[CEPC Fudan WS 2023]
[18/08/2023]

Disclaimer: Following results are preliminary

BSM From Tau Decay

ALPs x Flavor Crossover Edition

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with Lorenzo Calibbi (Nankai U.), Xu-Hui Jiang (HKUST), Lingfeng Li (Brown U.), Tao Liu (HKUST)

(QCD) Axion

$$\mathcal{L} \supset \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

Strong CP Problem: Measurement of neutron EDM $\implies \bar{\theta} < 10^{-10}$

Possible solution: Make $\bar{\theta}$ dynamical

Breaking $U(1)_{\mathrm{PQ}}$ symmetry (at energy scale f_a) gives pNGB (axion)

Extension: Invisible axion (KSVZ, DFSZ) when $f_a \gg \Lambda_{\mathrm{EW}}$.

Additionally: DM candidate!

Axion-Like Particles (ALPs)

QCD Axion is quite constrained!

Class of similar models (ALPs):

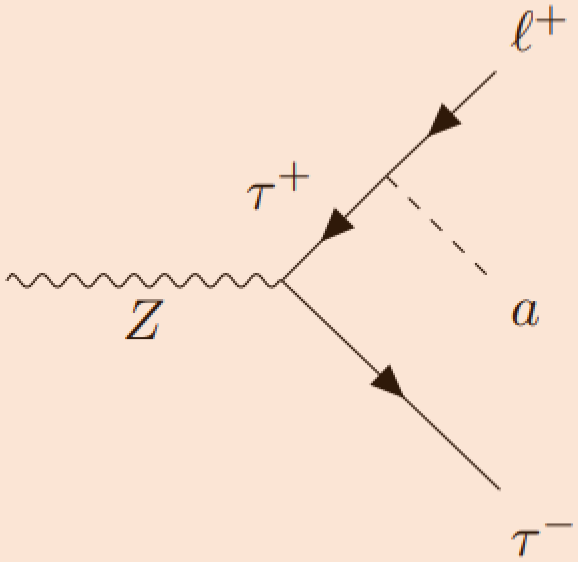
- **pNGB from breaking of global symmetry, enjoy** $a \to a + \mathrm{const.}$
  - **Global lepton number symmetry → Majoron**
  - **Global family symmetry → Familon**
    [See Lorenzo's talk]

Pheno: Interesting effect with Flavor Physics(?)

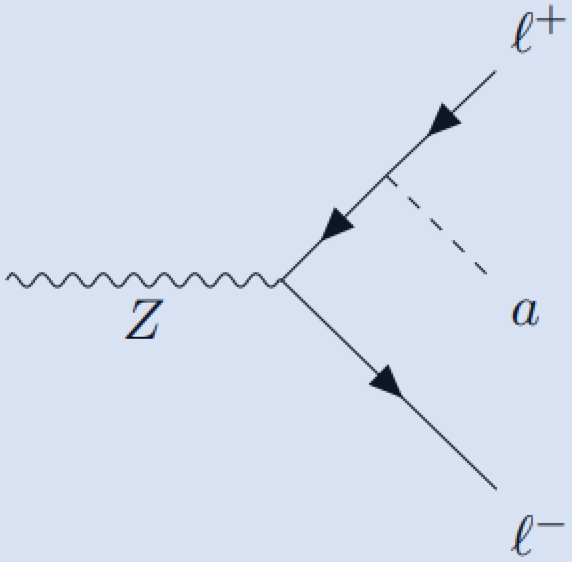
ALP-Lepton interactions (@ Z-pole)

$$\mathcal{L}_{\text{eff}} \supset \sum_{i\neq j} \frac{\partial_\mu a}{2f_a} \bar{\ell}_i (C^V_{\ell_i\ell_j}\gamma^\mu + C^A_{\ell_i\ell_j}\gamma^\mu\gamma_5)\ell_j + \sum_i \frac{\partial_\mu a}{2f_a}\bar{\ell}_i C^A_{\ell_i\ell_i}\gamma^\mu\gamma_5\ell_i$$

Off diagonal coupling (cLFV)



Diagonal coupling (radiation)



ALP-Tau interactions [See also Lorenzo's talk]

Theoretically:

- BSM (more likely) has greater impact on heavy states.
- Larger event yields (compared with electron, muon)

[See 2006.04795]

for simplicity we neglected the mass of the final-state lepton

$$\Gamma(\ell_i \to \ell_j\, a) = \frac{1}{16\pi} \frac{m_{\ell_i}^3}{F_{\ell_i \ell_j}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2$$

$$F_{\ell_i \ell_j} = \frac{2 f_a}{\sqrt{|C^V_{\ell_i \ell_j}|^2 + |C^A_{\ell_i \ell_j}|^2}}$$

[See 2212.02818]

	$\sigma(e^+e^- \to \ell^+\ell^- a)$
$\ell = e$	7.1×10^{-9} pb
$\ell = \mu$	7.6×10^{-5} pb
$\ell = \tau$	1.1×10^{-2} pb

LO cross sections of signal (for $f_a/C^A_{\ell\ell} = 100$ GeV, $m_a = 10^{-6}$ GeV)

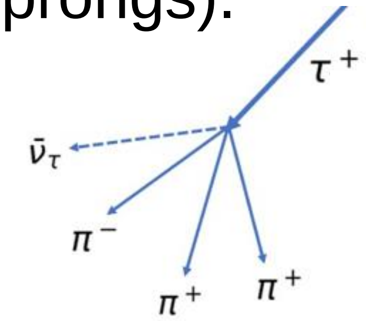
ALP-Tau interactions [See also Lorenzo's talk]

Phenomenologically (@CEPC):

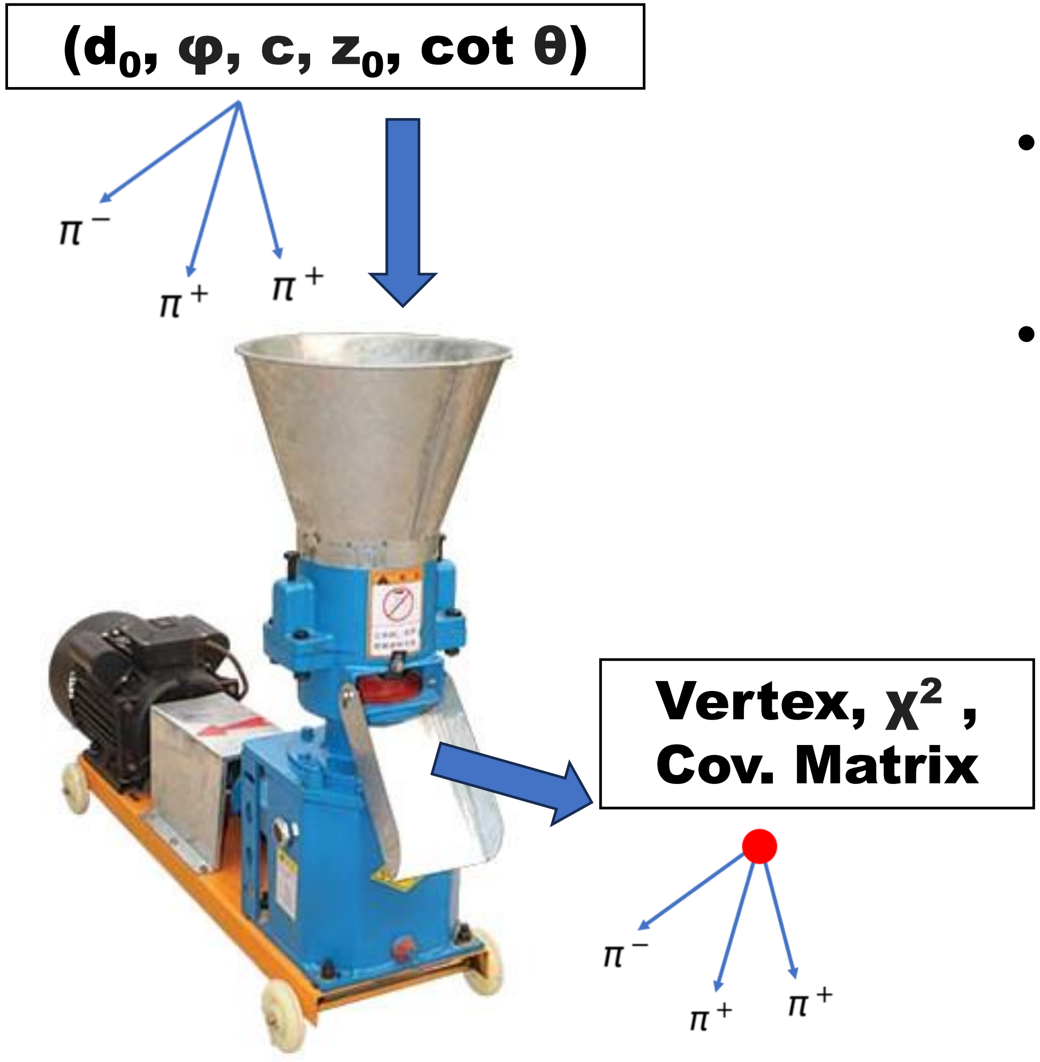
[See Lingfeng's talk]

Particle	Belle II	CEPC (4×Tera-Z)
$\tau^\pm$	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	1.2×10^{11}

- Many tau pairs
- More boosted tau pairs (vs B factories) from $Z \to \tau^+\tau^-$
- Excellent tracking for tau 3-prongs decay $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu$ (or 5-prongs).
- ALP-Electron/Muon can be done in other experiments, ALP-Tau is unique opportunity for CEPC!



Sim. & Vertex Reco.



- Pythia → Delphes (IDEA card)
- Vertexing is VERY importance here
  - Need to fit the tau decay vertex!
  - Using delphes/external/TrackCovariance/VertexFit.cc

Can do more realistic vertexing with fast simulation!

Sim. & Vertex Reco. Nowadays

Simple assumption:
Fast but
not super realistic

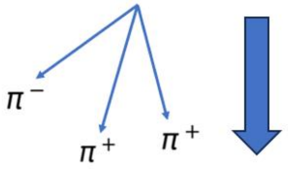
(e.g. manually smear the truth level vertex)

Full simulation:
Sophisticated but
time-consuming

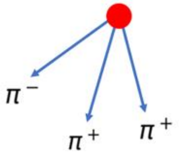
Can do more realistic vertexing with fast simulation!

Can vary detector parameters
Can study detector design!

(d_0, φ, c, z_0, cot θ)



Vertex, χ^2 ,
Cov. Matrix



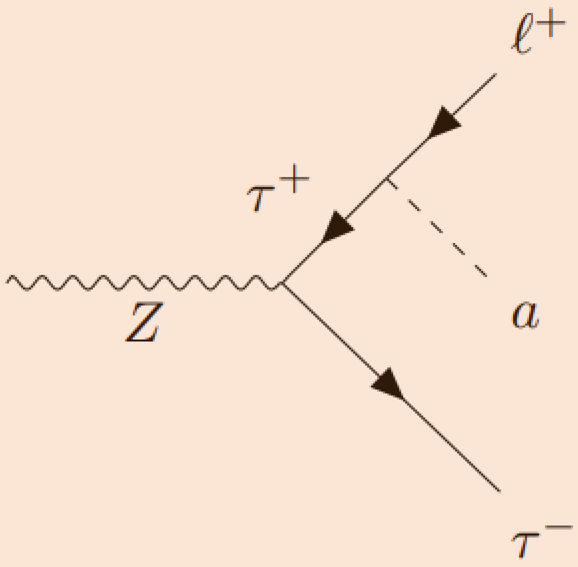
Relevant part in the detector card:

delphes/cards/delphes_card_IDEA.tcl

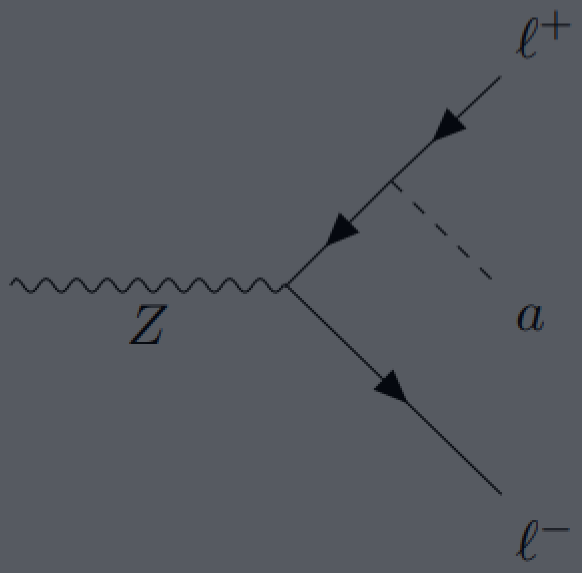
barrel	name	zmin	zmax	r	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
1	PIPE	-100	100	0.01	0.00235	0.35276	0	0	0	0	0	0
1	VTXLOW	-0.0965	0.0965	0.012	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.1609	0.1609	0.02	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.2575	0.2575	0.031525	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXLOW	-0.1609	0.1609	0.15	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1
1	VTXHIGH	-0.3263	0.3263	0.315	0.00047	0.0937	2	0	1.5708	7.00E-06	7.00E-06	1
1	DCHCANI	-2.125	2.125	0.345	0.0002	0.237223	0	0	0	0	0	0
1	DCH	-2	2	0.36	0.014775	1400	1	0.0203738	0	0.0001	0	1
1	DCH	-2	2	0.374775	0.014775	1400	1	-0.0212097	0	0.0001	0	1

Pheno (Off Diagonal Channel)

Off diagonal coupling (cLFV)



Diagonal coupling (radiation)



Off Diagonal Channel (cLFV)

Extra theoretical interest of cLFV: [See 2006.04795]

- **Current cLFV searches (** $\mu \to e\gamma, \tau \to \ell\gamma, \mu \to eee, \tau \to \ell\ell\ell, \ldots$ **)**

  are related to dim-6 operators $\implies \text{BR} \sim 1/\Lambda^4$

- **ALPs searches (** $\mu \to ea, \tau \to \ell a$ **)**

  are relates to dim-5 operators $\implies \text{BR} \sim 1/f_a^2$

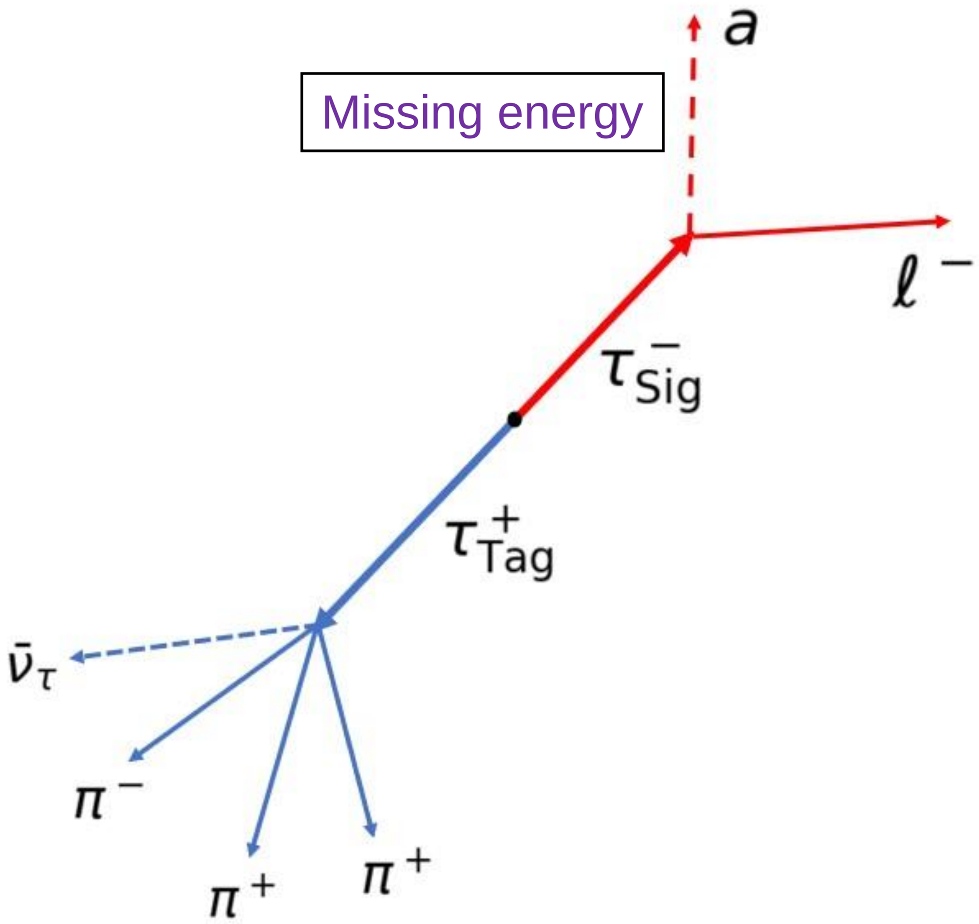
Off Diagonal Channel (cLFV)

Constraints:

- τ_{Tag} decay vertex
- (assuming) PV=0
- Z boson 2 body decay
- τ on-shell
- Energy momentum conversation (assuming no ISR)

Can solve:

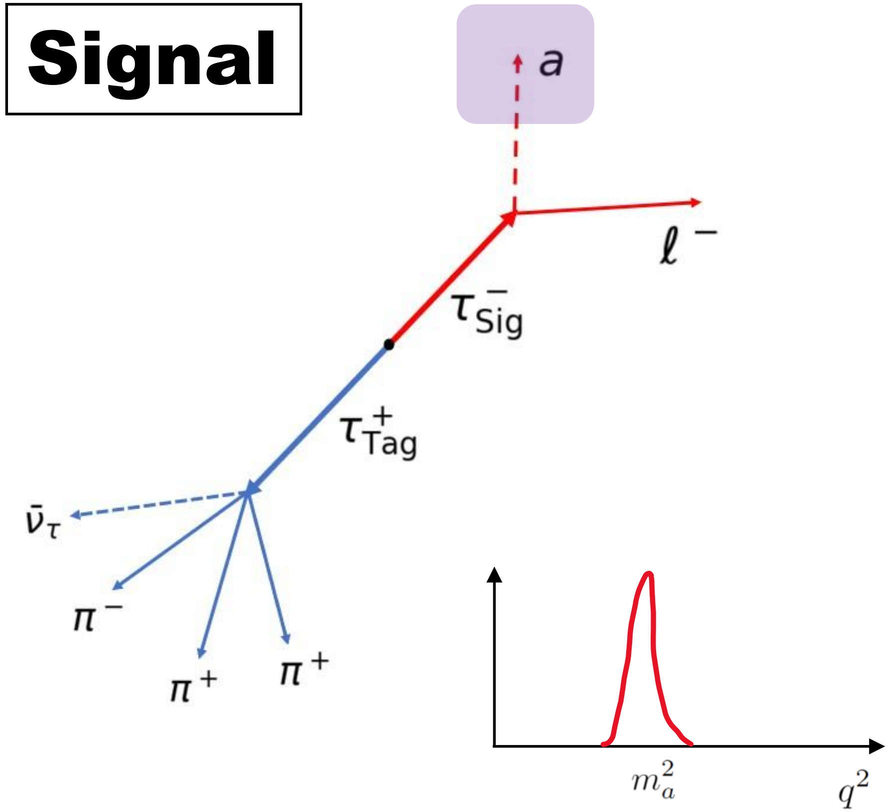
4-momentum $p(\tau_{Sig})$, thus $p(a)$



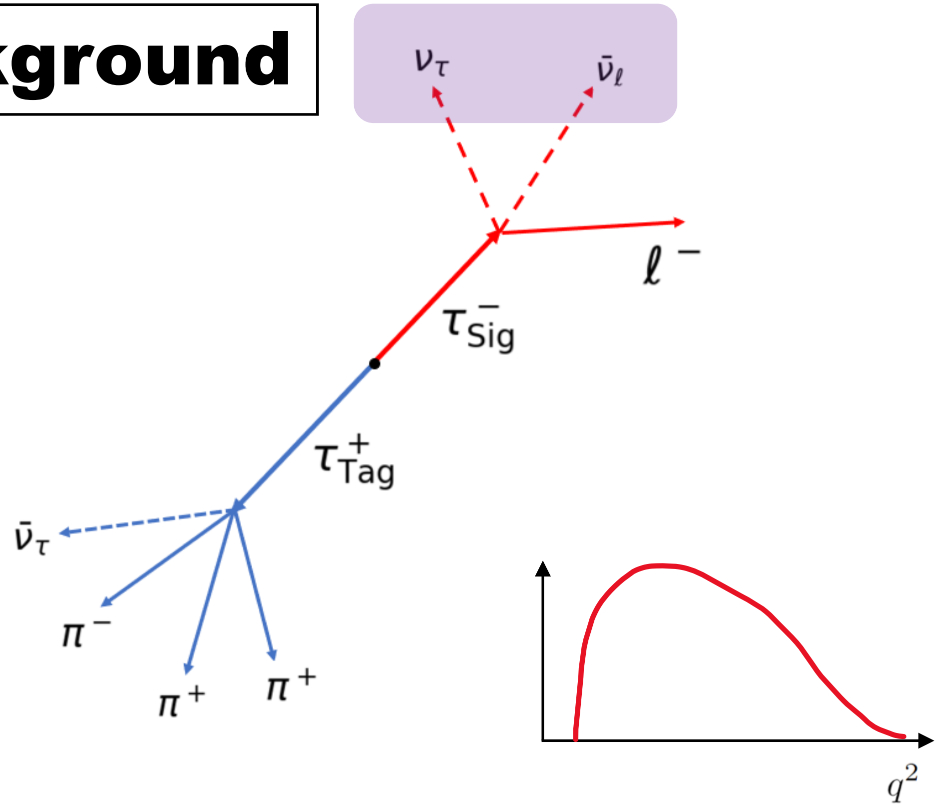
Collider Signature

$$q^2 \equiv (p_{\tau_{\text{Sig}}} - p_\ell)^2$$

Signal

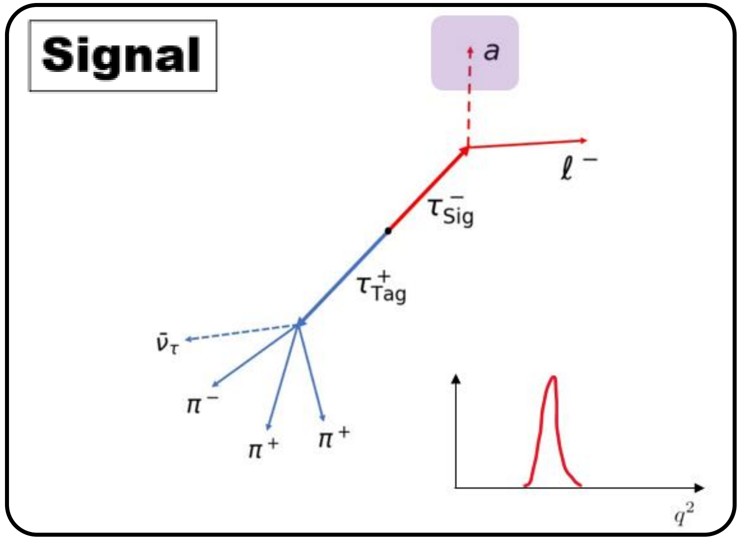


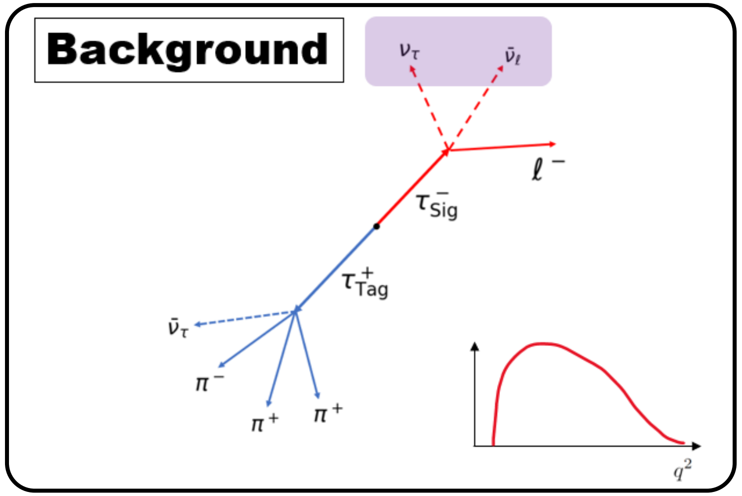
Background

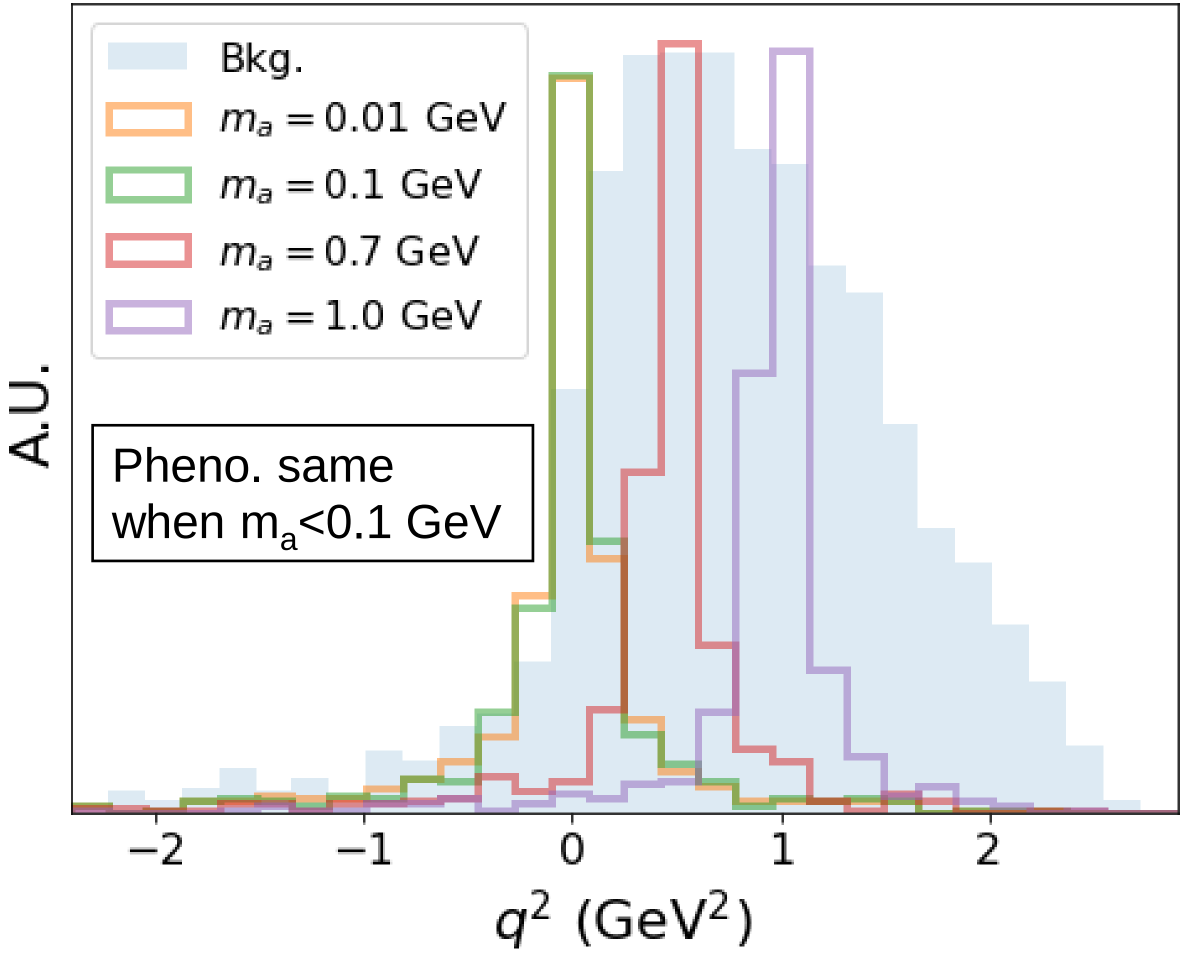


Collider Signature

$$q^2 \equiv (p_{\tau_{\text{Sig}}} - p_\ell)^2$$







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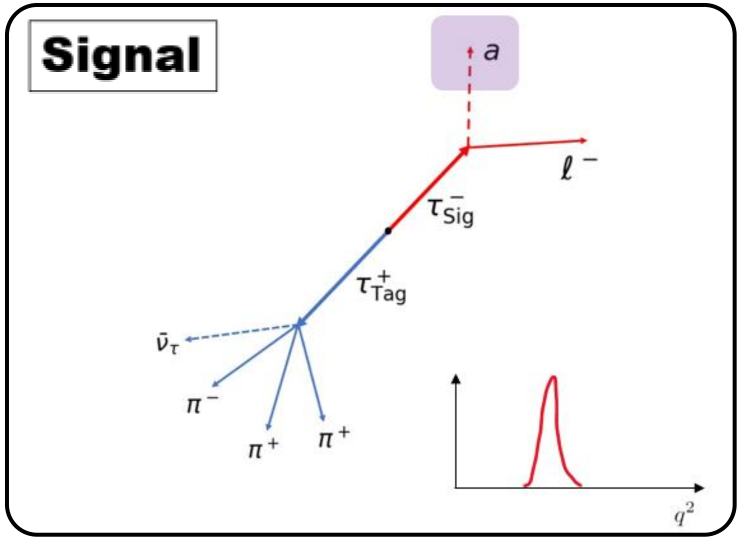
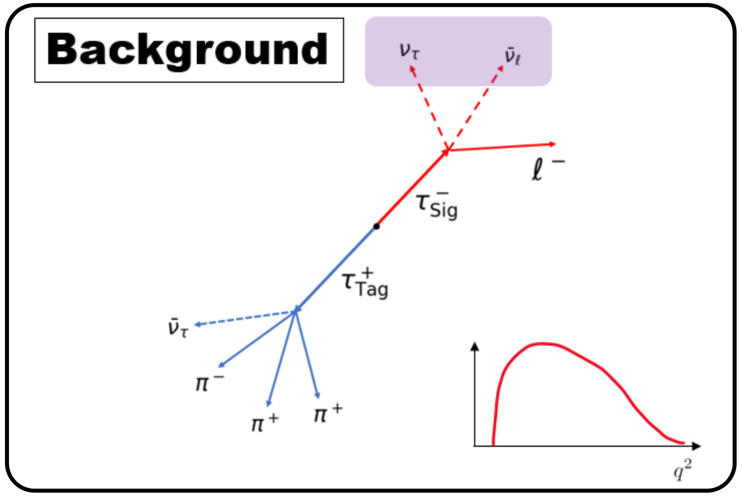
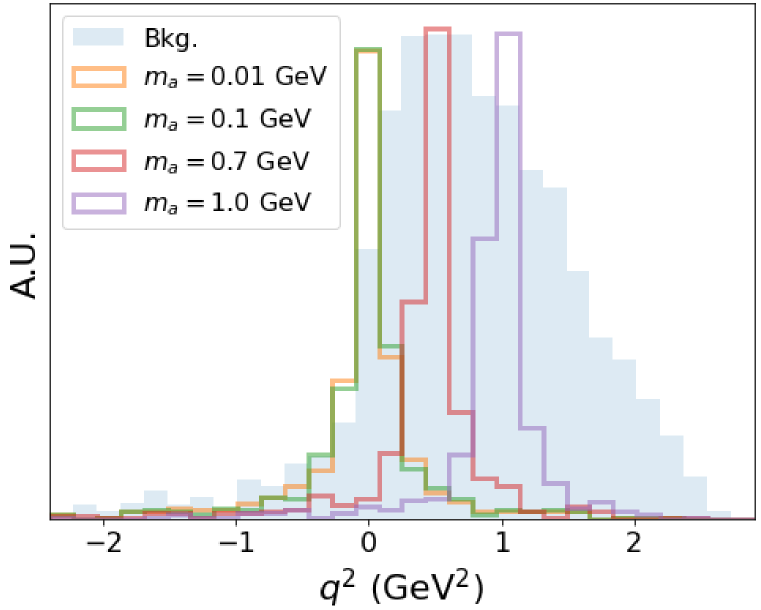


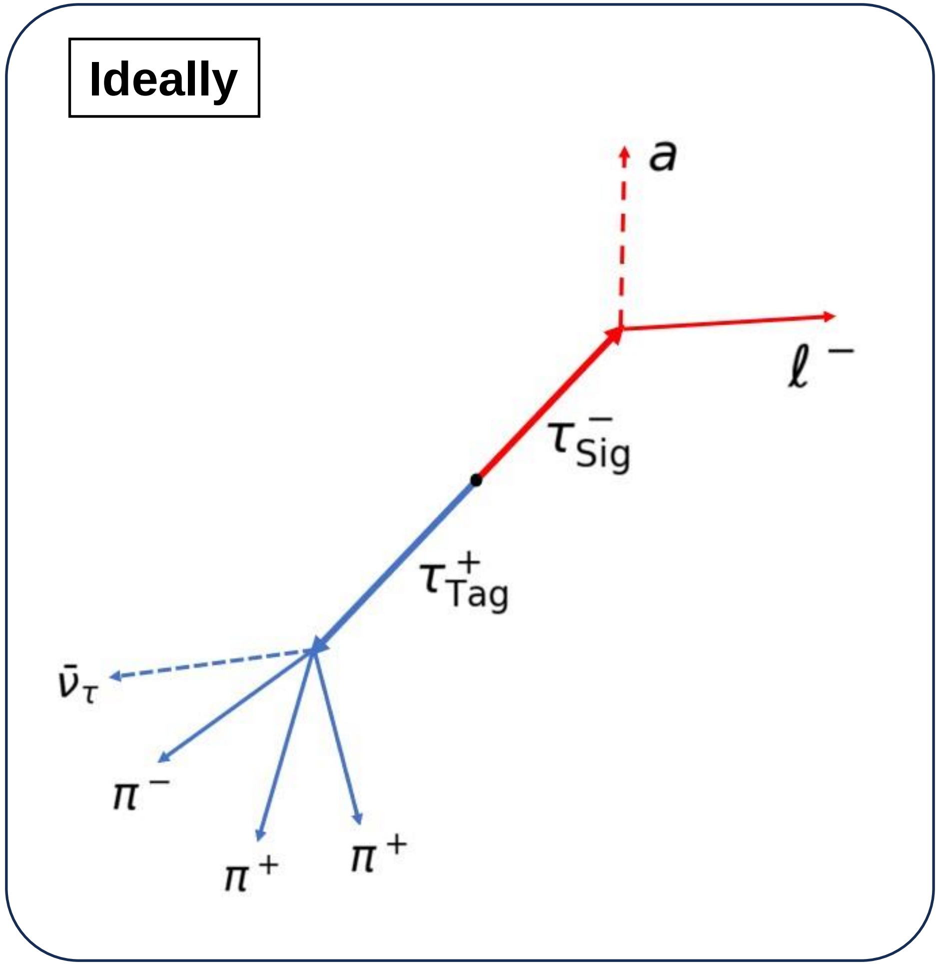


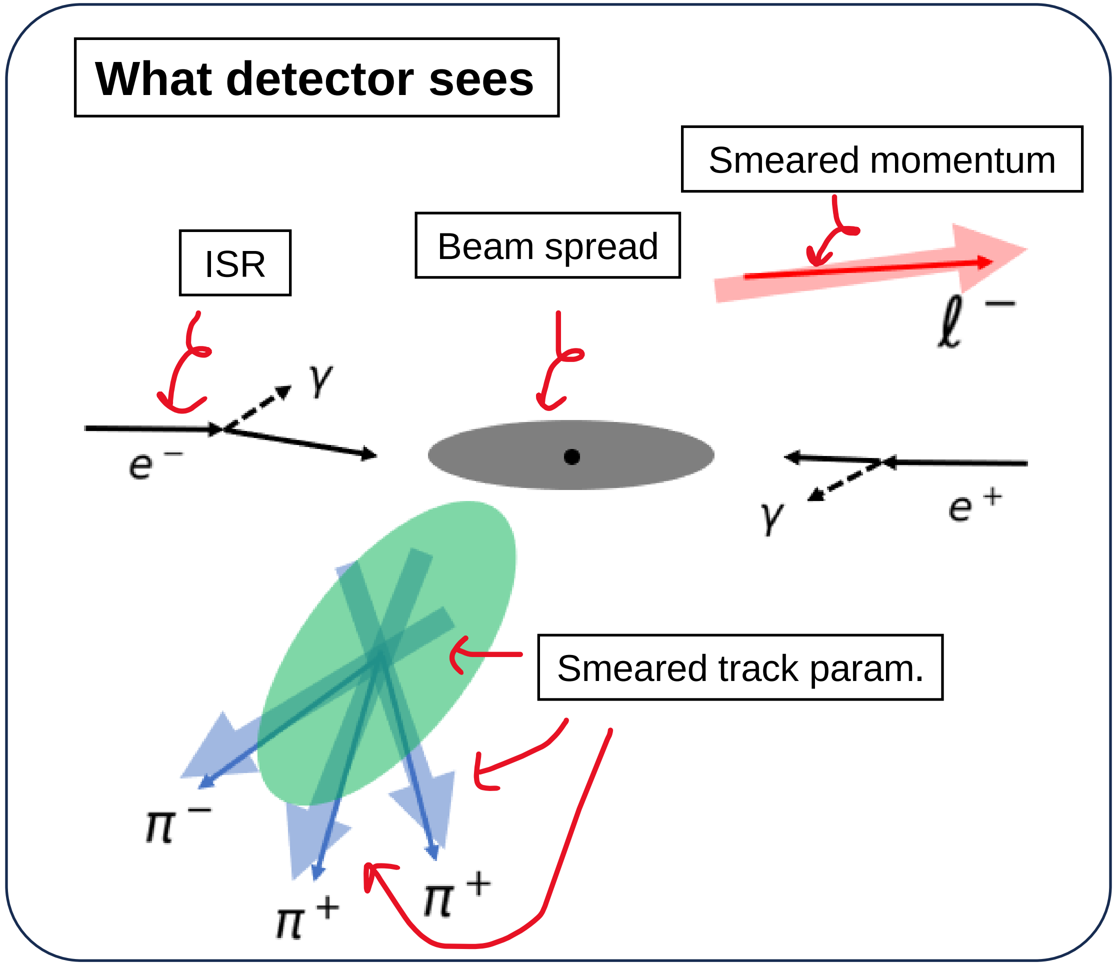


The narrower the peak, the better the constraints

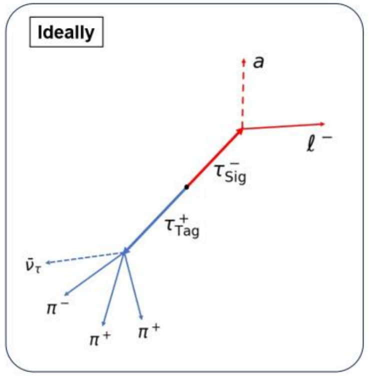
But how to understand the resolution here?

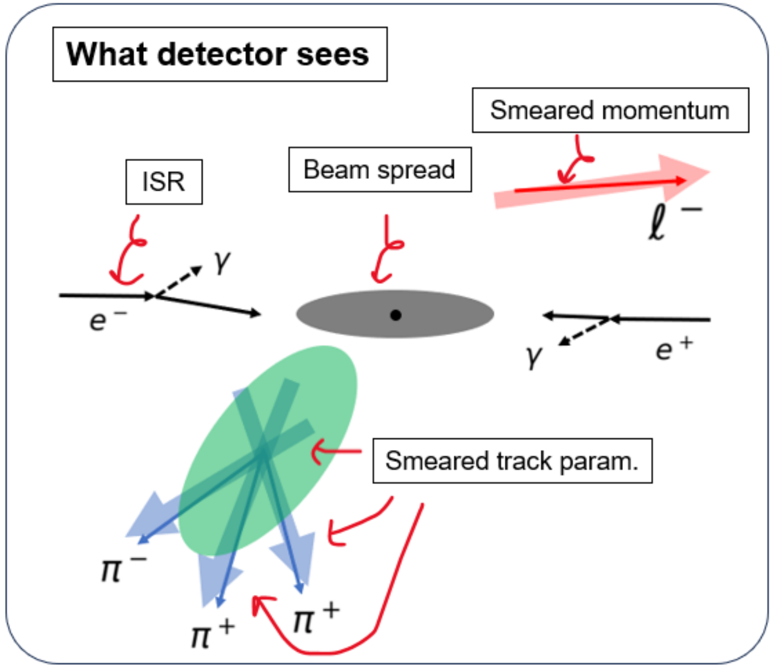
More Realistic Collider Picture

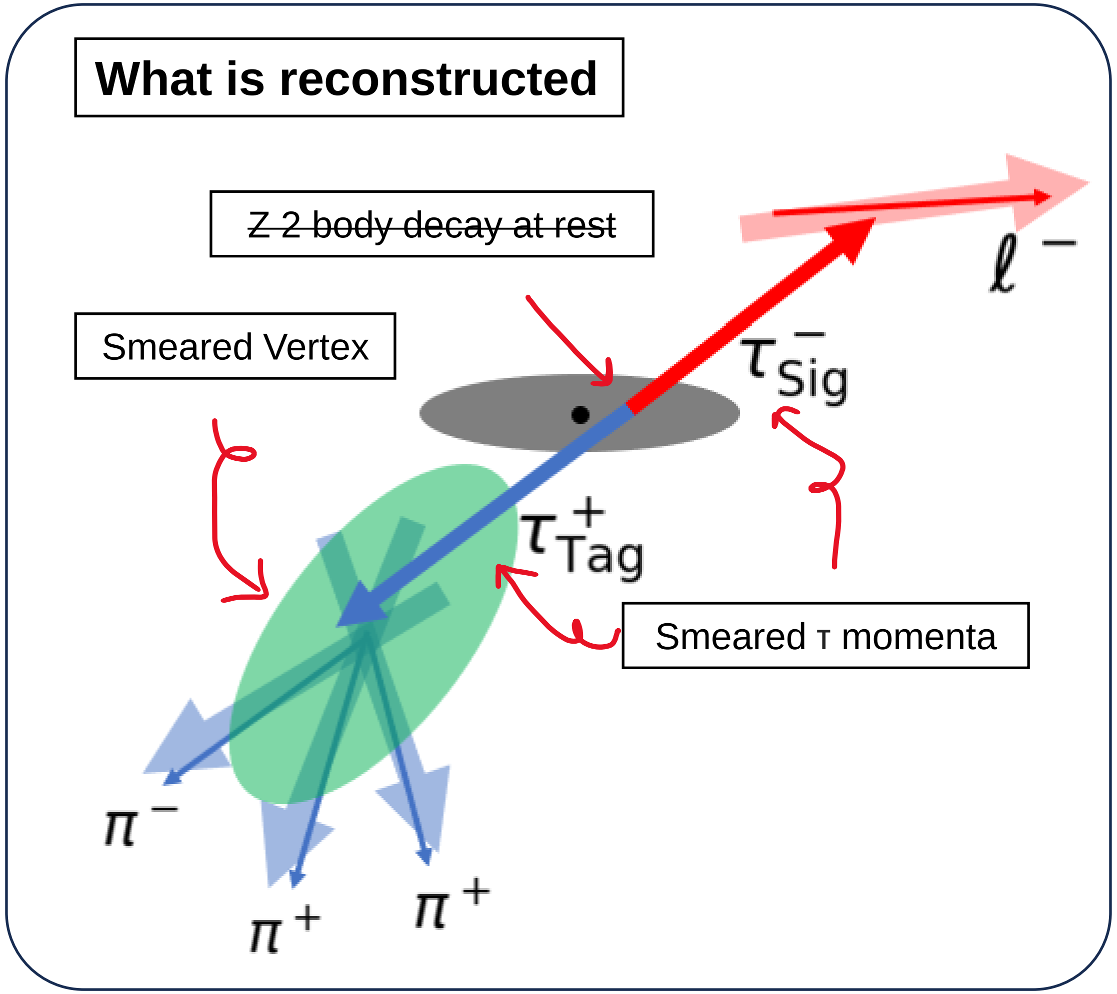


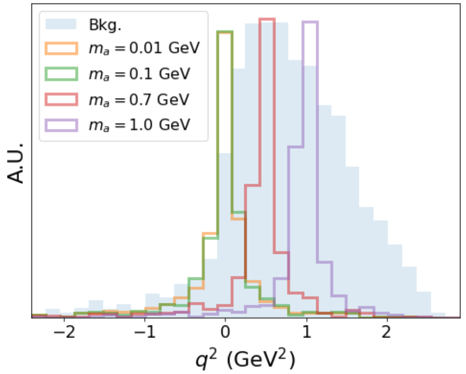


More Realistic Collider Picture



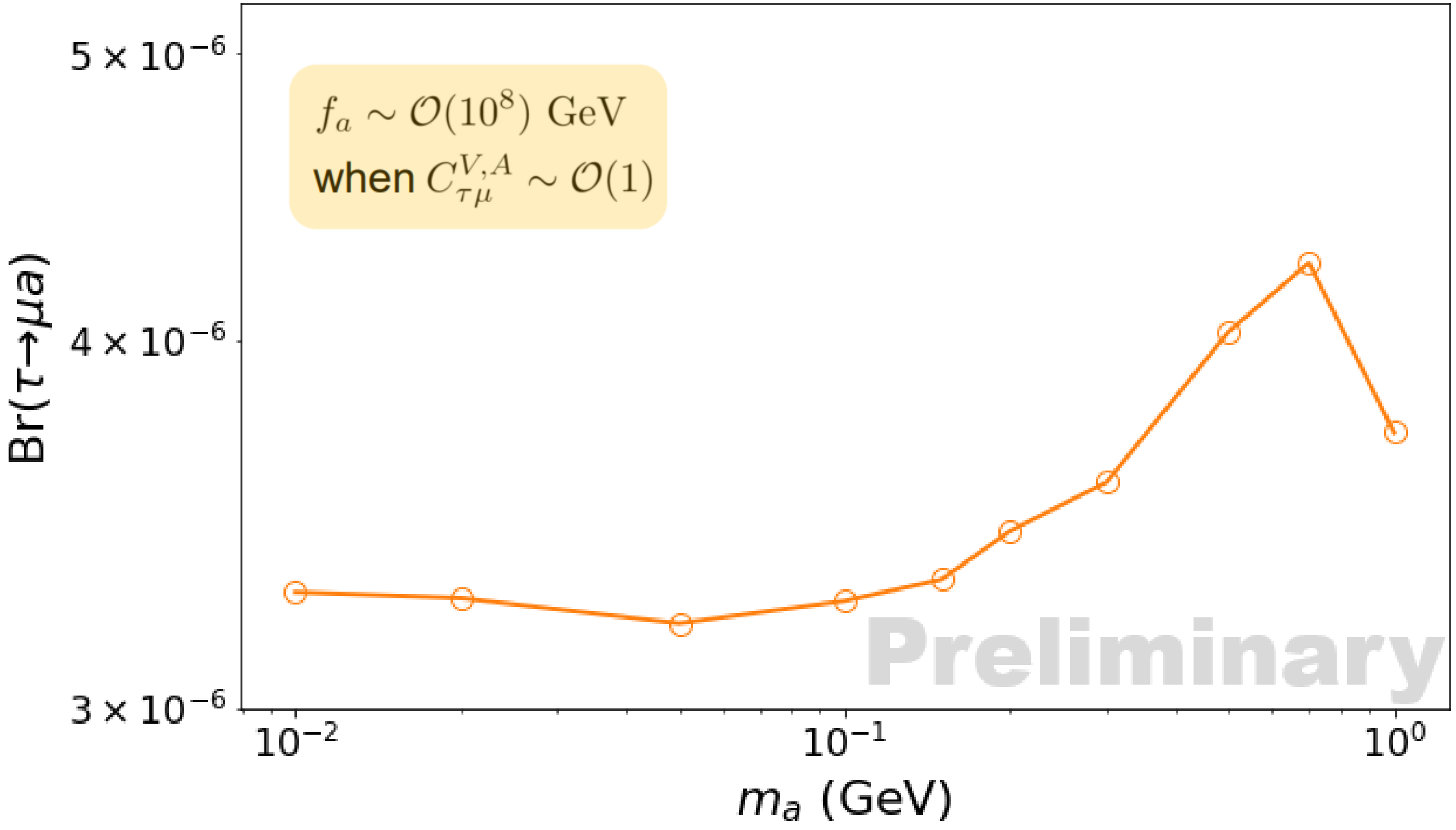




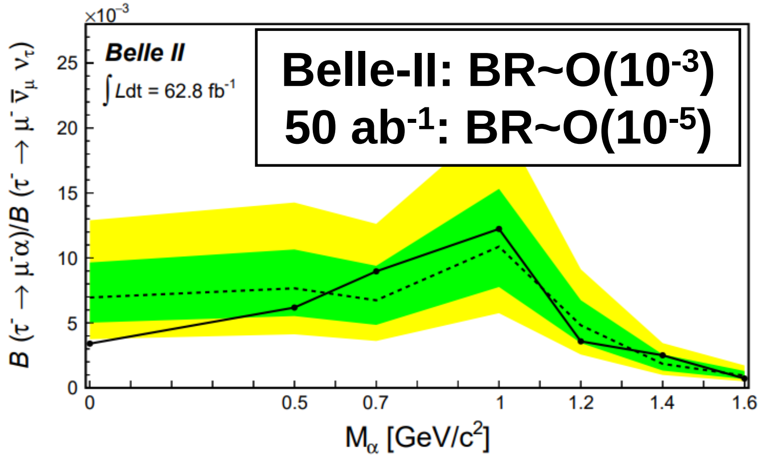


One may use more advanced methods:
- χ^2 fit,
- ML

Exclusion Limit



Comparison:



Belle-II: BR~O(10^{-3})
50 ab^{-1}: BR~O(10^{-5})

[See 2212.03634, also Lorenzo's talk]

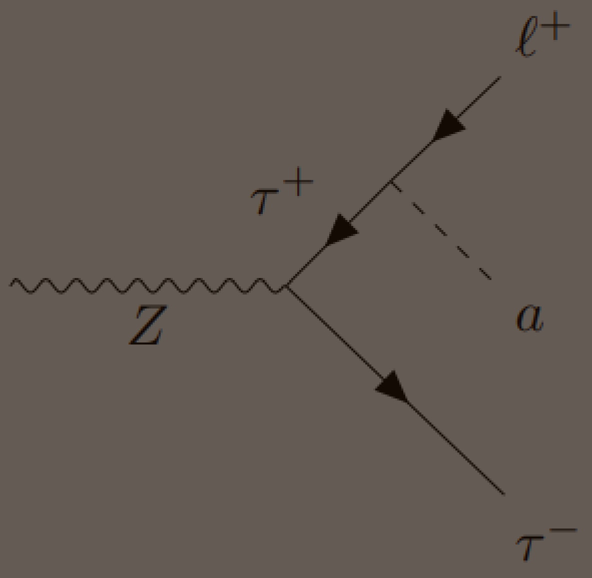
FCC-ee τ_τ: BR~O(10^{-4})

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

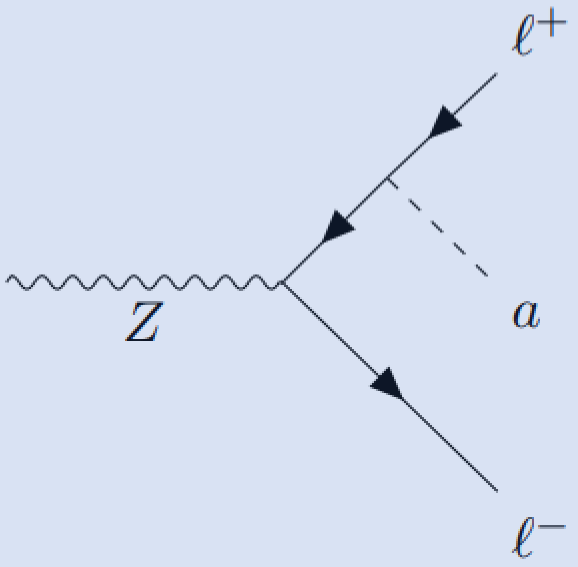
[See 1811.09408]

Pheno (Diagonal Channel)

Off diagonal coupling (cLFV)



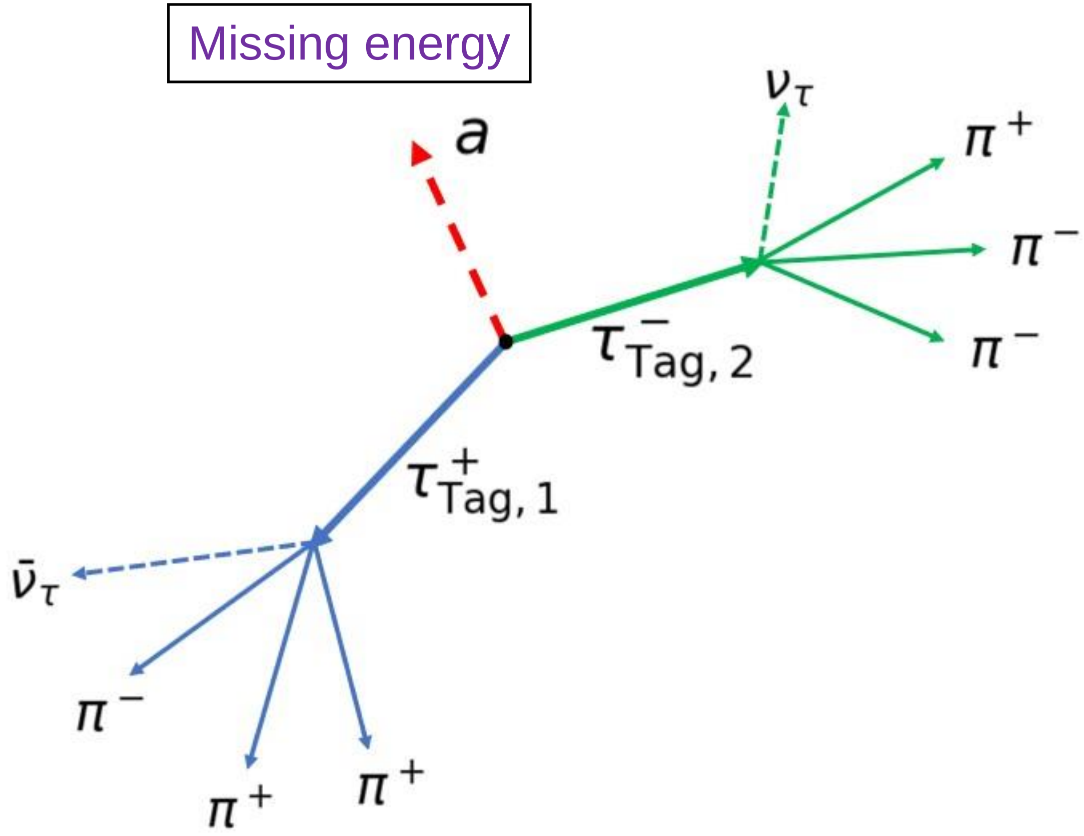
Diagonal coupling (radiation)



Diagonal Channel (radiation)

Constraints:

- $\tau_{Tag,1}$, $\tau_{Tag,2}$ decay vertices
- (assuming) PV=0
- τ on-shell
- Energy momentum conversation (assuming no ISR)



Can solve:

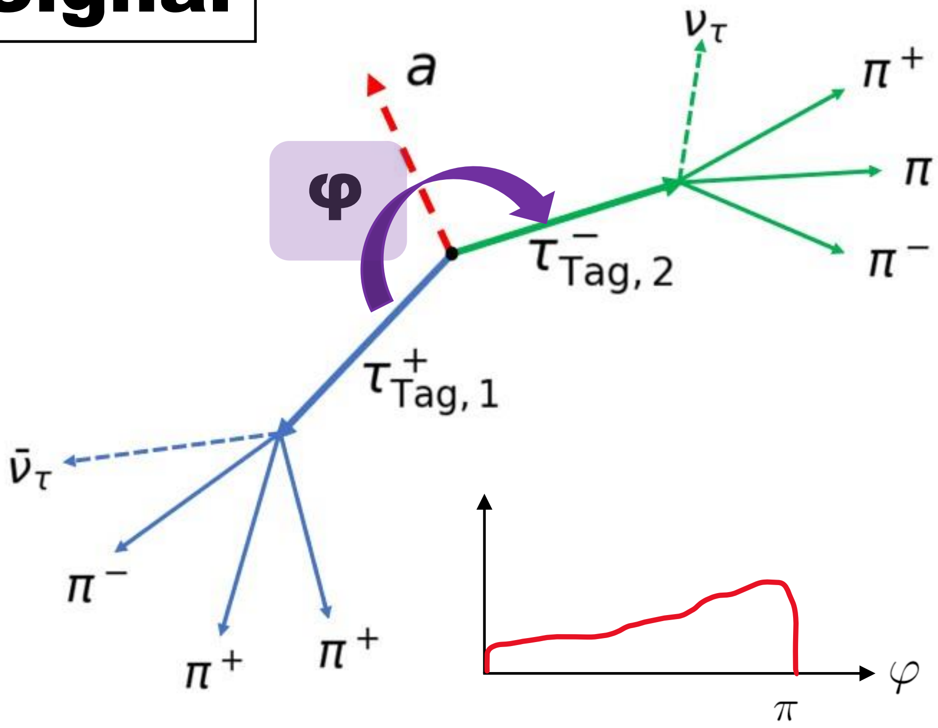
4-momenta $p(\tau_{Tag,1})$, $p(\tau_{Tag,2})$, thus $p(a)$

More advanced methods:

χ^2 fit, Machine Learning

Collider Signature

Signal



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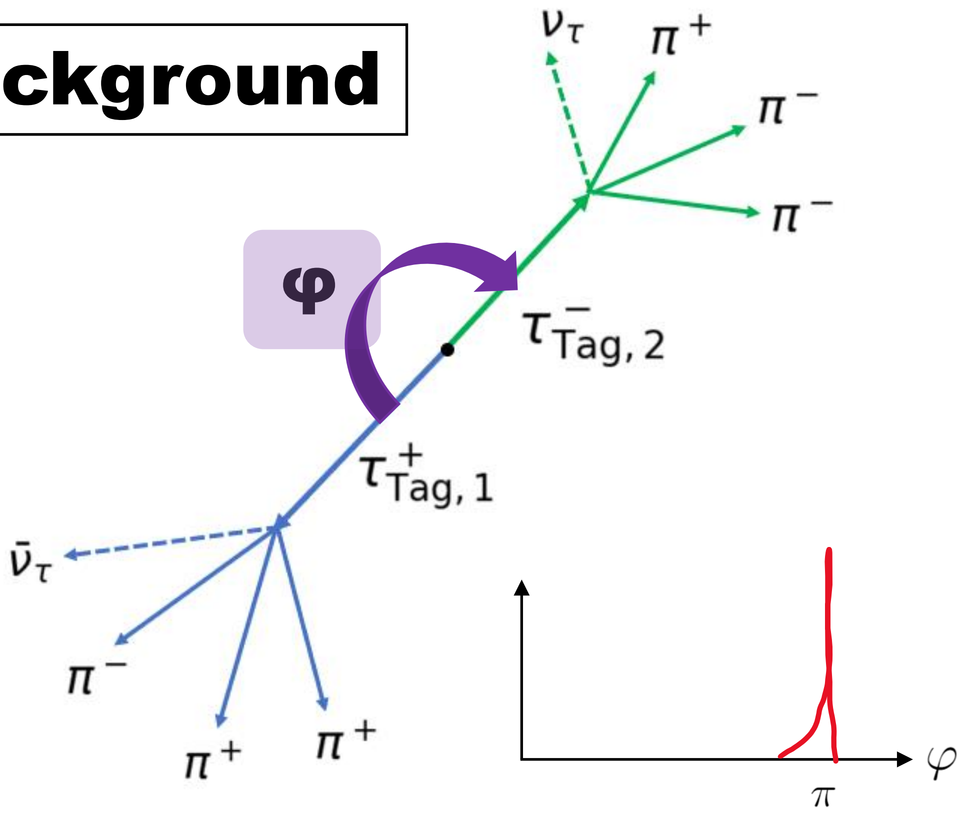
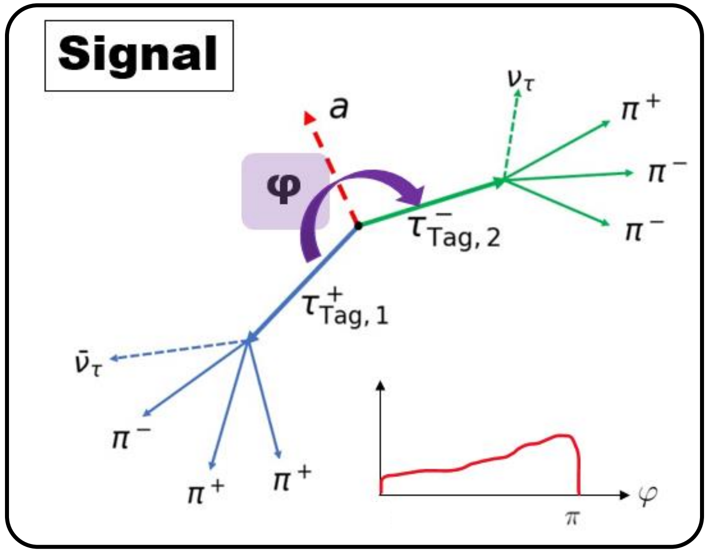
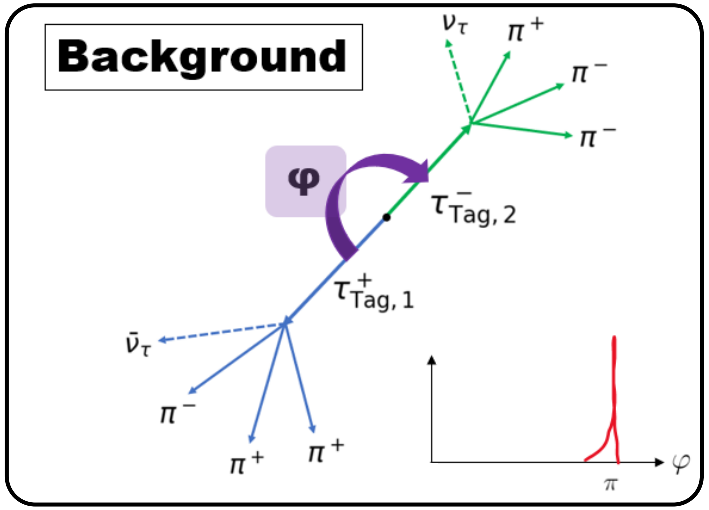
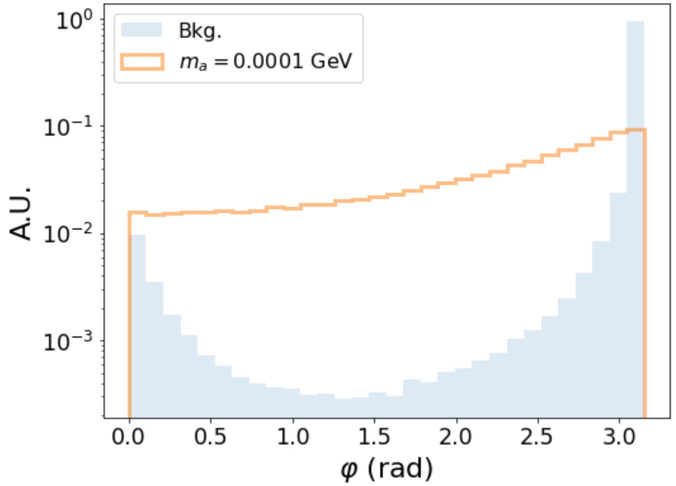
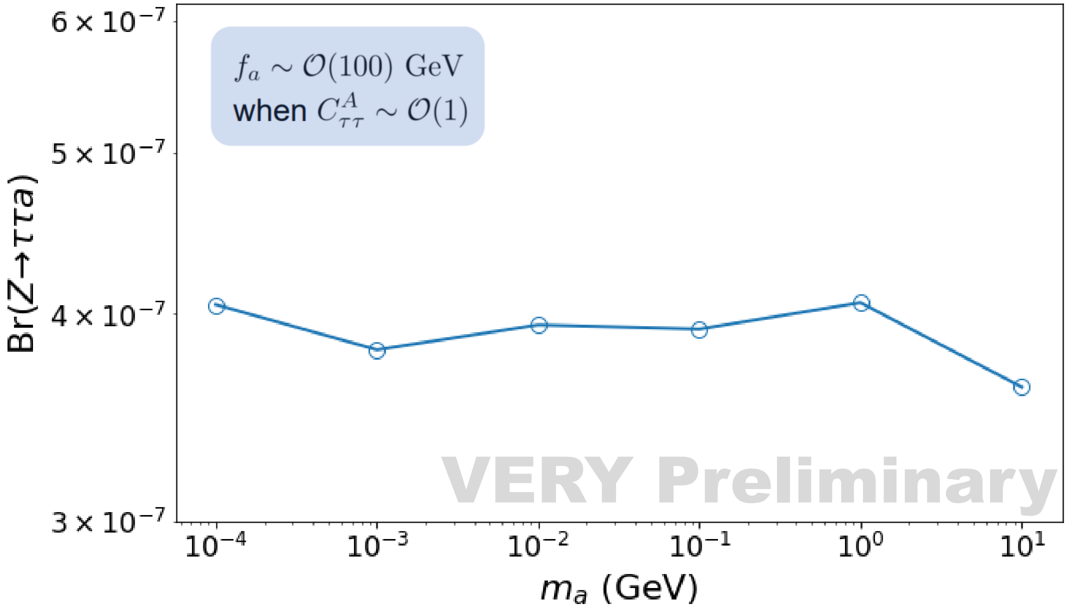


Collider Signature









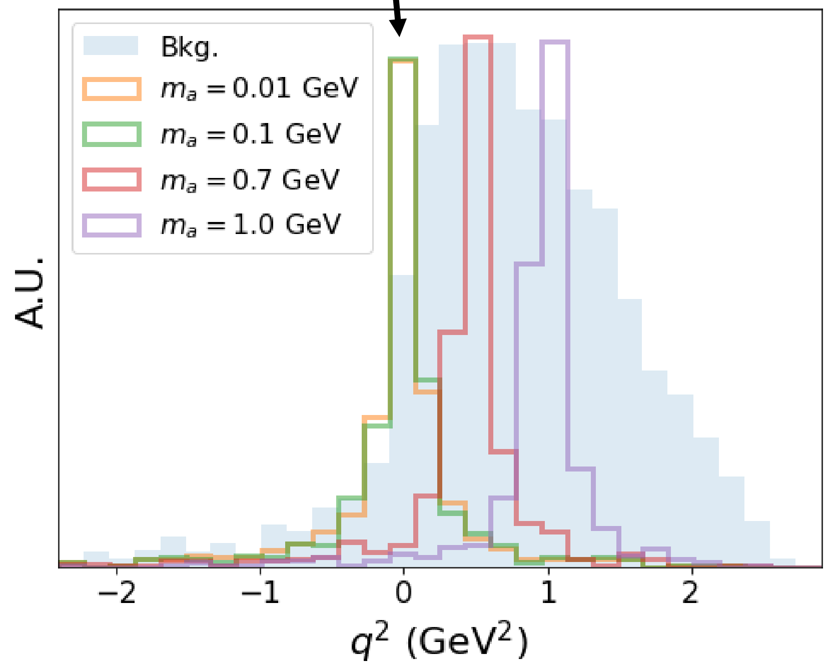
Take Home Message

- ALPs are nice hypothetical particle but still no evidence yet.
- ALP-Lepton gives interesting pheno.
  - Especially ALP-Tau
- CEPC is a unique playground and can put strong limit.

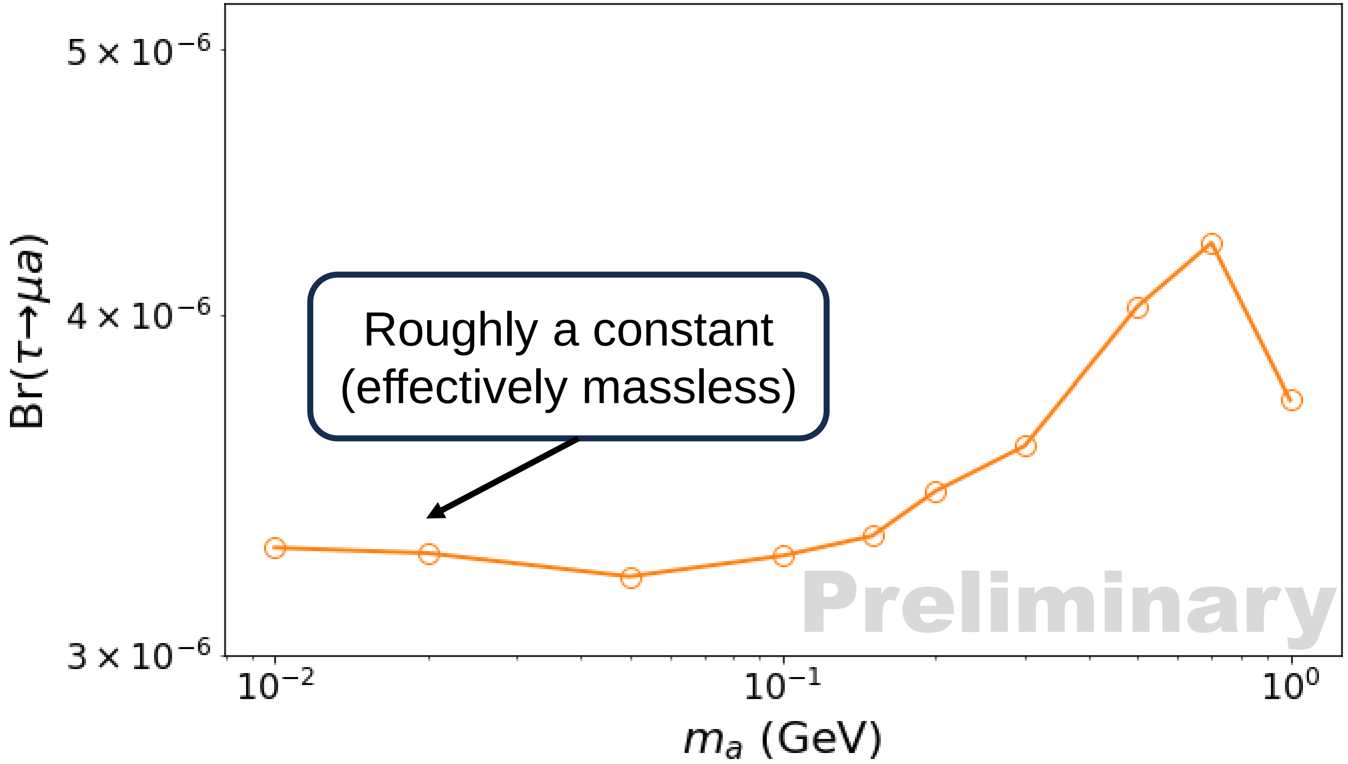
Backup

Some Features of the Exclusion Limit

Light masses are pheno. the same



Roughly a constant (effectively massless)



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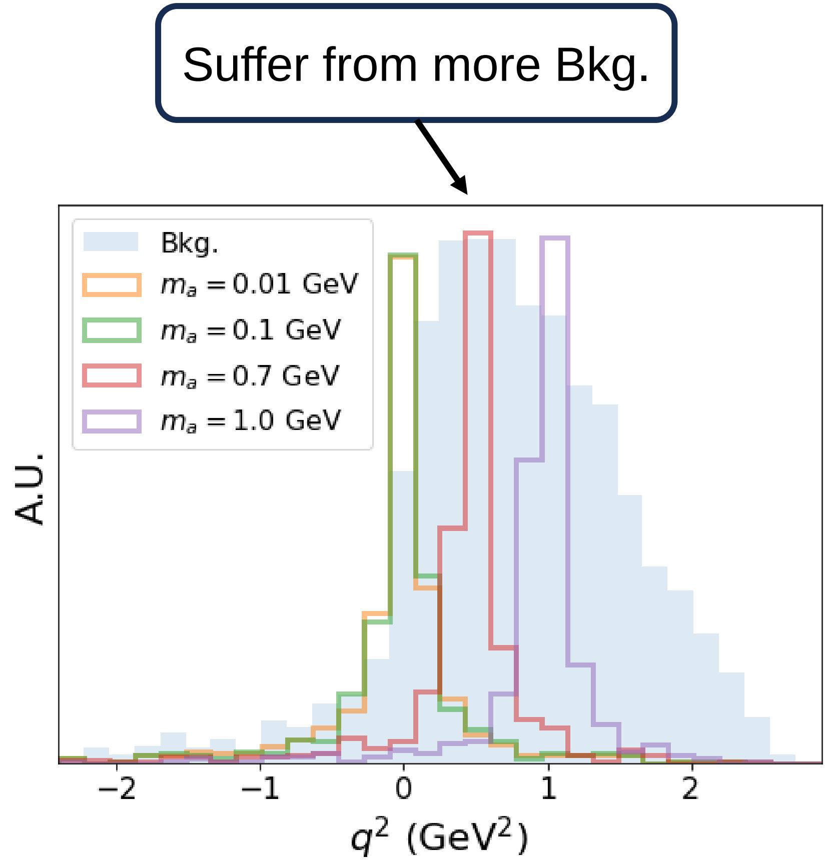

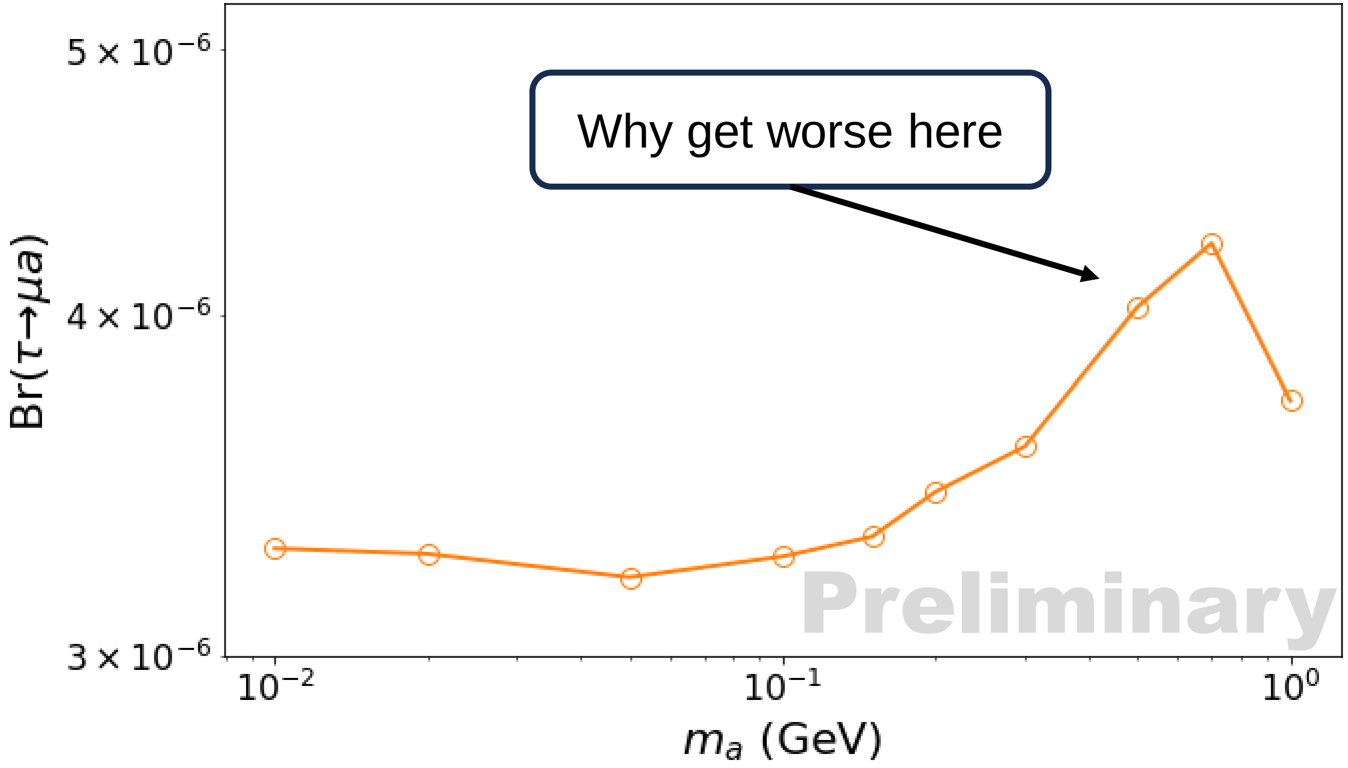

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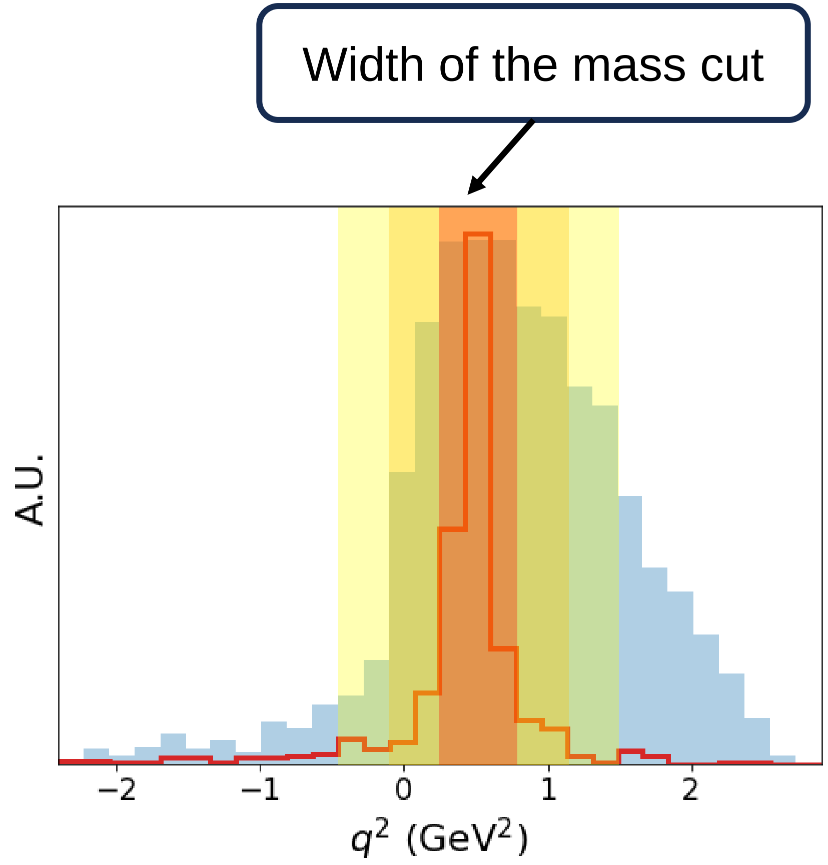
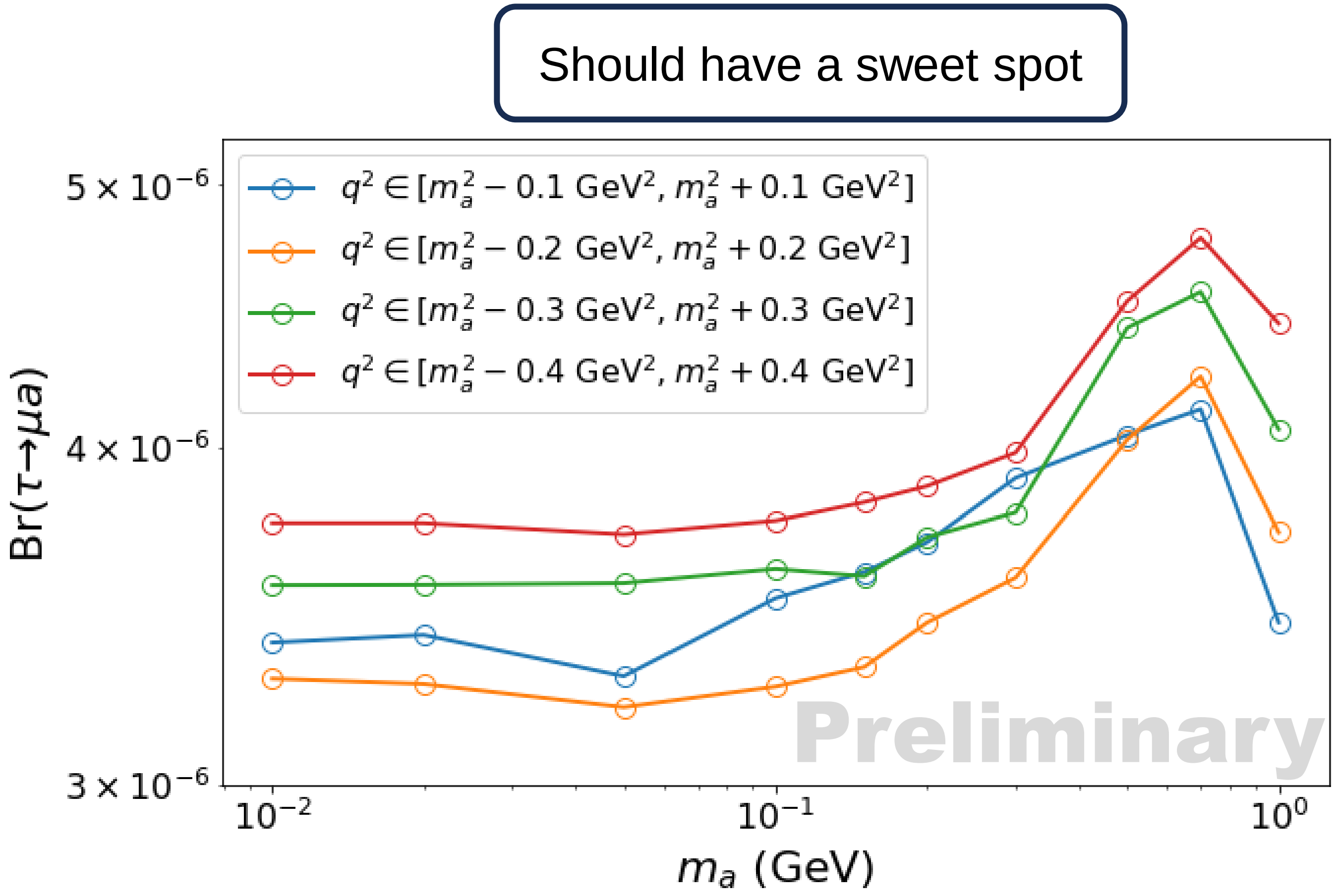
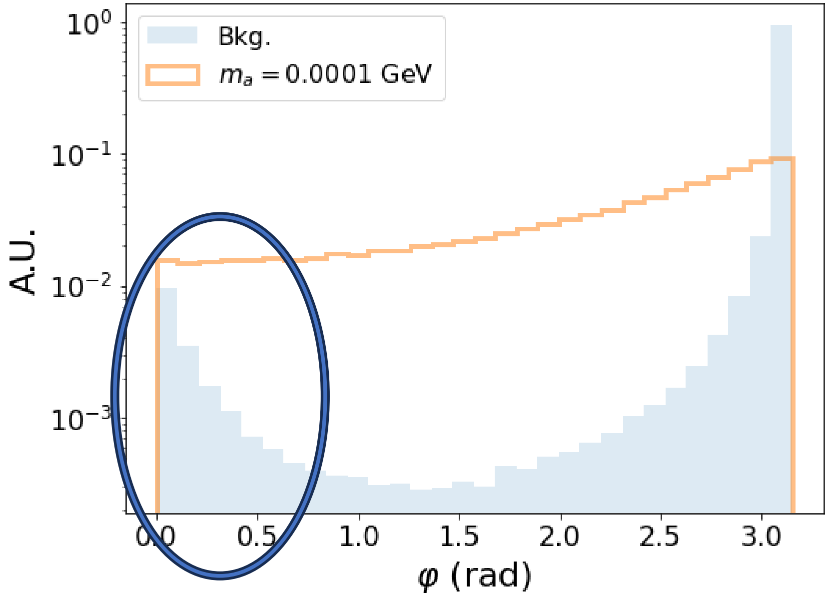
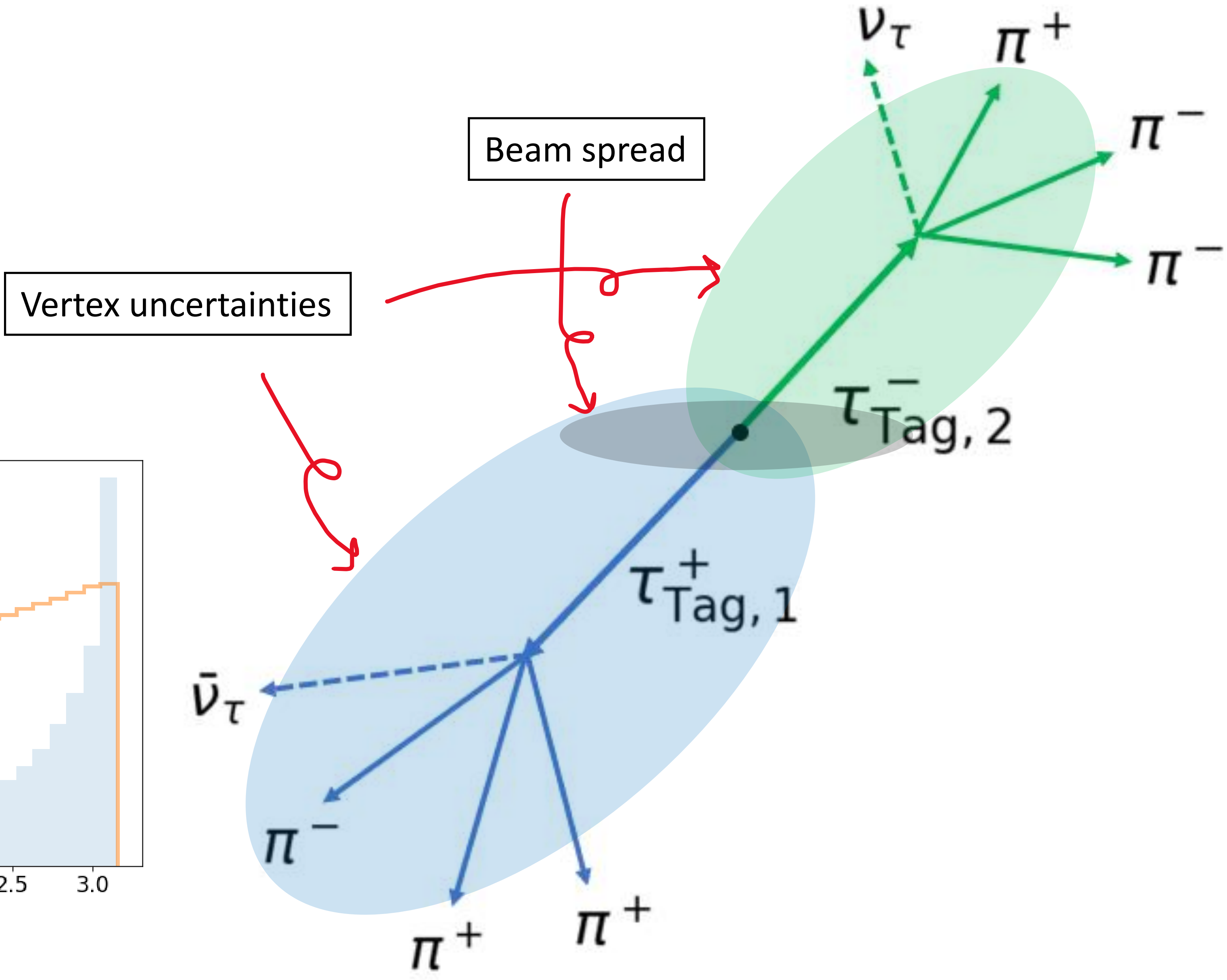


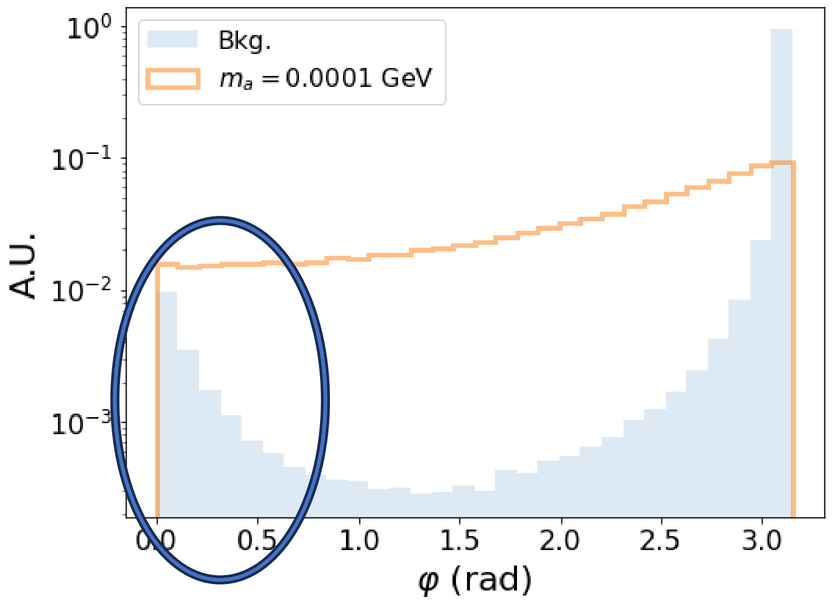




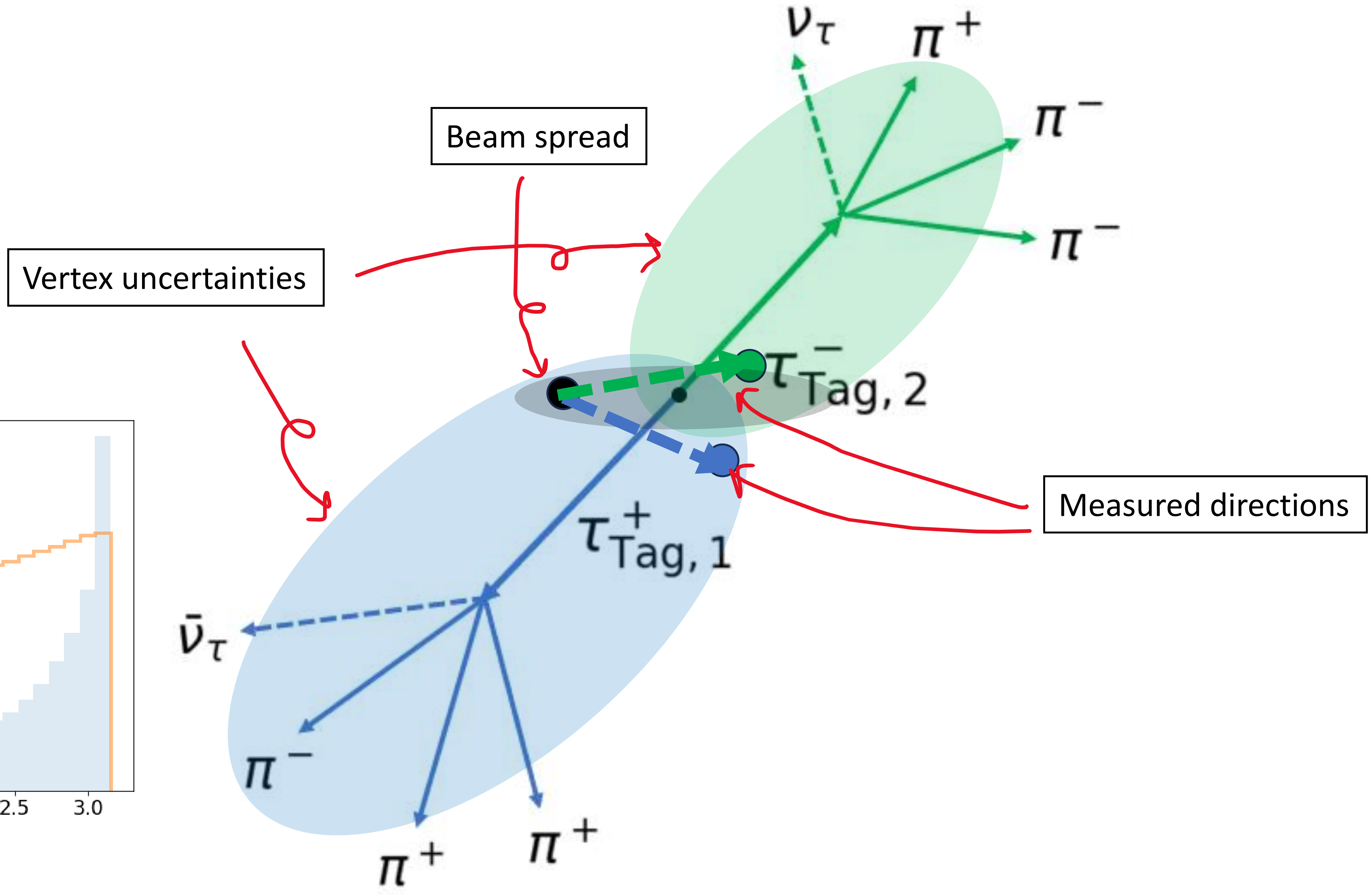
Bkg.
$m_a = 0.0001$ GeV
A.U.
10^0
10^{-1}
10^{-2}
10^{-3}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
φ (rad)



Beam spread
Vertex uncertainties
ν_τ
π^+
π^-
π^-
$\tau^-_{\mathrm{Tag},2}$
$\tau^+_{\mathrm{Tag},1}$
$\bar{\nu}_\tau$
π^-
π^+
π^+



Bkg.
$m_a = 0.0001$ GeV
A.U.
10^0
10^{-1}
10^{-2}
10^{-3}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
φ (rad)



Beam spread
Vertex uncertainties
Measured directions
ν_τ
π^+
π^-
π^-
$\tau^-_{\mathrm{Tag},2}$
$\tau^+_{\mathrm{Tag},1}$
$\bar{\nu}_\tau$
π^-
π^+
π^+