Field Theory & the EW Standard Model
Part III: EW tests and phenomenology

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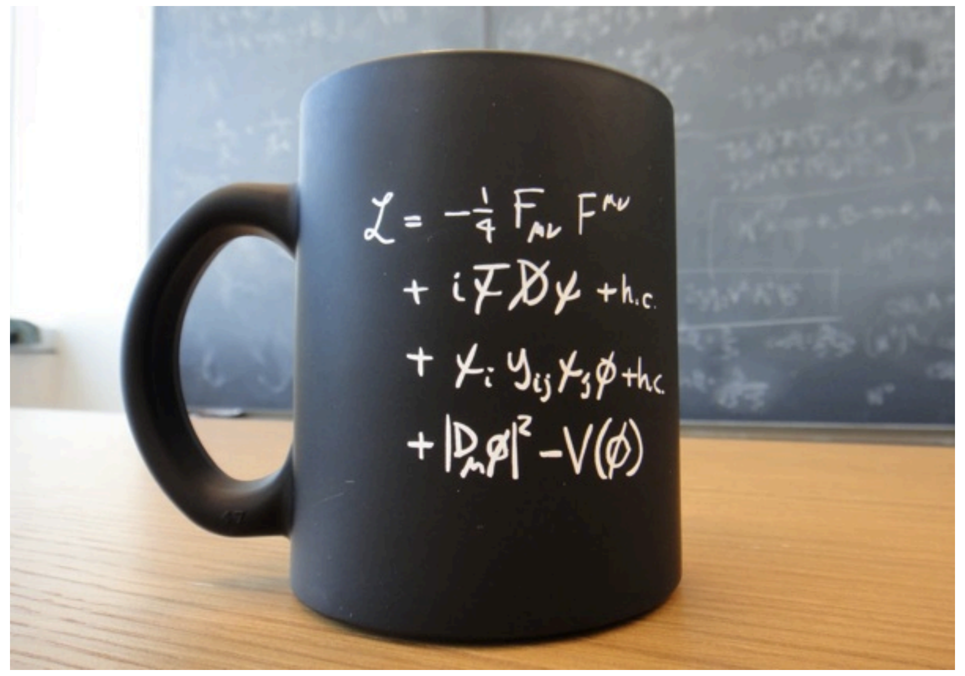

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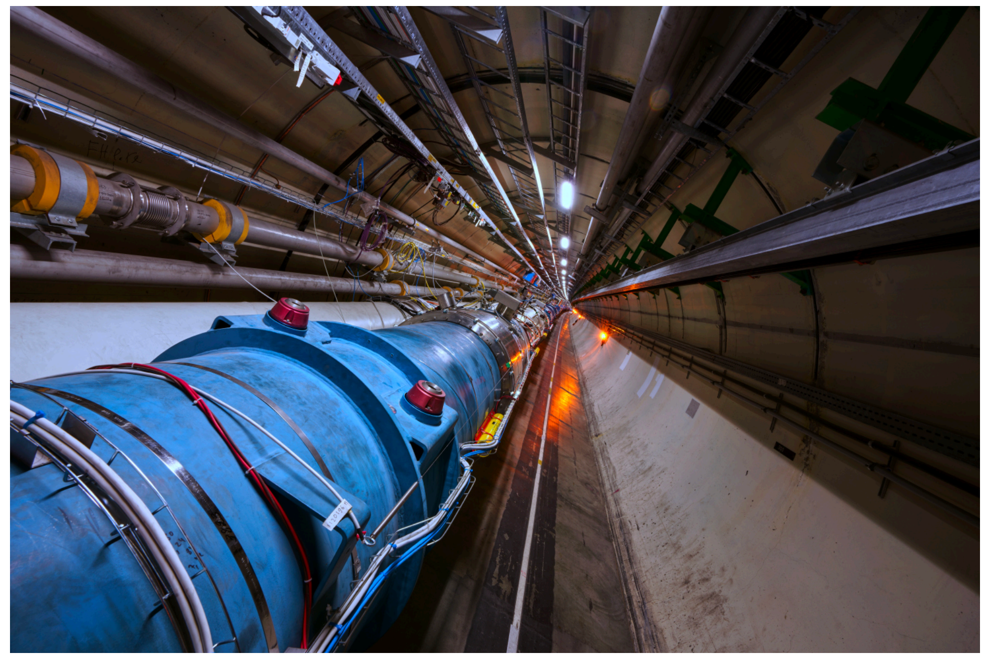


EW precision observables

The EW SM

Global EW/EFT fit

EW radiative corrections

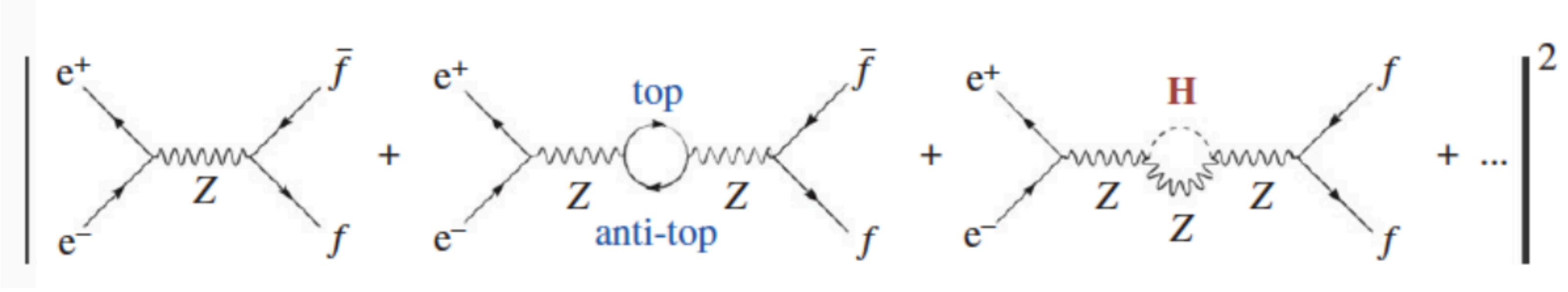
➡Study dynamics of the EW SM at the TeV scale

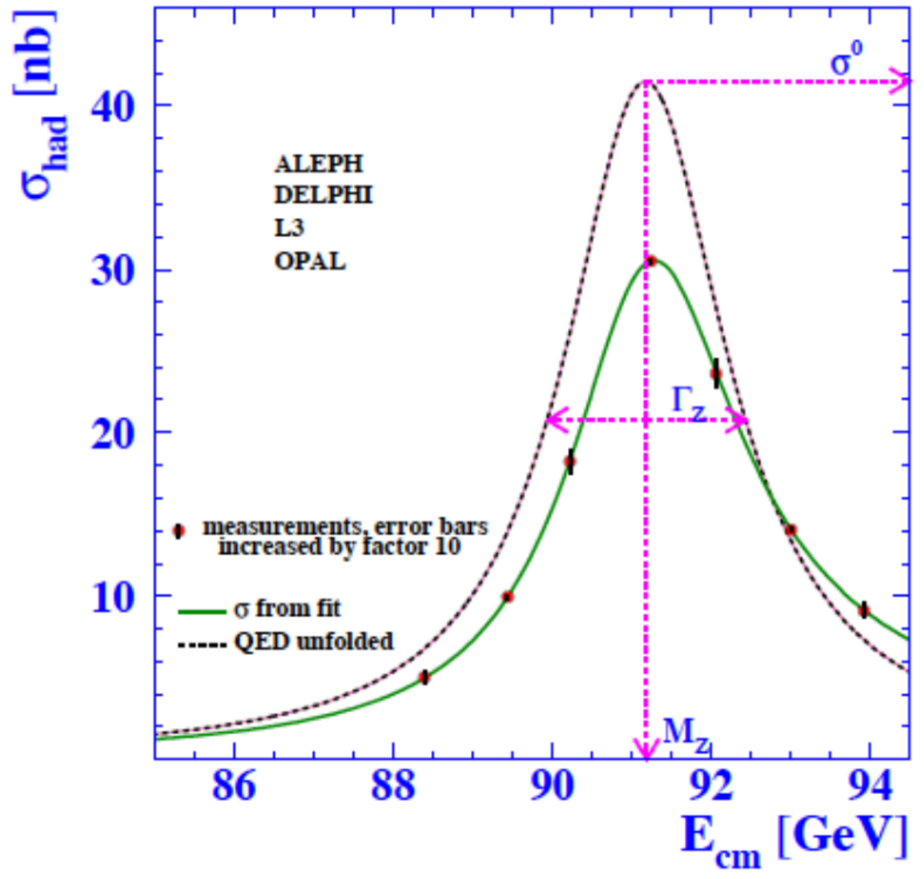
➡Test BSM via indirect EW probes

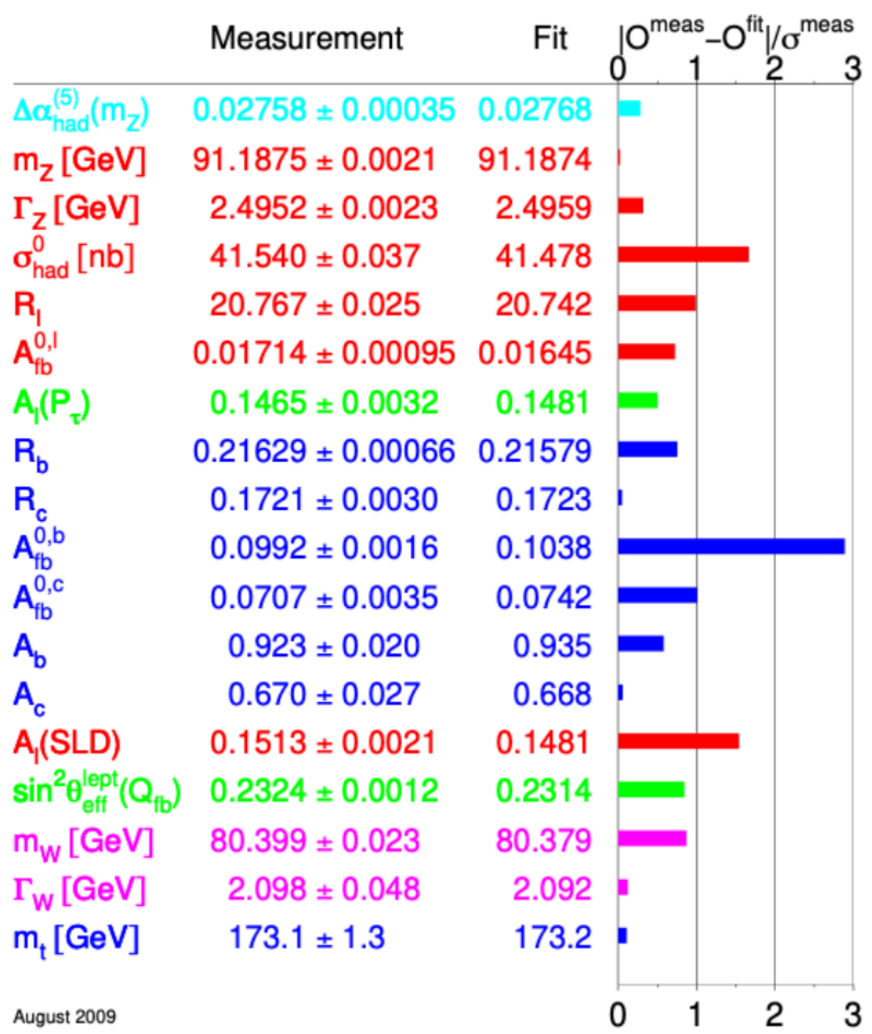
➡Constrain backgrounds in direct searches for New Physics

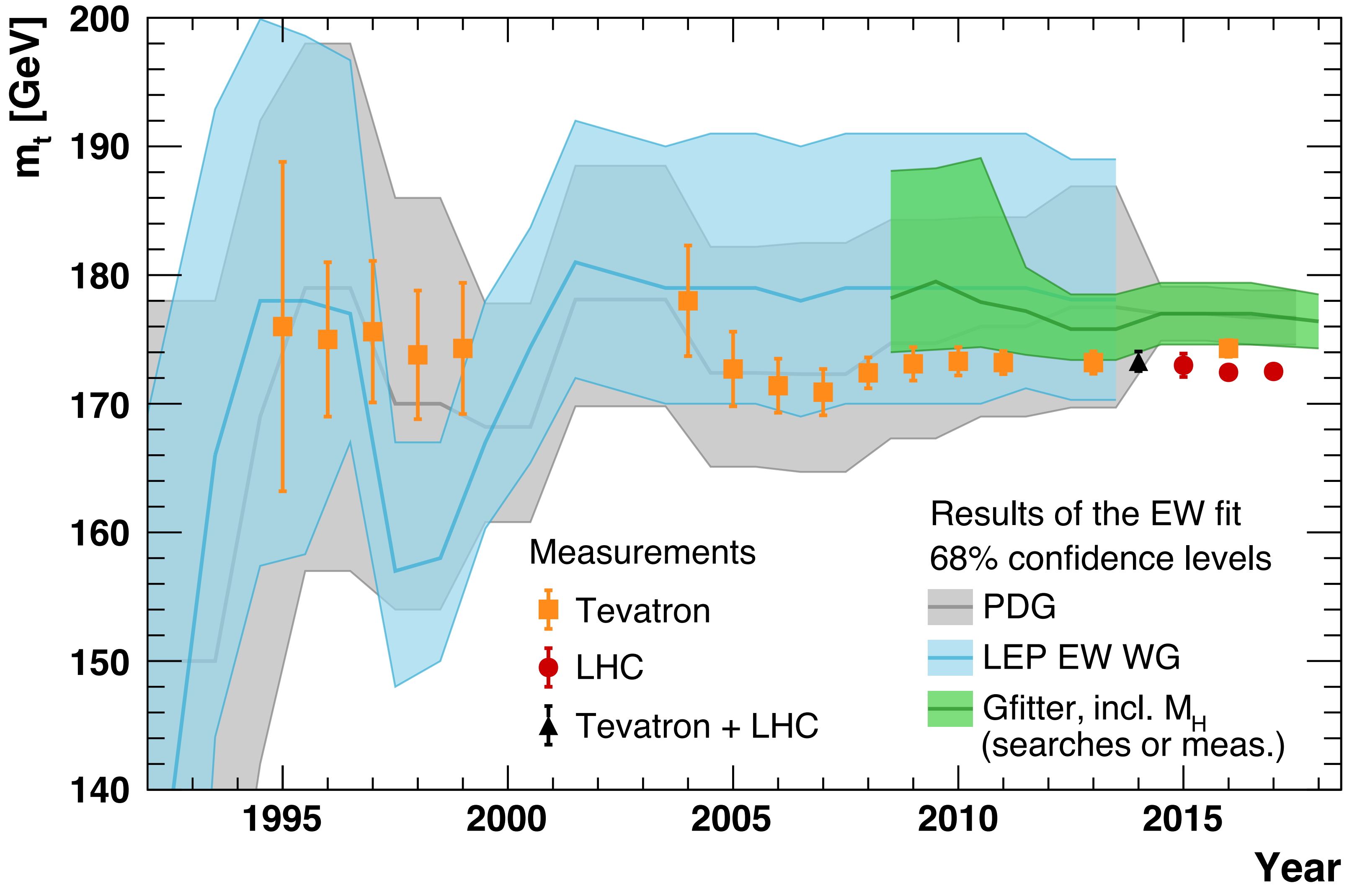
Classical tests I of EW theory @ LEP

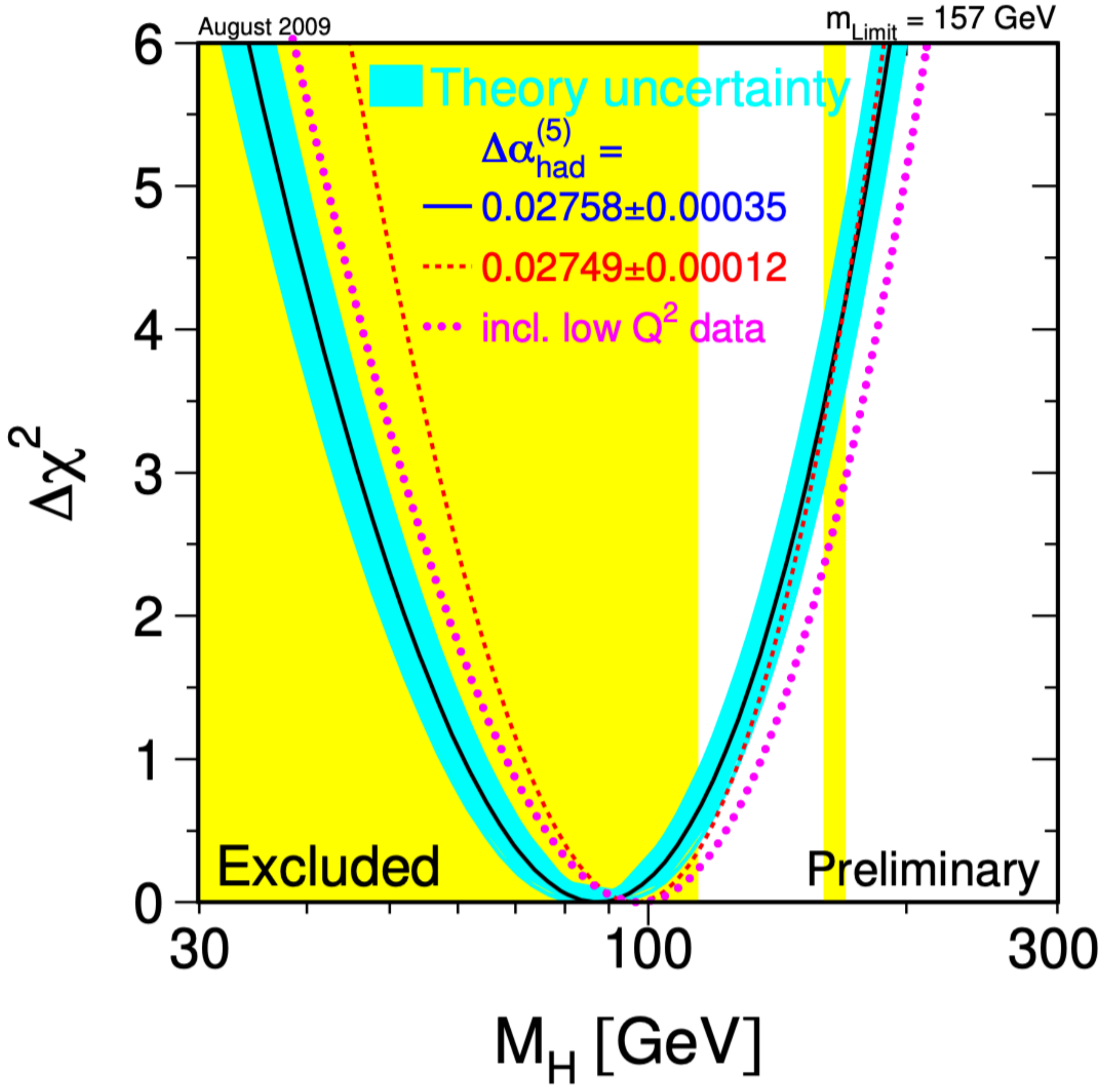
- Correlation between different EW parameters (at higher-order)
  - $m_W = \frac{1}{2} g_2 v$
  - $\sin\theta_W = m_W / m_Z$
  - Z-pole observables →







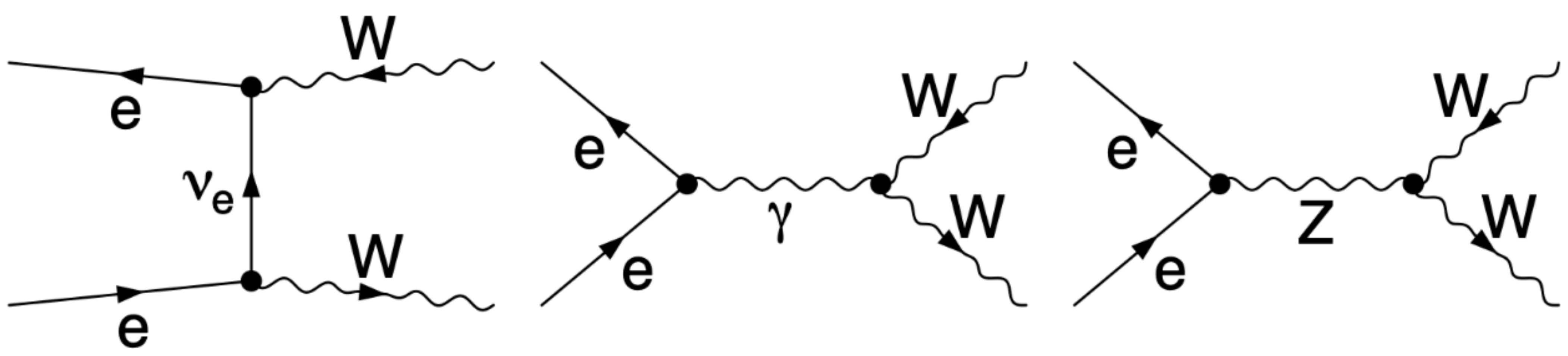


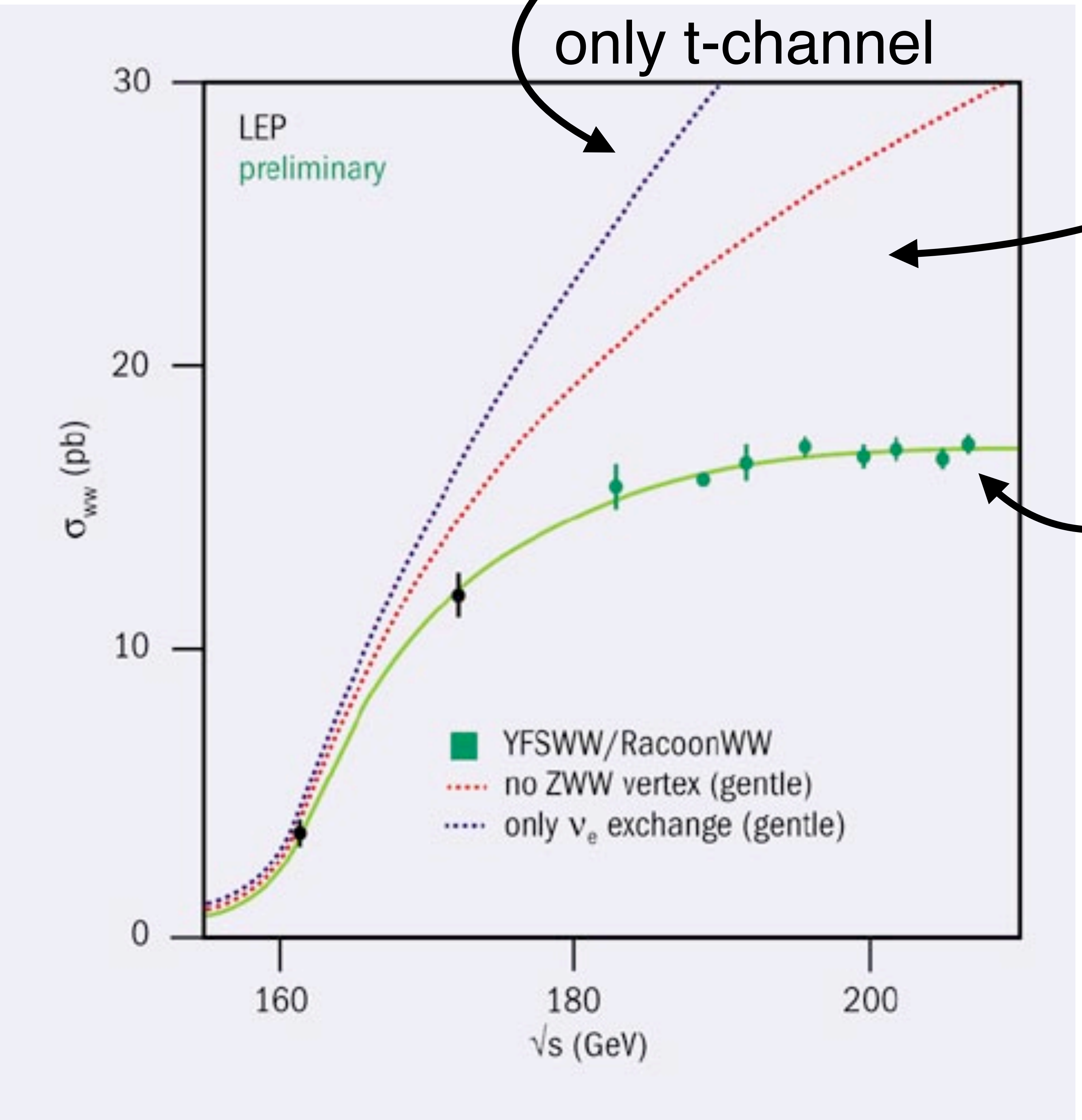


→ **EW precision observables**

Classical tests II of EW theory @ LEP

$$e^+e^- \to W^+W^-$$





no ZWW vertex

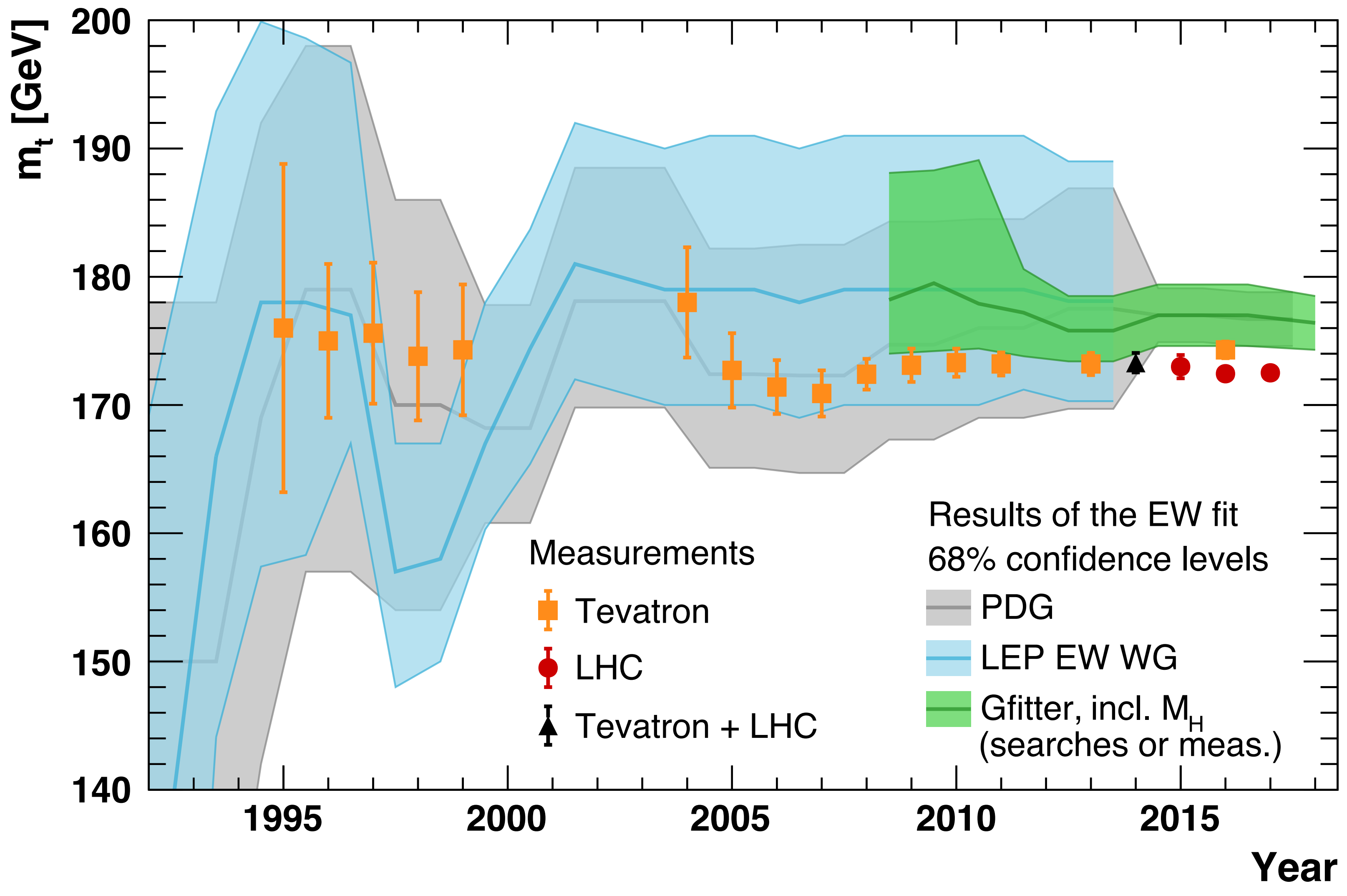
SM @ NLO EW

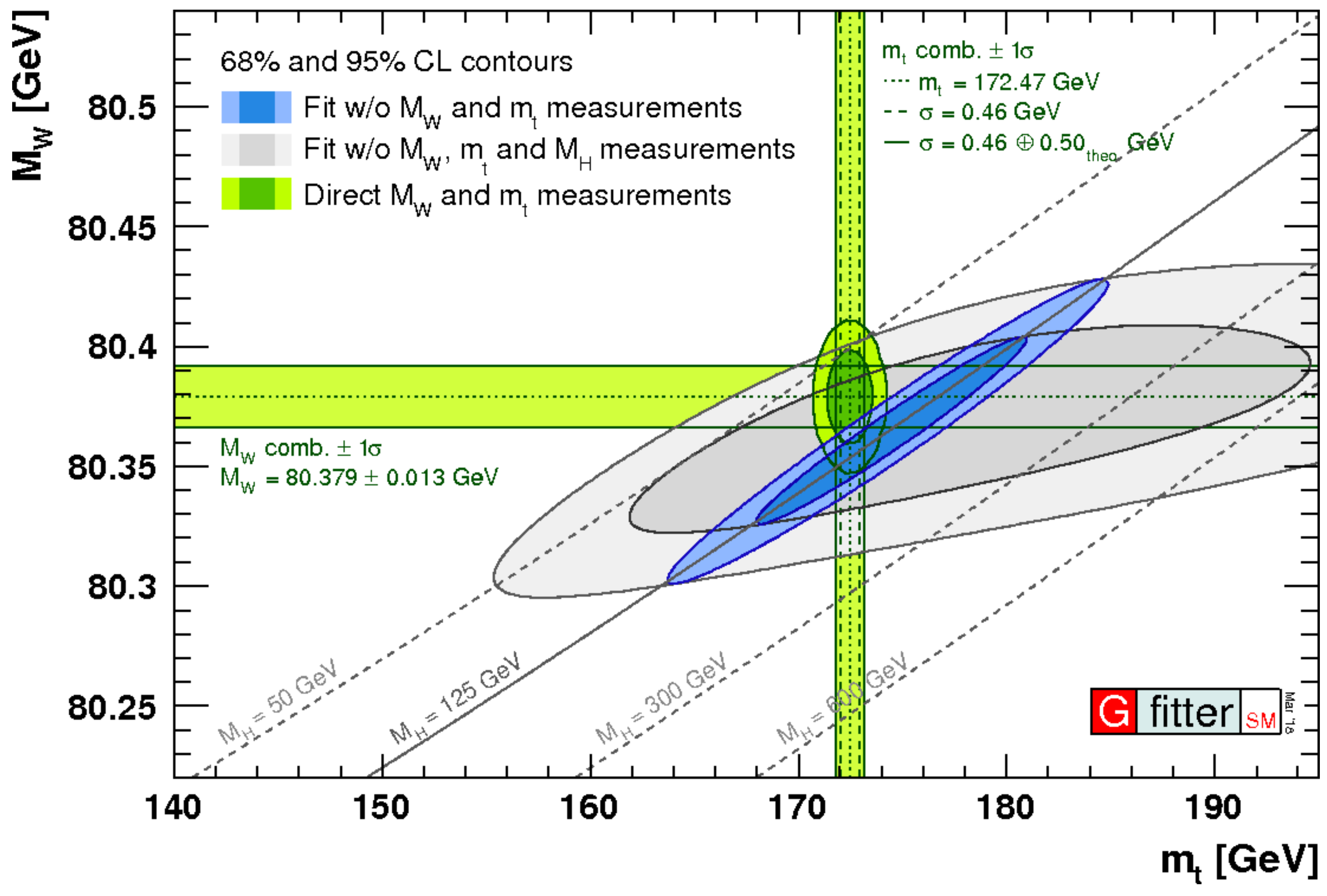
→ **tails of kinematic distributions**

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]$^{(\bigtriangledown)}$	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 $A_\ell = 0.1471 \pm 0.0005$ ($A_\ell = 0.1469 \pm 0.0005$). $^{(\bigtriangledown)}$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.

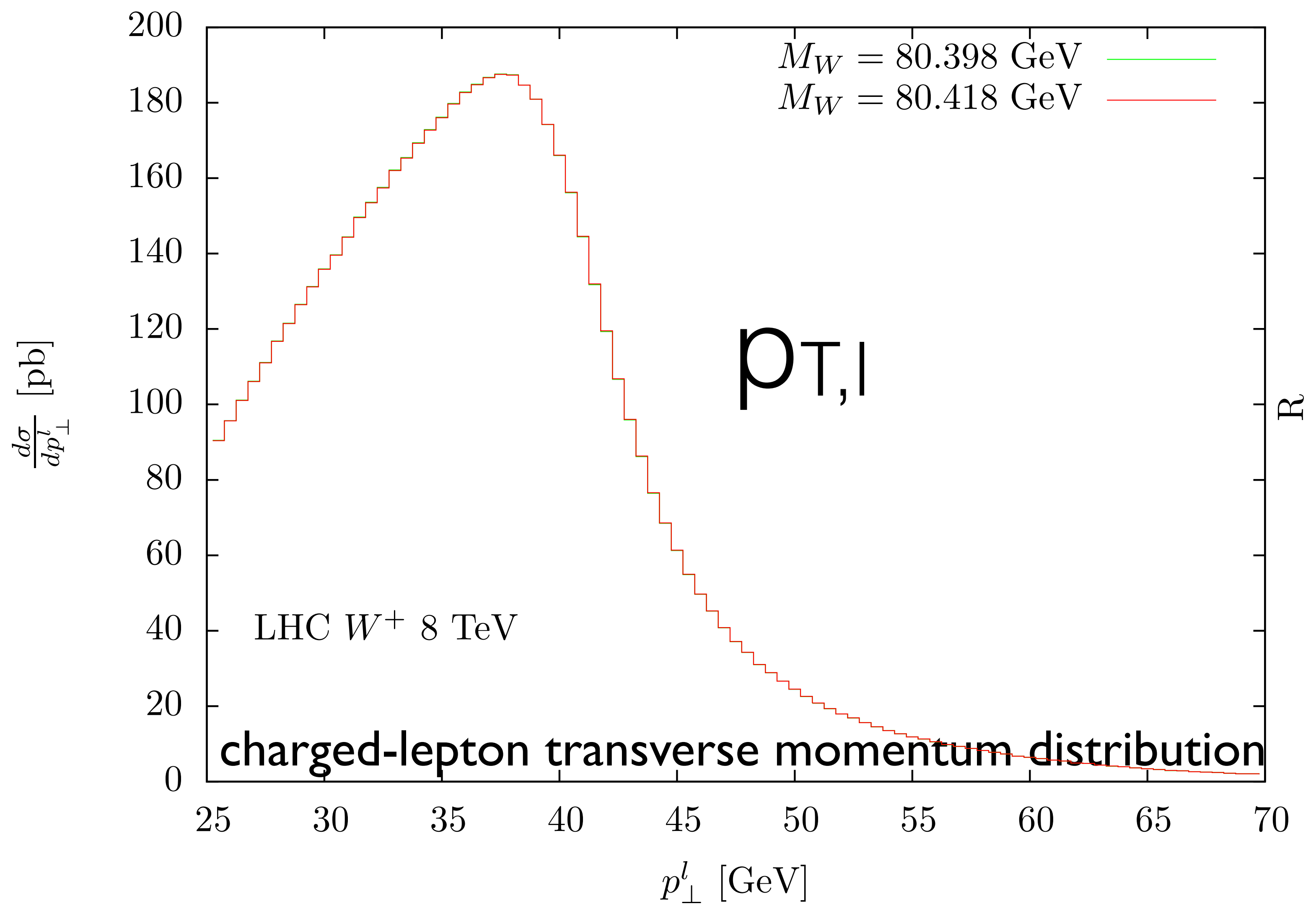




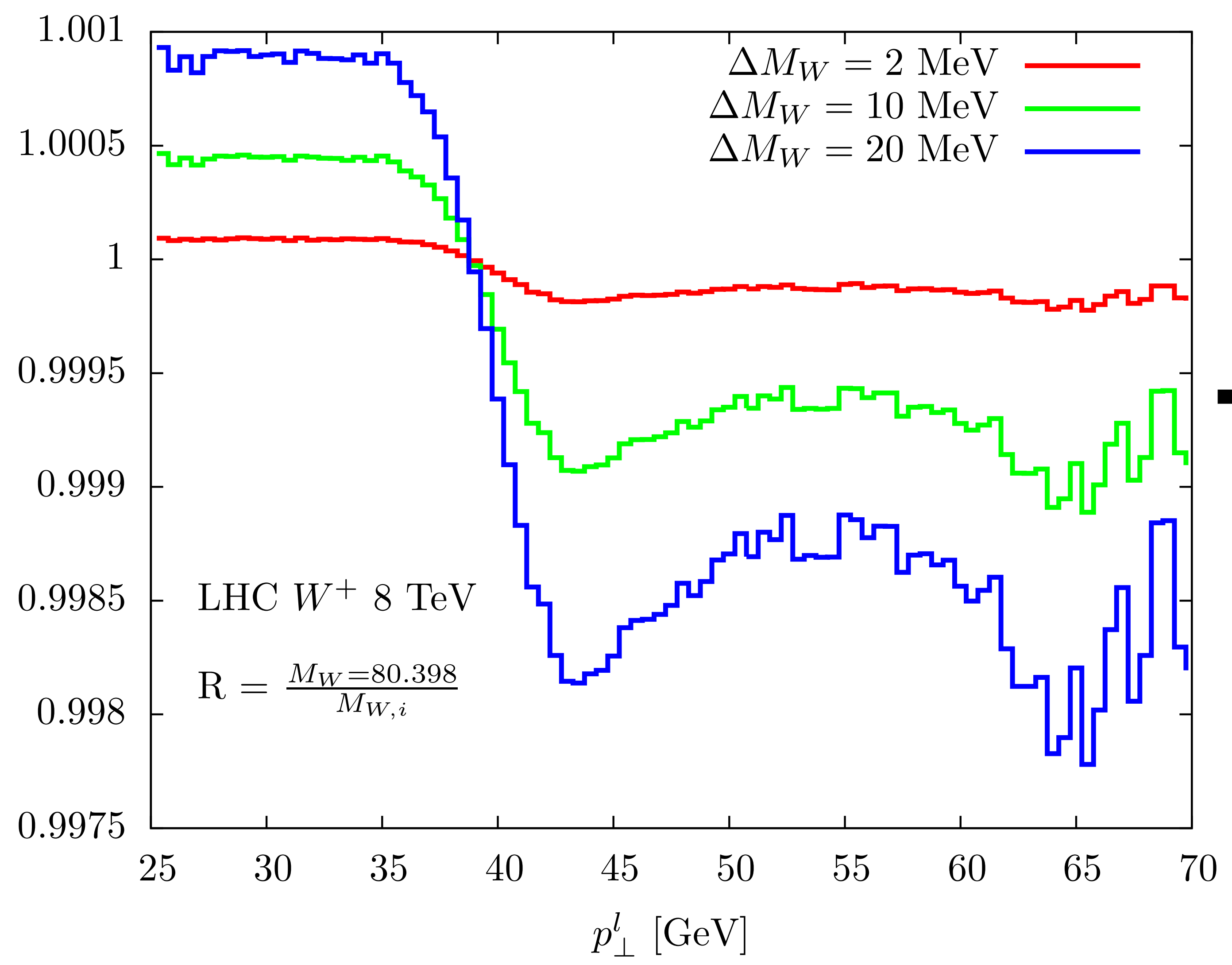
Drell-Yan: M_W measurements

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

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



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

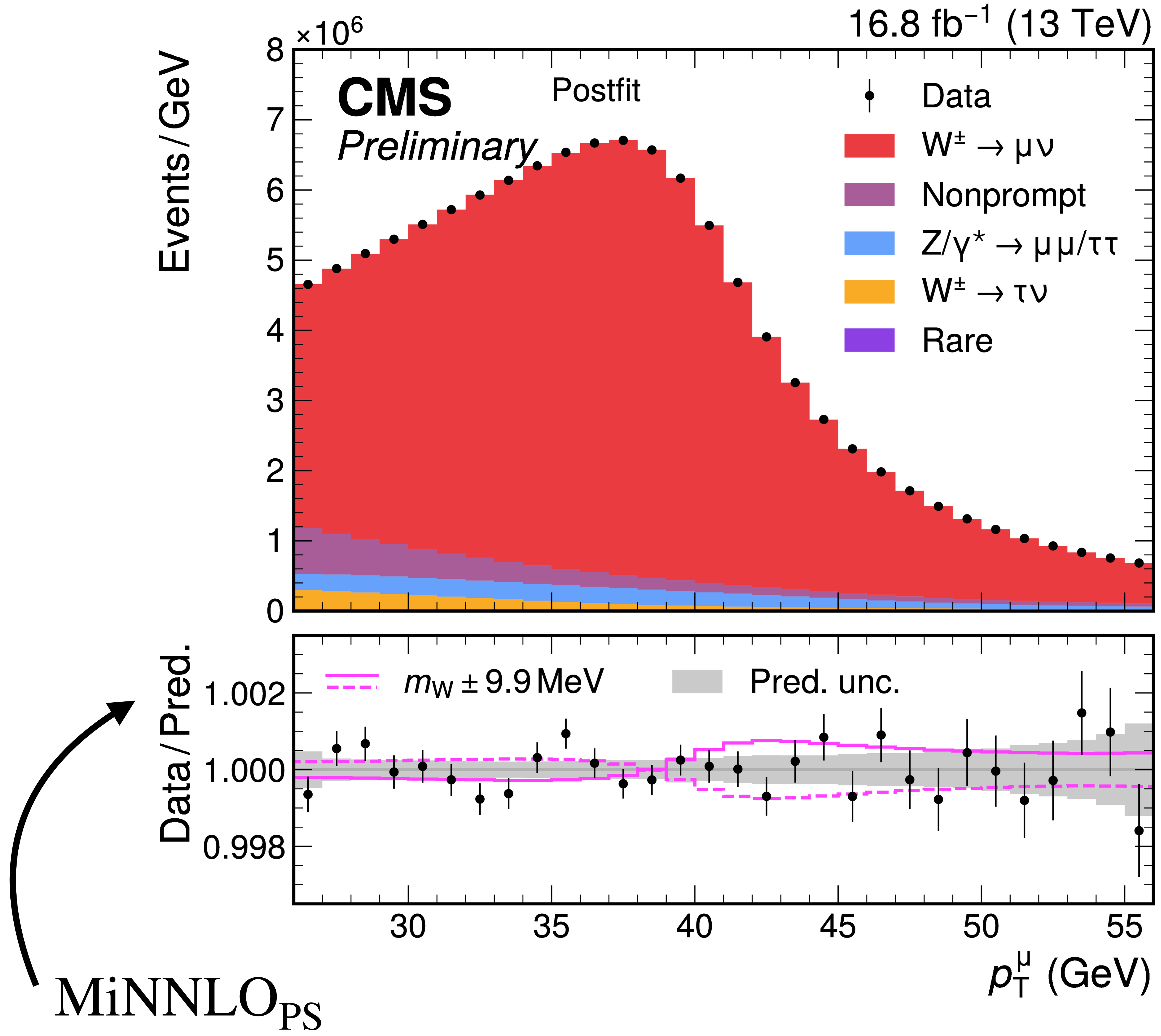


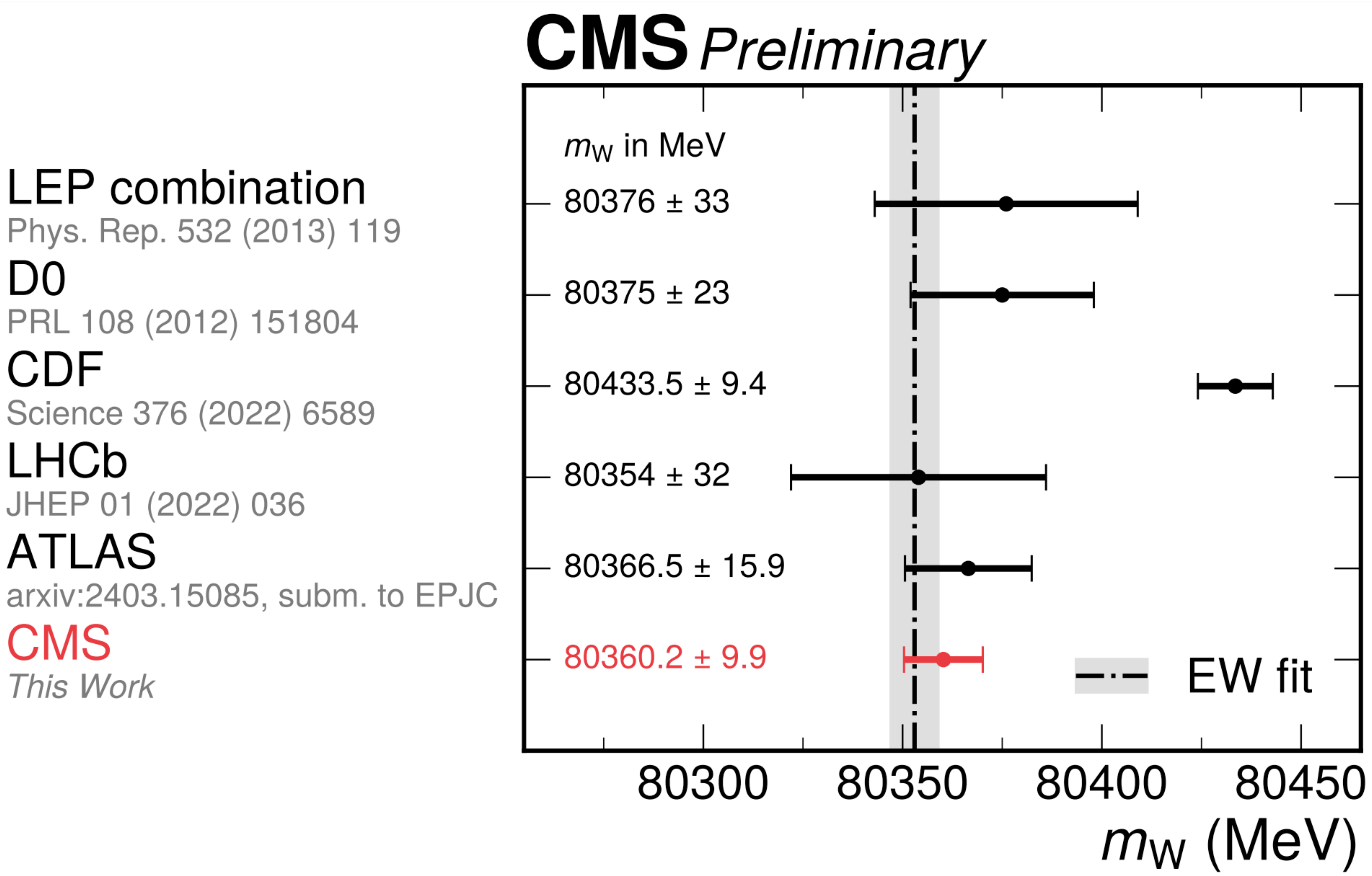
- Need to control shape effects at the sub-1% level!
- Dominant effects: QCD ISR and QED FSR

→Theory precision essential for improvements in mW determination!

Drell-Yan: M_W measurements

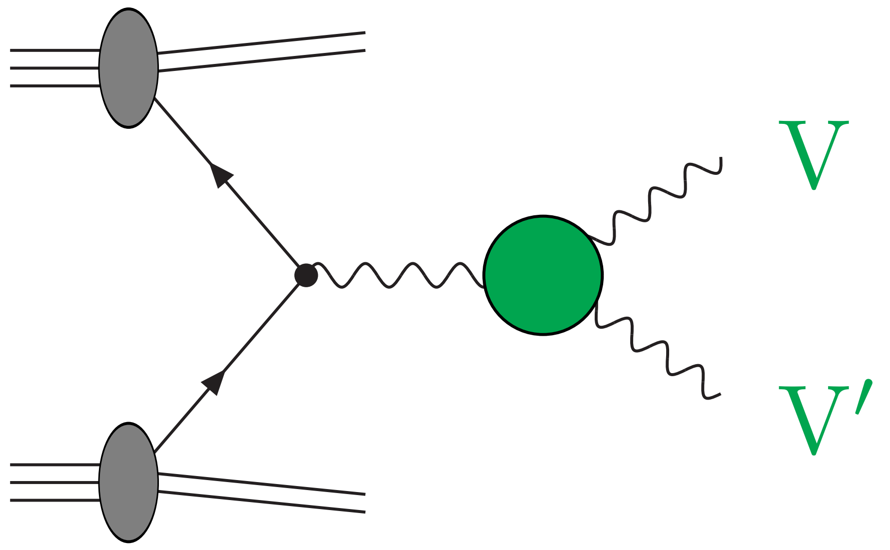
CMS-PAS-SMP-23-002

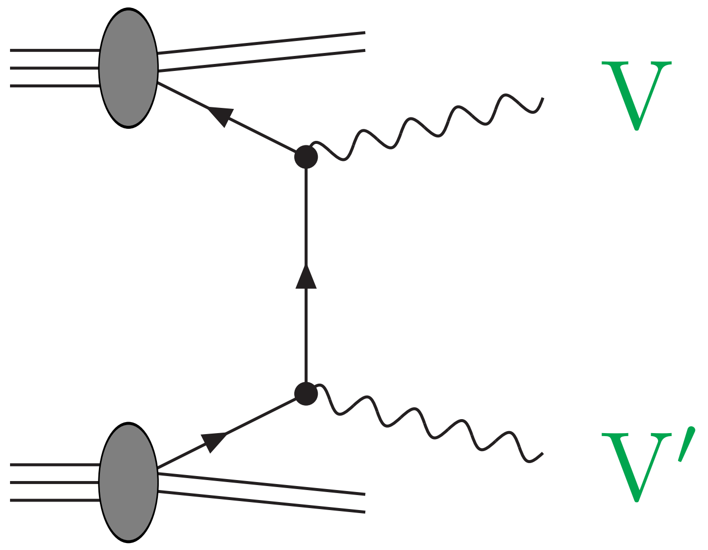




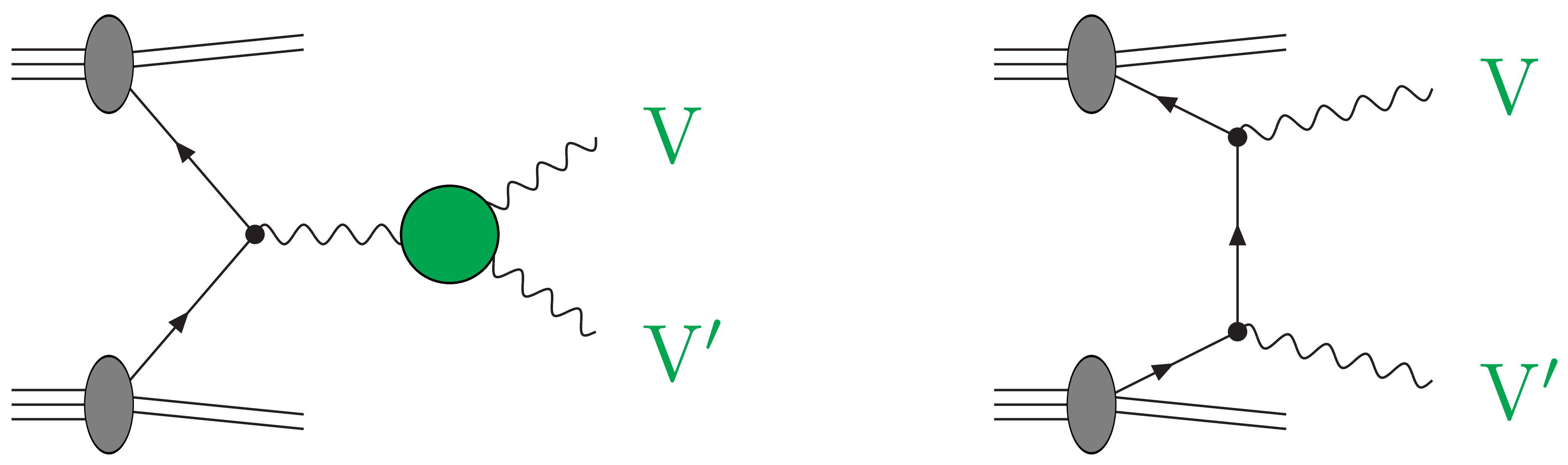
→The LHC is an EW precision machine!

Diboson production at the LHC





Diboson production at the LHC

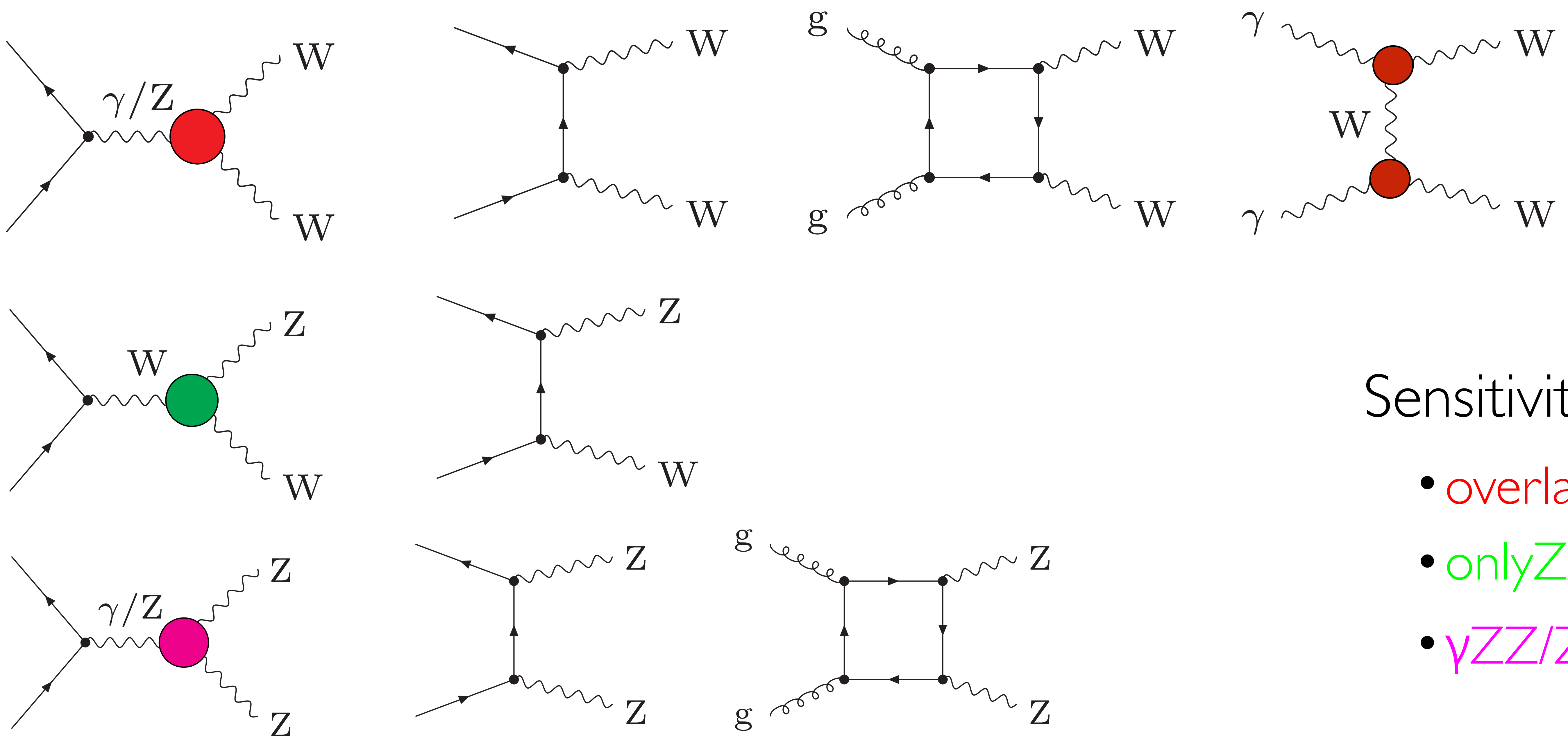


Complementarity in WW / WZ / ZZ production

WW

WZ

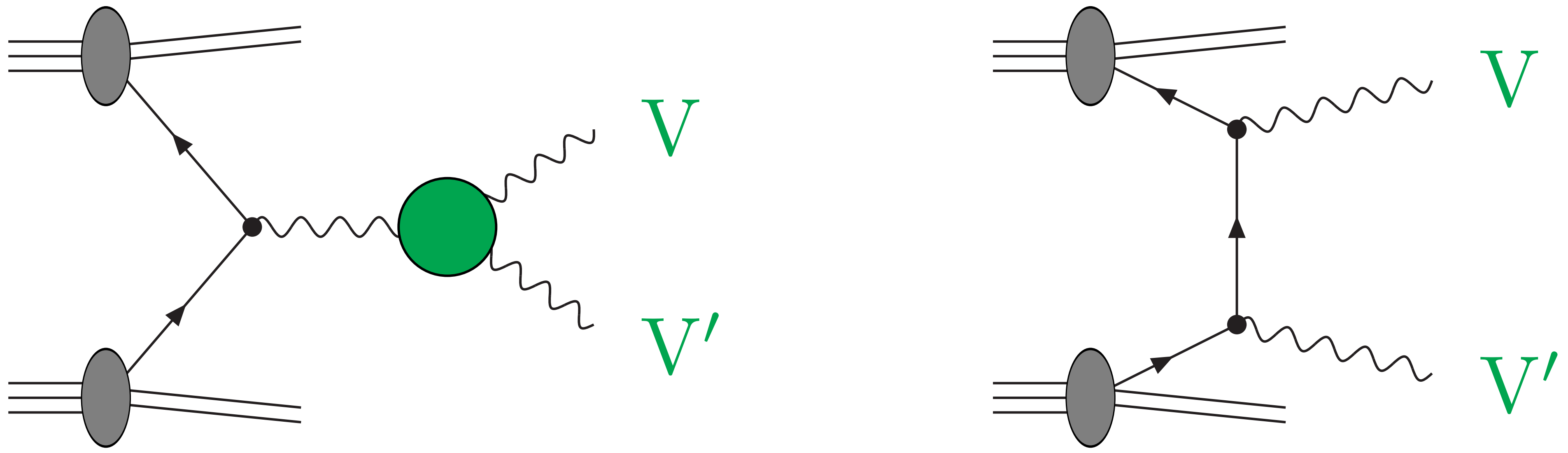
ZZ



Sensitivity to different aTGCs:

- overlay of γWW/ZWW in WW
- onlyZWW inWZ
- γZZ/ZZZ in ZZ

Diboson production at the LHC

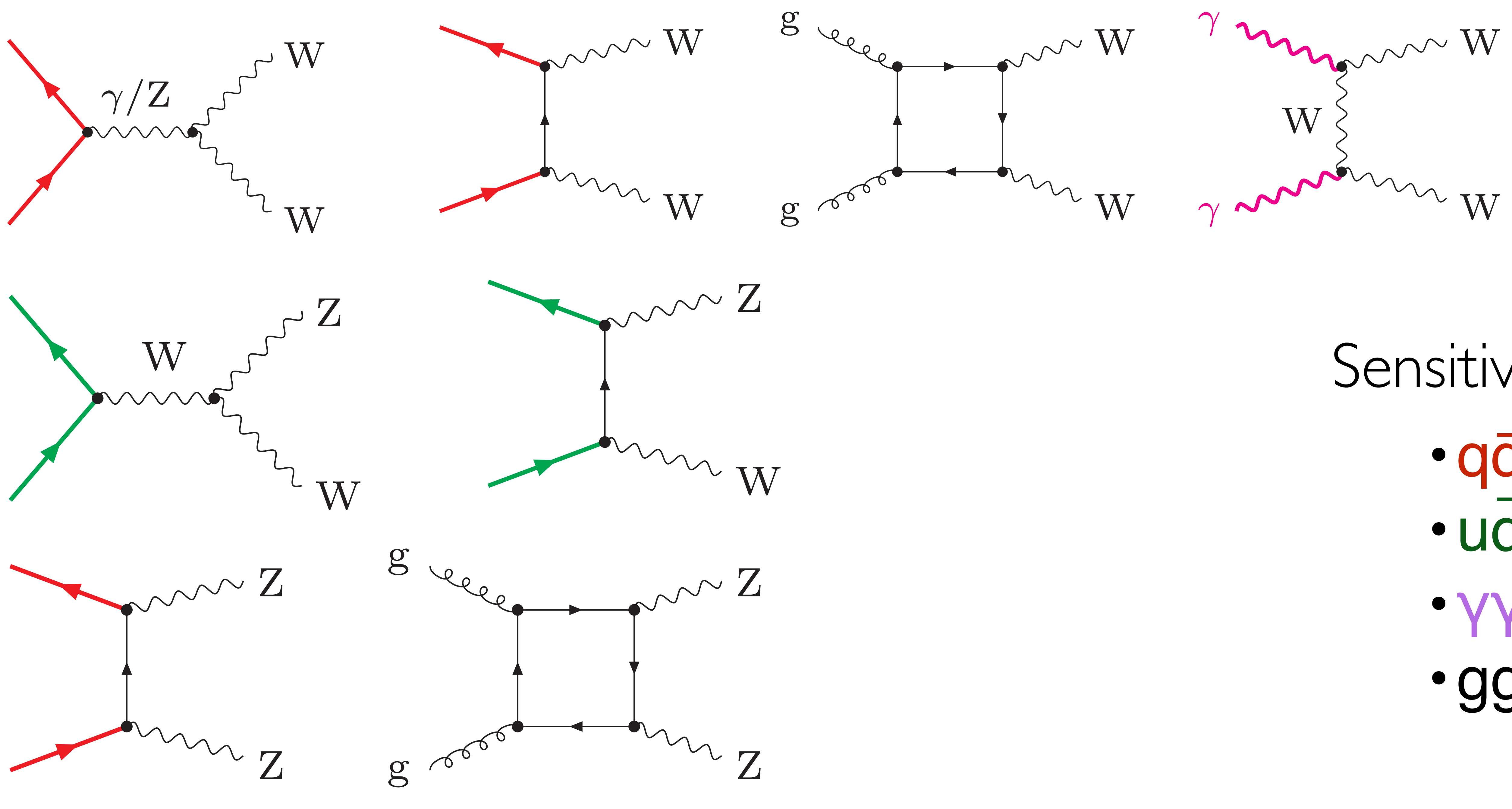


Complementarity in WW / WZ / ZZ production

WW

WZ

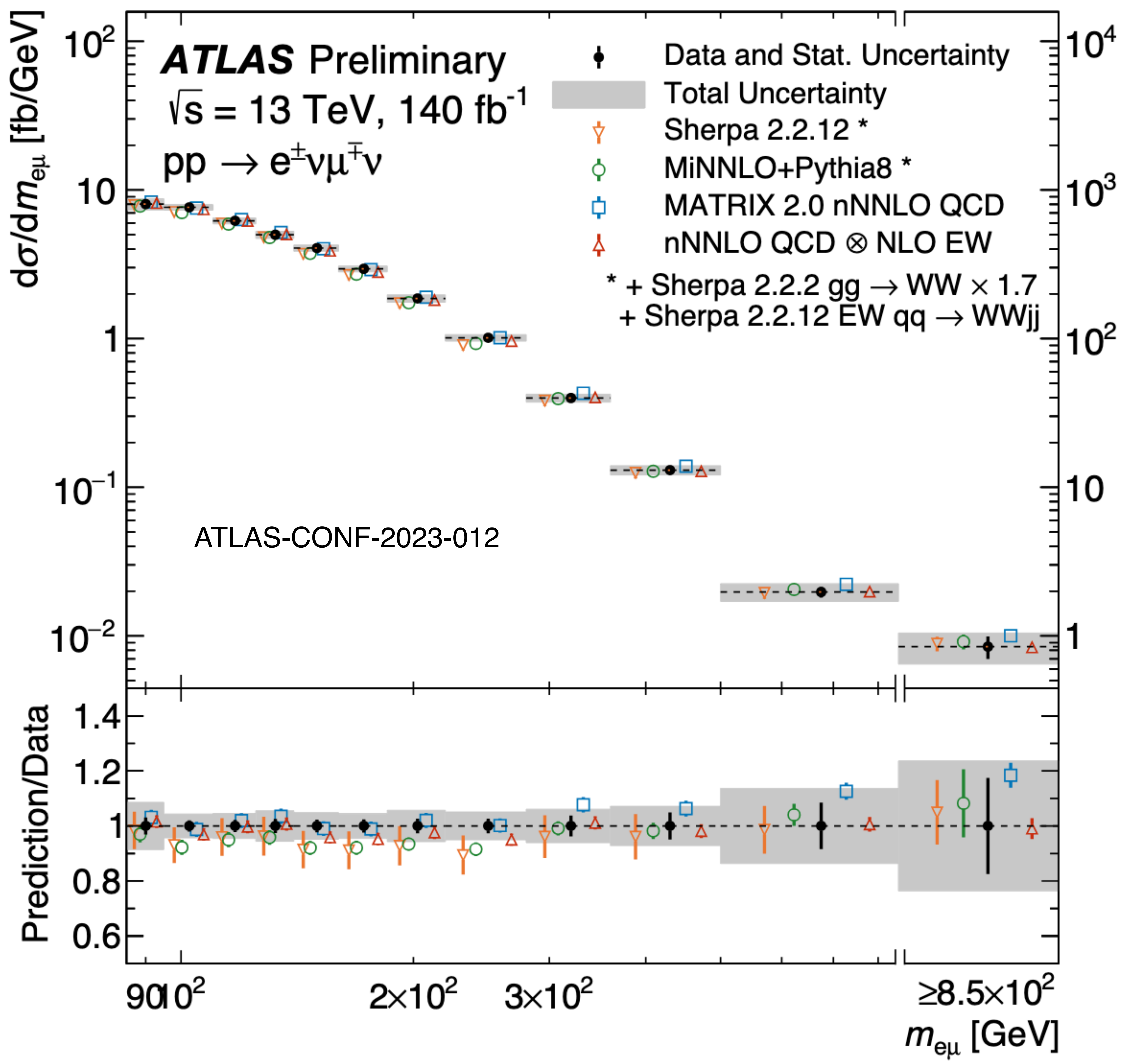
ZZ



Sensitivity to different PDF combinations:

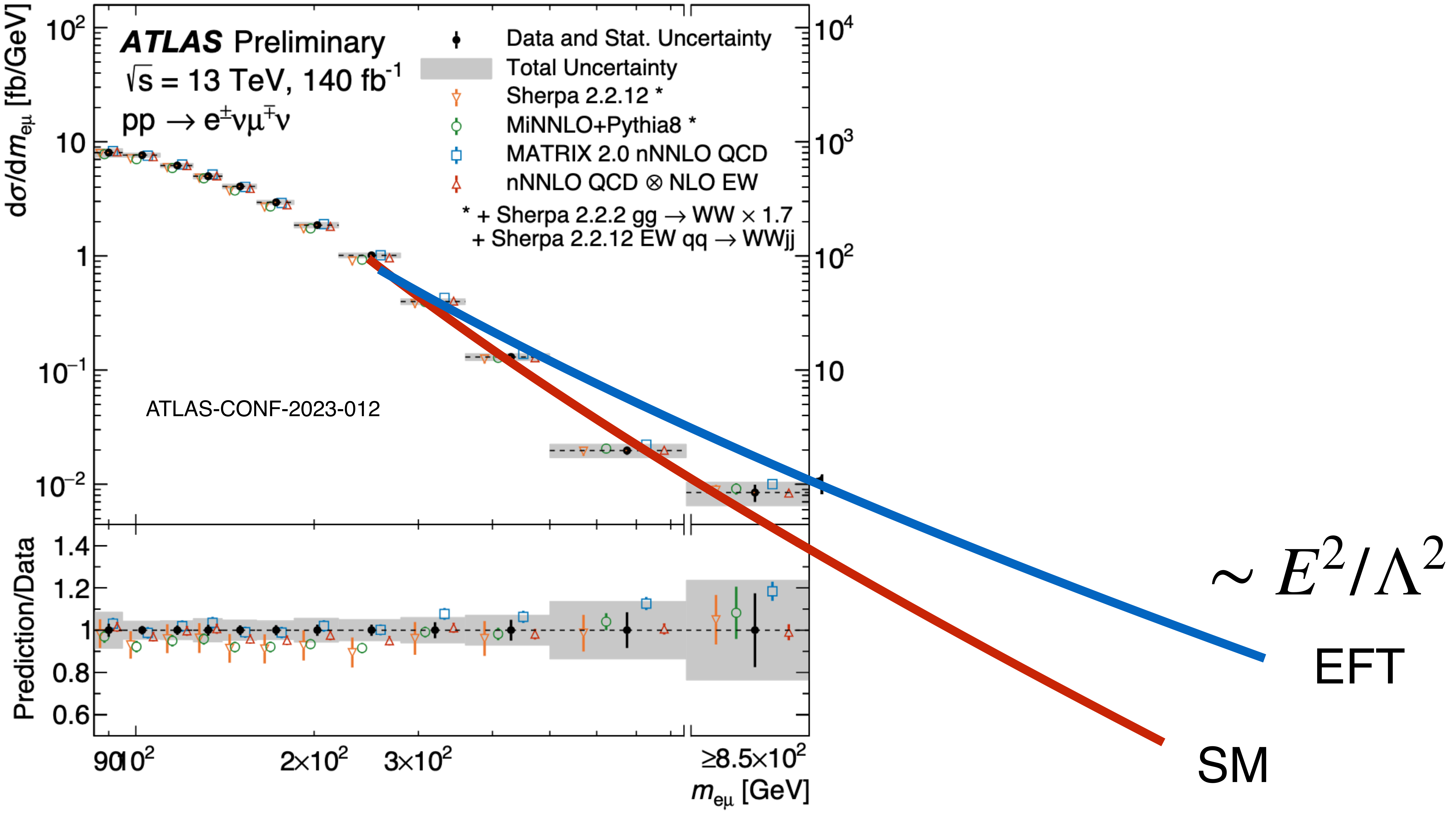
- $q\bar{q}$ in WW/ZZ
- $u\bar{d}/d\bar{u}$ in WZ
- $\gamma\gamma$ in WW
- gg in WW/ZZ

Kinematic tails



→ **tails of kinematic distributions**

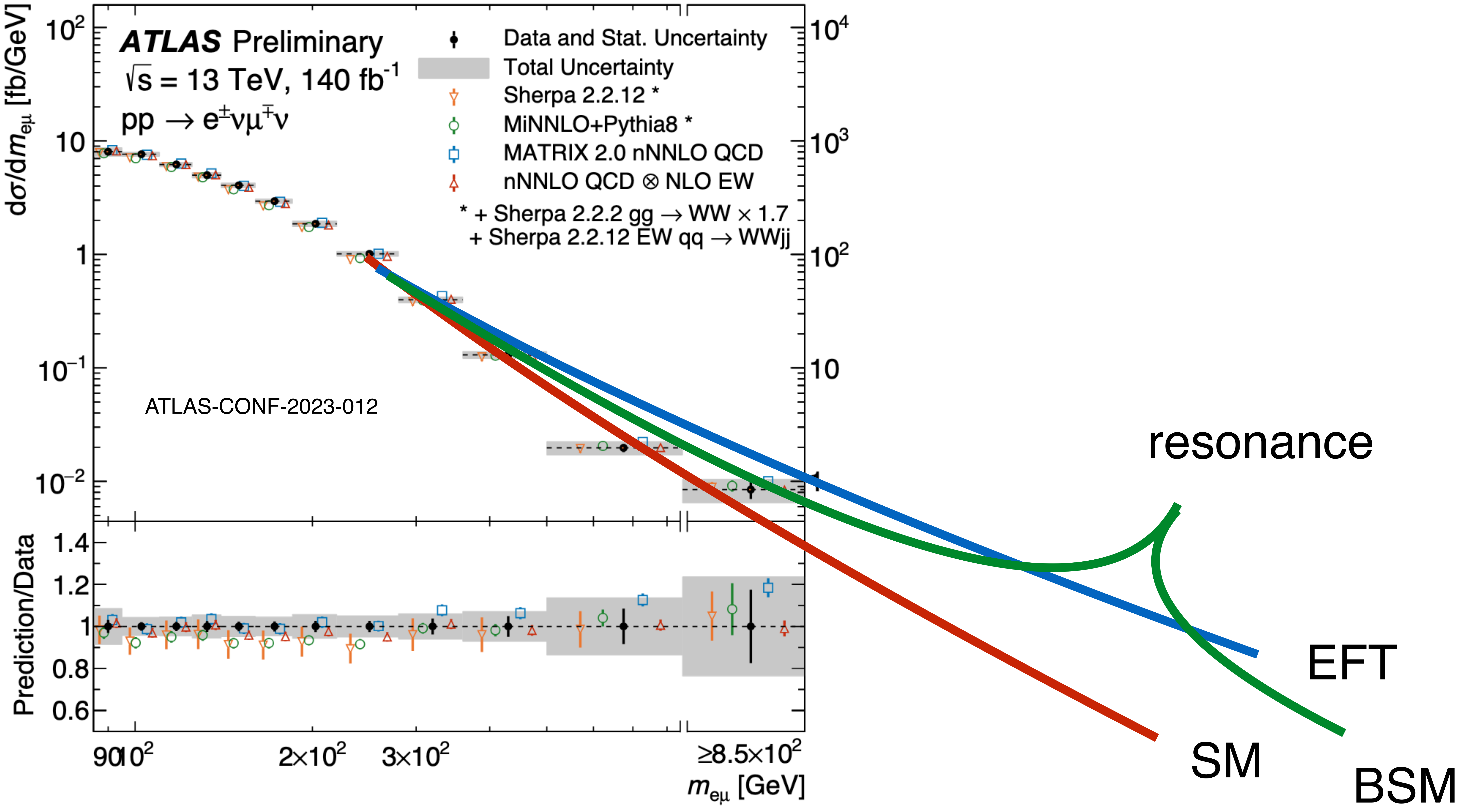
Kinematic tails



$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i^{D6}}{\Lambda^2} \mathscr{O}_i^{D6}$$

→ **tails of kinematic distributions**

Kinematic tails



$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i^{D6}}{\Lambda^2} \mathcal{O}_i^{D6}$$

→ **tails of kinematic distributions**

The global EFT/SMEFT fit

Wilson coefficients

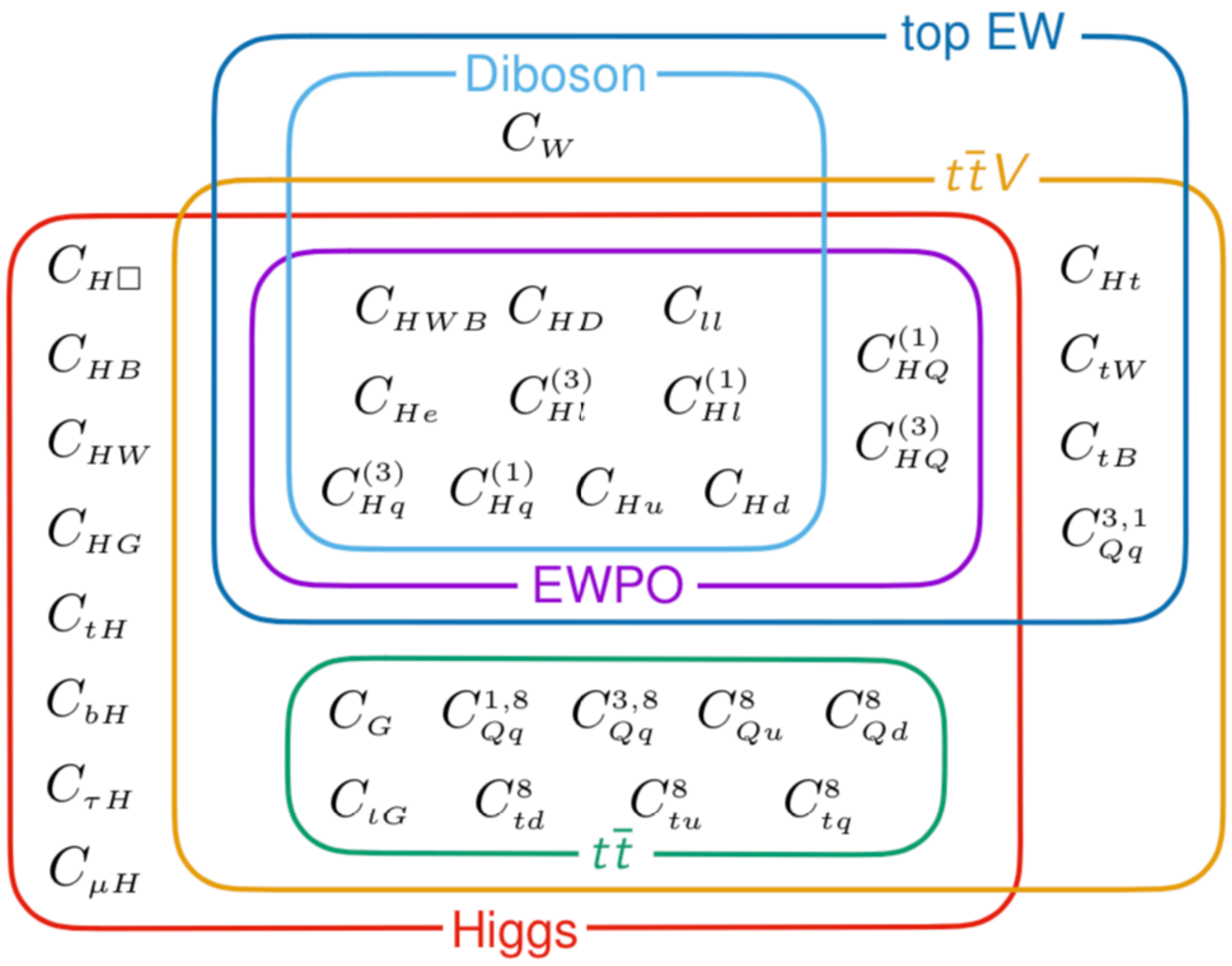
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i^{D6}}{\Lambda^2}\mathscr{O}_i^{D6}$$

dimensional scale

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

→ flavour universality

[Ellis, Madigan, Mimasu, Sanze, You]



→ John's course on Higgs, Top & Beyond starting next Thursday

The global EFT/SMEFT fit

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i^{D6}}{\Lambda^2}\mathscr{O}_i^{D6} + \sum_{i=1}^{\sim 50000} \frac{C_i^{D8}}{\Lambda^4}\mathscr{O}_i^{D8} + \ldots$$

Wilson coefficients

dimensional scale

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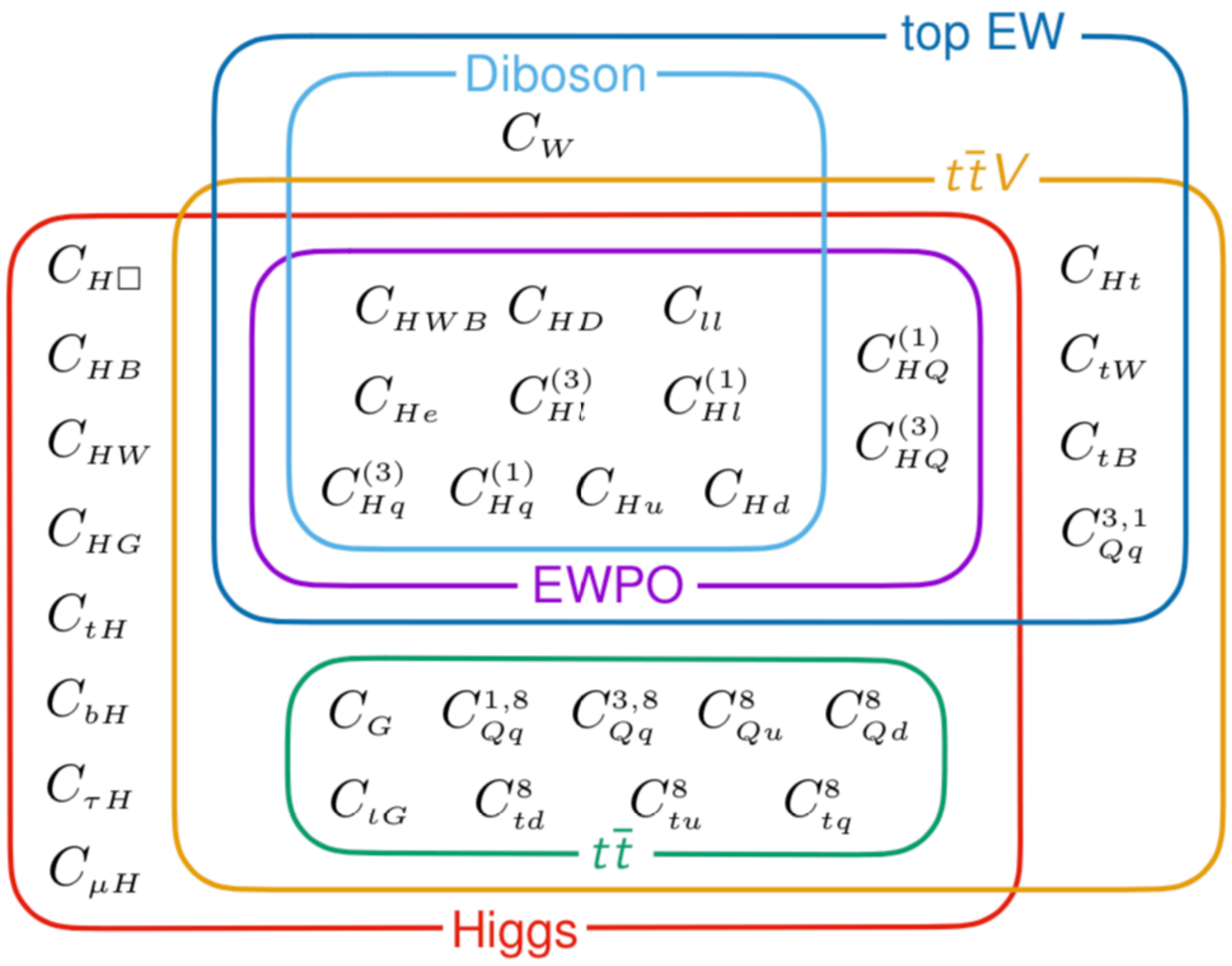
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$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

→ flavour universality

[Ellis, Madigan, Mimasu, Sanze, You]



→ John's course on Higgs, Top & Beyond starting next Thursday

EW standard candles at the LHC

Precision EW
- DY
- VV
- V+jets

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

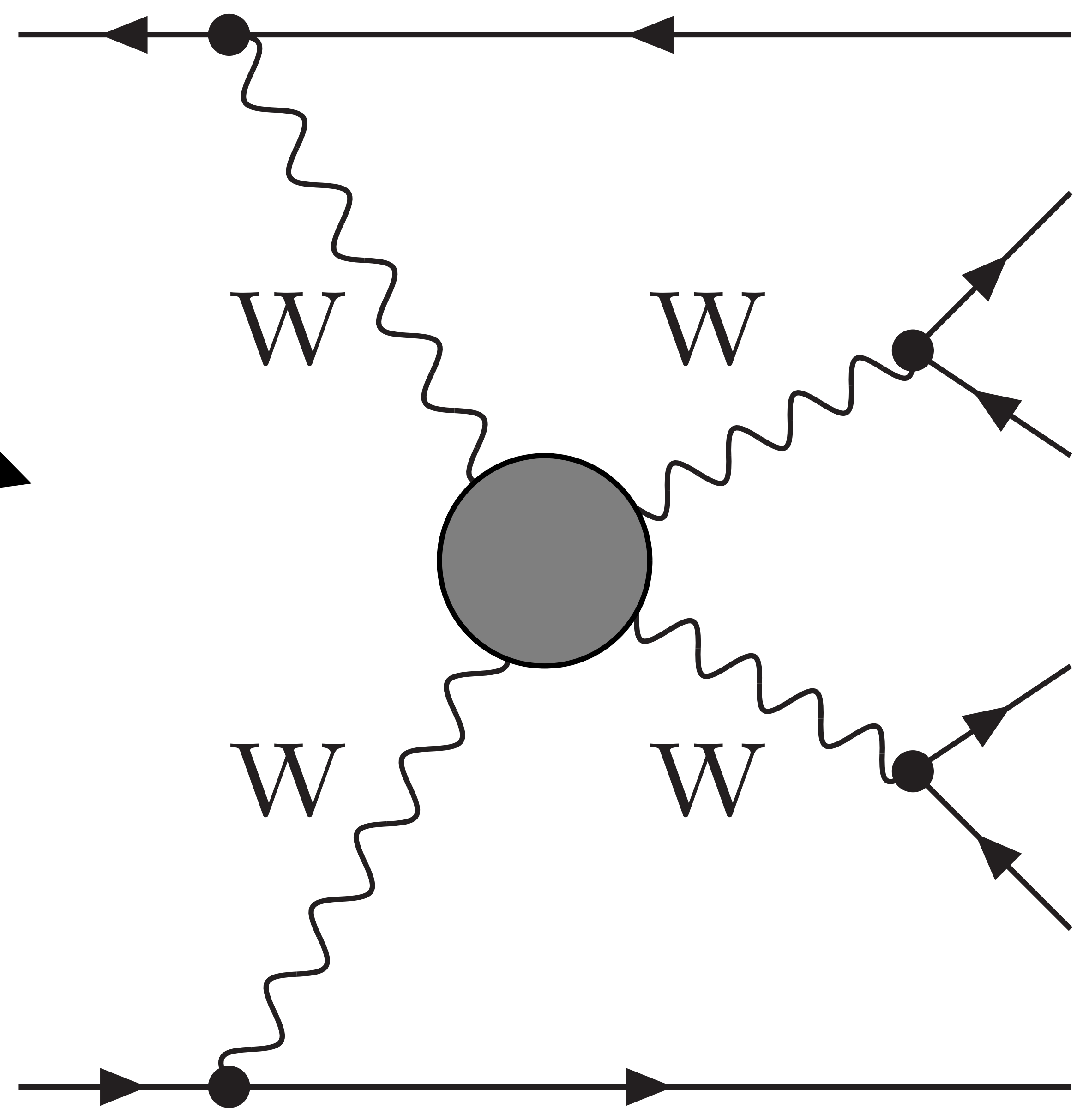
Rare processes
- VBS
- VVV
- ….

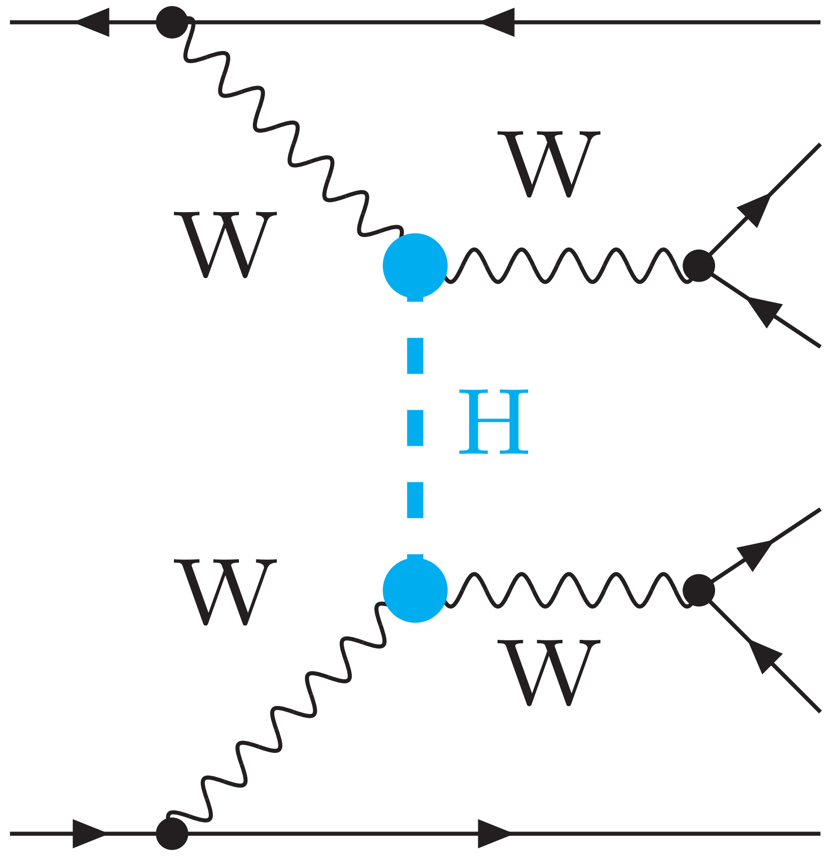
Higgs
- precision couplings
- high-pT
- HH

→ John's course on Higgs, Top & Beyond starting next Thursday

Vector-boson scattering at LHC

- 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)





Signatures:

ssWW-VBS: $\ell^+\ell^+ + \bar{\nu}\bar{\nu} + 2\text{jets}$

WW-VBS: $\ell^+\ell^- + \bar{\nu}\nu + 2\text{jets}$

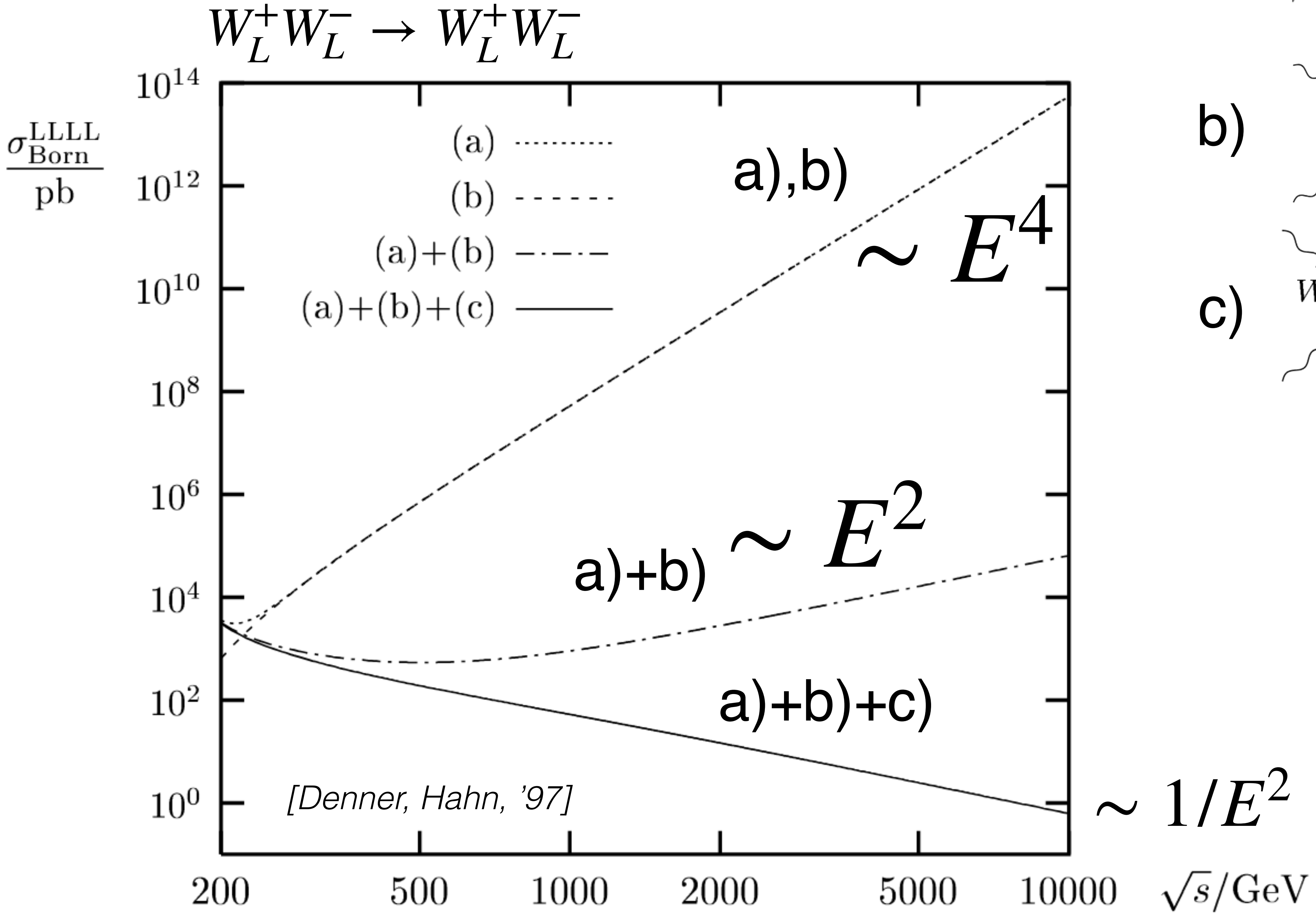
ZZ-VBS: $\ell^+\ell^-\ell^+\ell^- + 2\text{jets}$

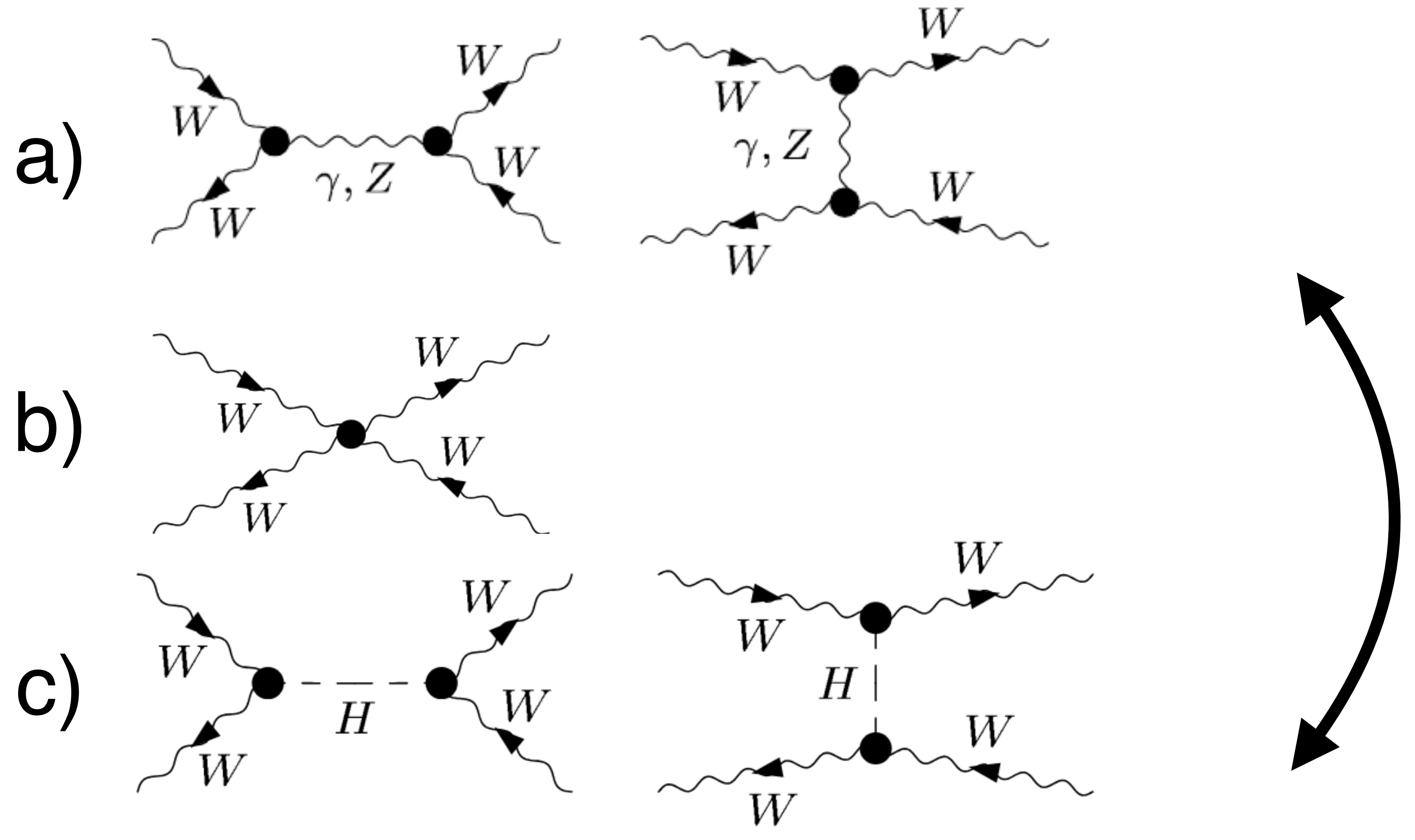
WZ-VBS: $\ell^+\ell^-\ell^+\bar{\nu} + 2\text{jets}$

Wγ-VBS: $\ell^\pm\nu + \gamma + 2\text{jets}$

Zγ-VBS: $\ell^+\ell^- + \gamma + 2\text{jets}$

Polarisation measurements



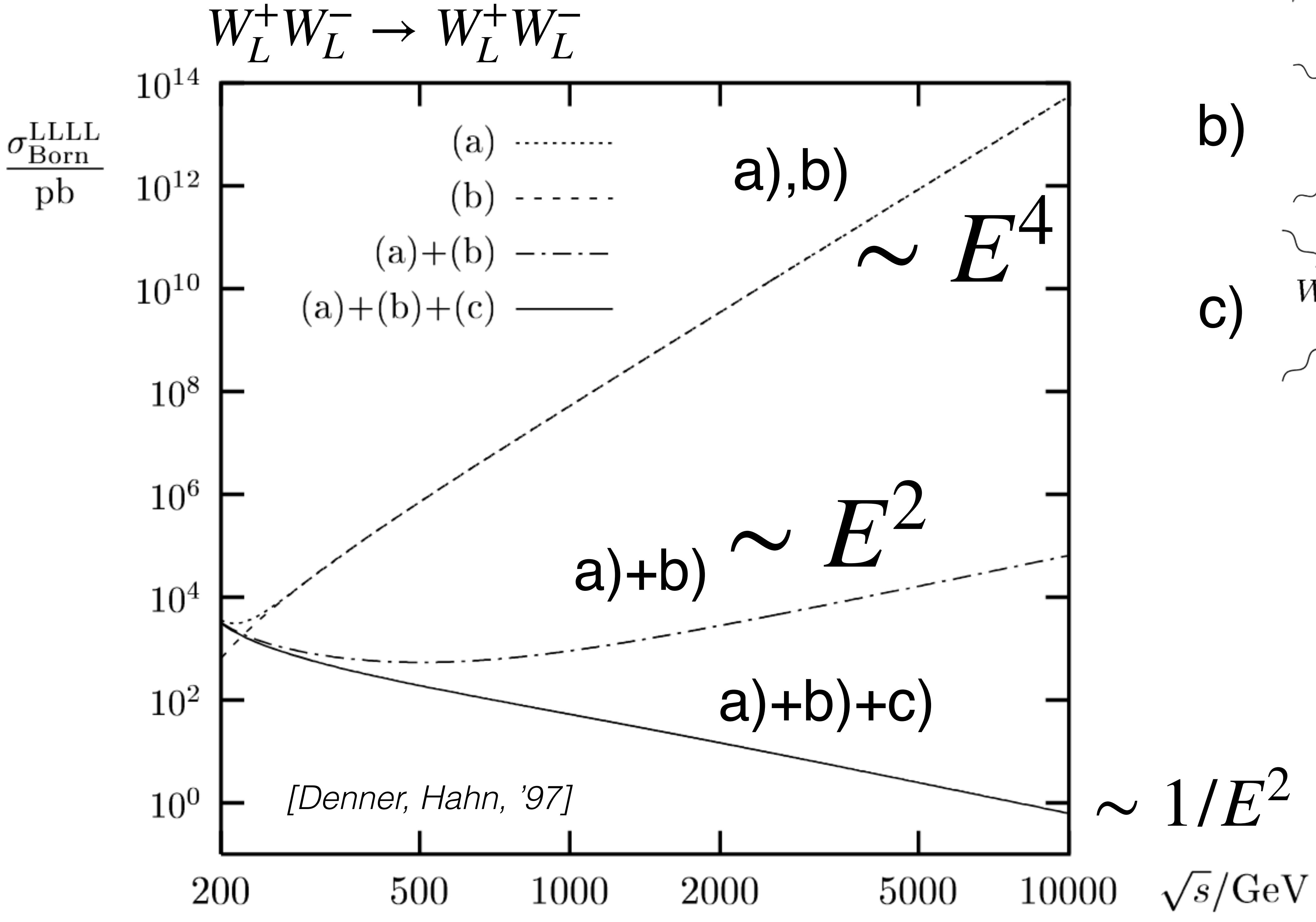


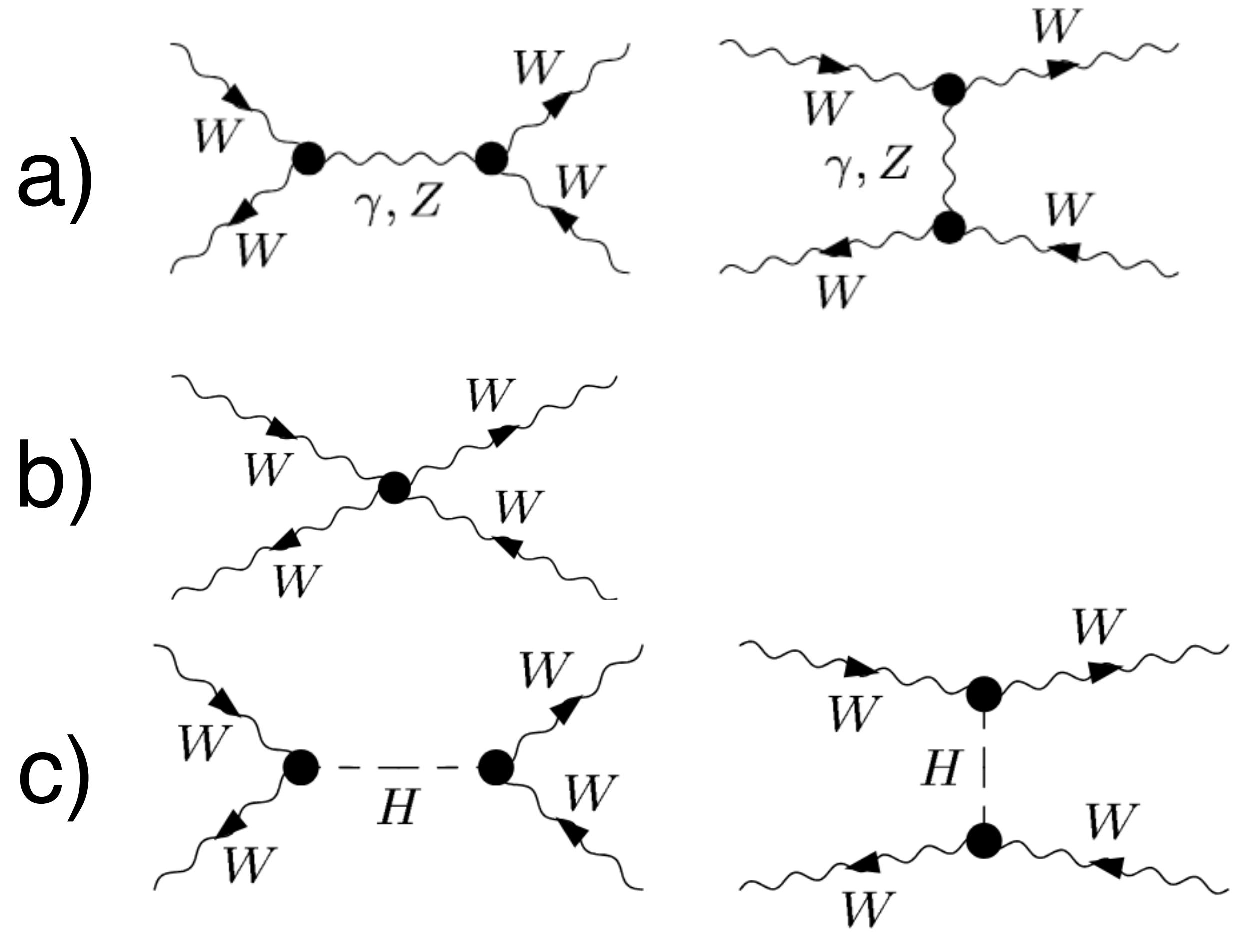
cancellation ensures unitarity!

→ crucial test of EWSB

→ problem: we can't directly observe longitudinal vector-bosons

Polarisation measurements





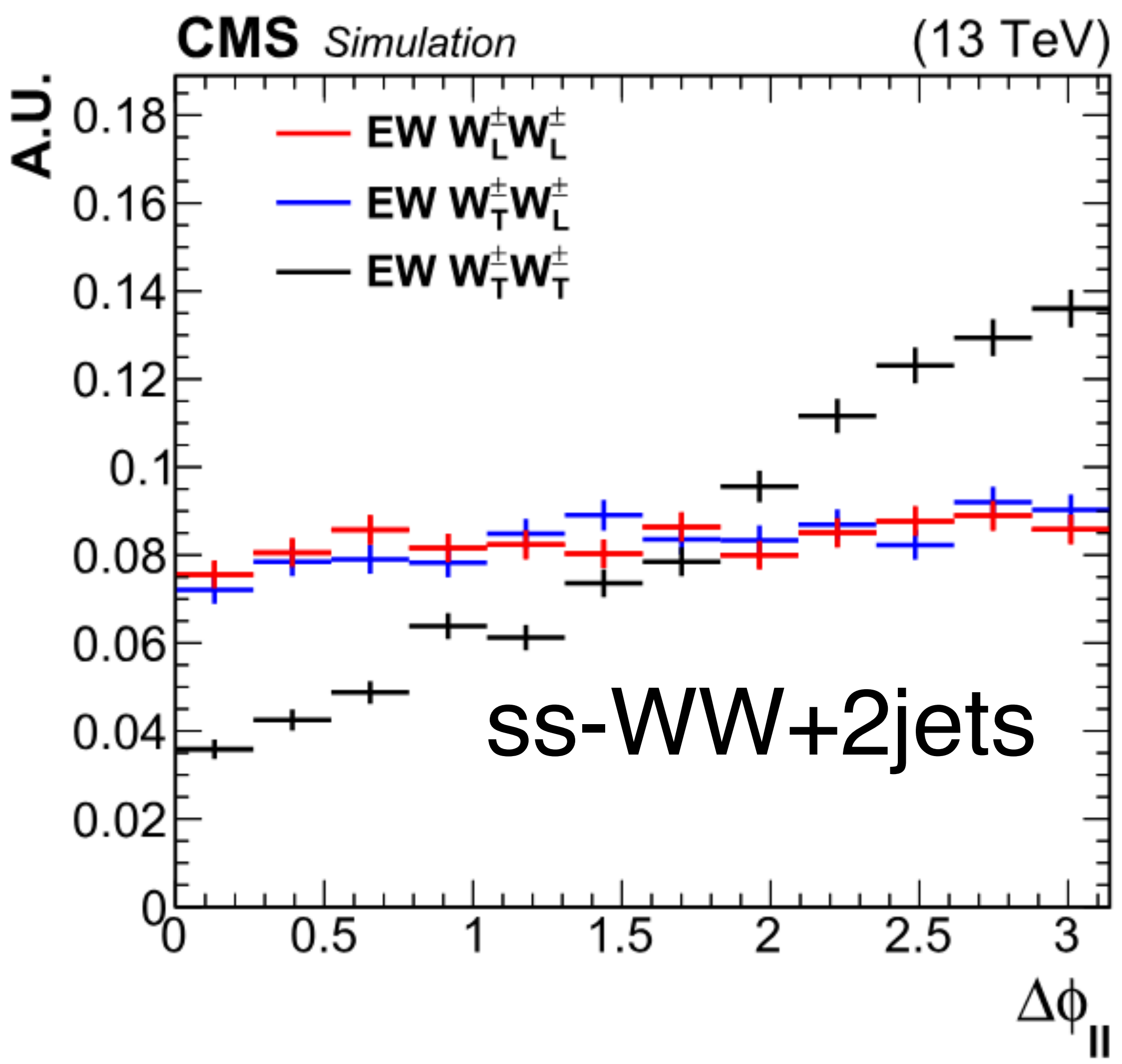
cancellation ensures unitarity!

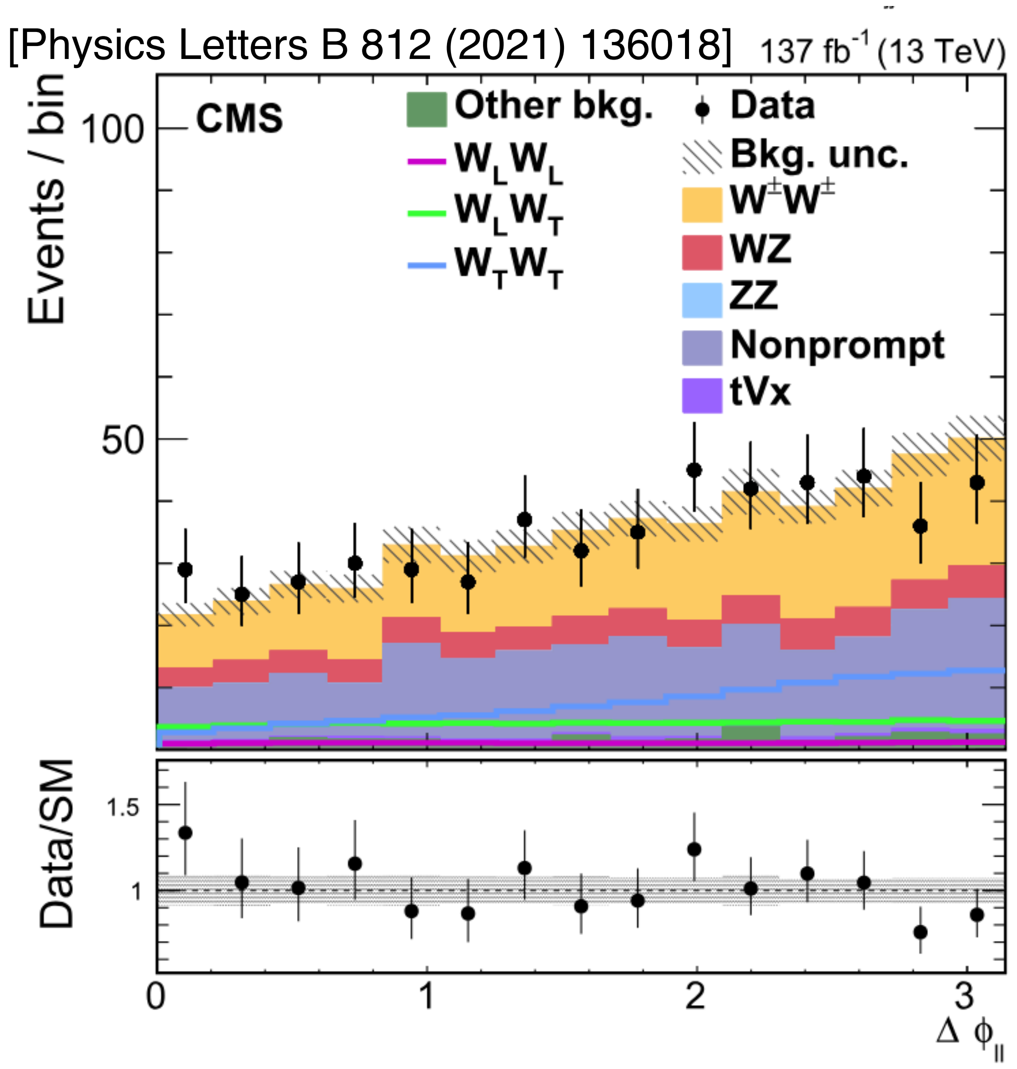
→ crucial test of EWSB

→ problem: we can't directly observe longitudinal vector-bosons

→ exploit angular information

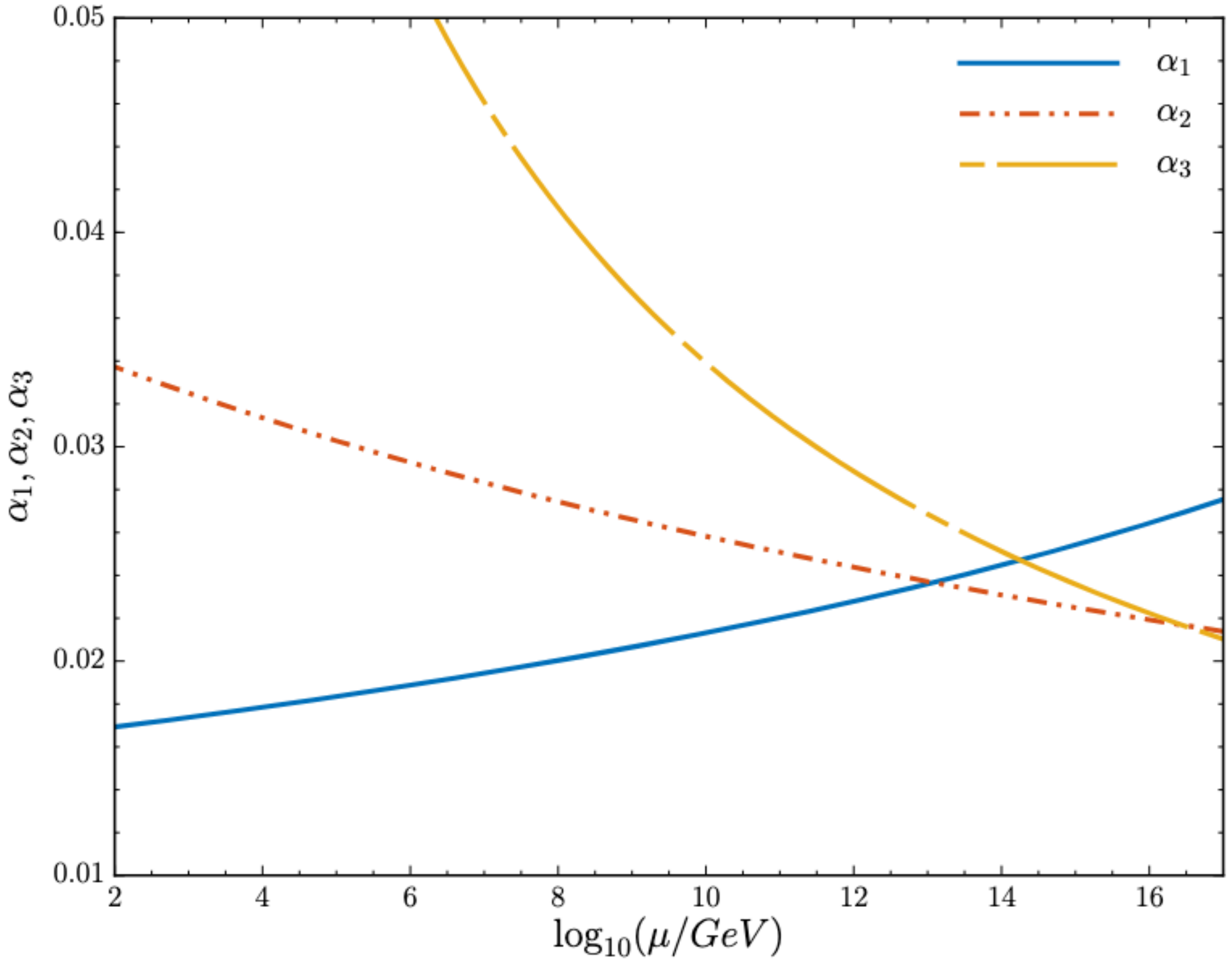
→ currently limited by stats





Running couplings

Also the g_1, g_2 couplings run!



Hint of gauge unification?

→ Gavin's lecture yesterday

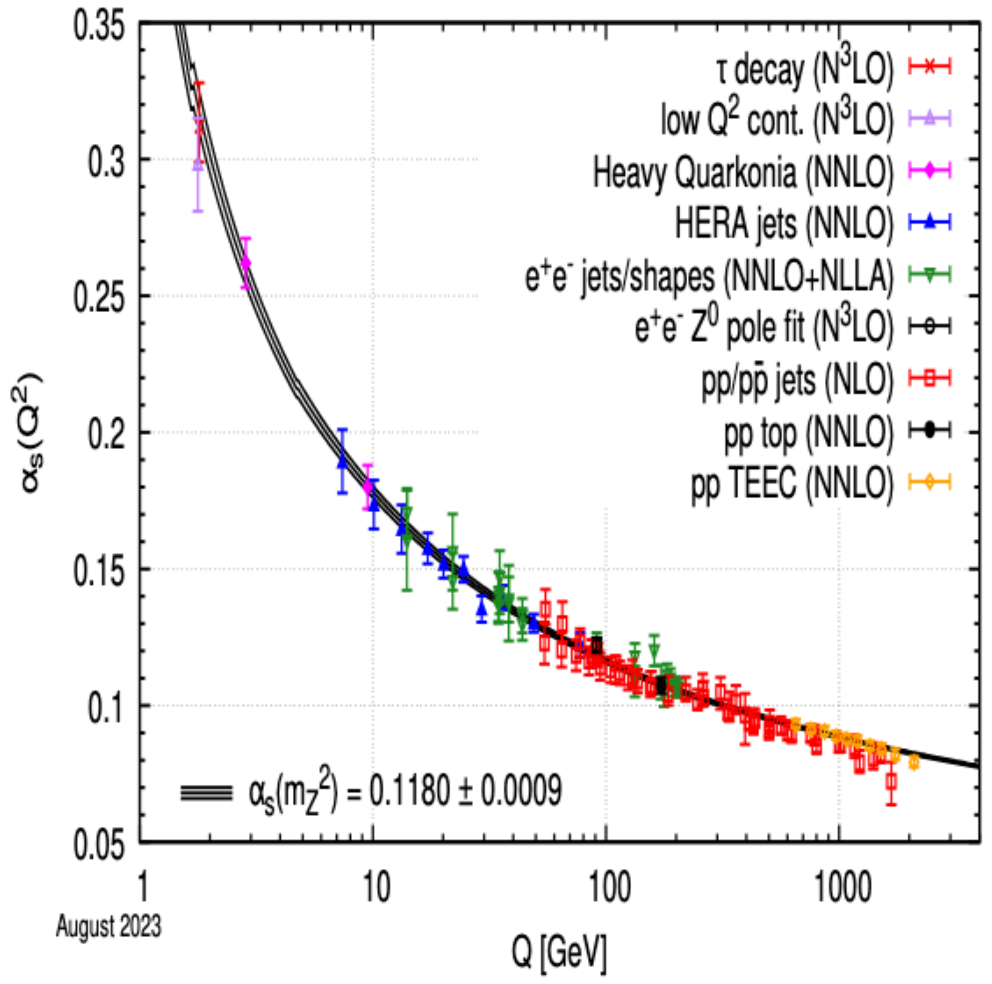
QCD lecture 1 (p. 20)
Basic methods
Perturbation theory

Running coupling (cont.)

Solve $Q^2 \frac{\partial \alpha_s}{\partial Q^2} = -b_0 \alpha_s^2 \quad \Rightarrow \quad \alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + b_0 \alpha_s(Q_0^2) \ln \frac{Q^2}{Q_0^2}} = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}}$

$\Lambda \simeq 0.2$ GeV (aka Λ_{QCD}) is the fundamental scale of QCD, at which coupling blows up.

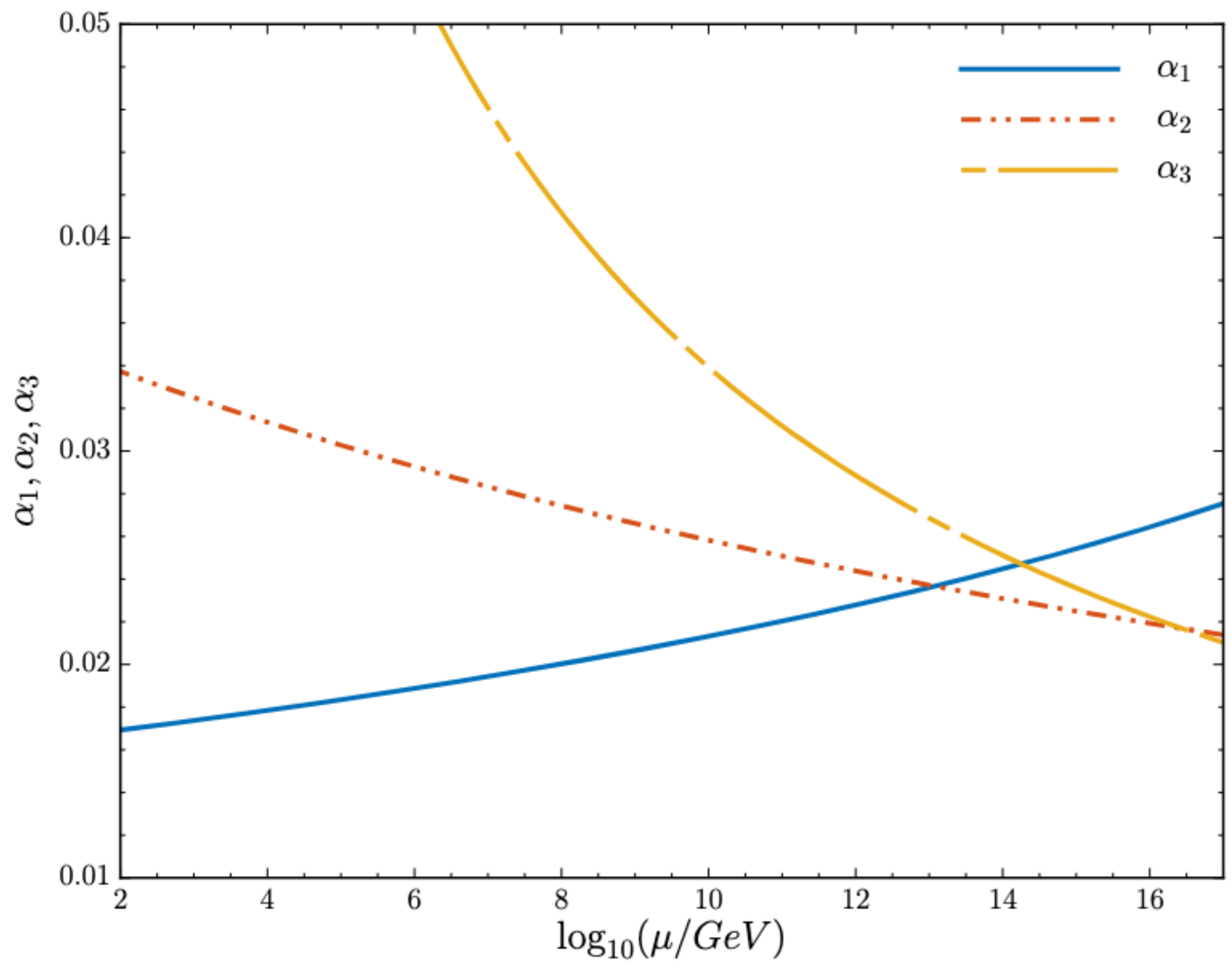
- Λ sets the scale for hadron masses (NB: Λ not unambiguously defined wrt higher orders)
- Perturbative calculations valid for scales $Q \gg \Lambda$.



2023 PDG, QCD chapter

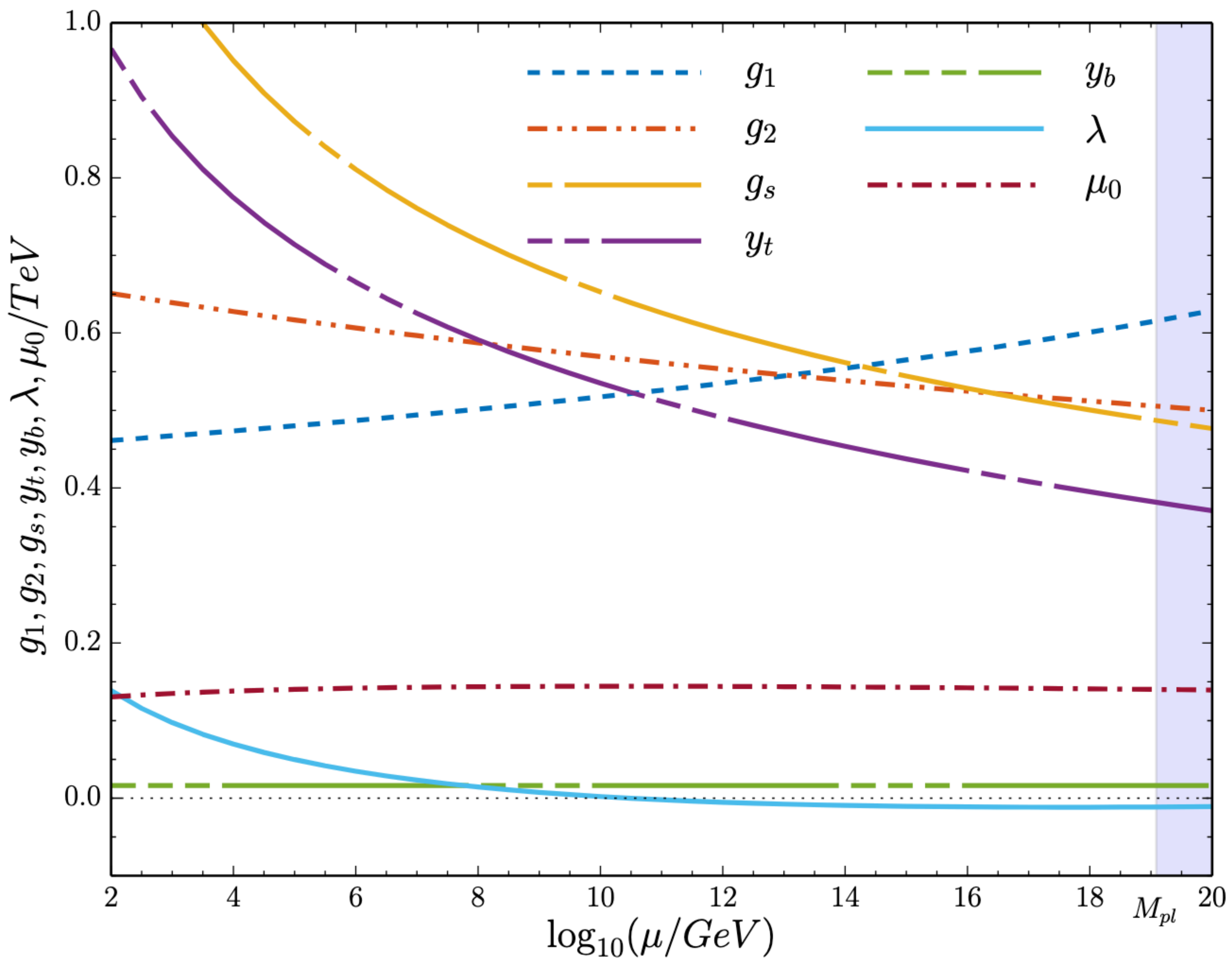
Running couplings

Also the g_1, g_2 couplings run!



Hint of gauge unification?

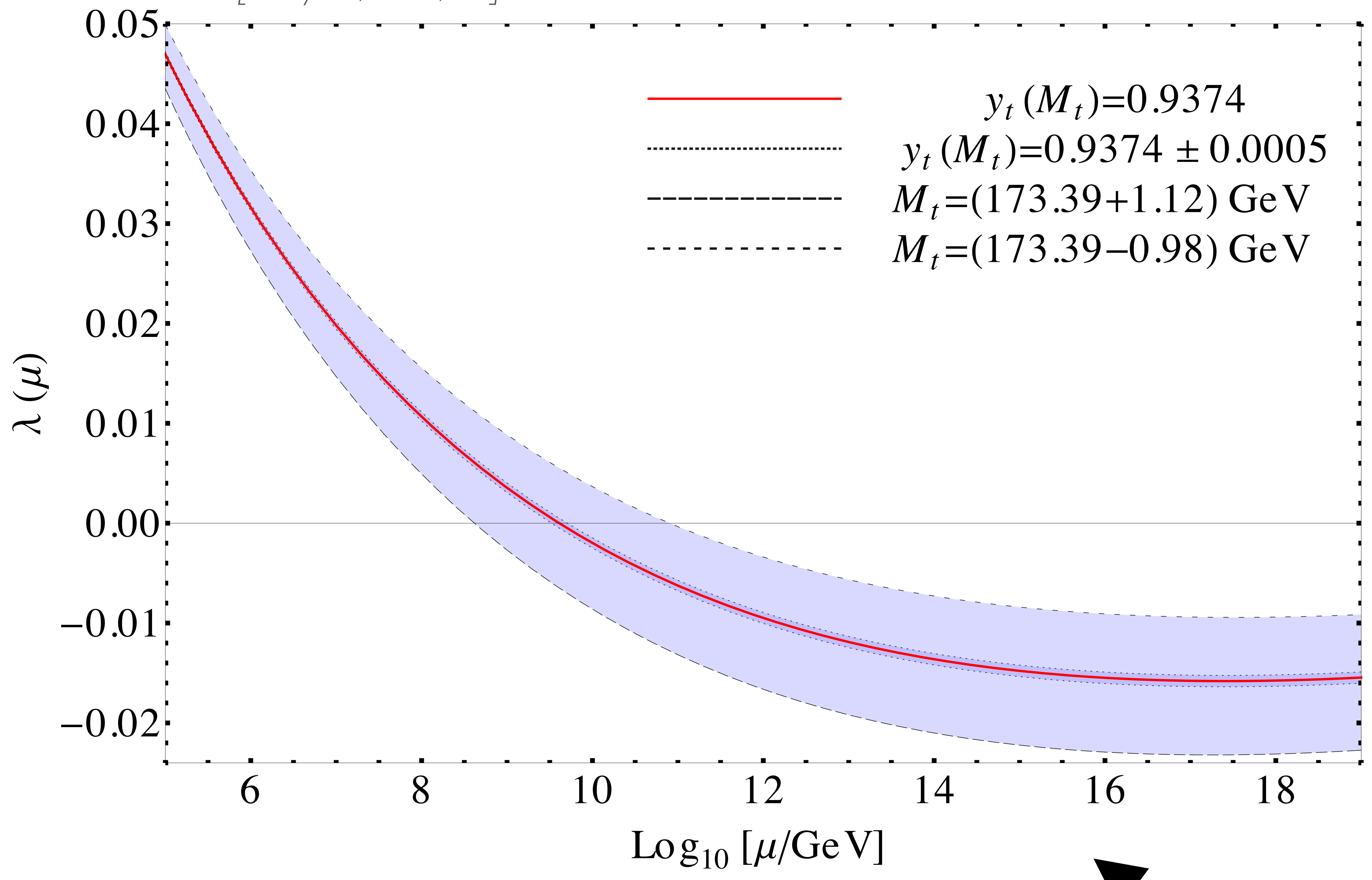
All couplings run! Incl. yukawas, trilinear

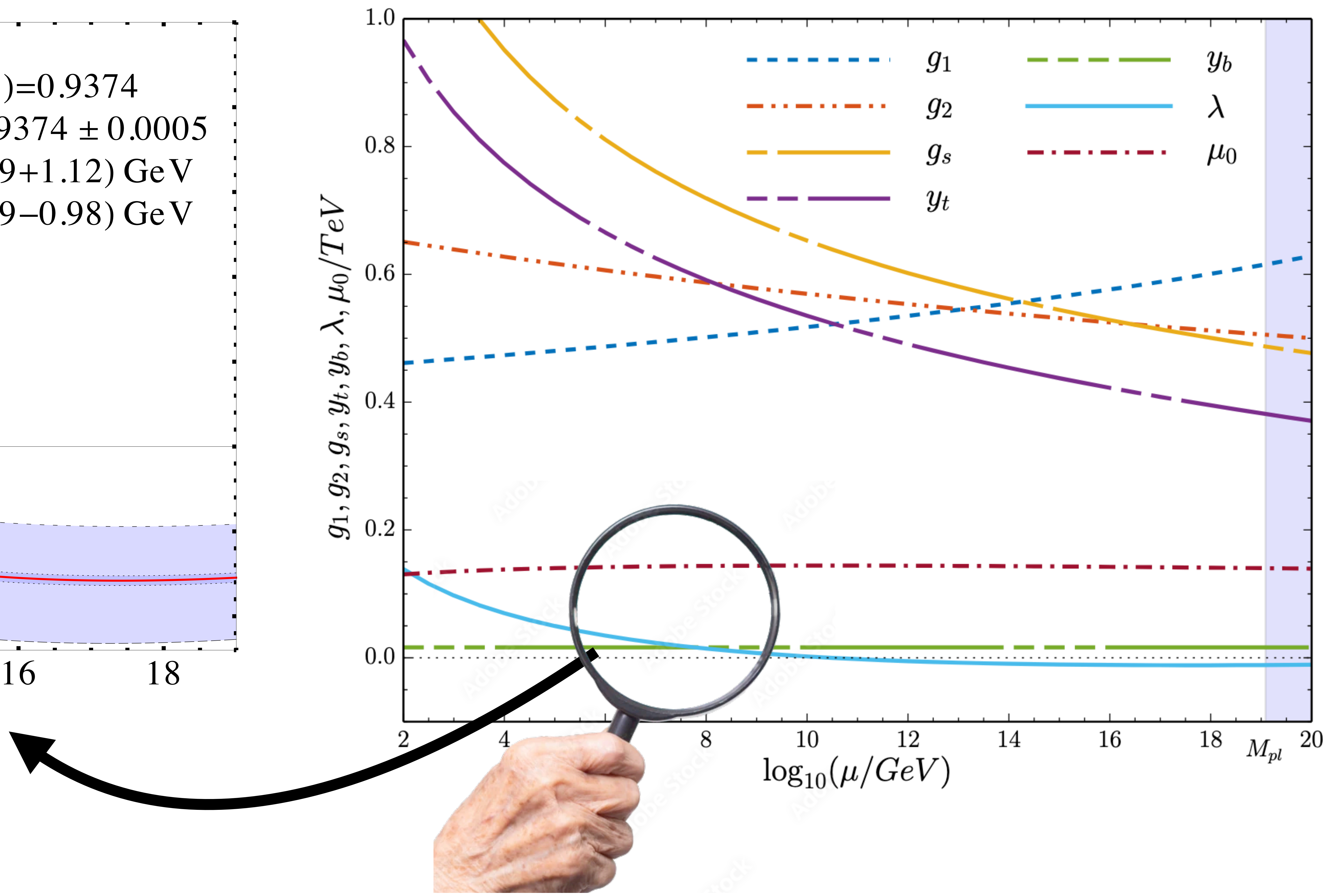


Running couplings

All couplings run! Incl. yukawas, trilinear

[Chetyrkin, Zoller, '16]

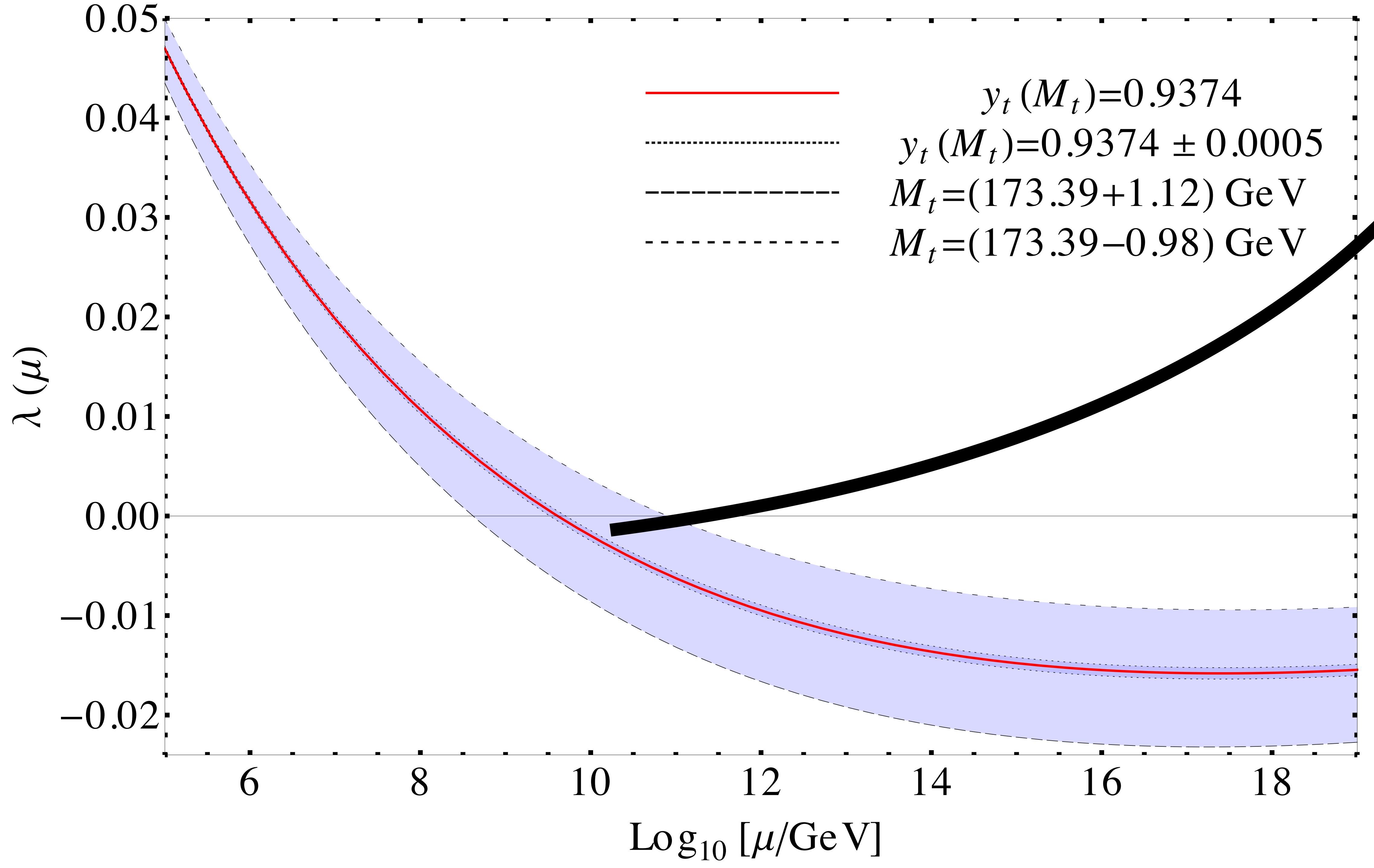


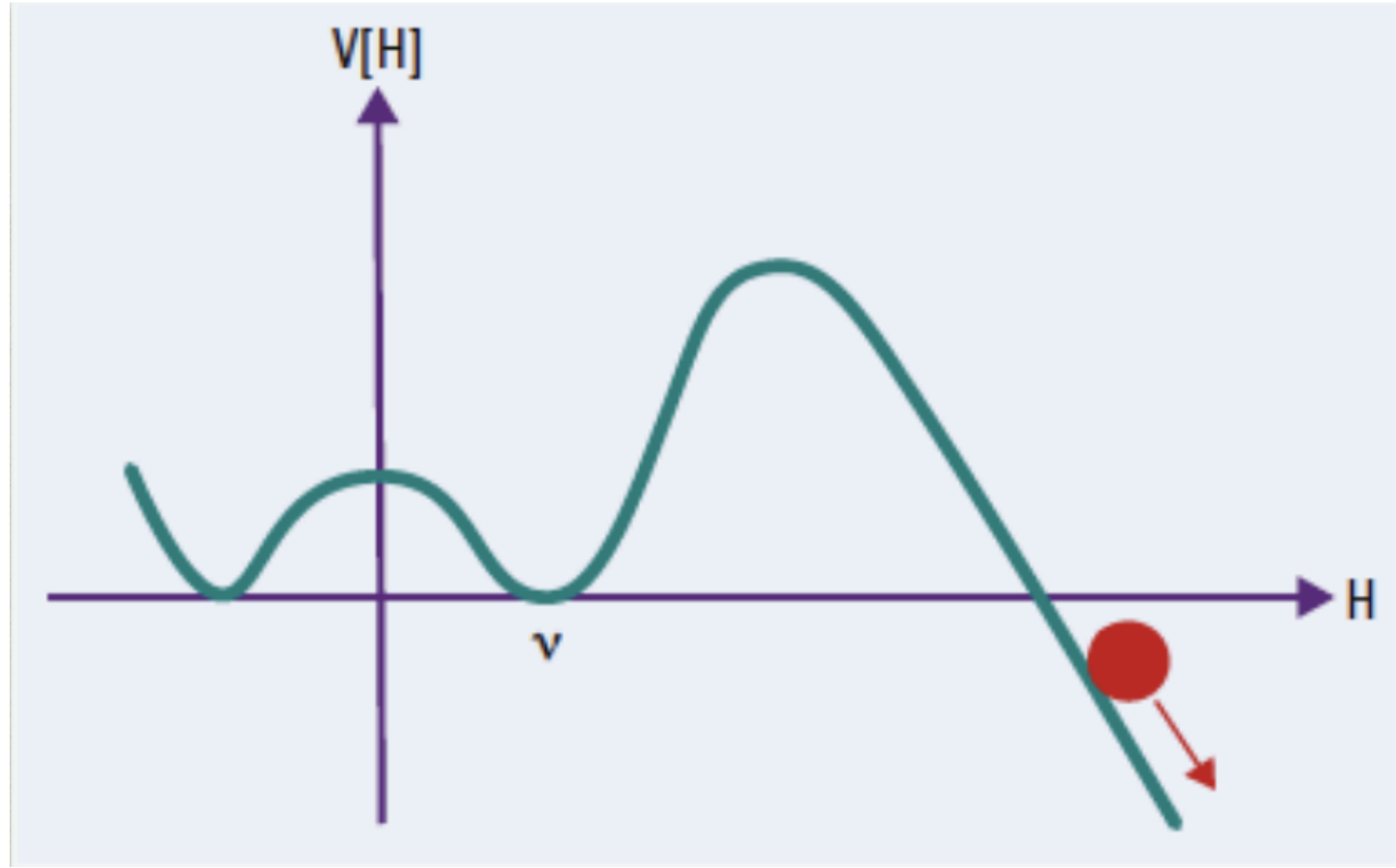


Running couplings

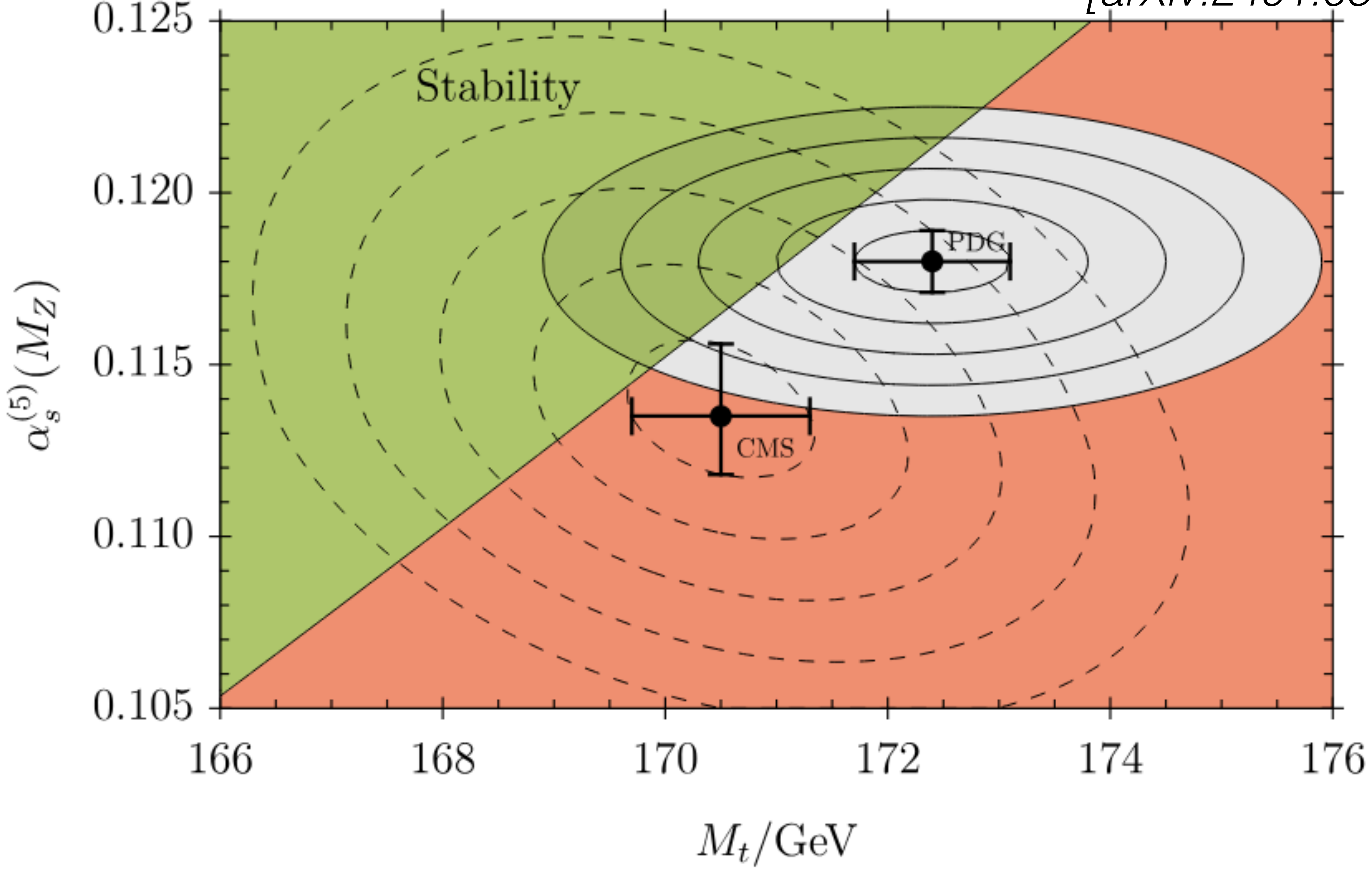
$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2$$

[Chetyrkin, Zoller, '16]





[arXiv:2401.08811]



➡Precise knowledge of top mass and α_S crucial!

The need for precision

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

NLO QCD O(100%)

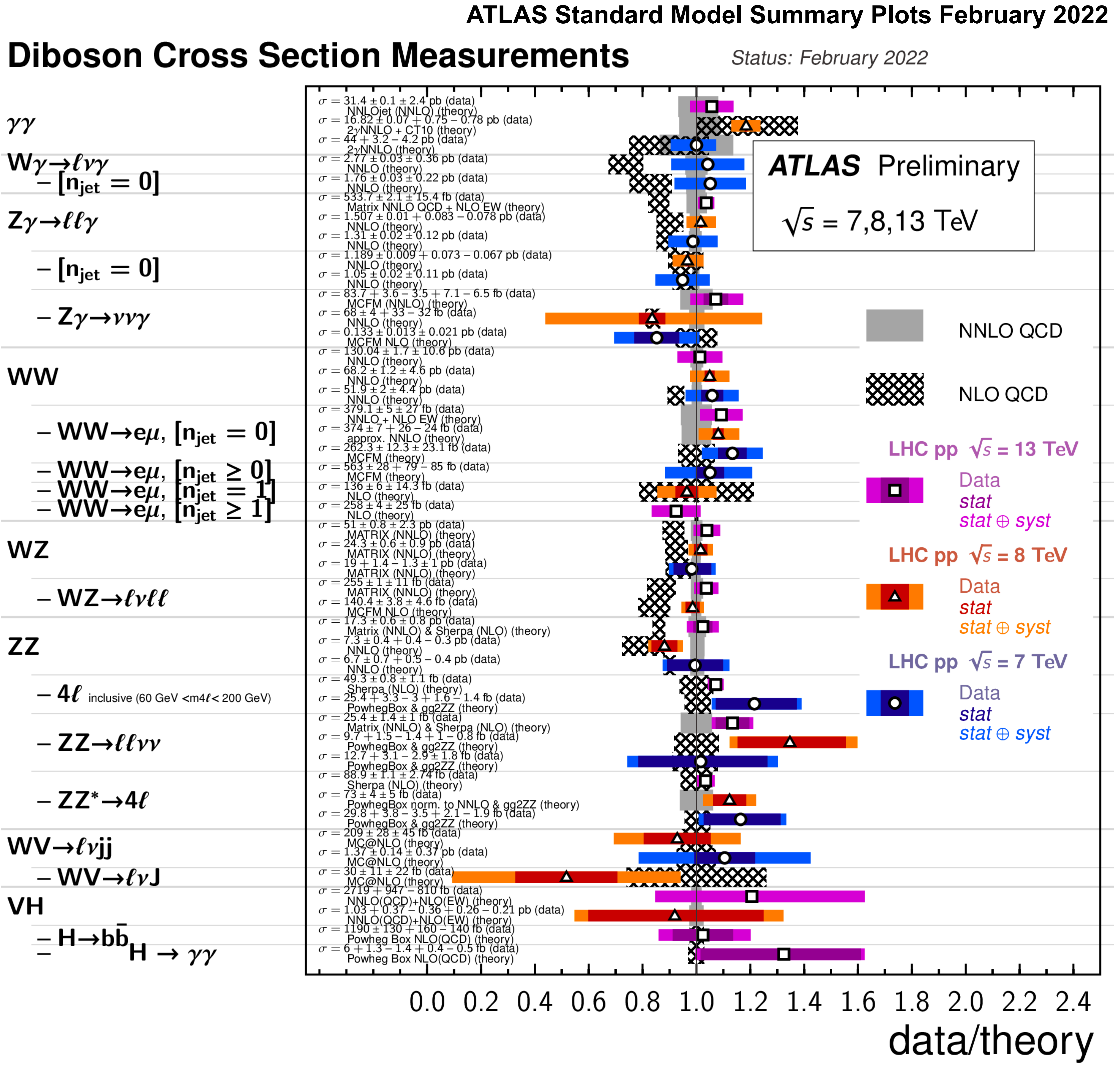
$$+\alpha_S^2 \, d\sigma_{\mathrm{NNLO}}$$

NNLO QCD O(10%)

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

N3LO QCD O(1%)

$\alpha_S \sim 0.1$



➡Higher-order predictions mandatory for reliable predictions

The need for precision

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

NLO QCD   NLO EW

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

NNLO QCD

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

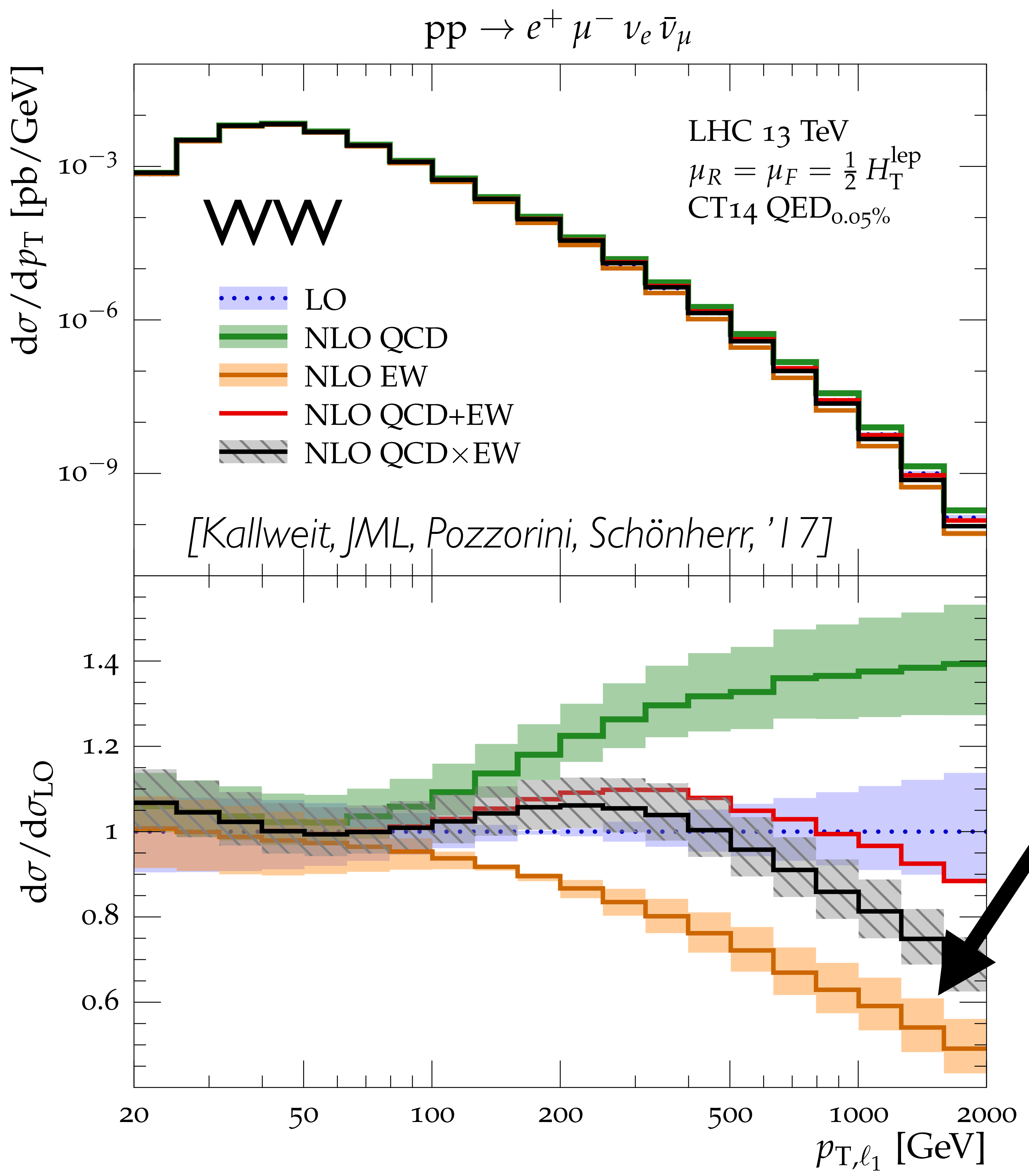
N3LO QCD

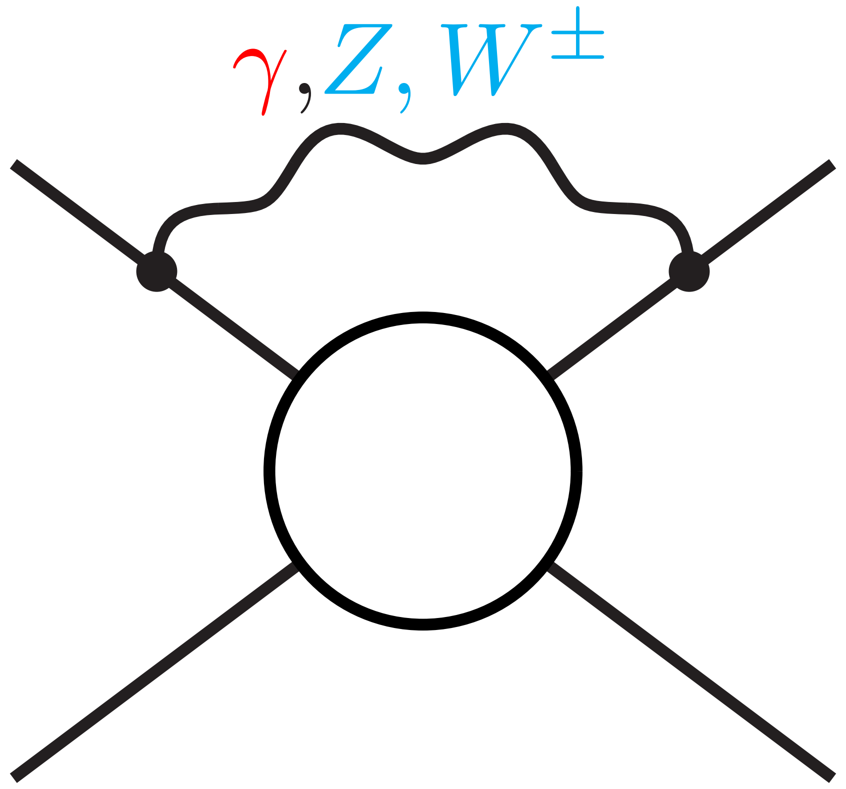
$\alpha_S \sim 0.1$ $\alpha_{\mathrm{EW}} \sim 0.01$ $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ NLO EW ~ NNLO QCD

➡Higher-order predictions mandatory for reliable predictions

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]

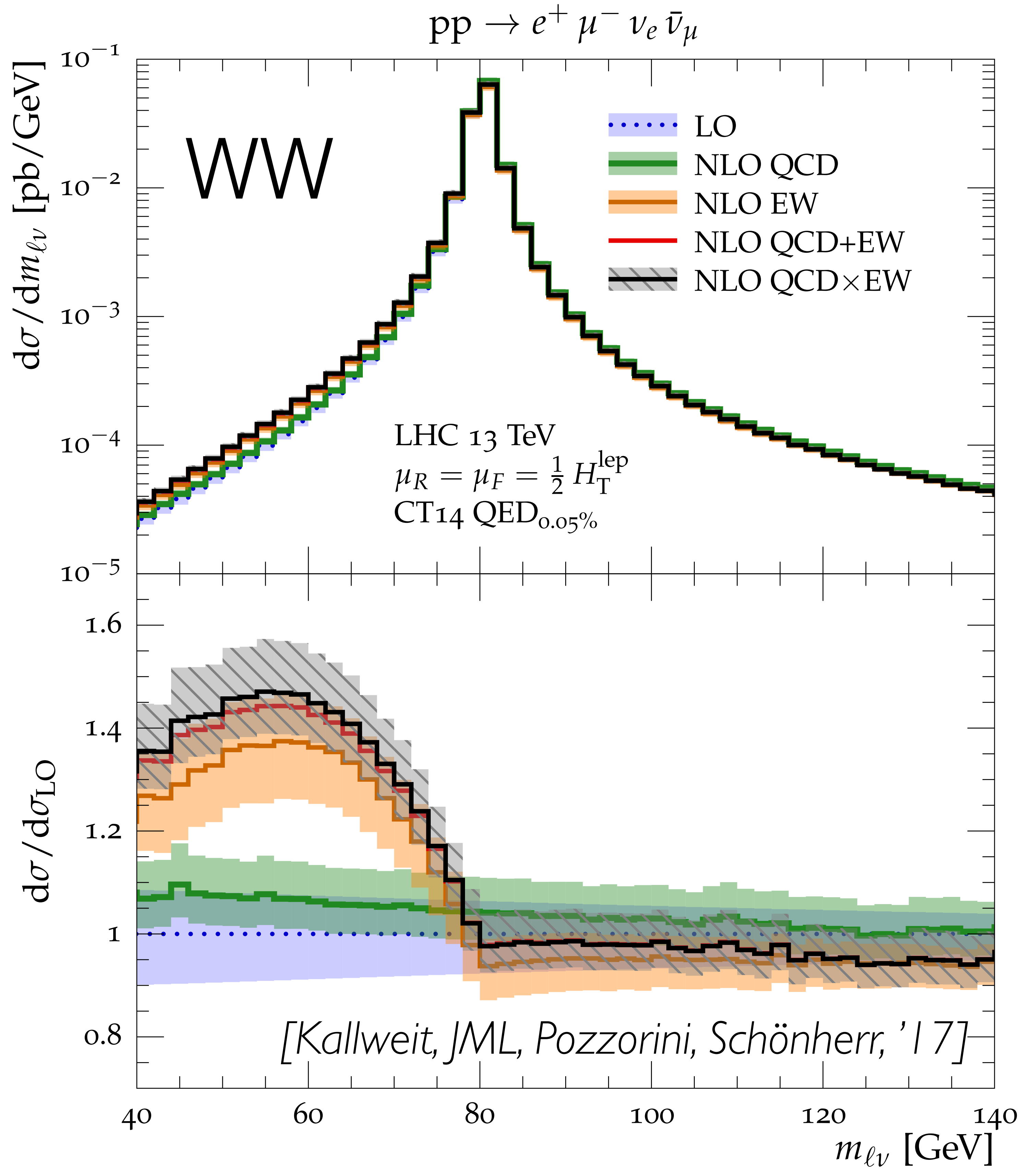
Universality and factorisation: *[Denner, Pozzorini; '01]*

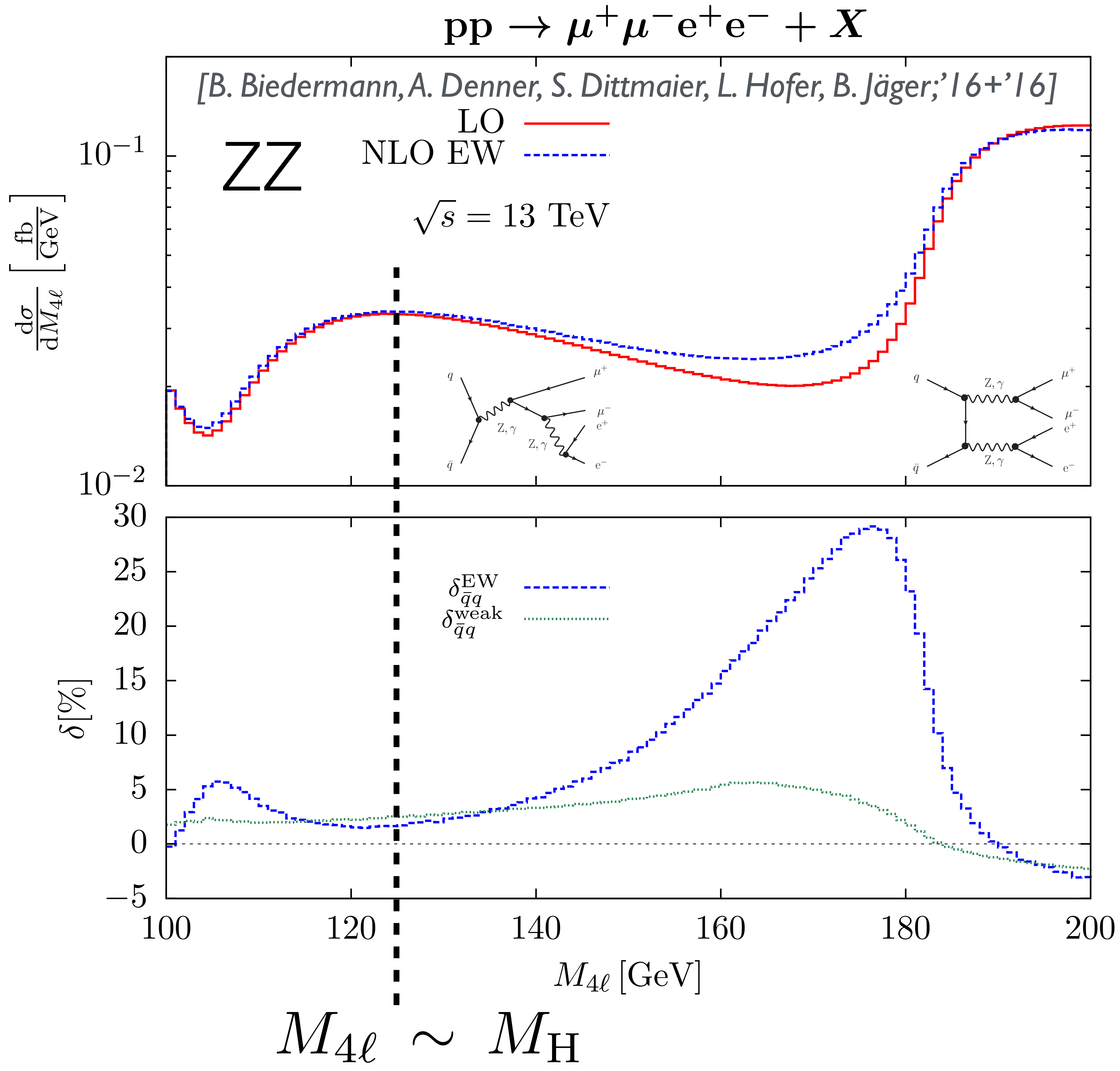
$$\delta\mathcal{M}^{1-\text{loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ 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.





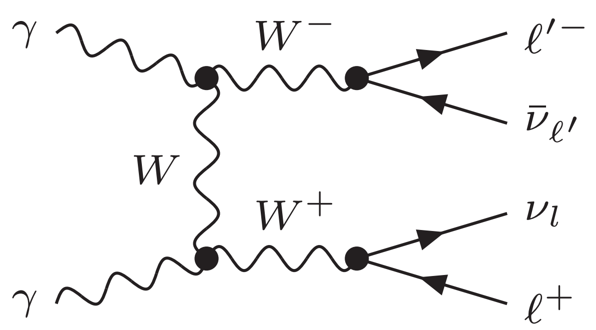
➜ important for radiative tails, Higgs backgrounds etc.

➜typically considered via QED PS (PHOTOS / YFS)

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

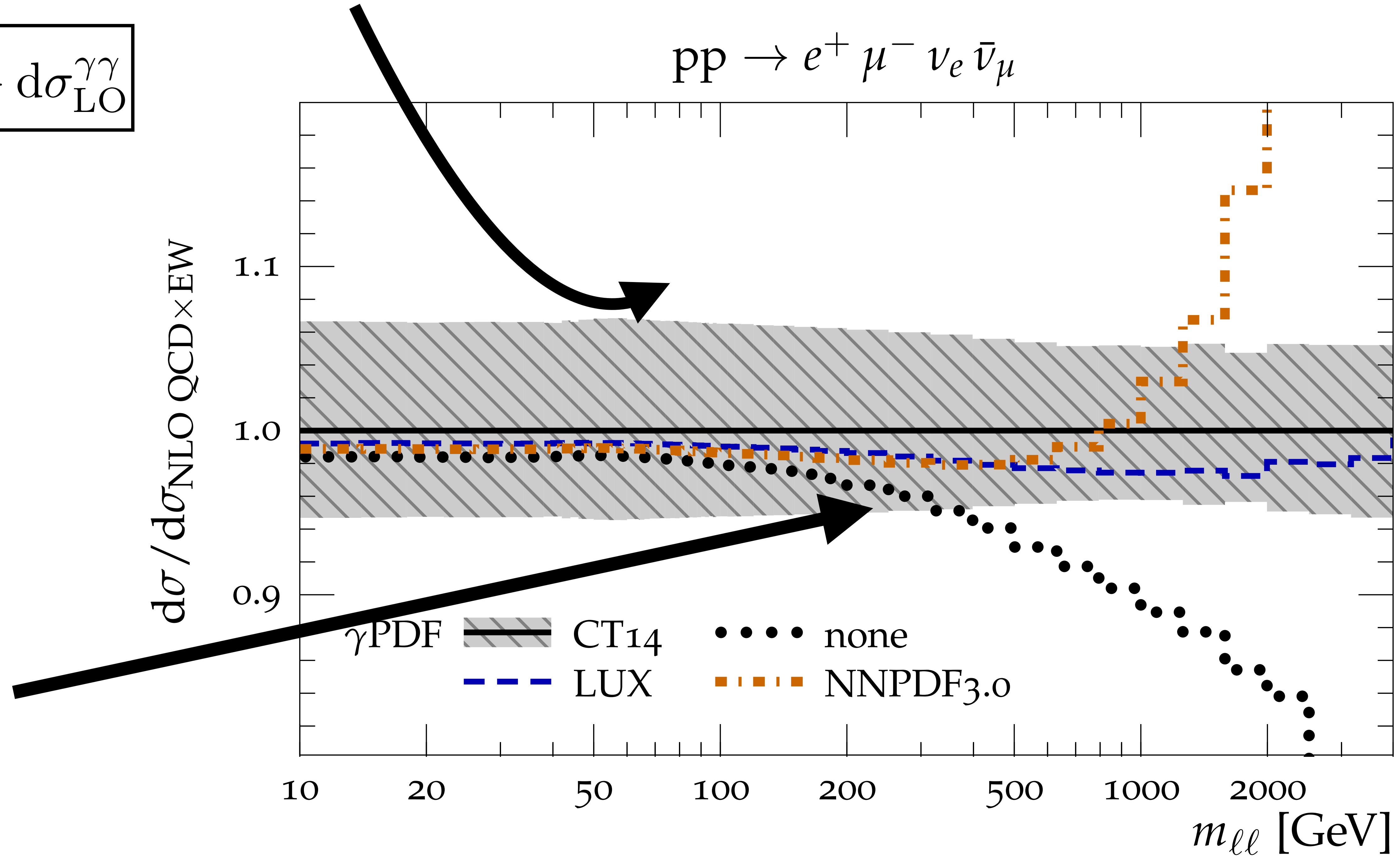
III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

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

in particular in WW: 

(t-channel enhancement)

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



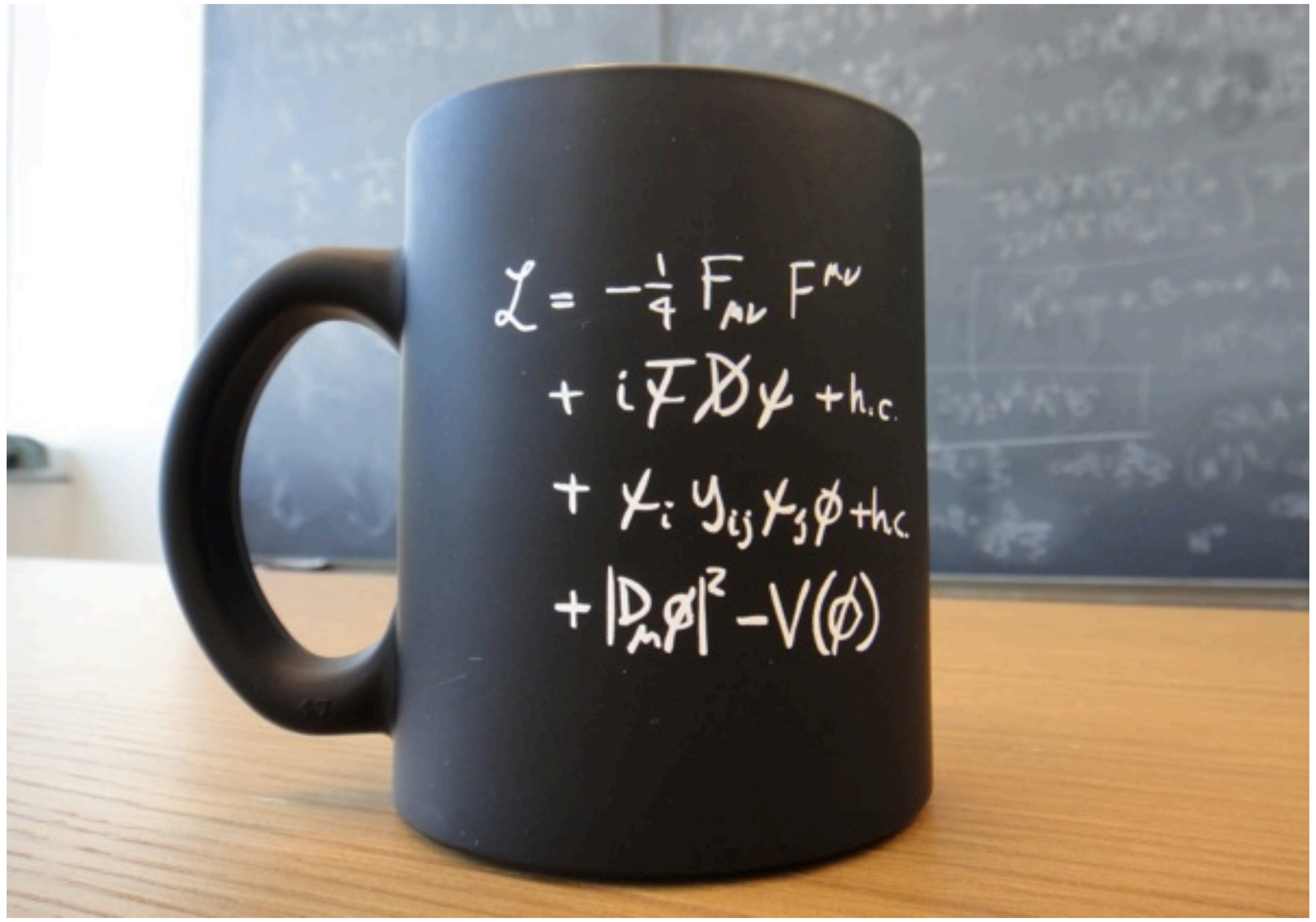
no γ

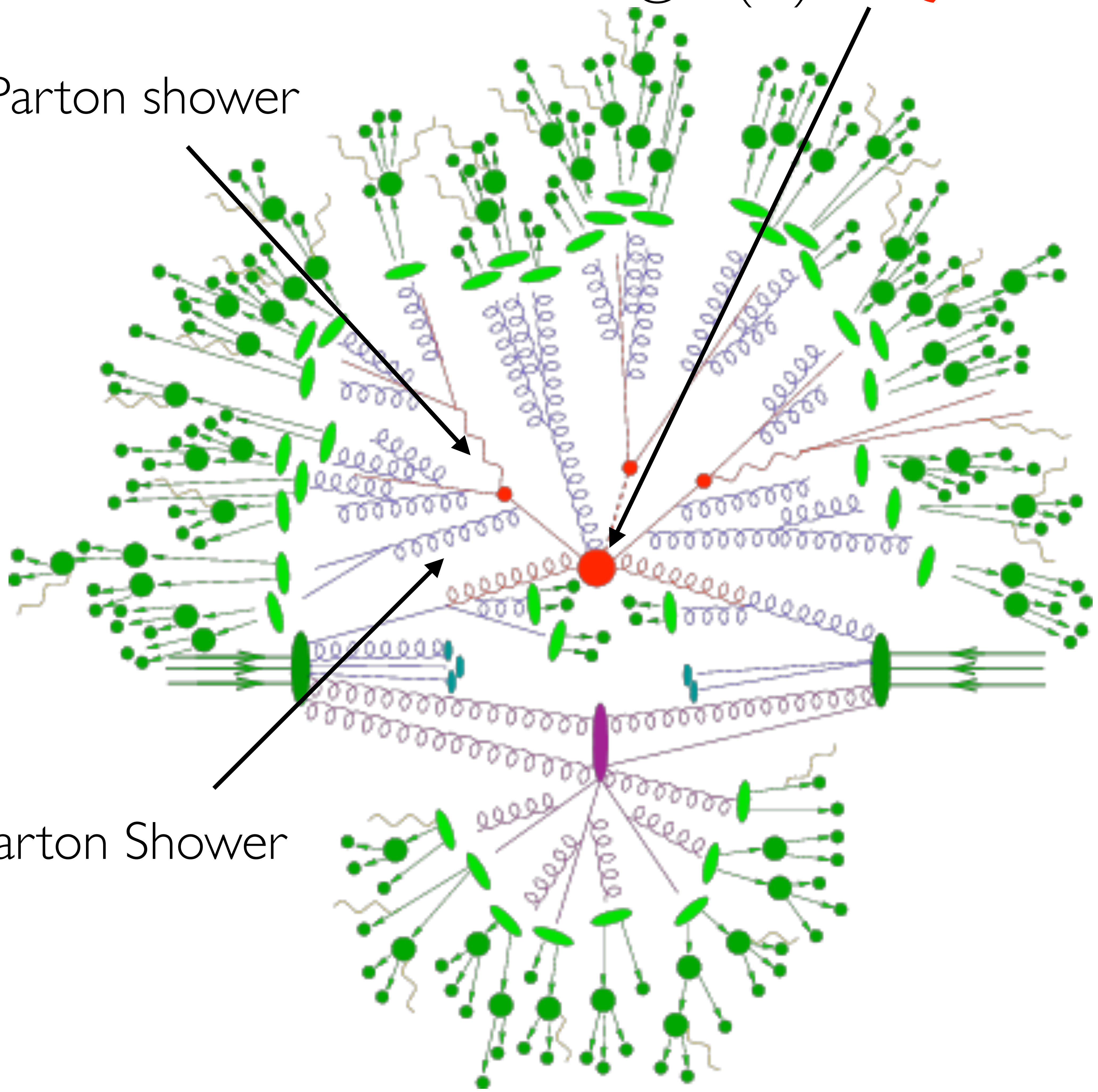
→ ask Gavin!

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

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

EW Theoretical Predictions for the LHC





The EW SM at quantum level in a nutshell

$$\mathscr{L}_{\rm SM}^{\rm classical} = \mathscr{L}_{\rm YM} + \mathscr{L}_{\rm Dirac} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yukawa}$$

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)

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

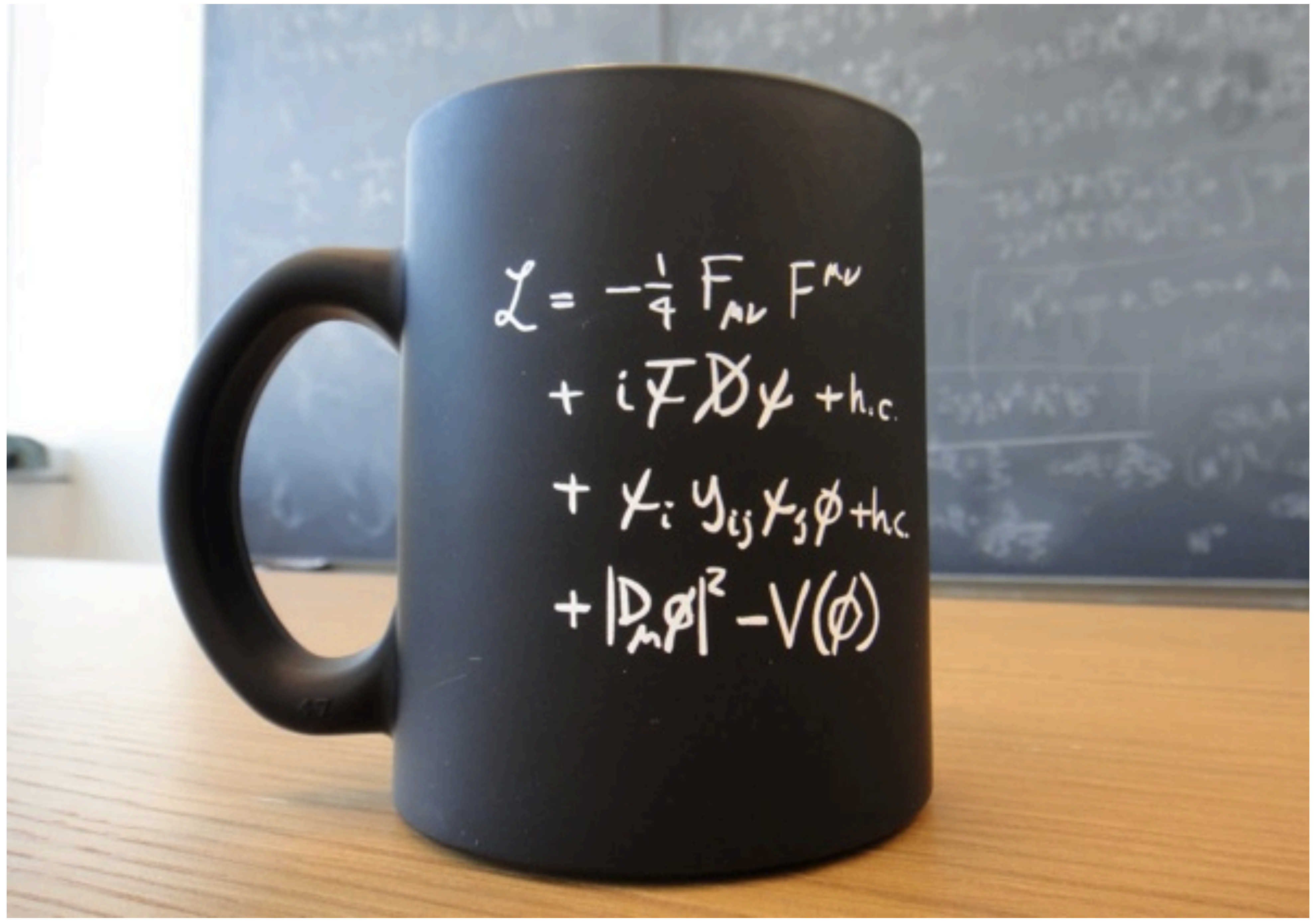
$$\mathcal{L}_{\rm ghost} = \bar{u}^\alpha(x)\frac{\delta F^\alpha}{\delta\theta^\beta(x)}u^\beta(x)$$

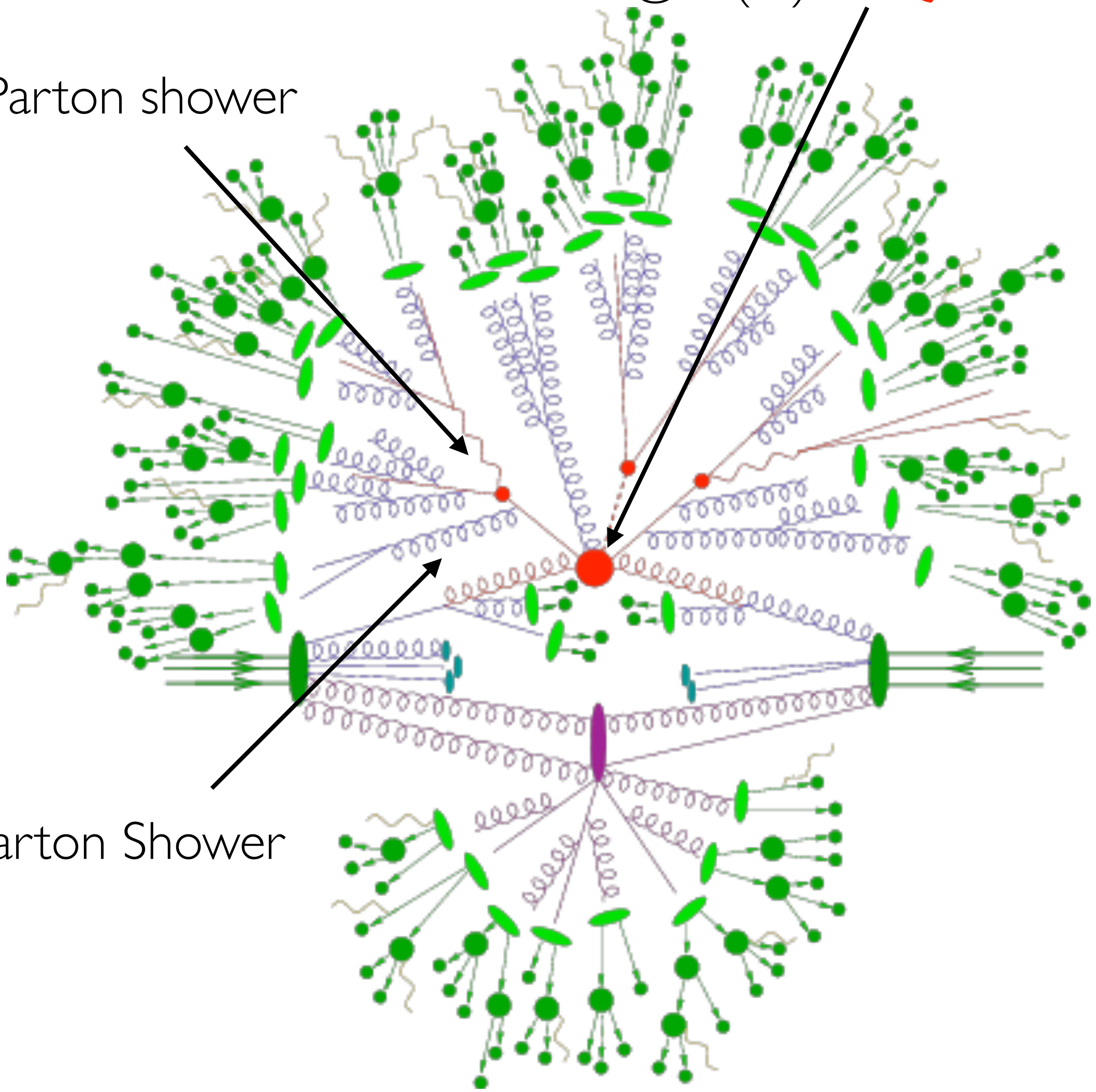
$$F_A = \frac{1}{\xi^A}\partial^\mu A_\mu\,, \qquad F_{G^a} = \frac{1}{\xi^G}\partial^\mu G^a_\mu\,,$$

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

Gauge fixing parameter

EW Theoretical Predictions for the LHC



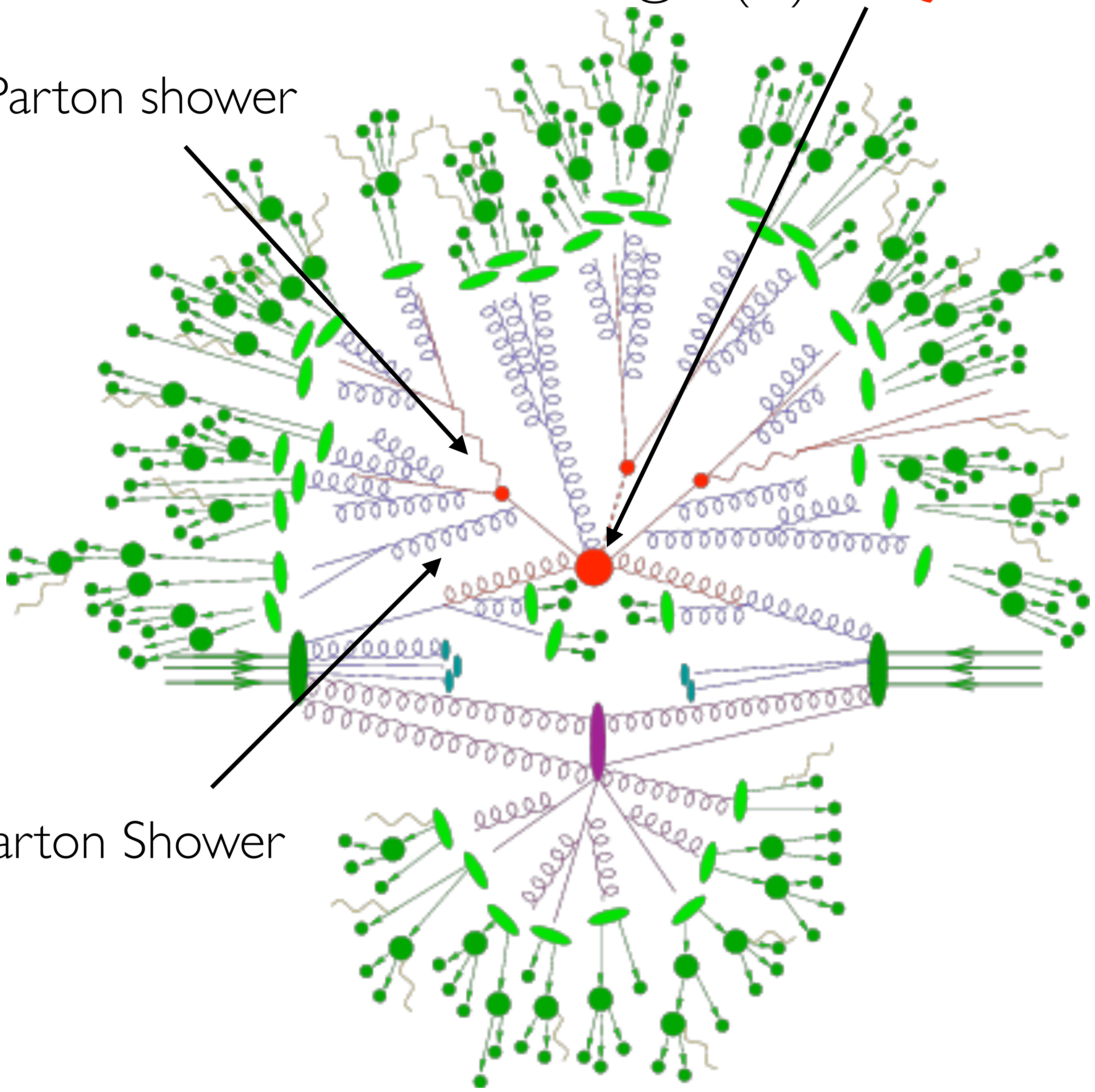


EW Theoretical Predictions for the LHC

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

$$
\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_w MA_\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_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\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^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\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^2 s_w^2 A_\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_w A_\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) - \\
\overline{\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^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\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^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^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^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\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}^0 X^0 H\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}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

QED Parton shower



QCD Parton Shower

NLO Ingredients

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

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

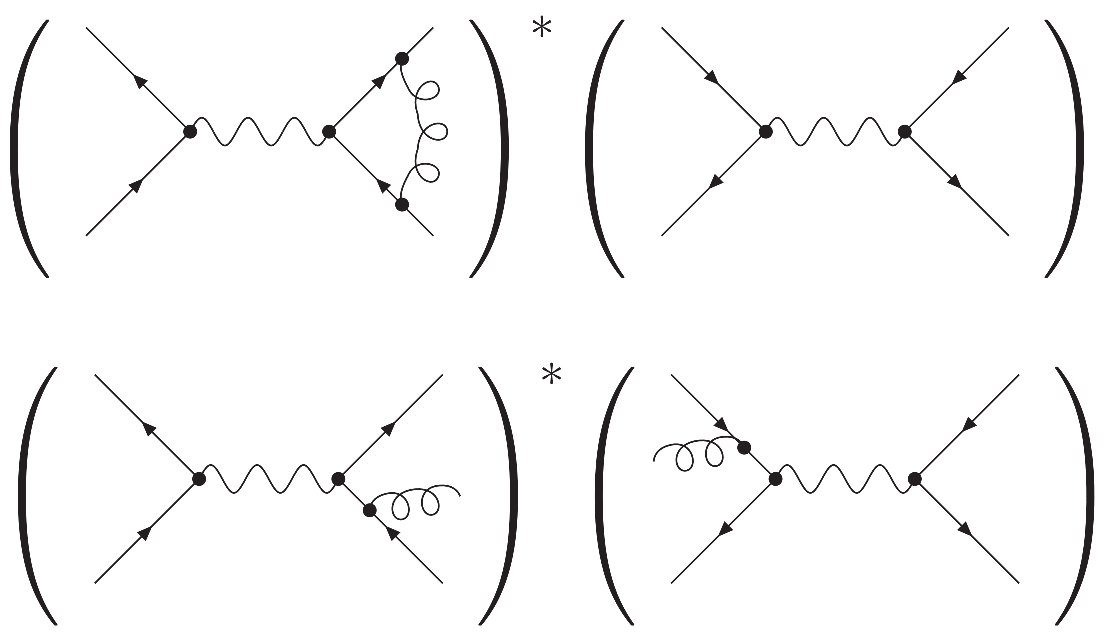
NLO = B + V +R

$\int d\Phi_{n(+1)}$ 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

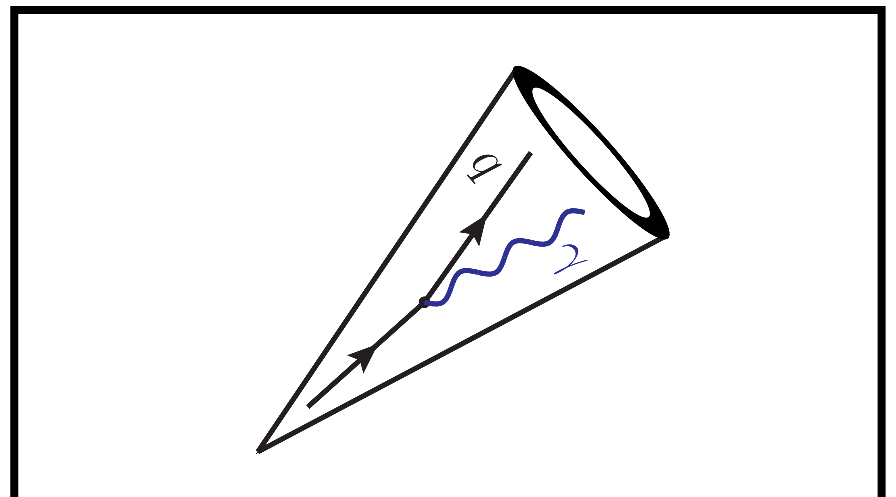
- Add local subtraction terms S, and corresponding integrated subtraction term I

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

- 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
  - …

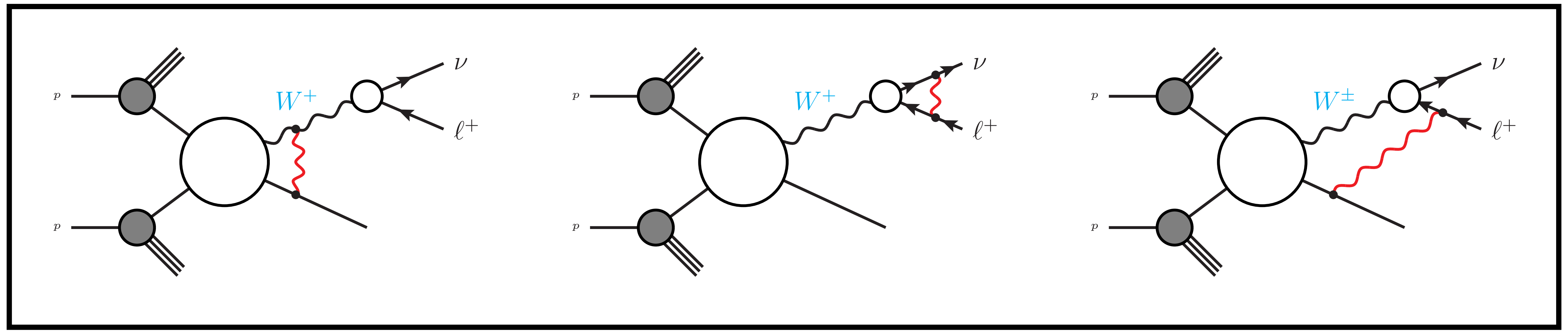
Nontrivial features in NLO QCD → NLO EW

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

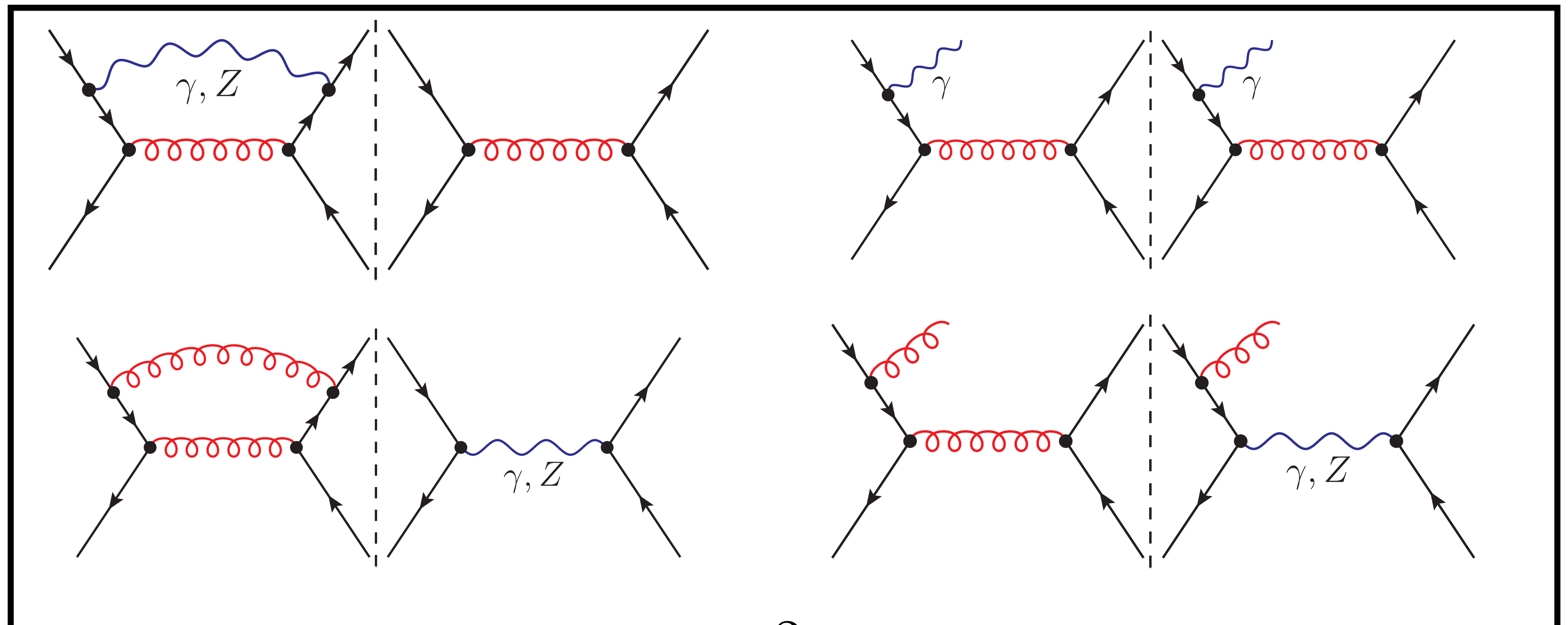


collinear q → qγ singularities

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

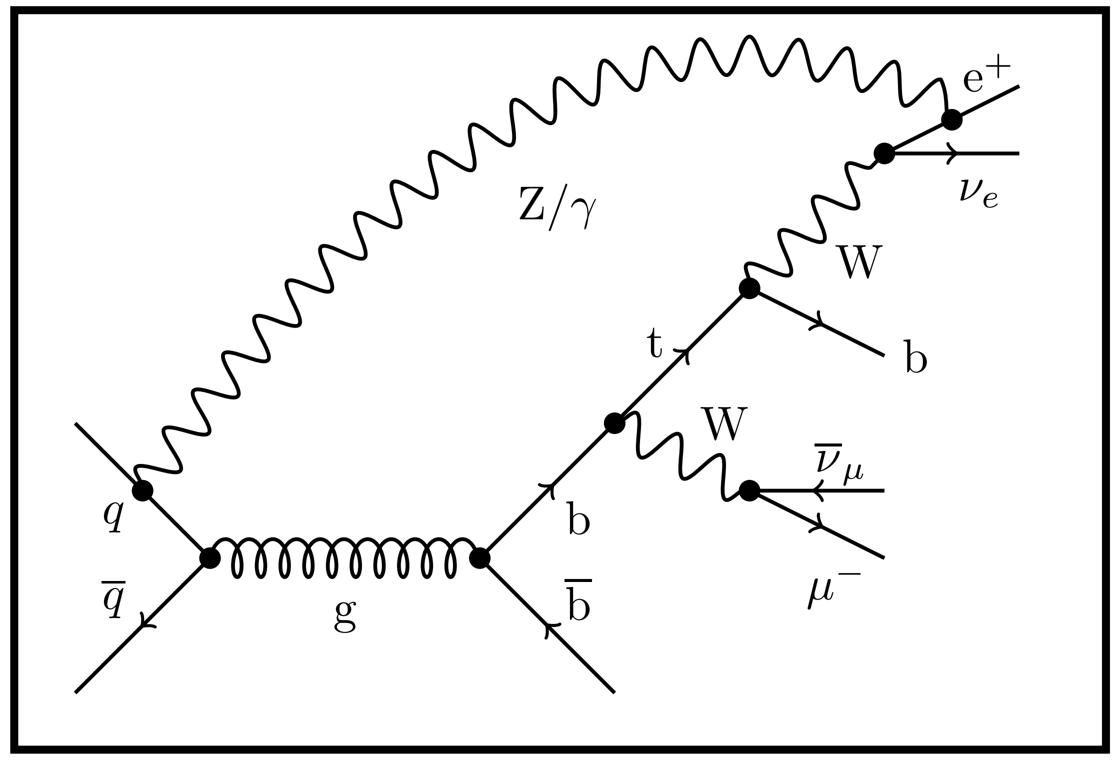


3. **QCD-EW interplay**

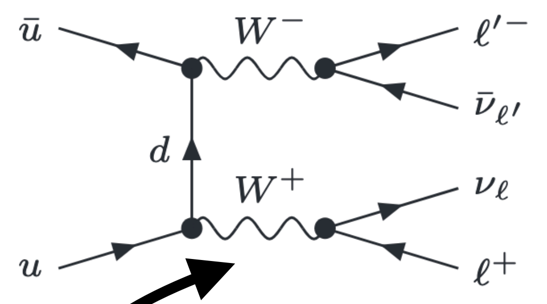


$O(\alpha_S^2\alpha)$

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

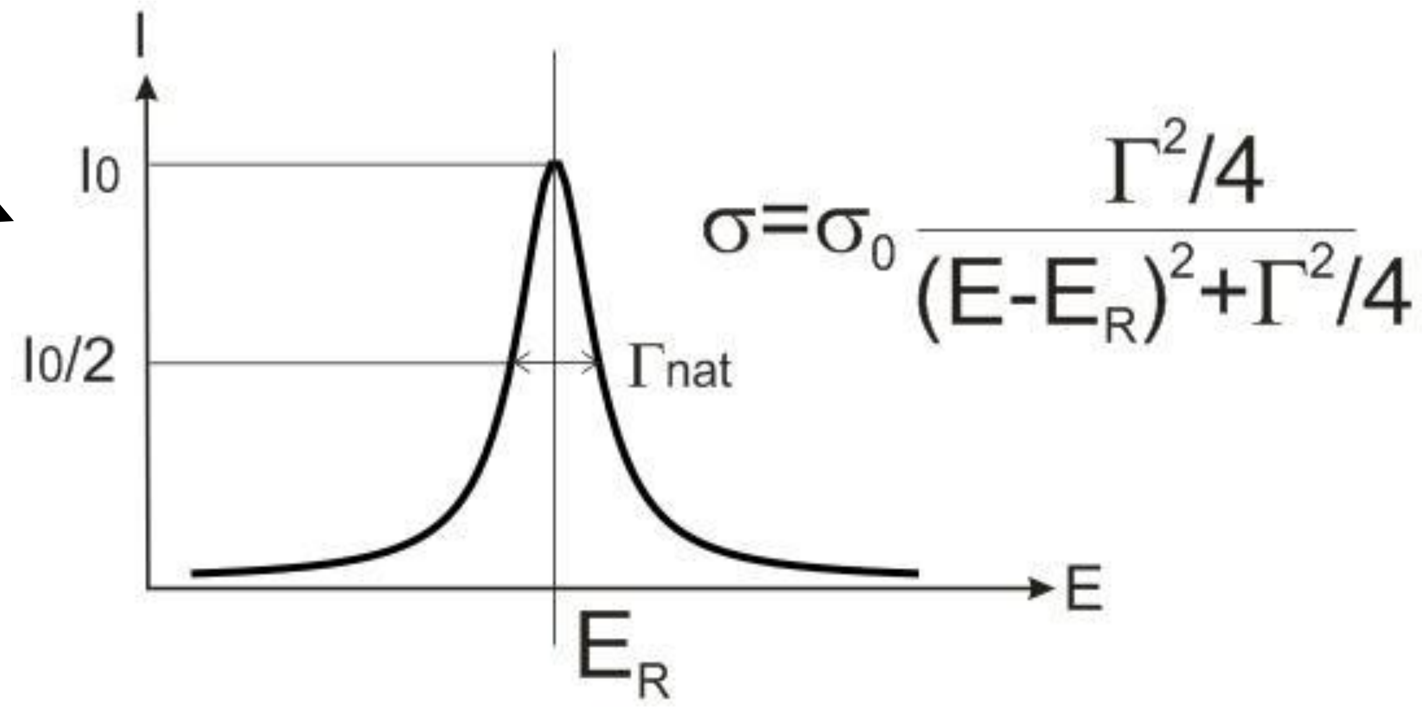


Decays of heavy particles



propagator ~ $\dfrac{1}{p^2 - M^2}$

- Naively processes with a massive s-channel propagator diverge when $p^2 = M^2$
- Experimentally we know resonances follow **Breit-Wigner** (BW) shape



Decays of heavy particles

- Naively processes with a massive s-channel propagator diverge when $p^2 = M^2$
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- origin: all-order summation of 1PI corrections to propagator of massive particles

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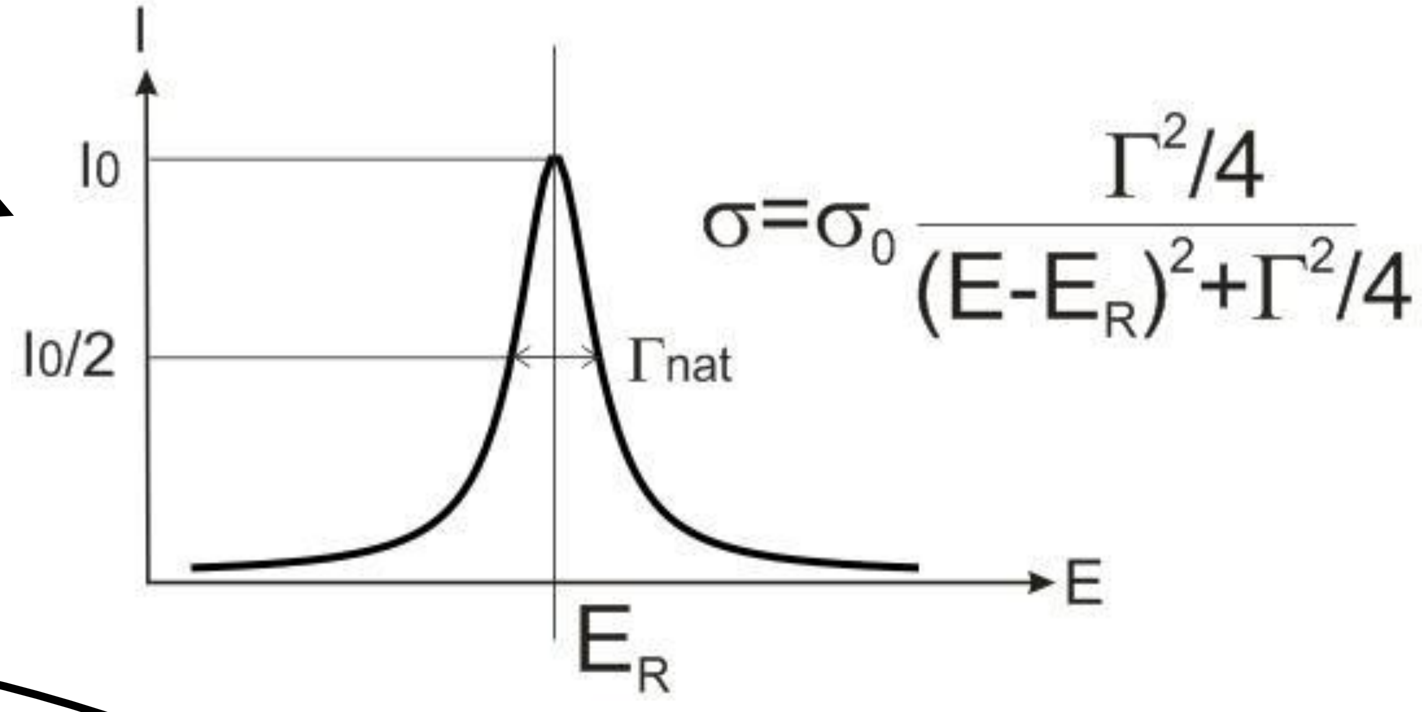
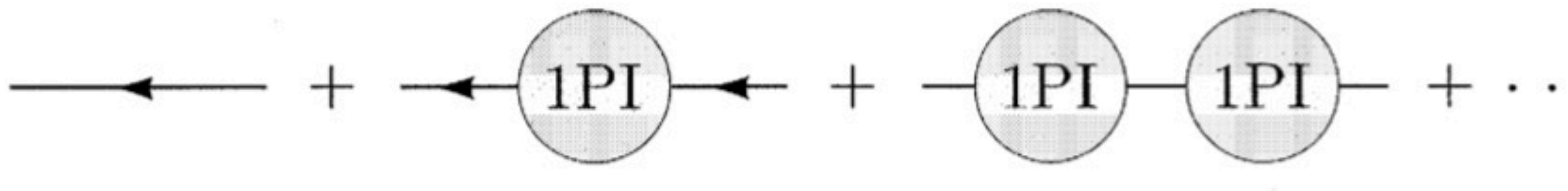


propagator ~



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

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→

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

Decays of heavy particles

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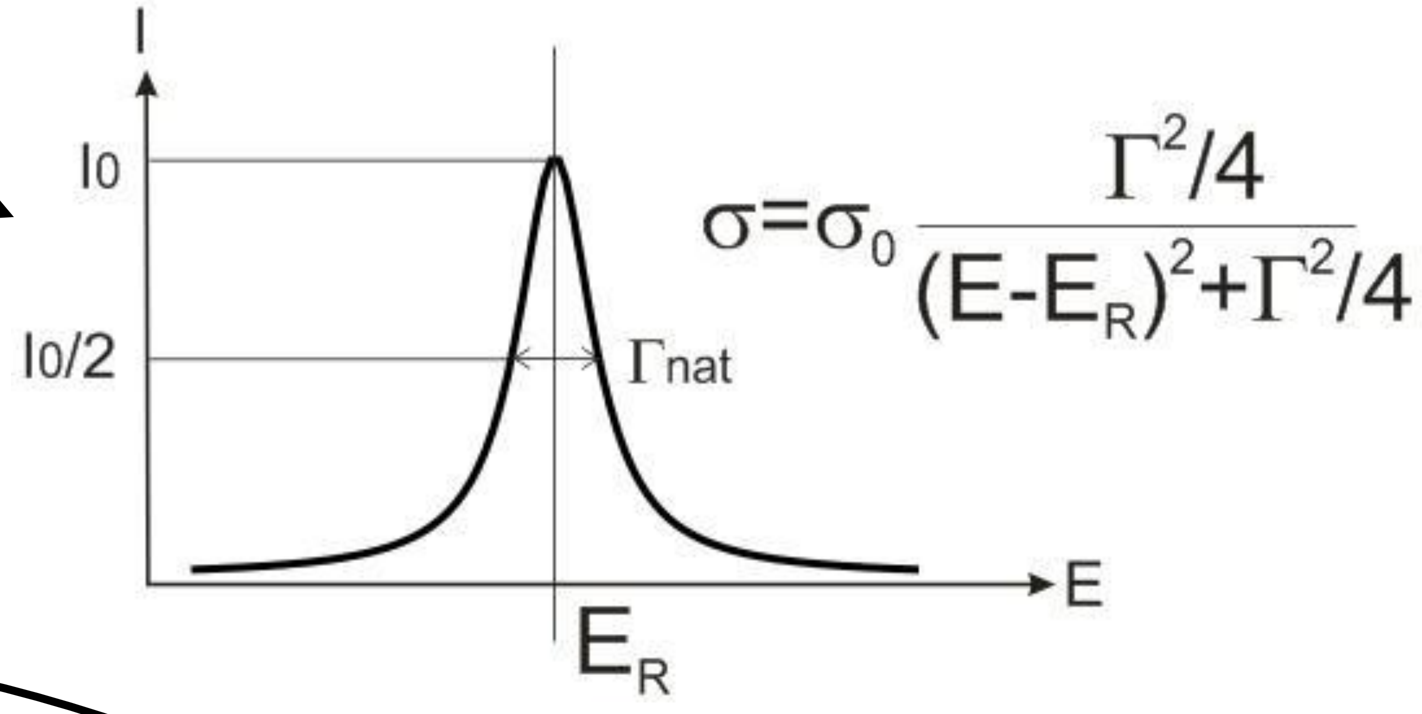
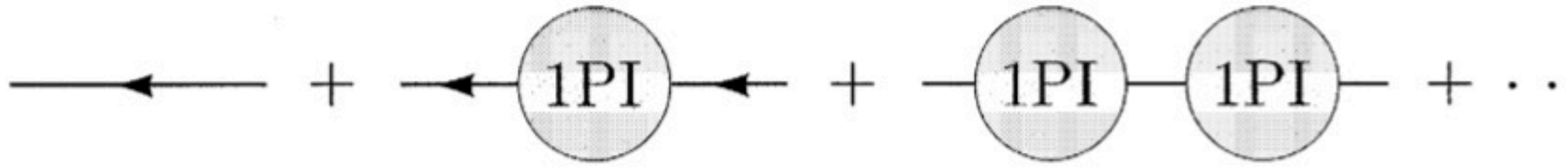


propagator ~ 

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

Geometric series

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

Optical theorem→

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

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

Decays of heavy particles

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

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

  ➡ Advantage: reduces complexity in NLO computation
  ➡ However: unable to capture off-shell effects

- **Complex Mass Scheme (CMS):** $M \to \mu = M - i\Gamma M$ analytical continuation at Lagrangian level
  ➡ regularises propagators (effects also propagator numerators)
  ➡ effects 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

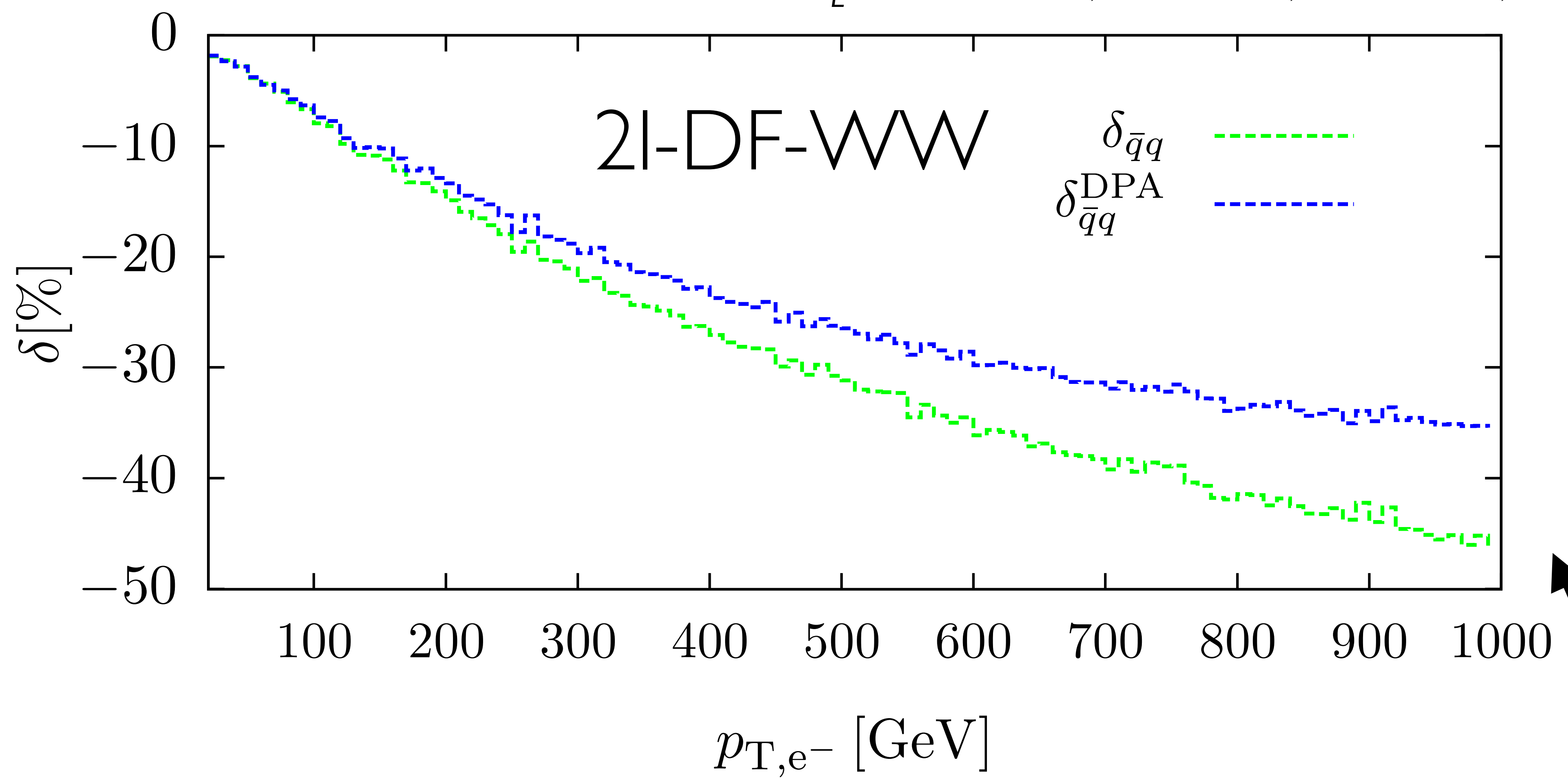
Renormalised self-energy:

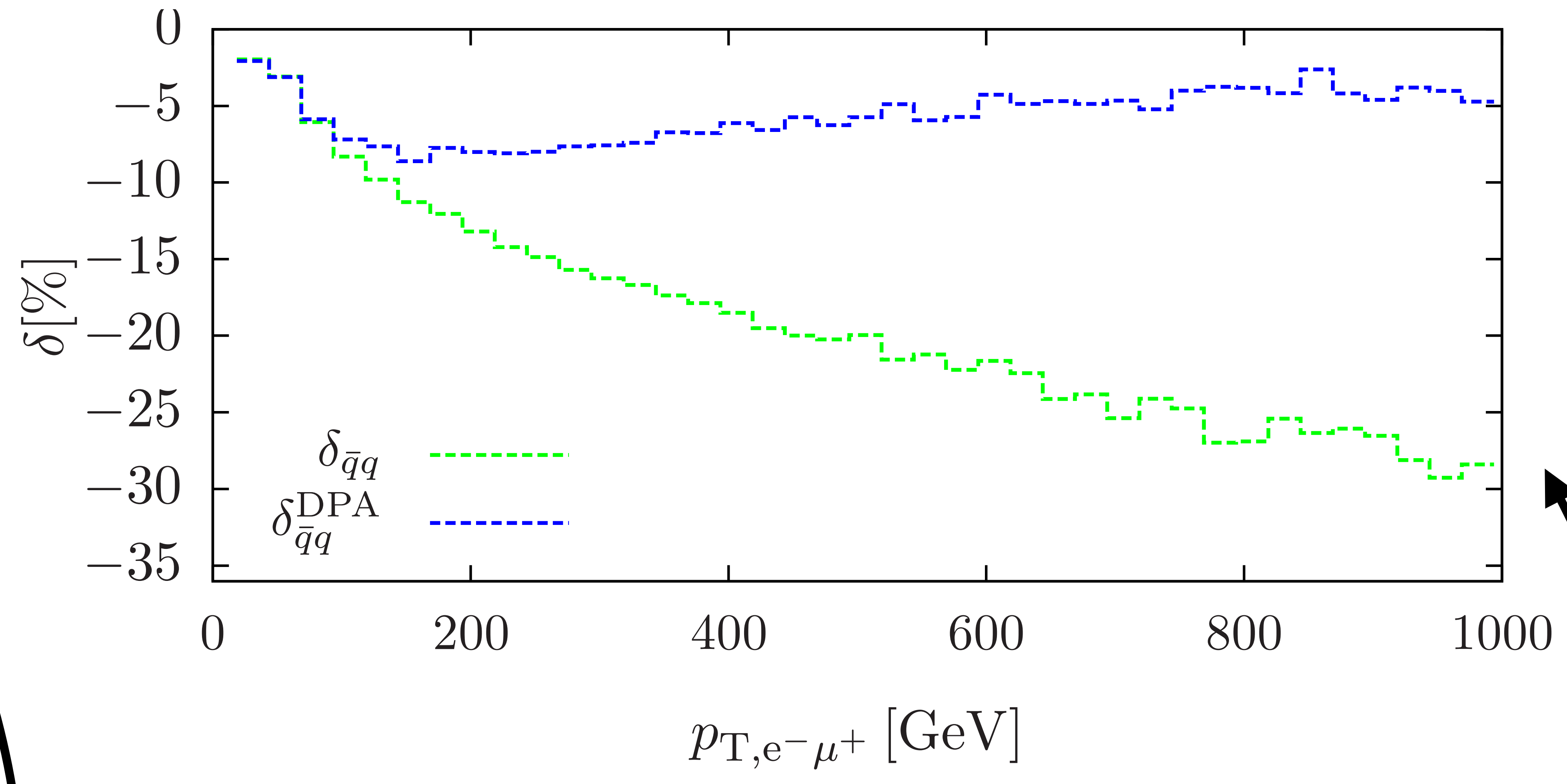
$$\hat{\Sigma}^i(p^2) = \Sigma^i(p^2) - \delta\mu_i^2$$

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

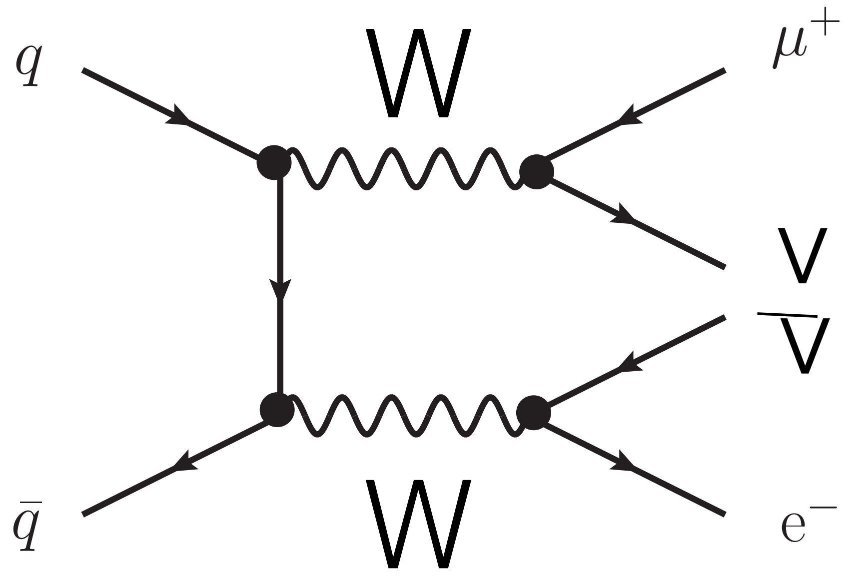
The need for off-shell computations: VV

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



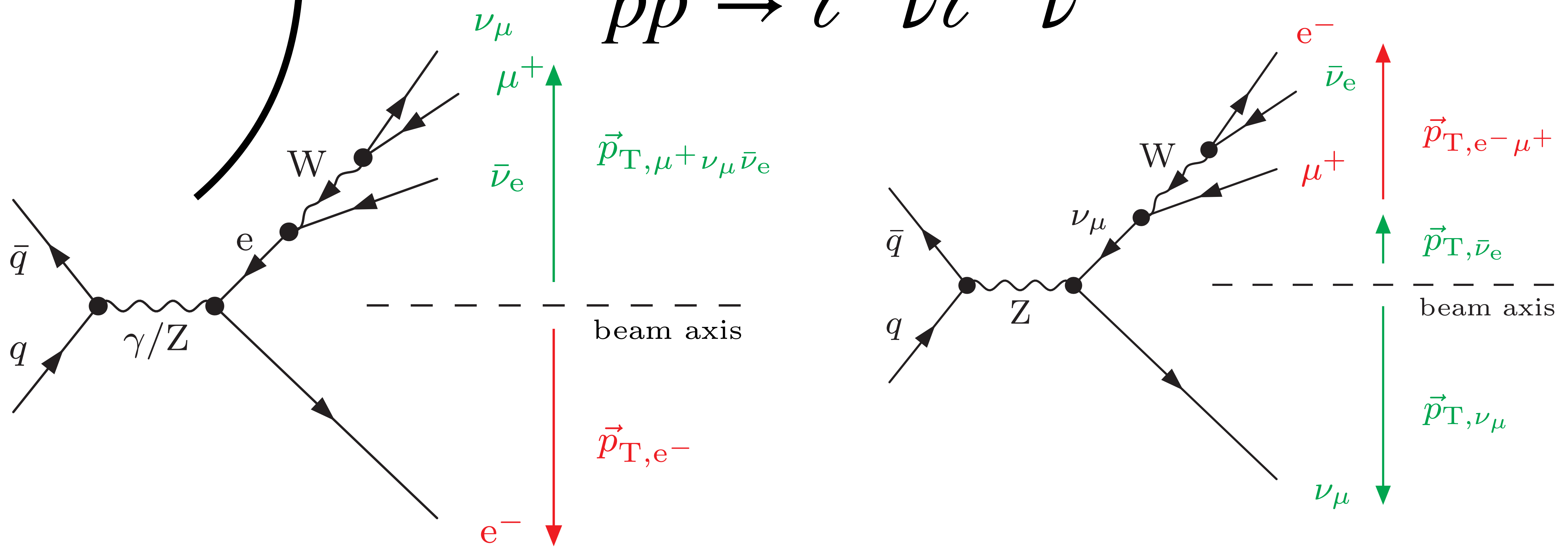


$pp \to W(\ell^+\nu)W(\ell'^-\bar{\nu}')$



VS.

$pp \to \ell^+\nu\ell'^-\bar{\nu}'$



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

Perturbative expansion: revised

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

NLO QCD NLO EW

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

NNLO QCD

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

dedicated MC's: Matrix, …

Perturbative expansion: revised

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NLO QCD NLO EW

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

? ?

NNLO QCD NNLO EW NNLO QCD-EW

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

?

N3LO QCD

scale variation at NNLO

Perturbative expansion: revised

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

dedicated MC's: Matrix, …

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

NLO QCD   NLO EW

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

NNLO QCD   NNLO EW ?   NNLO QCD-EW ?

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

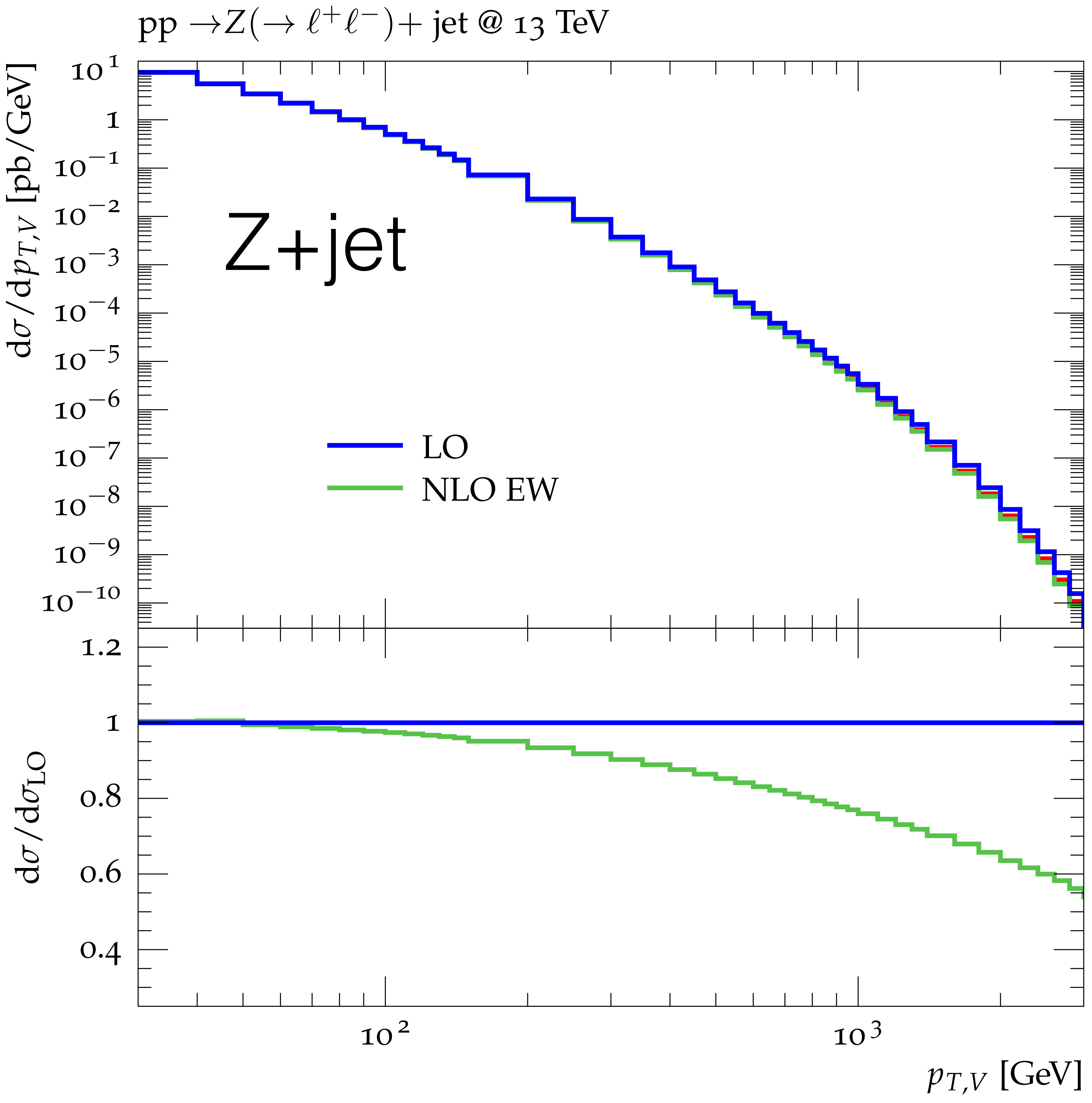
N3LO QCD ?

scale variation at NNLO

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

sufficient?

EW uncertainties: Sudakov

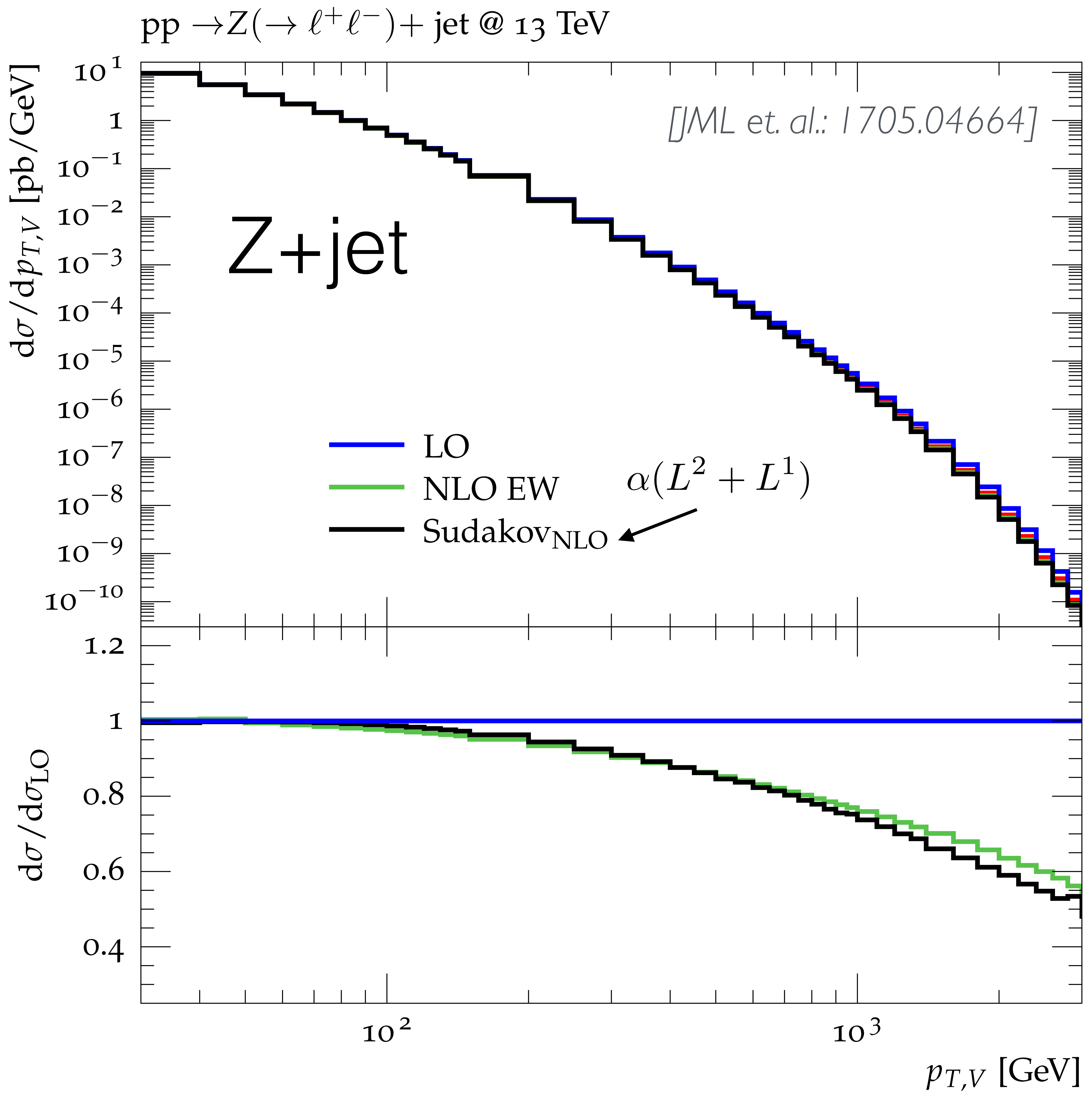


EW corrections become sizeable at large $p_{T,V}$: -30% @ 1 TeV

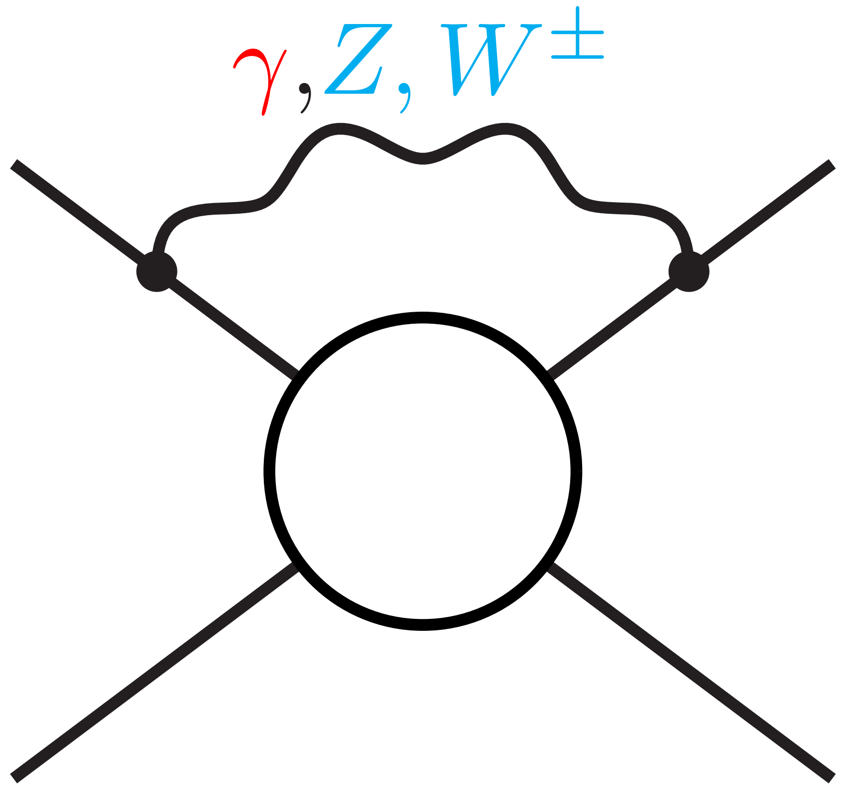
Origin: virtual EW Sudakov logarithms

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

EW uncertainties: Sudakov



Large EW corrections dominated by Sudakov logs

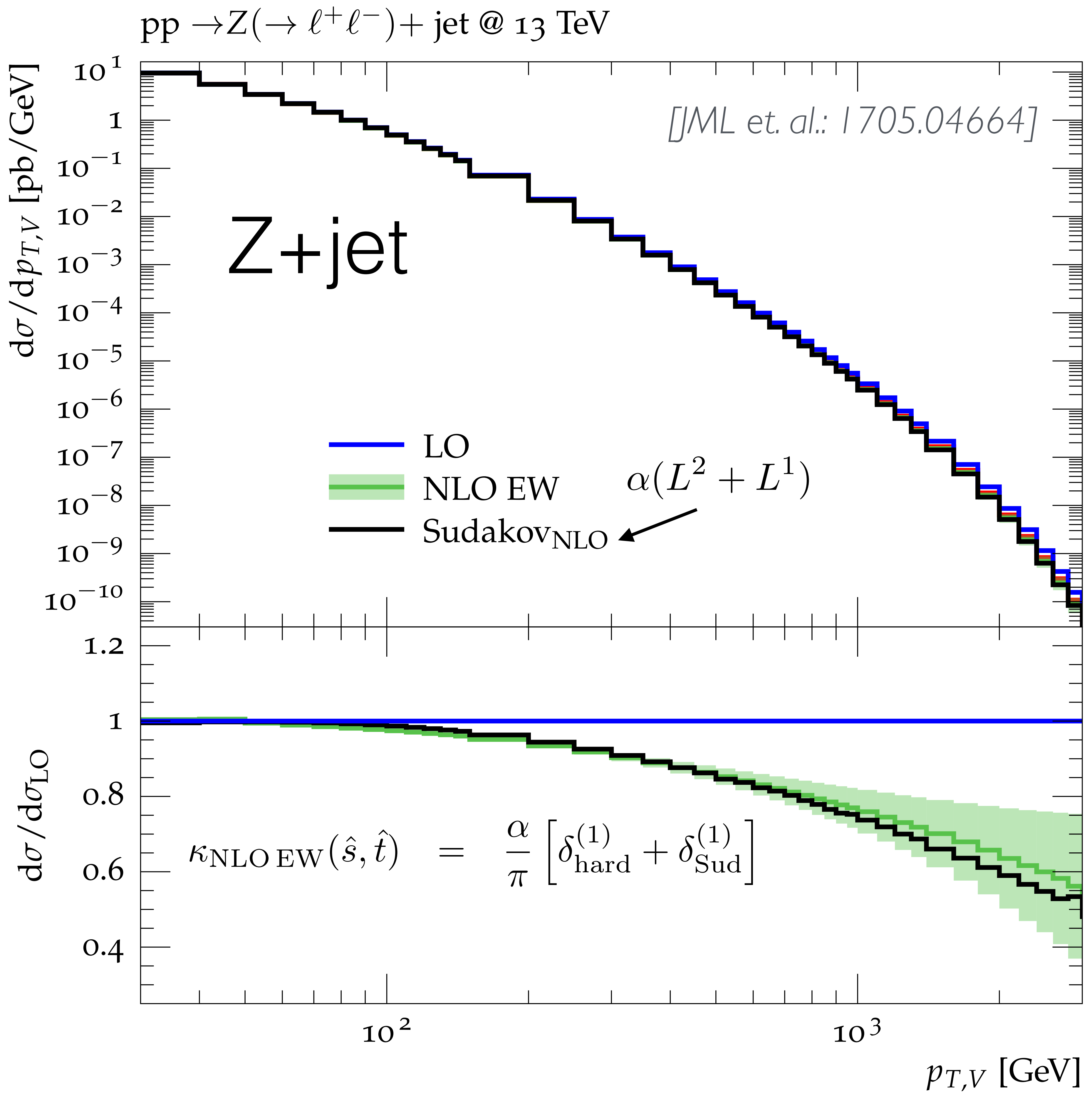


[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]

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



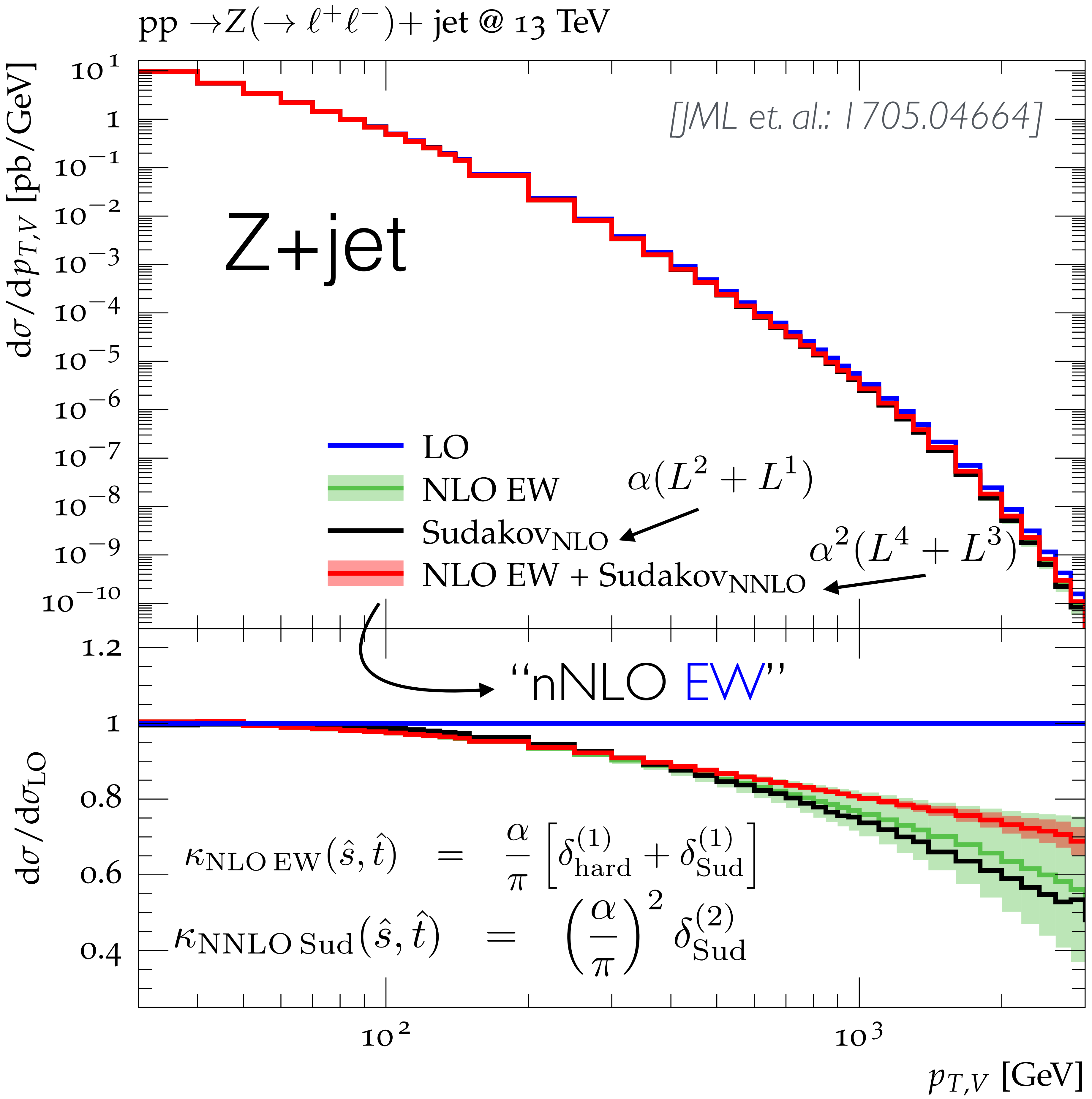
Large EW corrections dominated by Sudakov logs

↓

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

$$\Delta_{\mathrm{EW}}^{\mathrm{Sud}} \approx \left(k_{\mathrm{NLOEW}}\right)^2$$

EW uncertainties: Sudakov



Large EW corrections dominated by Sudakov logs

↓

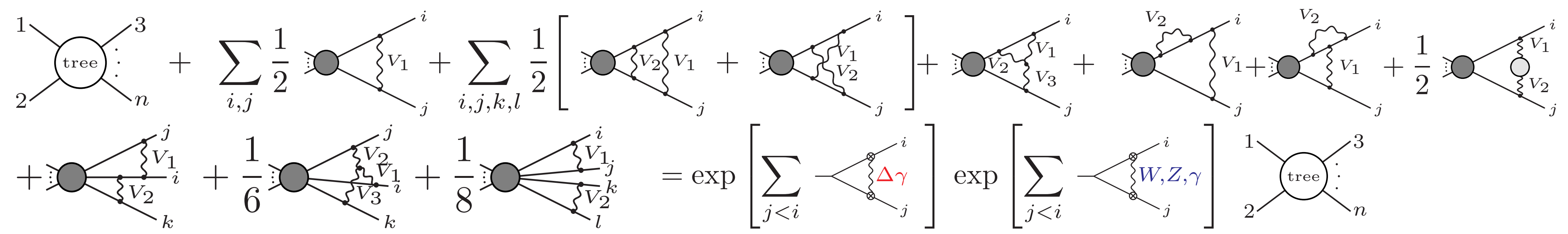
Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

$$\Delta_{\rm EW}^{\rm Sud} \approx (k_{\rm NLOEW})^2$$

↓

check against two-loop Sudakov logs

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



$$\Delta_{\rm EW}^{\rm hard} \approx \mathcal{O}(1\%)$$

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

Perturbative expansion: revised

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

dedicated MC's: Matrix, …

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

NLO QCD   NLO EW

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

NNLO QCD   NNLO EW   NNLO QCD-EW

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

N3LO QCD

only known for DY (so far)

→ ask Luca!

scale variation at NNLO

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

sufficient?

Mixed QCD-EW uncertainties

Bold estimate:

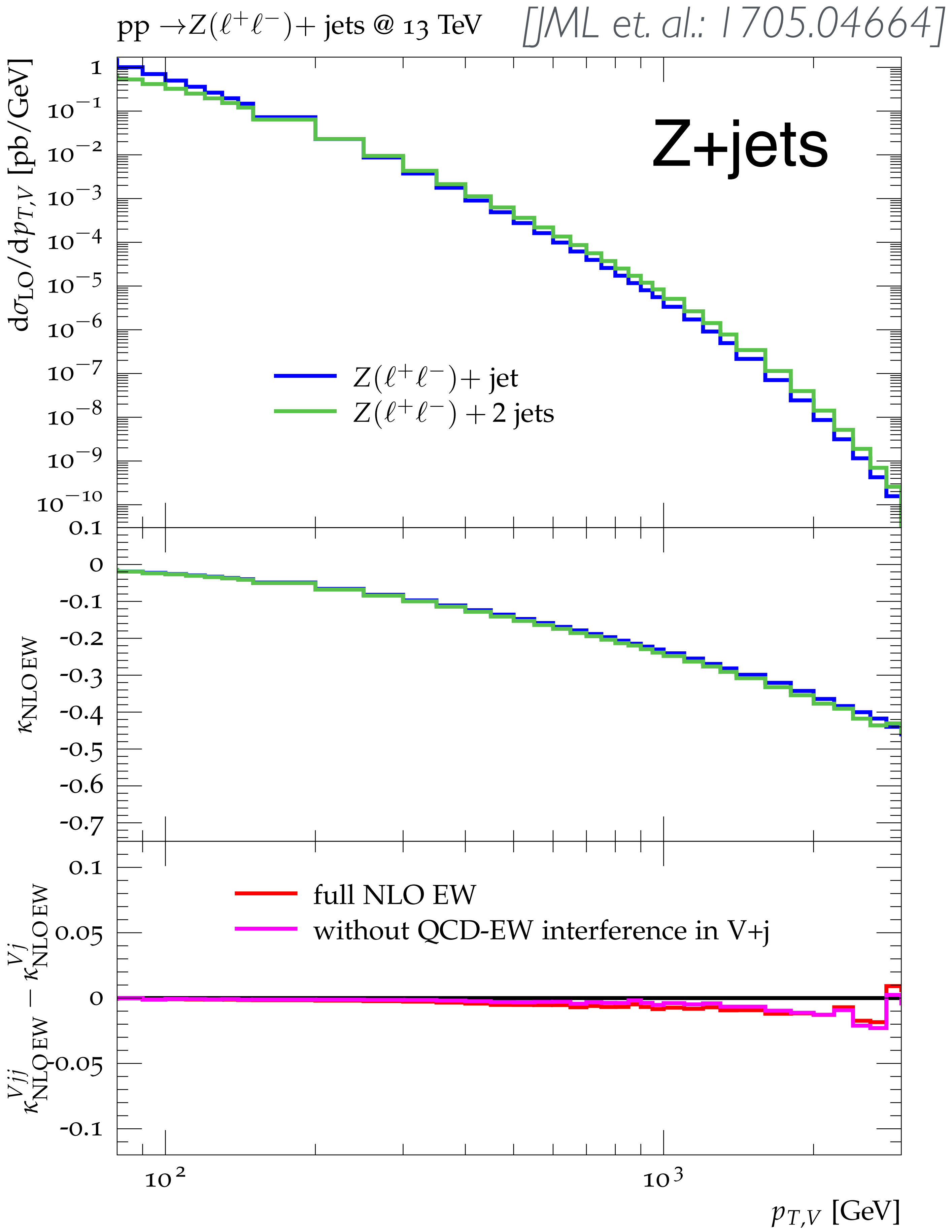
Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to X production $\simeq$ NLO EW to X+1jets

and we often observe

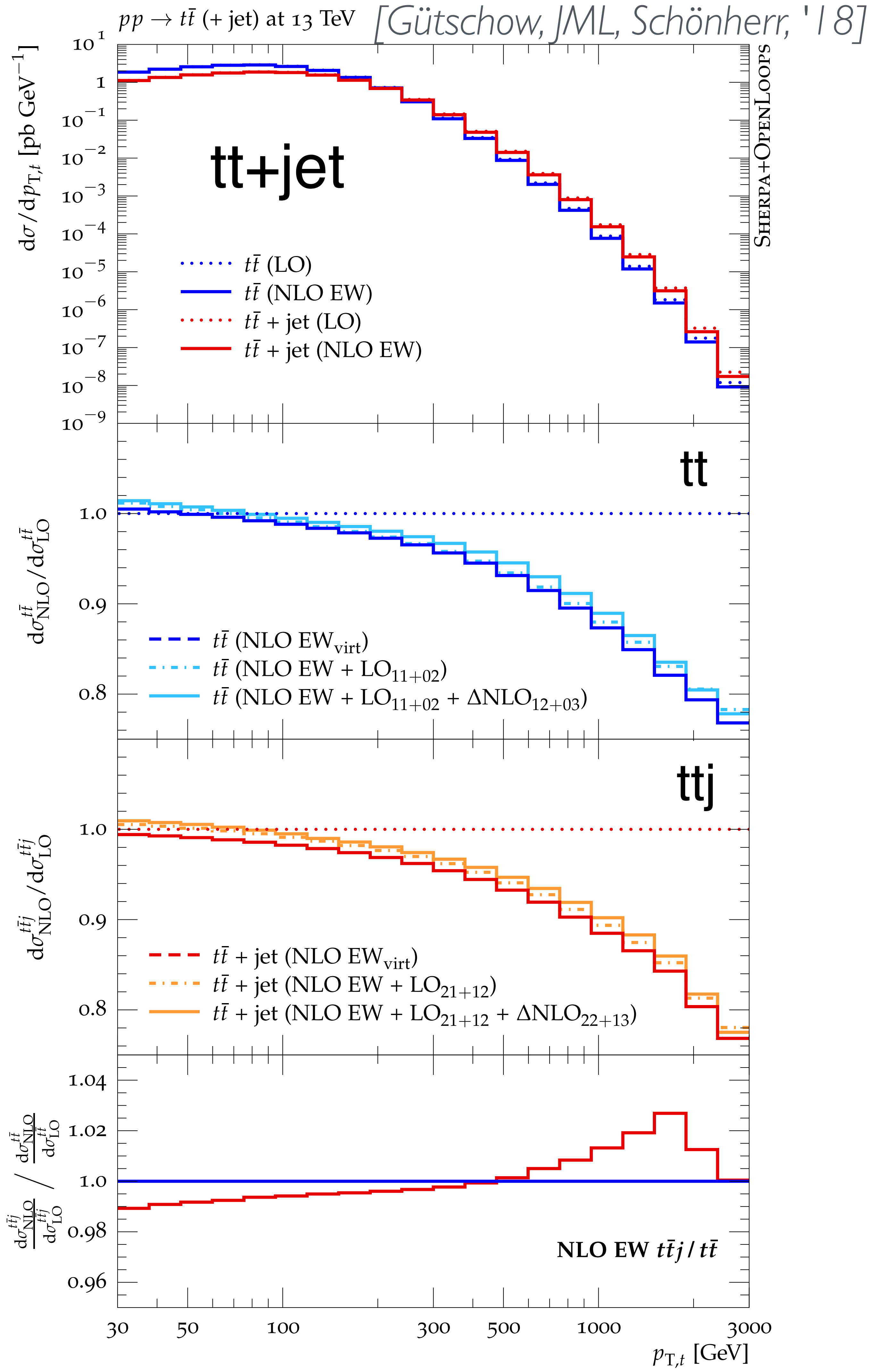
$$\left.\frac{\mathrm{d}\sigma_{\mathrm{NLO\,EW}}}{\mathrm{d}\sigma_{\mathrm{LO}}}\right|_{X+\mathrm{jet}} - \left.\frac{\mathrm{d}\sigma_{\mathrm{NLO\,EW}}}{\mathrm{d}\sigma_{\mathrm{LO}}}\right|_{X} \lesssim 1\%$$

In these cases strong support for
- factorisation
- multiplicative QCD x EW combination

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



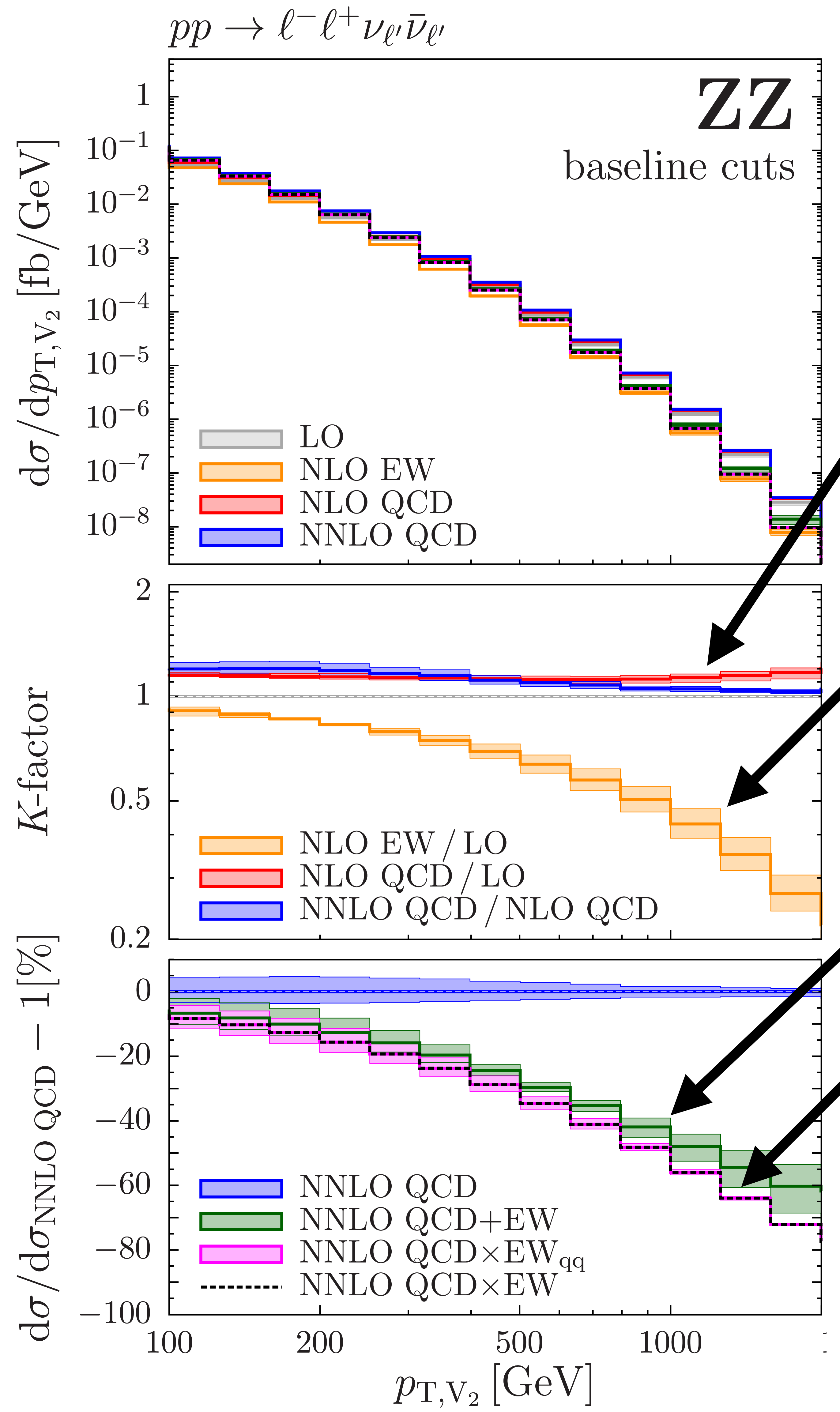
$pT_{j,2} > 30$ GeV



$pT_j > 30$ GeV

EW uncertainties: QCD-EW interplay

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



pTV2

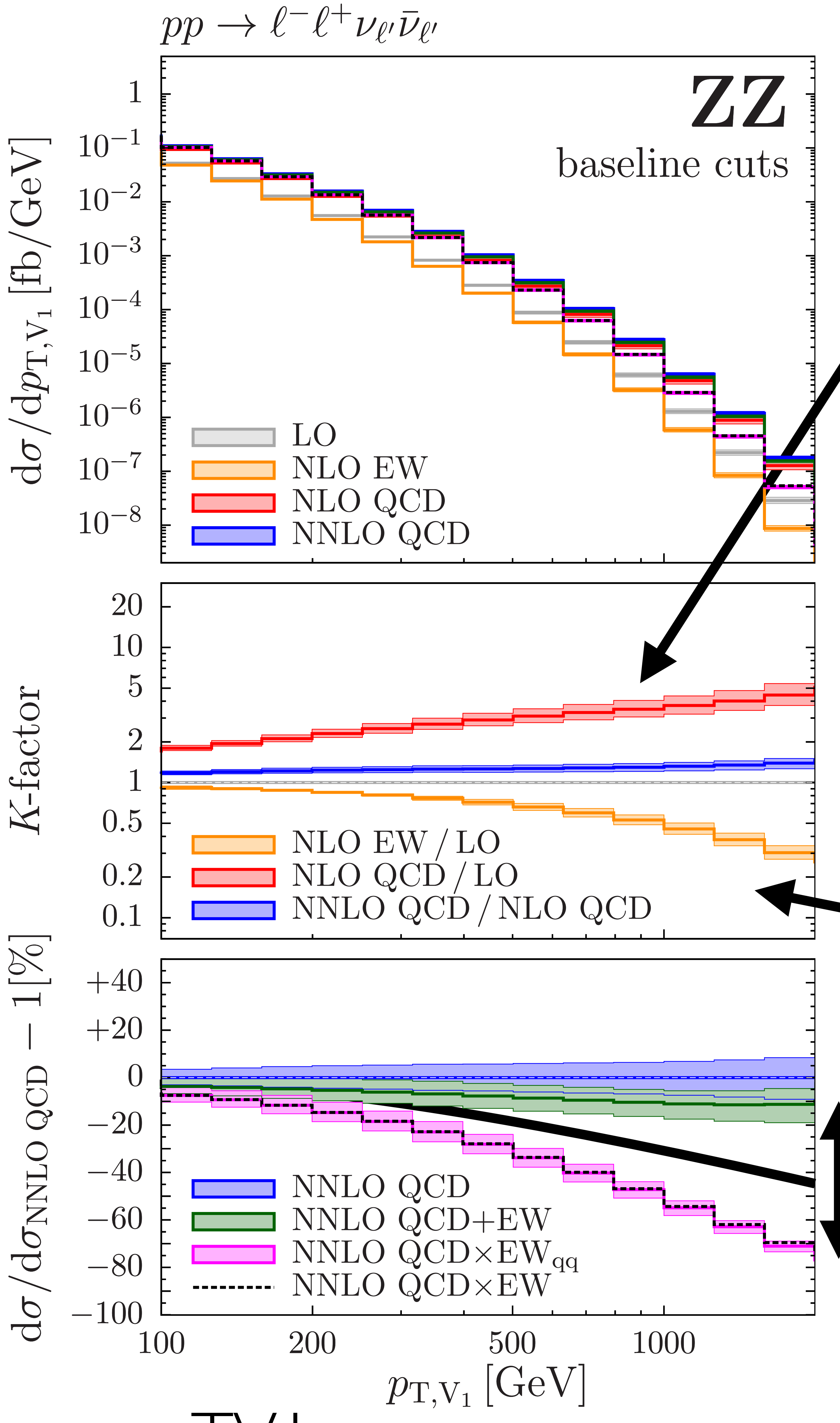
- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent
- NLO EW/LO=-(50-60)% @ 1 TeV

$$d\sigma_{\mathrm{NNLO\,QCD+EW}}$$

$$d\sigma_{\mathrm{NNLO\,QCD\times EW}}$$

- multiplicative/factorised combination superior (EW Sudakov logs x soft QCD)

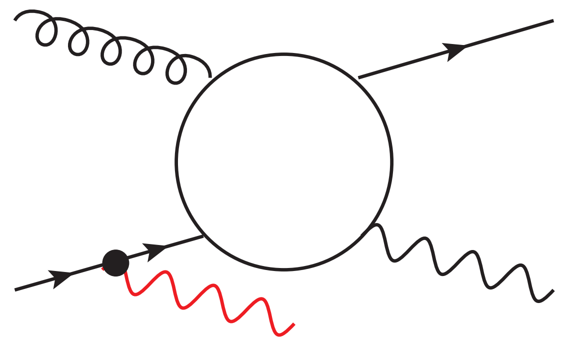
Combination of QCD and EW corrections



pTV1

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

- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



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

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%

- NLO EW/LO=-(40-50)%

- Very large difference $d\sigma_{\rm NNLO\,QCD+EW}$ vs. $d\sigma_{\rm NNLO\,QCD\times EW}$

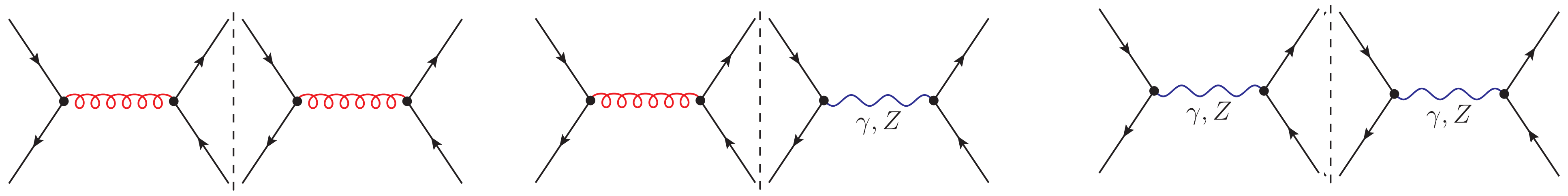
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process

Perturbative expansion: revised II

- In general combined expansion in α_S and α necessary:

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

LO "subleading Born contributions": LO2, LO3



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

Perturbative expansion: revised II

- In general combined expansion in α_S and α necessary:

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

LO "subleading Born contributions": LO2, LO3

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

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

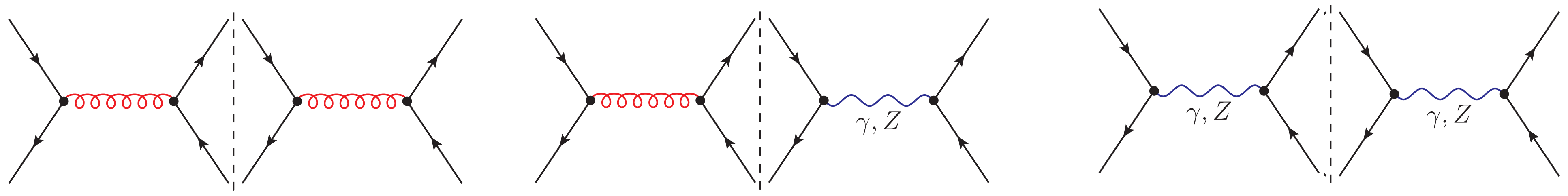
"NLO QCD" "NLO EW" "subleading one-loop contributions": NLO3, NLO4

Perturbative expansion: revised II

- In general combined expansion in α_S and α necessary:

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

LO "subleading Born contributions": LO2, LO3

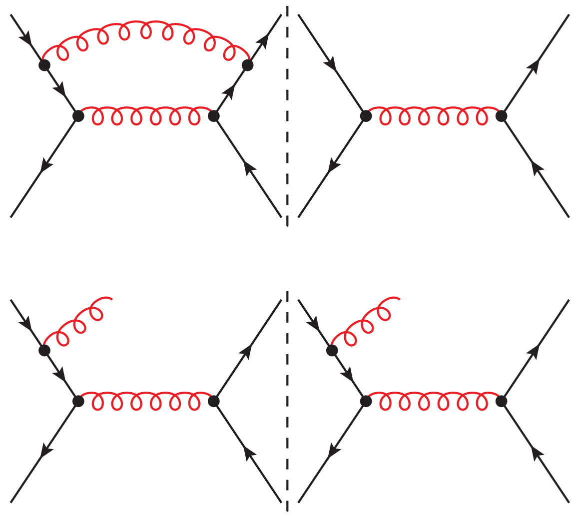


Example: $q\bar{q} \to q\bar{q}$

- also at NLO:

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

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

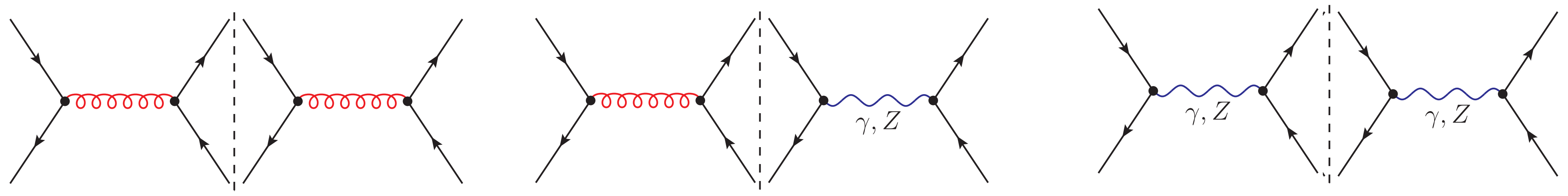


Perturbative expansion: revised II

- 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

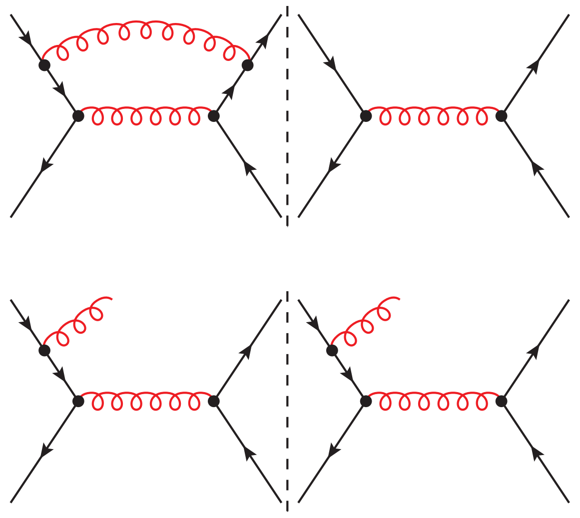


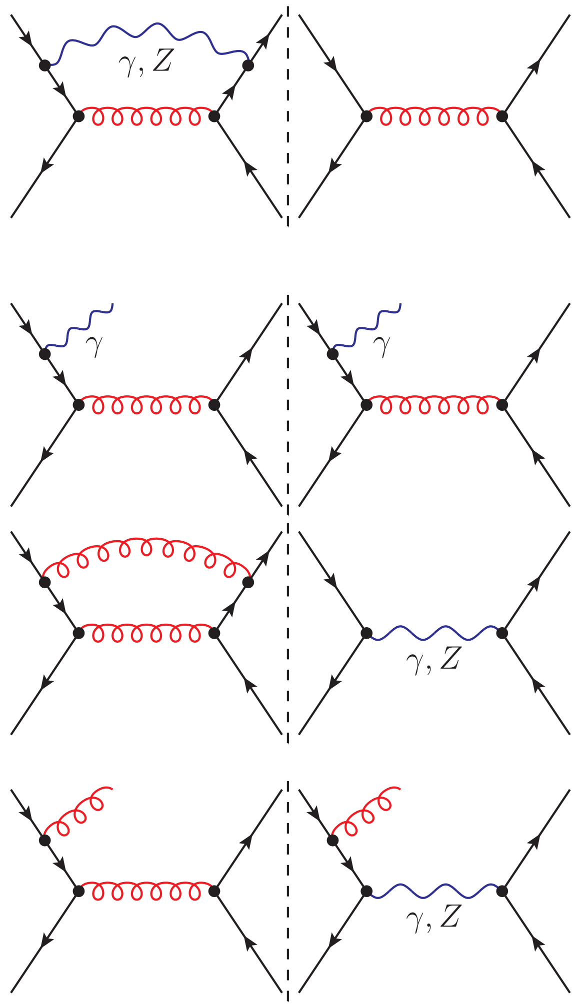
Example: $q\bar{q} \to q\bar{q}$

- also at NLO:

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

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



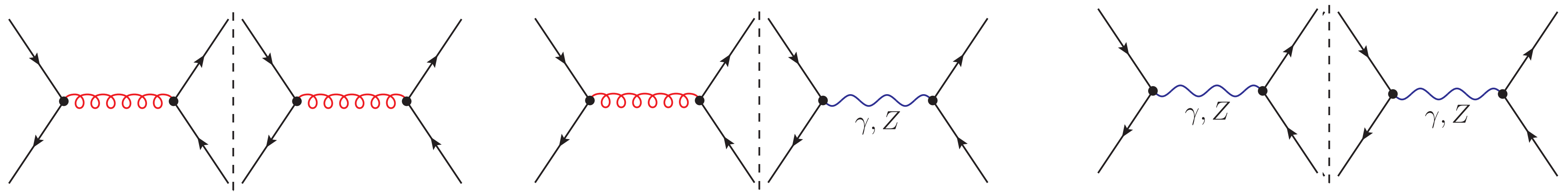


Perturbative expansion: revised II

- In general combined expansion in α_S and α necessary:

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

LO "subleading Born contributions": LO2, LO3

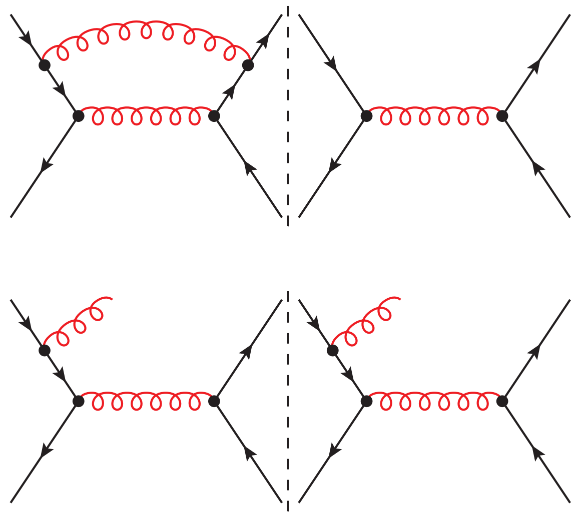


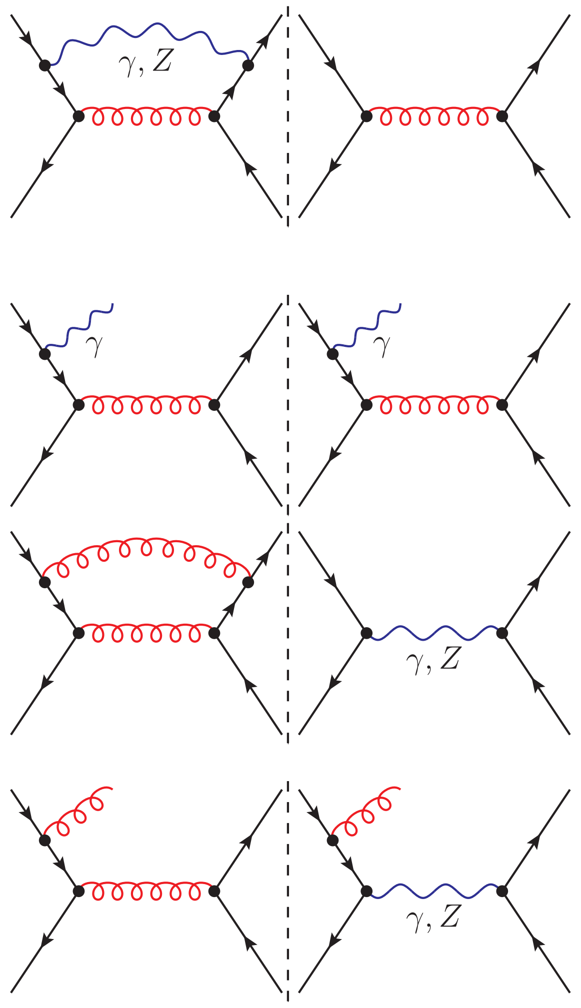
Example: **q$\bar{\text{q}}$ → q$\bar{\text{q}}$**

- also at NLO:

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

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

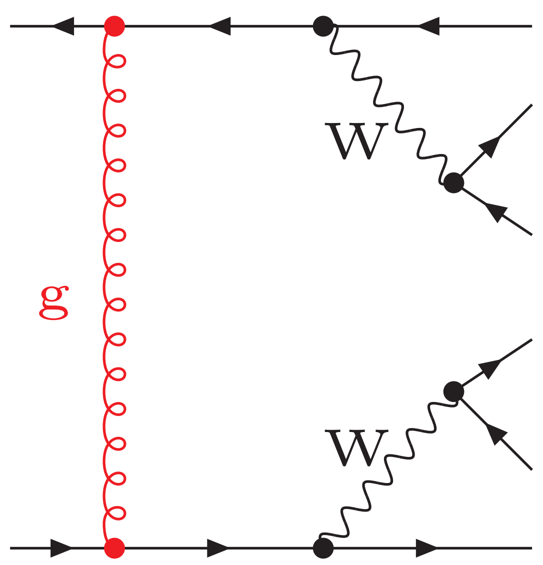




Note:

- 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.

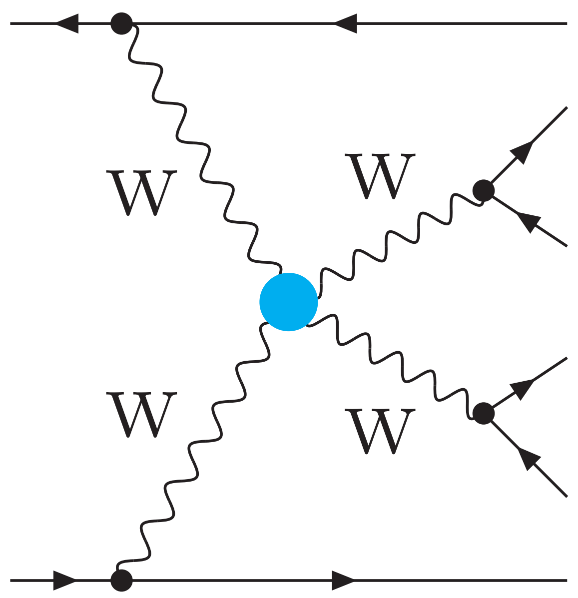
Example: VV+2jets production



QCD-background

vs.

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

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

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

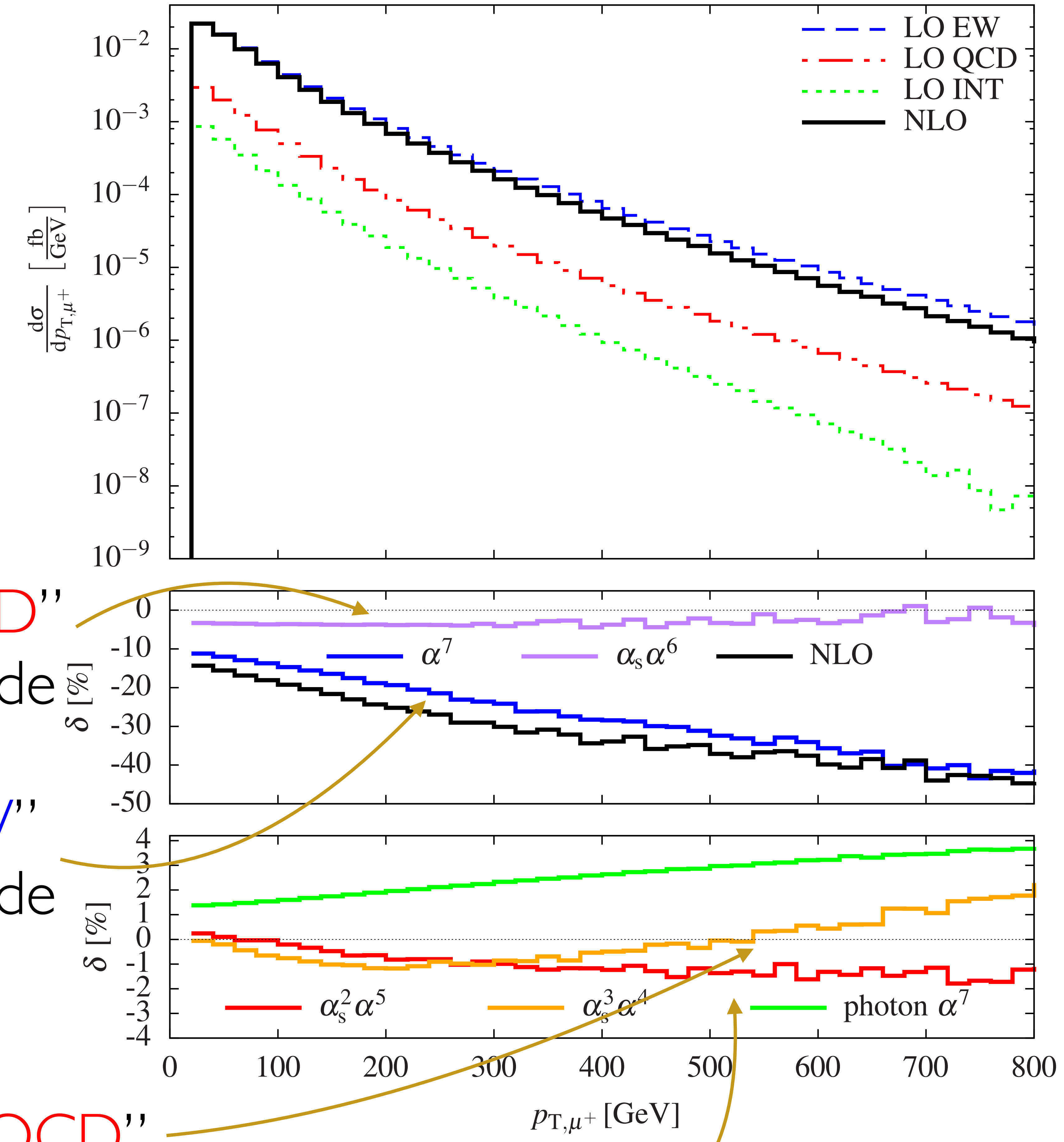
"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

➡ 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]

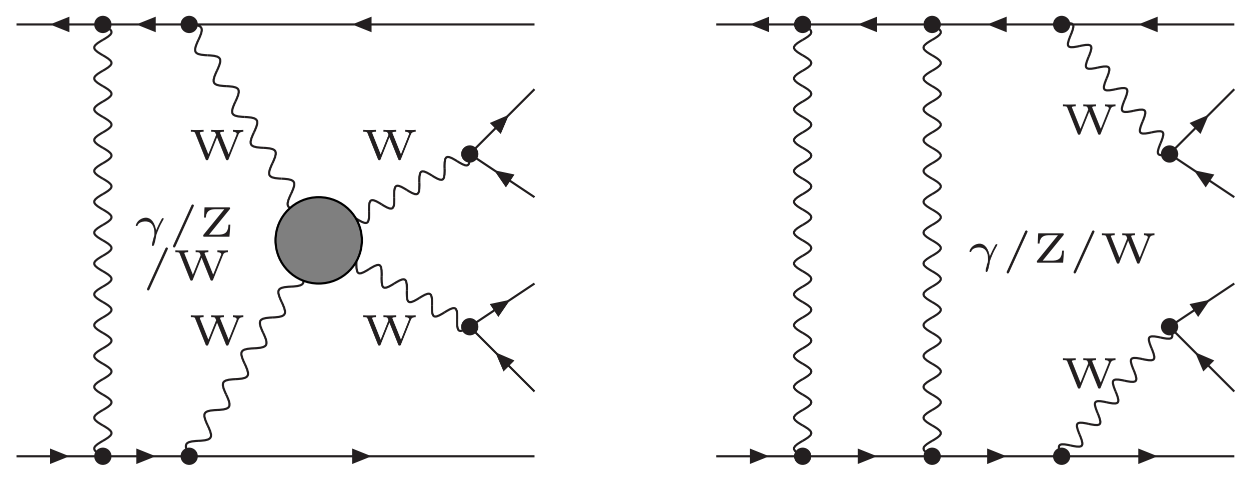


"NLO QCD" to EW mode

"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
$\delta\sigma_{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

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

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

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

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

Conclusions

- LHC is turning into a precision EW machine
- ..and precision is key for SM probes, global EFT fits, as well as for searches.
- EW corrections become large at the TeV scale
- Fixed-order NLO EW largely automated
- Higher-order EW and mixed QCD-EW uncertainties are becoming relevant.

Questions?

References

These Lectures are partly based on:

Various previous ESHEP school lectures, in particular

- Wolfgang Hollik, European School of High-Energy Physics, 2009
- Anna Kulesza, European School of High-Energy Physics, 2023

and

- Ansgar Denner, DESY Monte Carlo school, 2014
- Gavin Salam, Basics of QCD, ICTP–SAIFR school on QCD and LHC physics, 2015

Backup

LO Ingredients

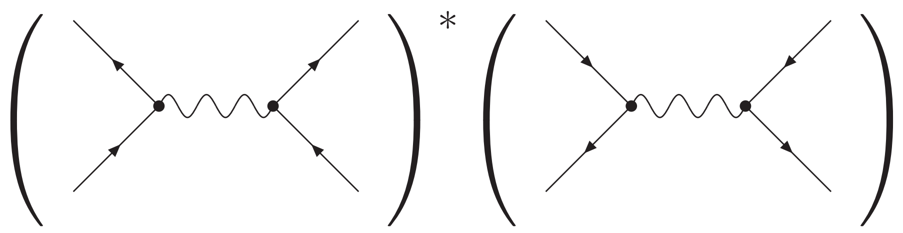
- LO partonic cross section for a 2→n process can be written as

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

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

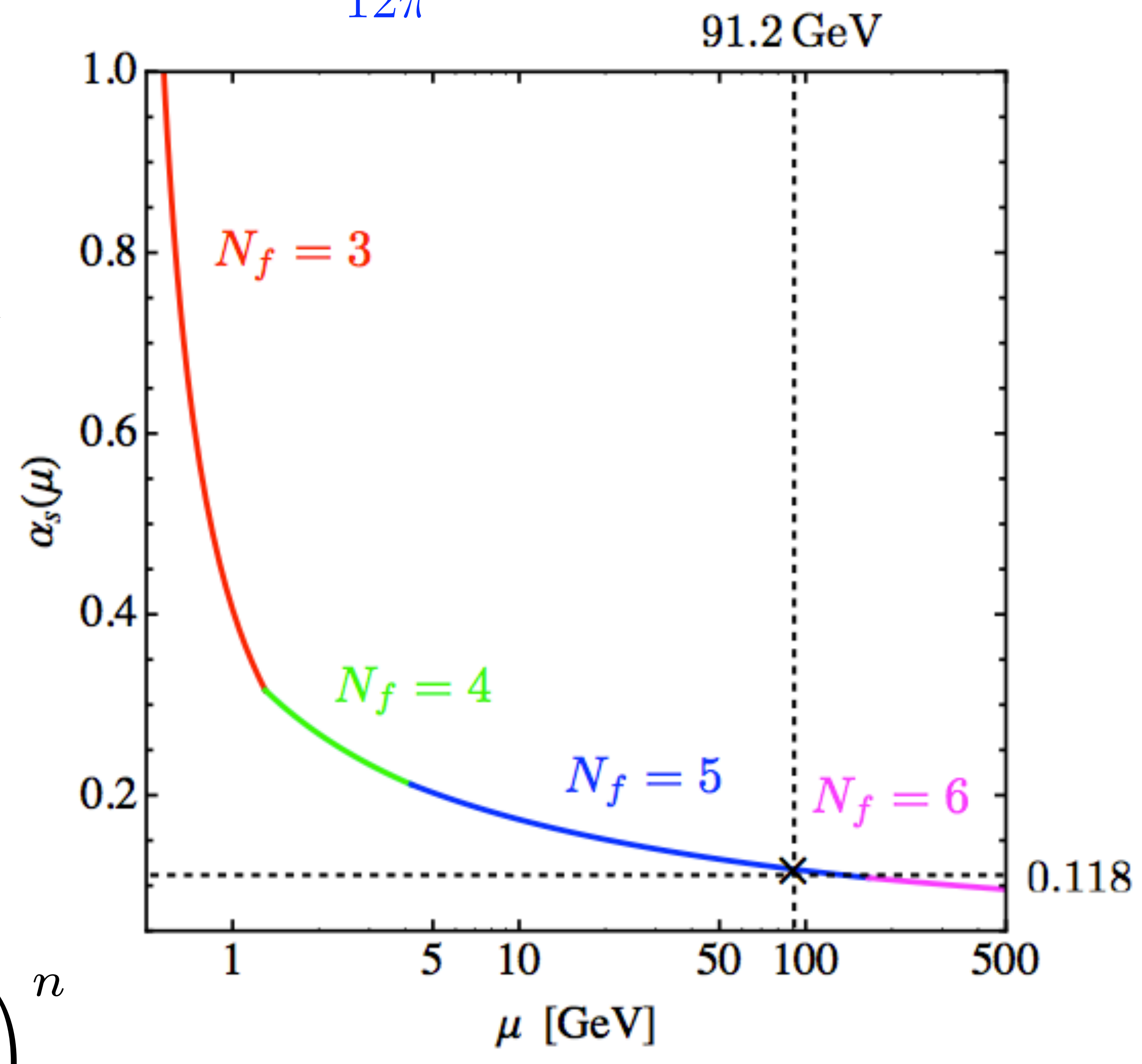
$$d\sigma = d\sigma(\alpha^n) + d\sigma(\alpha^{n+1}) + d\sigma(\alpha^{n+2}) + d\sigma(\alpha^{n+3}) + \dots$$

LO NLO NNLO N3LO

- at the LHC consider in particular $\alpha = \alpha_S$ (QCD coupling), but also $\alpha = \alpha_{EW}$ (EW coupling) relevant → later!

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

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



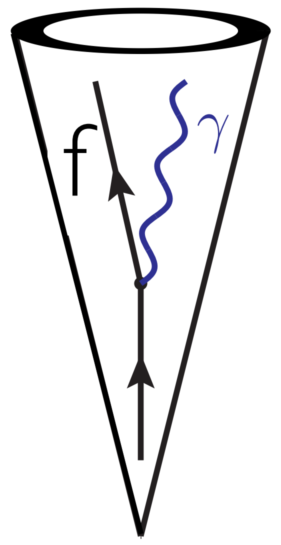
$$d\sigma^{\mathrm{LO}}(\mu) = \alpha_S(\mu)^n A^{\mathrm{LO}}$$

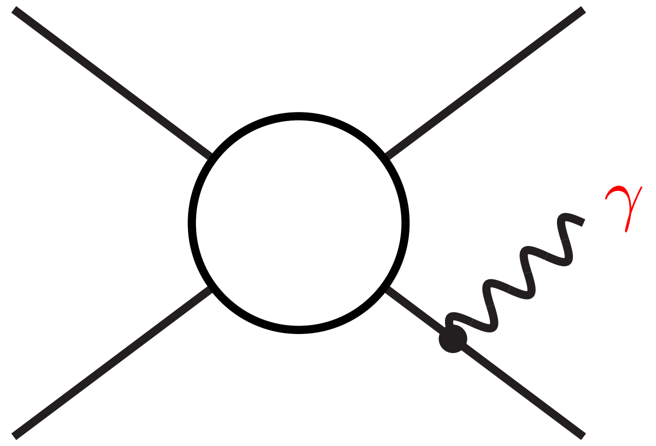
$$\to d\sigma^{\mathrm{LO}}(\mu') = \alpha_S(\mu')^n A^{\mathrm{LO}} = \alpha_S(\mu)^n \left(1 + n b_0 \alpha_S(\mu) \ln \frac{\mu^2}{\mu'^2} + \dots\right) A^{\mathrm{LO}}$$

- So the change of scale is an NLO effect ($\propto \alpha_S$).

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

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!

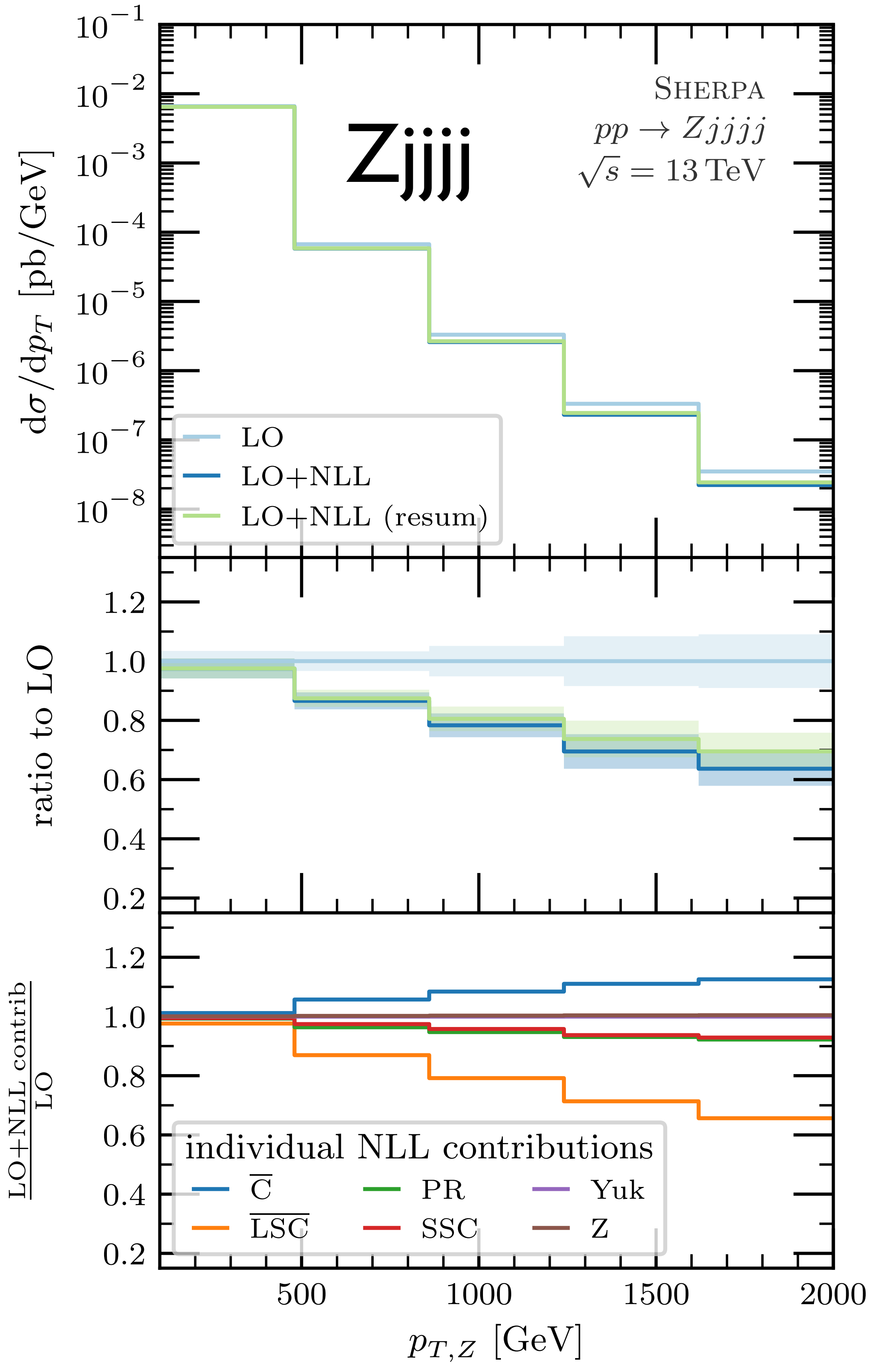
  → problematic for QCD IR safety

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

Tools for EW Sudakov corrections

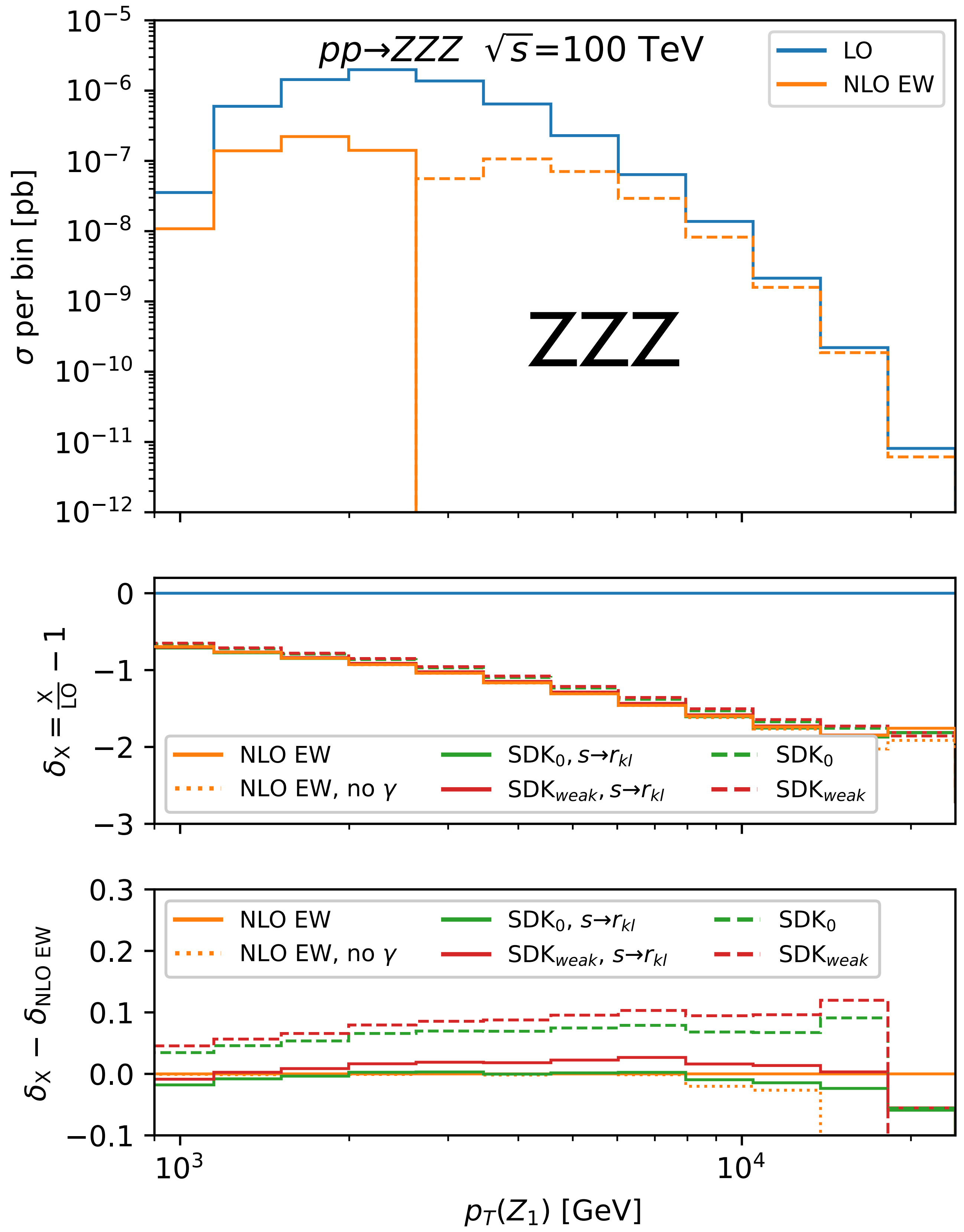
Sherpa

[Bothmann, Napoletano, '20]



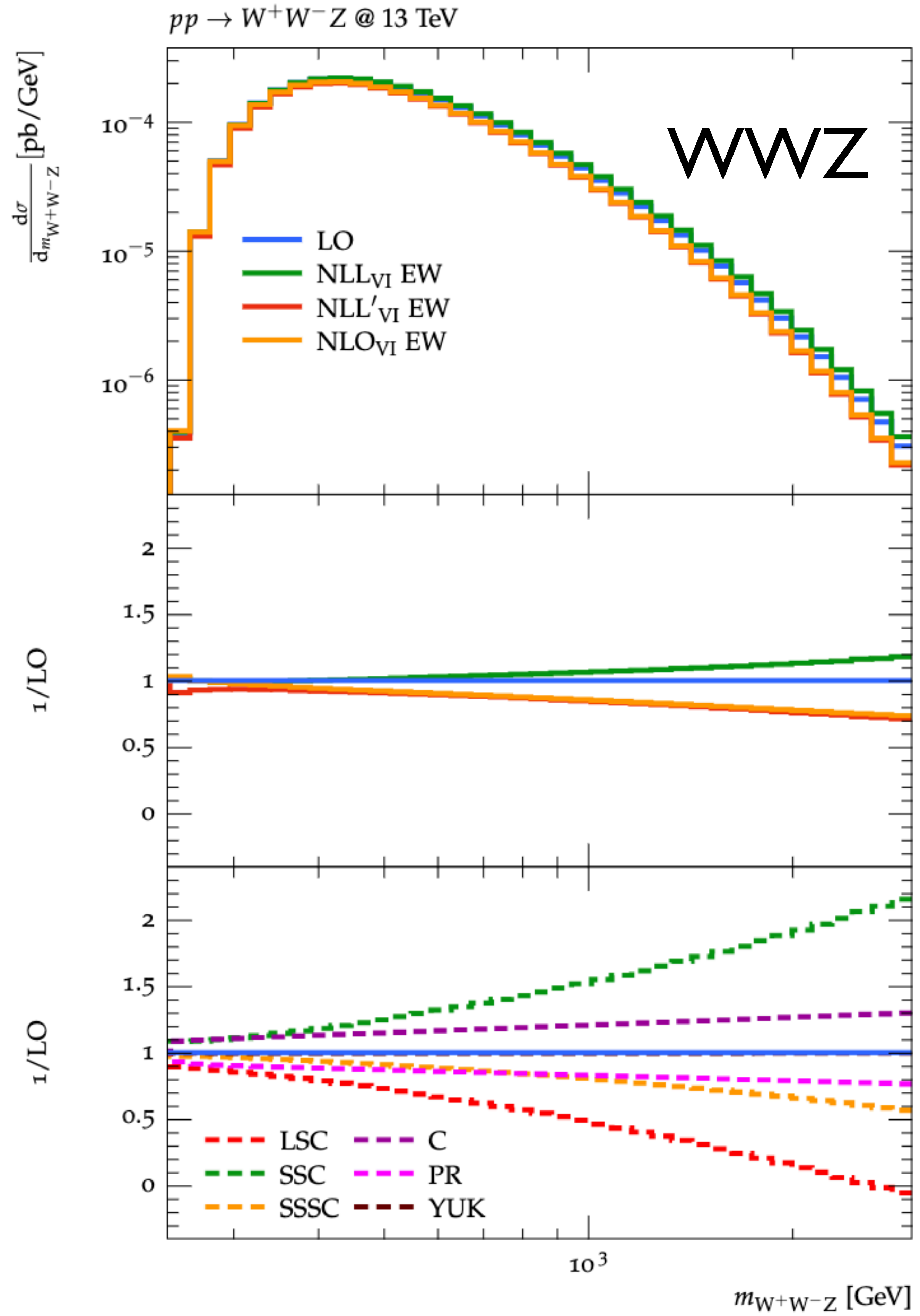
MadGraph5_aMC@NLO

[Pagani, Zaro, '21]



OpenLoops

[JML, Mai, '23]



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

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

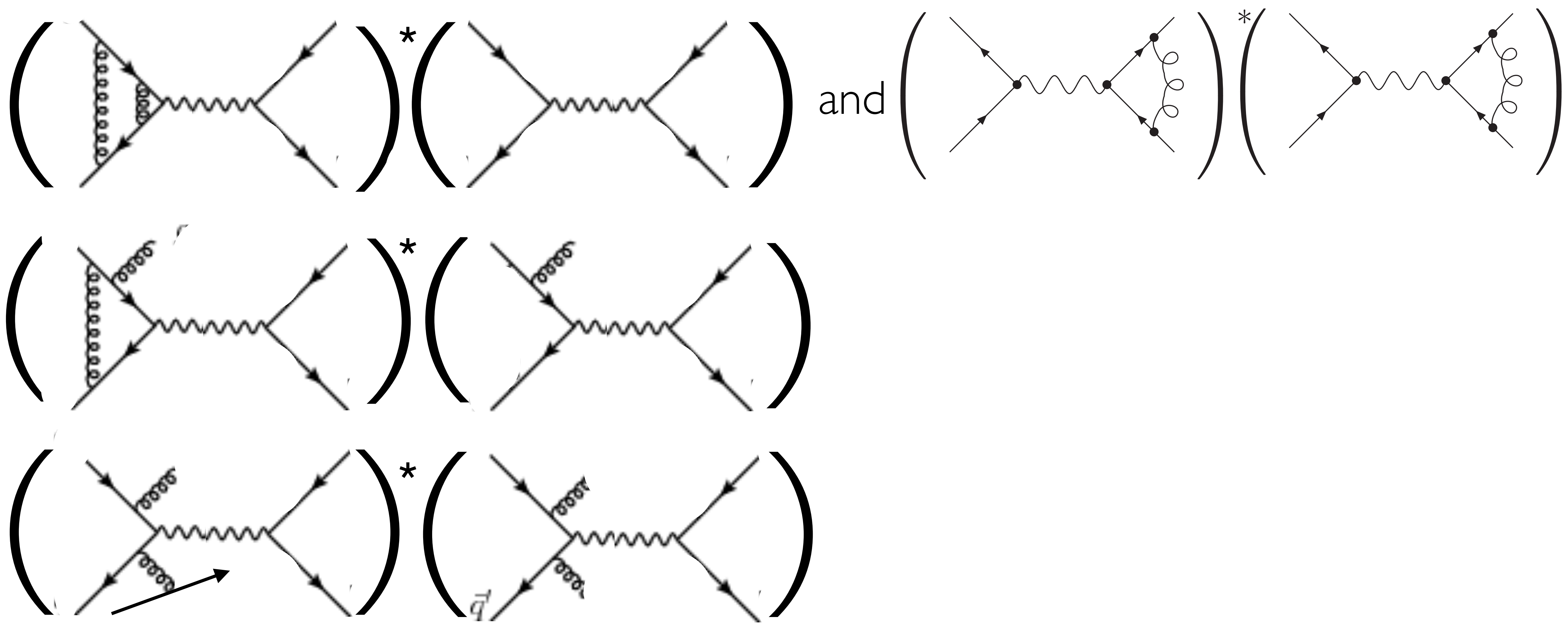
$\int d\Phi_{n(+1)}$ n, n+1, n+2 particle phase space

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



EW uncertainties: QED radiation

Conservative estimate of higher-order QED radiation:

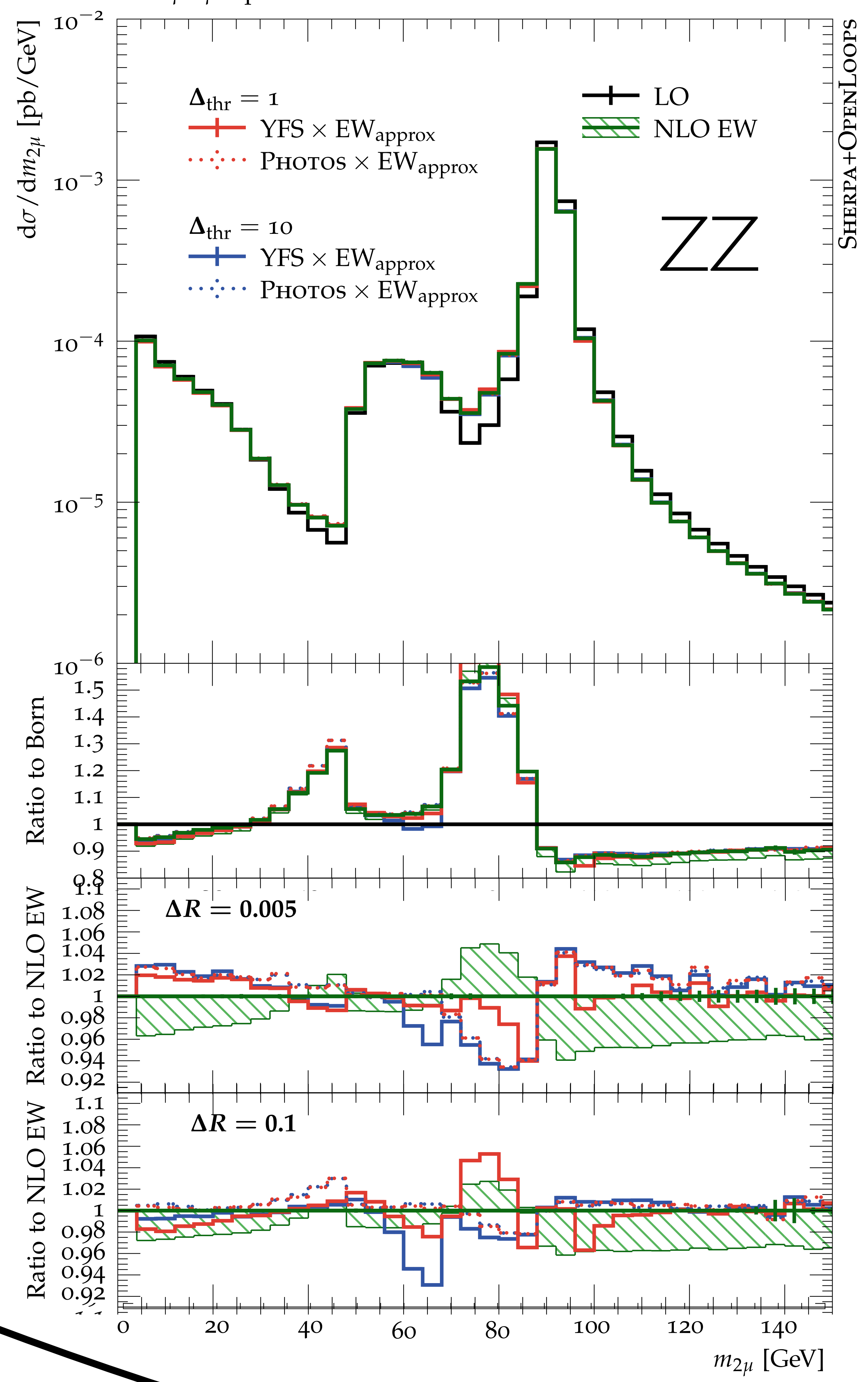
NLO EW

vs.

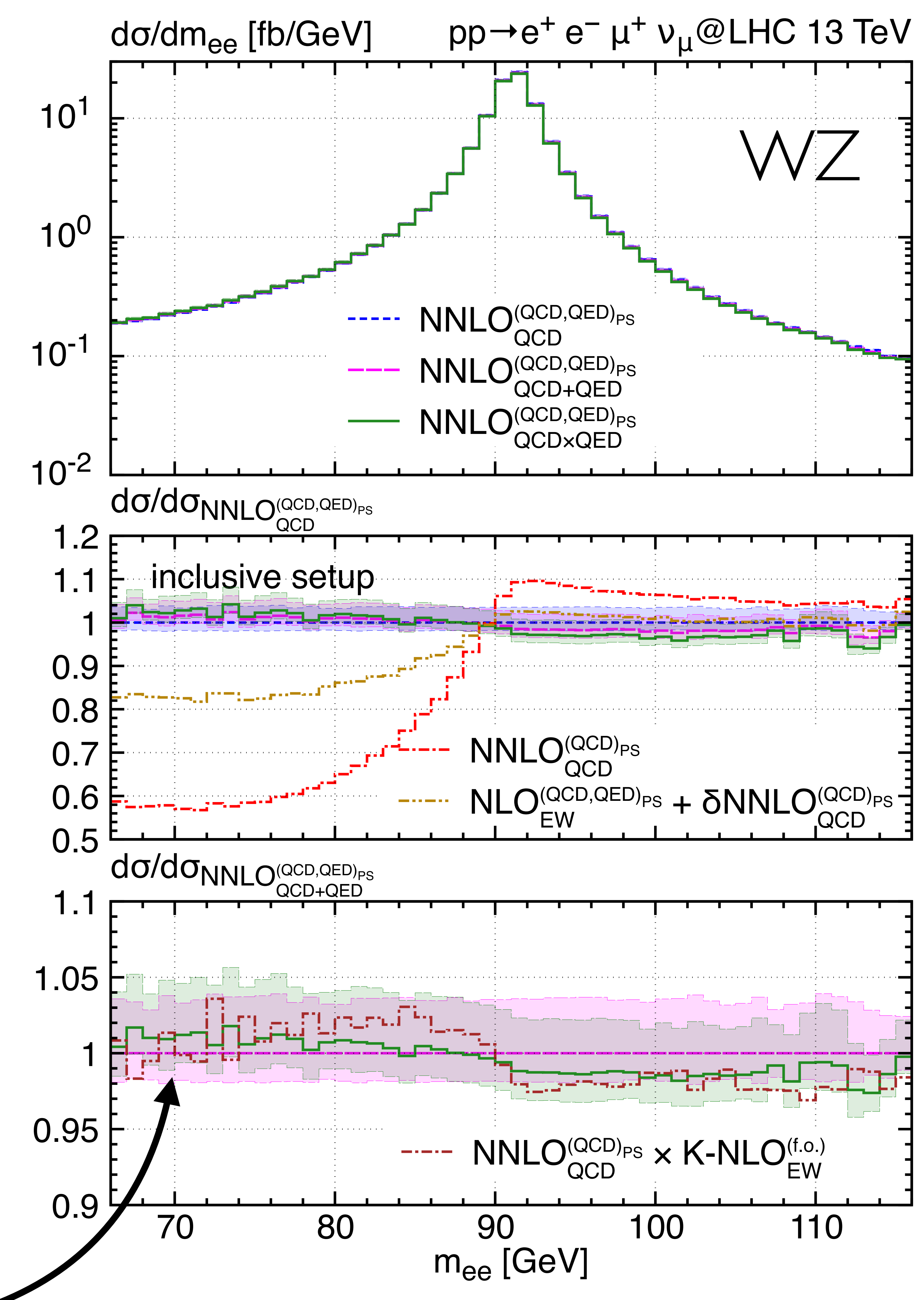
multi-photon radiation (YFS)
or
QED-PS

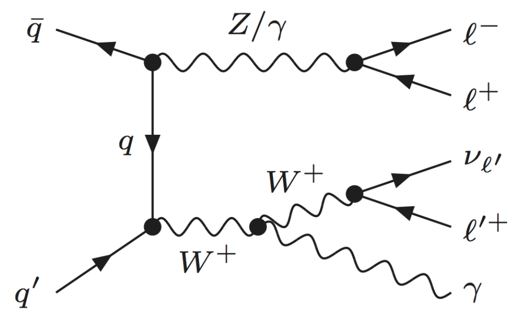
$$\Delta_{\mathrm{EW}}^{\mathrm{QED}} = |\delta_{\mathrm{EW}} - \delta_{\mathrm{EW+PS/YFS}}|$$

[Gütschow, Schönherr, '20]



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





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

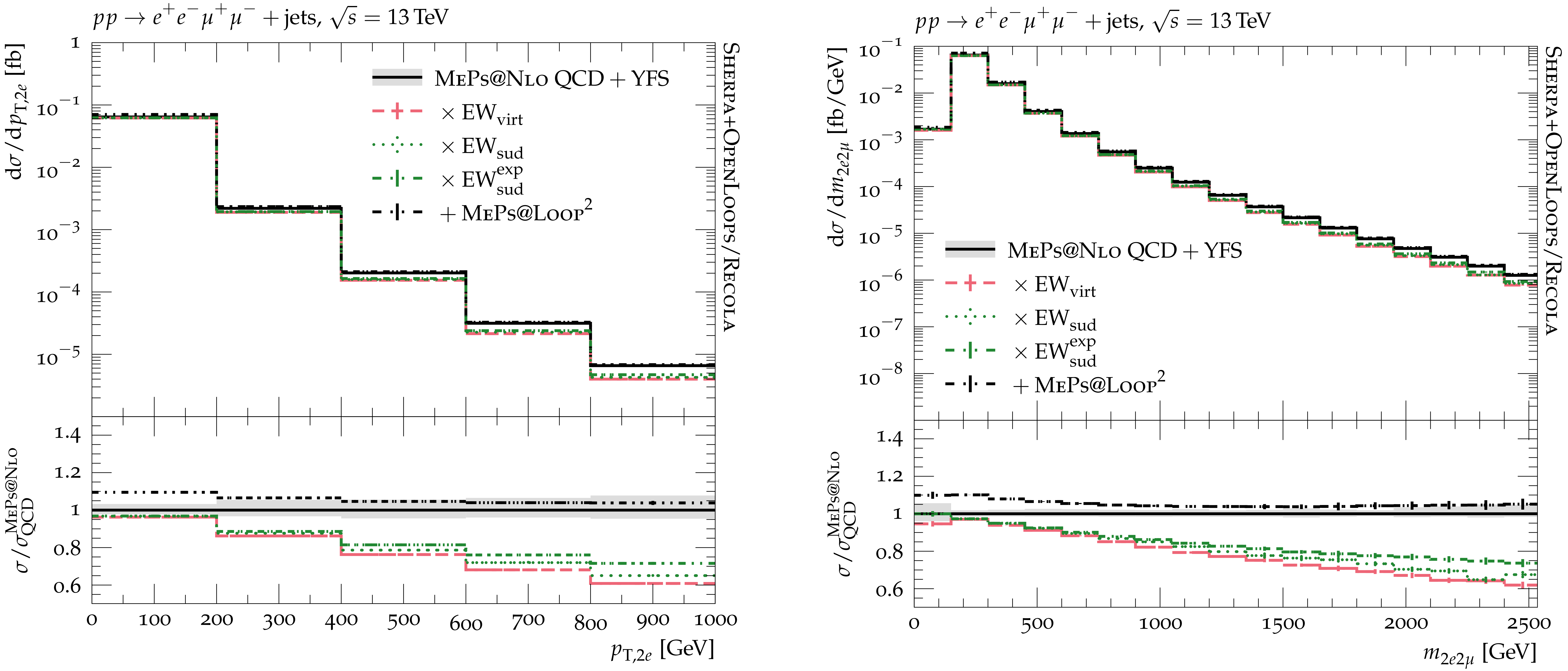
$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)$$

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]

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ASSOCIATED_CONTRIBUTIONS_VARIATIONS EW;
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