Improving theory predictions for SM processes

Jonas M. Lindert

University of Sussex

Science & Technology Facilities Council

UK Research and Innovation

PITT PACC Workshop: LHC physics for Run 3

7th April 21

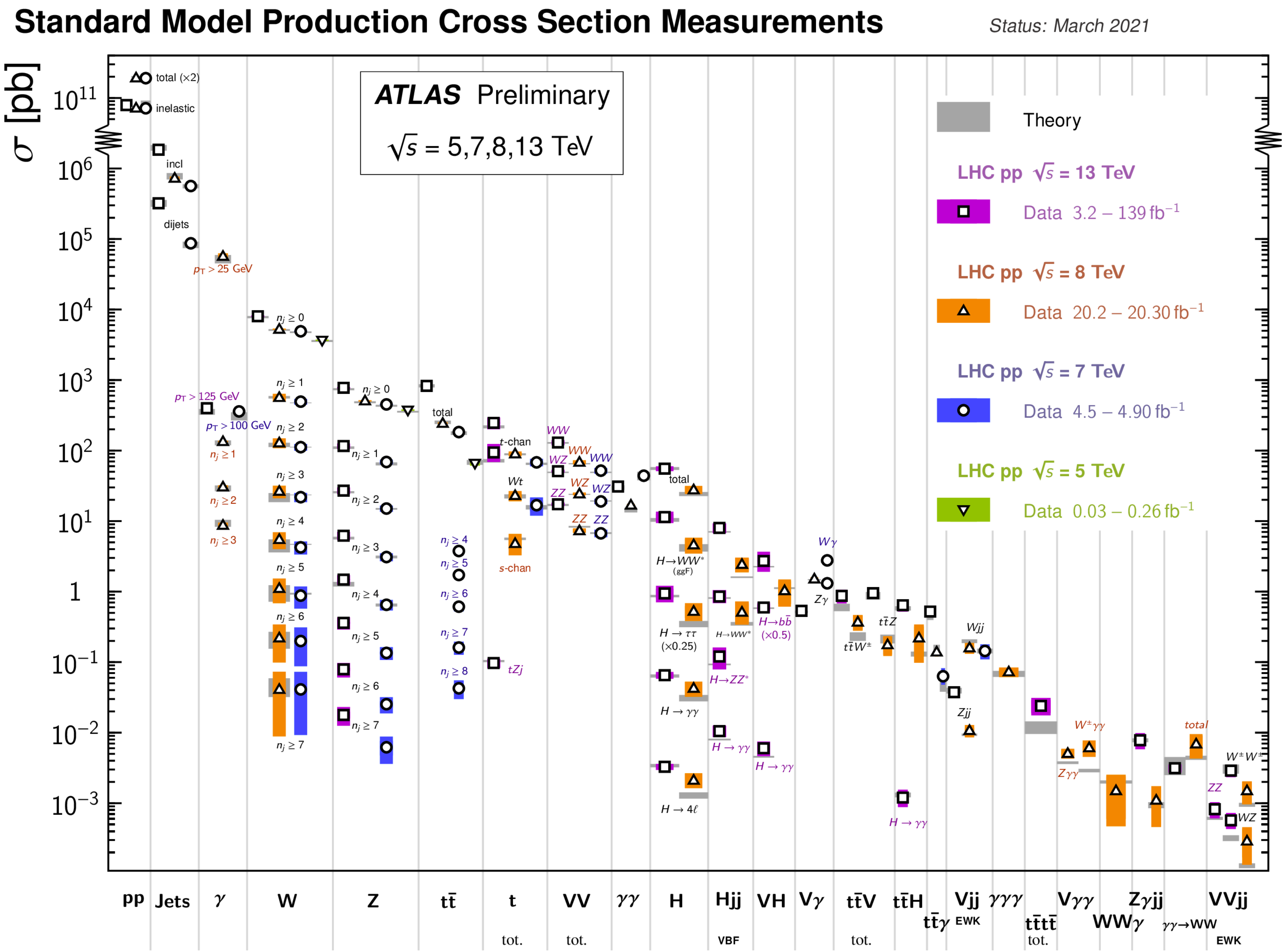
Improving theory predictions for SM processes

…to help to discover new physics in Run 3

What lessons have been learned from Run 2 analyses?

How to apply these lessons to Run 3?

The success of the SM



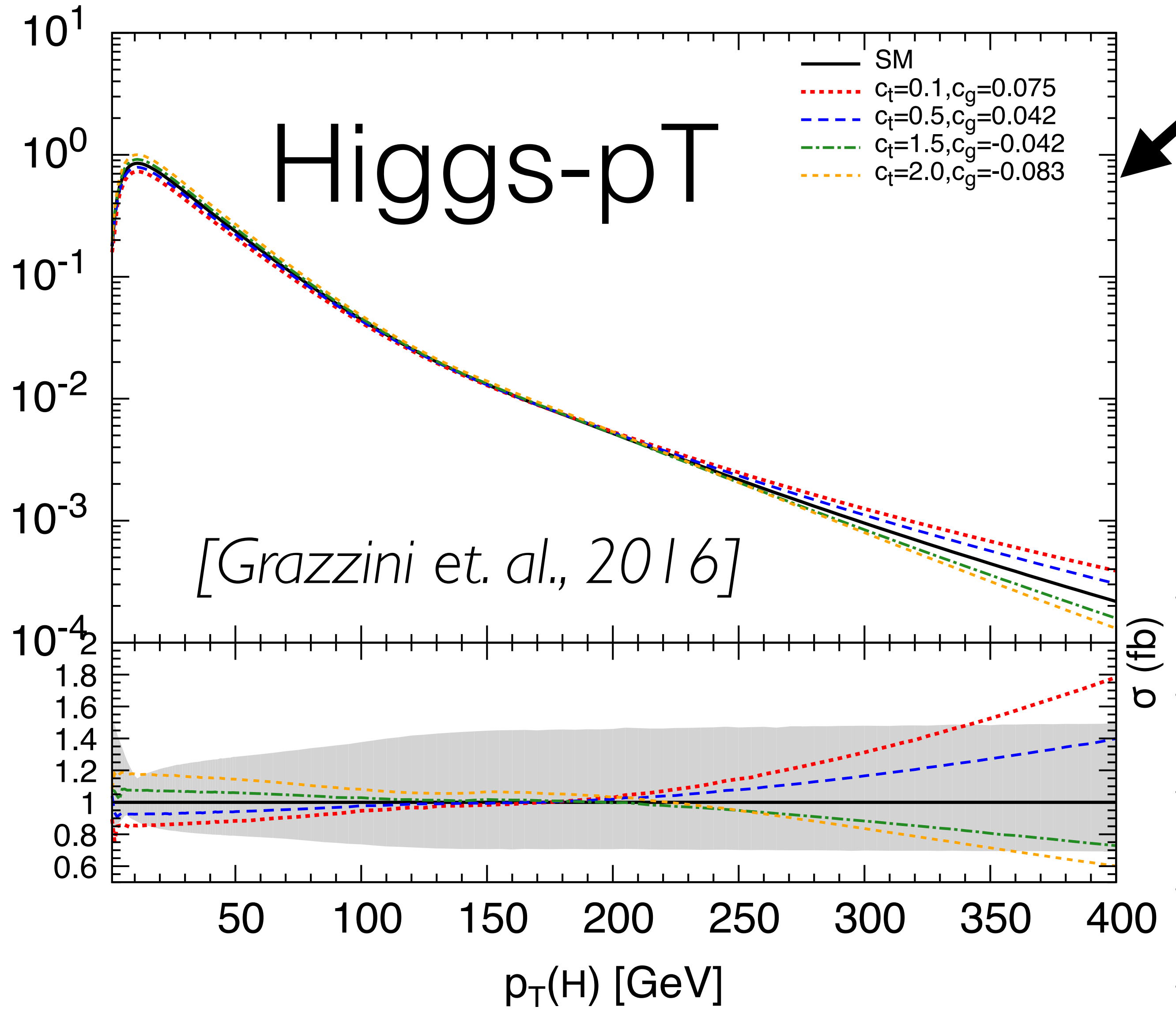
Overall extremely good experiment-theory agreement

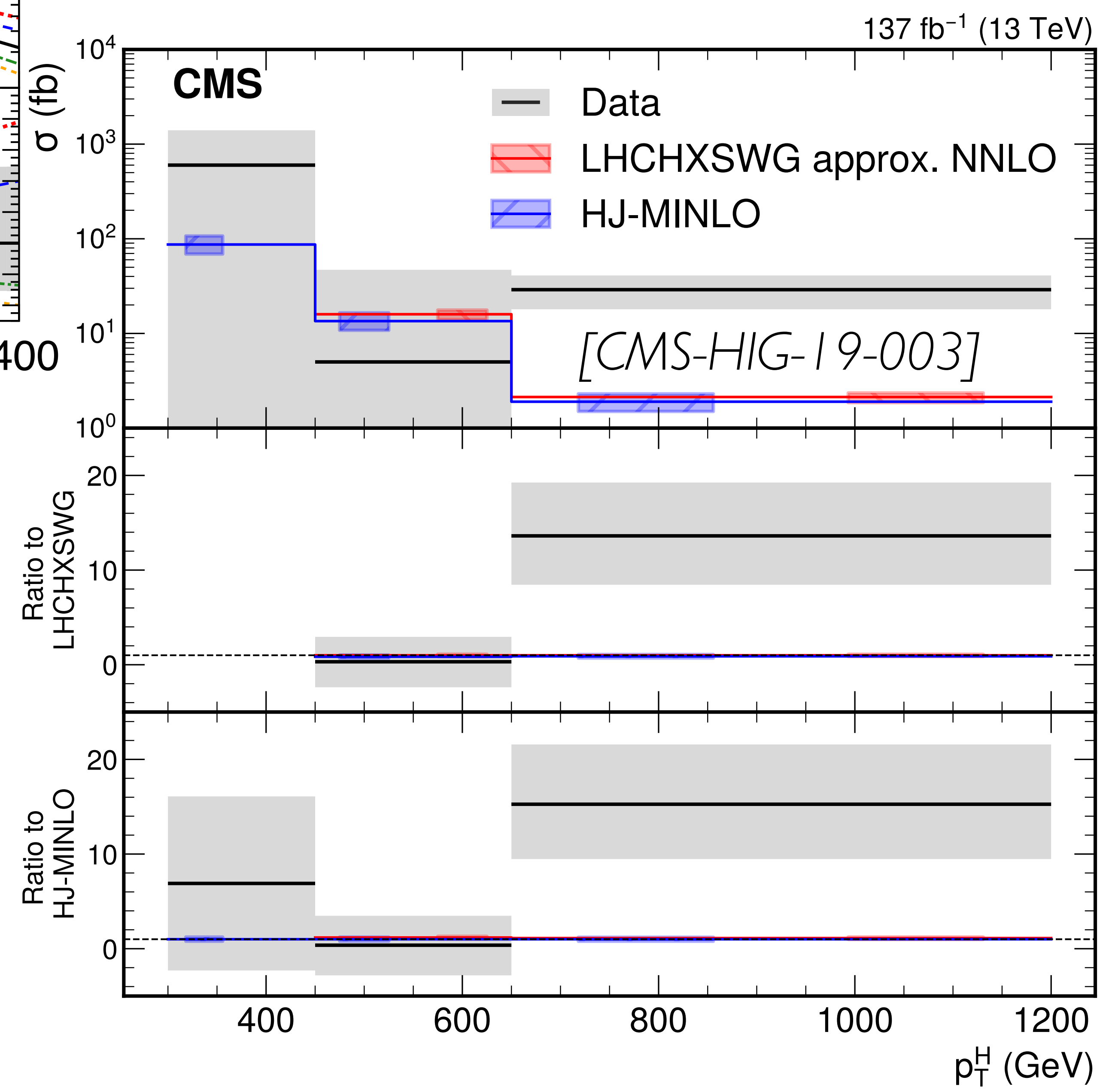
Goal: go differential

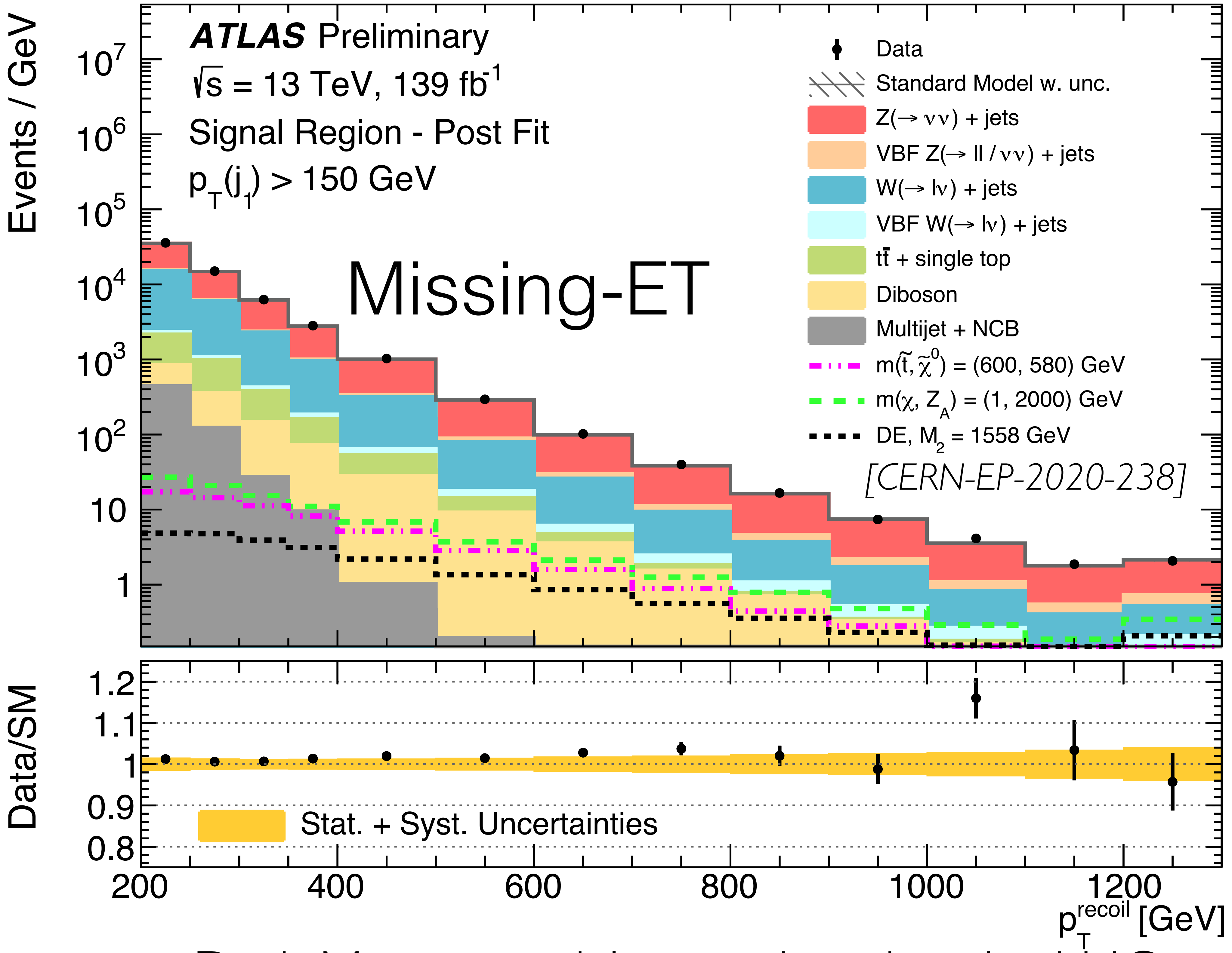
The need for precision in tails

Indirect searches

Direct searches







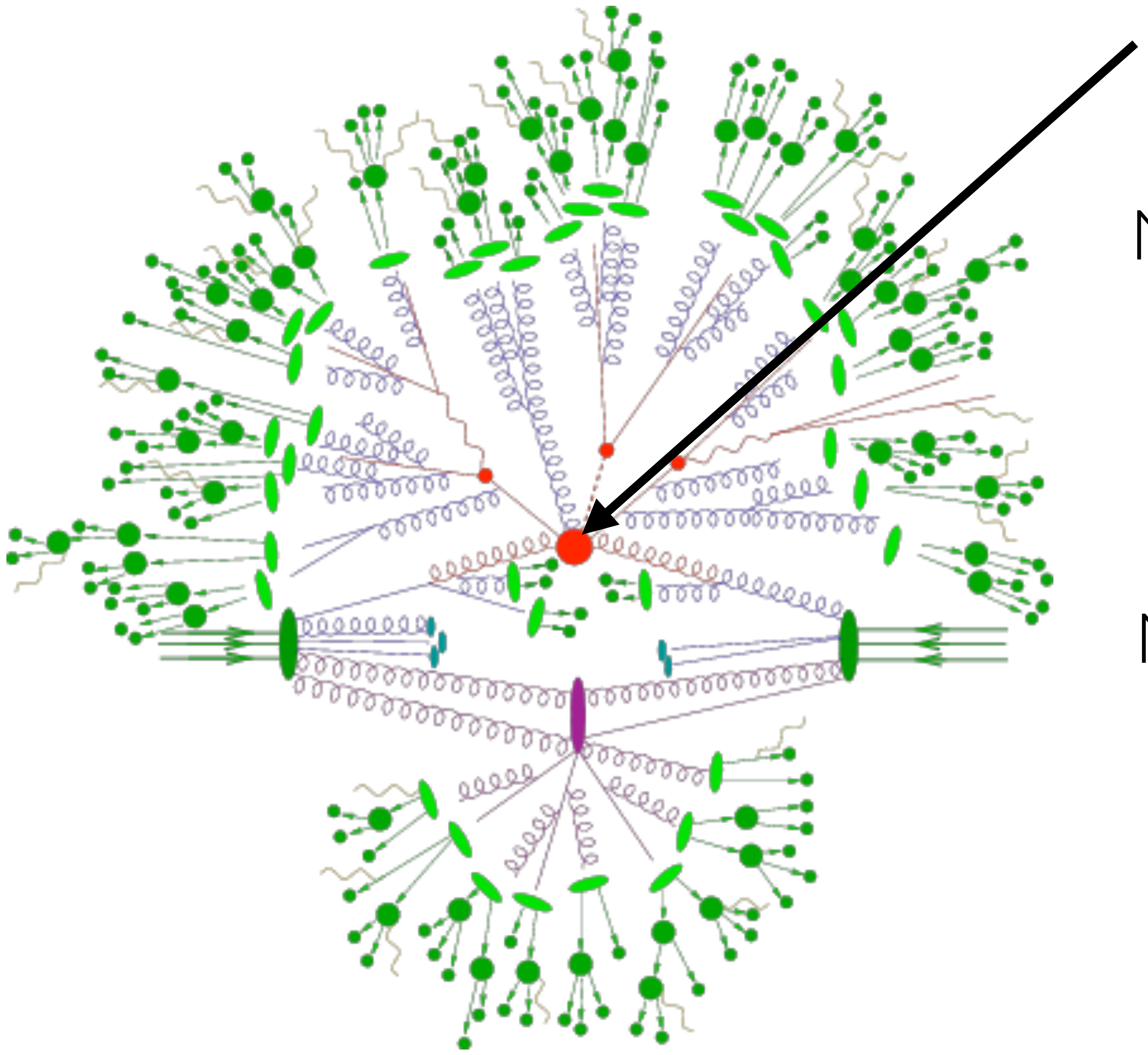
- In case new physics is heavy: expect small deviations in tails of distributions

→ **good control on theory necessary!**

- Dark Matter particles produced at the LHC leave the detectors unobserved: signature missing transverse energy
- large irreducible SM backgrounds

→ **good control on theory necessary!**

Theoretical Predictions for the LHC



Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\rm LO} + \alpha_S\, d\sigma_{\rm NLO} + \alpha_{\rm EW}\, d\sigma_{\rm NLO\,EW}$$
$$+\alpha_S^2\, d\sigma_{\rm NNLO} + \alpha_{\rm EW}^2\, d\sigma_{\rm NNLO\,EW} + \alpha_S\alpha_{\rm EW}\, d\sigma_{\rm NNLO\,QCDxEW}$$

NLO QCD (standard in NLOPS MC's):

- O(10-100%) corrections with respect to LO
- often not covered by LO scale variations
- opening up of new channels / phase space

NNLO QCD (known for pretty much all 2→2 SM processes)

- O(1-10%) corrections with respect to NLO QCD
- remaining uncertainty: O(1%)

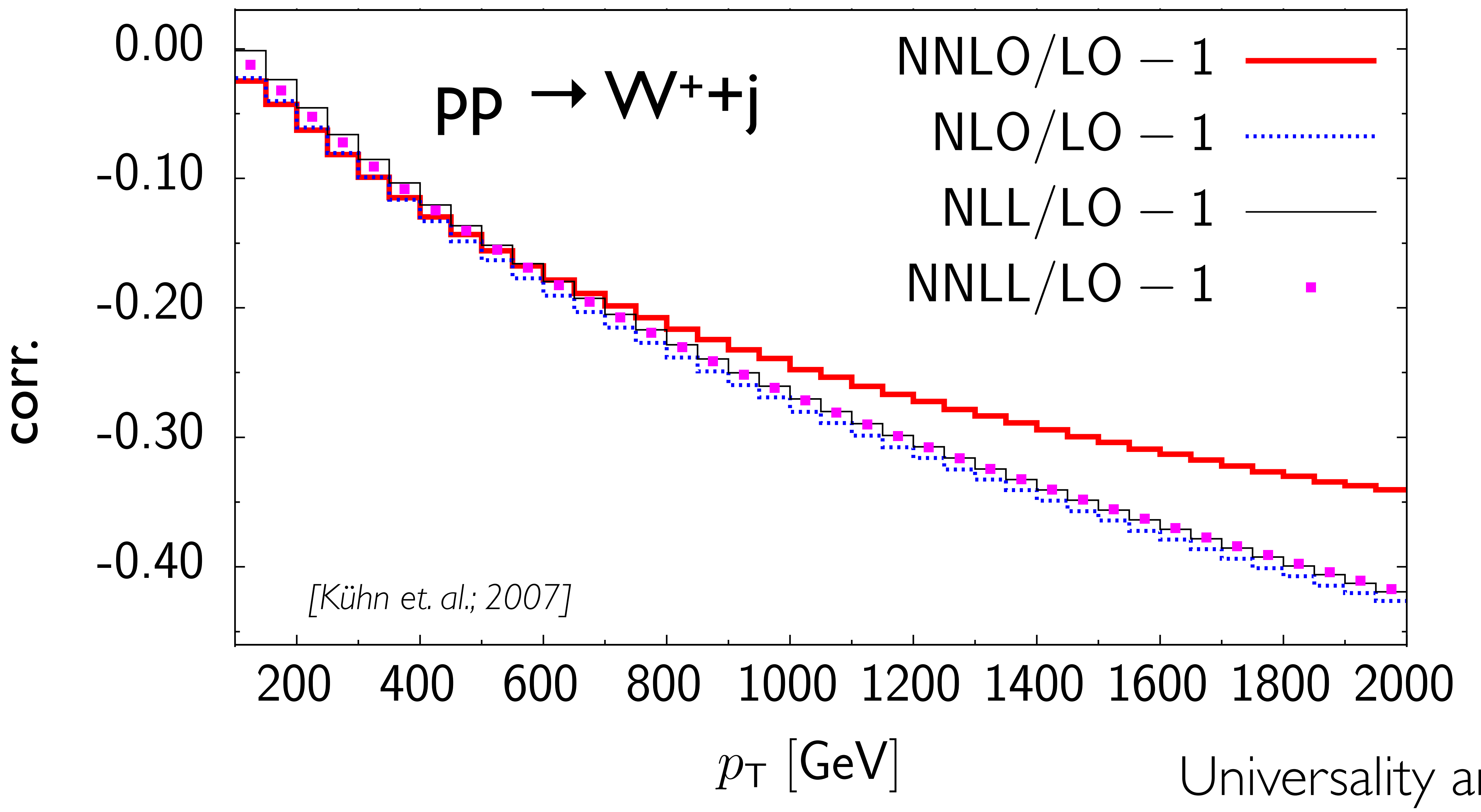
NLO EW (available at fixed-order for any SM process):

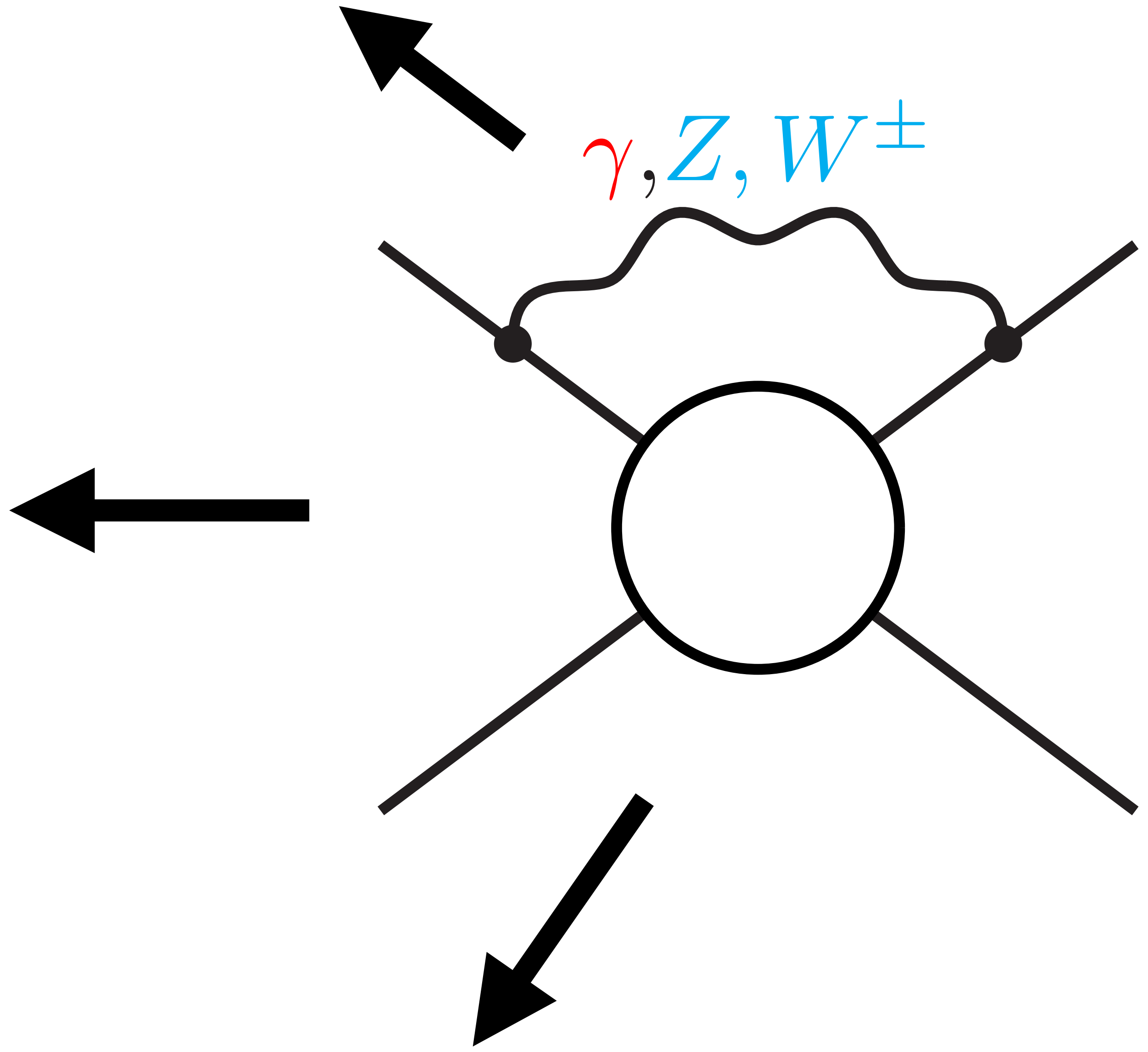
- O(1%) inclusive corrections
- O(10%) negative corrections at large energies due to Sudakov logs

Relevance of EW higher-order corrections

Numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ **NLO EW ~ NNLO QCD**

Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:





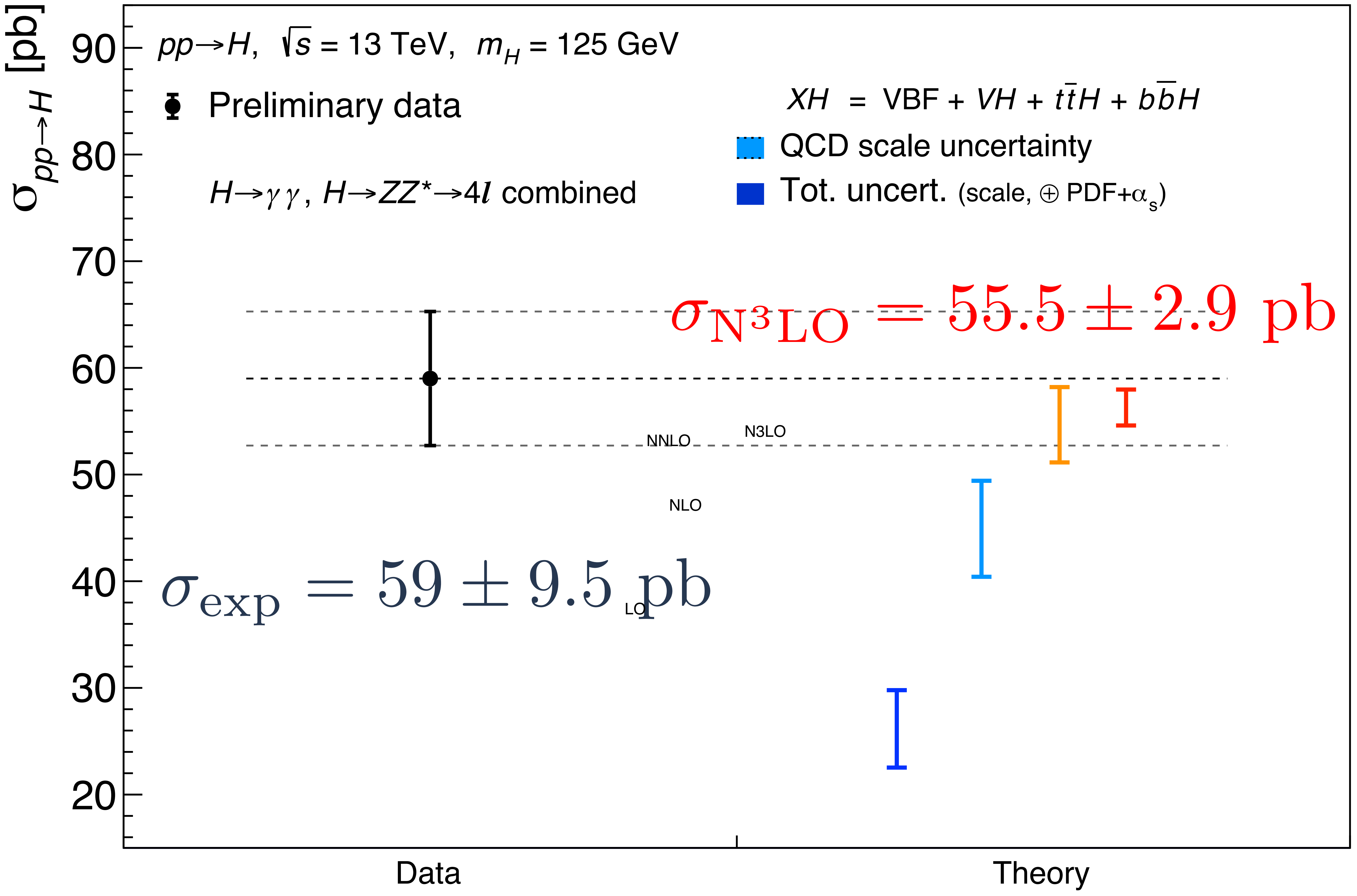
[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]

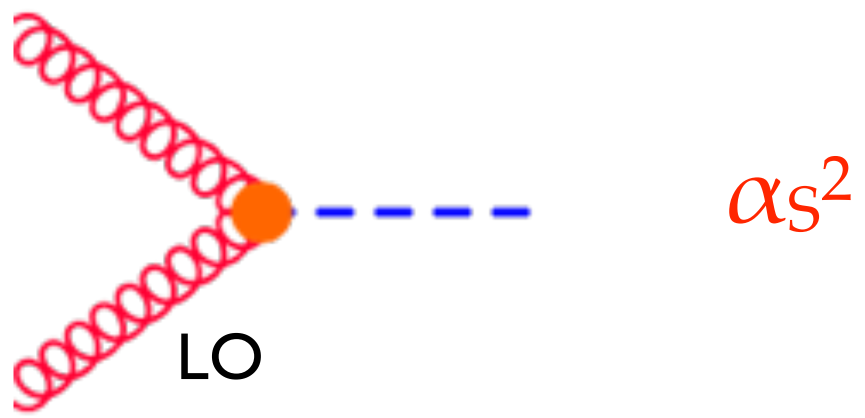
Universality and factorisation: *[Denner, Pozzorini; '01]*

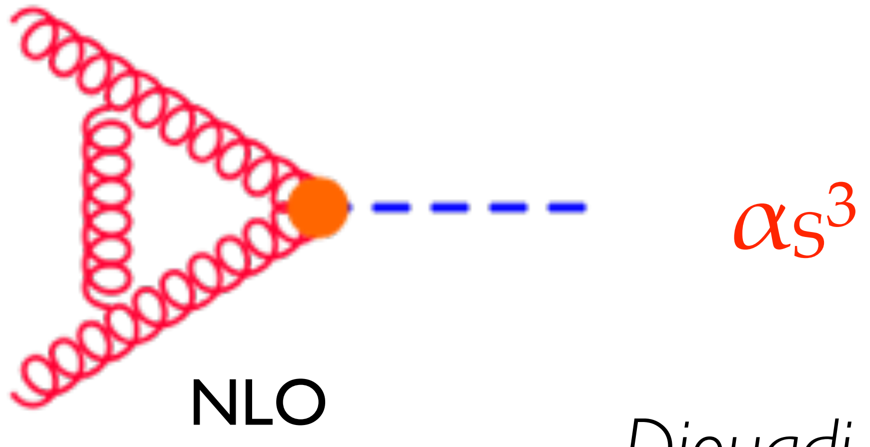
$$\delta\mathcal{M}^{\text{1-loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^{\pm}} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ overall large effect in the tails of distributions: p_T, m_{inv}, H_T,… (relevant for BSM searches!)

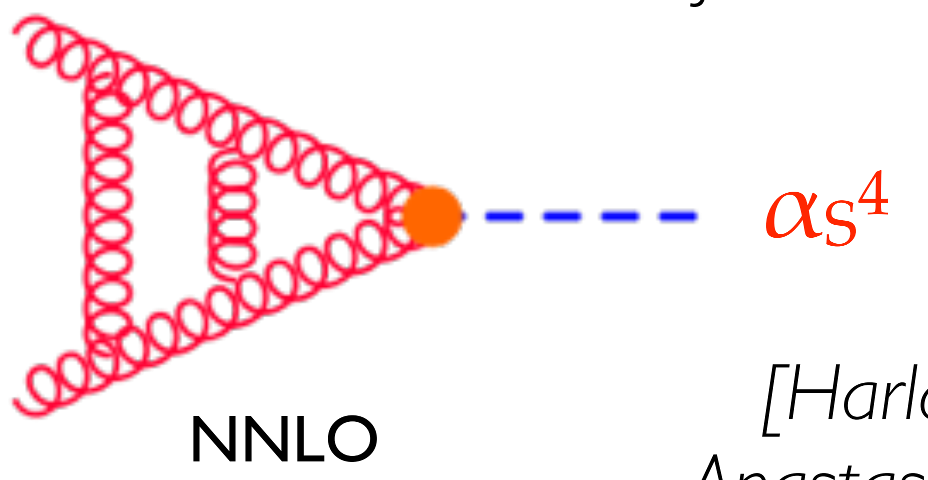
Convergence of the perturbative expansion: inclusive Higgs



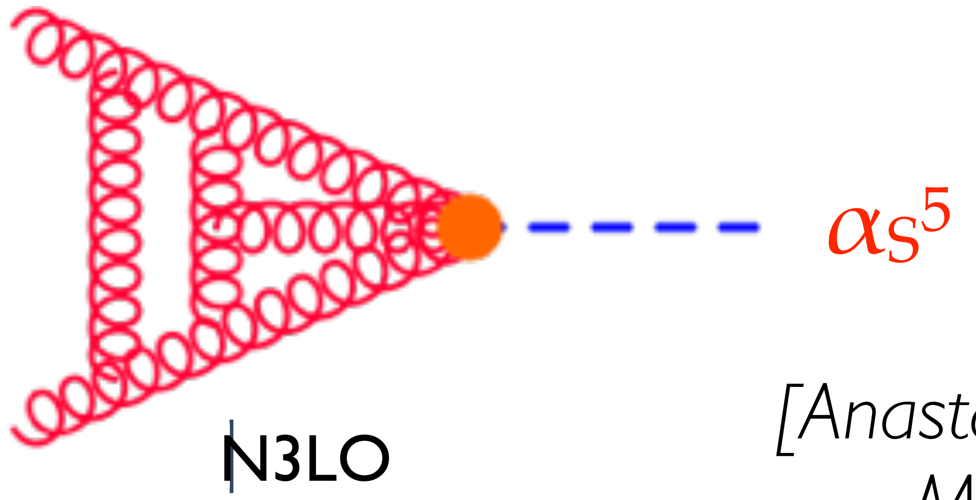




[Dawson; 1991
Djouadi, Spira, Zerwas;1991]



[Harlander, Kilgore; 2002
Anastasiou, Melnikov;2002]



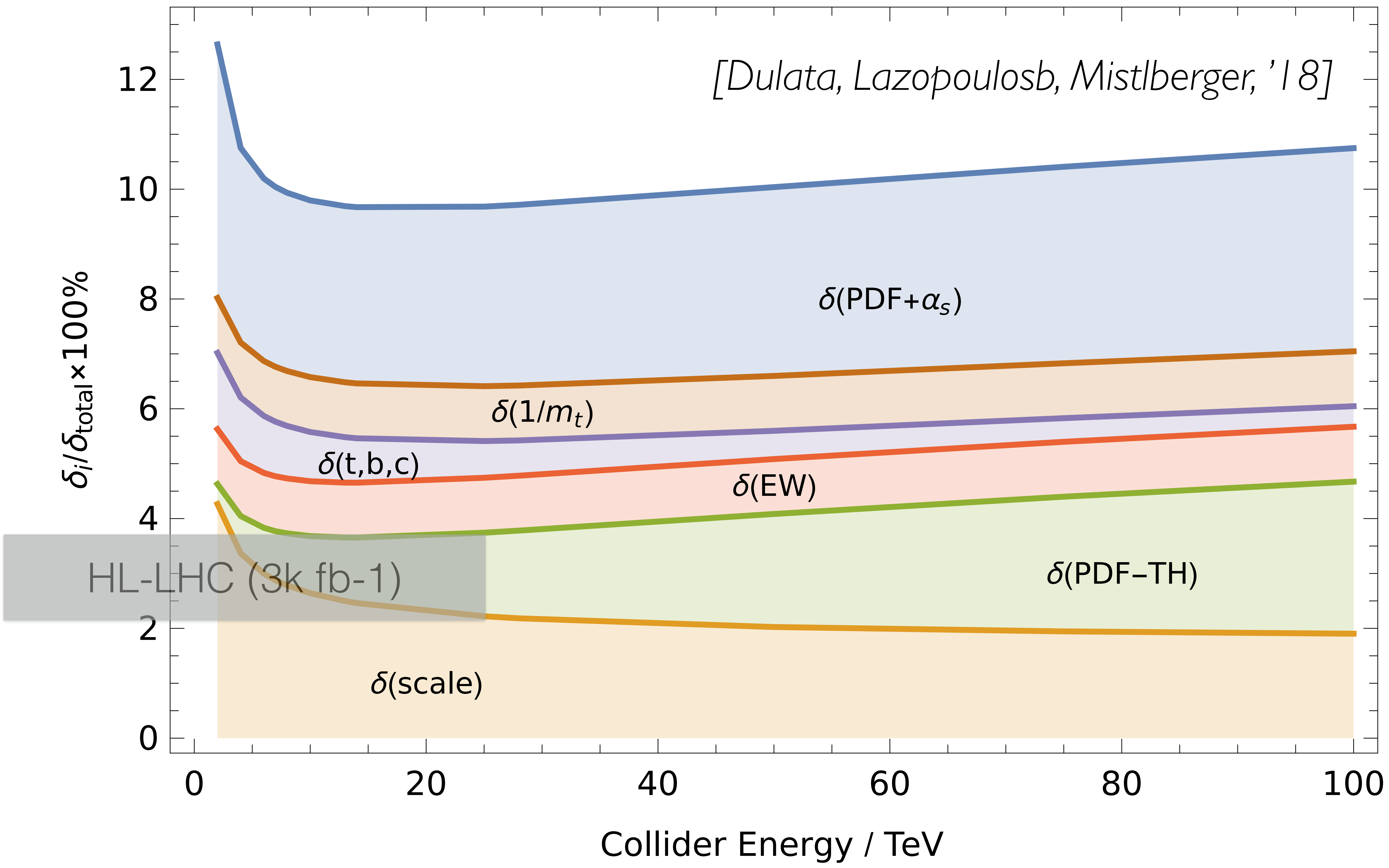
[Anastasiou et al.;2015
Mistlberger; 2018]

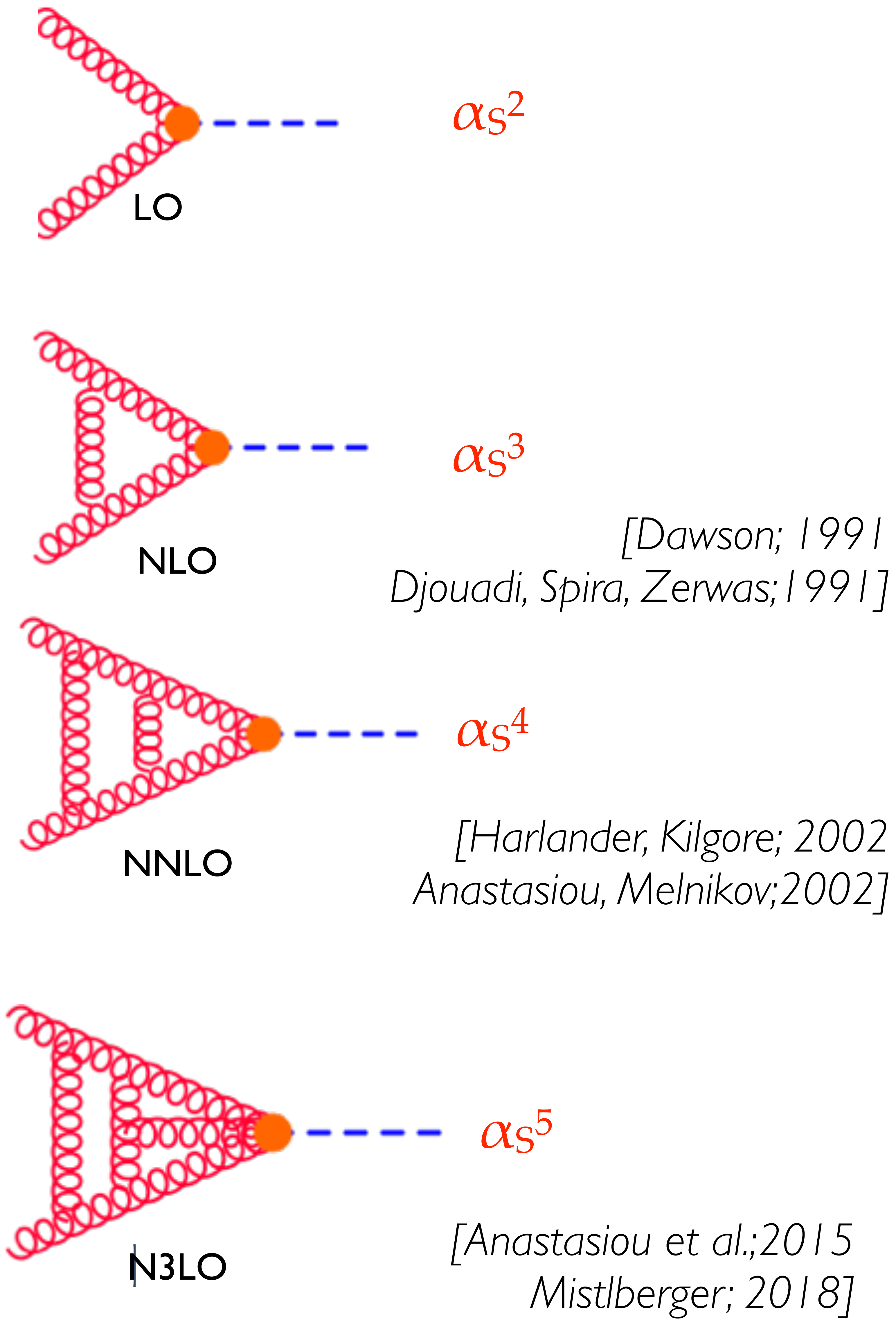
➡ Error estimate at LO largely underestimated!

➡ N3LO ~ 2 LO

➡ Higher-orders are crucial for reliable predictions and precision tests of Higgs properties

Convergence of the perturbative expansion: inclusive Higgs up to N3LO

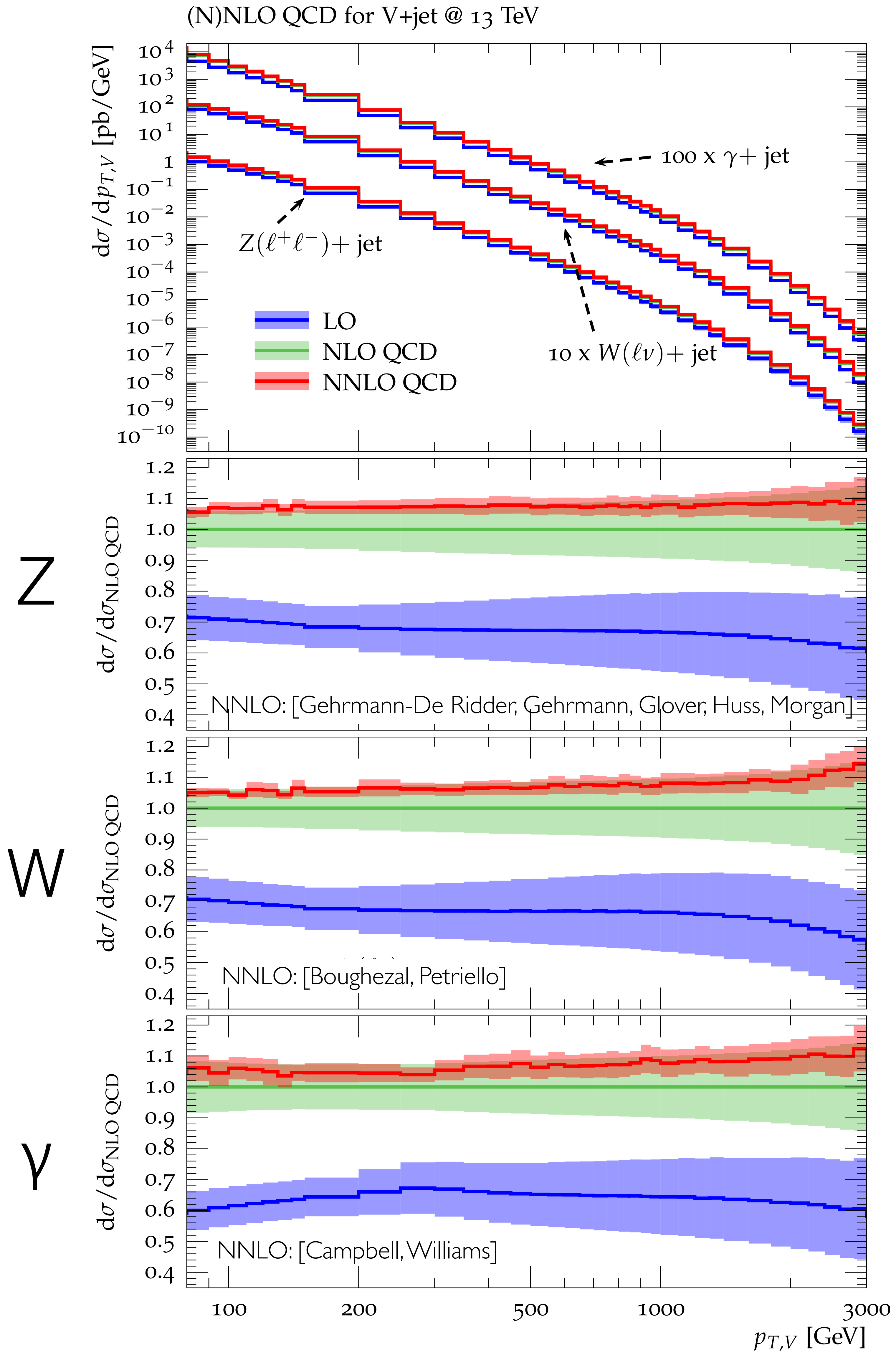




➡ At this level: crucial to investigate any possible uncertainty beyond naive scale variations

Convergence of the perturbative expansion: V+jets @ NNLO

[JML et. al.: 1705.04664]



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

$$\mu_0 = \frac{1}{2}\left(\sqrt{p^2_{\mathrm{T},\ell^+\ell^-} + m^2_{\ell^+\ell^-}} + \sum_{i\in\{q,g,\gamma\}} |p_{\mathrm{T},i}|\right)$$

this is a 'good' scale for V+jets

- at large pTV: HT'/2 ≈ pTV
- modest higher-order corrections
- sufficient convergence

scale uncertainties due to 7-pt variations:

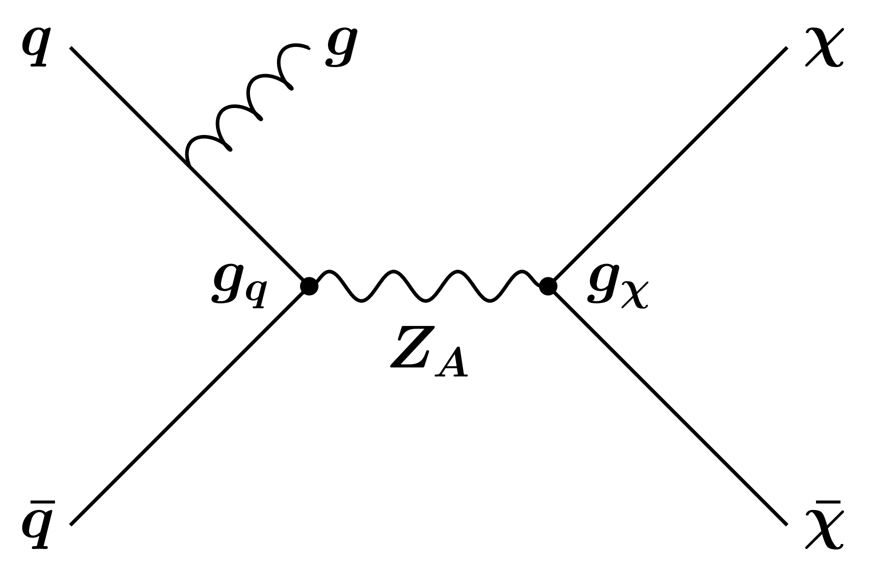
O(20%) uncertainties at LO
O(10%) uncertainties at NLO
O(5%) uncertainties at NNLO

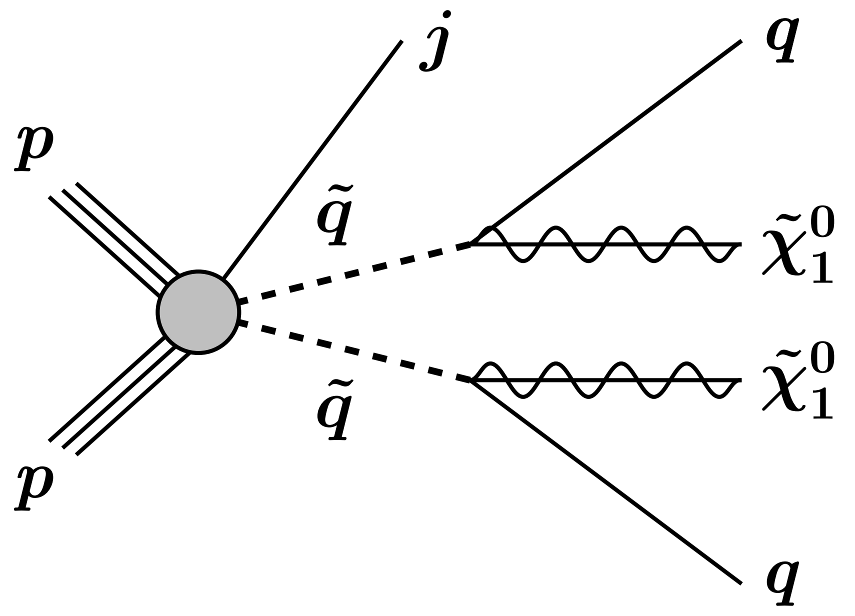
with minor shape variations.

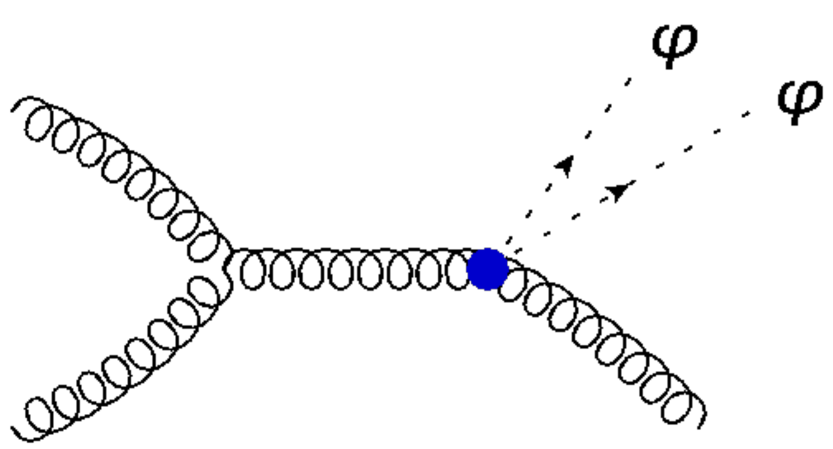
This level of precision for V+jets allows to boost the sensitivity of MET+X searches.

MET+X searches

- Allows to access a broad range of BSM hypotheses

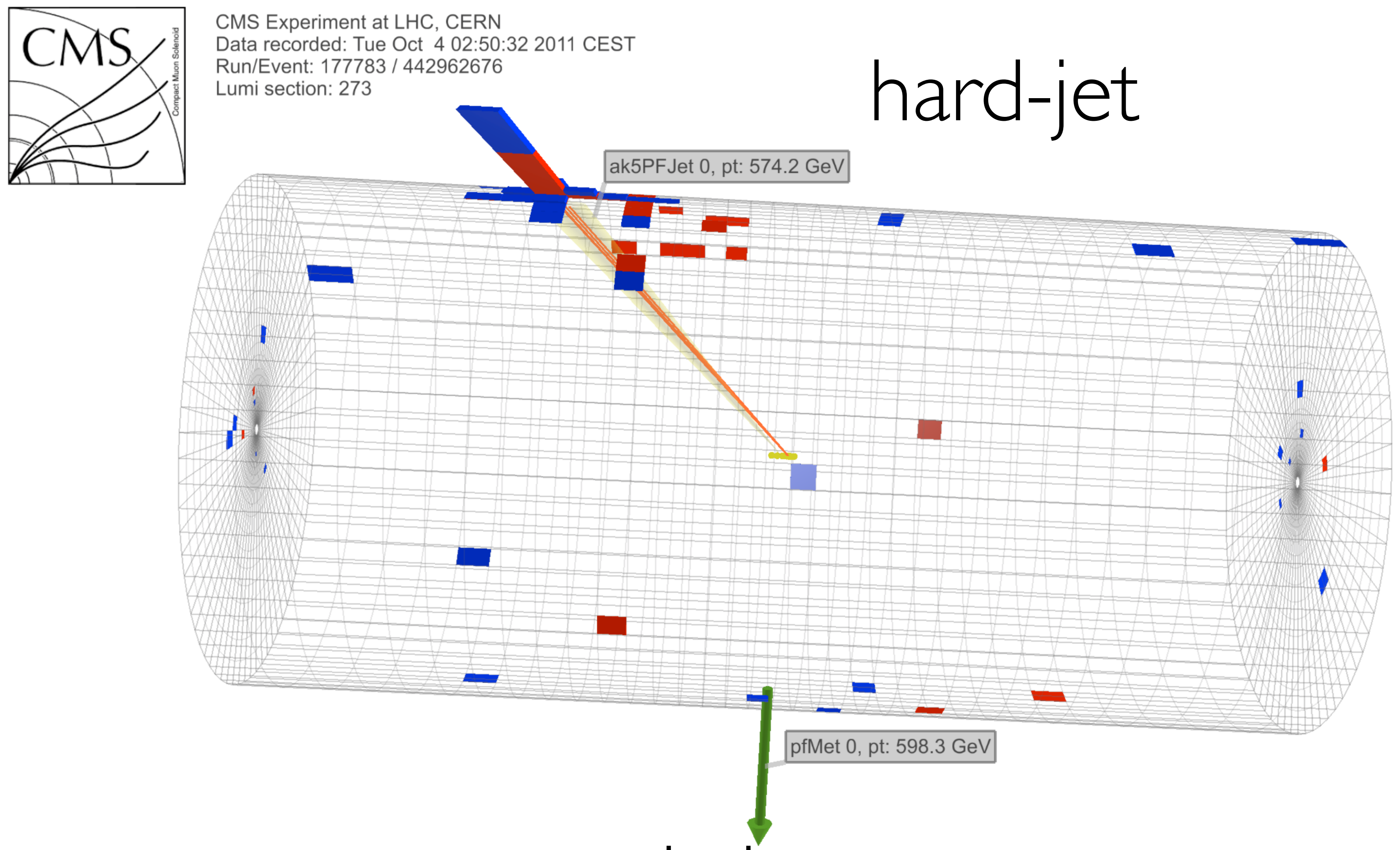






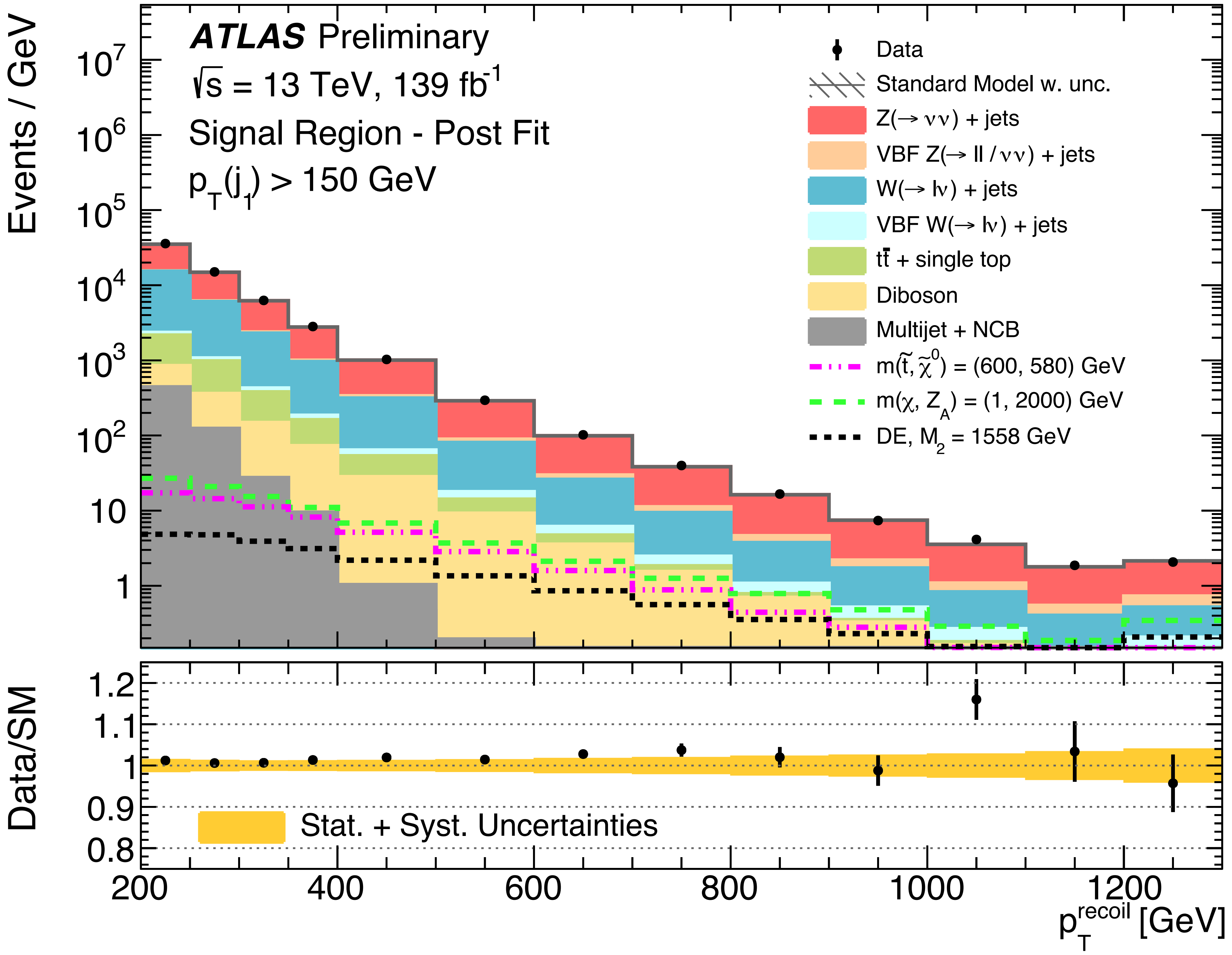
(c)

experimental signal:



hard-jet

missing transverse energy



irreducible SM backgrounds:

pp→Z(→$\nu\bar{\nu}$)+jets ⟹ MET + jets

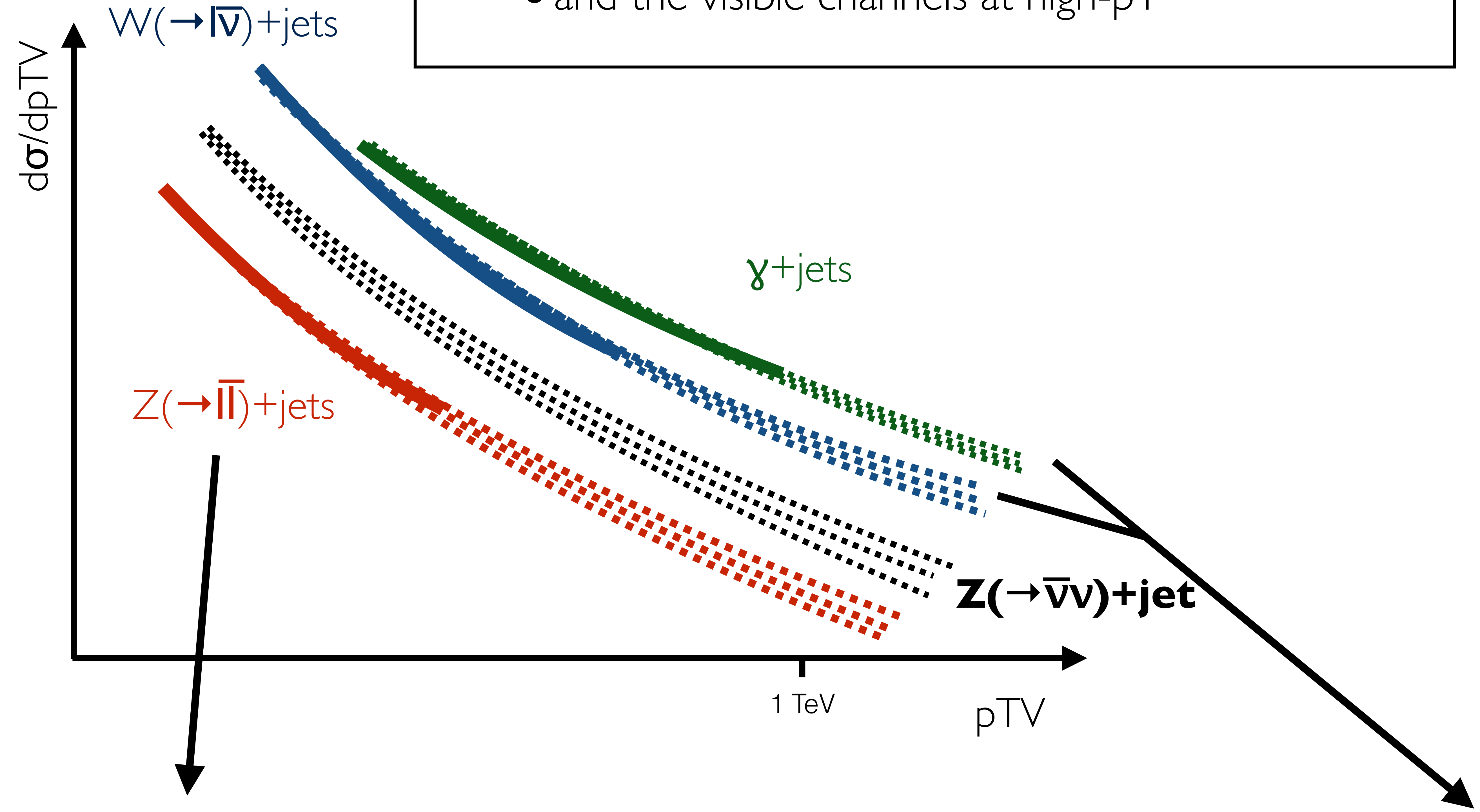
pp→W(→lν)+jets ⟹ MET + jets (lepton lost)

} V + jets

Determine V+jets DM backgrounds

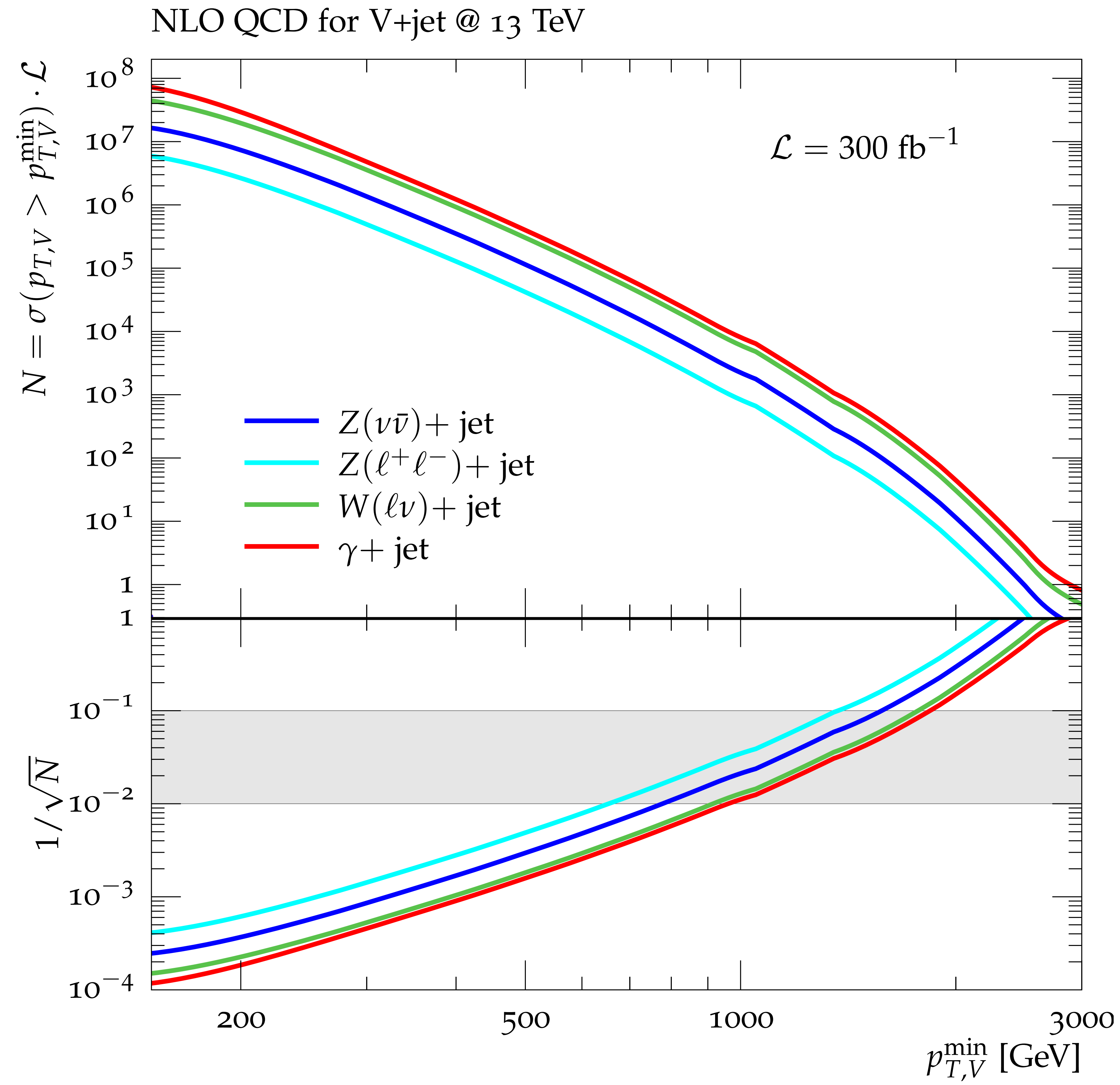
global fit of Z(→ll̄)+jets, W(→lν̄)+jets and γ+jets measurements

- to determine Z(→ν̄ν)+jet
- and the visible channels at high-pT



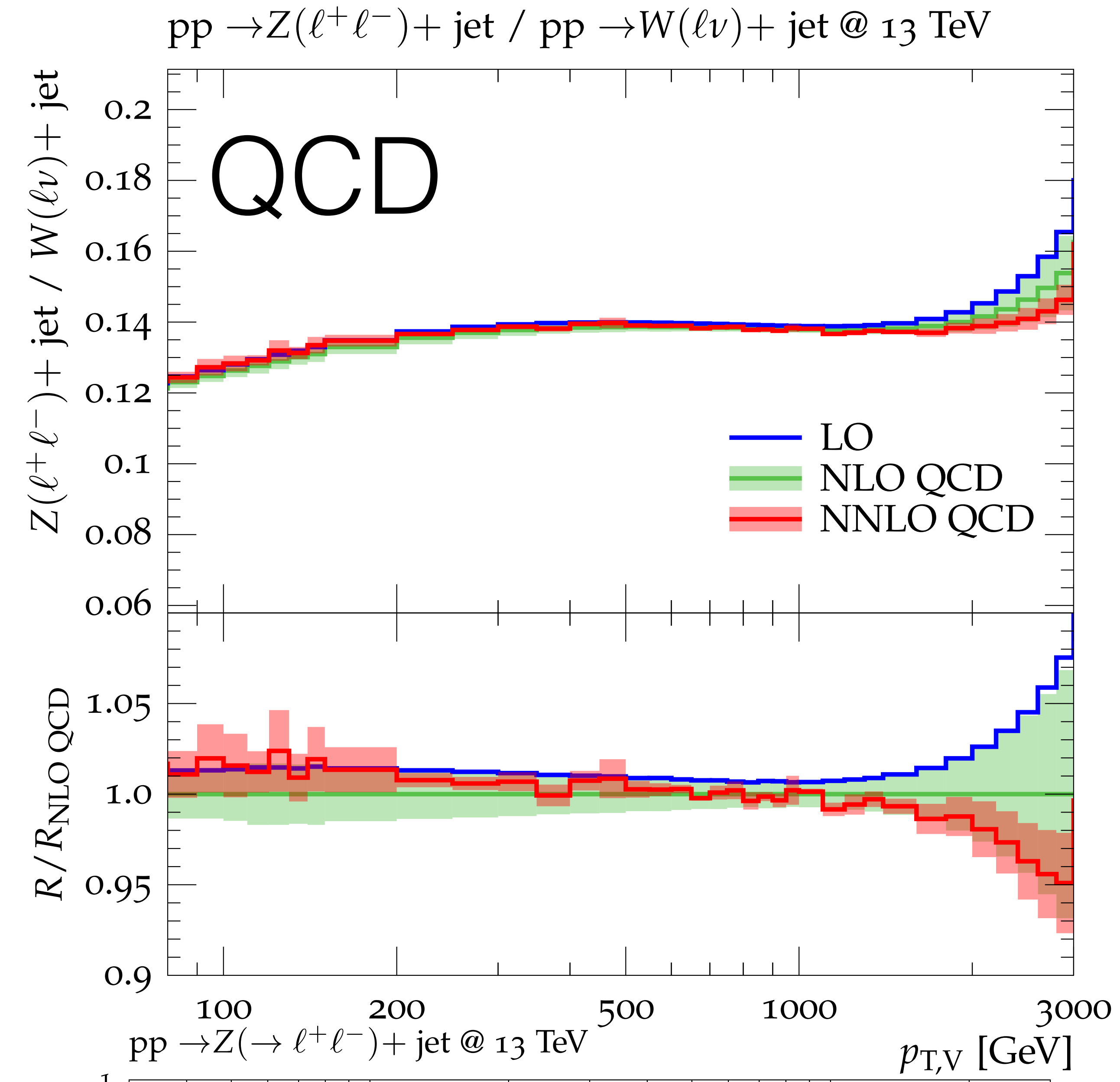
- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT

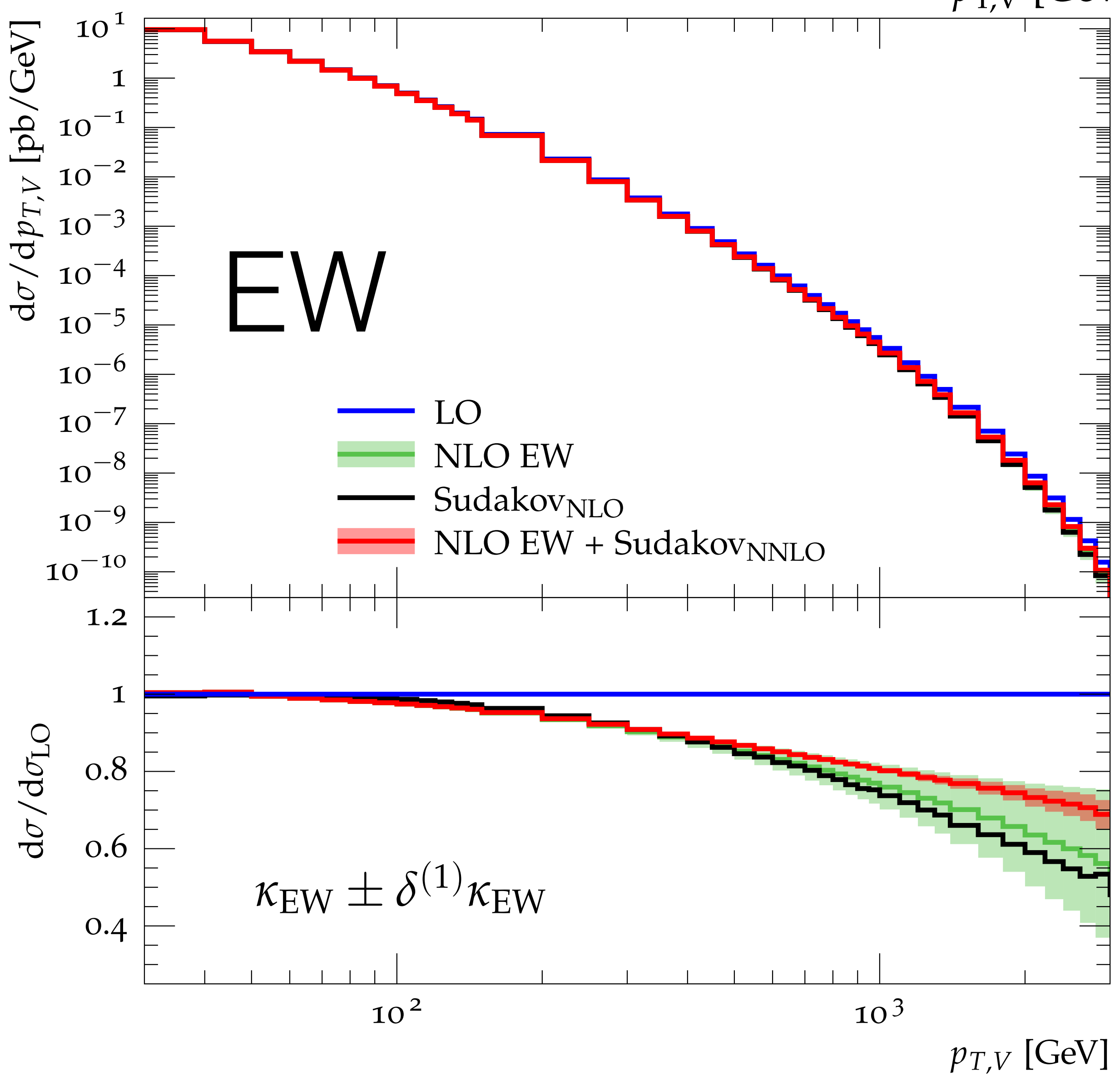
- fairly large data samples at large pT
- systematics from transfer factors

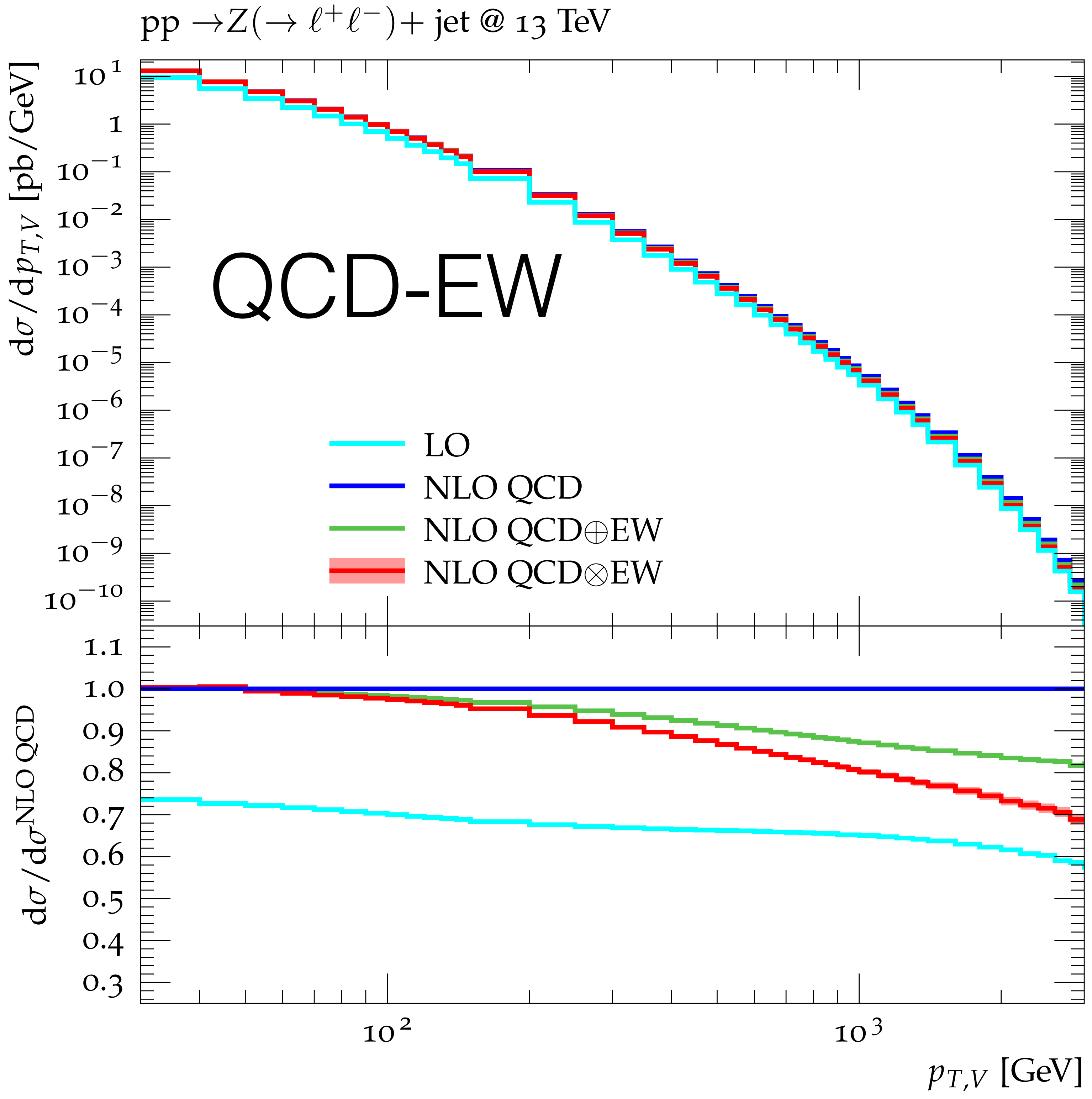


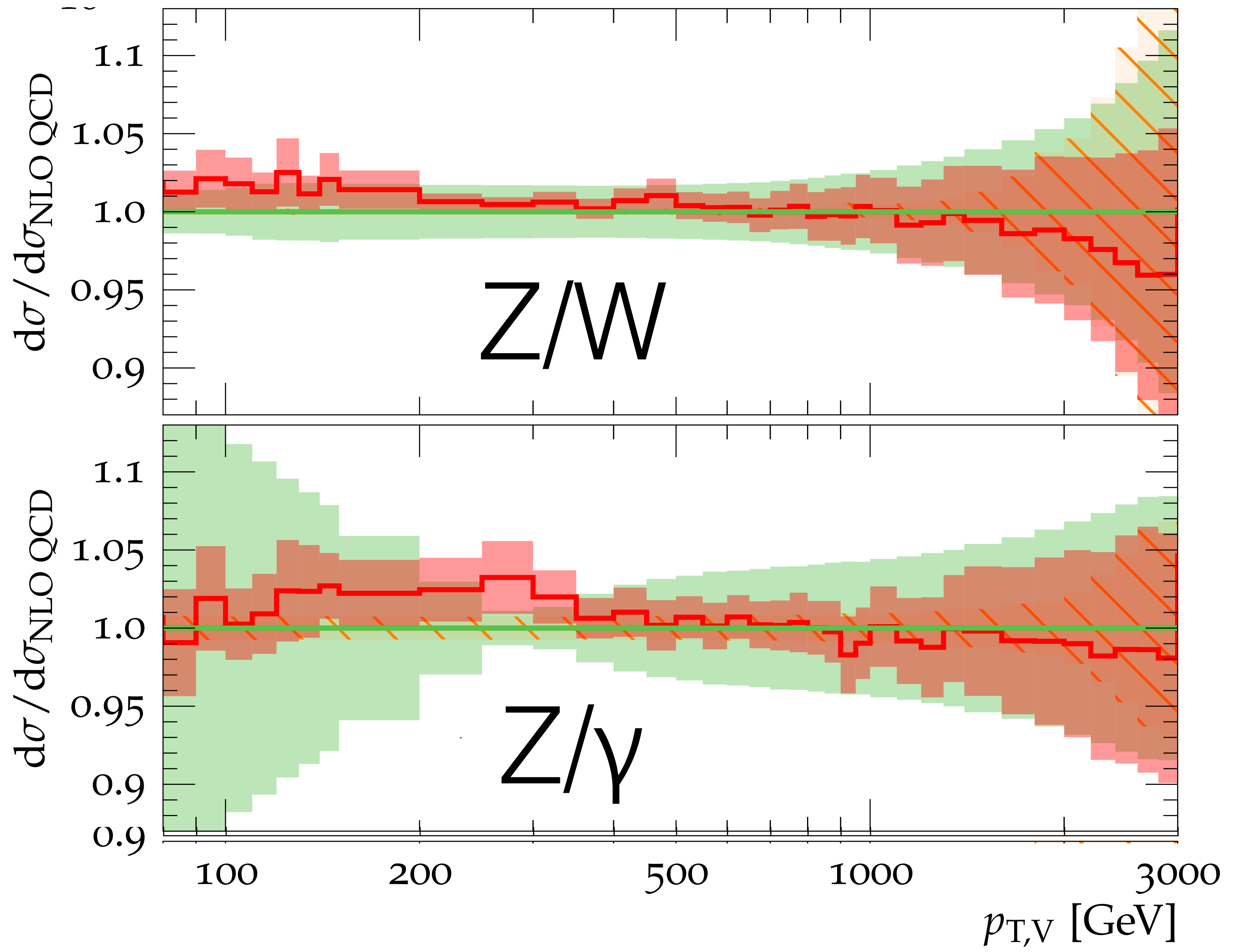
- for 500 GeV < pTV < 1000 GeV: background statistics will be at **1% level**
- this level of precision is theoretically possible @ **NNLO QCD + NNLO EW**

Improving MET+X searches with precision



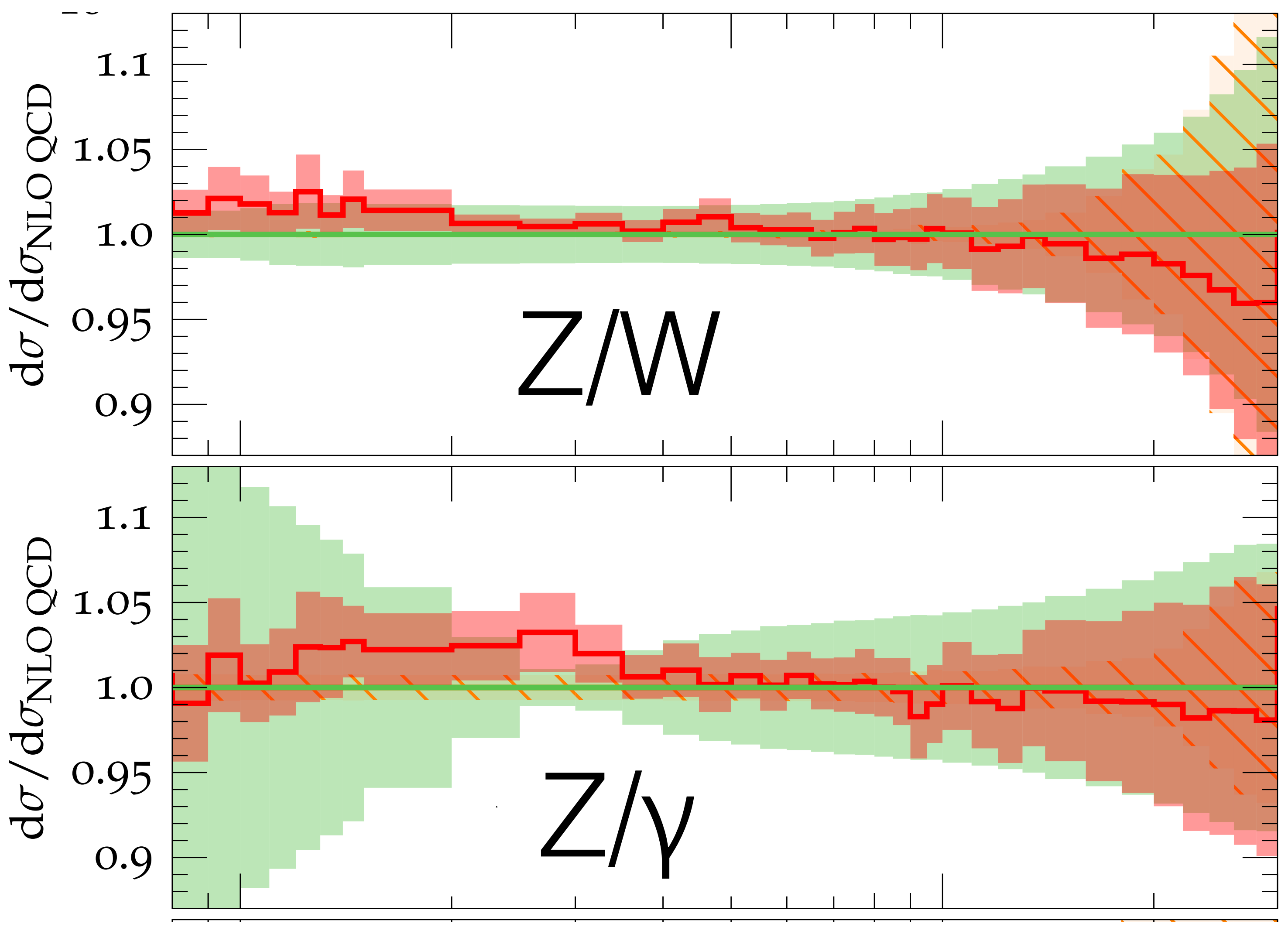






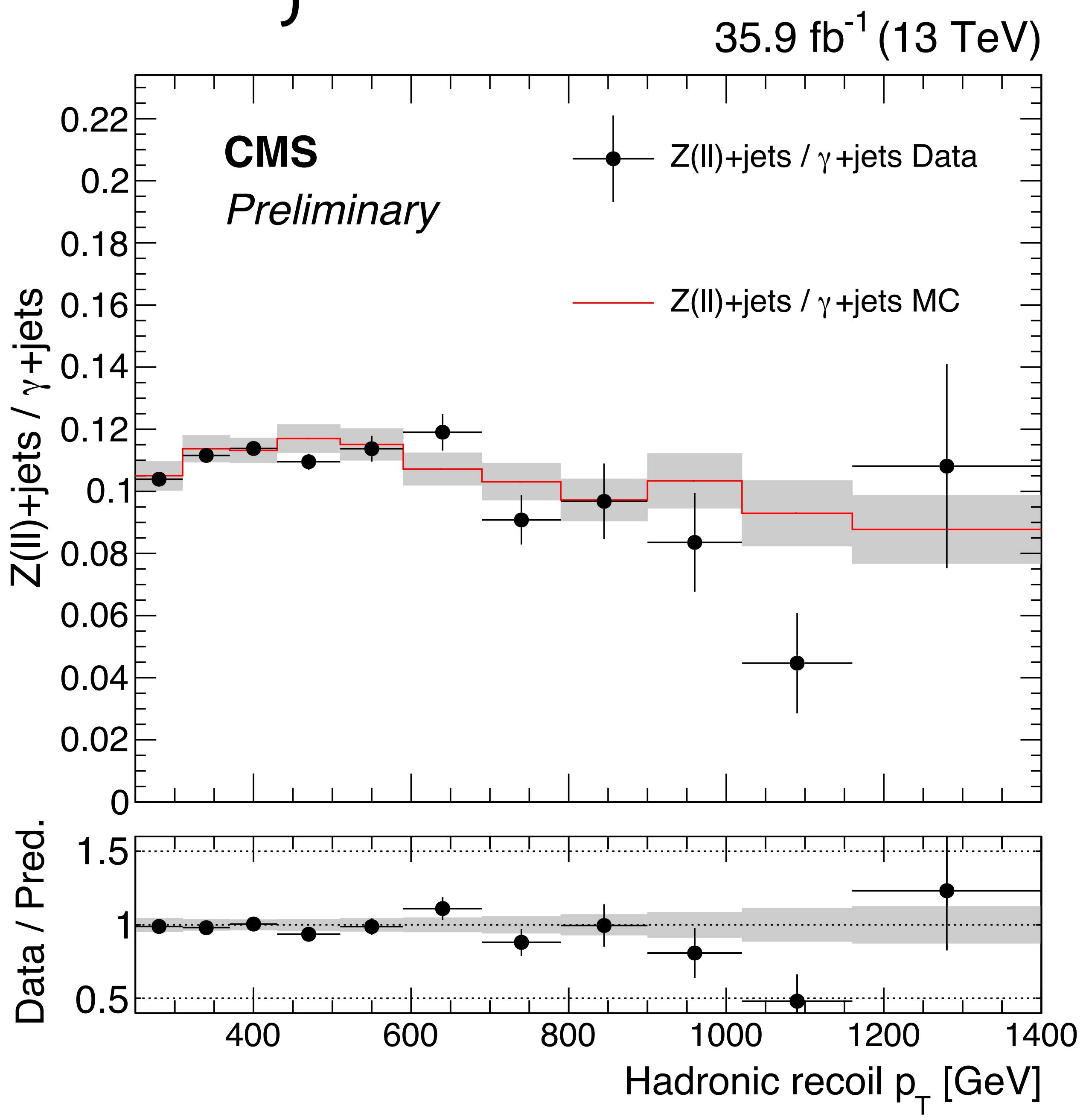
- $\delta_{Z/W}$ =1-3% for pT < 1 TeV
- $\delta_{Z/\gamma}$ = 3-5% for pT < 1 TeV

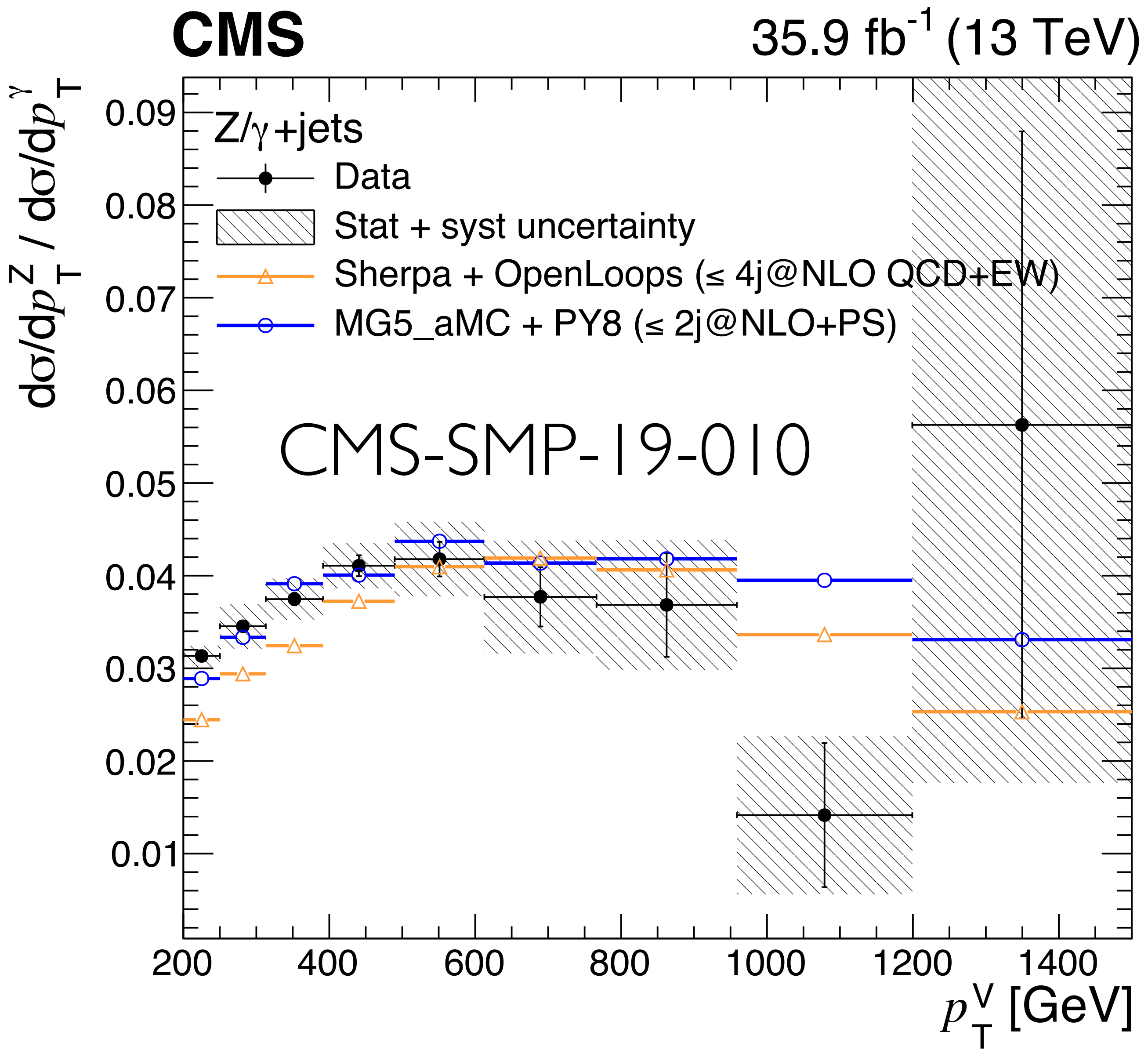
Combined uncertainties on V+jets ratios



CR

dedicated
SM measurements



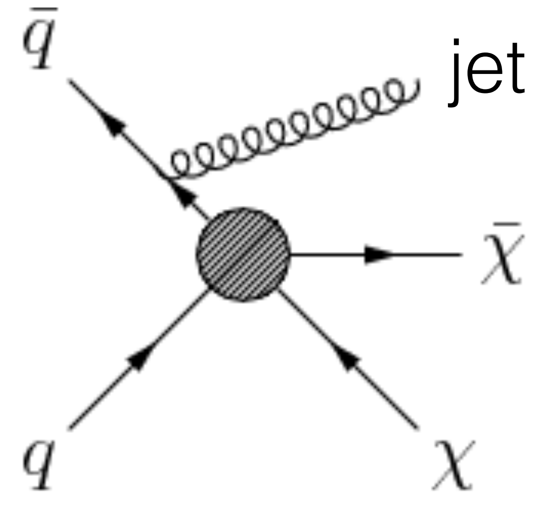


- $\delta_{Z/W}$ =1-3% for pT < 1 TeV
- $\delta_{Z/\gamma}$ = 3-5% for pT < 1 TeV

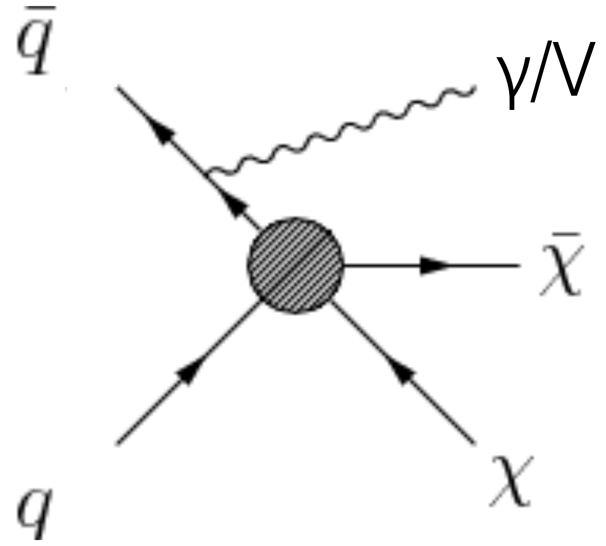
The Zoo of MET+X searches

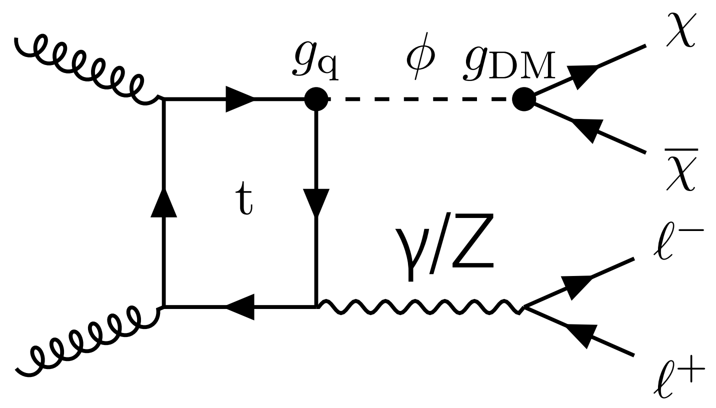
ISR

Mono-jet



Mono-γ/V

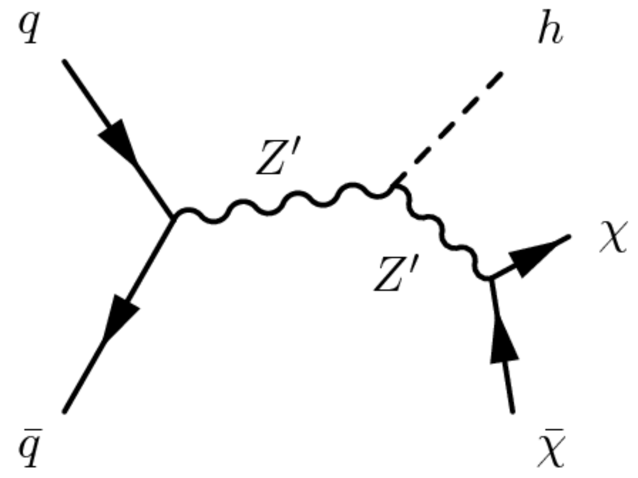




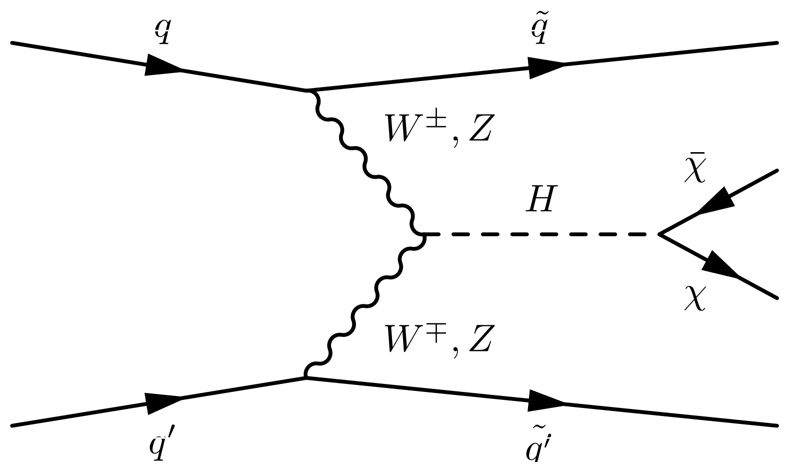
Loop-induced

Higgs-Strahlung

Mono-H



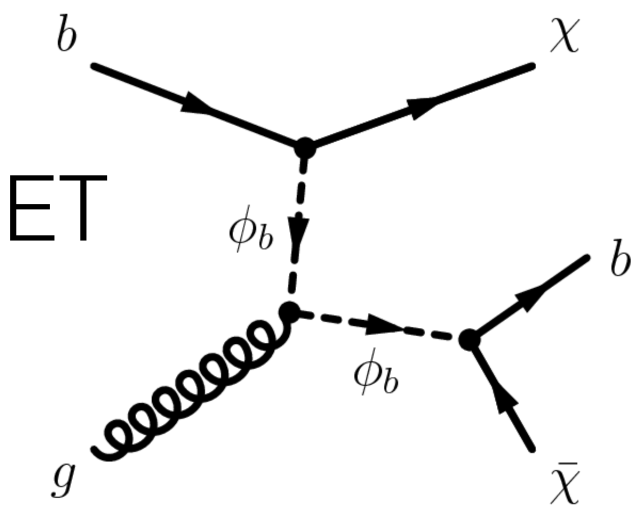
VBF



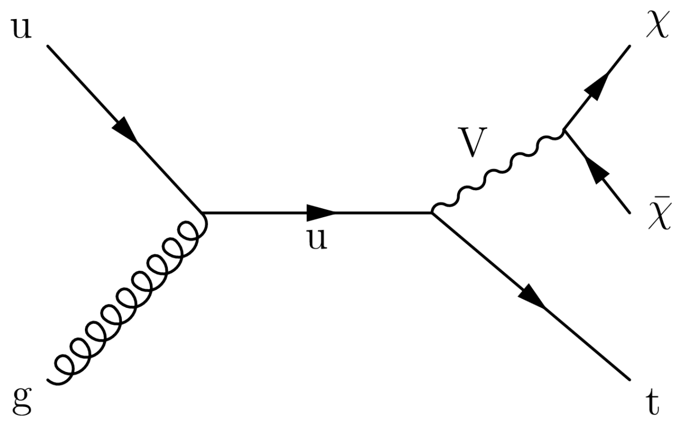
and many more….

HF-associated

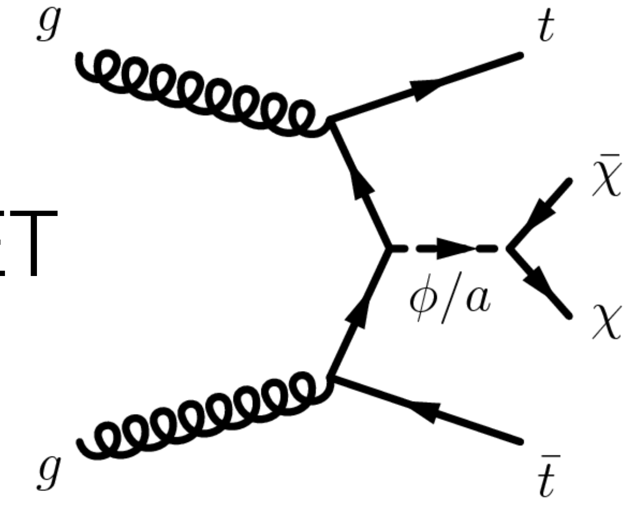
b+MET



t+MET



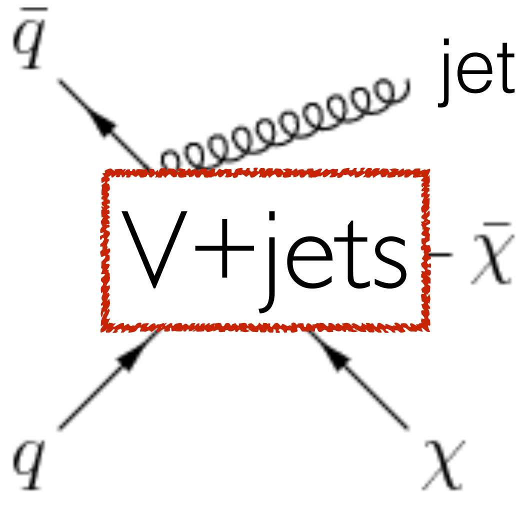
tt+MET



The Zoo of MET+X searches: backgrounds

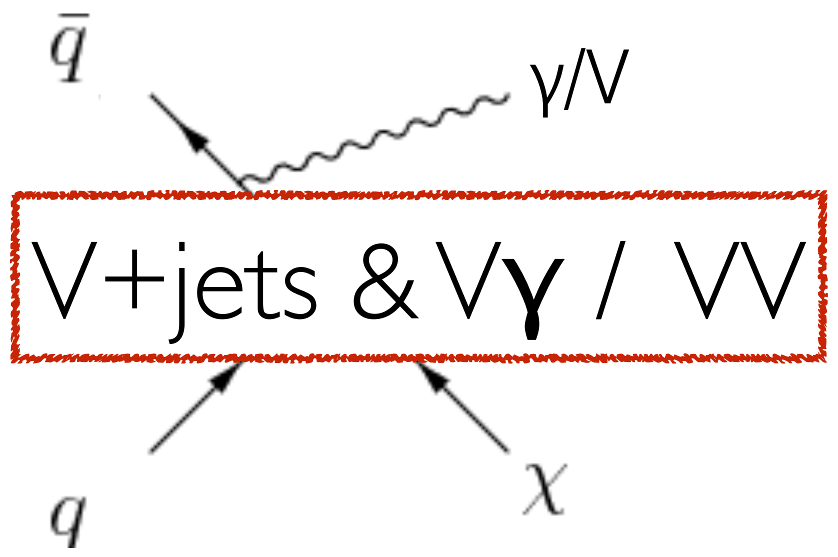
ISR

Mono-jet

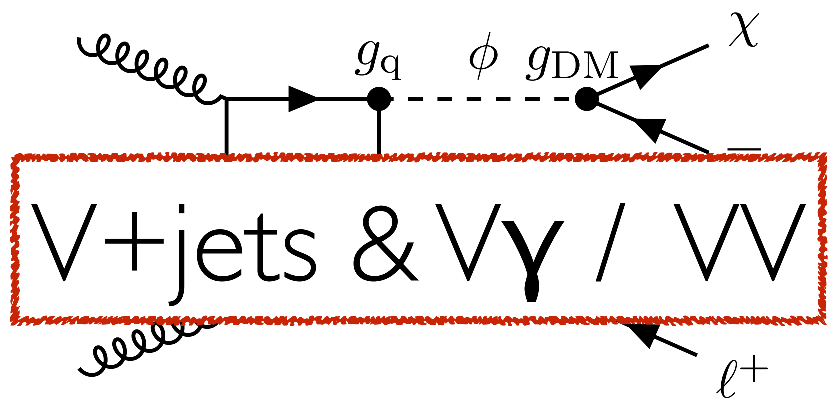


V+jets

Mono-γ/V



V+jets & Vγ / VV

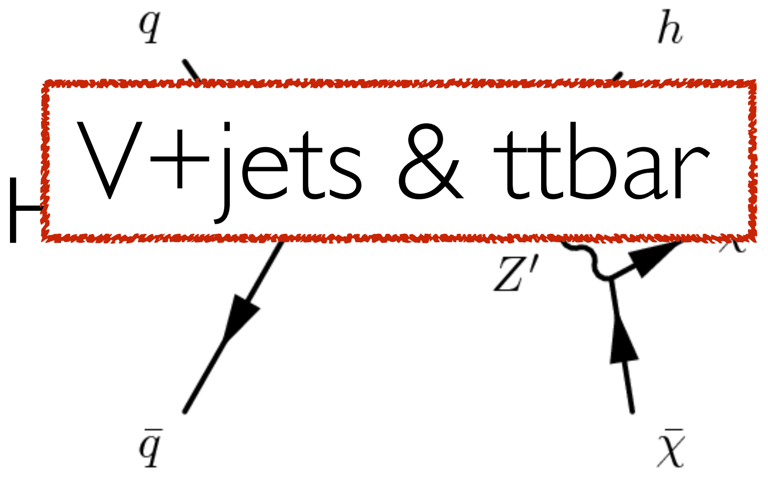


V+jets & Vγ / VV

Loop-induced

Higgs-Strahlung

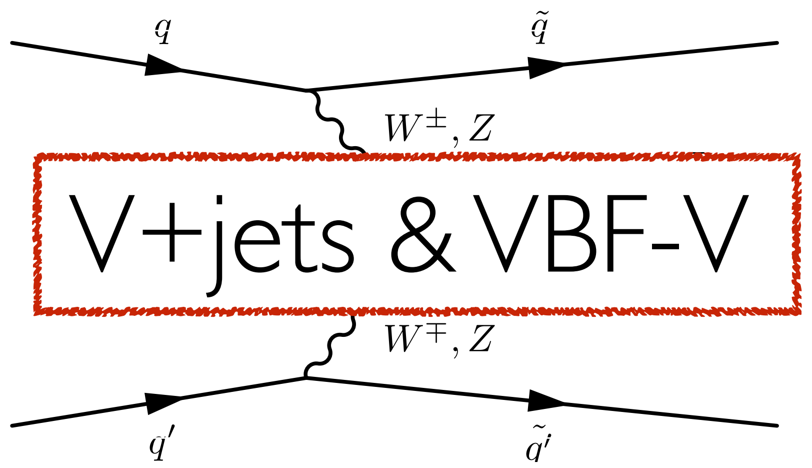
Mono-H



V+jets & ttbar

VV ratios

VBF

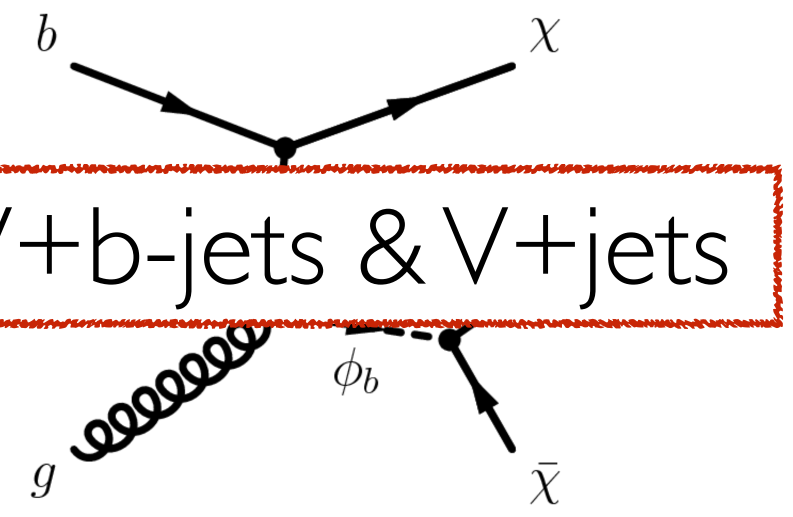


V+jets & VBF-V

VBF-V ratios

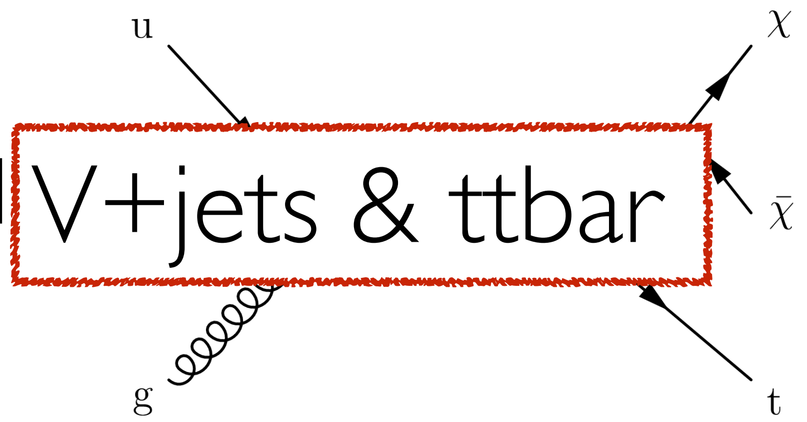
HF-associated

b+M



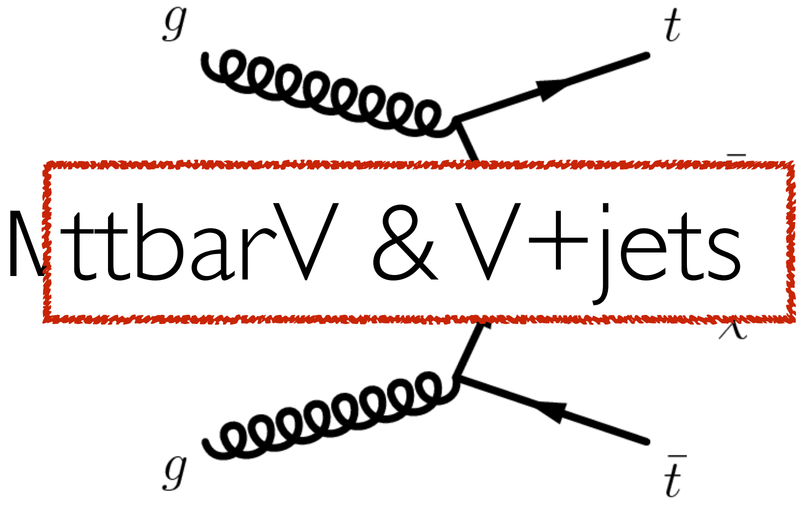
V+b-jets & V+jets

t+M



V+jets & ttbar

tt+M

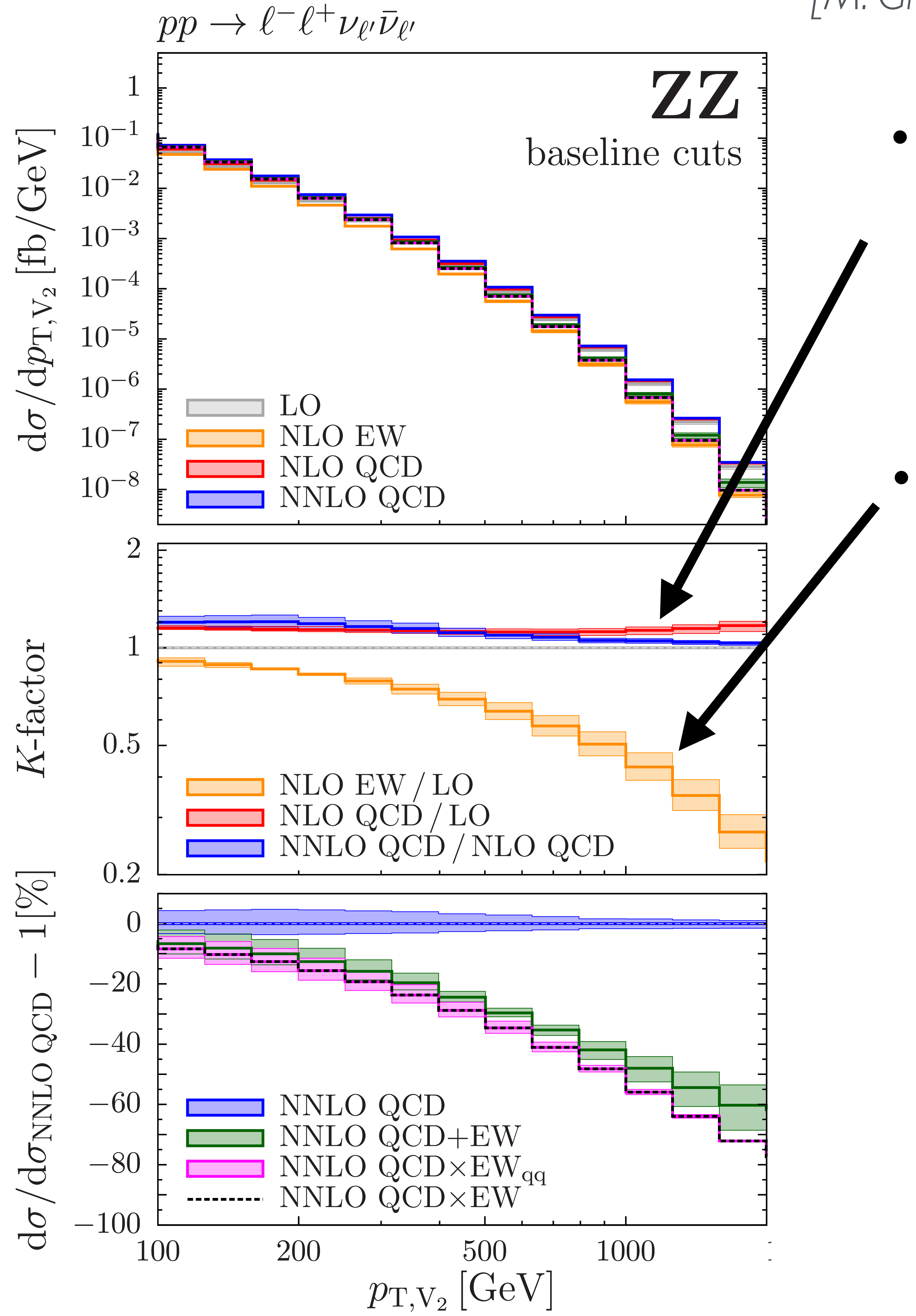


ttbarV & V+jets

…work in progress…stay tuned!

NNLO QCD + NLO EW for VV: pTV2

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]



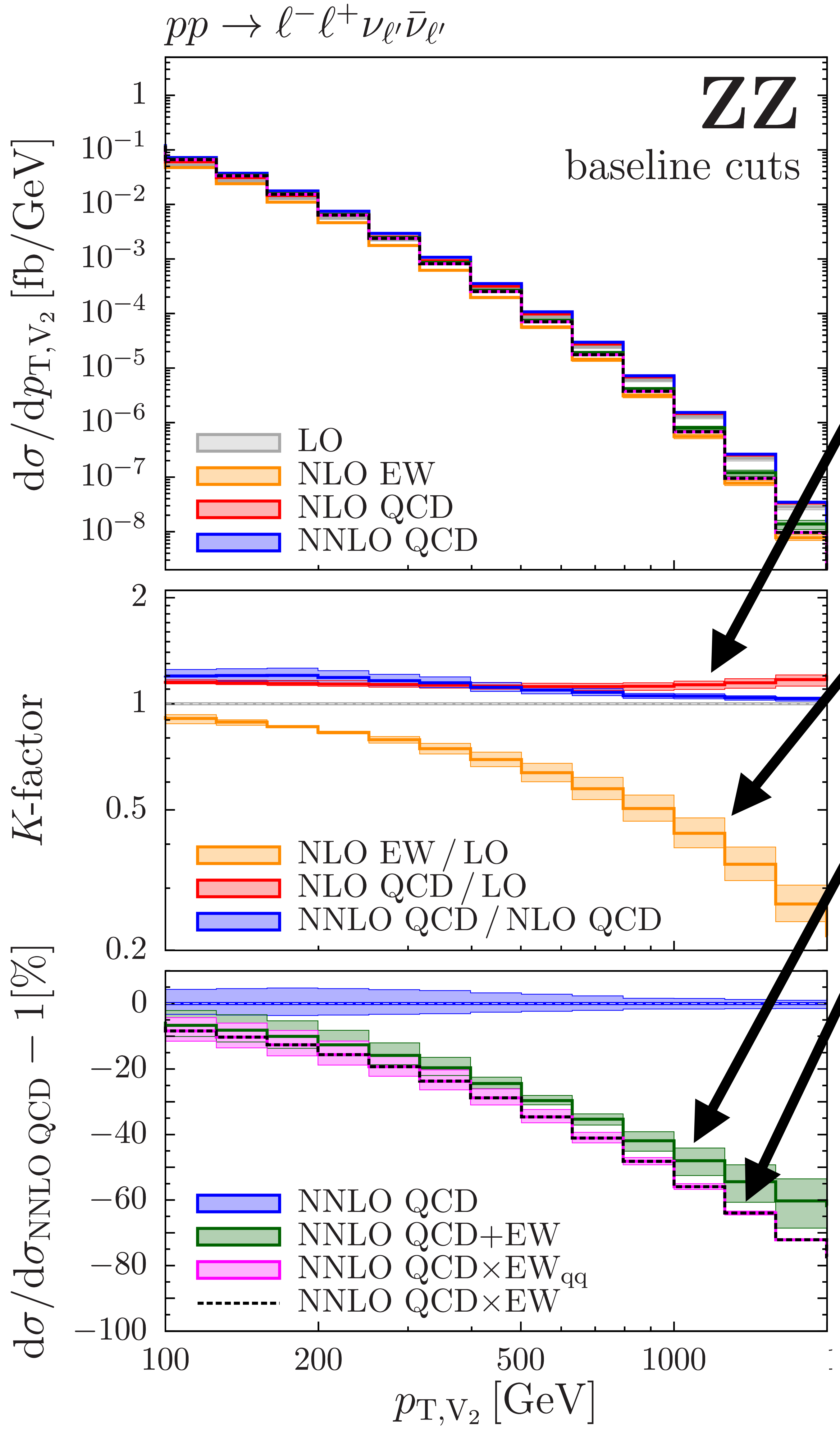
pTV2

- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent

- NLO EW/LO=-(50-60)% @ 1 TeV

NNLO QCD + NLO EW for VV: pTV2

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]



pTV2

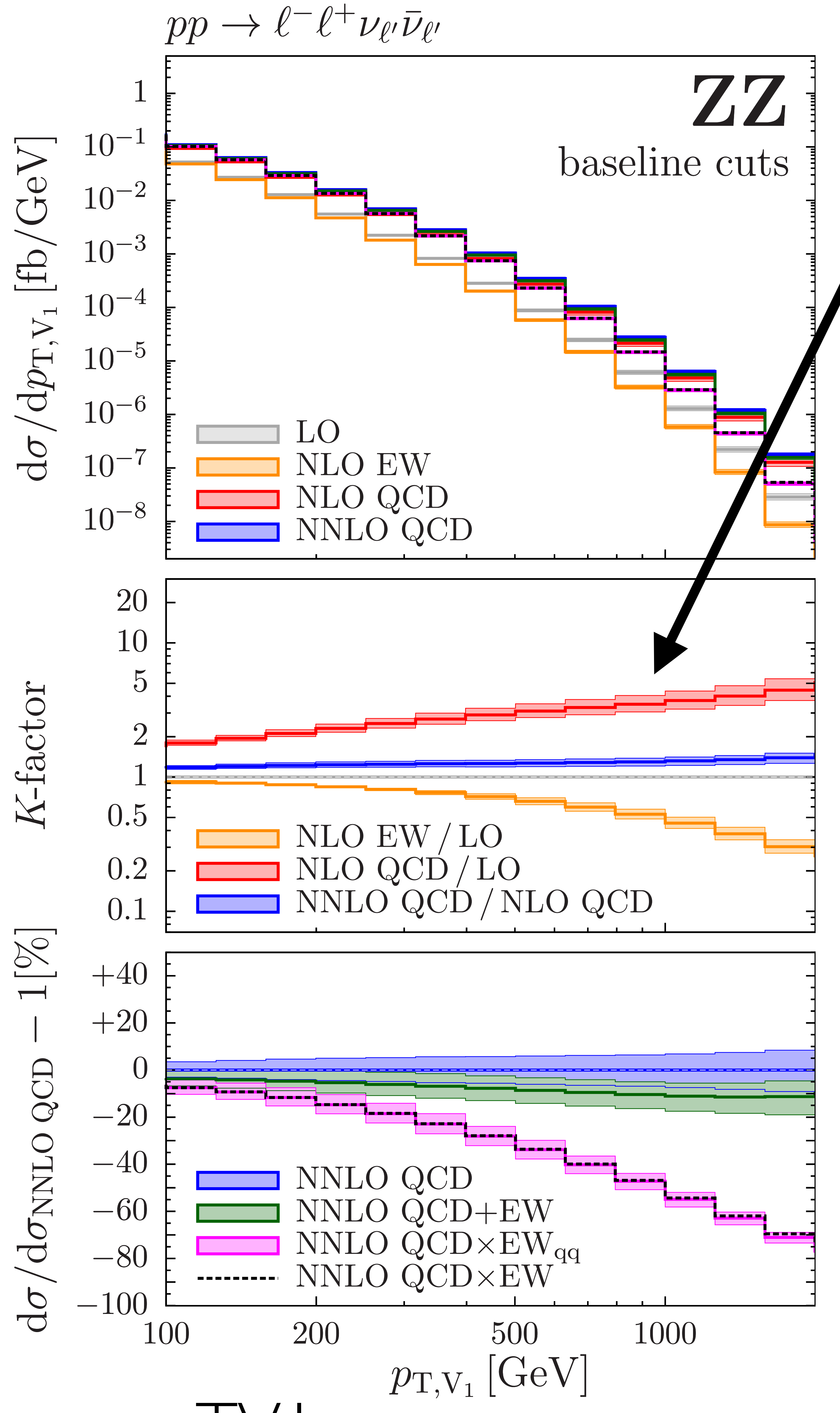
- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent
- NLO EW/LO=-(50-60)% @ 1 TeV

$$d\sigma_{NNLO\,QCD+EW} = d\sigma_{LO}\left(1+\delta_{QCD}+\delta_{EW}\right) + d\sigma_{LO}^{gg}$$
$$d\sigma_{NNLO\,QCD\times EW} = d\sigma_{LO}\left(1+\delta_{QCD}\right)\left(1+\delta_{EW}\right) + d\sigma_{LO}^{gg}$$
$$= d\sigma_{NNLO\,QCD+EW} + d\sigma_{LO}\delta_{QCD}\,\delta_{EW}$$

- difference very **conservative upper bound on** $\mathcal{O}(\alpha_S\alpha)$
- multiplicative/factorised combination clearly superior (EW Sudakov logs x soft QCD)
- dominant uncertainty at large pTV2: $\mathcal{O}(\alpha^2) \sim \alpha_w^2 \log^4(Q^2/M_W^2)$

Estimate: $\boxed{\frac{1}{2}\delta_{EW}^2}$

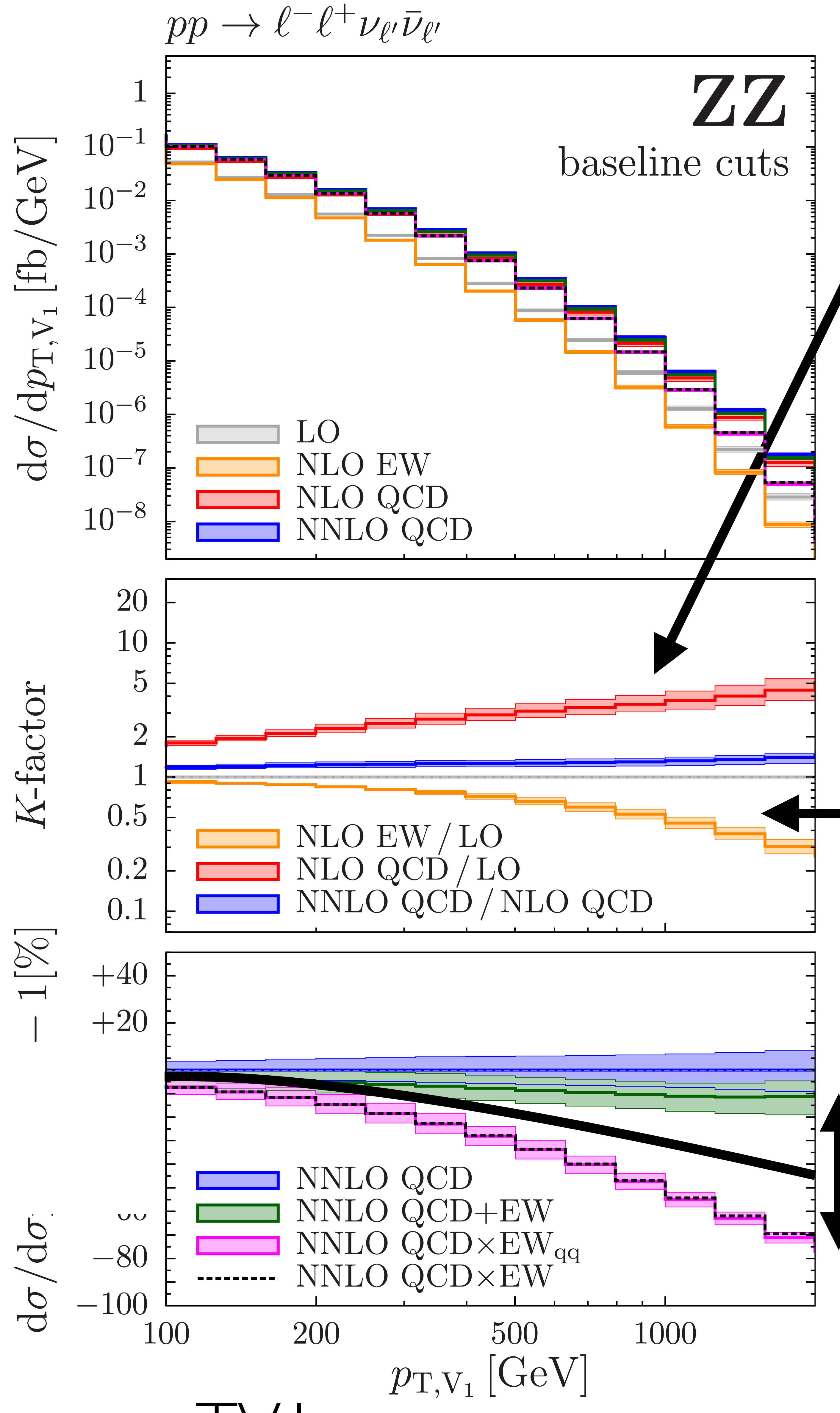
Giant QCD K-factors and EW corrections: pTV1



pTV1

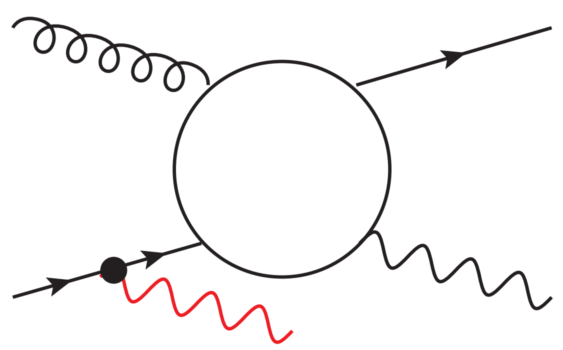
- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta, '10])

Giant QCD K-factors and EW corrections: pTV1



pTV1

- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta,'10])
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



$$\longrightarrow \quad \frac{d\sigma^{V(V)j}}{d\sigma^{\mathrm{LO}}_{VV}} \propto \alpha_{\mathrm{S}} \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\mathrm{TeV}$$

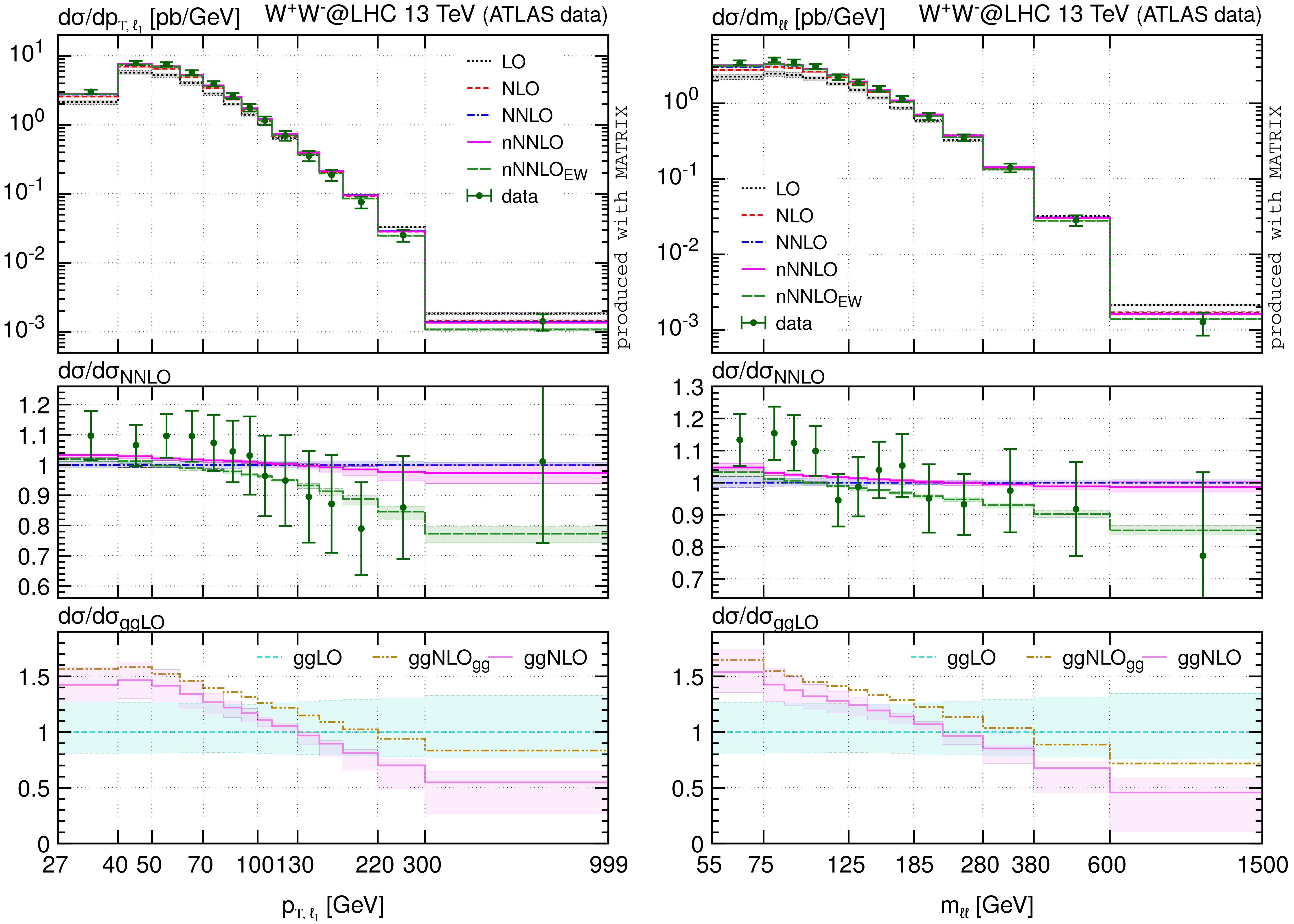
- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $\mathrm{d}\sigma_{\mathrm{NNLO\,QCD+EW}}$ vs. $\mathrm{d}\sigma_{\mathrm{NNLO\,QCD\times EW}}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

First steps in this direction: NLO QCD + EW$_{\mathrm{virt}}$ in Sherpa's MEPS@NLO

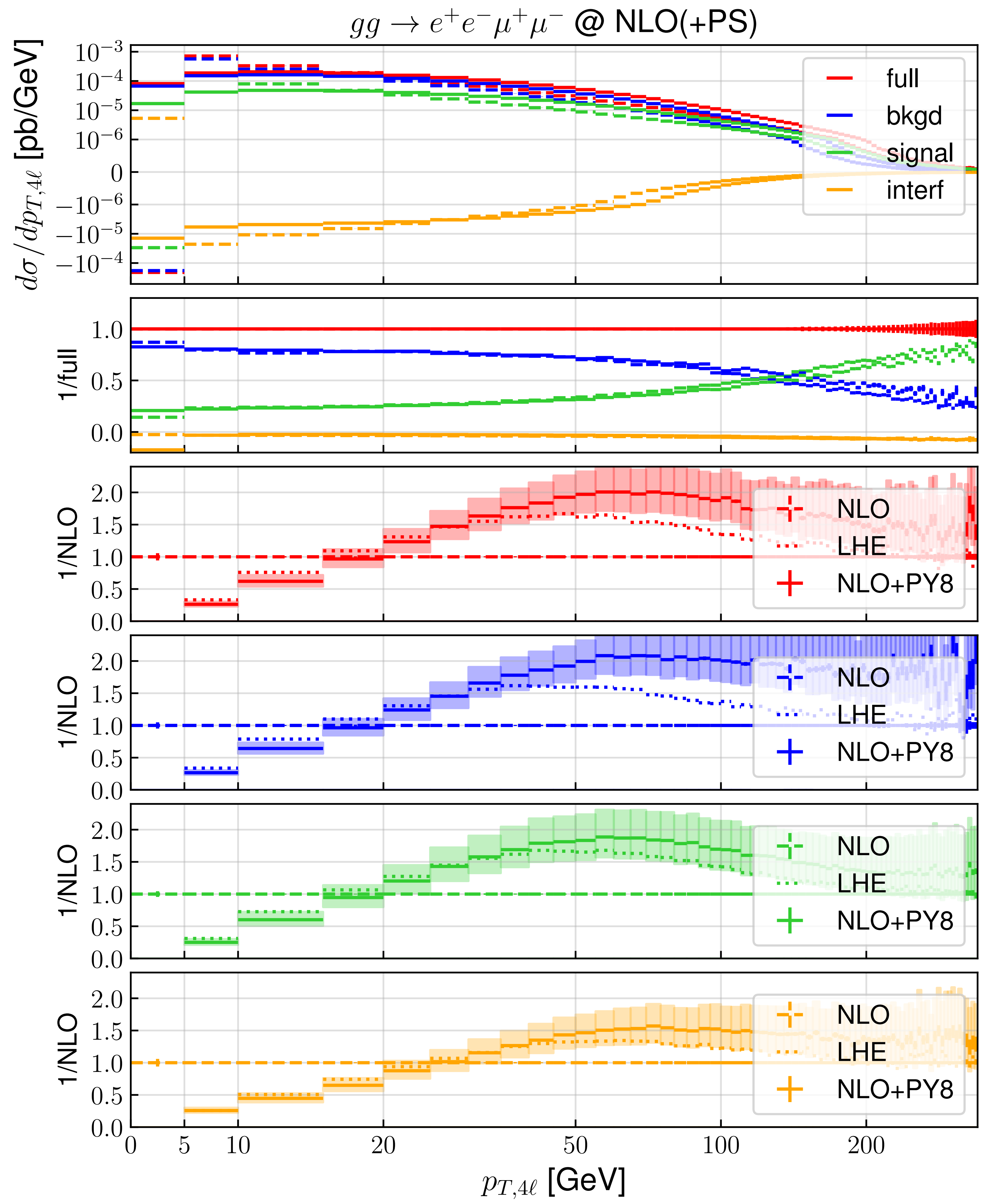
[Bräuer, et. al. '20, 2005.12128]

NNLO QCD + NLO QCDgg + NLO EW vs. data

[M. Grazzini, S. Kallweit, J.Y. Yook, M. Wiesemann; 2002.01877]



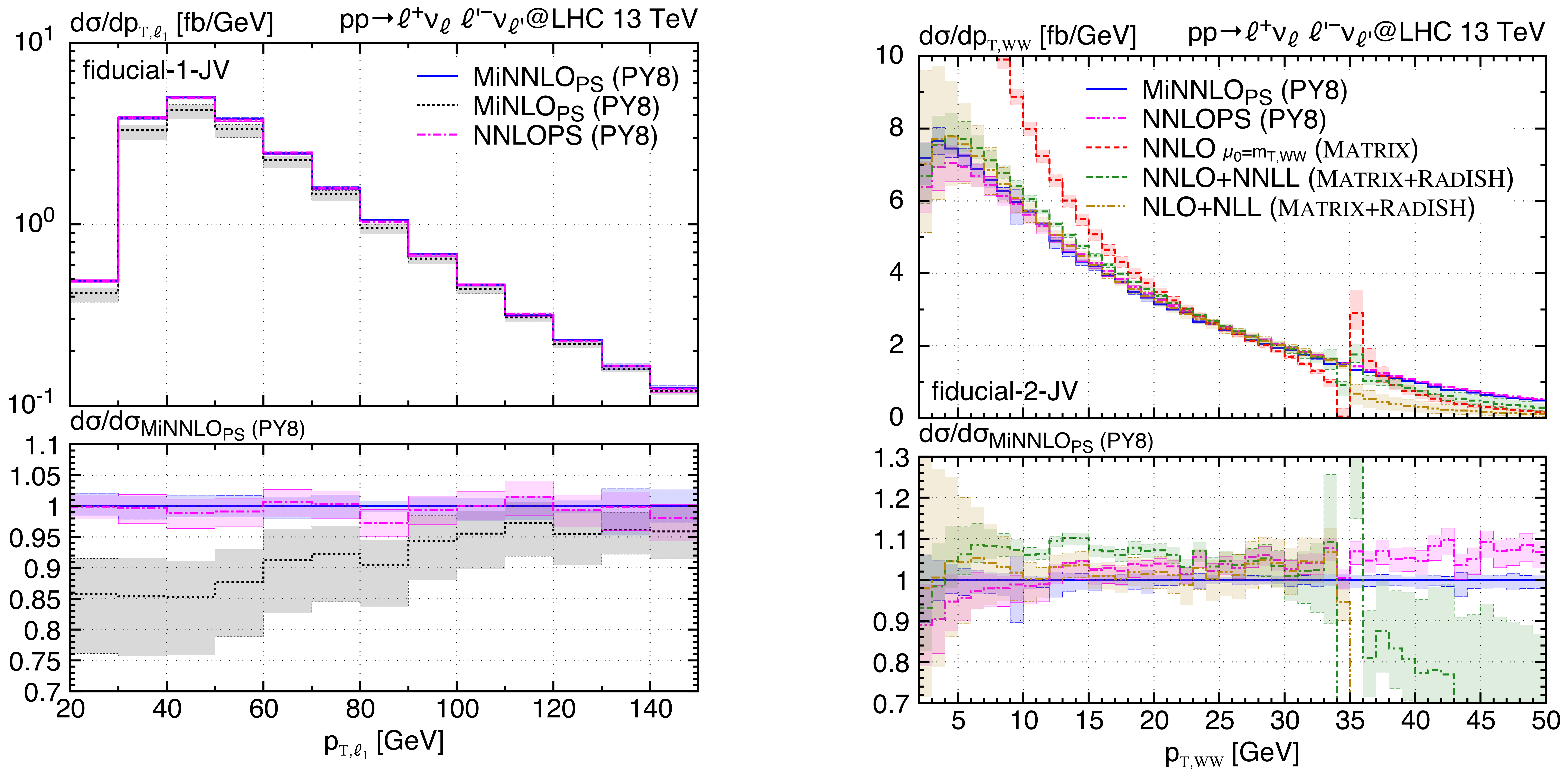
[Alioli, Ferrario Ravasio, JML, Röntsch, '21]



- Very good data vs. theory agreement
- gg @ NLO QCD + PS now available!

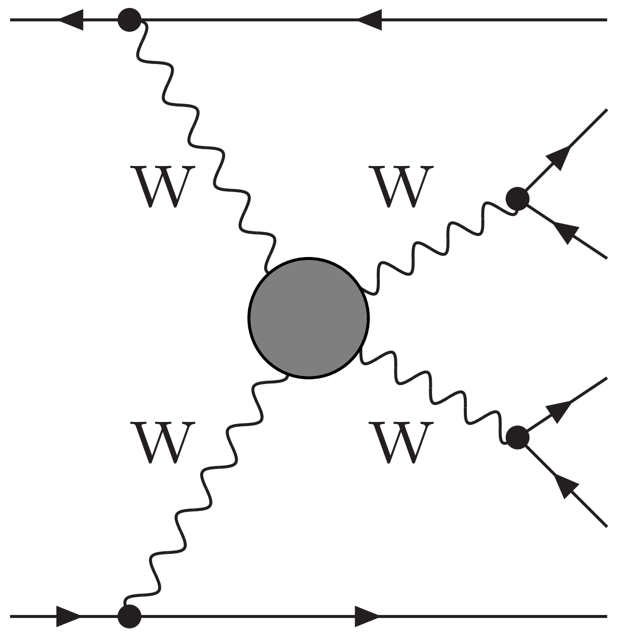
NNLO QCD + PS

[D. Lombardi, M. Wiesemann, G. Zanderighi; 2103.12077]

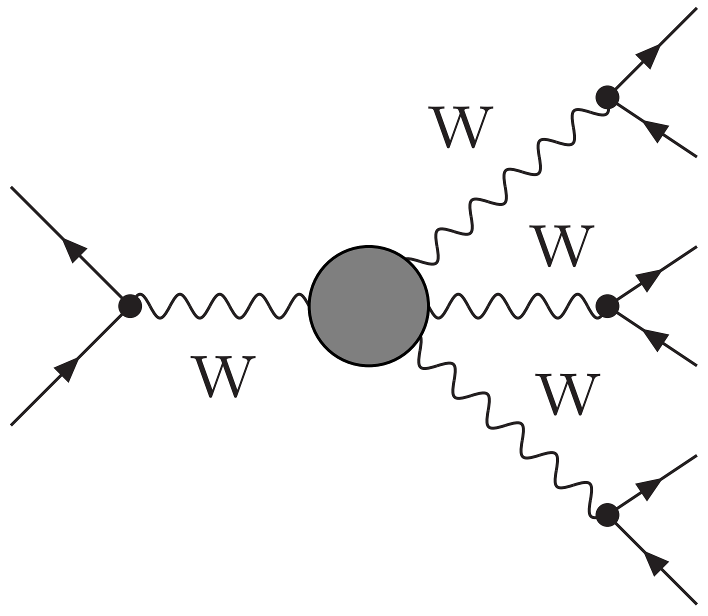


- Very small PS corrections for inclusive observables.
- Inclusion mandatory for (jet) exclusive observables

Rare EW processes

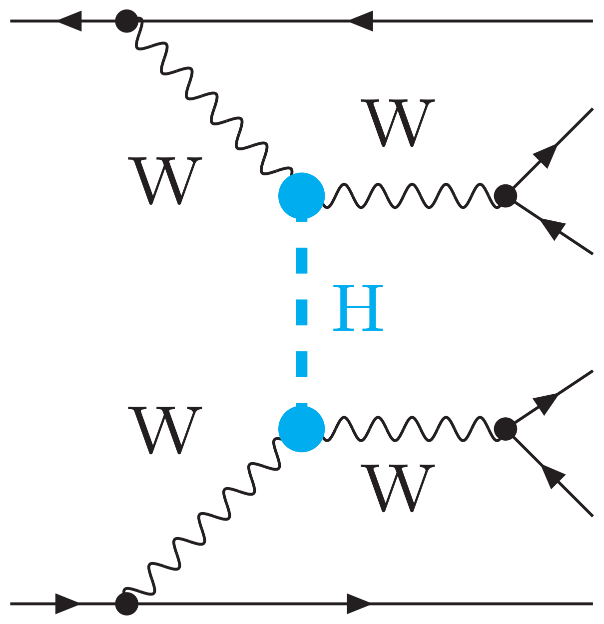


VBS



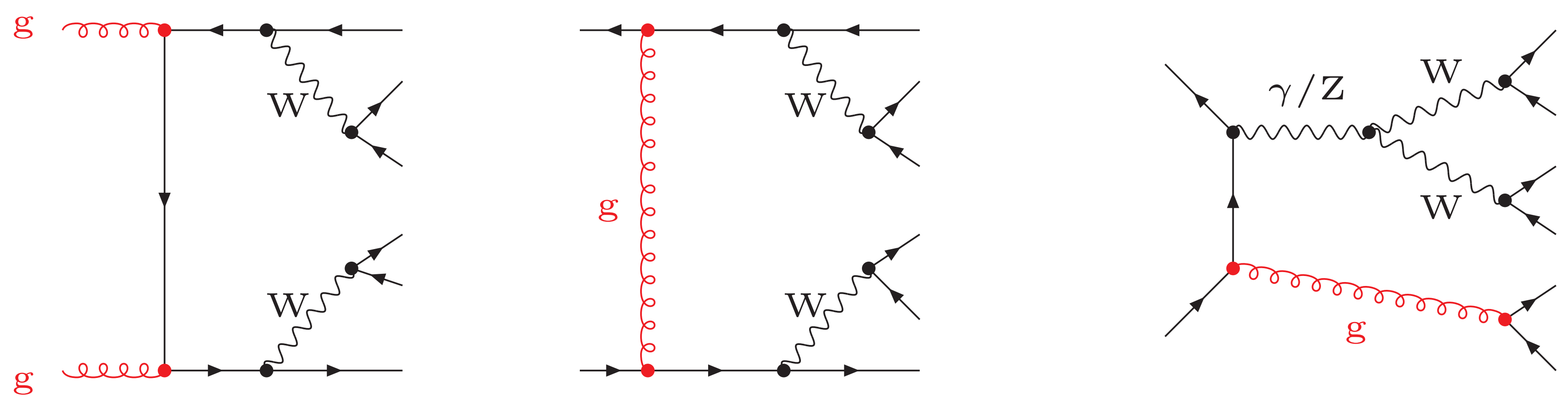
Triboson

- direct access to quartic EW gauge couplings
- VBS: longitudinal gauge bosons at high energies
- window to electroweak symmetry breaking via off-shell Higgs exchange

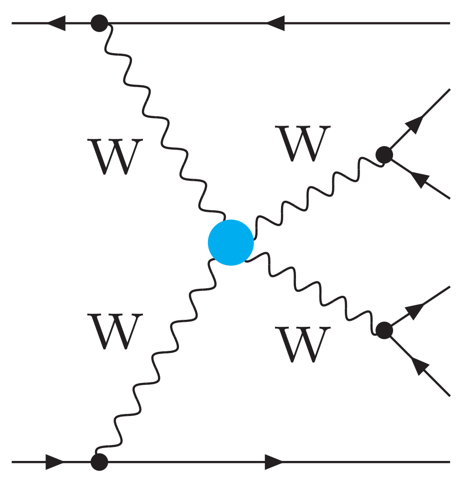


VBS

Note: severe QCD background to VBS signatures + interference:



vs.

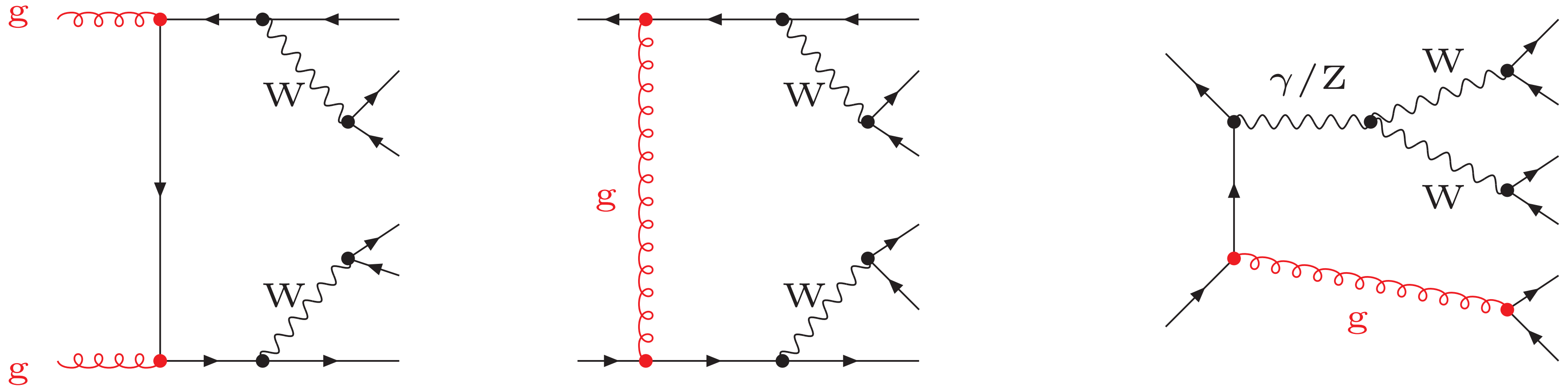


$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$ LO

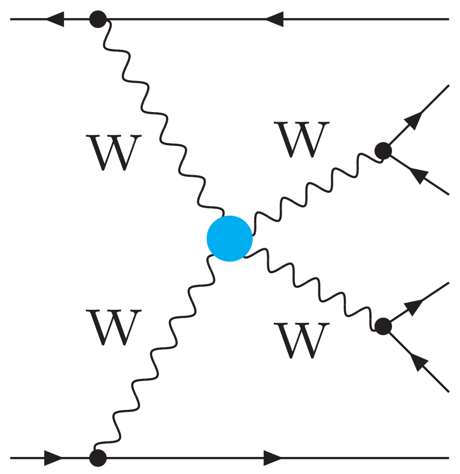
QCD-background interference VBS-signal

VBS

Note: severe QCD background to VBS signatures + interference:



vs.



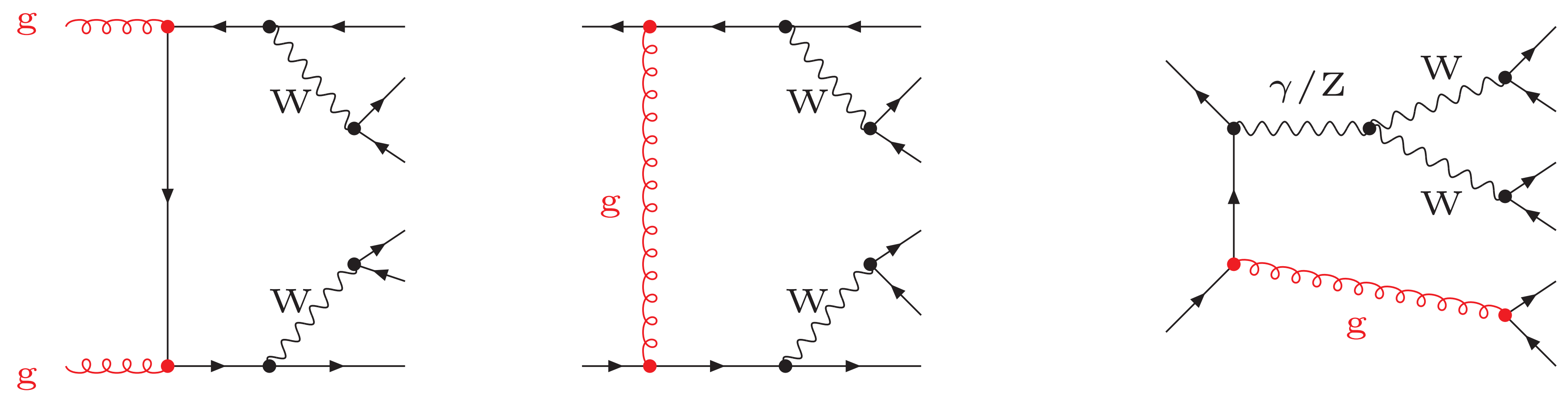
$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$ LO

QCD-background interference VBS-signal

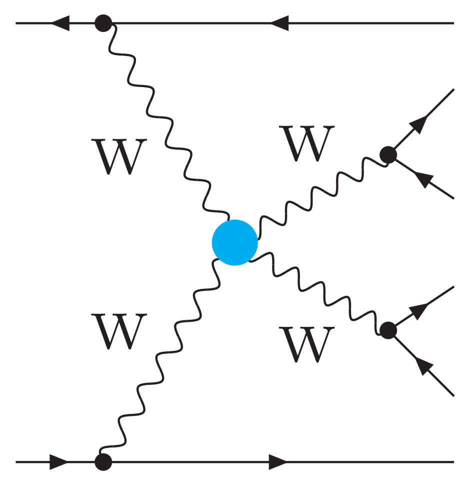
$$\cdots + d\sigma(\alpha_S^3\alpha^4) + d\sigma(\alpha_S^2\alpha^5) + d\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

VBS

Note: severe QCD background to VBS signatures + interference:



vs.



$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$ LO

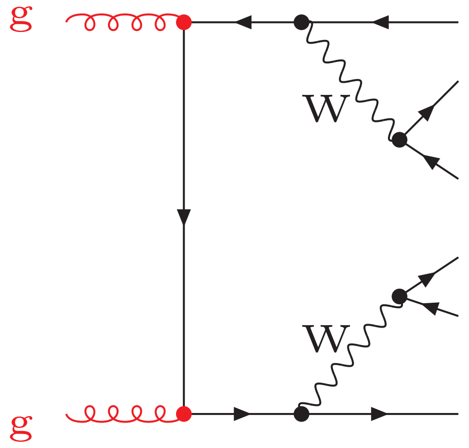
QCD-background $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ interference $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ VBS-signal

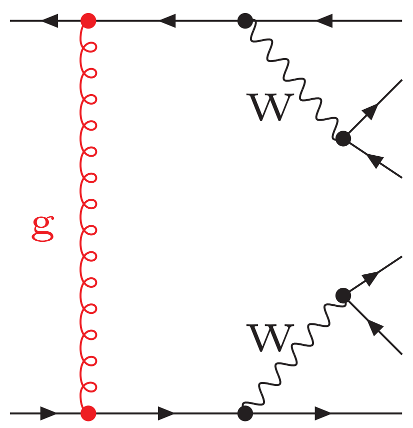
$$\cdots + d\sigma(\alpha_S^3\alpha^4) + d\sigma(\alpha_S^2\alpha^5) + d\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

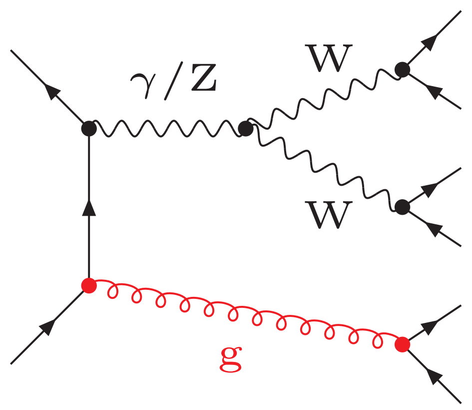
"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

VBS

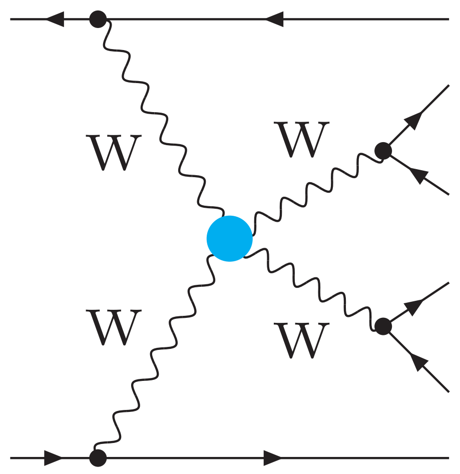
Note: severe QCD background to VBS signatures + interference:







vs.



$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_S^2\alpha^4) + \mathrm{d}\sigma(\alpha_S\alpha^5) + \mathrm{d}\sigma(\alpha^6) + \ldots$$ LO

QCD-background | interference | VBS-signal

$\mathcal{O}(\alpha_s)$ | $\mathcal{O}(\alpha)$

$$\cdots + \mathrm{d}\sigma(\alpha_S^3\alpha^4) + \mathrm{d}\sigma(\alpha_S^2\alpha^5) + \mathrm{d}\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

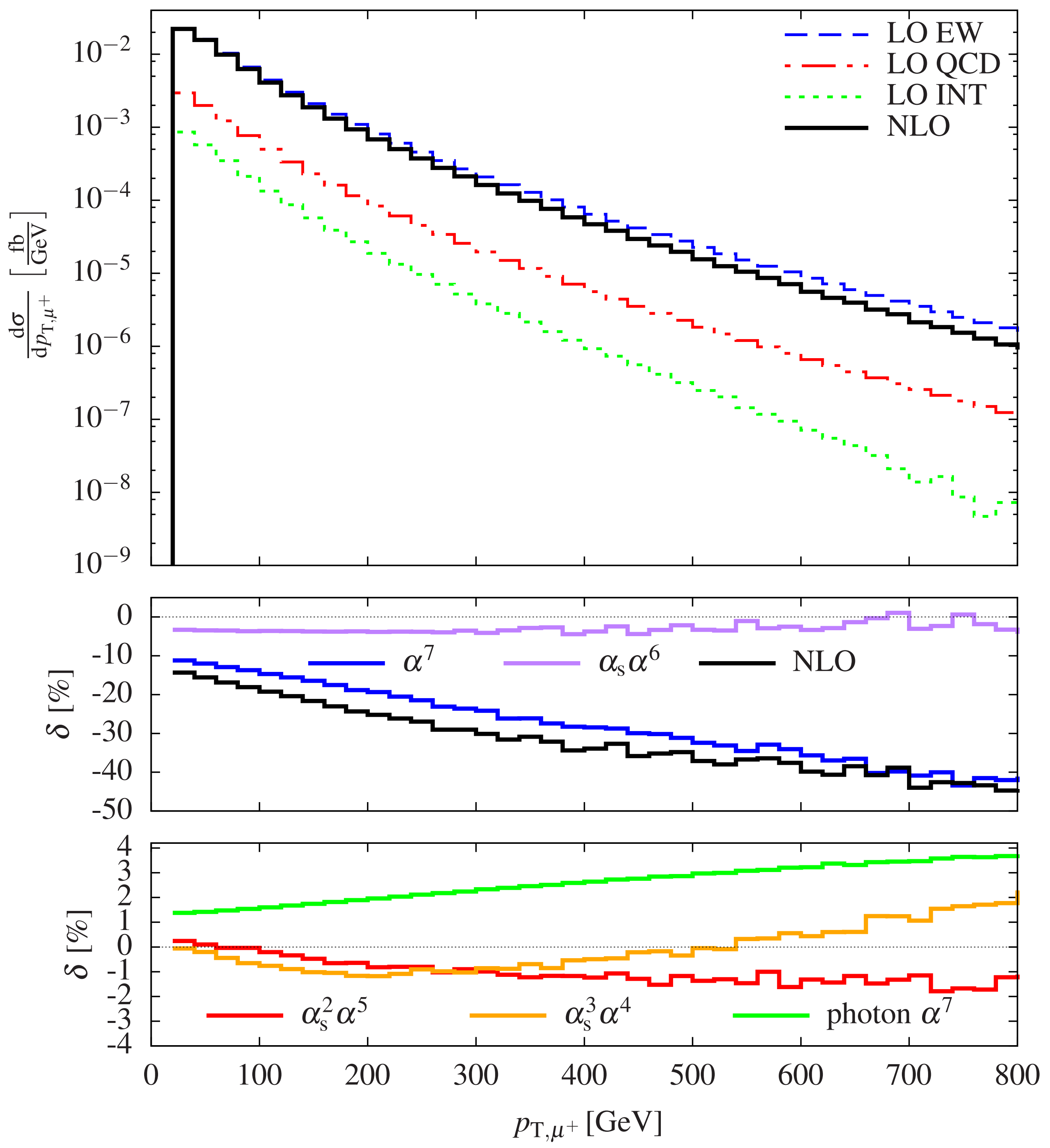
➡separation meaningless at NLO

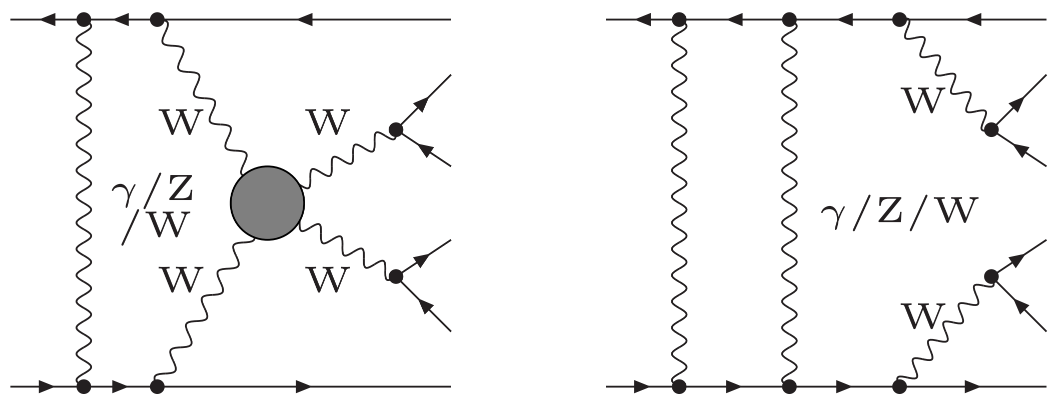
VBS-@ full NLO

WW full NLO: *[Biedermann, Denner, Pellen '16+'17]*

WZ-EW NLO QCD+EW: *[Denner, Dittmaier, Maierhöfer, Pellen, Schwan, 19]*

ZZ-EW NLO QCD+EW: *[Denner, Franken, Pellen, Schmidt, '20]*





- 2 → 6 particles at NLO EW !
- highly challenging computation!

- NLO corrections dominated by α^7 :

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\rm NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\rm NLO}/\sigma_{\rm LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

with $M_{jj} > 500\,{\rm GeV},\ p_{T,j} > 30\,{\rm GeV},\ p_{T,\ell} > 20\,{\rm GeV},$

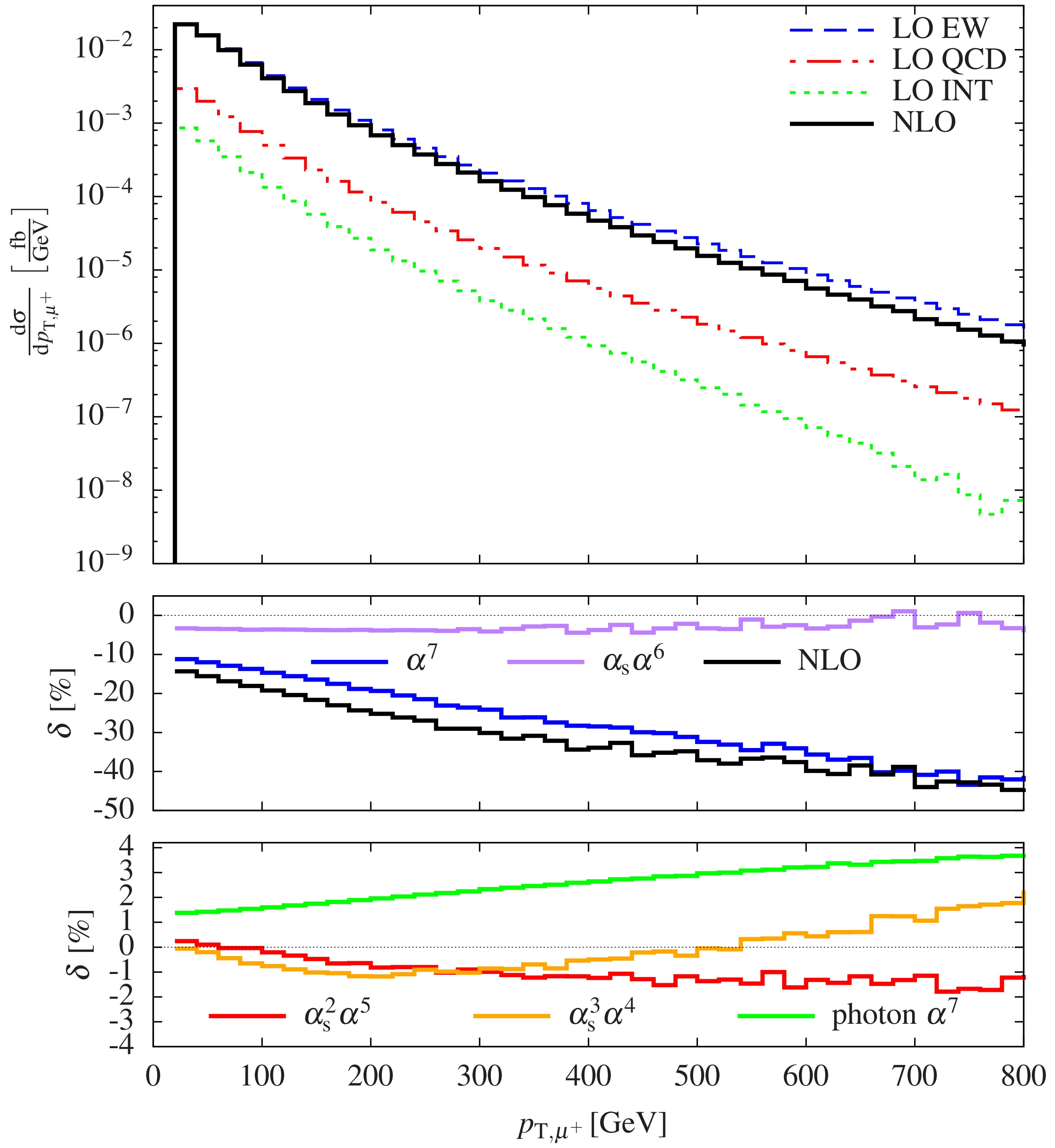
LO: $\mathcal{O}(\alpha^6)$
NLO: $\mathcal{O}(\alpha^7)$

$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}_{\rm EW}$ [fb]	$\delta_{\rm EW}$ [%]
1.5348(2)	1.2895(6)	-16.0

- VERY large inclusive EW corrections (dominated by Sudakov logs)

VBS-W⁺W⁺ @ full NLO

[Biedermann, Denner, Pellen '16+'17]



- VERY large EW corrections (dominated by Sudakov logs)

LO: $\mathcal{O}(\alpha^6)$
NLO: $\mathcal{O}(\alpha^7)$

σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	δ_{EW} [%]
1.5348(2)	1.2895(6)	−16.0

Leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]

$$\sigma_{LL} = \sigma_{LO}\left[1 - \frac{\alpha}{4\pi}4C^{ew}_{W}\log^2\left(\frac{Q^2}{M_W^2}\right) + \frac{\alpha}{4\pi}2b^{ew}_{W}\log\left(\frac{Q^2}{M_W^2}\right)\right]$$

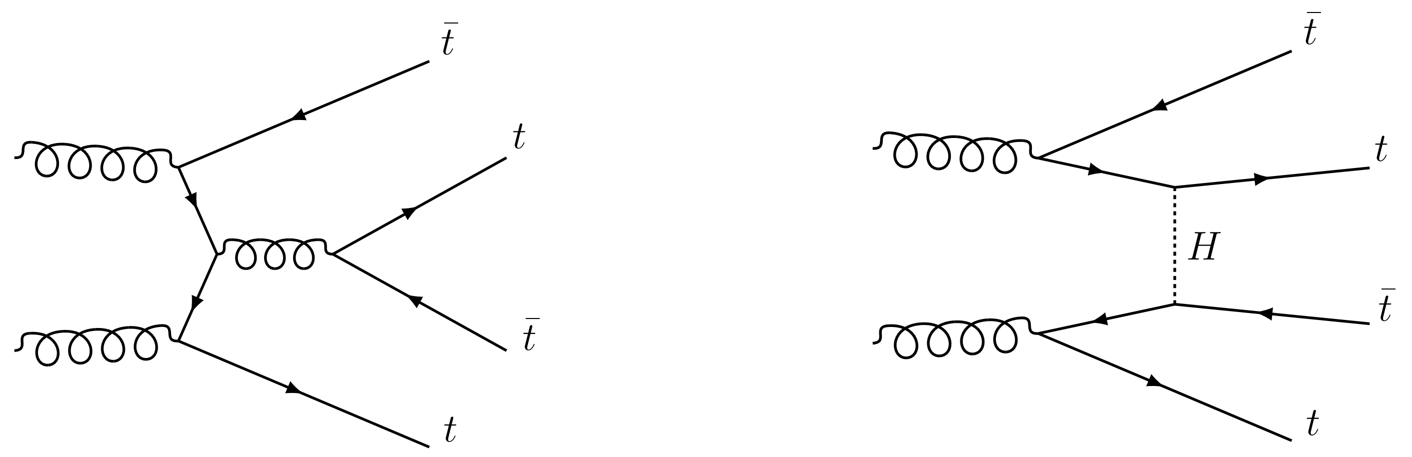
$= -16\%$ (!)

For $Q = \langle m_{4\ell}\rangle \sim 390$ GeV

$\langle m_{4\ell}\rangle$ larger for VBS (massive t-channel
NB: $\langle m_{4\ell}\rangle \sim 250$ GeV for $q\bar{q} \to W^+W^+$

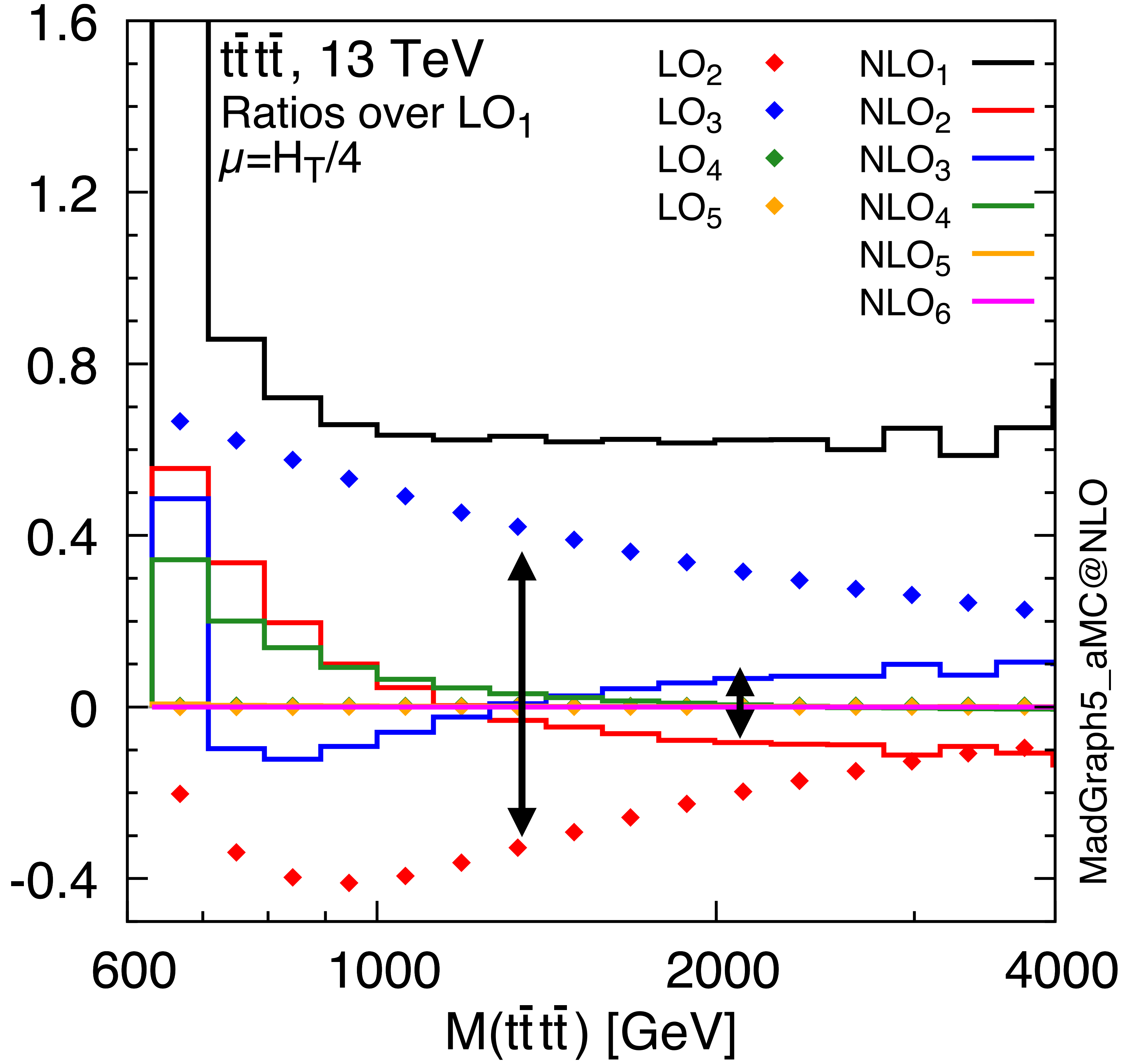
➡Large NLO EW corrections: intrinsic feature of VBS at the LHC

Rare top processes



Motivation:

- Constraining top-quark flavour violation [1804.05598]
- Constraining qqtt operators [1708.05928
- Higgs width and top quark Yukawa coupling [1602.01934]



[Frederix, Pagani, Zaro; '17]

$$\Sigma_{\rm LO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^4\Sigma_{4,0}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,1}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^2\Sigma_{4,2}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,3}^{t\bar{t}t\bar{t}} + \alpha^4\Sigma_{4,4}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm LO_1} + \Sigma_{\rm LO_2} + \Sigma_{\rm LO_3} + \Sigma_{\rm LO_4} + \Sigma_{\rm LO_5}\,.$$

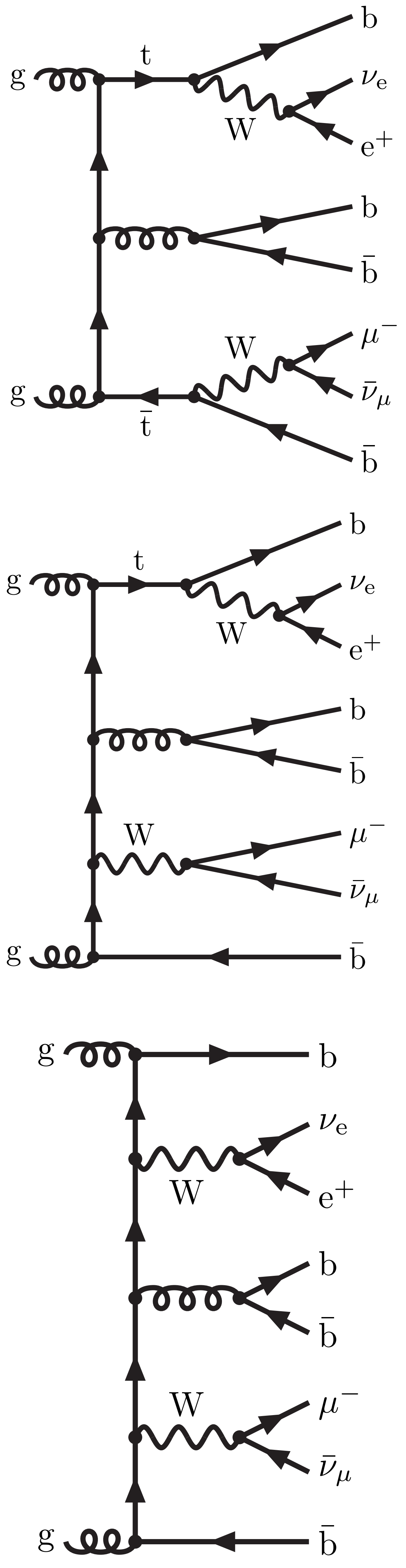
$$\Sigma_{\rm NLO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^5\Sigma_{5,0}^{t\bar{t}t\bar{t}} + \alpha_s^4\alpha^1\Sigma_{5,1}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha^2\Sigma_{5,2}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^3\Sigma_{5,3}^{t\bar{t}t\bar{t}} + \alpha_s^1\alpha^4\Sigma_{5,4}^{t\bar{t}t\bar{t}} + \alpha^5\Sigma_{5,5}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm NLO_1} + \Sigma_{\rm NLO_2} + \Sigma_{\rm NLO_3} + \Sigma_{\rm NLO_4} + \Sigma_{\rm NLO_5} + \Sigma_{\rm NLO_6}\,.$$

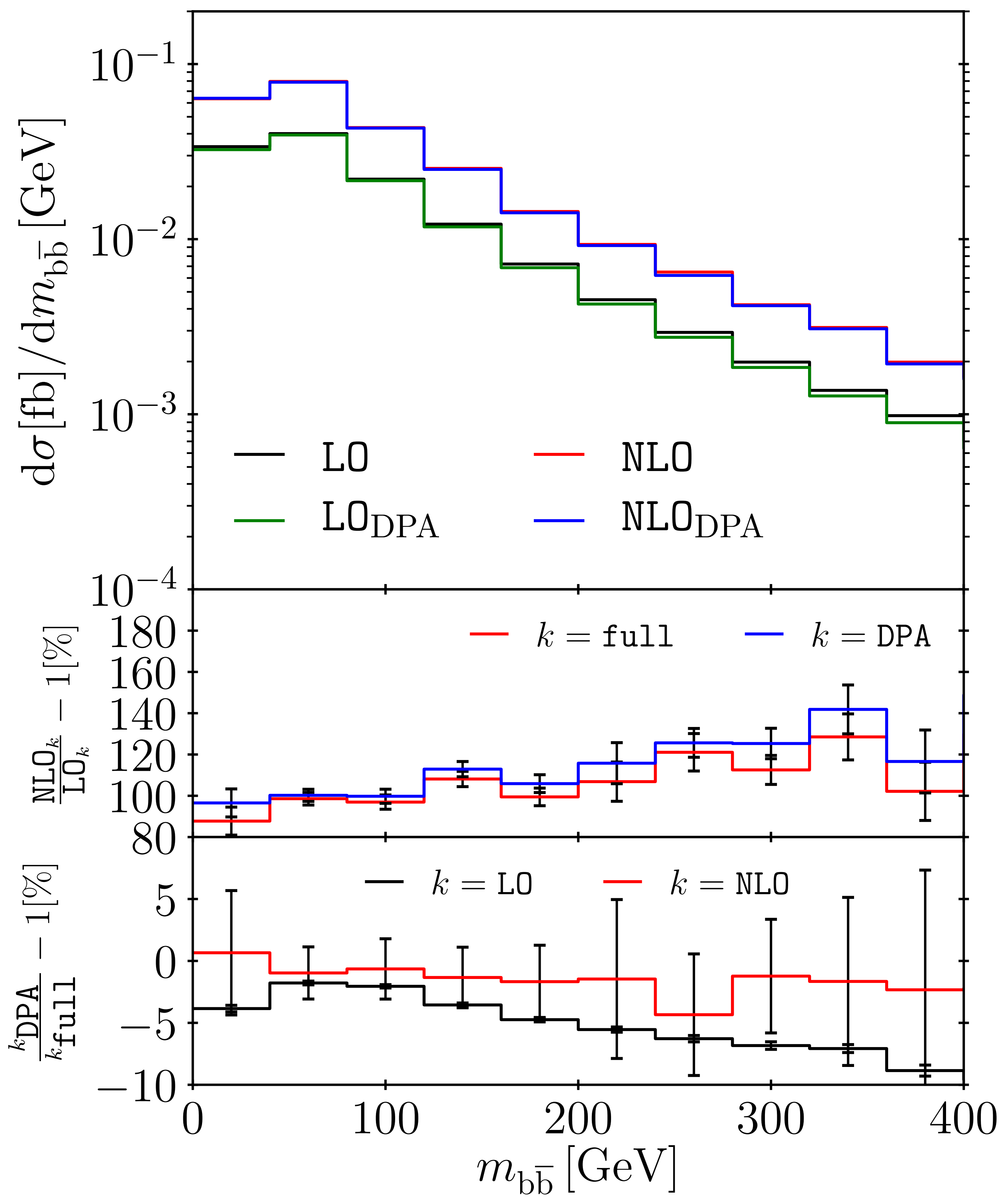
- Sizeable (accidental) cancellation between different LO and NLO orders
- calculation of only part of the complete-NLO results would be misleading
- cancellation could be spiked by BSM effects

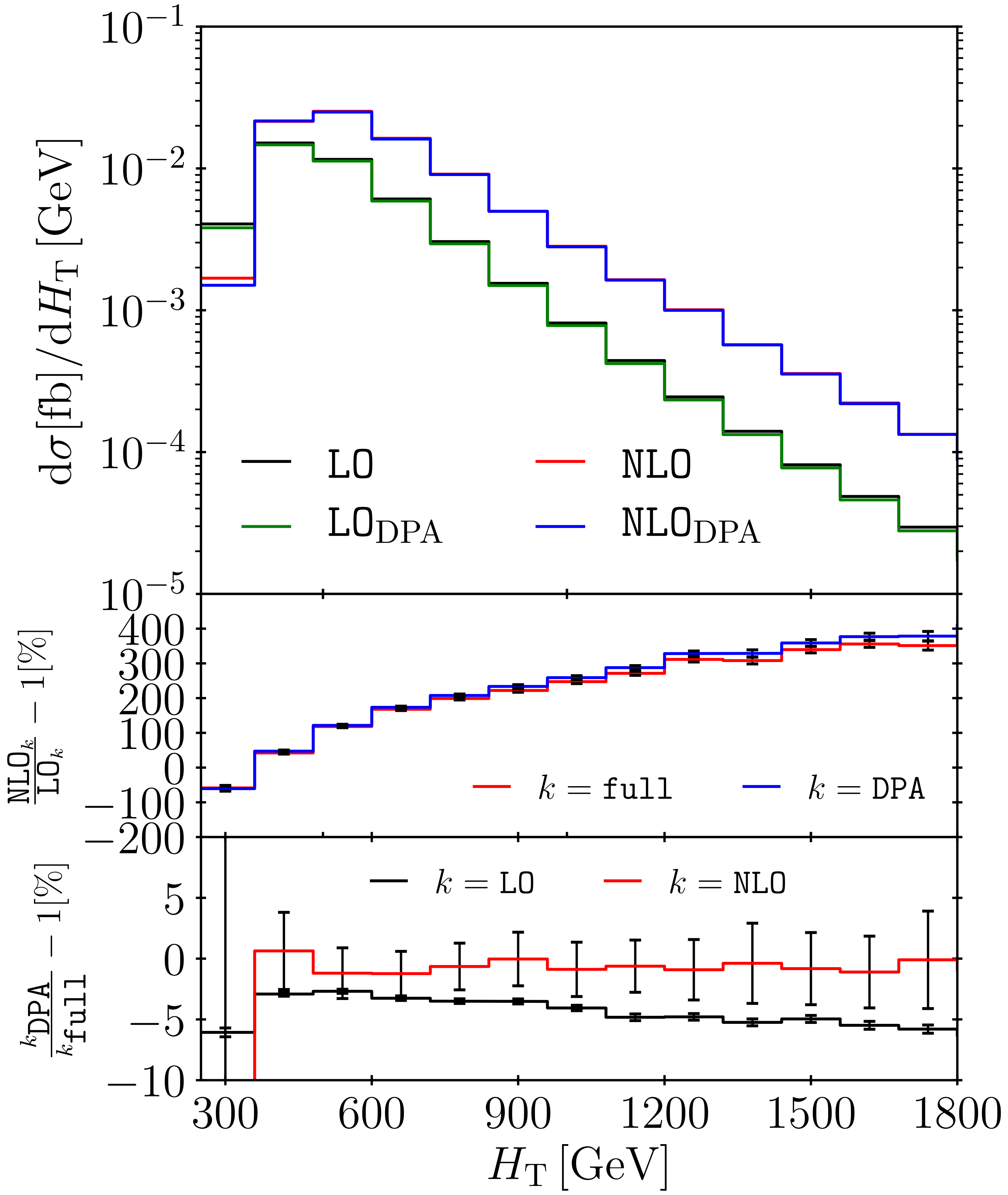
Precision for the highest multiplicities

[Denner, Lang, Pellen `20]

$pp \to 2\ell 2\nu b\bar{b}b\bar{b}$ @ NLO QCD



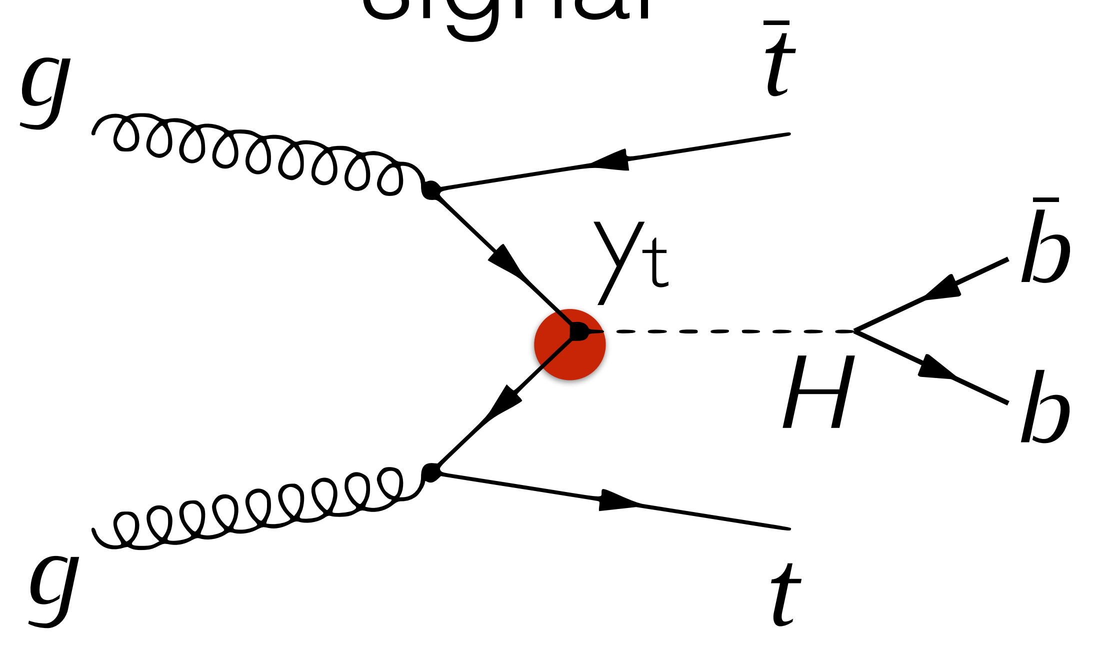




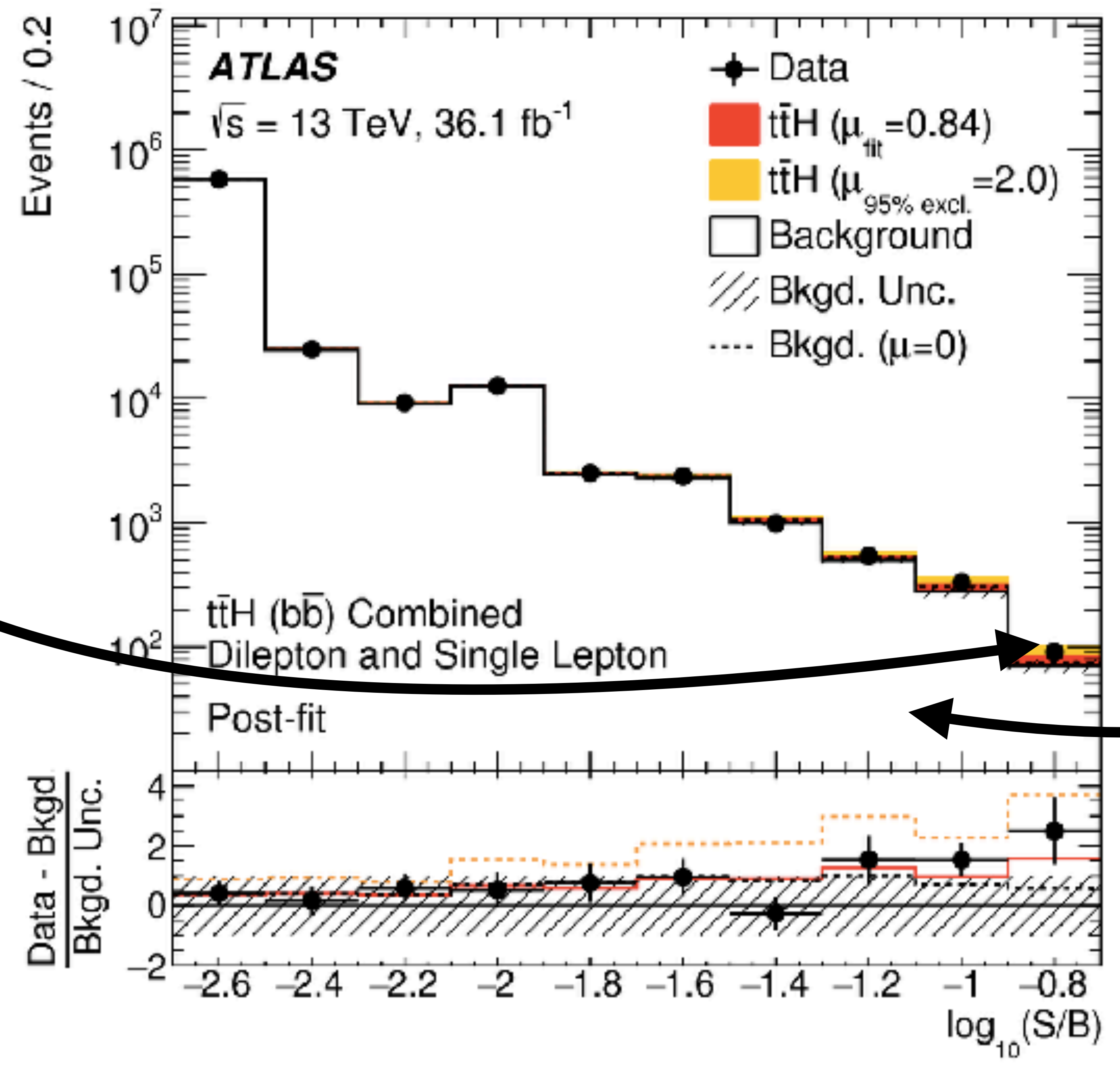
- Thorough understanding of theory systematics in this channel crucial for ttH measurements where H->bb
- ttbb receives sizeable QCD corrections
- Very important confirmation of (ttbb) double pole approximation

Taming tt̄H backgrounds

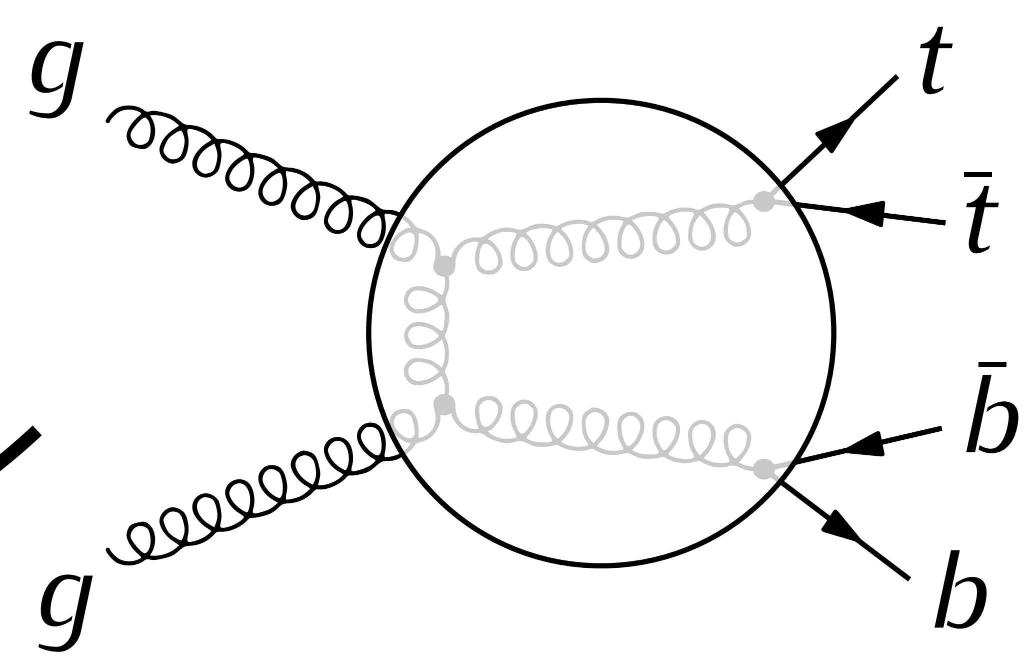
signal



- ➡ direct probe of the top Yukawa coupling
- ➡ unfortunately very small cross section
- ➡ have to consider H→bb̄ decay with large BR
- ➡ large QCD background: tt̄+b-jets with sizeable uncertainties



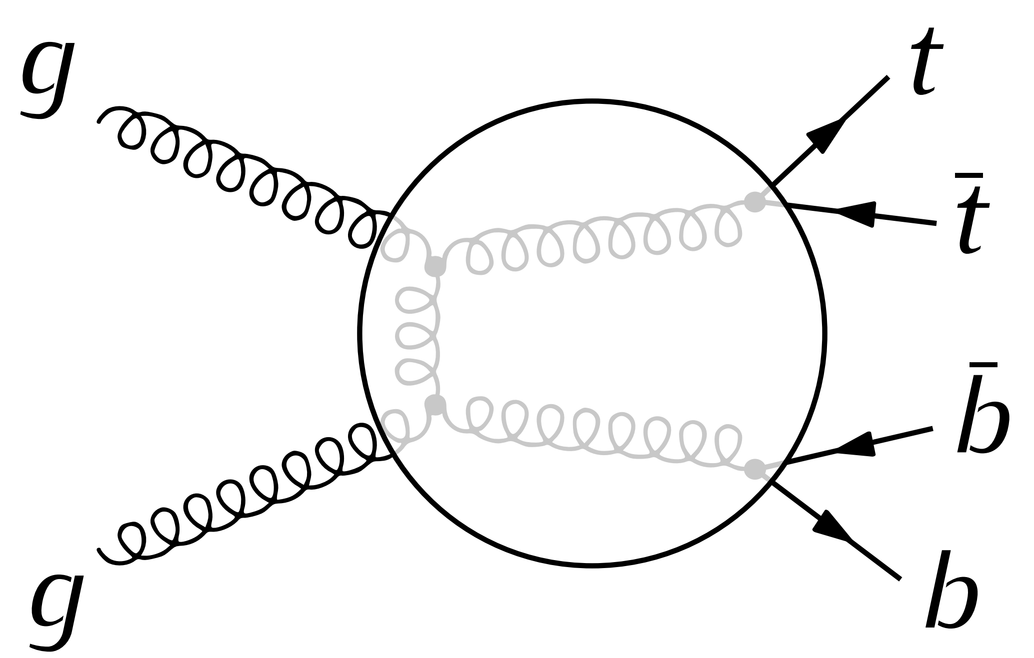
background



Taming $t\bar{t}H$ backgrounds

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]
[Bredenstein, Denner, Dittmaier, Pozzorini '10]

background

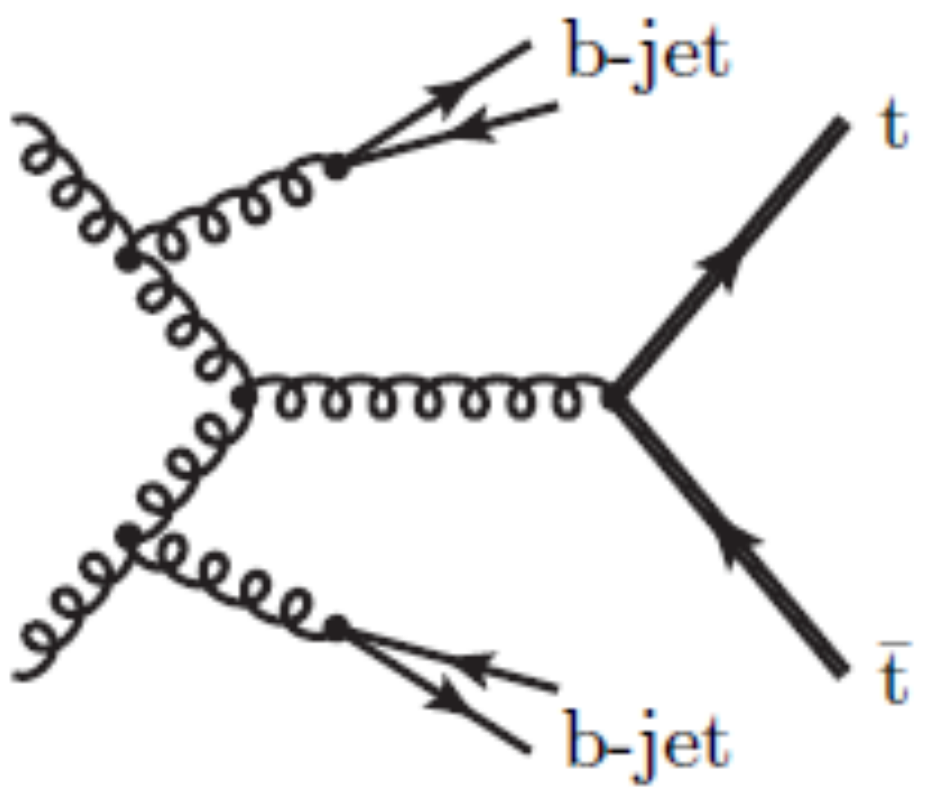


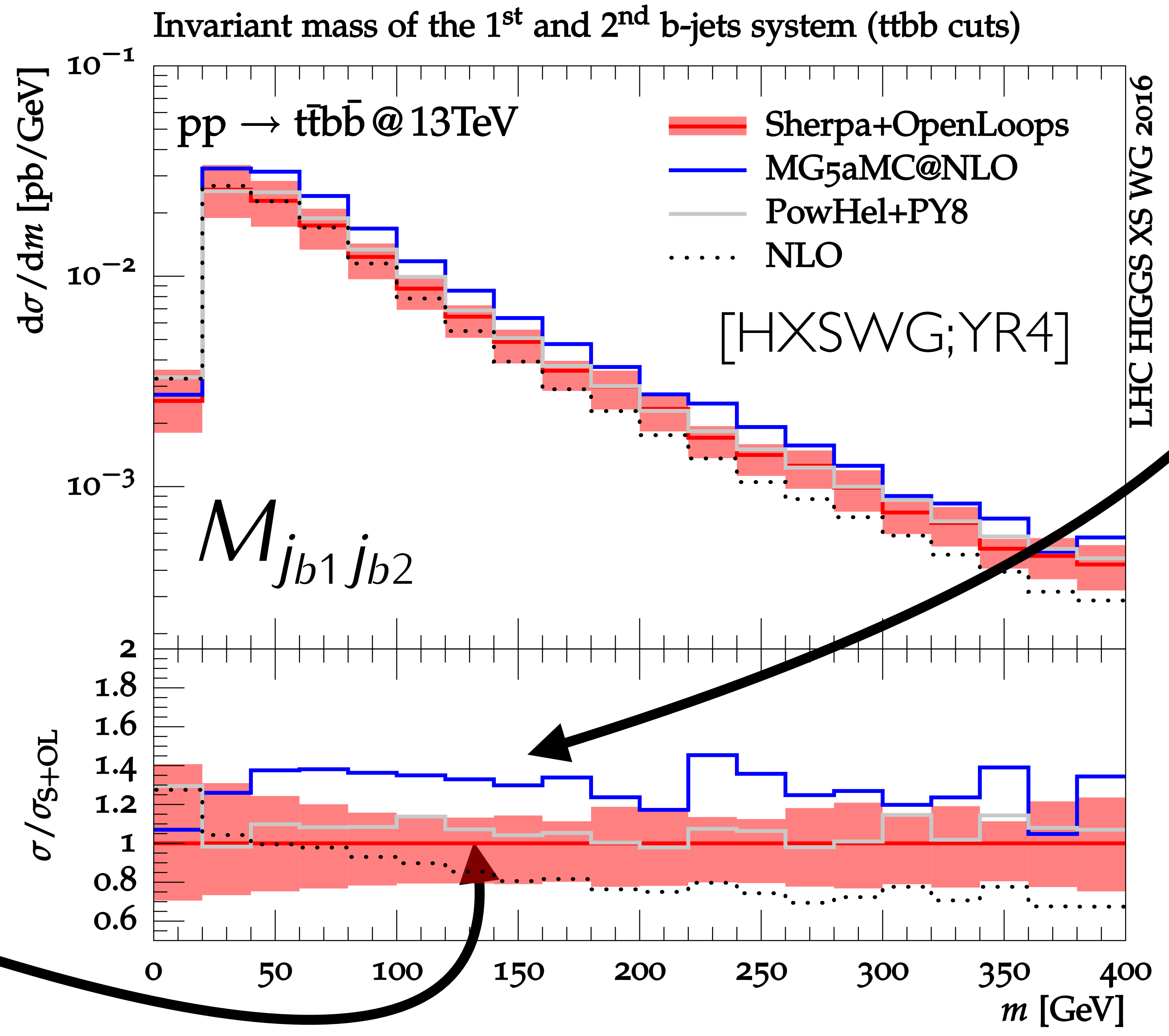
➡ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%

➡ However: notoriously difficult multi-scale problem: ET_t, $ET_{\bar{t}}$, ET_b, $ET_{\bar{b}}$

➡ Large shower effects, in particular from double $g \rightarrow b\bar{b}$ splittings

➡ Large systematic uncertainties from parton shower matching

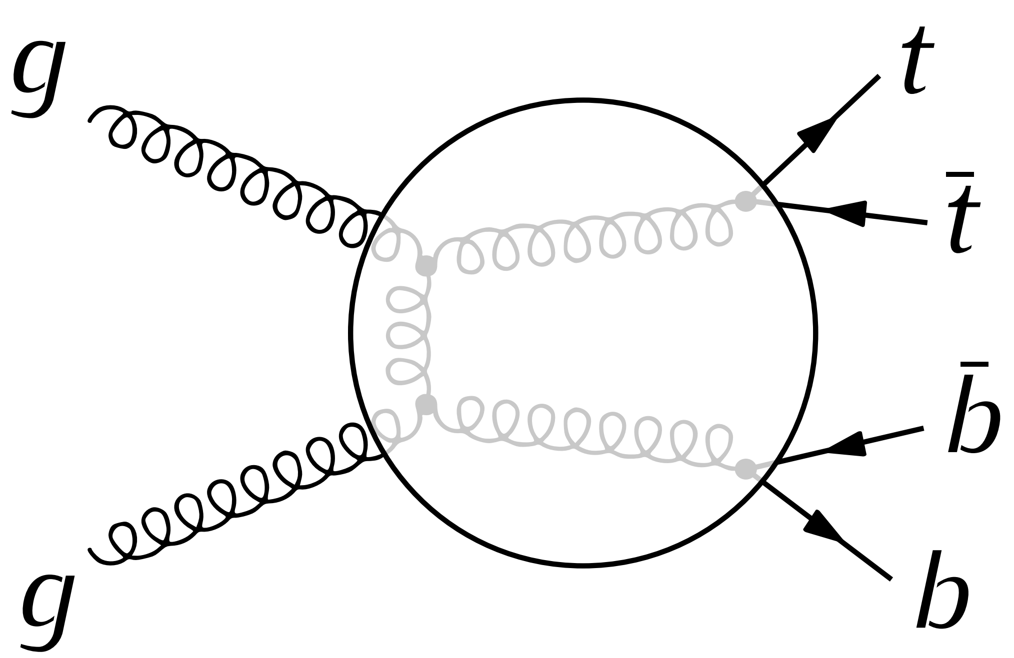




~20% in the signal region

Taming $t\bar{t}H$ backgrounds

background



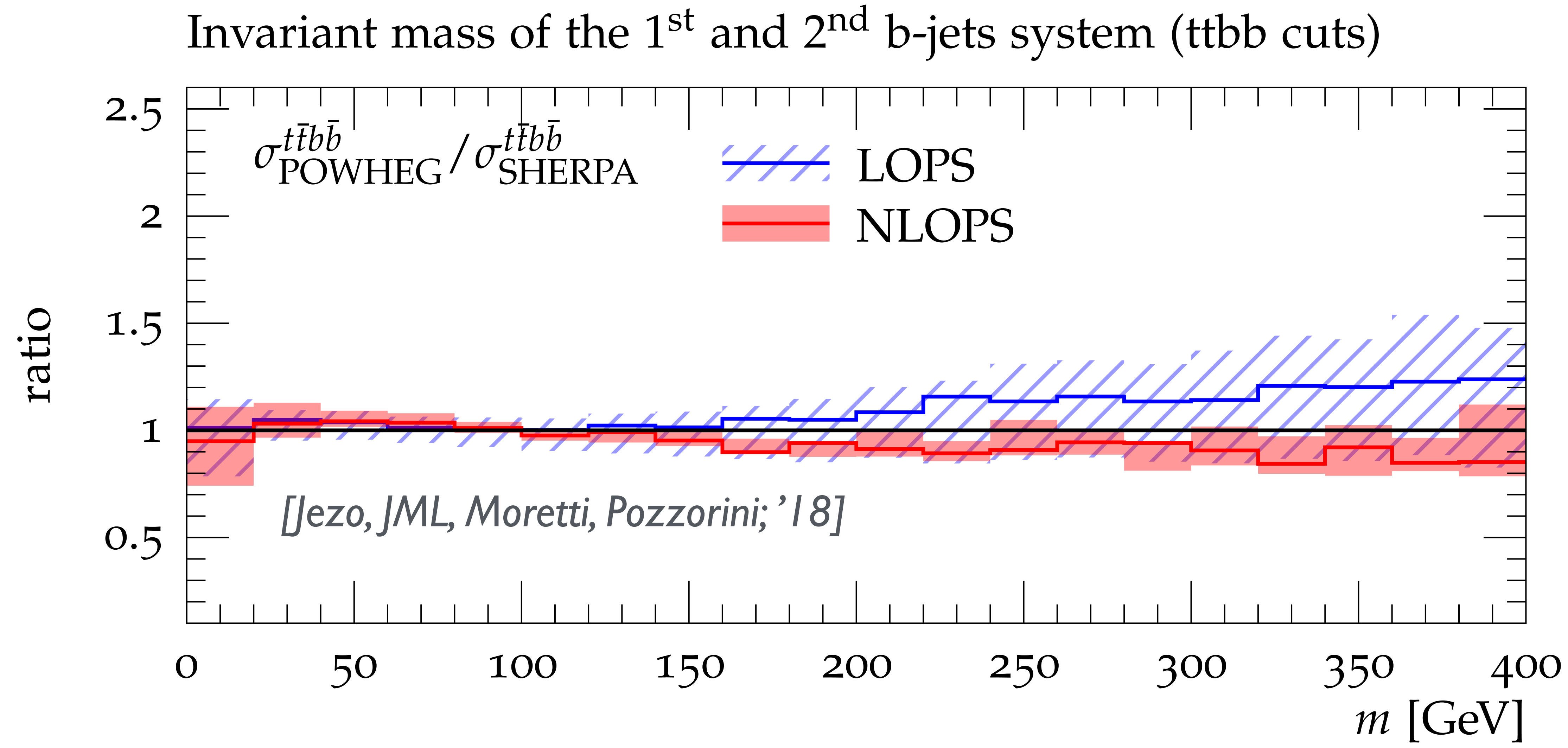
➡ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%

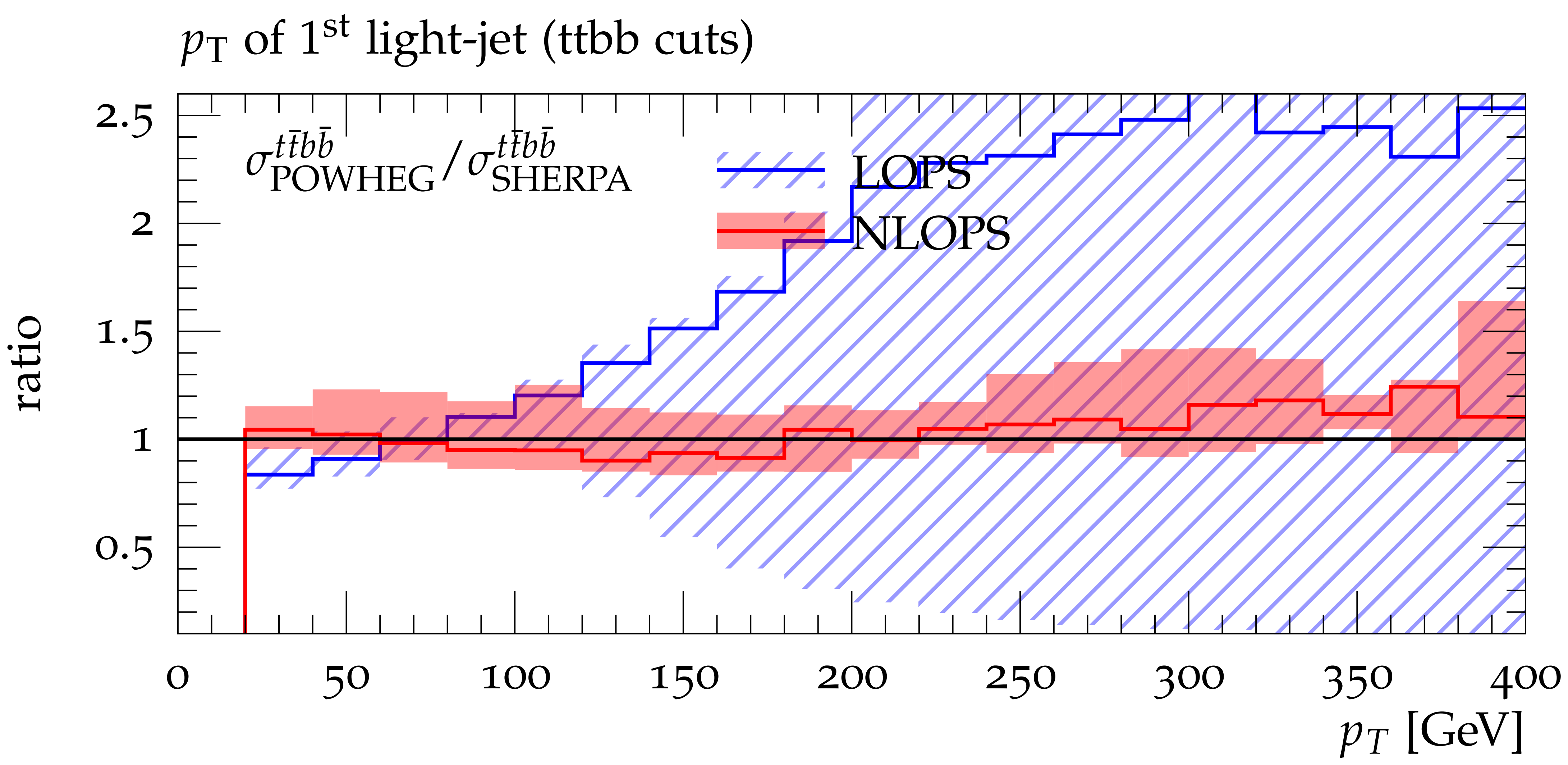
➡ However: notoriously difficult multi-scale problem: E_{T_t}, $E_{T_{\bar{t}}}$, E_{T_b}, $E_{T_{\bar{b}}}$

➡ Large shower effects, in particular from double $g \to b\bar{b}$ splittings

➡ Large systematic uncertainties from parton shower matching

➡ Careful study required to understand these systematics

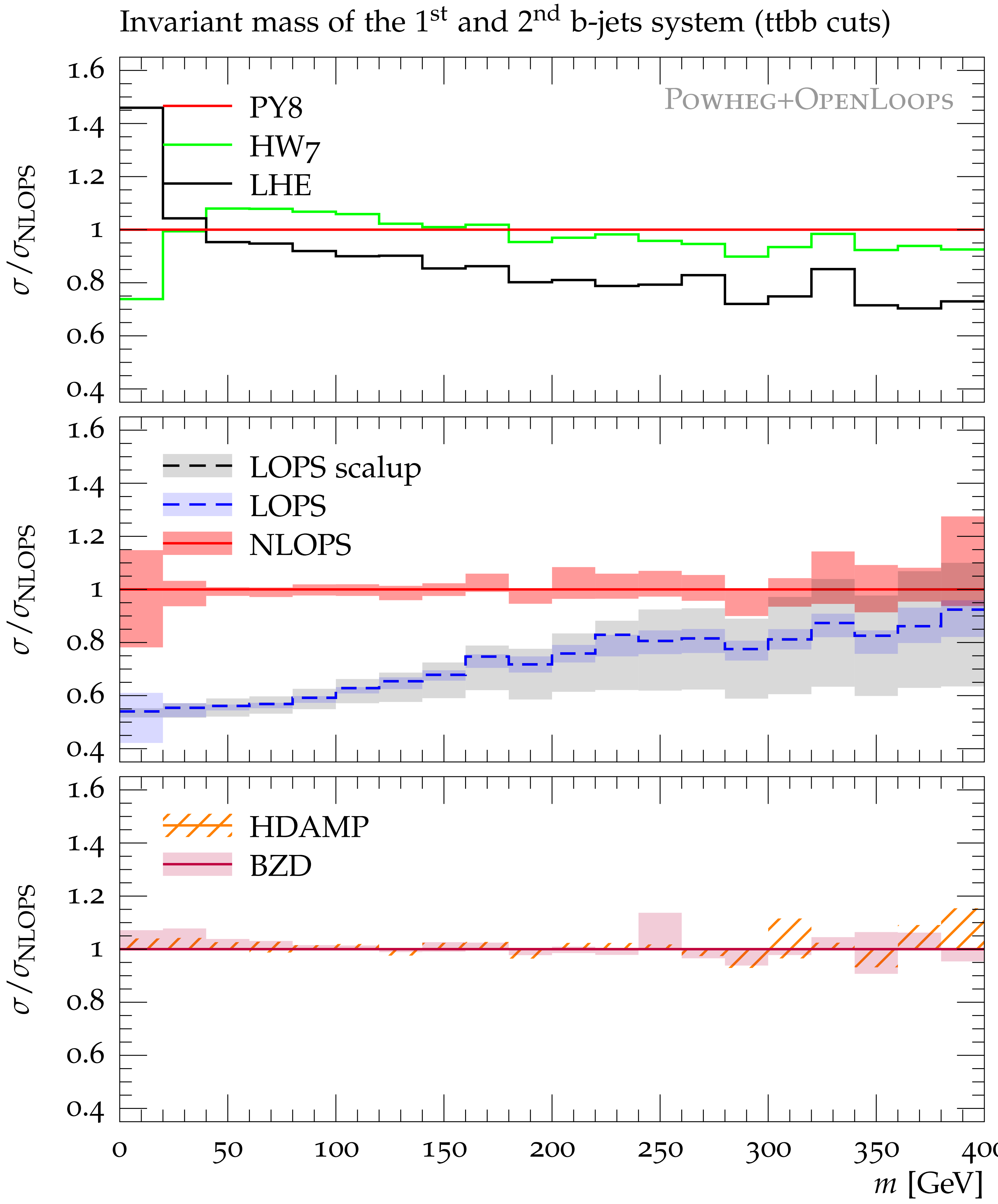


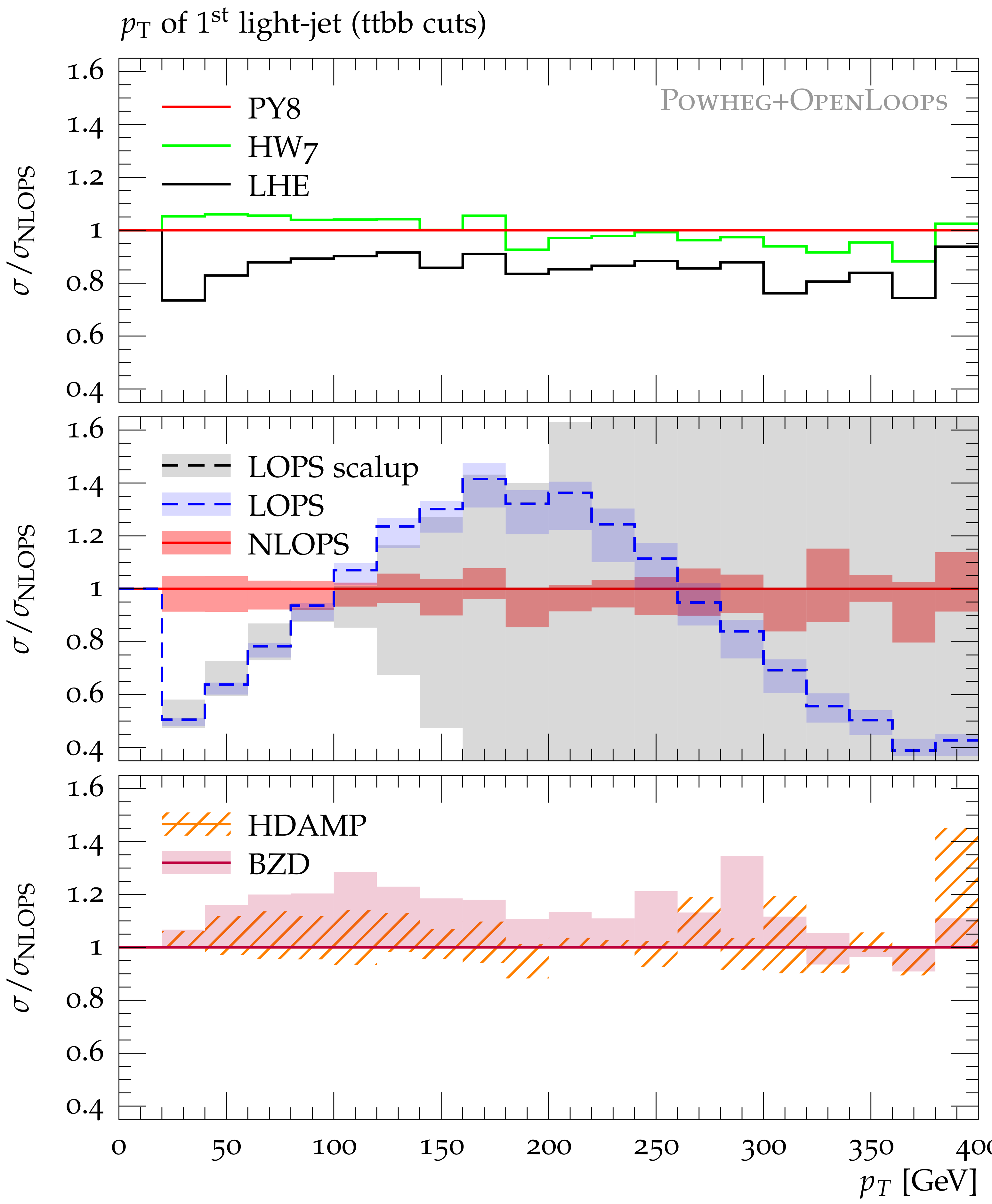


➡Sherpa vs. POWHEG+PY8 (both in 4-FS) in very good agreement

Taming $t\bar{t}H$ backgrounds

[Jezo, JML, Moretti, Pozzorini; '18]



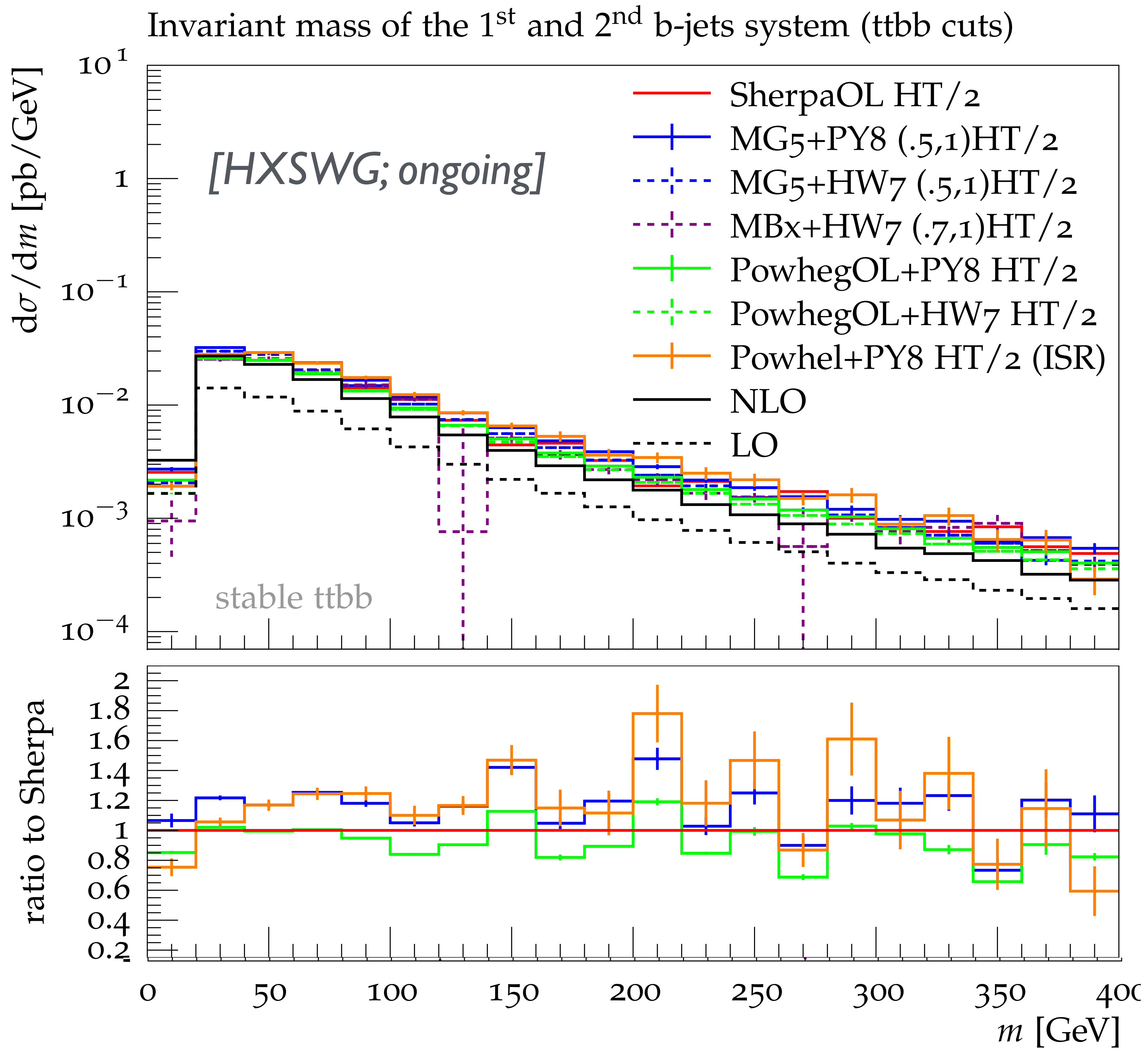


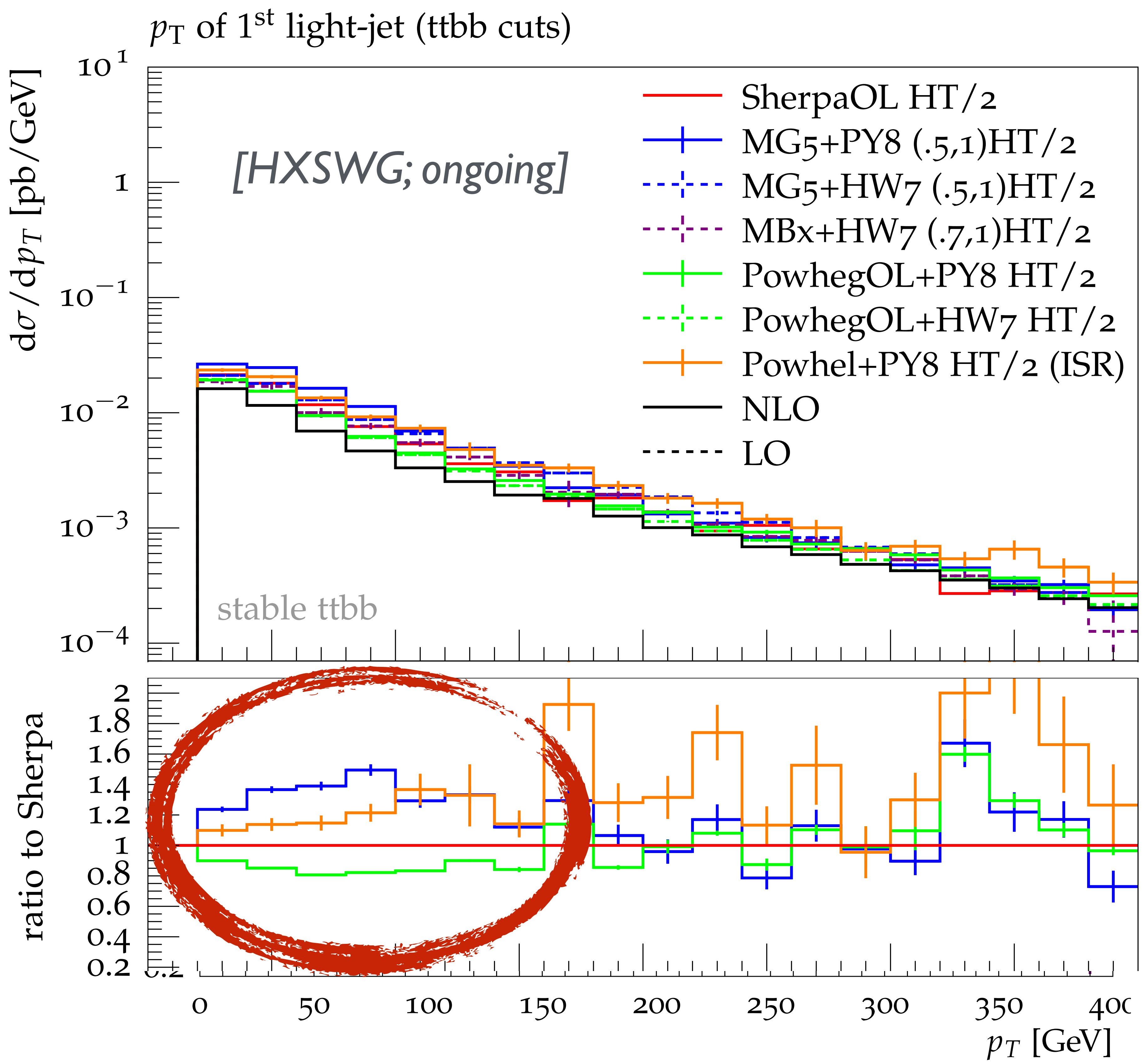
- Shower variations
- α_S & $g \to b\bar{b}$ variations
- hdamp & bzd variations

$$g_{\rm soft}(\Phi_{\rm rad}, h_{\rm damp}, h_{\rm bzd}) = \frac{h_{\rm damp}^2}{h_{\rm damp}^2 + k_T^2}\, \theta\Big(h_{\rm bzd} B(\Phi_B) \otimes K_{\rm soft/coll}(\Phi_{\rm rad}) - R(\Phi_R)\Big)$$

➡Intrinsic shower systematics in POWHEG+PY8/HW7 under very good control

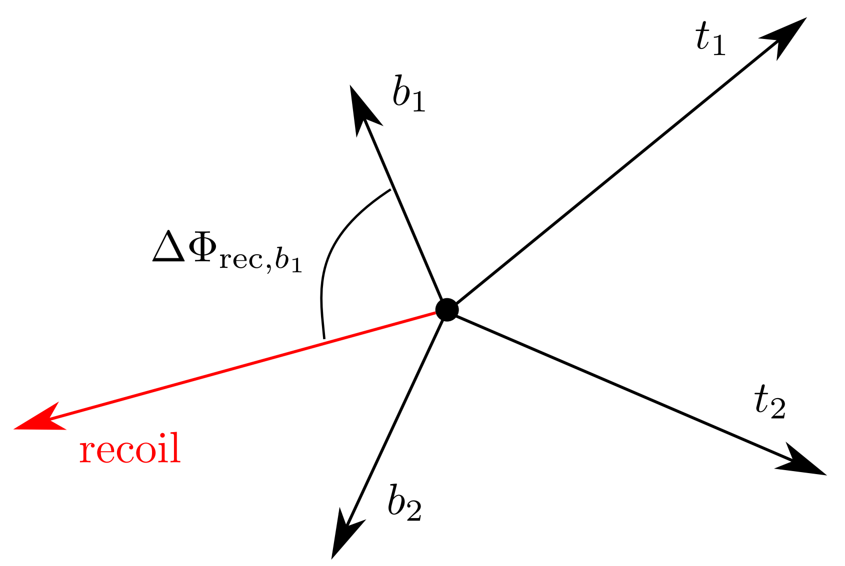
Taming $t\bar{t}H$ backgrounds



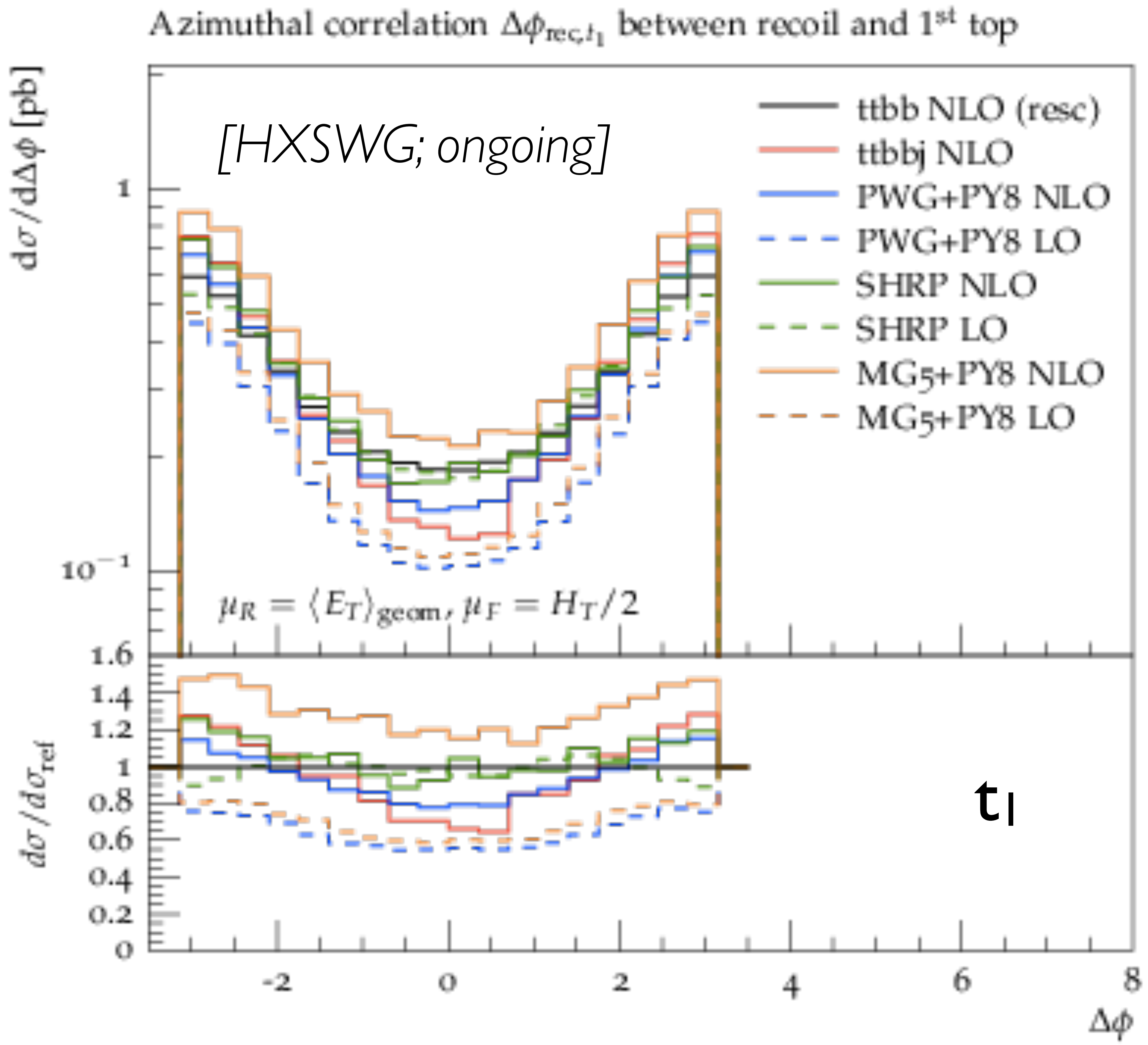


- ➡ Sizable differences between different generators: in particular in radiation/recoil spectrum
- ➡ Without understanding their origin (physical or not?) we should not use MC differences as theory uncertainty!
- ➡ **Careful look inside the NLO+PS black-boxes necessary**: ongoing within HXSWG!

The smoking gun



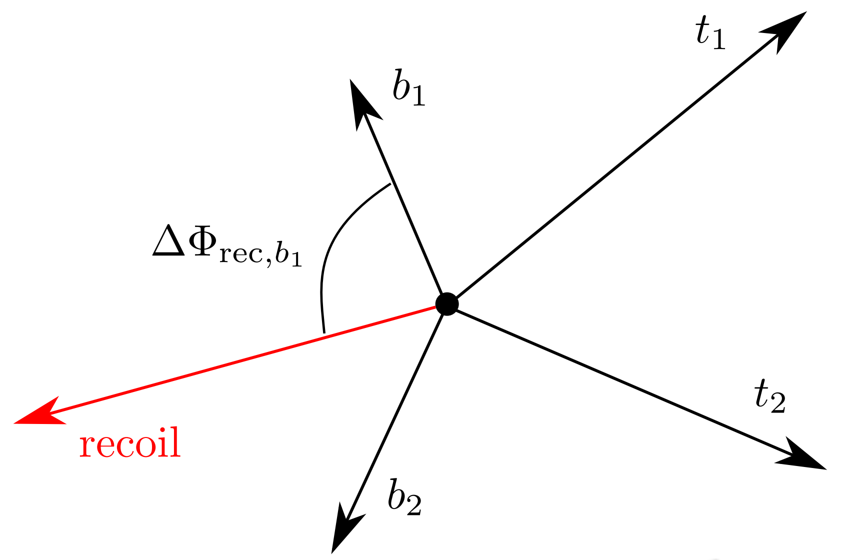
Study recoil observables: $\Delta\phi_{\mathrm{rec},X} = \Delta\phi\,(\vec{p}_{\mathrm{rec}}, \vec{p}_X)\,, \qquad \vec{p}_{\mathrm{rec}} = -\sum_{t,\bar{t},b_1,b_2} \vec{p}_i\,,$



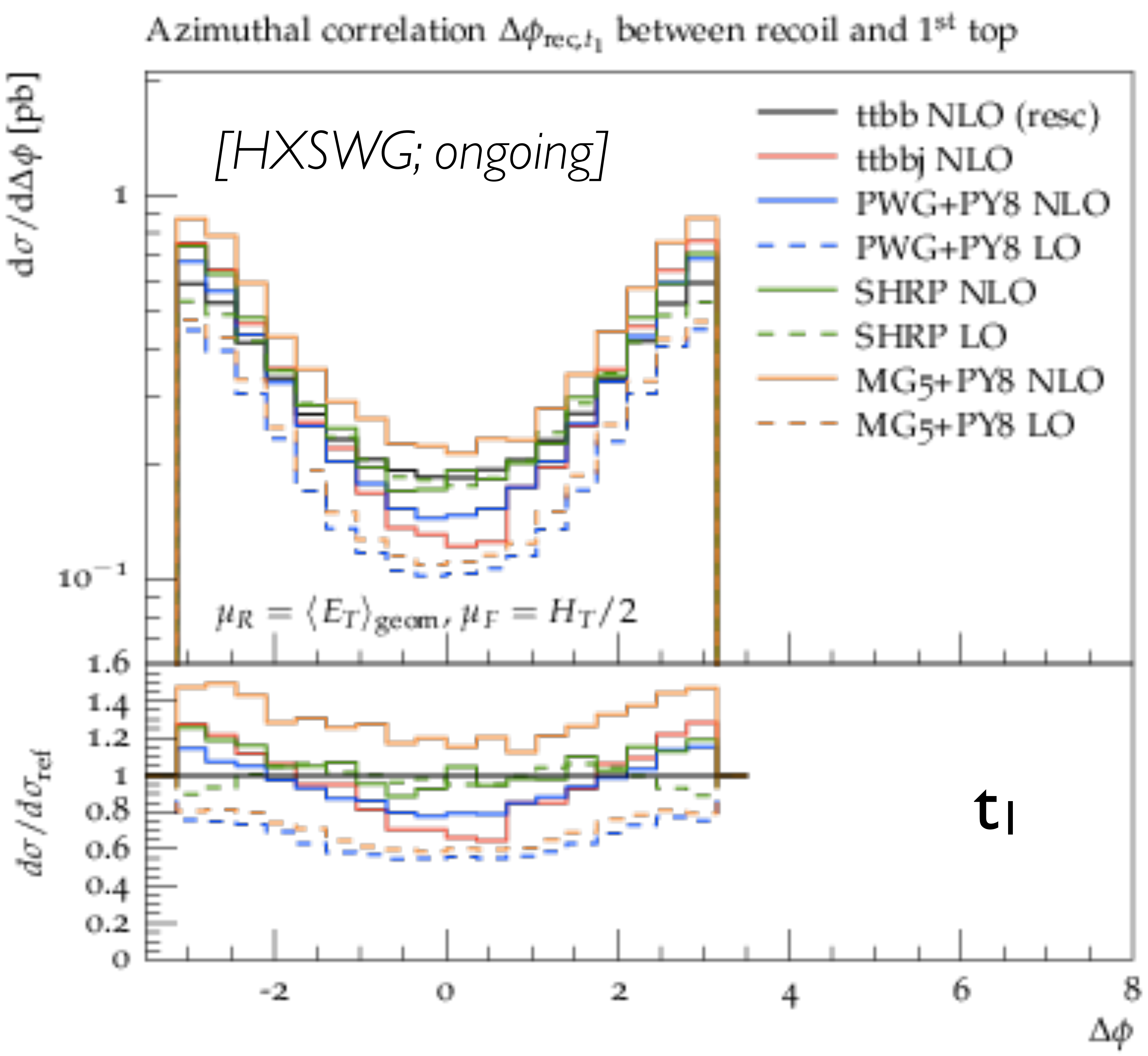
- leading top absorbs strong recoil form QCD radiation
- NLOPS enhancement of recoil well consistent with **ttbbj at NLO** (nontrivial!)

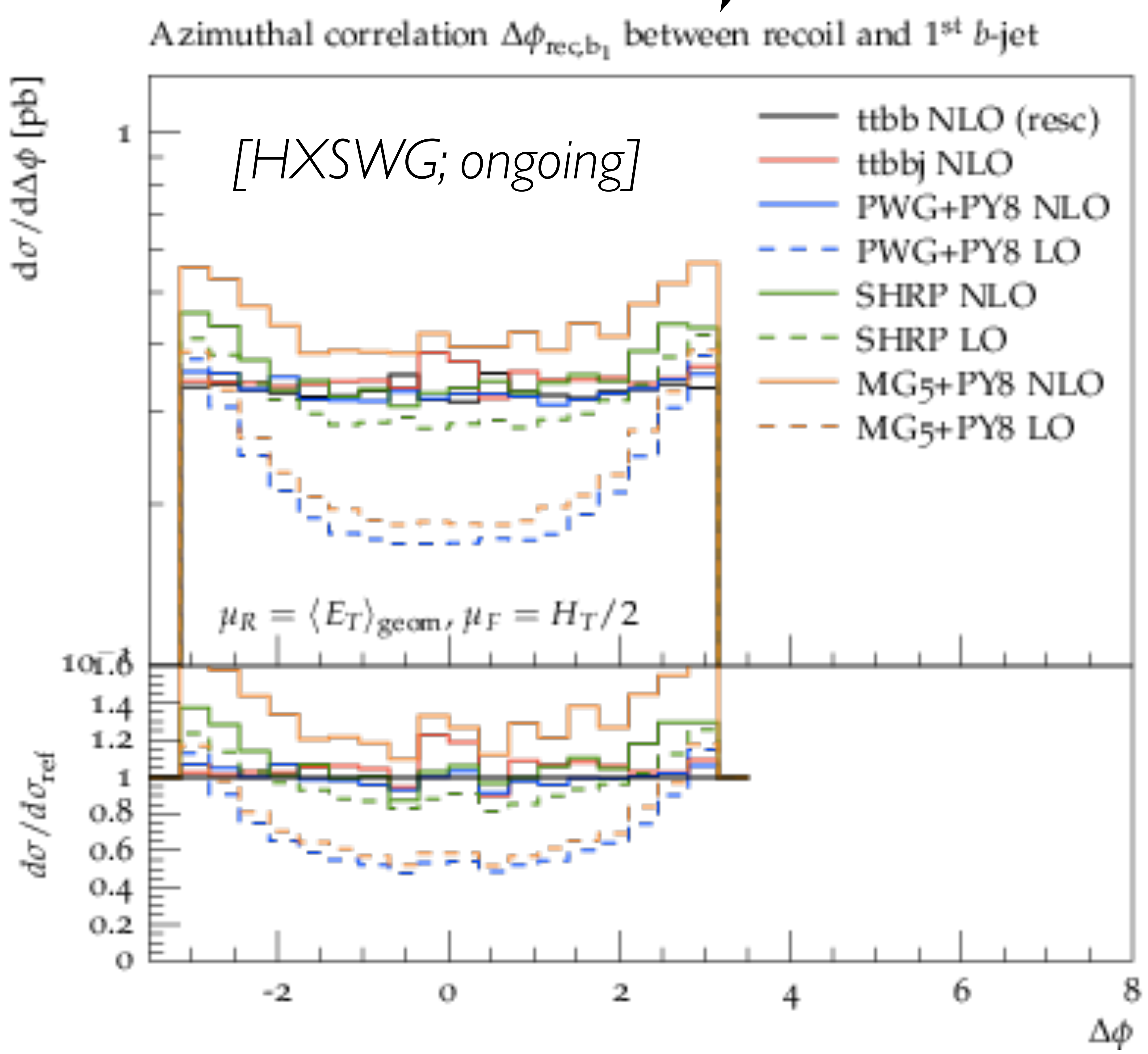
[Buccioni, Pozzorini, Zoller, 1907.13624]

The smoking gun



Study recoil observables: $\Delta\phi_{\mathrm{rec},X} = \Delta\phi\left(\vec{p}_{\mathrm{rec}}, \vec{p}_X\right)\,, \qquad \vec{p}_{\mathrm{rec}} = -\sum_{t,\bar{t},b_1,b_2} \vec{p}_i\,,$





- leading top absorbs strong recoil form QCD radiation
- NLOPS enhancement of recoil well consistent with **ttbbj at NLO** (nontrivial!)

[Buccioni, Pozzorini, Zoller, 1907.13624]

- leading bottom gets strong **UNPHYSICAL** recoil in LO+PY8
- unphysical since no evidence of recoil in ttbb, ttbbj, or PWG+PY8 at NLO
- unphysical recoil strongly suppressed only by Powheg / attenuated by MC@NLO matching (MG and Sherpa)

Conclusions

- SM is in excellent shape
- High-precision (Theo + Exp) allows to push limits to unprecedented levels
- NNLO QCD + NLO EW is the new standard: VV, V+jets, dijets, $t\bar{t}$, HV, VBF
- Use ratios for theory X exp background improvements
- Explore the unknown: **tail, tails, tails!!**

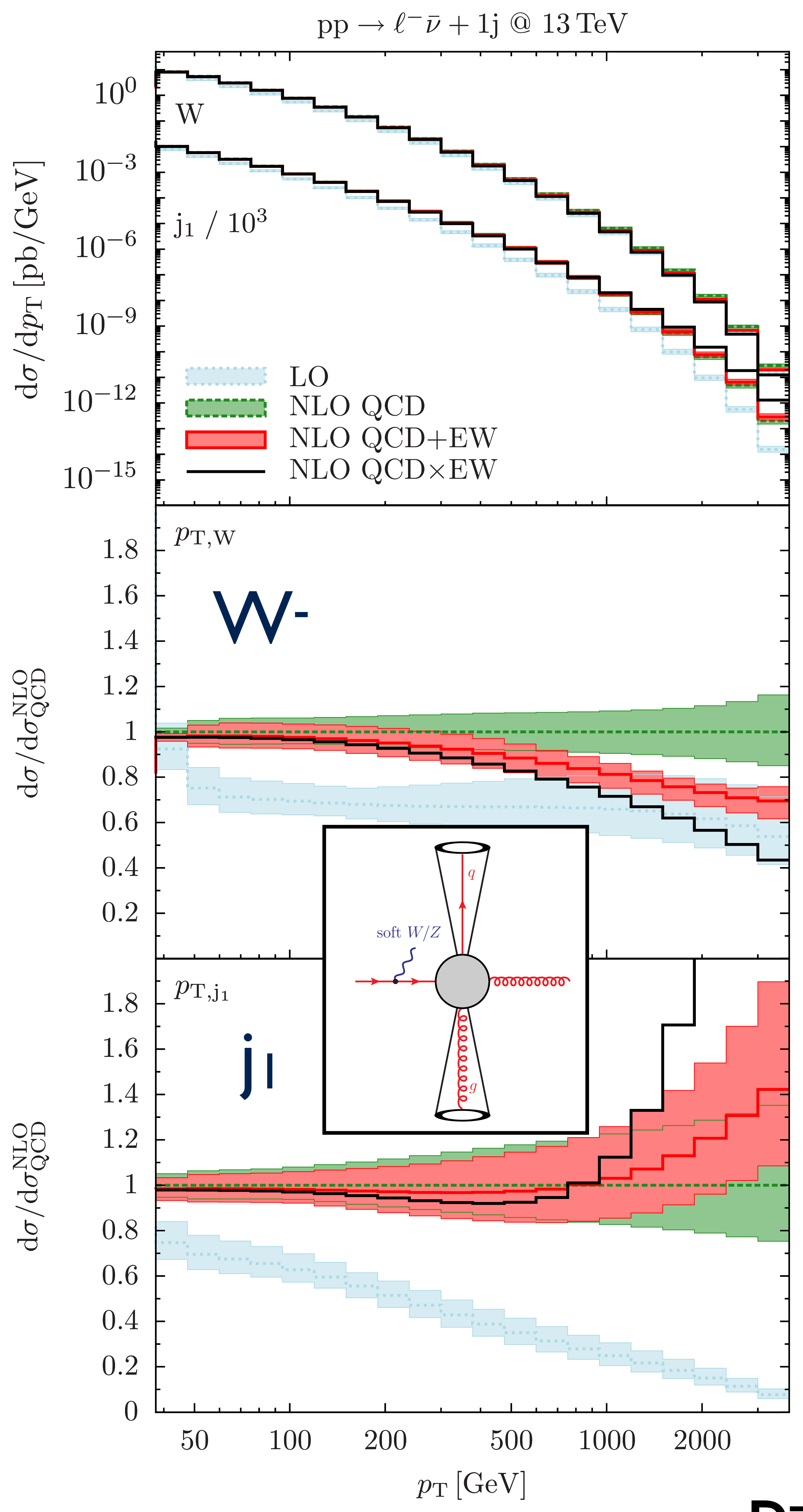
Developments relevant for Run-3 analyses

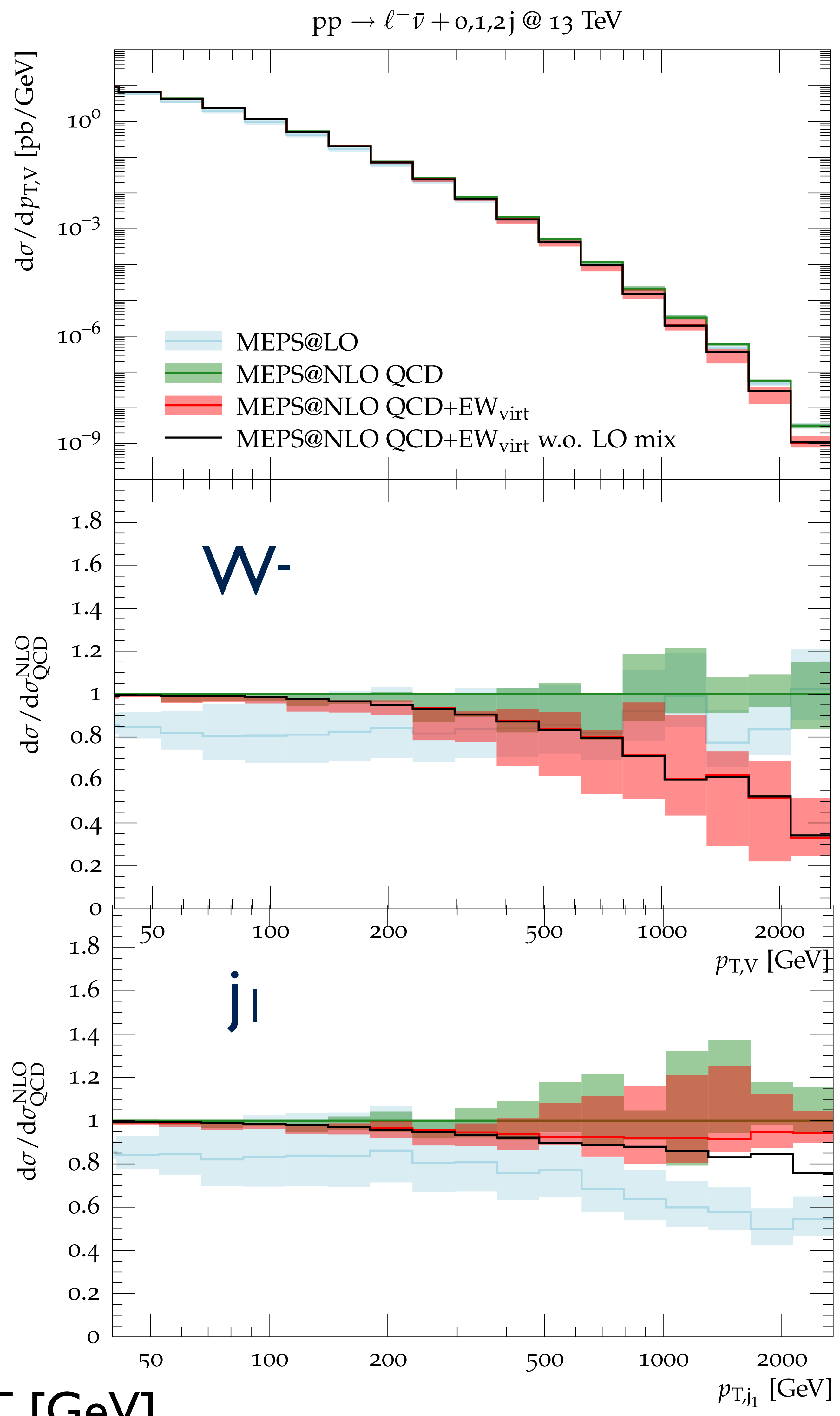
- NNLO QCD + PS
- PS matching and multi-jet merging @ NLO QCD+EW
- open the NLO PS black boxes (benchmark against NNLO or NLO multijet computations)
- NNLO QCDxEW & NNLO EW uncertainty estimates

precision for Run-3

Backup

inclusive V: MEPS@NLO QCD+EW_{virt}



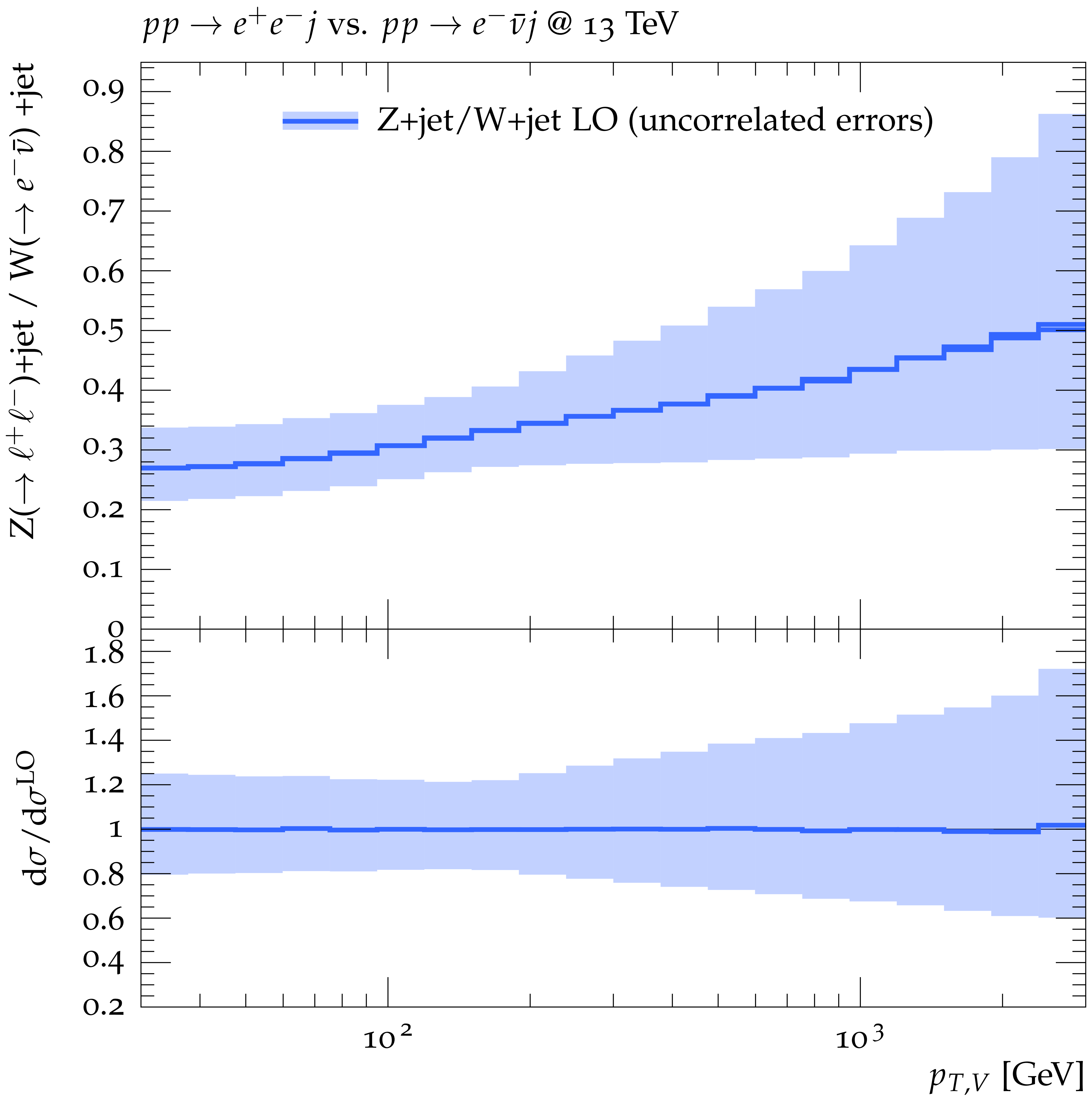


p_T [GeV]

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

- Bases on Sherpa's standard MEPS@NLO
- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations
- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$:
  - merging ensures stable results (dijet topology at LO)
  - compensation between negative Sudakov and LO mix

How to correlate QCD uncertainties across processes?

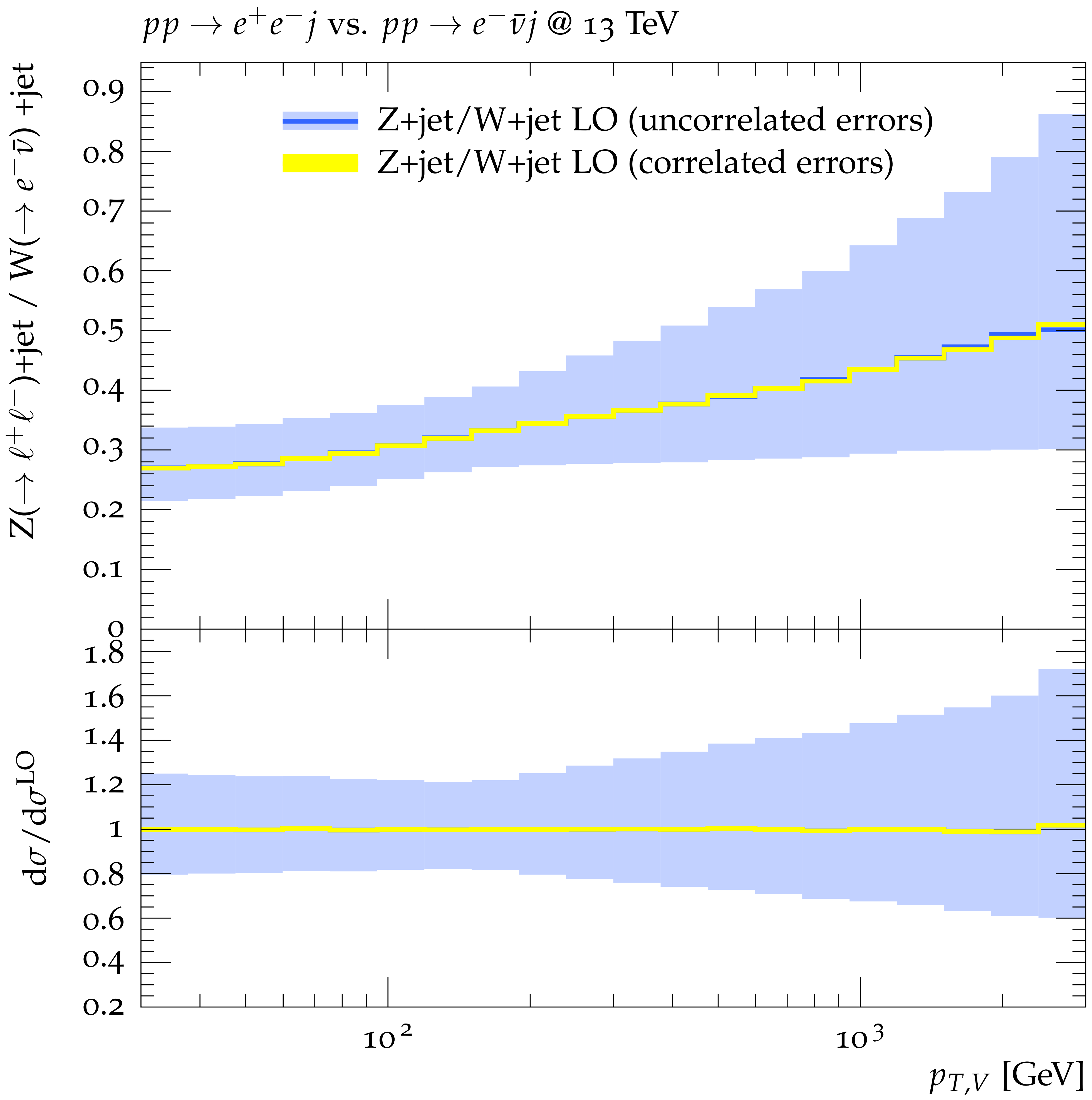


consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

How to correlate QCD uncertainties across processes?

[1705.04664]



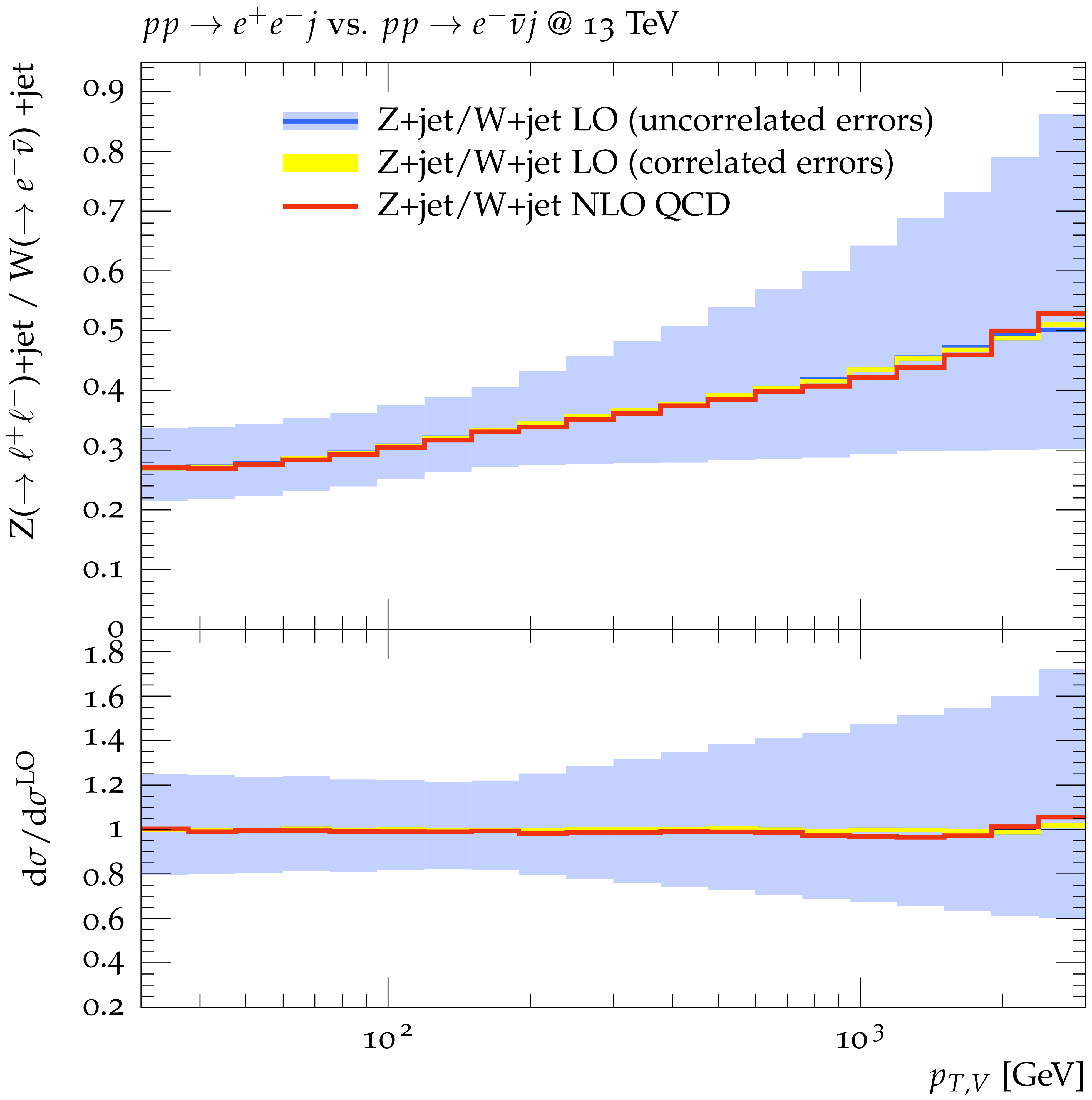
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

correlated treatment yields tiny O(<~ 1%) uncertainties

How to correlate QCD uncertainties across processes?

[1705.04664]



consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

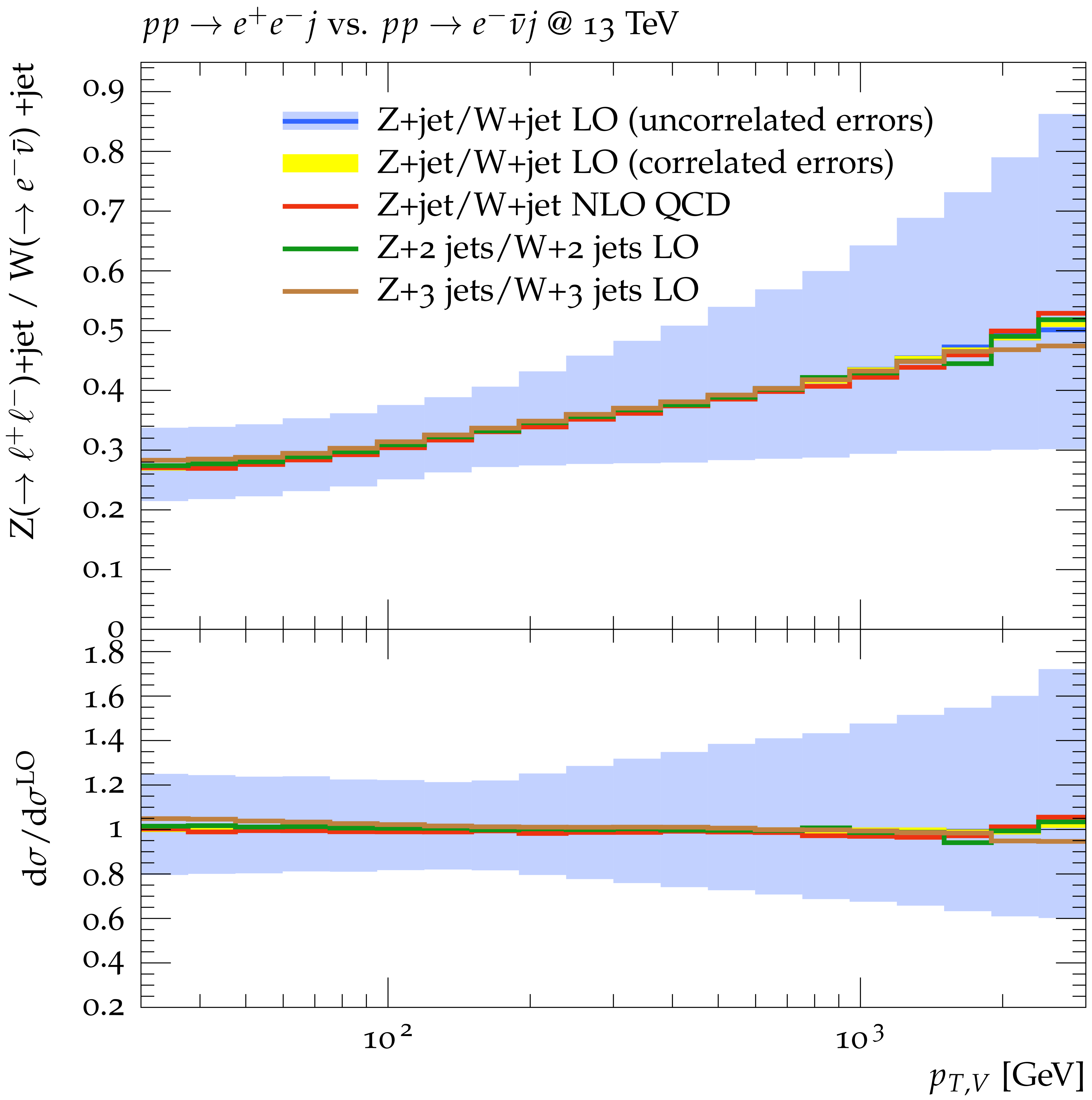
correlated treatment yields tiny O(<~ 1%) uncertainties

check against NLO QCD!

NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

How to correlate QCD uncertainties across processes?

[1705.04664]



consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

correlated treatment yields tiny O(<~ 1%) uncertainties

check against NLO QCD!

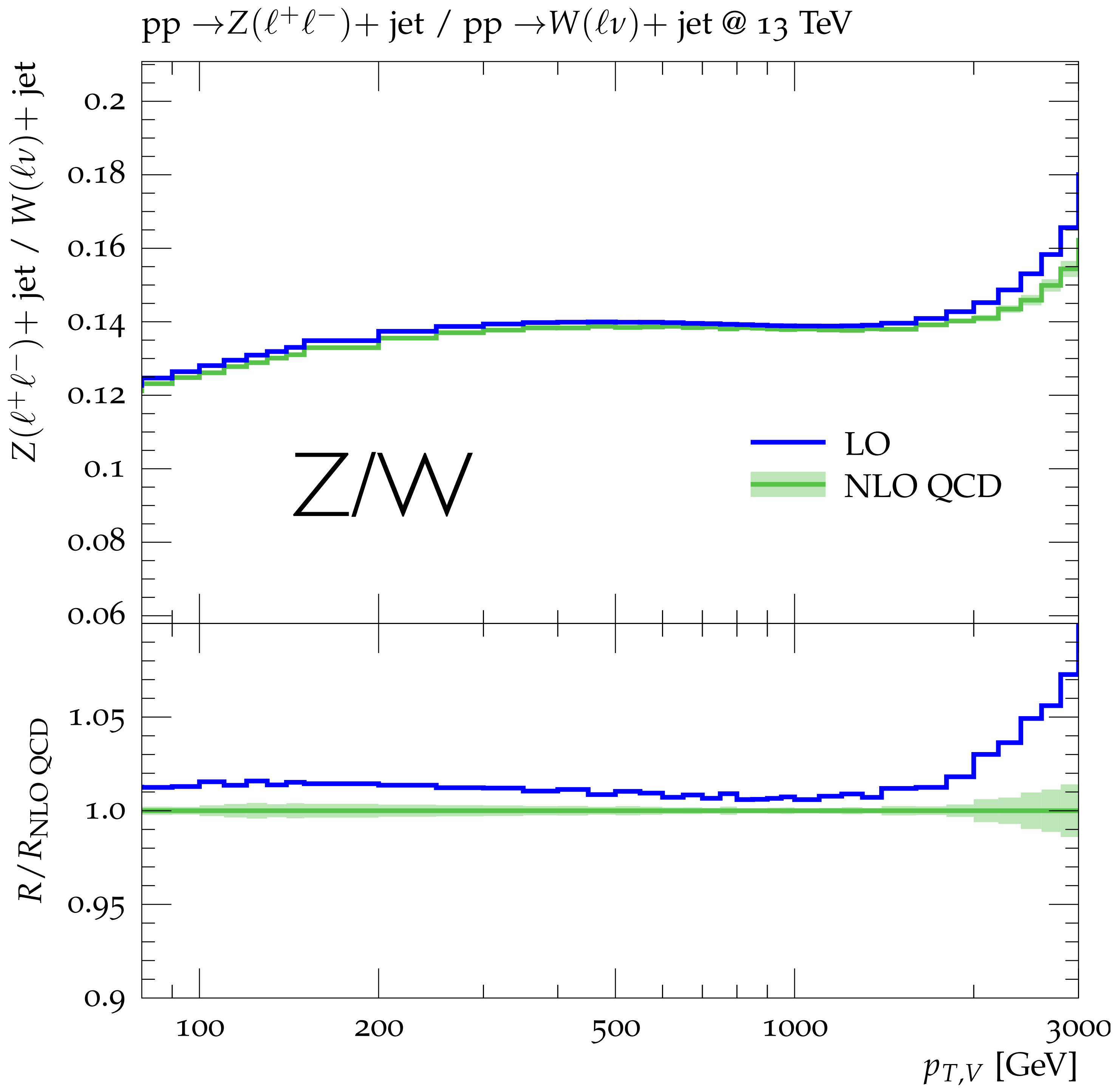
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

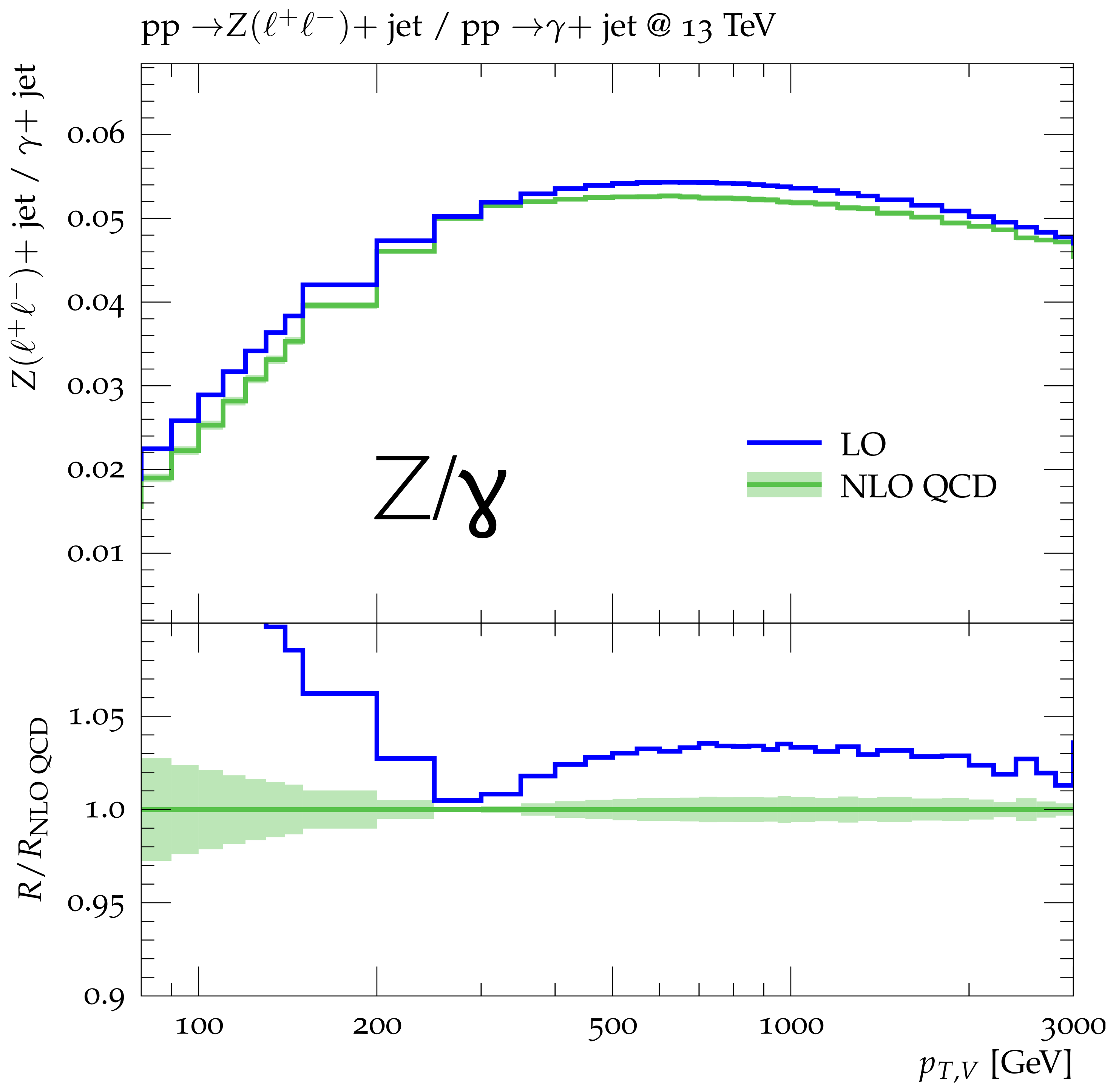
Also holds for higher jet-multiplicities
→ indication of correlation also in higher-order corrections beyond NLO!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level

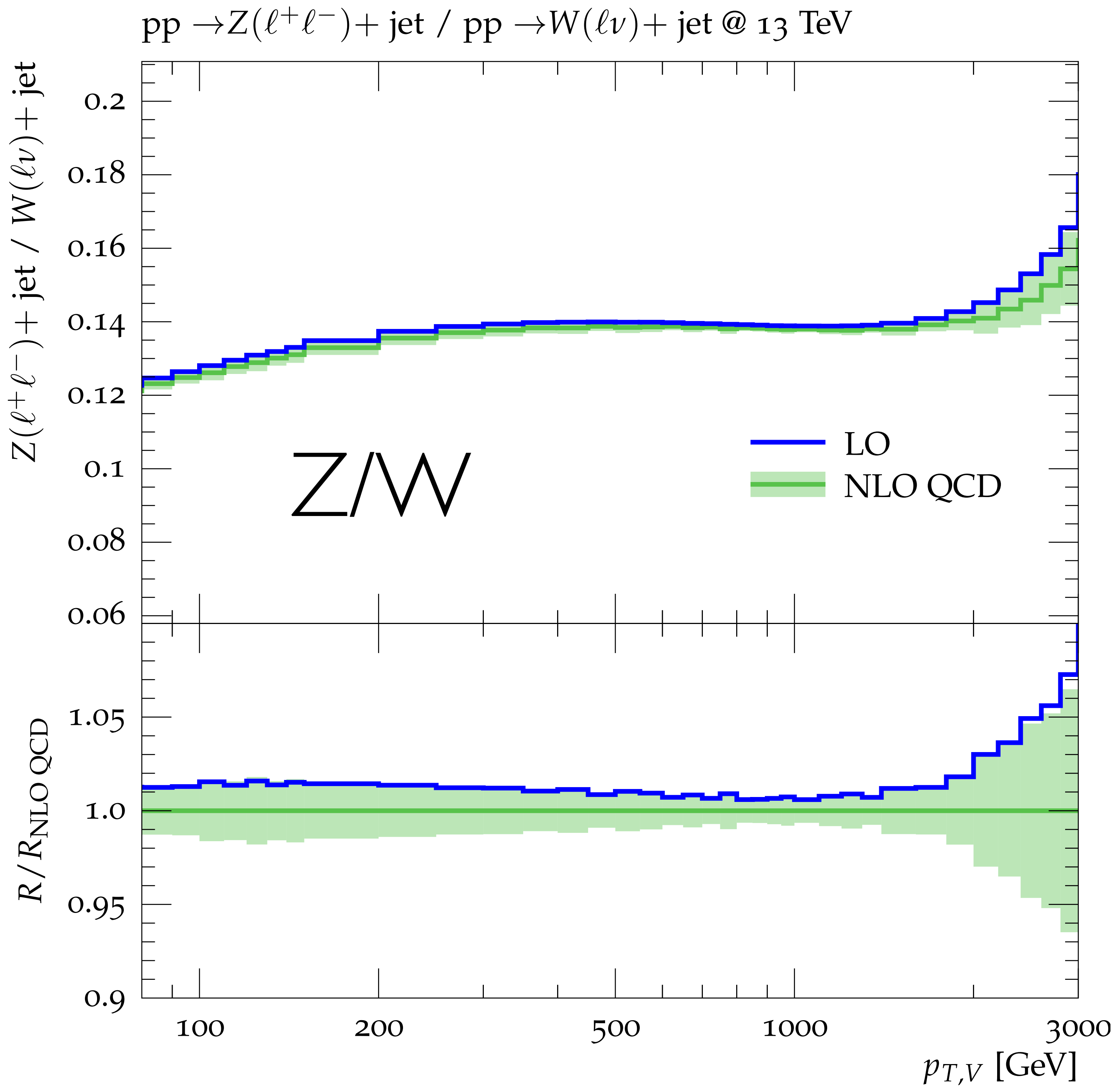




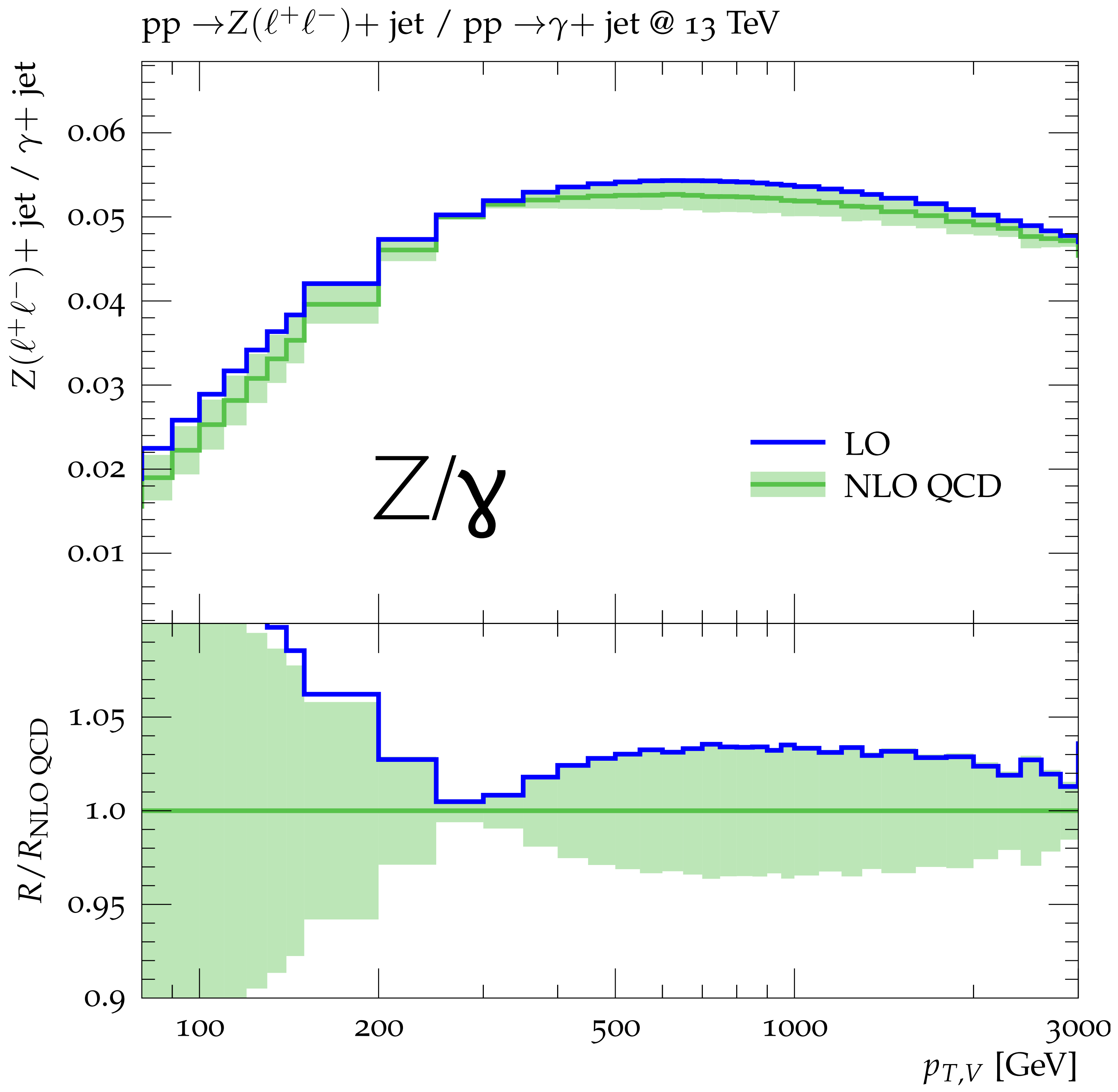
QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{NLO}} = K^{V}_{\mathrm{NLO}} - K^{Z}_{\mathrm{NLO}}$
  →effectively degrades precision of last calculated order



δ < 2 %

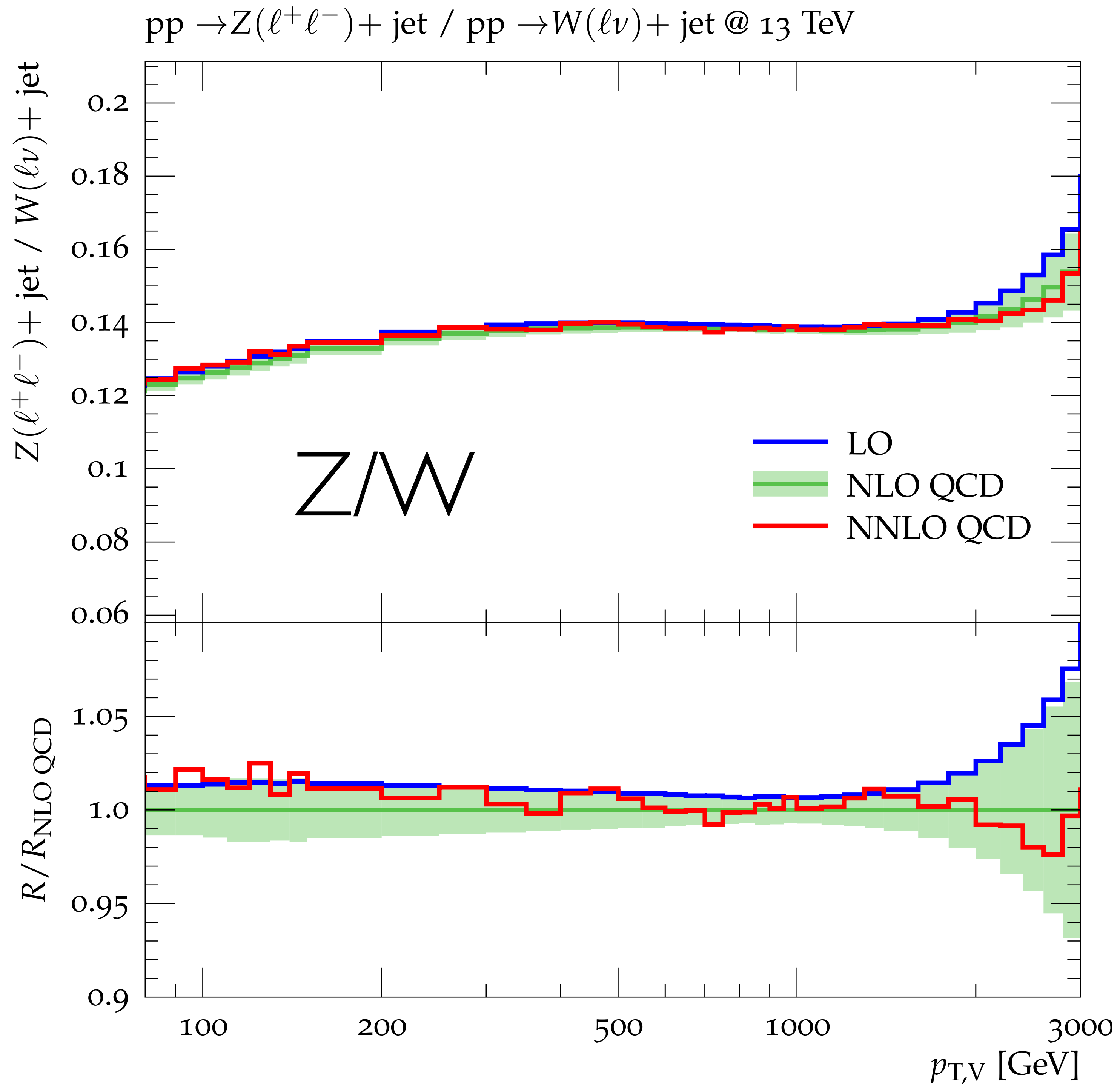


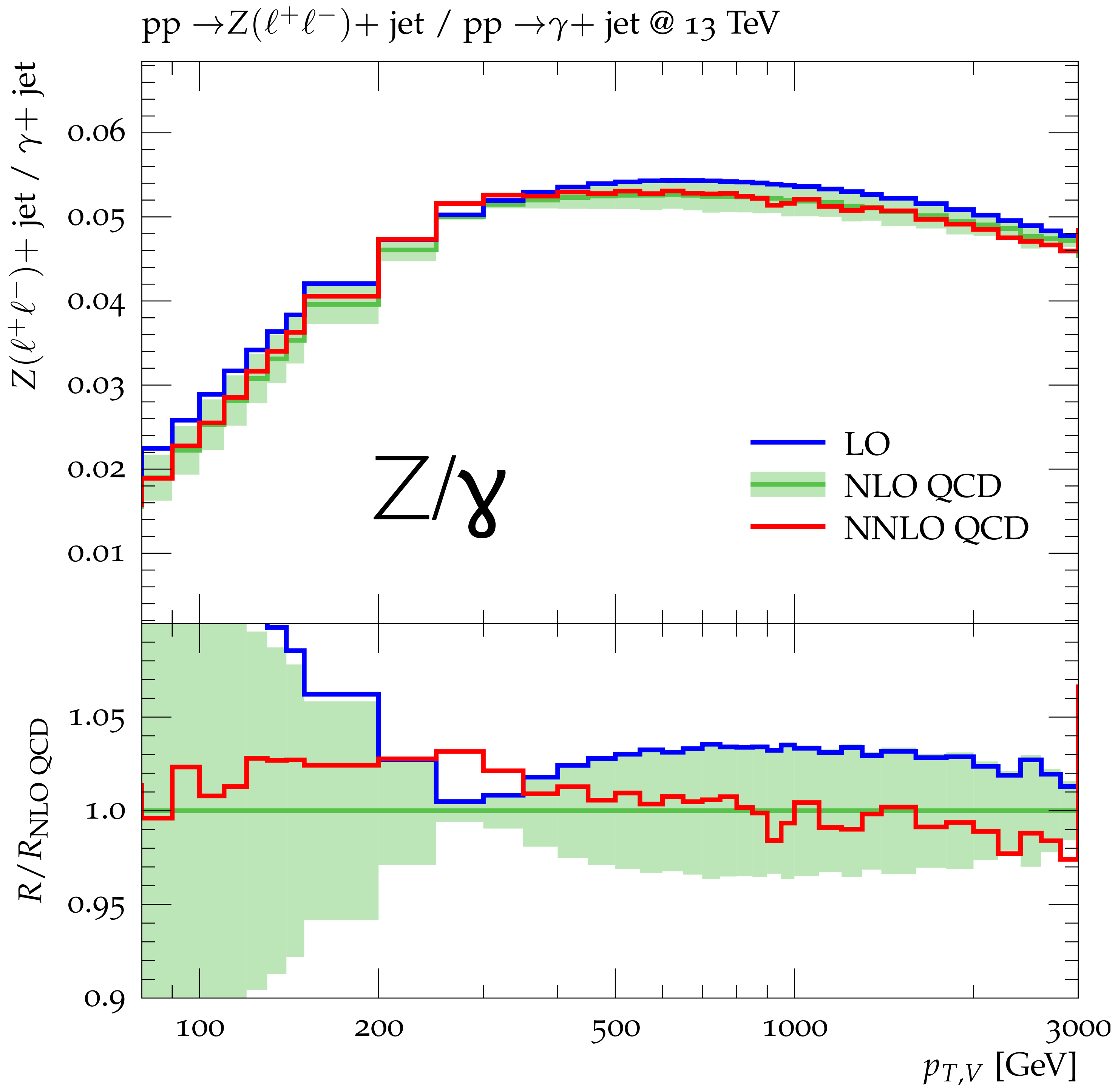
δ < 3-4 %

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{NLO}} = K^{V}_{\mathrm{NLO}} - K^{Z}_{\mathrm{NLO}}$
  →effectively degrades precision of last calculated order



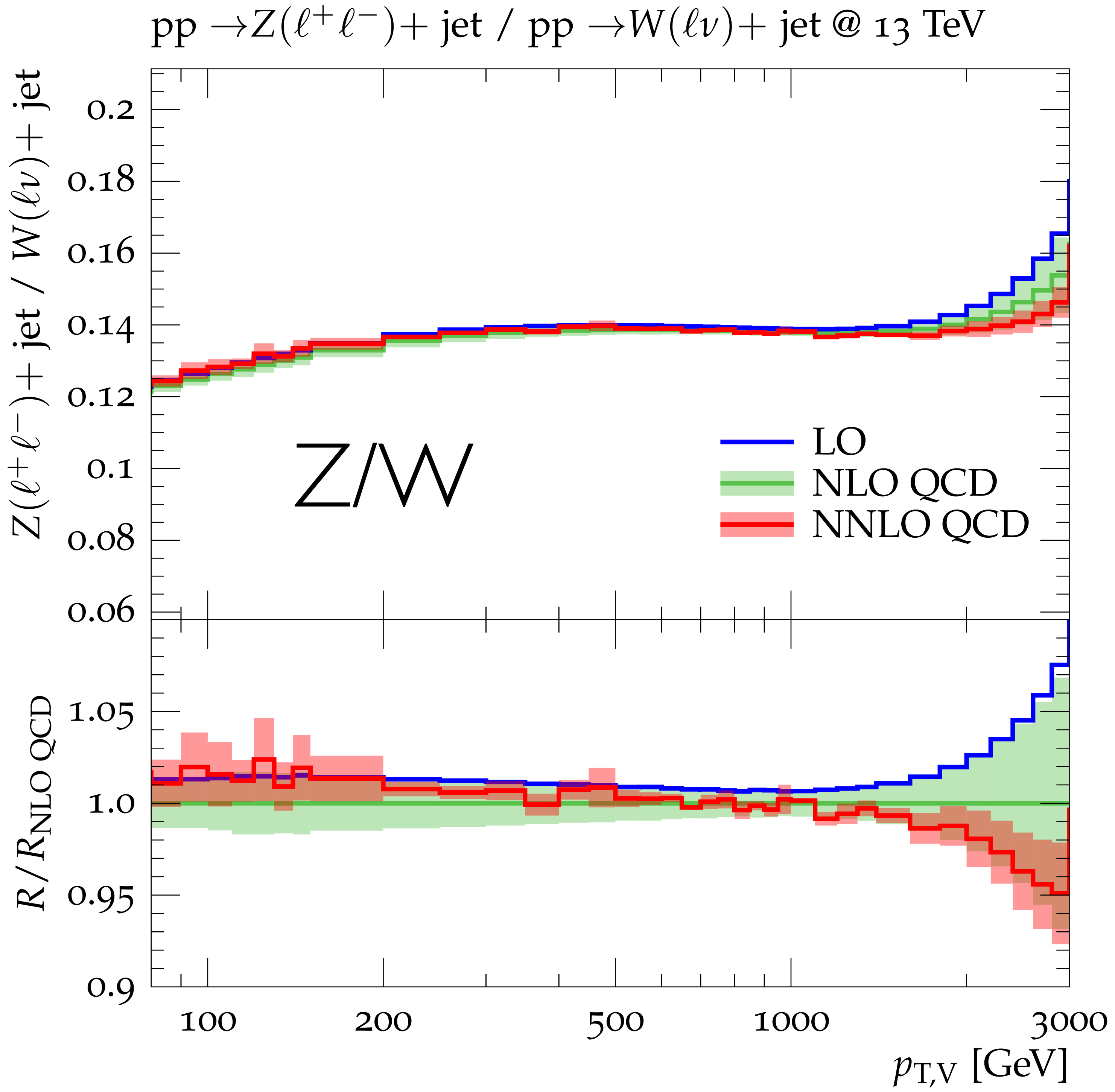


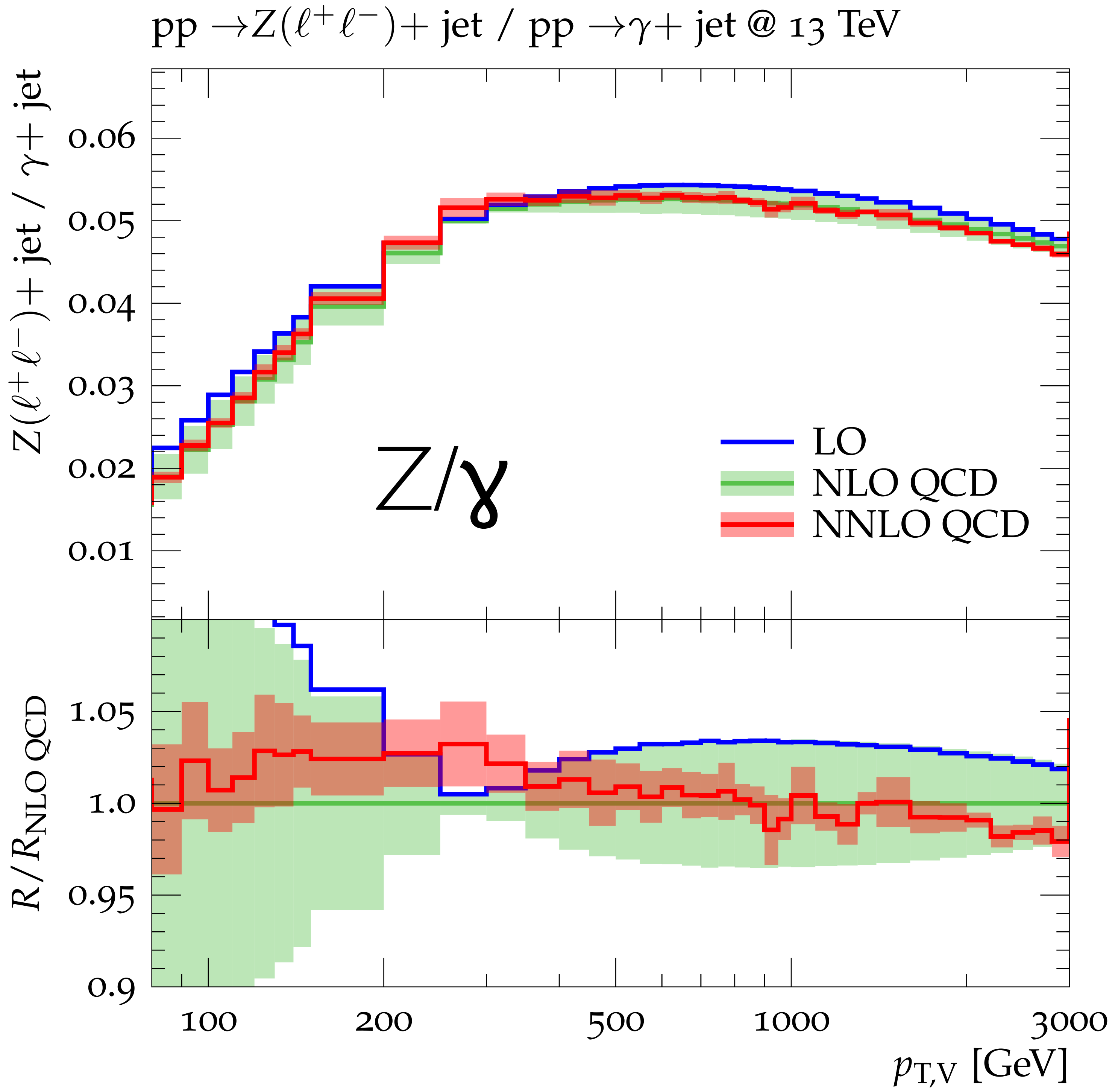
check against NNLO QCD!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{(N)NLO}} = K^{V}_{\mathrm{(N)NLO}} - K^{Z}_{\mathrm{(N)NLO}}$
  →effectively degrades precision of last calculated order

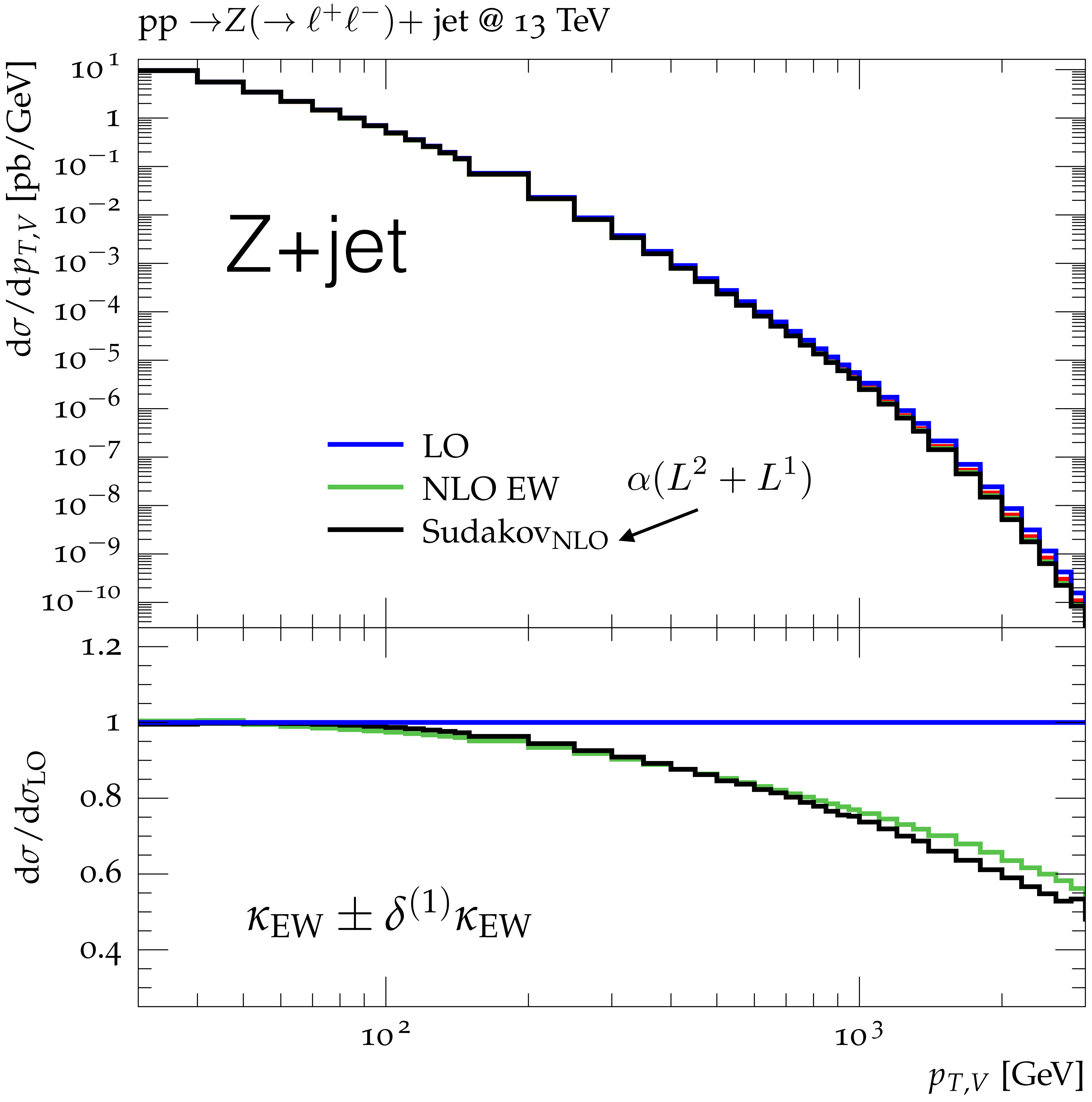




Uncertainty estimates at NNLO QCD

Pure EW uncertainties

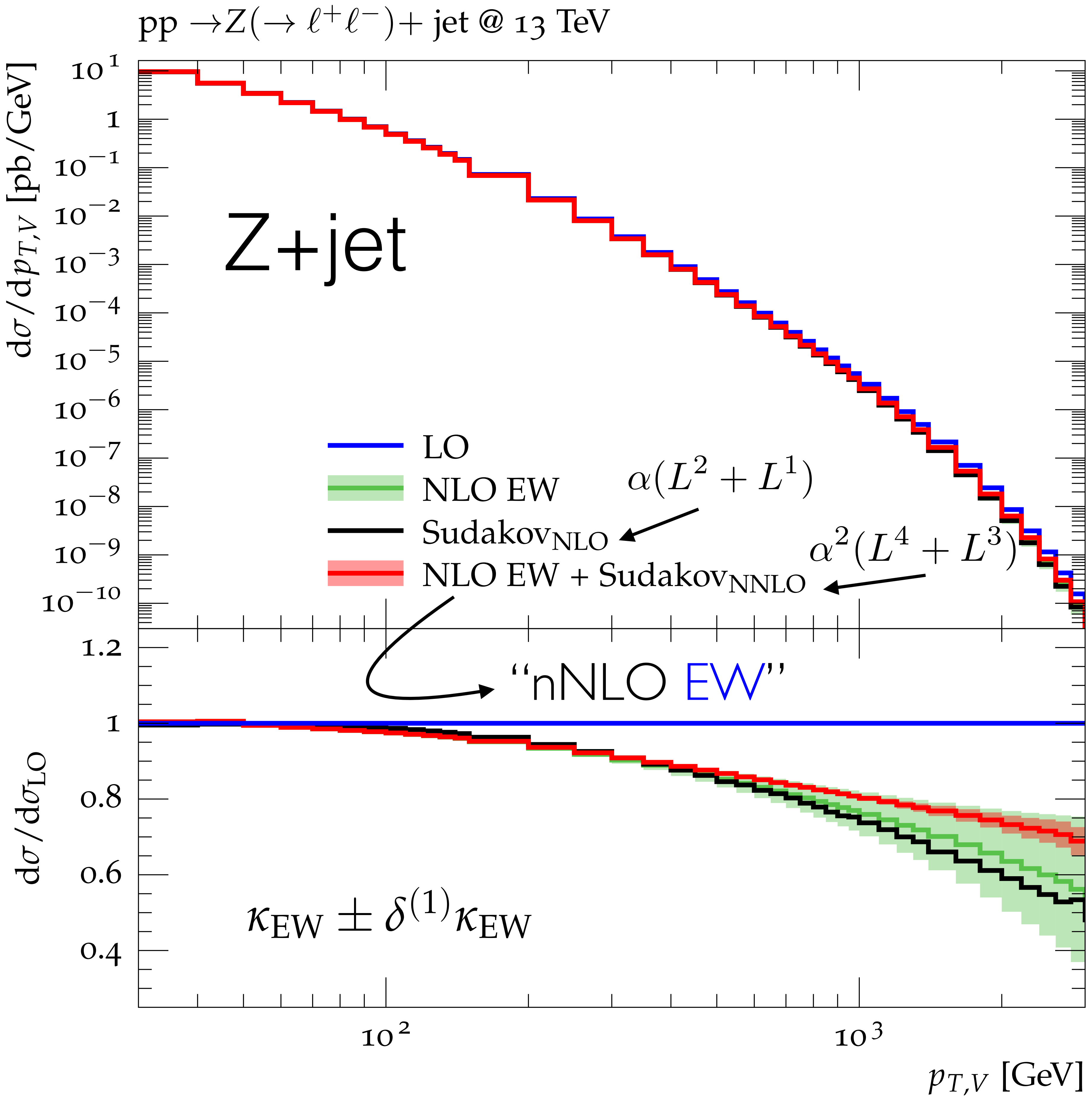
[JML et. al.: 1705.04664]



Large EW corrections dominated by Sudakov logs

Pure EW uncertainties

[JML et. al.: 1705.04664]



$$\kappa_{\text{NLO EW}}(\hat{s},\hat{t}) = \frac{\alpha}{\pi}\left[\delta^{(1)}_{\text{hard}} + \delta^{(1)}_{\text{Sud}}\right]$$

$$\kappa_{\text{NNLO Sud}}(\hat{s},\hat{t}) = \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\text{Sud}}$$

Large EW corrections dominated by Sudakov logs

↓

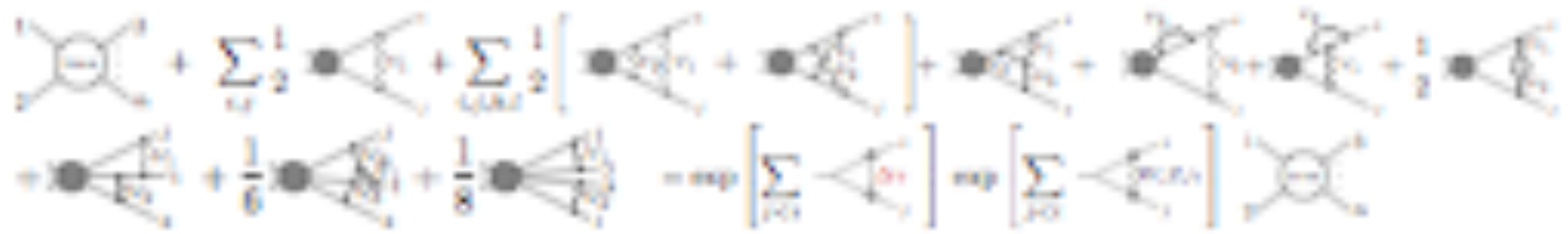
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

$$\delta^{(1)}\kappa_{\text{EW}} \simeq \frac{2}{k!}\left(\kappa_{\text{NLO,EW}}\right)^k \qquad \textit{(correlated)}$$

↓

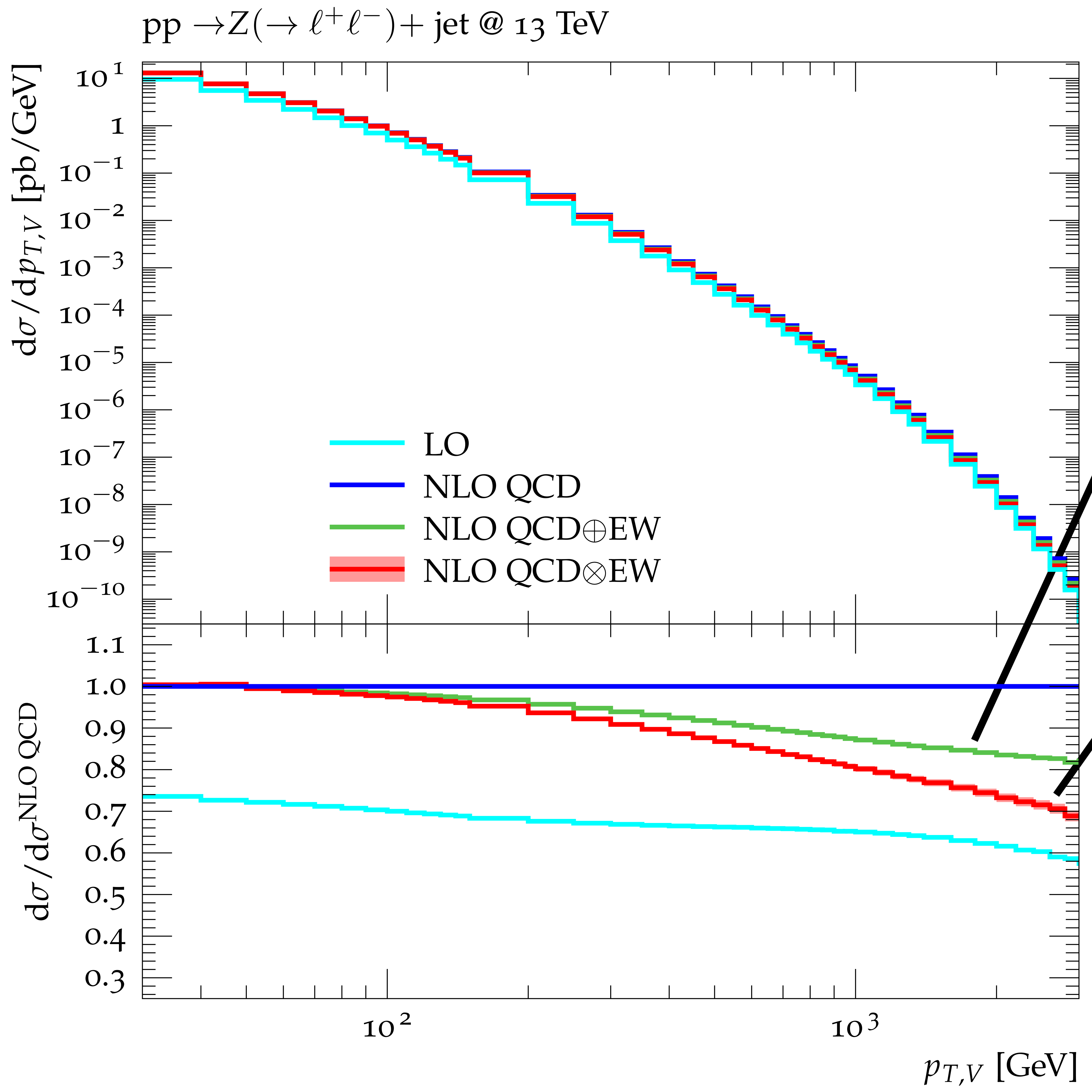
check against two-loop Sudakov logs

[Kühn, Kulesza, Pozzorini, Schulze; 05-07]



+ additional uncertainties for hard non-log NNLO EW effects *(uncorrelated)*

Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative $\mathcal{O}(\alpha\alpha_s)$ have to be considered.

Additive combination

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm LO} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

(no $\mathcal{O}(\alpha\alpha_s)$ contributions)

Multiplicative combination

$$\sigma^{\rm NLO}_{\rm QCD\times EW} = \sigma^{\rm NLO}_{\rm QCD}\left(1 + \frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$

(try to capture some $\mathcal{O}(\alpha\alpha_s)$ contributions, e.g. EW Sudakov logs × soft QCD)

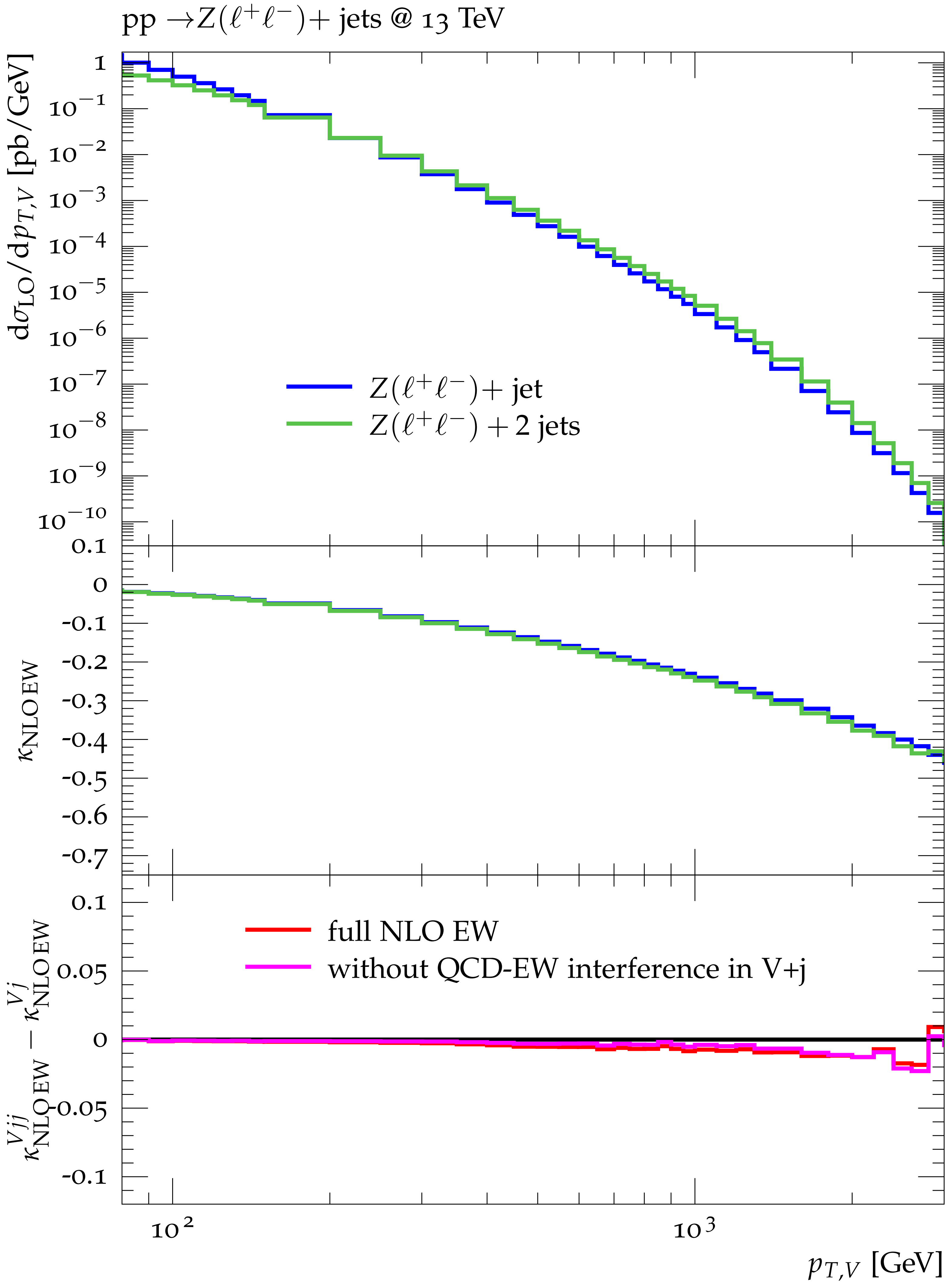
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

$$K_{\rm QCD\otimes EW} - K_{\rm QCD\oplus EW} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

Mixed QCD-EW uncertainties



Bold estimate:

Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to V+jet

$\simeq$ **NLO EW to V+2jets**

and we observe

$$\left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+2\mathrm{jet}} - \left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+1\mathrm{jet}} \lesssim 1\%$$

strong support for

- factorization
- multiplicative QCD × EW combination

Estimate of non-factorising contributions

(correlated)

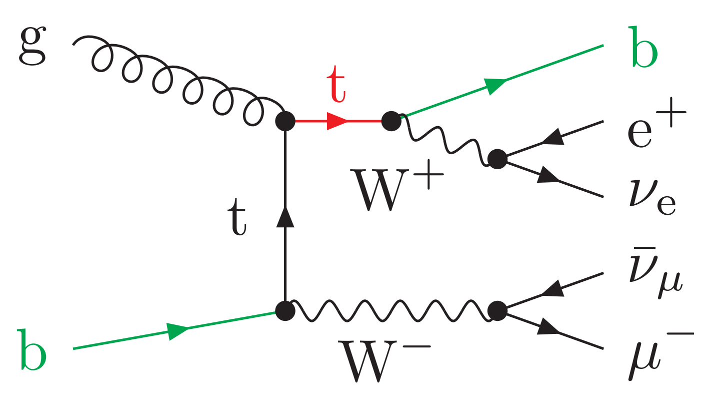
$$\delta K^{(V)}_{\mathrm{mix}}(x) \quad = \quad 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$

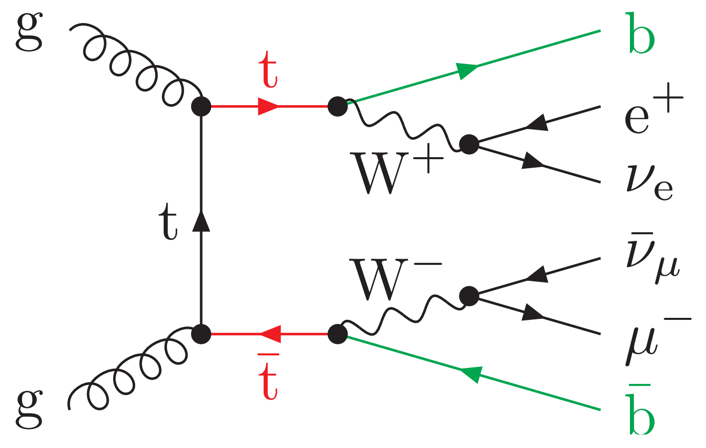
(tuned to cover above difference of EW K-factors)

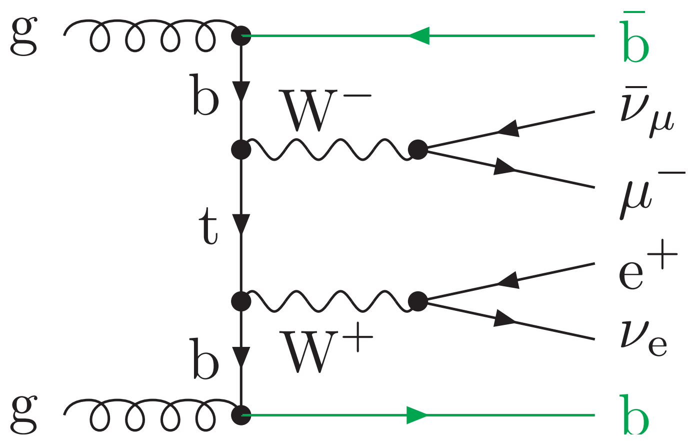
Top-free W^+W^- definitions

Huge Wt and $t\bar{t}$ contamination from $\overbrace{W^+W^-b}^{+40\%\ \mathrm{NLO}}$ and $\overbrace{W^+W^-b\bar{b}}^{+400\%\ \mathrm{NNLO}}$

- intimately connected with W^+W^- through $g \to b\bar{b}$ singularities
- top subtraction tricky and not unique $\Rightarrow$ theoretical ambiguity in $\sigma_{WW}^{\mathrm{(N)NLO}}$!







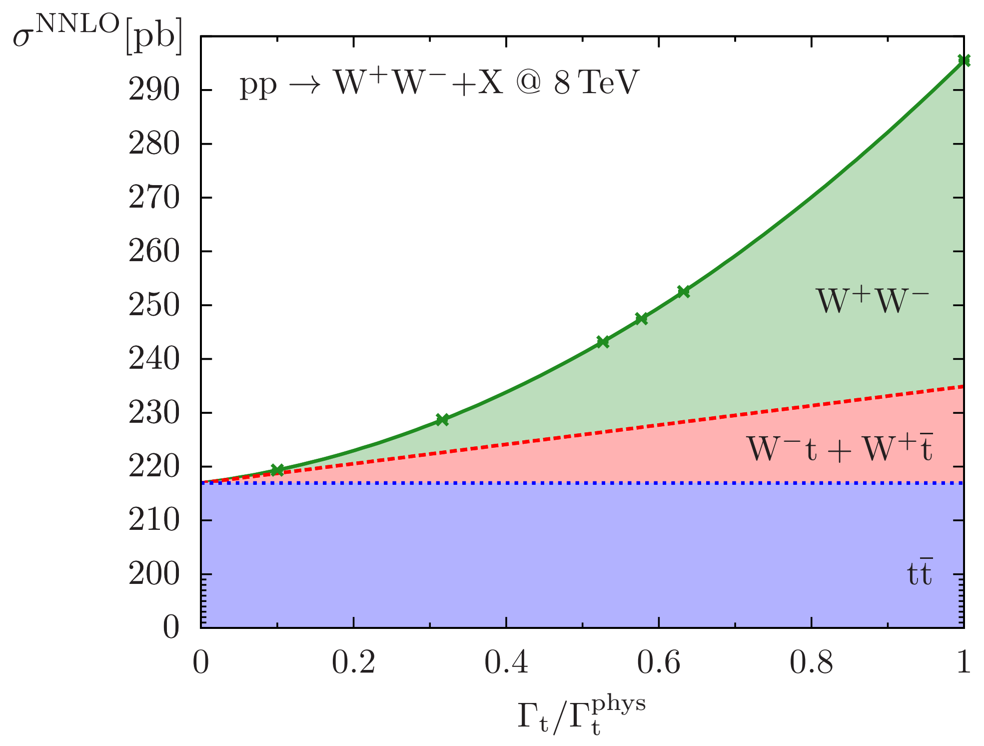
Definition A: **veto b-quark emissions in 4F scheme** $(m_b > 0)$

- $\Rightarrow \ln(m_b/M_W)$ terms might jeopardize NNLO accuracy!

Definition B: **top-resonance fit in 5F-scheme** $(m_b = 0)$

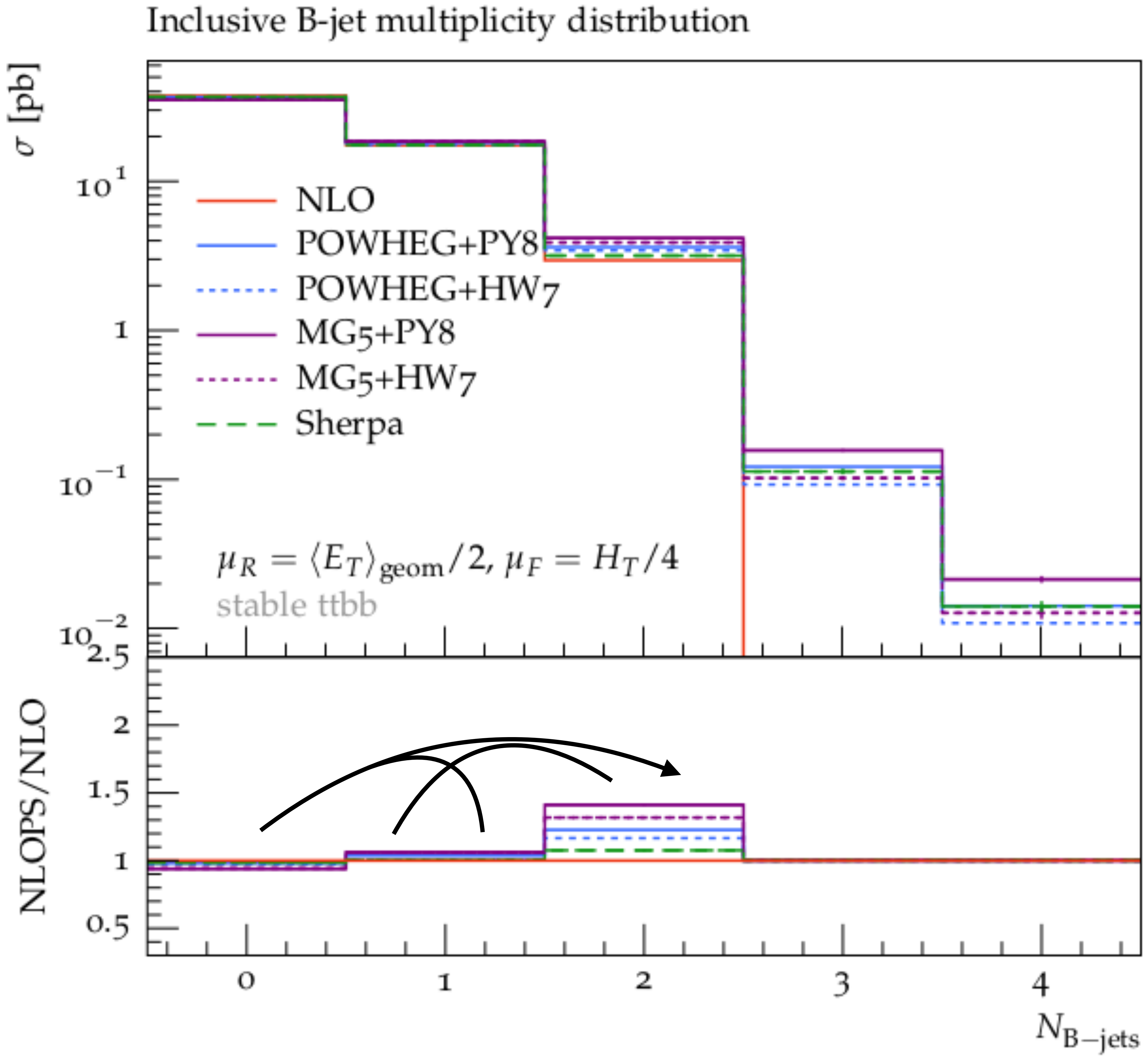
$$\lim_{\xi_t \to 0} \sigma_{\mathrm{full}}^{5\mathrm{F}}(\xi_t \Gamma_t) = \xi_t^{-2} \left[\sigma_{t\bar{t}}^{5\mathrm{F}} + \xi_t\, \sigma_{Wt}^{5\mathrm{F}} + \xi_t^2\, \sigma_{W^+W^-}^{5\mathrm{F}} \right]$$

$\Rightarrow$ for inclusive $\sigma_{WW}^{\mathrm{NNLO}}$ only 1–2% ambiguity (A vs B)



Relevant issue for percent-precision tests of W^+W^- physics! . . . Relation to $\sigma_{WW}^{\mathrm{EXP}}$?

Origin of these differences



- origin: different shower-induced bins migrations across b-jets cuts

anti-k_t, $R = 0.4$

cuts: $p_T > 25$ GeV, $\eta < 2.5$