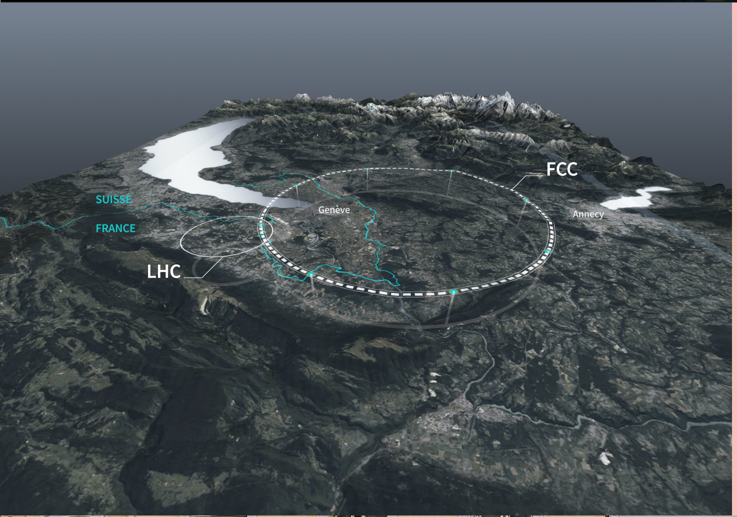


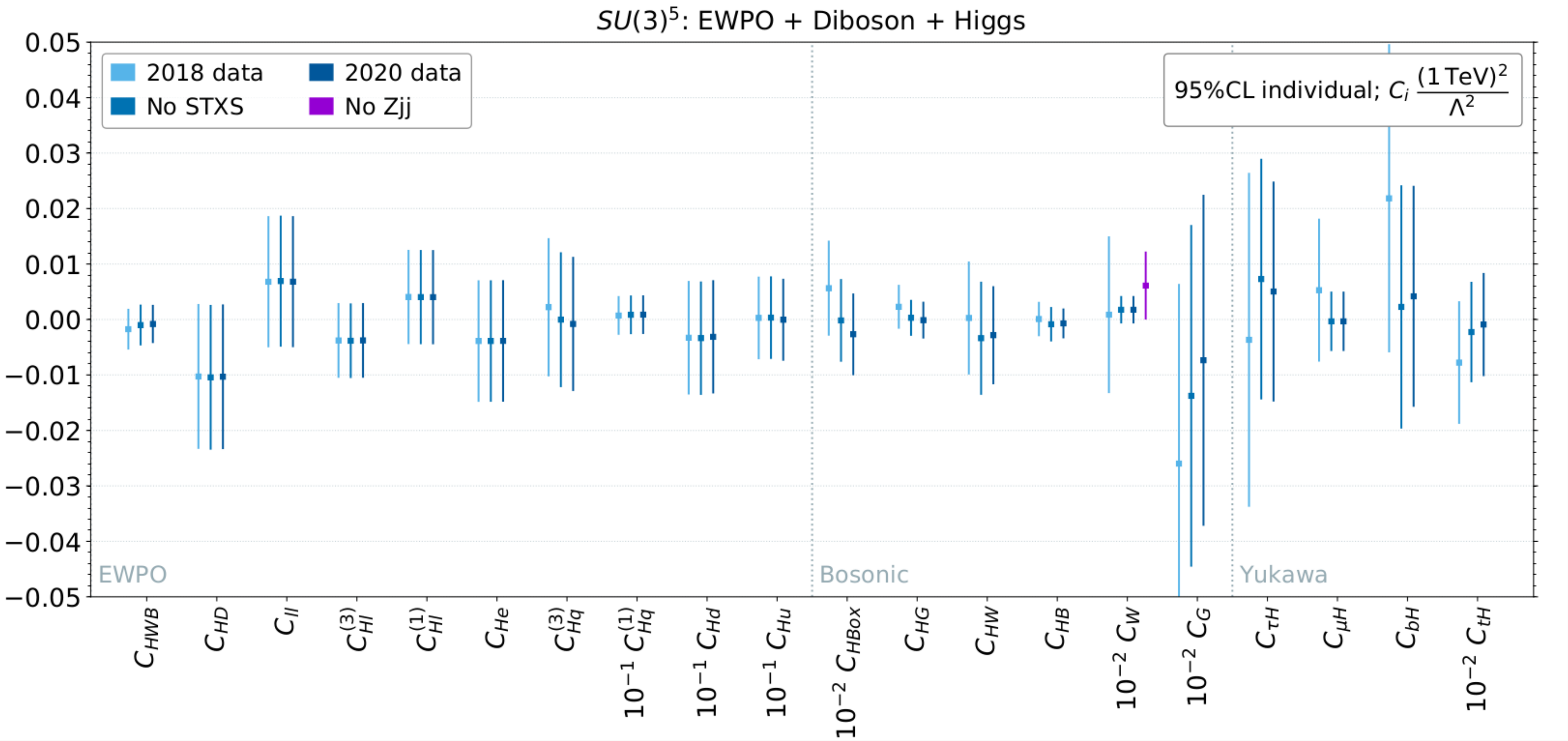
Probing Radiative Neutrino Masses and Extra Fermions at the Future Circular Collider

(Based on 2303.12232, CM and Aurora Melis)

Carlo Marzo, NICPB, Tallinn, Estonia

KBFI
NICPB

Theory&Pheno in the Standard Model: $\sim$ 60 years of harmony



Dim-6 operators live at TeV scale to appreciate per-cent level deviations

Heavy NP for $\sim$ 0.01 couplings

Top, Higgs, Diboson and EW Fit to the SM Effective Field Theory
John Ellis, Maeve Madigan, Ken Mimasu, Veronica Sanz, Tevong You

Theory&Pheno in the Standard Model:
$\sim$ 60 years of harmony ...

Heavy NP for
$\sim$ 0.01 couplings

but NP *unavoidable*

Neutrino Masses and Mixing

Strong CP

non-trivial CKM

Baryon Asymmetry

Inflation

Dark Matter

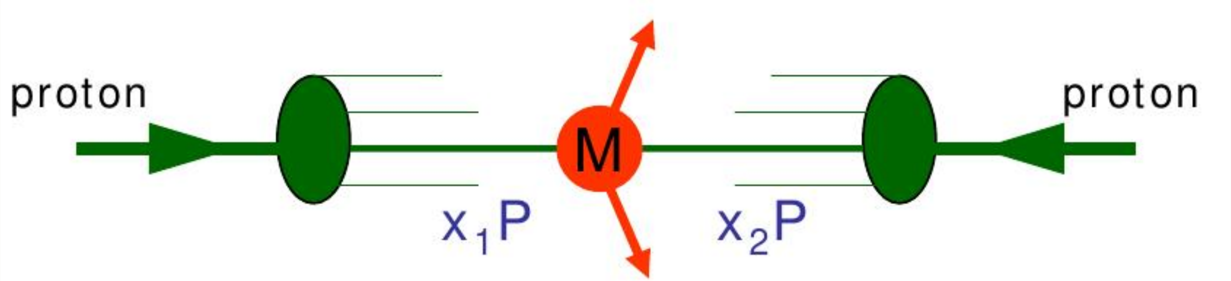
W-mass?

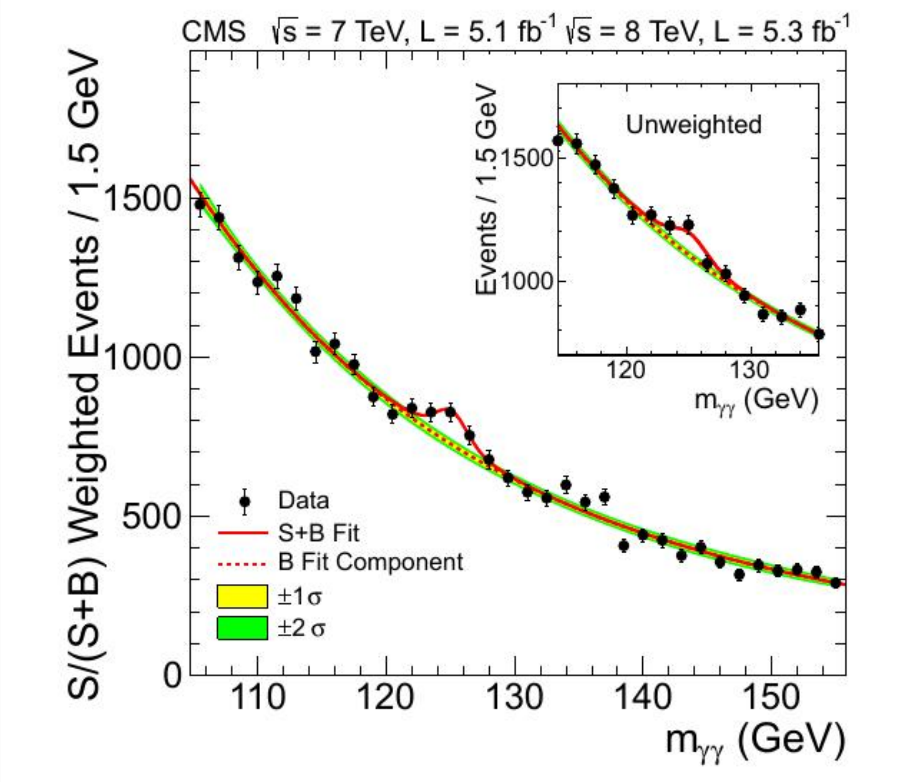
Dark Energy

g-2?

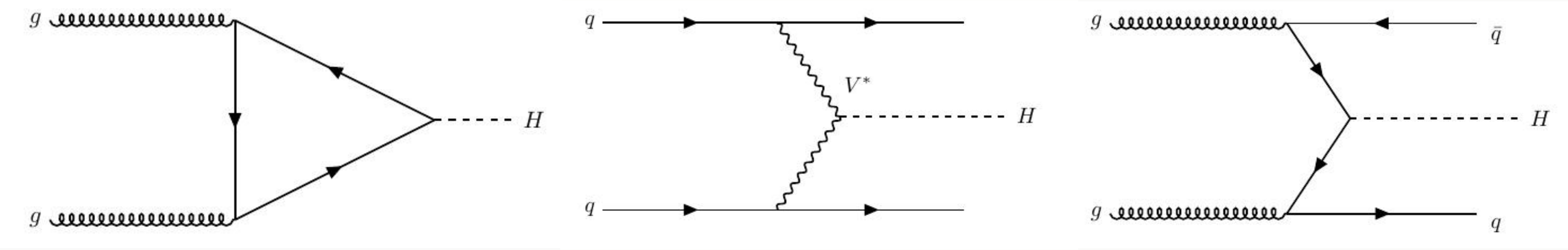
LHC: Discovery through production

We found the Higgs!





8 TeV for ∼ EW scale resonance



FCC-ee: Discovery* through precision (+ **HL-LHC**)

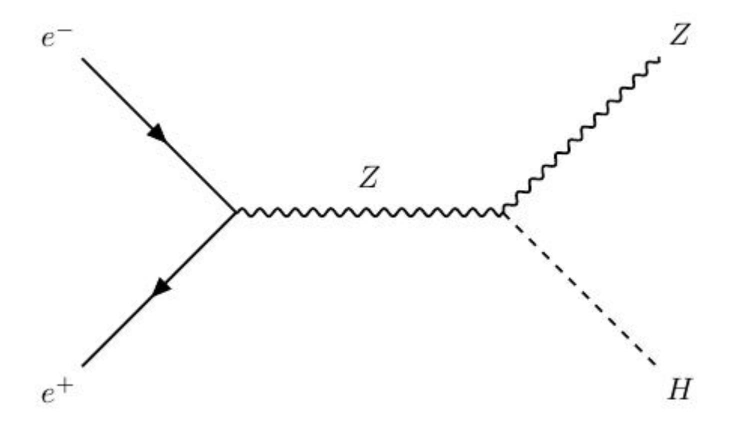
(*Of NP)

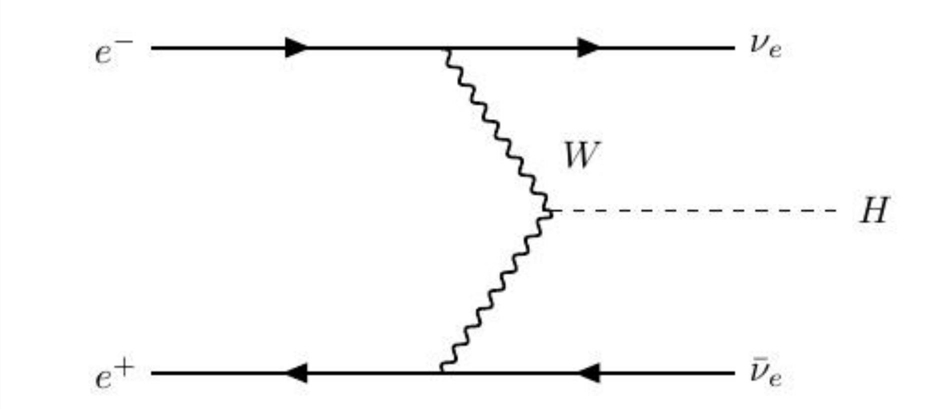
e^+e^- at $\sqrt{s} = 240, 365$ GeV

"Baseline plan:

$\sim 10^6$ events in ZH
$\sim 10^5$ events in WWH "

Higgs production:





"σ_{ZH} can be determined
...with an ultimate
statistical precision of 0.1%..."

$\sim$ SM radiative corrections

A special Higgs challenge
Paolo Azzurri, Gregorio Bernardi, Sylvie Braibant, Davide d'Enterria et al.

Opportunity for THEORY:
Heavy NP indirectly accessible

(like in LEP!)

FCC-ee: Discovery through precision : Higgs-strahlung

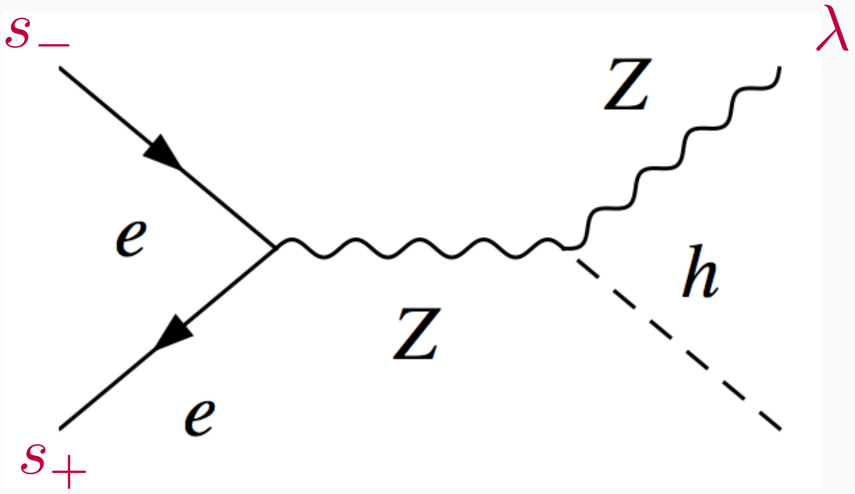
Opportunity for THEORY:
Heavy NP indirectly accessible

helicity/polarization structure

$$\mathcal{M}\left(\lambda; s_+, s_-\right) = \sum_j F_j \mathcal{M}_j \left(\lambda; s_+, s_-\right)$$

..if we have equally precise control over SM background

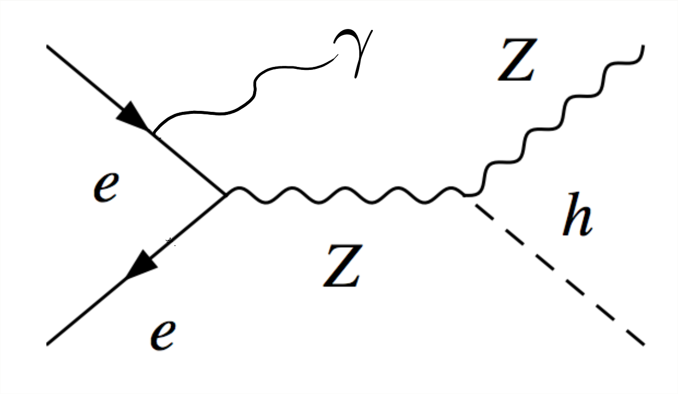
(+NLO)



$$|\mathcal{M}^{\text{NLO}}|^2 \simeq \sum_{ij} (F_i^{\text{LO}})^* (F_j^{\text{LO}} + 2\,\delta F_j) \text{Re}[\mathcal{M}_i^* \mathcal{M}_j],$$

2 SM NLO contributions:

FCC-ee: Discovery through precision : Higgs-strahlung

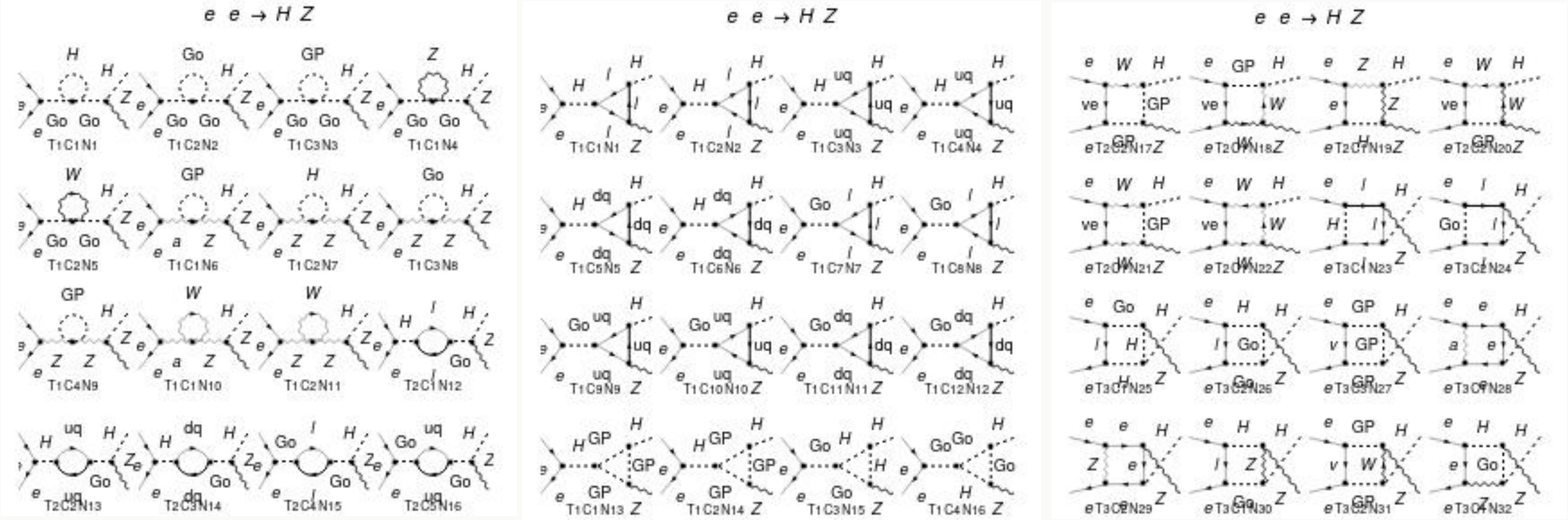


Opportunity for THEORY:
Heavy NP indirectly accessible

soft-γ radiation (IR)

..if we have equally precise control over SM background

+NLO



EW

FCC-ee: Discovery through precision : Higgs-strahlung

..if we have equally precise
control over SM background

Getting finite results is desiderable:

Dimensional regularization

+

ON-Shell renormalization (Sirlin '80, see also Denner '91)

$$g_1, g_w, Y_u, Y_d, Y_e, v_h, \lambda, \mu_1^2$$

$$\downarrow$$

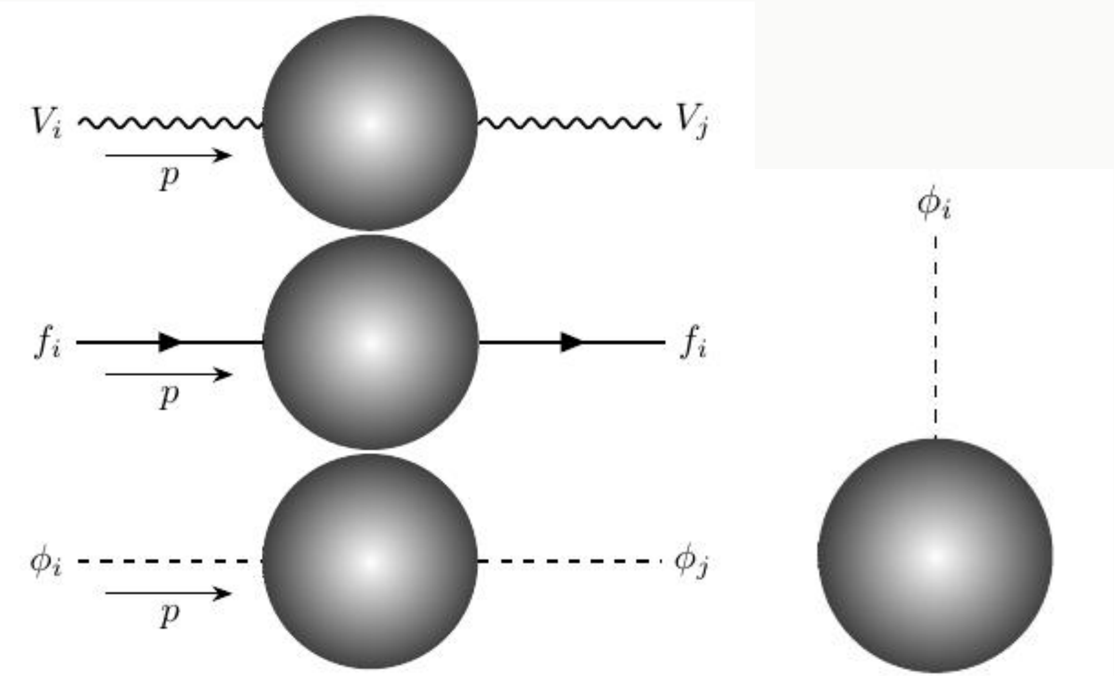
$$m_Z^2, m_W^2, \mathrm{e}, m_{u_i}, m_{d_i}, m_{l=e,\mu,\tau}, m_h^2, t$$

$$\downarrow$$

$$\begin{aligned}
&m_Z^2 \to m_Z^2 + \delta m_Z^2,\ m_W^2 \to m_W^2 + \delta m_W^2,\\
&m_f \to m_f + \delta m_f, \quad (f = u, d, l)\\
&m_h^2 \to m_h^2 + \delta m_h^2,\ t \to t + \delta t\,,\\
&\mathrm{e} \to \mathrm{e}\,(1 + \delta \mathrm{e})
\end{aligned}$$

$\longrightarrow$

Renormalization conditions:



FCC-ee: Discovery through precision : Higgs-strahlung

..if we have equally precise
control over <u>SM</u> background

Getting finite results is desiderable:

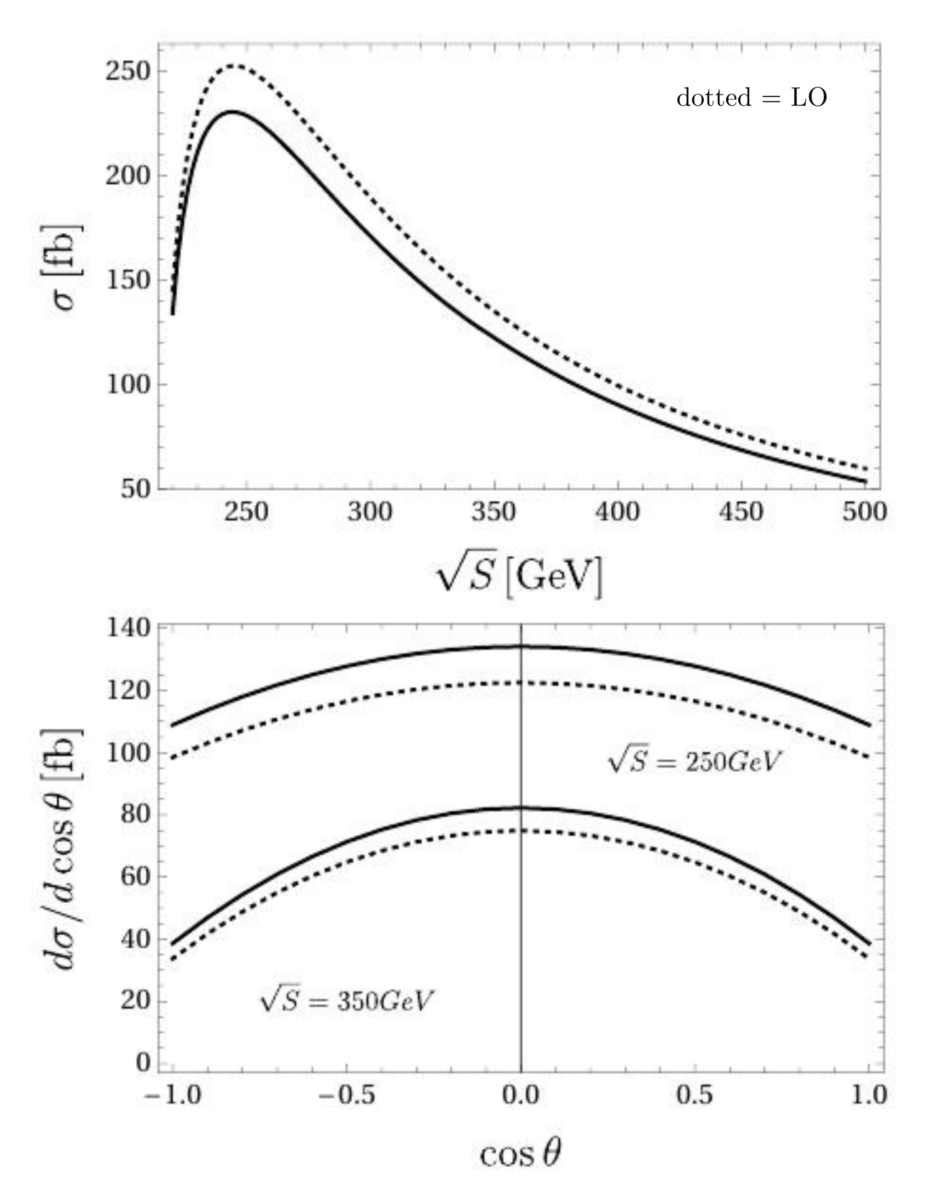
Dimensional regularization
+
ON-Shell renormalization (Sirlin '80, see also Denner '91)
=
IR and UV finite result

$$|\mathcal{M}^{\rm NLO}|^2 \simeq \sum_{ij} (F_i^{\rm LO})^* (F_j^{\rm LO} + 2\,\delta F_j) {\rm Re}[\mathcal{M}_i^* \mathcal{M}_j]$$

$$\sigma_{Zh}^{\rm SM}(250{\rm GeV}) = 228.748[{\rm fb}],$$

$$\sigma_{Zh}^{\rm SM}(350{\rm GeV}) = 123.392[{\rm fb}]$$

unpol $\sigma_{Zh}^{SM} \sim 25$[fb] LO-NLO



FCC-ee: Discovery through precision : Higgs-strahlung

We are now ready to address BSM (affecting NLO):

$$\mathcal{M}\left(\lambda; s_+, s_-\right) = \sum_j F_j \mathcal{M}_j\left(\lambda; s_+, s_-\right)$$

$$|\mathcal{M}^{\rm NLO}|^2 \simeq \sum_{ij} (F_i^{\rm LO})^* (F_j^{\rm LO} + 2\,\delta F_j) {\rm Re}[\mathcal{M}_i^* \mathcal{M}_j]$$

$$F_j^{LO} = F_j^{Born}$$
$$\delta F_j = \delta F_j^{SM} + \delta F_j^{NP}$$

(where $F^{\rm LO}$ = LO and δF_j = NLO form factors)

$$|\mathcal{M}^{\rm NLO}|^2 \simeq |\mathcal{M}^{\rm Born}|^2 + 2{\rm Re}[\mathcal{M}^{*\,\rm Born}\left(\delta\mathcal{M}^{\rm SM} + \delta\mathcal{M}^{\rm NP}\right)]$$

$$|\mathcal{M}^{\rm NLO}|^2 \simeq |\mathcal{M}^{\rm NLO}_{SM}|^2 + 2{\rm Re}[\mathcal{M}^{*\,\rm Born}\delta\mathcal{M}^{\rm NP}]$$

σ_{Zh} linear in NP!

FCC-ee: Discovery through precision : Higgs-strahlung

A minimal/common extension: extra doublet.

Inert Doublet Model

(2009.03250, Abouabid, Arhrib, Benbrik et Al.)

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v_h + h + iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}$$

(EW vacuum, no vev for H_2)

$$\mathcal{L}^{\mathrm{IDM}} = \mathcal{L}^{\mathrm{SM}} + |D_\mu H_2|^2 - \mu_2^2 |H_2|^2 - \lambda_2 |H_2|^4$$
$$- \lambda_3 |H_1|^2 |H_2|^2 - \lambda_4 |H_1^\dagger H_2|^2$$
$$- \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \mathrm{h.c.}\right]$$

(no scalar mixing, no SM fermion coupling)

$$m_{H^\pm}^2 = m_0^2 - \lambda_4 \frac{v_h^2}{2},$$
$$m_{H^0}^2 = m_0^2 + \lambda_5 \frac{v_h^2}{2},$$
$$m_{A^0}^2 = m_0^2 - \lambda_5 \frac{v_h^2}{2}.$$

$(m_0^2 \equiv \frac{1}{2}(m_{H^0}^2 + m_{A^0}^2) = \mu_2^2 + (\lambda_3 + \lambda_4)\frac{v_h^2}{2})$

Inert Doublet Model: a portal for BSM NP

(from 2009.03250, Abouabid, Arhrib, Benbrik et Al.)

$\lambda_i < 8\pi$ (perturbativity)

Theo bounds:

$\lambda_2 > 0, \quad \lambda_3\,, \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2} \quad (\lambda_1 \sim 0.132)$ (vacuum stability)

$$|e_i^{\pm}| < 8\pi \qquad \begin{aligned} e_1^{\pm} &= \lambda_3 \pm \lambda_{4,5}\,, \quad e_2 = \lambda_3 + 2\lambda_4 \pm 3\lambda_5\,, \\ e_4^{\pm} &= -(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_{4,5}^2}\,, \\ e_5^{\pm} &= -3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2} \end{aligned}$$

(perturbative unitarity)

Pheno bounds:

Precise measurements of Z and W widths at **LEP** forbids $Z \to H^+H^-$, $Z \to H^0 A^0$ and $W^{\pm} \to H^{\pm}H^0(A^0)$:

$2m_{H^\pm} > m_Z\,, \quad m_{H^0} + m_{A^0} > m_Z\,, \quad m_{H^\pm} + m_{H^0,A^0} > m_W$

LEP II chargino searches: $m_{H^\pm} > \{70 - 90\}$ GeV

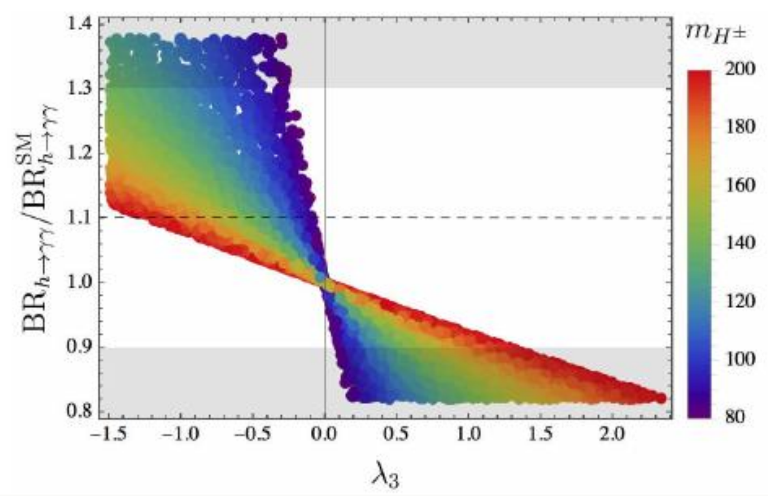
LEP II neutralino searches do not apply!

Higgs data at **LHC**

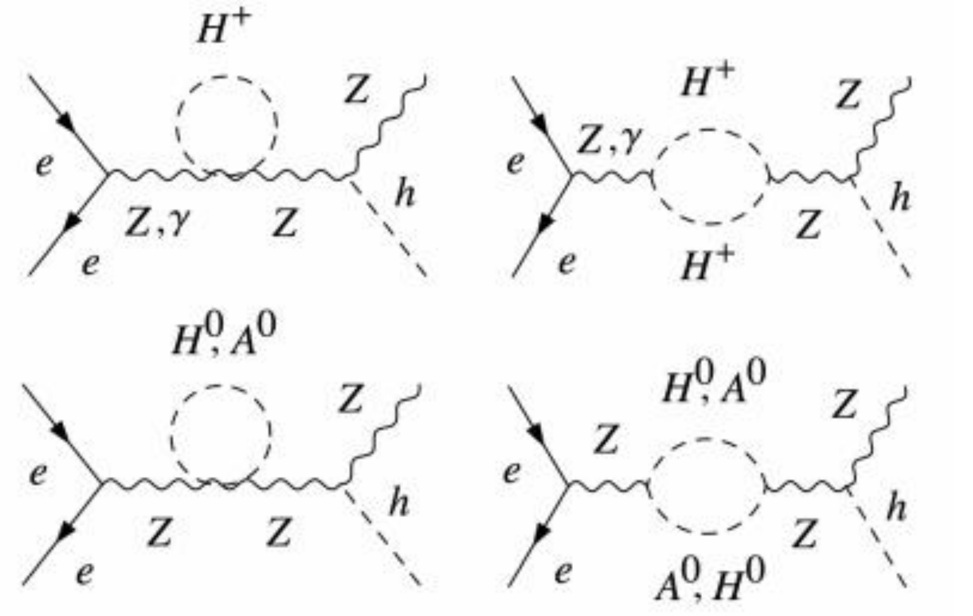
$h \to$ invisible: $m_{H^0,A^0} > m_h/2$

Radiative contributions on $h \to \gamma\gamma$ from $H^{\pm}$: constraint on λ_3

~~Oblique~~ Oblique Parameters?



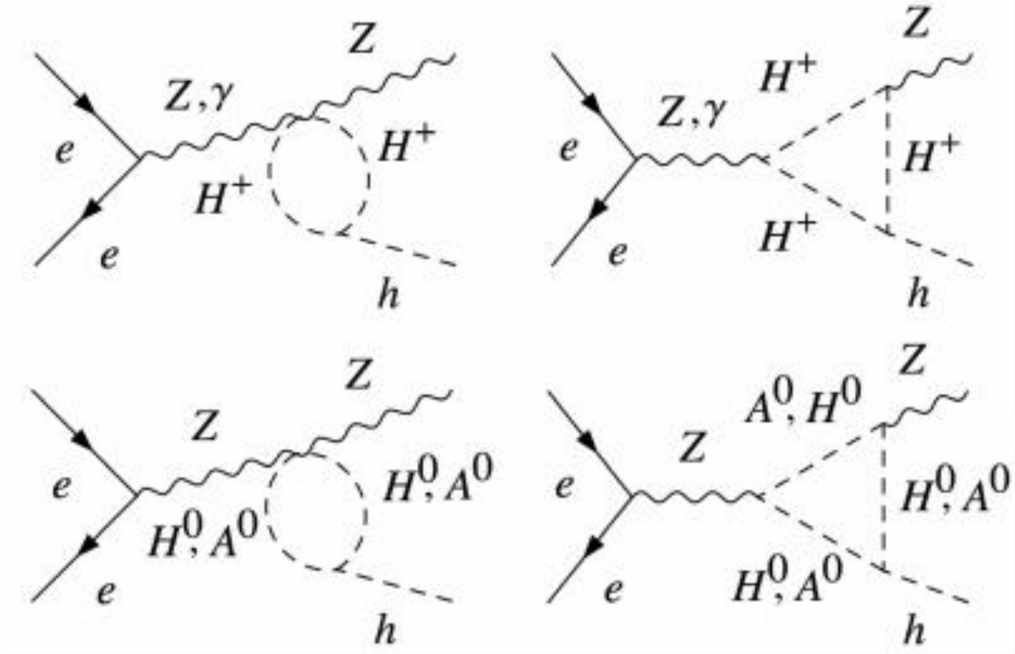
Inert Doublet Model



$$\delta F^{S,\mathrm{IDM}}_{L,R} = \frac{\alpha F^{\mathrm{LO}}_{L,R}}{8\pi c_W^2 s_W^2 (S - m_Z^2)} \times \Bigg\{ (c_W^2 - s_W^2)^2 \left[1 - \frac{2 c_W s_W (1 - m_Z^2/S)}{g^{Ze}_{L,R}(c_W^2 - s_W^2)} \right] \times \Big(2B_{00}[S, m_{H^\pm}, m_{H^\pm}] - A_0[m_{H^\pm}] \Big) + \left(2B_{00}[S, m_{A^0}, m_{H^0}] - \frac{A_0[m_{H^0}] + A_0[m_{A^0}]}{2} \right) \Bigg\},$$

$$(\delta F^{S,\mathrm{IDM}}_{L,R})^{ct} = F^{\mathrm{LO}}_{L,R} \left[\frac{\delta m_Z^2}{S - m_Z^2} - \delta_Z - \frac{\delta_{AZ}}{2 g^{Ze}_{L,R}} + \frac{\delta_{ZA}}{2 g^{Ze}_{L,R}} \left(1 - \frac{m_Z^2}{S} \right) \right]$$

Inert Doublet Model



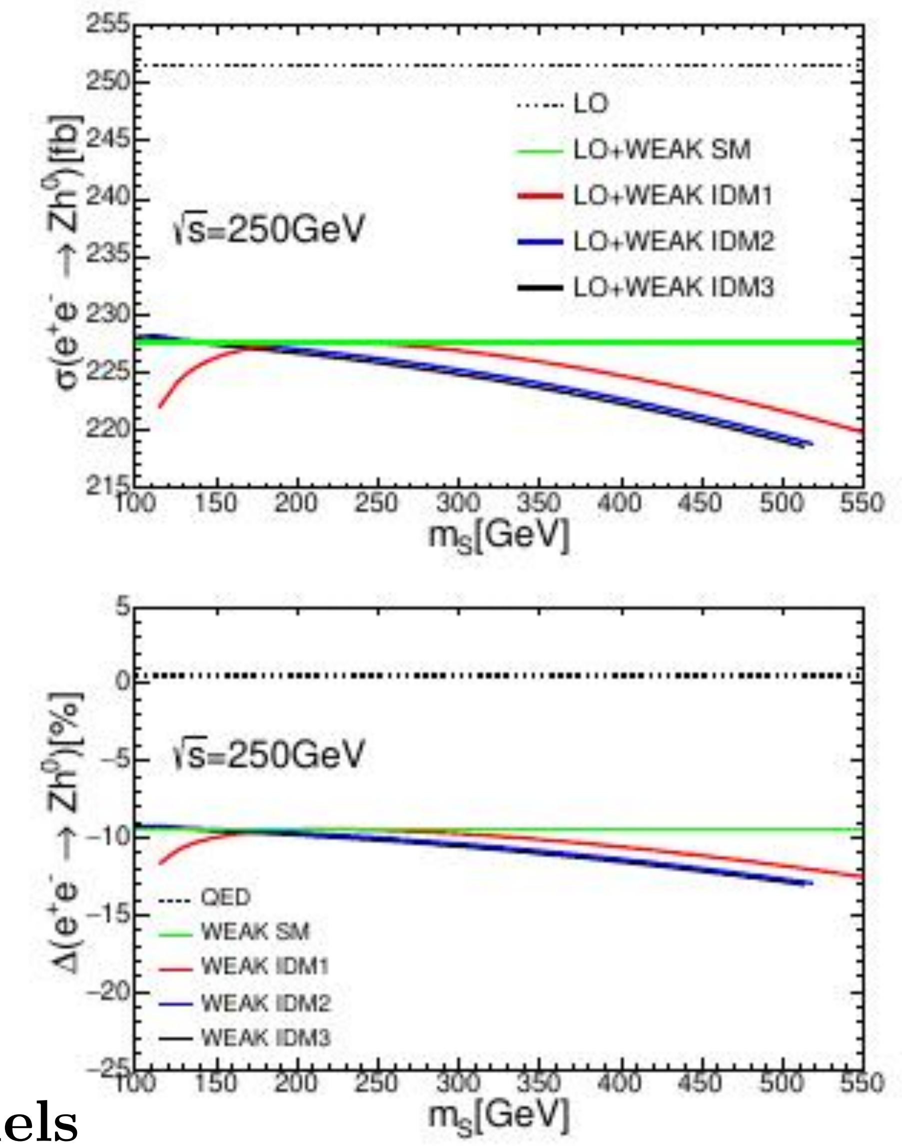
$$
\begin{aligned}
\delta F_{L,R}^{V,\mathrm{IDM}} = \frac{F_{L,R}^{\mathrm{LO}}}{16\pi^2}\Bigg\{ & (c_W^2 - s_W^2)^2 \left[1 - \frac{2c_W s_W (1 - m_Z^2/S)}{g_{L,R}^{Ze}(c_W^2 - s_W^2)}\right] \\
& \times \lambda_3 \Big(- B_0[m_h^2, m_{H^\pm}^2, m_{H^\pm}^2] \\
& \quad + 4C_{00}[m_Z^2, m_h^2, S, m_{H^\pm}^2, m_{H^\pm}^2, m_{H^\pm}^2] \Big) \\
& + \frac{\lambda_3 + \lambda_4 + \lambda_5}{2} \Big(- B_0[m_h^2, m_{H^0}^2, m_{H^0}^2] \\
& \quad + 4C_{00}[m_Z^2, m_h^2, S, m_{A^0}^2, m_{H^0}^2, m_{H^0}^2] \Big) \\
& + \frac{\lambda_3 + \lambda_4 - \lambda_5}{2} \Big(- B_0[m_h^2, m_{A^0}^2, m_{A^0}^2] \\
& \quad + 4C_{00}[m_Z^2, m_h^2, S, m_{H^0}^2, m_{A^0}^2, m_{A^0}^2] \Big) \Bigg\},
\end{aligned}
$$

$$
\begin{aligned}
(\delta F_{L,R}^{V,\mathrm{IDM}})^{ct} = F_{L,R}^{\mathrm{LO}} \Bigg[& \frac{\delta_h}{2} + \delta_Z + \delta \mathrm{e} + \frac{\delta m_Z^2}{2m_Z^2} \\
& + \frac{c_W^2 - s_W^2}{2s_W^2} \left(\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} \right) \Bigg]
\end{aligned}
$$

Inert Doublet Model (past results)

"… it is observed that weak corrections in the IDM are tipically negative and can reach 9%- 14% at $\sqrt{S} = 250$ GeV…"

(from 2009.03250, Abouabid, Arhrib, Benbrik et Al.)



The IDM, a common IR-tail, would provide a large background for many NP models

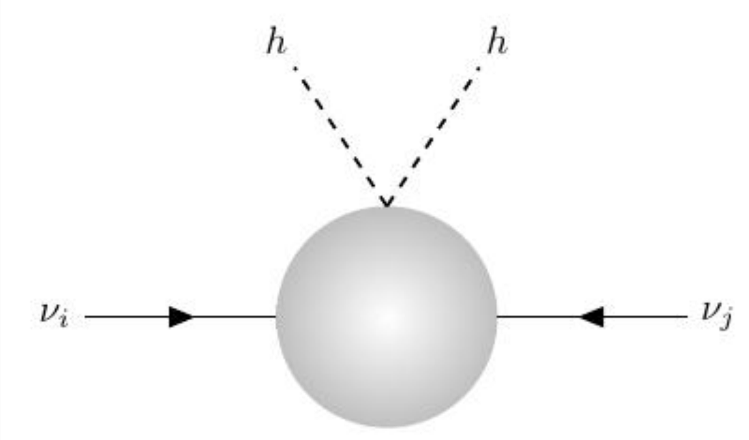
Inert Doublet Model + sterile fermions $\mathbf{N_k}$

A gift from the inert-doublet *portal*. By adding extra fermions:

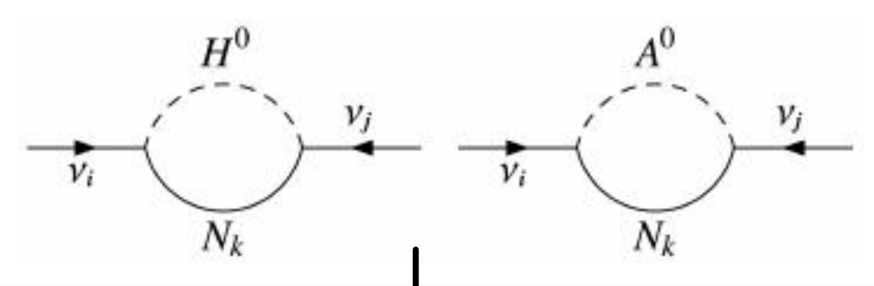
$(\mathcal{L}^{\text{Scoto}} = \mathcal{L}^{\text{IDM}} + \mathcal{L}^{\text{RHN}})$

$$\mathcal{L}^{\text{RHN}} = \overline{N}_k \gamma^\mu \partial_\mu N_k - y^N_{ik} \overline{L}_i \widetilde{H}_2 N_k - \frac{m_{N_k}}{2} \overline{N^c_k} N_k + \text{h.c.}$$

Radiative realization of dim-5 $\overline{L}_i \cdot \tilde{H}_1 H_1^T \cdot L_j^c$



SSB

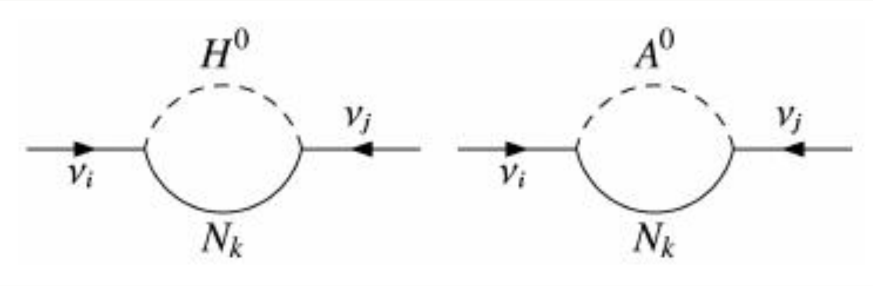


massive neutrino

Scotogenic (dark) model - (Ernest Ma, 2006)

Inert Doublet Model + sterile fermions $\mathbf{N_k}$

Radiative realization of dim-5 $\overline{L}_i \cdot \tilde{H}_1 H_1^T \cdot L_j^c$



$$(m_\nu)_{ij} = (Y_N \Lambda Y_N^T)_{ij} = \sum_{k=1}^{3} y_{ik}^N y_{jk}^N \Lambda_k$$

$$\Lambda_k = \frac{m_{N_k}}{16\pi^2}\left(B_0[0, m_{H^0}^2, m_{N_k}^2] - B_0[0, m_{A^0}^2, m_{N_k}^2]\right)$$

H^0 and A^0 give equals but opposite in sign contributions:
neutrino masses controlled by mass splitting $m_{H_0}^2 - m_{A_0}^2 = \lambda_5 v_h^2$

limit: $m_0 \simeq m_{N_k}$
$\lambda_5 \to 0$

$$(m_\nu)_{ij} \simeq \frac{\lambda_5 v_h^2}{32\pi^2} \sum_{k=1}^{3} \frac{y_{ik}^N y_{jk}^N}{m_{N_k}}$$

size of the see-saw scale reduced by a factor of

$$\lambda_5 v_h^2 / 32\pi^2$$

Scotogenic (dark) model - (Ernest Ma, 2006)

~~Radiative neutrino model meets FCC-ee~~

$$\mathcal{L}^{\mathrm{RHN}} = \overline{N}_k \gamma^\mu \partial_\mu N_k - y_{ik}^N \overline{L}_i \widetilde{H}_2 N_k - \frac{m_{N_k}}{2} \overline{N_k^c} N_k + \mathrm{h.c.}$$

..but also..

Portal Doublet + secluded N_k meet FCC-ee

$$\mathcal{L}^{\mathrm{RHN}} = \overline{N}_k \gamma^\mu \partial_\mu N_k - y_{ik}^N \overline{L}_i \widetilde{H}_2 N_k - \frac{m_{N_k}}{2} \overline{N_k^c} N_k + \mathrm{h.c.}$$

and no neutrino masses..

Radiative neutrino model meets FCC-ee

$$\mathcal{L}^{\mathrm{RHN}} = \overline{N}_k \gamma^\mu \partial_\mu N_k - y^N_{ik} \overline{L}_i \widetilde{H}_2 N_k - \frac{m_{N_k}}{2} \overline{N^c_k} N_k + \mathrm{h.c.}$$

pick a generation number

$$N_{k=1,2,3}$$

Different Neutrino Pheno
Different Lepton-Flavour signals

(*Generalizing the Scotogenic model* - Escribano, Reig, Vicente)

(*LFV in the Scotogenic model* - Toma, Vicente)

1) Neutrino Pheno
2) Survive LFV, address future LFV
3)Collider constraints (beyond oblique)
4) FCC-ee signal shaped by $\mathbf{N_k}$

Radiative neutrino model meets FCC-ee

Neutrino observable	NH	IH
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.42^{+0.21}_{-0.20}$	$7.42^{+0.21}_{-0.20}$
Δm^2_{3l} $[10^{-3}\text{eV}^2]$	$+2.515^{+0.028}_{-0.028}$	$-2.498^{+0.028}_{-0.029}$
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.304^{+0.012}_{-0.012}$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02238^{+0.00064}_{-0.00062}$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.578^{+0.017}_{-0.021}$
$\delta_{\text{CP}}[^\circ]$	194^{+52}_{-25}	287^{+27}_{-32}

(Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792)

1) Neutrino Pheno
2) Survive LFV, address future LFV
3) Collider constraints (beyond oblique)
4) FCC-ee signal shaped by $\mathbf{N_k}$

$$(m_\nu)_{ij} \simeq \frac{\lambda_5 v_h^2}{32\pi^2} \sum_{k=1}^{3} \frac{y^N_{ik} y^N_{jk}}{m_{N_k}}$$

must comply with data (PMNS): Casas-Ibarra reverse problem

$$Y_N = U^{\nu *}\sqrt{\widehat{m}_\nu}\, R \sqrt{\Lambda_k}^{-1}$$

We have some freedom: $R \in \mathbb{C}$ such $R^T R = \mathbb{I}$

escaping LFV!

$$y^N_{ik} = \frac{\sqrt{m_1}\, U^{\nu *}_{i1} R_{1k} + \sqrt{m_2}\, U^{\nu *}_{i2} R_{2k} + \sqrt{m_3}\, U^{\nu *}_{i3} R_{3k}}{\sqrt{\Lambda_k}}$$

Radiative neutrino model meets FCC-ee

LFV Process	Current Limit	Future Limit
$\text{BR}(\mu \to e\gamma)$	4.2×10^{-13} (MEG at PSI)	6×10^{-14} (MEG II)
$\text{BR}(\tau \to e\gamma)$	3.3×10^{-8} (BaBar)	5×10^{-9} (Belle II)
$\text{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar)	10^{-9} (Belle II)
$\text{BR}(\mu \to 3e)$	1.0×10^{-12} (SINDRUM)	10^{-16} (Mu3e)
$\text{BR}(\tau \to 3e)$	2.7×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\text{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\text{BR}(Z \to \mu e)$	7.5×10^{-7} (LHC ATLAS)	$10^{-10} - 10^{-8}$ (FCC-ee)
$\text{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP OPAL)	10^{-9} (FCC-ee)
$\text{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LHC DELPHI)	10^{-9}(FCC-ee)
$\text{BR}(h \to \mu e)$	6.1×10^{-5} (LHC CMS)	–
$\text{BR}(h \to \tau e)$	4.7×10^{-3} (LHC CMS)	–
$\text{BR}(h \to \tau\mu)$	2.5×10^{-3} (LHC CMS)	–

1) Neutrino Pheno
2) Survive LFV, address future LFV
3) Collider constraints (beyond oblique)
4) FCC-ee signal shaped by $\mathrm{N_k}$

Need to compute:

$\text{BR}(l_i \to l_j\gamma)$, $\text{BR}(l_i \to 3l_j)$ and $\text{BR}(Z(h) \to l_j l_j)$

(*LFV in the Scotogenic model* - Toma, Vicente)

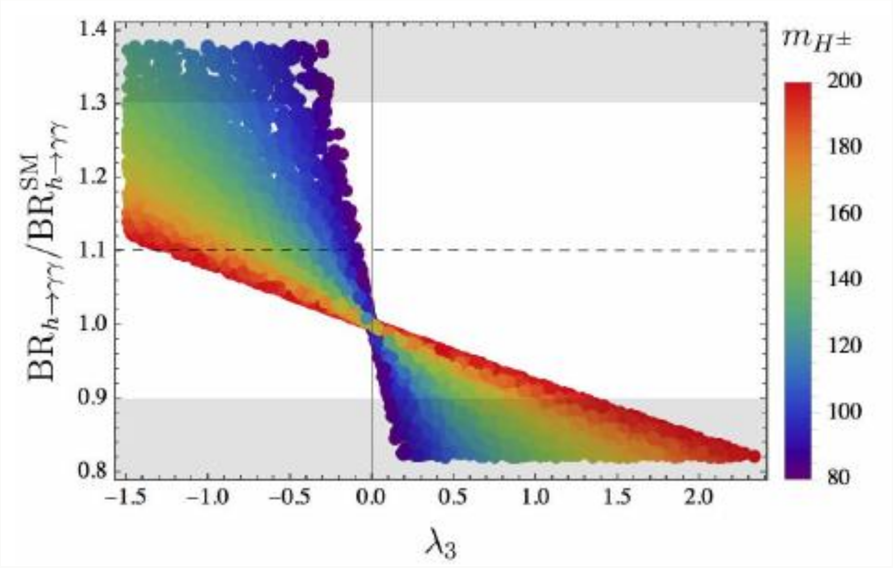
Most severe constraint from $\mu \to e\gamma$ MEG experiment.

Use R to elude $\mu \to e\gamma$.
Fix its value within MEG II experiment.

Radiative neutrino model meets FCC-ee

Sc.M. inherits IDM sector constraints

one more time:
Important bound on λ_3 from $H^\pm$ in $h \to \gamma\gamma$.



($H^\pm$ must be included to appreciate N_k)

1) Neutrino Pheno
2) Survive LFV, address future LFV
3) Collider constraints (beyond oblique)
4) **FCC-ee signal shaped by $\mathbf{N_k}$**

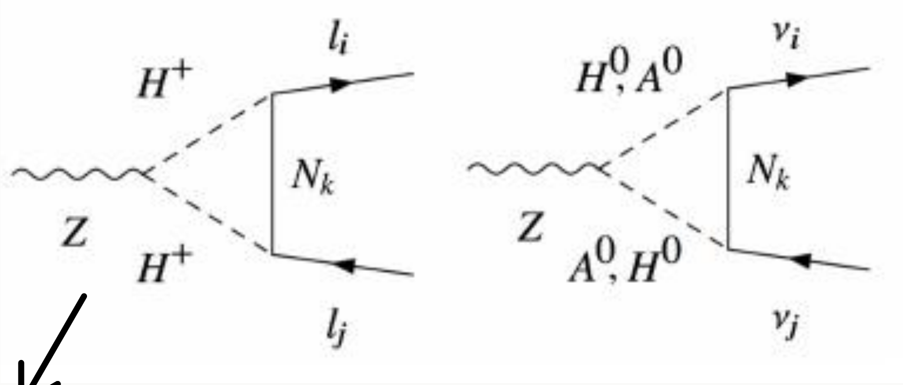
Unsuppressed (but perturbative)
NP couplings to light fermions +
NP scale comparable to M_Z and M_W :

↓

Explicit computation lepton-diagonal decays
$Z \to l^+ l^-$, $Z \to \nu_l \nu_l$ and $W^\pm \to l^\pm \nu_l$

Radiative neutrino model meets FCC-ee

Explicit computation lepton-diagonal decays
$Z \to l^+ l^-$, $Z \to \nu_l \nu_l$ and $W^\pm \to l^\pm \nu_l$



1) Neutrino Pheno
2) Survive LFV, address future LFV
3) Collider constraints (beyond oblique)
4) **FCC-ee signal shaped by $\mathbf{N_k}$**

$$\delta F_L^{Z\to l_i l_i} = \frac{\mathrm{e} g_L^{Ze}}{8\pi^2} \sum_k |y_{ik}^N|^2$$
$$\times\, C_{00}\left[m_Z^2, 0, 0, m_{H^\pm}^2, m_{H^\pm}^2, m_{N_k}^2\right],$$
$$(\delta F_L^{Z\to l_i l_i})^{ct} = \mathrm{e} g_L^{Ze}\left[\frac{\delta_Z}{2} + \delta_{l_{Li}} + \delta \mathrm{e} + \frac{\delta_{AZ}}{2 g_L^{Ze}}\right.$$
$$\left. + \frac{1}{4 s_W^3 c_W g_L^{Ze}}\left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta m_Z^2}{m_Z^2}\right)\right]$$

$$\delta F_L^{Z\to \nu_i \nu_i} = \frac{\mathrm{e} g_L^{Z\nu}}{8\pi^2} \sum_k |y_{ik}^N|^2$$
$$\times\, C_{00}\left[m_Z^2, 0, 0, m_{A^0}^2, m_{H^0}^2, m_{N_k}^2\right],$$
$$(\delta F_L^{Z\to \nu_i \nu_i})^{ct} = \mathrm{e} g_L^{Z\nu}\left[\frac{\delta_Z}{2} + \delta_{\nu_{Li}} + \delta \mathrm{e}\right.$$
$$\left. + \frac{c_W^2 - s_W^2}{2 s_W^2}\left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta m_Z^2}{m_Z^2}\right)\right]$$

Full Sco.M. reno required! (Same for W decays)

Radiative neutrino model meets FCC-ee

Proper Sco.M. corrections: need for $H^{\pm}$

$$\delta F_L^{V,\text{RHN}} = -\frac{m_Z(c_W^2 - s_W^2)}{16\pi^2}\sum_{k=1}^{3}|y_{1k}^N|^2$$
$$\times\Bigg(\frac{4\pi\alpha}{c_W^2 s_W^2(S-m_Z^2)}C_{00}\left[S,0,0,m_{H^\pm}^2,m_{H^\pm}^2,m_{N_k}^2\right]$$
$$-\lambda_3\,C_1\left[m_h^2,T,0,m_{H^\pm}^2,m_{H^\pm}^2,m_{N_k}^2\right]$$
$$+\lambda_3\,C_1\left[m_h^2,U,0,m_{H^\pm}^2,m_{H^\pm}^2,m_{N_k}^2\right]\Bigg)$$

and properly OS-renormalized

$$(\delta F_L^{V,\text{RHN}})^{ct} = F_L^{\text{LO}}\left[\frac{\delta_Z}{2}+\delta_{e_L}+\delta\text{e}+\frac{\delta_{AZ}}{2g_L^{Ze}}\right.$$
$$\left.+\frac{1}{2s_W^2}\left(\frac{\delta m_W^2}{m_W^2}-\frac{\delta m_Z^2}{m_Z^2}\right)\right]$$

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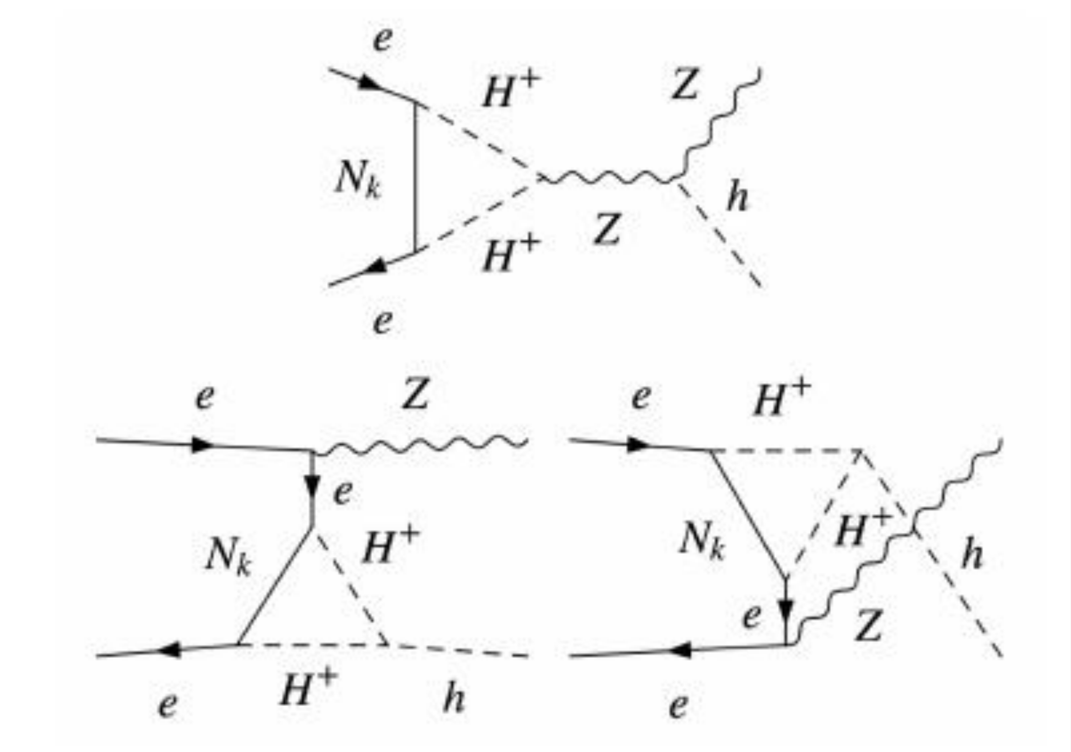

Radiative neutrino model meets FCC-ee

Proper Sco.M. corrections: need for $H^{\pm}$

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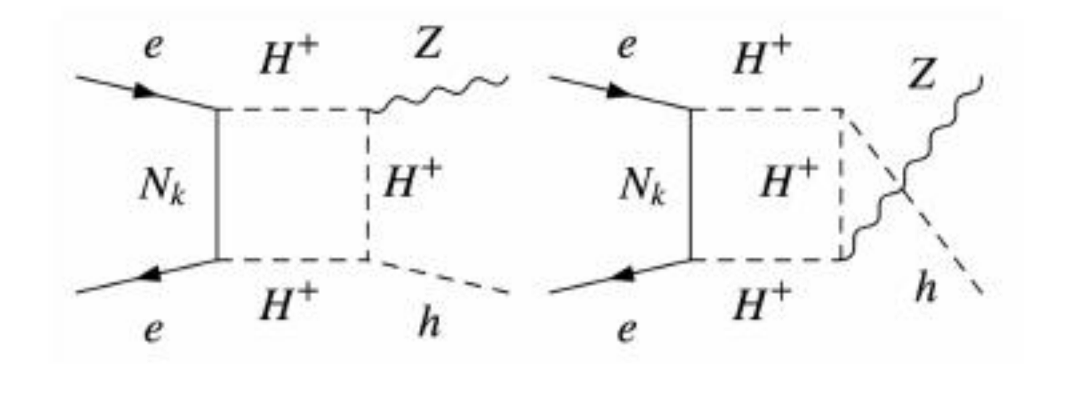
And the finite box contributions:

$$\delta F_L^{B,\mathrm{RHN}} = -\lambda_3 \frac{m_Z(c_W^2 - s_W^2)}{8\pi^2} \sum_{k=1}^{3} |y_{1k}^N|^2$$
$$\times \Big(D_{00}\left[m_h^2, m_Z^2, 0, 0, S, U, m_{H^\pm}^2, m_{H^\pm}^2, m_{H^\pm}^2, m_{N_k}^2\right]$$
$$+ D_{00}\left[m_Z^2, m_h^2, 0, 0, S, T, m_{H^\pm}^2, m_{H^\pm}^2, m_{H^\pm}^2, m_{N_k}^2\right] \Big)$$



(approximation! Full formulas and missing amplitudes in the paper)

Radiative neutrino model meets FCC-ee

1) **Neutrino Pheno**
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caveat N1

$\lambda_5 = 0$, YES, but forget massive ν_l

$\lambda_5 \neq 0$, challenging!

(theory and pheno) constraints + σ_{Zh}^{scoto}:
can we "see" the RHN?

big λ_5, too big scale of RHN

target: enhancing

$$\delta\sigma_{Zh}^{\text{RHN}} = \frac{\sigma_{Zh}^{\text{Scoto}} - \sigma_{Zh}^{\text{IDM}}}{\sigma_{Zh}^{\text{SM}}}$$

need tiny λ_5, $\leq 10^{-7}$, <u>protected by $U(1)_{PQ}$</u>

WIMP Dark Matter and Neutrino Mass from Peccei-Quinn Symmetry
Dasgupta, Ma,Tsumura

Radiative neutrino model meets FCC-ee

1) **Neutrino Pheno**
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caveat N2

Cannot send to zero the IDM SE
in a full degenerate scenario ($\lambda_3 = 0$)

we tried.

Big IDM background
prerequisite for sizable $\delta\sigma_{Zh}^{RHN}$

We need large λ_3 and light $H^\pm$

Radiative neutrino model meets FCC-ee

Big IDM background
prerequisite for sizable $\delta\sigma^{RHN}_{Zh}$

The search for favourable points is split in two stages:

Stage 1

Scan within IDM parameter space.
We find IDM outposts with sizable σ_{Zh} surviving theo and pheno constraints.

$m_{H^\pm,H^0} = \{80, 200\}$ GeV	$\lambda_2 = \{0, 4\pi/3\}$
$m_{H_0} - m_{A_0} = \{10^{-9}, 10^{-7}\}$ GeV	$\lambda_3 = \{-1.49, 1.4\}$

Stage 2

Over surviving benchmarks, full exploration of Yukawa and RH masses

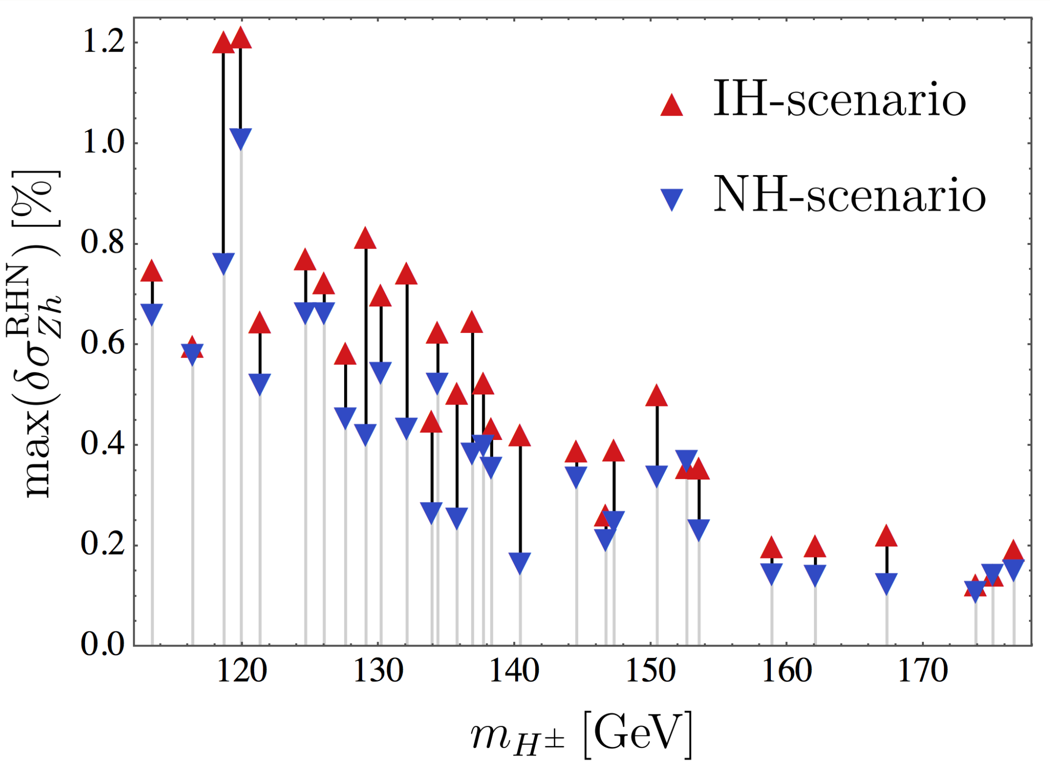
$m_{N_i} \in \{0.01, 2\}\, m_{H^\pm}$

$m_{\nu_{\rm inf}} \in \{10^{-7}, 10^{-1}\}\, eV$

Generating Y_N via Casas-Ibarra for NH and IH .
BR$(\mu \to e\gamma)$ tuned to future probing!

Results: can we see the RHN?

The Sc.M. reduces the negative (compared to SM) IDM contribution.



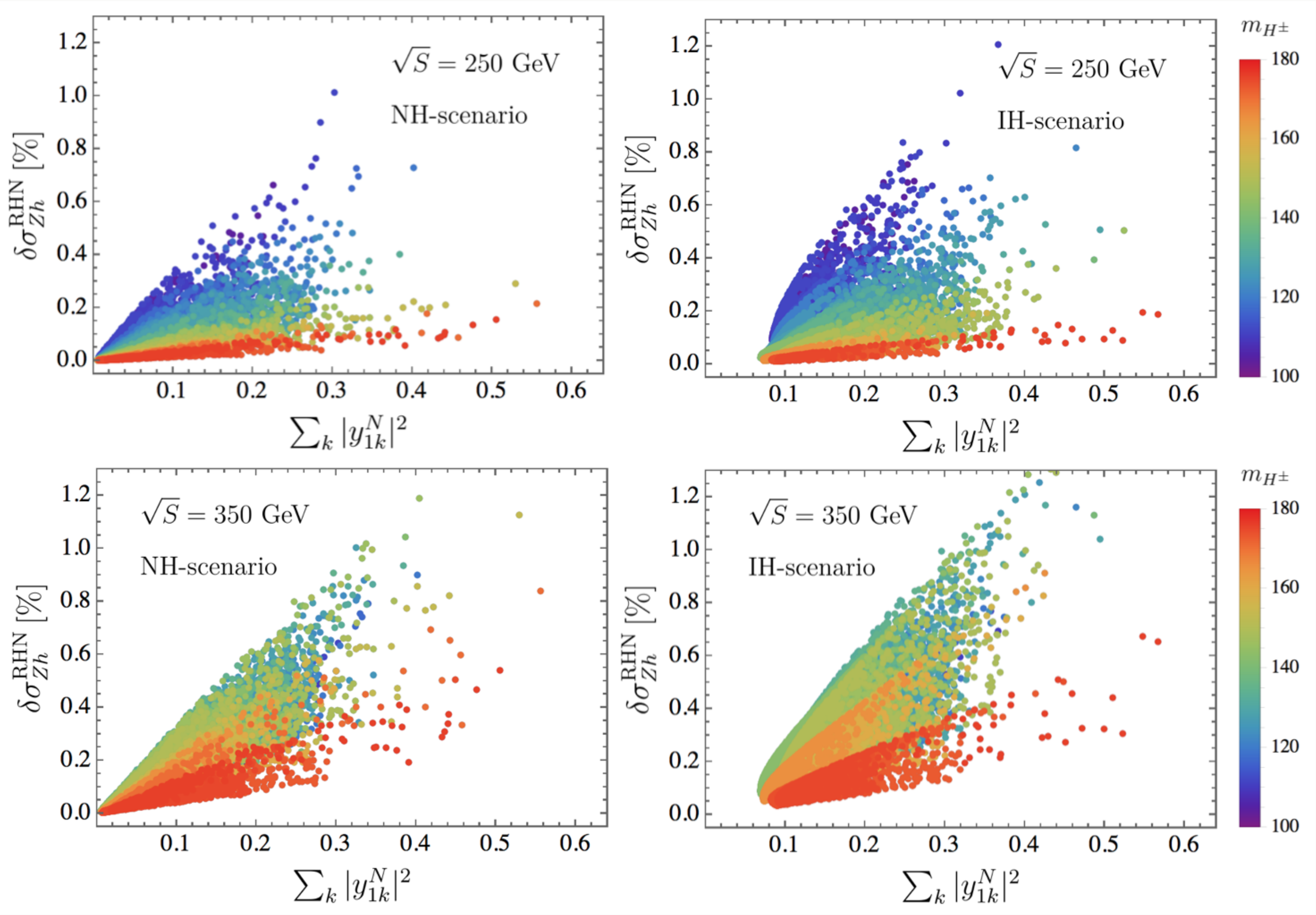
$\sqrt{S} = 250$ GeV

prerequisite:
$\delta\sigma_{Zh}^{IDM} > 2\%$

the maximal values reached at $m_{H^\pm} \simeq 120$ GeV:
NH-scenario it amounts to $\delta\sigma_{Zh}^{\rm RHN} \simeq 1.01\%$
while in the IH scenario, we reach up to $\delta\sigma_{Zh}^{\rm RHN} \simeq 1.22\%$.

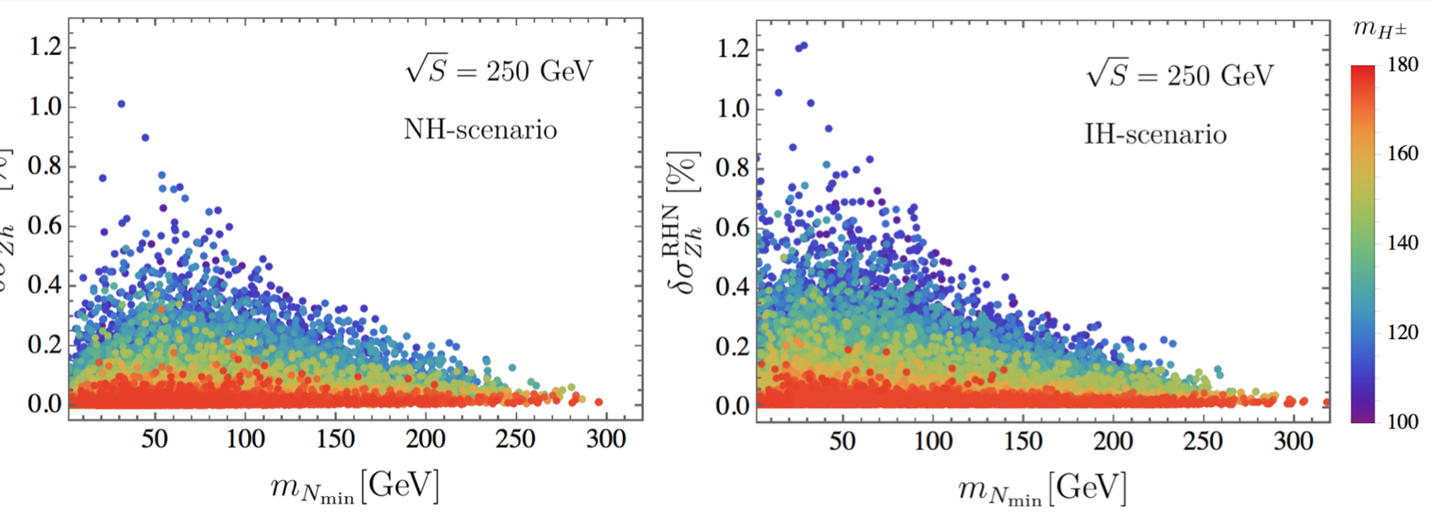
Point with the largest $\delta\sigma_{Zh}^{\rm RHN}$ for NH-scenario (black points) and IH-scenario (red points). The blue and red points along a vertical line share the same values of $\lambda_2, \lambda_3, m_{H^0}, m_{A^0}$ and $m_{H^\pm}$.

Results: can we see the RHN?



$N_{i=1,2,3}$: challenging but possible!

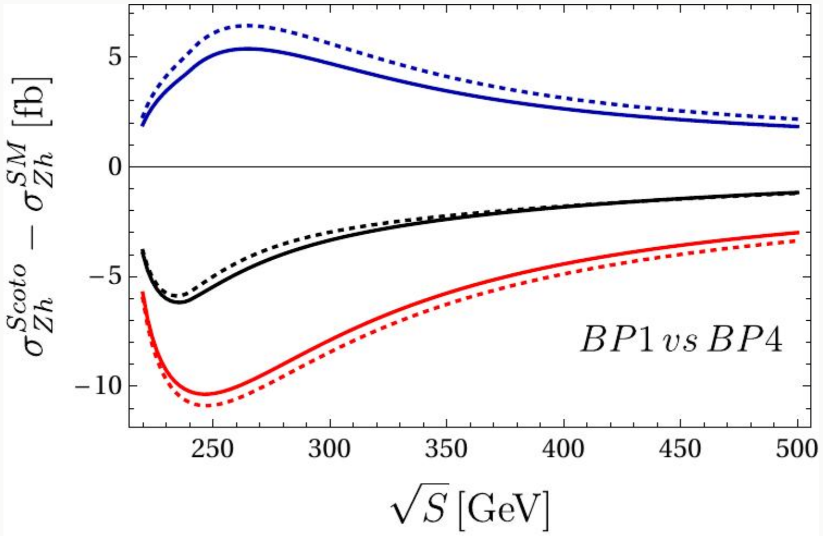
Results: can we see the RHN?



$N_{i=1,2,3}$: challenging but possible!

Mapping $e^+e^- \to ZH$ to future LFV: selecting Sc.M. benchmarks

Cross-section	**BP1** NH	**BP2** NH	**BP3** IH	**BP4** IH	**BP5** IH	**BP6** IH
$\sigma_{Zh}^{\rm Scoto}$(250 GeV) [fb]	223.261	220.897	222.085	223.729	221.060	222.157
$\sigma_{Zh}^{\rm IDM}$(250 GeV) [fb]	220.946	219.693	221.593	220.946	219.693	221.593
$\delta\sigma_{Zh}^{\rm RHN}$(250 GeV)	1.0122%	0.5262%	0.2150%	1.2168%	0.5973%	0.2464%
$\sigma_{Zh}^{\rm Scoto}$(350 GeV) [fb]	120.986	120.702	120.973	121.138	120.868	121.121
$\sigma_{Zh}^{\rm IDM}$(350 GeV) [fb]	120.191	119.464	119.983	120.191	119.464	119.983
$\delta\sigma_{Zh}^{\rm RHN}$(350 GeV)	0.6442%	1.0016%	0.8024%	0.7678%	1.1377%	0.9222%
$\delta\Gamma(Z \to ee)^{\rm RHN}$ [MeV]	0.04388	0.08528	0.09608	0.04026	0.08453	0.09552
$\delta\Gamma(Z \to \mu\mu)^{\rm RHN}$ [MeV]	0.04502	0.08861	0.09738	0.04390	0.08892	0.09693
$\delta\Gamma(Z \to \tau\tau)^{\rm RHN}$ [MeV]	0.04459	0.08518	0.09687	0.04803	0.3916	0.08615
$\delta\Gamma(Z \to inv.)^{\rm RHN}$ [MeV]	0.1678	0.3724	0.4419	0.1734	0.3754	0.4318



Mapping $e^+e^- \to ZH$ to future LFV: selecting Sc.M. benchmarks

LFV process	**BP1** NH	**BP2** NH	**BP3** IH	**BP4** IH	**BP5** IH	**BP6** IH
BR($\mu \to e\gamma$)	3.24×10^{-13}	1.02×10^{-13}	2.28×10^{-13}	2.43×10^{-13}	6.22×10^{-14}	1.05×10^{-13}
BR($\tau \to e\gamma$)	1.38×10^{-8}	1.09×10^{-8}	3.06×10^{-8}	1.16×10^{-8}	3.10×10^{-8}	8.39×10^{-9}
BR($\tau \to \mu\gamma$)	3.60×10^{-9}	2.09×10^{-8}	1.02×10^{-9}	9.90×10^{-9}	3.78×10^{-8}	3.89×10^{-9}
BR($\mu \to 3e$)	3.52×10^{-13}	1.63×10^{-13}	5.71×10^{-14}	5.37×10^{-13}	4.13×10^{-13}	1.00×10^{-13}
BR($\tau \to 3e$)	3.32×10^{-10}	2.73×10^{-10}	4.96×10^{-10}	3.11×10^{-10}	8.80×10^{-10}	1.44×10^{-10}
BR($\tau \to 3\mu$)	5.29×10^{-11}	5.43×10^{-11}	1.02×10^{-11}	1.55×10^{-10}	1.54×10^{-10}	3.33×10^{-11}
BR($Z \to \mu e$)	1.80×10^{-15}	3.71×10^{-15}	1.07×10^{-16}	1.01×10^{-15}	4.21×10^{-15}	4.89×10^{-16}
BR($Z \to \tau e$)	1.04×10^{-12}	8.92×10^{-13}	2.16×10^{-12}	9.47×10^{-13}	2.59×10^{-12}	6.26×10^{-13}
BR($Z \to \tau\mu$)	1.39×10^{-13}	2.15×10^{-12}	3.51×10^{-14}	4.98×10^{-13}	2.00×10^{-12}	1.61×10^{-13}
BR($h \to \mu e$)	7.75×10^{-15}	2.18×10^{-14}	4.91×10^{-16}	5.05×10^{-15}	2.47×10^{-14}	2.53×10^{-15}
BR($h \to \tau e$)	4.33×10^{-9}	4.11×10^{-9}	8.80×10^{-9}	3.94×10^{-9}	1.16×10^{-8}	2.50×10^{-9}
BR($h \to \tau\mu$)	8.12×10^{-10}	9.27×10^{-9}	1.99×10^{-10}	2.55×10^{-9}	1.12×10^{-8}	8.35×10^{-10}

Barely out of LFV limits . Future LFV ready.
Combined signals for revealing Sc. M. .

(in particular $l_i \to l_j\gamma$ and $\mu \to 3e$)

Conclusions:

Focus on minimal models of NP.

Inert Doublet a likely background for many Dark Sectors proposal
IDM provides sizable signal $\sim 10\%$ from which NP can be distinguished

Theoretical NLO control over the precise Higgs-strahlung determination is a great opportunity, enhanced by parallel signatures in different observables.

QFT a multiscale - multisignal coherent theory

Dark Sector, Neutrino Mass Models visible at collider and LFV (with NLO!)

Future:

Less minimal, complex Yukawas, CP violations, polarization effects...