Theoretical studies for FCC-ee

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(LPTHE)

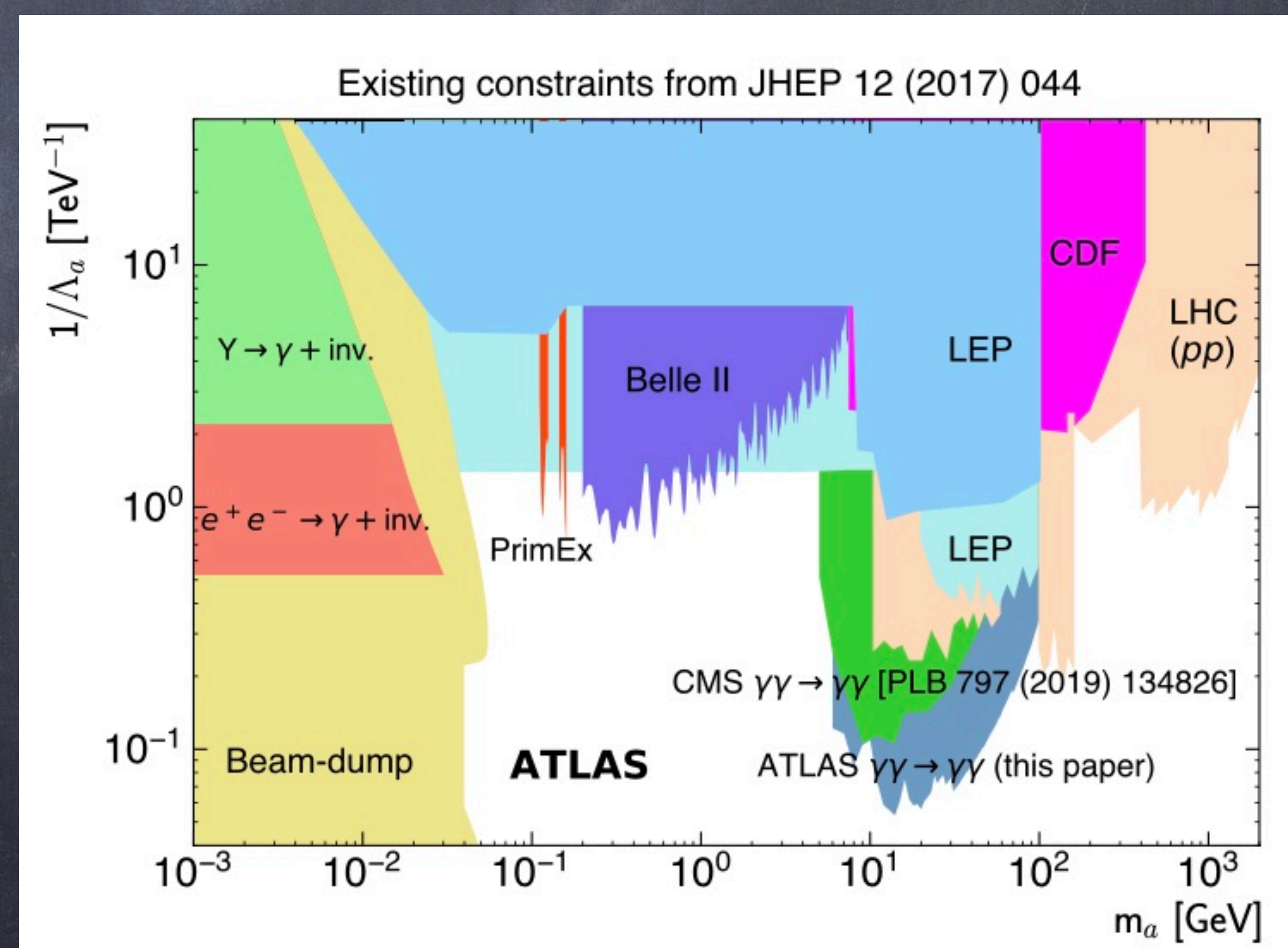
5th FCC/DRD France workshop
Paris, November 2025

Outlook

- Main effort in France from Aldo Deandrea and myself (as far as I know)
- Composite Higgs models offer a natural physics case for the FCC programme
- Case study 1: Axion-Like Particles can be directly produced
- Case study 2: indirect probes via Higgs and EW precision measurements
- Case study 3: high energy probes (beyond e+e-)

Axion-Like Particles

- ALPs arise from spontaneously broken global symmetries, not related to QCD.
- Predicted by many BSM models.



Caveat: bounds and searches are not model-independent!

Here, assumed 'only' coupling to photons…

Typical ALP Lagrangian:

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$

$$+\, g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde G^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + g'^{\,2}\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde B^{\mu\nu}\,,$$

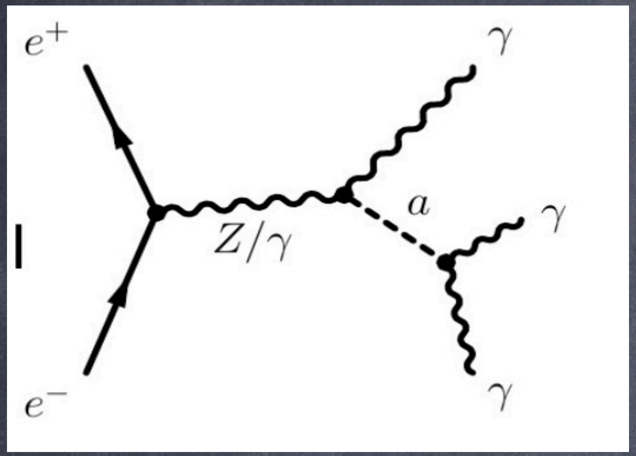
At low energies:

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

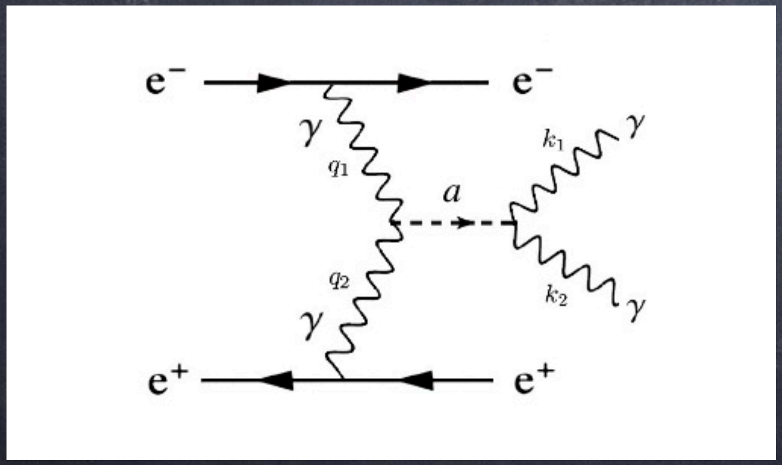
where

$$C_{\gamma\gamma} = C_{WW} + C_{BB} \qquad\qquad C_{Z\gamma} = c_W^2 C_{WW} - s_W^2 C_{BB}$$

Typical ALP Lagrangian:



At tera-Z, the production depends on $C_{Z\gamma}$



VBF depends on $C_{\gamma\gamma}$, etc

EW ALP scenario:

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda} G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda} B_{\mu\nu}\tilde{B}^{\mu\nu},$$

Composite Higgs case:

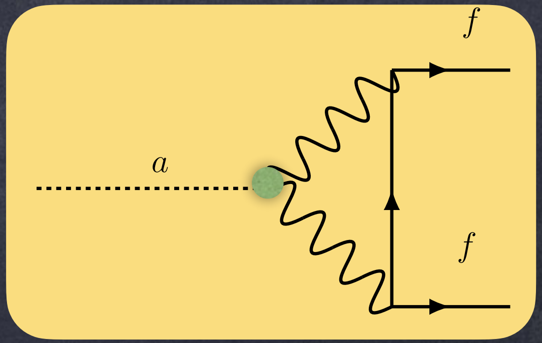
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\rm TC}}{64\sqrt{2}\,\pi^2 f}$$

$$\frac{C_{GG}}{\Lambda} = 0$$

(Poor bounds at the LHC)

$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

$\mathbf{C}_F$ is loop-induced:



M.Bauer et al, 1708.00443

EW ALP scenario:

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$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde G^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde W^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde B^{\mu\nu},$$

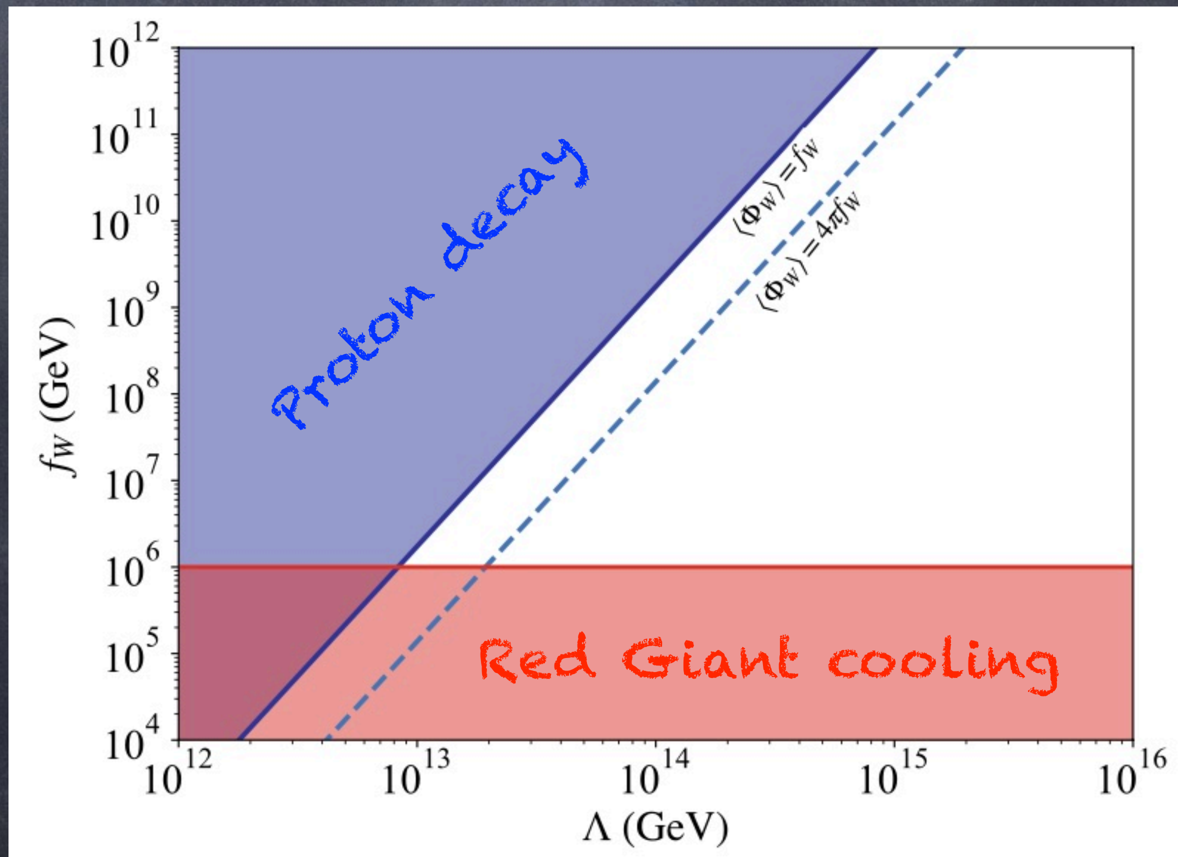
Weak axion (from B+L)

G.Cacciapaglia, F.Sannino, J.Turner, 2510.14104

$$m_{a_W} \sim \kappa \frac{v_{\rm EW}^2}{f_W} e^{-\pi/\alpha_2} \sim \kappa \frac{(1\ {\rm TeV})}{f_W} \times 6\cdot 10^{-29}\ {\rm eV}$$

$$\frac{\langle\Phi_W\rangle}{\Lambda^3}qqql + i\frac{a_W}{\sqrt{2}f_W}\frac{\langle\Phi_W\rangle}{\Lambda^3}qqql + \cdots$$

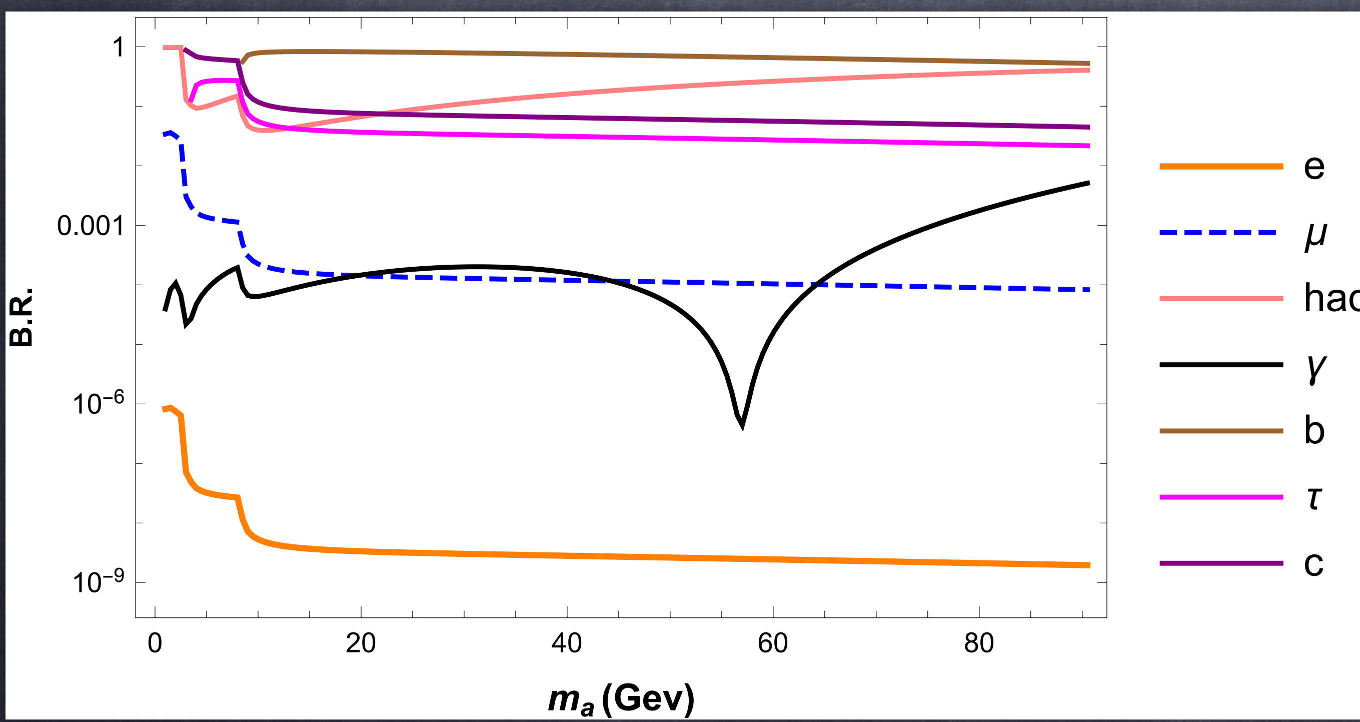
Larger mass to avoid stellar cooling bounds



Tera-Z portal to compositeness (via ALPs)

G.Cacciapaglia et al. 2104.11064

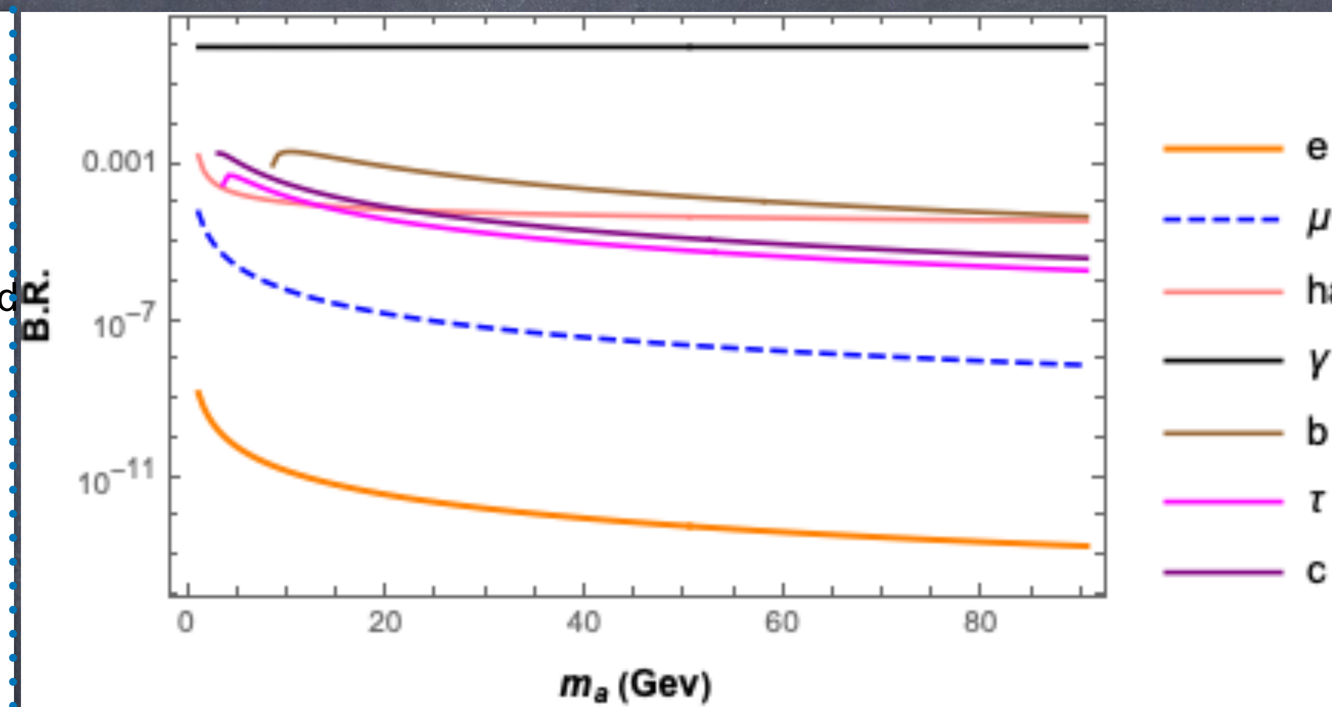
Photo-phobic



No leading order coupling to Photons (WZW interaction is Zero!!)

eg. SU(4)/SP(4), SU(4)xSU(4)/SU(4)

Photo-philic

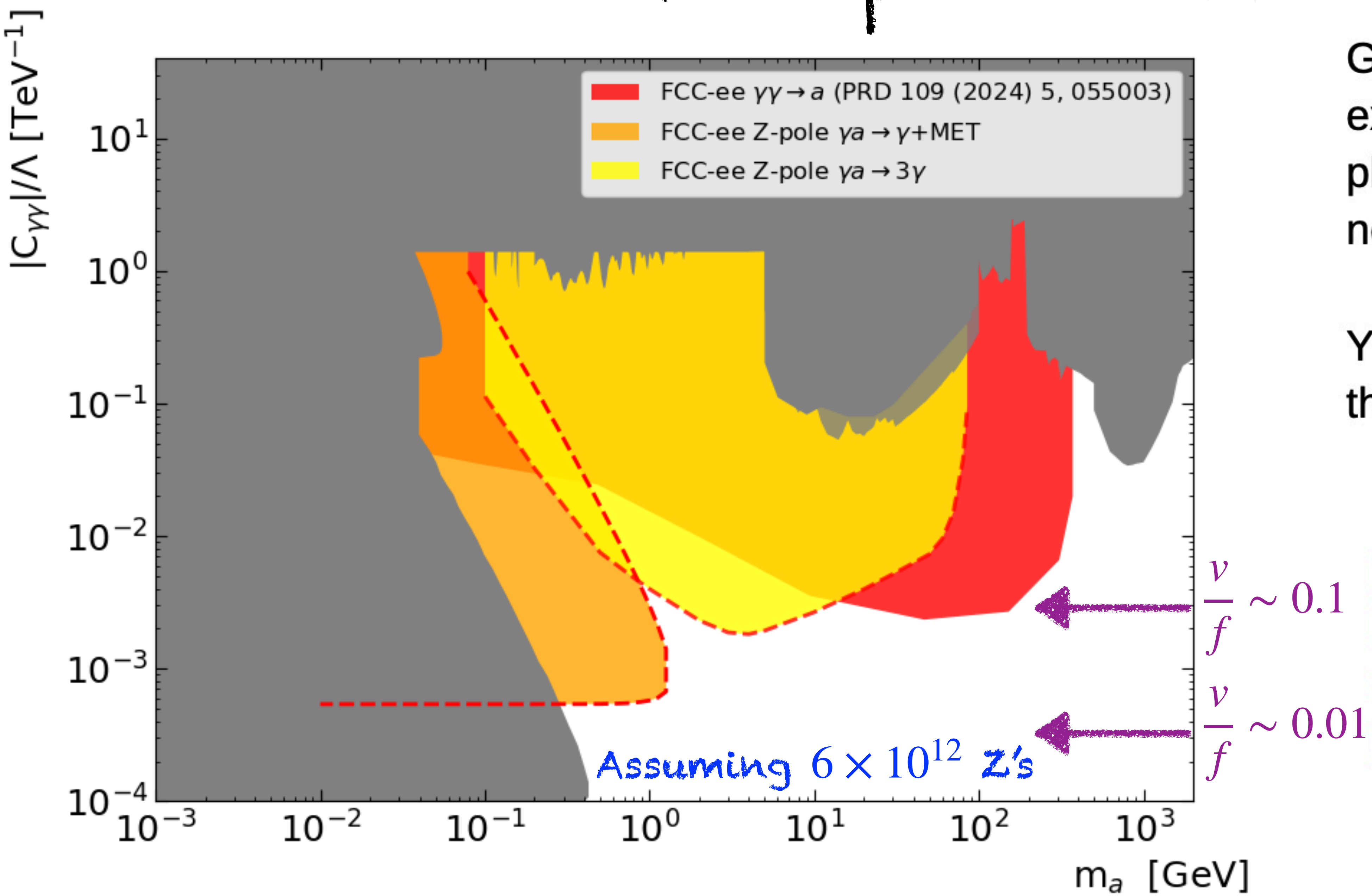


WZW interaction to photons (like the pion)

eg. SU(5)/SO(5), SU(6)/SO(6)

Combined plot FCC-ee

Photophilic case

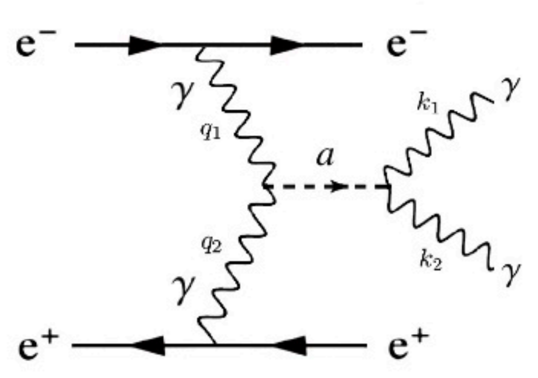


Plot for $C_{WW} = C_{BB}$

Grey areas :existing exclusions taken from ATLAS plot, to be updated with newest results

Yellow and orange areas are the two analyses of this talk

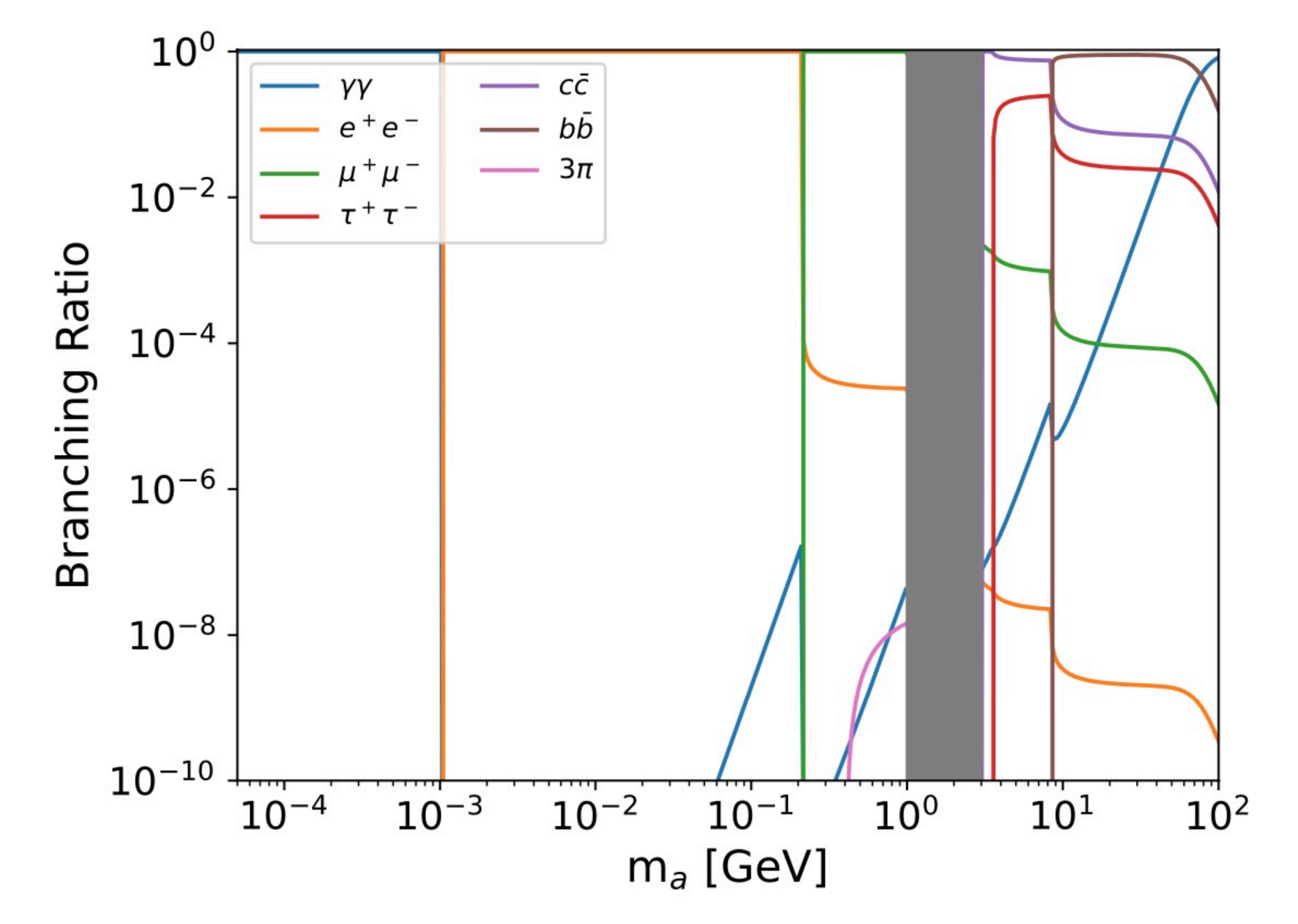
Red area is analysis of Rebello Teles et al. addressing ALP production in photon-photon fusion

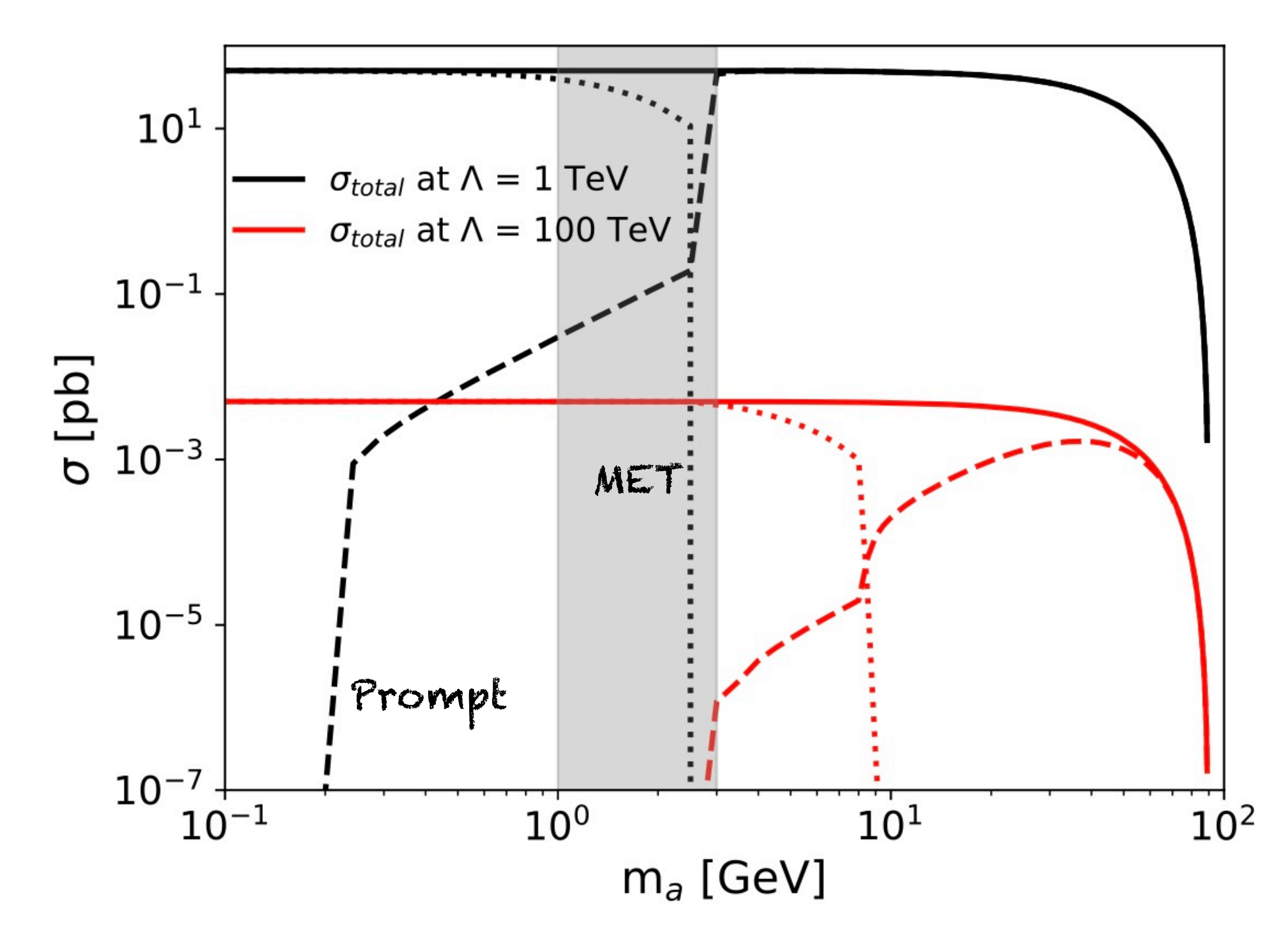


Photophobic case

S.Y. Wang, Y.P. Jiang, G.Cacciapaglia, H.H. Zhang
2509.17718

- Focus on leptons: muons and taus
- ...and missing energy!





Photophobic case

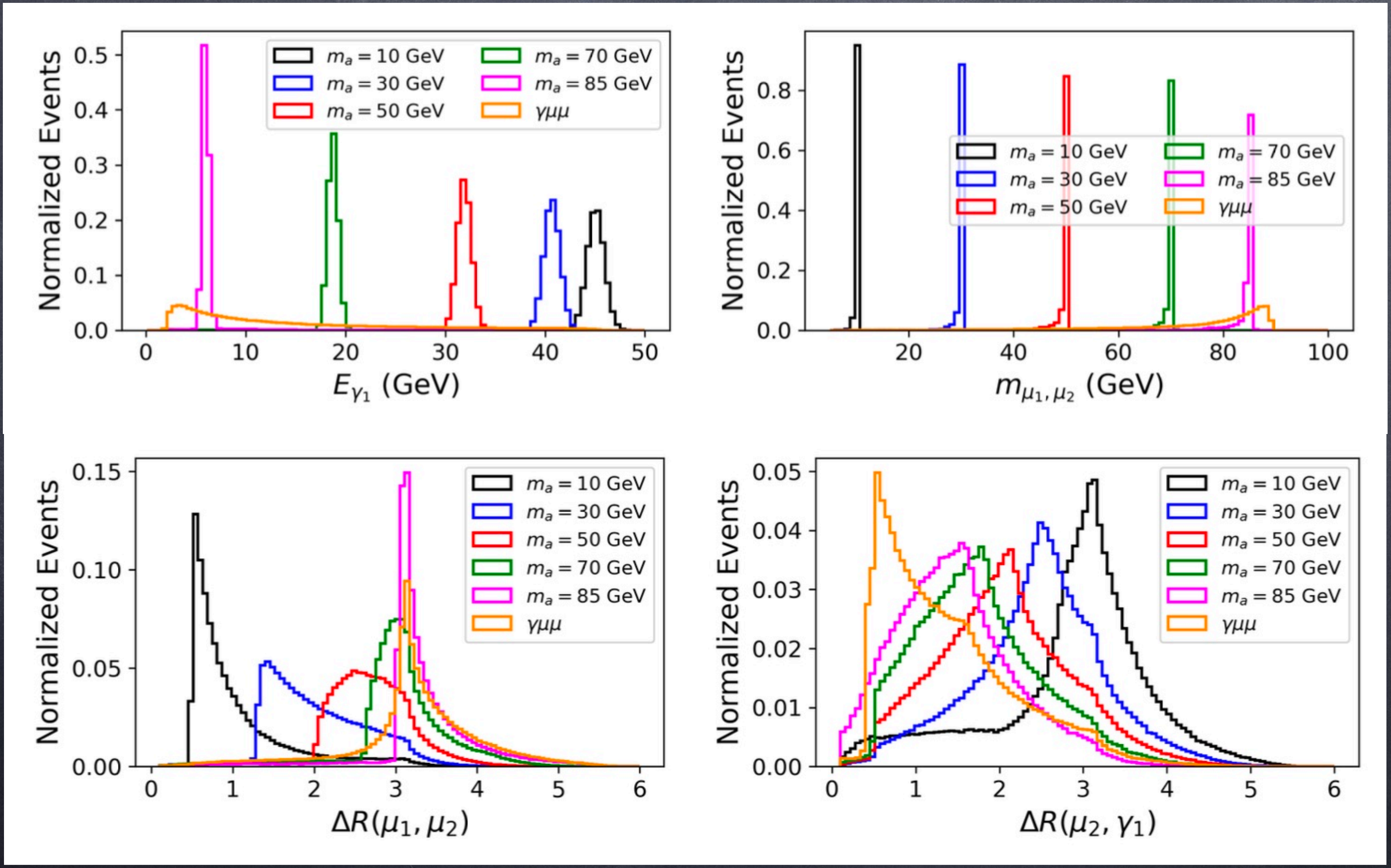
S.Y. Wang, Y.P. Jiang, G.Cacciapaglia, H.H. Zhang
2509.17718

- We set up a XGBoost classifier to distinguish signals from irreducible backgrounds.

m_a [GeV]	**10**	**30**	**50**	**70**	**80**	**88**
$\sigma_{\rm total}^{e^+e^-\to\gamma a}$ [pb]	0.0048	0.0035	0.0017	0.0003	6.11×10^{-5}	1.2×10^{-6}
$BR(a\to\mu^+\mu^-)$	0.00014	8.4×10^{-5}	7.3×10^{-5}	4.9×10^{-5}	3.4×10^{-5}	2.4×10^{-5}
$BR(a\to\tau^+\tau^-)$	0.038	0.024	0.020	0.014	0.0097	0.0068
$P_{\rm prompt}$	0.041	0.45	0.80	0.98	1.0	1.0
$\sigma_{\rm eff}^{e^+e^-\to\gamma a}$ [pb]	1.9×10^{-5}	0.0015	0.0013	0.00029	6.1×10^{-5}	1.16×10^{-6}

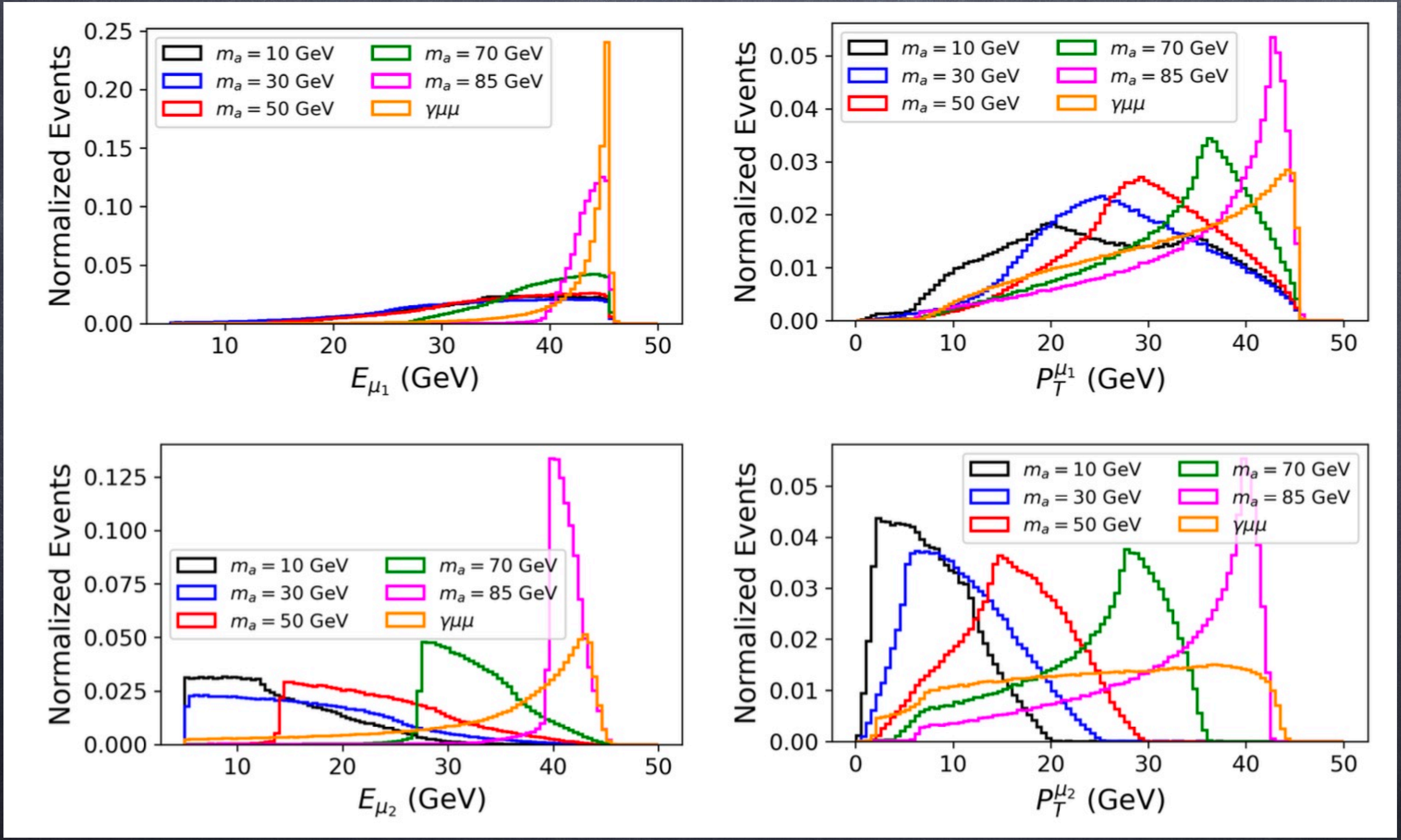
TABLE I. Benchmark values of ALP total cross sections, branching ratios, prompt decay probabilities, and effective cross sections at $\Lambda = 100$ TeV.

Muons:



Normalized Events
$m_a = 10$ GeV
$m_a = 30$ GeV
$m_a = 50$ GeV
$m_a = 70$ GeV
$m_a = 85$ GeV
$\gamma\mu\mu$
E_{γ_1} (GeV)
m_{μ_1,μ_2} (GeV)
$\Delta R(\mu_1, \mu_2)$
$\Delta R(\mu_2, \gamma_1)$

Muons: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$m_a = 10$ GeV
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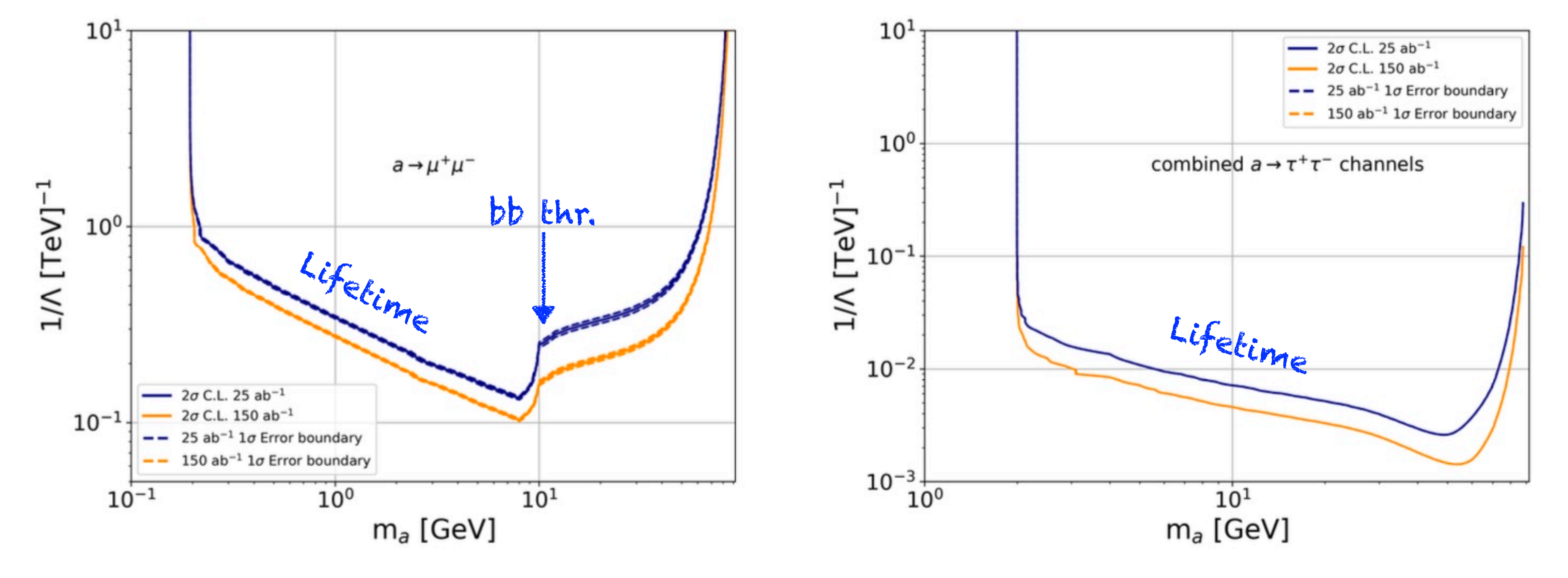
$m_a = 50$ GeV
$m_a = 70$ GeV
$m_a = 85$ GeV
$\gamma\mu\mu$
E_{μ_1} (GeV)
$P_T^{\mu_1}$ (GeV)
E_{μ_2} (GeV)
$P_T^{\mu_2}$ (GeV)

Leptonic Limits



- Muons dominate at low mass, but limited by long lifetime
- Taus dominant above threshold.

Combined Limits

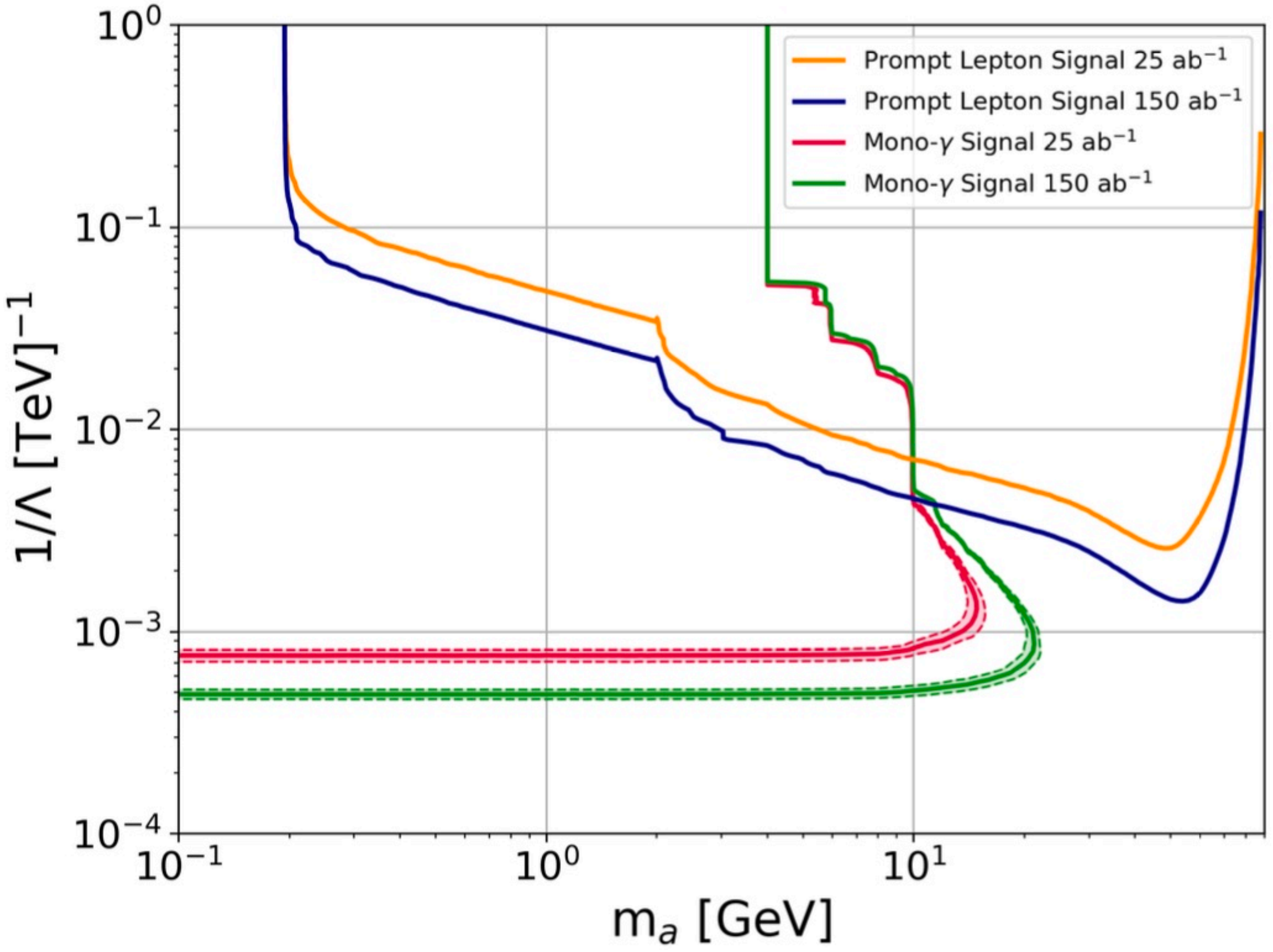
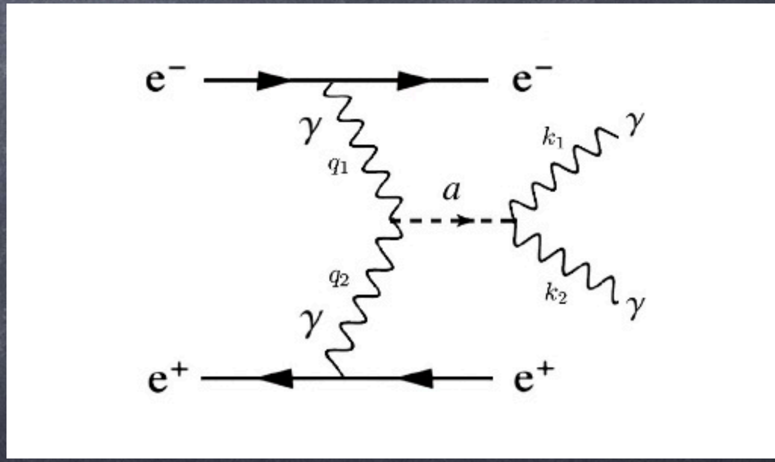


FIG. 11. Combined 95% C.L. exclusion limits on $1/\Lambda$ at $\sqrt{s} = 91.2$ GeV. The dark blue and yellow solid lines represent the exclusion limits after combining all leptonic decay channels at integrated luminosities of 25 ab^{-1} and 150 ab^{-1}, respectively. The red and green lines indicate the exclusion limits from the Mono-γ signal at the corresponding luminosities. The dashed lines represent the 1σ uncertainty bands, which coincide with the central values for the leptonic decay channels.

Perspectives on ALPS @ FCC

- Other channels, such as bb, ...
- Can one distinguish photo-philic from -phobic from VBF?

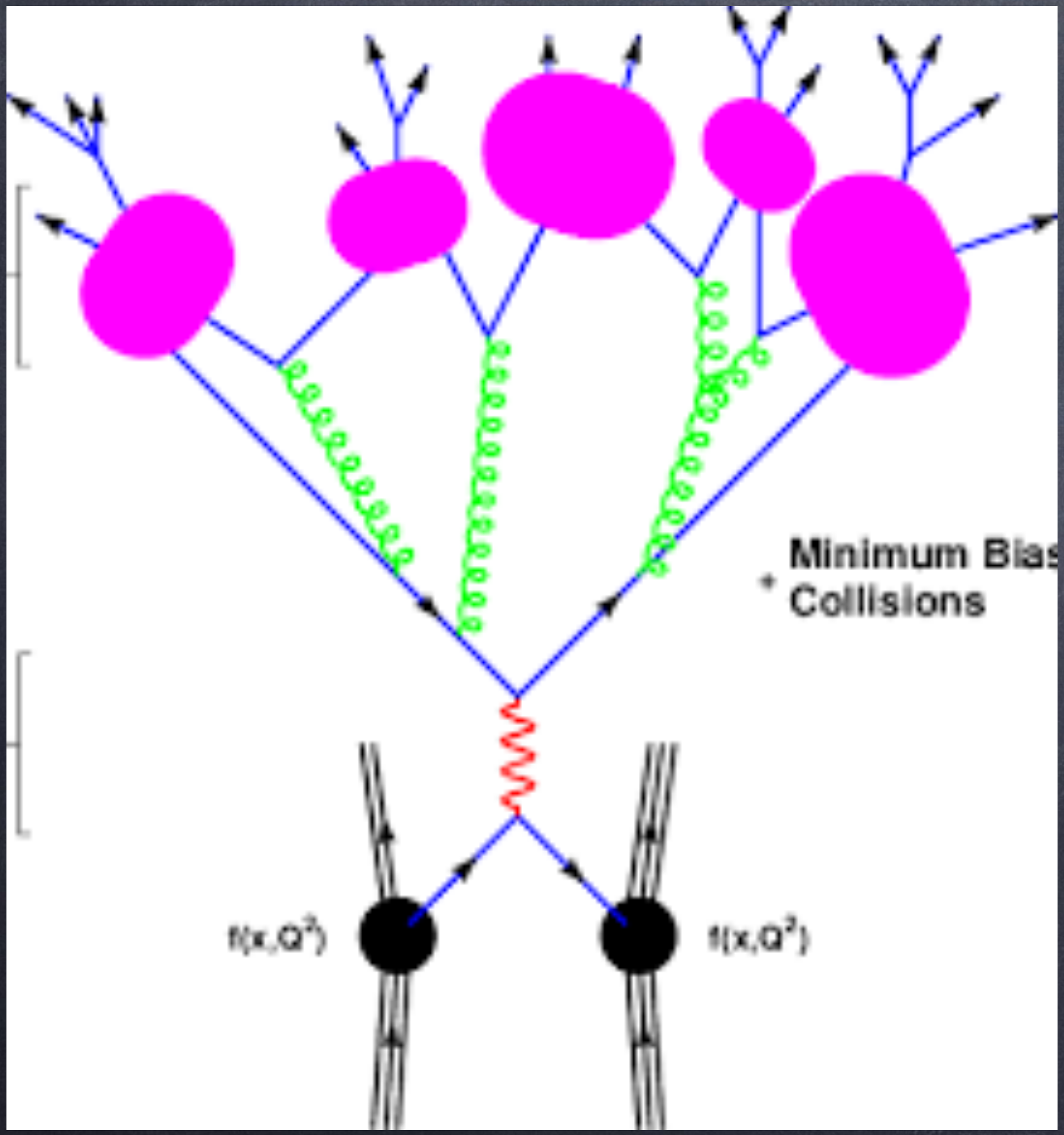


Roadmap to Higgs compositeness

- The HL-LHC will leave an important legacy, but NOT covering the whole interesting parameter space! (i.e. 10TeV is the target)
- A Tera-Z run will fully test the presence of a light composite ALP -> well beyond the 10 TeV mark
- Case 1 : discovery + EWPTs can fix the scale
- Case 2 : non-discovery + EWPTs
- In both cases, the results will strongly constraint the model building, providing testable predictions for a high energy pp collider.

EW-boson splashes at Future Colliders

G.Cacciapaglia, A.Deandrea, A.Iyer, A.Singh, S.Kulkarni
2506.19413



- At sufficiently high energies, production of techno-quarks...
- followed by techni-hadronization.
- Final state consisting on electroweak bosons (W, Z, H, ...)

EW-boson splashes at Future Colliders

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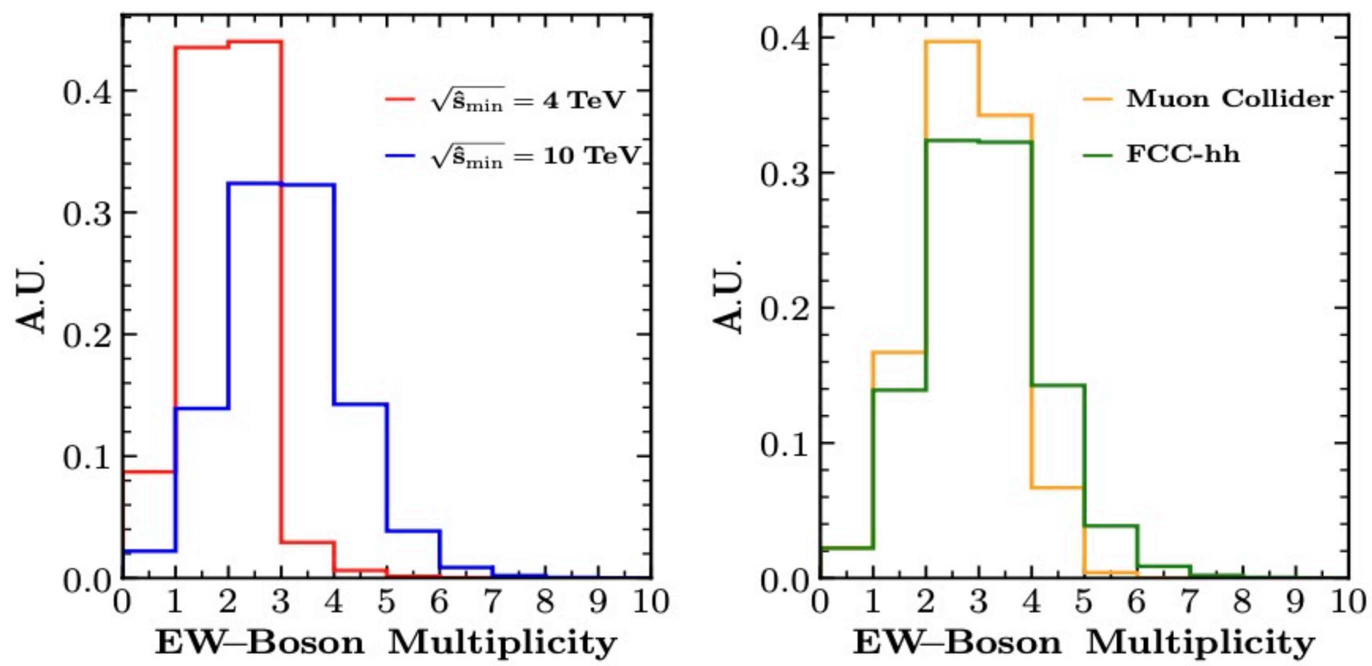
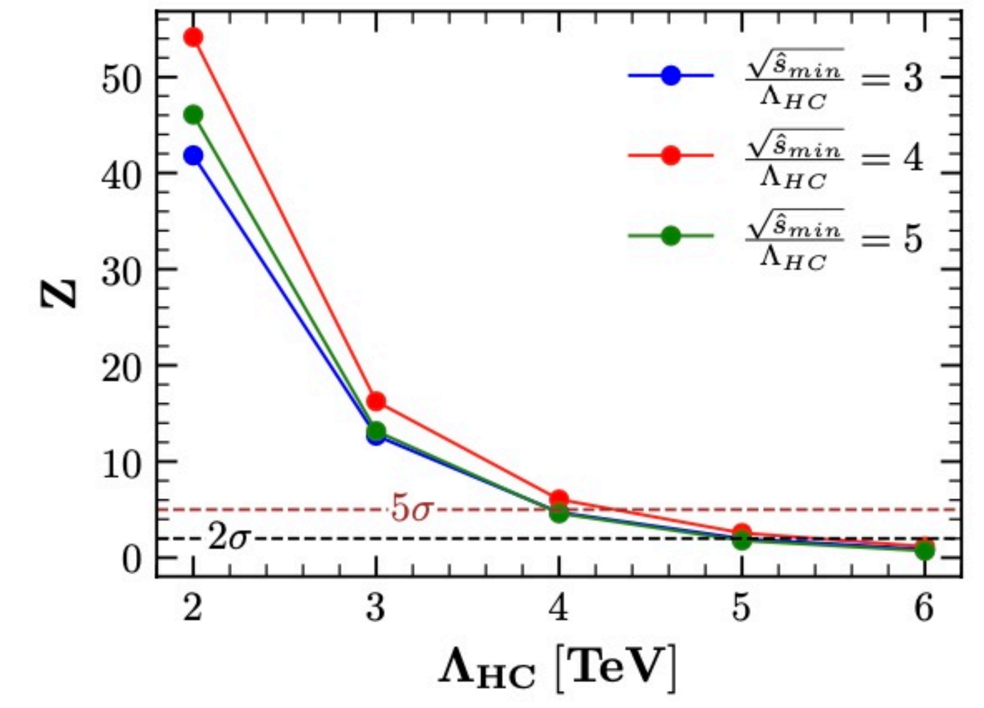


FIG. 1: Final state EW-boson multiplicity. **Left:** Distribution at FCC-hh for $\sqrt{\hat{s}_{min}} = 4$ TeV (red) and $\sqrt{\hat{s}_{min}} = 10$ TeV (blue). **Right:** Comparison between the FCC-hh at $\sqrt{\hat{s}_{min}} = 10$ TeV (green) and a muon collider at fixed $\sqrt{\hat{s}} = 10$ TeV (orange)



Feasible to probe directly composite scales up to a few TeV.

Bonus track

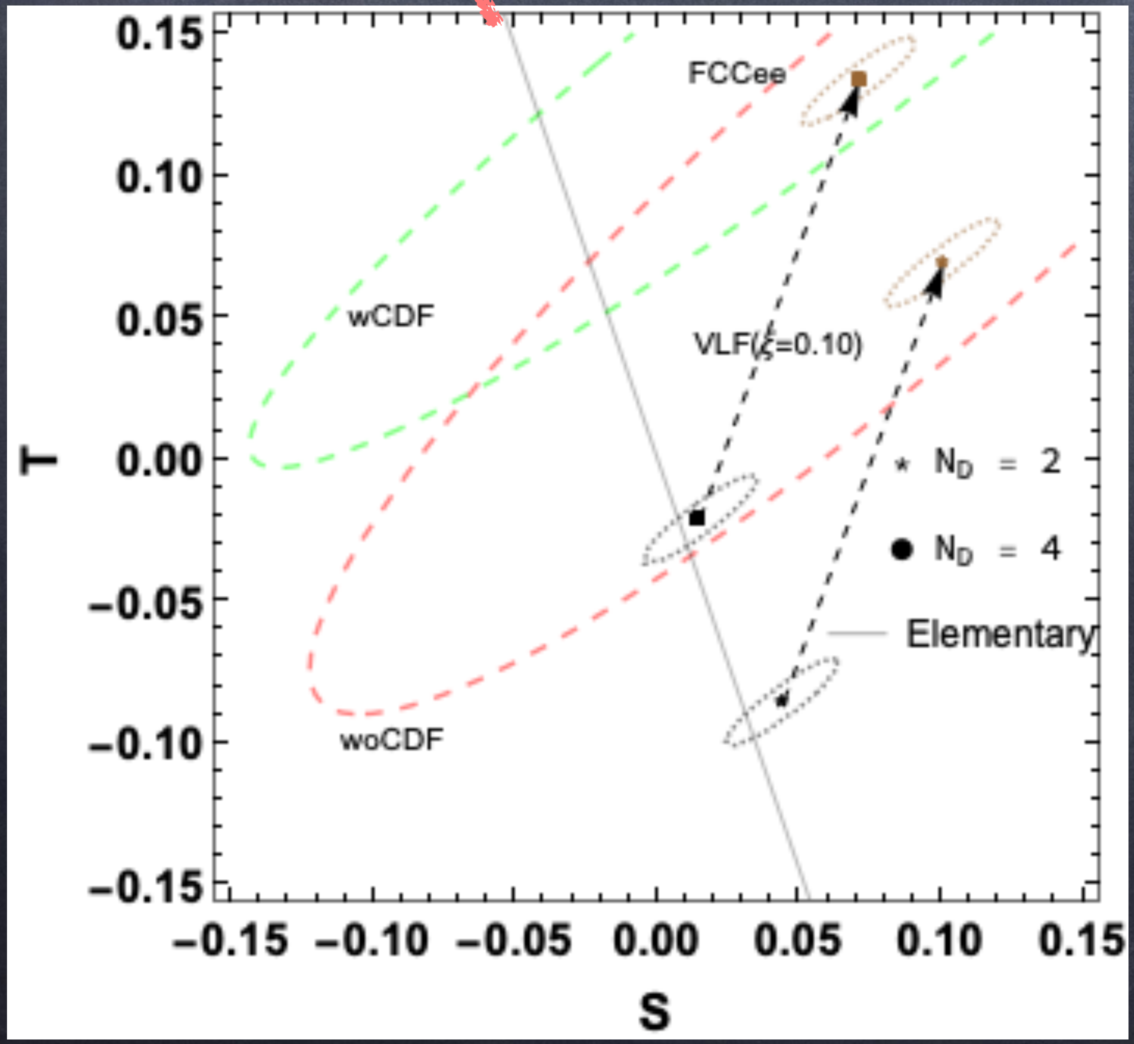
What if FCC-ee discovers Z > γa?

G.Cacciapaglia et al.
2211.00961

- Is it possible to distinguish the composite scenario, from an elementary mock-up model?

EWPT only depend on H loops in the elementary case

composite case: see 1502.04718



For fixed BR = 10^-8, i.e. discovery.

Arrows: "naive" contribution of top partner loops.

Indirect access to top partners and coset!