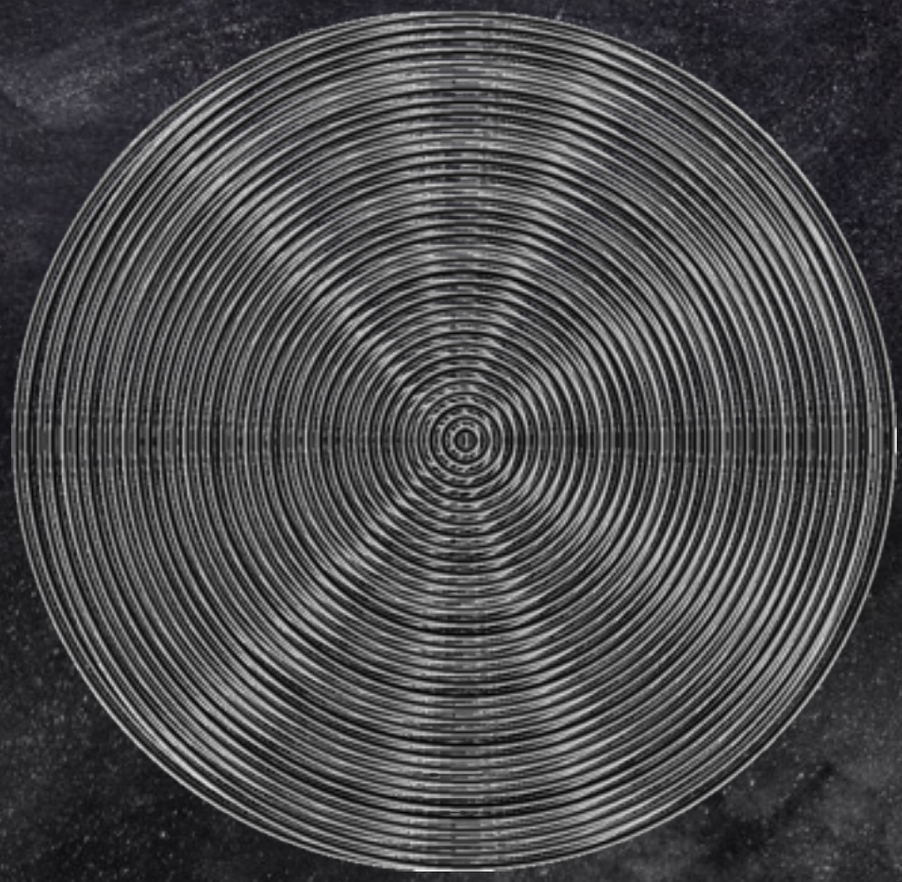
Di-boson Interference: Death and Resurrection

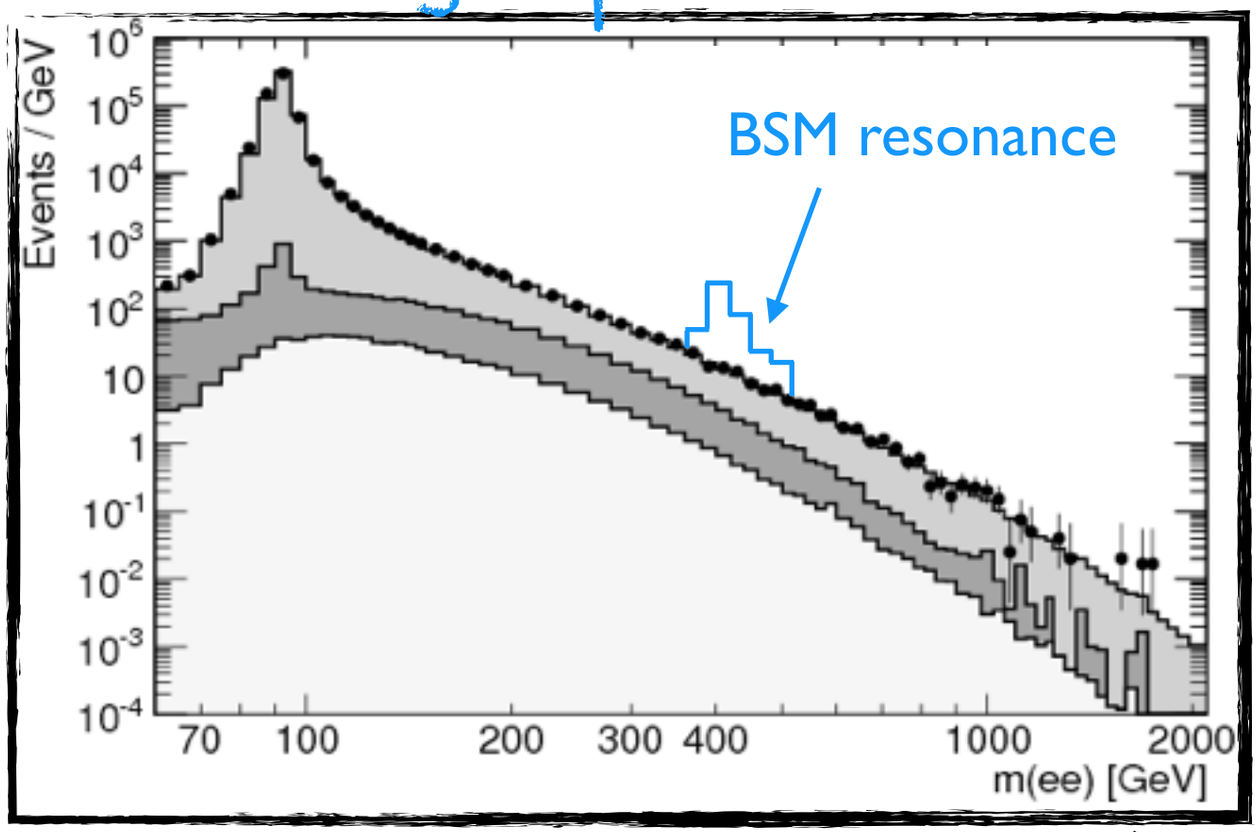


Francesco Riva
(CERN)

In collaboration with
Panico, Wulzer 1708.07823,
Azatov, Contino, Machado 1607.05236
Liu, Pomarol, Rattazzi 1603.03064

LHC Exploration
(so far 2009-2015)

Focus: Search for new light particles



Energy frontier (13 TeV)

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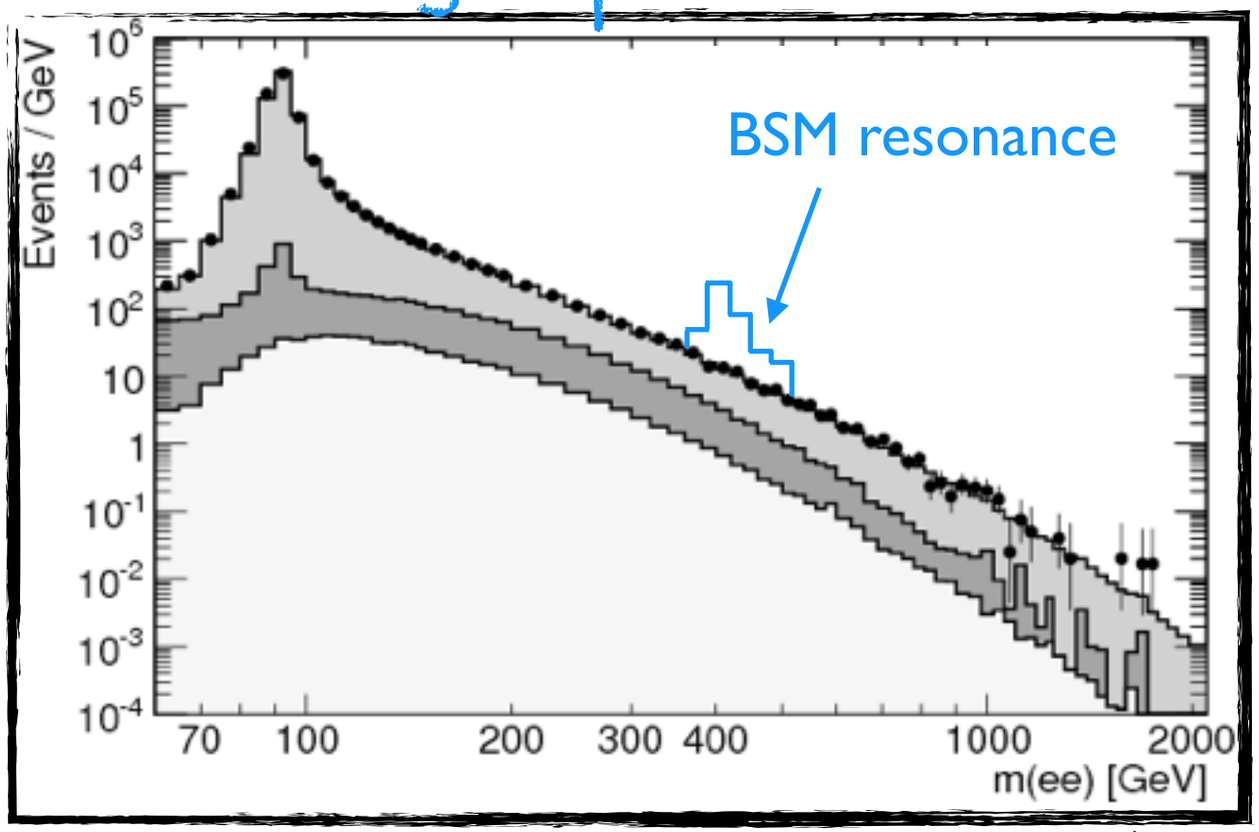

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- Experimentally: First accessible signal/Easy to study

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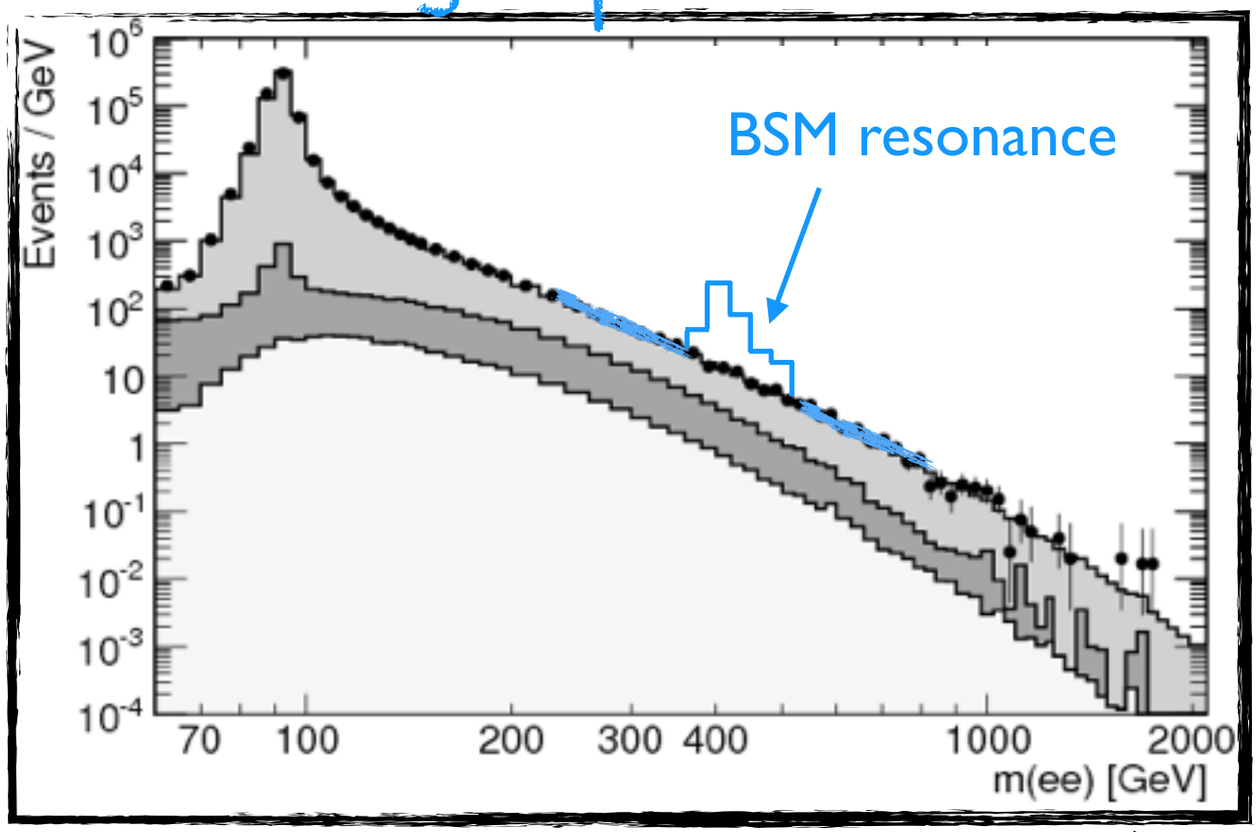

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LHC Exploration

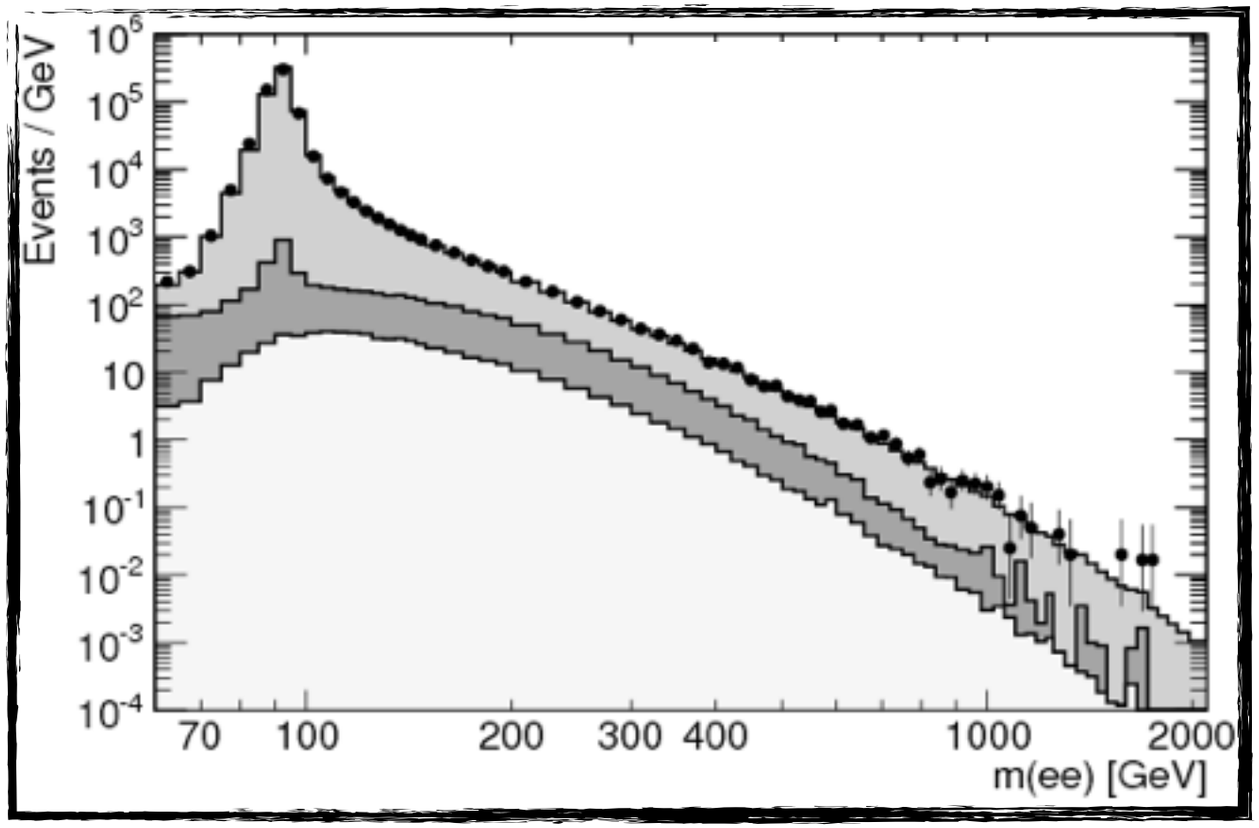
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb^{-1})

intensity frontier

(2016: 40 fb^{-1})



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Focus: Standard Model Precision Tests

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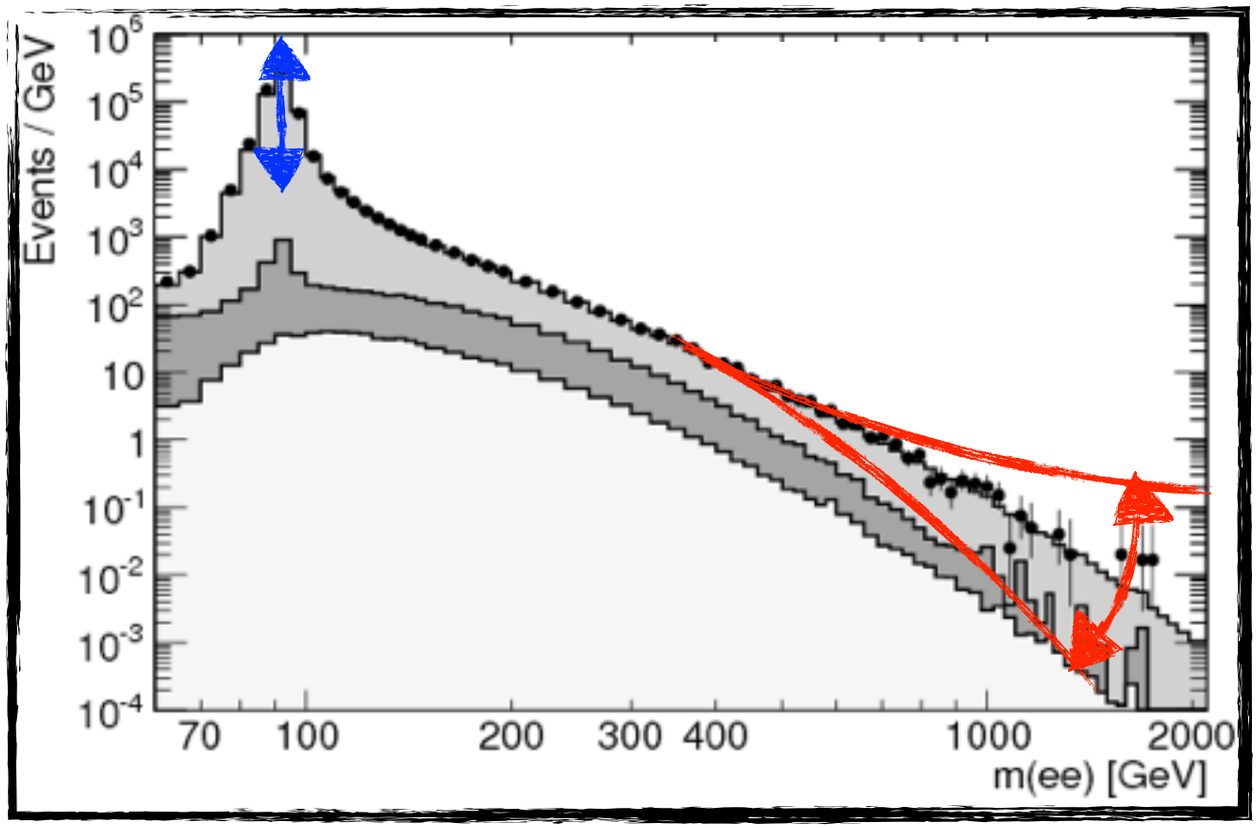
intensity frontier

(2016: 40 fb^{-1})



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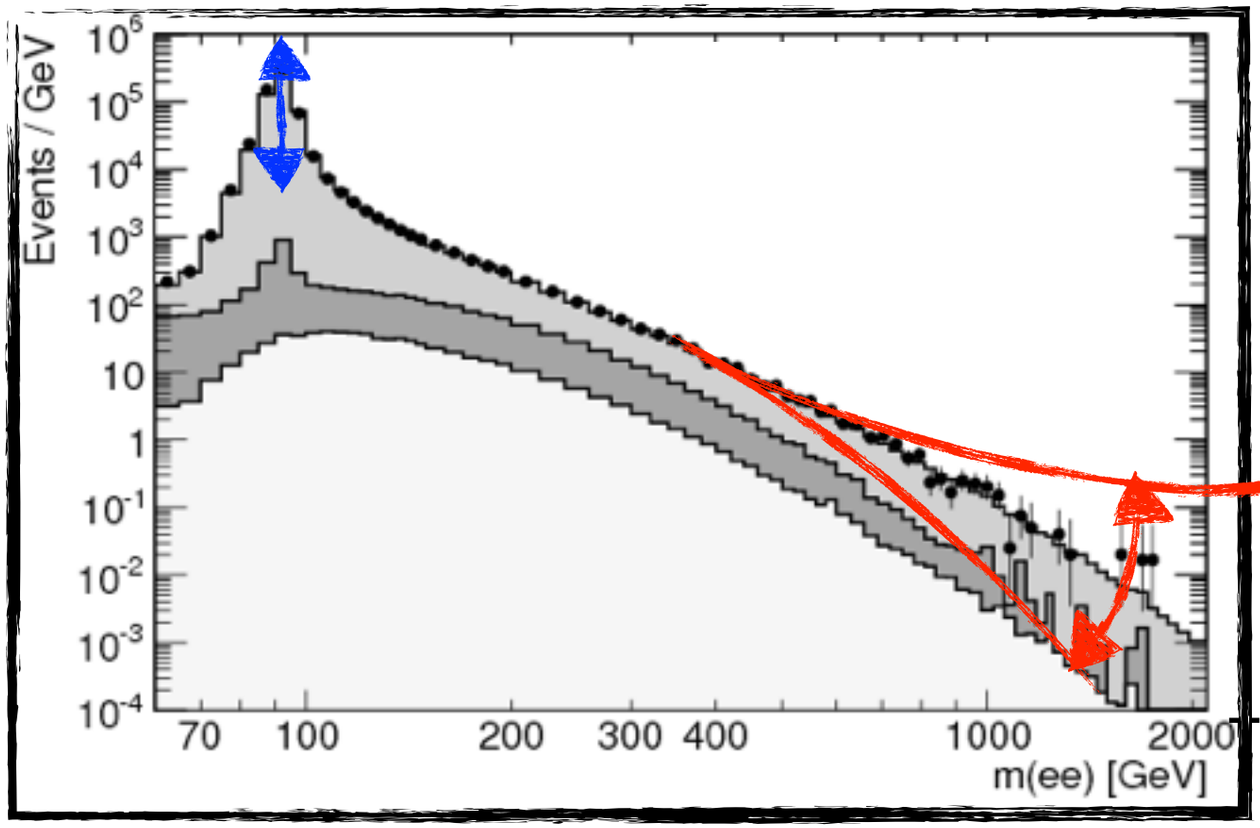

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10-100 TeV

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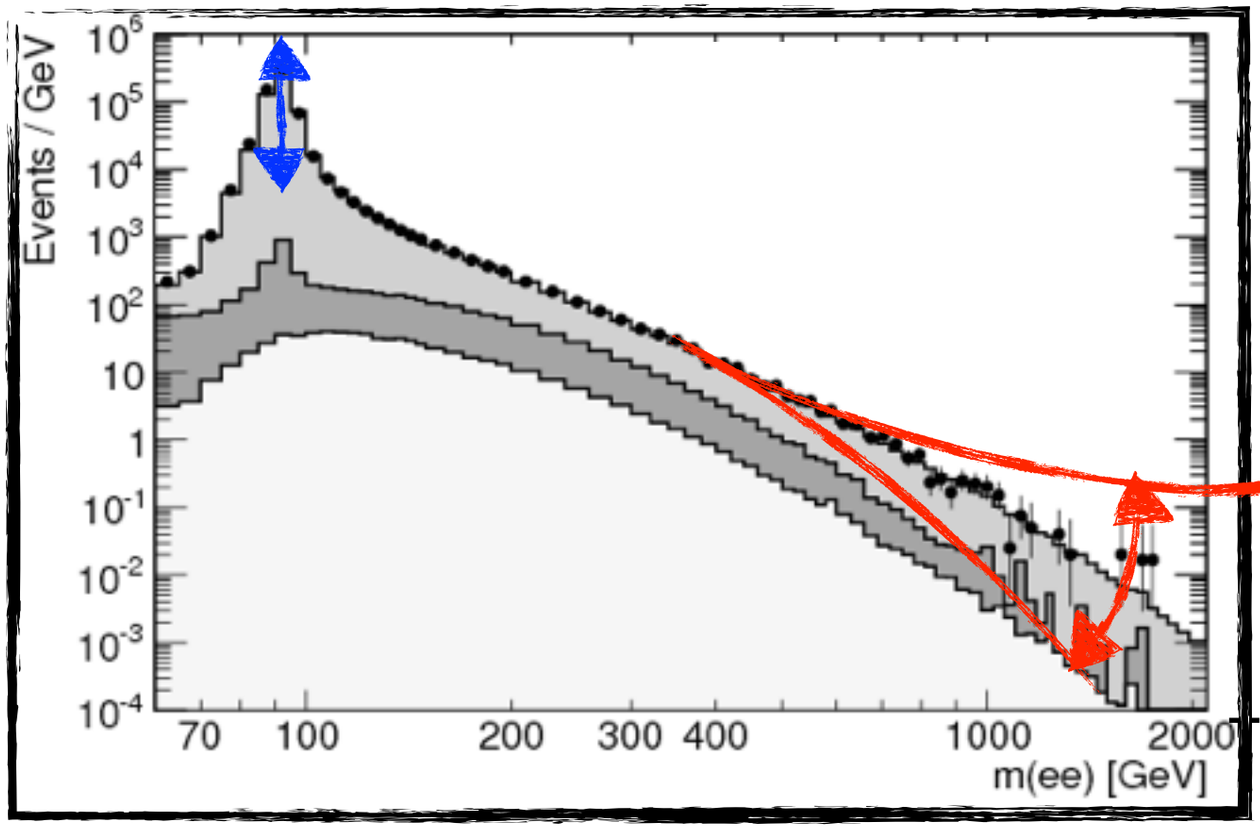

10-100 TeV

M

$$Amp = SM\left(1 + c\frac{E^2}{M^2}\right) - \text{Effective Field Theory}$$

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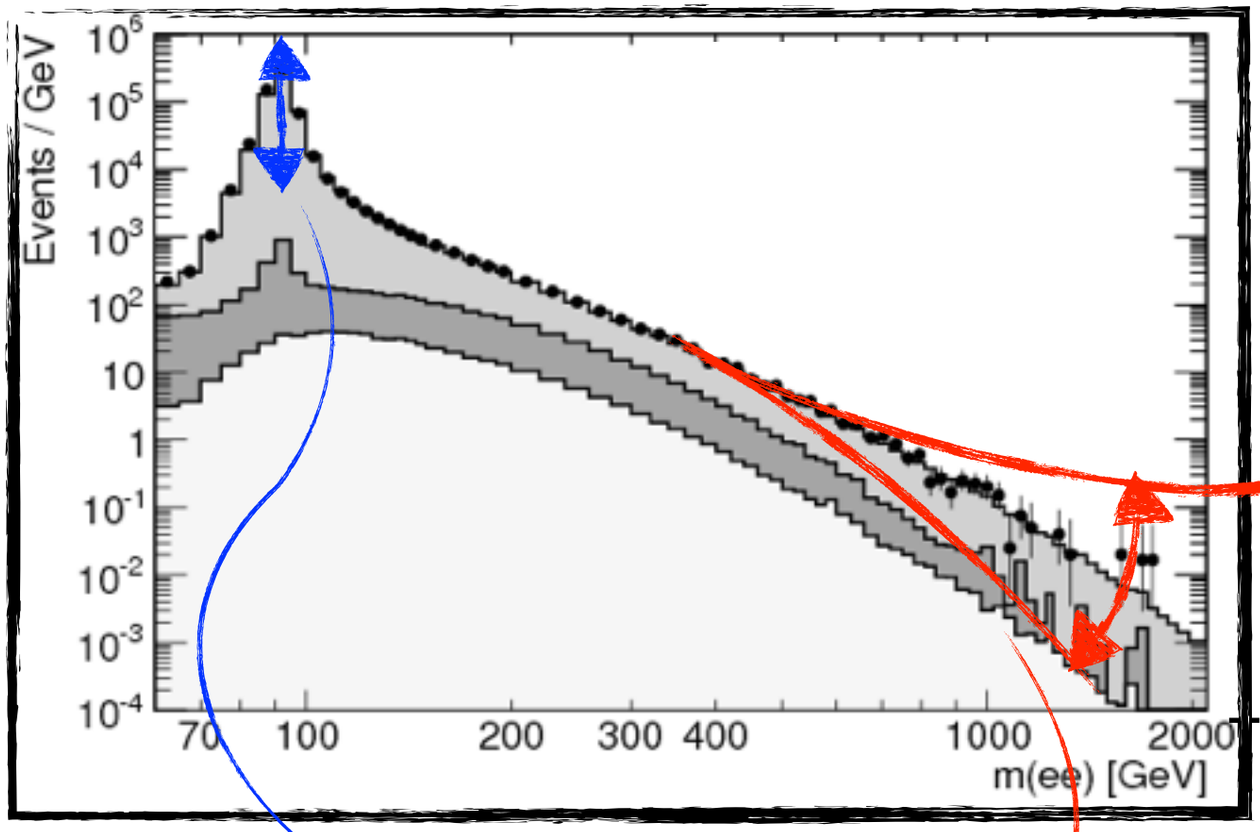

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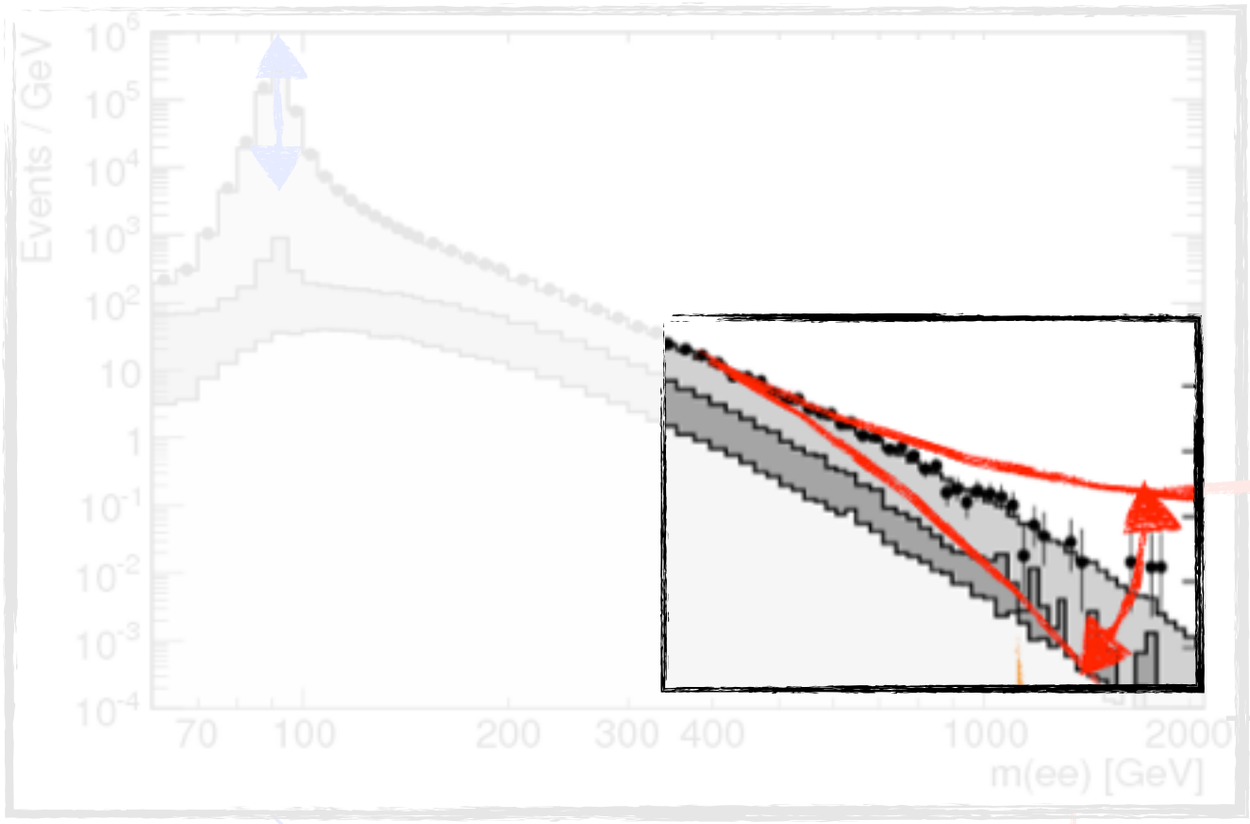

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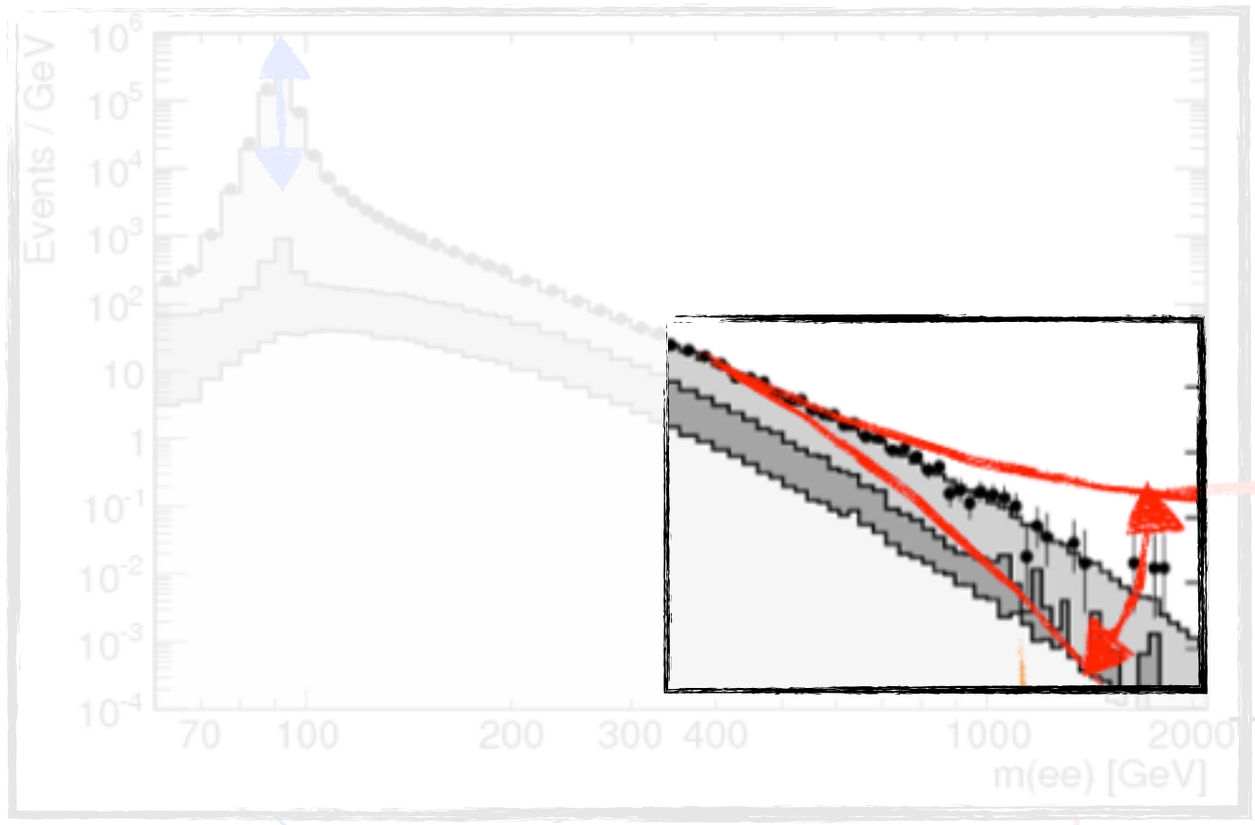

?

10-100 TeV

M

— Effective Field Theory

$$Amp = SM\left(1 + c\frac{E^2}{M^2}\right)$$

- **Experimentally:** Already very difficult...

and comes with a fundamental challenge: **non-interference**

Outline

1- Why SM/BSM Interference?
2- No Interference
3- Interference

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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When SM and BSM contribute to the same amplitude:

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

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

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

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

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

Non-Interference?

If SM and BSM contribute to different amplitudes:

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

interference vanishes

Non-Interference?

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interference vanishes

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

(the same order as dimension-8 that do interfere)

- Small effects, even smaller!

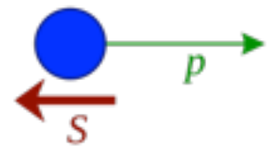
Interference is important... can we always count on it?

Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

Exploit:

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



Amplitudes for 2→2 with different total h don't interfere

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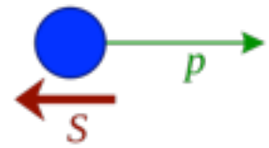


Amplitudes for 2→2 with different total h don't interfere

Theorem:

Any BSM dim-6 operator

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

Massless limit + tree level + at least one transverse vector

- SM and BSM_6 contribute to different helicity amplitudes
- No interference

(

proof

Non-Interference for BSM_6 amplitudes

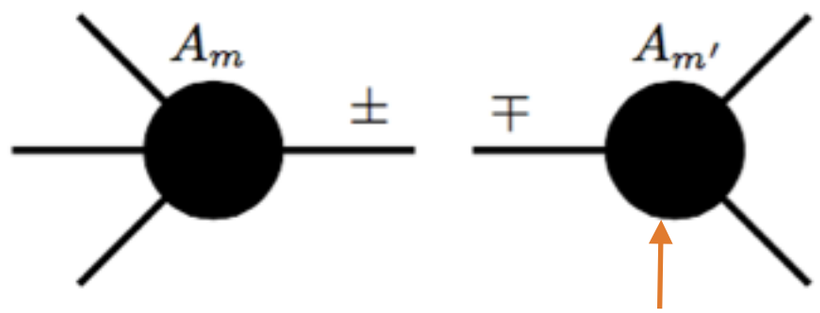
Azatov,Contino,Machado,FR'16

How?

i) Helicity sums for amplitudes on-shell:

$$h(A_n) = h(A_m) + h(A_{m'})$$

n=m+m'-2 legs



SM or BSM_6

Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

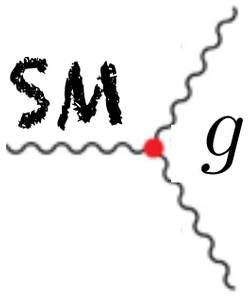
How?

ii) For massless theories 3-point amplitude determined:

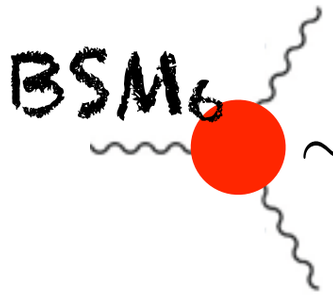
Poincaré
Dim. Analysis
3-point kinematics

Helicity of 3-point $\leftrightarrow$ coupling dimension,

$$|h(A_3)| = 1 - [g]$$



$$\Rightarrow |h^{SM}| = 1$$



$$\sim \frac{1}{\Lambda^2} \Rightarrow |h^{BSM}| = 3$$

Non-Interference for BSM$_6$ amplitudes

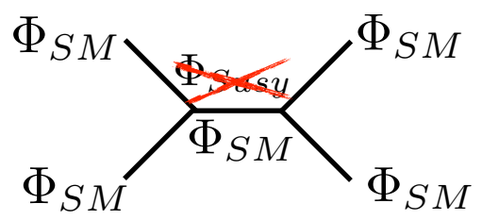
Azatov,Contino,Machado,FR'16

How?

iii) SUSY* Ward Identities: $|h(A_4^{SM})| < 2$ (except $\psi^+\psi^+\psi^+\psi^+$)
(maximal helicity violation)

*For y_u=0 or y_d=y_l=0: SM upliftable to SUSY+R-parity (1 Higgs doublett)

Grisaru,Pendleton,vanNieuwenhuizen'77



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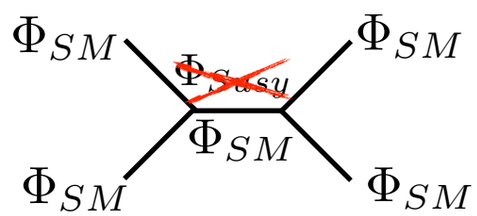

e.g. $0 = \langle 0|[Q, \Psi^+V^+V^+V^+]|0\rangle = \sum_i \langle 0|\Psi^+ ... [Q, V^+] ... V^+|0\rangle \propto \langle 0|V^+V^+V^+V^+|0\rangle$

$[Q,\psi] \sim V$ $\quad [Q,V] \sim \psi$ $\quad \psi^+\psi^+ \cdots = 0$

- $A(V^+V^+V^+V^-) = A(V^+V^+\psi^+\psi^-) = A(V^+V^+\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0$

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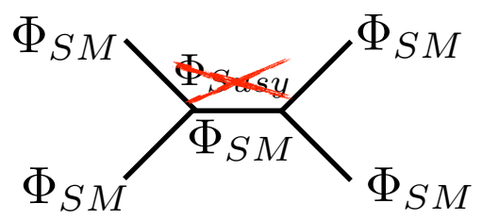

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BSM not supersymmetrizable in general

Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

How?

i) Helicity sums $h(A_n) = h(A_m) + h(A_{m'})$

ii) Helicity of 3-point $\leftrightarrow$ coupling dimension $|h(A_3)| = 1 - [g]$

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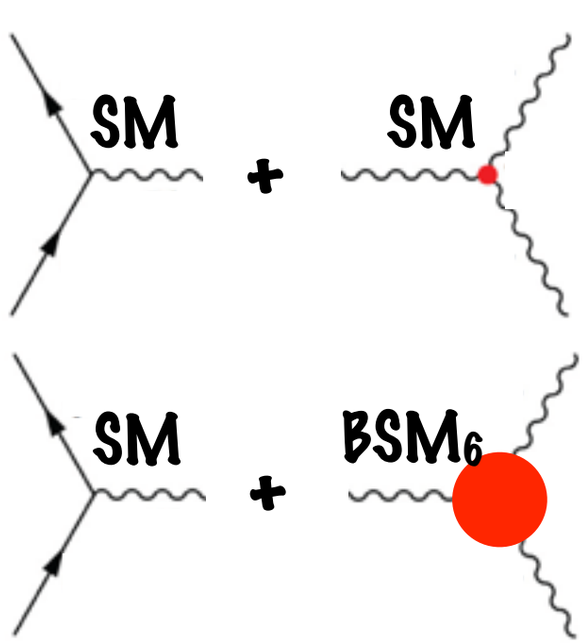

$h^{tot} = 1 - 1 = 0$

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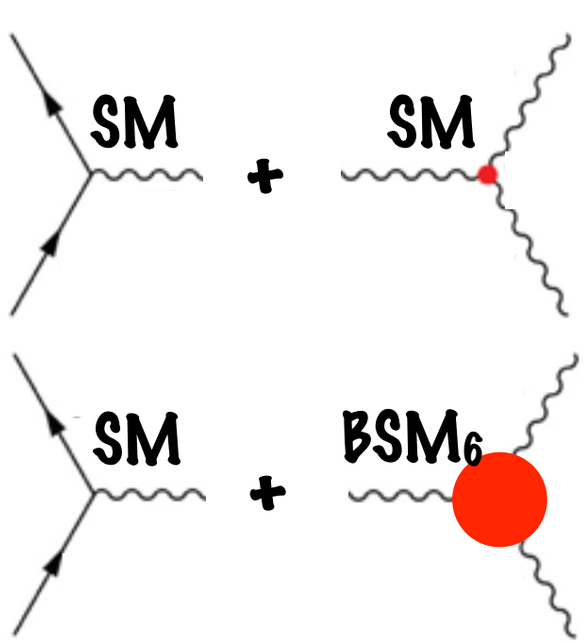

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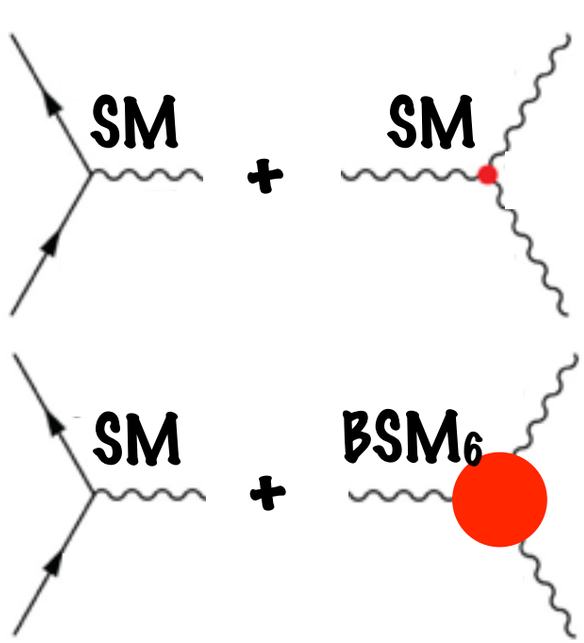

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Massless limit + tree level + at least one transverse vector

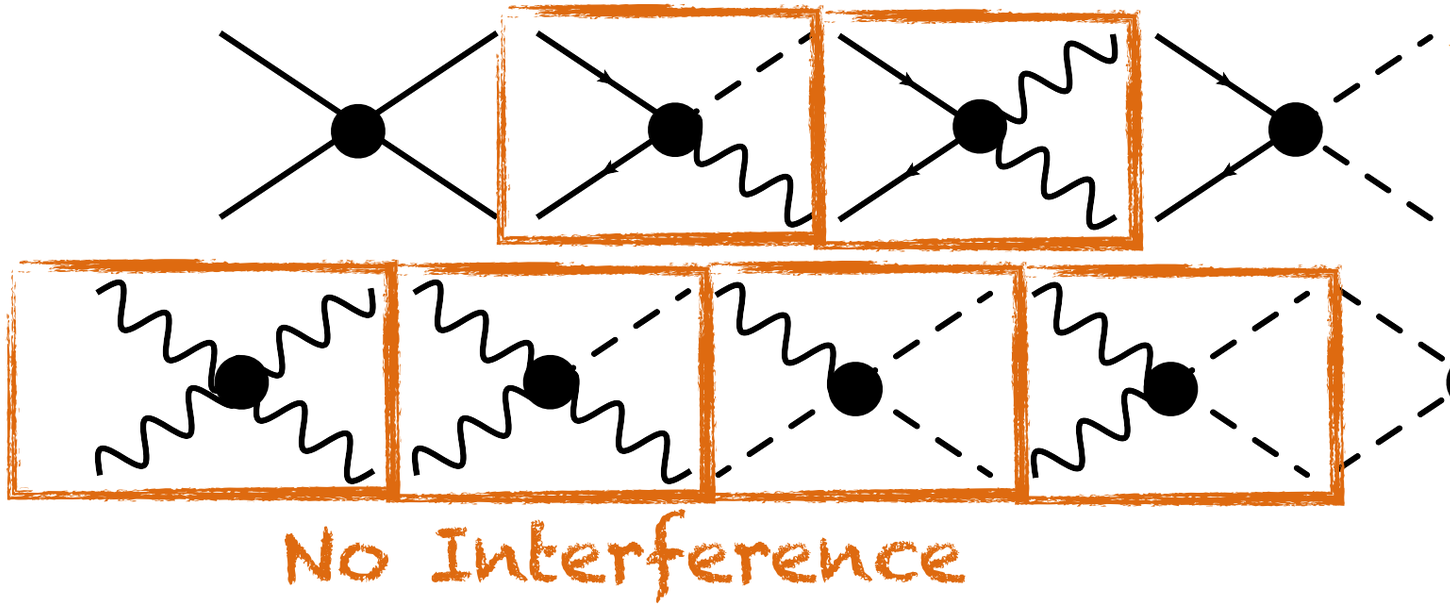
- SM and BSM_6 no interference

proof

Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

2->2 processes:



What to do to test transverse vectors?

1) BSM with large effects can be tested consistently

see Pomarol's talk

2) Vectors in interfering amplitudes

3) NLO effects that do interfere

4) Interference Resurrection

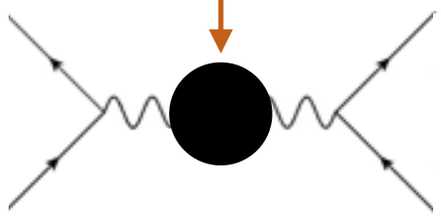
2. Vectors in interfering amplitudes

- Effects in transverse 2-point function affect interfering 4-point amplitude

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

Liu,Pomarol,Rattazzi,FR'16

See Wulzer talk



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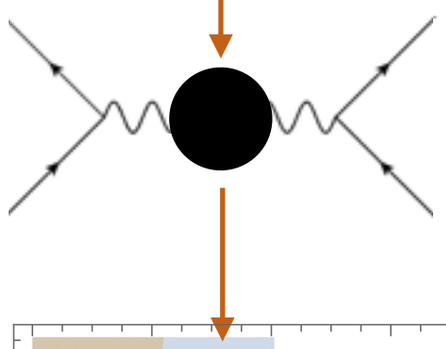
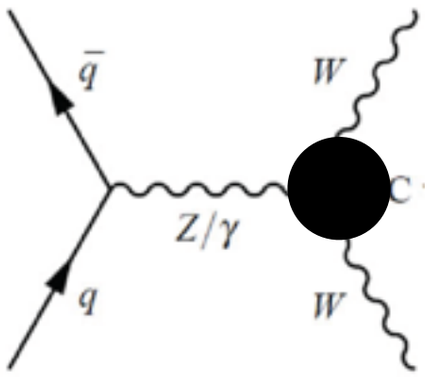
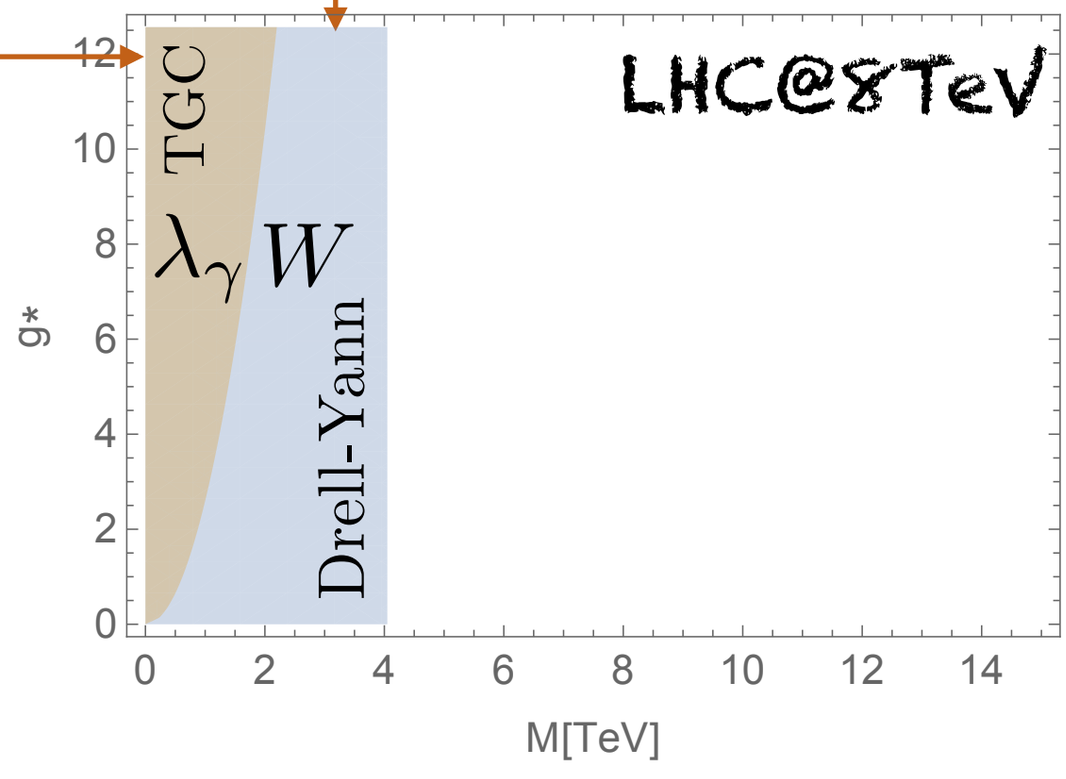


$\frac{g_*}{M^2}\epsilon_{abc}W_\mu^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$





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Non-interference only for massless/tree-level/2->2 processes!

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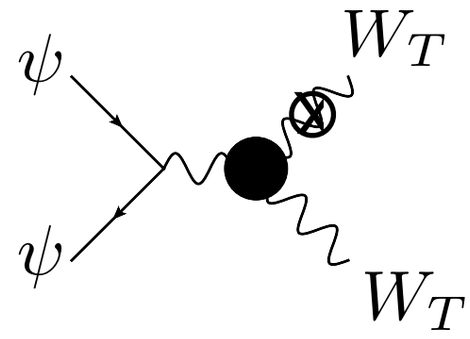
- EW finite mass effects $\sim \frac{m_W^2}{E^2}$



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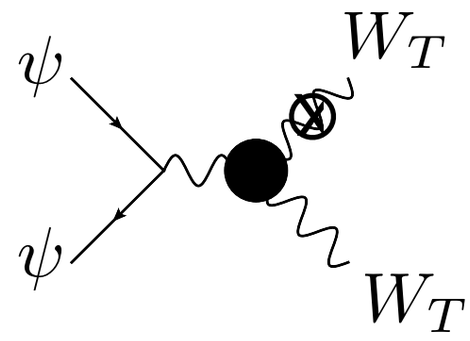
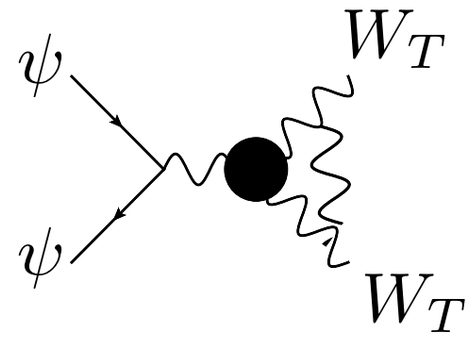


- Loop effects $\sim \frac{\alpha_{s,em}}{4\pi}$

(no soft-limit enhancement, at high-energy)



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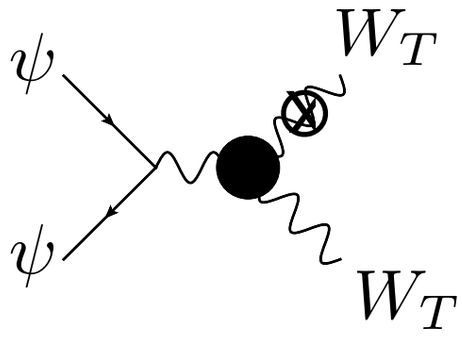

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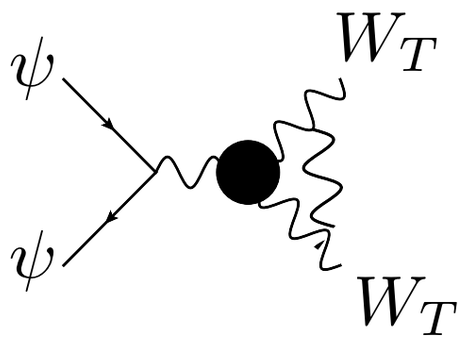

} Only signal suppressed

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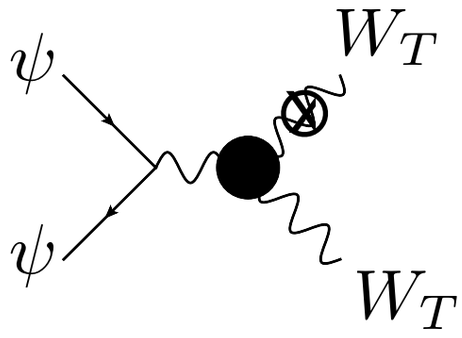

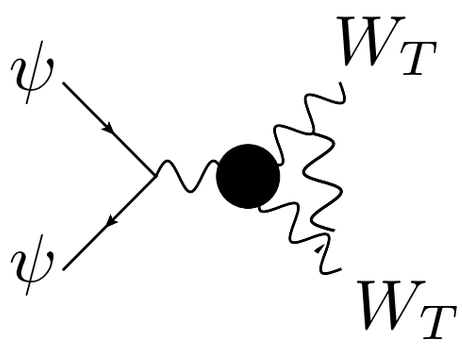

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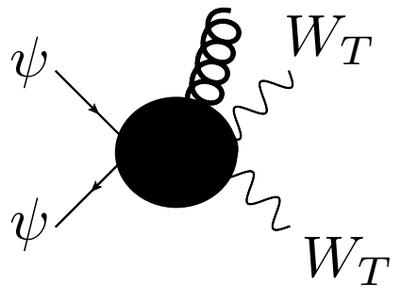
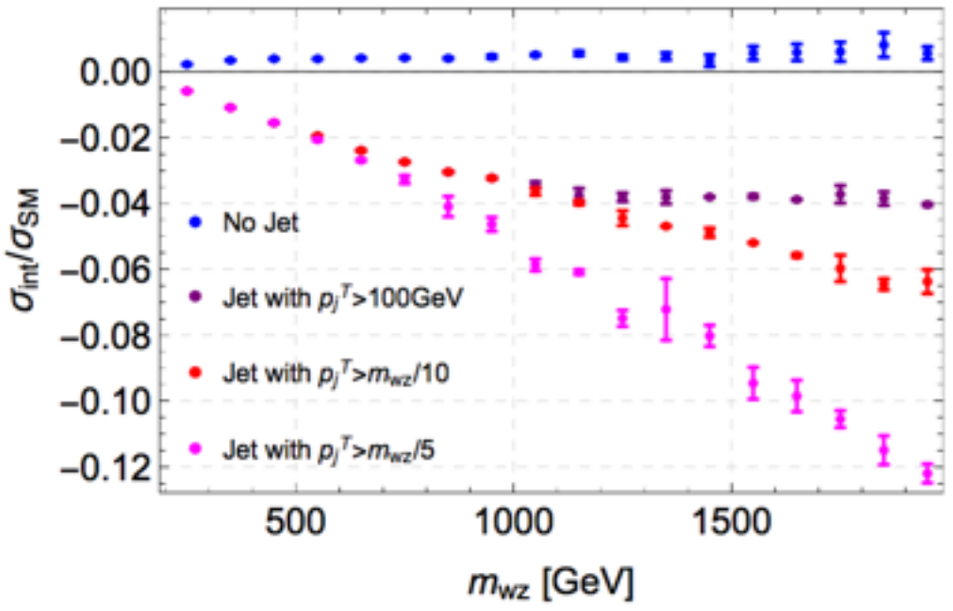
- Loop effects $\sim \frac{\alpha_{s,em}}{4\pi}$ (no soft-limit enhancement, at high-energy)

- Hard radiation 2->3

$$\frac{S}{\sqrt{B}} \sim \sqrt{\frac{4\pi}{\alpha_s}} \times \frac{\alpha_{s,em}}{4\pi}$$



for gluons see Dixon,Shadmi'93;

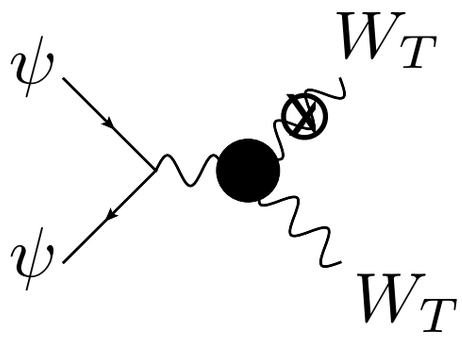


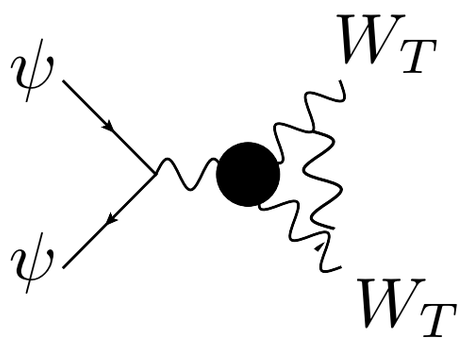
Azatov,Elias-Miro,Reyimuaji,Venturini'17

3. NLO

Non-interference only for massless/tree-level/2->2 processes!

- EW finite mass effects $\sim \frac{m_W^2}{E^2}$



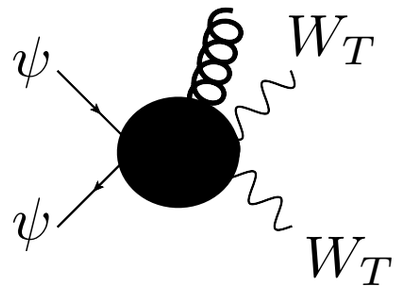


} Only signal suppressed

- Loop effects $\sim \frac{\alpha_{s,em}}{4\pi}$ (no soft-limit enhancement, at high-energy)

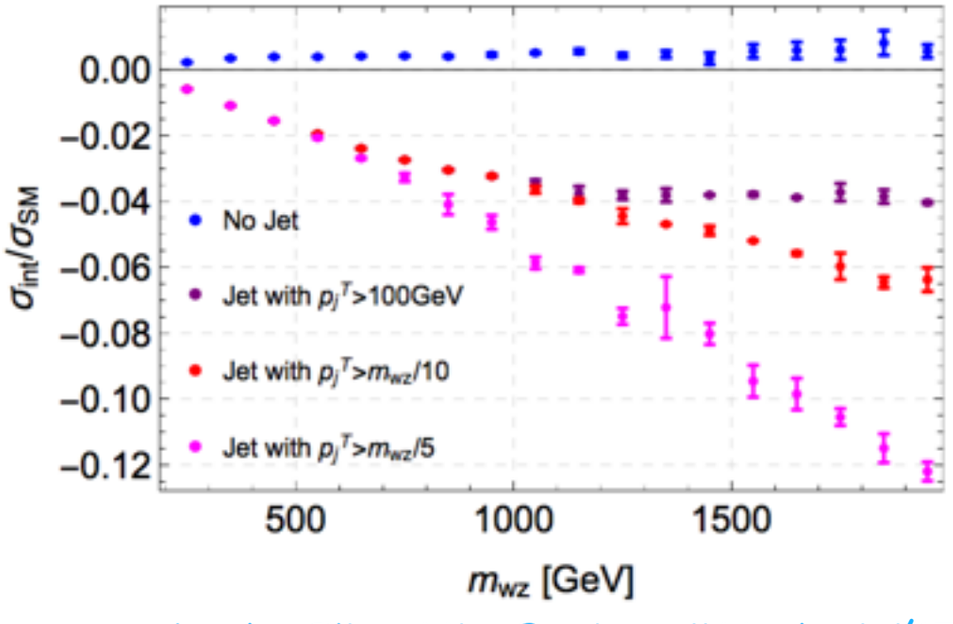
- Hard radiation 2->3

$$\frac{S}{\sqrt{B}} \sim \sqrt{\frac{4\pi}{\alpha_s}} \times \frac{\alpha_{s,em}}{4\pi}$$



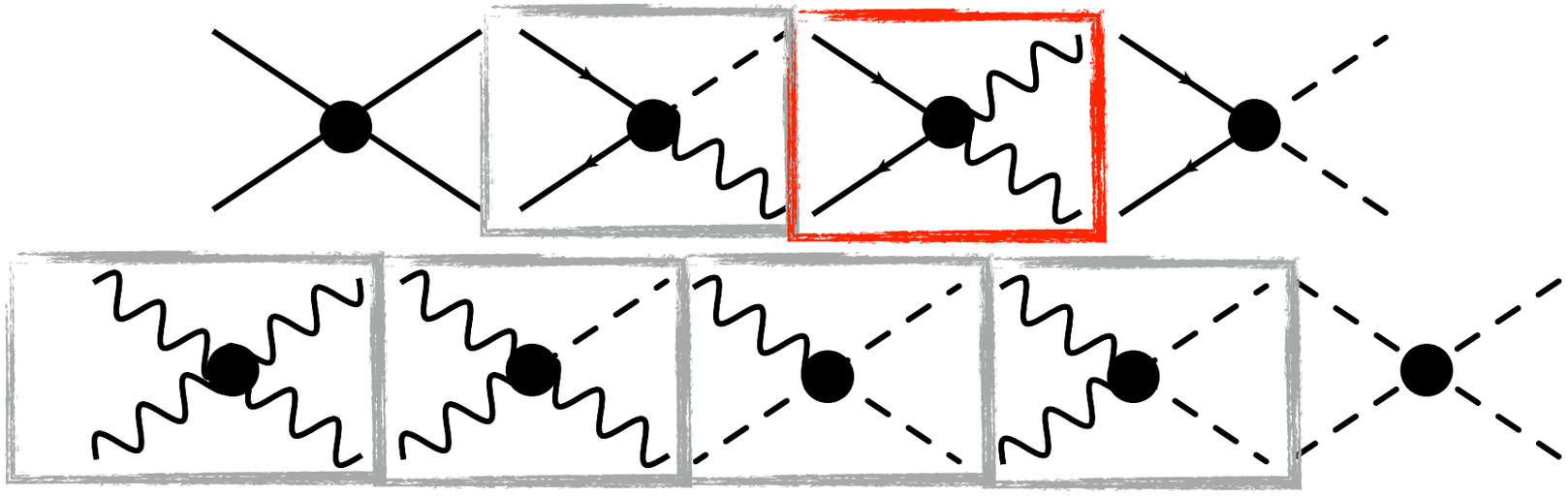
for gluons see Dixon,Shadmi'93;

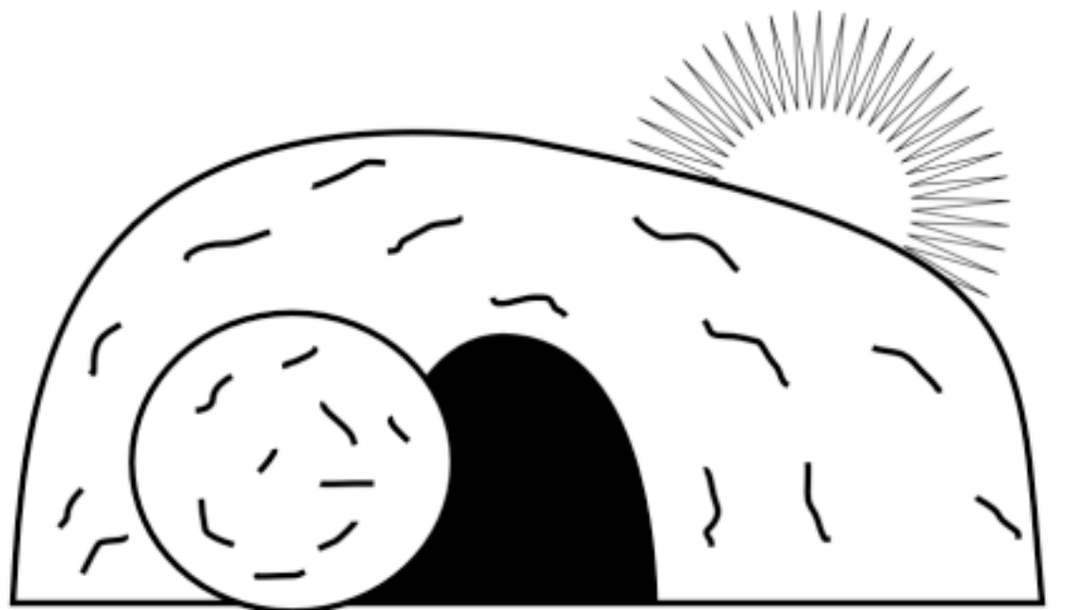
...but small statistics for EW processes!



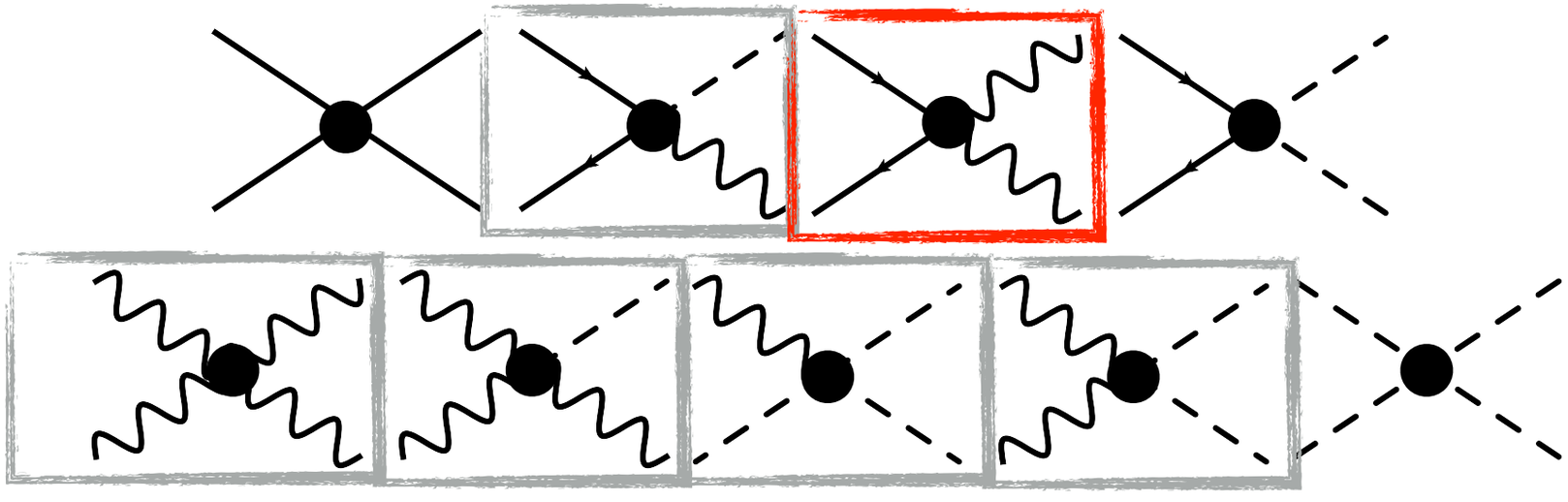
Azatov,Elias-Miro,Reyimuaji,Venturini'17

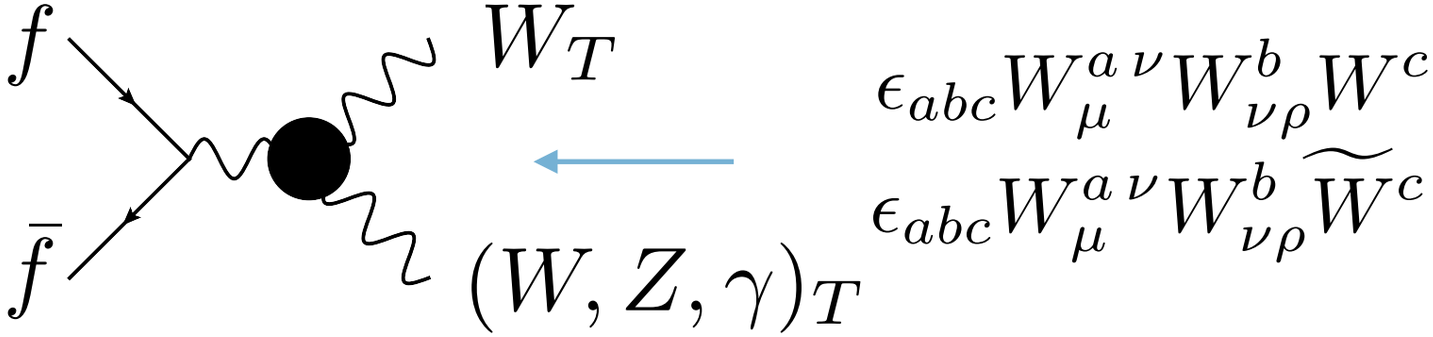
4. Interference Resurrection





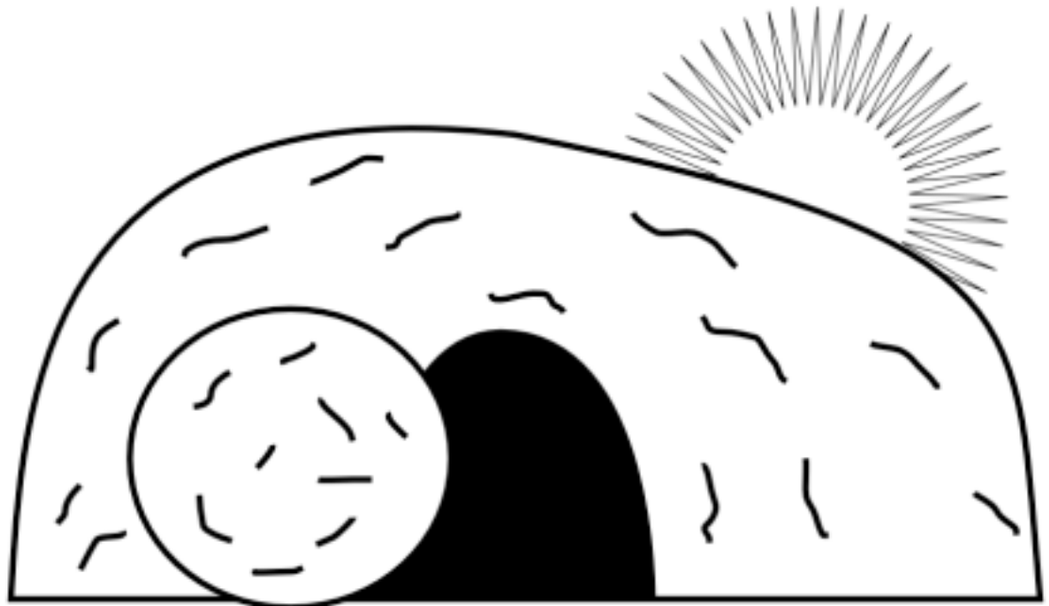
4. Interference Resurrection



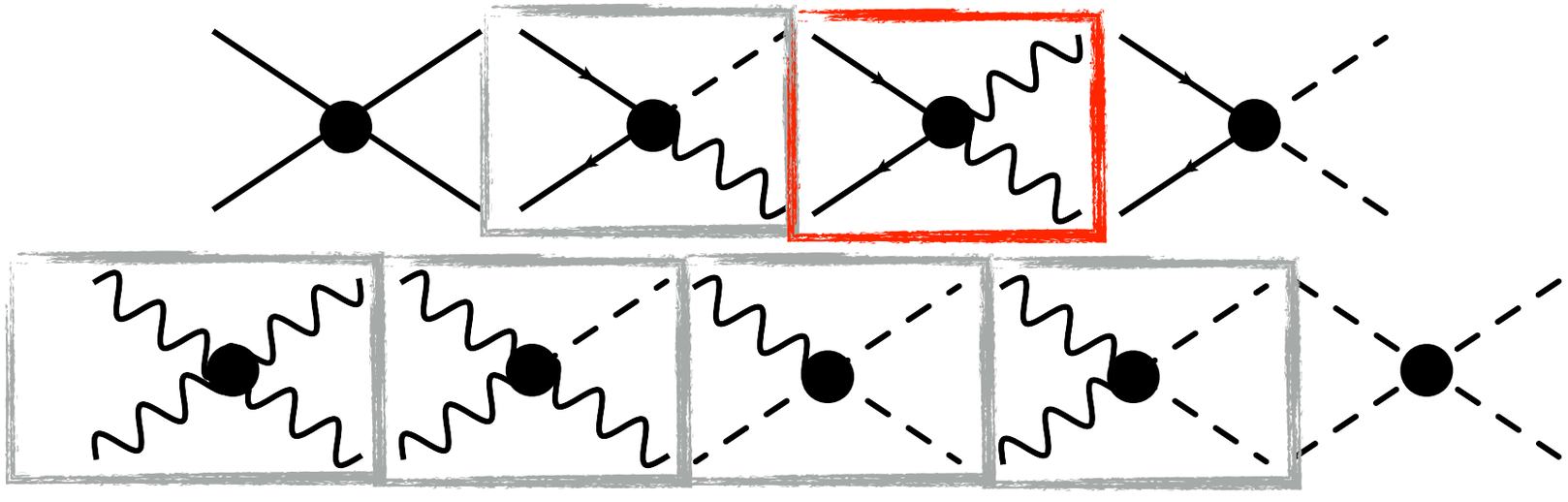


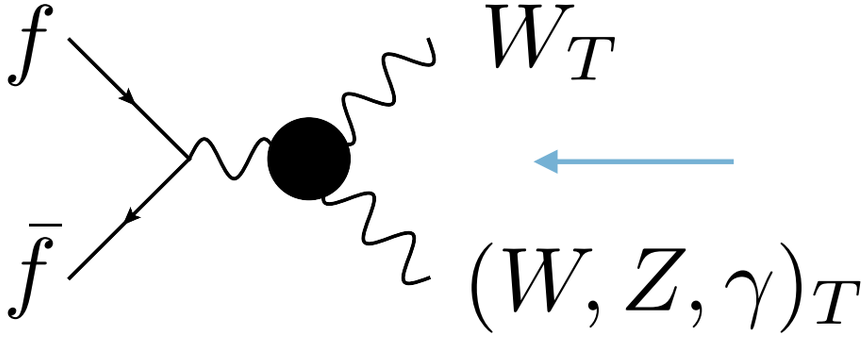
$\epsilon_{abc} W_\mu^{a\,\nu} W_{\nu\rho}^b W^{c\,\rho\mu}$ CP-even

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



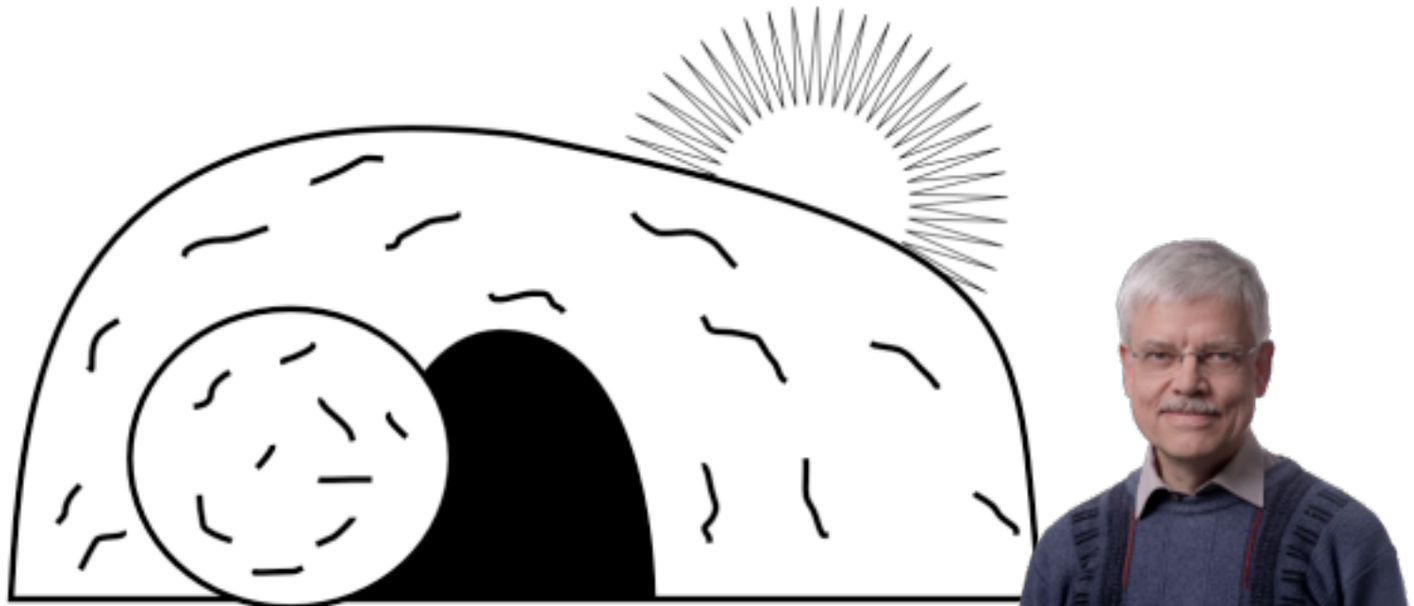
4. Interference Resurrection





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

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



...resurrecting ideas from 1986

PROBING THE WEAK BOSON SECTOR IN $e^+e^- \to W^+W^-$

K. HAGIWARA[1], R.D. PECCEI and D. ZEPPENFELD[2]

DESY, Theory Group, D-2000 Hamburg 52, Fed. Rep. Germany

K. HIKASA[3]

Physics Department, University of Wisconsin, Madison, Wisconsin 53706, USA

Received 23 June 1986

4. Angular correlations for final state fermions

In this section we present the most general angular distributions of the decay products in the process

$$e^-(k,\sigma) + e^+(\bar{k},\bar{\sigma}) \to W^-(q,\lambda) + W^+(\bar{q},\bar{\lambda}),$$

$$W^-(q,\lambda) \to f_1(p_1,\sigma_1) + \bar{f}_2(p_2,\sigma_2),$$

$$W^+(\bar{q},\bar{\lambda}) \to f_3(p_3,\sigma_3) + \bar{f}_4(p_4,\sigma_4), \qquad (4.1)$$

MEASURING THE WWZ COUPLING AT THE TEVATRON

K. HAGIWARA,[1] J. WOODSIDE,[2] AND D. ZEPPENFELD[3]

[1] *Physics Department, University of Durham, Durham, England*

[2] *Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA*

[3] *Physics Department, University of Wisconsin Madison, WI 53706, USA*

ABSTRACT

Hadroproduction of weak boson pairs, $W^{\pm}Z$ and W^+W^-, is studied quantitatively at Tevatron energies. Although the cross sections are expected to be

VOLUME 55, NUMBER 8 PHYSICAL RE

New Standard-Model Test for Future Colliders

M. J. Duncan and G. L. Kane

Randall Physics Laboratory, University of Michigan, Ann Arbor, Michigan 48109

and

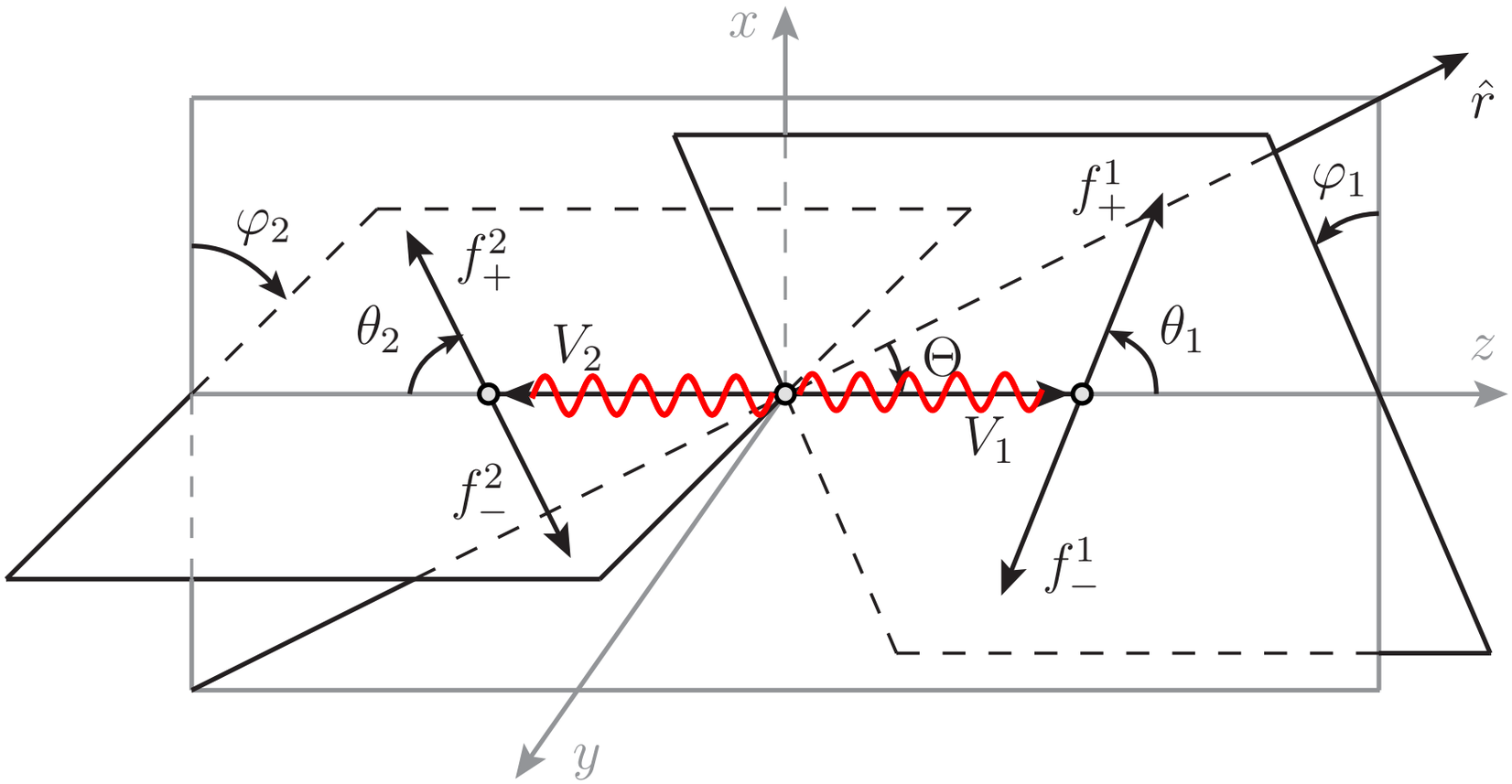
Wayne W. Repko

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

(Received 28 May 1985)

We point out that for W-pair production from e^+e^- or $q\bar{q}$ beams, the correlation between the decay planes of the W's is numerically negligible (at tree level) in the standard model. This occurs for the production of WW via intermediate fermions or gauge bosons and independently for WW produced via Higgs-boson exchange, and is not restricted to two-body diagrams. In general, the correlation need not vanish, and so a nonzero correlation would be a clear signal of physics beyond the standard model. Definition of the W-decay plane should be fairly straightforward from the decay $W \to ff$ and, hence, the correlation measurement is experimentally feasible.

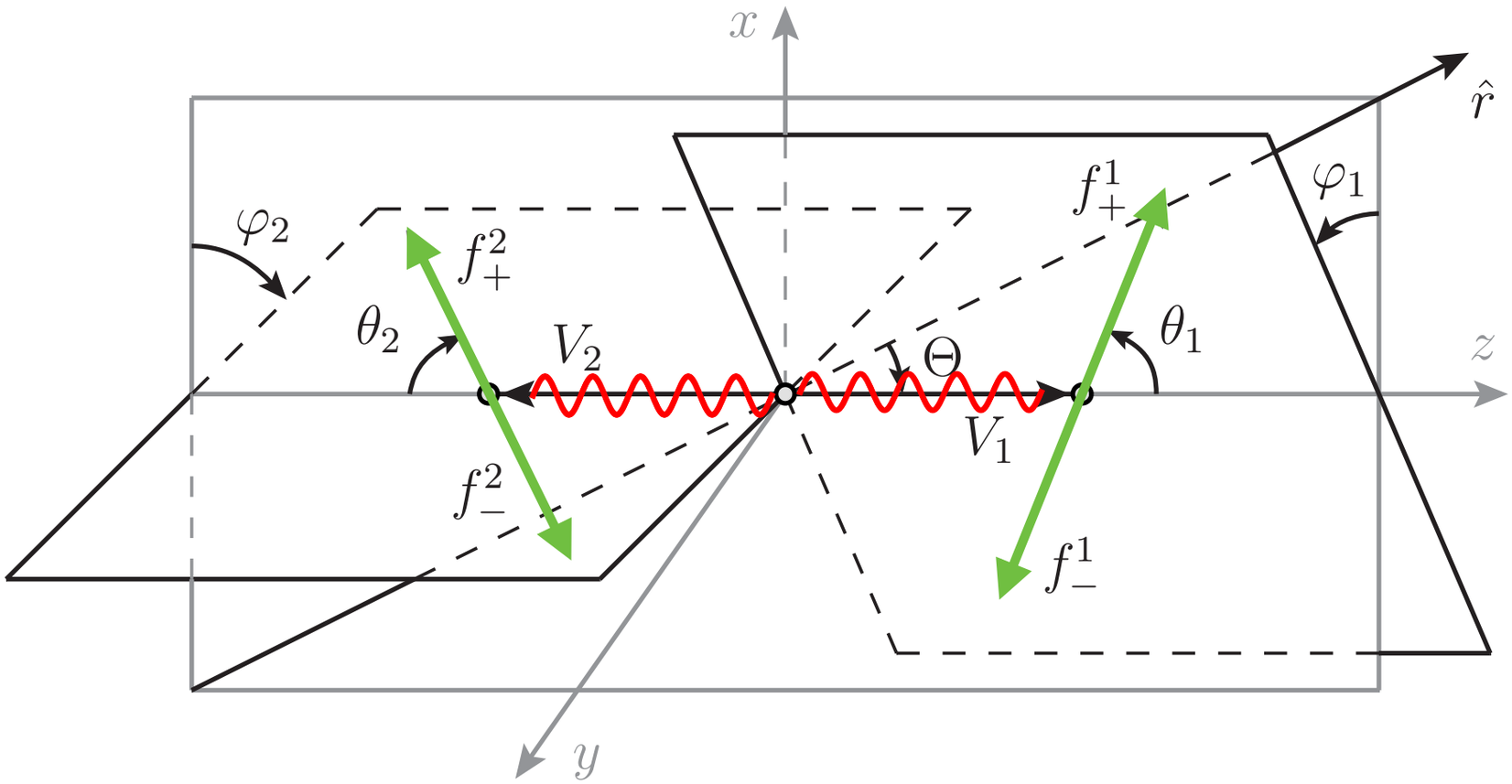
Differential measurements WW, WZ



$V_{1,2}$: Helicity $\pm\mp/\pm\pm$ in SM/BSM

- Quantum mechanically different, no interference

Differential measurements WW, WZ



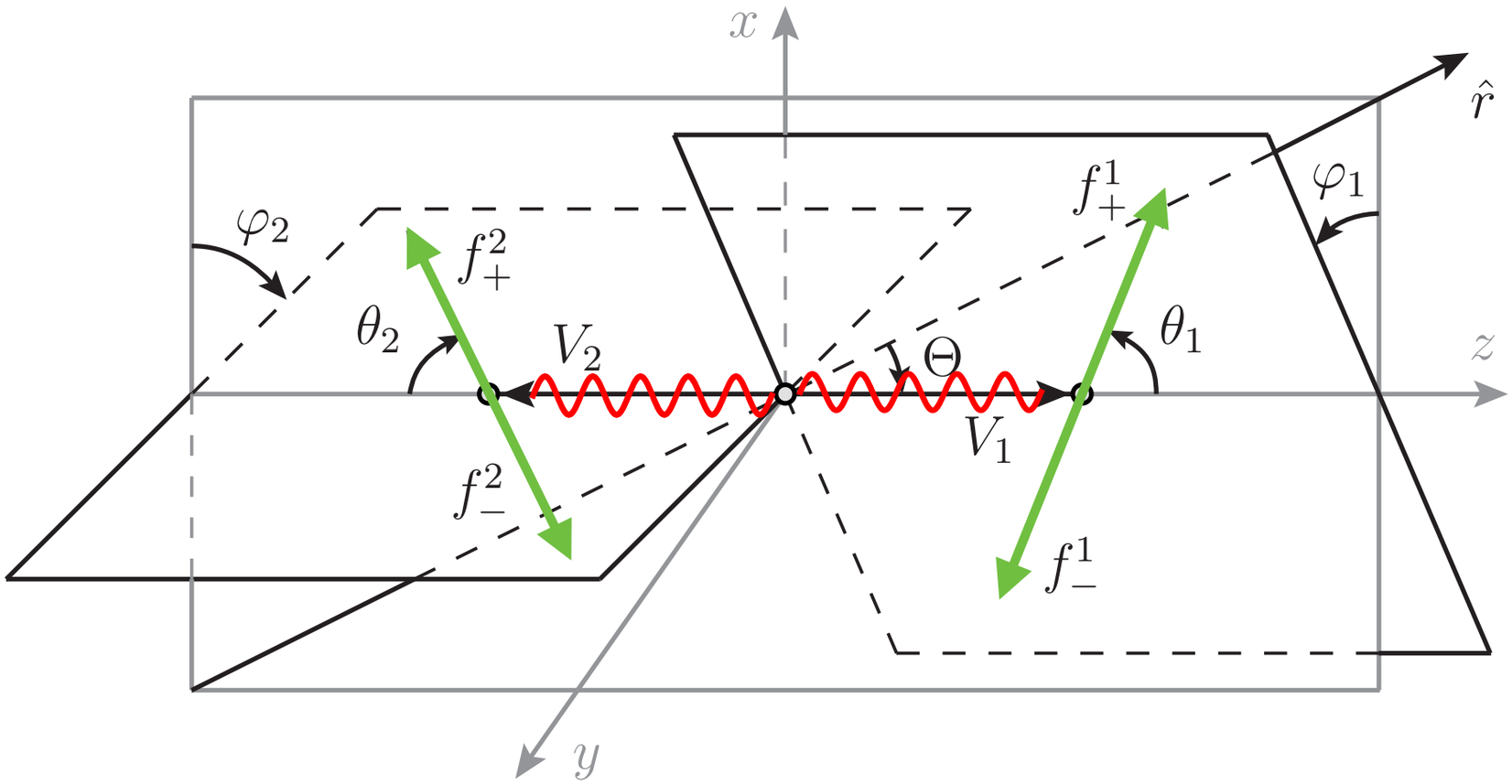
$V_{1,2}$: Helicity $\pm\mp/\pm\pm$ in SM/BSM

- 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

Differential measurements WW, WZ

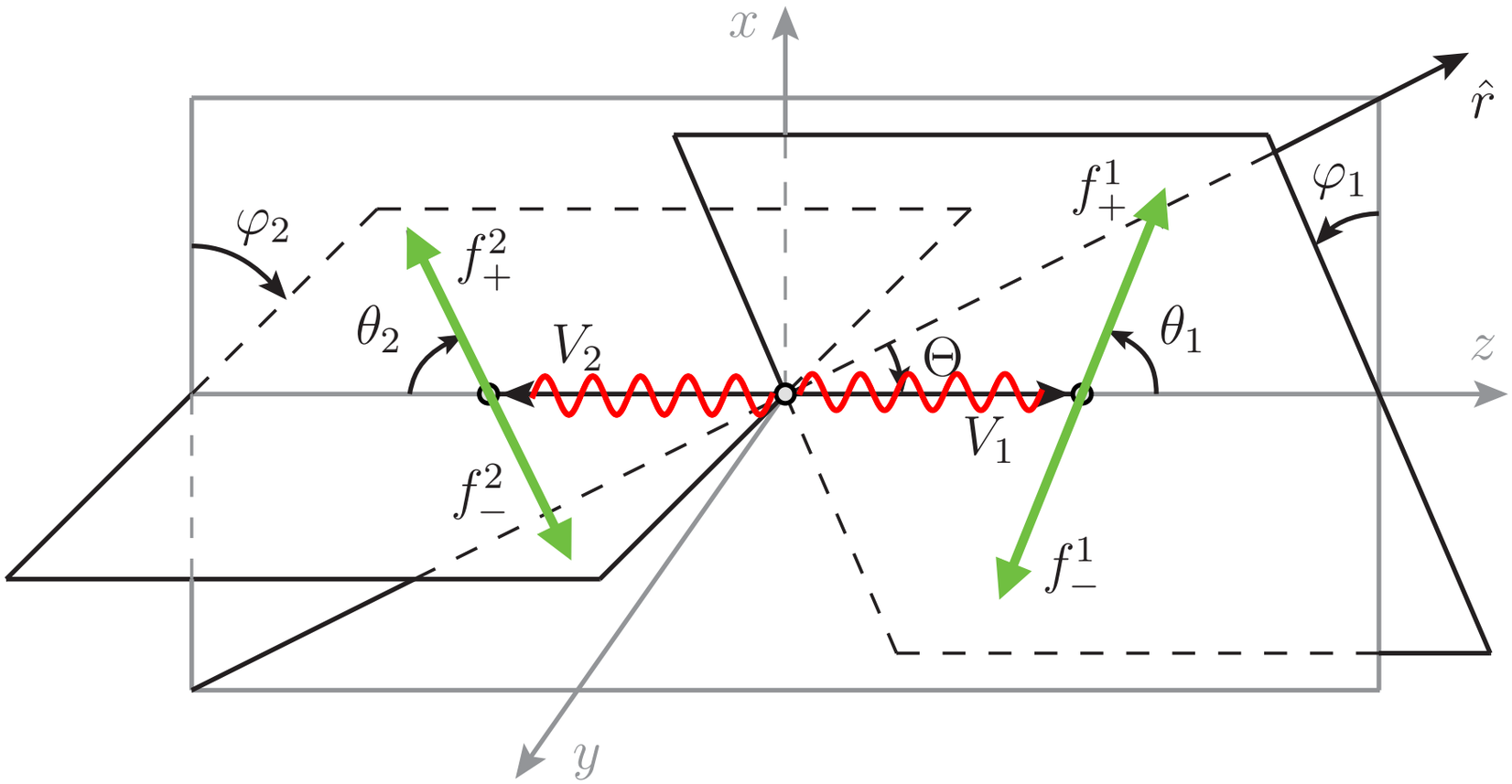


$$Int^{\mathrm{CP}} \propto \mathcal{A}_{\mathbf{h}}^{\mathrm{SM}} \mathcal{A}_{\mathbf{h'}}^{\mathrm{BSM}+} \cos\left[\boldsymbol{\Delta h} \cdot \boldsymbol{\varphi}\right]$$

$(+1,-1)$ $(+1,+1)$ $(h_1 - h_1', h_2 - h_2')$ (φ_1, φ_2)

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

Differential measurements WW, WZ



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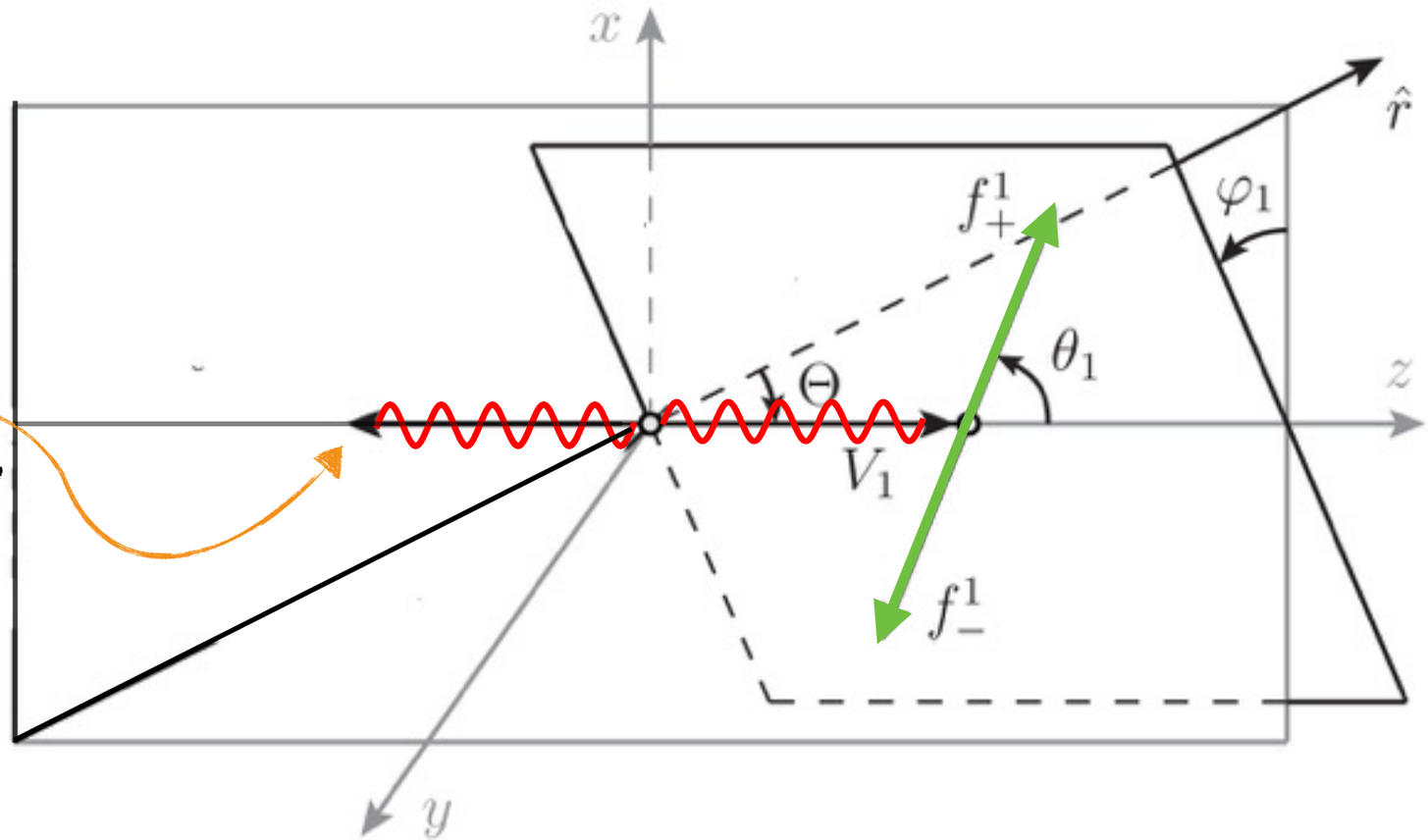
$$Int^{\not{\mathrm{CP}}} \propto \mathcal{A}_{\mathbf{h}}^{\mathrm{SM}} \mathcal{A}_{\mathbf{h'}}^{\mathrm{BSM}-} \sin\left[\boldsymbol{\Delta h} \cdot \boldsymbol{\varphi}\right]$$

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

Differential measurements $W\gamma$

$W\gamma$

No (leptonic)
Branching Ratio



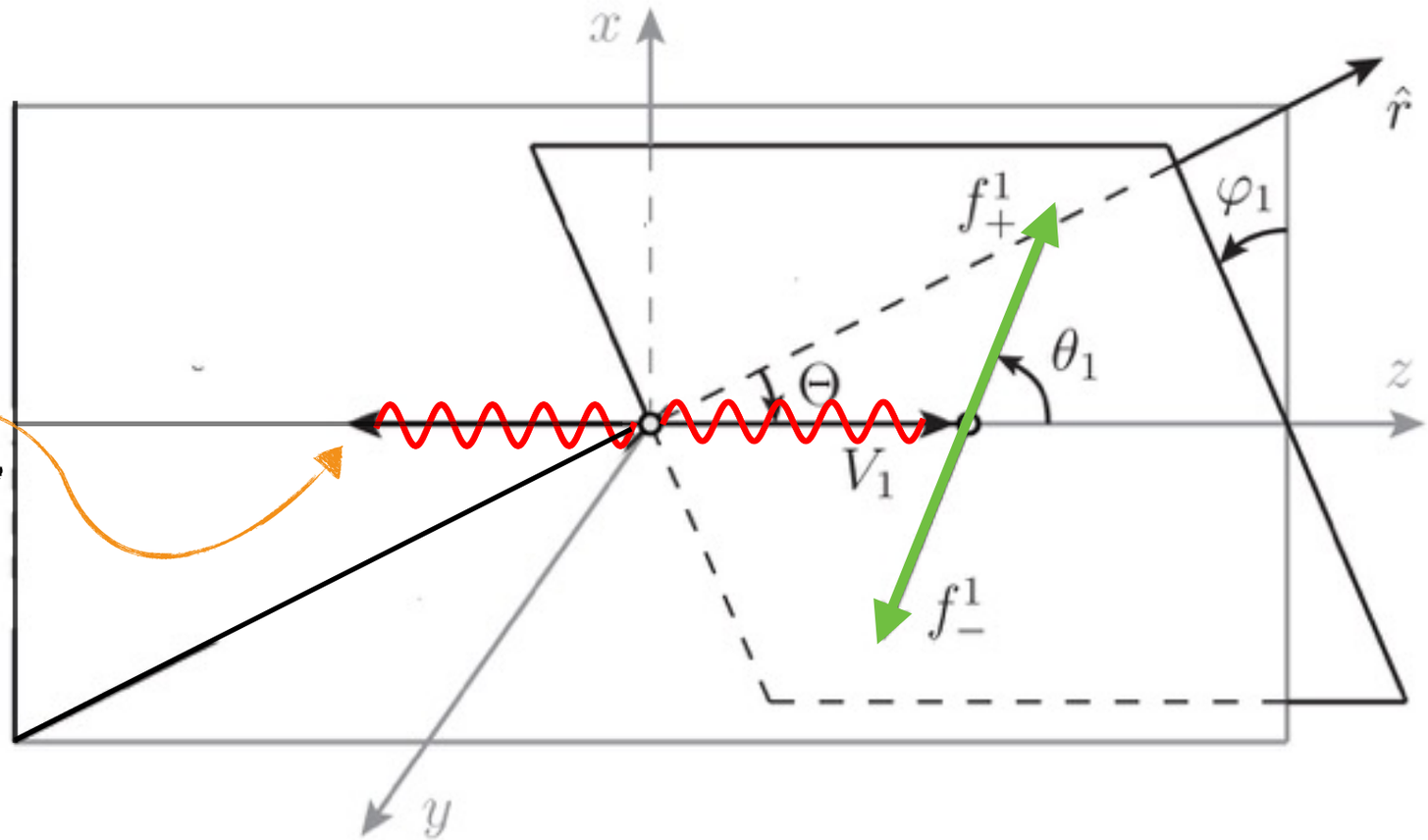
$$Int^{\mathrm{CP}} = 2g^2\sin^2\theta\mathcal{A}_{++}^{\mathrm{BSM}+}\left[\mathcal{A}_{-+}^{\mathrm{SM}}+\mathcal{A}_{+-}^{\mathrm{SM}}\right]\cos 2\varphi\,,$$

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

Differential measurements $W\gamma$

$W\gamma$

No (leptonic)
Branching Ratio



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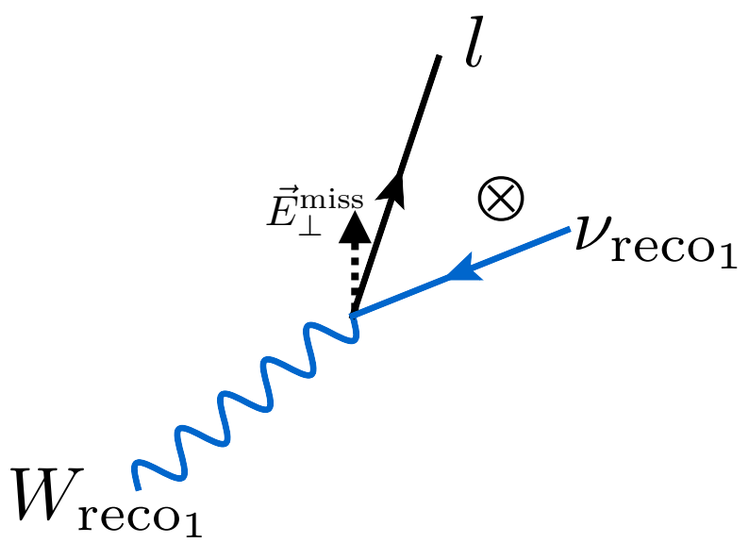
$$Int^{\not{\mathrm{CP}}} = 2ig^2\sin^2\theta\mathcal{A}_{++}^{\mathrm{BSM}-}\left[\mathcal{A}_{-+}^{\mathrm{SM}}-\mathcal{A}_{+-}^{\mathrm{SM}}\right]\sin 2\varphi$$

Differential azimuthal distributions = SM-BSM interference

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)

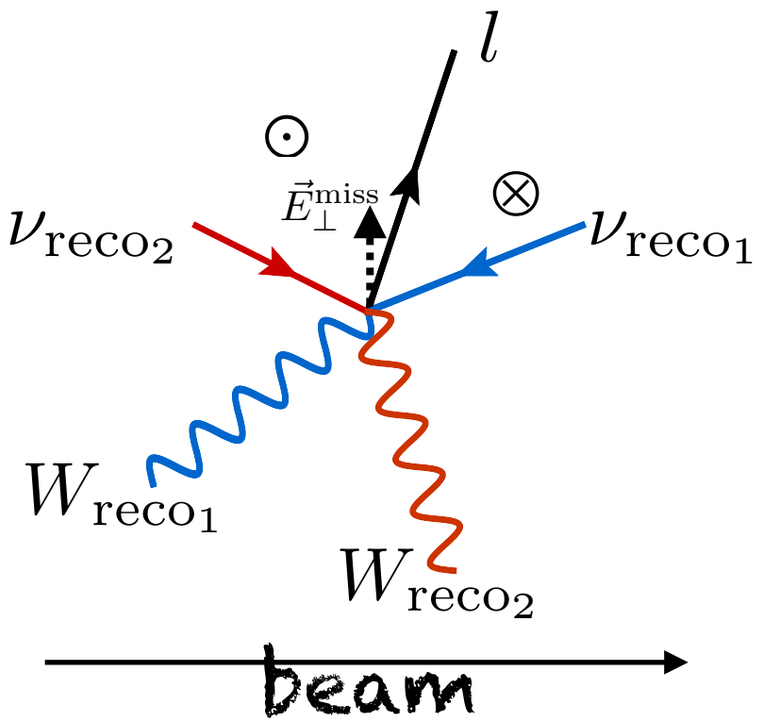


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

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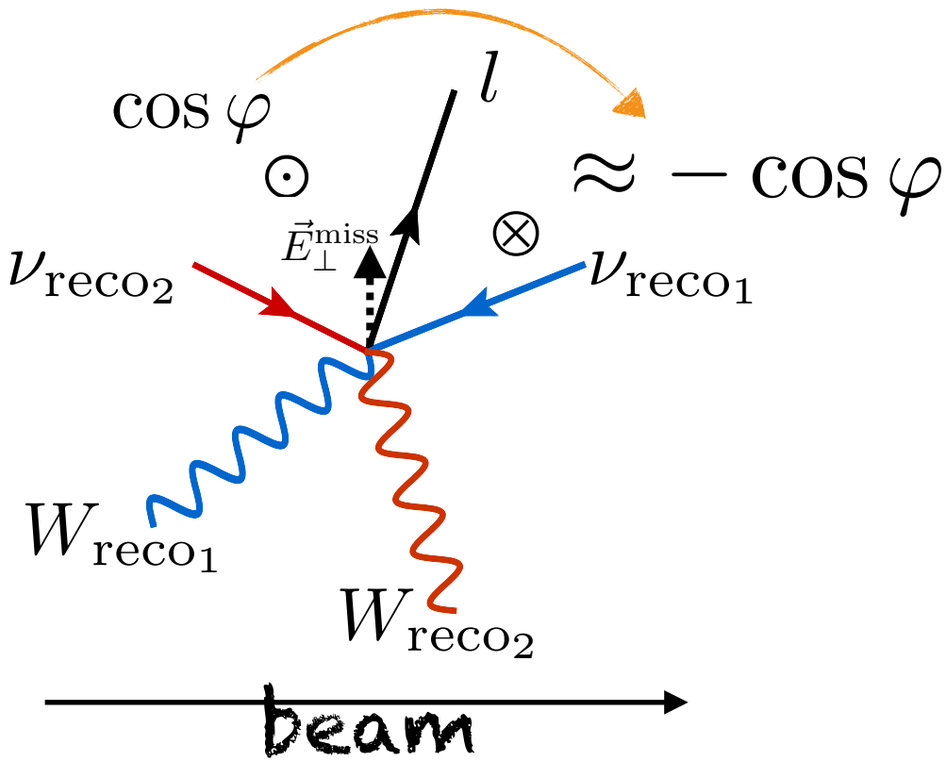
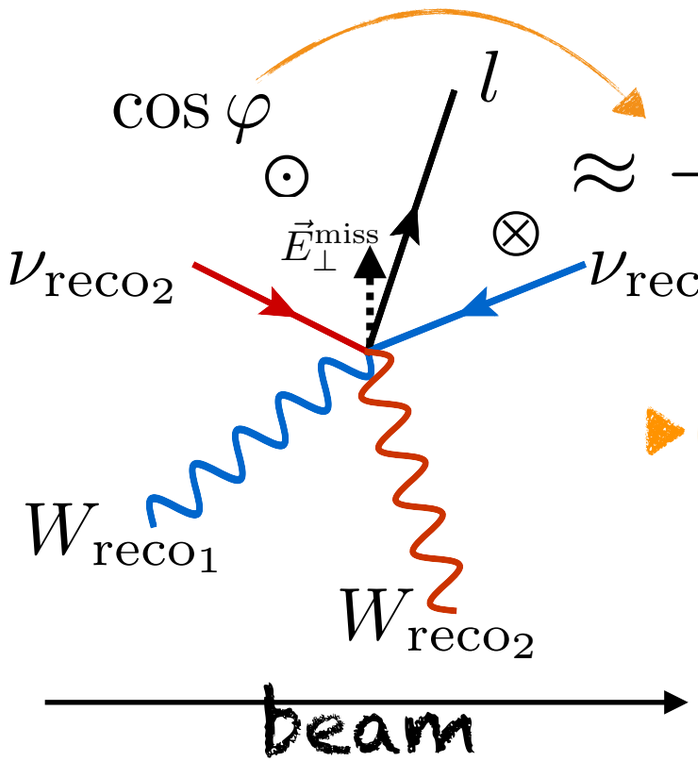


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass



1)

φ_{reco}

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

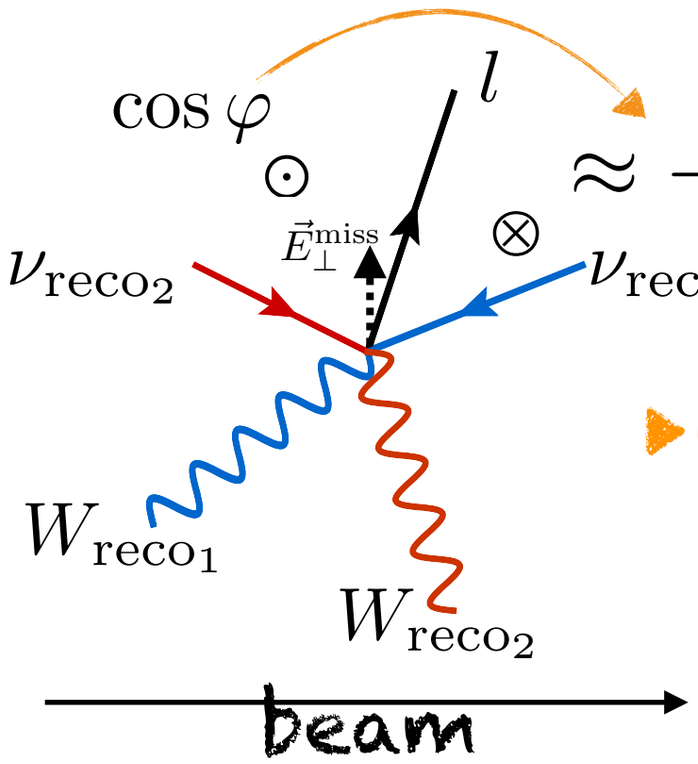
φ_{true}

Panico,FR,Wulzer'17

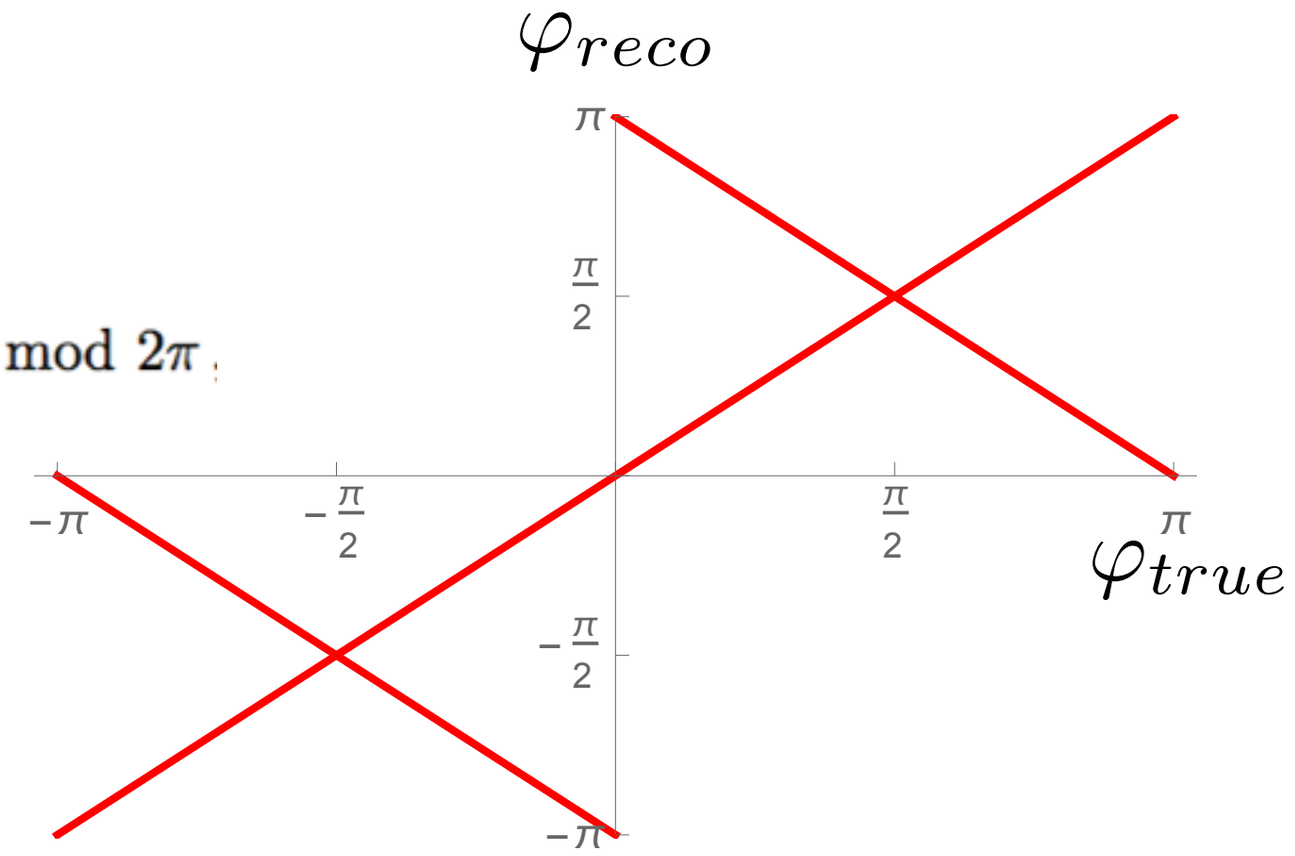
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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

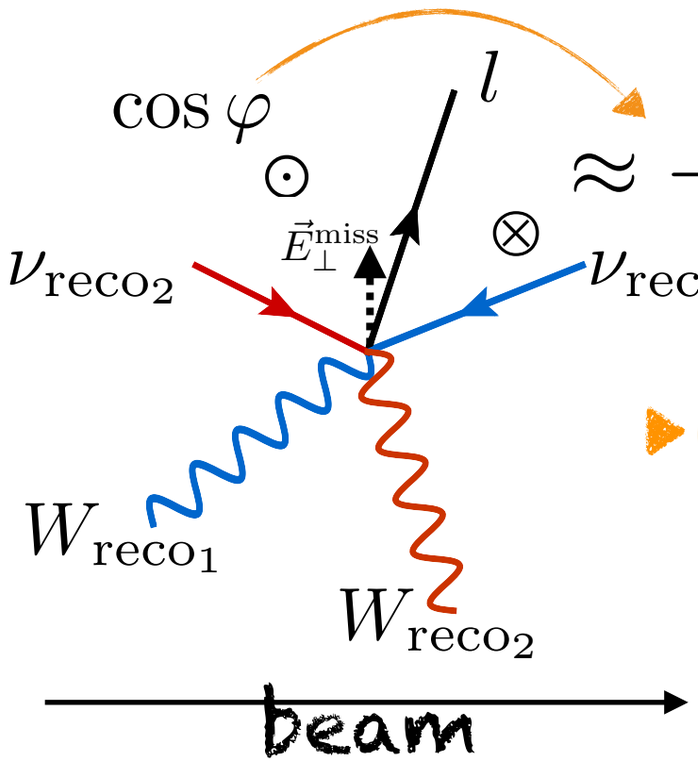


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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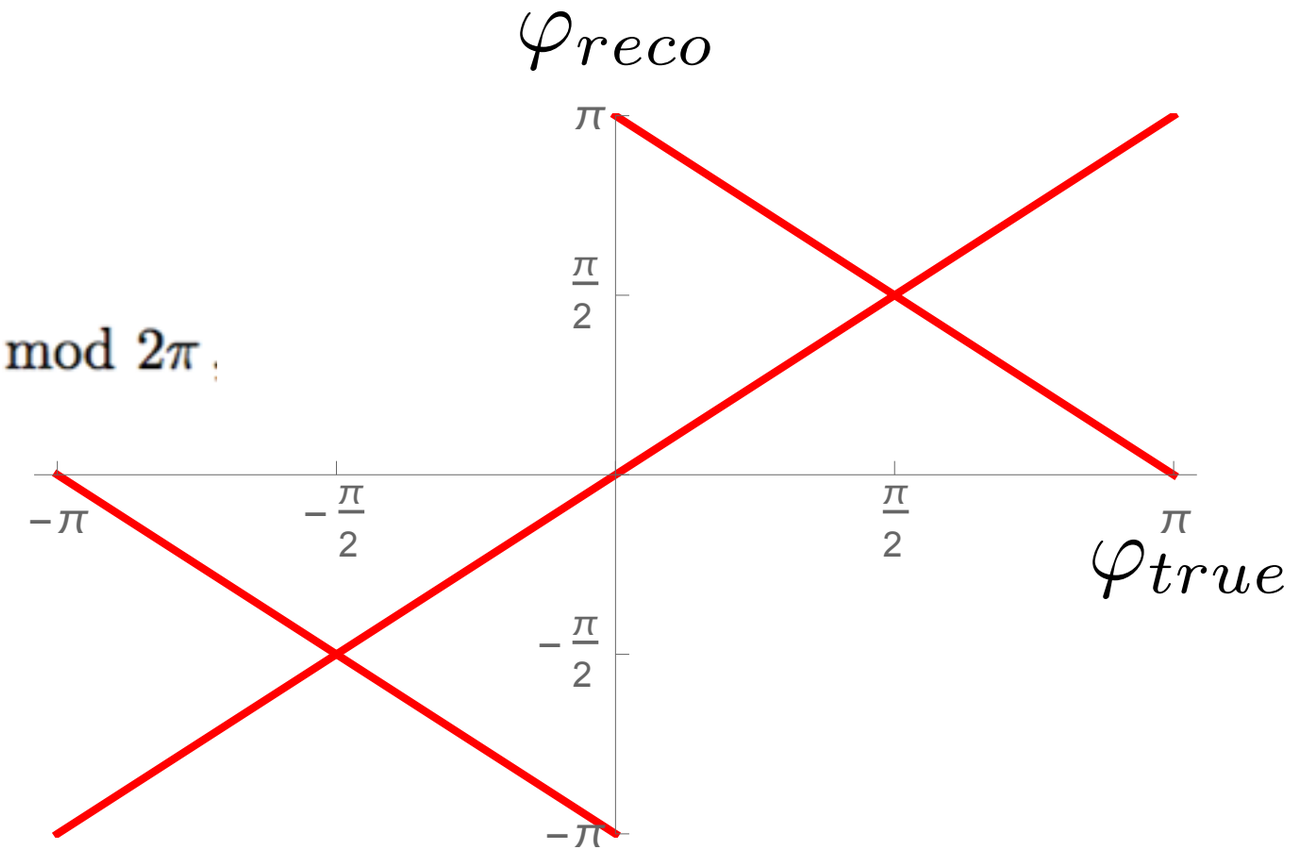


2) Some events: $m_\perp^2 > m_W^2$
(off-shell, exp.error)

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

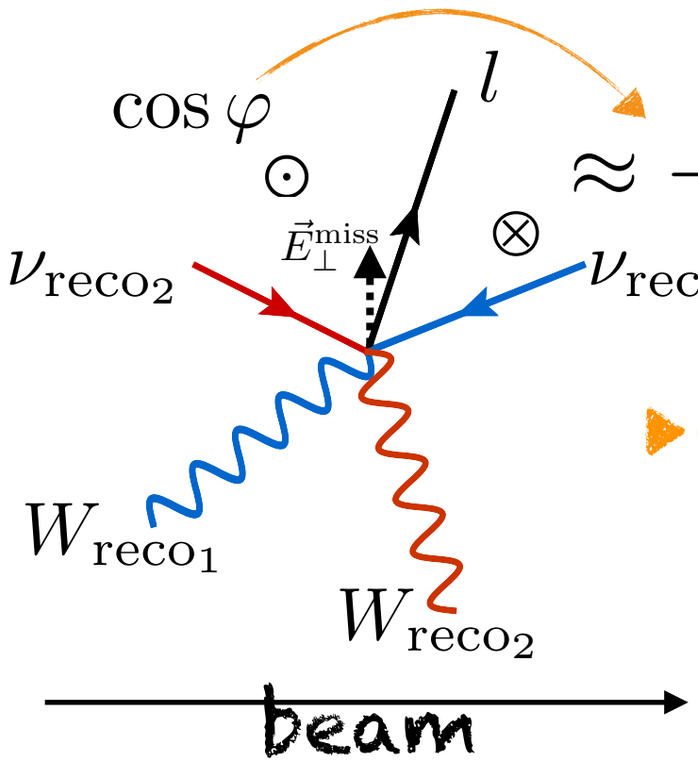
- $\varphi = \pi/2 \quad \text{or} \quad \varphi = -\pi/2.$

Panico,FR,Wulzer'17

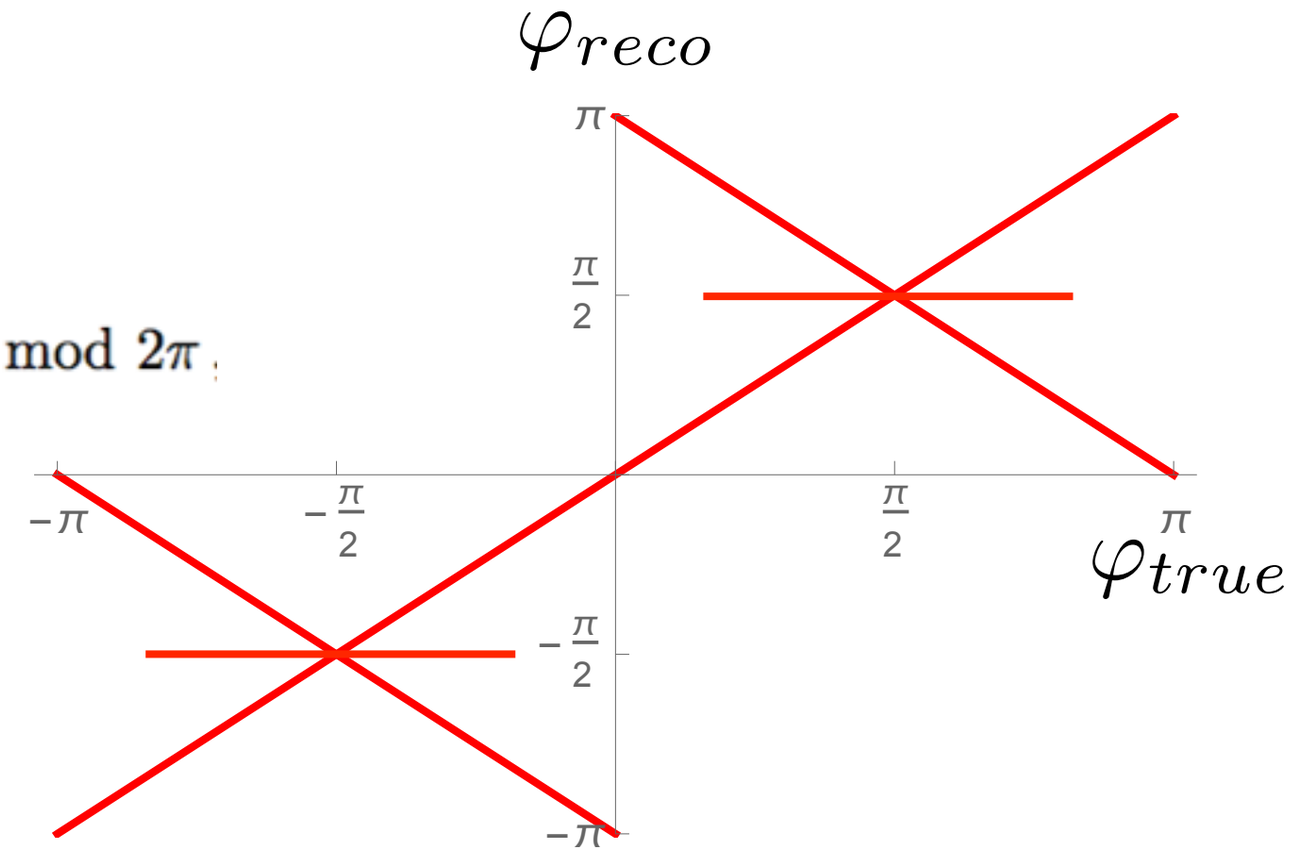
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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



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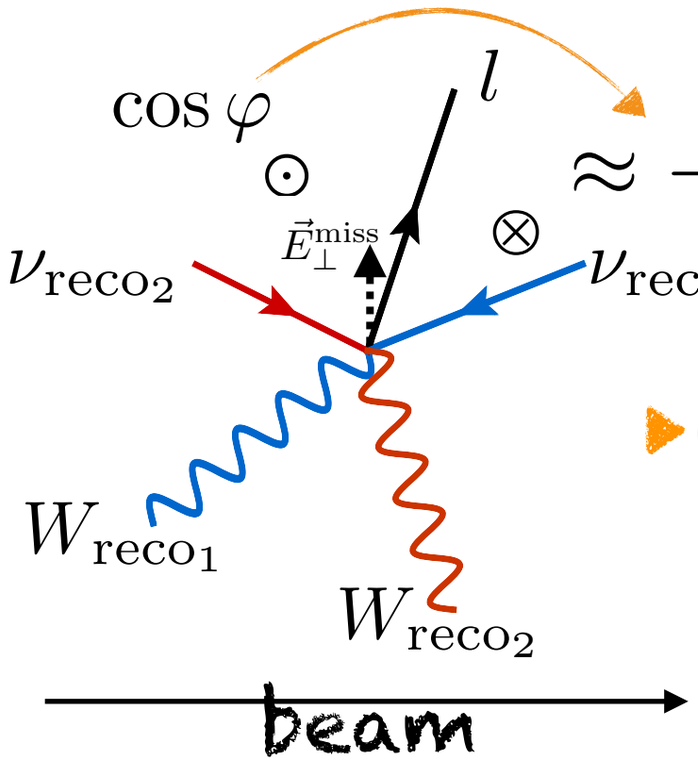
Panico,FR,Wulzer'17

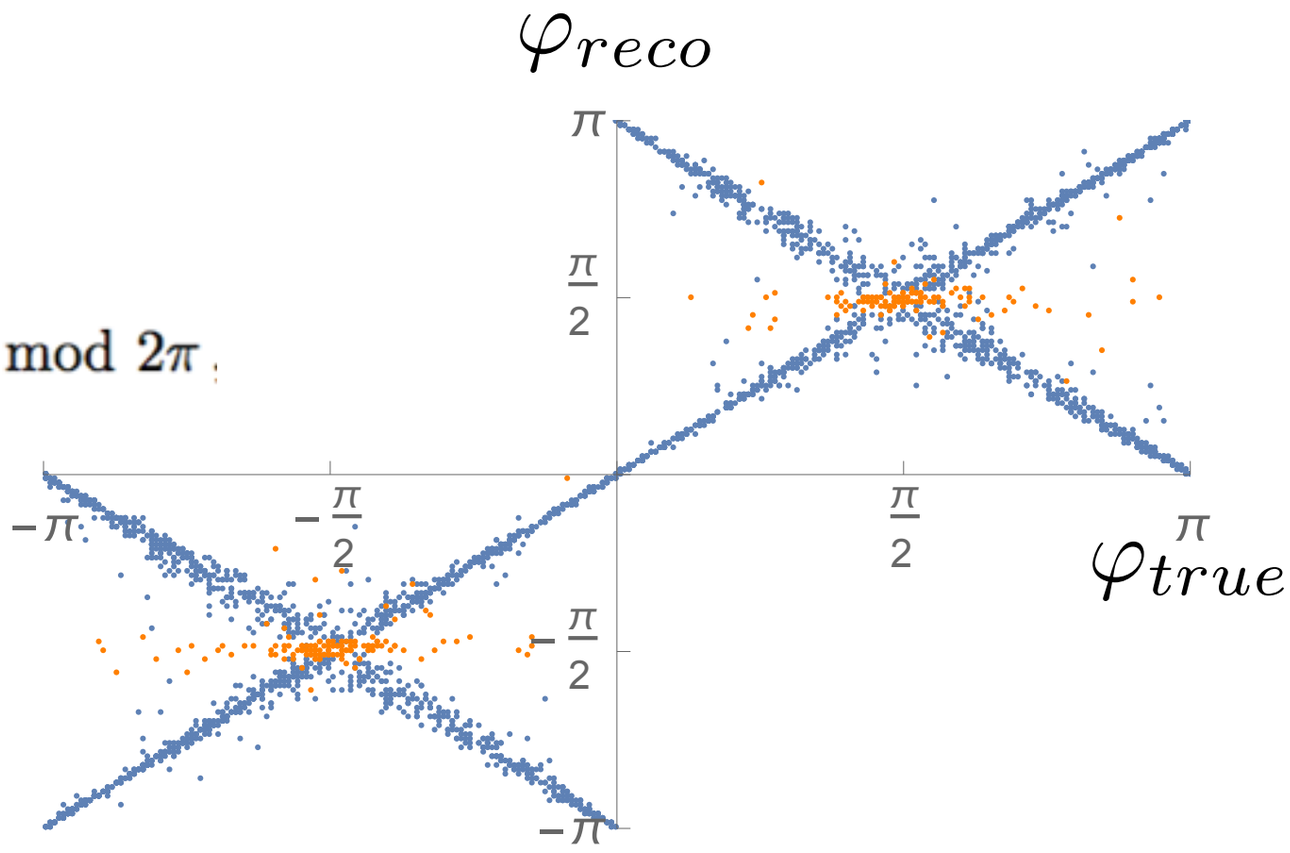
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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



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

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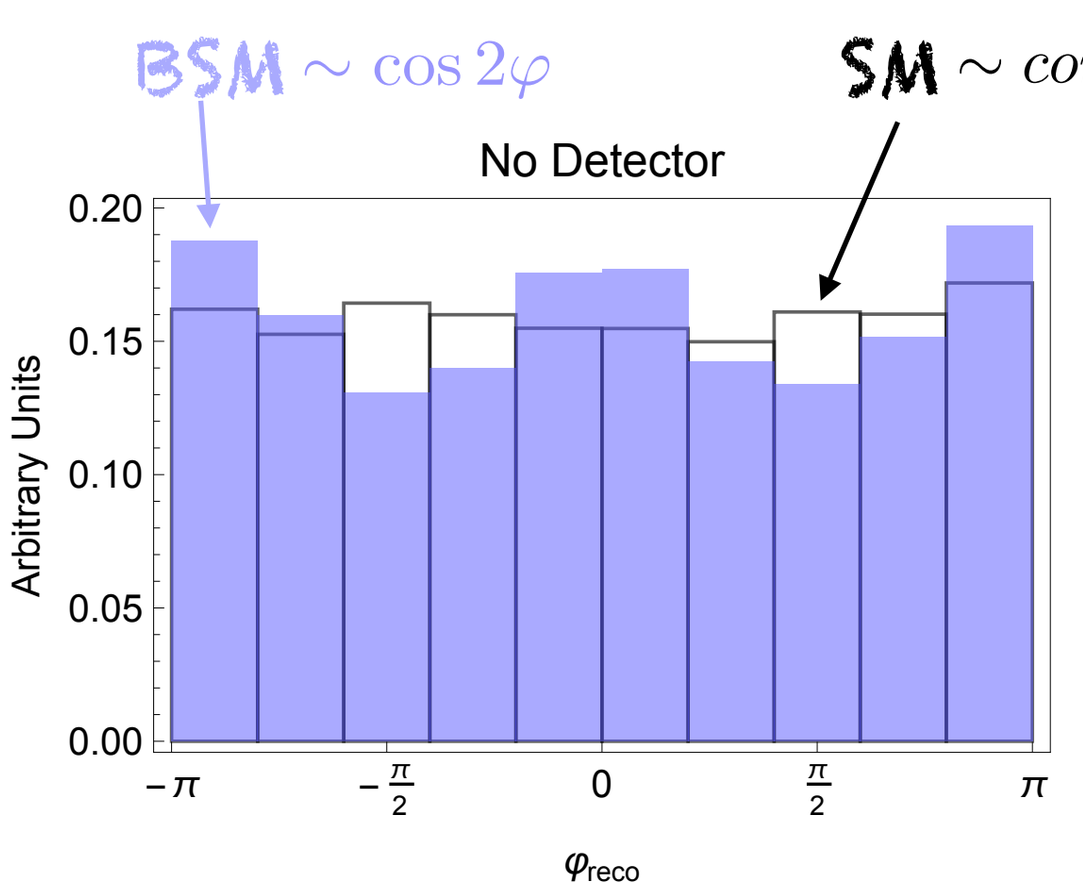
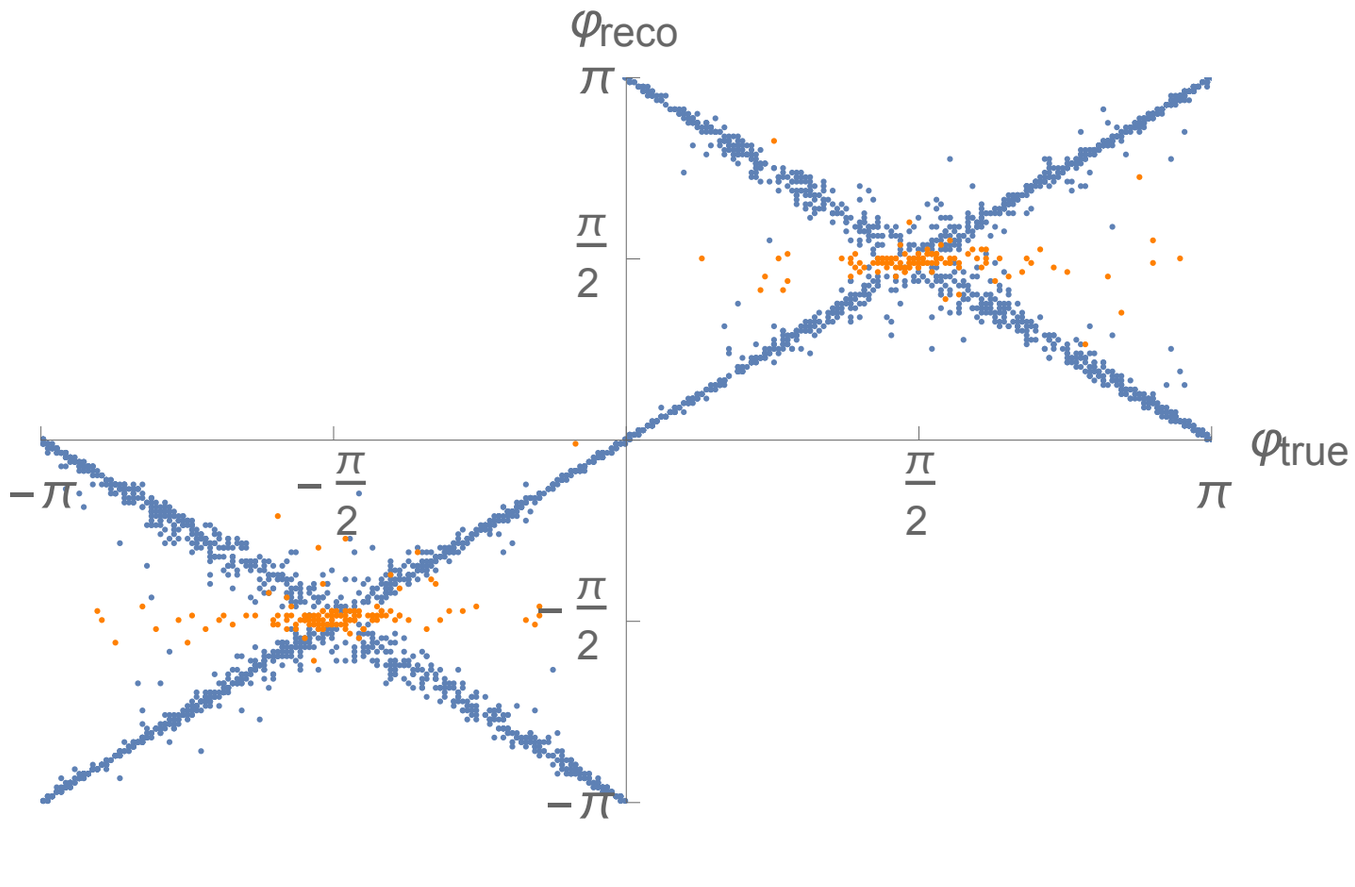
Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass



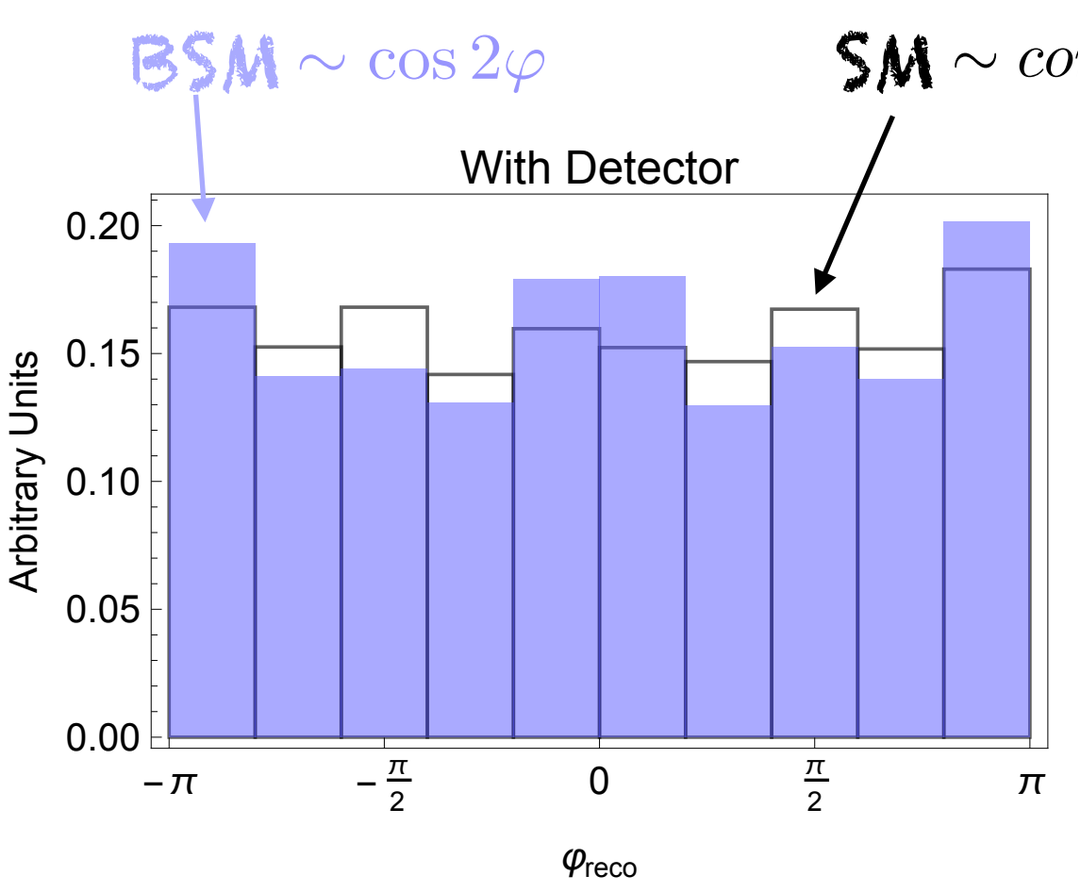


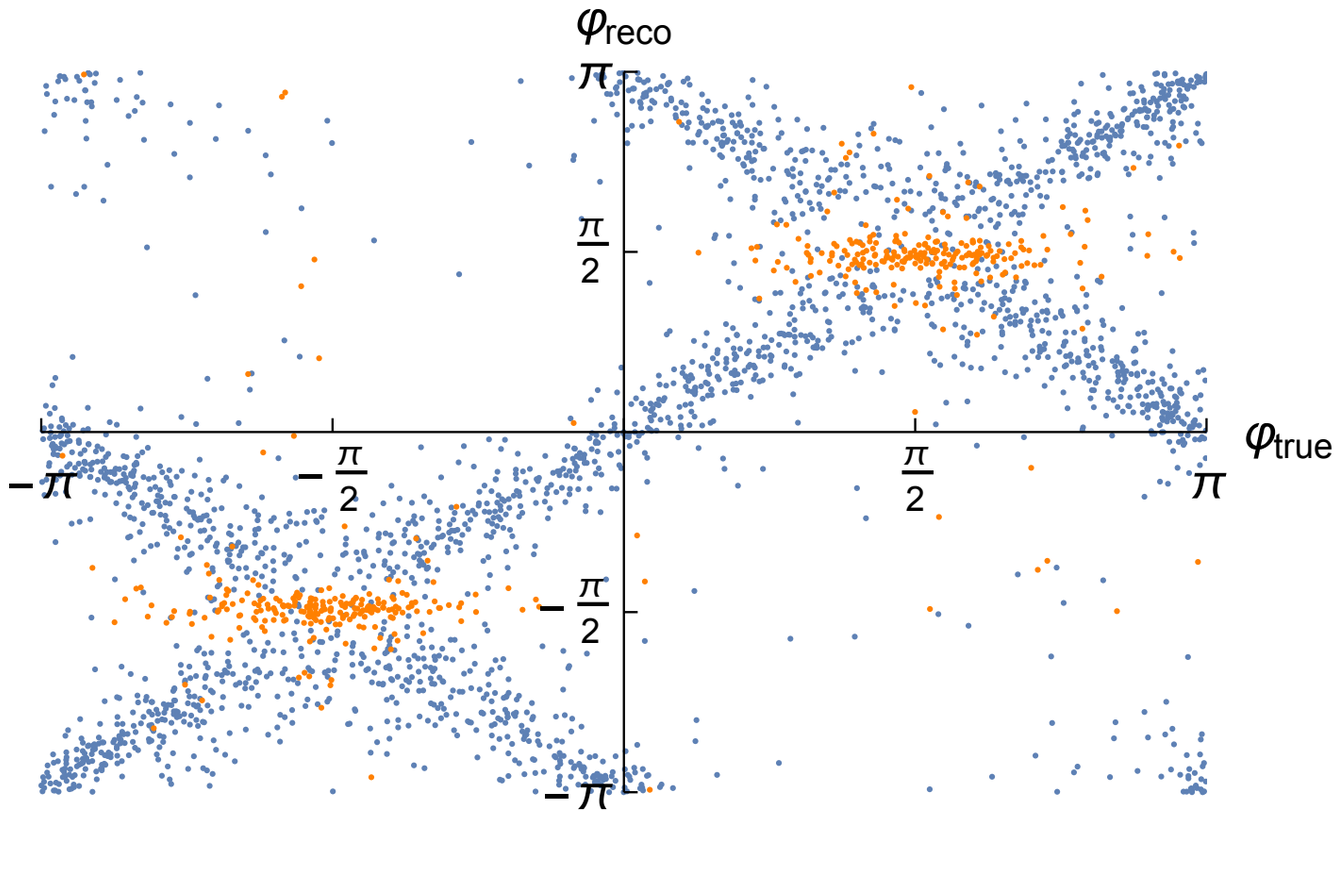
Panico,FR,Wulzer'17

Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation



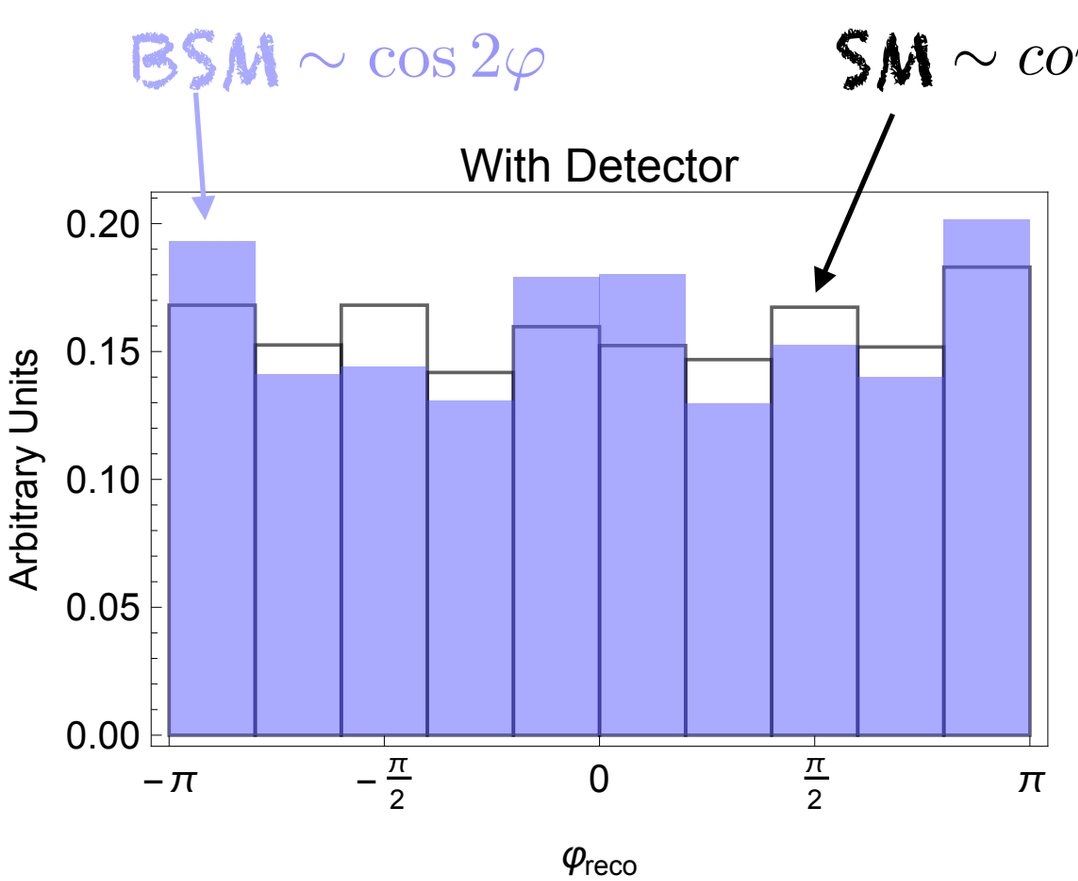


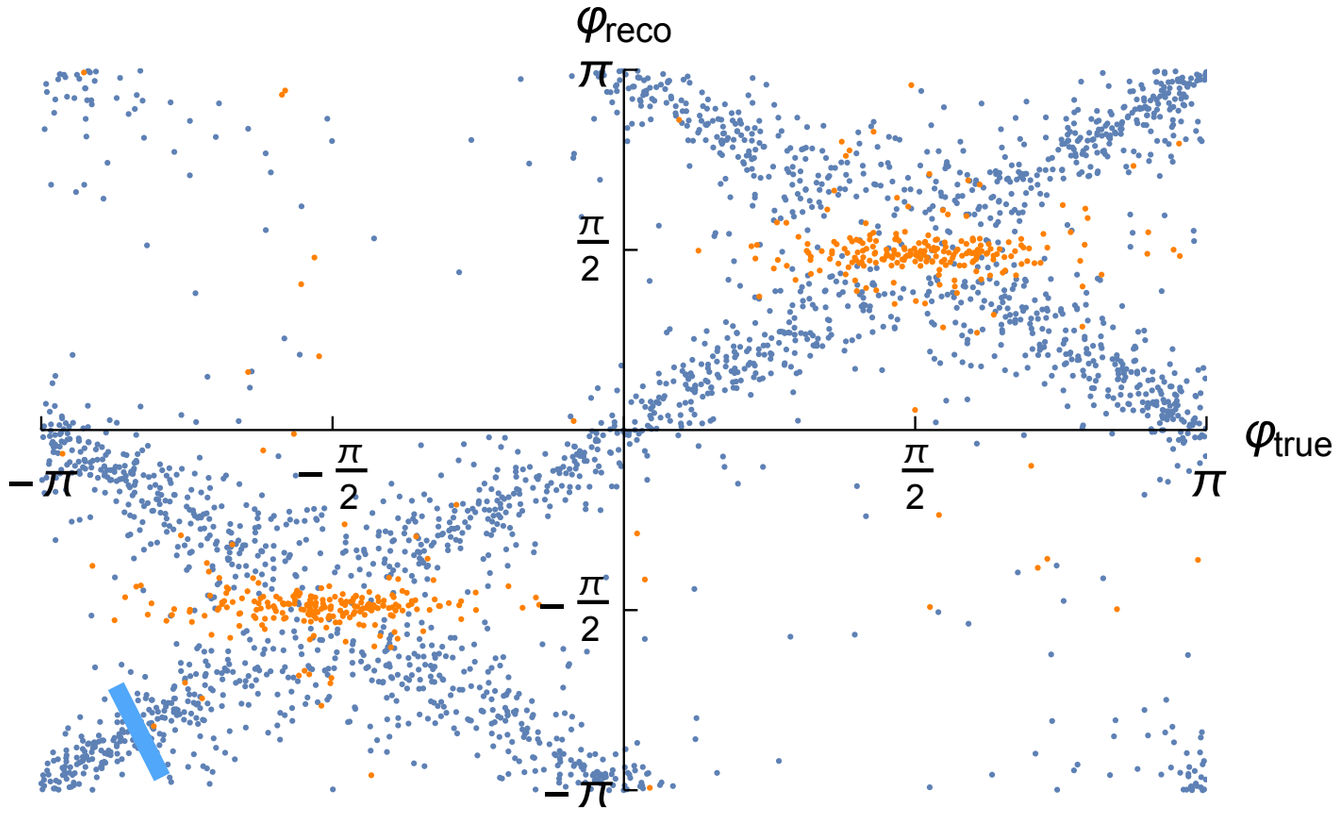
Panico,FR,Wulzer'17

Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation





Spread under control

Panico,FR,Wulzer'17

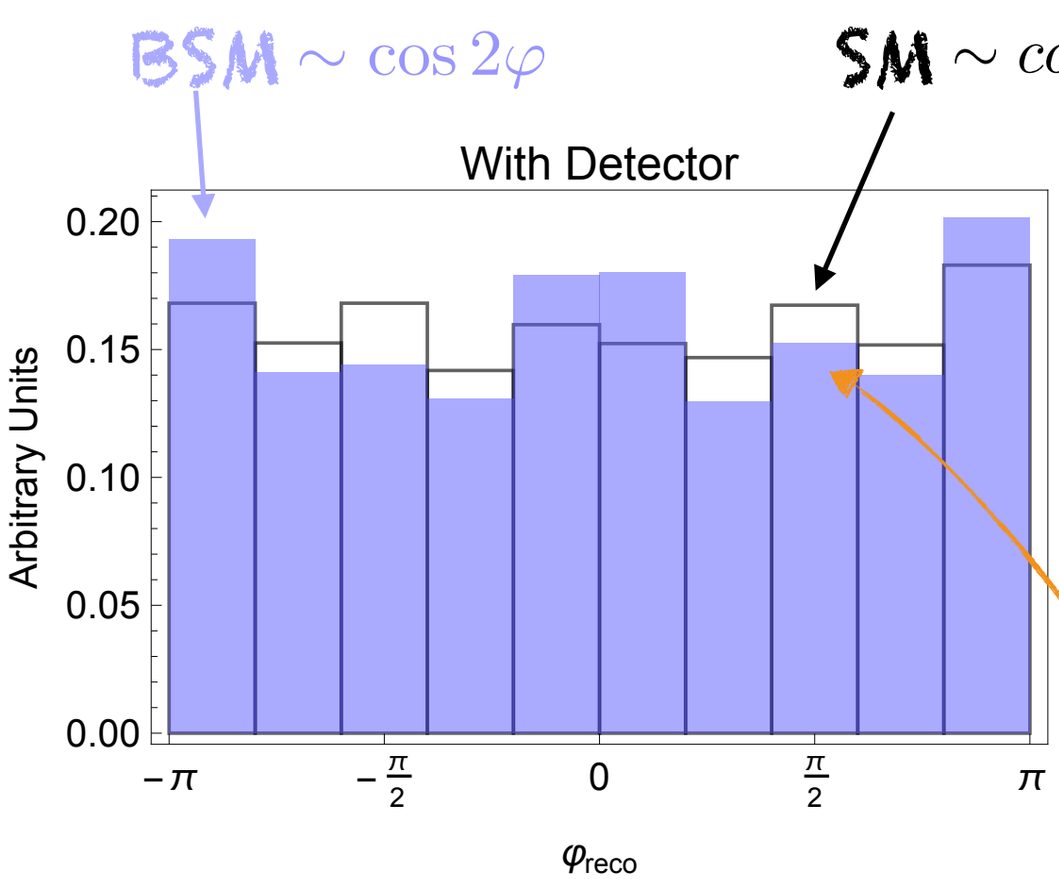
Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

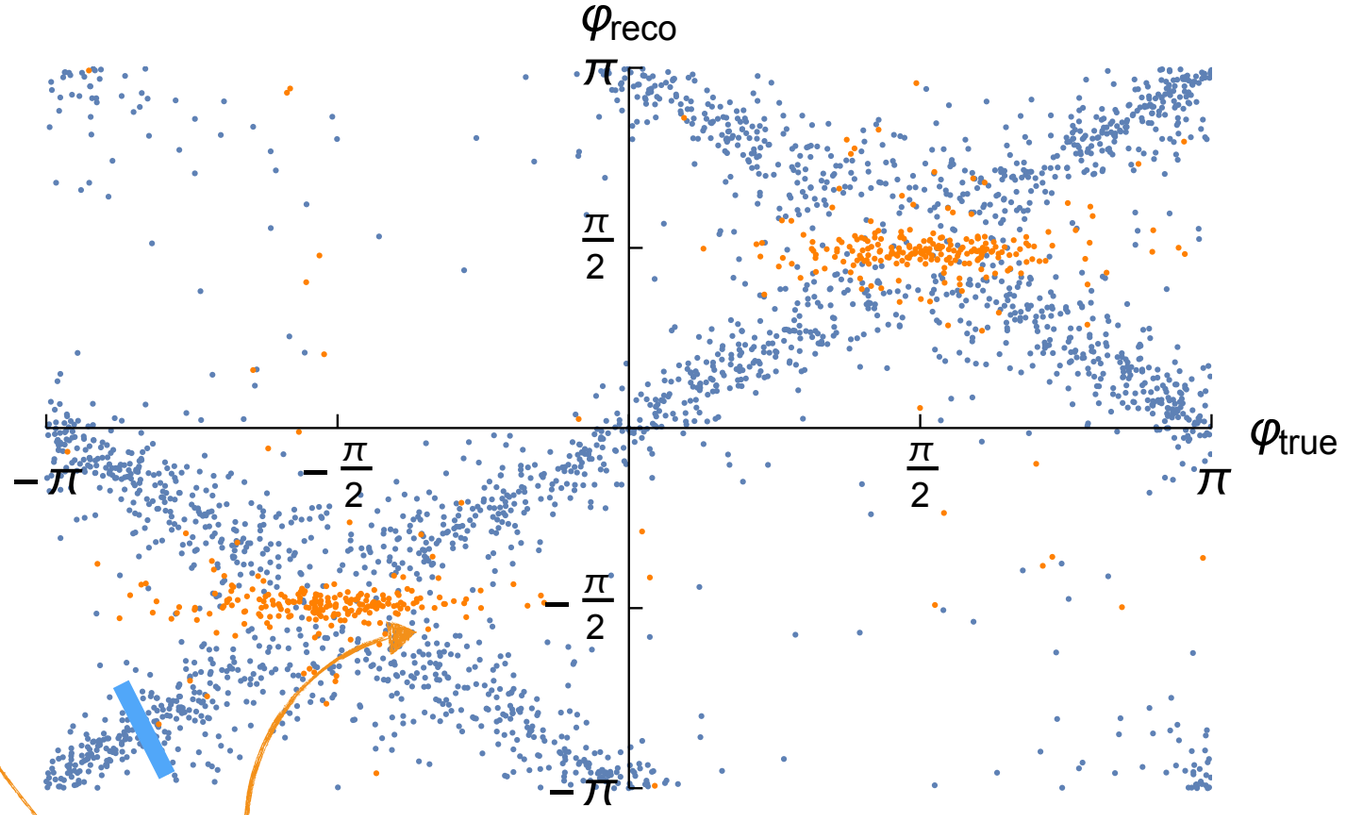
With (DELPHES) detector simulation

BSM $\sim \cos 2\varphi$

SM $\sim const.$



Spread under control



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

Panico,FR,Wulzer'17

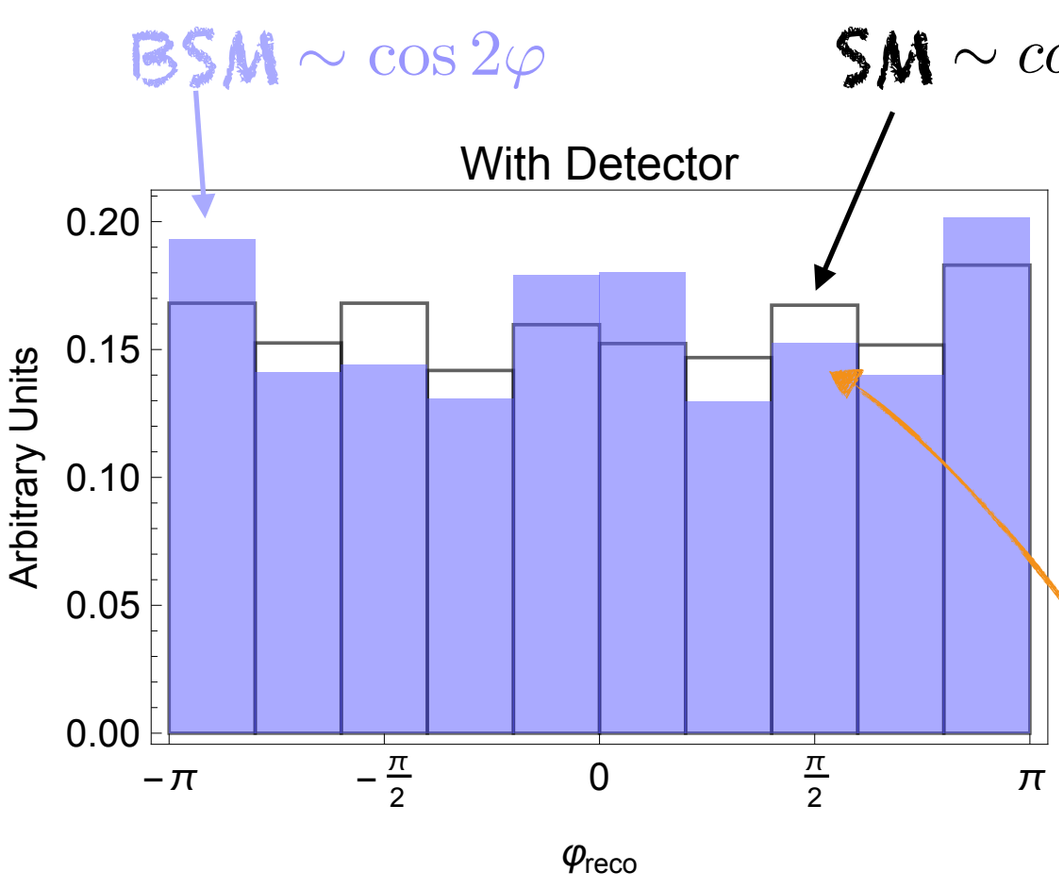
Azimuthal Angle... more in reality

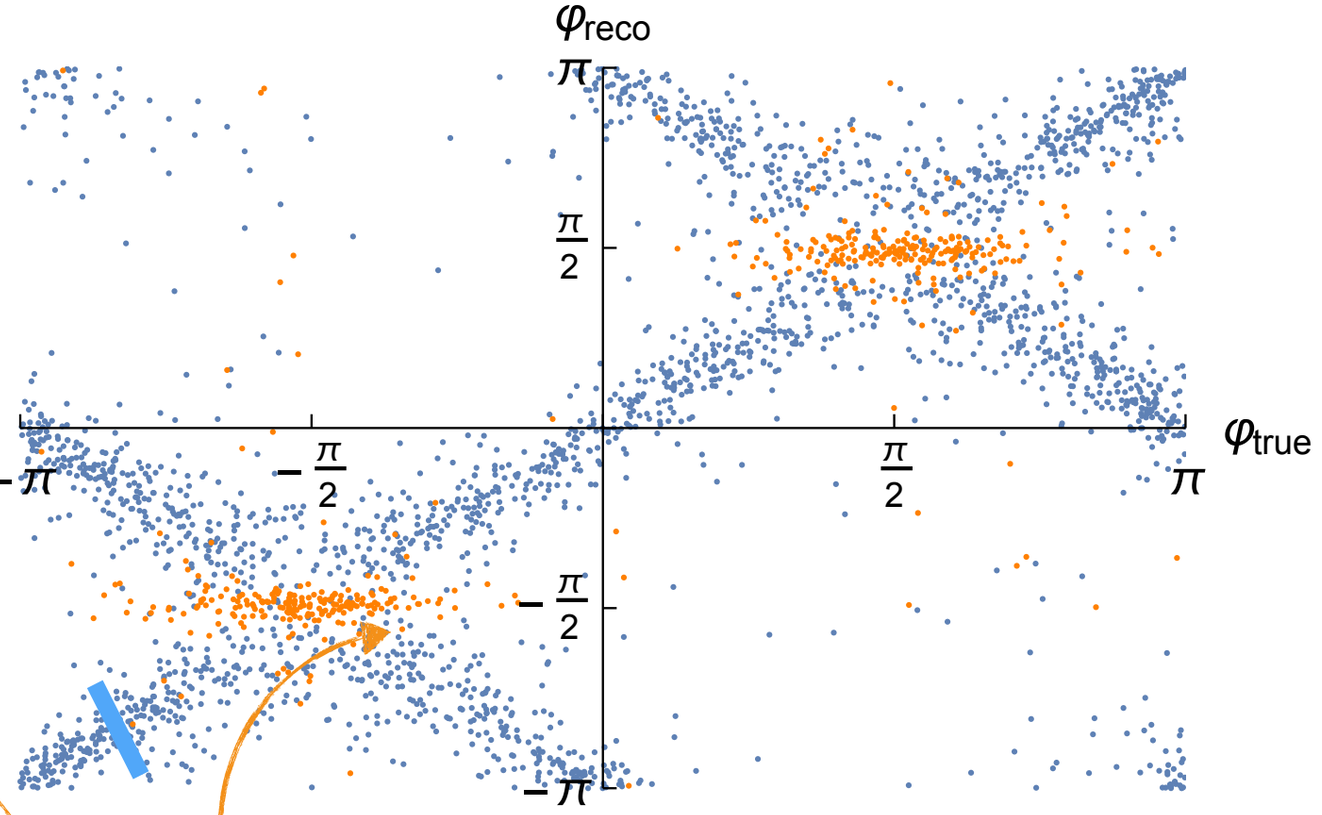
Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation

BSM $\sim \cos 2\varphi$

SM $\sim const.$





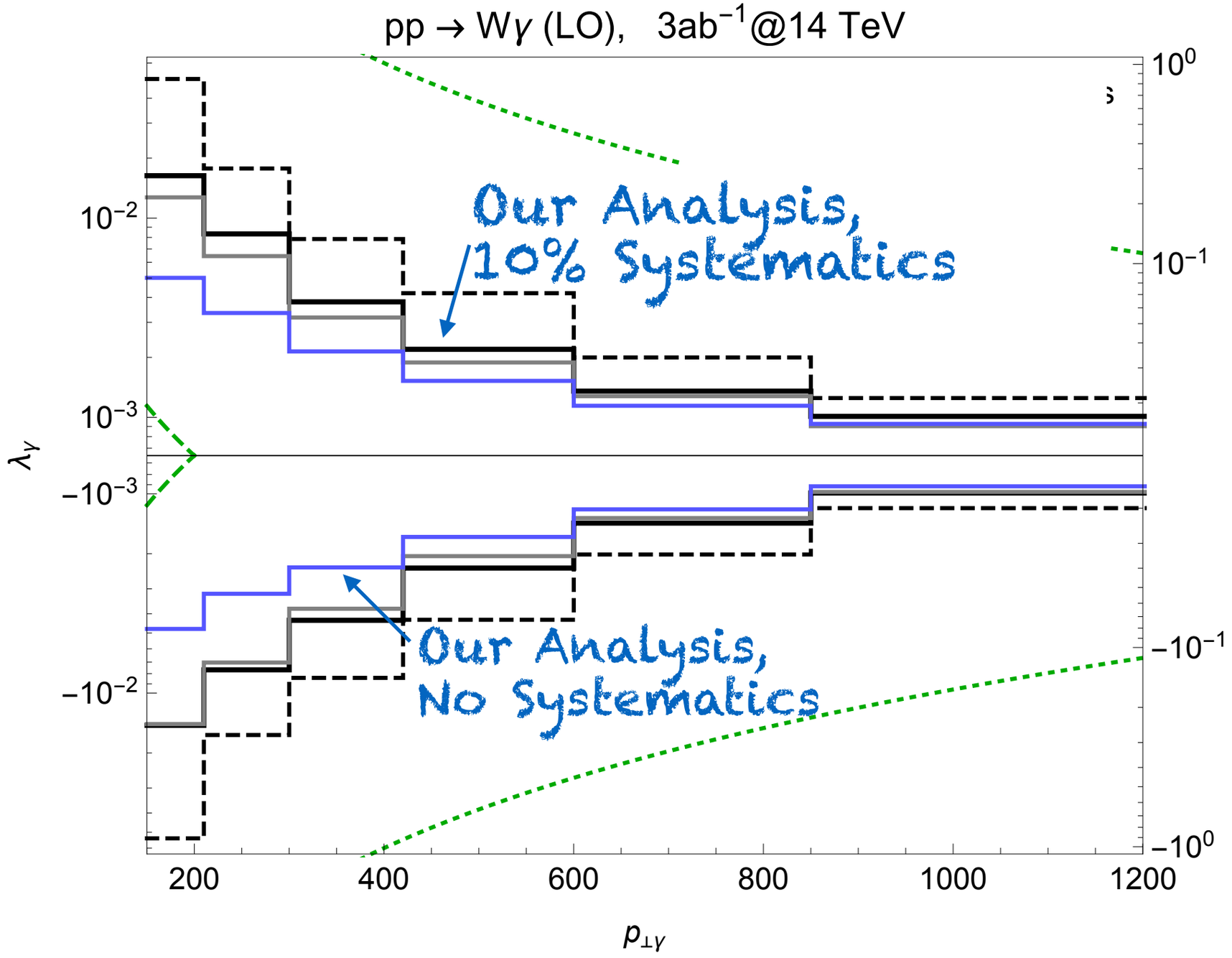
Spread under control

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

- Resurrection is real

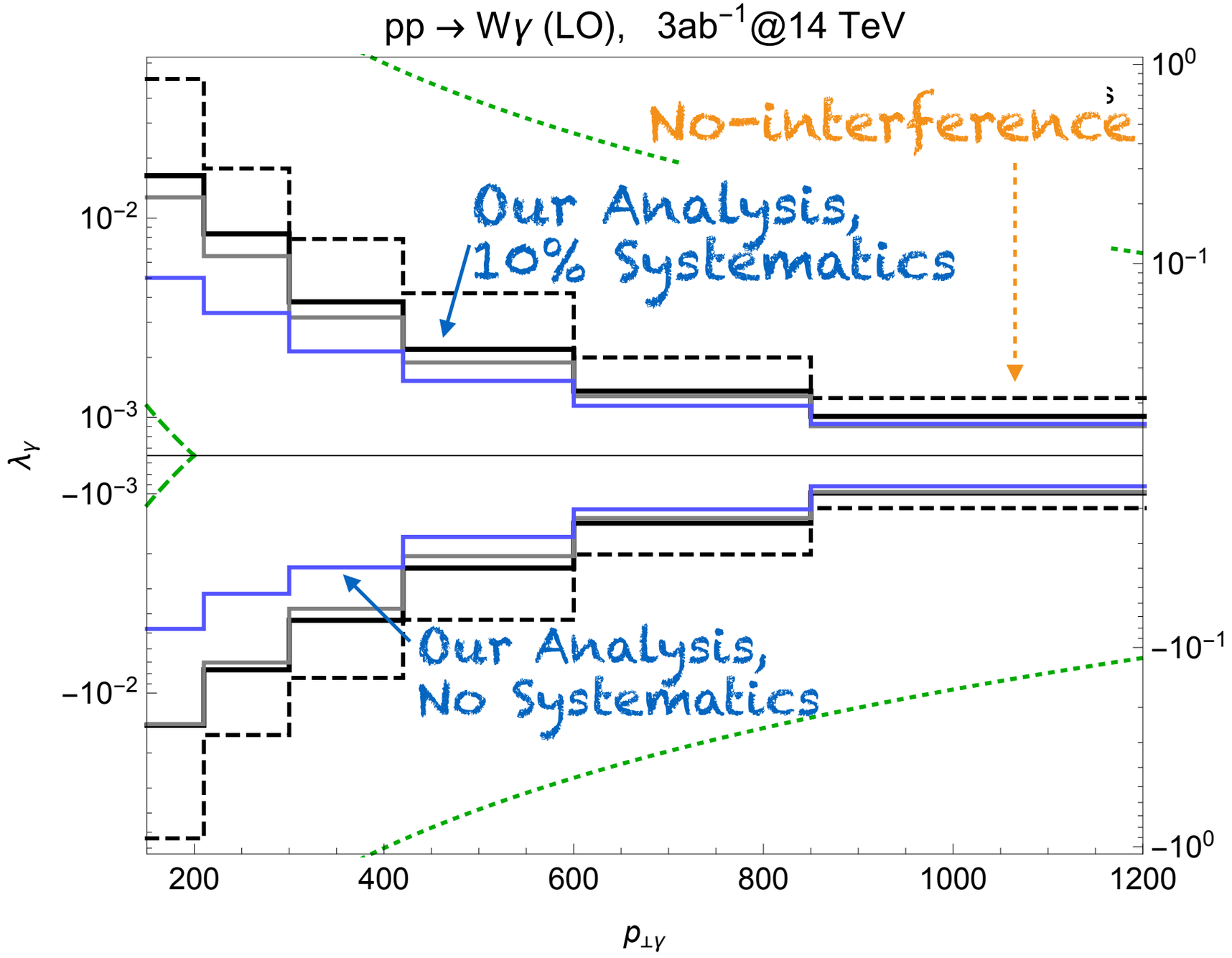
Panico,FR,Wulzer'17

Results



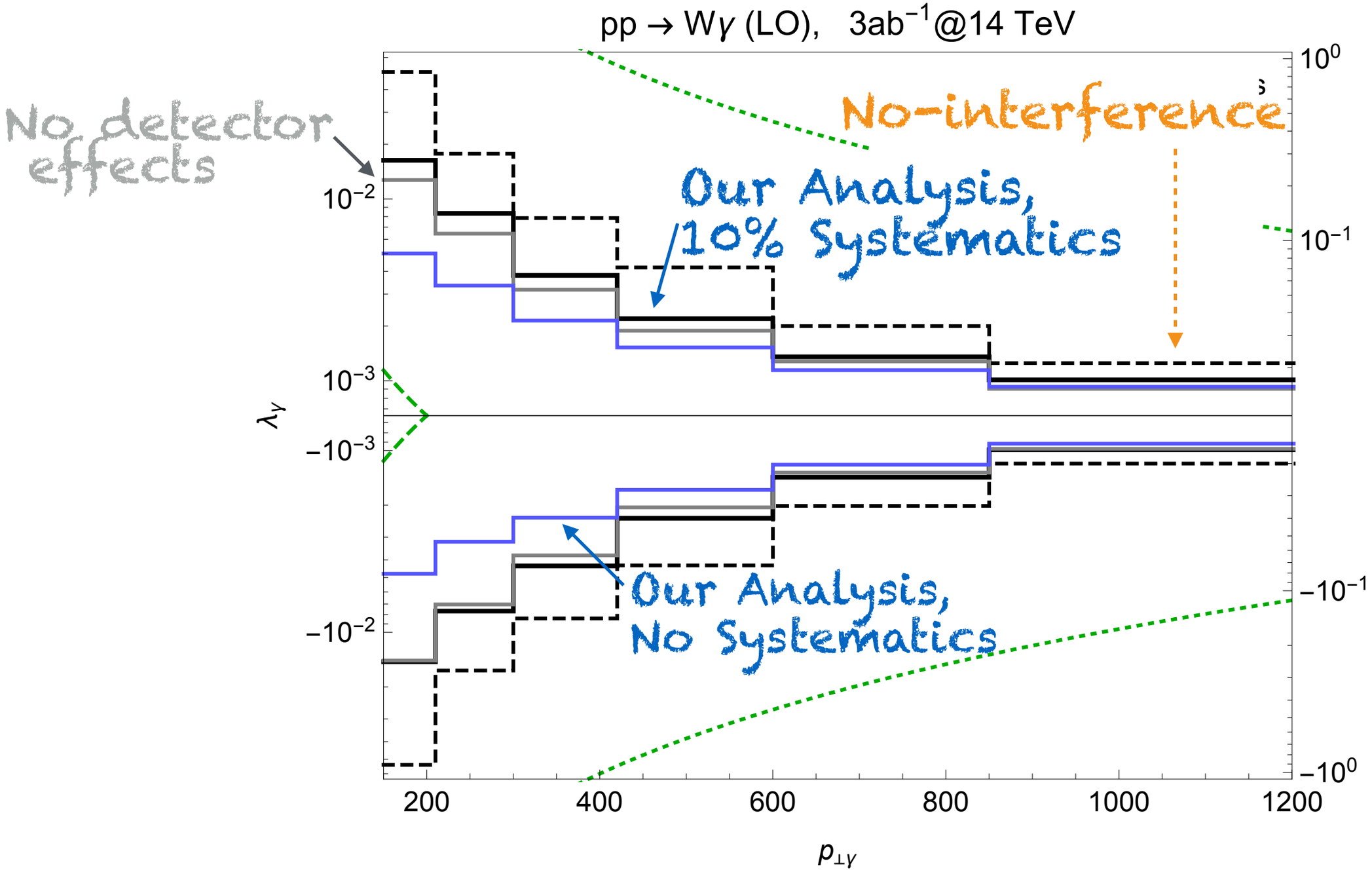
Panico,FR,Wulzer'17

Results



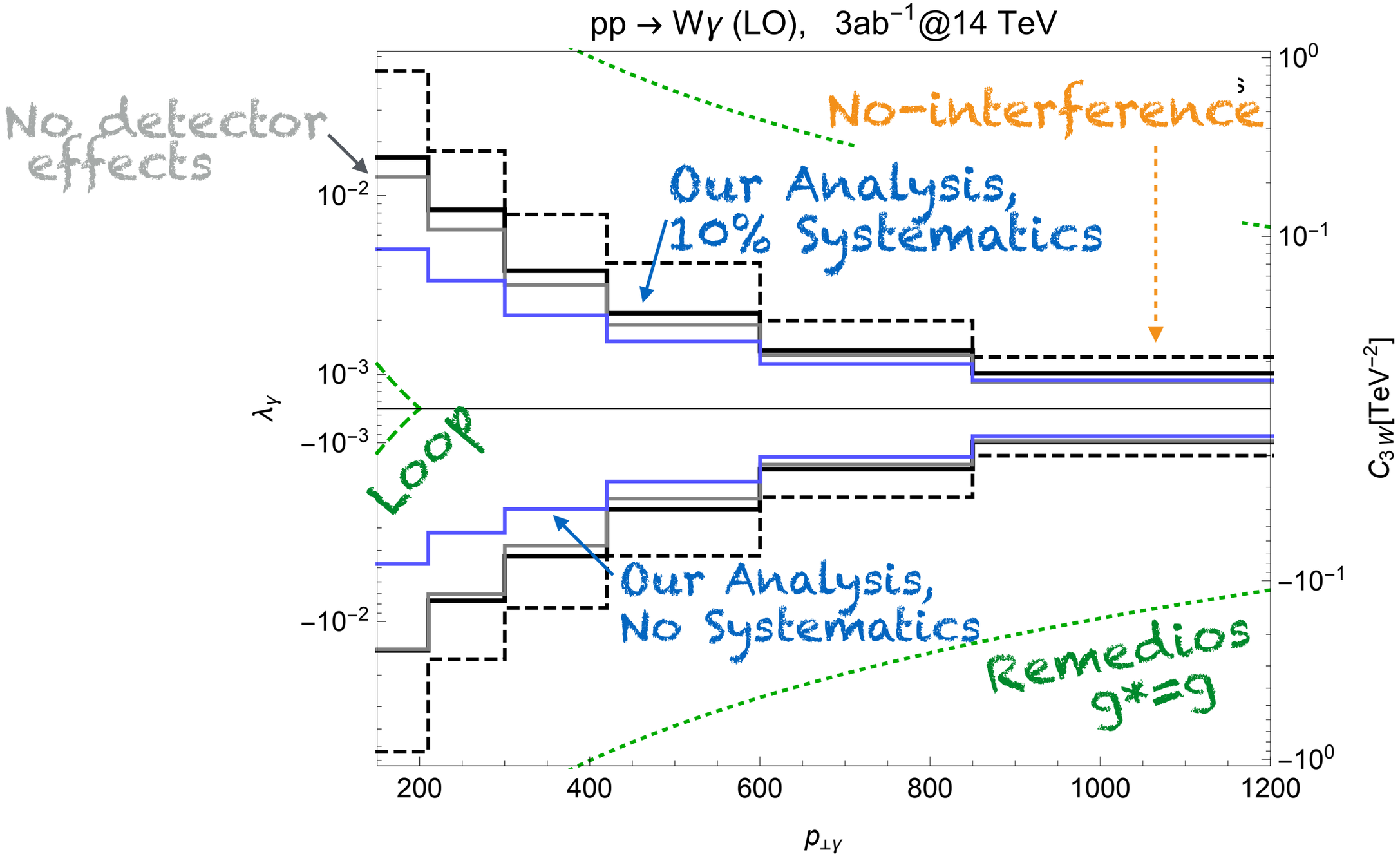
Panico,FR,Wulzer'17

Results



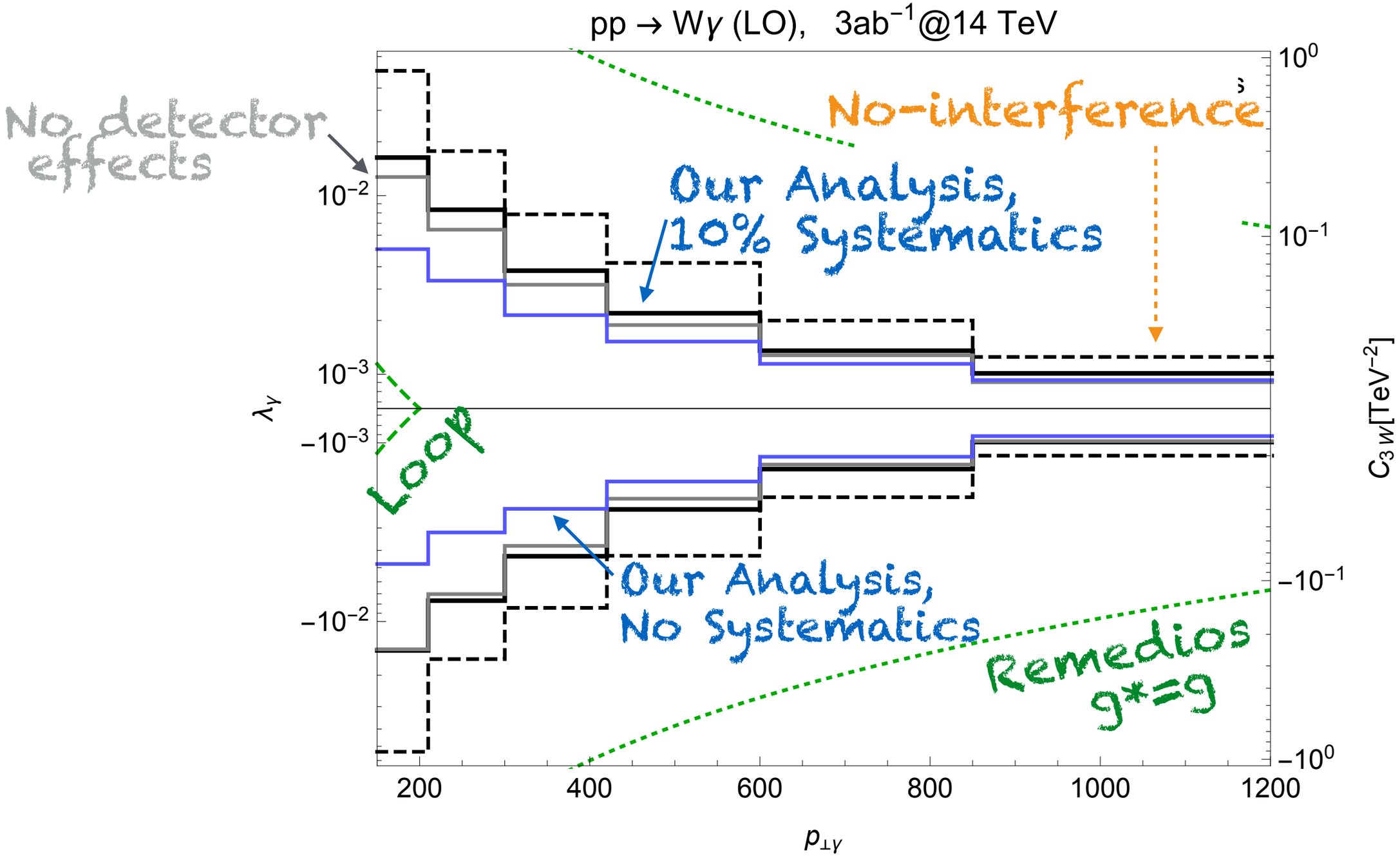
Panico,FR,Wulzer'17

Results



Panico,FR,Wulzer'17

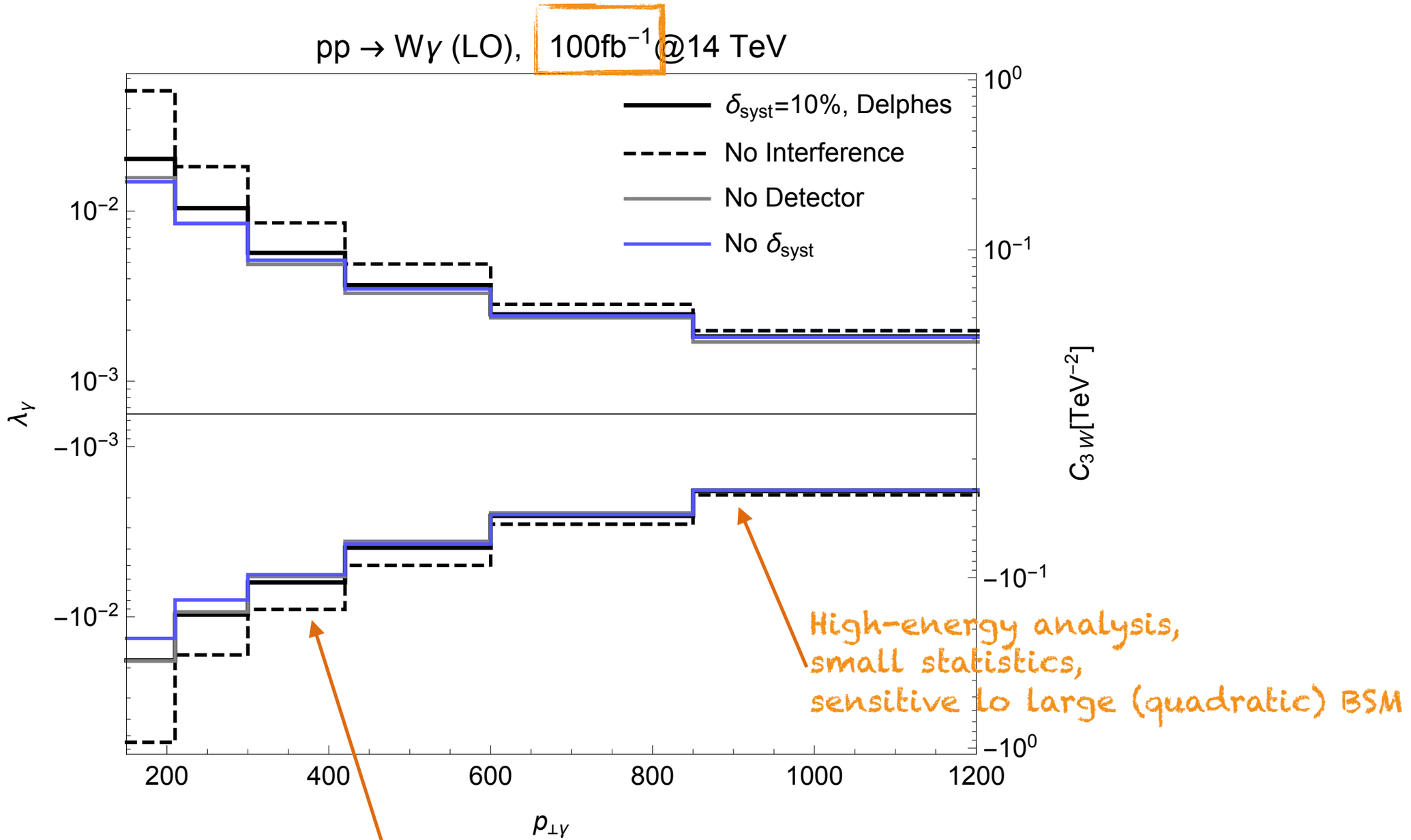
Results



- Important improvement, though not yet there for weakly coupled/loop-generated new physics

Panico,FR,Wulzer'17

Results

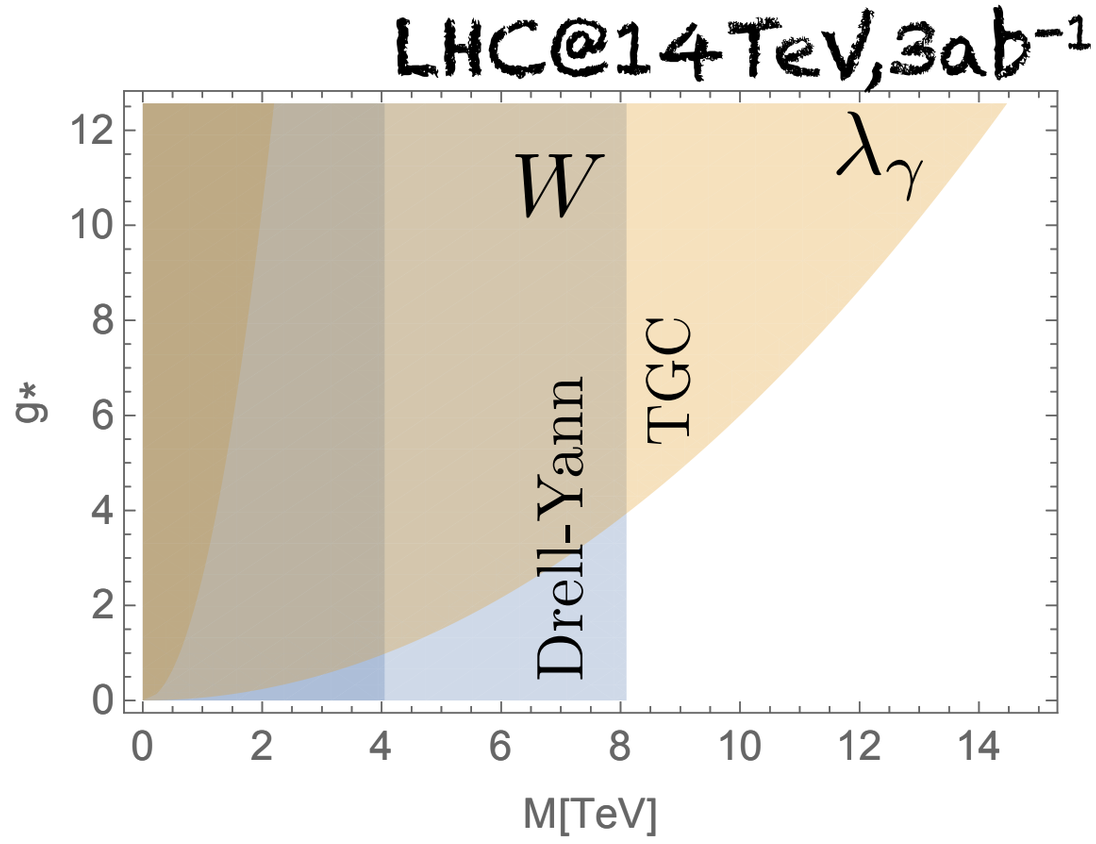


Panico,FR,Wulzer'17

Explicit Model (Remedios)

see Pomarol's talk

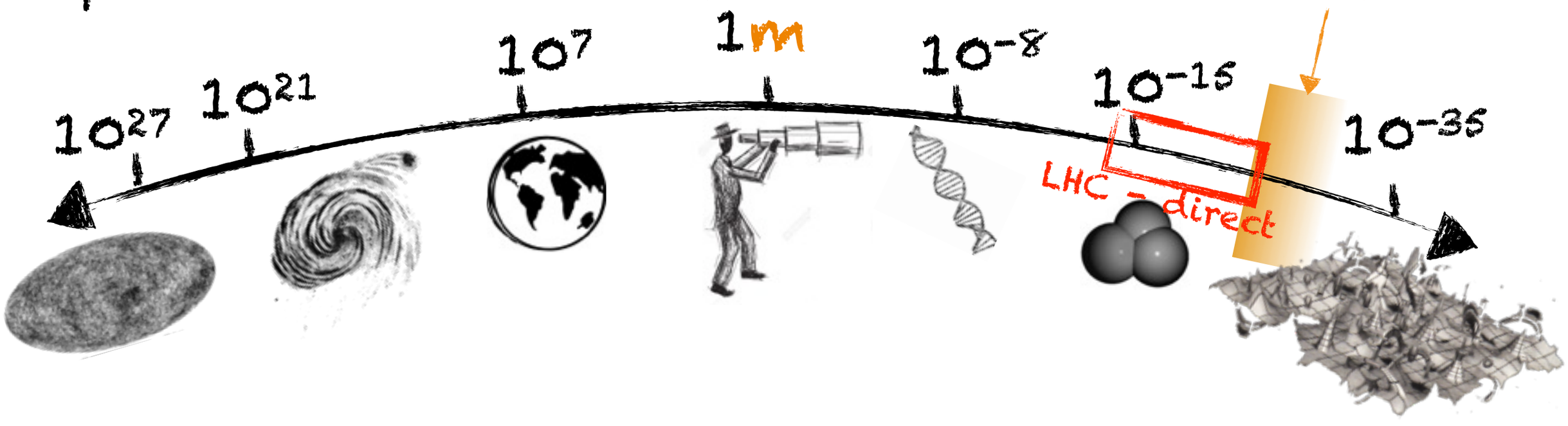
Liu,Pomarol,Rattazzi,FR'16



Interference Resurrection makes the difference.

Message

SM precision tests will define the new distance frontier



- LHC good in High-E 2>2 processes

Challenge:

non-interference limits precision in learning about transverse vectors

- Azimuthal distributions crucial

- Realistic in other processes? WZ? VBF?