UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Suppressed interference in the SMEFT and related topics

Celine Degrande

Plan

- Introduction to SMEFT
- SMEFT and interference
- CPV in EW diboson
- NLO corrections
- Dim-8 in diboson
- Further comments

Introduction to SMEFT

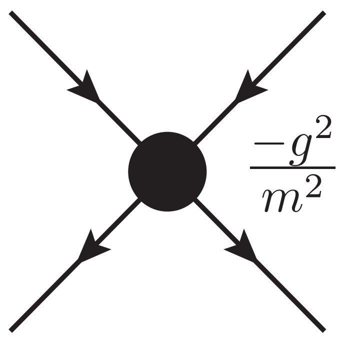
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments

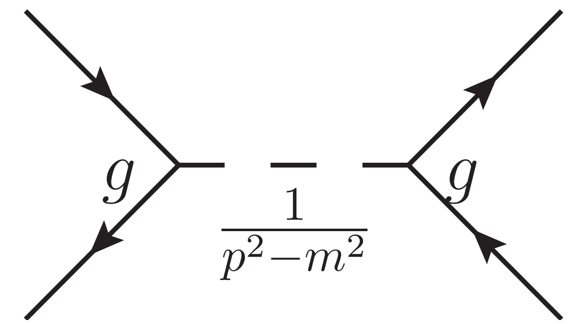
E

Exp. range

NP scale

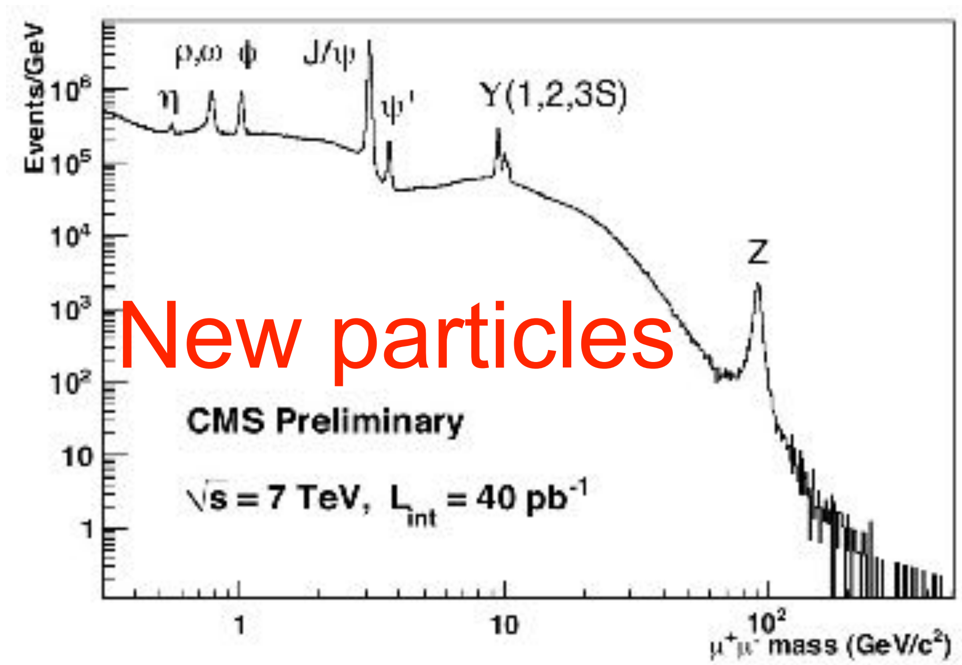


$$p^2 \ll m^2$$



One assumption : $p^2 \ll m^2$

New/modified interactions between SM particles



C. Degrande

EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SM fields & sym.

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

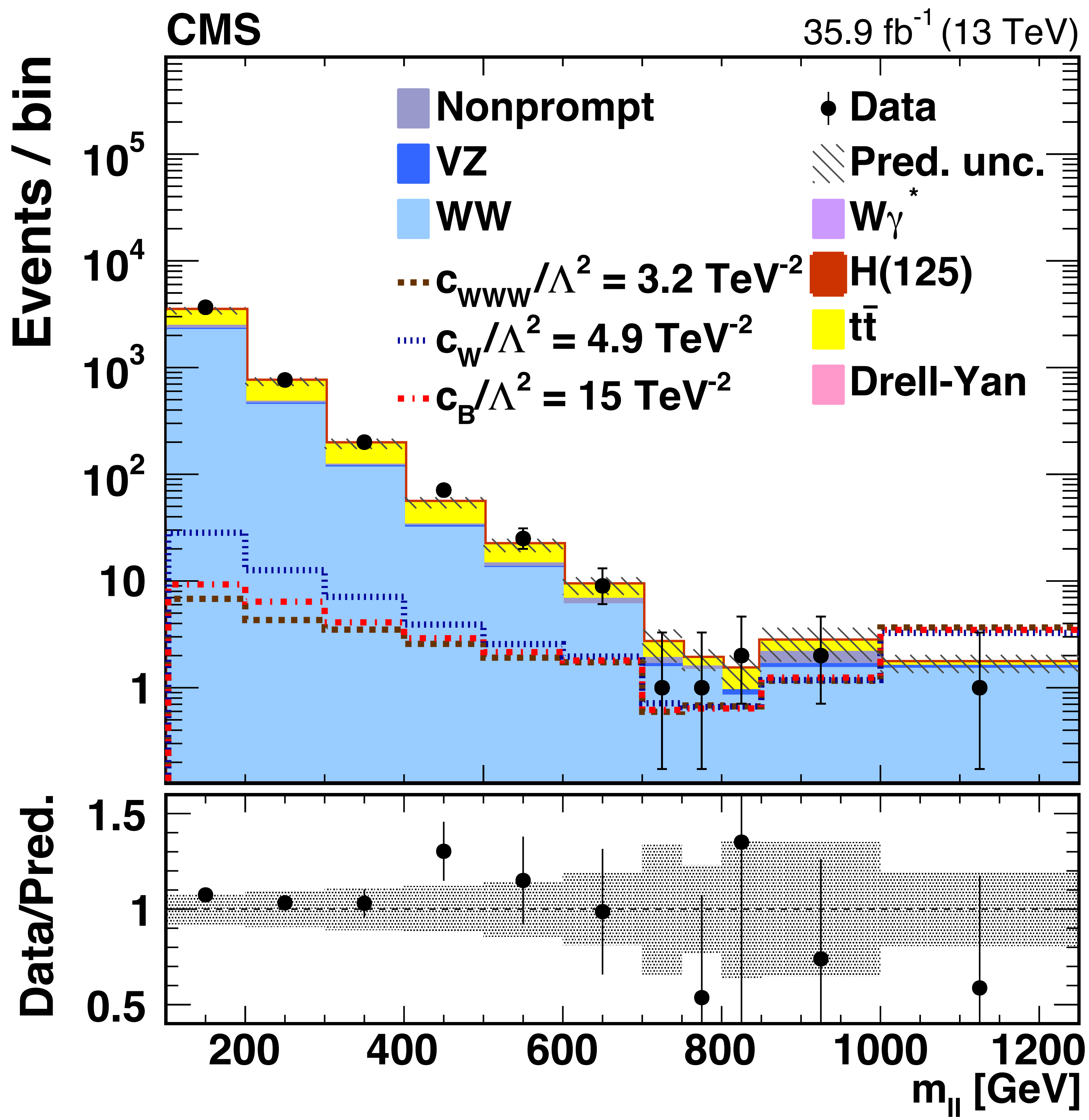
measure only C_i/Λ^2

a finite number of coefficients =>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP
- SM is the leading term : EFT for precision physics
- higher the exp. precision => smaller EFT error

C. Degrande

High energy tails



2009.00119

Cross-sections and precision plummet at high energy

EFT/SM is larger at H.E. but so are the EFT errors

C. Degrande

SMEFT and interference

Errors : higher power of $1/\Lambda$

$$|M(x)|^2 = \underbrace{|M_{SM}(x)|^2}_{\Lambda^0} + \underbrace{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}_{\Lambda^{-2}} + \underbrace{|M_{d6}(x)|^2 + \dots}_{\mathcal{O}\left(\Lambda^{-4}\right)}$$

$\mathcal{O}(1)$	$\mathcal{O}(0.1)$	10%	$\mathcal{O}(0.01)$
$\mathcal{O}(1)$	$\mathcal{O}(0.5)$	50%	$\mathcal{O}(0.25)$

- Contains :
  - 1 dim6 insertion squared
  - interference with 2 dim6 insertions
  - interference with 1 dim8 insertion
  - … at $1/\Lambda^{-6}$
- Error (estimate)

usually not included

Dimension 8 basis: Li et al., 2005.00008

C. Degrande

interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\lvert h(A_4^{\text{SM}})\rvert$	$\lvert h(A_4^{\text{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2

$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

$$|M(x)|^2 = \underbrace{|M_{SM}(x)|^2}_{\Lambda^0} + \underbrace{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}_{\Lambda^{-2}} + \underbrace{|M_{d6}(x)|^2 + \ldots}_{\Lambda^{-4}} + \mathcal{O}(\Lambda^{-6})$$

$\mathcal{O}(1)$ ~0 $\mathcal{O}(0.1)$ 30% $\mathcal{O}(0.03)$

Assuming ~0

C. Degrande

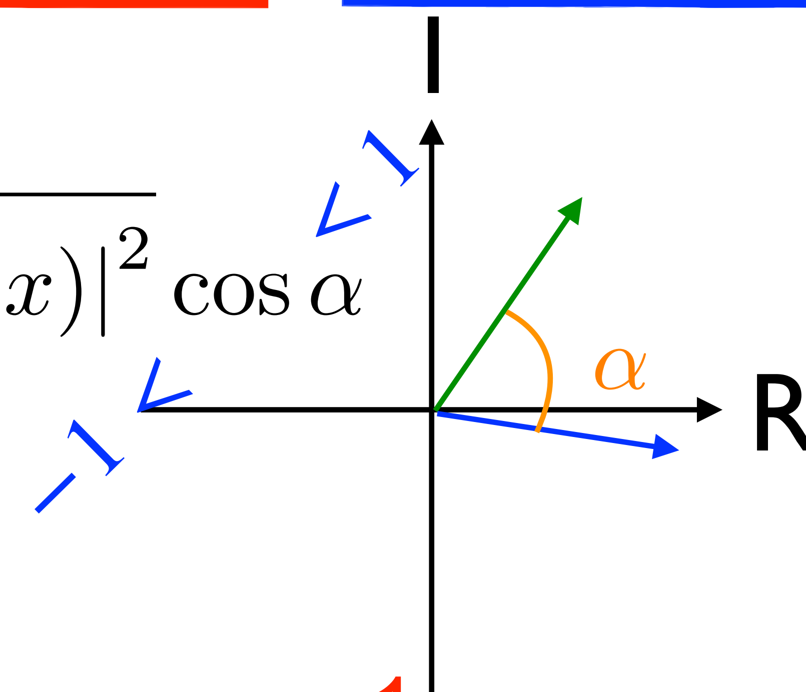
Interference

$$|M(x)|^2 = \underbrace{|M_{SM}(x)|^2}_{\Lambda^0} + \underbrace{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}_{\Lambda^{-2}} + \underbrace{|M_{d6}(x)|^2 + \dots}_{\mathcal{O}\left(\Lambda^{-4}\right)}$$

$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2\,|M_{d6}(x)|^2}\cos\alpha$$

mom&spin

Not always positive



Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2$$ if

$$M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \cancel{0}\ 1$$

$$M_{d6}(x_1) = \cancel{0}\ -1,\ M_{d6}(x_2) = 1$$

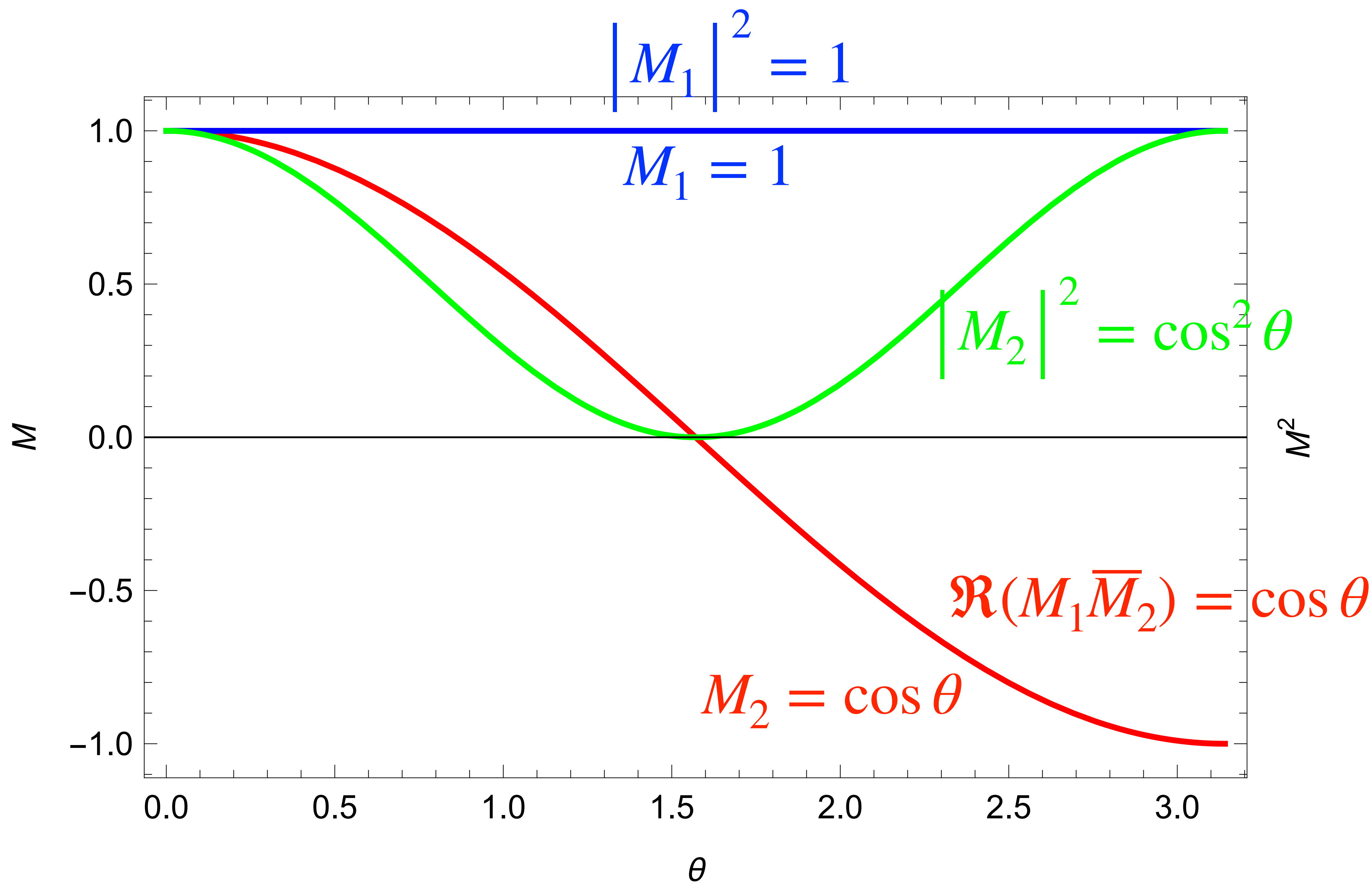
$$\sigma_{int} = 0$$

Observable dependent

or $\alpha \approx \pi/2$ $\quad M^2 \to M^2 - i\Gamma M \quad \sigma_{int} \propto \Gamma$

C. Degrande

Interference suppression from phase space



$$\sigma_{int} = \int_0^\pi 2\Re(M_1\overline{M}_2)d\theta = \int_0^\pi 2\cos\theta d\theta = 0$$

C. Degrande

Interference revival: Formalism

C.D., M. Maltoni 2012.06595

$$\sigma^{|int|} \equiv \int d\Phi \left| \frac{d\sigma_{int}}{d\Phi} \right| \quad >> \sigma_{int}$$

=Phase space Suppression

$$\sigma^{|meas|} \equiv \int d\Phi_{meas} \left| \sum_{\{um\}} \frac{d\sigma}{d\Phi} \right|$$

$$= \lim_{N\to\infty} \sum_{i=1}^{N} w_i * \text{sign}\left(\sum_{um} ME(\vec{p}_i, um) \right)$$

Experimentally accessible?

neutrino momenta, helicities, jet flavours, initial parton direction,…

Fully: $\frac{d\sigma_{int}}{d\theta}(pp \to Z\gamma) \propto \cos\theta$

Not at all: $\sigma_{int}(\mu_L) = -\,\sigma_{int}(\mu_R)$

CPV in EWdiboson

dominant CP operators

at the interference level

$m_t \neq 0 \neq m_b$

(X^3)		$(\psi^2\phi^3)$		$(\psi^2\phi^2 D)$	
$O_{\tilde{G}GG}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$O_{t\phi}$	$(\phi^\dagger\phi)(\bar{q}_3 t\tilde{\phi})$	$O_{\phi tb}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{t}\gamma^\mu b)$
$O_{\tilde{W}WW}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$O_{b\phi}$	$(\phi^\dagger\phi)(\bar{q}_3 b\phi)$		
$(X^2\phi^2)$		(ψ^4)		$(X\psi^2\phi)$	
$O_{\phi\tilde{G}}$	$\phi^\dagger\phi\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$O_{qtqb}^{(1)}$	$(\bar{q}_3^j t)\epsilon_{jk}(\bar{q}_3^k b)$	O_{tG}	$(\bar{q}_3\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}^A$
$O_{\phi\tilde{W}}$	$\phi^\dagger\phi\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$O_{qtqb}^{(8)}$	$(\bar{q}_3^j T_A t)\epsilon_{jk}(\bar{q}_3^k T_A b)$	O_{tW}	$(\bar{q}_3\sigma^{\mu\nu}t)\tau^I\tilde{\phi}W_{\mu\nu}^I$
$O_{\phi\tilde{B}}$	$\phi^\dagger\phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$			O_{tB}	$(\bar{q}_3\sigma^{\mu\nu}t)\tilde{\phi}B_{\mu\nu}$
$O_{\phi\tilde{W}B}$	$\phi^\dagger\tau^I\phi\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$			O_{bG}	$(\bar{q}_3\sigma^{\mu\nu}T^A b)\phi G_{\mu\nu}^A$
				O_{bW}	$(\bar{q}_3\sigma^{\mu\nu}b)\tau^I\phi W_{\mu\nu}^I$
				O_{bB}	$(\bar{q}_3\sigma^{\mu\nu}b)\phi B_{\mu\nu}$

if imaginary coefficient

Table 4: List of CP-odd dimension-6 operators in our reduced basis under the $U(1)^{13}$ symmetry.

C.D., J. Touchèque, 2110.02993
Bonnefoy et al., 2112.03889

Basis reduction

If b is massless,

$$b_R \rightarrow e^{-i\varphi_{bG}} b'_R$$

leaves the SM Lagrangian invariant but

$$e^{i\varphi_{bG}}|C_{bG}|(\bar{Q}\sigma^{\mu\nu}T^A b)\tilde{\phi}G^A_{\mu\nu} \rightarrow |C_{bG}|(\bar{Q}\sigma^{\mu\nu}T^A b')\tilde{\phi}G^A_{\mu\nu}$$

No CP violation from C_{bG} in the massless b limit

The relative phase of operators only matter at $\mathcal{O}\left(\Lambda^{-4}\right)$

CPV

neglecting CKM phase

$\sigma_{int}(C - even) = 0$

Int $0 \neq O^{CP-odd} = 0$ SM/dim6²

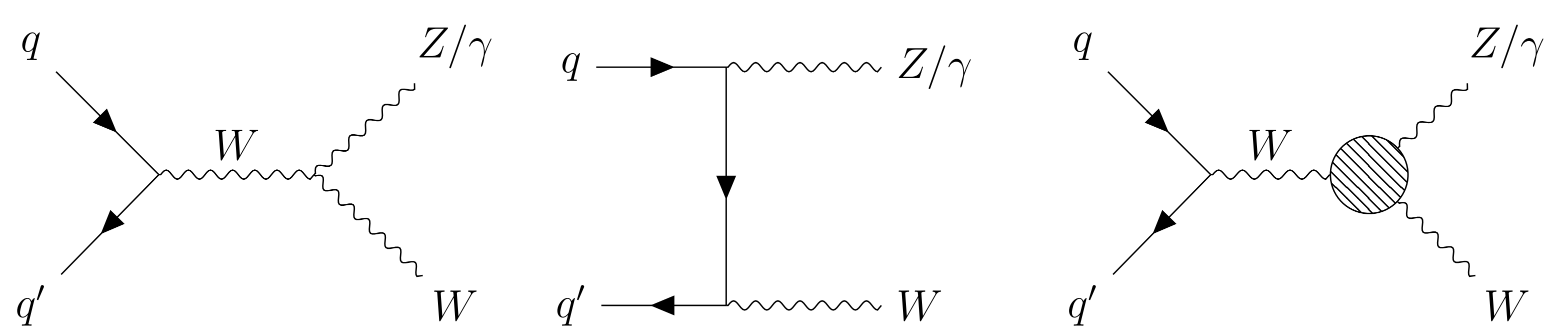
Only visible in distributions

WZ/γ are not C-even processes but $\sigma_{int} \approx 0$

$O^{CP-odd}_{SM} \approx 0$

Large enough cross-sections for accurate differential meas.

Leptonic and mostly visible decays



$\mathcal{O}_{\widetilde{W}WW}, O_{\phi\widetilde{W}B}$

C. Degrande

Interference suppression

Process	$W^+Z \to \mu^-\mu^+e^+\nu_e$	$W^-Z \to \mu^-\mu^+e^-\tilde{\nu}_e$
$\sigma(SM)$	15.74(2) fb	9.88(1) fb
δ_{PDF}	3.45%	3.78%
$\sigma(\mathcal{O}_{\widetilde{W}WW})$	0.047(4) fb	-0.033(3) fb
Schwartz Bound	16.13 fb	8.85 fb
$\sigma^{\lvert int\rvert}(\mathcal{O}_{\widetilde{W}WW})$	3.302(4) fb	2.028(3) fb
$\sigma^{\lvert meas\rvert}(\mathcal{O}_{\widetilde{W}WW})$	1.084(4) fb	0.634(3) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\widetilde{W}WW})$	4.133(5) fb	1.982(3) fb
$\sigma(\mathcal{O}_{\phi\widetilde{W}B})$	0.0086(7) fb	-0.0066(4) fb
Schwartz Bound	1.21 fb	0.76 fb
$\sigma^{\lvert int\rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	0.5467(7) fb	0.3533(4) fb
$\sigma^{\lvert meas\rvert}(\mathcal{O}_{\phi\widetilde{W}B})$	0.1807(7) fb	0.1100(4) fb
$\sigma_{\Lambda^{-4}}(\mathcal{O}_{\phi\widetilde{W}B})$	0.0231(3) fb	0.0145(2) fb

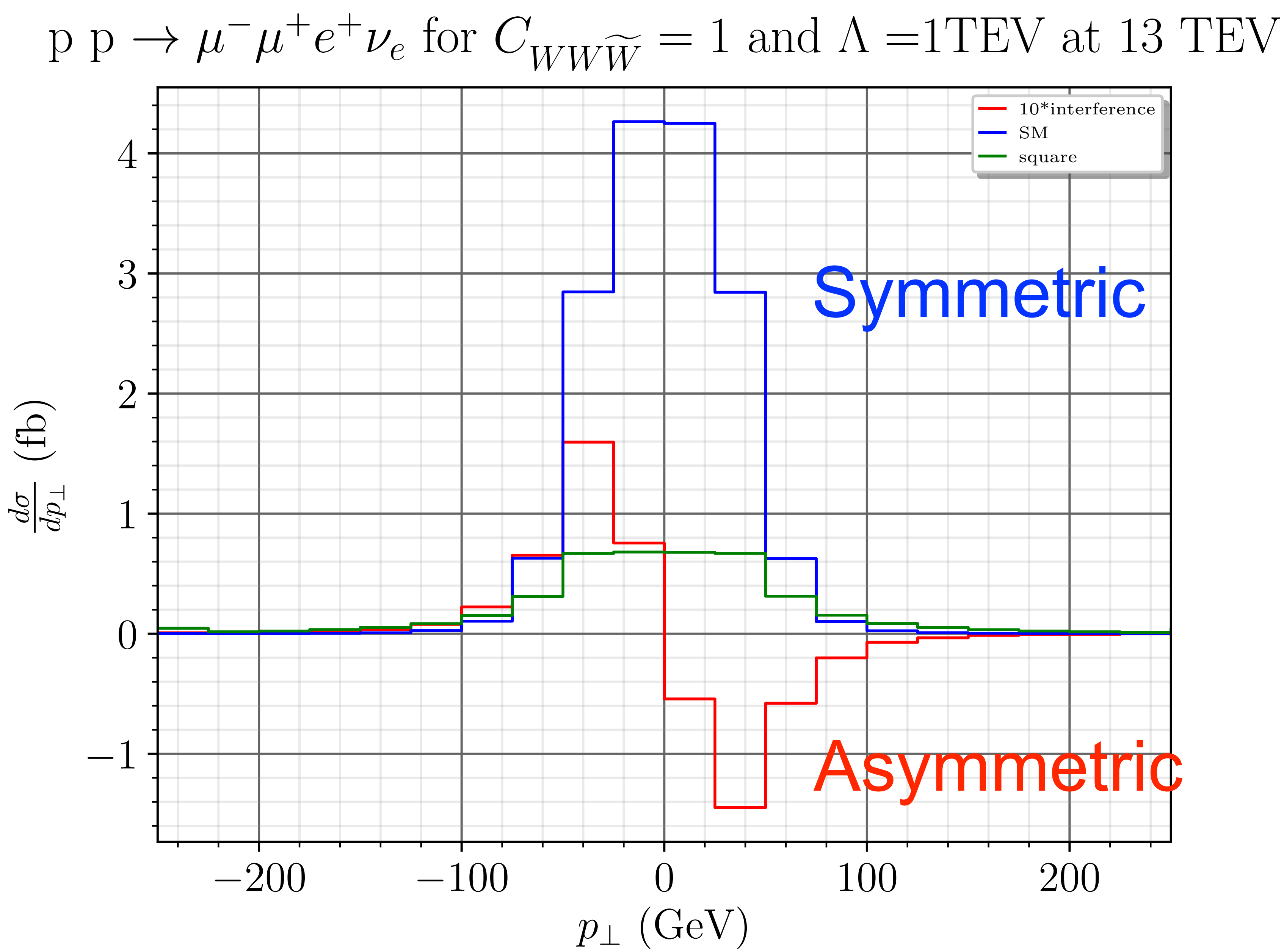
Suppressed from phase space

largely available

$C = 1, \Lambda = 1$TeV

C. Degrande

Towards asymmetries



$$\vec{p}_e \cdot \frac{(\vec{p}_q \times \vec{p}_Z)}{\left|(\vec{p}_q \times \vec{p}_Z)\right|}$$

C. Degrande

Comparison with other variable

Process	$W^+Z \to \mu^-\mu^+e^+\nu_e$		
Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\phi\widetilde{W}B}$
$\Delta p_\perp(p_e, p_q)$	-0.04(2)	-1.612(4)	-0.3888(7)
$\Delta p_\perp(p_e, p^z_\sum)$	-0.02(2)	-0.628(4)	-0.1207(7)
$\Delta p_\perp(p_e, p^z_e)$	0.0(2)	-0.535(4)	-0.1173(7)
$\Delta p_\perp(p_e, p^z_Z)$	-0.01(2)	-0.527(4)	-0.0874(7)
$\Delta \sin\phi_{WZ}$	-0.03(2)	-0.321(4)	0.0031(7)
$\Delta\,(\Delta\phi_{eZ})$	0.07(2)	0.196(4)	0.0688(7)
SM stat err 30 fb^{-1}	0.7		
SM stat err 100 fb^{-1}	0.4		
SM stat err 3000 fb^{-1}	0.07		

Process	$W^-Z \to \mu^-\mu^+e^-\tilde{\nu}_e$		
Operators	SM	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\phi\widetilde{W}B}$
$\Delta p_\perp(p_e, p_q)$	-0.08(1)	1.006(3)	0.2522(4)
$\Delta p_\perp(p_e, p^z_\sum)$	-0.03(1)	-0.331(3)	0.0810(4)
$\Delta p_\perp(p_e, p^z_e)$	-0.01(1)	0.295(3)	0.0514(4)
$\Delta p_\perp(p_e, p^z_Z)$	0.00(1)	0.295(3)	0.0627(4)
$\Delta \sin\phi_{WZ}$	-0.02(1)	-0.190(3)	0.0013(4)
$\Delta\,(\Delta\phi_{eZ})$	-0.05(1)	0.022(3)	0.0109(4)
SM stat err 30 fb^{-1}	0.6		
SM stat err 100 fb^{-1}	0.3		
SM stat err 3000 fb^{-1}	0.06		

≈ 0

knowing the quark direction

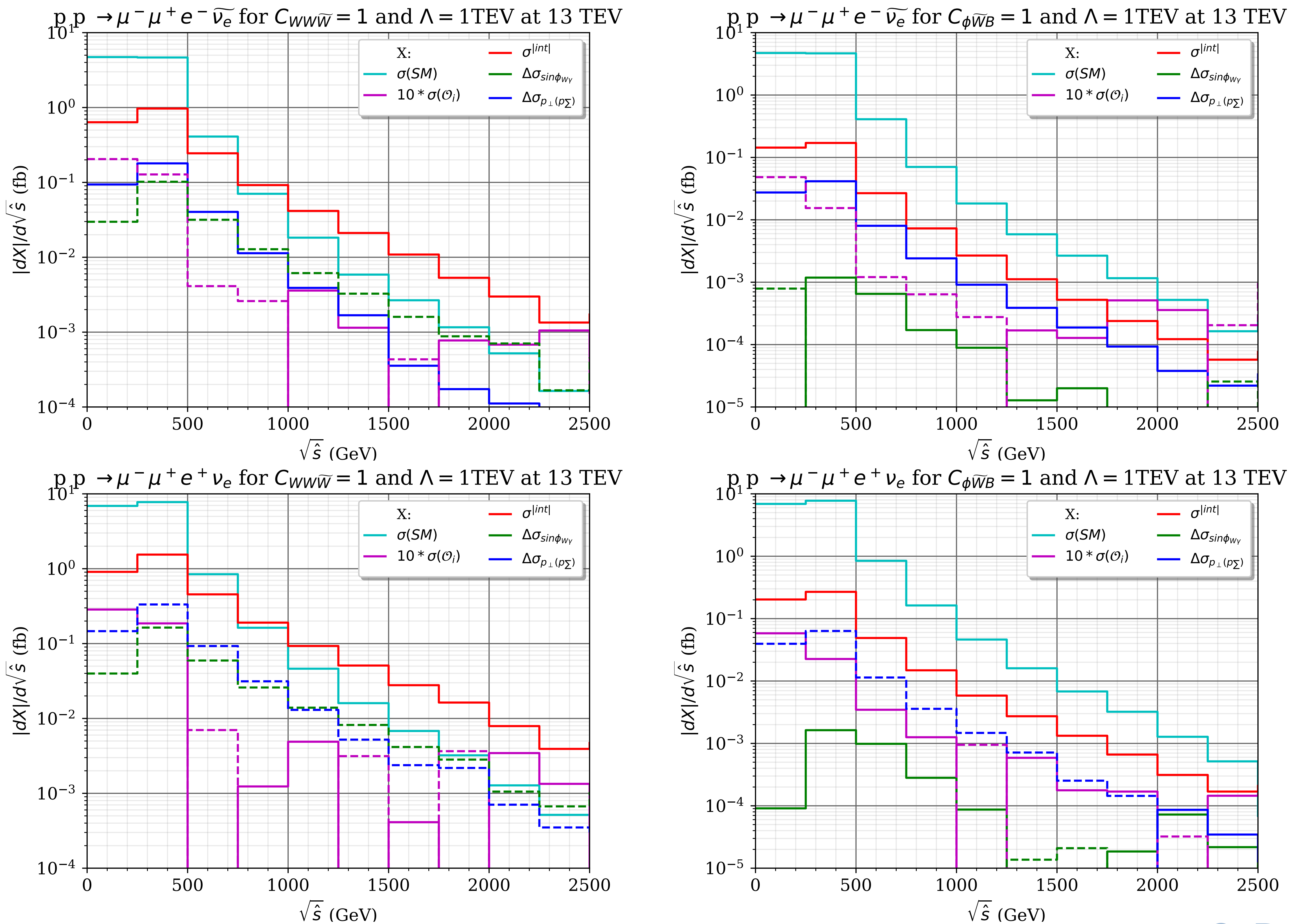
50-70% efficiency

80-90% in $W\gamma$

Better than HE observables

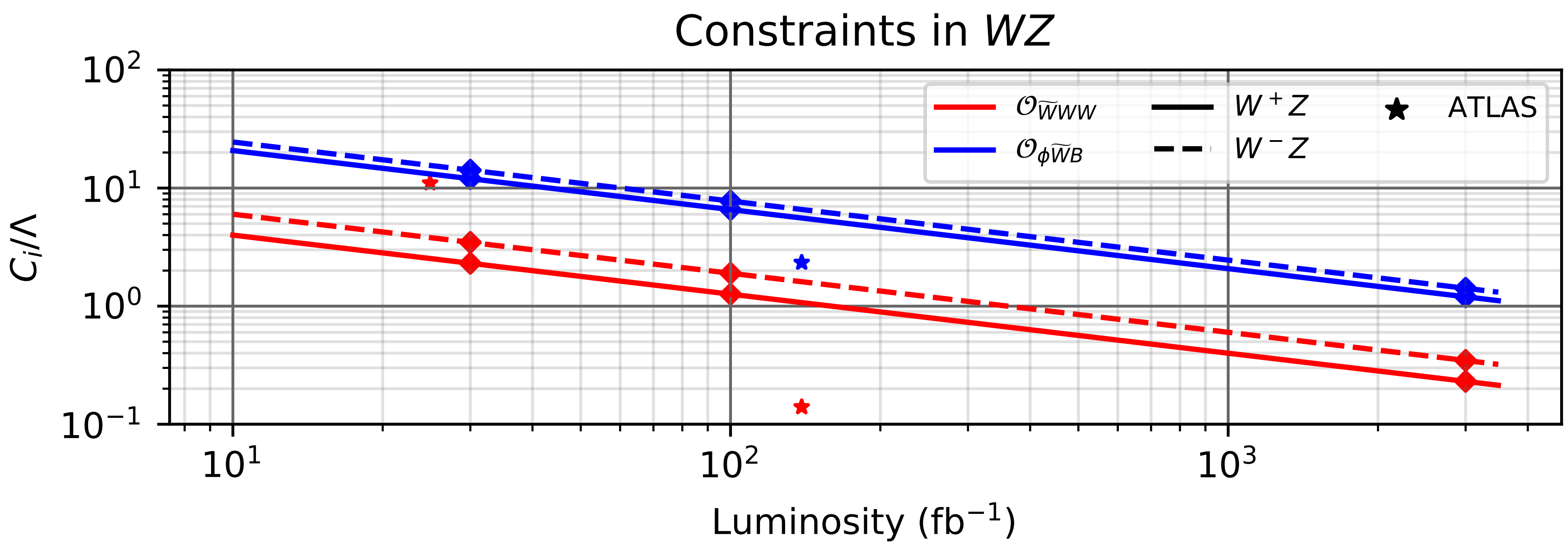
C. Degrande

HE behaviour

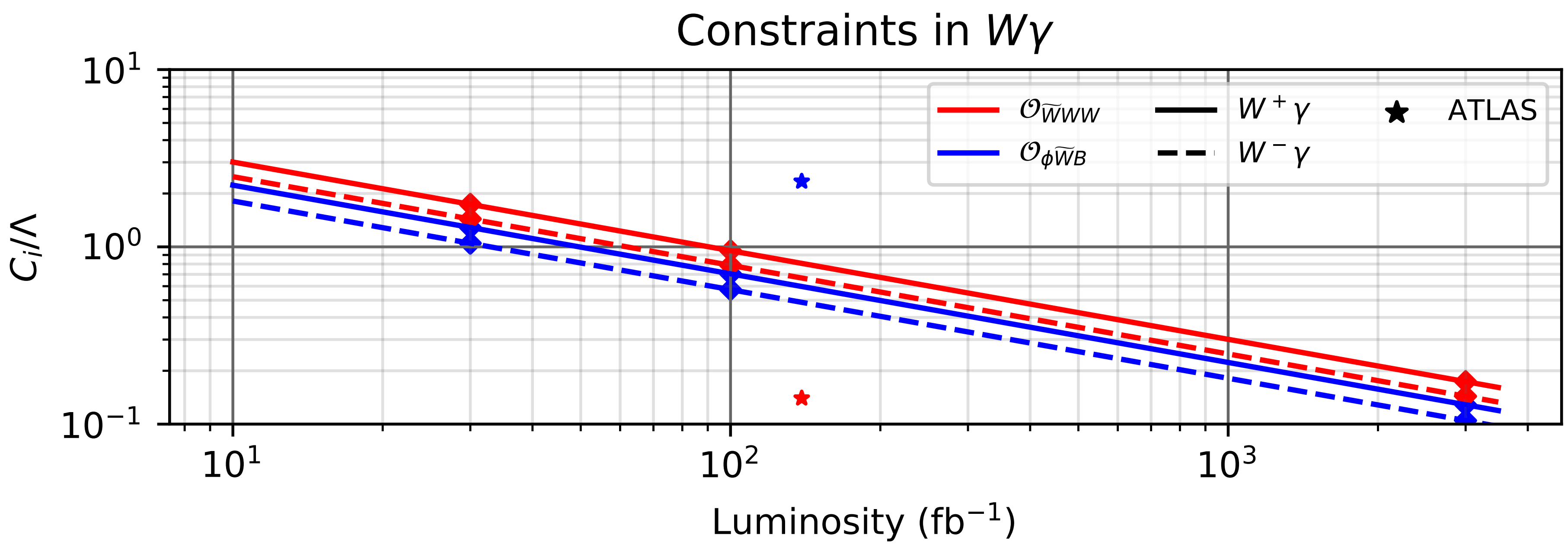


C. Degrande

Constraints



$\Lambda \approx 1TeV$



$\Lambda \approx 3TeV$

EFT validity & Errors ~ $(0.2TeV/1TeV)^2$ ~4%

Bulk vs small HE tail

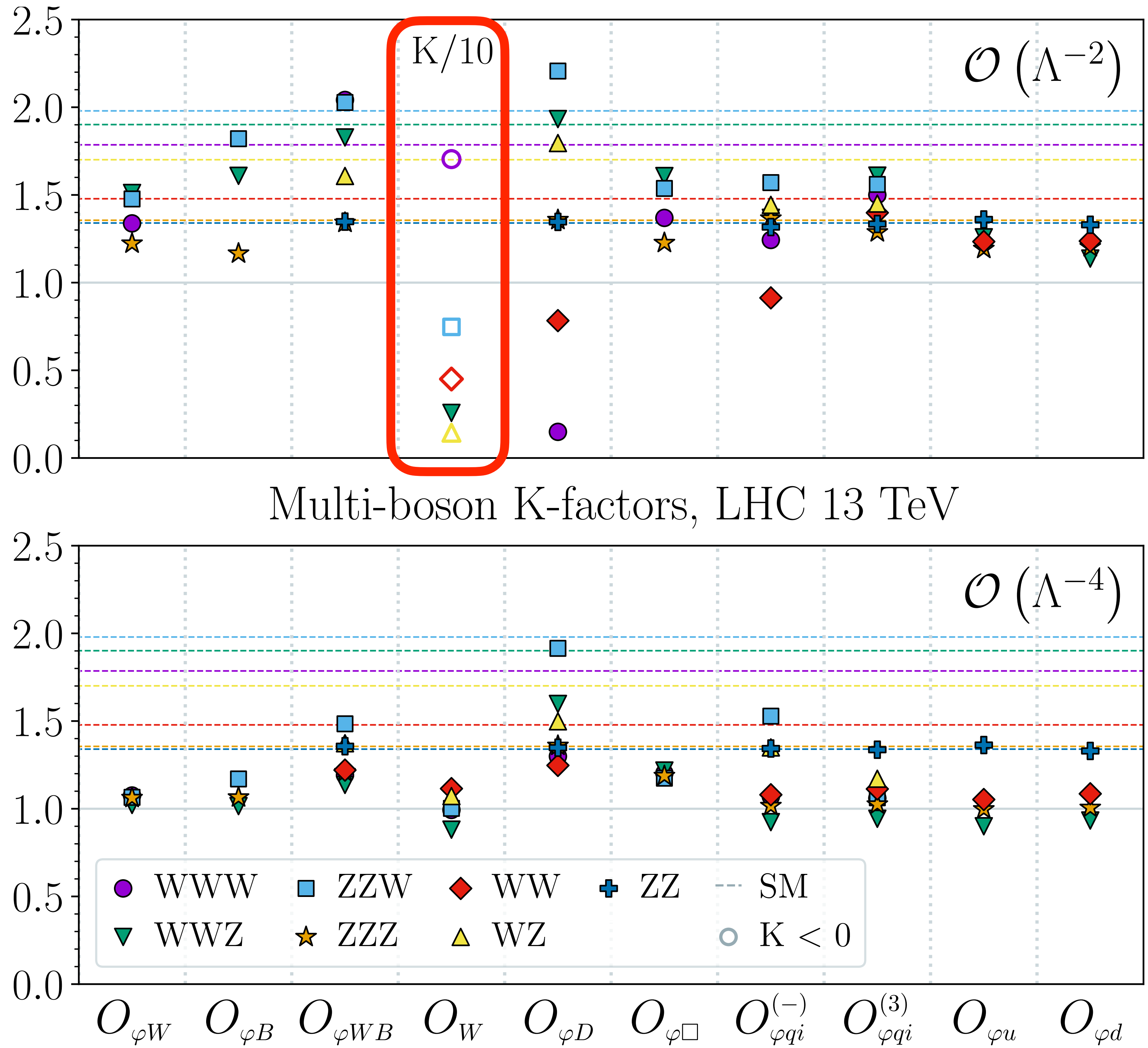
C. Degrande

Keeping uncertainties under control

EW bosons production

Large negative K-factors

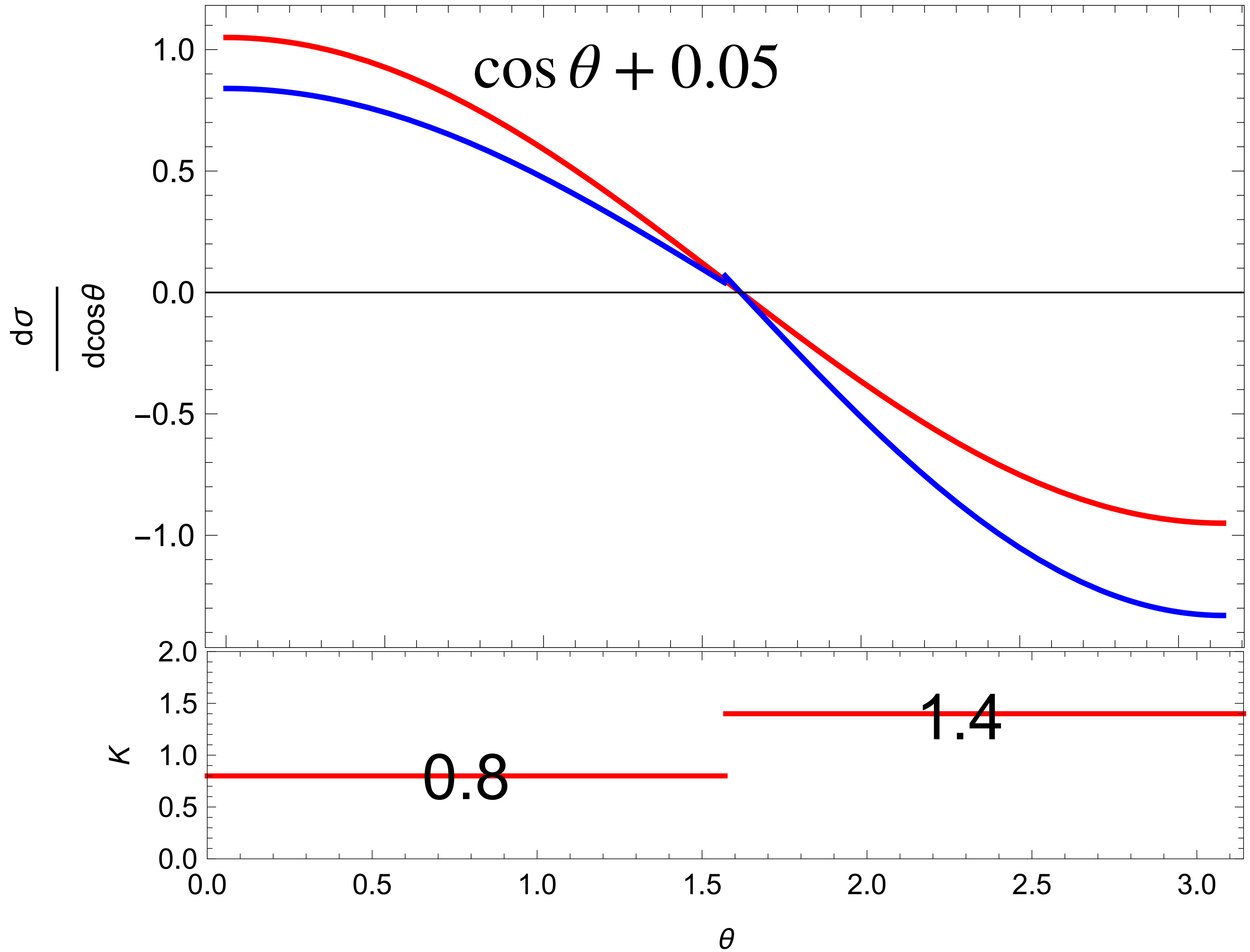
Converge?



SMEFT@NLO
2008.11743

C. Degrande

Large/small K-factor



$$\sigma_{int}^{LO} = 0.16$$

$$\sigma_{int}^{NLO} = -0.43$$

$$K_\sigma \approx -3$$

Uncertainty

σ is not the right variable to probe the interference

C. Degrande

Interference revival: toy example

$$A = d\sigma(\cos\theta > 0) - d\sigma(\cos\theta < 0)$$

$$A_{int}^{LO} = 2 \qquad >> \sigma_{int}^{LO} = 0.16$$

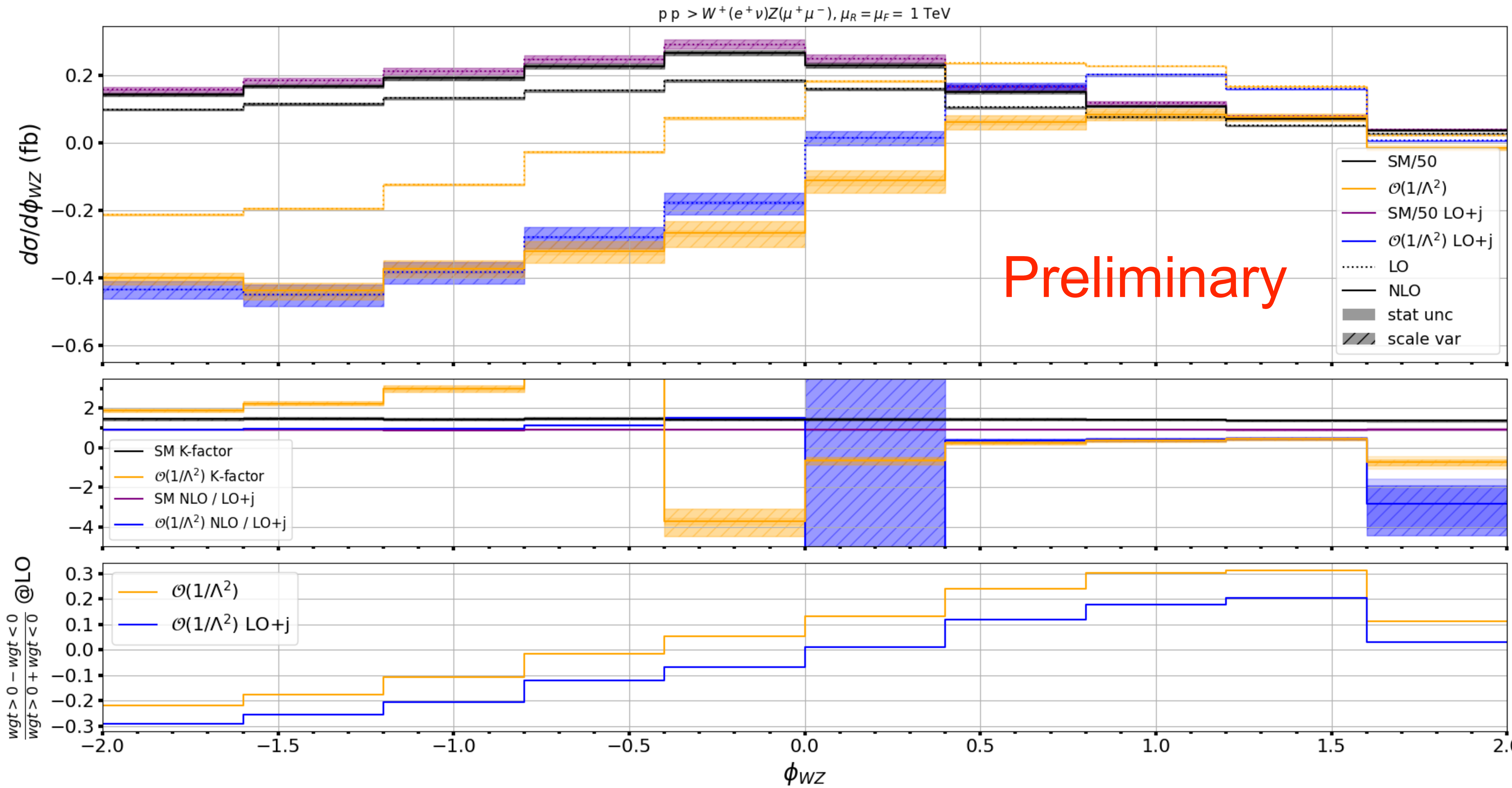
$$A_{int}^{NLO} = 2.15$$

$$K_A = 1.1$$

No/little cancellation
(Much) larger sensitivity
Less sensitive to corrections (smaller errors)

C. Degrande

O_{WWW}



with M. Maltoni

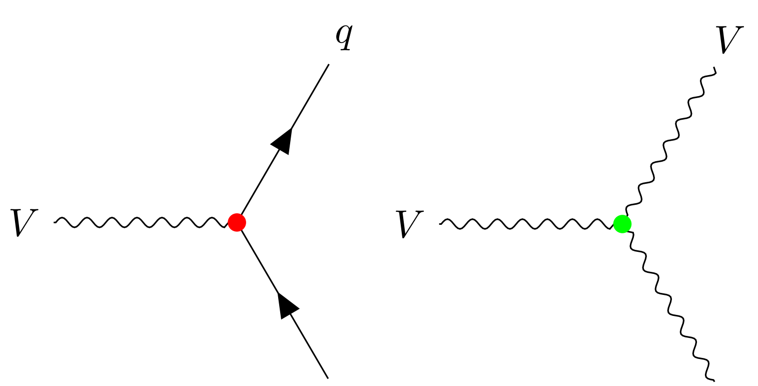
C. Degrande

Dim-8 in diboson

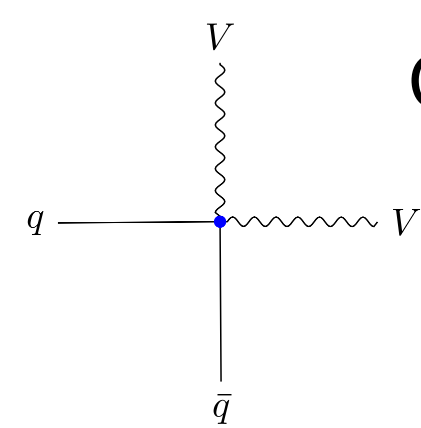
dim-8 operators

$$\mathcal{O}_1 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_2 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$
$$\mathcal{O}_3 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right),$$
$$\mathcal{O}_4 = iW^{I\mu}{}_{\lambda}B^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_5 = iW^{I\mu}{}_{\lambda}\tilde{B}^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_6 = iW^{I\nu}{}_{\lambda}B^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_7 = iW^{I\nu}{}_{\lambda}\tilde{B}^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_8 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_9 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$

$$\mathcal{O}_{10} = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right),$$
$$\mathcal{O}_{11} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{12} = i\epsilon^{IJK}\tilde{W}^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{13} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}\tilde{W}^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{14} = i\left(\bar{u}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{15} = i\left(\bar{d}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{16} = i\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{17} = i\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\tau^{K}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right)\left(D_{\lambda}H^{\dagger}\tau^{K}D^{\mu}H\right),$$
$$\mathcal{O}_{18} = i(\bar{u}_{\mathrm{R}p}\gamma^{\mu}\overleftrightarrow{D}^{\nu}d_{\mathrm{R}r})\epsilon^{ij}(D^{\mu}H_{i}D^{\nu}H_{j}),$$



(a) dim-6 vertex corrections



(b) dim-8 contact corrections

CD,H.-L. Li, 2303.10493

C. Degrande

Interference behaviour

Operator	$2\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$	$2\int d\Omega\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$
$\mathcal{O}_8$	$d\bar{d}:\ b_8 S + c_8$	0
$\mathcal{O}_9$	$\bar{u}u:\ b_9 S + c_9$	0
$\mathcal{O}_{10}$	$u\bar{u}/d\bar{d}:\ a_{10}\cdot S^2 + b_{10}\cdot S + c_{10}$	$u\bar{u}/d\bar{d}:\ \bar{a}_{10}\cdot S^2 + \bar{b}_{10}\cdot S + \bar{c}_{10}$
$\mathcal{O}_{11}$	0	0
$\mathcal{O}_{12}$	$u\bar{u}:\ a^u_{12}S^2 + b^u_{12}S + c^u_{12}$	$u\bar{u}:\ \bar{a}^u_{12}S^2 + \bar{b}^u_{12}S + \bar{c}^u_{12} + \overline{D}^u_{12}\log S$
	$d\bar{d}:\ a^d_{12}S^2 + b^d_{12}S + c^d_{12}$	$d\bar{d}:\ \bar{a}^d_{12}S^2 + \bar{b}^d_{12}S + \bar{c}^d_{12} + \overline{D}^d_{12}\log S$
$\mathcal{O}_{13}$	$u\bar{u}:\ a^u_{13}S^2 + b^u_{13}S + c^u_{13}$	$u\bar{u}:\ \bar{a}^u_{13}S^2 + \bar{b}^u_{13}S + \bar{c}^u_{13} + \overline{D}^u_{13}\log S$
	$d\bar{d}:\ a^d_{13}S^2 + b^d_{13}S + c^d_{13}$	$d\bar{d}:\ \bar{a}^d_{13}S^2 + \bar{b}^d_{13}S + \bar{c}^d_{13} + \overline{D}^d_{13}\log S$
$\mathcal{O}_{14}$	$u\bar{u}:\ a_{14}S^2 + b_{14}S + c_{14}$	0
$\mathcal{O}_{15}$	$d\bar{d}:\ a_{15}S^2 + b_{15}S + c_{15}$	0
$\mathcal{O}_{16}$	$u\bar{u}:\ a^u_{16}S^2 + b^u_{16}S + c^u_{16}$	$u\bar{u}:\ \bar{b}^u_{16}S + \bar{c}^u_{16} + \overline{D}^u_{16}\log S$
	$d\bar{d}:\ a^d_{16}S^2 + b^d_{16}S + c^d_{16}$	$d\bar{d}:\ \bar{b}^d_{16}S + \bar{c}^d_{16} + \overline{D}^d_{16}\log S$
$\mathcal{O}_{17}$	$u\bar{u}:\ a^u_{17}S^2 + b^u_{17}S + c^u_{17}$	$u\bar{u}:\ \bar{b}^u_{17}S + \bar{c}^u_{17} + \overline{D}^u_{17}\log S$
	$d\bar{d}:\ a^d_{17}S^2 + b^d_{17}S + c^d_{17}$	$d\bar{d}:\ \bar{b}^d_{17}S + \bar{c}^d_{17} + \overline{D}^d_{17}\log S$

CPV

Asymmetric

Table 2: Scaling of $q\bar{q} \to WW$ interference amplitude after summing and averaging over spins and helicities.

C. Degrande

Interference by helicity (O_8)

(h_{W^+}, h_{W^-})		$\mathcal{A}^8_{h_i} / \frac{C_8}{\Lambda^4}$	$\mathcal{A}^{\rm SM}_{h_i}$	
$-,+$	S^2	$S\sin^2\left(\frac{\theta}{2}\right)\sin(\theta)\left(S-2M_W^2\right)\delta_{ab}$	0	S^0
$-,-$	S	$S\sin(\theta)\cos(\theta)M_W^2\delta_{ab}$	$\frac{4\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\sqrt{1-\frac{4M_W^2}{S}}}{3\left(S-M_Z^2\right)}$	S^{-1}
$-,0$	$S^{3/2}$	$\frac{S^{3/2}\sin^2\left(\frac{\theta}{2}\right)(2\cos(\theta)+1)M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\pi\alpha\sin^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{2S-8M_W^2}}{3SM_W-3M_WM_Z^2}$	$S^{-1/2}$
$+,+$	S	$S\sin(\theta)\cos(\theta)M_W^2\delta_{ab}$	$\frac{4\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\sqrt{1-\frac{4M_W^2}{S}}}{3\left(S-M_Z^2\right)}$	S^{-1}
$+,-$	S^2	$2S\sin\left(\frac{\theta}{2}\right)\cos^3\left(\frac{\theta}{2}\right)\delta_{ab}\left(S-2M_W^2\right)$	0	S^0
$+,0$	$S^{3/2}$	$\frac{S^{3/2}\cos^2\left(\frac{\theta}{2}\right)(2\cos(\theta)-1)M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{2S-8M_W^2}}{3SM_W-3M_WM_Z^2}$	$S^{-1/2}$
$0,+$	$S^{3/2}$	$-\frac{S^{3/2}\sin^2\left(\frac{\theta}{2}\right)(2\cos(\theta)+1)M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\sqrt{2}\pi\alpha\sin^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$	$S^{-1/2}$
$0,-$	$S^{3/2}$	$\frac{S^{3/2}\cos^2\left(\frac{\theta}{2}\right)(1-2\cos(\theta))M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\sqrt{2}\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$	$S^{-1/2}$
$0,0$	S	$-S\sin 2\theta M_W^2\delta_{ab}$	$\frac{2\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\left(2M_W^2+S\right)\sqrt{1-\frac{4M_W^2}{S}}}{3M_W^2\left(M_Z^2-S\right)}$	S^0

Table 3: Helicity amplitudes for $d\bar{d}\to WW$ for $h_d = 1$ and $h_{\bar{d}} = -1$, where $\mathcal{A}^8_{h_i}$ is generated by $\mathcal{O}_8$.

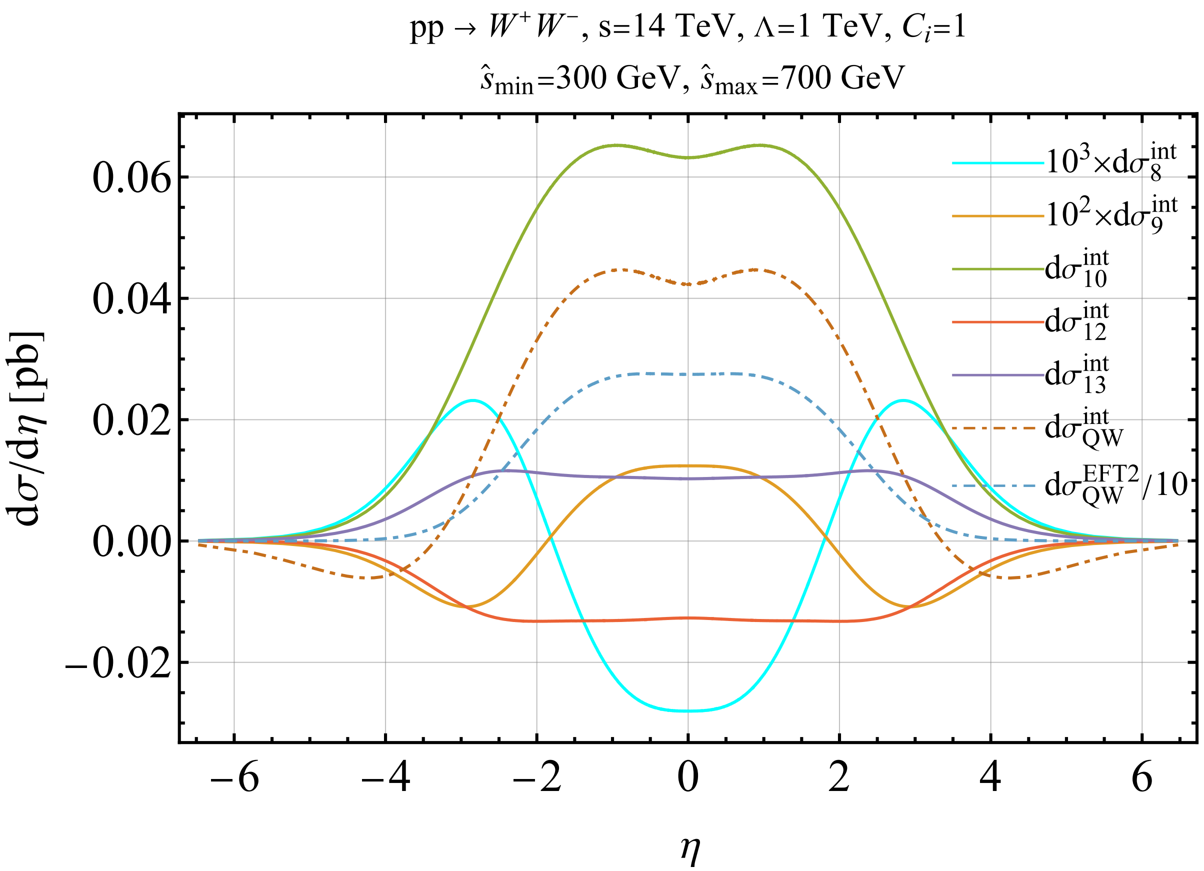
C. Degrande

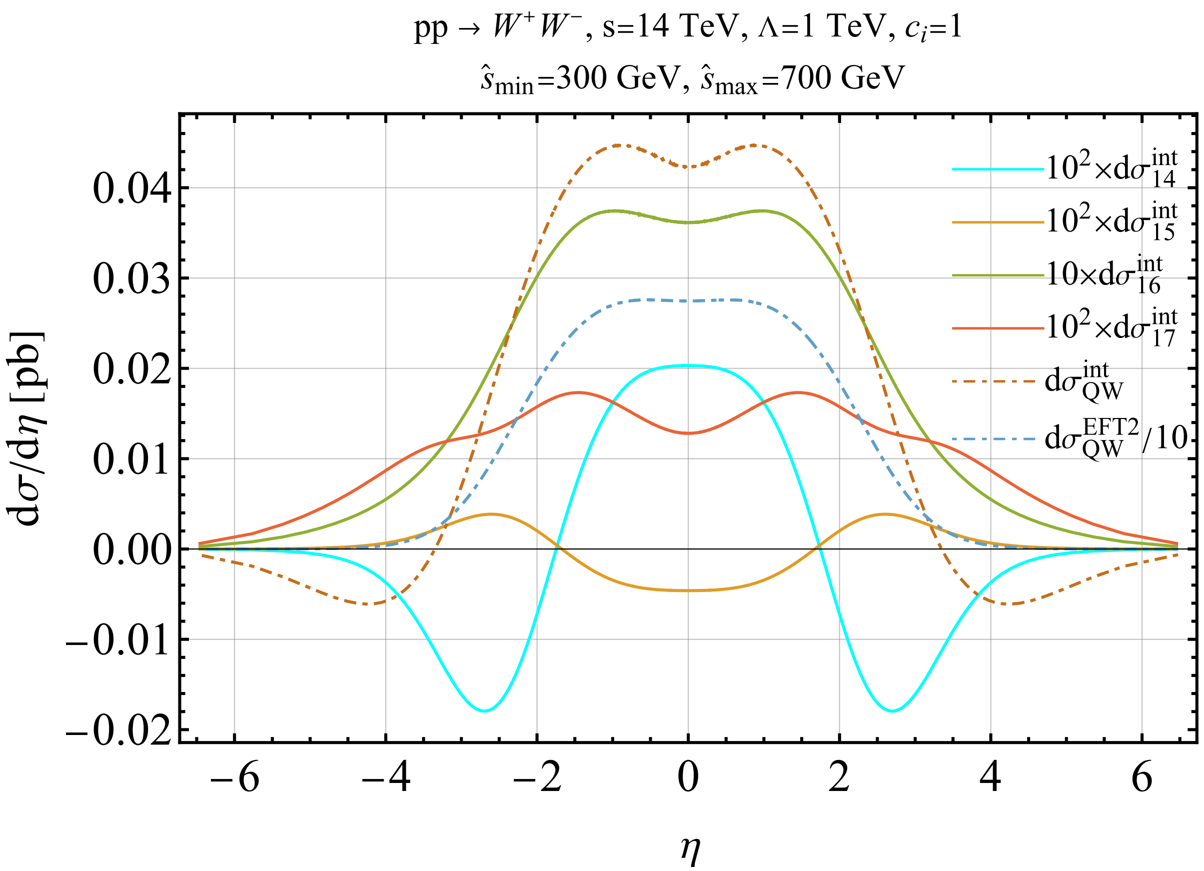
Interference by helicity (O_{15})

(h_{W^+}, h_{W^-})		$\mathcal{A}^{15}_{h_i}/\frac{C_{15}}{\Lambda^4}$	$\mathcal{A}^{SM}_{h_i}$	
$-,+$	S	$S\sin^2\left(\frac{\theta}{2}\right)\sin(\theta)M_W^2\delta_{ab}$	0	
$-,-$	S	$-S\sin^2\left(\frac{\theta}{2}\right)\sin(\theta)M_W^2\delta_{ab}$	$\frac{4\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\sqrt{1-\frac{4M_W^2}{S}}}{3\left(S-M_Z^2\right)}$	S^{-1}
$-,0$	$S^{3/2}$	$\frac{S^{3/2}\sin^2\left(\frac{\theta}{2}\right)\cos(\theta)M_W\delta_{ab}}{\sqrt{2}}$	$\frac{4\pi\alpha\sin^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{2S-8M_W^2}}{3SM_W-3M_WM_Z^2}$	$S^{-1/2}$
$+,+$	S	$S\sin(\theta)\cos^2\left(\frac{\theta}{2}\right)M_W^2\delta_{ab}$	$\frac{4\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\sqrt{1-\frac{4M_W^2}{S}}}{3\left(S-M_Z^2\right)}$	S^{-1}
$+,-$	S	$-S\sin(\theta)\cos^2\left(\frac{\theta}{2}\right)M_W^2\delta_{ab}$	0	
$+,0$	$S^{3/2}$	$\frac{S^{3/2}\cos^2\left(\frac{\theta}{2}\right)\cos(\theta)M_W\delta_{ab}}{\sqrt{2}}$	$\frac{4\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{2S-8M_W^2}}{3SM_W-3M_WM_Z^2}$	$S^{-1/2}$
$0,+$	$S^{3/2}$	$-\frac{S^{3/2}\sin^2(\theta)M_W\delta_{ab}}{2\sqrt{2}}$	$\frac{4\sqrt{2}\pi\alpha\sin^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$	$S^{-1/2}$
$0,-$	$S^{3/2}$	$\frac{S^{3/2}\sin^2(\theta)M_W\delta_{ab}}{2\sqrt{2}}$	$\frac{4\sqrt{2}\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$	$S^{-1/2}$
$0,0$	S^2	$-\frac{1}{8}S^2\sin(2\theta)\delta_{ab}$	$\frac{2\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\left(2M_W^2+S\right)\sqrt{1-\frac{4M_W^2}{S}}}{3M_W^2\left(M_Z^2-S\right)}$	S^0

C. Degrande

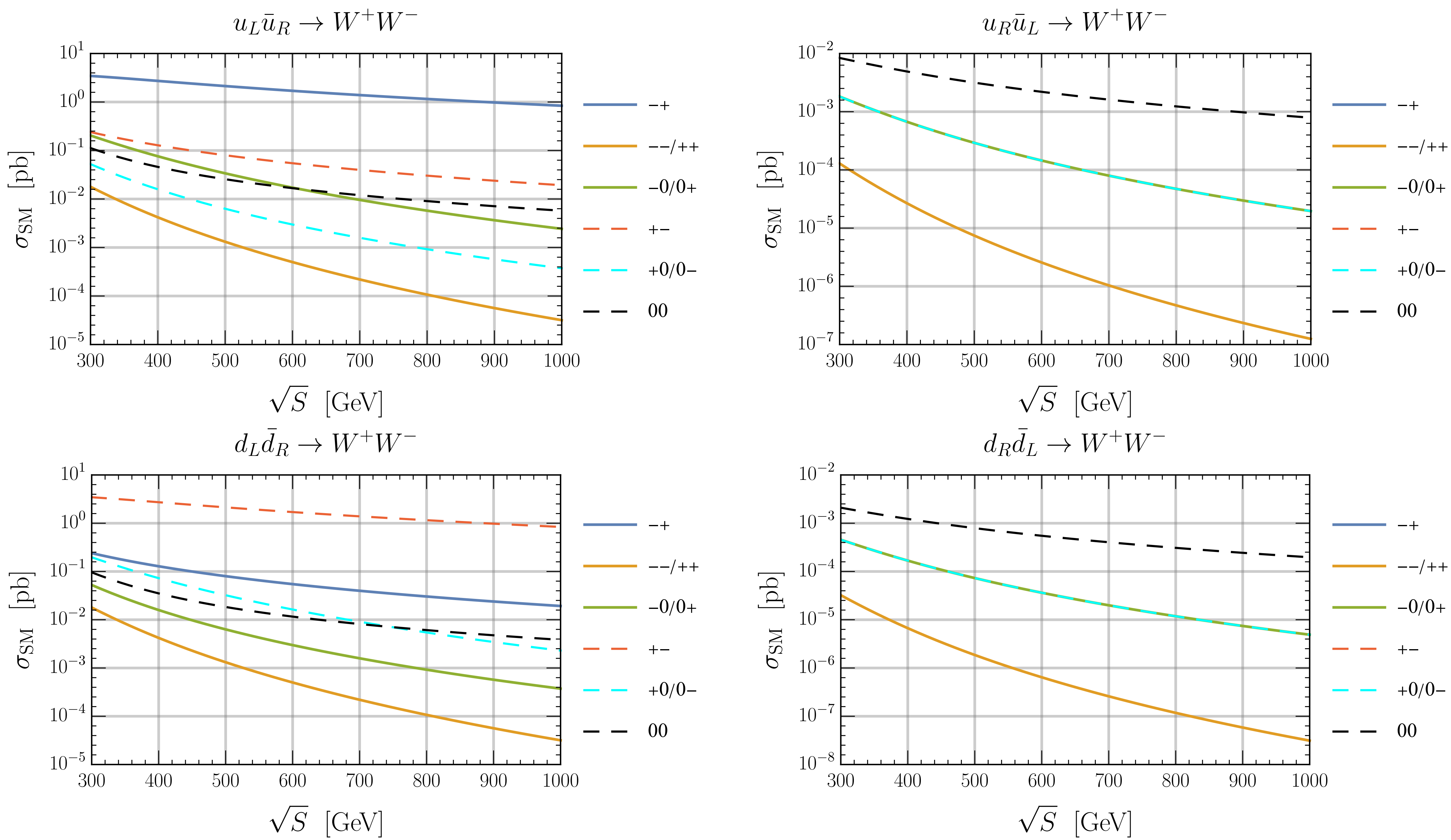
Distributions





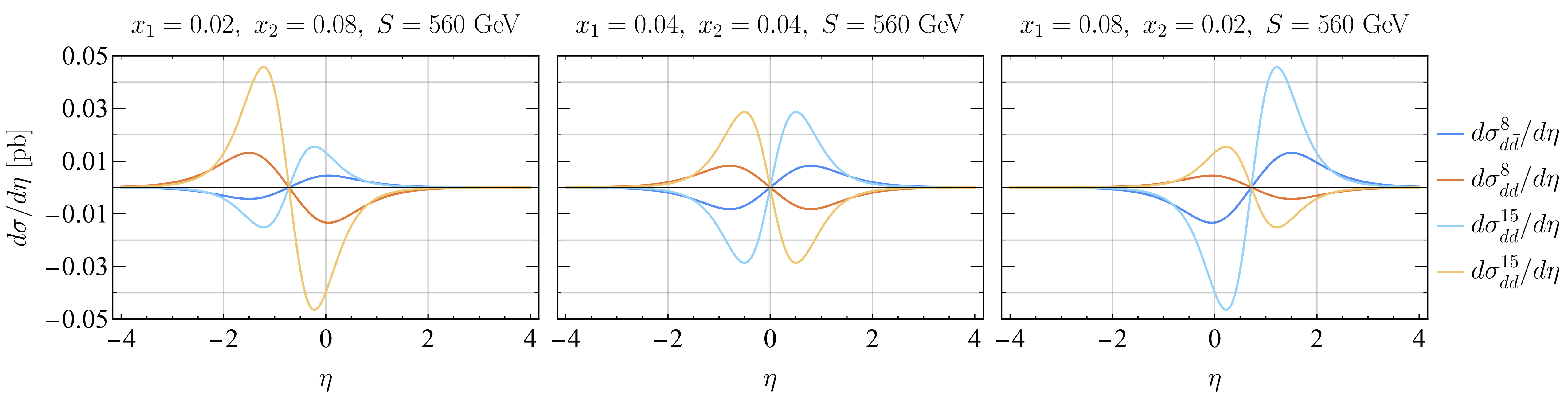
C. Degrande

SM Parton level



C. Degrande

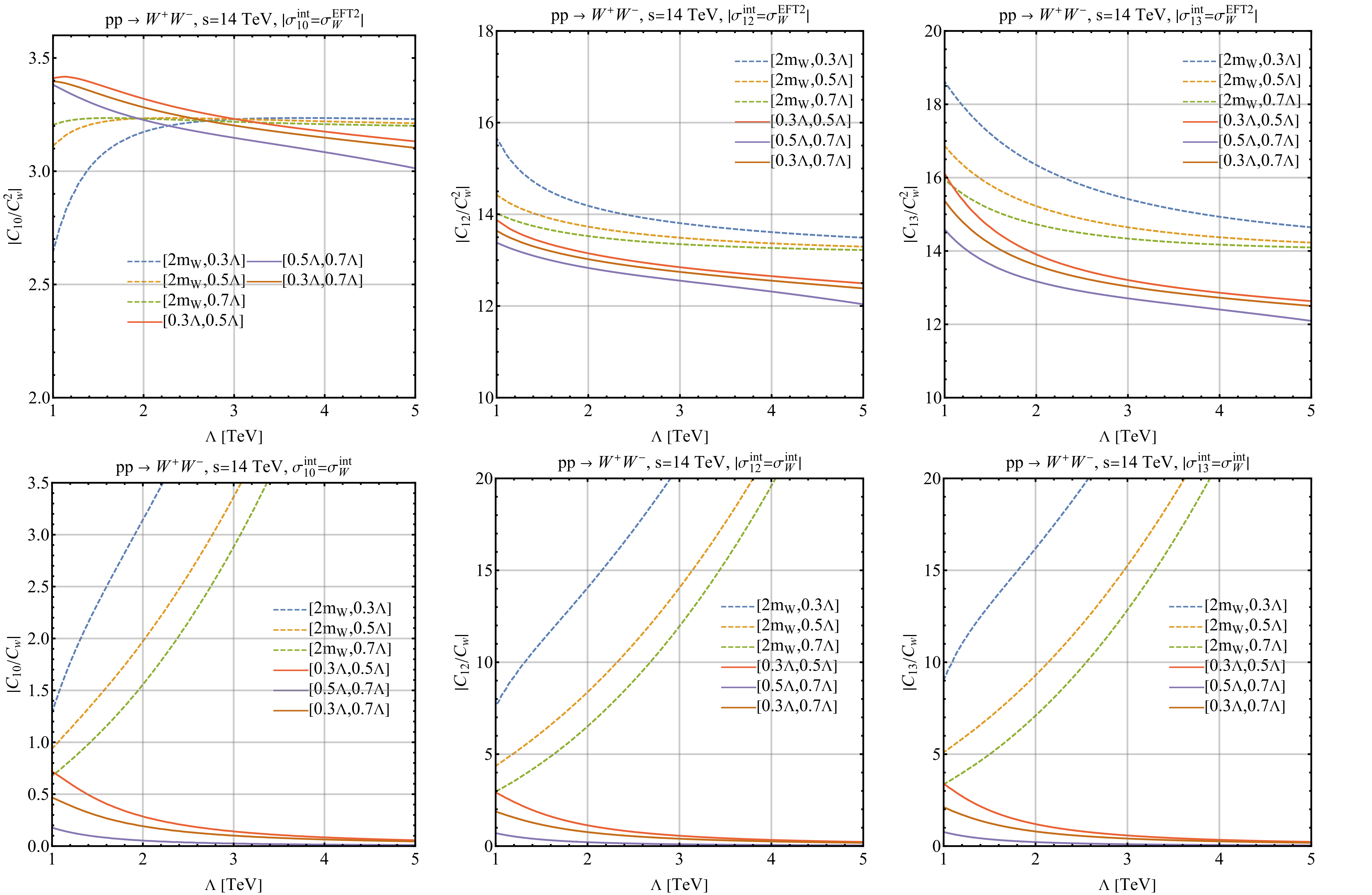
LHC symmetry cancellation



Not present at lepton colliders

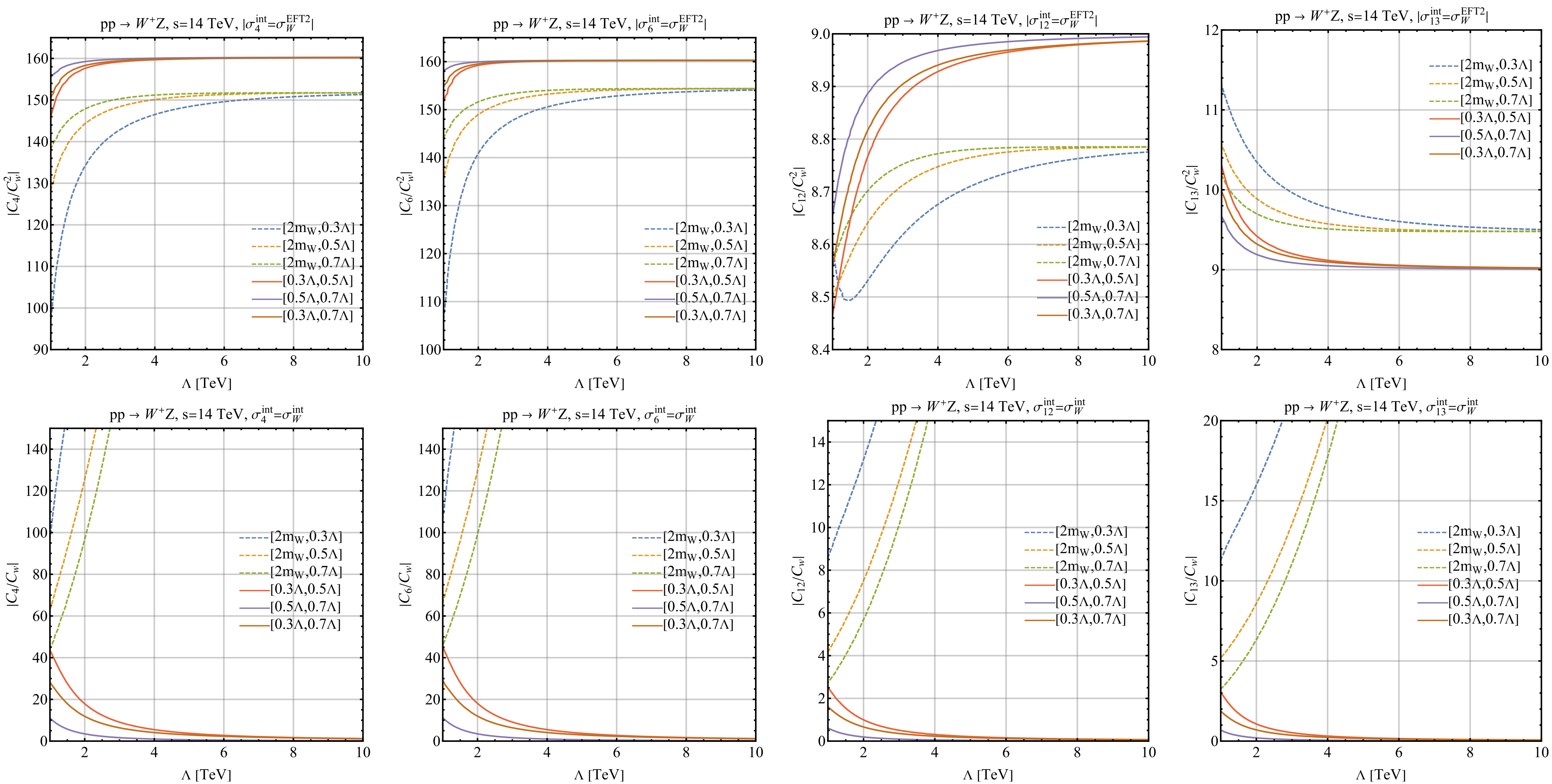
C. Degrande

Comparison to dim6



C. Degrande

WZ



C. Degrande

Further comments

Comments

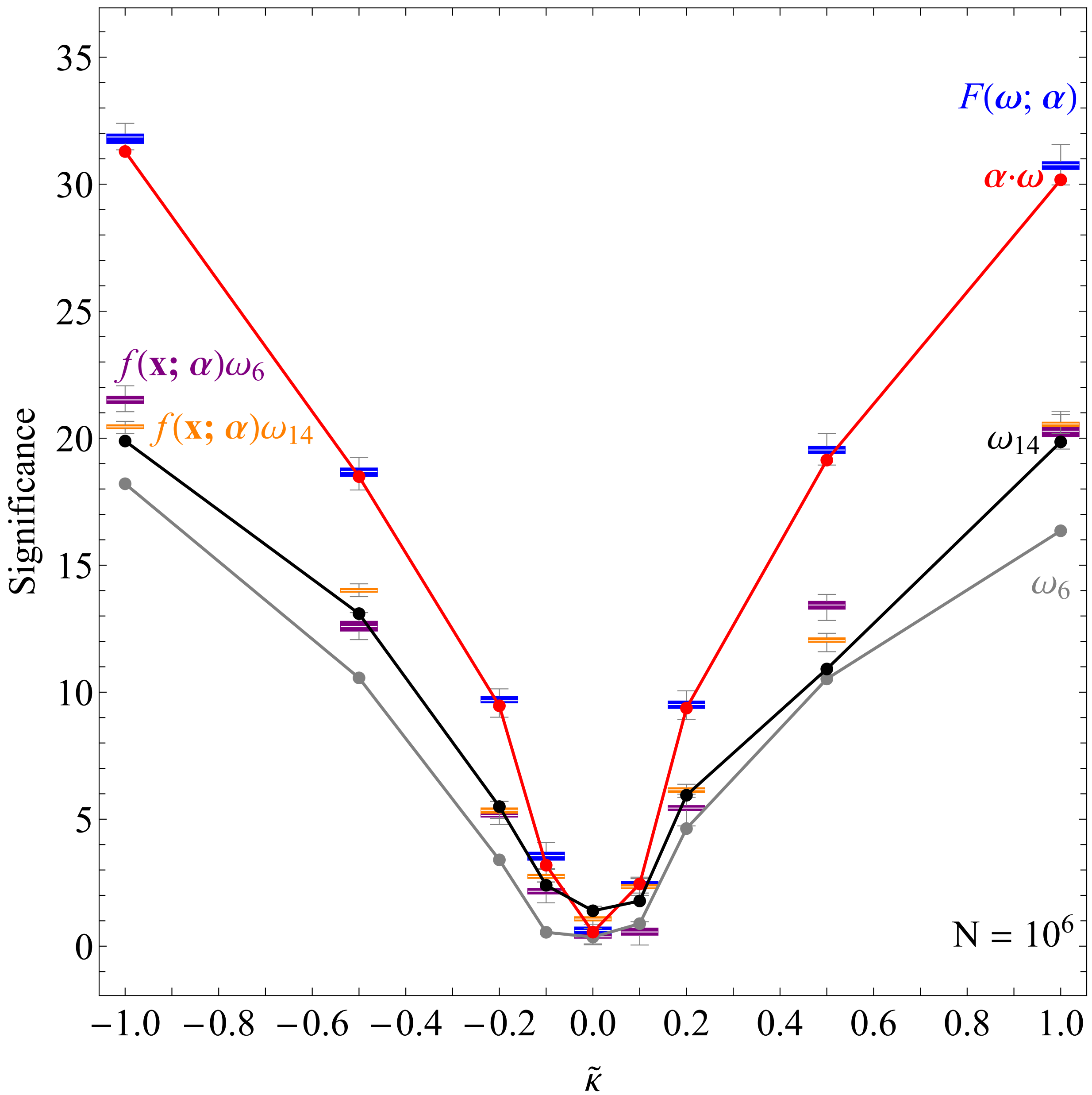
- ME/ML trained vs Observable

- Efficient observables
  - more sensitive
  - smaller errors
- Both CP and dim8 encourage more differential measurements

C. Degrande

Observables vs ML trained on model

Faroughy, Bortolato, Kamenik, Kosnik Smolkovic,
Symmetry 13 (2021) no.7, 1129



Neural network

Linear combination

$$\omega_{14} \sim [(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b - \boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_b - \boldsymbol{p}_{\bar{b}}) \cdot (\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+})]$$

$$\omega_6 \sim [(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]$$

Comments

- ME/ML trained vs Observable

- Efficient observables
  - more sensitive
  - smaller errors
- Both CP and dim8 encourage more differential measurements

C. Degrande

CPV in WW

Preliminary

$C_{11} = 1, \Lambda = 1\text{TeV}$

w+/w- helicities	x-sect. in fb (LHC13)
- -	0.0705
- o	0.0865
- +	0
o -	0.0784
o o	0
o +	-0.0849
+ -	0
+ o	-0.0785
+ +	-0.0684

$A \propto s^0$

$\sigma_{10} \approx -1\text{pb}$

$C_{10} = 1, \Lambda = 1\text{TeV}$

$A = 0.4fb$

C. Degrande