Aspects of the EW Standard Model

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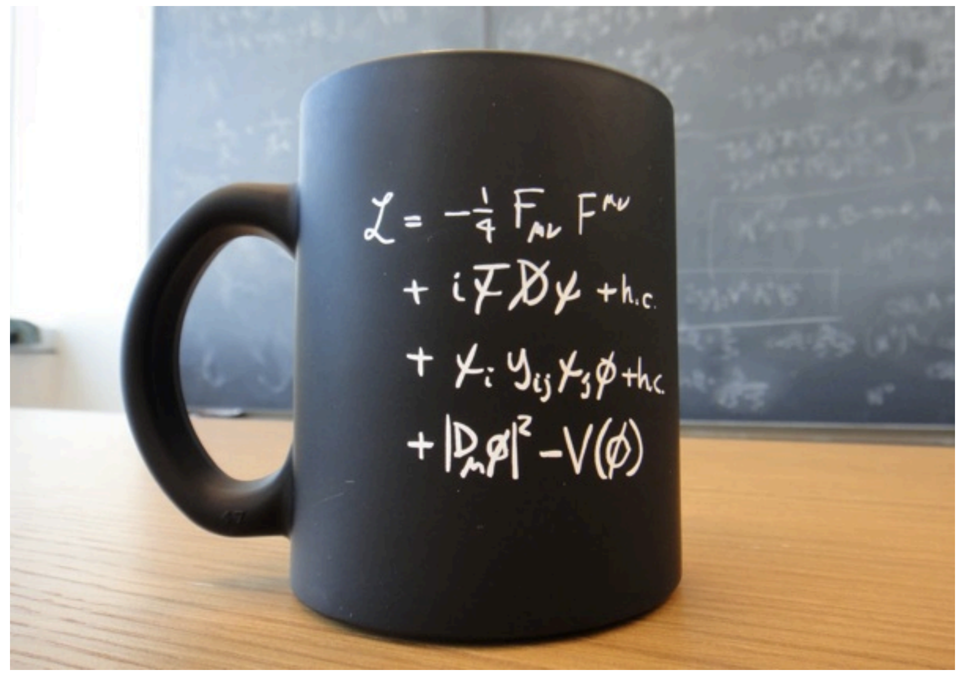

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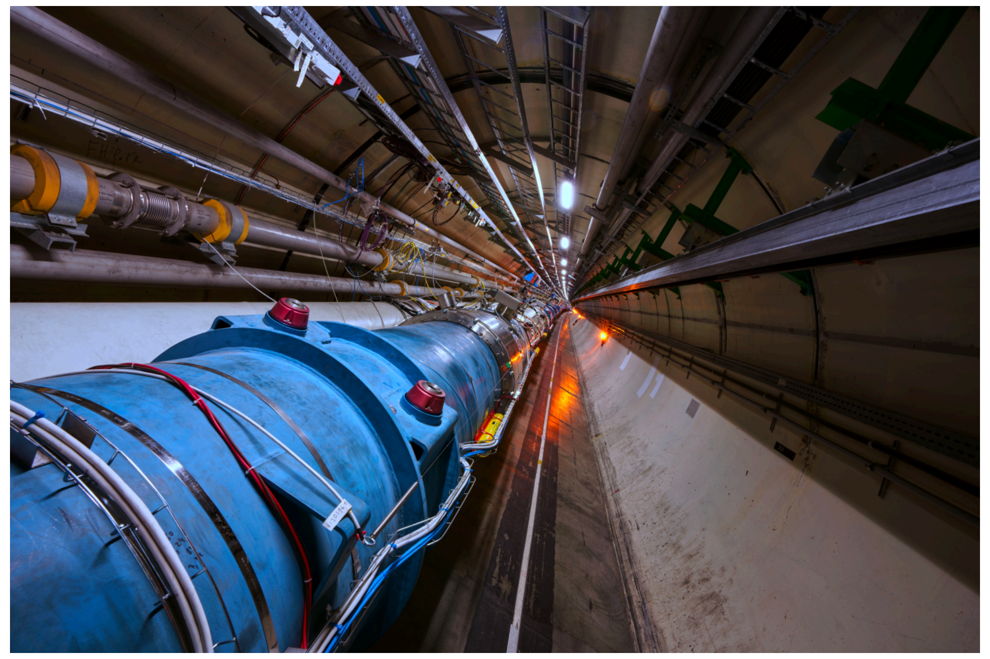


EW precision observables

The EW SM

Global EW fit

EW radiative corrections

➡Study dynamics of the EW SM at the TeV scale
➡Test BSM via indirect EW probes
➡Constrain backgrounds in direct searches for New Physics

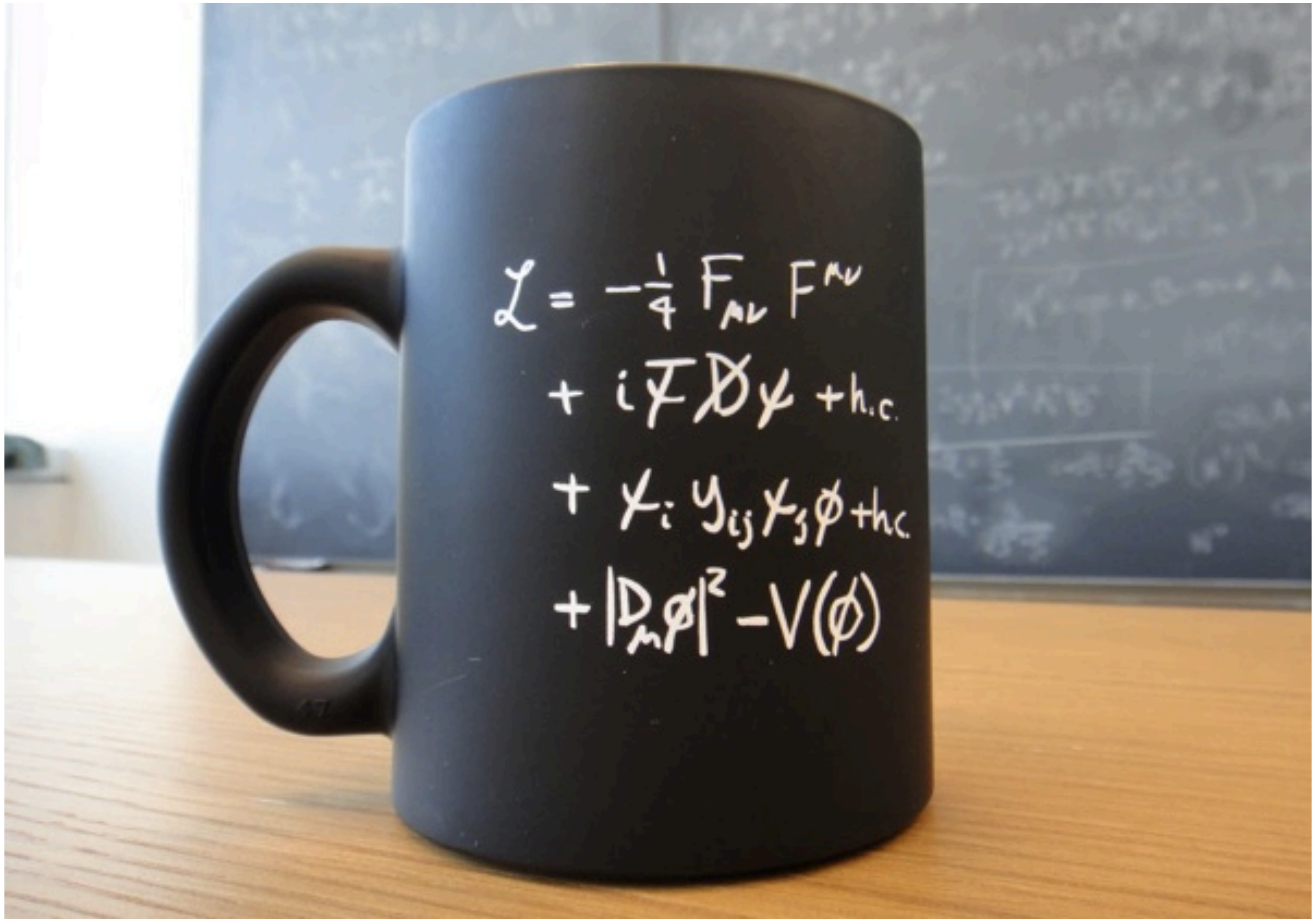
The EW SM

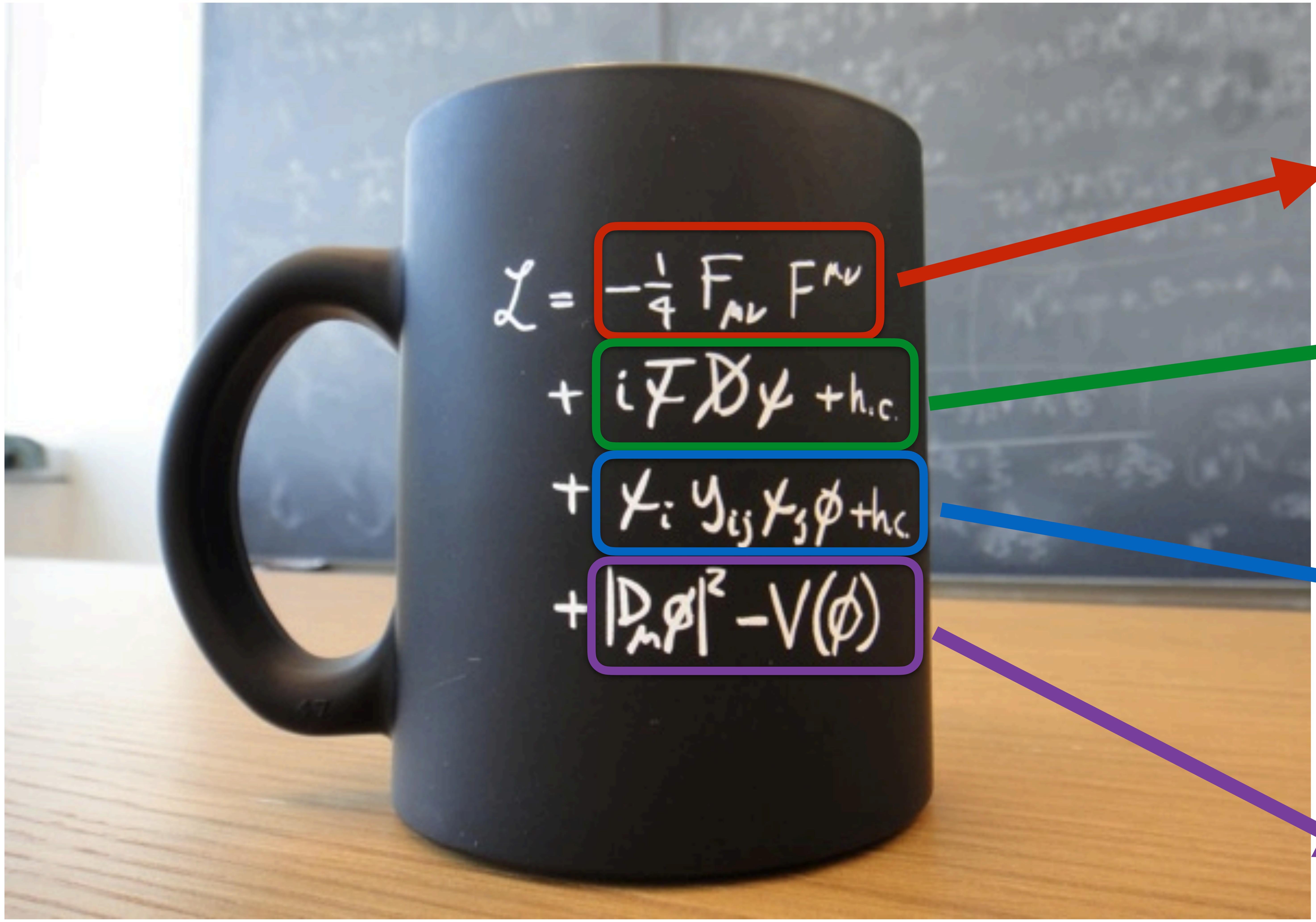
Symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{<H>} SU(3)_C \times U(1)_{\rm EM}$$

Matter content:

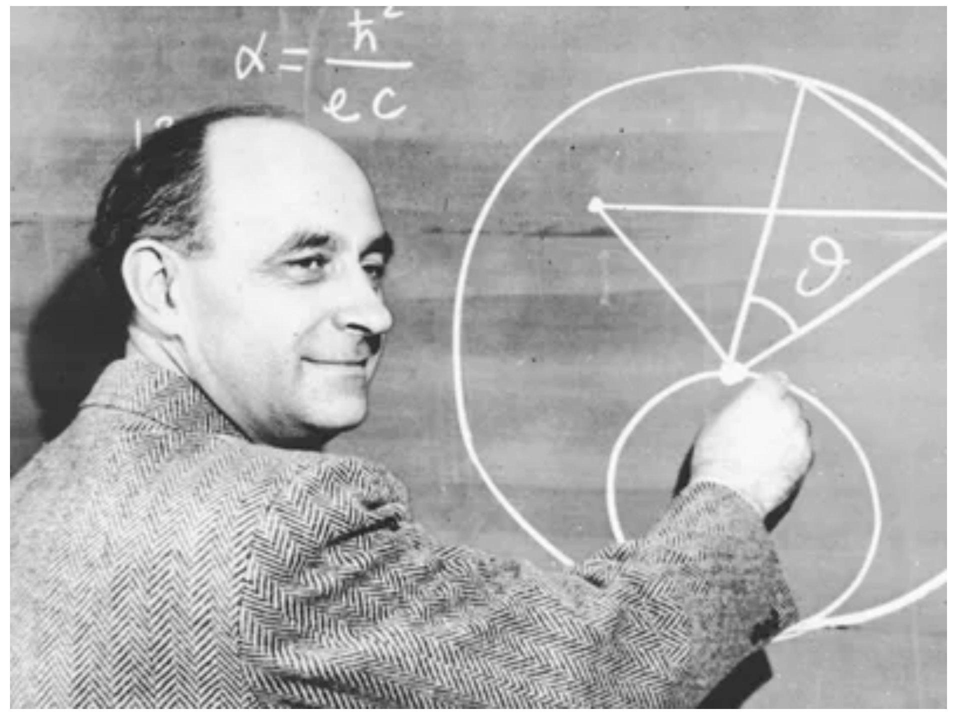
- 3 families of matter particles (quarks and leptons) in fundamental representations
- 8+3+1 Gauge fields in adjoint representations
- 1 Higgs doublet in fundamental representation of SU(2) acquires vacuum expectation → electroweak symmetry breaking (EWSB)


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$



$\mathcal{L}_{\text{Yang-Mills}}$

$\mathcal{L}_{\text{Fermi}}$



$\mathcal{L}_{\text{Yukawa}}$

$\mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{\text{SM}}^{\text{classical}} = \mathcal{L}_{\text{Yang-Mills}} + \mathcal{L}_{\text{Fermi}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{Higgs}}$$

The EW SM in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\rm Yang\text{-}Mills} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

$$\mathcal{L}_{\rm Yang\text{-}Mills} = -\frac{1}{4} G^{a\,\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^{i\,\mu\nu} W^i_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$$

with the *field strength tensors:*

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu \,,$$
$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \epsilon^{ijk} W^j_\mu W^k_\nu \,,$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

structure constants

$$\mathcal{L}_{\rm Fermi} = \sum_{i=1}^{3} [{q^i_L}^\dagger \bar\sigma^\mu D_\mu q^i_L + {u^i_R}^\dagger \sigma^\mu D_\mu u^i_R + {d^i_R}^\dagger \sigma^\mu D_\mu d^i_R + {l^i_L}^\dagger \bar\sigma^\mu D_\mu l^i_L + {e^i_R}^\dagger \sigma^\mu D_\mu e^i_R \,]$$

with the *gauge covariant derivative:*

$$D_\mu = \partial_\mu + i g_s \mathbf{T}^a G^a_\mu + i g_2 \mathbf{I}^i W^i_\mu + i g_1 \frac{Y}{2} \mathbf{1} B_\mu$$

gauge couplings

The EW SM in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\text{Yang-Mills}} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

$$\mathcal{L}_{\text{Yang-Mills}} = -\frac{1}{4}G^{a\,\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{i\,\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

$$\mathcal{L}_{\rm Fermi} = \sum_{i=1}^{3}[{q_L^i}^\dagger\bar{\sigma}^\mu D_\mu q_L^i + {u_R^i}^\dagger\sigma^\mu D_\mu u_R^i + {d_R^i}^\dagger\sigma^\mu D_\mu d_R^i + {l_L^i}^\dagger\bar{\sigma}^\mu D_\mu l_L^i + {e_R^i}^\dagger\sigma^\mu D_\mu e_R^i\,]$$

with the *field strength tensors:*

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu\,,$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \epsilon^{ijk} W^j_\mu W^k_\nu\,,$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

with the *gauge covariant derivative:*

$$D_\mu = \partial_\mu + i g_s \mathbf{T}^a G^a_\mu + i g_2 \mathbf{I}^i W^i_\mu + i g_1 \frac{Y}{2}\mathbf{1} B_\mu$$

structure constants   *gauge couplings*

➡ F-F-V, V-V-V (TG) and V-V-V-V (QG) **couplings are related!**

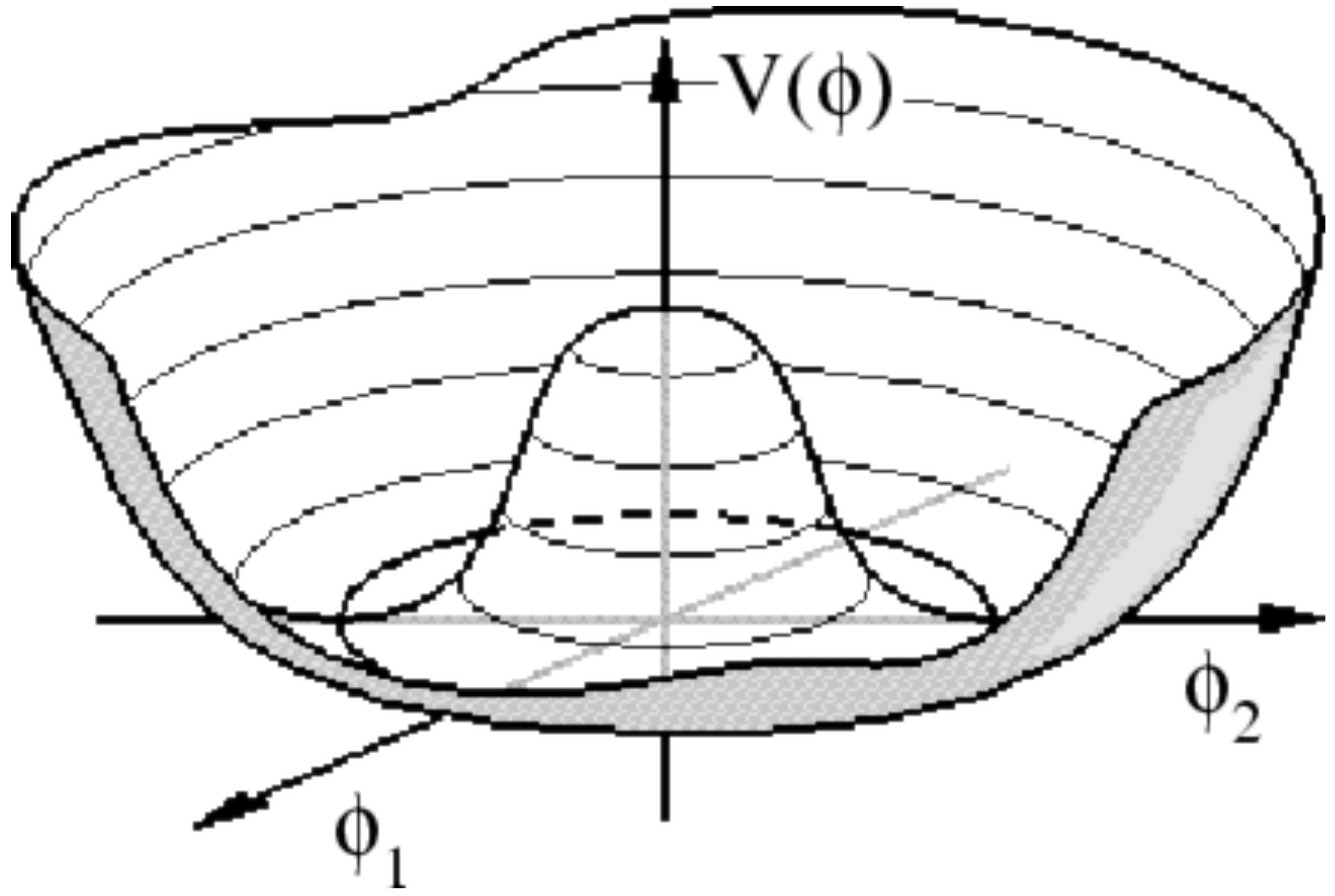
➡ $f_L = \mathbf{2}, f_R = 1$ under $SU(2)$

➡ Y such that $Q = I_3 + \frac{Y}{2}$ (Gell-Mann-Nishijima relation)

The EW SM in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\rm Yang\text{-}Mills} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

$$\mathcal{L}_{\rm Higgs} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi)$$



with *Higgs potential:*

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2\,,\quad \mu^2,\lambda > 0$$

minimum at $v = \frac{2\mu}{\sqrt{\lambda}}$

Expand Φ-field around minimum:

Would-be Goldstone bosons

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \frac{1}{\sqrt{2}}(v + h^0(x) + i\chi^0(x)) \end{pmatrix}$$

$\rightarrow m_h^0 = \sqrt{2}\mu = \frac{v\lambda}{2}$

→ mass terms for W, B (however, not diagonal)

→ unbroken fields are not eigenstates of $U(1)_{\rm EM}$

The EW SM in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\rm Yang\text{-}Mills} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

$$\mathcal{L}_{\rm Higgs} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi)$$

→ diagonalization of W, B fields:

$$W^\pm_\mu = \frac{1}{2}(W^1_\mu \pm W^2_\mu)\,,$$
$$Z^0_\mu = \cos\theta_W W^3_\mu - \sin\theta_W B_\mu\,,$$
$$A_\mu = \sin\theta_W W^3_\mu + \cos\theta_W B_\mu\,,$$

physical fields

unbroken fields

where:

$$\cos\theta_W = \frac{g_2}{\sqrt{g_1^2+g_2^2}} = \frac{m_W}{m_Z}\,,$$
$$\sin\theta_W = \frac{g_1}{\sqrt{g_1^2+g_2^2}}$$

and:

$$m_W = \frac{g_2 v}{2}$$
$$m_Z = \frac{v}{2}\sqrt{g_1^2+g_2^2}$$

gauge coupling of remaining $U(1)_{\rm EM}$ →

$$e = \frac{g_1 g_2}{\sqrt{g_1^2+g_2^2}}$$

➡couplings and gauge boson masses are related!

The EW SM in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\rm Yang\text{-}Mills} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

$$\mathcal{L}_{\rm Yukawa} = -\sum_{i,j=1}^{3}\left[y_{ij}^{d}(q_L^i)^\dagger \Phi d_R^j \;+ y_{ij}^{u}(q_L^i)^\dagger \Phi^c u_R^j \;+ y_{ij}^{l}(l_L^i)^\dagger \Phi e_R^j \;+ \text{h.c.}\right]$$

Yukawa couplings

After EWSB:

$$m_{ij}^f = \frac{v}{\sqrt{2}} y_{ij}^f$$

These can be diagonalised:

$$m_{f,i} = \frac{v}{\sqrt{2}} \sum_{k,m}^{3} U_{ik}^{f,L} y_{km}^f \left(U_{mi}^{f,R}\right)^\dagger \equiv \frac{v}{\sqrt{2}}\lambda_i^f$$

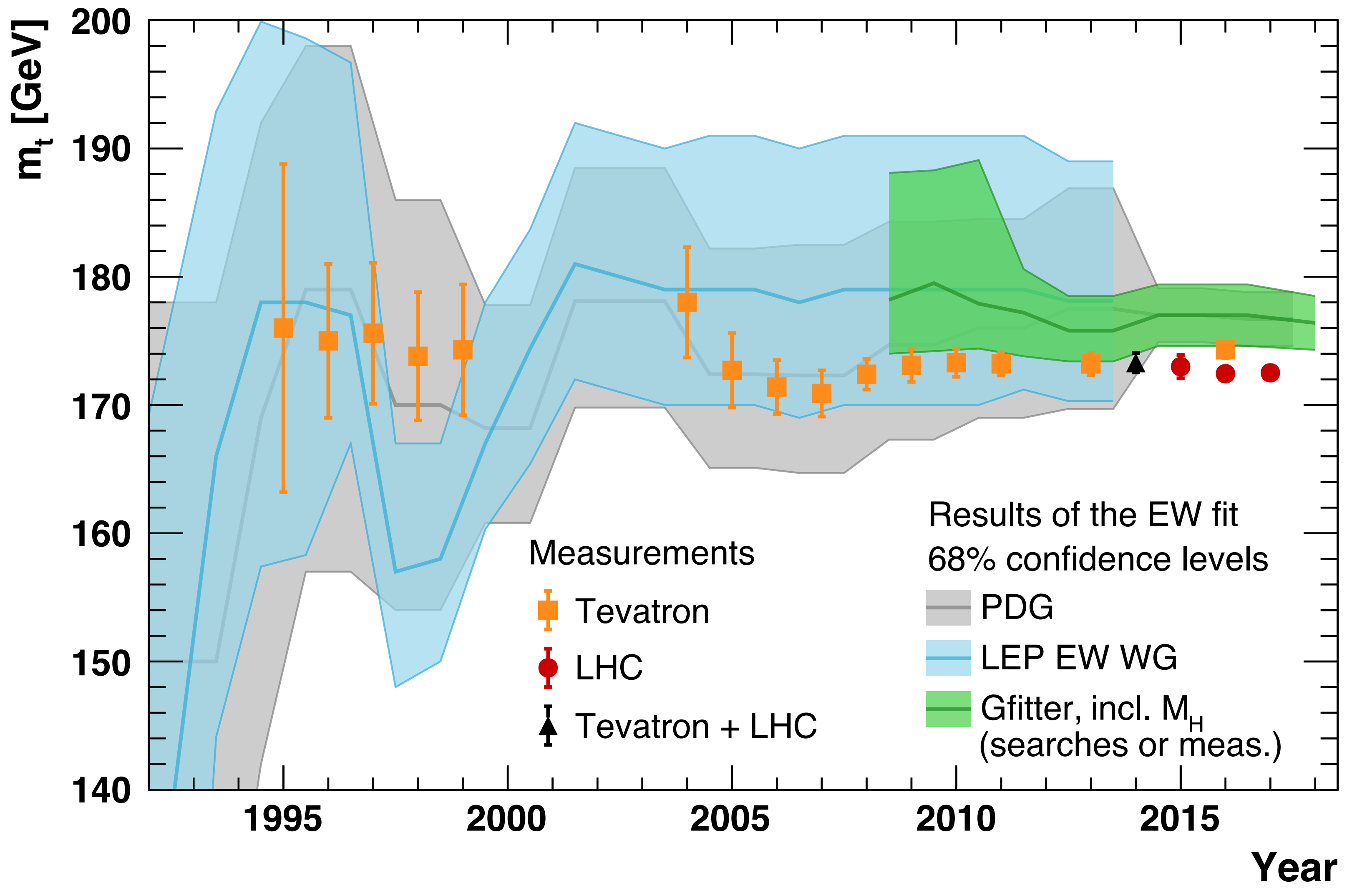
- due to unitarity these matrices drop out in NC interactions: no FCNCs in the SM
- a non-trivial matrix remains in CC interactions: CKM matrix

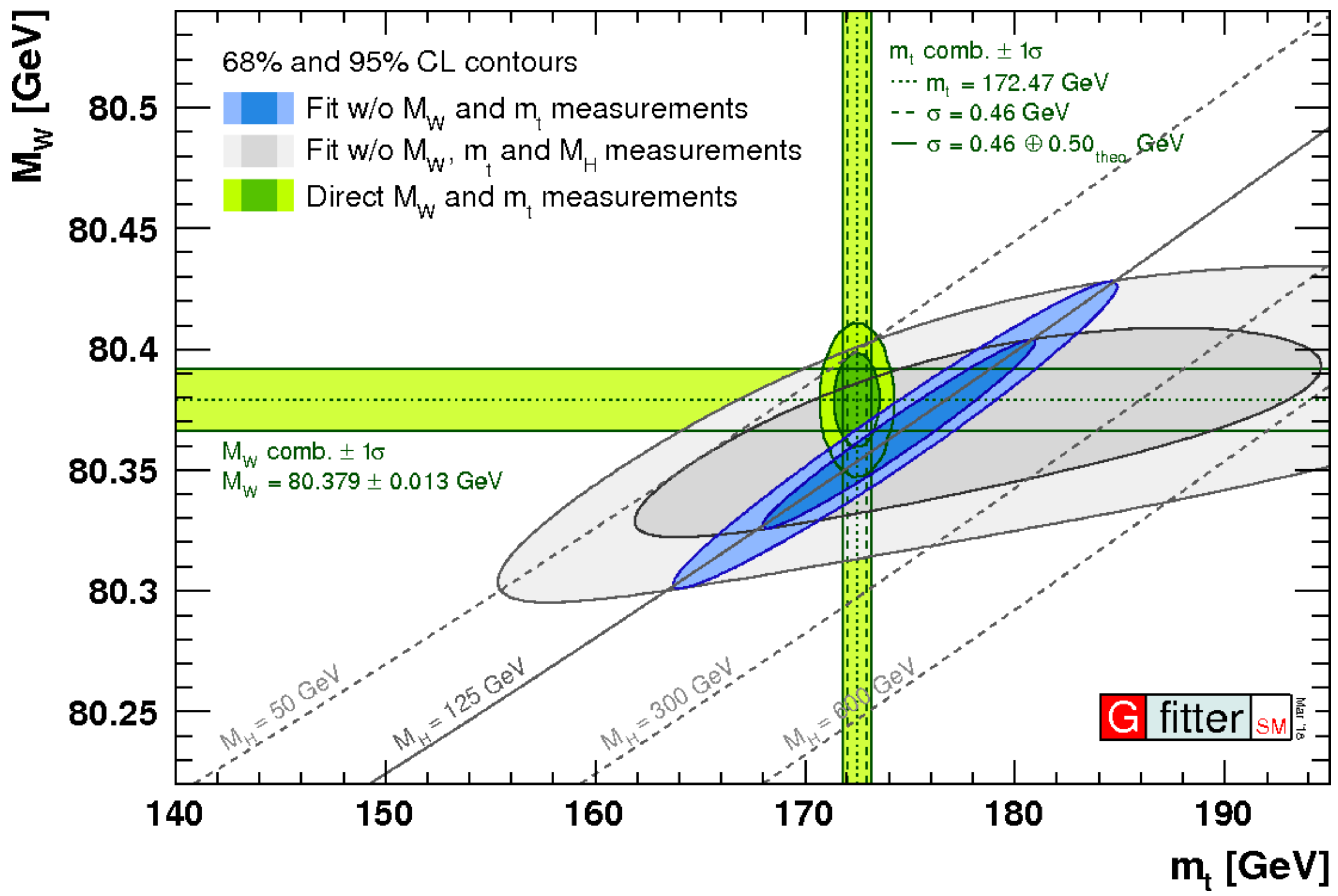
$\Phi^c \equiv i\sigma^2\Phi^*$

The global EW fit

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]	125.1 ± 0.2	yes	$125.1^{+0.2}_{-0.2}$	$100.2^{+24.4}_{-20.6}$	$100.3^{+23.5}_{-19.9}$
M_W [GeV]	80.379 ± 0.013	–	80.363 ± 0.007	80.356 ± 0.008	80.356 ± 0.007
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1879 ± 0.0020	91.1967 ± 0.0099	91.1969 ± 0.0096
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4945 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.483 ± 0.015	41.474 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.744 ± 0.017	20.725 ± 0.026	20.724 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01623 ± 0.0001	0.01622 ± 0.0001	0.01624 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1471 ± 0.0005	0.1471 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23151 ± 0.00006	0.23151 ± 0.00006	0.23150 ± 0.00005
$\sin^2\theta^\ell_{\rm eff}$(TEV)	0.2318 ± 0.0003	–	0.23151 ± 0.00006	0.23150 ± 0.00006	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6679 ± 0.00022	0.6679 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0737 ± 0.0003	0.0737 ± 0.0003	0.0737 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1031 ± 0.0003	0.1033 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21579 ± 0.00011	0.21578 ± 0.00012	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\triangledown)}$	173.06 ± 0.94	yes	173.54 ± 0.86	$175.97^{+2.11}_{-2.12}$	$176.00^{+2.03}_{-2.04}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2758 ± 10	yes	2756 ± 10	2738 ± 41	2739 ± 39
$\alpha_s(M^2_Z)$	–	yes	$0.1197^{+0.0030}_{-0.0029}$	0.1197 ± 0.0030	0.1198 ± 0.0028

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1471 \pm 0.0005$ ($A_\ell = 0.1469 \pm 0.0005$). $^{(\triangledown)}$Combination of experimental (0.8 GeV) and theory uncertainty (0.5 GeV).$^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

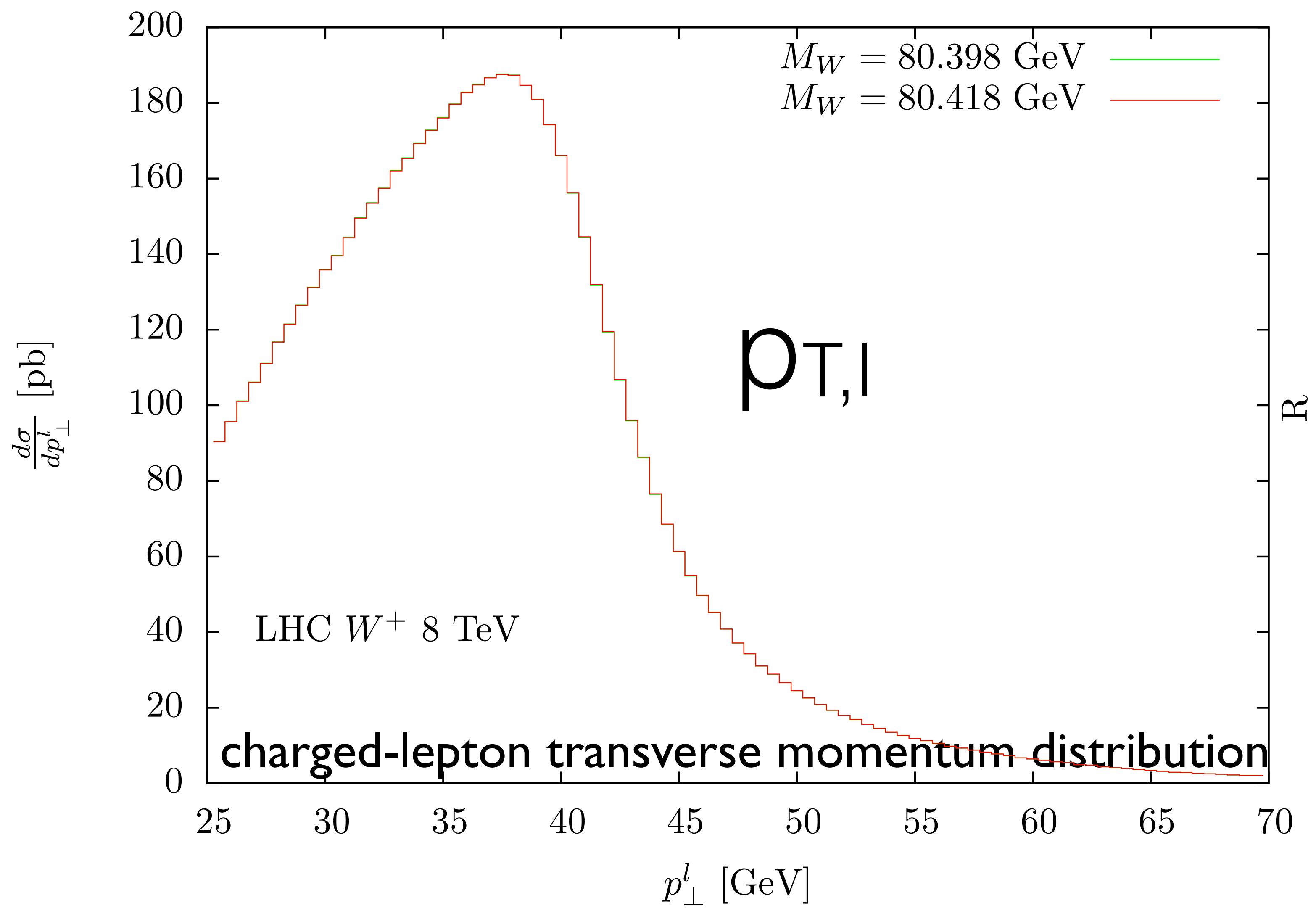


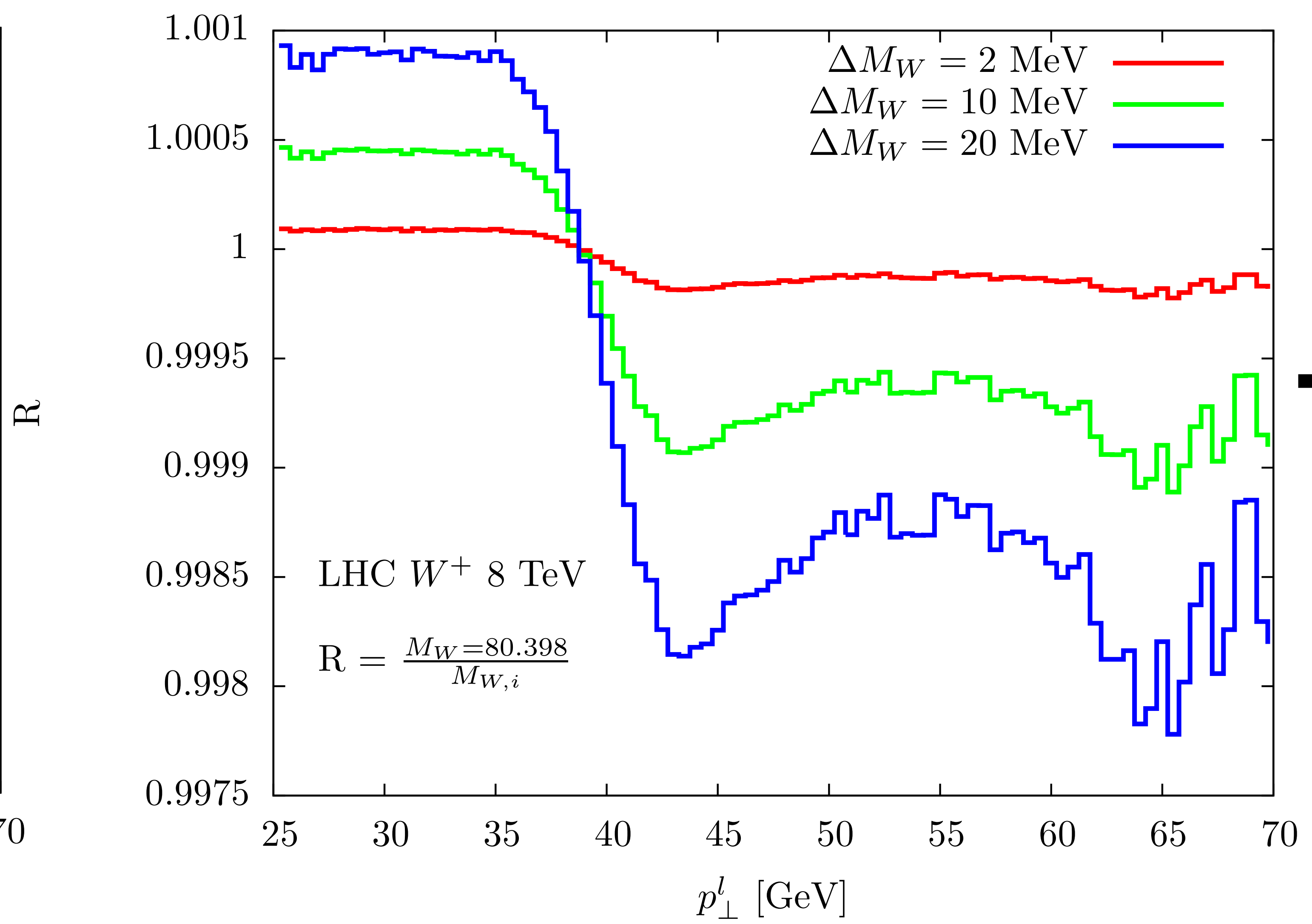


Drell-Yan: M_W measurements

- 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, $E_{\rm miss}$)

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





[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!

EW standard candles at hadron colliders

Precision EW
- DY
- VV
- V+jets

Top
- $t\bar{t}$
- $t\bar{t} + X$

Rare processes
- VBS
- VVV
- ….

Higgs
- precision couplings
- high-pT
- HH

The global EFT/SMEFT fit

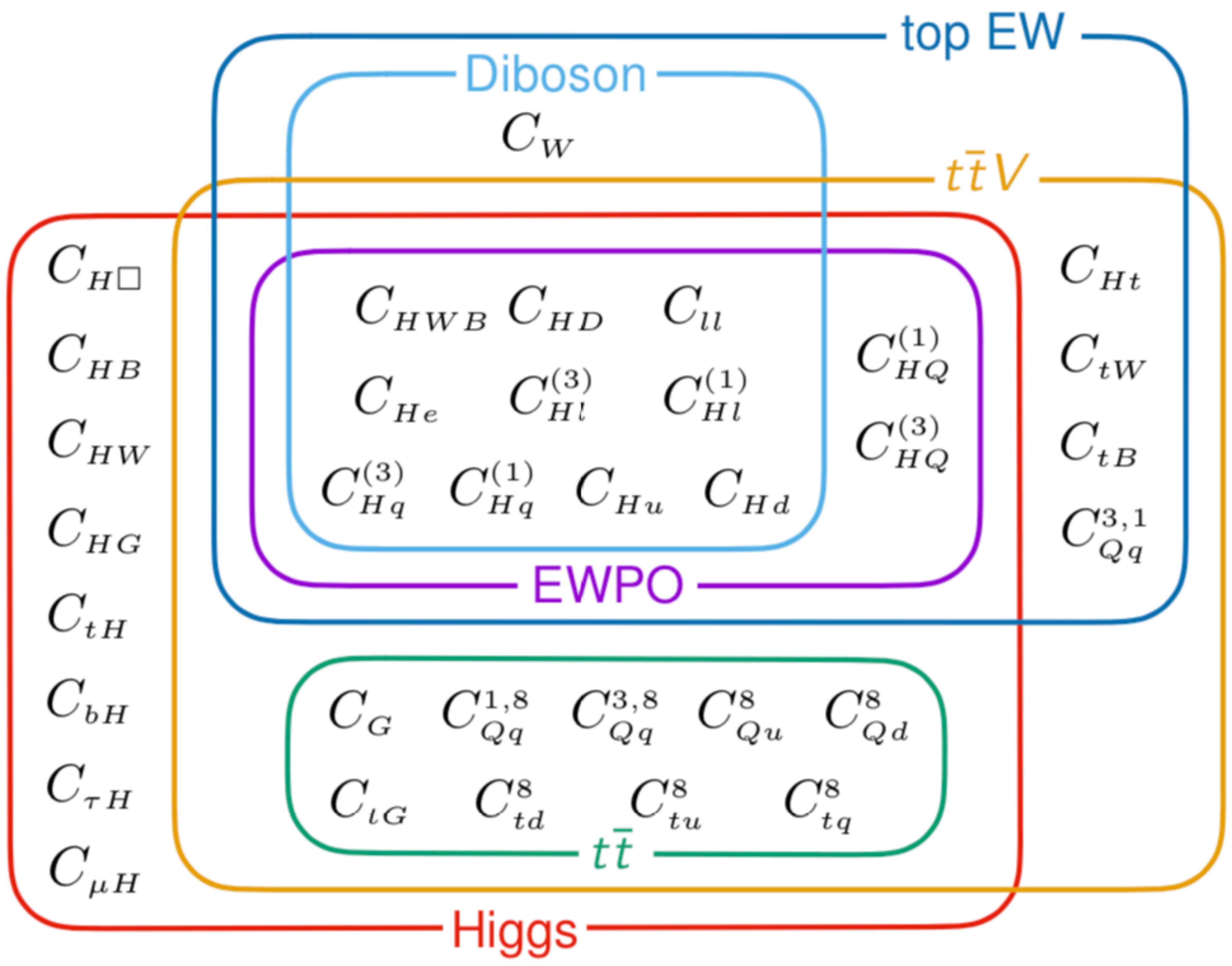
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

Wilson coefficients

dimensional scale

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
X^2H^2		$\psi^2 XH$		$\psi^2 H^2 D$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d^\alpha_p)^T C u^\beta_r\right] \left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r) \varepsilon_{jk} (\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right] \left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \varepsilon_{jk} (\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jn} \varepsilon_{km} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right] \left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r) \varepsilon_{jk} (\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma} \left[(d^\alpha_p)^T C u^\beta_r\right] \left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$				

→ flavour universality



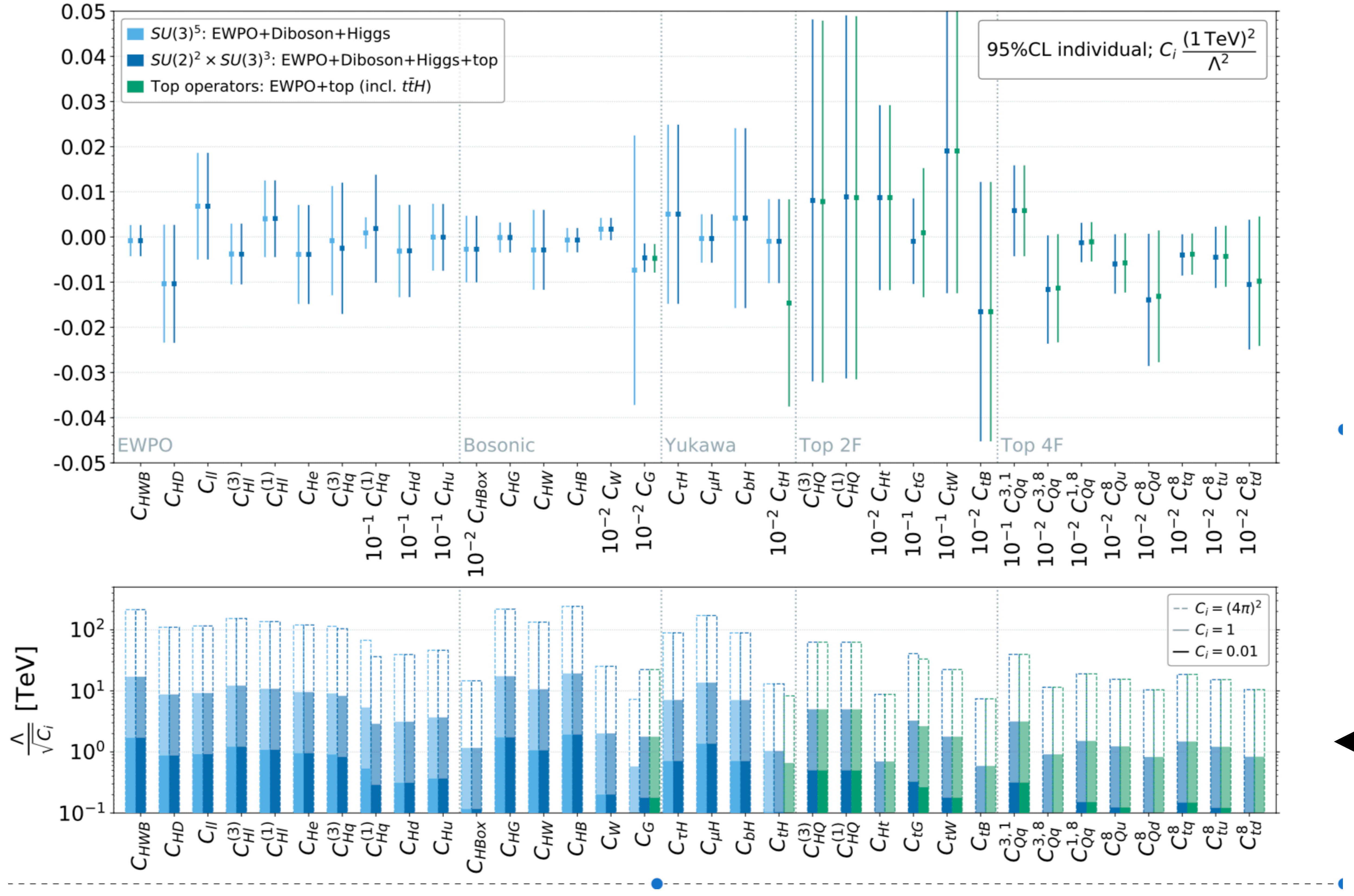
[Ellis, Madigan, Mimasu, Sanze, You]

The global EFT/SMEFT fit

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

Wilson coefficients

dimensional scale



Constraints on scale of BSM

[Ellis, Madigan, Mimasu, Sanze, You]

The need for precision

$$d\sigma = d\sigma_{\rm LO} + {\color{red}\alpha_S}\, d\sigma_{\rm NLO}$$

NLO QCD O(100%)

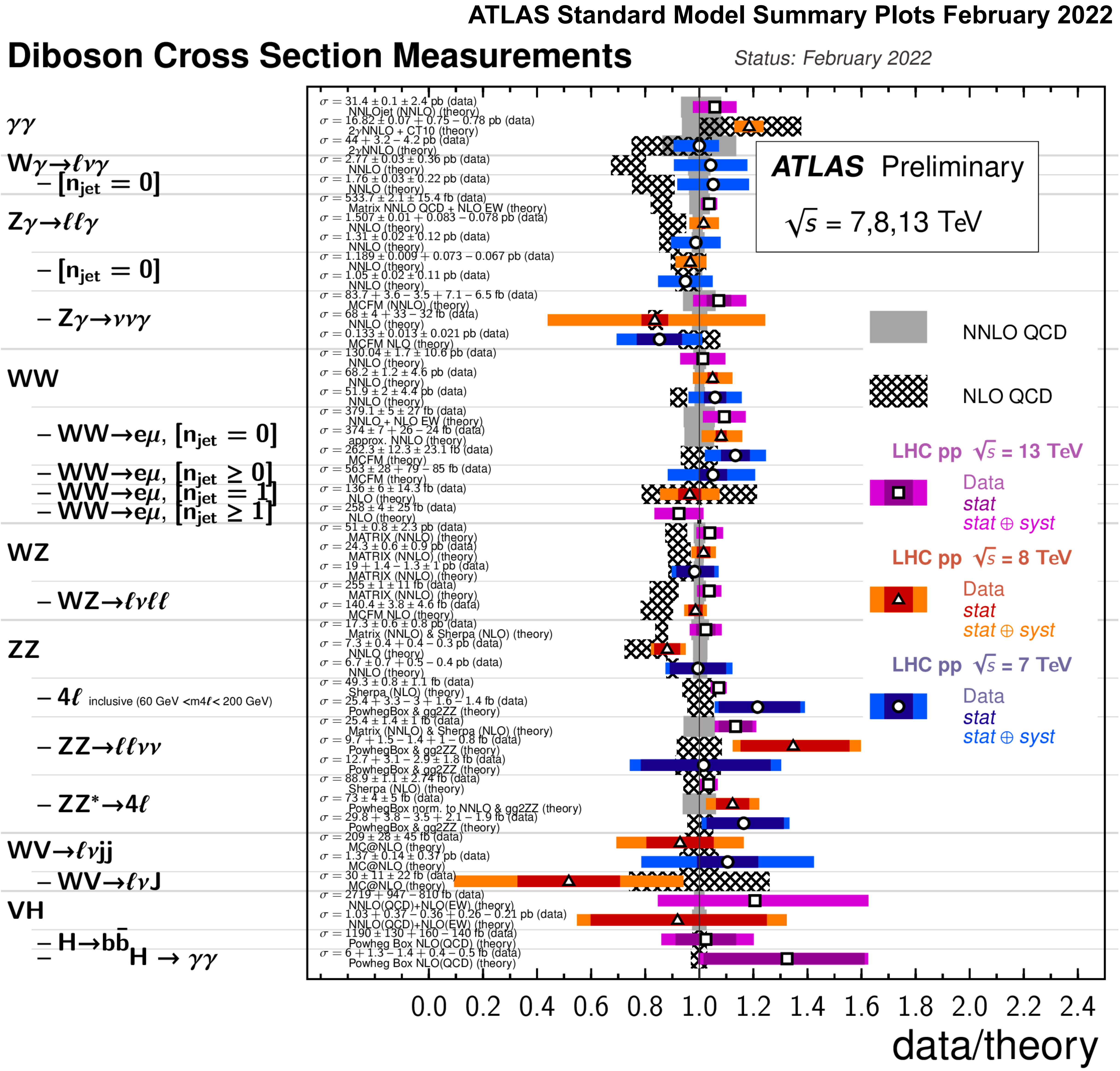
$$+{\color{red}\alpha_S^2}\, d\sigma_{\rm NNLO}$$

NNLO QCD O(10%)

$$+{\color{red}\alpha_S^3}\, d\sigma_{\rm NNLO} + \dots$$

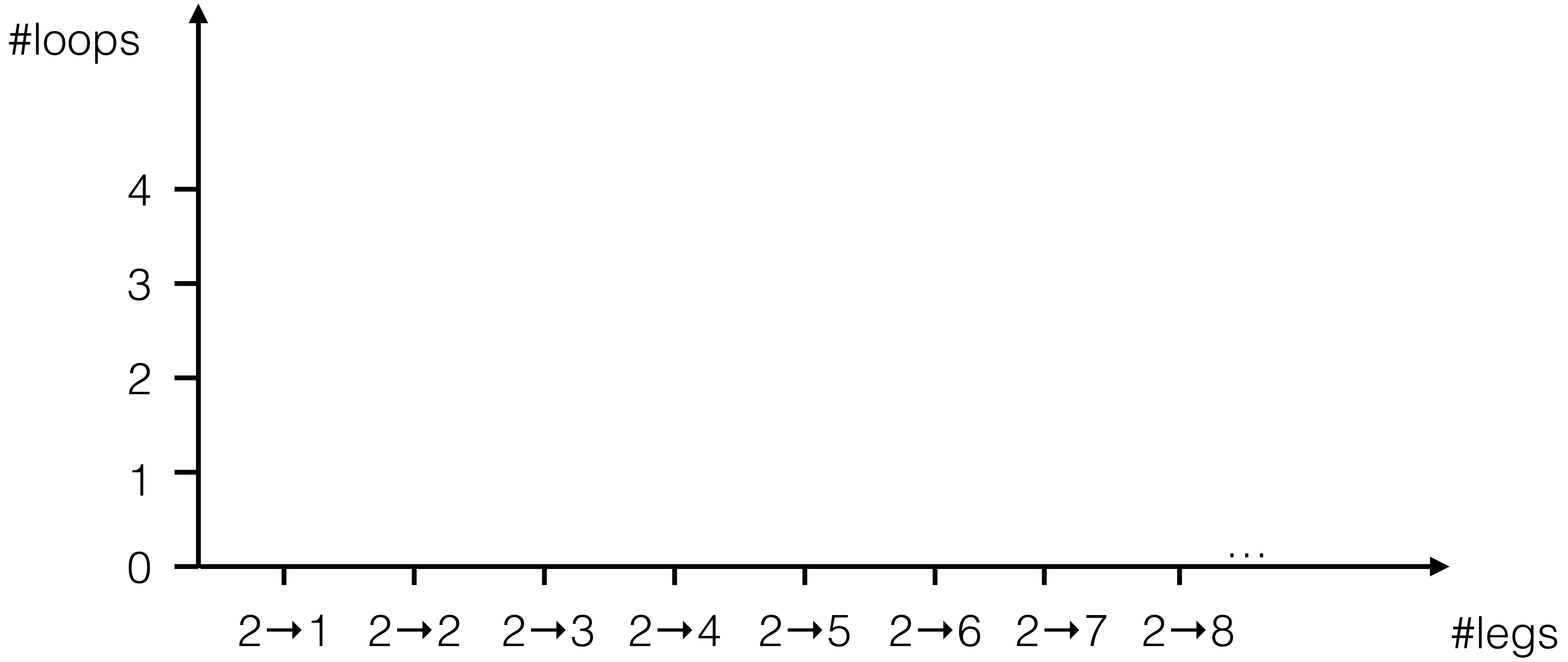
N3LO QCD O(1%)

$${\color{red}\alpha_S} \sim 0.1$$

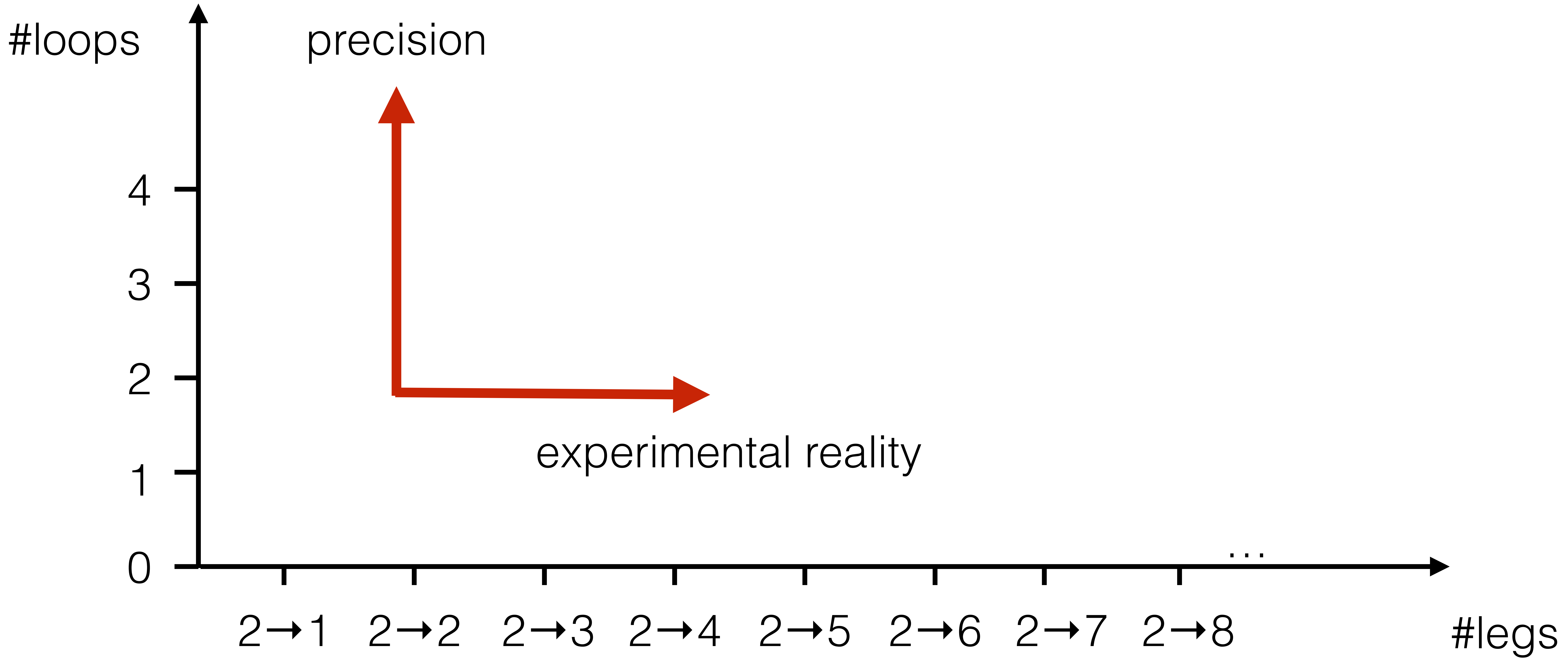


➡Higher-order predictions mandatory for reliable predictions

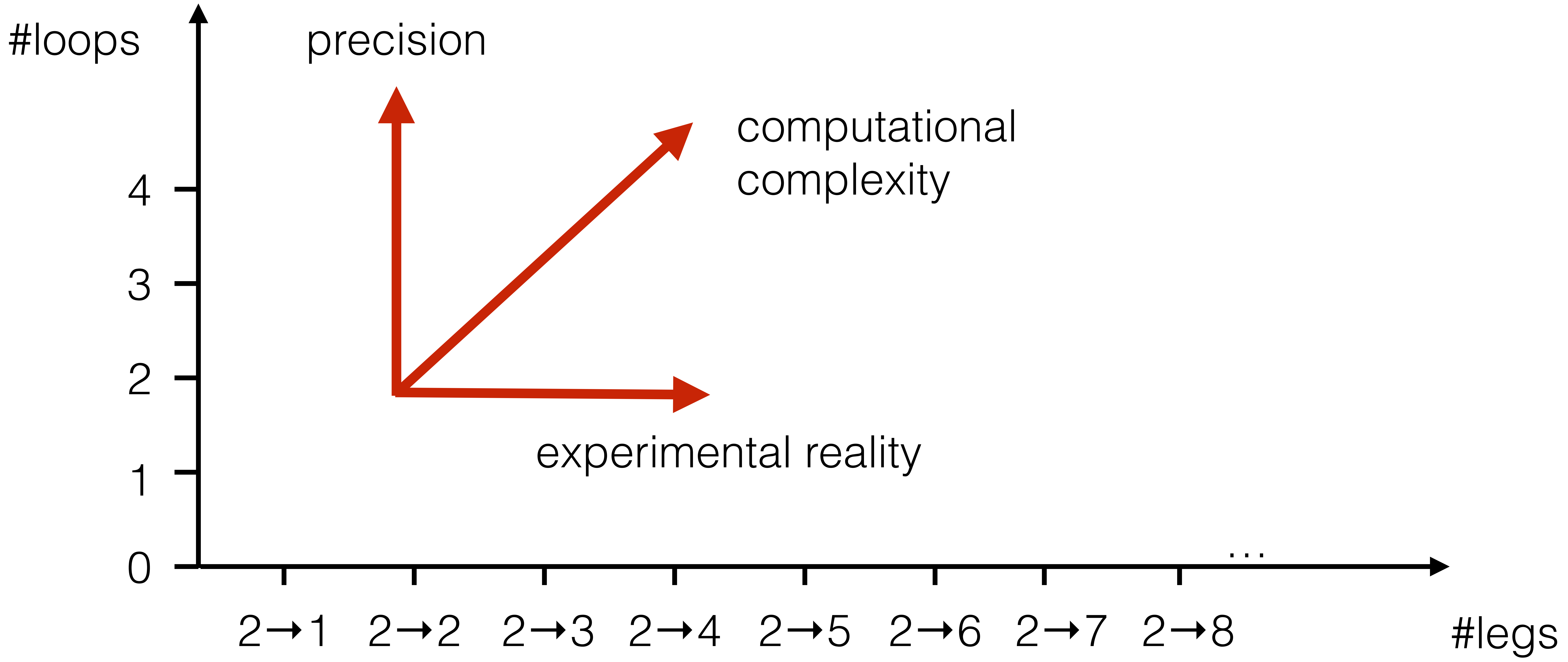
Theory frontier



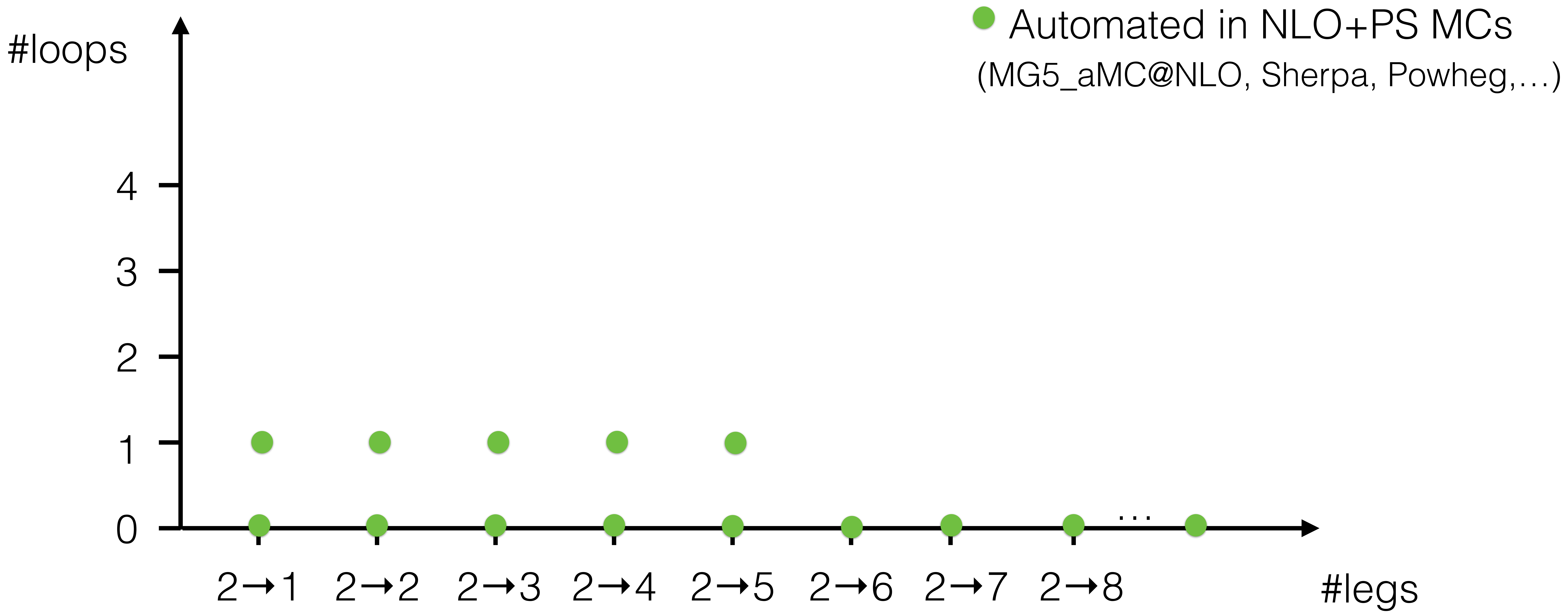
Theory frontier



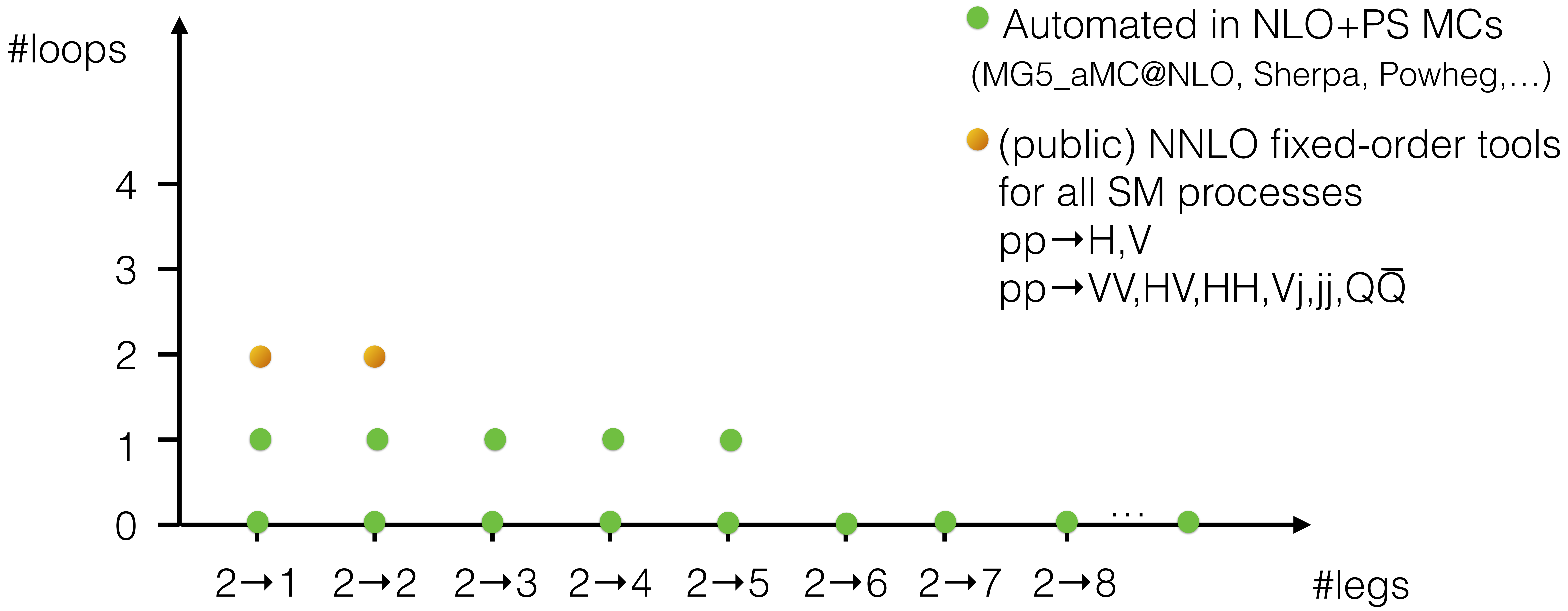
Theory frontier



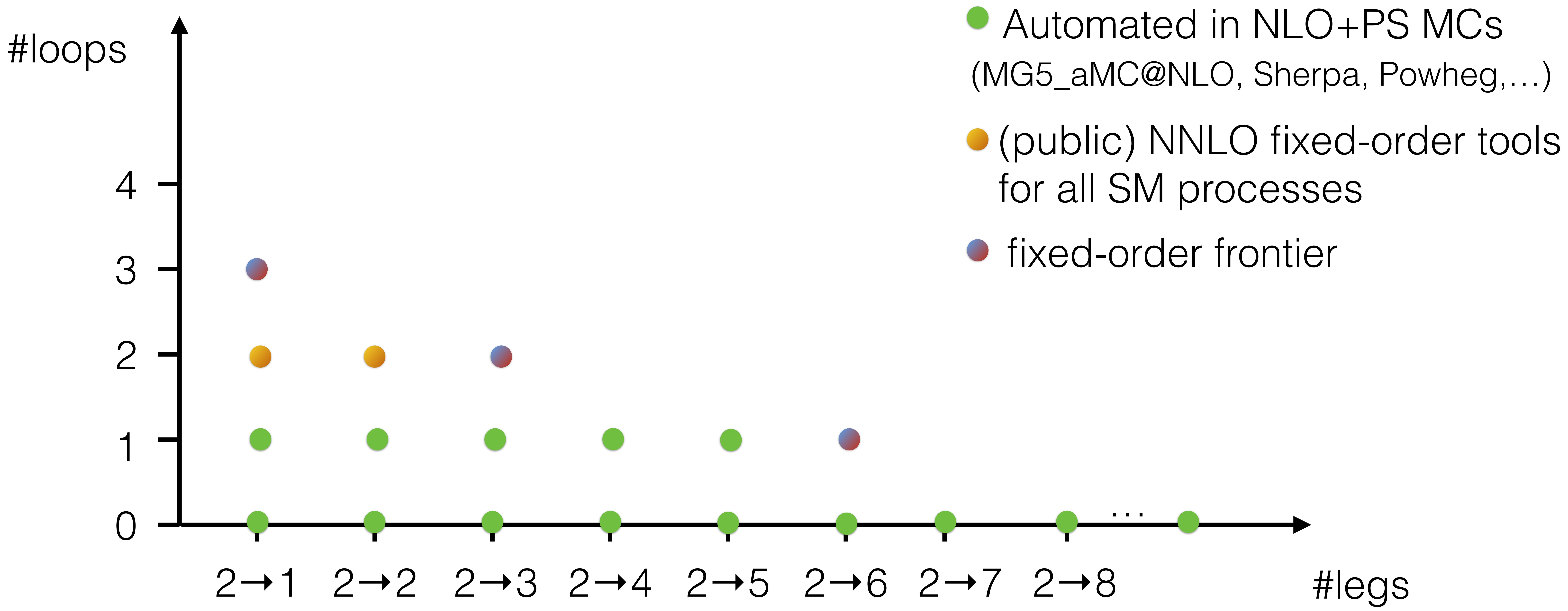
Theory frontier



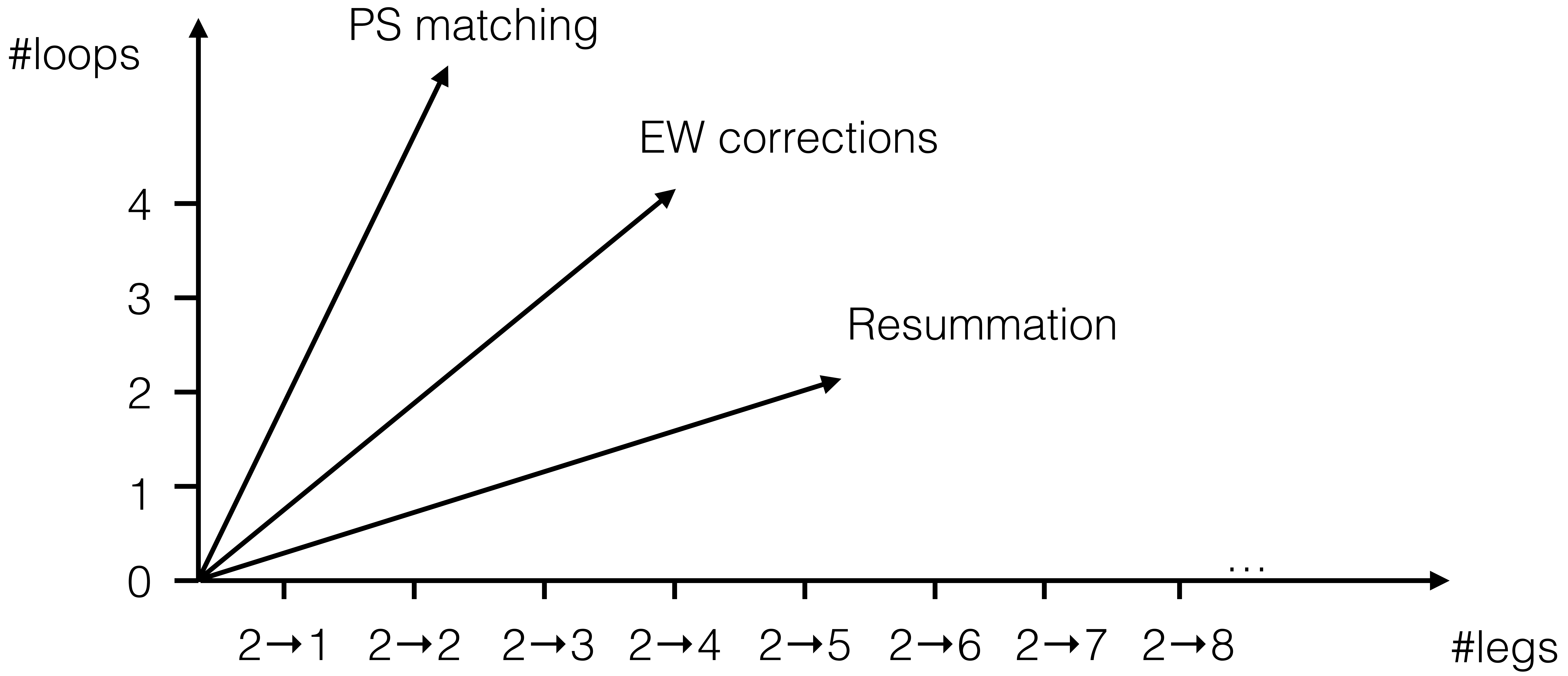
Theory frontier



Theory frontier



Theory frontier



The need for precision

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

dedicated MC's: Matrix, …

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

NLO QCD NLO EW

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

NNLO QCD

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

N3LO QCD

→ only known for inclusive-H, DY

- 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, VV, HV)

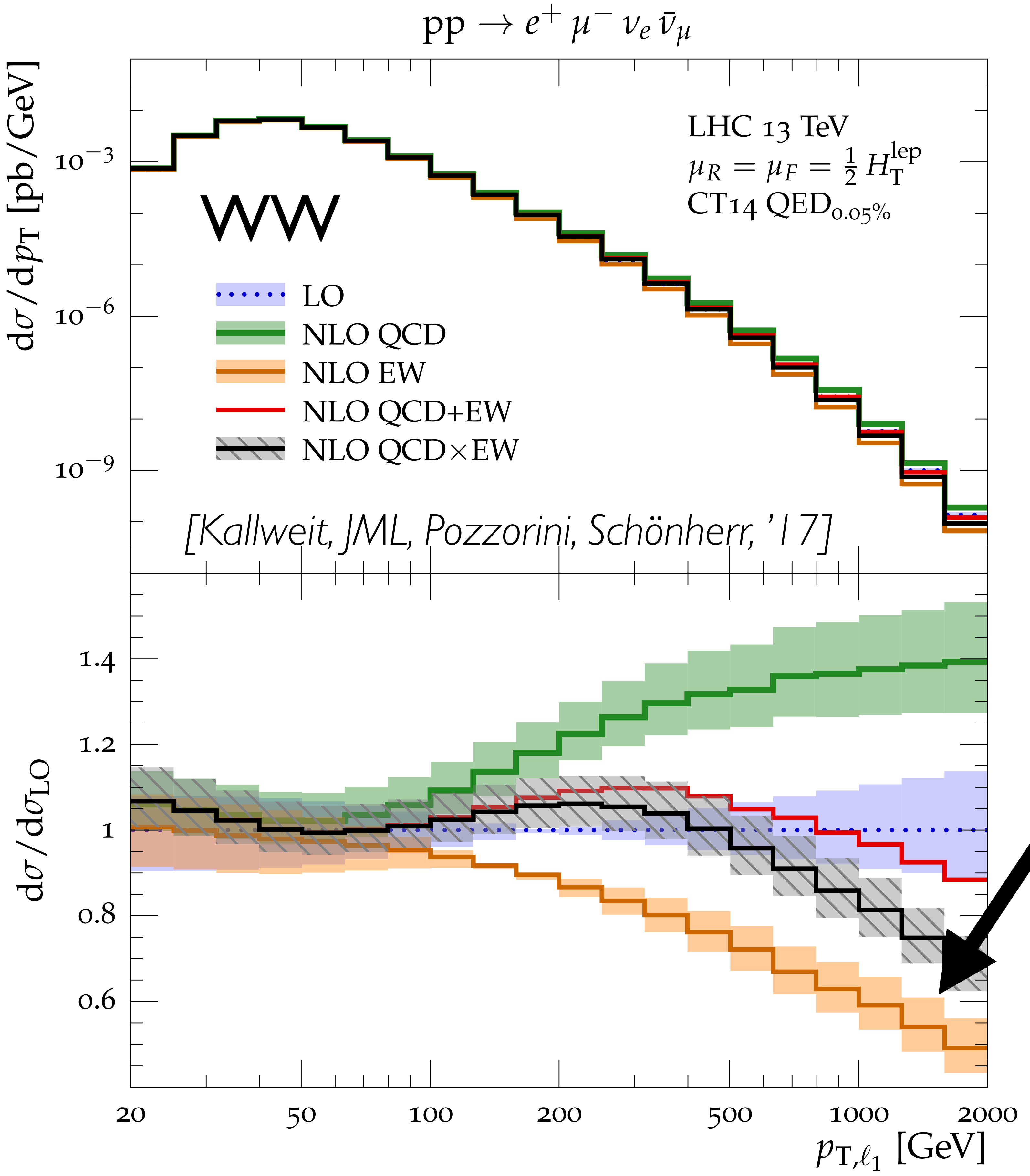
$\alpha_S \sim 0.1$

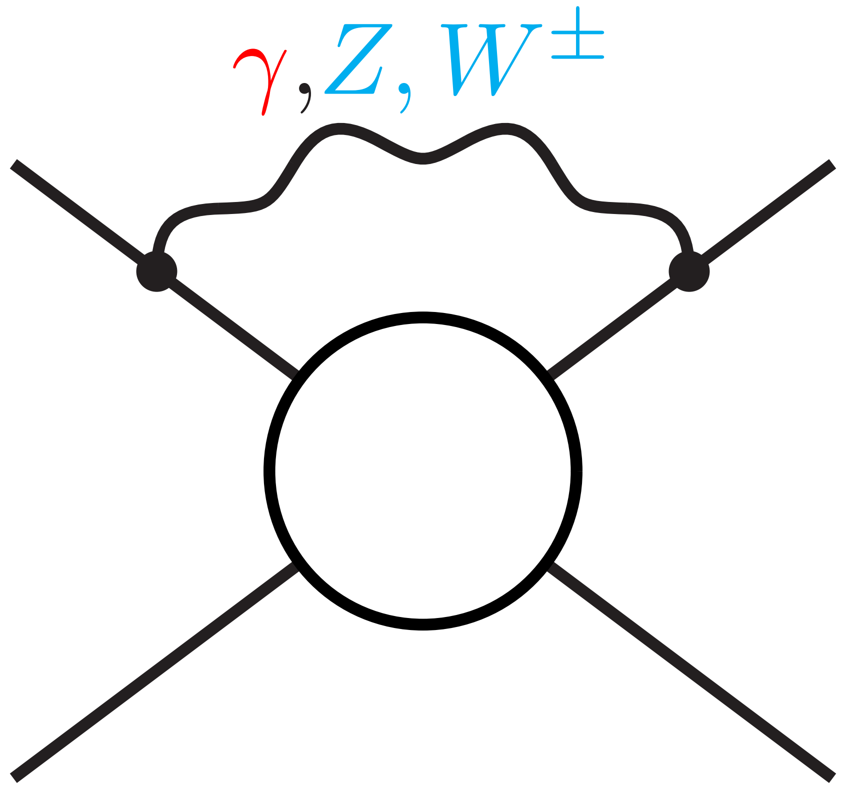
$\alpha_{\mathrm{EW}} \sim 0.01$

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

Relevance of EW higher-order corrections: **virtual** Sudakov logs in the tails

I. 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]

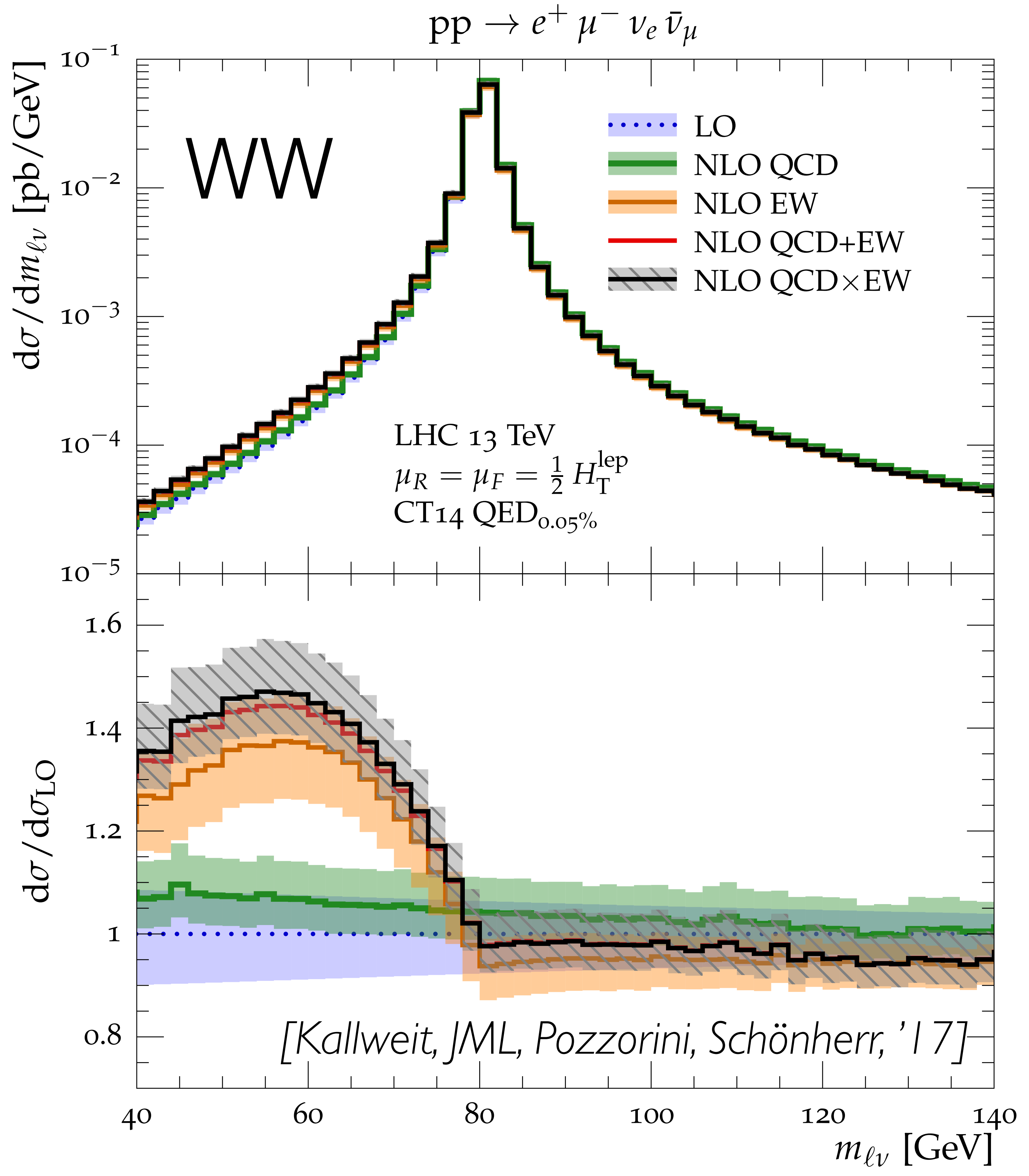
Universality and factorisation: *[Denner, Pozzorini; '01]*

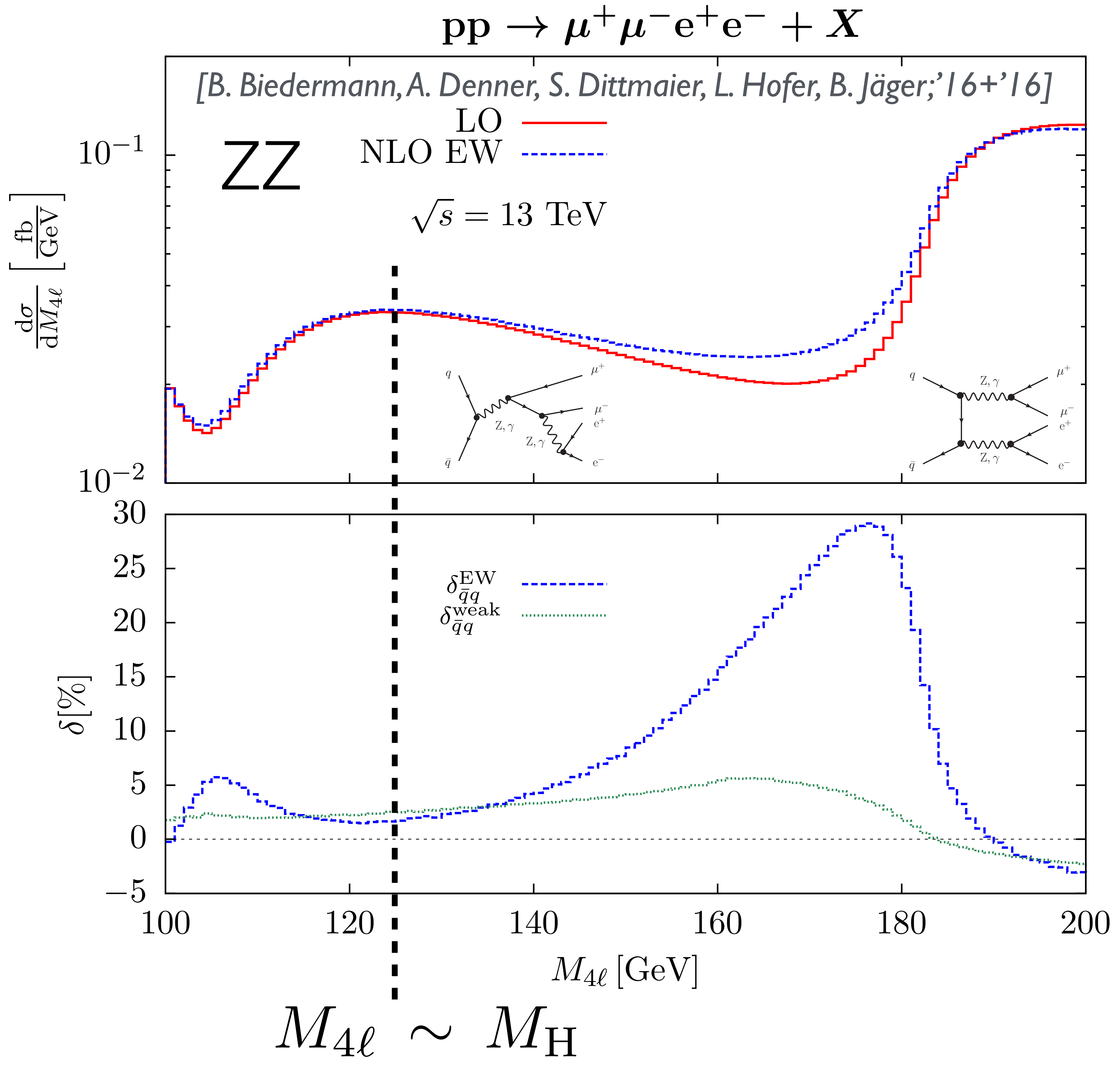
$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

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

Relevance of EW higher-order corrections: collinear QED radiation

II. Possible large enhancement due to soft/collinear **logs** from photon radiation ~ $\alpha \log\left(\frac{m_f^2}{Q^2}\right)$ in sufficiently exclusive observables.





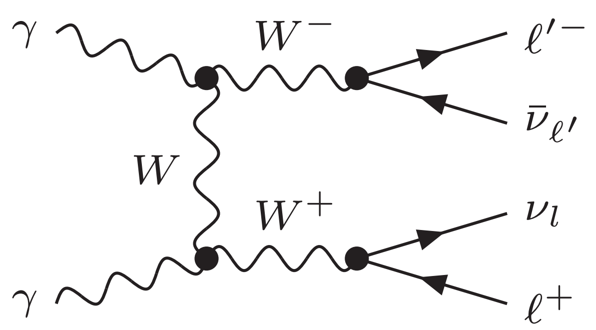
➜ important for radiative tails, Higgs backgrounds etc.

➜typically considered via QED PS (PHOTOS / YFS)

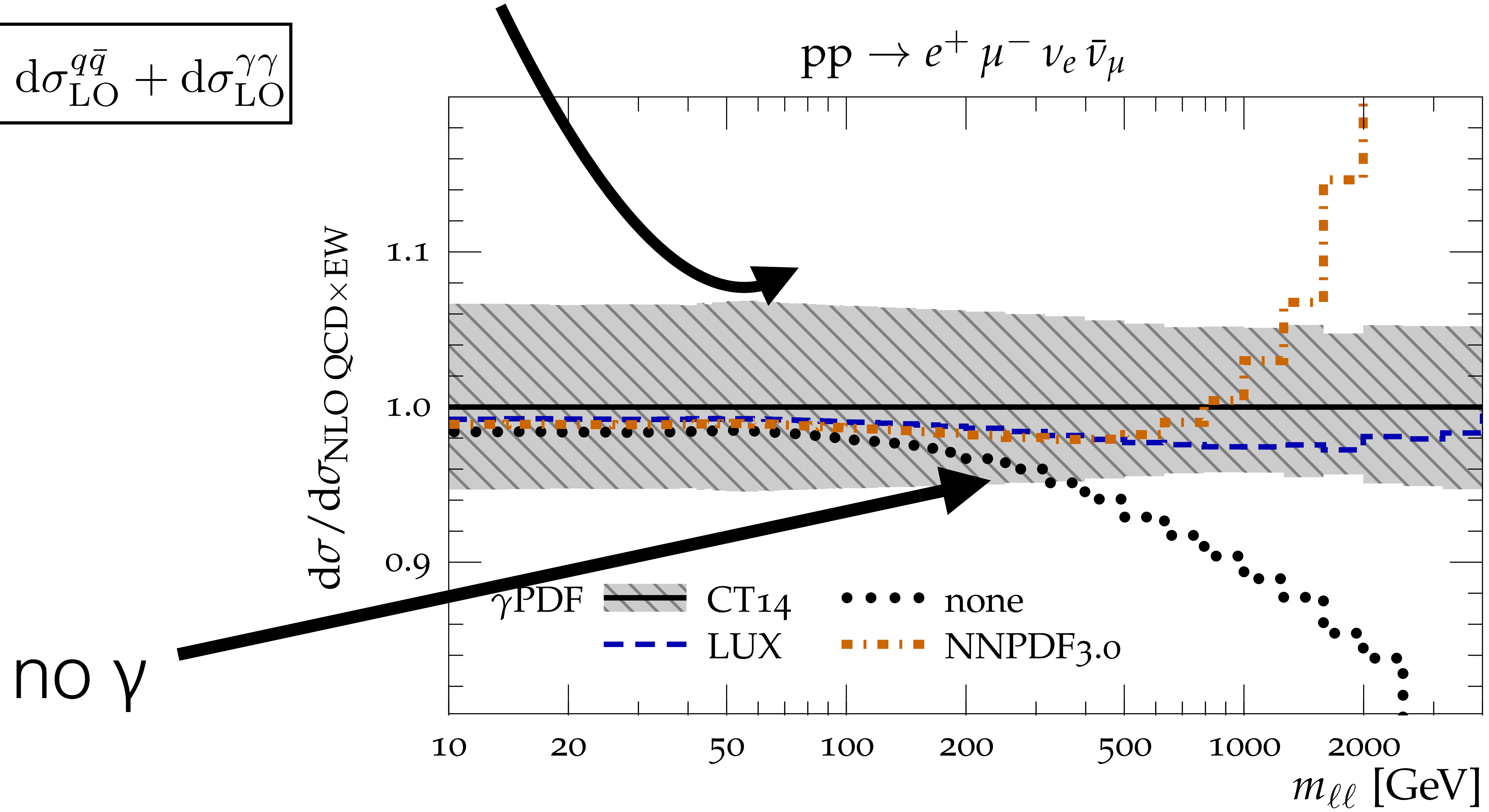
Relevance of EW higher-order corrections: photon-induced channels

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)

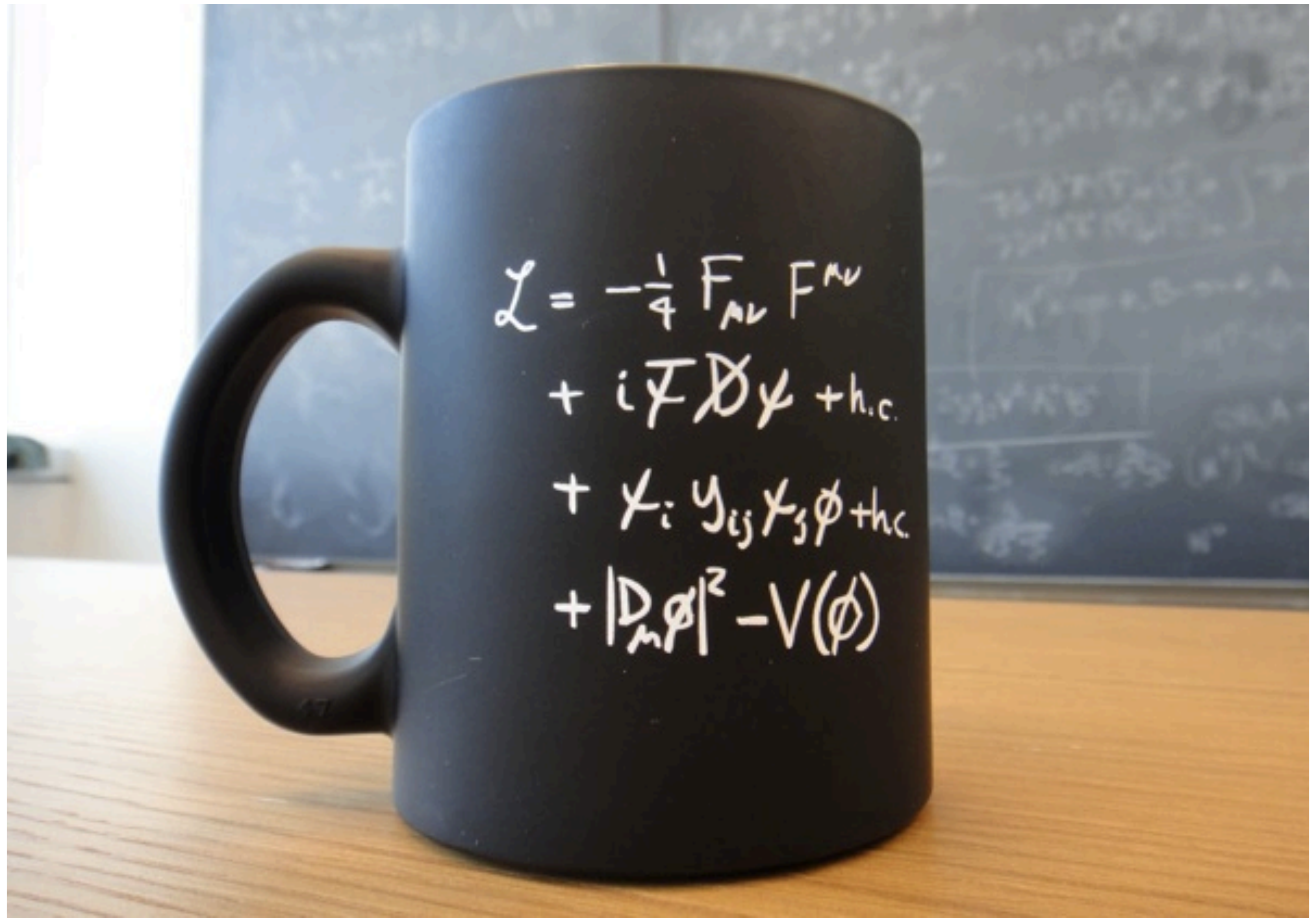
$$\mathrm{d}\sigma_{\mathrm{LO}} = \mathrm{d}\sigma_{\mathrm{LO}}^{q\bar{q}} + \mathrm{d}\sigma_{\mathrm{LO}}^{\gamma\gamma}$$



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

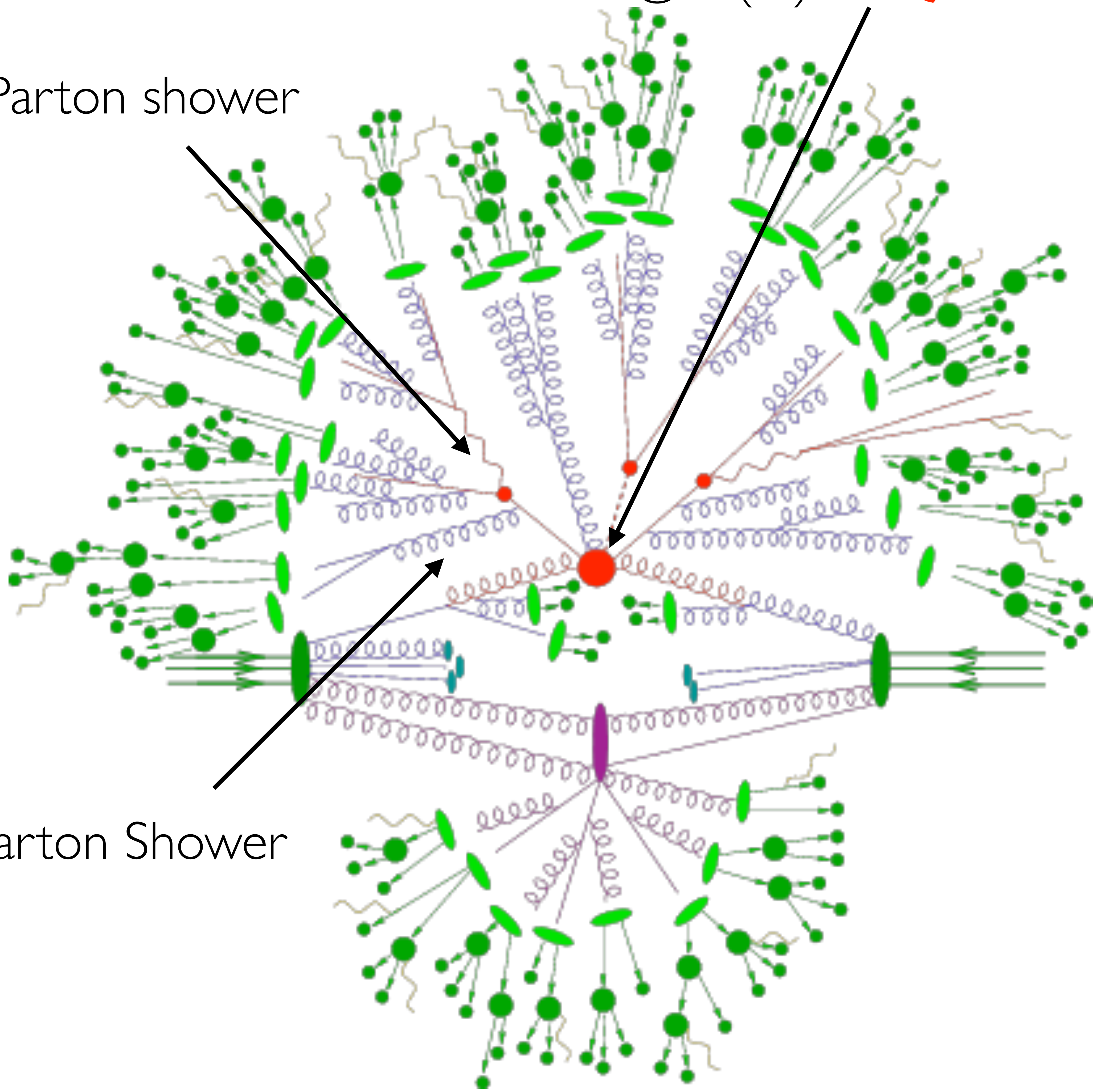
➜ O(10%) contributions from photon-induced channels

EW Theoretical Predictions for the LHC



Hard (perturbative) scattering process @ N(N)LO QCD + EW

QED Parton shower



QCD Parton Shower

The EW SM at quantum level in a nutshell

$$\mathcal{L}_{\rm SM}^{\rm classical} = \mathcal{L}_{\rm Yang\text{-}Mills} + \mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs}$$

At quantum level:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{\rm classical} + \mathcal{L}_{\rm gauge\text{-}fix} + \mathcal{L}_{\rm ghost}$$

(unitary gauge unfeasible at higher-orders in EW)

$$\mathcal{L}_{\rm gauge\text{-}fix} = -\frac{1}{2}\left(F_A^2 + F_Z^2 + 2F_+F_- + F_{G^a}^2\right),$$

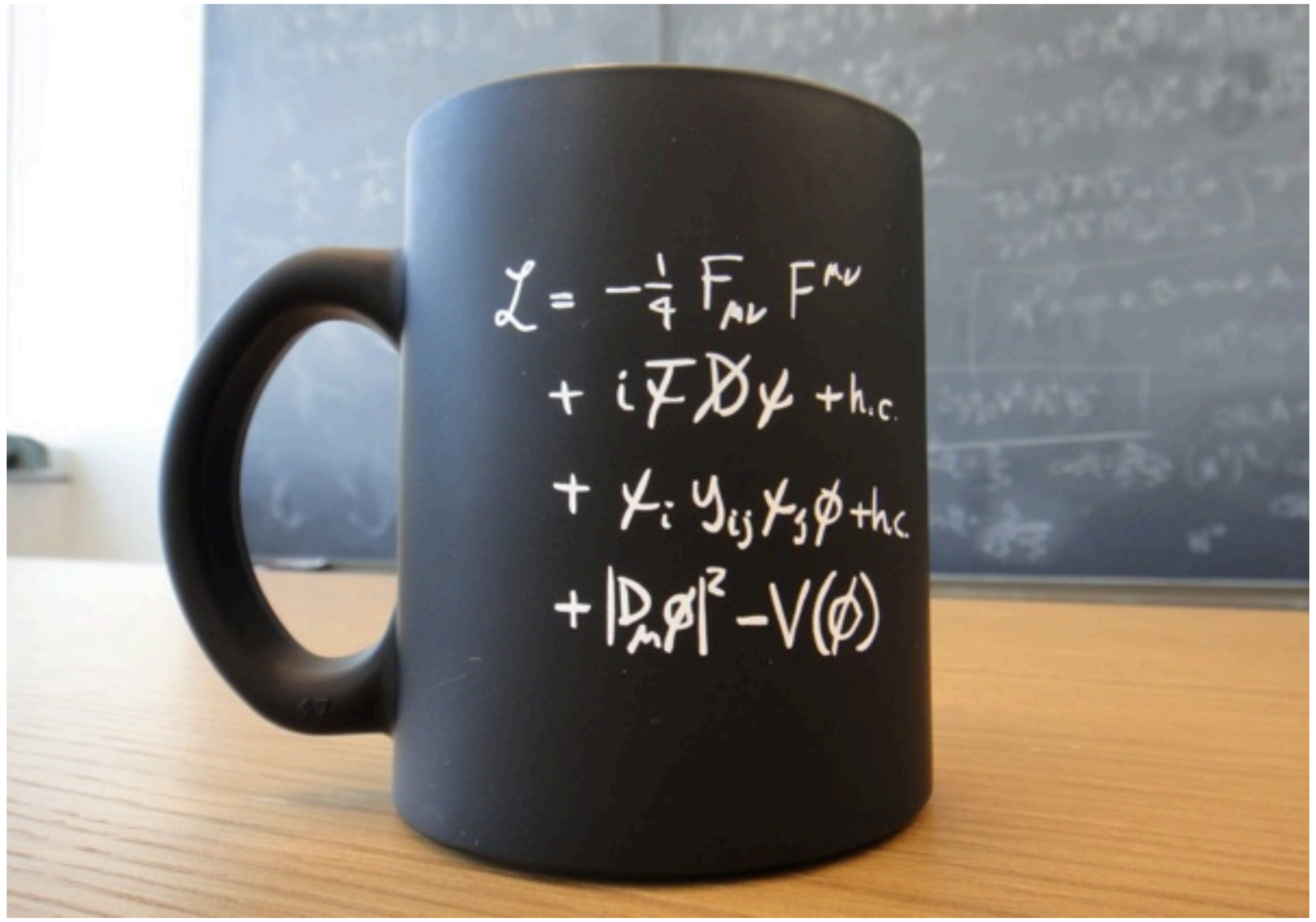
$$\mathcal{L}_{\rm ghost} = \bar{u}^\alpha(x)\frac{\delta F^\alpha}{\delta\theta^\beta(x)}u^\beta(x)$$

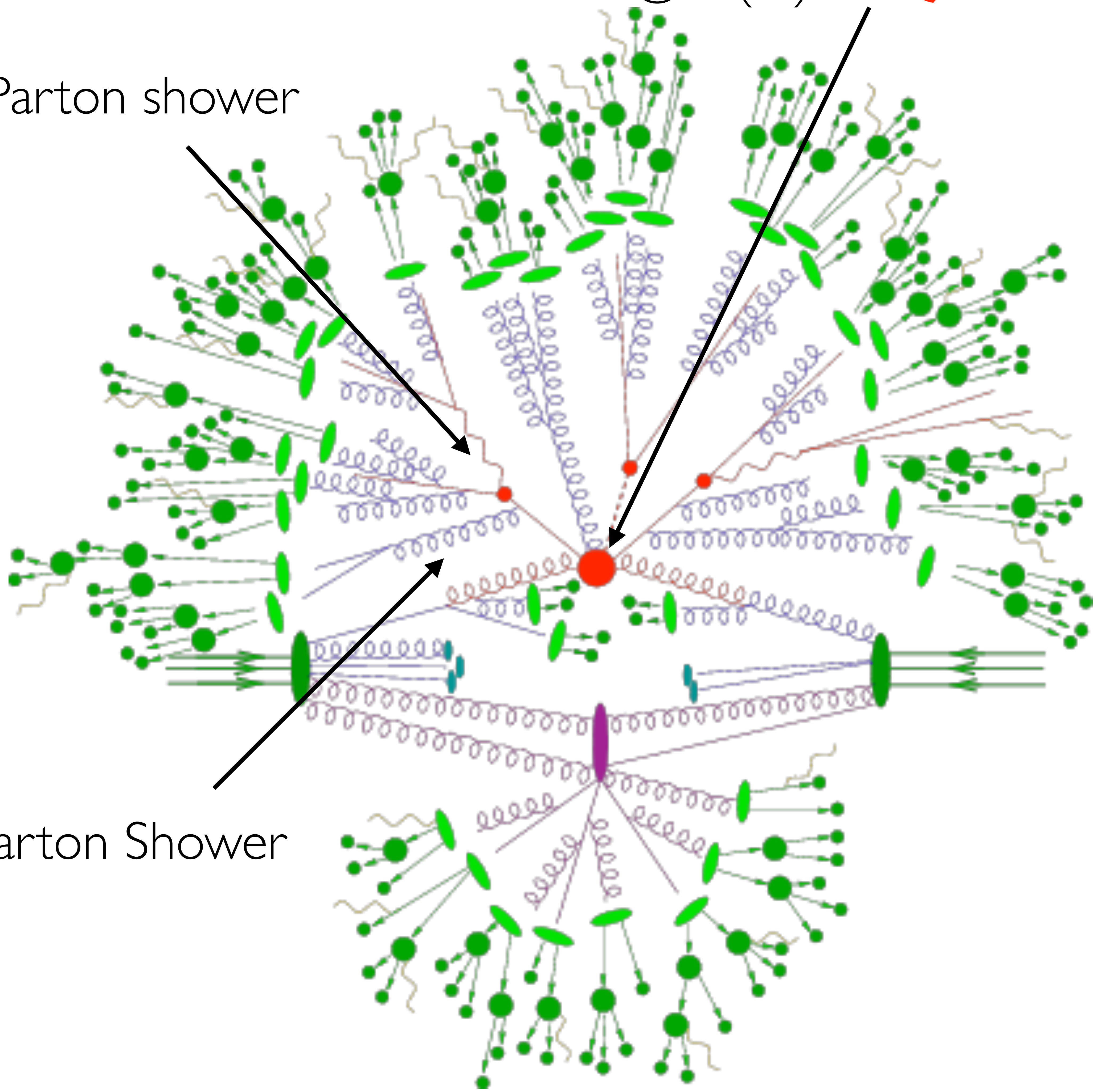
$$F_A = \frac{1}{\xi^A}\partial^\mu A_\mu\,, \qquad F_{G^a} = \frac{1}{\xi^G}\partial^\mu G^a_\mu\,,$$

$$F_Z = \frac{1}{\xi^Z}(\partial^\mu Z^0_\mu - m_Z\xi^Z\chi^0)\,, \qquad F_\pm = \frac{1}{\xi^W}(\partial^\mu W^\pm_\mu \mp i m_W \xi^W \phi^\pm)$$

Gauge fixing parameter

EW Theoretical Predictions for the LHC





Hard (perturbative) scattering process @ N(N)LO QCD + EW

QED Parton shower

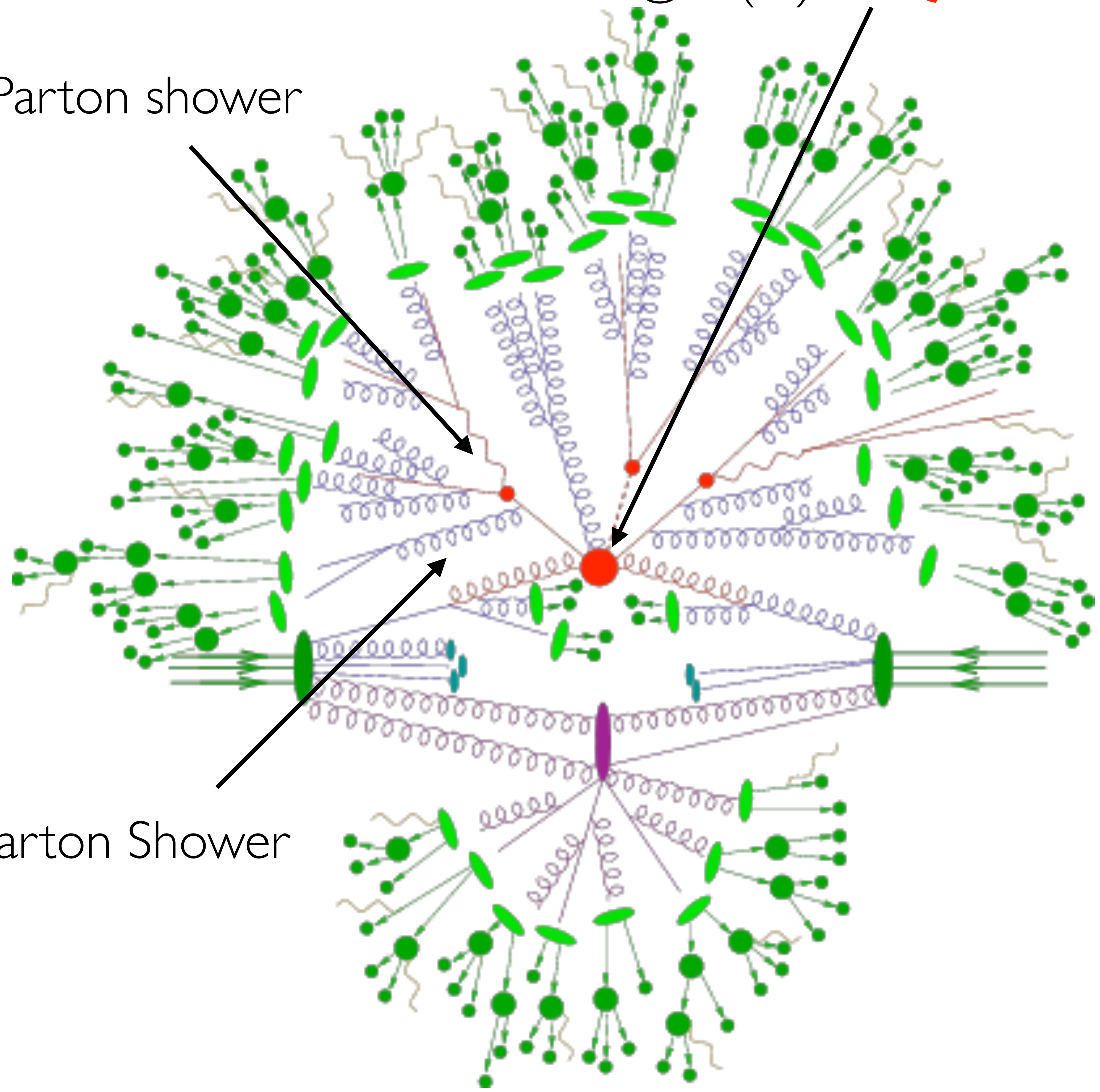
QCD Parton Shower

EW Theoretical Predictions for the LHC

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right) .
\end{gathered}
$$

Hard (perturbative) scattering process @ N(N)LO QCD + EW

QED Parton shower



QCD Parton Shower

NLO Ingredients

- NLO partonic cross section for a 2→n process can be written as

$$d\hat{\sigma}_{\mathrm{NLO}} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\mathrm{LO}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\}\right] + \frac{1}{2s}\int d\Phi_{n+1}|\mathcal{M}_{\mathrm{NLO,R}}|^2$$

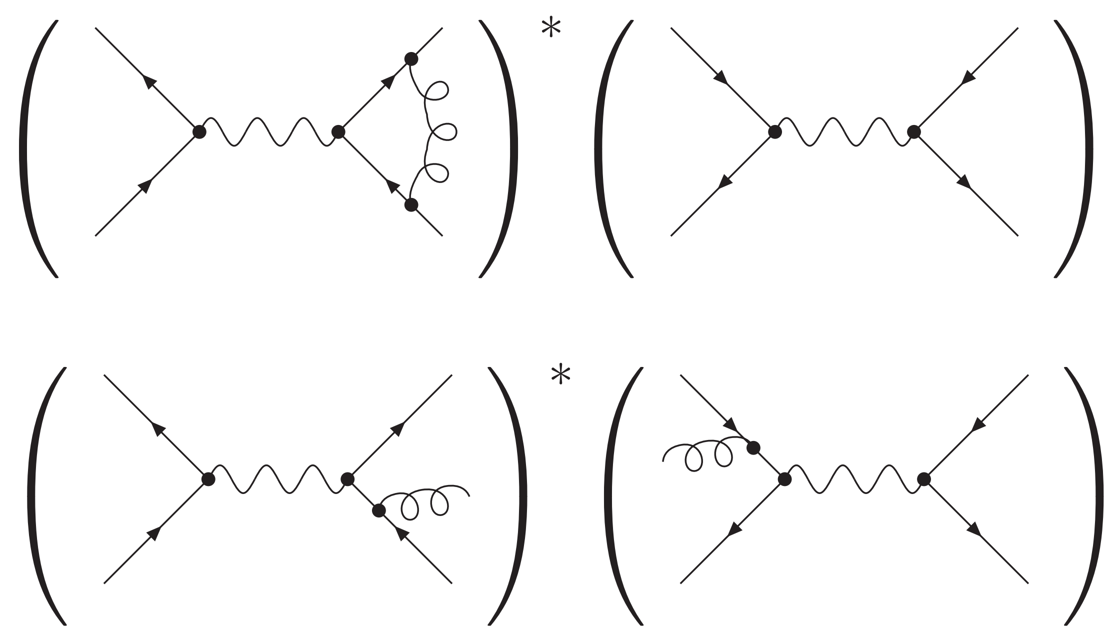
NLO = B + V + R

$\int d\Phi_{n(+1)}$ n or n+1 particle phase space

$\propto \alpha$ {
- $\mathcal{M}_{\mathrm{NLO,V}}$ **virtual** one-loop matrix element
- $\mathcal{M}_{\mathrm{NLO,R}}$ **real** tree-level matrix element

$\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\}$

$|\mathcal{M}_{\mathrm{NLO,R}}|^2$



Note: real radiation might open up new partonic channels!

NLO Tools: automation of NLO EW

- Add local subtraction terms S, and corresponding integrated subtraction term I

$$d\hat{\sigma}_{\rm NLO} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\rm LO}|^2 + 2{\rm Re}\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\rm NLO,V}\} + I\right] + \frac{1}{2s}\int d\Phi_{n+1}|\mathcal{M}_{\rm NLO,R}|^2 - S$$

- NLO Monte-Carlo integrators (+subtraction):
  - MadGraph_aMC@NLO (FKS)
  - Sherpa (CS)
  - POWHEG-BOX (FKS)

- NLO fixed-order integrators:
  - MUNICH/Matrix (CS)
  - ...

- one-loop (& tree) amplitude provider:
  - MadLoop (OpenLoops)
  - GoSam (Unitarity & OPP)
  - OpenLoops (OpenLoops)
  - Recola (NLO Recursion)
  - ...

- integral reduction libraries:
  - CutTools
  - Golem95
  - COLLIER
  - Ninja
  - ...

- scaler one-loop libraries
  - QCDLoop
  - OneLoop
  - COLLIER
  - ...

NNLO Ingredients

- NNLO partonic cross section for a 2→n process can be written as

$$d\hat{\sigma}_{\mathrm{NNLO}} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\mathrm{LO}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\} + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NNLO,V}}\}\right]$$

NNLO = B + V + V2 + ...

$$+\frac{1}{2s}\int d\Phi_{n+1}\left[|\mathcal{M}_{\mathrm{NLO,R}}|^2 + 2\mathrm{Re}|\mathcal{M}_{\mathrm{NLO,R}}\mathcal{M}^*_{\mathrm{NNLO,RV}}|\right] + \frac{1}{2s}\int d\Phi_{n+2}|\mathcal{M}_{\mathrm{NNLO,RR}}|^2$$

+ R + RV + RR

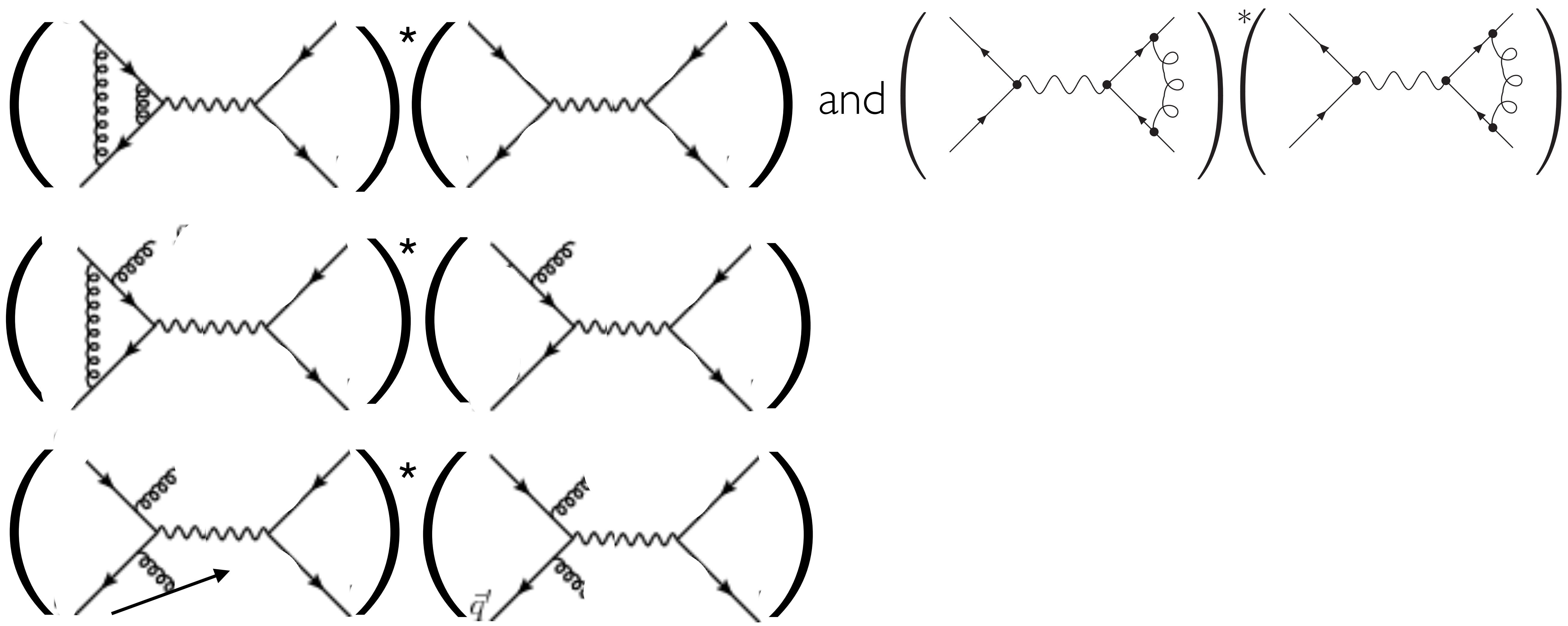
$\int d\Phi_{n(+1)}$ n, n+1, n+2 particle phase space

ΔNLO $\propto \alpha$

- $\mathcal{M}_{\mathrm{NLO,V}}$ **virtual** one-loop matrix element
- $\mathcal{M}_{\mathrm{NLO,R}}$ **real** tree-level matrix element

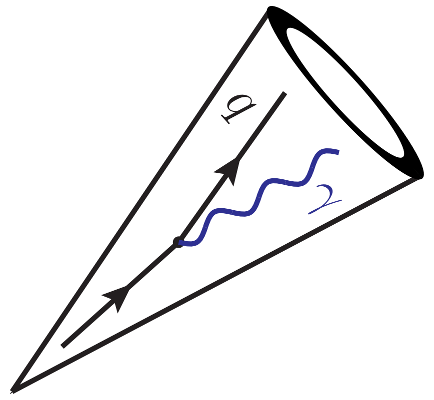
ΔNNLO $\propto \alpha^2$

- $M_{\mathrm{NNLO,V}}$ **double-virtual** two-loop matrix element
- $M_{\mathrm{NNLO,RV}}$ **real-virtual** one-loop matrix element
- $\mathcal{M}_{\mathrm{NNLO,RR}}$ **double-real** tree-level matrix element



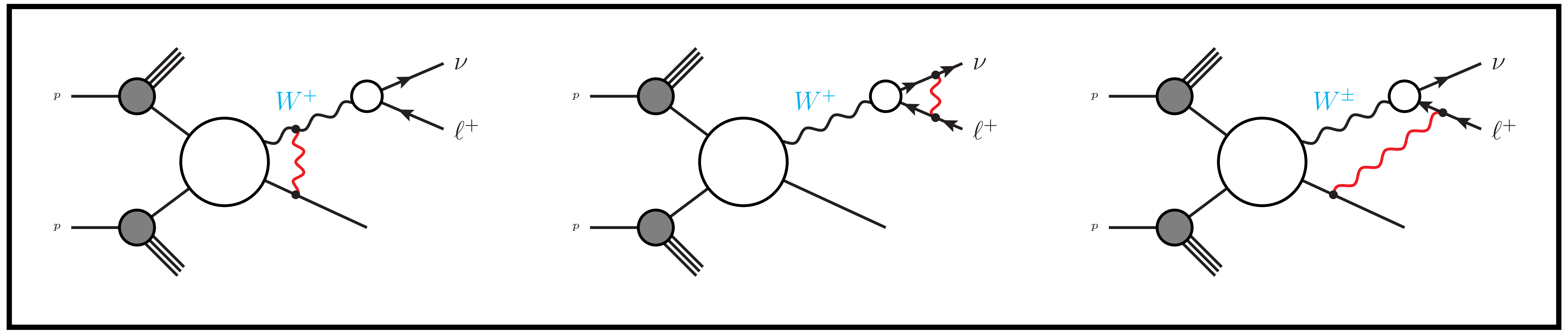
Nontrivial features in NLO QCD → NLO EW

1. photon contributions in jets and proton
   → **photon-jet separation, γPDF**

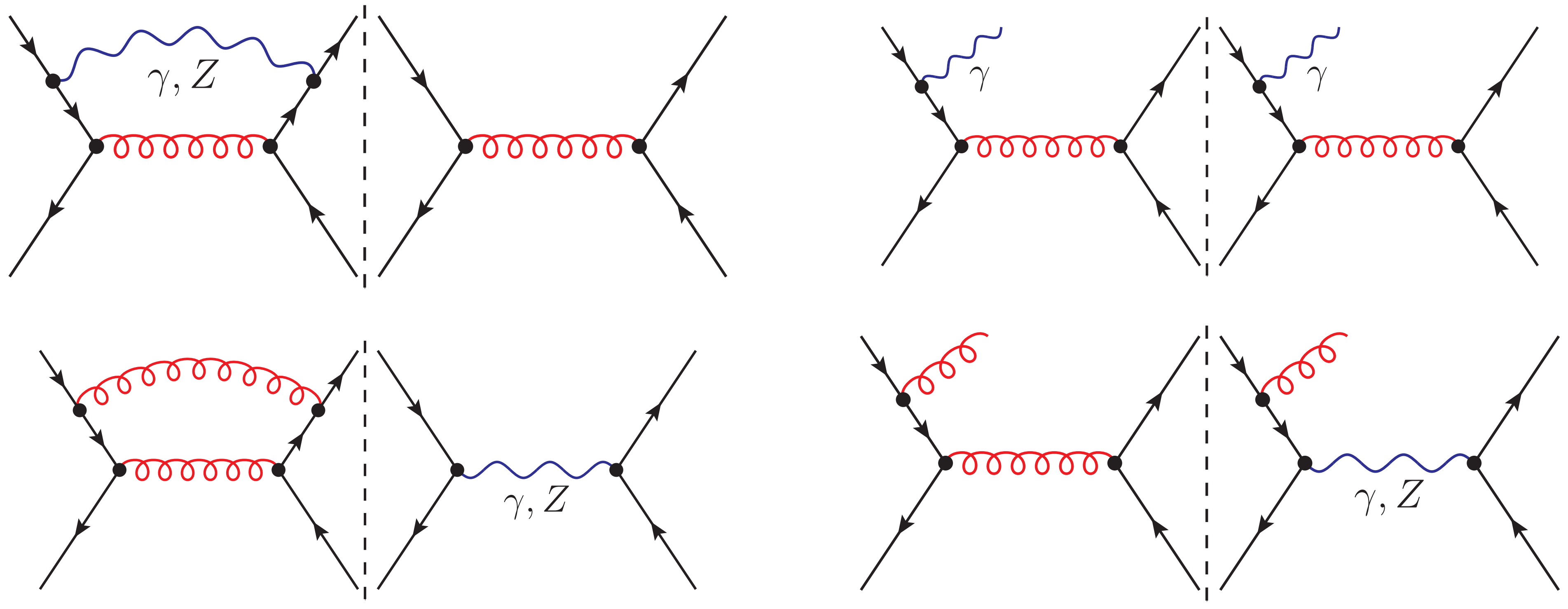


collinear q → qγ singularities

2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays
   → **complex-mass-scheme**

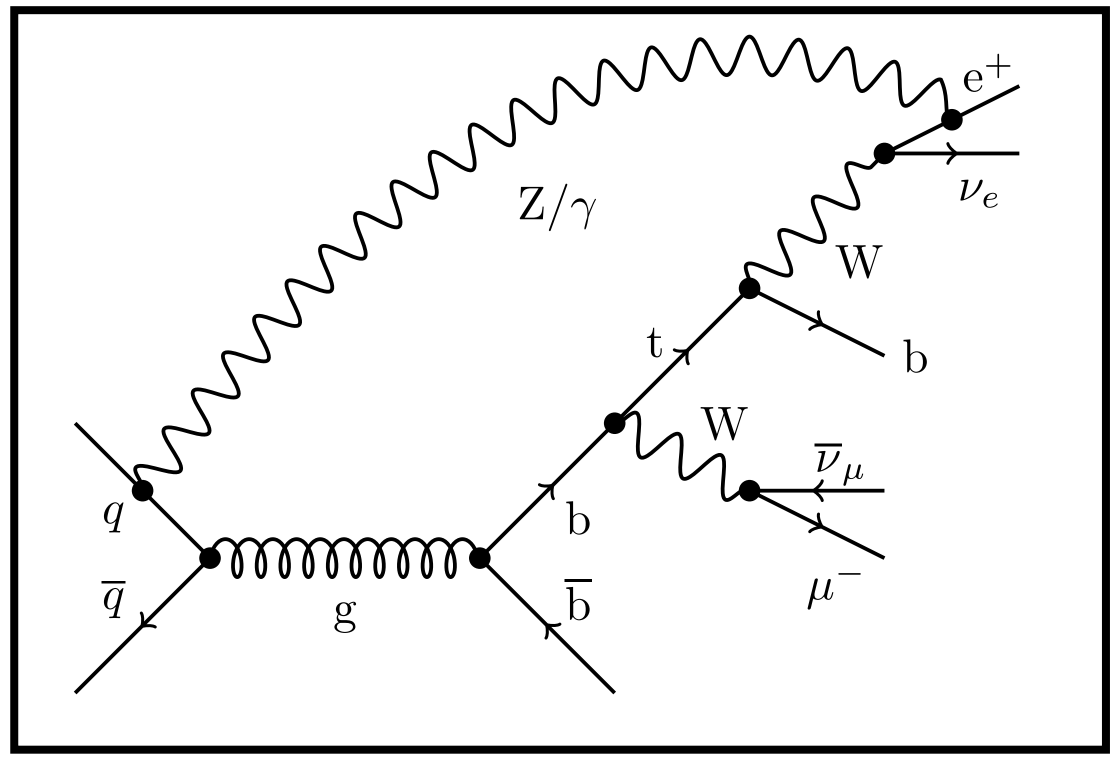


3. **QCD-EW interplay**



$O(\alpha_S^2\alpha)$

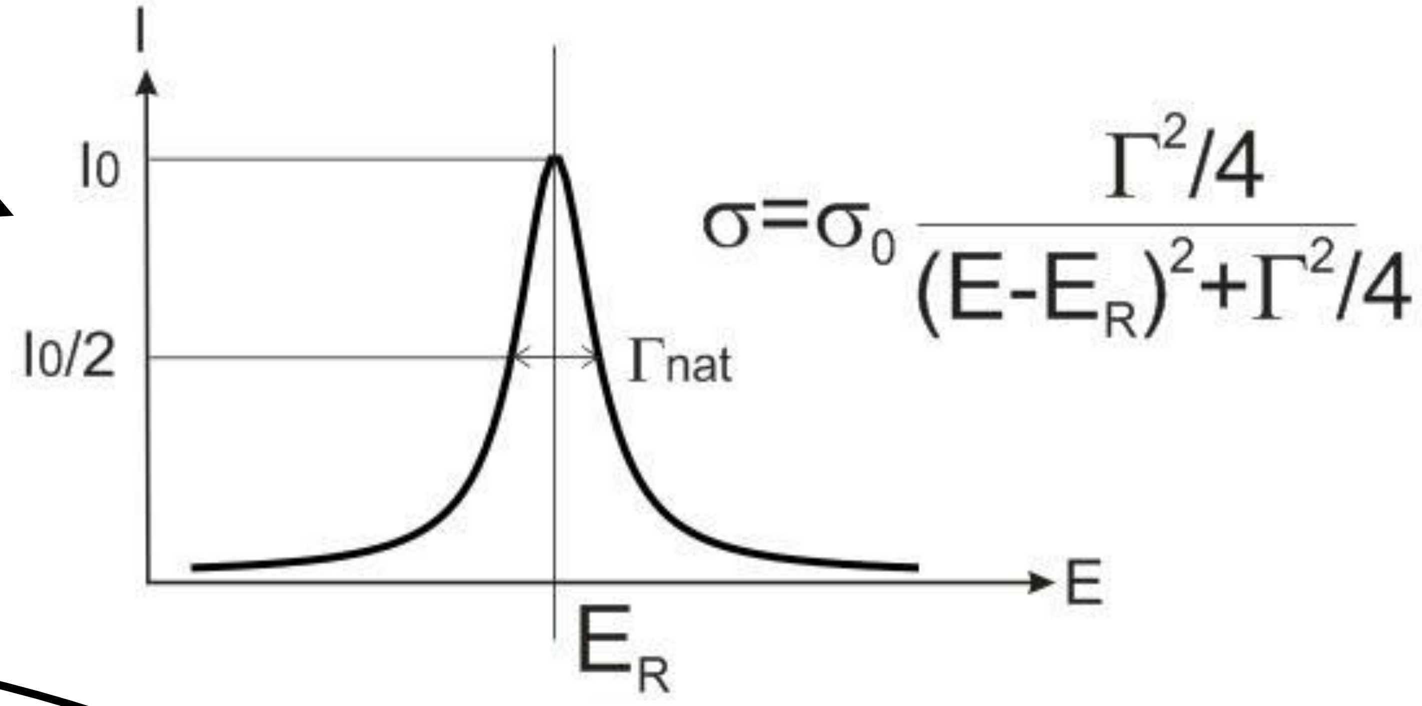
4. **virtual EW corrections** more involved than QCD
   (many internal masses)

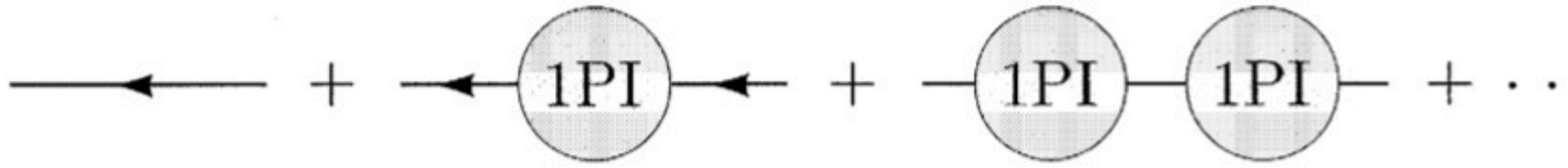


Decays of heavy particles

- Naively processes with a massive s-channel propagator diverge when $p^2 = M^2$
- Experimentally we now resonances follow **Breit-Wigner** (BW) shape
- Origin: all-order summation of 1PI corrections to propagator of massive particles

$$\text{propagator} \sim \frac{1}{p^2 - M^2}$$



propagator ~ 

$$= \frac{1}{p^2 - M_0} + \frac{1}{p^2 - M_0}(-i\Sigma)\frac{1}{p^2 - M_0} + \ldots$$

Geometric series

$$= \frac{1}{k^2 - M_0^2}\sum_{n=0}^{\infty}\left(\frac{-\Sigma(k^2)}{k^2 - M_0^2}\right)^n = \frac{1}{k^2 - M_0^2 + \Sigma(k^2)} = \frac{1}{k^2 - M_0^2 - iM_0\Gamma}$$

$$\int dk^2 |M|^2 \sim \int_{-\infty}^{\infty} \frac{dk^2}{(k^2 - m^2)^2 + m^2\Gamma} \sim \text{BW}$$

Optical theorem →

$$\Gamma \sim \frac{1}{M}\,\mathrm{Im}\,\Sigma(M^2)$$

- However: this summation mixes different order of perturbation theory. Thus, in general it might (and will) ***break gauge invariance when applied naively***.
- (Usually) not a problem at LO, i.e. also not for vector boson decays into leptons at NLO QCD

$$\Gamma/M \to 0: \int_{-\infty}^{\infty} \frac{dk^2}{(k^2 - m^2)^2 + m^2\Gamma} = \frac{\pi}{m\Gamma}\delta(k^2 - m^2)$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{prod}}\frac{\mathrm{d}\Gamma_{\mathrm{dec}}}{\Gamma}$$

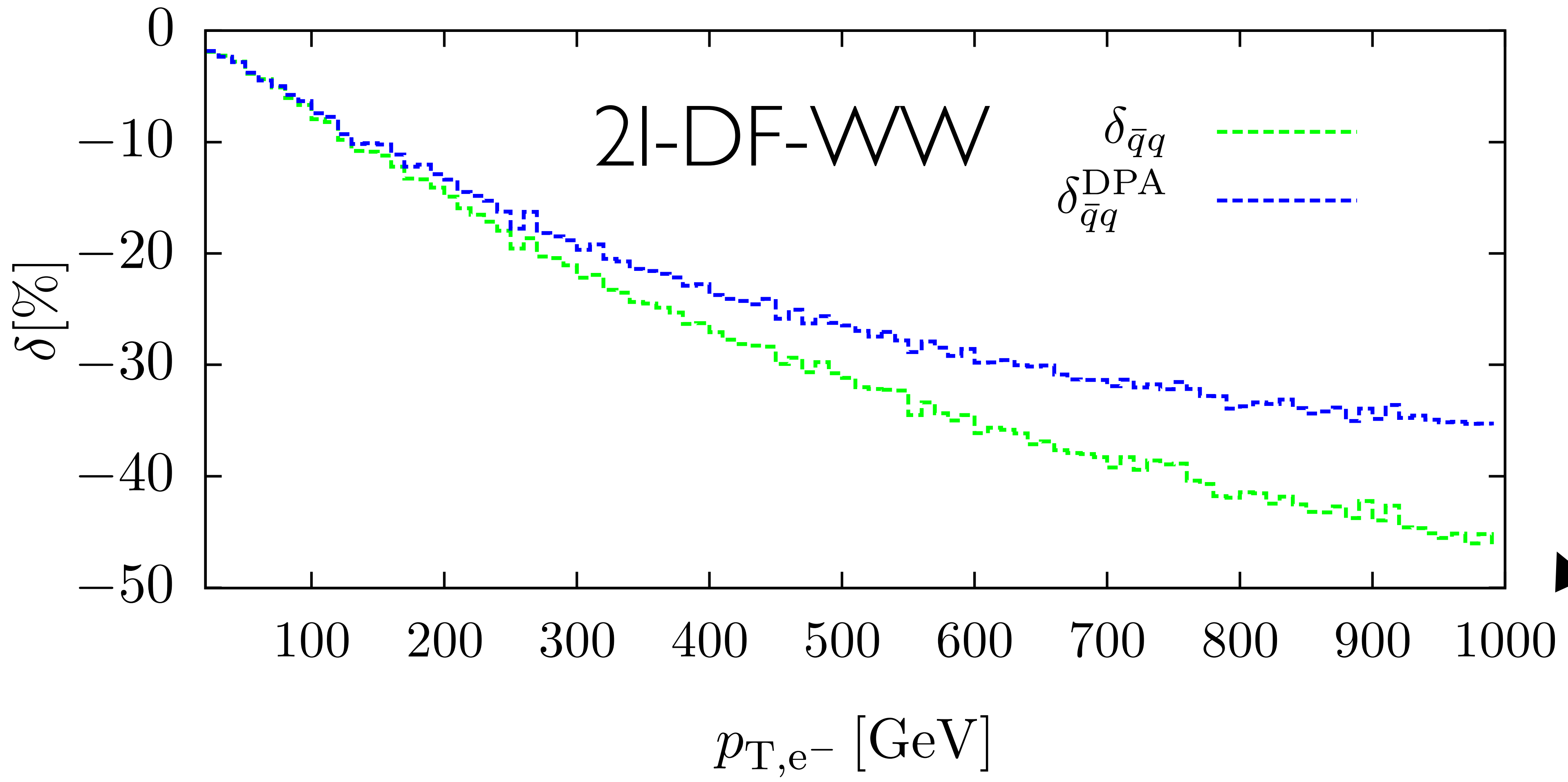
- Alternative: **narrow-width approximation (NWA)**

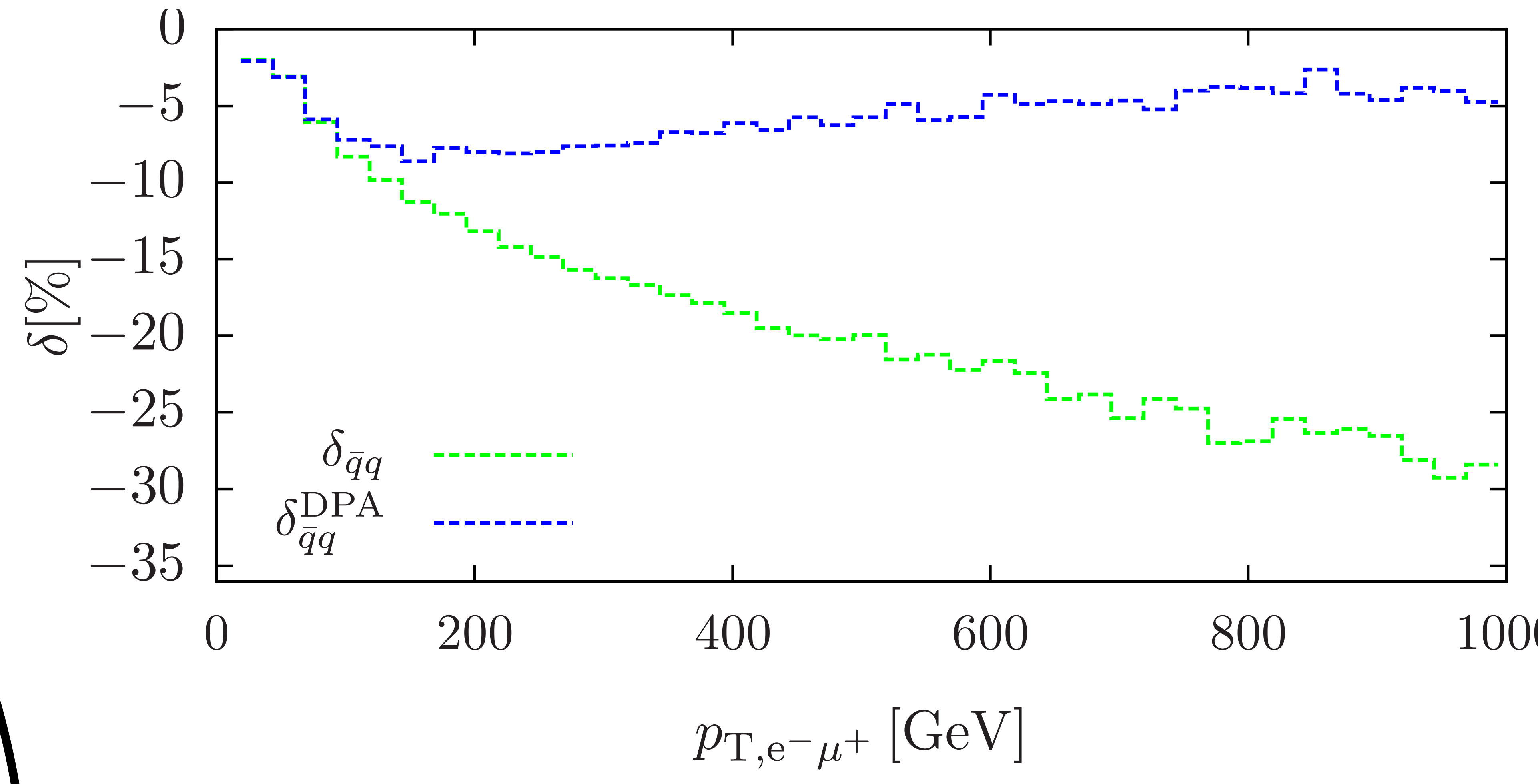
  Advantage: reduces complexity in NLO computation

  However: unable to capture off-shell effects

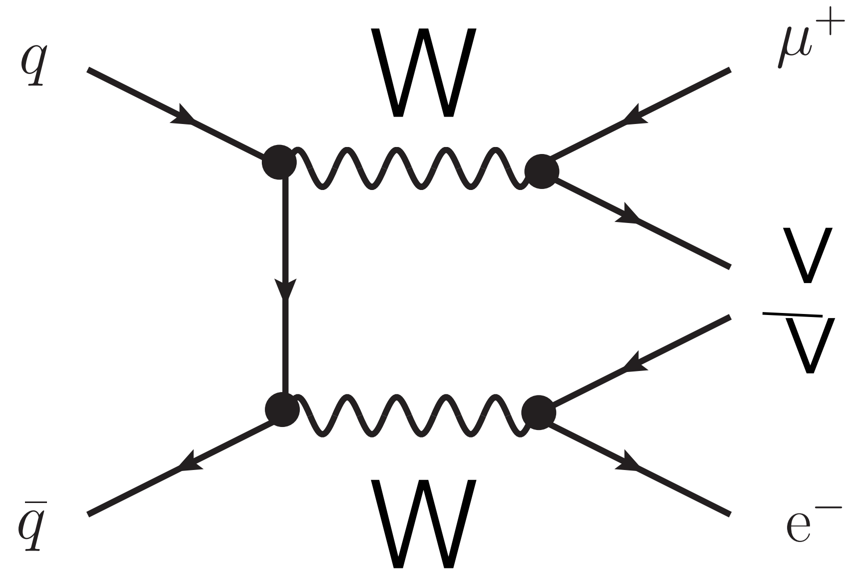
The need for off-shell computations: VV

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



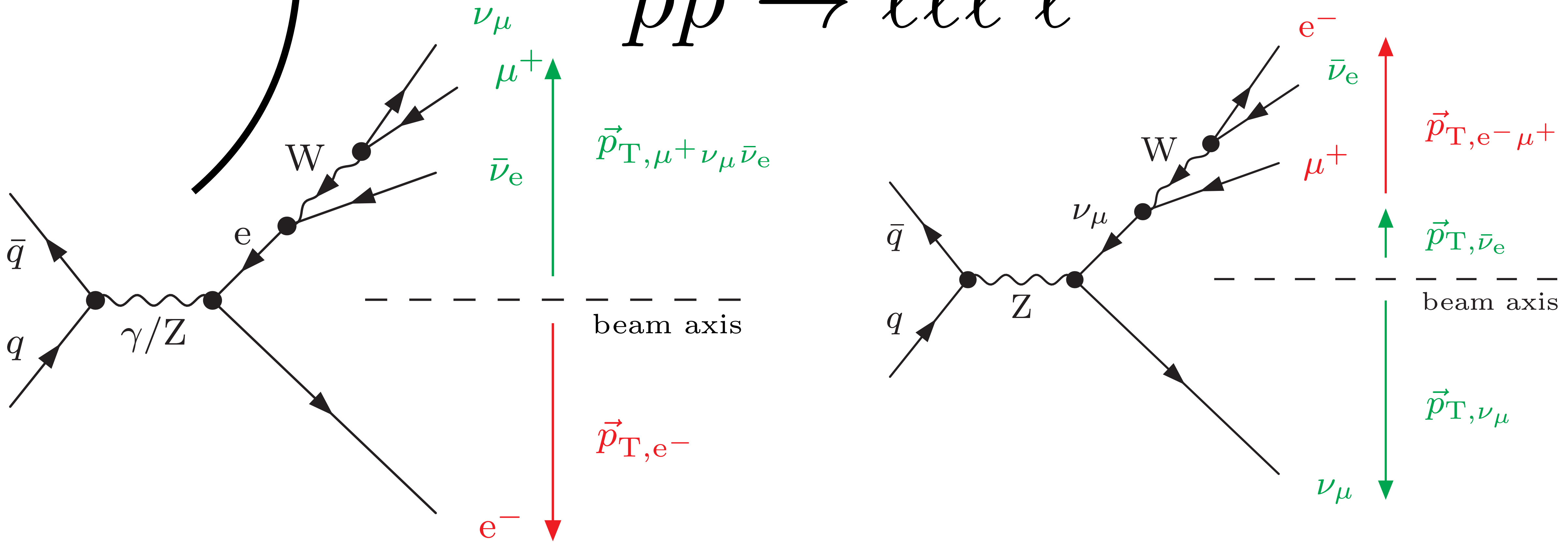


$$pp \to V(\to \ell\bar{\ell})V'(\to \ell'\bar{\ell}')$$



vs.

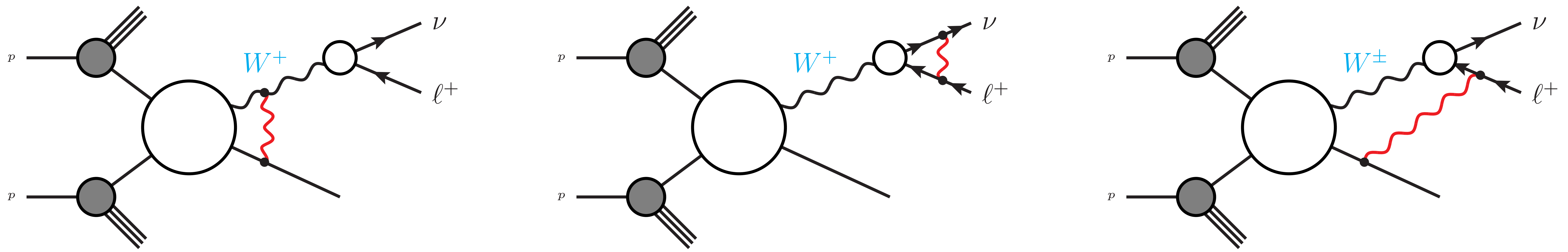
$$pp \to \ell\bar{\ell}\ell'\bar{\ell}'$$



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

Decays of heavy particles

- Leptonic decays of gauge bosons are trivial at NLO QCD. At NLO EW corrections in production, decay and non-factorizable contributions have to be considered.



- Scheme of choice: complex-mass-scheme *[Denner, Dittmaier, et. al.]*
  - gauge invariant and exact NLO
  - **computationally expensive**: one extra leg per two-body decay

- Analytical continuation at the level of the Lagrangian: $M \to \mu = M - i\Gamma M$

➡effects propagators, incl. numerators

➡all derived couplings, incl. weak mixing angle: $\sin\theta_W^2 = 1 - \frac{\mu_W^2}{\mu_Z^2}$

➡position of the pole in the renormalisation

Renormalised self-energy:

$$\hat{\Sigma}^i(p^2) \quad = \quad \Sigma^i(p^2) - \delta\mu_i^2$$

$$\text{with} \qquad \delta\mu_i^2 = \Sigma^i\left(p^2\right)\Big|_{p^2=\mu_i^2}$$

Perturbative expansion: revised

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

NLO QCD

NLO EW

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

NNLO QCD

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

dedicated MC's: Matrix, …

Perturbative expansion: revised

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

dedicated MC's: Matrix, …

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

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

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

N3LO QCD

scale variation at NNLO

Perturbative expansion: revised

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

dedicated MC's: Matrix, …

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

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

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

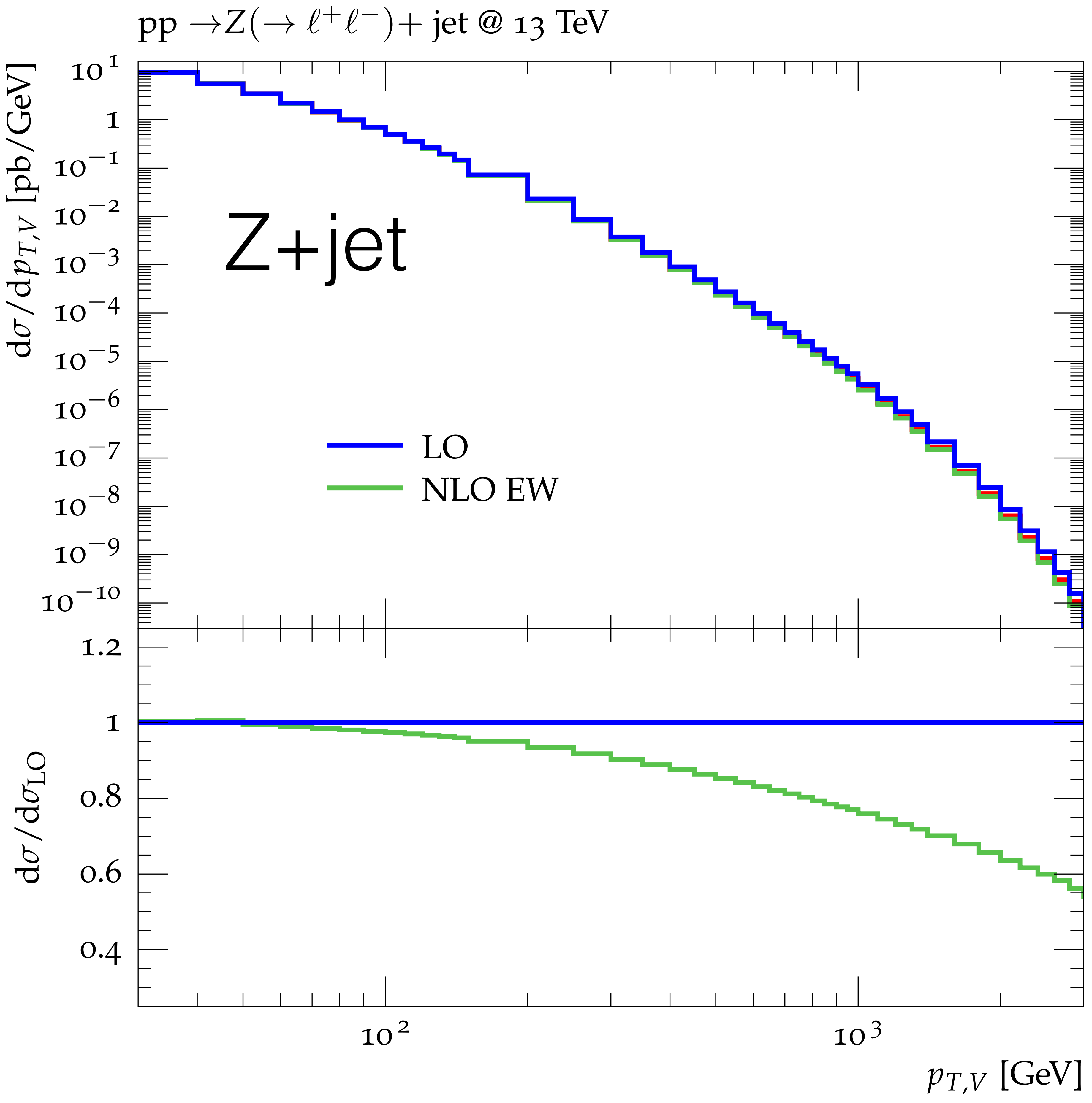
N3LO QCD

scale variation at NLO

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

sufficient?

EW uncertainties: Sudakov

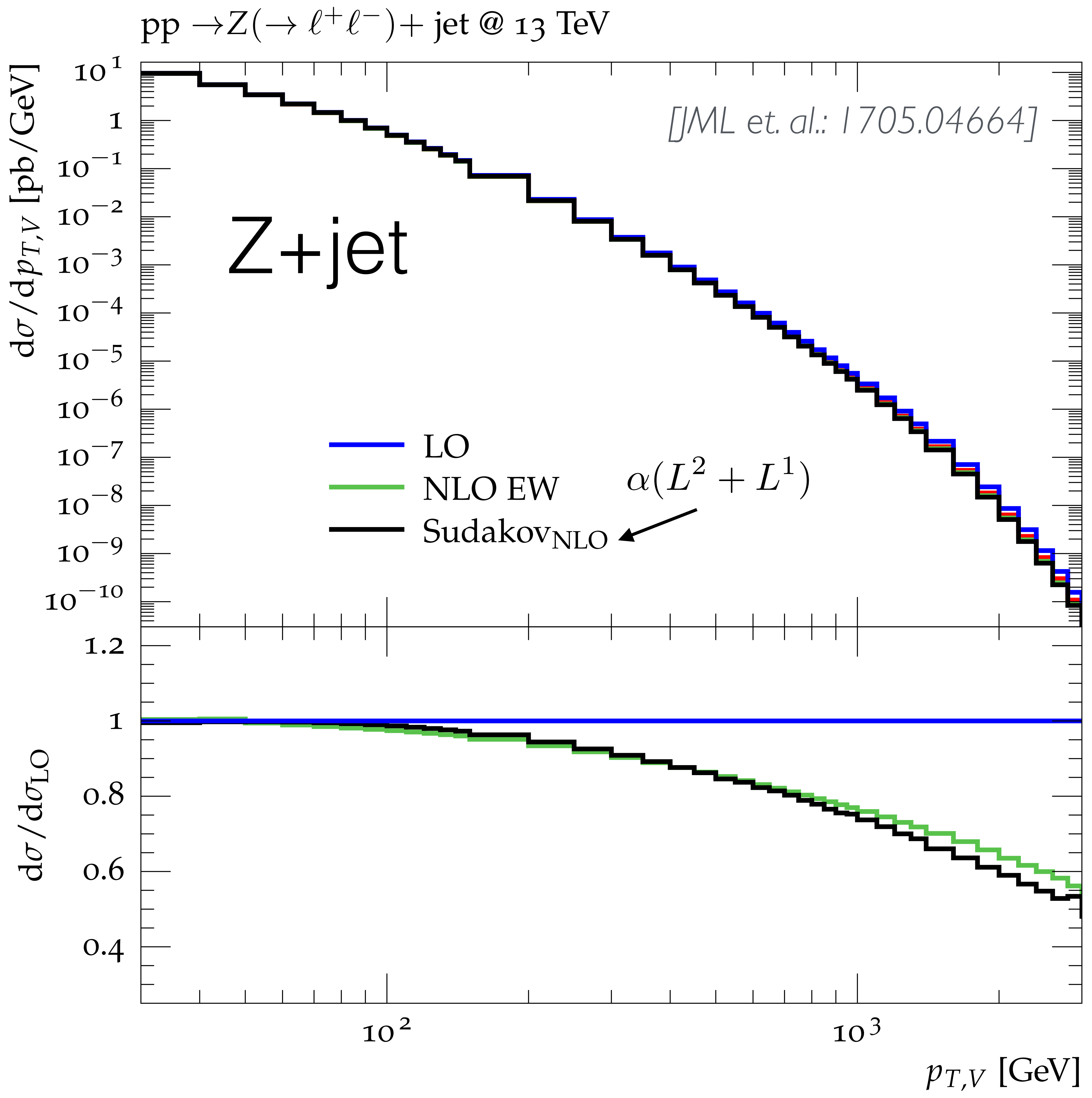


EW corrections become sizeable at large $p_{T,V}$: -30% @ 1 TeV

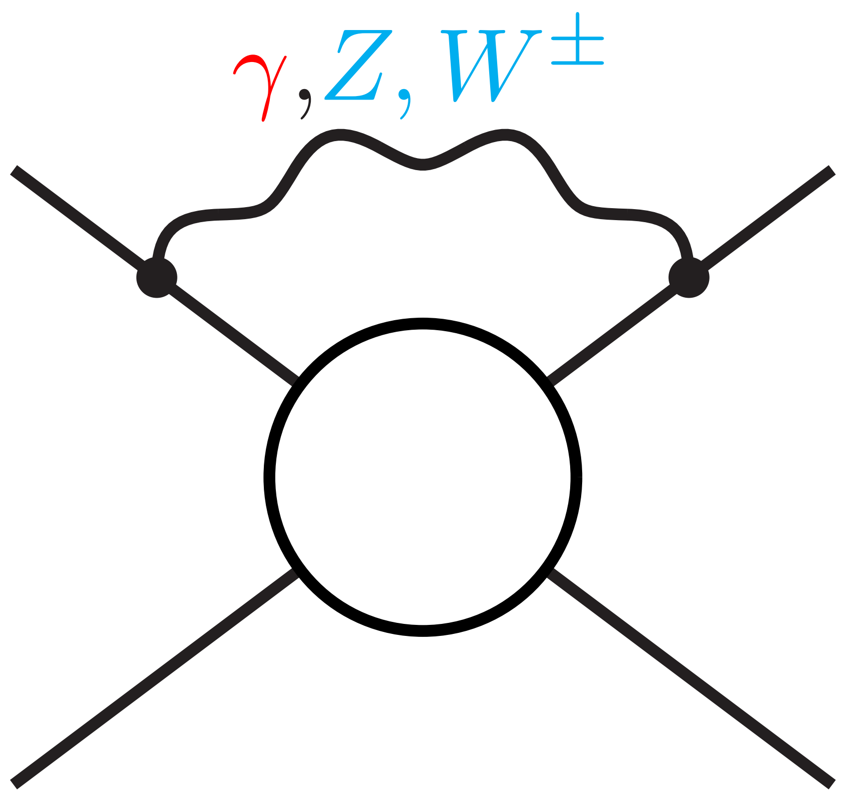
Origin: virtual EW Sudakov logarithms

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

EW uncertainties: Sudakov



Large EW corrections dominated by Sudakov logs

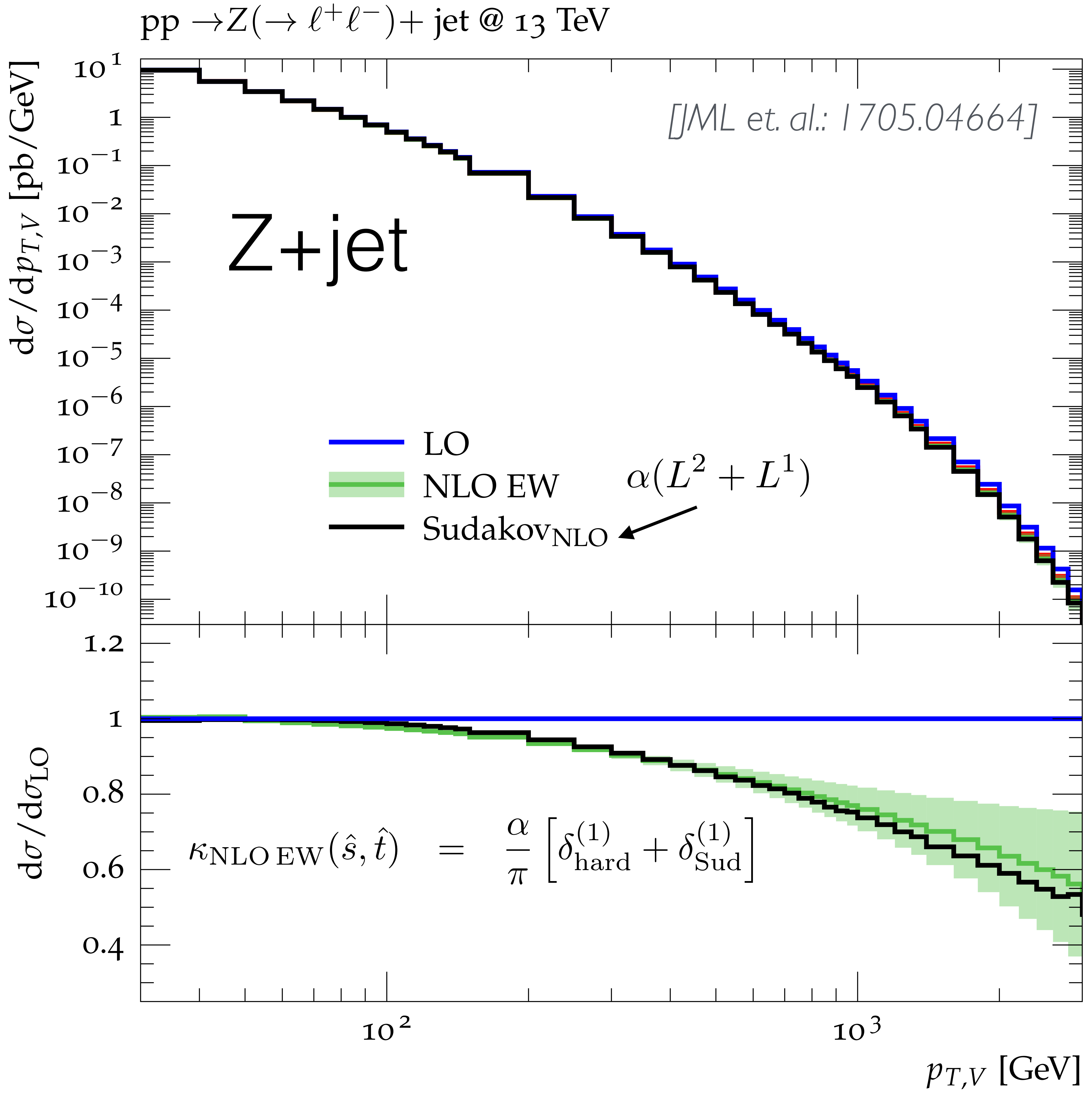


[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]

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

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

EW uncertainties: Sudakov



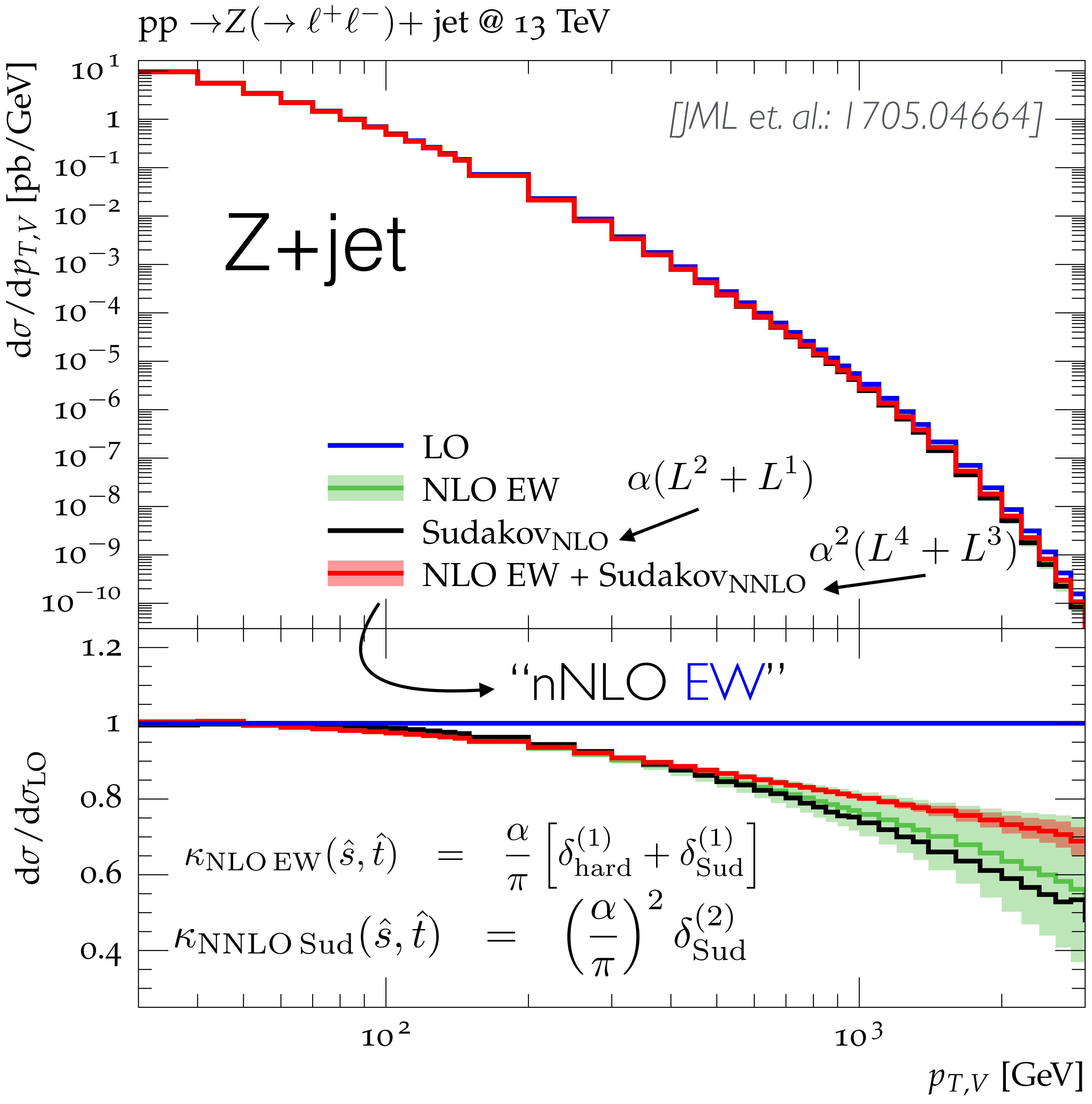
Large EW corrections dominated by Sudakov logs

↓

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

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

EW uncertainties: Sudakov



Large EW corrections dominated by Sudakov logs

↓

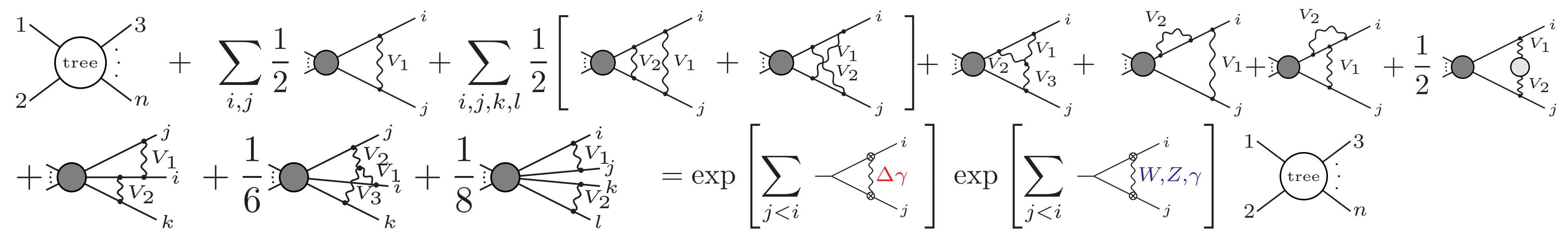
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

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

↓

check against two-loop Sudakov logs

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



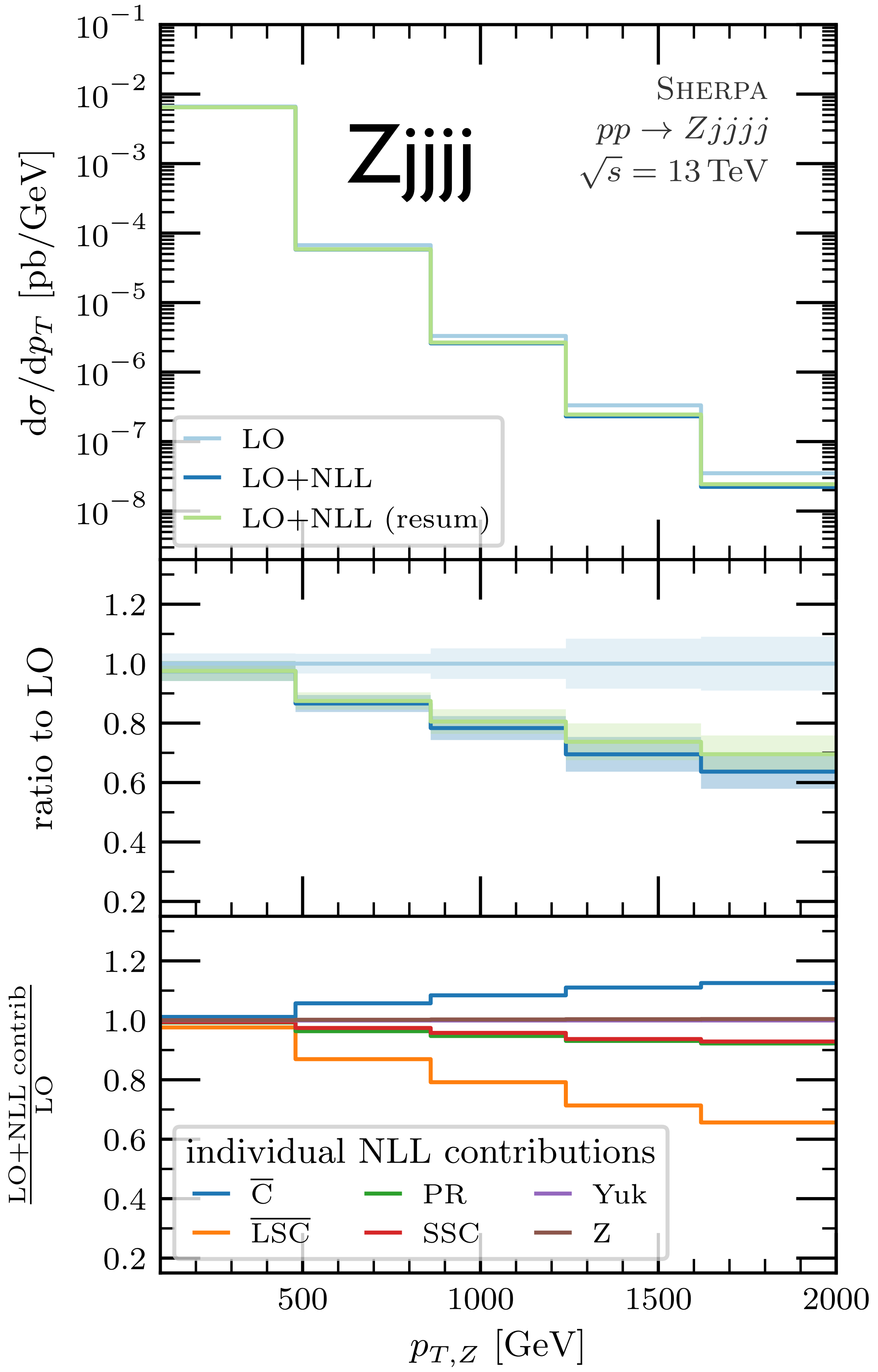
$$\Delta^{\mathrm{hard}}_{\mathrm{EW}} \approx \mathrm{O}(1\%)$$

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

Tools for EW Sudakov corrections

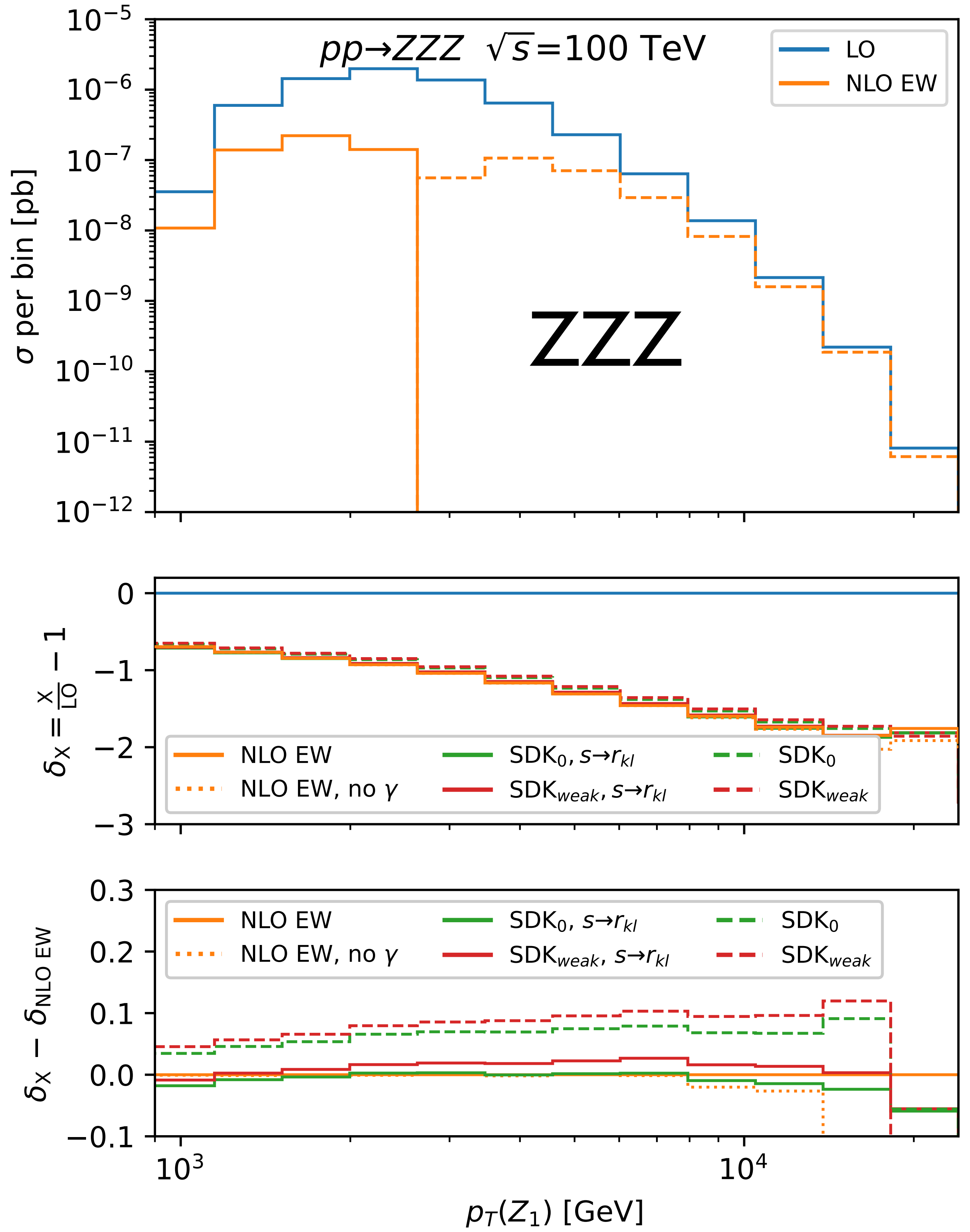
Sherpa

[Bothmann, Napoletano, '20]



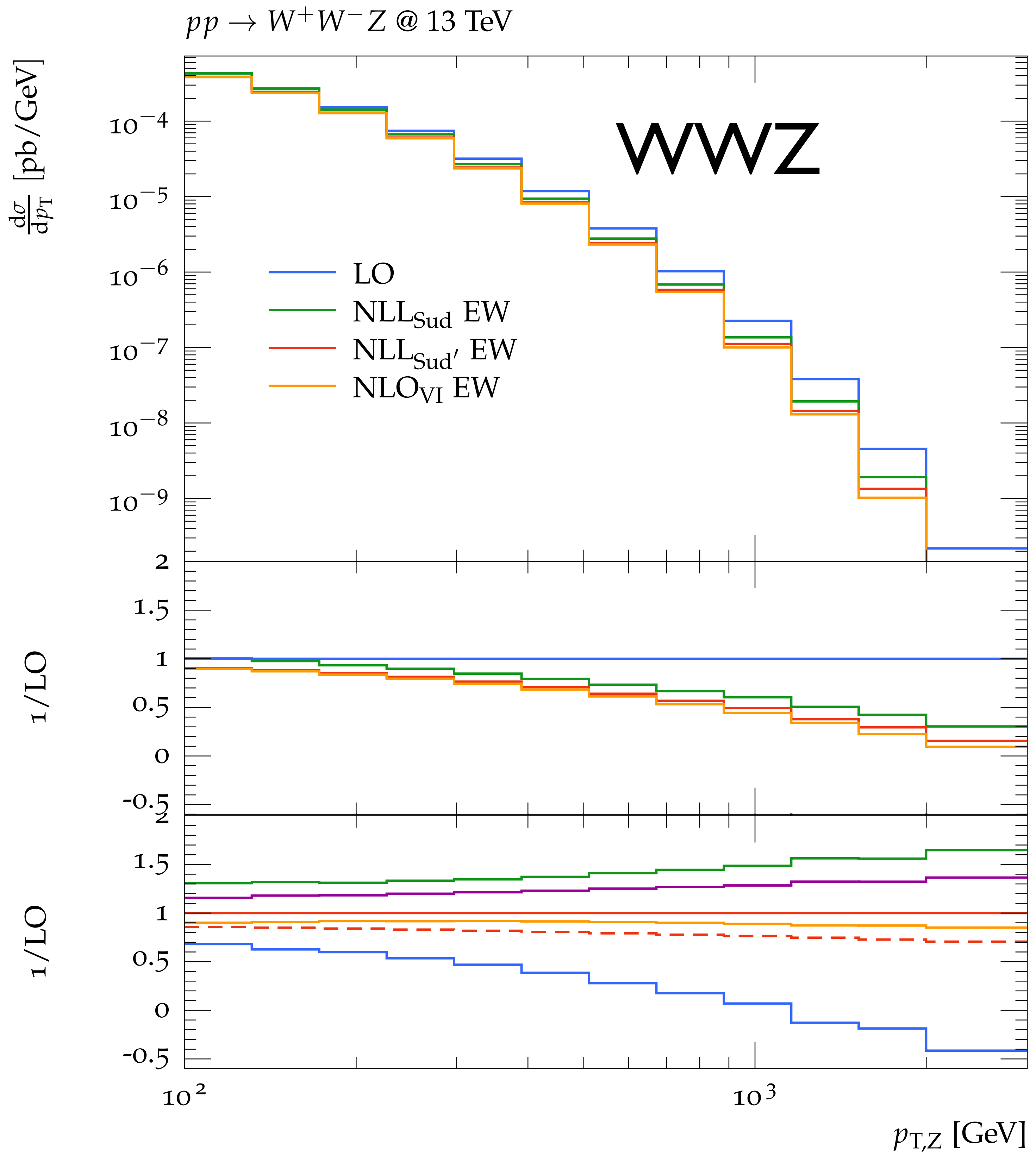
MadGraph5_aMC@NLO

[Pagani, Zaro, '21]

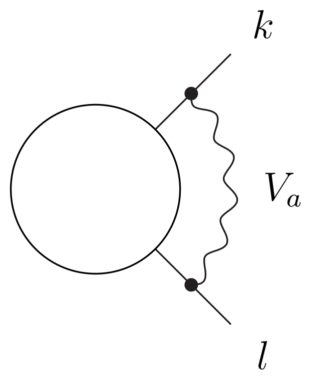


OpenLoops

[JML, Mai, to appear]



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



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

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

$\color{blue}{EW}$ uncertainties: QED radiation

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

Conservative estimate of higher-order QED radiation:

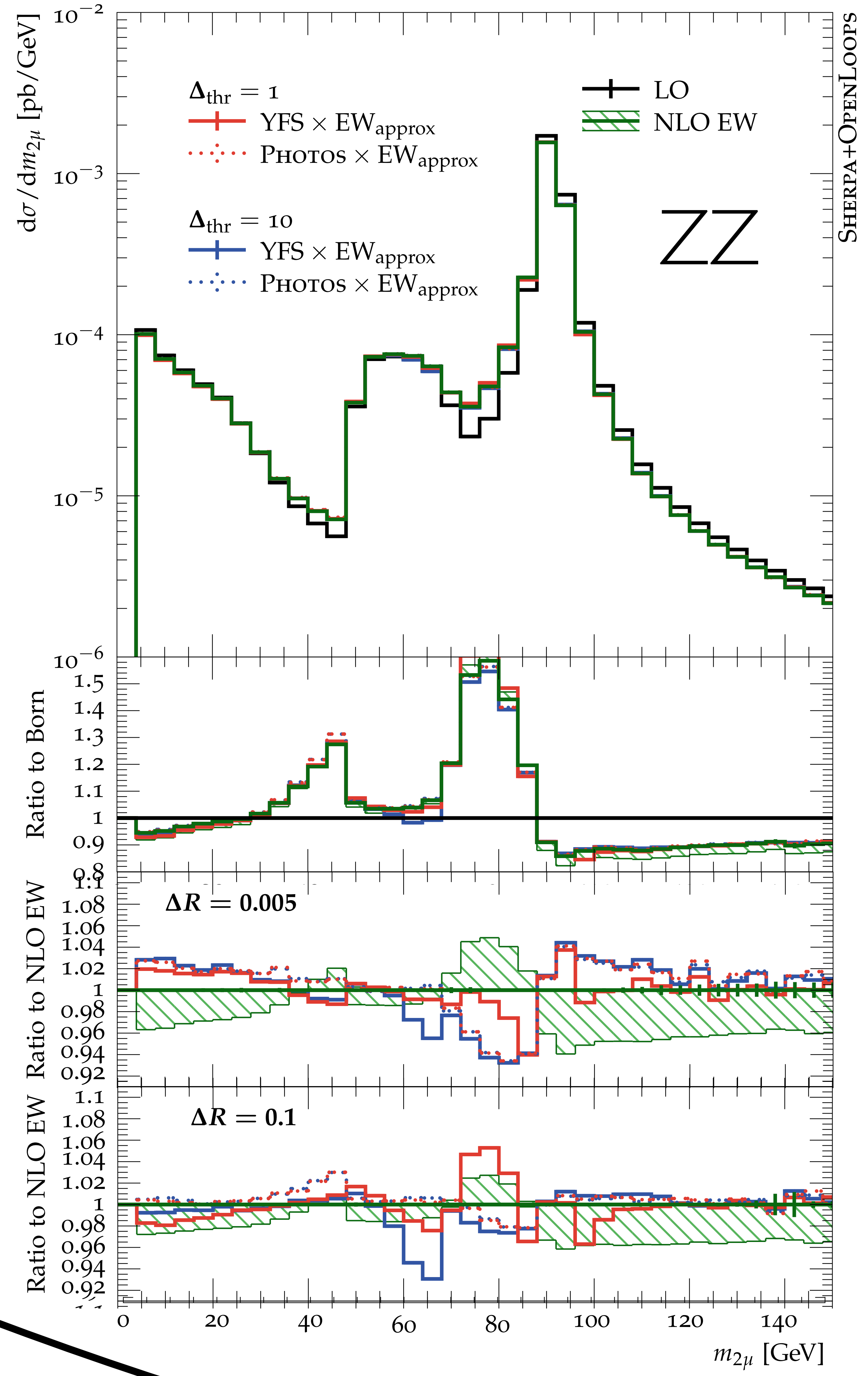
NLO EW

vs.

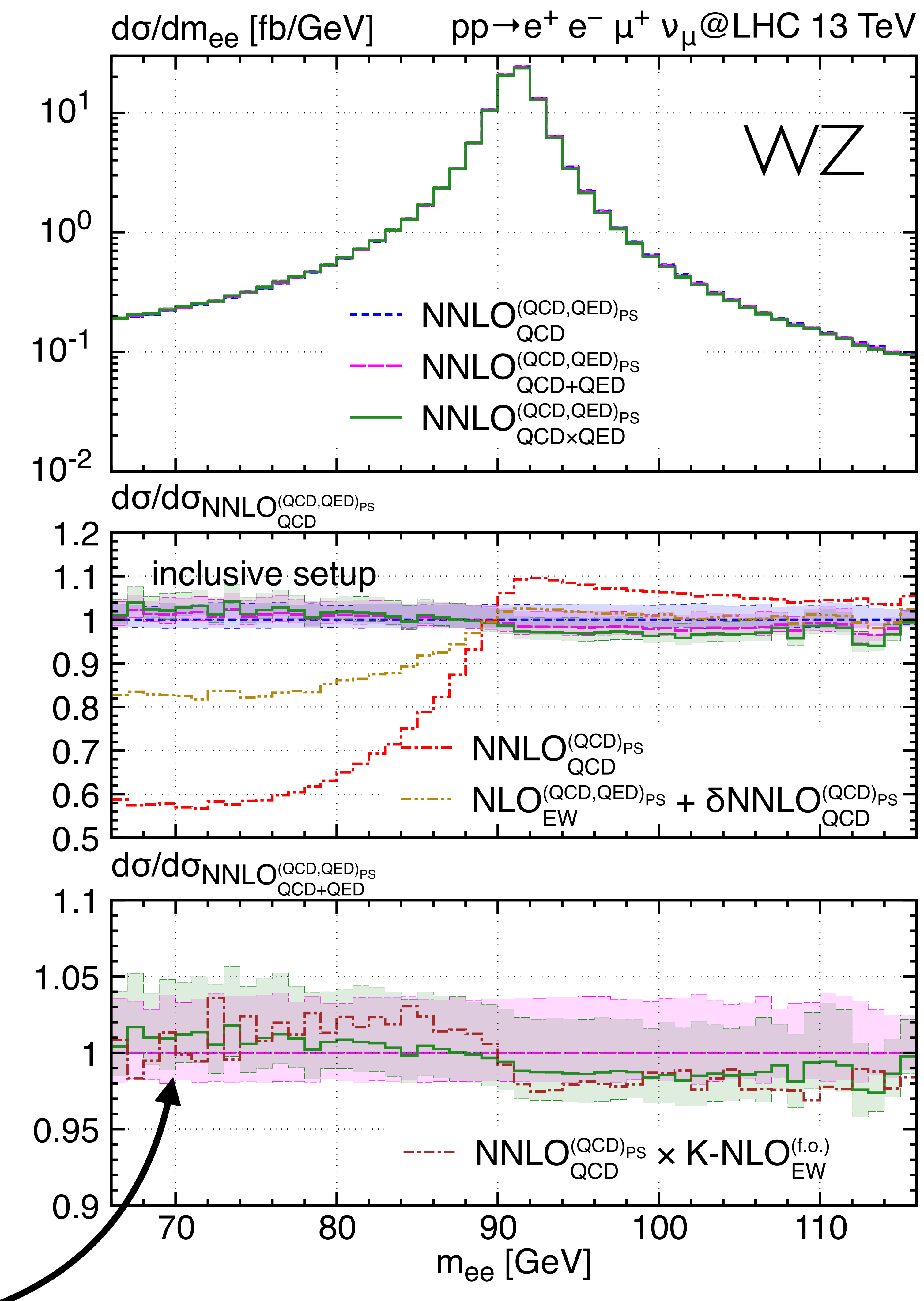
multi-photon radiation (YFS) or QED-PS

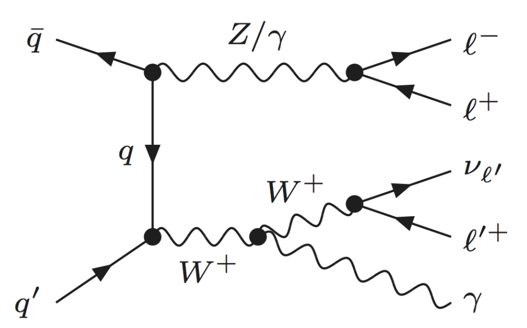
$$\Delta_{\text{EW}}^{\text{QED}} = |\delta_{\text{EW}} - \delta_{\text{EW+PS/YFS}}|$$

[Gütschow, Schönherr, '20]



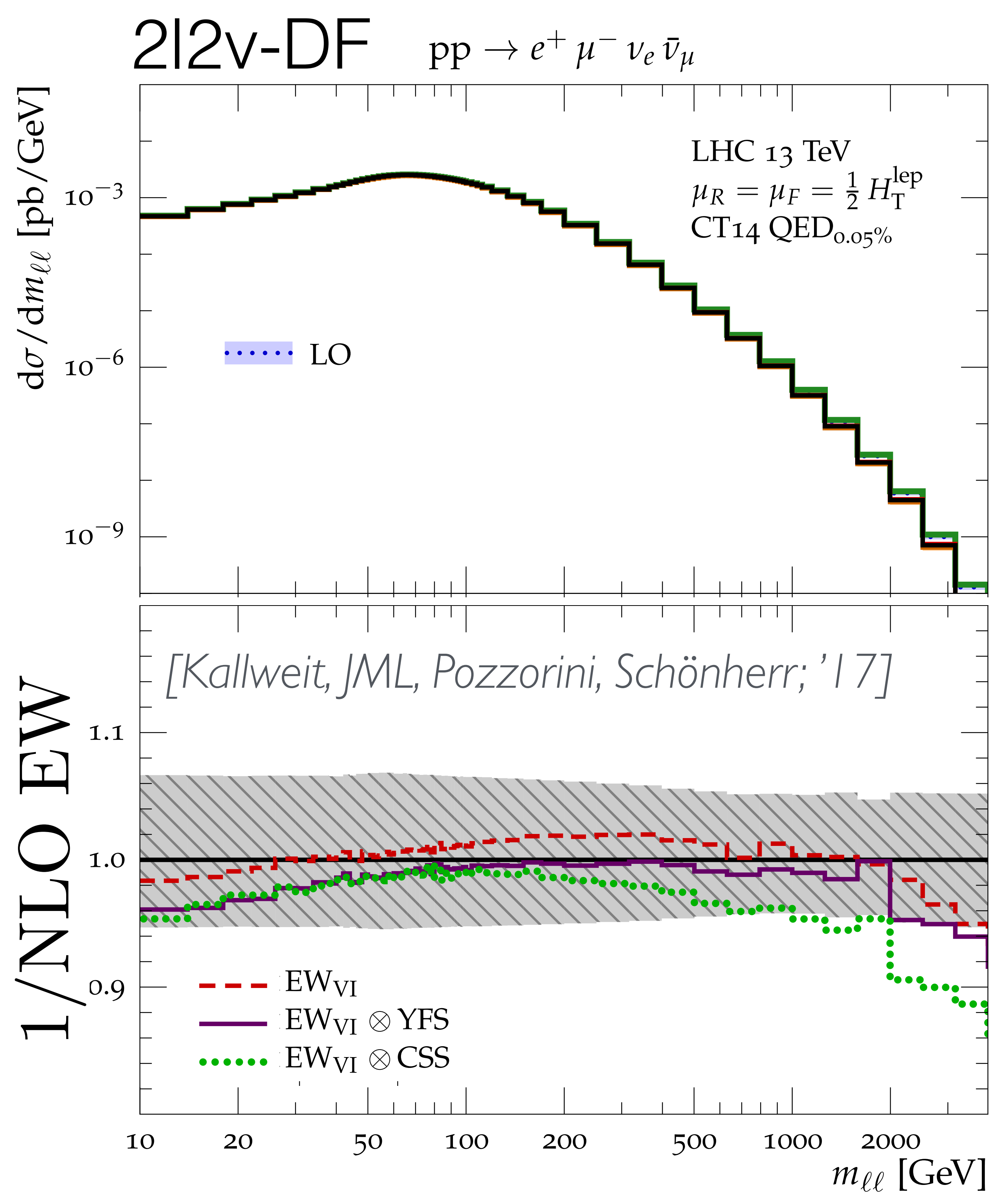
[JML, Lombardi, Wiesemann, Zanderighi, Zanoli, '22]

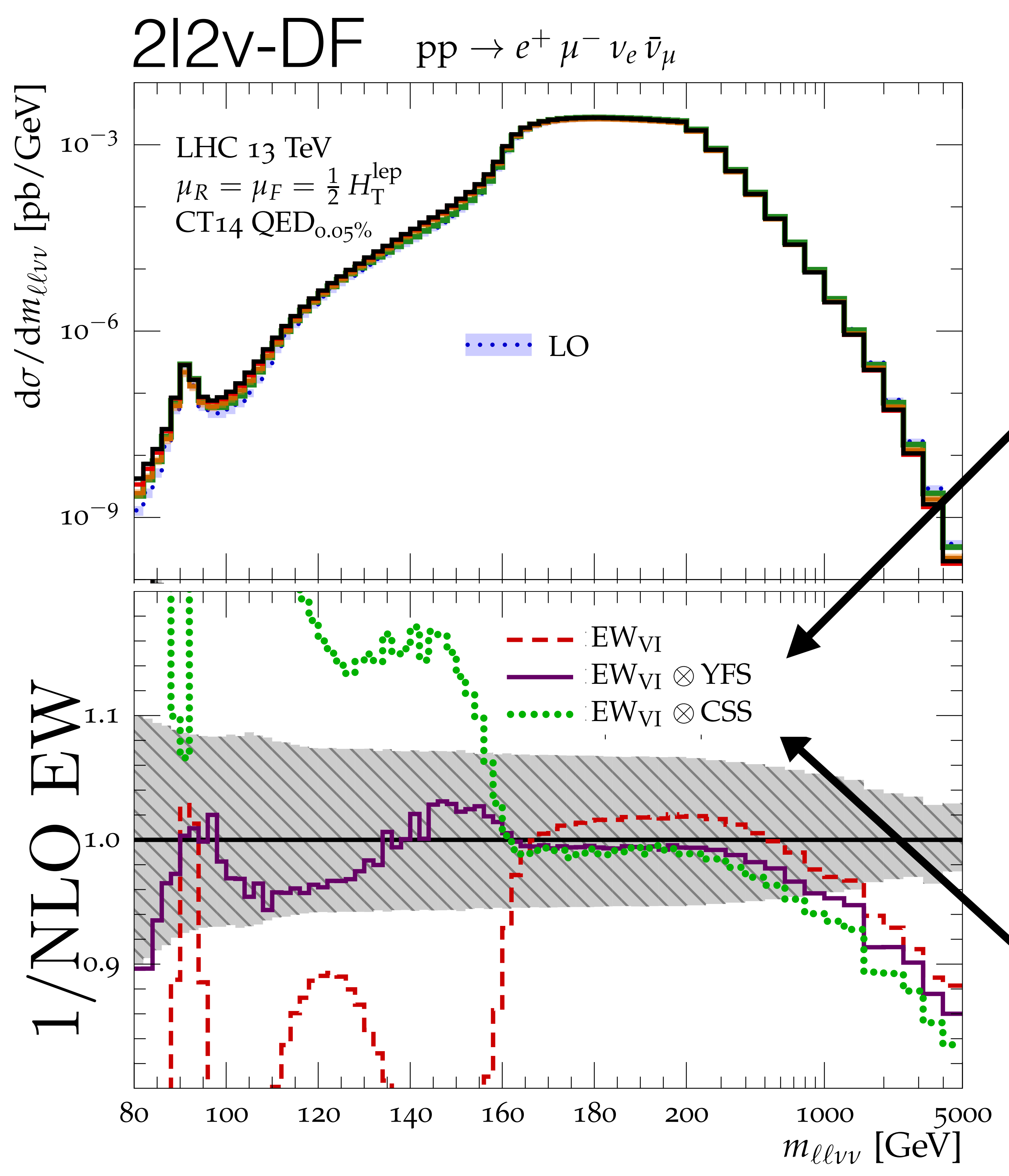




Towards matching of NLO EW to parton showers

- Naive **NLO$_{VI}$** EW+PS matching available in Sherpa
  - ➡CSS dipole shower (not resonance aware) ⇒ significant mismodelling
  - ➡YFS resummation **(resonance aware)** ⇒ valid approximation



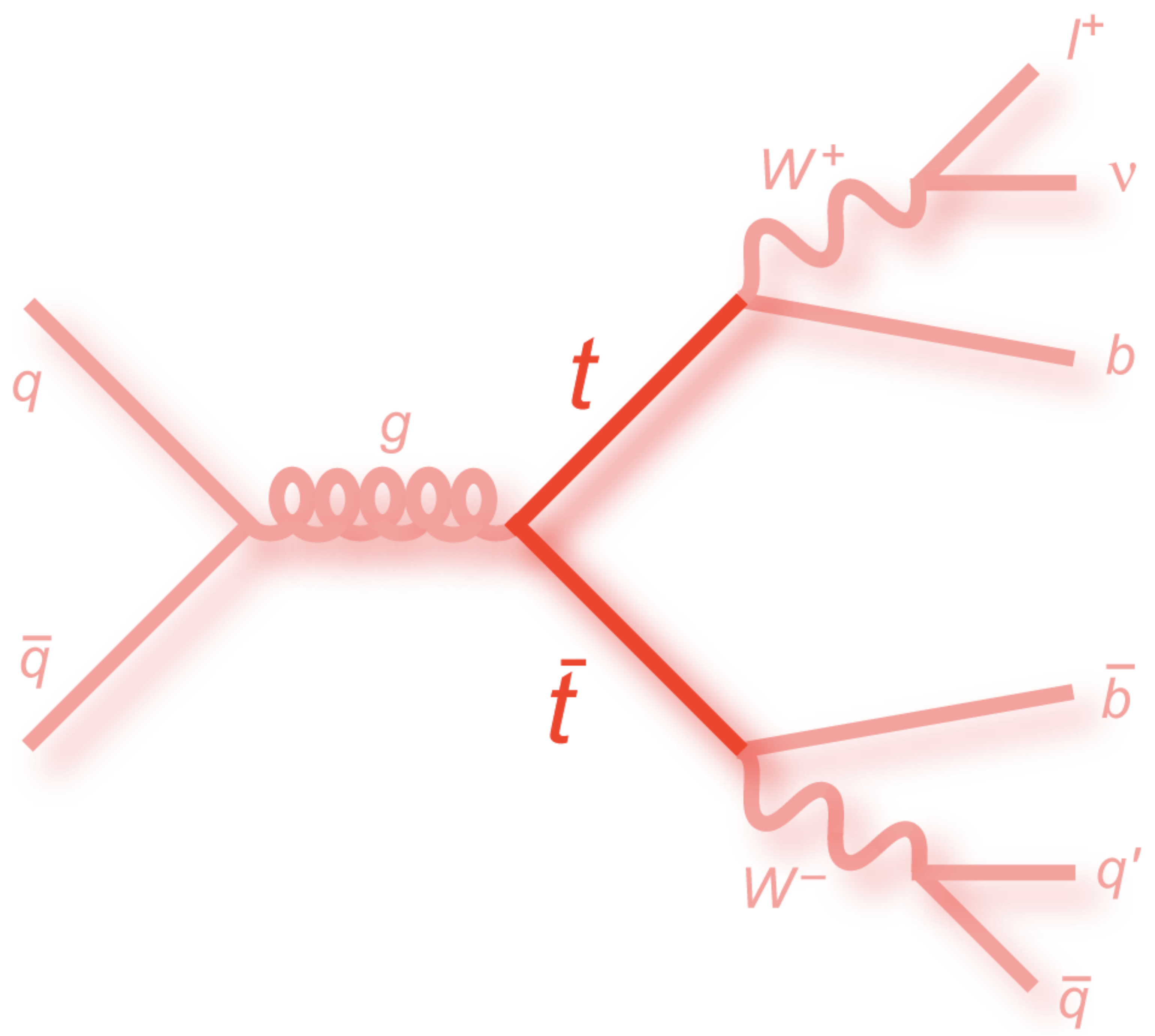


YFS (Multi-Photon-Resummation) **preserves resonance structure** → EW effects agree at the few percent level.

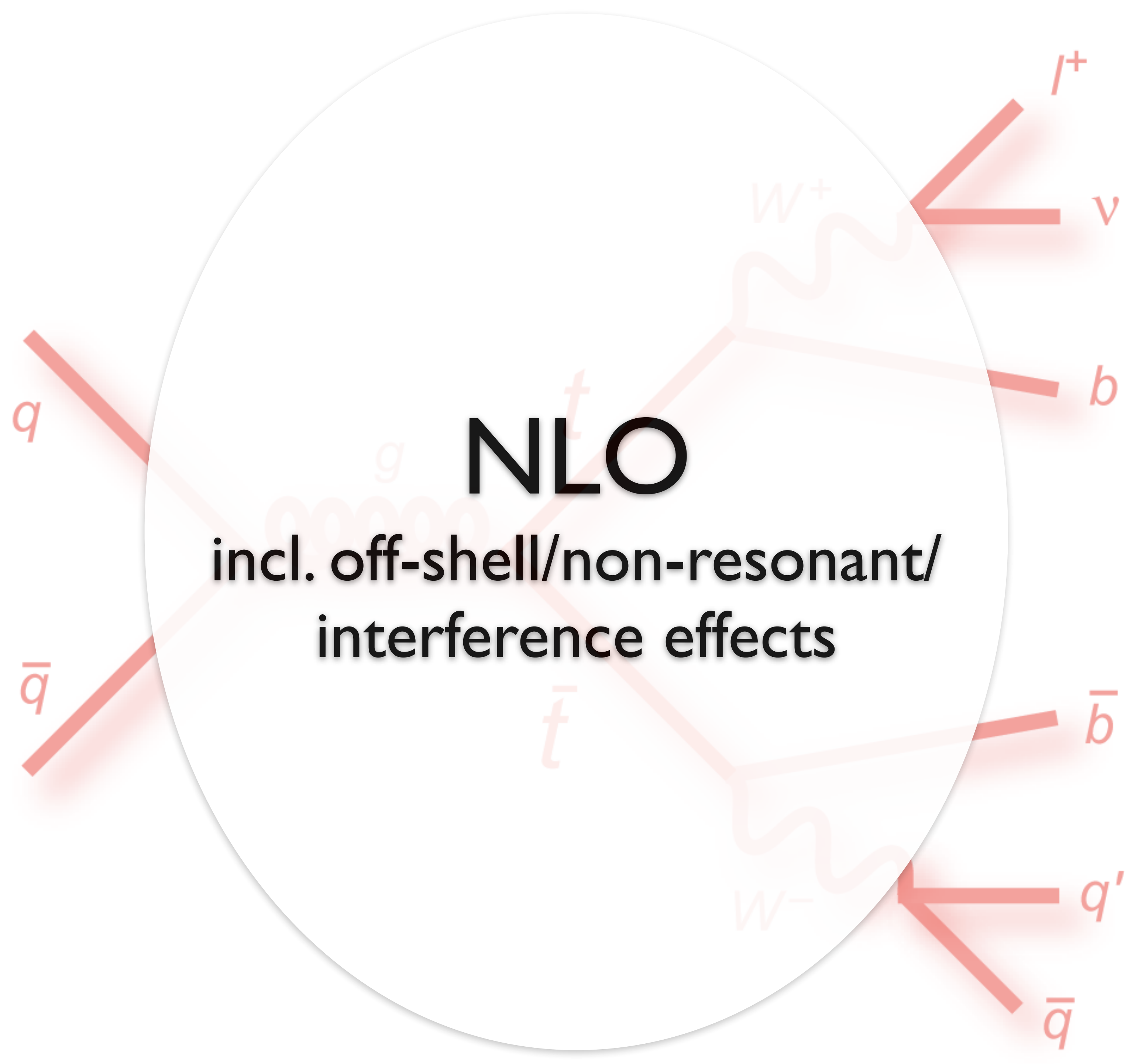
Source of differences:
- Multi-poton effects in YFS
- Resonance-assignment in YFS

CSS (Catani-Seymour-Shower) unaware of resonance structure → QED effects largely overestimated

Resonance-aware matching: off-shell top-pair



Resonance-aware matching: off-shell top-pair



- In a traditional off-shell NLO+PS calculation:
  subtraction, matching and PS do not see/preserve intermediate resonances
- any (necessary) reshuffling/recoil might distort kinematic shapes!

Problem in POWHEG language

- Already at **NLO**:
  - FKS (and similar CS) subtraction does not preserve virtuality of intermediate resonances
  - Real (R) and Subtraction-term (S~B) with different virtuality of intermediate resonances

    $$(\Phi_{\rm B}, \Phi_{\rm rad}) \longleftrightarrow \Phi_{\rm R}^{(\alpha)} \quad \text{from FKS mappings}$$

  - IR cancellation spoiled

    $\Longrightarrow$ **severe efficiency problem!**

- More severe problems at **NLO+PS**:
  - in POWHEG:
    $$\mathrm{d}\sigma = \bar{B}(\Phi_{\rm B})\,\mathrm{d}\Phi_{\rm B}\left[\Delta(q_{\rm cut}) + \sum_\alpha \Delta(k_T^\alpha)\frac{R_\alpha(\Phi_\alpha(\Phi_{\rm B}, \Phi_{\rm rad}))}{B(\Phi_{\rm B})}\,\mathrm{d}\Phi_{\rm rad}\right]$$

    Sudakov form-factor generated from uncontrollable R/B ratios:

    $$\Delta\left(\Phi_B, p_{\rm T}\right) = \exp\left\{-\sum_\alpha \int_{k_{\rm T} > p_{\rm T}} \frac{R(\Phi_{\rm R}^{(\alpha)})}{B(\Phi_{\rm B})}\,\mathrm{d}\Phi_{\rm rad}^{(\alpha)}\right\}$$

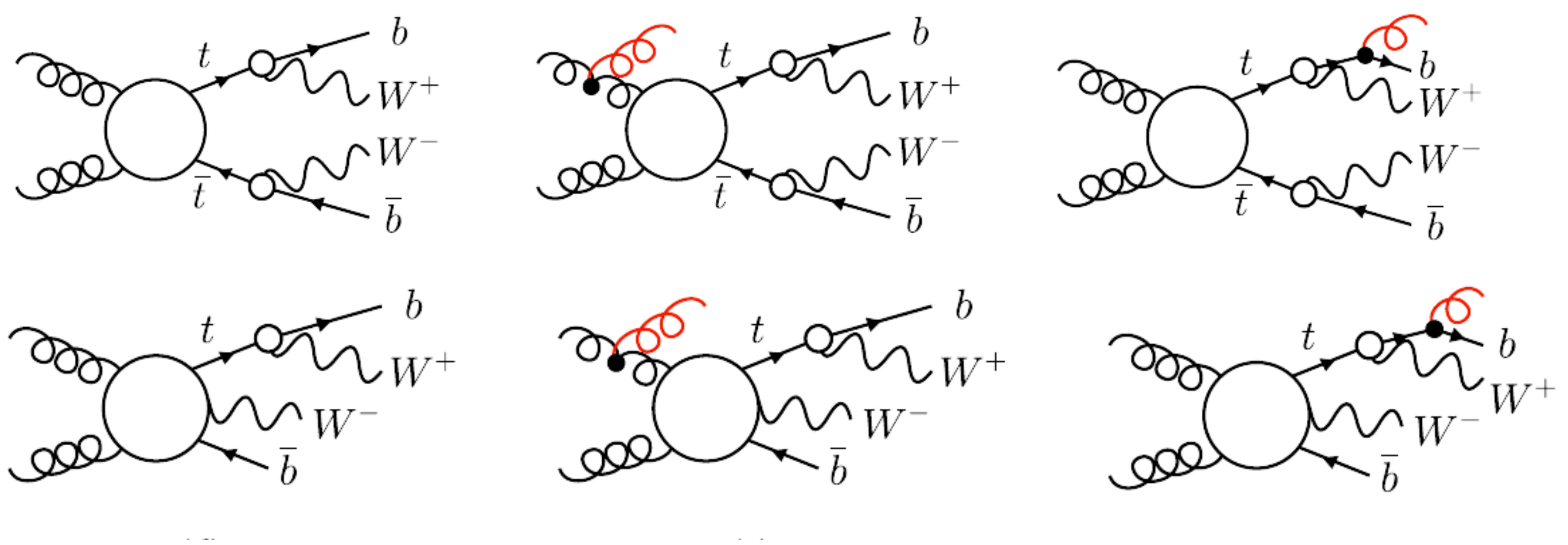
  - also subsequent radiation by the **PS** itself reshuffles internal momenta and does in general not preserve the virtuality of intermediate resonances.

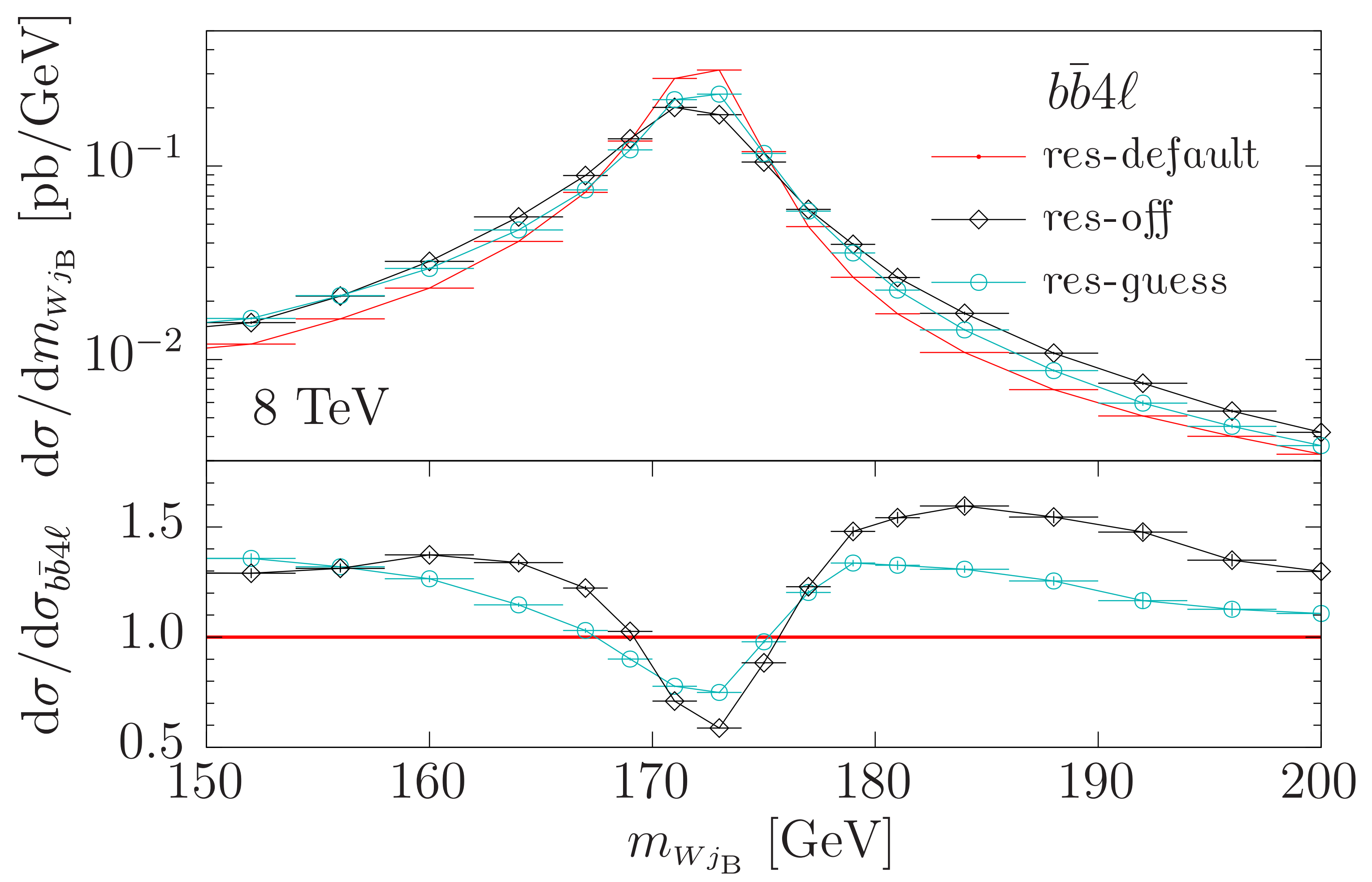
    $\Longrightarrow$ **expect uncontrollable distortion of important kinematic shapes!**

The resonance-aware bb4l generator

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

- Full process $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ 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
- **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

Perturbative expansion: revised

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

dedicated MC's: Matrix, …

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

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

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

N3LO QCD

only known for DY (so far)

scale variation at NNLO

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

sufficient?

Mixed QCD-EW uncertainties

Bold estimate:

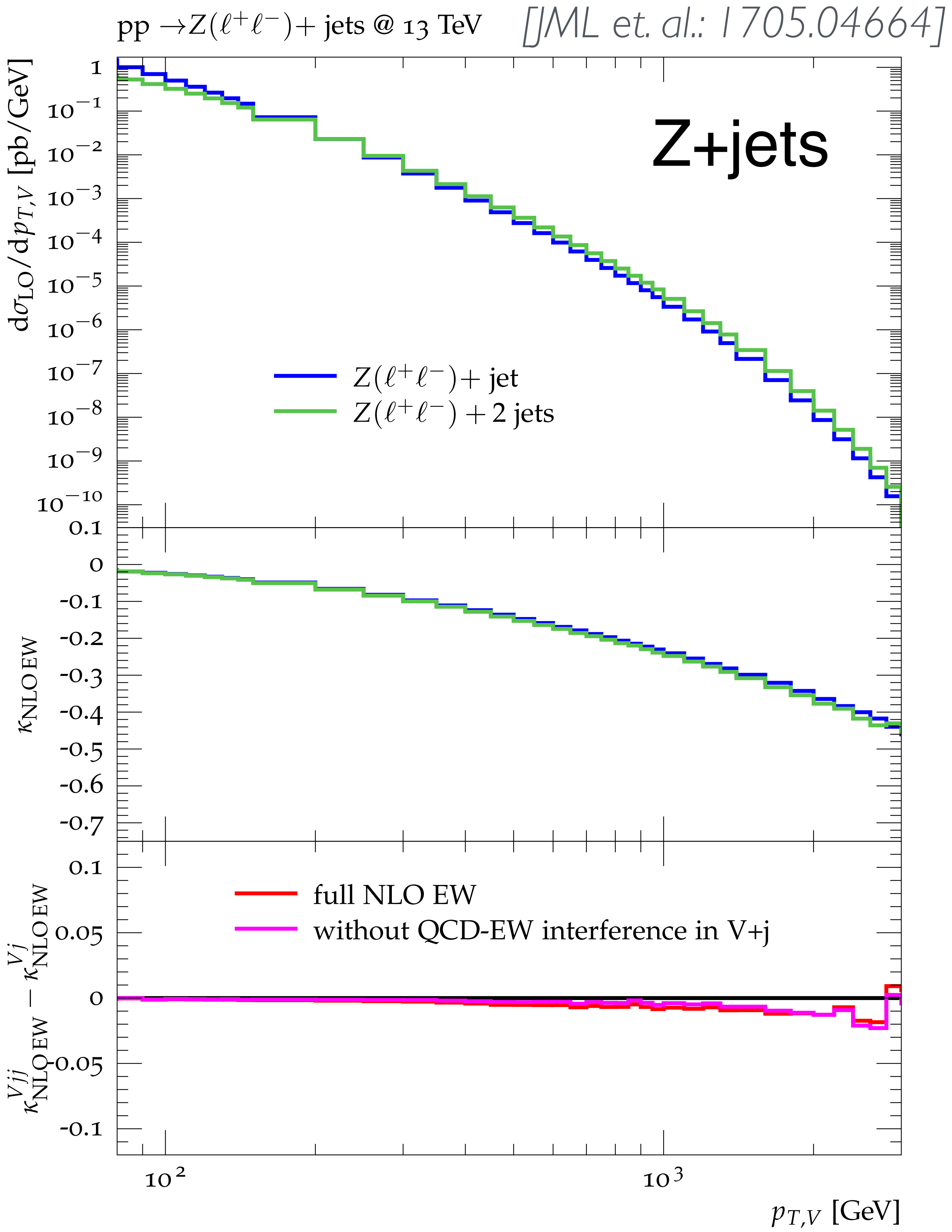
Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to X production $\simeq$ NLO EW to X+1jets

and we often observe

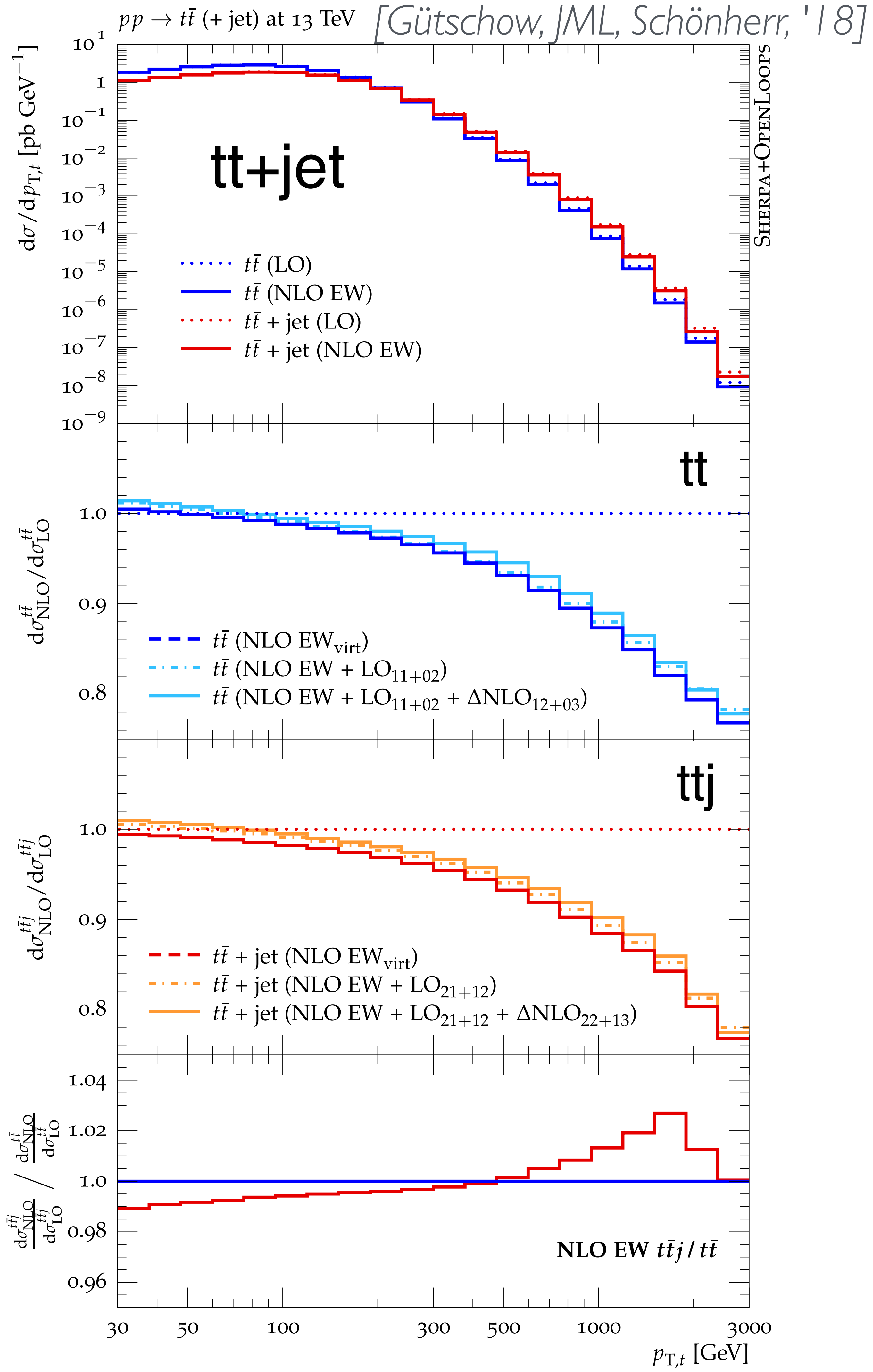
$$\left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{X+\mathrm{jet}} - \left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{X} \lesssim 1\%$$

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

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



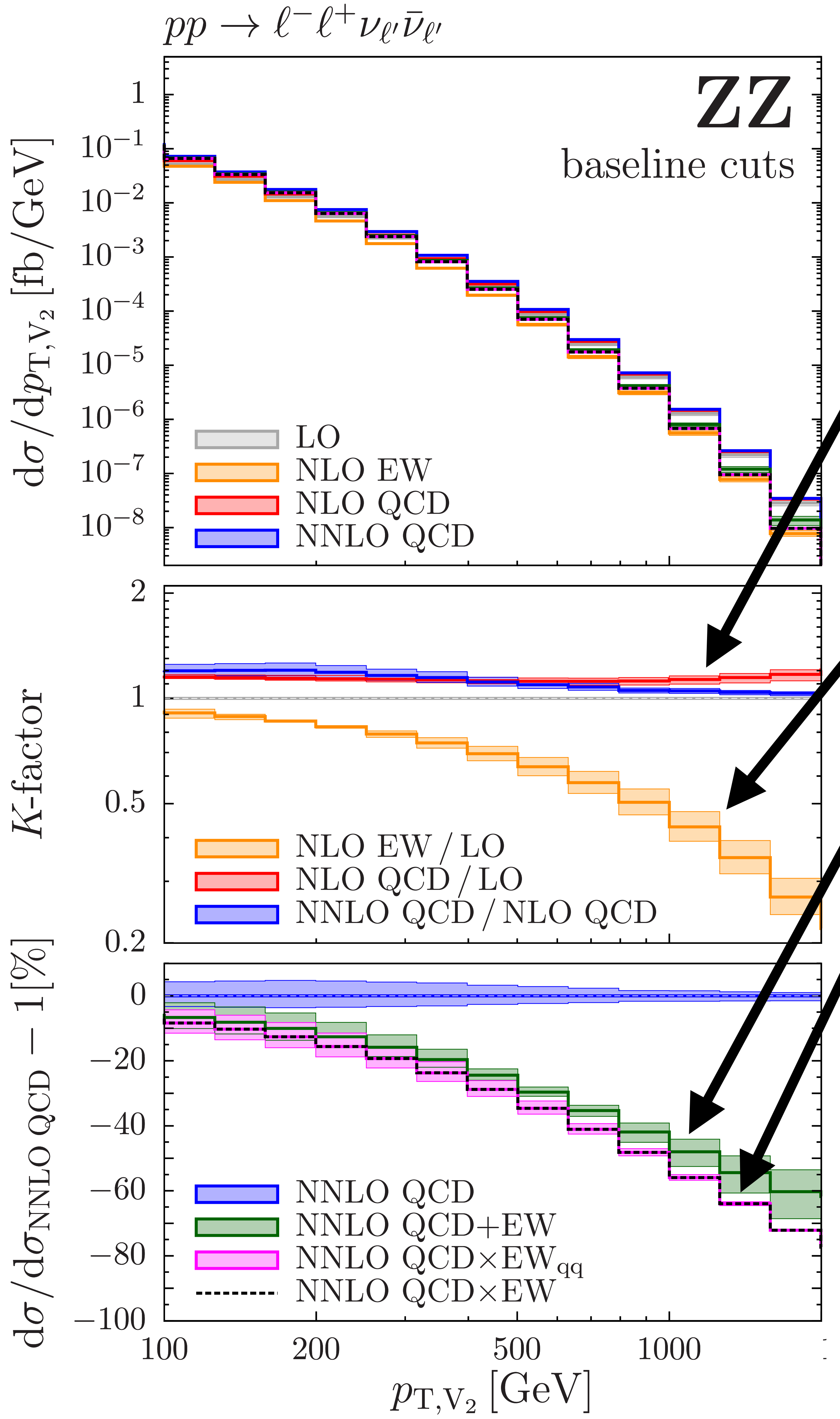
$pT_{j,2} > 30$ GeV



$pT_{j} > 30$ GeV

EW uncertainties: QCD-EW interplay

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



pTV2

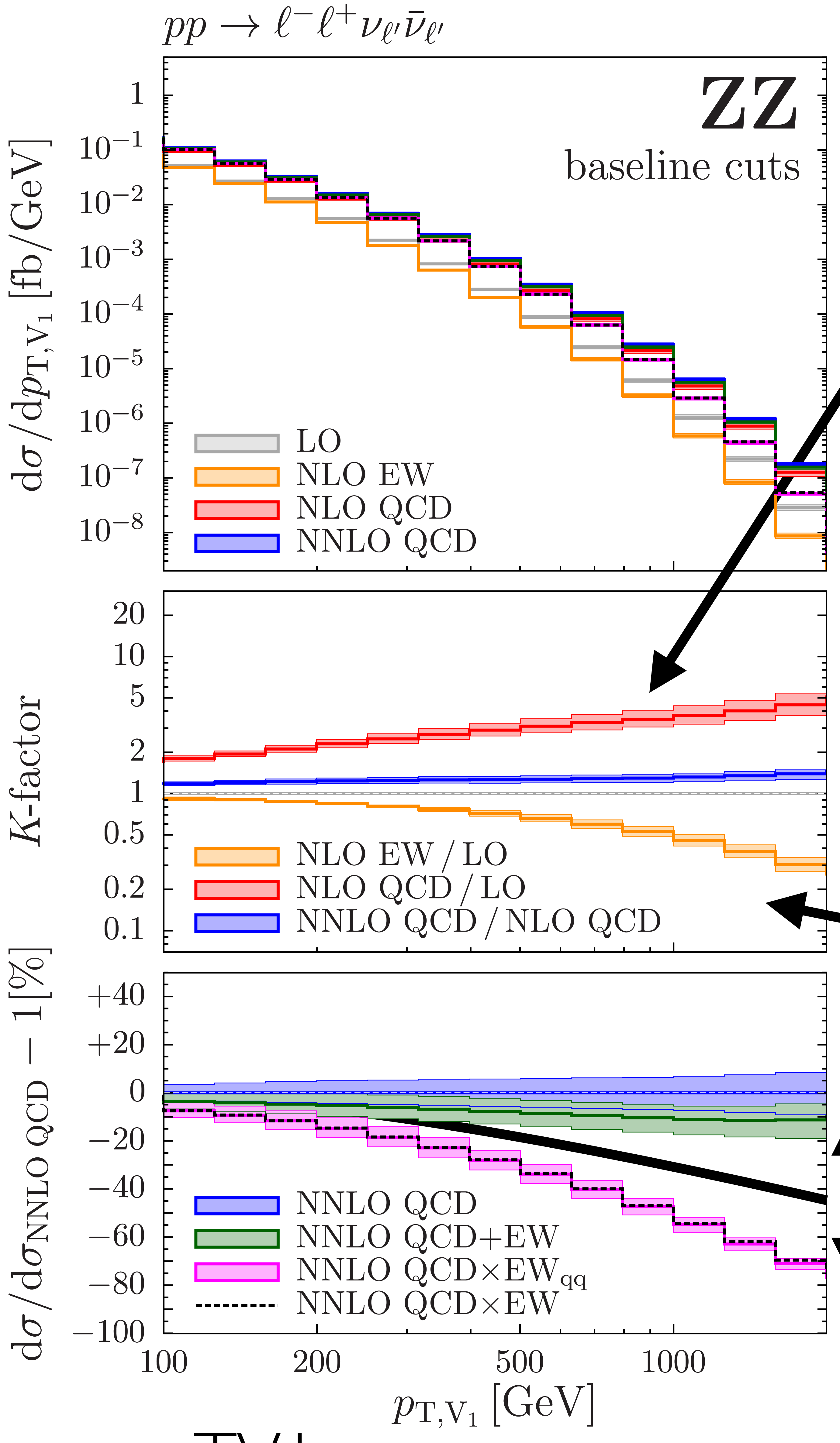
- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent
- NLO EW/LO=-(50-60)% @ 1 TeV

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

- difference very conservative upper bound on $\mathcal{O}(\alpha_S\alpha)$: $d\sigma_{LO}\,\delta_{QCD}\,\delta_{EW}$
- multiplicative/factorised combination superior (EW Sudakov logs x soft QCD)

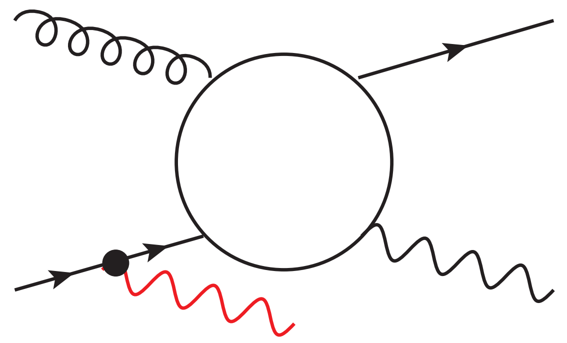
- alternative: $\delta^{NLL}_{EW} = \delta^{DL}_{EW} + \delta^{SL}_{EW} + \delta^{non-log}_{EW}$
  $\to \mathcal{O}(\alpha_S\alpha) = d\sigma_{LO}\,\delta_{QCD}\,(\delta^{SL}_{EW} + \delta^{non-log}_{EW})$

Combination of QCD and EW corrections



pTV1

- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



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

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

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

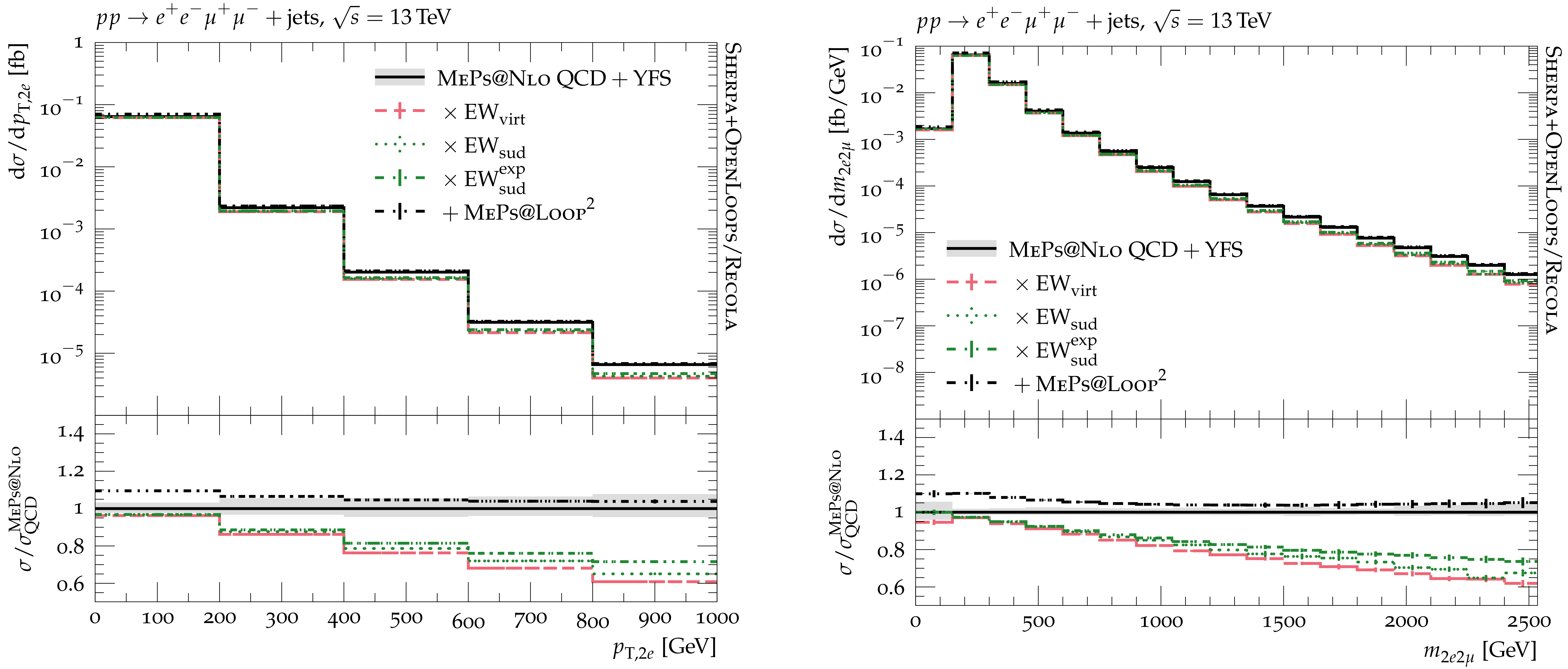
$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)$$

exact virtual contribution ($\mathrm{V}_{n,\mathrm{EW}}$)

approximate integrated real contribution ($\mathrm{I}_{n,\mathrm{EW}}$)

MEPS @ NLO QCD + EW: ZZ(+jet)

[Bothmann, Napoletano, Schönherr, Schumann, Villani; '21]



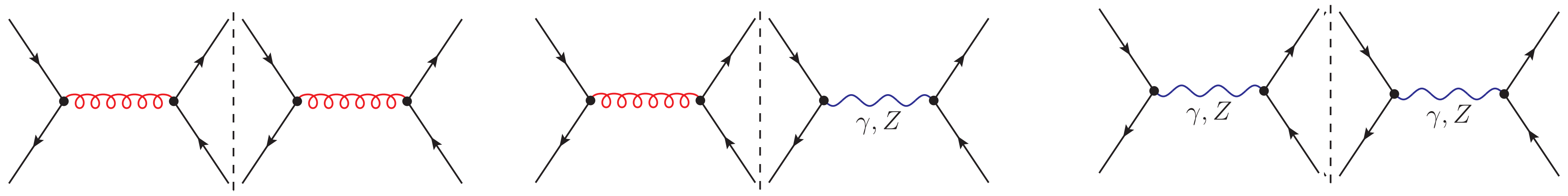

```
ASSOCIATED_CONTRIBUTIONS_VARIATIONS EW;
```

Perturbative expansion: revised II

- In general combined expansion in α_S and α necessary:

$$d\sigma = d\sigma(\alpha_s^n \alpha^m) + d\sigma(\alpha_s^{n-1}\alpha^{m+1}) + \sigma(\alpha_s^{n-2}\alpha^{m+2}) + \dots$$

LO "subleading Born contributions": LO2, LO3



Example: $q\bar{q} \rightarrow q\bar{q}$

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- also at NLO: $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$

$$\cdots + \sigma(\alpha_s^{n+1}\alpha^m) + d\sigma(\alpha_s^n \alpha^{m+1}) + \sigma(\alpha_s^{n-1}\alpha^{m+2}) + \sigma(\alpha_s^{n-2}\alpha^{m+3}) + \ldots$$

"NLO QCD" "NLO EW" "subleading one-loop contributions": NLO3, NLO4

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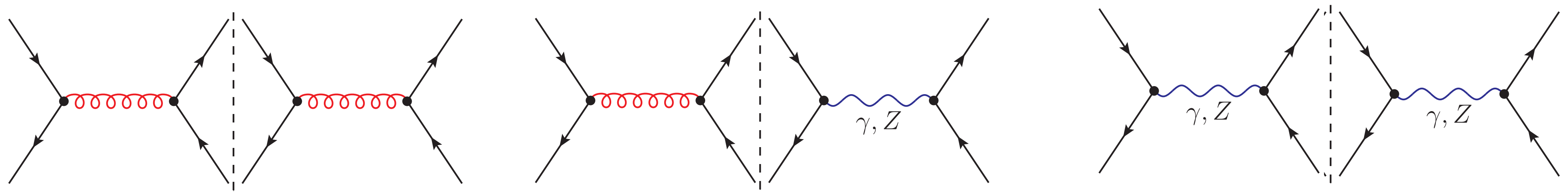

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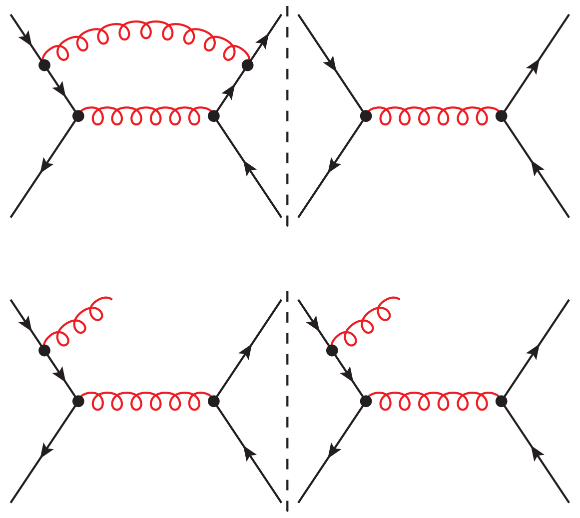
"NLO QCD"   "NLO EW"   "subleading one-loop contributions": NLO3, NLO4



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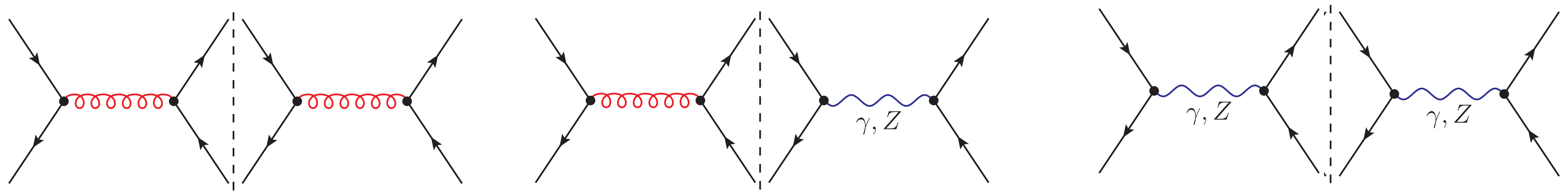

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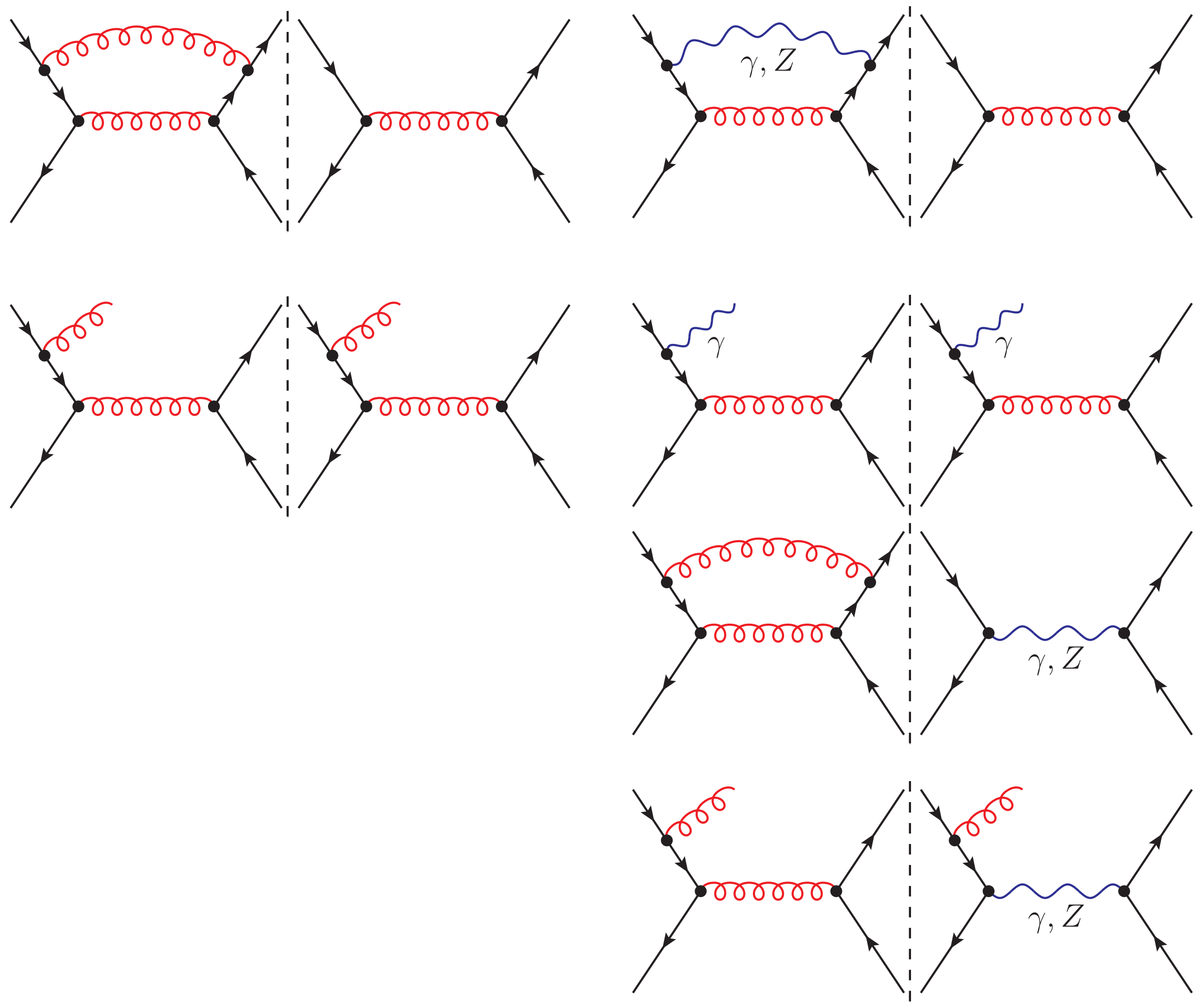

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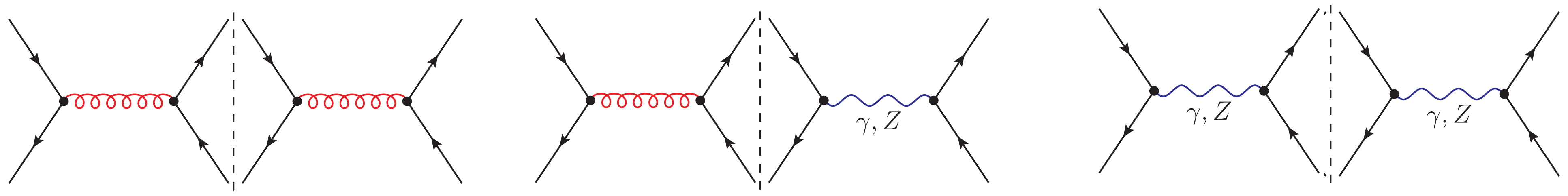

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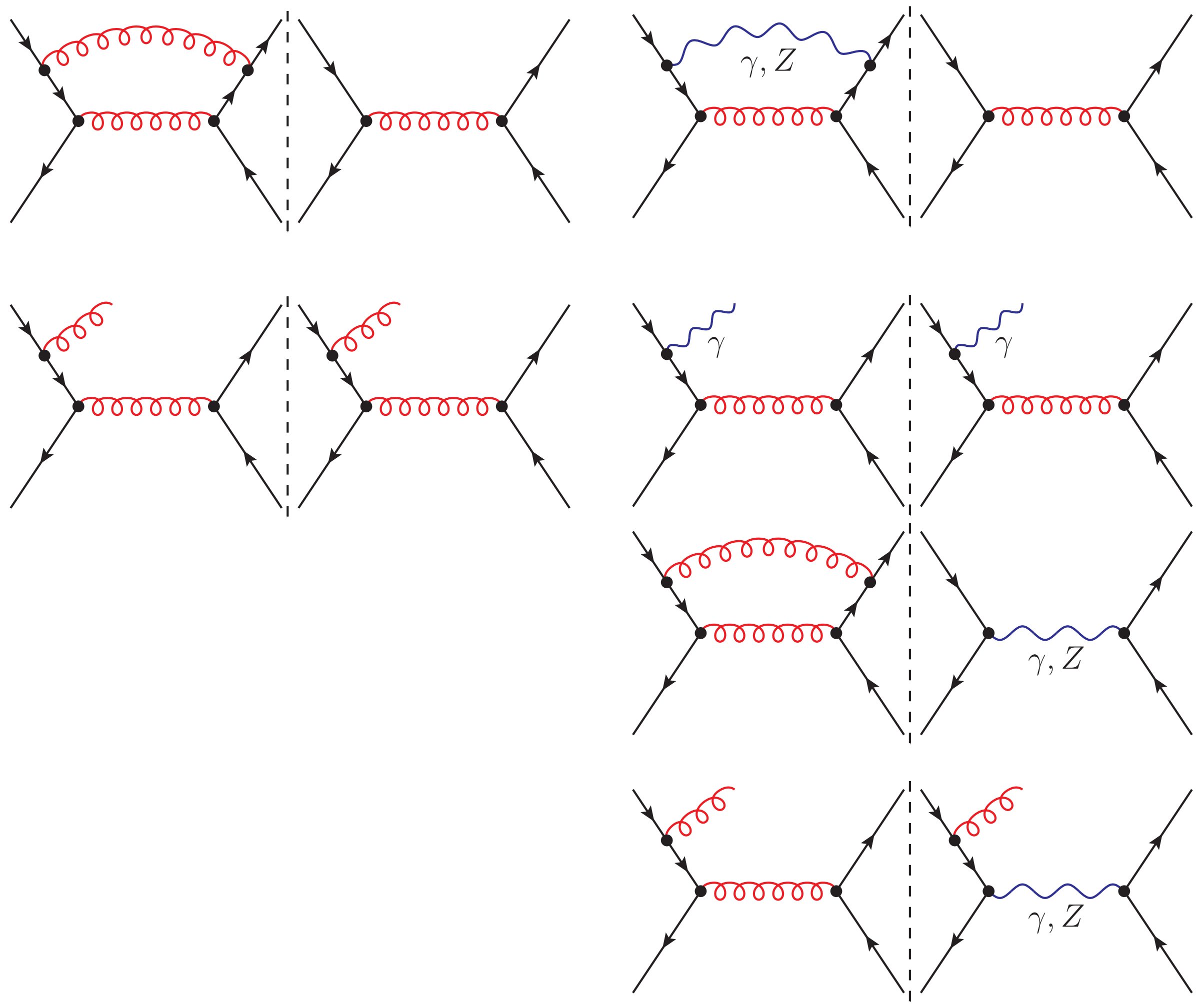
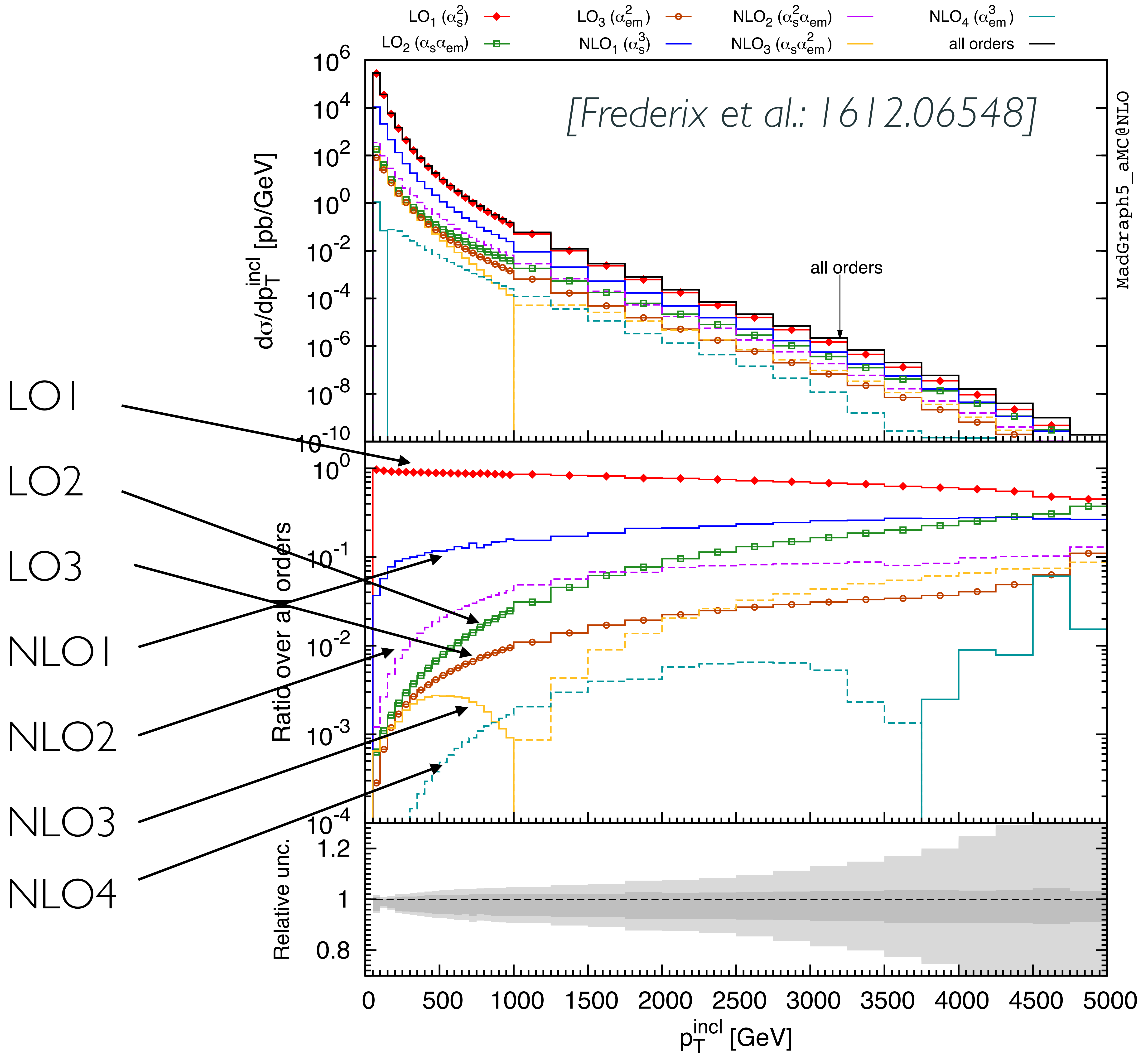


Note:

- No diagrammatic separation in NLO QCD and EW
- An IR finite & gauge invariant result is only obtained including all virtual and real contributions of a given perturbative order.

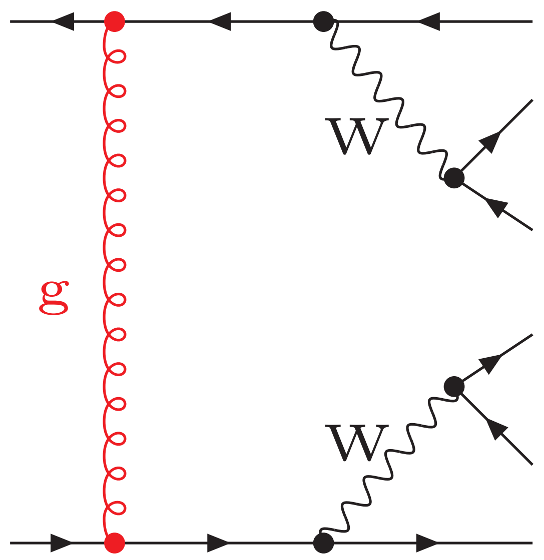
Example: dijet production at the LHC



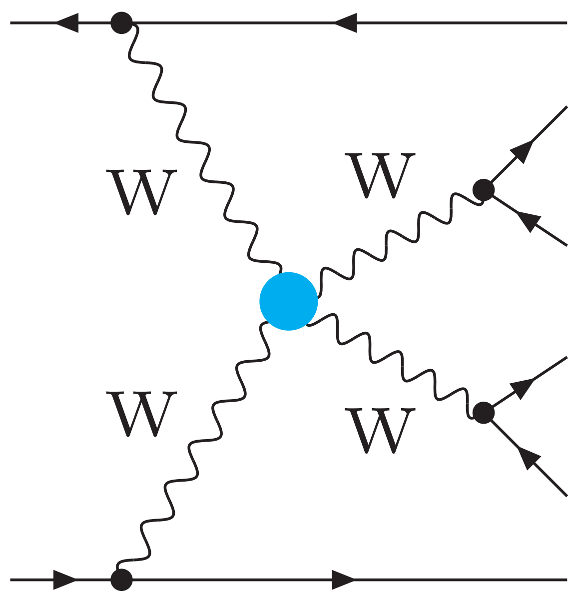
Be aware of double counting: LO3 = DY with hadronic decays

VV+2jets production

Note: severe QCD background to VBS signatures + interference:



vs.



QCD-background interference VBS-signal

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

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

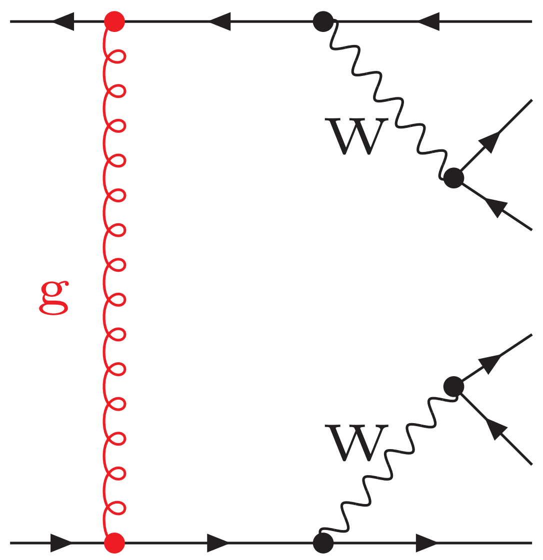
$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$

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

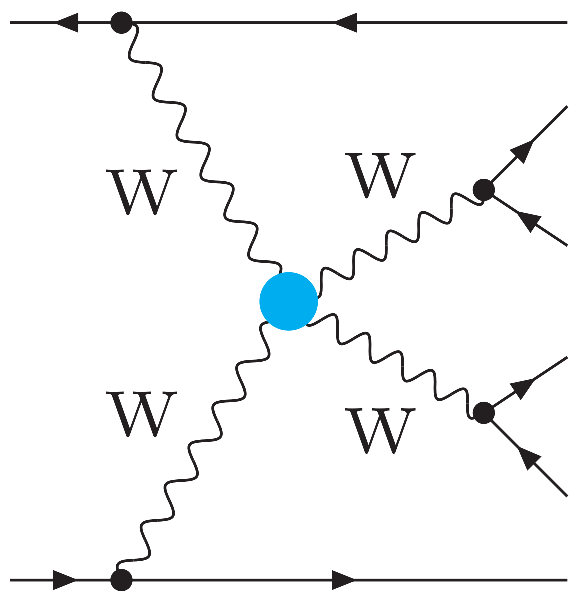
"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

VV+2jets production

Note: severe QCD background to VBS signatures + interference:



vs.



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

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

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

➡ separation formally meaningless at NLO

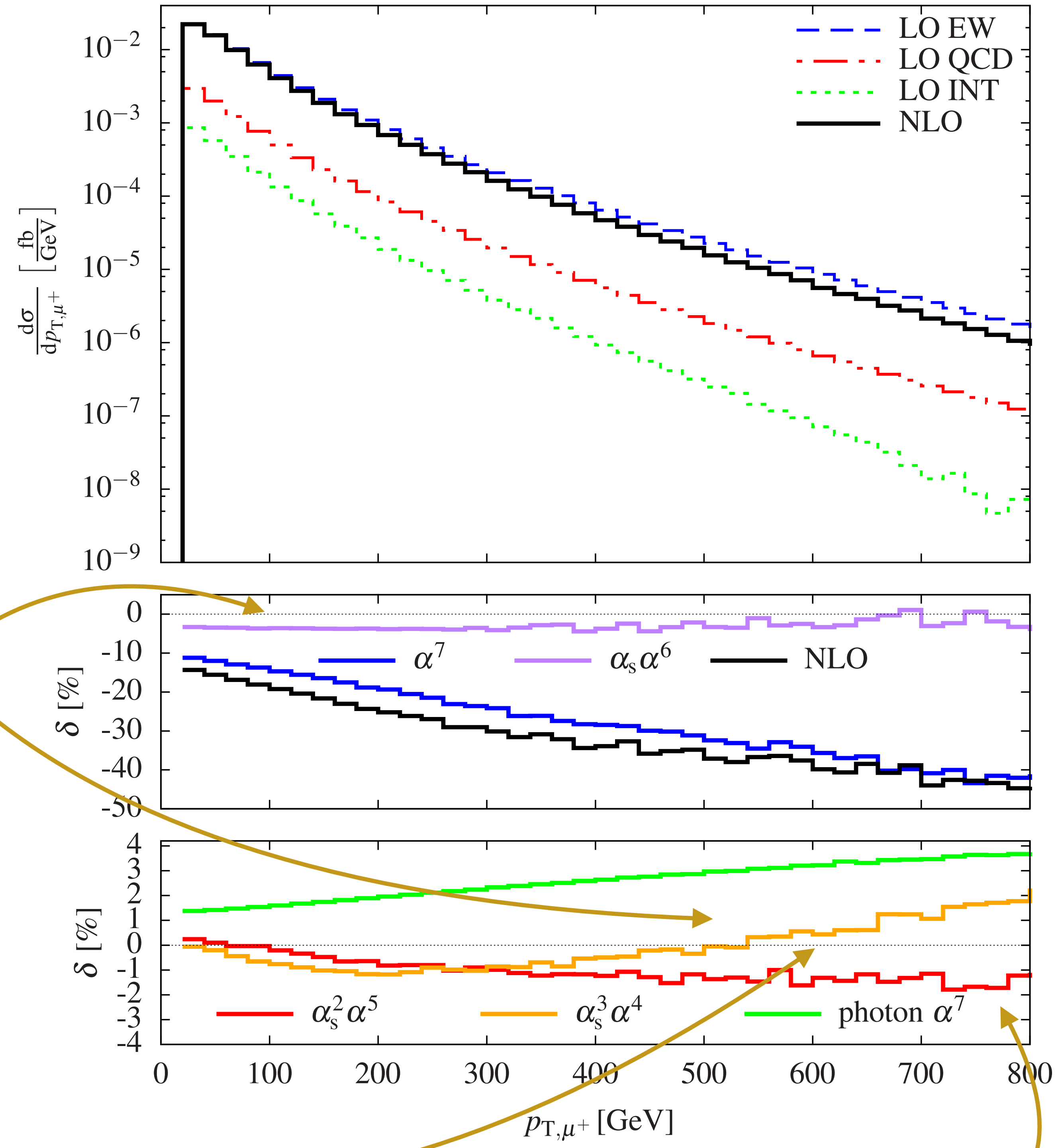
➡ always also consider measurements: fiducial cross sections without QCD subtraction

VBS-W⁺W⁺ @ full NLO

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

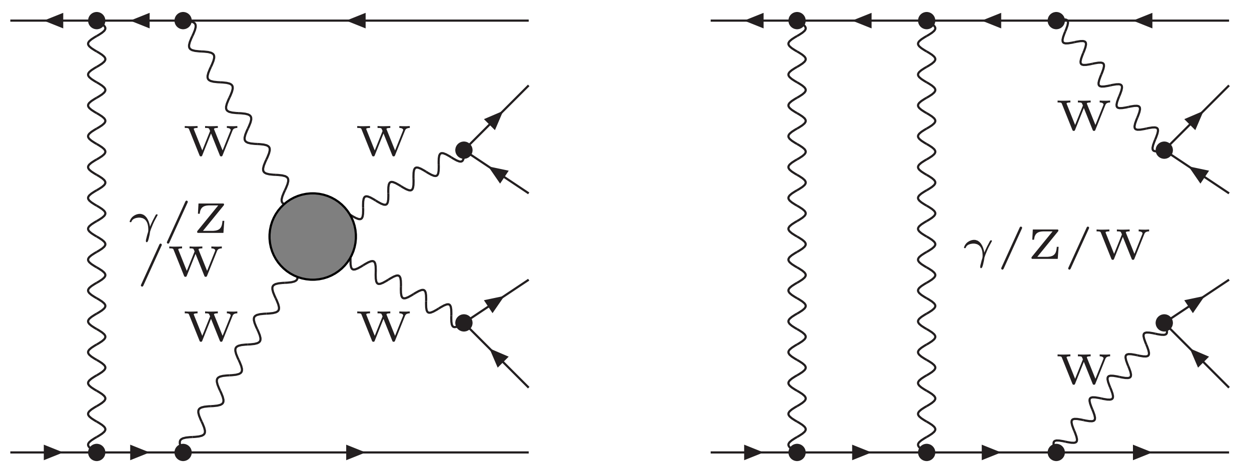
"NLO QCD" to EW mode

"NLO EW" to EW mode



"NLO QCD" to QCD mode

"NLO EW" to QCD mode



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

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)

Conclusions

- Precision is key for EW measurements, as well as for searches.
- Global EFT/SMEFT allows to constrain BSM at higher scales
- EW corrections become large at the TeV scale
- Fixed-order NLO EW largely automated
- NLOPS including EW corrections available for dedicated processes and in different approximations
- Higher-order EW and mixed QCD-EW uncertainties are becoming relevant.

Questions?

References

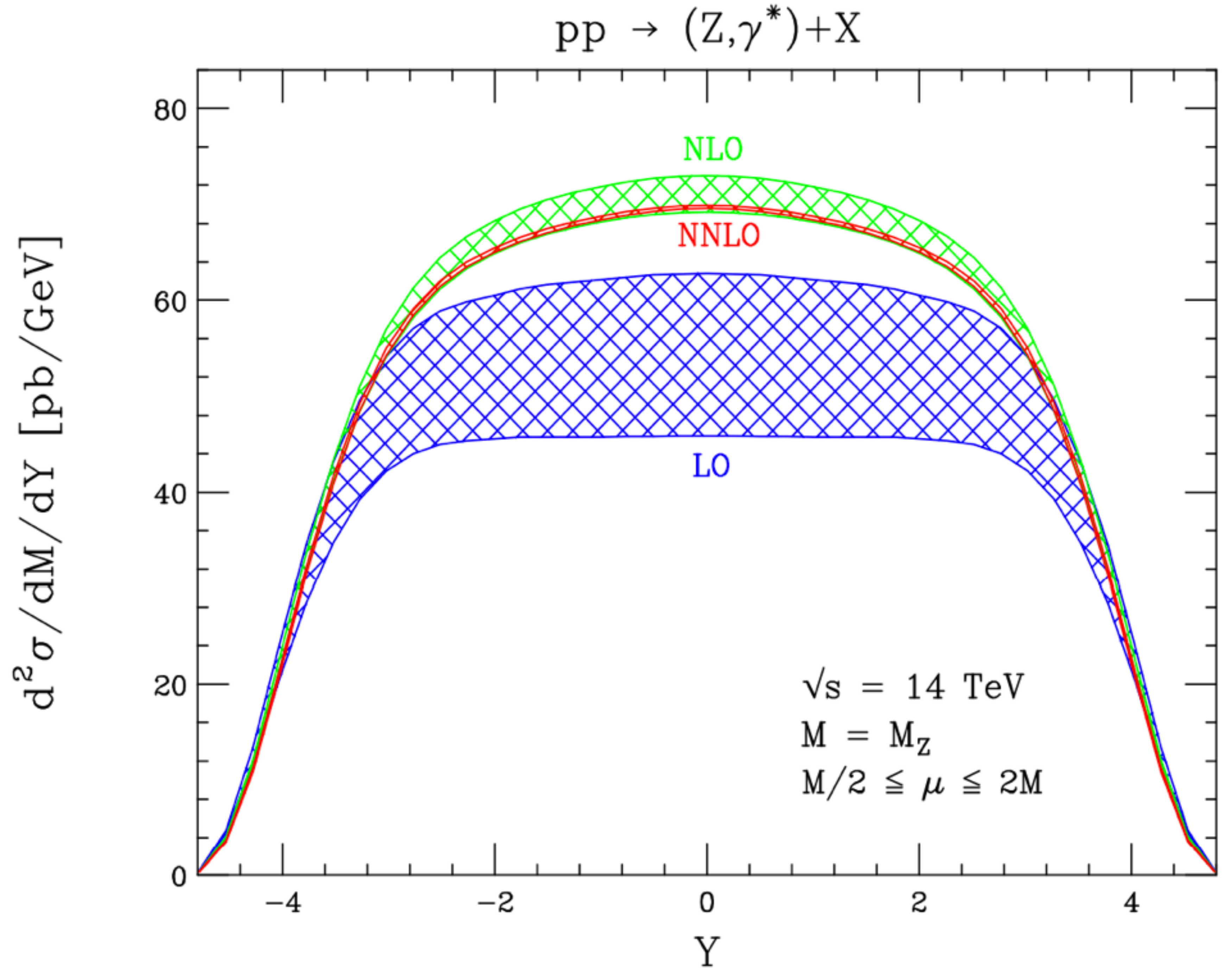
These Lectures are partly based on:

- Stefan Weinzierl, DESY Monte Carlo school, 2012
- Ansgar Denner, DESY Monte Carlo school, 2014
- Andreas van Hameren, DESY Monte Carlo school, 2017
- Giulia Zanderighi, Graduate Course on QCD, 2013
- Rikkert Frederix, MCnet Summer School, 2015
- Gavin Salam, Basics of QCD, ICTP–SAIFR school on QCD and LHC physics, 2015
- Marek Schönherr, CTEQ-MCnet School, 2021

Backup

Convergence of the perturbative expansion: Drell-Yan

[Anastasiou et al.,2003]

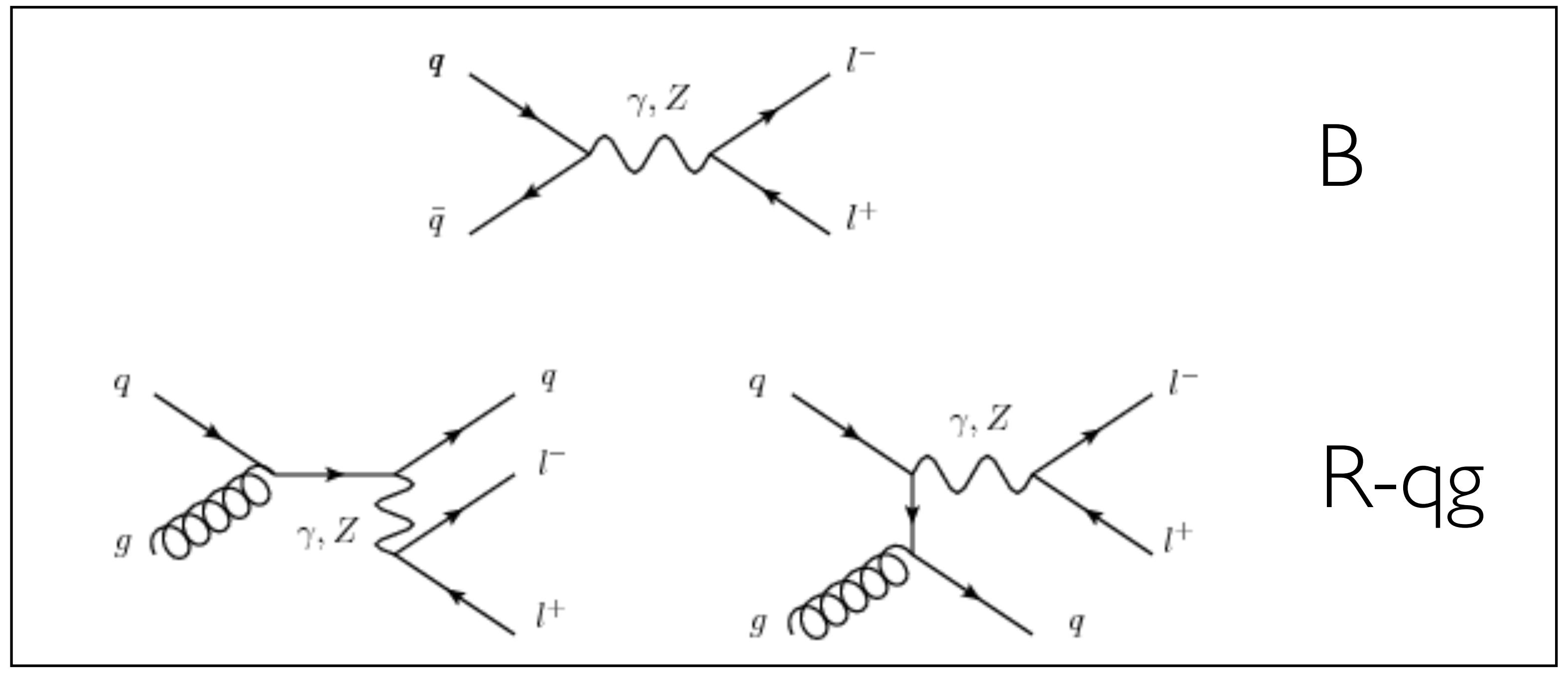


- NNLO calculation first performed for the inclusive cross section *[Van Neerven et al., 1990]*
  → NNLO/NLO at the few percent level
- Rapidity distribution: 13 years later!
- Bands obtained by studying scale variations varied in $\mu=[m_Z/2,2m_Z]$
- LO and NLO bands do not overlap!
  ➡Error estimate at LO largely underestimated!
- large contribution coming from qg channel that opens up at NLO
- NLO and NNLO bands do overlap
  ➡Reliable error estimate only when all partonic channels contribute

➡Higher-orders are crucial for reliable predictions

➡Use these precision predictions to

- stress-test the SM: QCD and EW
- determine parameters and PDFs!



LO Ingredients

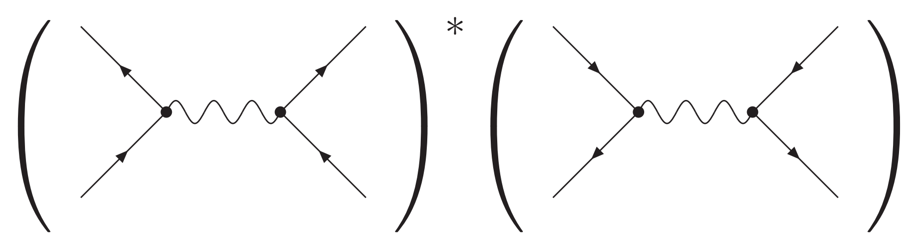
- LO partonic cross section for a 2→n process can be written as

$$\mathrm{d}\hat{\sigma}_{\mathrm{LO}} = \frac{1}{2s}\int \mathrm{d}\Phi_n |\mathcal{M}_{\mathrm{LO}}|^2$$

$$\int \mathrm{d}\Phi_n = (2\pi)^4 \delta^{(4)}\left(P - \sum_{i=1}^{n} q_i\right) \prod_{i=1}^{n} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}$$ n-particle phase-space

$\mathcal{M}_{\mathrm{LO}}$ LO matrix element: tree-level

$|\mathcal{M}_{\mathrm{LO}}|^2$



$s = P^2 = (\hat{p}_1 + \hat{p}_2)^2$ squared centre-of-mass energy of hard process

- Integration over phase space by Monte Carlo methods
  - ➡ any distribution/histogram can be determined simultaneously
  - ➡ Monte Carlo events can be unweighted
- Integration over phase space analytically
  - ➡ very fast evaluation
  - ➡ analytical structure of the result can be investigated

Perturbative expansion

- Expansion in a small coupling **α**:

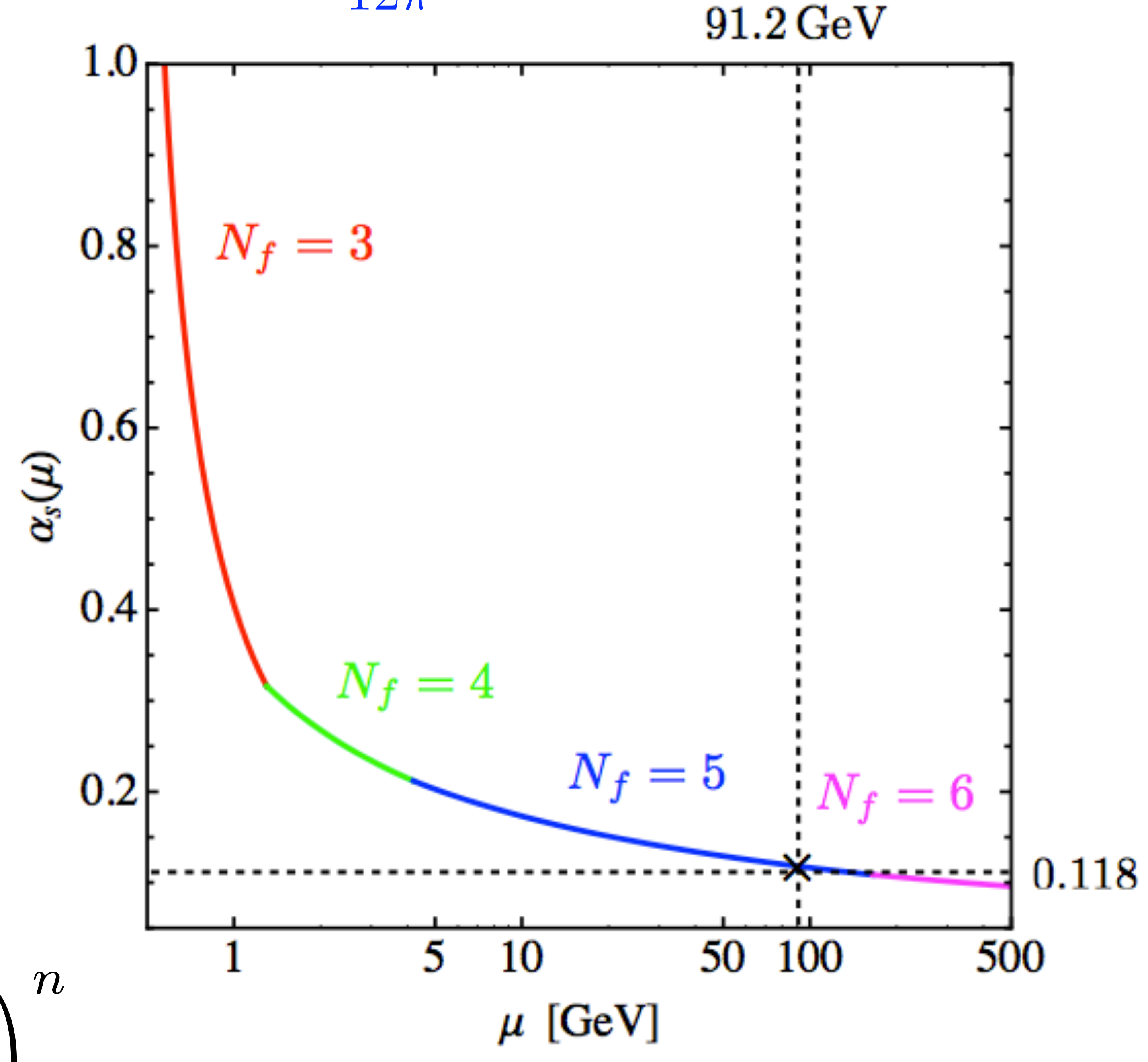
$$d\sigma = d\sigma(\alpha^n) + d\sigma(\alpha^{n+1}) + d\sigma(\alpha^{n+2}) + d\sigma(\alpha^{n+3}) + \ldots$$

LO NLO NNLO N3LO

- at the LHC consider in particular **α** = **α**S (QCD coupling), but also **α** = **α**EW (EW coupling) relevant → later!

- In QCD running strong coupling: $\alpha_S = \alpha_S(\mu) = \frac{1}{b_0 \ln \frac{\mu^2}{\Lambda^2}} + \ldots$

$$b_0 = \frac{11 N_c - 4 n_f T_R}{12\pi}$$



$$d\sigma^{\mathrm{LO}}(\mu) = \alpha_S(\mu)^n A^{\mathrm{LO}}$$

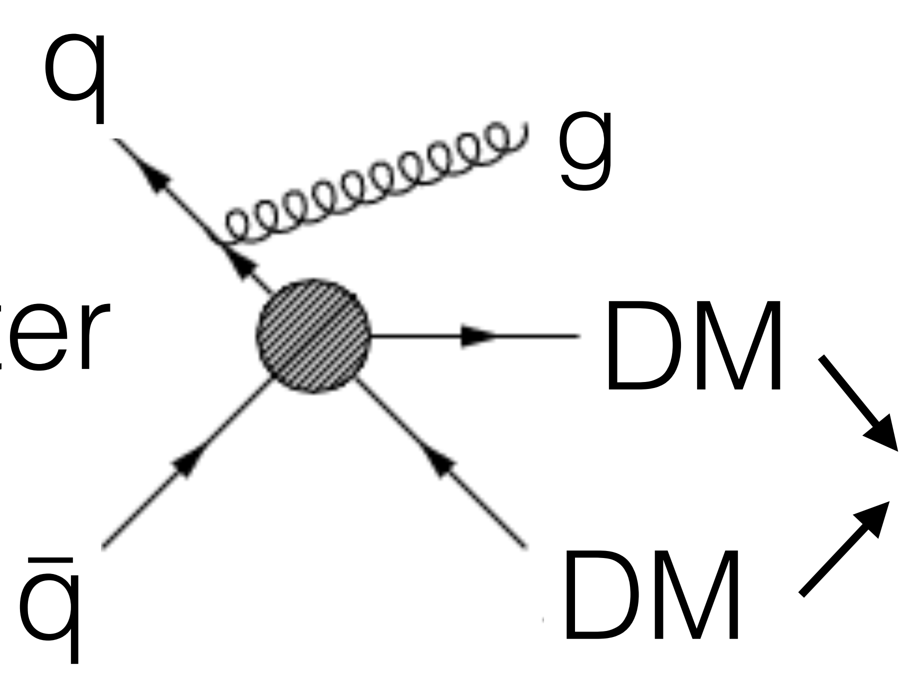
$$\to d\sigma^{\mathrm{LO}}(\mu') = \alpha_S(\mu')^n A^{\mathrm{LO}} = \alpha_S(\mu)^n \left(1 + n b_0 \alpha_S(\mu) \ln \frac{\mu^2}{\mu'^2} + \ldots\right) A^{\mathrm{LO}}$$

- So the change of scale is an NLO effect (∝**α**S).

- At LO the normalisation is not under control: $\frac{d\sigma^{\mathrm{LO}}(\mu)}{d\sigma^{\mathrm{LO}}(\mu')} = \left(\frac{\alpha_S(\mu)}{\alpha_S(\mu')}\right)^n$

Precision for tails of kinematic distributions: direct searches for new physics

e.g.
Dark Matter



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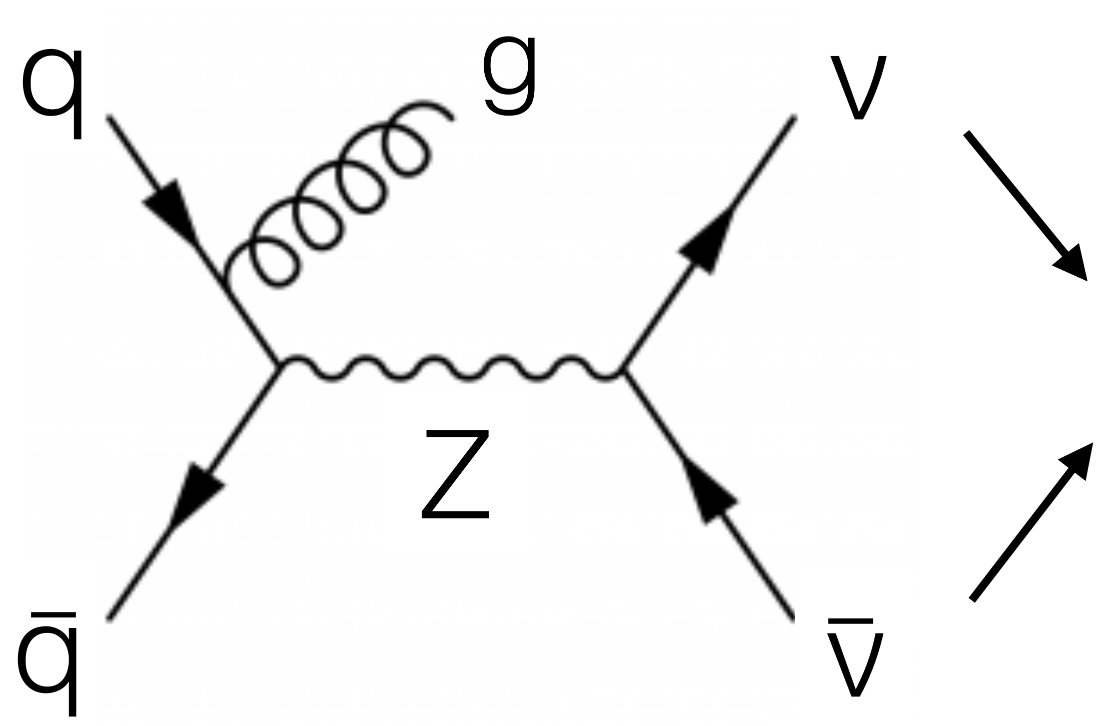
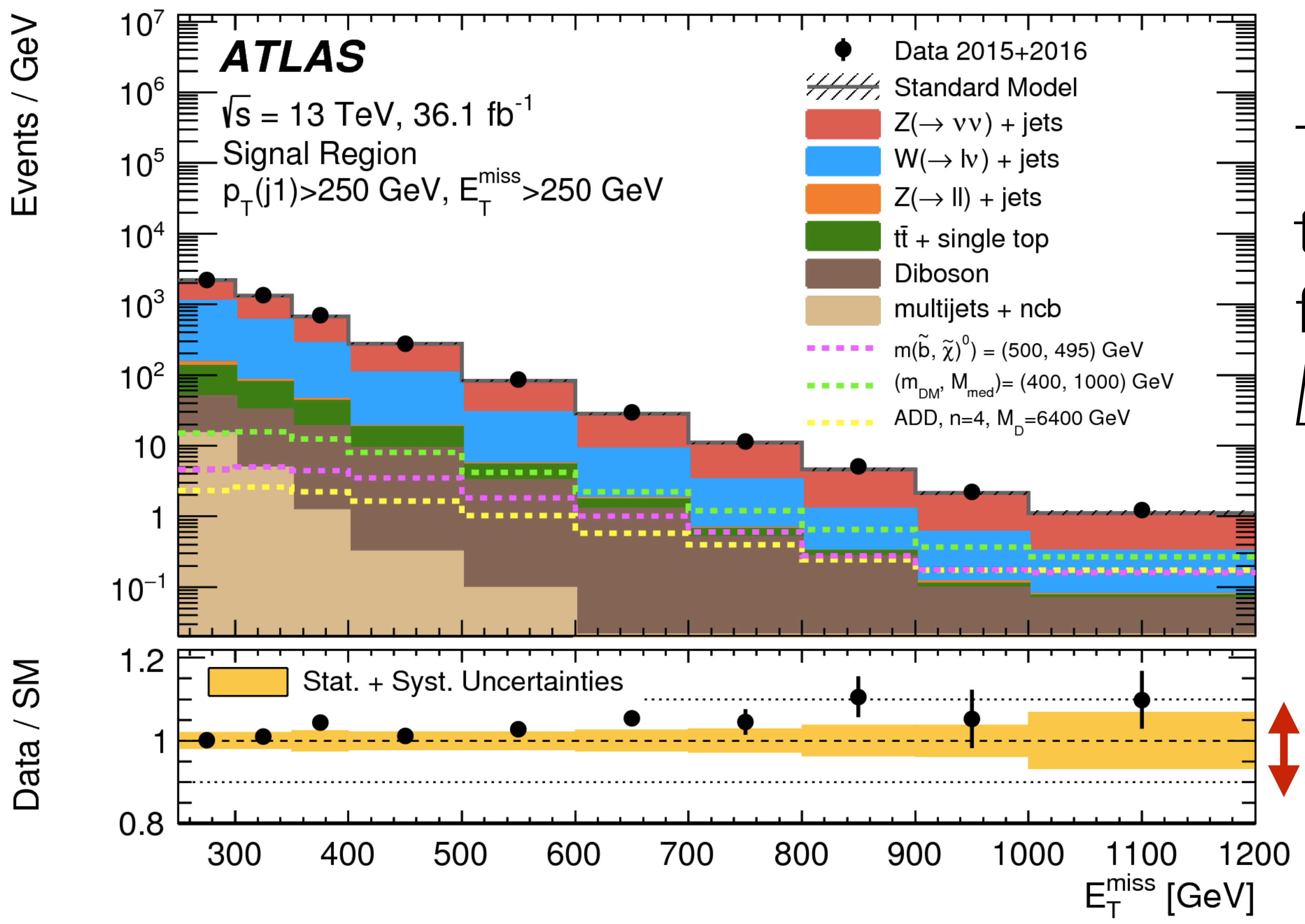
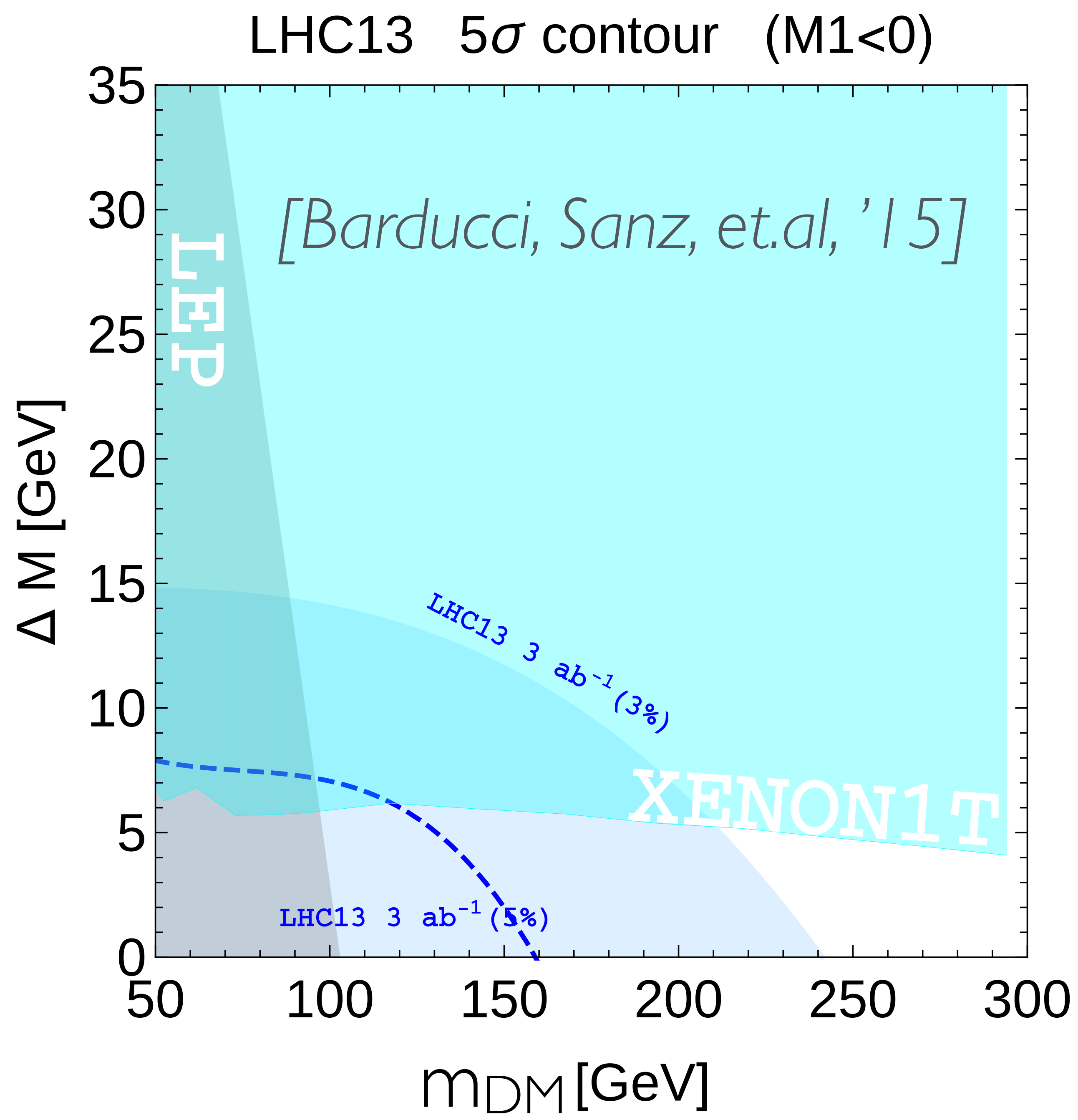




Thanks to state-of-the-art theory predictions+uncertainties for SM backgrounds *[JML, et.al., '17]*

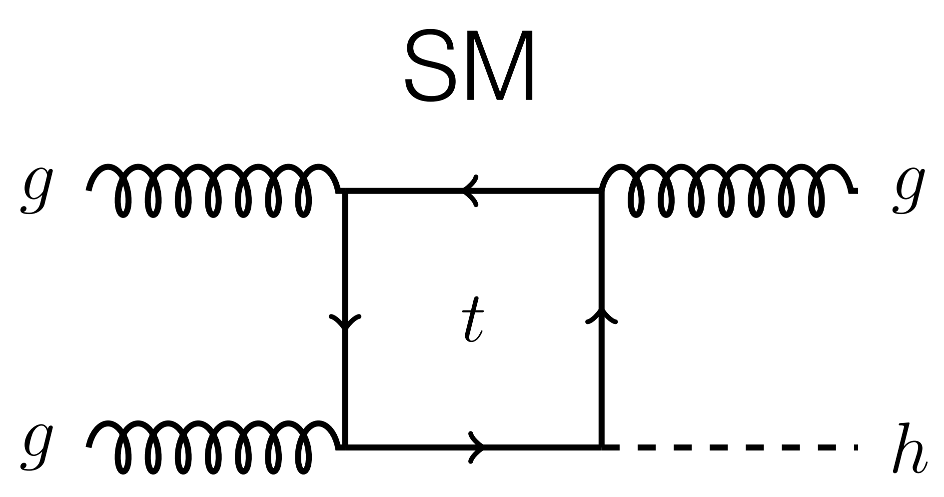
↕few percent!



→Theory precision is key to harness full potential of LHC data!

Precision for tails of kinematic distributions: indirect searches for new physics

e.g.



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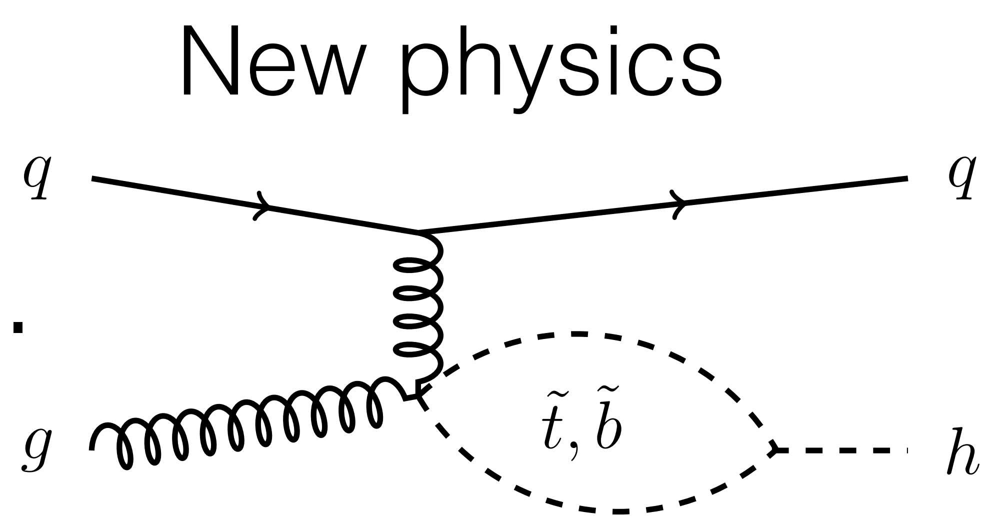
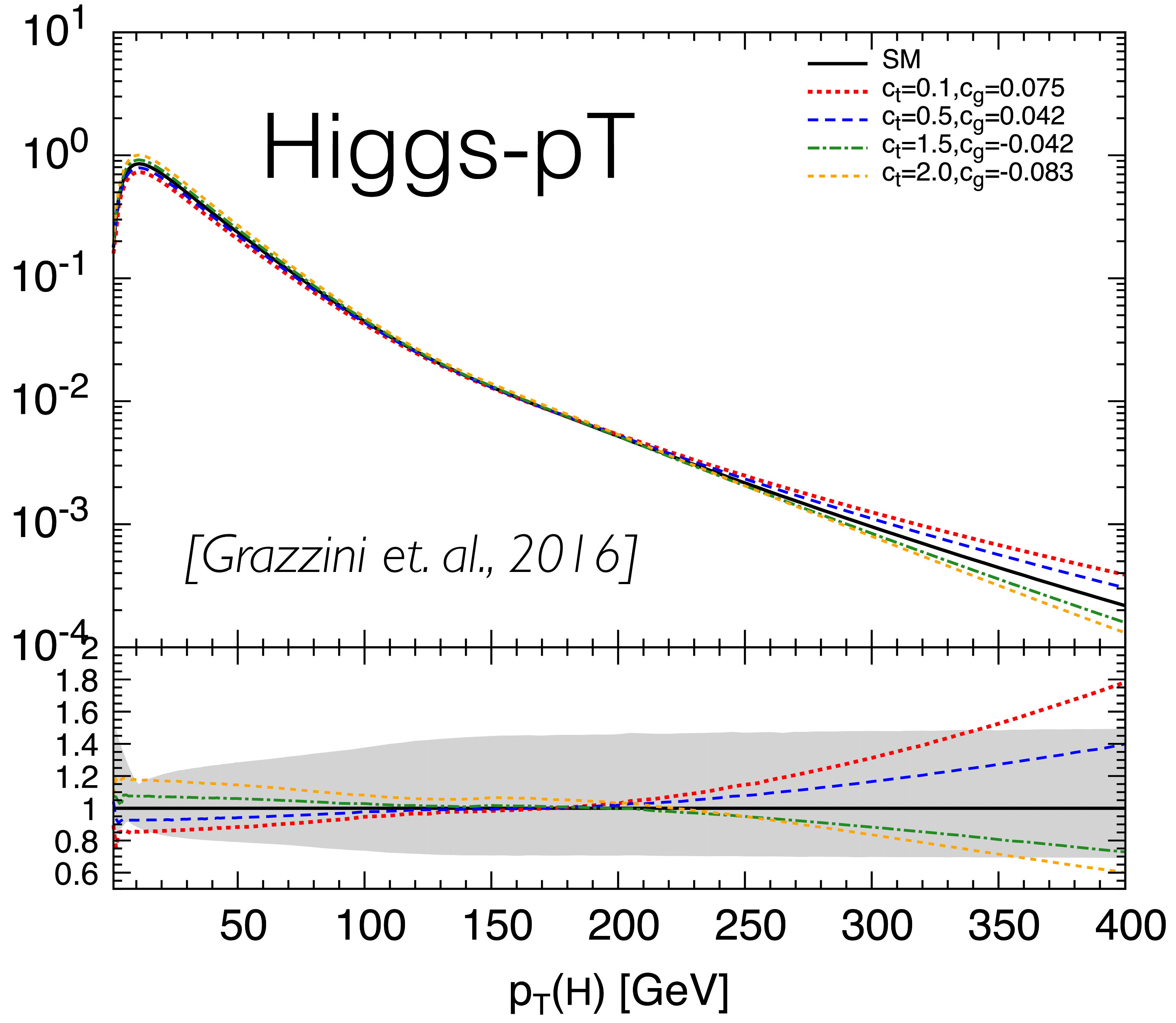


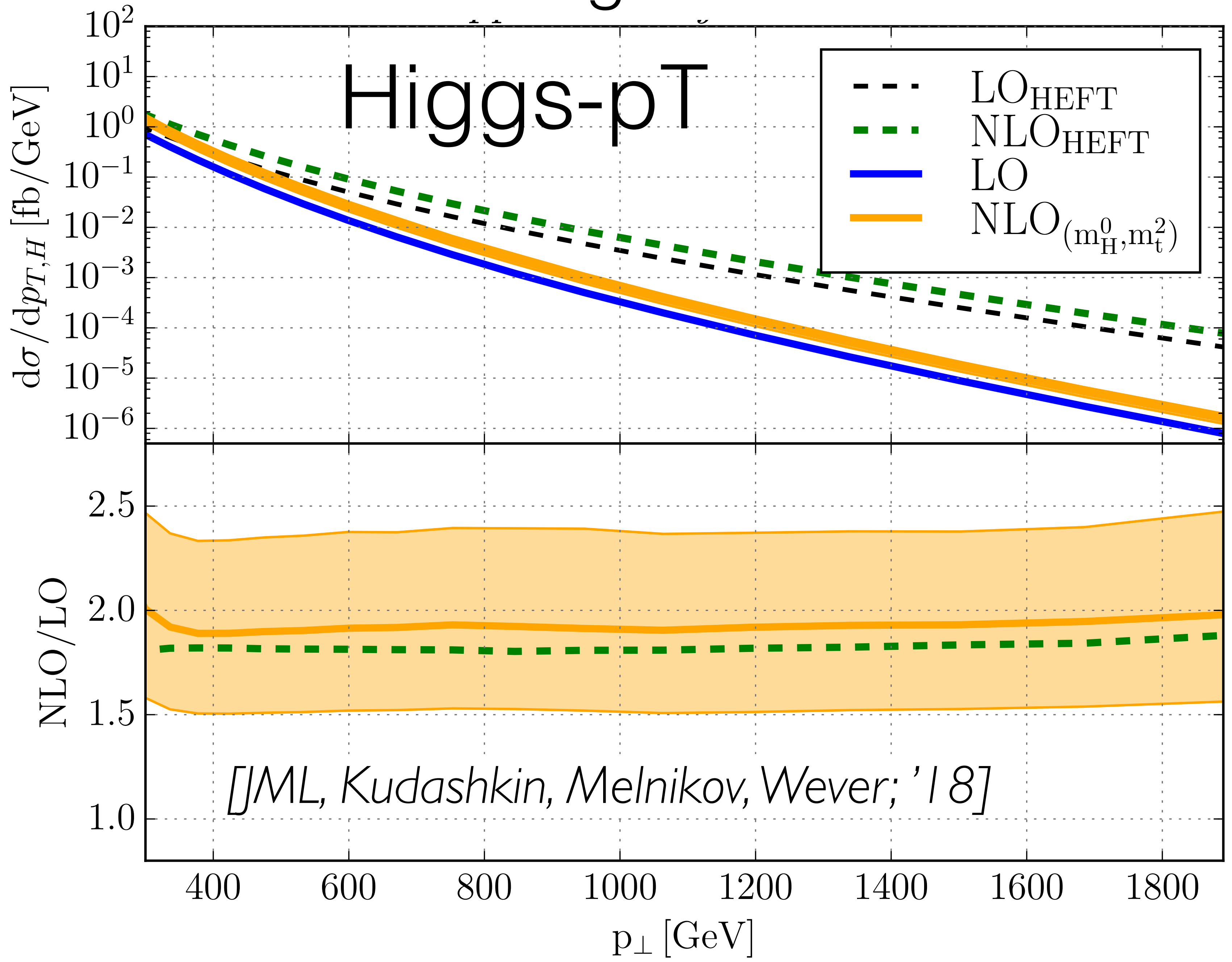
Look for BSM effects in small deviations from SM predictions:

→ Higgs processes natural place to look at

→ **very good control on theory necessary!**

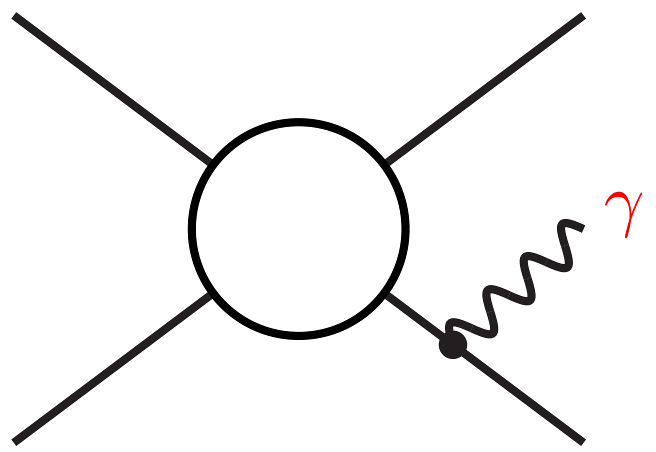


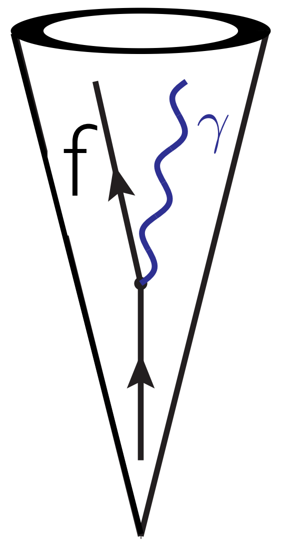
next-to-leading order corrections



→Theory precision opens the door to new analysis strategies!

QED radiation: IR safety



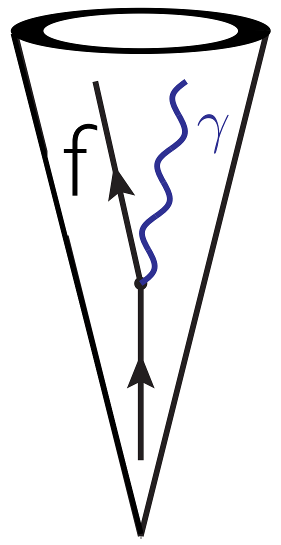


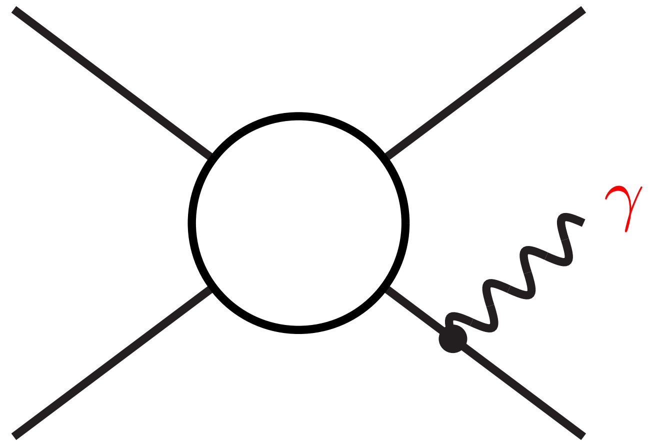
- **collinear f → fγ singularities**
  - cancelled clustering f and γ, within cone of $\Delta R_{f\gamma}$, typically $\Delta R_{f\gamma} = 0.1$
  - or regularised via fermion masses (at LHC only relevant for $f = \mu$)

- However: for processes with jets at LO this spoils universality between quarks and gluons!

  → problematic for QCD IR safety

QED radiation: IR safety





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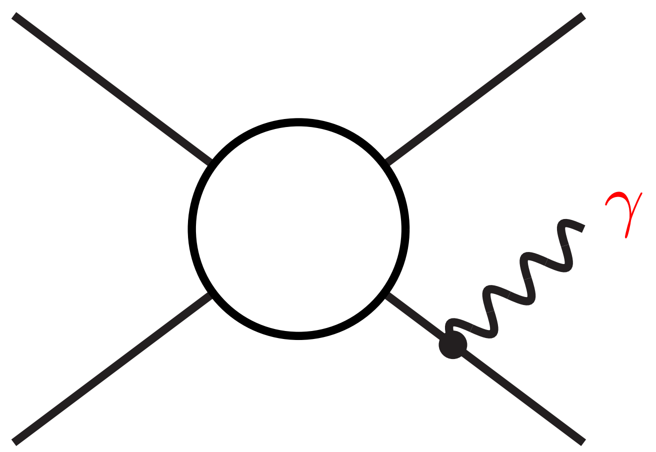
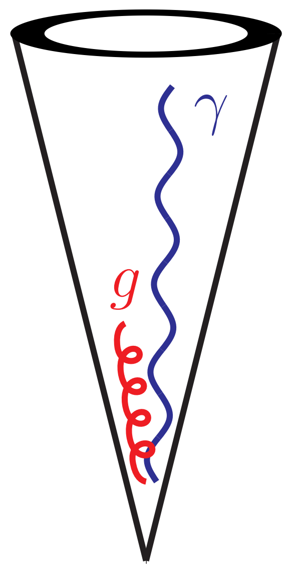
- Solution: *democratic jet-algorithm approach*, partonic jets ≡ {q, g, γ, l)

QED radiation: IR safety



- Solution: *democratic jet-algorithm approach*, partonic jets ≡ {q, g, γ, l)



However: this yields **soft gluon singularities** ↔ hard photons inside jets

cancelled in jet-production at NLO EW
combined with γ-production at NLO QCD

- Solution: *democratic parton approach* p ≡ {q, g, γ, l) already at the level of the process definition

- E.g.: $pp \to V + \text{jets}$ @ NLO EW

$$\left.\begin{array}{ll} pp \to V + j & \text{@ NLO EW} \\ pp \to V + \gamma & \text{@ NLO QCD} \end{array}\right\} \mathcal{O}(\alpha^2 \alpha_S)$$

QED radiation: IR safety

- Solution: democratic *parton approach* p ≡ {q, g, γ, l) already at the level of the process definition.
- In this democratic approach a single isolated photon or lepton constitutes a jet.
  I.e. this essentially means: one multi-jet merged $pp \to \mathrm{n\,jets}$ sample for all SM processes.
- Problems:
  1. How can we now define physical objects that are not jets? I.e leptons and photons.
  2. Huge number of processes would have to be generated together. computationally not feasible.

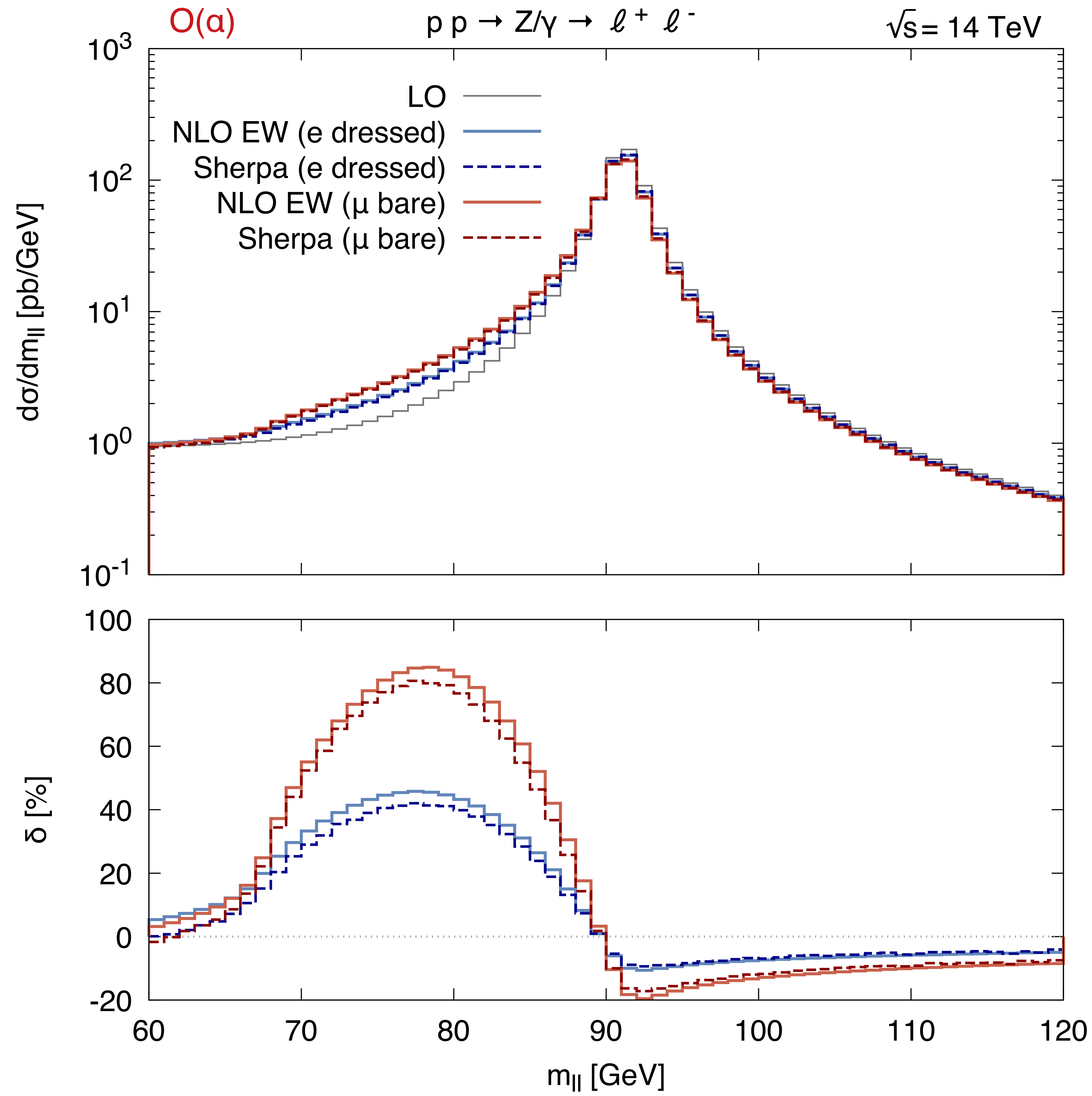
- Separation of jets from photons through $E_\gamma/E_{jet} < z_{thr}$ inside jets (same for leptons)
  - *rigorous approach*: fragmentation functions
  - *approximation*: qγ recombination in small cone

difference < 1% for typical z_{thr}~0.5 (analysis dependent)

QED parton showers: YFS

- The Sherpa module PHOTONS implements the YFS approach for higher-order QED corrections

- YFS:
  ➡ allows to **resum** universal leading soft logarithms to all orders.
  ➡ can systematically be **improved** order-by-order through the inclusion of full fixed-order matrix elements, e.g. for $V \rightarrow l^+l^-$
  ➡ available within any high-precision QCD simulation in Sherpa: MEPS@NLO, UN²LOPS → Allows to study $O(\alpha\alpha_S)$ effects.



[M. Schönherr, A. Huss in LH'15]

Resonance aware POWHEG

Rigorous solution to all these issues within POWHEG-BOX-RES *[Ježo, Nason; '15]*

Idea: ***preserve invariant mass of intermediate resonances at all stages!***

✓ **NLO**:

- Split phase-space integration into regions dominated by a single **resonance history**
- within a given resonance history **modify FKS mappings**, such that they *always* preserve intermediate resonances

$$(\Phi_B, \Phi_{rad}) \overset{\text{RES}}{\longleftrightarrow} \Phi_R^{(\alpha)}$$

  ⟹ R and S~B *always* with same virtuality of intermediate resonances

  ⟹ IR cancellation restored

✓ **NLO+PS**:

- R and B related via modified FKS mappings

  ⟹ R/B ratio with fixed virtuality of intermediate resonances

  ⟹ Sudakov form-factor preserves intermediate resonances

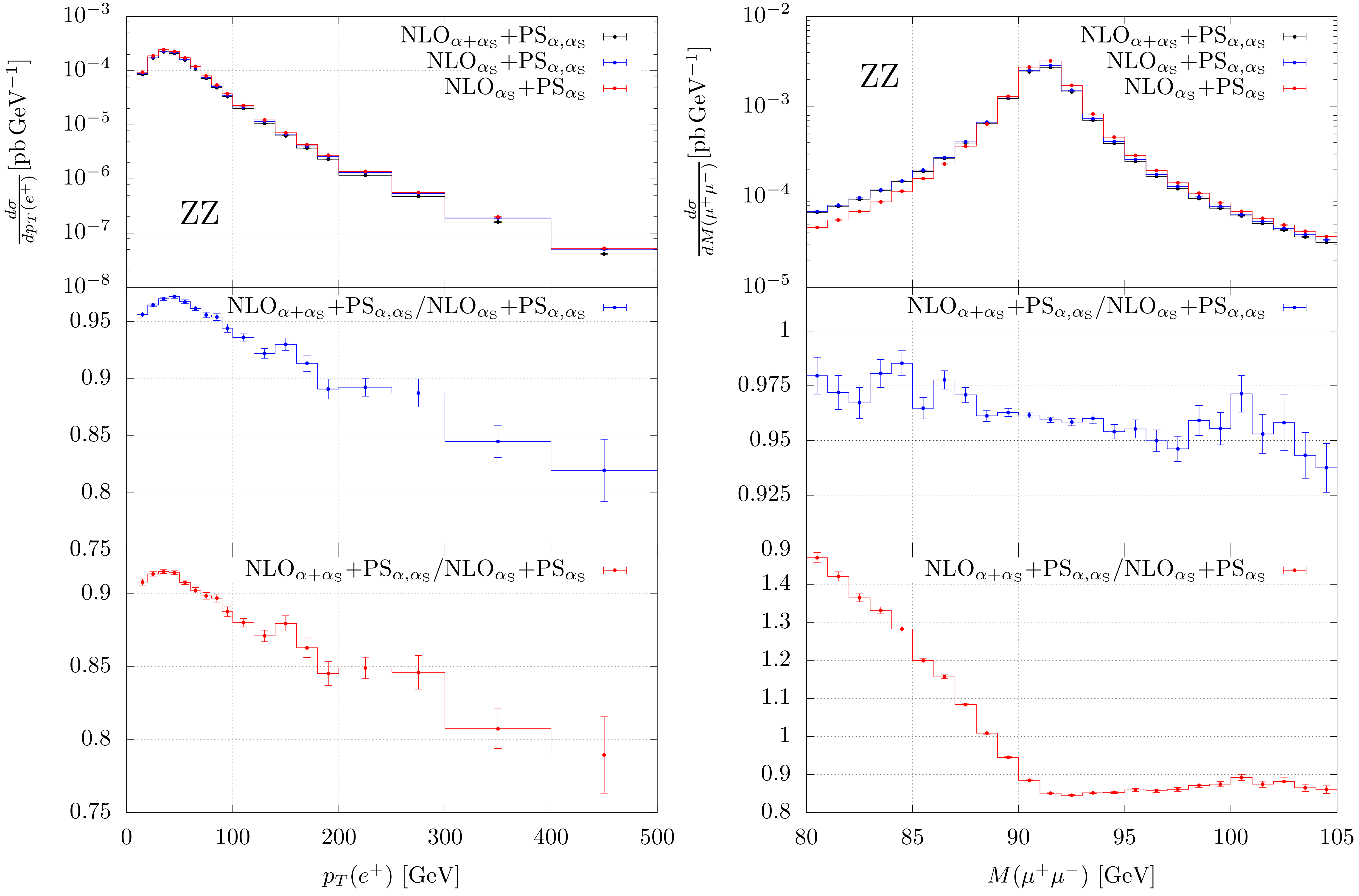
✓ **PS**:

- pass information about resonance histories to the shower (via extension of LHE)
- tell PS to respect intermediate resonances (available in Pythia8)

⟹ resulting resonance-aware MC indispensable for precision top-mass measurements

Resonance-aware PS matching @ NLO QCD + NLO EW

[Chiesa, Re, Oleari '20]



NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS (QCD + QED)

NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS QCD

- Missing: photon-induced channels