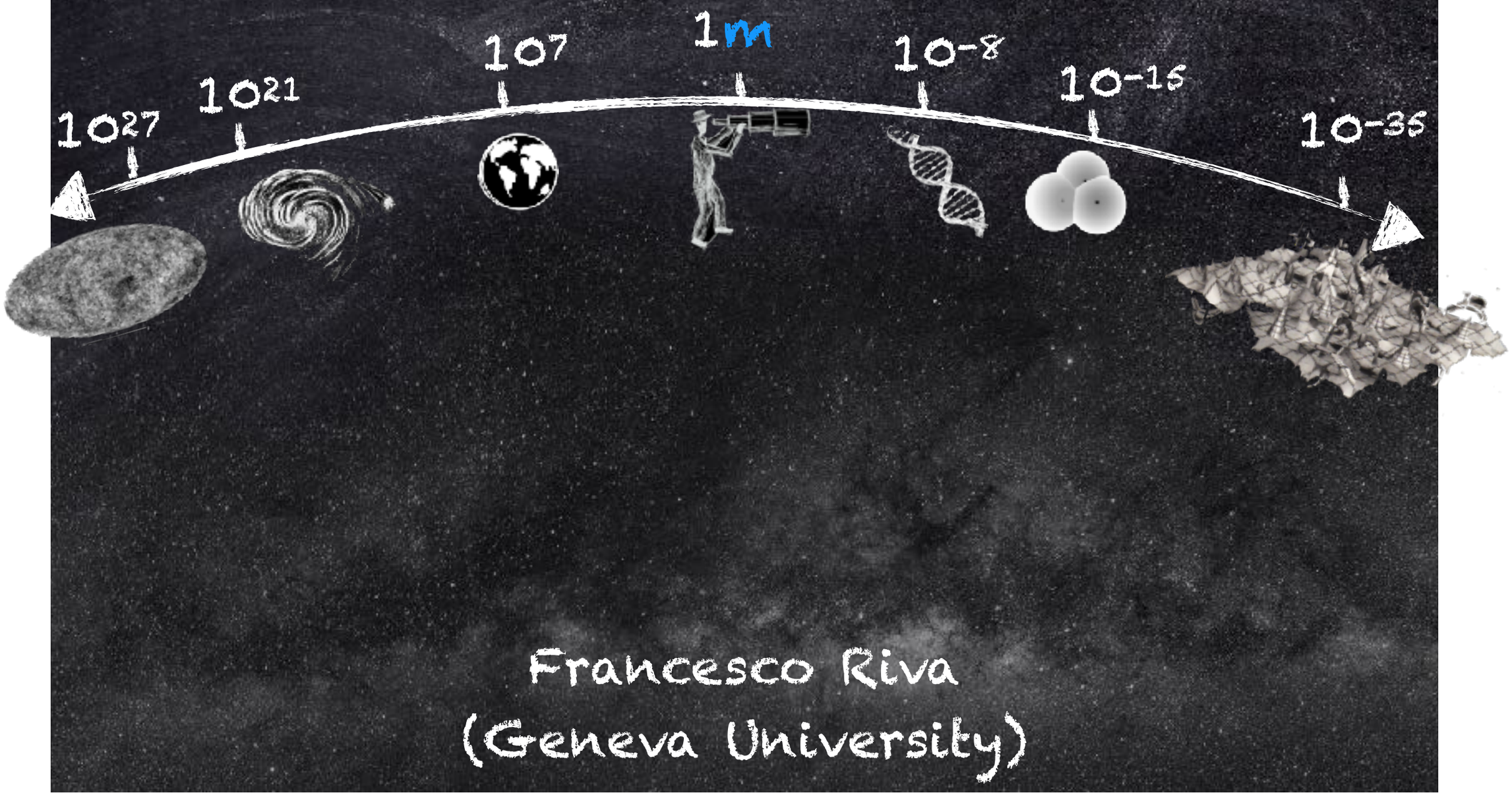
Priorities for EFTs at Colliders



Francesco Riva
(Geneva University)

SM ≠ BSM

LHC Future:

SM Precision Tests
(tailored to SM)

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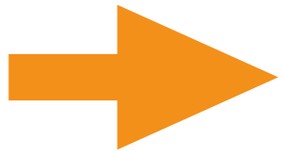

BSM Precision Searches
(tailored to BSM)

SM ≠ BSM

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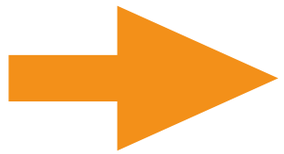


BSM Precision Searches
(tailored to BSM)

EFT provides a catalogue
of the most relevant targets

- Priority: optimal analyses for individual operators
  Ultimate target: global fit

SM ≠ BSM

1. SM–BSM Non-Interference

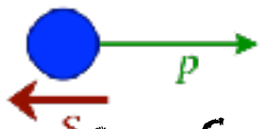
(and what measurements resurrect it)

Non-Interference

Azatov,Contino,Machado,FR'16

(2->2,high-E,tree-level)

For $E \gg m_W$ states have well defined helicity



Amplitudes for 2->2 with different total h don't interfere

SM

Any BSM dim-6 operator

helicity

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

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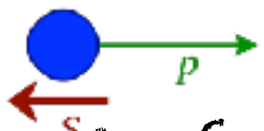

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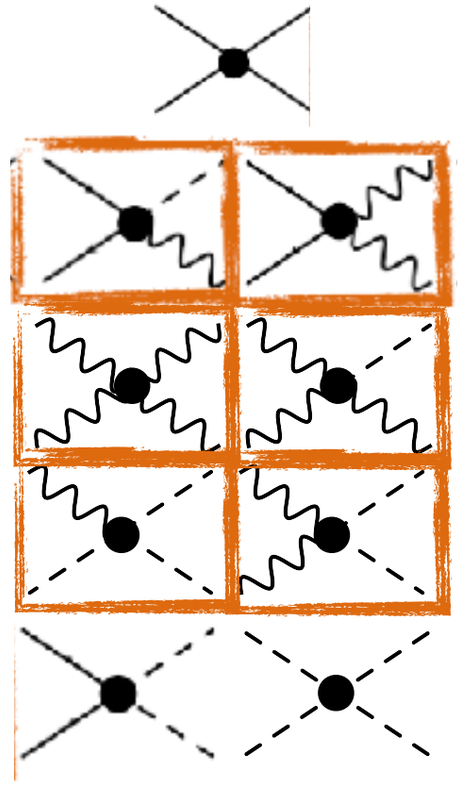
Different helicity

No-Interference

Poor reach in an inclusive (SM-targeted) measurement



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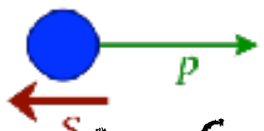

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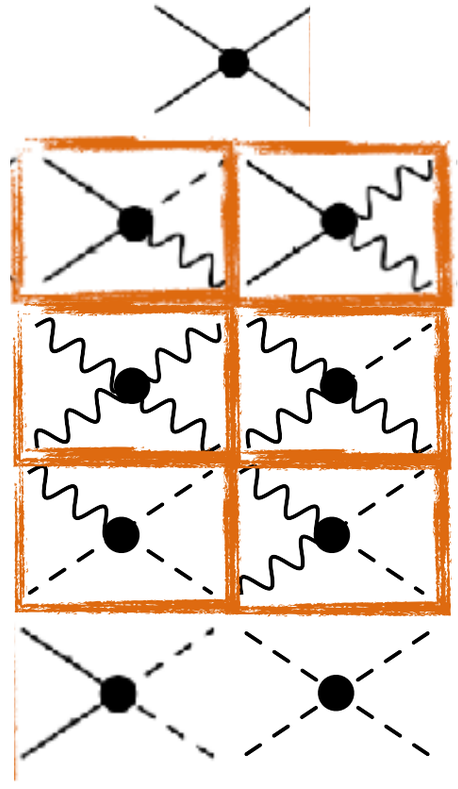
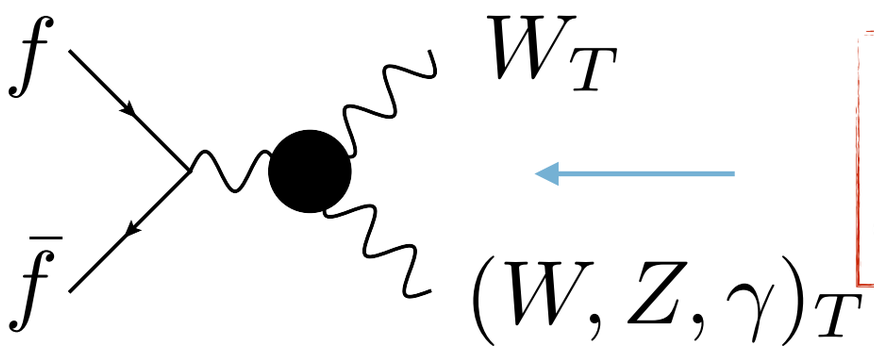


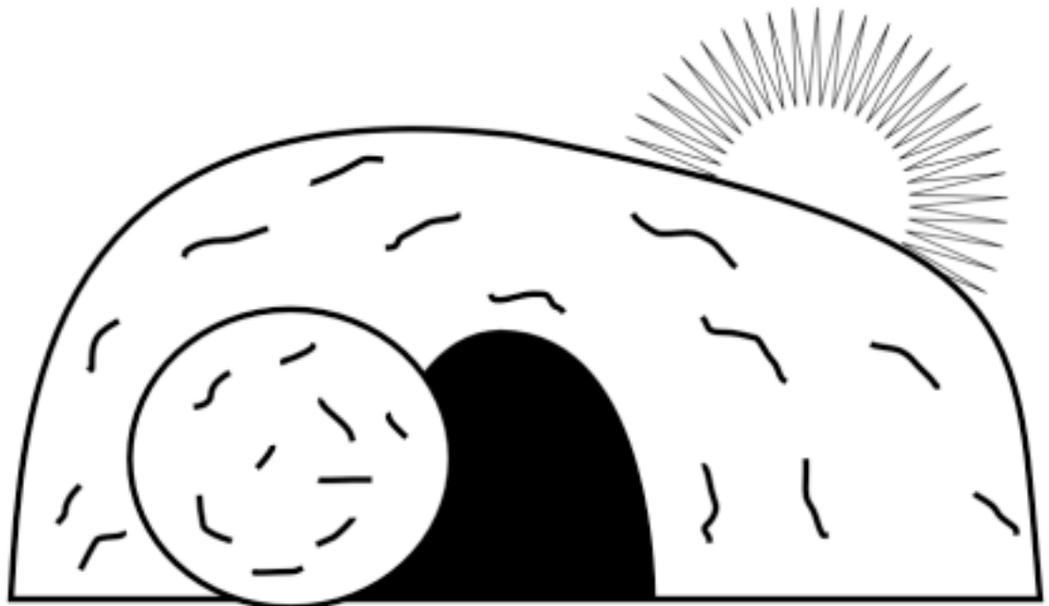
Interference Resurrection

Focus on dibosons, with these operators that do not interfere with the SM



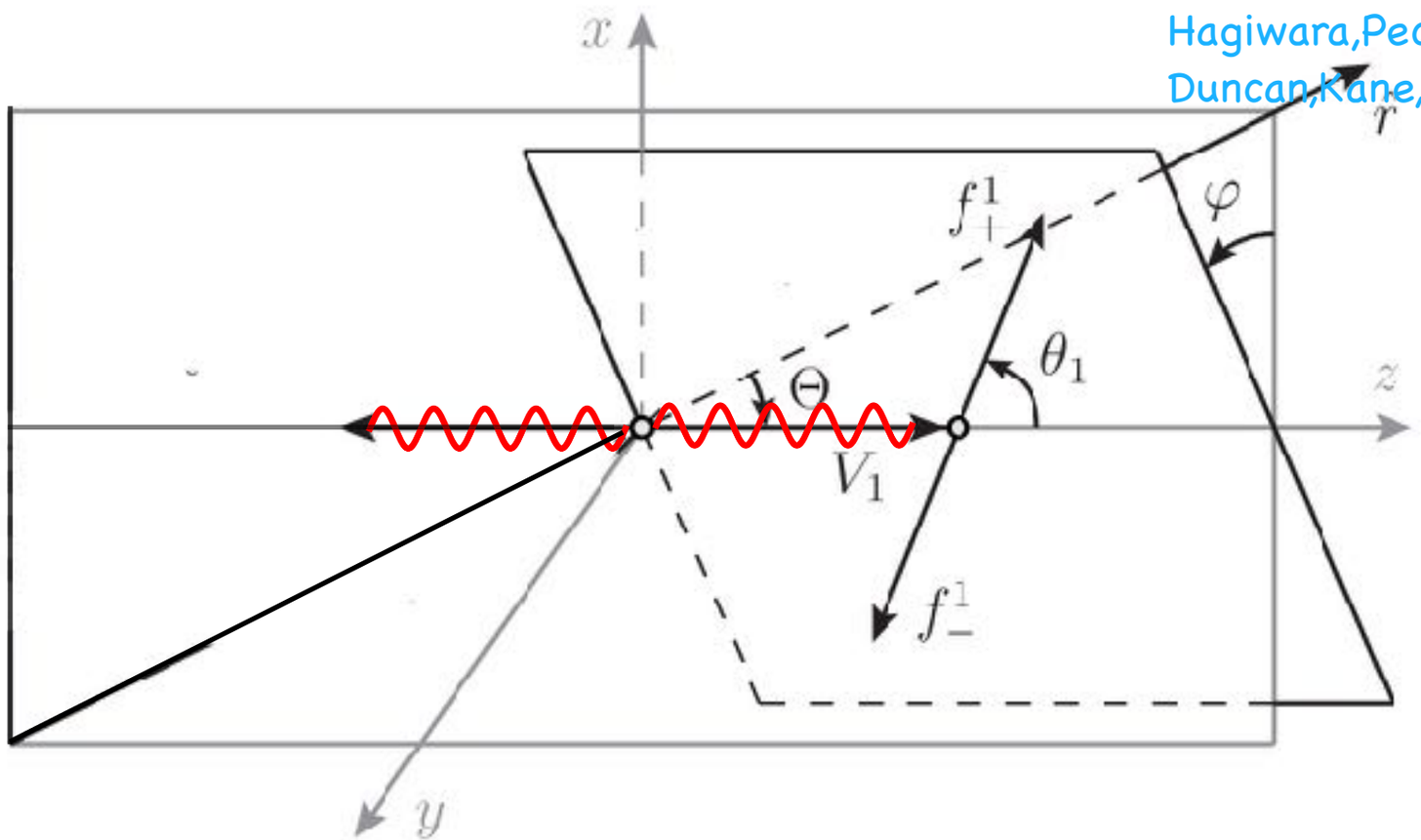
$$\epsilon_{abc} W_\mu^{a\,\nu} W_{\nu\rho}^{b} W^{c\,\rho\mu}$$ CP-even

$$\epsilon_{abc} W_\mu^{a\,\nu} W_{\nu\rho}^{b} \widetilde{W}^{c\,\rho\mu}$$ CP-odd



Differential measurements WY

Panico,FR,Wulzer'17,
Hagiwara,Peccei,Zeppenfeld,Hikasa'86
Duncan,Kane,Repko'86



SPin-1: Helicity ±∓/±± in SM/BSM

- Quantum mechanically different, no interference

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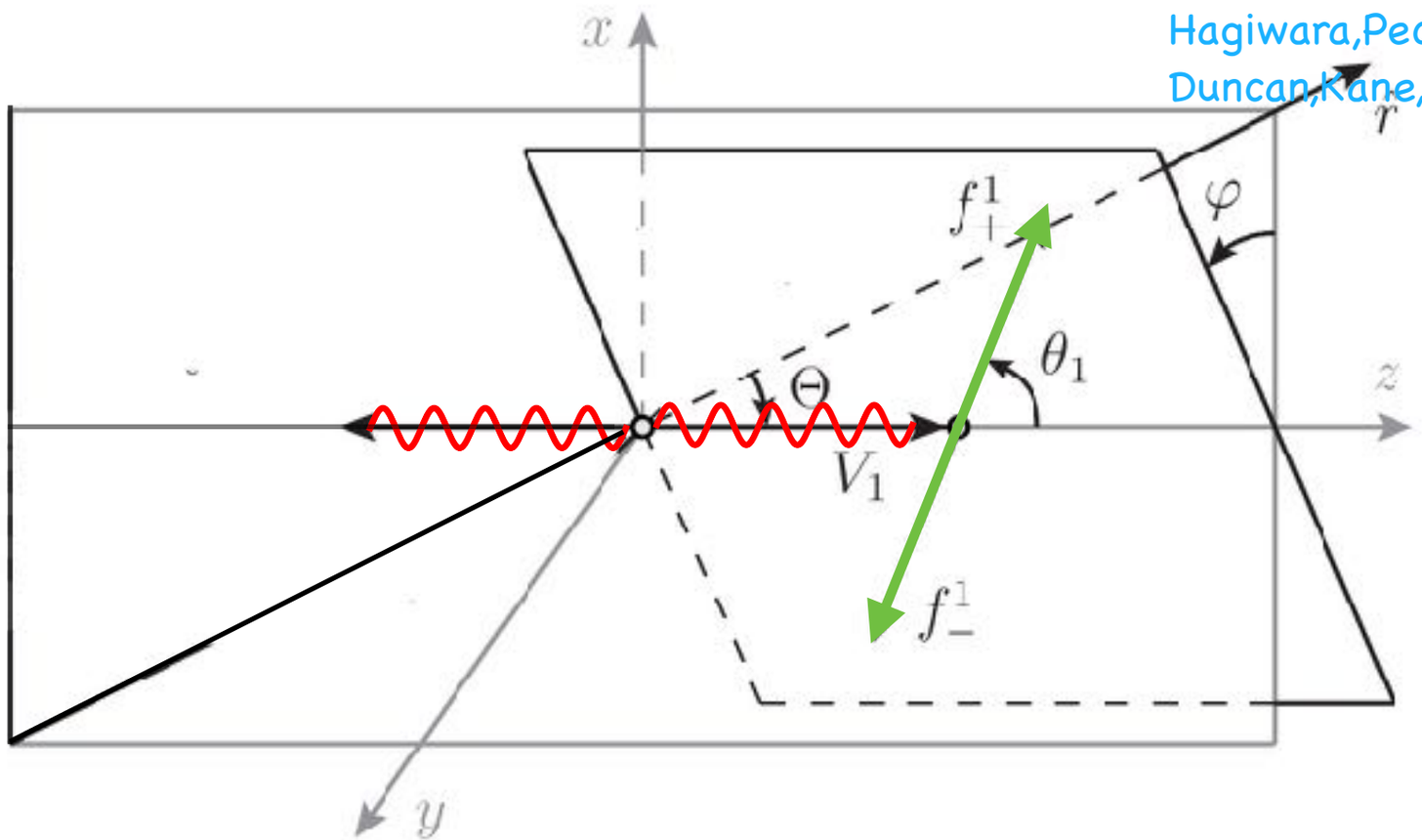

SPin-1: Helicity ±∓/±± in SM/BSM

- Quantum mechanically different, no interference

Decays into spin-1/2: Helicity +1/2 -1/2 in SM and in BSM

- QM same, interference possible

Differential measurements Wγ

Panico,FR,Wulzer'17,
Hagiwara,Peccei,Zeppenfeld,Hikasa'86
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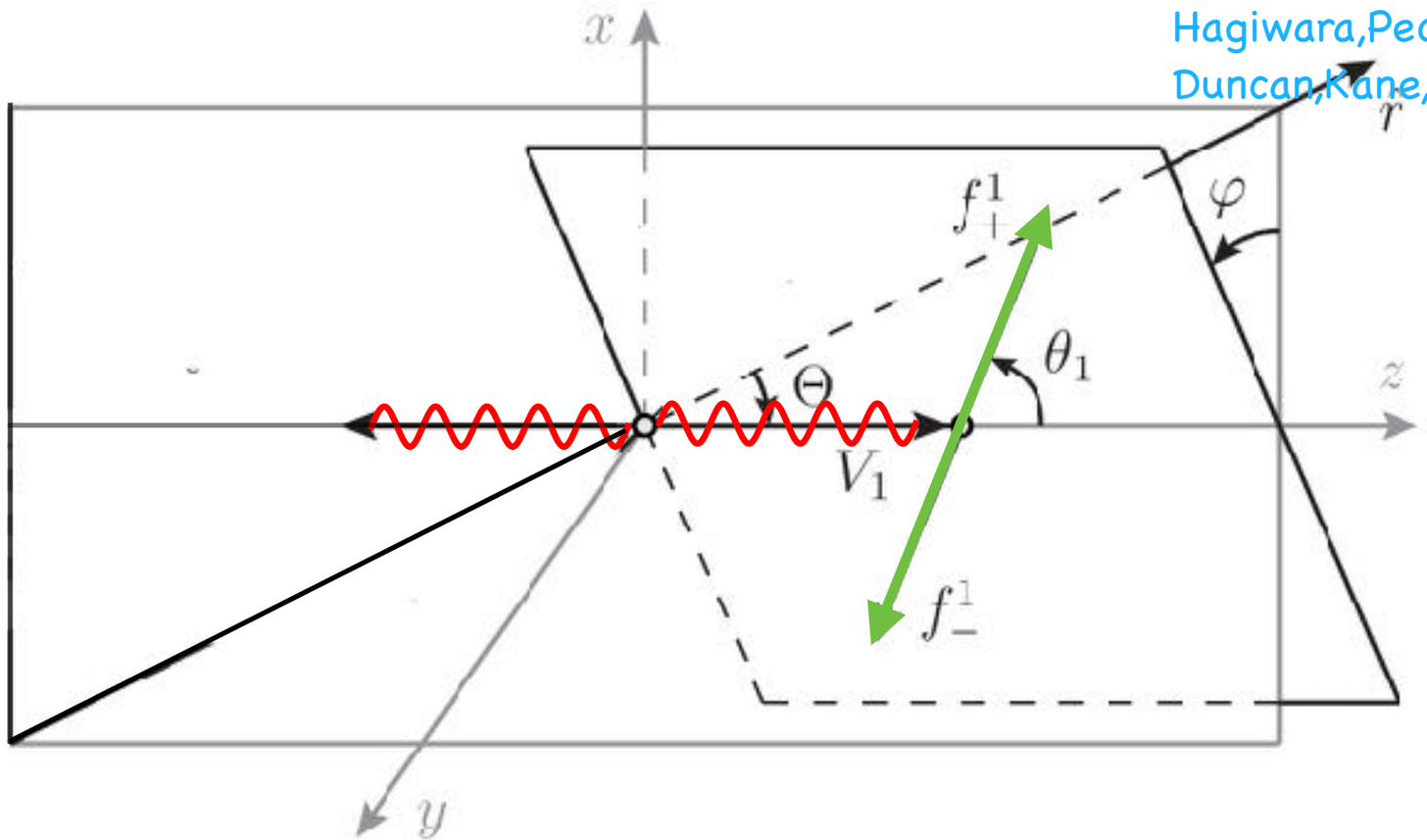

$$Int^{\rm CP} = 2g^2\sin^2\theta\mathcal{A}_{++}^{\rm BSM+}\left[\mathcal{A}_{-+}^{\rm SM}+\mathcal{A}_{+-}^{\rm SM}\right]\cos 2\varphi\,,$$

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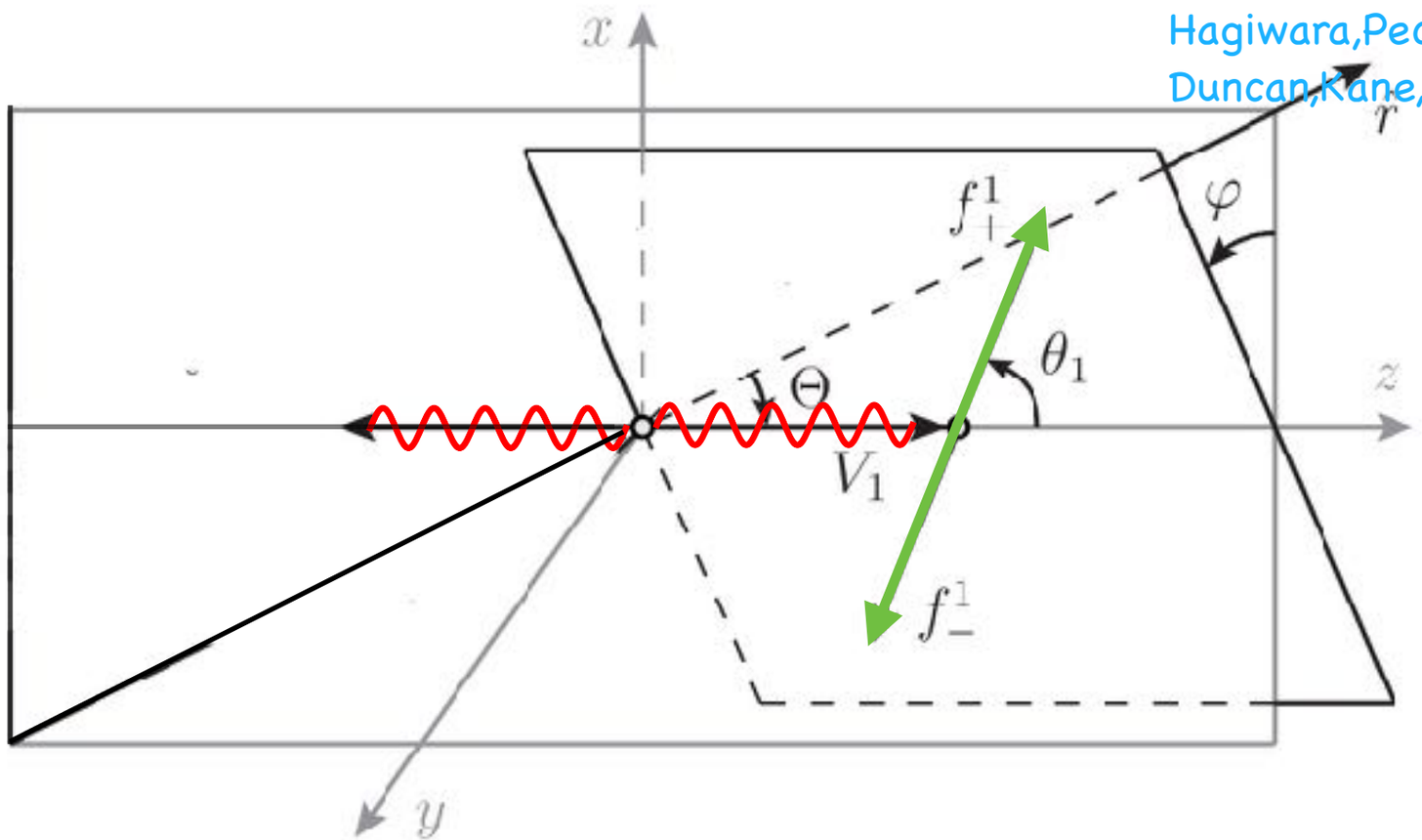

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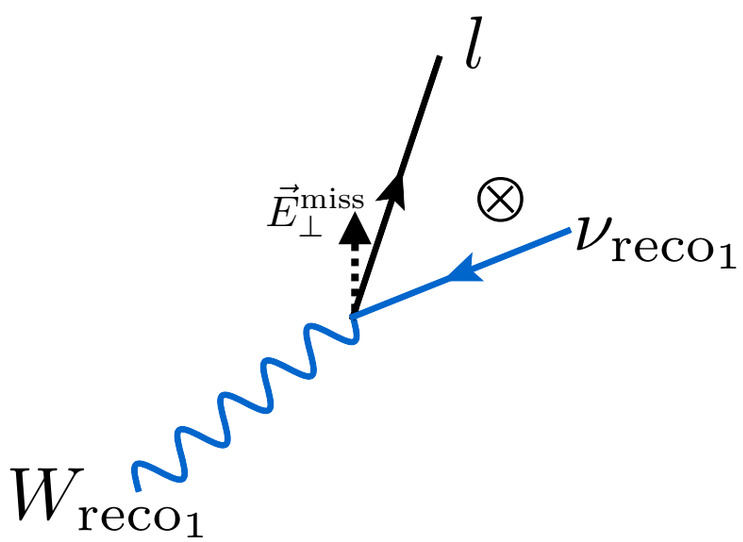
Differential azimuthal distributions = SM-BSM interference

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



Panico,FR,Wulzer'17

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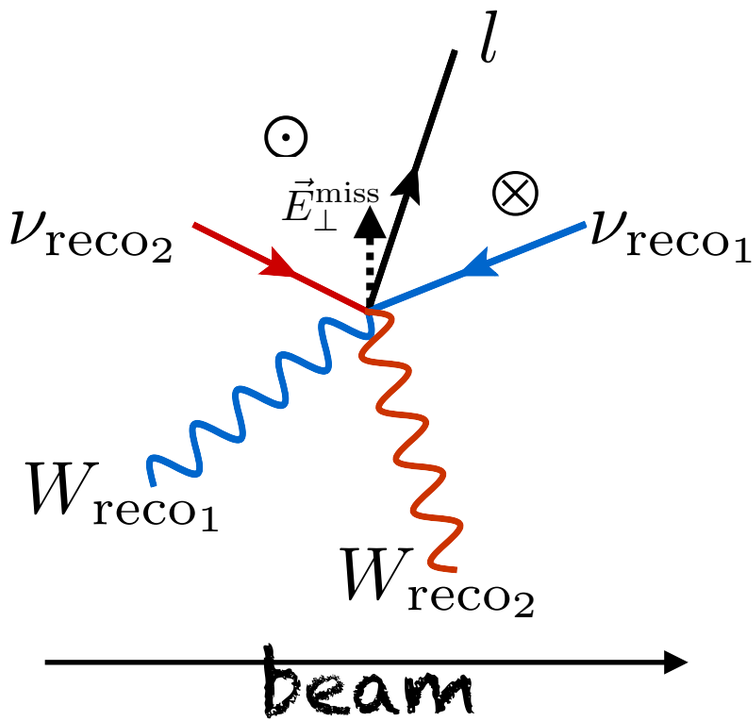

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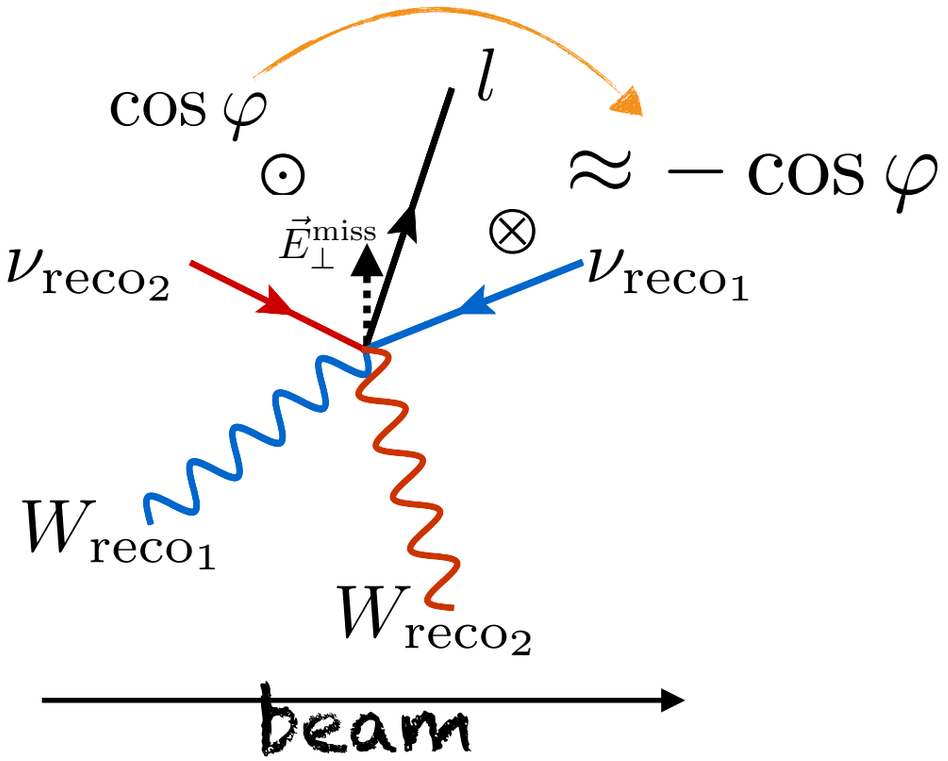

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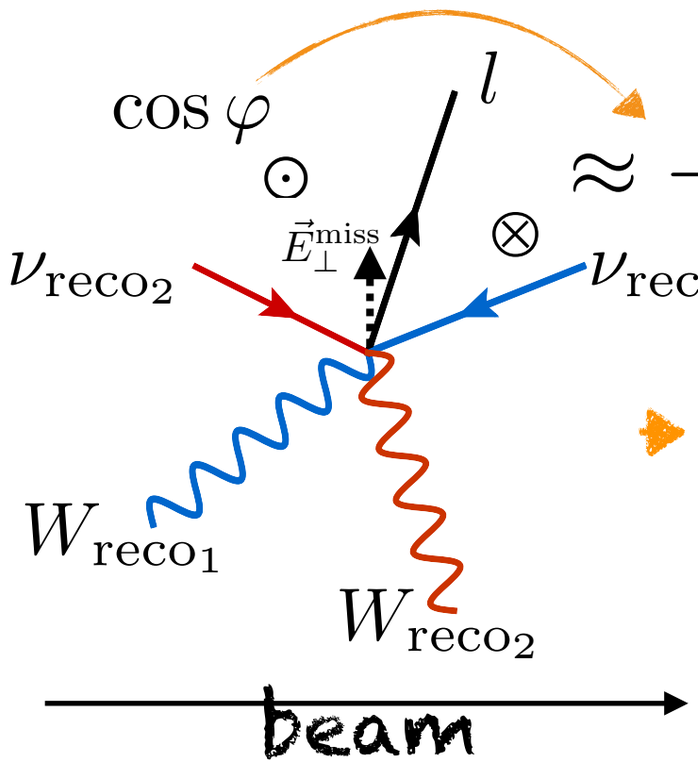

φ_{reco}

1)

$$\varphi^+ \cong \pi - \varphi^- \mod 2\pi$$

φ_{true}

Panico,FR,Wulzer'17

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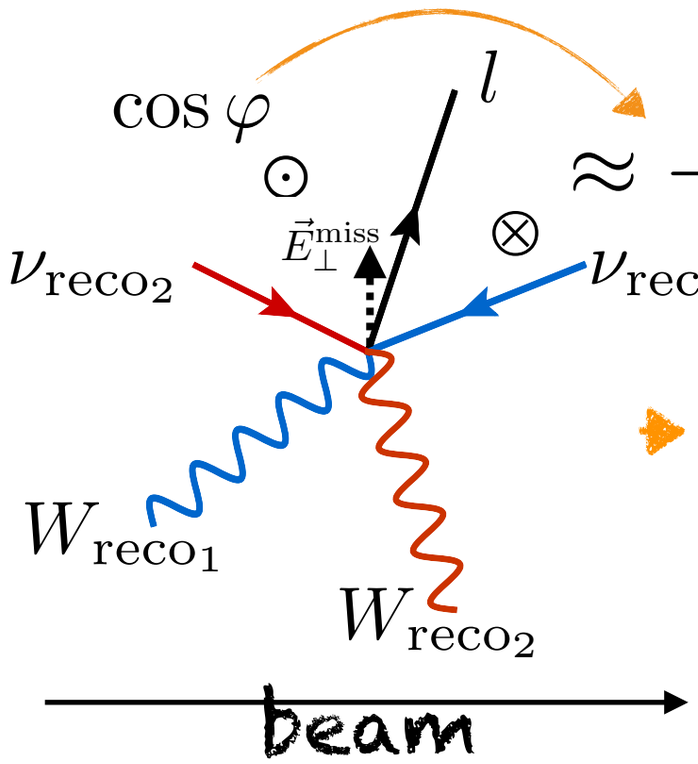

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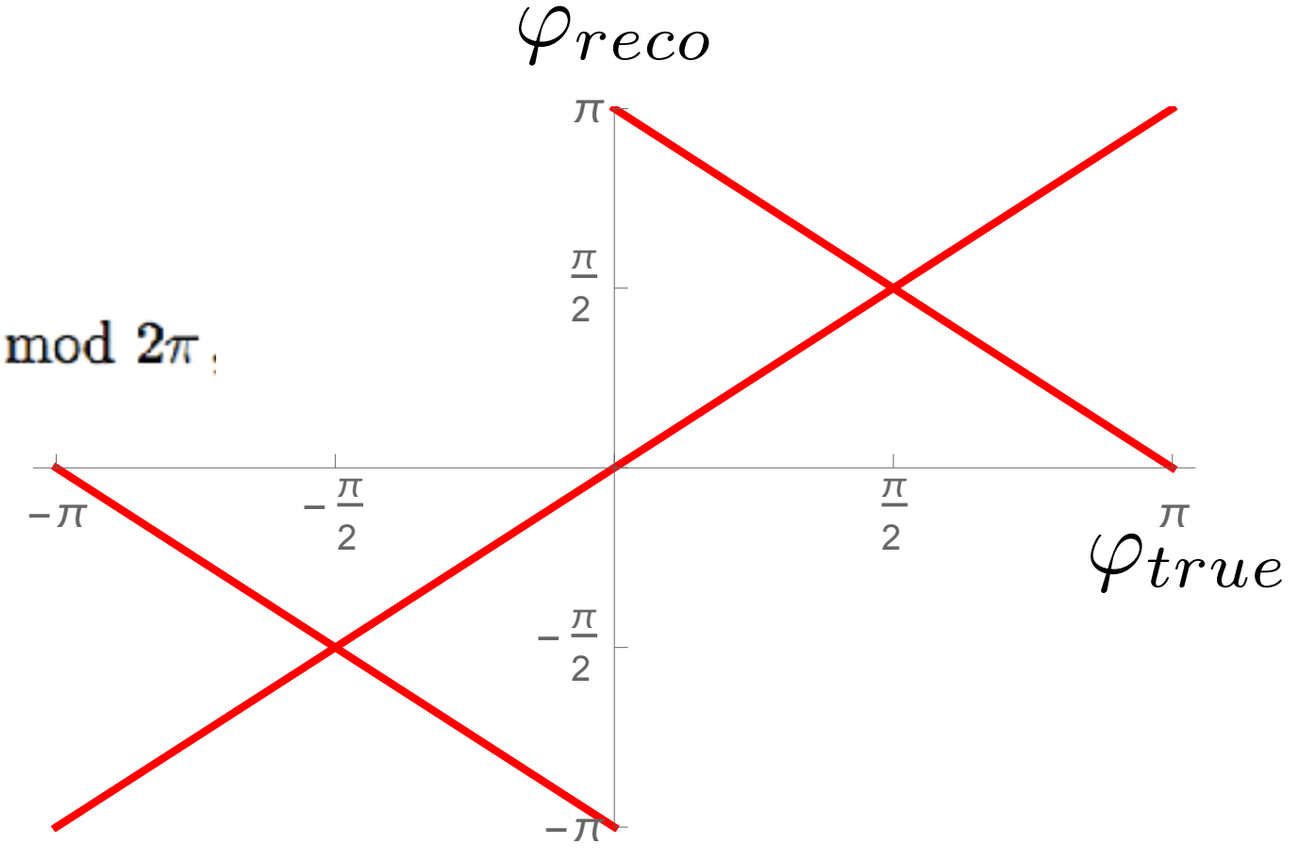

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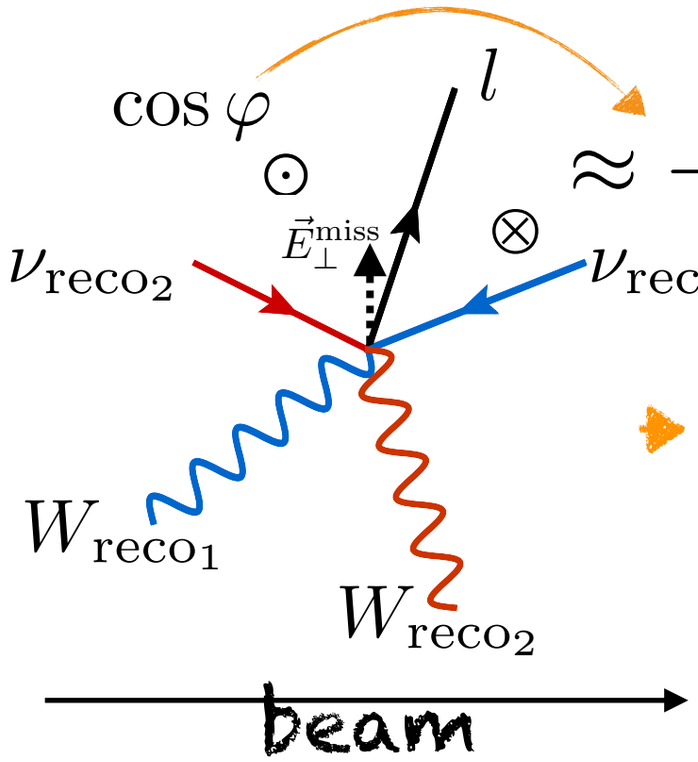

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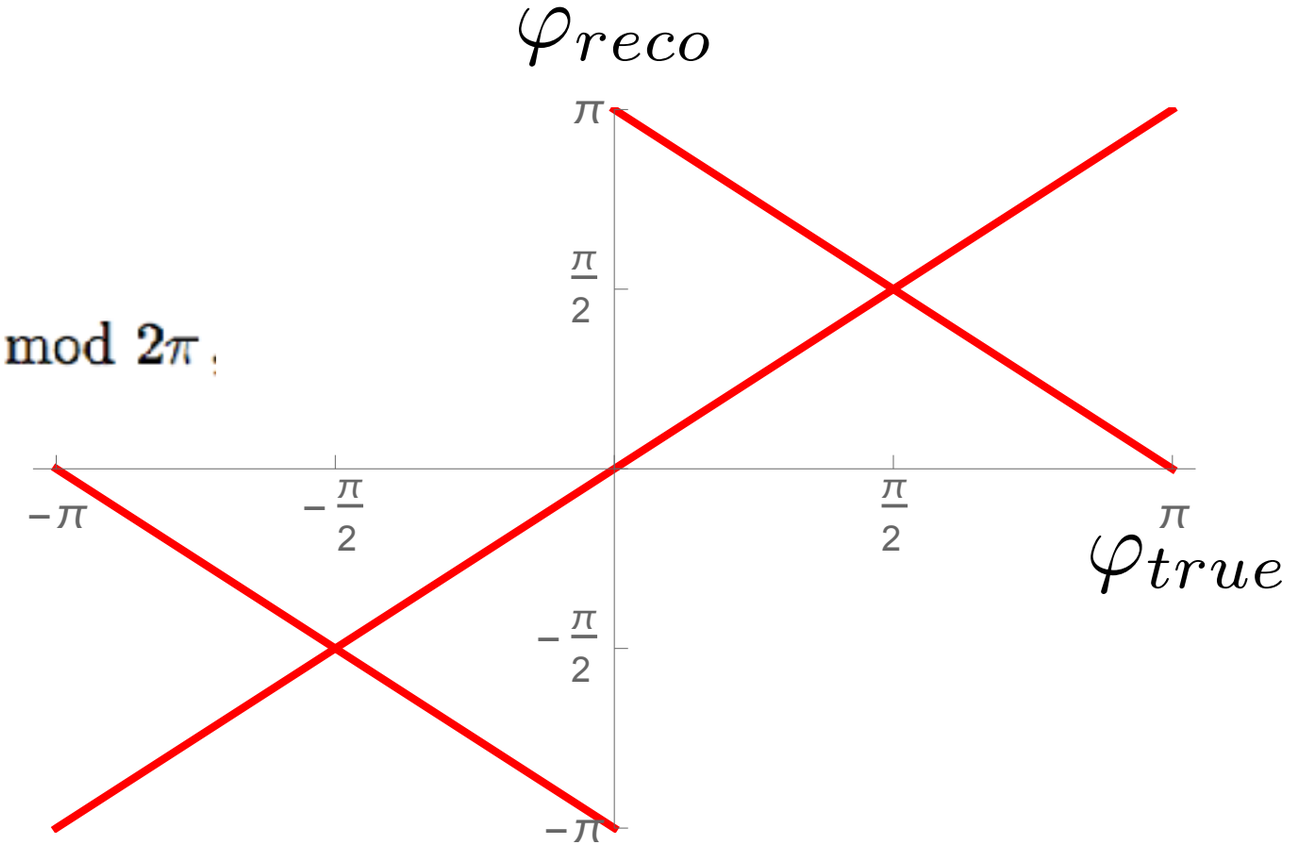

2) Some events: $m_\perp^2 > m_W^2$
(off-shell, exp.error)

reconstructed as $m_{\text{inv}}^2 = m_W^2$

$$\varphi = \pi/2 \quad \text{or} \quad \varphi = -\pi/2.$$

Panico,FR,Wulzer'17

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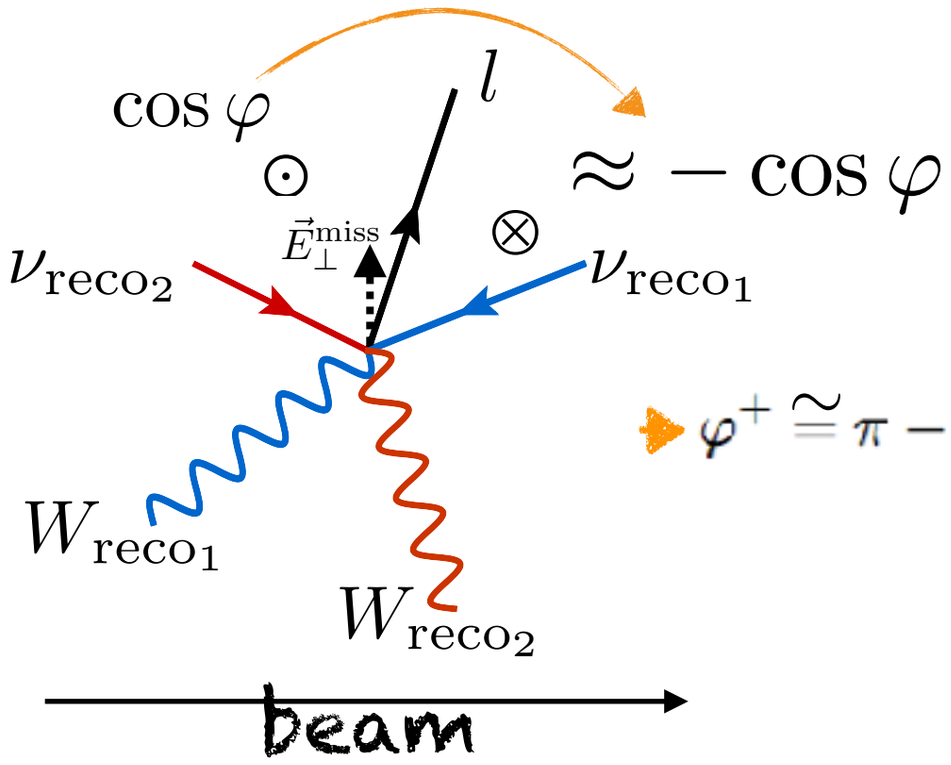

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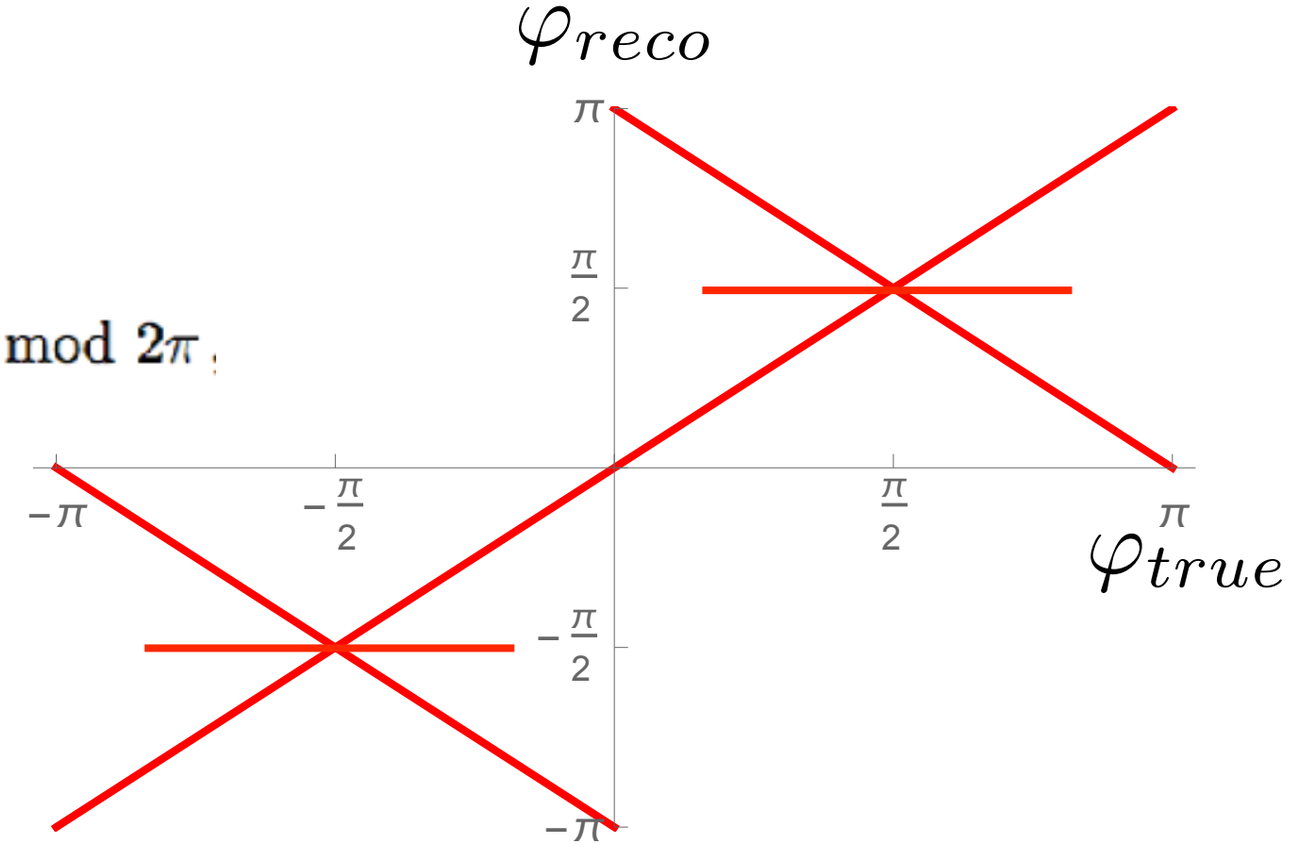

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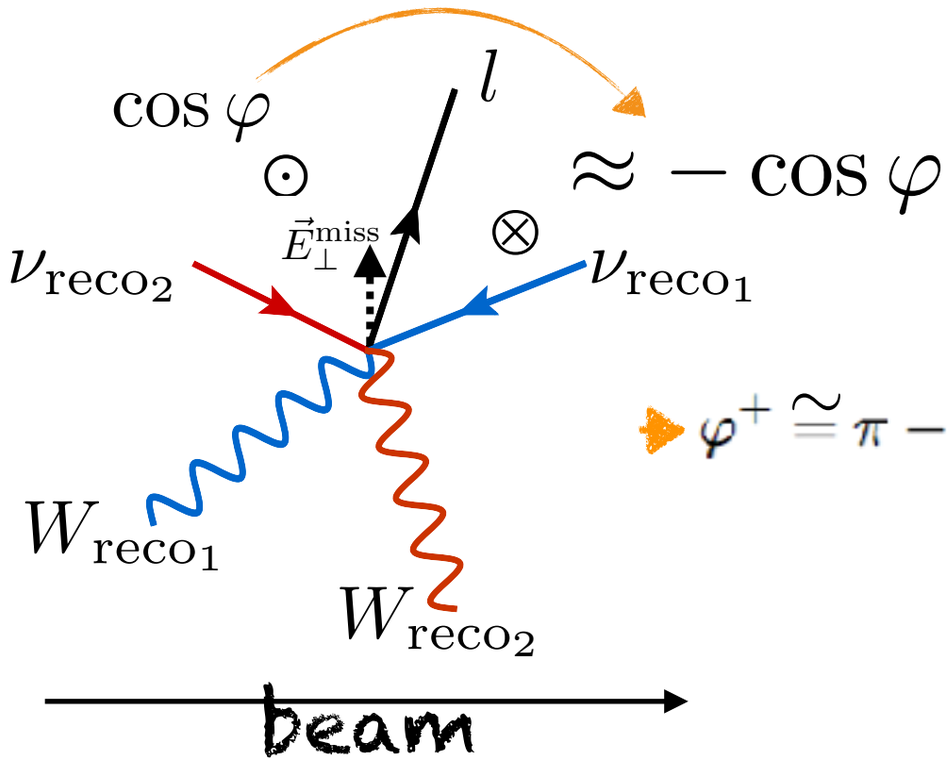

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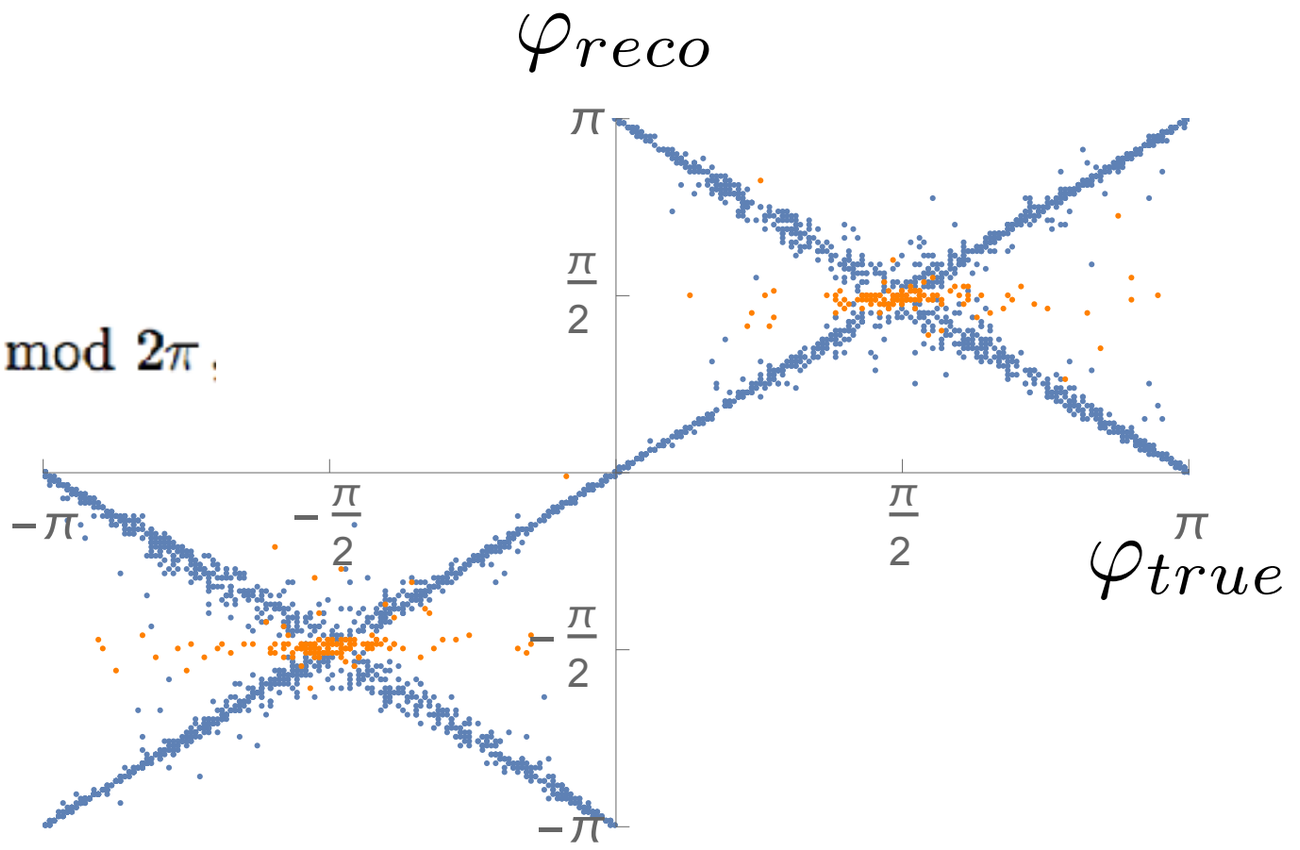

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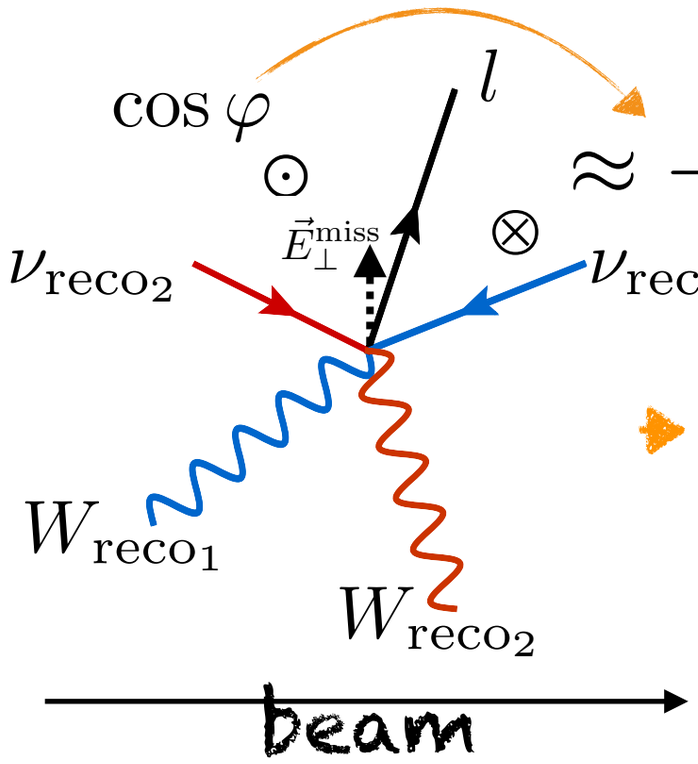

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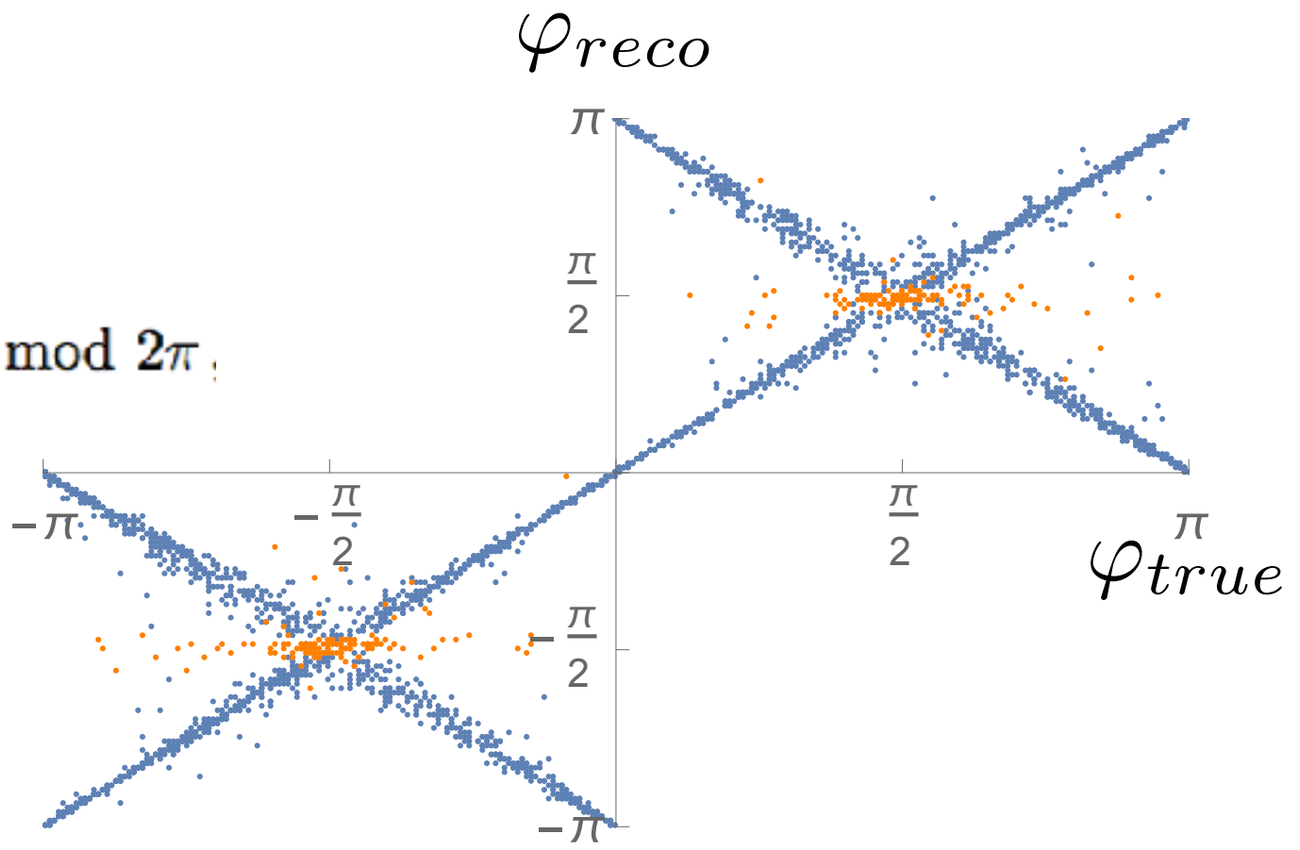

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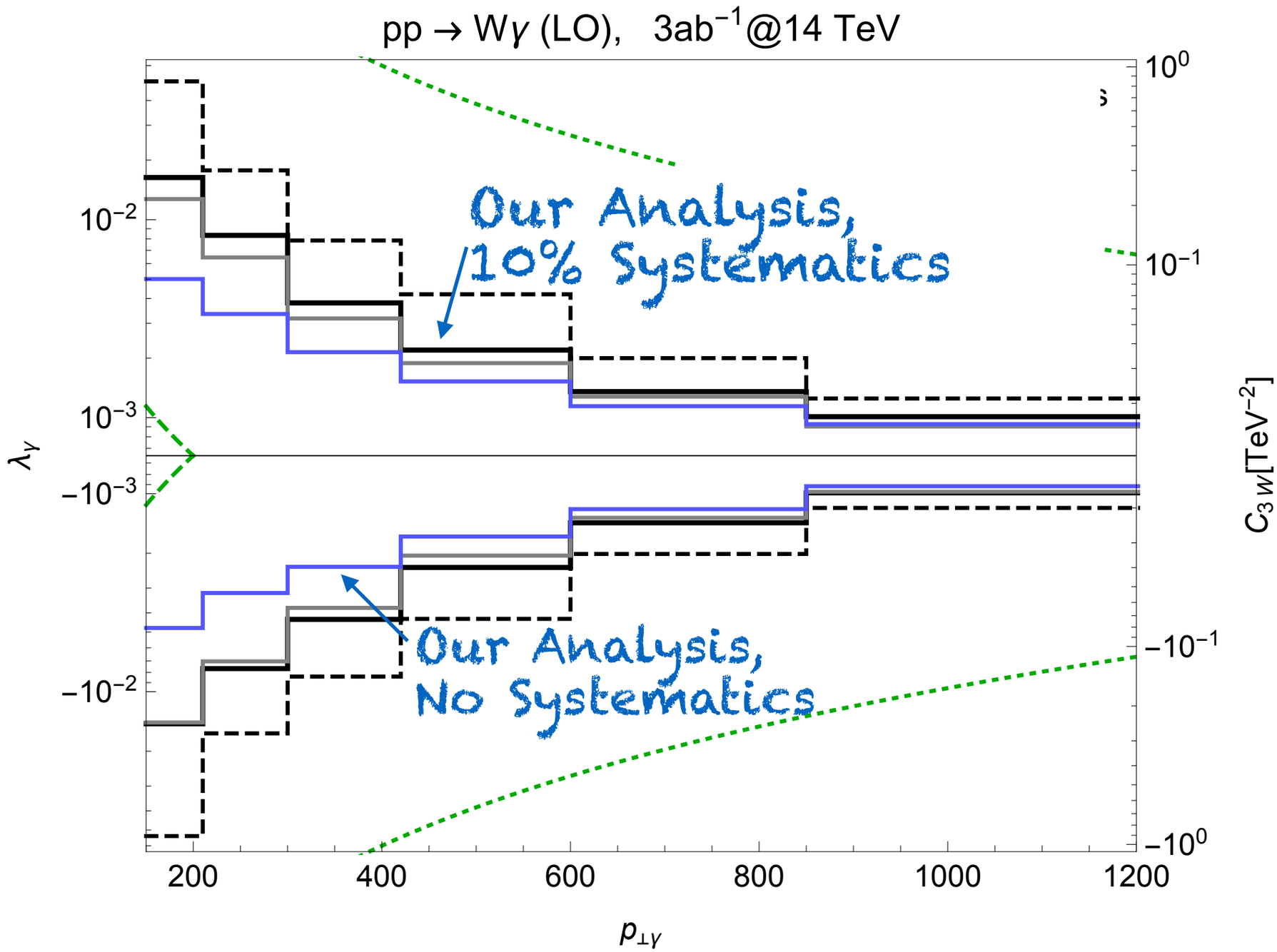
CP-odd unaccessible!

Panico,FR,Wulzer'17

Results



Panico,FR,Wulzer'17

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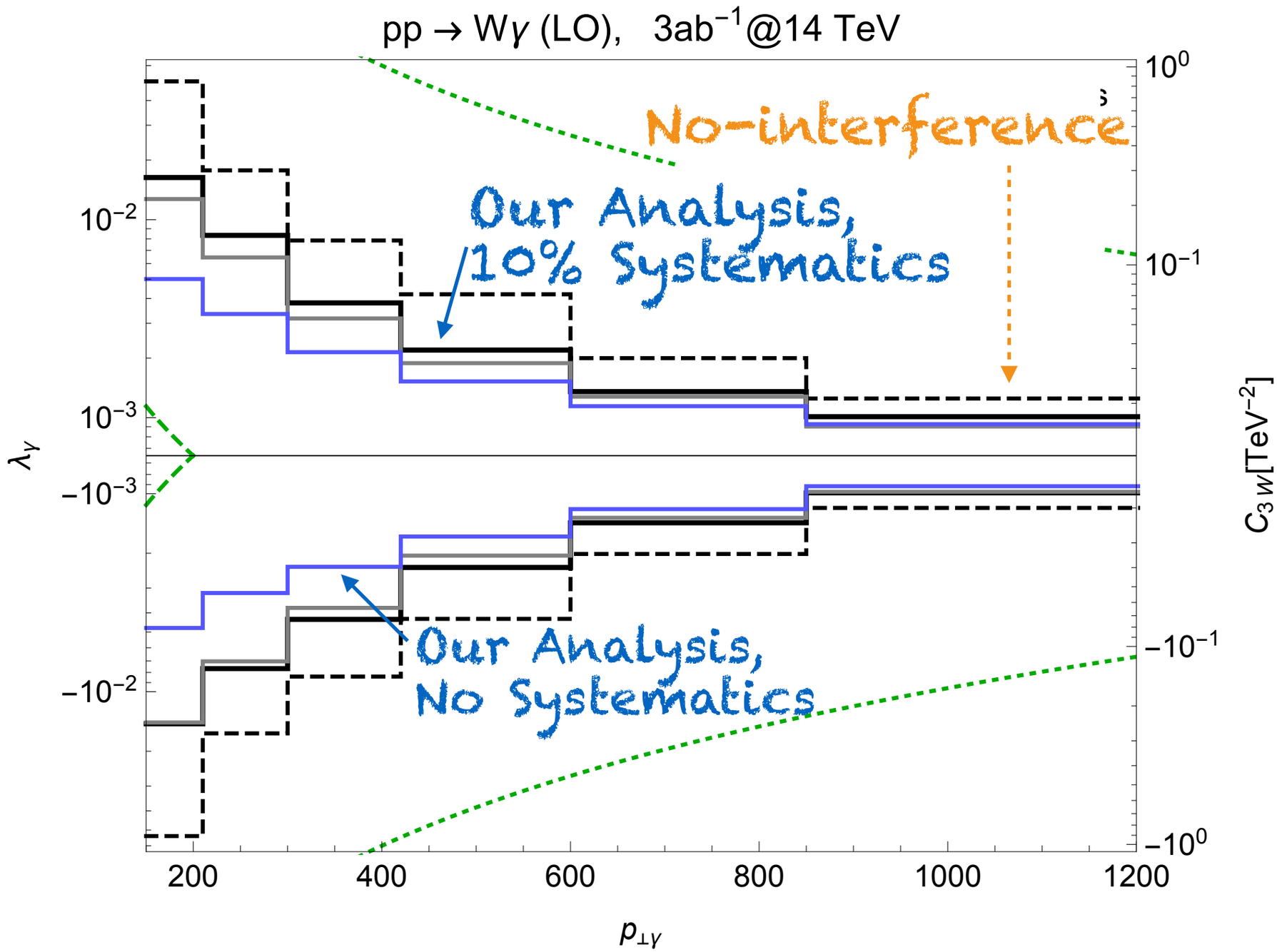

Panico,FR,Wulzer'17

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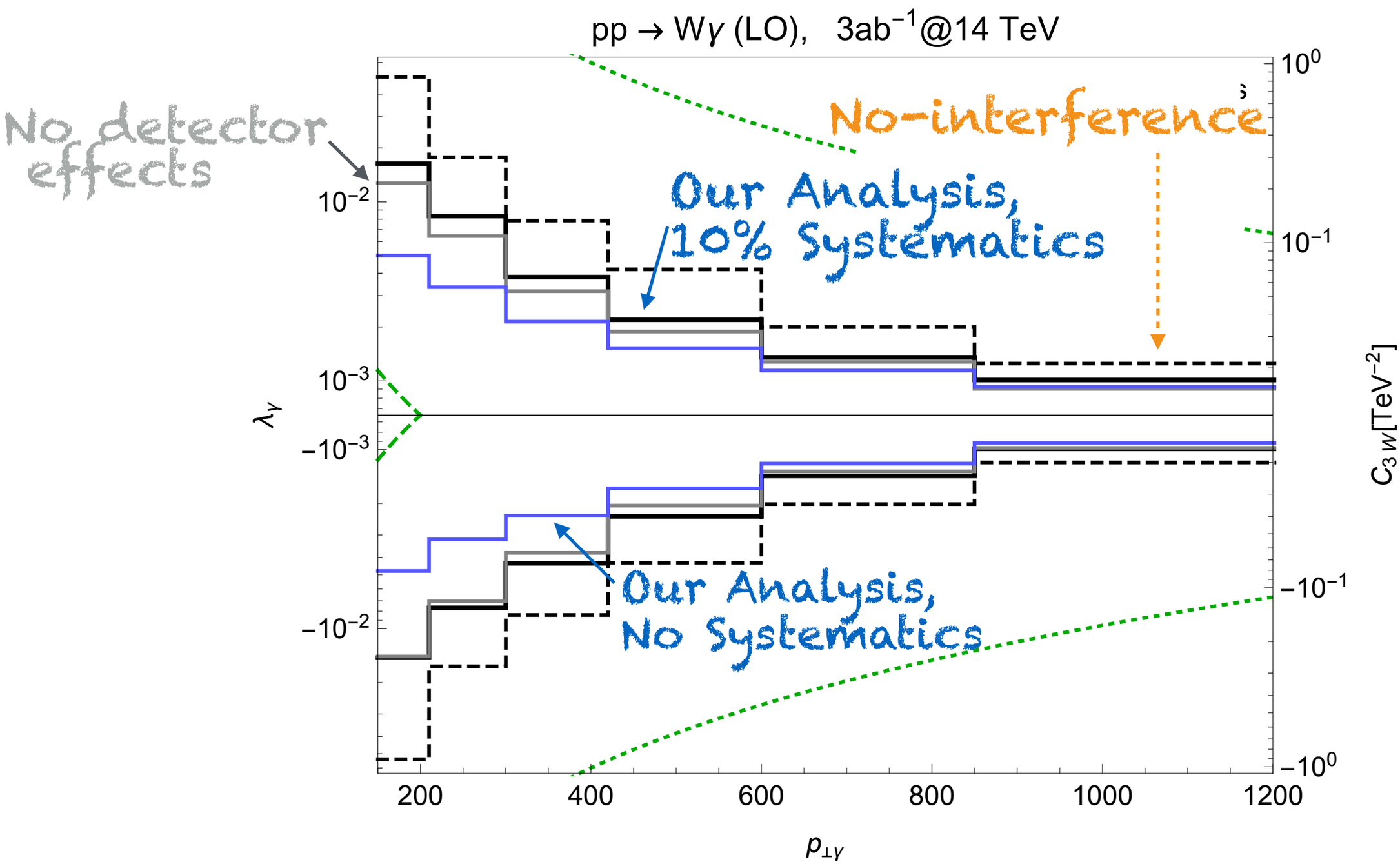


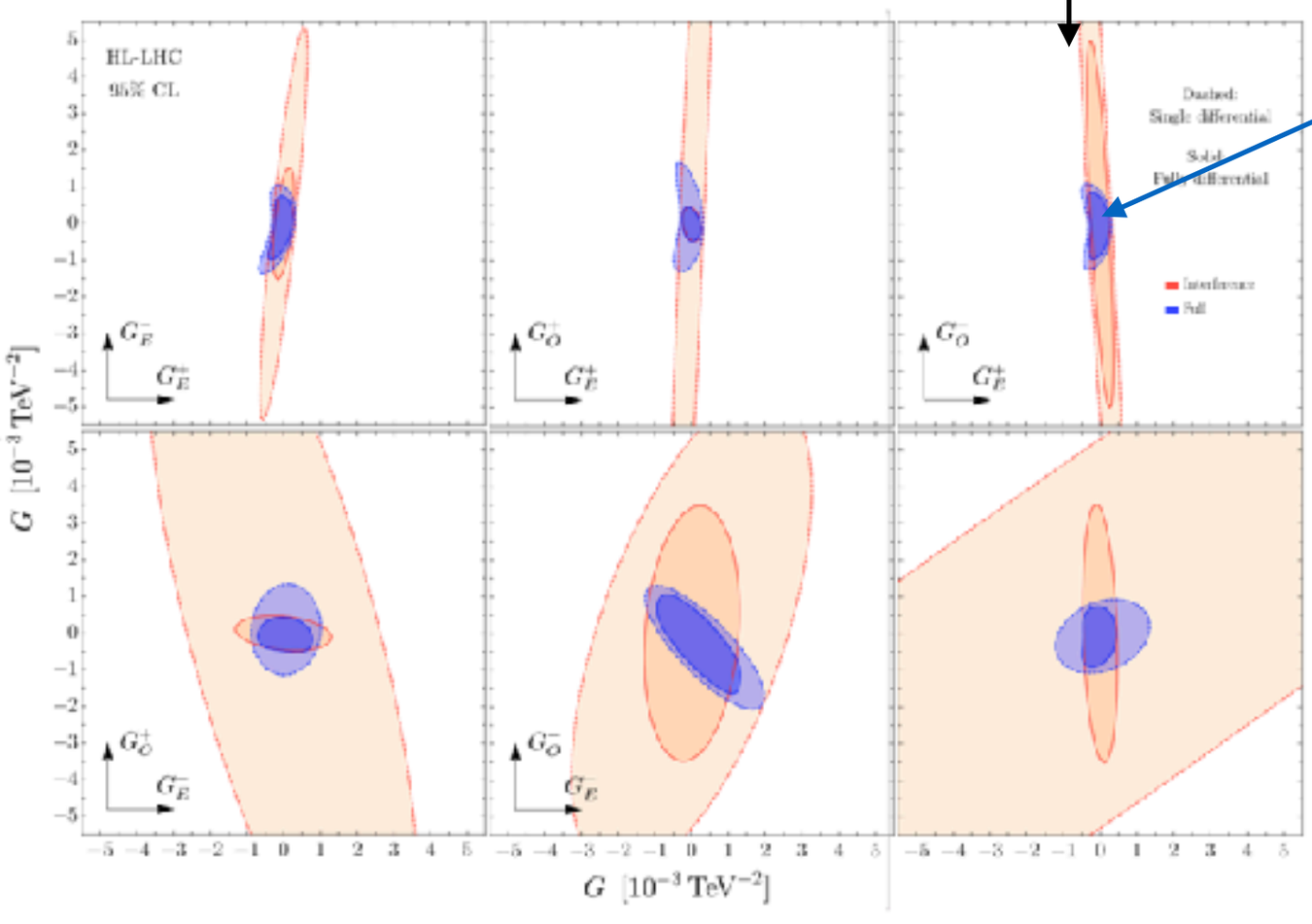
Panico,FR,Wulzer'17

Distributions to distinguish effects

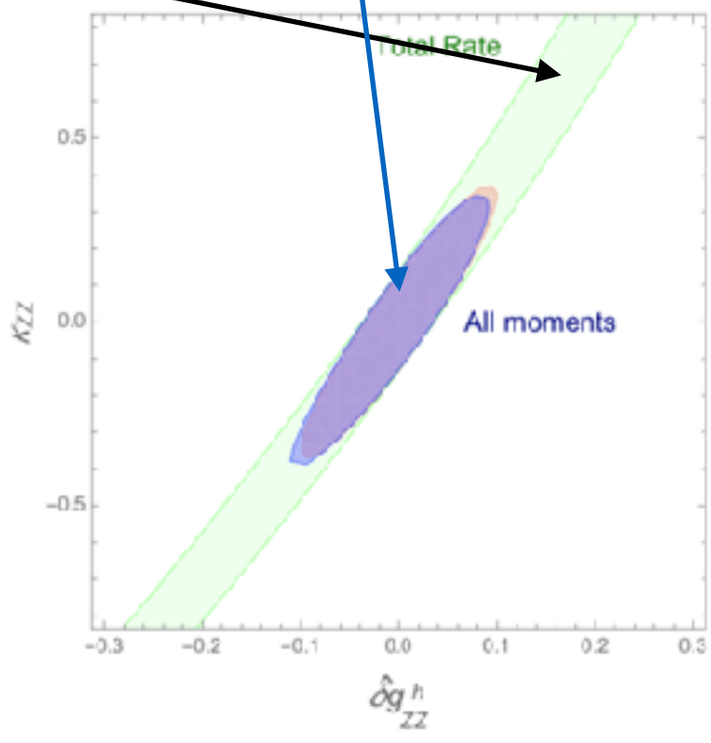
When more BSM effects (operators) are included, distributions allow access to individual ones

Inclusive Analyses

Exclusive (BSM targeted)



Panico,Ricci,Wulzer'21



Banerjee,Gupta,Ochoa-Valeriano, Spannowsky,Venturini'20

SM ≠ BSM

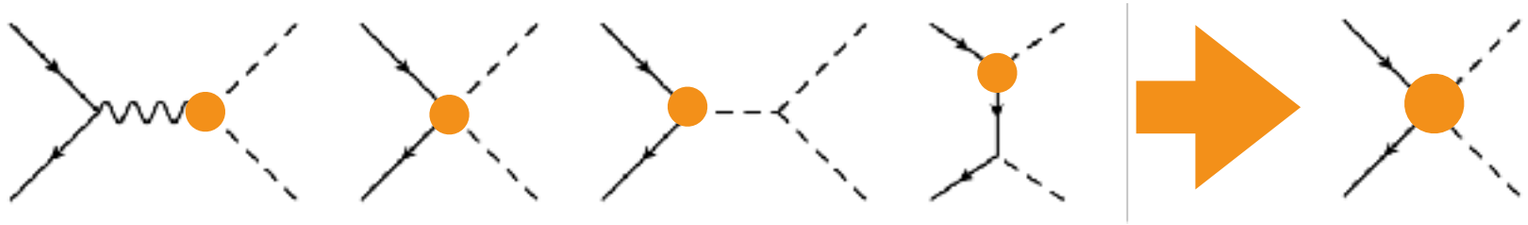
2. BSM Small in inclusive measures

(and where to look)

Longitudinal Polarisations in Dibosons

Franceschini,Panico,Pomarol,FR,Wulzer'17

- At high-E only one effect survives (for given i, f states)



$$\frac{a^{(3)}}{\mathrm{TeV}^2}\; iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{Q}\sigma^a\gamma^\mu Q$$

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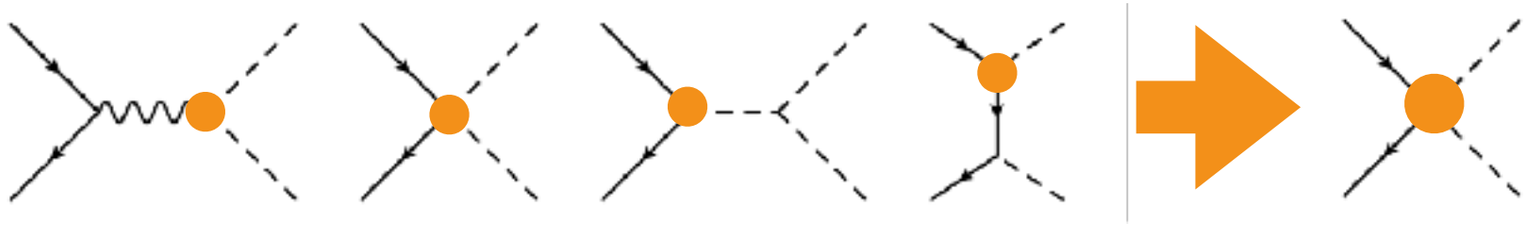

$$\frac{a^{(3)}}{\mathrm{TeV}^2}\, iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{Q}\sigma^a\gamma^\mu Q$$

- Estimate (no syst, LO,...):

Channel	Bound without bkg.	Bound with bkg.
Wh	$[-0.0024, 0.0024]$	$[-0.0089, 0.0078]$
Zh	$[-0.0074, 0.0070]$	–
WW	$[-0.0029, 0.0028]$	$[-0.011, 0.0093]$
WZ	$[-0.0032, 0.0031]$	$[-0.0057, 0.0052]$

Challenge:

} Boosted higgs for top:h->bb fakes?

} Large V_T bgnd

(WW pT>1000GeV 3/ab: 7 LL events, 70 TT events)

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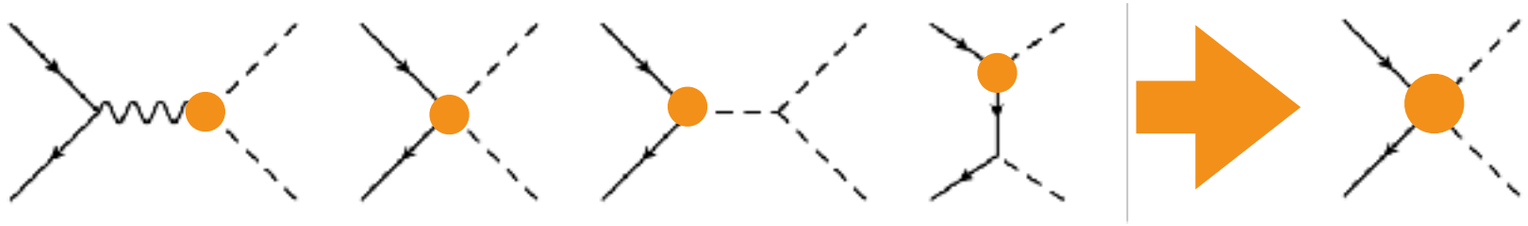

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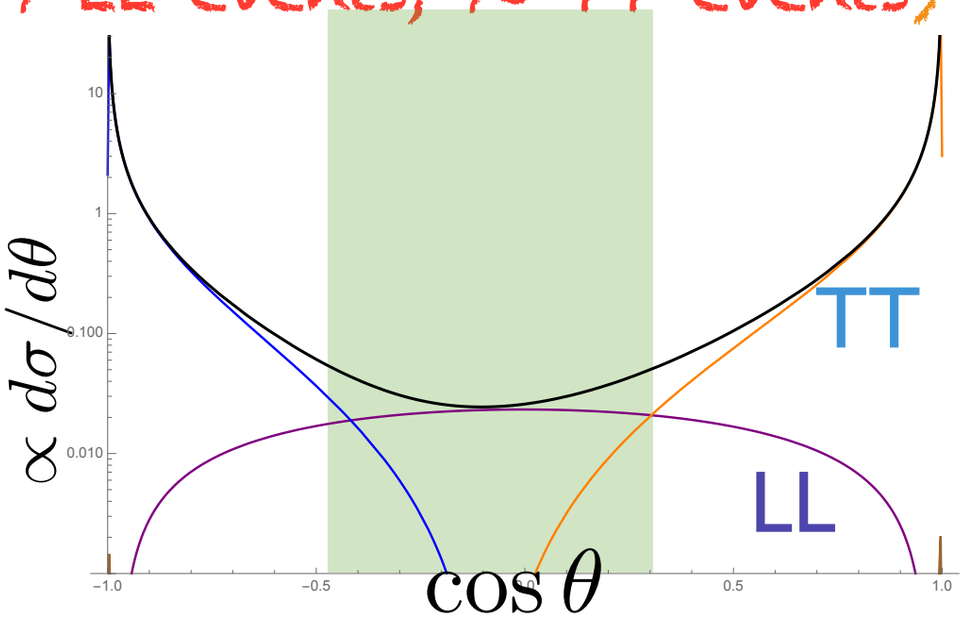
- WZ most promising

$$A^{+-}(\bar{d}u \to WZ) \propto \cos\theta - \frac{\tan\theta_W}{3}$$ Baur,Han,Ohnemus'95

TT has central zero at LO

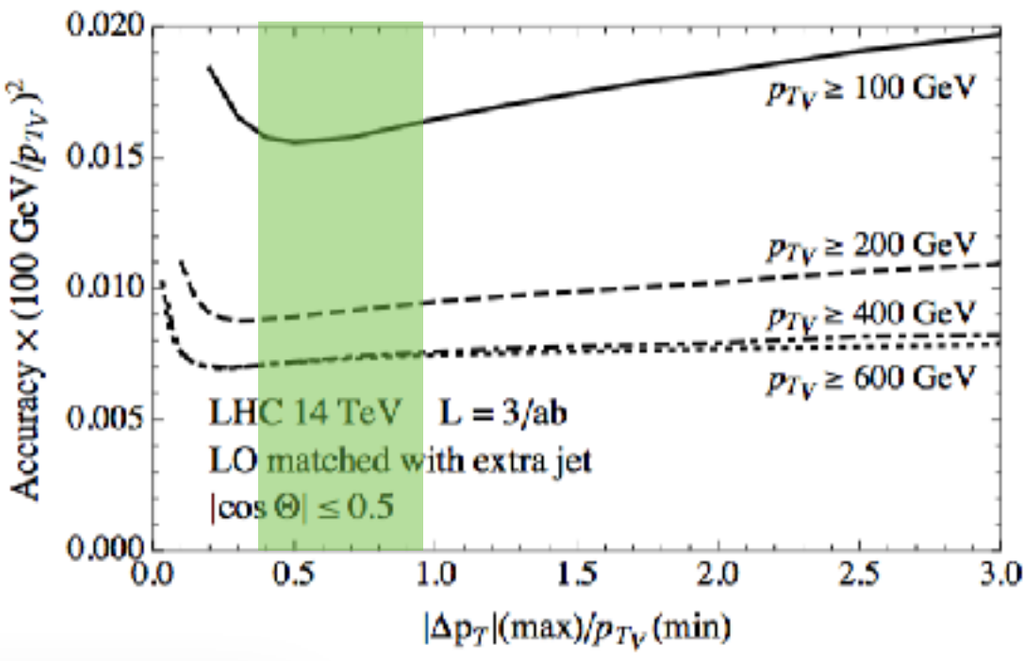
(not at NLO)



Fully leptonic WZ

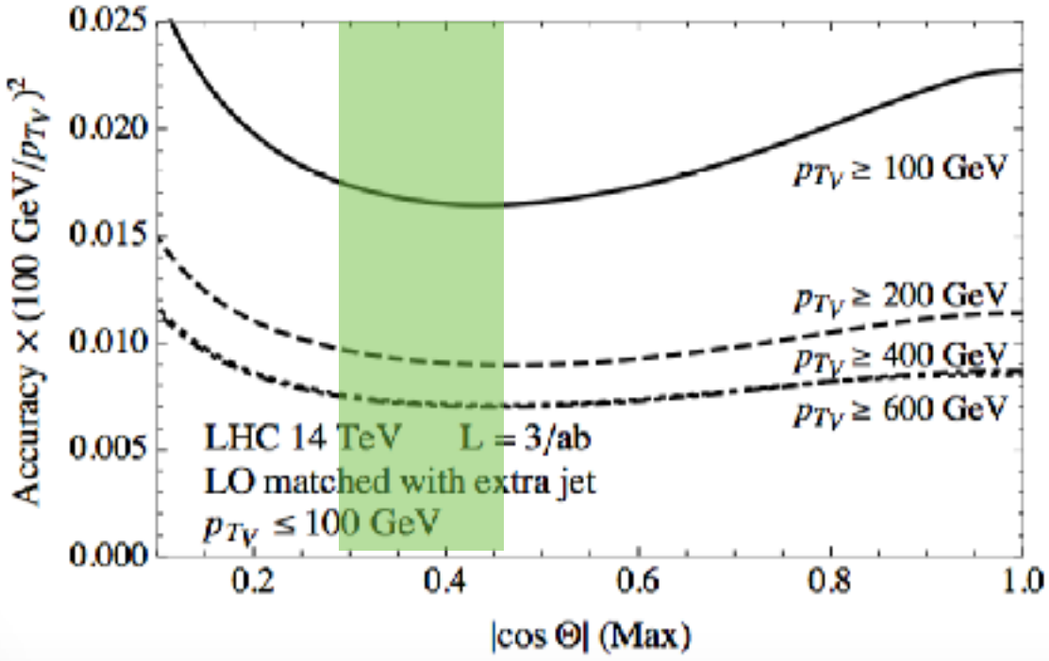
pT cut on extra radiation:

(kinematics close to LO)

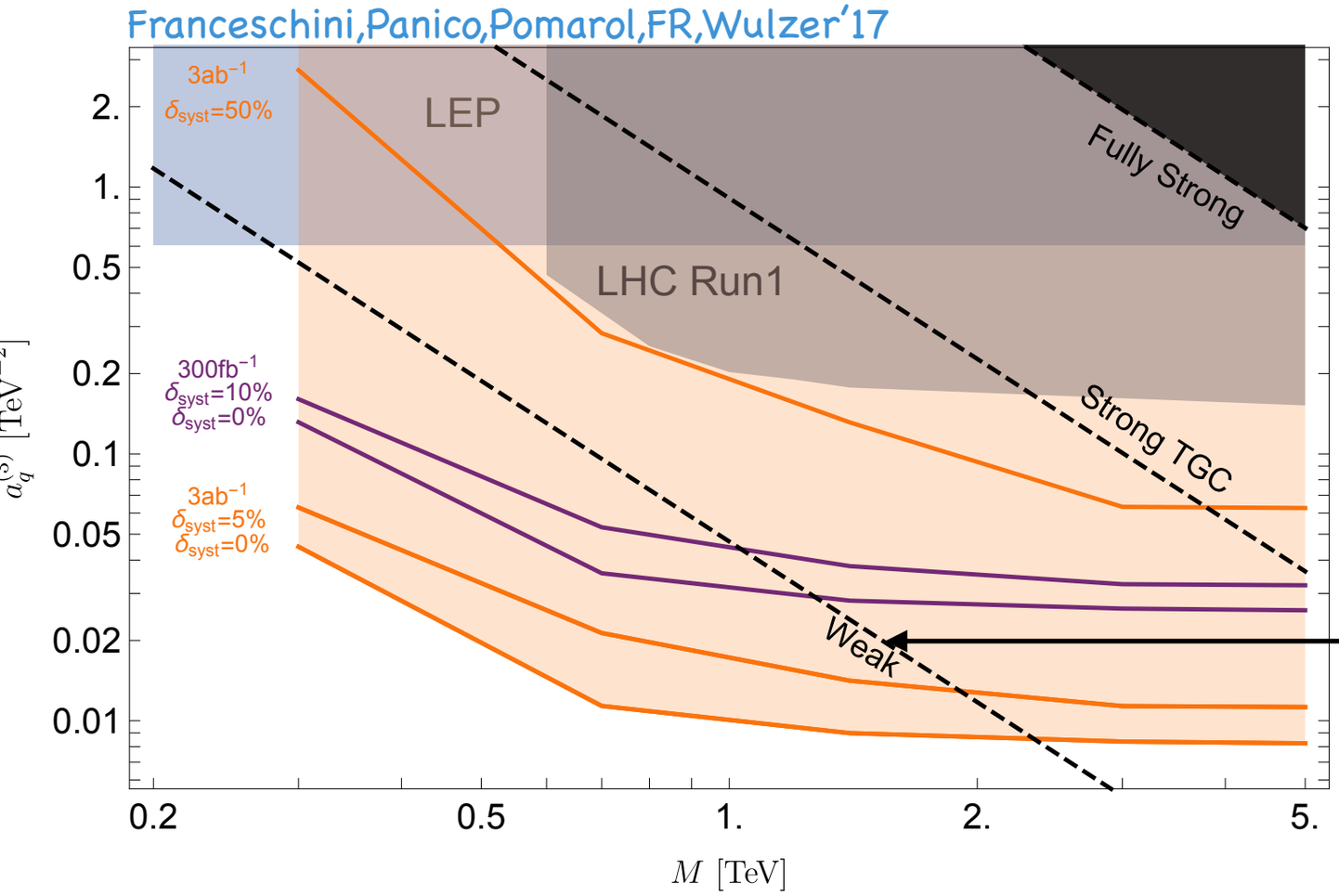


Cosθ cut close to central

(exploit radiation-zero)



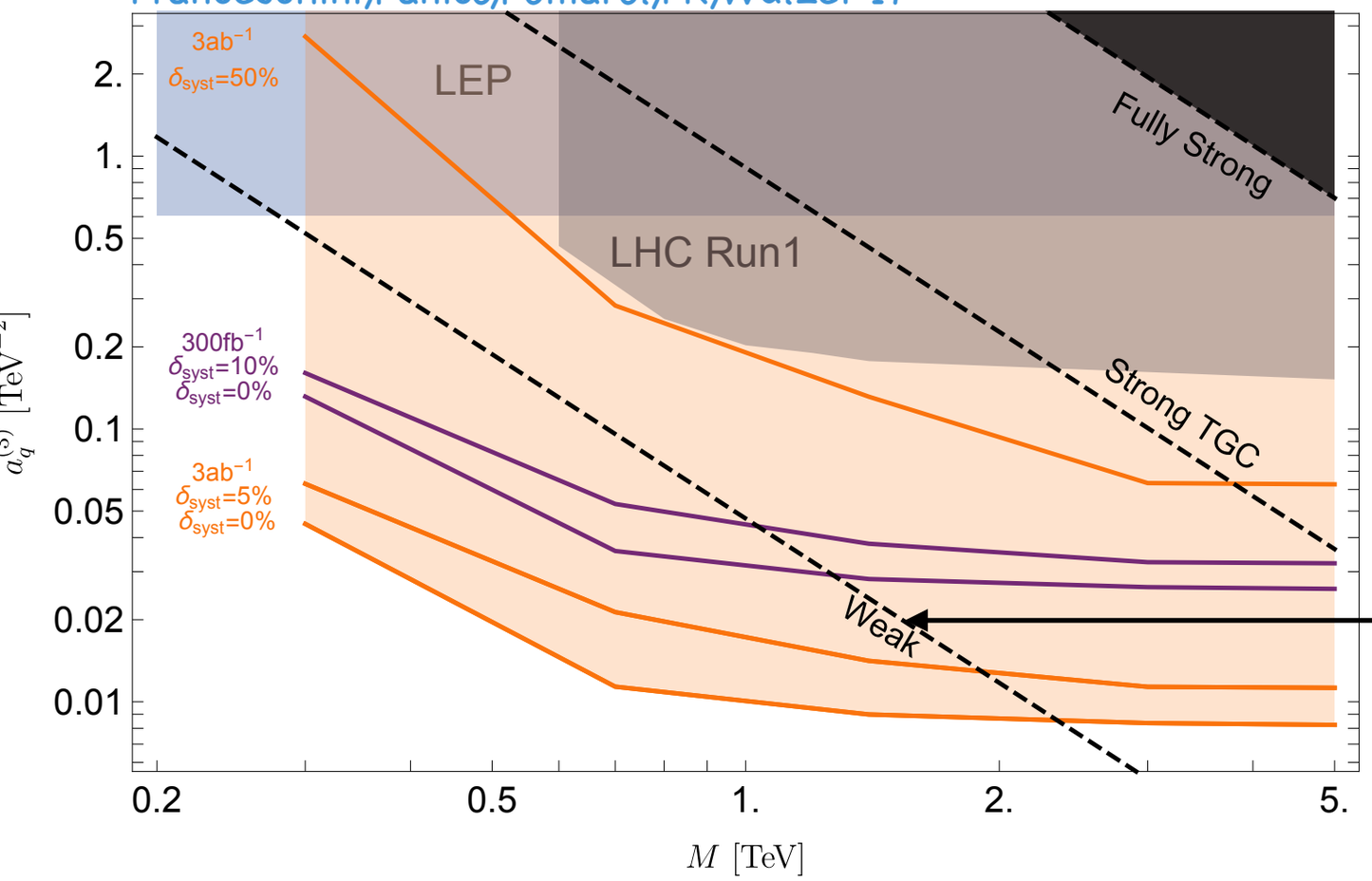
Results - NLO - LHC



Measurements here have wider interpretation in terms of UV models

Results - NLO - LHC

Franceschini,Panico,Pomarol,FR,Wulzer'17



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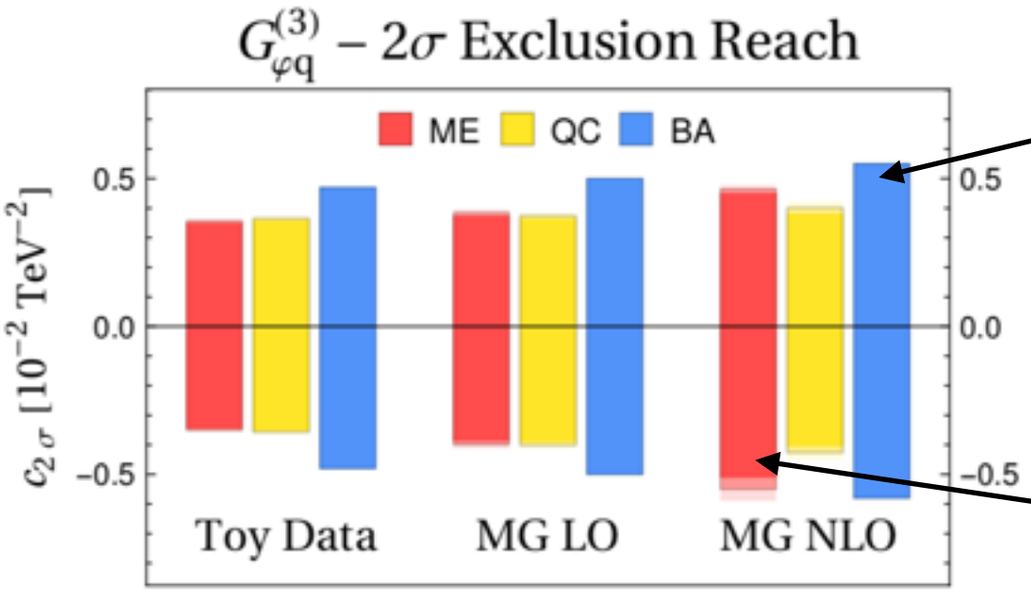


Binned Analysis

Machine Learning

Chen,Glioti,Panico,Wulzer'20

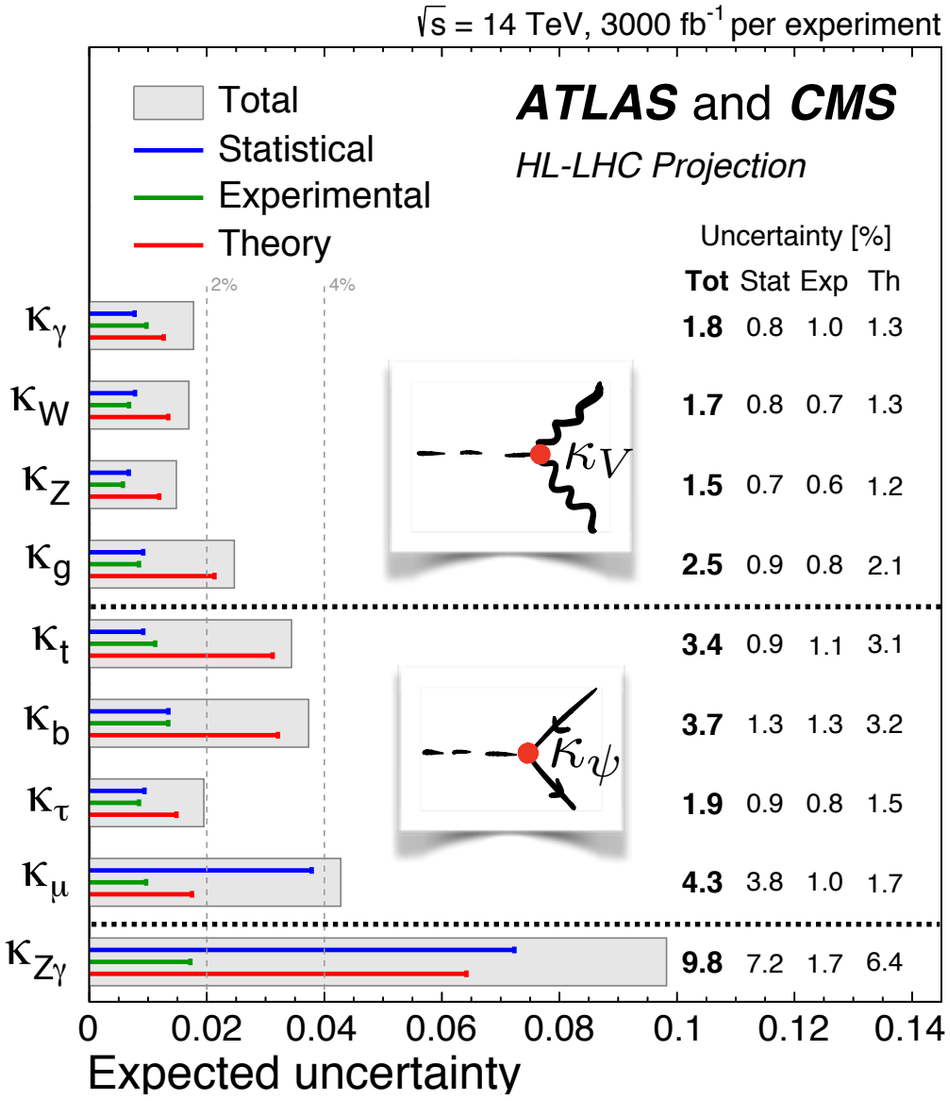
SM ≠ BSM

3. BSM in Multibosons

(processes that are not particularly interesting in SM, are sensitive to BSM)

HL-LHC Reach (3000 fb^{-1})

Higgs couplings (HC) are measured in processes with on-shell Higgs (E=125 GeV)



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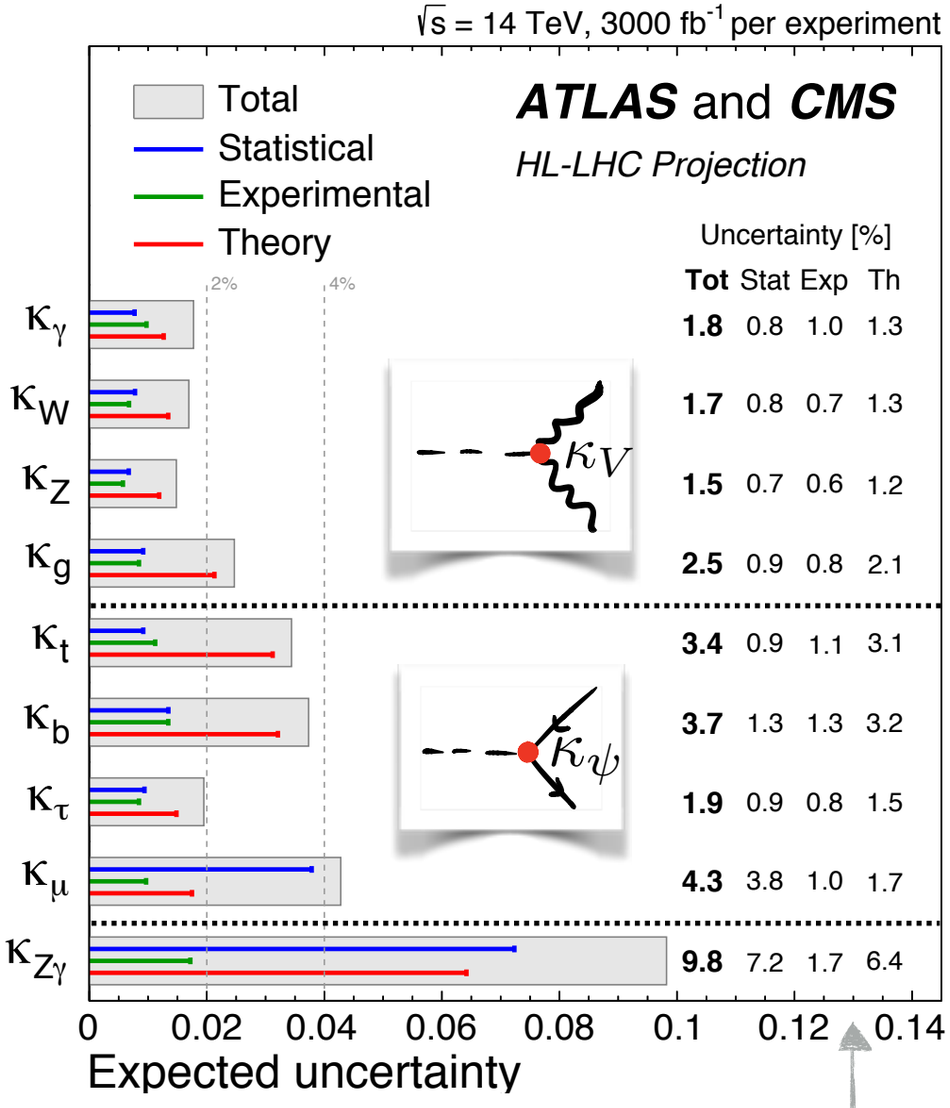
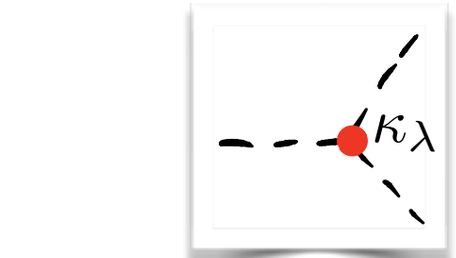
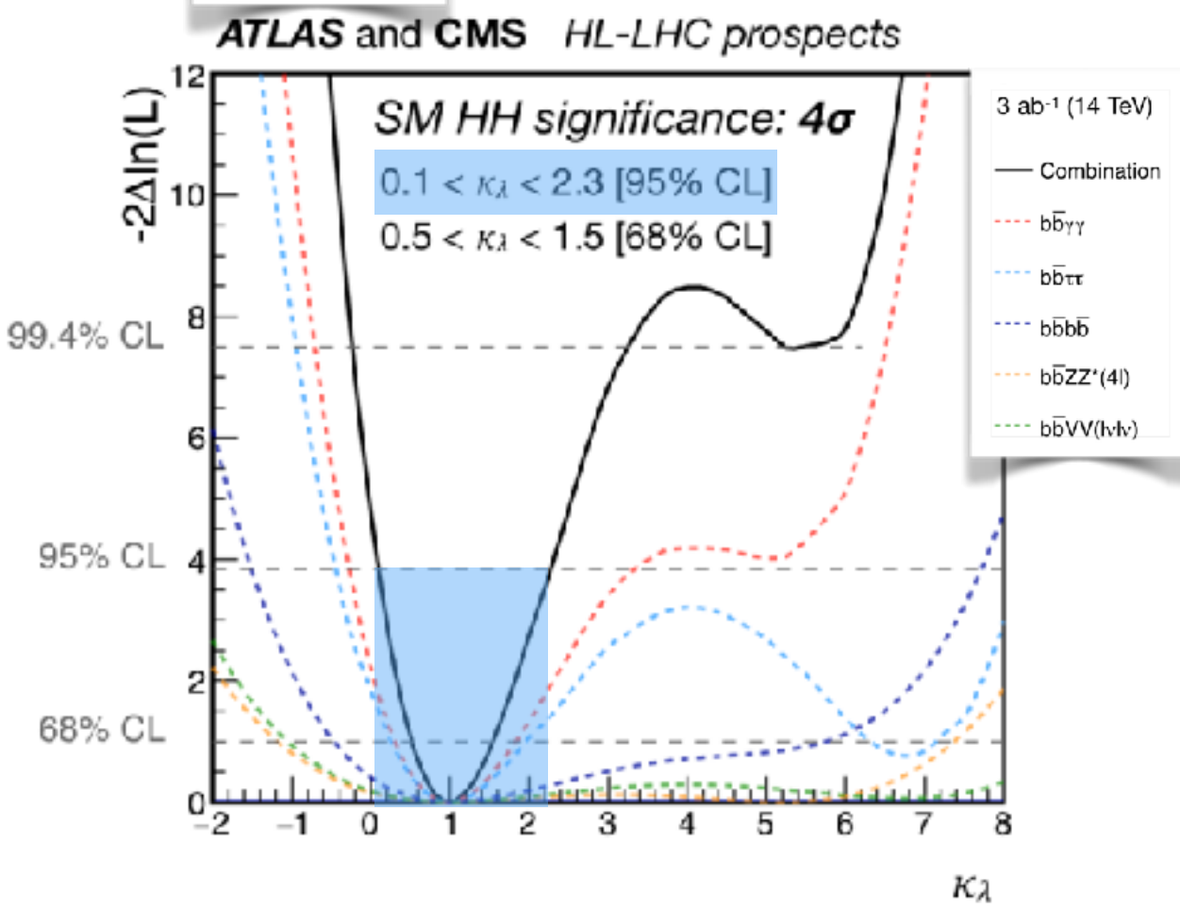


Optimistic Systematics (S2)



Combining 2 experiments



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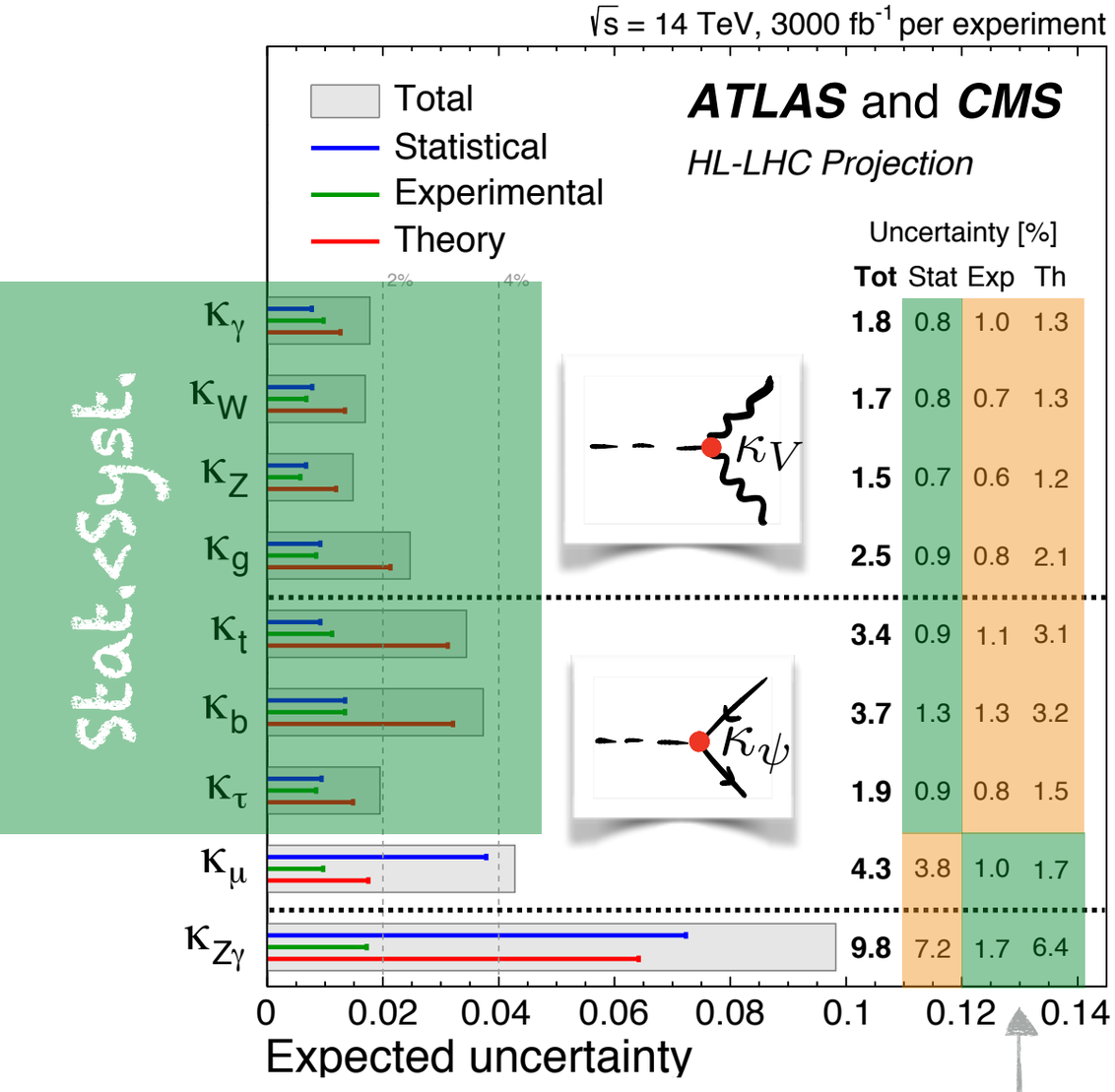

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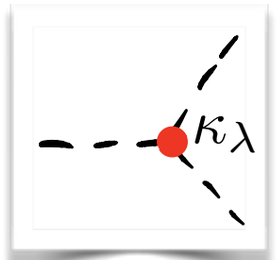

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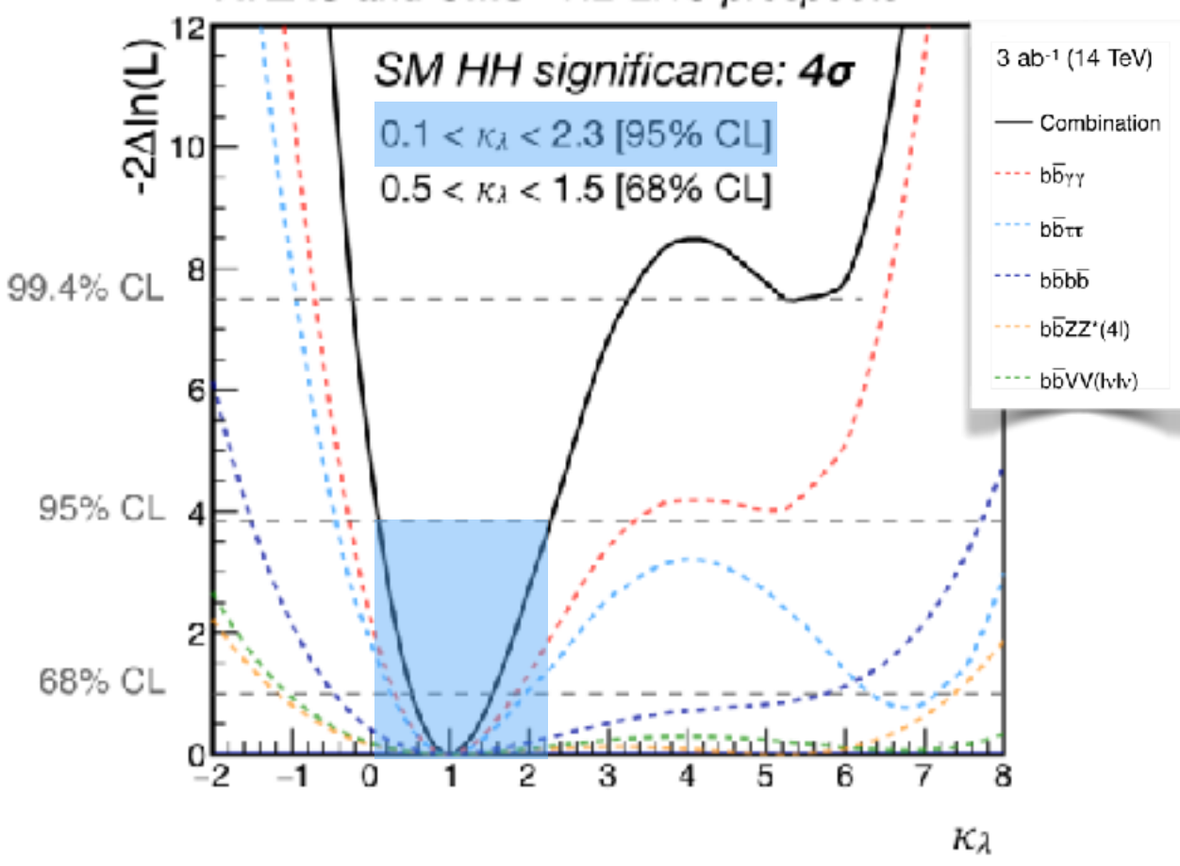


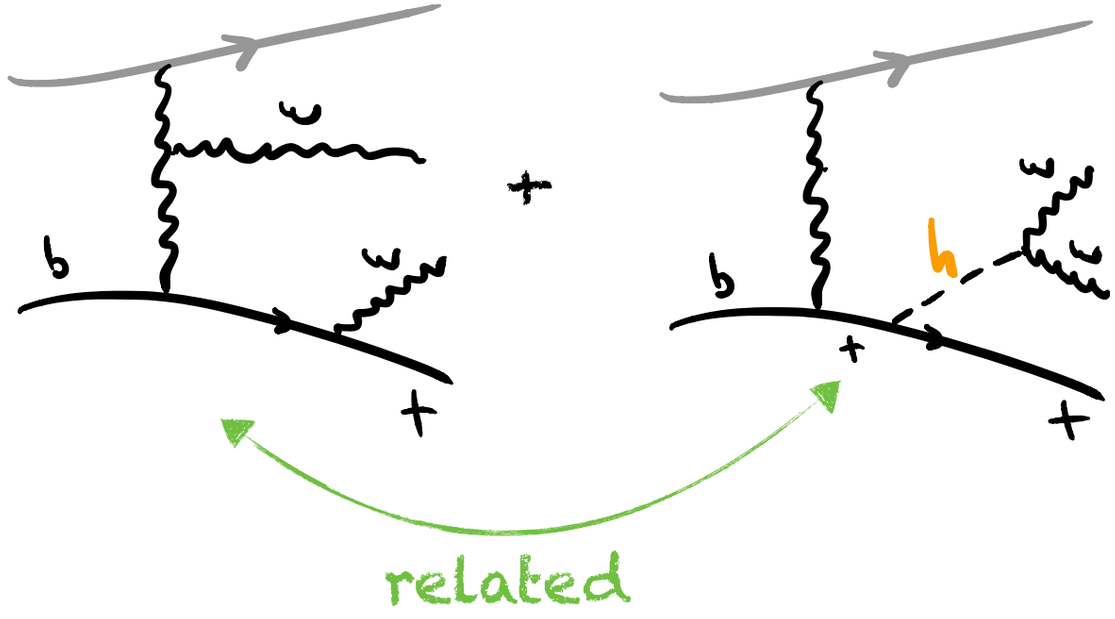
Higgs Couplings... without a Higgs (HwH)

Henning,Lombardo,Riembau,FR - PRL'19

It would be nice if Higgs Couplings would also deform distributions!

Any modifications of Higgs couplings induces
E^2 growth in some process with longitudinal W,Z bosons!

One way of seeing this:

SM = 

= finite

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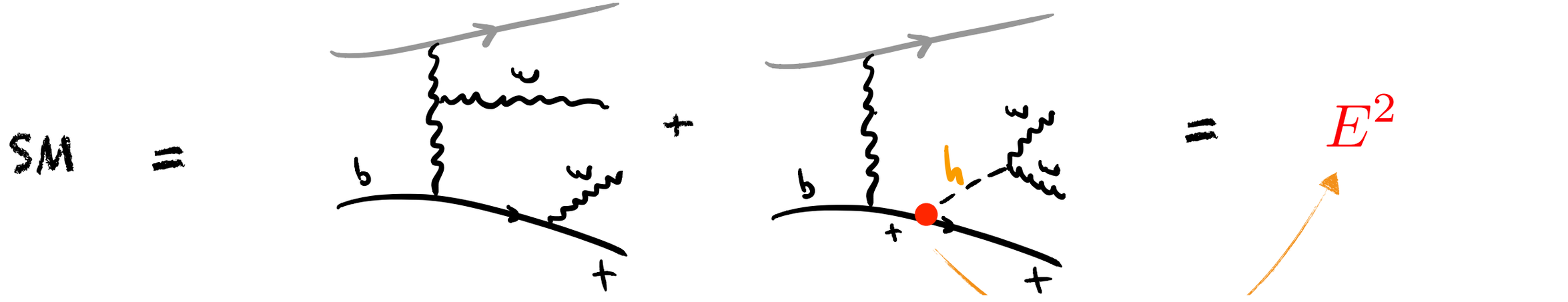

modification of top-yukawa
compromises gauge cancellations in the SM
▶ E-growth

Top Yukawa... without a Higgs

Another way of understanding E-growth:

modified Top-Yukawa κ_t $\Longleftrightarrow$ $\frac{|H|^2}{\Lambda^2} Q \tilde{H} t_R$

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$$H = \begin{pmatrix} \phi^+ \\ h + i\phi^0 \end{pmatrix}$$

Goldstones = W_L, Z_L

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

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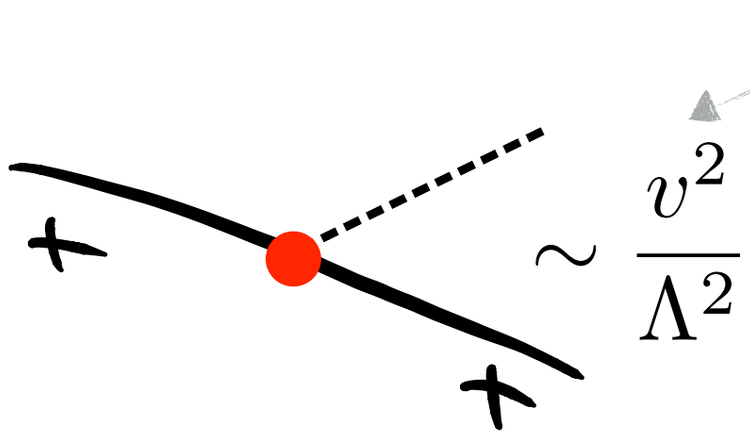

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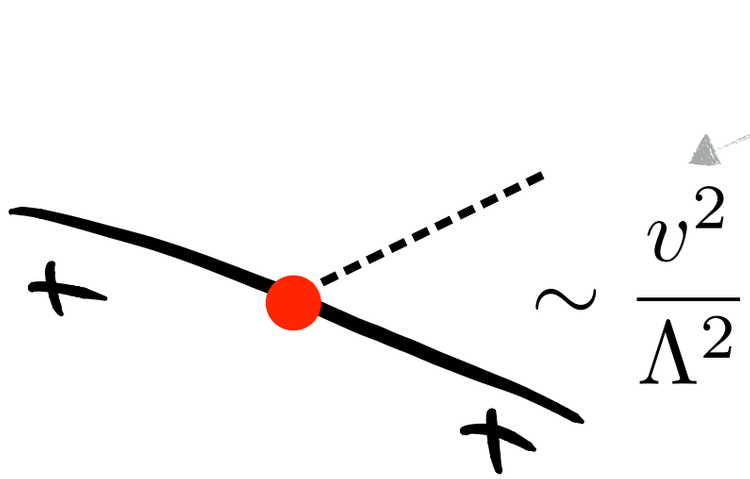

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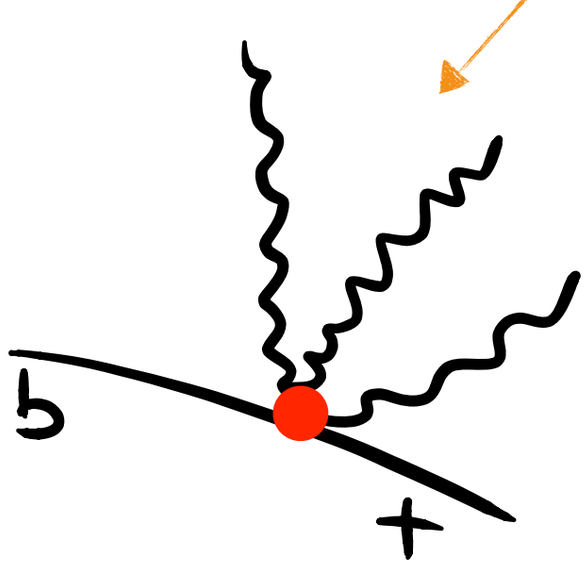

$$\sim \frac{E^2}{\Lambda^2}$$

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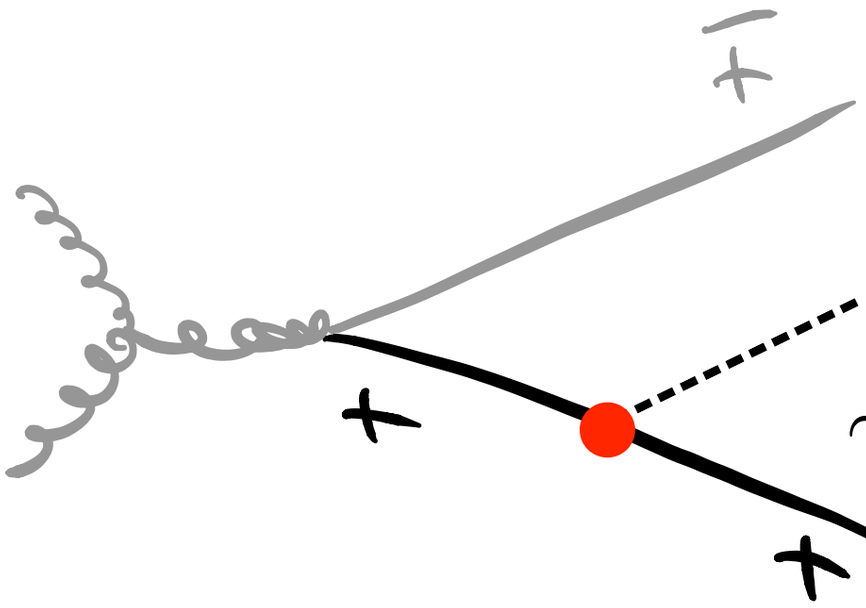

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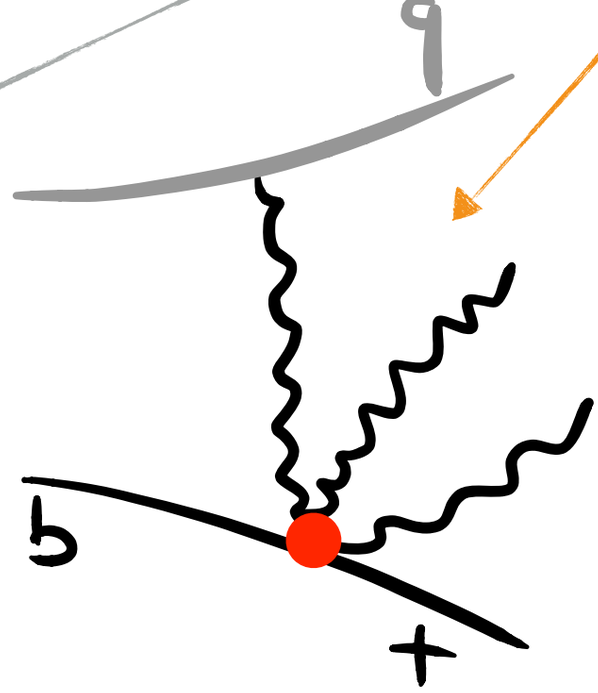

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statistics

signal

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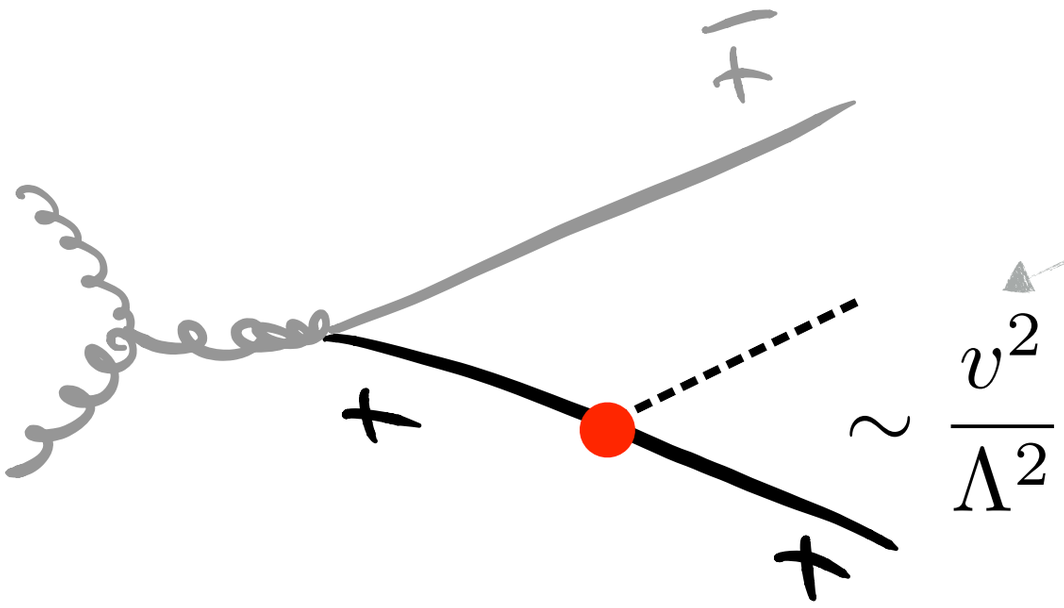

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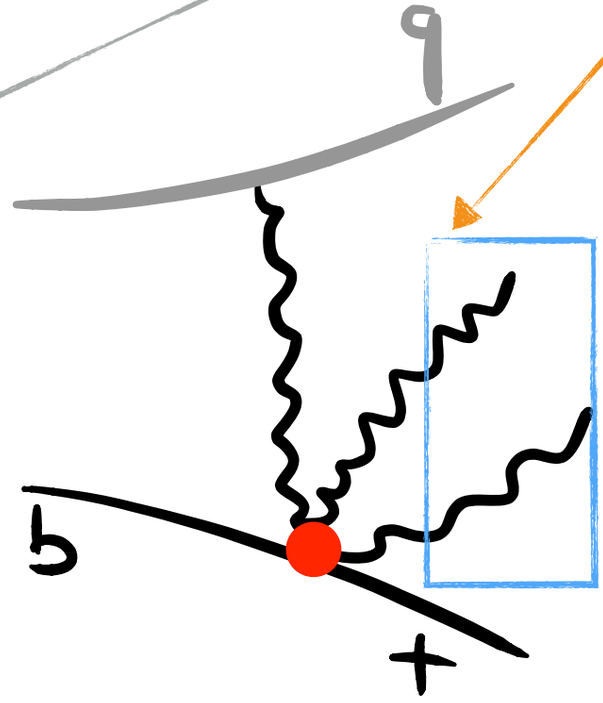

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Many final states (WW,WZ,ZZ)

statistics

signal

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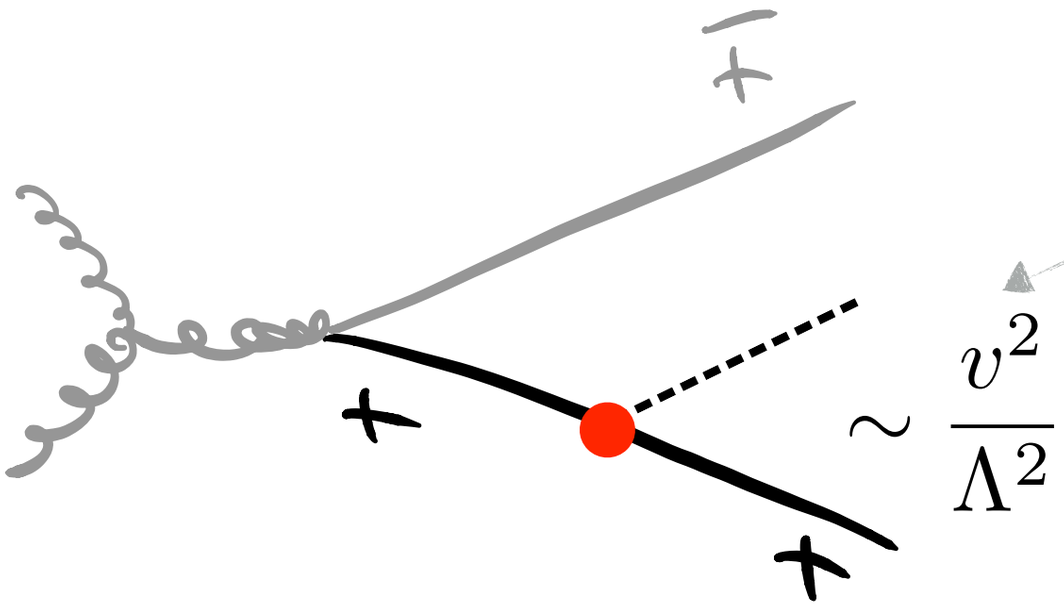

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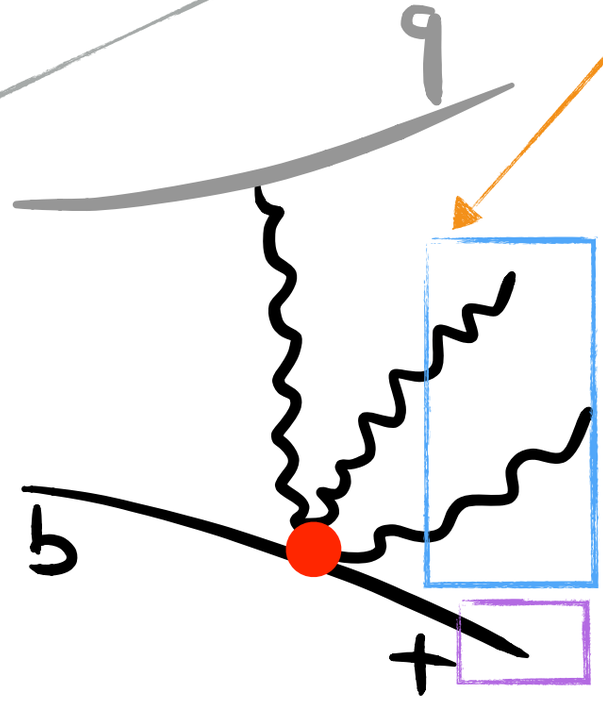

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Many final states (WW,WZ,ZZ)

Boosted top

statistics

signal

Top Yukawa... without a Higgs

$$pp \to VVjt$$

Top Yukawa... without a Higgs

$$pp \to VVjt$$

SM signal classified by #leptons:

Process	0ℓ	1ℓ	$\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$3\ell(4\ell)$
$W^\pm W^\mp$	3449/567	1724/283	216/35	-	-
$W^\pm W^\pm$	2850/398	1425/199	-	178/25	-
$W^\pm Z$	3860/632	965/158	273/45	-	68/11
ZZ	2484/364	-	351/49	-	(12/2)

$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

Top Yukawa... without a Higgs

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>2l: Small Background

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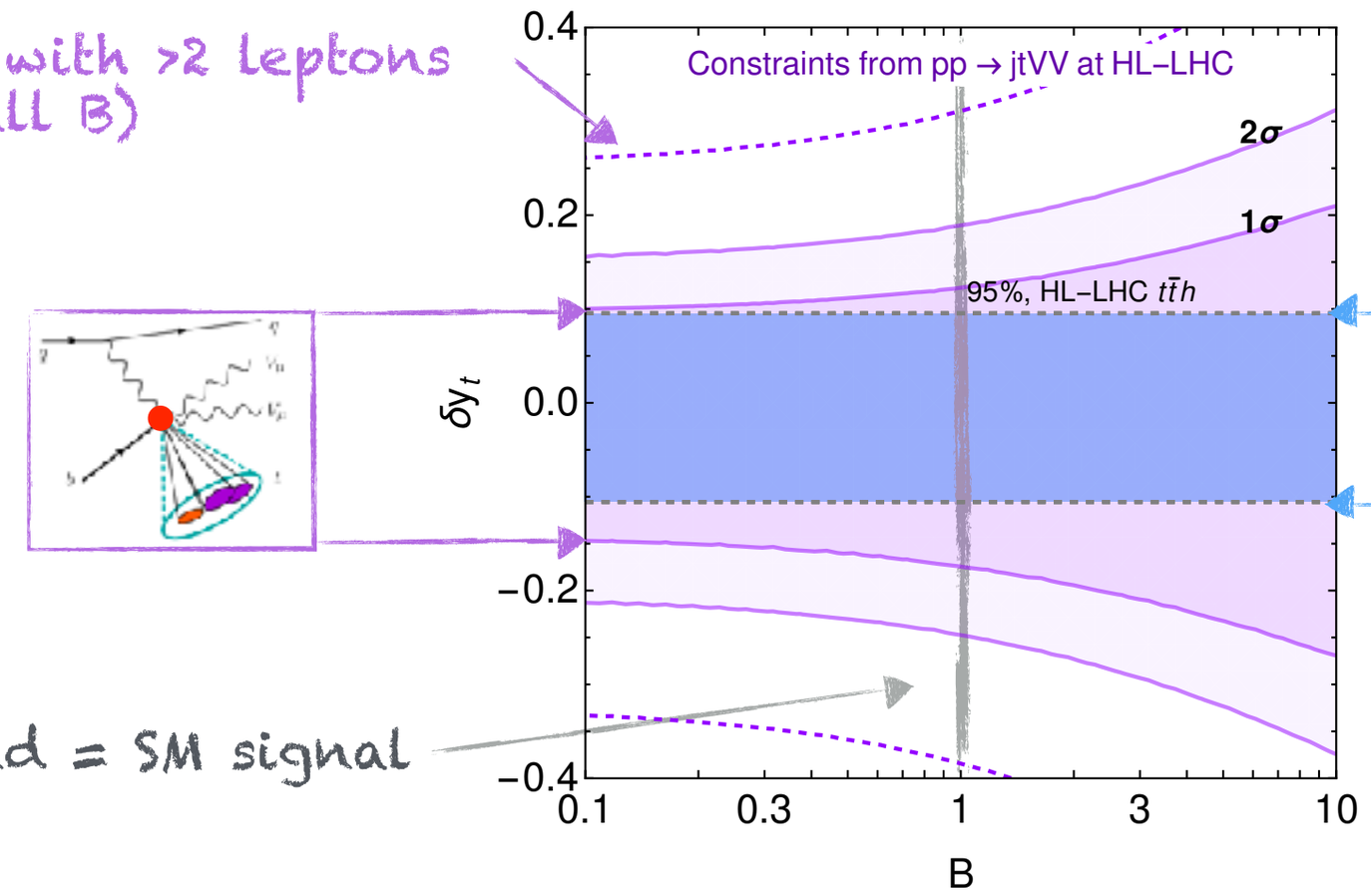
$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

only channels with >2 leptons (small B)



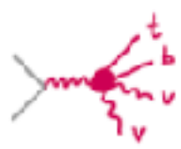
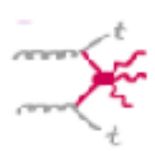
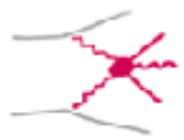
Background = SM signal

- Competitive with standard!

Top Yukawa... improvements

...work in progress...

Same amplitude enters in many channels...

Legs	Order	Diagram	Channels	Xsec[fb]	QCD bgnd	L/T
$1 \to 4$	QCD		$tW^{\pm}W^{\pm}W^{\mp}$	0.7	/	0.03
			$tW^{\pm}ZZ$	0.4	/	0.03
	EW		$tbW^{\pm}W^{\pm}$	3.5	/	0.10
			$tbW^{\pm}W^{\mp}$	3.5	/	0.20
			$tbW^{\pm}Z$	3.8	/	0.11
			$tbZZ$	0.02	0	0.09
$2 \to 3$	QCD^2		$ttZWW$	0.083	/	0.03
			$ttZZZ$	0.008	/	0.04
			$tbWWW$	19	/	0.04
			$tbWZZ$	3.8	/	0.07
	EW^2		ttZ	0.1	/	0.29
			$ttW^{\pm}$	0.3	/	0.32
			tbZ	0.2	/	0.31
			$tbW^{\pm}(SS)$	0.9	2	0.29
			$tbW^{\pm}(OS)$	19	/	0.45
	$EW * QCD$		$tbW^{\pm}W^{\mp}$	75	467	0.15
			$tbW^{\pm}W^{\pm}$	75	458	0.13
			$tbW^{\pm}Z$	26	215	0.15
			$tbZZ$	4	0	0.07
			$tW^{\pm}W^{\mp}W^{\pm}$	0.7	/	0.03
			$tW^{\pm}ZZ$	0.4	/	0.03
			$tW^{\pm}W^{\mp}$	9	7.15	0.09
			$tW^{\pm}W^{\pm}$	8	6.44	0.10
			$tW^{\pm}Z$	9	75.4	0.07
			tZZ	5	2.64	0.07

signal in longitudinal polarizations

t-channel gluon

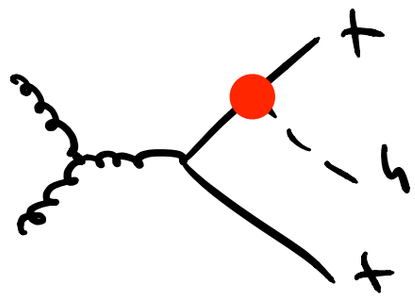
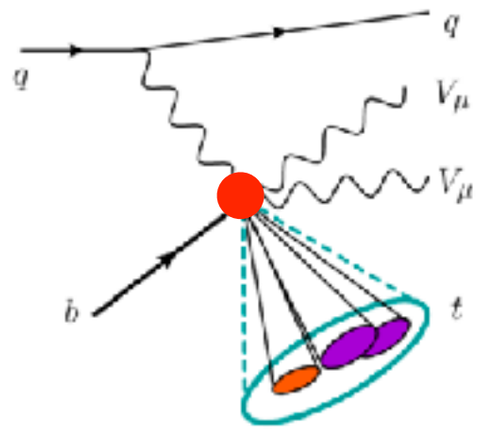
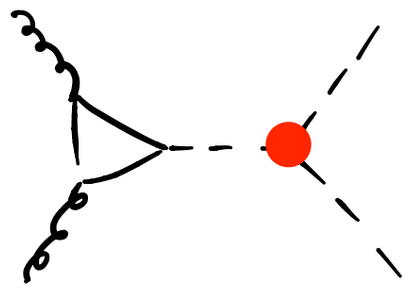
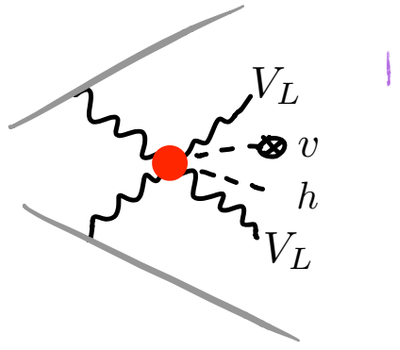
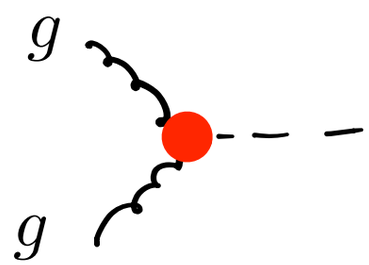
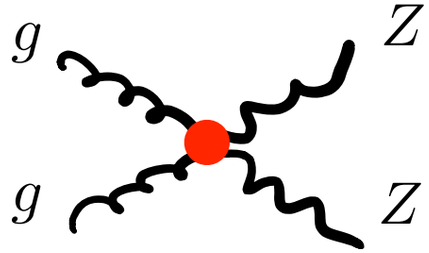
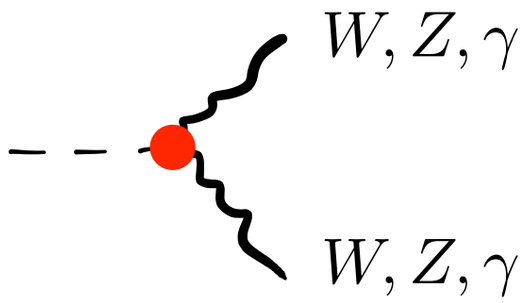
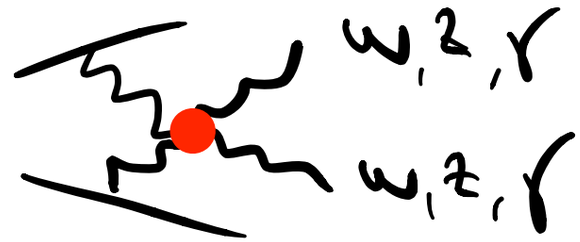
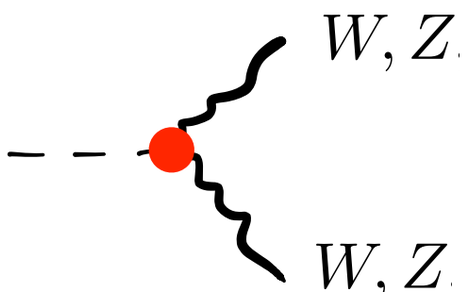
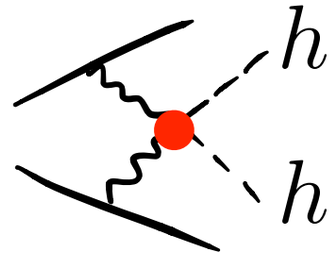
so far

Further improvements:

more channels

background estimate

differential distributions (into larger E^2)

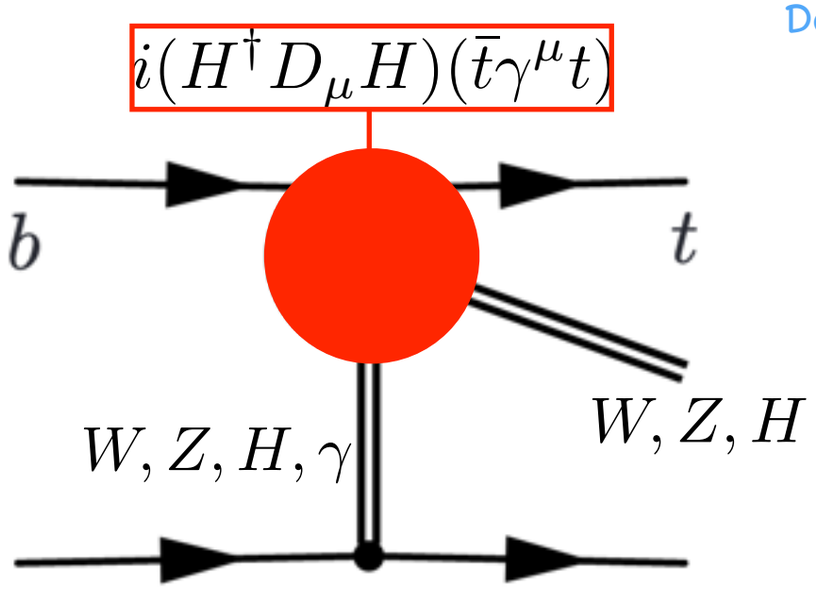
HwH Program		$\sim const$	$\sim E^2$
κ_t	$\lvert H\rvert^2 Q\tilde{H}t_R$		
κ_λ	$\lvert H\rvert^6$		
κ_G	$\lvert H\rvert^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\kappa_{Z\gamma}$	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\lvert H\rvert^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V	$\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

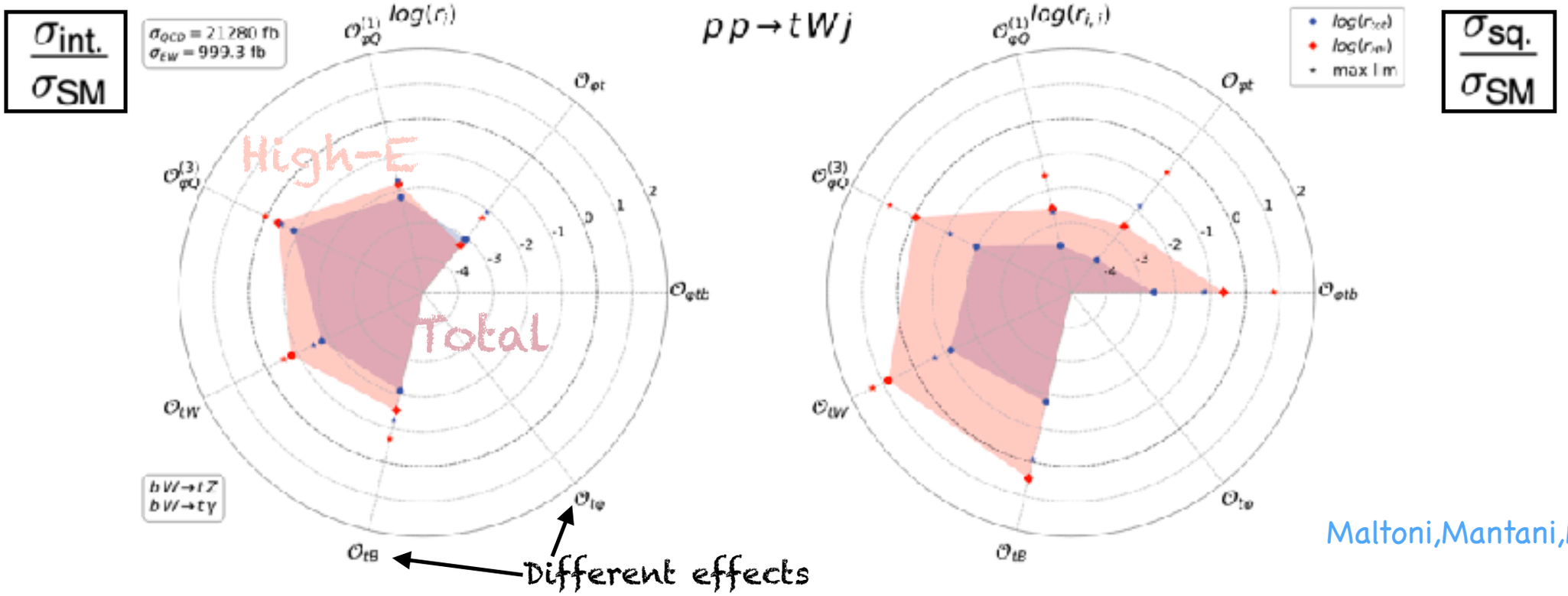
More Top and Higgs at High-Energy

Top-Higgs: well motivated by naturalness

Other Top-Higgs effects grow in single-top

Dror,Farina,Salvioni,Serra'16
Degrande,Maltoni,Mimasu,Vryonidou,Zhang'18





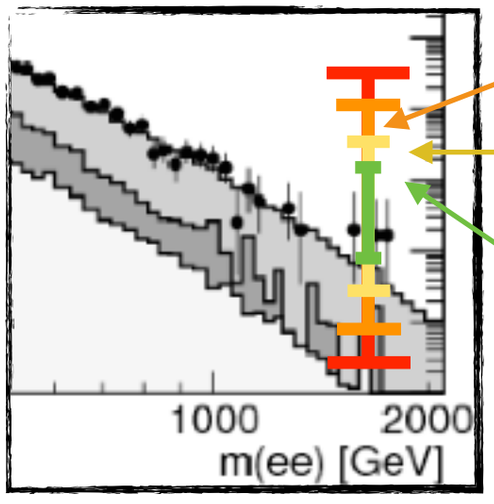
Maltoni,Mantani,Mimasu'19

Message

- More luminosity -> access to new observables:
  - high-energy tails
  - multidifferential distributions
  - multiboson processes

- Important to tailor analysis to BSM effects in form of EFT operators

- Many opportunities for improvement (contrary to HC):



Precise SM theoretical predictions

LHC Experimental control of systematics

BSM understanding