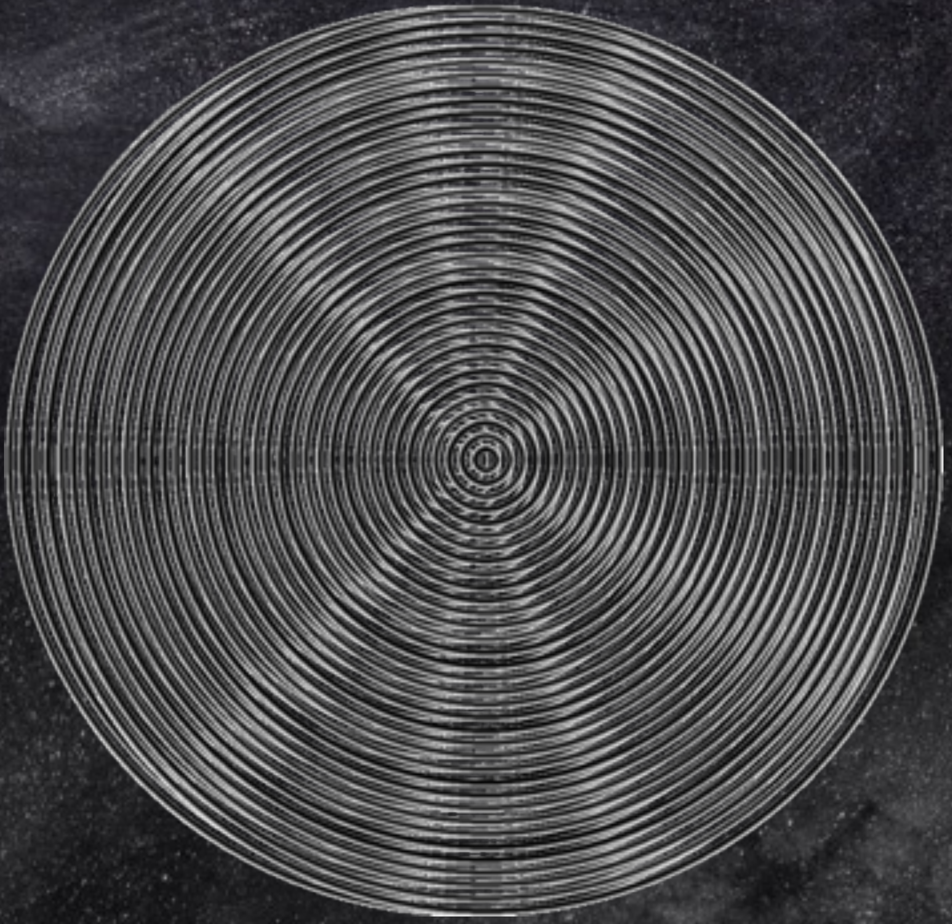
Di-bosons: Higgs' closest cousins

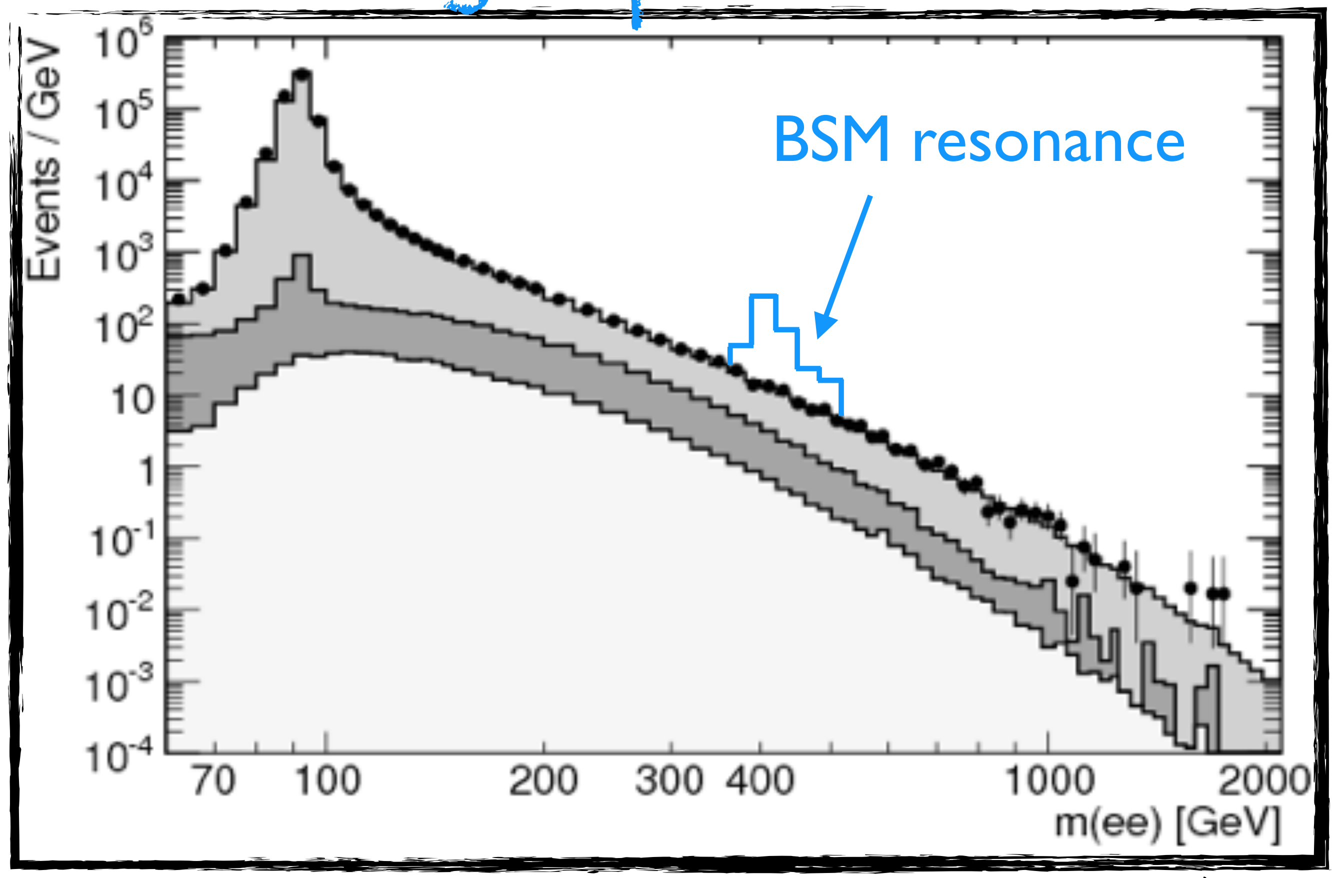


Francesco Riva
(CERN)

In collaboration with
Franceschini,Panico, Pomarol, Wulzer' last week (were it not for Catalunya)
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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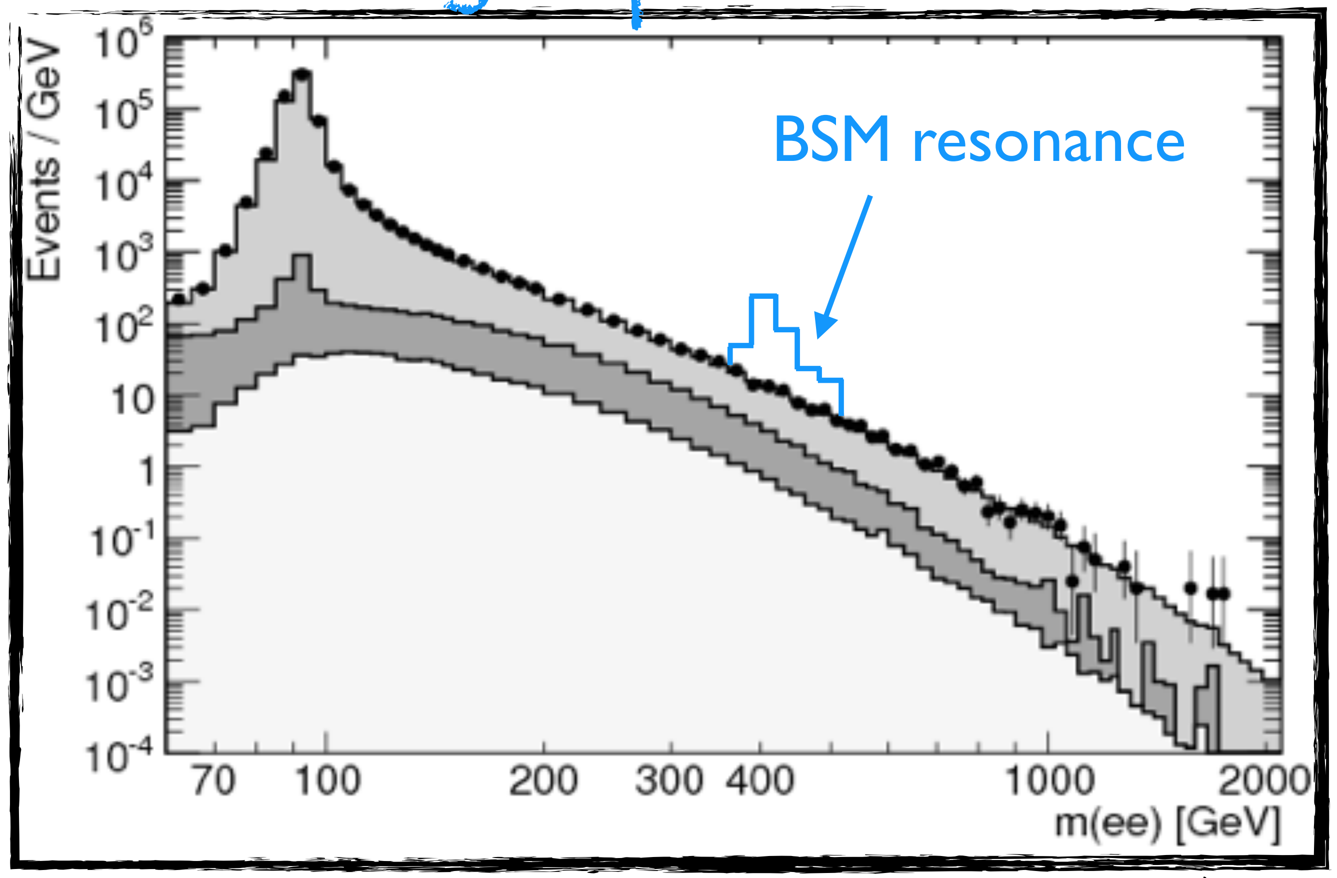

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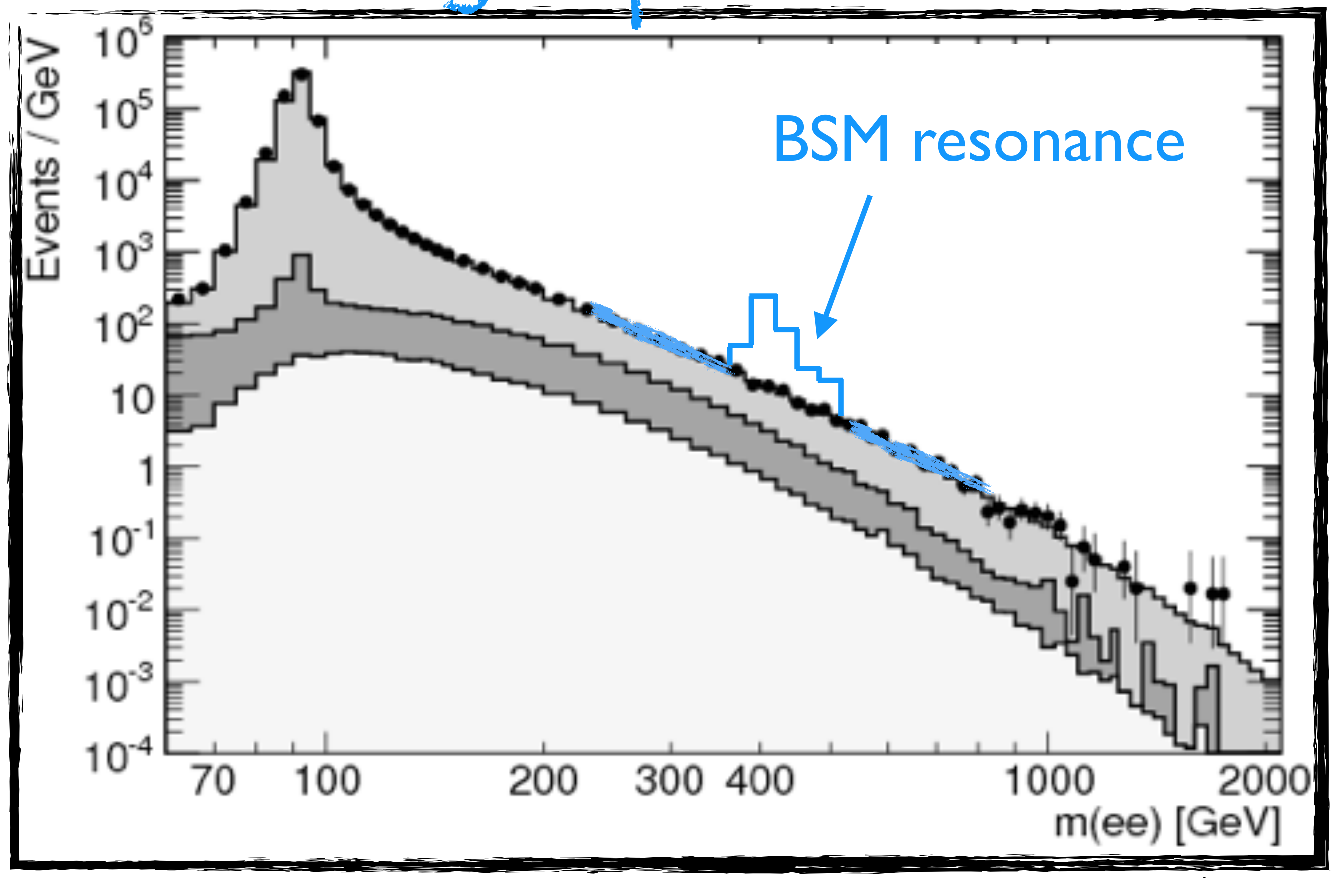

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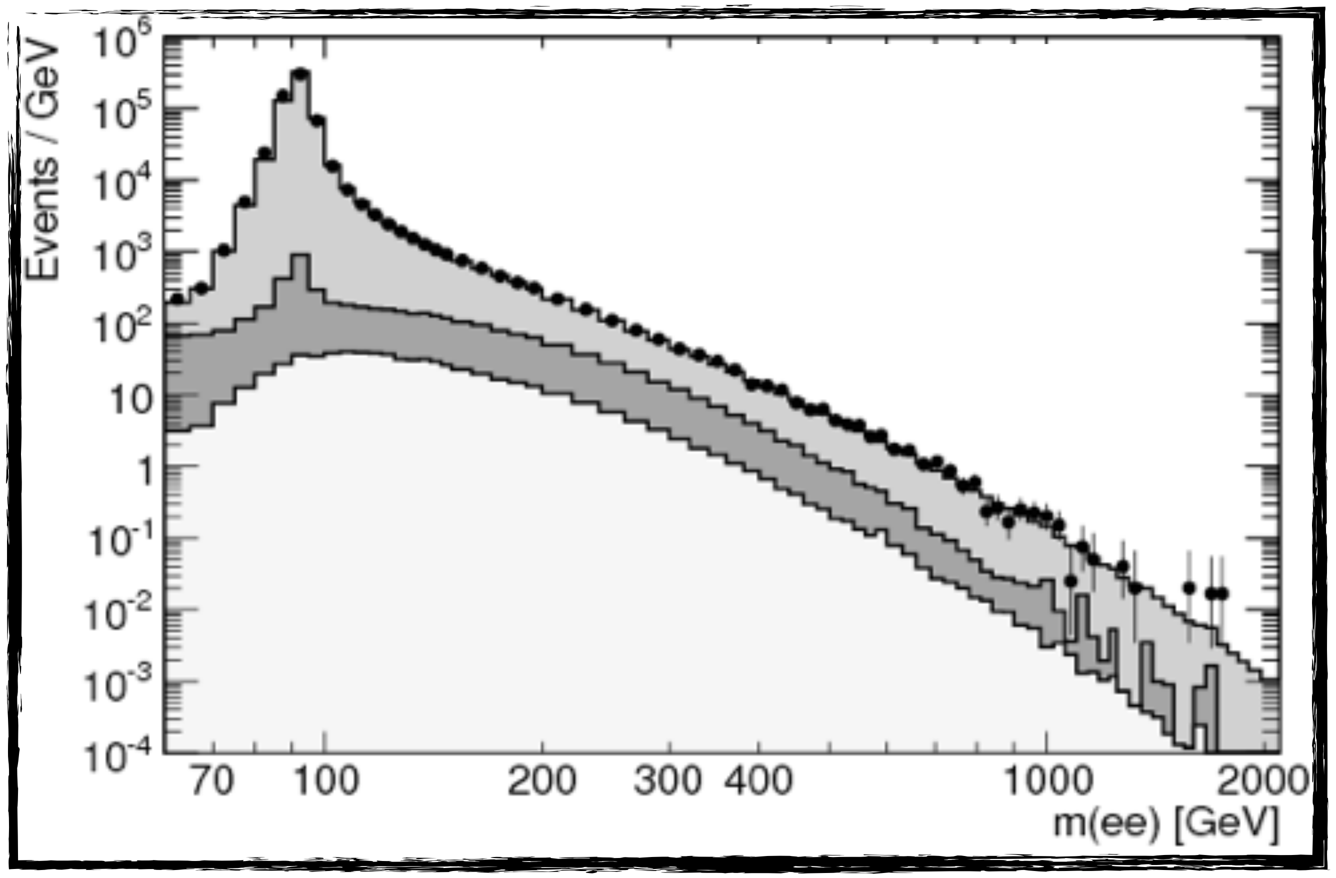
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb^{-1})

intensity frontier

(2016: 40 fb^{-1})



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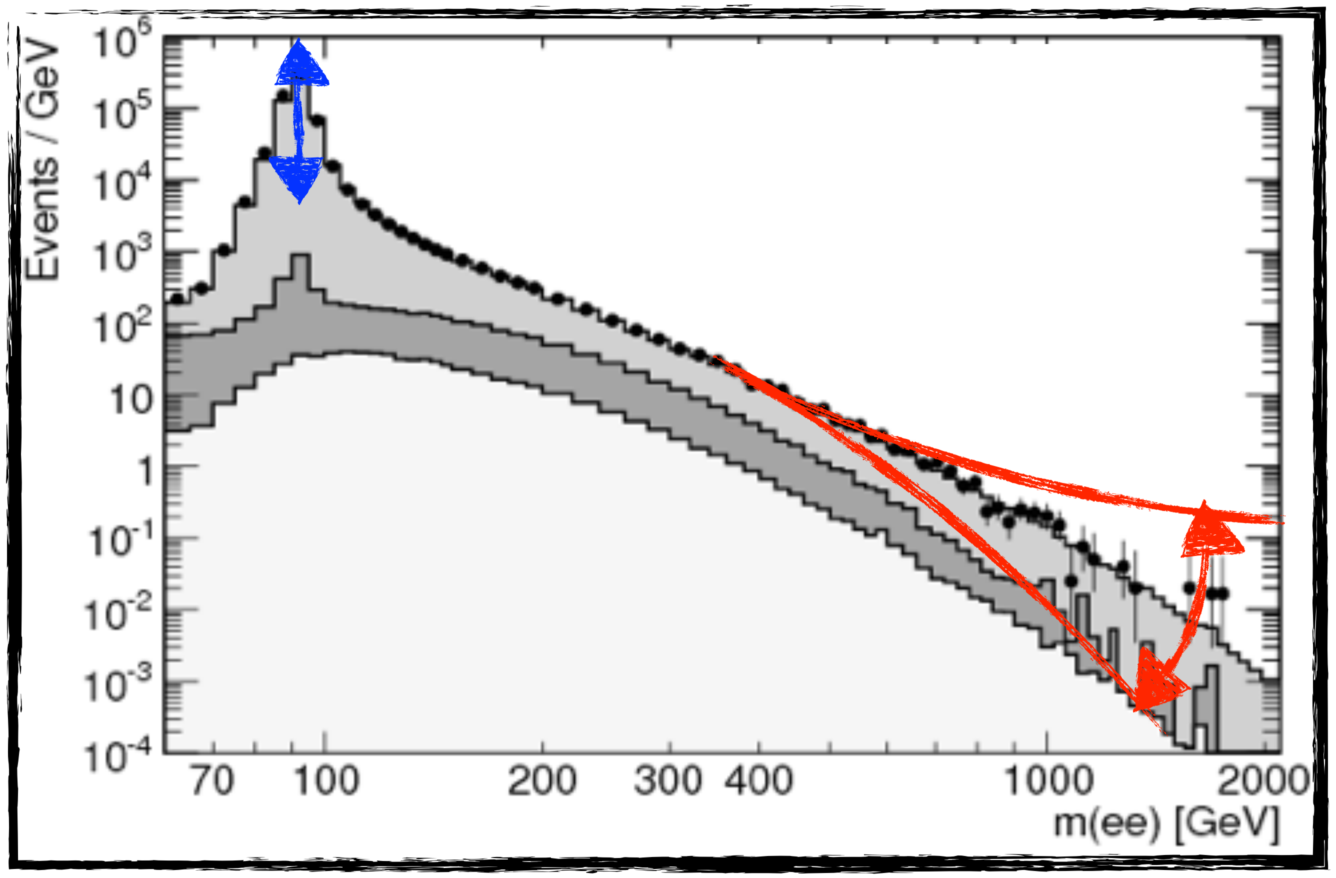

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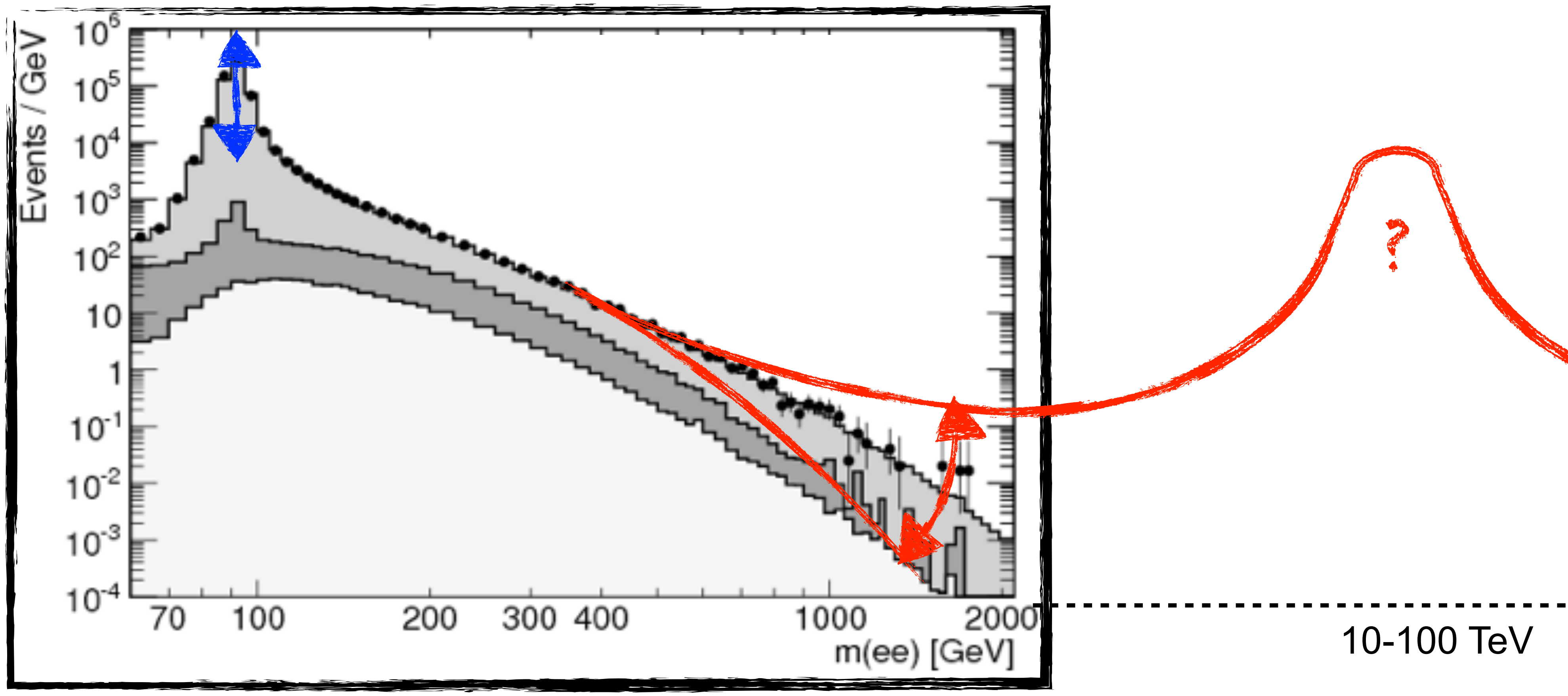

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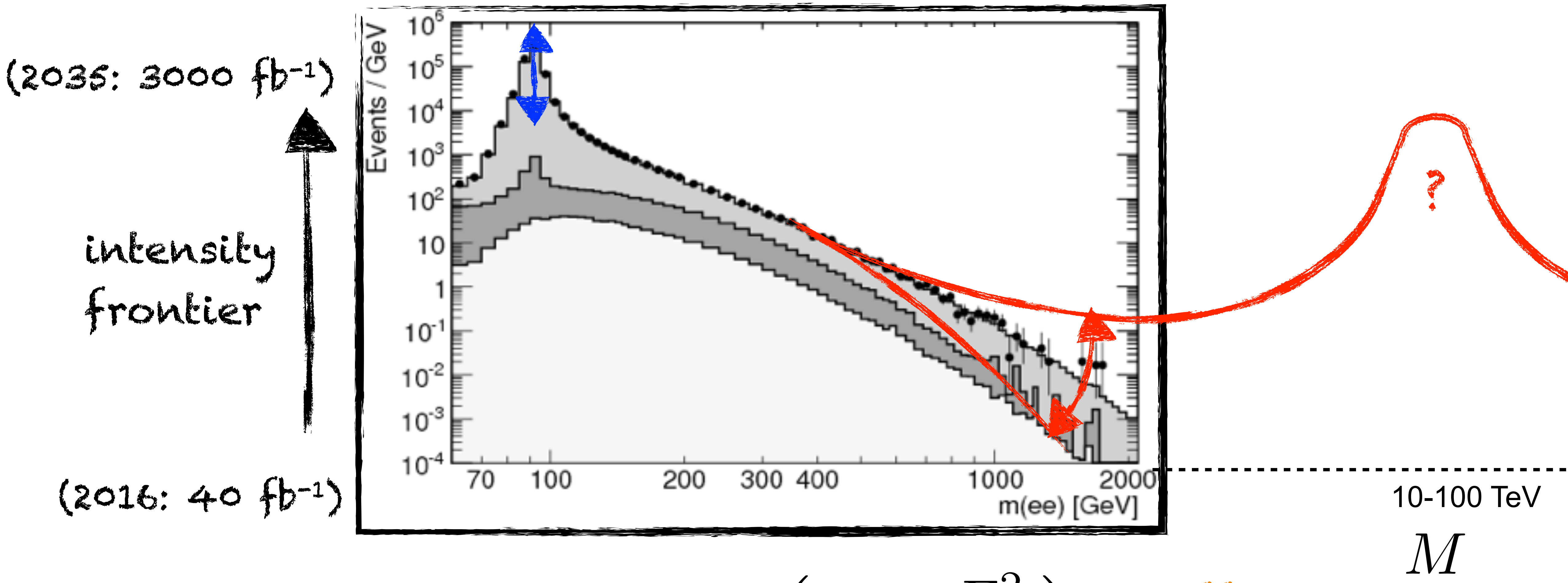

$$Amp = SM\left(1 + c\frac{E^2}{M^2}\right)$$ — Effective Field Theory

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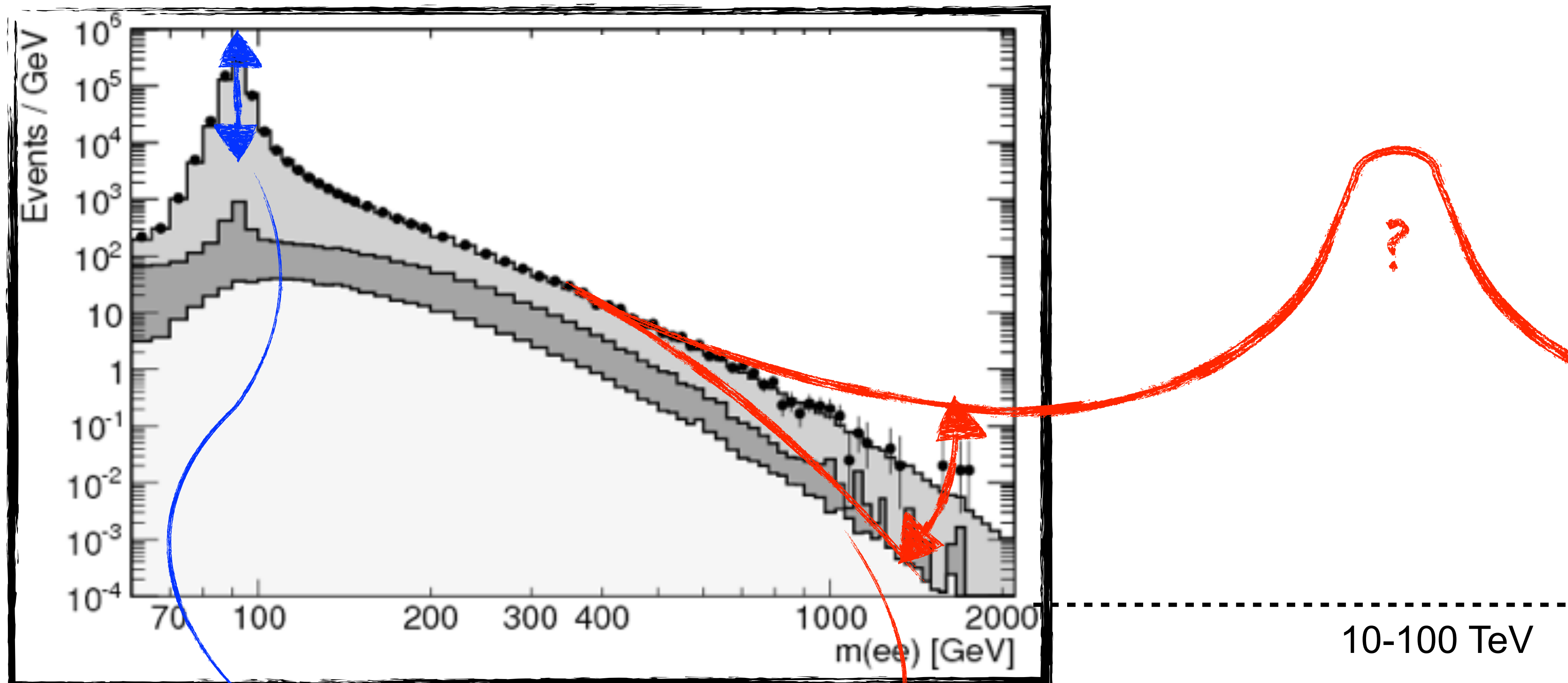

M

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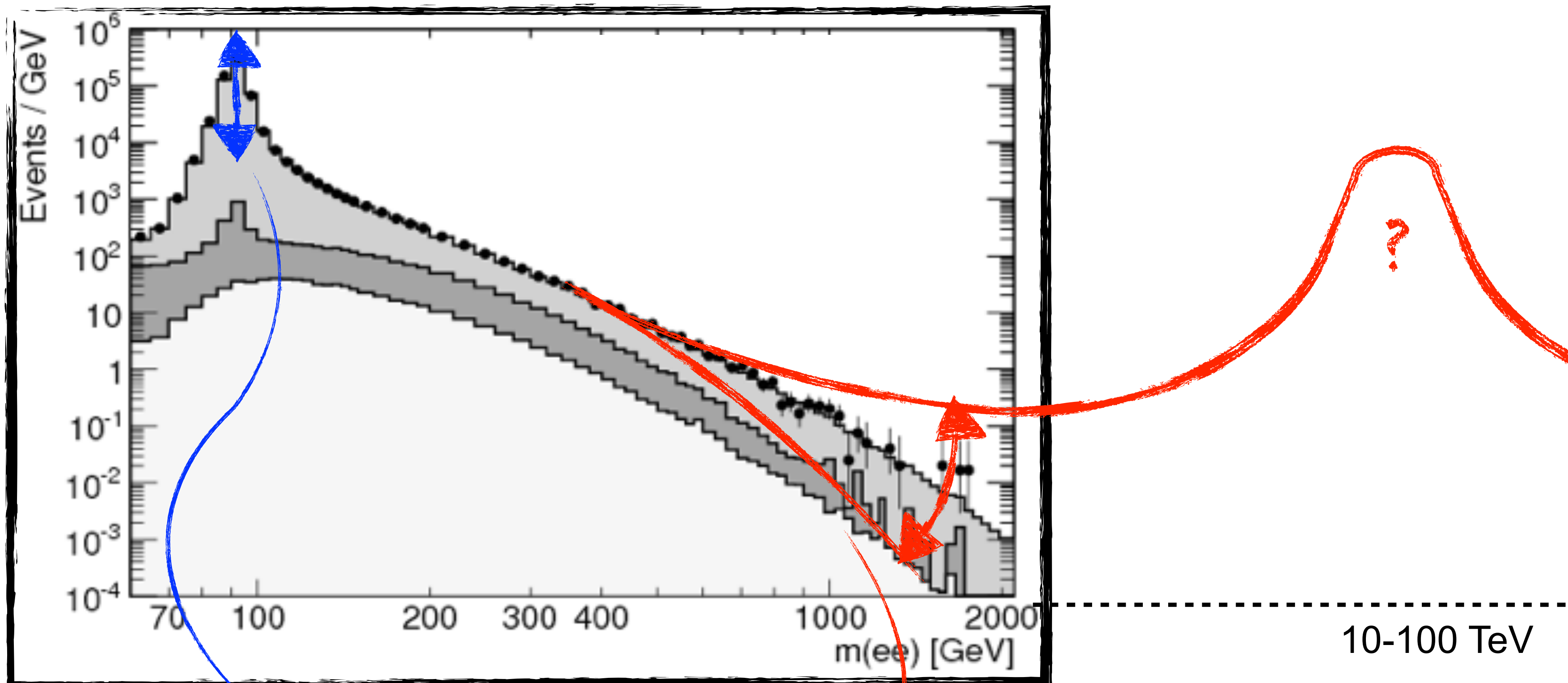

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e.g. Higgs Couplings,...

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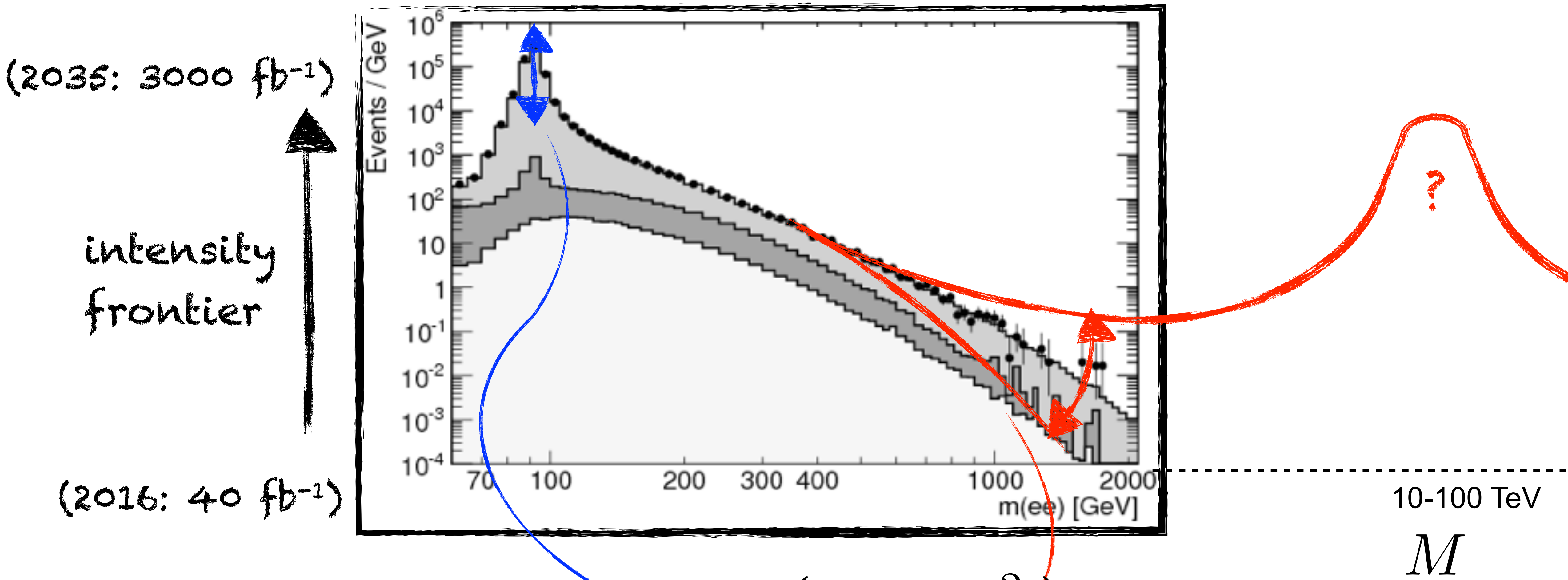

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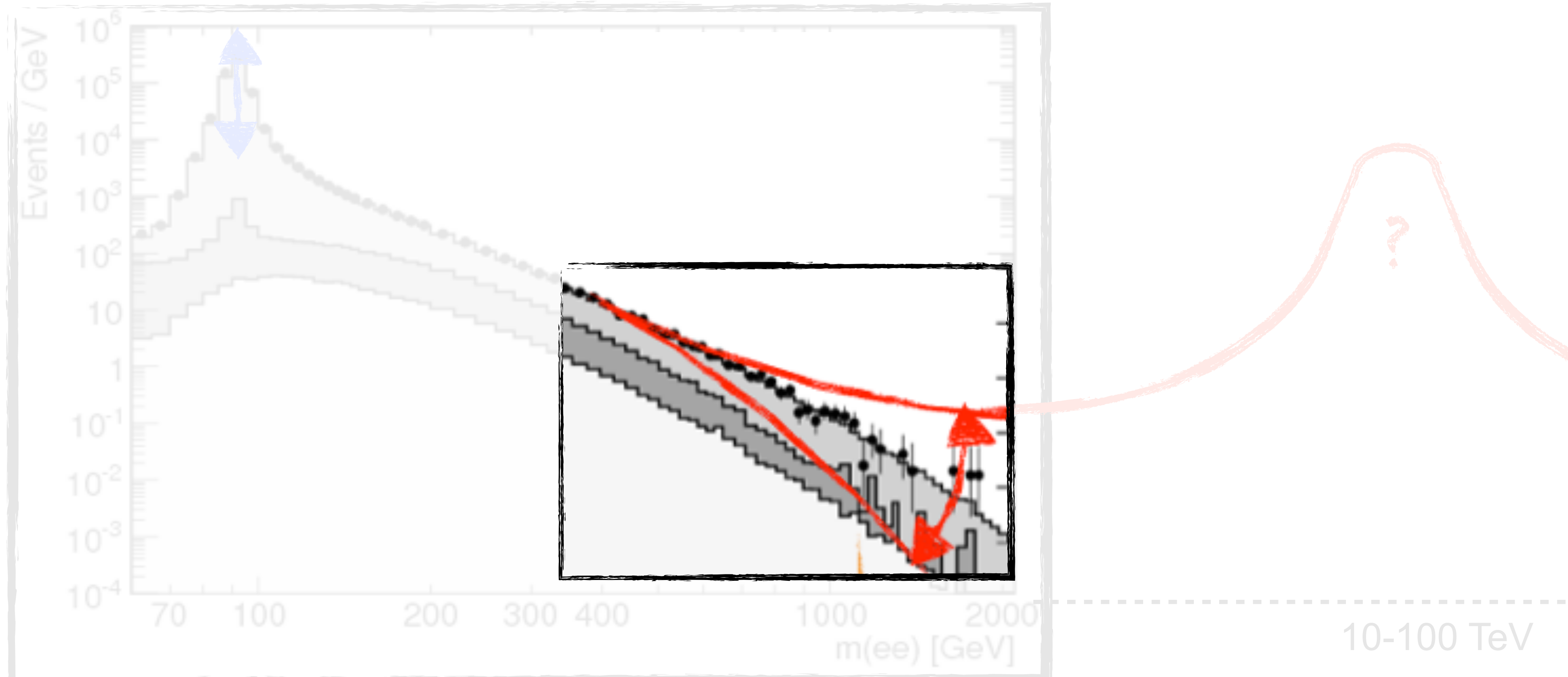

10-100 TeV

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

M

W_L

$$\begin{pmatrix} h^+ \\ h + ih^0 \end{pmatrix}$$

Z_L

Effective Field Theory

e.g. Drell-Yann, VH, VV',..

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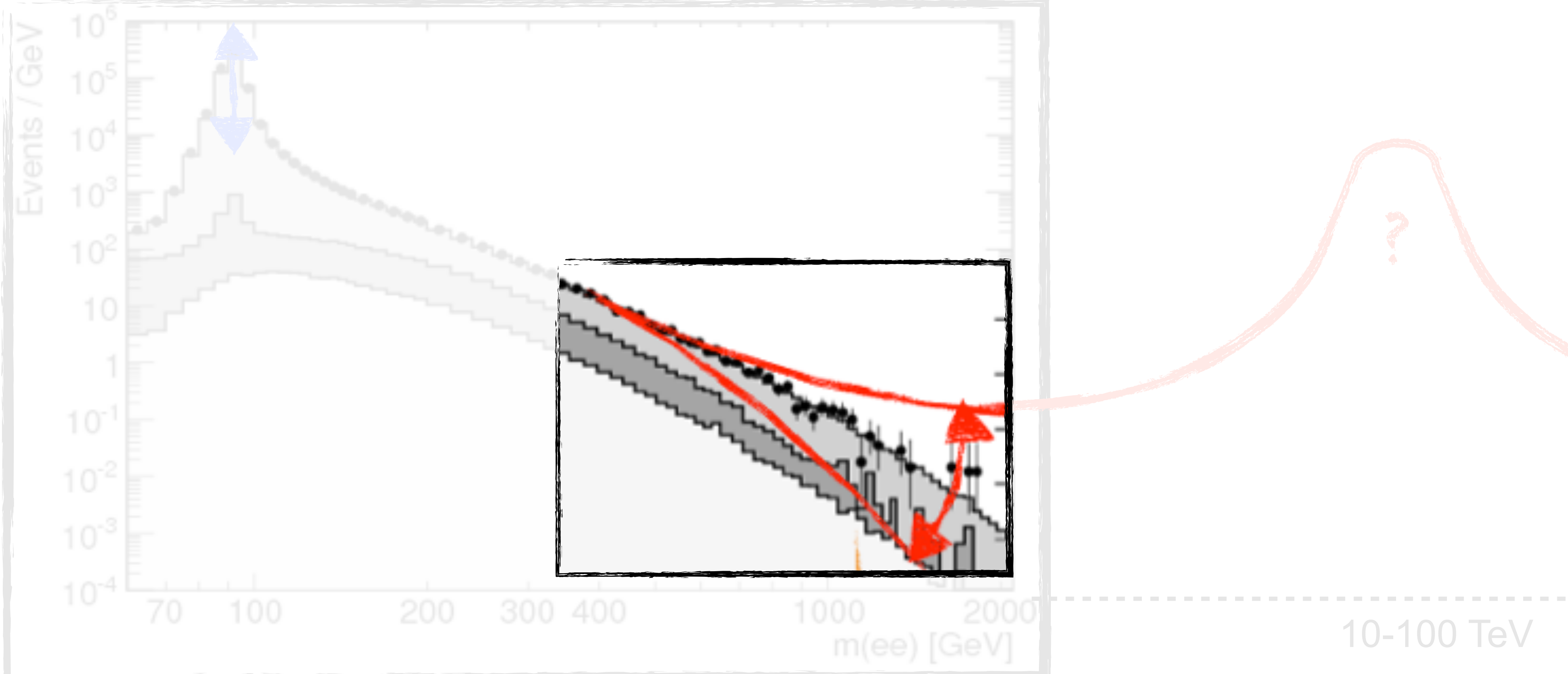

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W_L ; Z_L

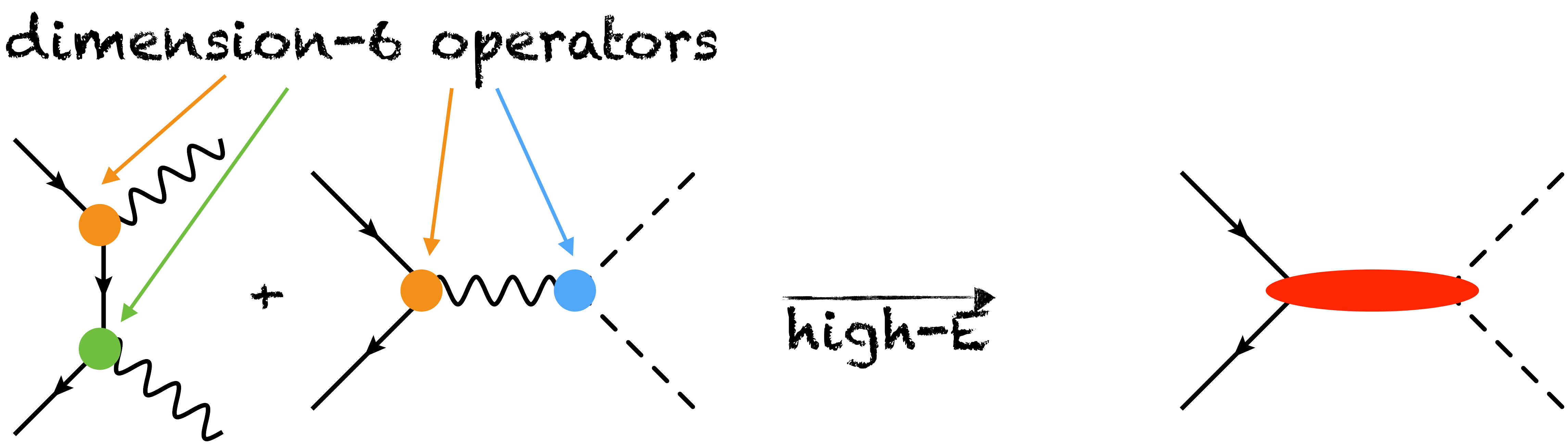
e.g. Drell-Yann, VH, VV',...

1. Longitudinals $\psi\psi \to V_L V_L$

2. Transverse $\psi\psi \to V_T V_T$

Longitudinal dibosons

Simplicity at High-E



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

Jackob,Wick'59, Franceschini,Panico,Pomarol,FR,Wulzer

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

Di-Bosons

Franceschini,Panico,Pomarol,FR,Wulzer'17

Which channel has the best reach?

- 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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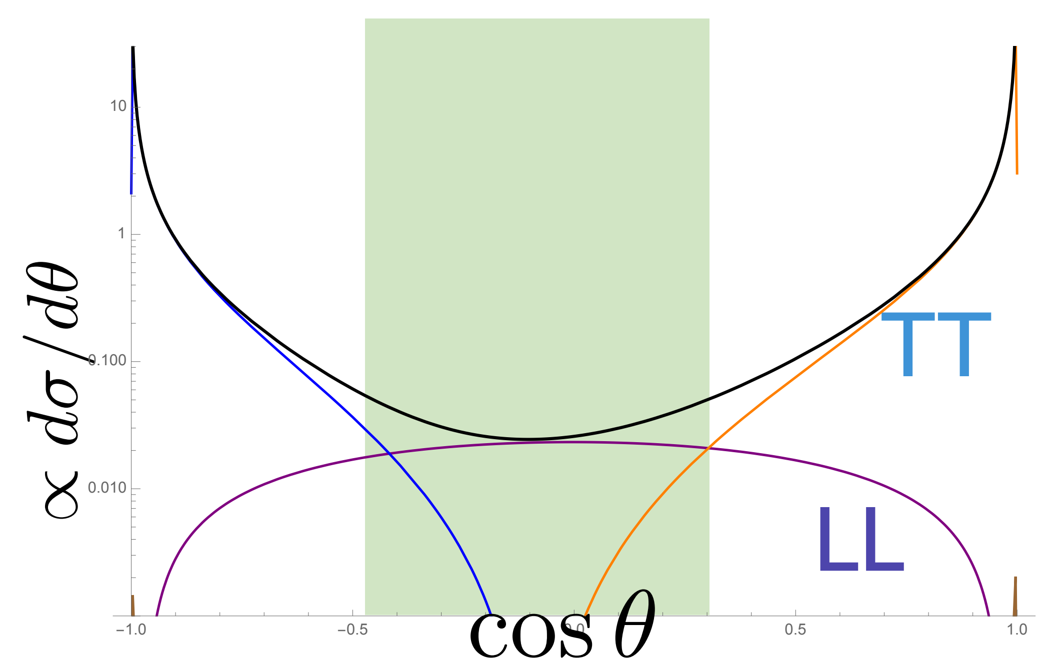
- **WZ** most promising

$$A^{+-}(\bar{d}u \to WZ) \propto \cos\theta - \frac{\tan\theta_W}{3}$$

Baur,Han,Ohnemus'95

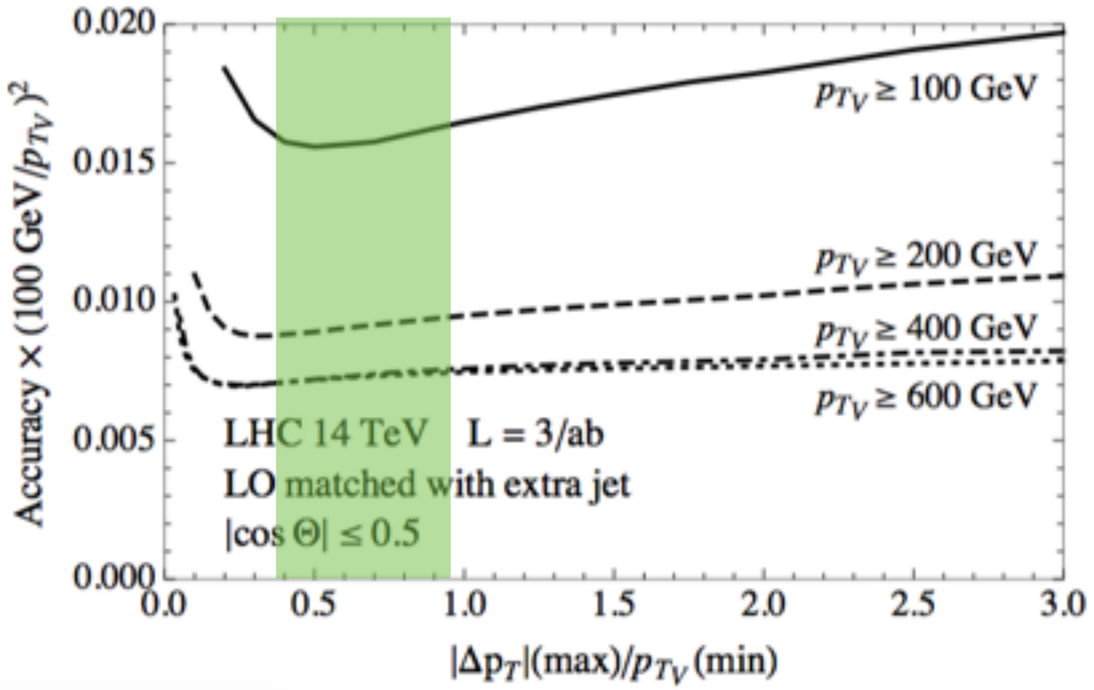
TT has central zero at LO

(not at NLO)

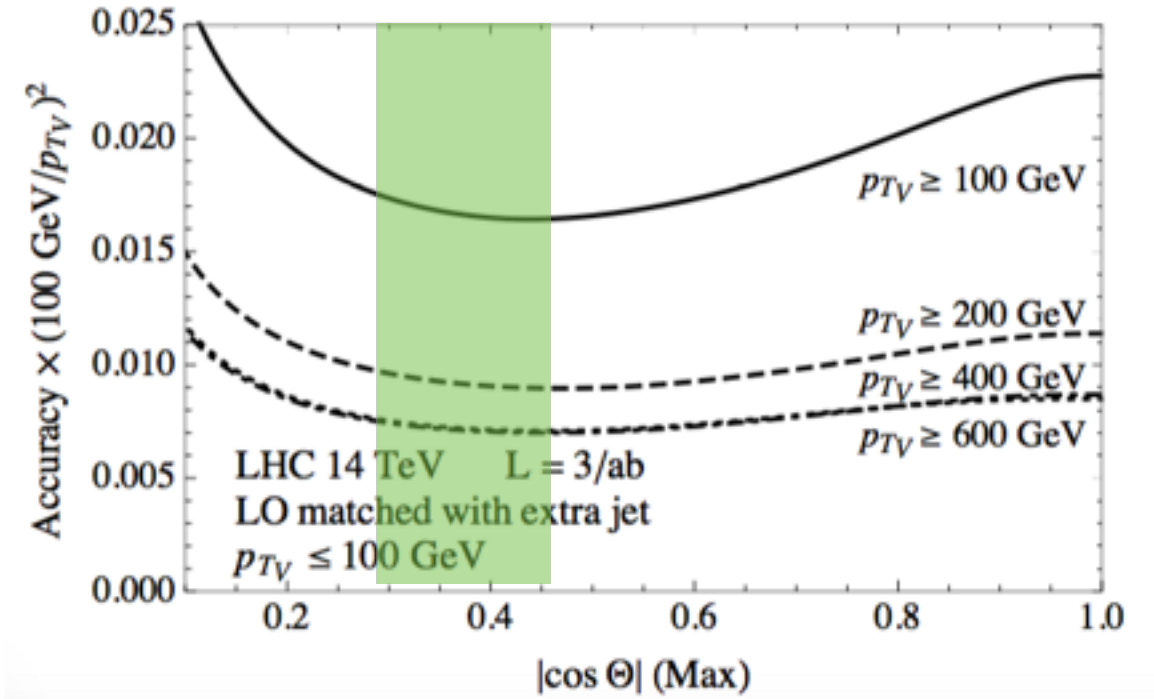


Fully leptonic WZ

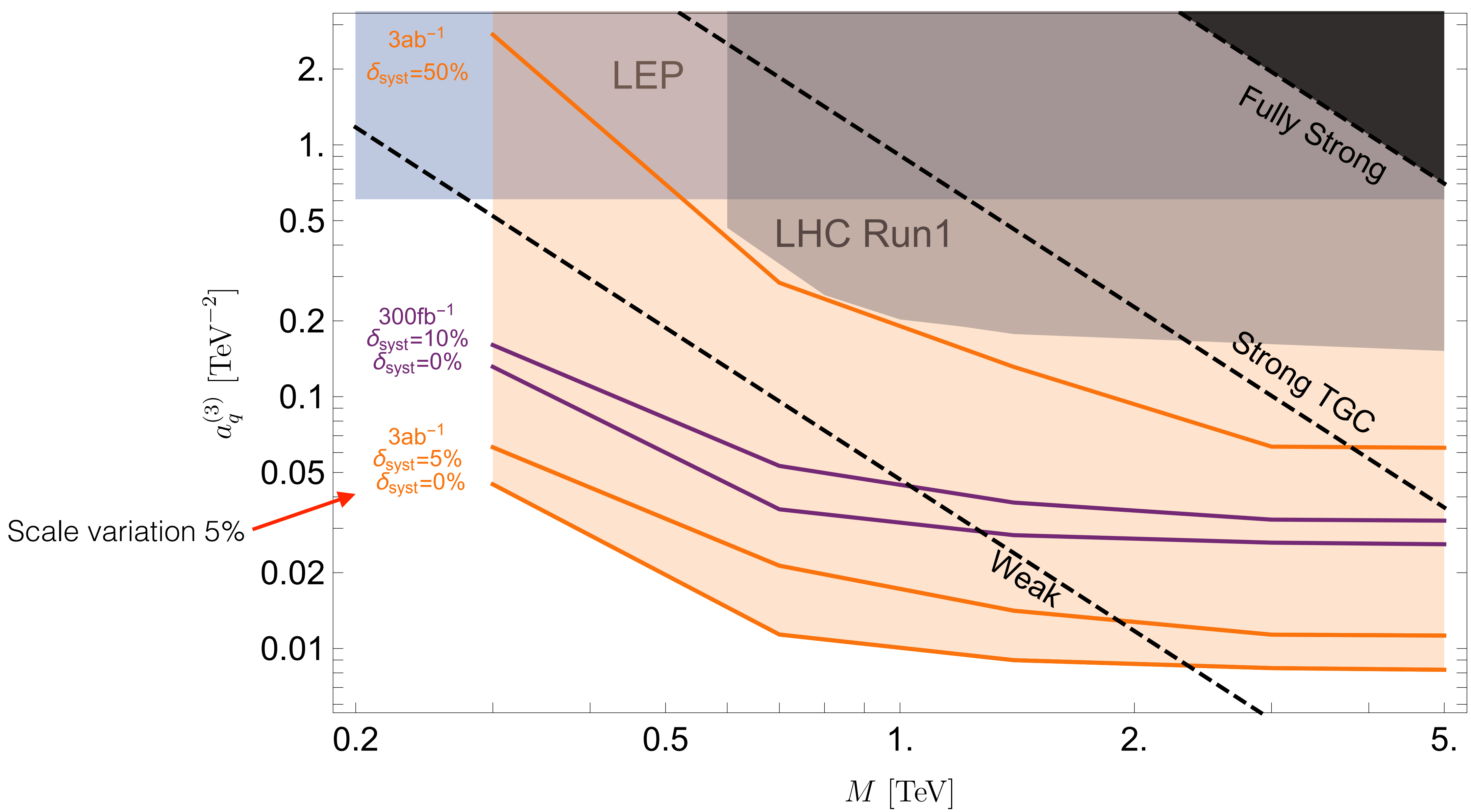
pT cut on extra radiation:
(kinematics close to LO)



Cosθ cut close to central
(exploit radiation-zero)



Results - NLO - LHC

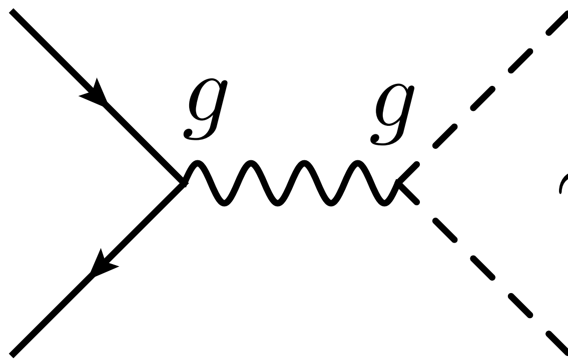


is this a good result?

BSM Perspective:

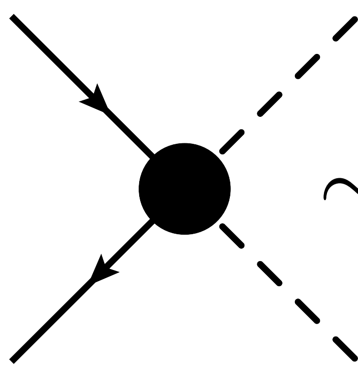
What are we after?

SM:



$$\sim g^2$$

Fully composite BSM:



$$\sim g_{NP}^2 \frac{E^2}{\Lambda^2} \gtrsim g^2$$

<<1

New Physics coupling can be >>1

BSM Perspective:

What are we after?

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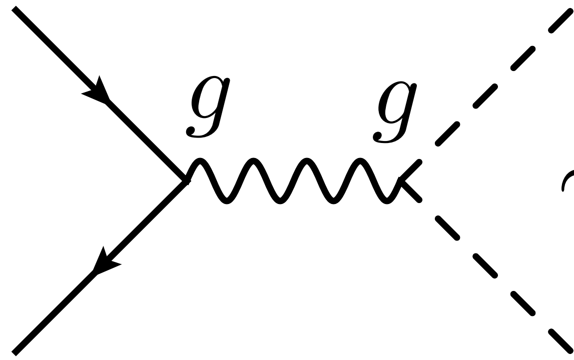

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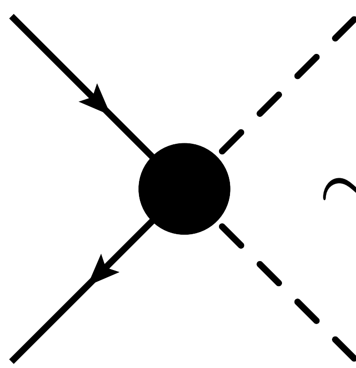

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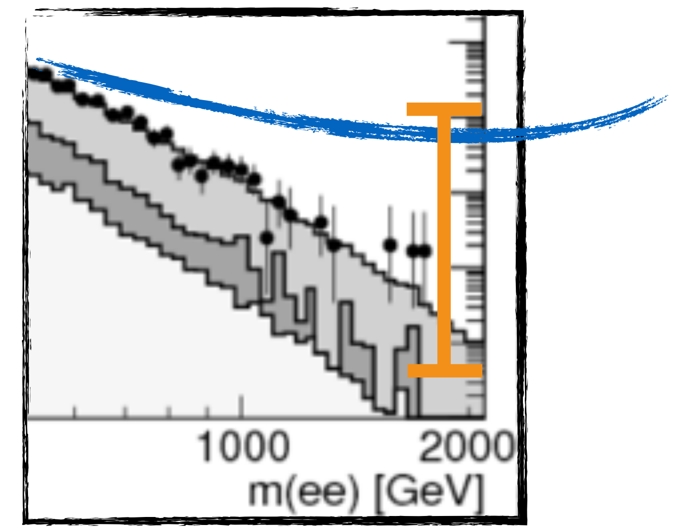

Testable also with inaccurate measurements

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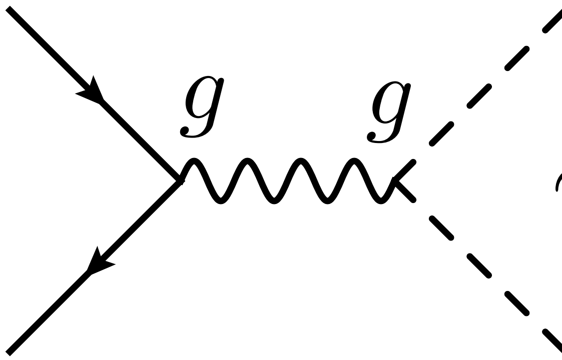

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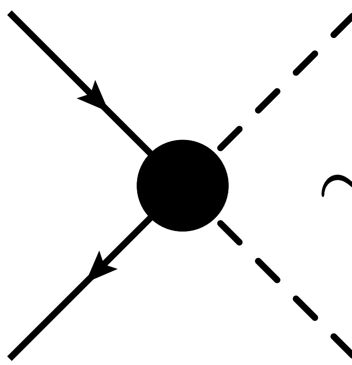

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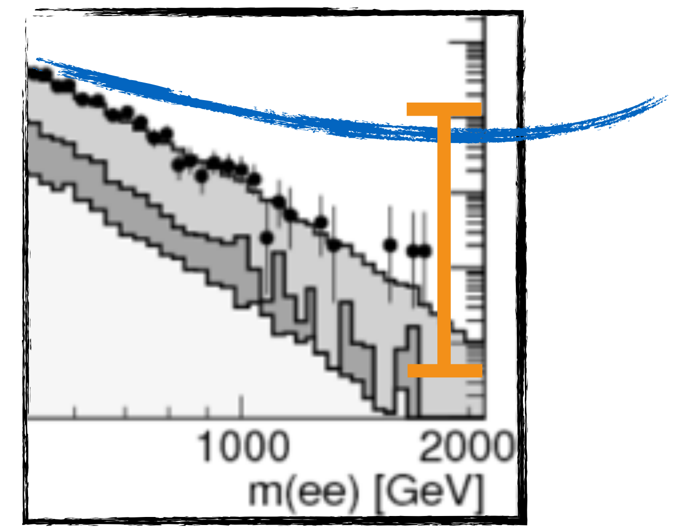
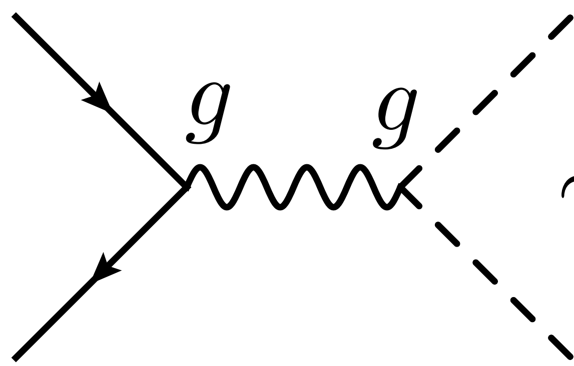


- Testable also with inaccurate measurements
- Not very interesting (composite light quarks well constrained in dijets)

BSM Perspective:

What are we after?

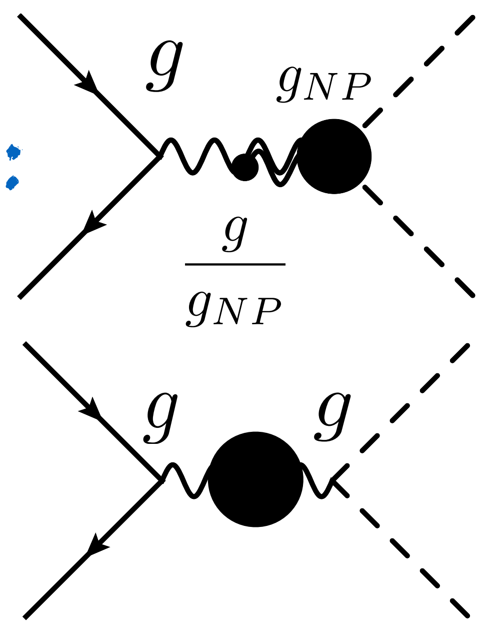
SM:



$\sim g^2$

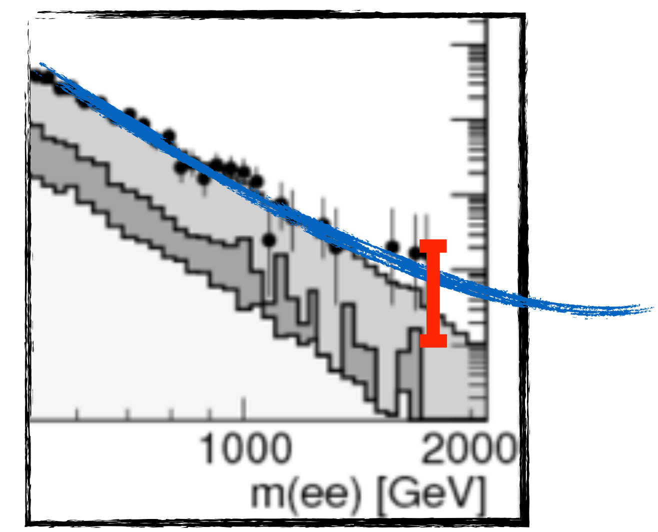
Composite Higgs:

Universal NP:



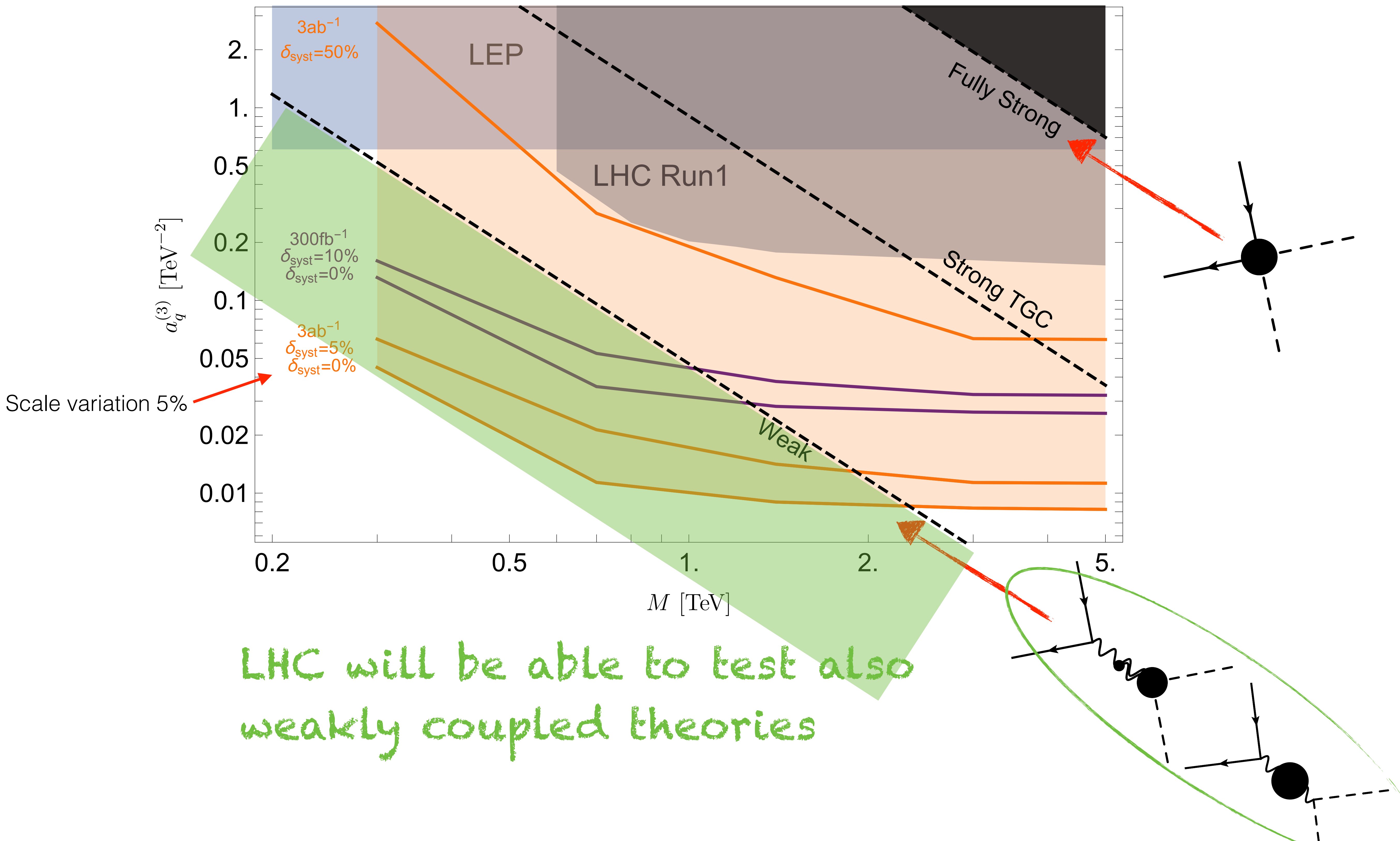
<<1

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



- Very interesting
- To test it we need accurate measurements $\frac{\delta\sigma}{\sigma_{SM}} \ll 1$

Results - NLO - LHC



LHC will be able to test also weakly coupled theories

Transverse dibosons

...are easy to study since dominate the x-sec...

Transverse dibosons

…are easy to study since dominate the x-sec…

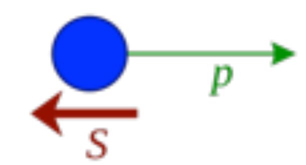
or not?

Challenge: 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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Azatov,Contino,Machado,FR'16

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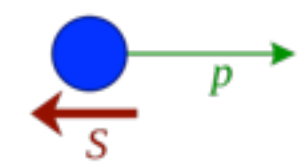
For $E \gg m_W$ states have well defined helicity 

Amplitudes for 2→2 with different total h dont interfere

Theorem:

Any BSM dim-6 operator

A_4	$\lvert h(A_4^{SM})\rvert$	$\lvert h(A_4^{BSM})\rvert$
$VVVV$	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

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

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:

interference vanishes

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

-

Non-Interference?

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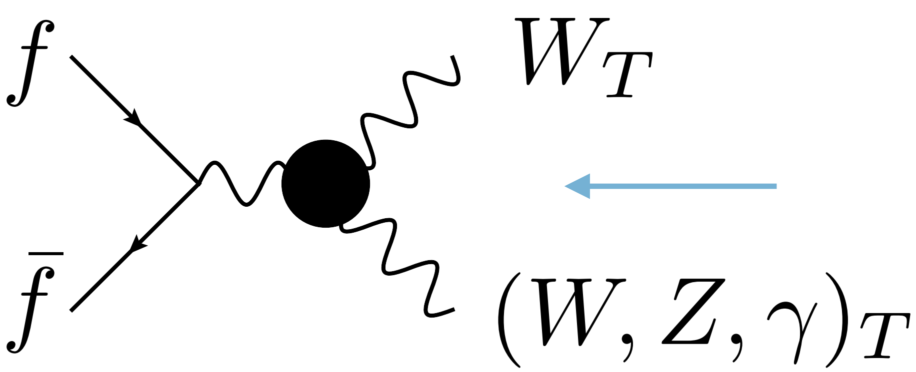
The leading effects BSM are $O\left(\frac{1}{\Lambda^4}\right)$:

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

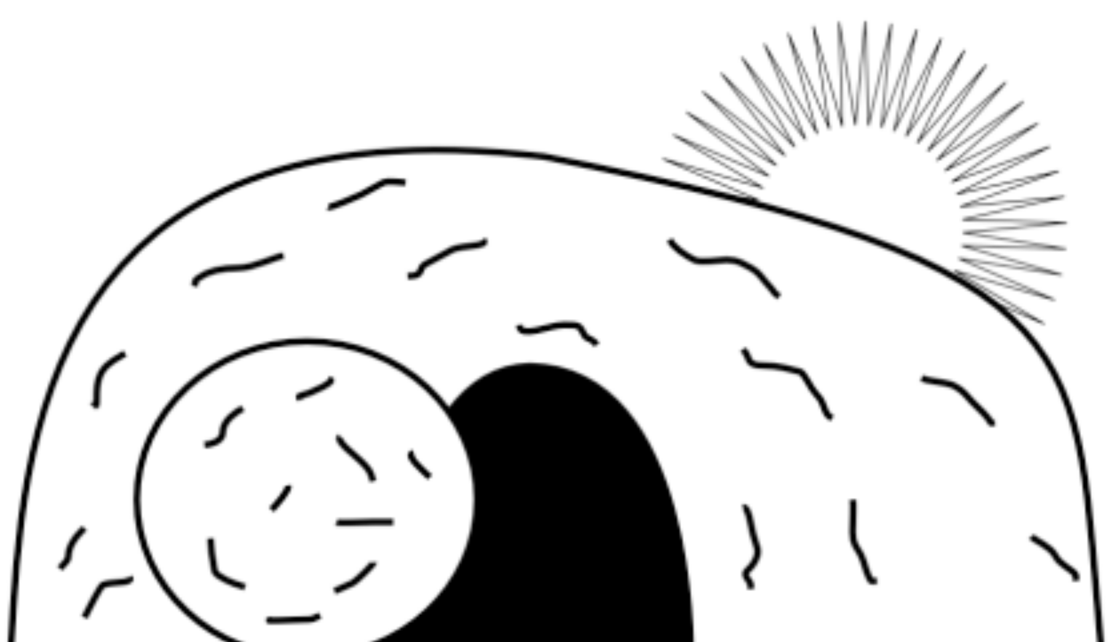
- Small effects, even smaller!
- Interference necessary in a precision program

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



3. NLO

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

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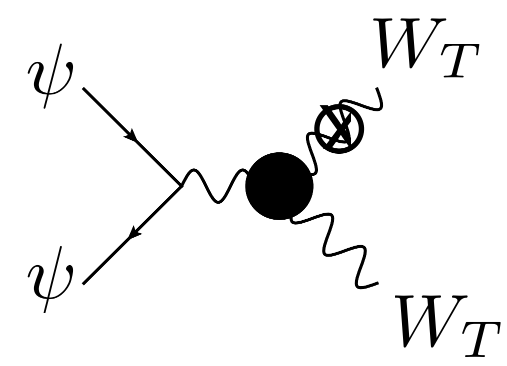
- EW finite mass effects $\sim \dfrac{m_W^2}{E^2}$



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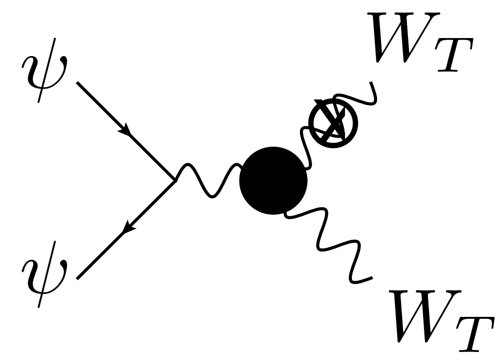
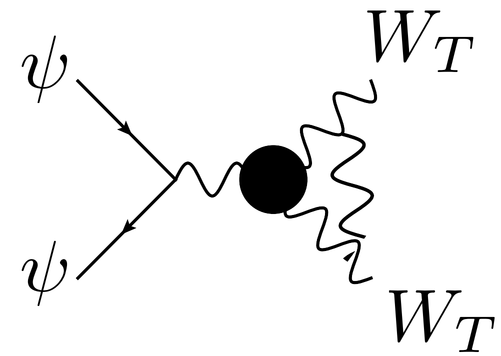


(no soft-limit enhancement, at high-energy)

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



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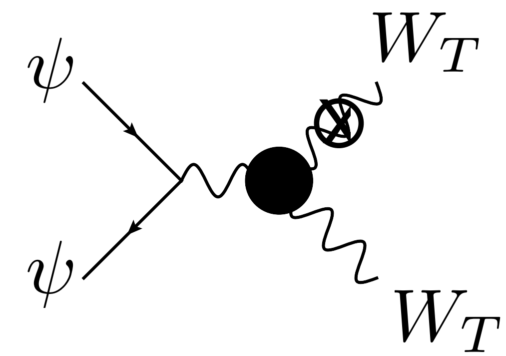

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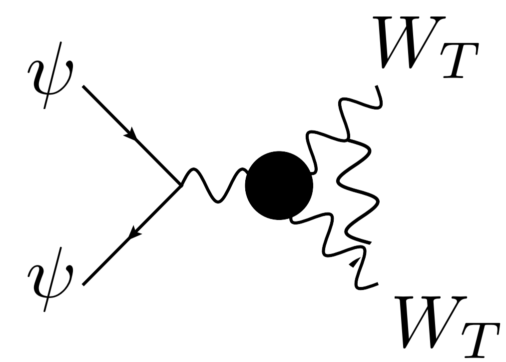

Only signal suppressed

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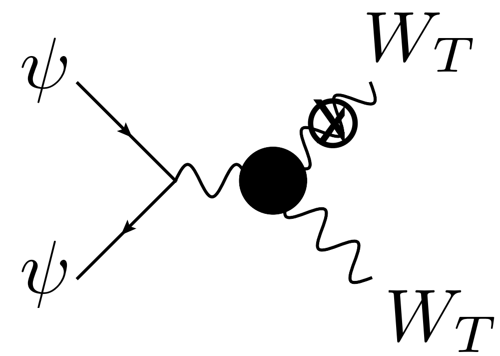

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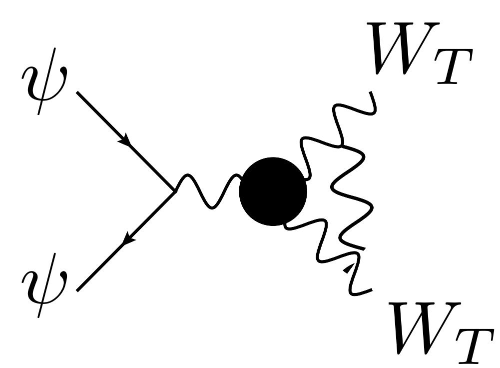
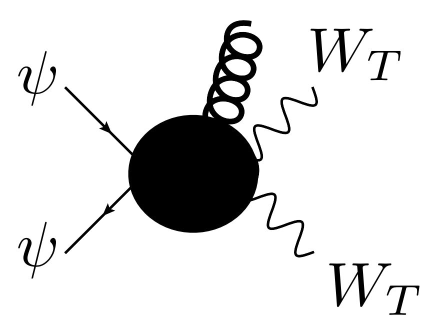


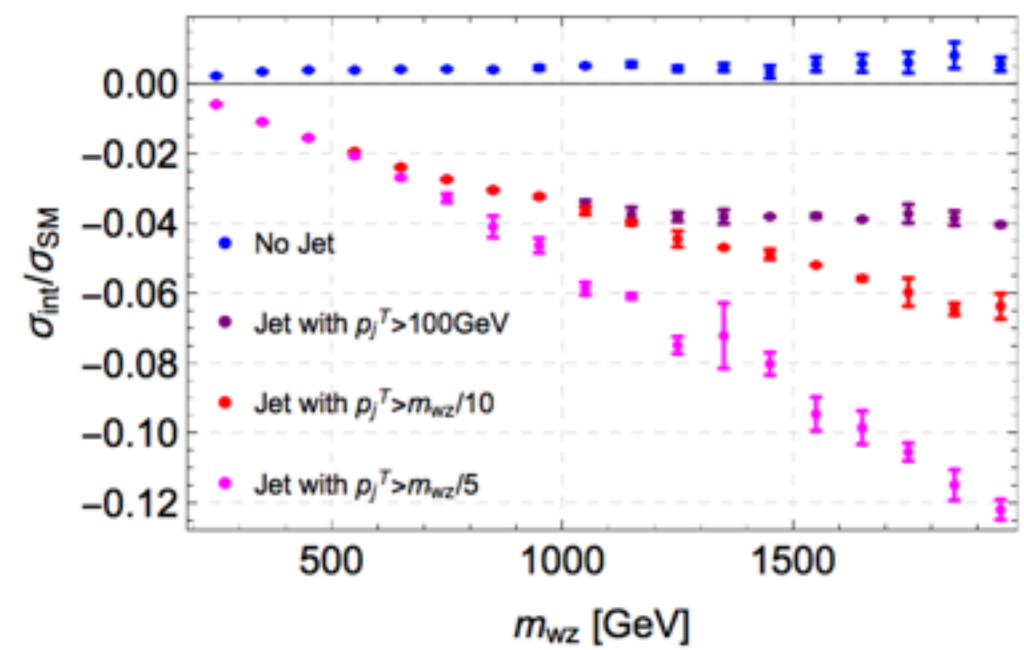
Only signal suppressed

- 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

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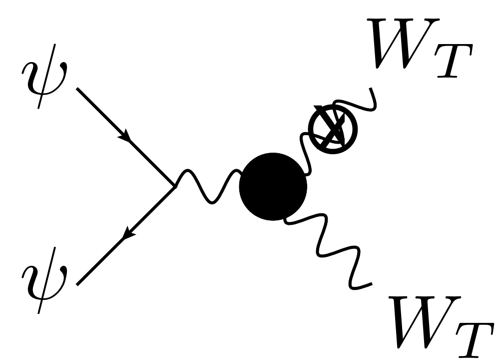

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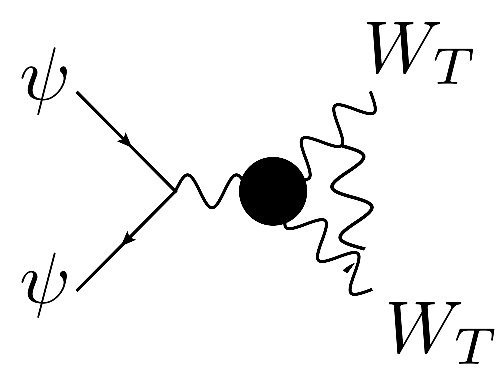

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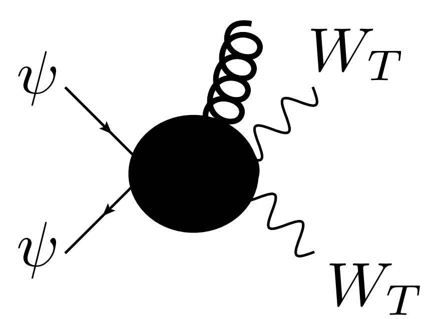
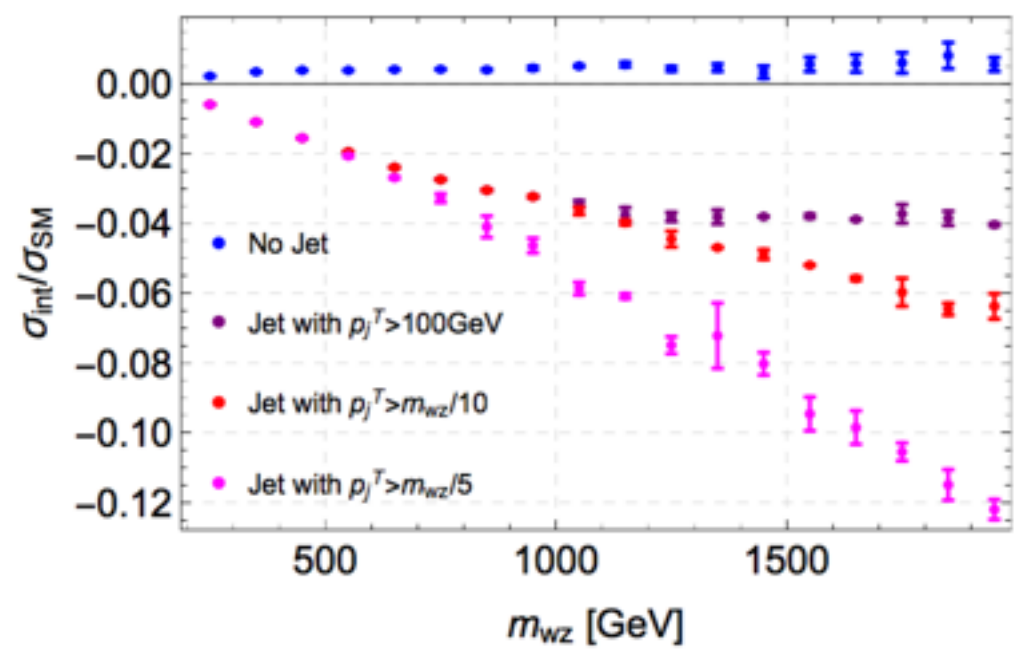
- Hard radiation 2->3

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



for gluons see Dixon,Shadmi'93;

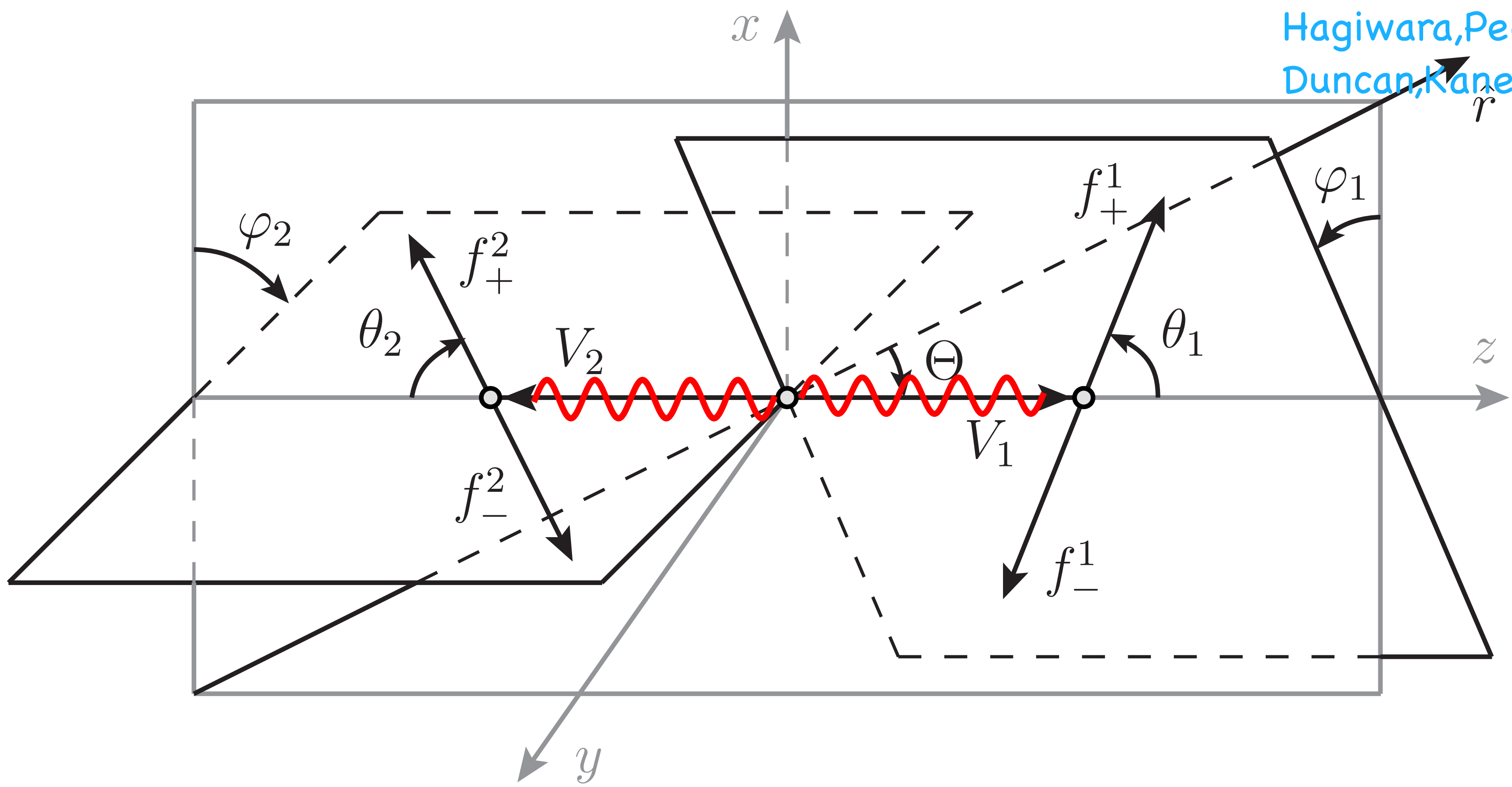
...but small statistics for EW processes!



Azatov,Elias-Miro,Reyimuaji,Venturini'17

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

Differential measurements WW, WZ

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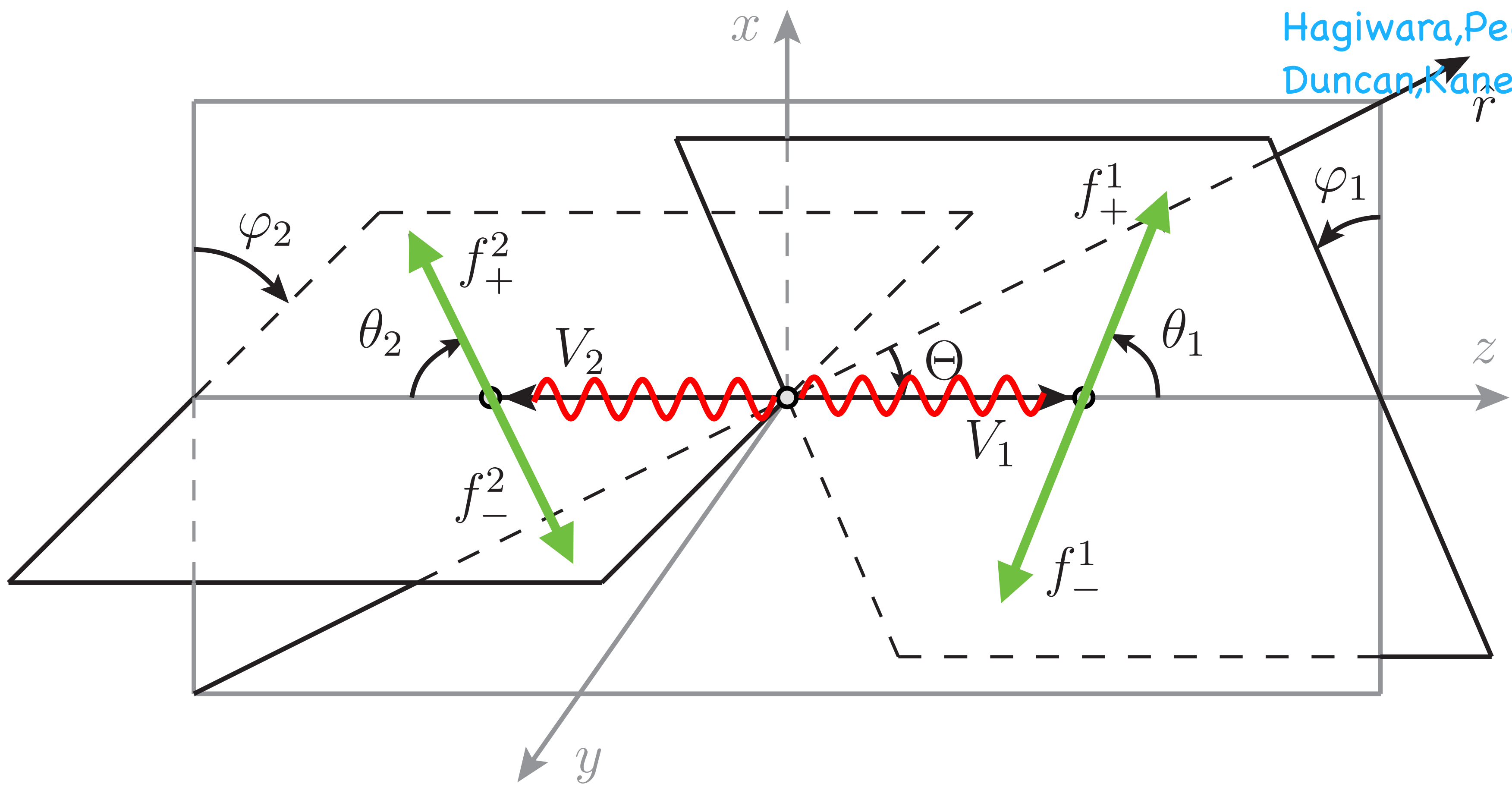


$V_{1,2}$: Helicity $\pm\mp/\pm\pm$ in SM/BSM

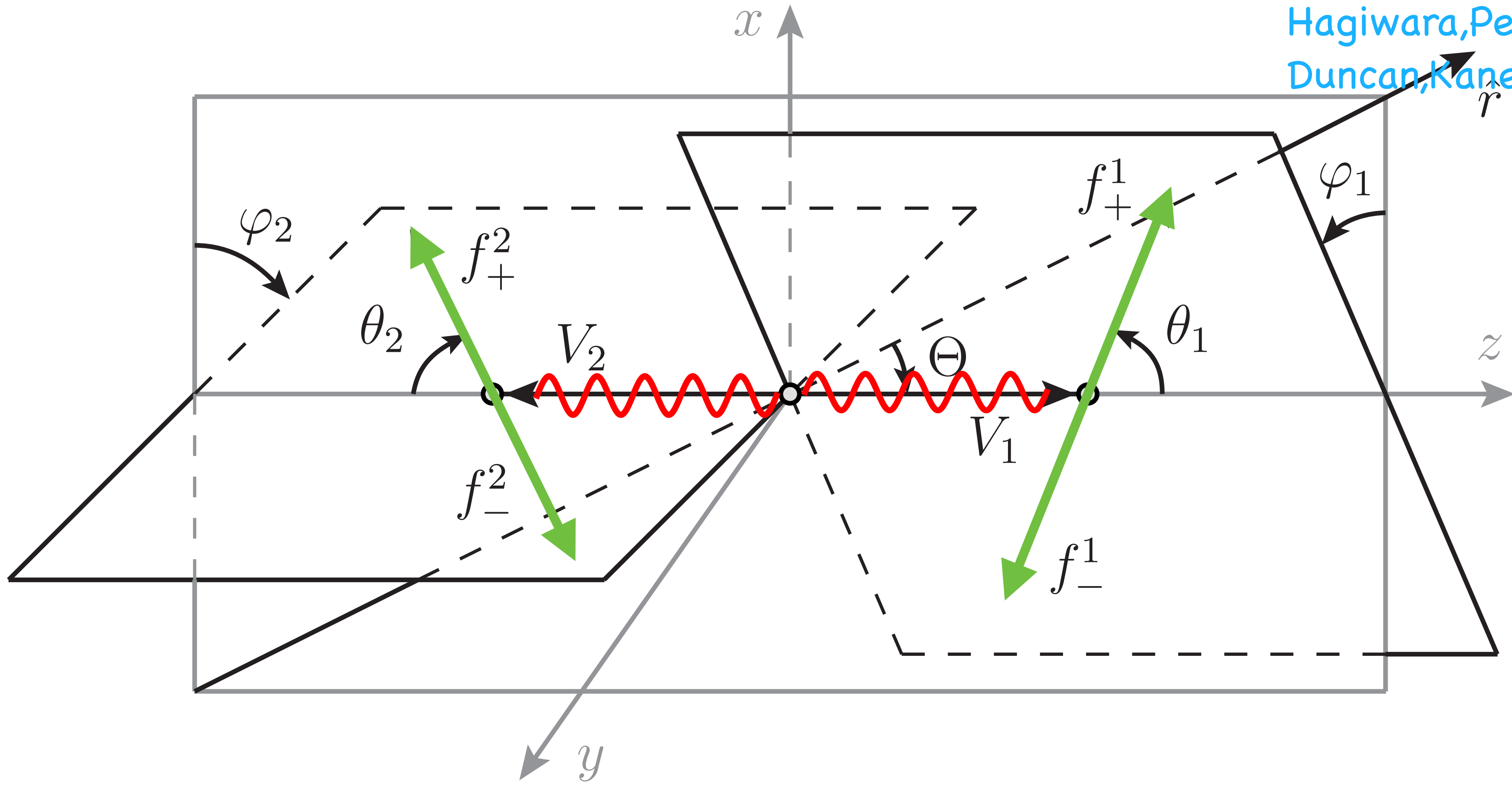
- Quantum mechanically different, no interference

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

- QM same, interference possible

Differential measurements WW, WZ

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



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

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

$(+1,-1)$ $\quad$ $(+1,+1)$ $\quad$ (φ_1, φ_2)

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

Differential measurements WW, WZ

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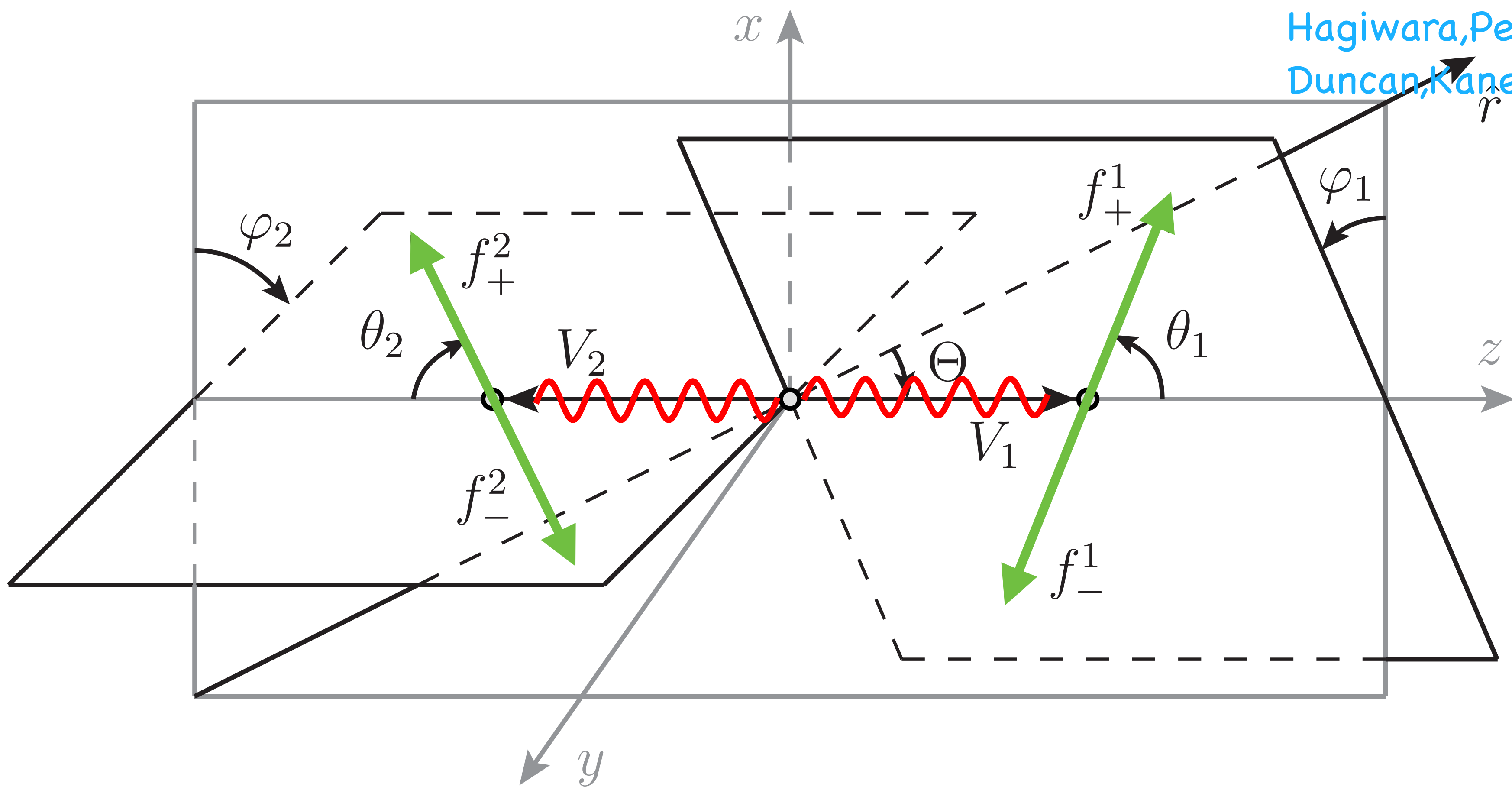


$$Int^{\mathrm{CP}} \propto \mathcal{A}_{\mathbf{h}}^{\mathrm{SM}} \mathcal{A}_{\mathbf{h}'}^{\mathrm{BSM}+} \cos\left[\boldsymbol{\Delta}\mathbf{h}\cdot\boldsymbol{\varphi}\right]$$

$(h_1 - h_1', h_2 - h_2')$ (for $\boldsymbol{\Delta}\mathbf{h}$); $(+1,-1)$ (for $\mathbf{h}$); $(+1,+1)$ (for $\mathbf{h}'$); (φ_1, φ_2) (for $\boldsymbol{\varphi}$)

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

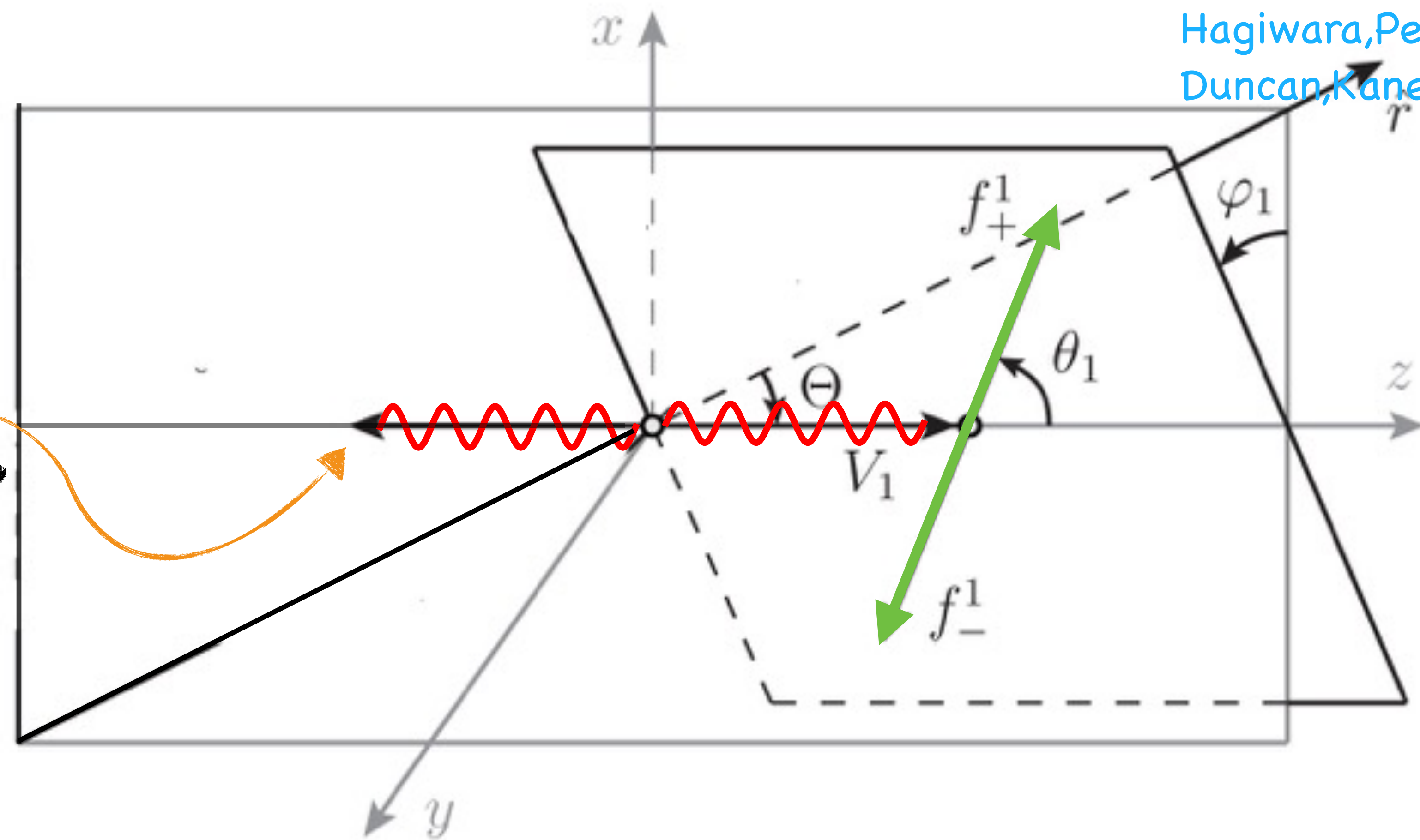
- Cancels when integrated over $\varphi \in [-\pi, \pi]$

Differential measurements Wγ

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

$W\gamma$

No (leptonic)
Branching Ratio



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

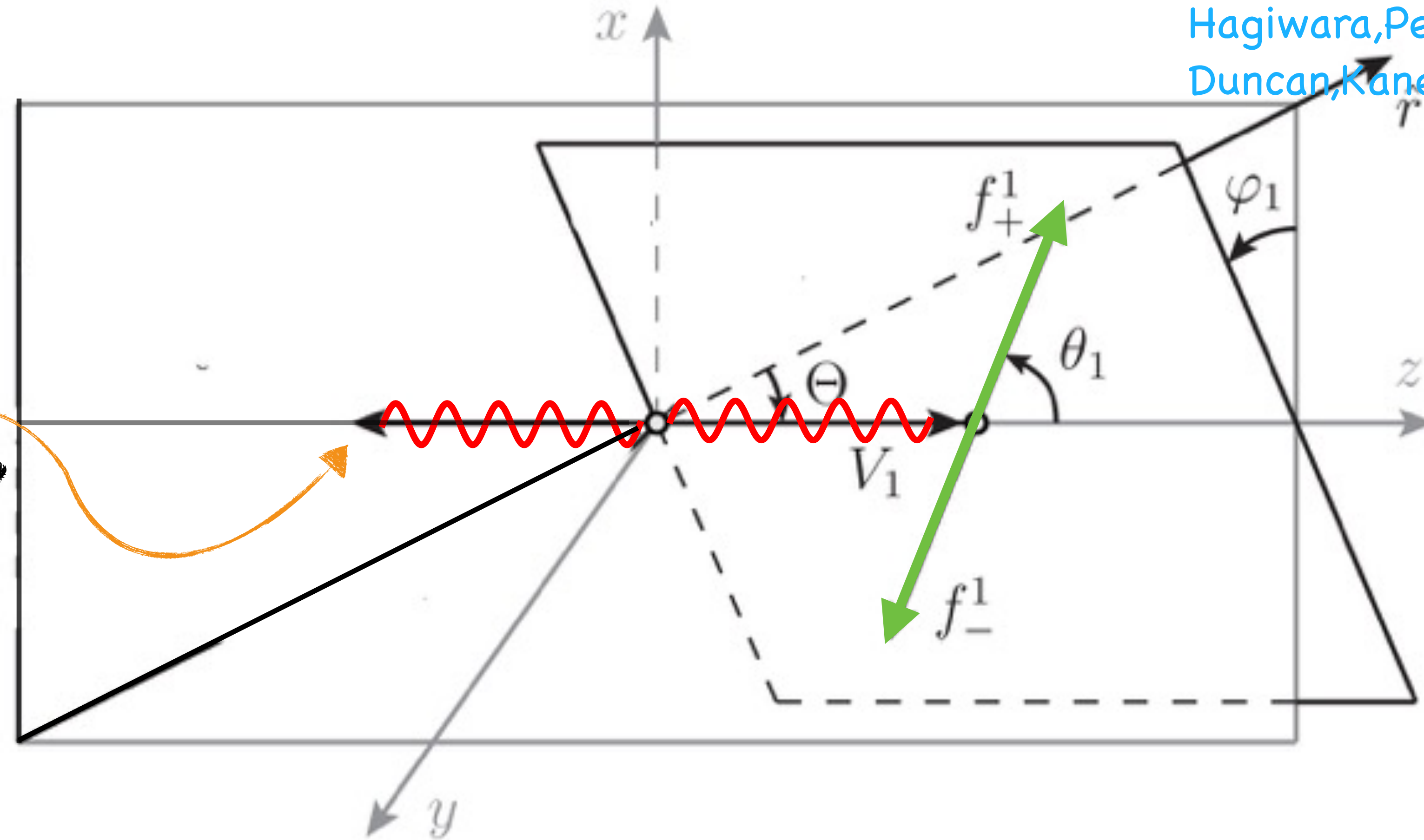
$$Int^{\not{\rm CP}} = 2ig^2 \sin^2\theta \mathcal{A}^{\rm BSM-}_{++} \left[\mathcal{A}^{\rm SM}_{-+} - \mathcal{A}^{\rm SM}_{+-}\right] \sin 2\varphi$$

Differential measurements Wγ

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

$W\gamma$

No (leptonic) Branching Ratio



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

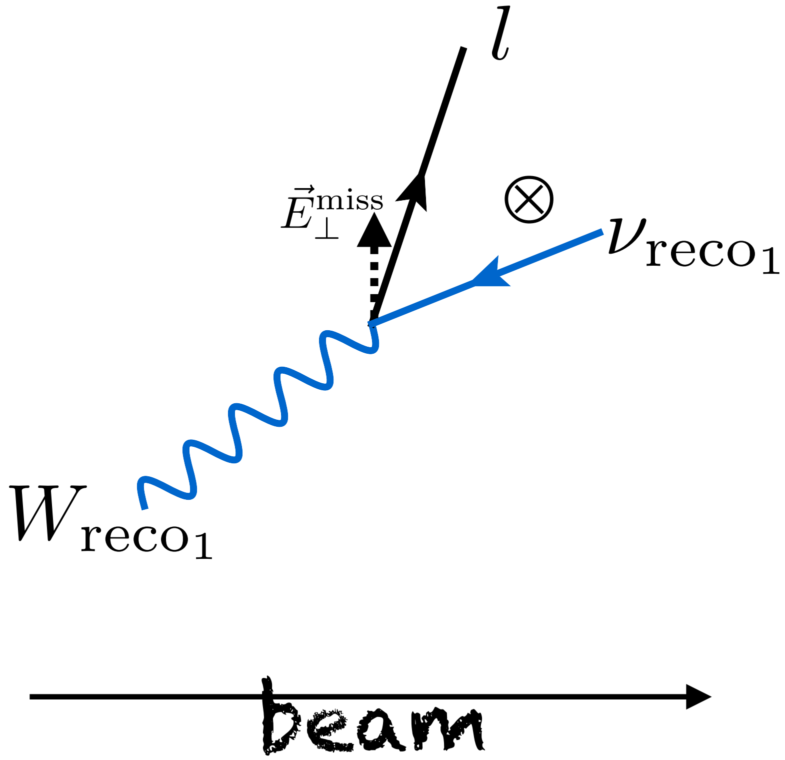
$$Int^{\not{\mathrm{C}}\mathrm{P}} = 2ig^2 \sin^2\theta \mathcal{A}_{++}^{\mathrm{BSM}-} \left[\mathcal{A}_{-+}^{\mathrm{SM}} - \mathcal{A}_{+-}^{\mathrm{SM}}\right] \sin 2\varphi$$

Differential azimuthal distributions = SM-BSM interference

Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

1)

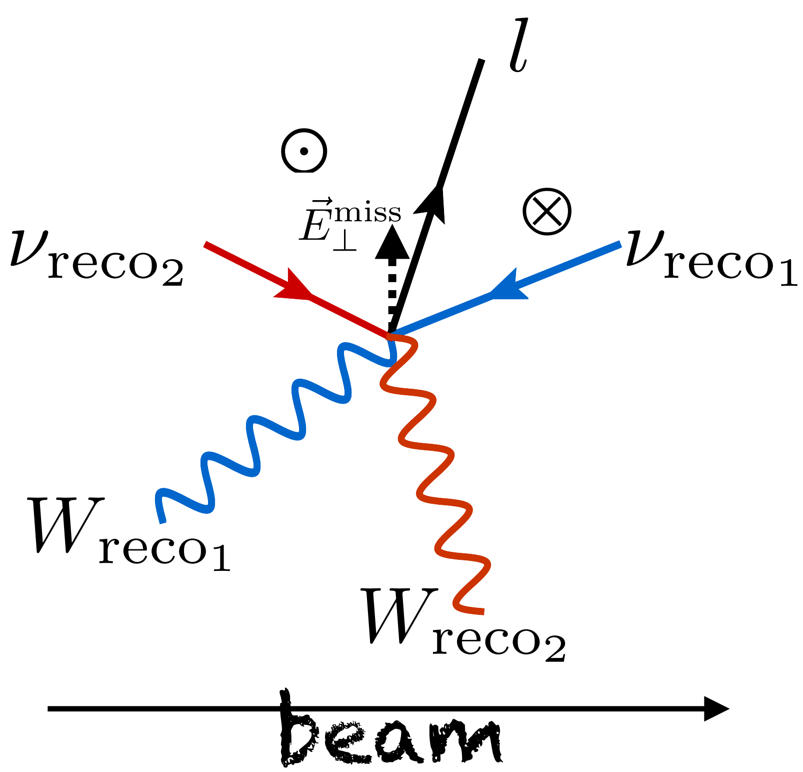


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)

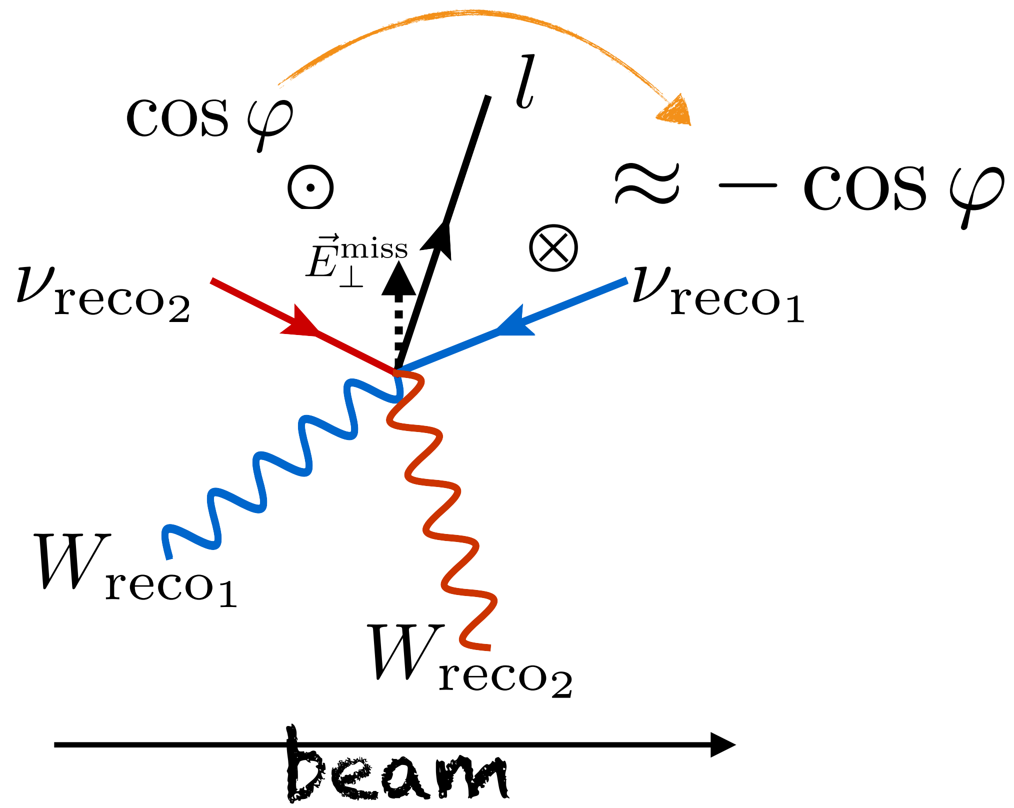


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

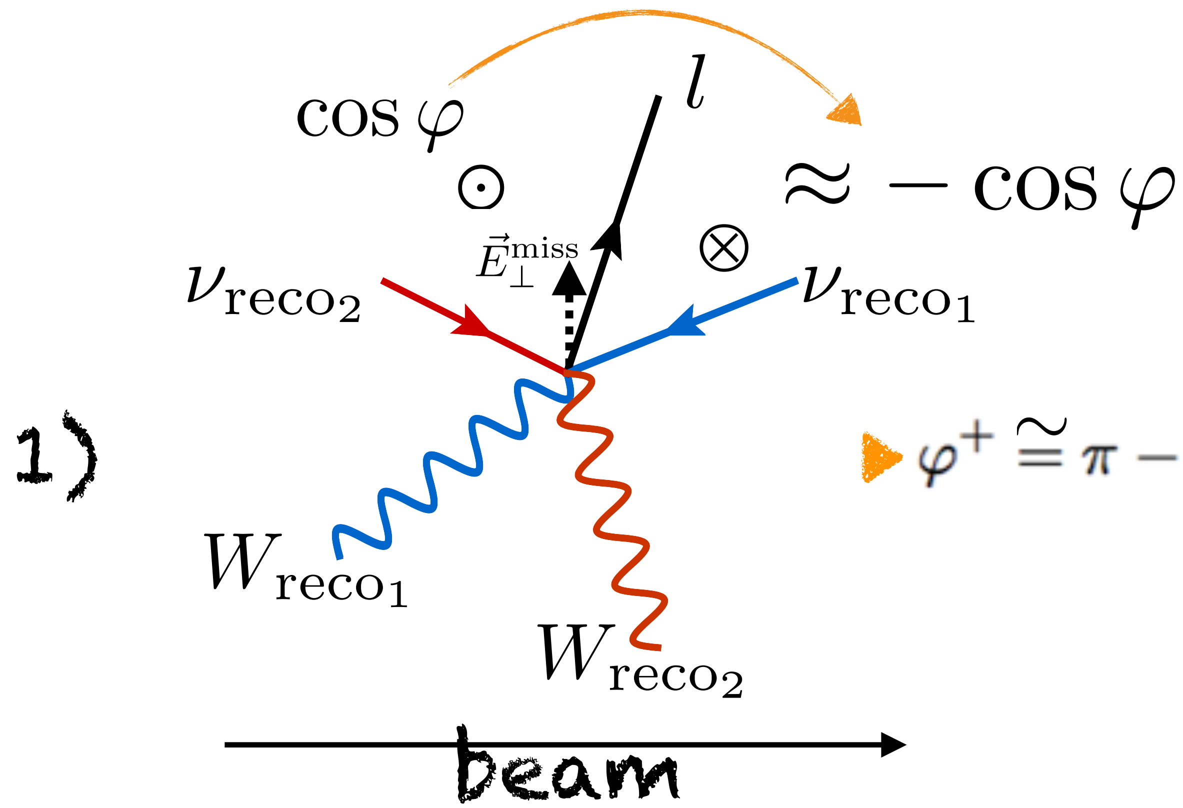
1)



Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass



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

φ_{reco}

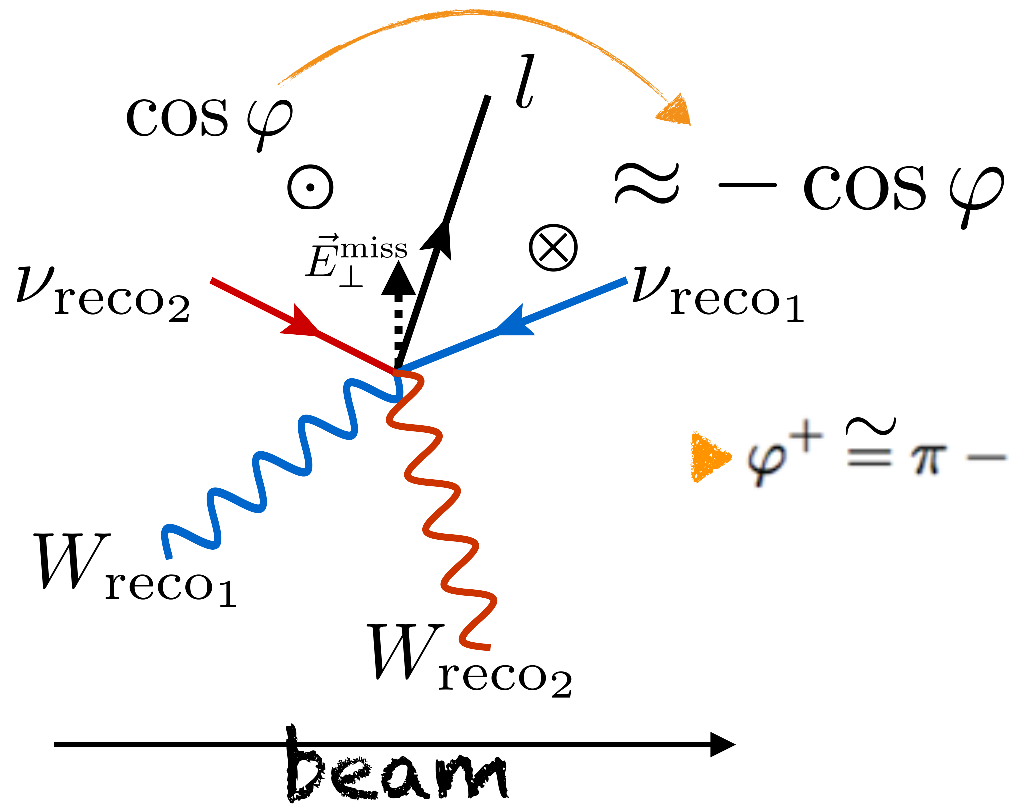
φ_{true}

Panico,FR,Wulzer'17

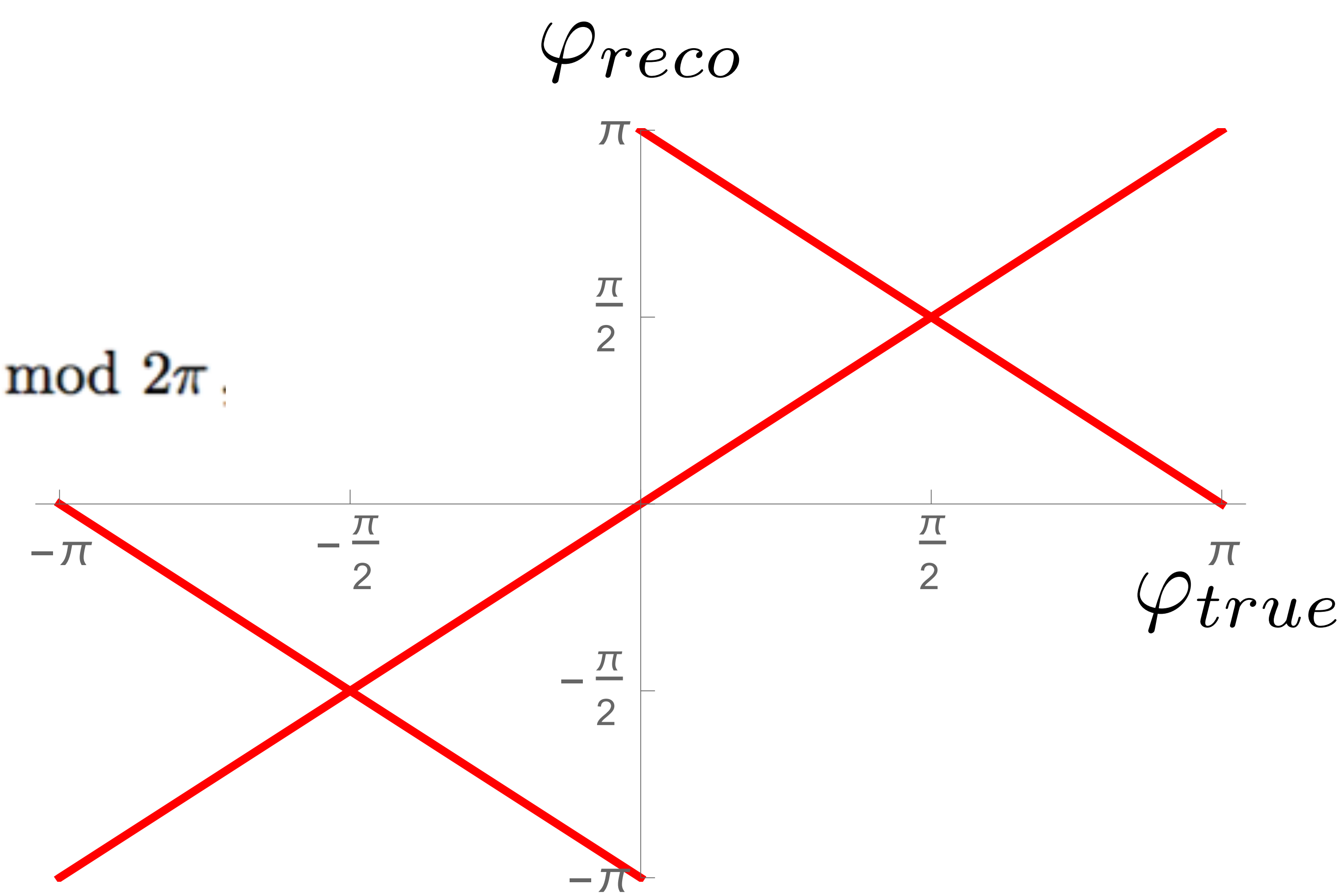
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



$\varphi^+ \cong \pi - \varphi^- \quad \mathrm{mod}\ 2\pi$

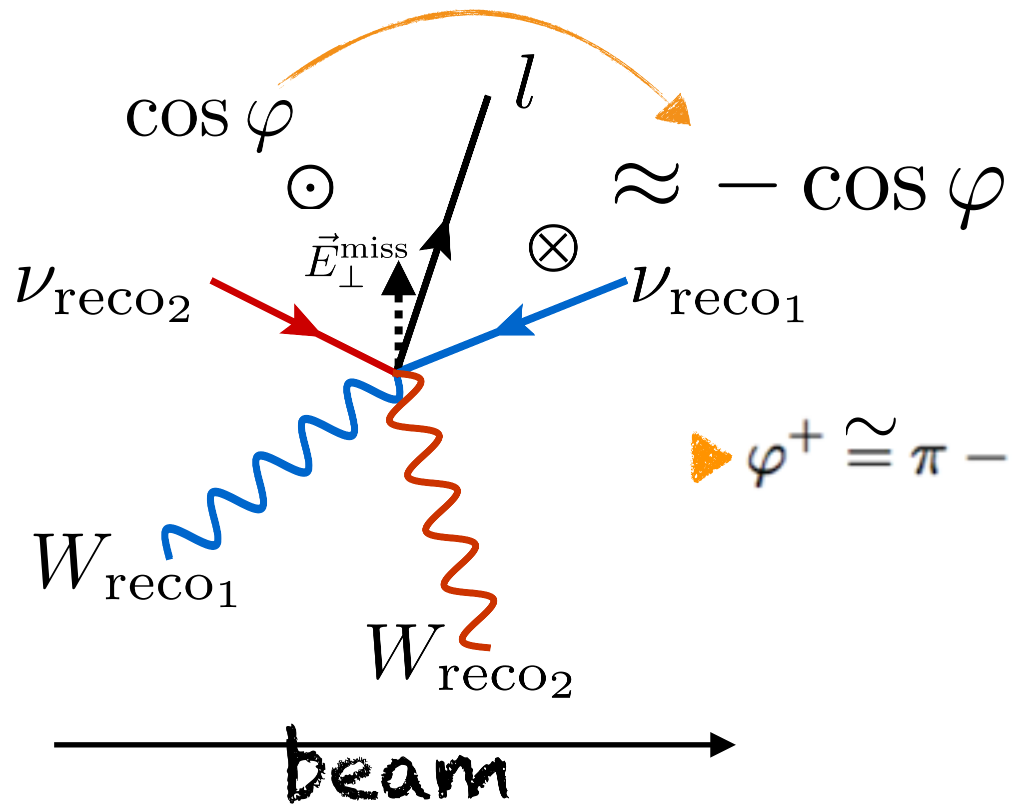


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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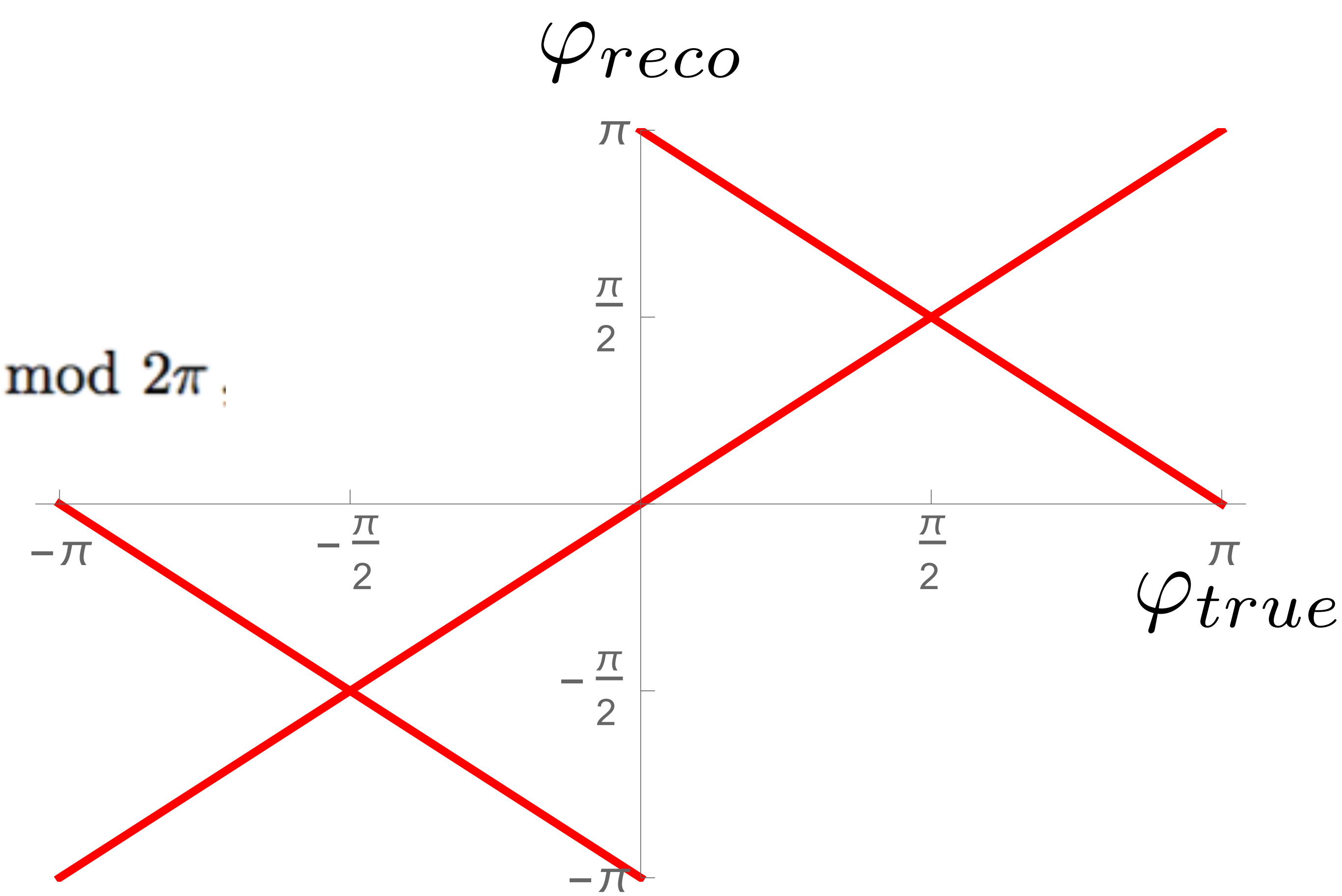


2) Some events: $m_\perp^2 > m_W^2$
(off-shell, exp.error)

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

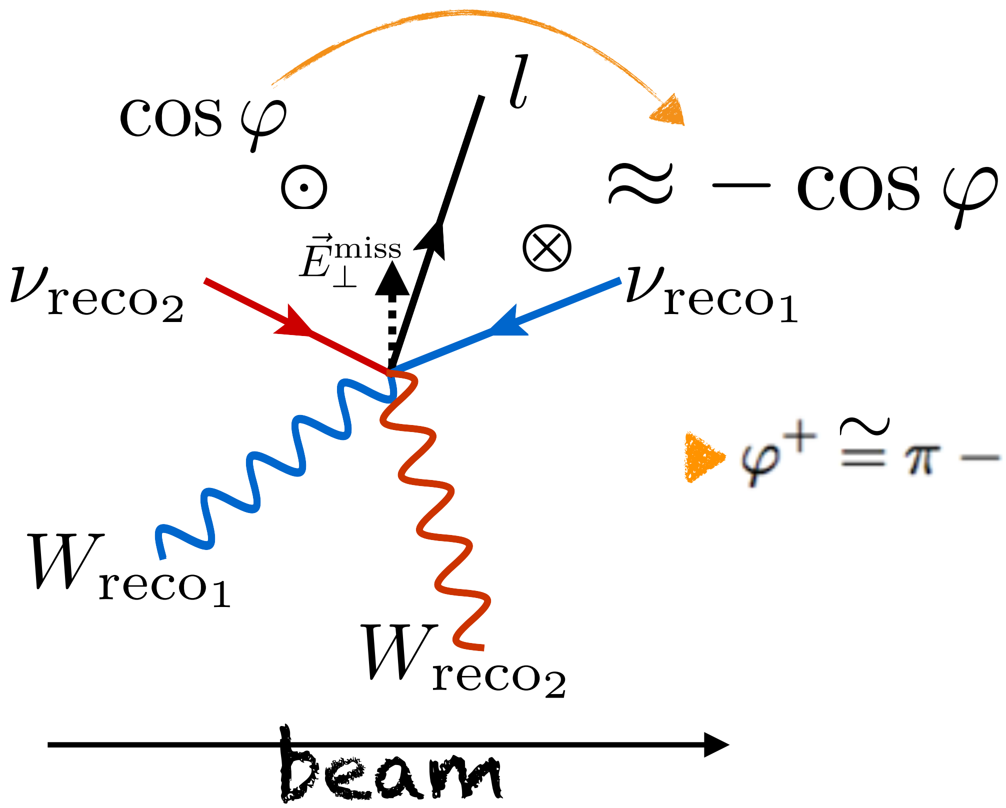
▶ $\varphi = \pi/2 \quad \text{or} \quad \varphi = -\pi/2.$

Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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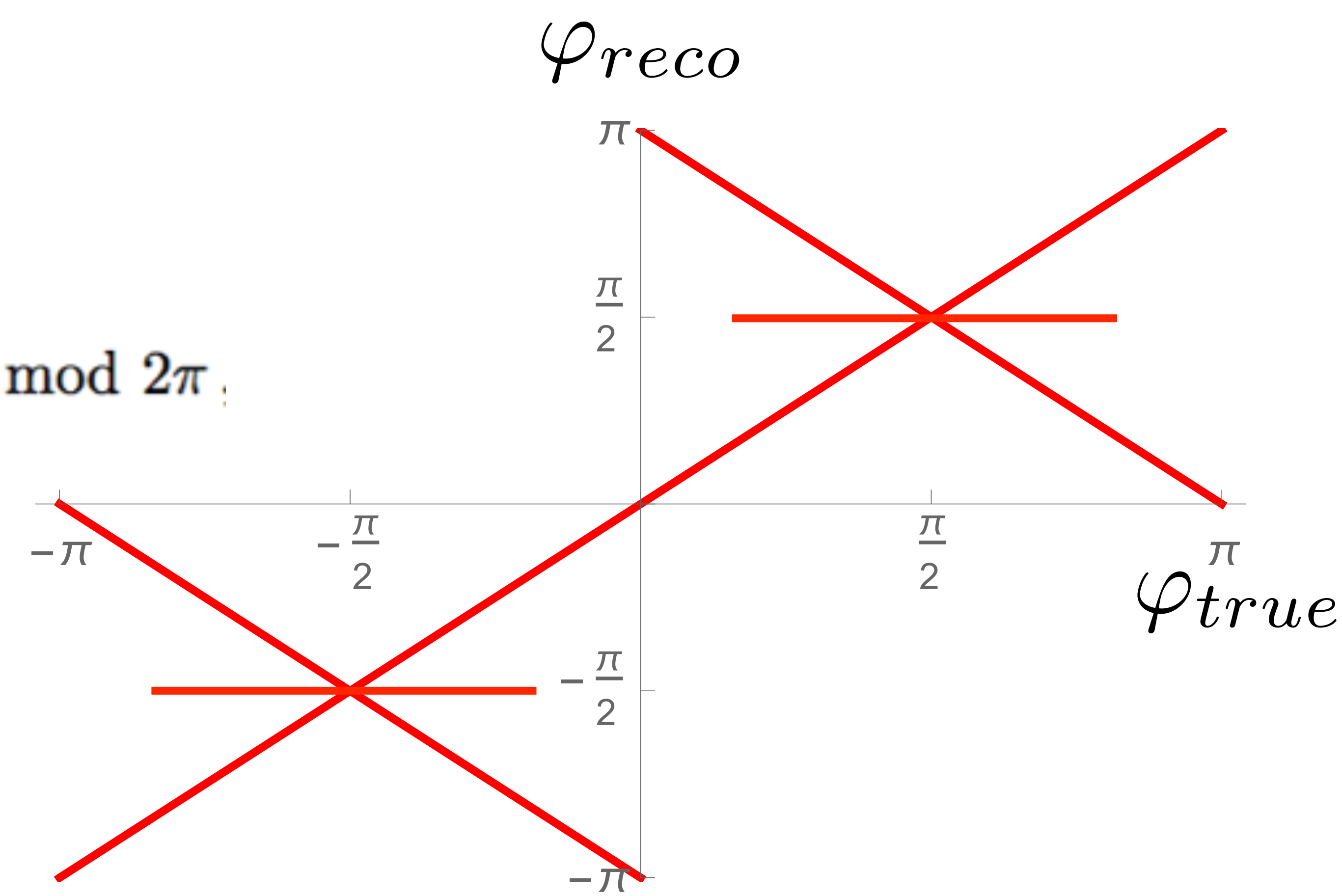

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Panico,FR,Wulzer'17

Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

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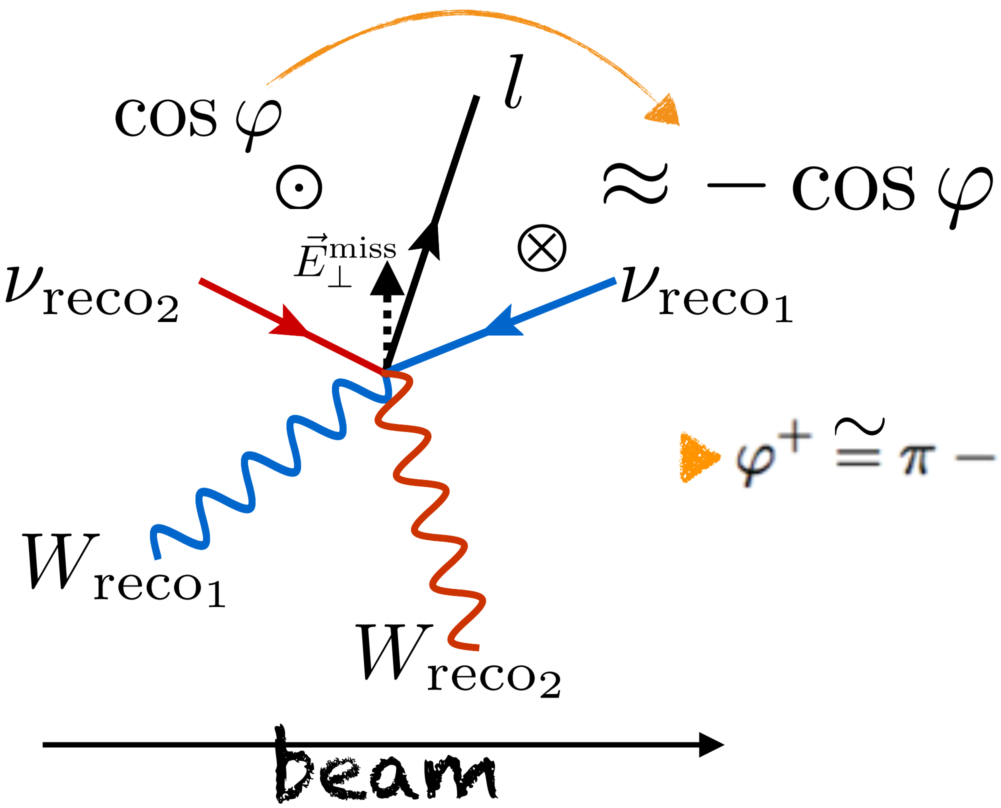

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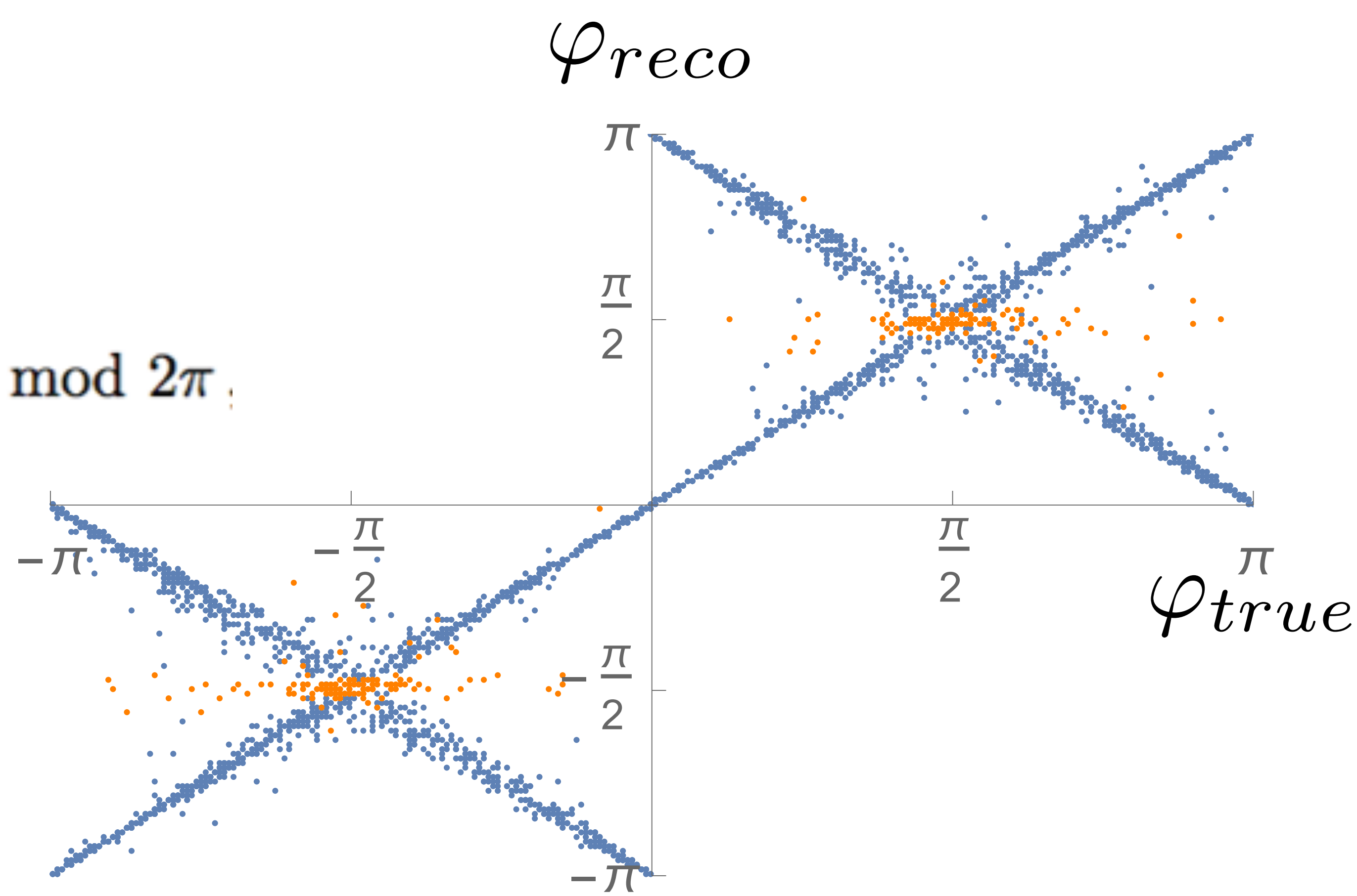

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Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

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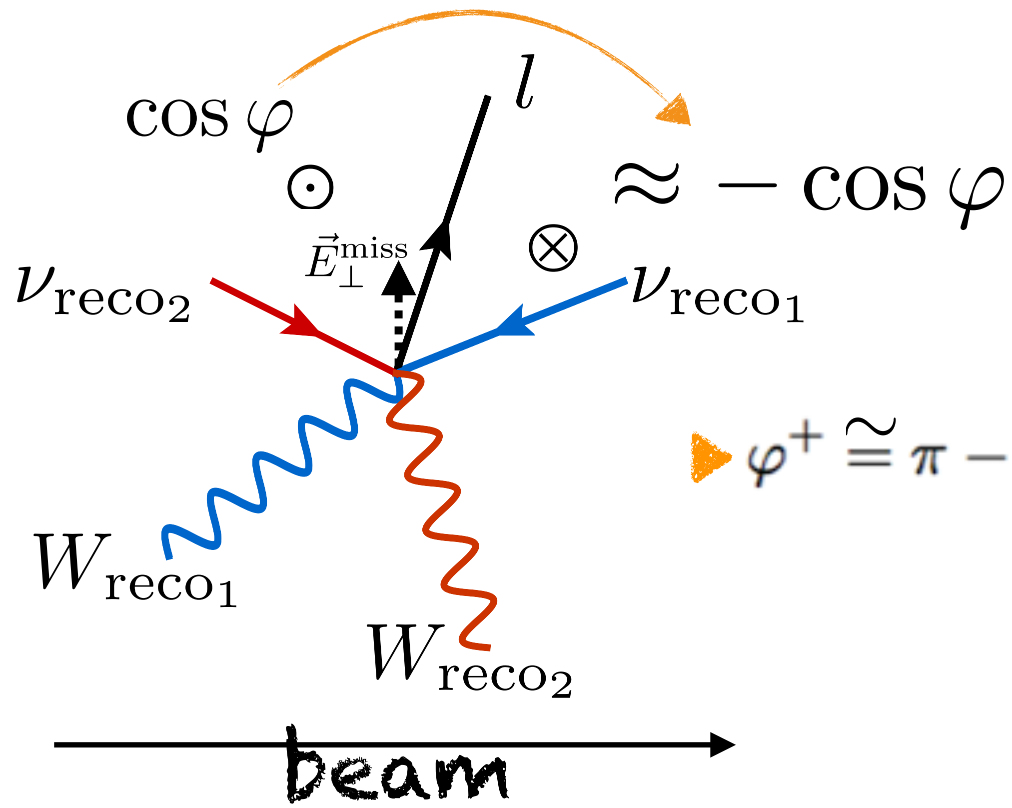

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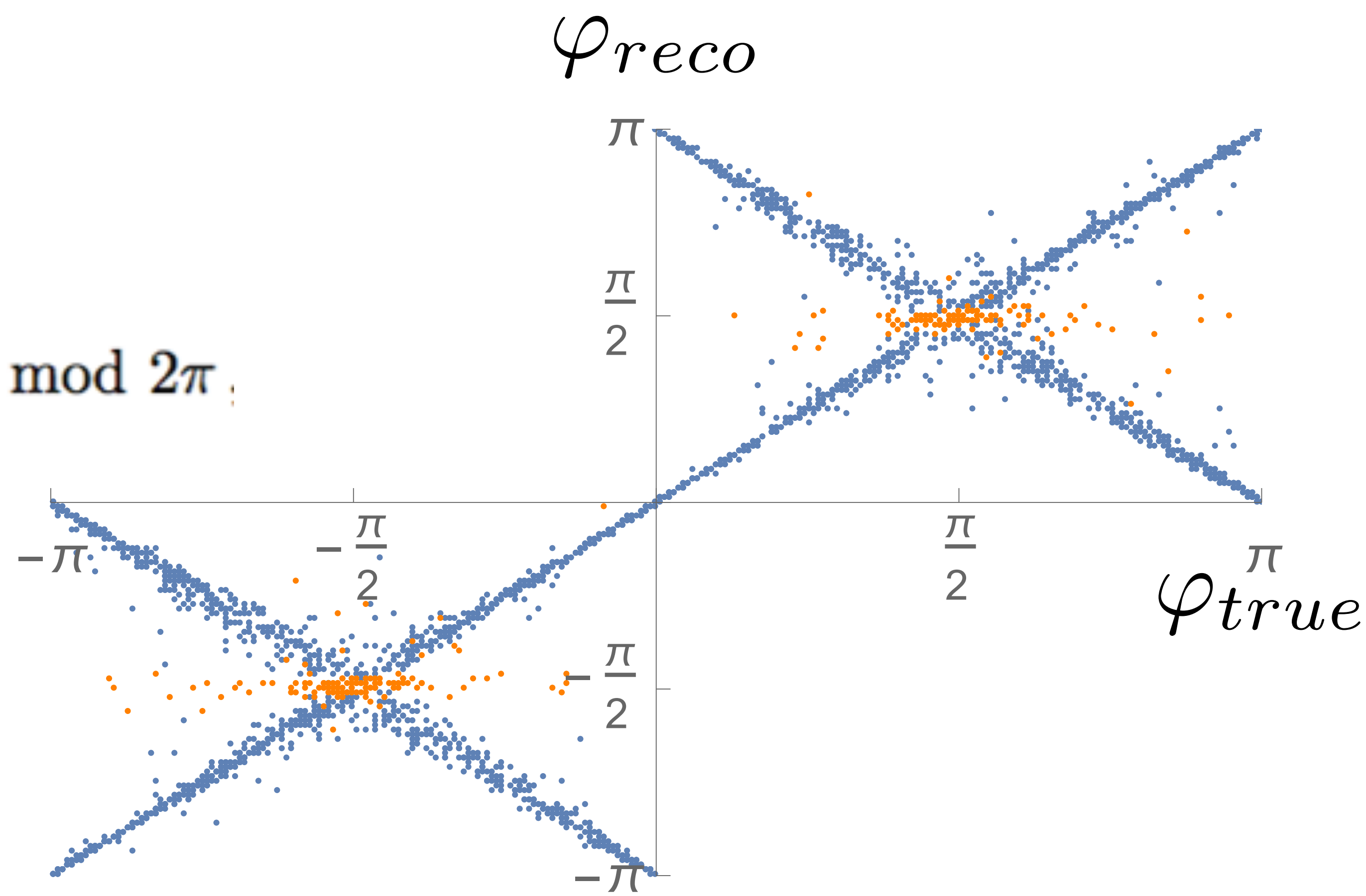


2) Some events: $m_\perp^2 > m_W^2$
(off-shell, exp.error)

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

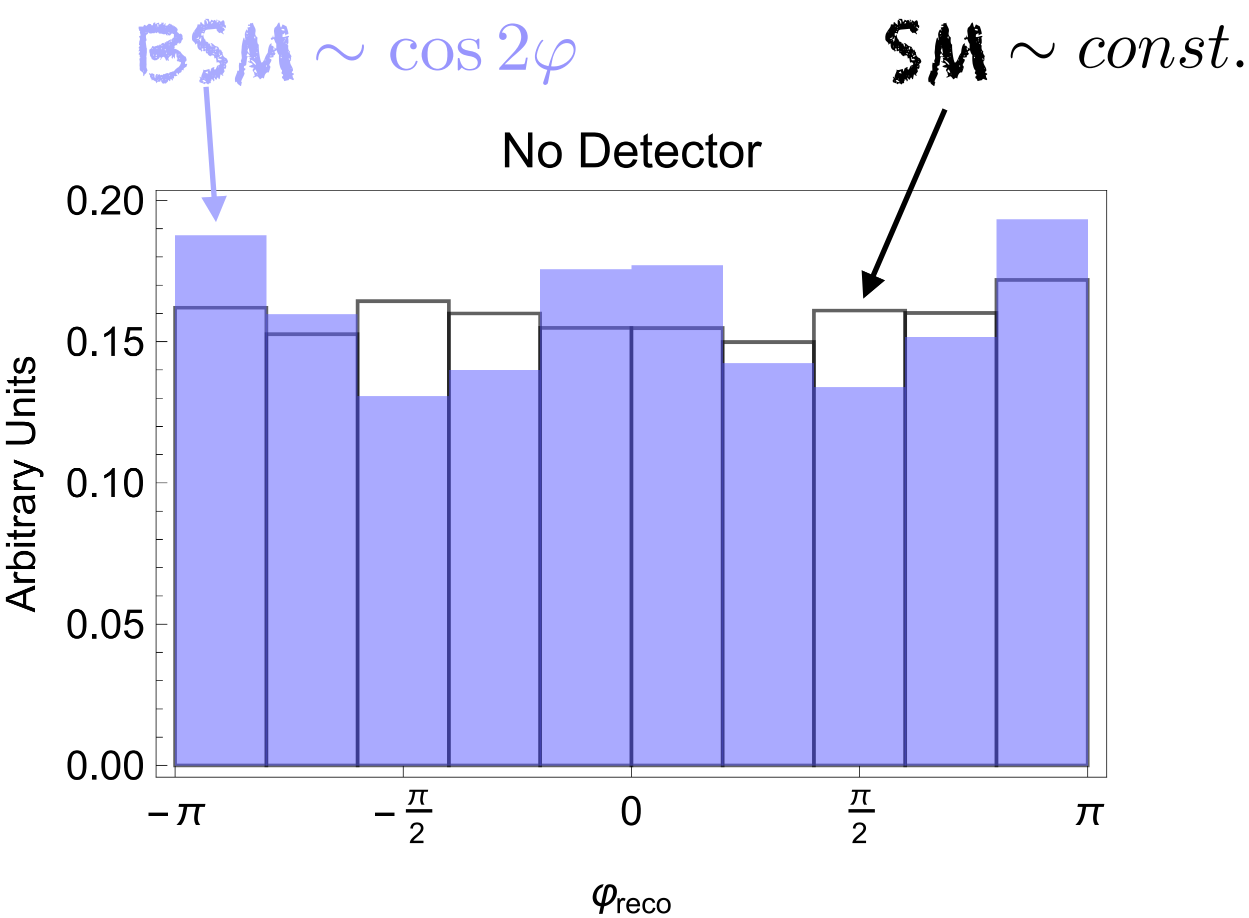
▶ $\varphi = \pi/2$ or $\varphi = -\pi/2$.

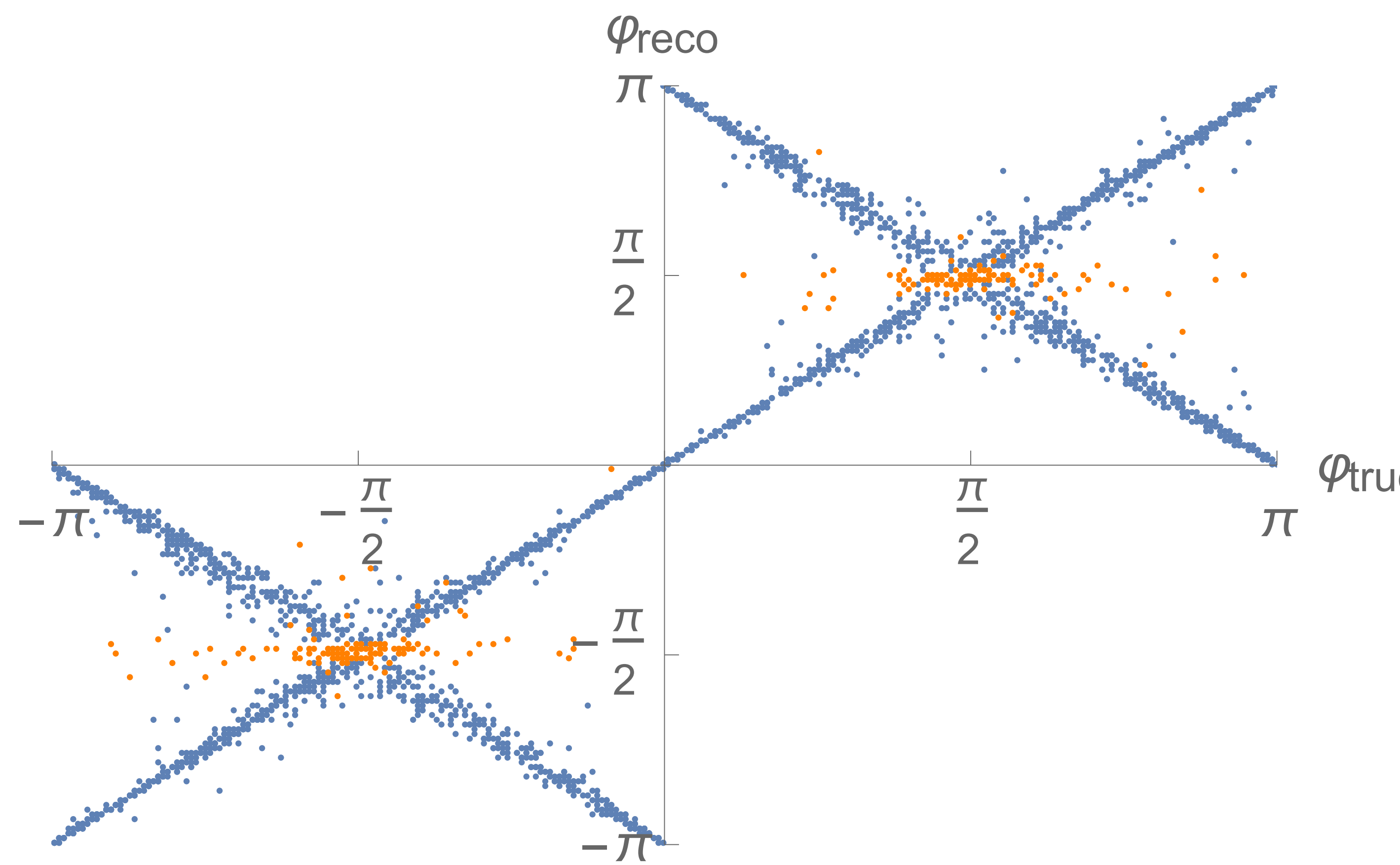
CP-odd unaccessible!

Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass



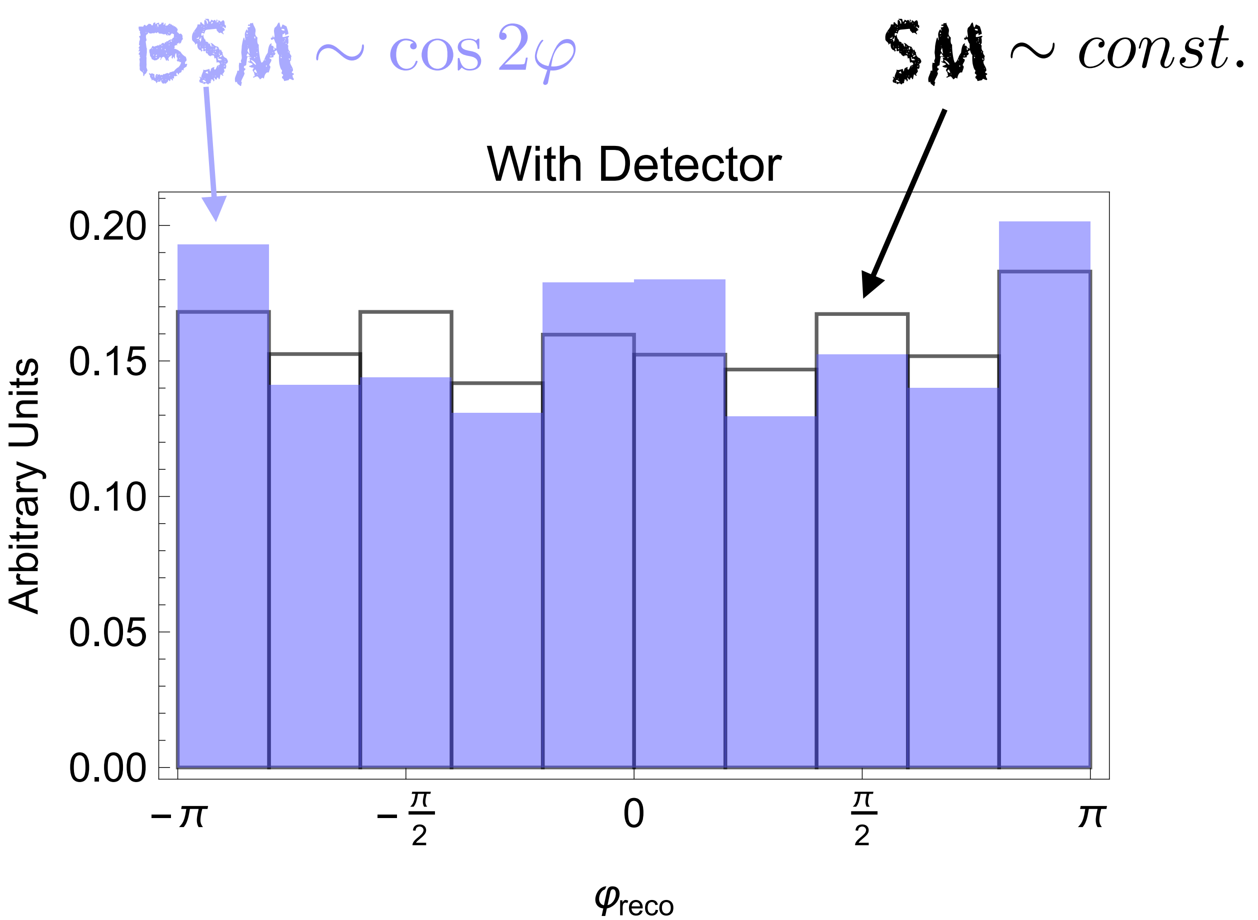


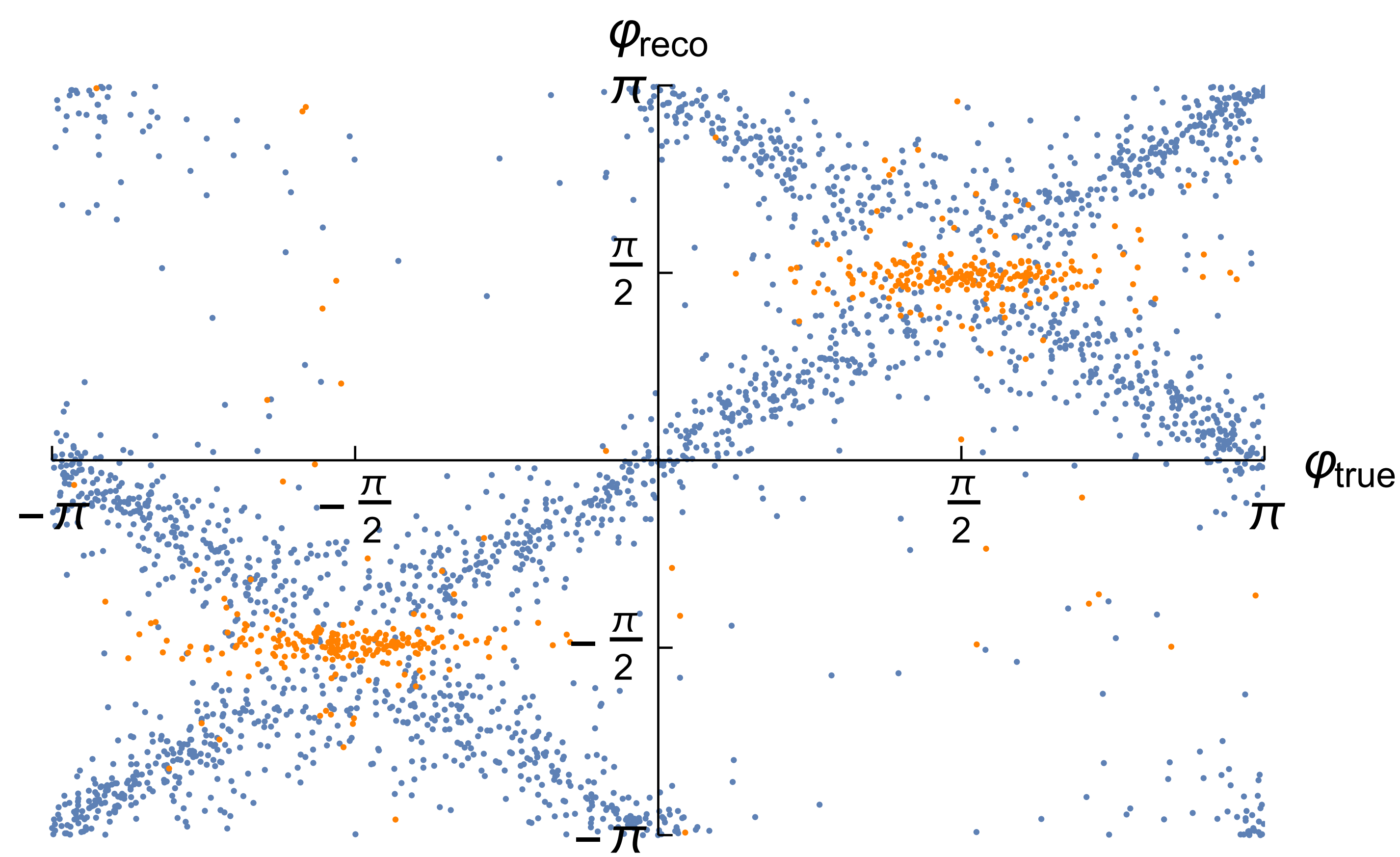
Panico,FR,Wulzer'17

Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation



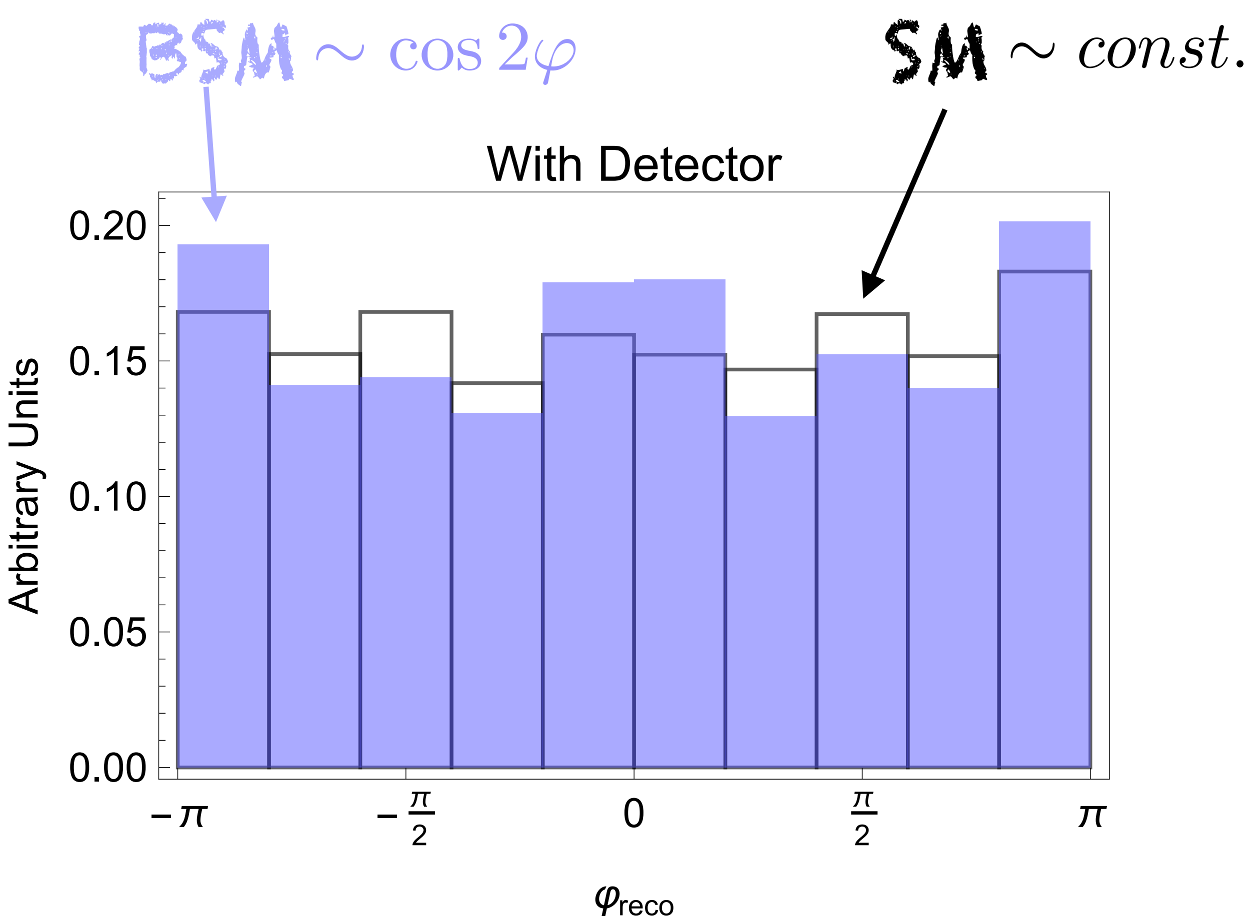


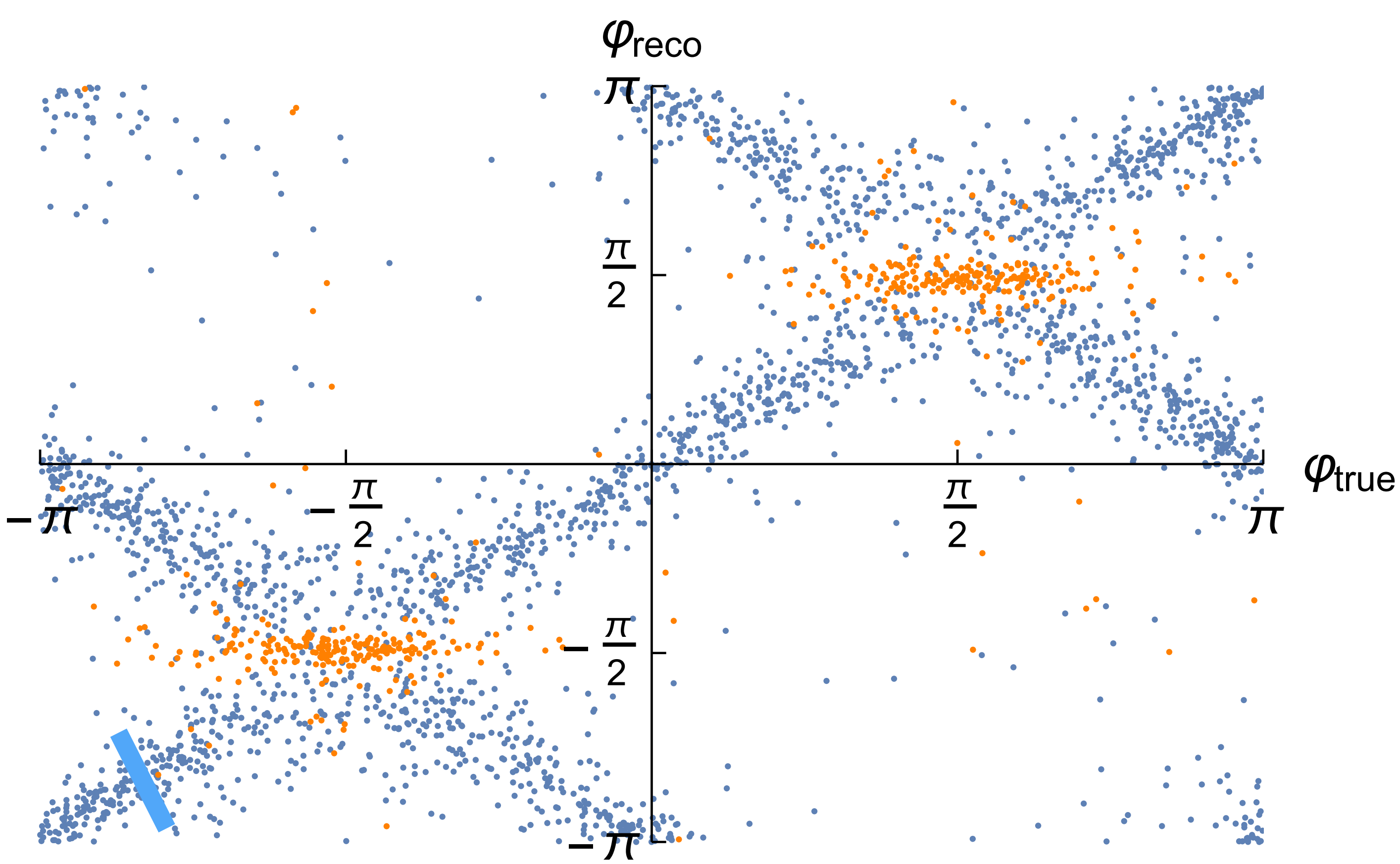
Panico,FR,Wulzer'17

Azimuthal Angle… more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation





Spread under control

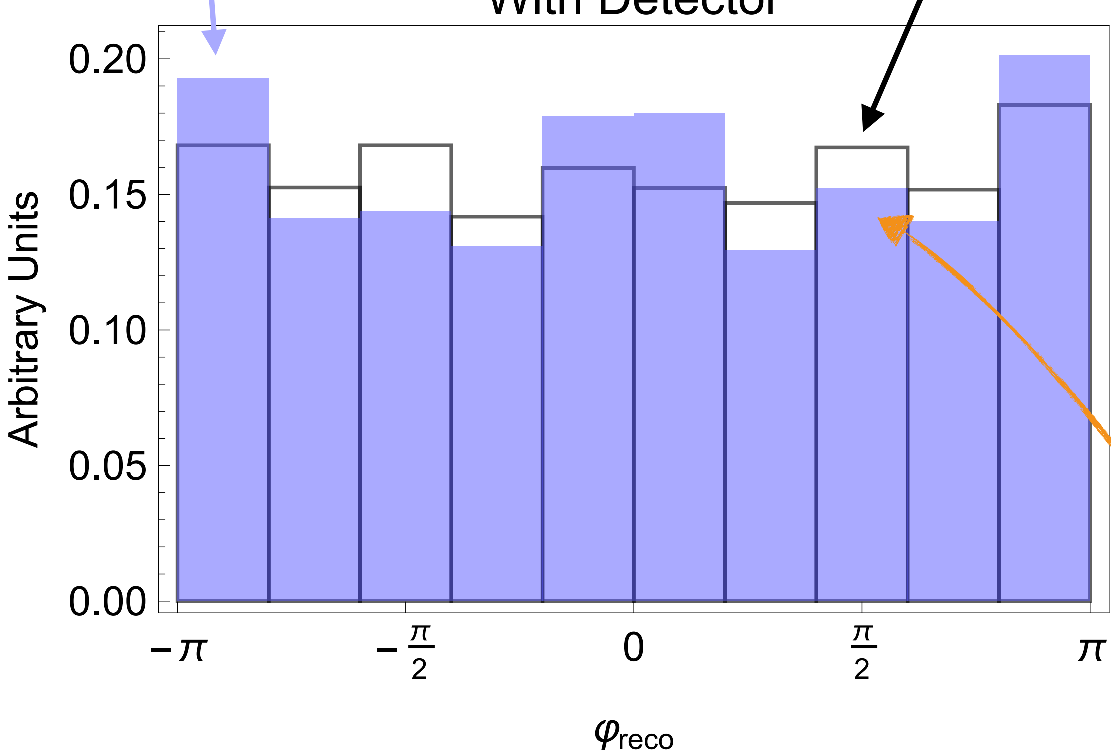
Panico,FR,Wulzer'17

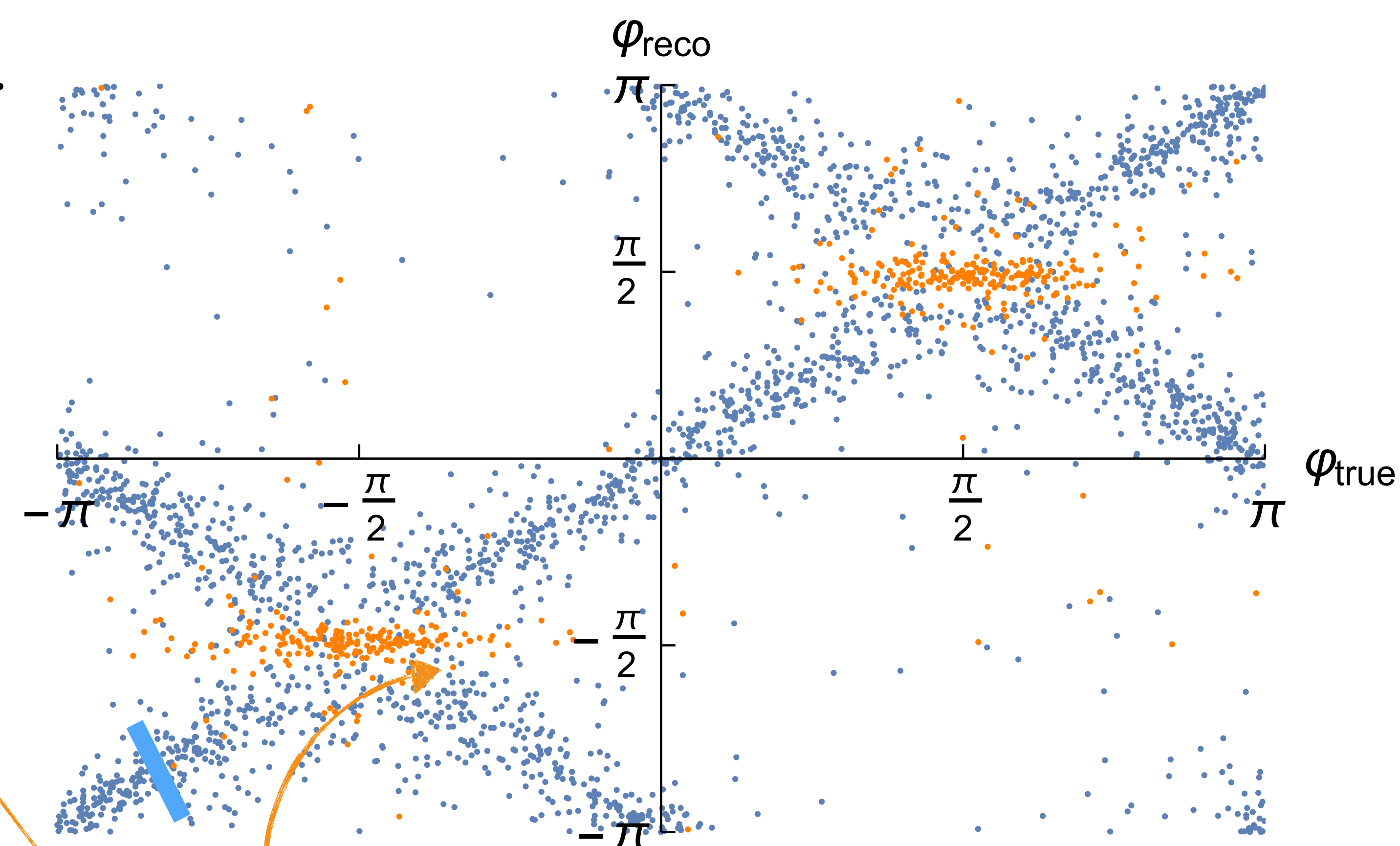
Azimuthal Angle... more in reality

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

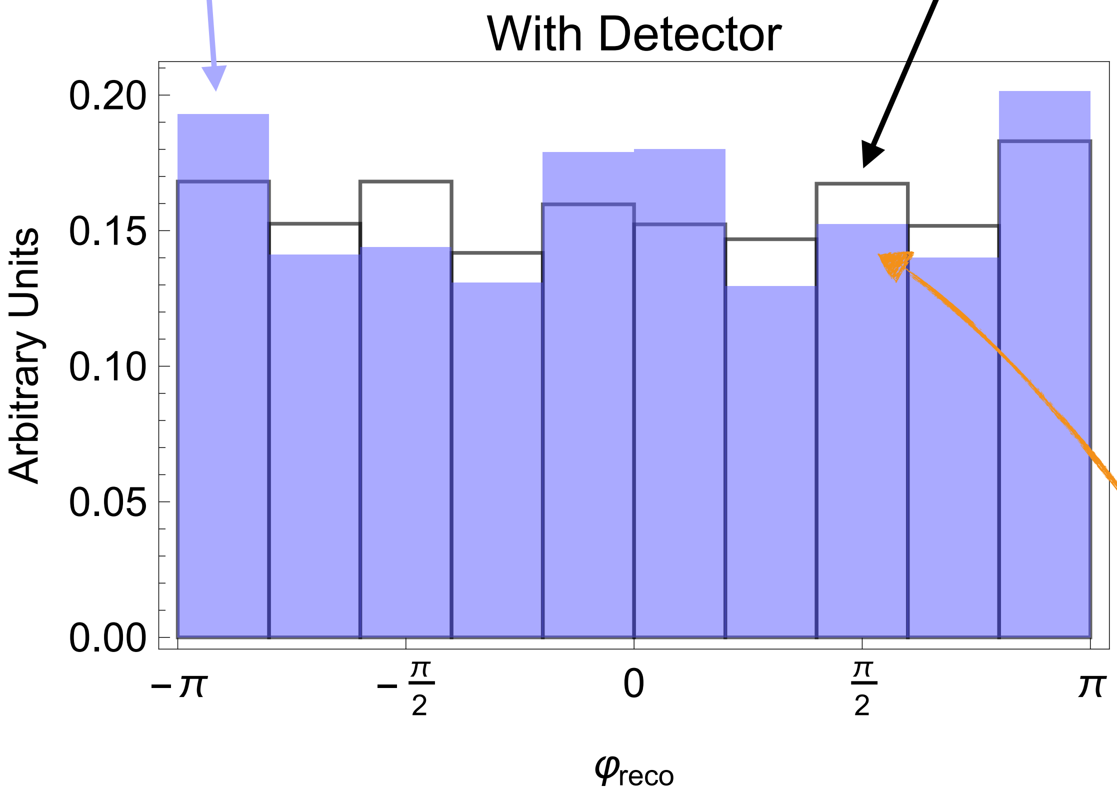
Azimuthal Angle… more in reality

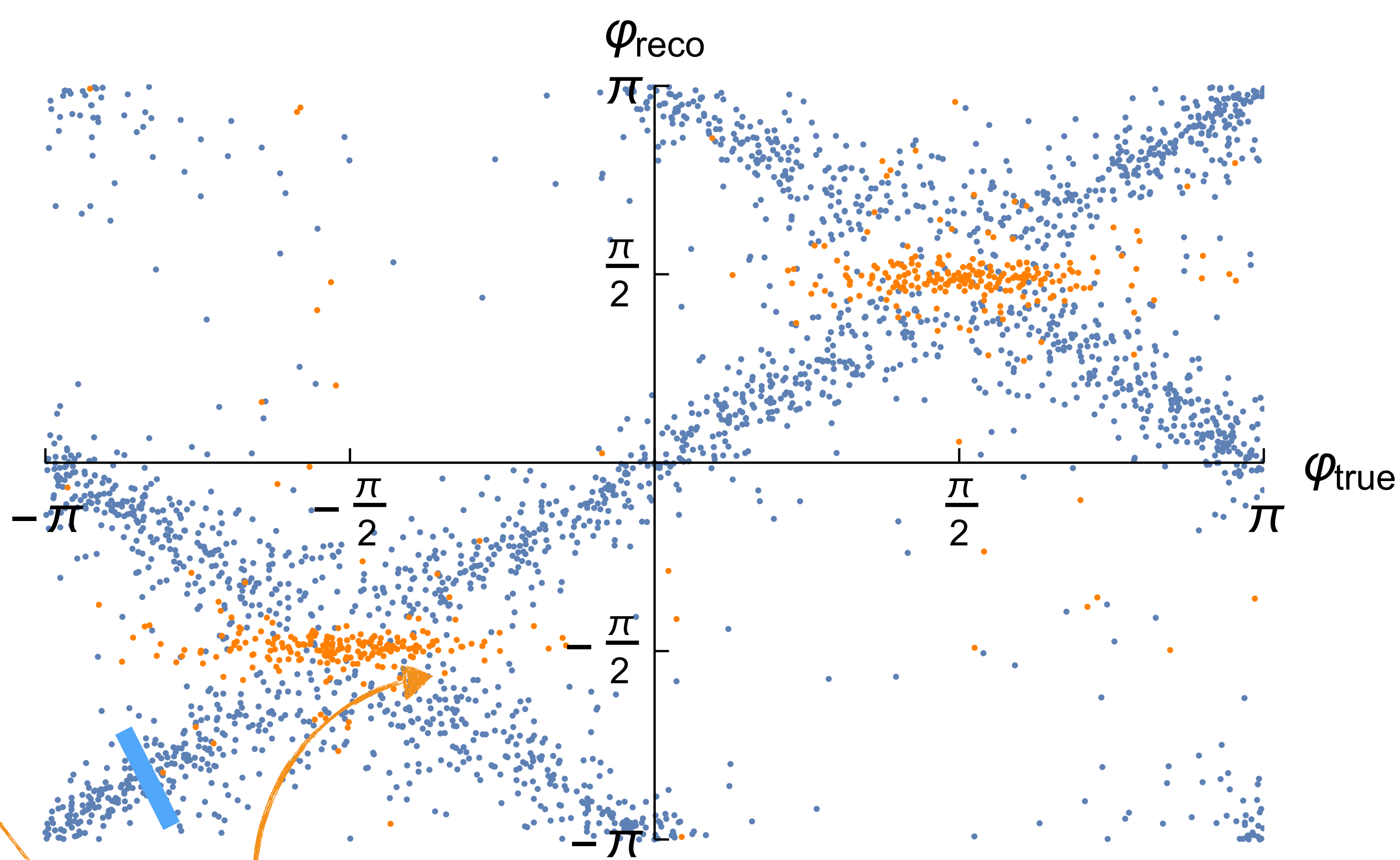
Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation

BSM $\sim \cos 2\varphi$

SM $\sim const.$





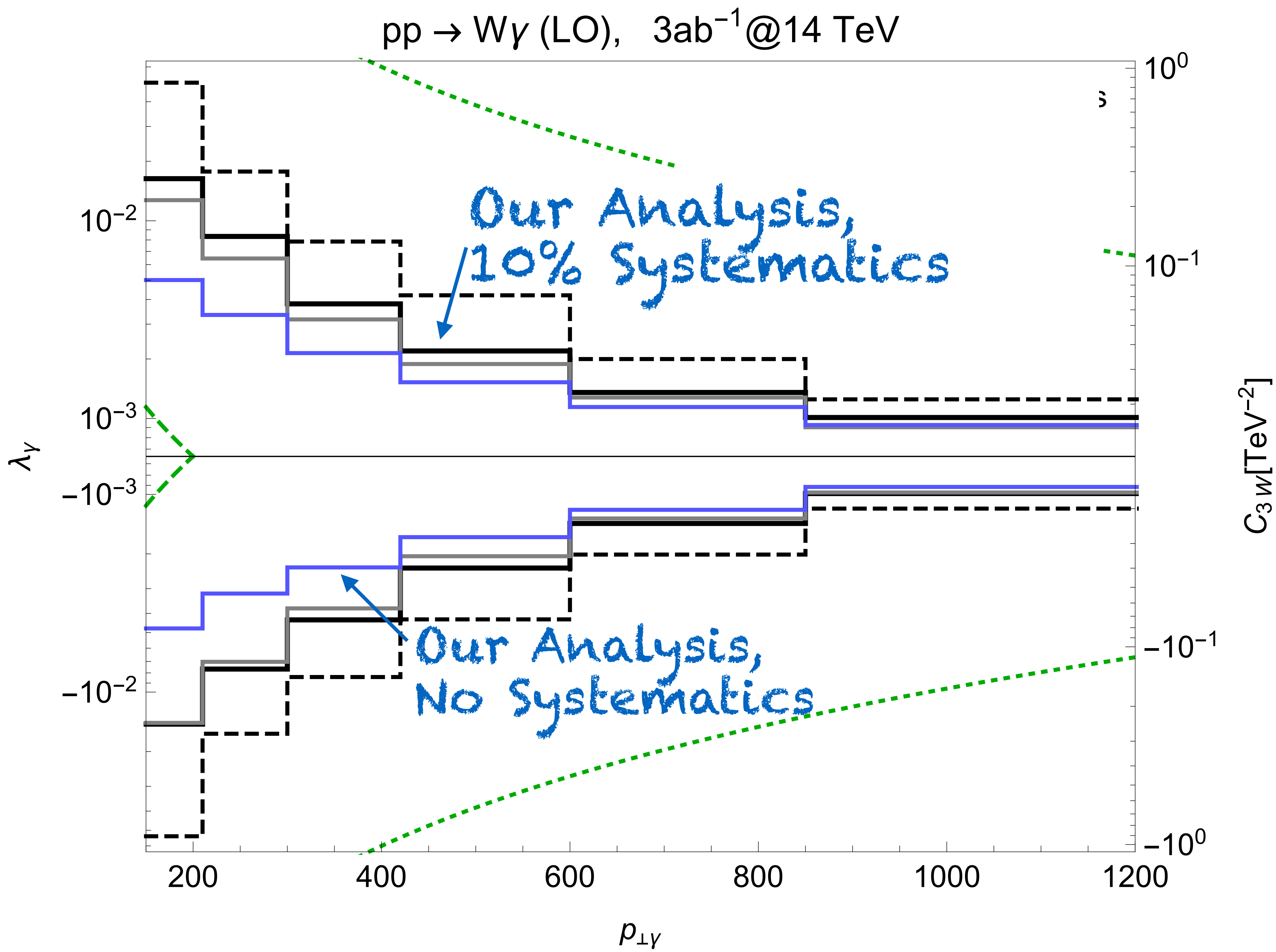
Spread under control

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

▸ Resurrection is real

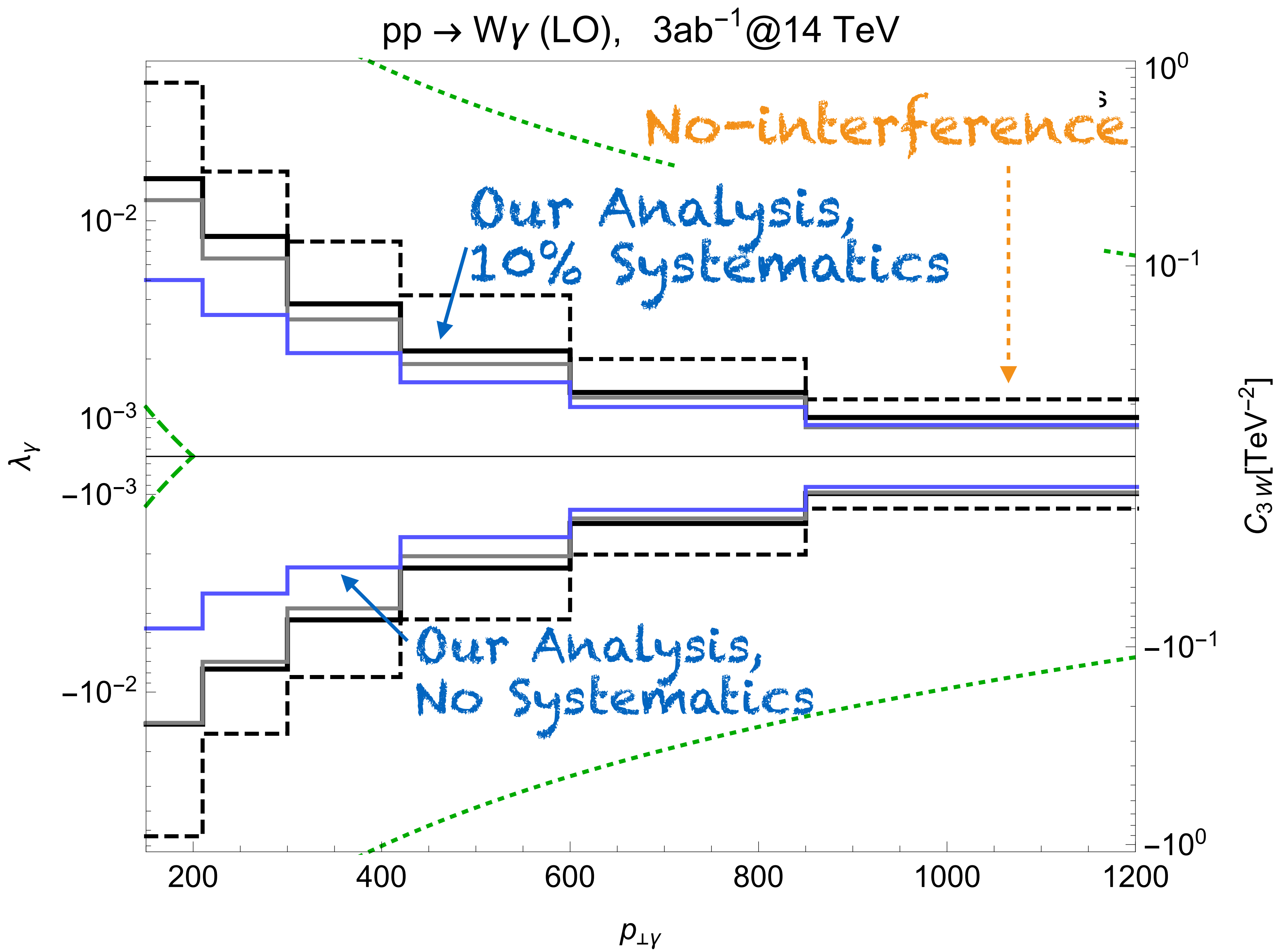
Panico,FR,Wulzer'17

Results



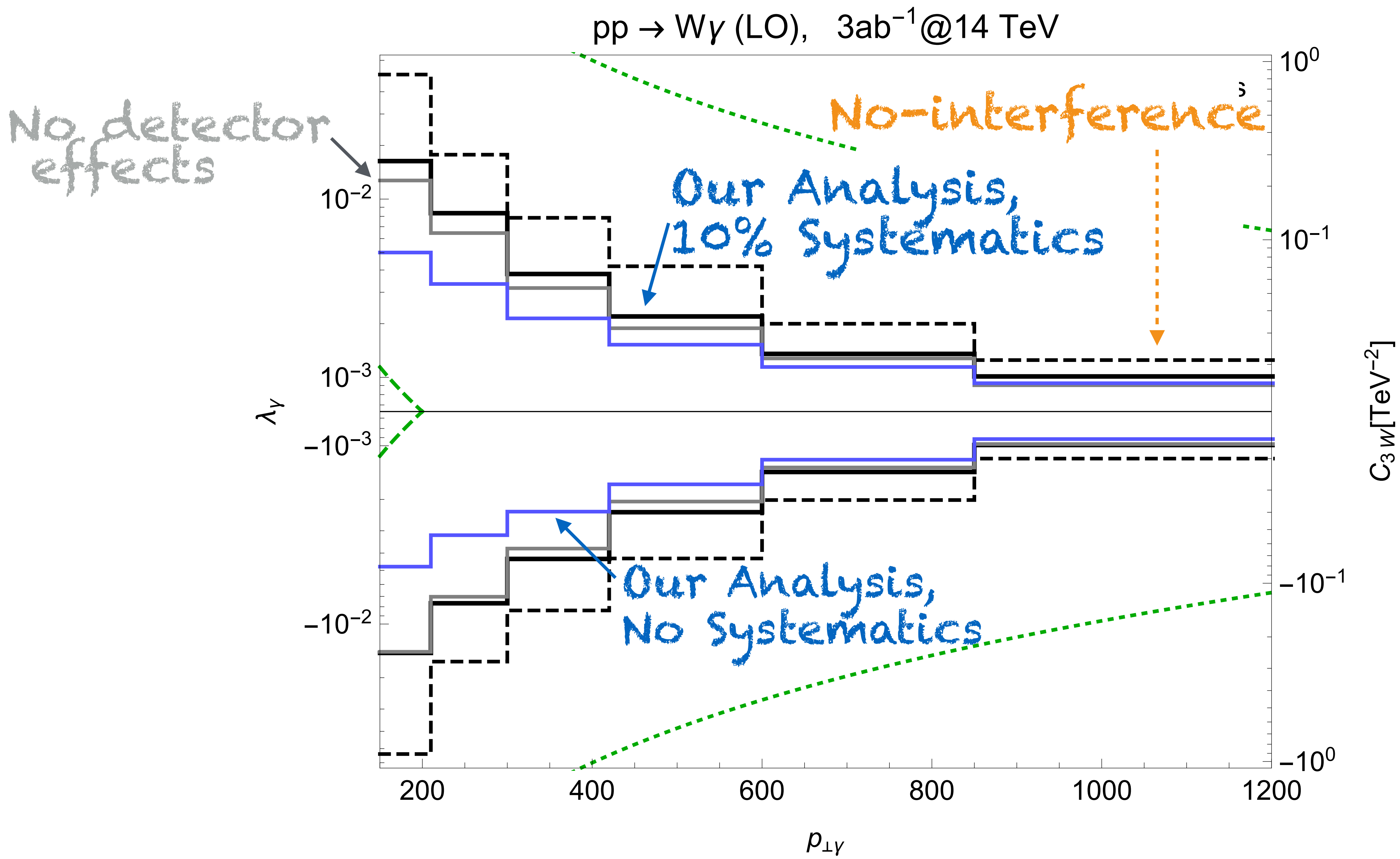
Panico,FR,Wulzer'17

Results



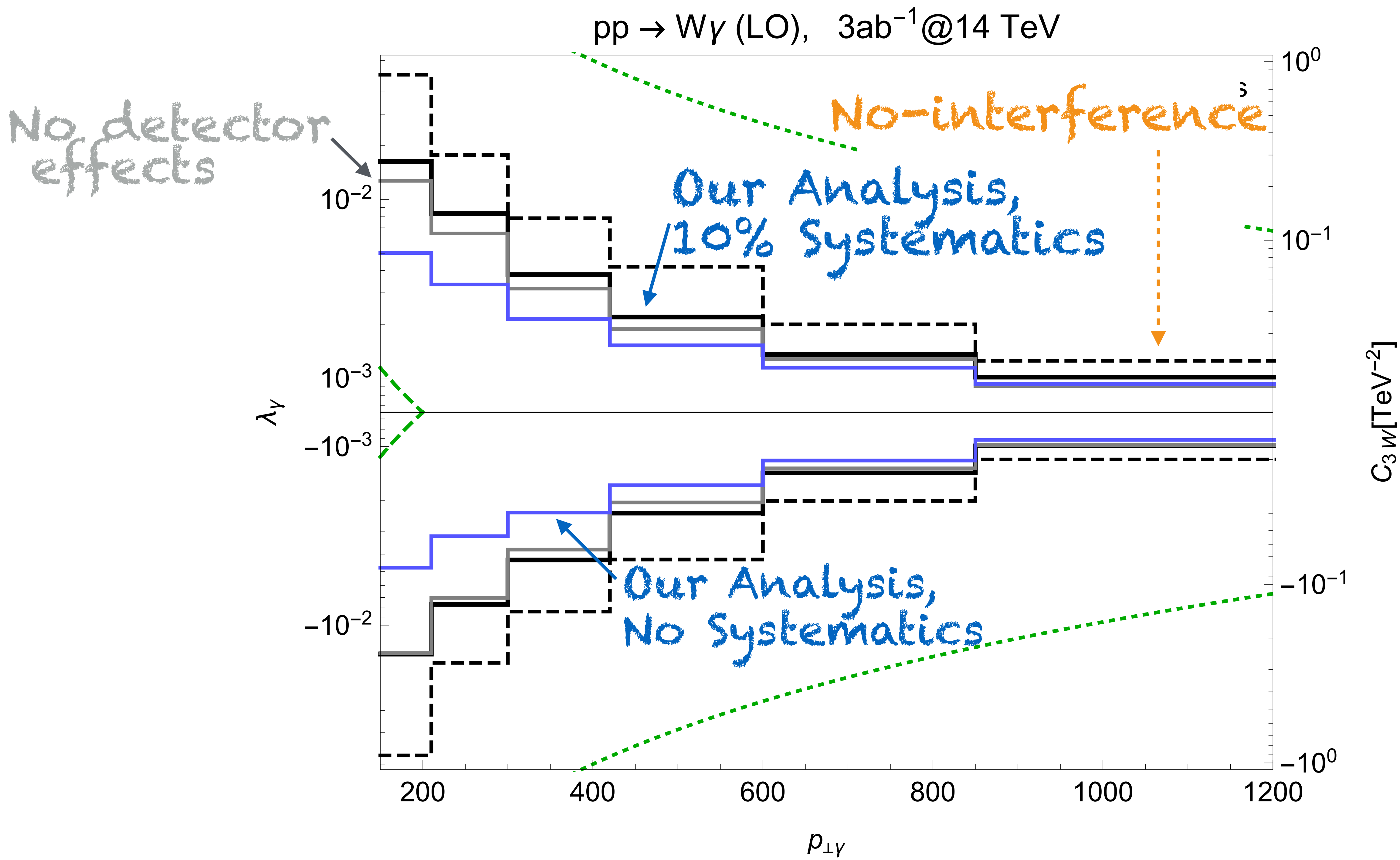
Panico,FR,Wulzer'17

Results



Panico,FR,Wulzer'17

Results



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

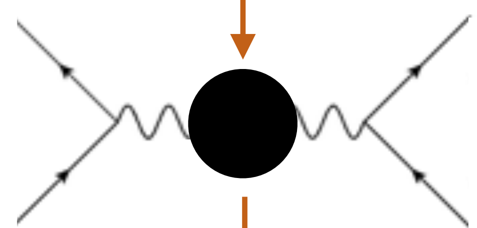
Panico,FR,Wulzer'17

Explicit Model (Remedios)

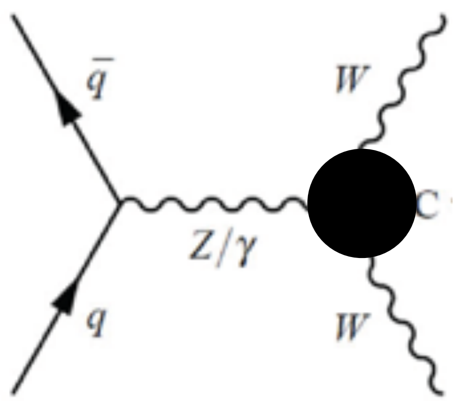
Remedios Scenario → $\frac{1}{M^2}(D_\rho W_\mu^{a,\nu})^2$

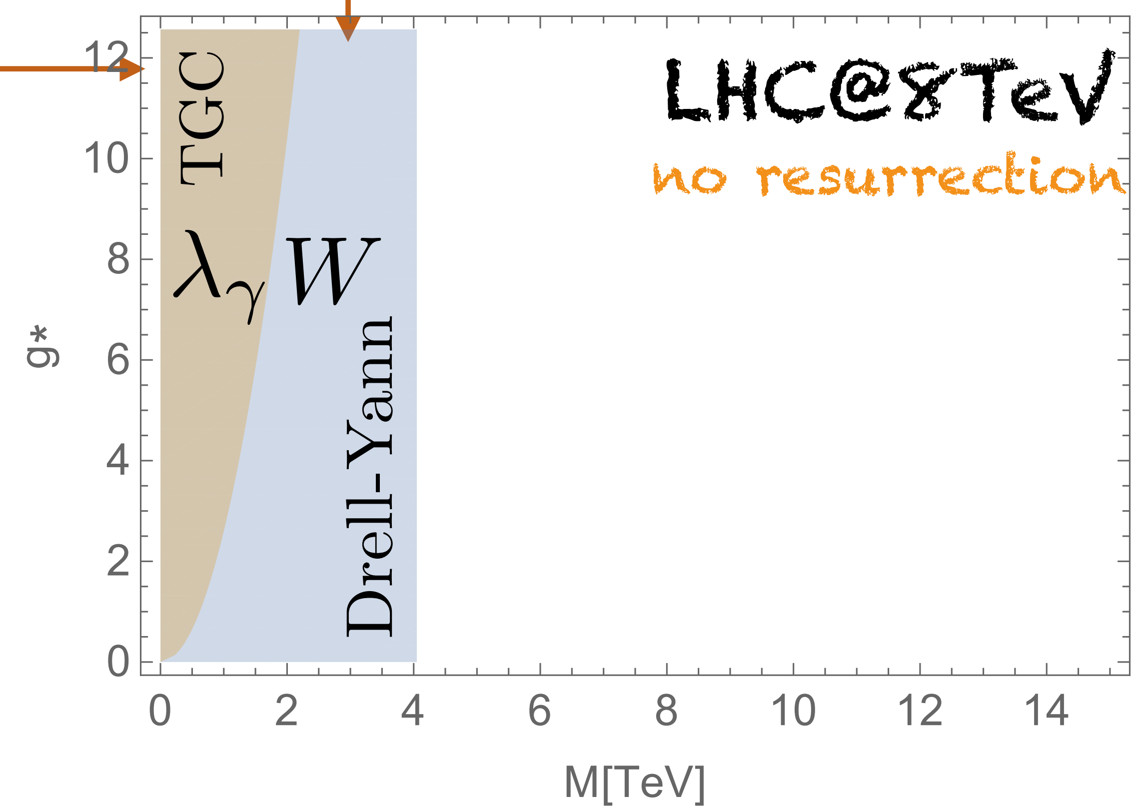
Liu,Pomarol,Rattazzi,FR'16

Liu,Pomarol,Rattazzi,FR'16



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





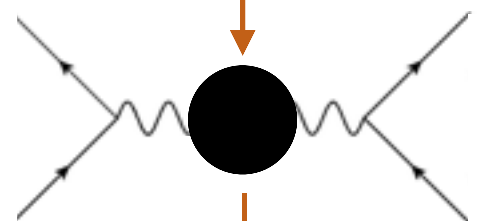
Interference Resurrection makes the difference.

Explicit Model (Remedios)

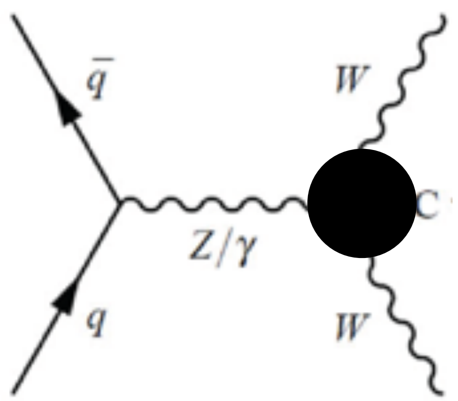
Liu,Pomarol,Rattazzi,FR'16

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

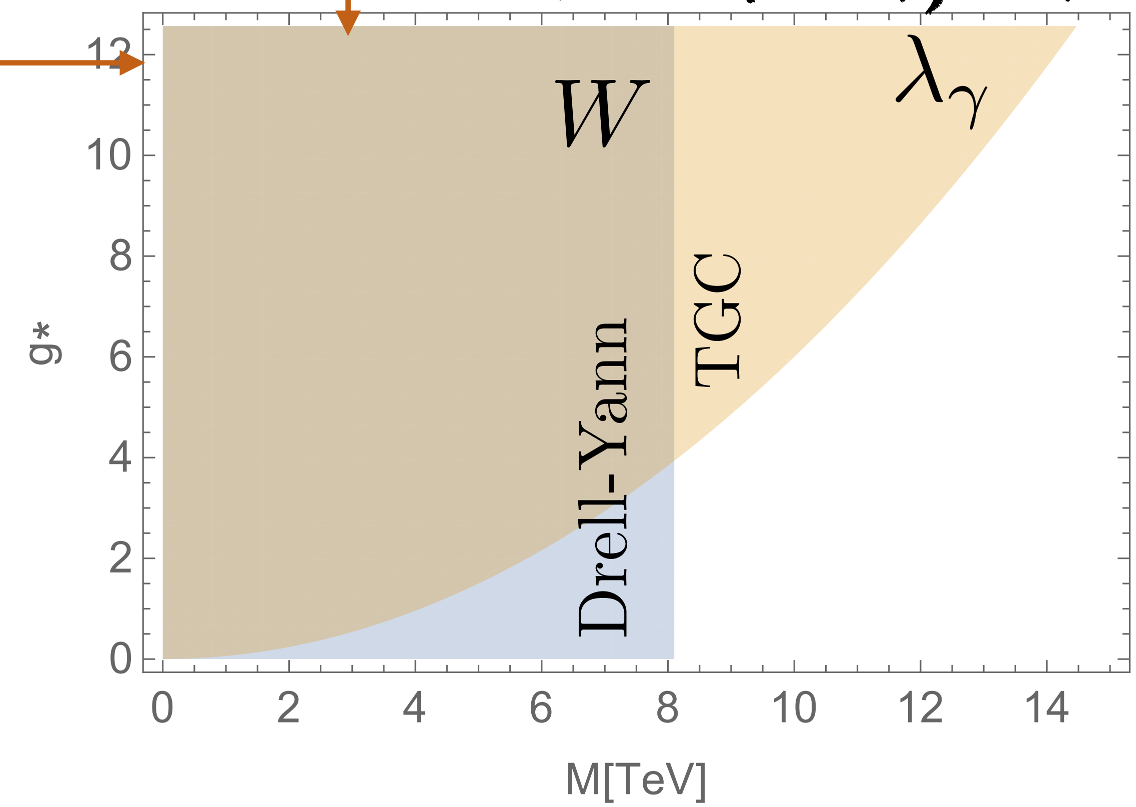
Liu,Pomarol,Rattazzi,FR'16



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



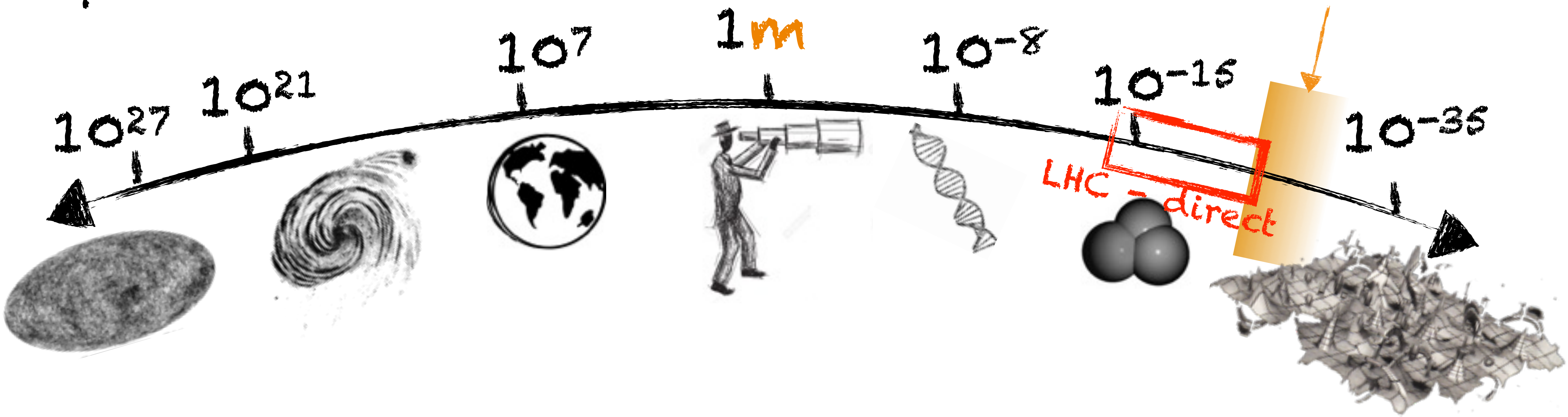
LHC@14TeV,3ab^{-1}



Interference Resurrection makes the difference.

Message

SM precision tests will define the new distance frontier



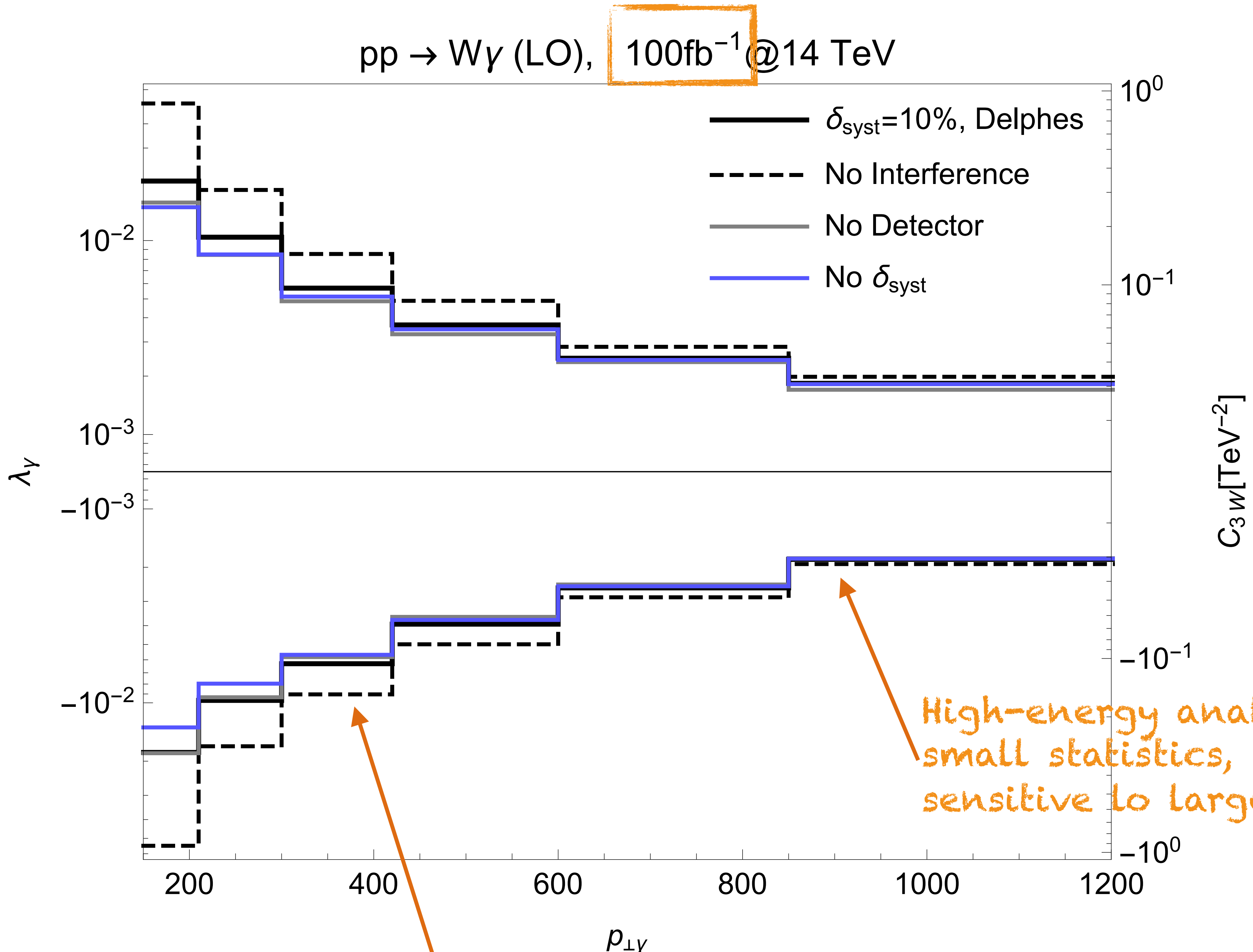
- LHC good in High-E 2>2 processes

Challenges:

- Non-interference limits precision in learning about transverse vectors
- longitudinals hidden in transverse background

- Azimuthal distributions crucial (Realistic in other processes? WZ? VBF?)
- SM precision program LHC completes LEP

Results



High-energy analysis,
small statistics,
sensitive to large (quadratic) BSM

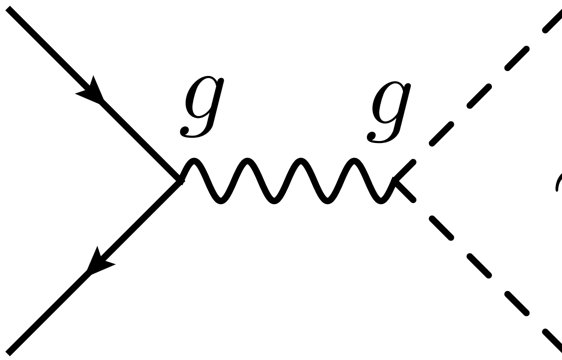
At small energy, interference has impact already now.
(improving low-energy measurement, important for validity)

Panico,FR,Wulzer'17

BSM Perspective:

What are we after?

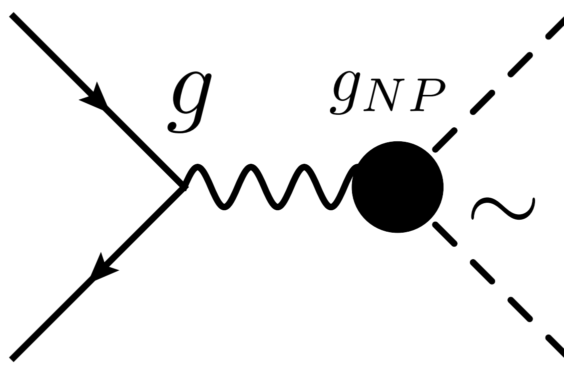
SM:



$$\sim g^2$$

Composite Higgs+Vectors

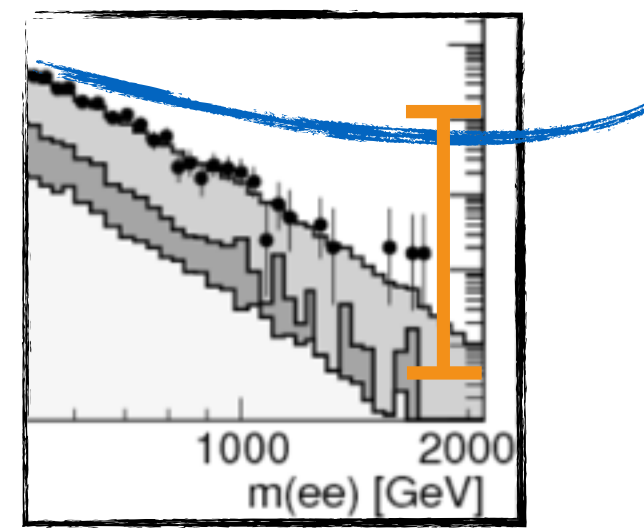
Liu,Pomarol,Rattazzi,FR'16



$$\sim g g_{NP} \frac{E^2}{\Lambda^2} \gtrsim g^2$$

g_{NP}: >>1

$\frac{E^2}{\Lambda^2}$: <<1



☹ Interesting-ish

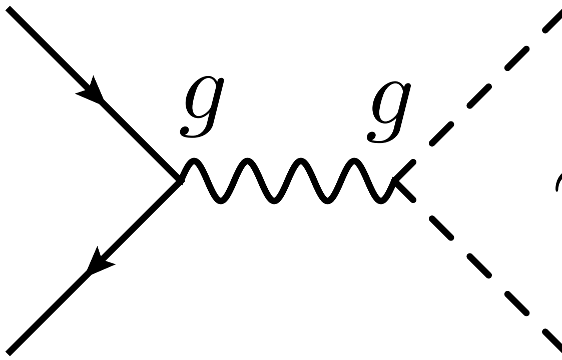
(for me. paper has 20 citations...)

☺ Testable also with inaccurate measurements

BSM Perspective:

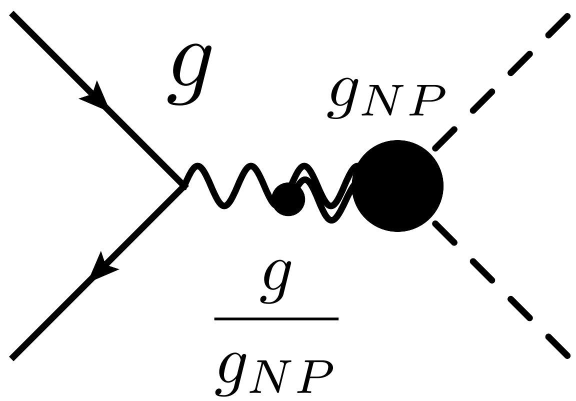
What are we after?

SM:



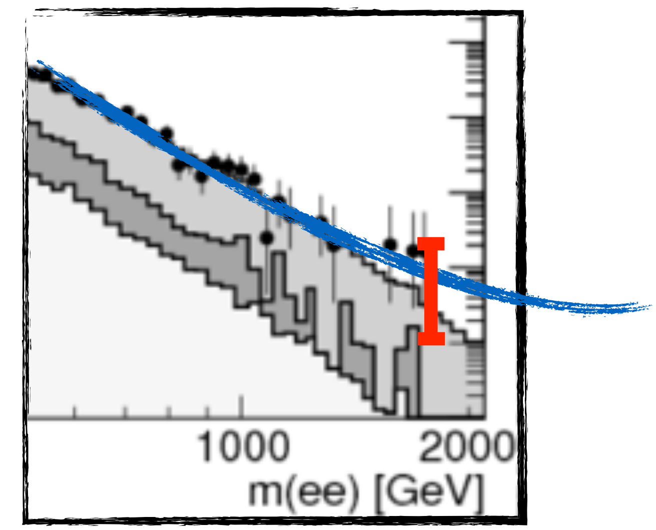
$$\sim g^2$$

Composite Higgs



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

<<1



Very interesting

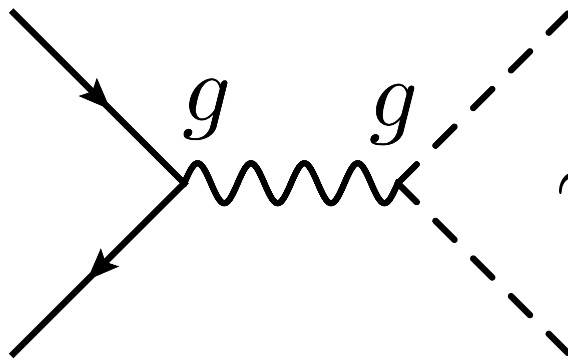
To test it we need **accurate** measurements

$$\frac{\delta\sigma}{\sigma_{SM}} \ll 1$$

BSM Perspective:

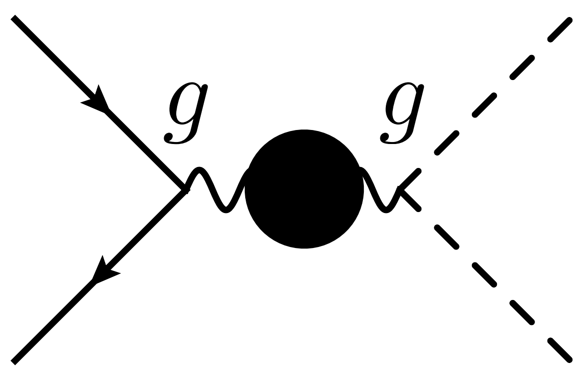
What are we after?

SM:



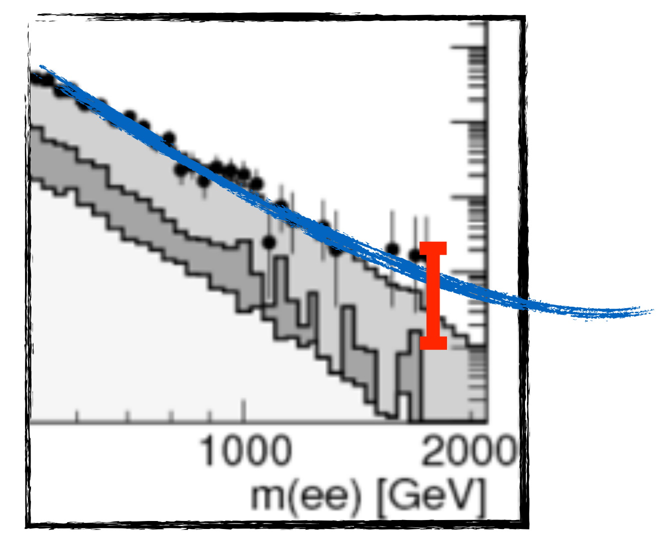
$\sim g^2$

Universal NP:



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

<<1



Very interesting

To test it we need accurate measurements

$$\frac{\delta\sigma}{\sigma_{SM}} \ll 1$$

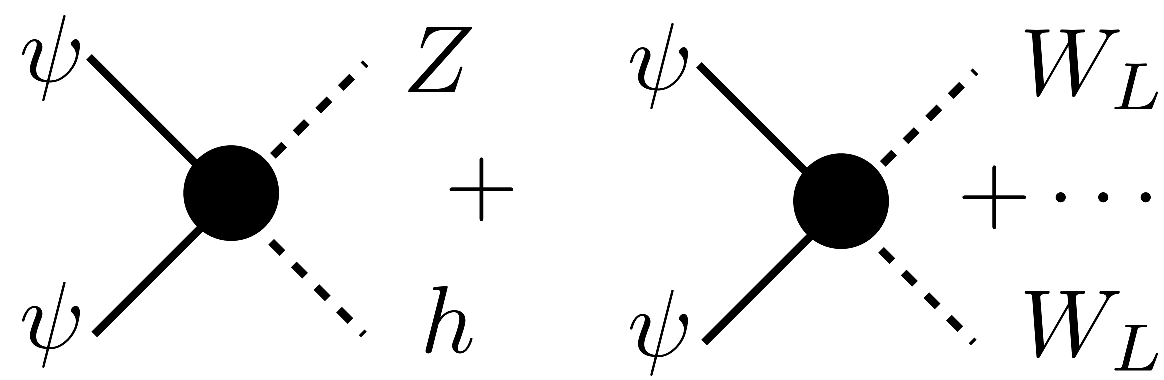
Accuracy target: $\frac{\delta\sigma}{\sigma_{SM}}$ <<1 also at high-energy

Higgs closest cousin

In the SM, all scalars belong to Higgs doublet $\begin{pmatrix} h^+ \\ h + ih^0 \end{pmatrix}$ ($h^+ \leftarrow W_L$, $ih^0 \leftarrow Z_L$)

- Their interactions are related also in BSM:

$$\frac{1}{\Lambda^2} H^\dagger D_\mu H \bar{\Psi}\gamma^\mu\Psi \longrightarrow$$



Higgs Physics ⟶ EW Physics

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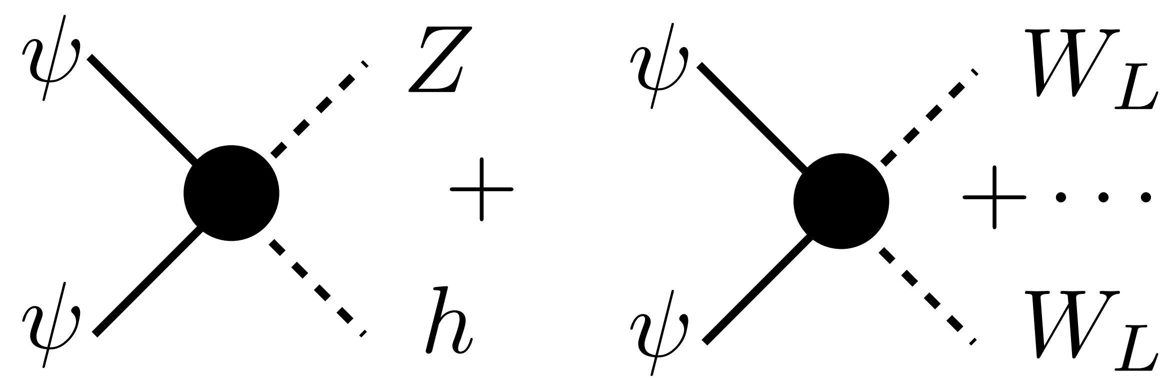


Higgs Physics ⟶ EW Physics

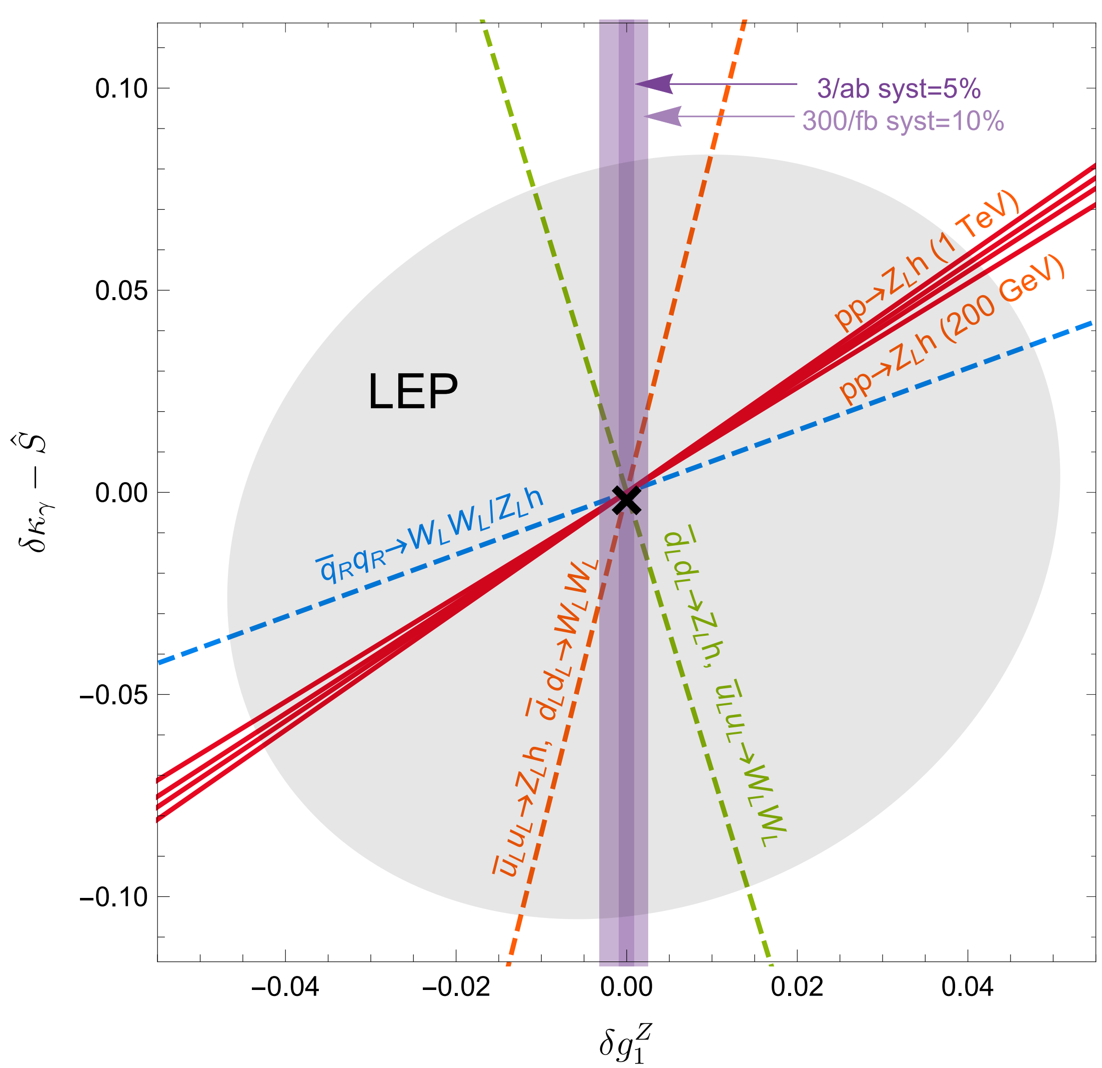
This talk: anatomy of high-E diboson processes

1. Longitudinals $\psi\psi \to V_L V_L$

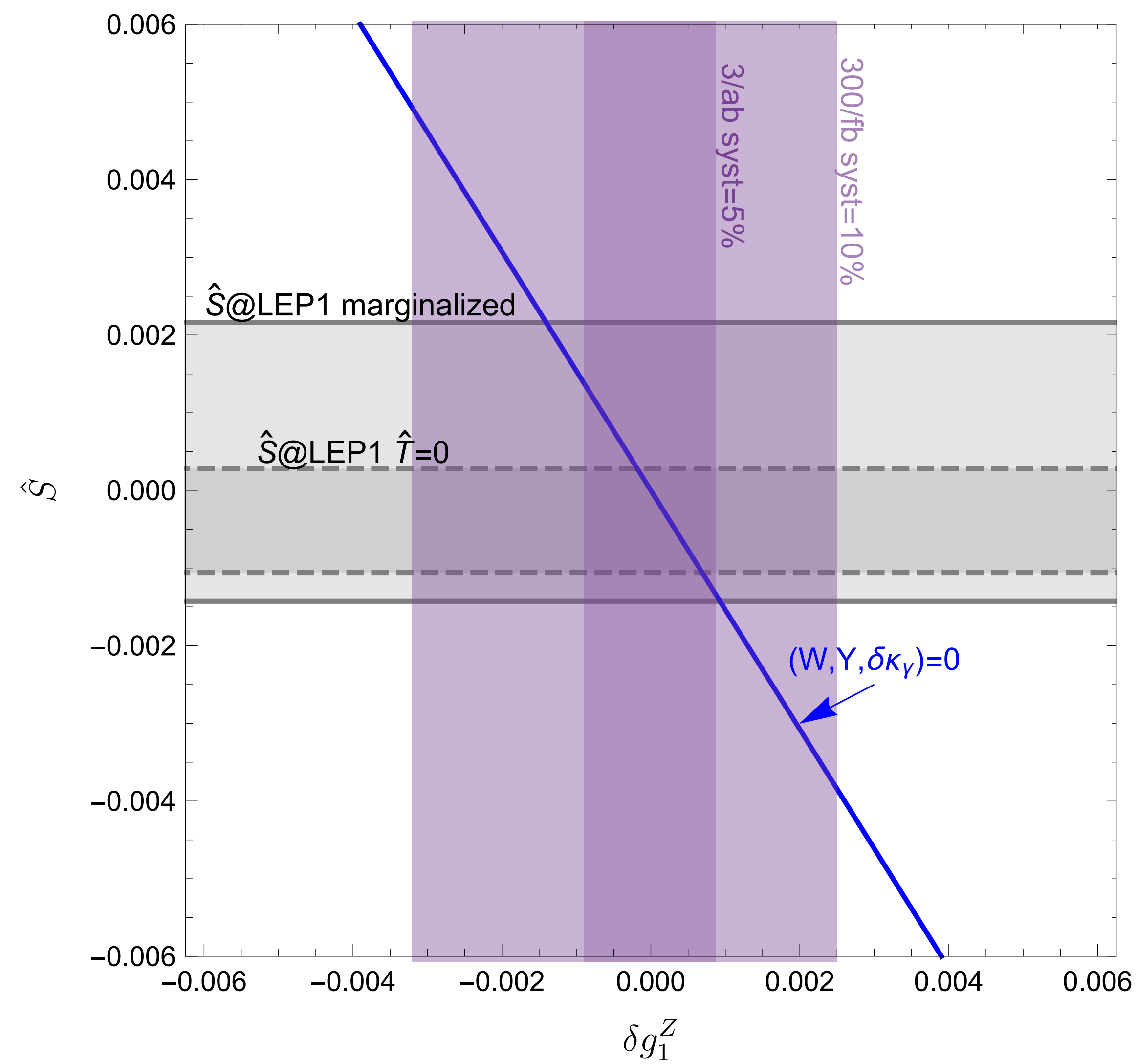
2. Transverse $\psi\psi \to V_T V_T$

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

Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

2->2 processes: