# EW precision predictions and QCD-EW interplay for the LHC

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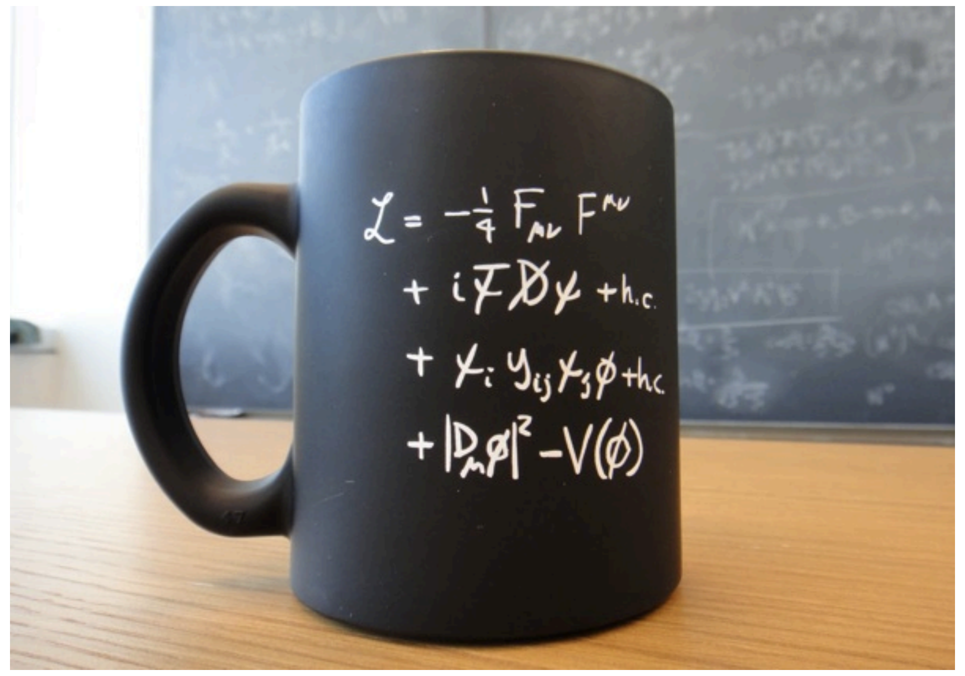
Science & Technology Facilities Council | UK Research and Innovation

LHCP
Belgrade
26th May 2023



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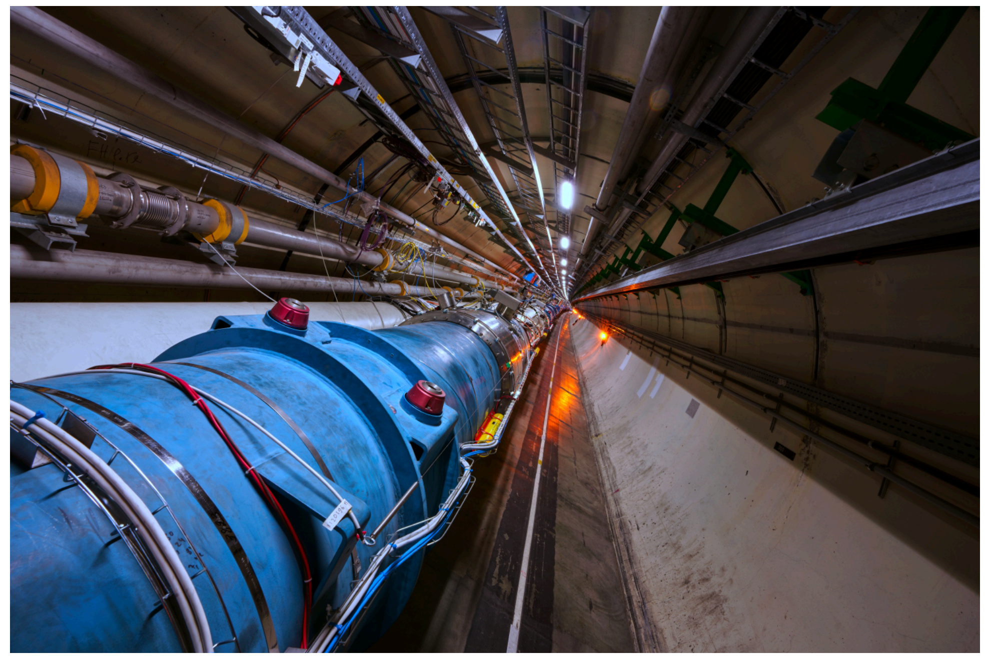

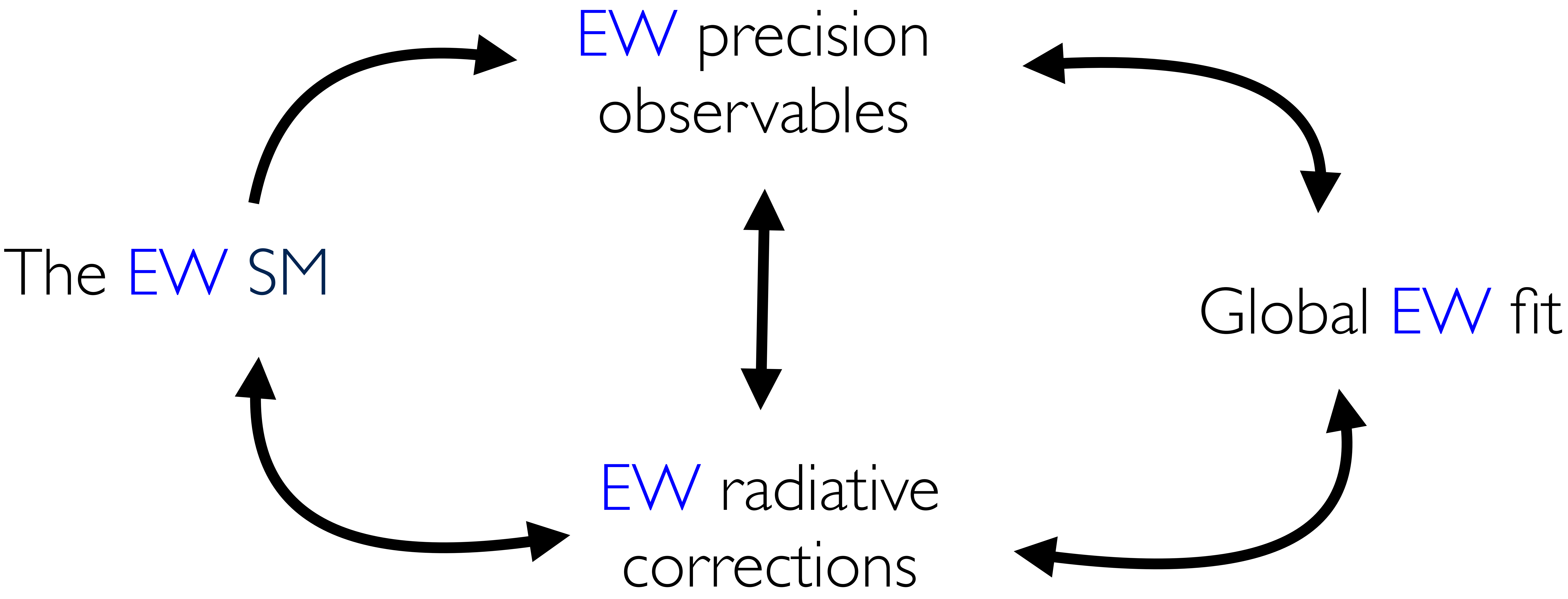

EW precision observables

The EW SM

Global EW fit

EW radiative corrections

➡Study dynamics of EWSB
➡Test BSM via indirect EW probes
➡Constrain backgrounds in searches

# Perturbative expansion

aMC@NLO, Sherpa, Herwig… &
Recola, Madloop, Gosam, OpenLoops

dedicated MC's: Matrix, MCFM,
NNLOjet, …

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}}$$

NLO QCD O(10%)

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}}$$

NNLO QCD O(1%)

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{N3LO}} \overset{?}{+} \ldots$$

N3LO QCD O(0.1%)

only known for inclusive-H, DY

scale variation at NNLO

# Perturbative expansion

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$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD

NLO EW

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}}$$

NNLO QCD

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{N3LO}} + \ldots$$

?

N3LO QCD

only known for inclusive-H, DY

scale variation at NNLO

- Fixed-order NLO EW largely automated
- Still computationally very challenging for high-multiplicity (2 → 5,6,7) processes: VBS, VVV, off-shell top-processes, …
- Consistent matching to parton showers only available for few selected processes (DY, HV, VV)

# Perturbative expansion

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$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_S\, d\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD NLO EW

$$+\alpha_S^2\, d\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, d\sigma_{\mathrm{NNLO\,EW}}^{\;?} + \alpha_S \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NNLO\,QCDxEW}}^{\;?}$$

NNLO QCD NNLO EW NNLO QCD-EW

only known for DY (so far)

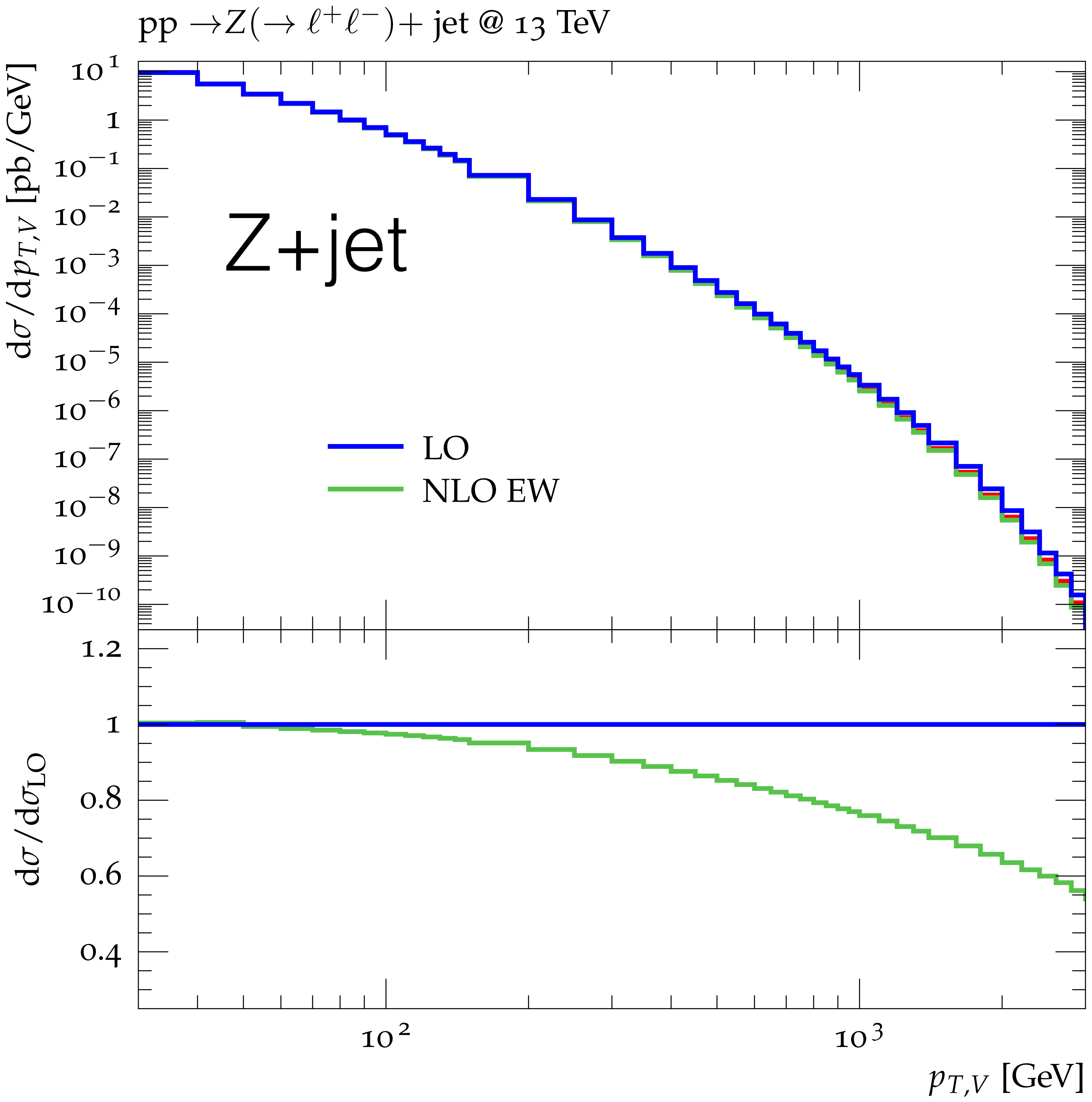
$$+\alpha_S^3\, d\sigma_{\mathrm{N3LO}} +^{?} \dots$$

N3LO QCD

only known for DY (so far)

scale variation at NNLO

# EW uncertainties: Sudakov

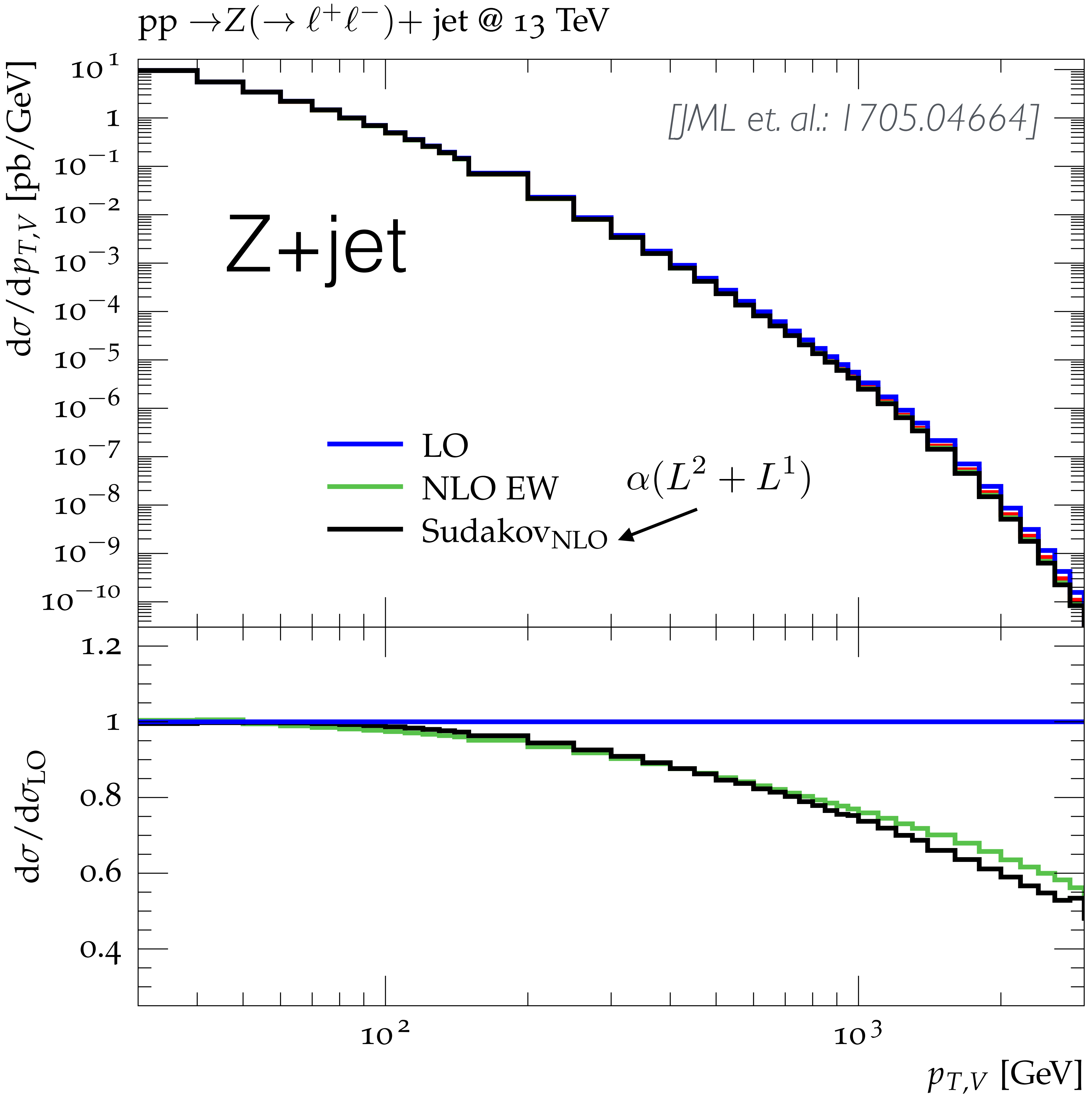


EW corrections become sizeable at large $p_{T,V}$: -30% @ 1 TeV

Origin: virtual EW Sudakov logarithms

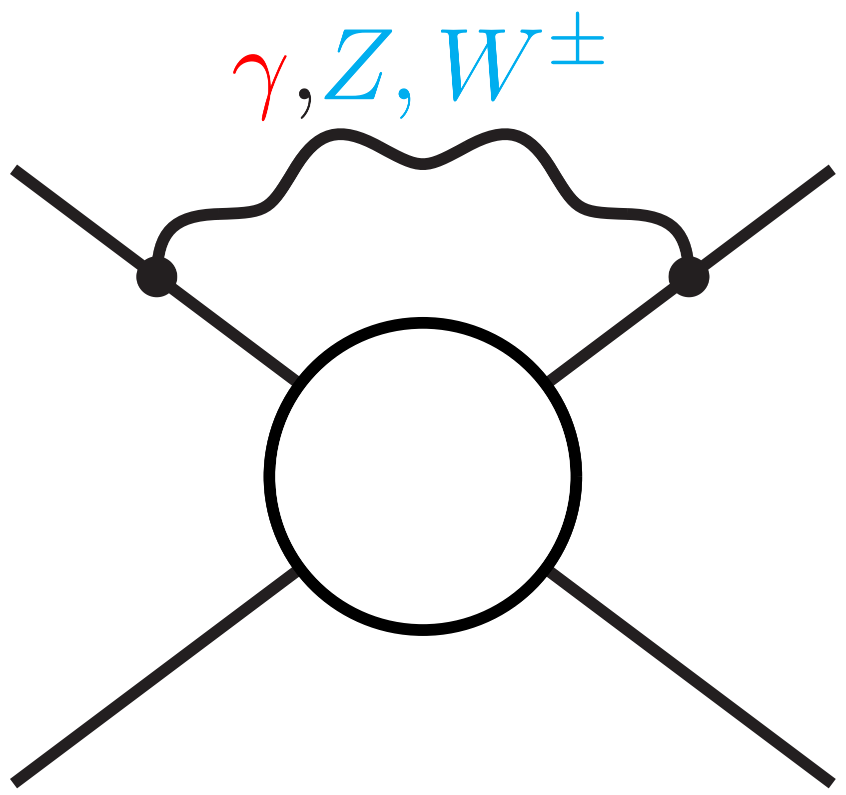
How to estimate corresponding pure EW uncertainties of relative $\mathcal{O}(\alpha^2)$ ?

# EW uncertainties: Sudakov



*[JML et. al.: 1705.04664]*

Large EW corrections dominated by Sudakov logs

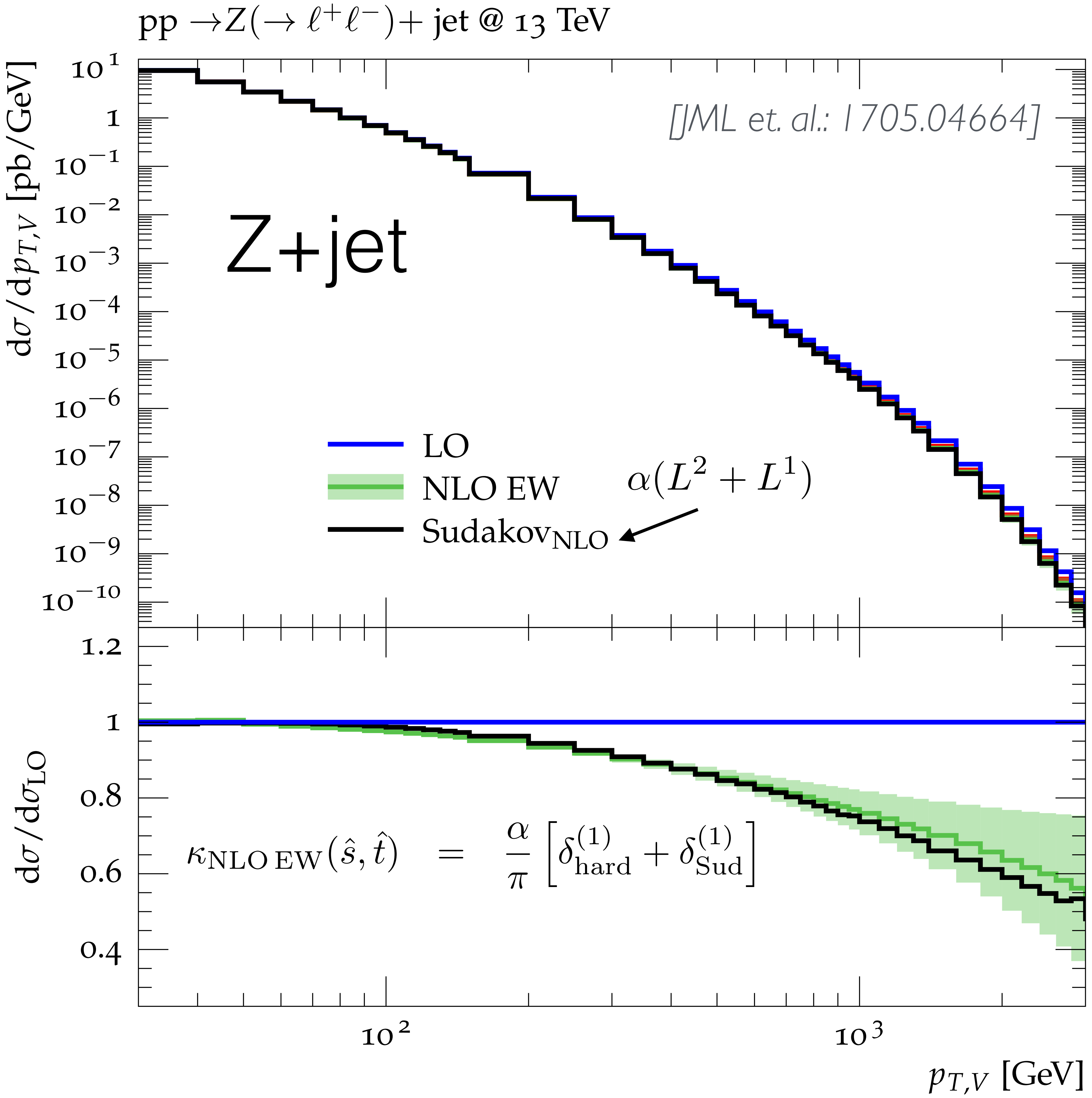


*[Ciafaloni, Comelli,'98;*
*Lipatov, Fadin, Martin, Melles, '99;*
*Kuehen, Penin, Smirnov, '99;*
*Denner, Pozzorini, '00]*

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

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

# EW uncertainties: Sudakov



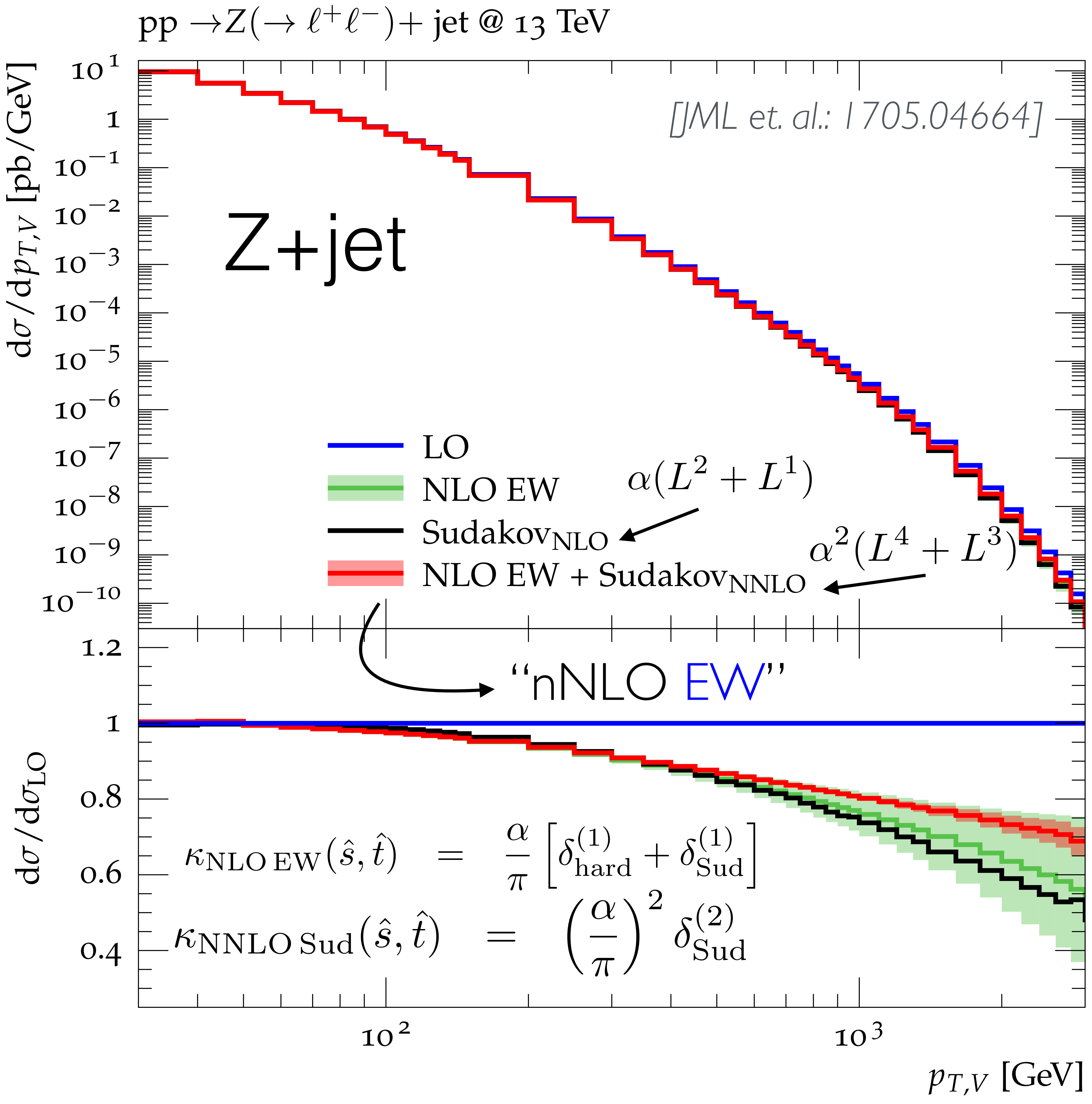
Large EW corrections dominated by Sudakov logs

↓

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

$$\boxed{\Delta^{\text{Sud}}_{\text{EW}} \approx (k_{\text{NLOEW}})^2}$$

# EW uncertainties: Sudakov



Large EW corrections dominated by Sudakov logs

↓

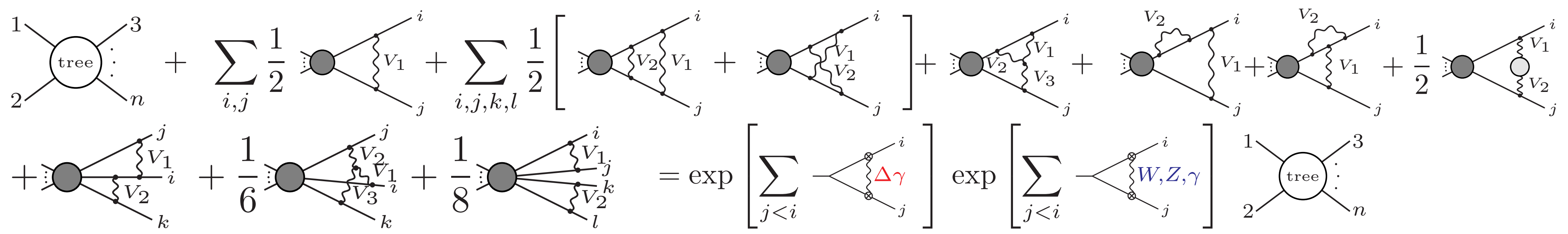
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

$$\boxed{\Delta^{\text{Sud}}_{\text{EW}} \approx (k_{\text{NLOEW}})^2}$$

↓

check against two-loop Sudakov logs

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



$$\boxed{\Delta^{\text{hard}}_{\text{EW}} \approx \text{O}(1\%)}$$

e.g. from scheme variation, e.g. Gmu vs. a(mZ)

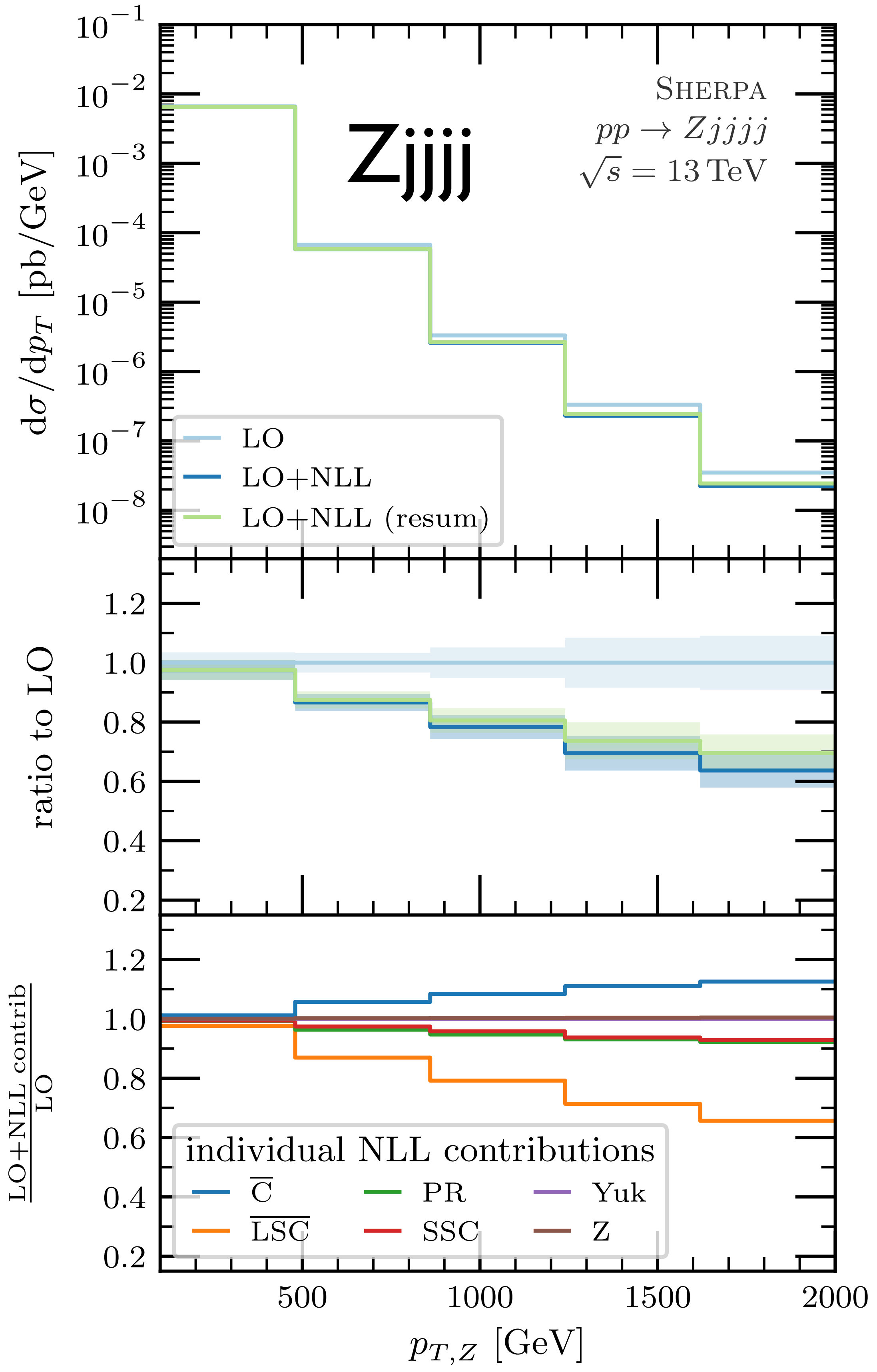
# Tools for EW Sudakov corrections

[Talk by M. Zaro]

also: alpgen *[Chiesa, et. al., '13]*

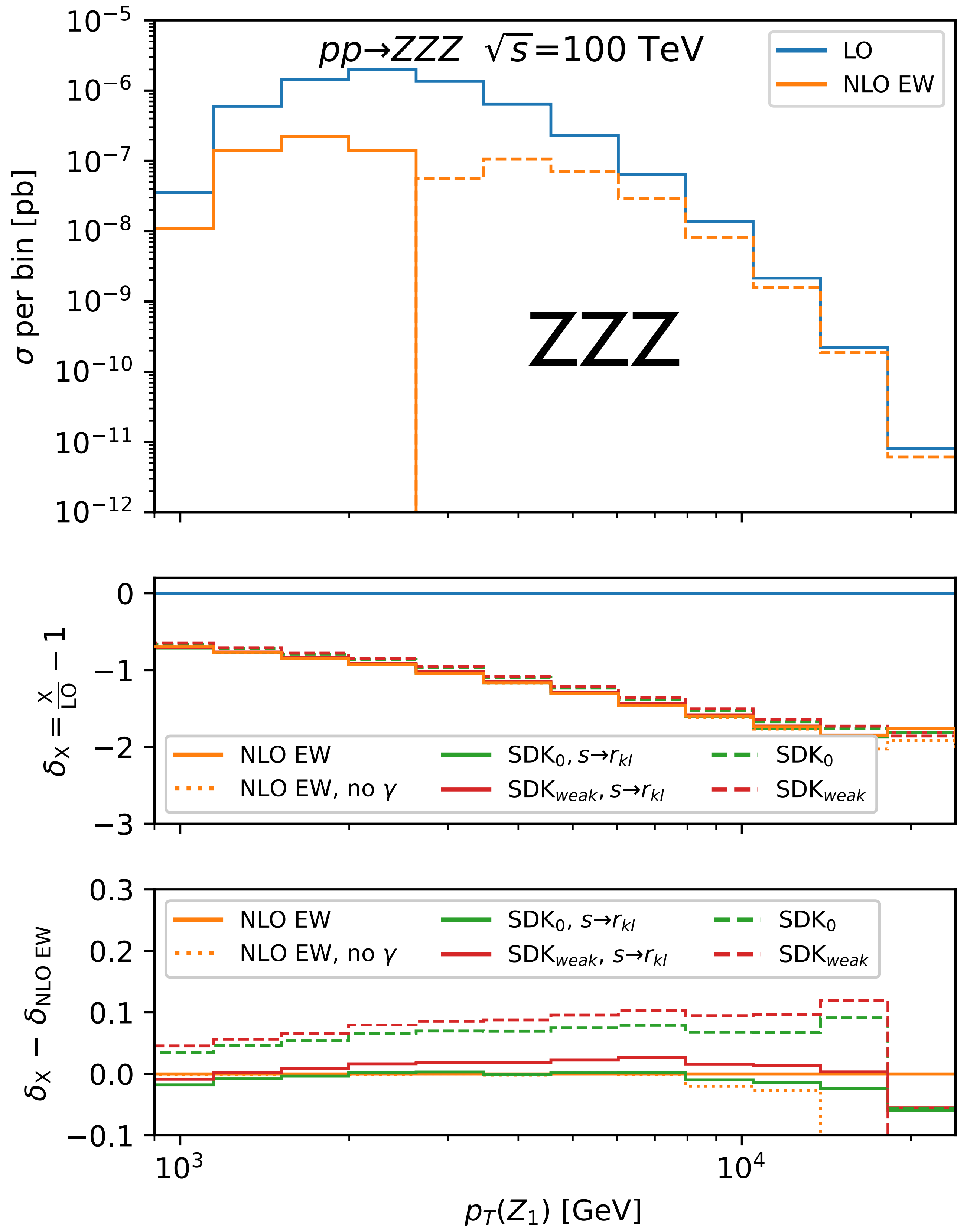
## Sherpa

*[Bothmann, Napoletano, '20]*



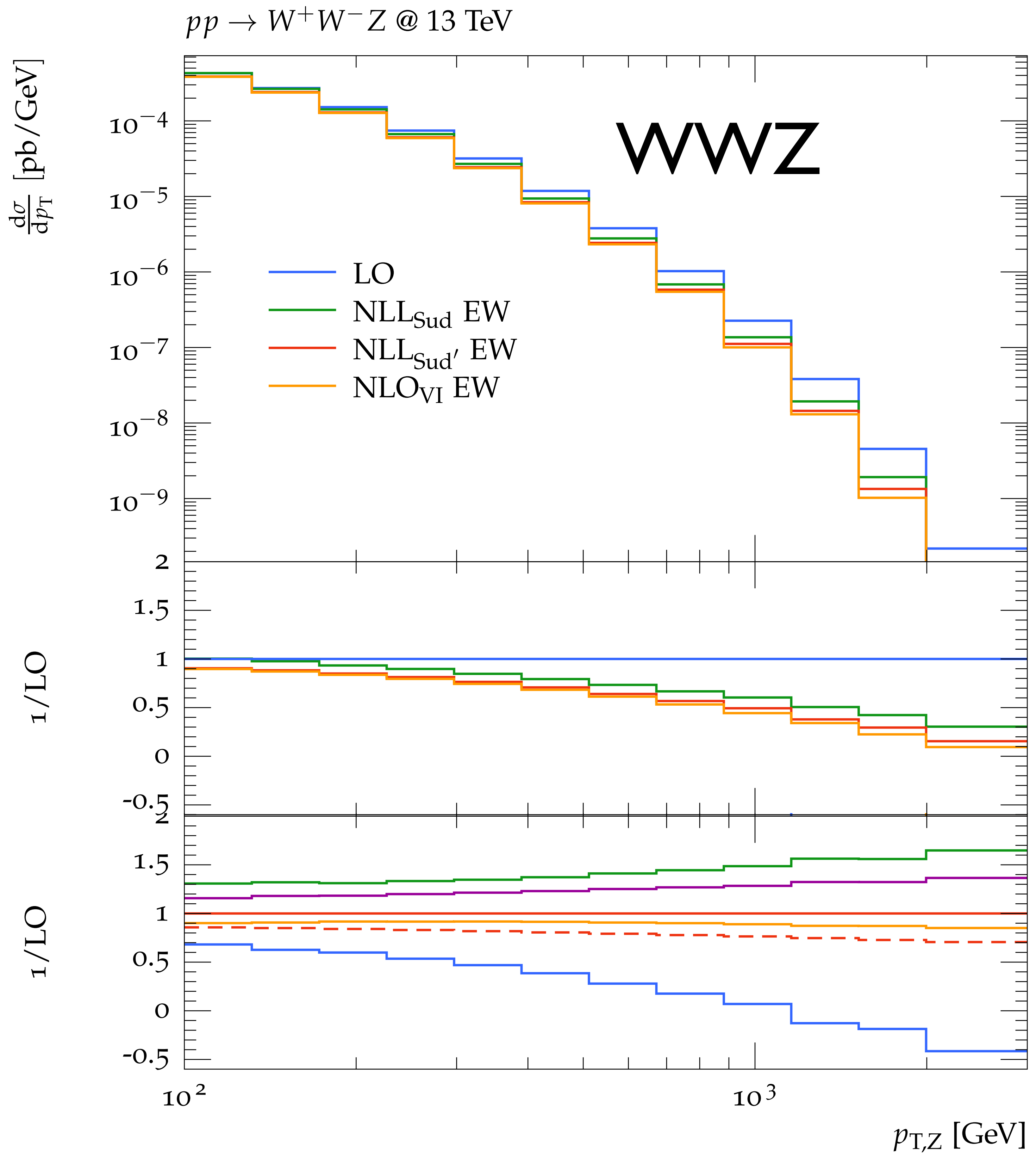
## MadGraph5_aMC@NLO

*[Pagani, Zaro, '21]*

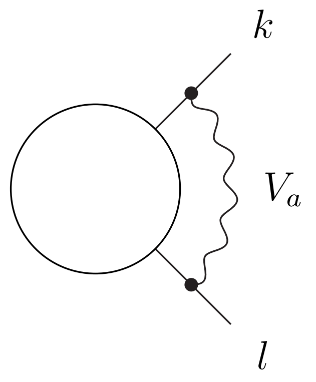


## OpenLoops

*[JML, Mai, to appear]*



- all based on *[Denner, Pozzorini, '00, '01]*



$$\delta_{kl}^{\mathrm{DL}}\mathcal{M}^{\varphi_{i_1}\dots\varphi_{i_n}} \overset{\mathrm{LA}}{=} \frac{\alpha}{4\pi}\sum_{\varphi_{i'_k},\varphi_{i'_l}} I^{V}_{\varphi_{i'_k}\varphi_{i_k}} I^{\bar{V}}_{\varphi_{i'_l}\varphi_{i_l}} \mathcal{M}_0^{\varphi_{i_1}\dots\varphi_{i'_k}\dots\varphi_{i'_l}\dots\varphi_{i_n}} C_0^{\mathrm{eik}}$$

$$C_0^{\mathrm{eik}} \equiv \frac{1}{(p_k+p_l)^2}\left[\log^2\frac{|r_{kl}|}{M_V^2} - 2i\pi\Theta(r_{kl})\log\frac{|r_{kl}|}{M_V^2}\right]$$

➡Applicable beyond SM
➡Two-loop Sudakov logs

[Talk by S. Zanoli]

# EW uncertainties: QED radiation

NLOPS EW needs to be **resonance-aware**: [Jezo, Nason, '15]

Conservative estimate of higher-order QED radiation:

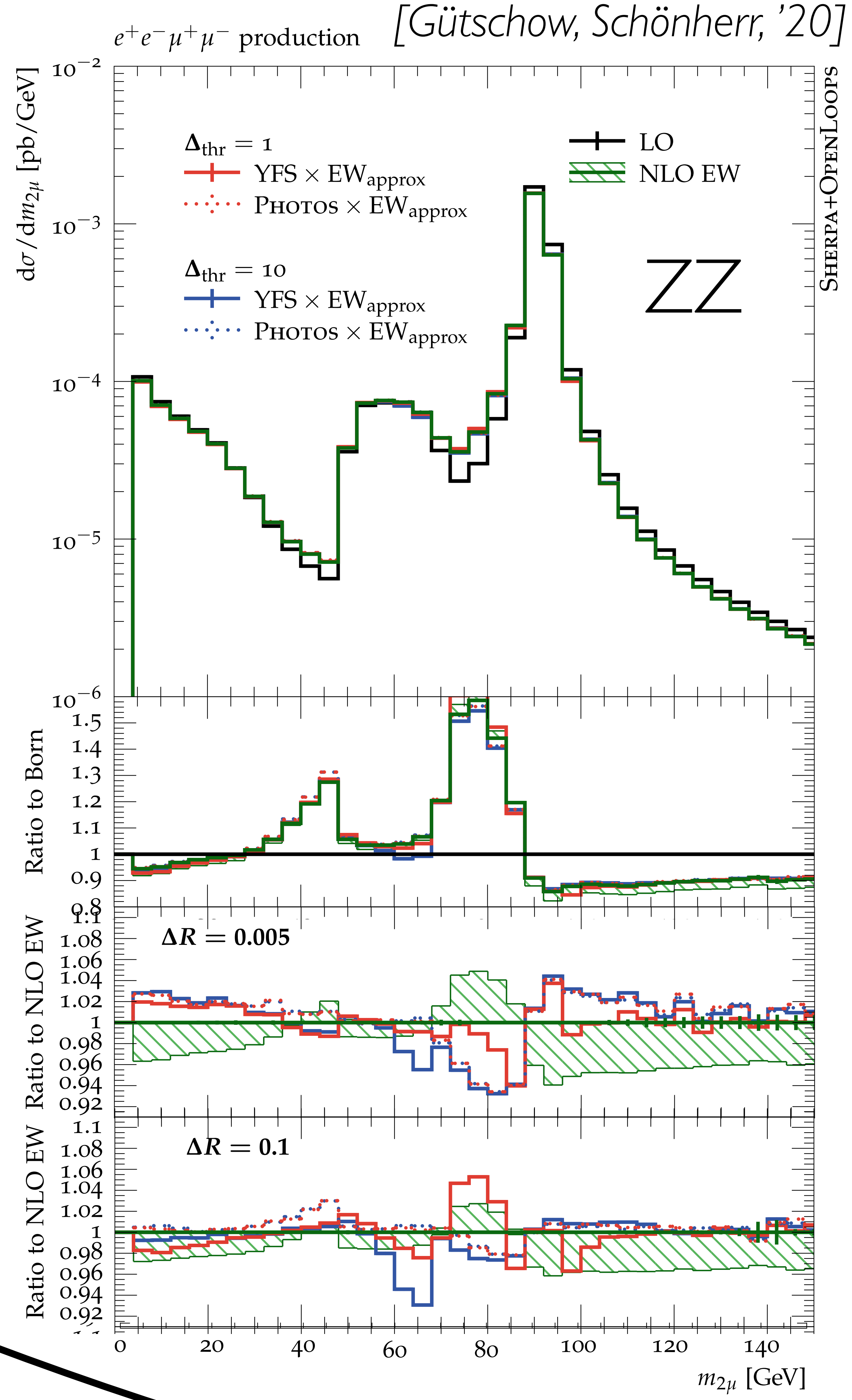
NLO EW

vs.

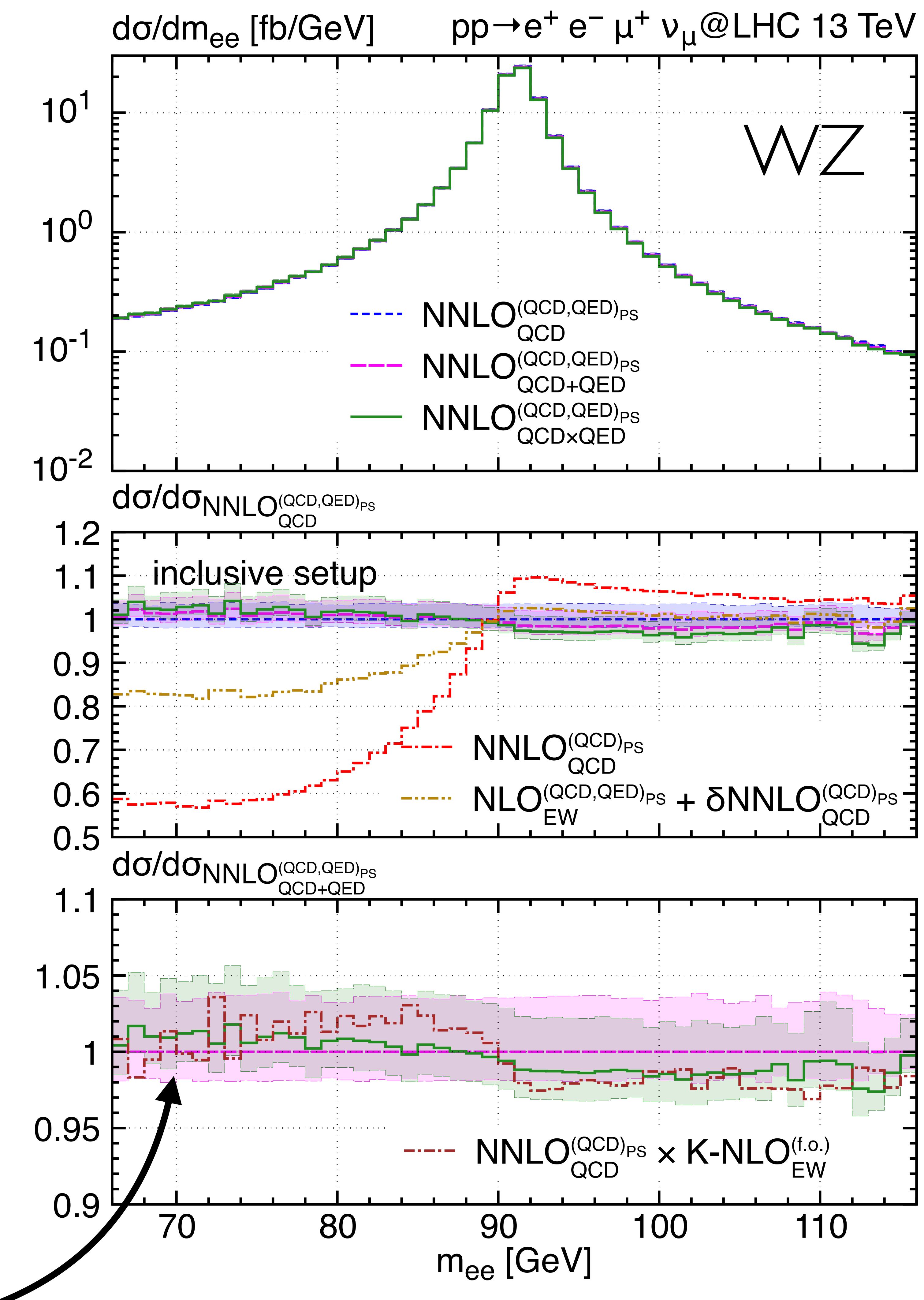
multi-photon radiation (YFS)
or
QED-PS

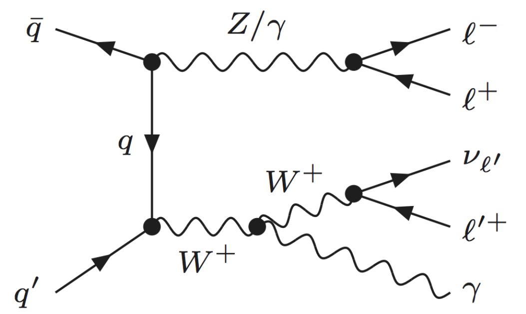
$$\boxed{\Delta_{\rm EW}^{\rm QED} = |\delta_{\rm EW} - \delta_{\rm EW+PS/YFS}|}$$

[Gütschow, Schönherr, '20]



[JML, Lombardi, Wiesemann, Zanderighi, Zanoli, '22]



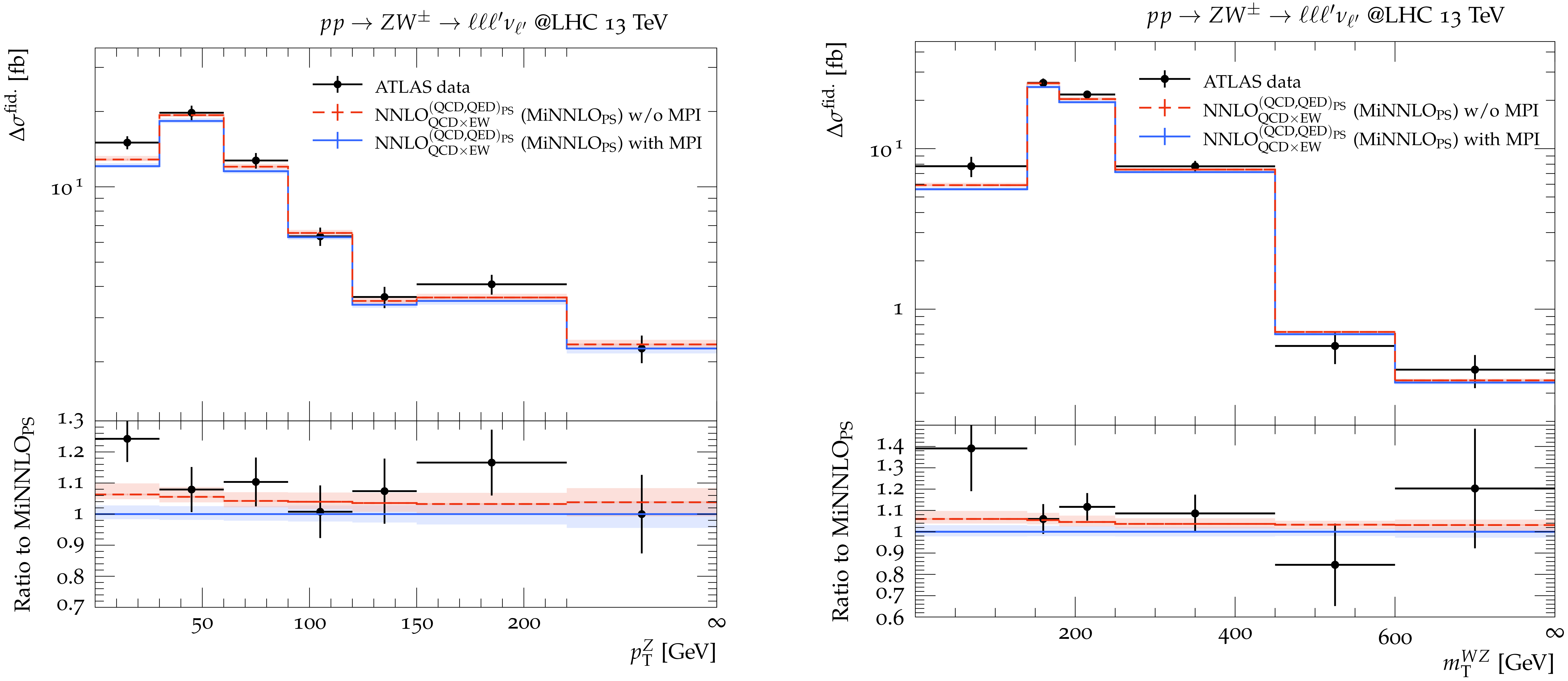


[Talk by S. Zanoli]

# MiNNLOPS QCD + NLOPS EW

*[JML, Lombardi, Wiesemann, Zanderighi, Zanoli, '22]*

for NLOPS QCD + EW also *[Chiesa, Re, Oleari '20]*



*[JML, Lombardi, Wiesemann, Zanderighi, Zanoli, '22]*

- Percent level precision in MiNNLOPS QCD + NLOPS EW predictions

# Mixed QCD-EW uncertainties

Bold estimate:

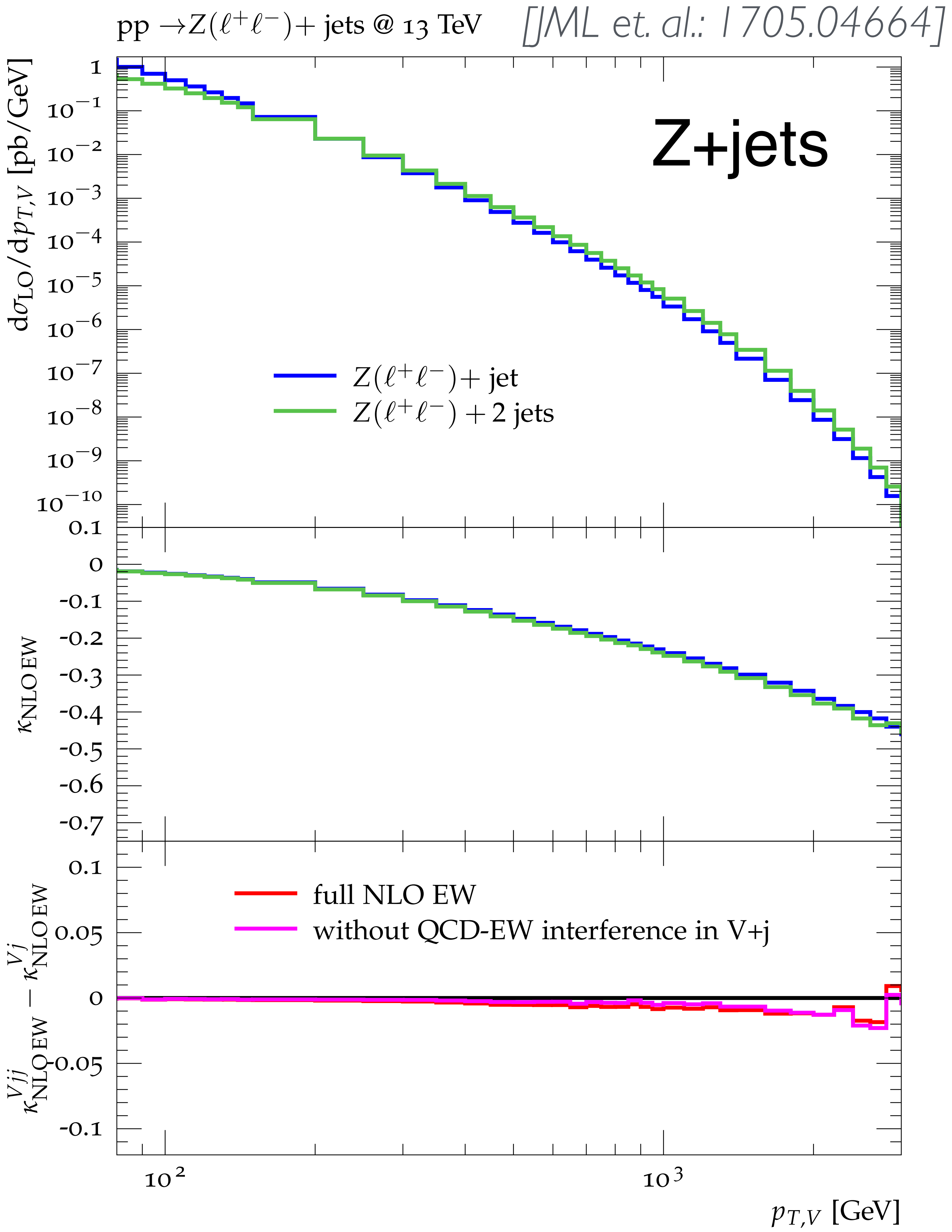
Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to X production $\simeq$ NLO EW to X+1jets

and we often observe

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

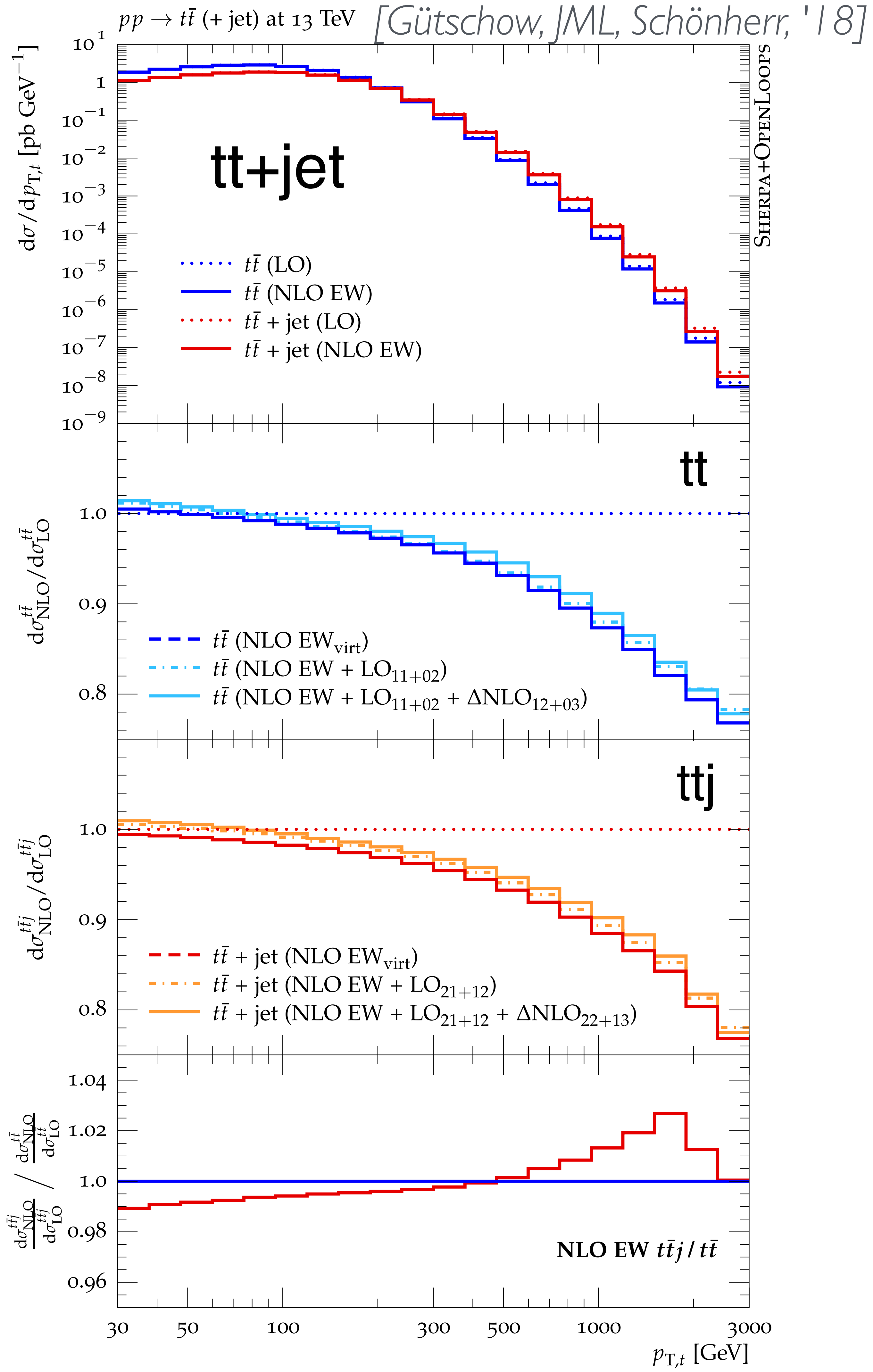
In these cases strong support for
- factorisation
- multiplicative QCD x EW combination
- Consider only such non-factorising effects as uncertainty!?

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



[JML et. al.: 1705.04664]

$pT_{j,2} > 30$ GeV



[Gütschow, JML, Schönherr, '18]

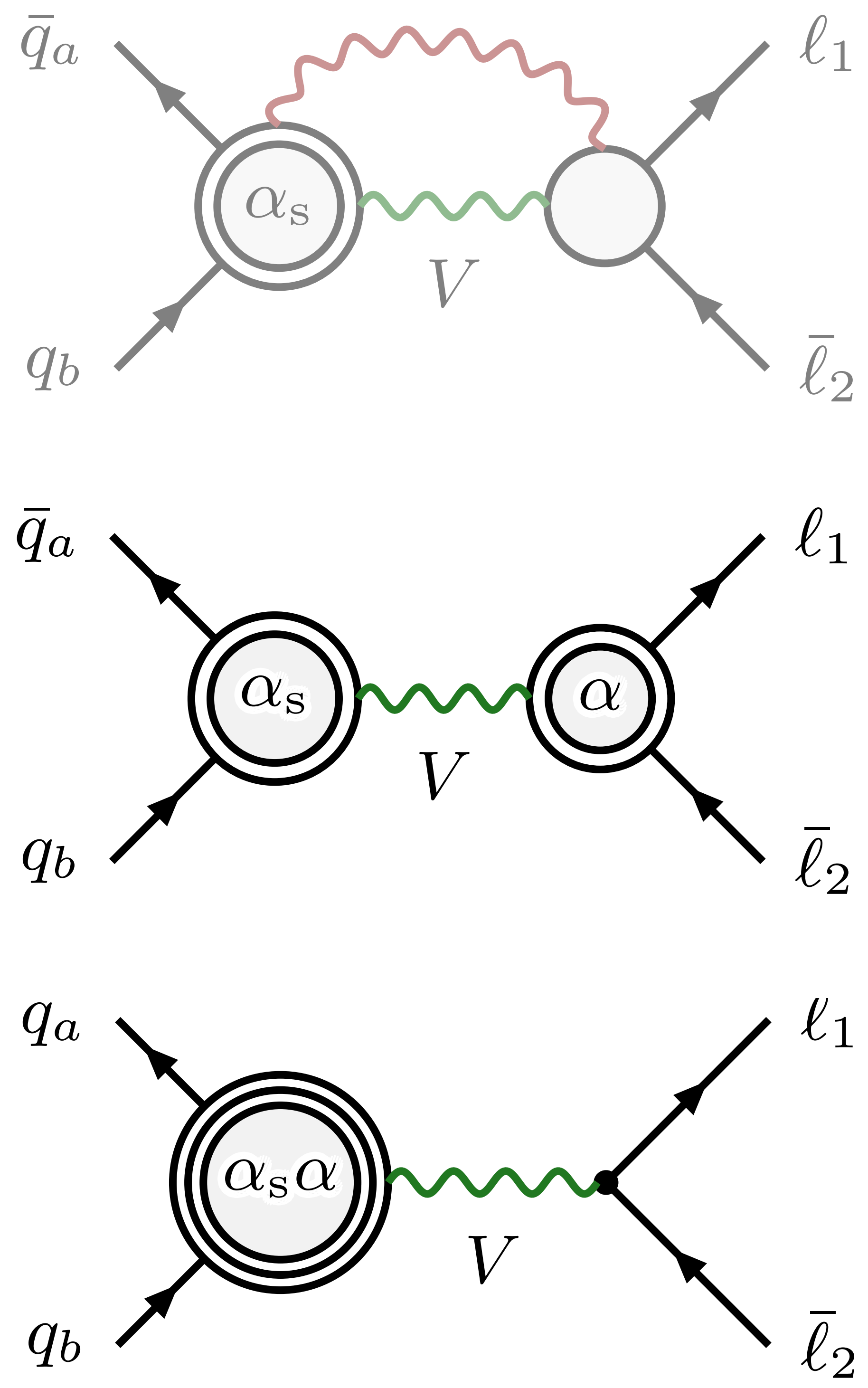
$pT_j > 30$ GeV

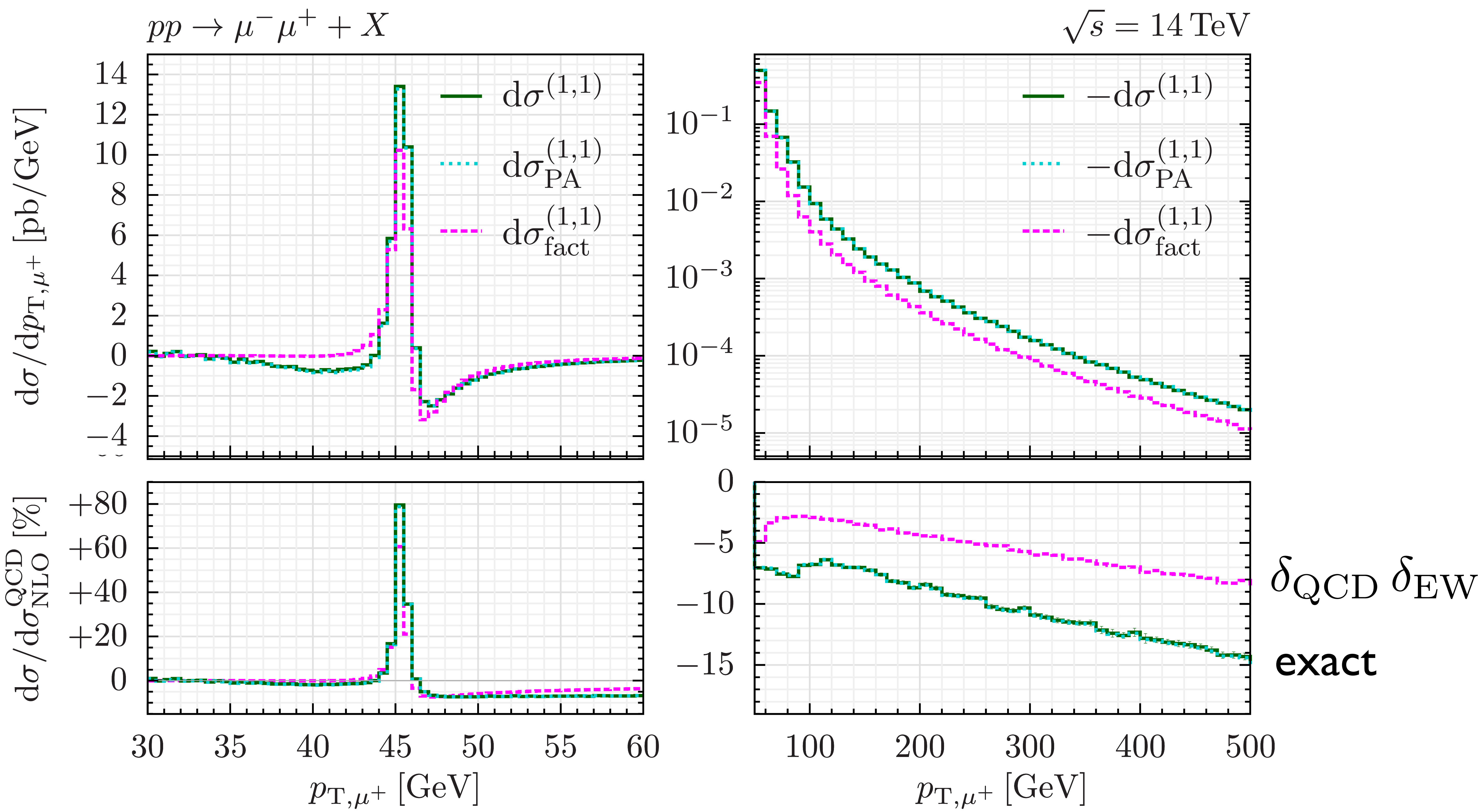
# Exact mixed QCD-EW for DY

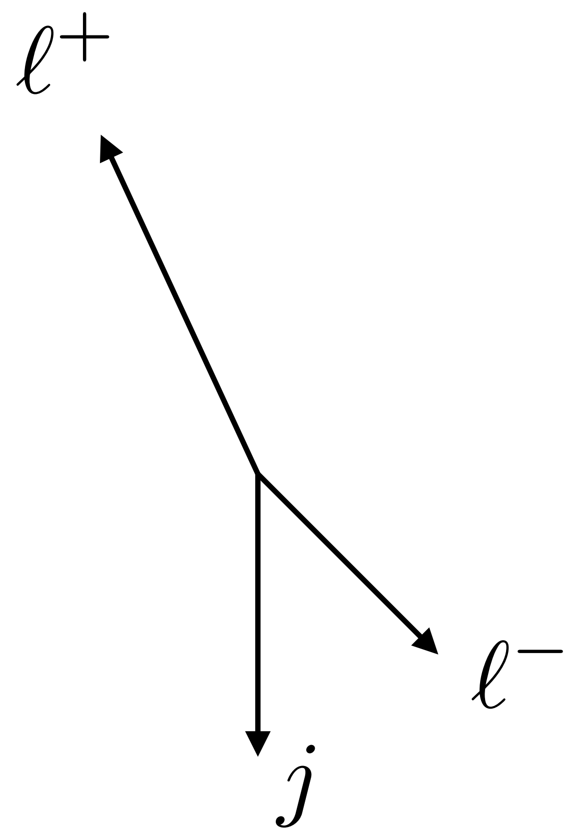
*[Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch, '20]*

*[Behring, Buccioni, Caola, et. al. '20]*

*[Bonciani, Buonocore, Grazzini, Kallweit et. al.  2 x '21]*



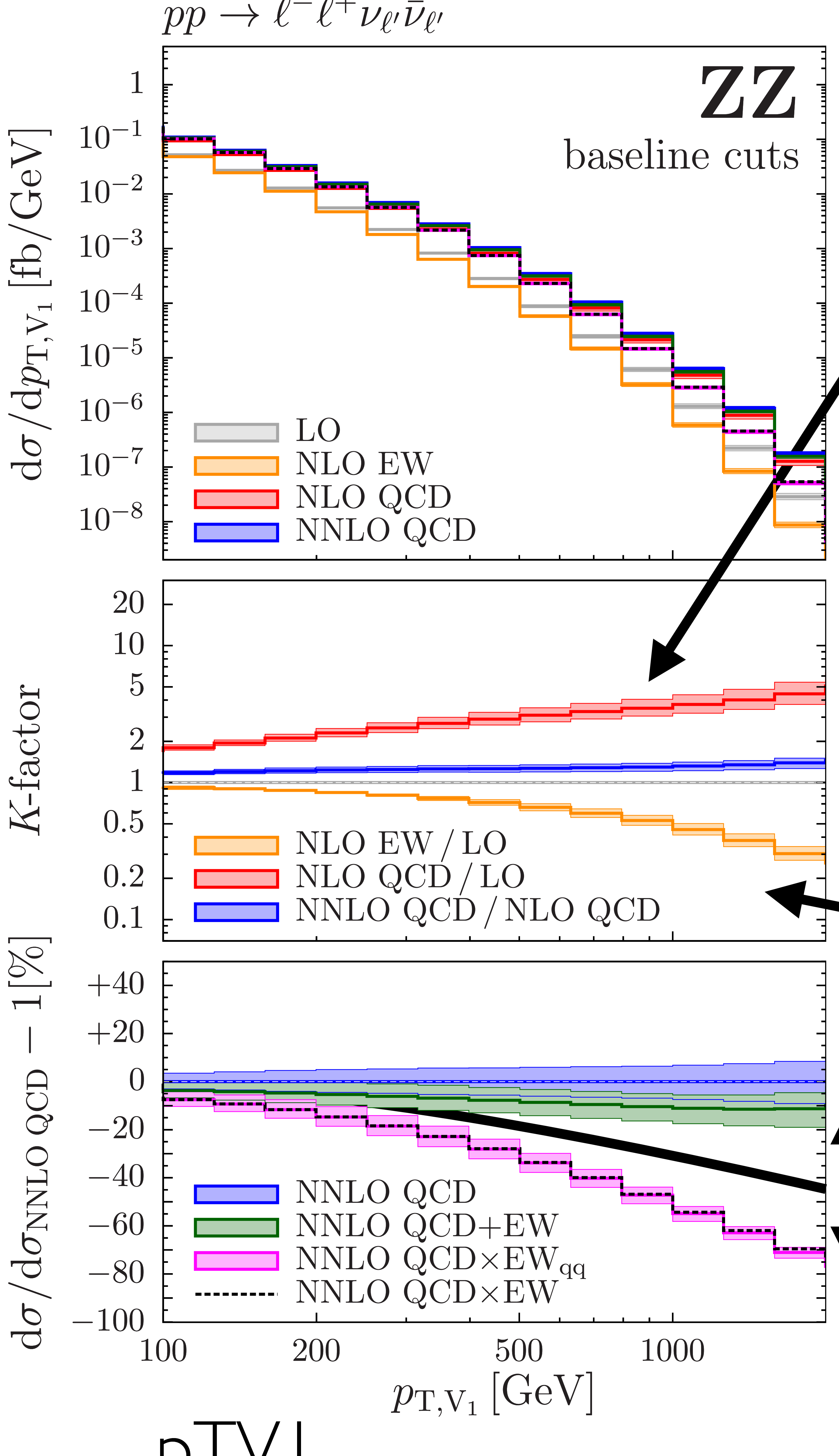




- pole approximation vs. full computation: agree below the percent level
- Comparison against naive factorised NLO QCD x NLO EW ansatz: fail at the 5-10% level
- At large $p_{T,\mu^+}$ in DY: sizeable contributions from $pp \to Vj$ which receives larger EW corrections

# Mixed QCD-EW uncertainties

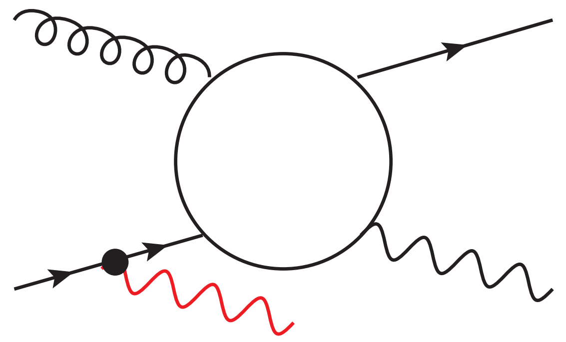
*[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; '19]*



pTV1

- NLO QCD/LO=2-5! ("giant K-factor")

- 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 $d\sigma_{\mathrm{NNLO\,QCD+EW}}$ vs. $d\sigma_{\mathrm{NNLO\,QCD\times EW}}$
- 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 I: **take average as nominal and spread as uncertainty**
- Pragmatic solution II: **apply jet veto to constrain Vj toplogoies**

# MEPS @ NLO QCD + EW

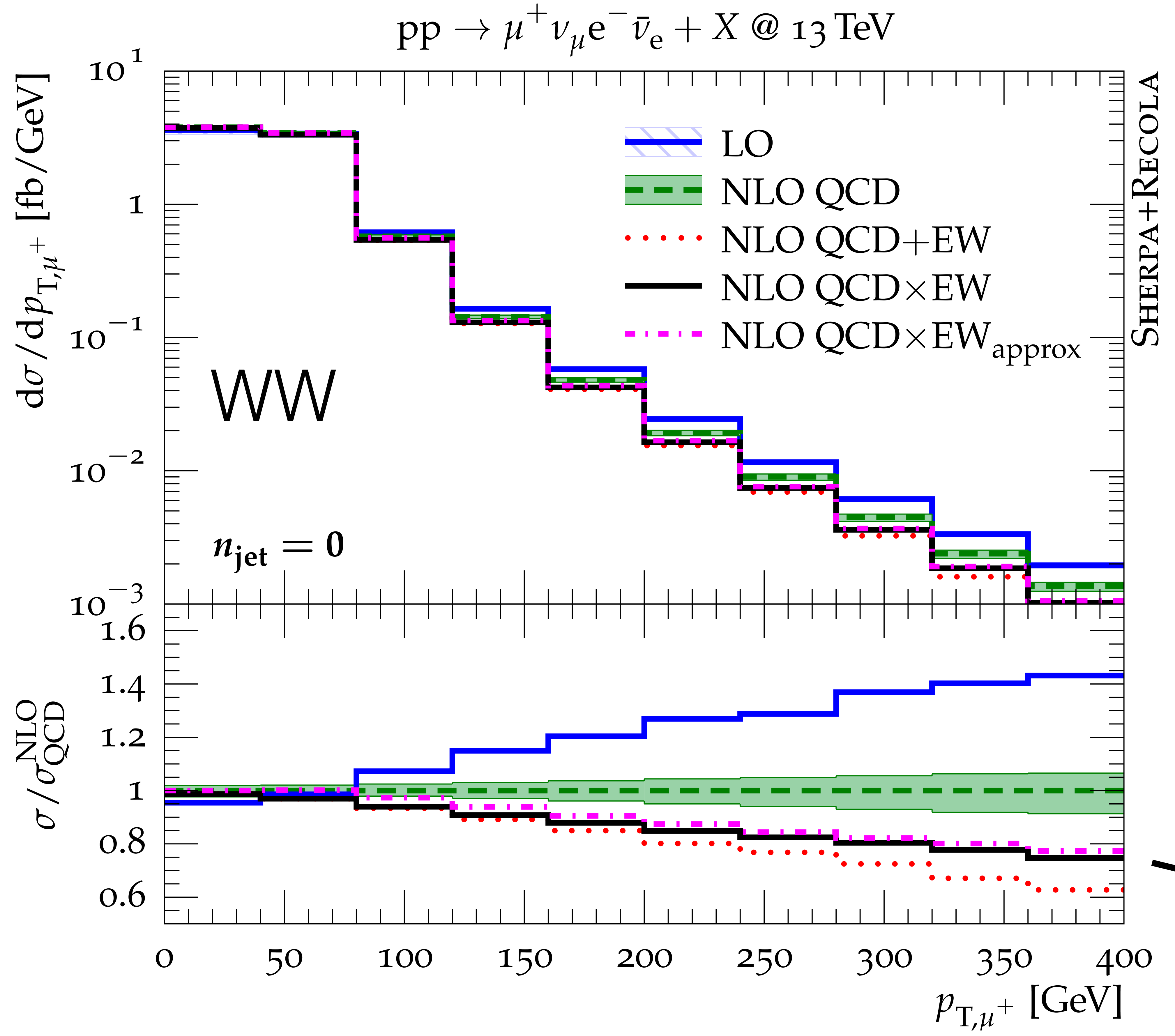
WW(+jet): [Bräuer, Denner, Pellen, Schönherr, Schumann; '20]
ZZ(+jet): [Bothmann, Napoletano, Schönherr, Schumann, Villani; '21]

Used in many ATLAS modern multi-purpose samples: V+jets, VV+jets, tt+jets

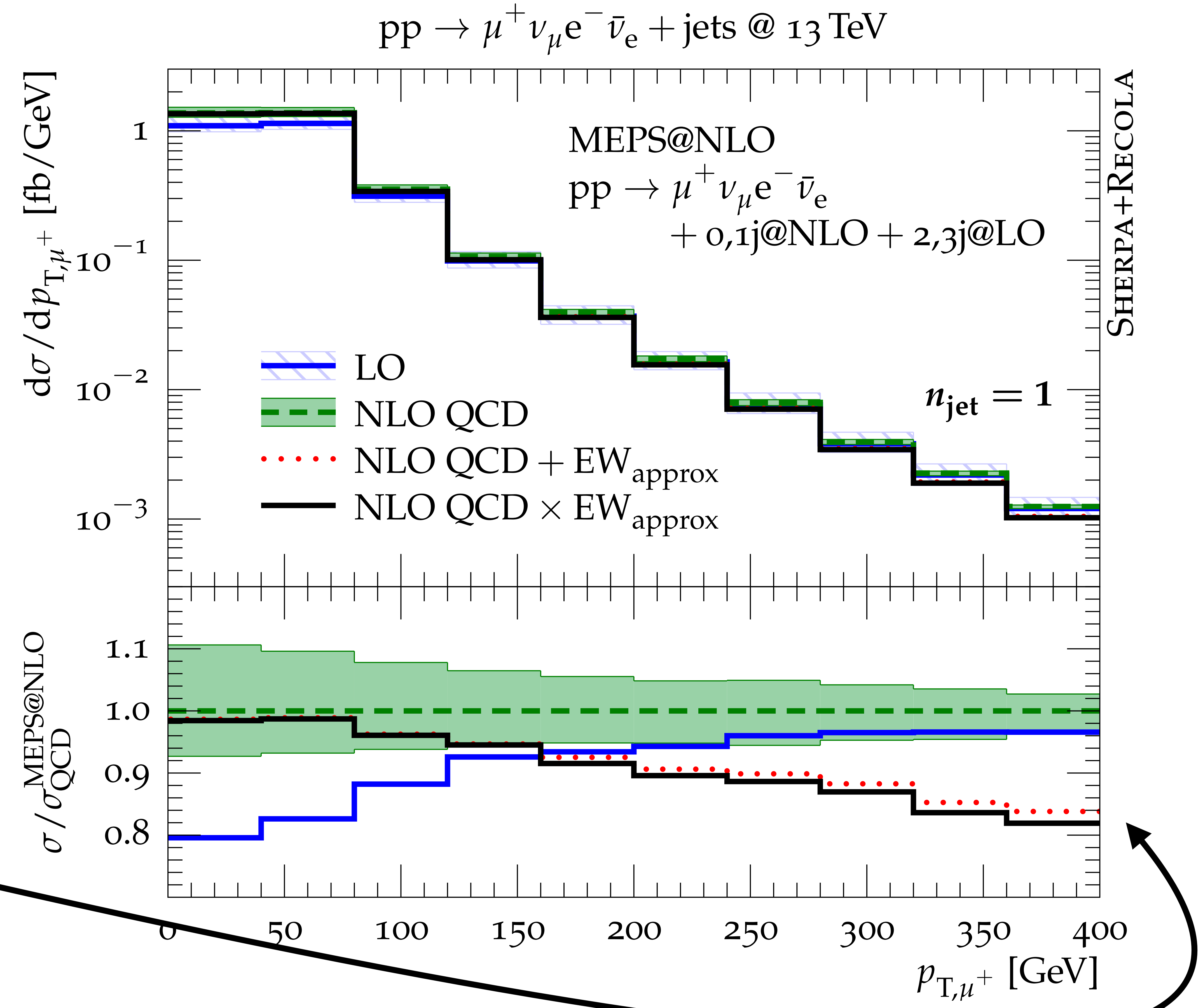
*[Kallweit, JML, et. al.; '15]*

- More rigorous solution: merge VVj incl. approx. EW corrections with VV with Sherpa's MEPS@NLO QCD + EWvirt

## FO



## MEPS@NLO QCD + EWvirt

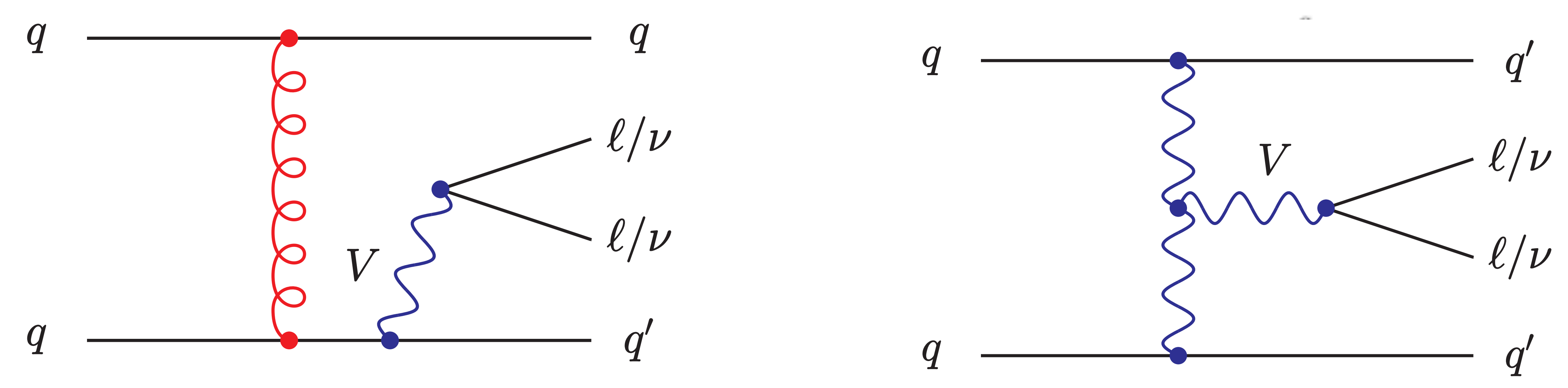


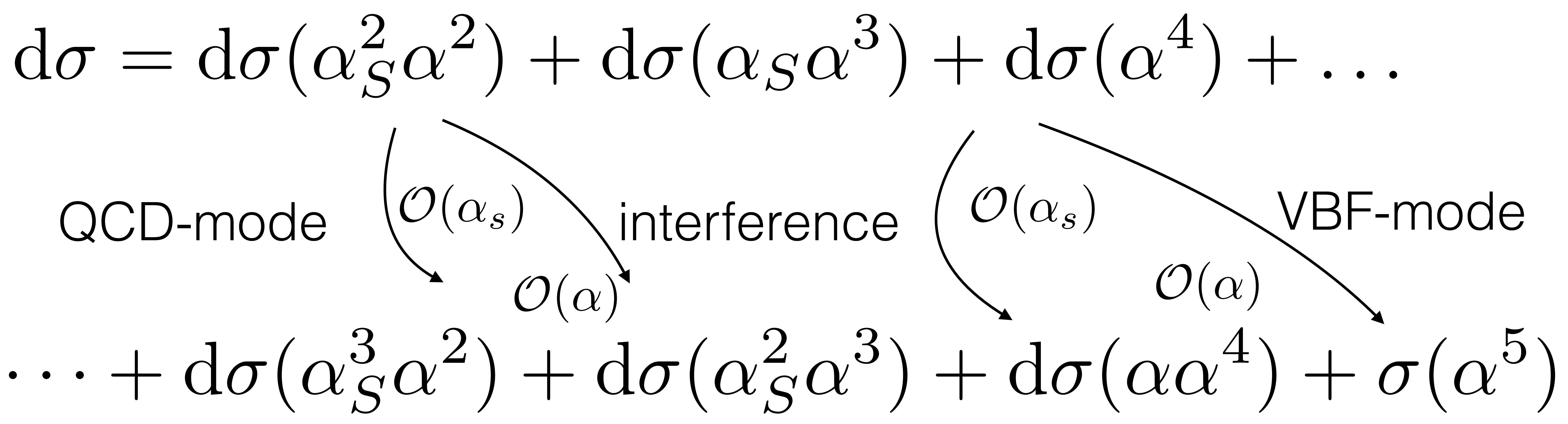
# Perturbative expansion: tower of contributions

[see also:
Talk by G. Pelliccioli]

- For processes with at least 4-quarks there is a tower of LO(NLO) contributions.
- E.g.: multijets, $t\bar{t} + X$,V+jets (VBF-V),VV+jets (VBS-VV),

V+2 jets:





$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_S^2\alpha^2) + \mathrm{d}\sigma(\alpha_S\alpha^3) + \mathrm{d}\sigma(\alpha^4) + \ldots$$

LO

QCD-mode $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ interference $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ VBF-mode

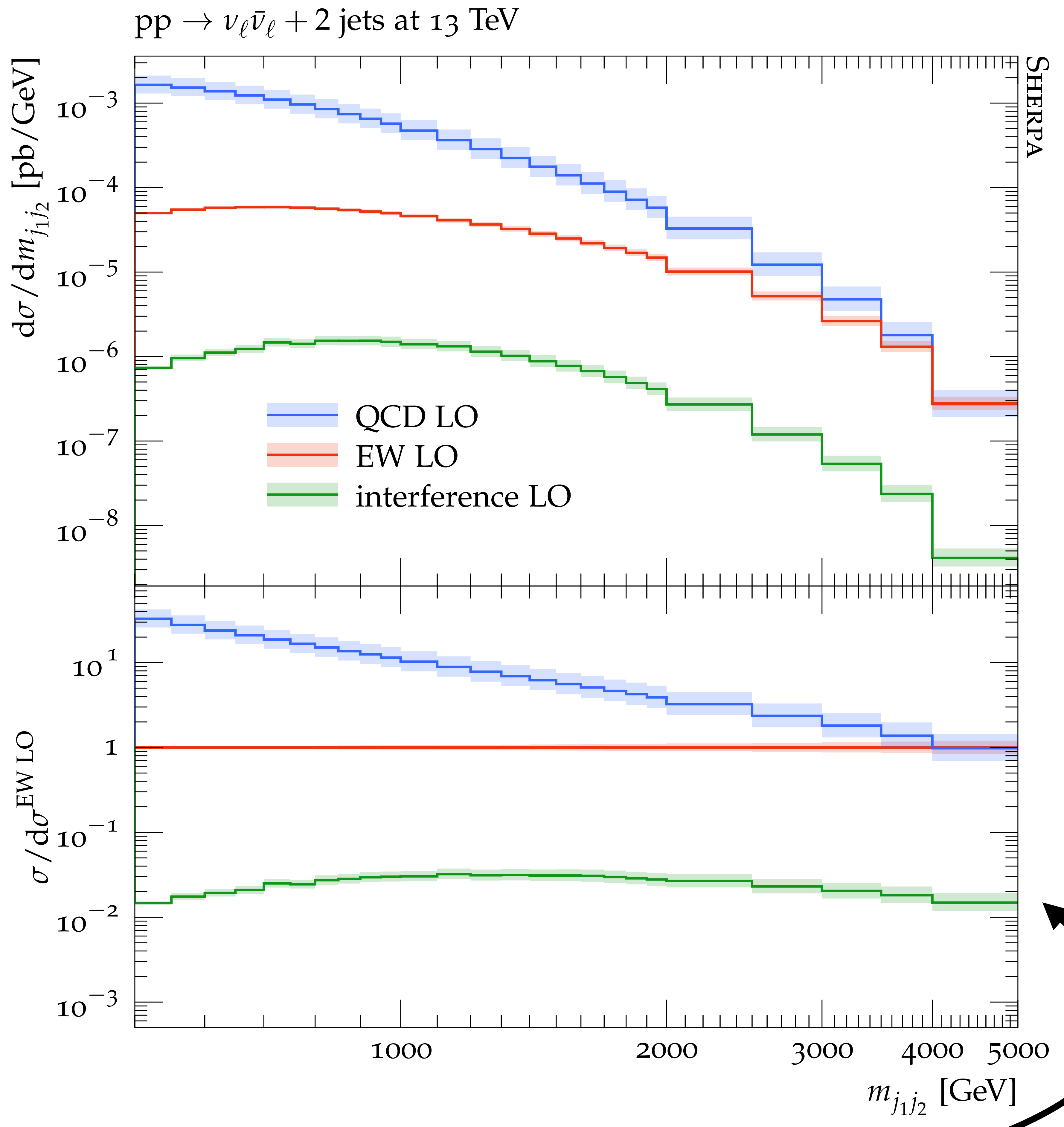
$$\cdots + \mathrm{d}\sigma(\alpha_S^3\alpha^2) + \mathrm{d}\sigma(\alpha_S^2\alpha^3) + \mathrm{d}\sigma(\alpha\alpha^4) + \sigma(\alpha^5)$$

NLO

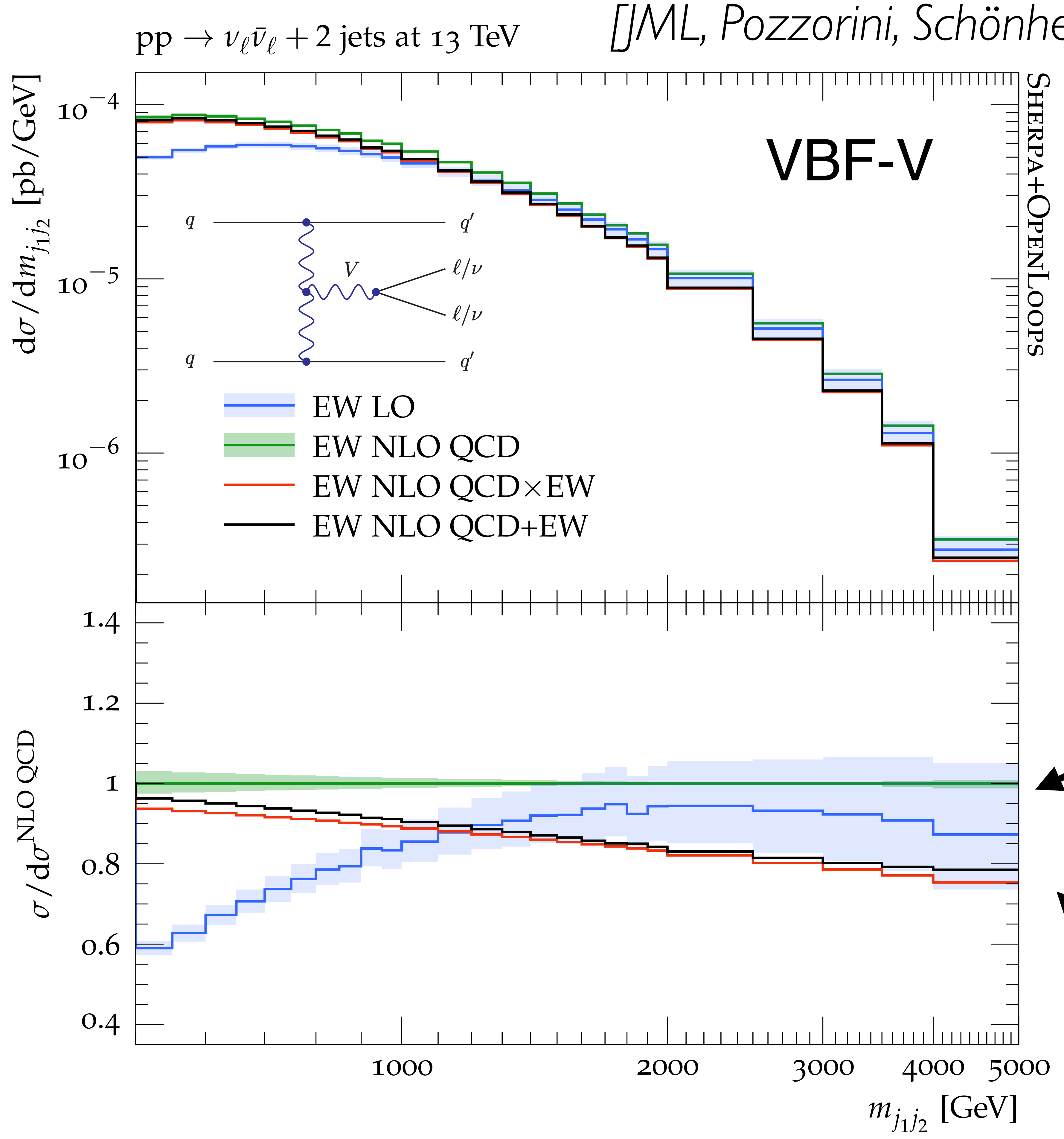
“NLO QCD” “NLO EW” “NLO QCD” “NLO EW”

# VBF-V @ NLO QCD + EW

First complete NLO QCD
vs. VBF-approximation
*[Oleari, Zeppenfeld, '04]*



*[JML, Pozzorini, Schönherr, '22]*

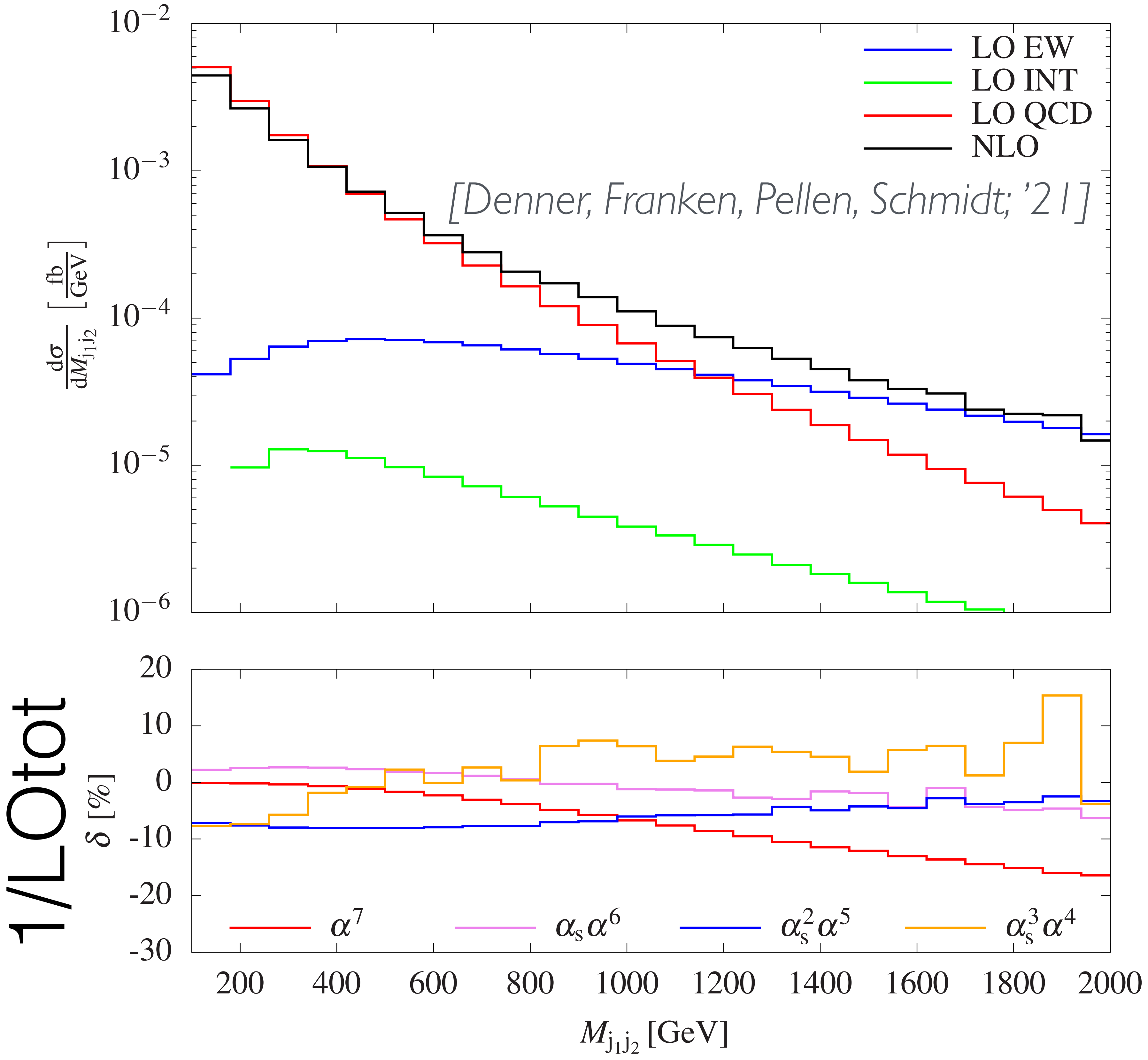


- If LO interference is small: possible to consider QCD and EW production modes as independent and factorise QCD and EW corrections to the respective processes
- Otherwise, still factorise but consider QCD+EW combination as nominal (and QCD×EW as uncertainty)

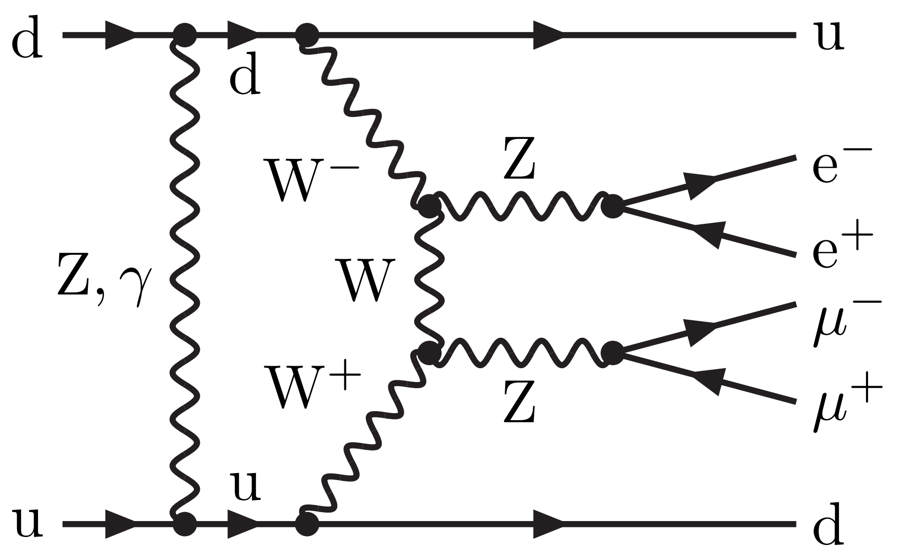
# VBS @ NLO QCD + EW

- QCD and EW **ss-WWjj** at NLO QCD+EW: *[Biedermann, Denner, Pellen '16+'17]*
- EW **WZjj** at NLO QCD+EW: *[Denner, Dittmaier, Maierhöfer, Pellen, Schwan, '19]*
- QCD and EW **ZZjj** at NLO QCD+EW: *[Denner, Franken, Pellen, Schmidt, '20+'21]*
- EW **WWjj** at NLO QCD+EW: *[Denner, Franken, Schmidt, Schwan, '22]*

## EW ZZ+2jets @ NLO QCD + EW



*[Denner, Franken, Pellen, Schmidt; '21]*



- 2 → 6 particles at NLO EW !

| Order | $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)$ | $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)$ | $\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)+\mathcal{O}(\alpha_s\alpha^6)$ |
|---|---|---|---|
| $M_{j_1j_2} > 500\,\text{GeV}$ | | | |
| $\sigma_{\text{NLO}}$[fb] | 0.06069(4) | 0.07375(25) | 0.06077(25) |
| $\delta$[%] | −17.6 | 0.1 | −17.5 |

- In the VBS phase-space EW mode receives:
  - very small QCD corrections (percent level)
  - O(20%) EW corrections

- Always measure also combined QCD-mode + EW-mode fiducial xsections!

[Talk by M. Grazzini]

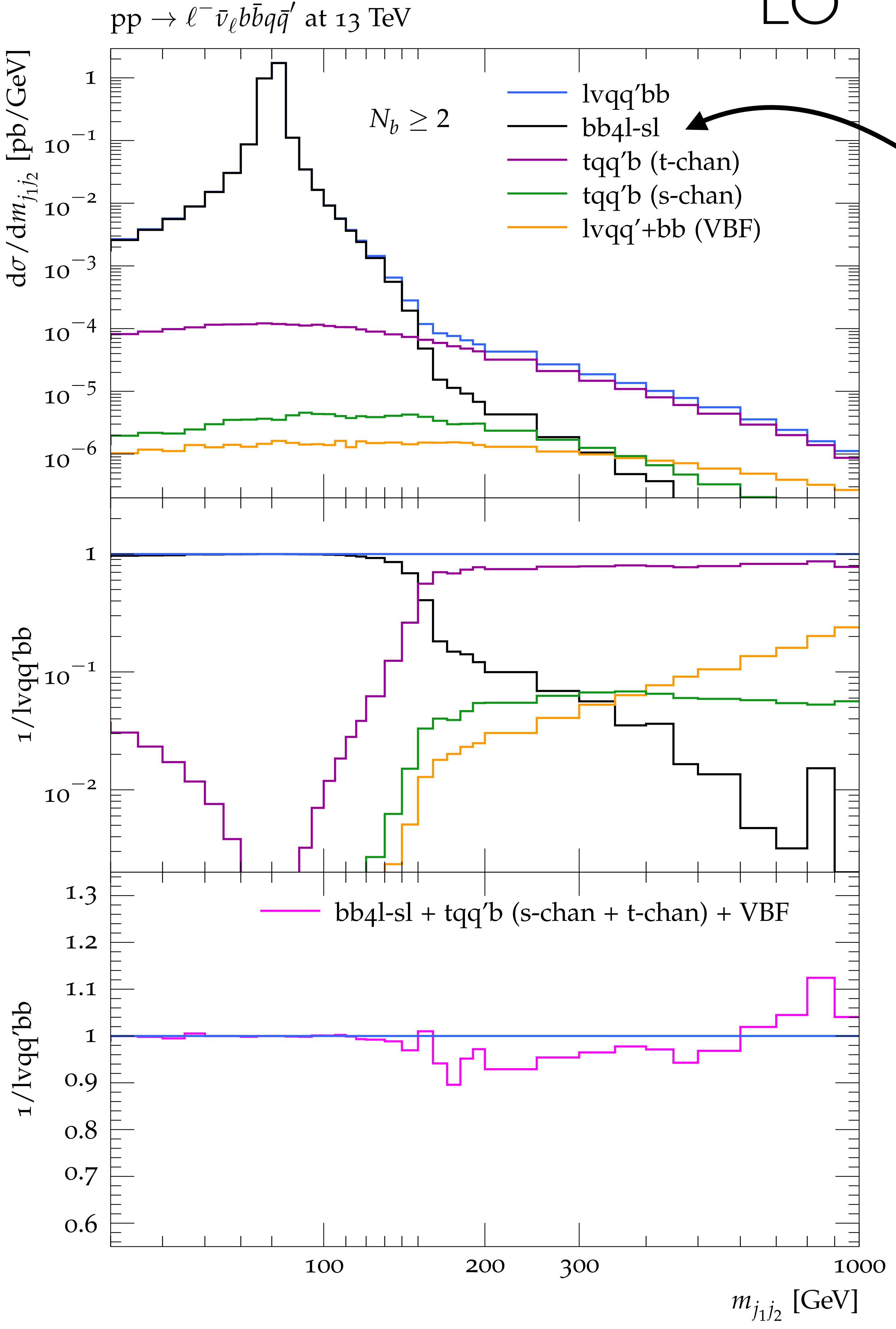
# Off-shell semi-leptonic $t\bar{t}$+decay @ NLOPS

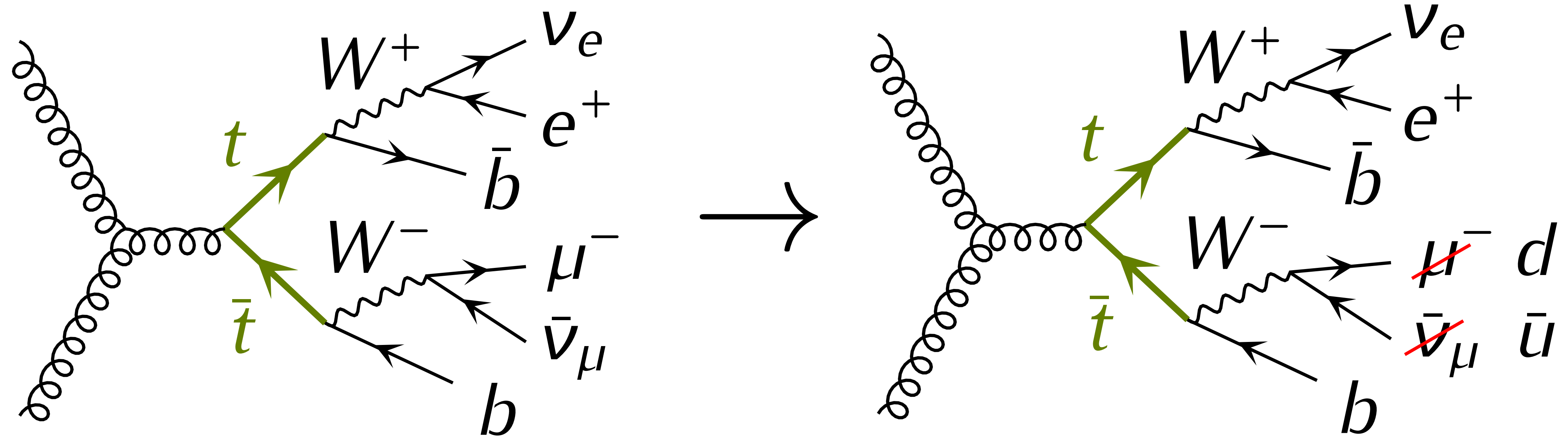
*[Jezo, JML, Pozzorini, to appear]*

POWHEG-BOX-RES
[Jezo, Nason, '15]

$pp \to \ell^{\pm}\nu_\ell j j b\bar{b}$

LO





$$d\sigma^{\mathrm{LO}}(\mathrm{bb4l-sl}) = d\sigma^{\mathrm{LO}}(\mathrm{bb4l-dl})\frac{\mathrm{BR_{SL}}}{\mathrm{BR_{DL}}}$$

- In this approximation we drop some off-shell/interference effects
- But: tt, wt and tt-wt interference is retained!
- POWHEG emission based on allrad approach:

`bb4l`

$$d\sigma = \bar{B}_{\mathtt{bb4l-sl}}(\Phi_{\mathrm{B}})\,d\Phi_{\mathrm{B}} \boxed{\prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\mathrm{ISR}}} \left[\Delta_\alpha^{\mathtt{bb4l}}(q_{\mathrm{cut}}) + \Delta_\alpha^{\mathtt{bb4l}}(k_T^\alpha)\frac{R_\alpha^{\mathtt{bb4l}}(\Phi_\alpha(\Phi_{\mathrm{B}},\Phi_{\mathrm{rad}}^\alpha))}{B^{\mathtt{bb4l}}(\Phi_{\mathrm{B}})}\,d\Phi_{\mathrm{rad}}^\alpha\right]}$$

$$\boxed{\times \left[\Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(q_{\mathrm{cut}}) + \Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(k_T^{\alpha_W})\frac{R_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_{\alpha_W}(\Phi_{\mathrm{B}},\Phi_{\mathrm{rad}}^{\alpha_W}))}{B^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_{\mathrm{B}})}\,d\Phi_{\mathrm{rad}}^{\alpha_W}\right]}$$

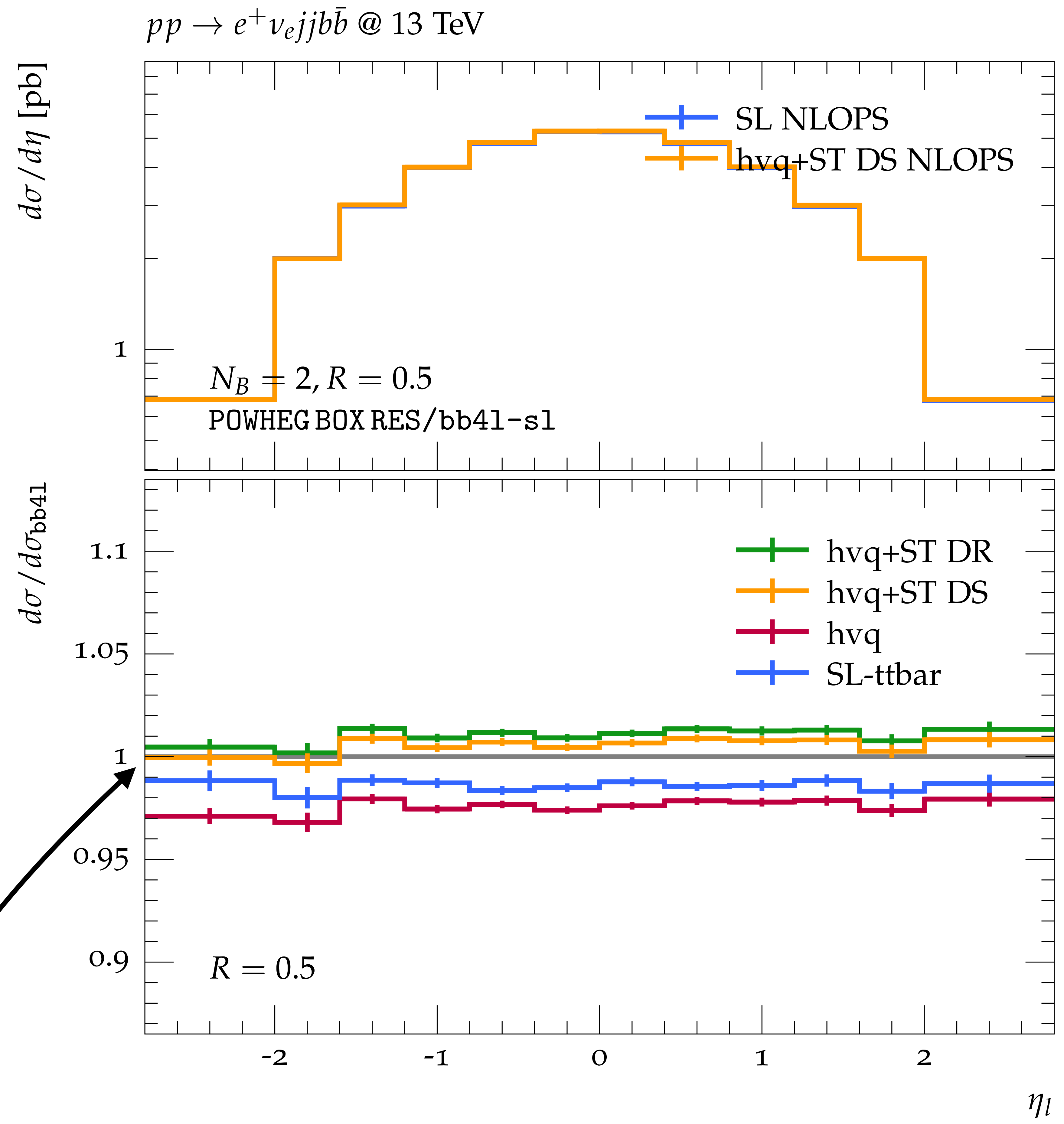
emission from $W^-$ or $W^-$

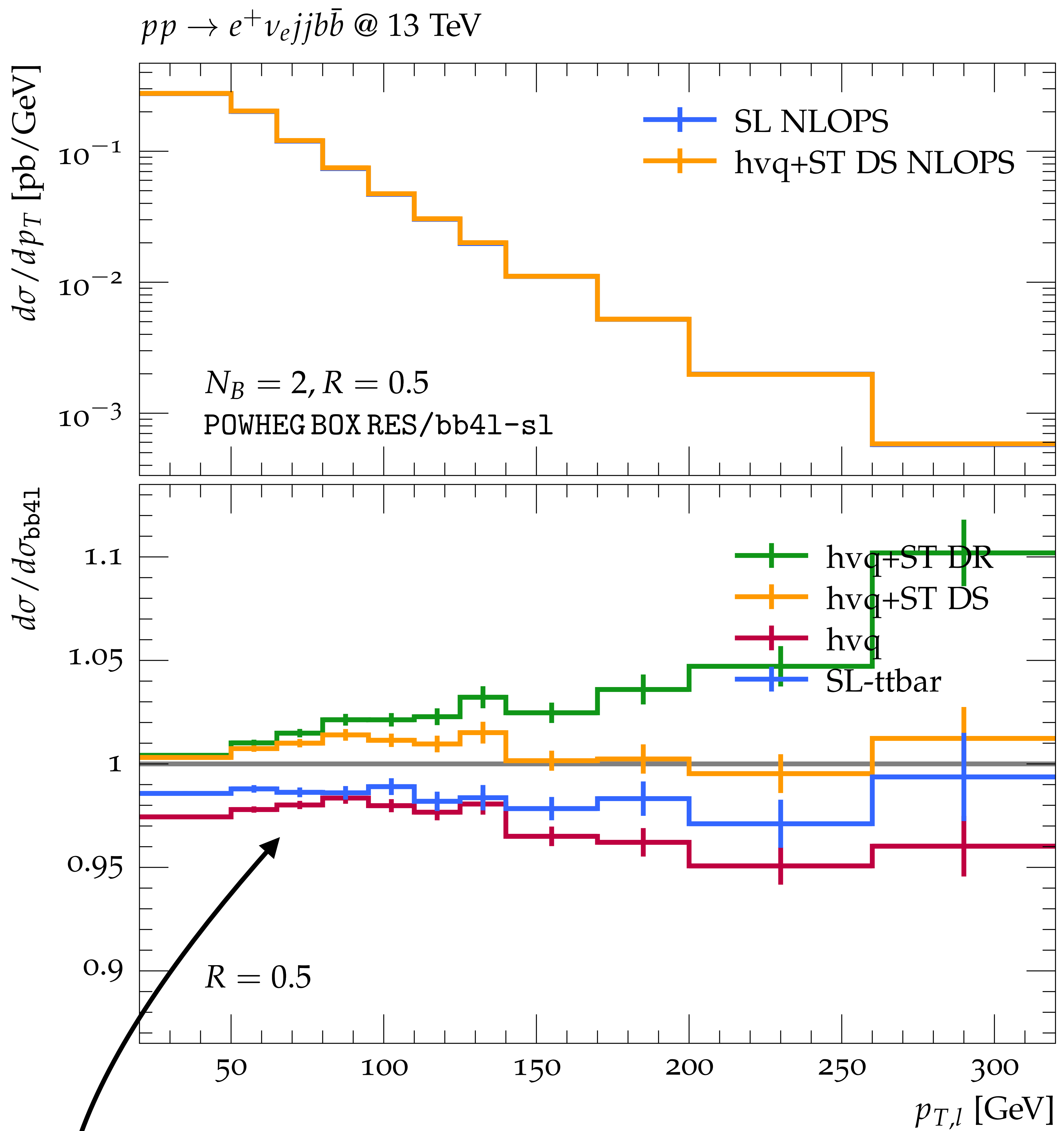
- Note: can also be used for full hadronic decays!

[Talk by M. Grazzini]

# bb4l-sl vs. on-shell $t\bar{t} + tW$ with decays

*[Jezo, JML, Pozzorini, to appear]*





- Percent-level agreement between bb4l and hvq+ST!
- O(1%) difference: tt-Wt interference + genuine off-shell

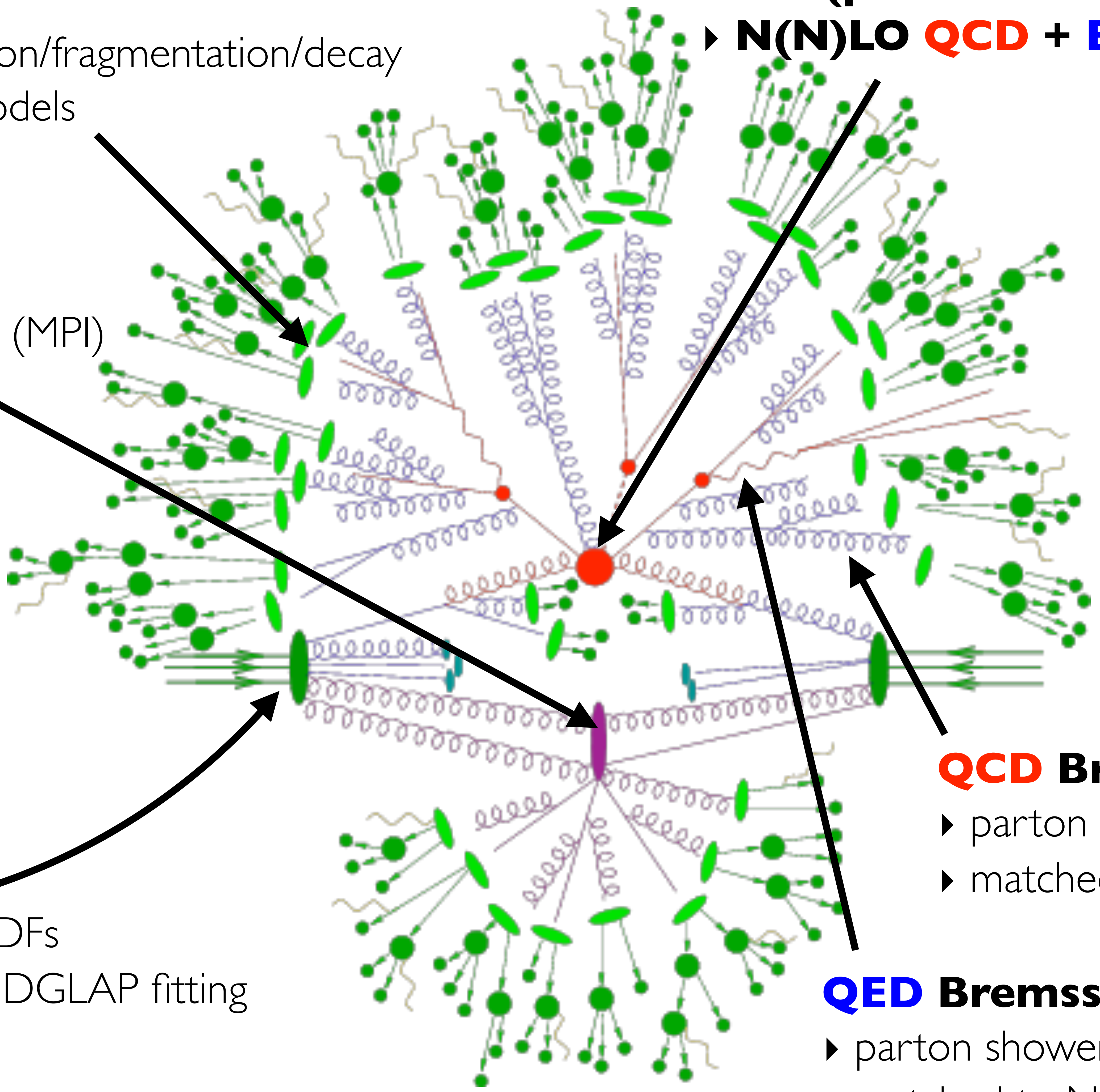
- Large differences between $tW$-DR and $tW$-DS e.g. in the tail of pTl
- bb4l agrees at O(1%) with $tW$-DS
- Thanks to new ME-based resonance-histories: $t\bar{t}$ fraction in bb4l

# Conclusions

- Precision is key for EW measurements,
  as well as for searches.
- EW corrections become large at the TeV scale
- Convincing progress in many directions:
  - ✓EW Sudakov logs
  - ✓QCD-EW
  - ✓(N)NLOPS QCD+EW
  - ✓Multi particle processes: 2 → 5/6/7
  - ✓Off-shell semi-leptonic $t\bar{t}$ @ NLOPS-RES
- Let's push the SM precision frontier!

# Backup

# Theoretical Predictions for the LHC



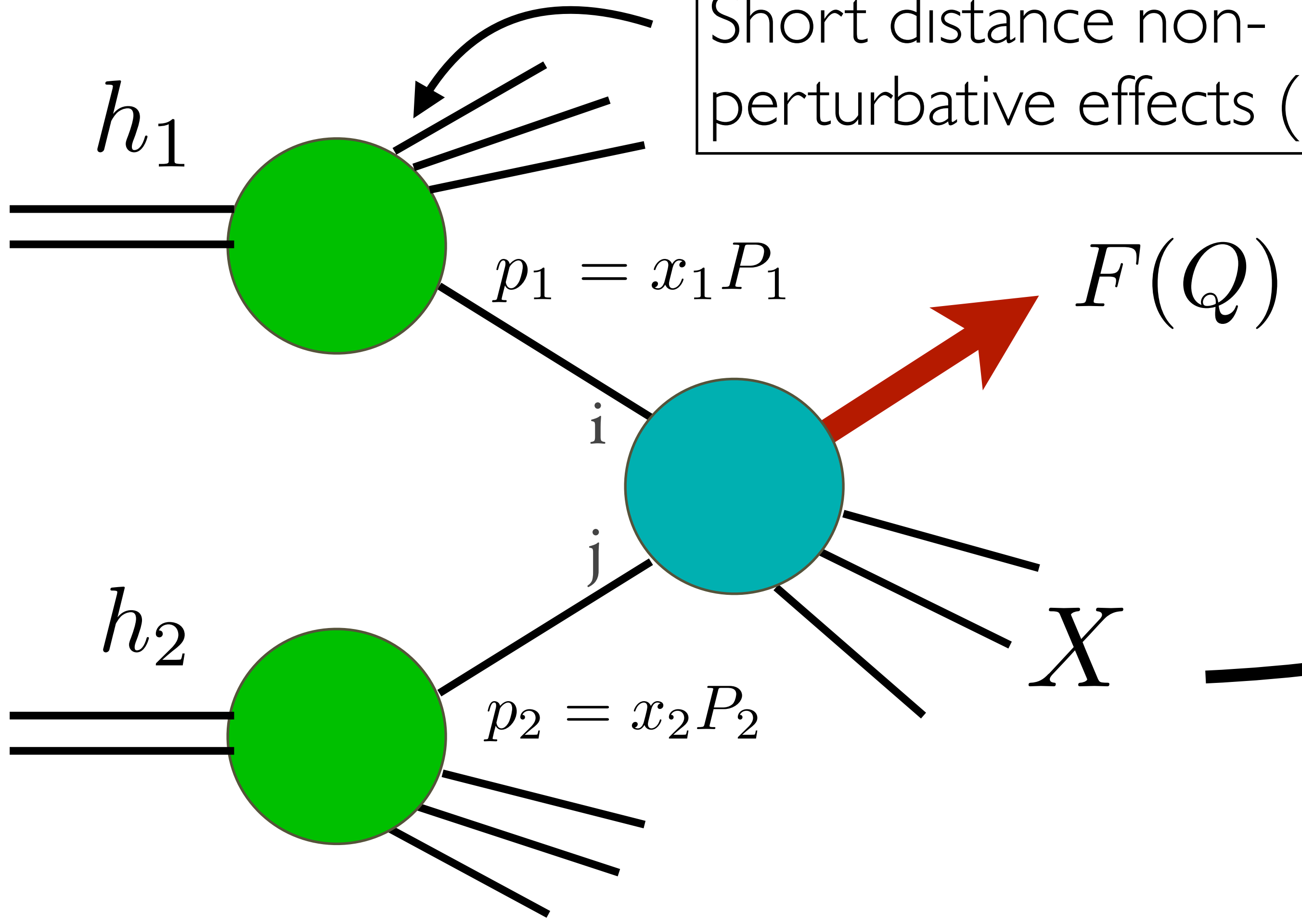
**Hard (perturbative) scattering process**
- **N(N)LO QCD + EW**

Hadronization/fragmentation/decay
- pheno models

Multi Particle Interactions (MPI)
- pheno model

Key: QCD factorization:

Short distance non-perturbative effects (PDFs)



PDFs
- DGLAP fitting

**QCD Bremsstrahlung**
- parton shower
- matched to NLO matrix elements

**QED Bremsstrahlung**
- parton shower
- matched to NLO matrix elements

$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

# EW standard candles at hadron colliders

**Precision EW**

- DY
  - N3LO QCD
  - +NLO EW
  - +NNLO QCD-EW
- V+jets
  - NNLO QCD
  - +NLO EW
- VV
  - NNLO QCD
  - +NLO EW
- VBF-V
  - NLO QCD
  - +NLO EW

**Top**

- $t\bar{t}$
  - NNLO QCD
  - +NLO EW
- single-$t$
  - N(N)LO QCD
  - +NLO EW
- $t\bar{t} + X$
  - N(N)LO QCD
  - +NLO EW

**Rare processes**

- VBS
  - NLO QCD
  - +NLO EW
- VVV
  - NLO QCD
  - +NLO EW
- ….

**Higgs**

- Inclusive
  - N3LO QCD
  - +NLO EW
- H+jet
  - NLO QCD
  - +(N)LO EW
- VH/VBF
  - NNLO QCD
  - +NLO EW
- HH
  - NLO QCD
  - +(N)LO EW

# Perturbative expansion

aMC@NLO, Sherpa, Herwig… & Recola, Madloop, Gosam, OpenLoops

dedicated MC's: Matrix, MCFM, NNLOjet, …

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD    NLO EW

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, \mathrm{d}\sigma_{\mathrm{NNLO\,EW}}{}^{?} + \alpha_S\alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}{}^{?}$$

NNLO QCD    NNLO EW    NNLO QCD-EW

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{N3LO}}{}^{?} + \ \ldots$$

N3LO QCD

scale variation at NNLO

scheme variation, e.g. Gmu vs. a(mZ)

+

in case of EW Sudakov dominance: exponentiation

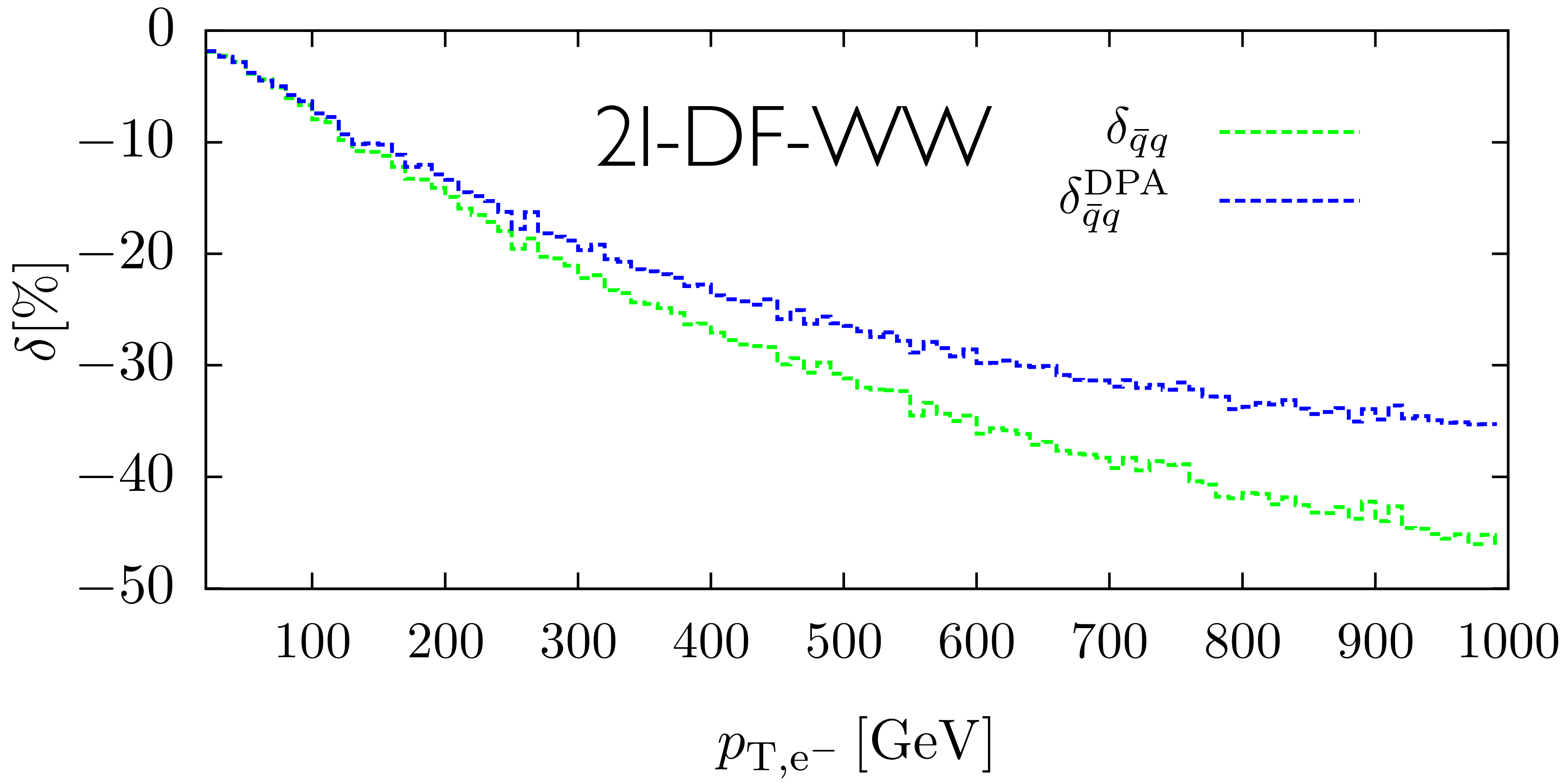
NLO QCD + EW

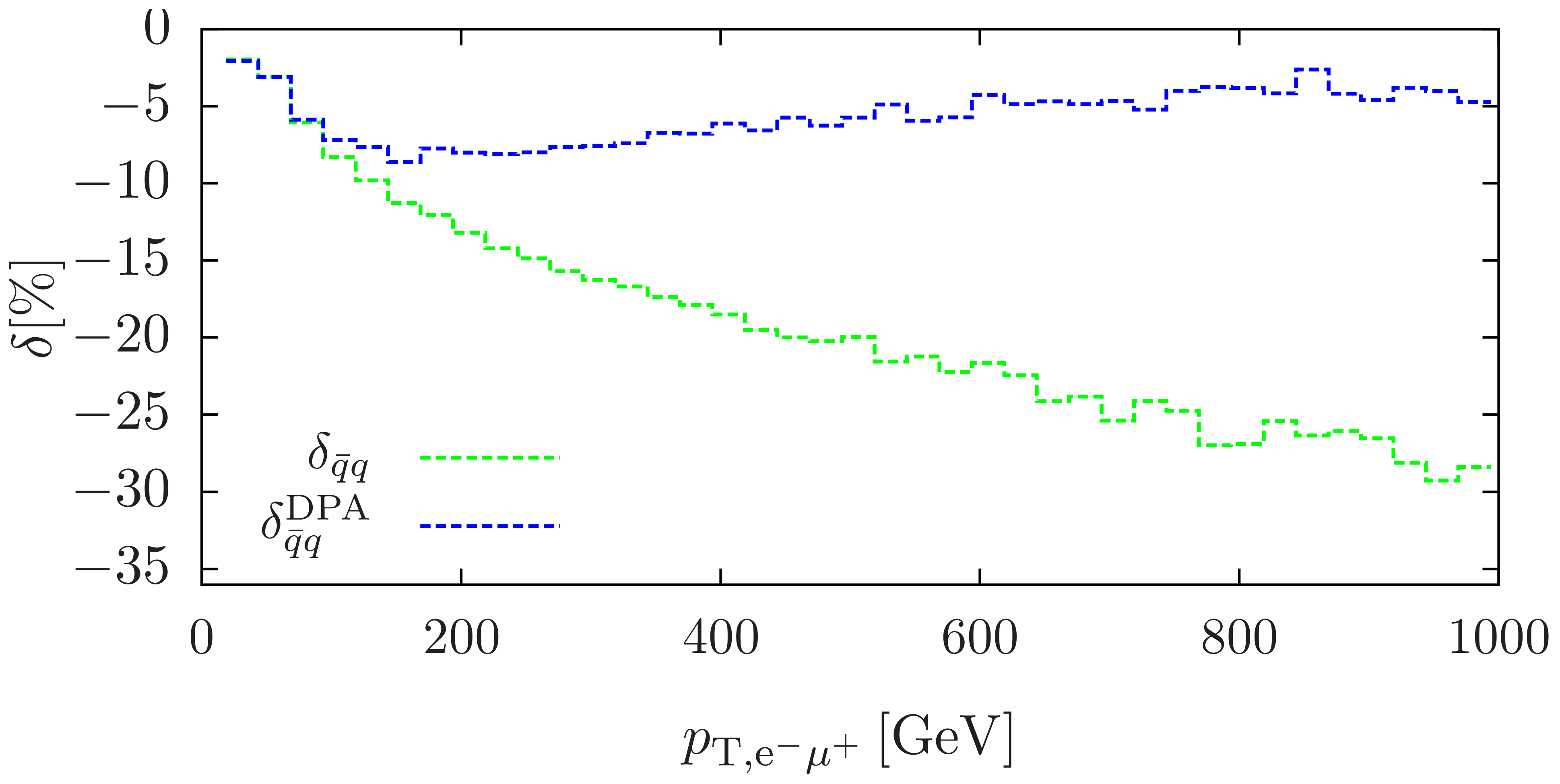
vs.

NLO QCD x EW

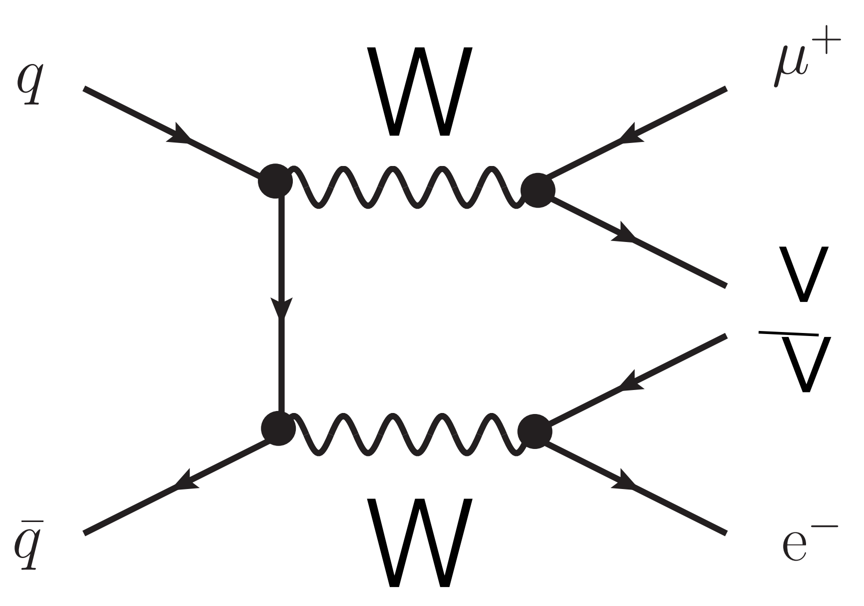
# The need for off-shell computations: VV

*[Biedermann, M. Billoni, A. Denner, S. Dittmaier, L. Hofer, B. Jäger, L. Salfelder ;'16]*

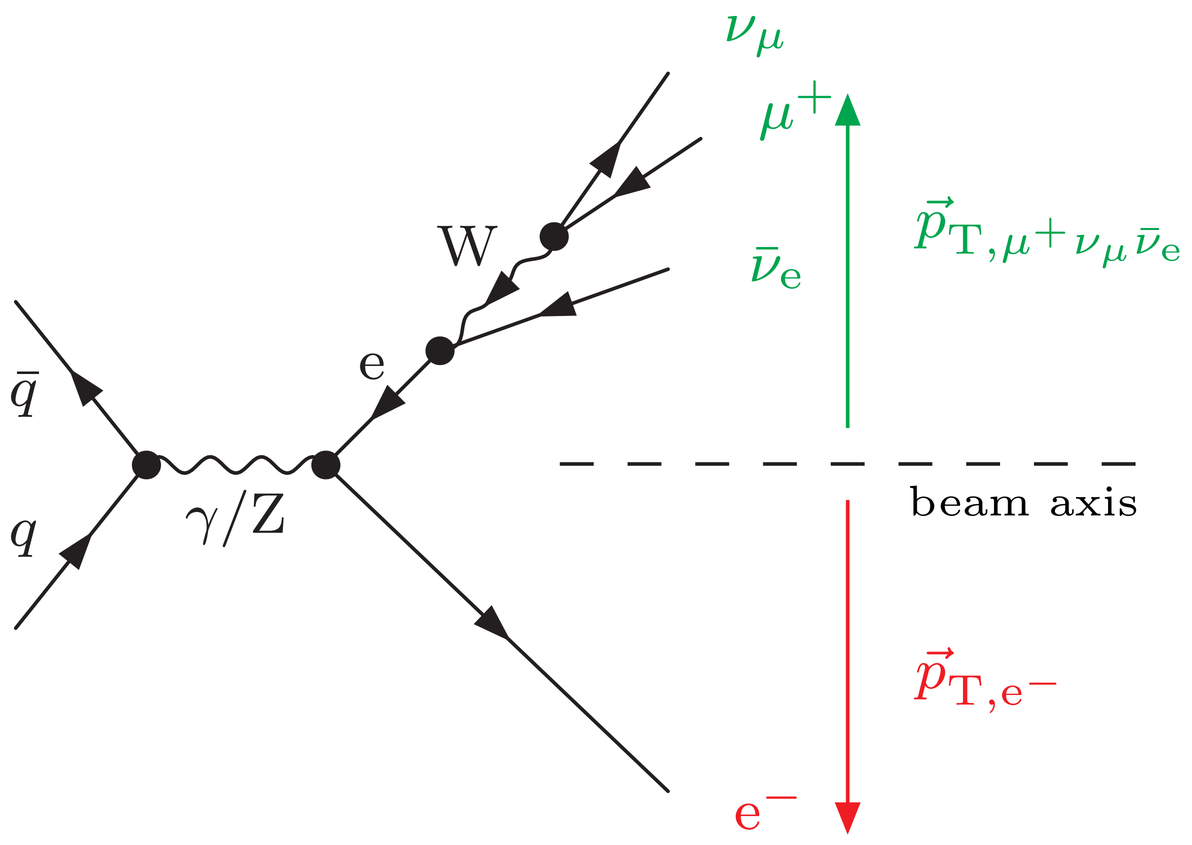




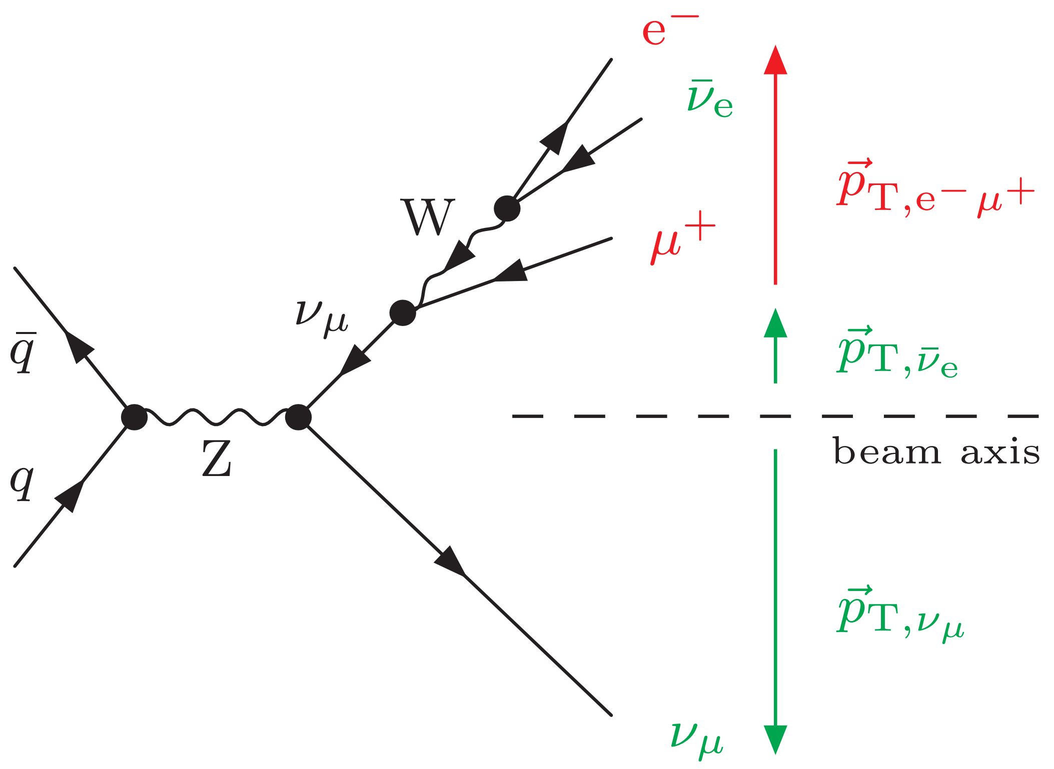
$$pp \to V(\to \ell\bar{\ell})V'(\to \ell'\bar{\ell}')$$



vs.



$$pp \to \ell\bar{\ell}\ell'\bar{\ell}'$$



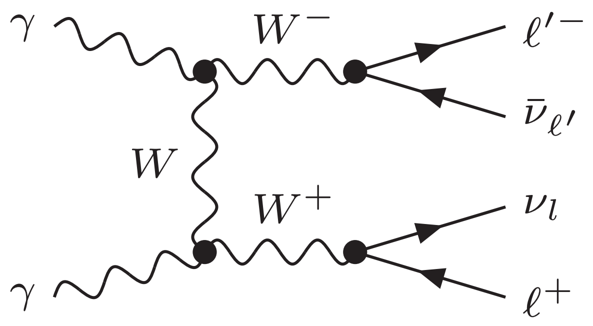
➡ sizeable differences in fully off-shell vs. double-pole approximation in tails

# Relevance of EW higher-order corrections: photon-induced channels

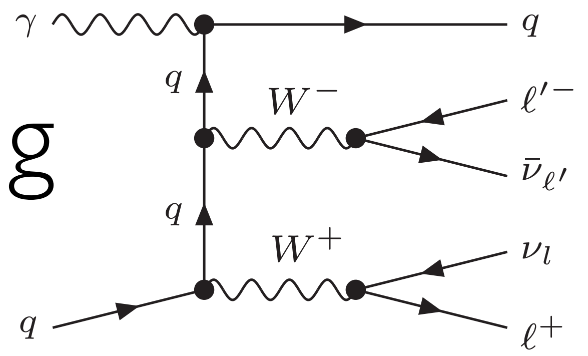
III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

→ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

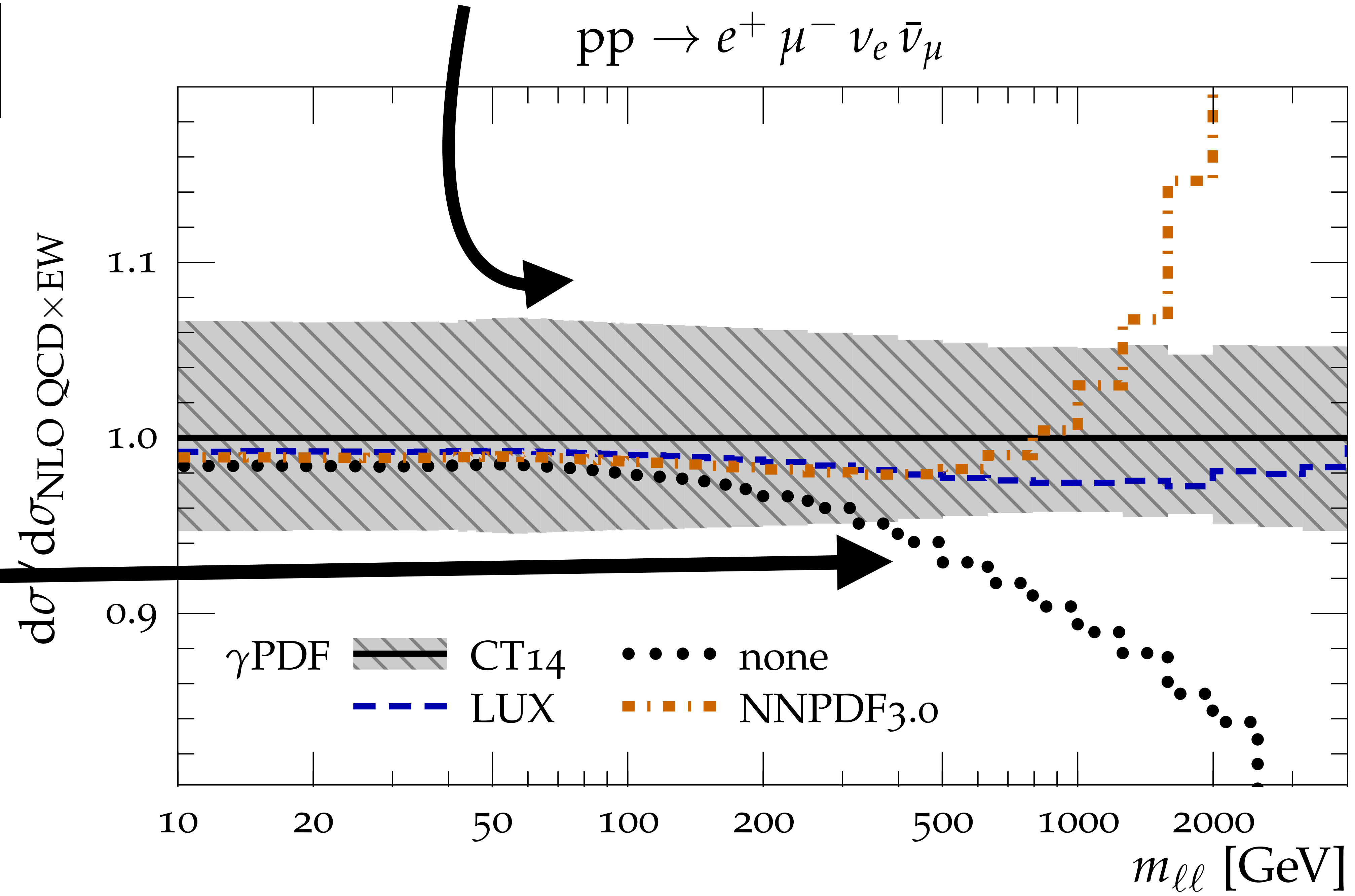
in particular in WW:

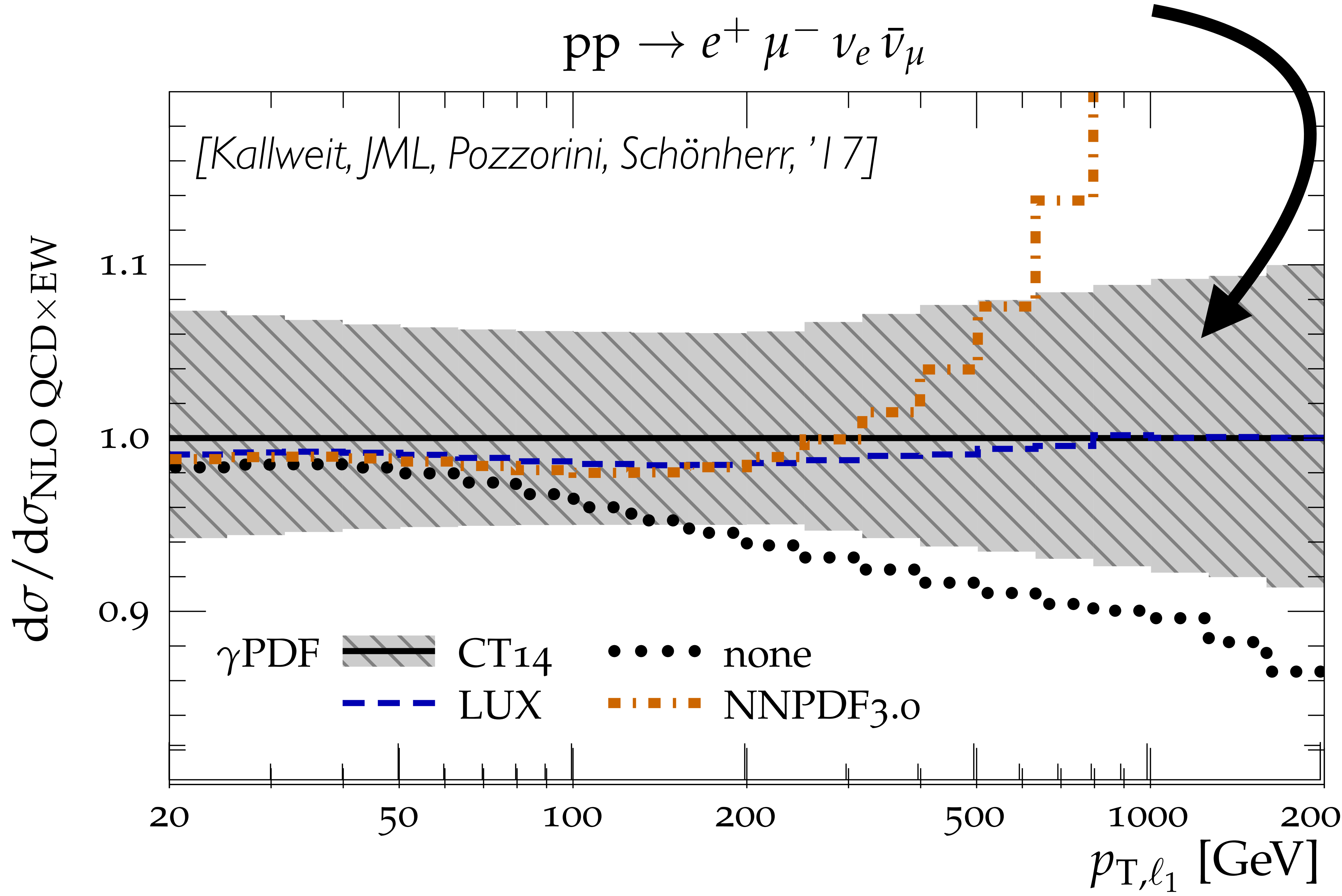


(t-channel enhancement), but also in Bremsstrahlung



$$\boxed{\mathrm{d}\sigma_{\mathrm{LO}} = \mathrm{d}\sigma_{\mathrm{LO}}^{q\bar{q}} + \mathrm{d}\sigma_{\mathrm{LO}}^{\gamma\gamma}}$$





no γ

→ **large differences between different photon descriptions. Now settled: LUXqed superior**

→ **O(10%) contributions from photon-induced channels**

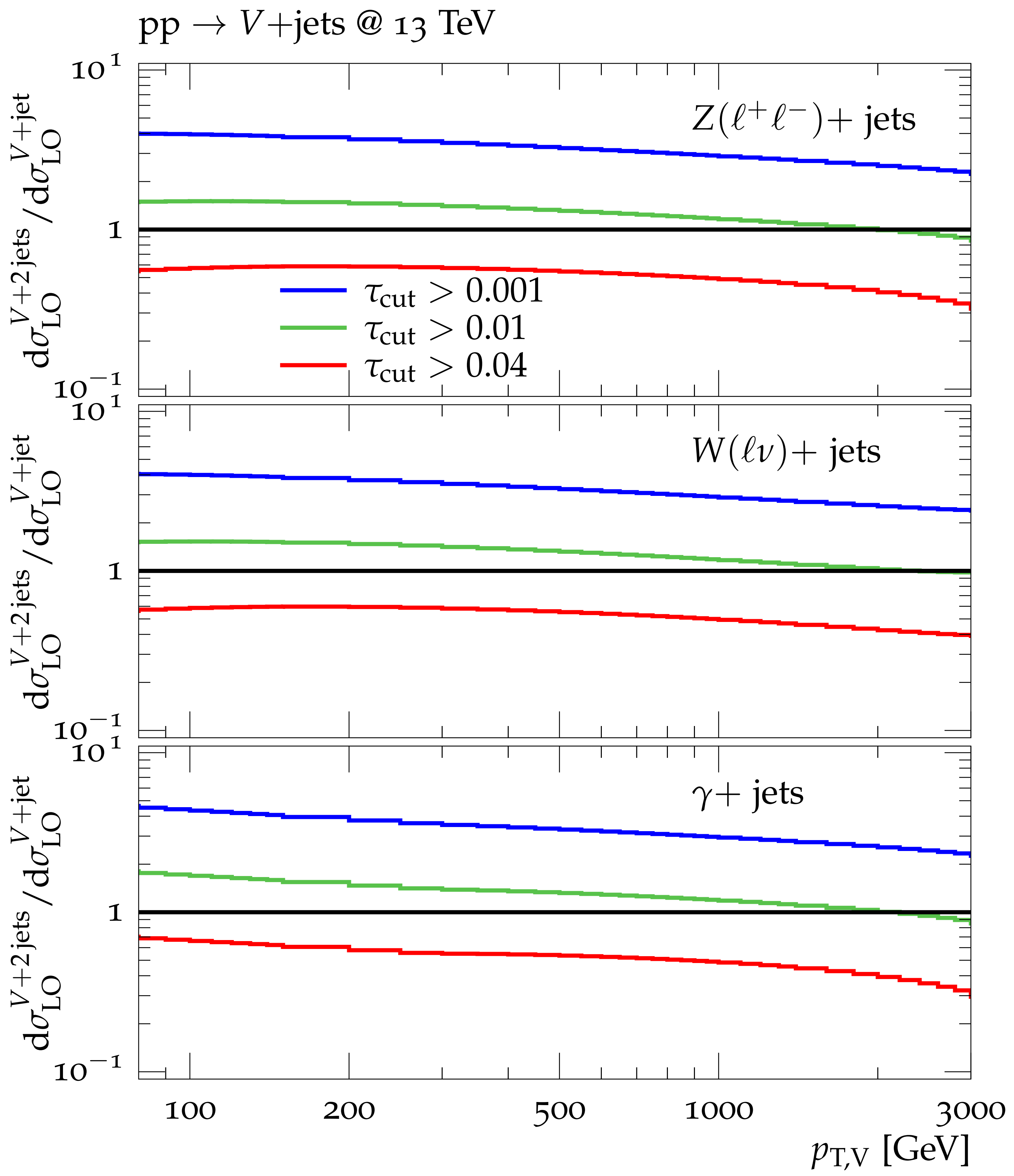
# Combination of QCD and EW corrections

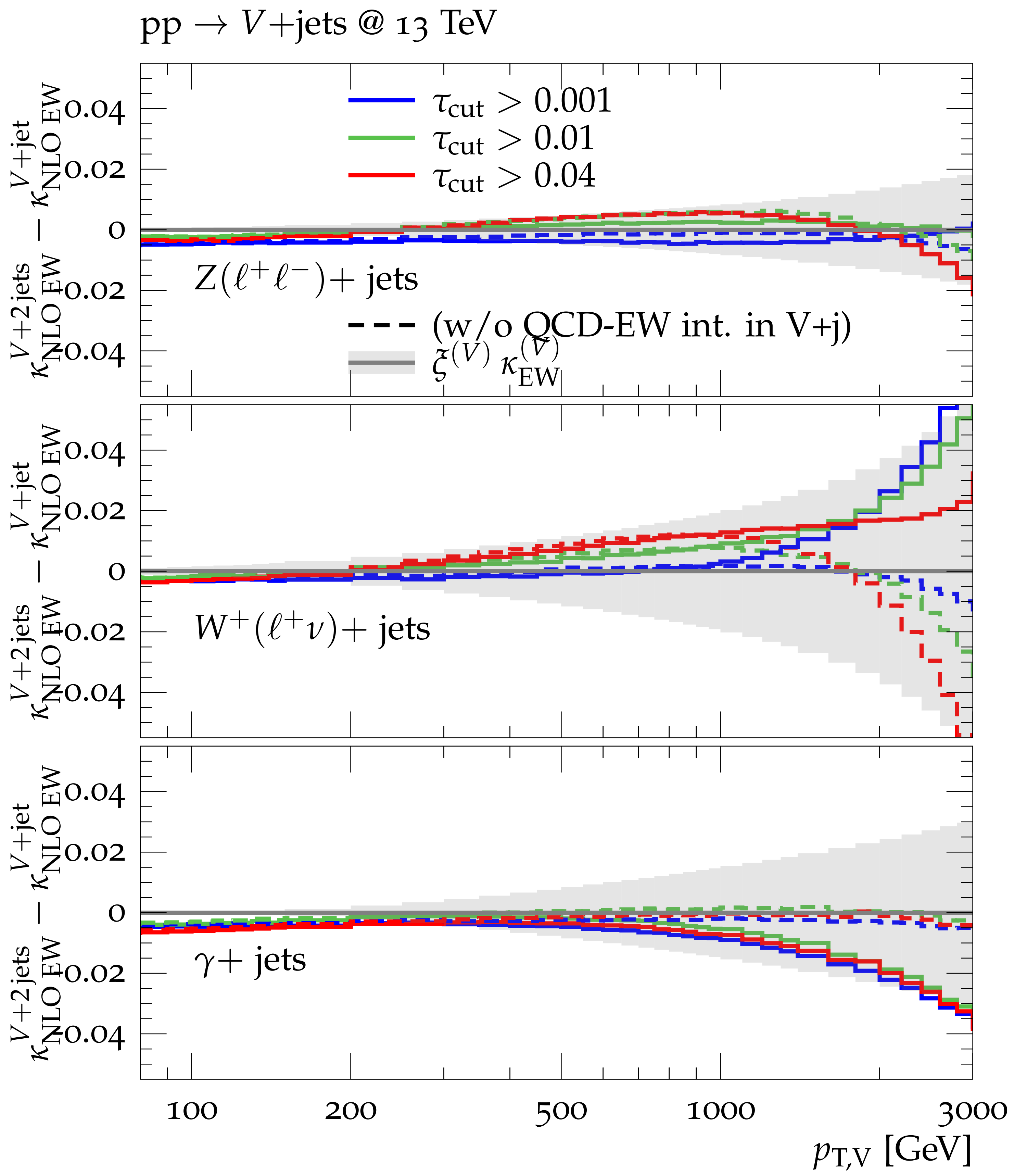
- full calculations of $\mathcal{O}(\alpha\alpha_s)$ out of reach
- Approximate combination: MEPS@NLO including (approximate) EW corrections
- key: QCD radiation receives EW corrections!
- strategy: modify MC@NLO B-function to include NLO EW virtual corrections and integrated approx. real corrections = VI

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \underset{\text{exact virtual contribution}}{\mathrm{V}_{n,\mathrm{EW}}(\Phi_n)} + \underset{\text{approximate integrated real contribution}}{\mathrm{I}_{n,\mathrm{EW}}(\Phi_n)}$$

# Mixed QCD-EW uncertainties

## Estimate of non-factorising contributions





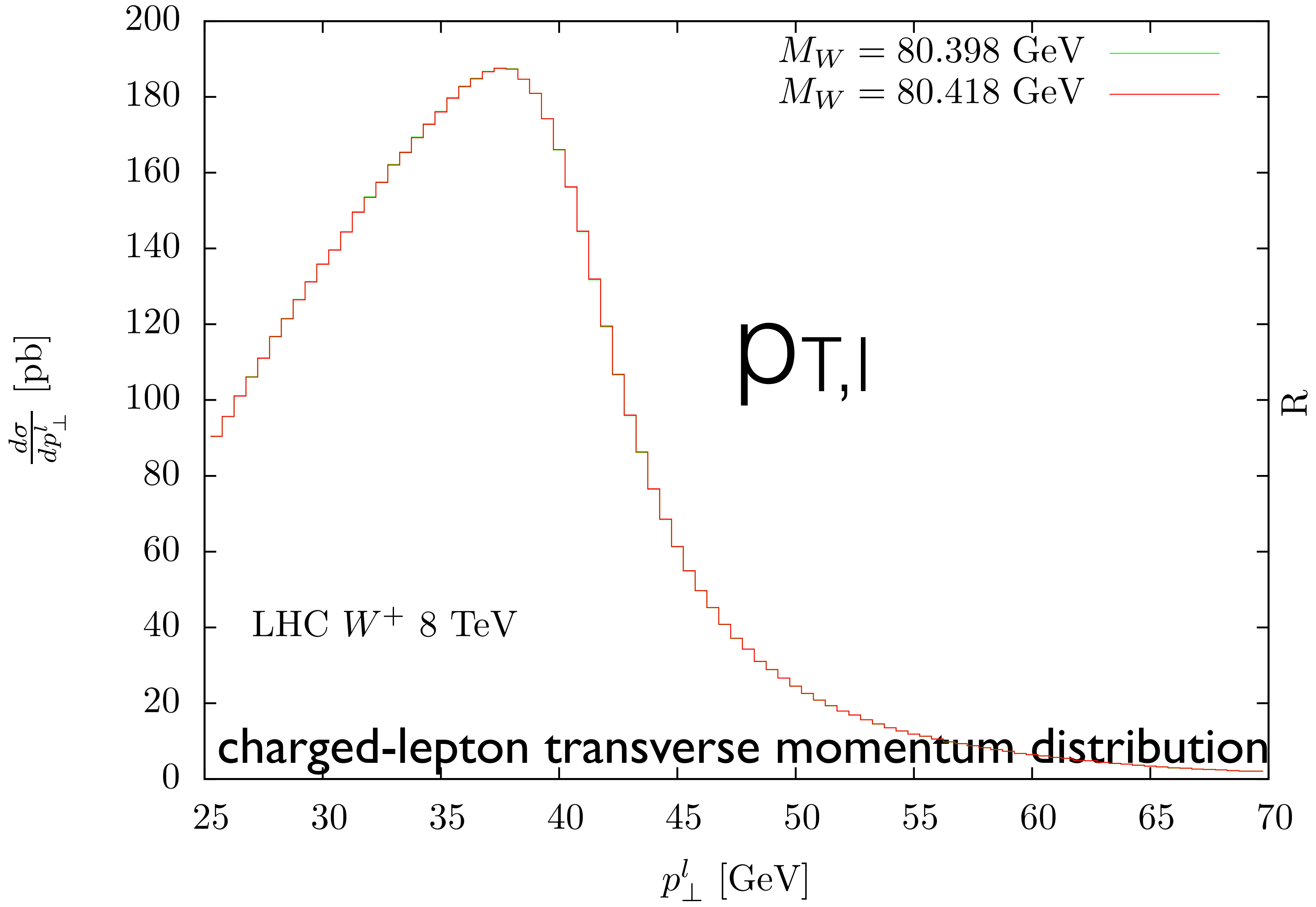
N-jettiness cut ensures approx. constant ratio V+2jets/V+jet

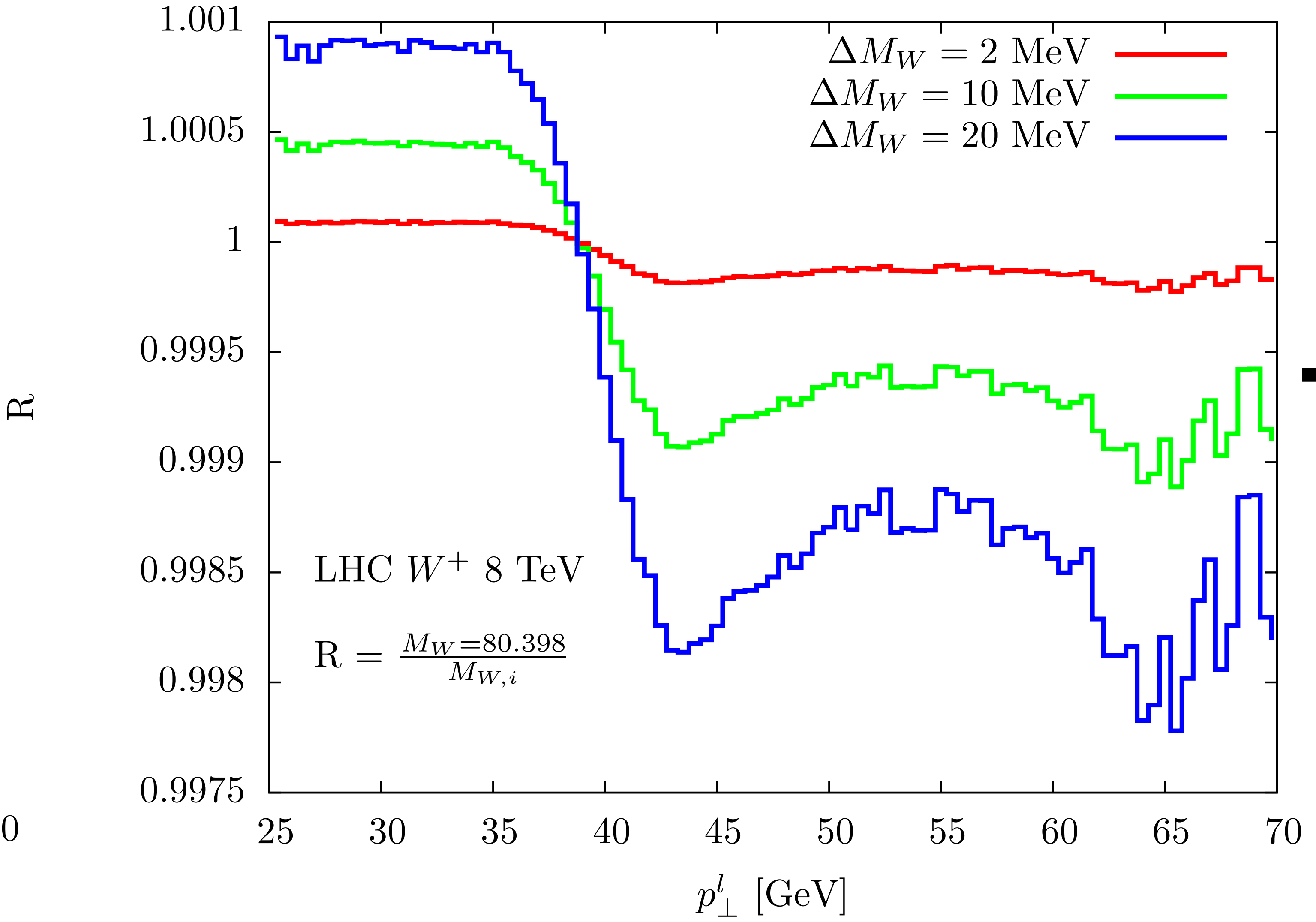
$$\tau_1 = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i \sqrt{\hat{s}}} \right\}$$

# Drell-Yan: $M_W$ measurements

- Motivation: $M_W$ is a derived quantity → precise measurement is a stringent test of SM!
- Method: **template fits** of sensitive CC DY distributions ($p_{T,l},\ M_T,\ E_{\text{miss}}$)

$$\boxed{M_W = 80.385 \pm 0.015\ \text{GeV}}$$





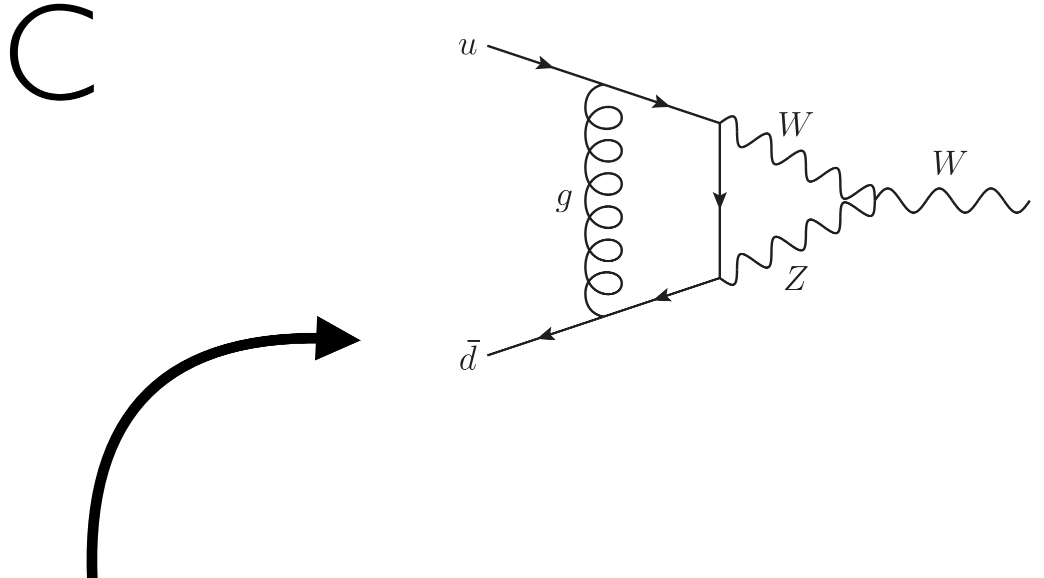
[Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini;'16]

→

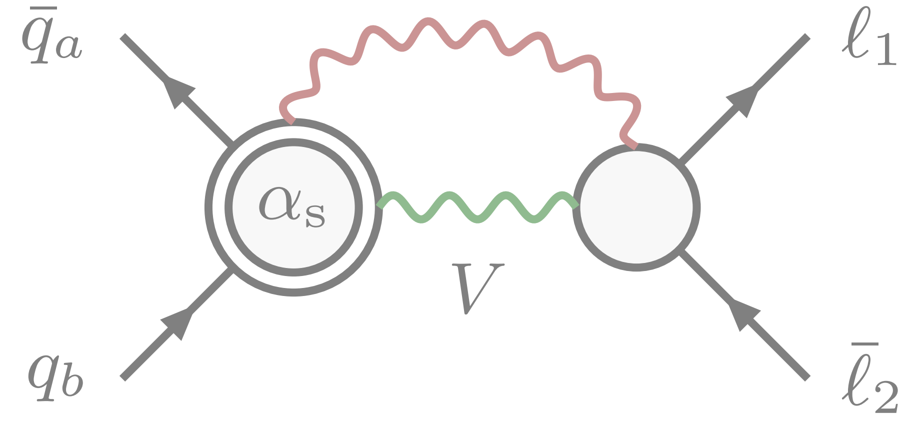
- Need to control shape effects at the sub-1% level!
- Dominant effects: QCD ISR and QED FSR

**→Theory precision essential for improvements in mW determination!**

# Mixed QCD-EW corrections to DY production: NC



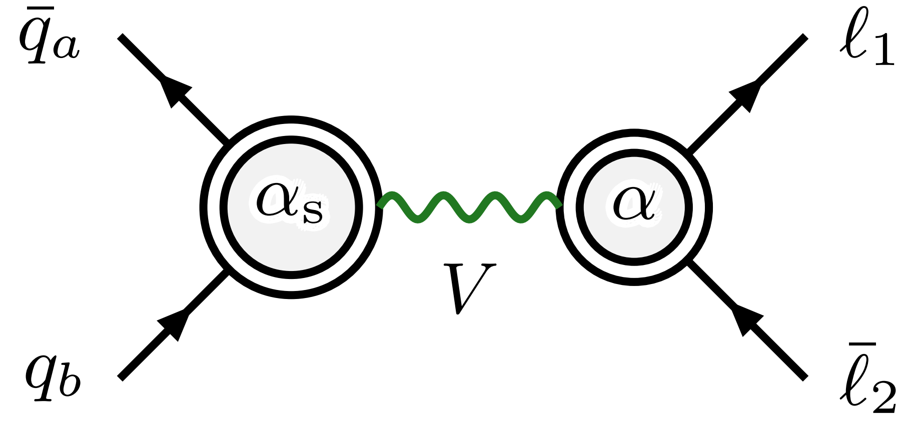
- For precision in resonant region: expand around M²



non-factorizable

*[Dittmaier, Huss, Schwinn, '14]*

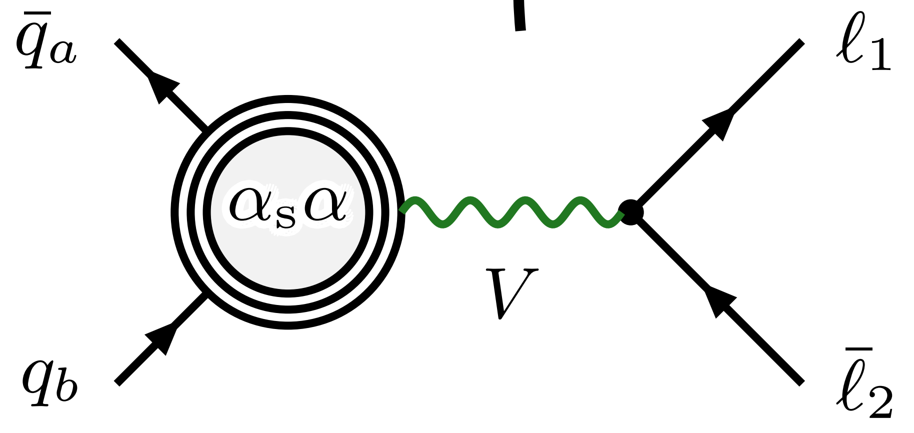
*negligible*



prod x decay

*[Dittmaier, Huss, Schwinn, '15]*

*dominant*



genuine QCD-EW in prod

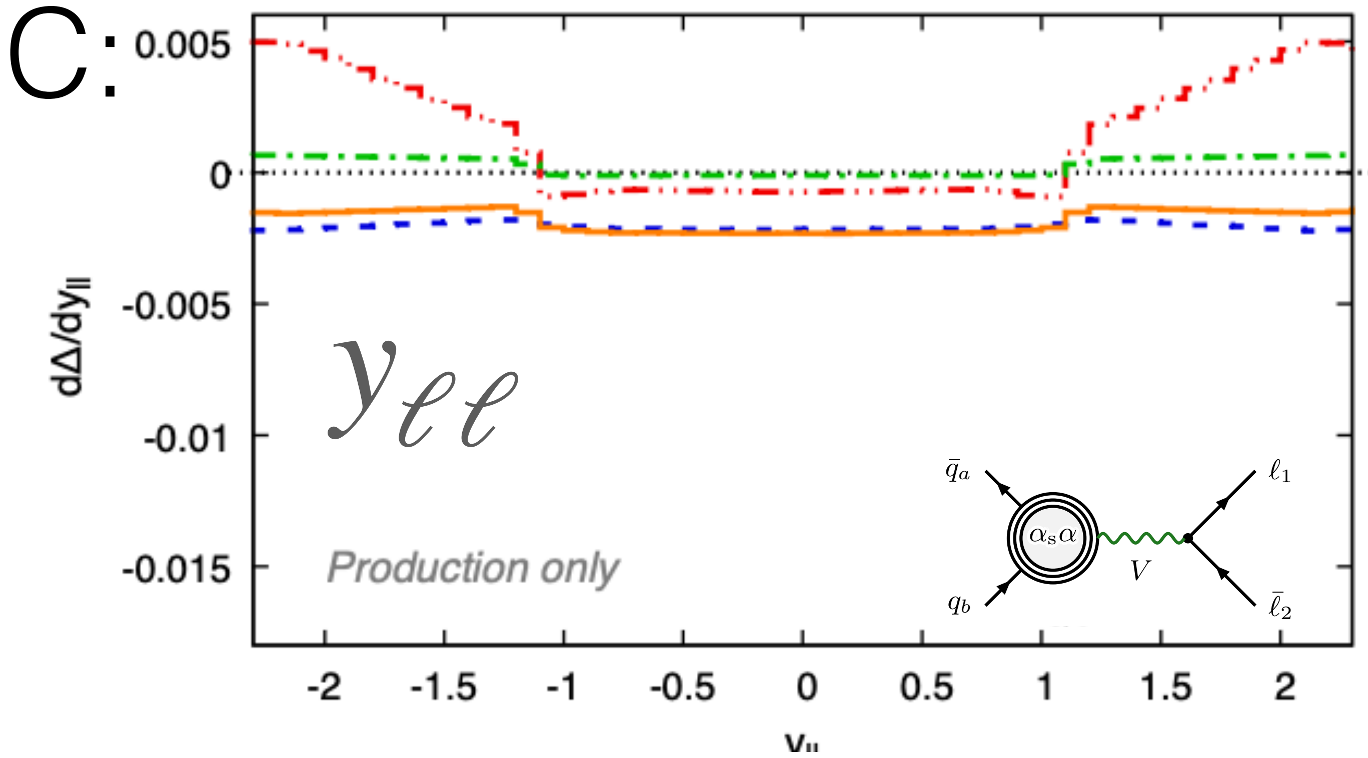
*[Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch, '20]*
*[Behring, Buccioni, Caola, et. al. '20]*

*last missing piece*

For production only

- QCD×weak dominant over QCD×QED
- net effect: few per-mille

NC:



🟥 QCD² / 10 🟩 QCD×QED 🟦 QCD×weak 🟧 { 🟩 + 🟦 }

CC+NC:

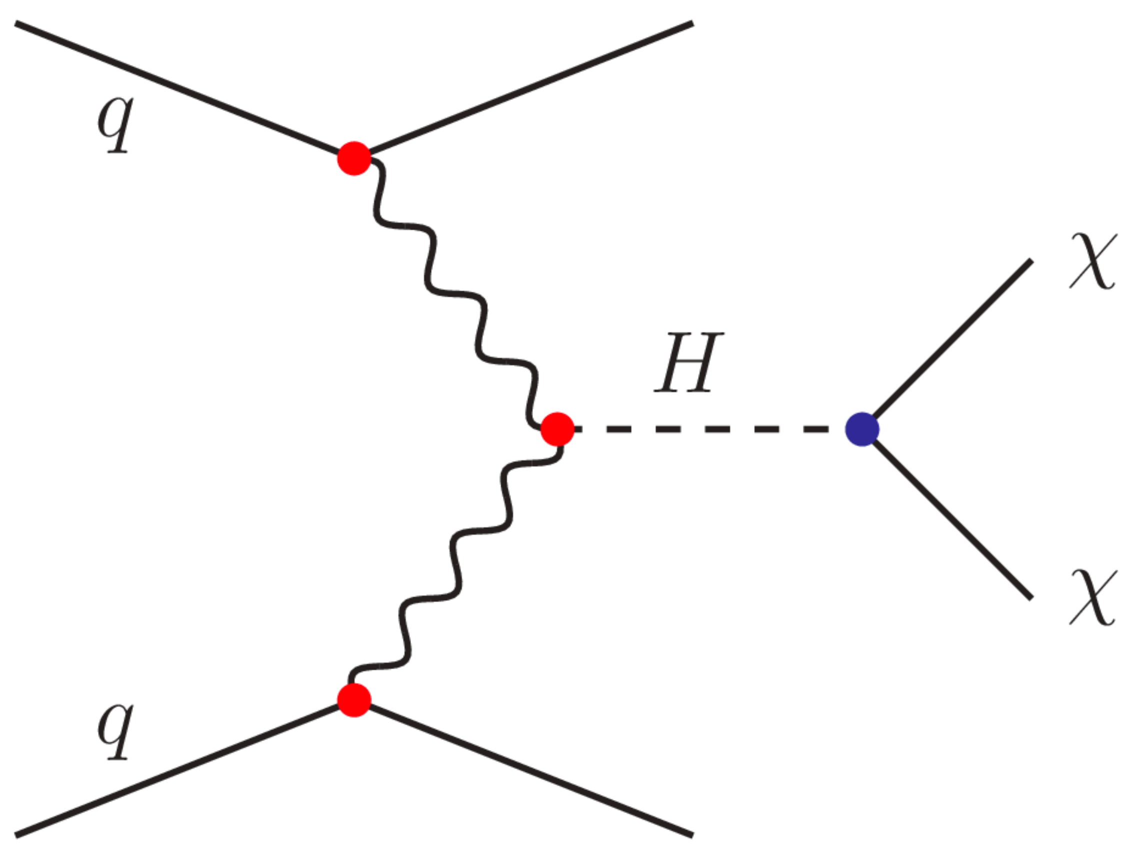
$$\frac{\delta m_W^{\rm meas}}{m_W^{\rm meas}} = \frac{\delta C_{\rm th}}{C_{\rm th}} = \frac{\delta\langle p_\perp^{l,Z}\rangle^{\rm th}}{\langle p_\perp^{l,Z}\rangle^{\rm th}} - \frac{\delta\langle p_\perp^{l,W}\rangle^{\rm th}}{\langle p_\perp^{l,W}\rangle^{\rm th}}$$

$$\boxed{\delta m_W^{\rm meas} = -17 \pm 2 \text{ MeV}}$$

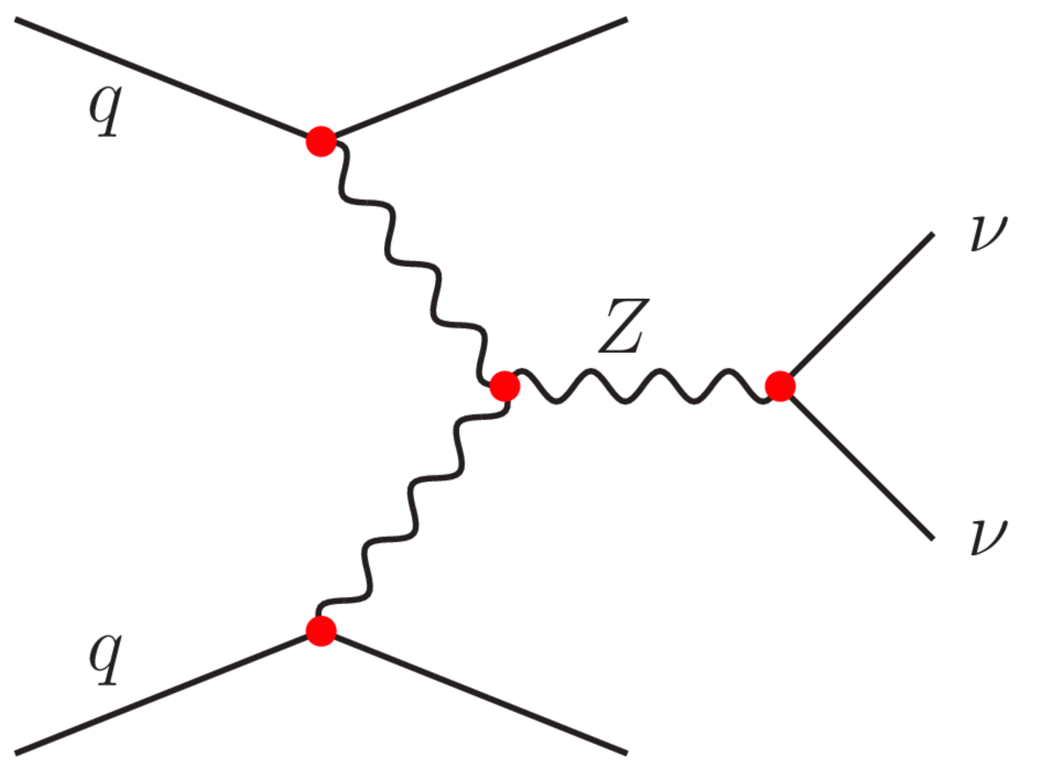
*[Behring, Buccioni, Caola, et. al. '21]*

# VBF-V as background of the invisible Higgs

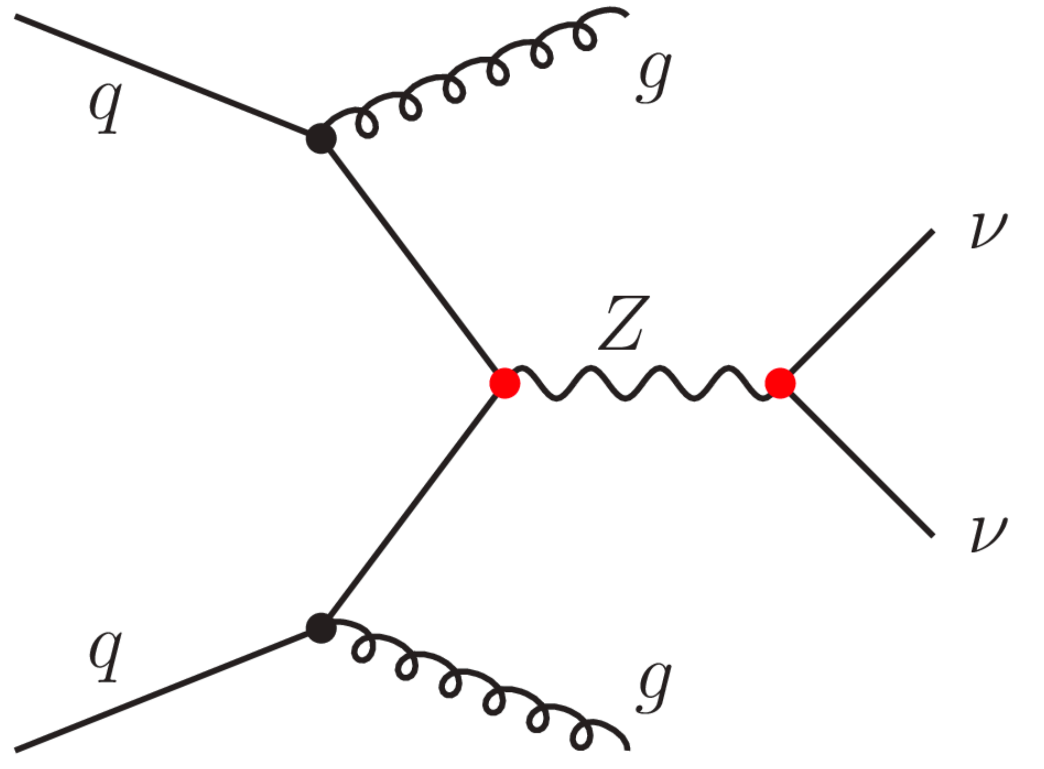
VBF



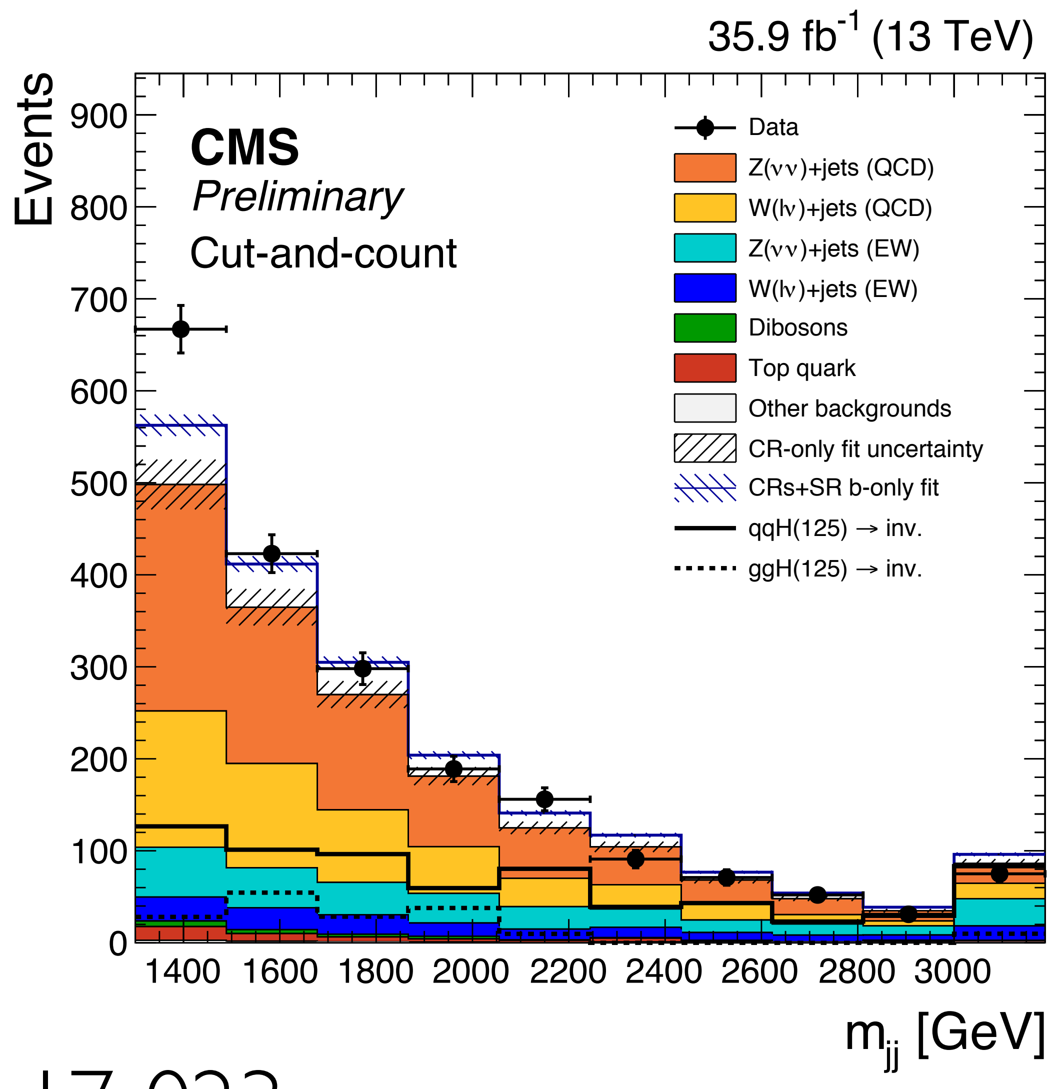
subject to large irreducible backgrounds



VBF-mode



QCD-mode



HIG-17-023-pas

irreducible SM backgrounds:

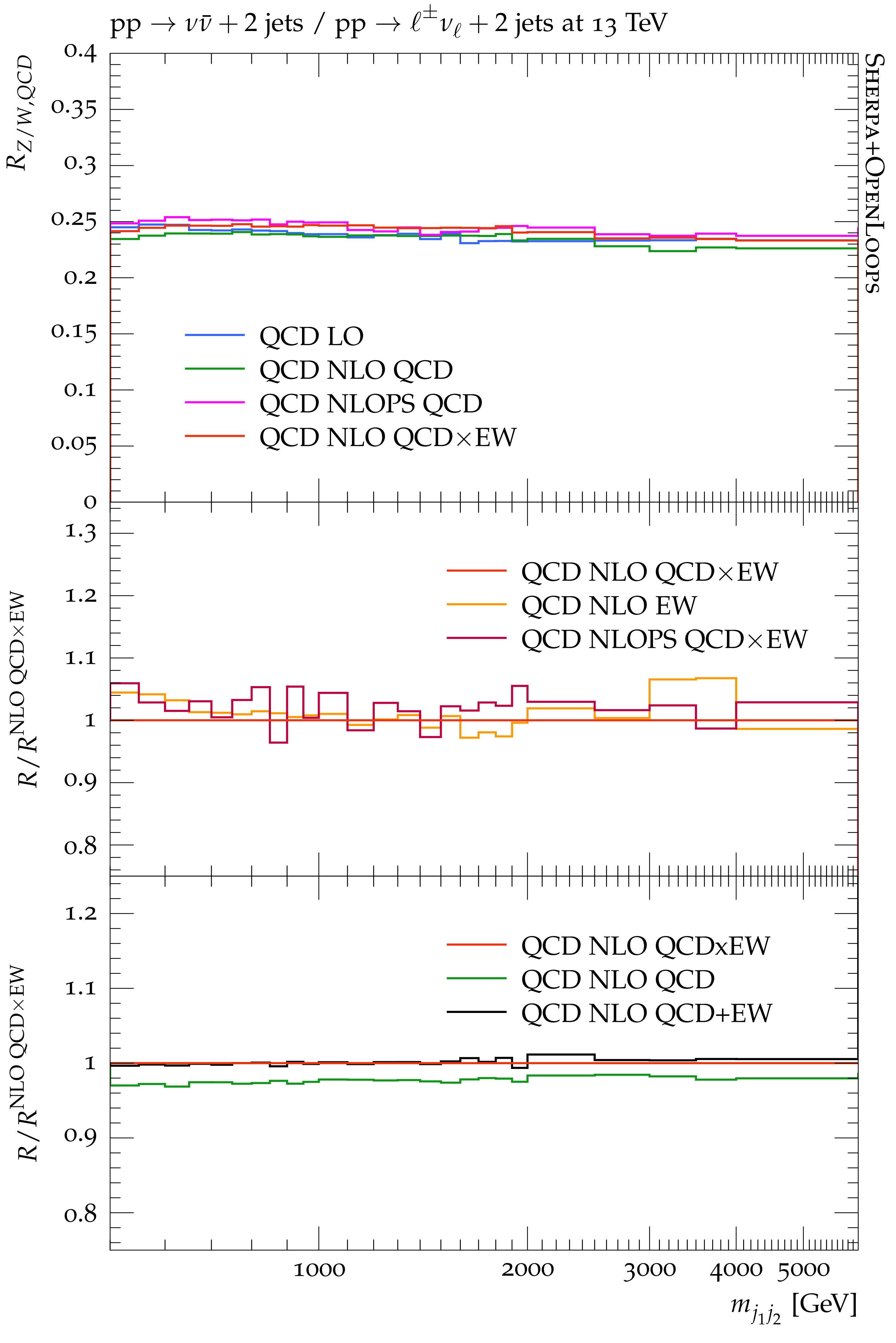
$$\left.\begin{array}{l} pp\to Z(\to\nu\bar{\nu})\text{+2 jets (QCD)} \Rightarrow \text{MET + 2 jets} \\ pp\to W(\to l\nu)\text{+2 jets (QCD)} \Rightarrow \text{MET + 2 jets (lepton lost)} \end{array}\right\} \text{V + 2 jets}$$

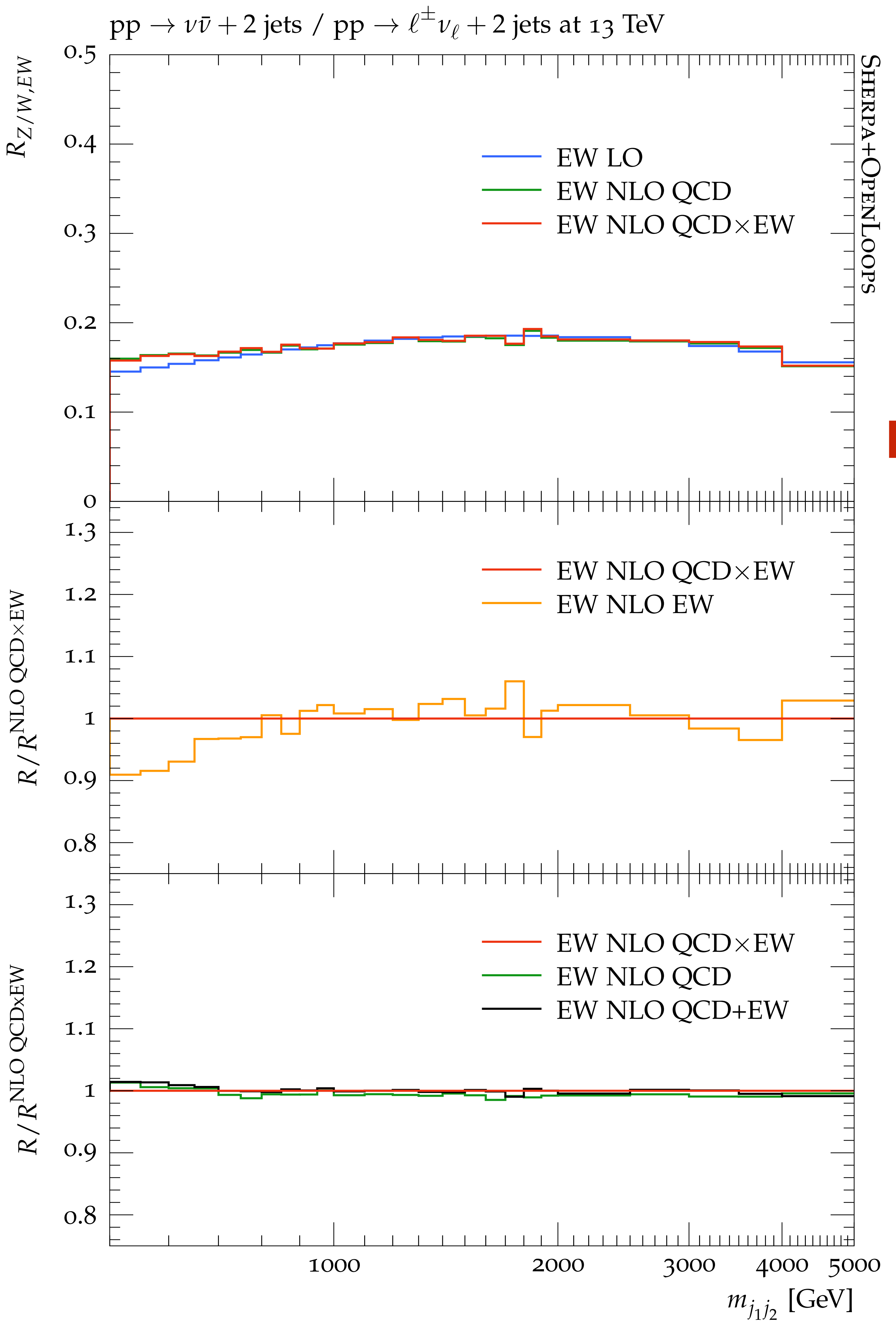
$$\left.\begin{array}{l} pp\to Z(\to\nu\bar{\nu})\text{+2 jets (EW)} \Rightarrow \text{MET + 2 jets} \\ pp\to W(\to l\nu)\text{+2 jets (EW)} \Rightarrow \text{MET + 2 jets (lepton lost)} \end{array}\right\} \text{VBF-V}$$

Need to control these backgrounds at below 10% level!

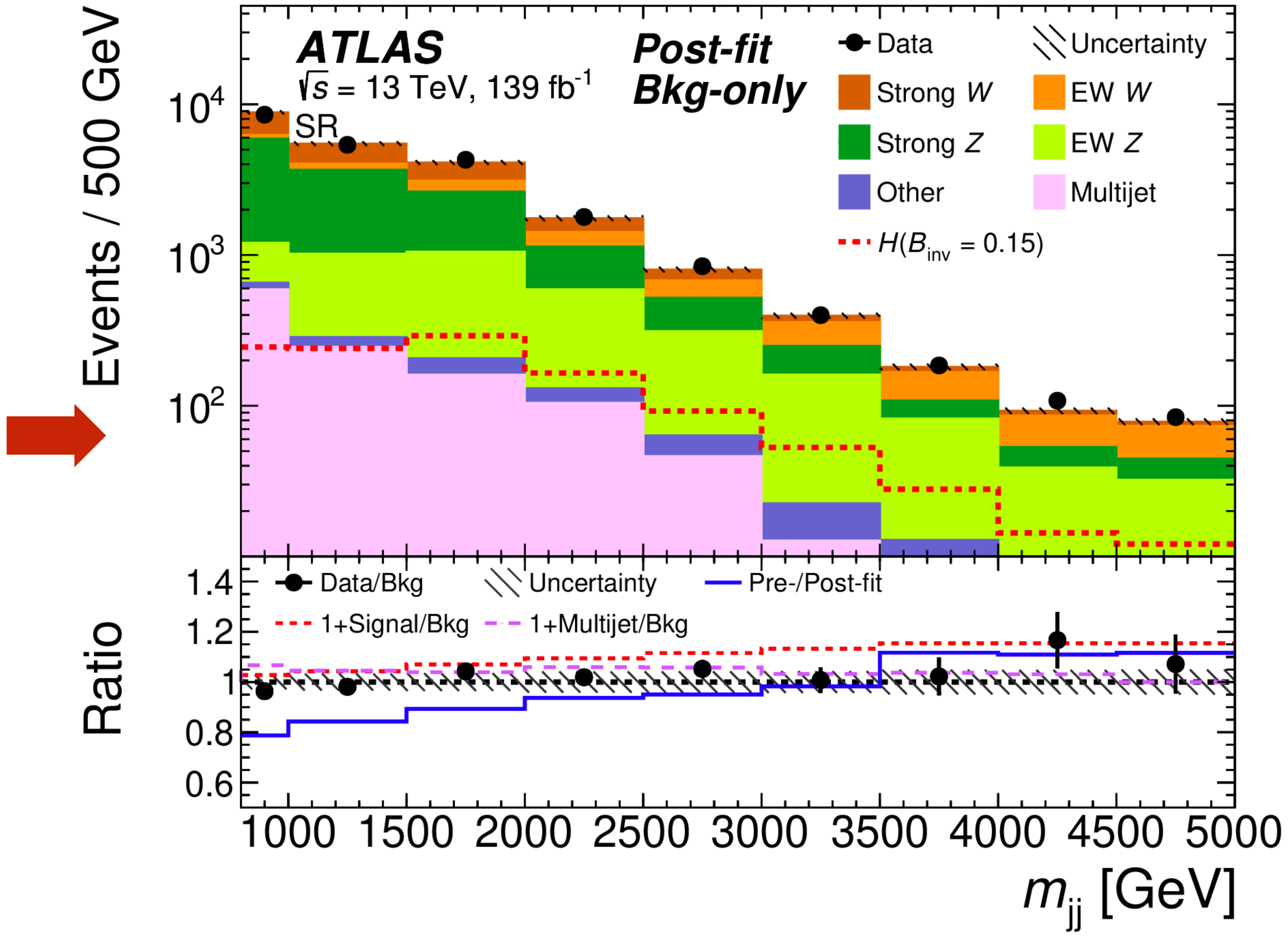
# Z+jets/W+jets ratios for H➝invisible

*[JML, Pozzorini, Schönherr, '22]*





[ATLAS *EXOT-2020-11*]



➡For SM Higgs:
BRinv < 0.145 @ 95% CL

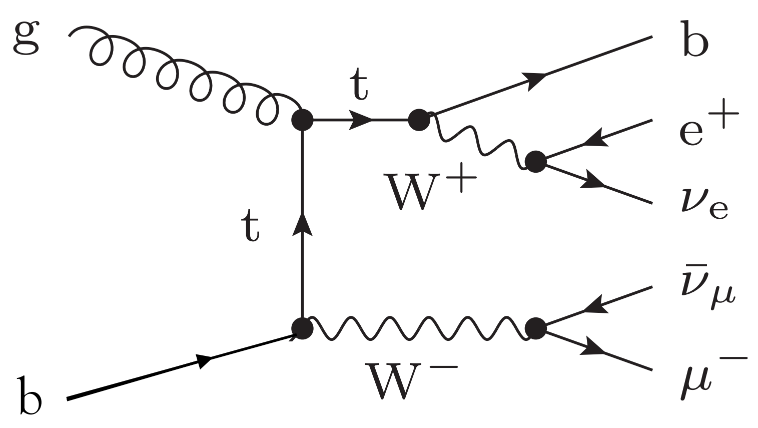
- Both QCD and EW ratios universal with respect to QCD and EW corrections at the percent level at large mjj

# Interplay between top-pair and Wt single-top production

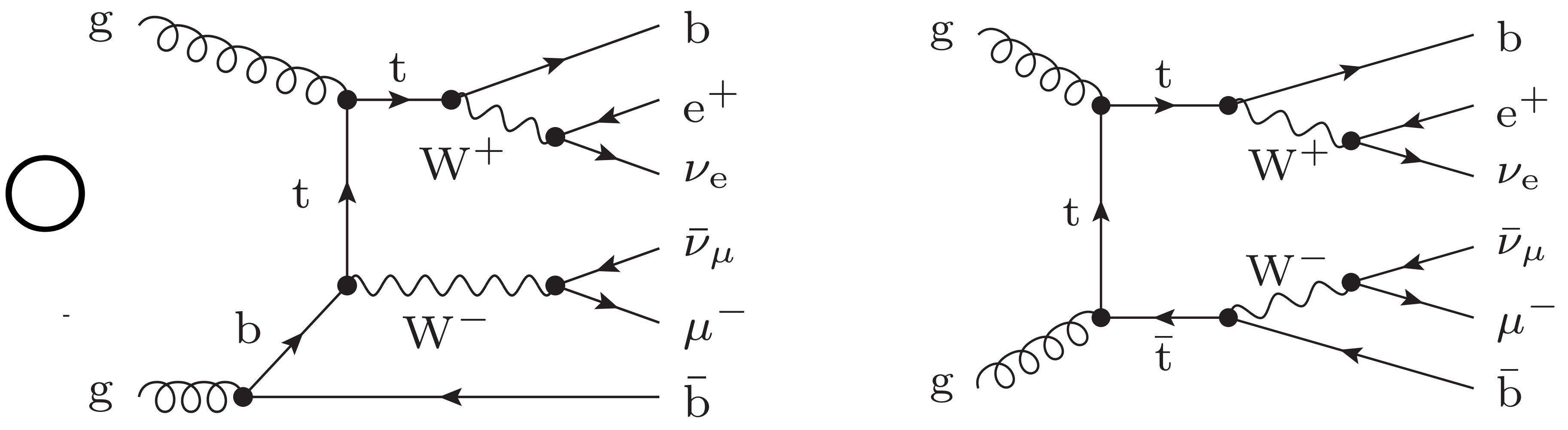
*same finale state!*

**5FS**

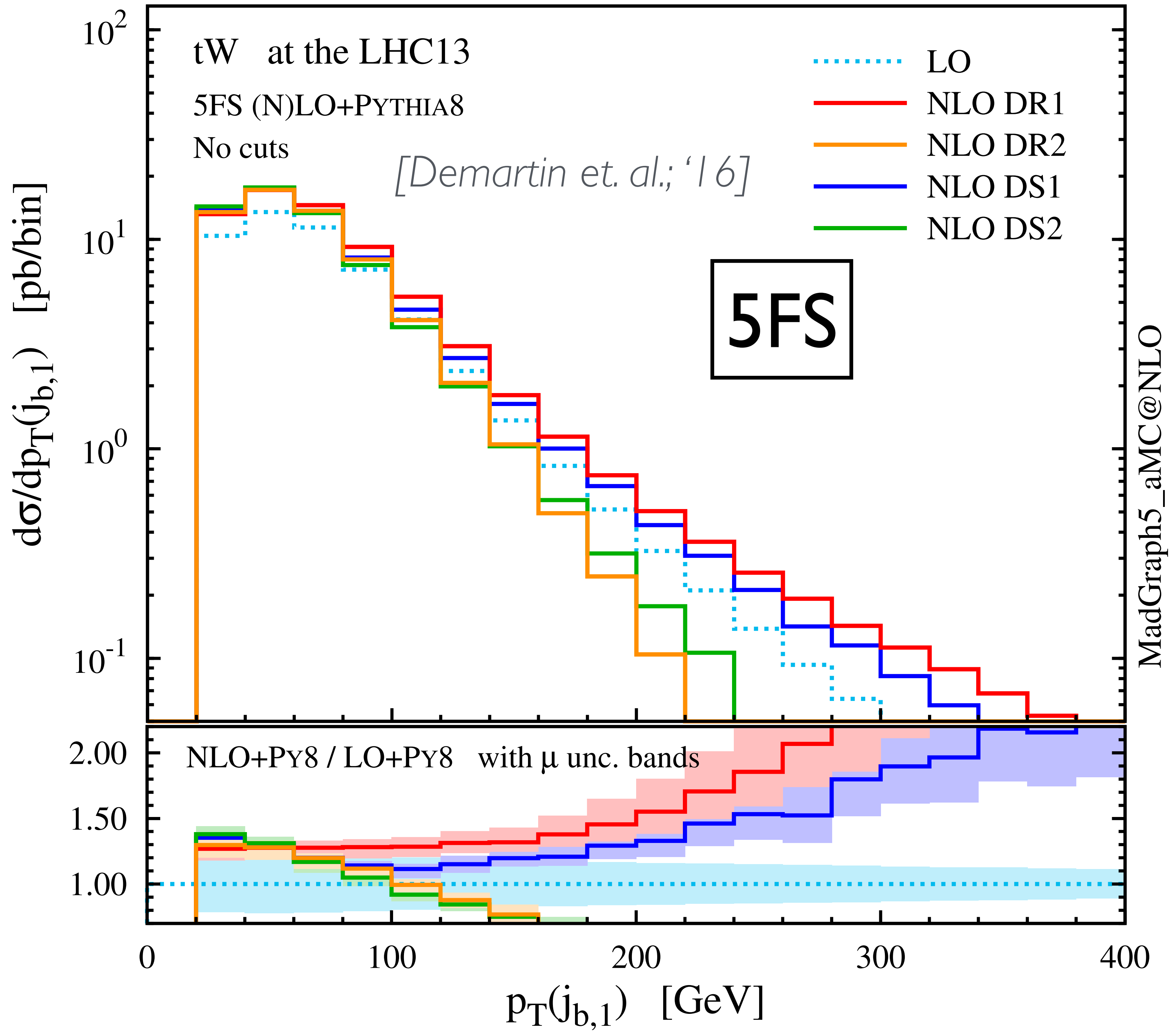
LO



NLO

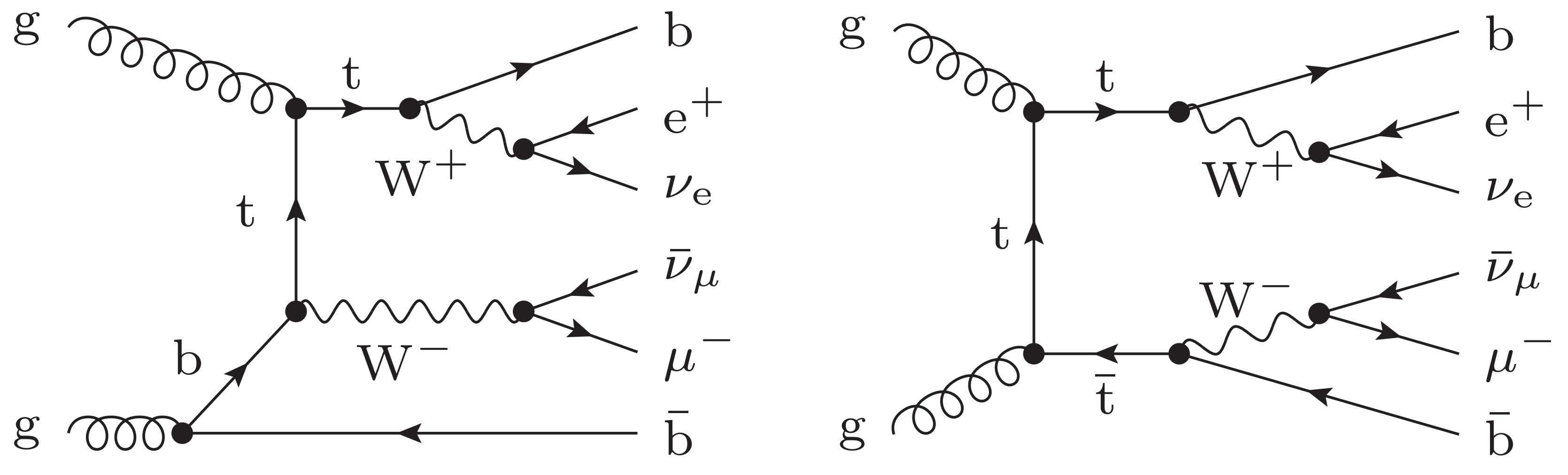


- NLO corrections to Wt swamped by LO $t\bar{t}$+decay
- requires ad-hoc subtraction prescription: DRI, DRII, DSI, DSII
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*



**4FS**

LO



Wt

$t\bar{t}$

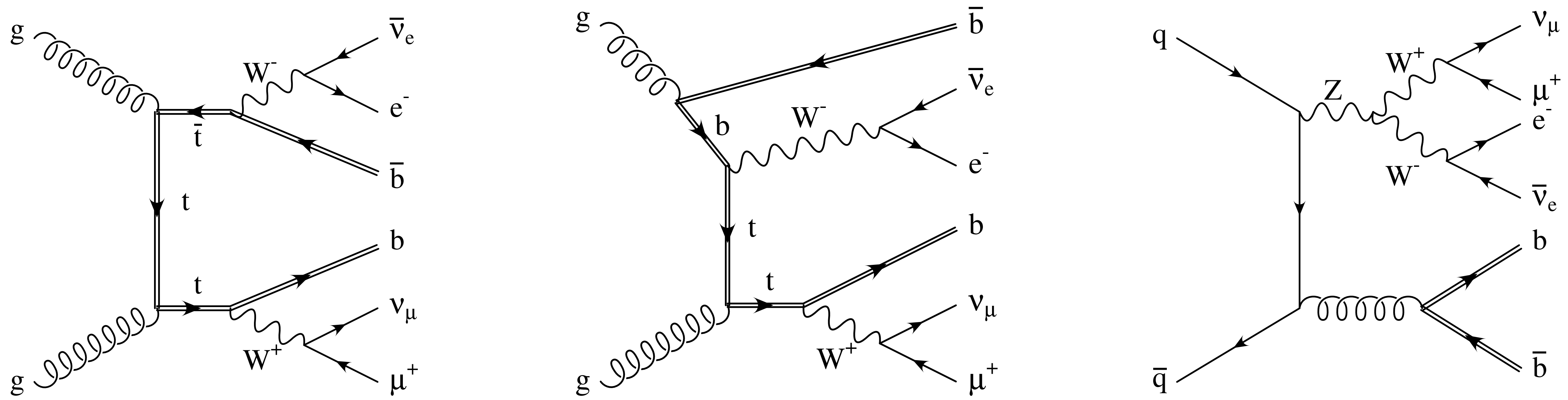
*same finale state!*

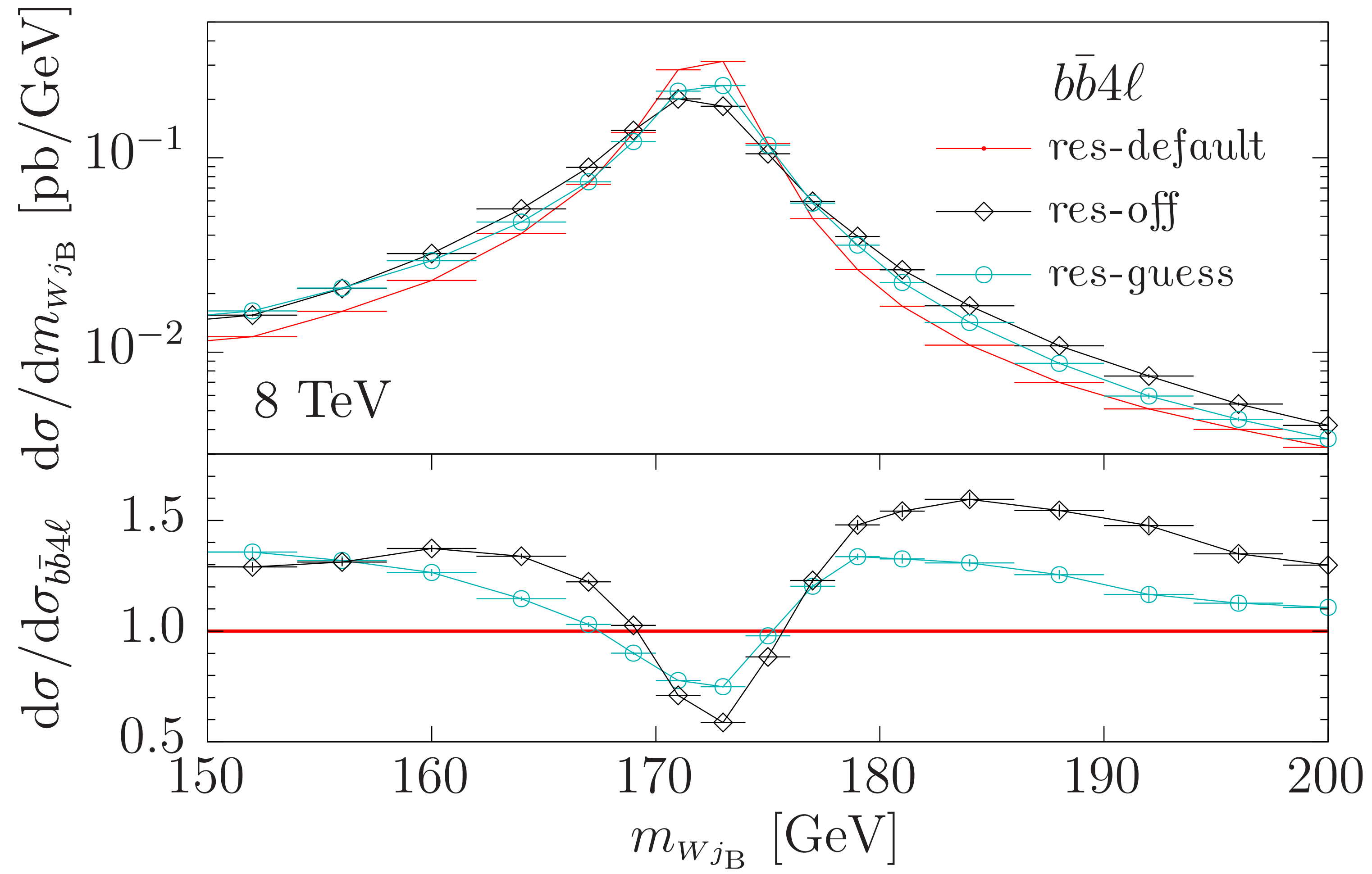
- **unified treatment of top-pair and Wt including *interference***
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

# The resonance-aware bb4l generator

*[Jezo, JML, Nason, Oleari, Pozzorini, '16]*

- Full process $pp \rightarrow b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ with massive b's (**4FS scheme**)
- Implemented in the **POWHEG-BOX-RES** framework





Physics features:

- exact **non-resonant** / **off-shell** / **interference** / **spin-correlation** effects at NLO
- unified treatment of **top-pair and Wt** production with interference at NLO
- access to phase-space regions with **unresolved b-quarks** and/or jet vetoes
- **consistent NLO+PS treatment of top resonances,** including quantum corrections to top propagators and off-shell top-decay chains

Standard POWHEG matching:

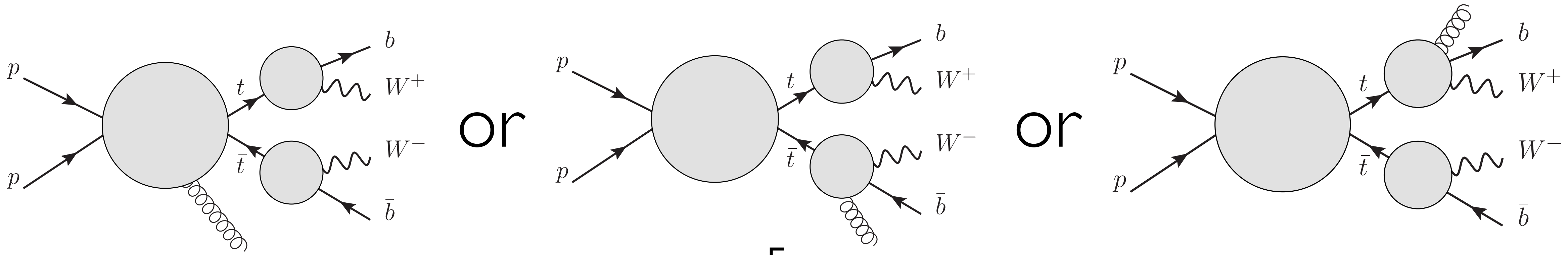
- Standard FKS/CS subtraction does not preserve virtuality of intermediate resonances ➝ R and B (~S) with different virtualities.
- R/B enters POWHEG matching via generation of radiation and via Sudakov form-factor
  ➝ **uncontrollable distortions**

**Resonance-aware POWHEG matching:** *[Jezo, Nason, '15]*

- Separate process in *resonances histories*
- Modified FKS mappings that retain virtualities

# Multiple-radiation scheme

- In traditional approach only hardest radiation is generated by POWHEG:

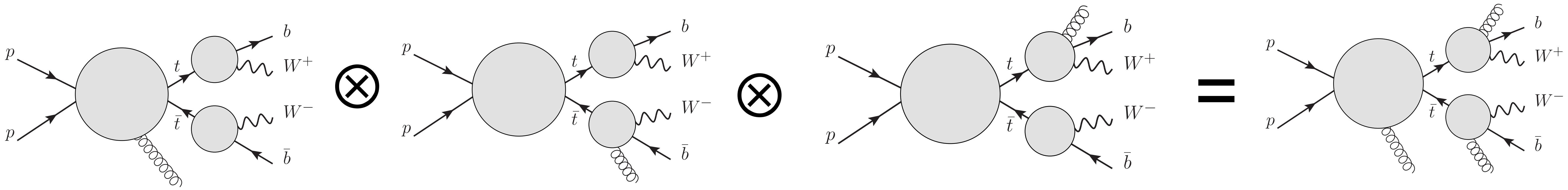


$$\Longleftrightarrow \qquad \mathrm{d}\sigma = \bar{B}(\Phi_\mathrm{B})\,\mathrm{d}\Phi_\mathrm{B}\left[\Delta(q_\mathrm{cut}) + \sum_\alpha \Delta(k_T^\alpha)\frac{R_\alpha(\Phi_\alpha(\Phi_\mathrm{B},\Phi_\mathrm{rad}))}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_\mathrm{rad}\right]$$

BUT: for top-pair (or single-top) production and decay, emission from production is almost always the hardest.

➡ emission off decays are mostly generated by the shower.

- **Multiple-radiation / allrad scheme**: *introduced in [Campbell, Ellis, Nason, Re; '15]*
  - keep hardest emission from all resonance histories.
  - merge emissions into a single radiation event with several radiated partons

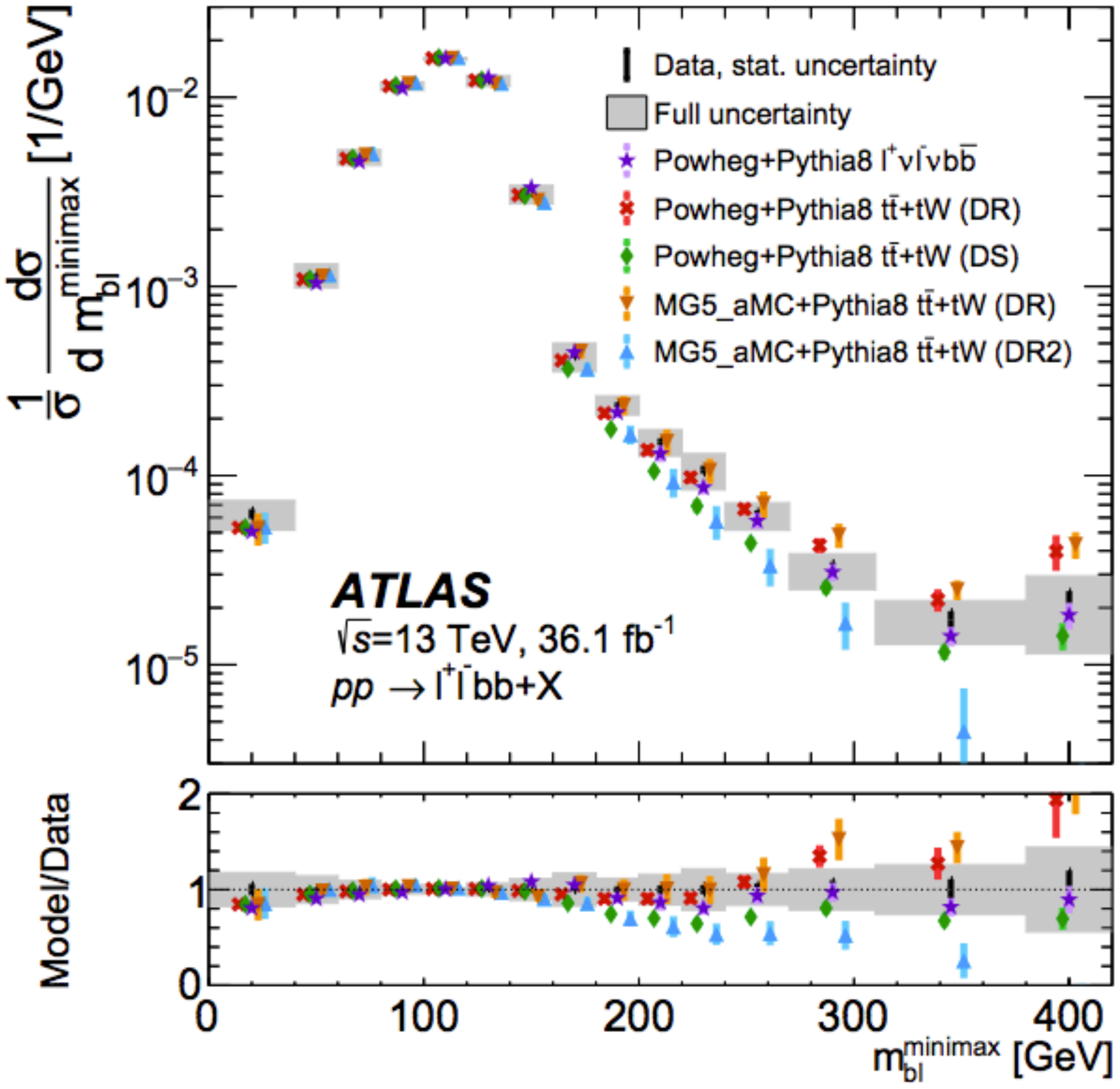


$$\Longleftrightarrow \qquad \mathrm{d}\sigma = \bar{B}(\Phi_\mathrm{B})\,\mathrm{d}\Phi_\mathrm{B} \prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_\mathrm{ISR}} \left[\Delta_\alpha(q_\mathrm{cut}) + \Delta_\alpha(k_T^\alpha)\frac{R_\alpha(\Phi_\alpha(\Phi_\mathrm{B},\Phi_\mathrm{rad}^\alpha))}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_\mathrm{rad}^\alpha\right]$$

# Off-shell effects in bb4l

“Probing the quantum interference between singly
and doubly resonant top-quark production in pp
collisions at √s = 13 TeV with the ATLAS detector"

Phys. Rev. Lett. 121 (2018) 152002

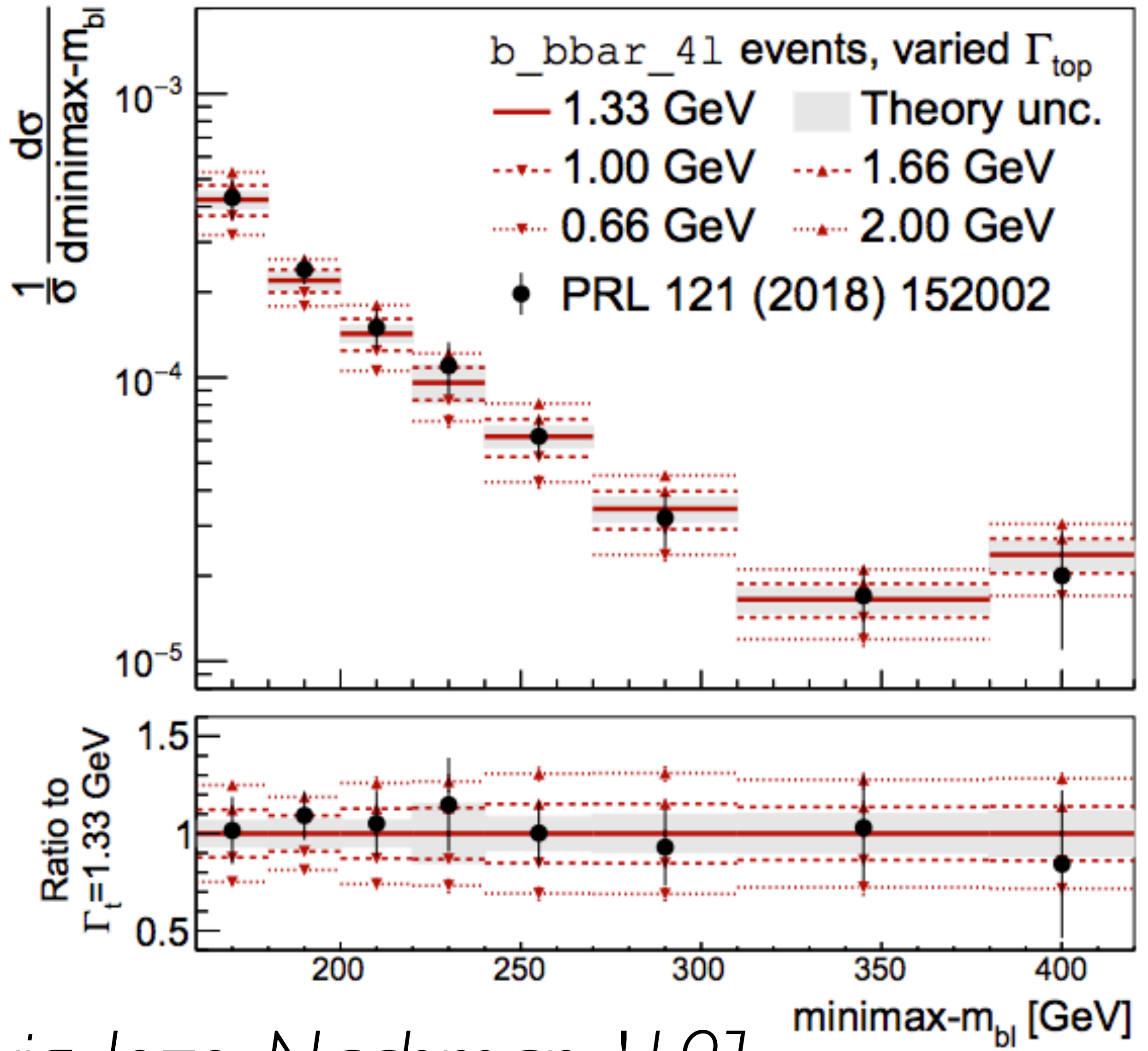


$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

For tt̄ (double-resonant) at LO: $m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$

→ sensitivity to off-shell effects/ tt-Wt interference beyond endpoint

→ measure top width

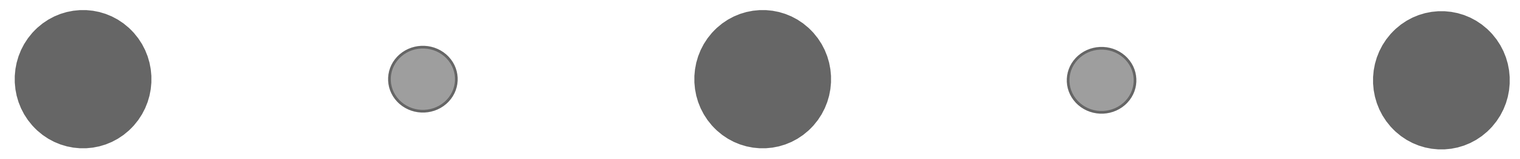


[Herwig, Jezo, Nachman, '19]

# Semi-leptonic $t\bar{t}$

$$pp \to \ell^\pm \nu_\ell jjb\bar{b}$$

$\alpha_S^4\alpha^2$ $\alpha_S^3\alpha^3$ $\alpha_S^2\alpha^4$ $\alpha_S\alpha^5$ $\alpha^6$



V + HF

$W^\pm b\bar{b}jj$

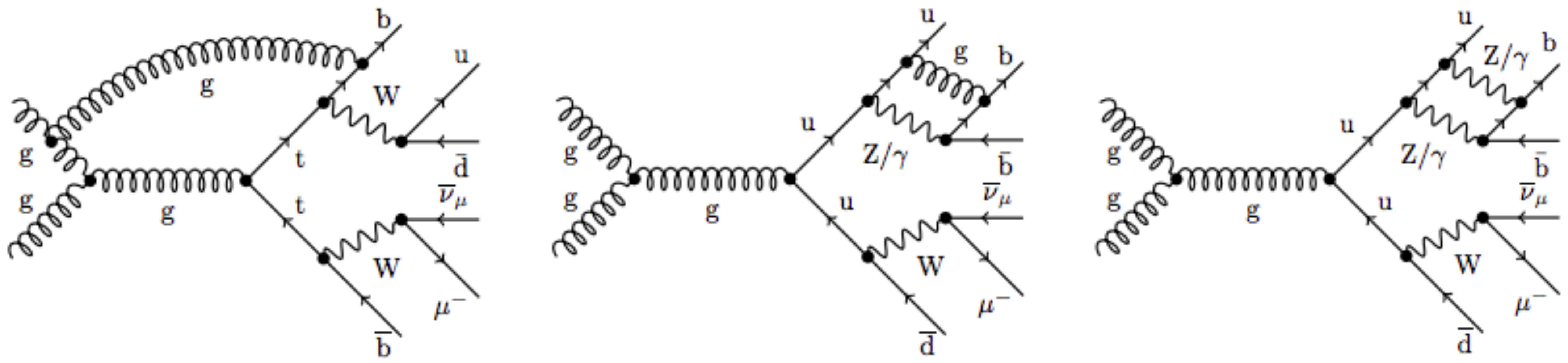
top production

$t\bar{t}$ + $tW$

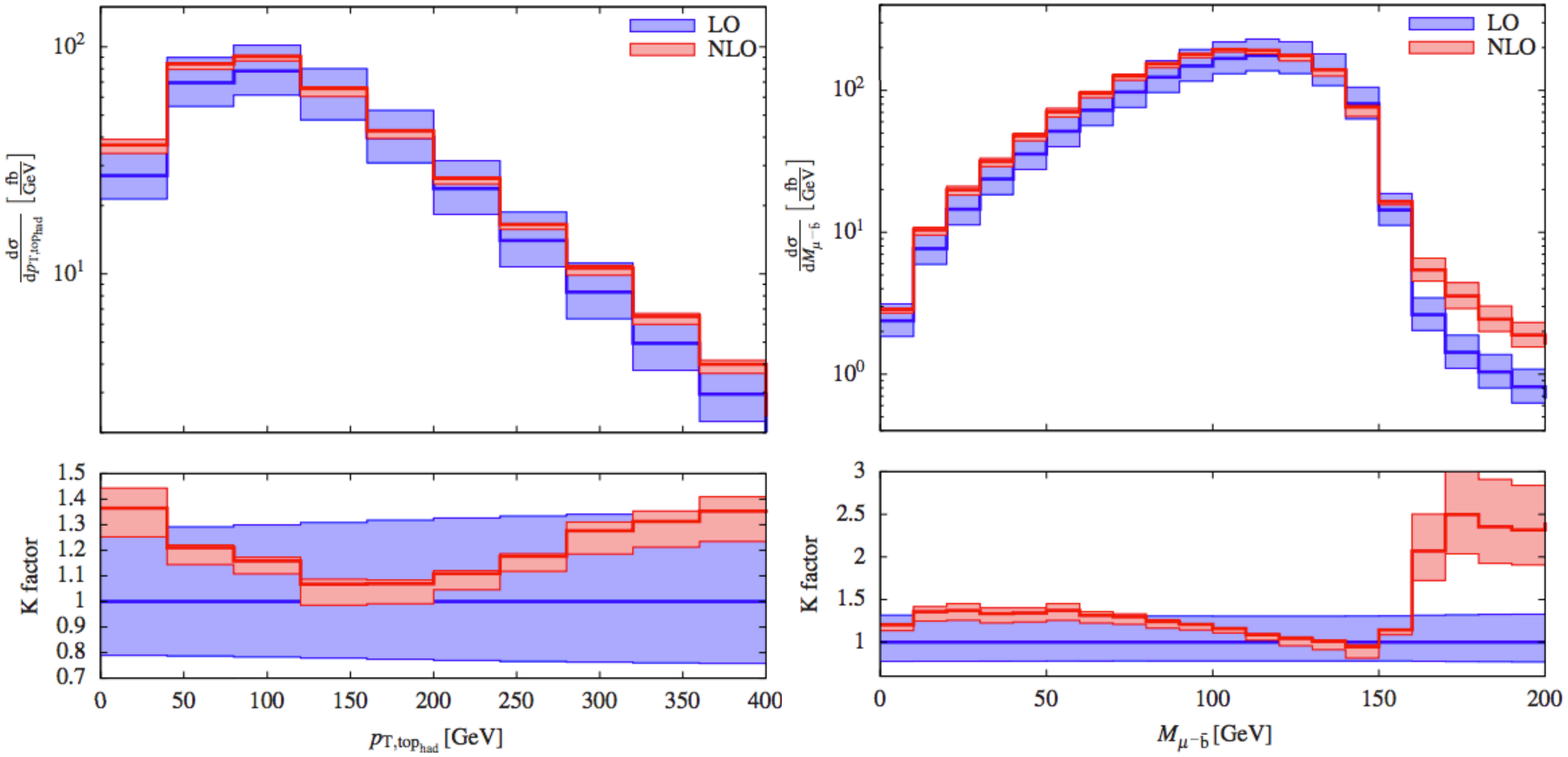
VBS+VVV

$W^\pm Zjj$ +
$W^\pm ZV$

Very high complexity in the full computation :

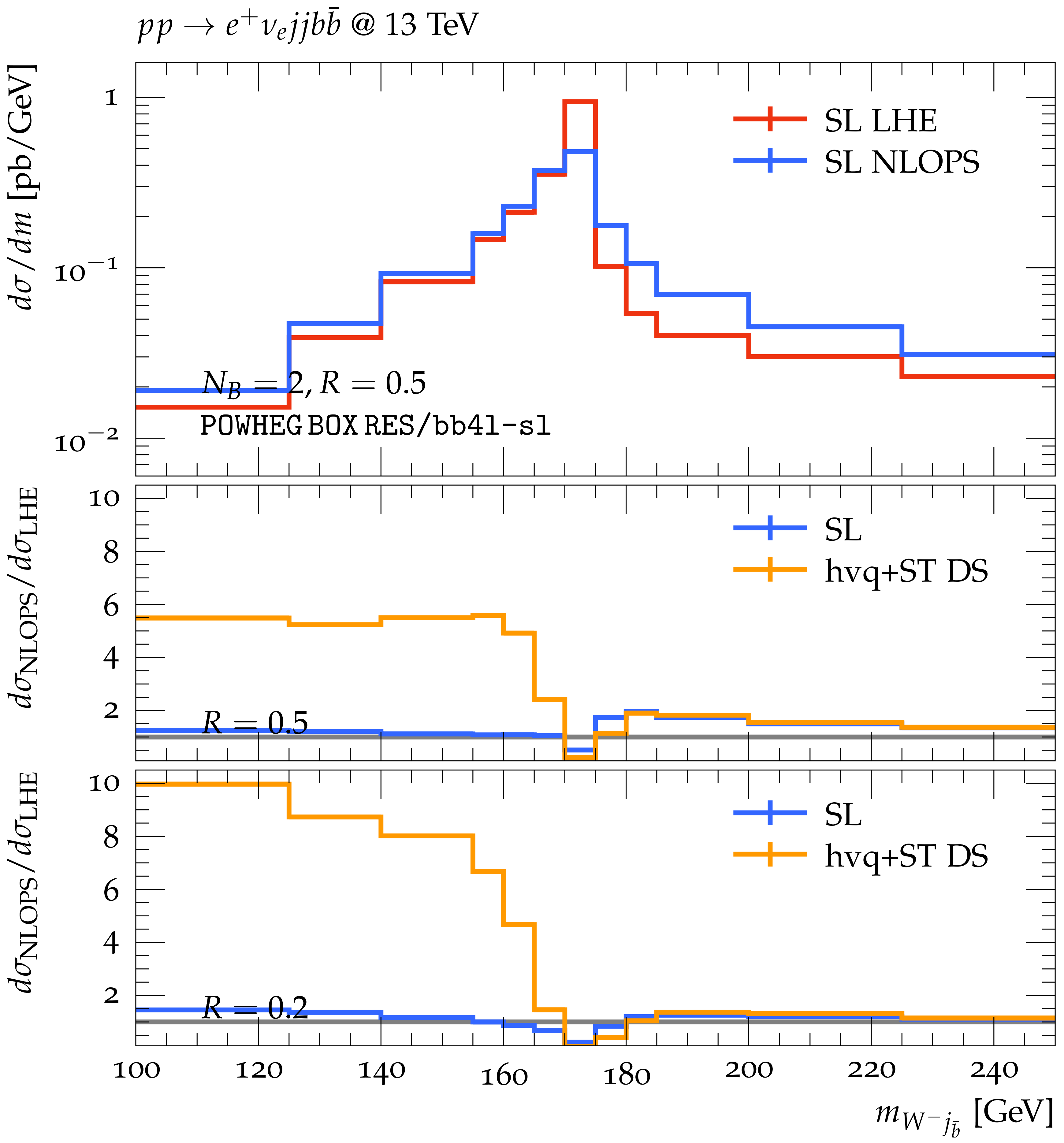


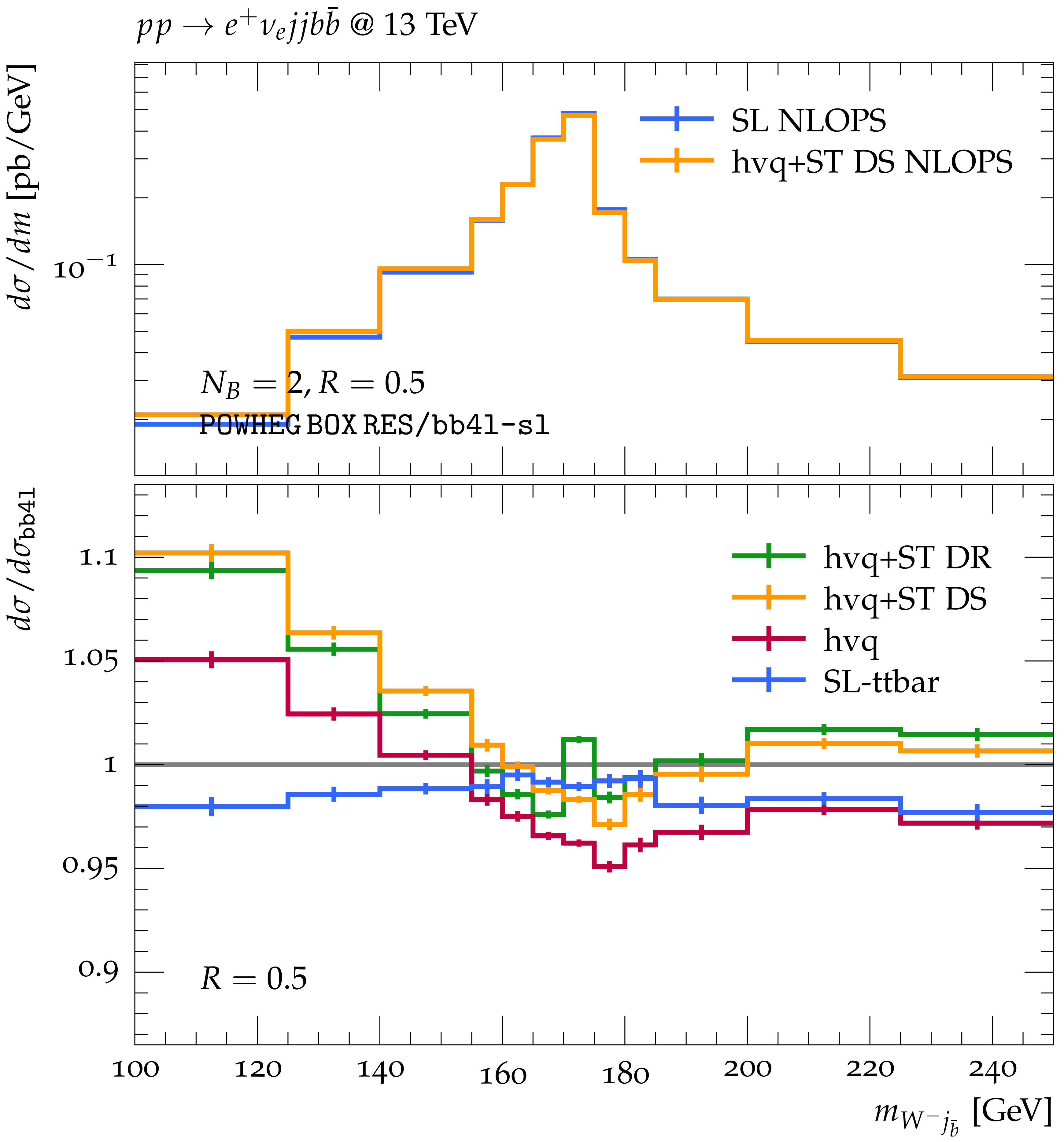
[Denner, Pellen, '18]



# bb4l-sl vs. on-shell top-pair plus single-top

*[Jezo, JML, Pozzorini, to appear]*

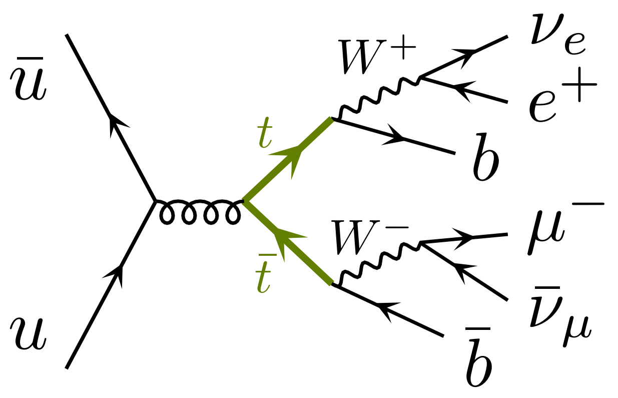


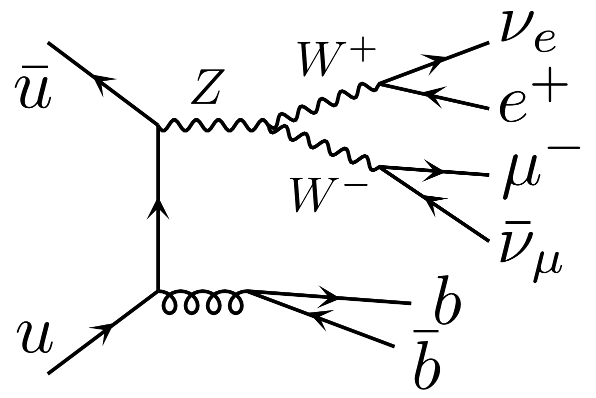


- Control of reconstructed top-mass crucial for top-mass measurements

# New features in bb4l-sl / bb4l-dl

*[Jezo, JML, Pozzorini, to appear]*



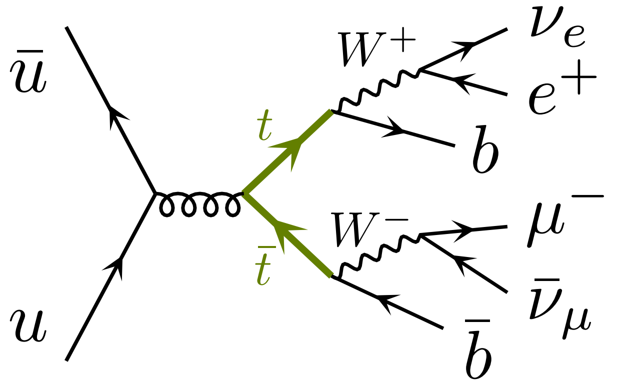


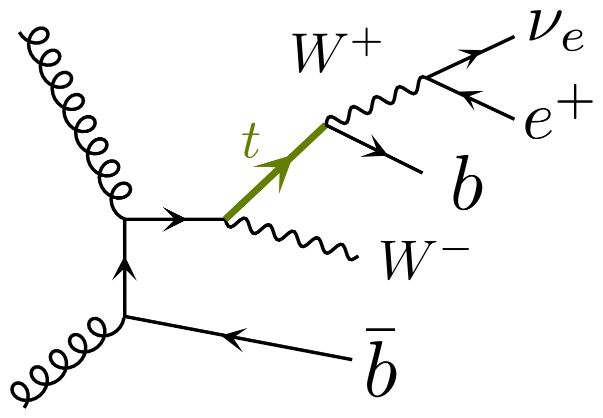
$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$

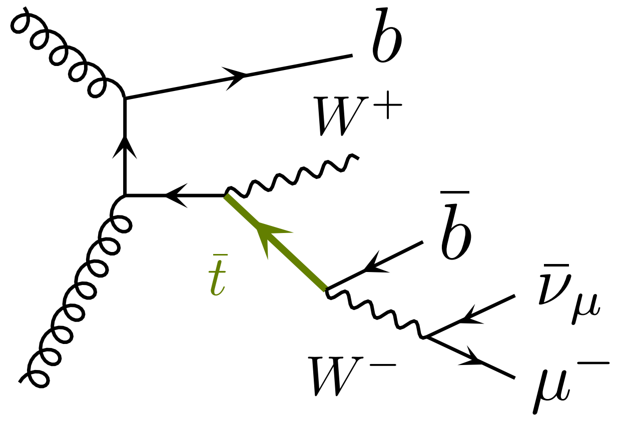
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

Kinematic projectors







$$d\sigma = \frac{P_1}{P_1+P_2+P_3} d\sigma + \frac{P_2}{P_1+P_2+P_3} d\sigma + \frac{P_3}{P_1+P_2+P_3} d\sigma$$

$P_1 = B_{t\bar{t}}$

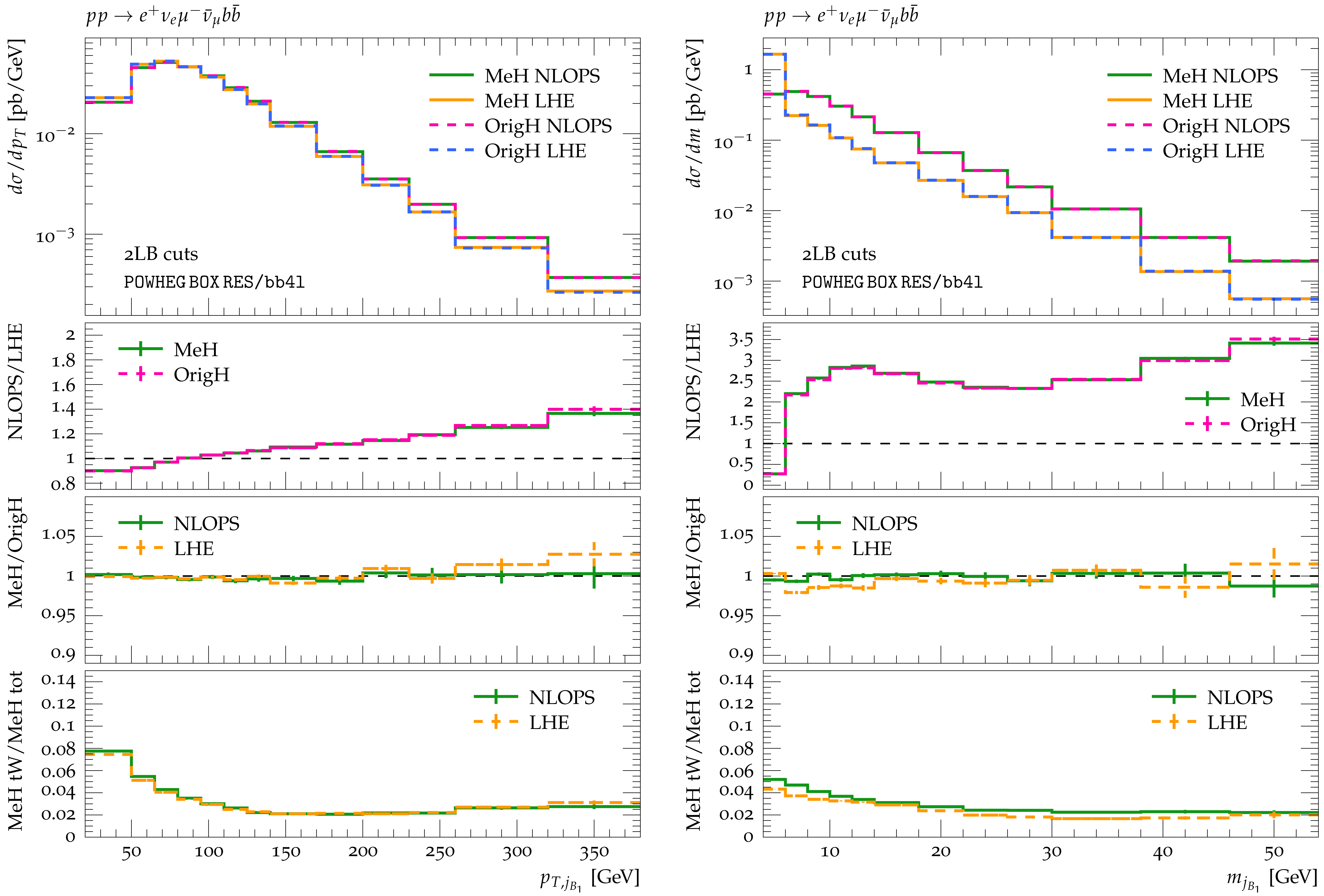
$P_2 = B_{tW^+}$

$P_3 = B_{\bar{t}W^-}$

ME projectors

# New features in bb4l-sl / bb4l-dl

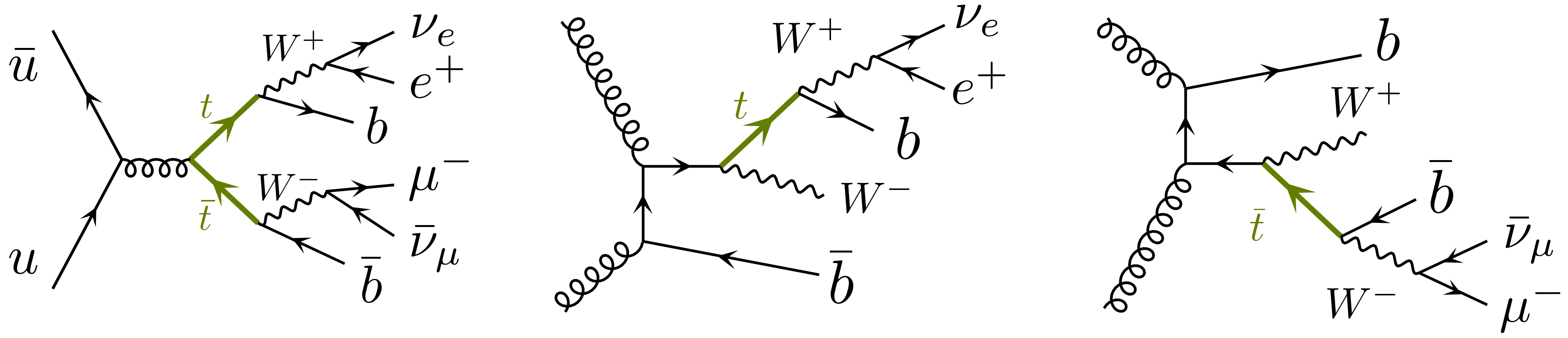
*[Jezo, JML, Pozzorini, to appear]*



- Excellent agreement between original and ME-based projectors

# New features in bb4l-sl / bb4l-dl

*[Jezo, JML, Pozzorini, to appear]*



$P_1 = B_{t\bar{t}}$

$P_2 = B_{tW^+}$

$P_3 = B_{\bar{t}W^-}$

ME projectors

$$d\sigma = \frac{P_1}{P_1+P_2+P_3} d\sigma + \frac{P_2}{P_1+P_2+P_3} d\sigma + \frac{P_3}{P_1+P_2+P_3} d\sigma$$

**ME projectors might allow to define single-top fractions in off-shell computation!**

$$\sigma_{t\bar{t}} = \lim_{\xi_t \to 0} \left( \xi_t^2 \, \sigma_{\mathrm{bb4l}} \Big|_{\Gamma_t \to \xi_t \Gamma_t} \right)$$

$$\rho_{t\bar{t}}^{(\mathrm{hist})}(\Phi_\mathrm{B})\big|_{\mathrm{ME}''} = |\mathcal{A}_{t\bar{t}}|^2 ,$$

$$\rho_{\bar{t}W^+}^{(\mathrm{hist})}(\Phi_\mathrm{B})\big|_{\mathrm{ME}''} = |\mathcal{A}_{\bar{t}W^+}|^2 ,$$

$$\rho_{tW^-}^{(\mathrm{hist})}(\Phi_\mathrm{B})\big|_{\mathrm{ME}''} = |\mathcal{A}_{tW^-}|^2 ,$$

$$\rho_{\mathrm{rem}}^{(\mathrm{hist})}(\Phi_\mathrm{B})\big|_{\mathrm{ME}''} = |\mathcal{A}_{\mathrm{full}}|^2 - |\mathcal{A}_{t\bar{t}}|^2 - |\mathcal{A}_{\bar{t}W^+}|^2 - |\mathcal{A}_{tW^-}|^2$$

| | naive | | matrix-element based | | | extrapolation |
|---|---|---|---|---|---|---|
| | $\chi = 1$ | $\chi = 0.1$ | ME | ME$'$ | ME$''$ | $\Gamma_t \to 0$ |
| $t\bar{t}$ | 90.6% | 95.3% | 94.2% | 93.7% | 95.3% | 96.0% |
| $tW$ | 9.4% | 4.7% | 5.8% | 6.3% | 6.2% | 4.0% |
| rem | | | | | – 1.5% | |