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

Efficiently probing the SMEFT interference

Celine Degrande

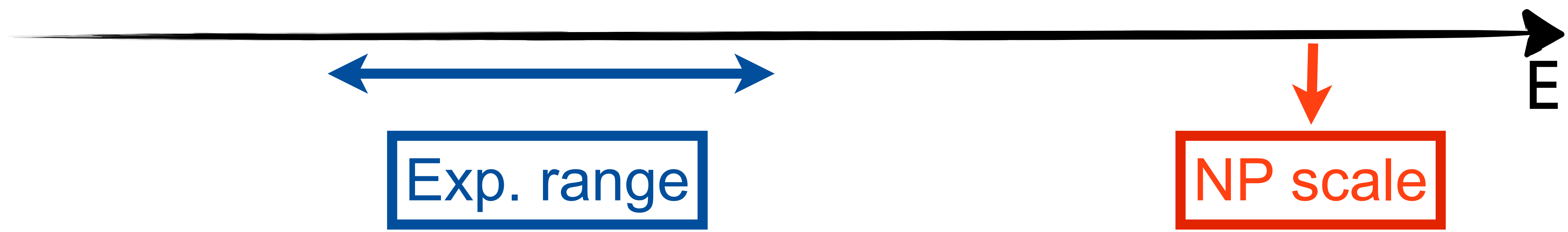
Plan

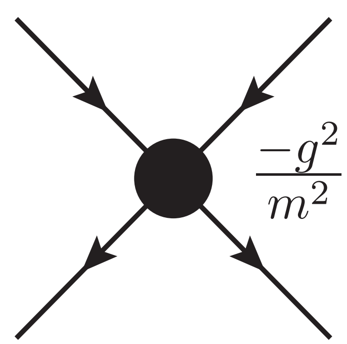
- Introduction to SMEFT
- SMEFT requires understanding the interference
- Interference resurrection
  - gluon operator
  - CPV in EW diboson
- Keeping uncertainties under control
- Final comments

Introduction to SMEFT

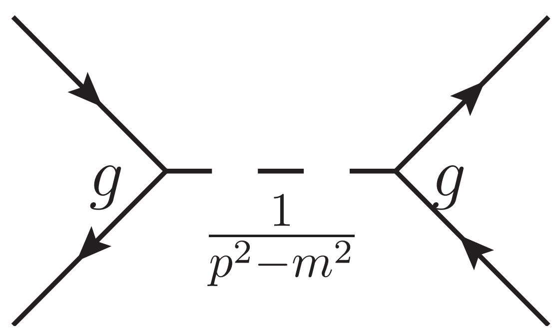
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments



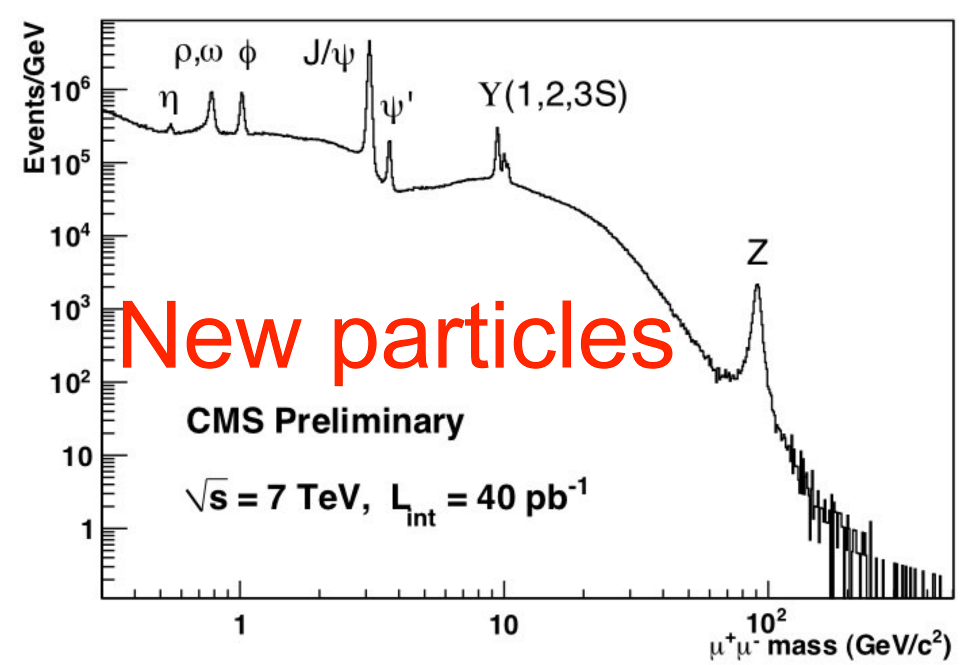


$$p^2 \ll m^2$$



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

New/modified interactions
between SM particles



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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

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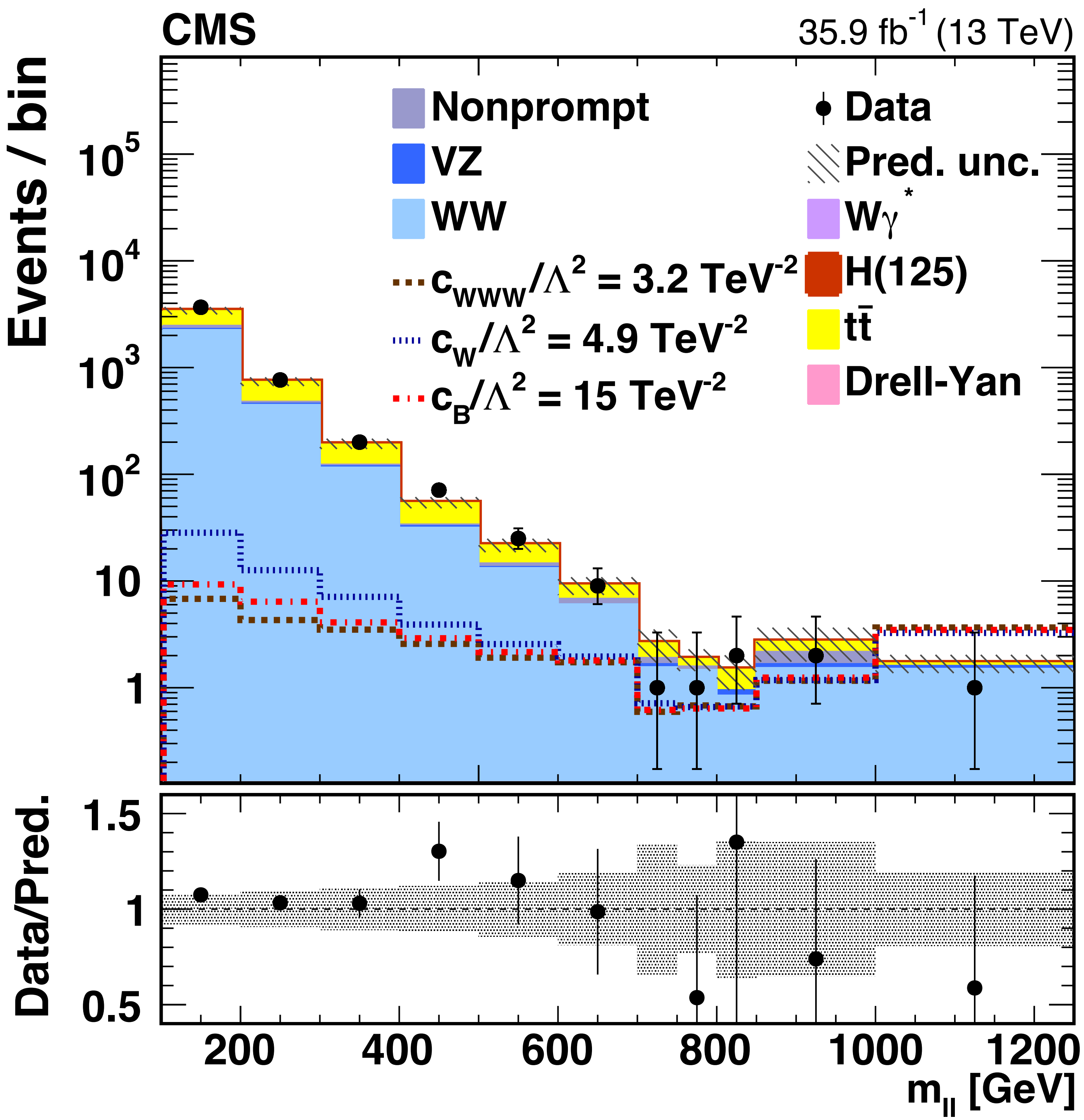
High energy tails



2009.00119

Cross-sections and precision plummet at high energy

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

SMEFT requires understanding the interference

Errors : higher power of $1/\Lambda$

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

- 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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Errors : higher power of $1/\Lambda$

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

$\mathcal{O}(1)$	$\mathcal{O}(0.1)$	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

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

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

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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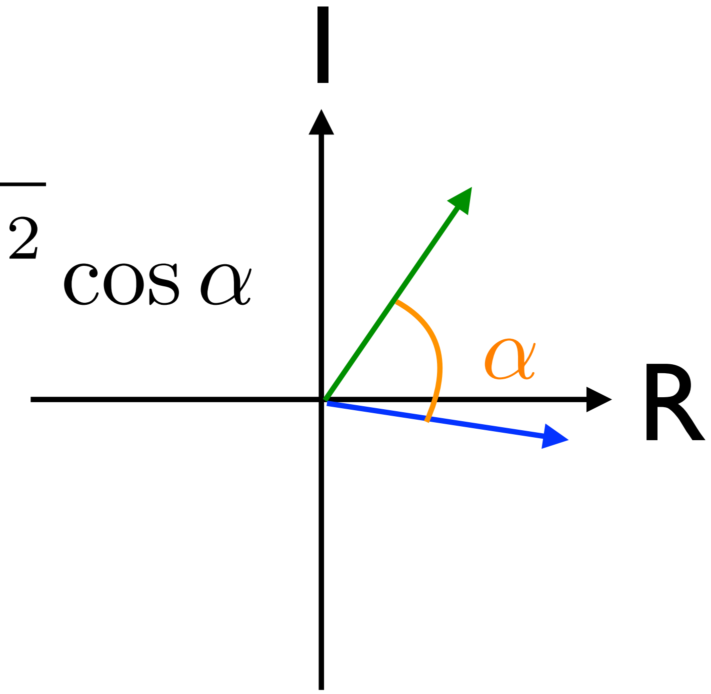
Interference

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

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



mom&spin

Not always positive

Can be suppressed

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

Observable dependent

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Interference

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

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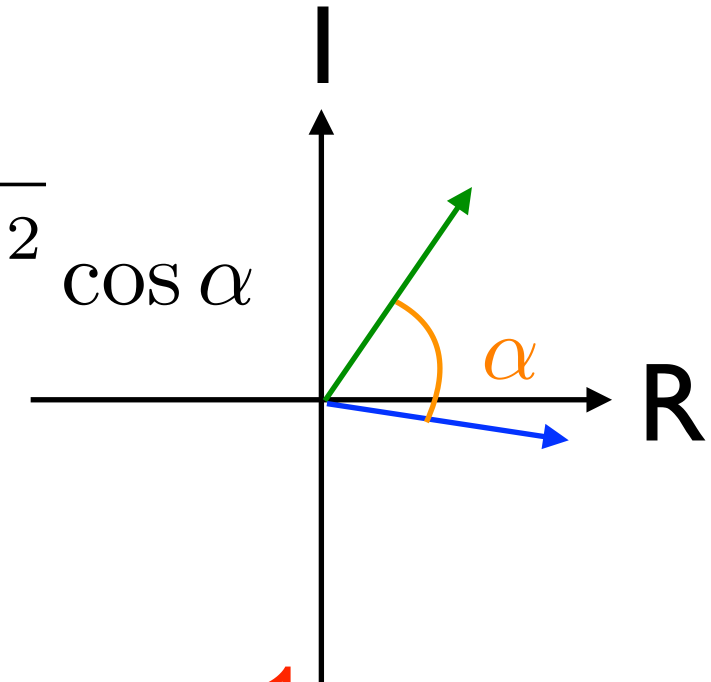

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Interference

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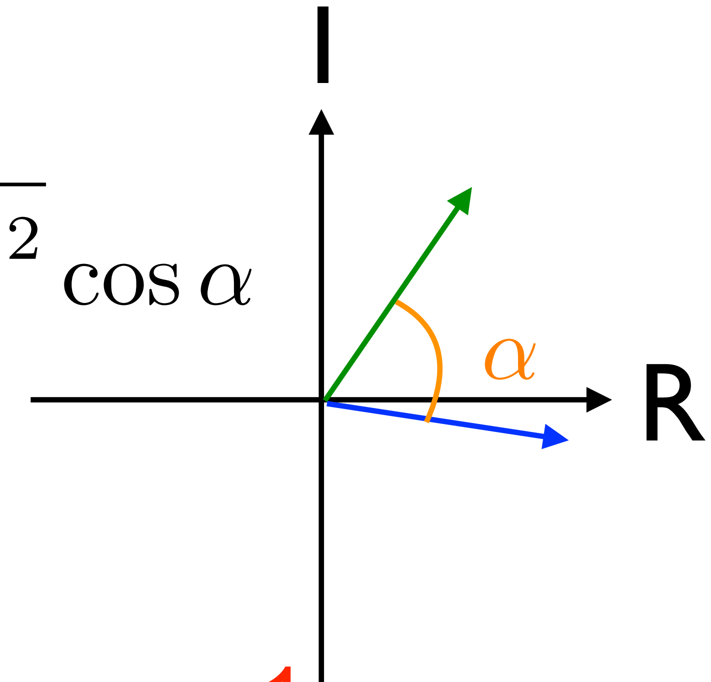

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Observable dependent

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

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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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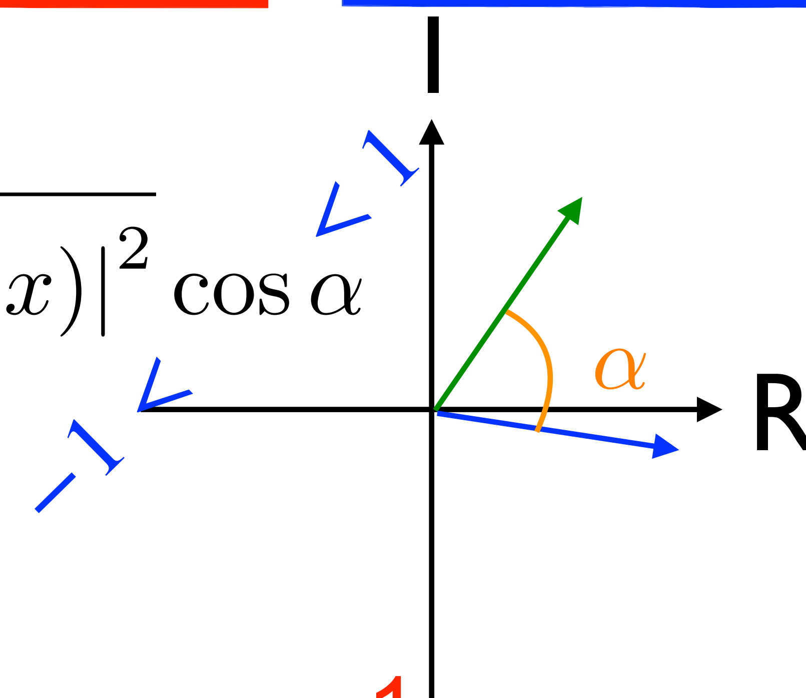

mom&spin

Not always positive

Can be suppressed

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Observable dependent

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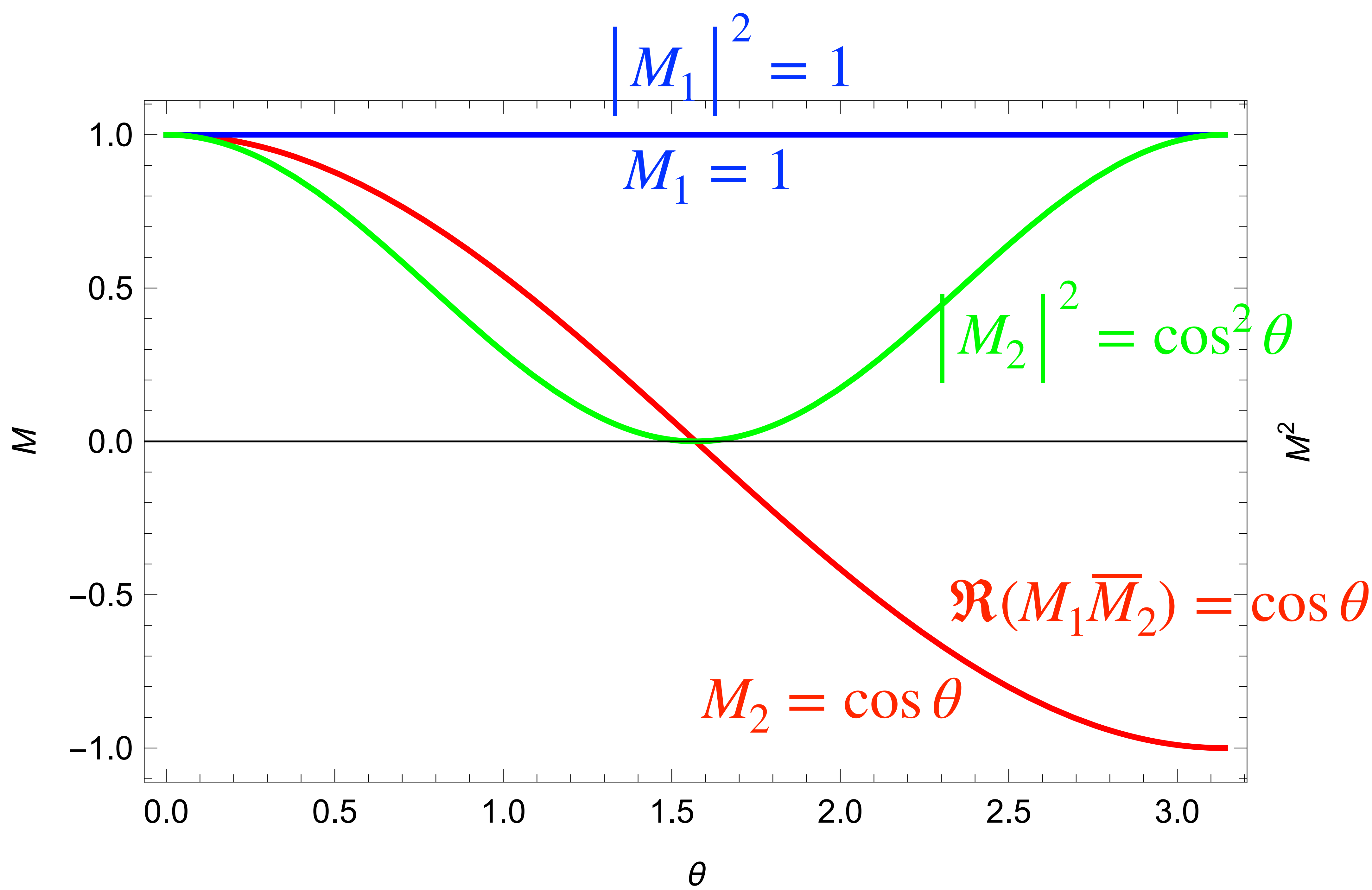
Interference suppression from phase space



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

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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

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

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

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: $\sigma_{int}(\mu_L) = -\sigma_{int}(\mu_R)$

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

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

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

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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%
$t\bar{t}j$	$5.20\cdot10^{-1}$	62%	$1.13\cdot10^{-1}$	60%	$1.37\cdot10^{-3}$	62%
jjj	$2.98\cdot10^{1}$	52%	$5.90\cdot10^{-1}$	52%	$4.91\cdot10^{-4}$	61%
$jjjj$	$-2.89\cdot10^{1}$	45%	$-2.50\cdot10^{-1}$	44%	$-4.12\cdot10^{-6}$	39%

Large SM x-sect
& int. cancellation

Part of the phase space with positive interference

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Triple gluon operator

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

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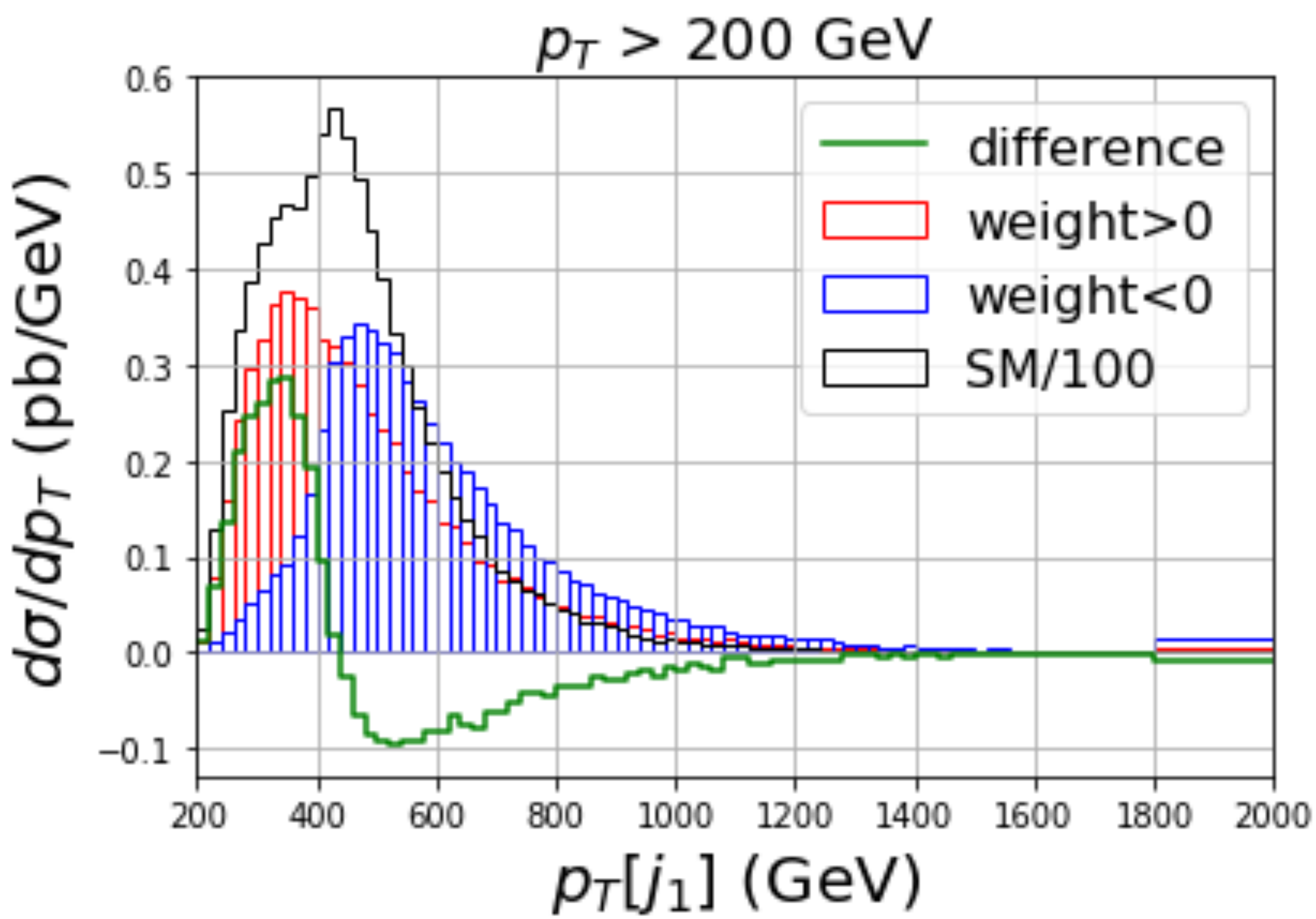
Transverse momentum

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



~40% efficiency

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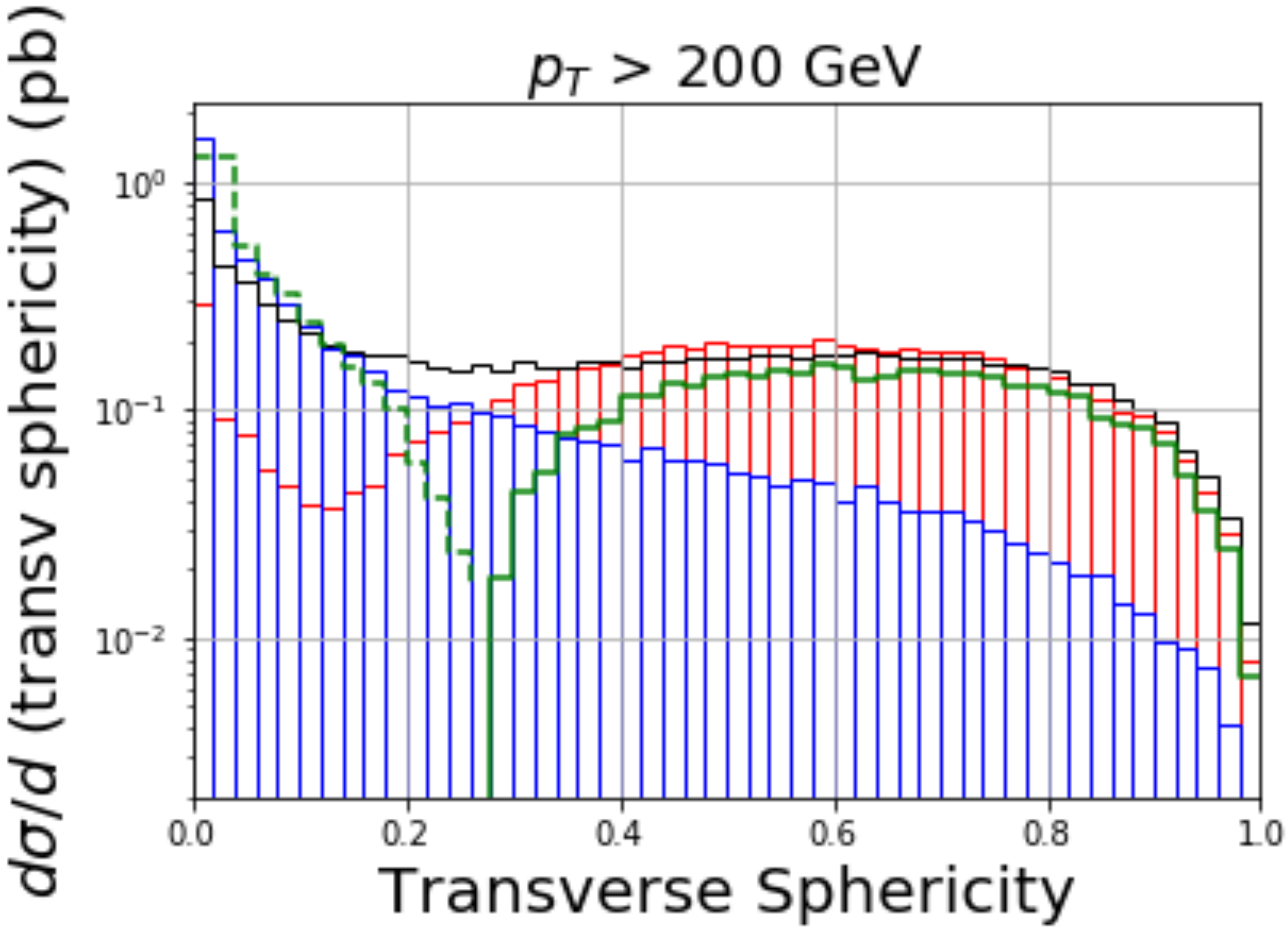
Transverse sphericity

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

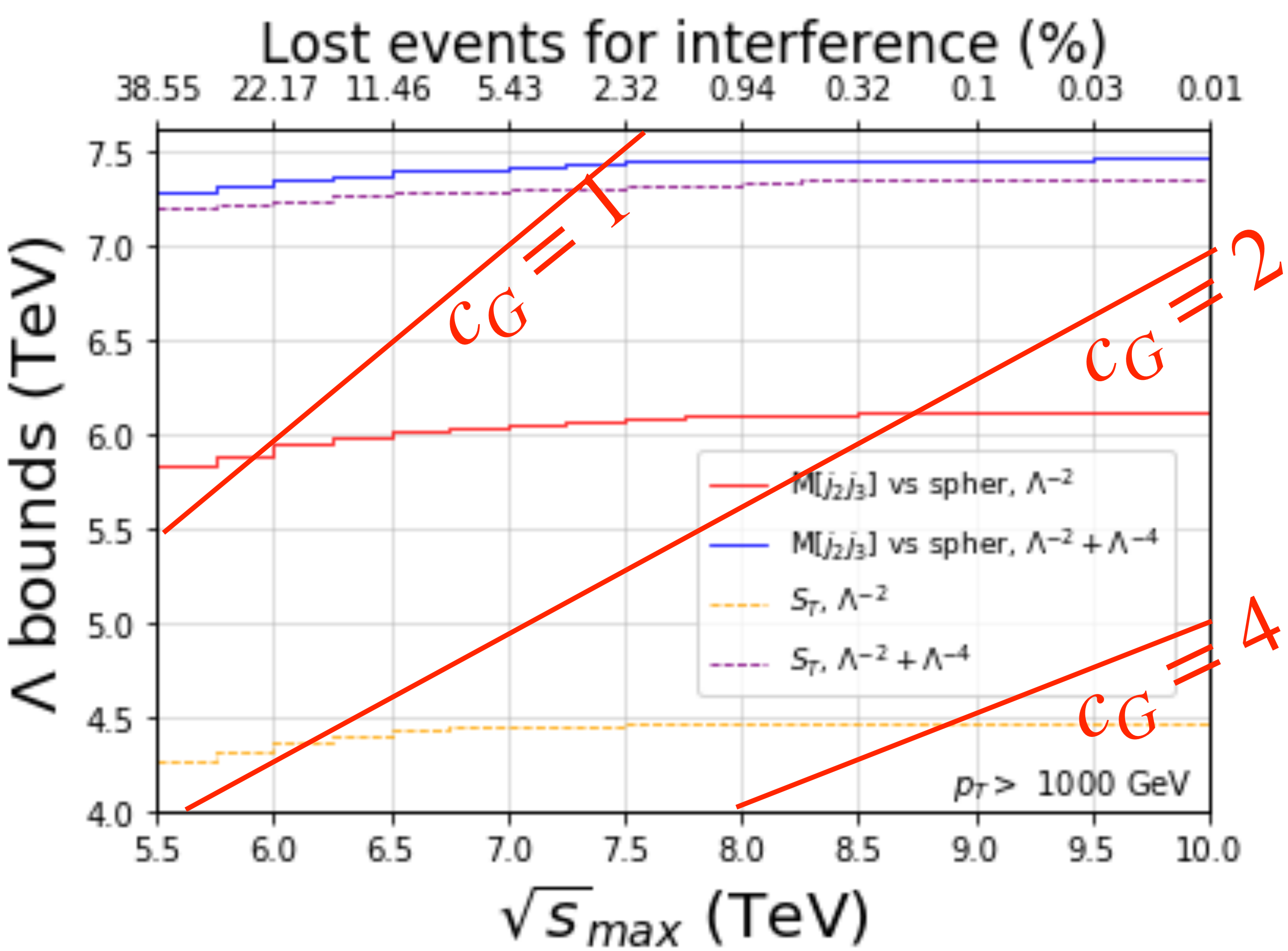


~80% efficiency

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	$M[j_2j_3]$ vs Sph_T	0.31	21	$5.5\cdot10^{-2}$ $(5.3\cdot10^{-2})$	$-5.5\cdot10^{-2}$ $(-3.5\cdot10^{-2})$
1000	$M[j_2j_3]$ 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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Better sensitivity

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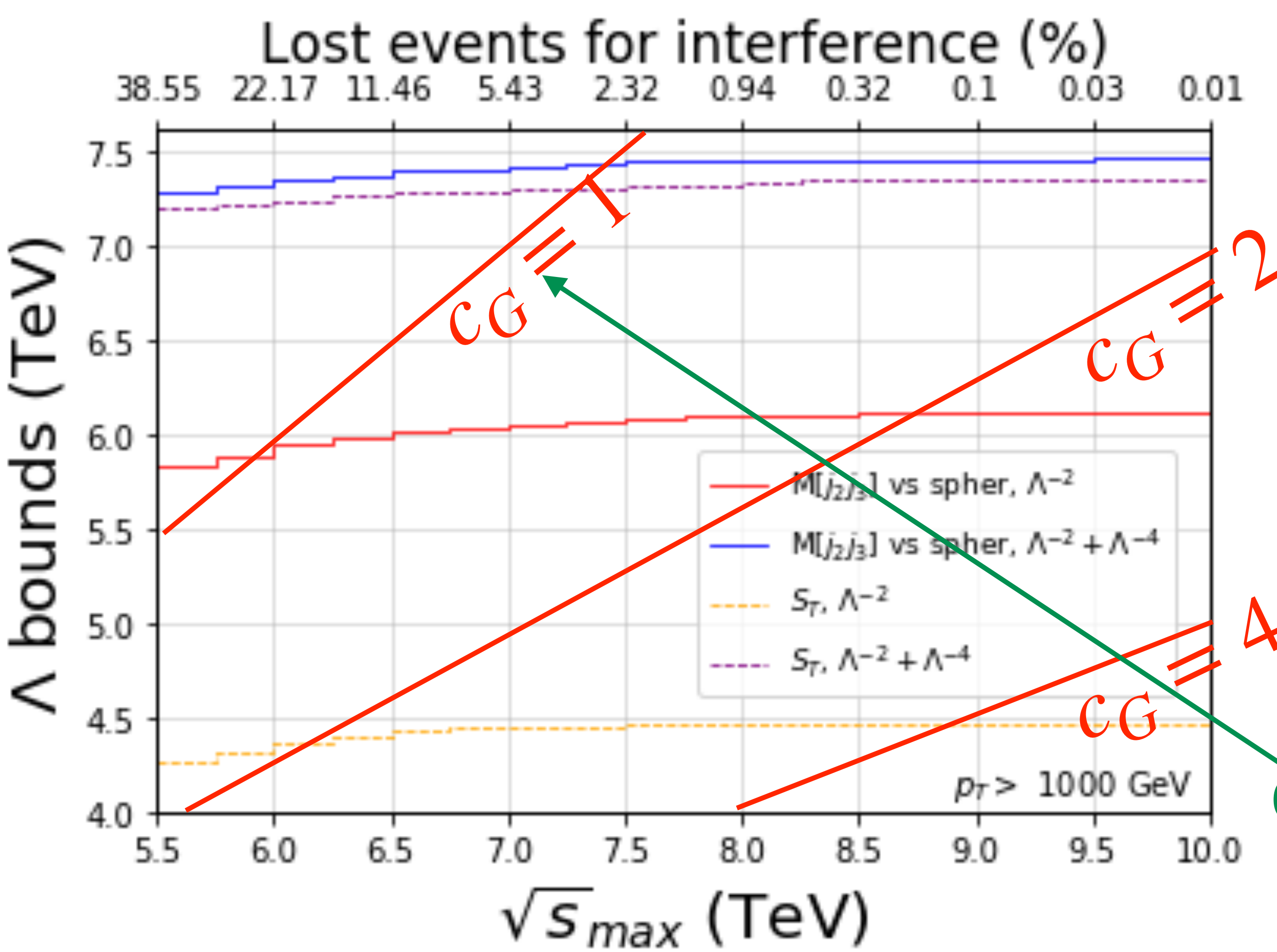

Bounds dominated by the interference

EFT validity & error:

(3TeV/6TeV)^2~0.25

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

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CPV in EWdiboson

CPV

neglecting CKM phase

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

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

Only visible in distributions

CPV

neglecting CKM phase

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

Int $0 \neq O^{CP-odd} = 0$ SM/dim6²

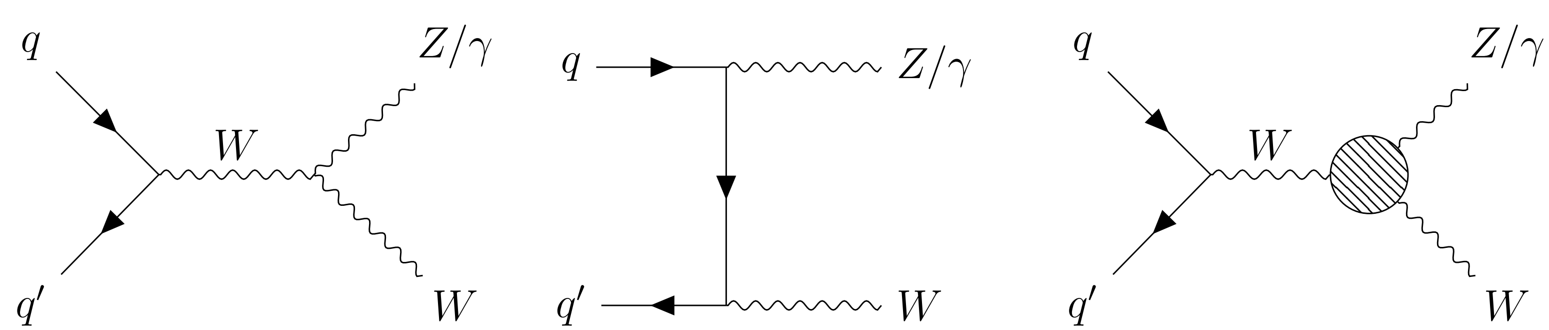
Only visible in distributions

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



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

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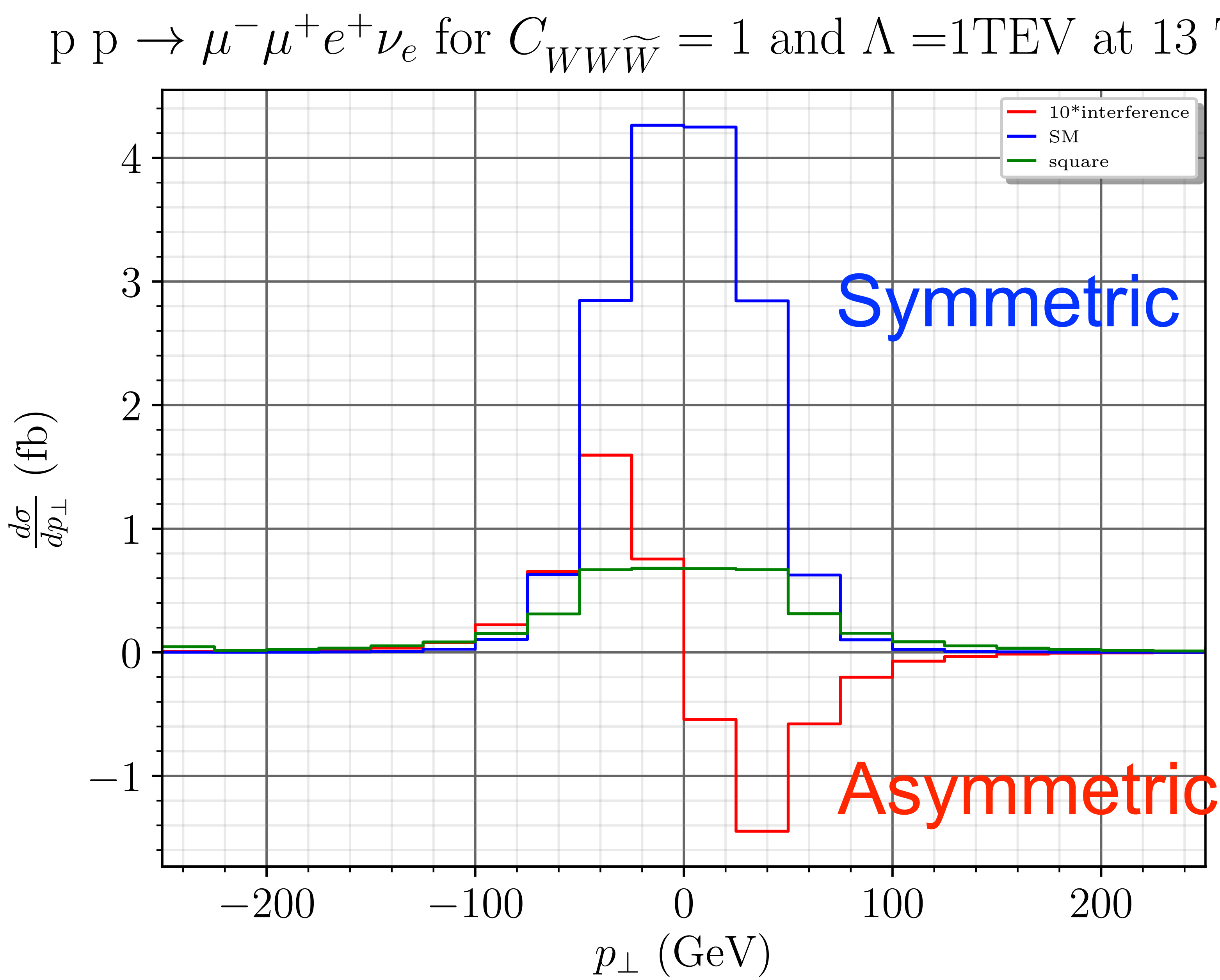
Towards asymmetries

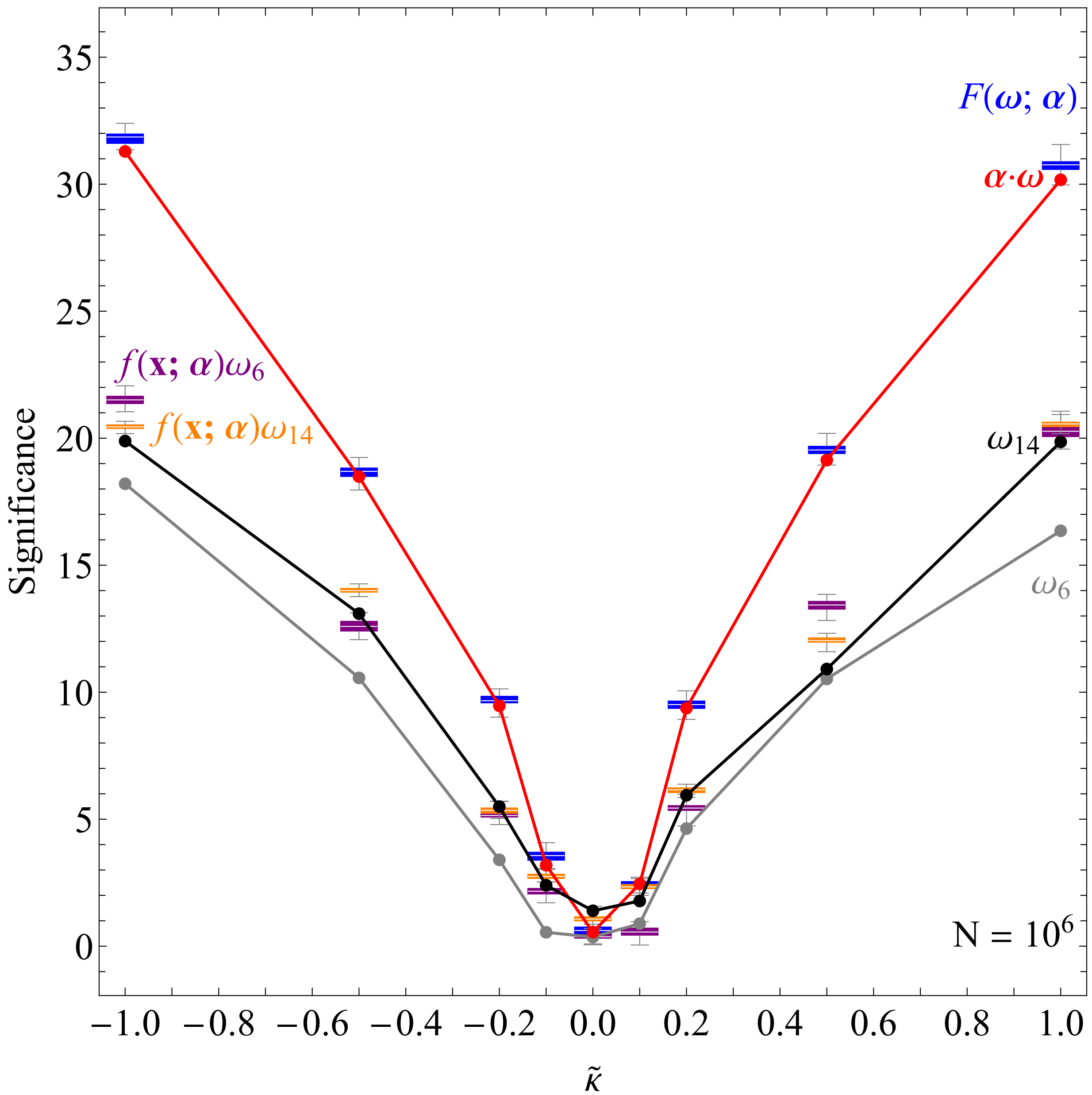


$$\vec{p}_e \cdot \frac{(\vec{p}_q \times \vec{p}_Z)}{\left|(\vec{p}_q \times \vec{p}_Z)\right|}$$

See J. Toucheque's talk this afternoon

Observables vs ML trained on model

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



Neural network

Linear combination

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

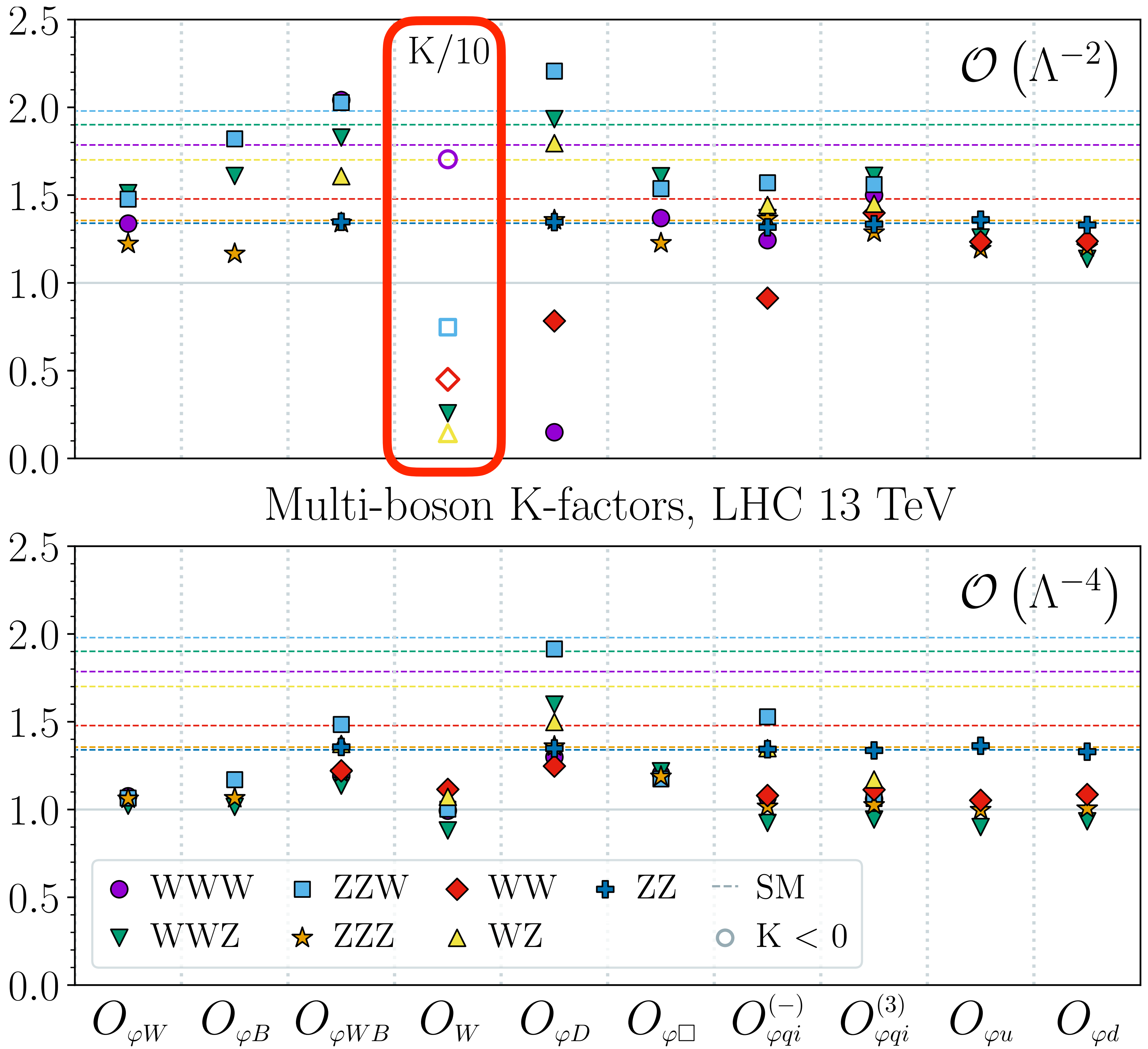
$$\omega_6 \sim [(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]$$

Keeping uncertainties under control

EW bosons production

Large negative K-factors

Converge?



SMEFT@NLO
2008.11743

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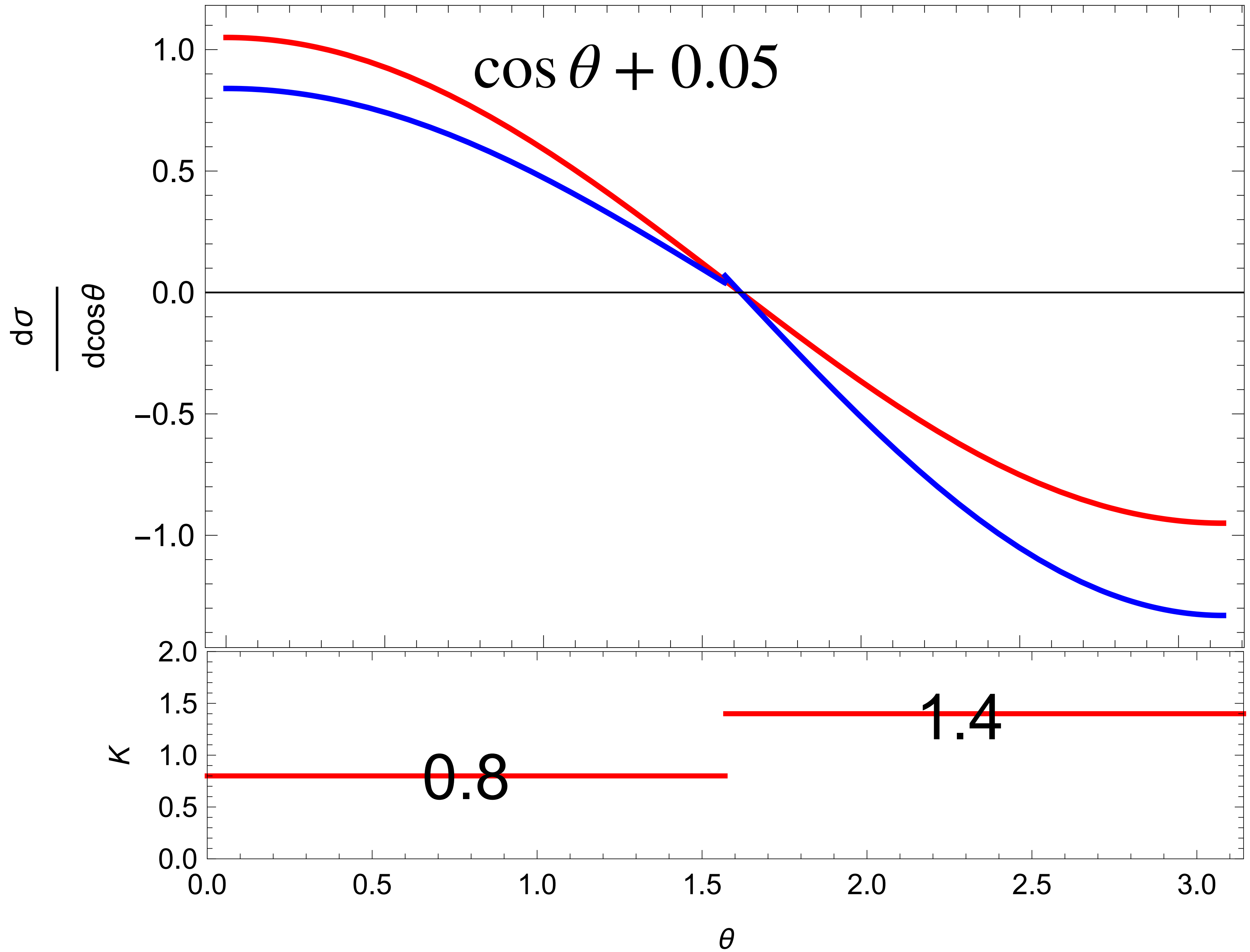
Large/small K-factor



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

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

$$K_\sigma \approx -3$$

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)

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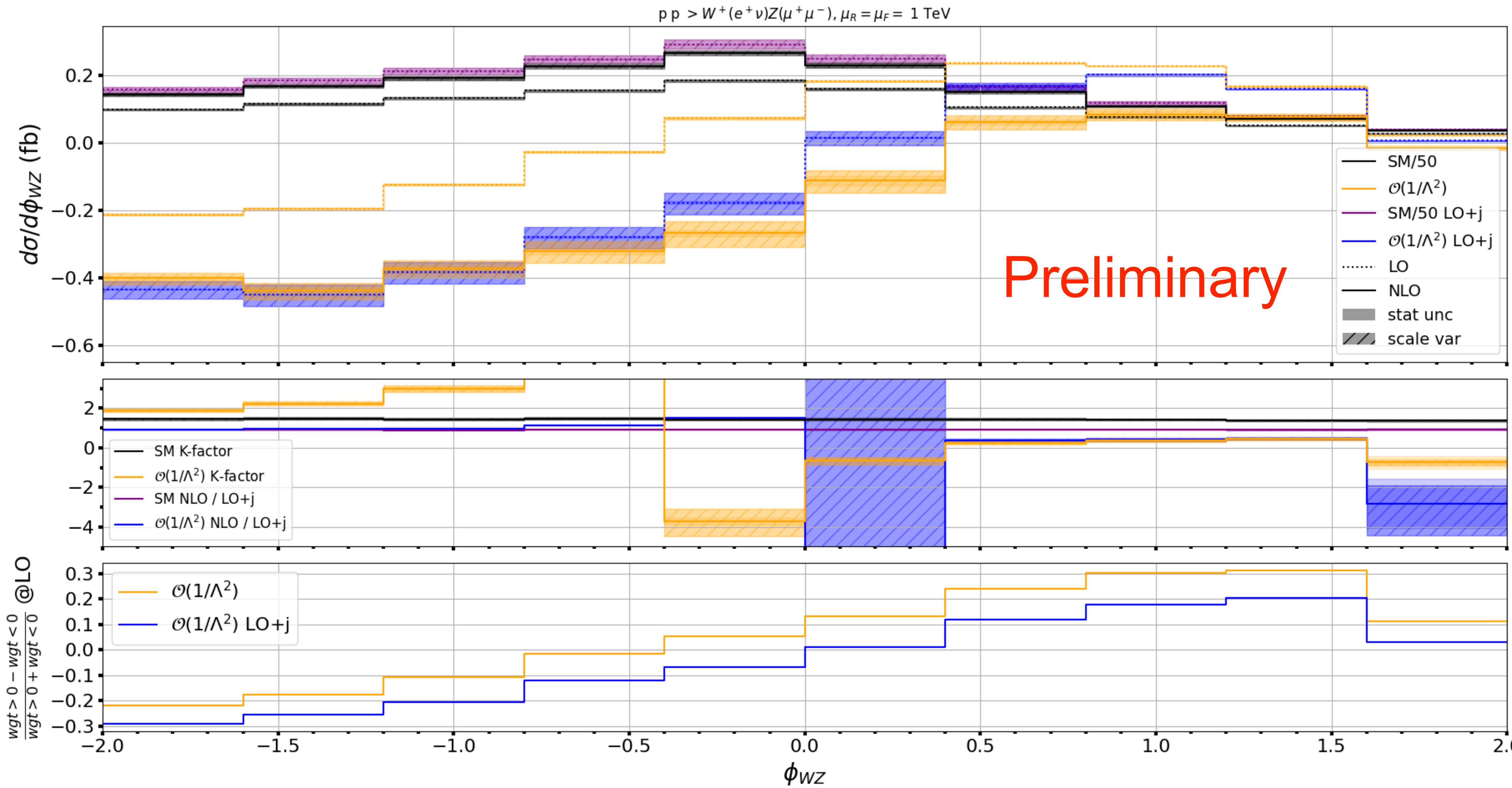
Owww



with M. Maltoni

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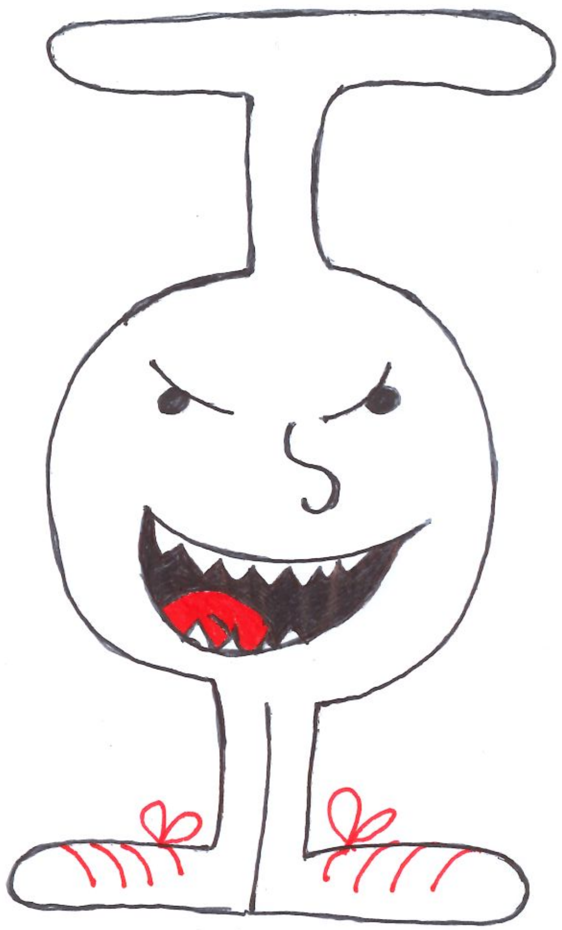
Final comments

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



C. Degrande