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

CP-violation in Diboson Production

Celine Degrande

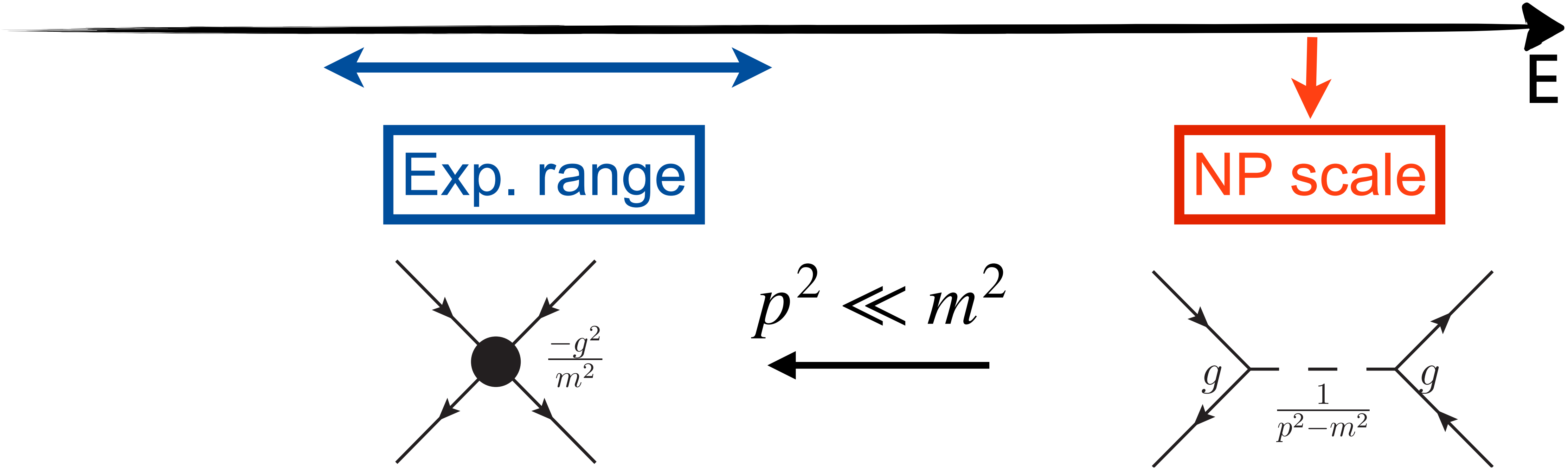
Plan

- Introduction to SMEFT
- SMEFT and interference
- CPV in EW diboson
- Further comments

Introduction to SMEFT

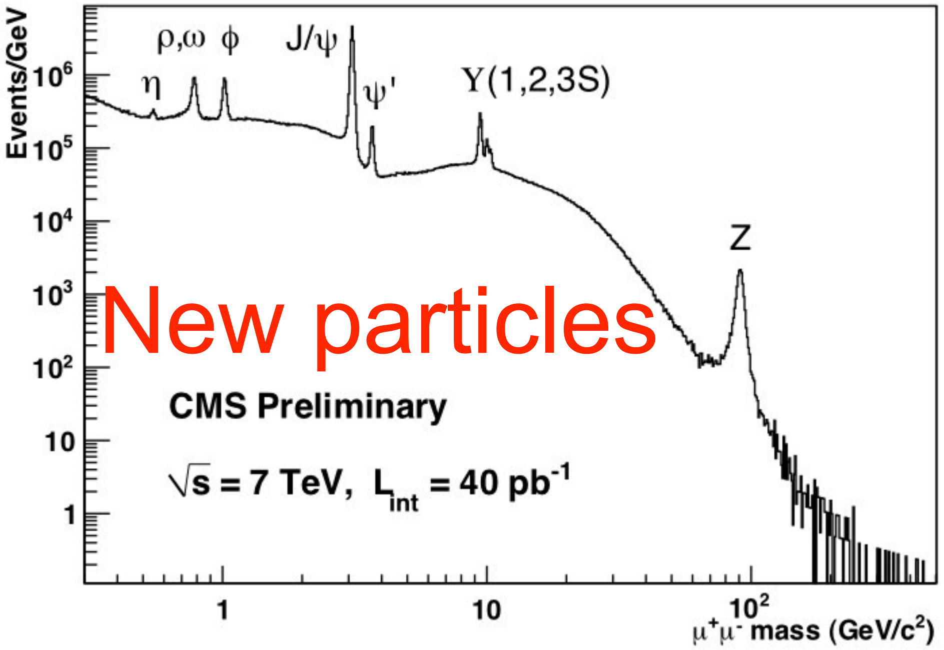
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments



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

New/modified interactions between SM particles



New particles

EFT

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

← SM fields & sym.

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EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4}\sum_{i} \frac{C_i}{\Lambda^{d-4}}\mathcal{O}_i^d \longleftarrow \text{SM fields \& sym.}$$

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

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

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

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EFT

Parametrize any NP but an ∞ number of coefficients

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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
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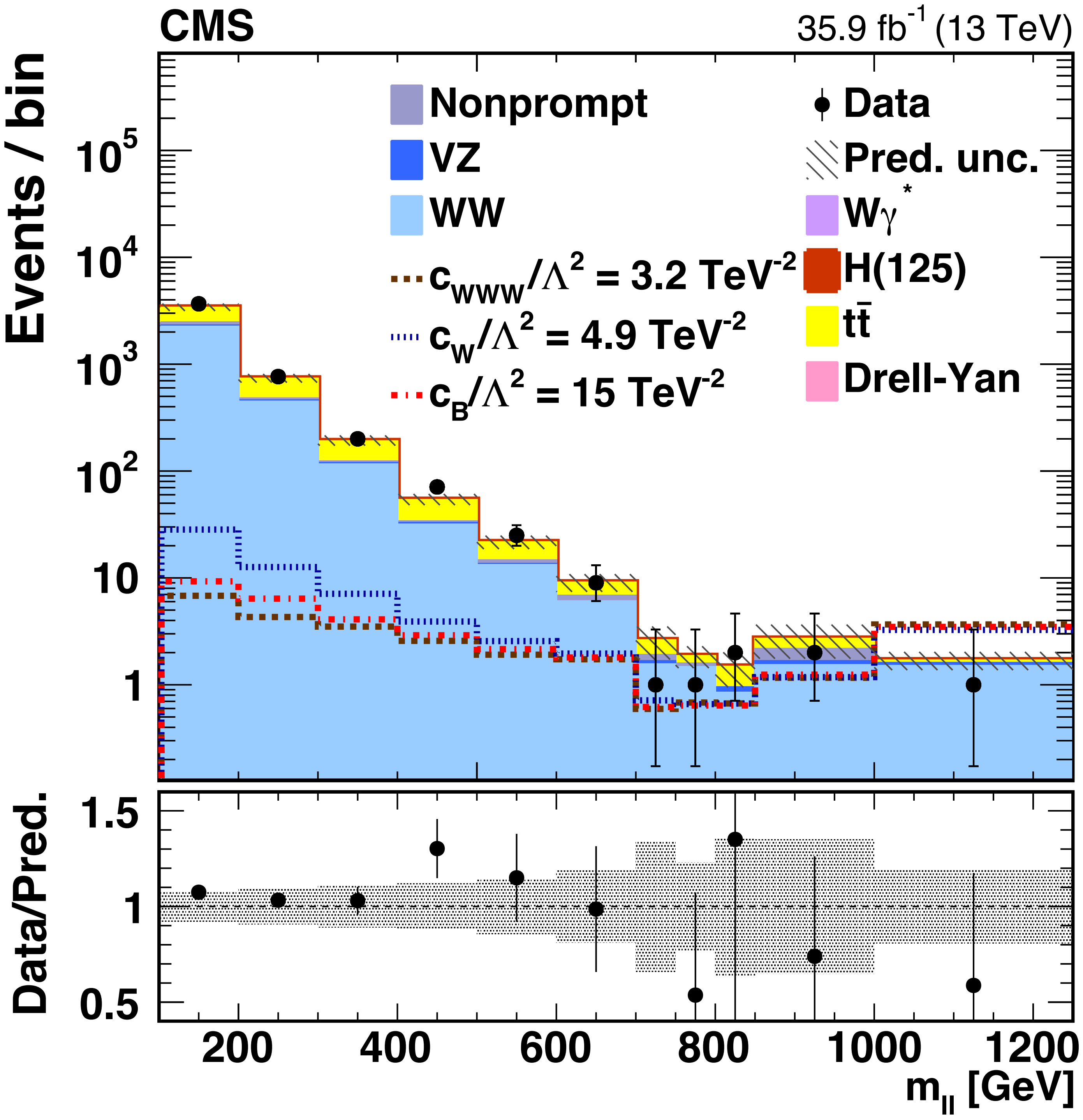
High energy tails



2009.00119

Cross-sections and precision plummet at high energy

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

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SMEFT and interference

Errors : higher power of $1/\Lambda$

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

- 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

Errors : higher power of $1/\Lambda$

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

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

- Contains :
  - 1 dim6 insertion squared
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interference suppression

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

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	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

interference suppression

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

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interference suppression

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

Assuming ~0

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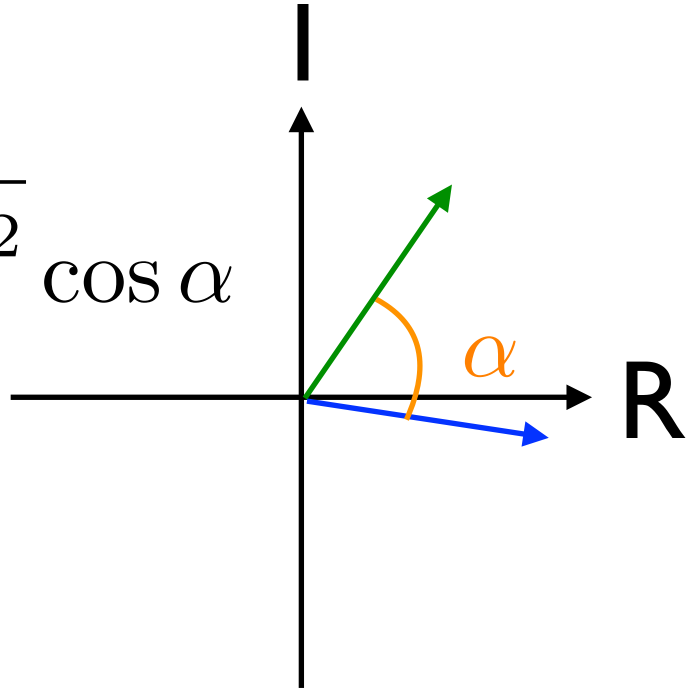
Interference

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

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

mom&spin



Not always positive

Can be suppressed

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

if

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

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

$$\sigma_{int} = 0$$

Observable dependent

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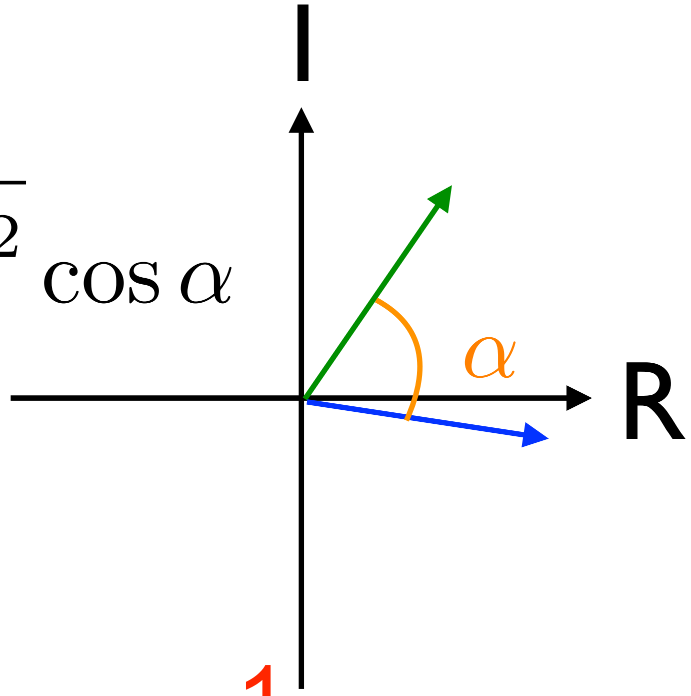
Interference

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



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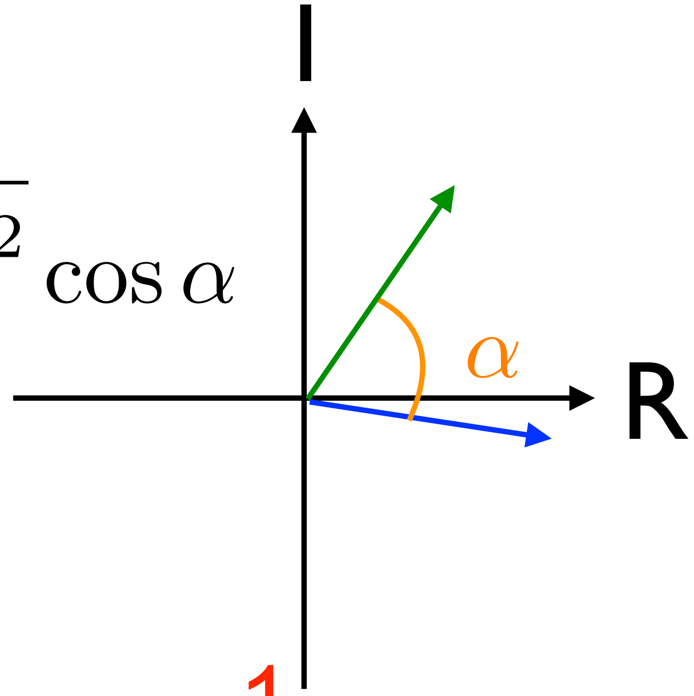

mom&spin

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$$\sigma \propto \sum_x |M(x)|^2 \quad \text{if} \quad \begin{array}{l} M_{SM}(x_1) = 1,\; M_{SM}(x_2) = \overset{1}{\cancel{0}} \\ M_{d6}(x_1) = \underset{-1}{\cancel{0}},\; M_{d6}(x_2) = 1 \end{array} \qquad \sigma_{int} = 0$$

Observable dependent

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

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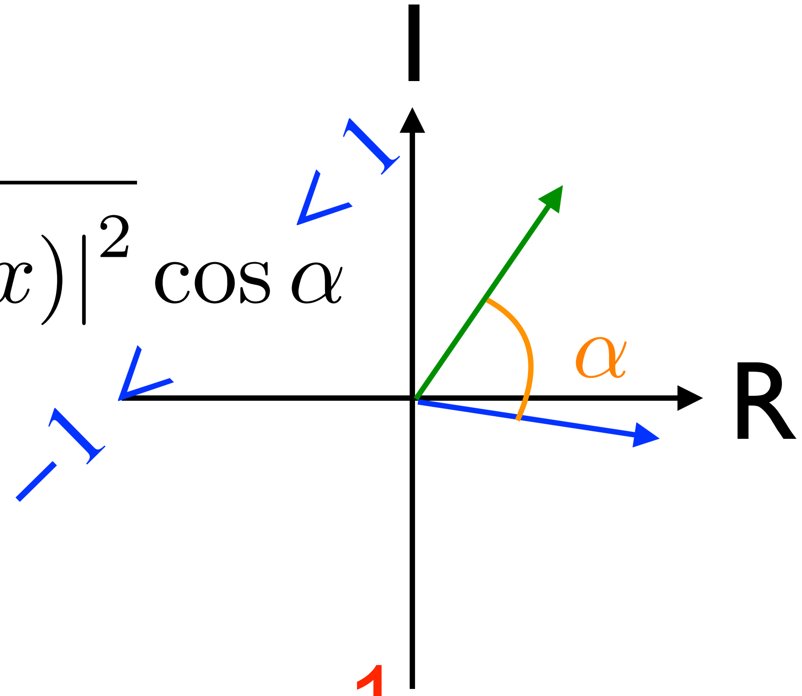
Interference

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

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



mom&spin

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Observable dependent

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

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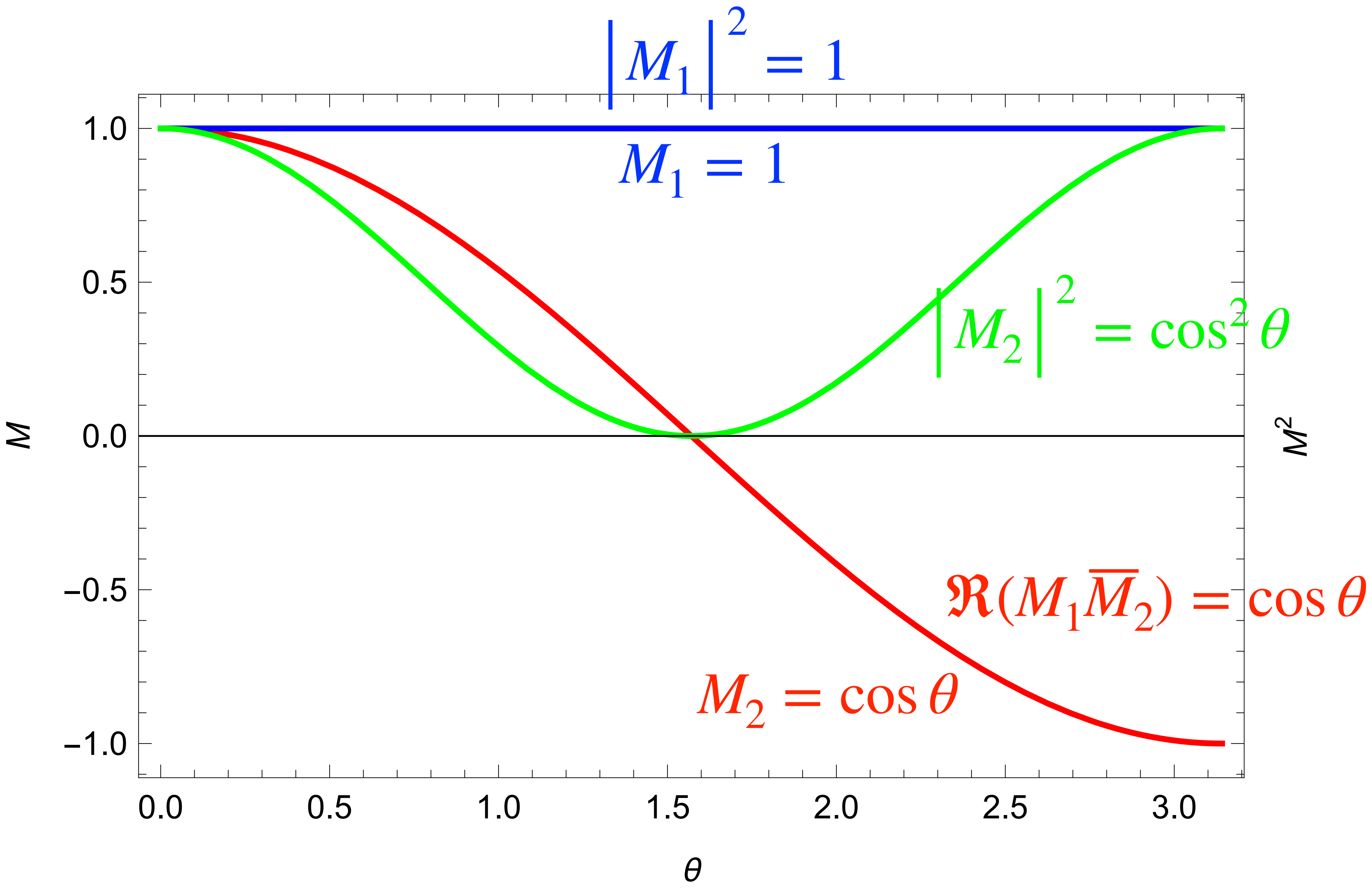
Interference suppression from phase space



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

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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

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

Experimentally accessible?

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

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

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

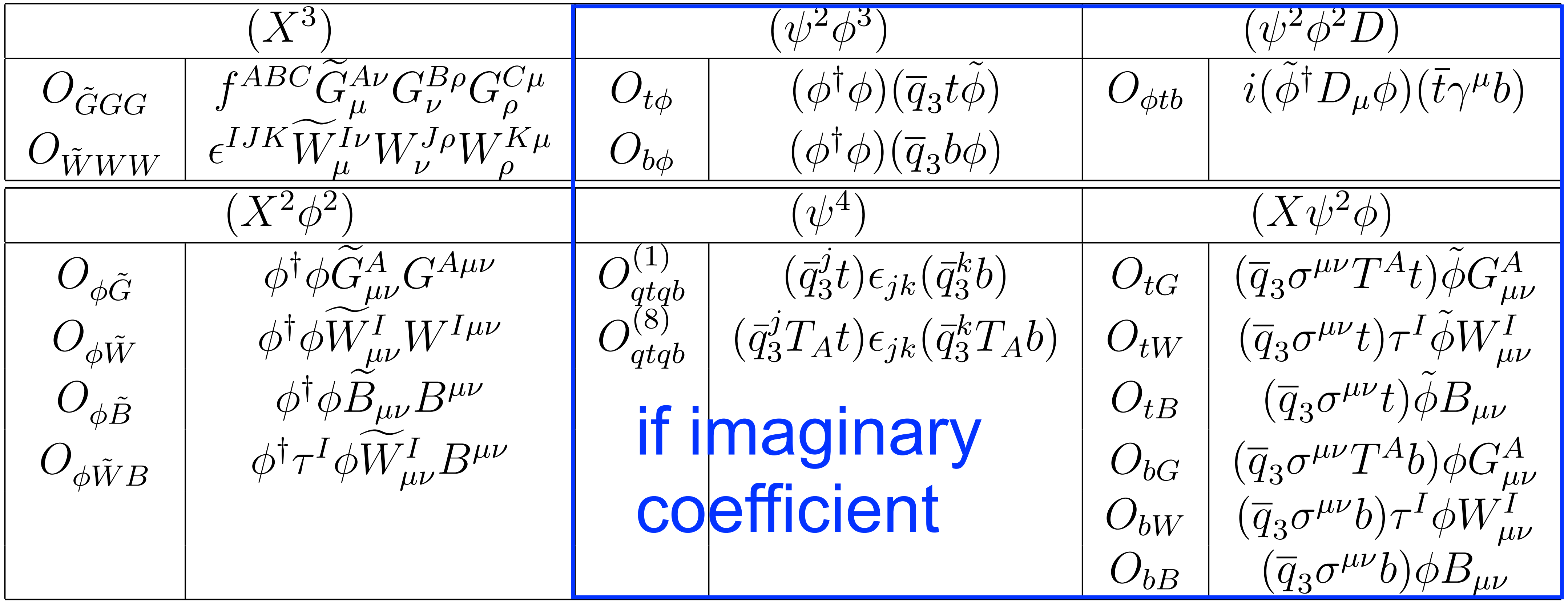
Not at all: $\sigma_{int}(\mu_L) = -\sigma_{int}(\mu_R)$

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)		$(X\psi^2\phi)$	
$O_{\phi\tilde{G}}$	$\phi^\dagger\phi\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$O^{(1)}_{qtqb}$	$(\bar{q}^j_3 t)\epsilon_{jk}(\bar{q}^k_3 b)$	O_{tG}	$(\bar{q}_3\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$
$O_{\phi\tilde{W}}$	$\phi^\dagger\phi\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$O^{(8)}_{qtqb}$	$(\bar{q}^j_3 T_A t)\epsilon_{jk}(\bar{q}^k_3 T_A b)$	O_{tW}	$(\bar{q}_3\sigma^{\mu\nu}t)\tau^I\tilde{\phi}W^I_{\mu\nu}$
$O_{\phi\tilde{B}}$	$\phi^\dagger\phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$			O_{tB}	$(\bar{q}_3\sigma^{\mu\nu}t)\tilde{\phi}B_{\mu\nu}$
$O_{\phi\tilde{W}B}$	$\phi^\dagger\tau^I\phi\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$			O_{bG}	$(\bar{q}_3\sigma^{\mu\nu}T^A b)\phi G^A_{\mu\nu}$
				O_{bW}	$(\bar{q}_3\sigma^{\mu\nu}b)\tau^I\phi W^I_{\mu\nu}$
				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,

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

leaves the SM Lagrangian invariant but

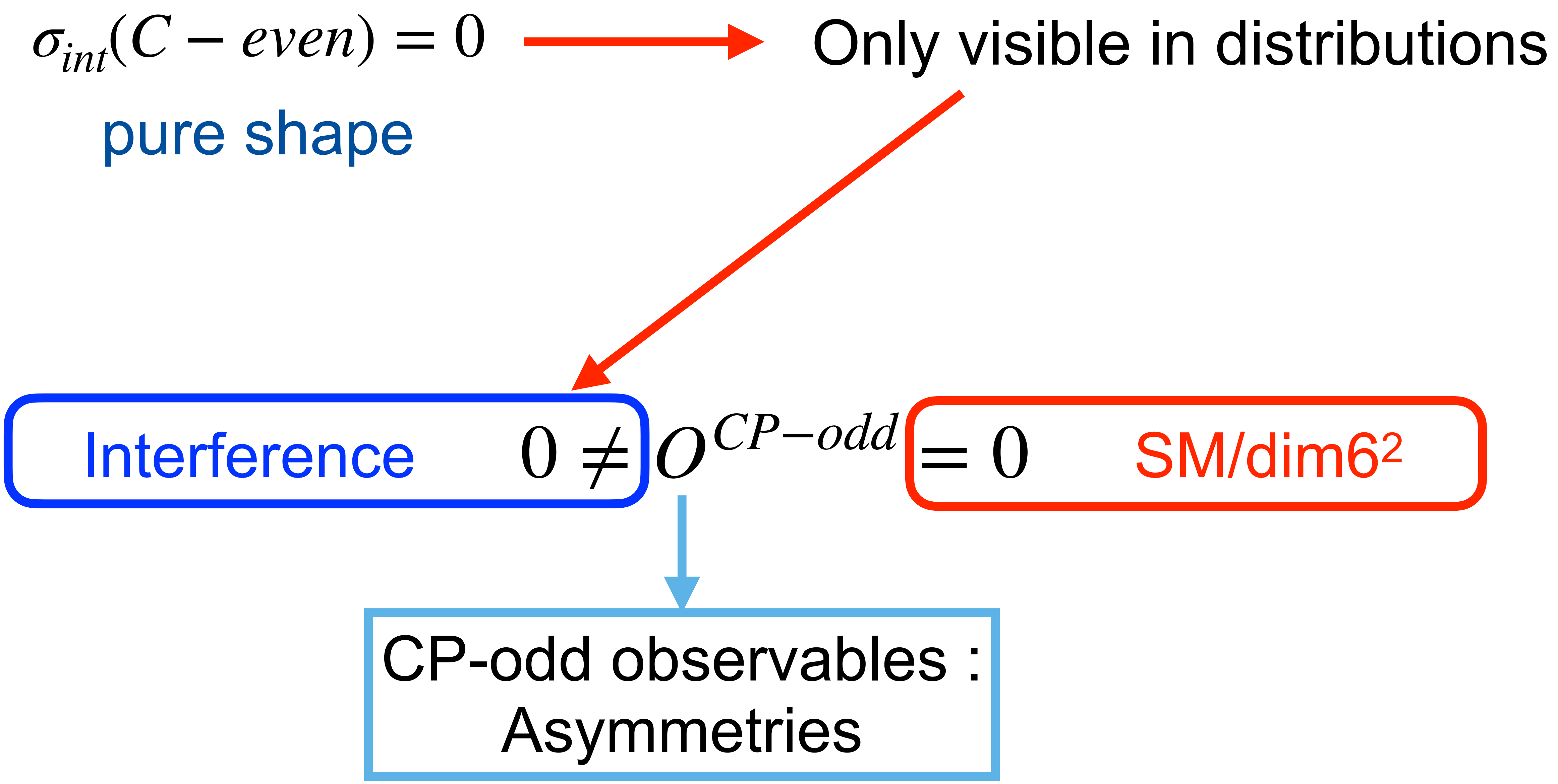
$$e^{i\varphi_{bG}} |C_{bG}| (\bar{Q}\sigma^{\mu\nu} T^A b) \tilde{\phi} G^A_{\mu\nu} \to |C_{bG}| (\bar{Q}\sigma^{\mu\nu} T^A b') \tilde{\phi} G^A_{\mu\nu}$$

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



$\sigma_{int}(C-even)=0$ → Only visible in distributions

pure shape

Interference $0 \neq O^{CP-odd} = 0$ SM/dim6^2

CP-odd observables :
Asymmetries

CPV

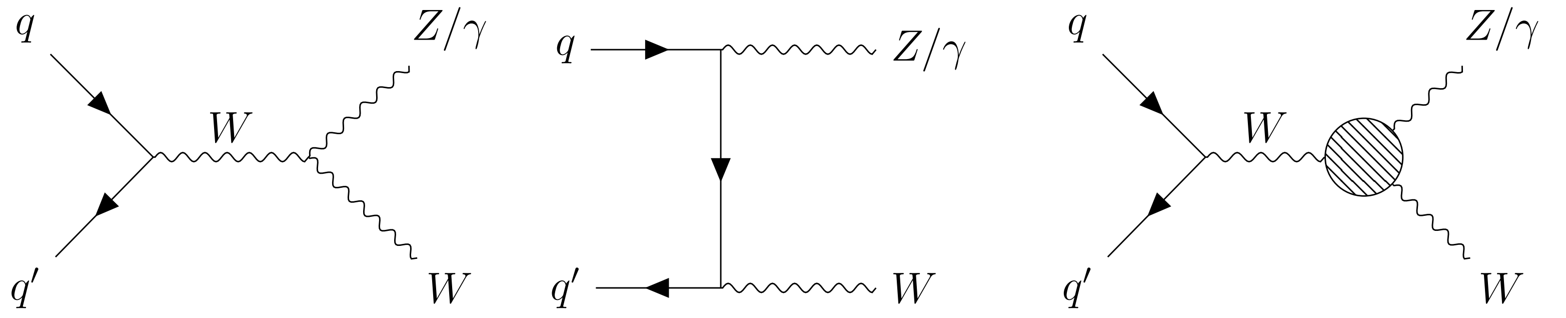
WZ/γ are not C-even processes but $\sigma_{int} \approx 0$

$O_{SM}^{CP-odd} \approx 0$ }

Asymmetries ← Approximatively like CP-even

Large enough cross-sections for **accurate** meas.

Leptonic and mostly visible decays



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

No FFV when $m_f \rightarrow 0$

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
$\sigma^{\|int\|}(\mathcal{O}_{\widetilde{W}WW})$	3.302(4) fb	2.028(3) fb
$\sigma^{\|meas\|}(\mathcal{O}_{\widetilde{W}WW})$	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
$\sigma^{\|int\|}(\mathcal{O}_{\phi\widetilde{W}B})$	0.5467(7) fb	0.3533(4) fb
$\sigma^{\|meas\|}(\mathcal{O}_{\phi\widetilde{W}B})$	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

$C = 1, \Lambda = 1$TeV

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Suppressed from phase space

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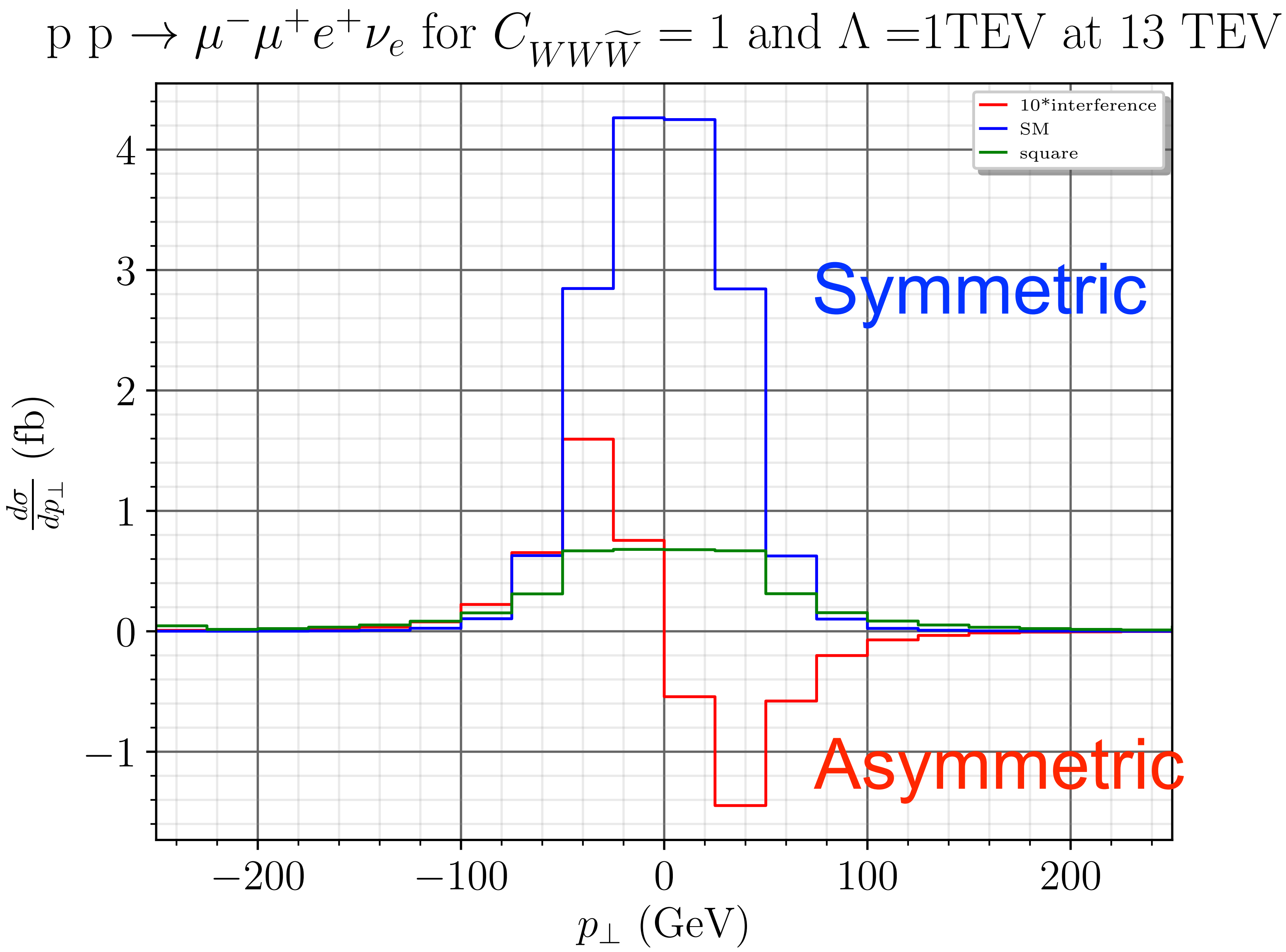
Suppressed

from phase space

largely available

$C = 1, \Lambda = 1\text{TeV}$

Towards asymmetries



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

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)
$\Delta\left(\Delta\phi_{eZ}\right)$	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		

knowing the quark direction

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)
$\Delta\left(\Delta\phi_{eZ}\right)$	-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

50-70% efficiency

80-90% in $W\gamma$

Better than HE observables

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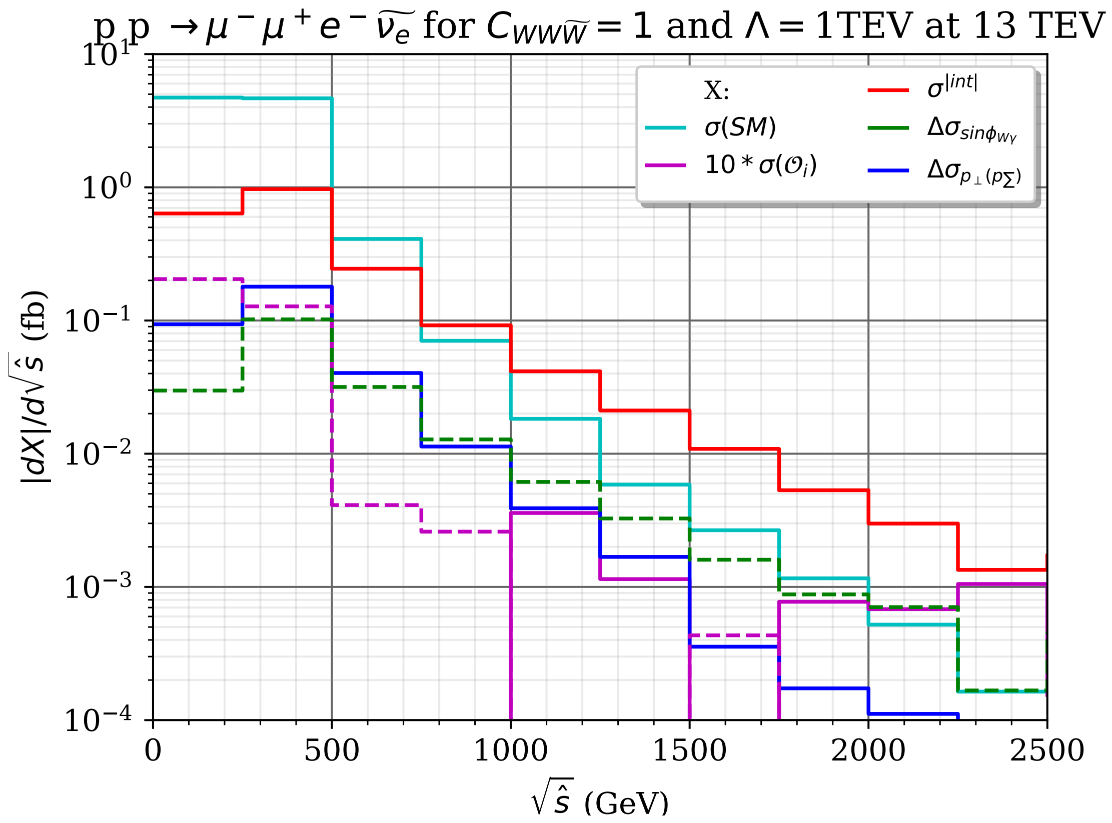
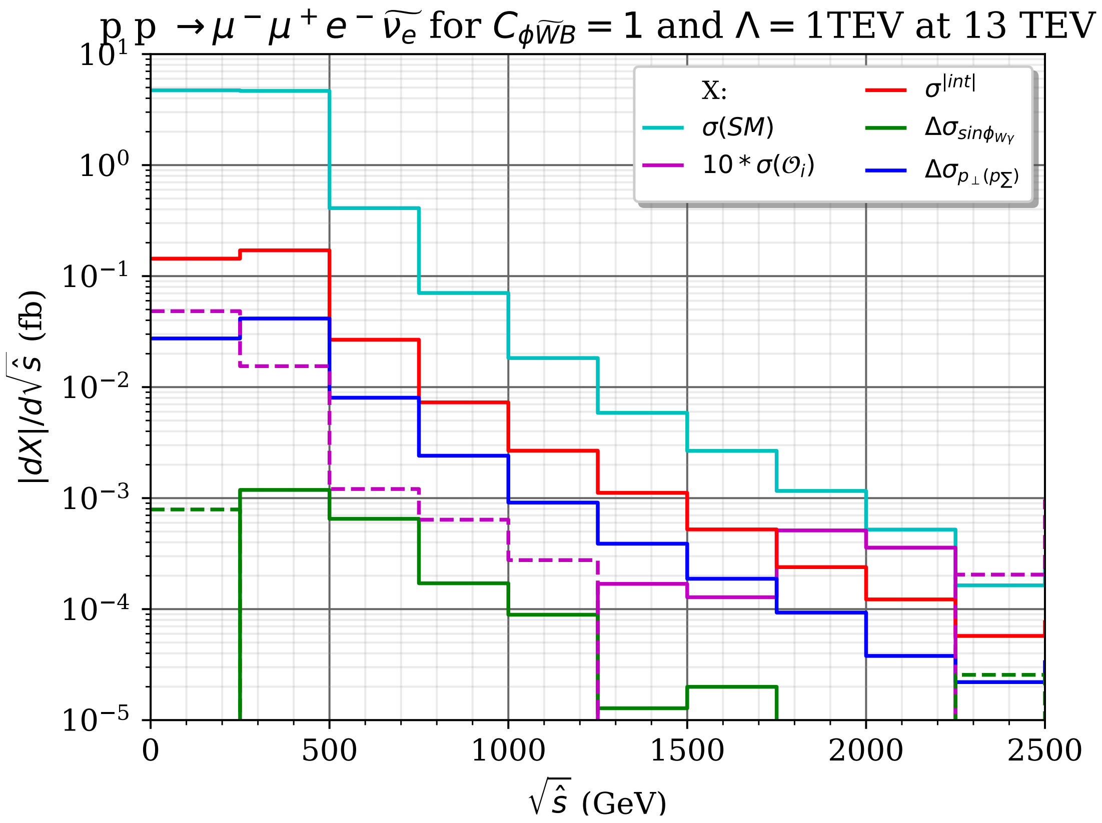
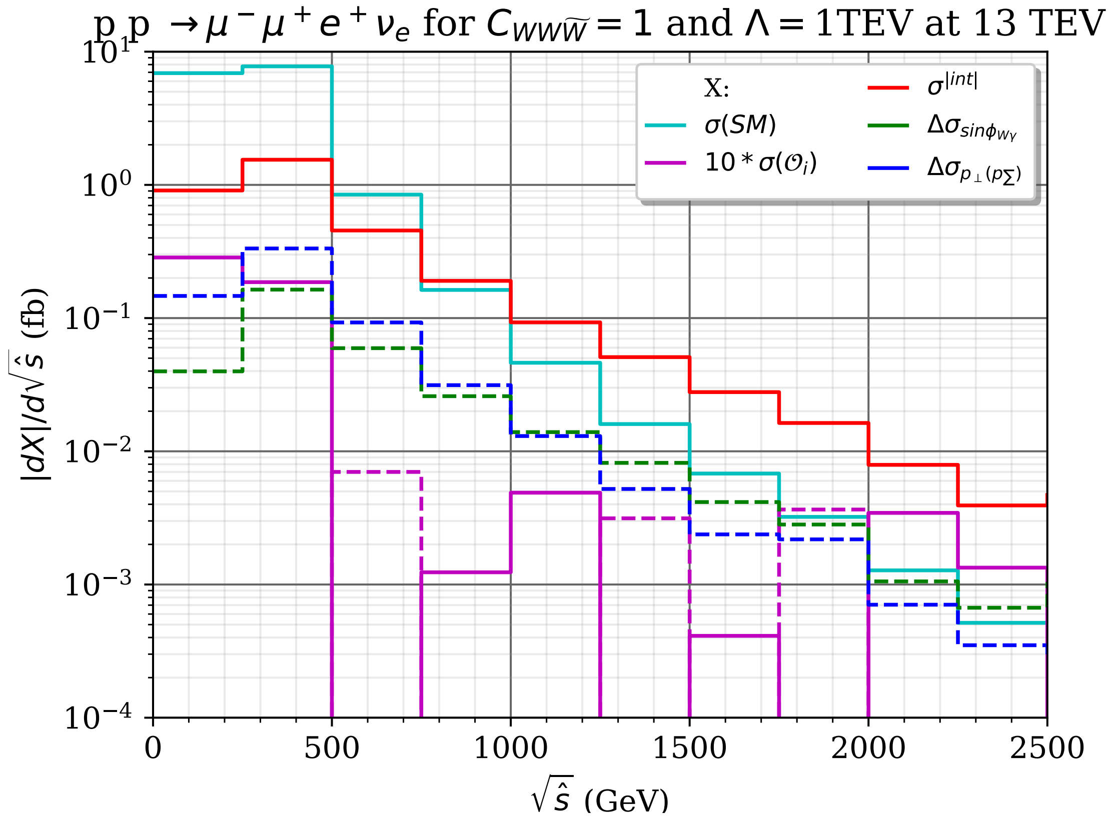
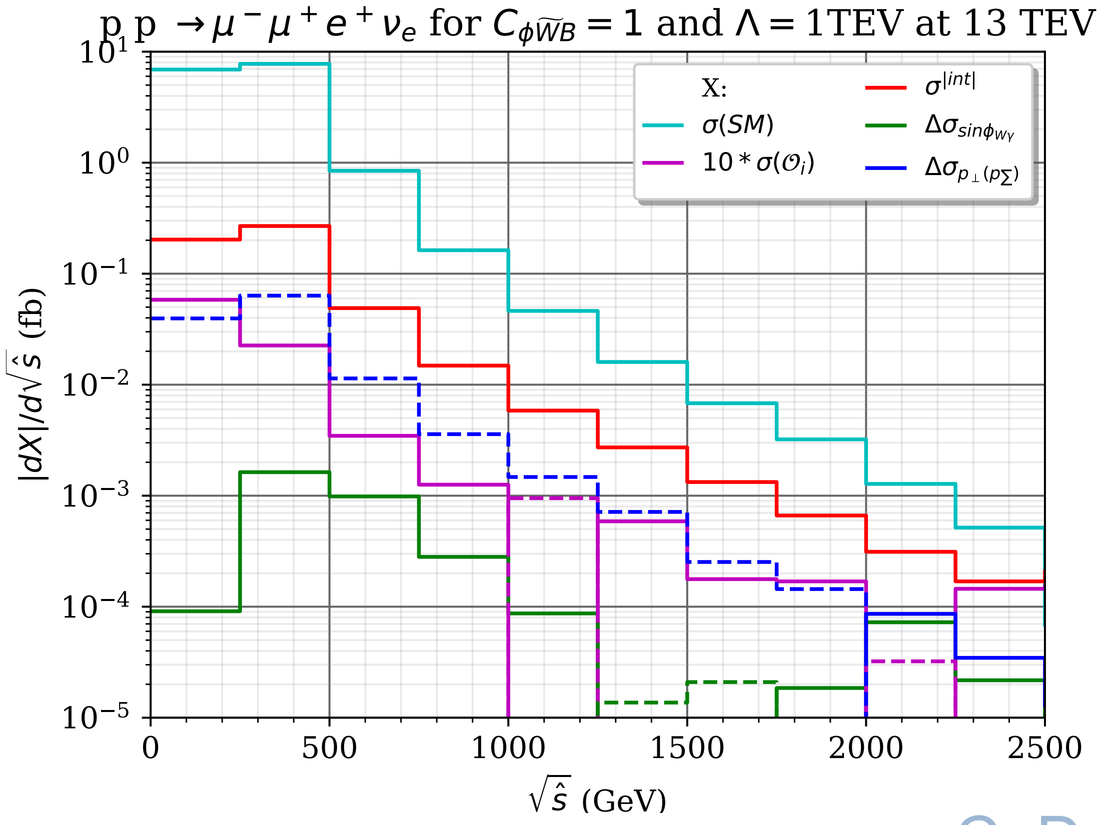
HE behaviour



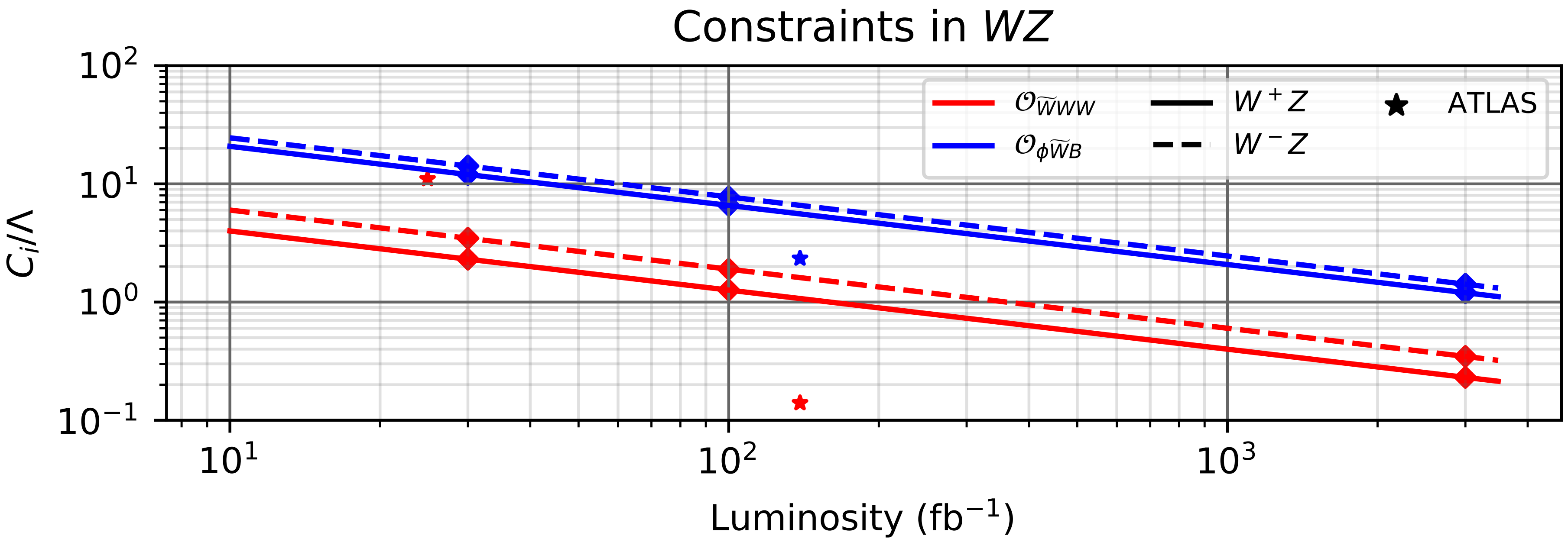




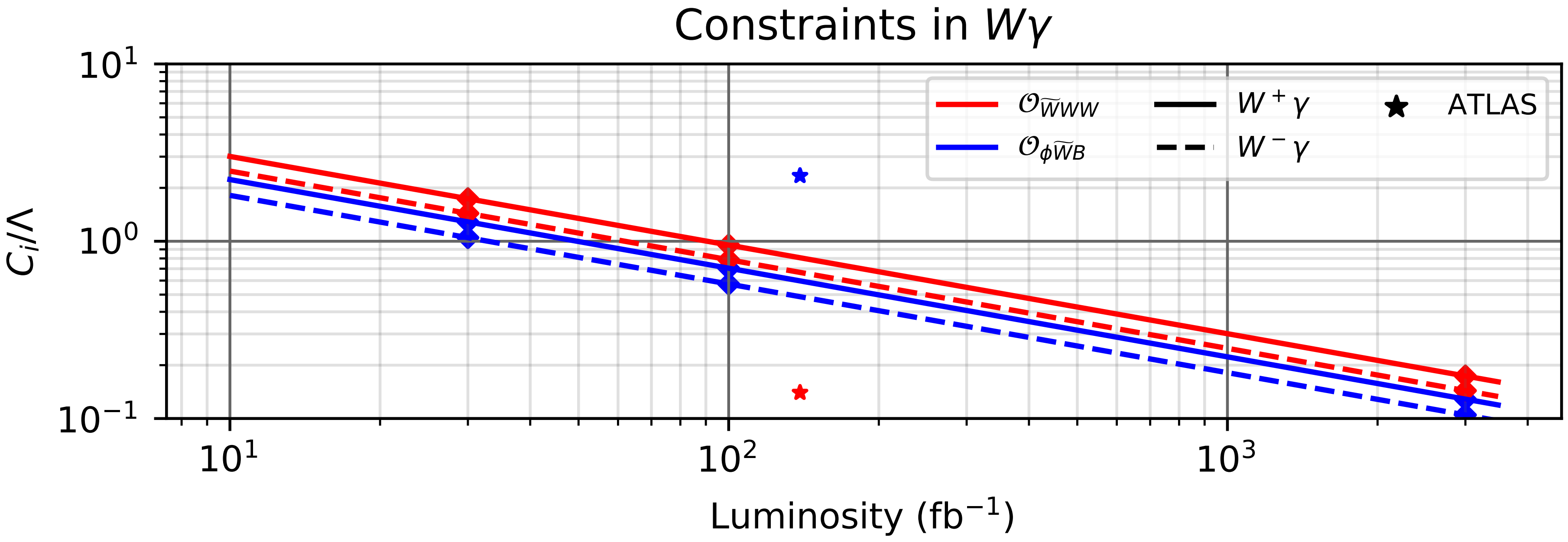


C. Degrande

Constraints



$\Lambda \approx 1TeV$



$\Lambda \approx 3TeV$

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

Bulk vs small HE tail

C. Degrande

Further comments

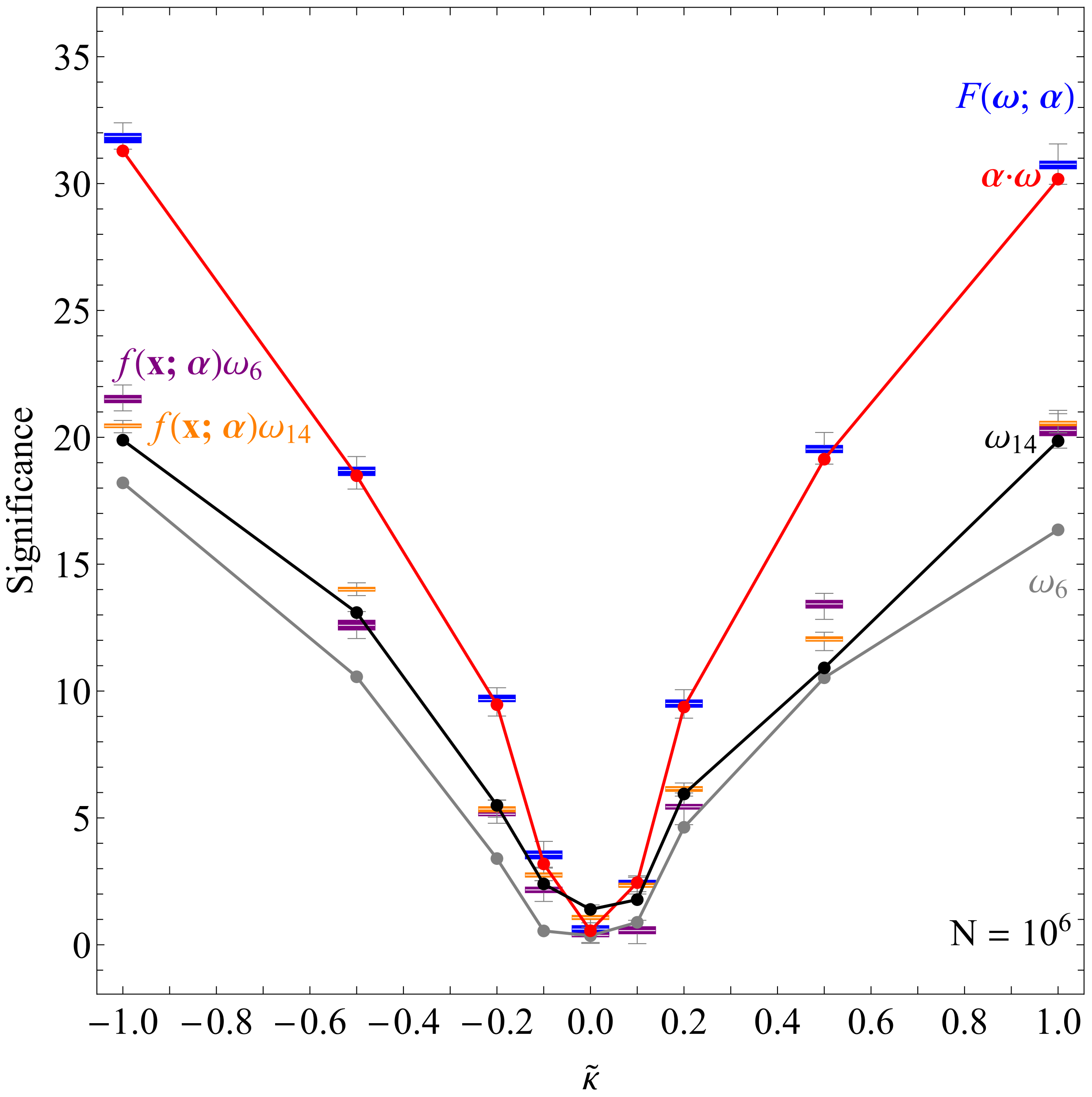
Comments

- ME/ML trained vs Observable

- Efficient observables
  - more sensitive
  - smaller errors
- CP-odd on their own
  - running
  - global fit if CP-odd observables only

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

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