Workshop on the Circular Electron-Positron Collider - EU edition
Università degli Studi Roma Tre, 24-26 May 2018

Beyond-SM Physics at CepC

Higgs Factory (10^6 Higgs)

Z & W Factory (10^{10} Z)

Flavor Factory (b,c,tau)

INFN Roma
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Outline

* why BSM
* CepC "fields of expertise"
* indirect effects: Higgs, Z, WW, ff precision physics
* weakly coupled particles production
  (WIMPs, heavy sterile neutrinos, …)
* Exotics
  * massless Dark Photons in e+e- collisions
* Outlook

(input from CepC, ILC, CLIC, FCC-ee studies)

huge (although hazy) expectations
for new BSM phenomena at colliders !

* two kinds of issues with the SM :

* existence of "external" phenomena :

(quantum ?) Gravity

+ empirical evidences :

- Dark Matter
- Barion asymmetry
- neutrino masses
- . . .

* "internal" poor consistency :

mainly connected to the EWSB/Higgs sector

what's so tricky about the Higgs

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) \boxed{- \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger}$$

$$V(\phi^\dagger \phi) = \boxed{-\mu^2 \phi^\dagger \phi} + \boxed{\frac{1}{2}\lambda (\phi^\dagger \phi)^2}$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

- the only "fundamental" scalar particle (microscopic interpretation ?)
- not protected by symmetries (the less constrained SM sector):
  - naturalness problem : $m_H \sim g \times \Lambda_{cutoff}$
- many different couplings all fixed by masses (?)
  - proliferation of parameters historically leads to breakdown in TH models
- fermion masses/Yukawa's hierarchy (?)
  - have neutrinos a special role ?!!!
- λ determines shape and evolution of Higgs potential → cosmology !

four paths to advance in HEP today at colliders:

- by exploring the characteristics of the Higgs sector and confirming/spoiling the SM picture
  (primary relevance since the Higgs sector is so critical !)
- by searching for new heavy states coupled to the SM,
  [acting as a cut-off for the SM
  possibly solving the naturalness issues and/or
  non-SM phenomena (dark matter, ...)]
- by exploring $\Lambda >> o(1\text{TeV})$ indirect effects through high-accuracy studies of SM x-sections/distributions and searches for rare processes (EFT parametrization)
- by looking for new DARK states (i.e.,uncoupled to SM at tree level) either in production or/and heavy-state (H,t...) decays (elusive signatures, may be long-lived p.les)

four paths to advance in HEP today at colliders:

* Higgs
* new particles
* indirect effects
* Dark signals

* every single method is of fundamental importance to make progress !
* e+e- colliders great opportunities in all sectors (cleanness [→ model independence], accuracy…)

BSM impact on Higgs couplings

- up to few percent for natural model not showing up by heavy states production at LHC

	$\Delta g(hVV)$	$\Delta g(ht\bar{t})$	$\Delta g(hb\bar{b})$
Composite Higgs	10%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	tens of %
Mixed-in Singlet	6%	6%	6%

- different patterns of deviations from SM for different NP models

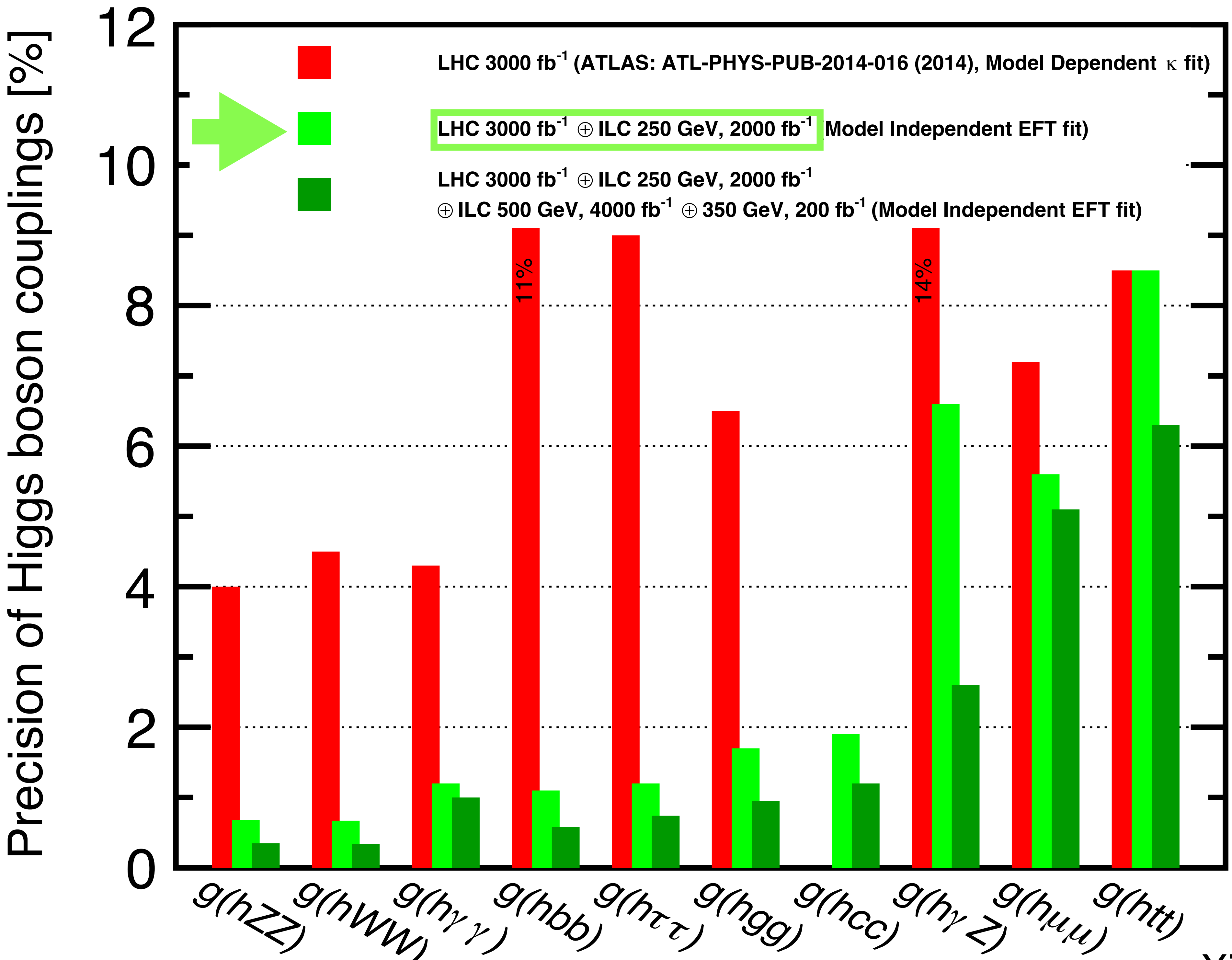
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [41]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [42]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [43]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [44]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

arXiv:1710.07621

Higgs coupling accuracy in e+e- (EFT approach)

(%) arXiv:1708.08912	ILC250 $2\ \mathrm{ab}^{-1}$ w. pol.	CLIC350 $2\ \mathrm{ab}^{-1}$ 350 GeV	CEPC $5\ \mathrm{ab}^{-1}$ no pol.	FCC-ee $+\ 1.5\ \mathrm{ab}^{-1}$ at 350 GeV	ILC250+500 full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

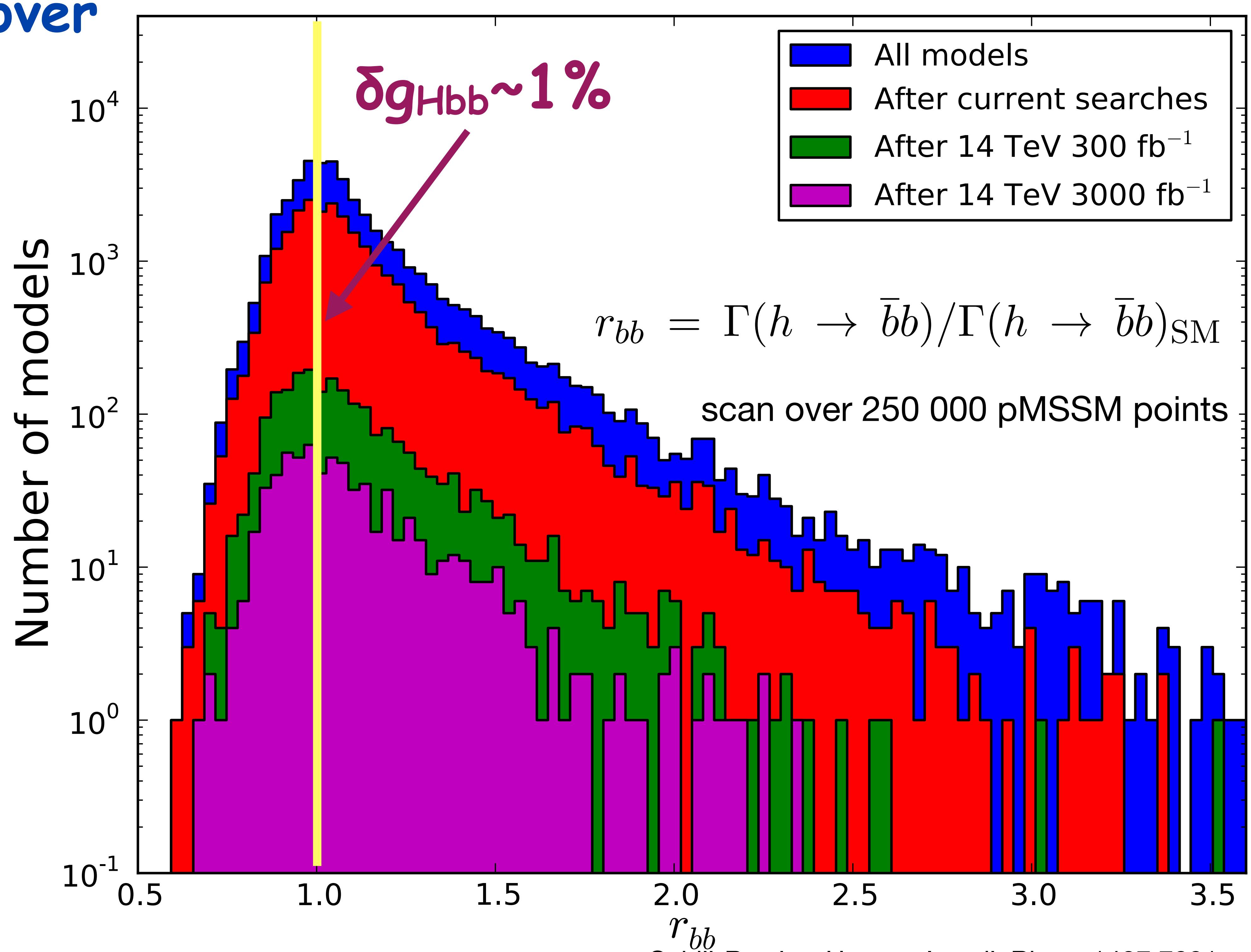
HL-LHC (κ fit) versus adding e+e- (250 GeV, 2ab-1) (EFT fit)



arXiv:1710.07621

new handles to constrain MSSM

* 1% accuracy on Hbb coupling gives excellent resolution on LHC left over

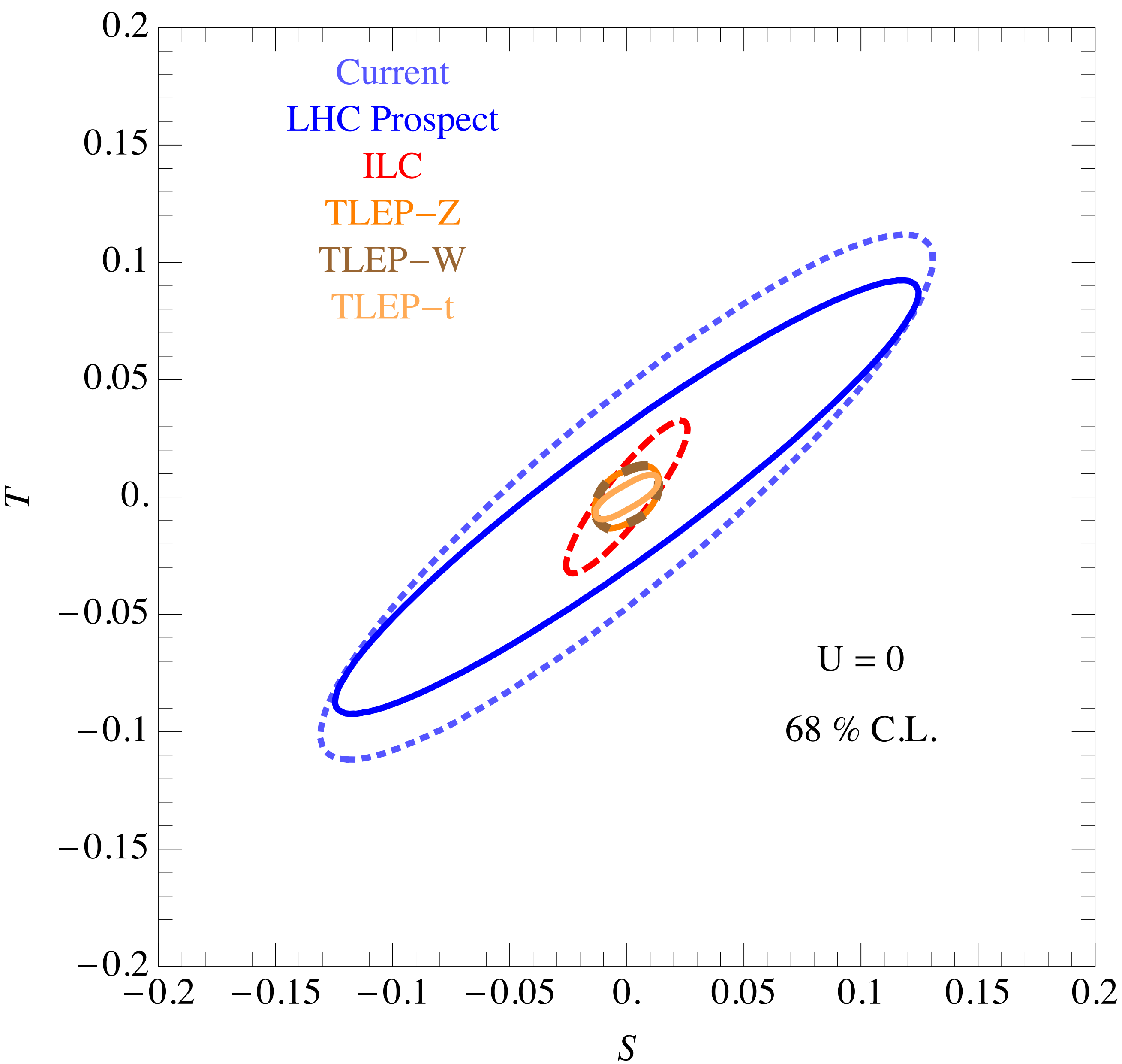


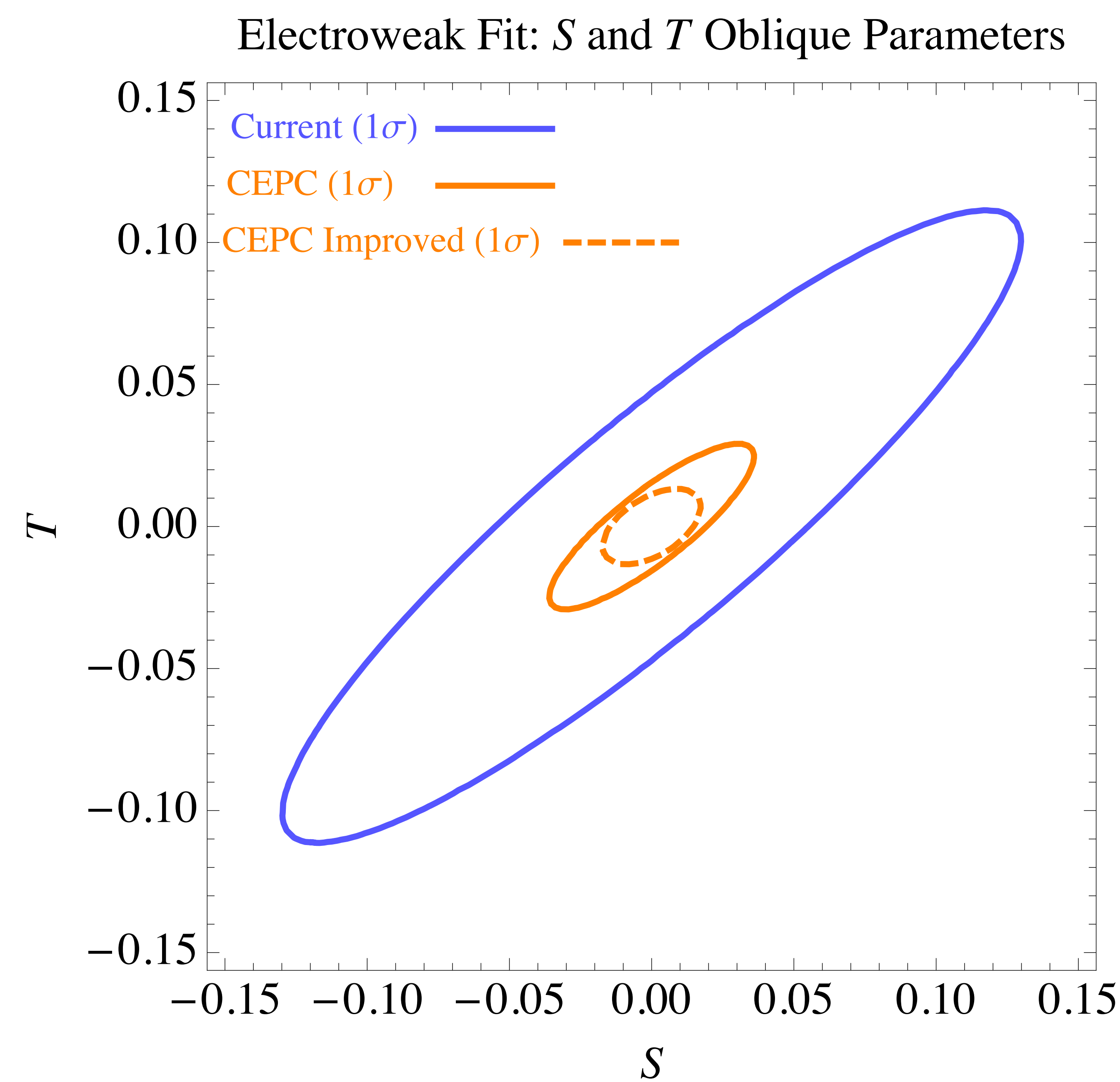
arXiv:1710.07621

Cahill-Rowley, Hewett, Ismail, Rizzo, 1407.7021

EWPT at the Z pole

- order-of-magnitude improvement from CepC
  → probe NP scale up to o(10-100) TeV !

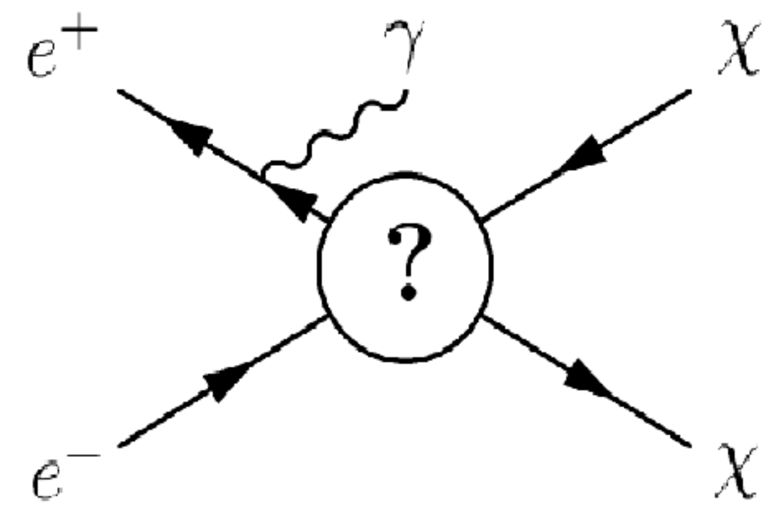


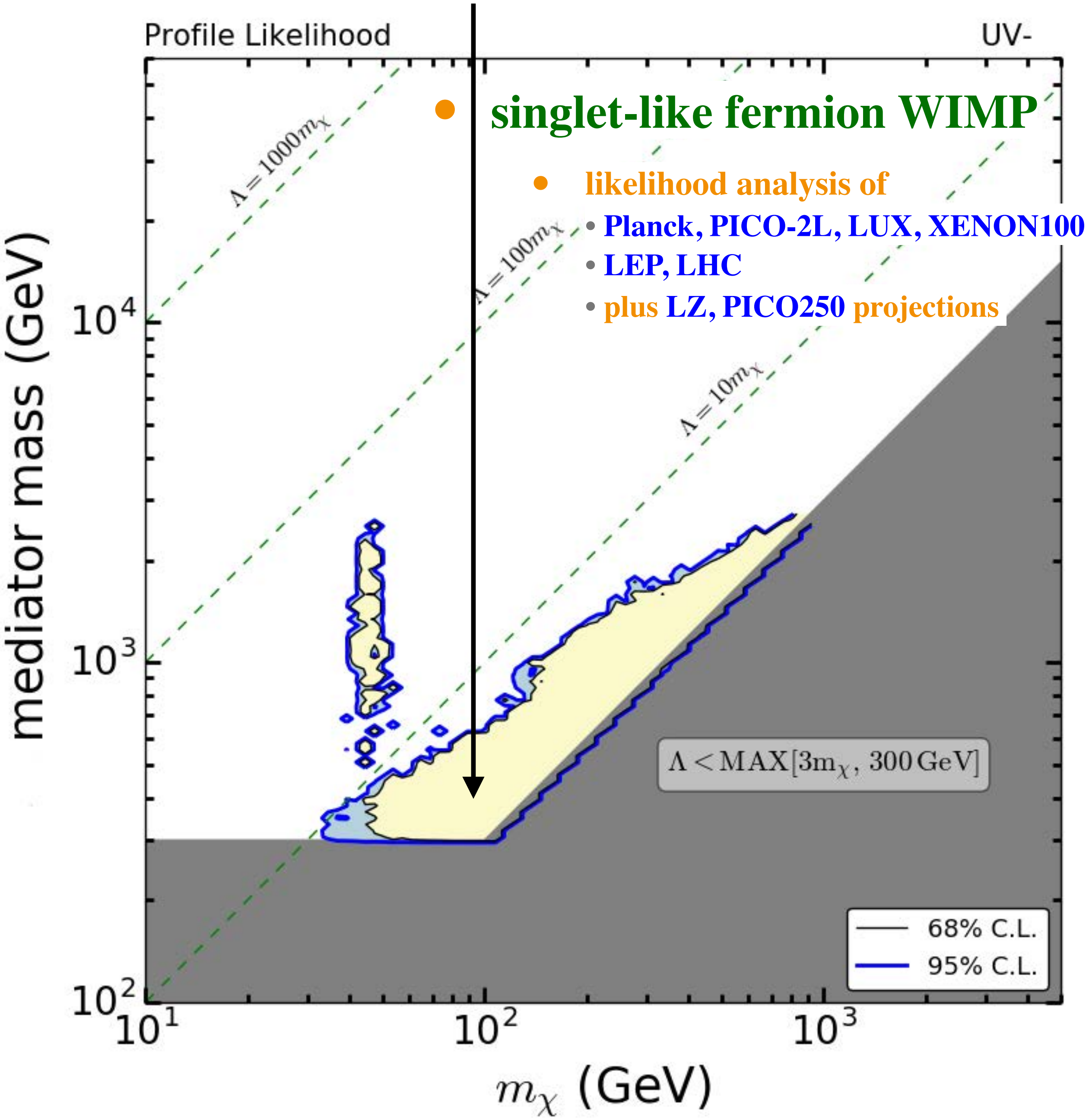


Fan, M. Reece, LT Wang, 1411.1054

WIMP search in mono-photon events

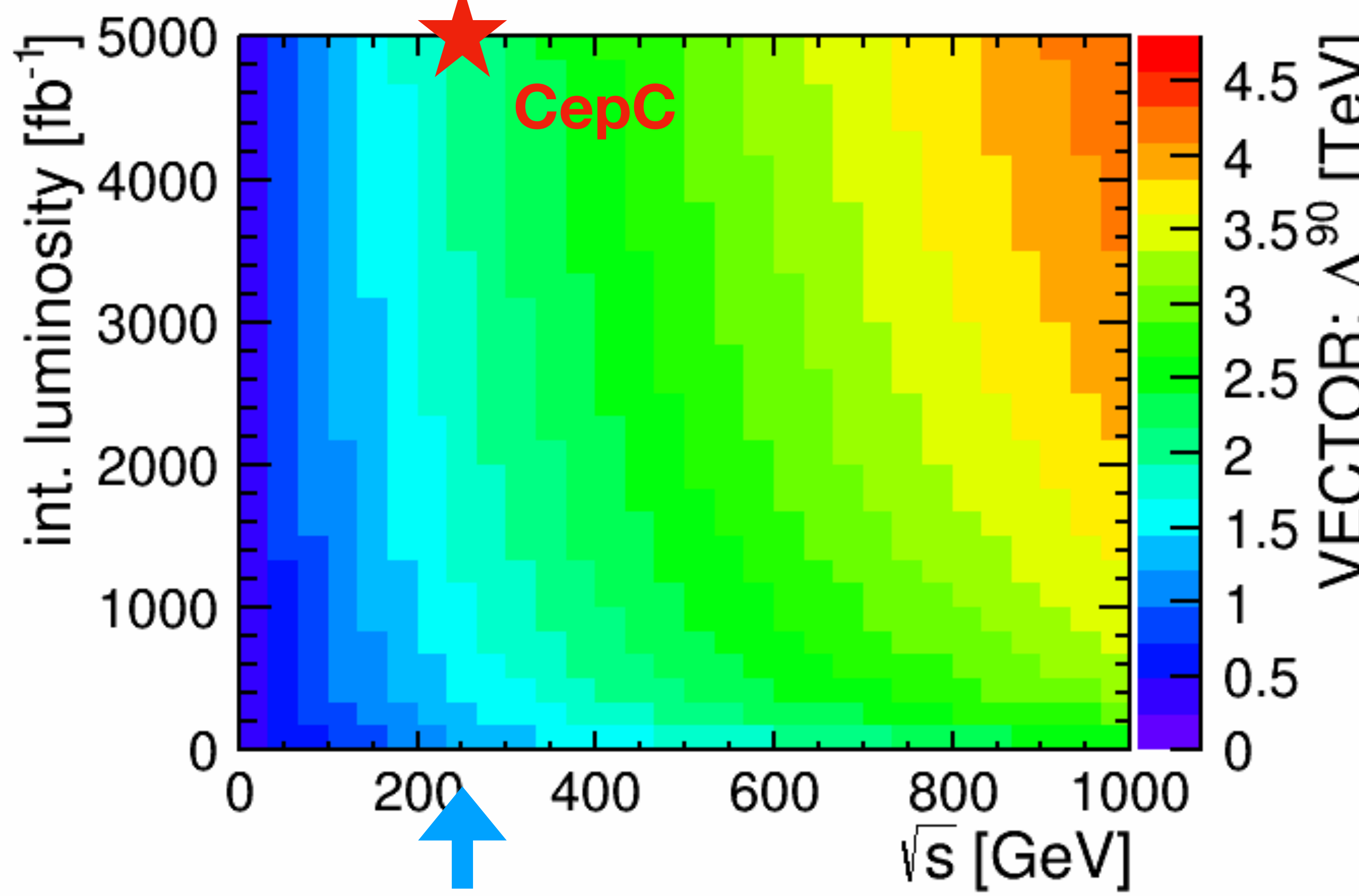
- by extrapolating present expts results
  → yellow area still allowed before ILC startup!





Habermehl et al, arXiv:1702.05377

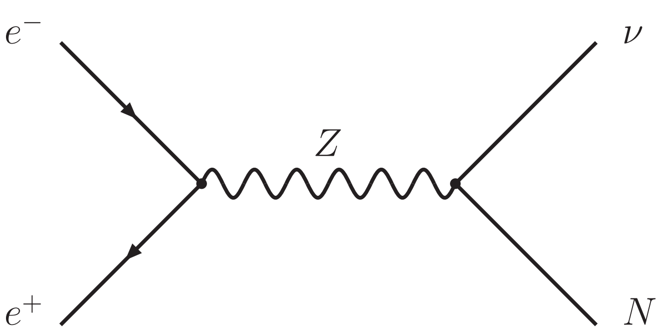
ILC reach in EFT scale Λ (22% of polarised events)



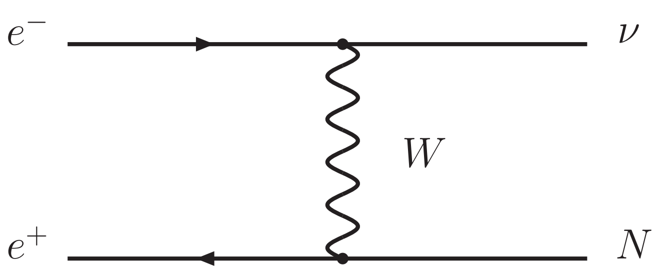
for M_χ < 100 GeV probes up to Λ~2 TeV @ 240 GeV with 5 ab^{-1}

heavy sterile neutrinos

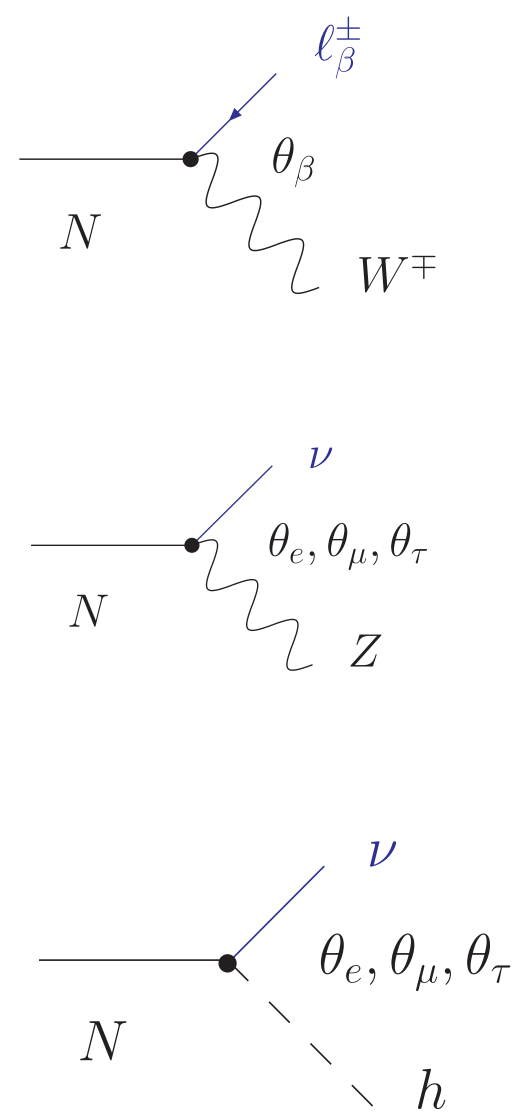
- Symmetry-protected seesaw allows for EW-scale M_{nu} and o(1) mixing
- mix with active nu's by $\theta_\alpha = y_{\nu_\alpha} \frac{v}{\sqrt{2}M}$
- presently $|\theta|^2 \leq 10^{-3}$

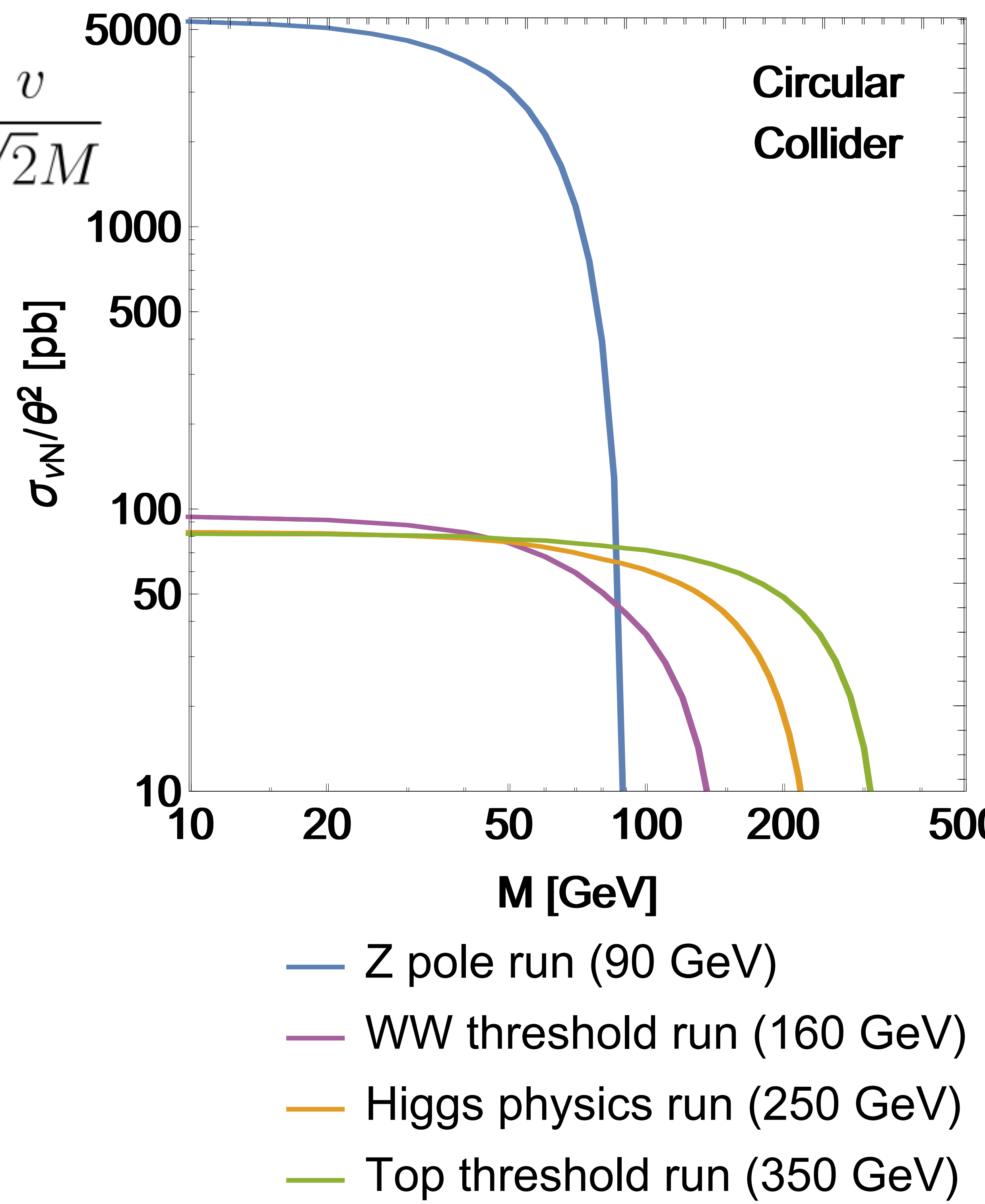


production channel: $\mathbf{Z_s}$



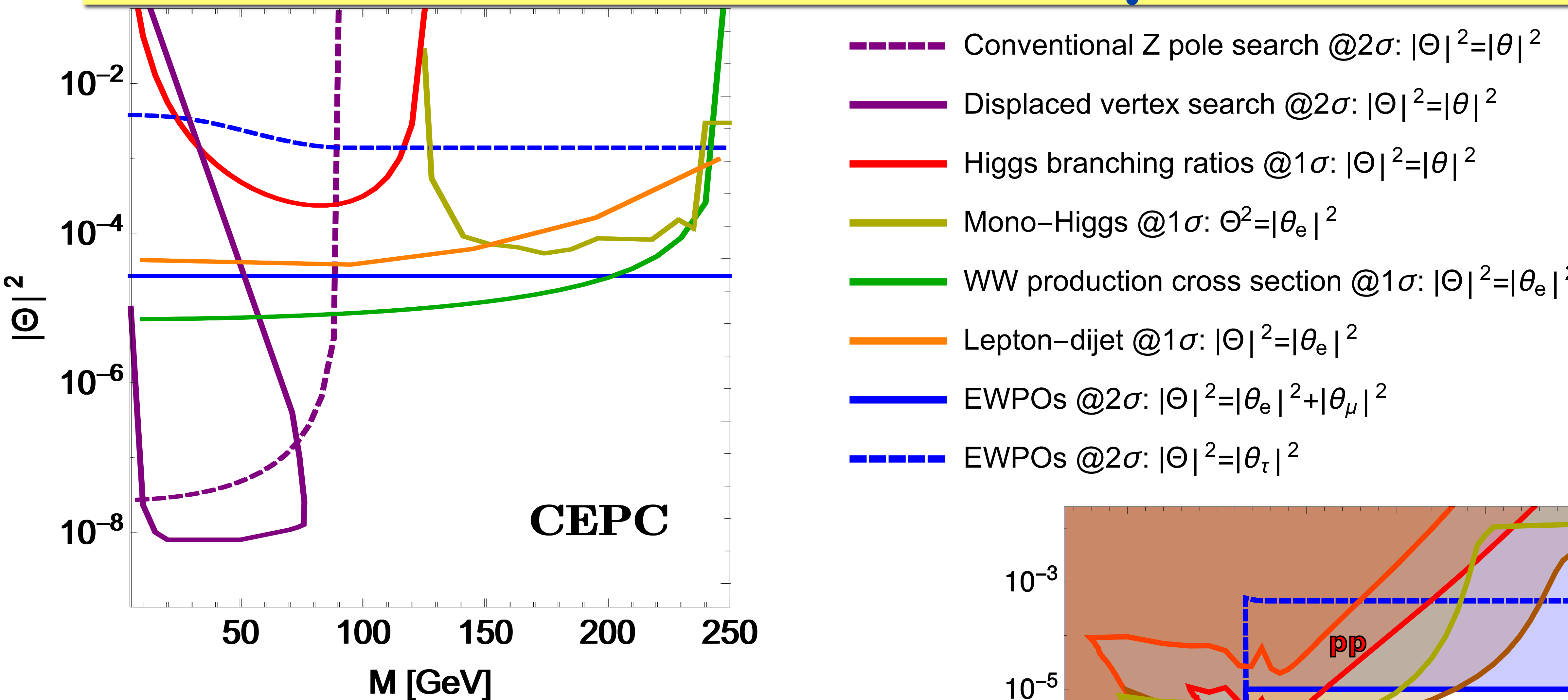
production channel: $\mathbf{W_t}$



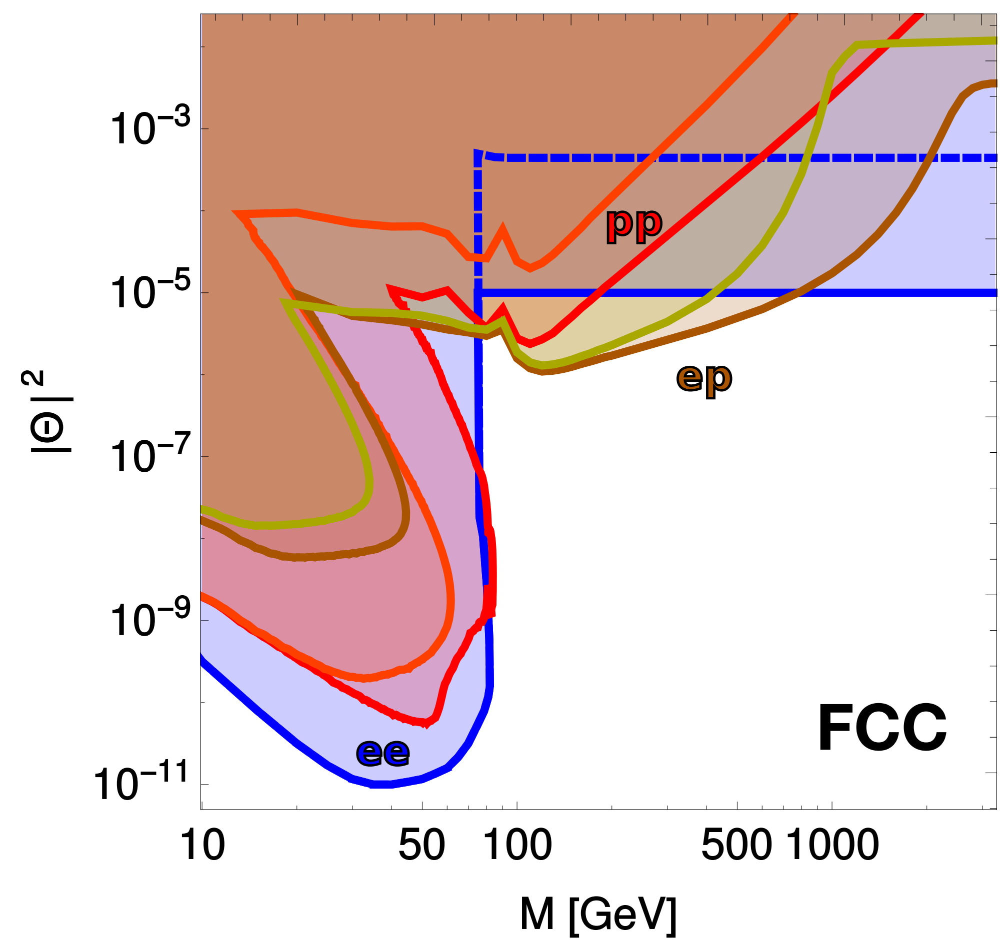


Antusch, Cazzato, Fischer

sterile neutrinos at CepC and FCC



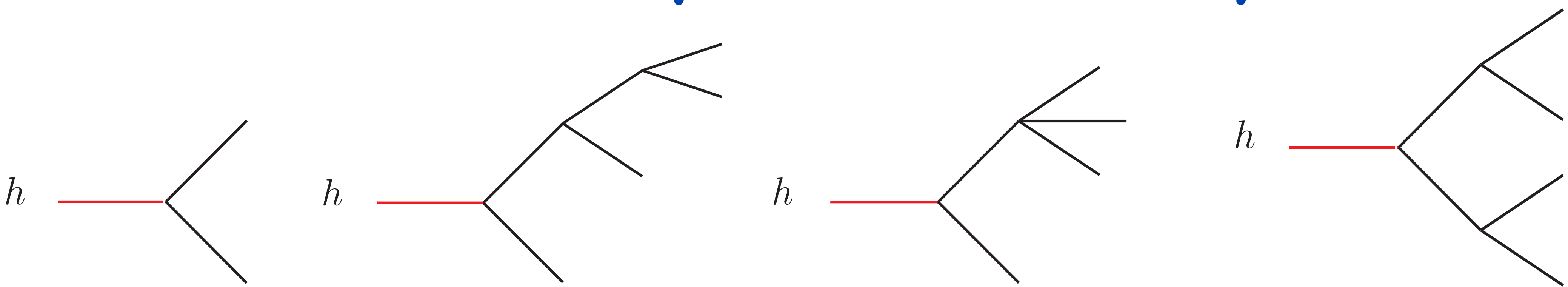
- for M_{nu}>>TeV → best sensitivity from EWPT@ee
- for light M_{nu} → best sensitivity from displaced vertices @ ee

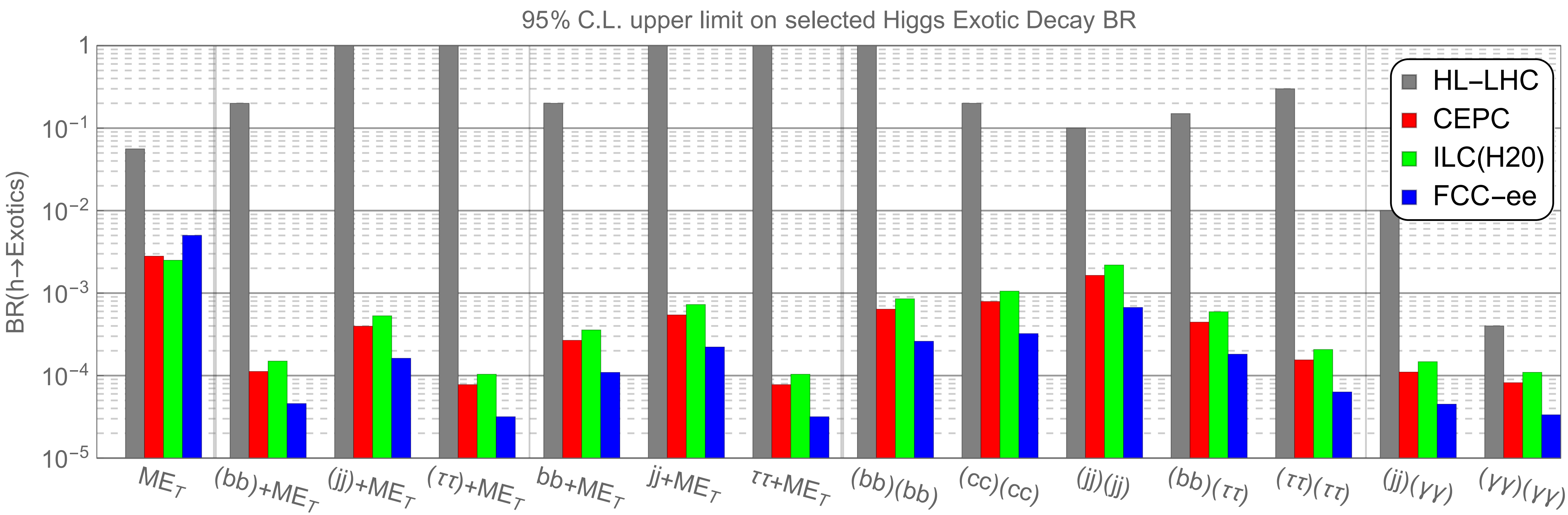


S. Antusch, E. Cazzato, OF; Int. J. Mod. Phys. A **32** (2017) no.14, 175007

Exotic Higgs decays

* e+e- environment superior on final states with **MET** and **hadronic** activity → BR sensitivity better than 10^{-3}

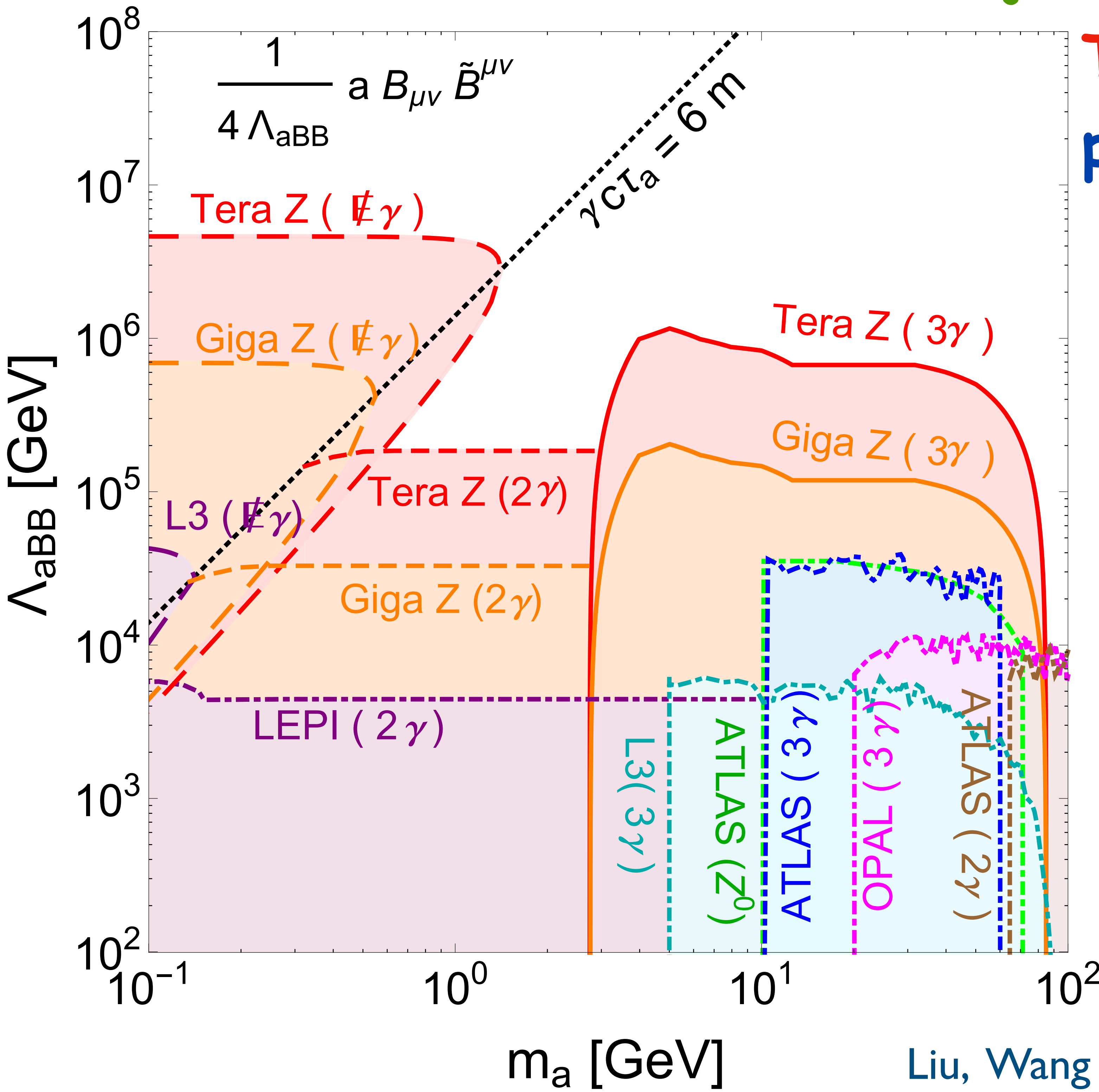


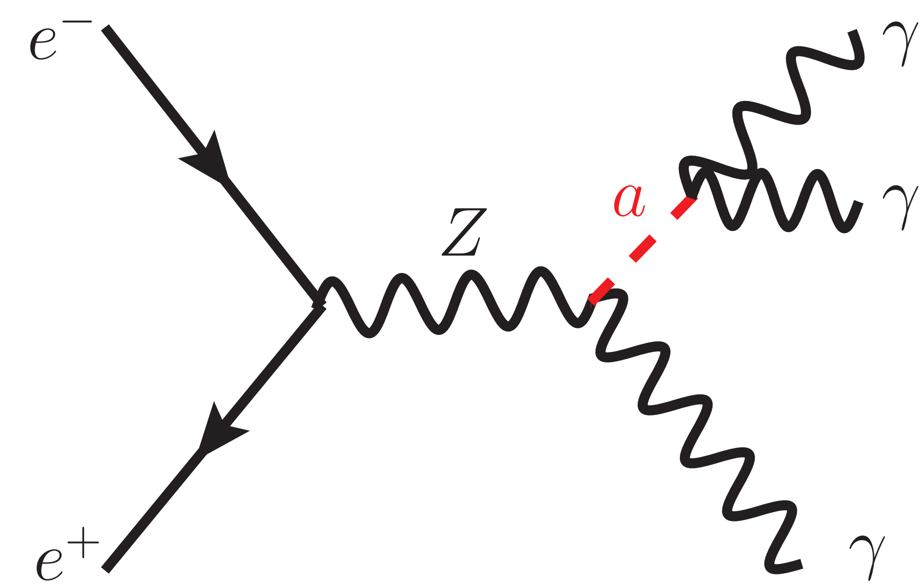


Zhen Liu, Hao Zhang, LT Wang 1612.09284

Exotic Z decays

* **Axion-like particles : Tera/Giga Z widely extend present LEP/LHC bounds**



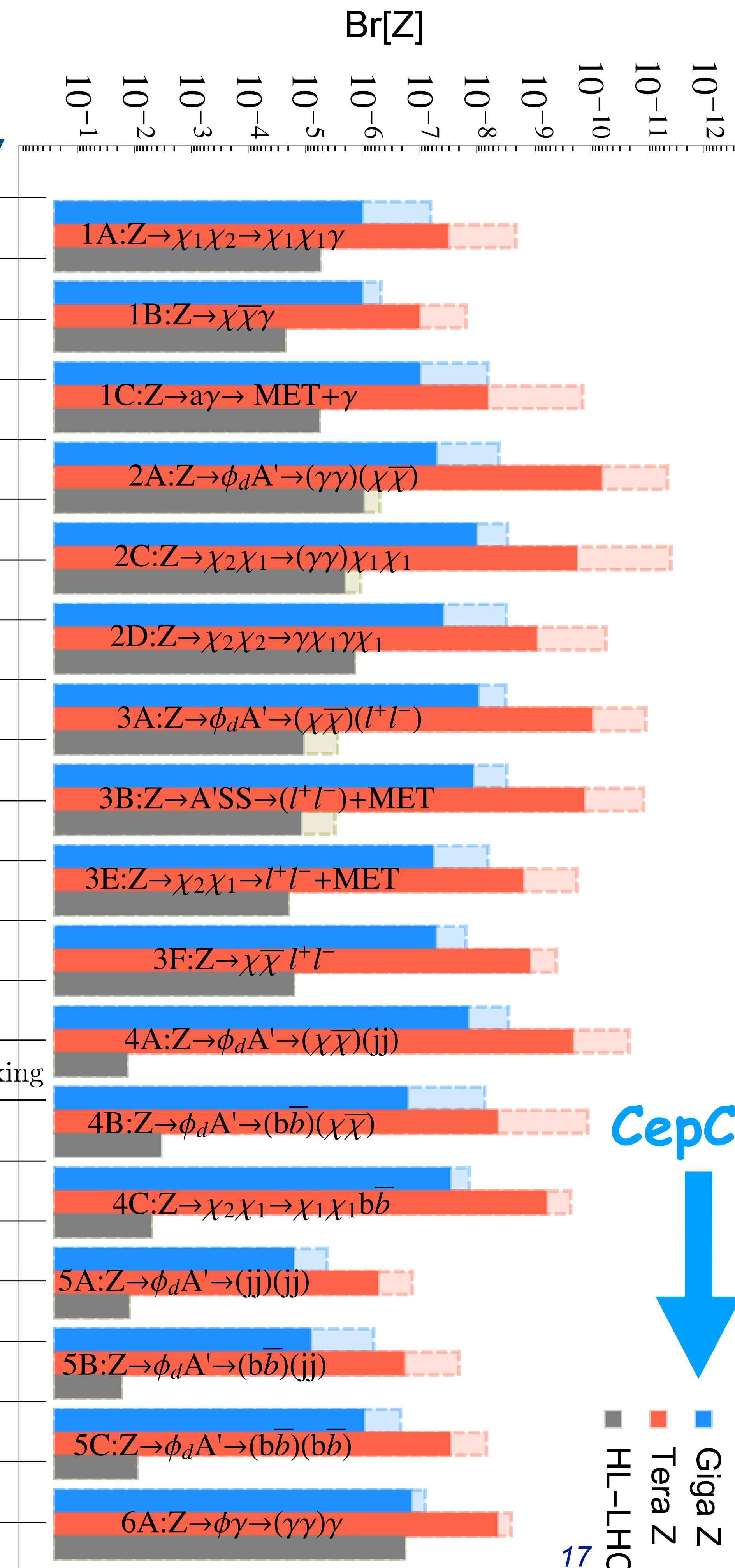


Liu, Wang , Wang, Xue, 1712.07237

* long list of models/signatures

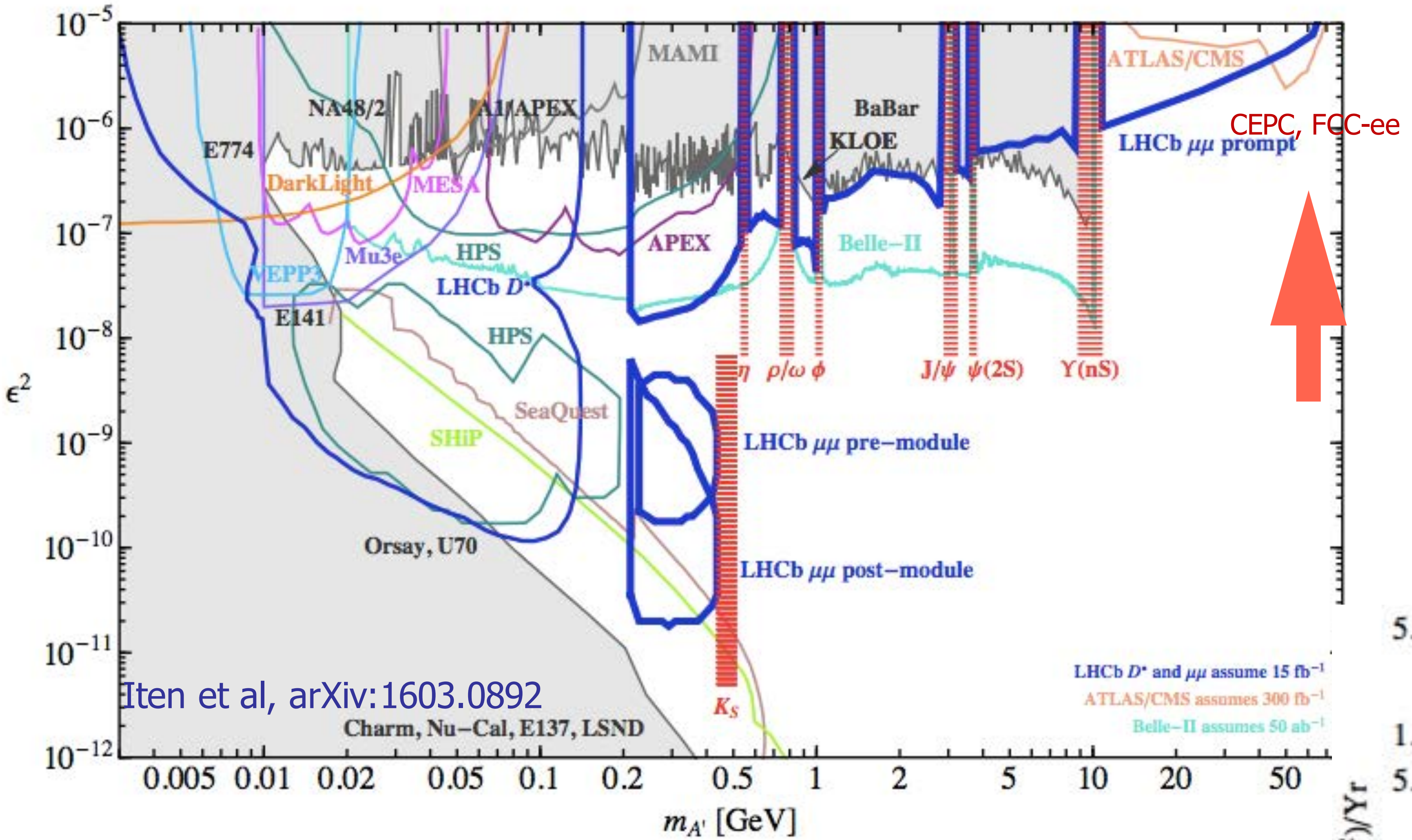
Liu, Wang, Wang, Xue, 1712.07237

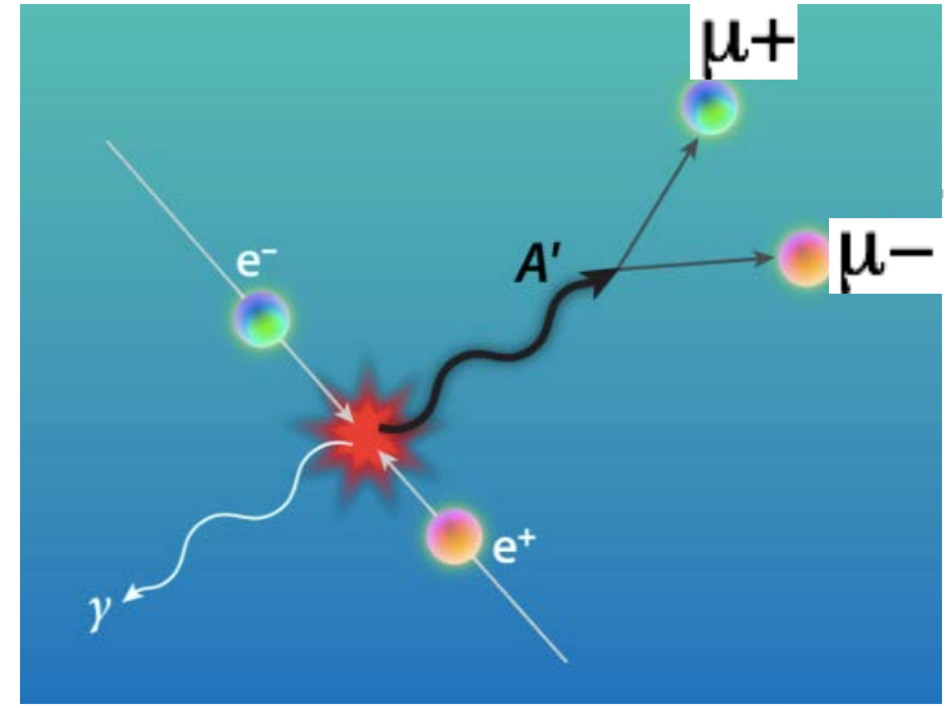
exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}} a B_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_{\mu}B_{\nu}\partial_{\rho}B_{\sigma}$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$, $\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal

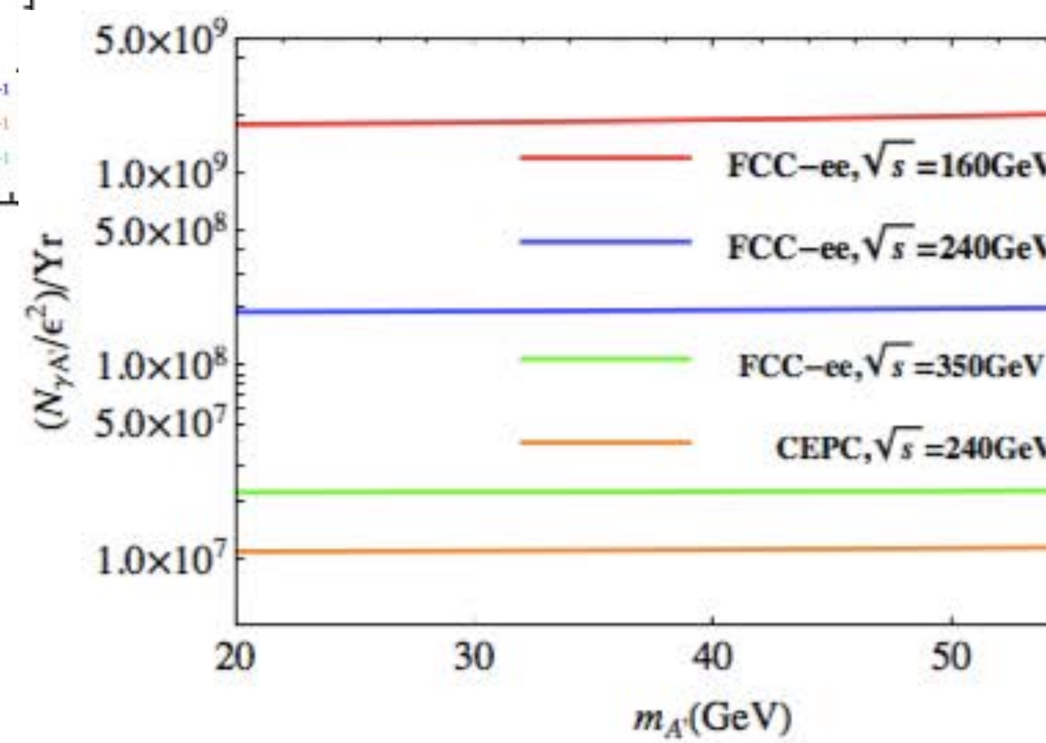


Looking for Dark Photons in ee → $\gamma A'$

- CEPC may have advantage probing dark photon at 10 to a few 10s ($<<m_Z$) GeV mass range.







X.He, M.He, Huang

what if Dark-Photon mass vanishes ?

massive DP

direct coupling to SM

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$g' q_f \bar{\psi}_i \gamma^\mu \psi_f A'_\mu$$

massless DP

no direct coupling to SM

only higher dimensional operators

$$\frac{g}{\Lambda} \bar{\psi} \sigma^{\mu\nu} \psi \bar{F}_{\mu\nu}$$

on-shell massless DP's can be fully decoupled from SM sector at tree level !

B. Holdom, *Phys. Lett.* **166B** (1986) 196

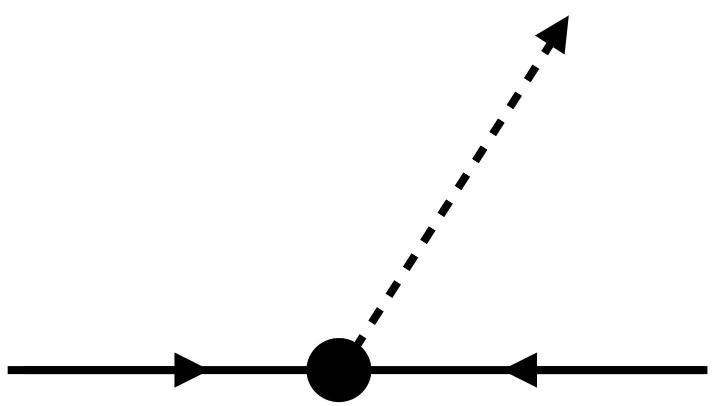
massless DP's interact with the SM sector only through higher-dimensional (→ suppressed by $1/M^{D-4}$) interactions via messenger (if any) exchange !

evading most of present exp bounds on massive DP's !

→ potentially large DP couplings $\bar{\alpha}$ in the Hidden Sector (HS) allowed !

massless-Dark-Photon signatures :

when produced in collisions :



➜ stable + noninteracting

➜ neutrino-like signature

<u>Flavor models predicting both flavour hierarchy and DM include massless dark-photons</u>

Gabrielli, Raidal, arXiv:1310.1090 (PRD)

Explaining Yukawa hierarchy via HS and extra $U(1)_F$

- Hidden Sectors (HS) possibly explaining Flavor hierarchy + Dark Matter

Gabrielli, Raidal, arXiv:1310.1090

- Yukawa's are not fundamental constants but effective low-energy couplings
  (→ scalar messengers transfer radiatively *Flavor and Chiral Symm. Breaking* from HS fermions to SM fermions giving Yukawa couplings at one-loop)
- introducing extra unbroken $U(1)_F$ → massless DP's
- for integer-$q_{(\text{dark fermions})}$ sequence :
  → exponential hierarchy in $M_{(\text{Dark fermions})}$
  → exponential hierarchy in radiative $Y_{(\text{SM fermions})}$!!

$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

DP coupling

- Dark fermions as dark-matter candidates

massless-Dark-Photon production mechanisms

→ plenty of new signatures !

* via Higgs bosons

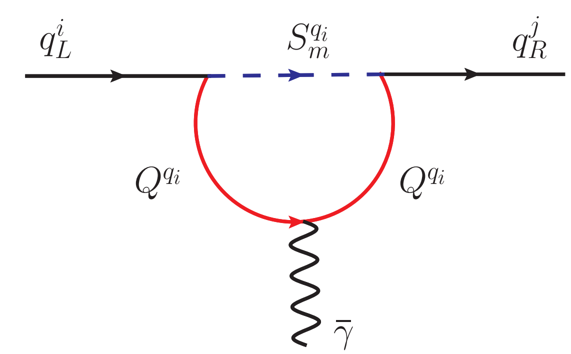
→ both in production and decay...

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli,Heikinheimo, BM, Raidal, arXiv:1405.5196 (PRD)
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)

* via FCNC mediated by Dark Photon's

→ new class of FCNC signatures from top, b, c, s, tau, mu decays $f \to f' \bar{\gamma}$

(very distinctive → bounds expected to be just limited by statistics in e^+e^- !)



$$\hat{Q} = (\bar{s}\, \sigma^{\mu\nu}\, d)\, \bar{F}_{\mu\nu}$$

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli, BM, Raidal, Venturini, arXiv:1607.05928 (PRD)
Fabbrichesi, Gabrielli, BM, arXiv: 1705.03470 (PRL)

* via Z bosons (evading Landau-Yang theorem)

$$Z \to \gamma \bar{\gamma}$$

Fabbrichesi, Gabrielli, BM, arXiv: 1712.05412 (PRL)

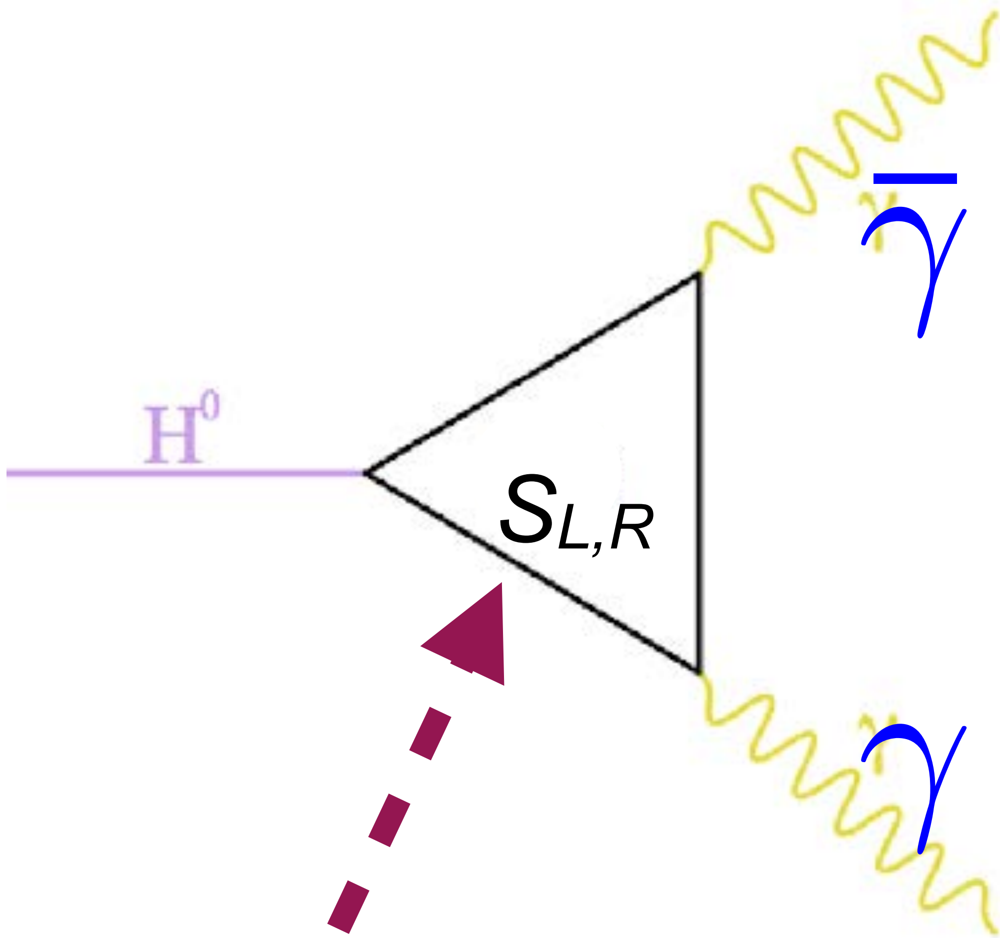
* ...

Higgs as a "source" of Dark Photons

$$H \to \gamma\bar{\gamma}$$

mono-photon resonant signature

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli,Heikinheimo, BM, Raidal, arXiv:1405.5196 (PRD)
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)



massless (invisible) Dark Photon

$H \to \bar{\gamma}\bar{\gamma}$ contributing to Γ_H^{inv}

Higgs non-decoupling effects can enhance BR up to a few % !

heavy scalar messengers (squark/slepton-like) connecting SM to HS

$$\Gamma(H \to \gamma\bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \to \frac{1}{v^2}$$

model-independent bounds @ LHC 14 TeV

(including shower effects)

$gg \to H \to \bar{\gamma}\gamma$ vs $VV \to H \to \bar{\gamma}\gamma$

(γj-bckgr modelling critical !)

$\mathrm{BR}_{\gamma\bar{\gamma}}$ (%)	L= $100\,\mathrm{fb}^{-1}$		L=$300\,\mathrm{fb}^{-1}$		L=$3\,\mathrm{ab}^{-1}$	
Significance	2σ	5σ	2σ	5σ	2σ	5σ
$\mathrm{BR}_{\gamma\bar{\gamma}}$(VBF)	0.76	1.9	0.43	1.1	0.14	0.34
$\mathrm{BR}_{\gamma\bar{\gamma}}$($ggF$)	0.064	0.16	0.037	0.092	0.012	0.029

gg fusion sensitive down to $\mathrm{BR}_{DP} \sim 10^{-4}$–$10^{-3}$

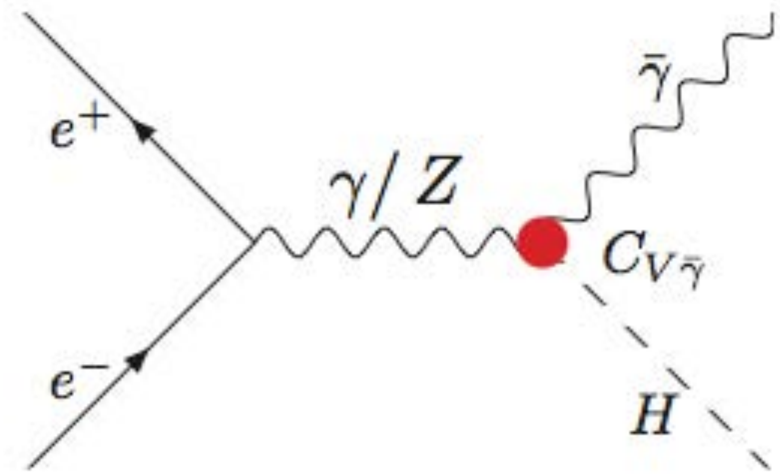
(VBF ~10 times worse …)

Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1603.01377 (PRD)

new Higgs signatures @ e^+e^- colliders from massless invisible dark photons

* $$e^+e^- \to H\,\bar{\gamma} \to b\bar{b}\,\bar{\gamma}$$

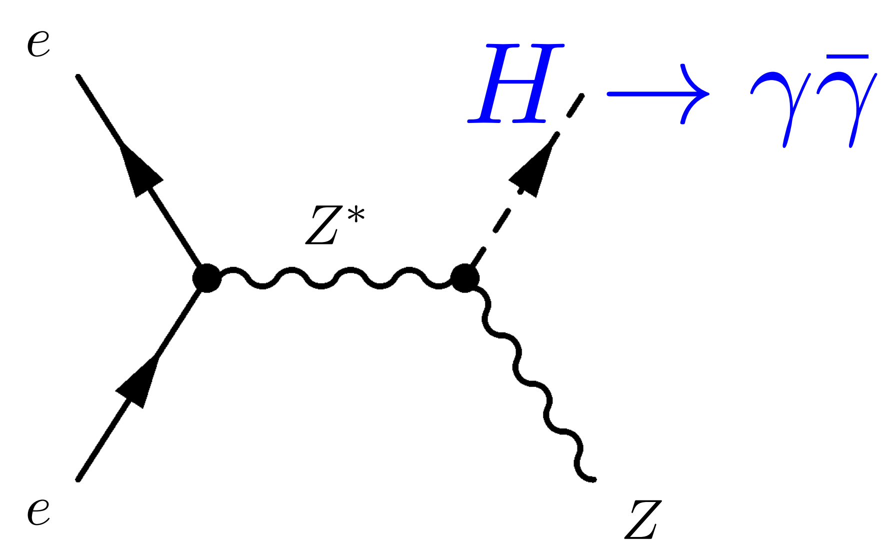
p_{Higgs} balanced by a massless invisible system



Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1503.05836 (JHEP)

* $$e^+e^- \to ZH \to Z\,\gamma\bar{\gamma}$$

(photon + E_{miss}) resonant signature



Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1703.00402 (PRD)

S vs B at √S = 240 GeV & ∫L ~ 10 ab^{-1}

$$e^+e^- \to H\bar{\gamma} \to \boxed{b b\bar{\gamma}}$$

large rates, moderate bckgrs

* signature ➜ two b jets + (massless) missing E/p

MadGraph5_aMC@NLO (Eff.Lag. in FeynRules)
+ PYTHIA for showering and hadronization ;
b-jets via jet-cone (R_j=1.5); E_j smearing ➜ $\sigma(E)/E = 30\%/\sqrt{E}$
b-tag. eff.~80% ; light-jet rejection ~ 100

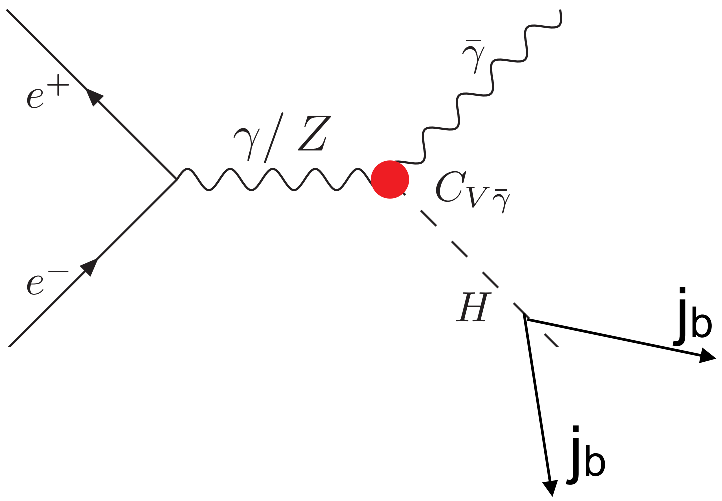
* main backgrounds :

$$ZZ \to \nu\bar{\nu}b\bar{b} \quad \nu\bar{\nu}q\bar{q}$$
$$ZH \to \nu\bar{\nu}b\bar{b}$$
$$H\nu\bar{\nu}$$ (VBF)

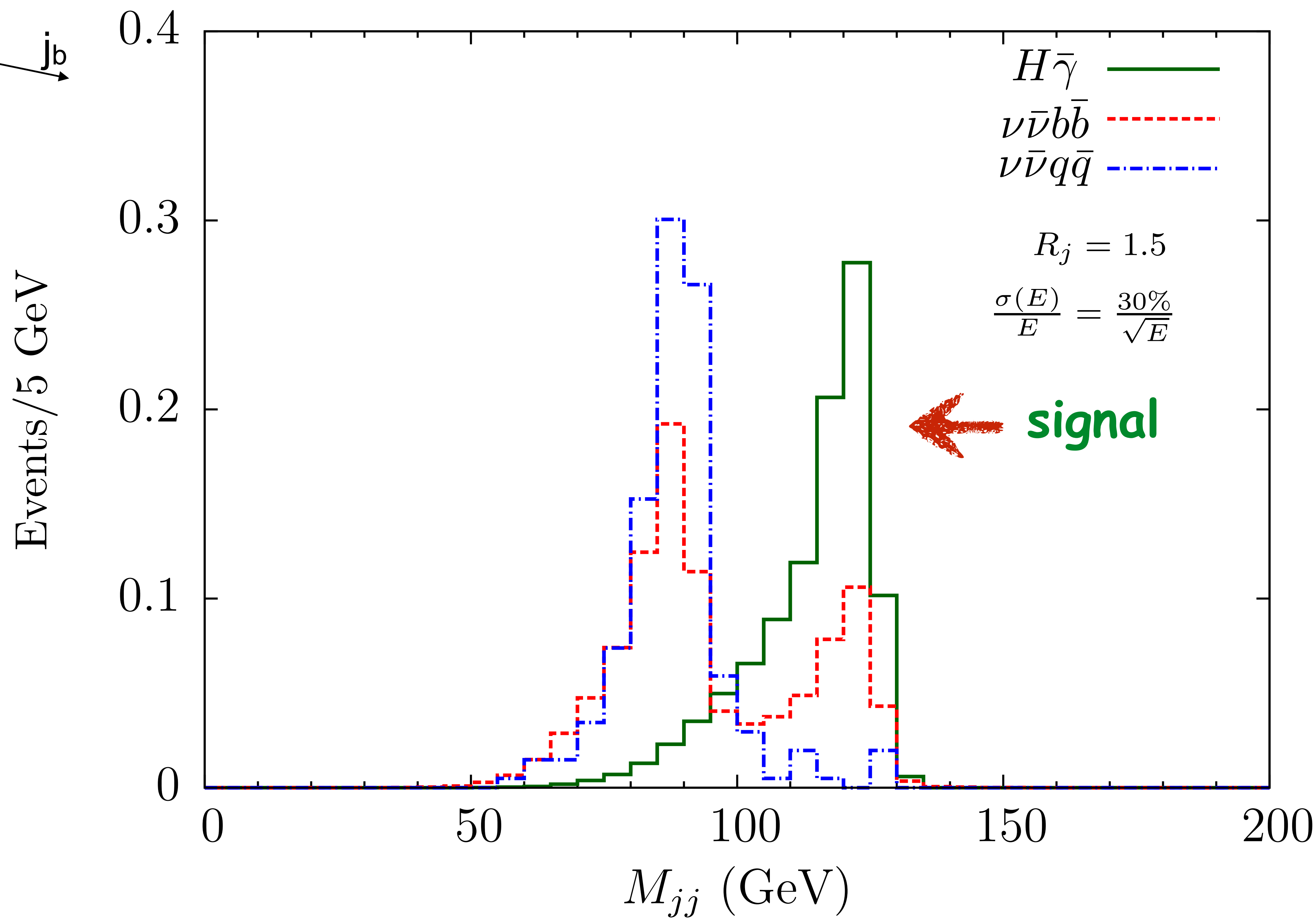
Basic cuts
$$\begin{cases} p_T^b > 20 \text{ GeV}, & |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4, & \not{E} > 40 \text{ GeV} \end{cases}$$

* two particularly efficient observables for separating S from B

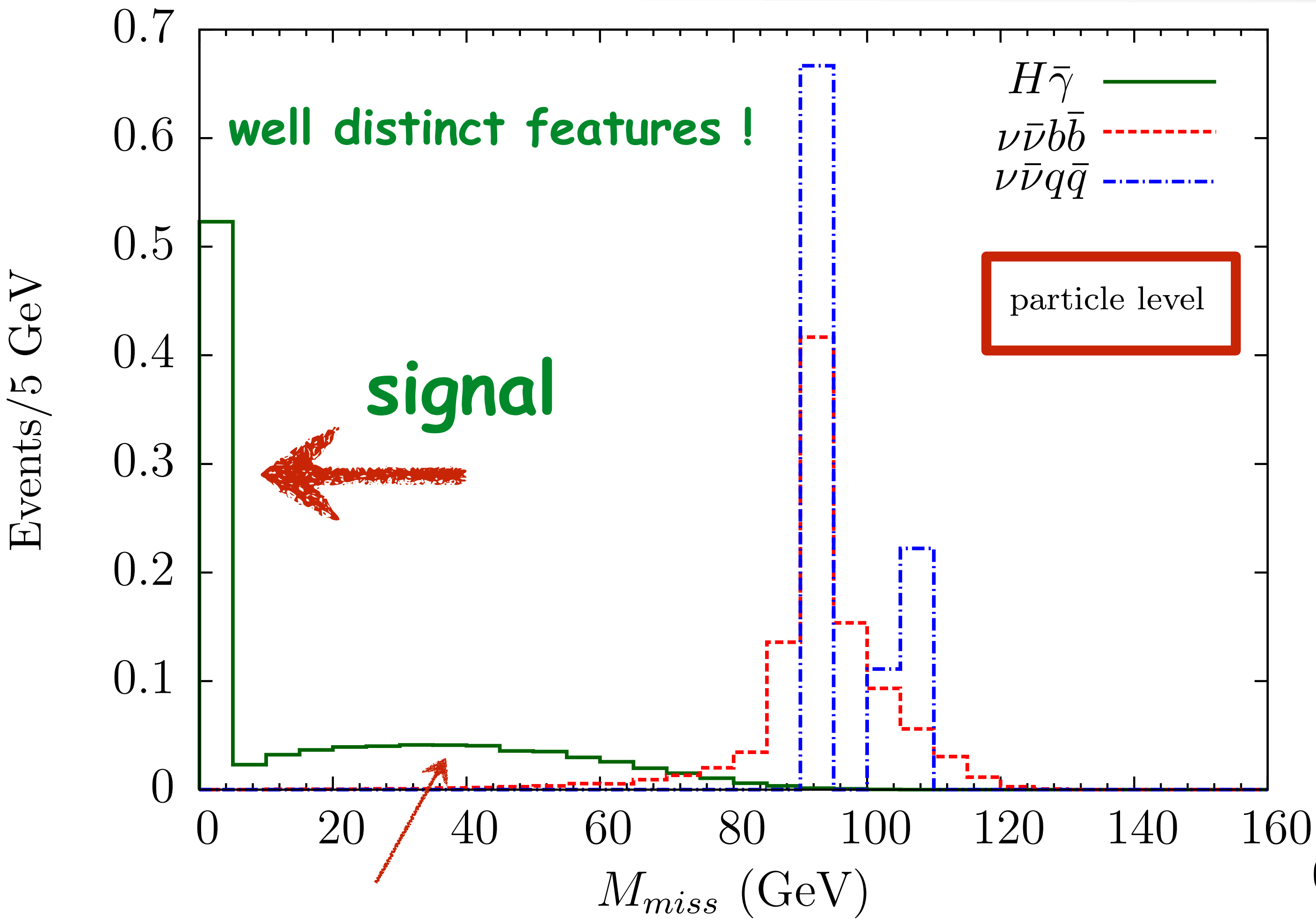
(normalized) M_{jj} distributions



jj ➜ two jets with largest p_T



(norm.) M_{miss} distrib.s before and after Pythia



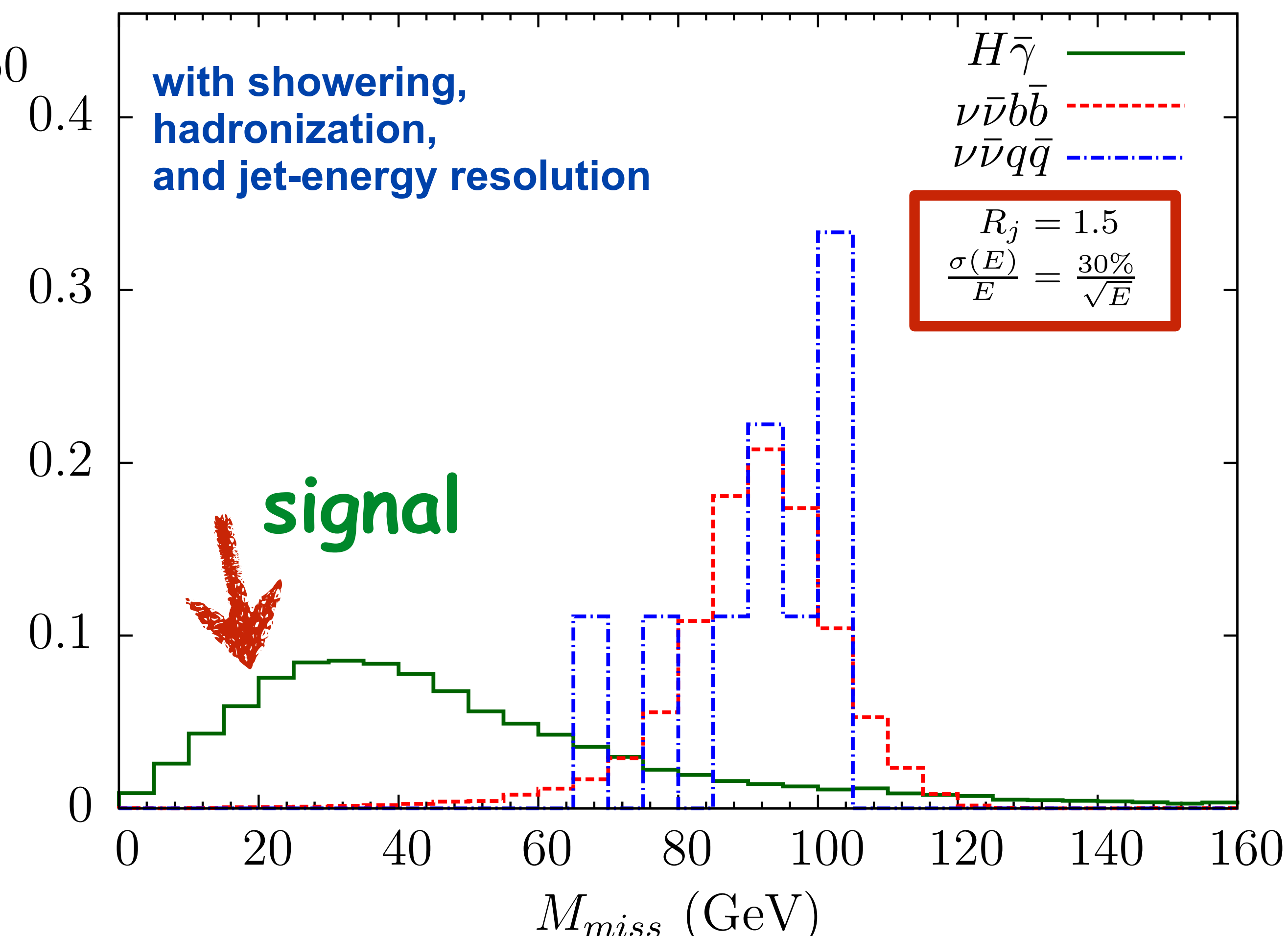
due to finite acceptance

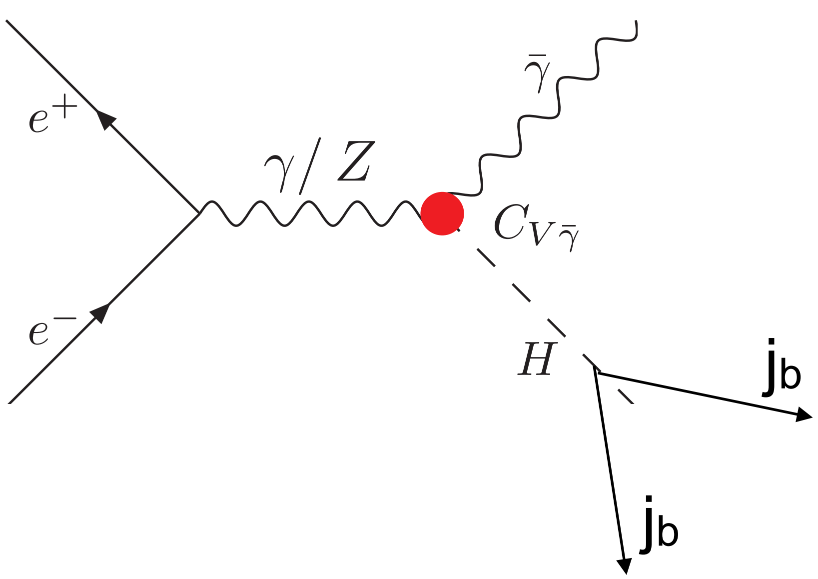
$$M_{\rm miss} = \sqrt{\not{E}^2 - \not{\mathbf{p}}^2}$$

$$\not{E} = \sqrt{s} - \sum \mathrm{E}_{visible}$$

$$\not{\mathbf{p}} = -\sum \mathbf{p}_{visible}$$

includes lower-E particles escaping jet reconstruct.





signal significance at $\sqrt{S}$ = 240 GeV & $\int L$ ~ 10 ab^{-1}

$$\mathcal{L}_{\mathrm{DP_H}} = \frac{\alpha}{\pi}\left(\frac{C_{\gamma\bar{\gamma}}}{v}\gamma^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{Z\bar{\gamma}}}{v}Z^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{\bar{\gamma}\bar{\gamma}}}{v}\bar{\gamma}^{\mu\nu}\bar{\gamma}_{\mu\nu}H\right)$$

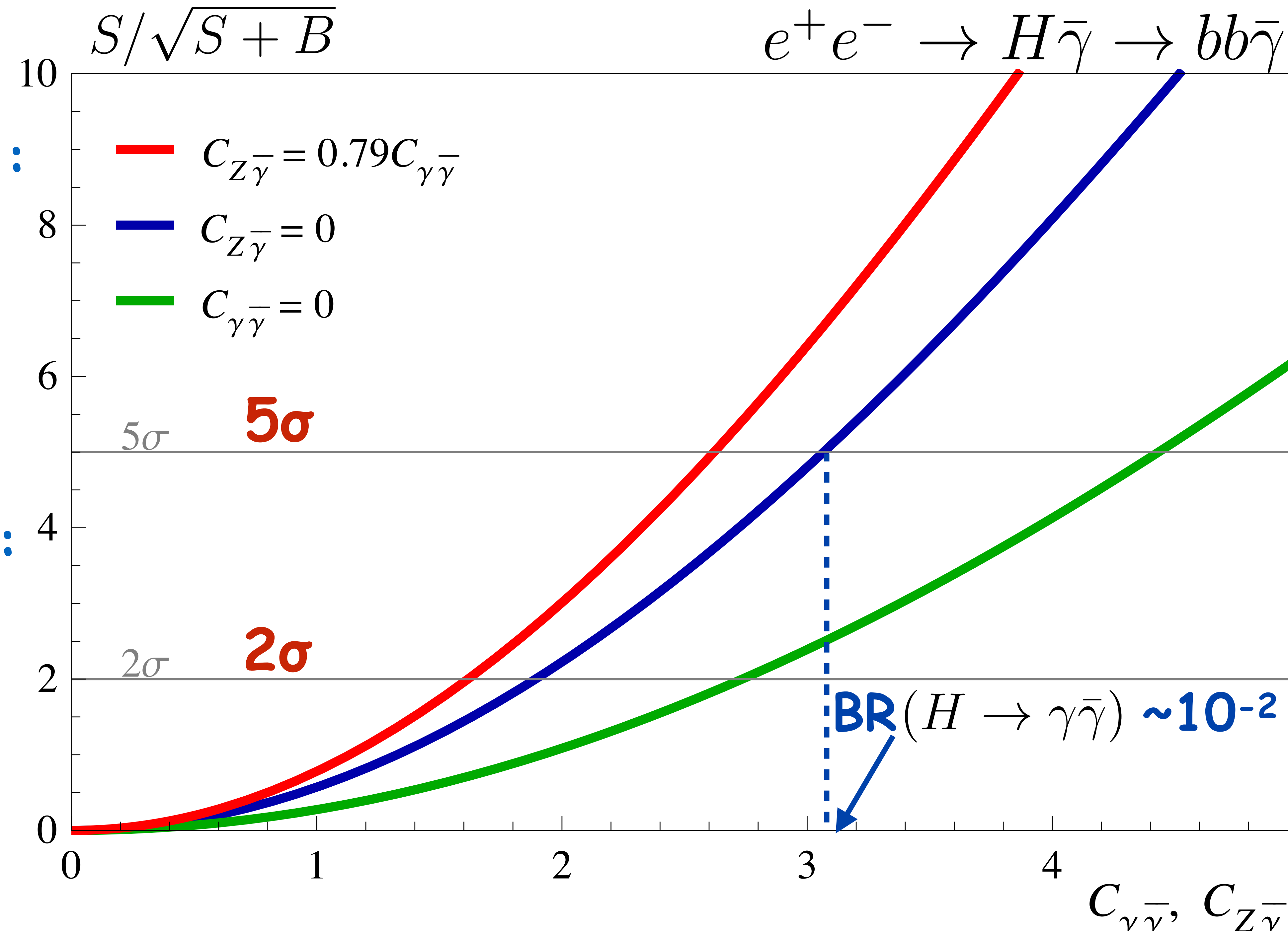
for $C_{Z\bar{\gamma}} = 0$,

- **excludes** couplings giving :

$$\mathrm{BR}(H \to \gamma\bar{\gamma}) \gtrsim 3\ \mathrm{BR}(H \to \gamma\gamma)$$

- **discovers** couplings giving :

$$\mathrm{BR}(H \to \gamma\bar{\gamma}) \gtrsim 10^{-2}$$

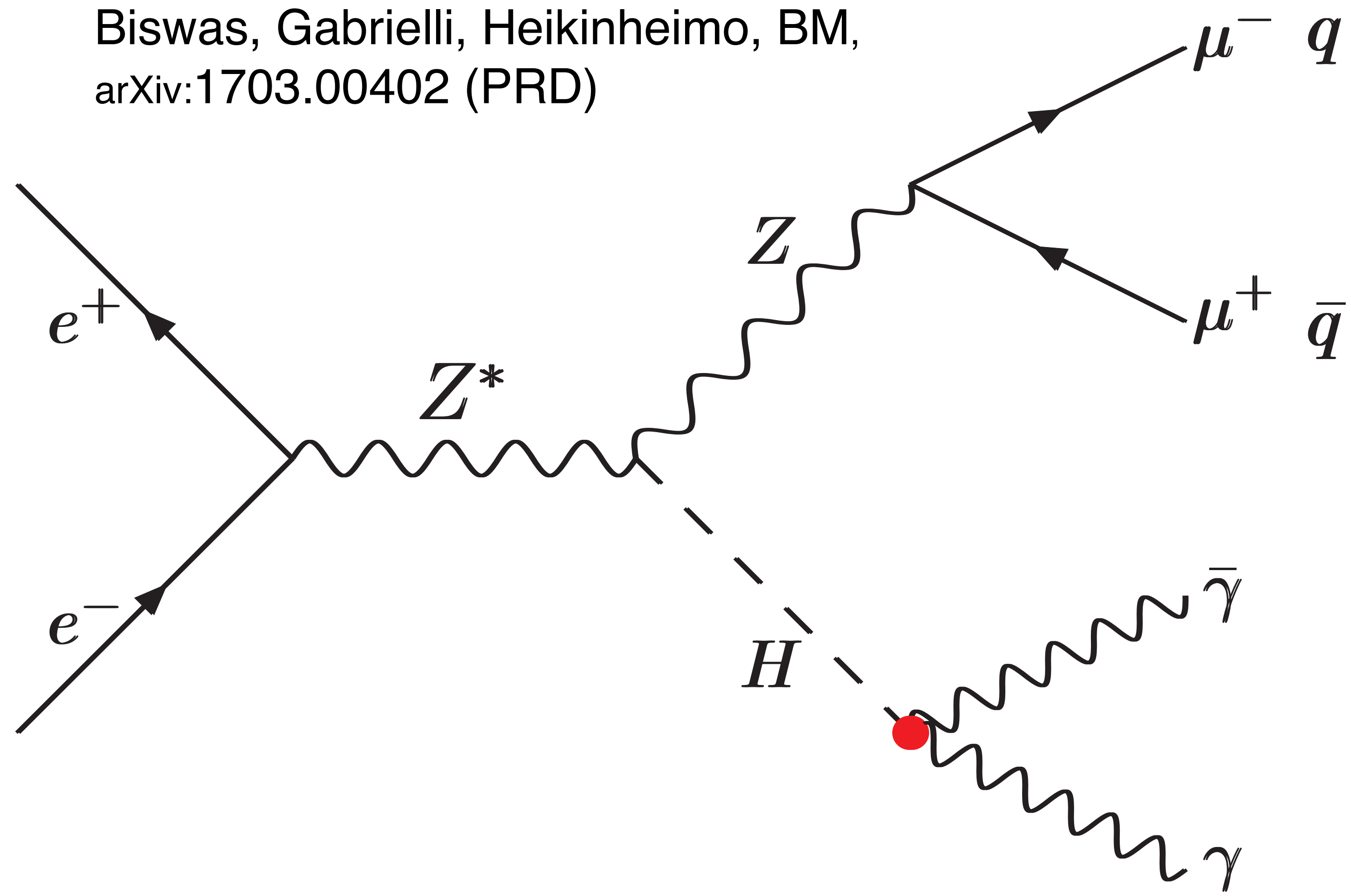


Biswas, Gabrielli, Heikinheimo, BM, arXiv:1503.05836 (JHEP)

← natural range for U(1)$_F$ Flavor models →

$e^+e^- \to ZH \to \mu^+\mu^-\gamma\bar{\gamma},\, q\bar{q}\,\gamma\bar{\gamma}$

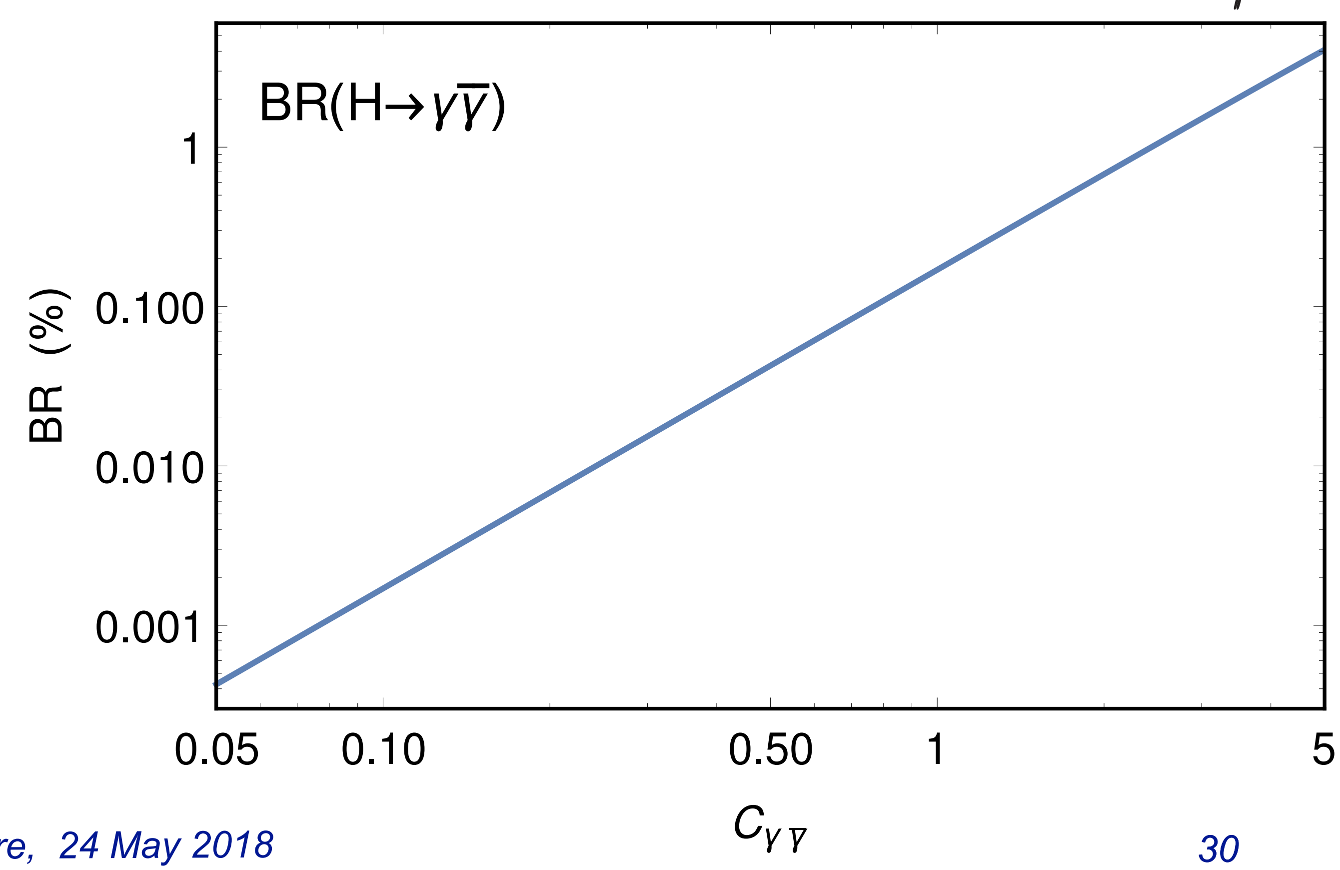
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1703.00402 (PRD)



- signature:
  a massless invisible p.le
  + a photon
  resonating at m_H plus
  a mu/jet pair resonating
  at M_Z

- one-parameter study
  (model-independent)

$$\Gamma(H \to \gamma\bar{\gamma}) = \frac{m_H^3 \alpha^2 |C_{\gamma\bar{\gamma}}|^2}{8\pi^3 v^2}$$



main backgrounds

* **leptonic channel :** resonant plus t-channel

$$e^+e^- \to \mu^+\mu^-\nu\bar{\nu}\gamma \qquad \begin{matrix} ZZ\gamma \\ WW\gamma \end{matrix} \qquad e^+e^- \to \nu\bar{\nu}Z\gamma$$

$Z\gamma$ plus fake missing energy

* **hadronic channel :**

$$e^+e^- \to q\bar{q}\nu\bar{\nu}\gamma$$

$$e^+e^- \to q\bar{q}\gamma \to jj\gamma$$ plus fake missing energy

simulation

PYTHIA for signal and MadGraph5_aMC@NLO + PYTHIA for bckgrds

ISR/FSR effects described by PYTHIA

Finite detector resolutions for γ, μ, j

(as for ILD detector)

$$\Delta E/E = 16.6\%/\sqrt{E/\text{ GeV}} + 1.1\%.$$

$$\Delta p/p = 0.1\% + p_T/(10^5 \text{ GeV}) \text{ for } |\eta| < 1$$

$$\Delta E/E_{\mathrm{j}} = 30\%/\sqrt{E/\text{ GeV}}$$

Event yield (after sequential cuts)

leptonic channel

$$e^+e^- \to ZH \to \mu^+\mu^- \; \gamma\bar{\gamma}$$

$$BR_{\gamma\bar{\gamma}} = 0.1\%$$

for √S = 240 GeV ∫ L ~ 10 ab-1

Process	Basic cuts	$M_{\ell\ell}$ cut	$M_{\gamma\bar{\gamma}}$ cut	$M_{\rm miss}$ cut
$\mu^+\mu^-\gamma\bar{\gamma}$ $(BR_{\gamma\bar{\gamma}} = 0.1\%)$	65.3	54.9	49.7	47.3
$\mu^+\mu^-\nu\bar{\nu}\gamma$	5.00×10^4	5.73×10^3	1.09×10^3	15

$$86\ \text{GeV} < M_{\mu^+\mu^-} < 96\ \text{GeV}$$

$$120\ \text{GeV} < M_{\gamma\bar{\gamma}} < 130\ \text{GeV}$$

$$M_{\rm miss} < 20\ \text{GeV}$$

Event yield (after sequential cuts)

hadronic channel

$$e^+e^- \to ZH \to q\bar{q}\gamma\bar{\gamma}$$

$$BR_{\gamma\bar{\gamma}} = 0.1\%$$

for $\sqrt{S}$ = 240 GeV $\int L \sim 10$ ab^{-1}

Process	Basic cuts	M_{jj} cut	$M_{\gamma\bar{\gamma}}$ cut	$M_{\rm miss}$ cut	$\not{E}$ cut
$jj\gamma\bar{\gamma}$ $(BR_{\gamma\bar{\gamma}} = 0.1\%)$	804	669	154	110	72
$jj\gamma$	3.39×10^7	2.26×10^7	1.47×10^5	6.5×10^4	–
$jj\nu\bar{\nu}\gamma$	3.9×10^4	3.1×10^4	5.9×10^3	2.2	–

$50 \text{ GeV} < M_{jj} < 90 \text{ GeV}$

$120 \text{ GeV} < M_{\gamma\bar{\gamma}} < 130 \text{ GeV}$

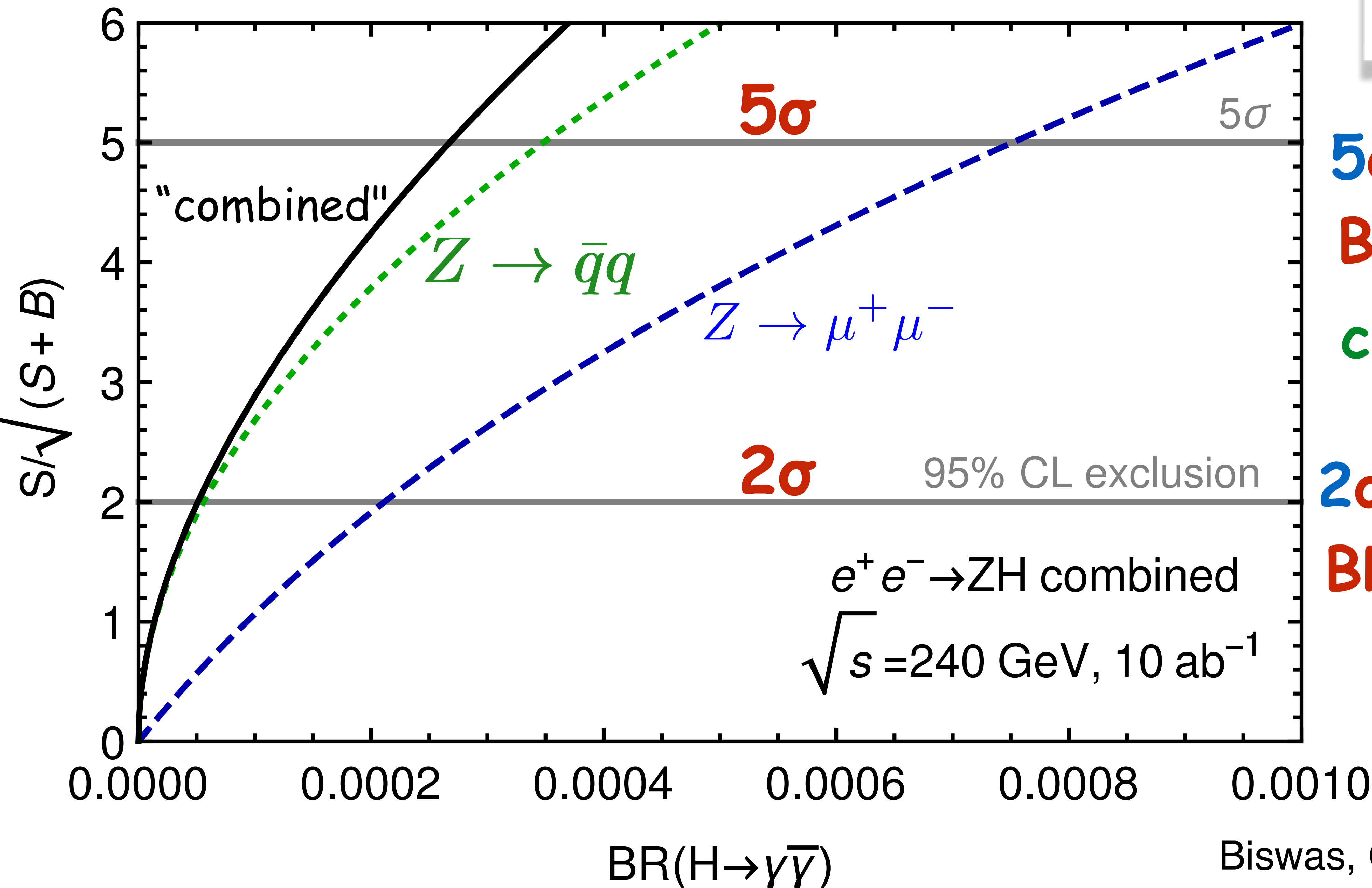
$M_{\rm miss} < 20 \text{ GeV}$

$\not{E} > 59 \text{ GeV}$

$$e^+e^- \to ZH \to \mu^+\mu^- \; \gamma\bar{\gamma} \; + \; q\bar{q} \; \gamma\bar{\gamma}$$

signal significance

$\sqrt{S}$ = 240 GeV, $\int L \sim 10\ ab^{-1}$



hadronic Z most sensitive channel !

5σ sensitivity for $BR_{DP} \sim 3\times10^{-4}$!!!

combined

2σ sensitivity for $BR_{DP} \sim 5\times10^{-5}$!!!

(2 times better than HL-LHC)

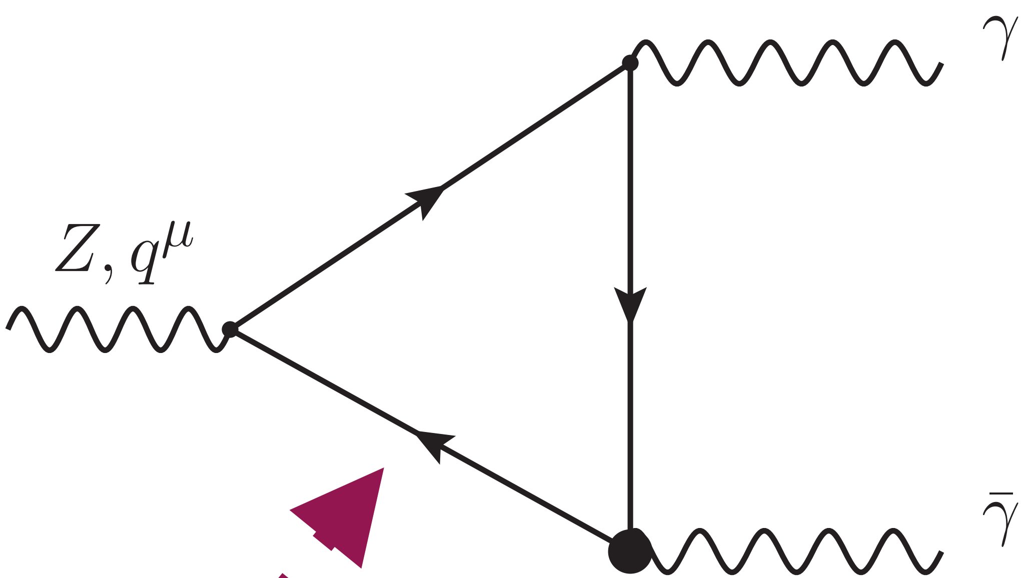
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1703.00402 (PRD)

Z bosons as "source" of massless Dark Photons

Fabbrichesi, Gabrielli, BM, arXiv:1712.05412 (PRL)

$$Z \to \gamma\bar{\gamma}$$

mono-photon resonant signature at M_Z

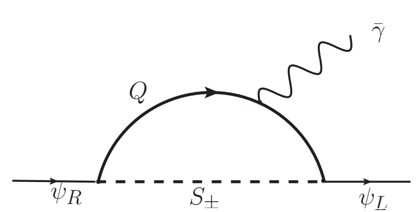


evading Landau-Yang theorem !

BR < 10^{-6} from LEP

SM fermions

$$\mathcal{L} \sim \bar{\psi}\,\sigma_{\mu\nu}\,(d_M + i\gamma_5\,d_E)\,\psi\,B^{\mu\nu}$$



BR ~ 10^{-9} allowed in simplified models !

manageable at hadron colliders ???

200 evs at HL-LHC, 10^4 at FCC-hh,ee

Outlook

- an ee circular collider running at ZH, WW, Z with $L \sim 10^{(34\text{-}36)}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ can go beyond LHC reach in many different BSM sectors

- it is "not just" a wonderful Higgs precision probe !

- EWPT : order of magnitudes improvements wrt LEP

- ideal setup for discovering (very) new weakly interacting pls

  (additional light Higgses with reduced coupling not covered here…)

- Hidden/Dark (SM-uncharged) Sectors can provide new signatures to scrutinise

- many different studies, just mentioned a few…