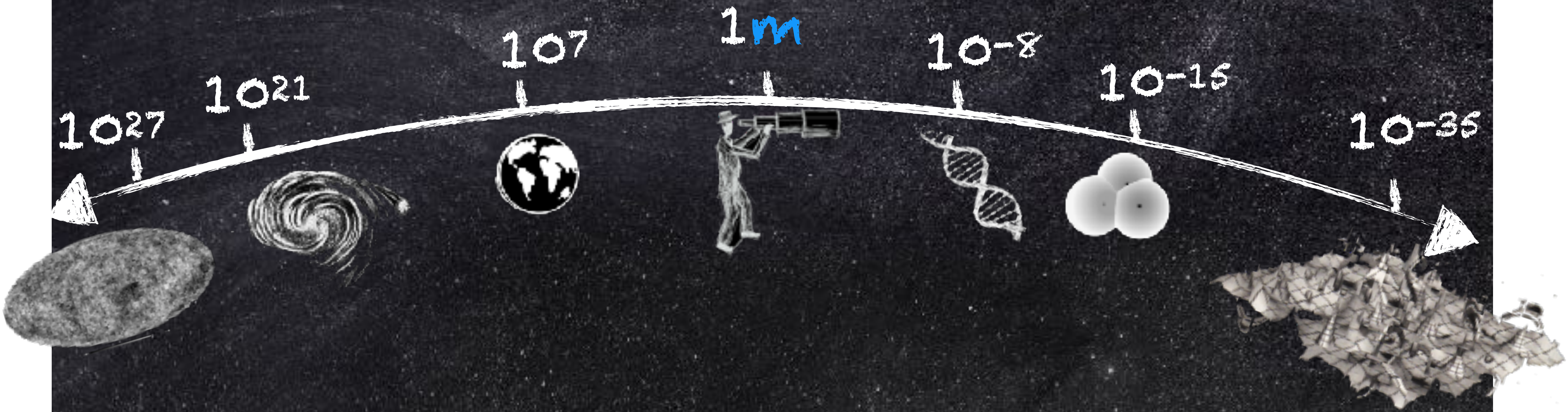
Precision Tests in the High Energy Era

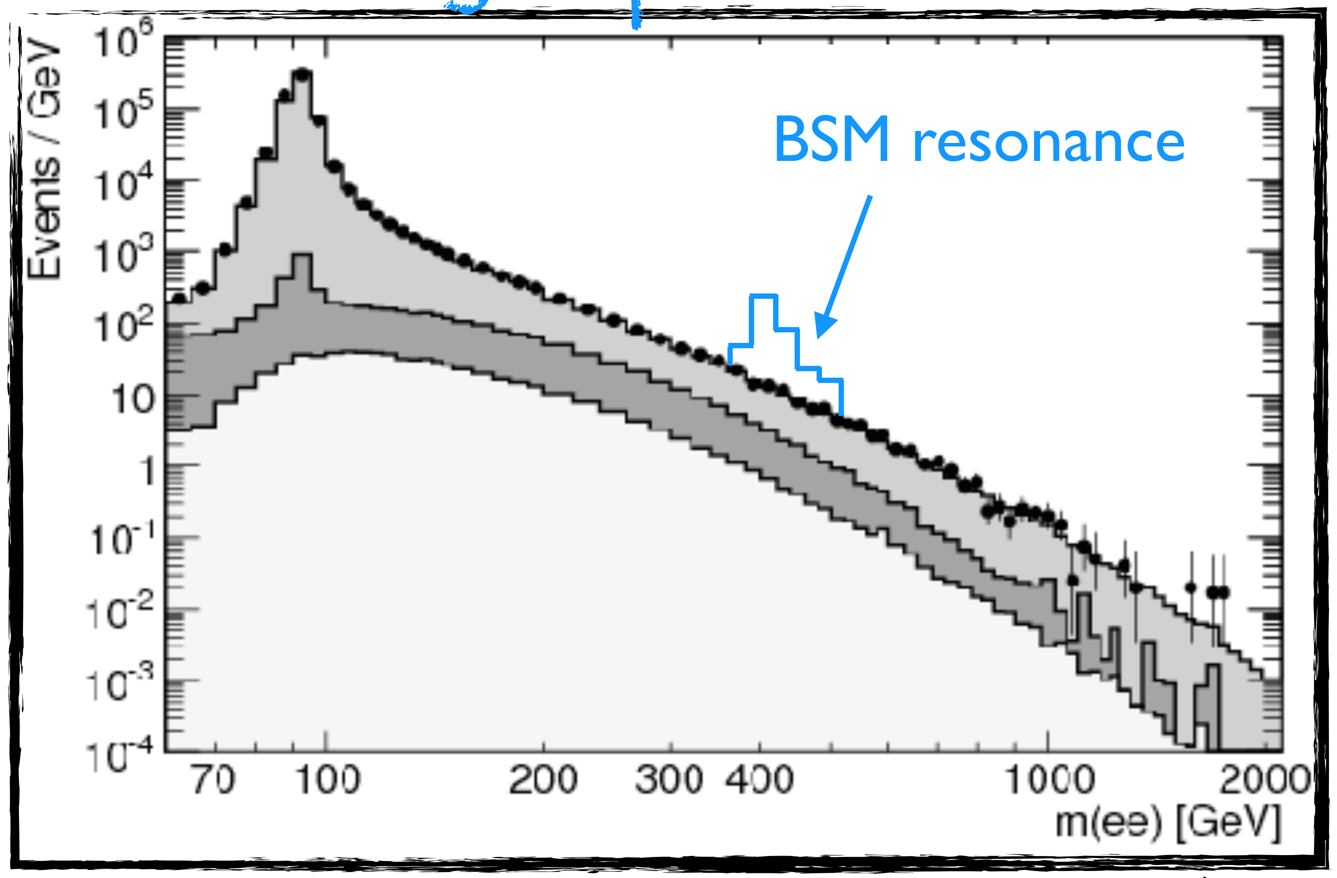


Francesco Riva
(UNIGE)

In collaboration with
Bellazzini 1806.09640
Franceschini, Panico, Pomarol, Wulzer 1712.01310
Panico, Wulzer 1708.07823,
Azatov, Contino, Machado 1607.05236

LHC Exploration
(so far 2009-2017)

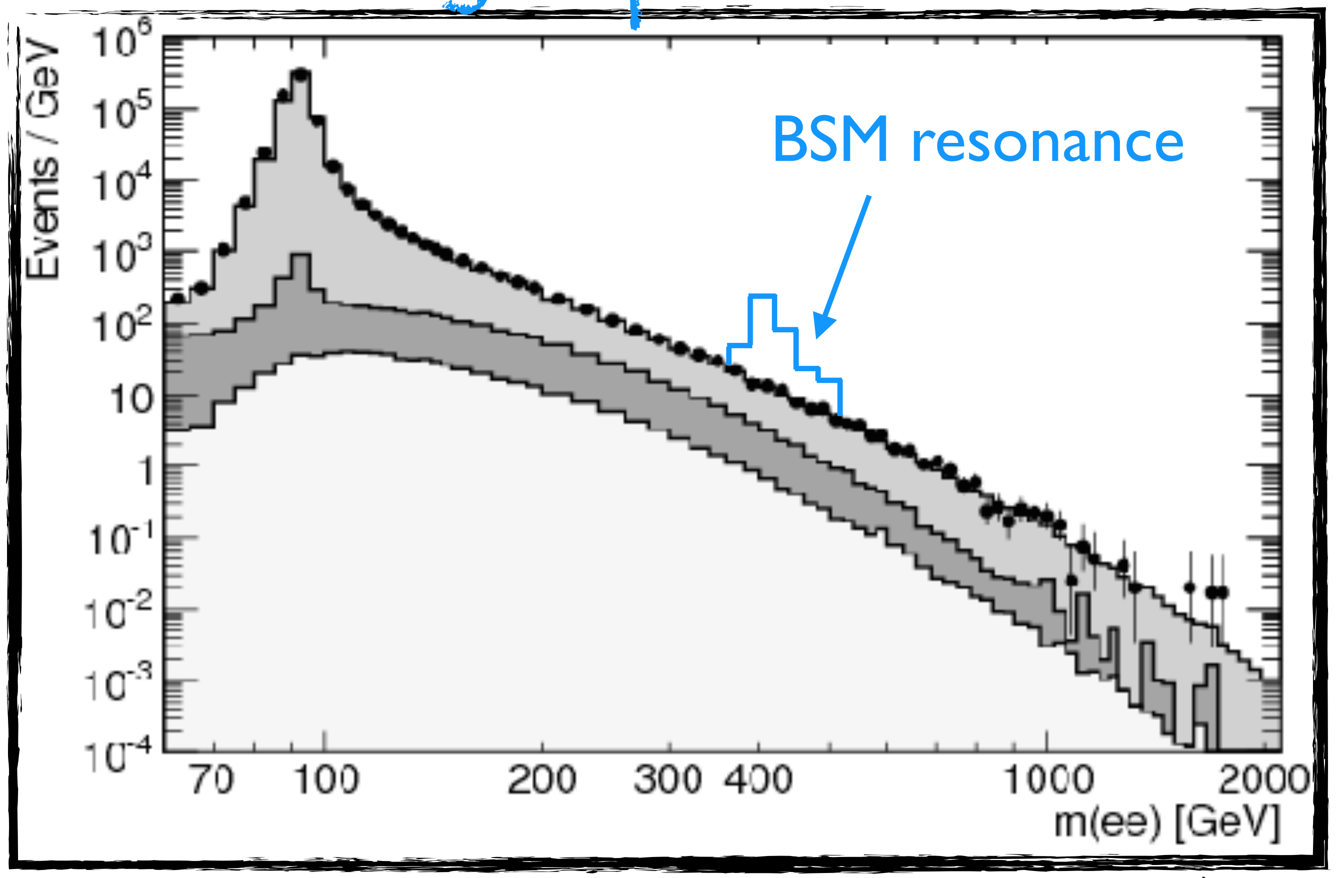
Focus: Search for new light particles



Energy frontier (13 TeV)

LHC Exploration
(so far 2009-2017)

Focus: Search for new light particles

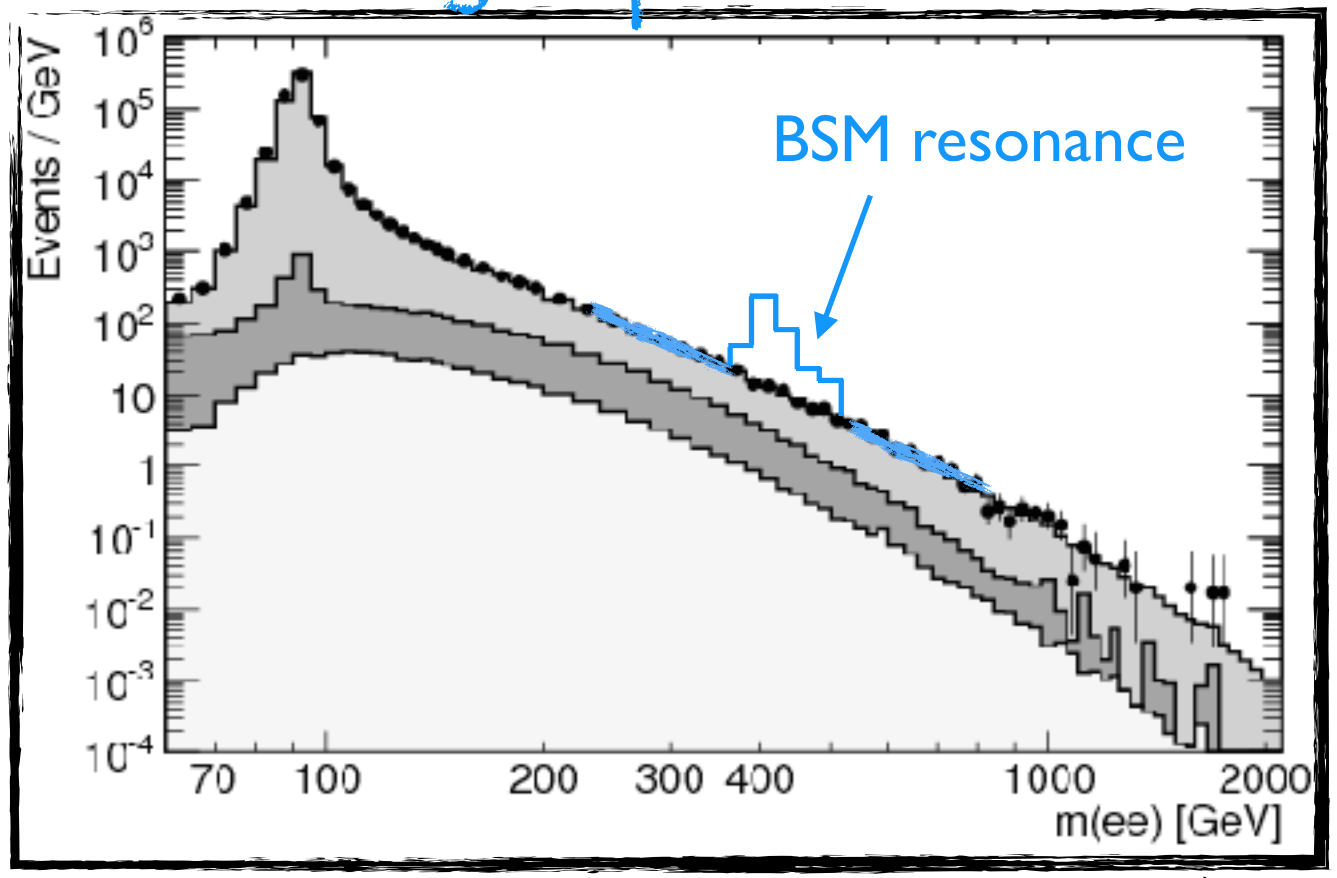


Energy frontier (13 TeV)

- Experimentally: First accessible signal/Easy to study

LHC Exploration
(so far 2009-2017)

Focus: Search for new light particles



Energy frontier (13 TeV)

- Experimentally: First accessible signal/Easy to study

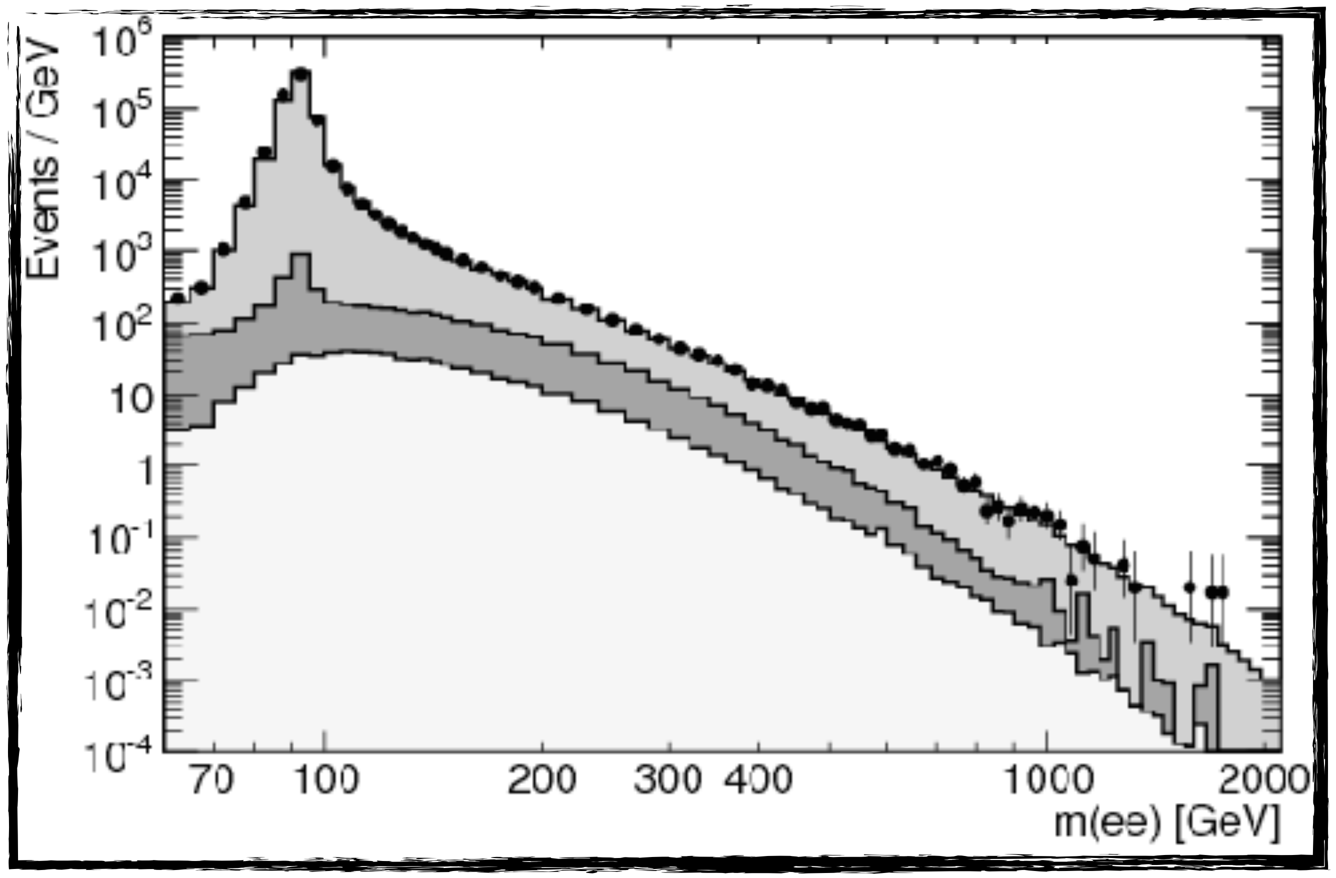
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)



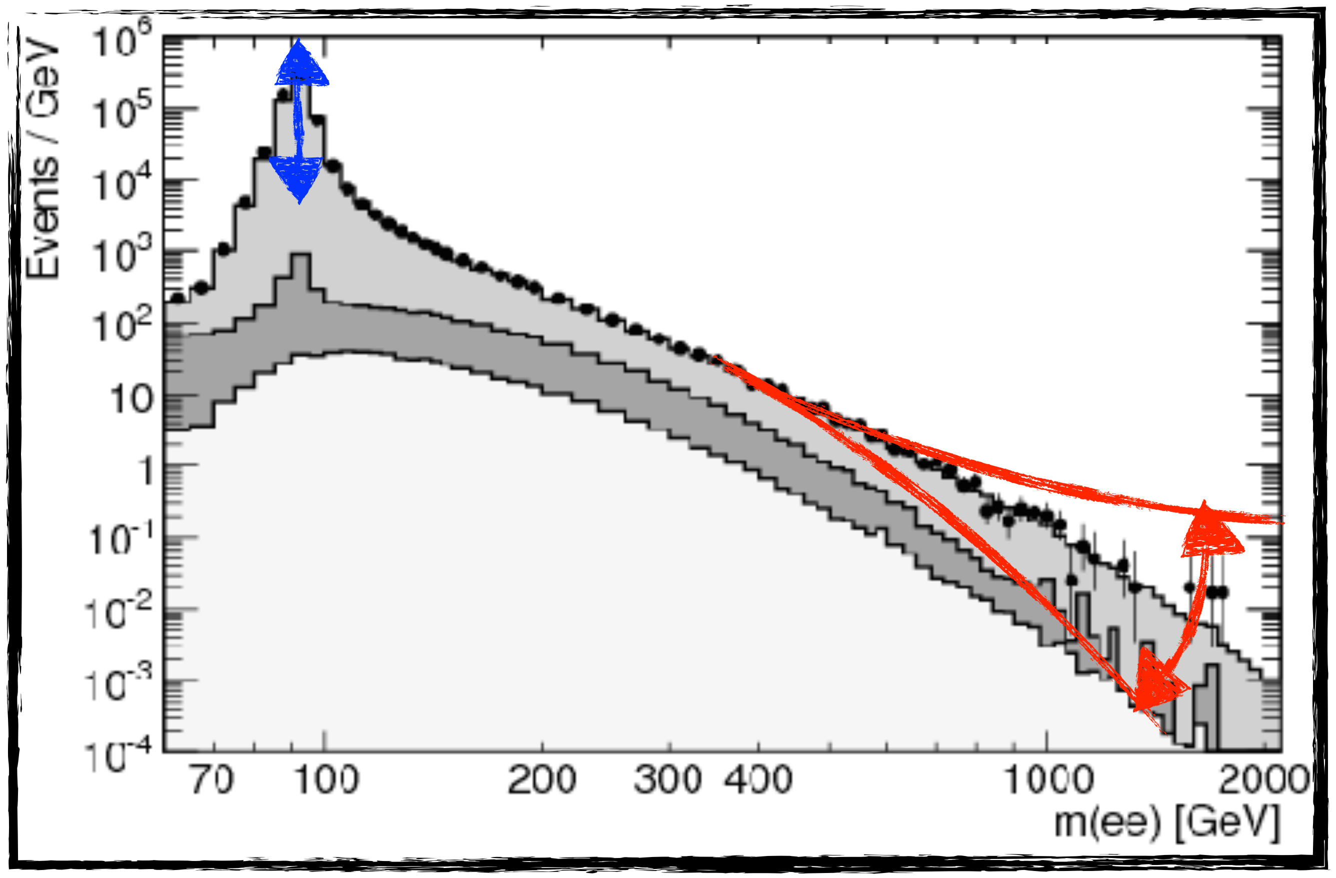
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)



LHC Exploration

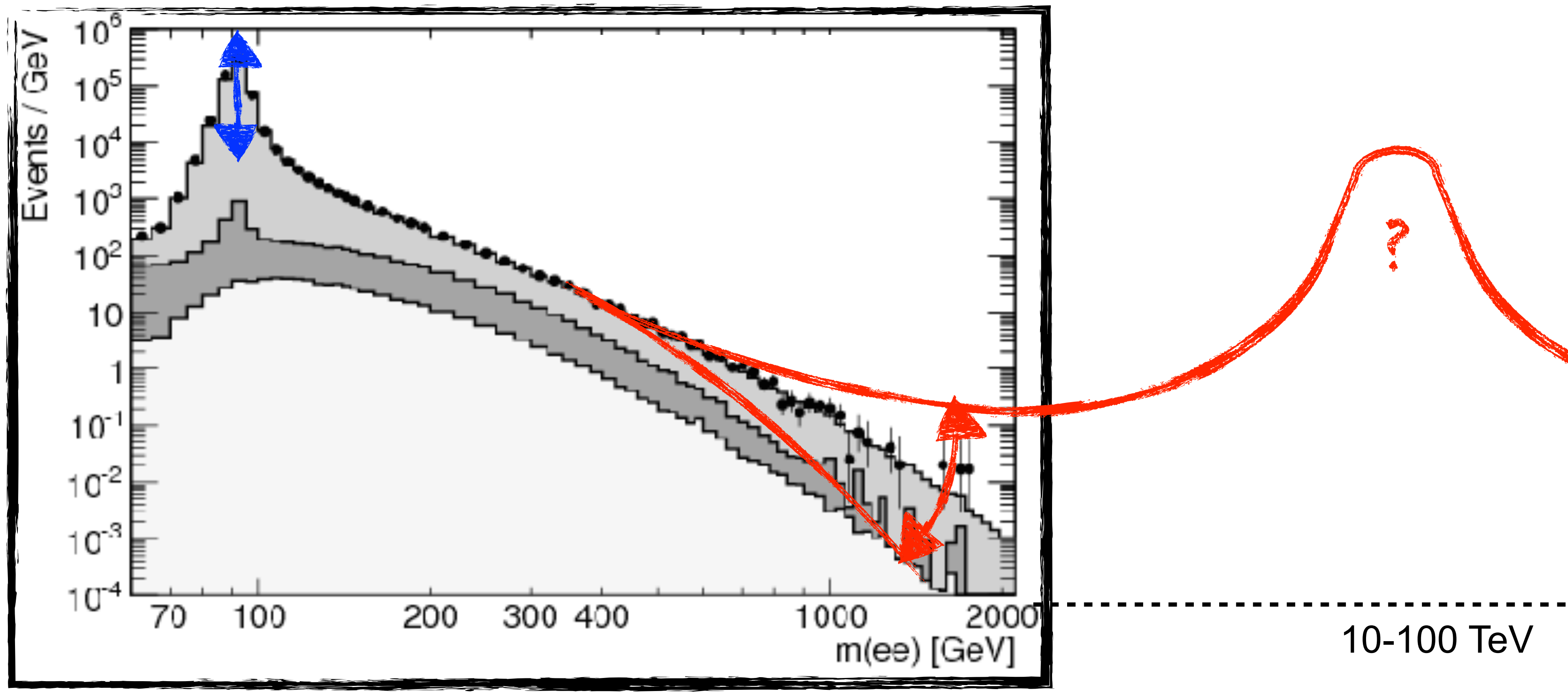
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

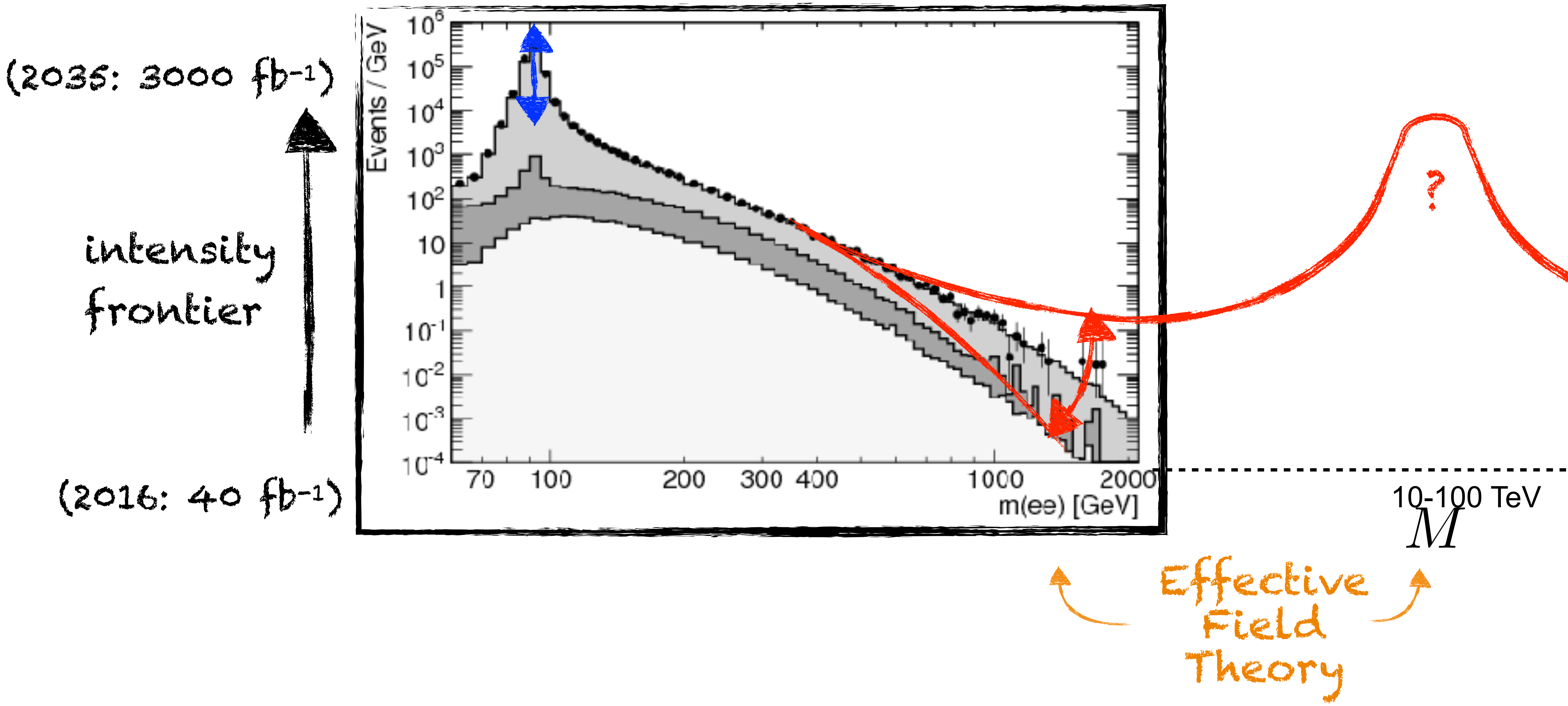
intensity frontier

(2016: 40 fb-1)



LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests



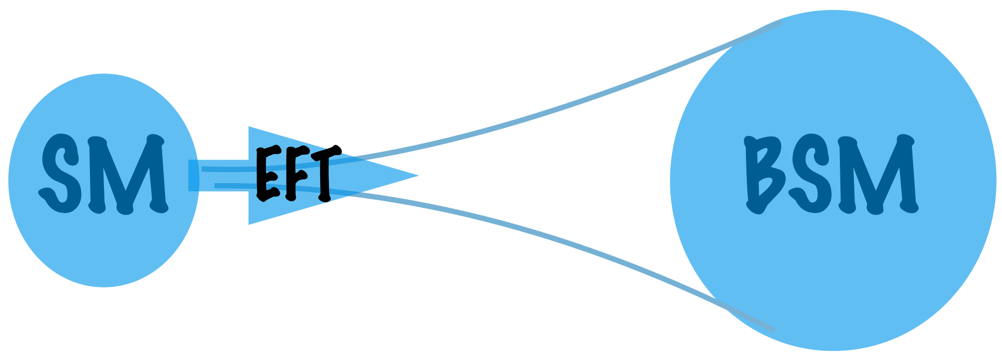
LHC Exploration

(now -> 2030's)

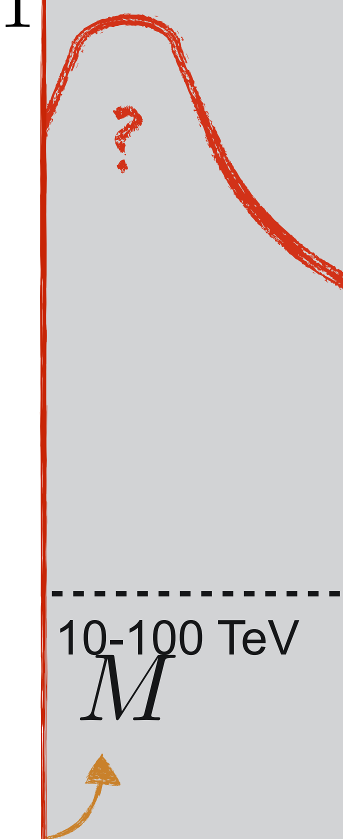
Foc

Effective Field Theories

A way to capture the most relevant effects that survive at E<<M and characterise broad BSM hypotheses $E/M \ll 1$



$$\mathcal{L}_4 + \mathcal{L}_6 + \cdots = \mathcal{L}^{eff} = L\left(\frac{g_H H}{M}, \frac{g_V W^{\mu\nu}}{M^2}, \frac{D_\mu}{M}, \frac{g_\Psi \Psi}{M^{3/2}}\right)$$



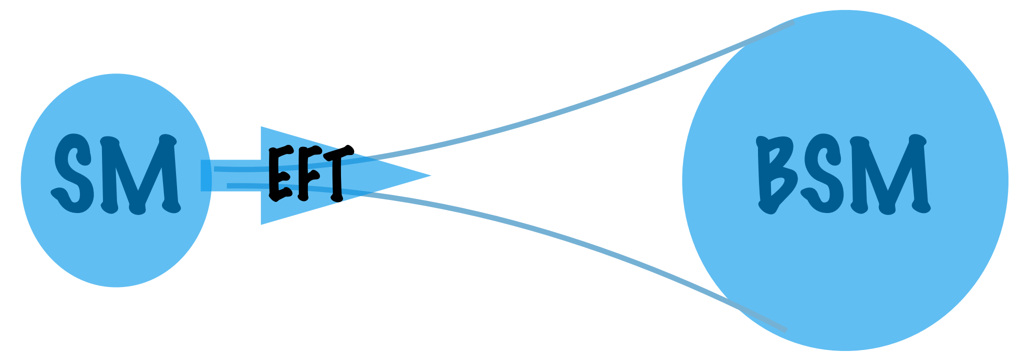
LHC Exploration

(now -> 2030's)

Foc

Effective Field Theories

A way to capture the most relevant effects that survive at E<<M and characterise broad BSM hypotheses $E/M \ll 1$



$$\mathcal{L}_4 + \mathcal{L}_6 + \cdots = \mathcal{L}^{eff} = L\left(\frac{g_H H}{M}, \frac{g_V W^{\mu\nu}}{M^2}, \frac{D_\mu}{M}, \frac{g_\Psi \Psi}{M^{3/2}}\right)$$

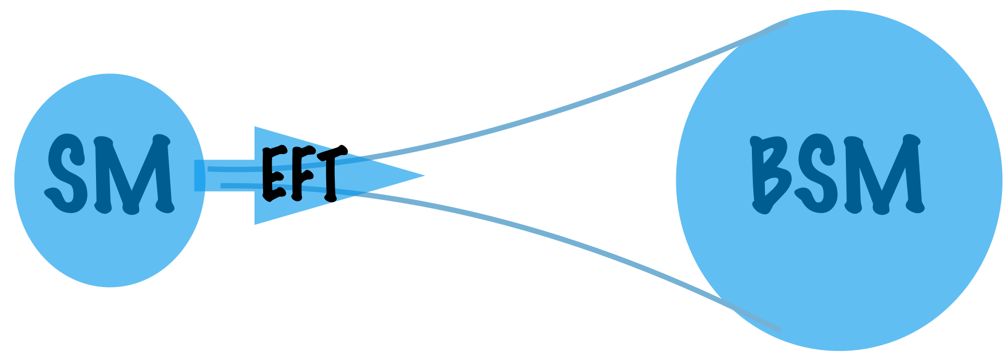
$\mathcal{L}_{SM}$

LHC Exploration
(now -> 2030's)

Foc

Effective Field Theories

A way to capture the most relevant effects that survive at E<<M and characterise broad BSM hypotheses $E/M \ll 1$

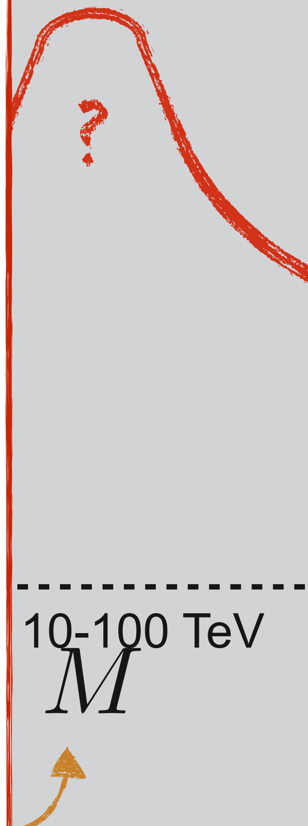


$$\mathcal{L}_4 + \mathcal{L}_6 + \cdots = \mathcal{L}^{eff} = L\left(\frac{g_H H}{M}, \frac{g_V W^{\mu\nu}}{M^2}, \frac{D_\mu}{M}, \frac{g_\Psi \Psi}{M^{3/2}}\right)$$

$\mathcal{L}_{SM}$ $\quad \sum_i c_i \frac{\mathcal{O}_i}{M^2}$

e.g: $\mathcal{O}_i = \bar{Q}_L \gamma^\mu Q_L \bar{L} \gamma_\mu L$

dimension-6 = leading effects



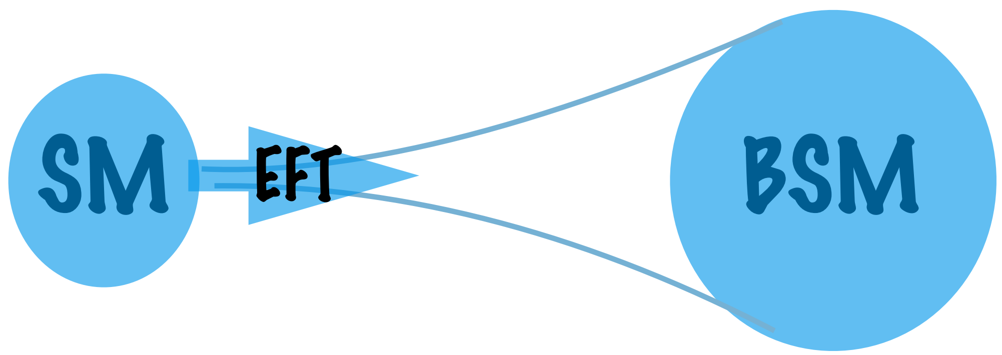
LHC Exploration

(now -> 2030's)

Foc

Effective Field Theories

A way to capture the most relevant effects that survive at E<<M and characterise broad BSM hypotheses $E/M \ll 1$



$$\mathcal{L}_4 + \mathcal{L}_6 + \cdots = \mathcal{L}^{eff} = L\left(\frac{g_H H}{M}, \frac{g_V W^{\mu\nu}}{M^2}, \frac{D_\mu}{M}, \frac{g_\Psi \Psi}{M^{3/2}}\right)$$

$\mathcal{L}_{SM}$ $\sum_i c_i \frac{\mathcal{O}_i}{M^2}$

e.g: $\mathcal{O}_i = \bar{Q}_L \gamma^\mu Q_L \bar{L} \gamma_\mu L$

dimension-6 = leading effects

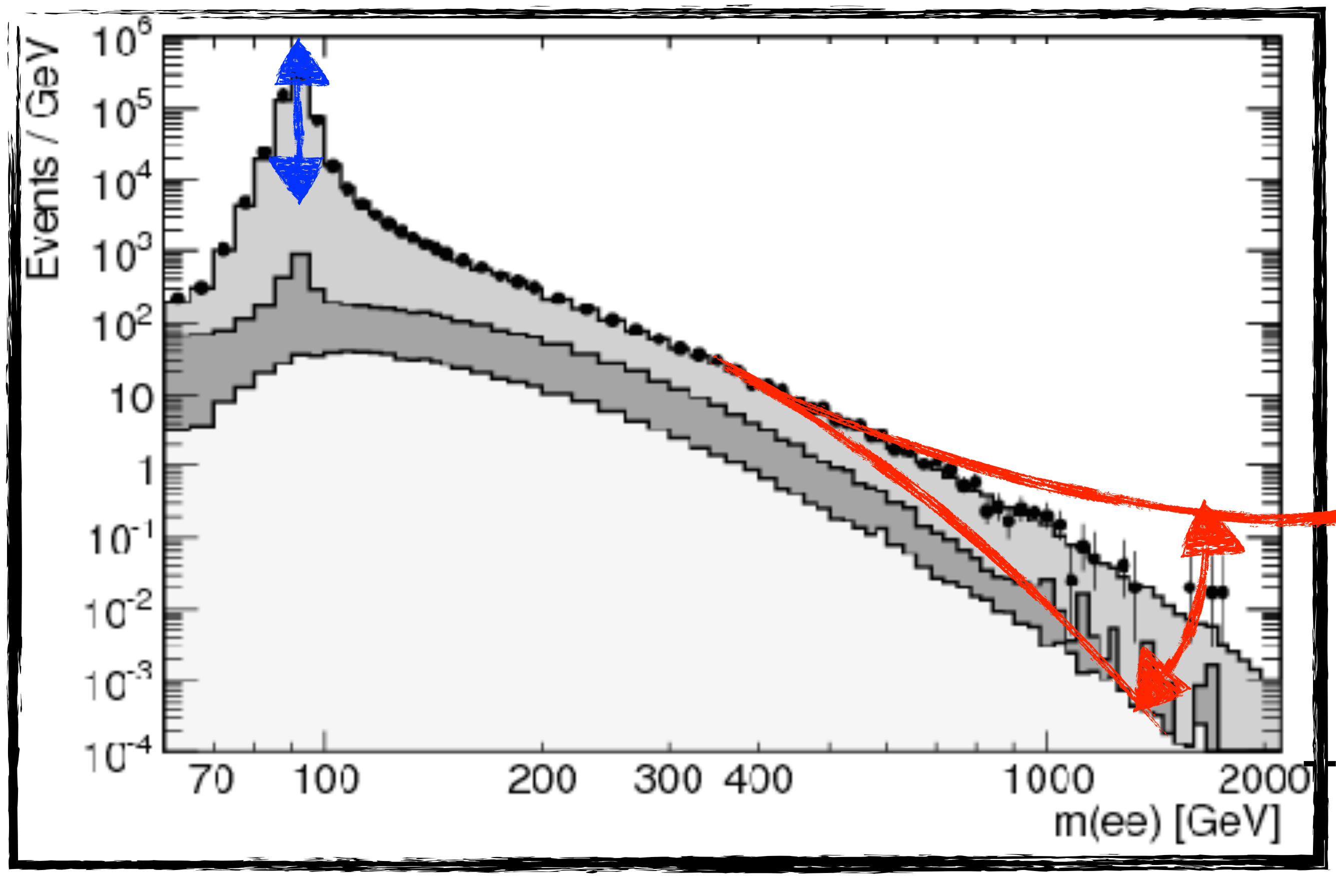
LHC Exploration
(now -> 2030's)

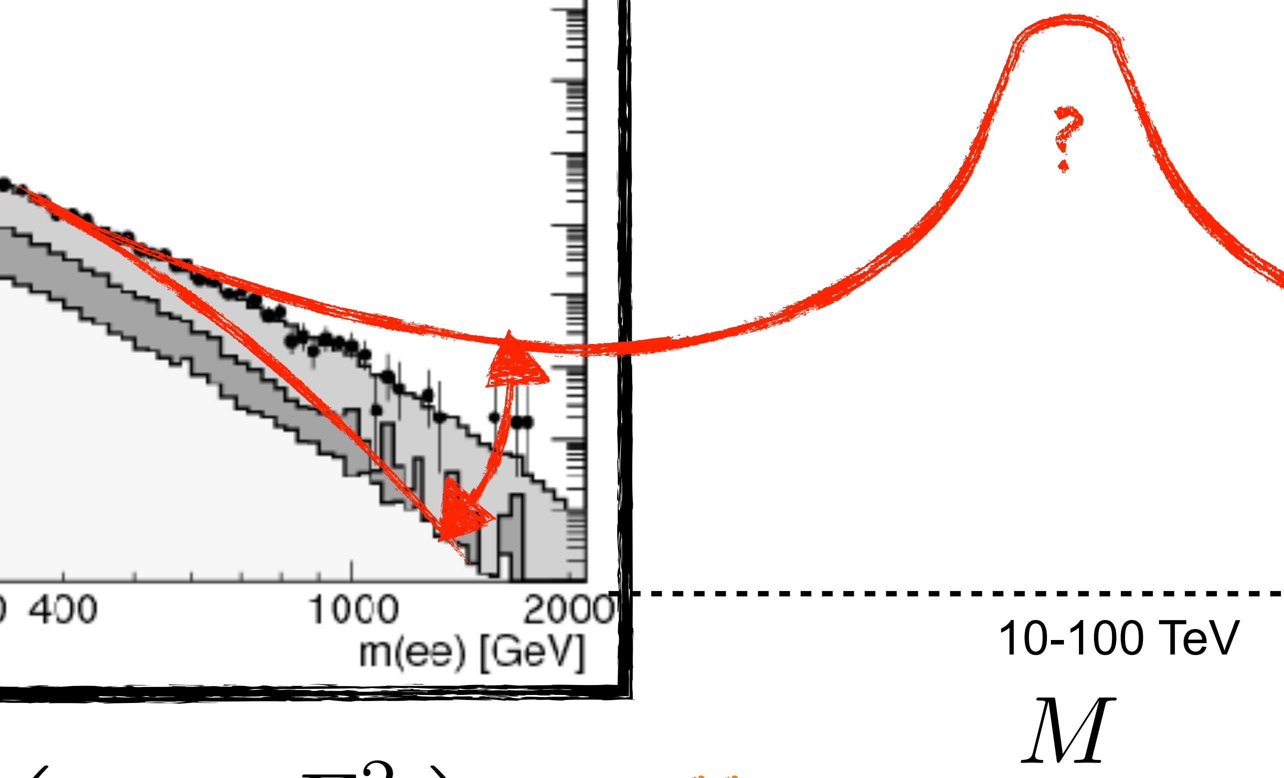
Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)





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

Effective Field Theory

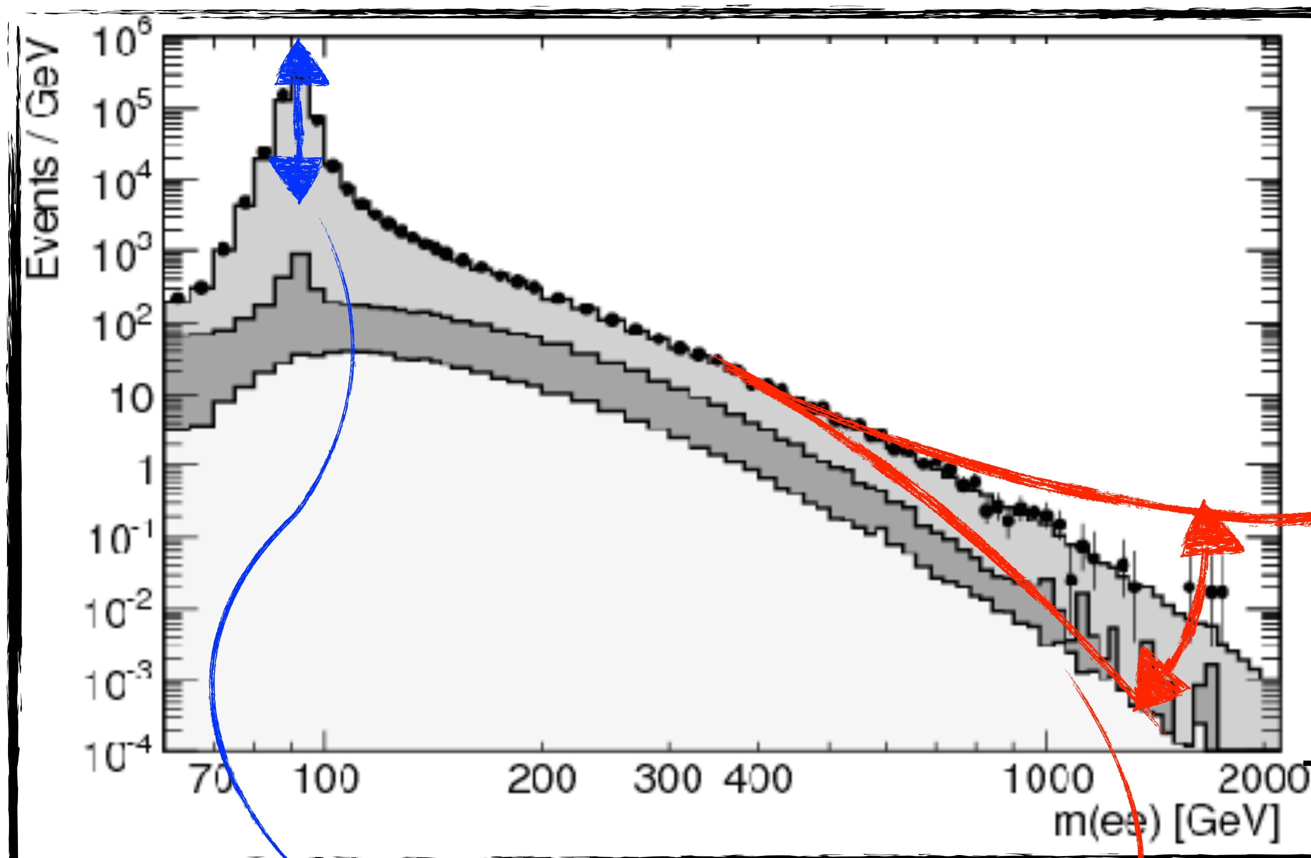
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)



?

10-100 TeV

M

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

— Effective Field Theory

LHC Exploration

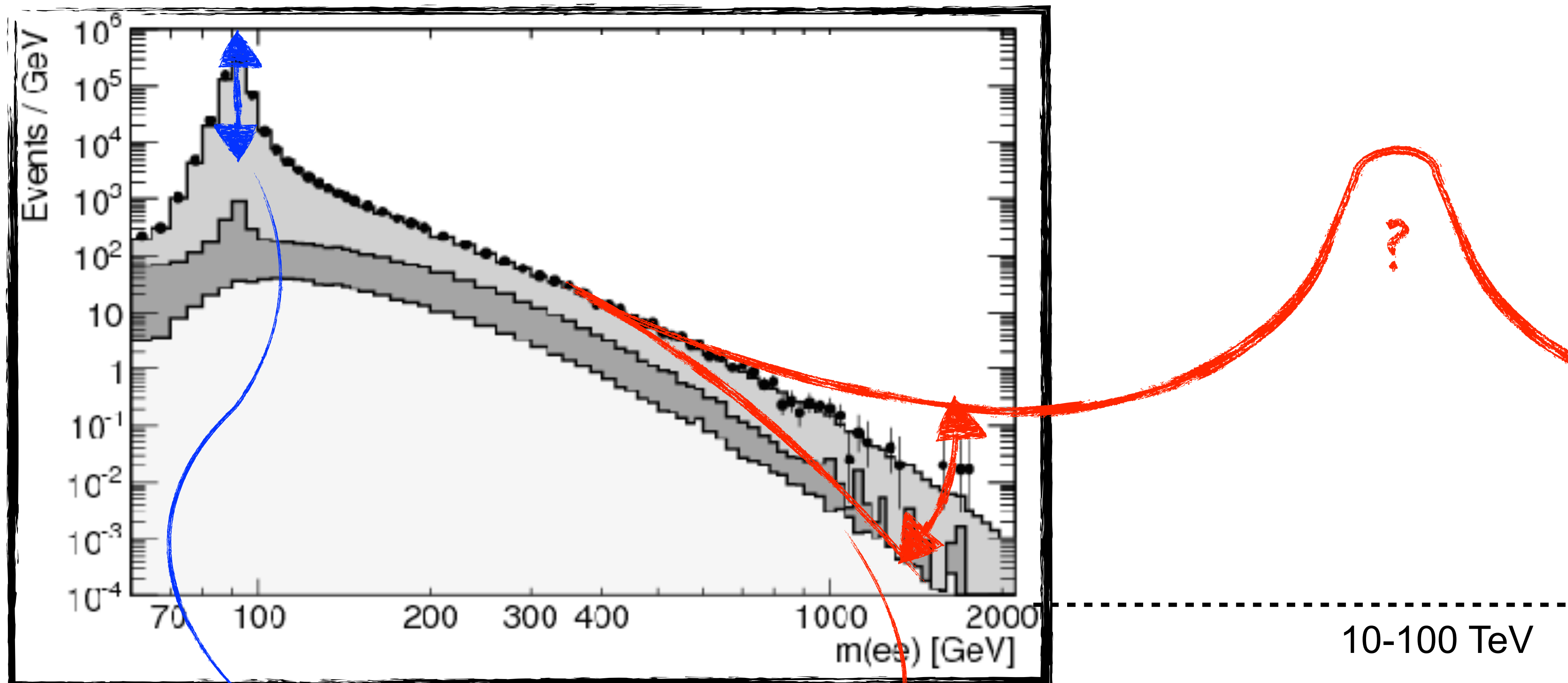
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb^{-1})

intensity frontier

(2016: 40 fb^{-1})



10-100 TeV

M

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

— Effective Field Theory

e.g. measurements of Higgs Couplings,...

- big statistics
- soon systematic limited

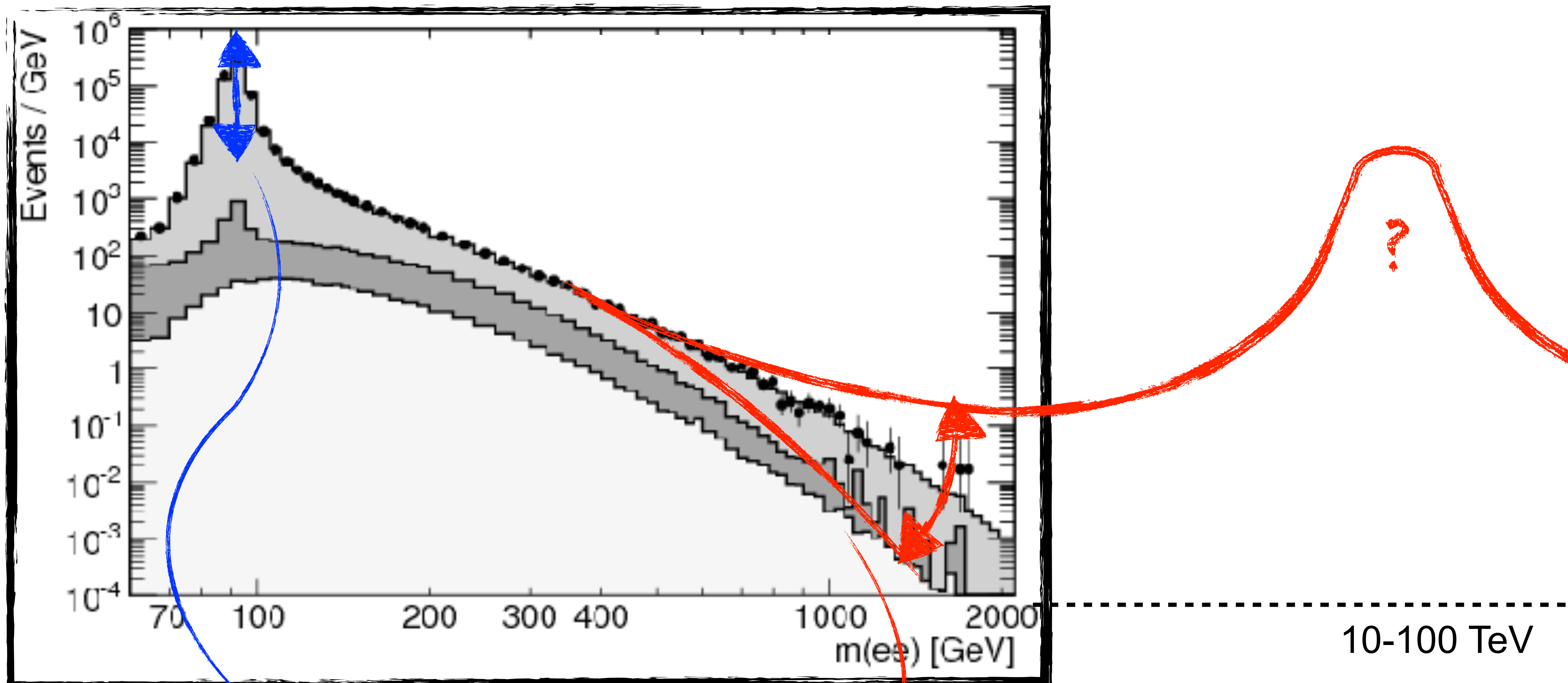
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)



$$M$$

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

— Effective Field Theory

e.g. measurements of Higgs Couplings,...

- big statistics
- soon systematic limited

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

- small statistics
- more challenging measurement
- more space for improvement

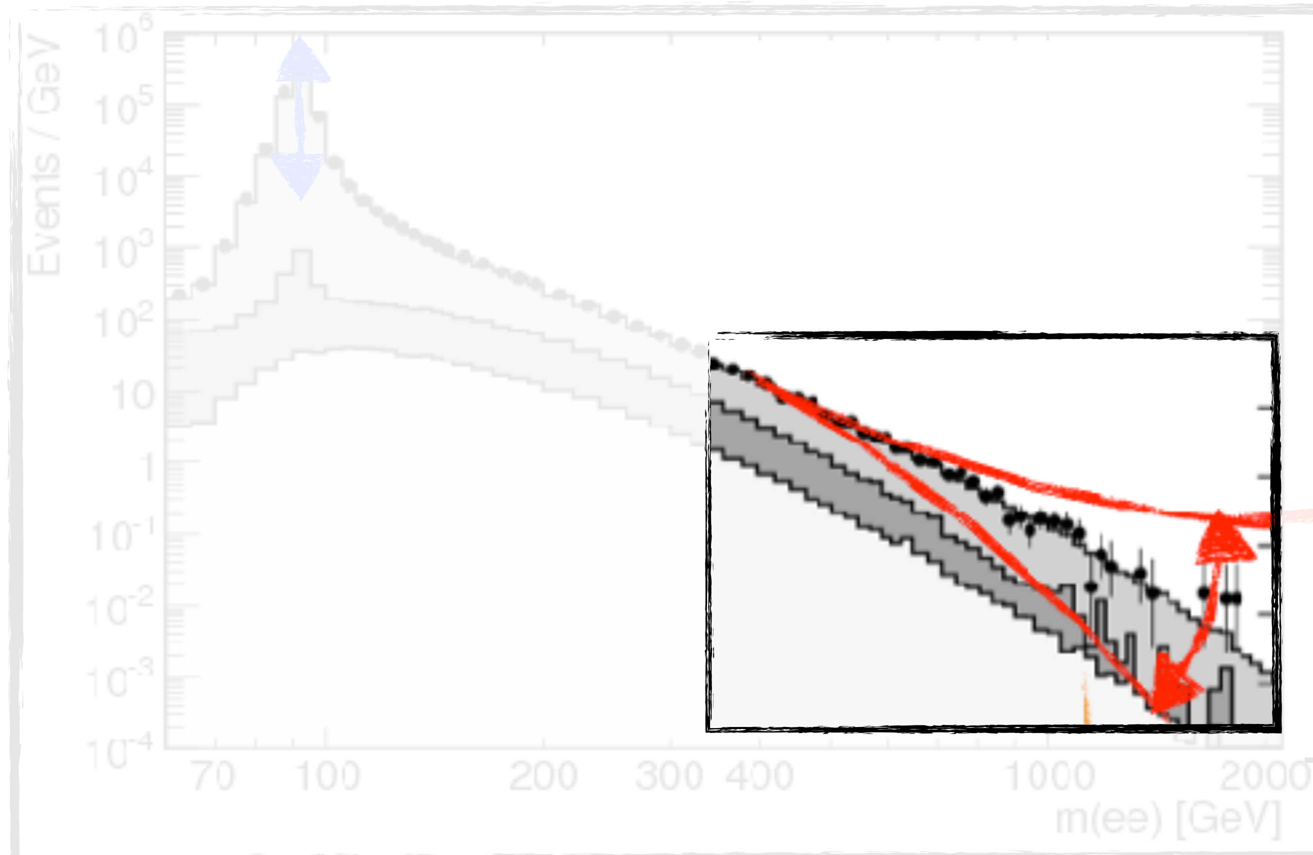
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb-1)

intensity frontier

(2016: 40 fb-1)



10-100 TeV

M

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

Effective Field Theory

- small statistics
- more challenging measurement
- more space for improvement

Outline

Intro

→ A challenge at high-E: non-interference

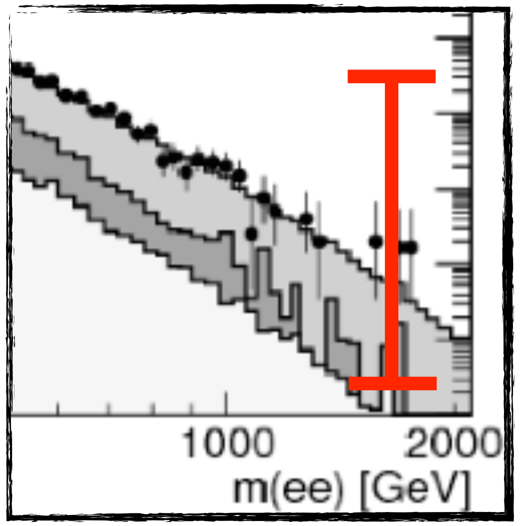
Transverse Dibosons: Interference resurrection

Longitudinal Dibosons: Interference revitalization

ZZ,Zgamma: what to search for?

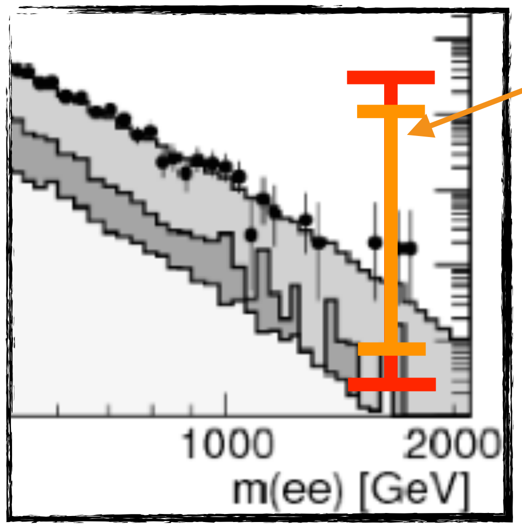
Precision at high-E

Difficult measurement with many challenges:



Precision at high-E

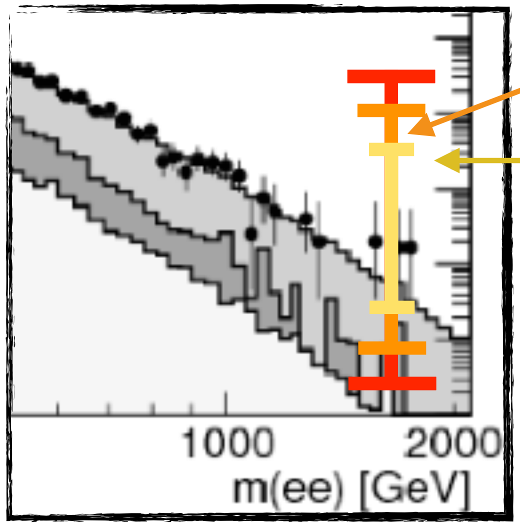
Difficult measurement with many challenges:



Precise SM theoretical predictions

Precision at high-E

Difficult measurement with many challenges:

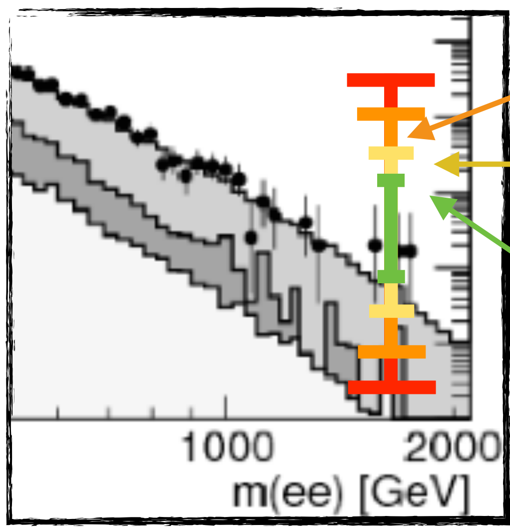


Precise SM theoretical predictions

LHC Experimental control of systematics

Precision at high-E

Difficult measurement with many challenges:



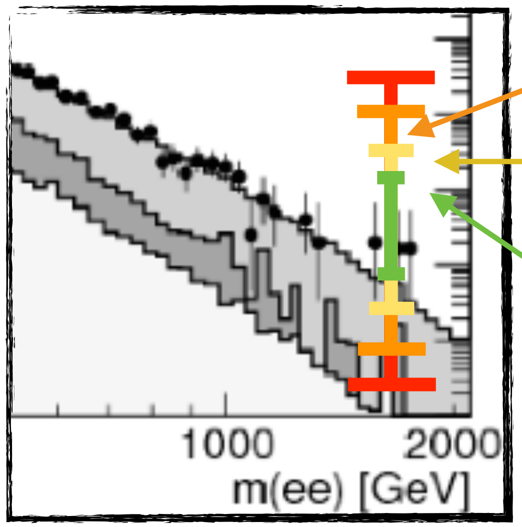
Precise SM theoretical predictions

LHC Experimental control of systematics

BSM understanding

Precision at high-E

Difficult measurement with many challenges:



Precise SM theoretical predictions

LHC Experimental control of systematics

BSM understanding

!(non-)interference!

Why Interference?

When SM and BSM contribute to the same amplitude:

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

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

Why Interference?

When SM and BSM contribute to the same amplitude:

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

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

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

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?

If SM and BSM contribute to different amplitudes:

interference vanishes

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

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

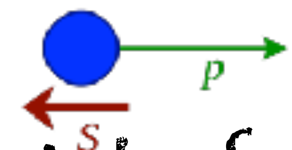
- Small effects, even smaller!

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

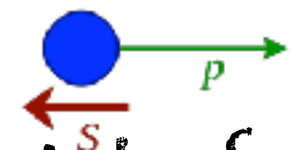
helicity

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

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

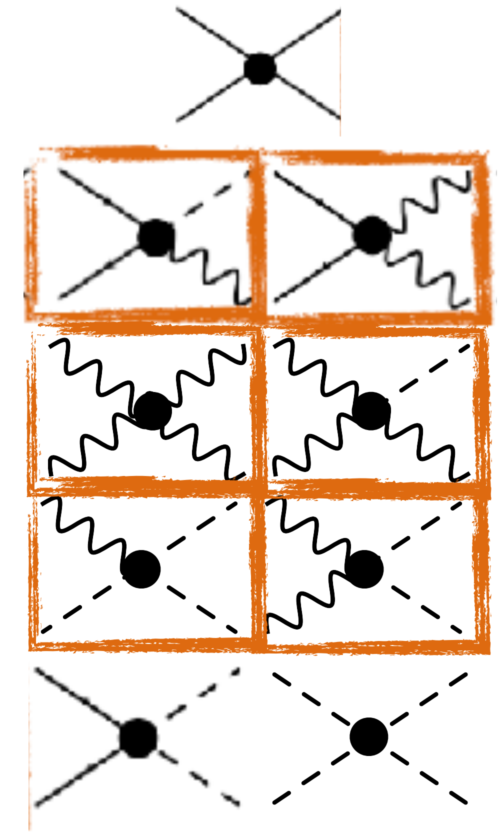
helicity

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
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Different helicity

No-Interference

Poor Measurement

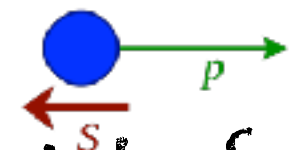


Non-Interference

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

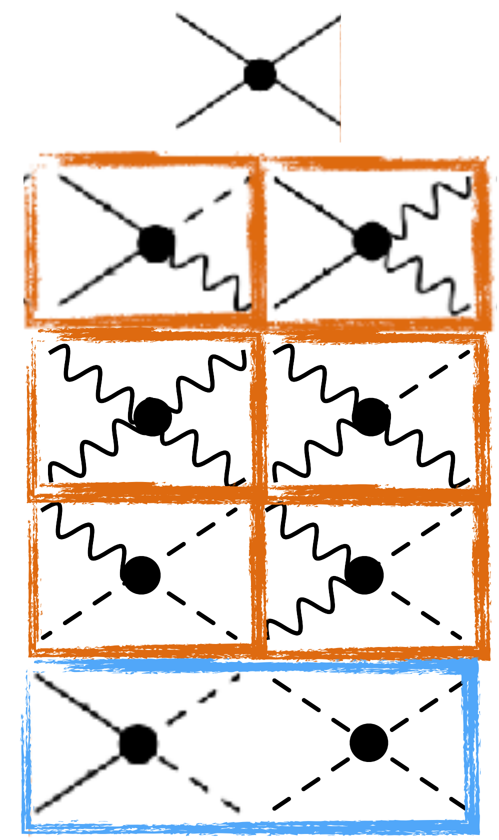
helicity

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
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Different helicity

No-Interference

Poor Measurement



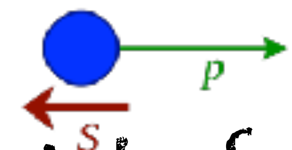
Small in inclusive xsec

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

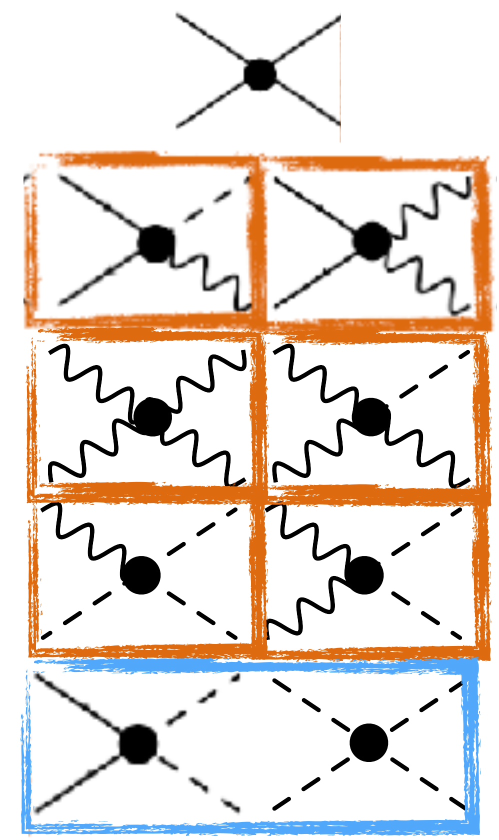
helicity

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Different helicity

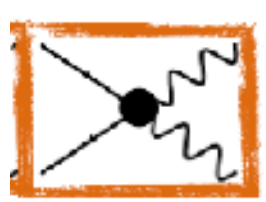
No-Interference

Poor Measurement

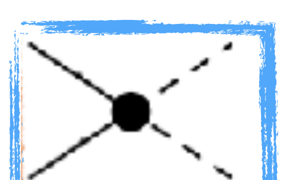


Small in inclusive xsec

I will discuss:



Resurrect Interference



Revitalize Interference

Outline

Intro

A challenge at high-E: non-interference

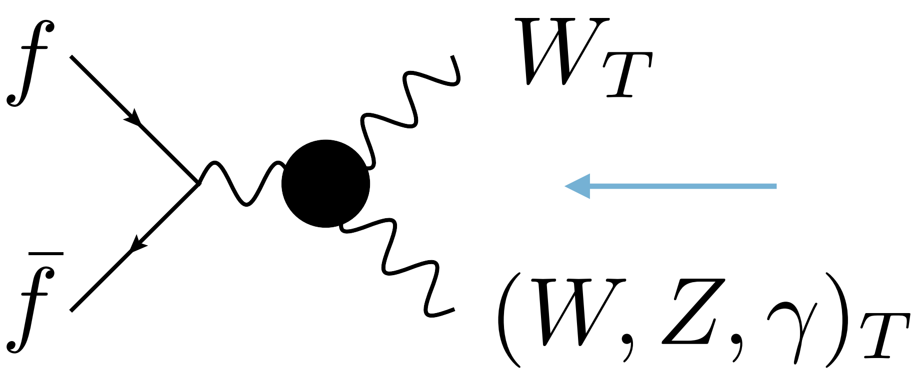
Transverse Dibosons: Interference resurrection

Longitudinal Dibosons: Interference revitalization

ZZ,Zgamma: what to search for?

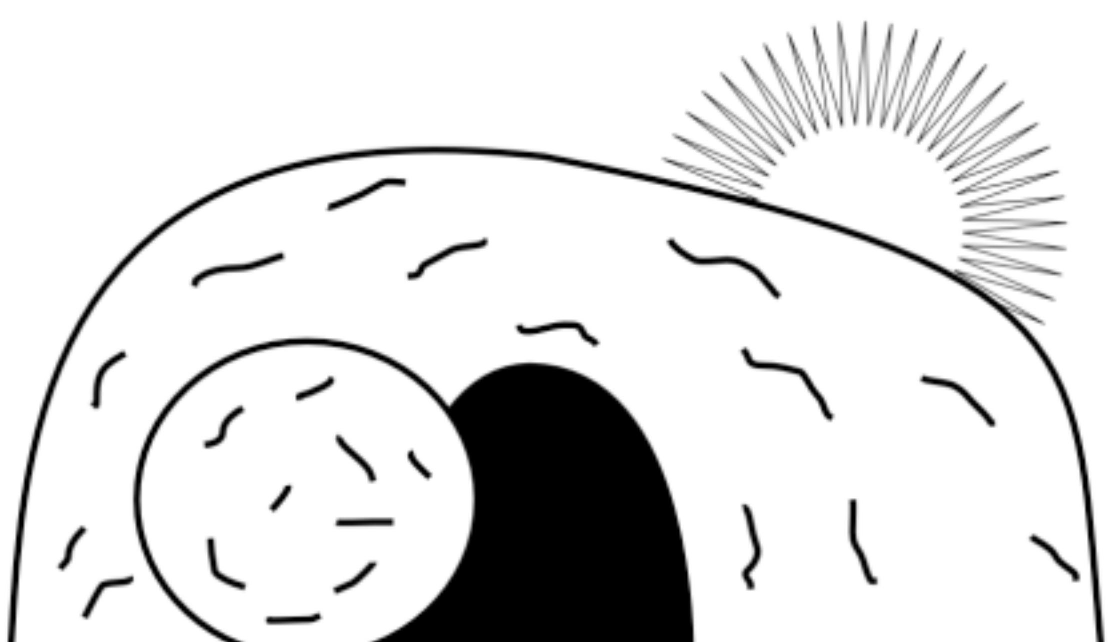
Interference Resurrection

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



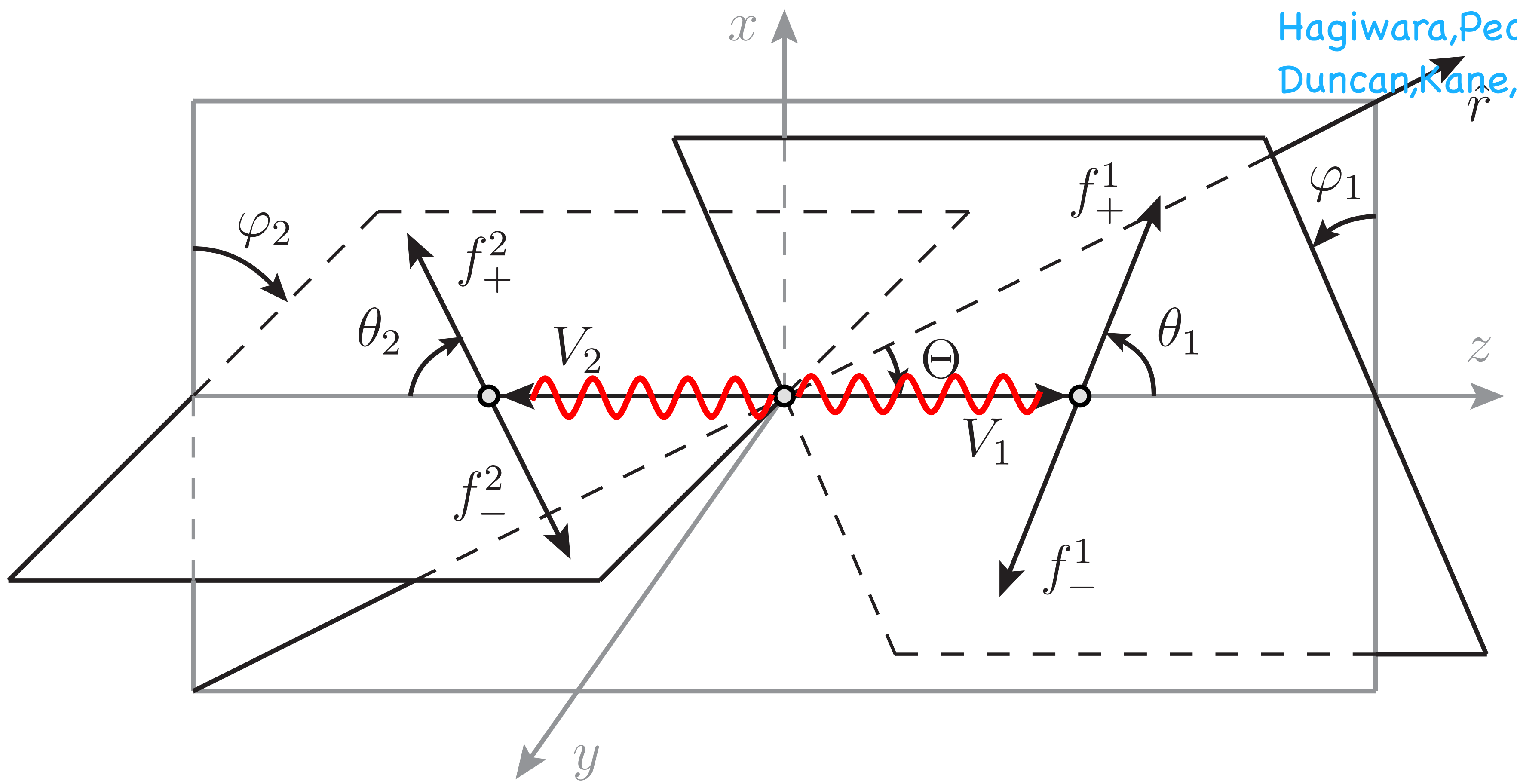
$$\epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu} \quad \text{CP-even}$$

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



Differential measurements WW, WZ

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

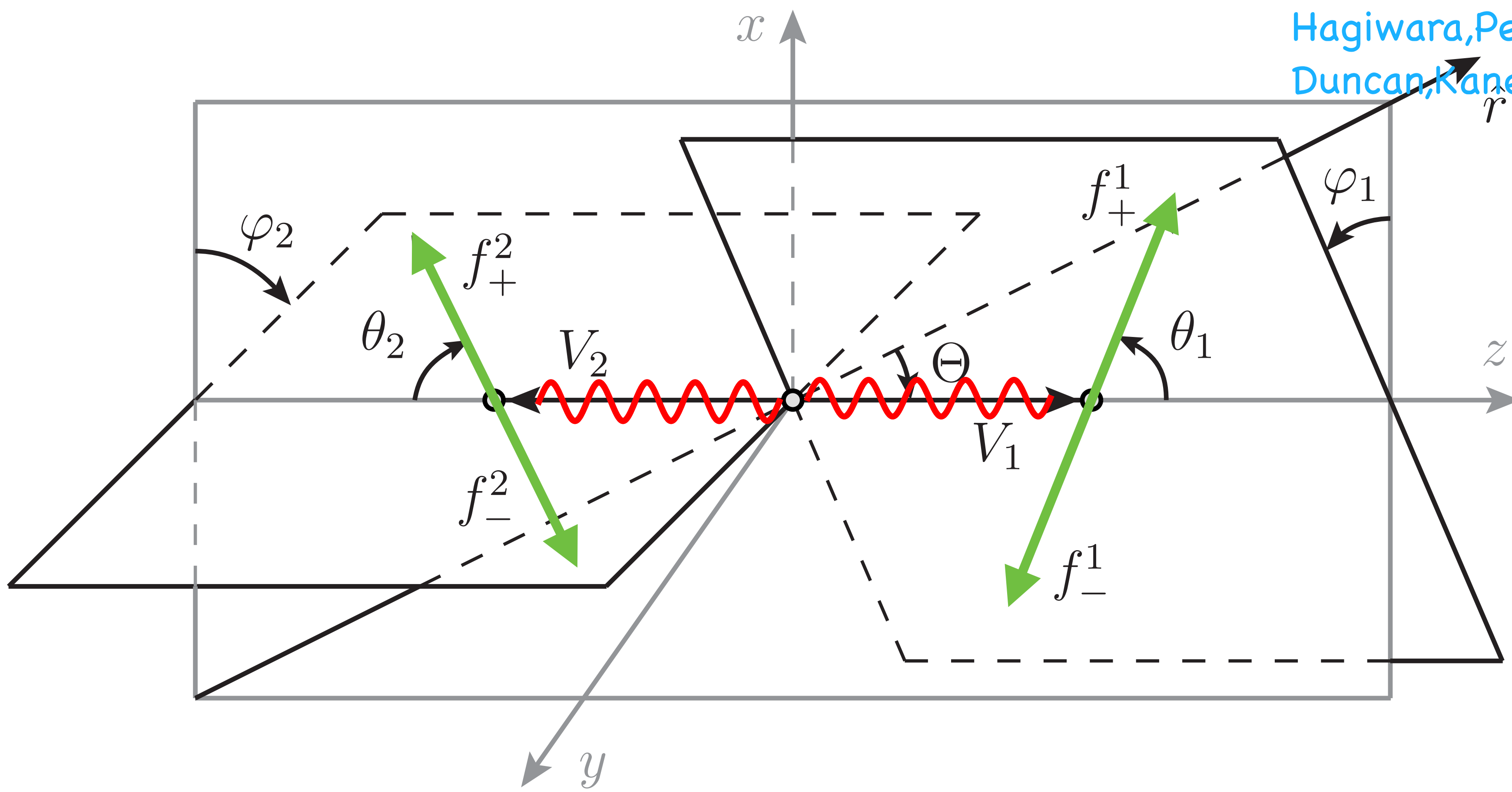


$V_{1,2}$: Helicity ±∓/±± in SM/BSM

- Quantum mechanically different, no interference

Differential measurements WW, WZ

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



$V_{1,2}$: Helicity ±∓/±± in SM/BSM

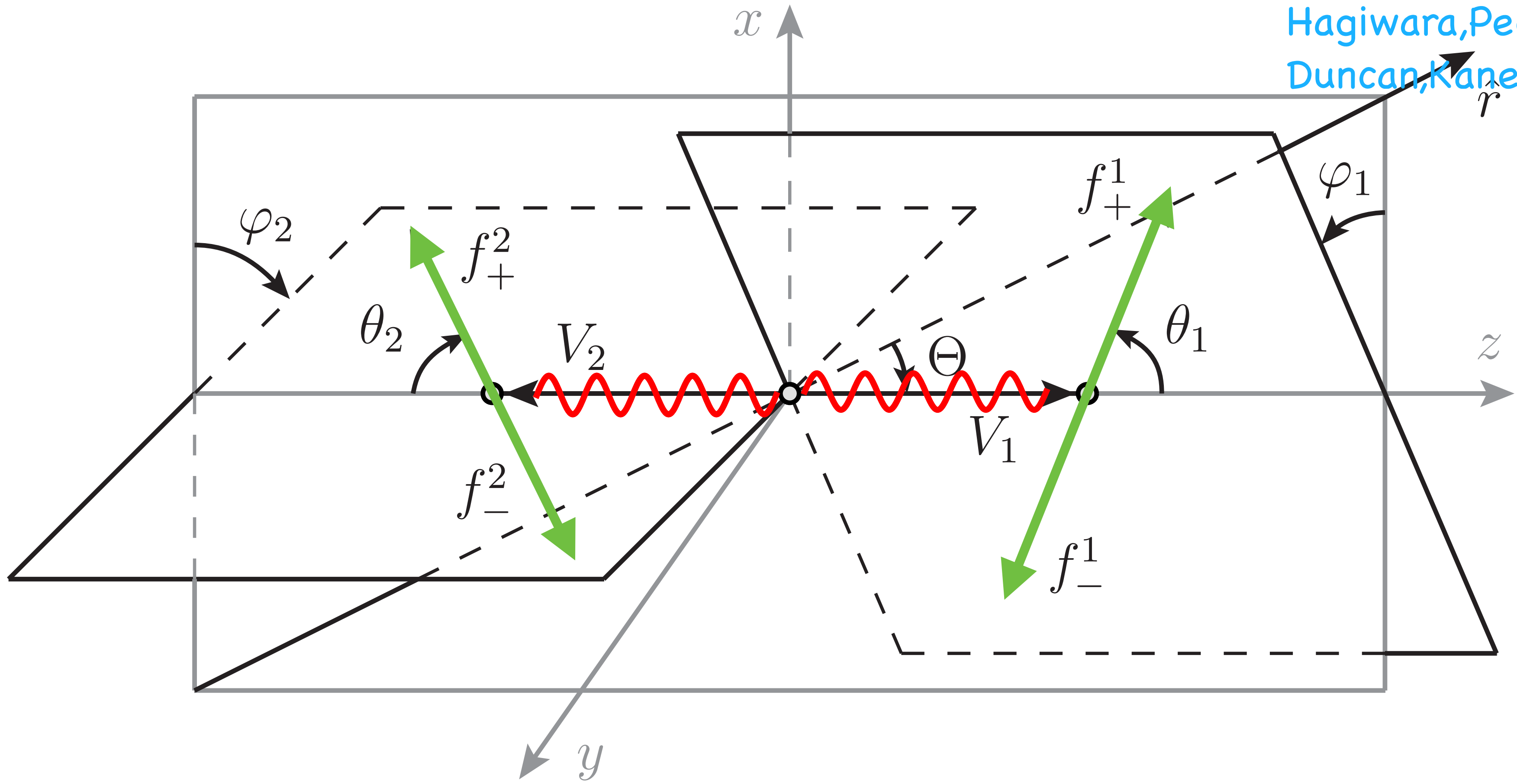
- Quantum mechanically different, no interference

$f_{(1,3)}$ $f_{(2,4)}$: 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



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

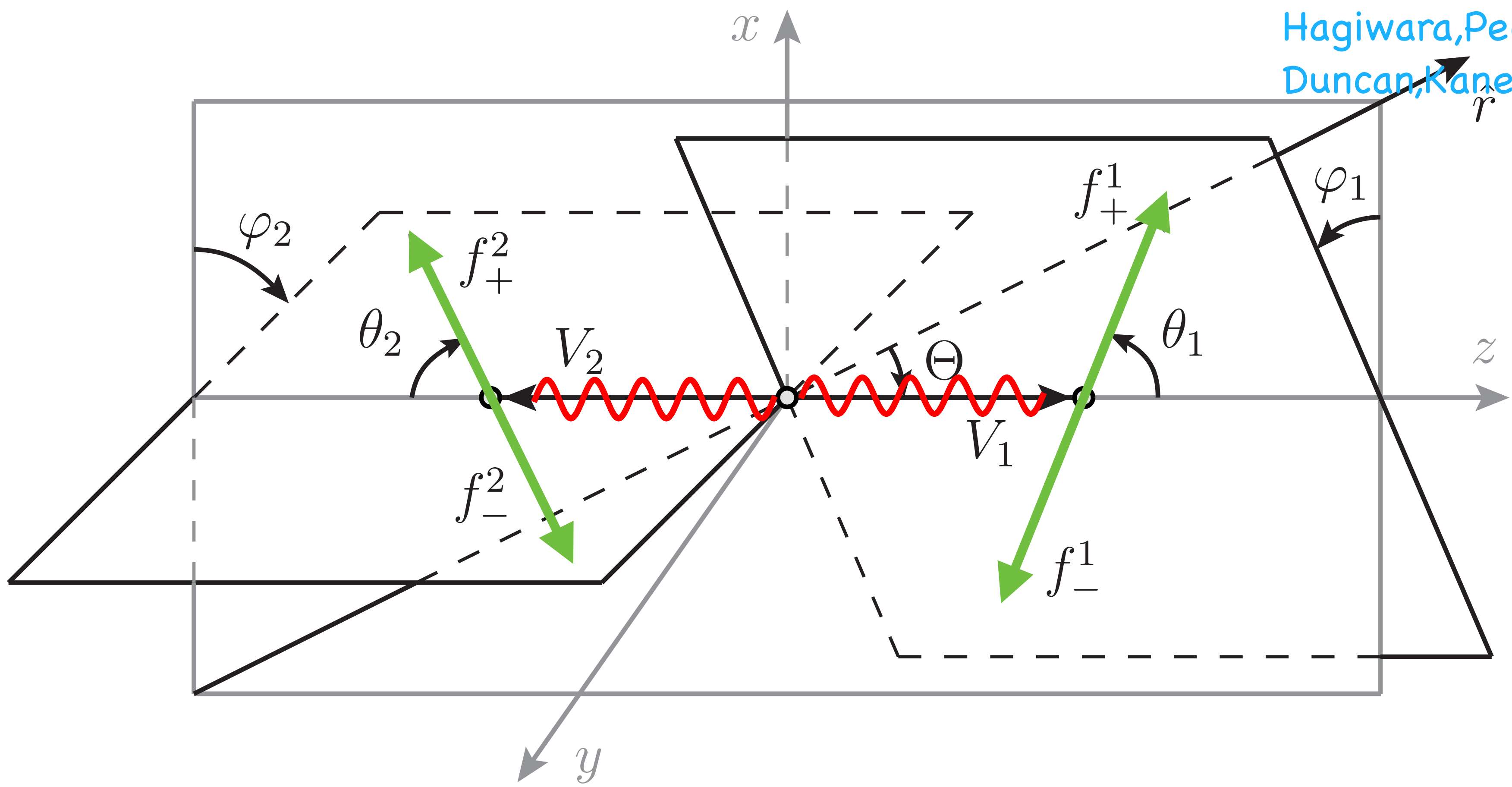
$$Int^{\text{CP}} \propto \mathcal{A}^{\text{SM}}_{\mathbf{h}} \mathcal{A}^{\text{BSM}+}_{\mathbf{h}'} \cos[\boldsymbol{\Delta}\mathbf{h} \cdot \boldsymbol{\varphi}]$$

$(+1, -1)$ $(+1, +1)$ (φ_1, φ_2)

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

Differential measurements WW, WZ

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



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

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

$(+1,-1)$ $(+1,+1)$ (φ_1, φ_2)

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

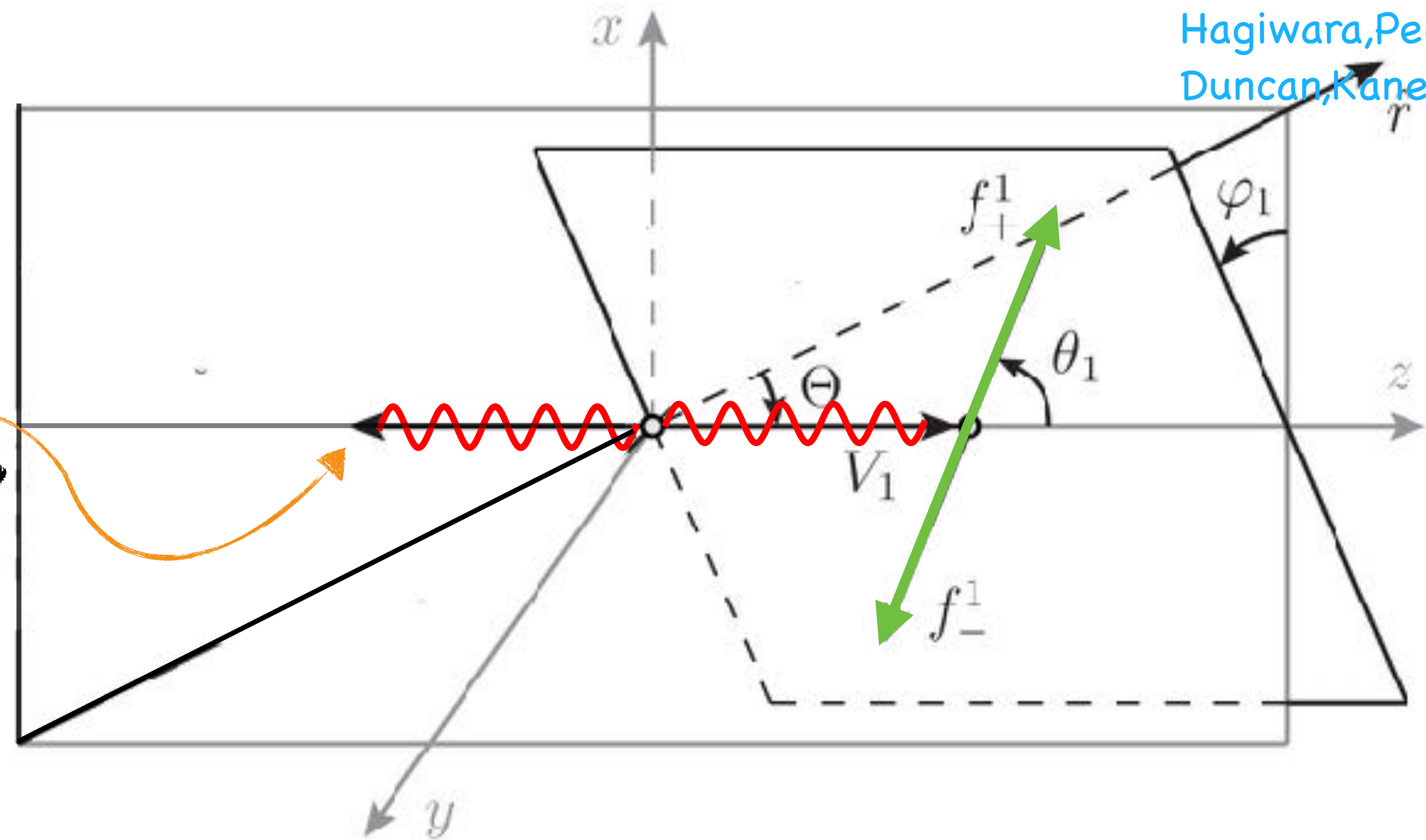
- Cancels when integrated over $\varphi \in [-\pi, \pi]$

Differential measurements Wγ

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

$W\gamma$

No (leptonic) Branching Ratio



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

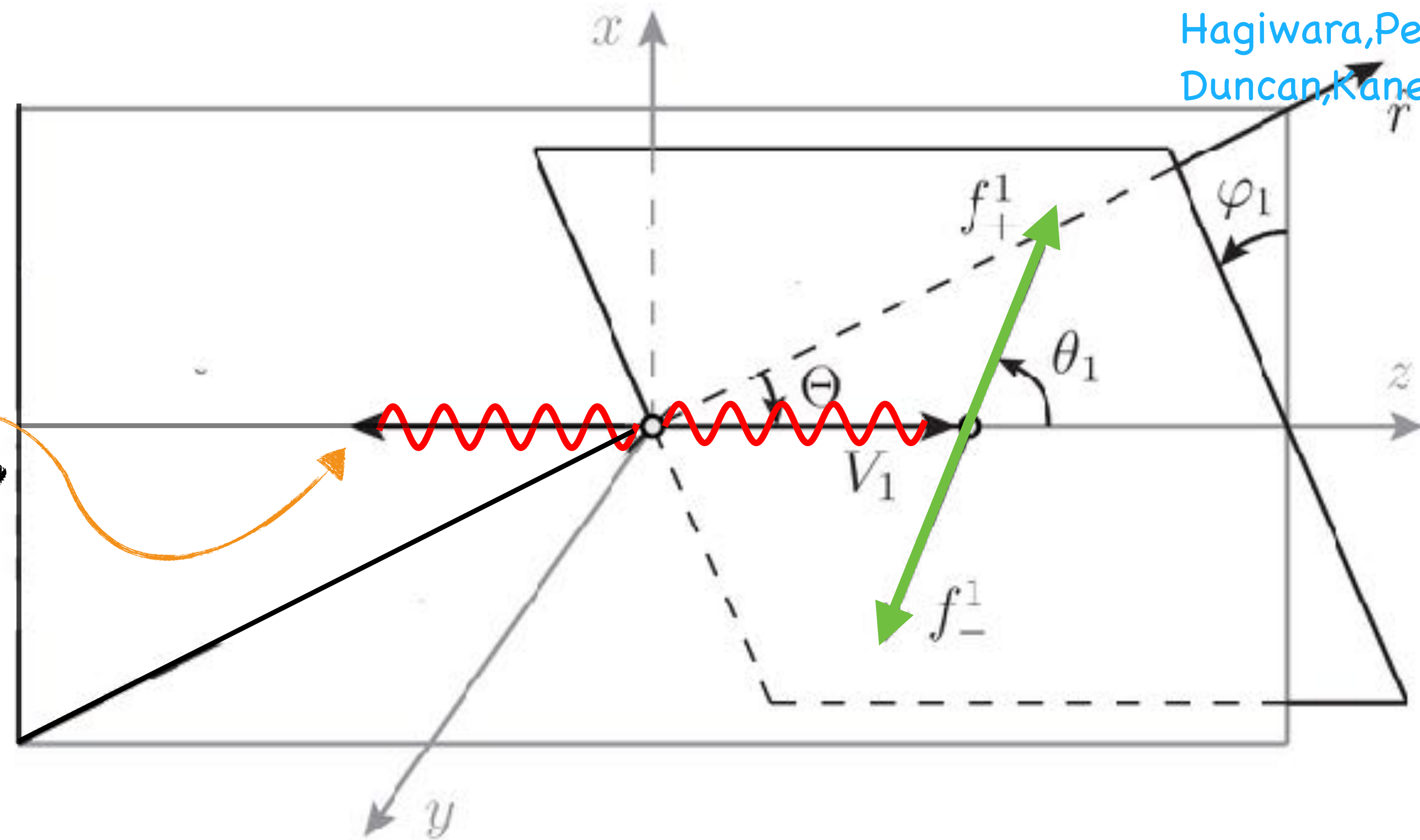
$$Int^{\not{\rm C}\rm P} = 2ig^2 \sin^2\theta \mathcal{A}_{++}^{\rm BSM-} \left[\mathcal{A}_{-+}^{\rm SM} - \mathcal{A}_{+-}^{\rm SM}\right] \sin 2\varphi$$

Differential measurements Wγ

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

$W\gamma$

No (leptonic) Branching Ratio



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

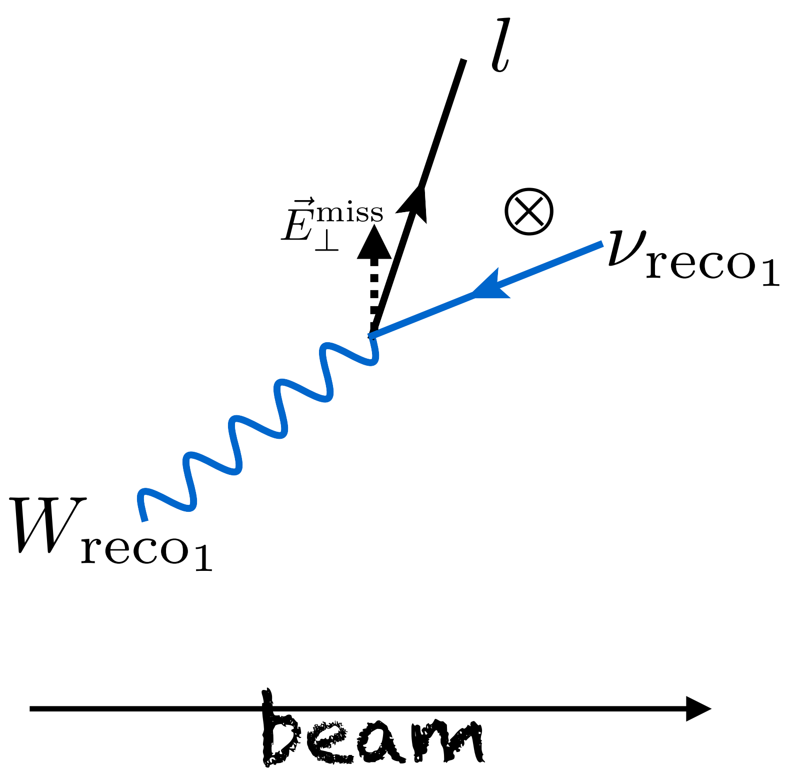
$$Int^{\not{\rm C}\not{\rm P}} = 2ig^2 \sin^2\theta \mathcal{A}^{\rm BSM-}_{++}\left[\mathcal{A}^{\rm SM}_{-+} - \mathcal{A}^{\rm SM}_{+-}\right]\sin 2\varphi$$

Differential azimuthal distributions = SM-BSM interference

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)

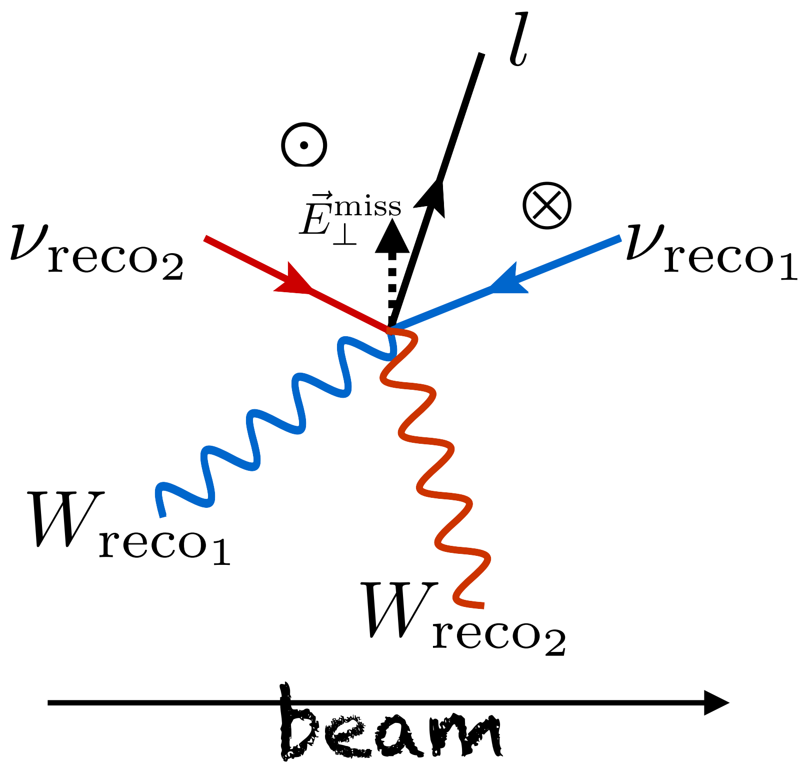


Panico,FR,Wulzer'17

Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

1)

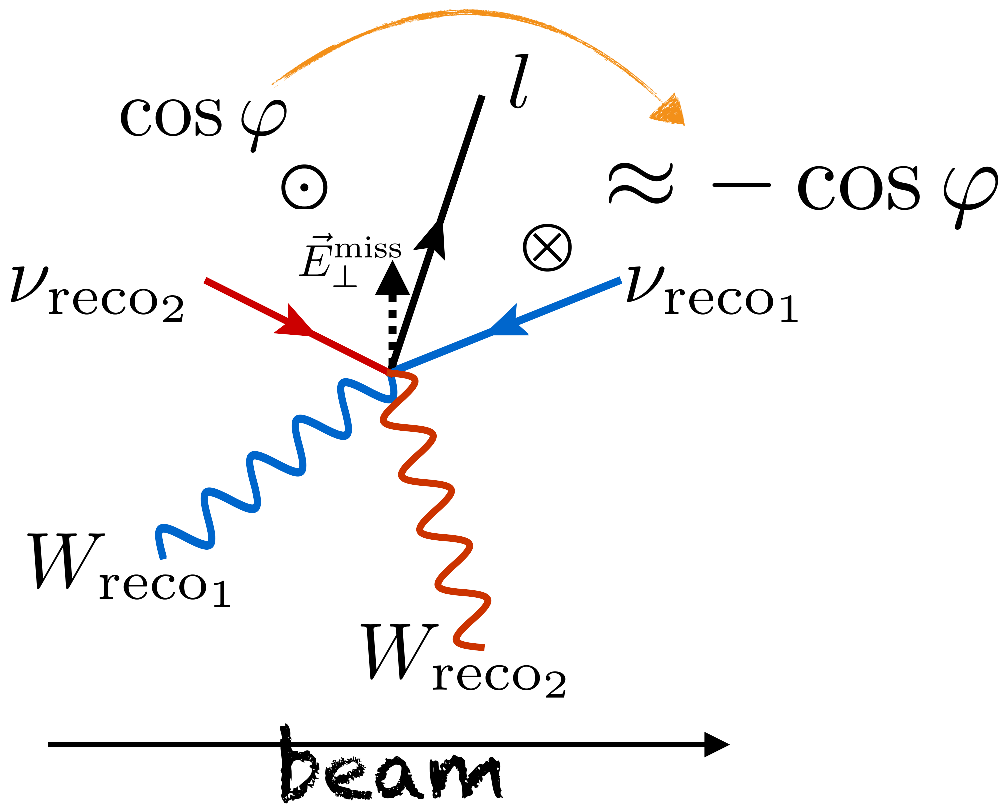


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)

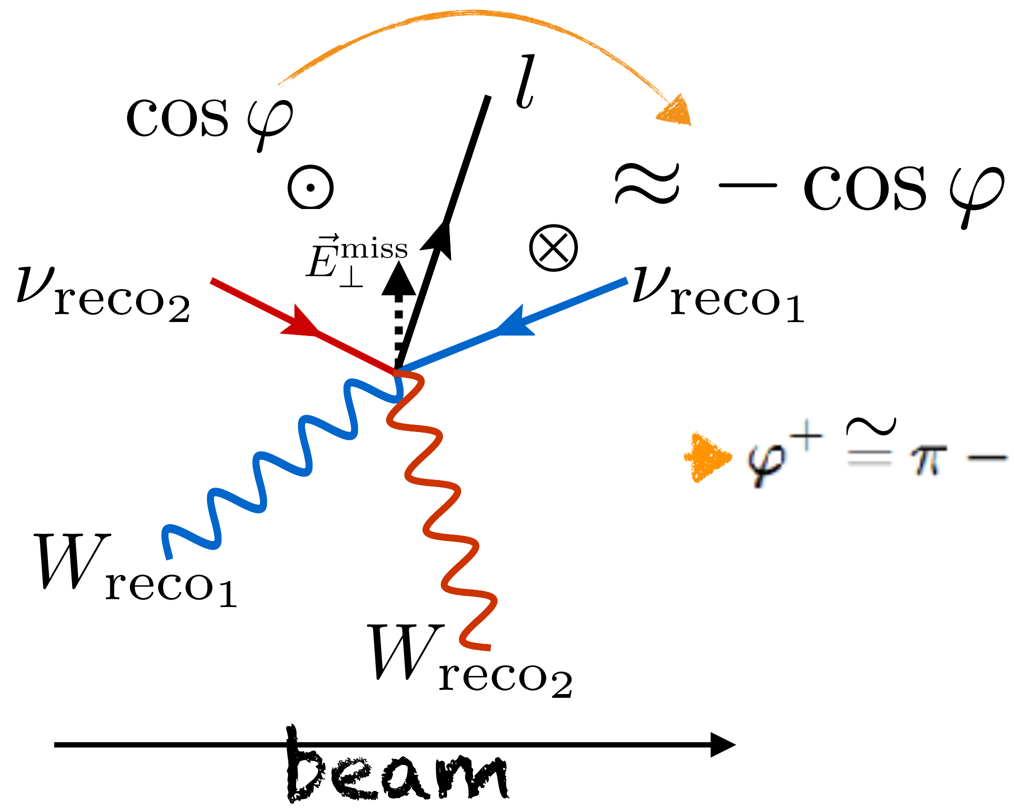


Panico,FR,Wulzer'17

Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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

φ_{reco}

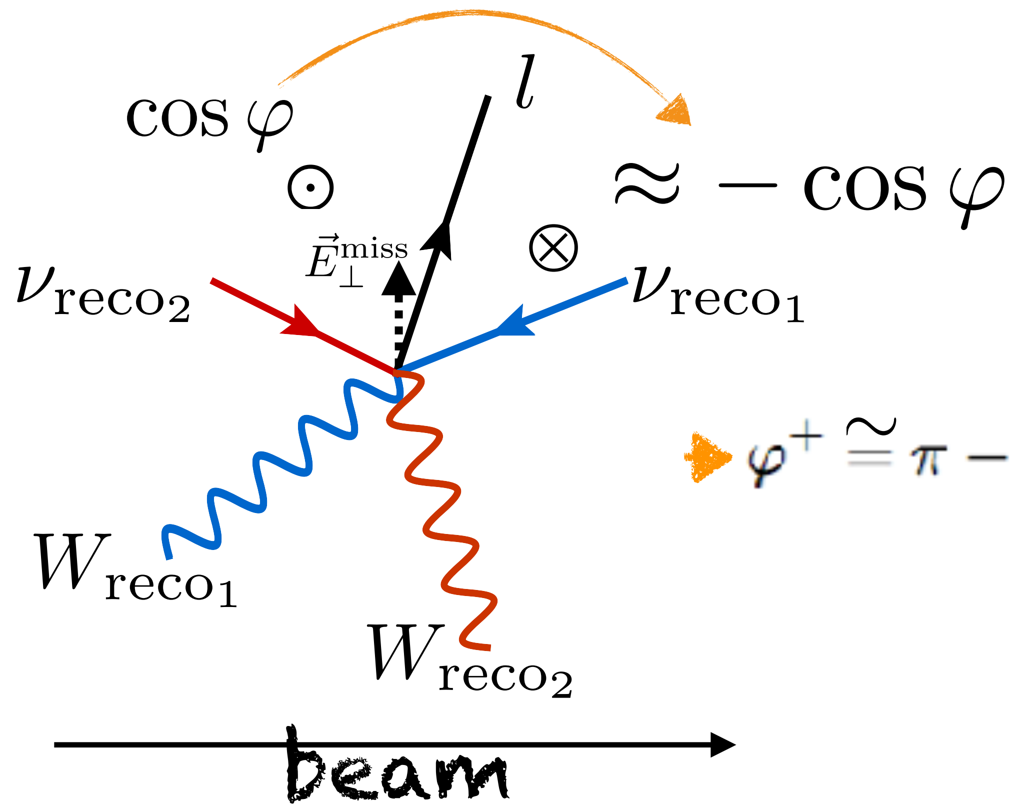
φ_{true}

Panico,FR,Wulzer'17

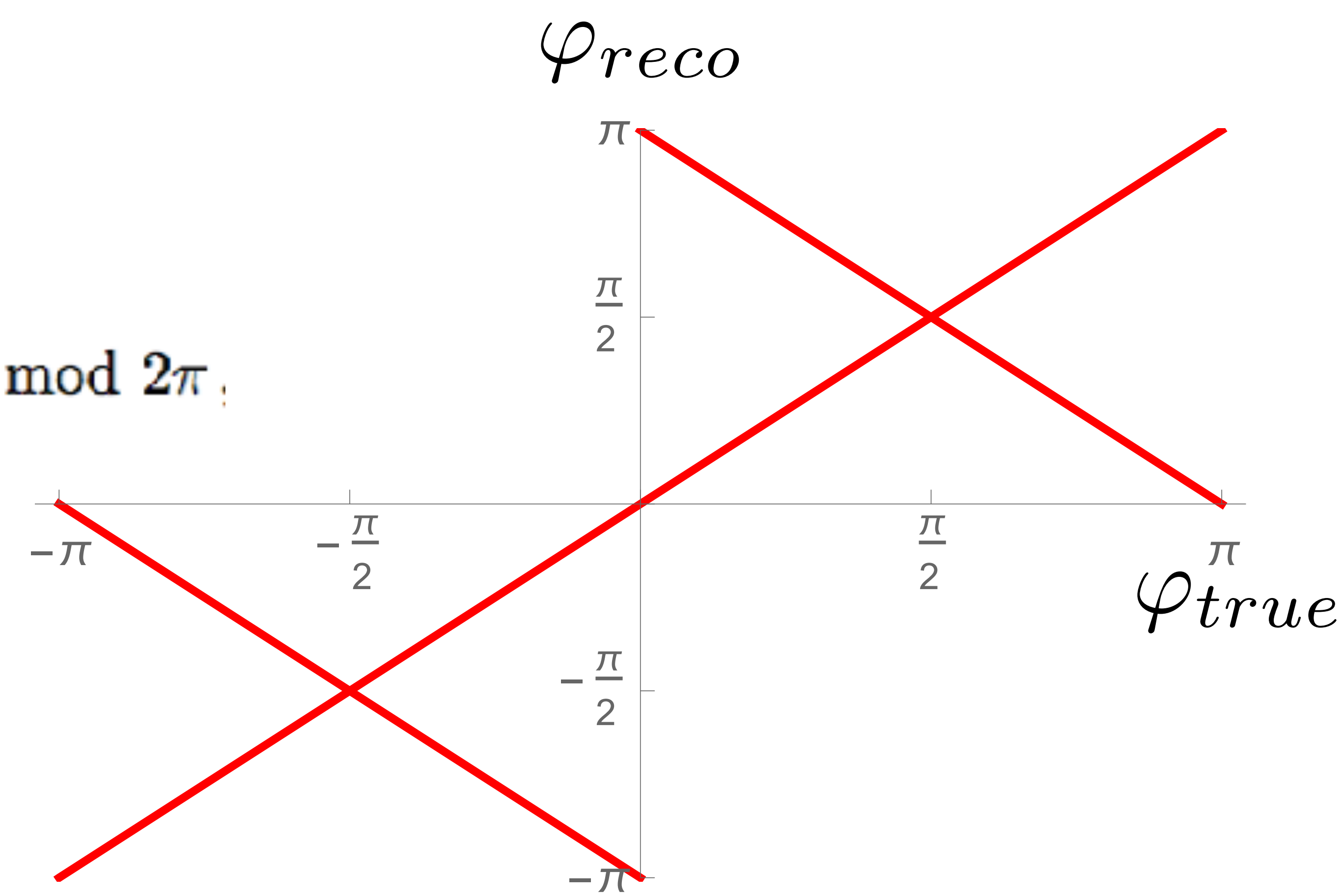
Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

1)



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

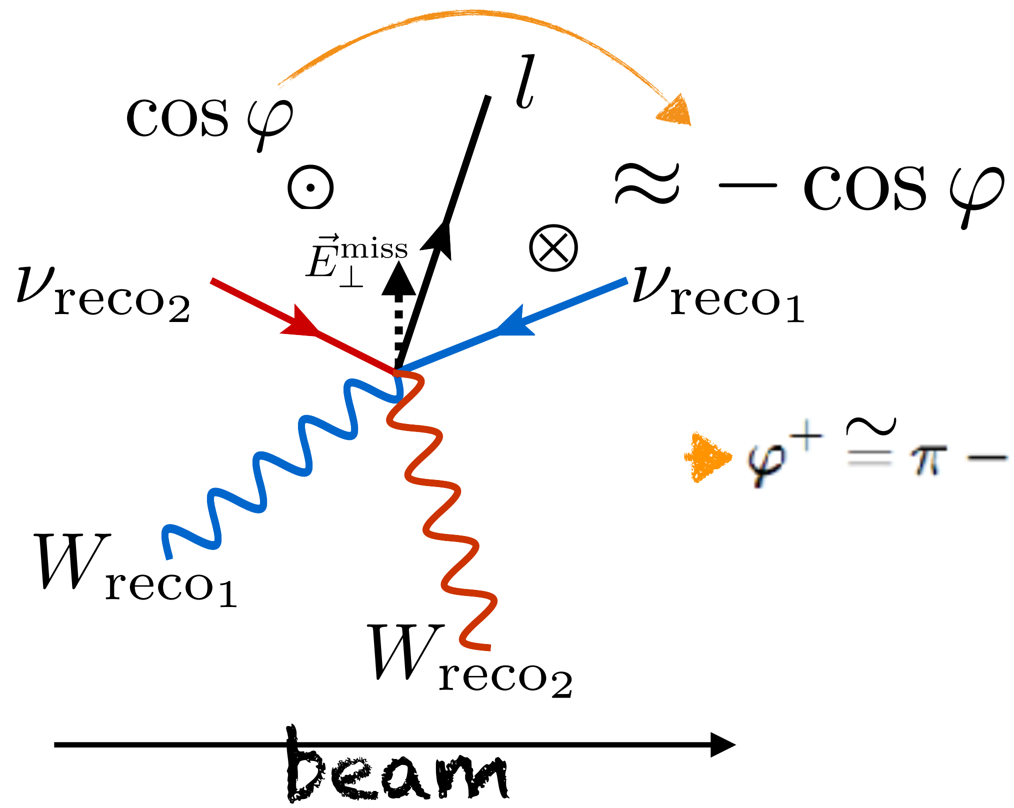


Panico,FR,Wulzer'17

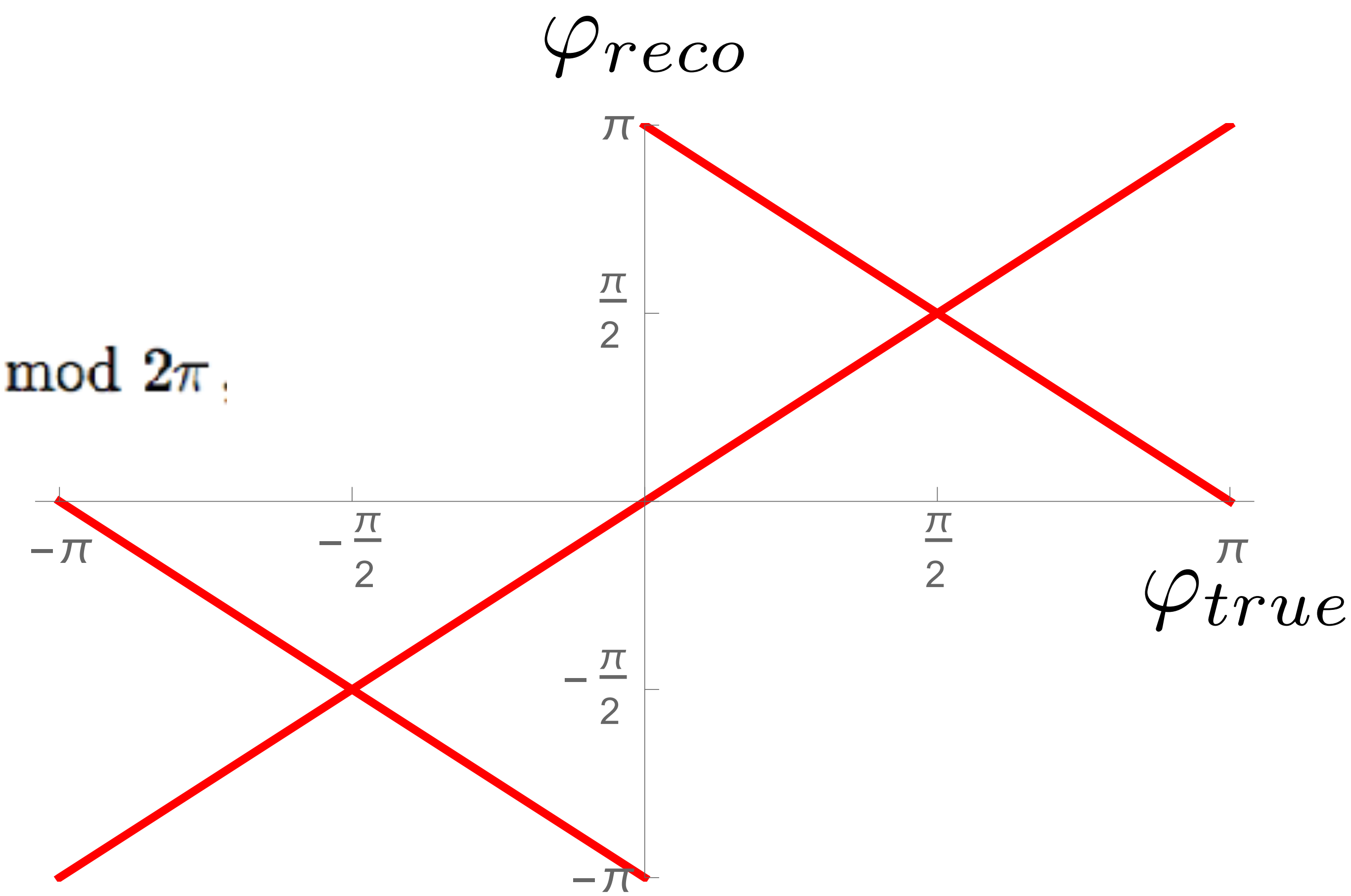
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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



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

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

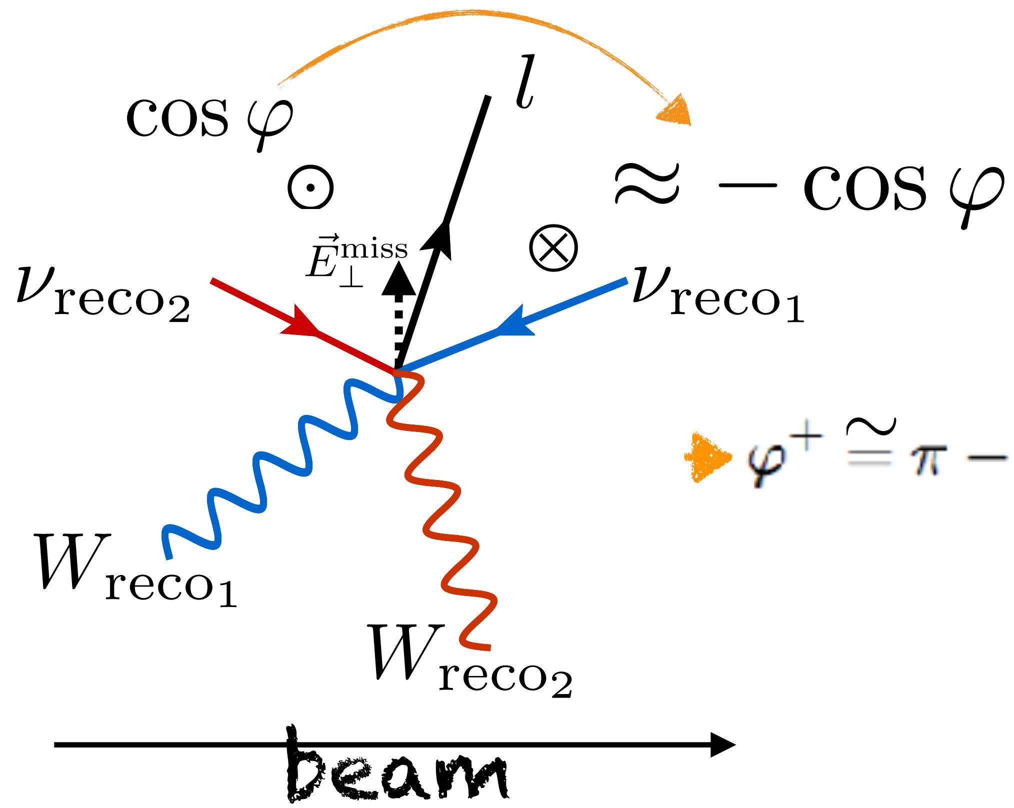
$\varphi = \pi/2 \quad \text{or} \quad \varphi = -\pi/2.$

Panico,FR,Wulzer'17

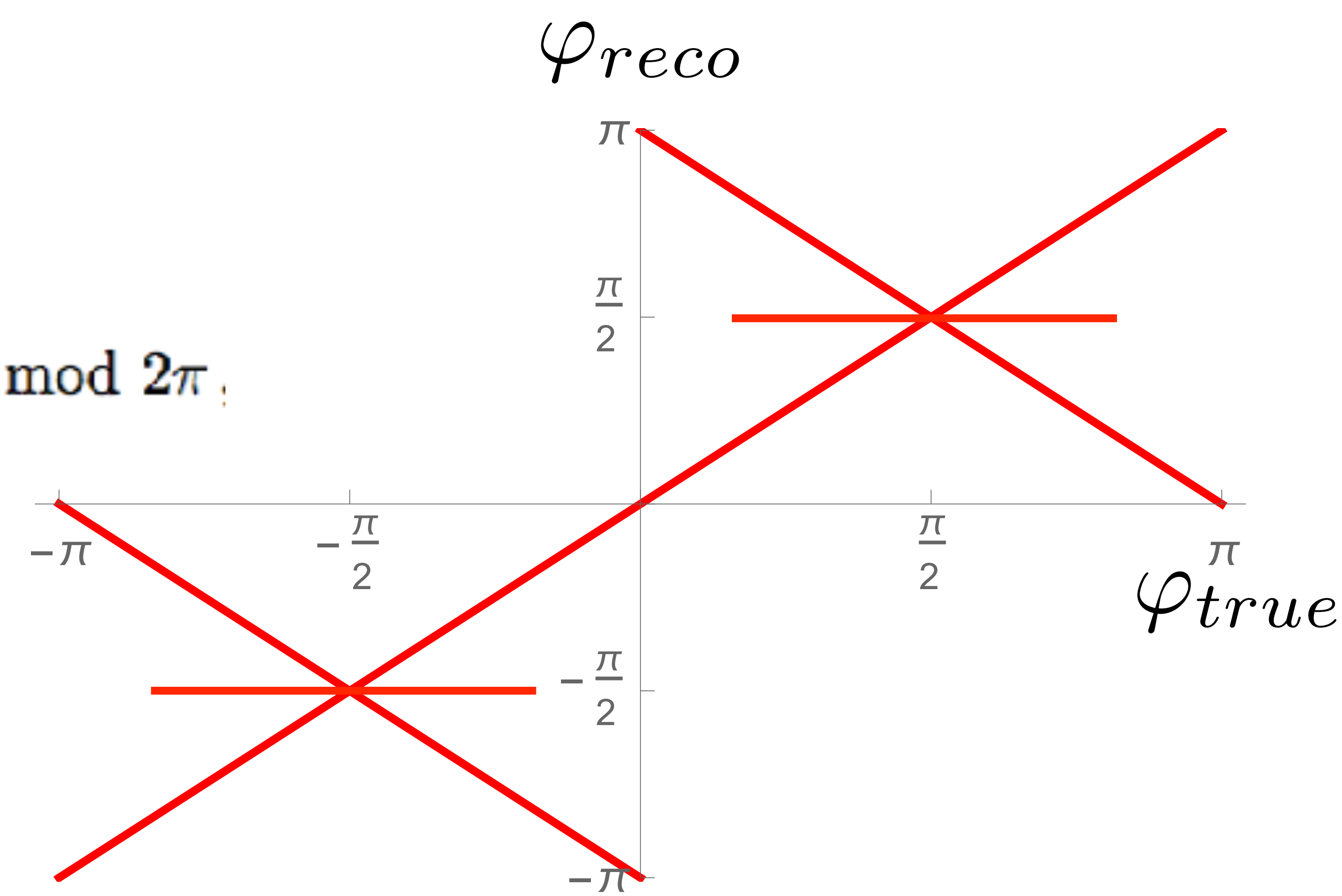
Azimuthal Angle… in reality

Neutrino: from missing energy + reconstruct W mass

1)



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



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

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

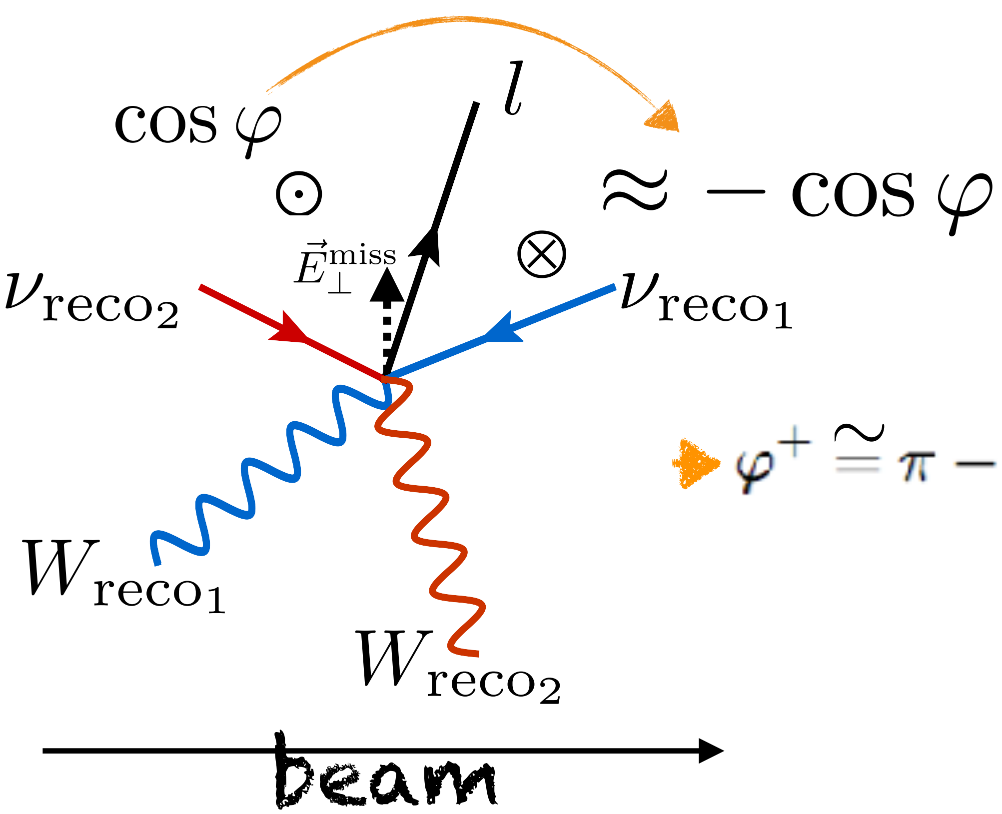
▸ $\varphi = \pi/2$ or $\varphi = -\pi/2$.

Panico,FR,Wulzer'17

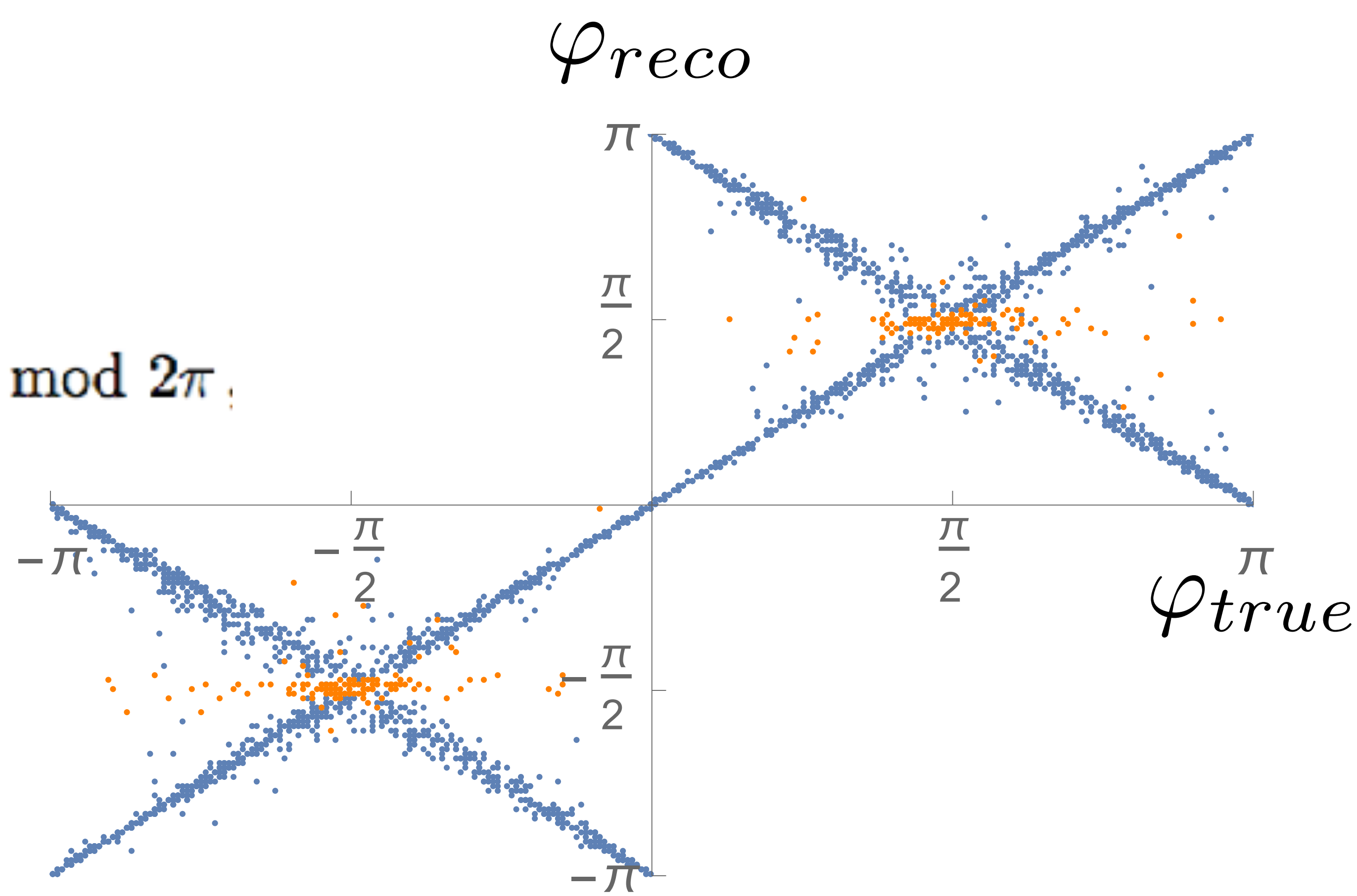
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



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



2) Some events: $m_\perp^2 > m_W^2$

(off-shell, exp.error)

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

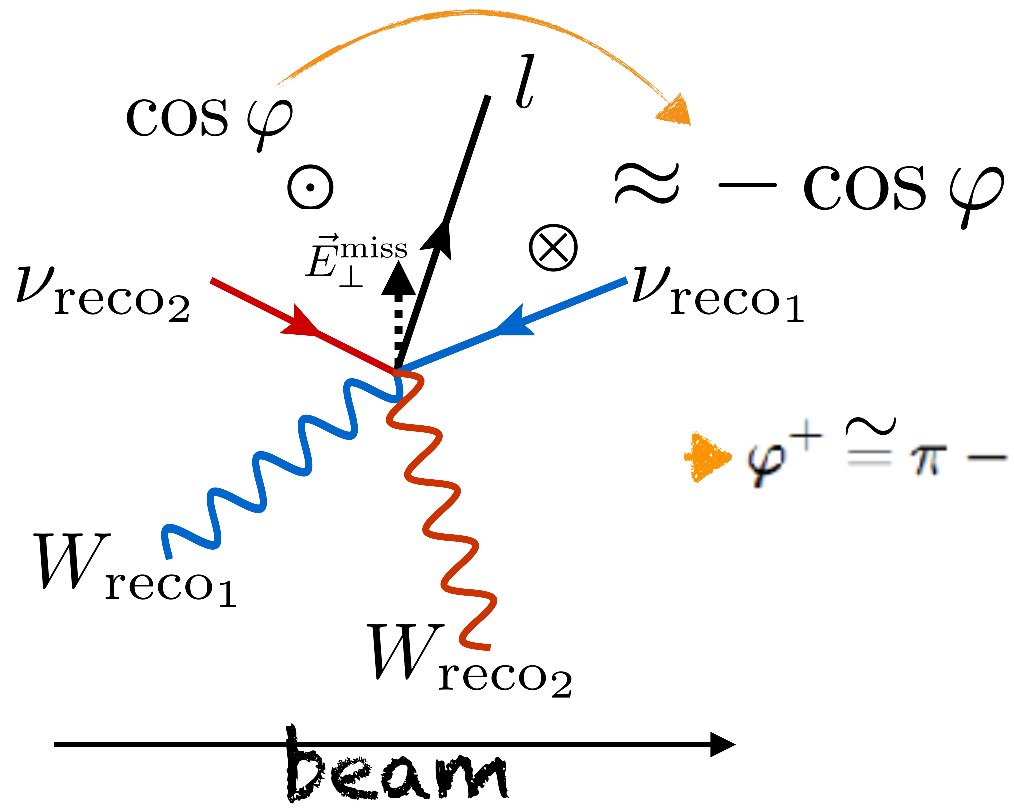
$\varphi = \pi/2 \quad \text{or} \quad \varphi = -\pi/2.$

Panico,FR,Wulzer'17

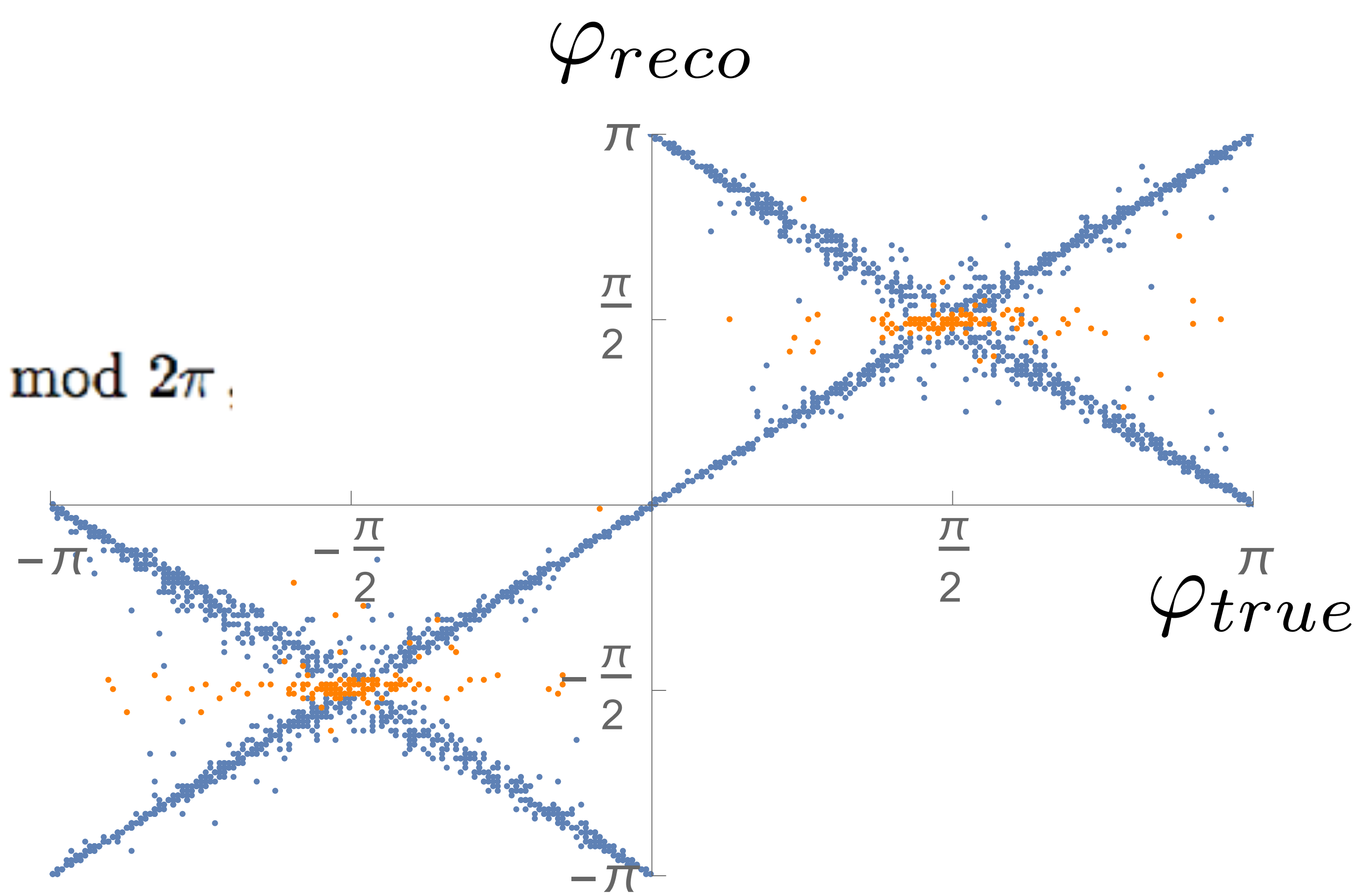
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

1)



$\varphi^+ \simeq \pi - \varphi^- \quad \text{mod } 2\pi$



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

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

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

CP-odd unaccessible!

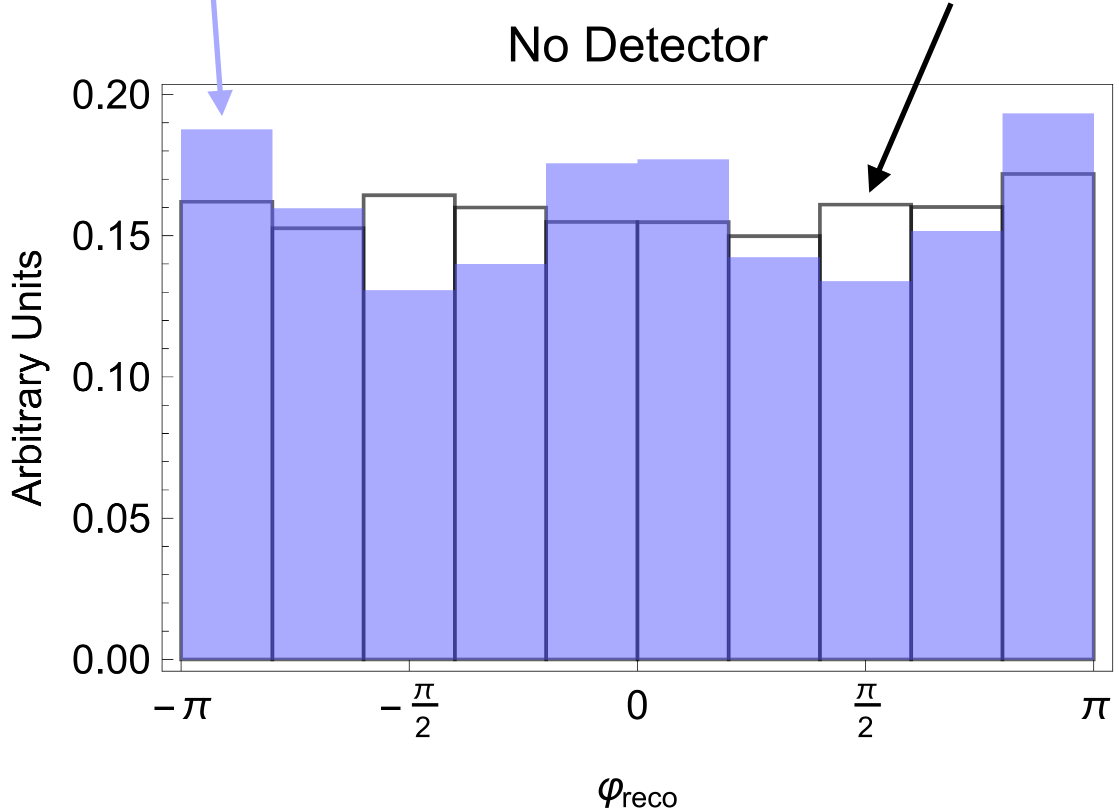
Panico,FR,Wulzer'17

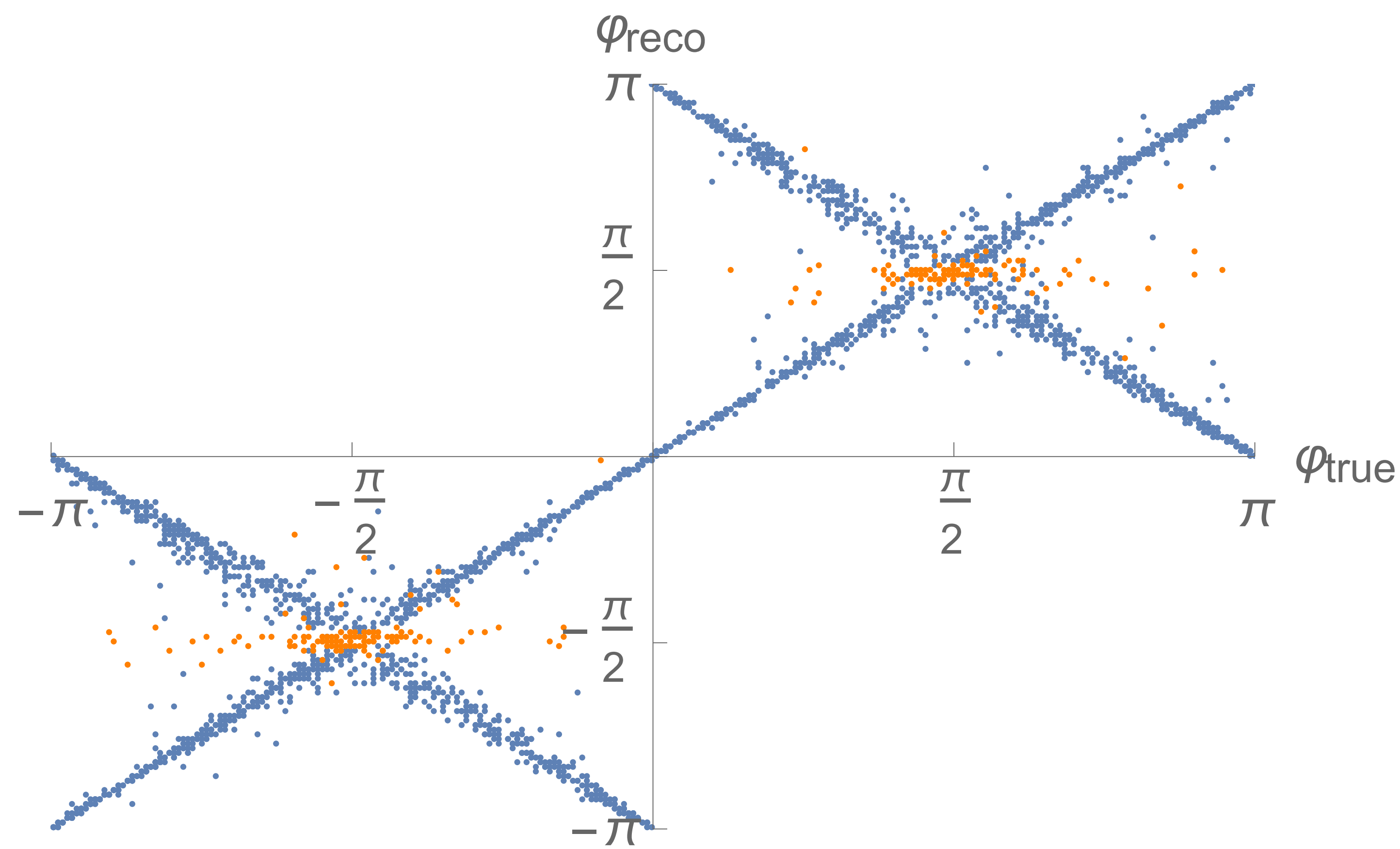
Azimuthal Angle... in reality

Neutrino: from missing energy + reconstruct W mass

BSM $\sim \cos 2\varphi$

SM $\sim const.$



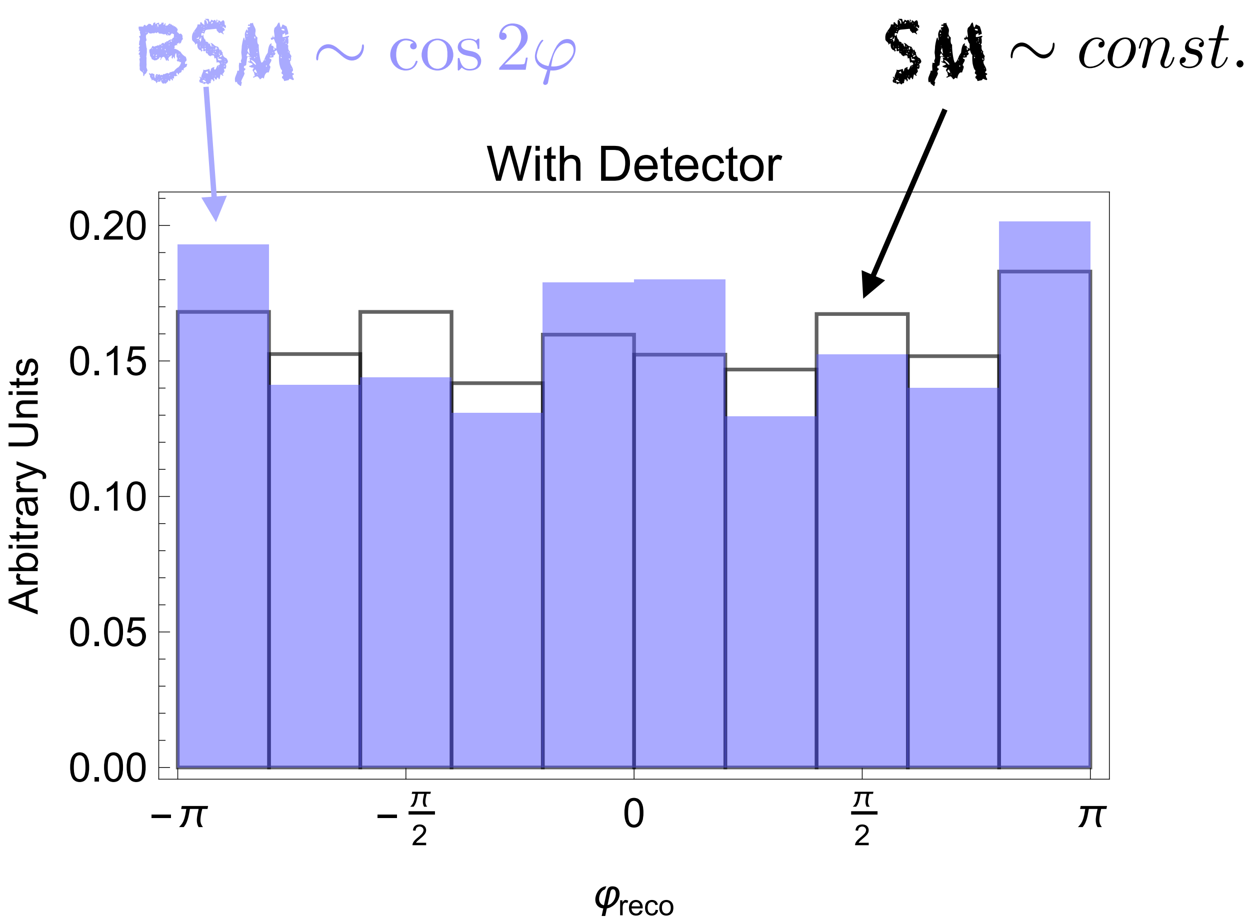


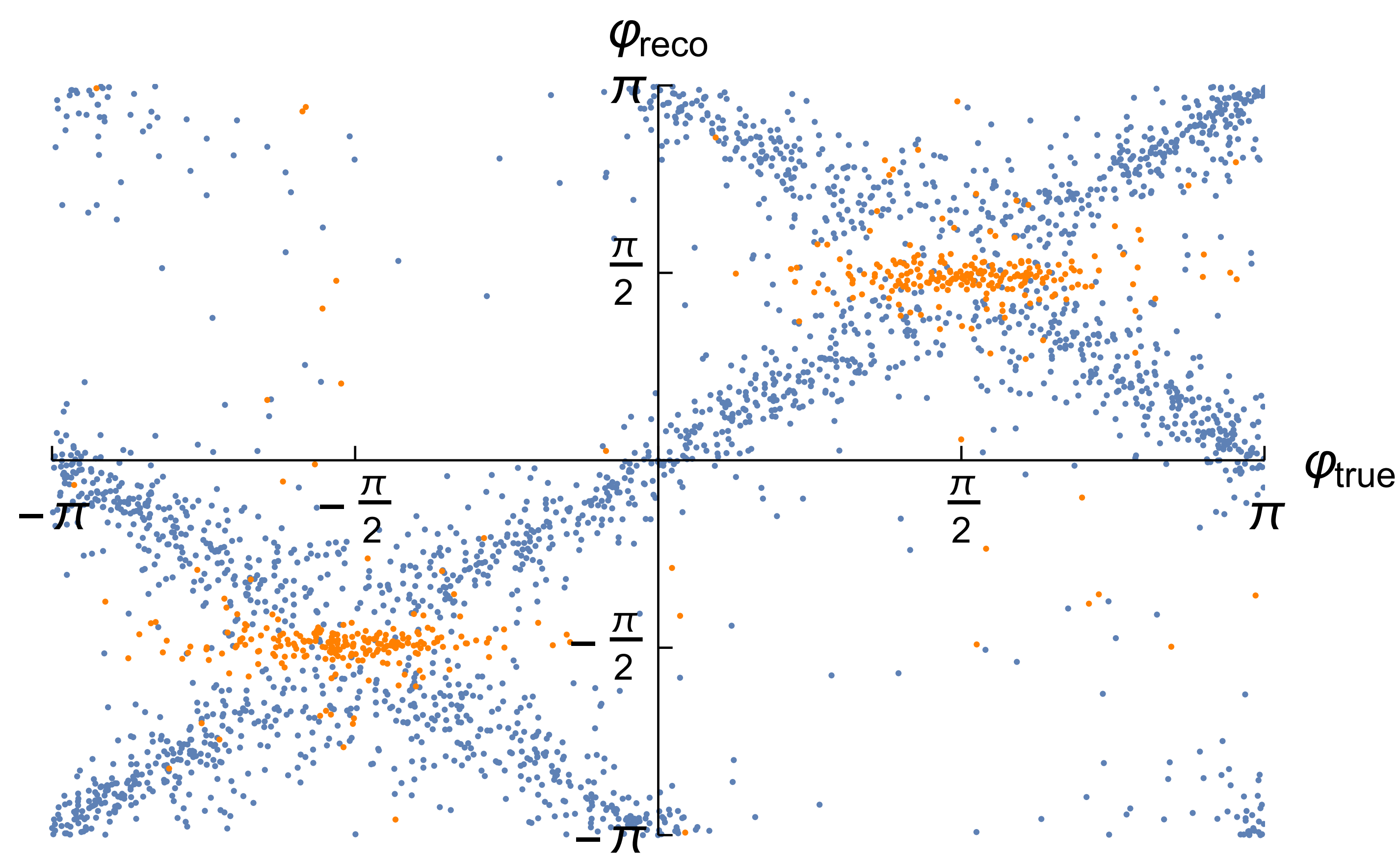
Panico,FR,Wulzer'17

Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation



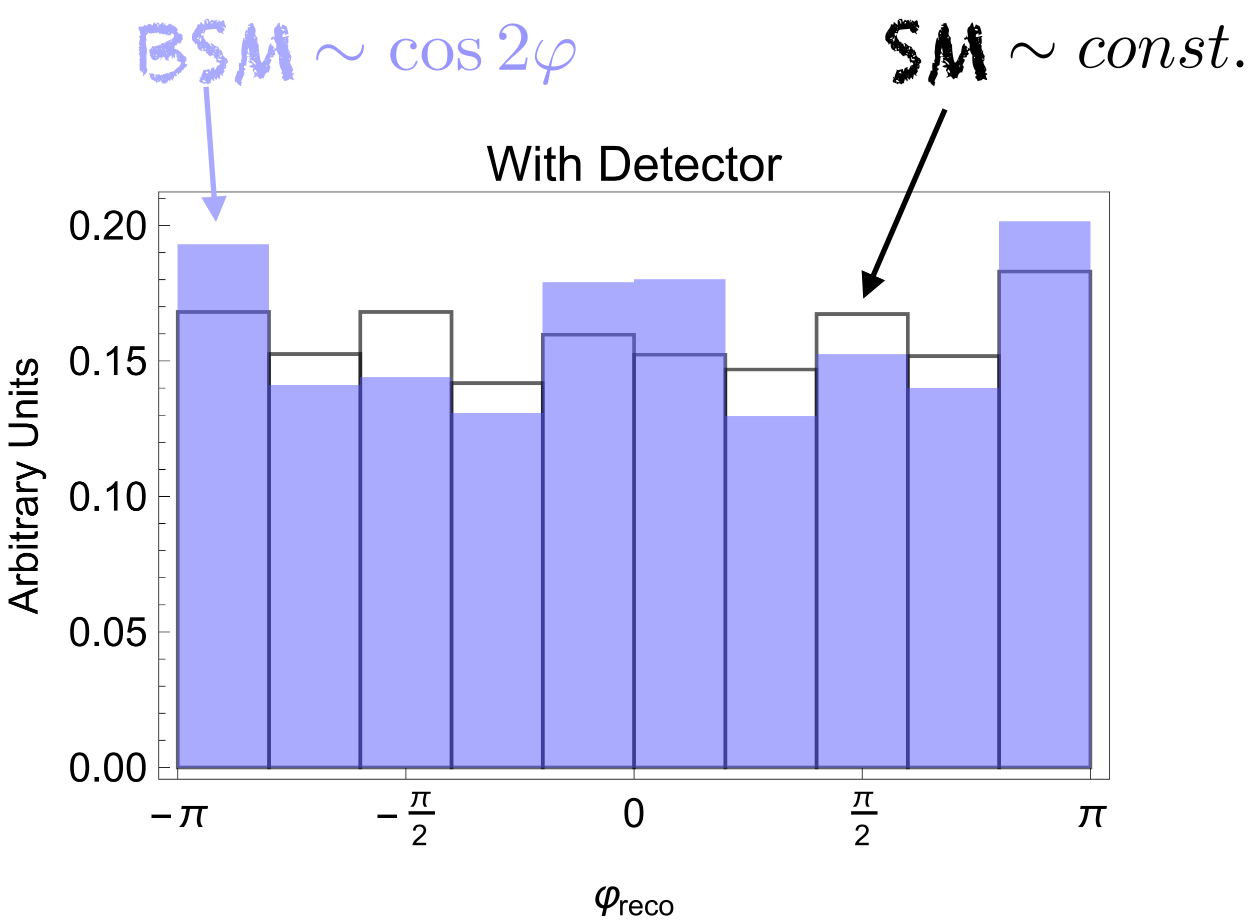


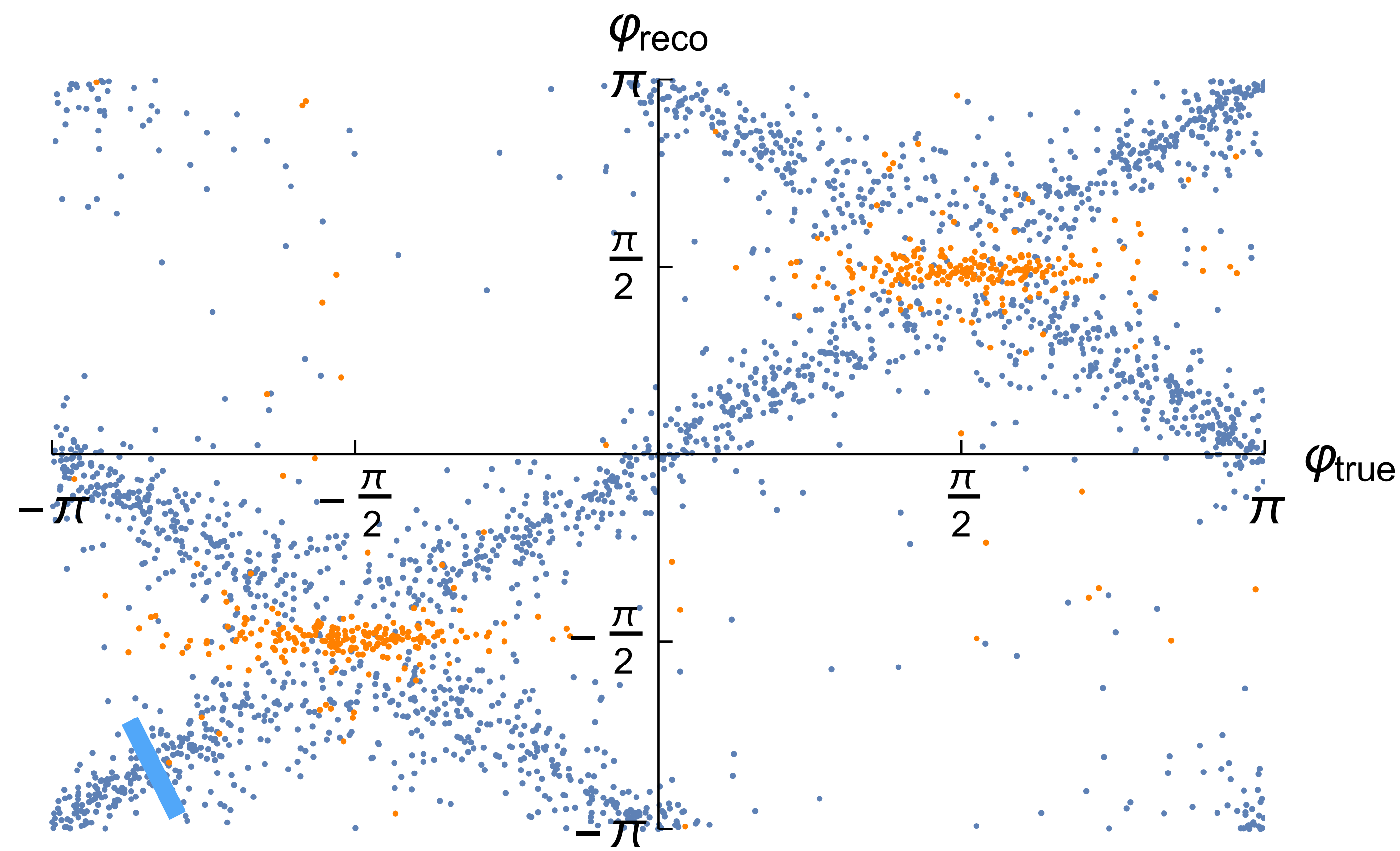
Panico,FR,Wulzer'17

Azimuthal Angle… more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation





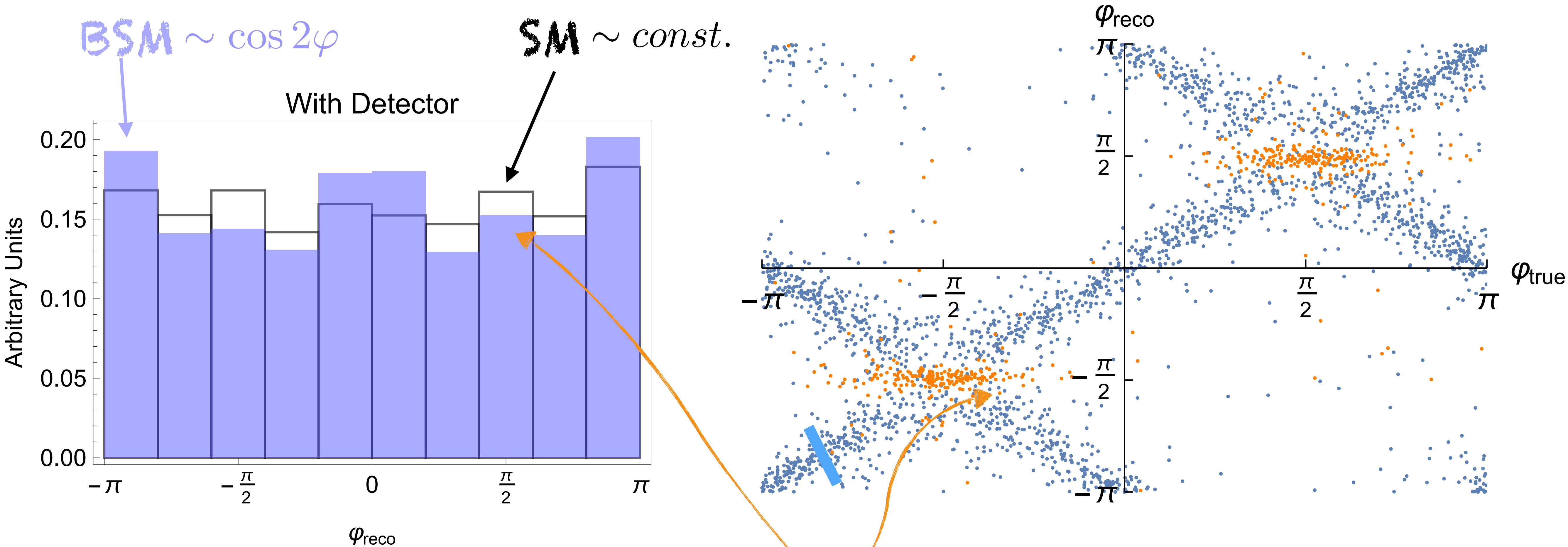
Spread under control

Panico,FR,Wulzer'17

Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation



Spread under control

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

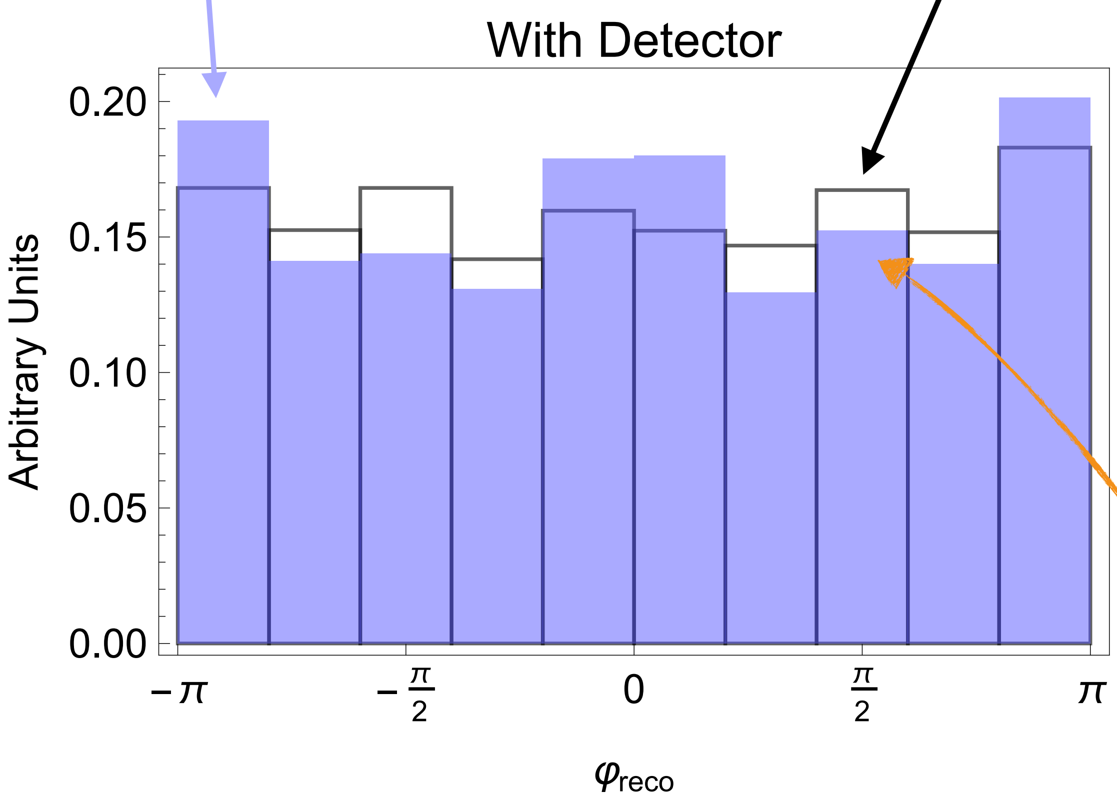
Panico,FR,Wulzer'17

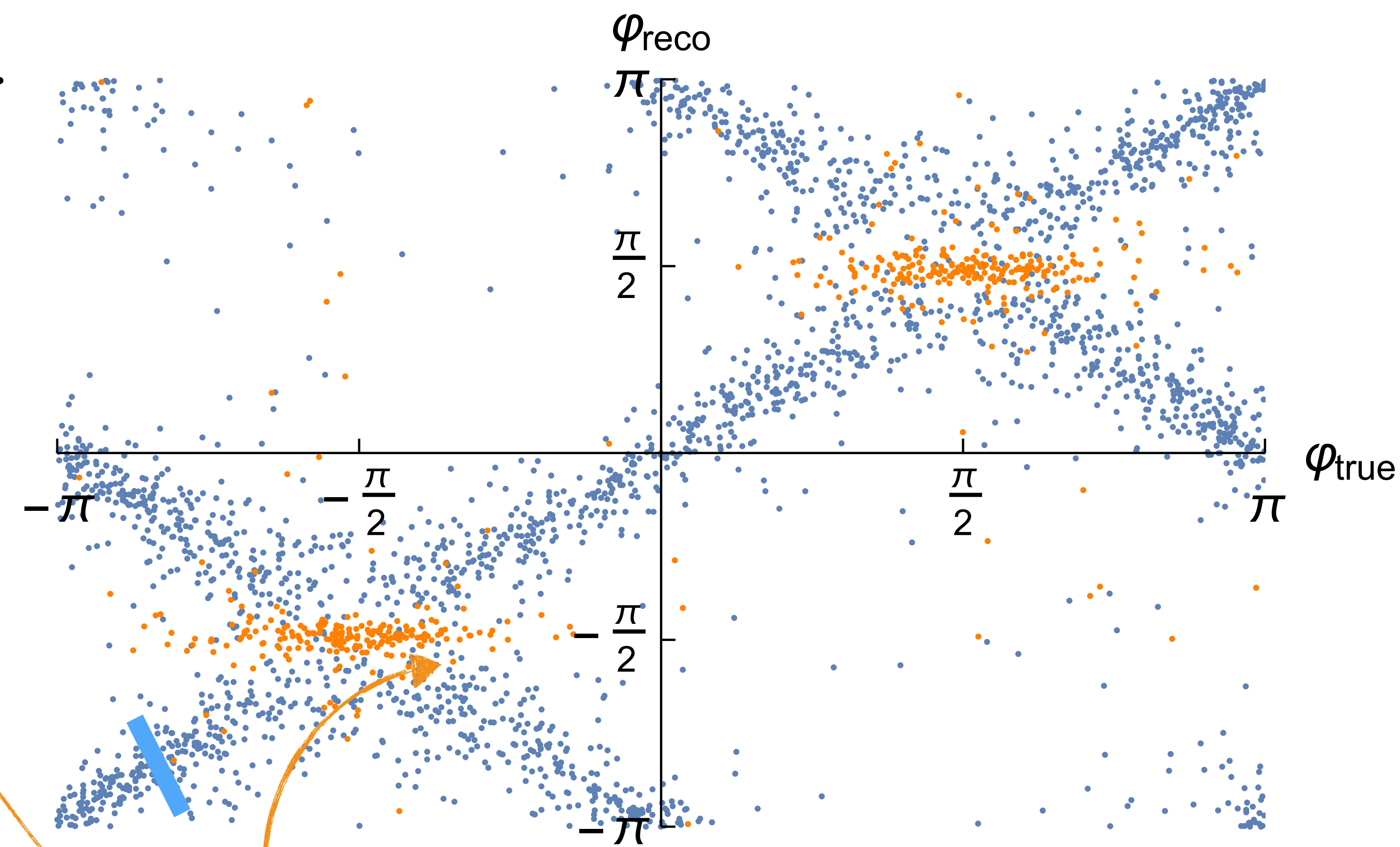
Azimuthal Angle... more in reality

Neutrino: from missing energy + reconstruct W mass

With (DELPHES) detector simulation

BSM $\sim \cos 2\varphi$ SM $\sim const.$





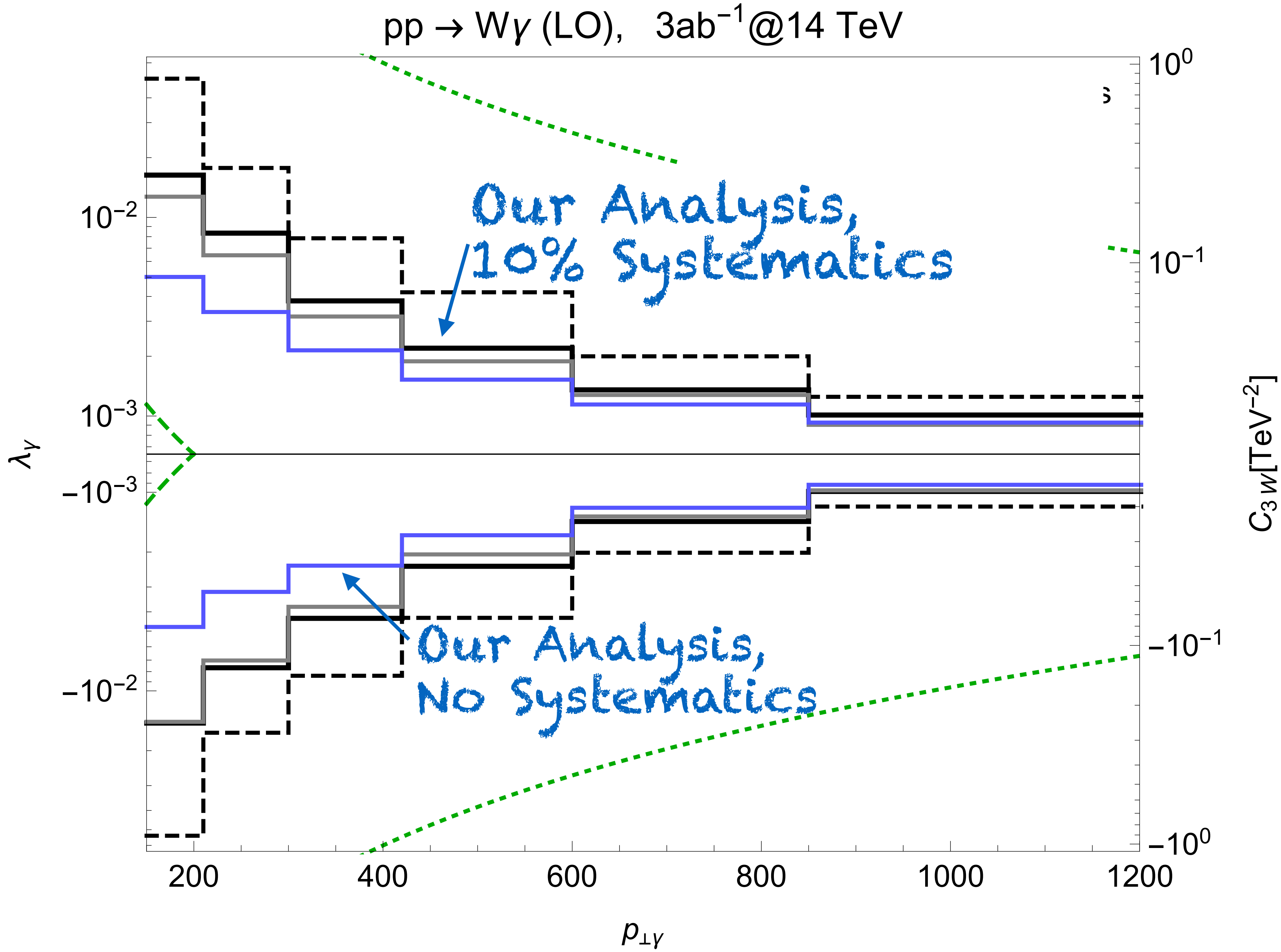
Spread under control

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

- Resurrection is real

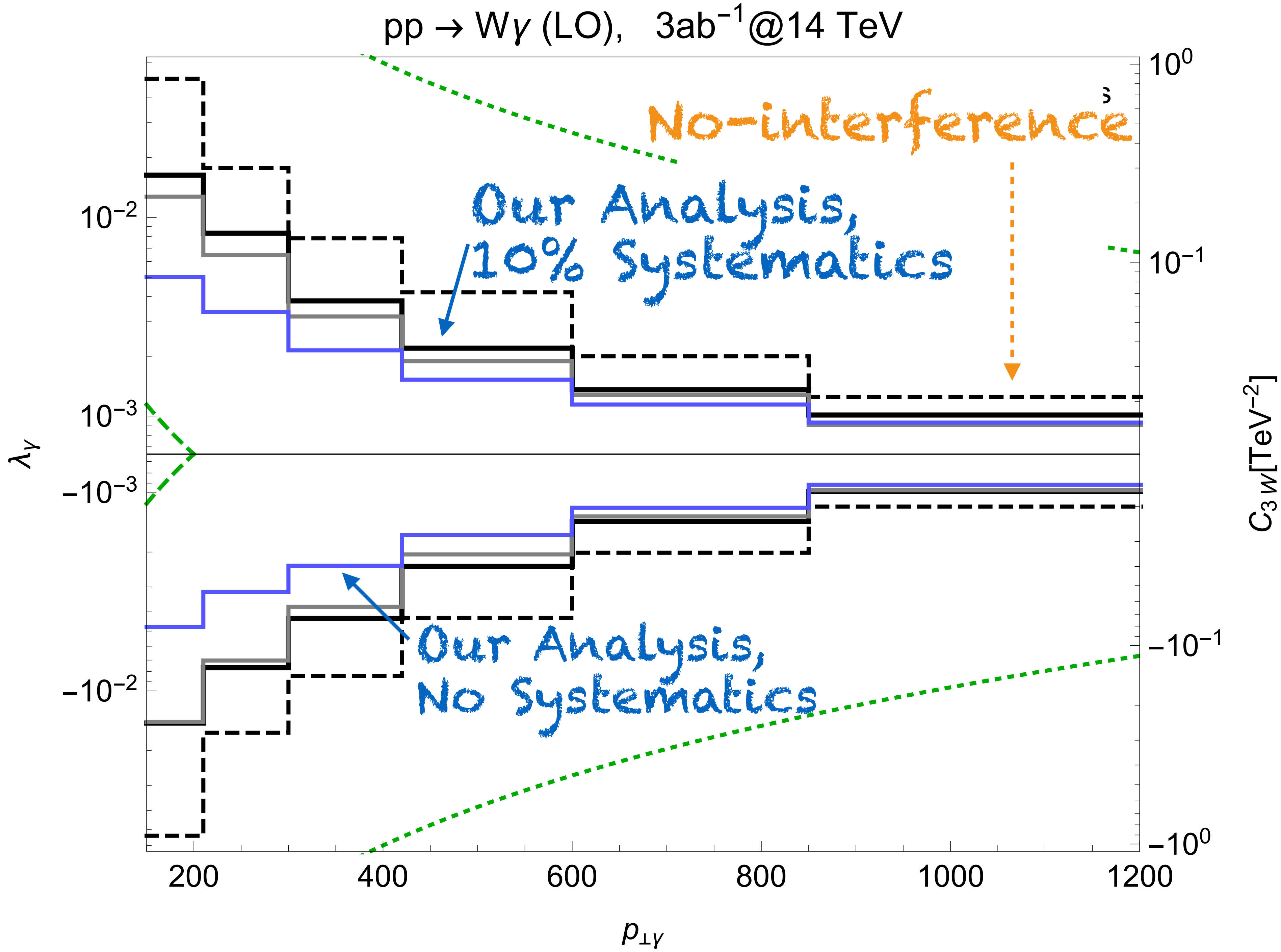
Panico,FR,Wulzer'17

Results



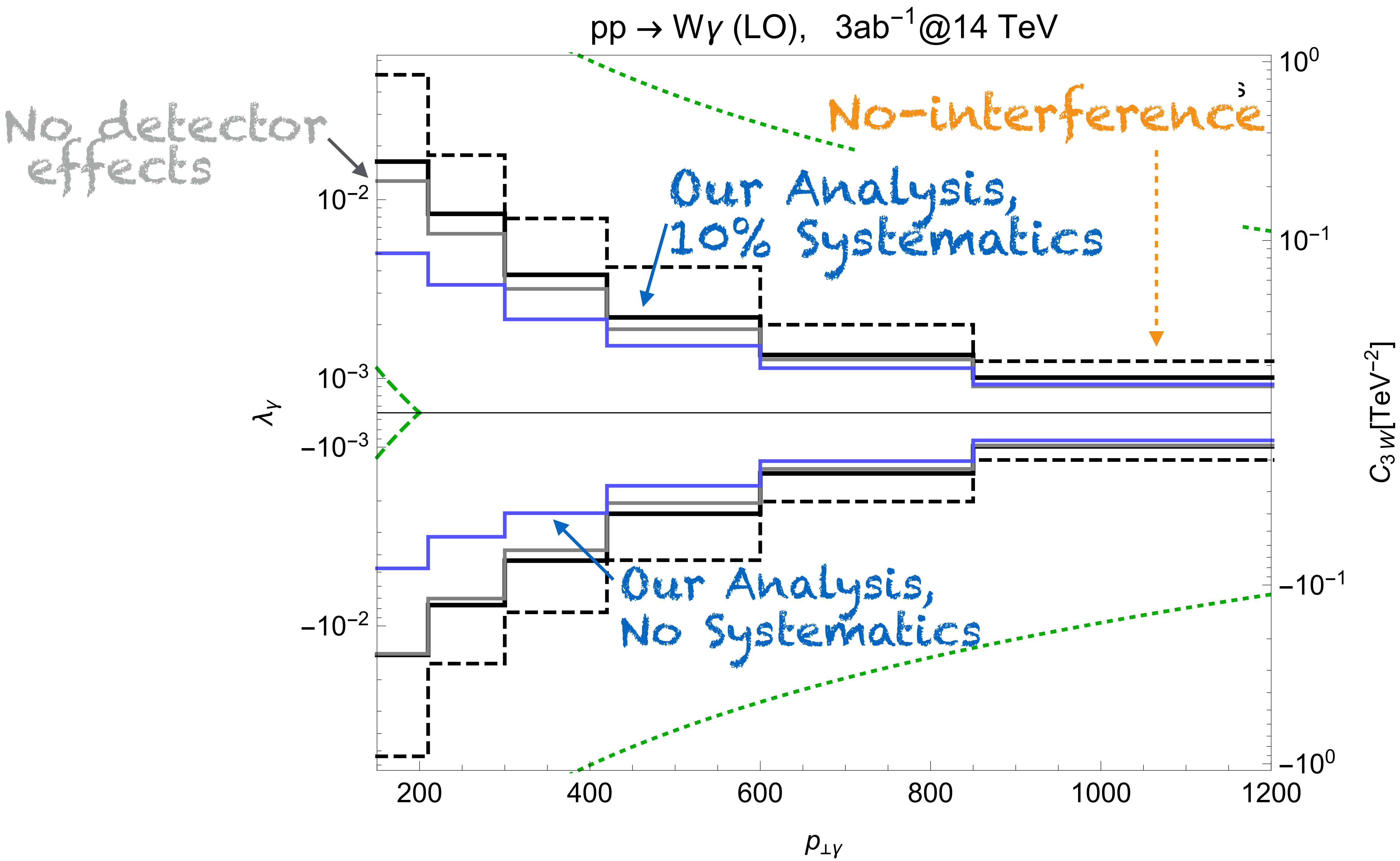
Panico,FR,Wulzer'17

Results



Panico,FR,Wulzer'17

Results

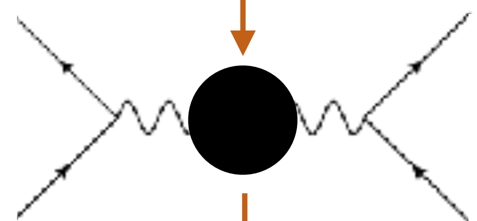


Panico,FR,Wulzer'17

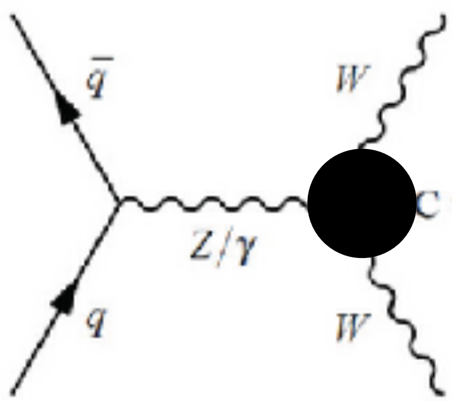
Explicit Model (Remedios)

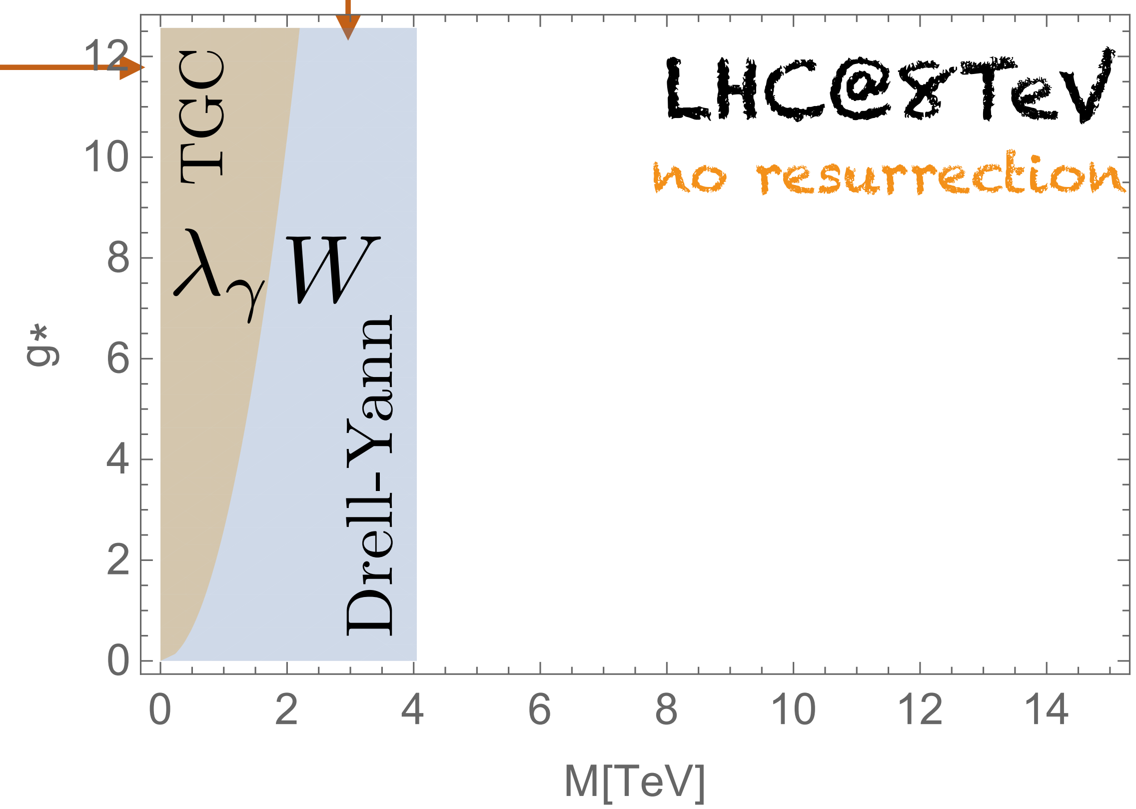
Remedios Scenario → $\frac{1}{M^2}(D_\rho W_\mu^{a,\nu})^2$

Liu,Pomarol,Rattazzi,FR'16



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





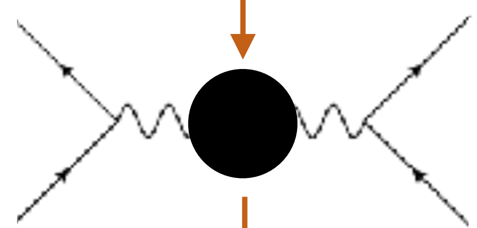
Interference Resurrection makes the difference.

Explicit Model (Remedios)

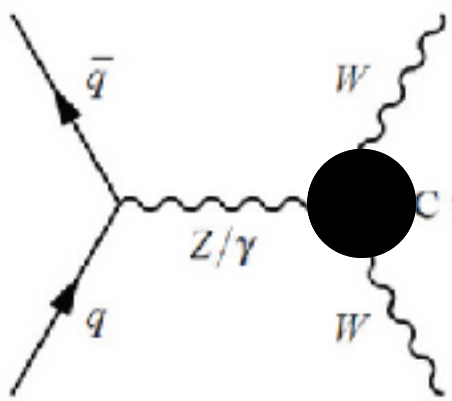
Liu,Pomarol,Rattazzi,FR'16

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

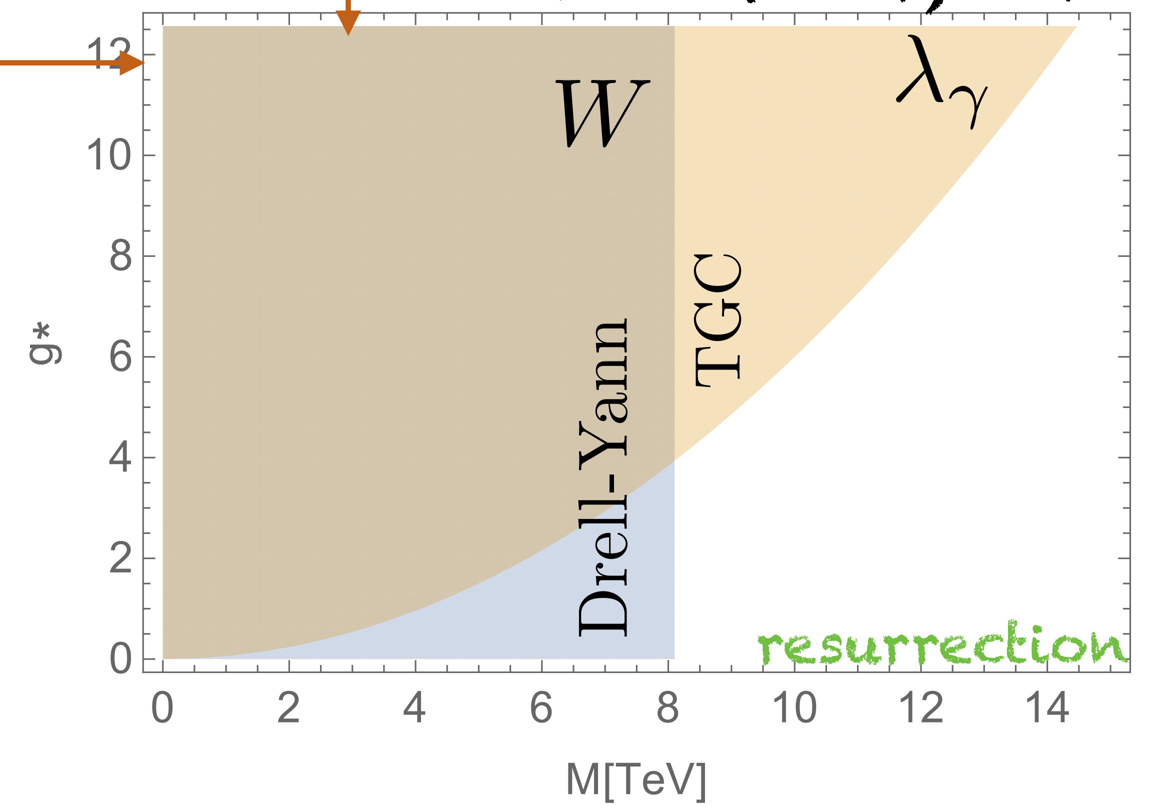
Liu,Pomarol,Rattazzi,FR'16



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



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



Interference Resurrection makes the difference.

Outline

Intro

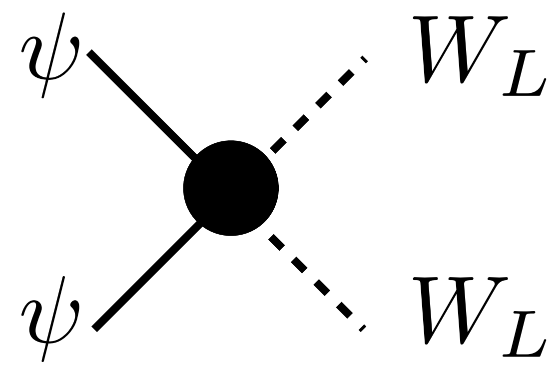
A challenge at high-E: non-interference

Transverse Dibosons: Interference resurrection

➡ Longitudinal Dibosons: Interference revitalization

ZZ,Zgamma: what to search for?

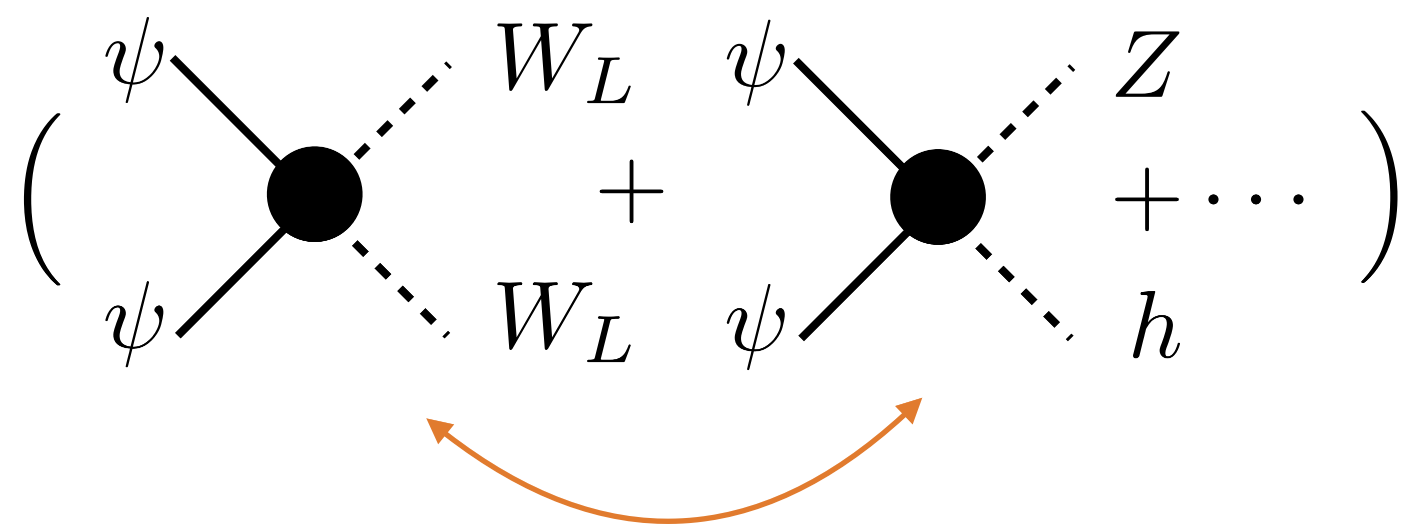
Longitudinal gauge bosons



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

- Their interactions are related*:

$$H^\dagger D_\mu H \bar{\Psi}\gamma^\mu\Psi =$$

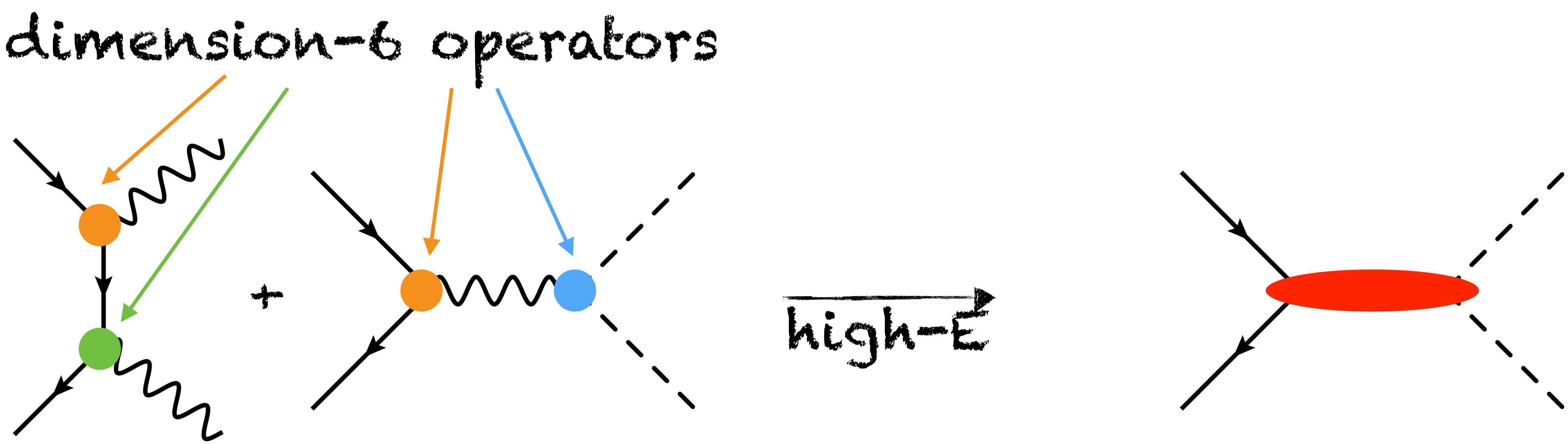


- di-boson experiments complementary to Higgs Physics (->combination)

* This relation is valid at leading order in the EFT

See 1405.0181 for specific relations

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)

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)

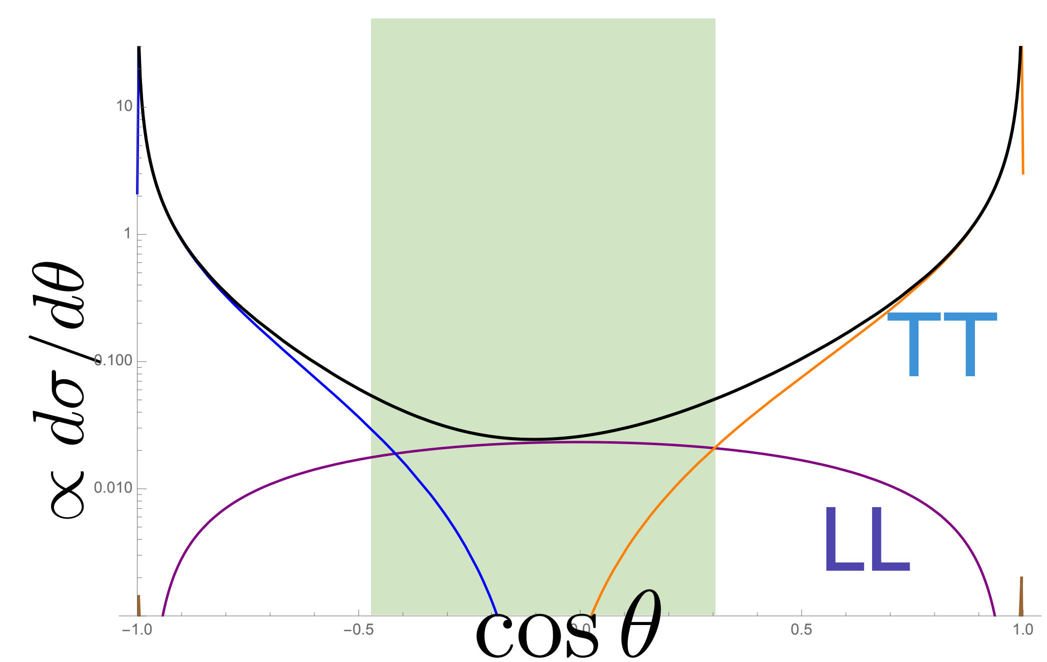
- **WZ** most promising

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

Baur,Han,Ohnemus'95

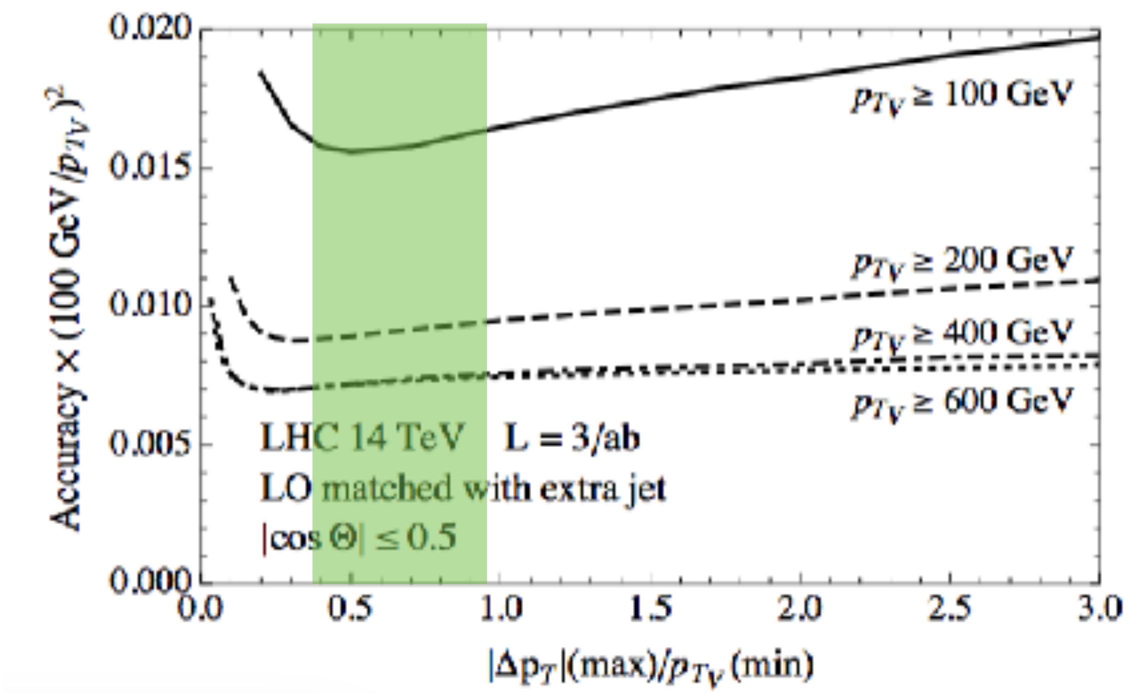
TT has central zero at LO

(not at NLO)

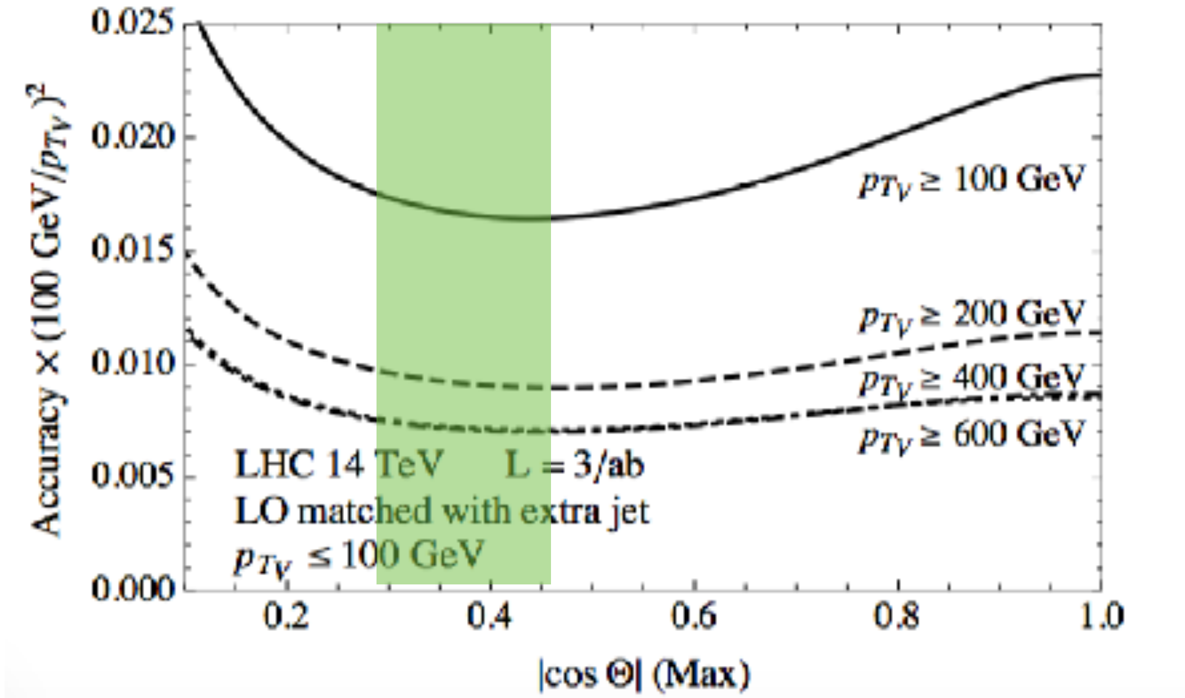


Fully leptonic WZ

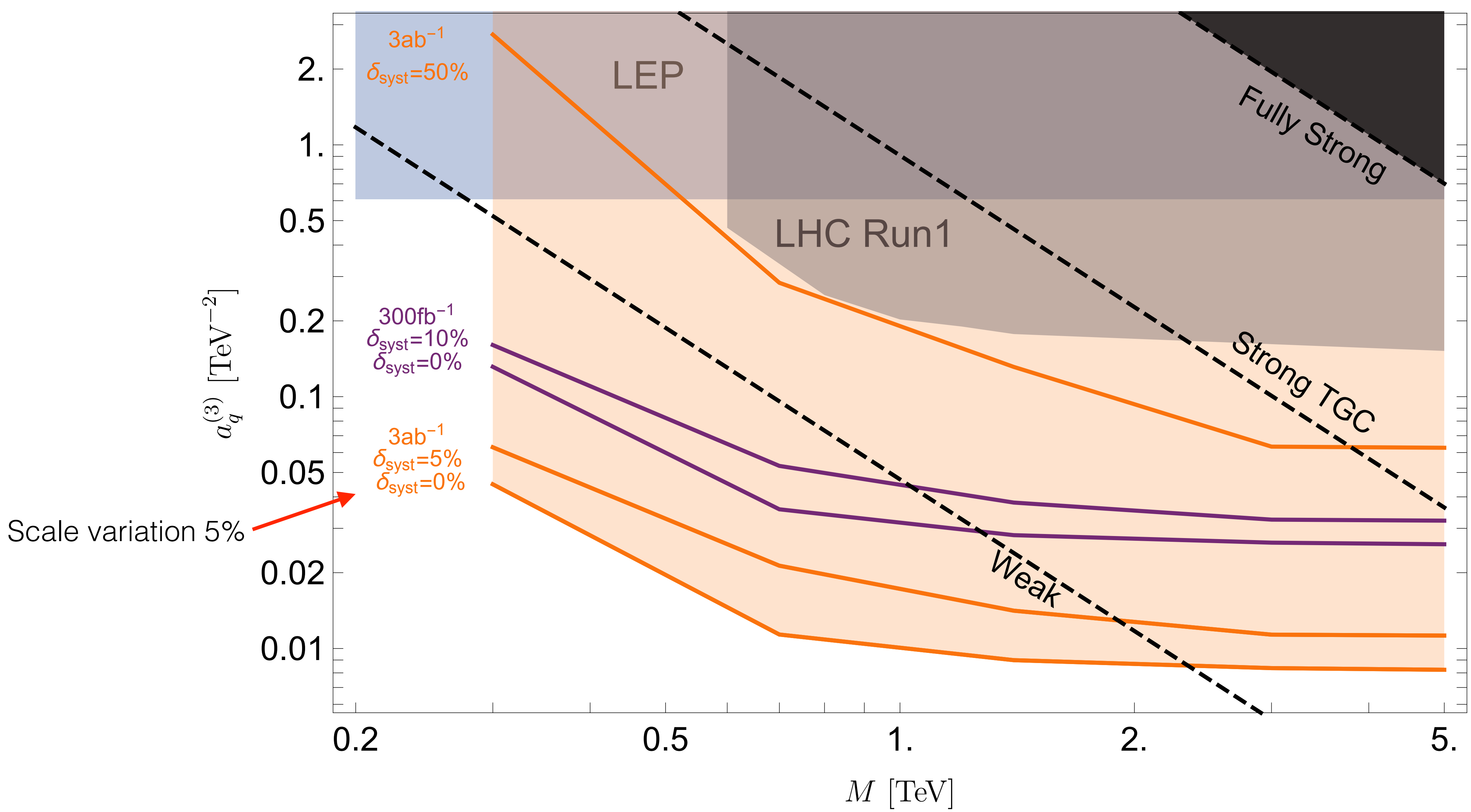
pT cut on extra radiation:
(kinematics close to LO)



Cosθ cut close to central
(exploit radiation-zero)

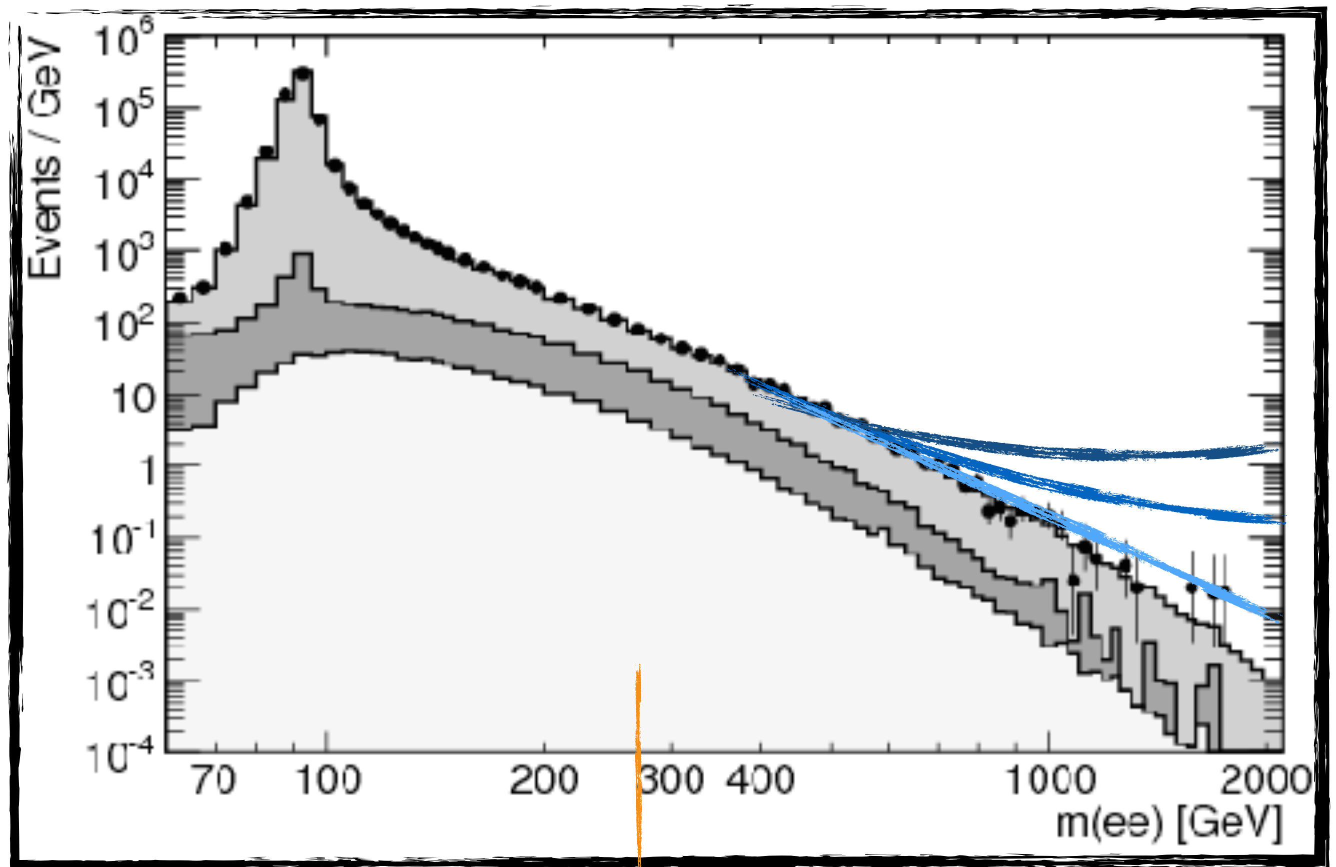


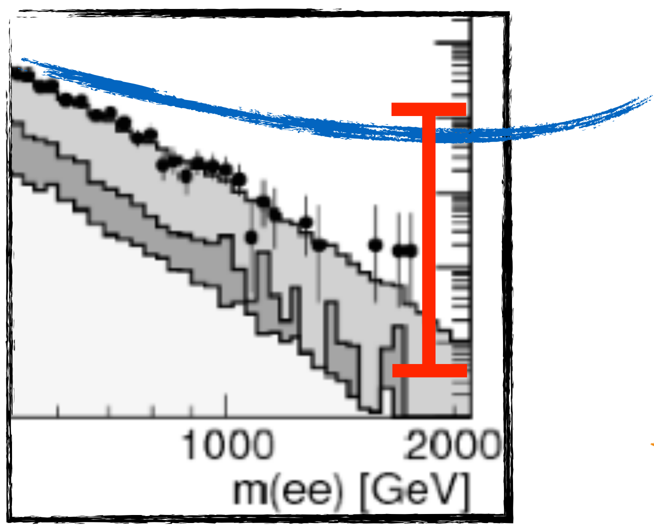
Results - NLO - LHC



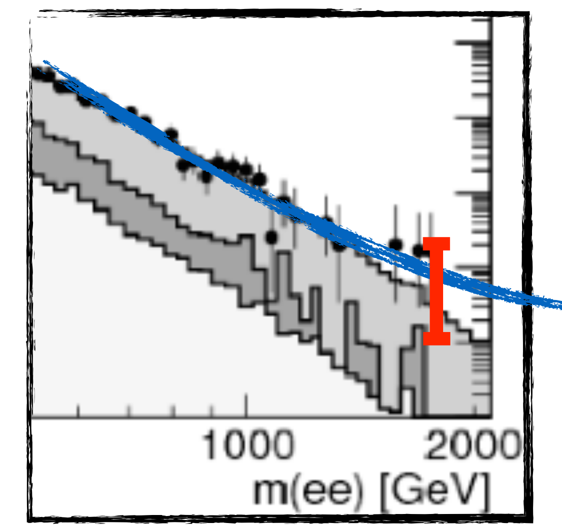
is this a good result?

High-E Precision (B)SM tests





2 BSM regimes



Big effects

Strong Coupling BSM

Measurable with O(1) precision

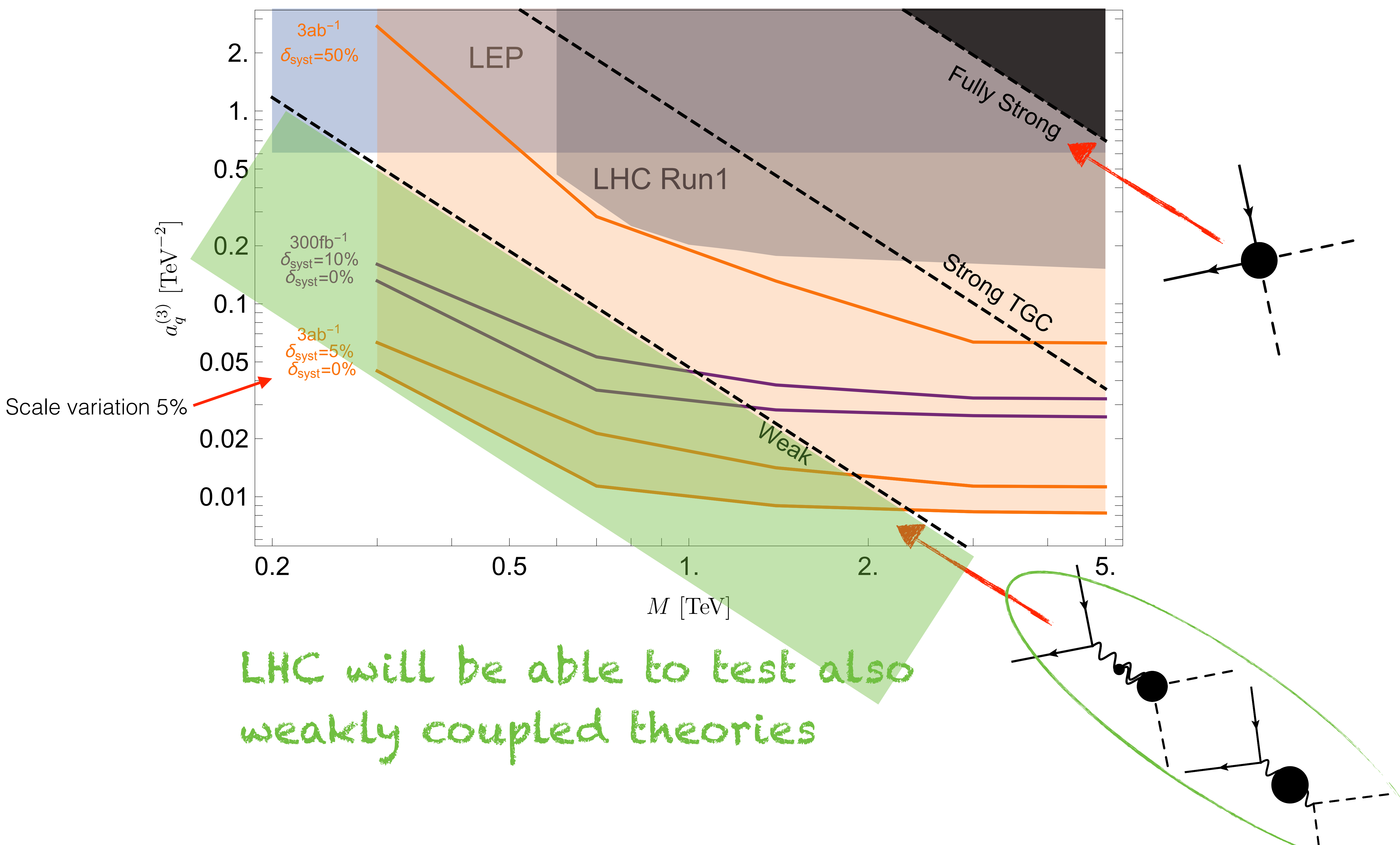
Small effects

Weak Coupling BSM

Measurable only with precision

Results from experiments of this kind can be applied to broader BSM scenarios

Results - NLO - LHC



LHC will be able to test also weakly coupled theories

Outline

Intro

A challenge at high-E: non-interference

Transverse Dibosons: Interference resurrection

Longitudinal Dibosons: Interference revitalization

ZZ,Zgamma: what to search for?

nTGC so far

Anomalous Couplings

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

Gounaris,Laysacc,Renard'99

→

EFT

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

nTGC so far

Anomalous Couplings

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

Gounaris,Laysacc,Renard'99

EFT

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

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

nTGC so far

Anomalous Couplings

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

Gounaris,Laysacc,Renard'99

EFT

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

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

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

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

nTGC so far

Anomalous Couplings

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

Gounaris,Laysacc,Renard'99

→

EFT

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

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

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

  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 ☹

Dimension-8 and ZZ, Zγ

Is there a symmetry/theory such that first effects in ZZ/Zγ?

YES! (non-linearly realized Supersymmetry 1706.03070 or tree-level Kaluza-Klein graviton exchange)

What is the EFT? ...surprise...

Dimension-8 and ZZ, Zγ

Is there a symmetry/theory such that first effects in ZZ/Zγ?

YES! (non-linearly realized Supersymmetry 1706.03070 or tree-level Kaluza-Klein graviton exchange)

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

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

LL final states (ZZ only)

TT final states (ZZ,Zγ,γγ)

Energy-Growth

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

LL final states (ZZ only)

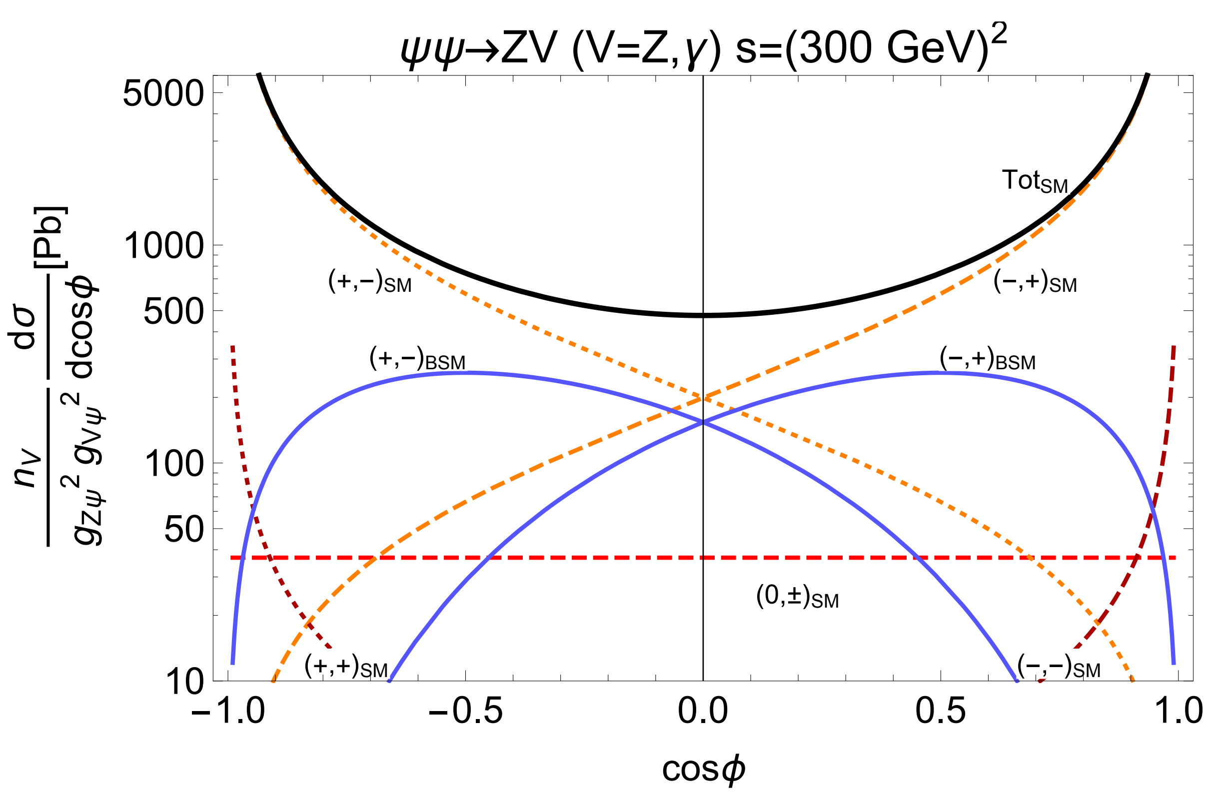
TT final states (ZZ,Zγ,γγ)

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

Helicity

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

→ 00 → +−



- **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

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

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

Positivity Constraints

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

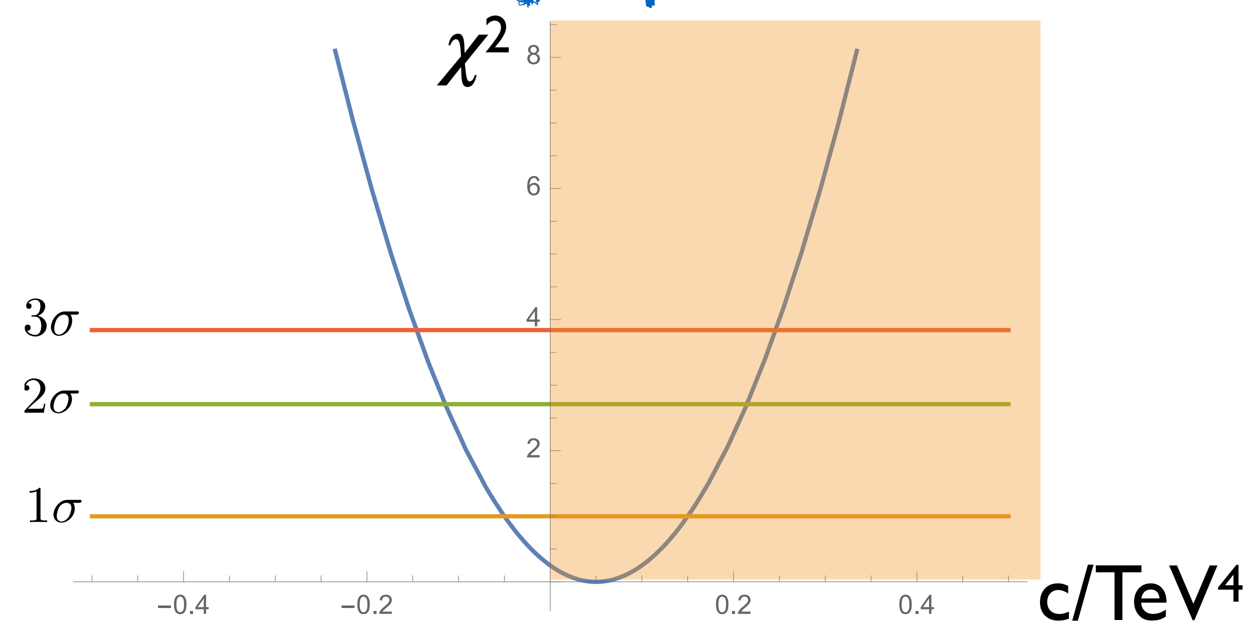
Adams,Arkani-Hamed,Dubovsky,Nicolis,Rattazzi'hep-th/0602178
Bellazzini'1605.06111

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

c=0

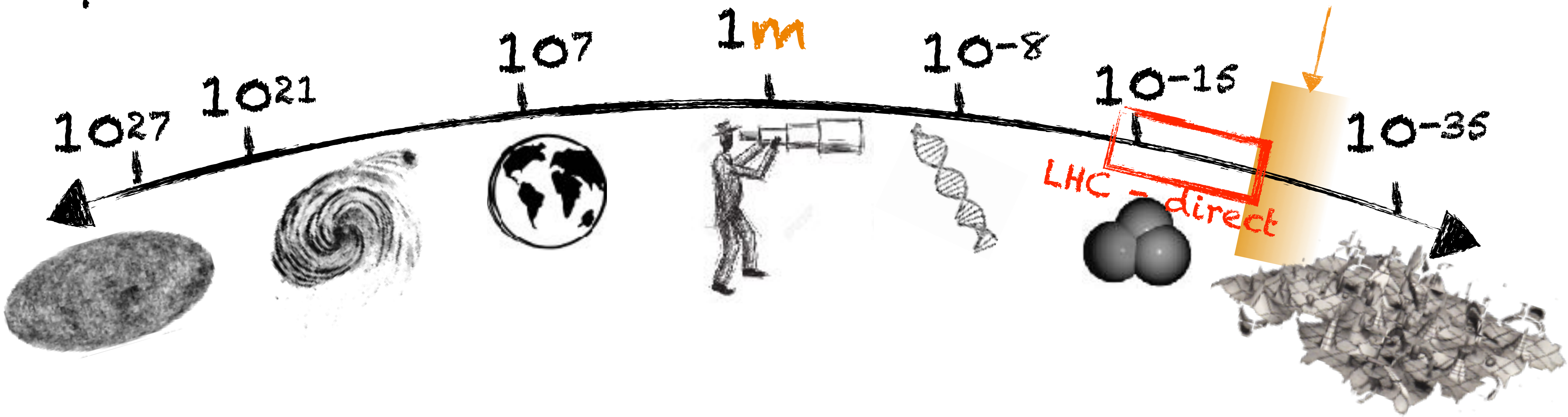
Smaller viable parameter space

c>0 (always positive!)

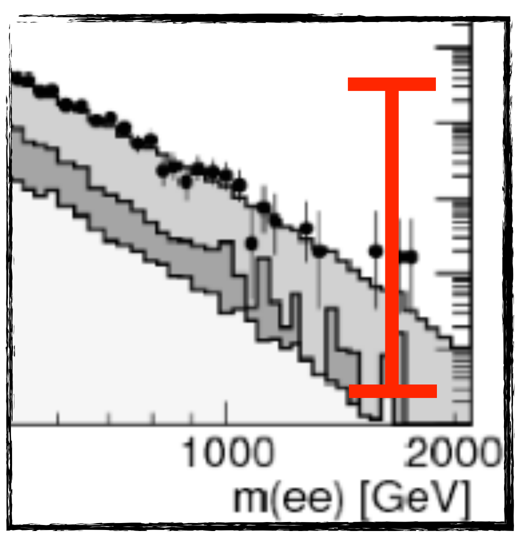


Message

SM precision tests will define the new distance frontier



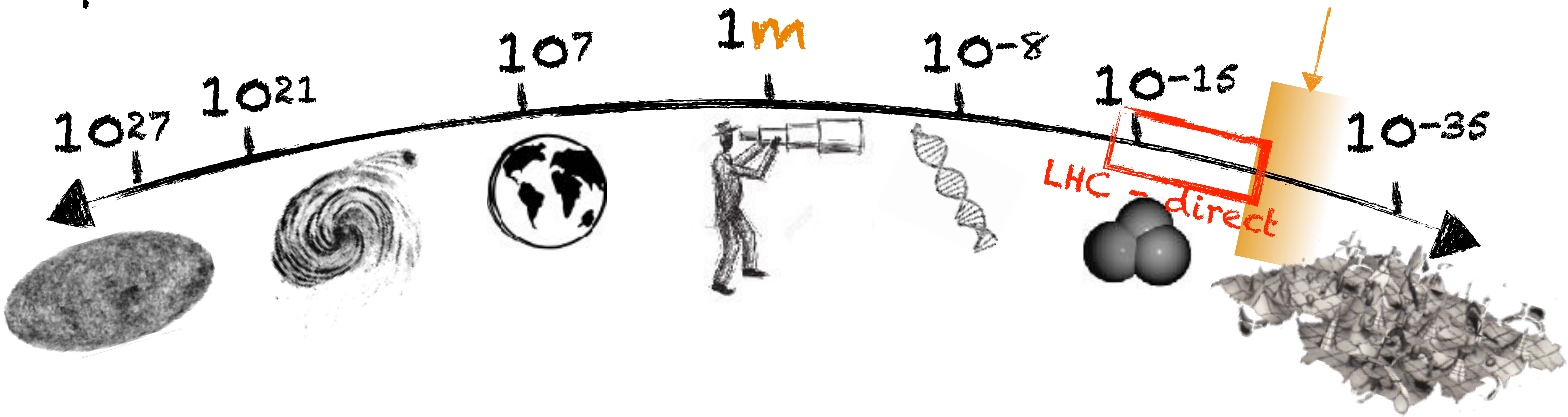
Precision is a collective goal:



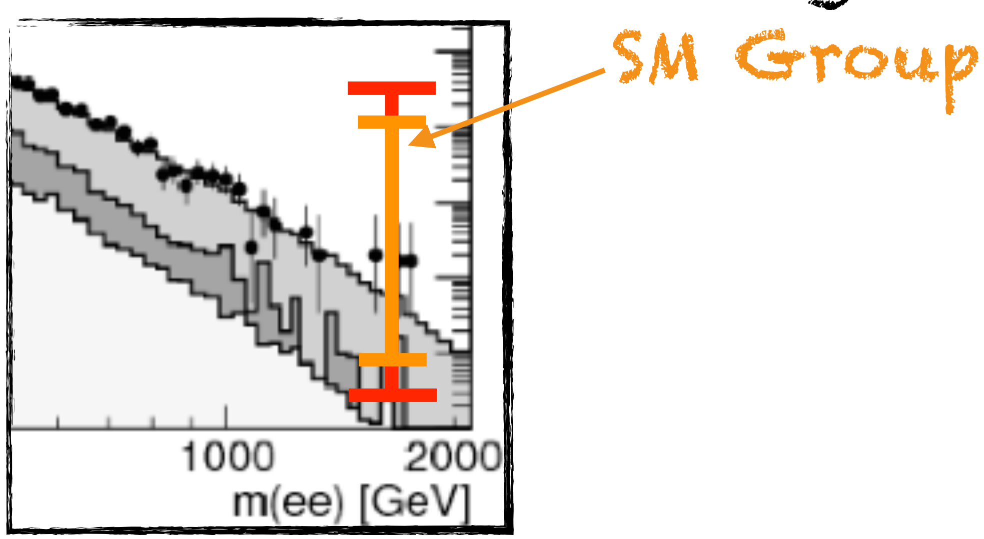
- Precision SM tests more similar to BSM searches now

Message

SM precision tests will define the new distance frontier



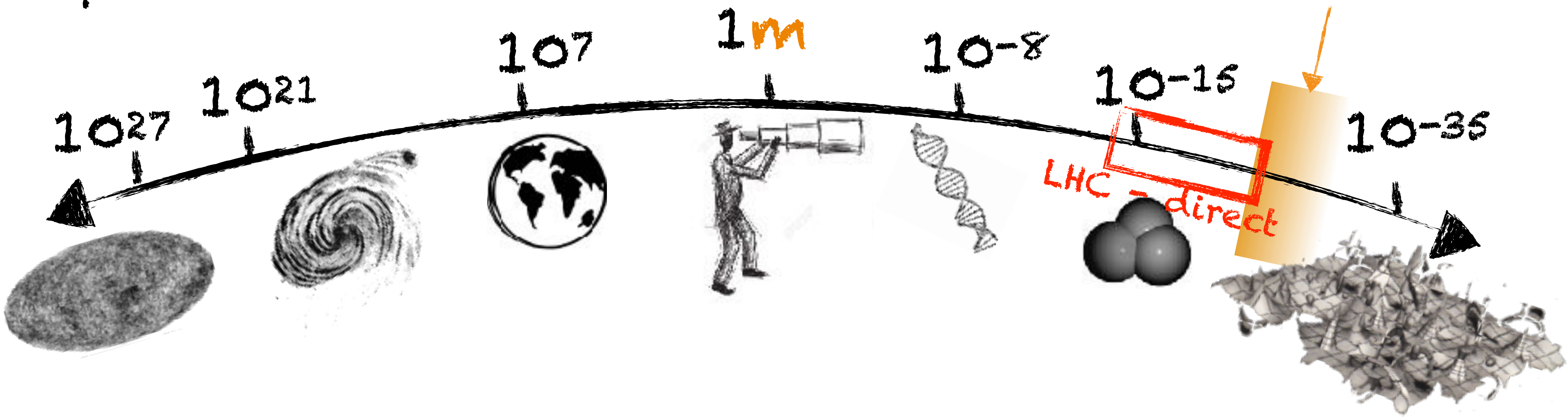
Precision is a collective goal:



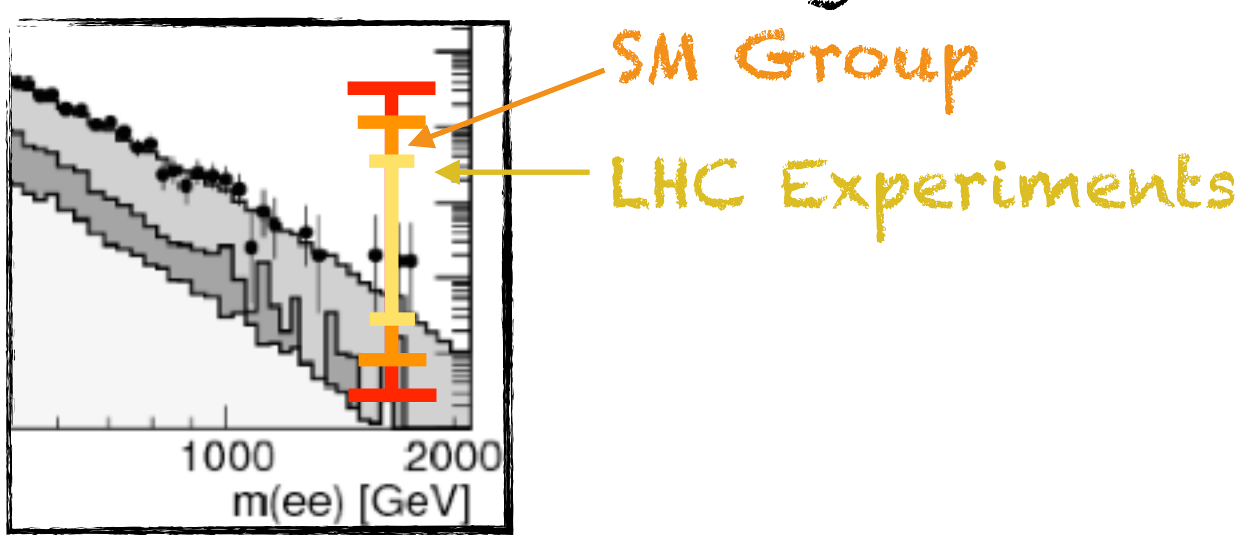
- Precision SM tests more similar to BSM searches now

Message

SM precision tests will define the new distance frontier



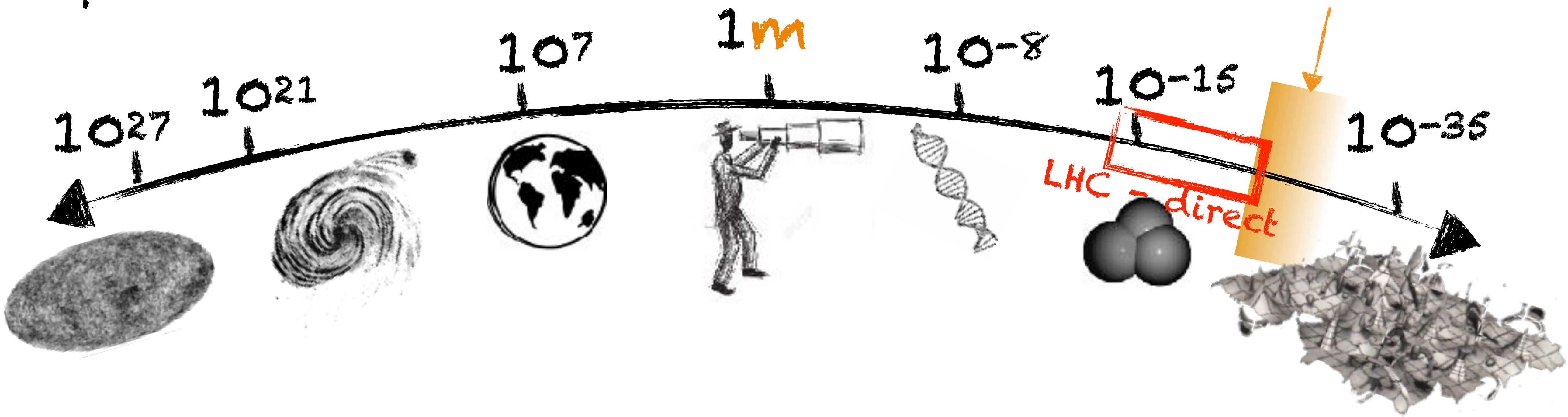
Precision is a collective goal:



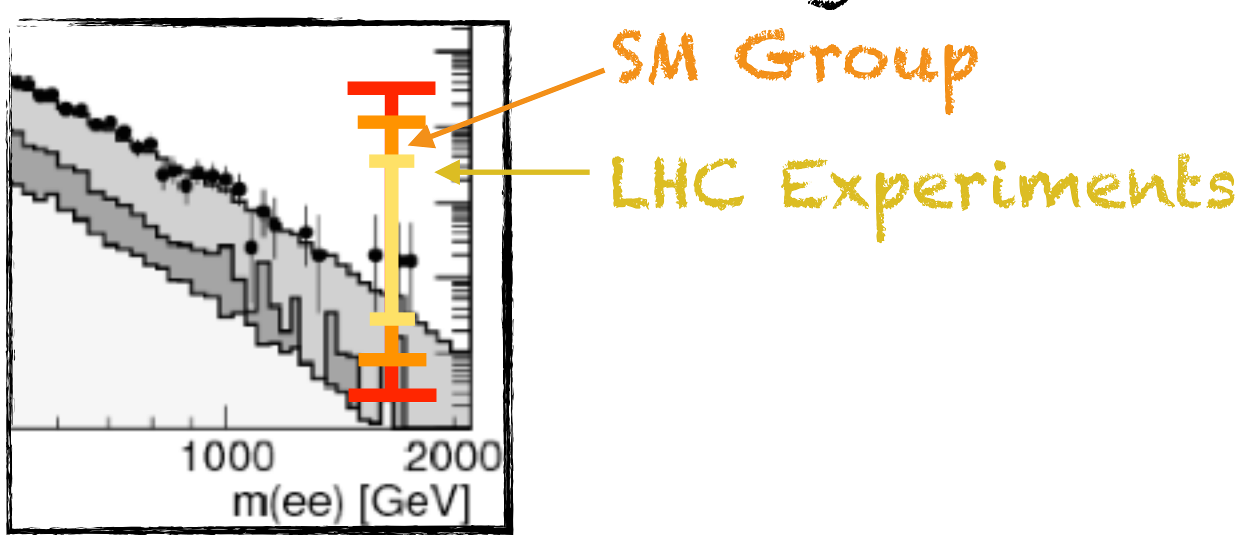
- Precision SM tests more similar to BSM searches now

Message

SM precision tests will define the new distance frontier



Precision is a collective goal:

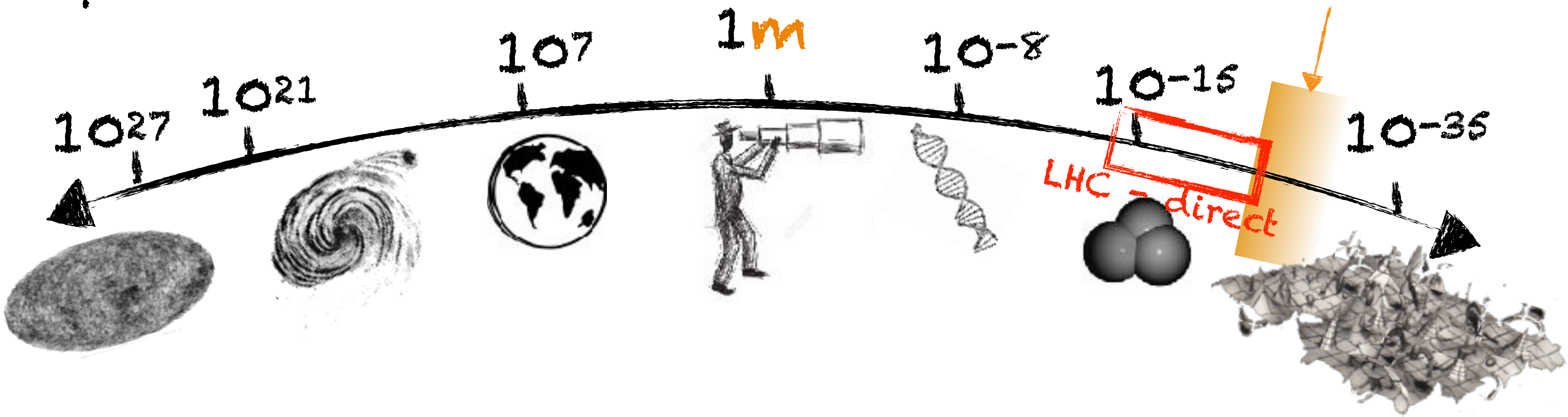


} Precision SM...

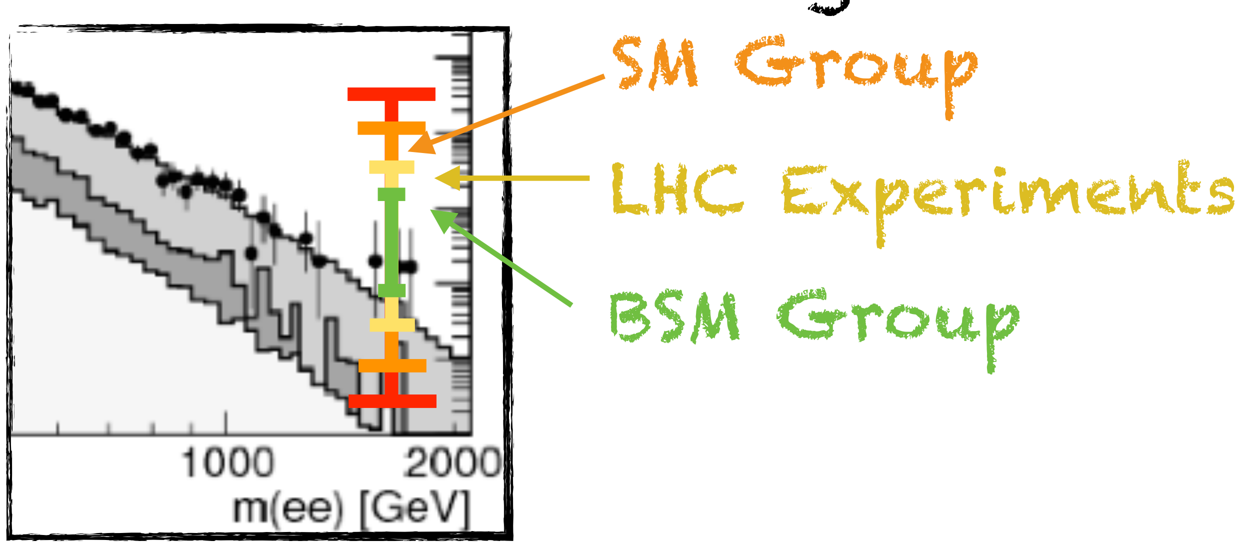
- Precision SM tests more similar to BSM searches now

Message

SM precision tests will define the new distance frontier



Precision is a collective goal:



} Precision SM...

...as a tool for BSM

- Precision SM tests more similar to BSM searches now

Message

- LHC good in High-E 2>2 processes

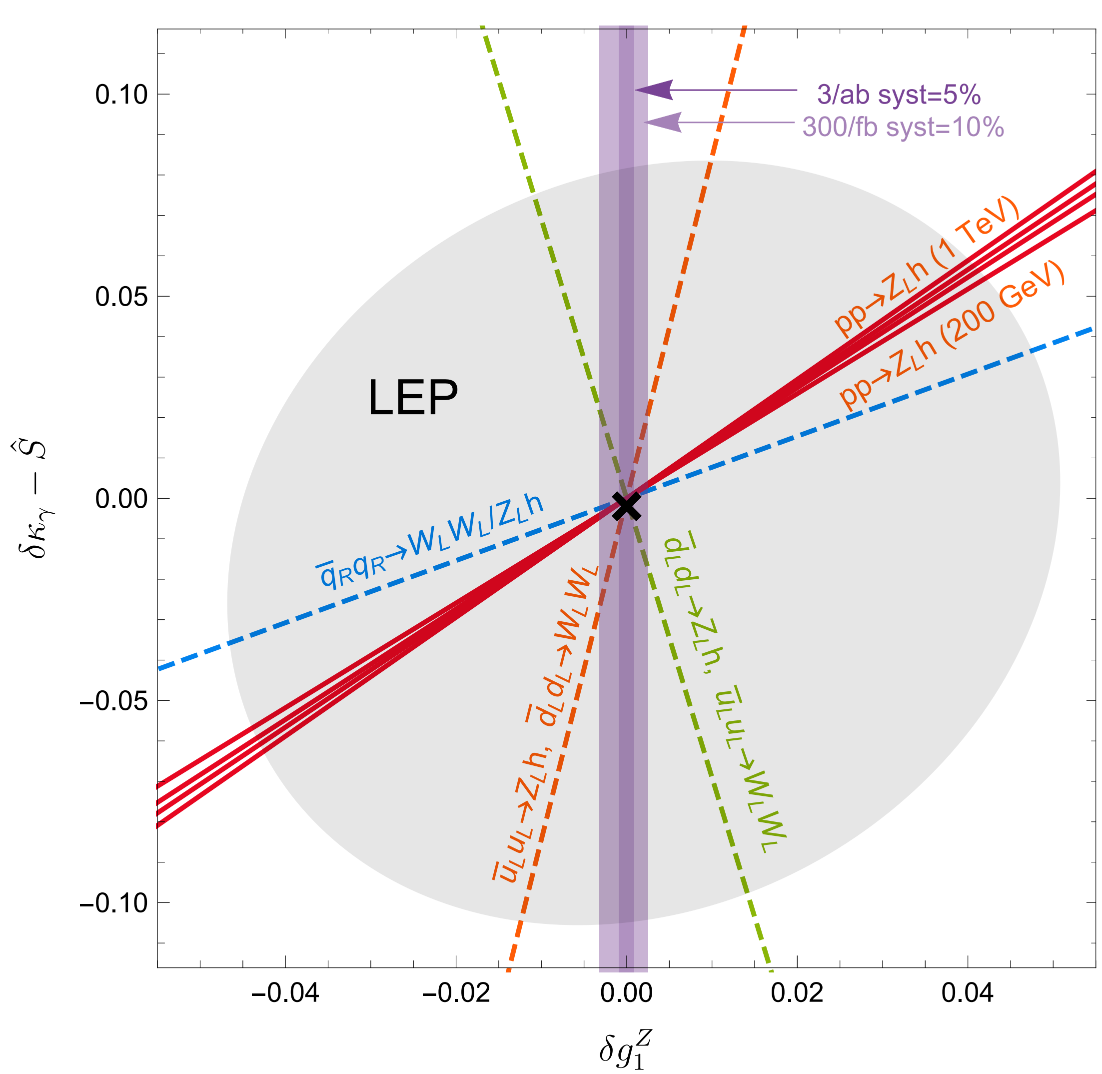
Challenges:

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

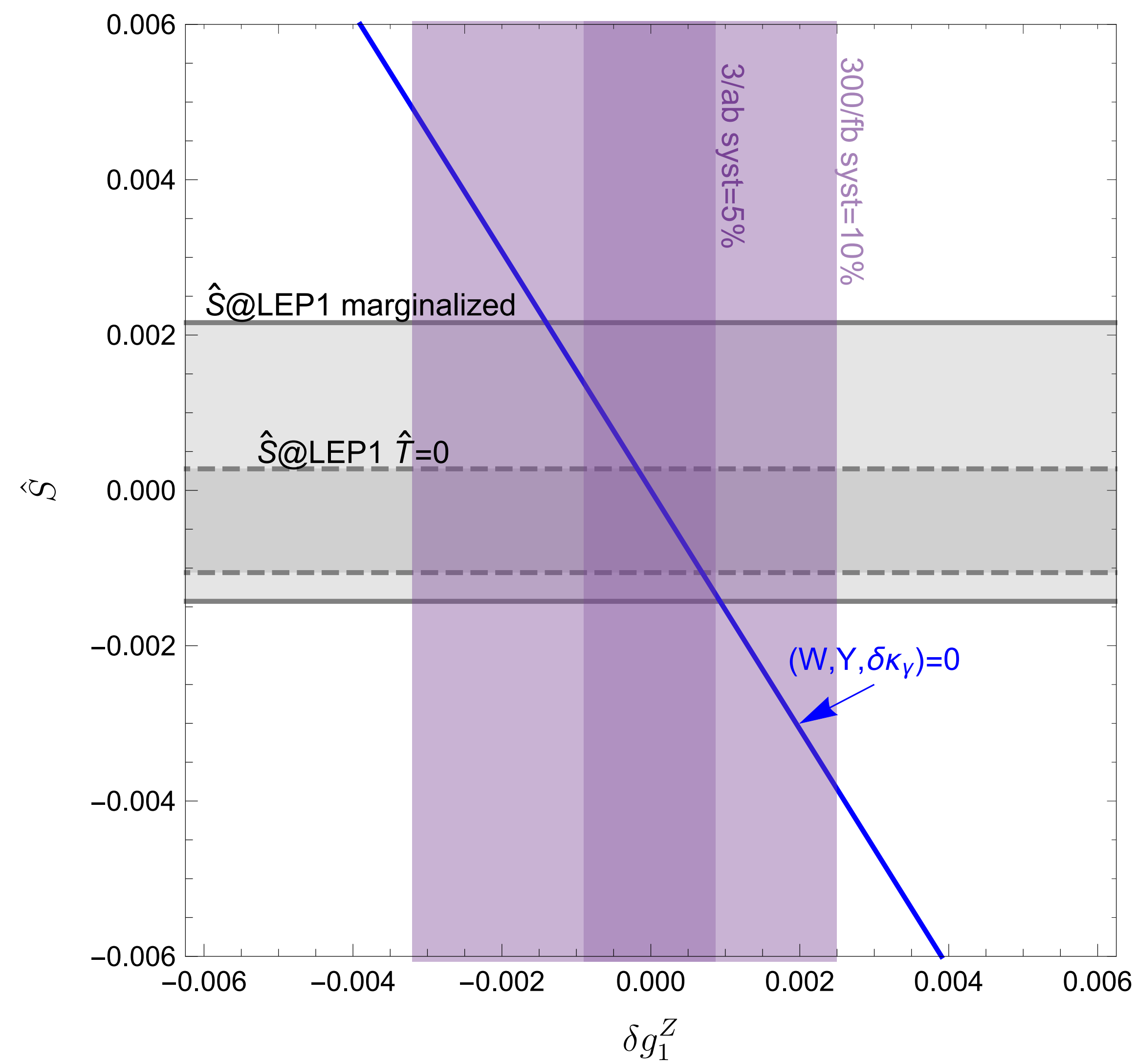
- Azimuthal distributions crucial (Realistic in other processes? WZ? VBF?)
- SM precision program LHC completes LEP

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