Interplay of ALP couplings at a Future Muon Collider

Sudhakantha Girmohanta

Aug 07, 2024

Based on:

1. S. Chigusa, S. Girmohanta, Y. Nakai and Y. Zhang JHEP 01, 077 (2024)

ALP EFT Framework

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❖ ALP (a) : CP-odd pNGB of spontaneously broken global $U(1)$ at a scale f_a.

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 - c_W \mathscr{A}_{\widetilde{W}} - c_B \mathscr{A}_{\widetilde{B}} - c_G \mathscr{A}_{\widetilde{G}} - \frac{c_{a\Phi}}{2}\frac{\partial_\mu a}{f_a}\sum_{\psi=Q,L}\bar{\psi}\gamma^\mu\gamma_5\sigma_3\psi + \text{h.c.}$$

ALP-gauge boson coupling

$$\mathscr{A}_{\widetilde{X}} = \left(\frac{\alpha_X}{4\pi}\right)\frac{a}{f_a}X_{\mu\nu}\widetilde{X}^{\mu\nu} \; ; \; X \in \{B, W, G\}$$

ALP-fermion coupling

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ALP-fermion coupling

- We are interested in ALP with m_a and $f_a \sim$ TeV [composite models, extra-dimensional models, heavy axion models…]
  Rubakov (1997), Fukuda+(2015), Gherghetta+(2016) , Gaillard+(2018)…

$$\tau(a \to t\bar{t}) \sim 10^{-25}\text{s}\left(\frac{f_a/\text{TeV}}{c_{a\Phi}}\right)^2\left(\frac{\text{TeV}}{m_a}\right)$$

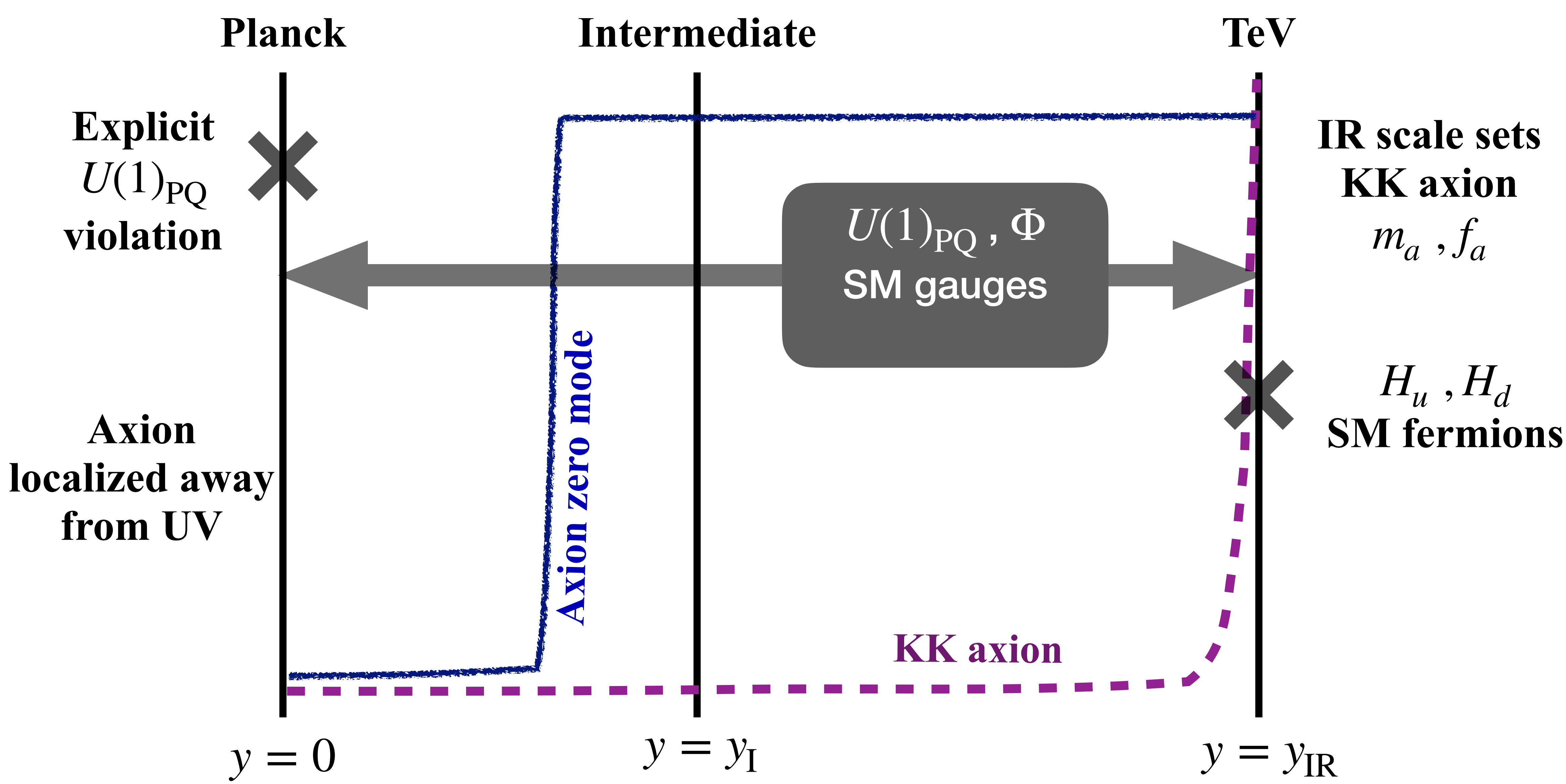
ALP decays promptly

- A multi-TeV muon collider has great potential to explore TeV-scale ALPs.

Motivation: TeV scale ALPs

Choi PRL 92 101602 (2003)
Cox et. al. JHEP 01 188 (2020)
Lee et. al. JHEP 03 038 (2022)

- Simultaneous solution of the **QCD axion quality problem** and **electroweak naturalness problem** using a doubly composite dynamics.
- **Consequence: TeV scale KK axion with ~ TeV scale decay constant.**



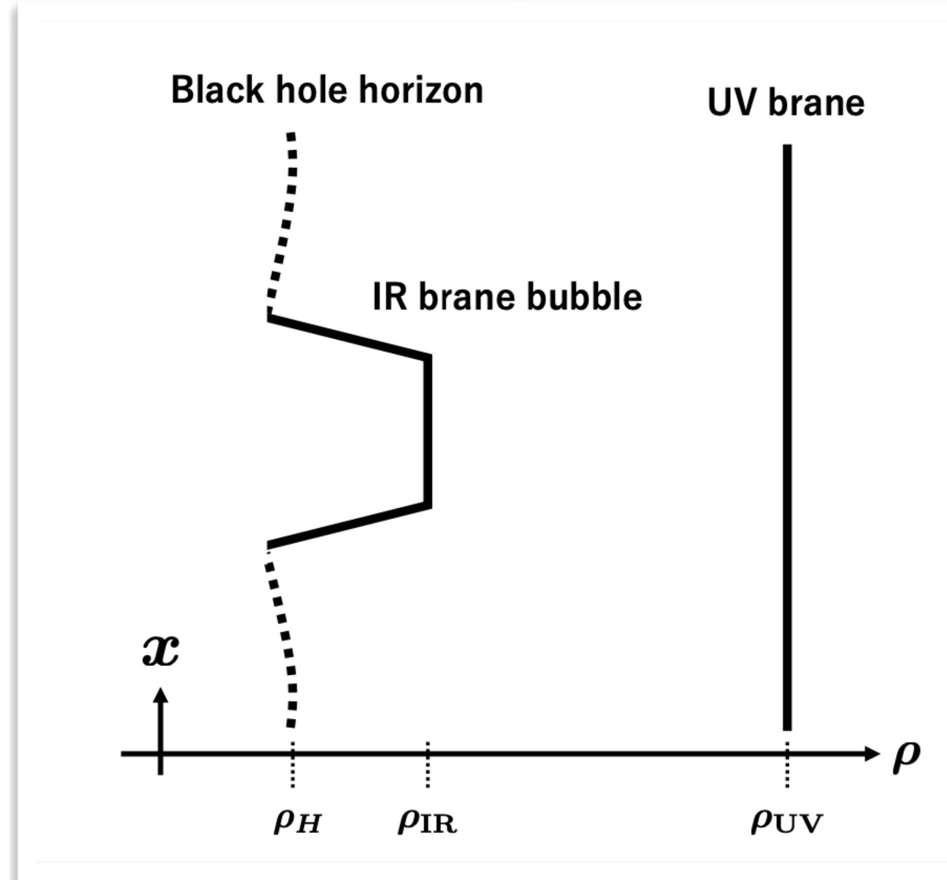
Related works: Multi-brane cosmology

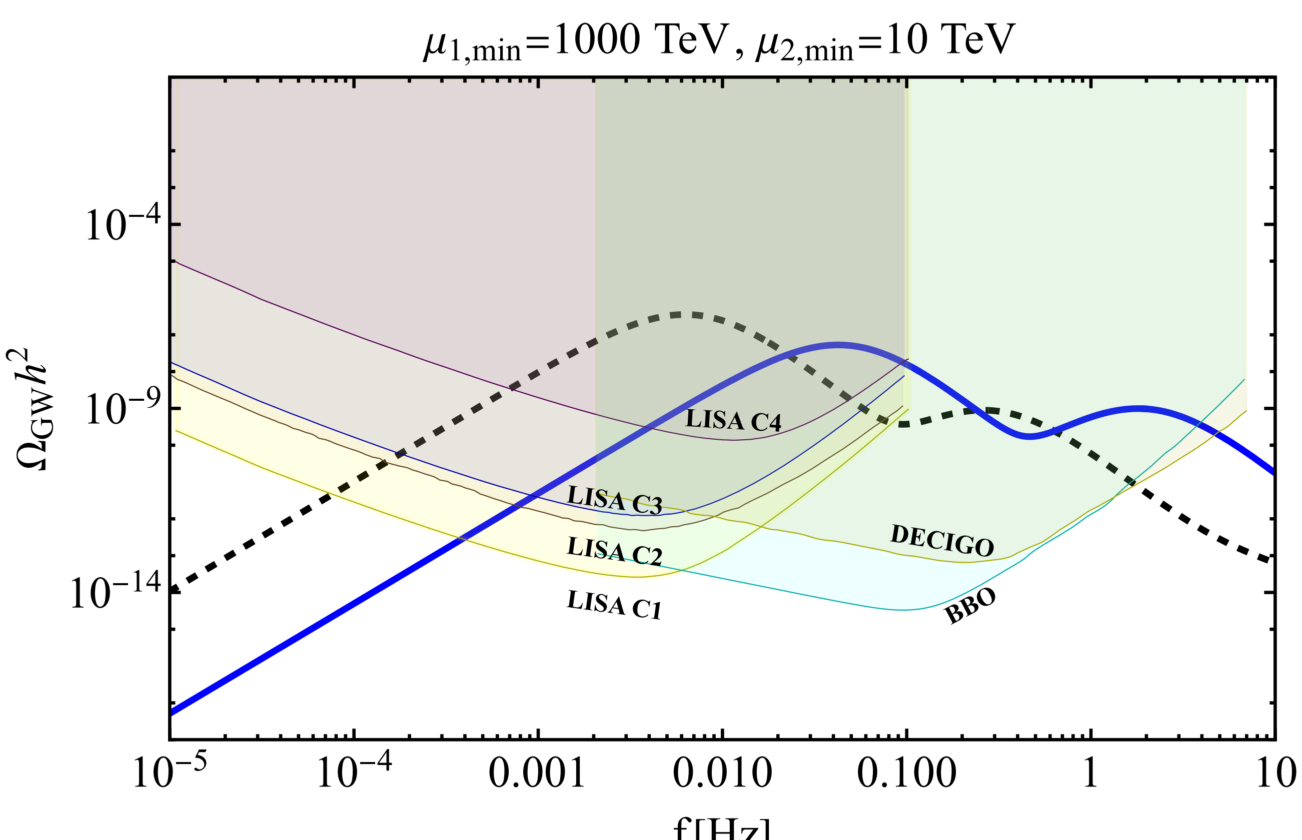
Creminelli et. al. (2002) ; Fujikura et. al. (2020)

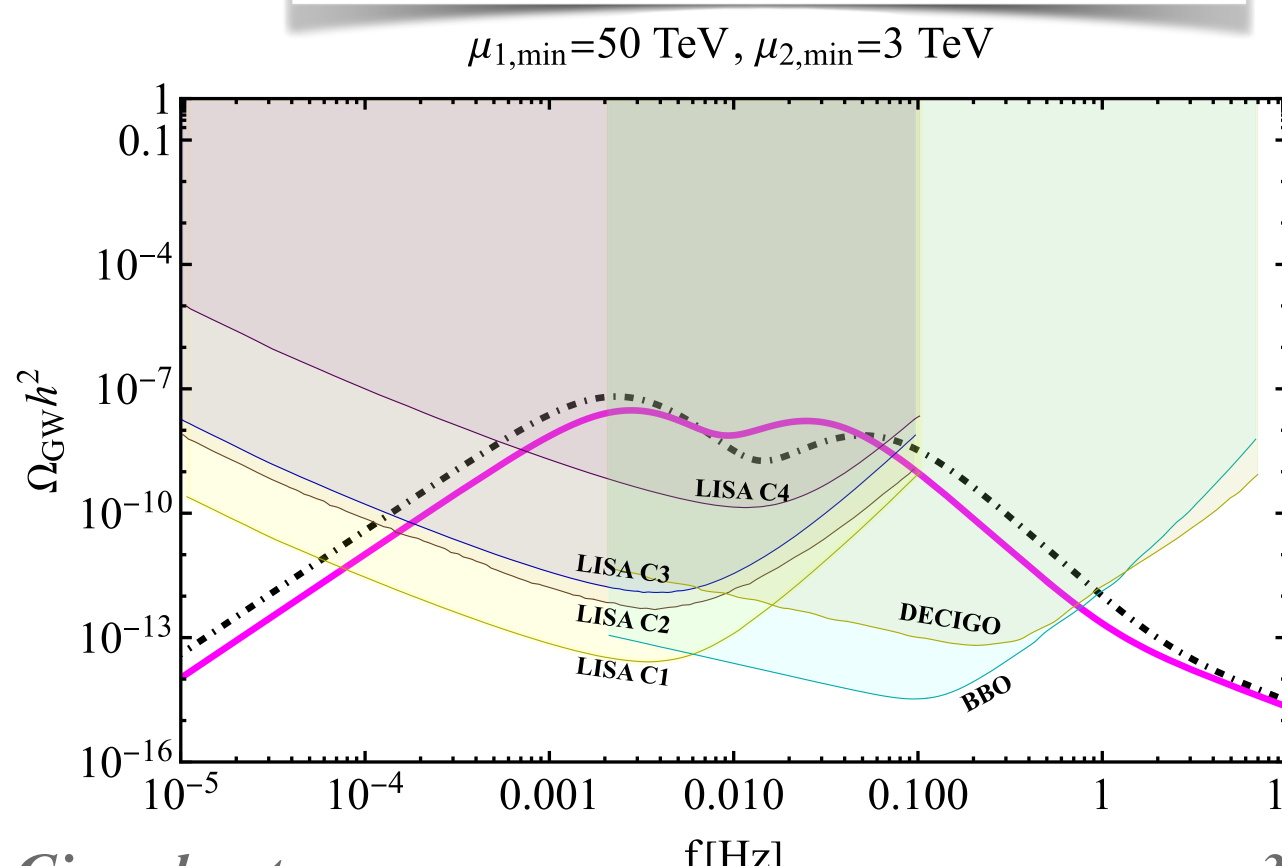
❖ Stabilization of multi-brane setup and cosmology (Nelson-Barr, axion quality…):
Lee, Nakai, Suzuki (2022); Girmohanta, Lee, Nakai, Suzuki (2022)

❖ Multi-peaks from consecutive phase transitions.
Girmohanta, Lee, Nakai, Suzuki (2023)

❖ Explanation of PTA signal, baryogenesis & dark matter with dark sector phase transition.
Fujikura, Girmohanta, Nakai, Suzuki (2023) ;
Fujikura, Girmohanta, Nakai, Zhang (2024)



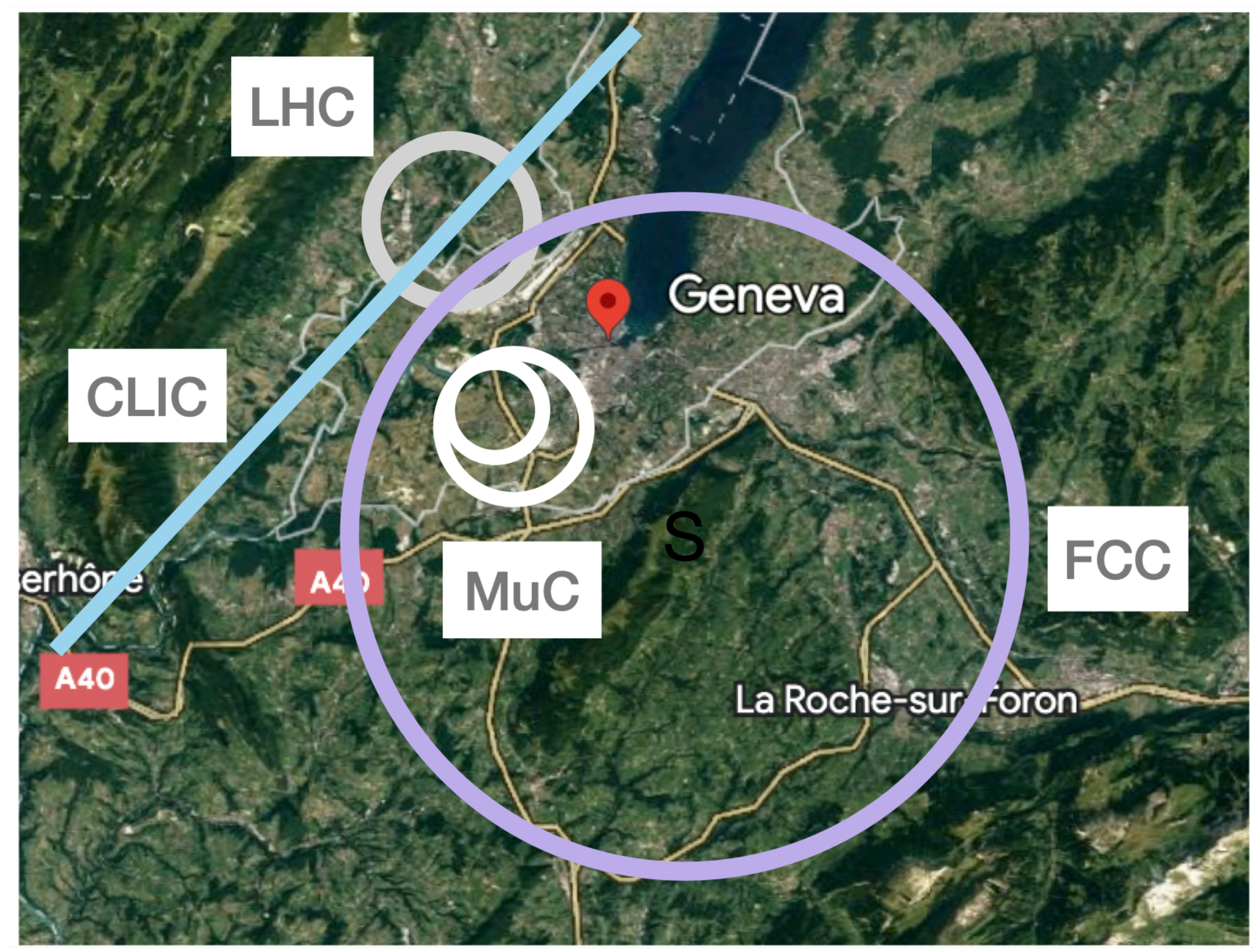




Muon Collider & TeV scale ALPs

Muon Collider & TeV scale ALPs

- **Synchrotron energy loss** ($\propto m_\mu^{-4}$) much smaller than electrons.
- Circular design can achieve **high luminosity** with multi-TeV $\sqrt{s}$.
- Significant beam energy is carried by **fundamental muons**, advantageous for producing TeV scale ALPs.
- **Multiple production channels** through VBF and $\mu^+\mu^-$ annihilation.
- Less overall background with larger $\sqrt{s}$ as inclusive cross-section remains small.



DiPetrillo's talk PASCOS 2024

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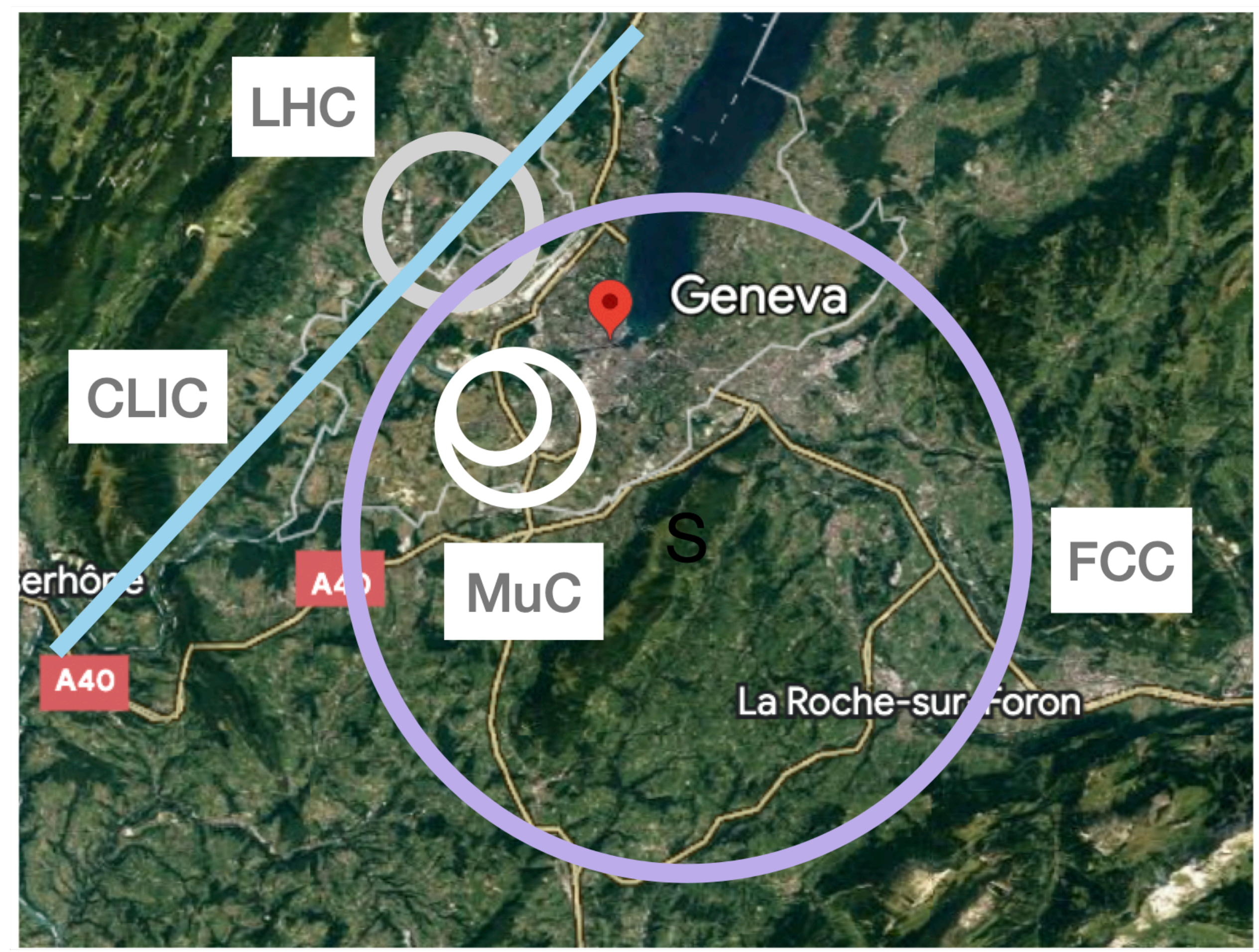
- **Multiple production channels** through VBF and $\mu^+\mu^-$ annihilation.
- Less overall background with larger $\sqrt{s}$ as inclusive cross-section remains small.
- **Beam induced background** (BIB) poses significant challenge.
- Recent progress in 1.5 TeV detector design and dedicated mitigation of BIB.



DiPetrillo's talk PASCOS 2024

Tops of ALPs

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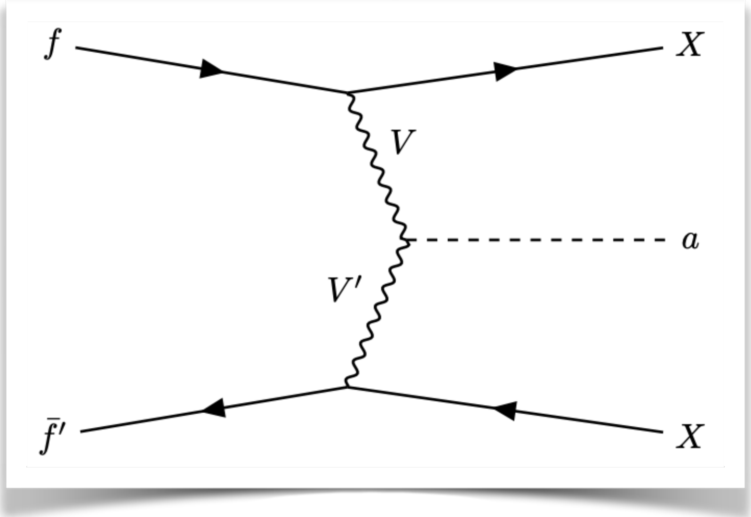
❖ Studies have focussed on the **ALP-EW gauge boson** interactions. ***Bao et. al. (2022)*** ***Han et. al. (2022)***



High energy muon collider is also a VBF machine: cross-section enhancement $\sim \ln\left(\hat{s}/m_V^2\right)$**.**

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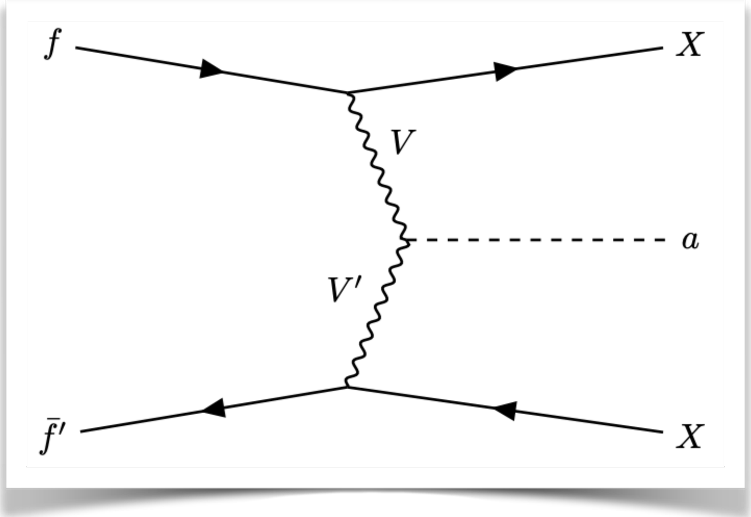
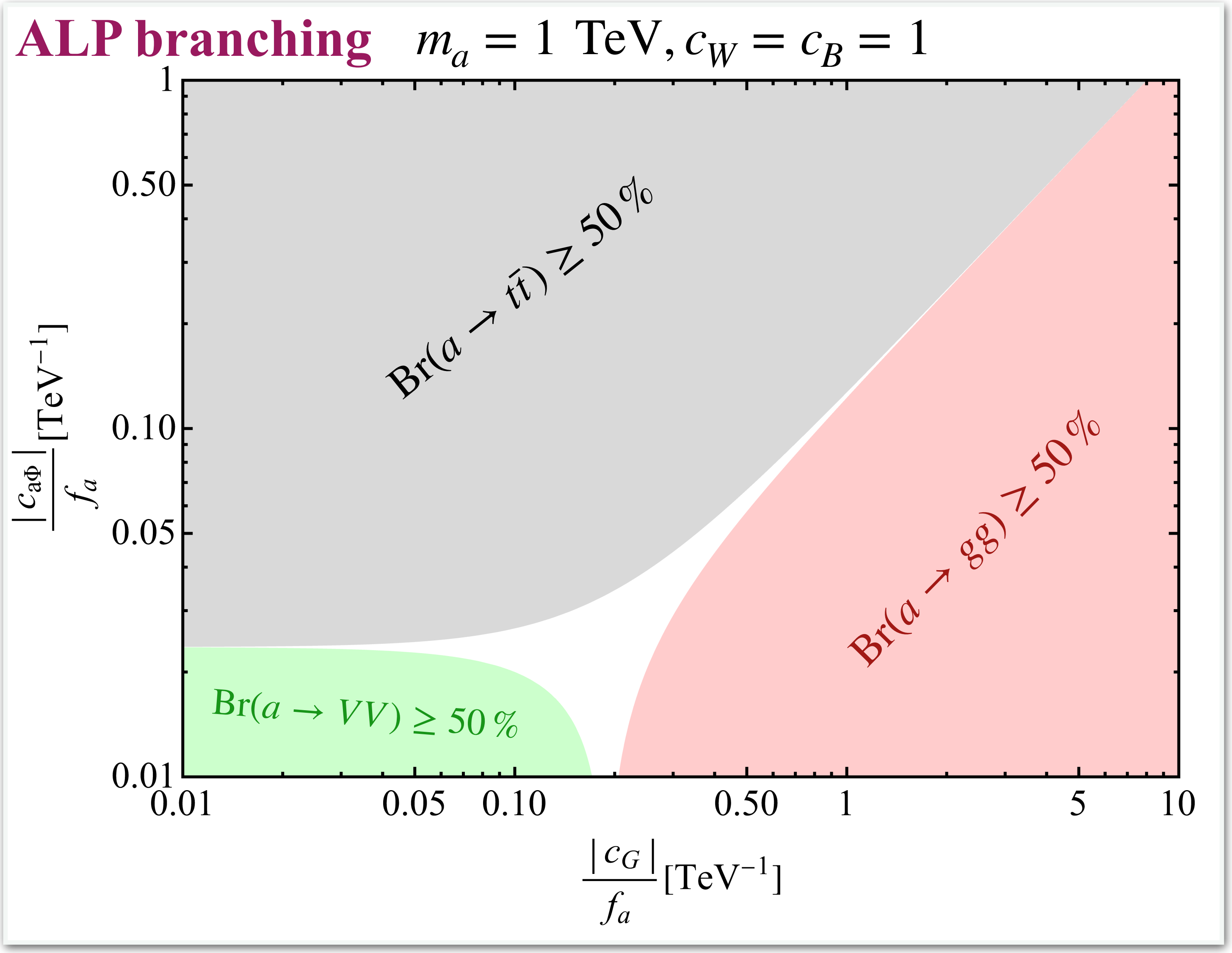


High energy muon collider is also a VBF machine: cross-section enhancement $\sim \ln\left(\hat{s}/m_V^2\right)$.

- **ALP-fermion** and gluon couplings are present in general and modify the phenomenology drastically.

- TeV scale ALPs dominantly decay to $t\bar{t}$ when $c_{a\Phi} \sim \mathcal{O}(1)$.

- **How large can these couplings be?**



Unitarity as a guiding principle

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- ALP EFT operators lead to rapid increase in scattering amplitude of $2 \rightarrow 2$ processes with CM energy $\sqrt{s} \implies$ **constrained by partial wave unitarity.**

$\left(\frac{\alpha_s}{4\pi}\right)\left\|c_G\right\| \lesssim 0.3\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right)$	$\left(\frac{\alpha_2}{4\pi}\right)\left\|c_W\right\| \lesssim 2.1\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right)$
$\left(\frac{\alpha_1}{4\pi}\right)\left\|c_B\right\| \lesssim 2.7\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right)$	$\left\|c_{a\Phi}\right\| \lesssim 30\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right)$

Brivio et. al. (2021)

ALP-fermion coupling loosely constrained

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$$\left(\frac{\alpha_1}{4\pi}\right)|c_B| \lesssim 2.7\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right) \qquad |c_{a\Phi}| \lesssim 30\left(\frac{f_a}{\text{TeV}}\right)\left(\frac{\text{TeV}}{\sqrt{s}}\right)$$

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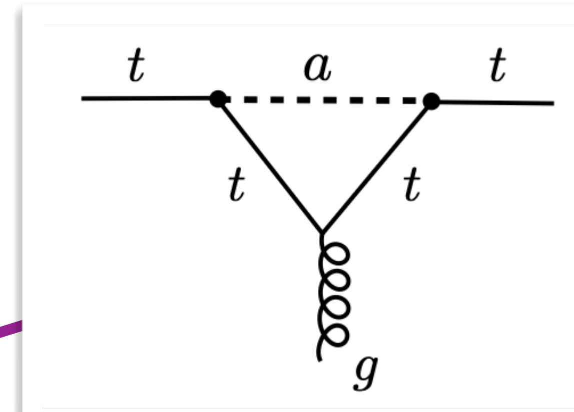
ALP-fermion coupling loosely constrained

- Simplified benchmark parameters to explore ALP-fermion couplings.

c_W	c_B	c_G	$\|c_{a\Phi}\|/f_a$ [TeV^{-1}]	m_a [TeV]
0	0	0	6	1



- Contribution to top chromomagnetic moment $\hat{\mu}_t \sim -7 \times 10^{-4}$, well below the CMS bound $-0.014 < \mathfrak{R}(\hat{\mu}_t) < 0.004$. Contribution to $g_\mu - 2$ negligible.

Top associated ALP production

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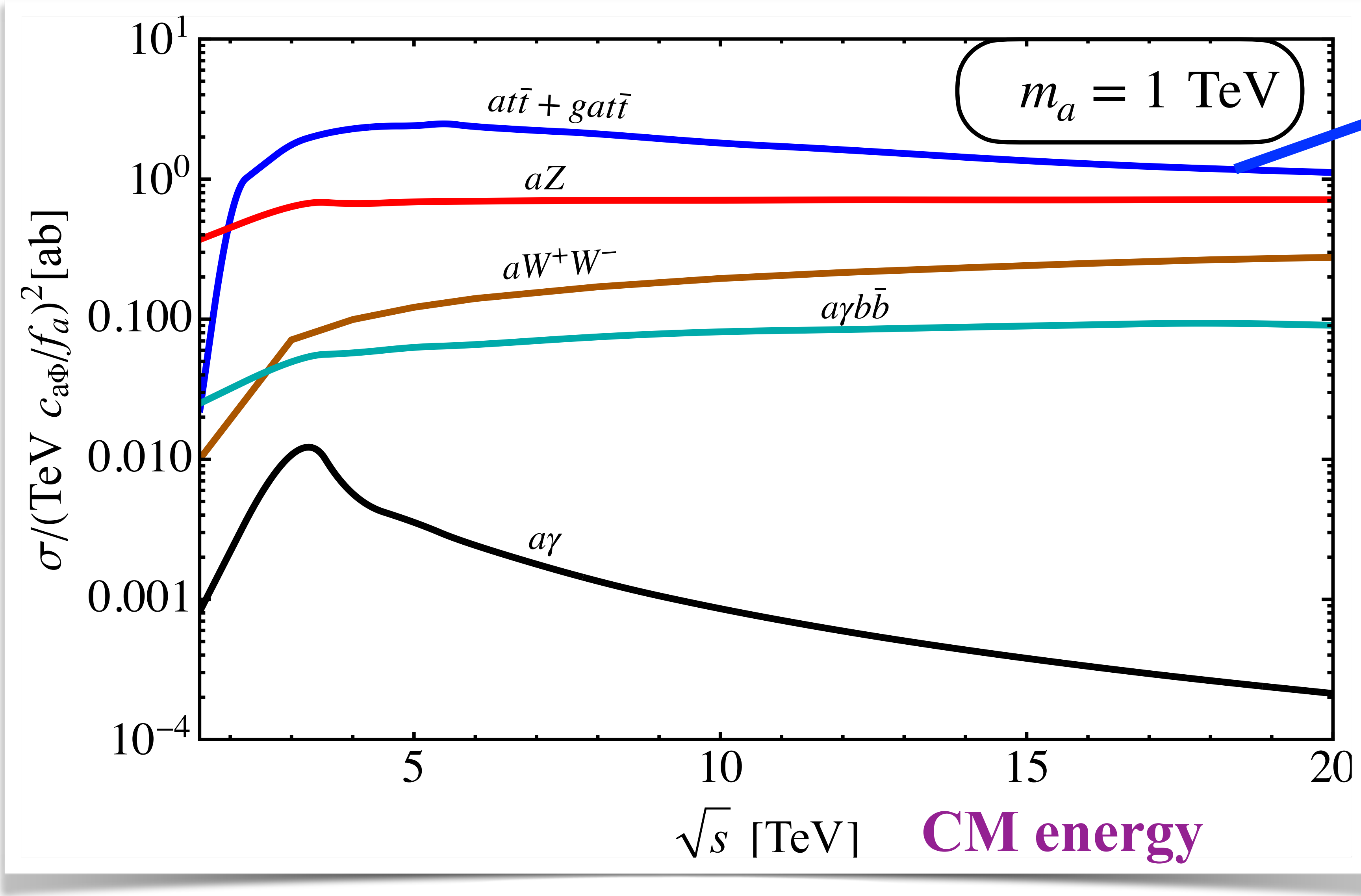

$\mu^+\mu^- \to t\bar{t}a(+g)$
dominant production channel.

VBF contribution & more than one gluon emission $\lesssim \mathcal{O}(10\%)$ **correction.**

a **promptly decays to** $t\bar{t}$**.**
$c\tau_a \sim 200$ fm.

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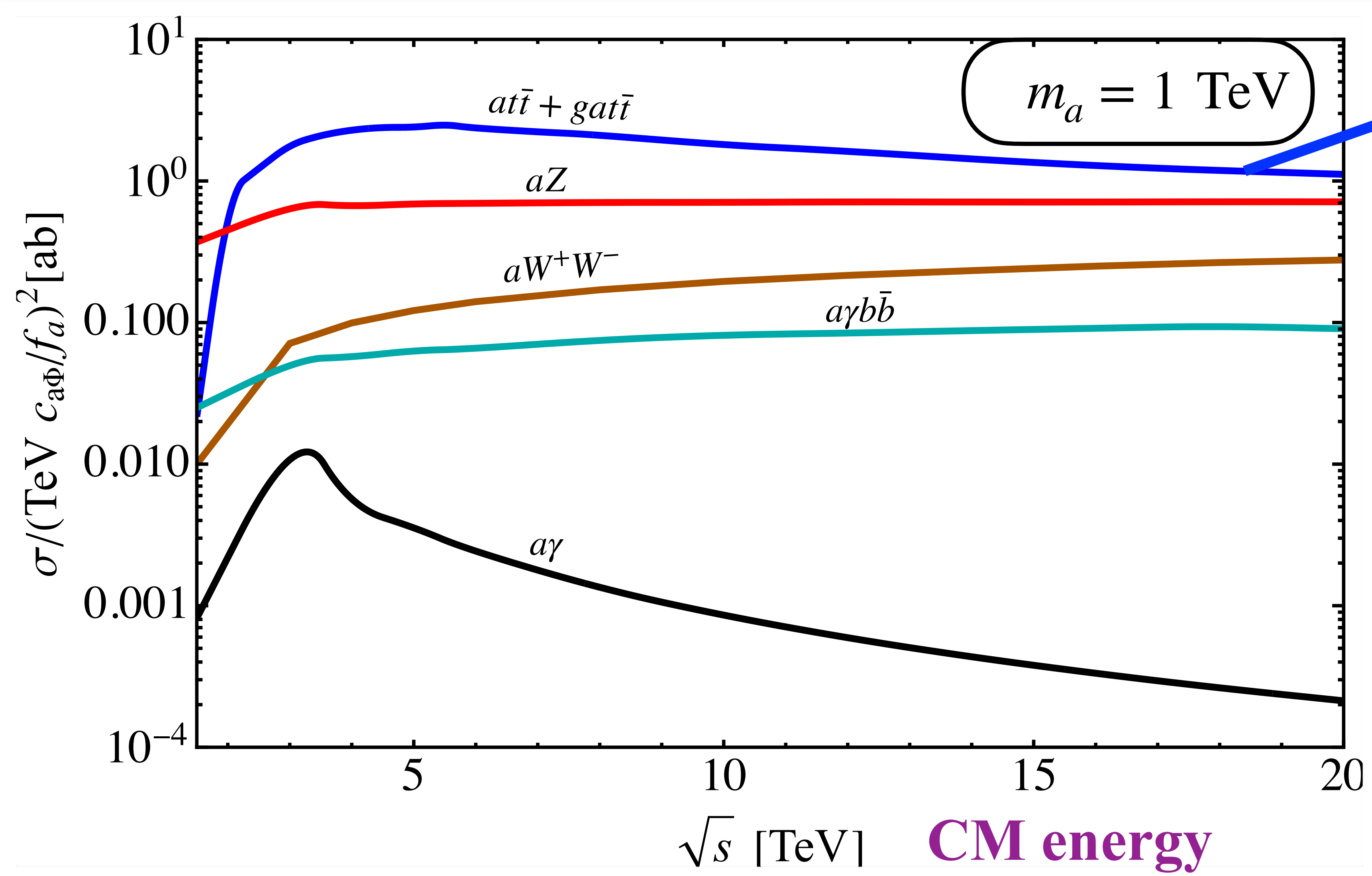
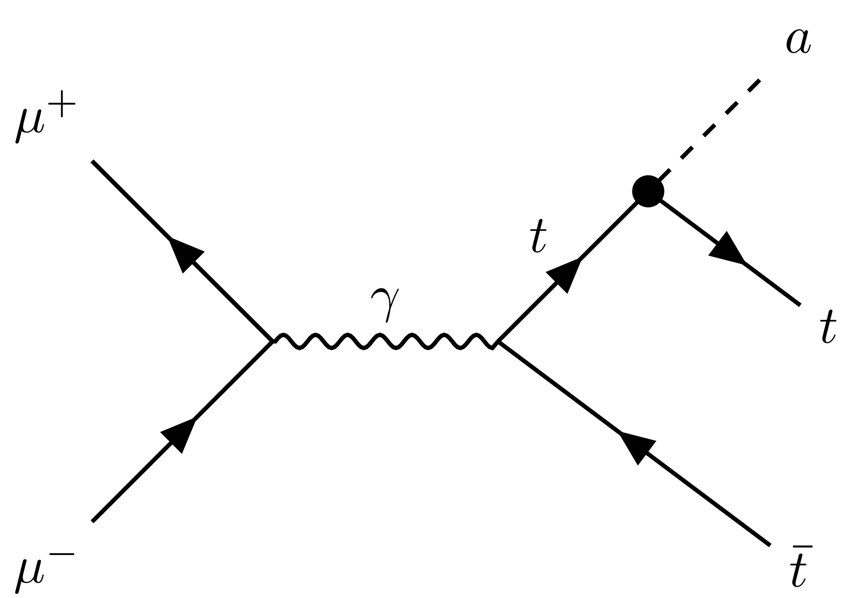


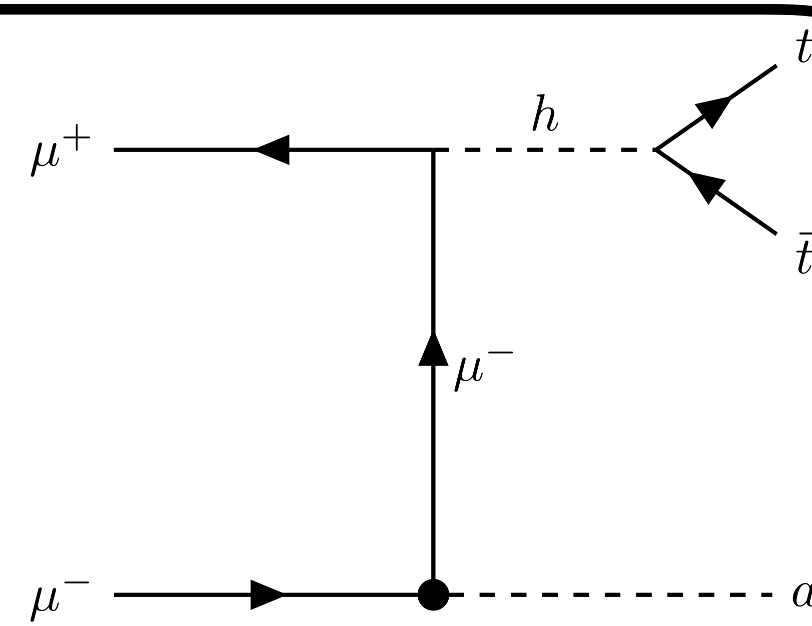
$\mu^+\mu^- \to t\bar{t}a(+g)$ **dominant production channel.**

VBF contribution & more than one gluon emission $\lesssim \mathcal{O}(10\%)$ correction.

a promptly decays to $t\bar{t}$.
$c\tau_a \sim 200$ fm.

Look for 4-top signal events ($t\bar{t}t\bar{t}$).





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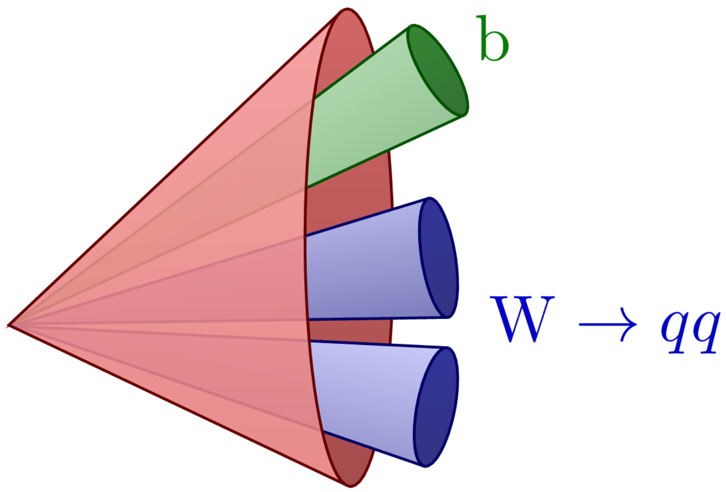
- We utilize **hadronic decays** of the top and identify **boosted top-jet candidate** using jet reconstructed mass.

- In hadron colliders, due to smaller partonic energy for 4-top events, analysis with leptonic decays is preferable.

ATLAS (2023), CMS (2023)



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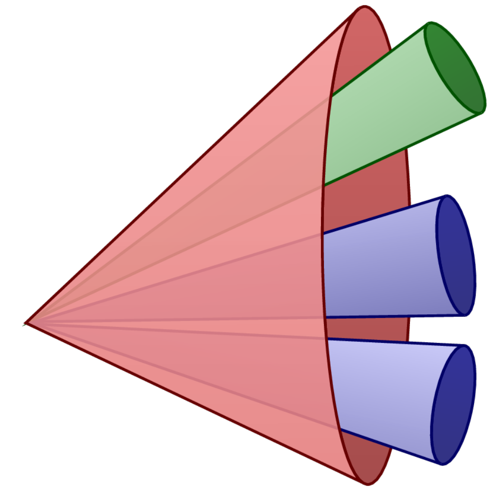

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ATLAS (2023), CMS (2023)

- Short muon lifetime (2.2 μs) $\Longrightarrow$ decay products and secondary interactions give rise to beam induced background (BIB).
- Challenge: **separating true jets from BIB fake-jets**.
- Use **BIB characteristics** to discriminate. *Muon collider collaboration (2022)*

☑ Low transverse momenta p_{T}.

☑ Asynchronous time of arrival.

☑ Displaced origin.

☑ High absolute pseudo-rapidity η.

BIB Reduction and Backgrounds

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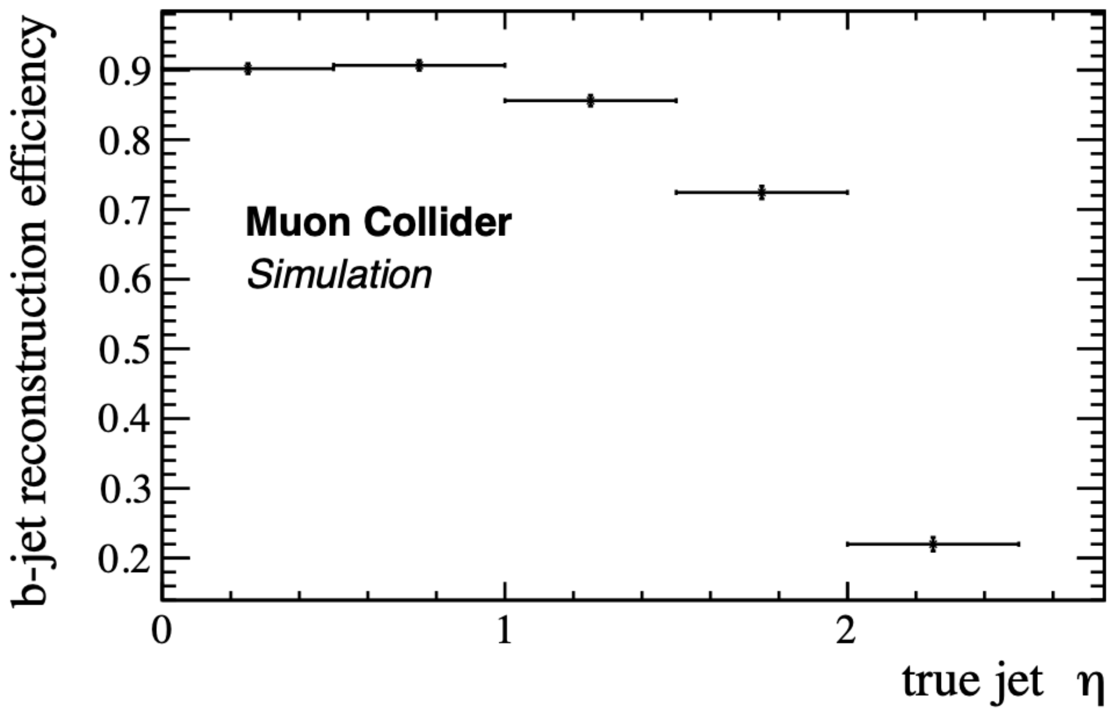
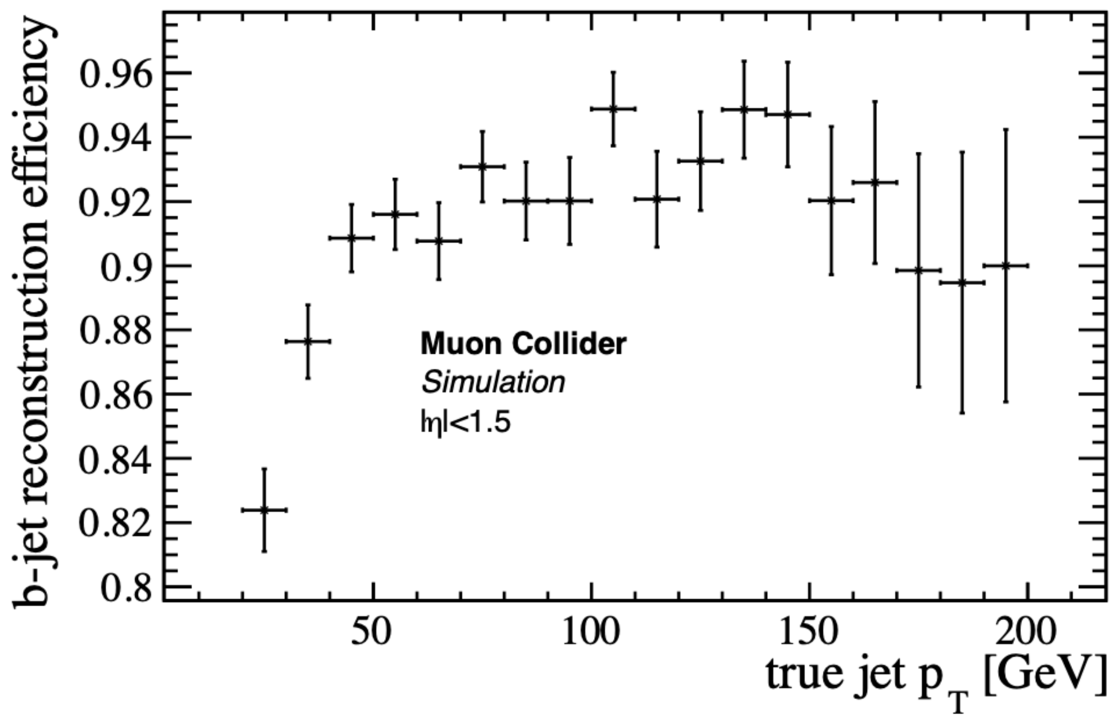
Muon collider collaboration (2022)





- **Jet selection (n_{jet}):** jets with $|\eta| < 1.5$ and $p_{\text{T,jet}} > 50$ GeV. Efficiency ~ 0.9.
- **Top candidate (n_{top}):** Selected jets with $140 \text{ GeV} \leq m_j \leq 220 \text{ GeV}$.

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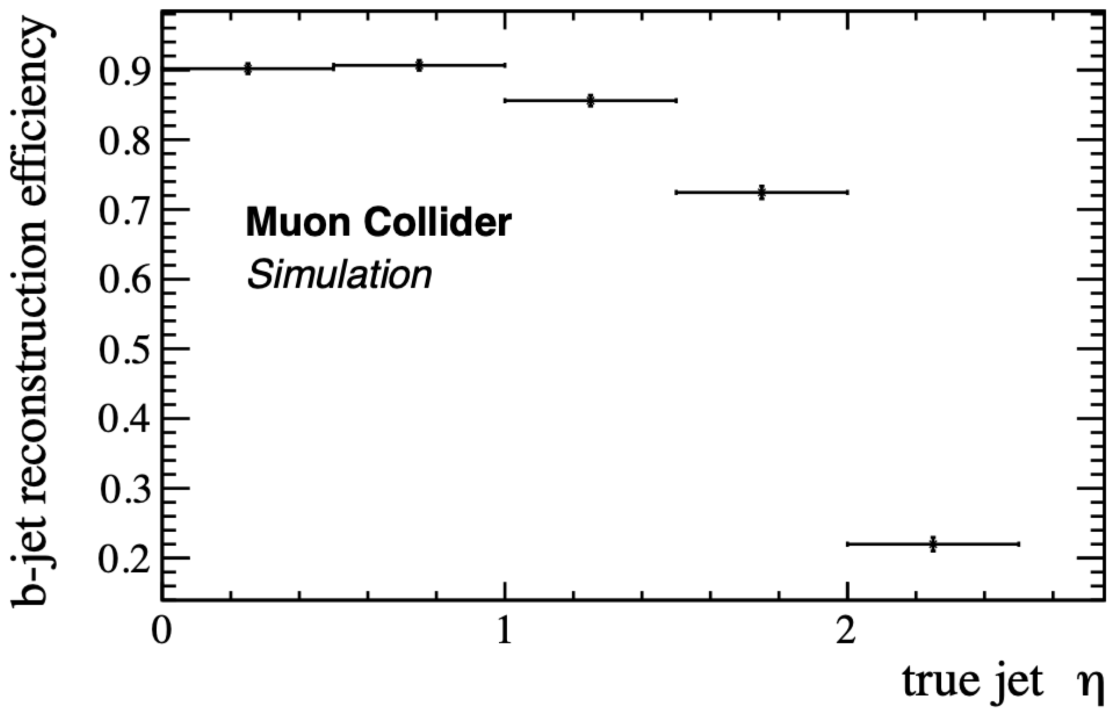

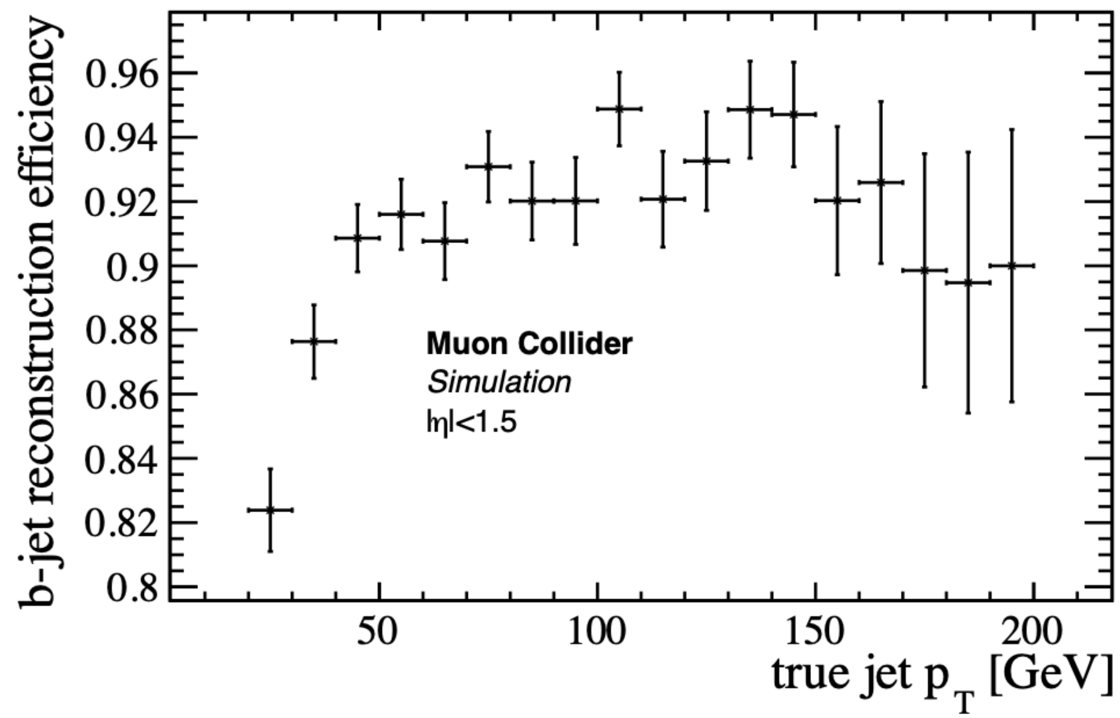

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- We demand $n_{\text{top}} \geq 3$ for signal events.
- Trims down plethora of backgrounds with less number of top candidates.
- **Dominant backgrounds considered: SM $t\bar{t}t\bar{t}$, $t\bar{t}W^+W^-$, $t\bar{t}h$, $t\bar{t}Z$.**

Event selection and cut-flow

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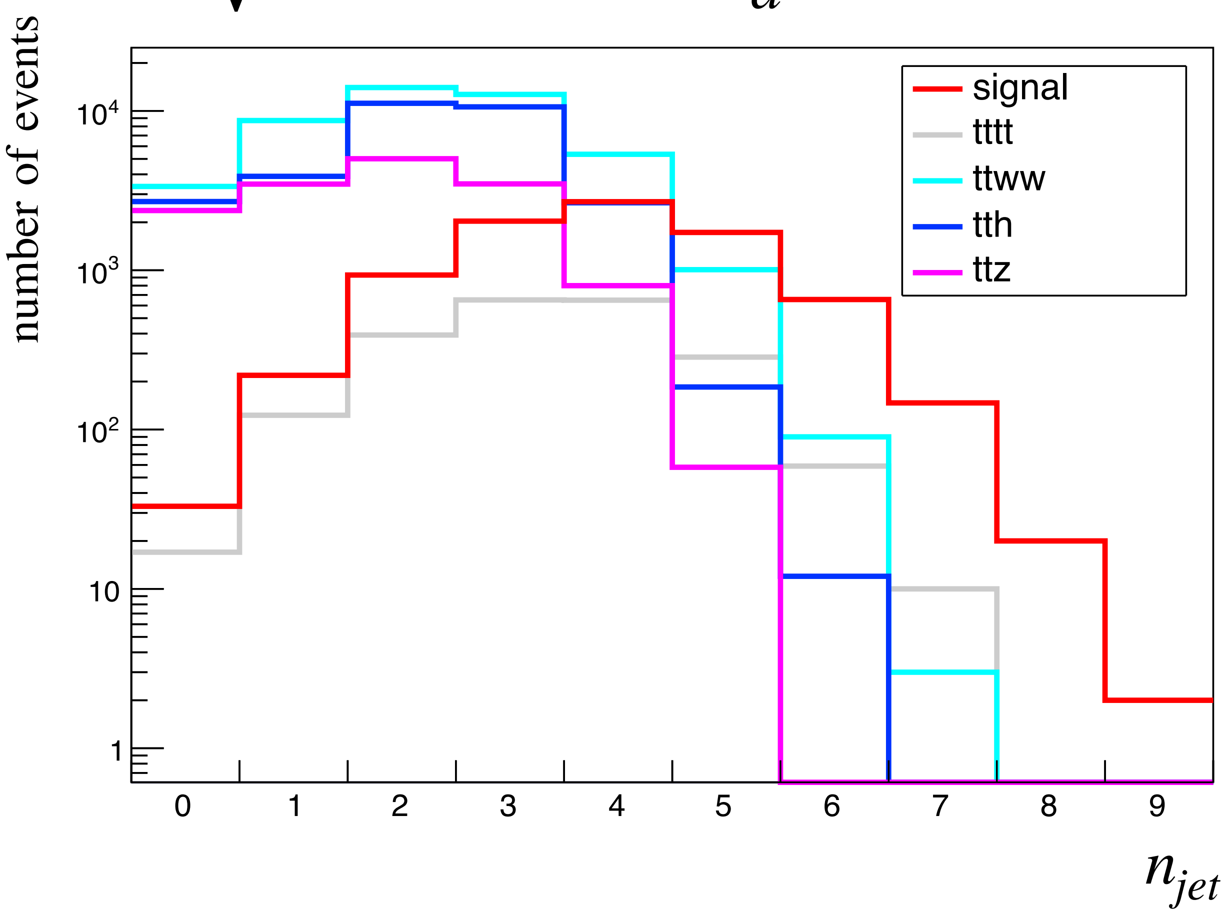
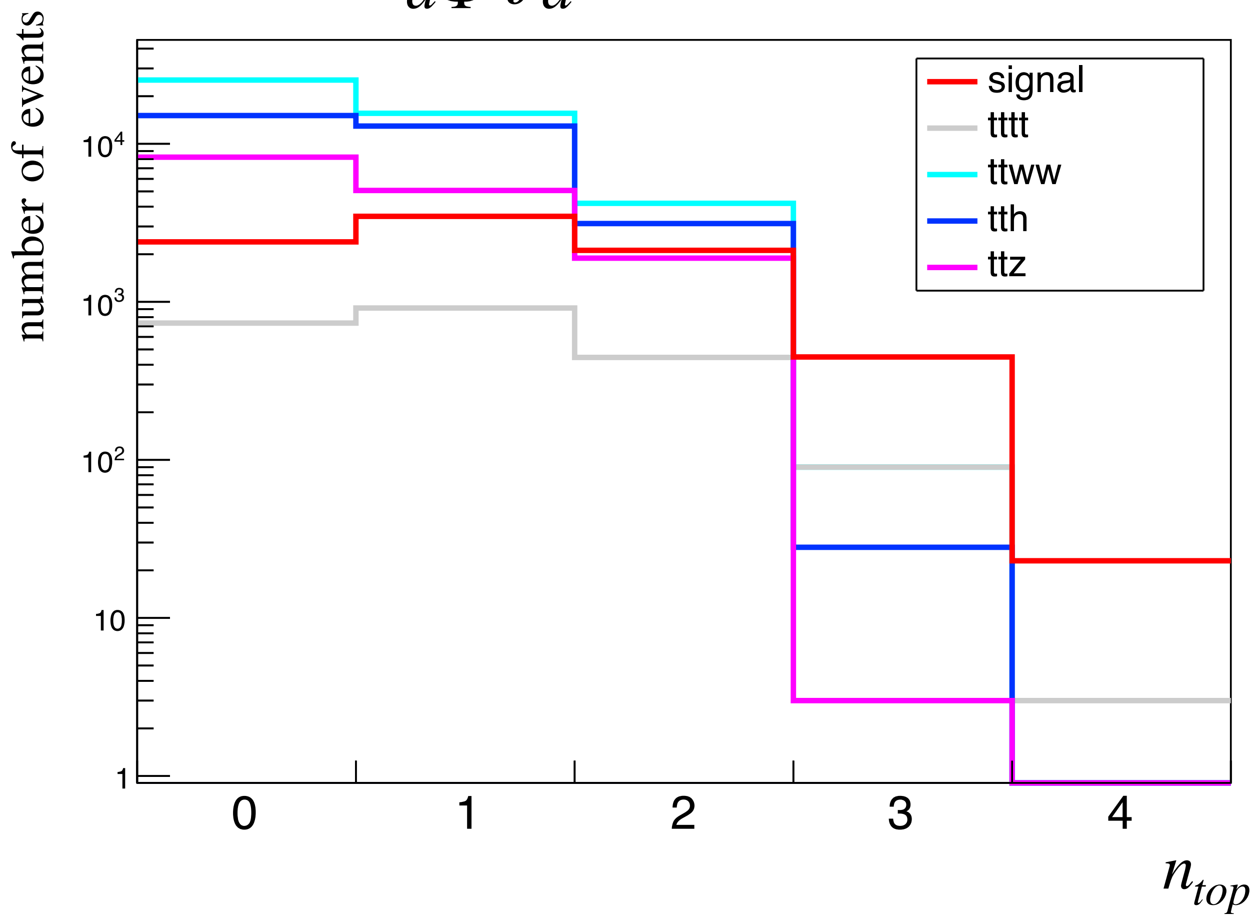
$$\sqrt{s} = 5\ \text{TeV}, m_a = 1\ \text{TeV}, \mathscr{L} = 100\ \text{ab}^{-1}, c_{a\Phi}/f_a = 6\ \text{TeV}^{-1}$$





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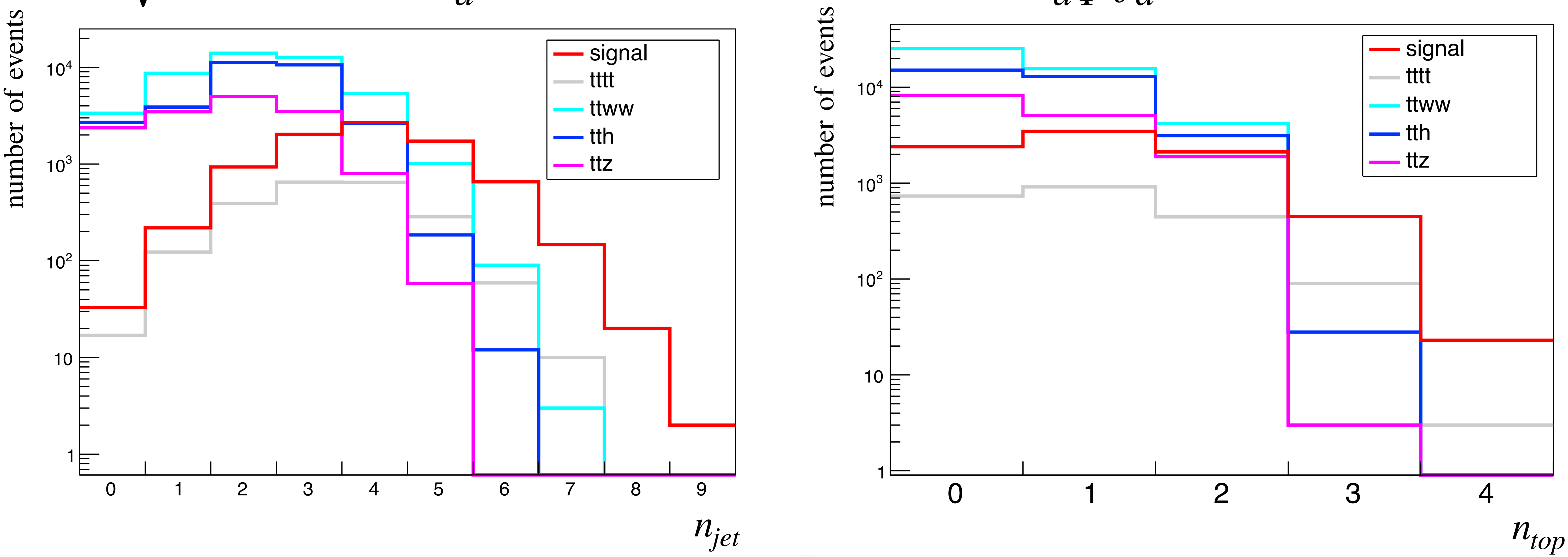

cut \ processes	$t\bar{t}a$ [Signal]	$t\bar{t}t\bar{t}$	$t\bar{t}W^+W^-$	$t\bar{t}h$	$t\bar{t}Z$
origin	9015	2285	46510	32380	15790
$n_{\text{top}} \geq 3$	495 (5.5%)	82 (4%)	37 (0.1%)	26 (0.1%)	3 (0.02%)
$n_{\text{jet}} \geq 4$	417 (4.6%)	65 (2.8%)	19 (0.04%)	< 1	< 1

Cut-flow

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$\sqrt{s} = 10$ TeV, $m_a = 1$ TeV, $\mathscr{L} = 100$ ab^{-1}, $c_{a\Phi}/f_a = 6$ TeV^{-1}

processes / cut	$t\bar{t}a$ [Signal]	$t\bar{t}t\bar{t}$	$t\bar{t}W^+W^-$	$t\bar{t}h$	$t\bar{t}Z$
origin	6625	1509	34970	12300	67730
$n_{\rm top} \geq 3$	784 (12%)	146 (10%)	49 (0.1%)	9 (0.1%)	61 (0.1%)
$n_{\rm jet} \geq 4$	757 (11%)	136 (9%)	24 (0.1%)	< 1	7 (0.01%)

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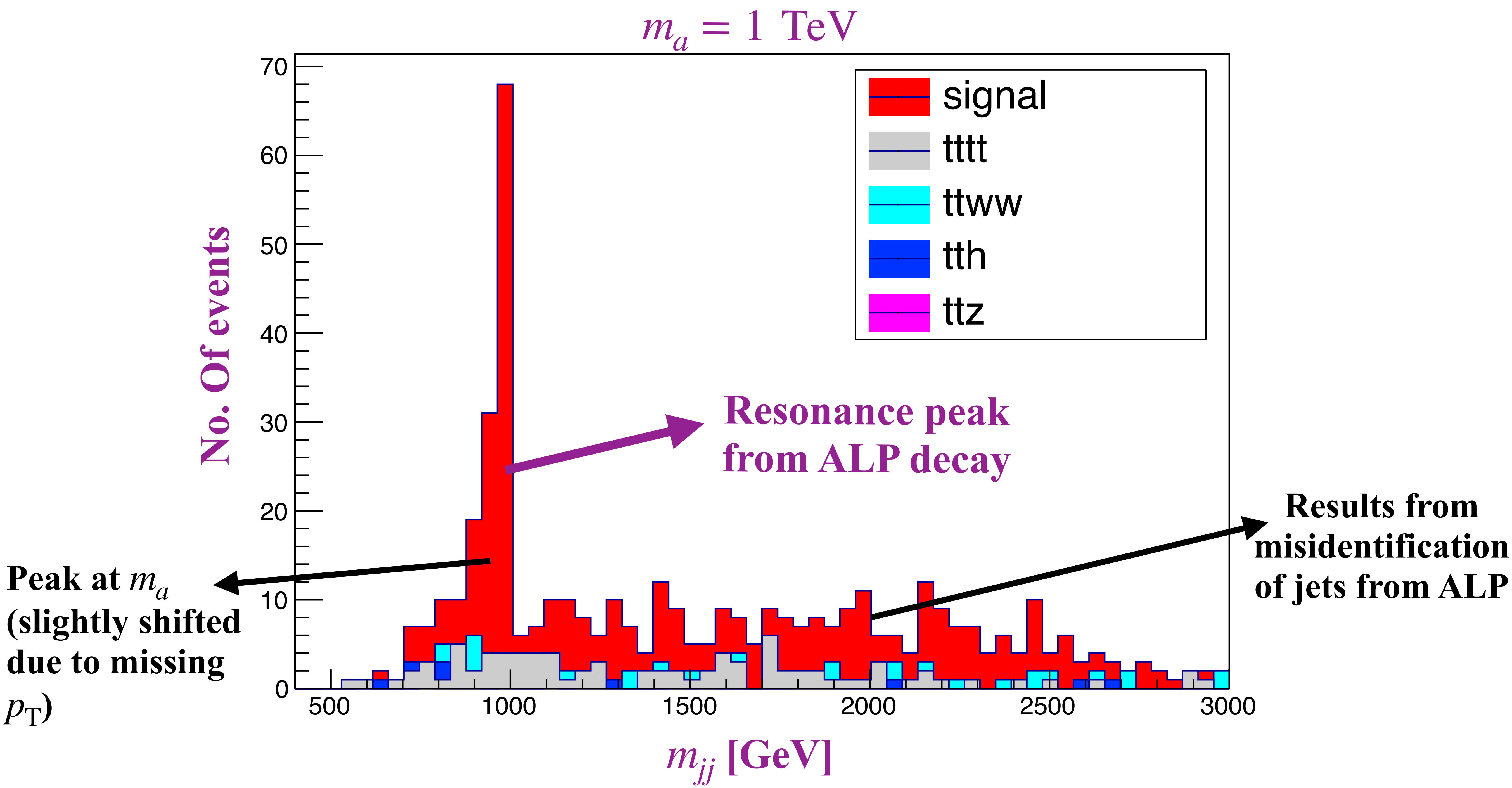
- Notice top reconstruction improves with increasing $\sqrt{s}$.
- Effective reduction of background using $n_{\rm top}$ and $n_{\rm jet}$.
- ALP decay: two top-jets with least $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ selected.
- Use of boosted top jets allows us to **reconstruct the resonance peak in dijet invariant mass distribution** m_{jj}.

Dijet invariant mass distribution



❖ Need to perform **fitting of this distribution** to evaluate signal significance.

Statistical Treatment

Statistical Treatment

- λ_i : Expected no. of events in the i^{th} bin.

b_i **: smooth distribution**

$$\lambda_i = \sum_{k=0}^{3} \beta_k \left(m_{jj}^{(i)}\right)^k + A \exp\left(-\frac{\left(m_{jj}^{(i)} - m_0\right)^2}{2\sigma^2}\right)$$

s_i **: peak structure**

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s_i : peak structure

- Prepared simulation data for multiple ALP mass m_a . Best fit gives:

$$\tilde{\lambda}_i(\mu) = \tilde{b}_i + \mu \tilde{s}_i \quad ; \; \tilde{\lambda}_i(\mu = 1) : \text{Expected events for ALP model}.$$

- $\tilde{b}_i$ contains both SM background + smooth contribution from intermediate ALP $\Longrightarrow$ robust against possible systematics altering the smooth dijet distribution.

Likelihood function:

$$L(\mathbf{o}; \mu) = \prod_{i=1}^{N_B} \frac{e^{-\tilde{\lambda}_i(\mu)} \tilde{\lambda}_i(\mu)^{o_i}}{\Gamma(o_i + 1)}$$

o_i : **histogram data**
N_{B} : **No. Of bins**

Test statistic

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Test-statistic :

$$q_0 = -2 \ln \frac{L(\mathbf{o}; \mu = 0)}{L(\mathbf{o}; \mu = 1)}$$

Wilks theorem

Asymptotically obeys

χ^2 **distribution with d.o.f** $= 1$**.**

5σ CL : $\sqrt{q_0} = 5$

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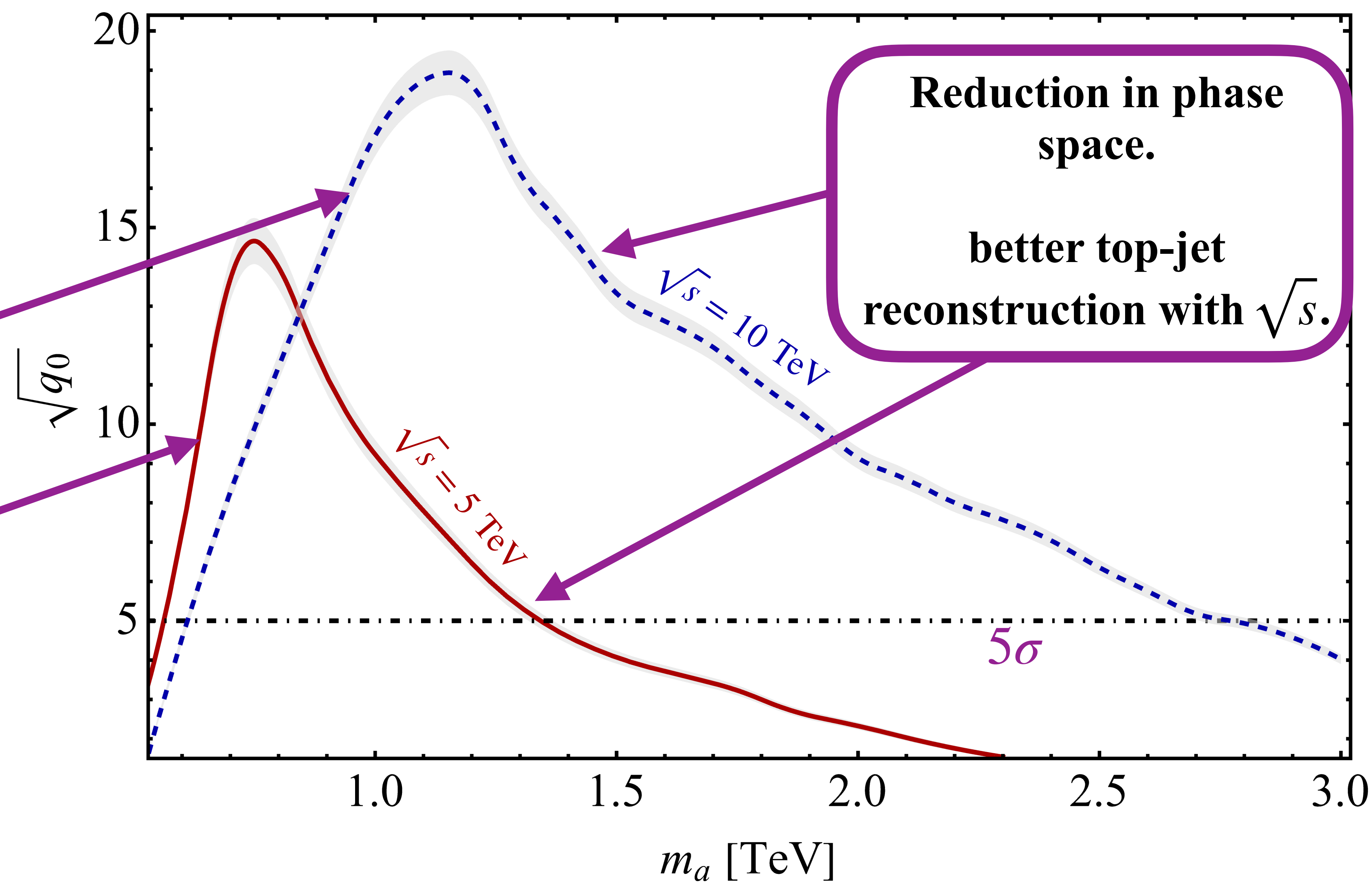
Wilks theorem

Asymptotically obeys χ^2 distribution with d.o.f $=1$.

5σ CL $: \sqrt{q_0} = 5$

Low m_a : tops from ALP decay highly collimated in the lab frame, clustered as single jet.

Verified by finding peak in jet mass histogram at m_a.



Results

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- 5σ reach in the coupling-mass plane? $\sqrt{q_0}$ **does not scale with coupling.** Non-trivial dependence on BG and jet-reconstruction efficiency.
- Nevertheless, **signal cross-section scales with** $(c_{a\Phi}/f_a)^2$. Get coupling corresponding to $\sqrt{q_0} = 5$ for fixed m_a with the same BG.

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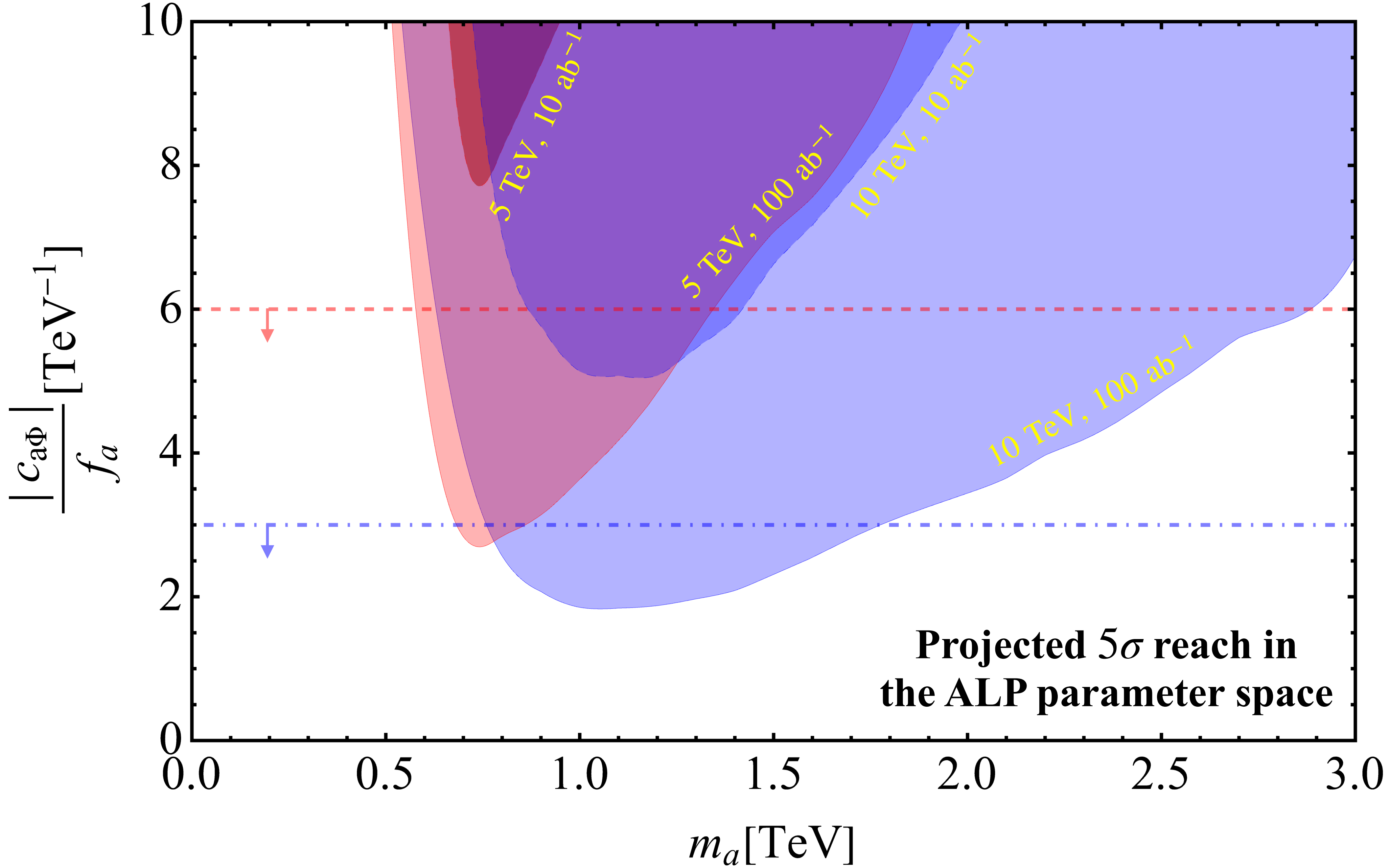
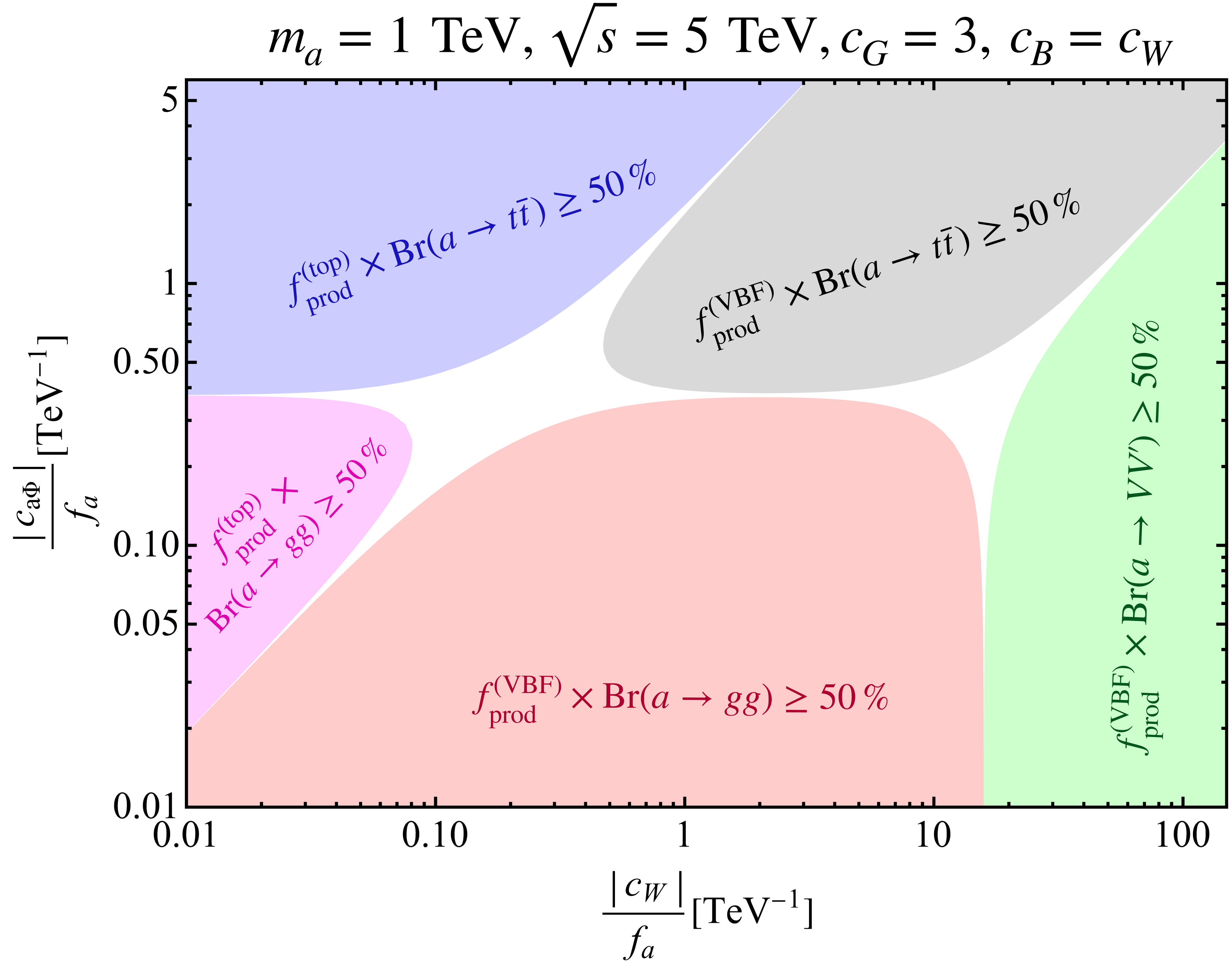


Exploring the uncharted : work in progress



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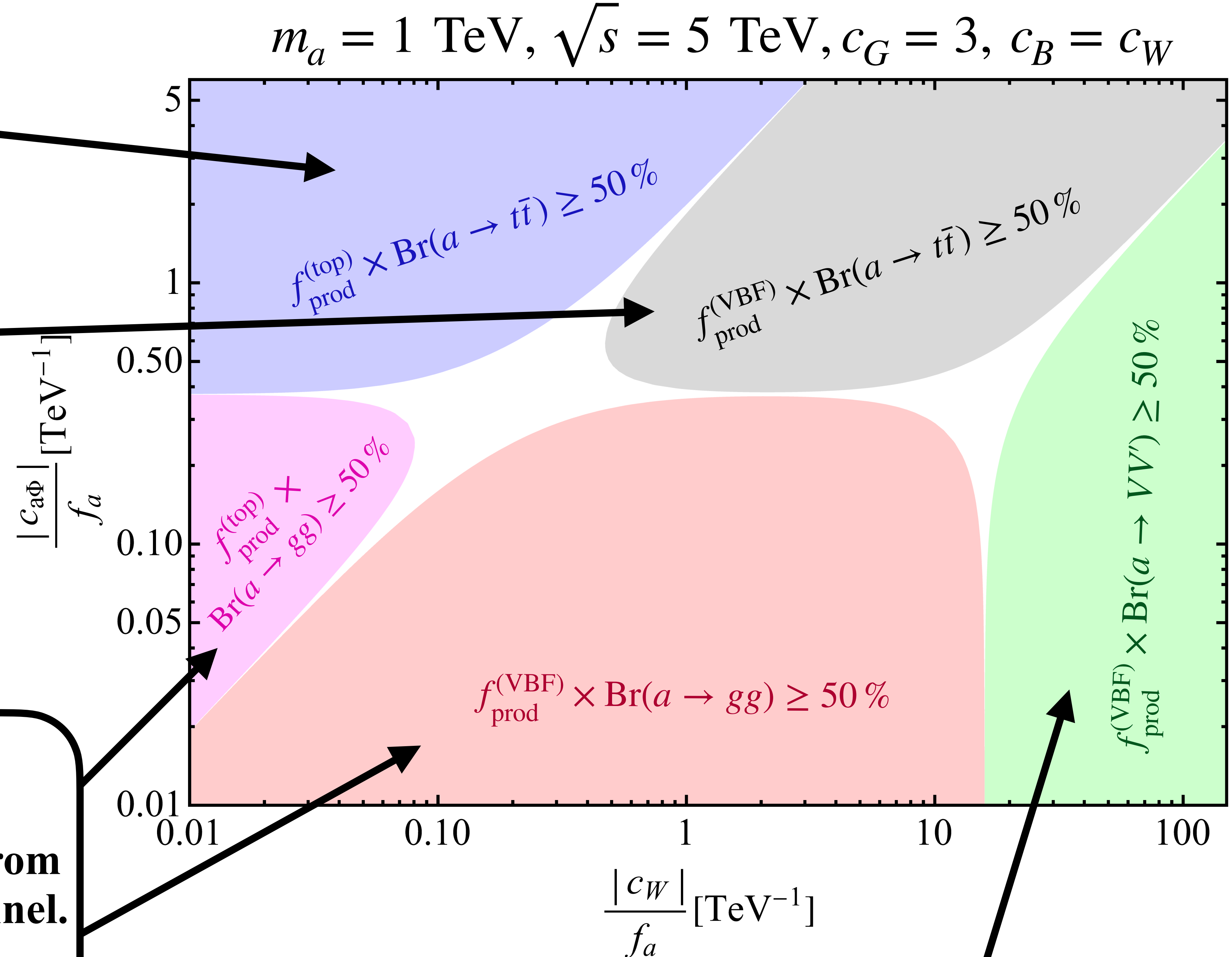


Present talk

Production by VBF but $a \to t\bar{t}$

Explore ALP-gluon coupling.

Challenge: Huge background from EW jets in VBF production channel.

Use of forward muons and jet-substructure can help.

Analyzed by Bao et. al. (2022), Han et. al. (2022)

Advertisement : Axion Quest Talk

Dr. Shota Nakagawa's talk on Friday Aug 09 at 3:30 PM

How Viable Is a QCD Axion near 10 MeV?

Sudhakantha Girmohanta, Shota Nakagawa, Yuichiro Nakai and Junxuan Xu

Tsung-Dao Lee Institute, Shanghai Jiao Tong University,
No. 1 Lisuo Road, Pudong New Area, Shanghai, 201210, China
School of Physics and Astronomy, Shanghai Jiao Tong University,
800 Dongchuan Road, Shanghai, 200240, China

Conclusions

- Multi-TeV future muon collider can have great capability in probing TeV scale ALP parameter space.
- ALP-fermion couplings are naturally present and can change the phenomenology drastically.
- We utilized ALP-top coupling and analyzed the 4-top channel.
- Peak in the dijet invariant mass distribution could be reconstructed, thanks to the boosted top decay products in a muon collider.
- A large territory uncharted in the TeV ALP parameter space where the interplay of ALP EFT couplings can be interesting.

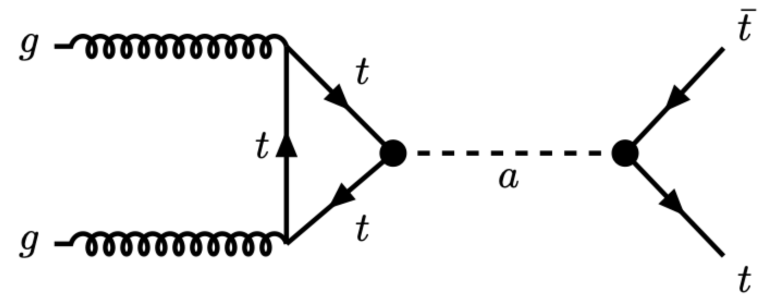
Thank you for your time! Questions?

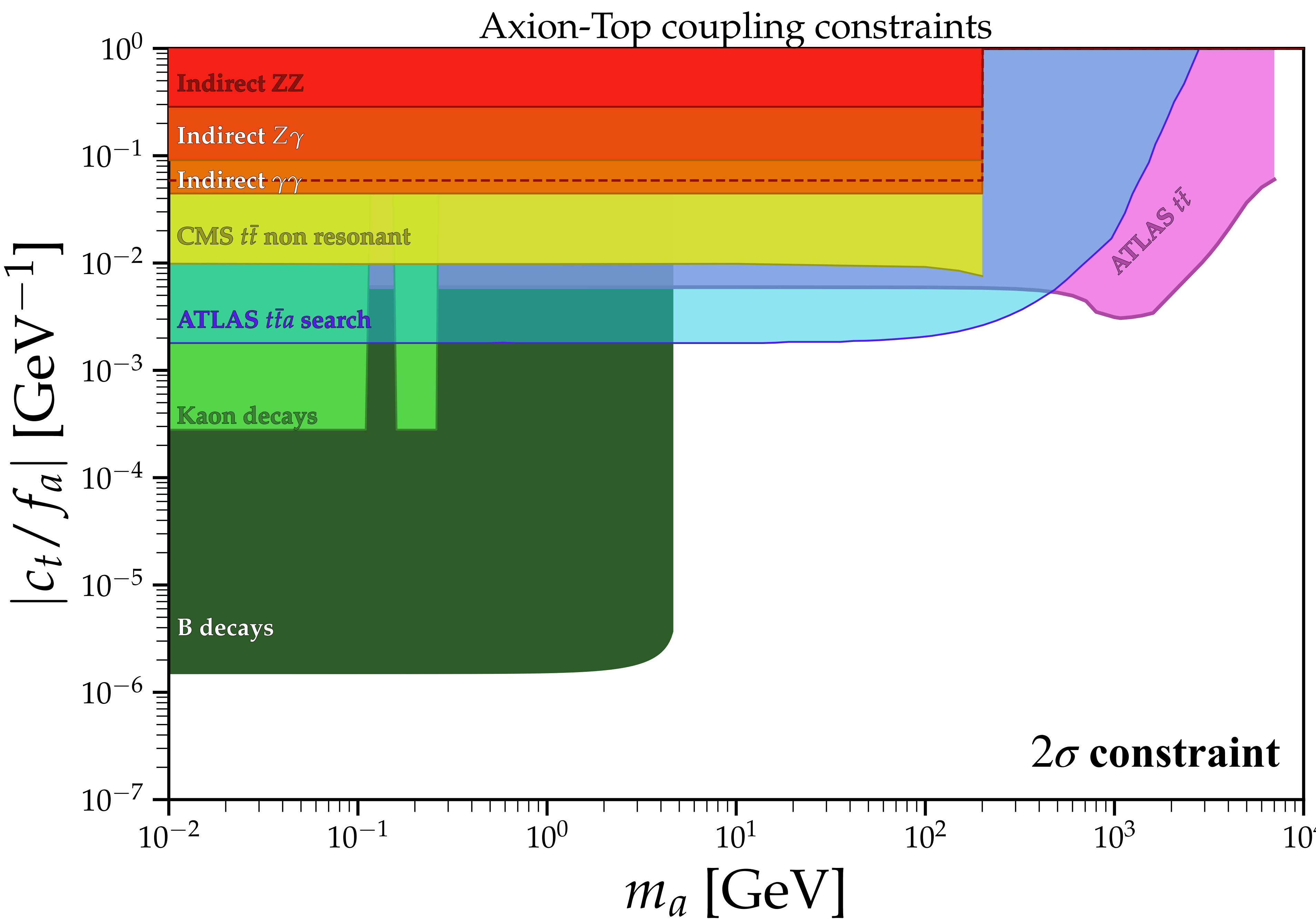
Backup

Backup

Esser et. al. 2023

Non-resonant ALP searches



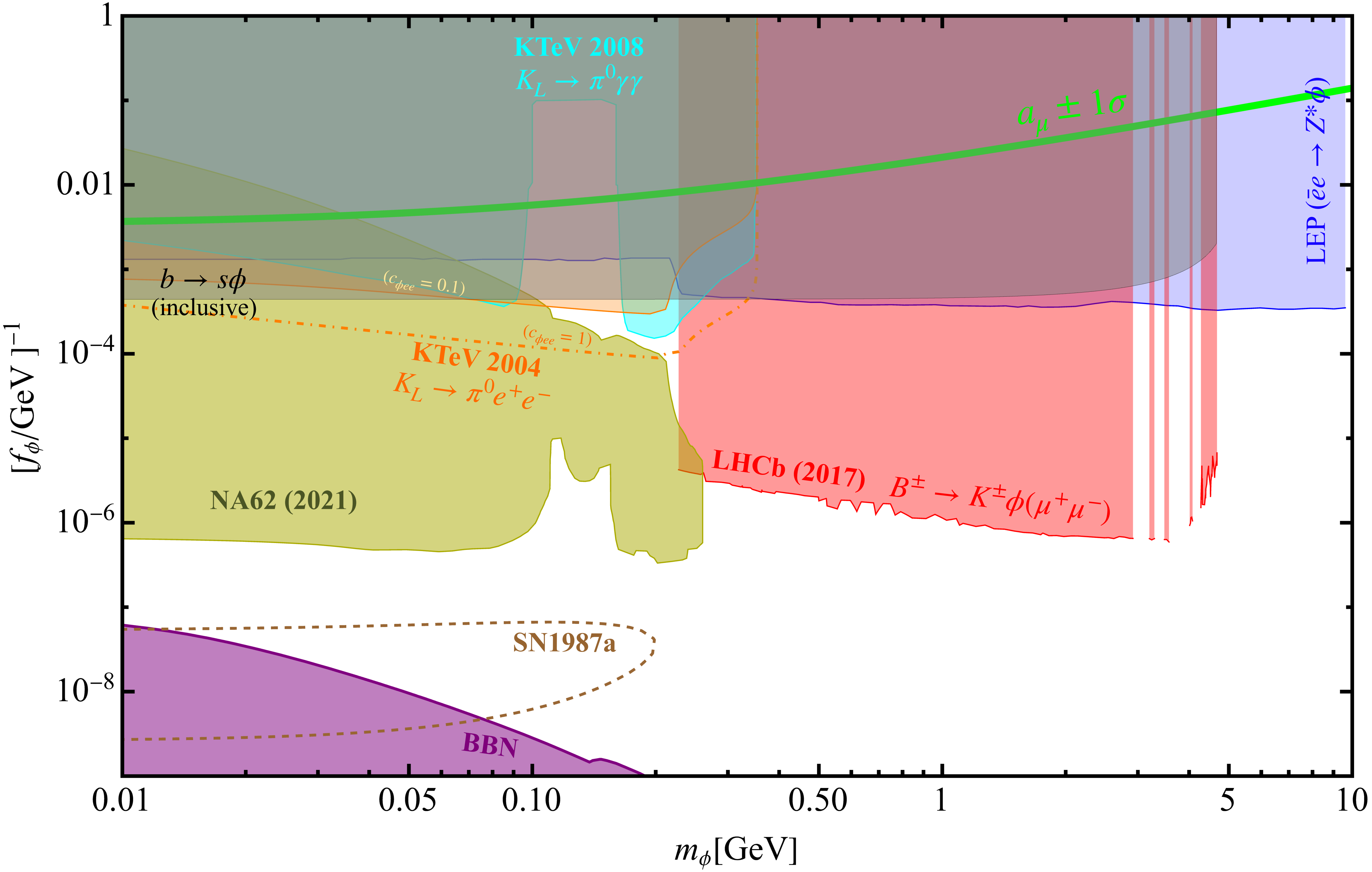


Production cross section

	$t\bar{t}a$	$t\bar{t}t\bar{t}$	$t\bar{t}W^+W^-$	$t\bar{t}h$	$t\bar{t}Z$
σ[ab]	90	23	465	324	158

Dilaton phenomenology: rare meson decays

S. Girmohanta, Y. Nakai, Y. Shigekami and K. Tobioka [JHEP 01, 153 (2024)]



Dilaton phenomenology: rare meson decays

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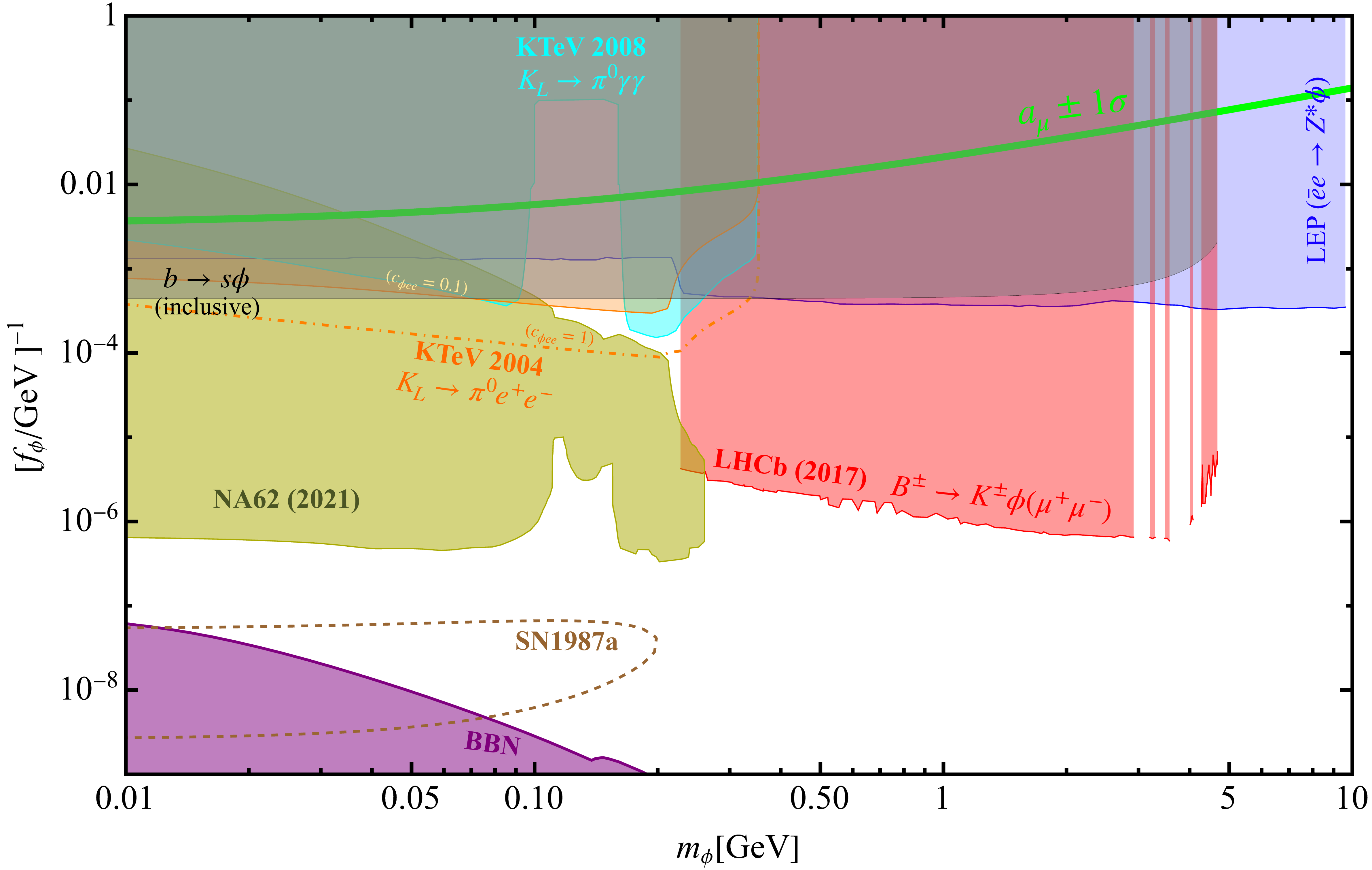

Light dilaton explanation of $g_\mu - 2$ anomaly is excluded. Distinction from Higgs-portal scalar in the photon coupling is properly taken into account → Belle II.

Probing the CP property of the dilaton at Belle II

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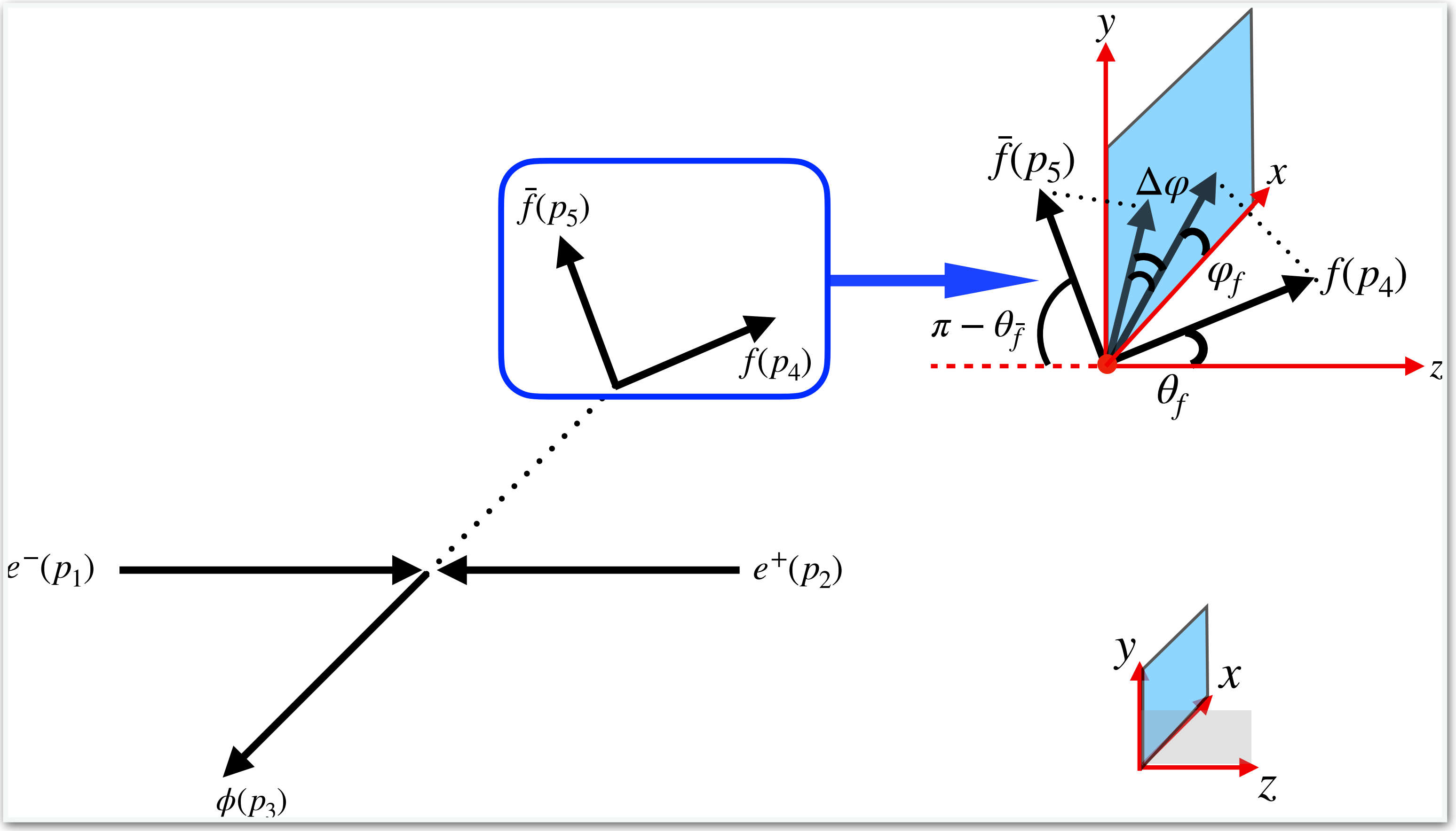
Imprint of the CP nature in $e^+e^- \to e^+e^-\phi$ with $\Delta\varphi$.

$\Delta\varphi$: Azimuthal angle between the outgoing e^+e^-.



Probing the CP property of the dilaton at Belle II

Imprint of the CP nature in $e^+e^- \to e^+e^-\phi$ with $\Delta\varphi$.

$\Delta\varphi$: Azimuthal angle between the outgoing e^+e^-.

Two benchmark points are shown where $\phi \to \mu^+\mu^-$ and $\phi \to$ inv .