# High-Energy Tests of a Low-Energy Theory

## -Transverse Vectors-


Francesco Riva
(Université de Genève)

In collaboration with
Bellazzini 1806.09640
Bellazzini,Serra,Sgarlata,1706.03070
Panico, Wulzer 1708.07823,
Azatov, Contino, Machado 1607.05236
Liu,Pomarol,Rattazzi, 1603.03064

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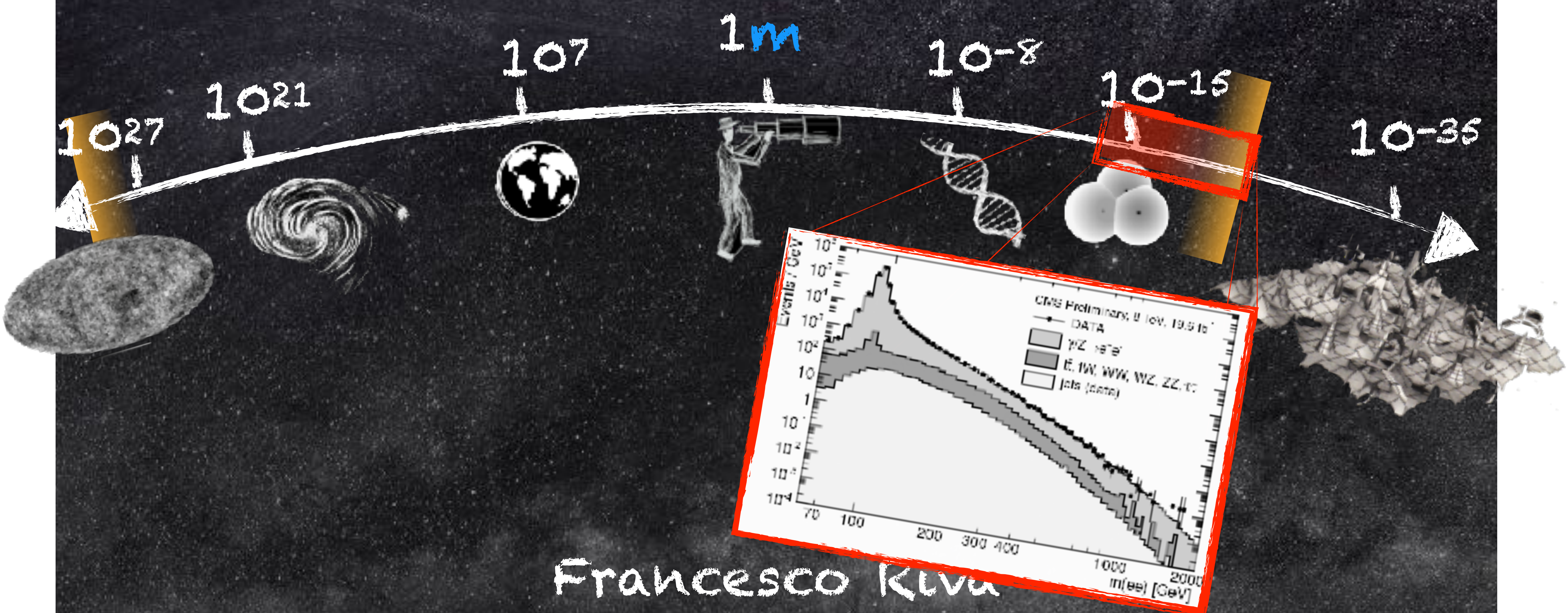



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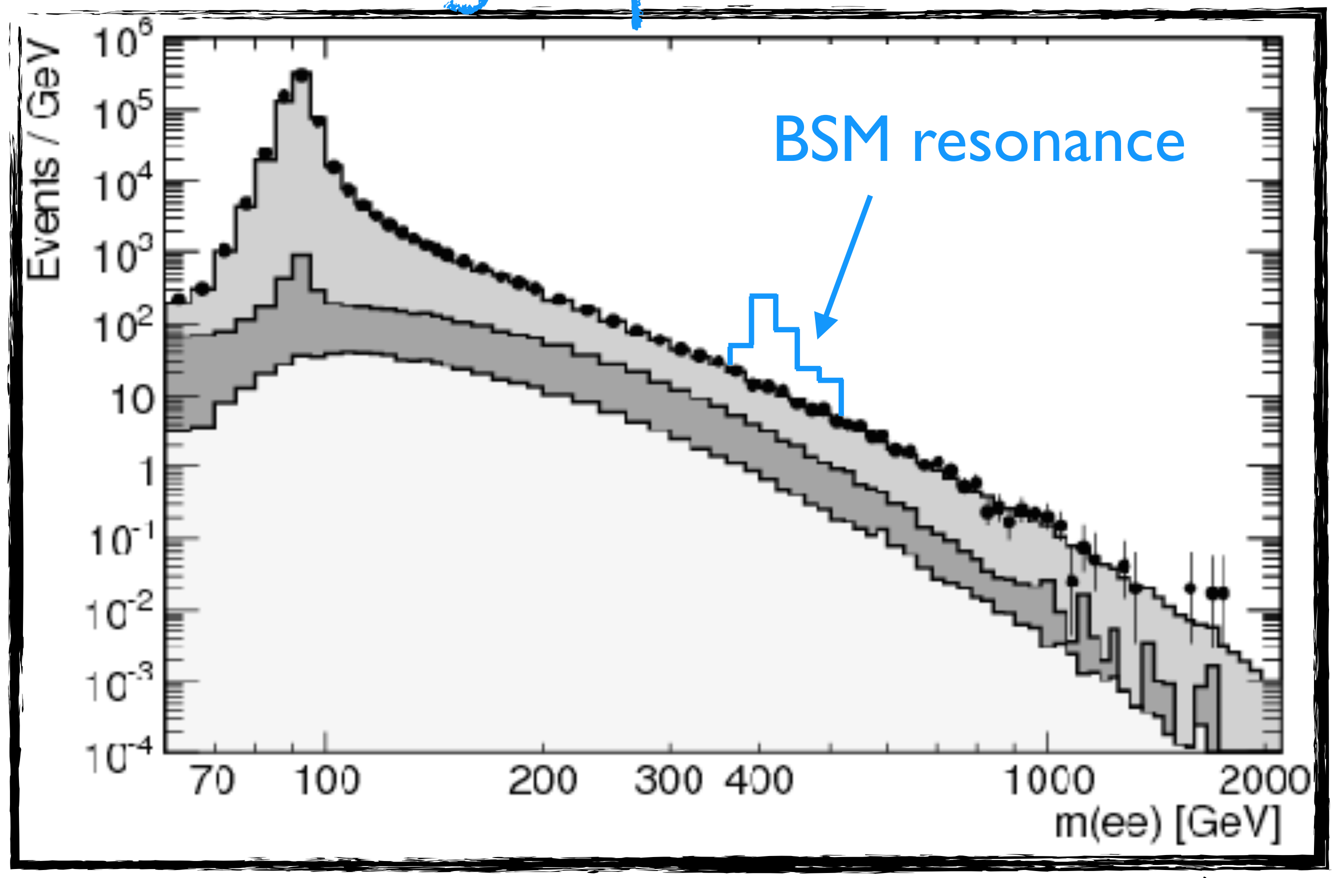
# Collider Exploration
(so far)

Focus: Search for new light particles



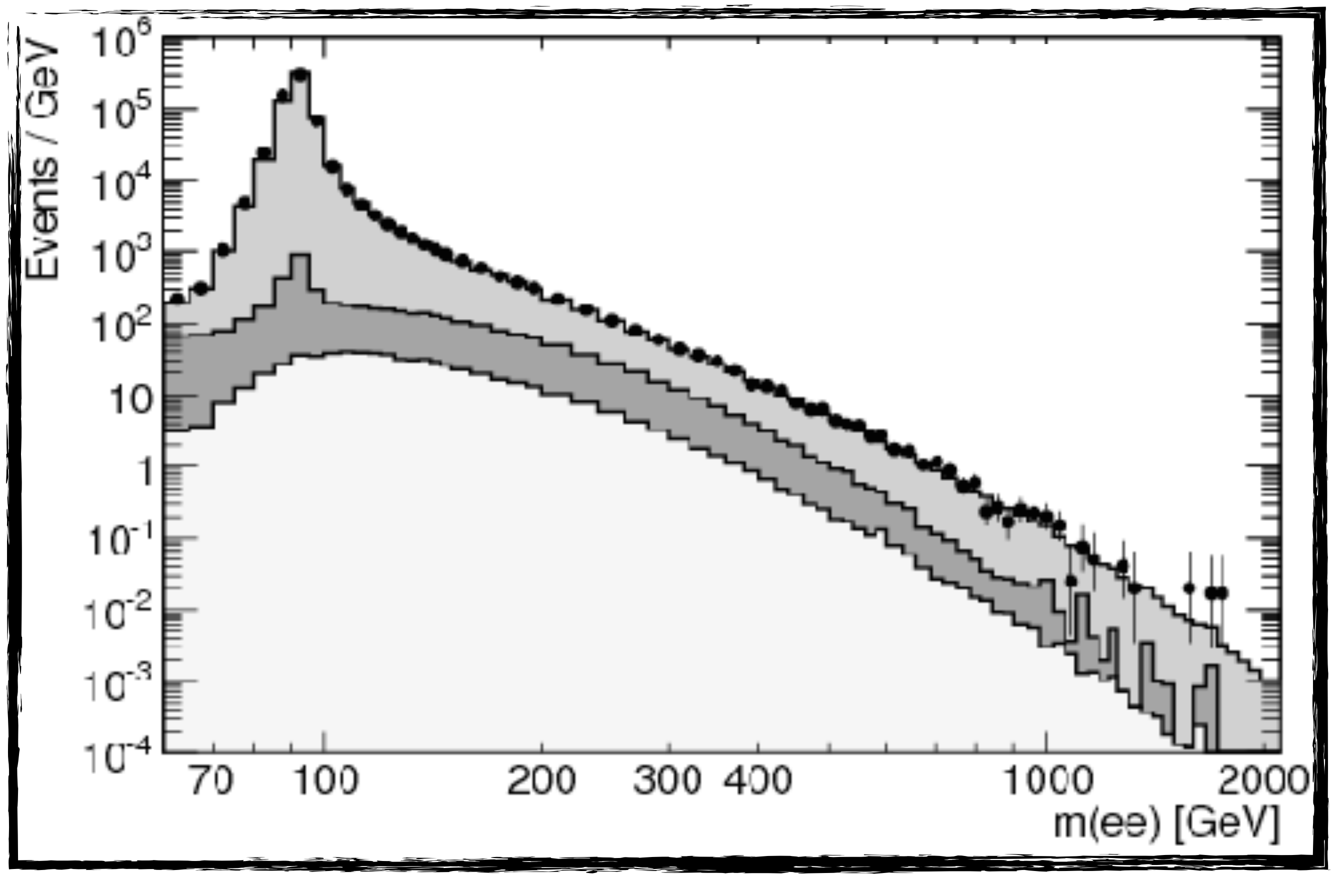

Energy frontier (13 TeV)

# Collider Exploration
## (from now)

**Focus: Standard Model Precision Tests**

(2035: 3000 fb-1)

intensity frontier



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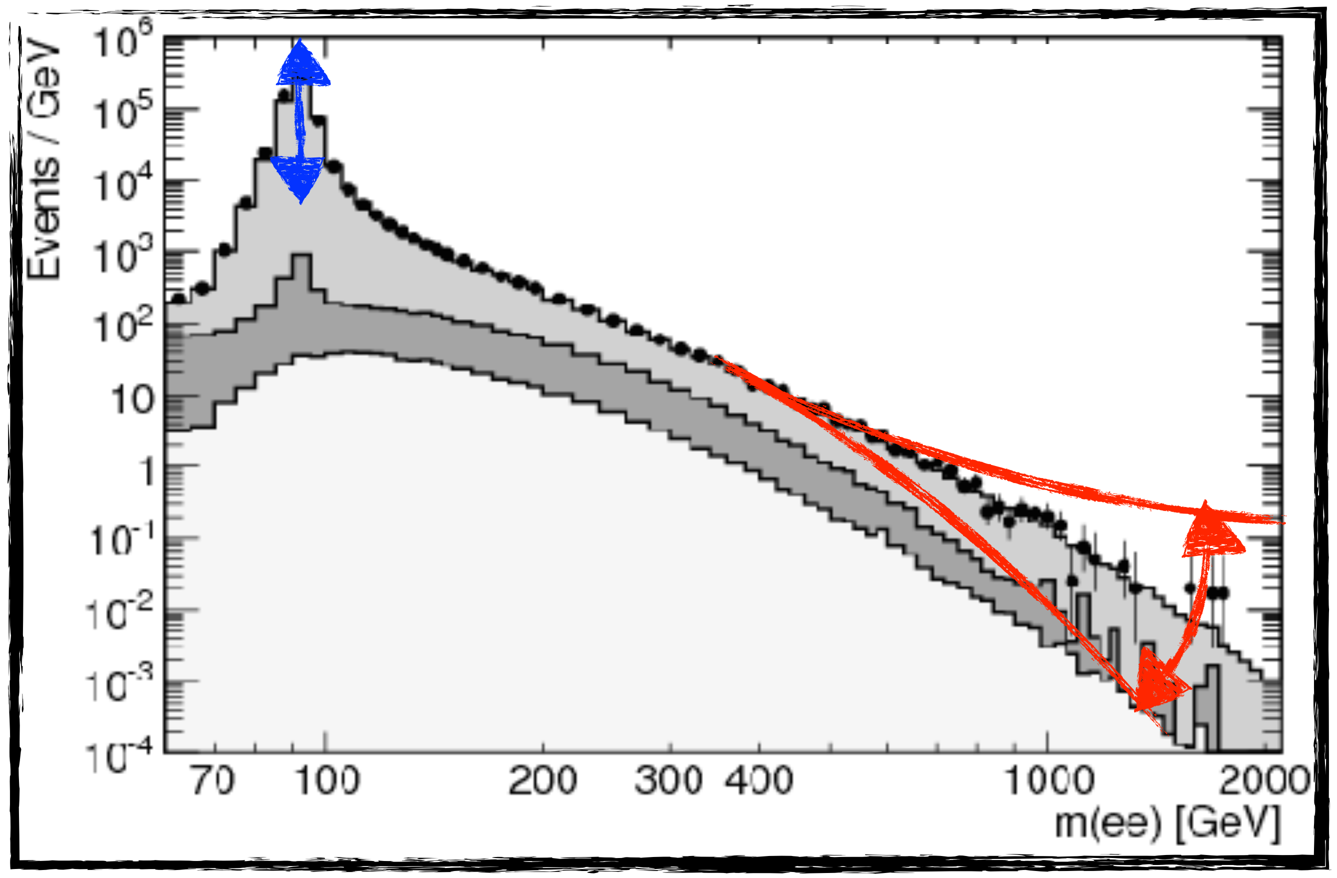
(2035: 3000 fb$^{-1}$)

intensity frontier



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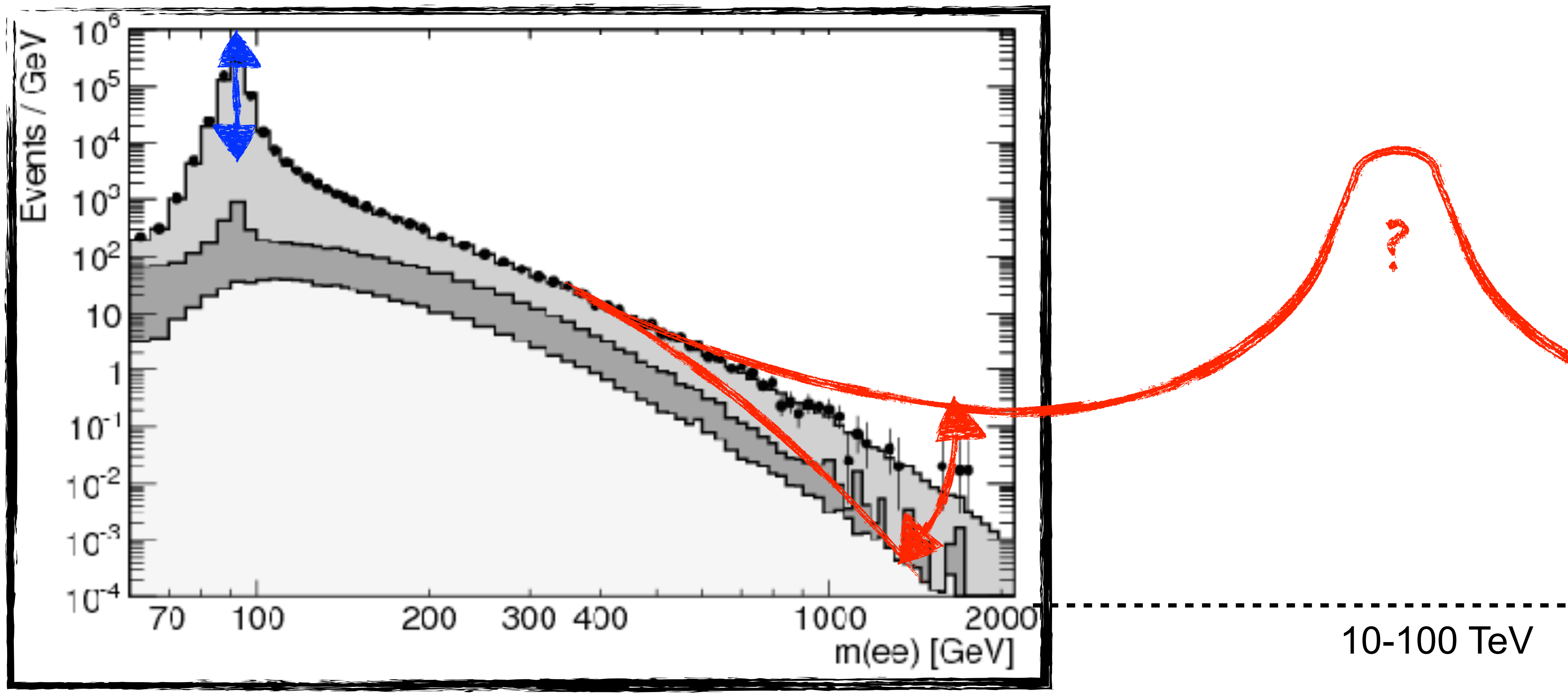

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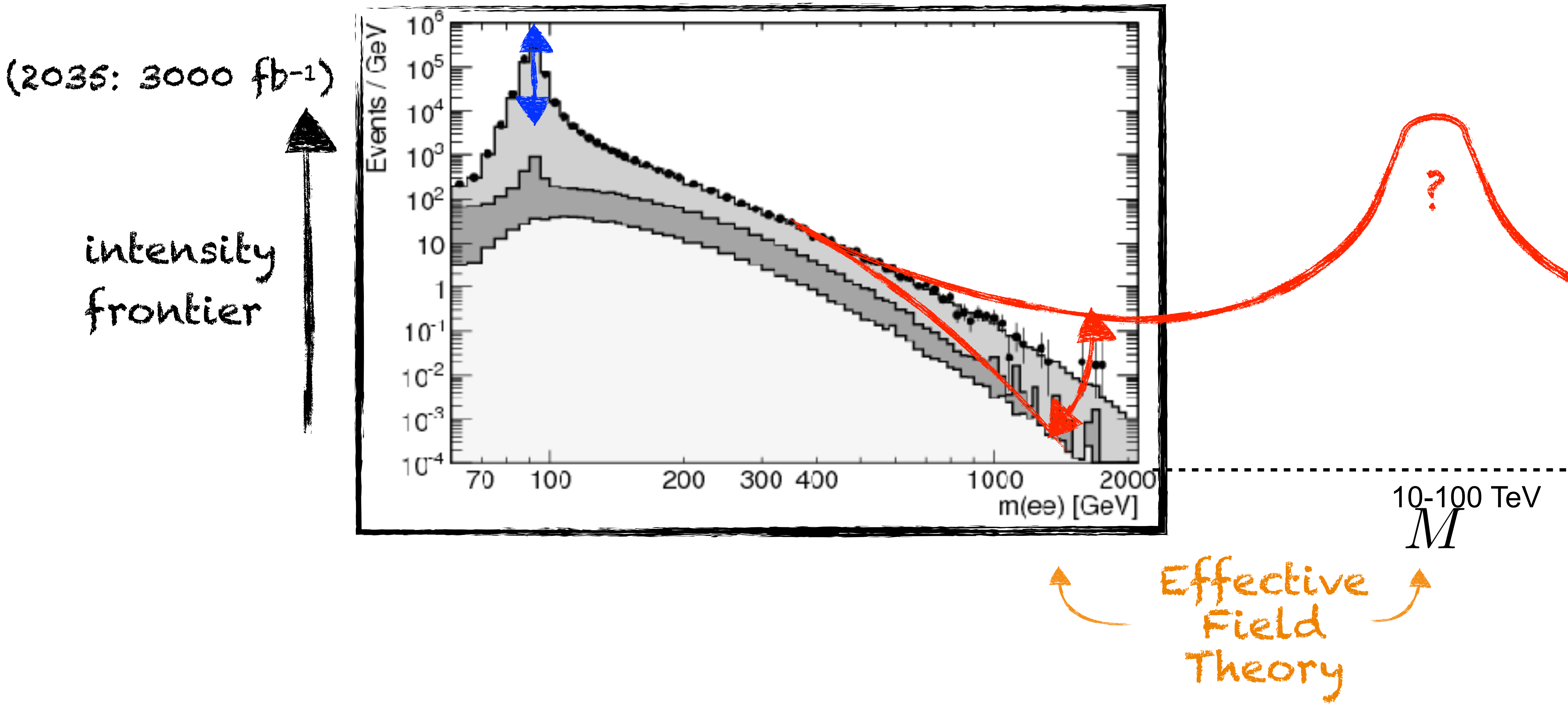

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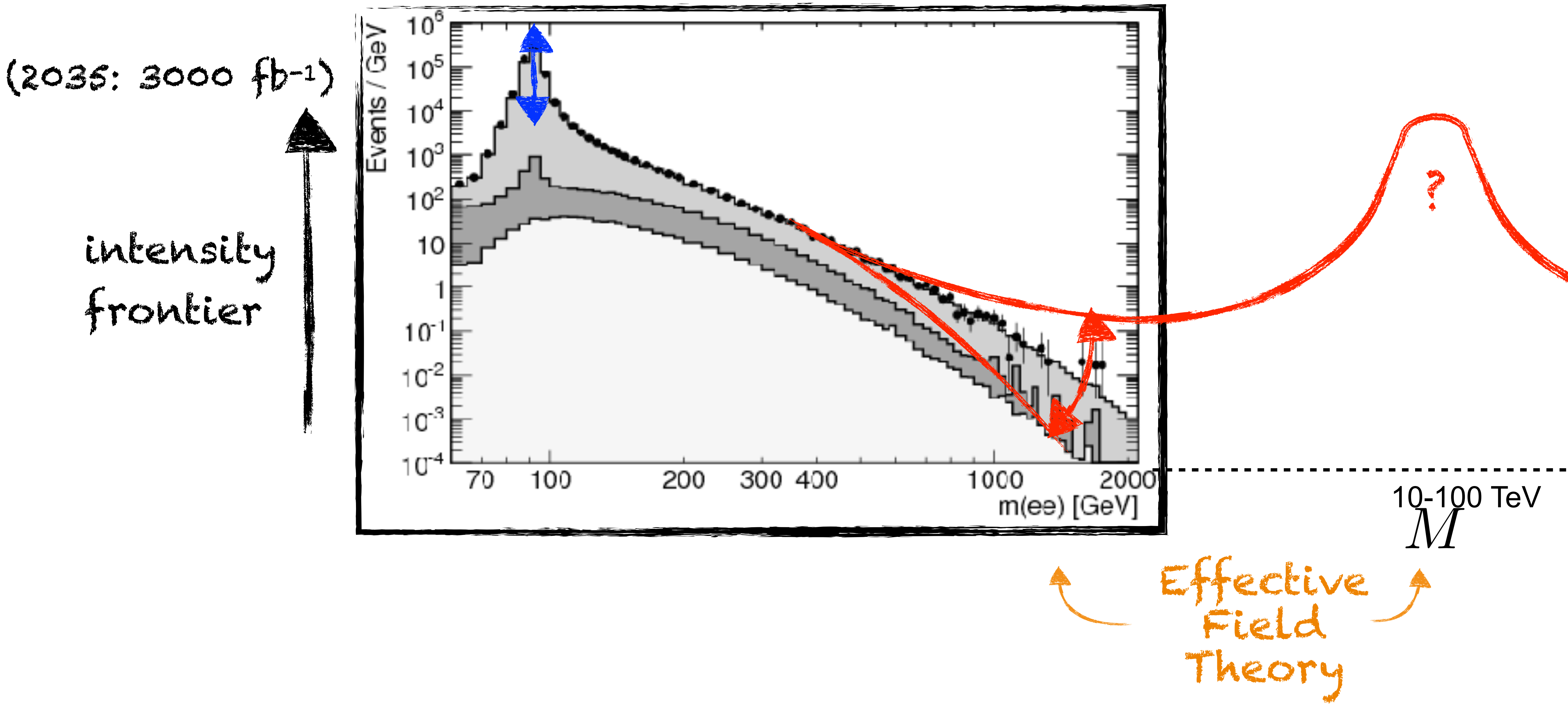


- Experimentally: Larger couplings → more visible effects
- Theoretically: strong coupling → radical departures from SM

# Collider Exploration
(from now)

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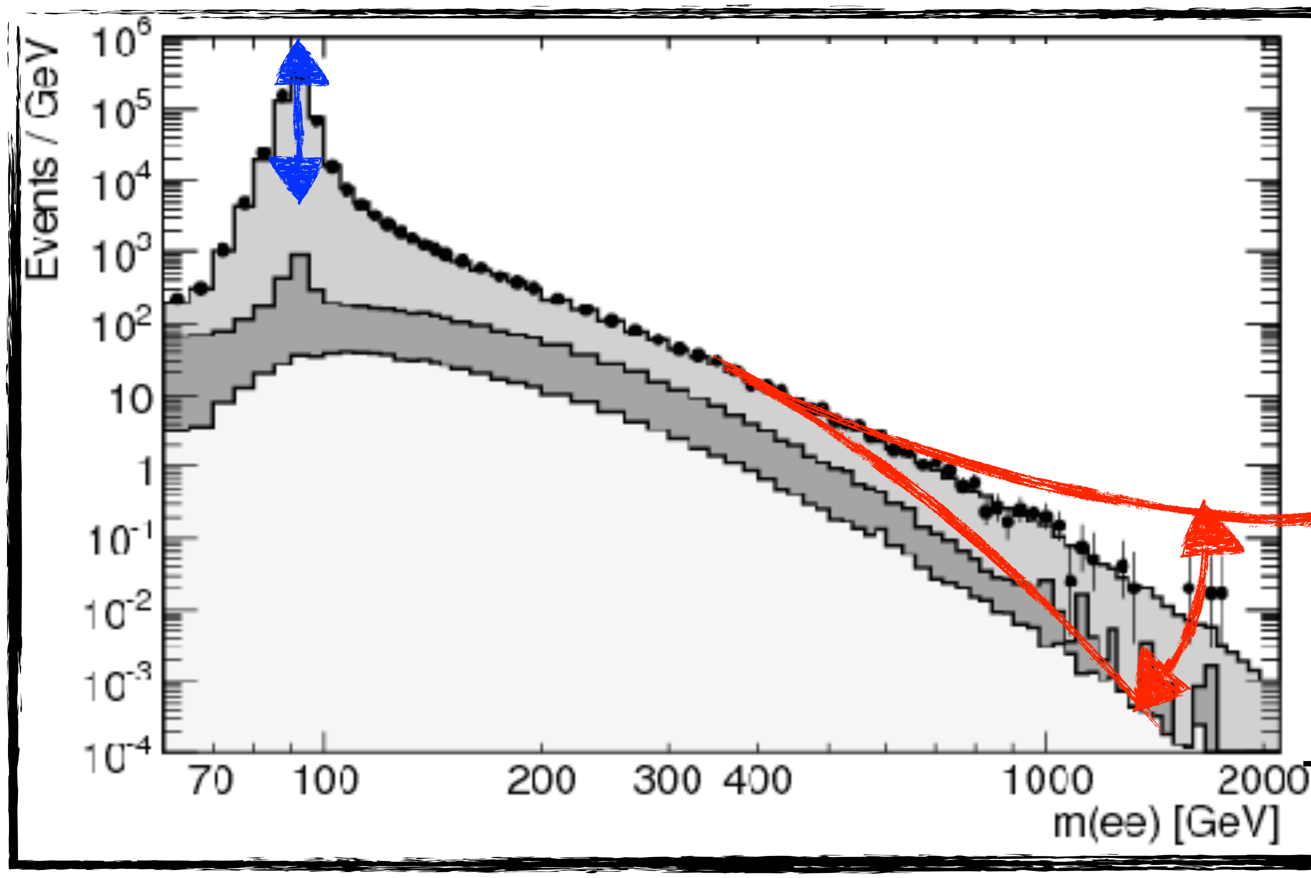
intensity frontier




(UV dof ≠ IR dof)

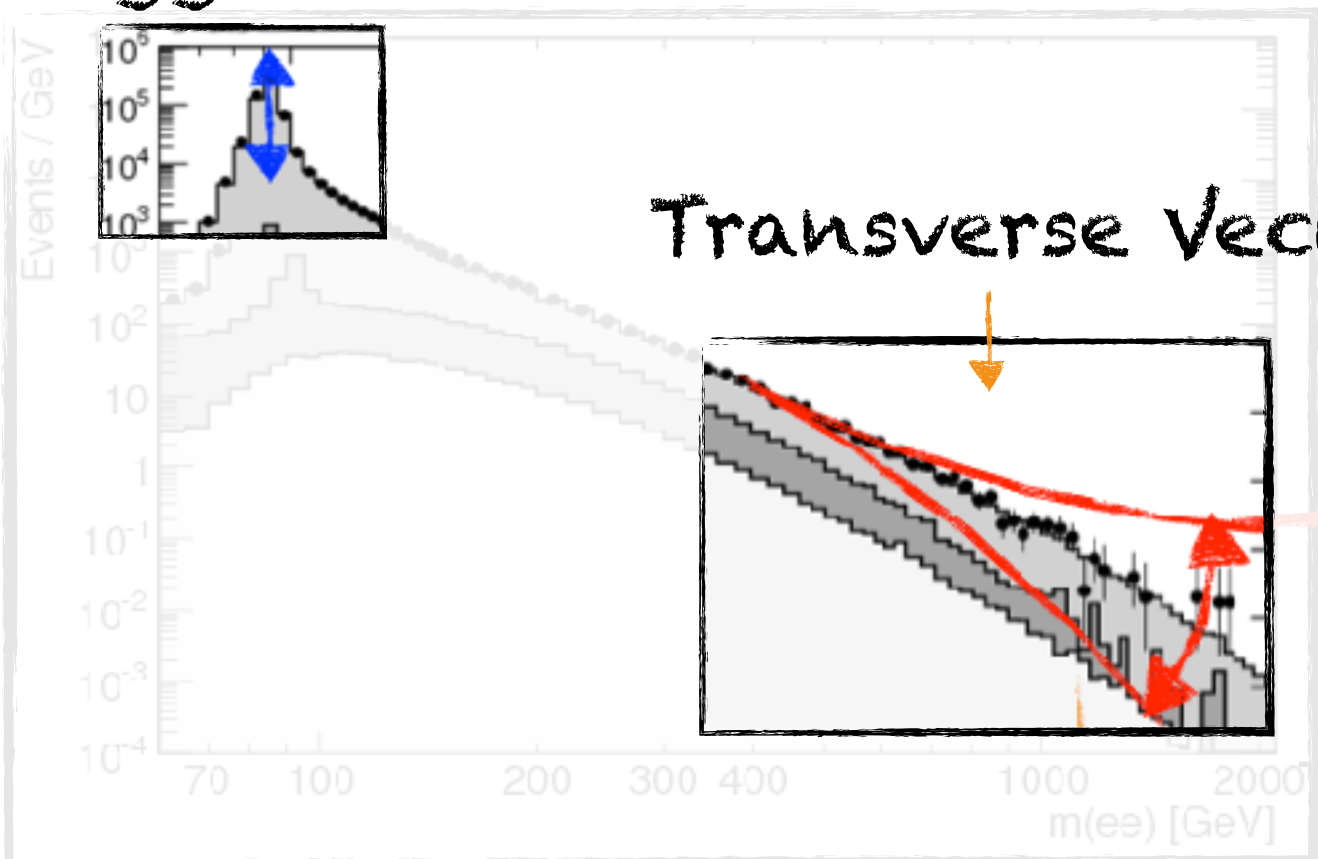
Effective Field Theory

- **Experimentally:** Larger couplings → more visible effects
- **Theoretically:** strong coupling → radical departures from SM

# Transverse Vectors => High Energy

Couplings $\sim \frac{v^2}{M^2}$

→ Higgs




Outline:

- No Interference and Resurrections (WW,WZ,Wγ)
- 8: before 6 (ZZ,Zγ)

# Transverse Vectors and Non-Interference

$\delta_{BSM} = c\frac{E^2}{M^2}$

$$\sigma \propto |Amp|^2 \simeq SM^2(1 + \delta_{BSM} + \delta_{BSM}^2)$$

Leading for
$1 \gg \delta_{BSM}$

# Transverse Vectors and Non-Interference

$$\delta_{BSM} = c\frac{E^2}{M^2}$$

$$\sigma \propto |Amp|^2 \simeq SM^2(1 + \delta_{BSM} + \delta^2_{BSM})$$

Leading for
$1 \gg \delta_{BSM}$

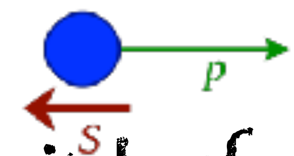
Small effects
->smaller
$\delta_{BSM} \gg \delta^2_{BSM}$

# 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 dont 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 |
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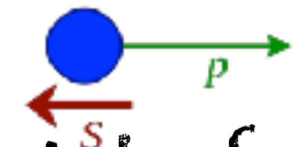


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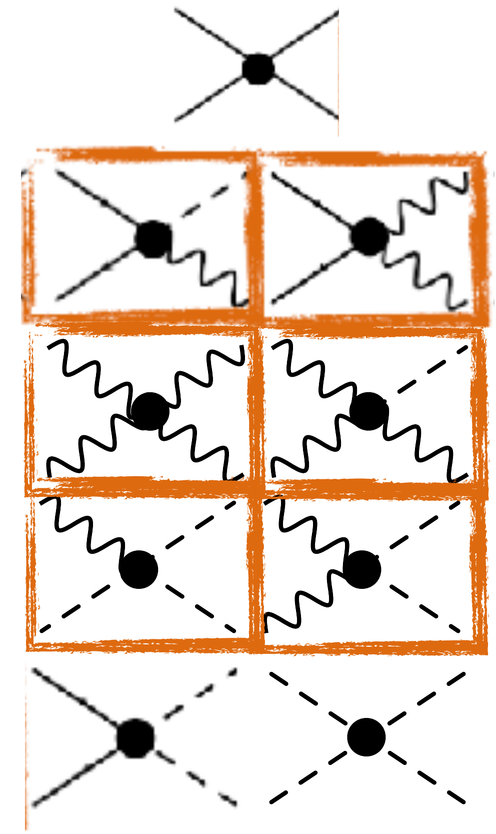
Different helicity

⇓

No-Interference

⇓

Poor Measurement



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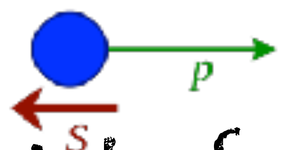


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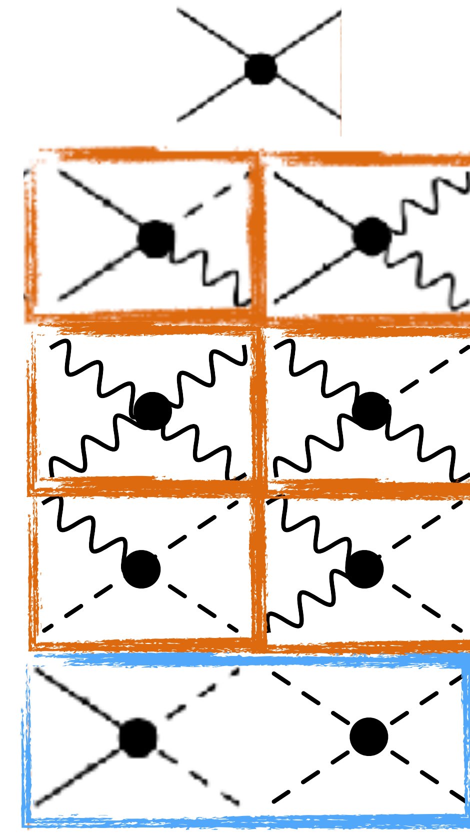

Small in inclusive xsec

# Non-Interference

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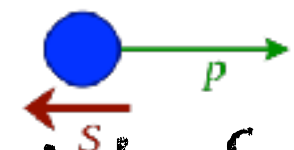


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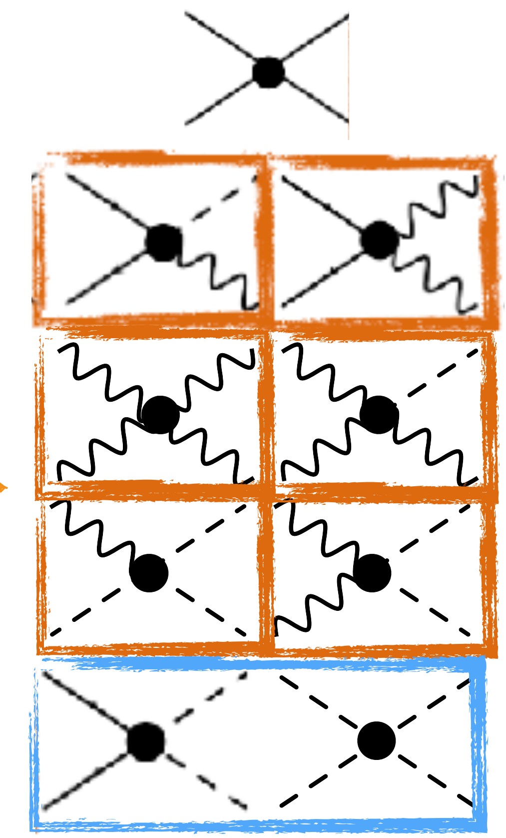
Different helicity

⇩

No-Interference

⇩

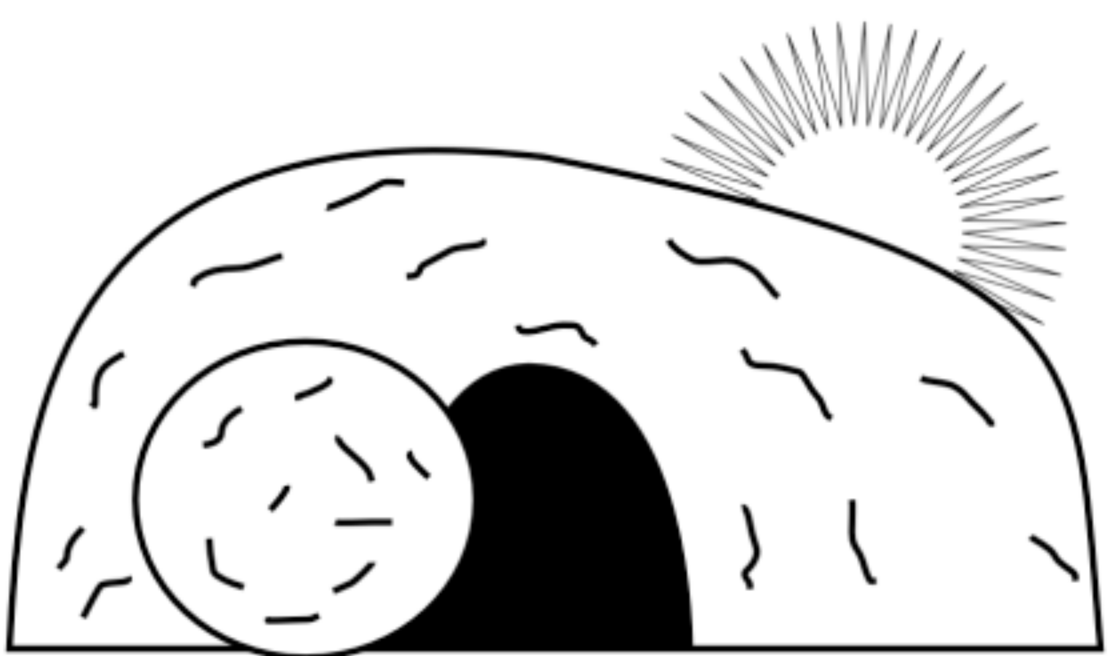
Poor Measurement



Small in inclusive xsec

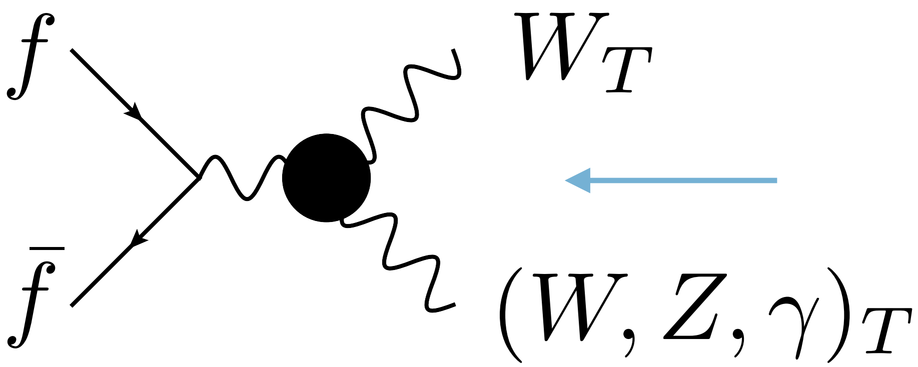
(See Wulzer's talk)

# WW, WZ, Wγ and their resurrection



# Interference Resurrection

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

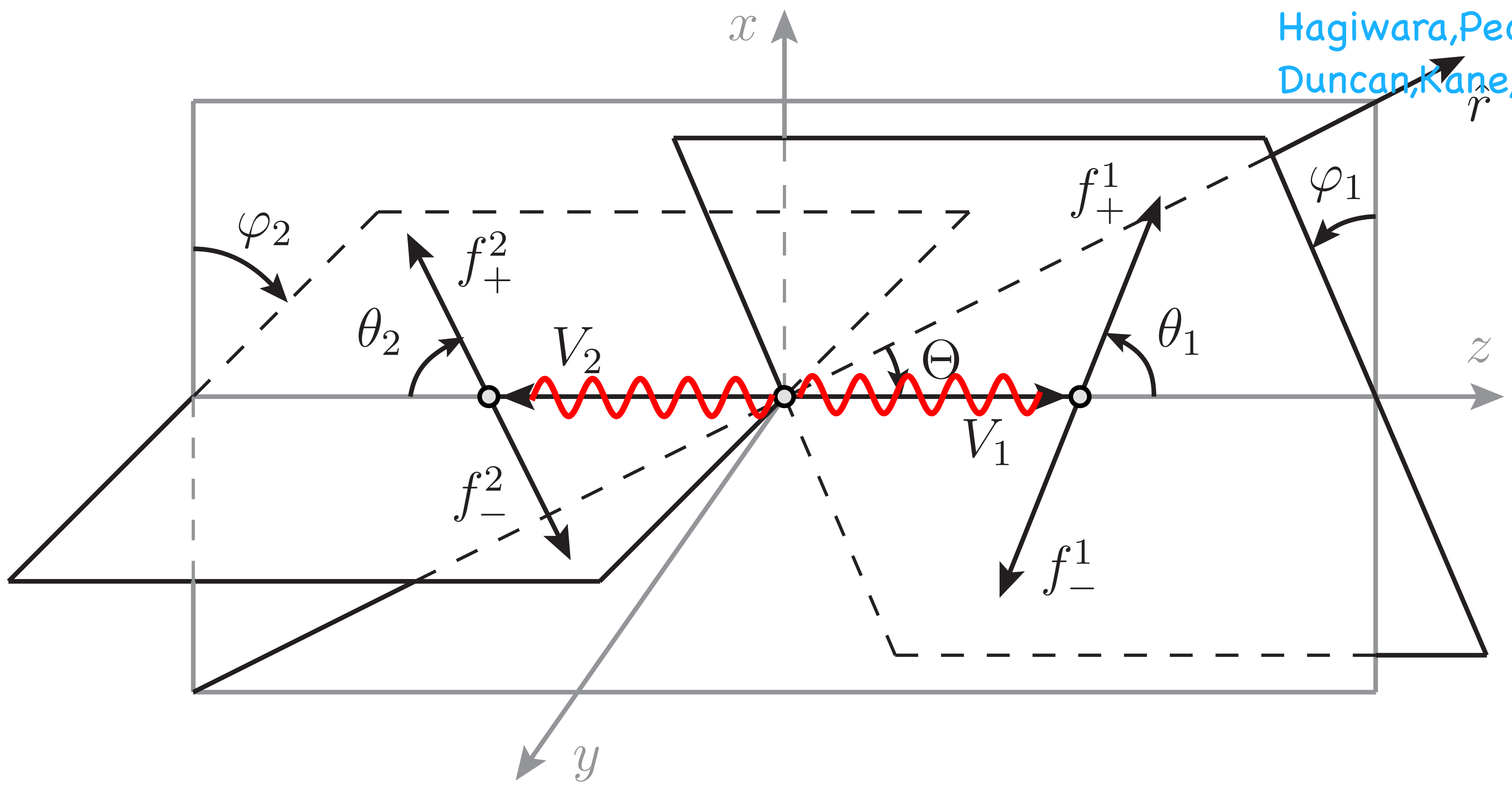



$$\epsilon_{abc} W_{\mu}^{a\,\nu} W_{\nu\rho}^{b} W^{c\,\rho\mu} \quad \text{CP-even}$$

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

# Differential measurements WW, WZ

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




$V_{1,2}$: Helicity ±∓/±± in SM/BSM

- Quantum mechanically different, no interference

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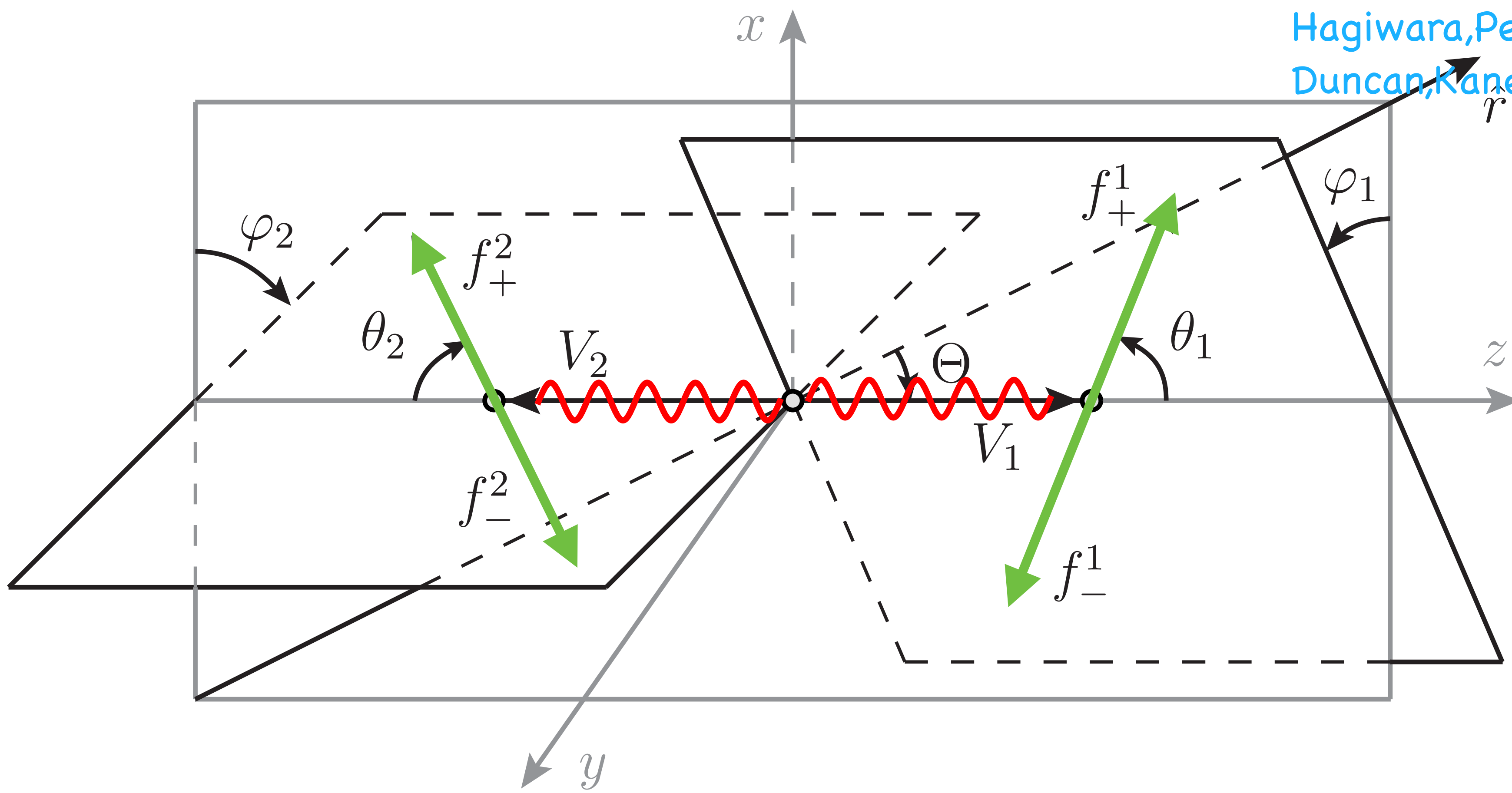


$V_{1,2}$: Helicity ±∓/±± in SM/BSM

- Quantum mechanically different, no interference

$f_{(1,3)}$ $f_{(2,4)}$: Helicity +1/2 −1/2 in SM and in BSM

- QM same, interference possible

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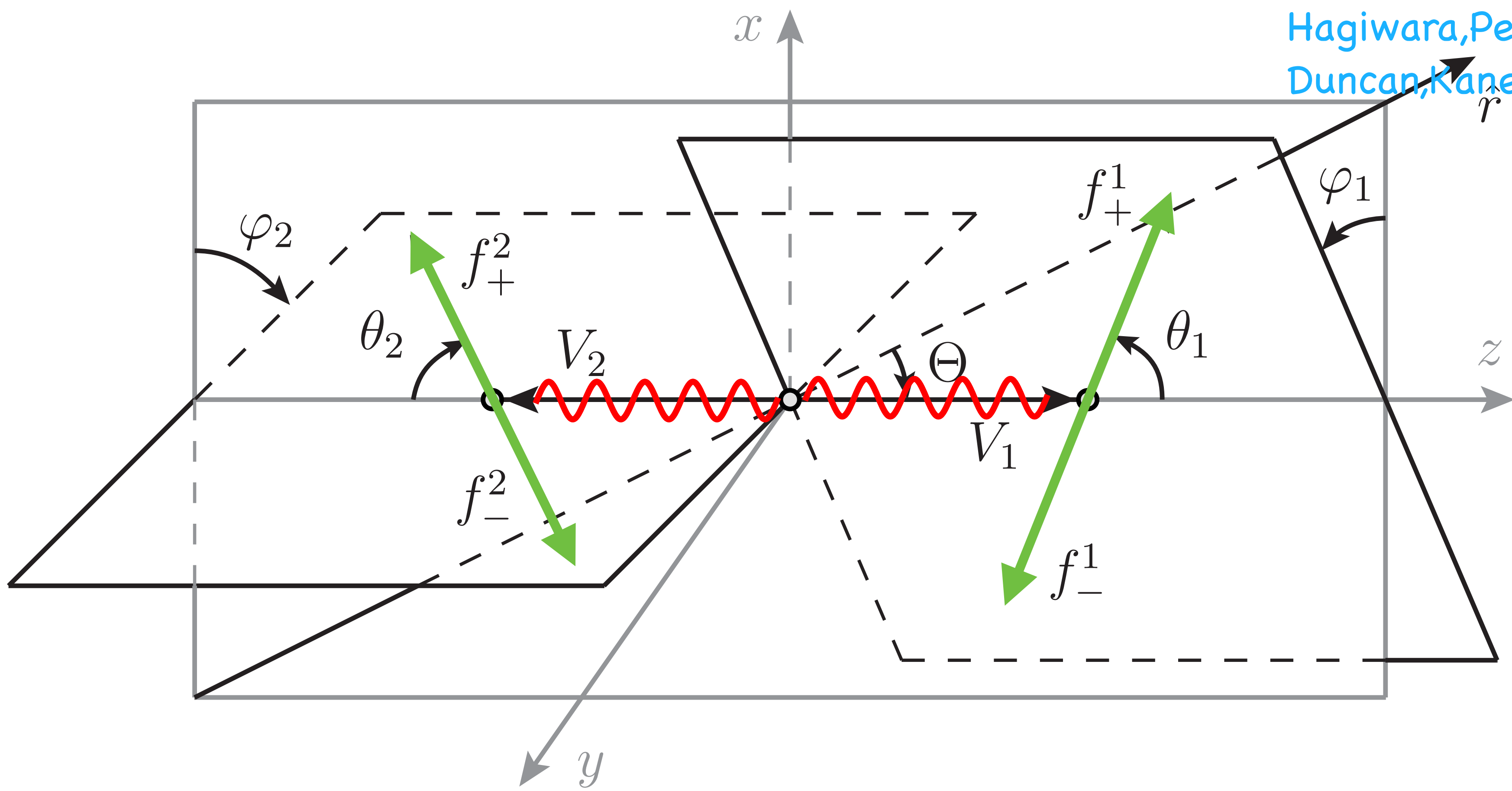


$(h_1 - h_1', h_2 - h_2')$

$$Int^{\mathrm{CP}} \propto \mathcal{A}^{\mathrm{SM}}_{\mathbf{h}} \mathcal{A}^{\mathrm{BSM}+}_{\mathbf{h}'} \cos\left[\mathbf{\Delta h} \cdot \boldsymbol{\varphi}\right]$$

$(+1,-1)$ $(+1,+1)$ $(\varphi_1, \varphi_2)$

$$Int^{\not{C}\mathrm{P}} \propto \mathcal{A}^{\mathrm{SM}}_{\mathbf{h}} \mathcal{A}^{\mathrm{BSM}-}_{\mathbf{h}'} \sin\left[\mathbf{\Delta h} \cdot \boldsymbol{\varphi}\right]$$

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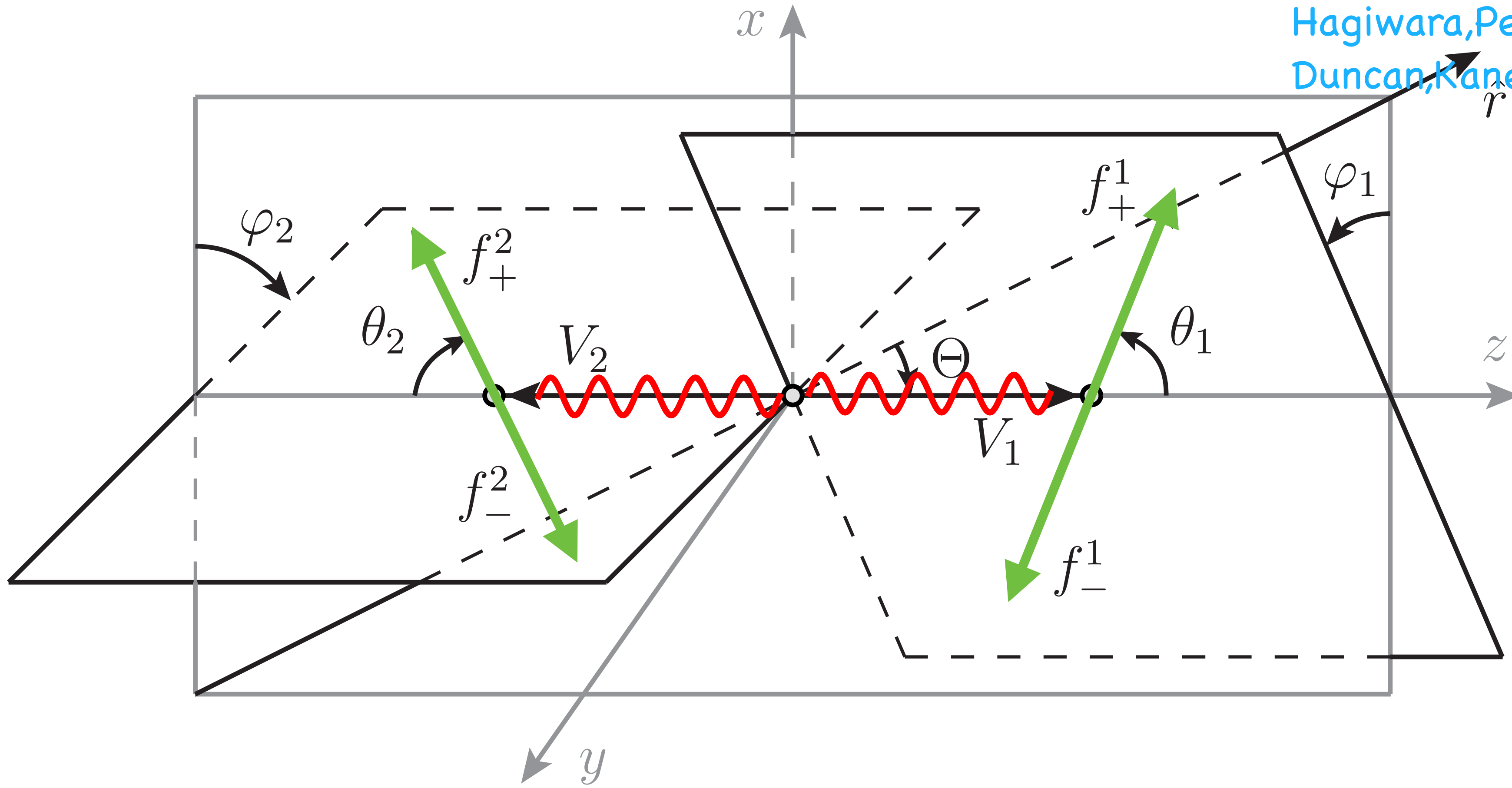



$(h_1 - h'_1, h_2 - h'_2)$

$$Int^{\rm CP} \propto \mathcal{A}^{\rm SM}_{\mathbf{h}} \mathcal{A}^{\rm BSM+}_{\mathbf{h}'} \quad \cos\left[\mathbf{\Delta h}\cdot\boldsymbol{\varphi}\right]$$

$(+1,-1)$ $(+1,+1)$ $(\varphi_1, \varphi_2)$

$$Int^{\not{\rm CP}} \propto \mathcal{A}^{\rm SM}_{\mathbf{h}} \mathcal{A}^{\rm BSM-}_{\mathbf{h}'} \quad \sin\left[\mathbf{\Delta h}\cdot\boldsymbol{\varphi}\right]$$

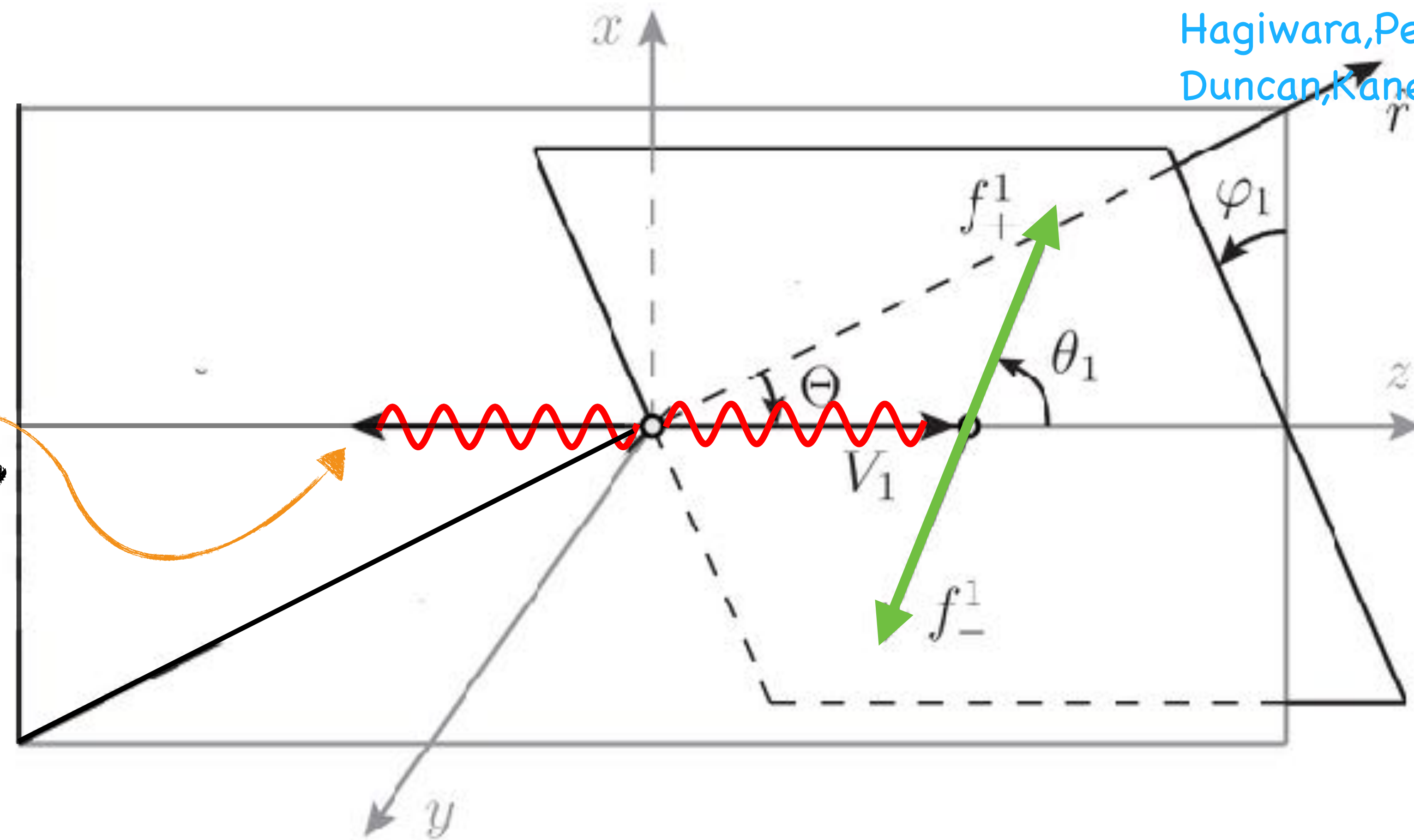
- Cancels when integrated over $\varphi \in [-\pi, \pi]$

# Differential measurements Wγ

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

$W\gamma$

No (leptonic) Branching Ratio




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

$$Int^{\not{\mathrm{C}}\mathrm{P}} = 2ig^2 \sin^2\theta \mathcal{A}_{++}^{\mathrm{BSM}-} \left[\mathcal{A}_{-+}^{\mathrm{SM}} - \mathcal{A}_{+-}^{\mathrm{SM}}\right] \sin 2\varphi$$

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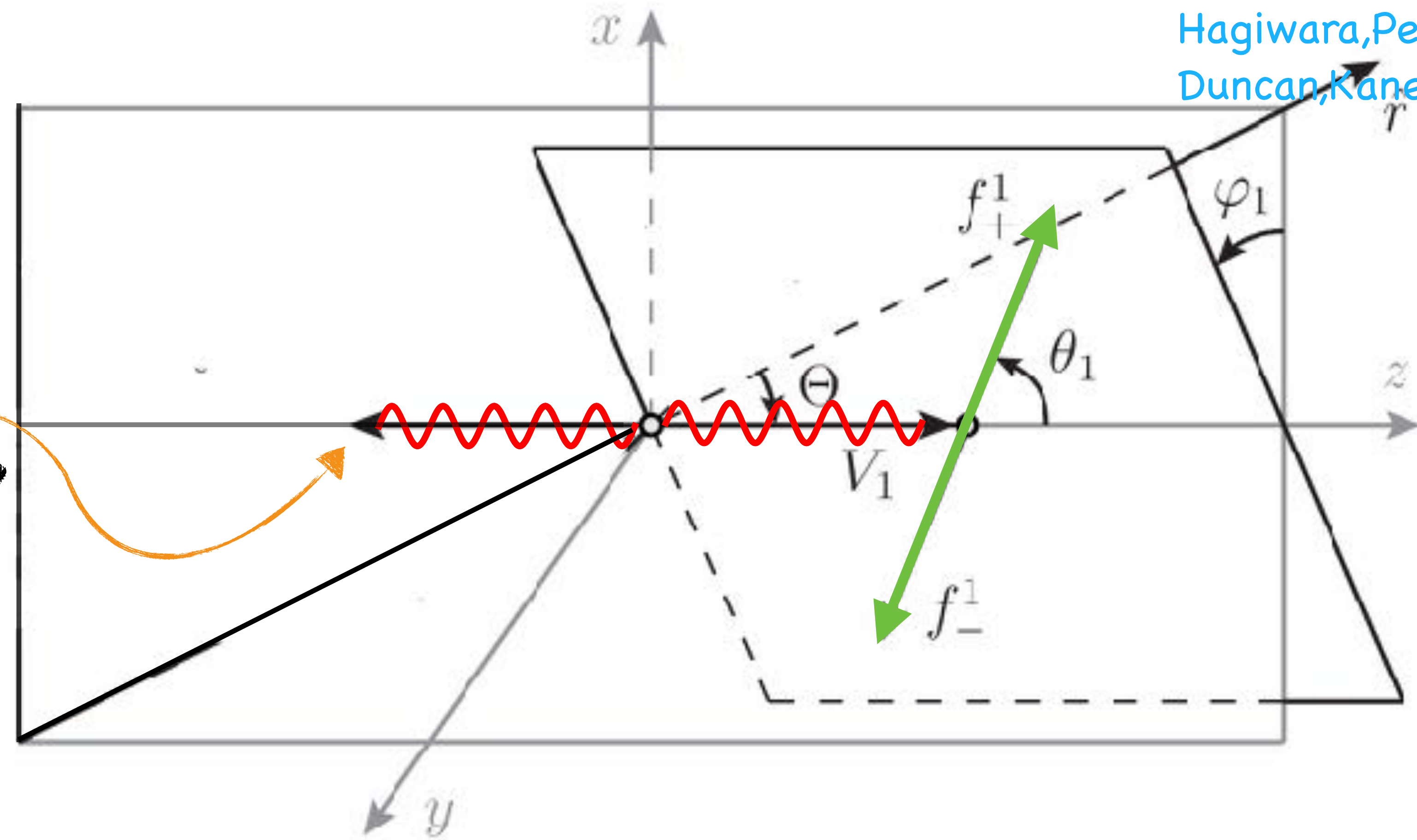



$$Int^{\rm CP} = 2g^2 \sin^2\theta \mathcal{A}_{++}^{\rm BSM+}\left[\mathcal{A}_{-+}^{\rm SM} + \mathcal{A}_{+-}^{\rm SM}\right]\cos 2\varphi\,,$$

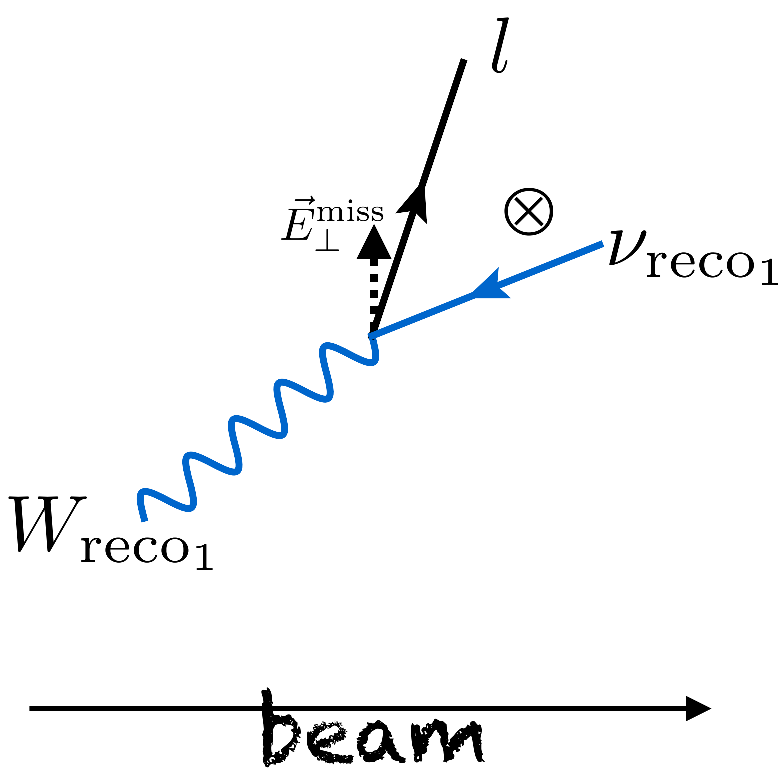
$$Int^{\not{C}\rm P} = 2ig^2 \sin^2\theta \mathcal{A}_{++}^{\rm BSM-}\left[\mathcal{A}_{-+}^{\rm SM} - \mathcal{A}_{+-}^{\rm SM}\right]\sin 2\varphi$$

Differential azimuthal distributions = SM-BSM interference

# Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

1)




Panico,FR,Wulzer'17
See also Azatov, Elias-Miro, Reyimuaji, Venturini'17

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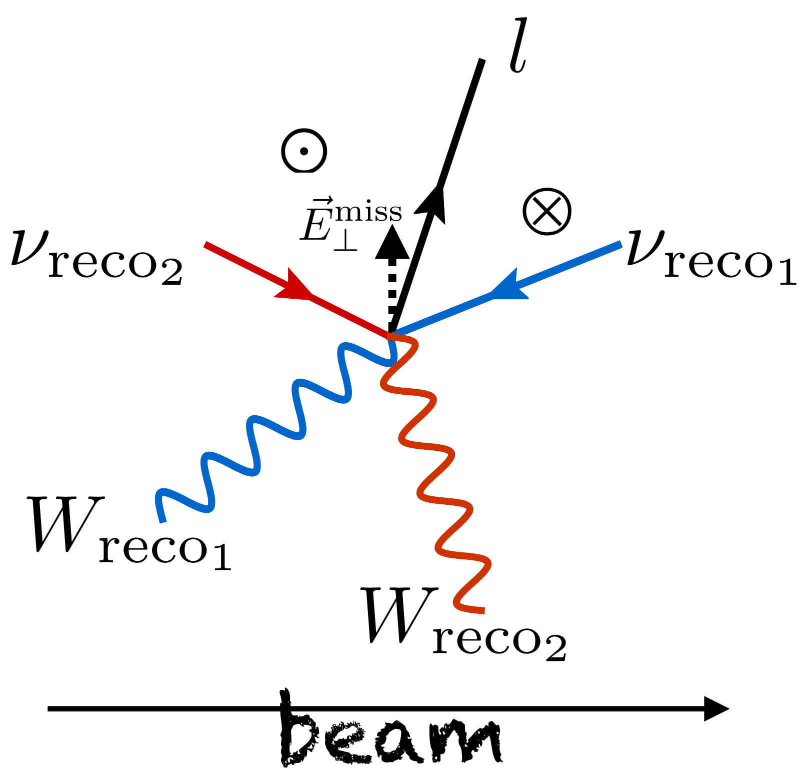


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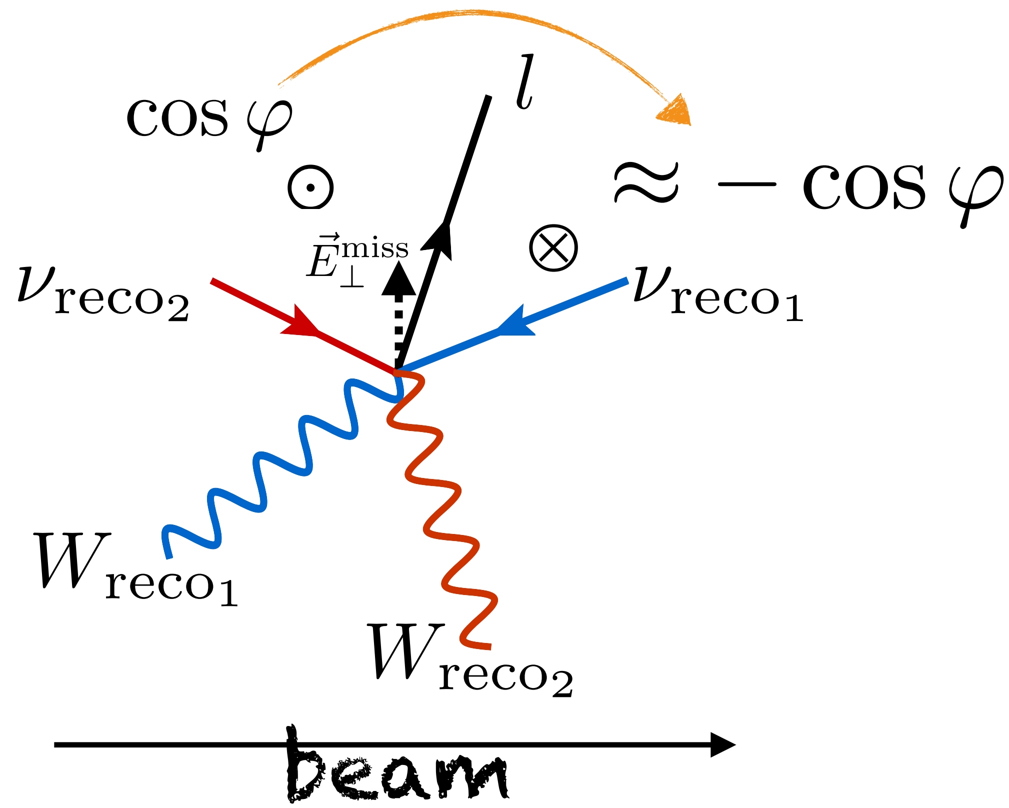


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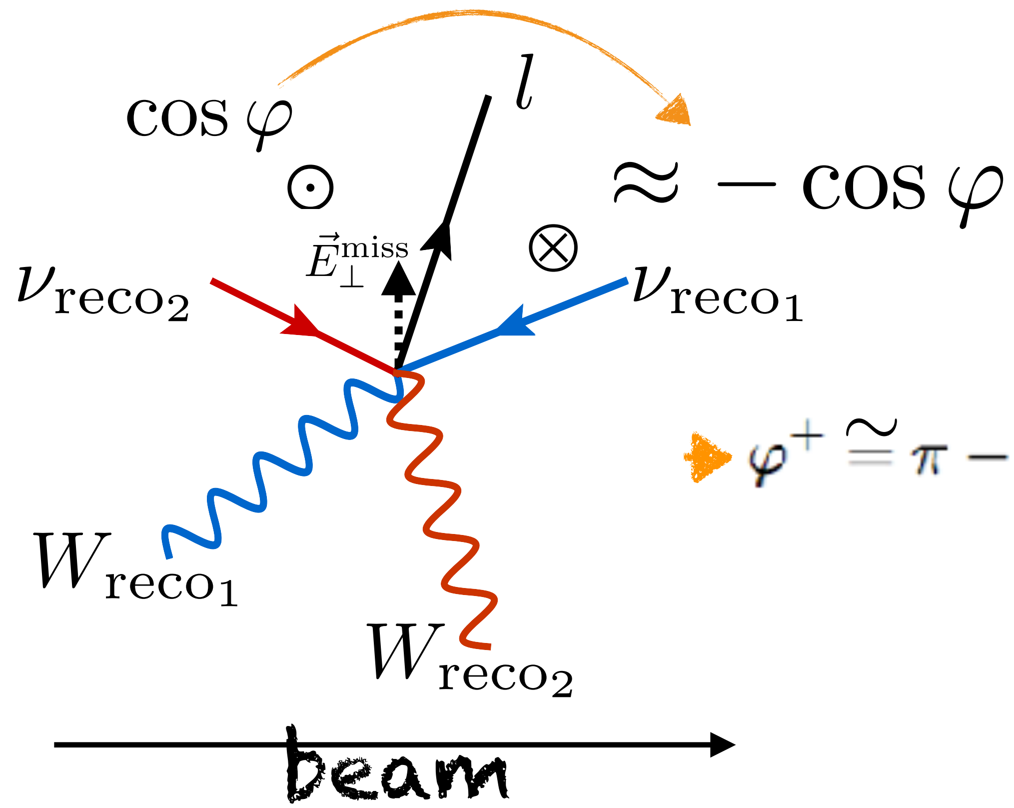


$\varphi^+ \cong \pi - \varphi^- \mod 2\pi$

$\varphi_{reco}$

$\varphi_{true}$

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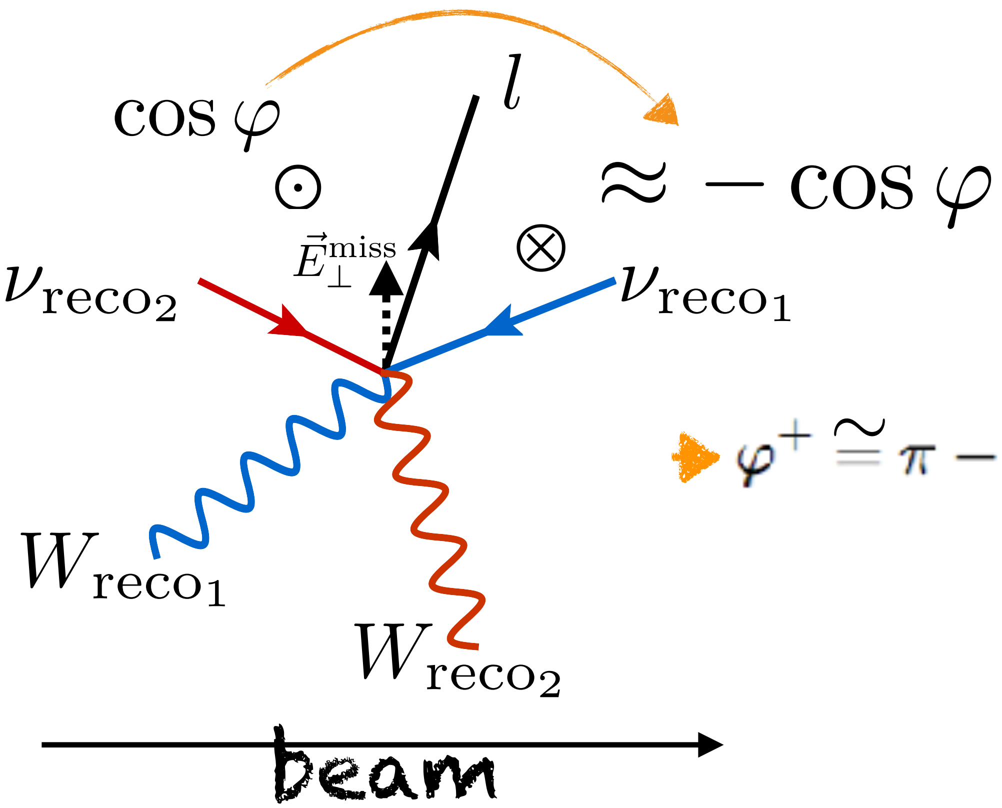


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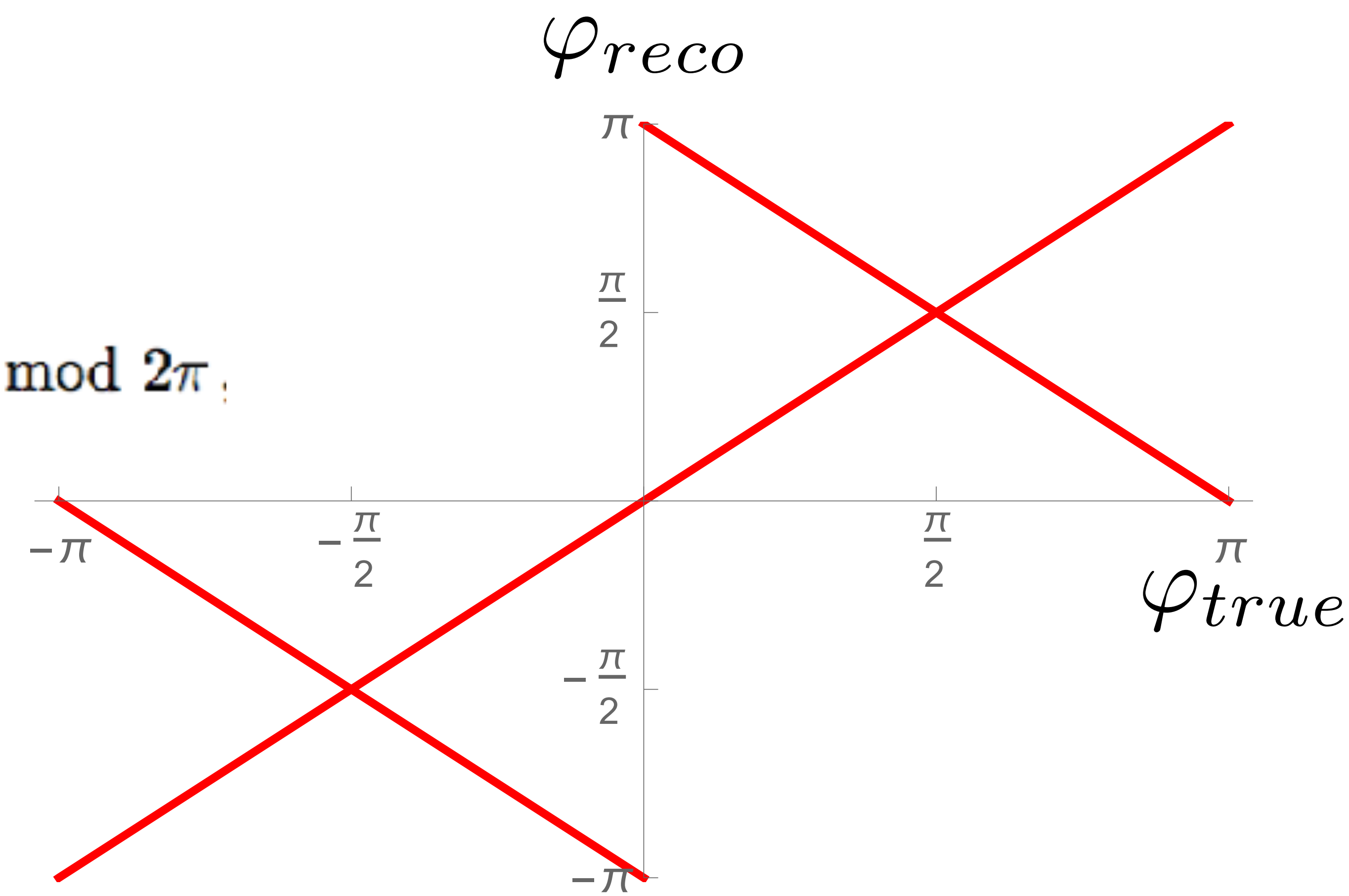


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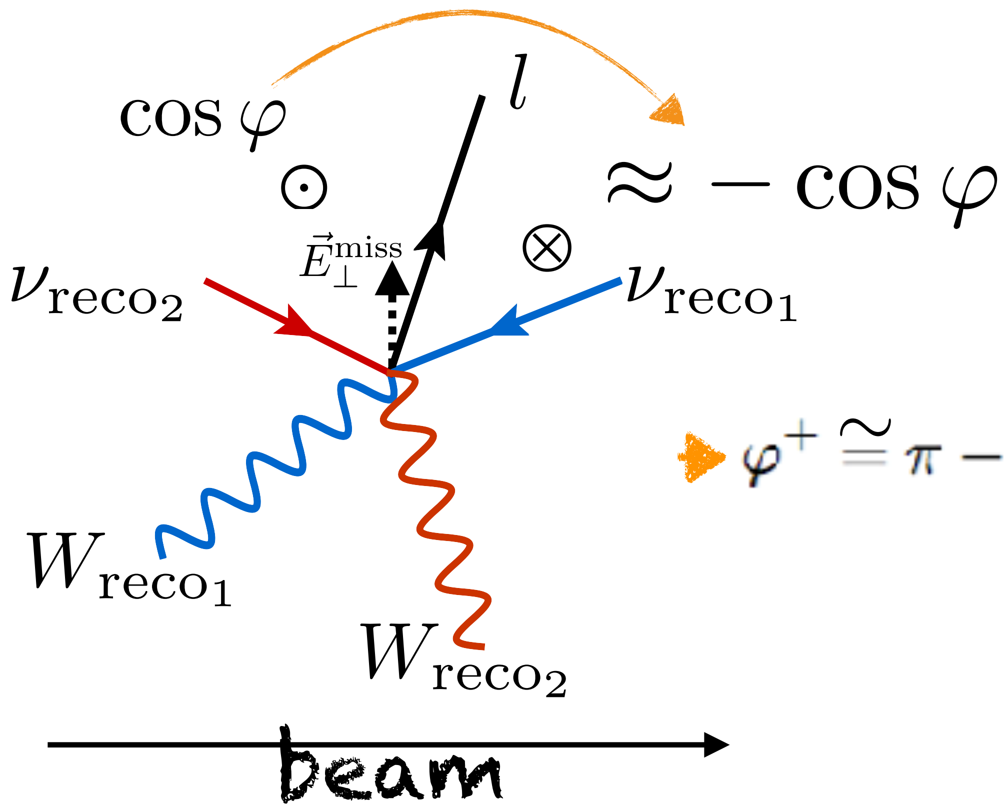


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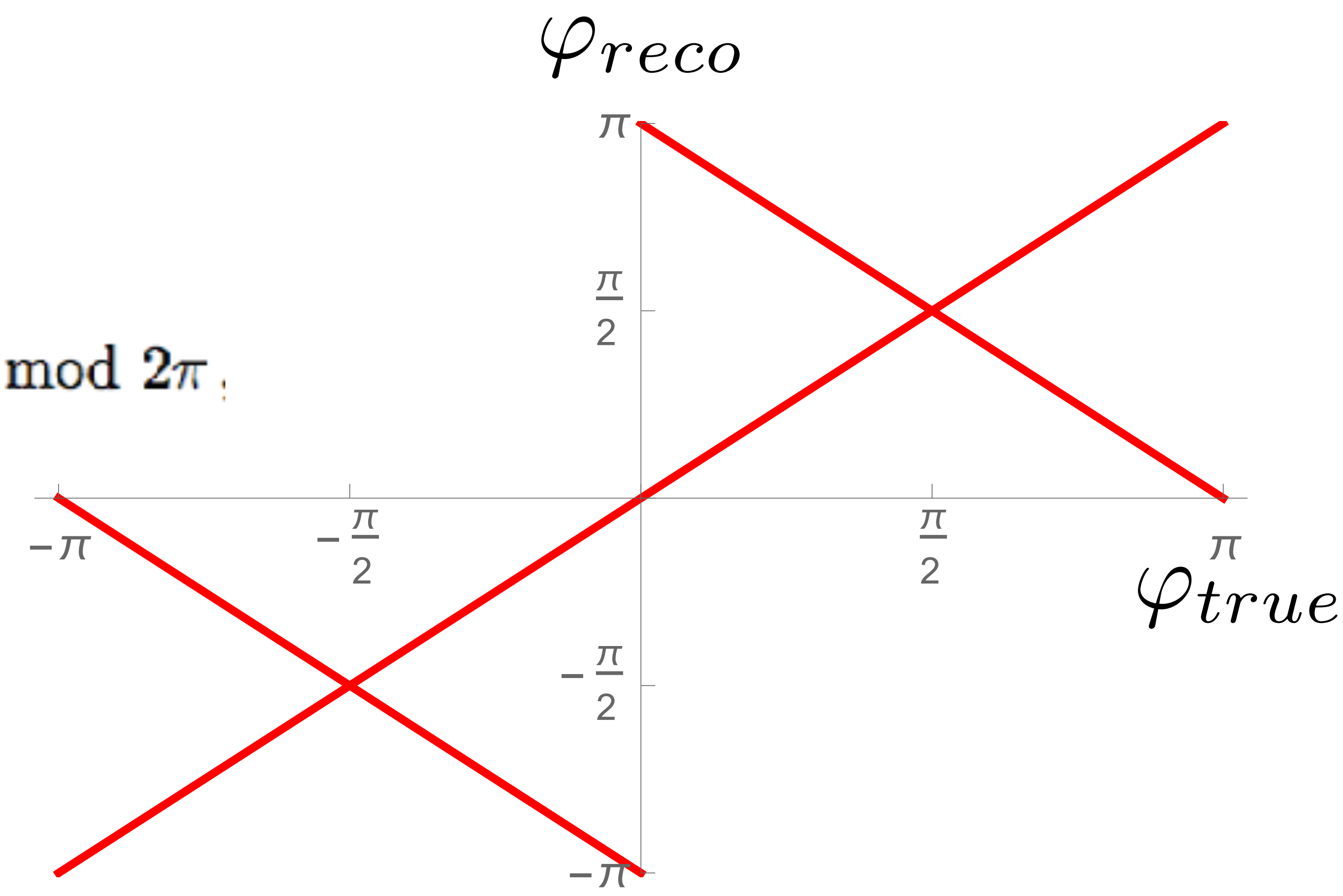


2) Some events: $m_\perp^2 > m_W^2$
(off-shell, exp.error)

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

$\varphi = \pi/2$ or $\varphi = -\pi/2.$

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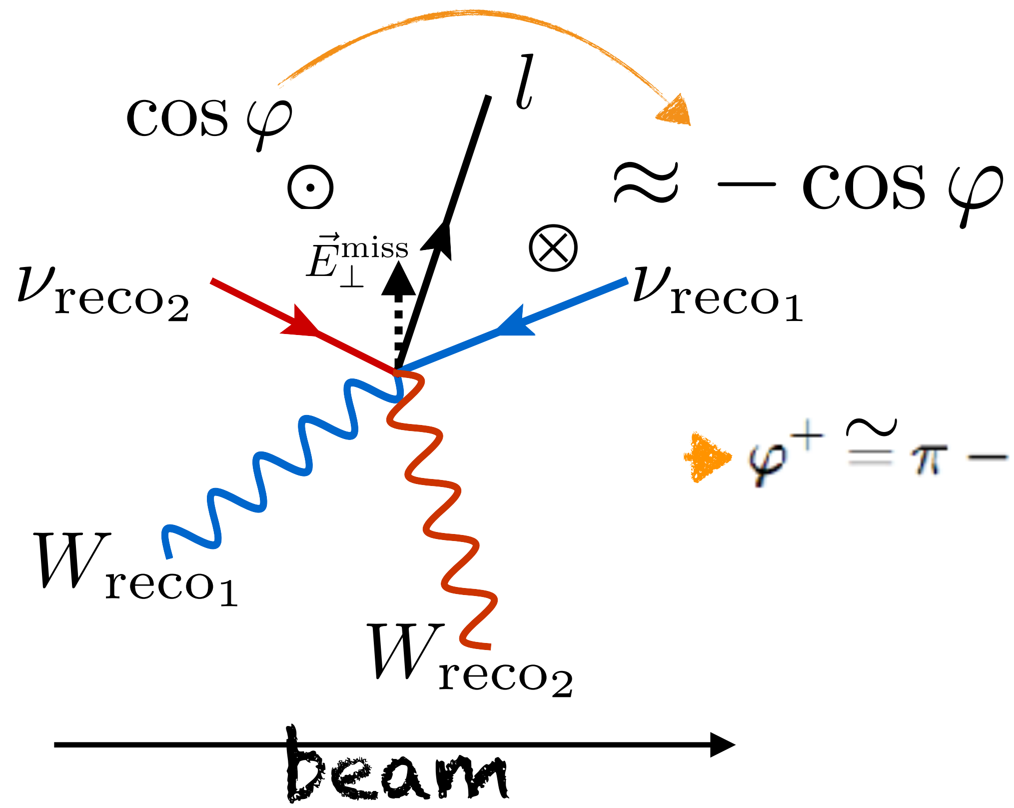


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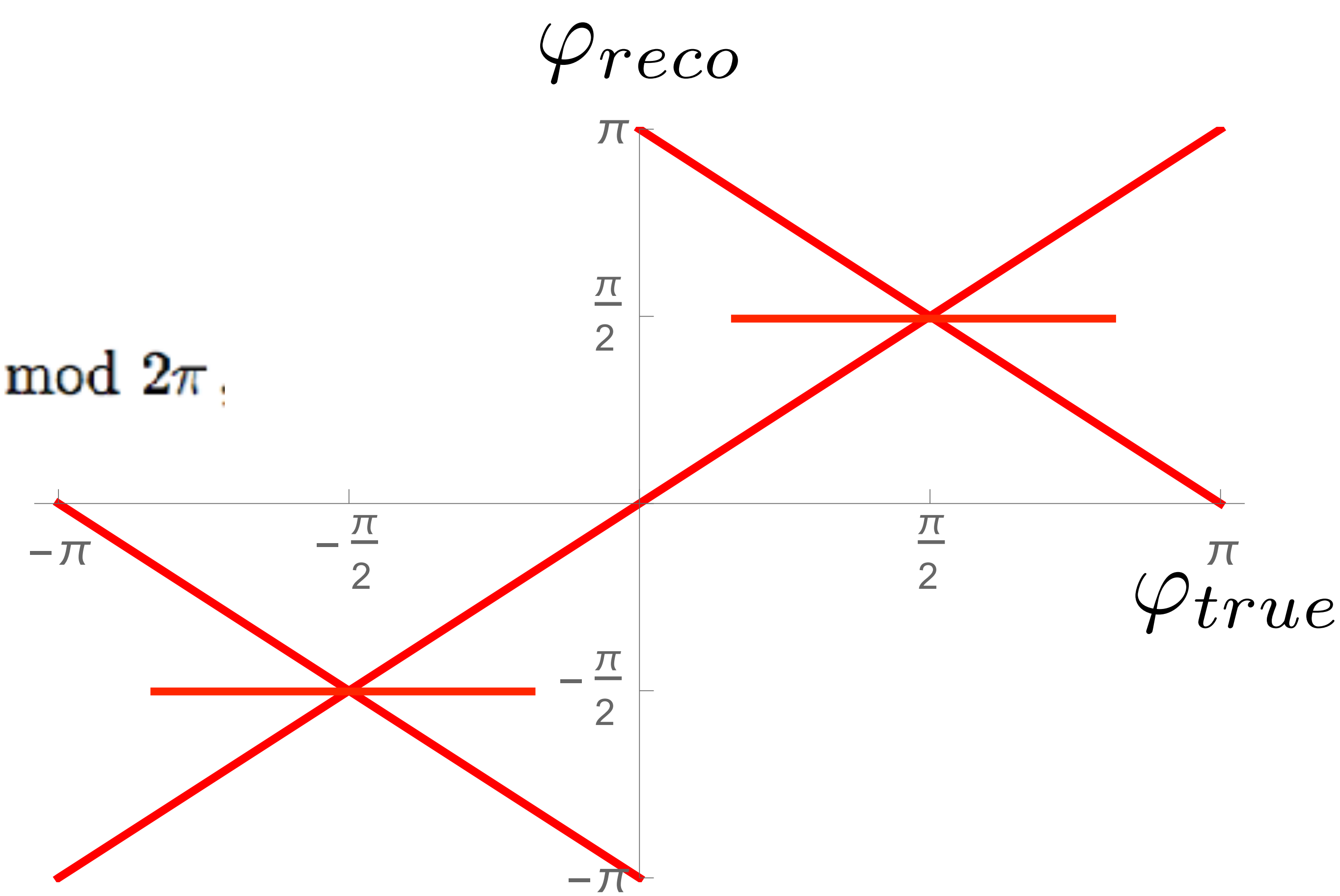


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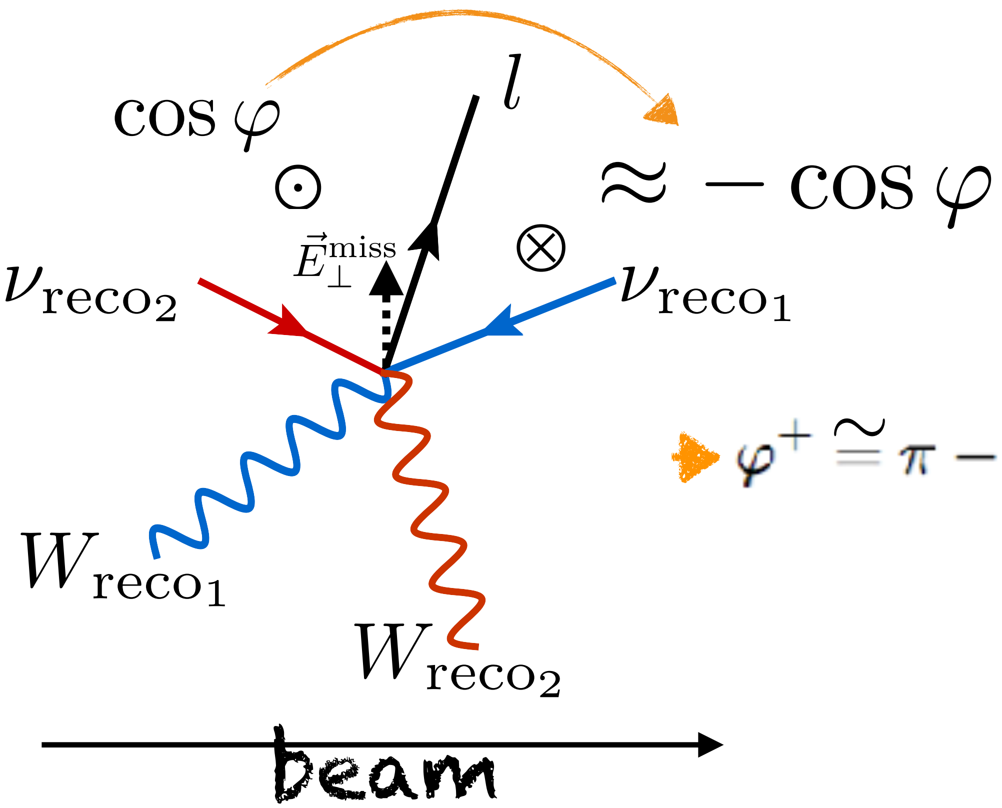


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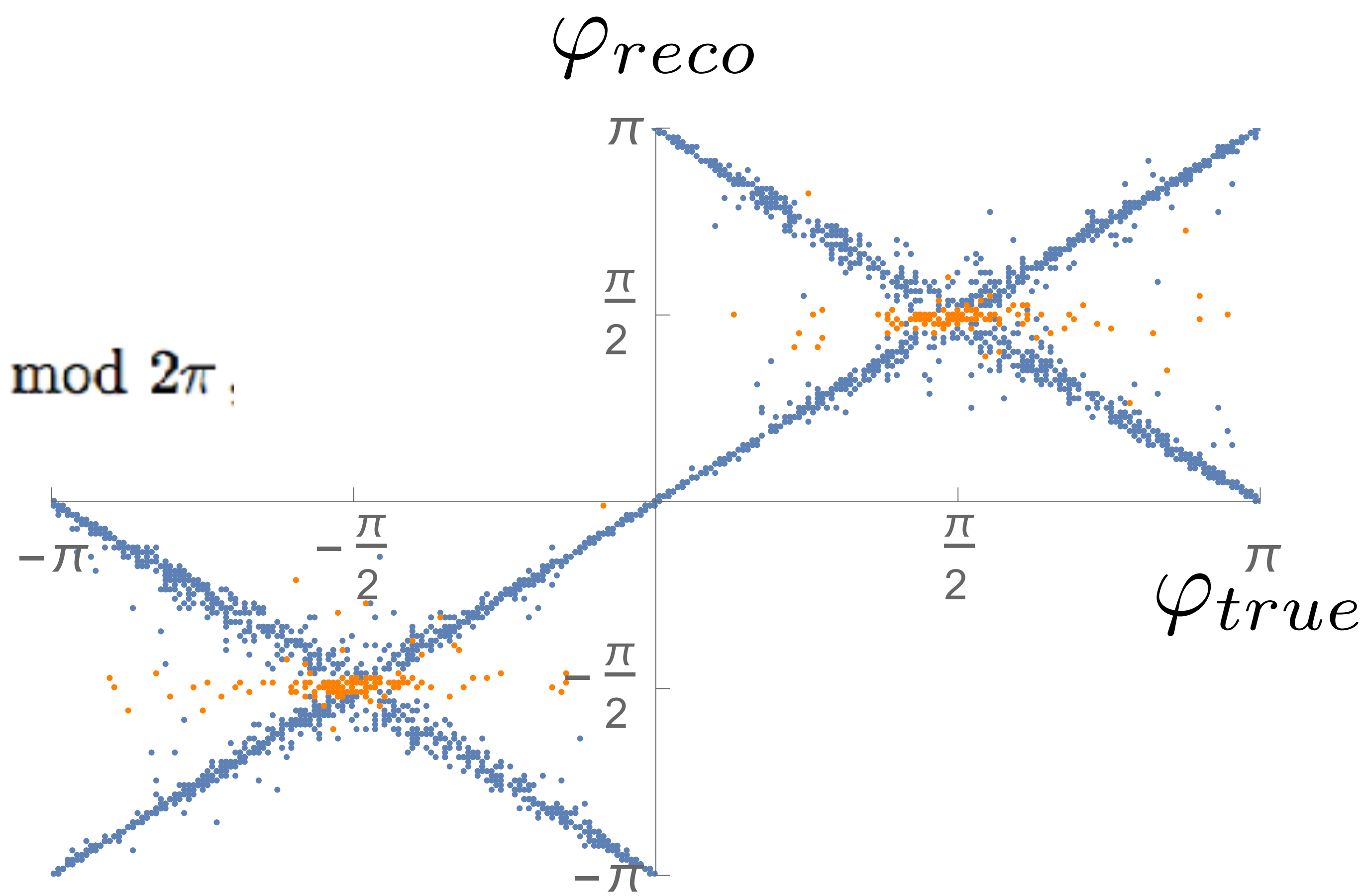


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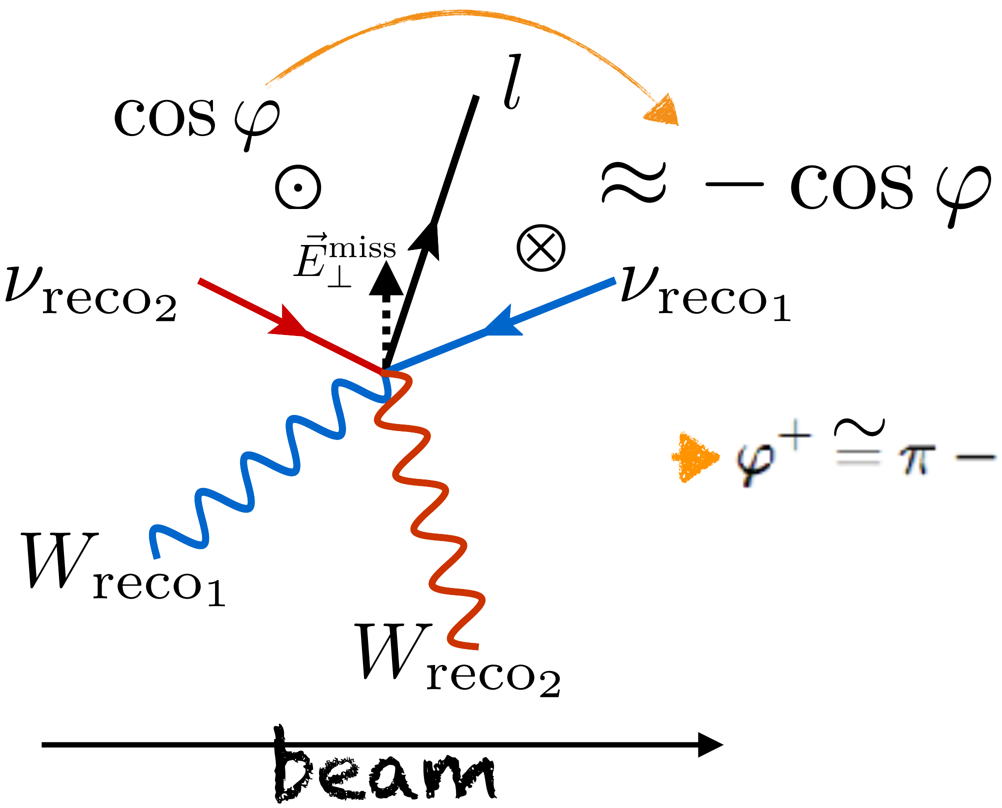


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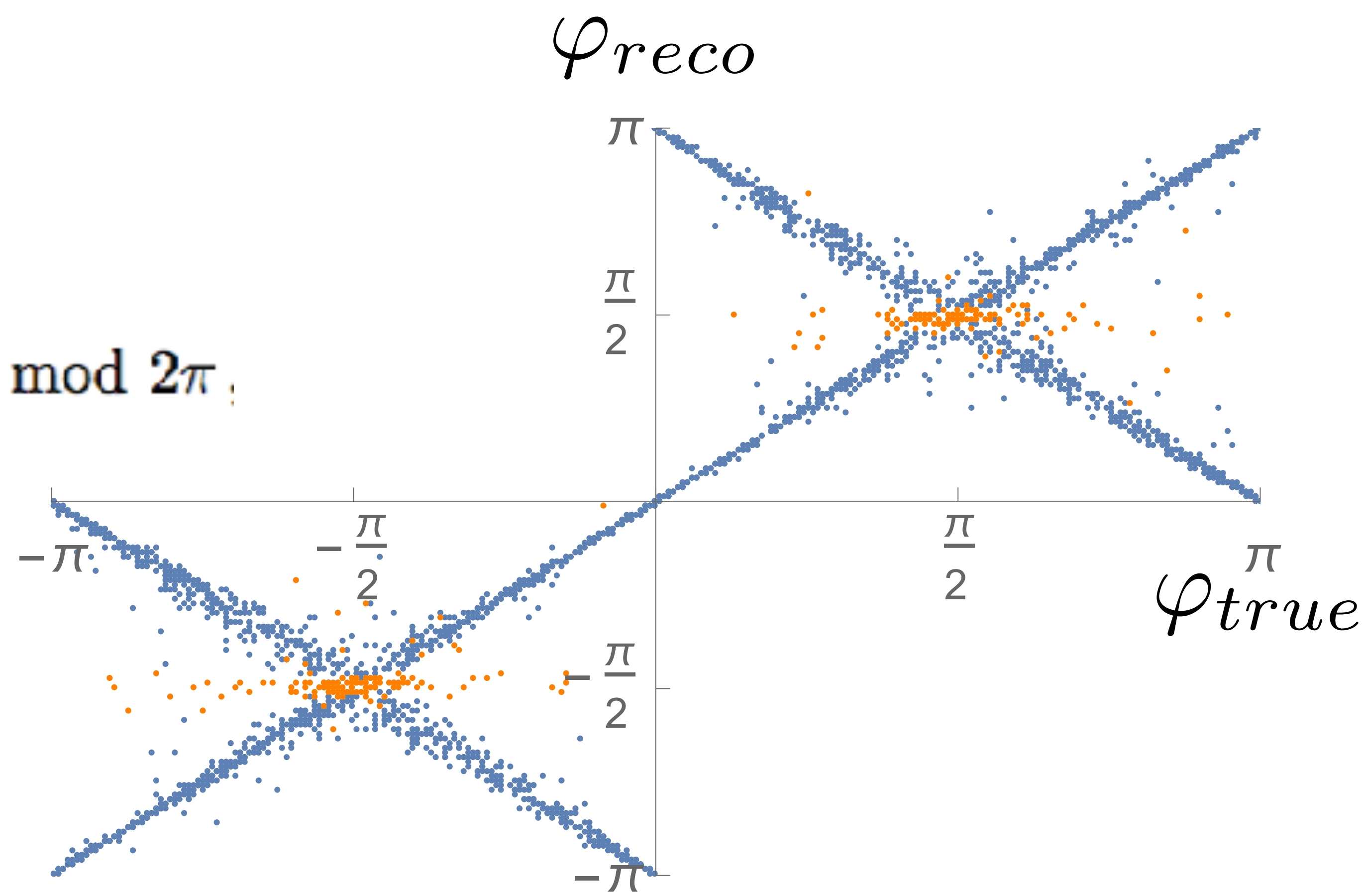


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CP-odd unaccessible!

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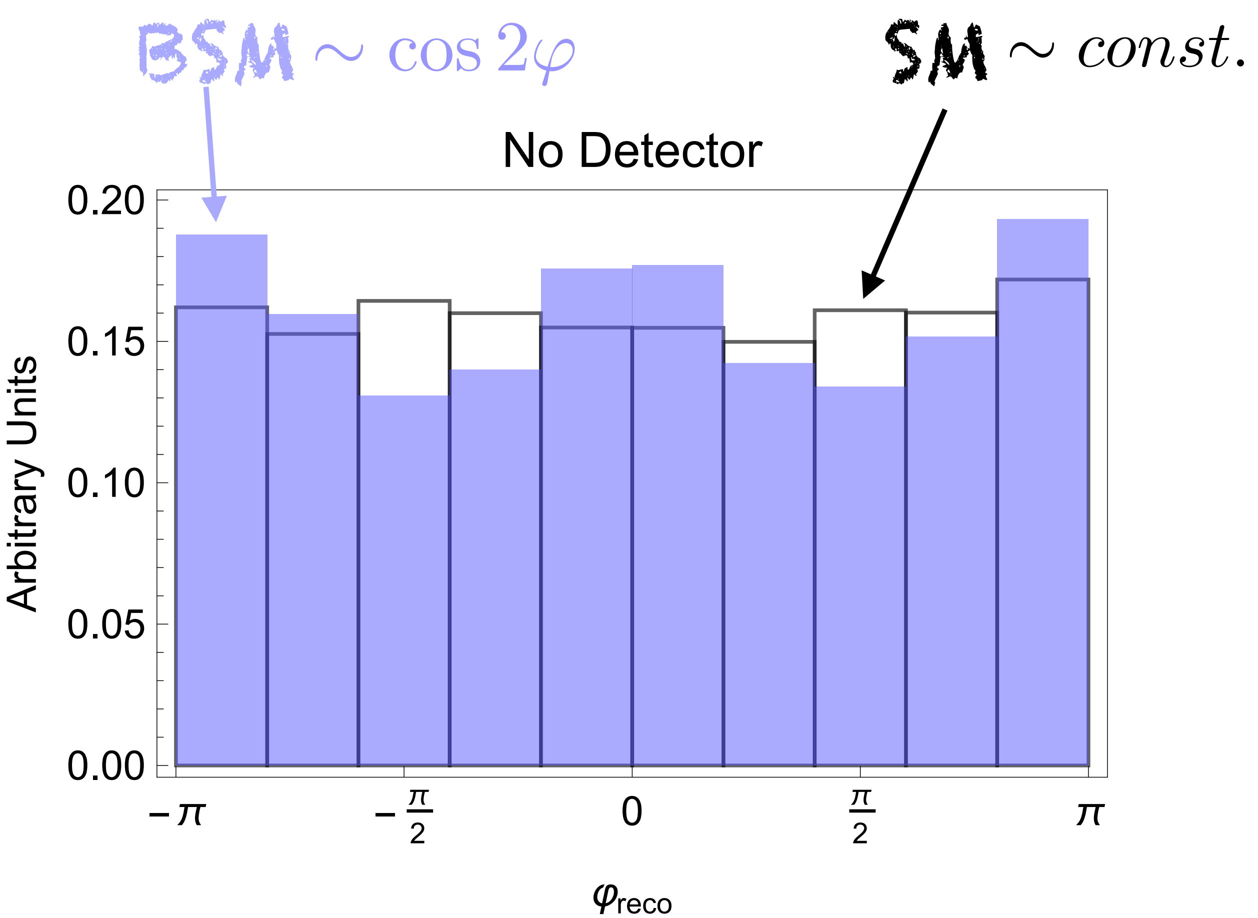
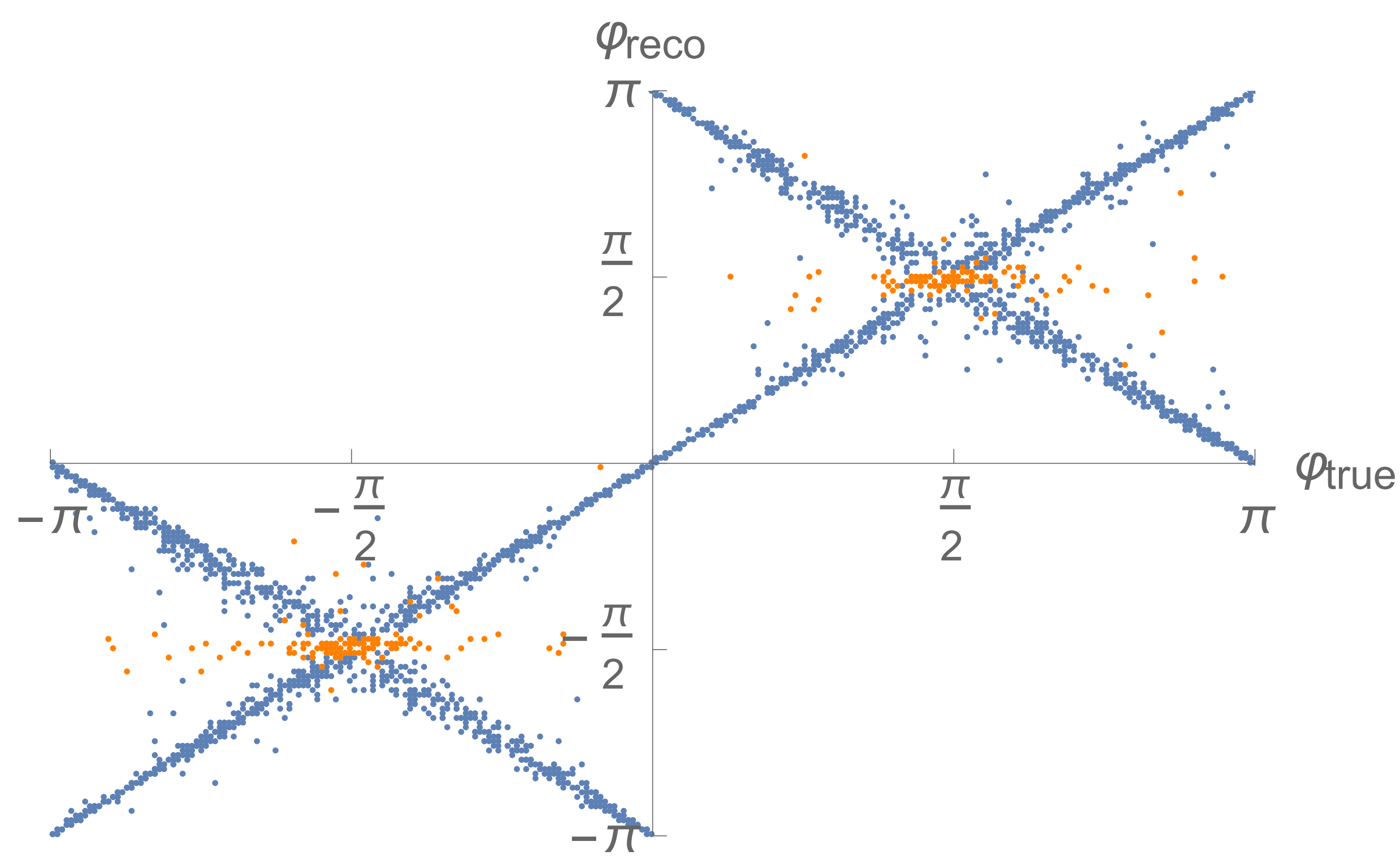
# Azimuthal Angle… in reality

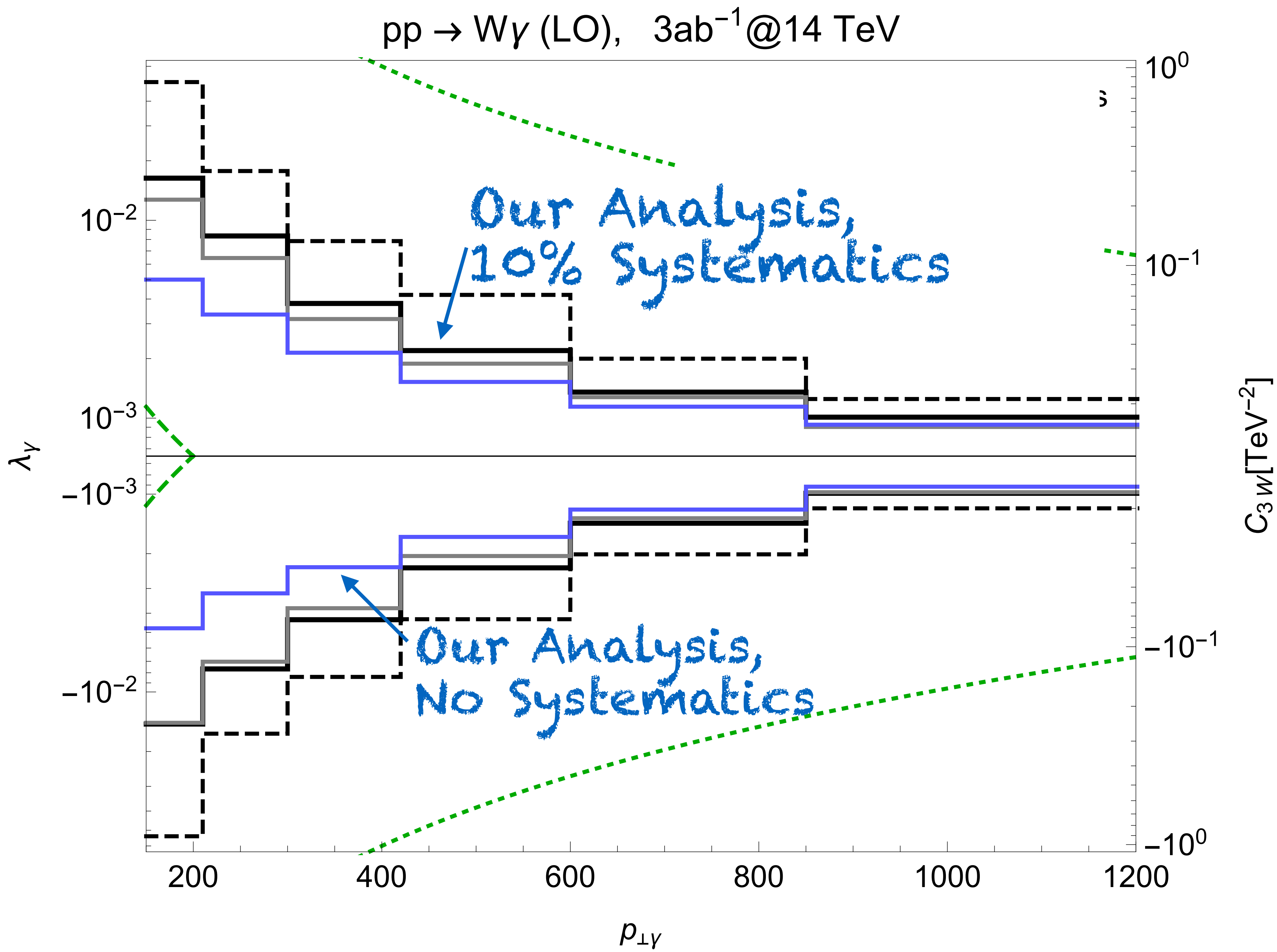
**Neutrino: from missing energy + reconstruct W mass**




Panico,FR,Wulzer'17
See also Azatov, Elias-Miro, Reyimuaji, Venturini'17

# Results

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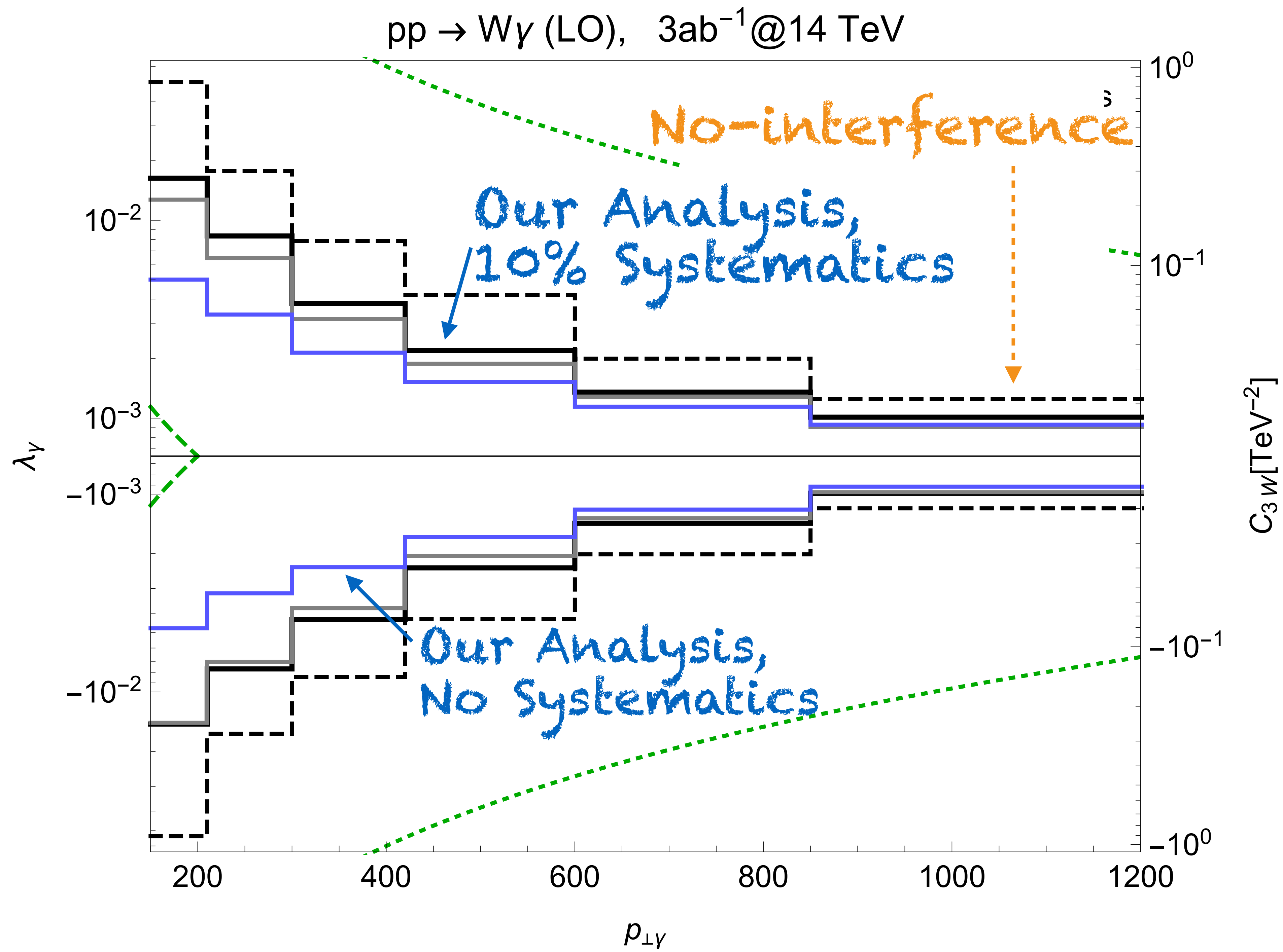


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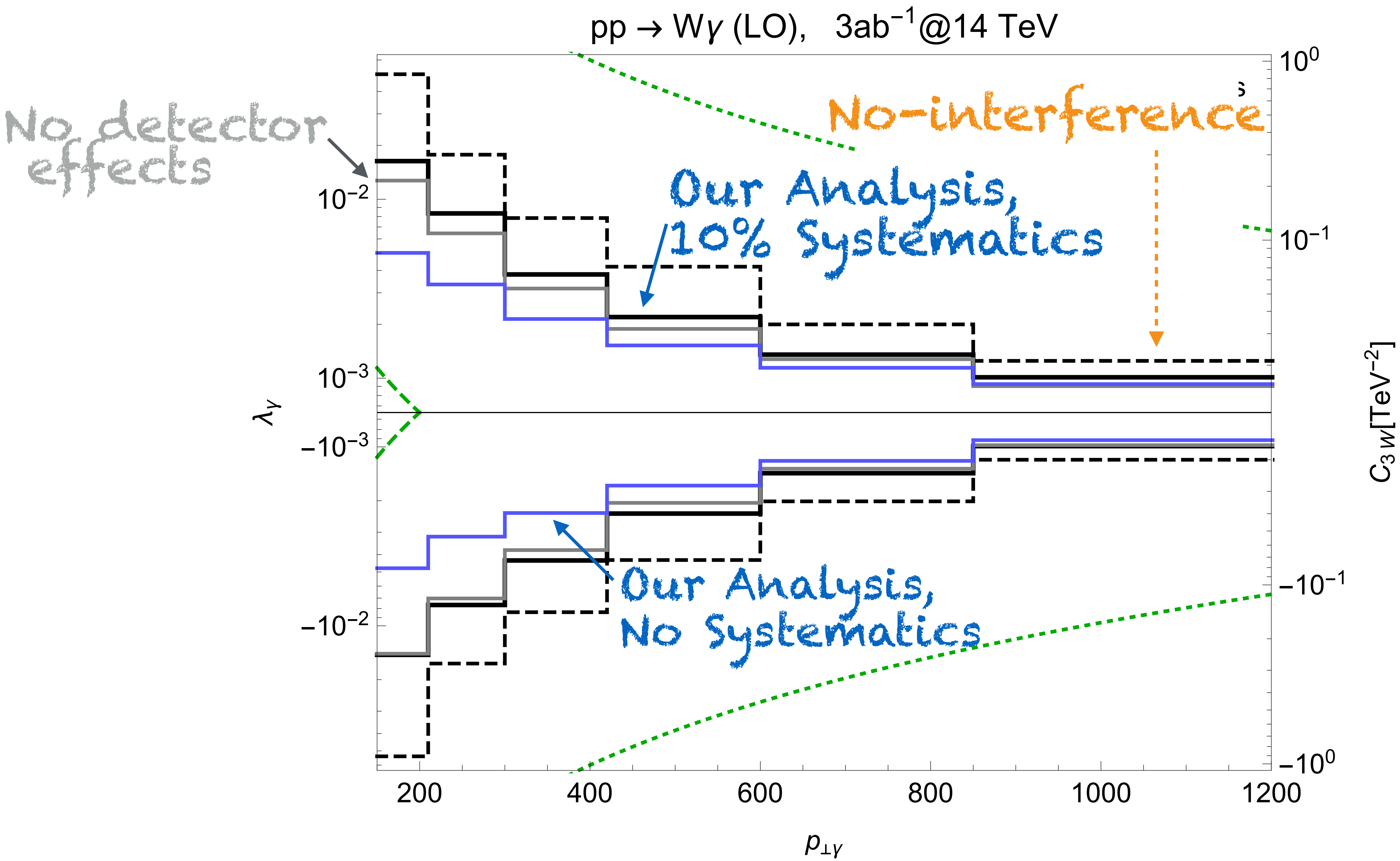


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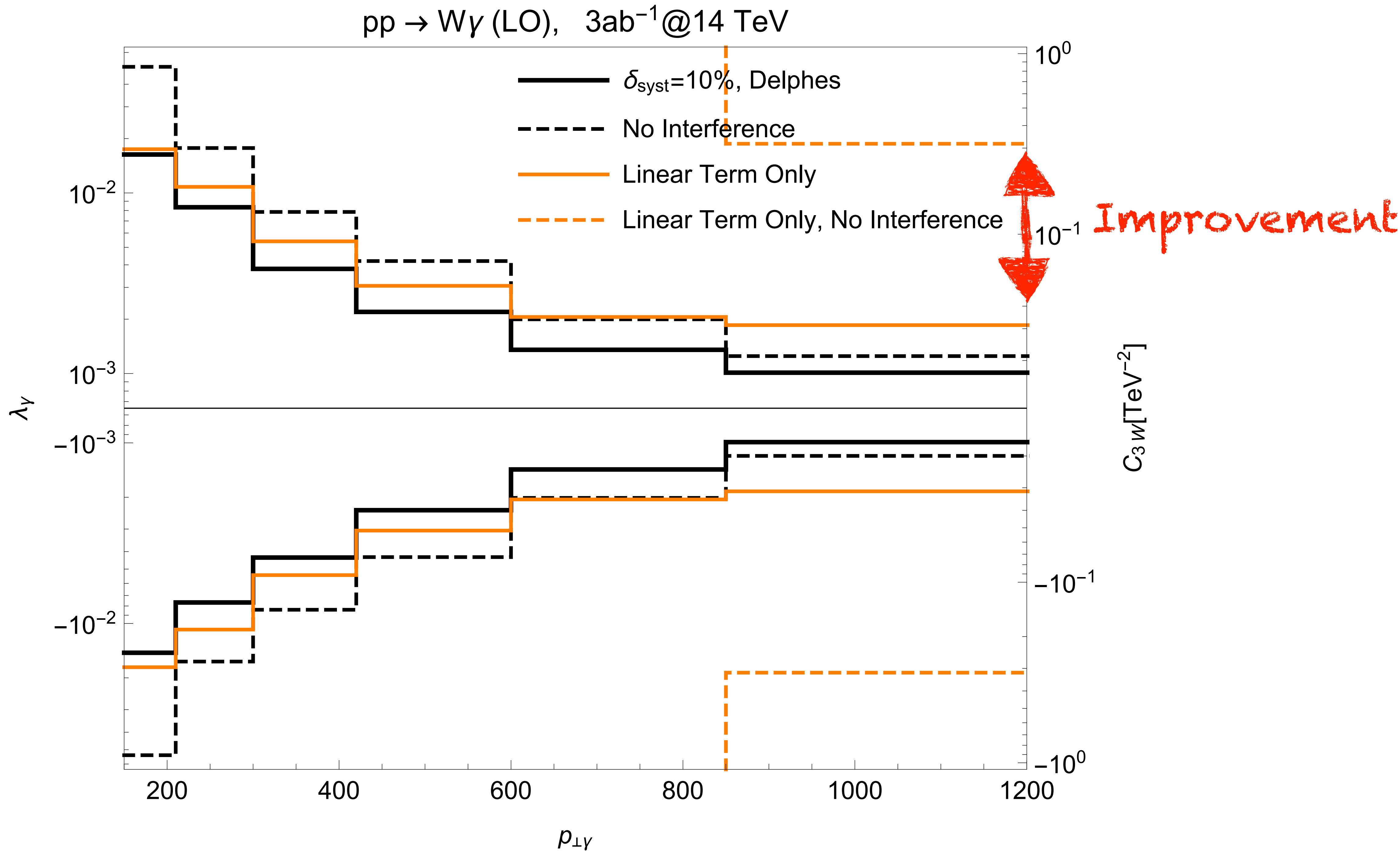


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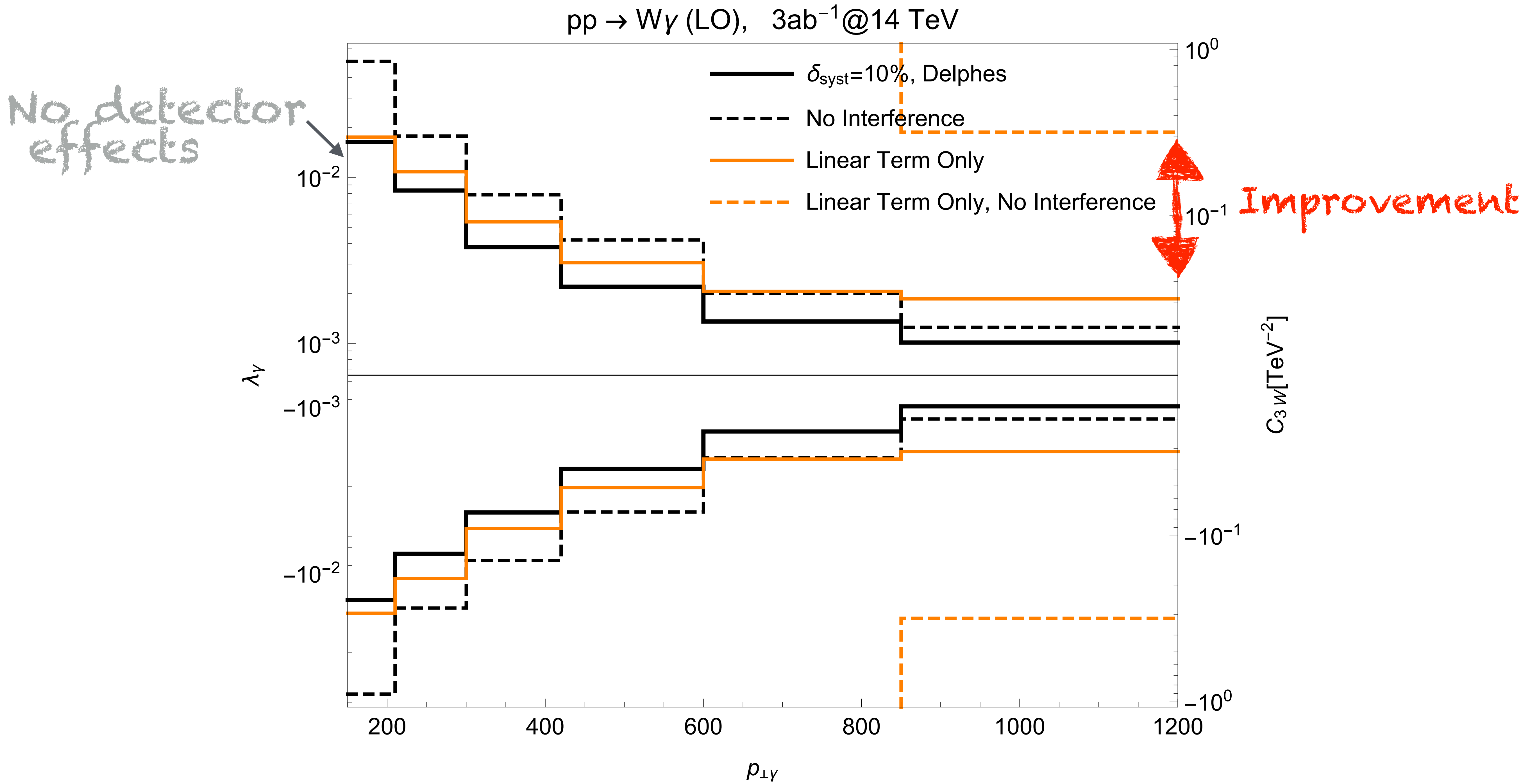


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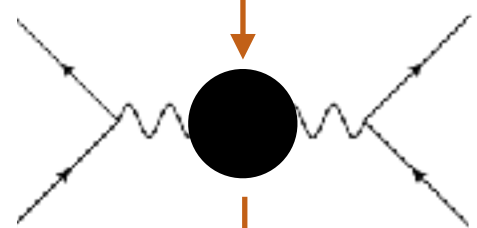
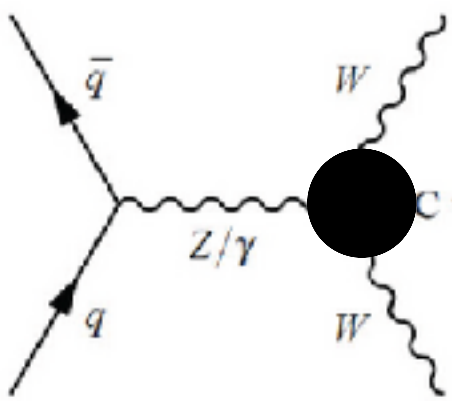
# Explicit Model (Remedios)

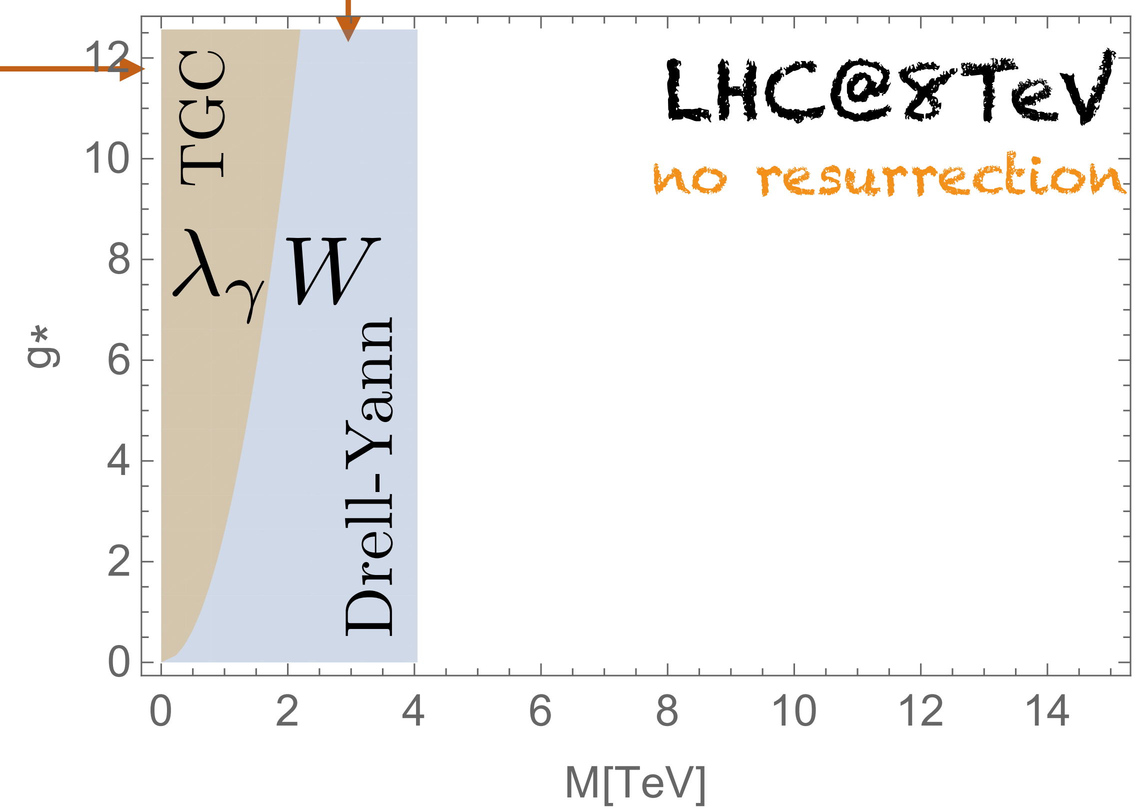
Remedios Scenario → $\frac{1}{M^2}(D_\rho W_\mu^{a,\nu})^2$

Liu,Pomarol,Rattazzi,FR'16



$$\frac{g_*}{M^2}\epsilon_{abc}W_\mu^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$$




Interference Resurrection makes the difference.

# Explicit Model (Remedios)

Liu,Pomarol,Rattazzi,FR'16

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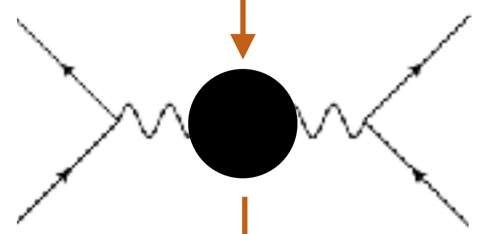
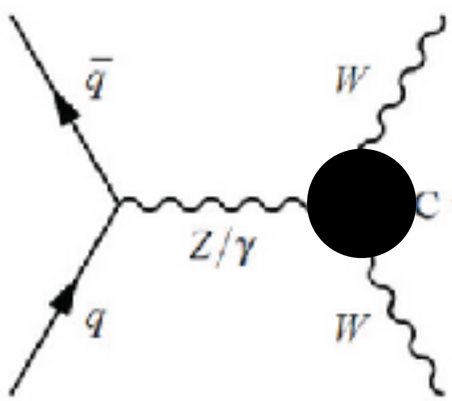
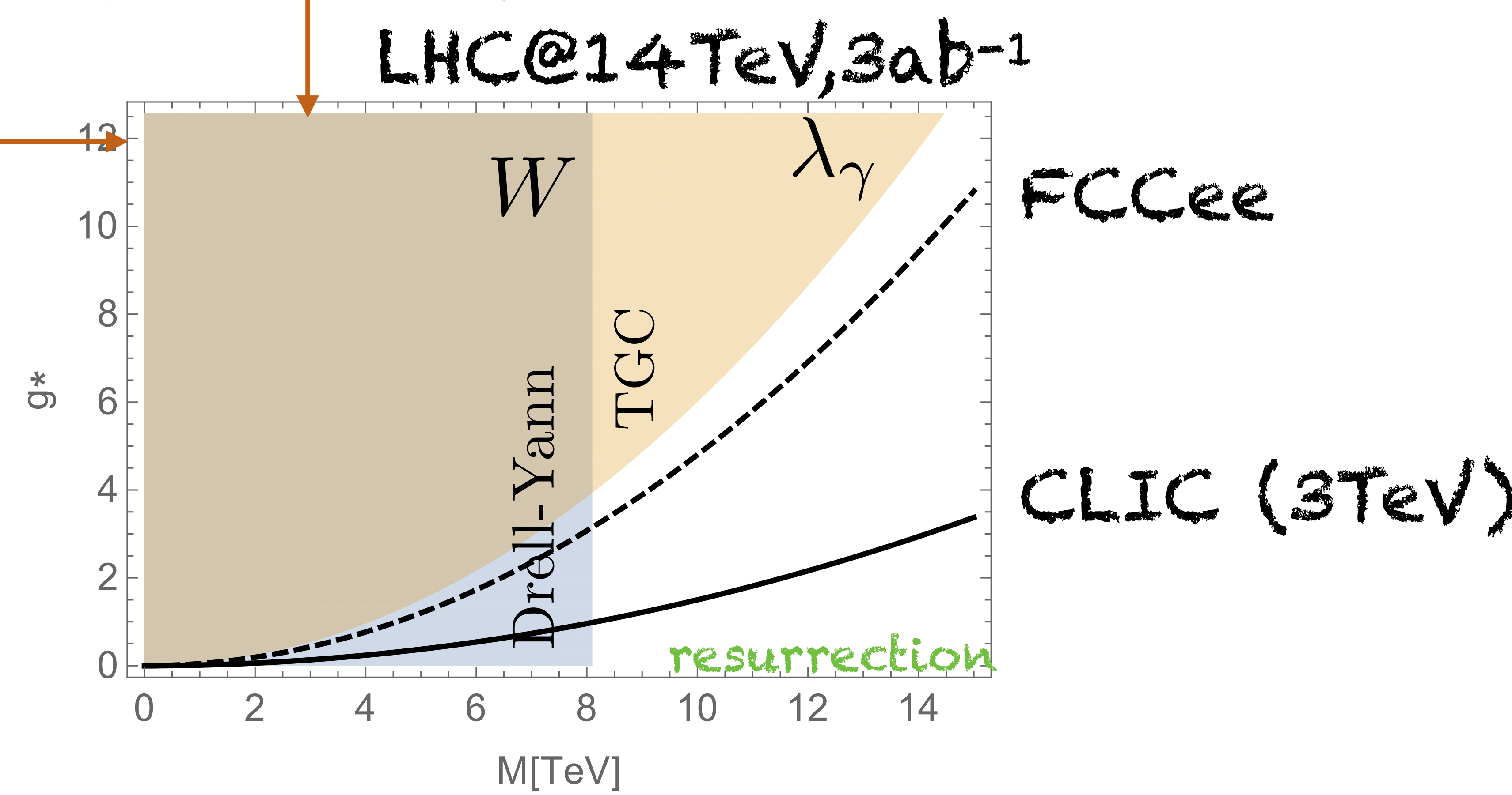


$\frac{g_*}{M^2}\epsilon_{abc}W^{a\,\nu}_{\mu}W^{b}_{\nu\rho}W^{c\,\rho\mu}$

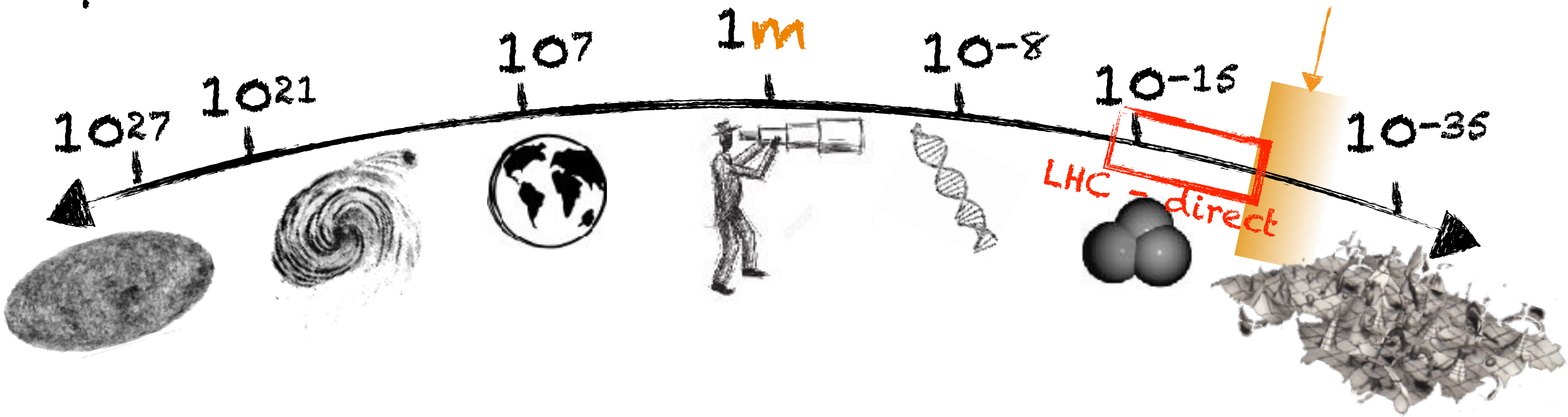



Interference Resurrection makes the difference.

# Message

SM precision tests will define the new distance frontier




Precision: qualitative change in BSM searches

- New search strategies become possible
- Precise measurements inspire new model building

# Beyond the SM $EFT_6$: ZZ, Zγ

No dimension-6 E-growing effects in pp-> ZZ, Zγ!

# What is being looked for so far: nTGC

## Anomalous Couplings

$$\mathcal{L}_{NP} = \frac{e}{m_Z^2}\Big[ -[f_4^\gamma(\partial_\mu F^{\mu\beta}) + f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta) + [f_5^\gamma(\partial^\sigma F_{\sigma\mu}) + f_5^Z(\partial^\sigma Z_{\sigma\mu})]\widetilde{Z}^{\mu\beta}Z_\beta$$
$$- [h_1^\gamma(\partial^\sigma F_{\sigma\mu}) + h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} - [h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha \widetilde{F}_{\rho\alpha}$$
$$- \left\{\frac{h_2^\gamma}{m_Z^2}[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}] + \frac{h_2^Z}{m_Z^2}[\partial_\alpha\partial_\beta(\Box + m_Z^2)Z_\mu]\right\} Z^\alpha F^{\mu\beta}$$
$$+ \left\{\frac{h_4^\gamma}{2m_Z^2}[\Box\partial^\sigma F^{\rho\alpha}] + \frac{h_4^Z}{2m_Z^2}[(\Box + m_Z^2)\partial^\sigma Z^{\rho\alpha}]\right\} Z_\sigma \widetilde{F}_{\rho\alpha}\Big], \quad (3)$$

Gounaris,Laysacc,Renard'99

## EFT

$$\frac{iH^\dagger \overleftrightarrow{D}_\mu H D^\nu B_{\nu\rho}B^{\mu\rho}}{\Lambda^4}$$

# What is being looked for so far: nTGC

**Anomalous Couplings**

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\begin{aligned}
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& - [h_1^\gamma(\partial^\sigma F_{\sigma\mu}) + h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} - [h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha \widetilde{F}_{\rho\alpha} \\
& - \left\{\frac{h_2^\gamma}{m_Z^2}[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}] + \frac{h_2^Z}{m_Z^2}[\partial_\alpha\partial_\beta(\Box + m_Z^2)Z_\mu]\right\} Z^\alpha F^{\mu\beta} \\
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Gounaris,Laysacc,Renard'99

**EFT**

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- **Dimension-8 effect:** Why shall we look at dim>6? ☹

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& - [h_1^\gamma(\partial^\sigma F_{\sigma\mu}) + h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} - [h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha \widetilde{F}_{\rho\alpha} \\
& - \left\{\frac{h_2^\gamma}{m_Z^2}[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}] + \frac{h_2^Z}{m_Z^2}[\partial_\alpha\partial_\beta(\Box + m_Z^2)Z_\mu]\right\} Z^\alpha F^{\mu\beta} \\
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Gounaris,Laysacc,Renard'99

→

**EFT**

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- **Dimension-8 effect:** Why shall we look at dim>6?

- **Modifies only the LT amplitude:** (longitudinal+Transverse)

  At high-Energy, every amplitude with odd number of L is suppressed by mZ/E ⟶ not maximally growing!

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## EFT

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- **Dimension-8 effect:** Why shall we look at dim>6? 

(longitudinal+Transverse)

- **Modifies only the LT amplitude:**

  At high-Energy, every amplitude with odd number of L is suppressed by mZ/E → not maximally growing! 

- **Contributes to +0/−0 helicity, while SM mainly in +−**

  nTGC dont modify the majority of the process 

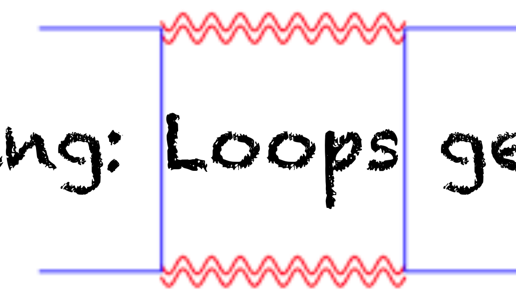
# When do dimension-8 make sense?

Symmetries or selection rules can give $C_6 \ll C_8$

## Massive spin-2 (KK graviton)

$$\mathcal{L}_g = -\frac{m_g^2}{2} h^{\mu\nu} P_{\mu\nu\rho\sigma} h^{\rho\sigma} - \frac{1}{\bar{M}_p} h^{\mu\nu} T_{\mu\nu} \xrightarrow{E \ll m_g} \mathcal{L}_g^{eff} = \frac{1}{2 m_g^2 \bar{M}_p^2}\left[(T^{\mu\nu}T_{\mu\nu}) - \frac{1}{3}(T^\mu_\mu)^2\right] + \cdots .$$

dim-8!



But only for weak coupling: Loops generate dim-6!

Giudice, Strumia, '03

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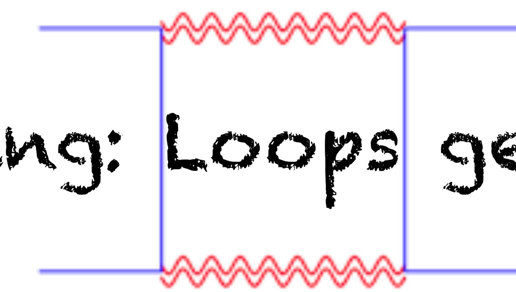

Giudice, Strumia, '03

## (Non-linear) Symmetries (at strong coupling)

- U(1) Goldstone-Boson: $\mathcal{L} = (\partial\phi)^2 + c\frac{(\partial\phi)^4}{\Lambda^4} + \cdots$

dim-8

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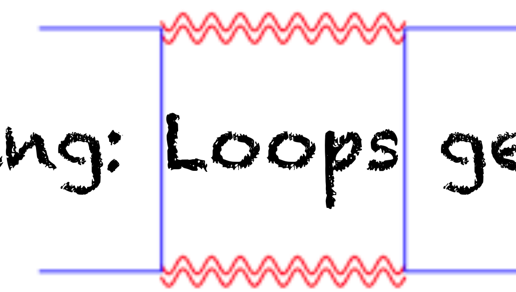


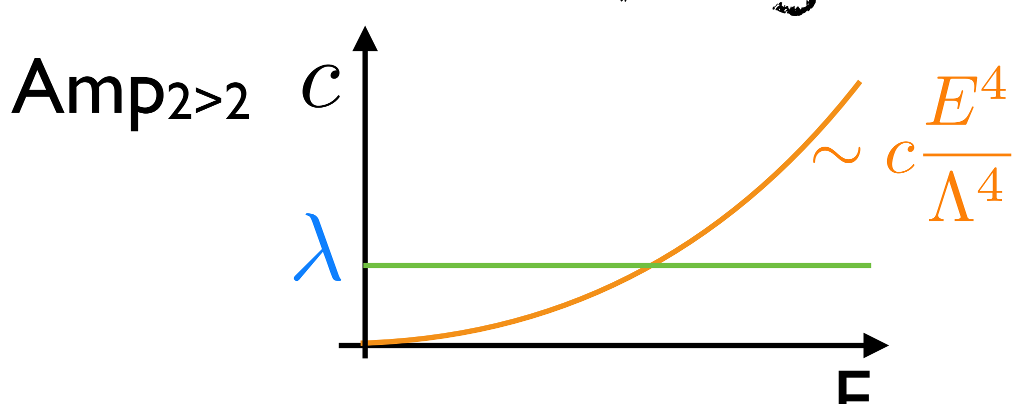
But only for weak coupling: Loops generate dim-6!

Giudice, Strumia, '03

## (Non-linear) Symmetries (at strong coupling)

- U(1) pseudo Goldstone-Boson: $\mathcal{L} = (\partial\phi)^2 + \lambda\phi^4 + c\frac{(\partial\phi)^4}{\Lambda^4} + \cdots$ (dim-8)

small $\lambda$ visible at low-E, big c visible at High-E $\lesssim \Lambda$



# Dimension-8 and ZZ, Zγ

## (Non-linear) Symmetries (at strong coupling)

- Fermions as pseudogoldstini: $g^{\mu\nu} = \eta^{\mu\nu} + \frac{1}{2F^2}\left(i\bar{\chi}\gamma^{\mu}\partial^{\nu}\chi + i\bar{\chi}\gamma^{\nu}\partial^{\mu}\chi + \text{h.c.}\right) + \ldots$

$$g^{\mu\nu} g^{\rho\sigma} W_{\mu\rho} W_{\nu\sigma} \quad \ni \quad \frac{1}{4F^2} W_{\nu\rho} W^{\nu}_{\sigma} \bar{\chi}\gamma^{\rho}\partial^{\sigma}\chi$$

Bardeen,Visnjic'81,
Liu,Pomaral,Rattazzi,FR'16,
Bellazzini,Serra,Sgarlata,FR'17

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Bardeen,Visnjic'81,
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What is the EFT? ...surprise...

| | |
|---|---|
| $\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.}\right)D_\mu H^\dagger D_\nu H$ | $-\frac{1}{4\Lambda^4}B_{\mu\nu}B^{\mu}{}_{\rho}\left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right)$ . |
| $\frac{1}{2\Lambda^4}\left(i\bar{Q}\sigma^a\gamma^{\{\mu}\partial^{\nu\}}Q + \text{h.c.}\right)D_\mu H^\dagger\sigma^a D_\nu H$ | $-\frac{1}{4\Lambda^4}W^a_{\mu\nu}W^{a\,\mu}{}_{\rho}\left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right)$ . |
| $\psi = Q, u_R, d_R$ | $-\frac{1}{4\Lambda^4}B_{\mu\nu}W^{a\,\mu}{}_{\rho}\left(i\bar{Q}\sigma^a\gamma^{\{\rho}\partial^{\nu\}}Q + \text{h.c.}\right)$ . |

very different from nTGC parametrization!

# Energy-Growth

| | |
|---|---|
| $\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.}\right) D_\mu H^\dagger D_\nu H$ | $-\frac{1}{4\Lambda^4} B_{\mu\nu} B^\mu{}_\rho \left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right).$ |
| $\frac{1}{2\Lambda^4}\left(i\bar{Q}\sigma^a\gamma^{\{\mu}\partial^{\nu\}}Q + \text{h.c.}\right) D_\mu H^\dagger \sigma^a D_\nu H$ | $-\frac{1}{4\Lambda^4} W^a_{\mu\nu} W^{a\,\mu}_{\ \rho} \left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right).$ |
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LL final states (ZZ only)

TT final states (ZZ, Zγ, γγ)

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LL final states (ZZ only)

TT final states (ZZ,Zγ,γγ)

- No LT (no mZ/E suppression)
- Both grow as $E^4/\Lambda^4$ in amplitude

# Helicity

| | |
|---|---|
| $\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.}\right) D_\mu H^\dagger D_\nu H$ | $-\frac{1}{4\Lambda^4} B_{\mu\nu} B^\mu{}_\rho \left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right)$ . |
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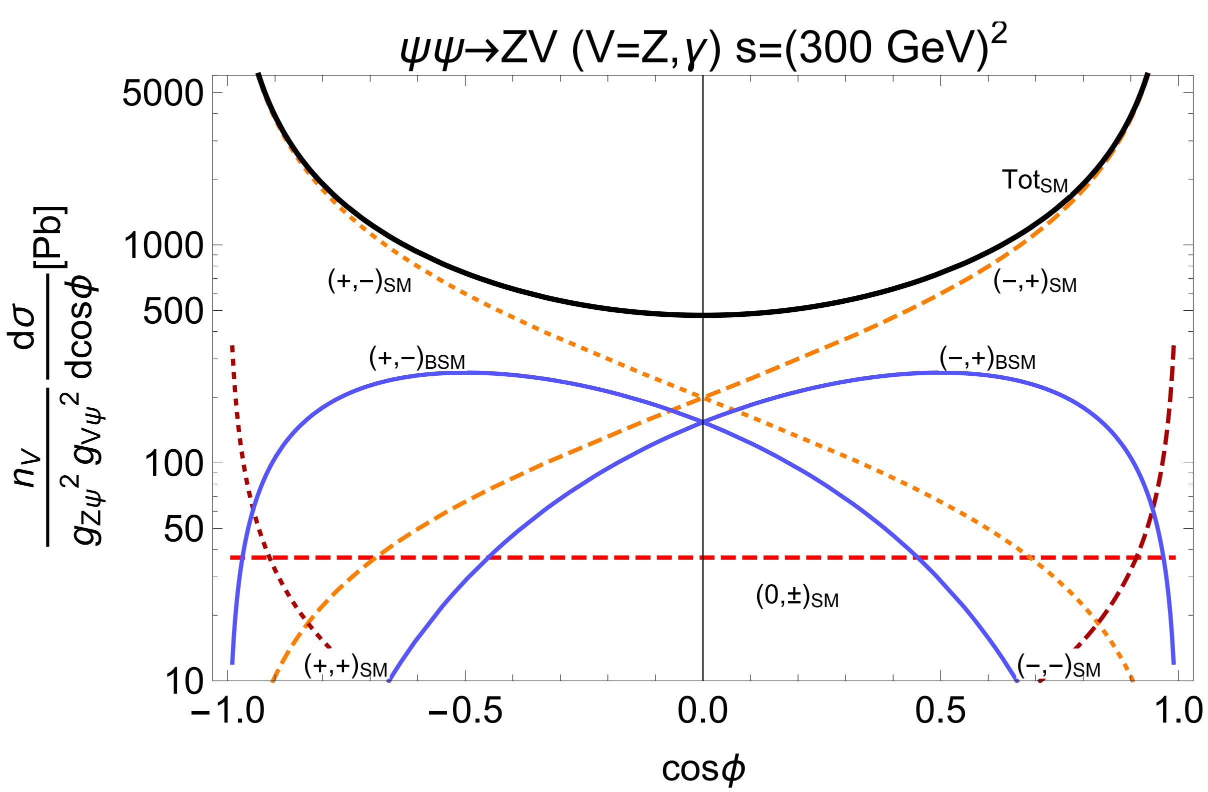
+−




- **Interferes** with largest SM contribution
  - → Sensitivity enhanced!

# Positivity Constraints

Fundamental principles from unitarity/analyticity imply constraints on coefficient in front! unique of these dimension-8

Adams,Arkani-Hamed,Dubovsky,Nicolis,Rattazzi'hep-th/0602178
Bellazzini'1605.06111

| | |
|---|---|
| $\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.}\right) D_\mu H^\dagger D_\nu H$ | $-\frac{1}{4\Lambda^4} B_{\mu\nu} B^{\mu}{}_{\rho}\left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi + \text{h.c.}\right)$ . |
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c=0

# Positivity Constraints

Fundamental principles from unitarity/analyticity imply constraints on coefficient in front! unique of these dimension-8

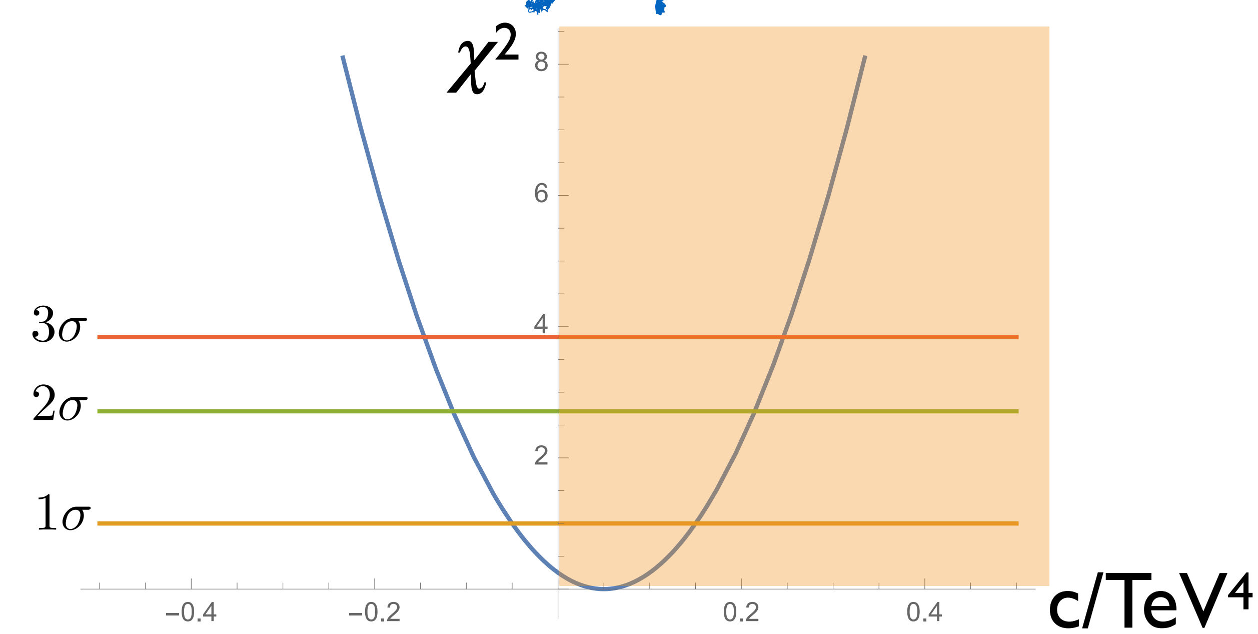
Adams,Arkani-Hamed,Dubovsky,Nicolis,Rattazzi'hep-th/0602178
Bellazzini'1605.06111

| | |
|---|---|
| $\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi+\text{h.c.}\right)D_\mu H^\dagger D_\nu H$ | $-\frac{1}{4\Lambda^4}B_{\mu\nu}B^{\mu}{}_{\rho}\left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi+\text{h.c.}\right).$ |
| ~~$\frac{1}{2\Lambda^4}\left(i\bar{Q}\sigma^a\gamma^{\{\mu}\partial^{\nu\}}Q+\text{h.c.}\right)D_\mu H^\dagger\sigma^a D_\nu H$~~ | $-\frac{1}{4\Lambda^4}W^a_{\mu\nu}W^{a\,\mu}{}_{\rho}\left(i\bar{\psi}\gamma^{\{\rho}\partial^{\nu\}}\psi+\text{h.c.}\right).$ |
| $\psi=Q,u_R,d_R$ | ~~$-\frac{1}{4\Lambda^4}B_{\mu\nu}W^{a\,\mu}{}_{\rho}\left(i\bar{Q}\sigma^a\gamma^{\{\rho}\partial^{\nu\}}Q+\text{h.c.}\right).$~~ |

c=0

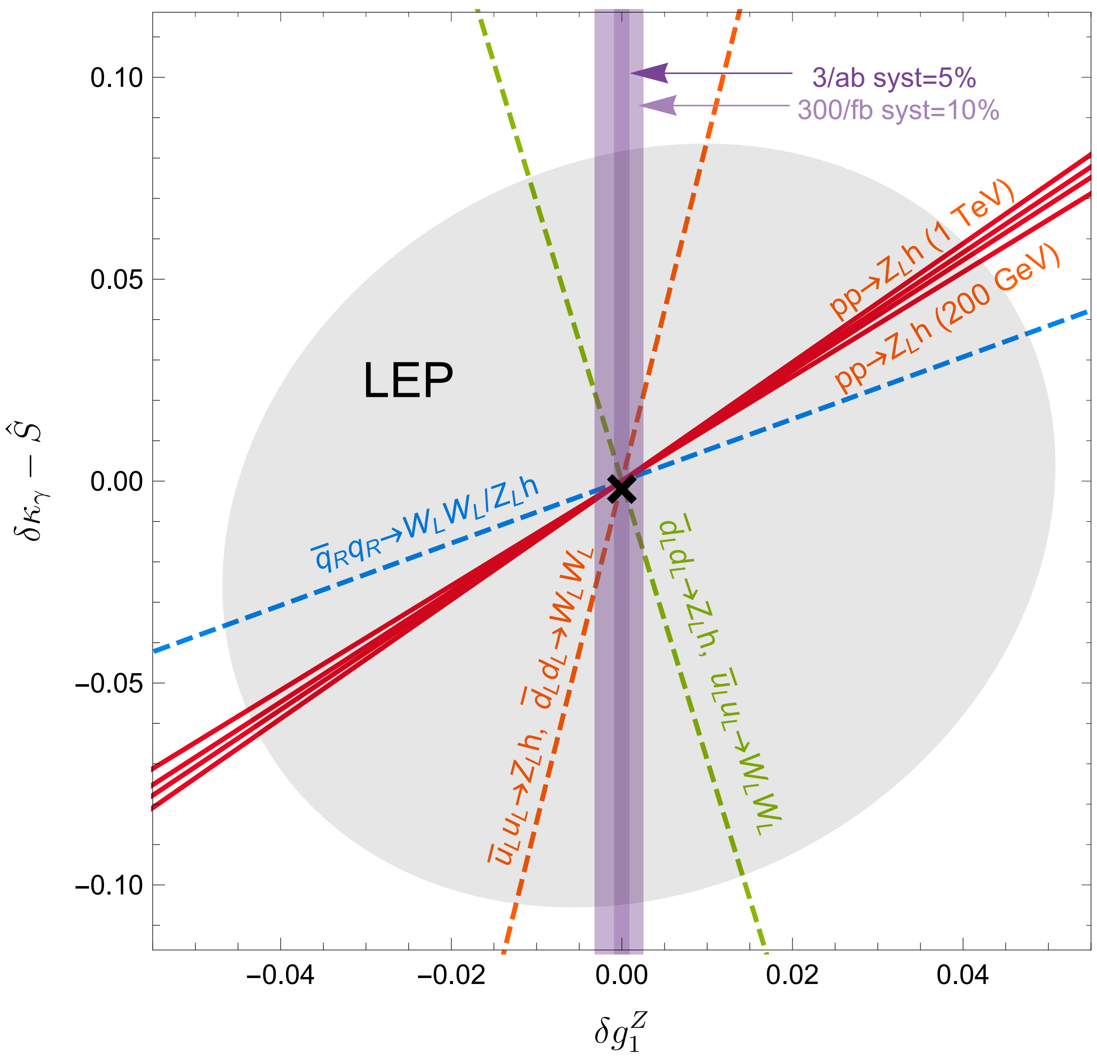
c>0 (always positive!)

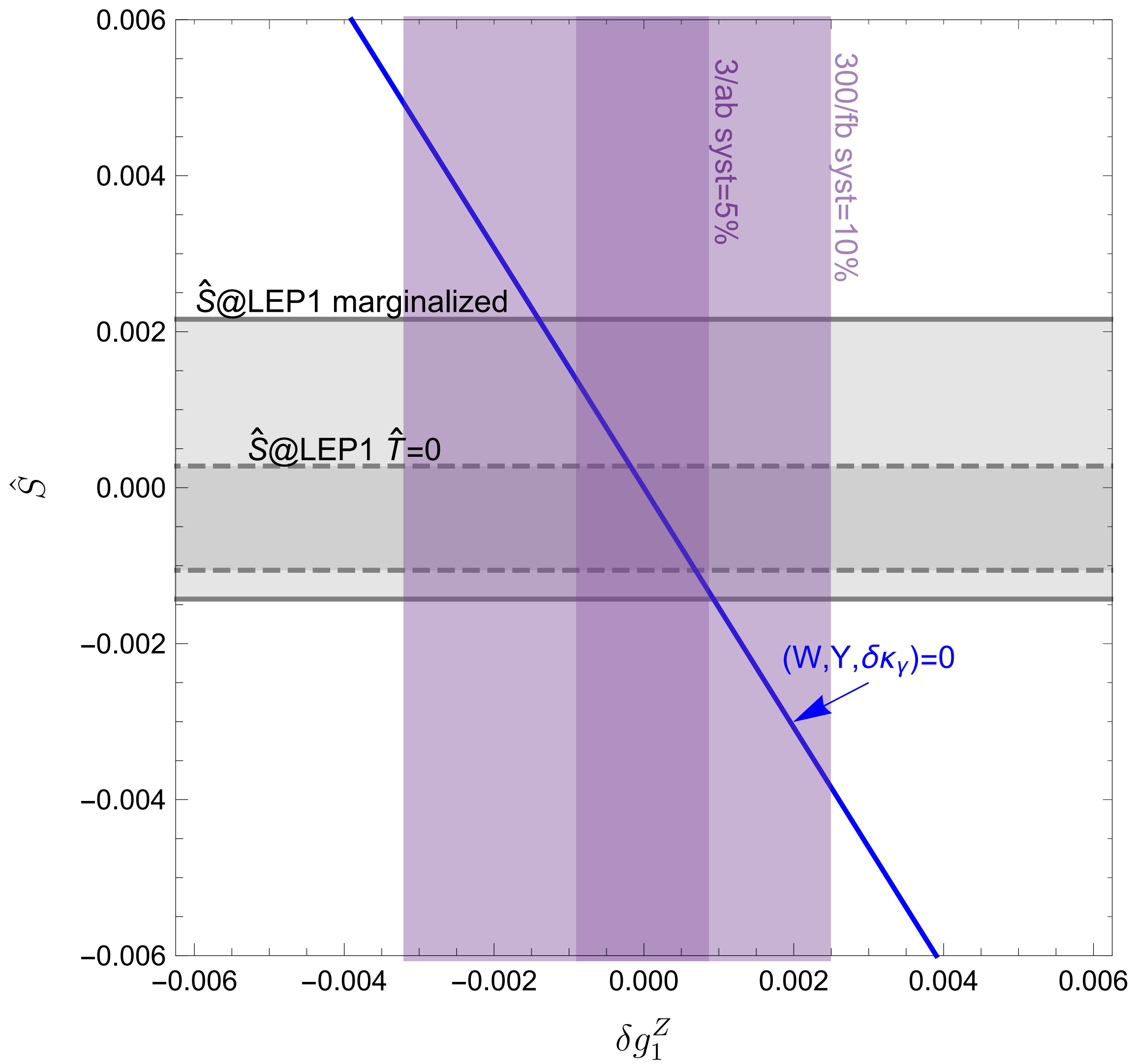
Smaller viable parameter space



# Comparisons

high-E is unique, but it compares at lower-E with different effects:




...with TGCs at LEP2

...with S-parameter at LEP1

- Genuine SM precision test

# Why Interference?

When SM and BSM contribute to the same amplitude:

$$Amp = SM + BSM = SM(1 + \delta_{BSM})$$

$$\delta_{BSM} = c\frac{E^2}{M^2}$$

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- $\sigma \propto |Amp|^2 \simeq SM^2(1 + \delta_{BSM} + \delta^2_{BSM})$

For small BSM effects $1 \gg \delta_{BSM}$ ,

interference dominates $\delta_{BSM} \gg \delta^2_{BSM}$

# Non-Interference?

If SM and BSM contribute to different amplitudes:

- $$\sigma \propto \sum |Amp|^2 \simeq SM^2 (1 + c_i \frac{E^2}{\Lambda^2} + c_i^2 \frac{E^4}{\Lambda^4})$$

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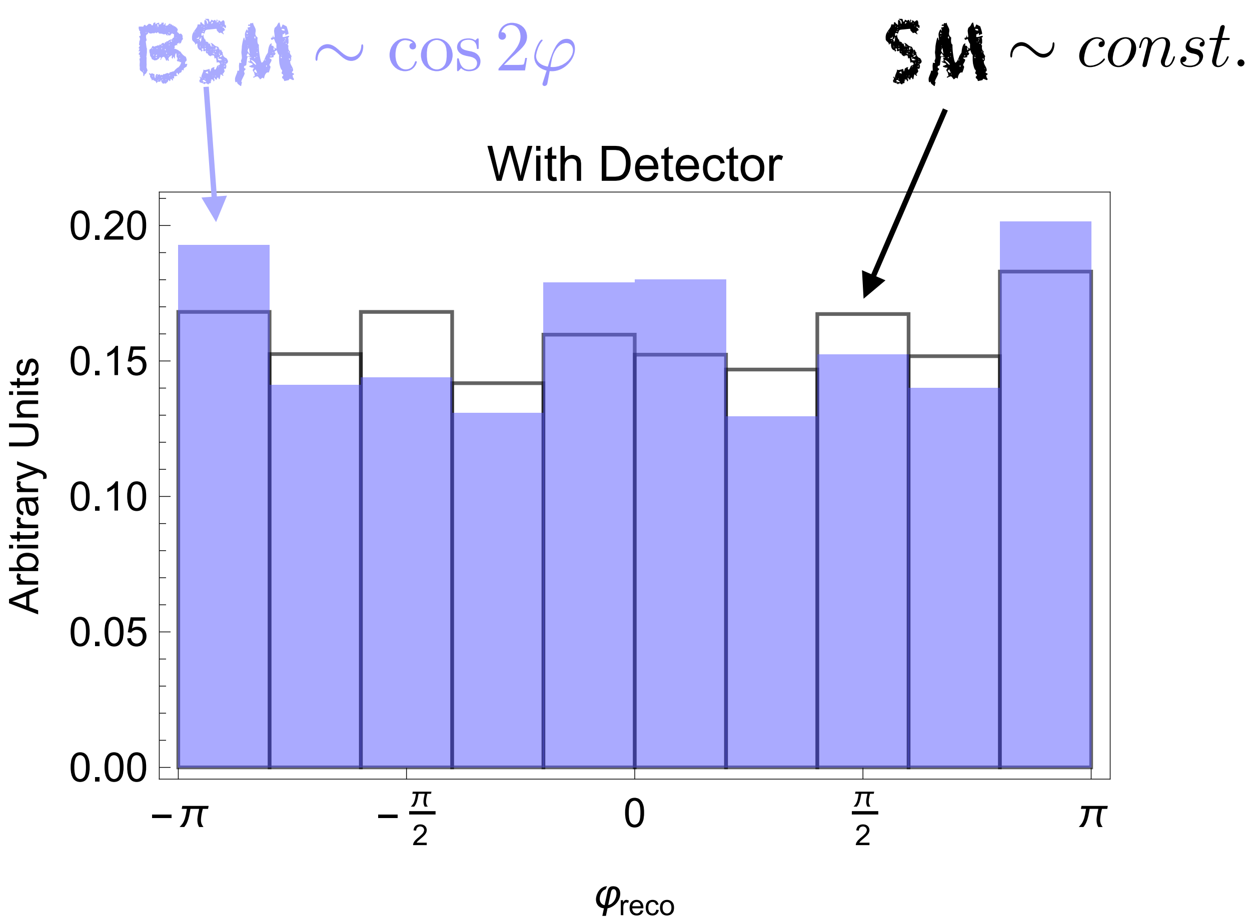
The leading effects BSM are $O\left(\frac{1}{\Lambda^4}\right)$

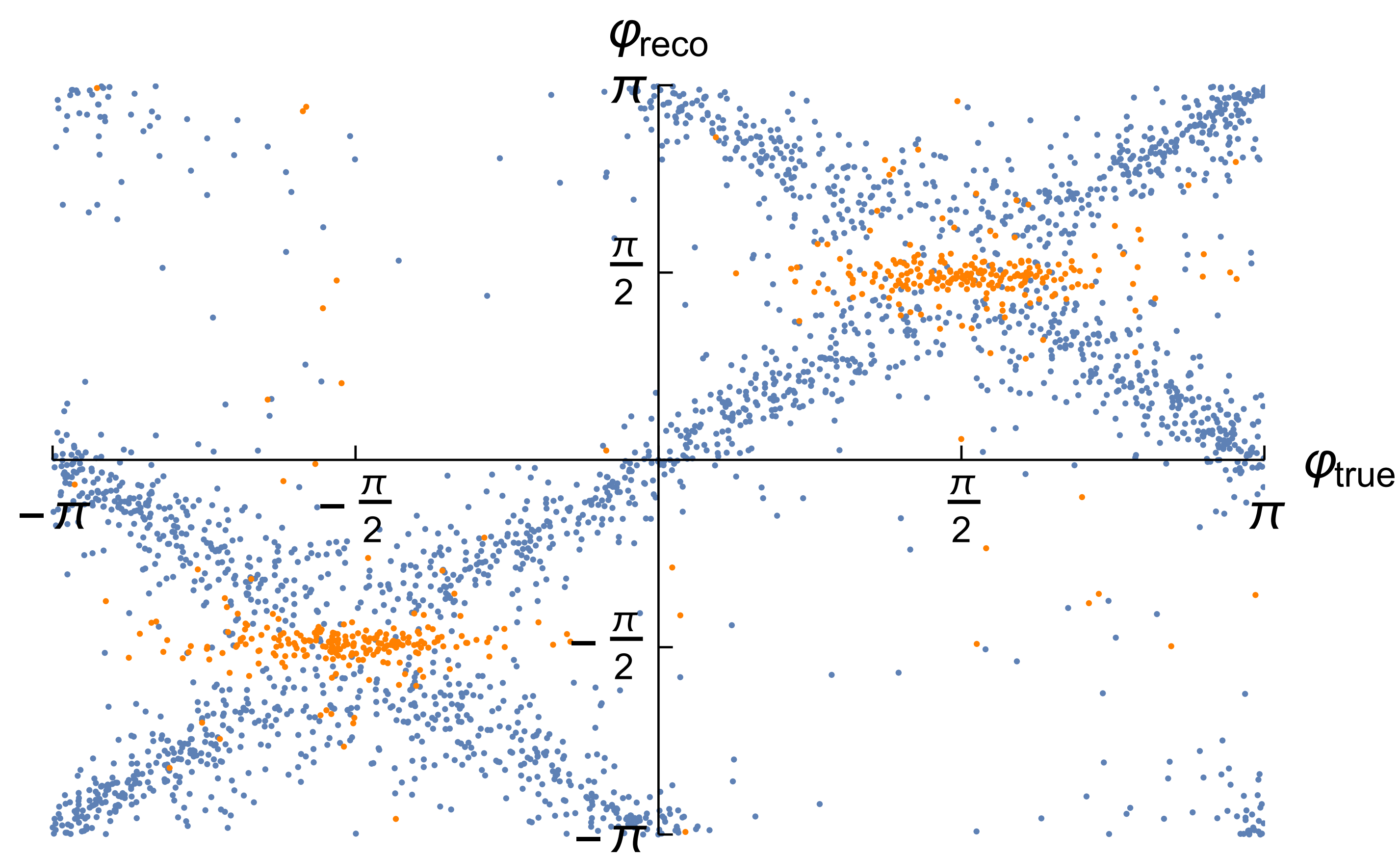
- Small effects, even smaller!

# Azimuthal Angle... more in reality

## Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation




Panico,FR,Wulzer'17
See also Azatov, Elias-Miro, Reyimuaji, Venturini'17

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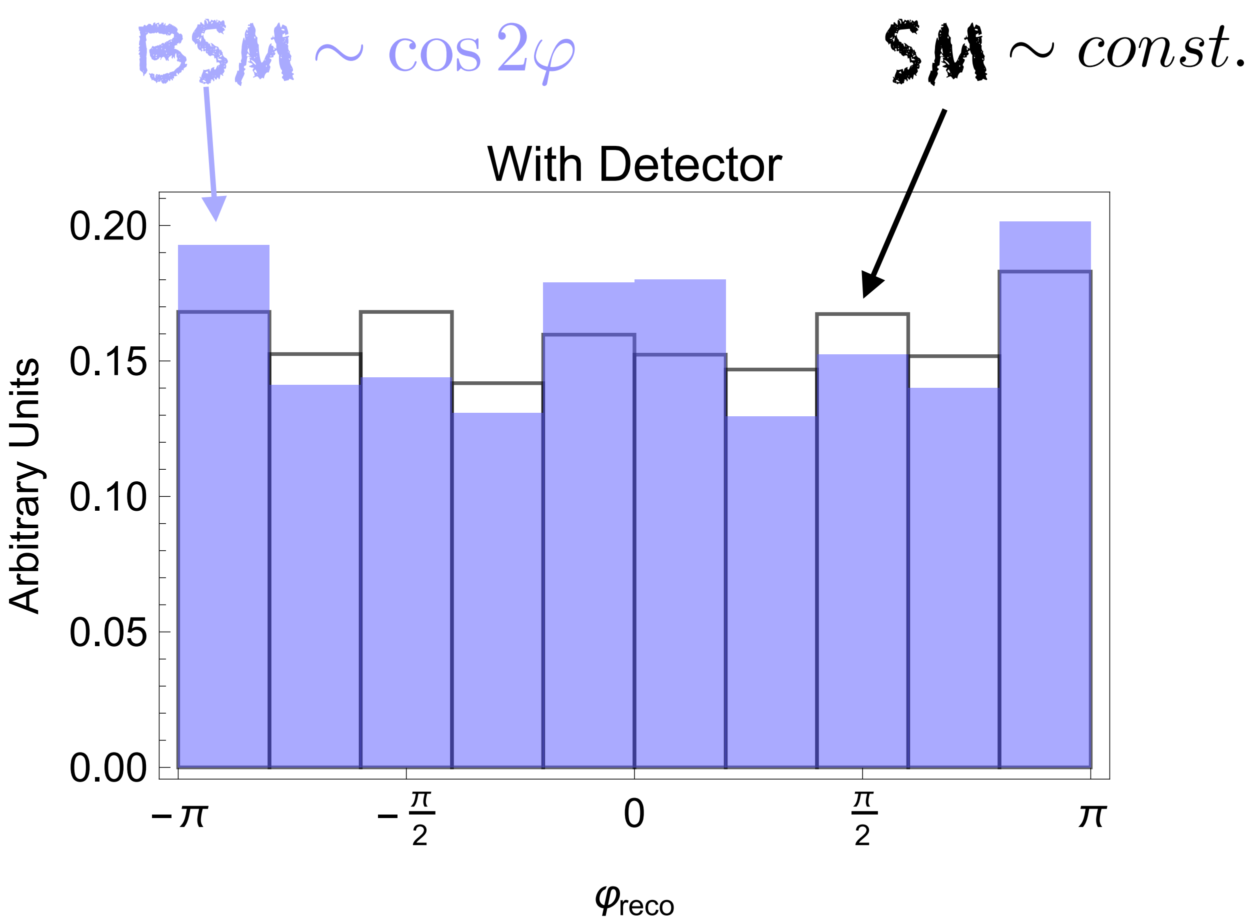


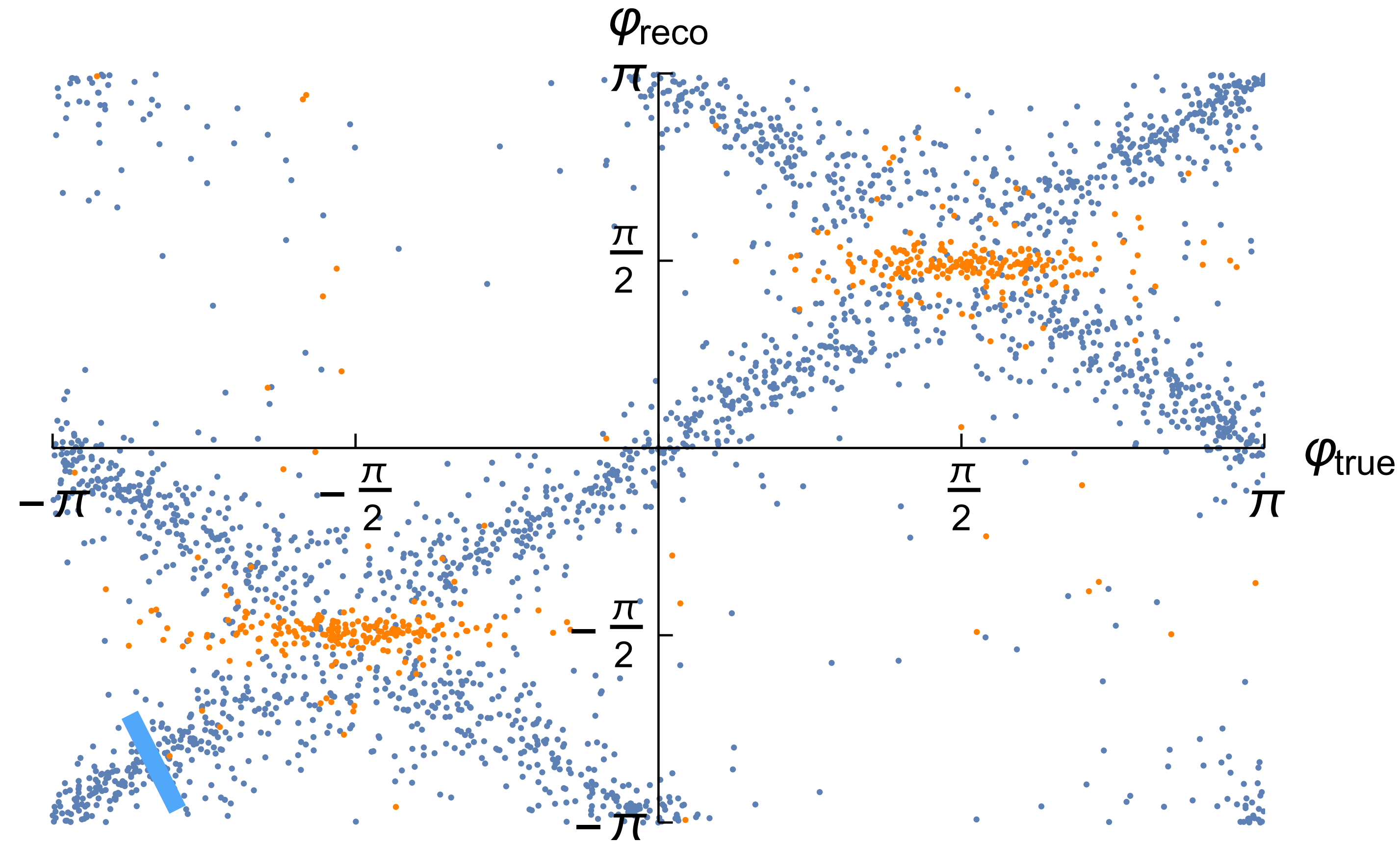


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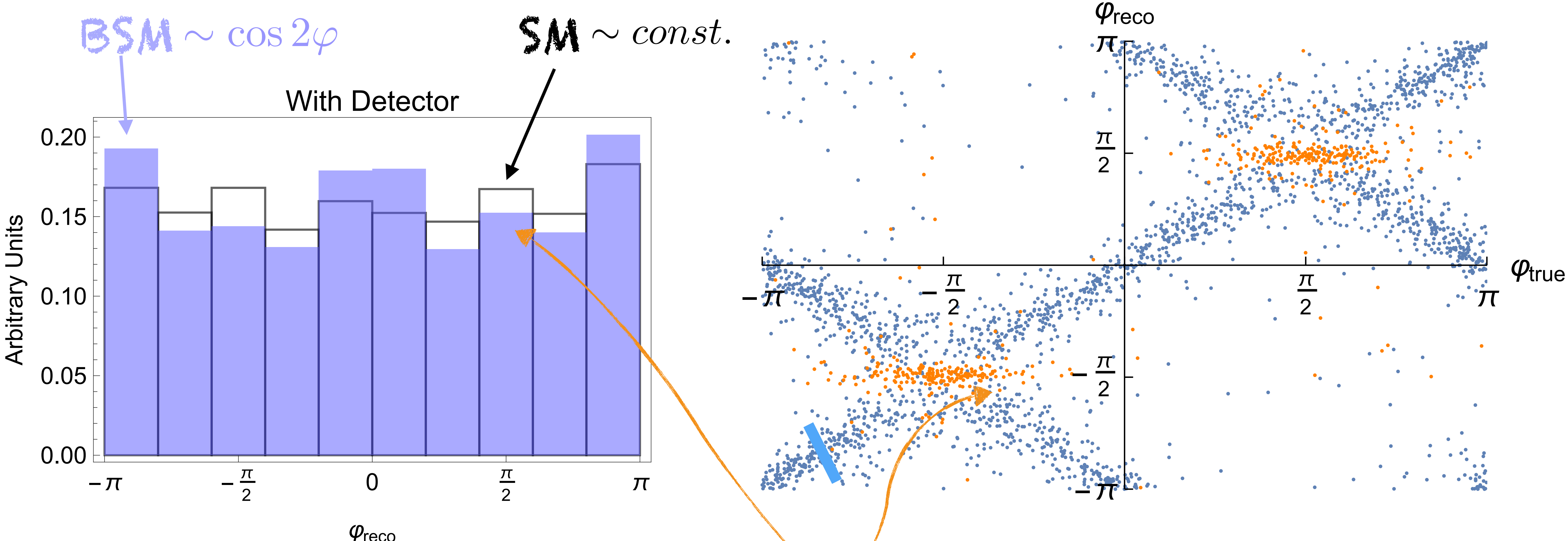


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More events with $m_\perp^2 > m_W^2$

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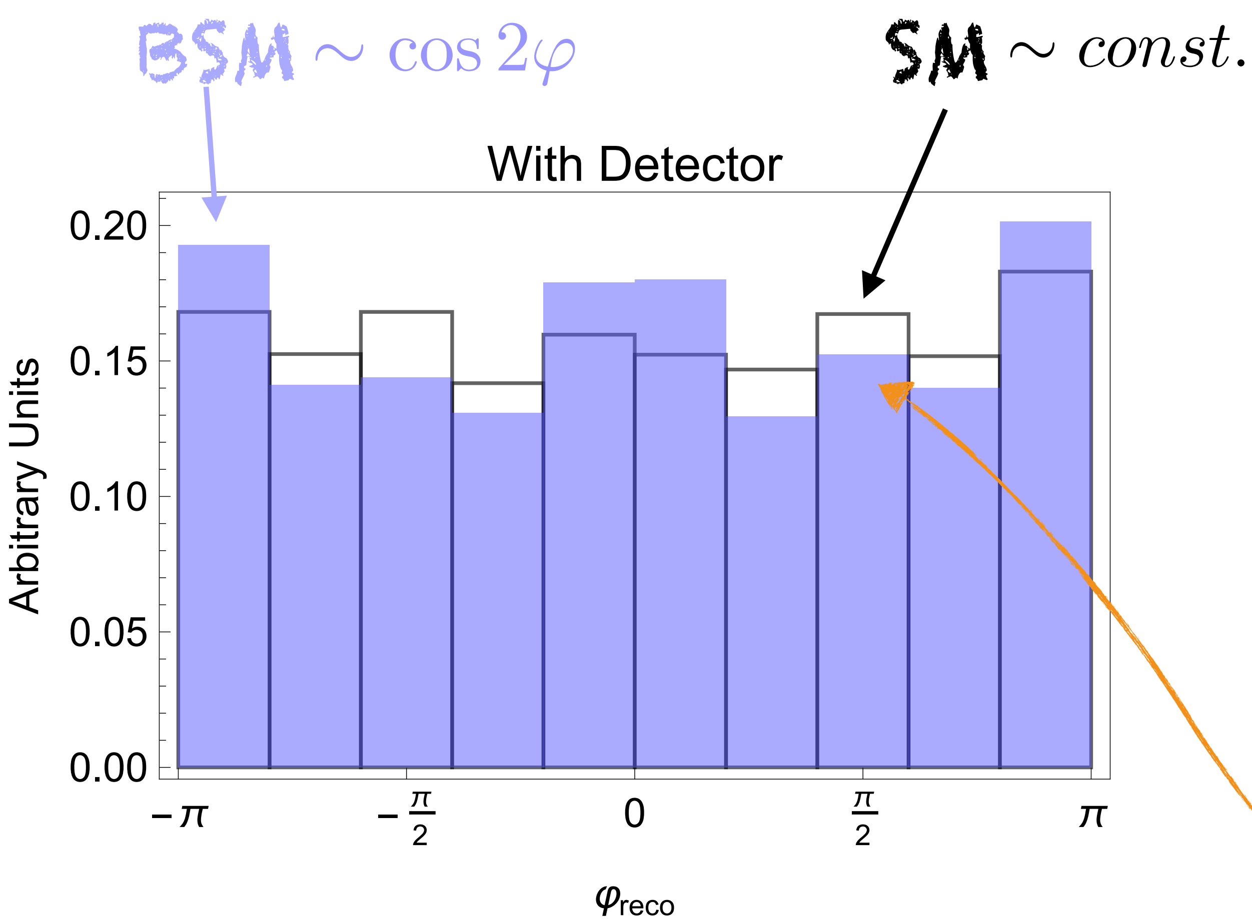


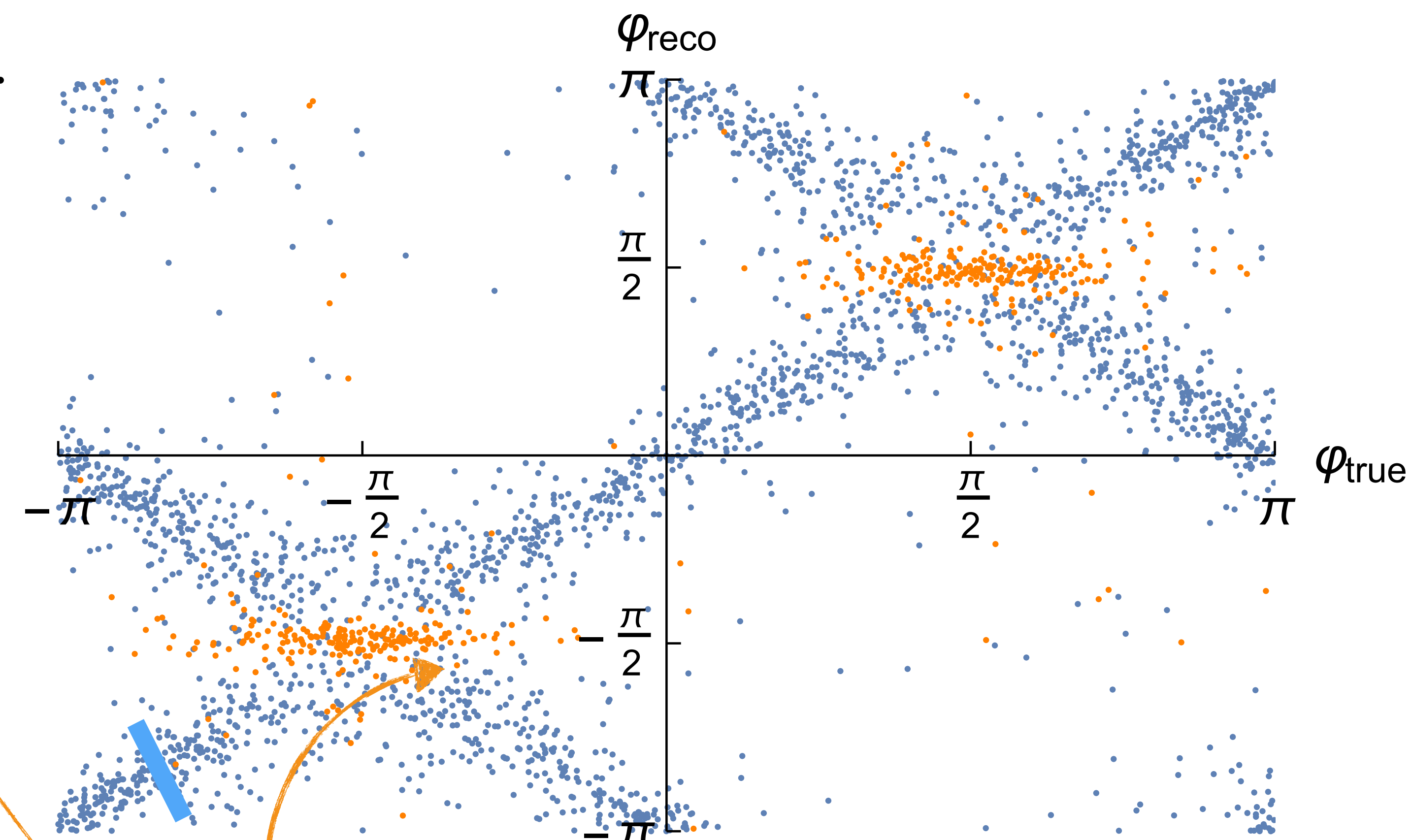


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▶ Resurrection is real

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