Heavy QCD Axions at the LHC and Neutrino Experiments

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w/ Raymond Co and Zhen Liu (in progress)

PHENO 2022

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Axion Solution to Strong CP Problem

- The problem:

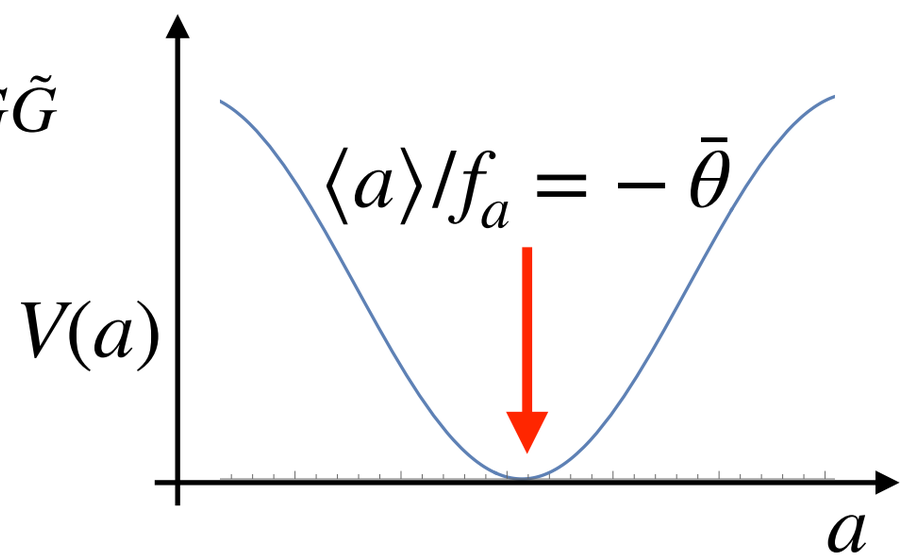
$$\mathscr{L}_{\text{SM}} \supset \frac{\alpha_3}{8\pi}\theta G\tilde{G} + Y_u \bar{Q}_L \tilde{H} u_R + Y_d \bar{Q}_L H d_R$$

$$\bar{\theta} = \theta + \arg\det(Y_u Y_d) < 10^{-10}$$

Neutron EDM, Abel et. al. ’20

- Axion solution: $\bar{\theta}$ is a dynamical quantity

$$\mathscr{L}_{\text{SM+Axion}} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G}$$



Peccei, Quinn ’77
Weinberg ’78
Wilczek ’78

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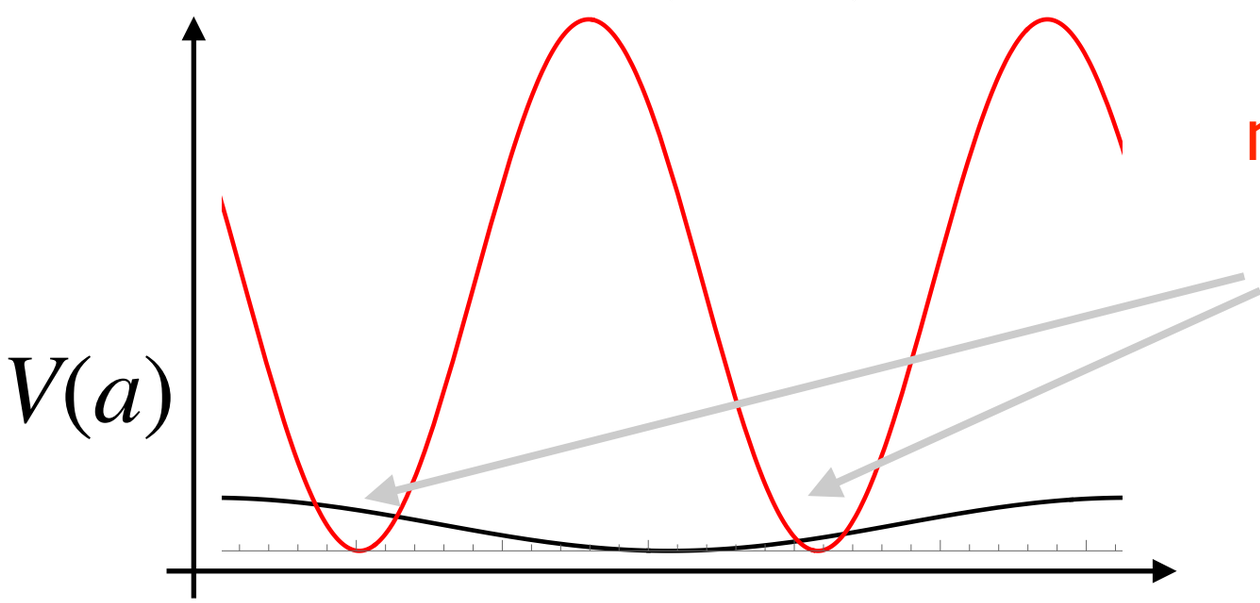
Axion Quality Problem

$$\Phi \sim f_a e^{ia/f_a}$$

- Gravity breaks $U(1)_{\rm PQ}$

$$\frac{\Phi^N}{M_{pl}^{N-4}} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a}+\bar{\theta}\right)+\frac{f_a^N}{M_{pl}^{N-4}}\cos\left(\frac{Na}{f_a}+\delta\right)$$



new axion minima, $\bar{\theta} \sim \mathcal{O}(1)$ again, axion no longer a solution

$$\langle a \rangle / f_a = -\bar{\theta}$$

to avoid, need to set at least 4 Planck-suppressed operators to zero by hand!

Kamionkowski et al.; Barr et al.; Ghigna et al.; Holman et al., '92

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Heavy QCD Axions

- Standard QCD axions $m_a^2 f_a^2 \sim \Lambda_{\rm QCD}^4$

stellar cooling constraints $f_a > 10^8$ GeV

- However, axions with $aG'\tilde{G}'$ coupling can solve both Strong CP and Quality Problem while being heavy

e.g., $m_a^2 f_a^2 \approx \Lambda_{\rm QCD'}^4 \gg \Lambda_{\rm QCD}^4$

m_a ⇧ avoid star, cosmo

f_a ⇩ stronger coupling

See e.g.,
Rubakov '97
Berezhiani et al. '00
Hook '14 …

"Heavy QCD Axions": perfect for terrestrial searches!

$m_a \sim 0.1 - 10$ GeV, $f_a \sim$ 1-100 TeV

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Axion Coupling

- Hallmark gluon coupling (essential for solving Strong CP)

$$\mathscr{L}_{\text{gauge}} \supset c_3 \frac{\alpha_s}{8\pi f_a} a G\tilde{G} + c_2 \frac{\alpha_2}{8\pi f_a} a W\tilde{W} + c_1 \frac{\alpha_1}{8\pi f_a} a B\tilde{B}$$

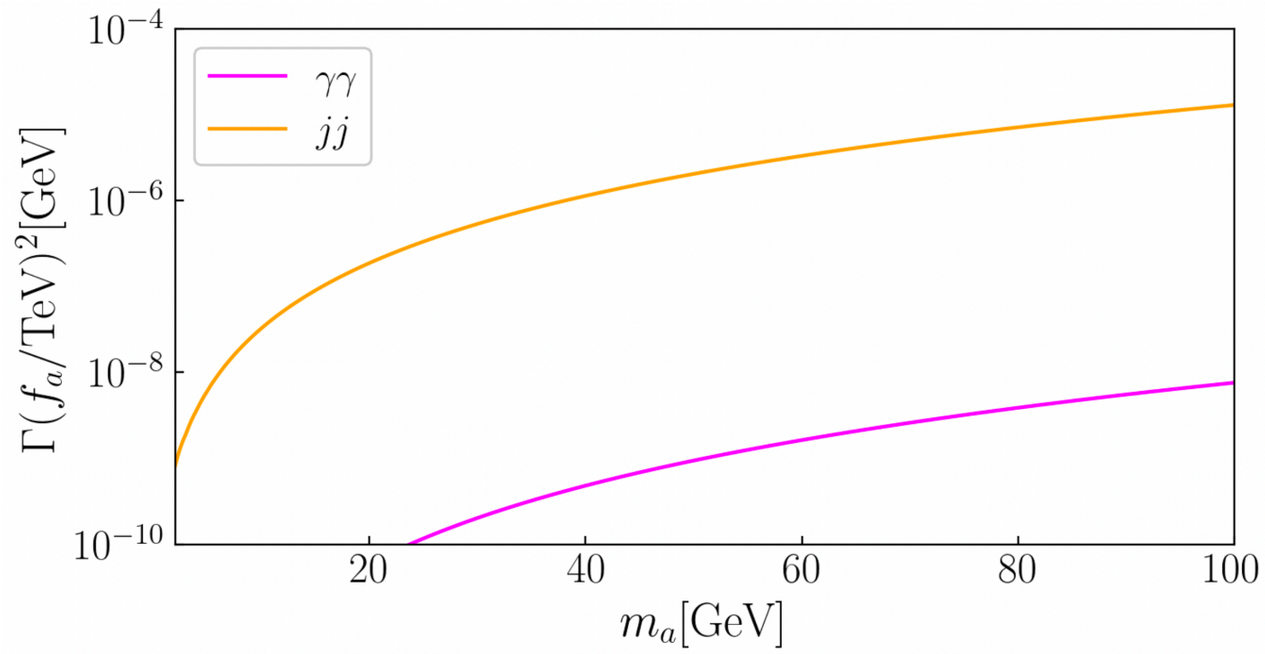
motivated by GUT

$$\mathscr{L}_{\text{lepton}} \supset \sum_{l=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} \left(C_{Vl} \bar{l}\gamma^\mu l + C_{Al} \bar{l}\gamma^\mu\gamma_5 l \right) + \sum_{l=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} C_\nu \bar{\nu}_l \gamma^\mu (1-\gamma_5)\nu_l$$

not relevant for this talk

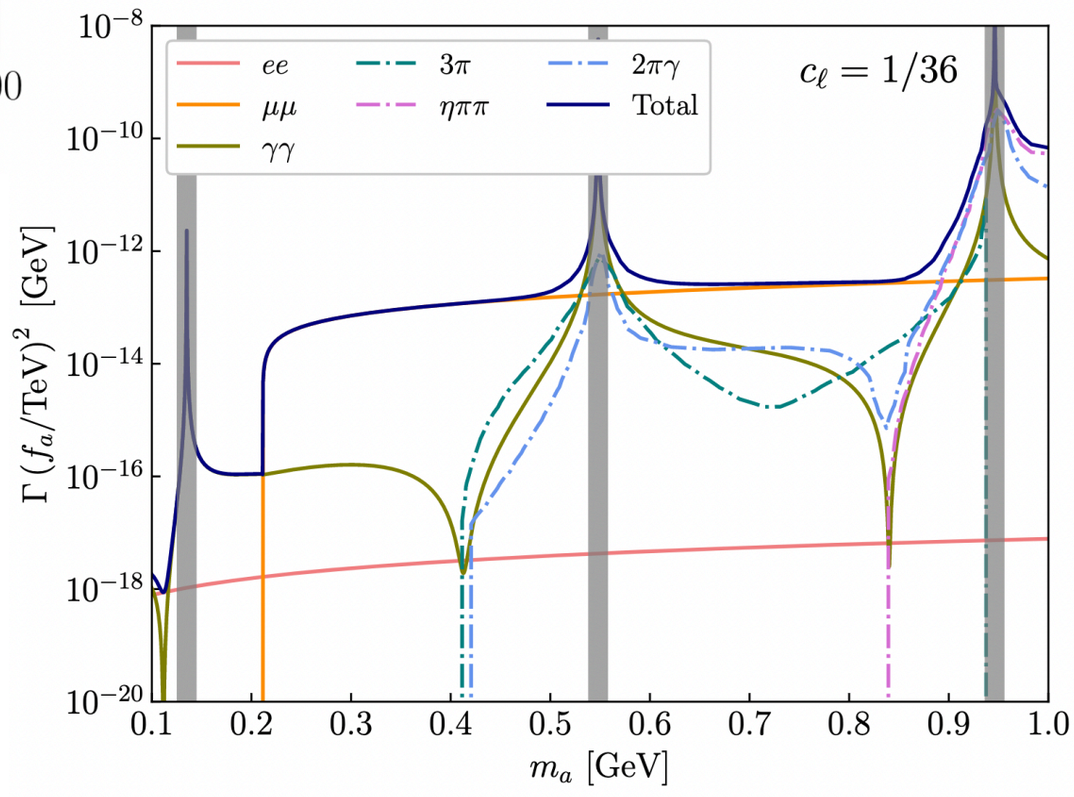
FCNC's extremely powerful,
so focus on flavor diagonal couplings

Axion Decay Modes



Prompt decay:
diphoton mode
more tractable

Long-lived decay:
dimuon mode
dominates



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Diphoton Search

Knapen, **SK**, Redigolo ’21

- Process: $pp \to a(j) \to \gamma\gamma(j)$ at $\sqrt{s} = 13$ TeV

- Collimated photons from light axions

  $m_{\gamma\gamma} \simeq \sqrt{p_{T_1}^{\gamma} p_{T_2}^{\gamma}}\, \Delta R_{\gamma\gamma}$

  One photon can spoil the other’s isolation criterion

- Two approaches:

  - data scouting (lower $p_T \Rightarrow$ higher event rate but reduced event size)

  - modified isolation (photon subtraction)

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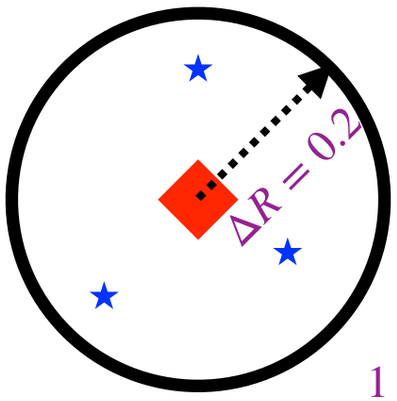
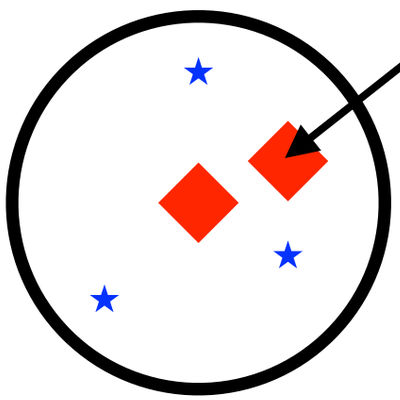
Modified Isolation

Knapen, **SK**, Redigolo '21

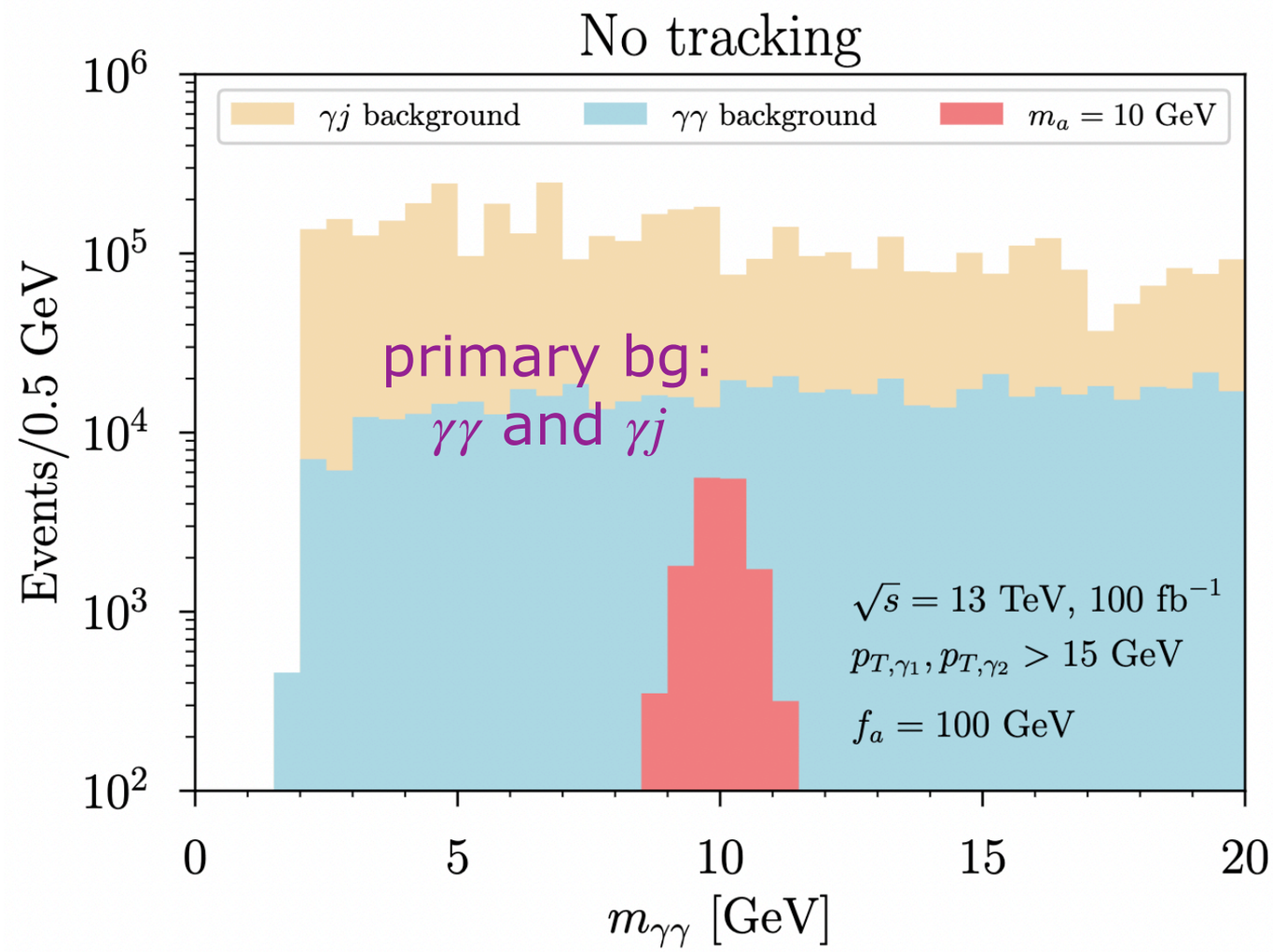


$$r_\gamma \equiv \frac{1}{p_{T_\gamma}} \left(\sum_{\substack{\Delta R < 0.2 \\ p_{T_i} > 0.5\text{GeV}}} p_{T_i} \right) < 0.05$$

subtract this deposit



$$r_{\gamma\gamma} \equiv \frac{1}{p_{T_\gamma}} \left(\sum_{\substack{\Delta R < 0.2 \\ p_{T_i} > 0.5\text{GeV}}} p_{T_i} - p_{T_{\gamma,1}} \right) < 0.05$$



MG5+Pythia8+ Delphes3 w/ modified isolation module

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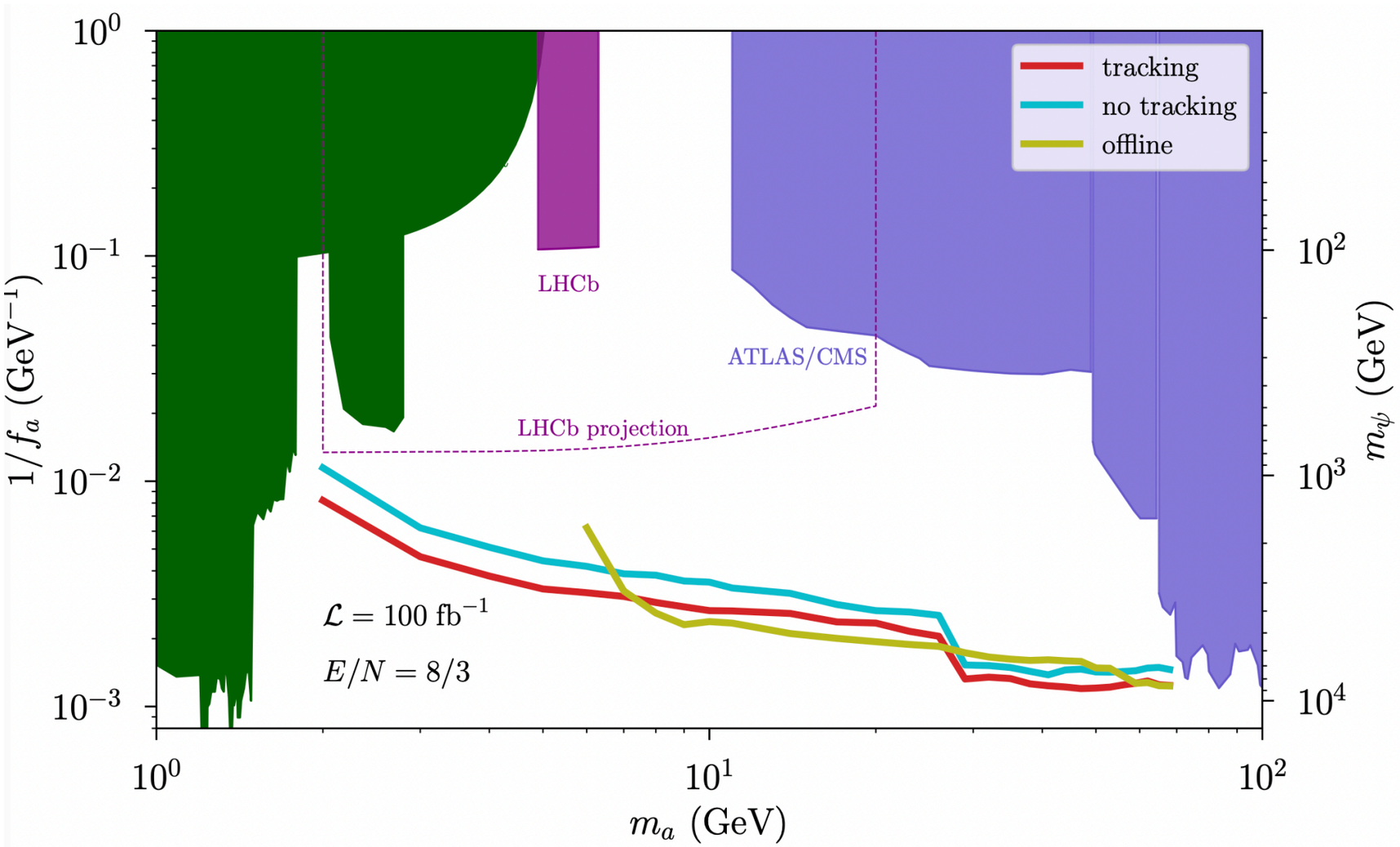
Reach

Knapen, **SK**, Redigolo ’21



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Dimuon Search

- No tree level quark coupling, but non-zero $aG\tilde{G}$ coupling induces axion-pseudo scalar mixing

- Dimuon search

- ArgoNeuT: background mitigation

work in progress
w/ ArgoNeuT collaboration

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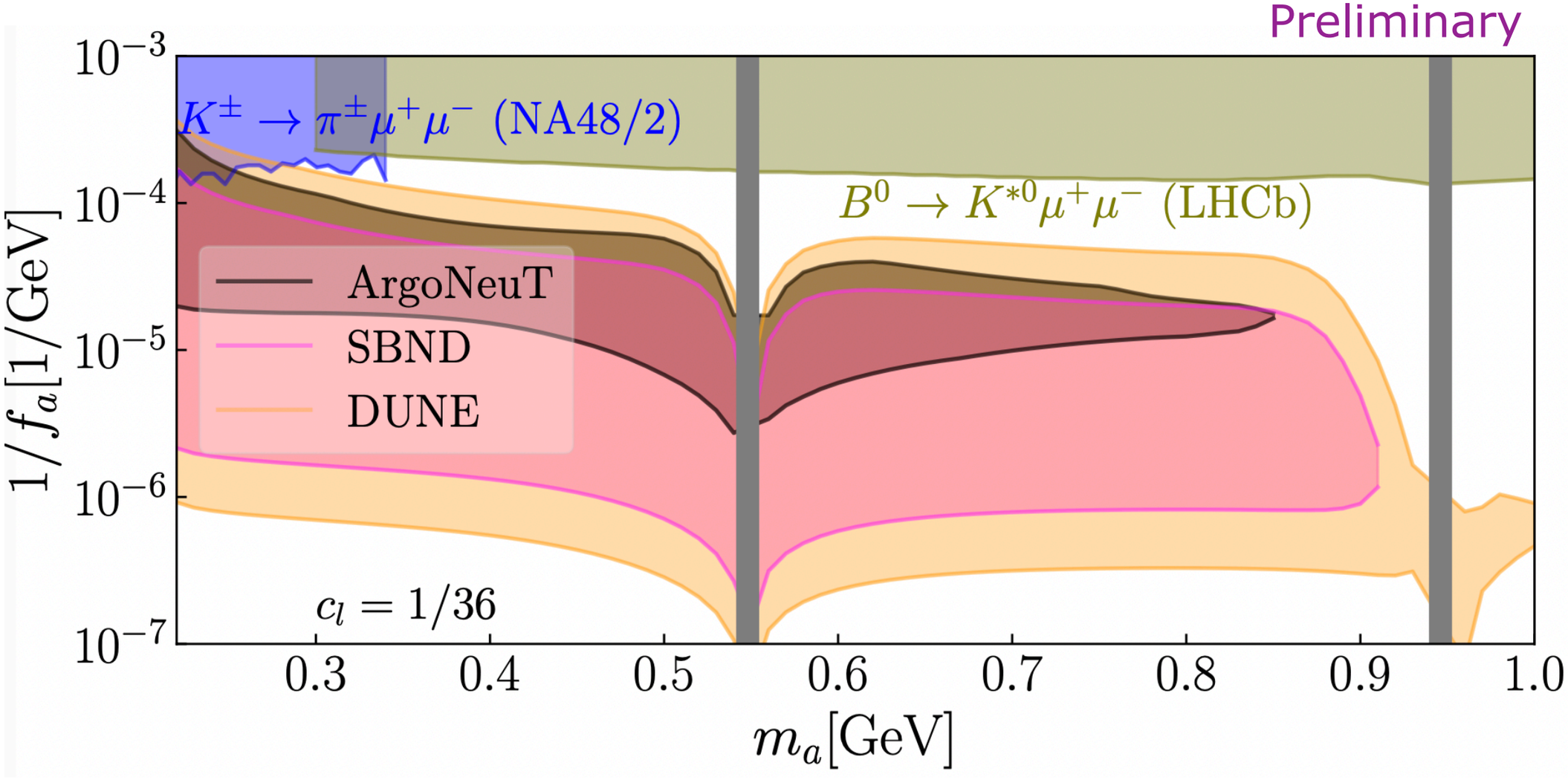
Prospects at Neutrino Detectors



Co, **SK**, Liu, in progress

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Conclusions

- Heavy axions theoretically well motivated: can address Strong CP, Quality Problem.

- Data scouting and/or modified isolation can cover new parameter space

- Leptonic flavor universal couplings less well constrained: dominant constraints from meson decays

- Di-muon decay mode dominates, ArgoNeuT, SBND, DUNE etc. can put strong constraints.

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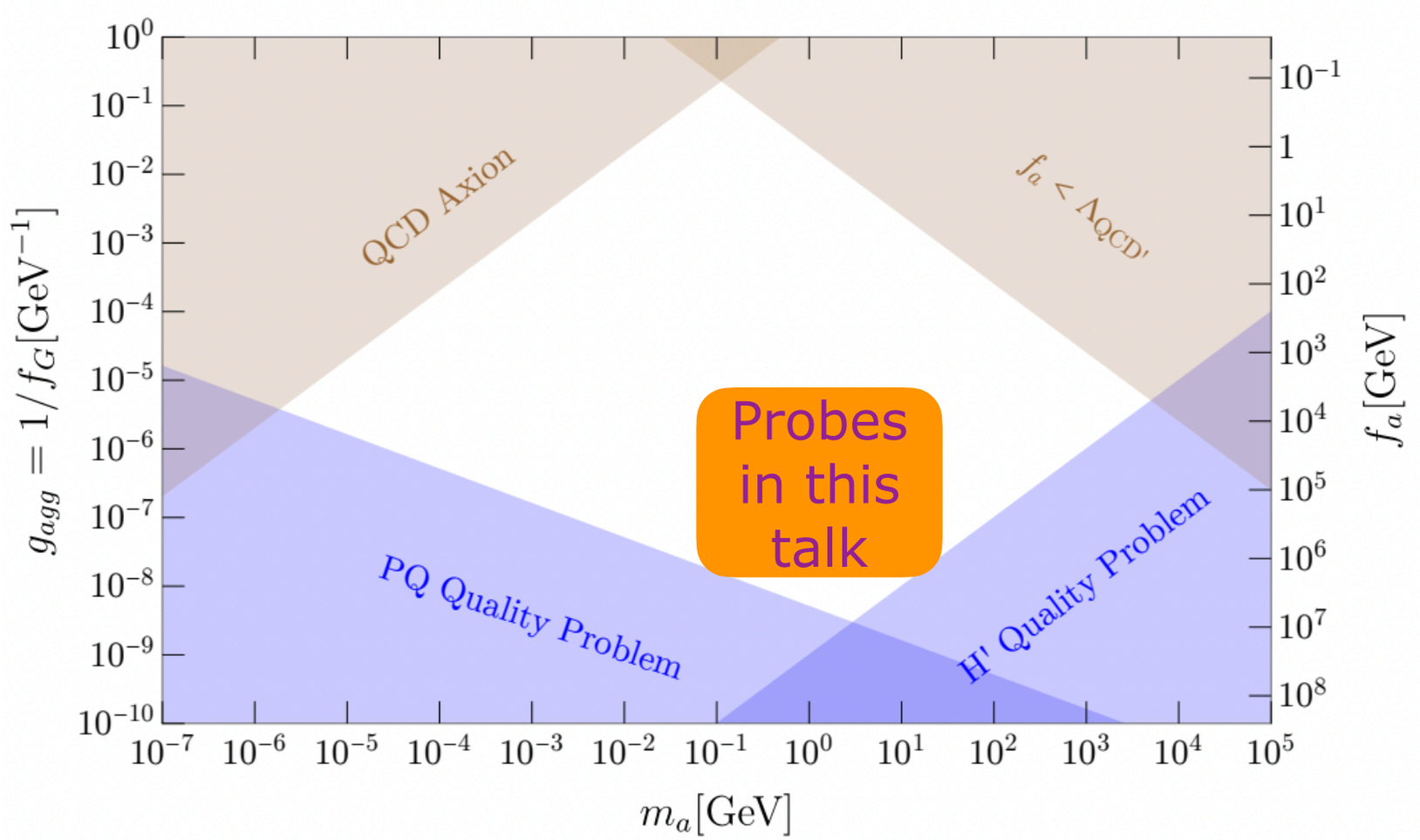
Thanks for your attention!

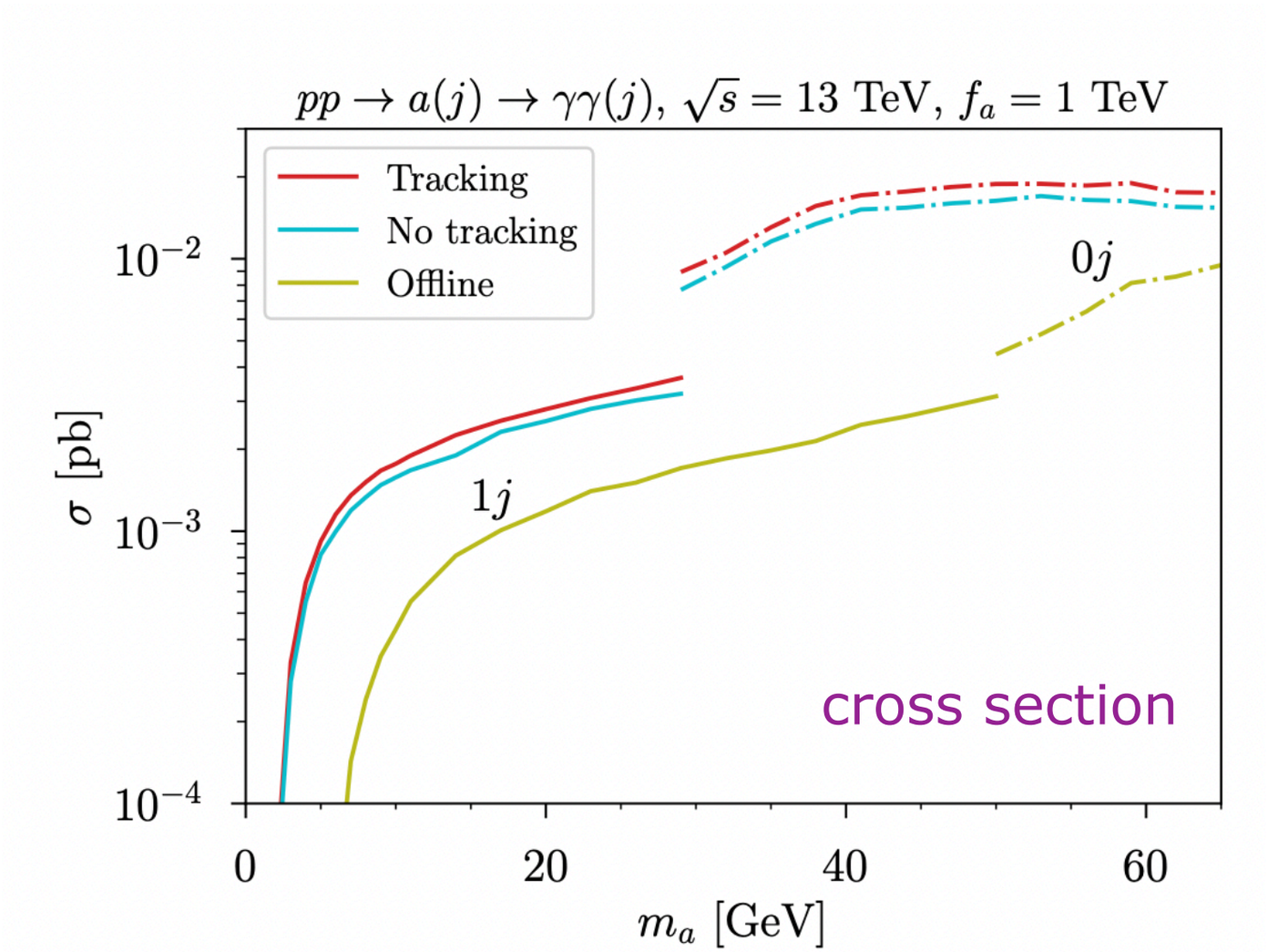
Theory Parameter Space for Heavy QCD Axions



Diphoton kinematics and xsec

$$m_{\gamma\gamma} = \sqrt{2p_{T_1}^{\gamma} p_{T_2}^{\gamma} (\cosh \Delta\eta_{\gamma\gamma} - \cos \Delta\phi_{\gamma\gamma})}$$
$$\simeq \sqrt{p_{T_1}^{\gamma} p_{T_2}^{\gamma}}\, \Delta R_{\gamma\gamma} \ ,$$

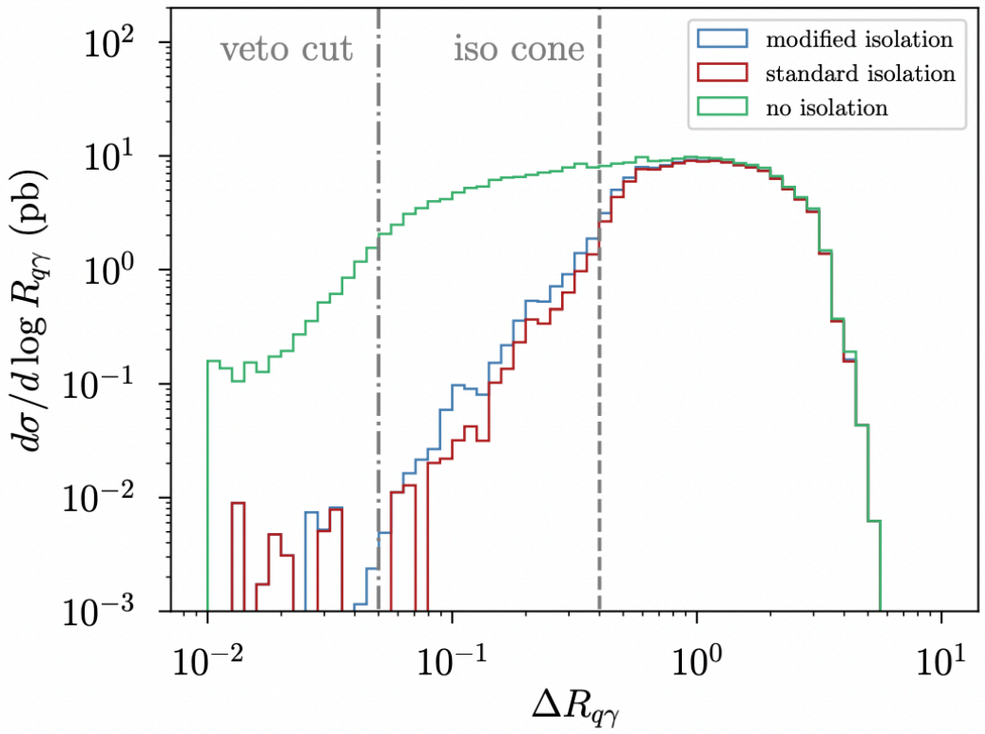
Photon invariant mass



cross section

γj Background

- Perturbative piece



angular separation
between frag. γ
and sister q

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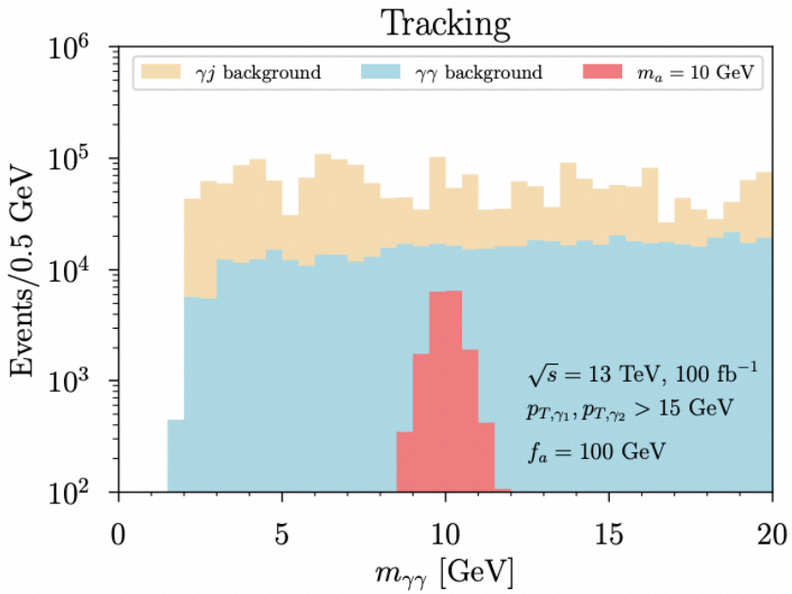
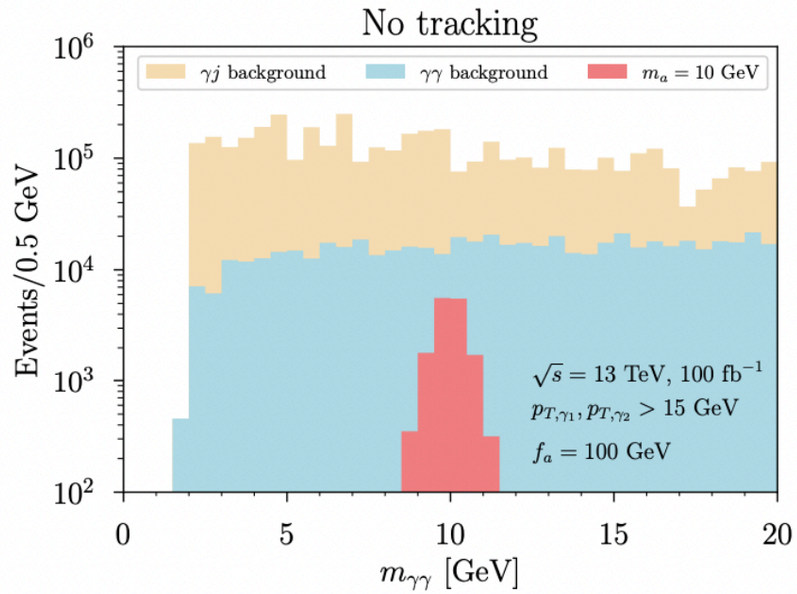
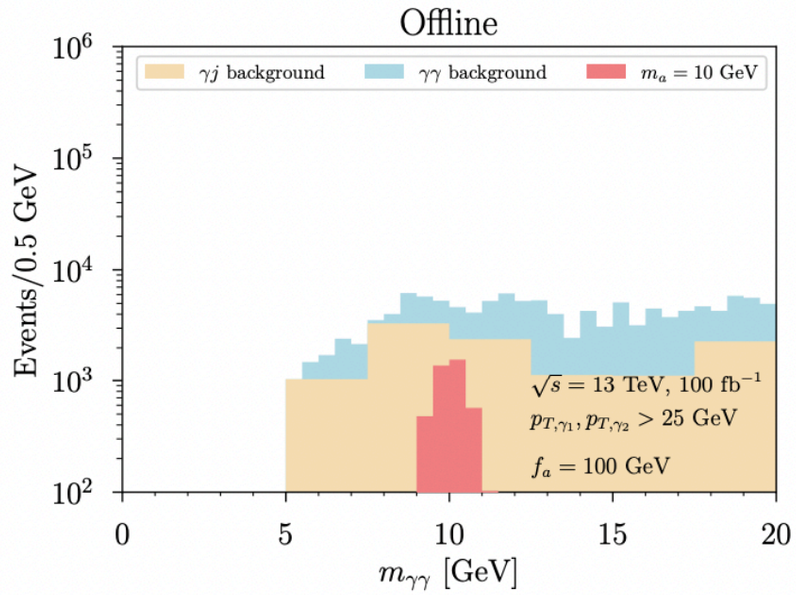
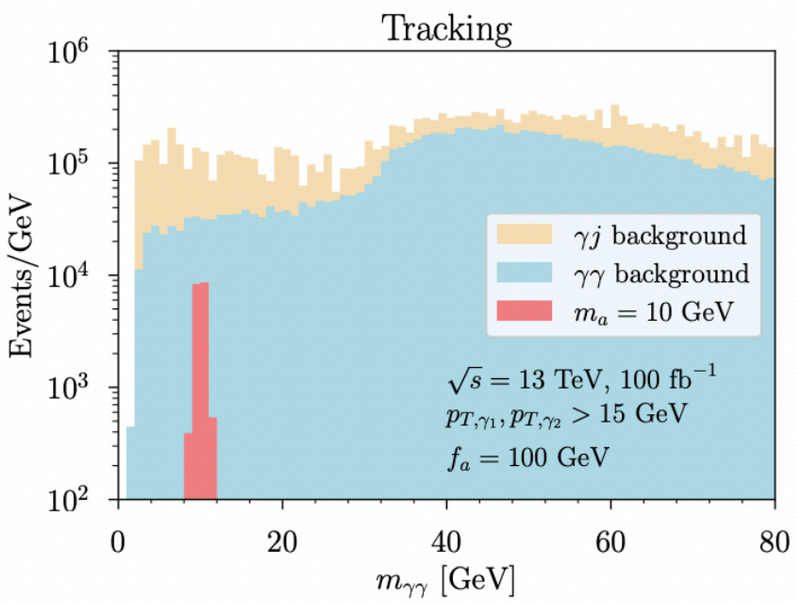
All Results

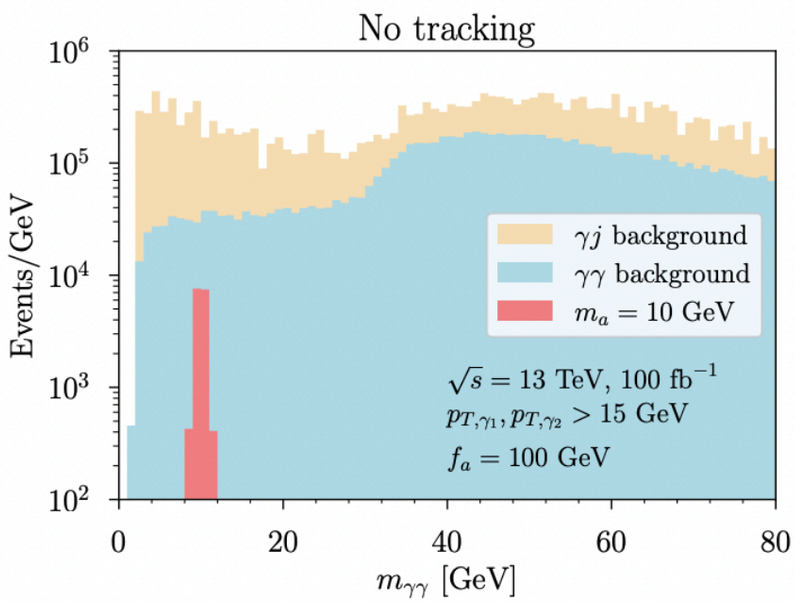
zoomed in

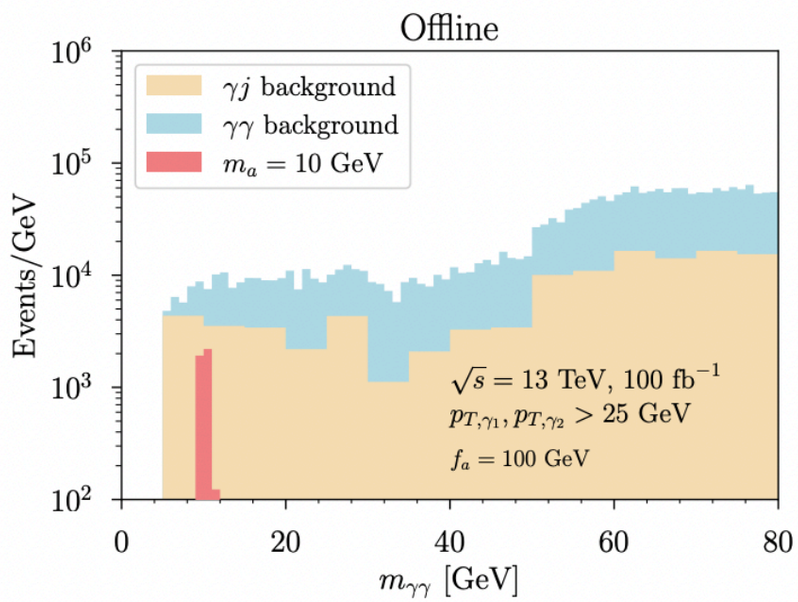




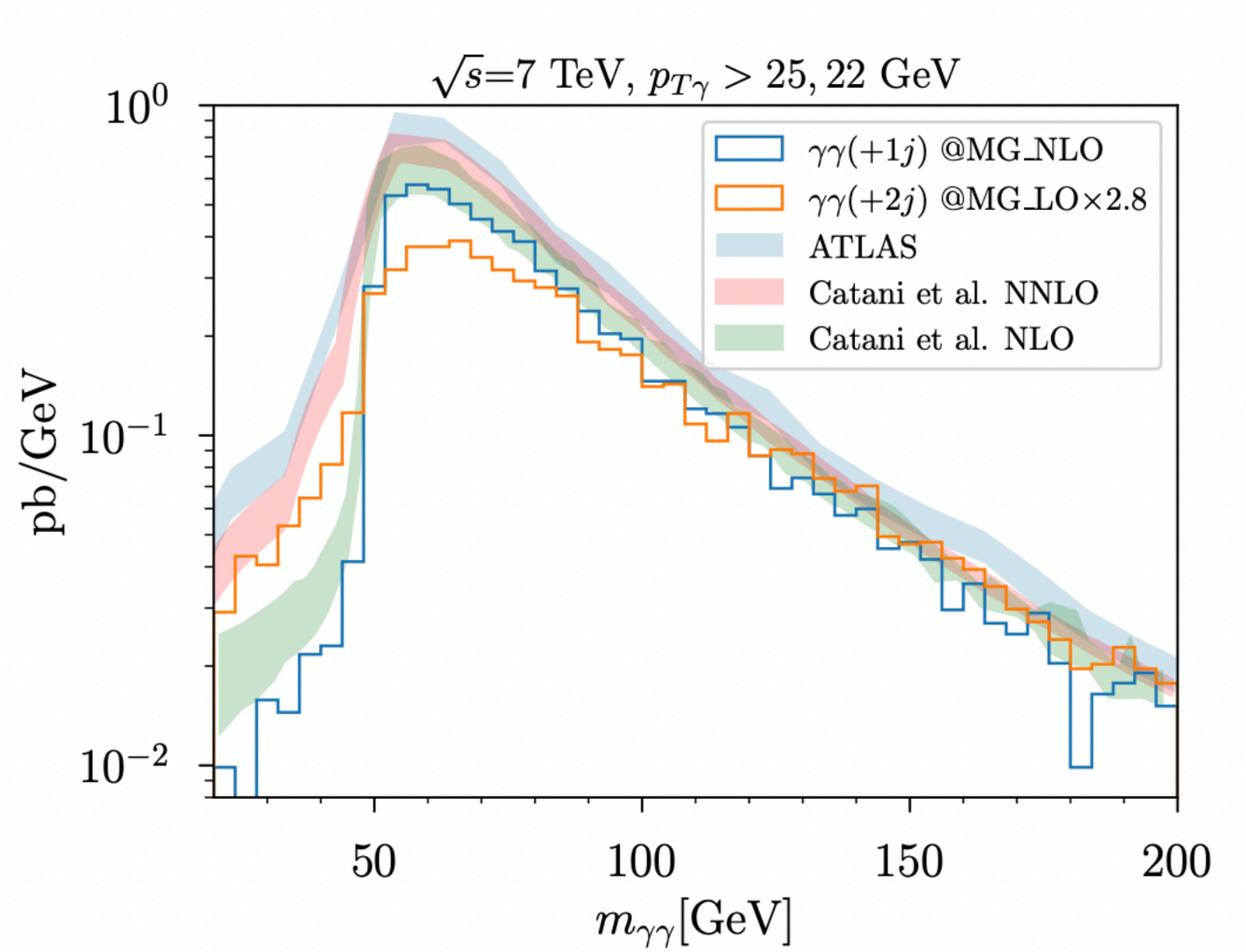




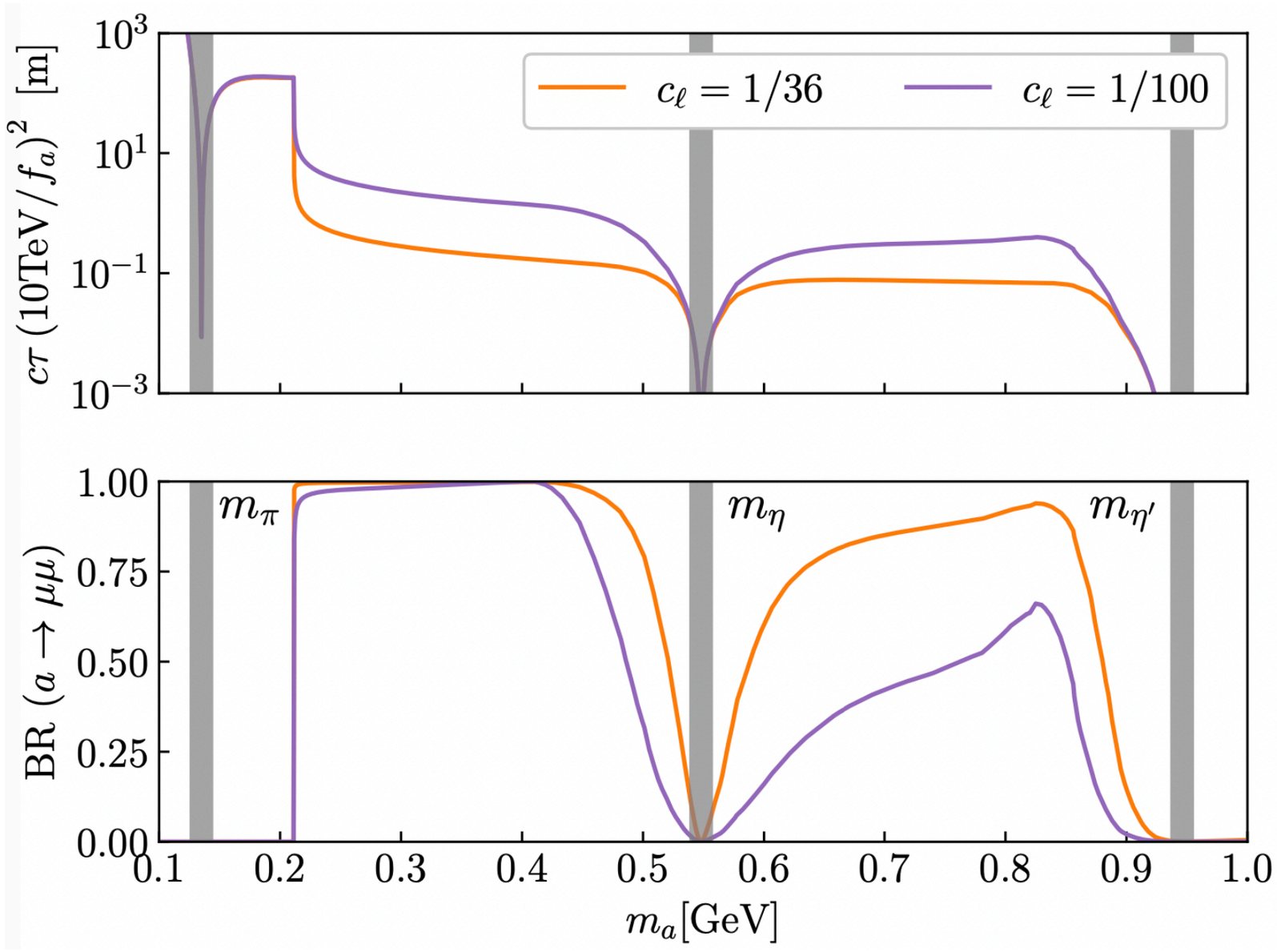




Background Validation



Dimuon Lifetime and BR



$$\mathscr{L}_{\text{gauge}} \supset \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

$$\mathscr{L}_{\text{lepton}} \supset \sum_{l=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} c_l \bar{l}\gamma^\mu\gamma_5 l$$

Smaller lepton coupling ensures sufficiently large lifetime

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