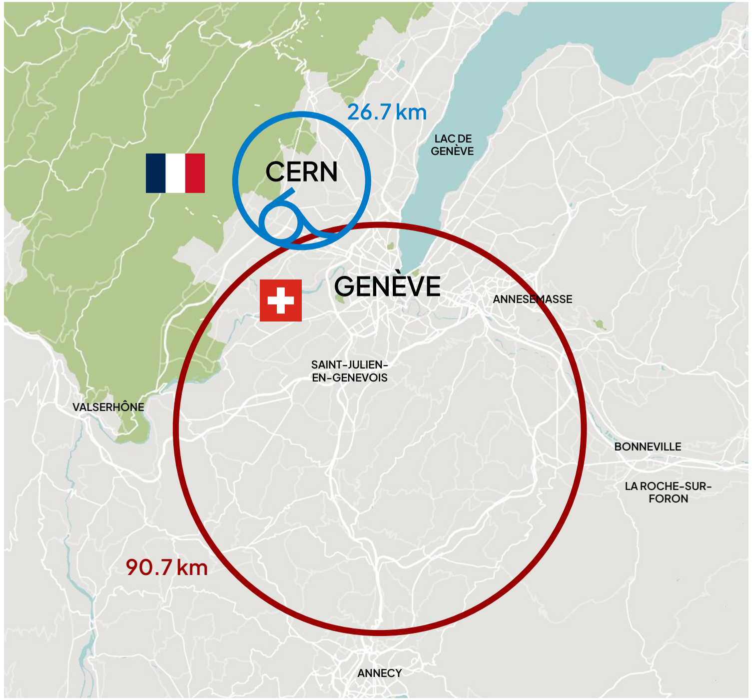
Sensitivity of the FCC-ee to ALPs decaying into two photons

Motivation

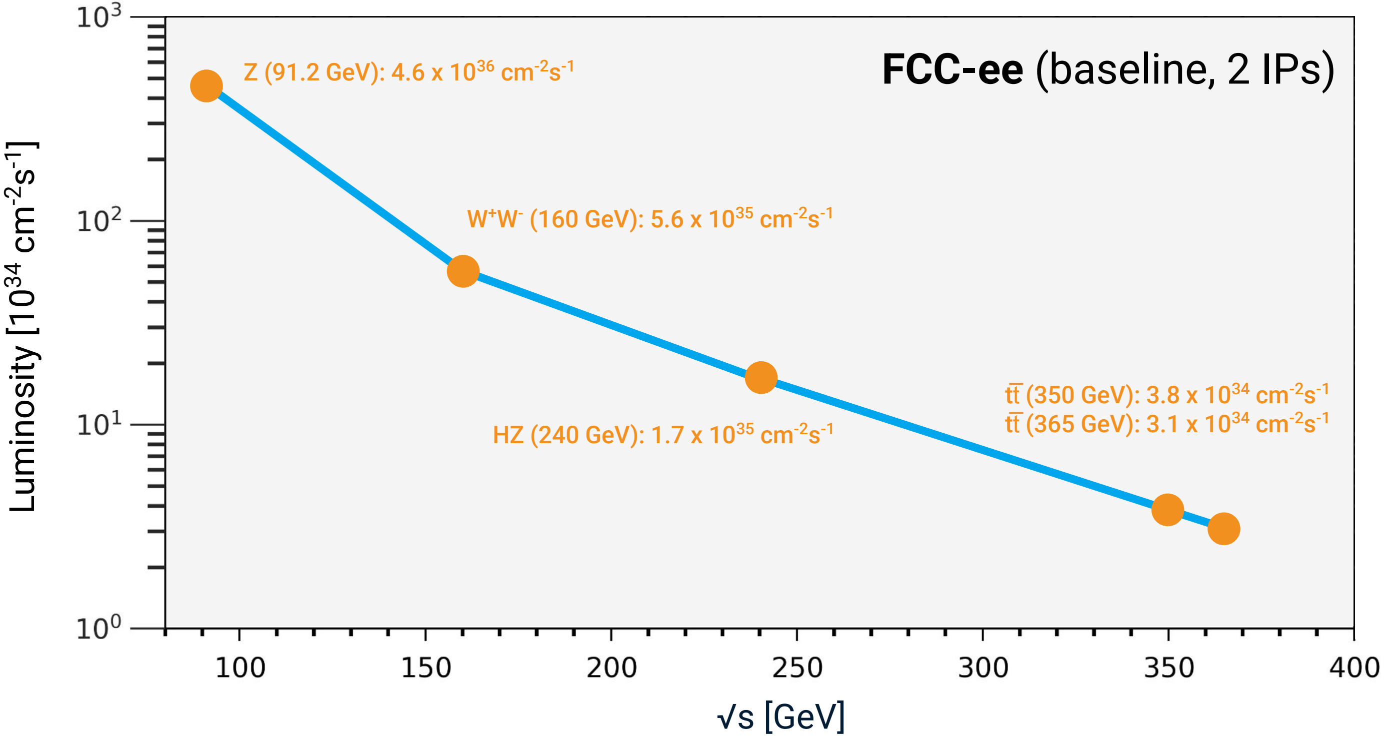
- The SM, while successful in many respects, fails to explain:
  - cosmological CP violation
  - baryon asymmetry
  - hierarchy problem
  - neutrino mass
  - gravity
  - dark energy
  - dark matter
- Yet, with no additional particles and only weak-scale couplings, the SM works remarkably well
- Where should we look next and what might we discover?

FCC-ee (Future Circular Lepton Collider)

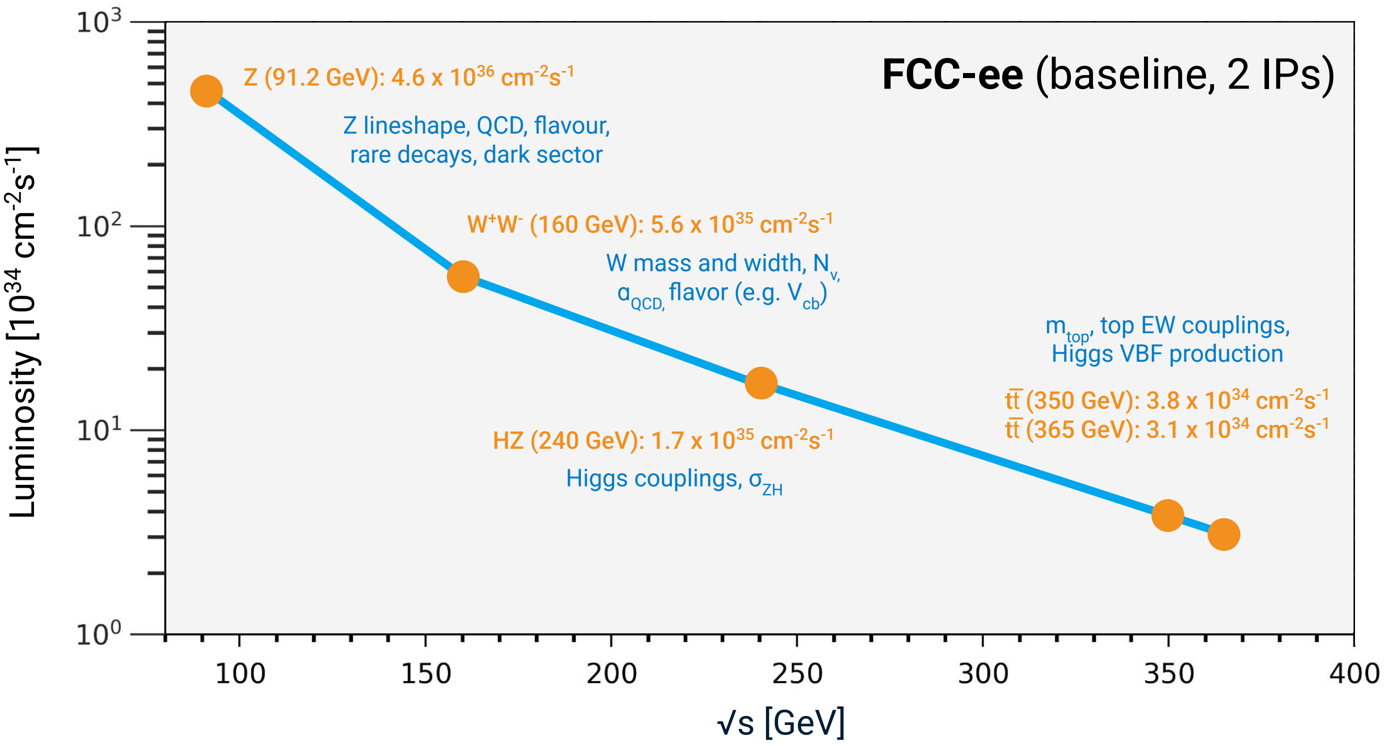
- First stage of FCC integrated project is e^+e^- collider
- Serve as Higgs factory, electroweak and top factory at highest luminosities



FCC-ee physics runs



FCC-ee physics runs. Highlights



DESY.

ALP Lagrangian

- ALP (a) couplings to the SM arise at dimension-5, described by an effective Lagrangian in the unbroken electroweak phase with a new physics scale Λ

[Georgi, Kaplan, Randall (1986)]

$$\mathcal{L}_{\mathrm{eff}}^{D\leq 5} = \underbrace{\frac{1}{2}(\partial_\mu a)(\partial^\mu a)}_{\text{kinetic term}} - \underbrace{\frac{m_a^2}{2}a^2}_{\text{mass term}} + \underbrace{\sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f}_{\text{derivative couplings to fermions}} + \underbrace{g_s^2 C_{GG}\frac{a}{\Lambda}G_{\mu\nu}^A\tilde{G}^{\mu\nu,A}}_{SU(3)_C\text{ gluons}} + \underbrace{g^2 C_{WW}\frac{a}{\Lambda}W_{\mu\nu}^A\tilde{W}^{\mu\nu,A}}_{SU(2)_L\text{ W gauge bosons}} + \underbrace{g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}}_{U(1)_Y\text{ hypercharge gauge bosons}}$$

- Additional interactions (Higgs interactions) arise at dimension-6 order and higher

$$\mathcal{L}_{\mathrm{eff}}^{D\geq 6} = \underbrace{\frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)\phi^\dagger\phi}_{h \to aa} + \underbrace{\frac{C_{Zh}}{\Lambda^3}(\partial^\mu a)\left(\phi^\dagger iD_\mu\phi + \text{ h.c. }\right)\phi^\dagger\phi}_{h \to Za} + \ldots$$

ALP Lagrangian cont.

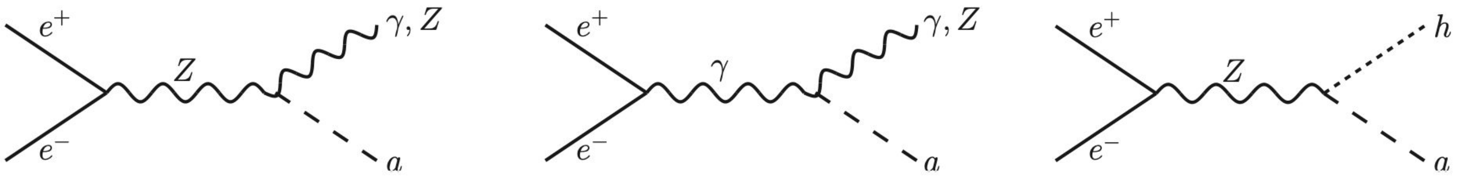
- In the electroweak symmetry-broken phase, the ALP interacts with the photon and Z boson through the following couplings:

$$\mathcal{L}_{\text{eff}} \ni e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$C_{\gamma\gamma} = C_{WW} + C_{BB} \qquad C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB} \qquad C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$$

- Following **Bauer, Neubert, Thamm** [1808.10323], we will assume ALP couples to hypercharge but not to $SU(2)_L$
- Thus, $C_{WW} = 0$ and $Br(a \to \gamma\gamma) = 1$

Differential cross sections



$$\frac{d\sigma(e^+e^- \to \gamma a)}{d\Omega} = 2\pi\alpha\alpha^2(s)\frac{s^2}{\Lambda^2}\left(1-\frac{m_a^2}{s}\right)^3 \left(1+\cos^2\theta\right)\left(|V_\gamma(s)|^2 + |A_\gamma(s)|^2\right), \tag{16}$$

$$\frac{d\sigma(e^+e^- \to Za)}{d\Omega} = 2\pi\alpha\alpha^2(s)\frac{s^2}{\Lambda^2}\lambda^{\frac{3}{2}}\left(x_a, x_Z\right)\left(1+\cos^2\theta\right)\left(|V_Z(s)|^2 + |A_Z(s)|^2\right), \tag{17}$$

$$\frac{d\sigma(e^+e^- \to ha)}{d\Omega} = \frac{\alpha}{128\pi\, c_w^2 s_w^2}\frac{|C_{Zh}^{\text{eff}}|^2}{\Lambda^2}\frac{s\, m_Z^2}{(s-m_Z^2)^2}\lambda^{\frac{3}{2}}\left(x_a, x_h\right)\sin^2\theta\left(g_V^2 + g_A^2\right), \tag{18}$$

$$V_\gamma(s) = \frac{C_{\gamma\gamma}^{\text{eff}}}{s} + \frac{g_V}{2c_w^2 s_w^2}\frac{C_{\gamma Z}^{\text{eff}}}{s-m_Z^2+im_Z\Gamma_Z}, \qquad A_\gamma(s) = \frac{g_A}{2c_w^2 s_w^2}\frac{C_{\gamma Z}^{\text{eff}}}{s-m_Z^2+im_Z\Gamma_Z}, \tag{19}$$

$$V_Z(s) = \frac{1}{c_w s_w}\frac{C_{\gamma Z}^{\text{eff}}}{s} + \frac{g_V}{2c_w^3 s_w^3}\frac{C_{ZZ}^{\text{eff}}}{s-m_Z^2+im_Z\Gamma_Z}, \qquad A_Z(s) = \frac{g_A}{2c_w^3 s_w^3}\frac{C_{ZZ}^{\text{eff}}}{s-m_Z^2+im_Z\Gamma_Z}, \tag{20}$$

UFO model testing

- **ALPnlo**
  - recently obtained from Bauer by Abu Dhabi colleagues, no known problem, except lack of phase space factors in decays into fermions

- **ALP**
  - obtained from Thamm in 2019, only works if mh is put high?

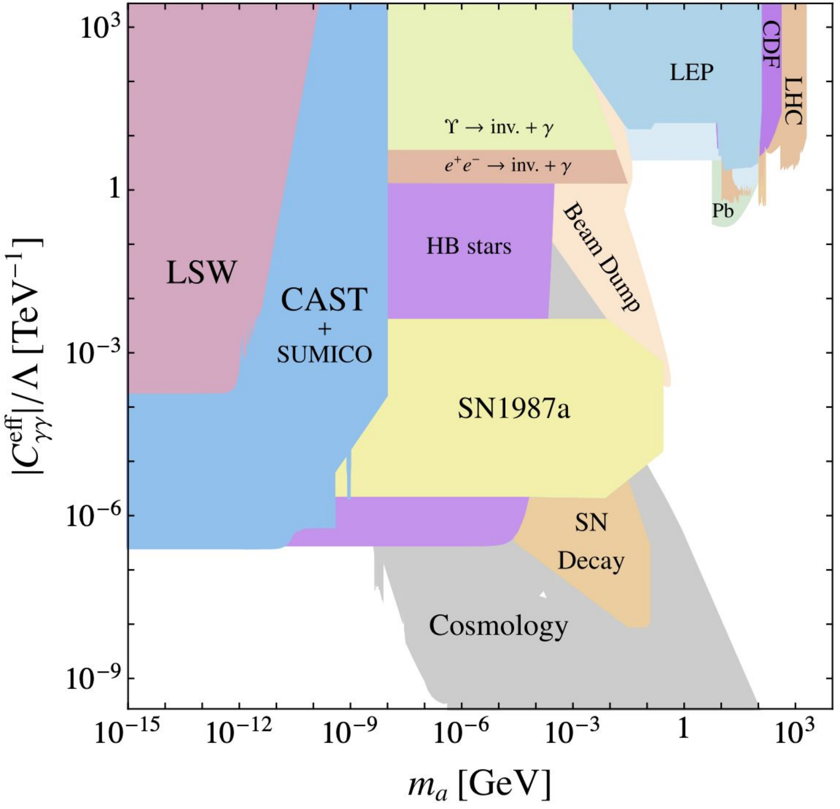
- **ALP_NLO_UFO**
  - used for Snowmass report, available in LLP git, seems to yield sensible results only for CWW=0

- **ALP_linear_UFO**
  - obtained from Brivio et al., uses different Lagrangian and requires conversion of parameters

See tests of models here (slides 46-52). Using ALP model moving forward

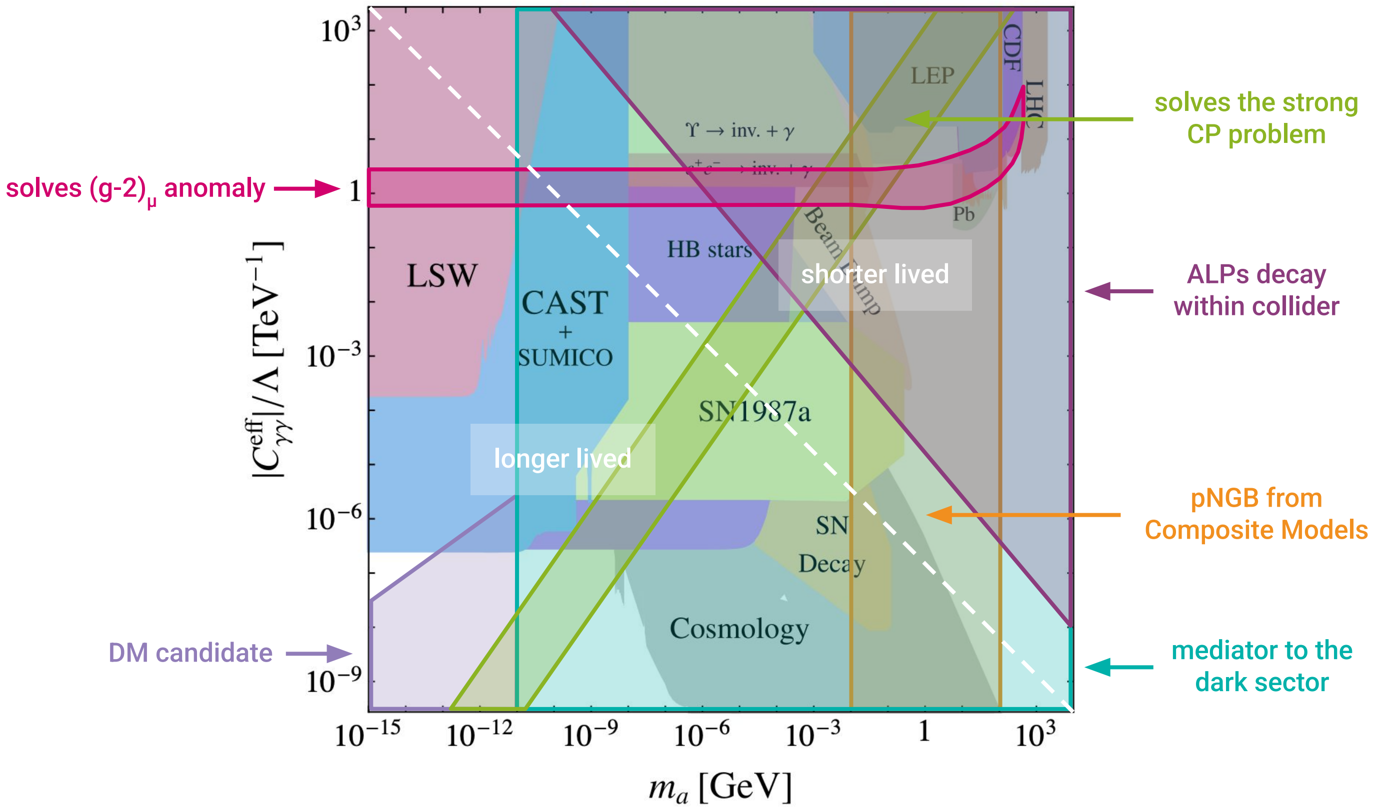
ALP Parameter Space

Adapted from [Thamm]

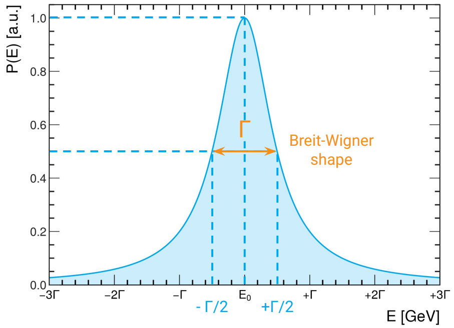


ALP Parameter Space cont.

Adapted from [Thamm]



Particle decay, width, and lifetime



- Two key quantities associated with decay process
  - decay width (**Γ**): measure of the rate of decay
  - lifetime (**τ**): average time that particle exists before it decays
- Quantities connected through the uncertainty principle

Uncertainty in energy (**ΔE**) and uncertainty in time (**Δt**) given by:	Uncertainty in **E** associated with **Γ** and uncertainty in **t** associated with **τ**	Rearranging the equation, find expression
$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$	$\Gamma \cdot \tau \geq \frac{\hbar}{2}$	$\tau \geq \frac{\hbar}{2\Gamma}$

- Inverse relationship between decay width and lifetime, sets a theoretical lower limit

$$\boxed{\tau = \frac{\hbar}{\Gamma}}$$

- In HEP, use natural units: Planck constant set to 1, speed of light set to 1
  - width in units of GeV (as opposed to inverse seconds) and lifetime in units of seconds

ALP lifetime

- From previous slide, lifetime is inverse of total decay width: $\tau = \frac{1}{\Gamma_{\text{total}}}$
- The branching ratio (BR) gives the fraction of particles decaying into a specific final state: $\mathrm{BR}_i = \frac{\Gamma_i}{\Gamma_{\text{total}}}$
- In this analysis, we assume the ALP only couples to photons, which implies: $\mathrm{BR}(\mathrm{a} \to \gamma\gamma) = 1$
- This further implies that: $\Gamma_i = \Gamma_{\text{total}}$
- Hence, the ALP lifetime is given by: $\tau = \frac{1}{\Gamma_{\text{total}}} = \frac{1}{\Gamma(\mathrm{a} \to \gamma\gamma)}$

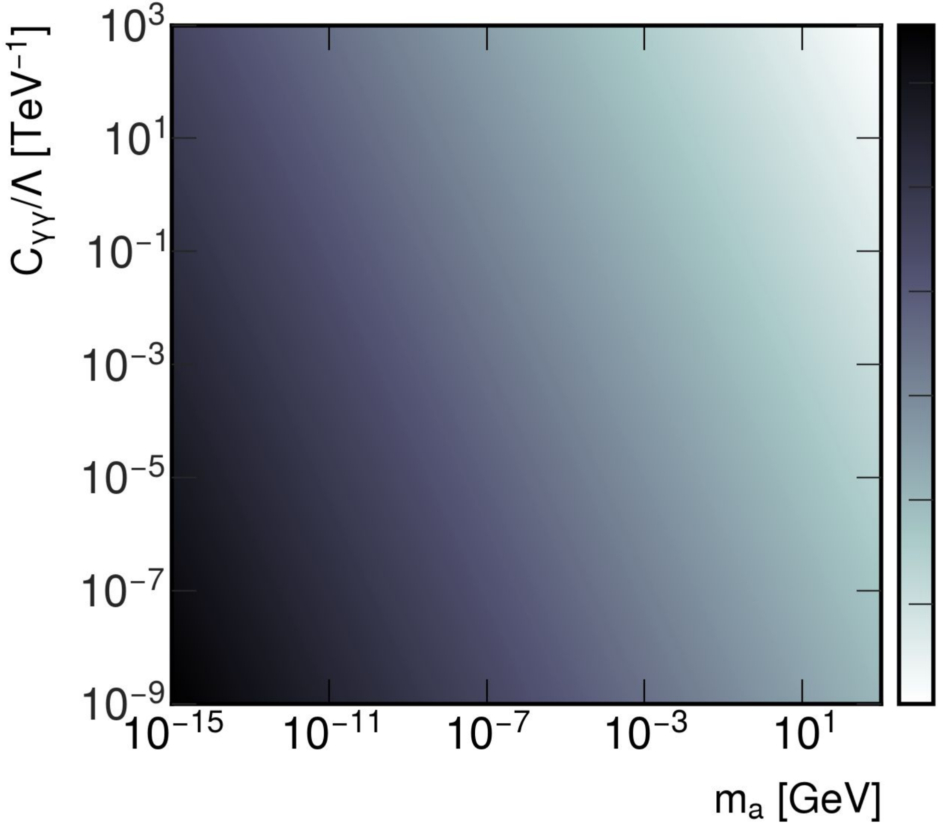
ALP decay width from **Bauer, Neubert, Thamm** [1808.10323]

$$\Gamma(a \to \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma}^{\text{eff}} \right|^2$$

Derived ALP lifetime (see above)

$$\tau = \frac{1}{\Gamma(a \to \gamma\gamma)} = \frac{\Lambda^2}{4\pi\alpha^2 m_a^3 \left| C_{\gamma\gamma}^{\text{eff}} \right|^2}$$

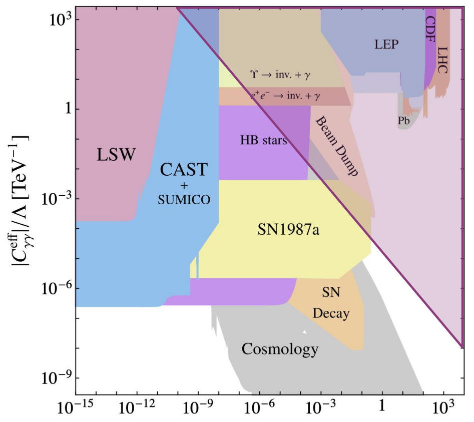
ALP lifetime (cont.) add z axis scale/units!

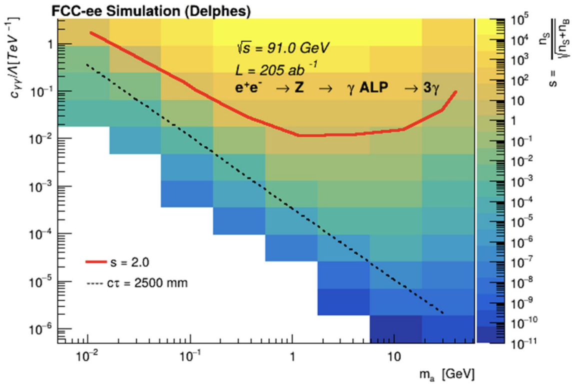


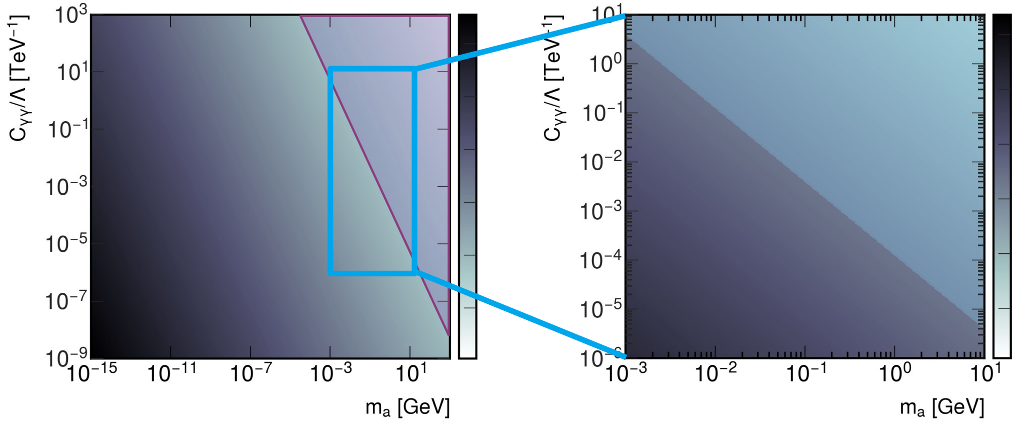
DESY.

ALP lifetime (cont.)

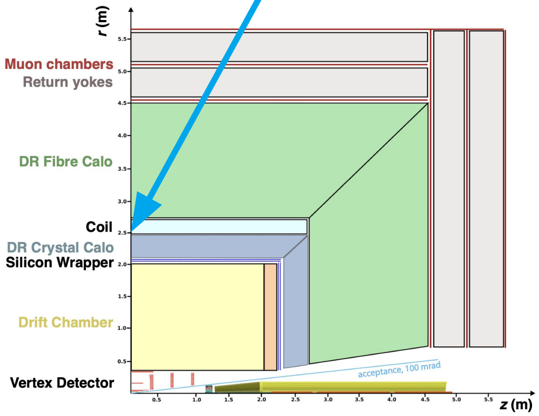
Adapted from Thamm





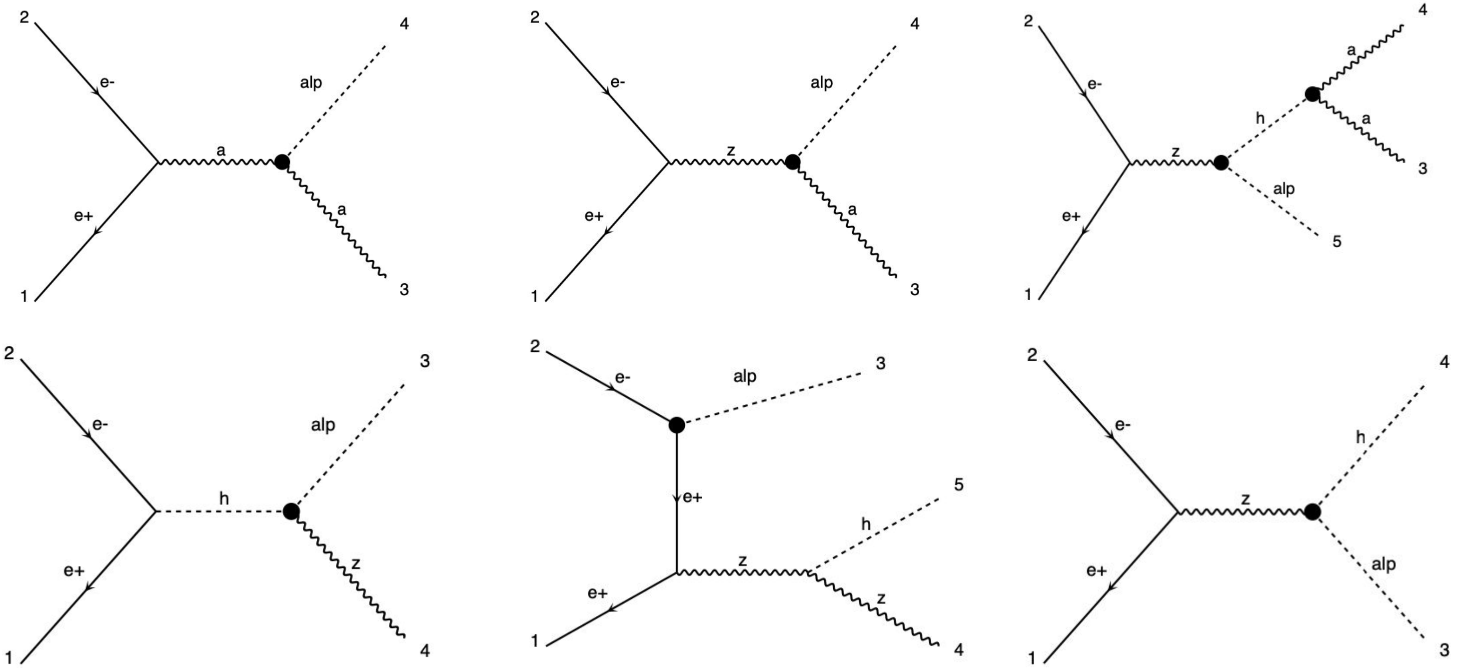


proper decay length of 2500 mm for the particle to correspond to inner part of the calorimeter



ALP production

- Example Feynman diagrams for possible processes



ALP cross sections

- Running **MadGraph5_aMC@NLO** ALP model: 1 event, $C_{WW} = 0$, $C_{\gamma\gamma} = C_{BB} = 1$, $m_a = 1$ GeV
- Dash (–) denotes no available phase space at that energy

$C_{\gamma\gamma}$ coupling only
$C_{\gamma\gamma} = 1$ →

Process	$\sqrt{s} = 9.119 \times 10^1$ GeV	1.600×10^2 GeV	2.400×10^2 GeV	3.650×10^2 GeV
$e^+e^- \to a\gamma$	2.471	2.212×10^{-2}	2.082×10^{-2}	2.051×10^{-2}
$e^+e^- \to a\gamma\gamma$	2.385×10^{-4}	1.645×10^{-3}	9.902×10^{-4}	9.210×10^{-4}
$e^+e^- \to aZ$	–	2.078×10^{-3}	3.879×10^{-3}	4.980×10^{-3}
$e^+e^- \to aZZ$	–	–	4.849×10^{-7}	5.376×10^{-6}
$e^+e^- \to aZH$	–	–	3.214×10^{-9}	2.247×10^{-7}
$e^+e^- \to a\gamma H$	–	2.752×10^{-10}	9.537×10^{-6}	4.975×10^{-6}

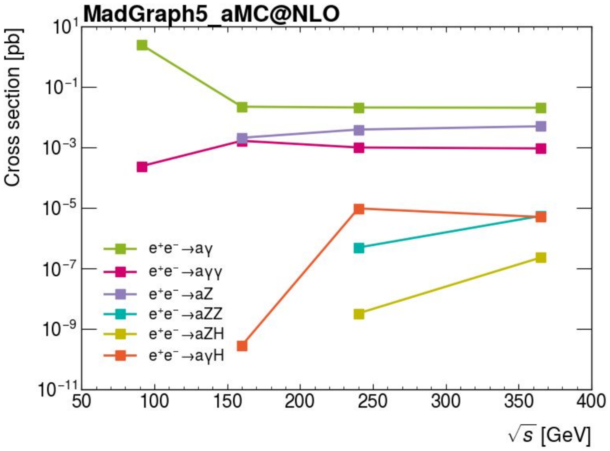
$C_{\gamma\gamma}$ and C_{aH} coupling
$C_{\gamma\gamma} = 1$, $C_{aH} = 1.34$ →

Process	$\sqrt{s} = 9.119 \times 10^1$ GeV	1.600×10^2 GeV	2.400×10^2 GeV	3.650×10^2 GeV
$e^+e^- \to aZZ$	–	–	4.847×10^{-7}	5.308×10^{-6}
$e^+e^- \to aZH$	–	–	3.187×10^{-9}	2.058×10^{-7}
$e^+e^- \to a\gamma H$	–	3.096×10^{-10}	9.524×10^{-6}	5.037×10^{-6}

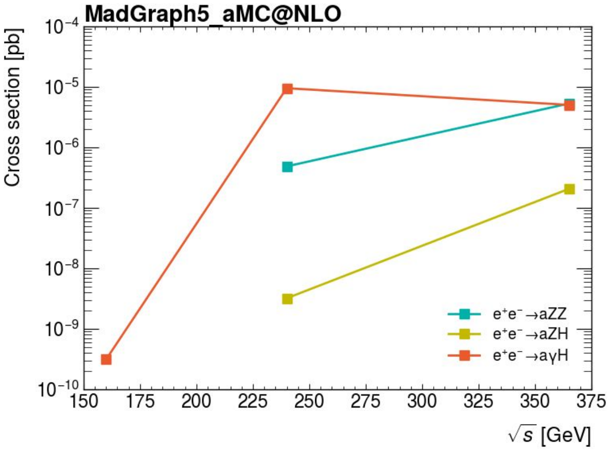
$C_{\gamma\gamma}$ and C_{ZH} coupling
$C_{\gamma\gamma} = 1$, $C_{ZH} = 0.72$ →

Process	$\sqrt{s} = 9.119 \times 10^1$ GeV	1.600×10^2 GeV	2.400×10^2 GeV	3.650×10^2 GeV
$e^+e^- \to aZ$	–	2.077×10^{-3}	3.874×10^{-3}	4.979×10^{-3}
$e^+e^- \to aZZ$	–	–	8.010×10^{-2}	3.916×10^{-2}
$e^+e^- \to aH$	–	1.937×10^{-3}	3.522×10^{-3}	2.256×10^{-3}
$e^+e^- \to aZH$	–	–	6.589×10^{-8}	4.357×10^{-6}
$e^+e^- \to a\gamma H$	–	4.284×10^{-6}	8.516×10^{-5}	1.063×10^{-4}

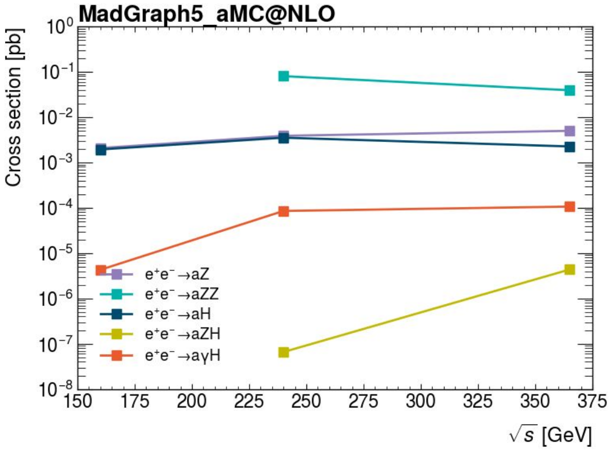
ALP cross sections



$C_{\gamma\gamma}$ coupling only
$C_{\gamma\gamma} = 1$

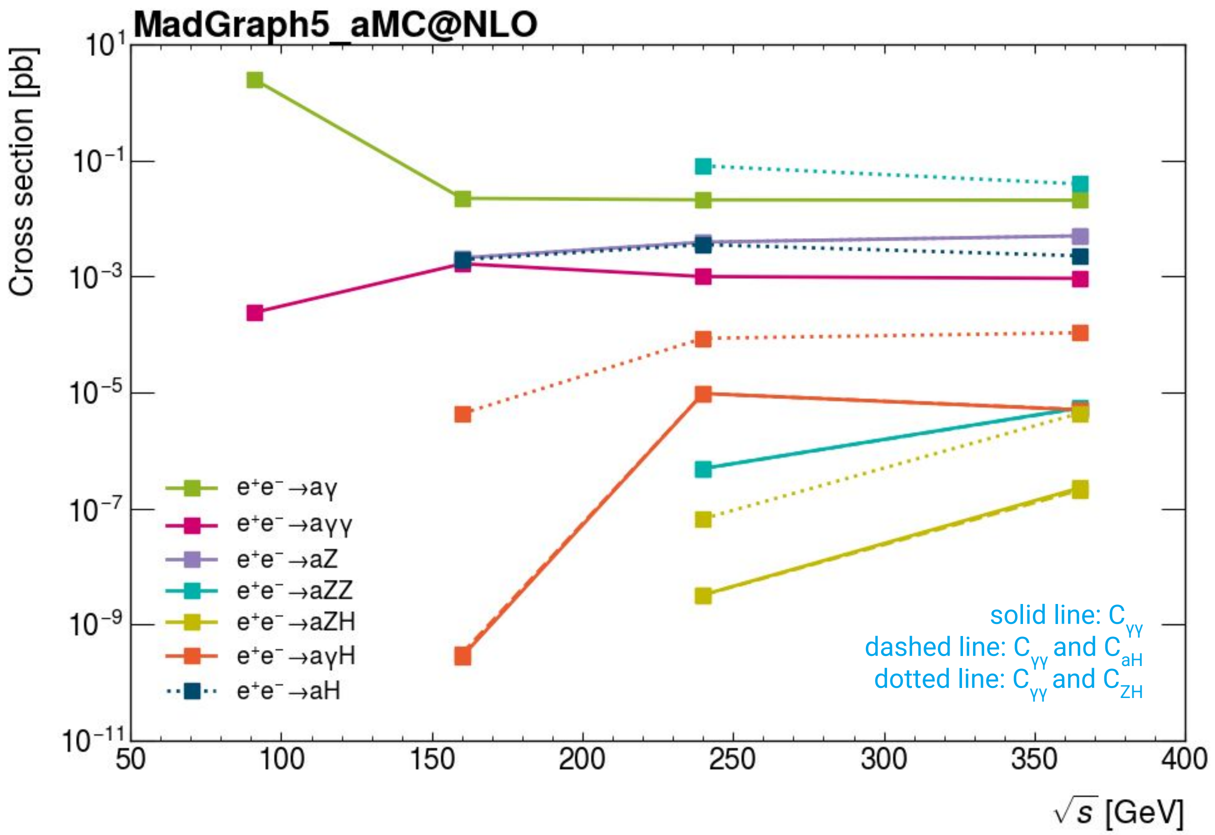


$C_{\gamma\gamma}$ and C_{aH} coupling
$C_{\gamma\gamma} = 1$, $C_{aH} = 1.34$



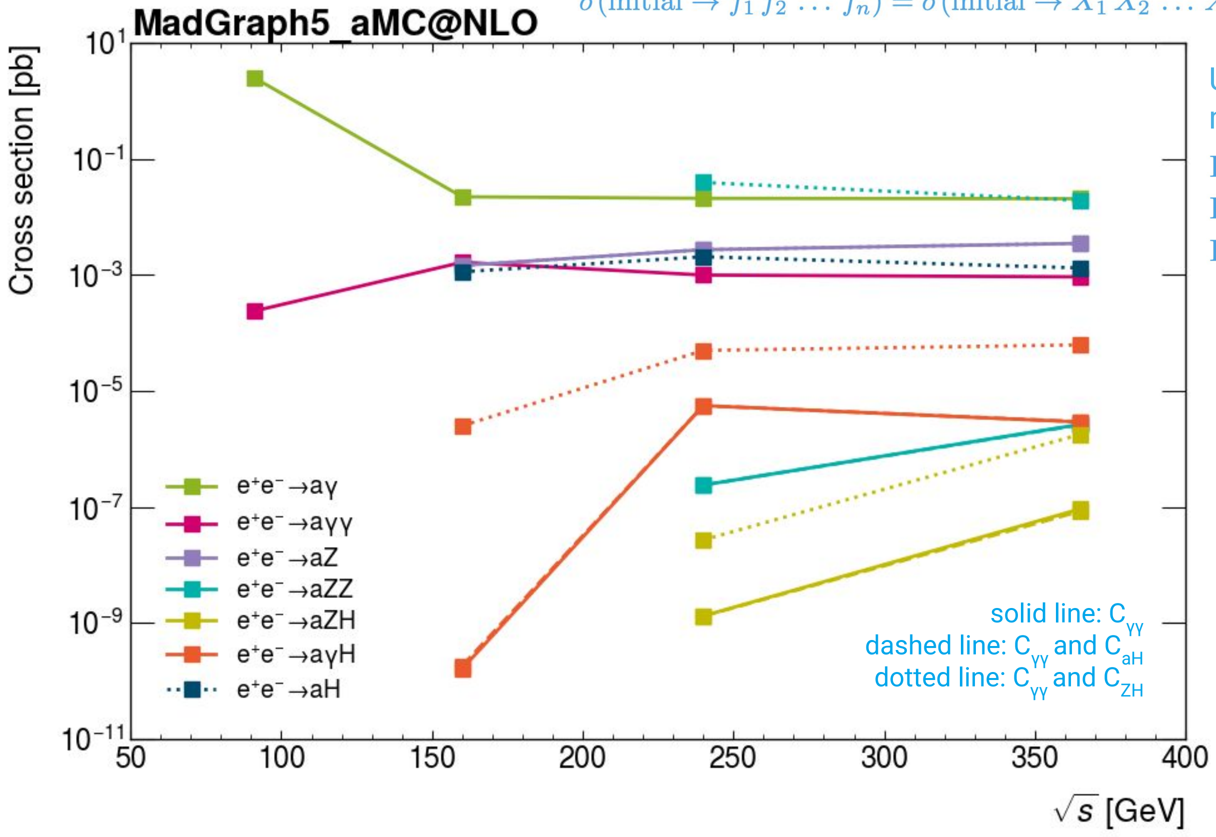
$C_{\gamma\gamma}$ and C_{ZH} coupling
$C_{\gamma\gamma} = 1$, $C_{ZH} = 0.72$

ALP cross sections



ALP cross sections

$$\sigma(\text{initial} \to f_1\, f_2\, \ldots\, f_n) = \sigma(\text{initial} \to X_1\, X_2\, \ldots\, X_n) \times \prod_{i=1}^{n} \text{BR}(X_i \to f_i)$$



Using following decay modes:

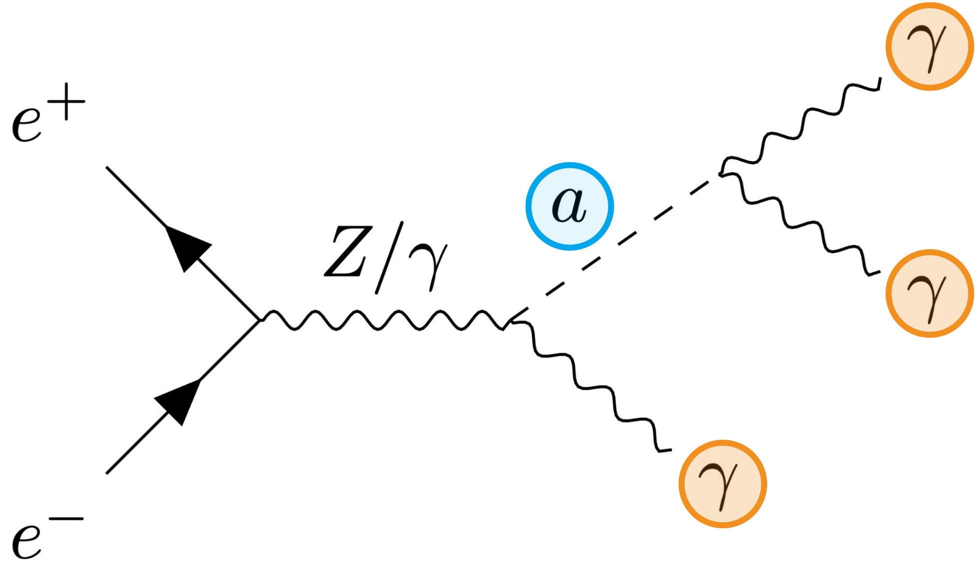
$\text{BR}(a \to \gamma\gamma) = 1.$

$\text{BR}(\text{Z} \to \text{hadrons}) = 0.699$

$\text{BR}(\text{H} \to b\bar{b}) = 0.582$

ALP signature

- Cross sections from previous slide motivate three photon channel, even at higher center-of-mass energies
- See enhancement in cross section at Z-pole, but process is still dominant at higher √s



Background cross sections

- As a cross-check, will initially only consider backgrounds from Z-pole study
- Results differ a bit from Elnura's cross sections. Different run_card.dat parameters?

Process	Elnura	$\sqrt{s} = 91.188$ GeV	160 GeV	240 GeV	365 GeV
$e^+e^- \to \gamma\gamma$	6.725×10^1	5.741×10^1	2.191×10^1	9.713	4.194
$e^+e^- \to \gamma\gamma\gamma$	2.995	4.629×10^{-1}	4.219×10^{-1}	2.777×10^{-1}	1.622×10^{-1}
$e^+e^- \to \gamma\gamma\gamma\gamma$	6.271×10^{-2}	1.124×10^{-3}	3.102×10^{-3}	3.453×10^{-3}	2.844×10^{-3}
$e^+e^- \to e^+e^-$	4.500×10^3	4.527×10^3	1.513×10^3	6.718×10^2	2.941×10^2
$e^+e^- \to e^+e^-\gamma$	1.184×10^2	2.989×10^1	9.478	7.284	4.583
$e^+e^- \to e^+e^-\gamma\gamma$	1.993	9.706×10^{-2}	7.171×10^{-2}	7.039×10^{-2}	5.642×10^{-2}
$e^+e^- \to e^+e^-\gamma\gamma\gamma$	2.369×10^{-2}	1.095×10^{-4}	4.285×10^{-4}	6.023×10^{-4}	6.255×10^{-4}

Background cross sections

- Indeed. Now we apply different cut selections to the processing card itself
- Cuts to pT of the photons, cut on ΔR, and cut on η (which is kept the same)
  - photon pT > 2 GeV, ΔR > 0.01, |η| < 2.5

```
set pta 2.0
set draa 0.01
set etaa 2.5
```

Process	Elnura	$\sqrt{s} = 91.188$ GeV	160 GeV	240 GeV	365 GeV
$e^+e^- \to \gamma\gamma$	6.725×10^1	6.725×10^1	2.183×10^1	9.672	4.198
$e^+e^- \to \gamma\gamma\gamma$	2.995	2.942	1.236	6.362×10^{-1}	3.332×10^{-1}
$e^+e^- \to \gamma\gamma\gamma\gamma$	6.271×10^{-2}	5.960×10^{-2}	3.382×10^{-2}	2.221×10^{-2}	1.206×10^{-2}
$e^+e^- \to e^+e^-$	4.500×10^3	4.547×10^3	1.525×10^3	6.648×10^2	2.940×10^2
$e^+e^- \to e^+e^-\gamma$	1.184×10^2	1.183×10^2	3.092×10^1	1.758×10^1	9.017
$e^+e^- \to e^+e^-\gamma\gamma$	1.993	1.966	5.867×10^{-1}	3.772×10^{-1}	2.253×10^{-1}
$e^+e^- \to e^+e^-\gamma\gamma\gamma$	2.369×10^{-2}	2.309×10^{-2}	1.149×10^{-2}	7.725×10^{-3}	4.996×10^{-3}

Background cross sections

- Cuts to pT of the photons, cut on ΔR, and cut on η (which is kept the same)
  - photon E > 0.1, photon pT > 0, , |η| < 2.6, ΔR > 0

set ea 0.1
set pta 0
set etaa 2.6
set draa 0

Process	$\sqrt{s} = 91.188$ GeV	160 GeV	240 GeV	365 GeV
$e^+e^- \to \gamma\gamma$	5.741×10^{1}	2.191×10^{1}	9.713	4.194
$e^+e^- \to \gamma\gamma\gamma$	4.629×10^{-1}	4.219×10^{-1}	2.777×10^{-1}	1.622×10^{-1}
$e^+e^- \to \gamma\gamma\gamma\gamma$	1.124×10^{-3}	3.102×10^{-3}	3.453×10^{-3}	2.844×10^{-3}
$e^+e^- \to e^+e^-$	4.527×10^{3}	1.513×10^{3}	6.718×10^{2}	2.941×10^{2}
$e^+e^- \to e^+e^-\gamma$	2.989×10^{1}	9.478	7.284	4.583
$e^+e^- \to e^+e^-\gamma\gamma$	9.706×10^{-2}	7.171×10^{-2}	7.039×10^{-2}	5.642×10^{-2}
$e^+e^- \to e^+e^-\gamma\gamma\gamma$	1.095×10^{-4}	4.285×10^{-4}	6.023×10^{-4}	6.255×10^{-4}

Process	$\sqrt{s} = 91.188$ GeV	160 GeV	240 GeV	365 GeV
$e^+e^- \to \gamma\gamma$	7.054×10^{1}	2.289×10^{1}	1.018×10^{1}	4.408
$e^+e^- \to \gamma\gamma\gamma$	9.020	3.083	1.427	6.656×10^{-1}
$e^+e^- \to \gamma\gamma\gamma\gamma$	5.752×10^{-1}	2.063×10^{-1}	1.037×10^{-1}	6.603×10^{-2}
$e^+e^- \to e^+e^-$	4.547×10^{3}	1.525×10^{3}	6.648×10^{2}	2.900×10^{2}
$e^+e^- \to e^+e^-\gamma$	4.641×10^{2}	8.423×10^{1}	4.022×10^{1}	1.786×10^{1}
$e^+e^- \to e^+e^-\gamma\gamma$	2.711×10^{1}	3.329	1.813	8.696×10^{-1}
$e^+e^- \to e^+e^-\gamma\gamma\gamma$	1.378	1.318×10^{-1}	7.332×10^{-2}	3.751×10^{-2}

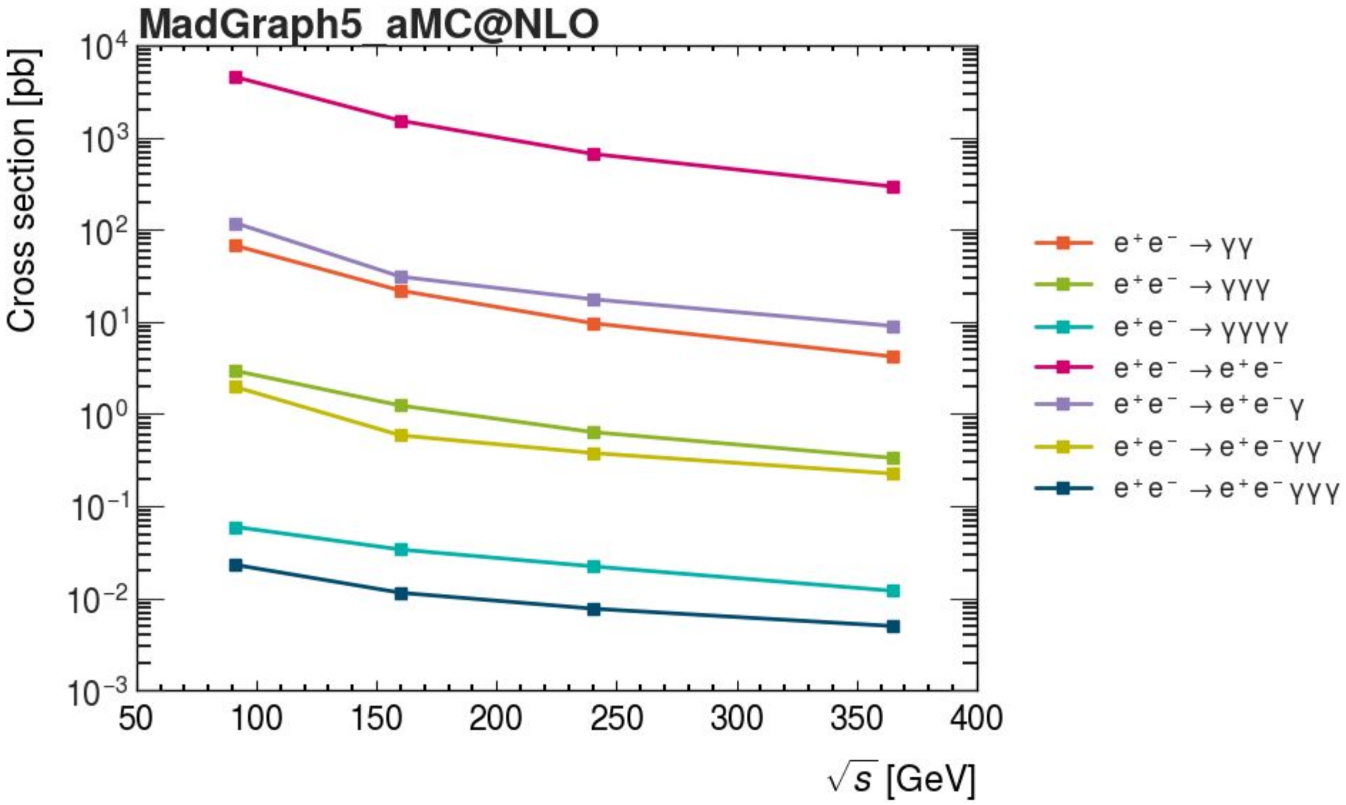
Cuts applied to signal

- Cuts to pT of the photons, cut on ΔR, and cut on η (which is kept the same)
  - photon E > 0.1, photon pT > 0, , |η| < 2.6, ΔR > 0

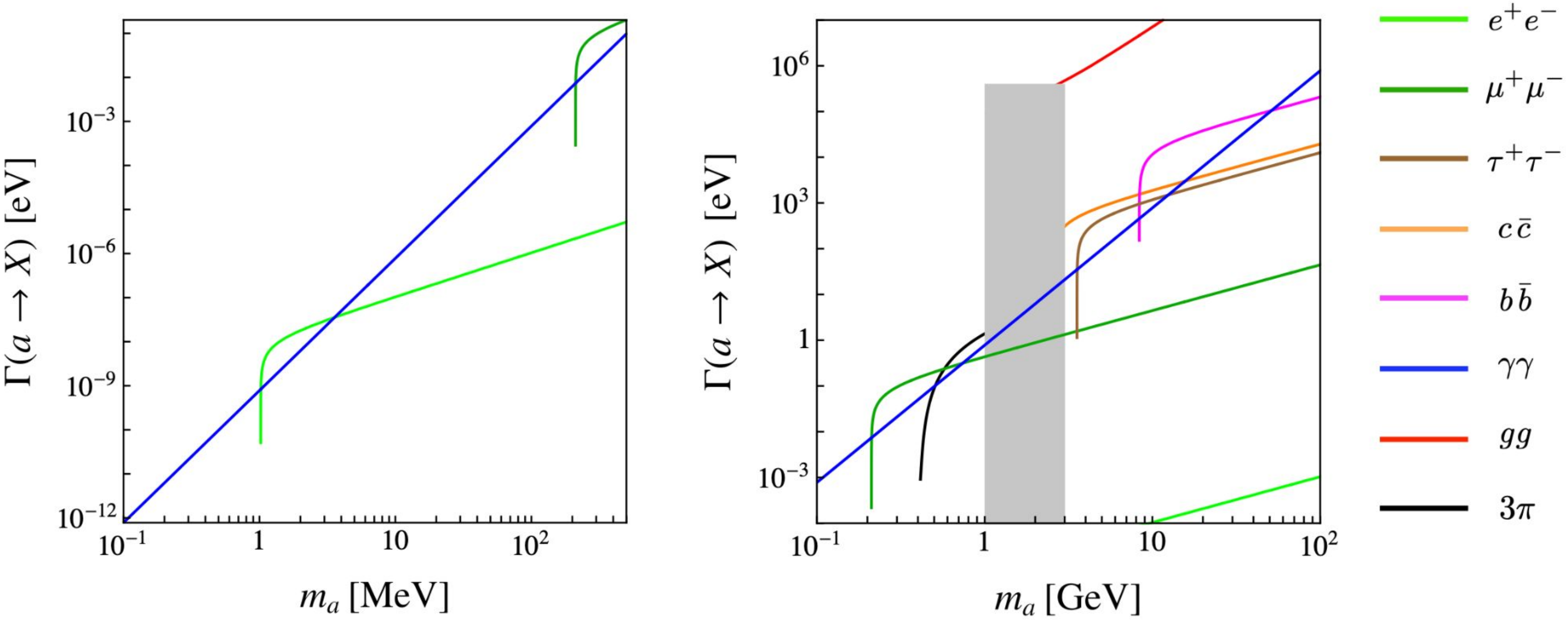
```
set ea 0.1
set pta 0
set etaa 2.6
set draa 0
```

Cuts	Process	$\sqrt{s} = 91.188$ GeV	160 GeV	240 GeV	365 GeV
No cuts	$e^+e^- \to a\gamma,\ a \to \gamma\gamma$	2.421	2.166×10^{-2}	2.037×10^{-2}	2.017×10^{-2}
With cuts	$e^+e^- \to a\gamma,\ a \to \gamma\gamma$	2.463	2.172×10^{-2}	2.045×10^{-2}	2.011×10^{-2}

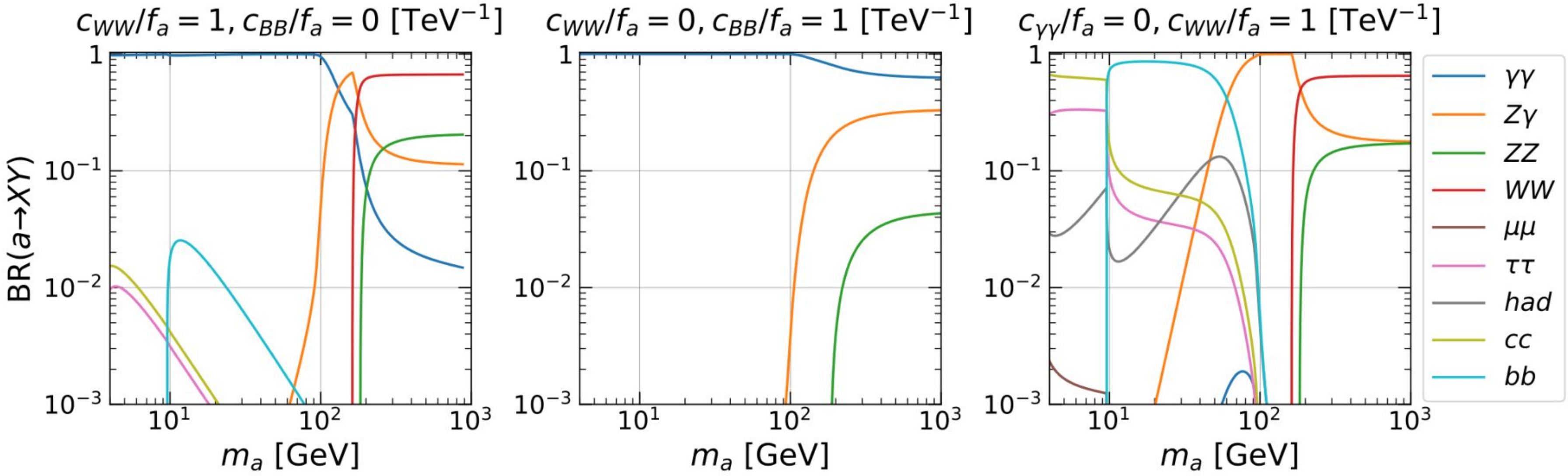
Background cross sections



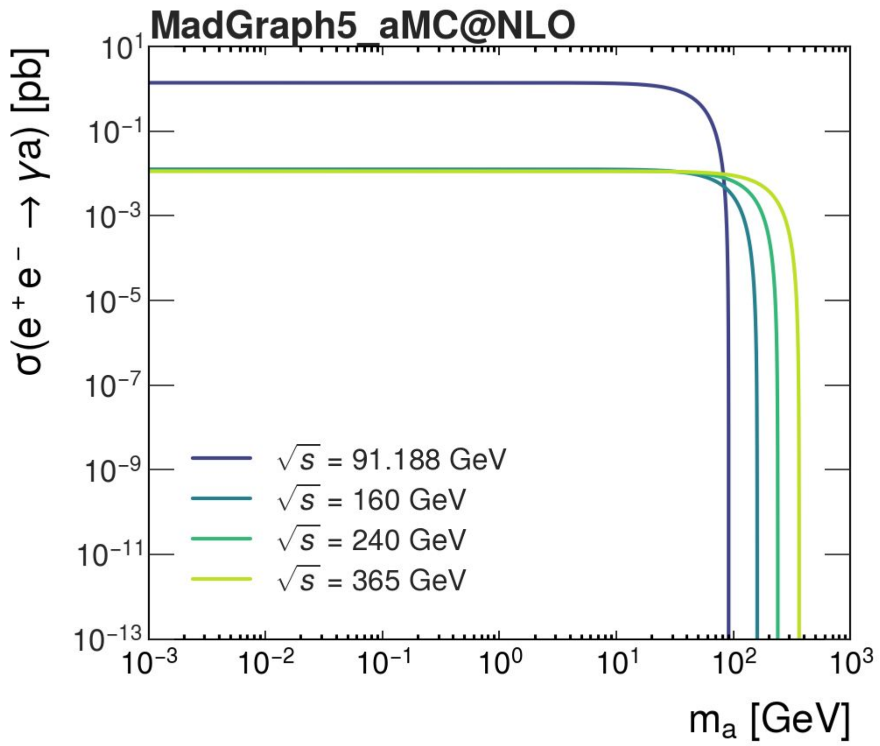
ALP decay modes

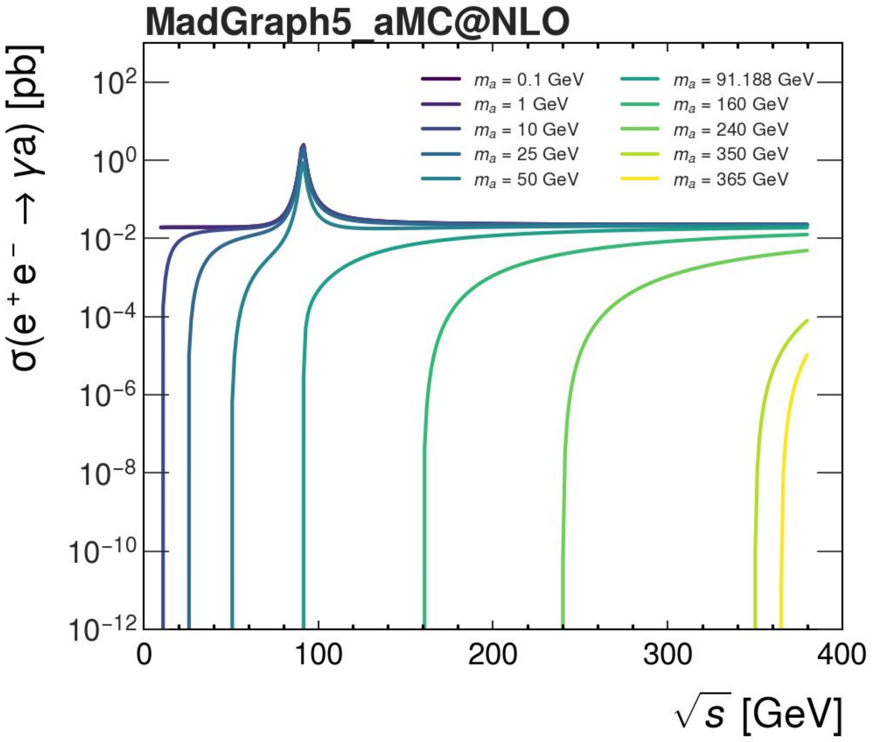


ALP decay modes



Cross sections





Effects on sensitivity at low mass

- Distance between two showers (if smaller than Moliére radius of calo, then showers are not separated)
    - Two photons seen as one or additional uncertainty on mass measurements from uncertainty on energy sharing of clusters
- Impact of long lifetime of ALP on kinematics measurements
    - Mass reco algorithm assumes ALP decays in center of detector (doesn't take into account displaced vertices)
    - Wrong angle used in invariant mass calculation

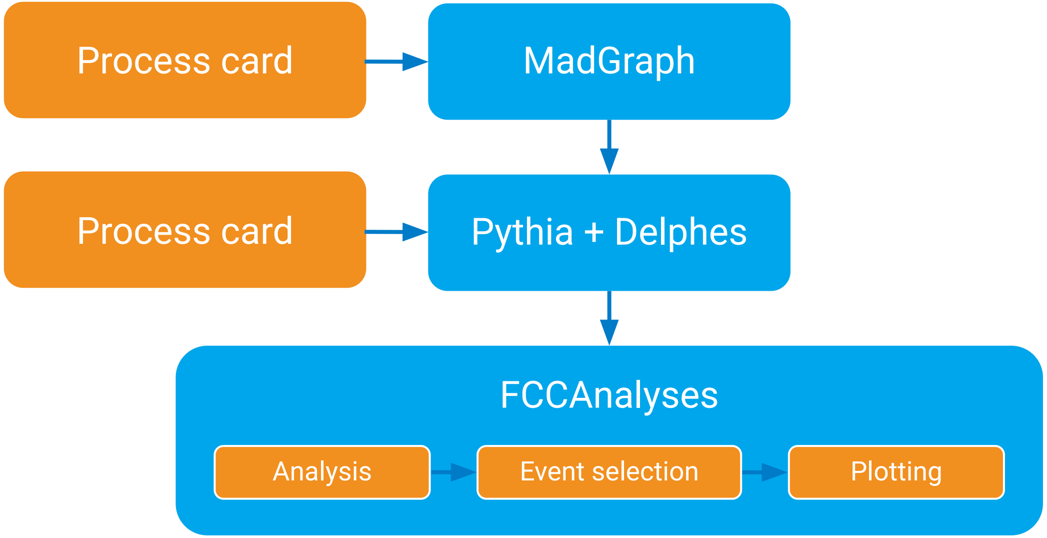
- What else might contribute at higher center of mass energy?

MadGraph vs. WHIZARD?

- MadGraph doesn't implement ISR, beamstrahlung and beam spectra properly → makes WHIZARD interesting as it accounts for beam effects
  - Beam spectrum files: https://whizard.hepforge.org/circe_files/FCCee/
- According to some sources, MadGraph and WHIZARD are in good agreement at LO but there are differences at NLO
- WHIZARD also supports UFO format, so was able to add ALP model
  - Still figuring out coupling and how to apply cuts
  - How to compare WHIZARD output to MadGraph?

Sample generation

- Using MadGraph5_aMC@NLO + Pythia + Delphes



Delphes cards

- Could be interesting to explore different detector configurations/geometries, but maybe only consider this if we have time…

FCC-config / FCCee / Delphes /

Add file

portalesHEP updated IDEA delphes card × 095c442 · last month History

This branch is 560 commits ahead of, 106 commits behind main.

Name	Last commit message	Last co...
..		
card_IDEA.tcl	Removed UnstableParticlePropagator from the delphes card - caused pro...	3 years ago
card_IDEA_3T.tcl	Delphes card, IDEA 3T	11 months ag
card_IDEA_SiTracking.tcl	add IDEA card with CLD Si tracking	last year
card_IDEA_better_TOFReso_3ps.tcl	Adding new Delphes cards for det config studies to be included in Fin...	last year
card_IDEA_better_singlehitReso_30pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_better_singlehitReso_30pc_lighterVXD_35pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_better_singlehitReso_30pc_lighterVXD_50pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_better_singlehitReso_65pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_better_singlehitReso_65pc_lighterVXD_75pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_heavierBP_100pc.tcl	Adding new Delphes cards for det config studies to be included in Fin...	last year
card_IDEA_lighterBP_50pc.tcl	Fixing all Delphes cards to new setpoints (WIP align endcaps for the ...	last year
card_IDEA_lighterVXD_35pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_lighterVXD_50pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_lighterVXD_50pc_lighterBP_50pc.tcl	Added alternative delphes card for tests, with lighter VXD layers AND...	last year
card_IDEA_lighterVXD_75pc.tcl	Added IDEA cards with variations of the VXD detector, for the KstarTa...	2 years ago
card_IDEA_shiftVXDr_plus500um.tcl	Adjust endcaps' max radius to keep geometrical acceptance after shift...	last year
card_IDEA_updated.tcl	updated IDEA delphes card	last month
card_IDEA_worse_HCalEReso_ATLAS.tcl	degraded E/HCal resolution cards update	10 months ag
card_IDEA_worse_HCalEReso_CMS.tcl	degraded E/HCal resolution cards update	10 months ag
card_IDEA_worse_singlehitReso_100pc_heavierVTXLOW_100pc.tcl	Fixing all Delphes cards to new setpoints (WIP align endcaps for the ...	last year
edm4hep_IDEA.tcl	Updates delphes card and edm4hep.card for winter2023	3 years ago
edm4hep_IDEA_3T.tcl	Delphes card, IDEA 3T	11 months ag
edm4hep_IDEA_SiTracking.tcl	Add edm4hep_IDEA_SiTracking.tcl for Delphes simulations of IDEA with ...	last year
edm4hep_IDEA_better_TOFReso_3ps.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_heavierBP_100pc.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_lighterBP_50pc.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_shiftVXDr_plus500um.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_updated.tcl	updated IDEA delphes card	last month
edm4hep_IDEA_worse_HCalEReso_ATLAS.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_worse_HCalEReso_CMS.tcl	edm4hep files for new delphes cards	last year
edm4hep_IDEA_worse_singlehitReso_100pc_heavierVTXLOW_100pc.tcl	edm4hep files for new delphes cards	last year

MadGraph scaling with # of events

91.188
set ea 0.1
set pta 0
set etaa 2.6
set draa 0

	1 event	10 events	100 events	1000 events
e+e- > aa	70.54 +- 0.1523 pb 9.41s user 2.74s system 218% cpu 5.559 total	70.54 +- 0.1523 pb 9.42s user 2.99s system 202% cpu 6.118 total	70.54 +- 0.1523 pb 9.15s user 3.22s system 190% cpu 6.477 total	70.64 +- 0.08462 pb 9.60s user 3.42s system 162% cpu 8.013 total
e+e- > aaa	9.02 +- 0.2395 pb 9.81s user 2.88s system 215% cpu 5.901 total	9.02 +- 0.2395 pb 9.64s user 2.97s system 206% cpu 6.111 total	9.02 +- 0.2395 pb 9.60s user 2.66s system 211% cpu 5.782 total	9.462 +- 0.06858 pb 11.88s user 3.21s system 189% cpu 7.968 total
e+e- > aaaa	0.5752 +- 0.03925 pb 10.61s user 3.20s system 193% cpu 7.152 total	0.5752 +- 0.03925 pb 10.55s user 2.68s system 201% cpu 6.580 total	0.5392 +- 0.02421 pb 14.43s user 2.81s system 159% cpu 10.812 total	0.6491 +- 0.004412 pb 39.41s user 2.90s system 161% cpu 26.272 total
e+e- > e+e-	4547 +- 18.55 pb 11.97s user 3.01s system 192% cpu 7.764 total	4547 +- 18.55 pb 11.84s user 3.50s system 171% cpu 8.952 total	4547 +- 18.55 pb 12.02s user 3.54s system 186% cpu 8.328 total	4494 +- 8.779 pb 12.08s user 3.11s system 180% cpu 8.408 total
e+e- > e+e-a	464.1 +- 6.365 pb 15.88s user 3.35s system 188% cpu 10.214 total	464.1 +- 6.365 pb 15.85s user 3.37s system 195% cpu 9.841 total	464.1 +- 6.365 pb 15.69s user 3.89s system 176% cpu 11.102 total	462 +- 3.65 pb 16.60s user 3.52s system 186% cpu 10.797 total
e+e- > e+e-aa	27.11 +- 0.6792 pb 43.73s user 3.99s system 334% cpu 14.288 total	27.11 +- 0.6792 pb 43.36s user 4.34s system 331% cpu 14.401 total	27.68 +- 0.5176 pb 48.84s user 4.67s system 276% cpu 19.390 total	28.3 +- 0.2504 pb **events : 376** 166.33s user 5.12s system 145% cpu 1:57.80 total
e+e- > e+e-aaa	1.378 +- 0.049 pb 604.12s user 6.91s system 501% cpu 2:01.72 total	1.378 +- 0.049 pb 602.38s user 6.49s system 510% cpu 1:59.28 total	1.382 +- 0.03908 pb 638.35s user 8.10s system 421% cpu 2:33.50 total	1.466 +- 0.01324 pb **events : 277** 2746.21s user 15.85s system 247% cpu 18:34.18 total