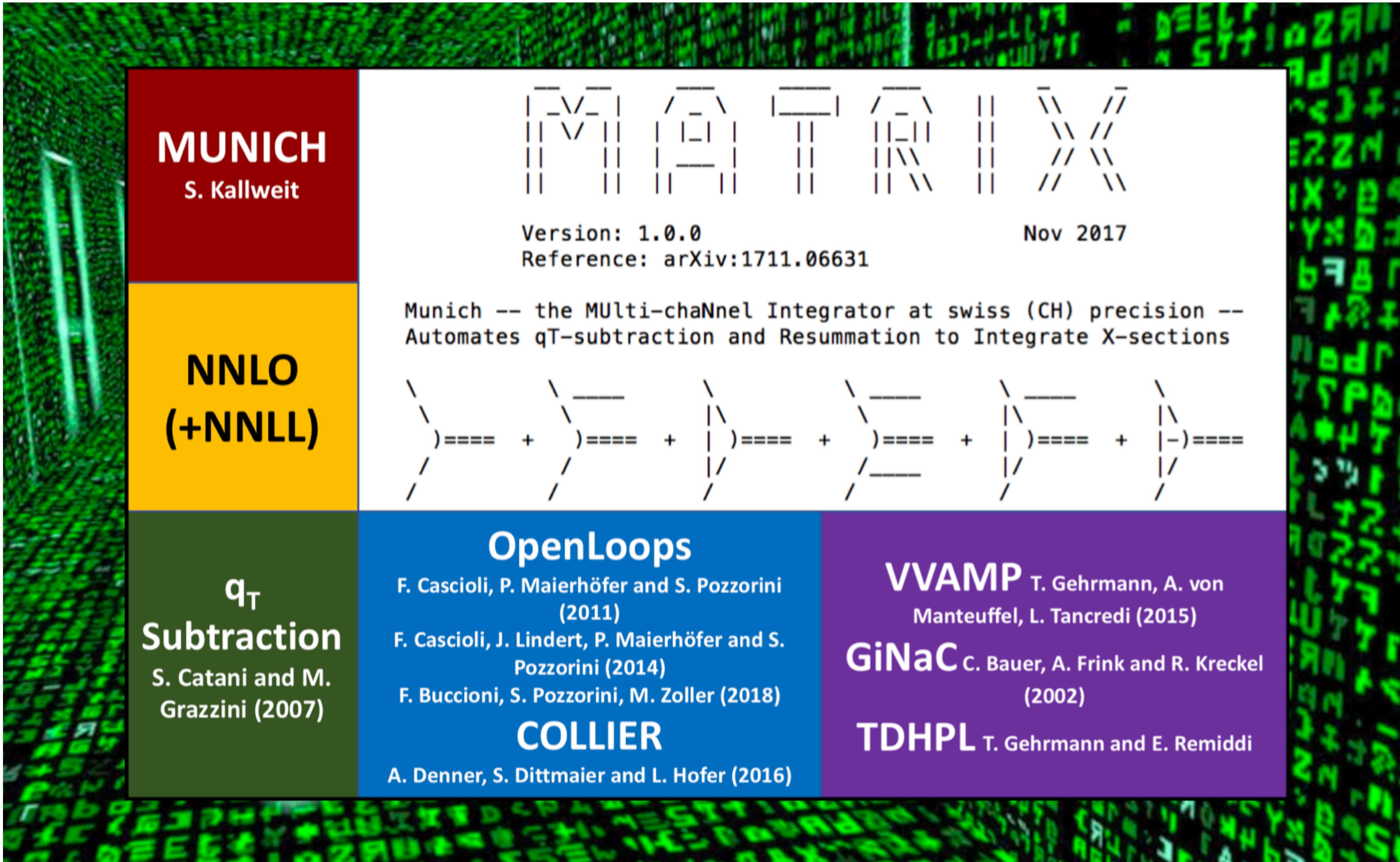


New implementation of H+jet helped to solve long standing discrepancies with other calculations

Campbell, Ellis, Seth (2019)

MATRIX

Kallweit, Wiesemann, MG (2017)
+ Devoto, Mazzitelli, Yook….



MATRIX

- $pp \to Z/\gamma^*$ $(\to l^+l^-)$ ✅
- $pp \to W(\to l\nu)$ ✅
- $pp \to H$ ✅
- $pp \to \gamma\gamma$ ✅
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^-\gamma$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to ZZ(\to 4l)$ ✅
- $pp \to WW \to (l\nu l'\nu')$ ✅

} Plus NLO for gluon fusion (not yet in public release) → **Talk by Yook**

- $pp \to HH$ ✅
- $pp \to t\bar{t}$ ✅

} not in public release

First public release out in November 2017

Runtime estimate for per mille accurate fiducial cross sections:

From O(10) CPU days for the simplest processes to O(1000) CPU days for $t\bar{t}$

Beyond $2 \to 2$

Talks by Badger, Tancredi....

Current NNLO results limited to $2 \to 1$ and $2 \to 2$

A number of important processes would benefit from NNLO extension: ttH, V+2j, 3j....

E.g. ttH: statistical accuracy could go down from O(15%) to O(2%) at the end of HL-LHC

- Analytical approach

  - five point amplitudes at leading colour — Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov (2019)

  - all master integrals for five point — Gehrmann et al. (2019)

  - master integrals for $t\bar{t}$ — Gehrmann et al. (2019); Bonciani et al. (2019)

  ....

- Numerical

  - $t\bar{t}$ — Czakon et al (2013)

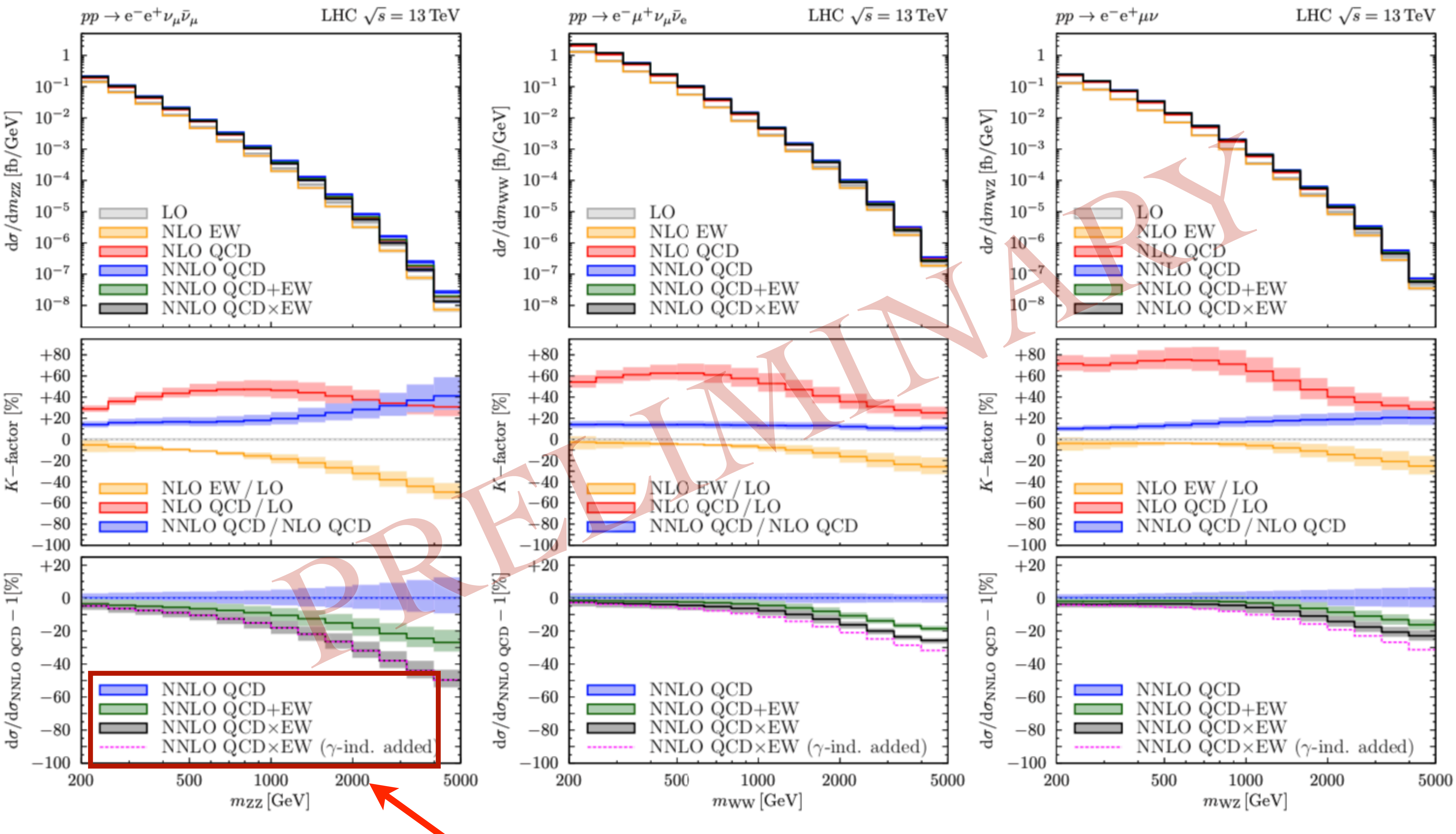
  - PySecDec (HH, H+jet...) — Borowka, Heinrich, Jones, Kerner....

  - HH — Spira et al. (2018)

Beyond NNLO QCD

NNLO QCD+NLO EW for dibosons

Kallweit, Lindert, Pozzorini, Wiesemann, MG (to appear)



Different combination prescriptions

NNLO QCD+NLO EW for dibosons

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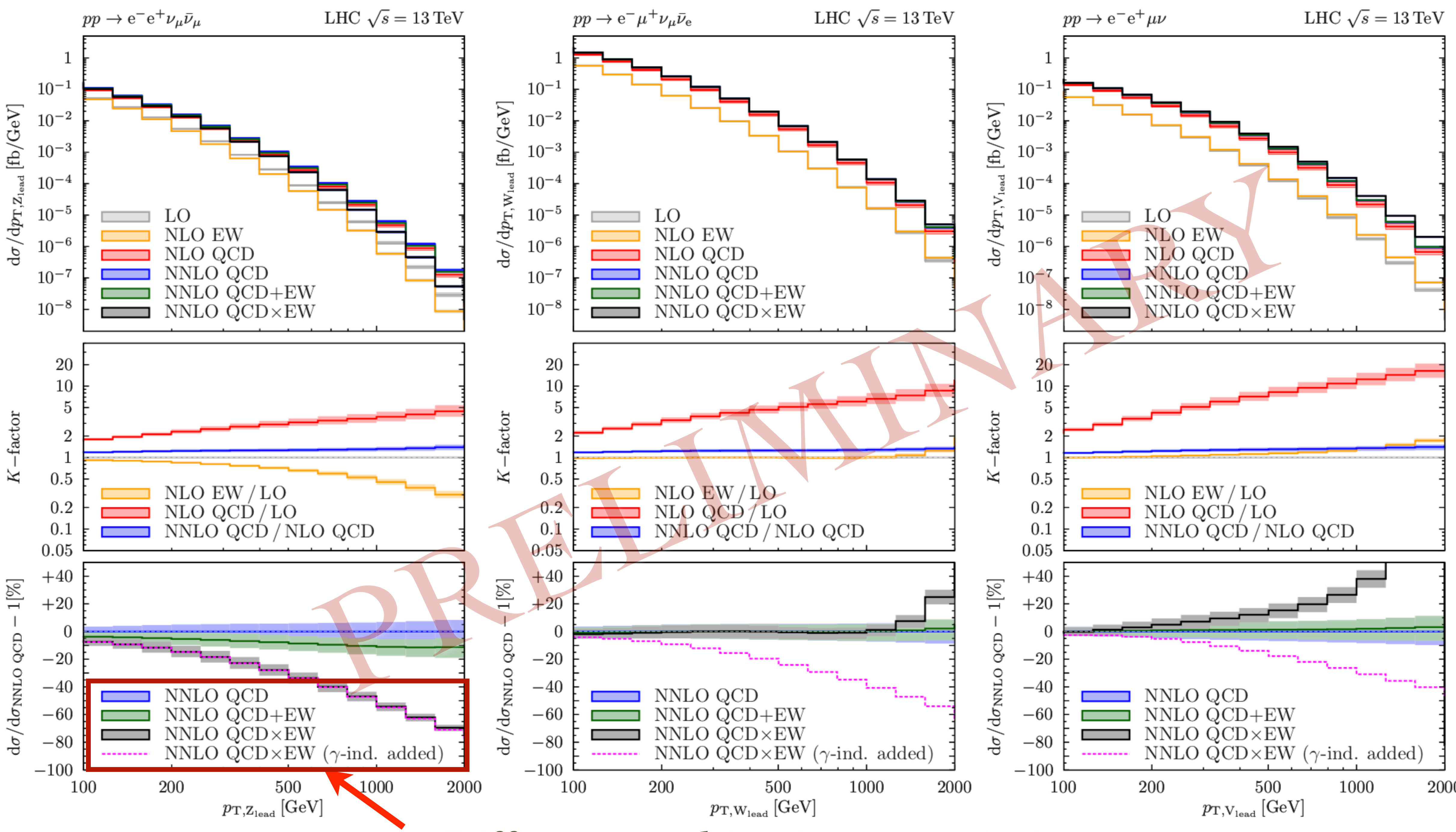

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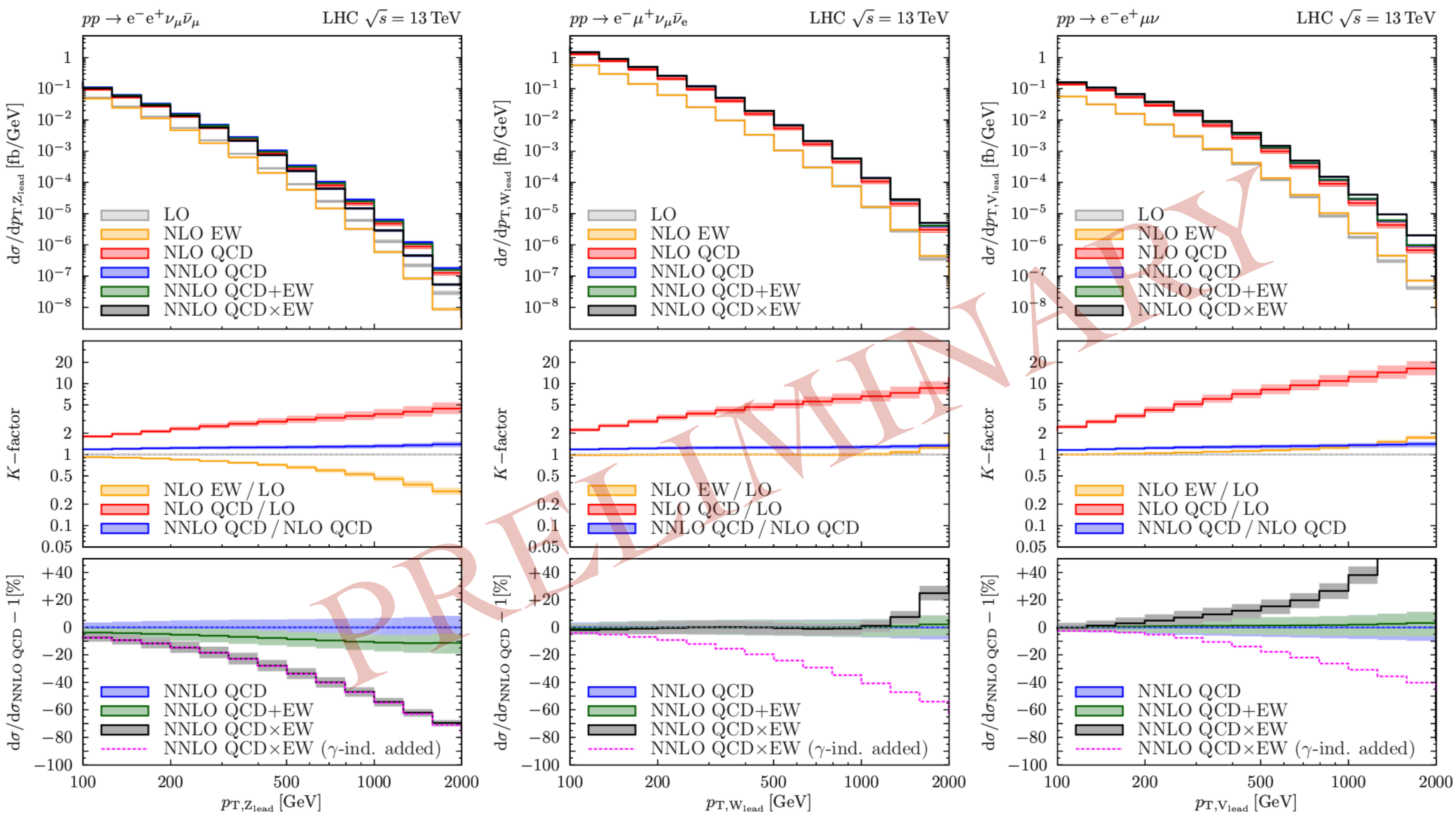

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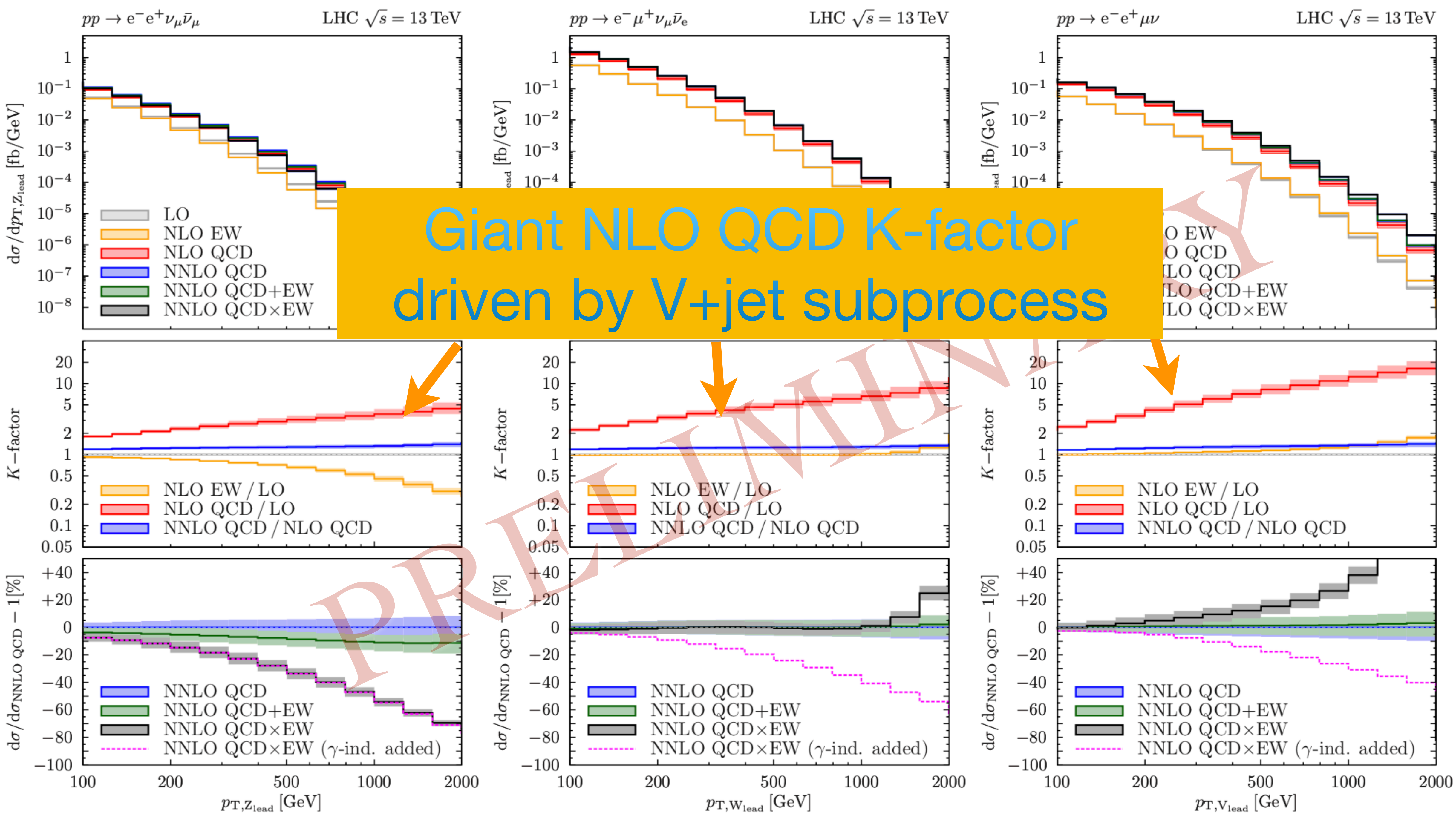

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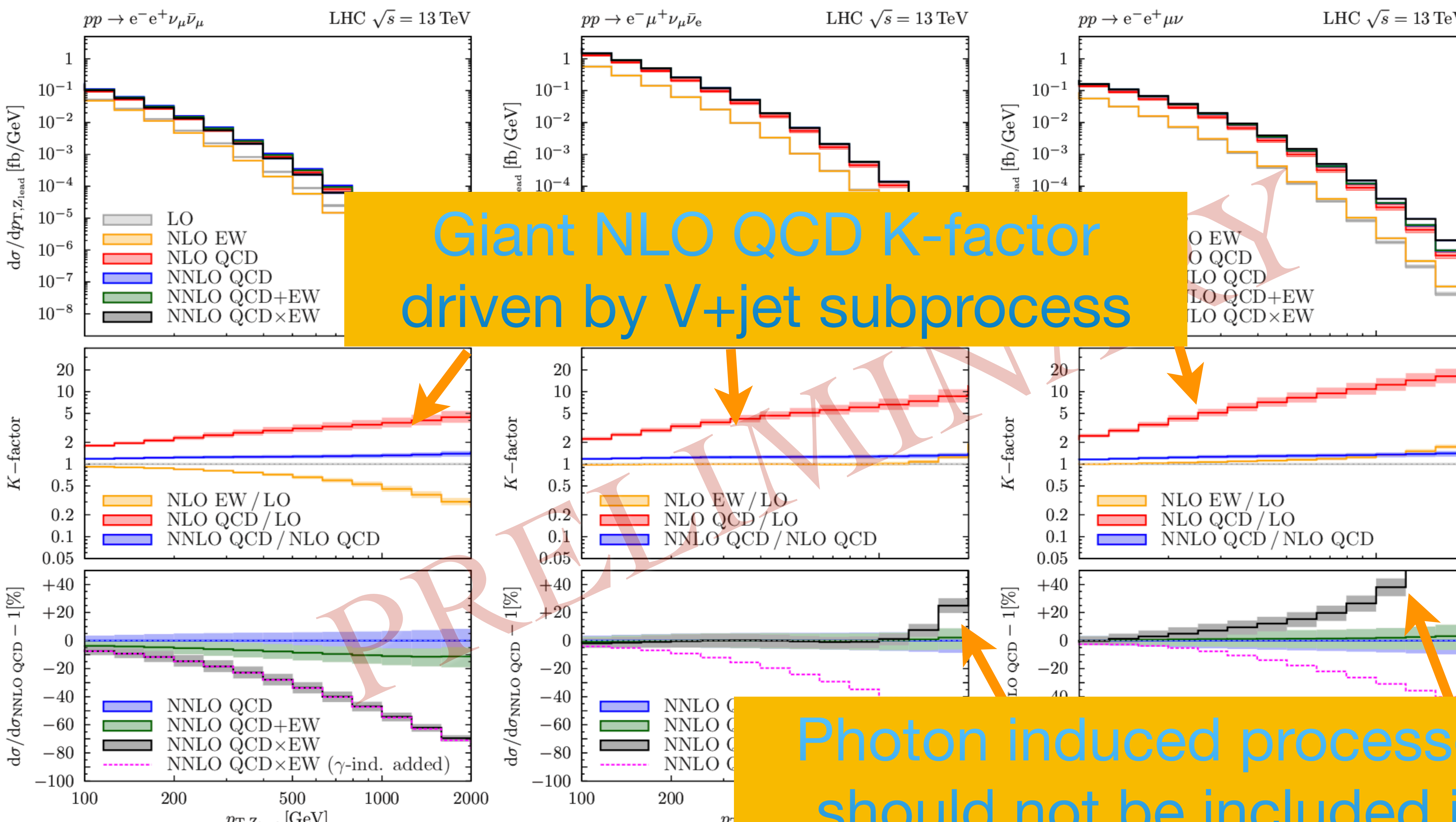

Giant NLO QCD K-factor driven by V+jet subprocess

Photon induced processes should not be included in multiplicative combination !

NNLO QCD+NLO EW for dibosons

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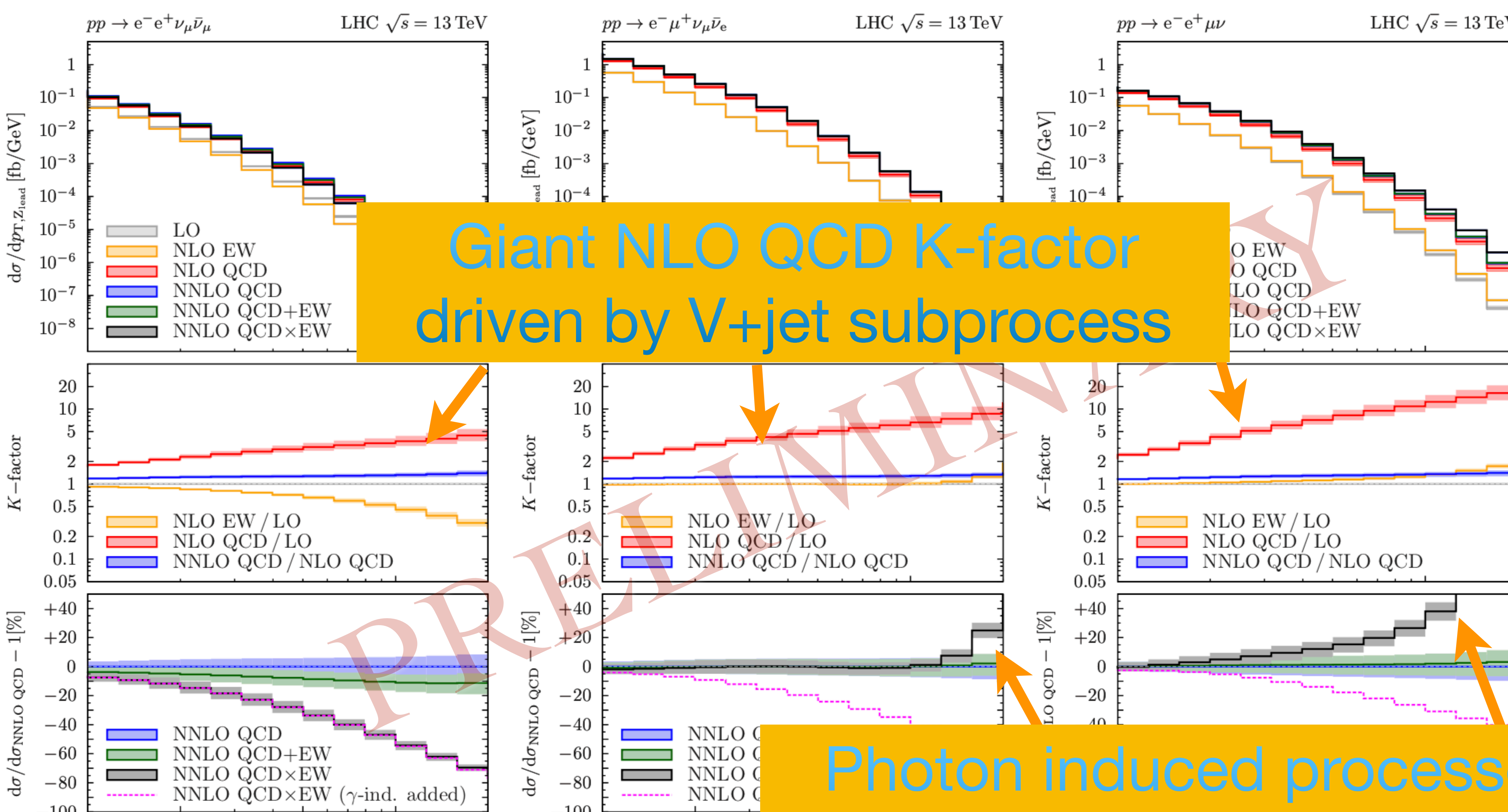

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High-p_T Sudakov suppression spoiled for WZ and WW

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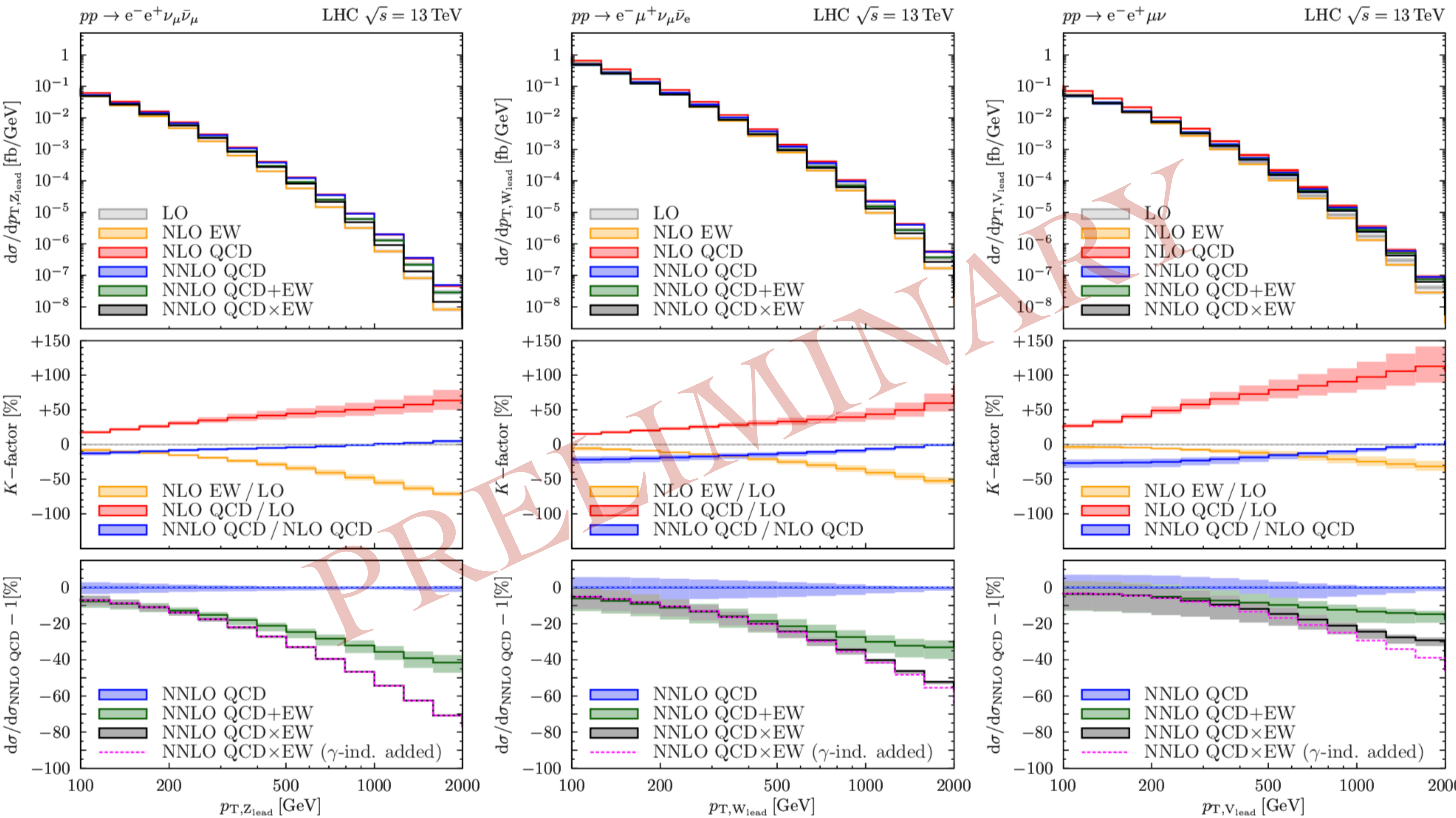

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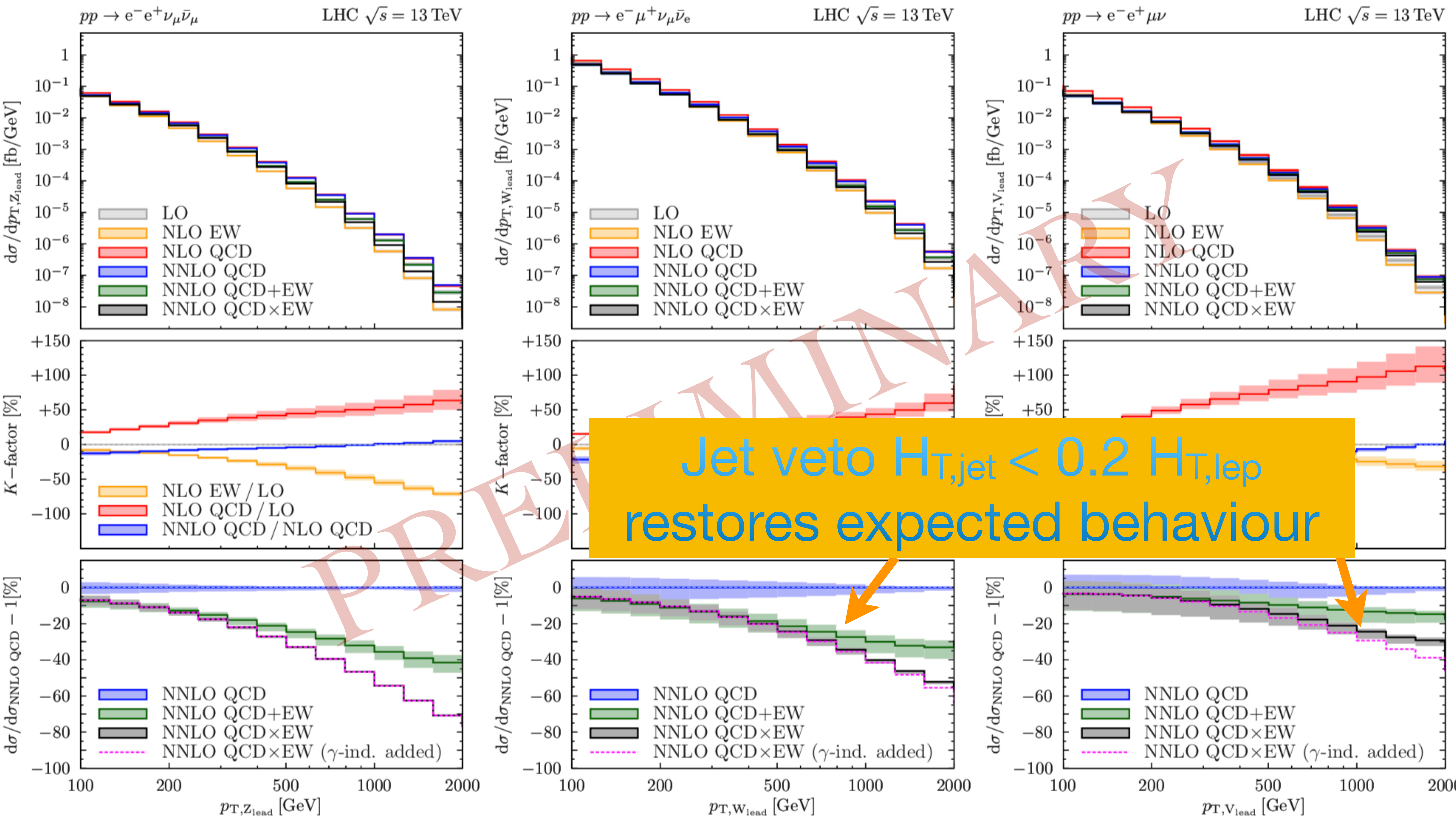

N^3LO

Talks by Dulat, Pelloni, Mondini

For some benchmark processes N^3LO leads to a reduction of theoretical uncertainties and increases our confidence on the perturbative convergence

- rapidity distribution in Higgs production — Dulat, Mistlberger, Pelloni (2019)
- Fully differential Higgs production (q_T subtraction) — Cieri et al (2018)
- $H \to bb$ (N-jettiness+P2B) — Mondini,Schiavi,Williams (2019)
- Inclusive $bb \to H$ — Duhr, Dulat, Mistlberger (2019)
- Inclusive H and HH in VBF — Karlberg, Dreyer (2018,2019)

I expect the major impact of N^3LO in the near future could be in the description of the Drell-Yan process where the data are already extremely precise and N^3LO could help constraining the p_T distribution at low p_T

Summary & Outlook

- LHC precision phenomenology is becoming a tool for BSM searches with new opportunities
- NNLO results now available for essentially all the relevant 2->1 and 2->2 processes and lead to an improved description of the data
- Cross validation of different computations essential in consolidating the results but improvements in subtraction/slicing techniques expected/needed
- Extension to 2->3 requires facing new challenges in the computations of two-loop amplitudes
- NNLO computations challenging also from the point of view of computing resources

  → Only a limited subset of the results are publicly available

- N^{3}LO era started with new exciting results