Search for Dark Photons at future e^+e^- colliders

FCC-ee physics zoom meeting
27/07/2020

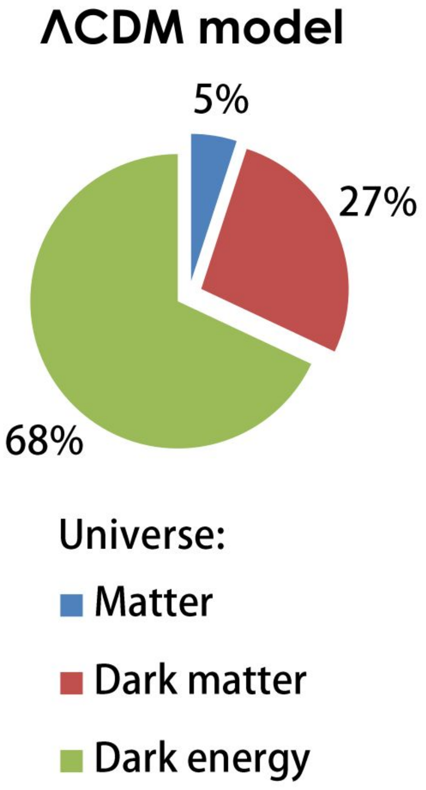
Brief Dark Matter intro

Evidences

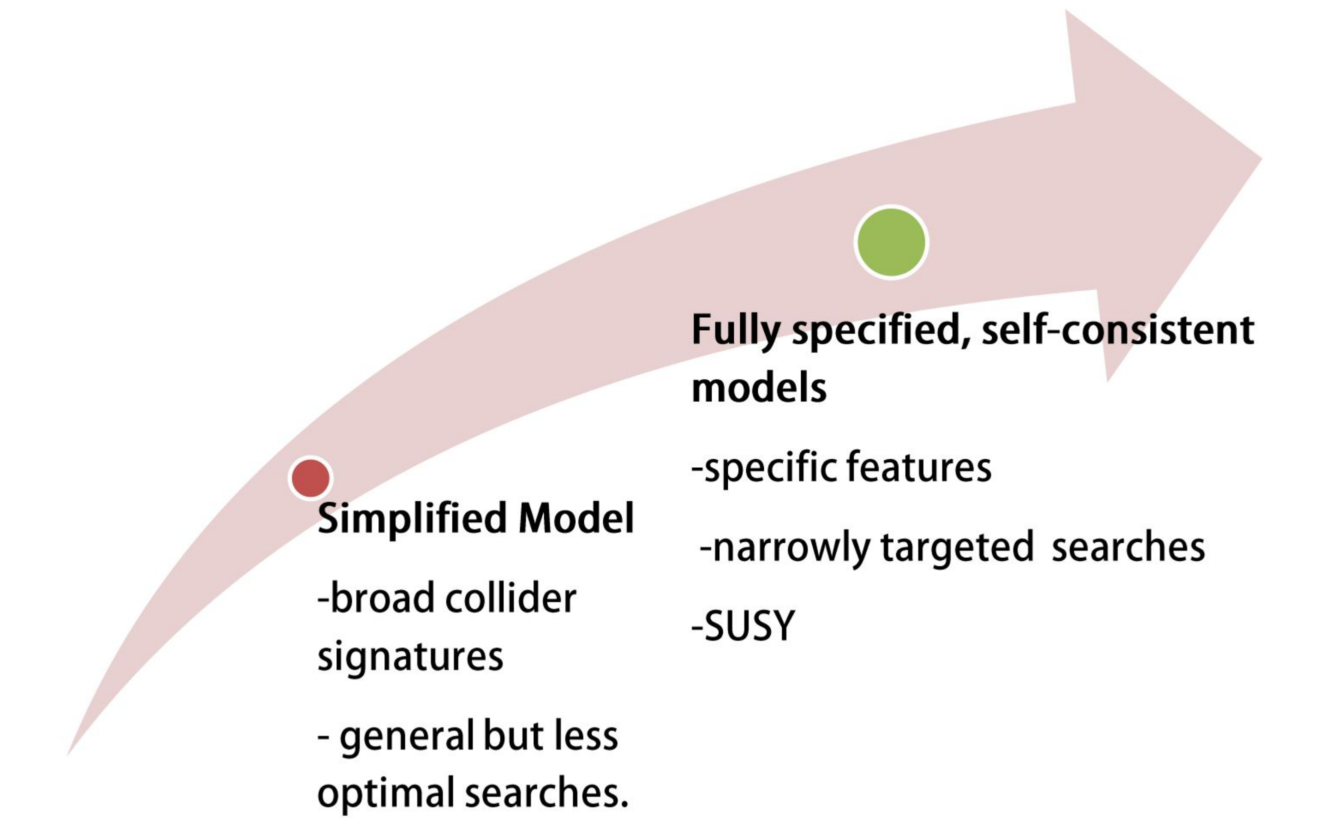
- Rotation curves of galaxies
- CMB fluctuations

Properties

- Dark
- Gravitational interaction
- Stable
- Non-relativistic
- Collisionless



DM models


Simplified Model
-broad collider signatures
- general but less optimal searches.
Fully specified, self-consistent models
-specific features
-narrowly targeted searches
-SUSY

DM traditional search strategies

Direct Detection

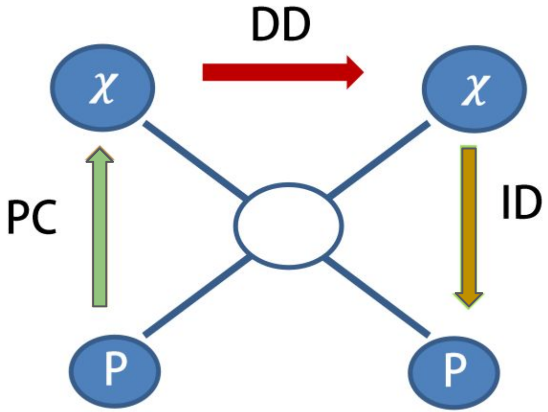
- Galactic DM colliding with underground targets made of ordinary matter

Indirect Detection

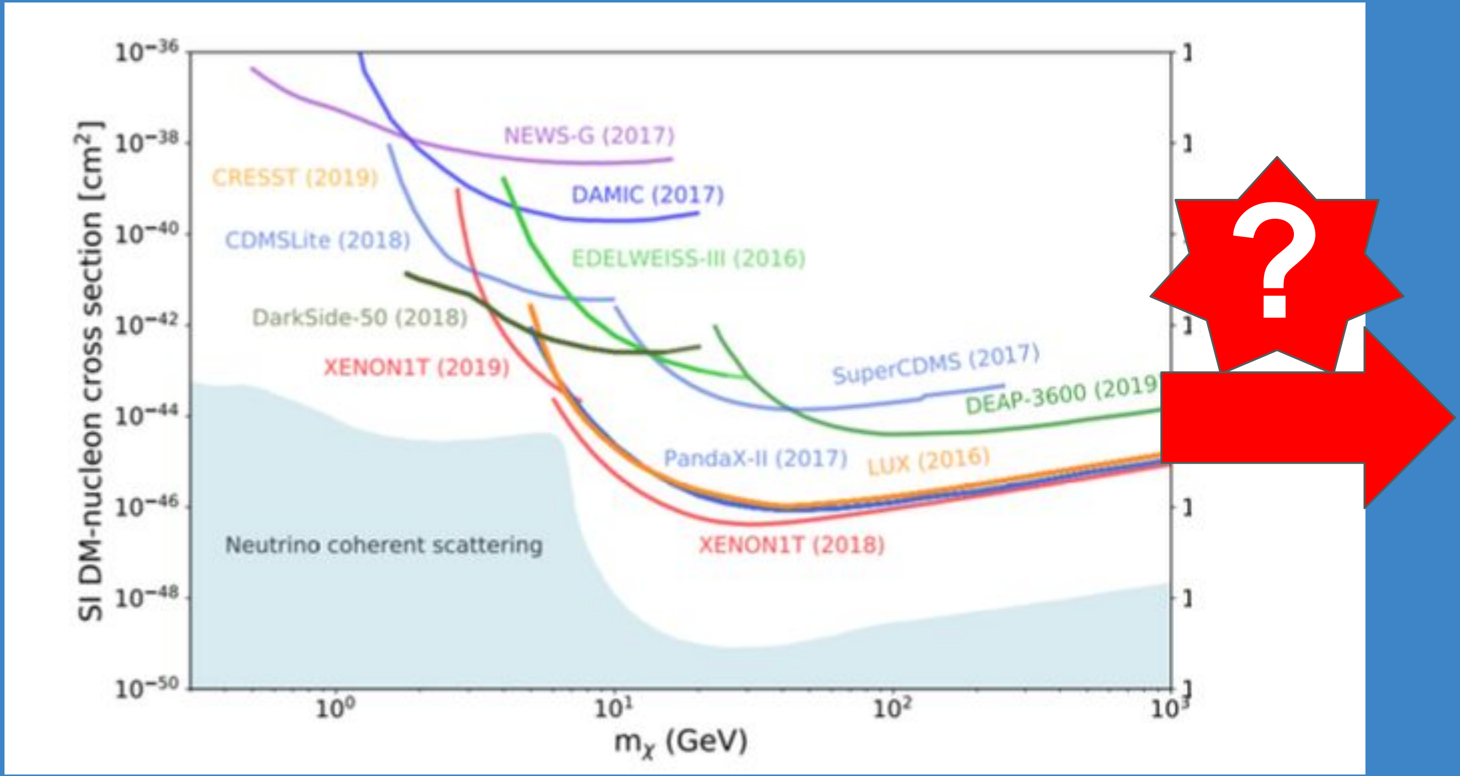
- Search for the products of annihilating DM

Production at Colliders

- Search for invisible particles at Colliders



DM bounds



SI DM-nucleon cross section [cm^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^0
10^1
10^2
10^3
m_χ (GeV)
NEWS-G (2017)
CRESST (2019)
DAMIC (2017)
CDMSLite (2018)
EDELWEISS-III (2016)
DarkSide-50 (2018)
XENON1T (2019)
SuperCDMS (2017)
DEAP-3600 (2019
PandaX-II (2017)
LUX (2016)
XENON1T (2018)
Neutrino coherent scattering
?

Dark photons

- "**photon**:" boson, spin 1 particle, neutral under $U(1)_{EM}$
- but "**dark**": not the gauge boson of $U(1)_{EM}$
  - do not interact (directly) with any $U(1)_{EM}$ charged particle

Despite from the name, both options are present in literature:

Massive (generically light)

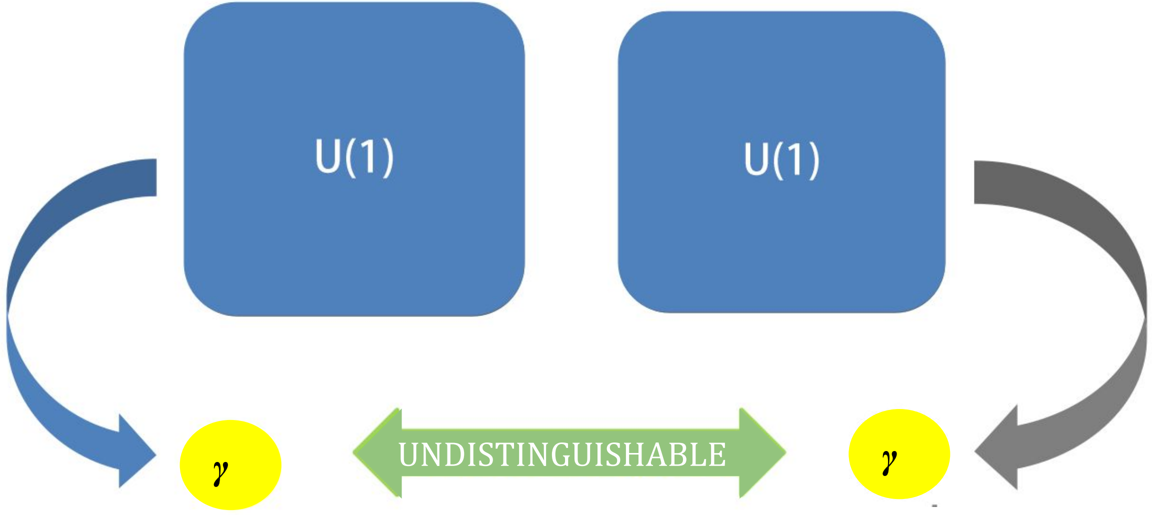
- Typically from (spontaneously) broken $U(1)_D$
- Always kinetic mixing with photon
- Can decay (loop level) to e^+e-

Massless

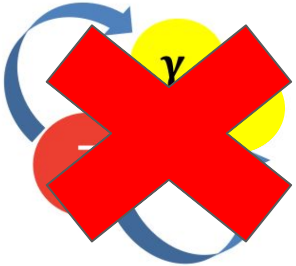
- Gauge boson of unbroken

Searching for what *keeps* dark matter candidates *stable*

Landau-Yang theorem

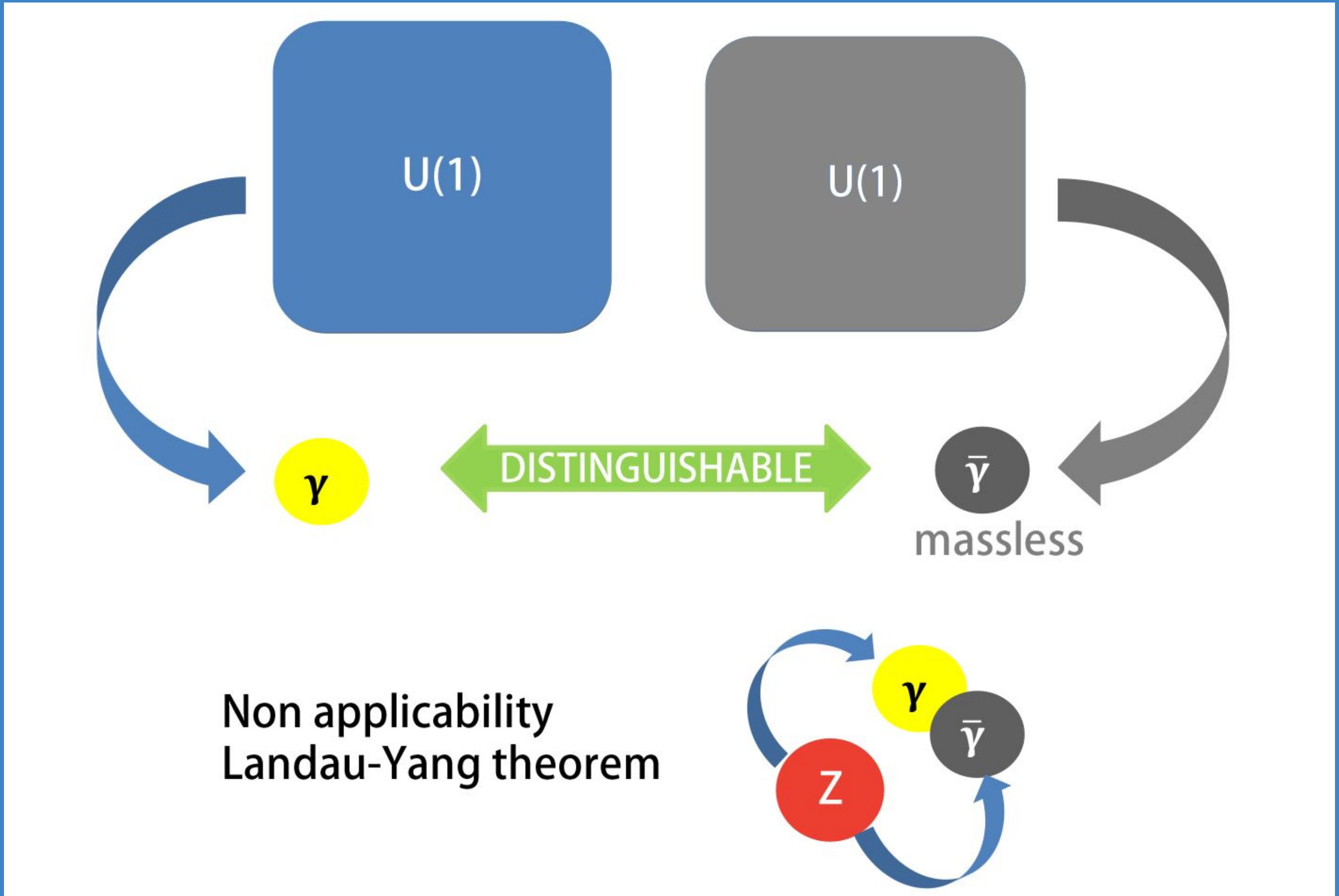


Forbids Z to two photons decay

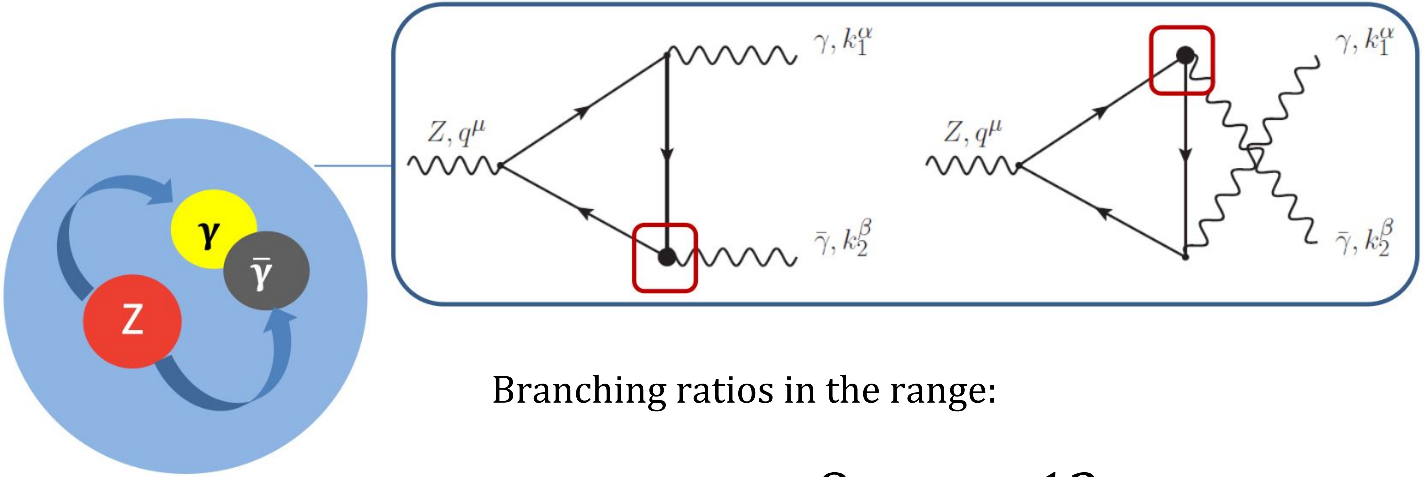


M. Fabbrichesi et al, Phys.Rev.Lett. 120 (2018) 17

Landau-Yang theorem



Evading
Landau-Yang theorem



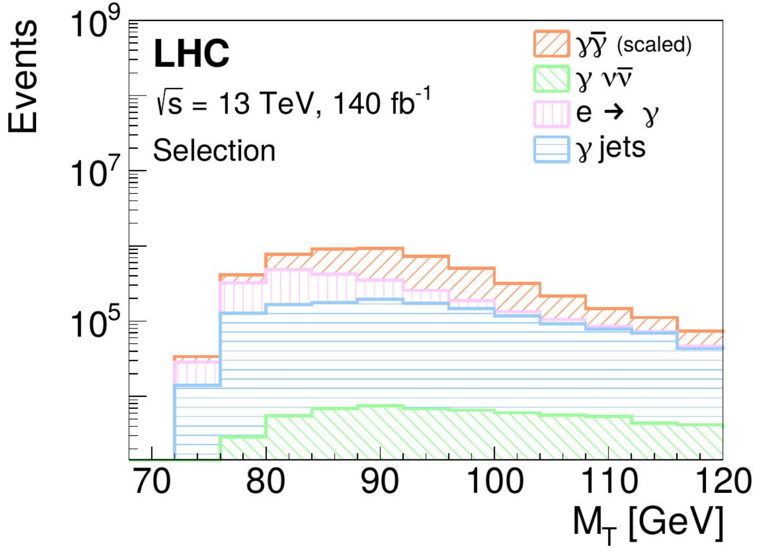
Branching ratios in the range:

$$BR \sim 10^{-8} - 10^{-12}$$

Sketch: LHC ...

- $L = 140\text{fb}^{-1}$
- $\text{BR}_{LHC} = \quad 8 \times 10^{-6}$

LHC



Observable	Systematic uncertainty	c_i
E_T^{miss}	1%	0.04
p_T^{γ}	0.3 %	< 0.01
σ_b	3.7%	0.04
$F_{e\to\gamma}$	70%	-

Cut
$p_T^{\gamma} > 35\,\text{GeV}$
$E_T^{\text{miss}} > 40\,\text{GeV}$
$\Delta\phi(\gamma, E_T^{\text{miss}}) > 2.8$ rad
$80\,\text{GeV} < M_T < 105\,\text{GeV}$

Sketch: ... and HL-LHC

LHC

- $L = 140\text{fb}^{-1}$
- $\text{BR}_{LHC} =$ 8×10^{-6}

HL-LHC

- $L = 3000\text{fb}^{-1}$
- $\text{BR}_{HL-LHC} =$ $\text{BR}_{LHC}\sqrt{L_{LHC}/L_{LHC}} =$ 2×10^{-6}

If systematic uncertainties $\propto \frac{1}{\sqrt{L}}$

Additional motivation for studies at future e+e- colliders ...

Analysis validation: LEP

“Search for New Phenomena Using Single Photon Events in the DELPHI Detector at LEP”,
Z.Phys. C74 (1997) 577-586

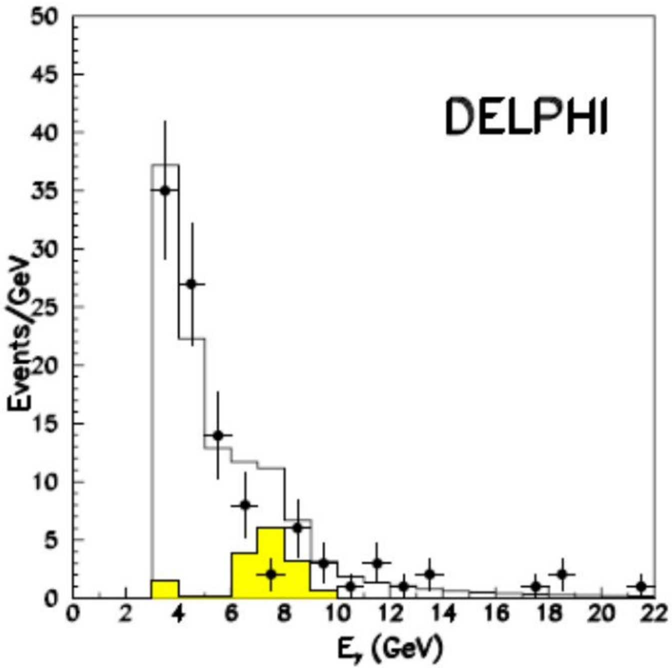


Fig. 3. Distribution in energy of the single photon events (*points*). The *histogram* shows the distribution expected from the signal $\nu\bar{\nu}\gamma$ events plus the background $e^+e^-\gamma$ events (*shaded region*) in which the final state positron and electron both escape detection

Analysis validation: LEP

	n_{sim}	n
$\nu\bar{\nu}\gamma$	99.1	92.6
$e^+e^-\gamma$	13.5	14.3

Exclusion limits in the presence of no background

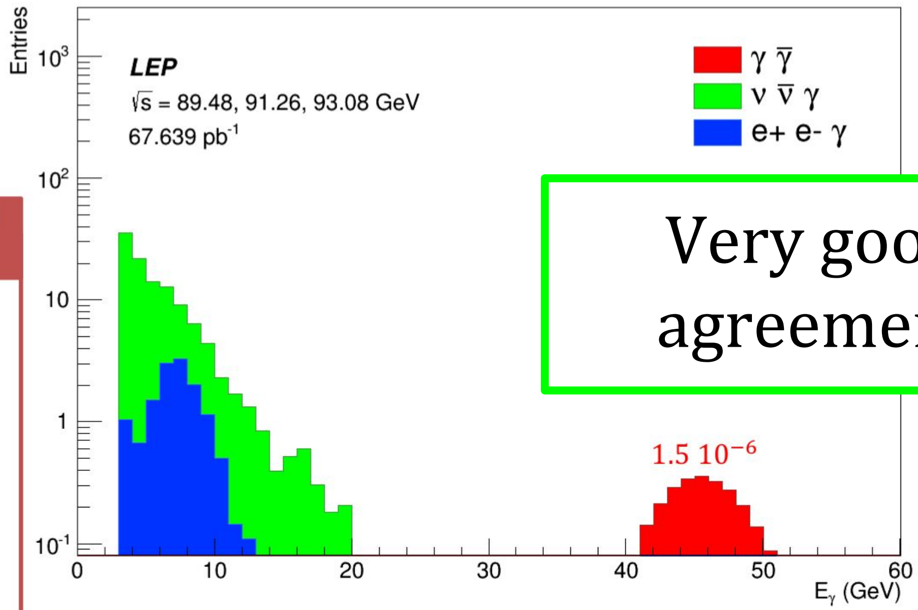
- $E_\gamma > 20$ GeV
- $n_o = b = 0$, $CL=0.95$

$$CL = 1 - \sum_{n=0}^{n_o} \frac{s^n e^{-s}}{n!}$$

- $s = 3$
- $s = \text{BR} \sum_i L_i \, \sigma_{Z_i}{}^{fid} \, \varepsilon_{int\,i} \, \varepsilon_{cut\,i}$

  $\varepsilon_{cut\,i} = 1$

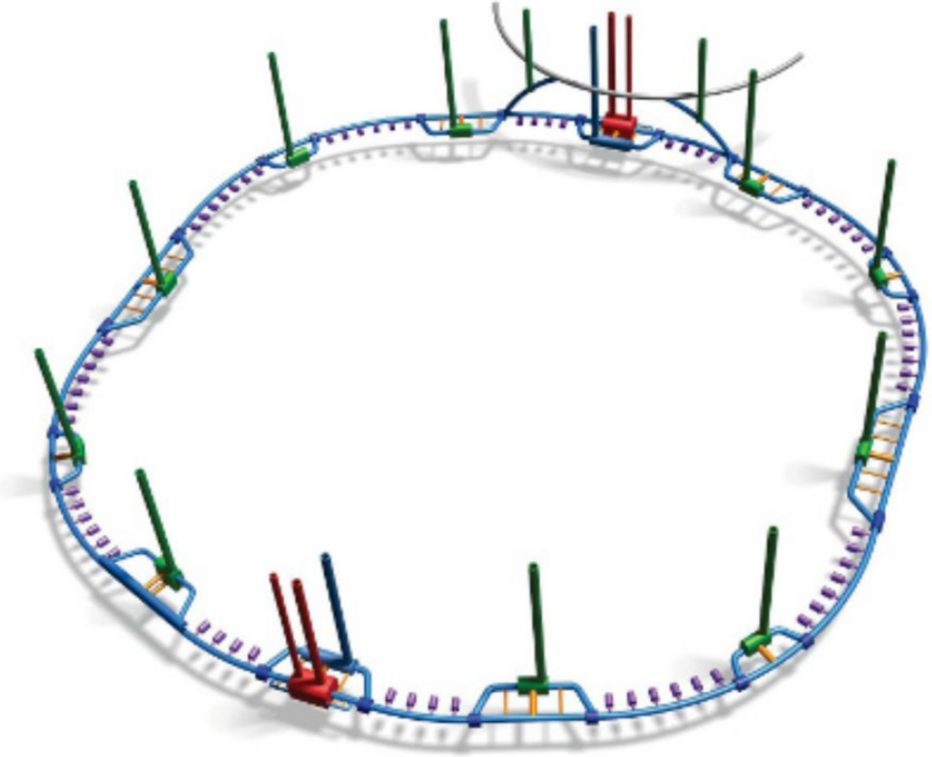
  $\varepsilon_{int\,i} = \varepsilon_{trig\,i} \varepsilon_{rec\,i} = 0.57$

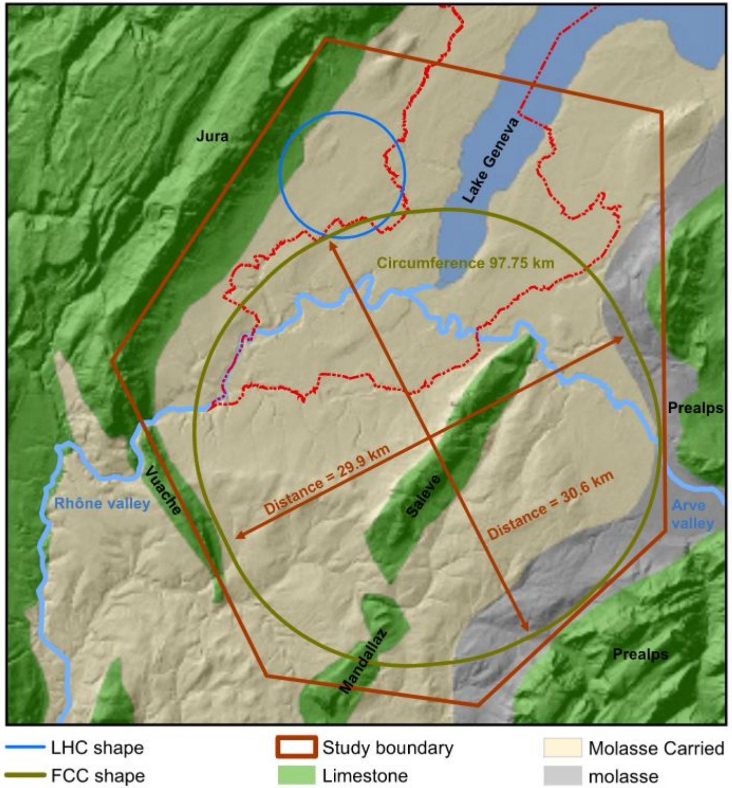


Very good agreement

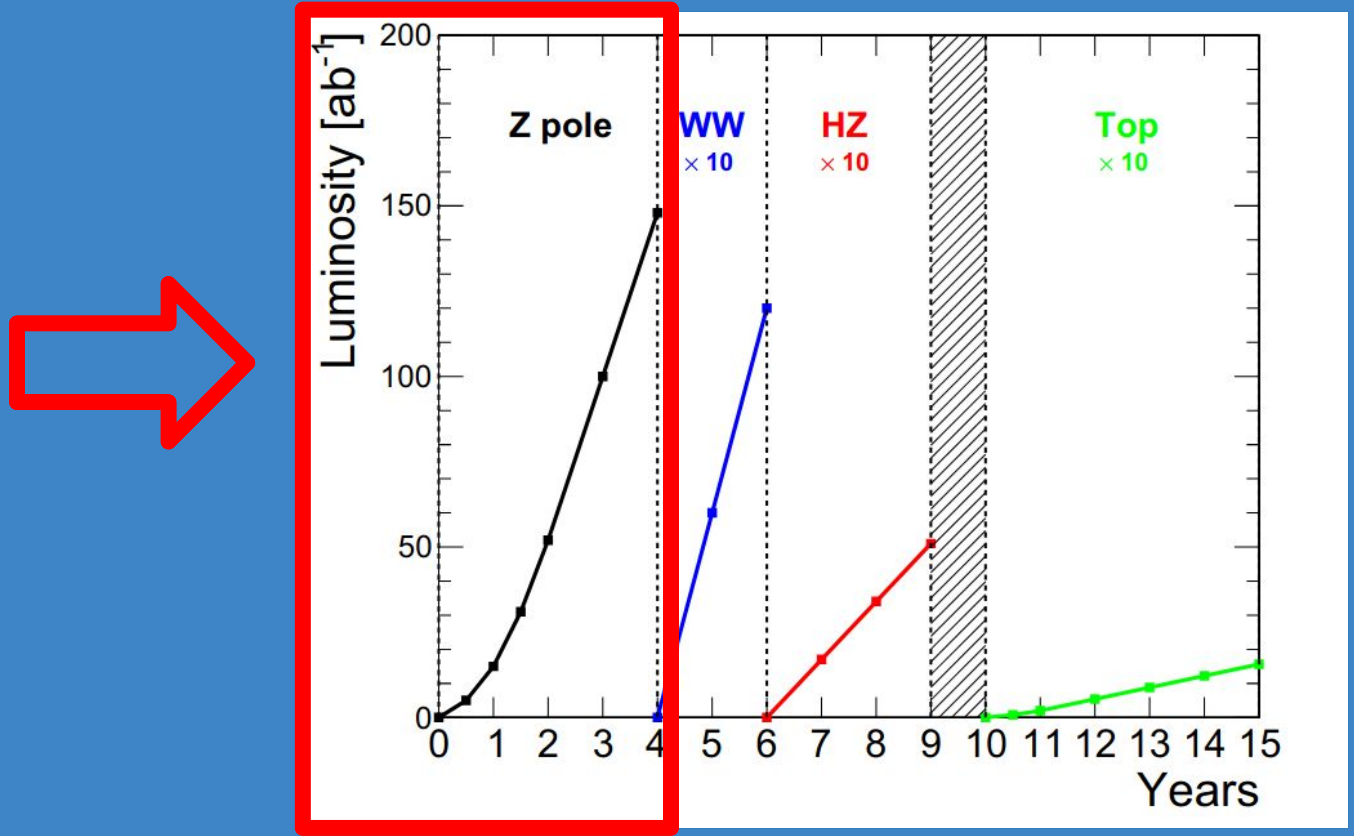
$BR_{\text{sim}} < 1.5 \times 10^{-6}$
$BR_{\text{LEP}} < 1.0 \times 10^{-6}$

FCC-ee




Jura
Lake Geneva
Circumference 97.75 km
Prealps
Distance = 29.9 km
Distance = 30.6 km
Rhône valley
Vuache
Saleve
Arve valley
Mandallaz
Prealps
LHC shape
FCC shape
Study boundary
Limestone
Molasse Carried
molasse

FCC-ee

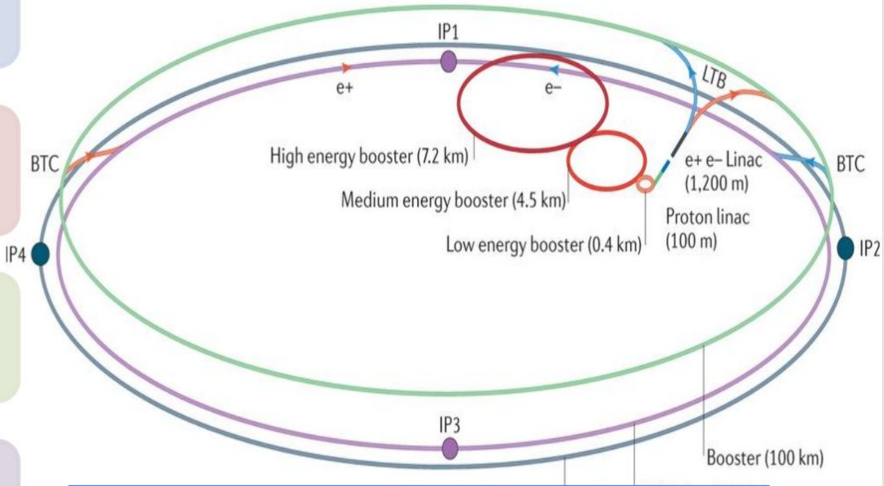


Luminosity [ab^{-1}]
Z pole
WW
× 10
HZ
× 10
Top
× 10
0
50
100
150
200
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Years

CEPC

Circular Electron-Positron Collider

Place	• China
Period	• Start construction: 2022 • Finish construction: 2030
c.m. energy	• 91.2 GeV (Z-factory) • 160 GeV (WW threshold scan) • 240 GeV (Higgs-factory)
L	• 8-16 ab^{-1} • 2.6 ab^{-1} • 5.6 ab^{-1}
Measurements	• Precision physics program: Higgs boson, Z boson, W boson



Comparable efficiencies wrt to FCC-ee, but **FCC-ee** with **higher luminosity** at 91.2 GeV and **better energy resolution**

Fast simulation setup

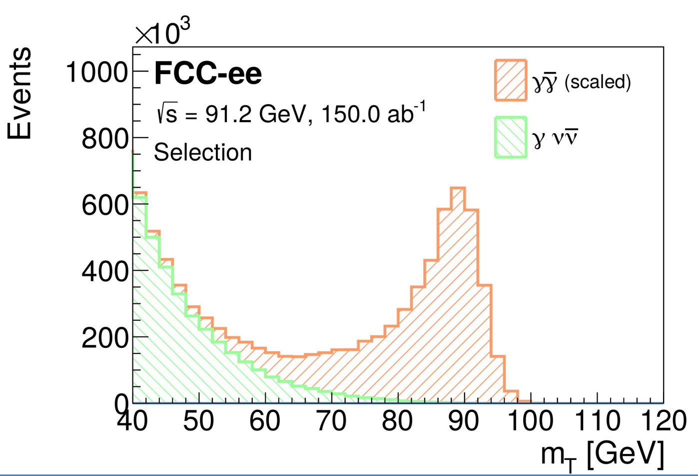
- MG5_aMC + Pythia8 **+ DELPHES 3**
- Detector cards shipped within:
  - **delphes_card_IDEA.tcl** (version of 23/08/2019)
    - E.Fontanesi, L. Pezzotti and M. Antonello
  - **delphes_card_CEPC.tcl** (vers. of 12/12/2016)

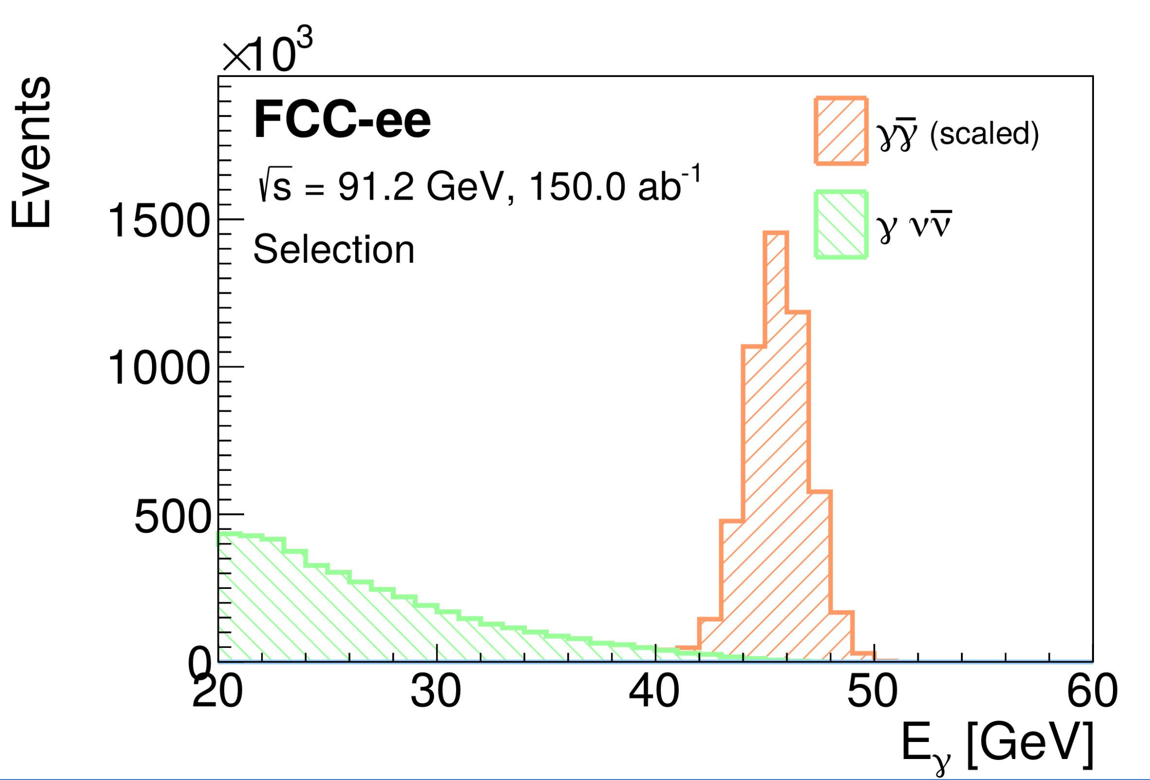
FCC-ee
Event selection

Cut	ϵ_s	ϵ_b
Preselection	0.96	0.067
$\lvert\cos\theta_\gamma\rvert < 0.905$	0.95	3.4×10^{-3}
$\lvert\cos\theta_\gamma\rvert < 0.905$ and $p_T^\gamma > 18$ GeV	0.95	2.3×10^{-6}

Process	Slice	N_{sim}	σ (pb)	E_γ^{min} (GeV)
$e^+e^- \to \gamma\bar{\gamma}$	-	50000	$(6.19 \pm 0.01) \times 10^4$	-
$e^+e^- \to \gamma\nu\bar{\nu}$	I	5000000	5025.0 ± 4.5	-
$e^+e^- \to \gamma\nu\bar{\nu}$	II	500000	0.1599 ± 0.0002	18
$e^+e^- \to \gamma e^+e^-$	I	5000000	8100 ± 1176	-
$e^+e^- \to \gamma e^+e^-$	II	500000	220.9 ± 0.4	30

FCC-ee





Background from e+e- γ do not pass selection requirements.

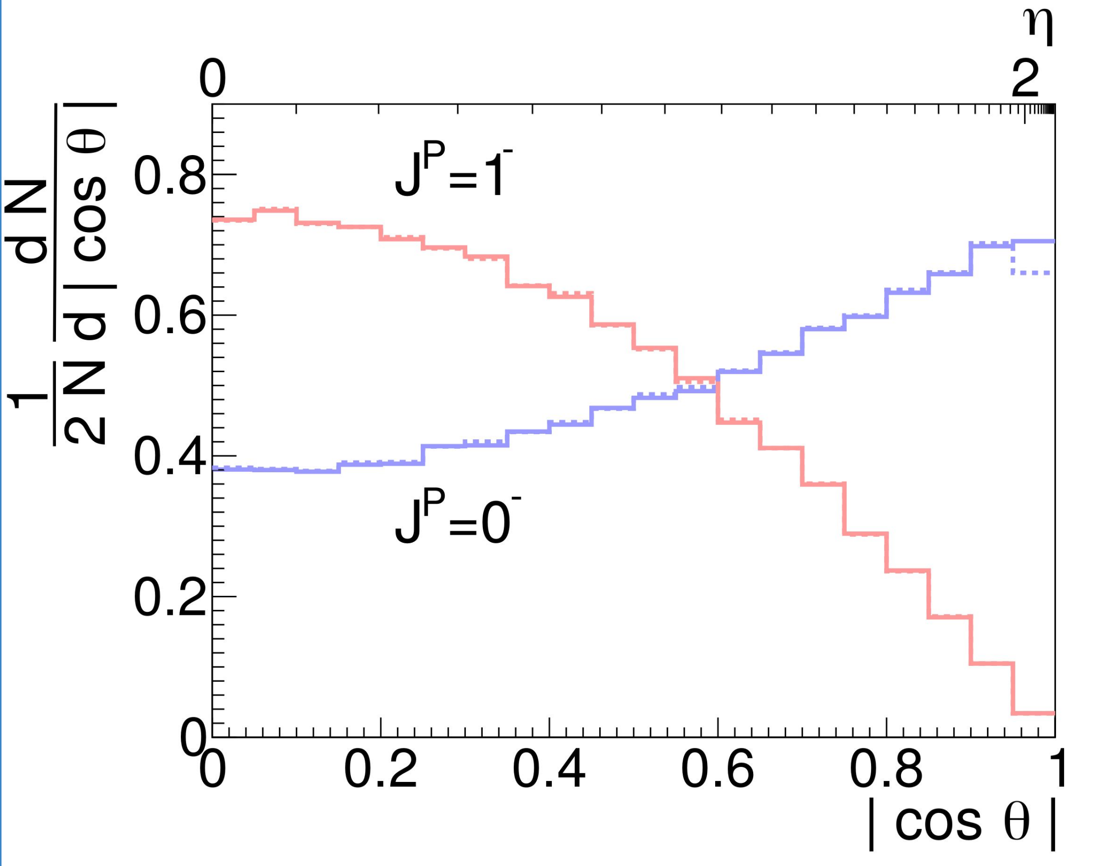
Summary of results

	$\sqrt{s}$	L (ab^{-1})	BR($Z \to \gamma\bar{\gamma}$) M_T	E_γ
LHC	13 TeV	0.14	8×10^{-6}	5×10^{-5}
HL-LHC	13 TeV	3	2×10^{-6}	1×10^{-5}
FCC-ee	91.2 GeV	150	2×10^{-11}	3×10^{-11}
CEPC	91.2 GeV	16	7×10^{-11}	8×10^{-11}

… and what if we find it?

Signal distribution pdfs

Comparison of the two spin hypotheses (dark photon wrt Axion-like particle ALP)

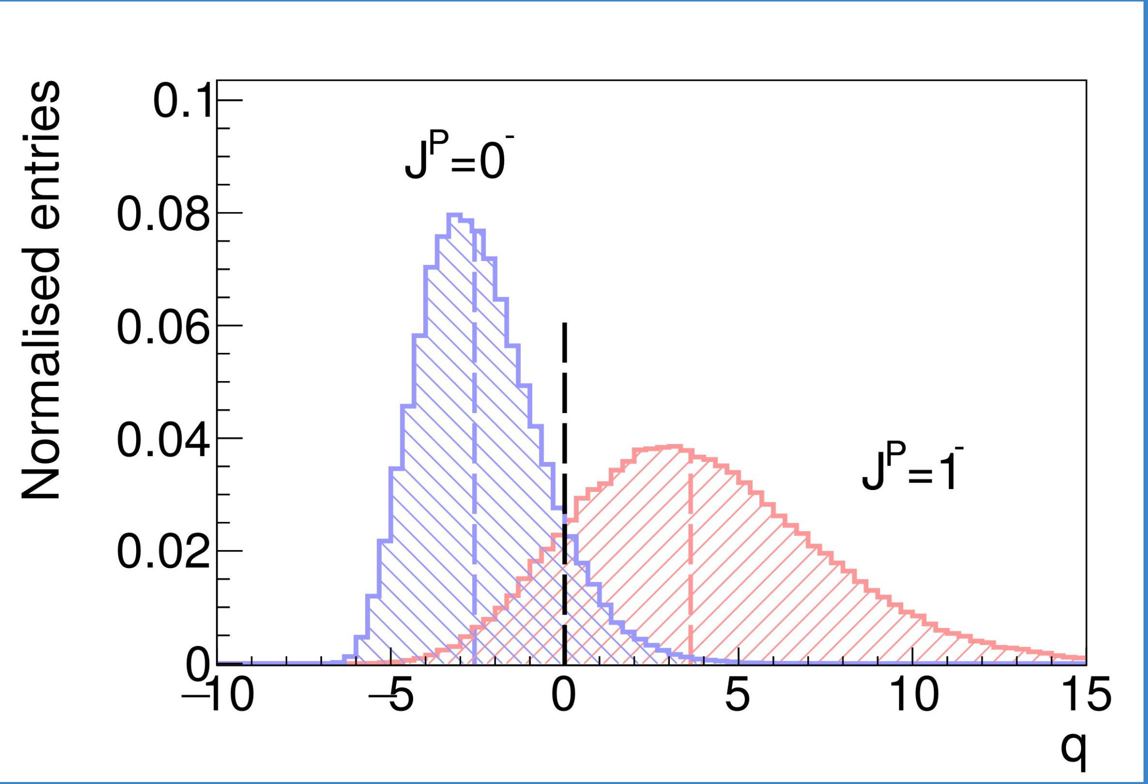


Signal distribution pdfs

Test statistics:

$$q = \log \frac{\mathcal{L}(J^P = 1^-, \hat{\hat{\mu}}_{1^-}, \hat{\hat{\boldsymbol{\theta}}}_{1^-})}{\mathcal{L}(J^P = 0^-, \hat{\hat{\mu}}_{0^-}, \hat{\hat{\boldsymbol{\theta}}}_{0^-})}$$

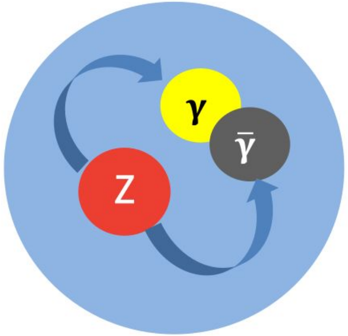
If syst. unc. on background ``well controlled”:
N>6 events can reject the ALP hypothesis at 95% CL

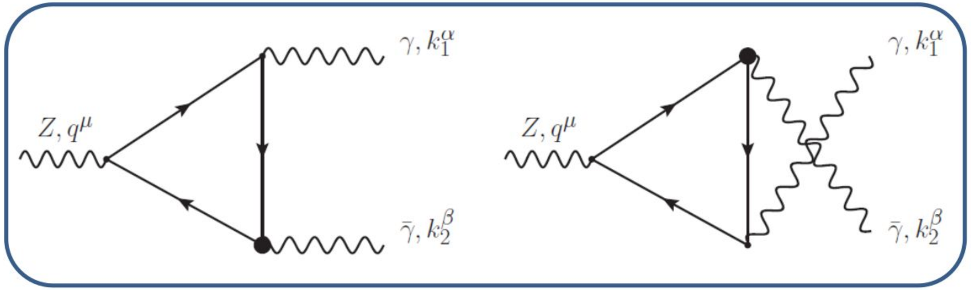


Thanks !

BACKUP

Evading
Landau-Yang theorem





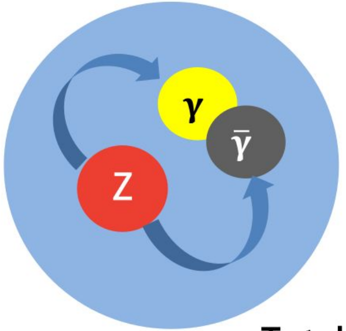
$$\mathcal{L} \sim \bar{\psi}\sigma_{\mu\nu}(d_M + i\gamma_5 d_E)\psi B^{\mu\nu}$$

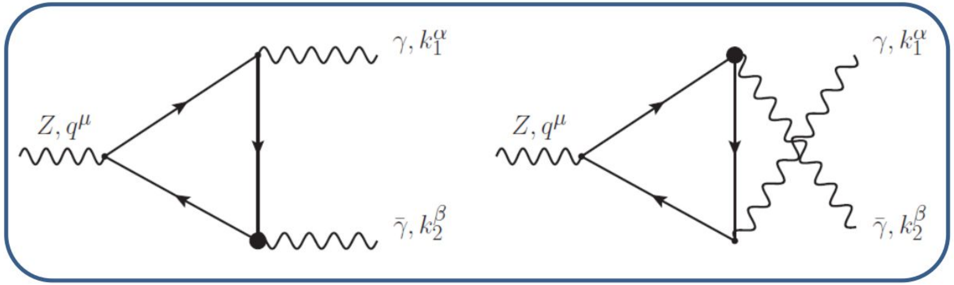
$$\mathcal{L}^{M}{}_{eff} = \sum_i k_i O_i(x)$$

$$\mathcal{L}^{E}{}_{eff} = k_E\ O(x)$$

$O_i(\mathrm{x})$ and $O(x)$: dimension-six operators defined through the field strengths $(Z, B, A)_{\mu\nu}$

Evading Landau-Yang theorem





Total amplitude $\mathcal{M} = \mathcal{M}_E + \mathcal{M}_M \rightarrow$ Total decay width $\Gamma(Z \rightarrow \gamma\bar{\gamma})$

$$BR_f = \frac{\Gamma_f}{\Gamma_Z} \rightarrow \sum_f \rightarrow \boldsymbol{BR(Z \rightarrow \gamma\bar{\gamma}) = \frac{2.52\alpha_D}{\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2}(|d_M|^2 + |d_E|^2)10^{-8}}$$

$$\alpha_D = 0.1, \Lambda = 1\ \mathrm{TeV}, d_E \cong d_M = \frac{1}{2} \rightarrow BR \cong 10^{-9}$$

$$\alpha_D = 0.1, \Lambda = 1\ \mathrm{TeV}, d_E \cong d_M = 0.1 \rightarrow BR \cong 10^{-11}$$

LHC and HL-LHC