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

Efficiently probing the SMEFT interference

Celine Degrande

Plan

- Introduction to SMEFT
- SMEFT requires understanding the interference
- Interference resurrection
  - gluon operator
- Keeping uncertainties under control (NLO QCD)
- Dimension 8 contribution
- Final comments

Introduction to SMEFT

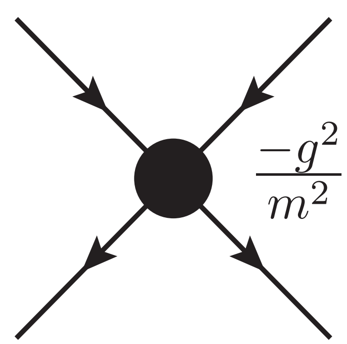
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments

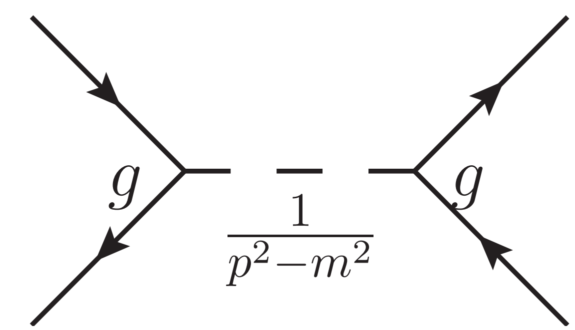
E

Exp. range

NP scale

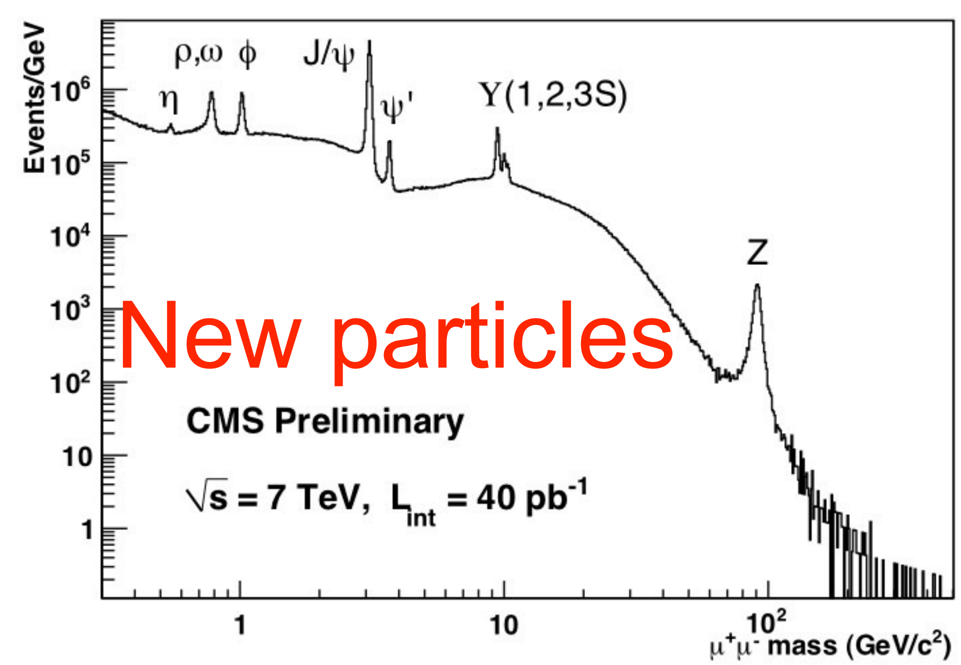


$$p^2 \ll m^2$$



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

New/modified interactions between SM particles



New particles

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Taylor expand : 1, 2 ,..parameters

~ stay at rest

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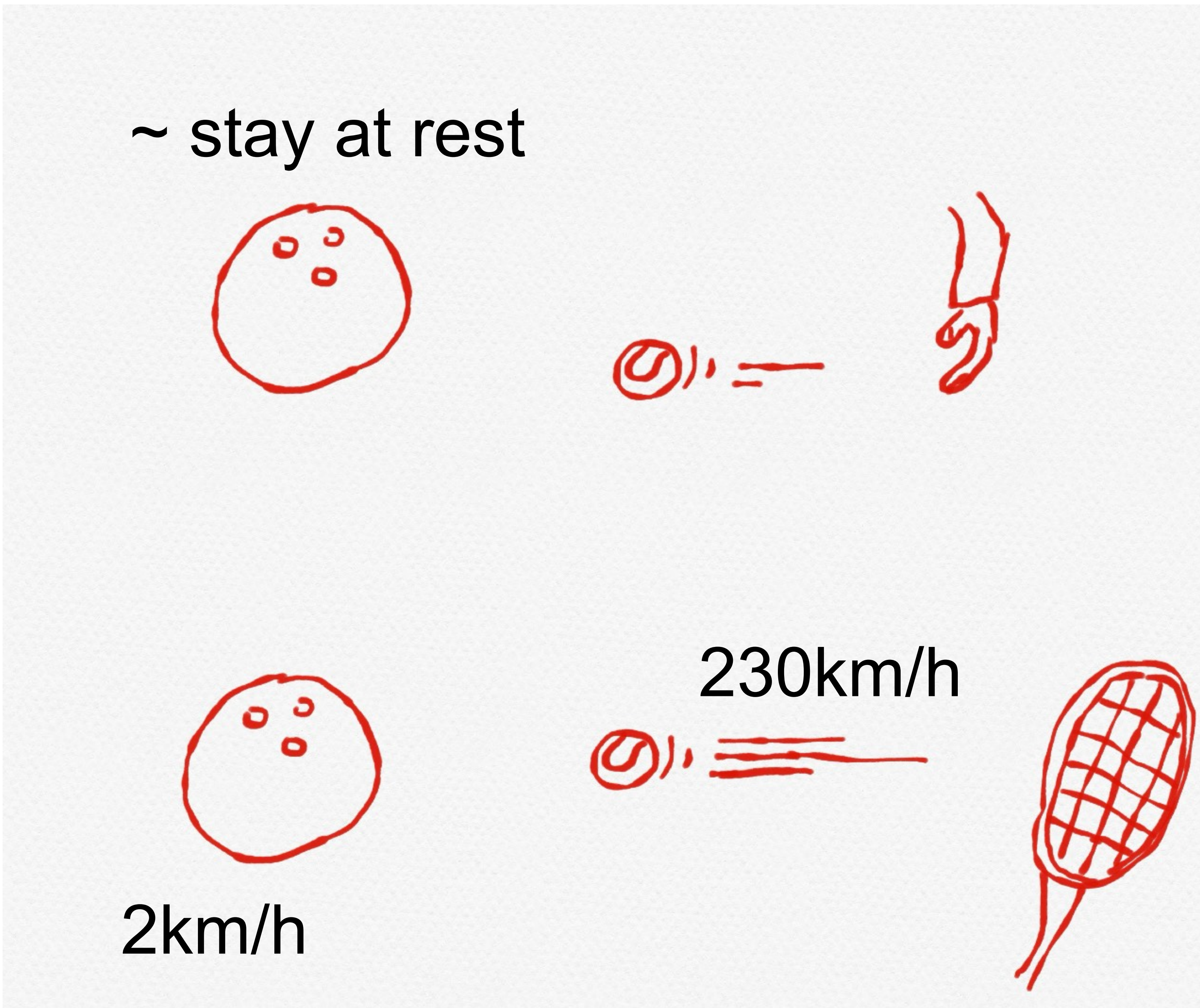
Taylor expand : 1, 2 ,..parameters



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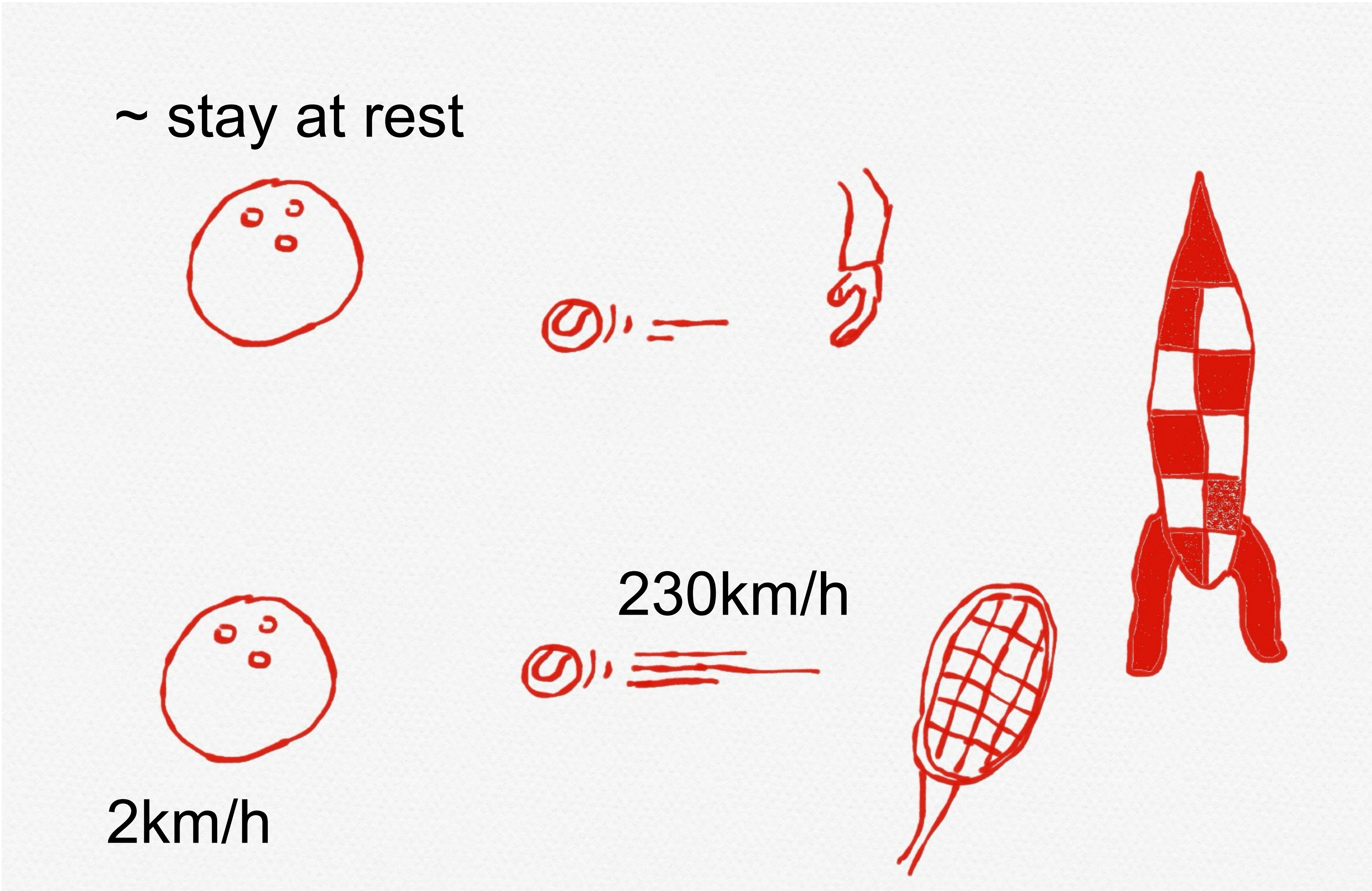
Taylor expand : 1, 2 ,..parameters



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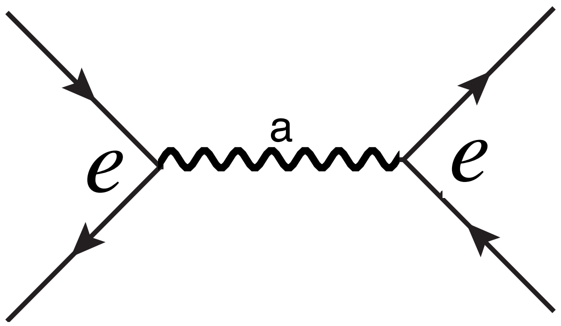
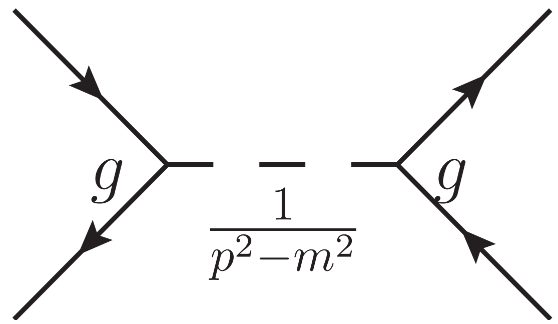
How big of a gap?





$$\frac{e^2}{p^2} + \ldots \frac{g^2}{m^2} + \mathcal{O}\left(\frac{p^2}{m^4}\right)$$

$$\frac{e^2}{p^2}\left(1 + \ldots g^2\frac{p^2}{m^2} + \mathcal{O}\left(\frac{p^4}{m^4}\right)\right)$$

$$\boxed{p^2/m^2 \sim 0.1}$$

Weakly $g^2 \lesssim 1$

p^2/m^2

dim

$$g^2\frac{p^2}{m^2} < g^2\frac{p^4}{m^4}$$

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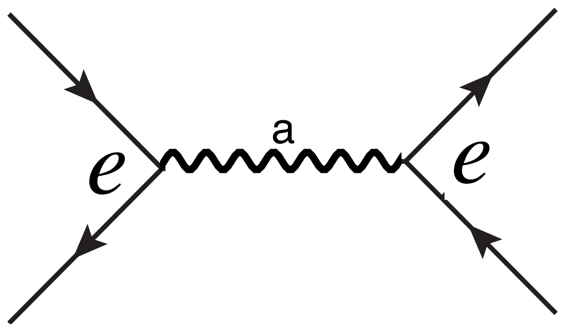
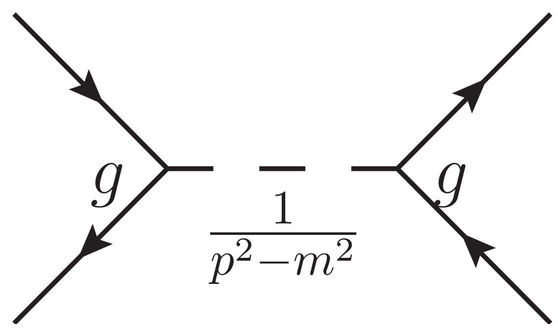
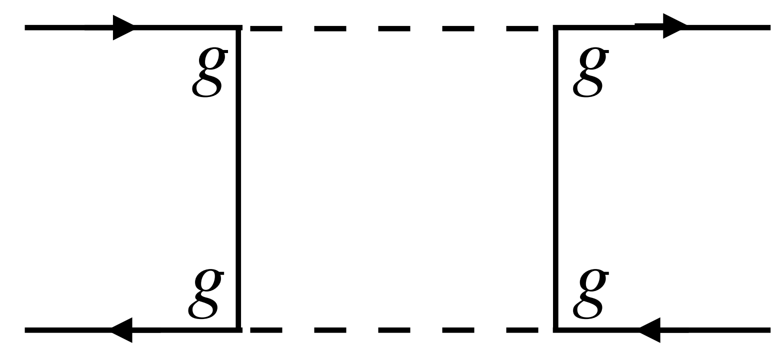
How big of a gap?







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dim

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$$g^4\frac{p^2}{m^2} \quad < \quad g^4\frac{p^4}{m^4}$$

g^2

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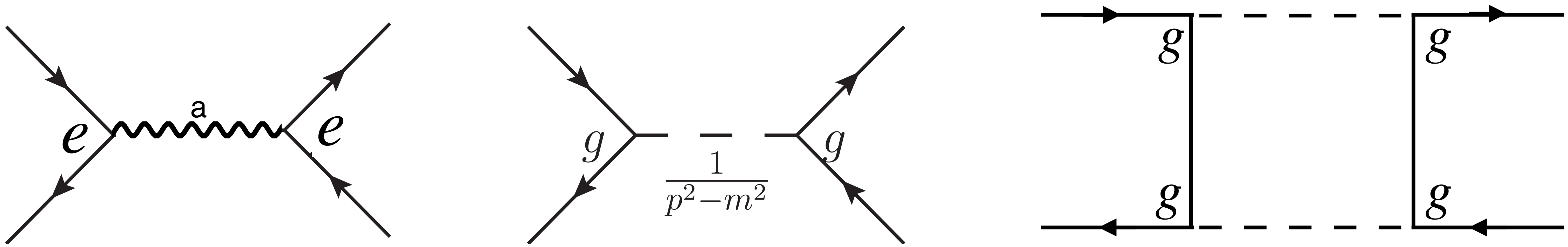

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$$\boxed{p^2/m^2 \sim 0.1}$$

Weakly $g^2 \lesssim 1$

Strongly $g^2 \sim 10$

p^2/m^2

dim

$$\begin{array}{ccc} g^2\frac{p^2}{m^2} & < & g^2\frac{p^4}{m^4} \\ & \approx & \\ g^4\frac{p^2}{m^2} & < & g^4\frac{p^4}{m^4} \end{array}$$

g^2

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EFT

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

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 : $E_{exp} << \Lambda$

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

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

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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!

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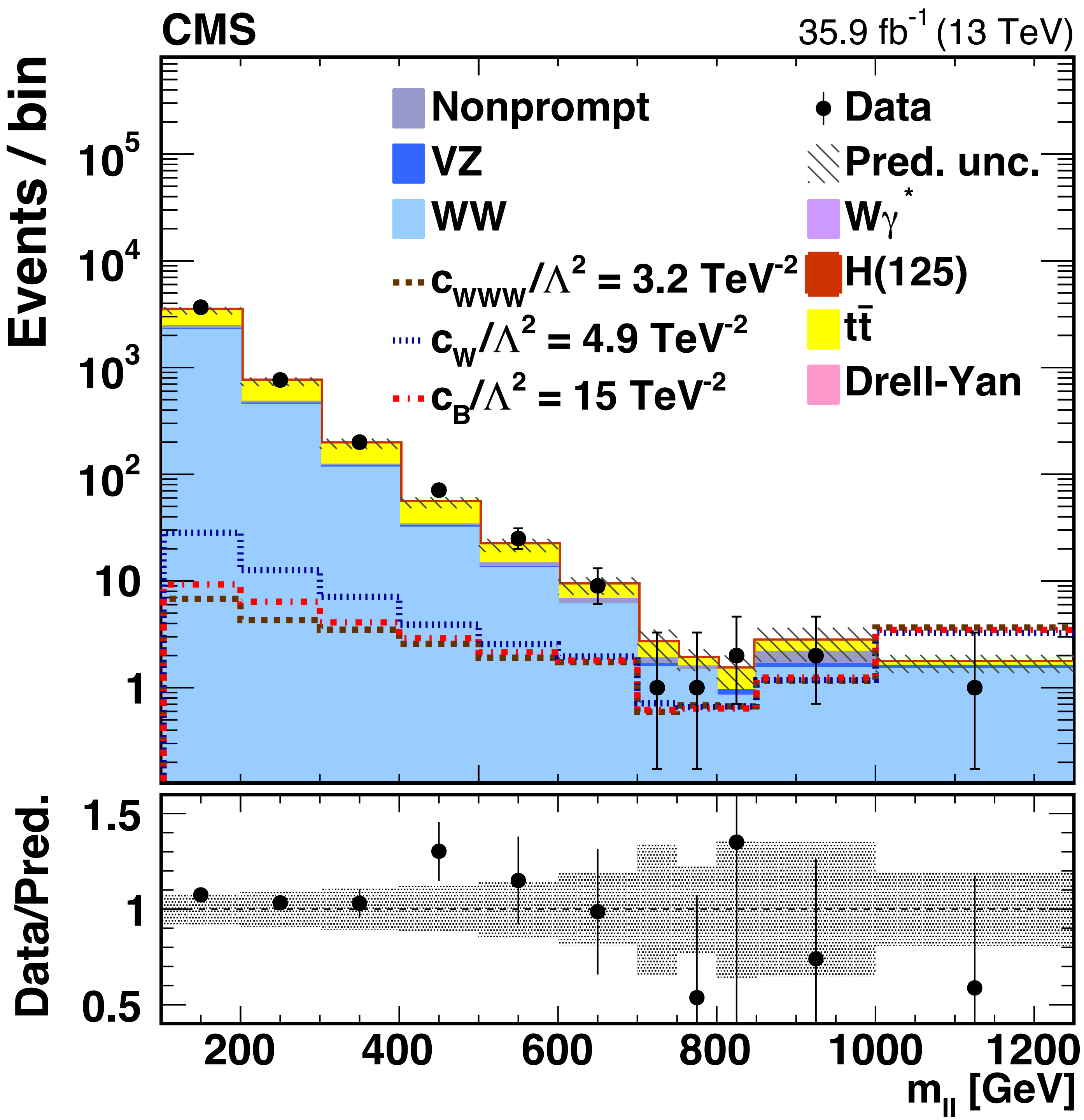
High energy tails



2009.00119

LHC vs LEP energy range less precision

Cross-sections and precision plummet at high energy

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

SMEFT requires understanding the interference

Errors : higher power of $1/\Lambda$

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

- 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

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

10%

50%

- 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

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Pushing the scale

interference : to double the scale, we need 4x better precision

dim6^2/dim8 : to double the scale, we need 16 better precision

HL-LHC :

- 10 x more data
- 3 x better precision
- 1.8 improvement of the scale from interference
- 1.3 improvement of the scale from dim8/dim6^2

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interference suppression

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

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	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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$\phi\phi\phi\phi$	0	0

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

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

Assuming ~0

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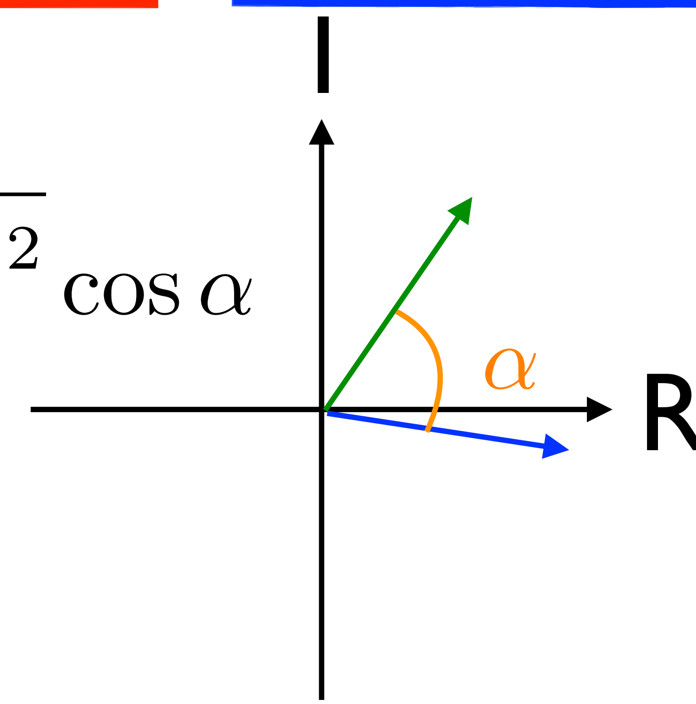
Interference

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

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

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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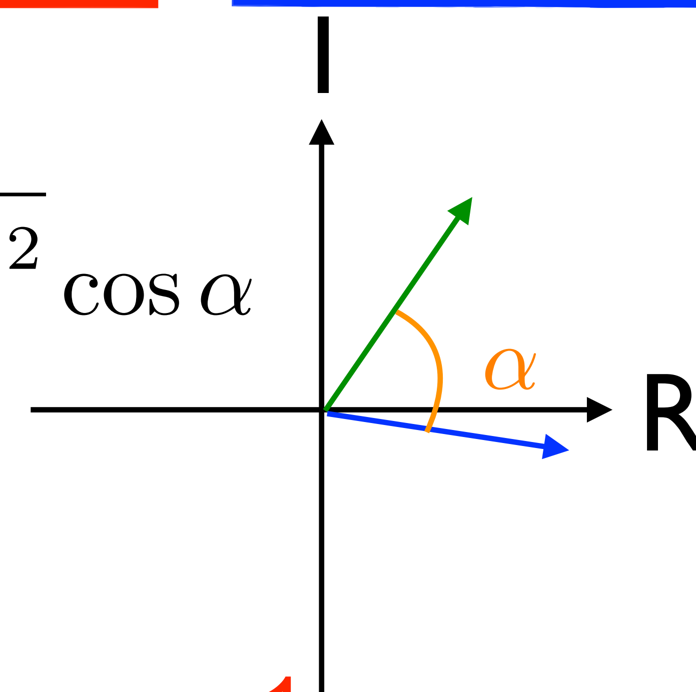
Interference

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

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



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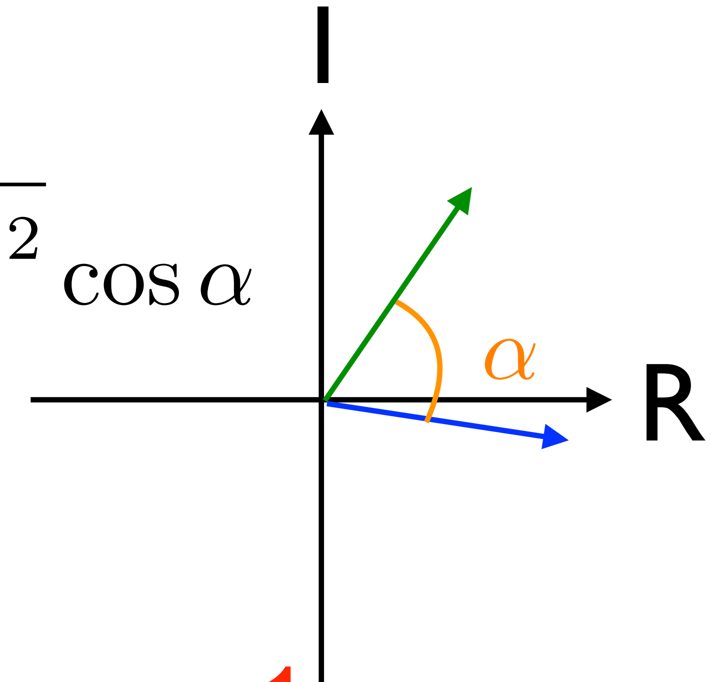

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Observable dependent

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

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Interference

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mom&spin

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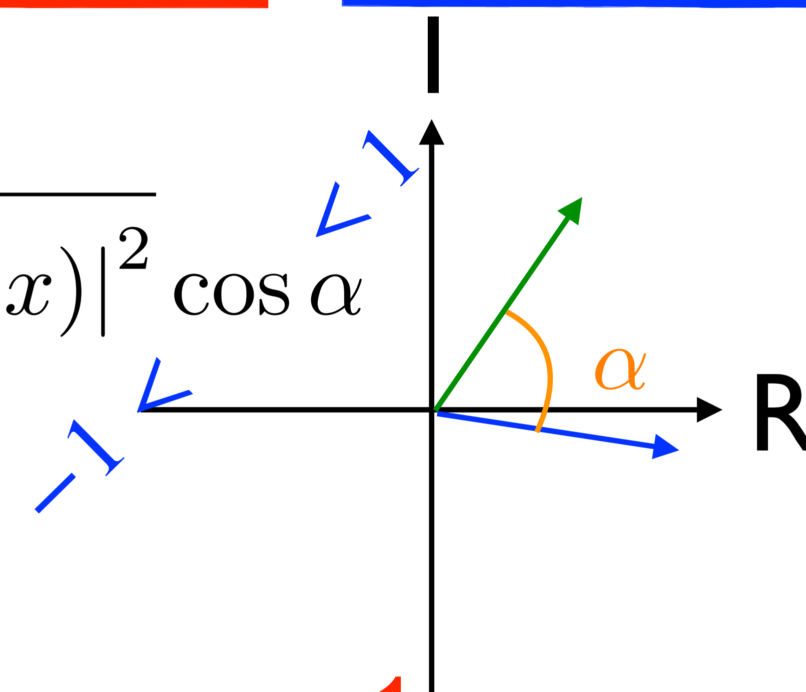

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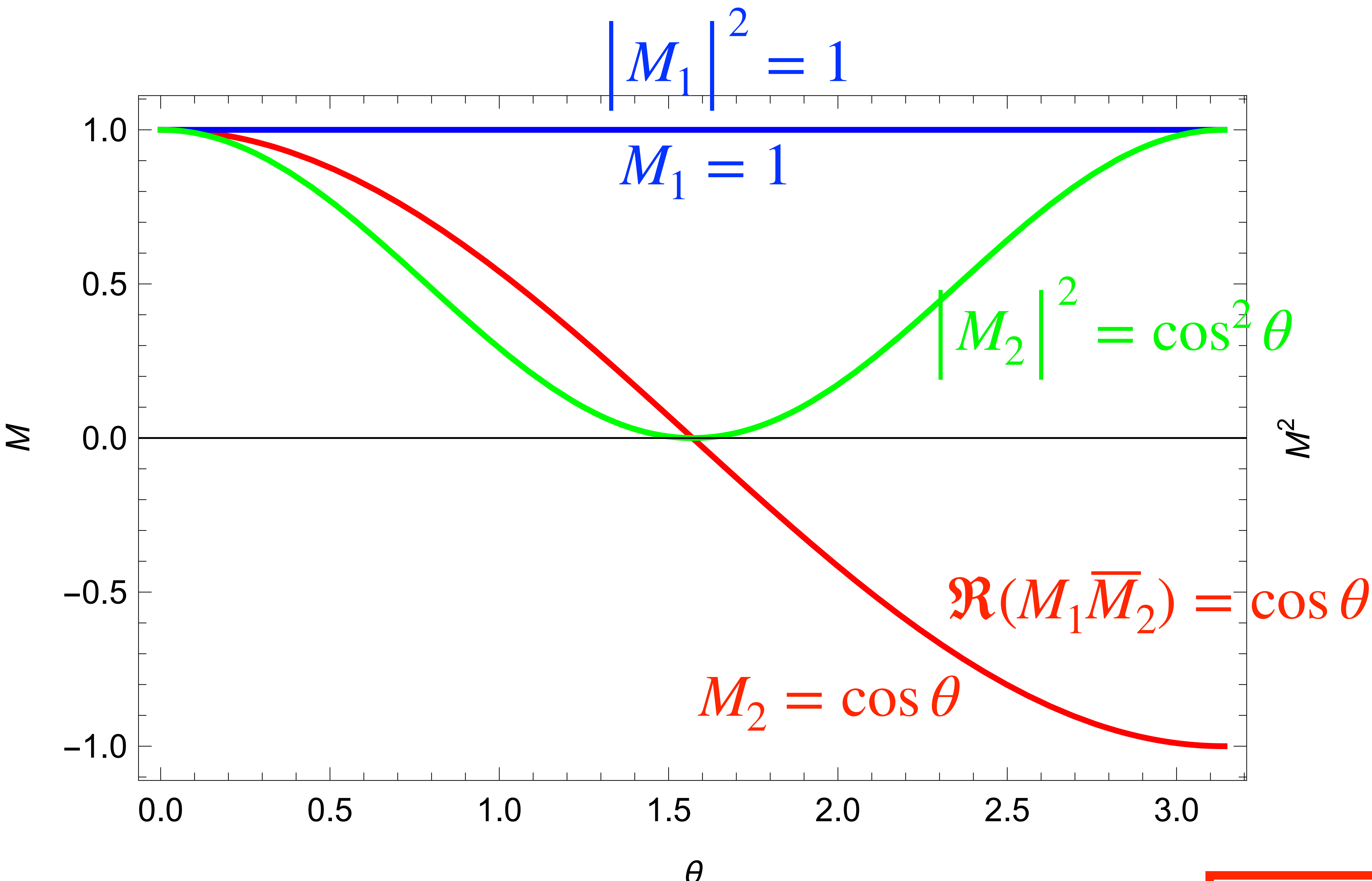
Interference suppression from phase space



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

~ scalar product of function

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Interference revival: Formalism

C.D., M. Maltoni [2012.06595]

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

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

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

gluon operator

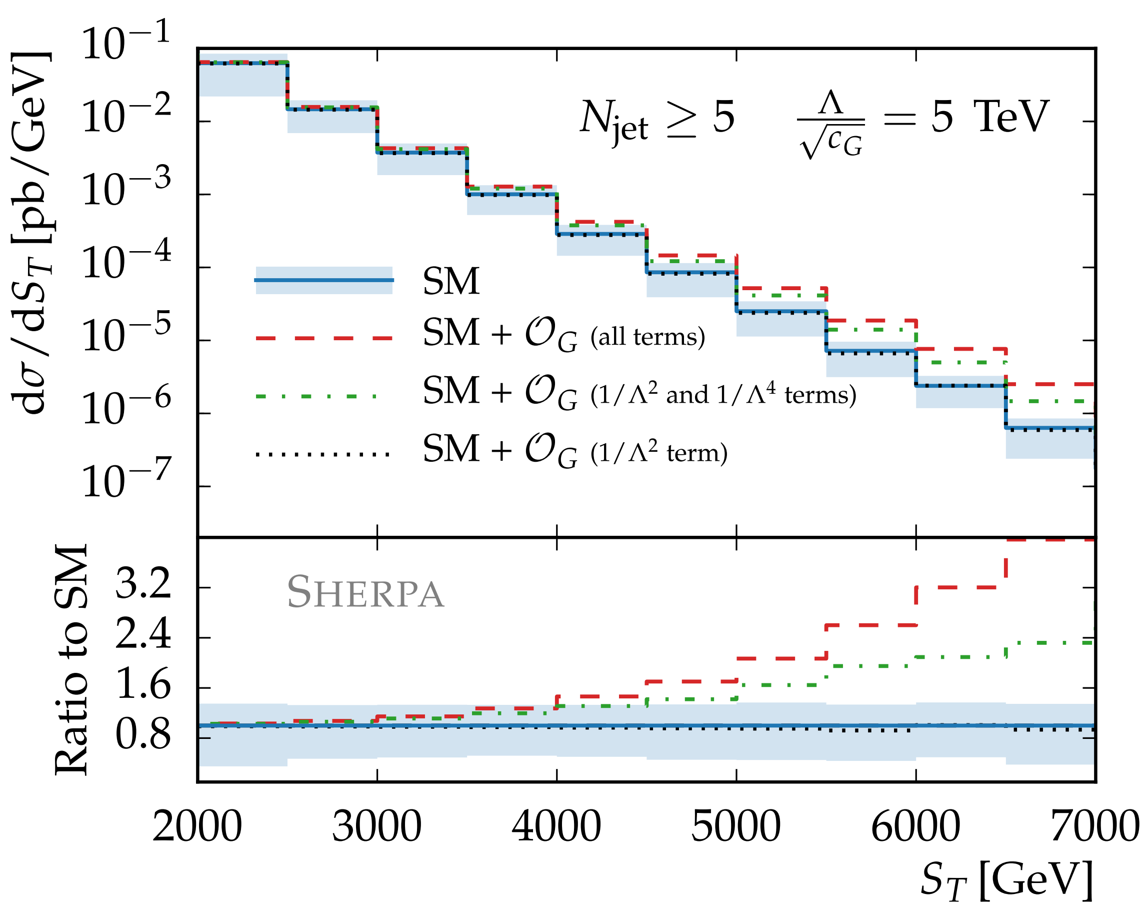
Interference revival : 1st example

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

Interference vanishes in dijet

R. Goldouzian, M. D. Hildreth, Phys. Lett. B **811**, 135889 (2020), arXiv:2001.02736

$$\frac{C_G}{\Lambda^2} < (0.031\ \mathrm{TeV})^{-2}$$ from dijet at $\mathcal{O}\left(1/\Lambda^4\right)$



Krauss et al, 1611.00767

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Triple gluon operator

add mass or more legs

$$\frac{c_G}{\Lambda^2} = 1\text{TeV}^{-2}$$

	$p_T > 50$ GeV		$p_T > 200$ GeV		$p_T > 1000$ GeV	
proc.	σ [pb]	w>0	σ [pb]	w>0	σ [pb]	w>0
$t\bar{t}$	1.384	85%	1.384	85%	1.384	85%
$t\bar{t}j$	$5.20 \cdot 10^{-1}$	62%	$1.13 \cdot 10^{-1}$	60%	$1.37 \cdot 10^{-3}$	62%
jjj	$2.98 \cdot 10^{1}$	52%	$5.90 \cdot 10^{-1}$	52%	$4.91 \cdot 10^{-4}$	61%
$jjjj$	$-2.89 \cdot 10^{1}$	45%	$-2.50 \cdot 10^{-1}$	44%	$-4.12 \cdot 10^{-6}$	39%

Large SM x-sect
& int. cancellation

Part of the phase space with
positive interference

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Triple gluon operator

Saturate the bound : same shape

Close to Schwartz bound

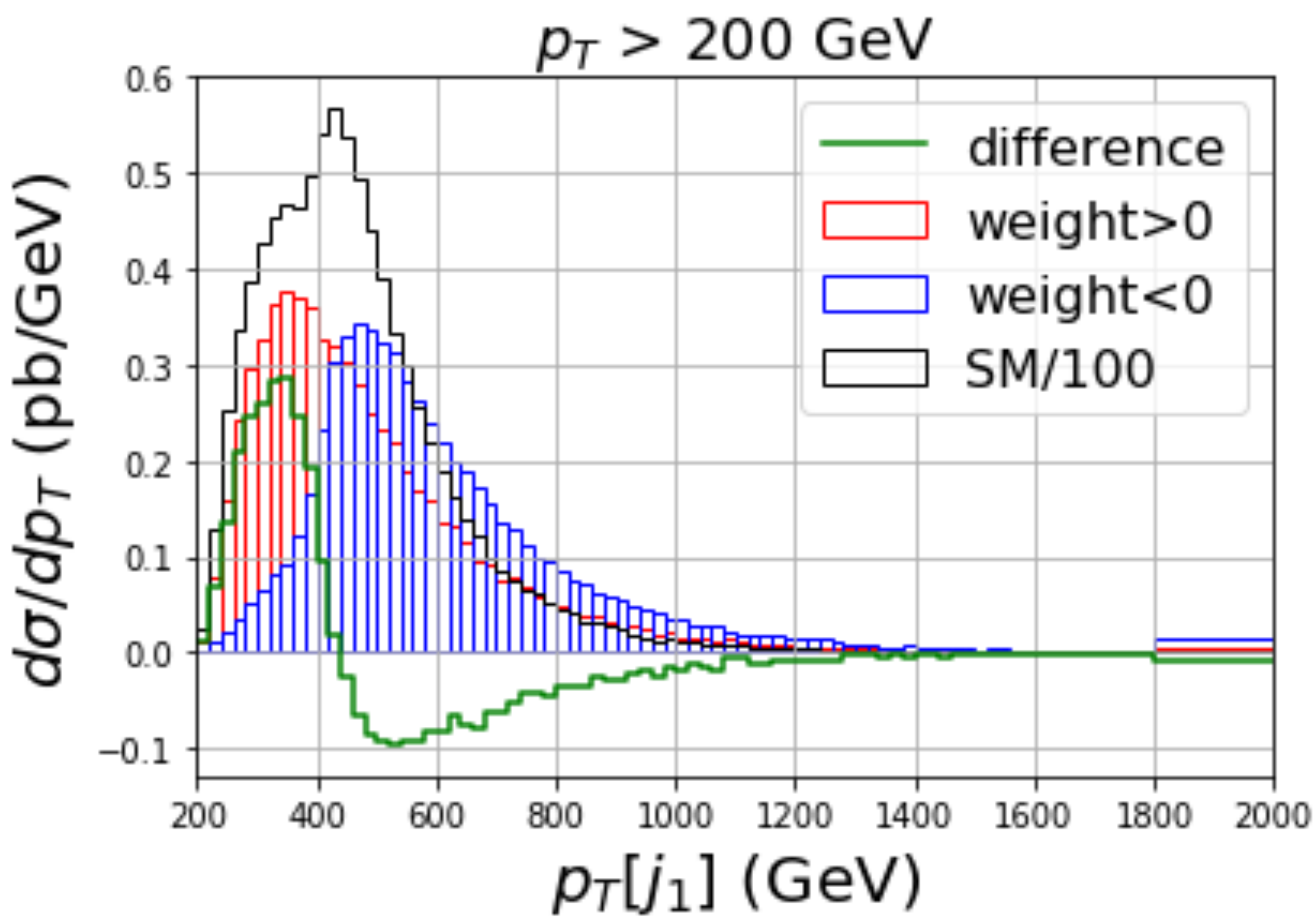
much smaller than

	SM	$\mathcal{O}(1/\Lambda^2)$				$\mathcal{O}(1/\Lambda^4)$
$p_{T,min}$ [GeV]	σ [pb]	σ [pb]	wgt>0	$\sigma^{\lvert meas \rvert}$ [pb]	$\sigma^{\lvert int \rvert}$ [pb]	σ [pb]
50	$9.70 \cdot 10^5$	4.08	50.4%	$7.83 \cdot 10^2$	$1.05 \cdot 10^3$	$3.93 \cdot 10^1$
200	$8.96 \cdot 10^2$	$2.92 \cdot 10^{-1}$	51.4%	$3.5 \cdot 10^1$	$5.02 \cdot 10^1$	2.73
500	3.10	$1.69 \cdot 10^{-2}$	54.0%	$6.04 \cdot 10^{-1}$	$8.96 \cdot 10^{-1}$	$1.48 \cdot 10^{-1}$
1000	$9.08 \cdot 10^{-3}$	$4.56 \cdot 10^{-4}$	60.1%	$1.46 \cdot 10^{-3}$	$2.29 \cdot 10^{-3}$	$3.05 \cdot 10^{-3}$

Mostly accessible

Transverse momentum

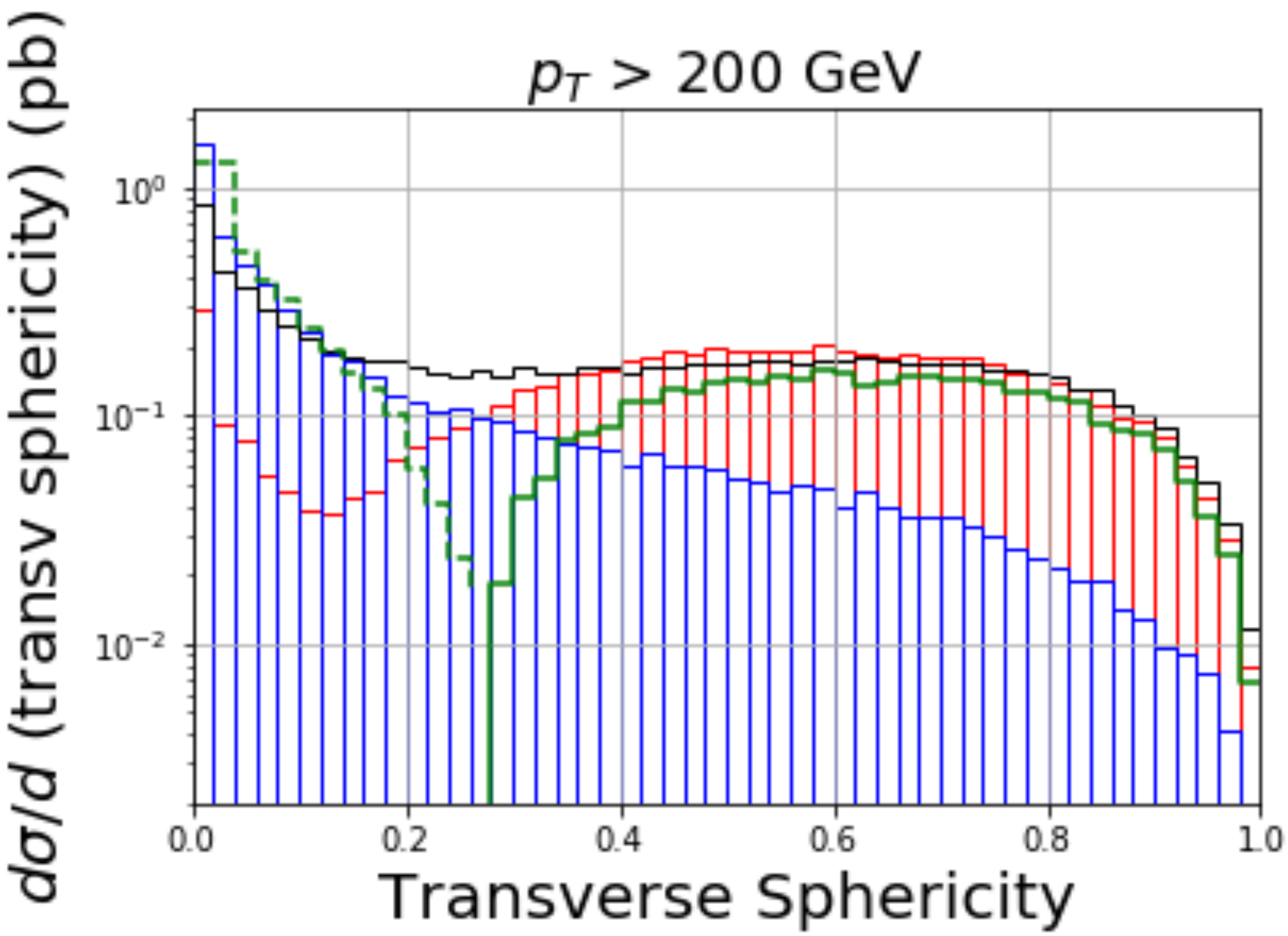
Efficiency of an observable to revive: $\dfrac{O}{\sigma^{|meas|}}$



~40% efficiency

Transverse sphericity

$$M_{xy} = \sum_{i=1}^{N_{jets}} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix}, \; Sph_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

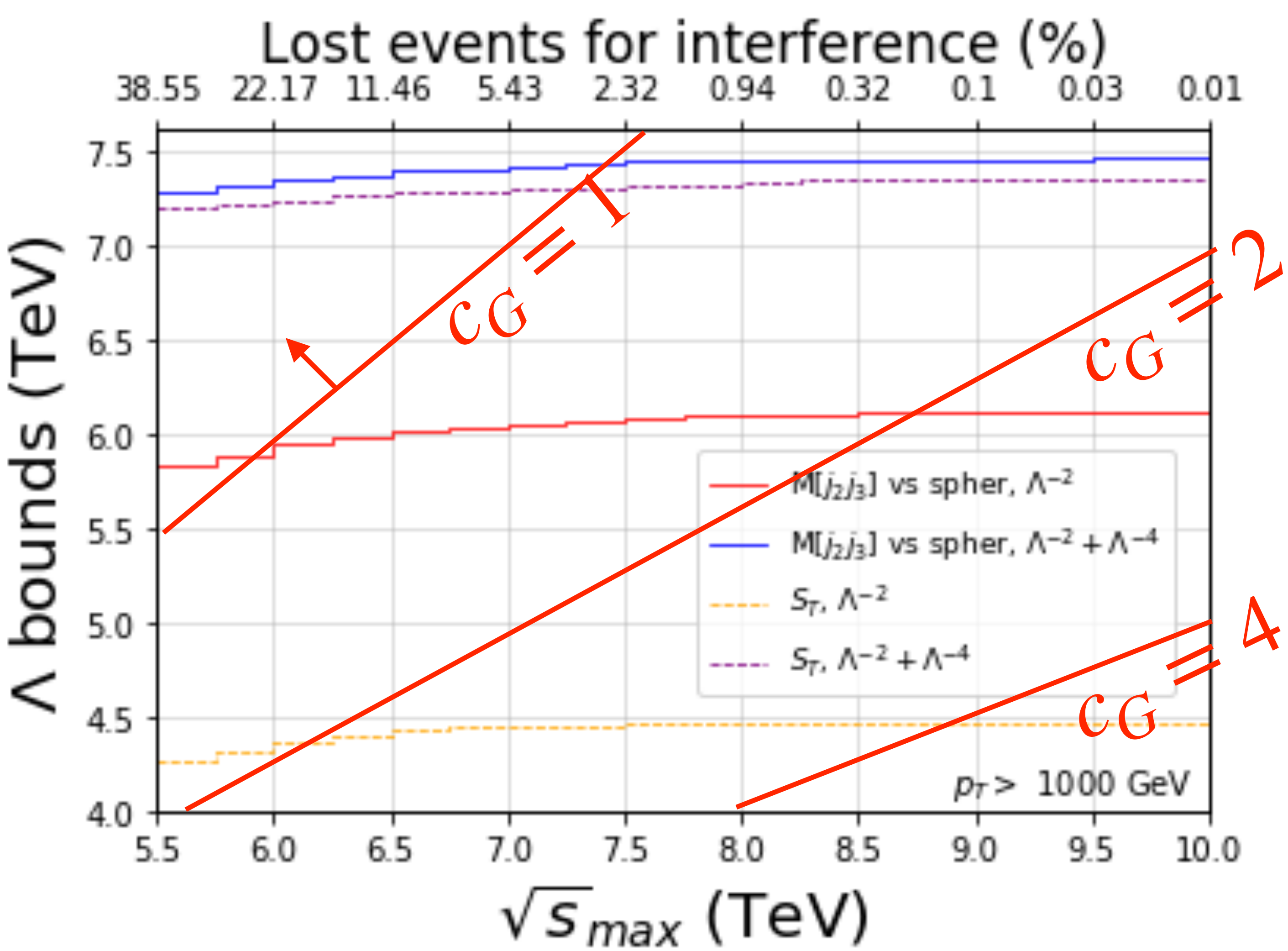


~80% efficiency

Better sensitivity

$p_{T,min}$ [GeV]	Distribution	Sph_T cut	Bins	Upper bound on C_G	Lower bound on C_G
50	$p_T[j_3]$ vs Sph_T	0.23	34	$2.5\cdot10^{-1}$ $(1.1\cdot10^{-1})$	$-2.5\cdot10^{-1}$ $(-1.2\cdot10^{-1})$
200	S_T vs Sph_T	0.27	34	$7.5\cdot10^{-2}$ $(2.3\cdot10^{-2})$	$-7.5\cdot10^{-2}$ $(-2.4\cdot10^{-2})$
500	$M[j_2 j_3]$ vs Sph_T	0.31	21	$5.5\cdot10^{-2}$ $(5.3\cdot10^{-2})$	$-5.5\cdot10^{-2}$ $(-3.5\cdot10^{-2})$
1000	$M[j_2 j_3]$ vs Sph_T	0.35	7	$2.6\cdot10^{-2}$ $(1.9\cdot10^{-2})$	$-2.6\cdot10^{-2}$ $(-1.8\cdot10^{-2})$

Λ^{-2} Λ^{-4}



Bounds dominated by the interference

EFT validity & error:

(3TeV/6TeV)^2~0.25

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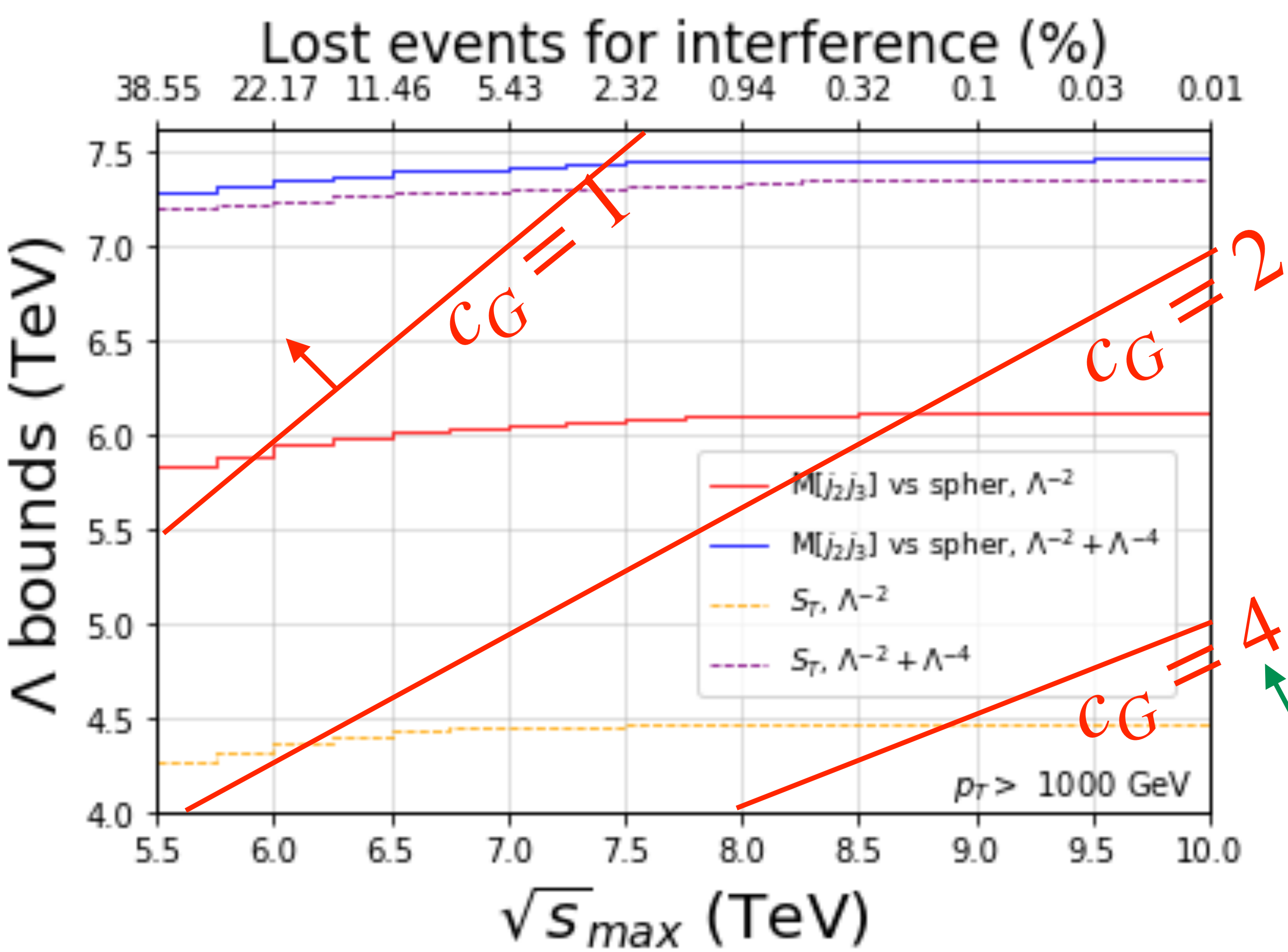
1000	$M[j_2j_3]$ vs Sph_T	0.35	7	$2.6{\cdot}10^{-2}$ $(1.9{\cdot}10^{-2})$	$-2.6{\cdot}10^{-2}$ $(-1.8{\cdot}10^{-2})$

Λ^{-2} Λ^{-4}



Bounds dominated by the interference

EFT validity & error:

(3TeV/6TeV)^2~0.25

or $c_G = 1$ and $E/\Lambda = 2$

C. Degrande

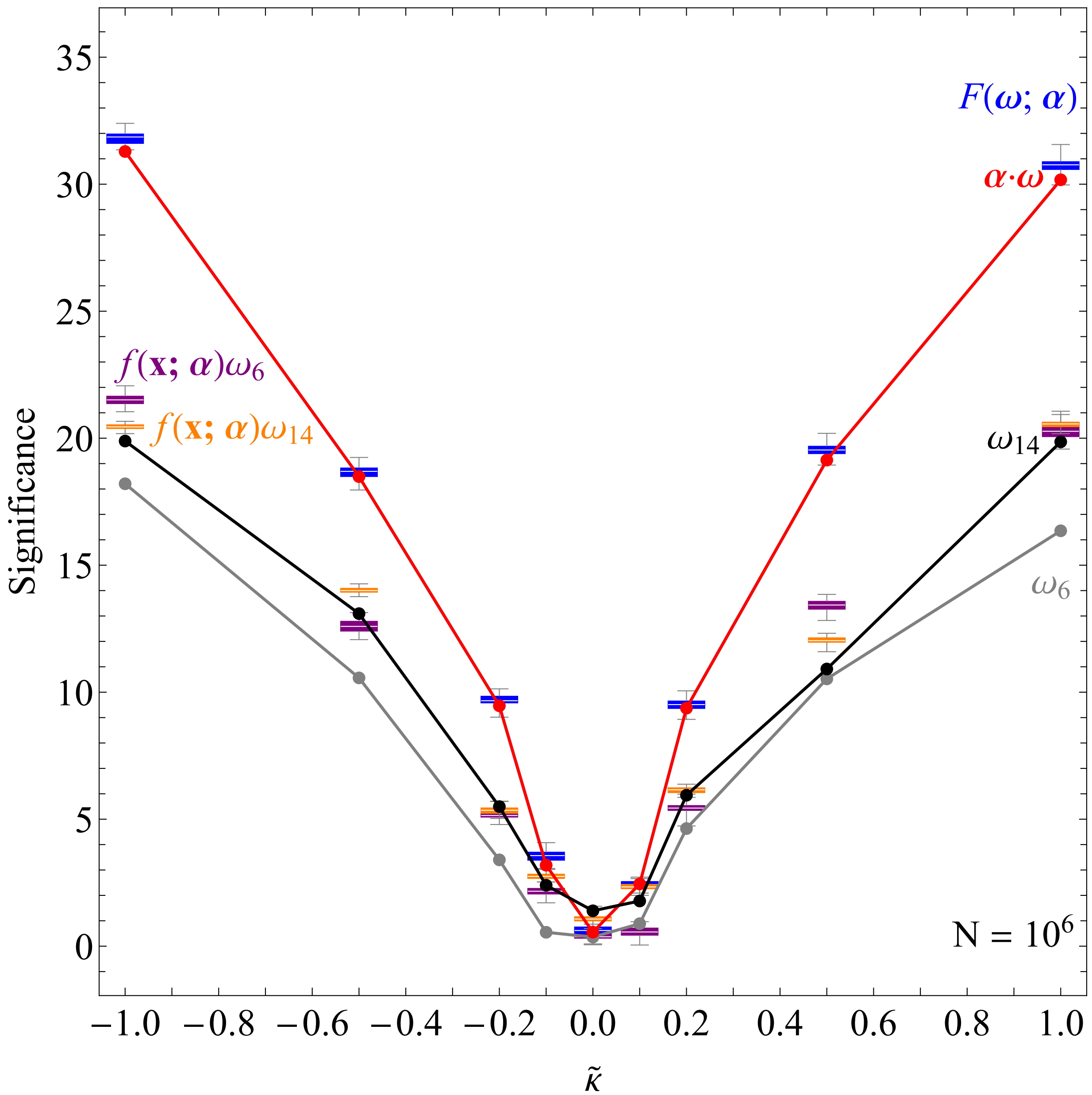
Special operators with no change of normalisation

If more than one operator contribute to one process:

- One linear combination for the cross-section
- all the orthogonal one are ‘pure’ shapes (at the interference level)

Observables vs ML trained on model

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



Neural network

Linear combination

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

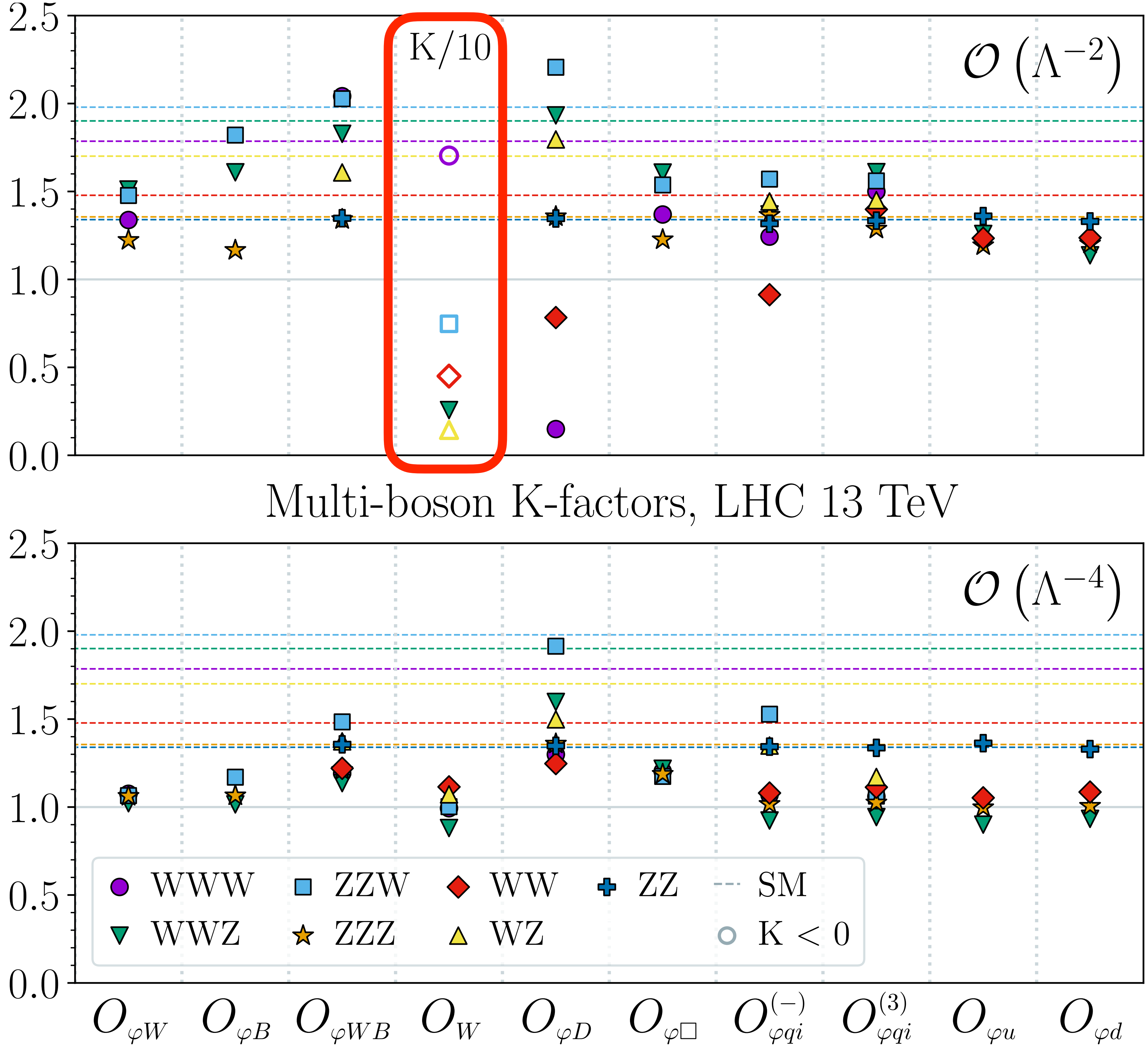
$$\omega_6 \sim [(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]$$

Keeping uncertainties under control

EW bosons production

Large negative K-factors

Converge?



SMEFT@NLO
2008.11743

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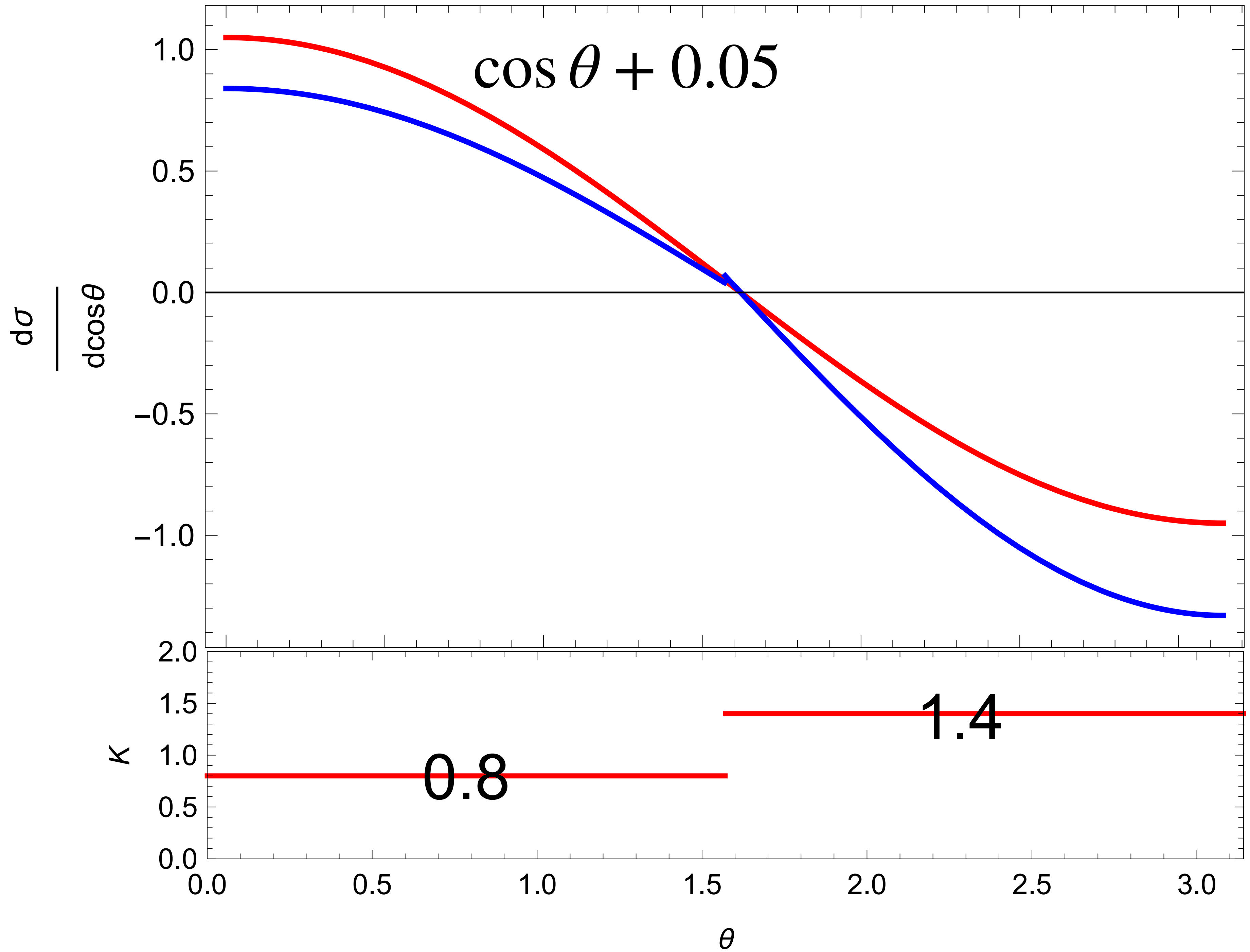
Large/small K-factor



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

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

$K_\sigma \approx -3$

Uncertainty

σ is not the right variable to probe the interference

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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)

Owww

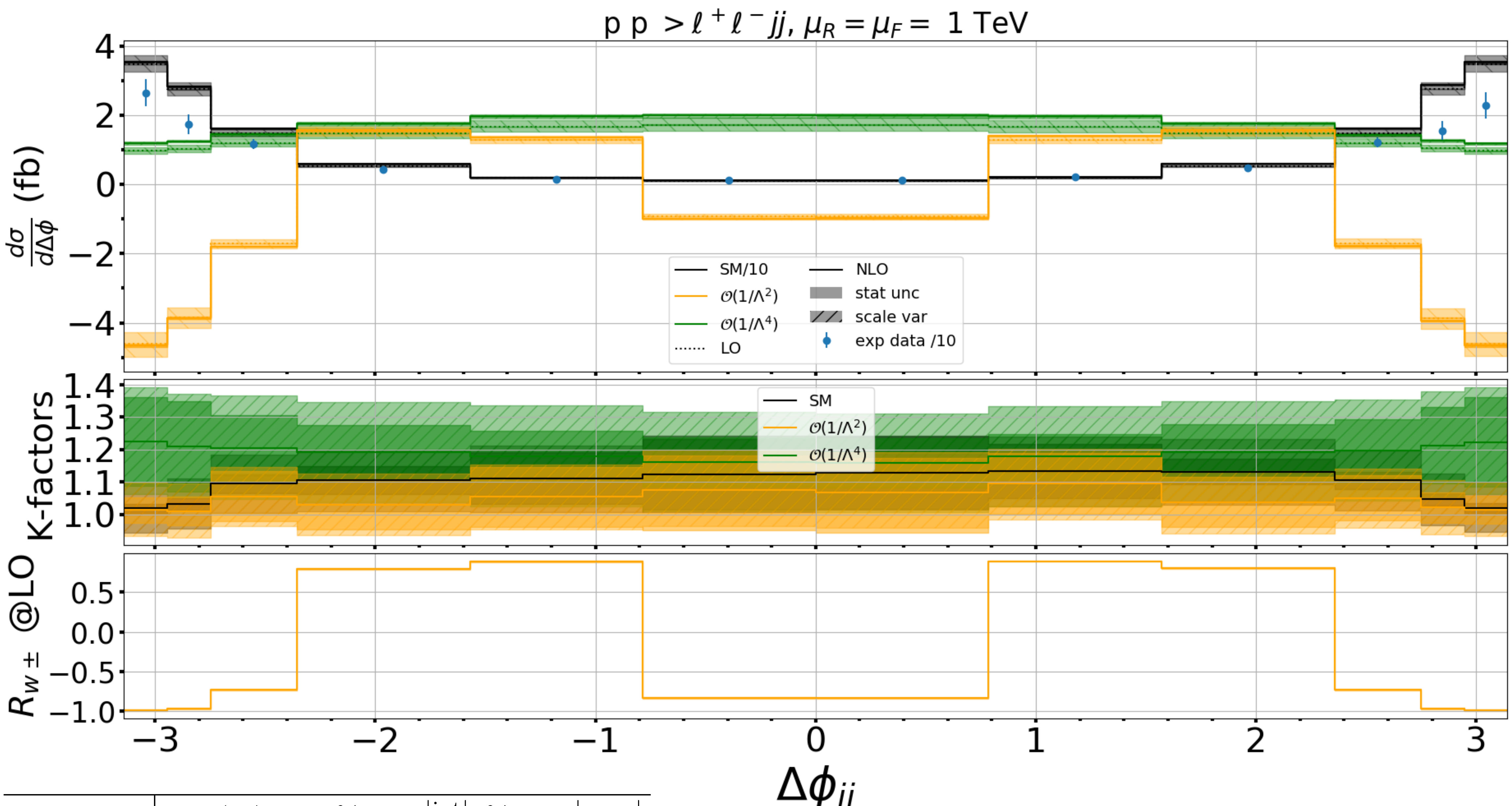
C.D., M. Maltoni, 2403.16894

$$O_W = \epsilon^{IJK} W_\mu^{I,\nu} W_\nu^{J,\rho} W_\rho^{K,\mu}$$

	SM	$\mathcal{O}(1/\Lambda^2)$	$\mathcal{O}(1/\Lambda^4)$
	$pp \to \ell^+\ell^- jj$ EW, $\ell = (e,\mu)$		
σ_{LO} (fb)	$49{\pm}0.06\%^{+8\%}_{-6\%}$	$-1.67{\pm}0.4\%^{+6\%}_{-7\%}$	$9.4{\pm}0.07\%^{+11\%}_{-10\%}$
σ_{NLO} (fb)	$52.2{\pm}0.19\%^{+0.8\%}_{-1.1\%}$	$-1.66{\pm}1.2\%^{+0.4\%}_{-0.8\%}$	$11.1{\pm}0.18\%^{+3\%}_{-4\%}$
K-factor	$1.07{\pm}0.19\%^{+9\%}_{-7\%}$	$0.99{\pm}1.2\%^{+6\%}_{-8\%}$	$1.18{\pm}0.17\%^{+14\%}_{-14\%}$
	$pp \to \ell^\pm \overset{(-)}{\nu} \ell^+\ell^-$, $\ell = (e,\mu)$		
σ_{LO} (fb)	$34.6{\pm}0.012\%^{+1.2\%}_{-1.4\%}$	$0.169{\pm}0.3\%^{+1.8\%}_{-2\%}$	$6.2{\pm}0.06\%^{+2\%}_{-1.6\%}$
σ_{NLO} (fb)	$50.5{\pm}0.02\%^{+1.6\%}_{-1.4\%}$	$-0.91{\pm}0.5\%^{+5\%}_{-7\%}$	$7.34{\pm}0.07\%^{+0.8\%}_{-0.7\%}$
σ_{N^2LO} (fb)	$62.8{\pm}0.3\%^{+1.4\%}_{-1.3\%}$	-	-
K-factor	$1.46{\pm}0.03\%^{+3\%}_{-3\%}$	$-5.4{\pm}0.6\%^{+7\%}_{-9\%}$	$1.18{\pm}0.09\%^{+3\%}_{-3\%}$
N^{2}LO / LO	$1.82{\pm}0.3\%^{+3\%}_{-3\%}$	-	-
	$pp \to \ell^\pm \overset{(-)}{\nu} \gamma$, $\ell = (e,\mu,\tau)$		
σ_{LO} (fb)	$20.7{\pm}0.4\%^{+1.4\%}_{-1.4\%}$	$-0.67{\pm}9\%^{+21\%}_{-9\%}$	$110{\pm}0.5\%^{+5\%}_{-4\%}$
σ_{NLO} (fb)	$29.8{\pm}0.6\%^{+3\%}_{-2\%}$	$-3.4{\pm}9\%^{+9\%}_{-11\%}$	$121{\pm}0.7\%^{+1.2\%}_{-1.2\%}$
K-factor	$1.44{\pm}0.5\%^{+4\%}_{-4\%}$	$5.1{\pm}12\%^{+29\%}_{-22\%}$	$1.10{\pm}0.7\%^{+6\%}_{-5\%}$

higher order underestimated

VBF

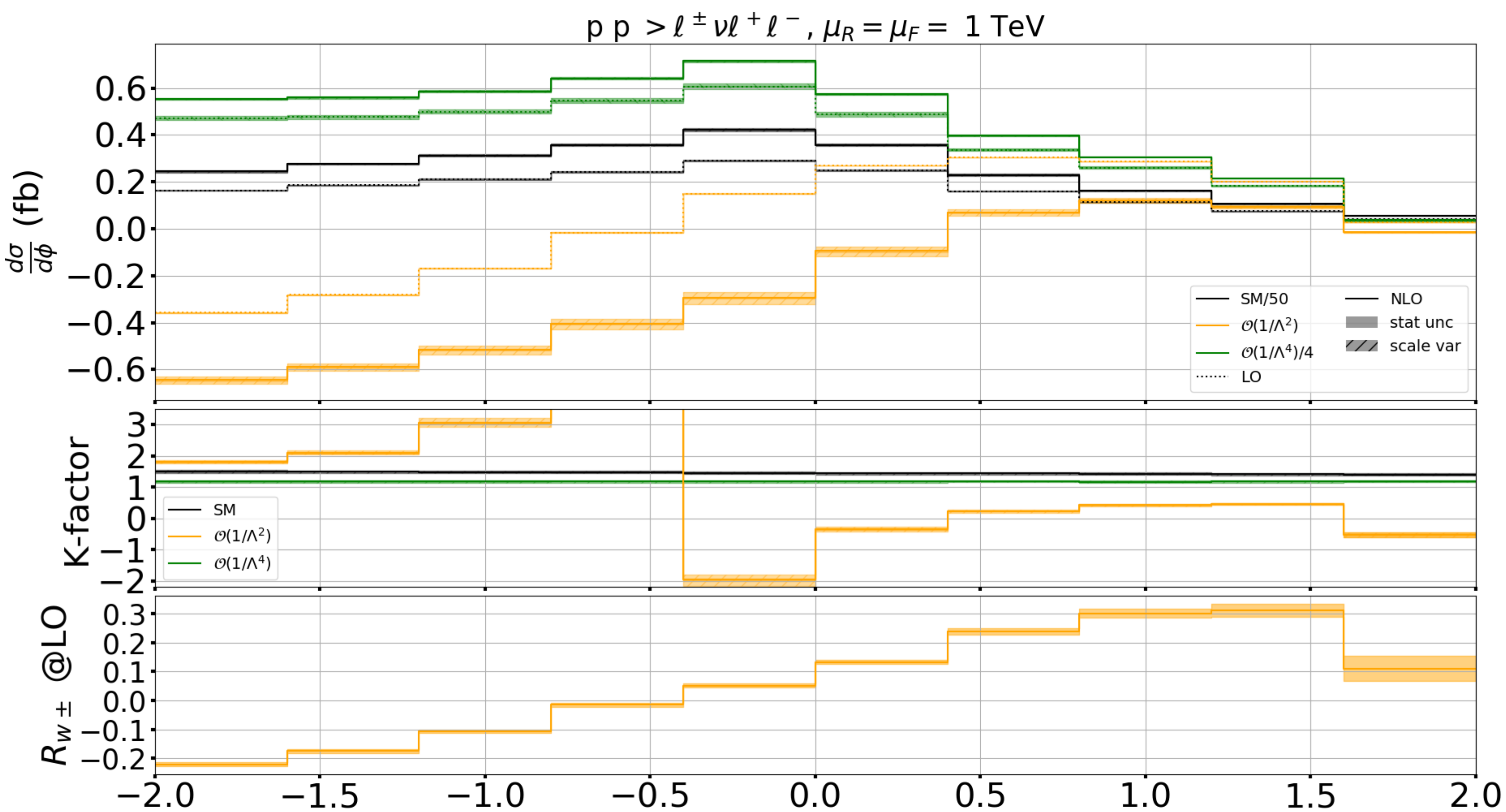


	(fb)	% of $\sigma^{\|\text{int}\|}$	% of $\sigma^{\|\text{meas}\|}$
$pp \to \ell^+\ell^- jj$ EW, $\ell = (e, \mu)$			
$\sigma^{\|\text{int}\|}$	13.27±0.3%	100	-
$\sigma^{\|\text{meas}\|}$	12.81±0.3%	97	100
$\Delta\phi_{jj}$	11.42±0.4%	86	89
$\sigma_{LO}^{1/\Lambda^2}$	-1.71±2%	13	13

$$R_{w\pm} = \frac{\text{wgt} > 0 - \text{wgt} < 0}{\text{wgt} > 0 + \text{wgt} < 0}$$

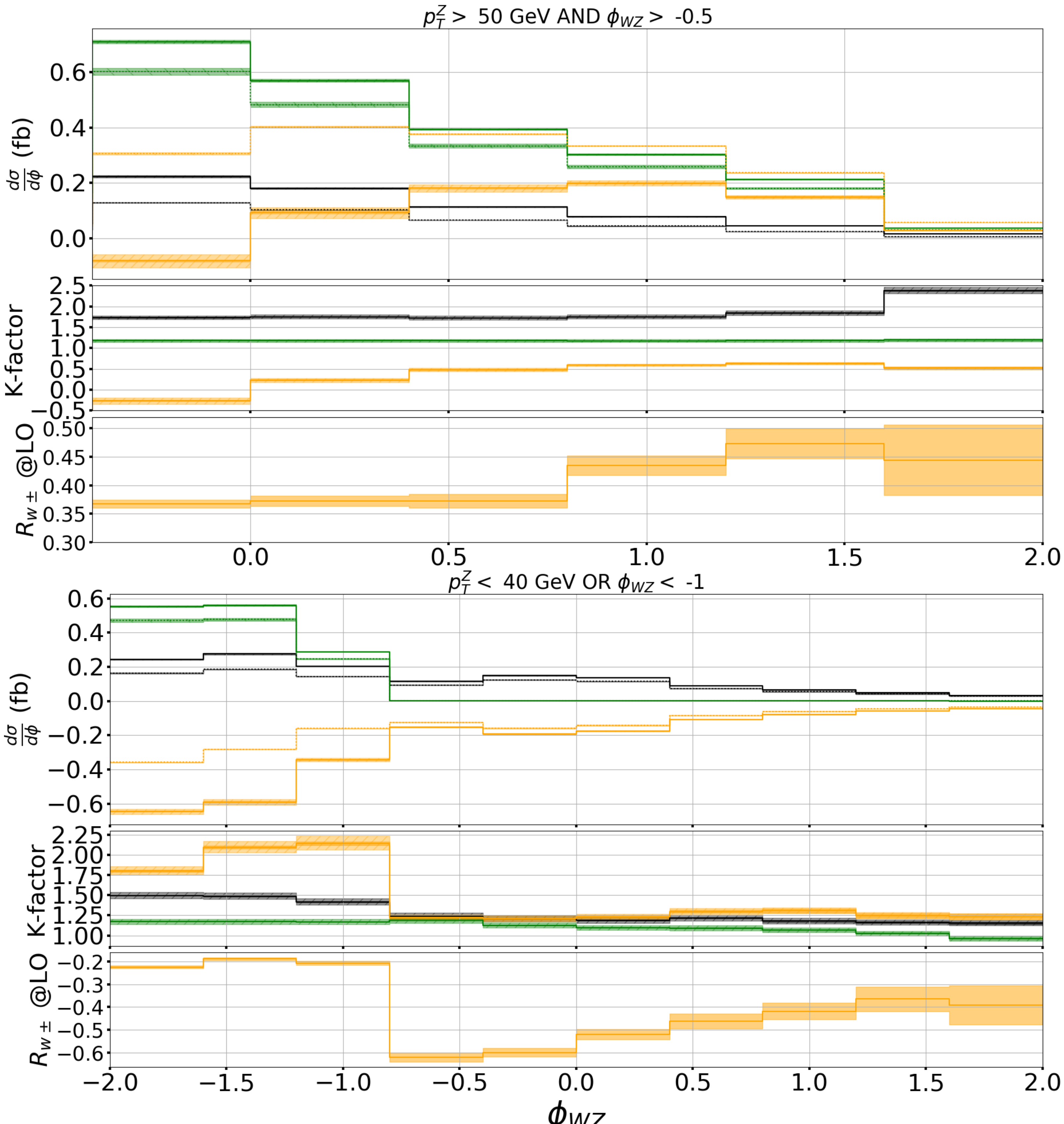
C. Degrande

WZ



	(fb)	% of $\sigma^{\lvert\mathrm{int}\rvert}$	% of $\sigma^{\lvert\mathrm{meas}\rvert}$
$pp \to \ell^\pm \overset{(-)}{\nu} \ell^+ \ell^-$, $\ell = (e, \mu)$			
$\sigma^{\lvert\mathrm{int}\rvert}$	4.93±0.4%	100	-
$\sigma^{\lvert\mathrm{meas}\rvert}$	2.04±1.0%	41	100
$p_T^Z \times \phi_{WZ}$	1.31±1.5%	27	64
ϕ_{WZ}	0.79±3%	16	39
M_T^{WZ}	0.66±3%	13	32
$\cos\theta^*_{\ell_Z^- Z}$	0.20±10%	4	10
$\sigma_{LO}^{1/\Lambda^2}$	0.20±10%	4	10
$p_T^Z >$ 50 GeV AND $\phi_{WZ} >$ -0.5			
$\sigma^{\lvert\mathrm{int}\rvert}$	2.260±0.7%	100	-
$\sigma^{\lvert\mathrm{meas}\rvert}$	0.873±1.7%	39	100
M_T^{WZ}	0.660±2%	29	76
$\sigma_{LO}^{1/\Lambda^2}$	0.660±2%	29	76
$p_T^Z <$ 40 GeV OR $\phi_{WZ} <$ -1			
$\sigma^{\lvert\mathrm{int}\rvert}$	1.810±0.5%	100	-
$\sigma^{\lvert\mathrm{meas}\rvert}$	0.870±1.1%	48	100
M_T^{WZ}	0.480±2%	27	55
$\sigma_{LO}^{1/\Lambda^2}$	-0.480±2%	27	55

WZ



	(fb)	% of $\sigma^{\|int\|}$	% of $\sigma^{\|meas\|}$
$pp \to \ell^\pm \overset{(-)}{\nu} \ell^+ \ell^-$, $\ell = (e, \mu)$			
$\sigma^{\|int\|}$	4.93±0.4%	100	-
$\sigma^{\|meas\|}$	2.04±1.0%	41	100
$p_T^Z \times \phi_{WZ}$	1.31±1.5%	27	64
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$\sigma^{\|meas\|}$	0.873±1.7%	39	100
M_T^{WZ}	0.660±2%	29	76
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$p_T^Z <$ 40 GeV OR $\phi_{WZ} <$ -1			
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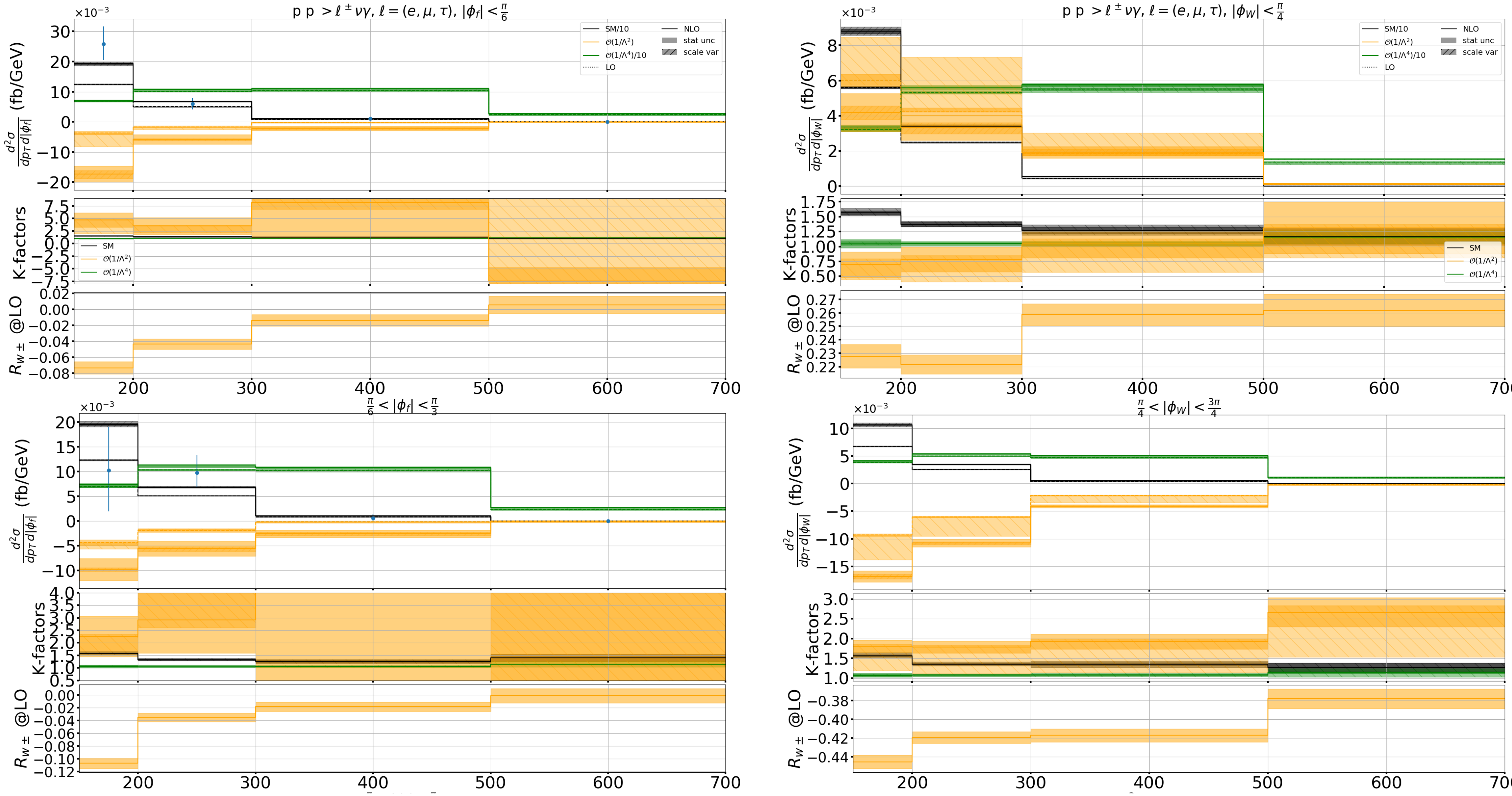
M_T^{WZ}	0.480±2%	27	55
$\sigma_{LO}^{1/\Lambda^2}$	-0.480±2%	27	55

C. Degrande

Wγ



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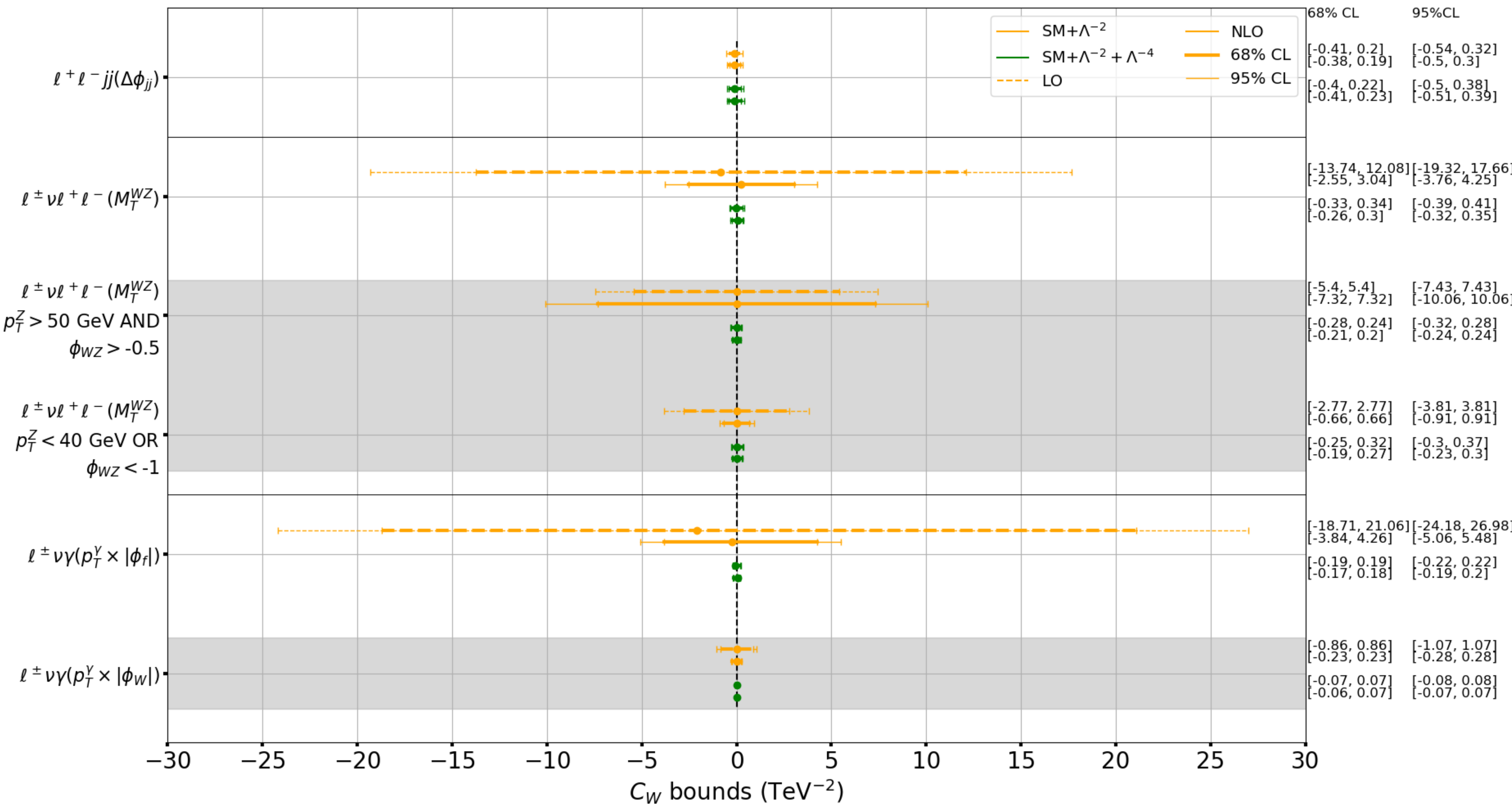
Constraints



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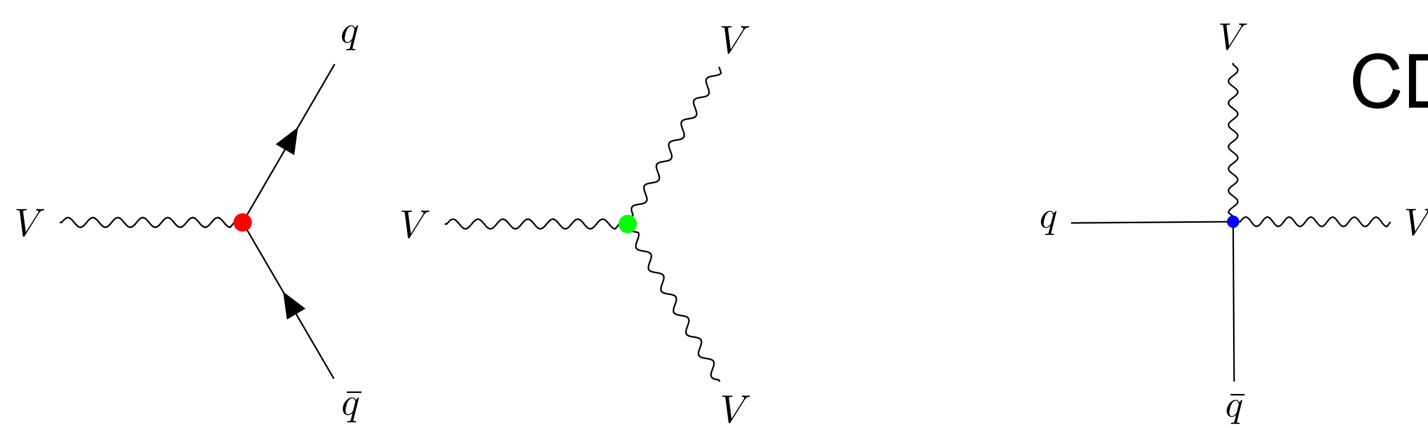
Dim-8 in diboson

dim-8 operators

$$\mathcal{O}_1 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_2 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$
$$\mathcal{O}_3 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right),$$
$$\mathcal{O}_4 = iW^{I\mu}{}_{\lambda}B^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_5 = iW^{I\mu}{}_{\lambda}\tilde{B}^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_6 = iW^{I\nu}{}_{\lambda}B^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_7 = iW^{I\nu}{}_{\lambda}\tilde{B}^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_8 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_9 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$
$$\mathcal{O}_{10} = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right),$$
$$\mathcal{O}_{11} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{12} = i\epsilon^{IJK}\tilde{W}^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{13} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}\tilde{W}^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{14} = i\left(\bar{u}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{15} = i\left(\bar{d}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{16} = i\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{17} = i\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\tau^{K}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right)\left(D_{\lambda}H^{\dagger}\tau^{K}D^{\mu}H\right),$$
$$\mathcal{O}_{18} = i(\bar{u}_{\mathrm{R}p}\gamma^{\mu}\overleftrightarrow{D}^{\nu}d_{\mathrm{R}r})\epsilon^{ij}(D^{\mu}H_iD^{\nu}H_j),$$



(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^-})	$\mathcal{A}^8_{h_i} / \frac{C_8}{\Lambda^4}$	$\mathcal{A}^{\mathrm{SM}}_{h_i}$
$-,+$	S^2 $S\sin^2\left(\frac{\theta}{2}\right)\sin(\theta)\left(S-2M_W^2\right)\delta_{ab}$	0
$-,-$	S $S\sin(\theta)\cos(\theta)M_W^2\delta_{ab}$	$\frac{4\pi\alpha\sin(\theta)M_Z^2\delta_{ab}\sqrt{1-\frac{4M_W^2}{S}}}{3\left(S-M_Z^2\right)}$ 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
$+,0$	$S^{3/2}$ $\frac{S^{3/2}\cos^2\left(\frac{\theta}{2}\right)(2\cos(\theta)-1)M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{2S-8M_W^2}}{3SM_W-3M_WM_Z^2}$ $S^{-1/2}$
$0,+$	$S^{3/2}$ $-\frac{S^{3/2}\sin^2\left(\frac{\theta}{2}\right)(2\cos(\theta)+1)M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\sqrt{2}\pi\alpha\sin^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$ $S^{-1/2}$
$0,-$	$S^{3/2}$ $\frac{S^{3/2}\cos^2\left(\frac{\theta}{2}\right)(1-2\cos(\theta))M_W^2\delta_{ab}}{\sqrt{2}M_W}$	$\frac{4\sqrt{2}\pi\alpha\cos^2\left(\frac{\theta}{2}\right)M_Z^2\delta_{ab}\sqrt{S-4M_W^2}}{3M_WM_Z^2-3SM_W}$ $S^{-1/2}$
$0,0$	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 $\mathcal{O}_8$.

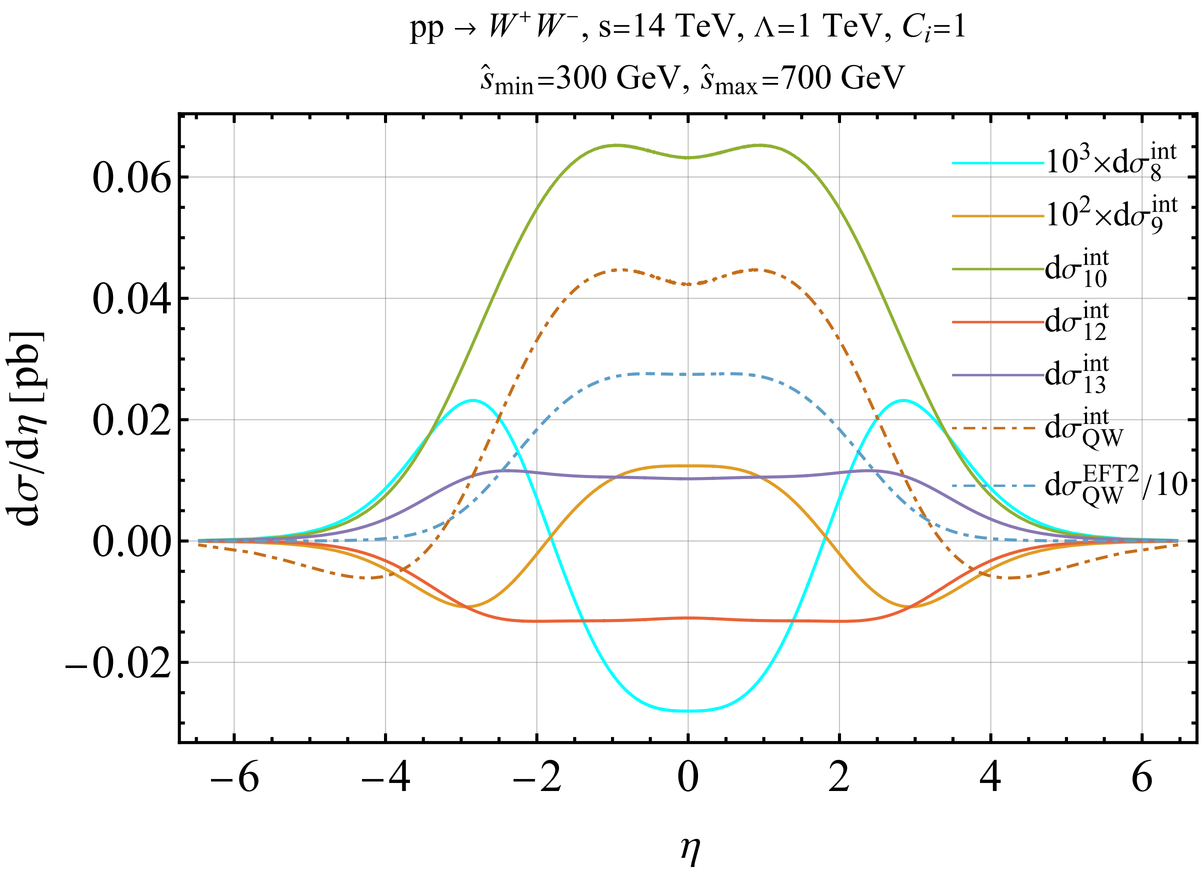
C. Degrande

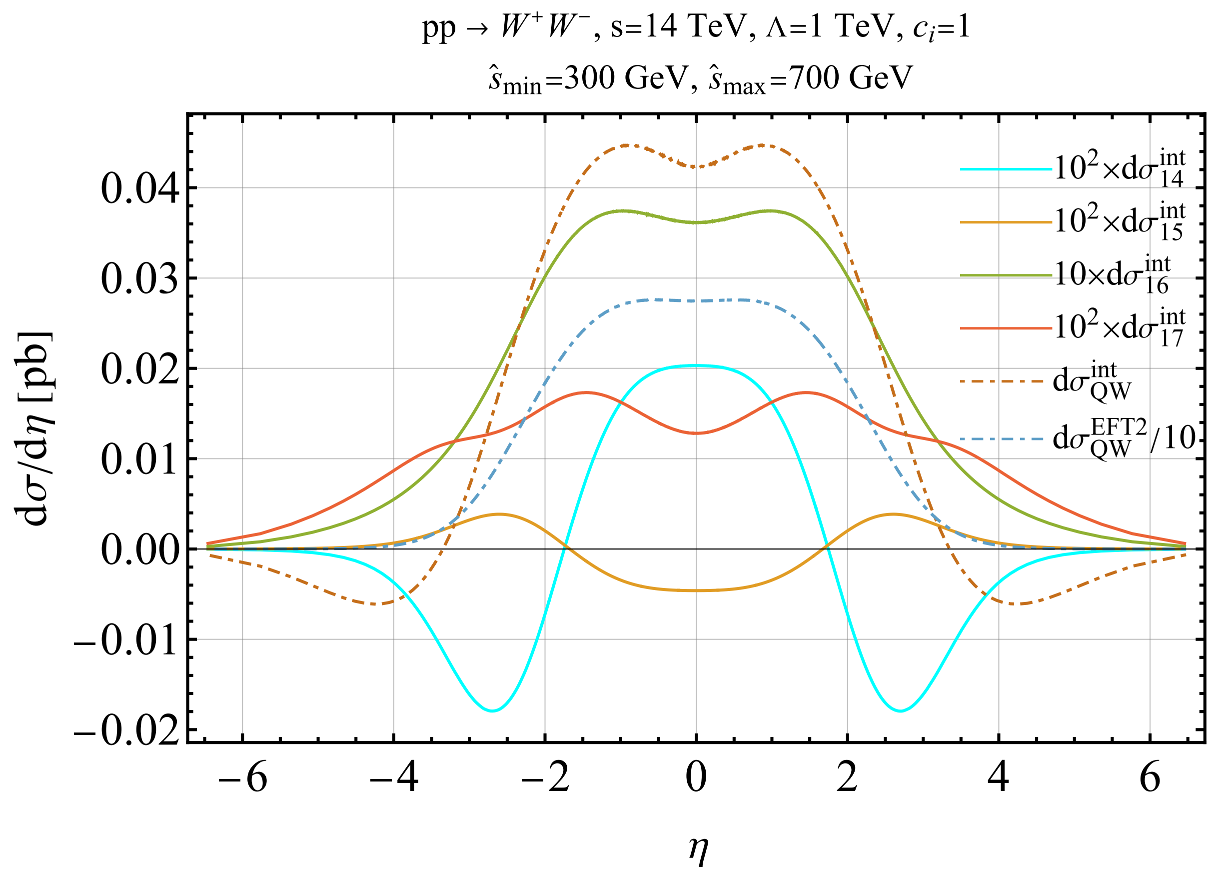
Interference by helicity (O_{15})

(h_{W^+}, h_{W^-})		$\mathcal{A}^{15}_{h_i} / \frac{C_{15}}{\Lambda^4}$	$\mathcal{A}^{\mathrm{SM}}_{h_i}$	
$-,+$	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

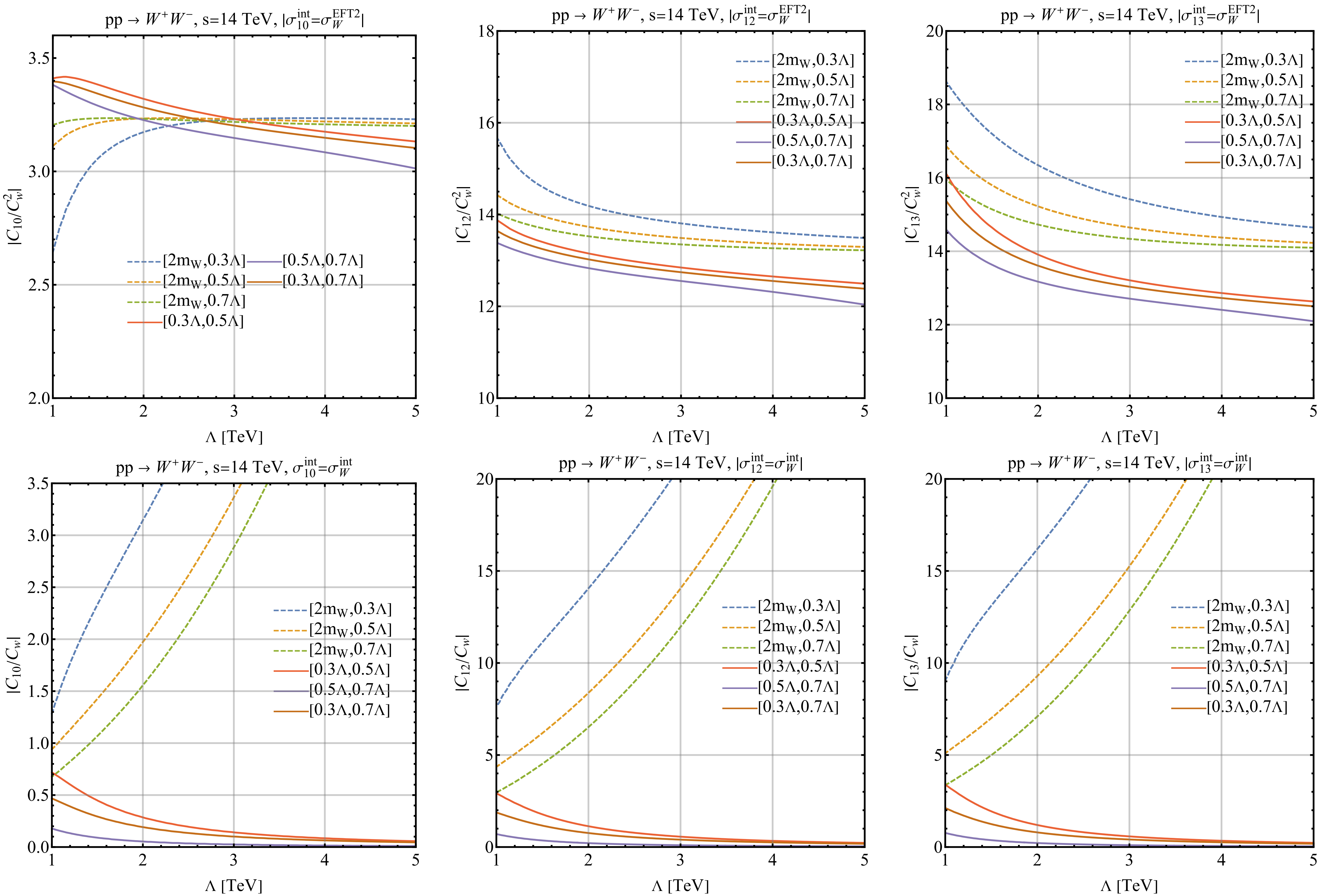
Distributions





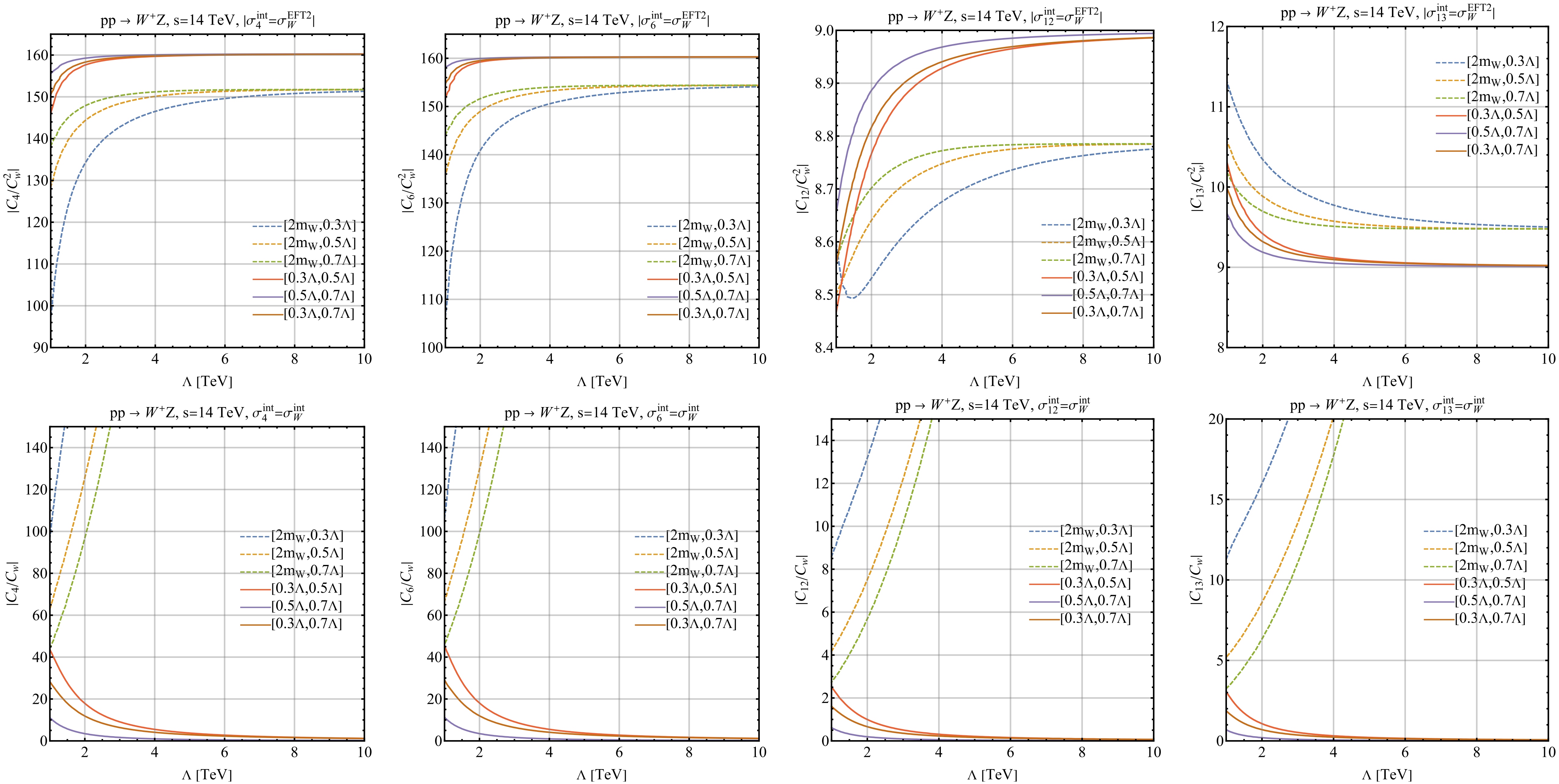
C. Degrande

Comparison to dim6



C. Degrande

WZ

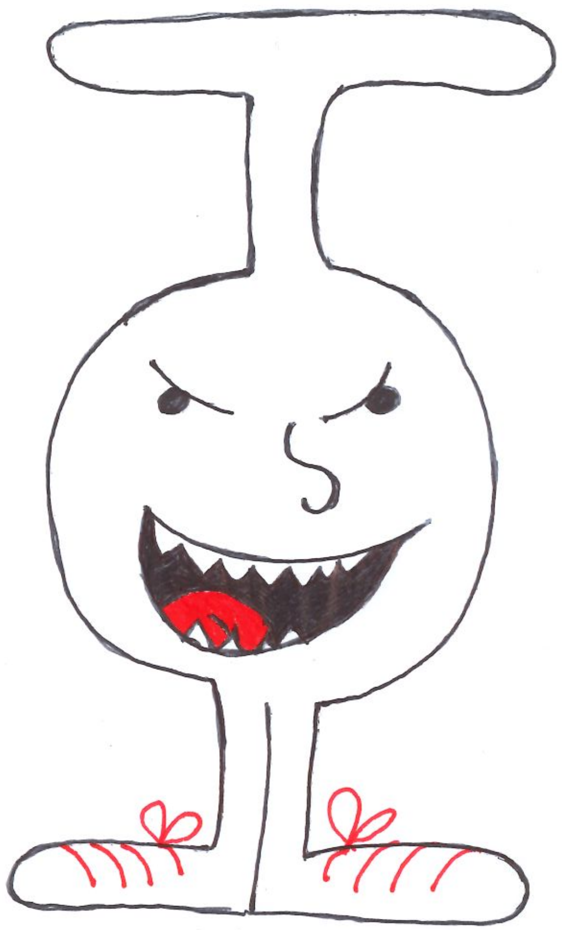


C. Degrande

Final comments

Final comments

- SMEFT is good to parametrise any heavy new physics BUT we need to
- understand the interference
- understand errors
  - from EFT : $1/\Lambda$ (dim8, …)
  - α_S, α_{EW}
- design specific observables
  - more model independent and intuitive
  - easier to understand/compute errors/uncertainties
  - learn about the SM
- Reduce uncertainties
  - SM predictions (pert and non-pert)
  - Experimental



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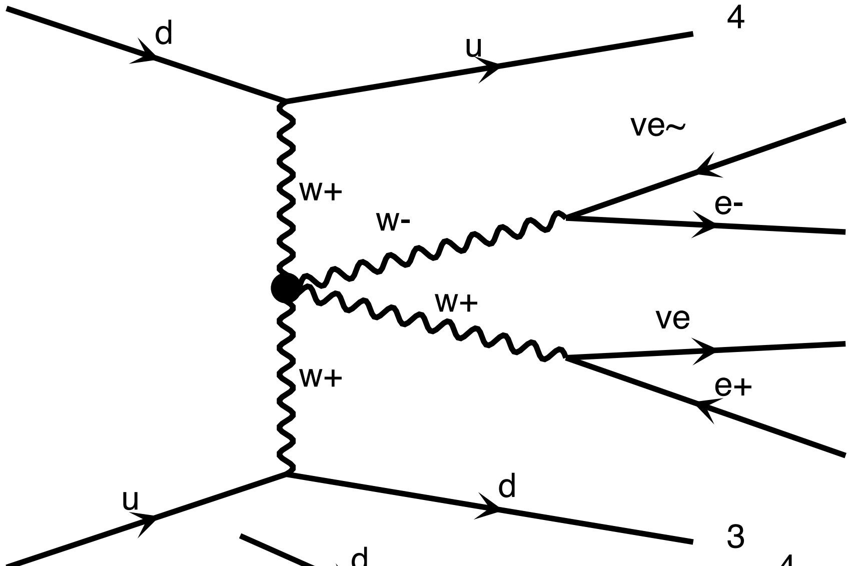
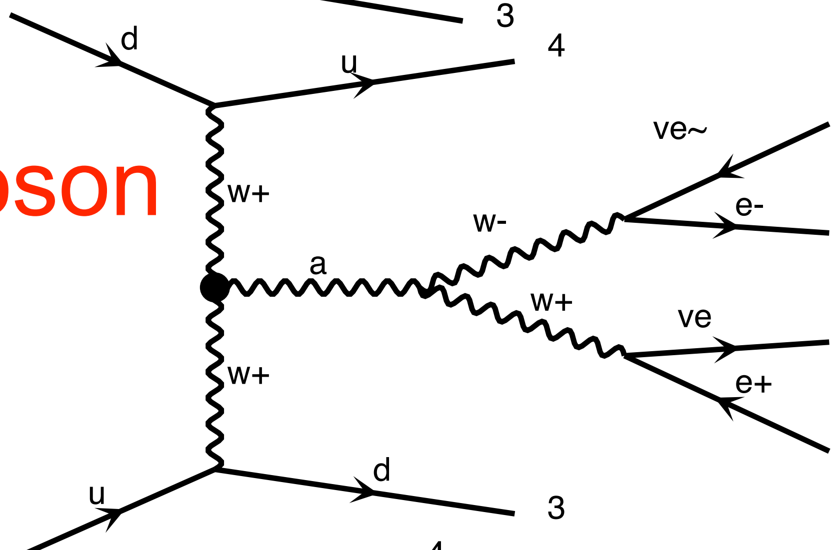
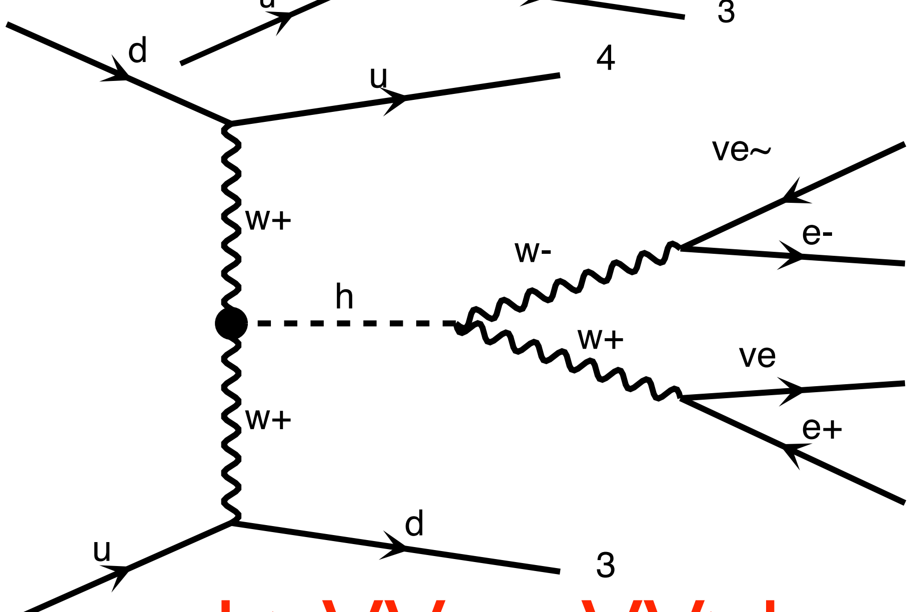
Back up

VBS



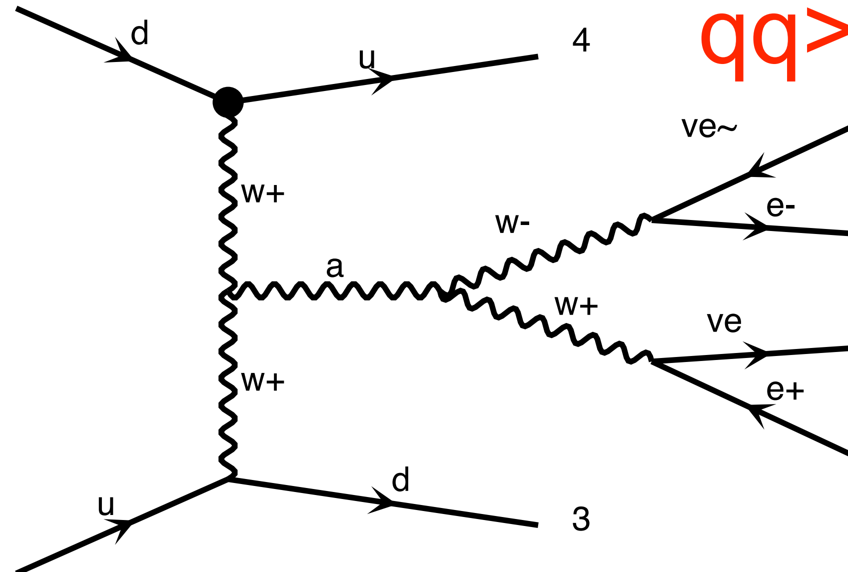
Diboson



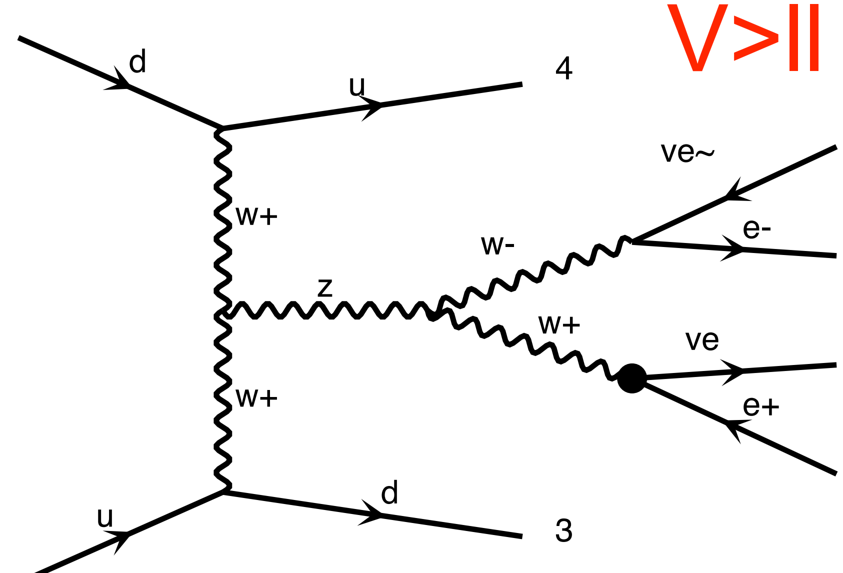


h>VV or VV>h

qq>V or V>qq



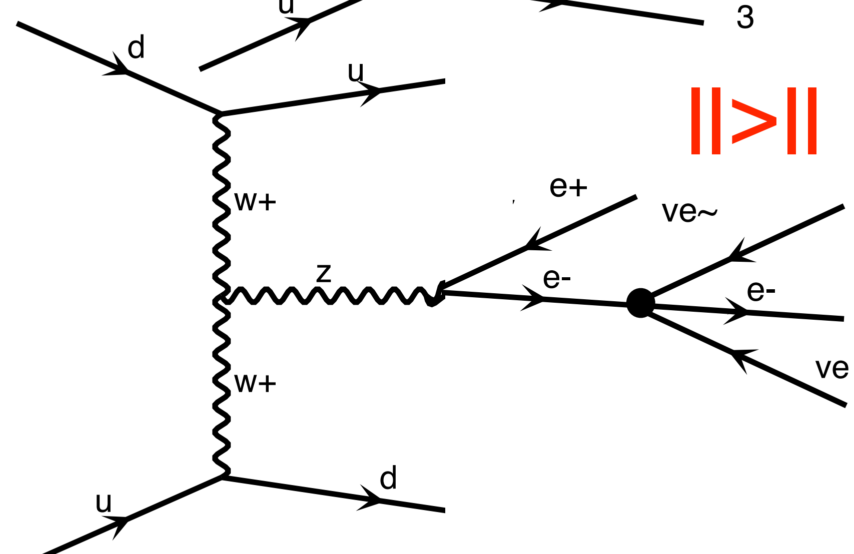
V>ll or ll>V



ll>ll

qq>qq

+ with 4q



C. Degrande