# High-precision for high-energy tails


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UK Research and Innovation


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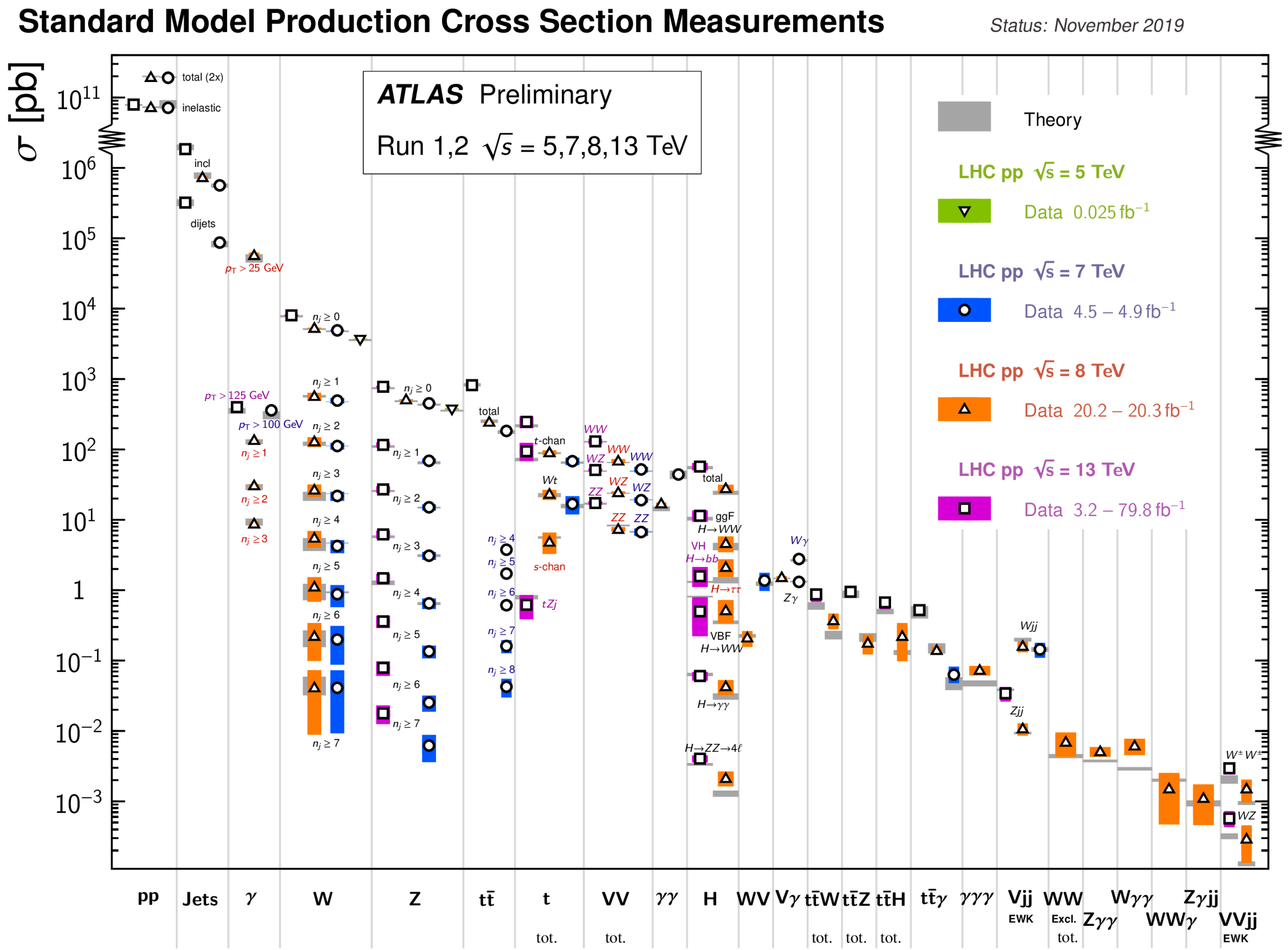
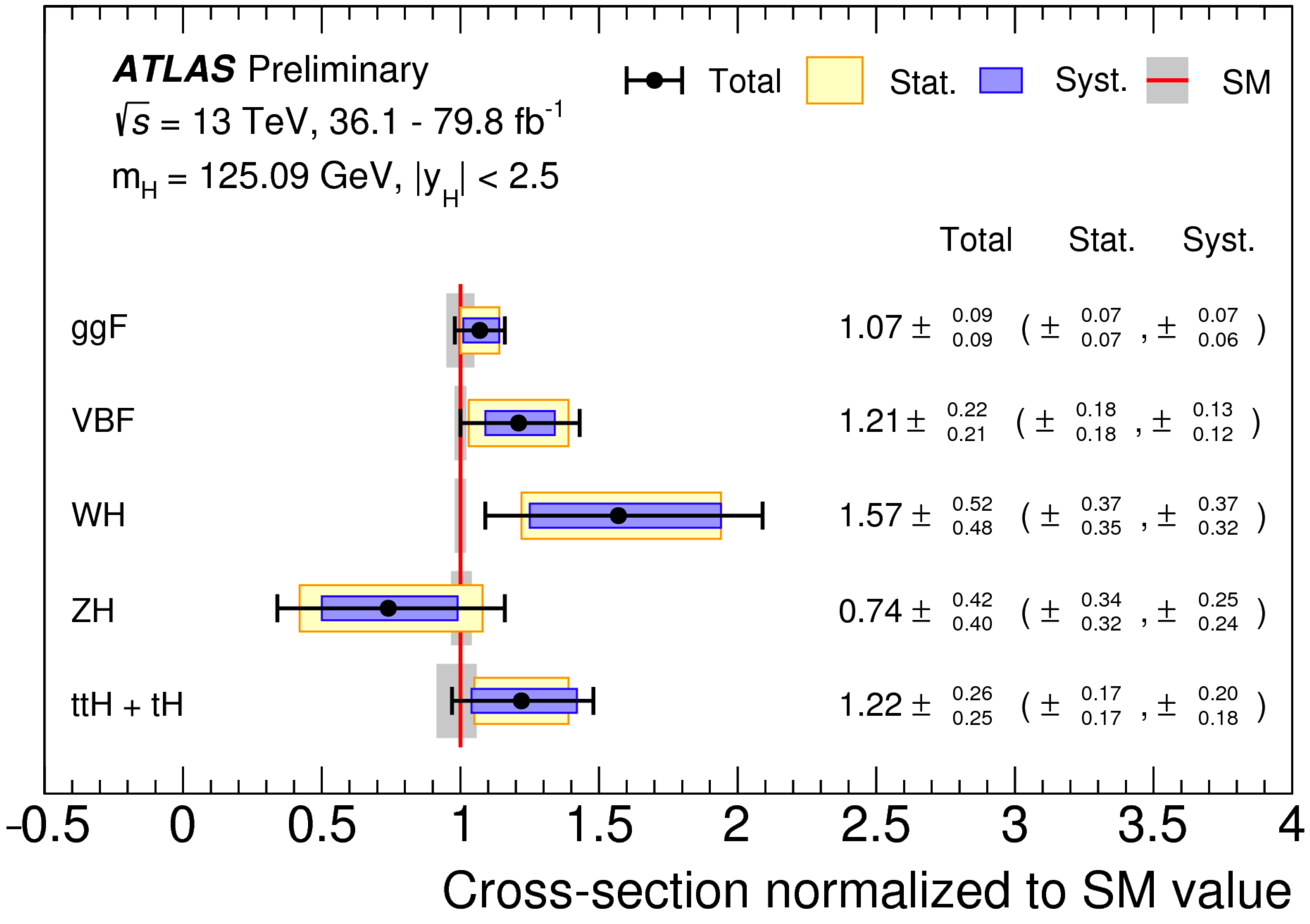
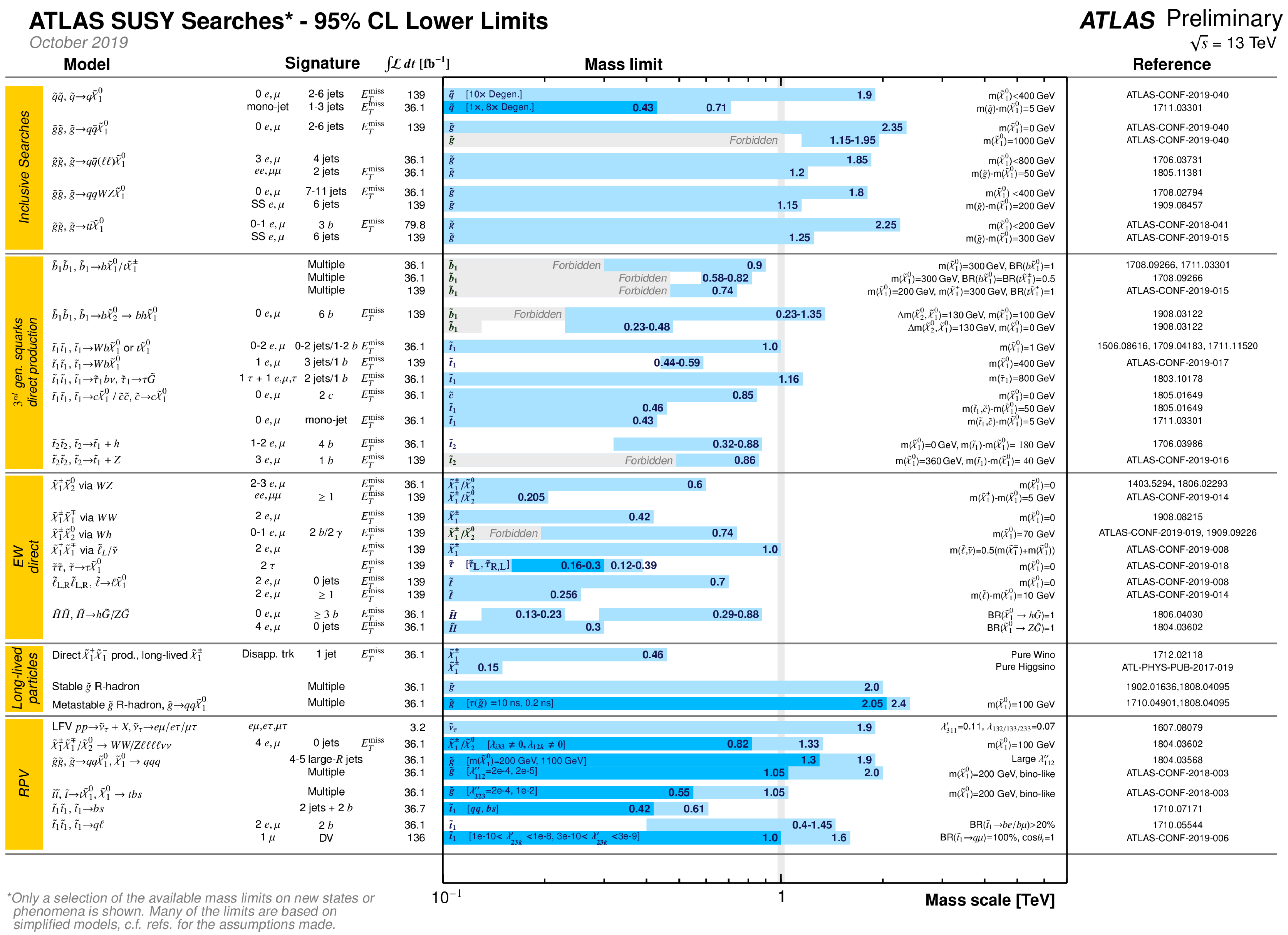
# Remarkable data vs. theory agreement in SM+Higgs measurements

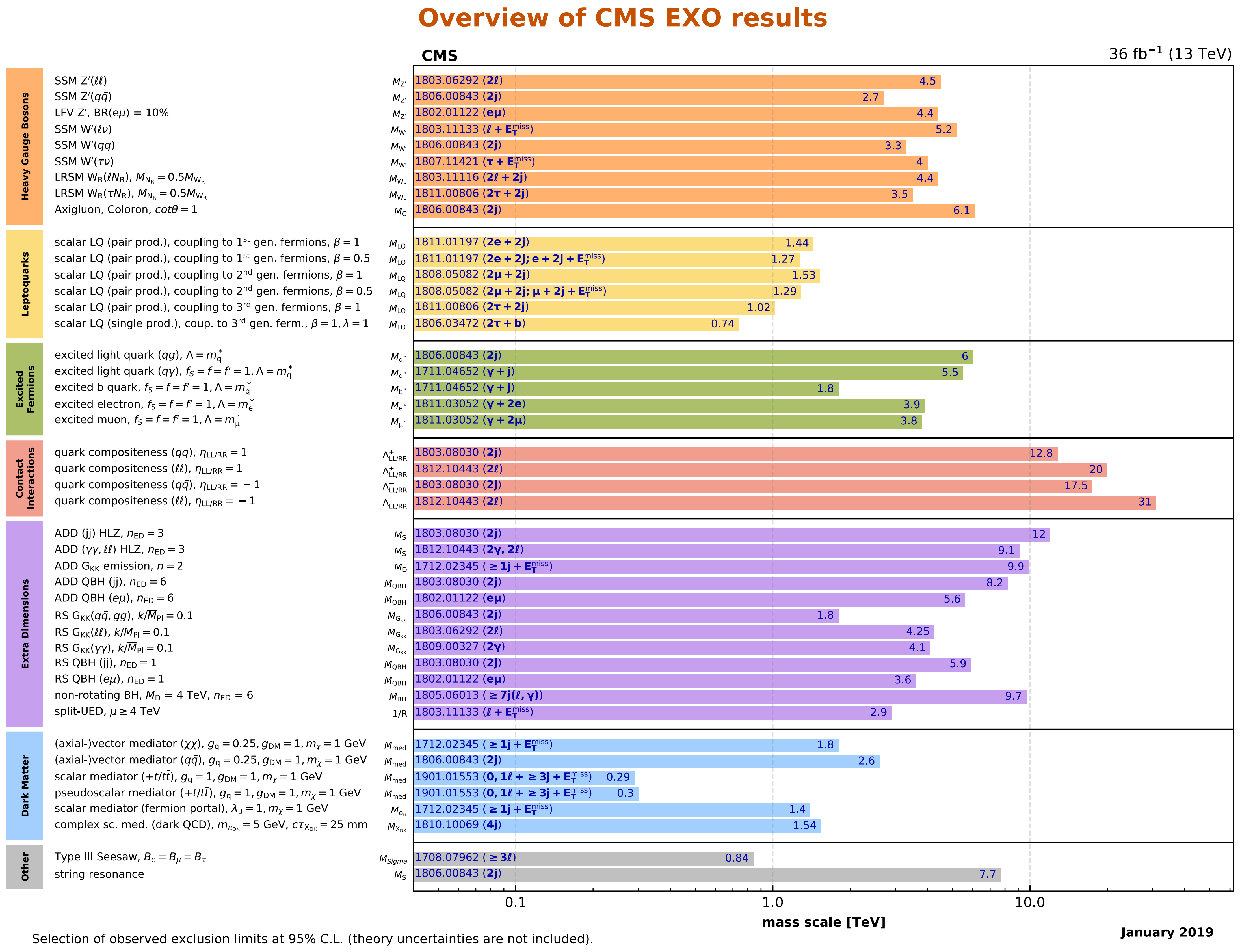



➡Precision tests of the SM at the quantum level

# BSM certainly not ‘around the corner’

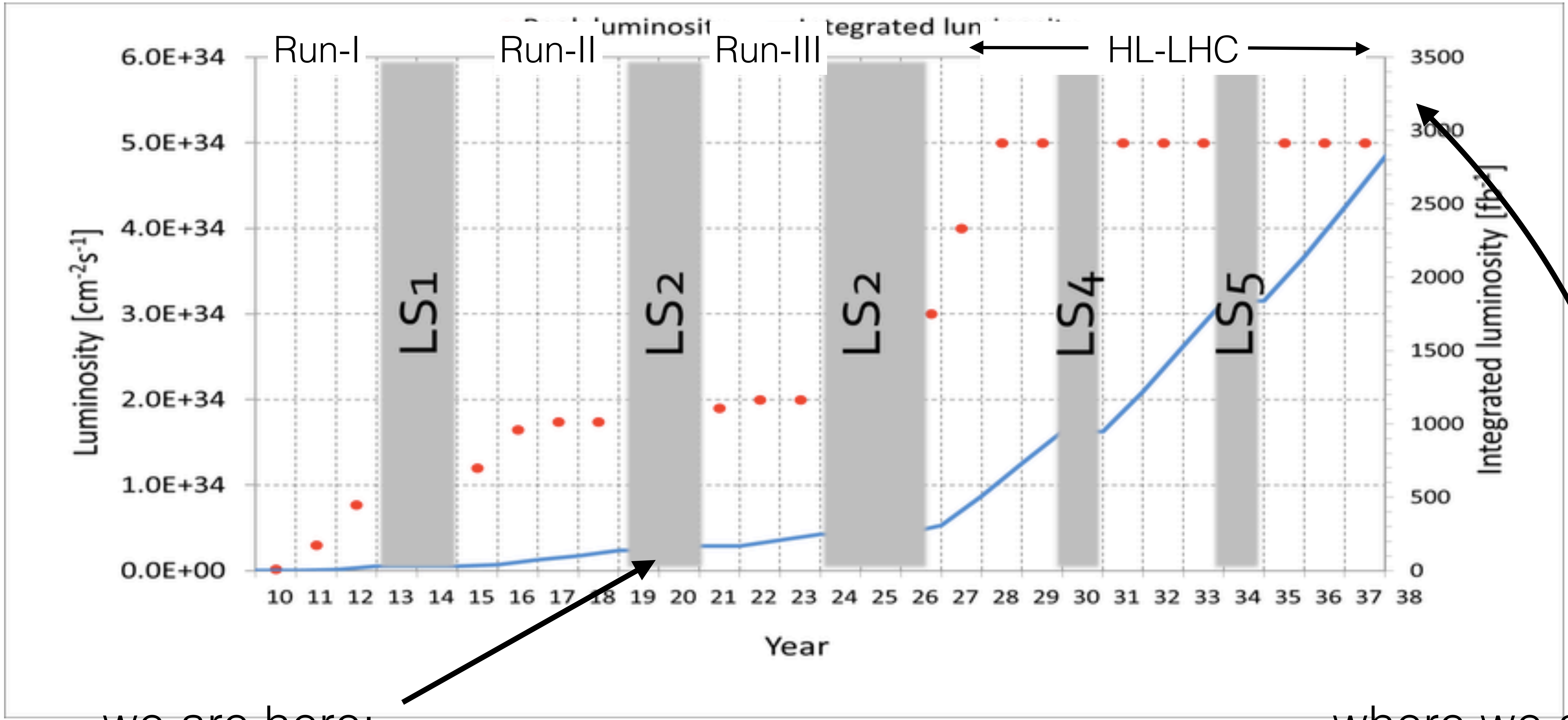



Mgluino > 2 TeV
Msquark > 0.7-2 TeV
Mstop > 400 GeV …

Z’ > 4.5 TeV
W’> 5 TeV
Mleptoquark > 1 TeV …

# Timescale of the LHC



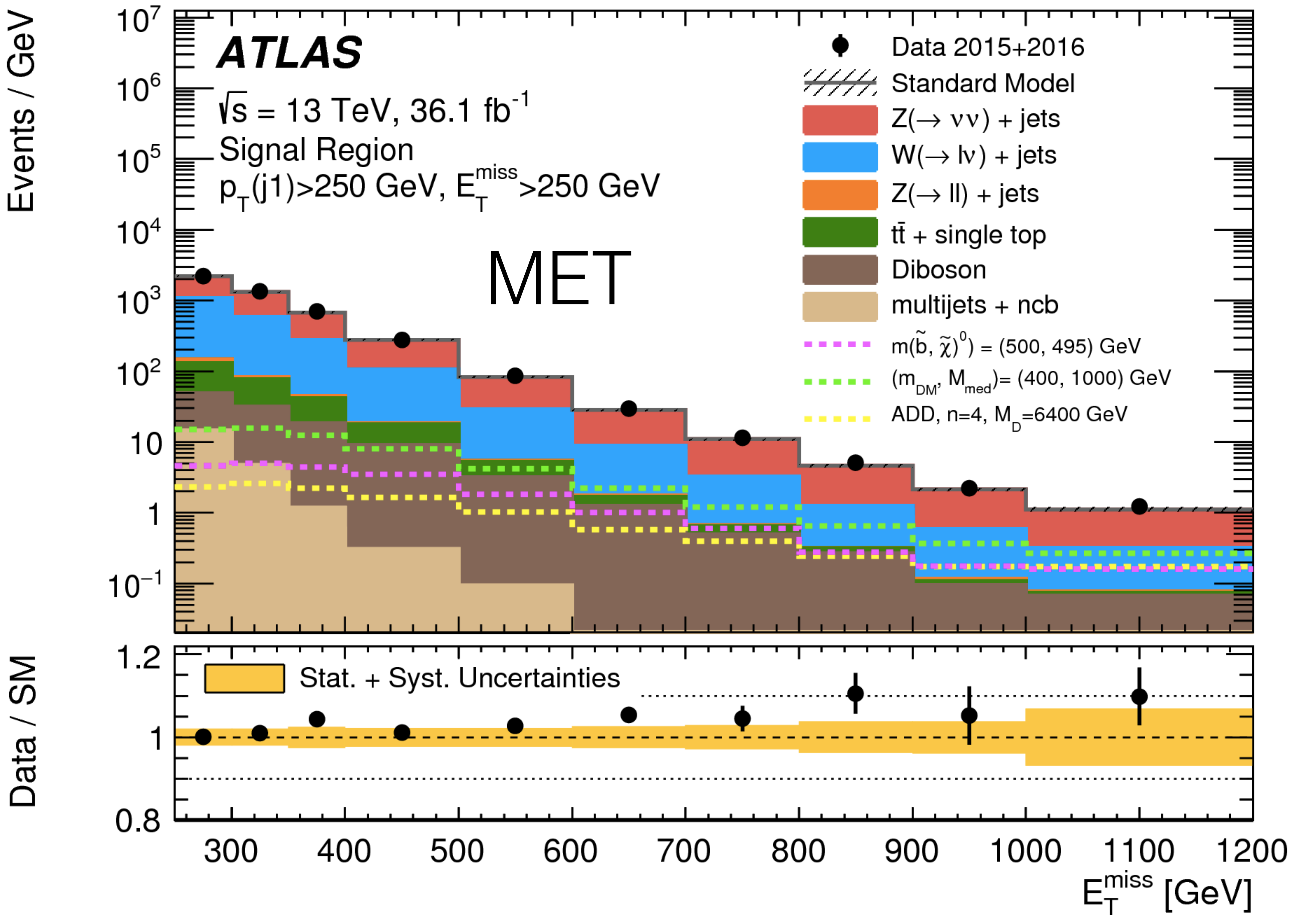

we are here:
$L=140\ fb^{-1}$

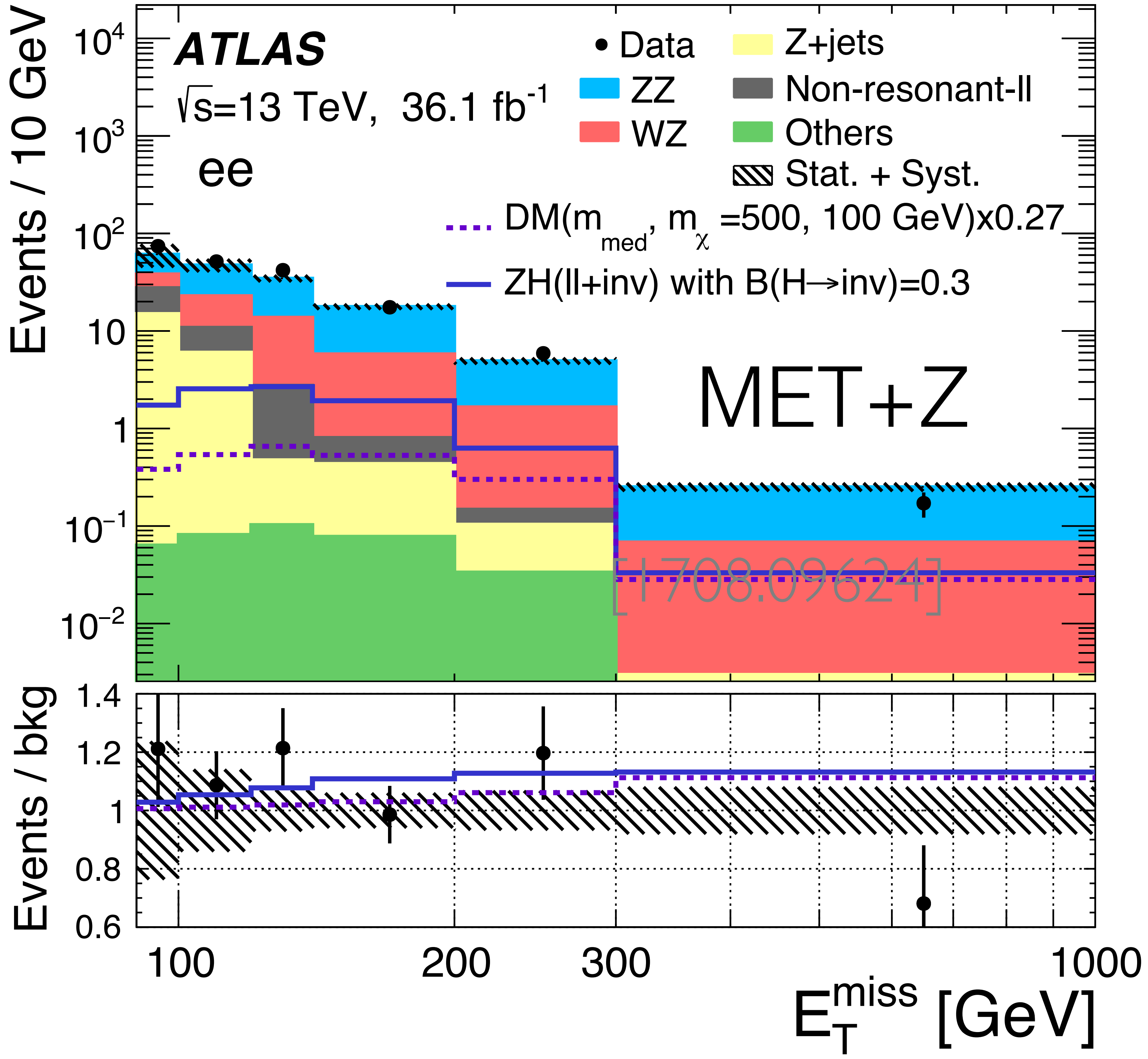
where we are going:
$L=3000\ fb^{-1}$

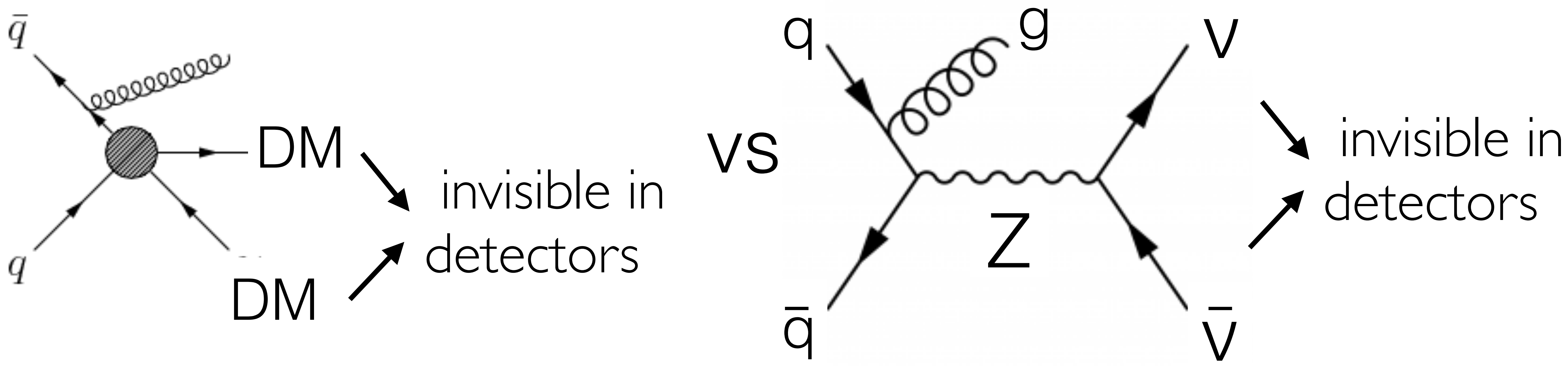
Experimental uncertainties will dramatically decrease in the future. Often reaching O(1%).

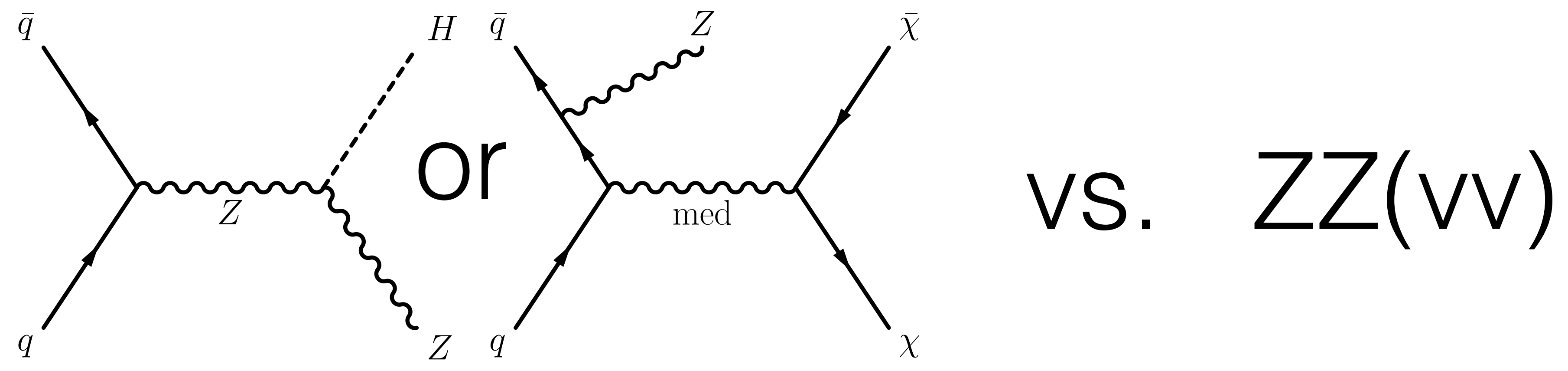
# Differential SM measurements

# The need for precision in tails: **Direct searches**



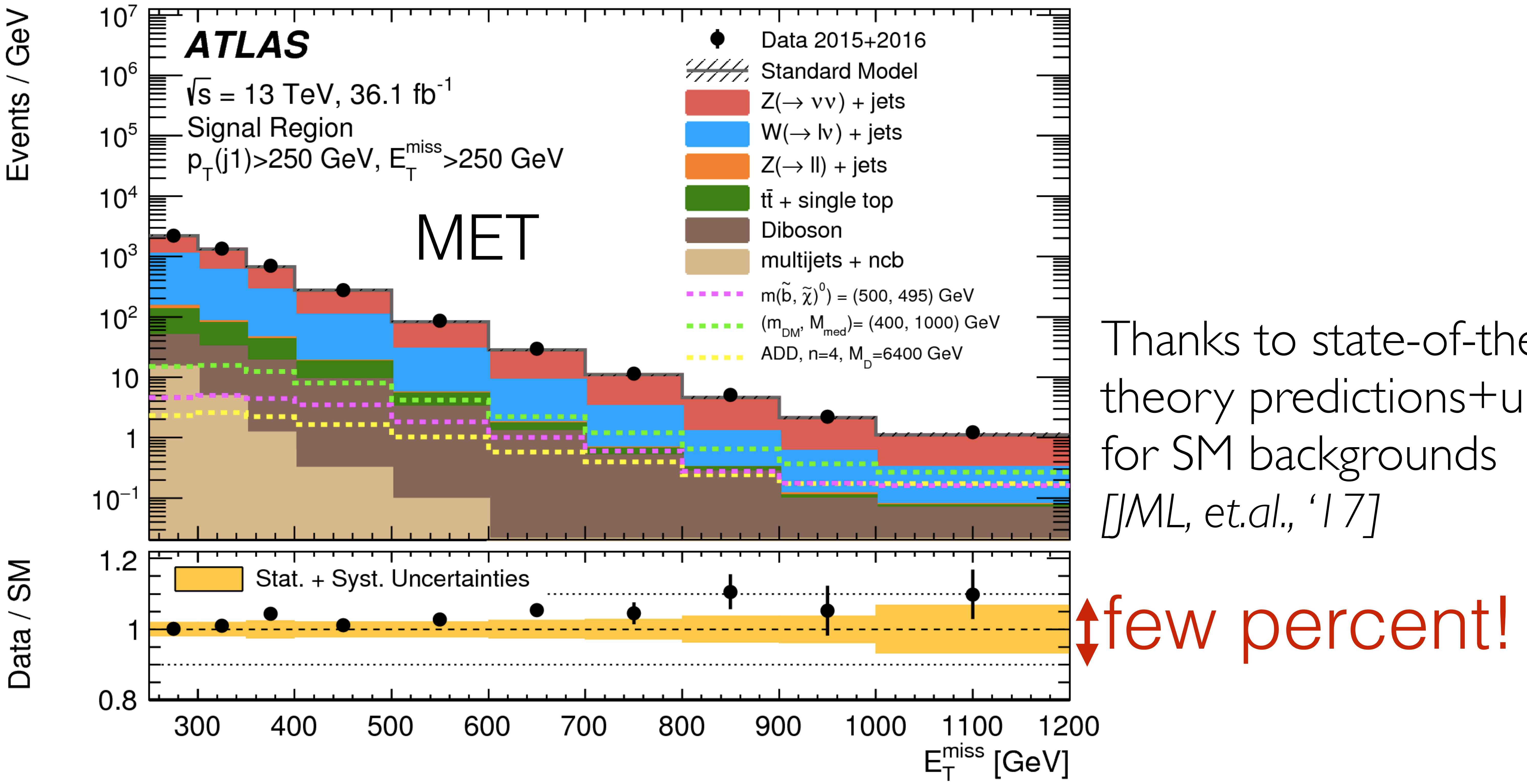



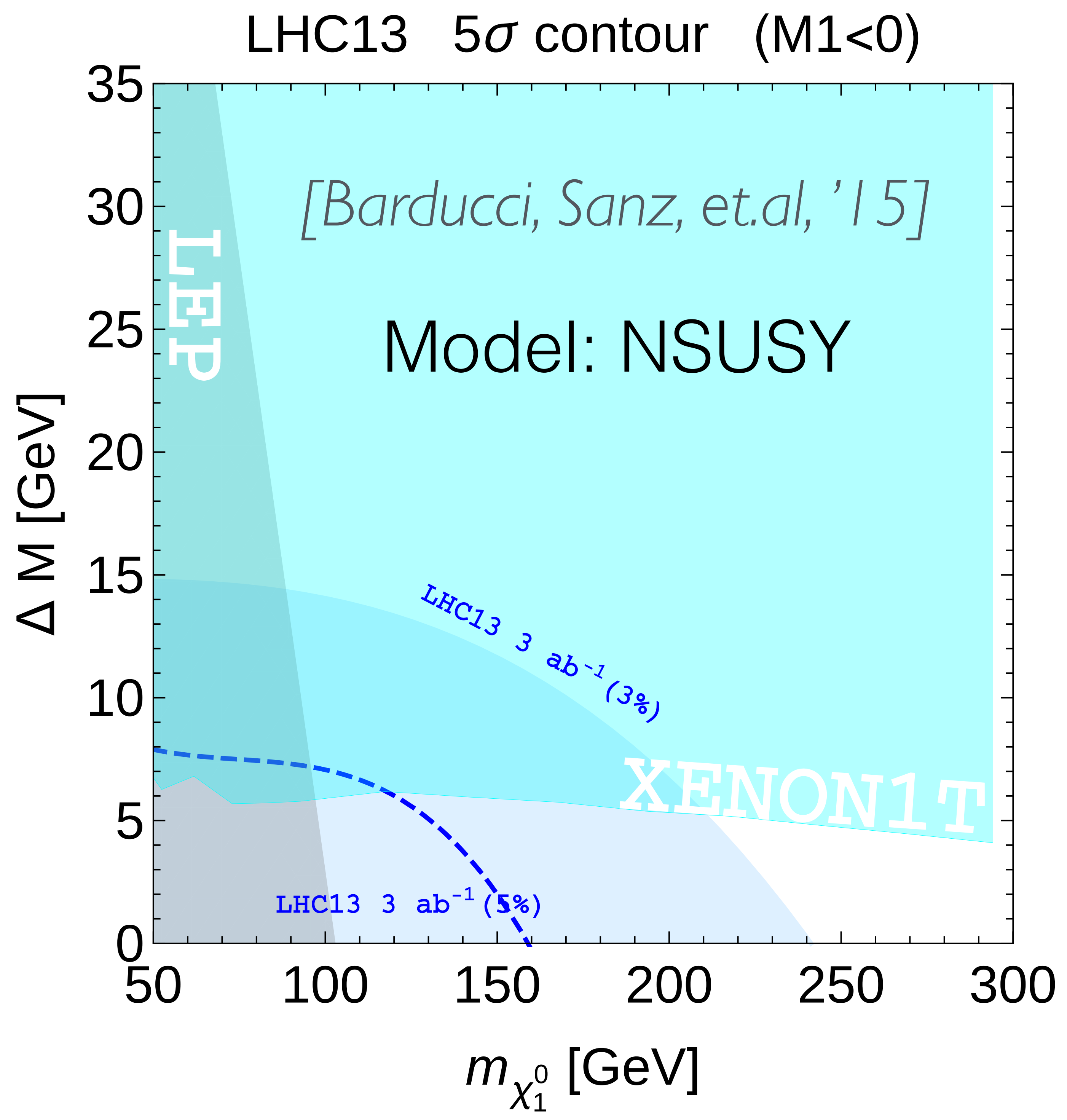



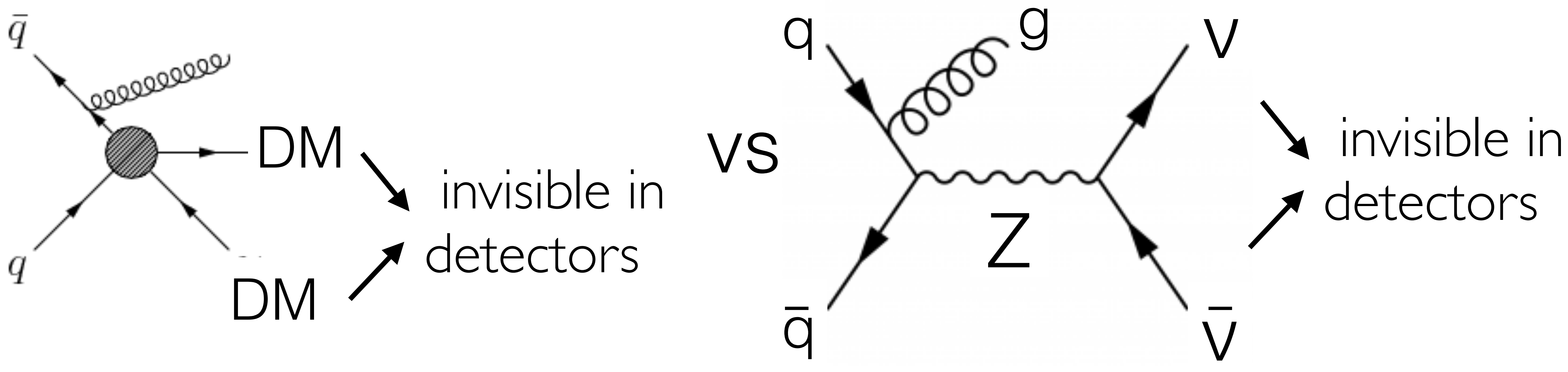

→very good control on large irreducible SM backgrounds necessary!

# The need for precision in tails: **Direct searches**



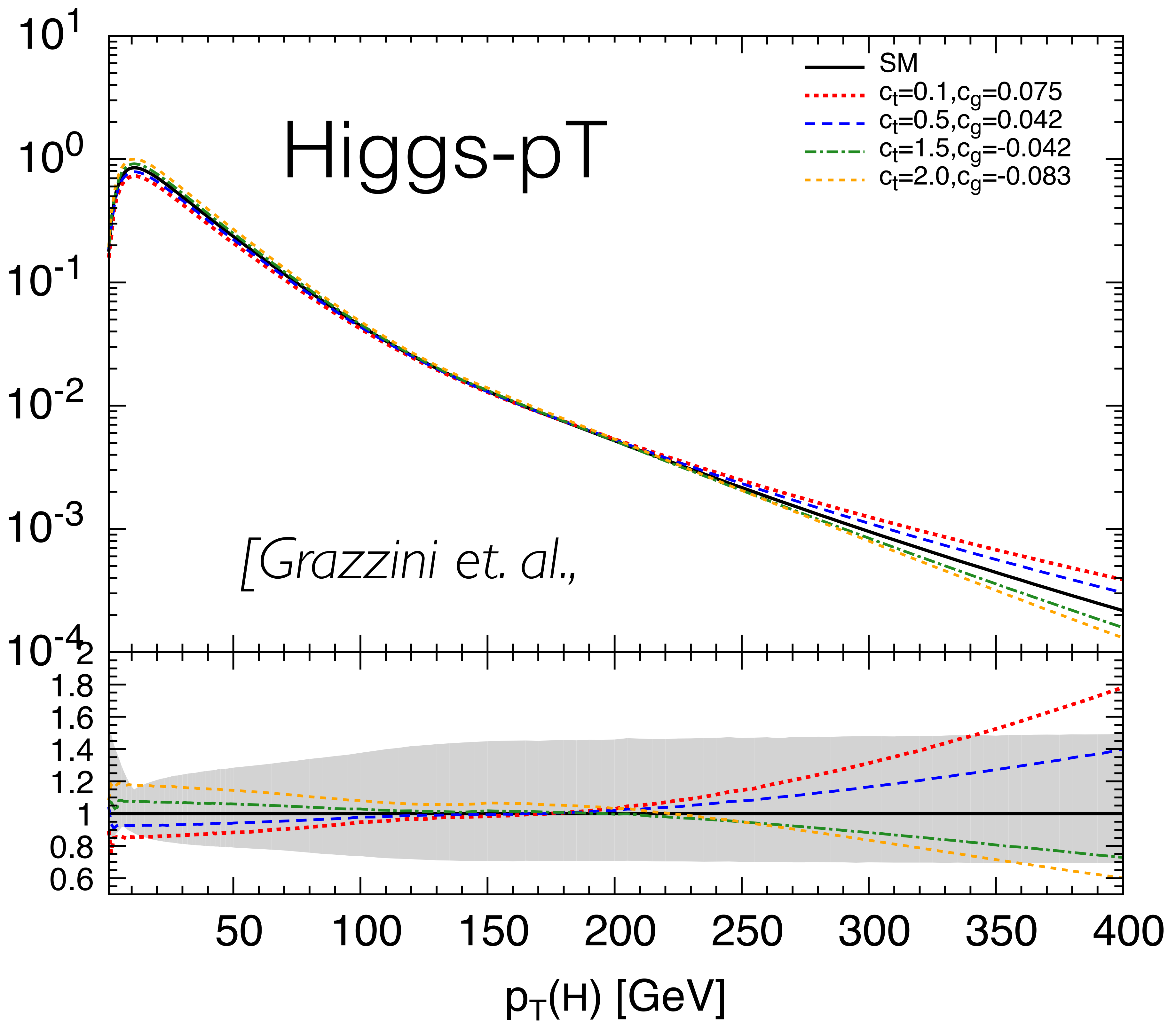

Thanks to state-of-the-art theory predictions+uncertainties for SM backgrounds *[JML, et.al., '17]*

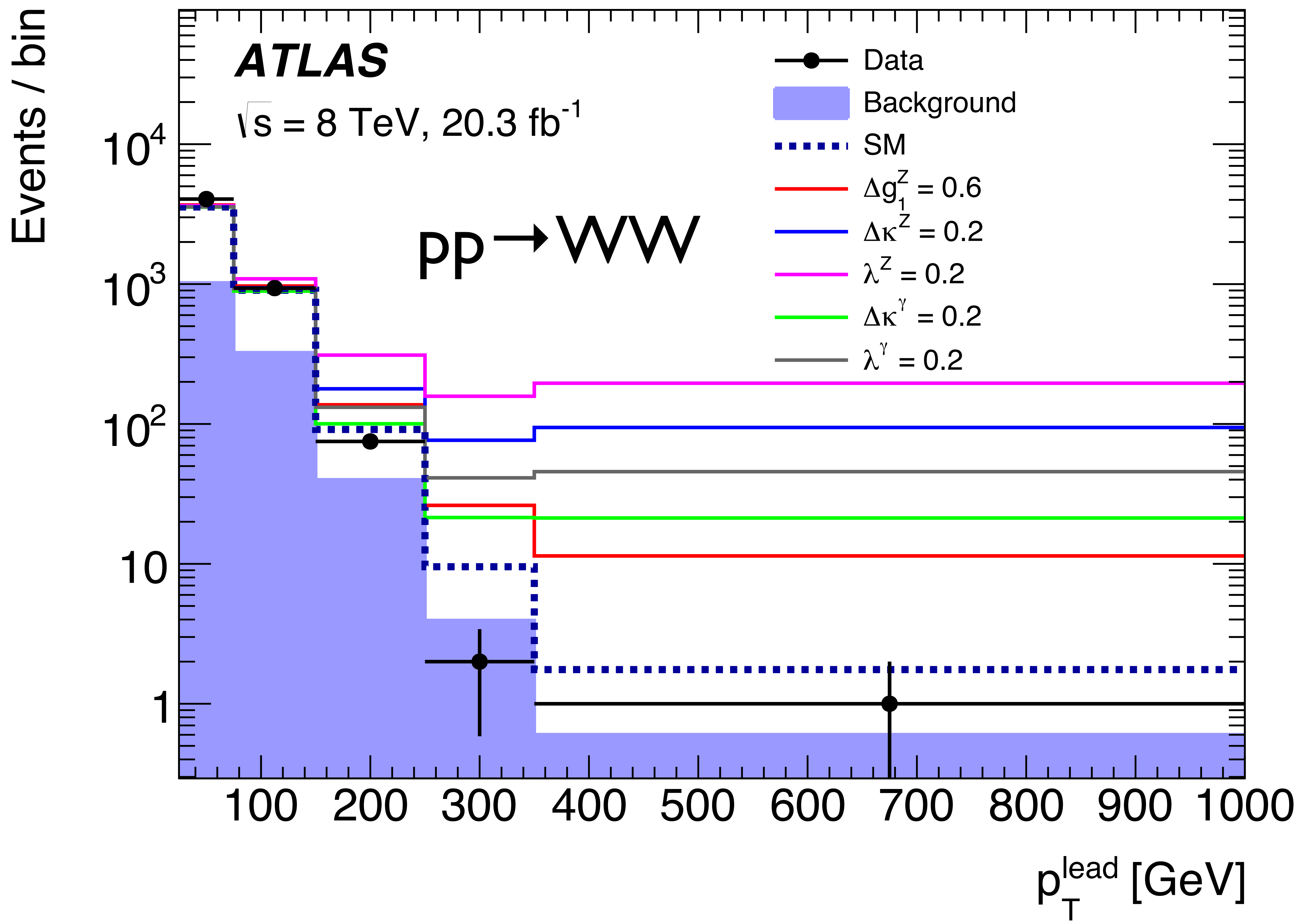



→very good control on large irreducible SM backgrounds necessary!

# The need for precision in tails: **Indirect searches**



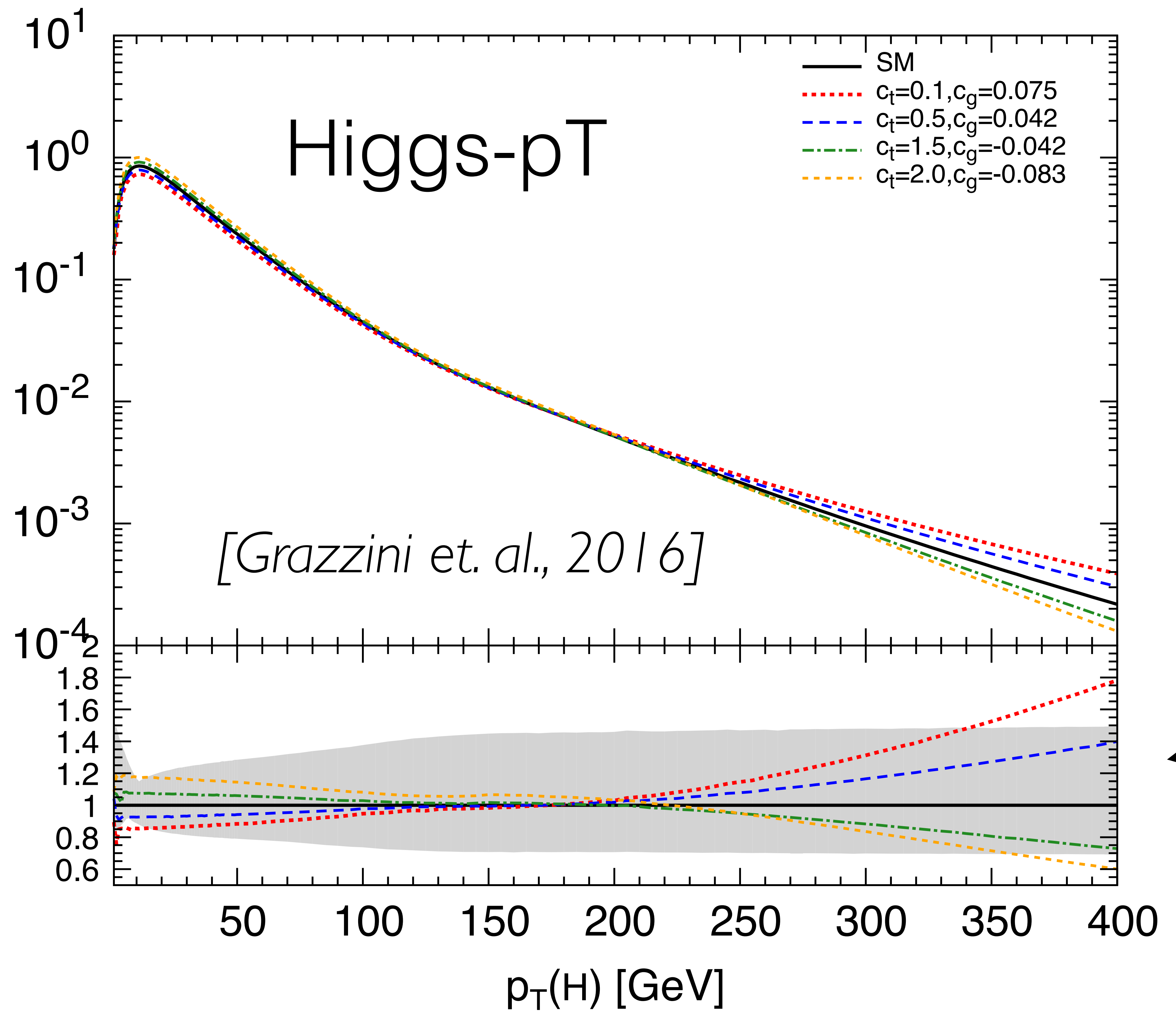



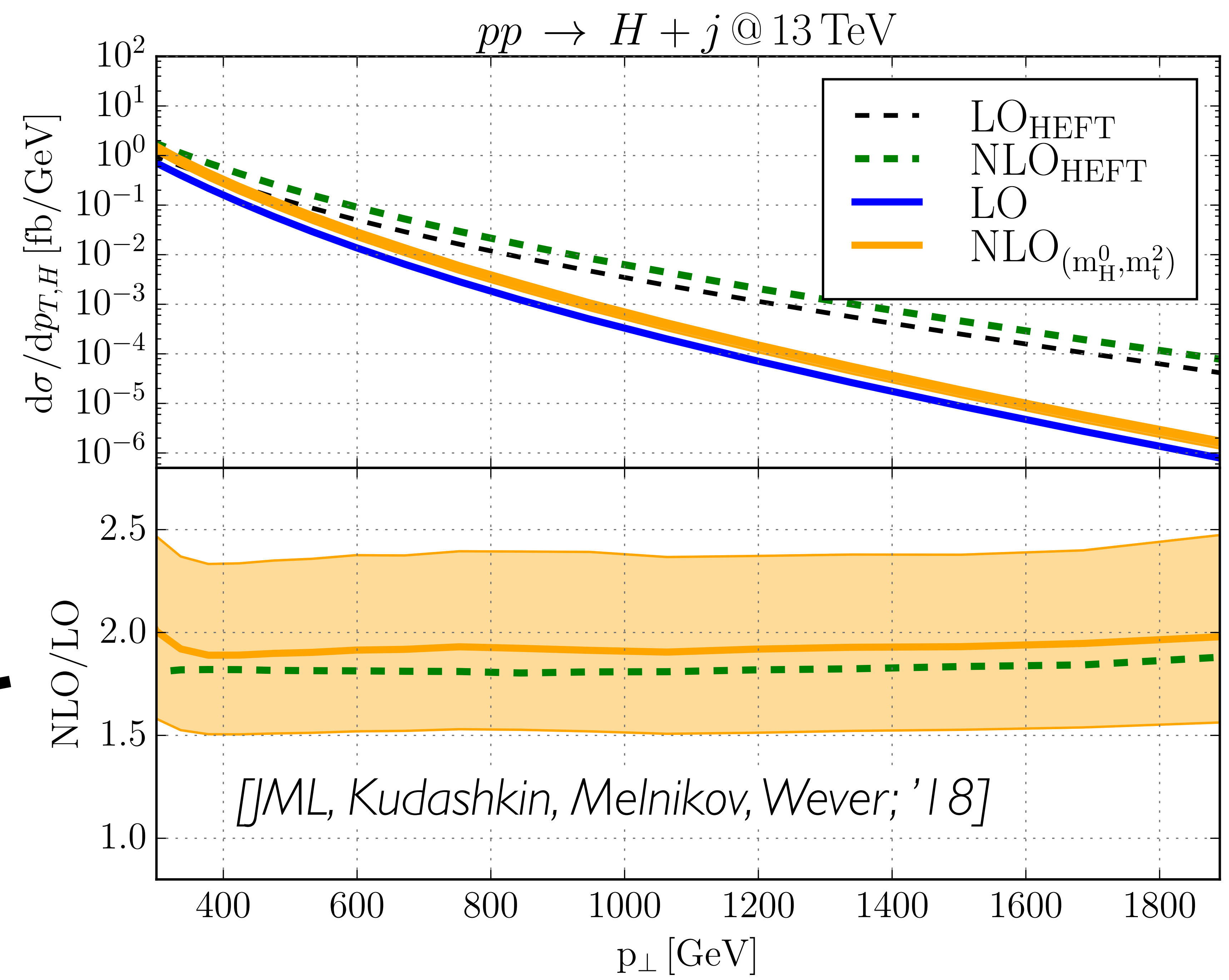

- many effective BSM operators yield growth with energy

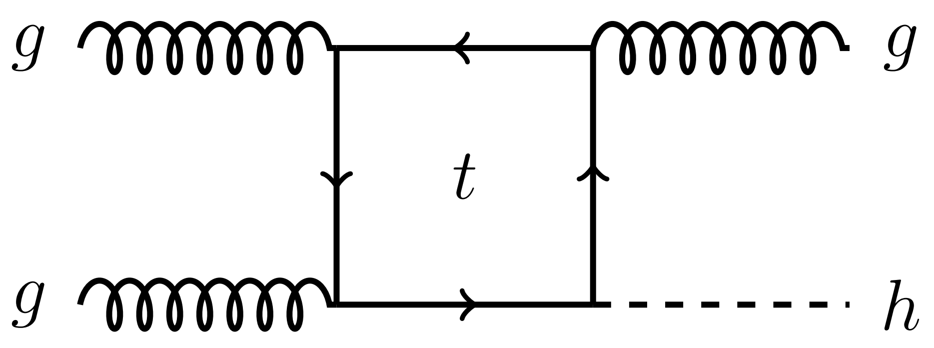
→ expect small deviations in tails of distributions:

→ **very good control on SM predictions necessary!**

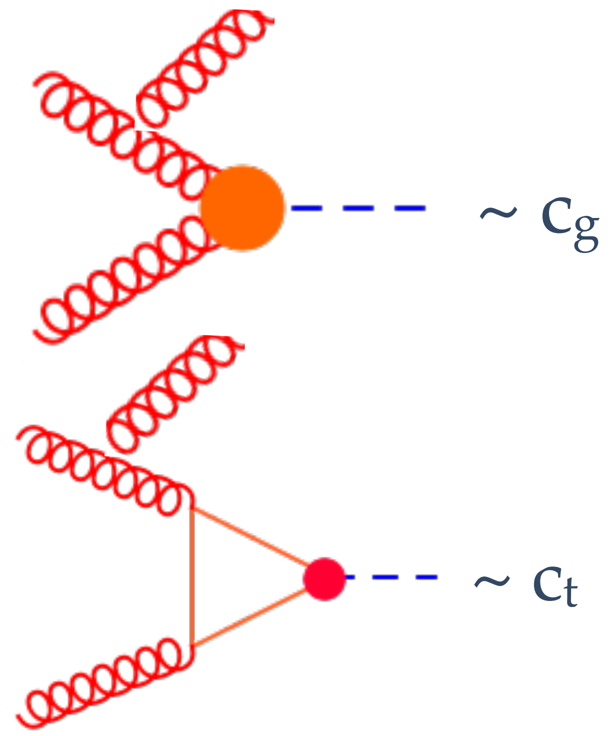
# The need for precision in tails: **Indirect searches**




vs.

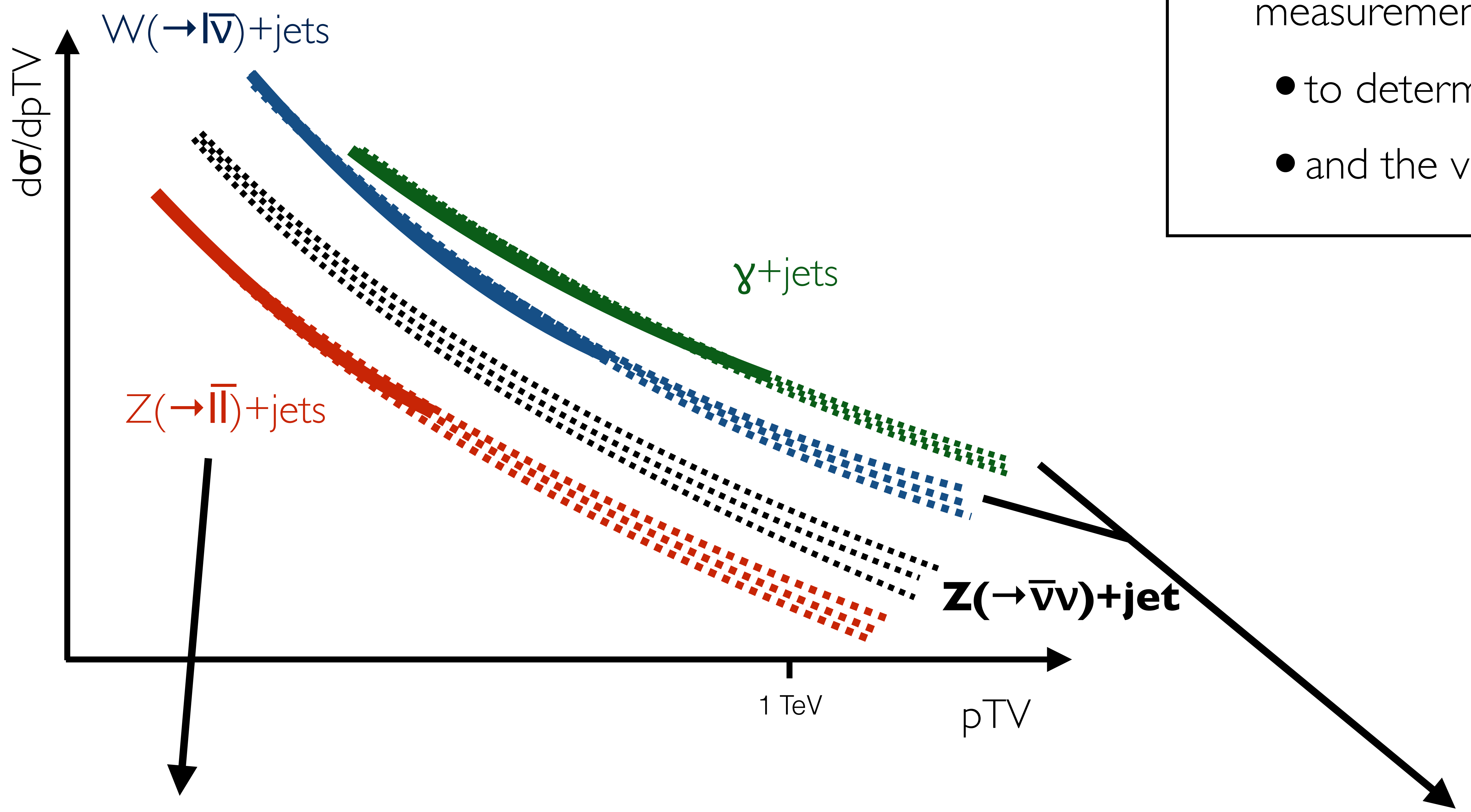



→Theory precision opens the door to the high H-pT laboratory!

# Determine V+jets backgrounds: the DM case

**global fit** of Z(→$l\bar{l}$)+jets, W(→$l\bar{\nu}$)+jets and γ+jets measurements

- to determine Z(→$\bar{\nu}\nu$)+jet
- and the visible channels at high-pT

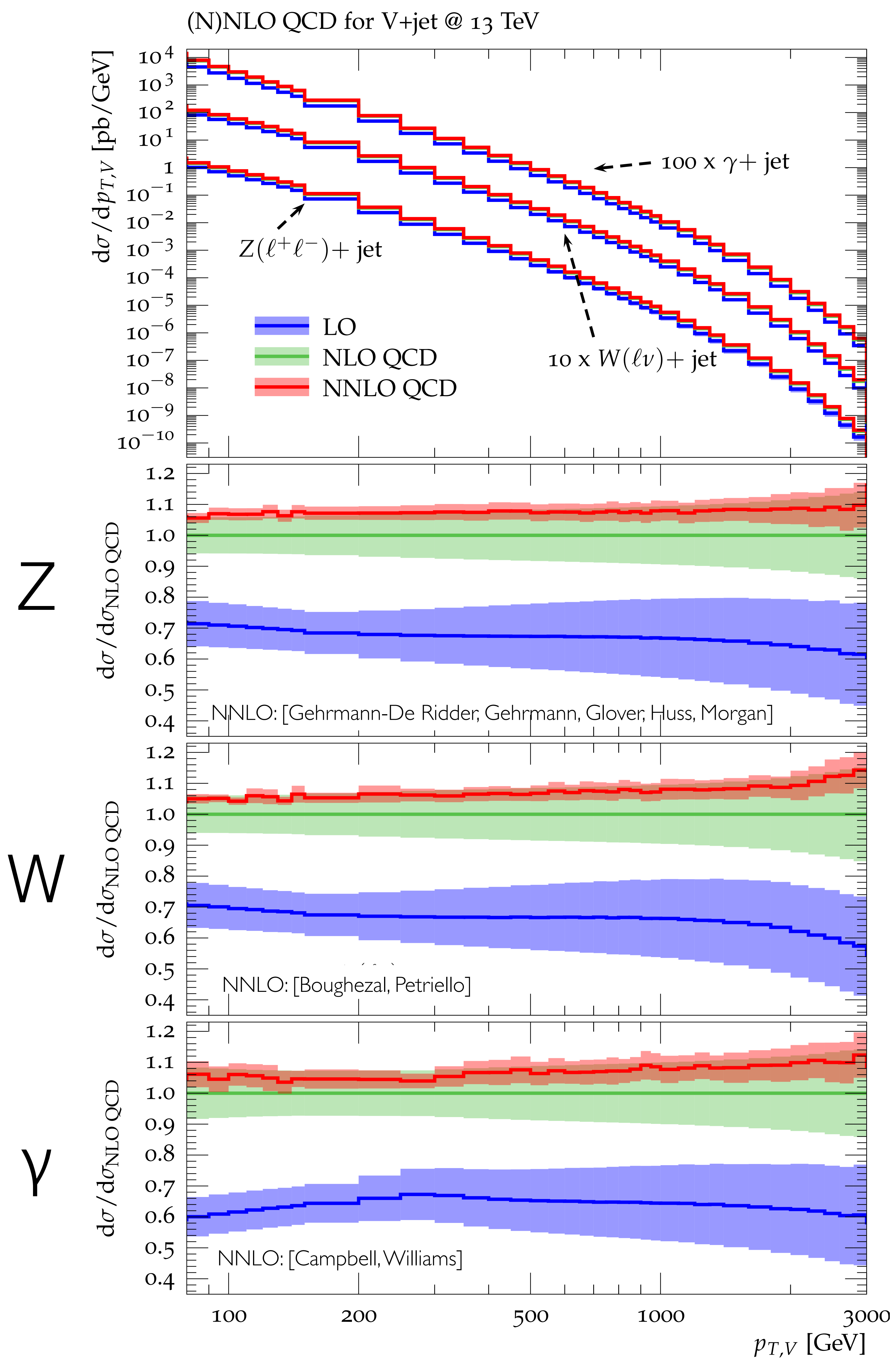



- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT

- fairly large data samples at large pT
- systematics from transfer factors: ratios of V+jets processes

# QCD uncertainties

[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

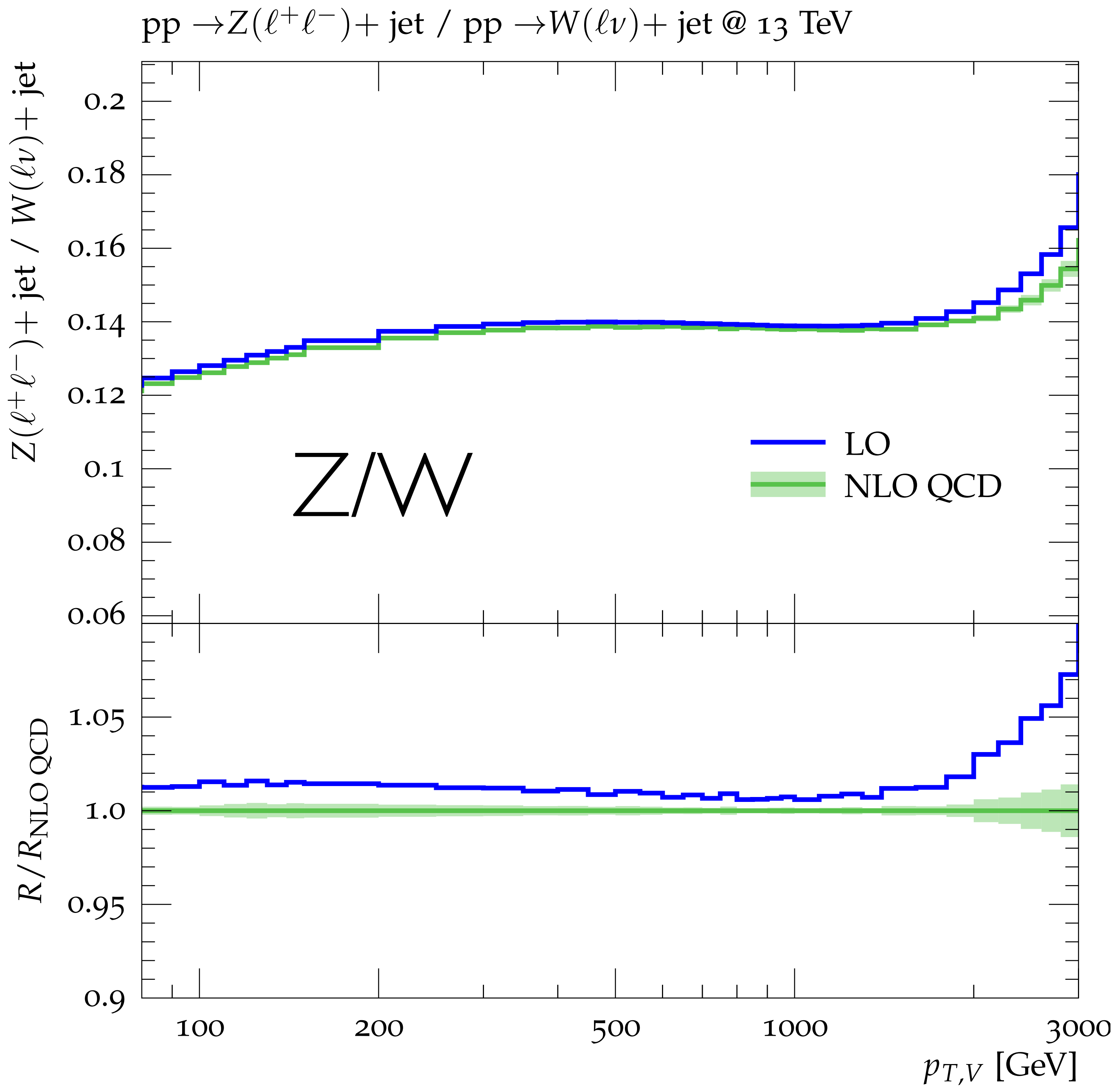
with minor shape variations

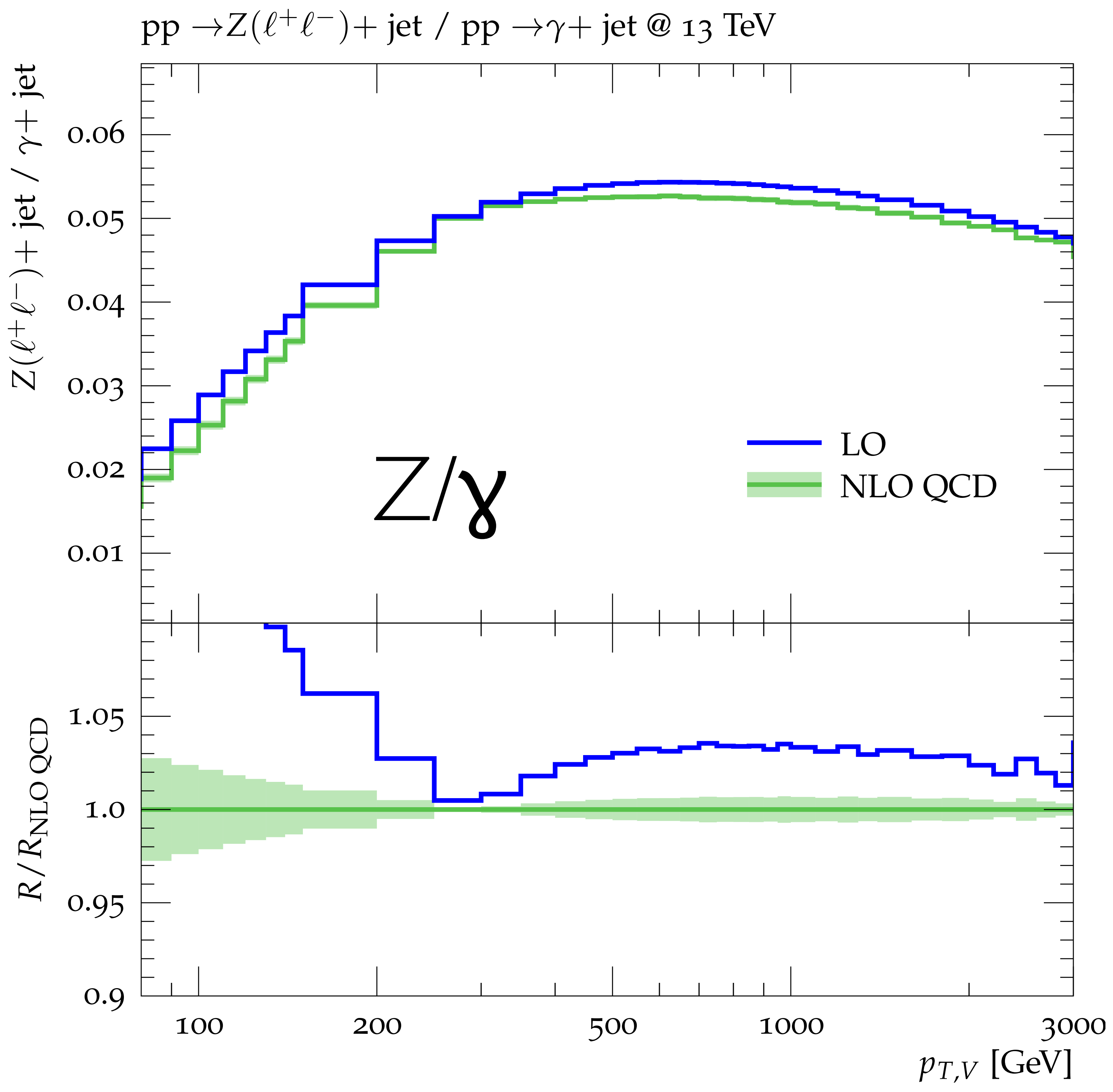
**How to correlate these uncertainties across processes?**

# QCD uncertainties: ratios

## How to correlate these uncertainties across processes?

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

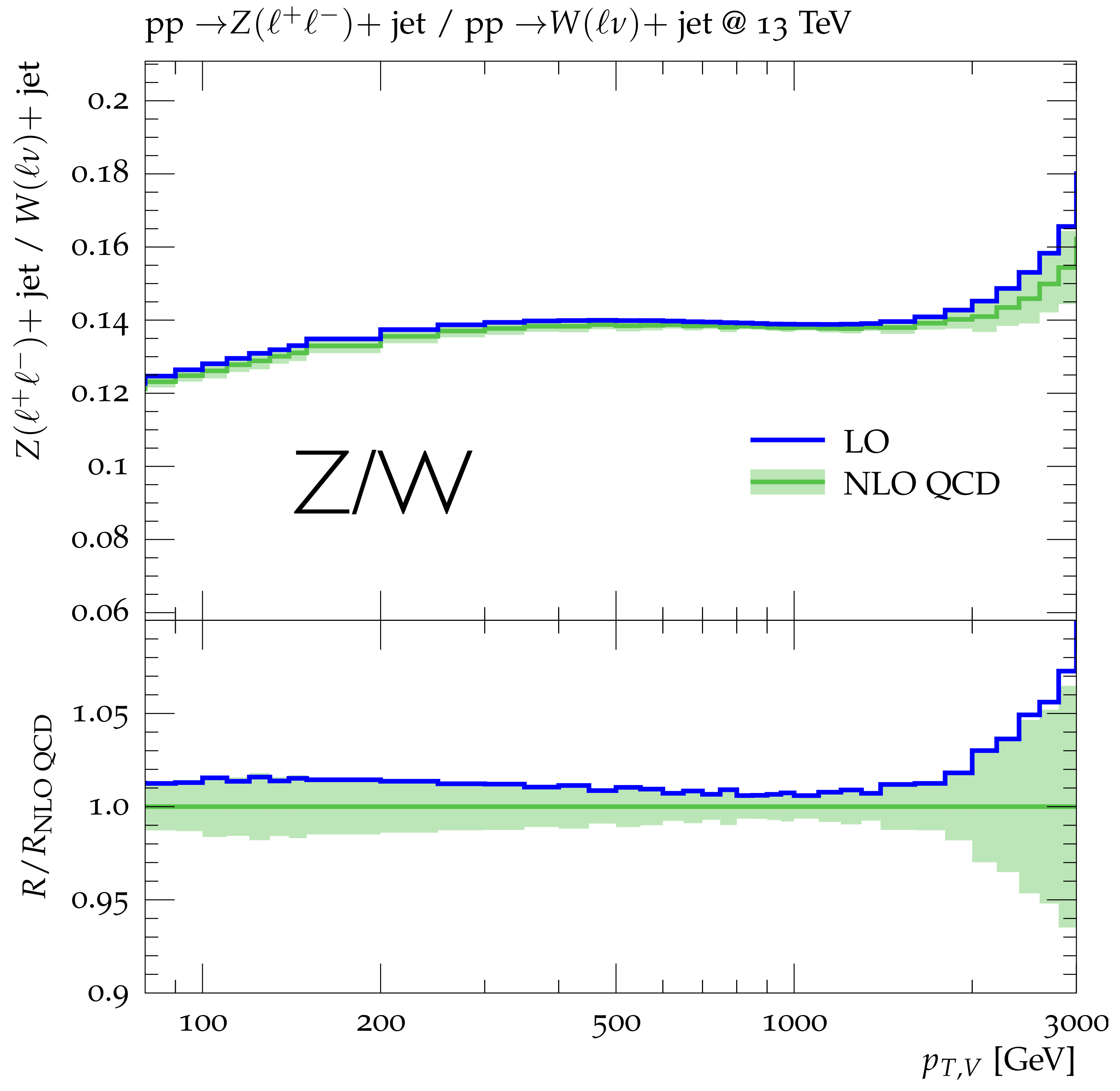


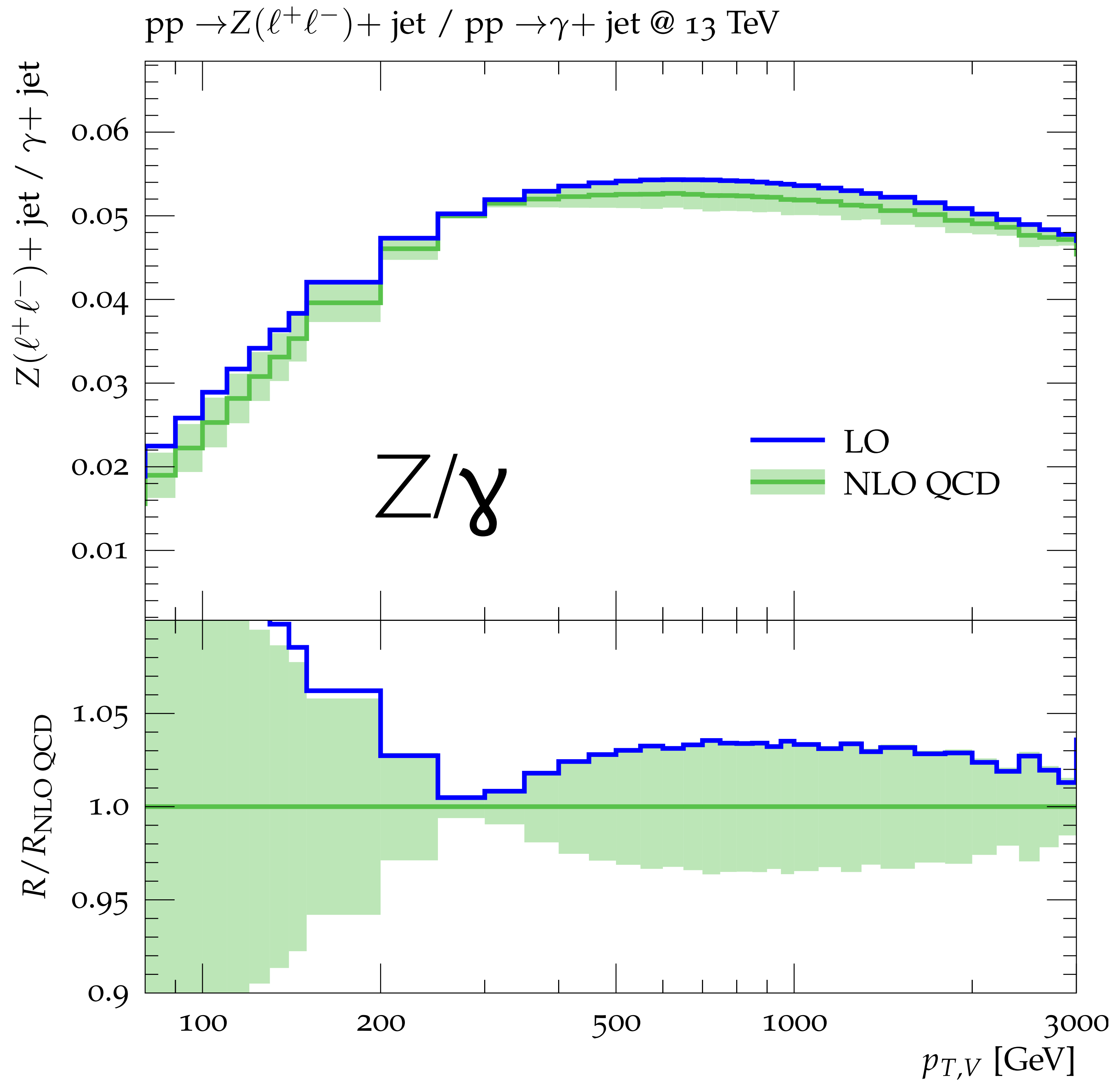
# QCD uncertainties: ratios

**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?**

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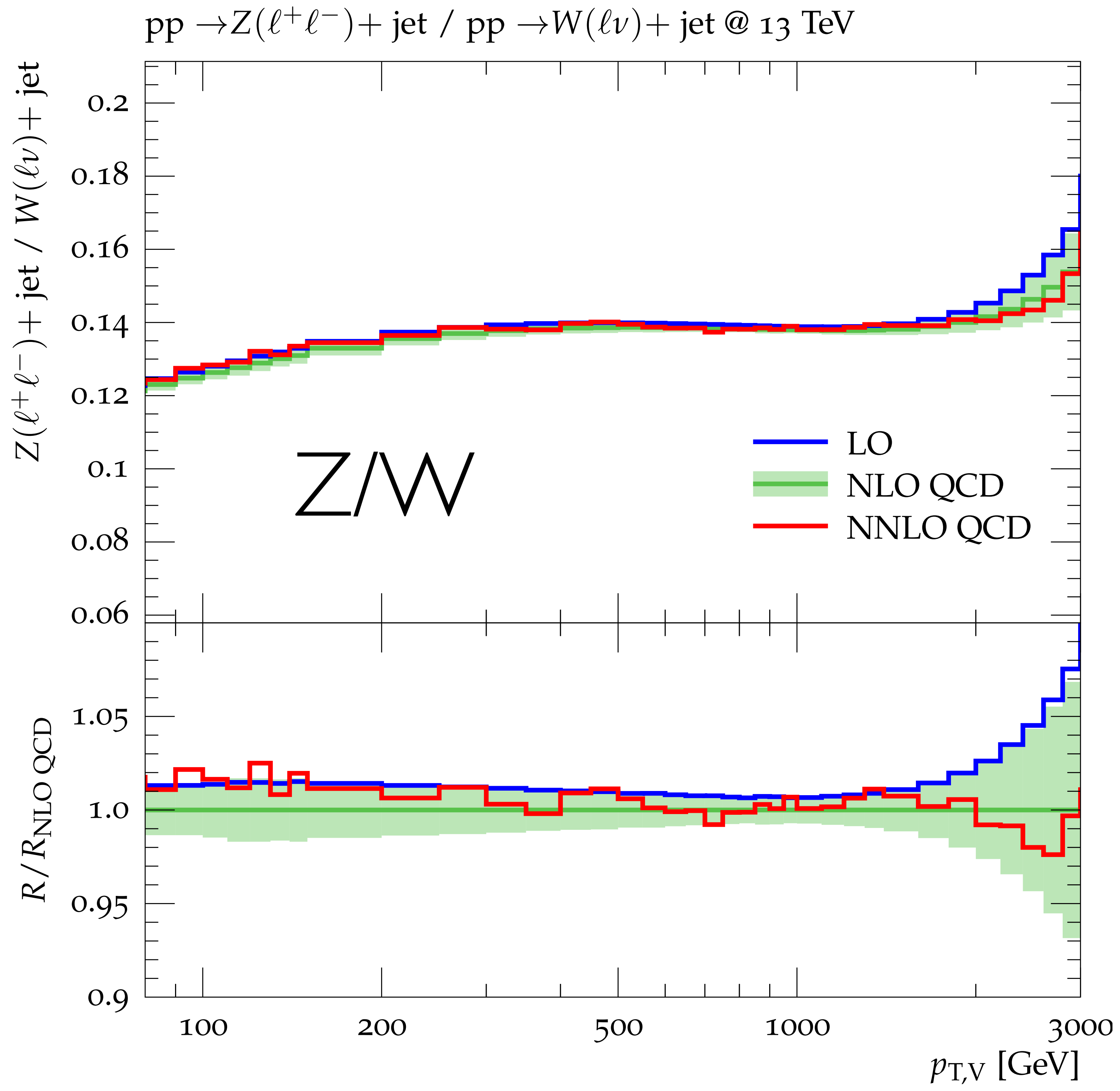
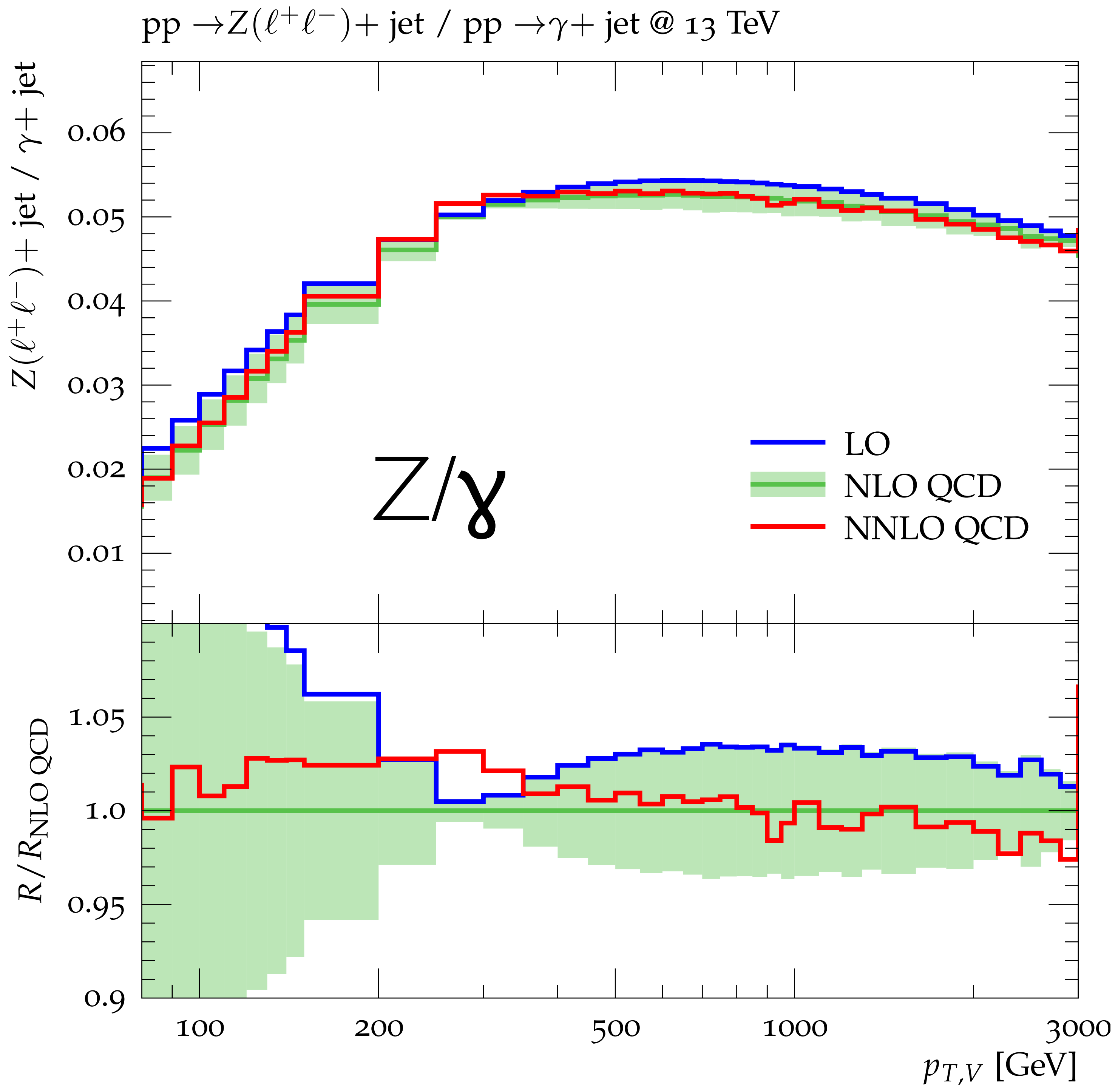


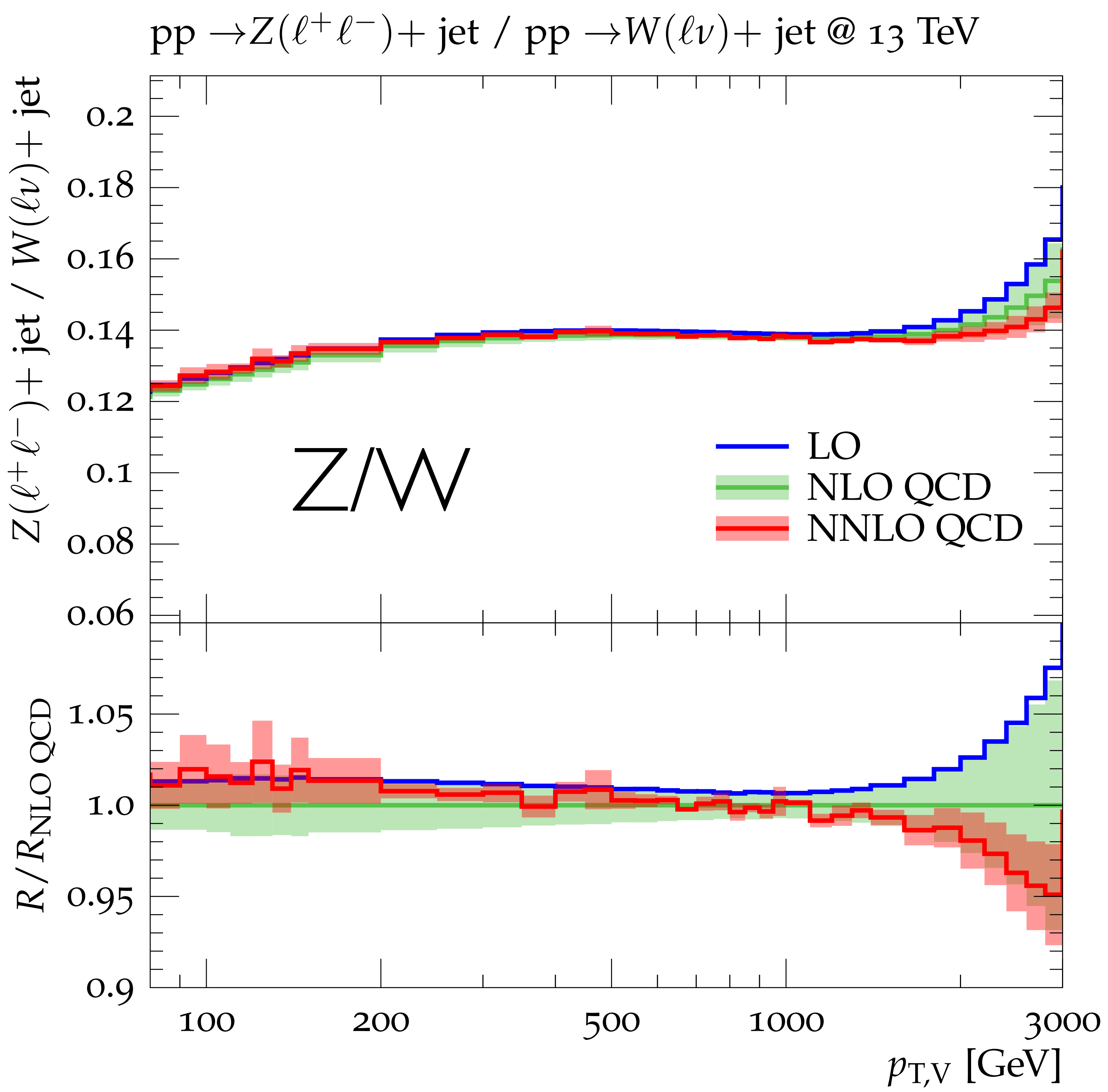



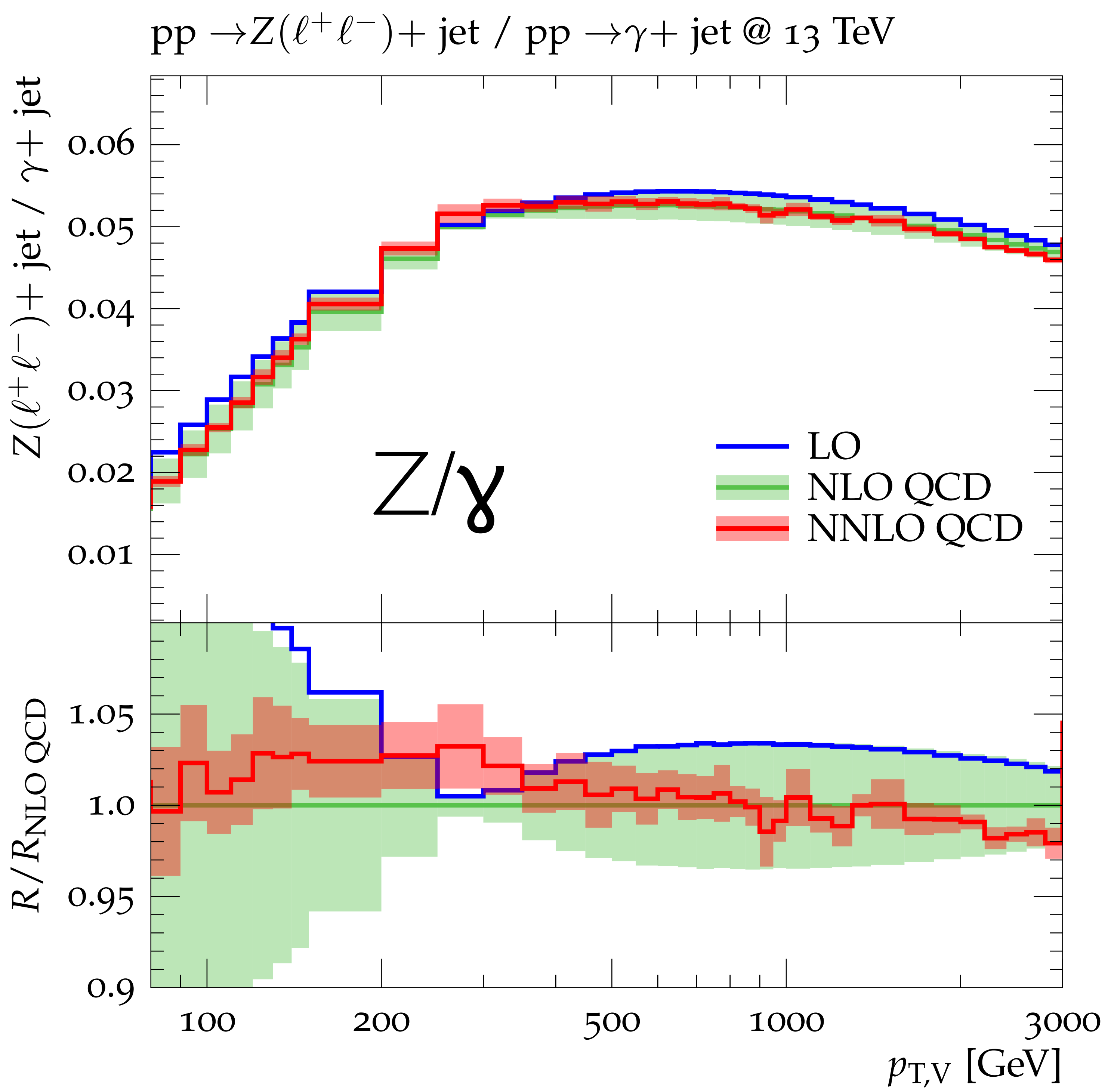

**check against NNLO QCD!**

# QCD uncertainties: ratios

**How to correlate these uncertainties across processes?**

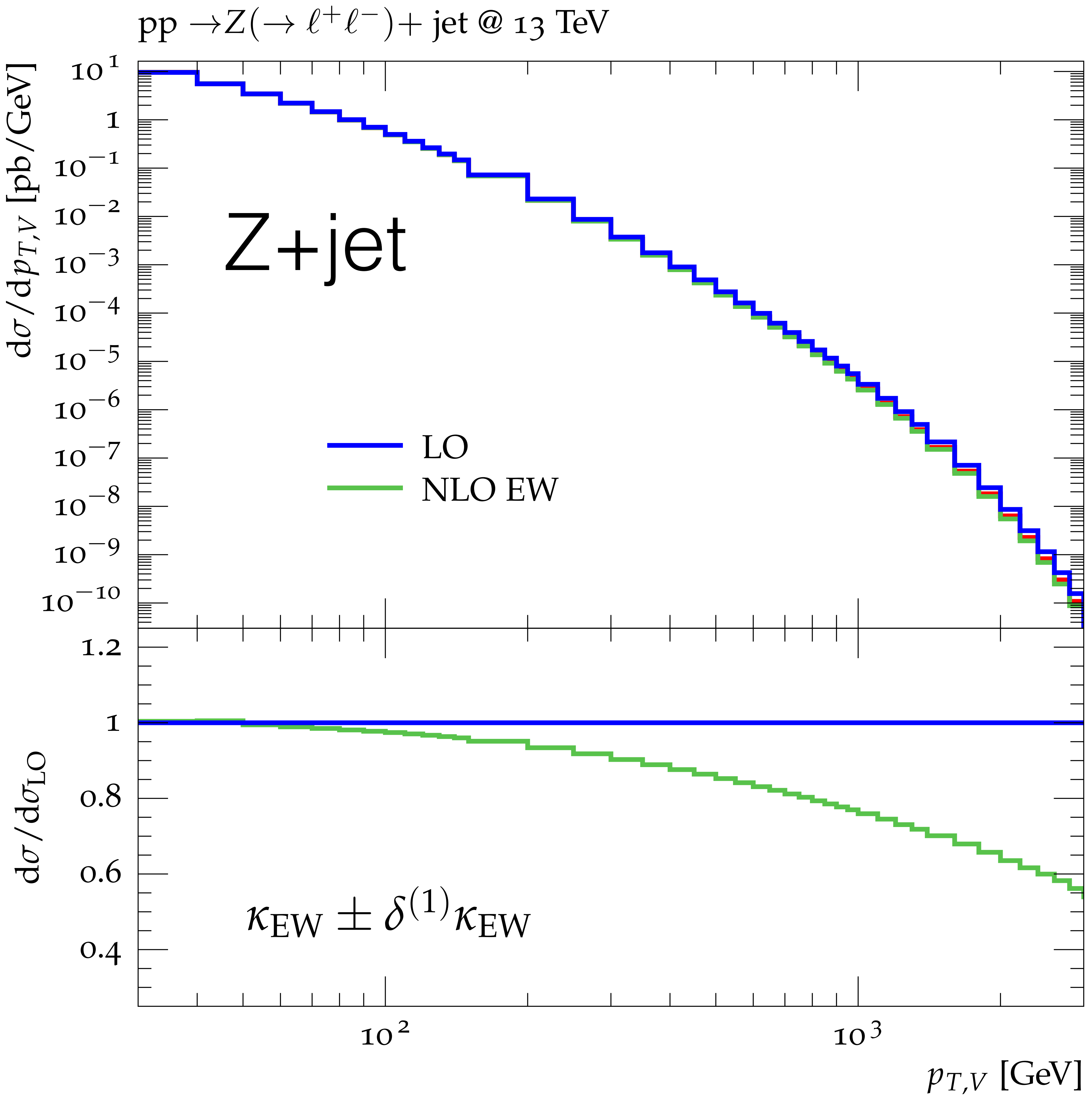
- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{(N)NLO}} = K^{V}_{\mathrm{(N)NLO}} - K^{Z}_{\mathrm{(N)NLO}}$
  →effectively degrades precision of last calculated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



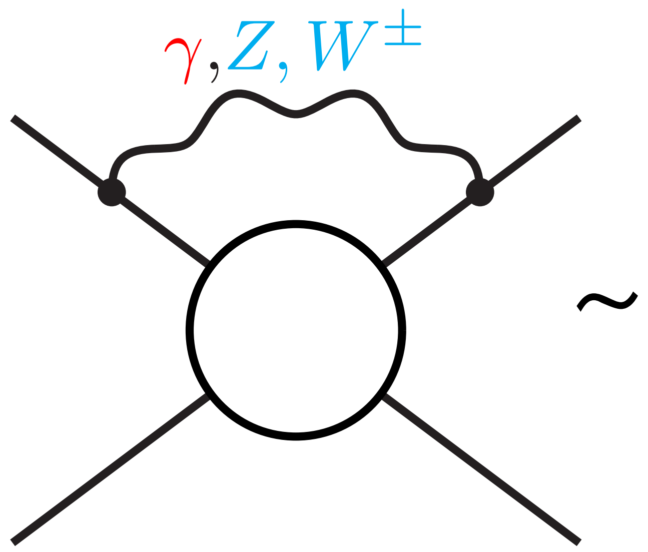

**Uncertainty estimates at NNLO QCD**

# EW uncertainties




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

Origin: virtual EW Sudakov logarithms




$$\sim \; -\log\left(\frac{p_T^2}{M_W^2}\right)$$

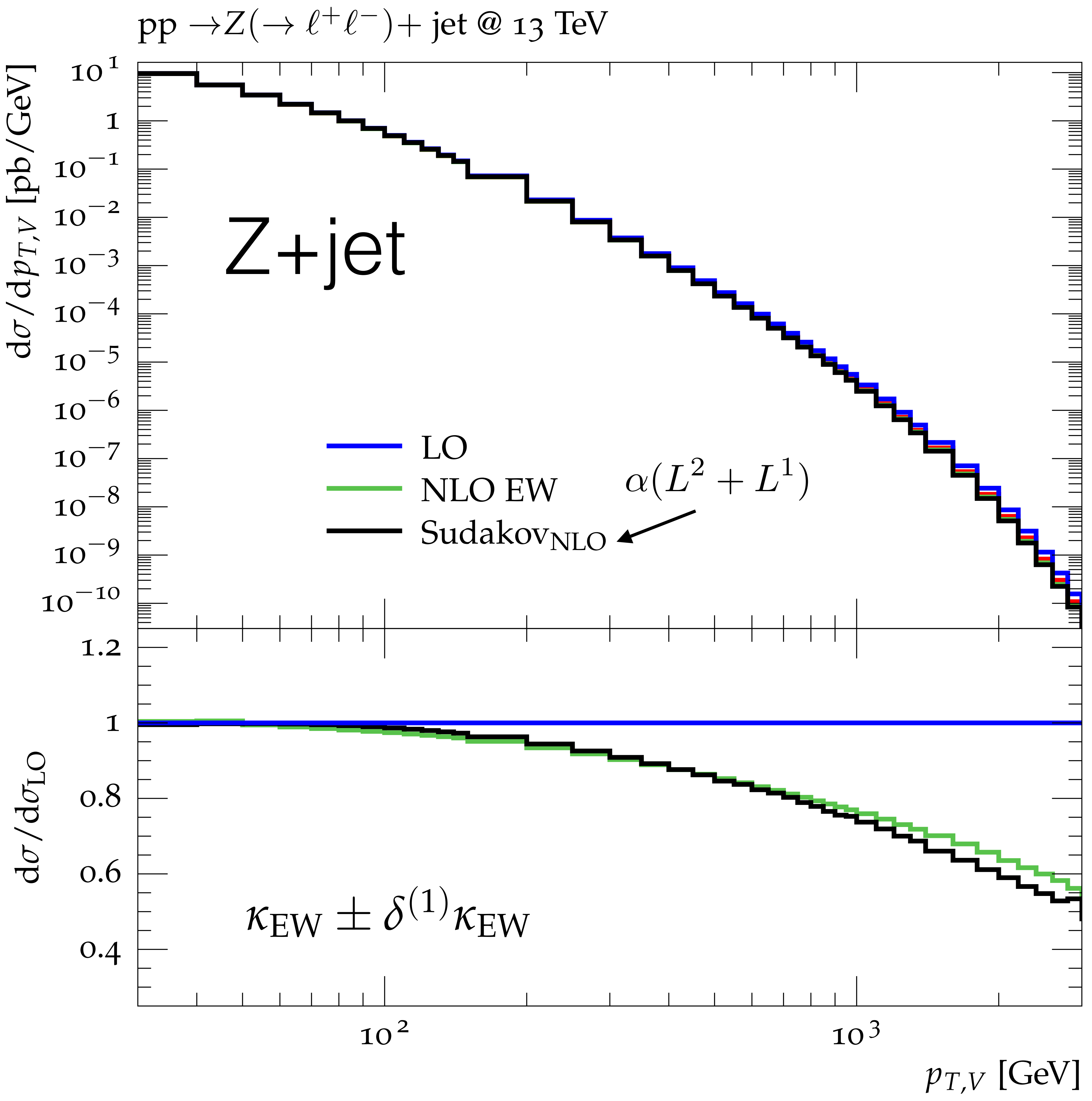
➜ increases with energy

➜large effect in the tails kinematic distributions (up to O(1) at the TeV scale)

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

# Pure EW uncertainties

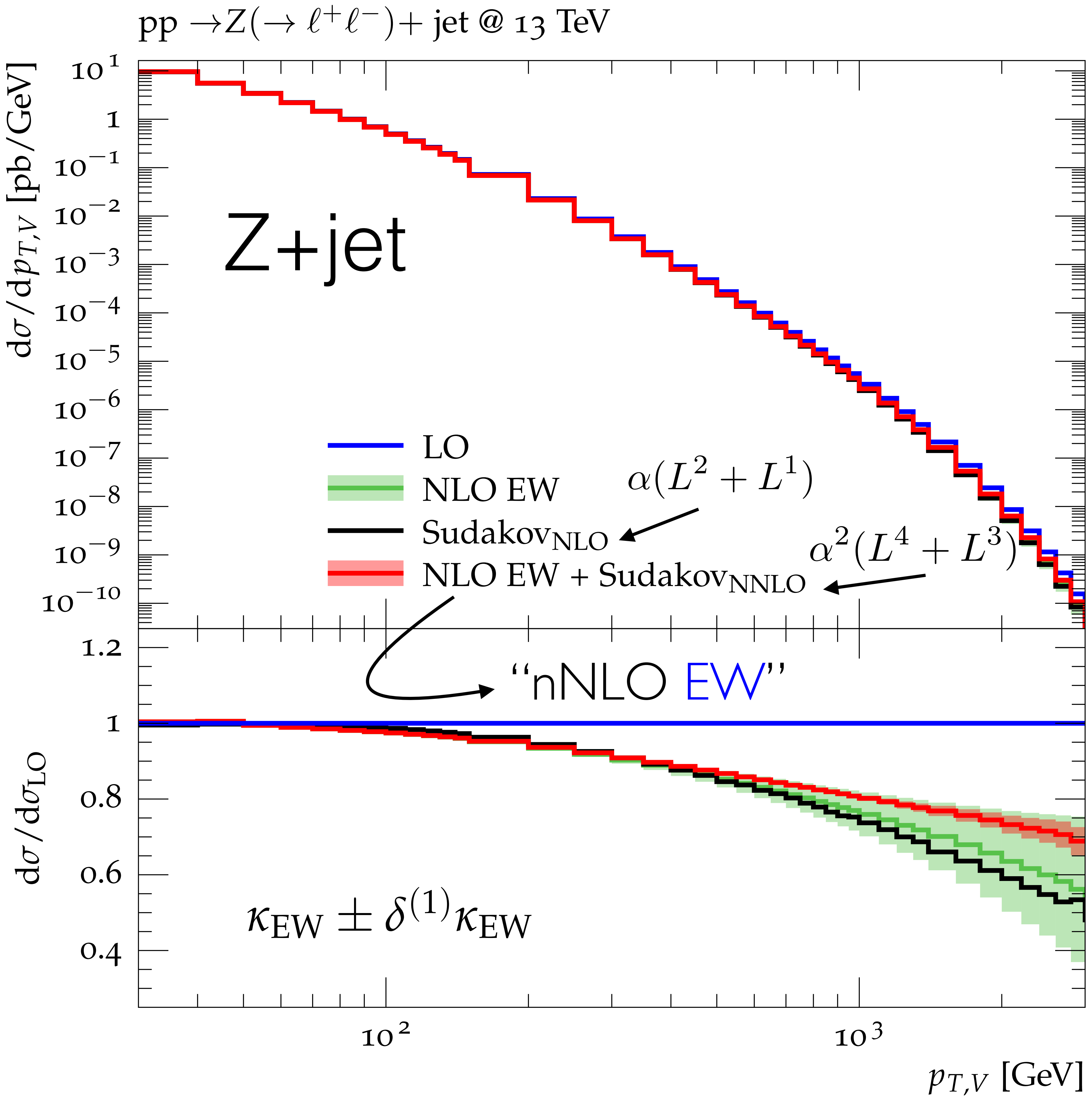
*[JML et. al.: 1705.04664]*




Large EW corrections dominated by Sudakov logs

# Pure EW uncertainties

*[JML et. al.: 1705.04664]*




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

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

Large EW corrections dominated by Sudakov logs

↓

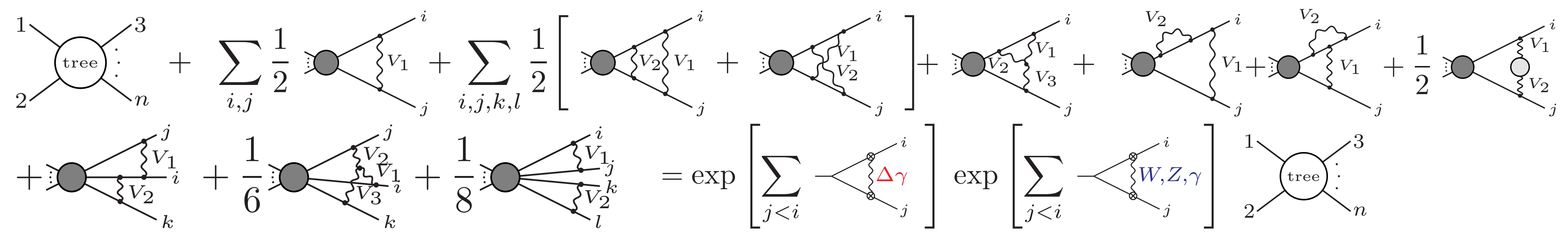
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

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

↓

check against two-loop Sudakov logs

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



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

# Precise predictions for V+jet DM backgrounds

[1705.04664]

*work in collaboration with:*

*R. Boughezal, J.M. Campell, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, S. Kallweit, M. L. Mangano, P. Maierhöfer, T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam, C.Williams*

- Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)

$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}(\vec{\varepsilon}_{\mathrm{MC}},\vec{\varepsilon}_{\mathrm{TH}}) := \frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})\left[\frac{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}}(\vec{\varepsilon}_{\mathrm{TH}})}{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})}\right]$$

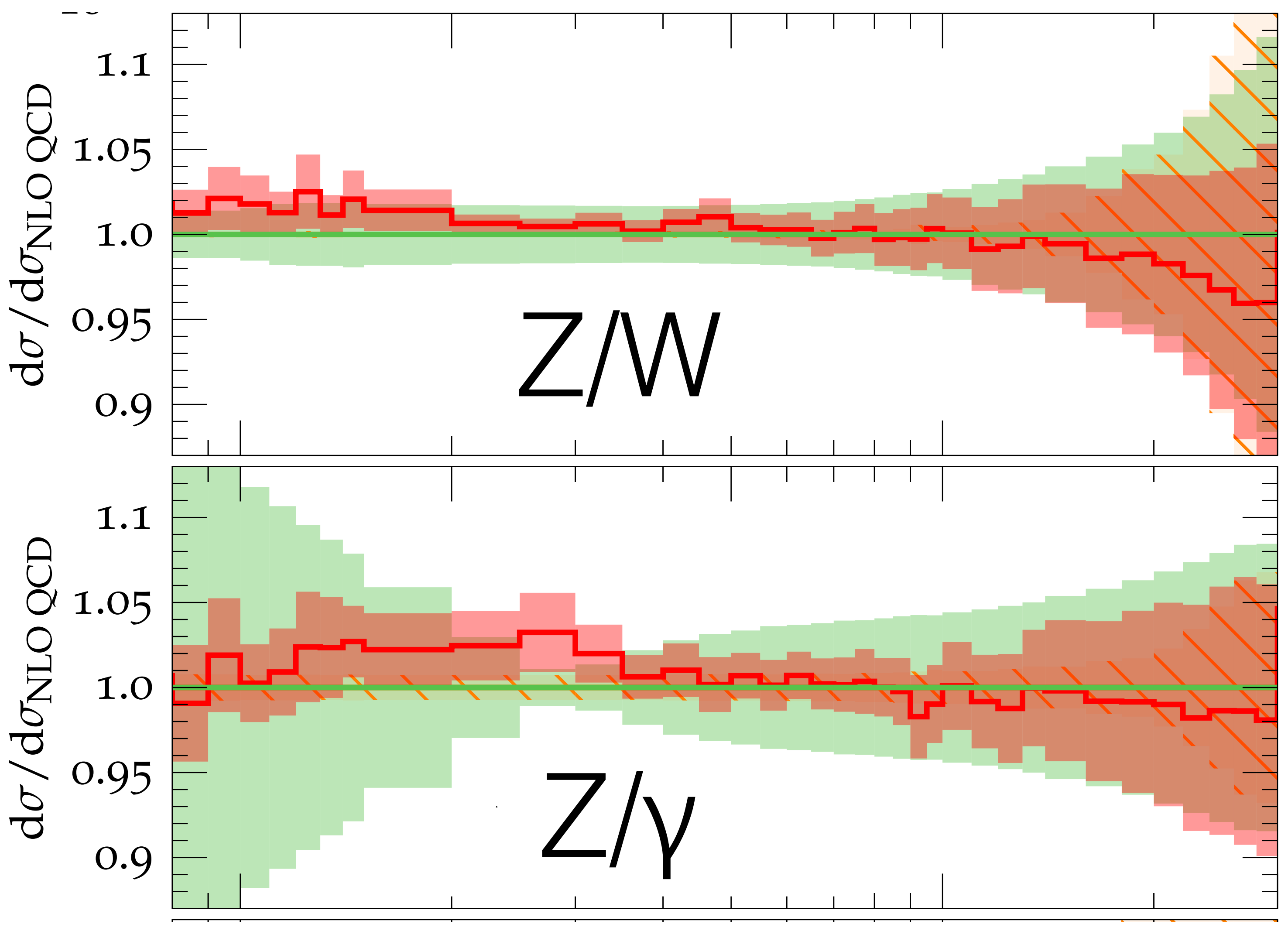
one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

with
$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{mix}} + \frac{\mathrm{d}}{\mathrm{d}x}\Delta\sigma^{(V)}_{\mathrm{EW}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}$$

- **Robust uncertainty estimates including**
  1. **Pure QCD uncertainties**
  2. **Pure EW uncertainties**
  3. **Mixed QCD-EW uncertainties**
  4. **PDF, γ-induced uncertainties ….**

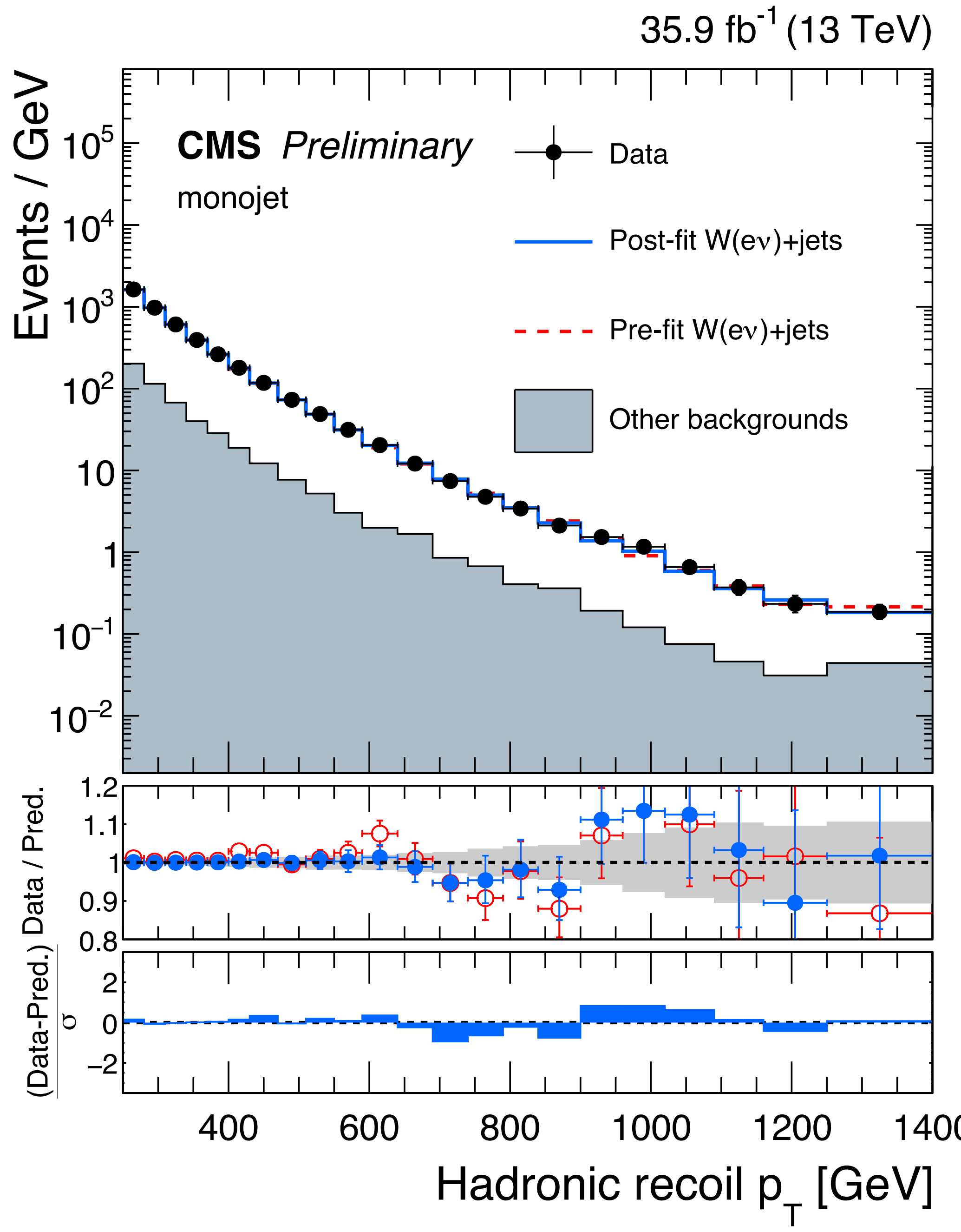
- Prescription for **correlation** of these uncertainties
  - within a process (between low-pT and high-pT)
  - across processes

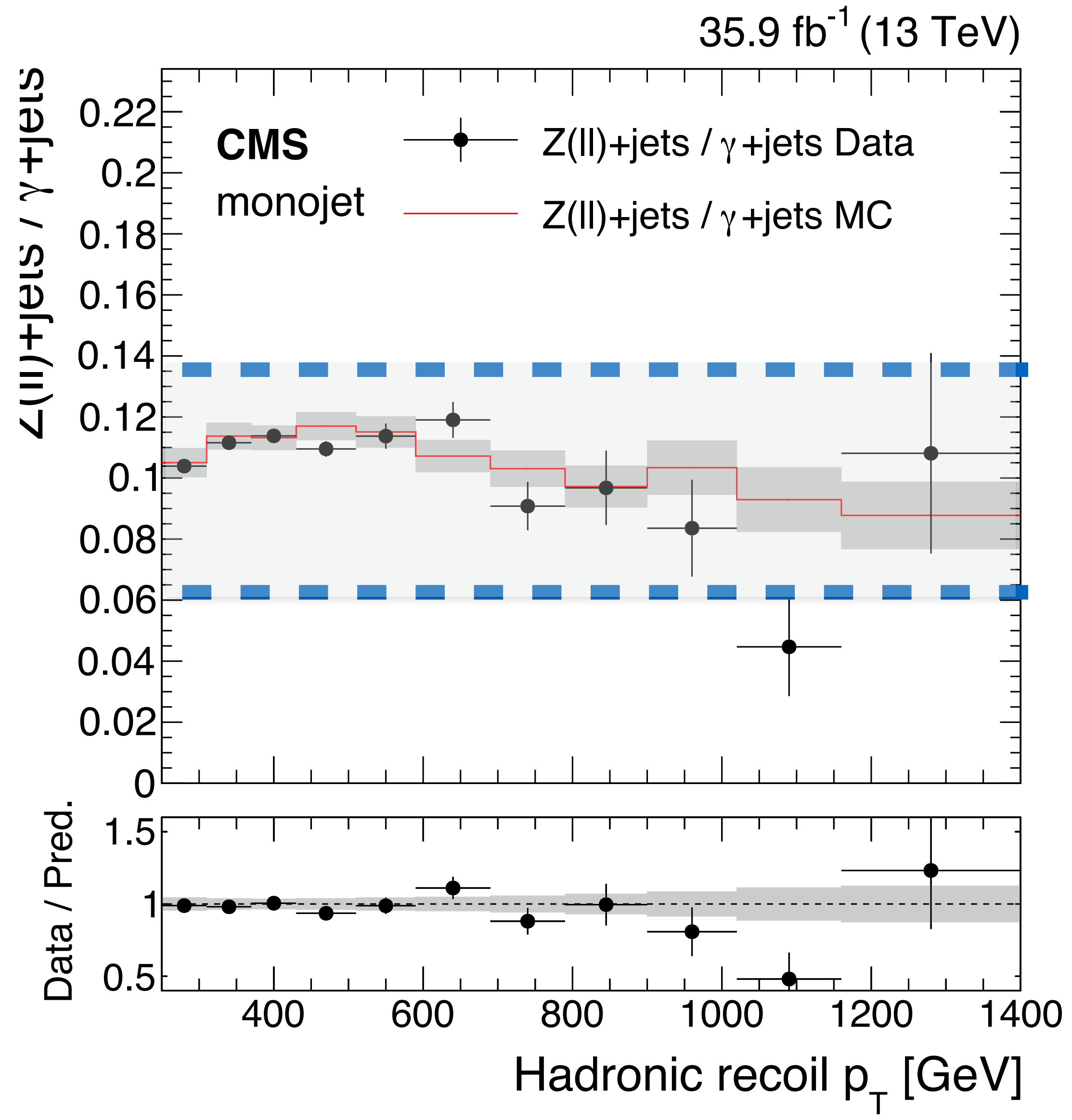
# Combined uncertainties on V+jets ratios




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

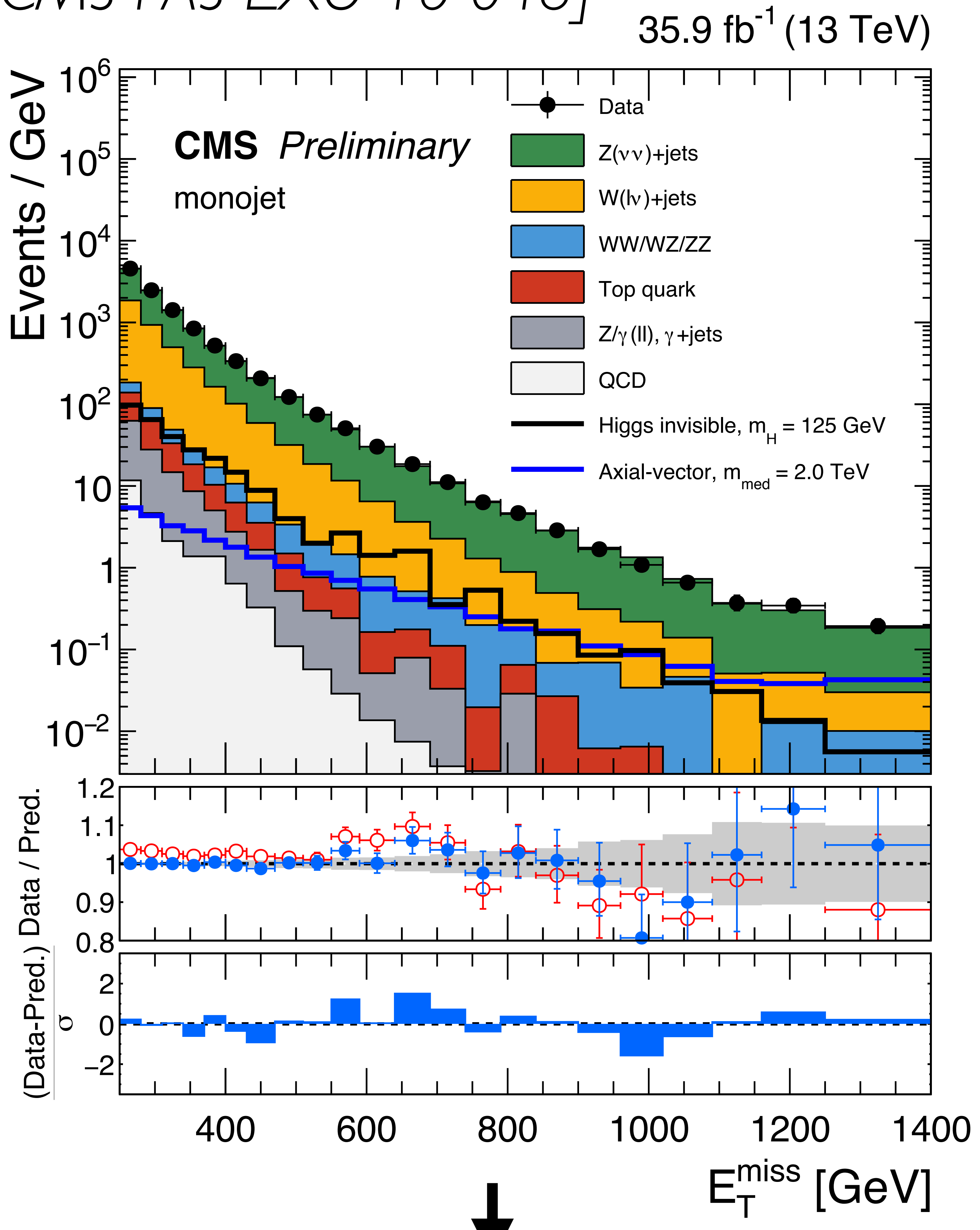
CR →




SR →

[CMS PAS EXO-16-048]

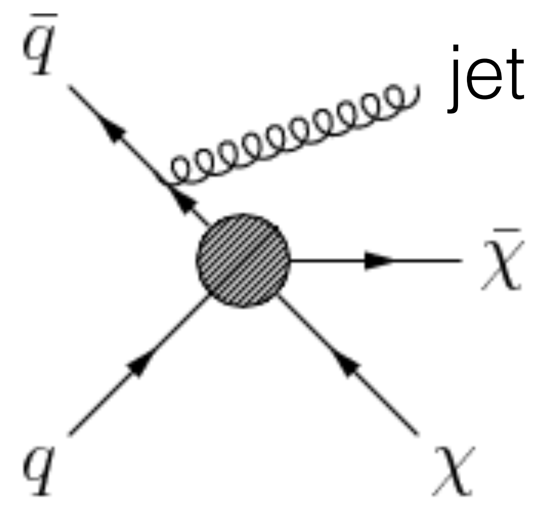



Unprecedented limits on monojet DM production!

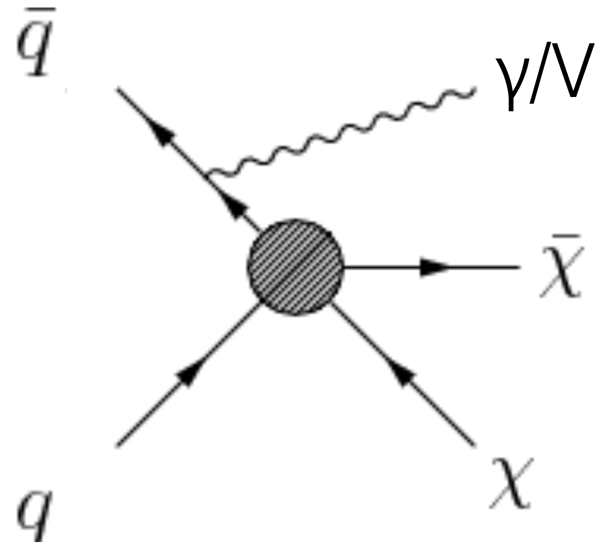
# The Zoo of DM+X searches

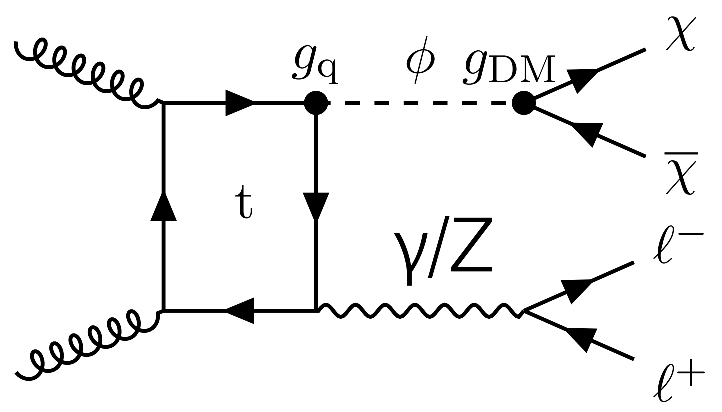
ISR

Mono-jet




Mono-γ/V

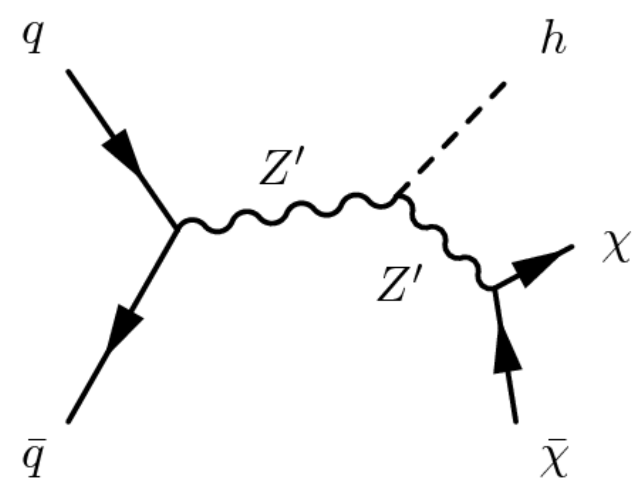


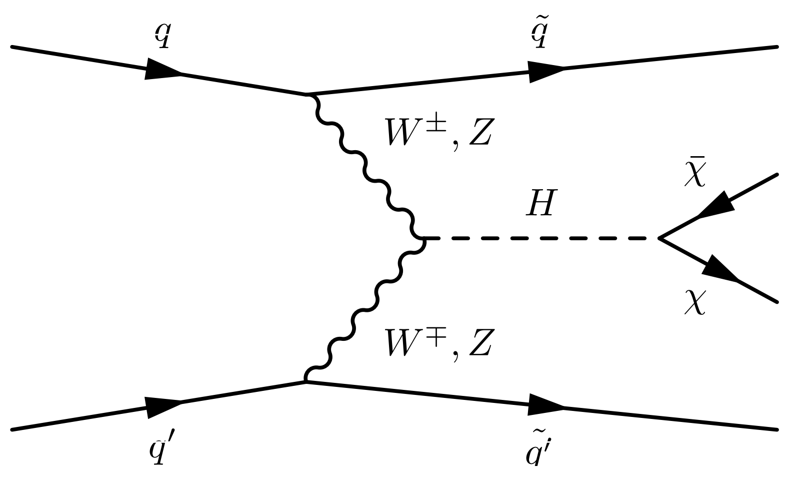

Loop-induced

Higgs-Strahlung

Mono-H



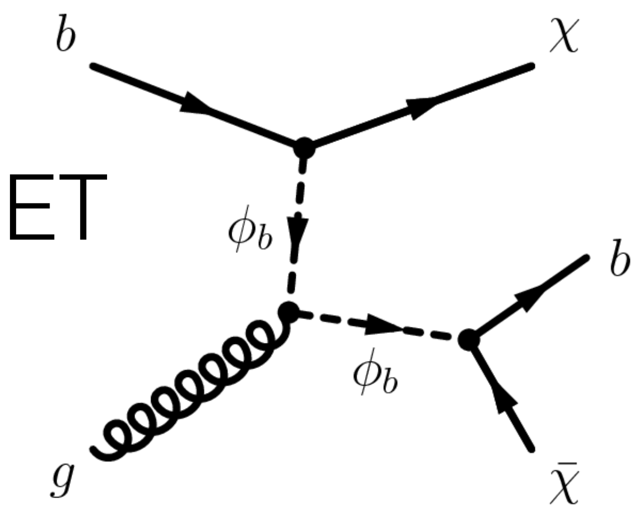

VBF



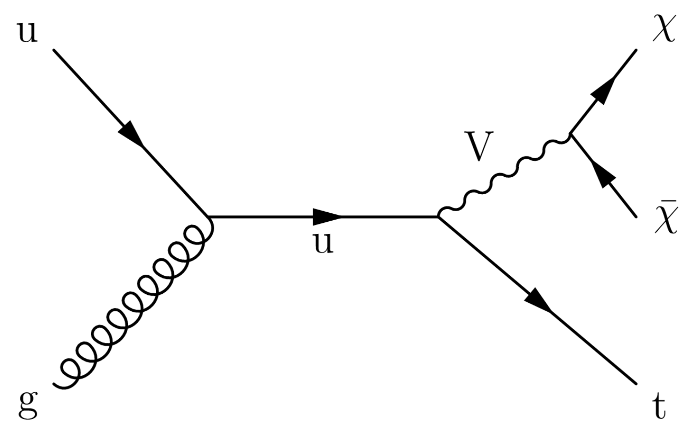

and many more….

HF-associated

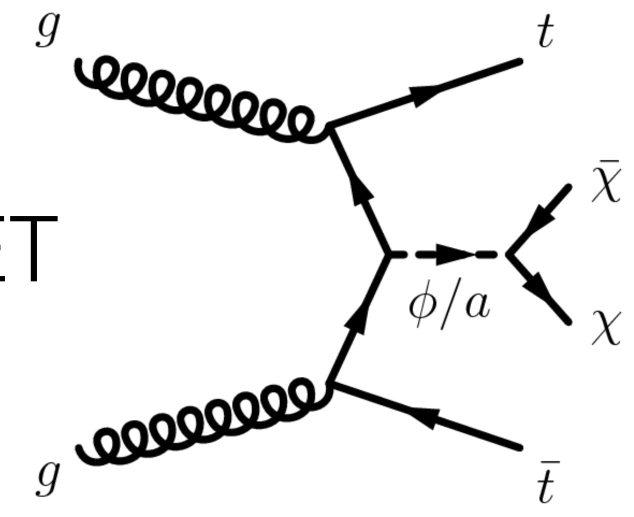
b+MET




t+MET



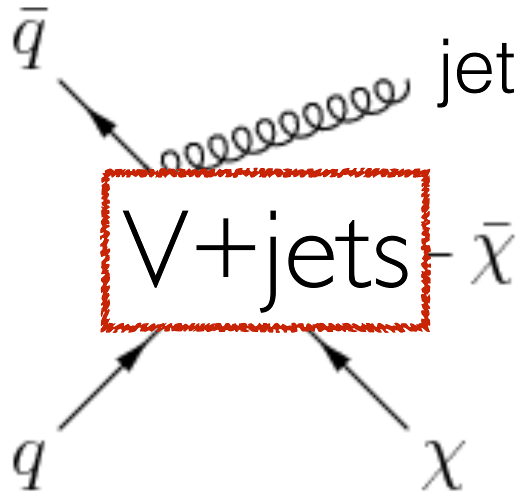

tt+MET



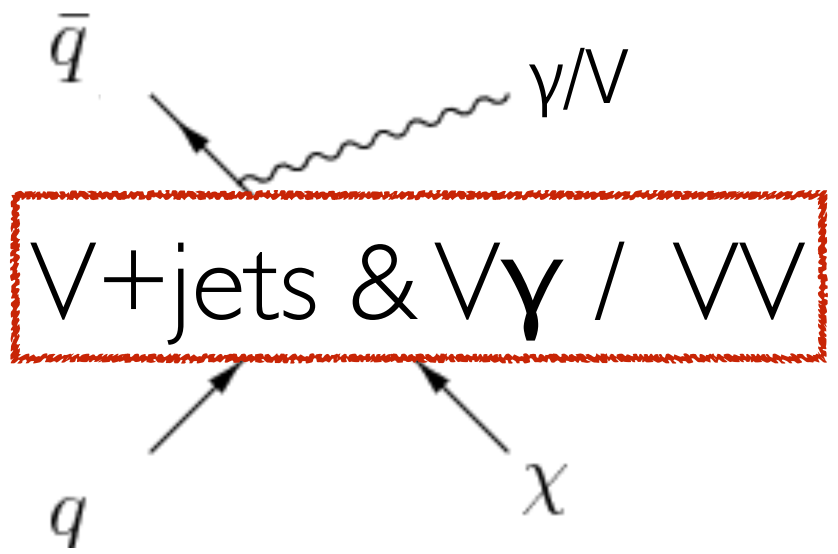
# The Zoo of DM+X searches: backgrounds

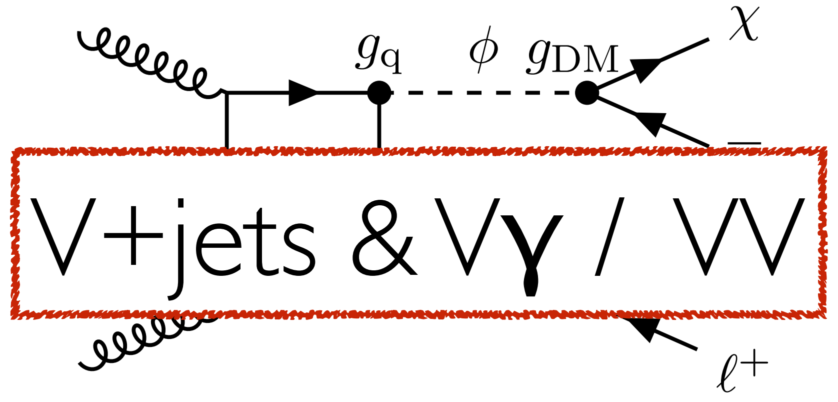
ISR

Mono-jet




Mono-γ/V

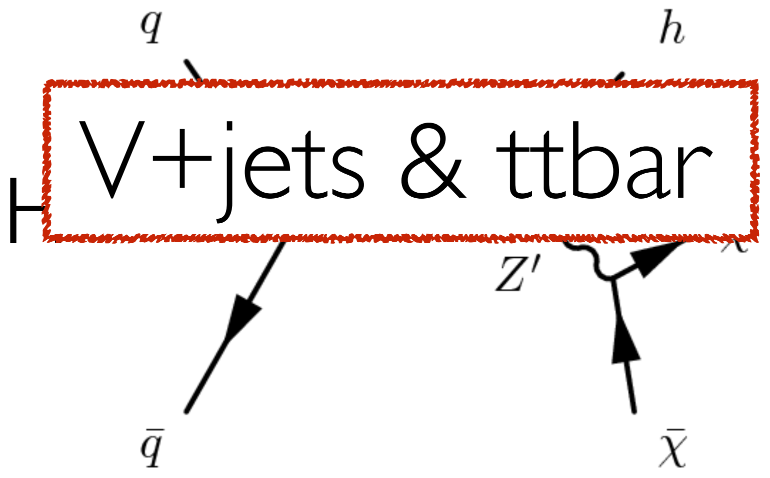


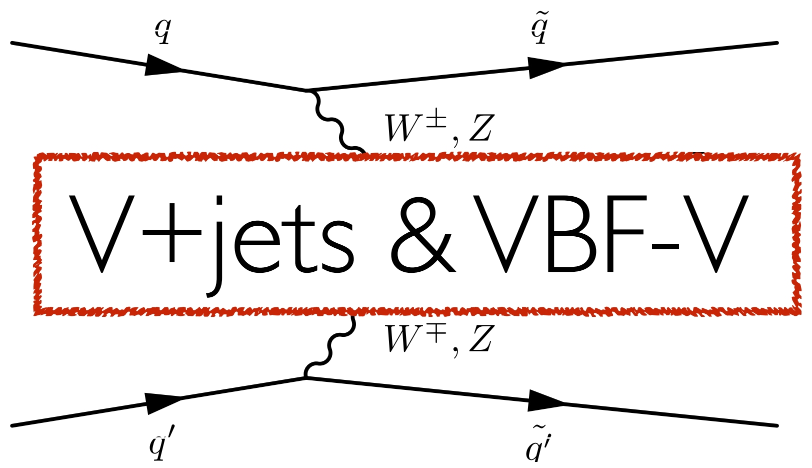

Loop-induced

Higgs-Strahlung

Mono-H

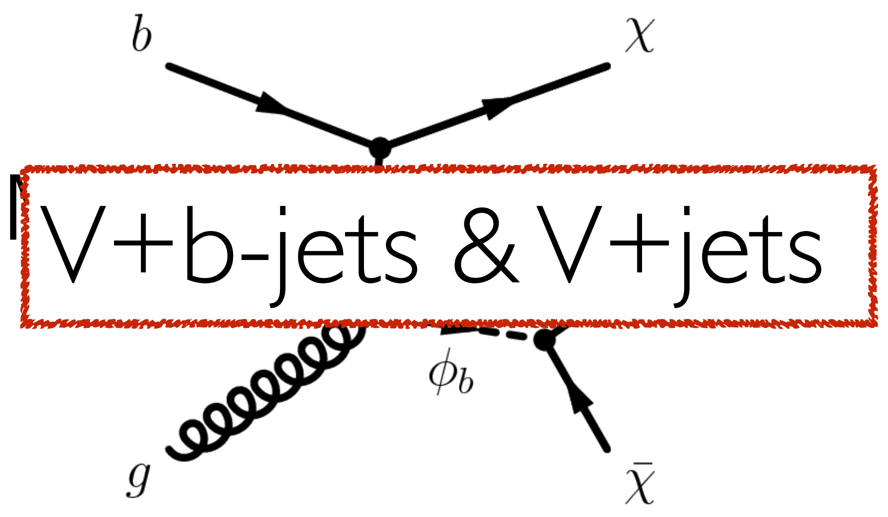



VBF

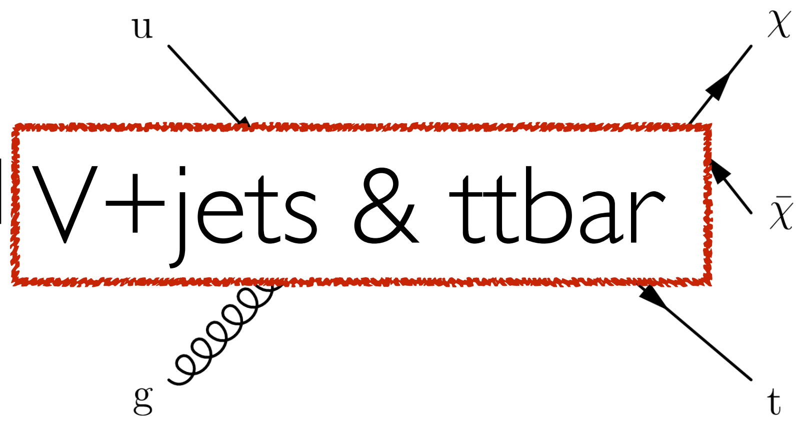



HF-associated

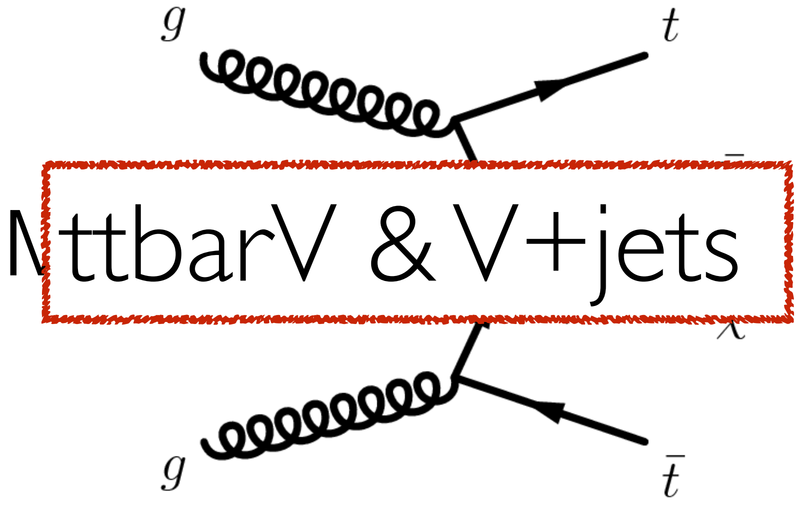
b+




t+M




tt+



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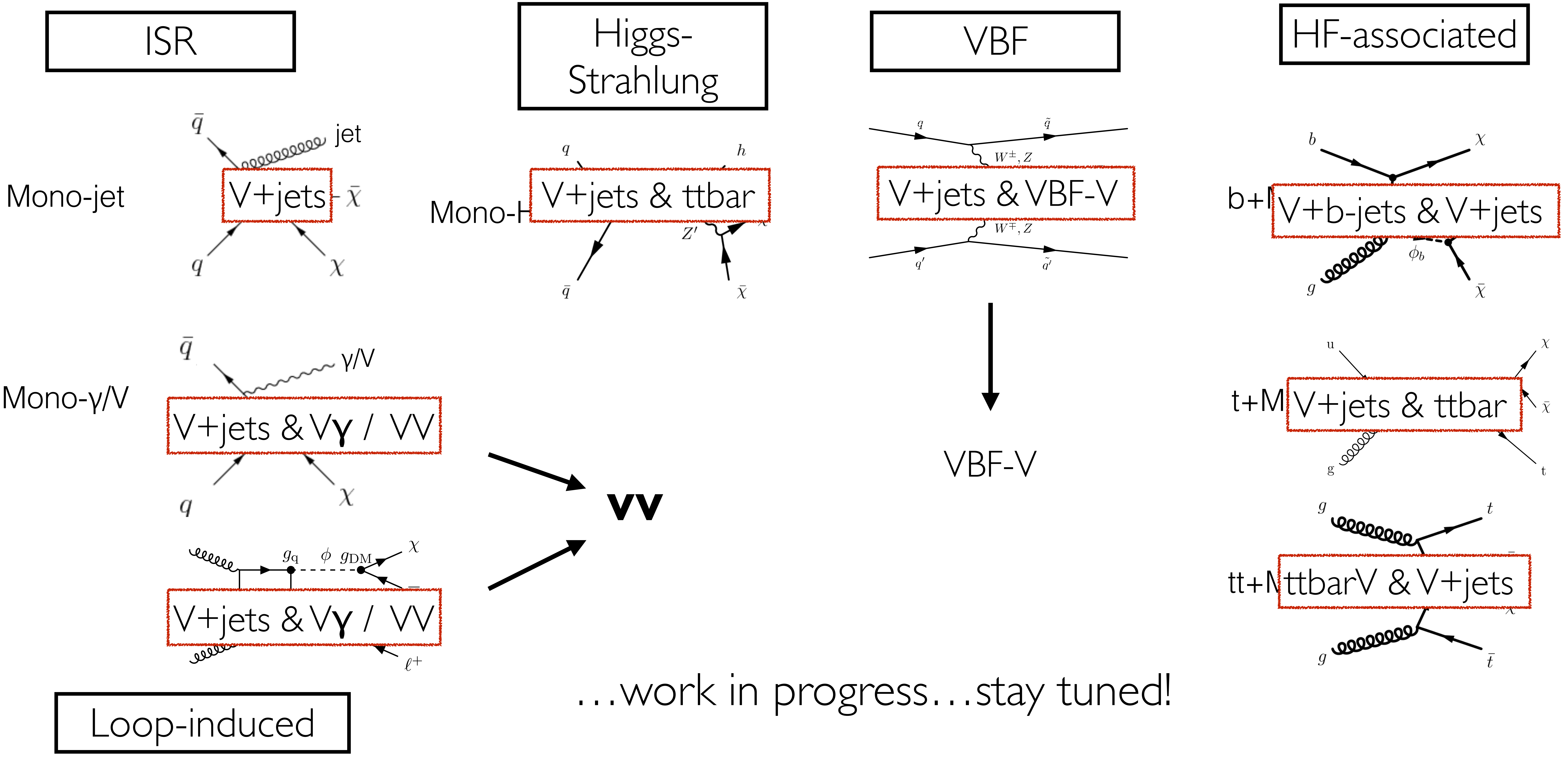
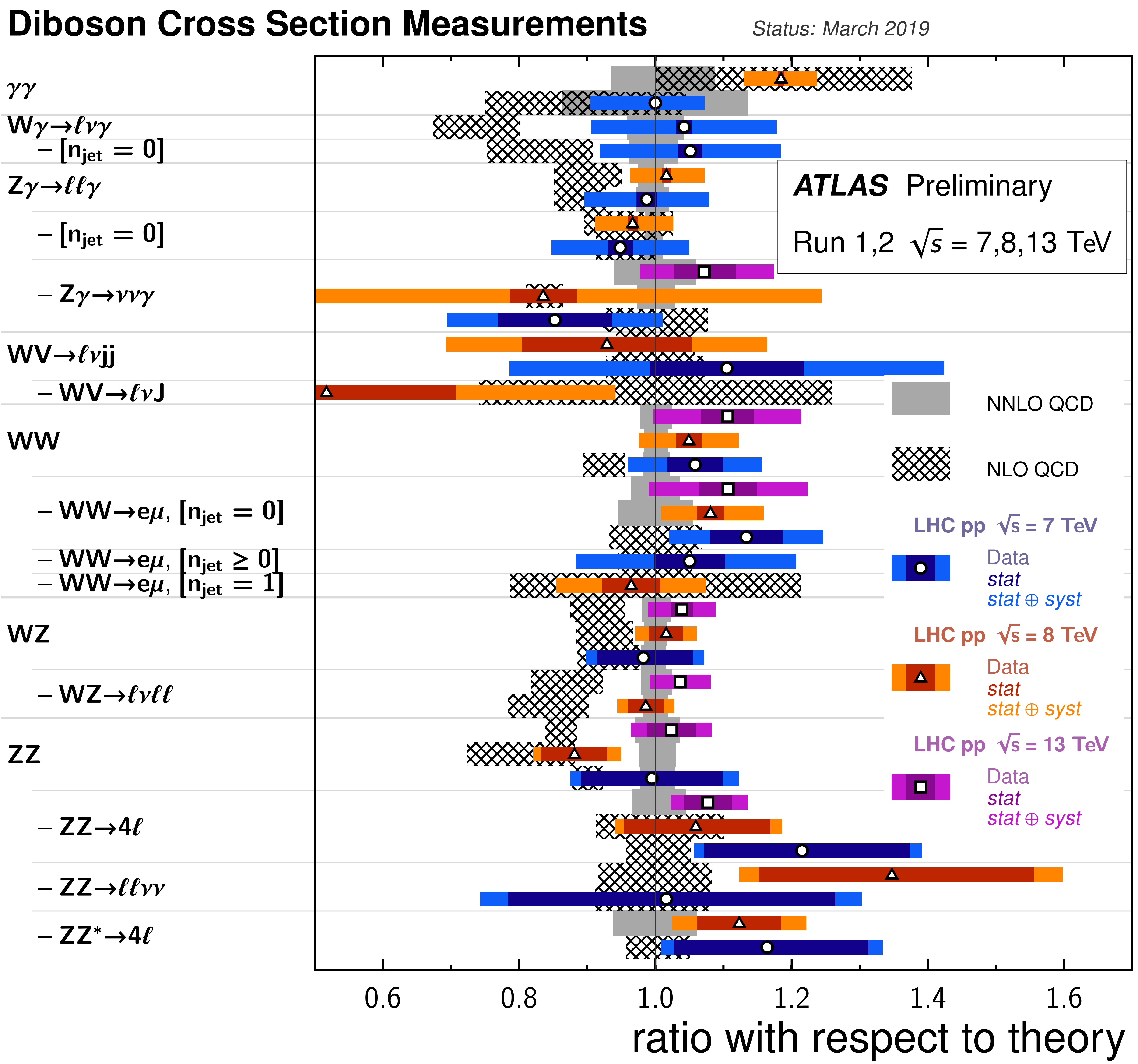


# Diboson Status

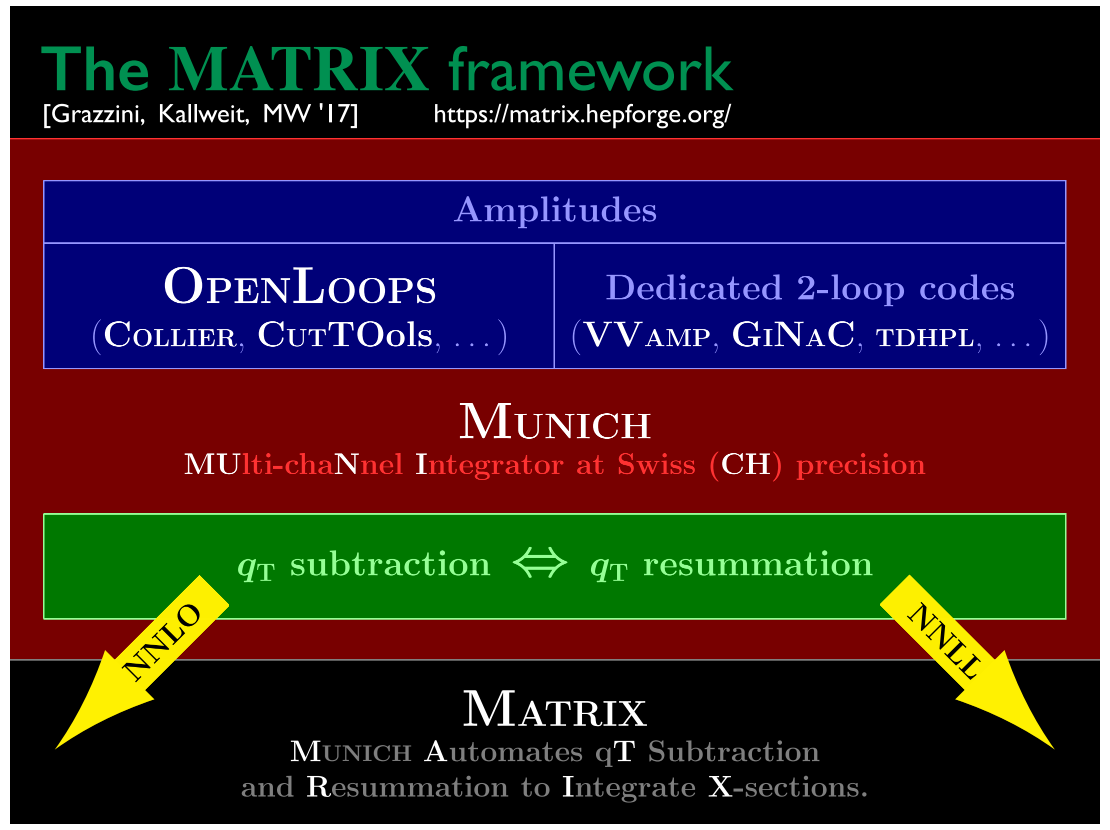



Remarkable agreement of inclusive diboson cross sections with **NNLO QCD**

Allows for stringent SM tests

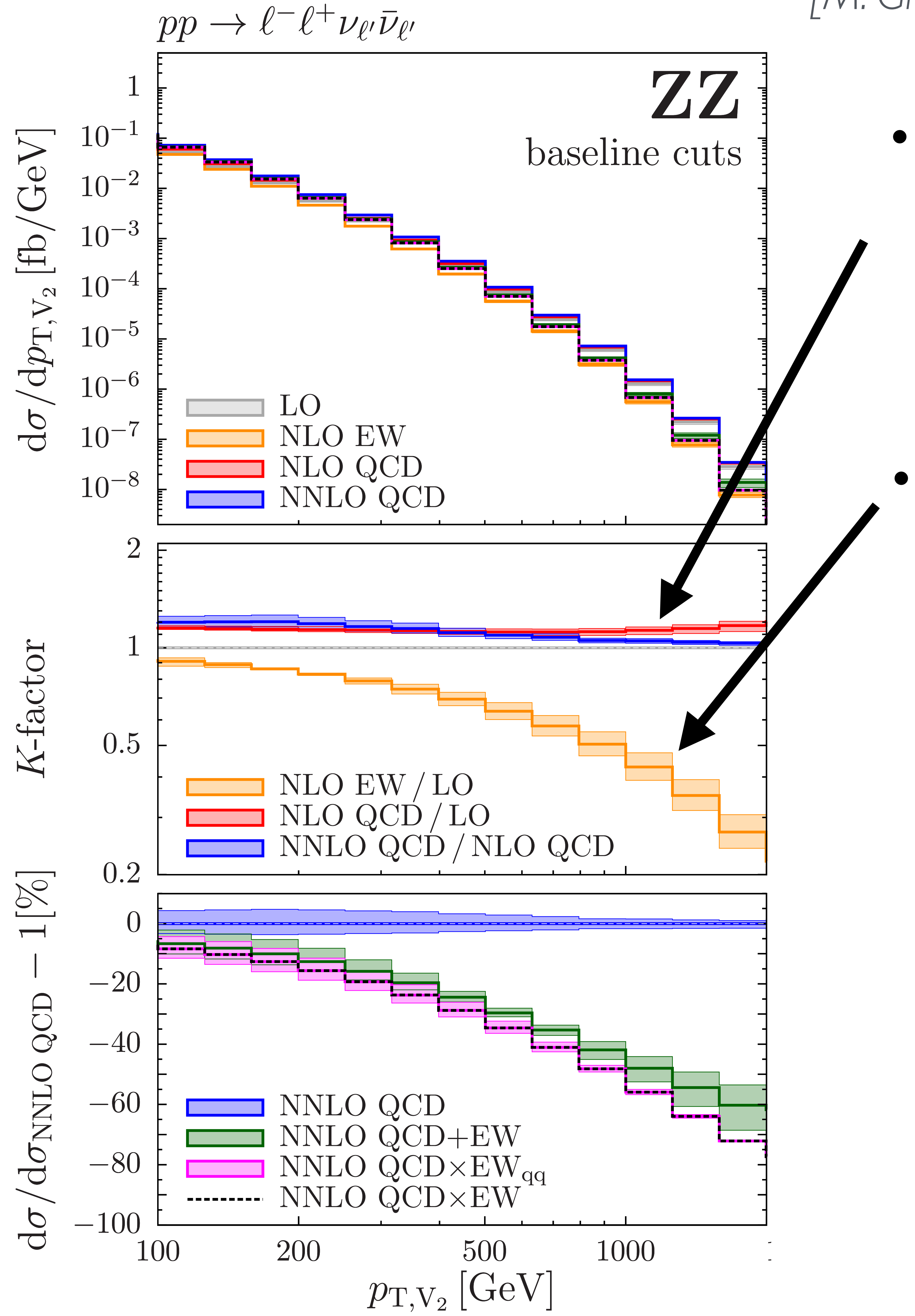
Dibosons important background for Higgs and BSM searches

In MATRIX *[Grazzini, Kallweit, Wiesemann '17]* all on-shell & off-shell diboson processes are available at NNLO QCD



# NNLO QCD + NLO EW for dibosons: 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

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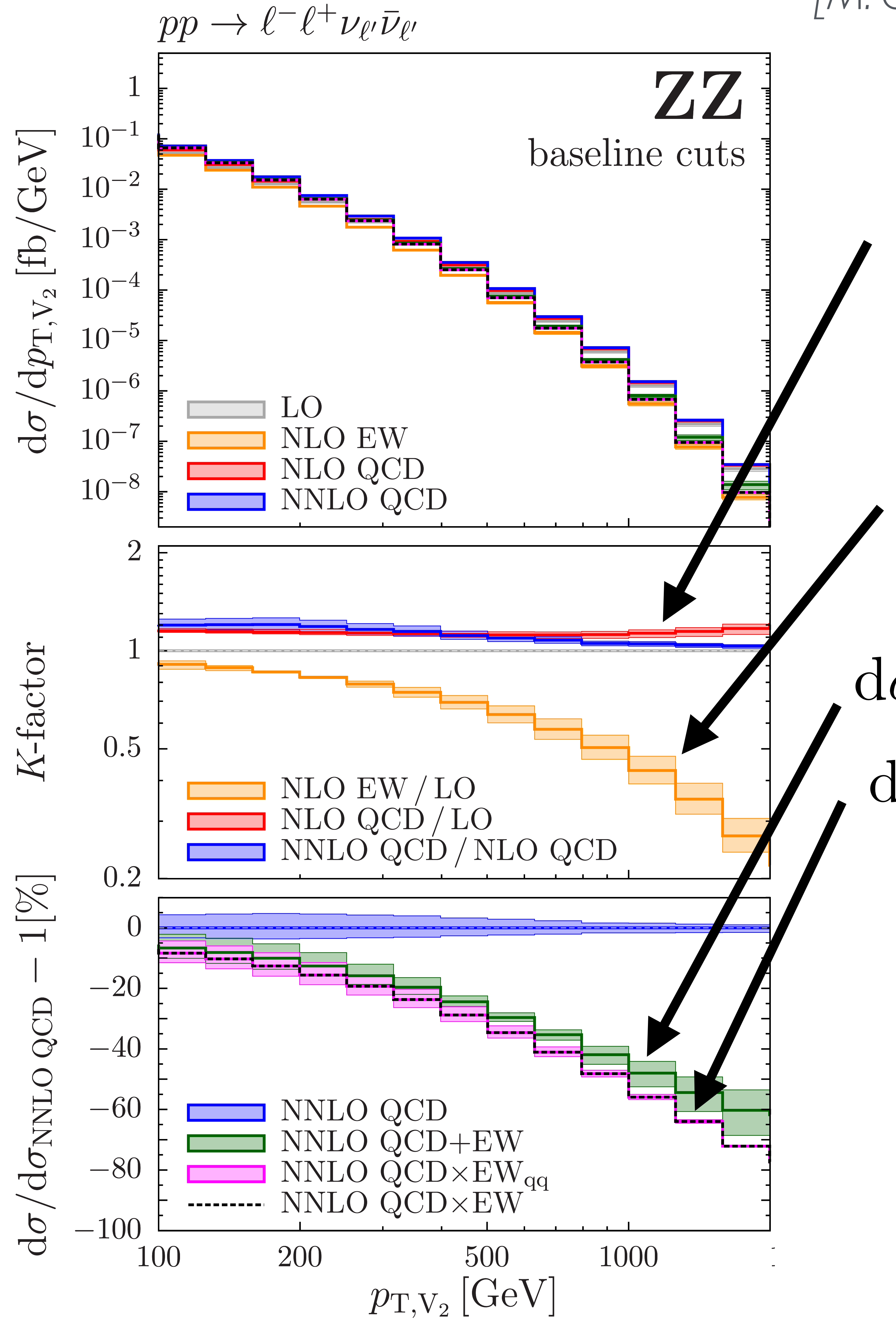


pTV2

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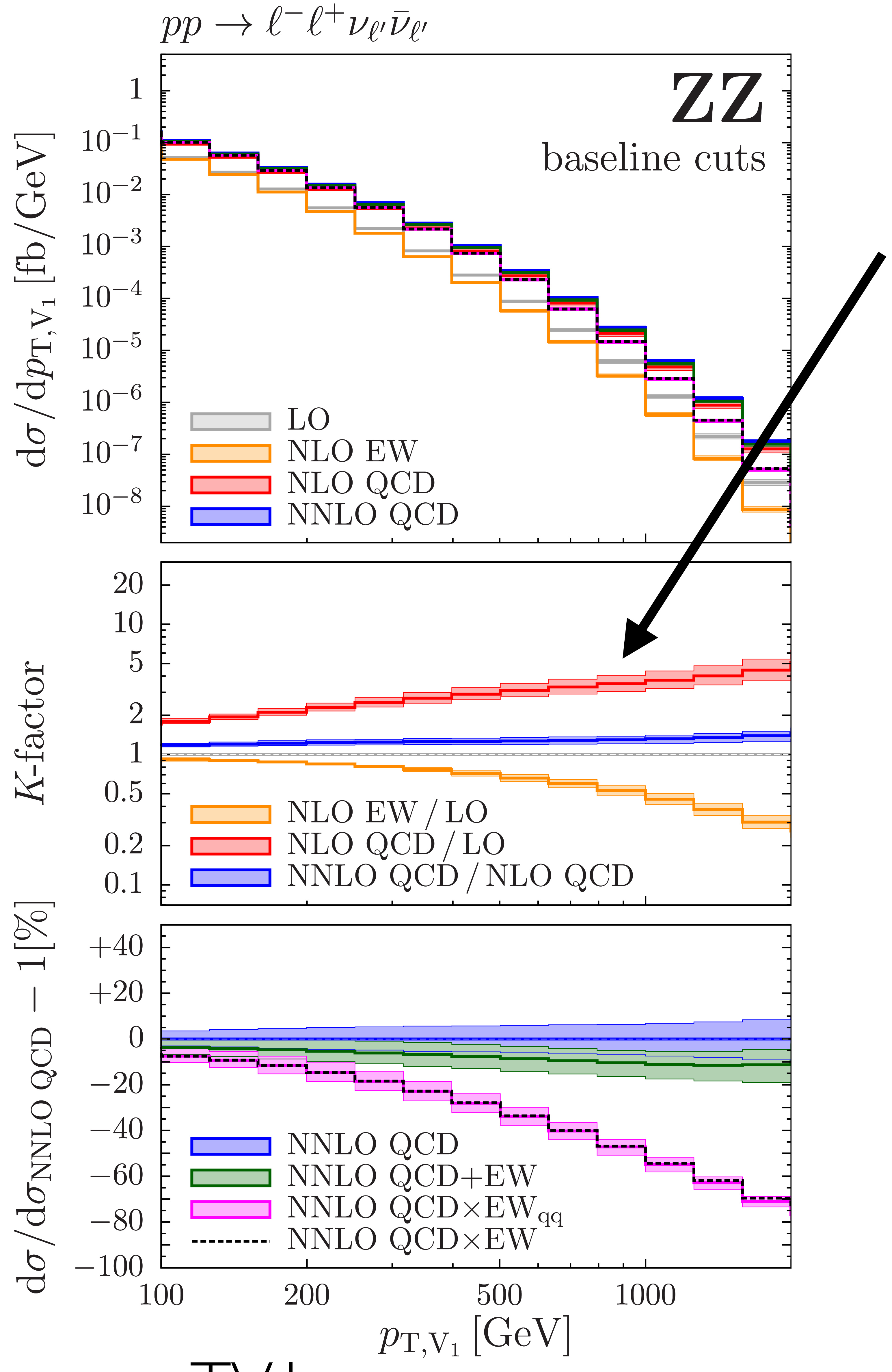
$$d\sigma_{\mathrm{NNLO\,QCD+EW}} = d\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}\right) + d\sigma^{gg}_{\mathrm{LO}}$$

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

- 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: $\boxed{\frac{1}{2}\delta^2_{\mathrm{EW}}}$

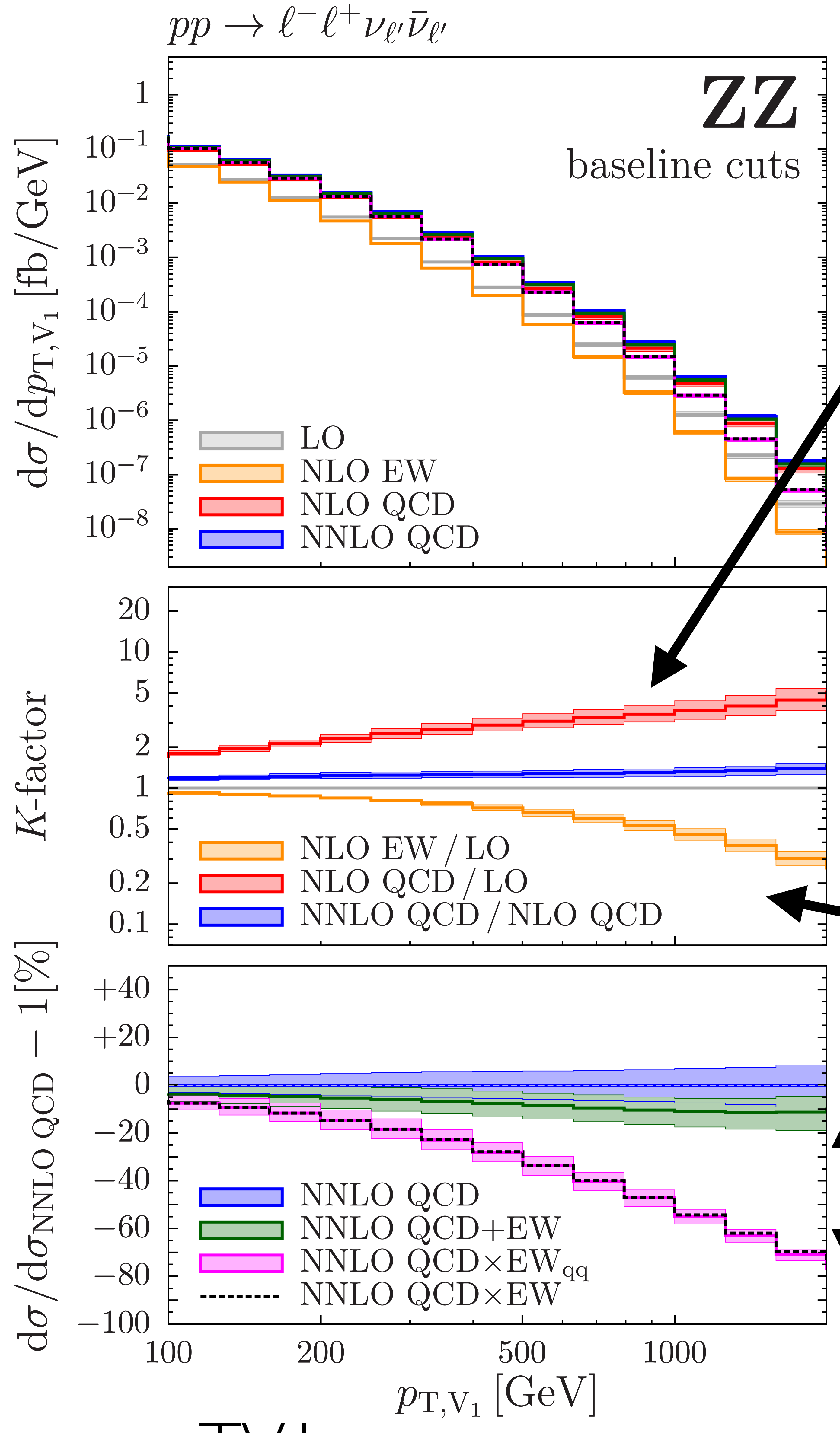
# Giant QCD K-factors and EW corrections: pTV1




pTV1

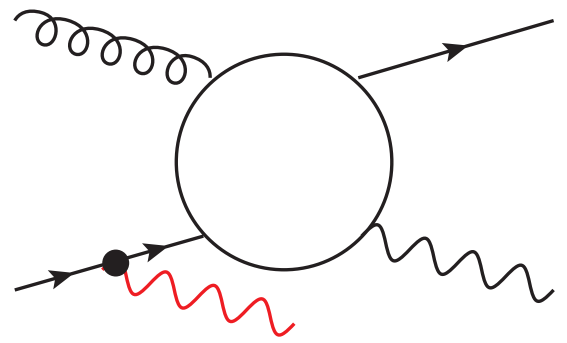
- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta,'10])

# Giant QCD K-factors and EW corrections: pTV1




pTV1

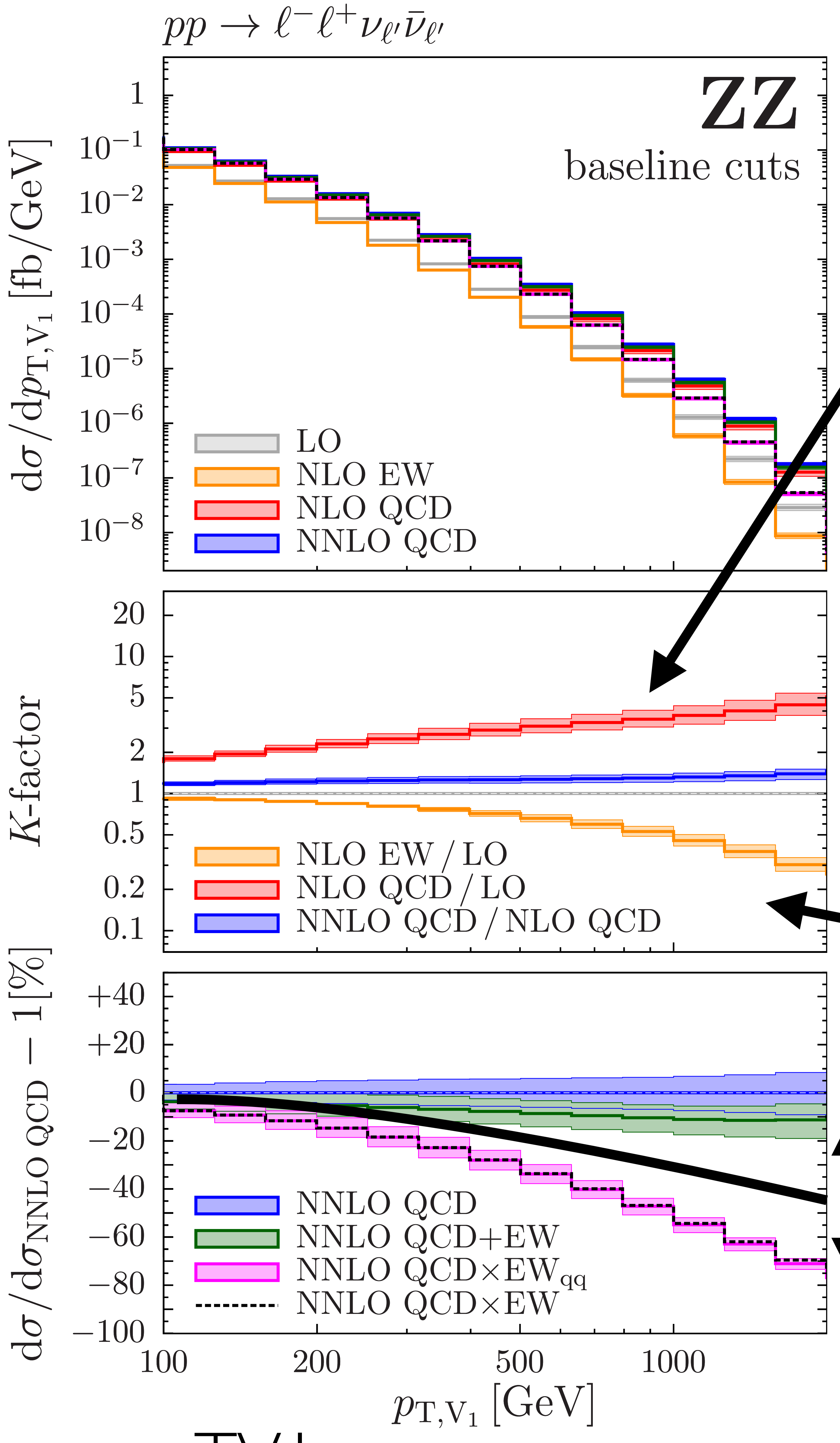
- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta, '10])
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



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

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{NNLO\,QCD+EW}$ vs. $d\sigma_{NNLO\,QCD\times EW}$
- 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

# Giant QCD K-factors and EW corrections: pTV1

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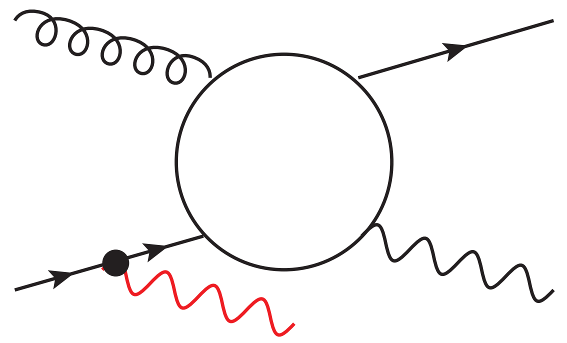

$$\longrightarrow \frac{d\sigma^{V(V)j}}{d\sigma^{LO}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

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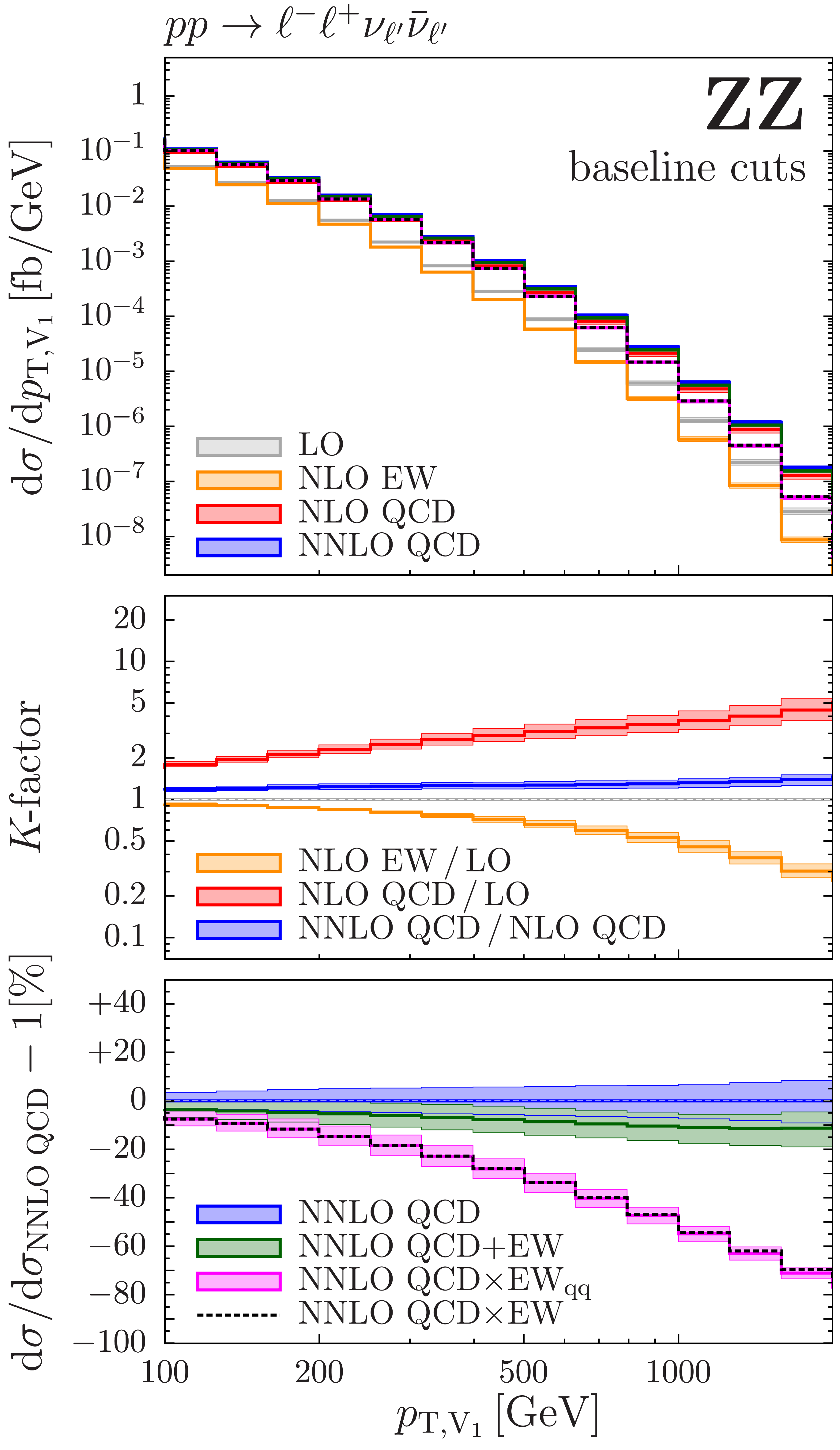
# Giant QCD K-factors and EW corrections: pTV1

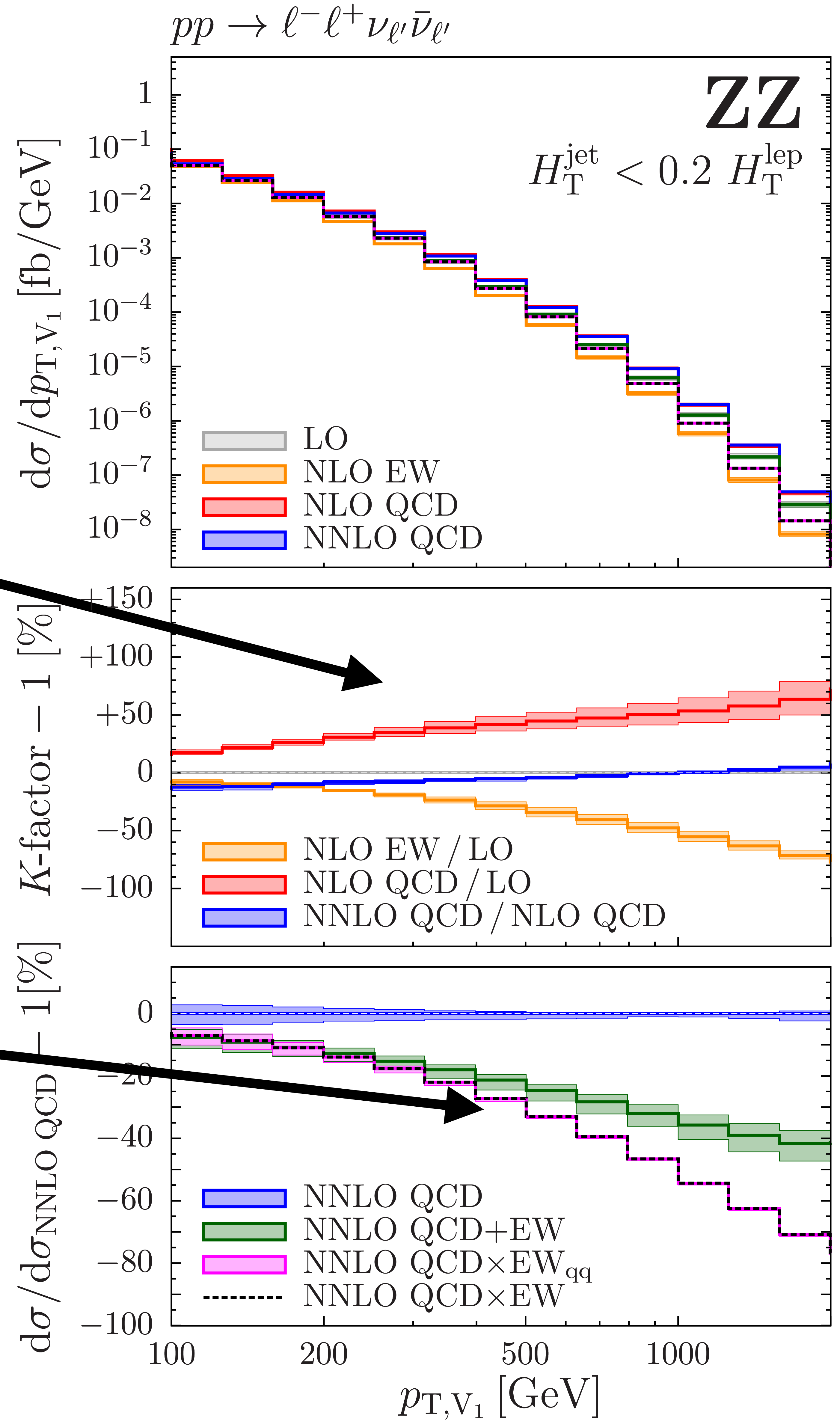



jet veto

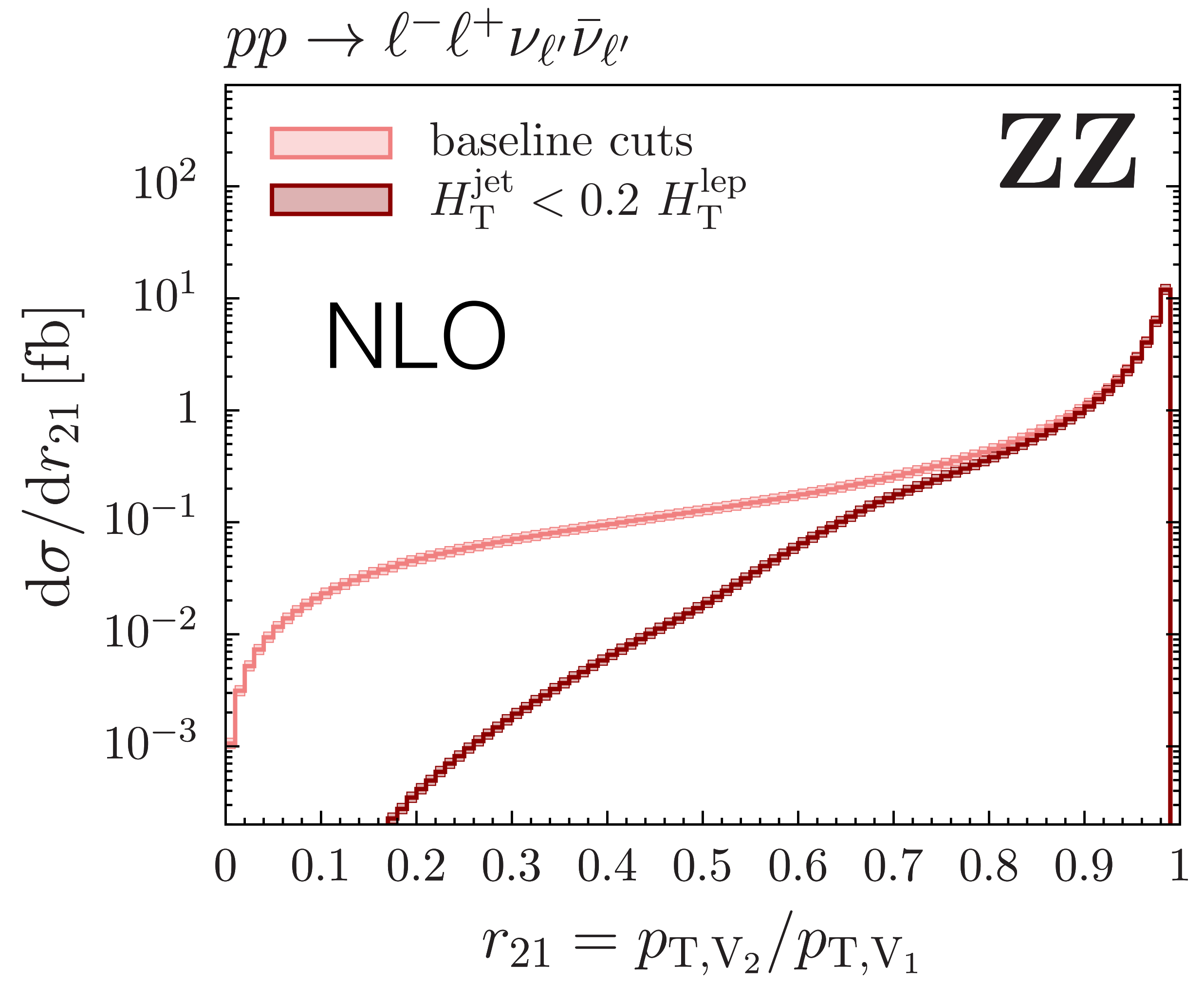
$H_T^{jet} < 0.2\, H_T^{lep}$

- NLO QCD/LO=~<1.5 ("normal K-factor")
- In case we are now really dominated by VV topologies: multiplicative dominations should be seen as superior

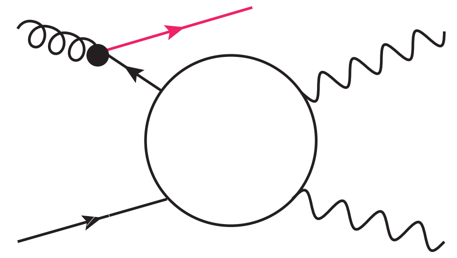
➡check!



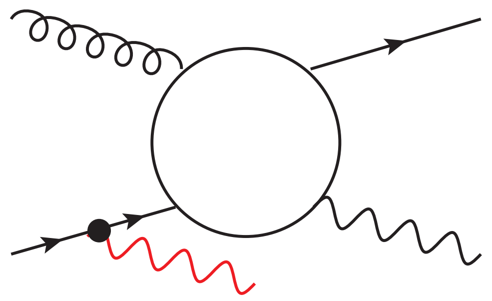
# Giant K-factors and effect of jet veto

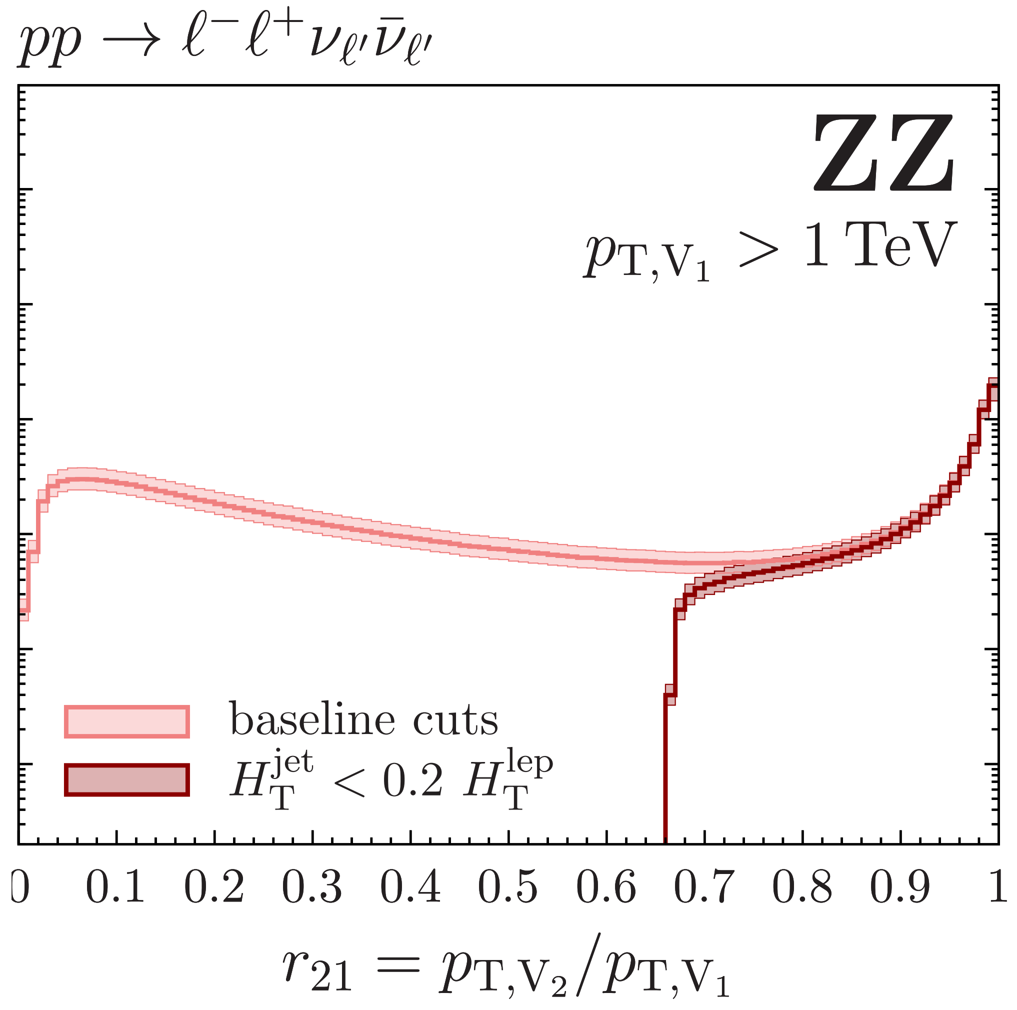



- at r21 → 1: hard-VV topologies



- at r21 → 0: hard-Vj topologies





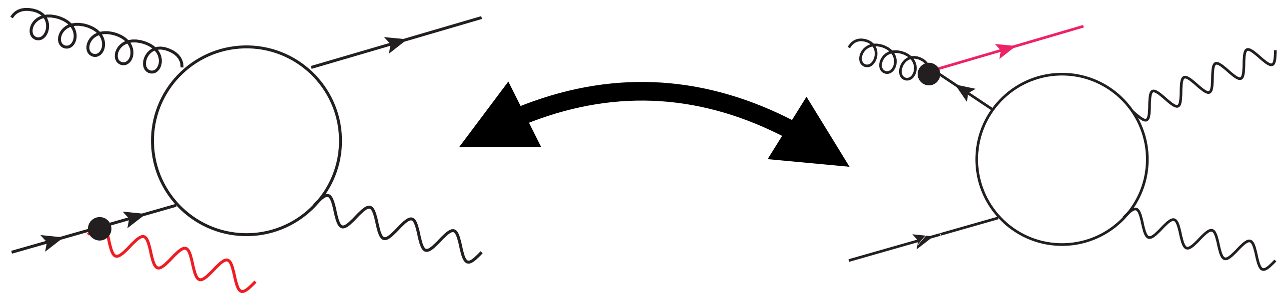

- for pTV1 > 1 TeV: hard-Vj topologies dominate over hard-VV

- Jet veto $H_T^{jet} < \xi_{veto}\ H_T^{lep}$ corresponds to

$$p_{T,V_2} \geq \frac{1-\xi_{veto}}{1+\xi_{veto}}\, p_{T,V_1} = \frac{2}{3}\, p_{T,V_1} \qquad \text{for} \quad \xi_{veto} = 0.2$$

(violated by off-shell topologies)

- Jet veto results in phase-space dominated by hard-VV



# Conclusions

- There is no clear scale/signature for new physics effects:

  Let's explore the unknown leaving no stone unturned!

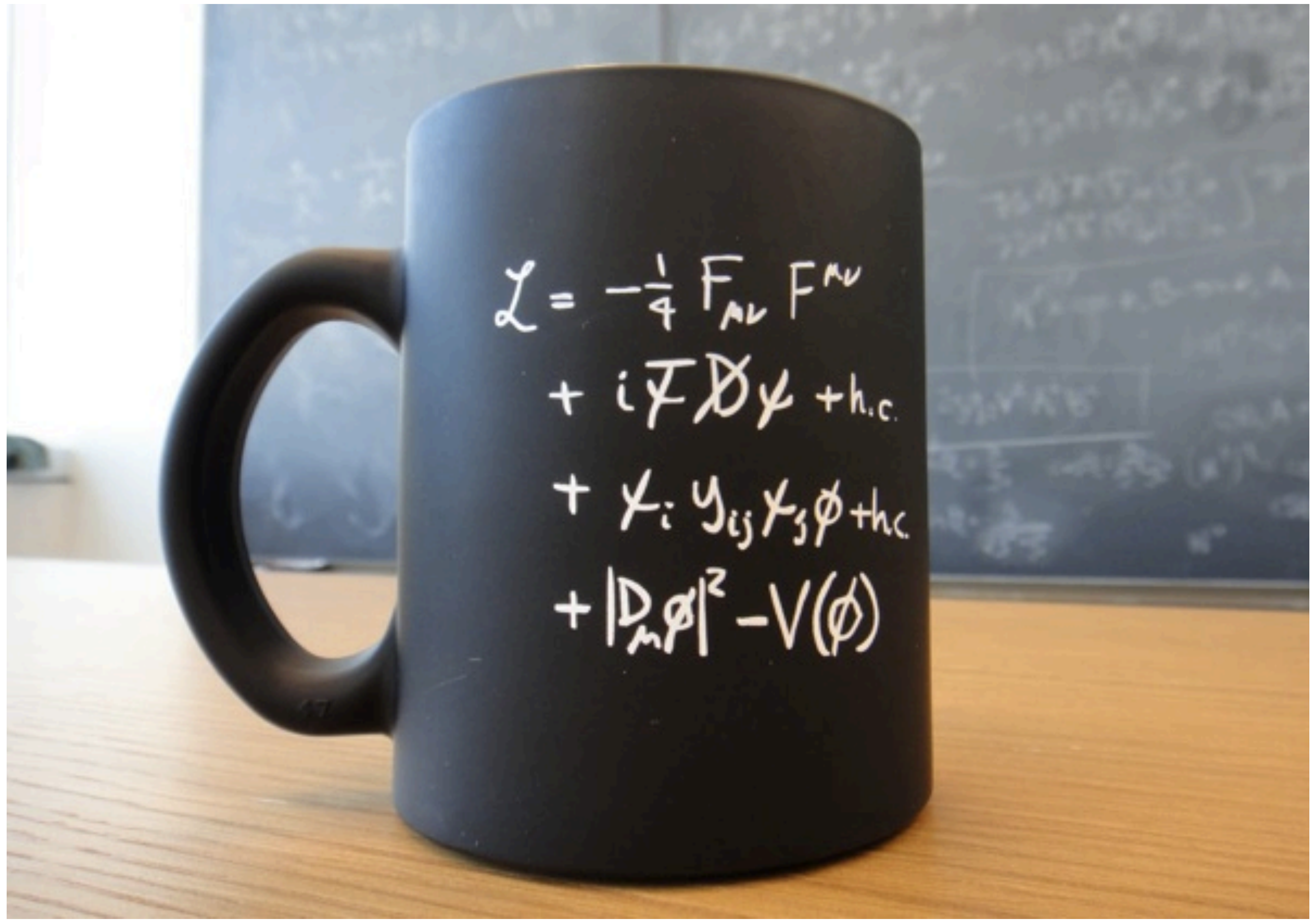
- Tails, tails, tails…!!

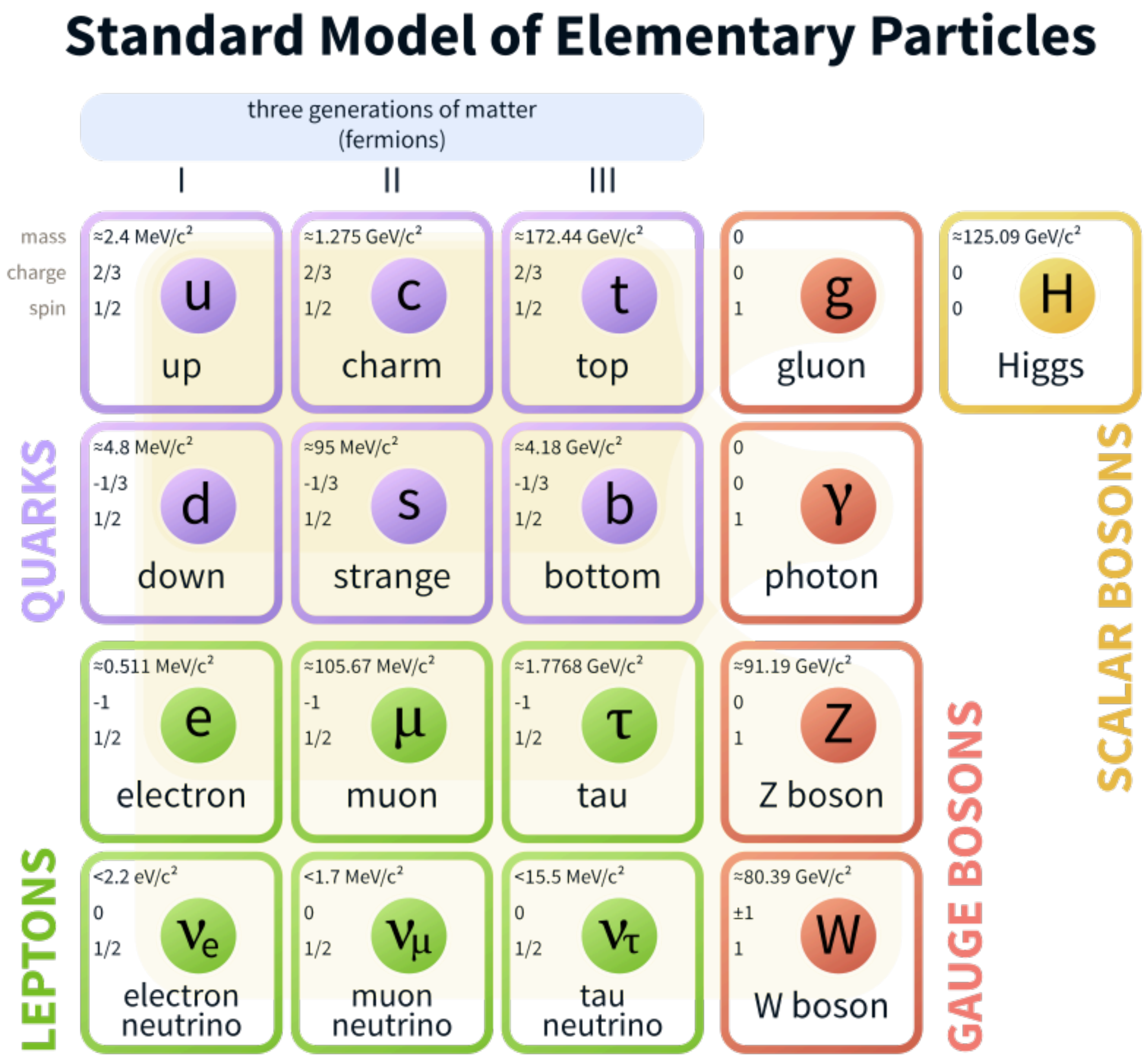
- State-of-the art NNLO QCD+NLO EW allows to control important kinematic distributions at the few percent level up to the multi TeV regime.


- Let's push the precision frontier!

# BACKUP

# With the discovery of the Higgs the SM is ‘complete’



# The motivation for BSM searches are as compelling as ever

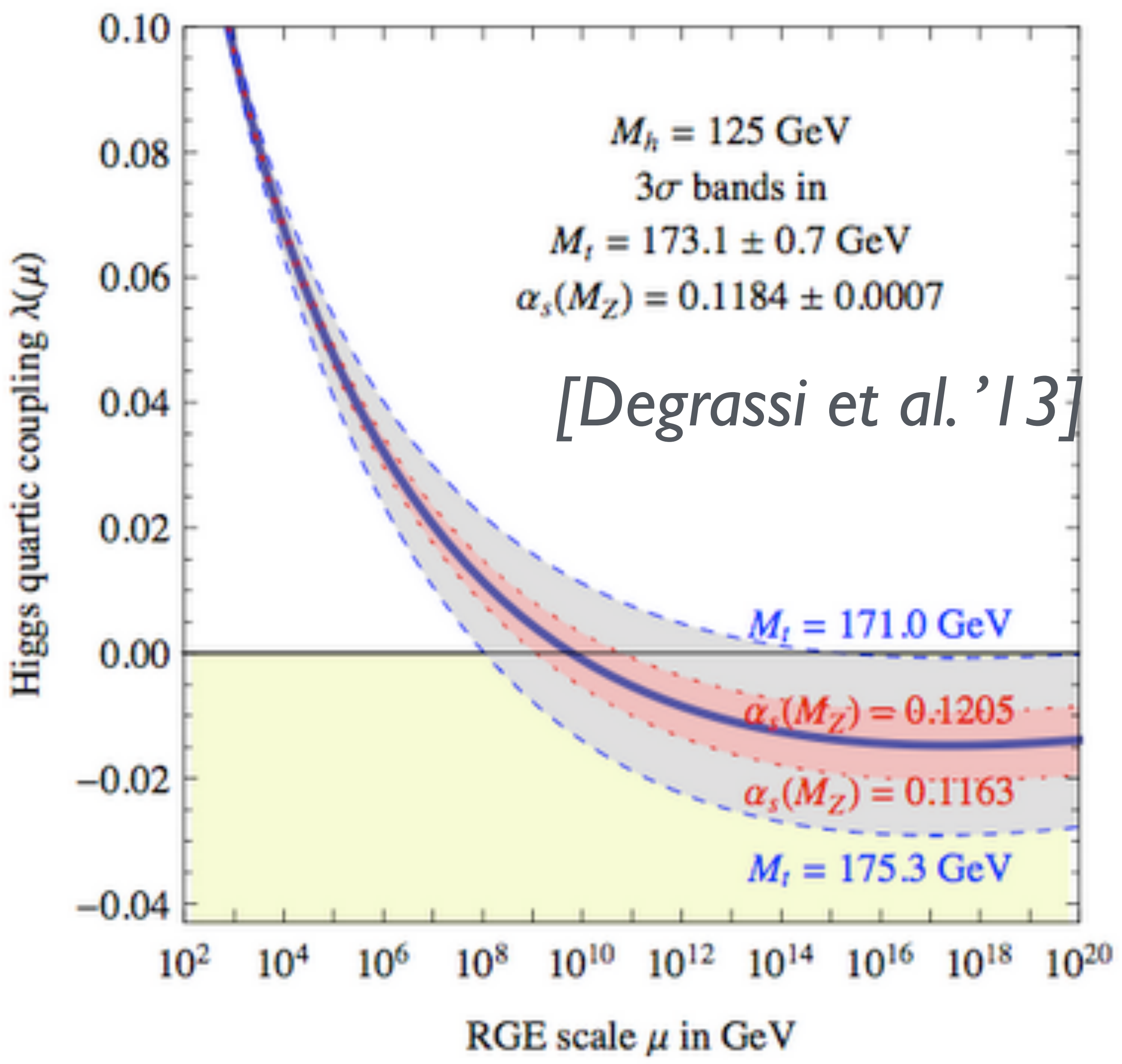
EW vacuum stability

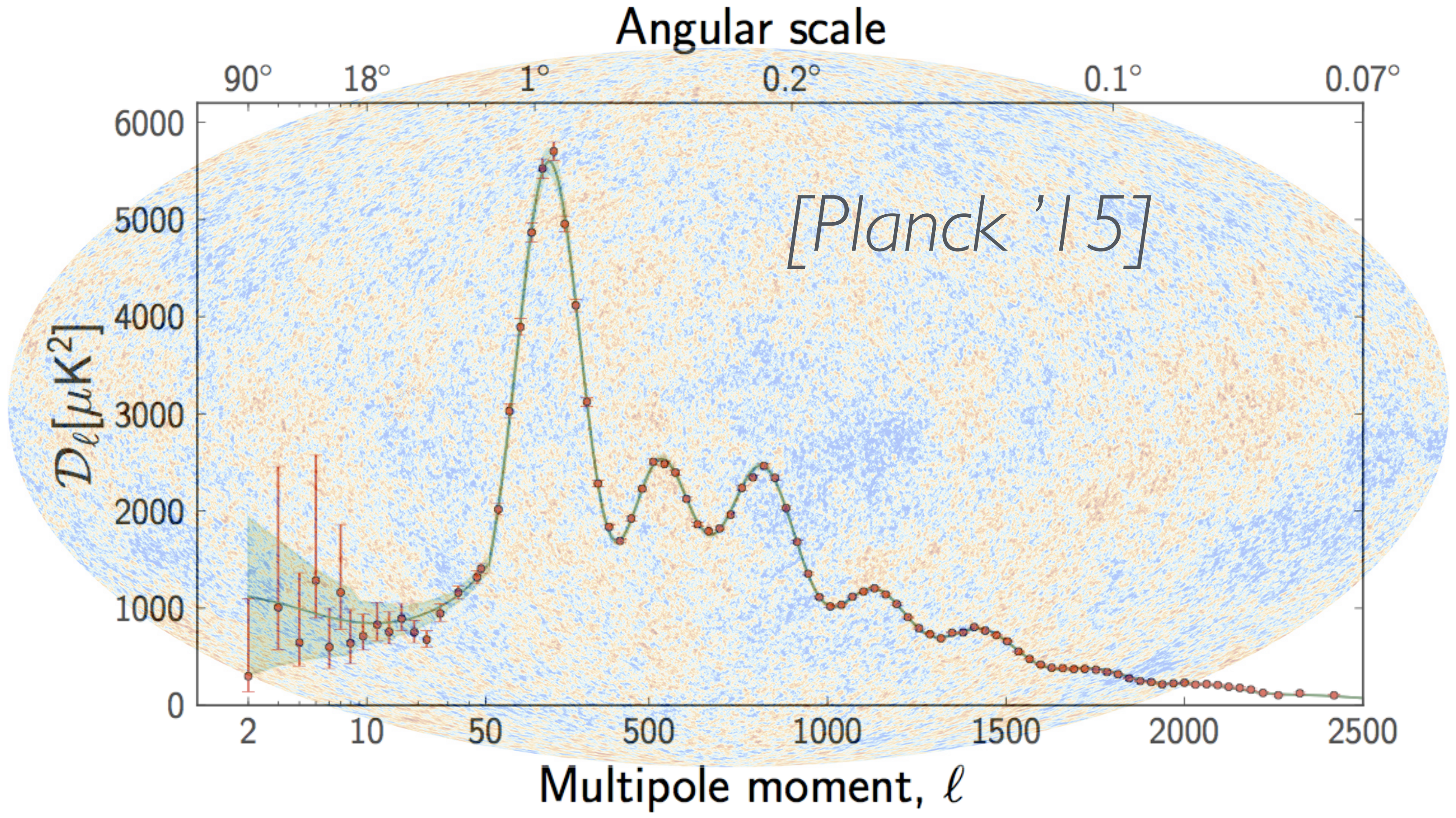
Dark Matter

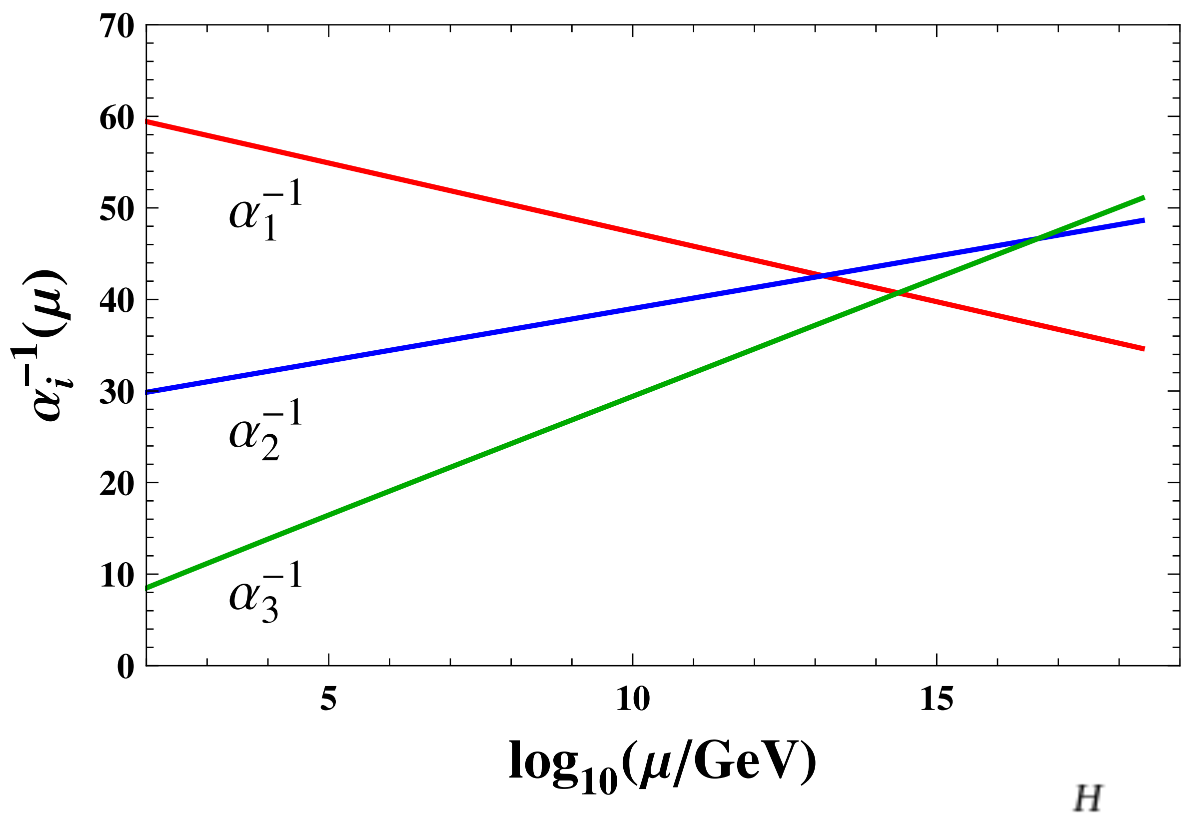
GUT unification

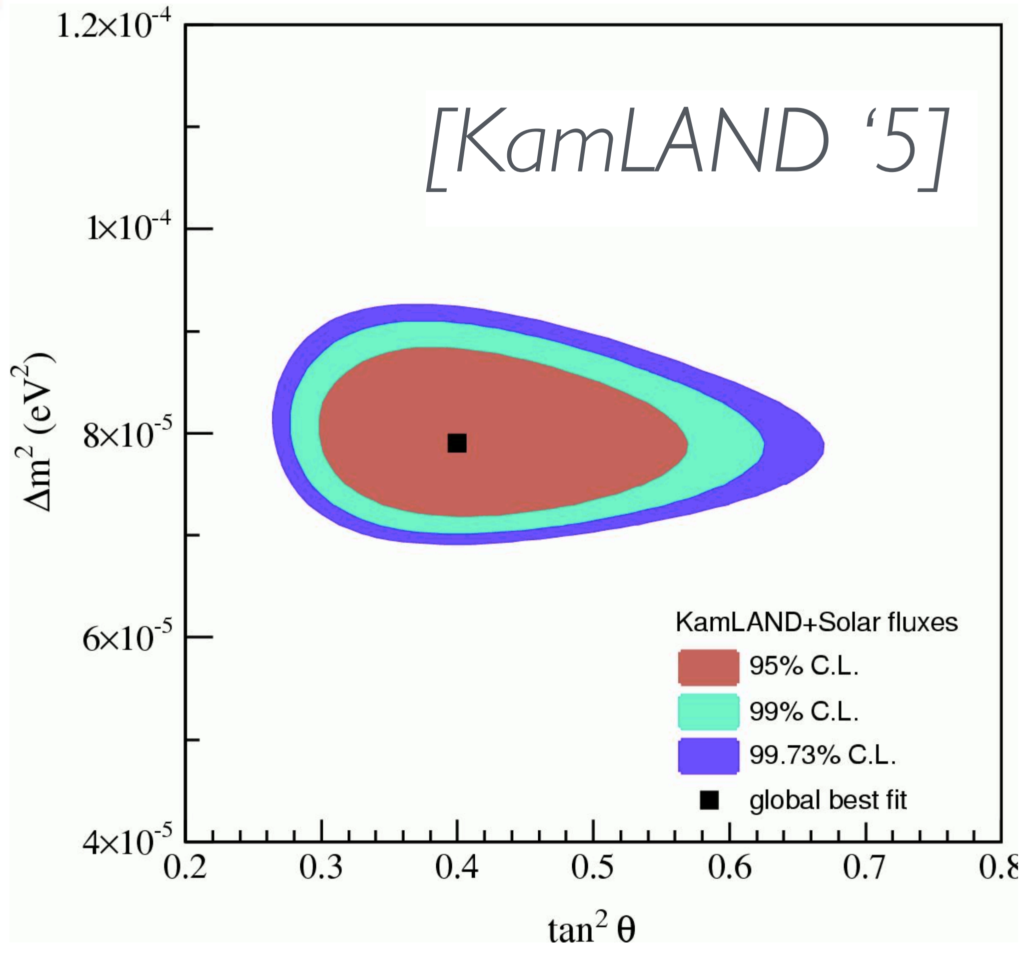
Neutrino masses

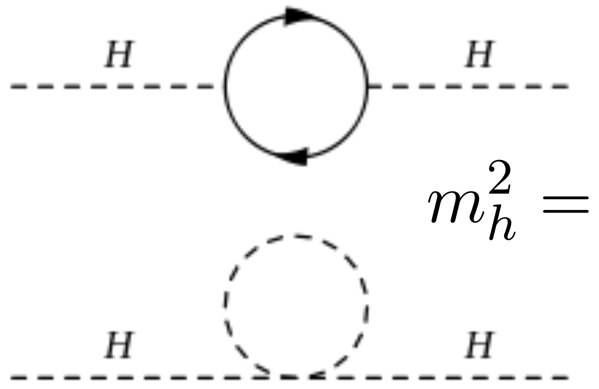
Hierarchy problem



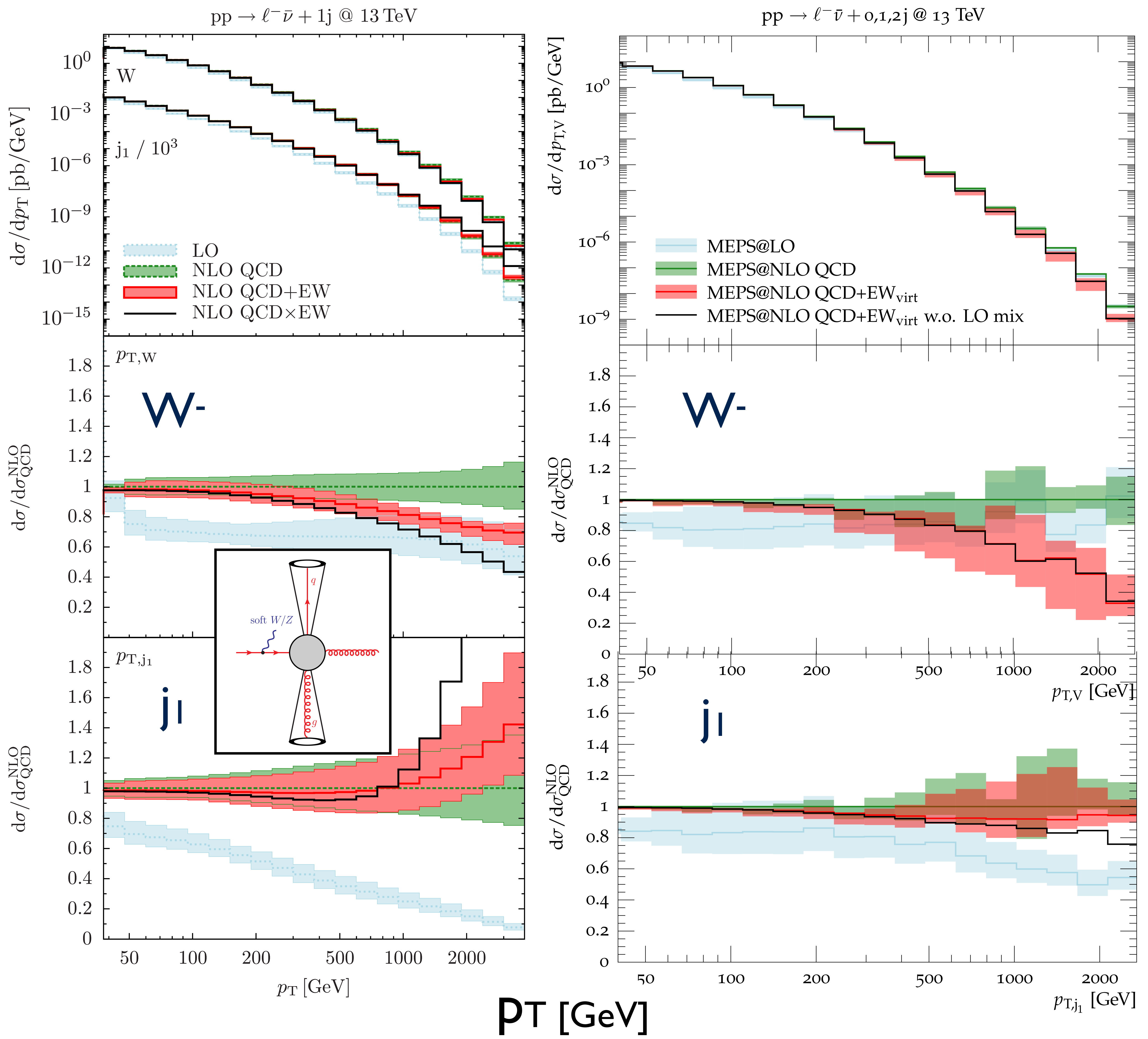




$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda_{UV}^2}{8\pi v^2}(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2)$$

# inclusive V: MEPS@NLO QCD+EW$_{virt}$

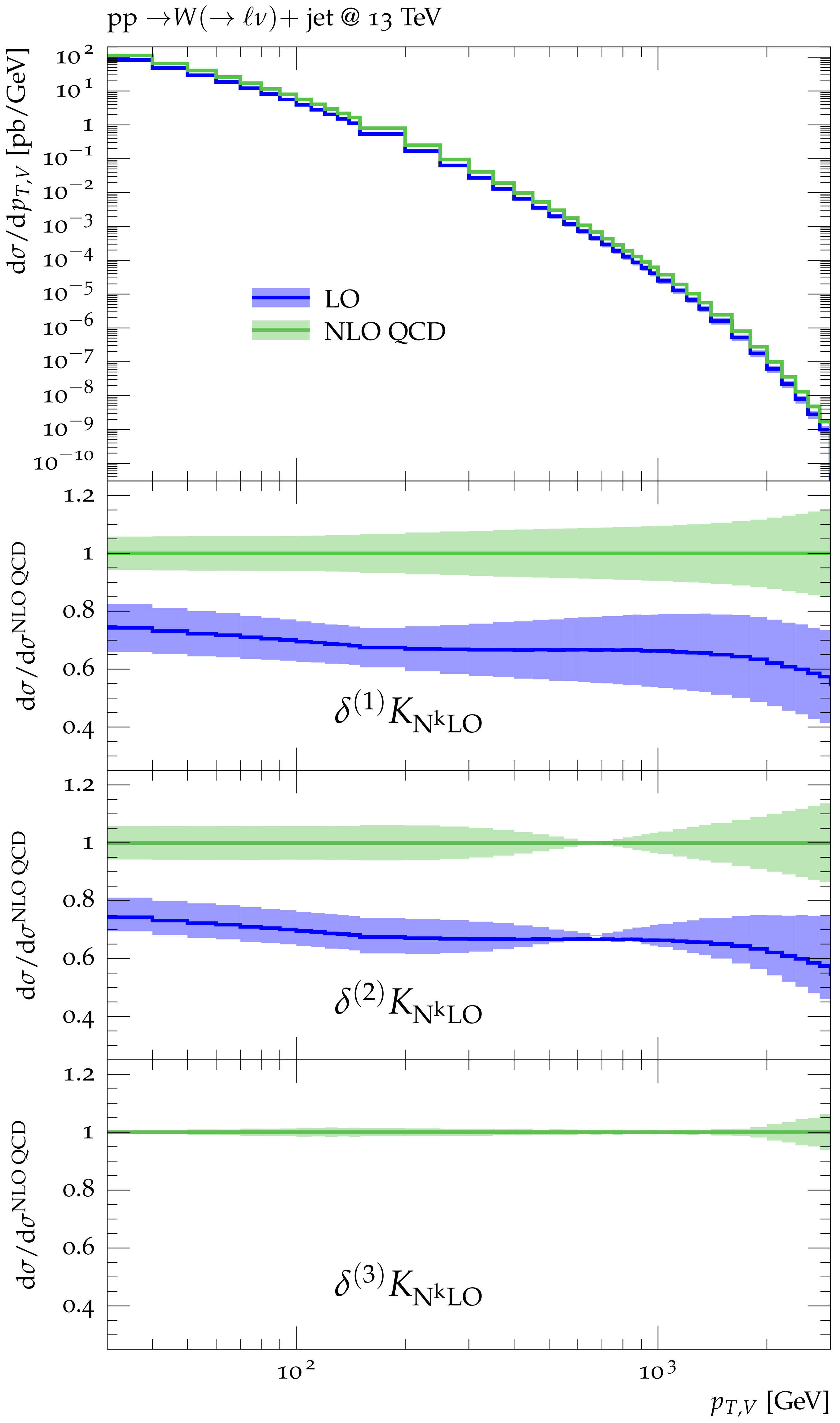



*[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]*

- 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

# QCD uncertainties




$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N^kLO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[K^{(V)}_{\mathrm{N^kLO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N^kLO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

nuisance parameters:

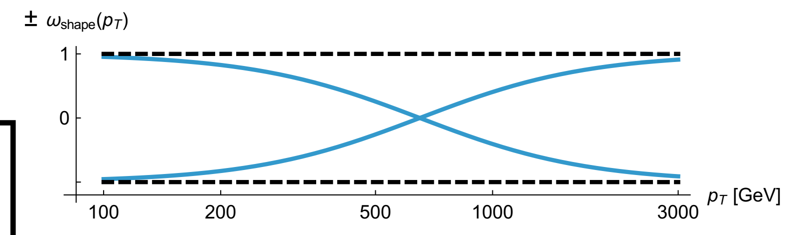
interpreted as 1σ Gaussian

$$\epsilon^{(Z)}_{\mathrm{QCD,i}} = \epsilon^{(W^\pm)}_{\mathrm{QCD,i}} = \epsilon^{(\gamma)}_{\mathrm{QCD,i}} = \epsilon_{\mathrm{QCD,i}}$$

- correlated across processes
- correlated across pT bins

- $$\delta^{(1)}K^{V}_{\mathrm{N^kLO}} = \frac{1}{2}\left[K^{V,\max}_{\mathrm{N^kLO}} - K^{V,\min}_{\mathrm{N^kLO}}\right]$$ *(correlated)*

  symmetrized **scale uncertainty**




- $$\delta^{(2)}K^{V}_{\mathrm{N^kLO}} = \frac{p_{\mathrm{T}}^2 - 650\ \mathrm{GeV}}{p_{\mathrm{T}}^2 + 650\ \mathrm{GeV}}\,\delta^{(1)}K^{V}_{\mathrm{N^kLO}}$$

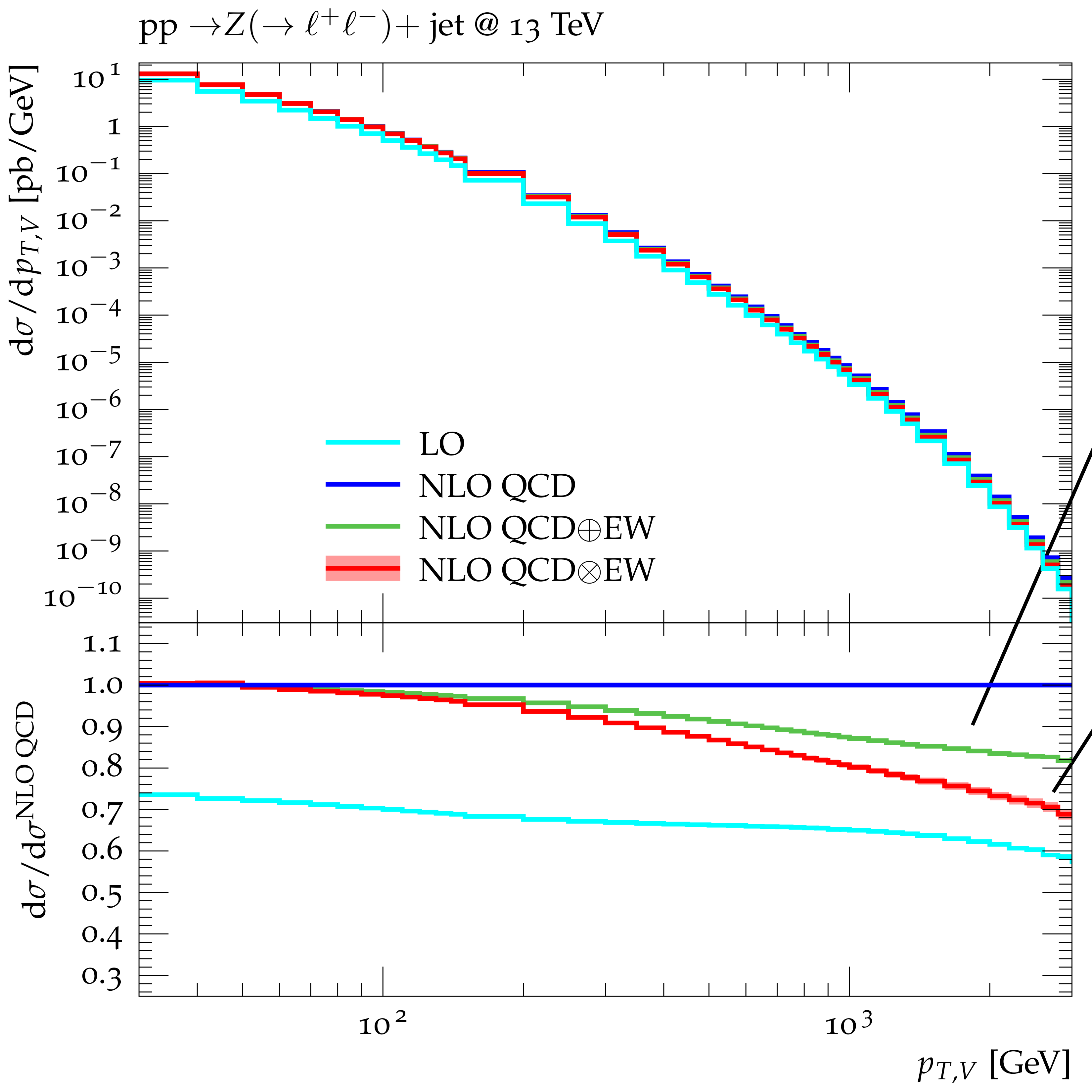
  yields max **shape distortion** within scale variation band *(correlated)*

(important for extrapolation from low-pT to high-pT)

- $$\delta^{(3)}K^{V}_{\mathrm{N^kLO}} = \frac{K^{V}_{\mathrm{N^kLO}}}{K^{V}_{\mathrm{N^{k-1}LO}}} - \frac{K^{Z}_{\mathrm{N^kLO}}}{K^{Z}_{\mathrm{N^{k-1}LO}}}$$ *(correlated)*

  Difference of (N)NLO corrections as **process correlation uncertainty**

# 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**

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

**Multiplicative combination**

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

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

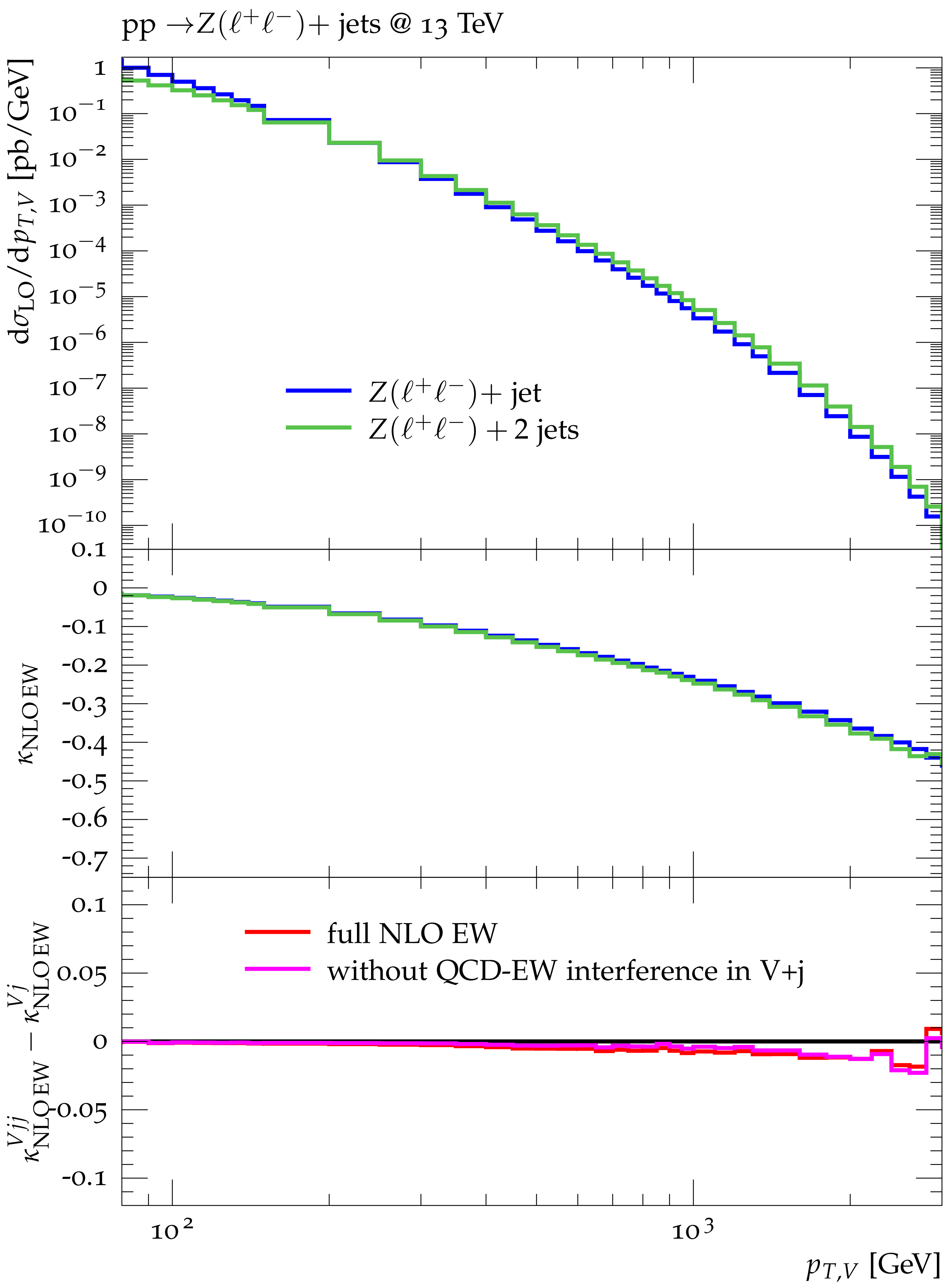
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

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

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

# Mixed QCD-EW uncertainties




pT$_{j,2}$ > 30 GeV

Bold estimate:

**Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to V+jet**
**$\simeq$ NLO EW to V+2jets**

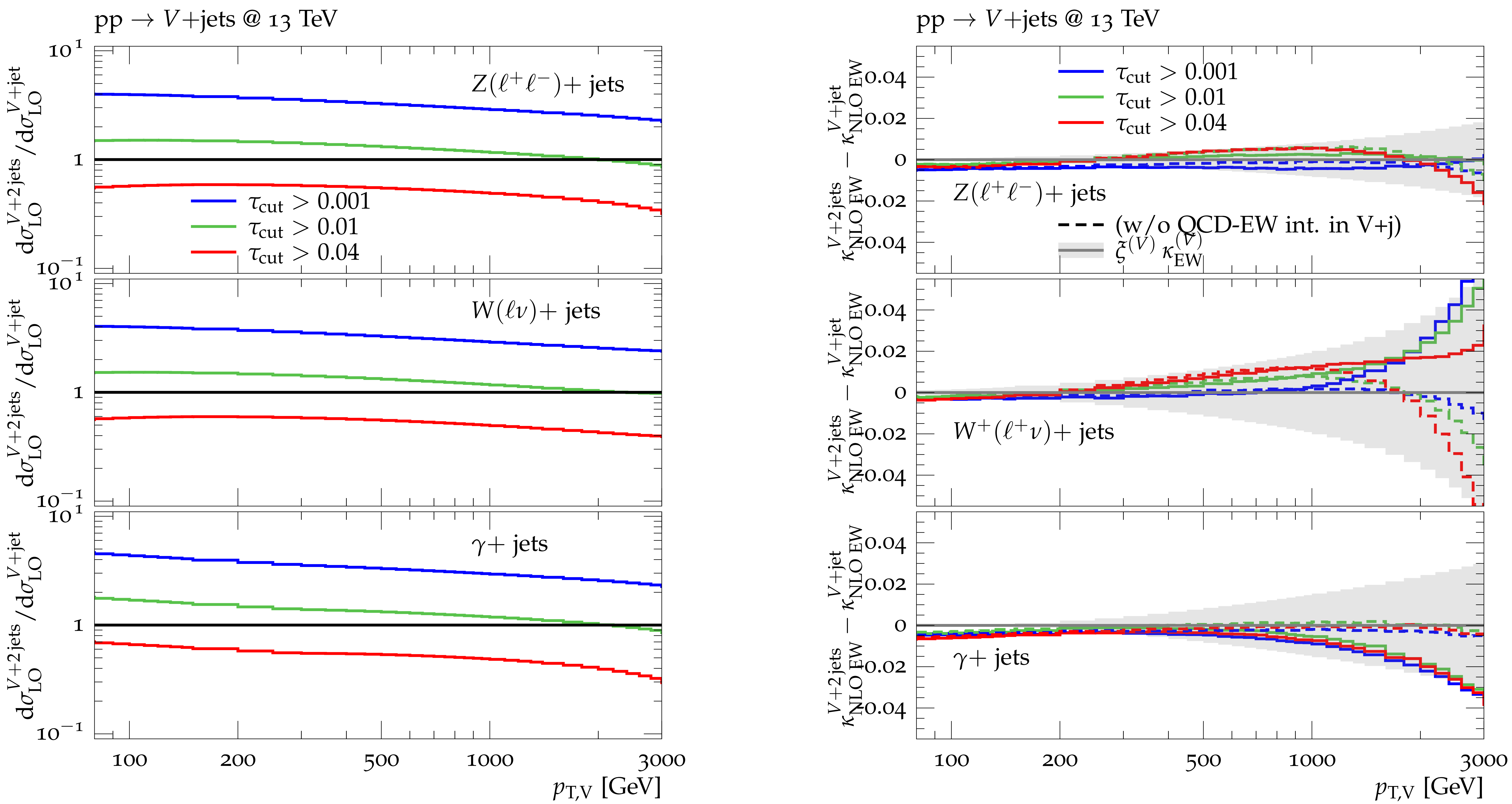
and we observe

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

strong support for
- factorization
- multiplicative QCD x EW combination

# Mixed QCD-EW uncertainties

Estimate of non-factorising contributions




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

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

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

$$\xi^Z = 0.1, \qquad \xi^W = 0.2, \qquad \xi^\gamma = 0.4$$

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