UCLouvain

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

Precision and multiboson measurements connection with EFT
Celine Degrande

Plan

- Introduction

- Assumption and precision

- Interference

- Number of operators and global fit

- final comments

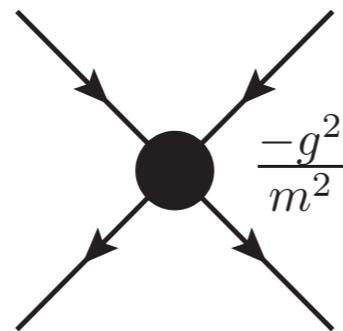# Introduction

Indirect detection of NP

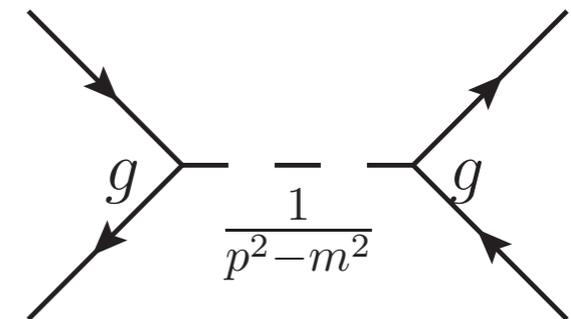- Assumption : NP scale >> energy probed in experiments
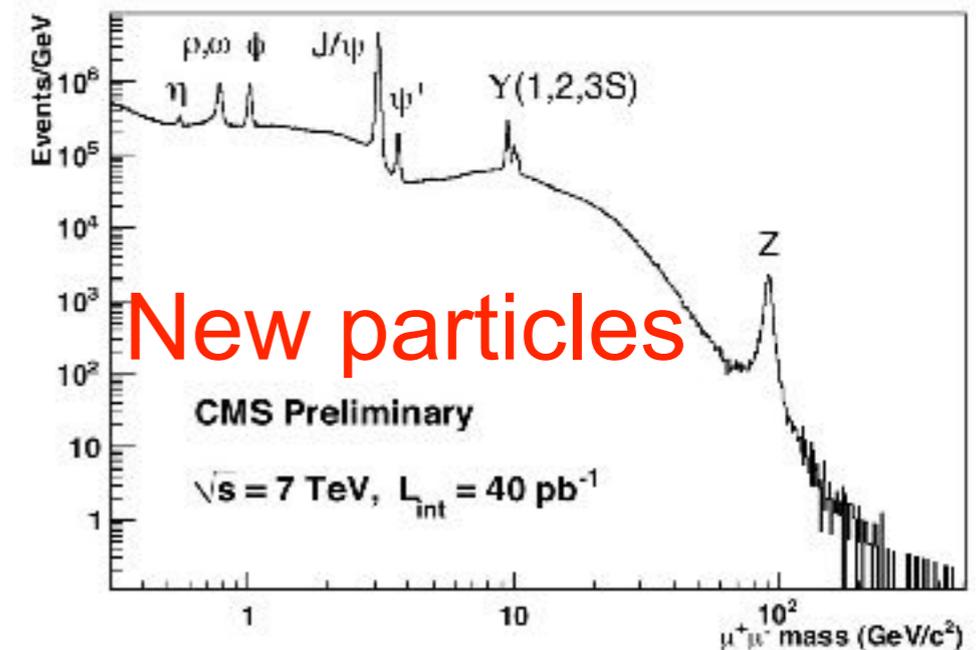
E

Exp. range

NP scale

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

$\dfrac{-g^2}{m^2}$

$g \quad \dfrac{1}{p^2-m^2} \quad g$

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

New particles

New/modified interactions between SM particles

Events/GeV

$\rho,\omega \quad \phi \qquad J/\psi$

η

ψ'

$\Upsilon(1,2,3S)$

Z

CMS Preliminary

$\sqrt{s}$ = 7 TeV, L_{int} = 40 pb^{-1}

$\mu^+\mu^-$ mass (GeV/c^2)

Indirect detection of new physics

!New physics is not just around the corner in EFT!

Assumption and precision

EFT

Parametrize any NP but an ∞ number of coefficients

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

- 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!

measure only C_i/Λ^2

- 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

Errors : higher power of $1/\Lambda$

$$|M(x)|^2 = |M_{SM}(x)|^2 + 2\Re\left(M_{SM}(x)M_{d6}^*(x)\right) + |M_{d6}(x)|^2 + \ldots$$

$$\Lambda^0 \qquad\qquad \Lambda^{-2} \qquad\qquad \mathcal{O}\left(\Lambda^{-4}\right)$$

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

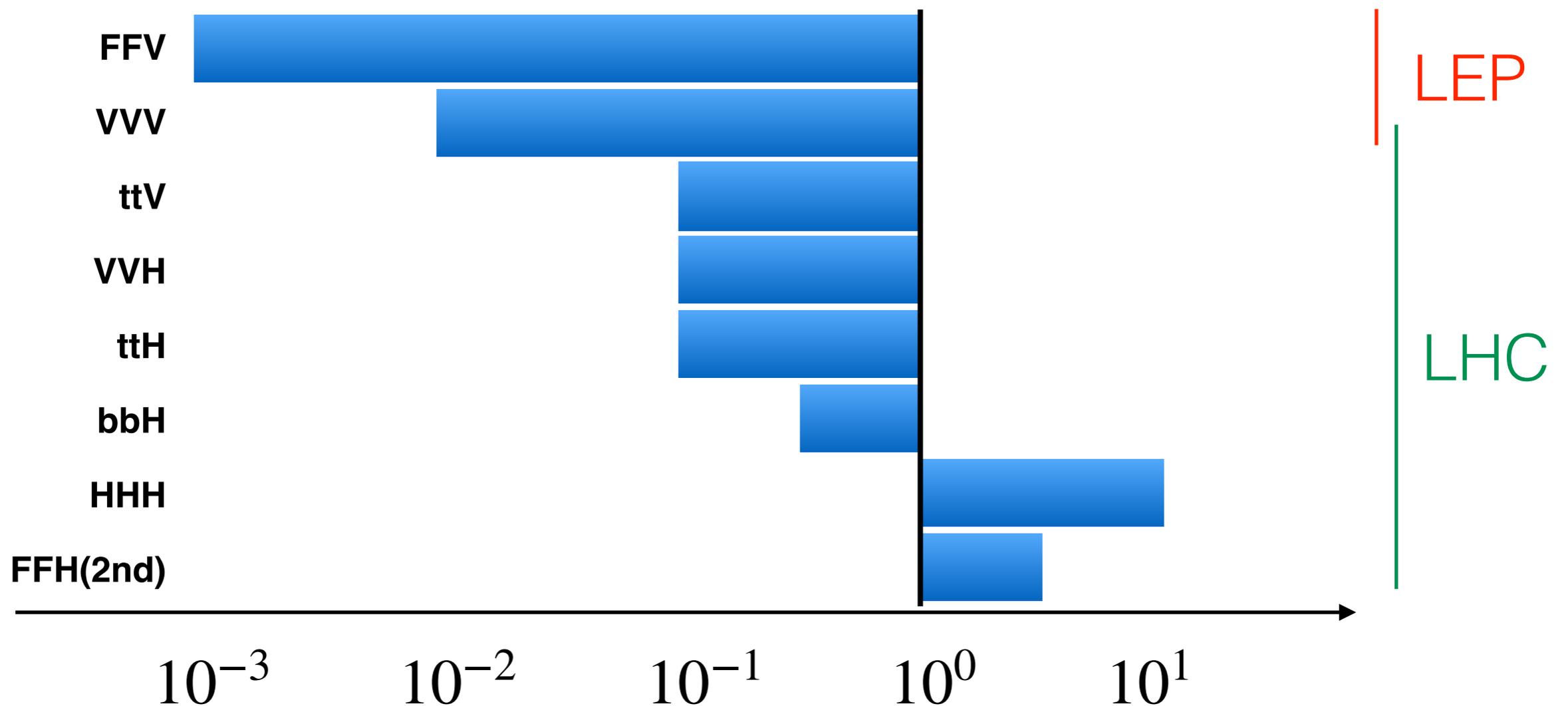$\mathcal{O}(1)$ $\mathcal{O}(0.5)$ 50% $\mathcal{O}(0.25)$

- 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
Study case: Dawson et al., 2110.06929

Precision: LEP vs LHC

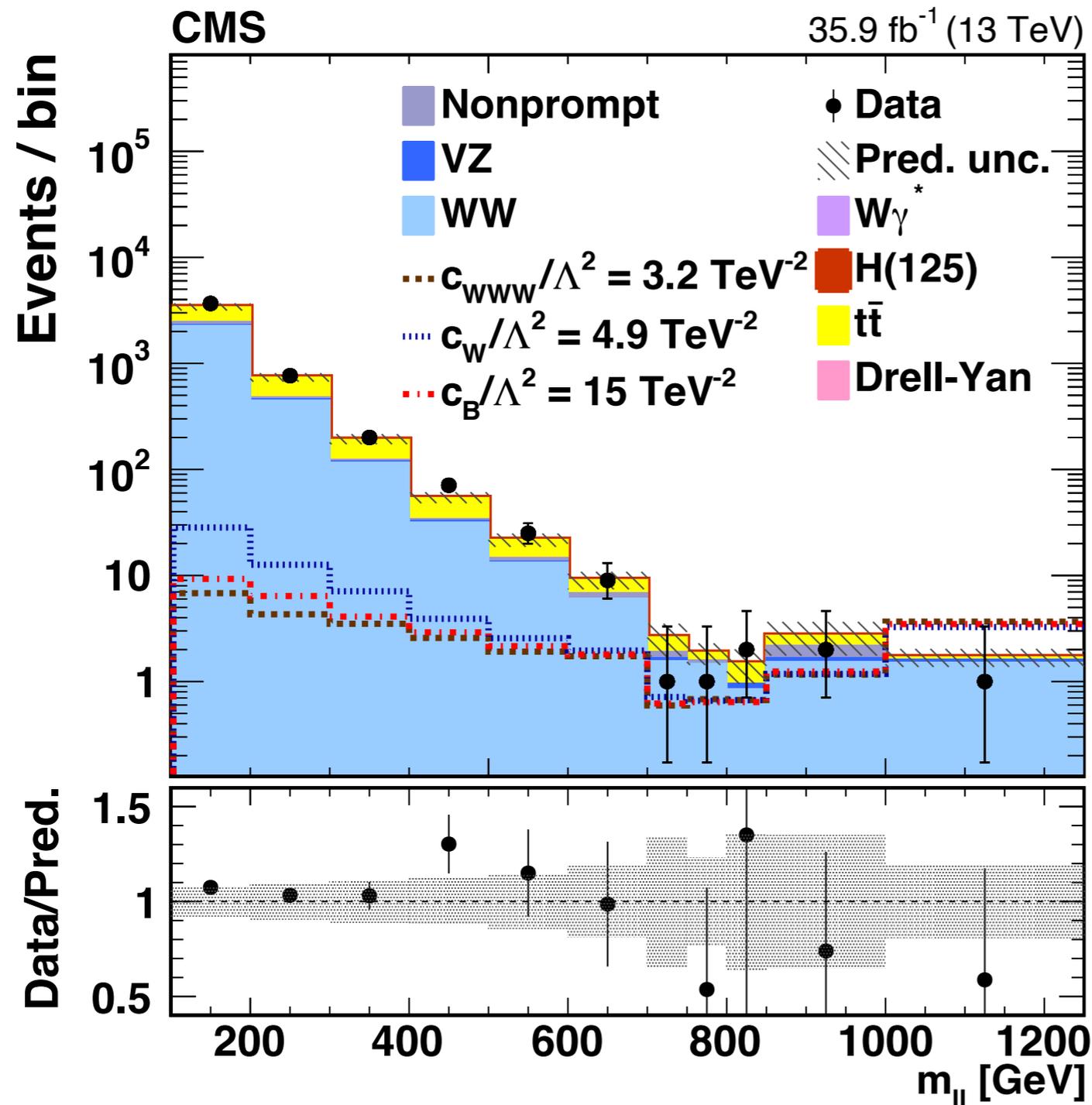## How well do we know the SM?

LHC<LEP: QCD perturbative (α_S) and non-pert. (PDF,hadronisation), backgrounds, ...

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

Interference

interference suppression

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

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

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

$$\Lambda^0 \qquad\qquad \Lambda^{-2} \qquad\qquad \Lambda^{-4}$$

$$\mathcal{O}(1) \qquad\qquad \sim 0 \qquad\qquad \mathcal{O}(0.1) \quad \boxed{30\%} \quad \mathcal{O}(0.03)$$

Assuming ~ 0

C. Degrande

Interference

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

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

mom&spin

Not always positive
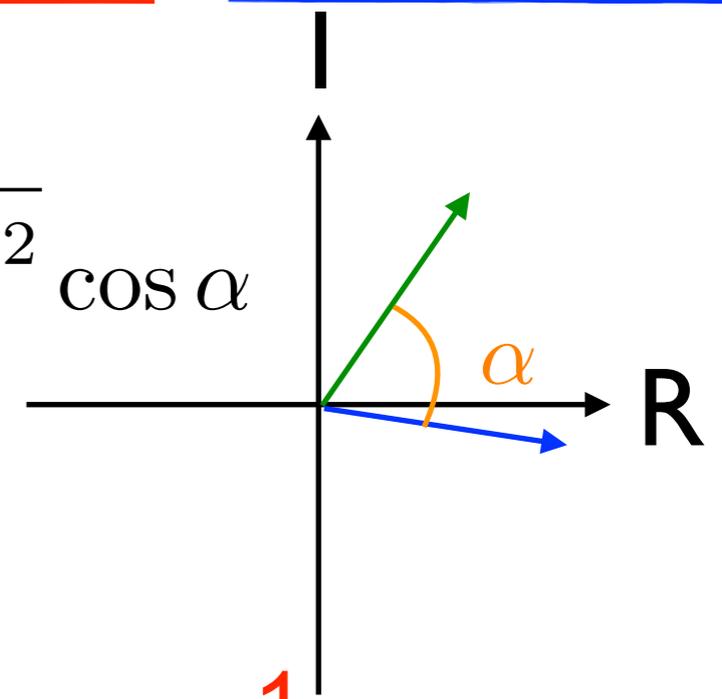
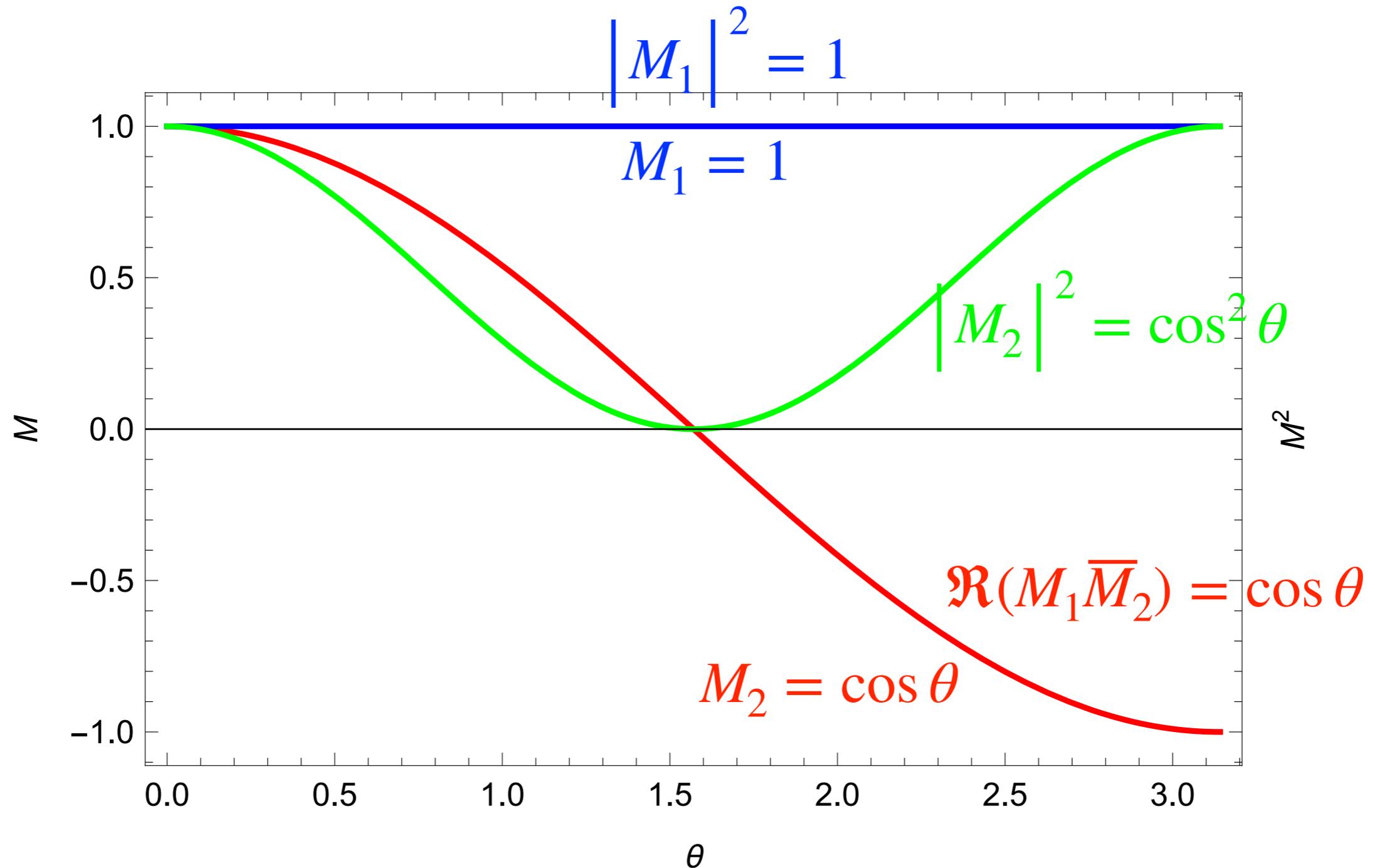Can be suppressed

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

-1

Observable dependent

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

Interference suppression from phase space

$$|M_1|^2 = 1$$

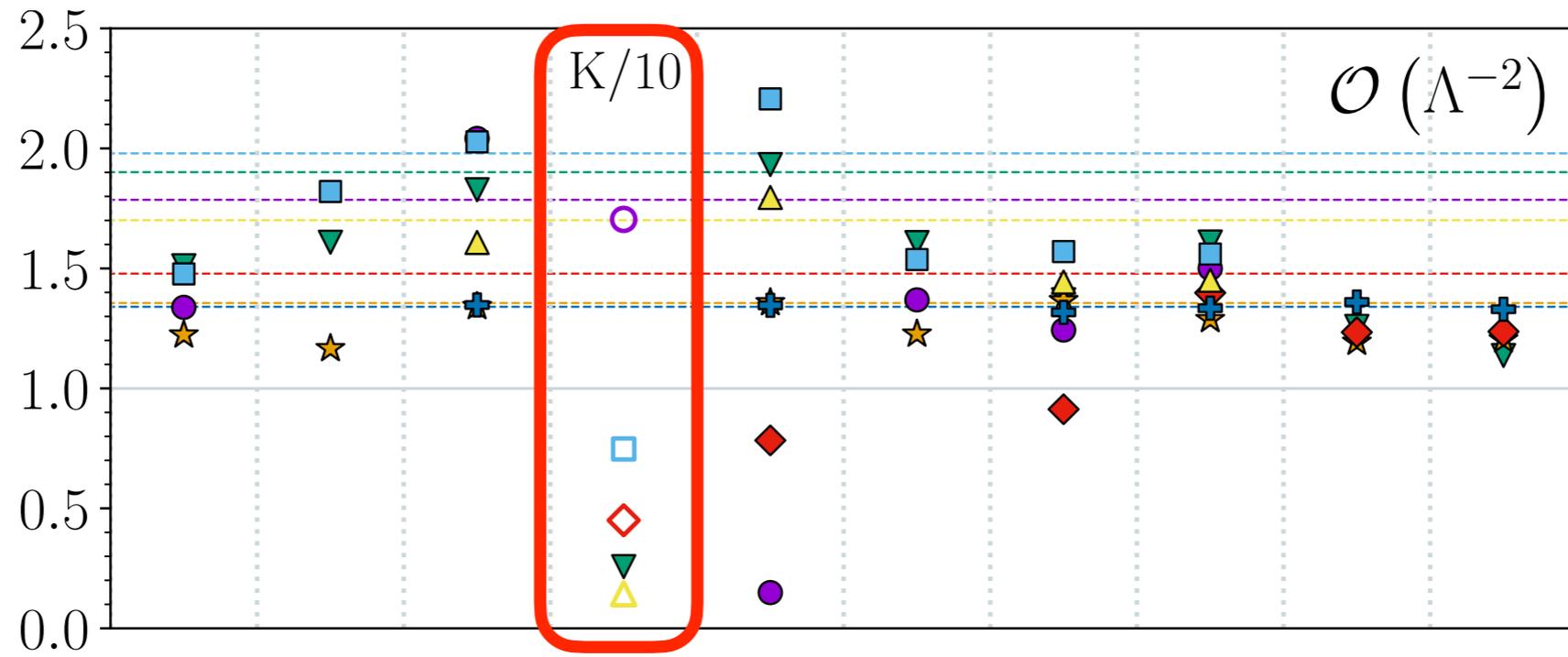$$M_1 = 1$$

$$|M_2|^2 = \cos^2 \theta$$

$$\mathfrak{R}(M_1 \overline{M}_2) = \cos \theta$$

$$M_2 = \cos \theta$$

$$\sigma_{int} = \int_0^\pi 2\mathfrak{R}(M_1 \overline{M}_2)d\theta = \int_0^\pi 2\cos\theta d\theta = 0$$
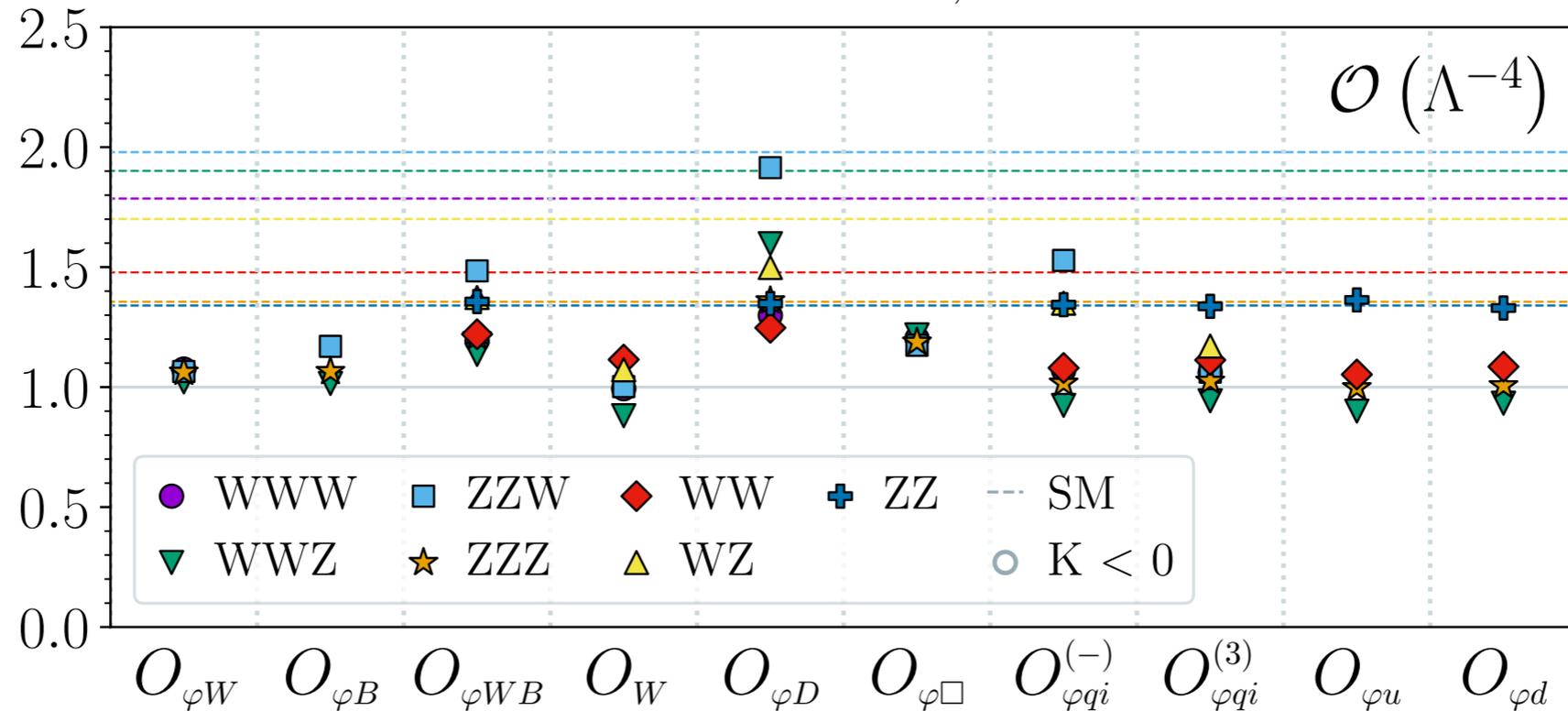
C. Degrande

EW bosons production

Large negative K-factors

Converge?

Multi-boson K-factors, LHC 13 TeV

SMEFT@NLO
2008.11743

C. Degrande

Large/small K-factor

$$\cos\theta + 0.05$$
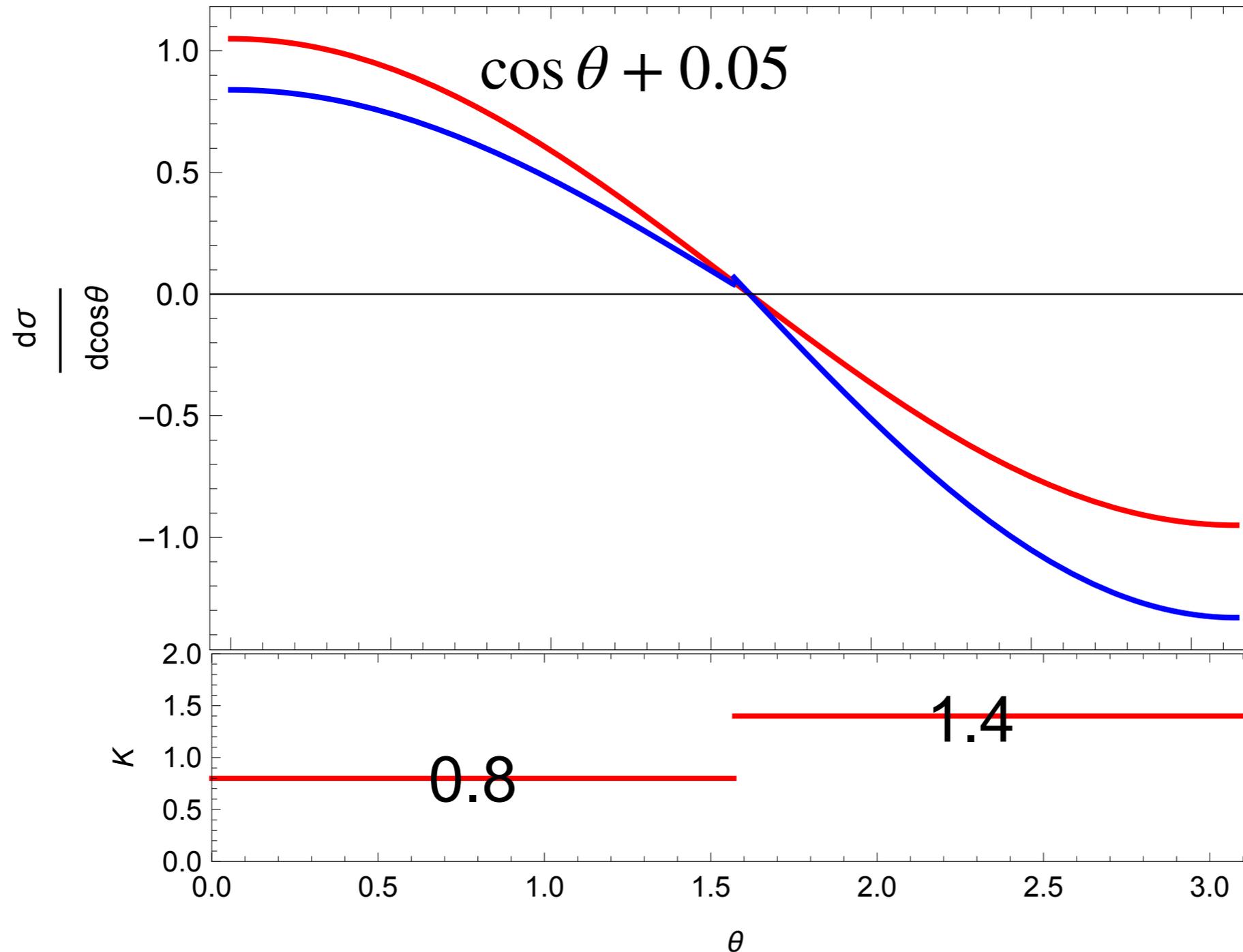
$$\sigma_{int}^{LO} = 0.16$$

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

$$K_\sigma \approx -3$$

Uncertainty

σ is not the right variable to probe the interference

Interference revival: toy example

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

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

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

$$K_A = 1.1$$

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

Interference revival: Formalism

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

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

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

Interference revival

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

Example: CPV in diboson (C.D., J. Toucheque 2110.02993)

On going: For $\mathcal{O}_{WWW}$ and connection with NLO and uncertainties (with M. Maltoni)

Number of operators and global fit

0/2F operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger \varphi)\square(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\star (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

| $X^2\varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger \varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi W B}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W} B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

New interactions + param/field redefinitions

4F operators

	$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

	$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Contribution to one process
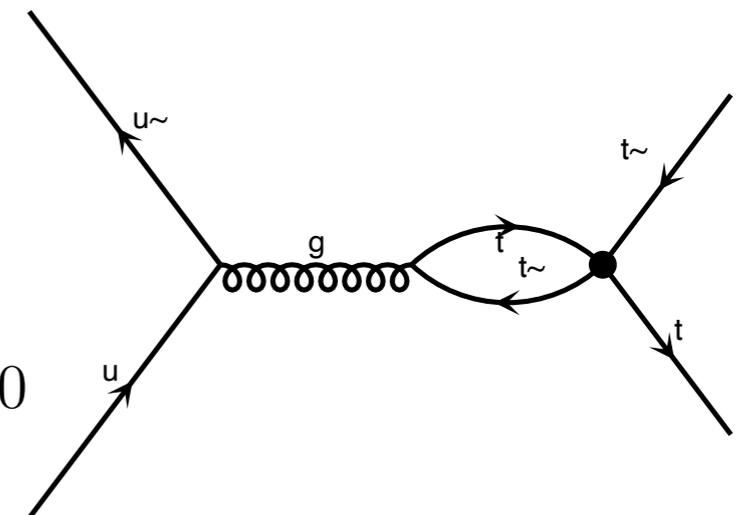
- limited number of operators contribute at the tree-level but it increases

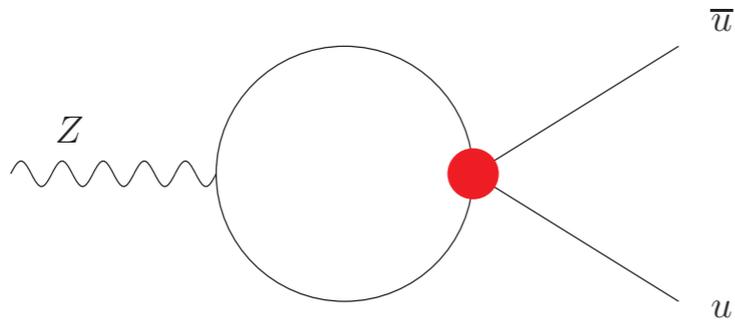 - with the number of loop

  - with the number of legs
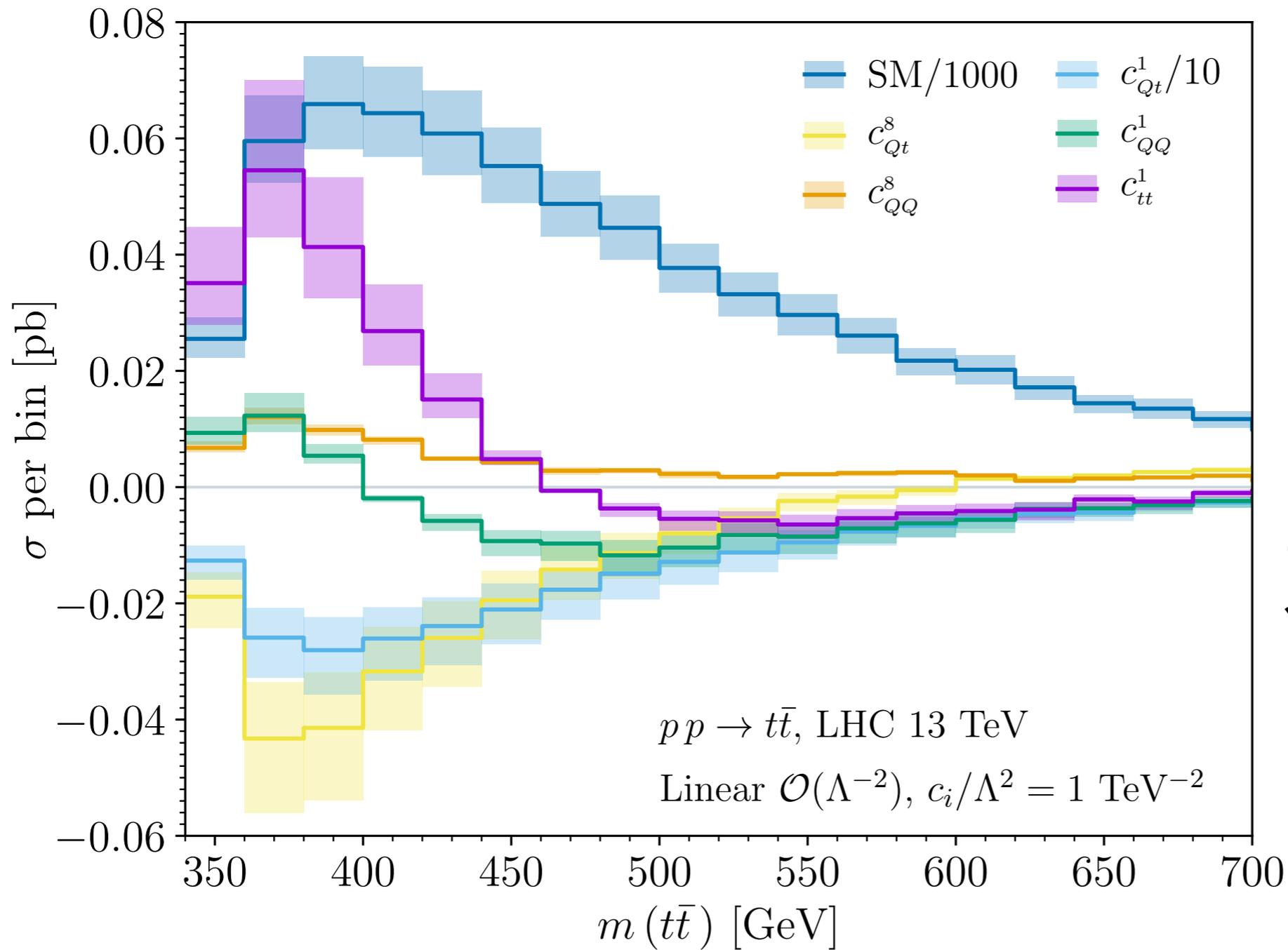
New operators contribute at NLO
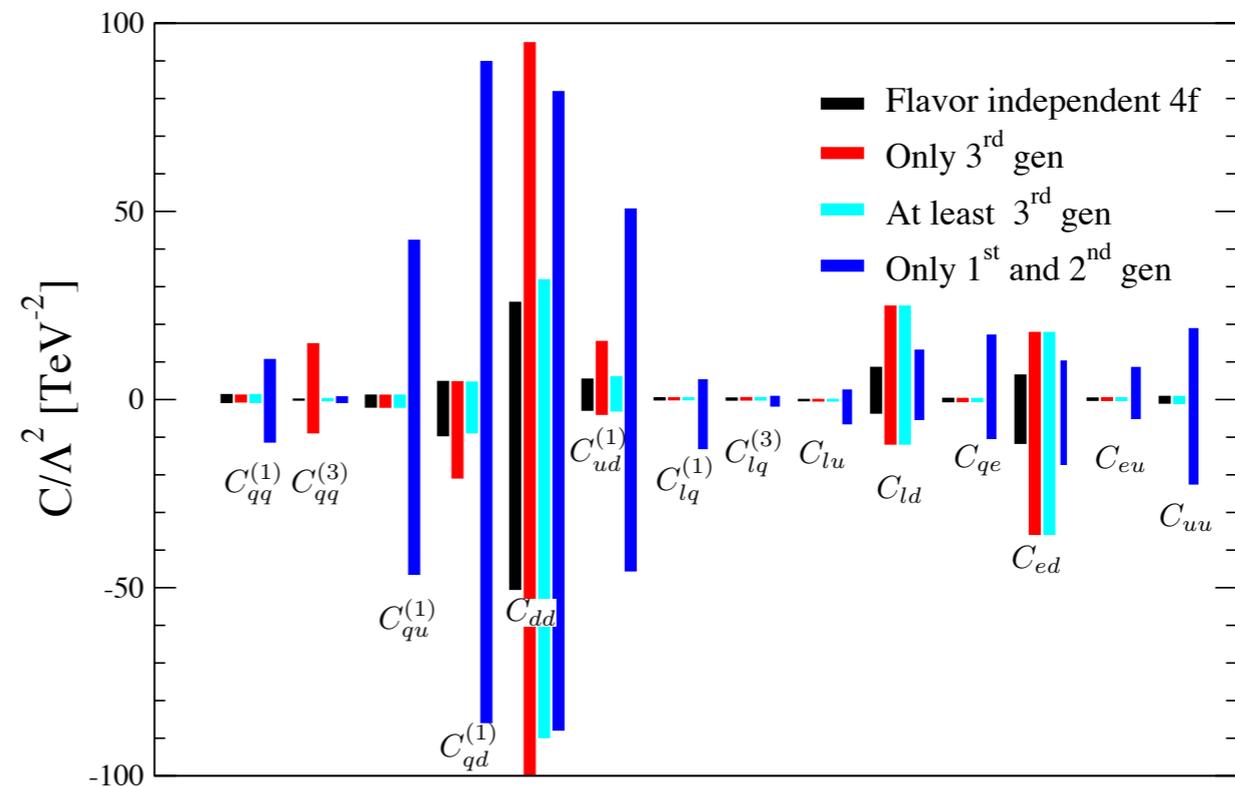
SMEFT@NLO
2008.11743

C. Degrande

Top to precision observables
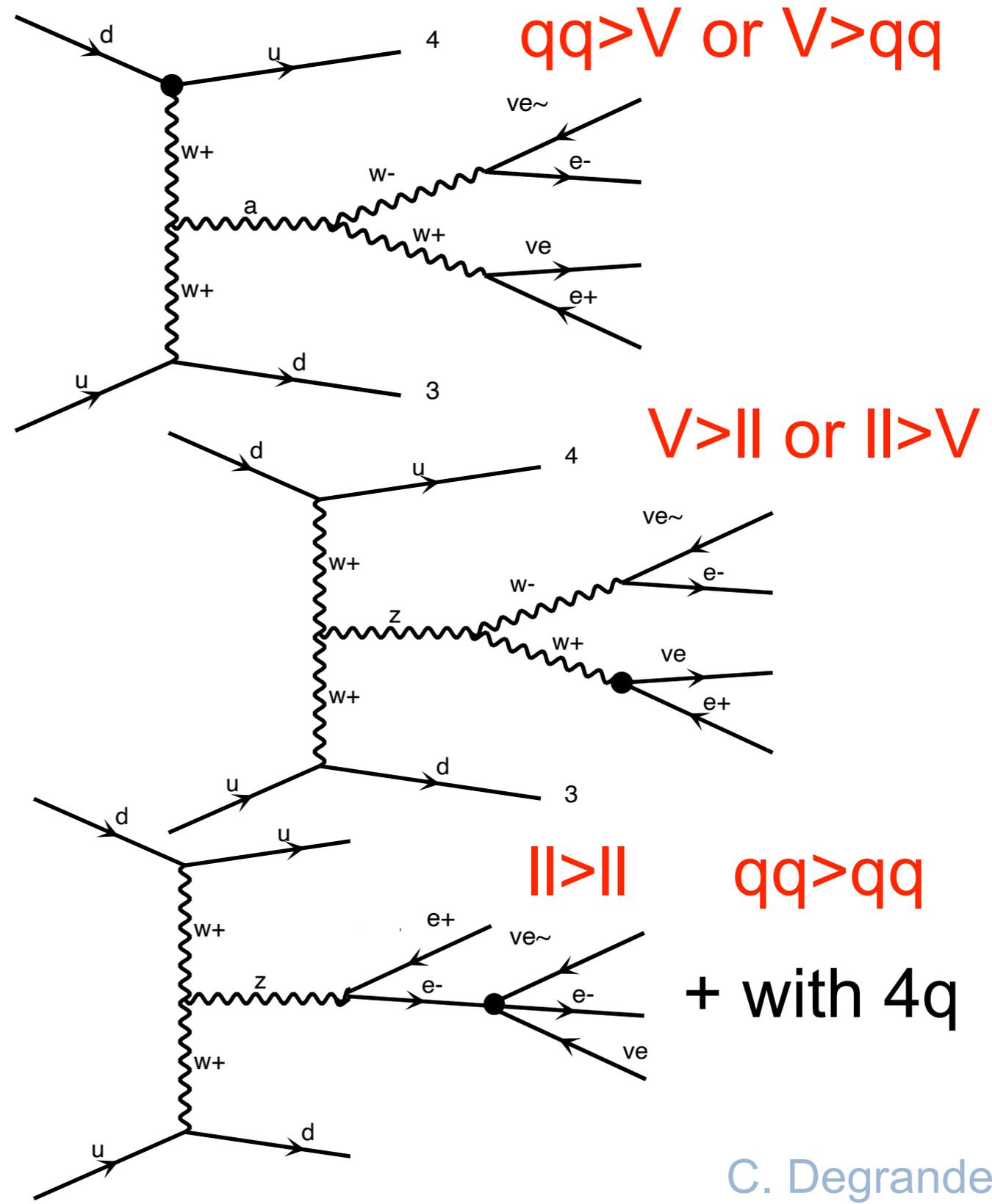
Dawson & Giardino, 2201.09887
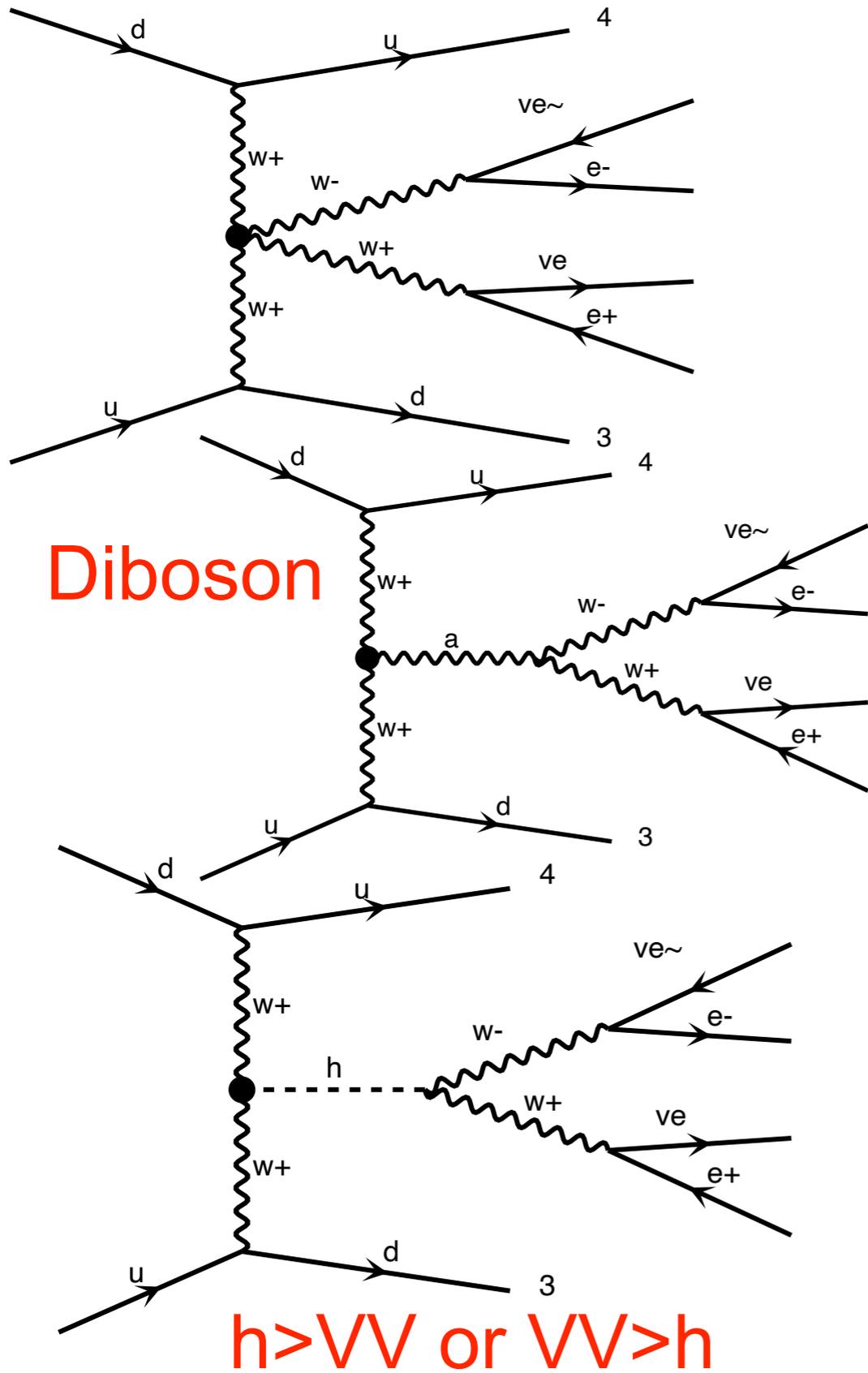
2 top 4F contribution to Z decay
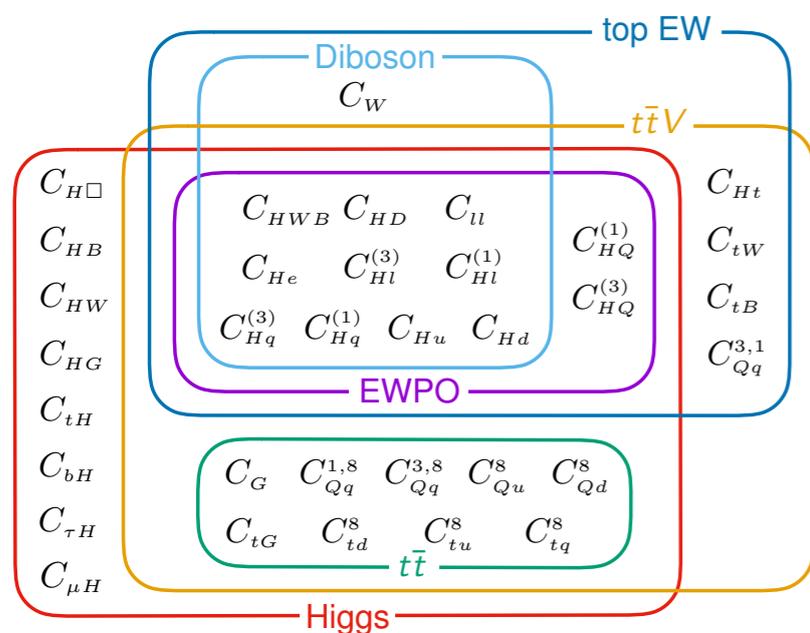

95% CL limits from NLO EWPO on 4-fermion operators

VBS

Operators → / ↓ Processes	Q_{HD}	$Q_{H\Box}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_W	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
SSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
OSWW+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ+2j QCD	✓		✓	✓			✓	✓	✓						(✓)
ZV+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					

Bellan et al., 2108.03199

C. Degrande

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

Top, Higgs and EW fit

Ellis et al.,2012.02779
SMEFiT, 2105.00006
Almeida et al, 2108.04828

C. Degrande

CPV : not so many

(X^3)		$(\psi^2\phi^3)$		$(\psi^2\phi^2 D)$	
$O_{\tilde{G}GG}$	$f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	$O_{t\phi}$	$(\phi^\dagger\phi)(\bar{q}_3 t\tilde{\phi})$	$O_{\phi tb}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{t}\gamma^\mu b)$
$O_{\tilde{W}WW}$	$\epsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$O_{b\phi}$	$(\phi^\dagger\phi)(\bar{q}_3 b\phi)$		
$(X^2\phi^2)$		(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}	$(\bar{q}_3\sigma^{\mu\nu}b)\phi B_{\mu\nu}$

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

$$m_t \neq 0 \neq m_b$$

at the interference level

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

C. Degrande

Flavour assumption
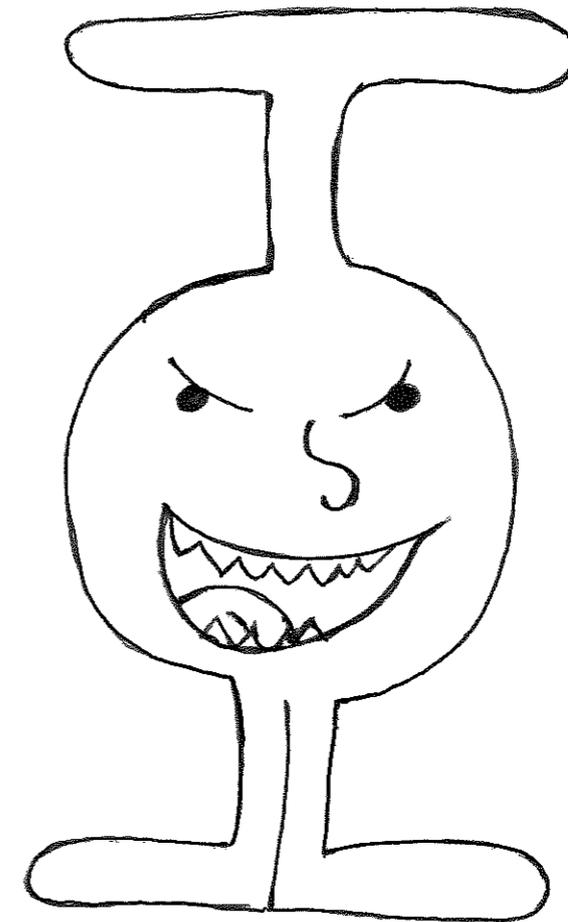
discussed at the LHCEFTWG
see next talk

Final comments

Final comments

- SMEFT is good to parametrise any heavy new physics BUT

- Understand error

    - from EFT : $1/\Lambda$ (dim8, …)

    - α_S, α_{EW}

    - interference

- Global fit

    - correlation

    - EFT in backgrounds

    - with SM parameters fit
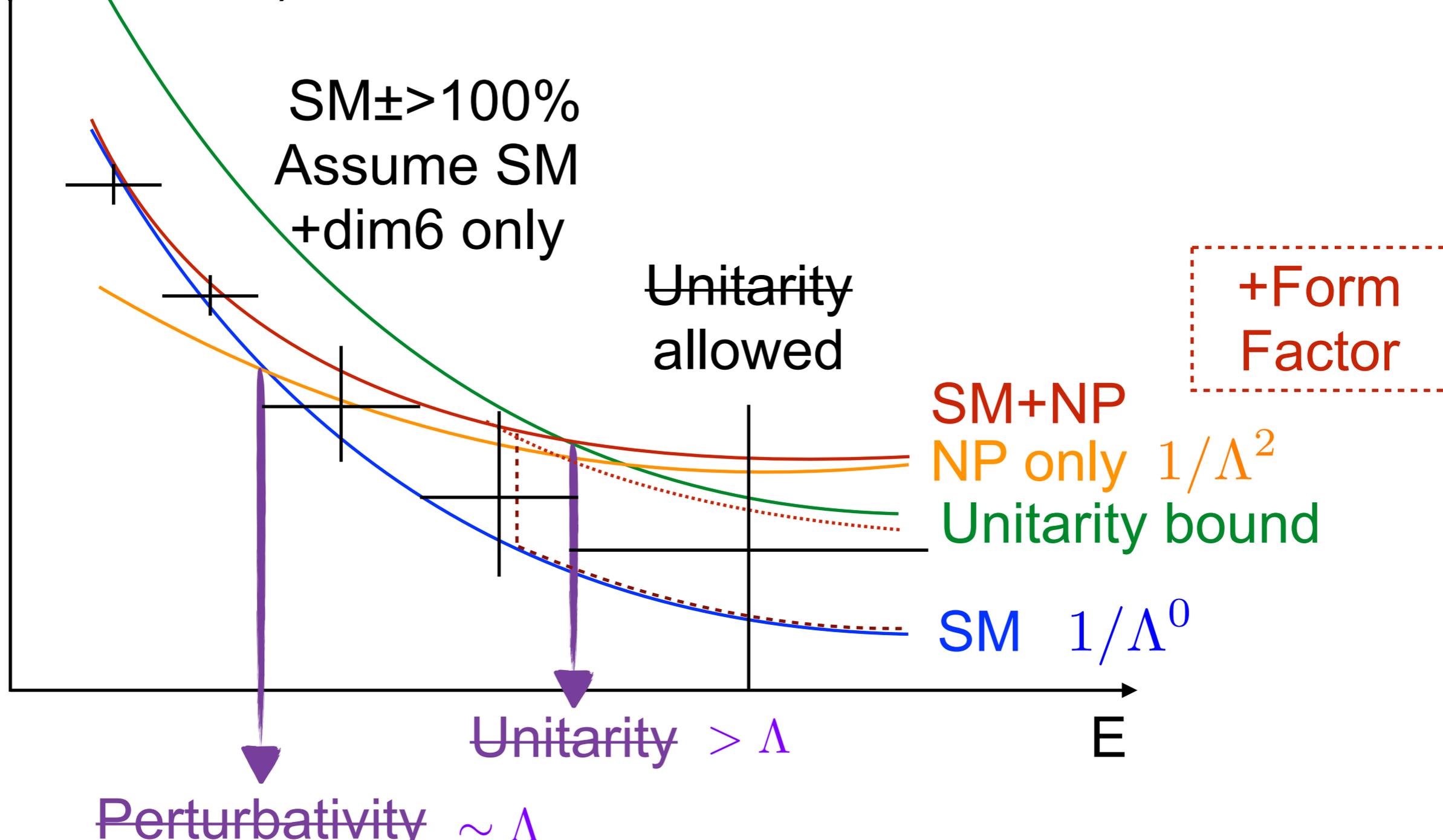
    - with PDF4EFT fit

    - +…?

C. Degrande

Back up

EFT & scales

Precise : EFT
(model ind.)

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?

SM±>100%
Assume SM
+dim6 only

~~Unitarity~~
allowed

+Form
Factor

SM+NP

NP only $1/\Lambda^2$

Unitarity bound

SM $1/\Lambda^0$

E

~~Unitarity~~ $> \Lambda$

~~Perturbativity~~ $\sim \Lambda$

C. Degrande

Precision era at the LHC

Multiplicity, power of α_{EW}, masses

Standard Model Production Cross Section Measurements
Status: July 2018

ATLAS Preliminary

Run 1,2 $\sqrt{s}$ = 7,8,13 TeV