FLORENCE THEORY GROUP DAY

22/02/2023

FRANCESCA ACANFORA

FUSING PHOTONS INTO DARK MATTER AT BELLE II

Work in progress

FA, R. Franceschini, A. Mastroddi, D. Redigolo

OUTLOOK

OUTLOOK

- What?

OUTLOOK

- What?
- Why?

OUTLOOK

- What?
- Why?
- How?

OUTLOOK

- What?
- Why?
- How?
- Results

WHAT?

ALP DISCOVERY @ BELLE II - INVISIBLE CHANNEL

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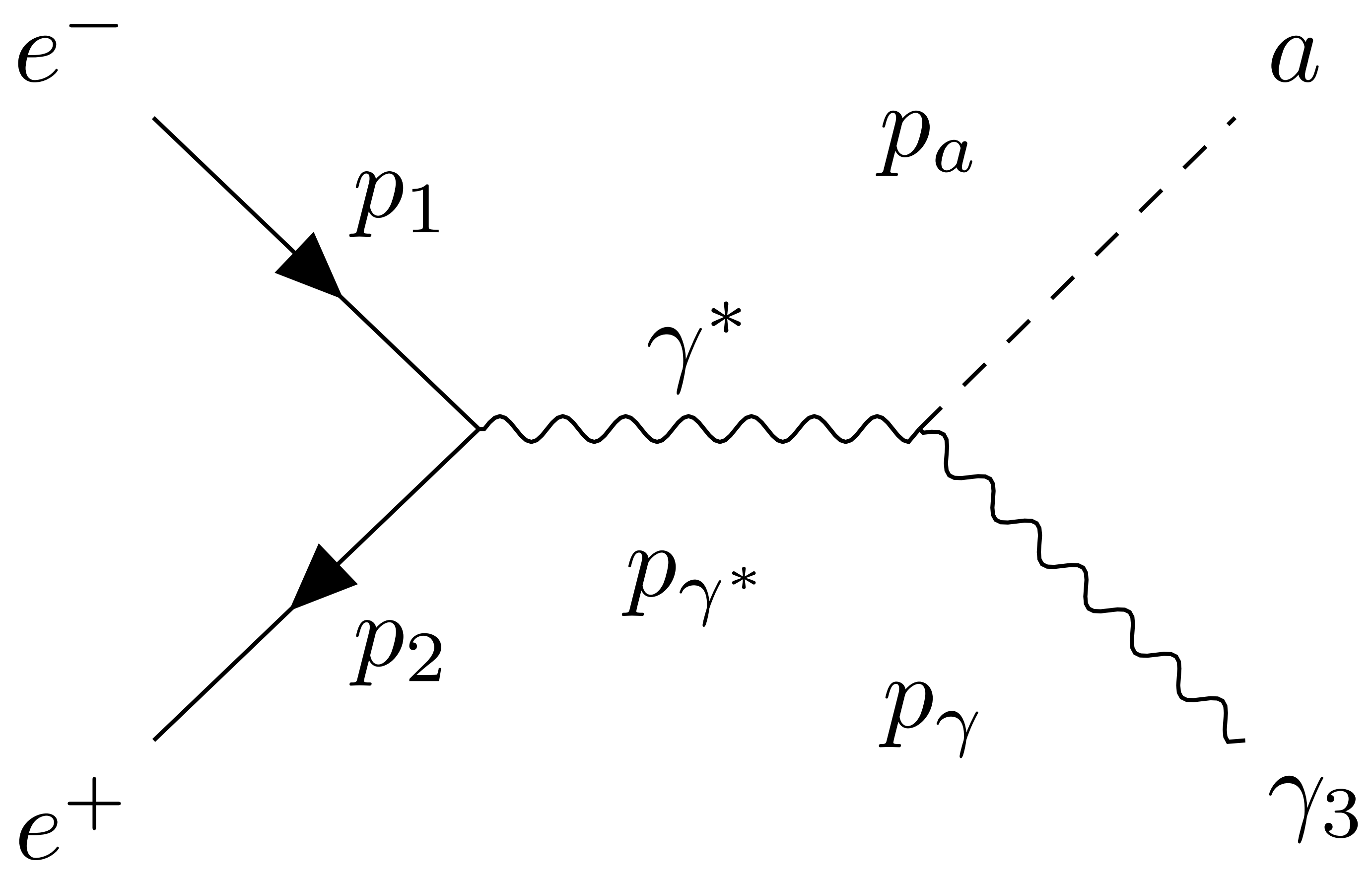

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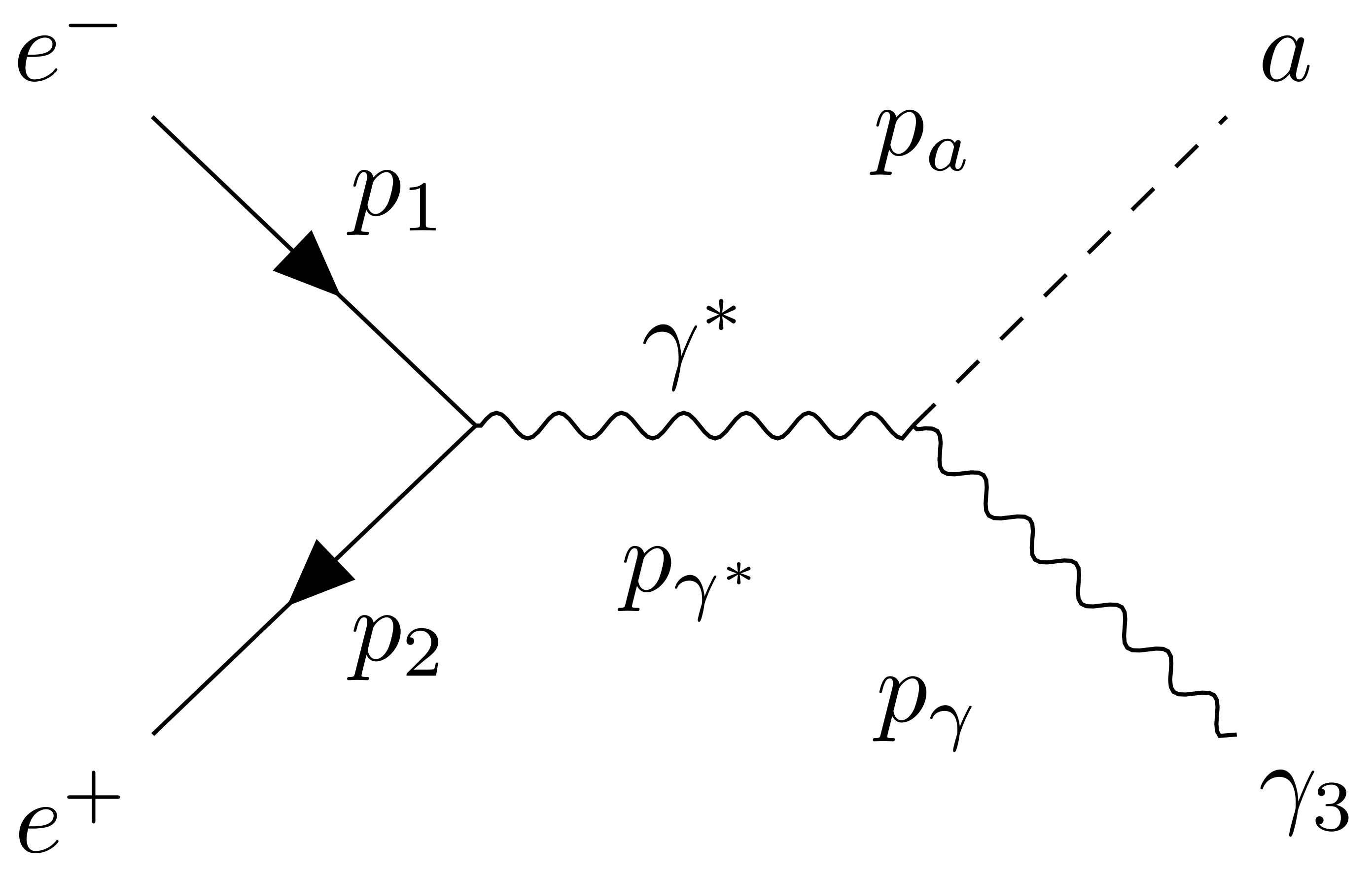

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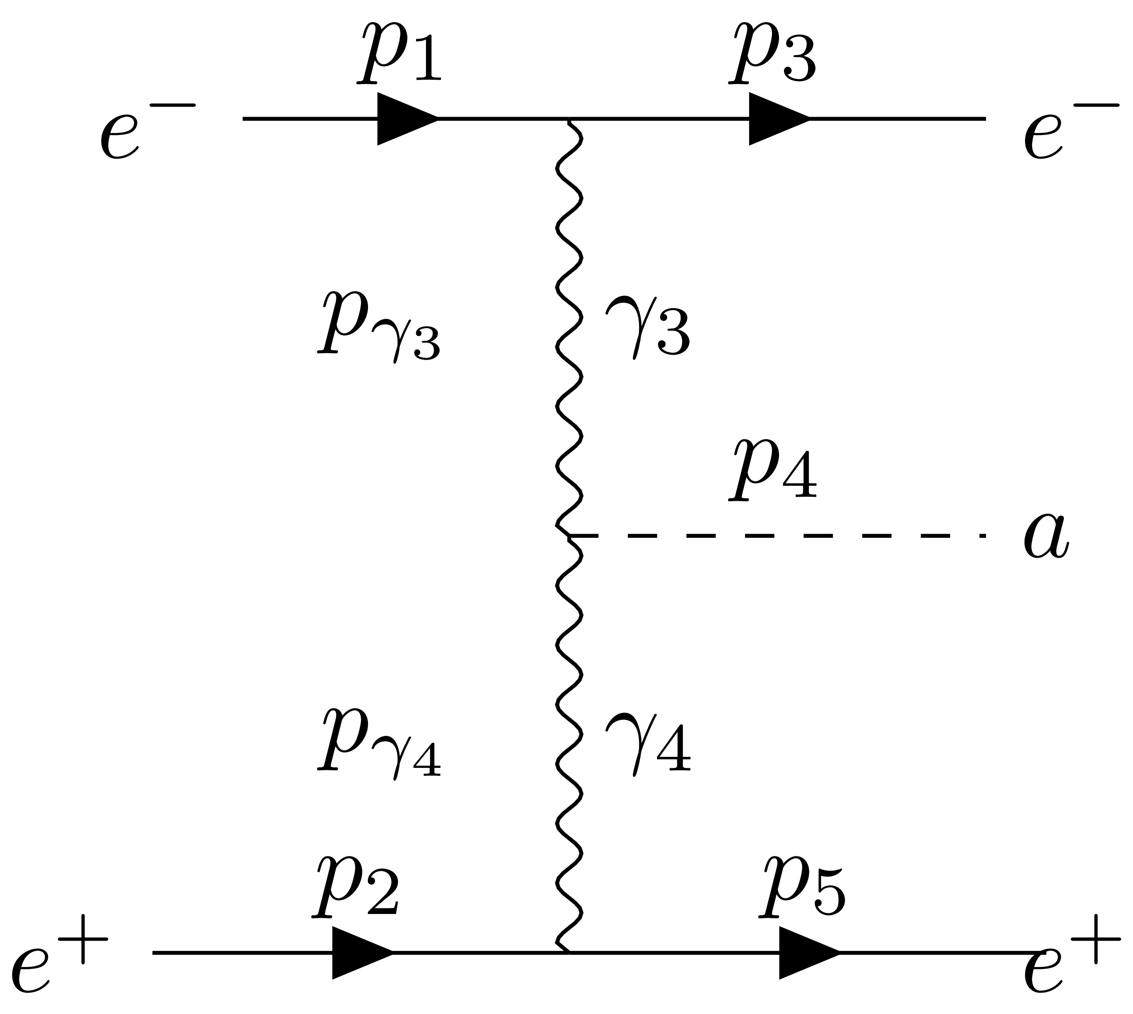

VECTOR BOSON FUSION

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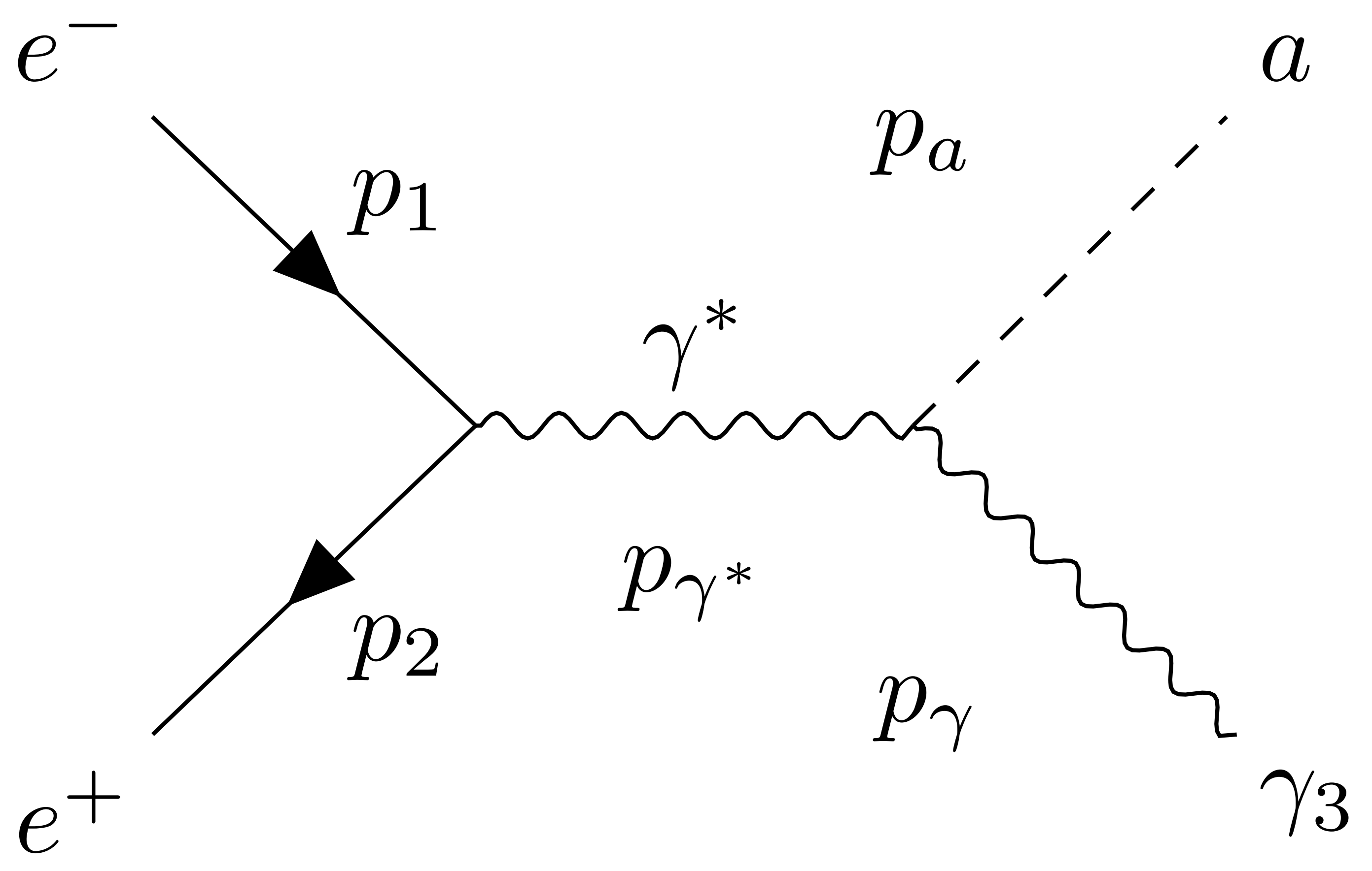

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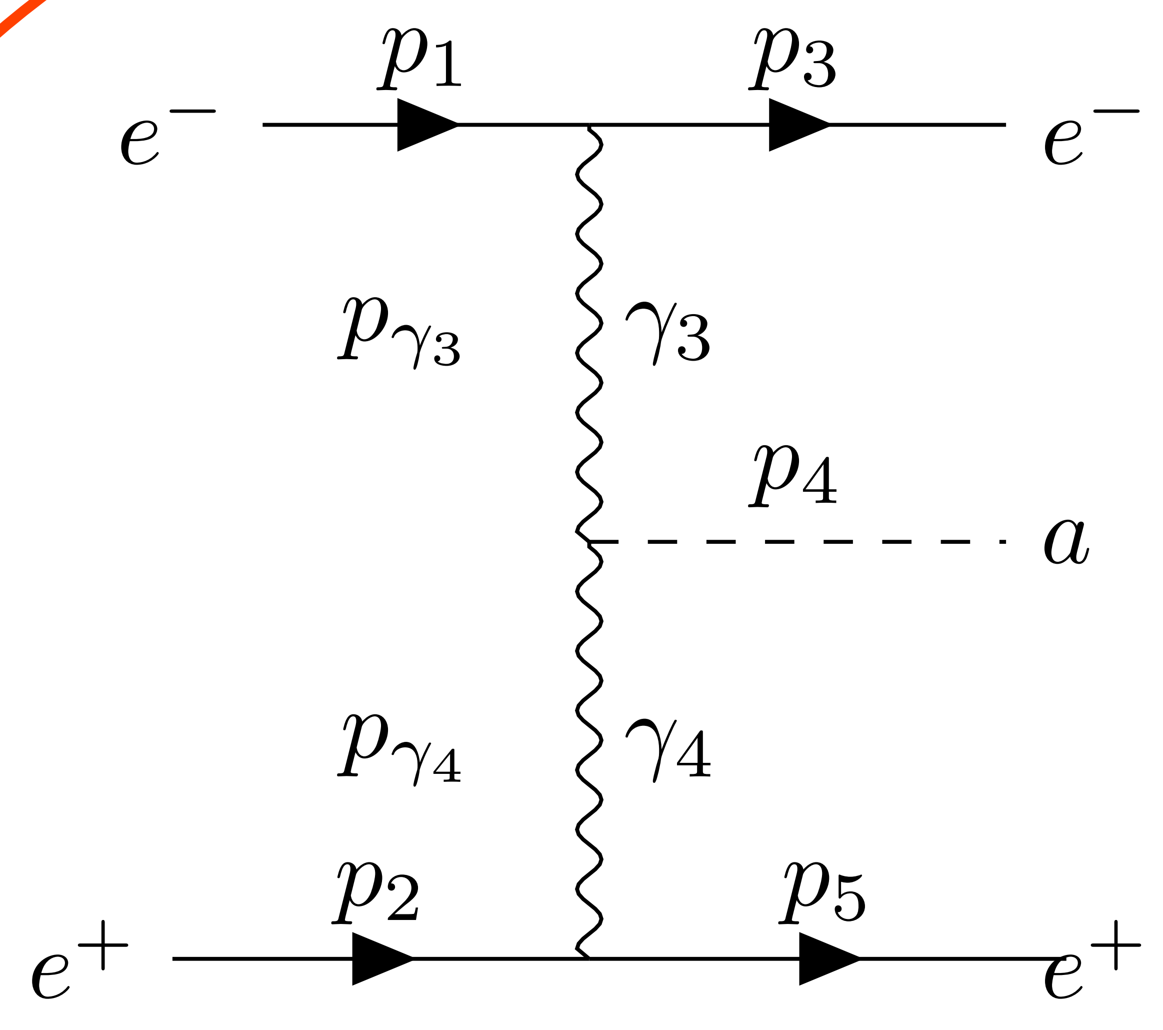

VECTOR BOSON FUSION

REMEMBER

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State of the art 1709.00009:

- **Signal:** $e^+e^- \to a\gamma$ **(mono-γ)**
- **Bg:**

$$\begin{cases} e^+e^- \to \gamma + n\gamma_{\textsf{inv}} \\ e^+e^- \to \gamma + e^-_{\textsf{inv}} + e^+_{\textsf{inv}} + n\gamma_{\textsf{inv}} \end{cases}$$

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ALP DOES NOT DECAY INTO PHOTONS WITHIN DETECTOR!

INVISIBLE PARTICLE

TOO FEW ENERGY OR TOO SMALL POLAR ANGLE

WHY?

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- Smoking gun of BSM Theories (String Theory, Supersymmetry…)
- Cosmological problems (over-efficient cooling of some stars, the transparency of the Universe to very high-energy γ-rays, 3.55 keV line from Andromeda…)

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- Can explore MeV-GeV scale where many BSM particles live $\sqrt{s} = 10.58$ GeV
- Is e^+e^- collider $\rightarrow$ the initial state is known and invisible states can be reconstructed

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- Will be important at high energy colliders
- Is more important that the strahlung when the detector polar angle acceptance is bigger
- Is an independent alternative to strahlung

HOW?

$$\frac{s}{\sqrt{b}}$$

USE NARROW WIDTH

- $$\boxed{\Gamma_a = \frac{g_{a\gamma\gamma}^2 M_a^3}{64\pi}}$$
- On $M_a \sim 0.1$ GeV, $g_{a\gamma\gamma} \sim 10^{-4}$ GeV^{-1}, $\Gamma_a \sim 50\mu$eV

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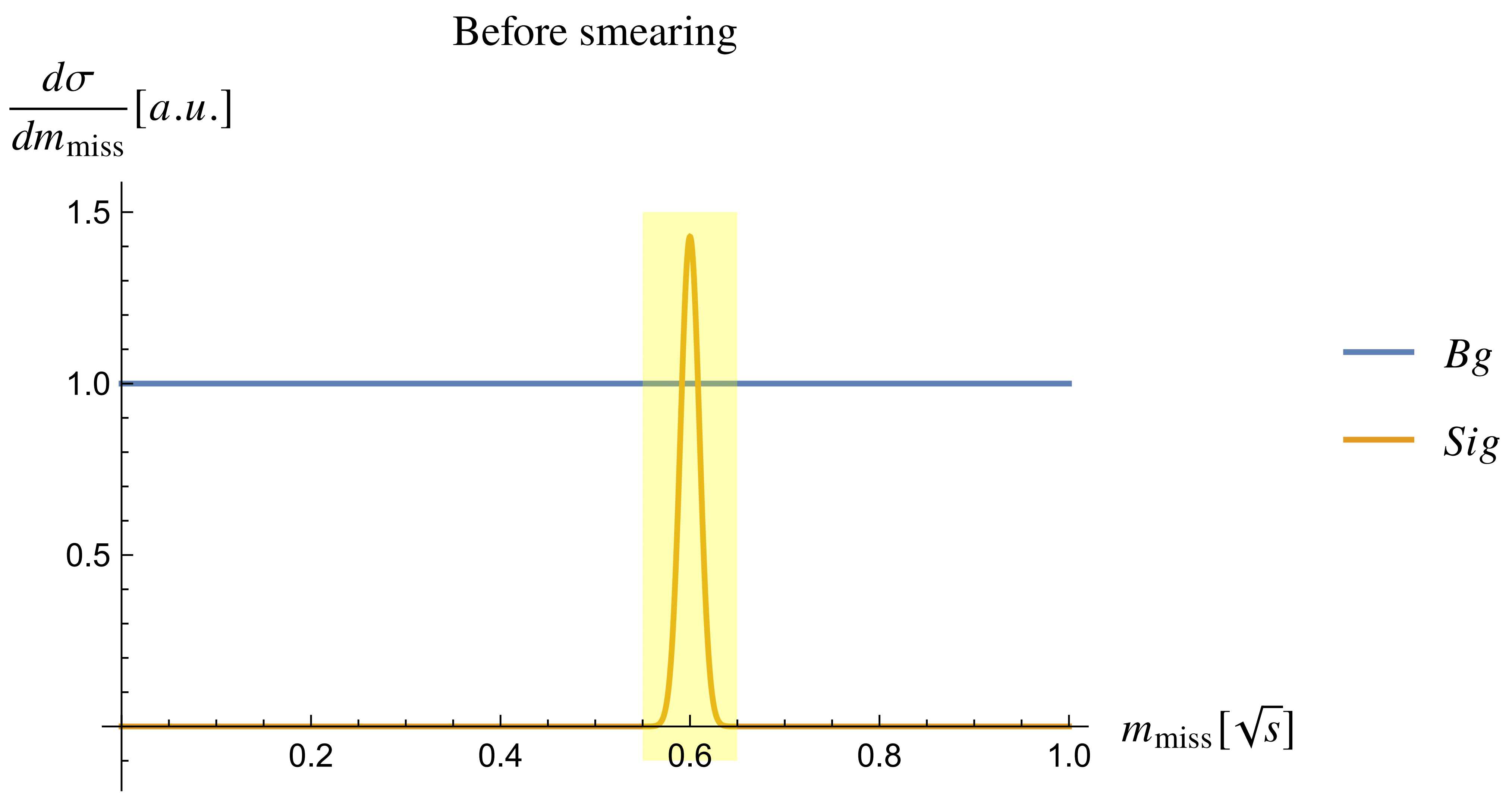
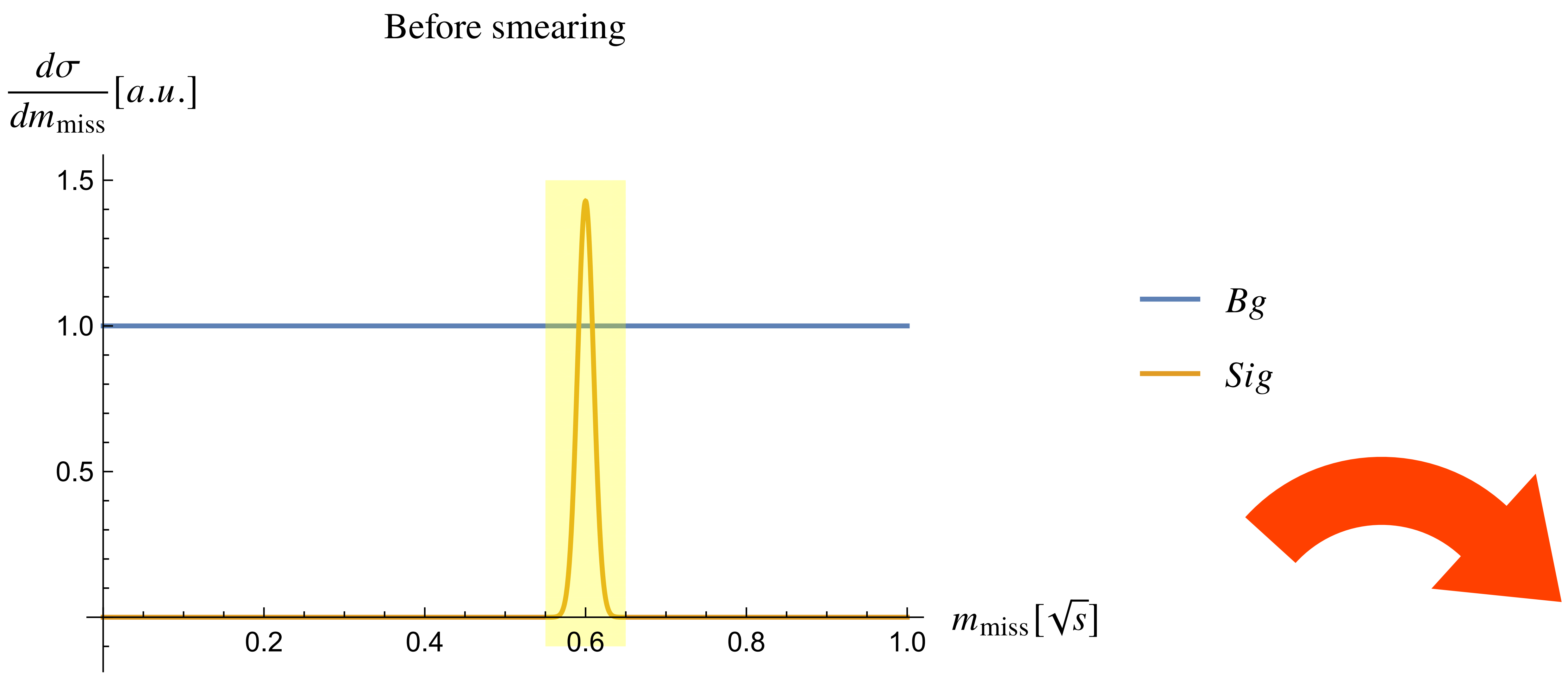


Before smearing
$\frac{d\sigma}{dm_{\text{miss}}}[a.u.]$
1.5
1.0
0.5
0.2
0.4
0.6
0.8
1.0
$m_{\text{miss}}[\sqrt{s}]$
Bg
Sig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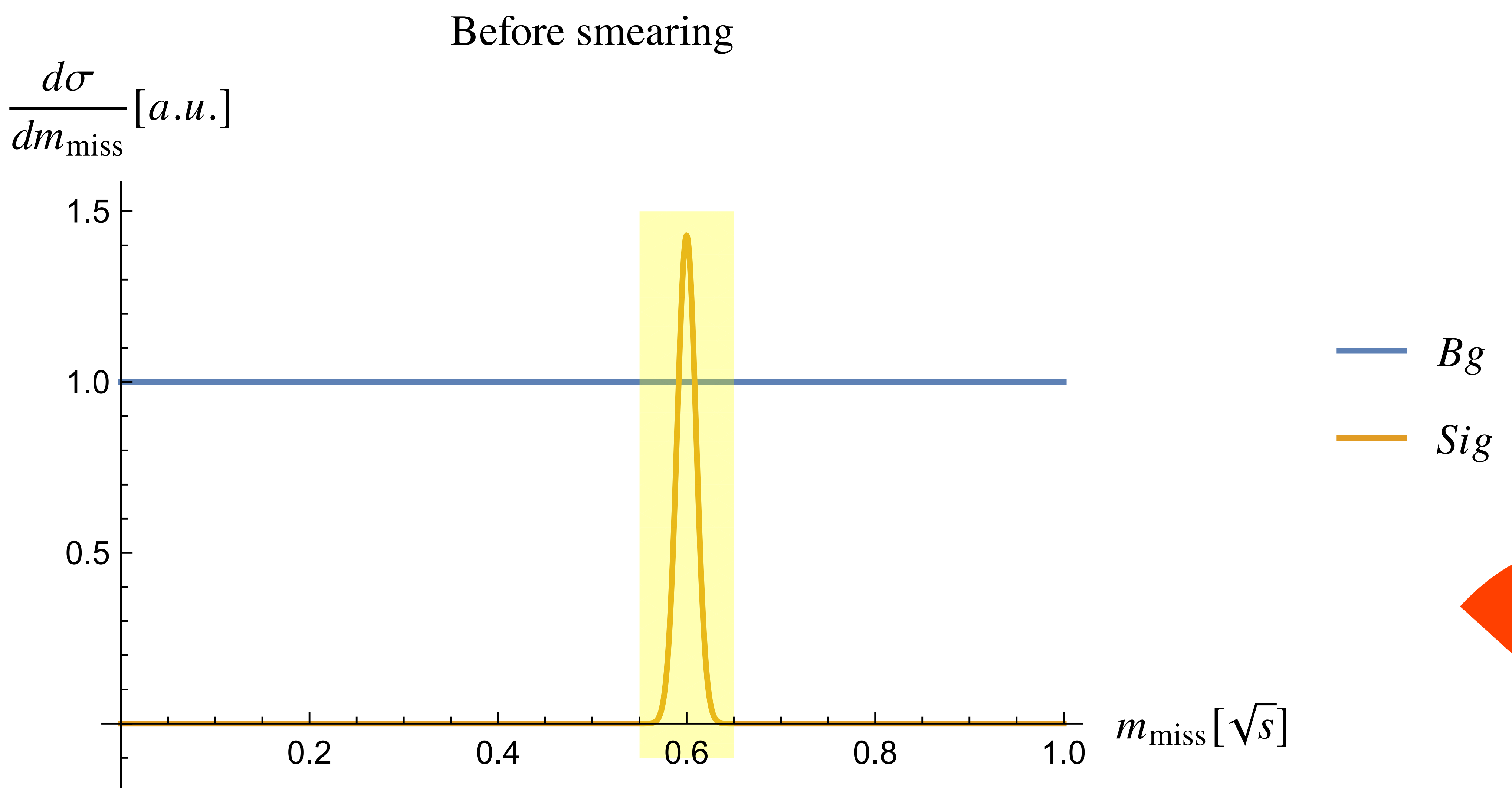

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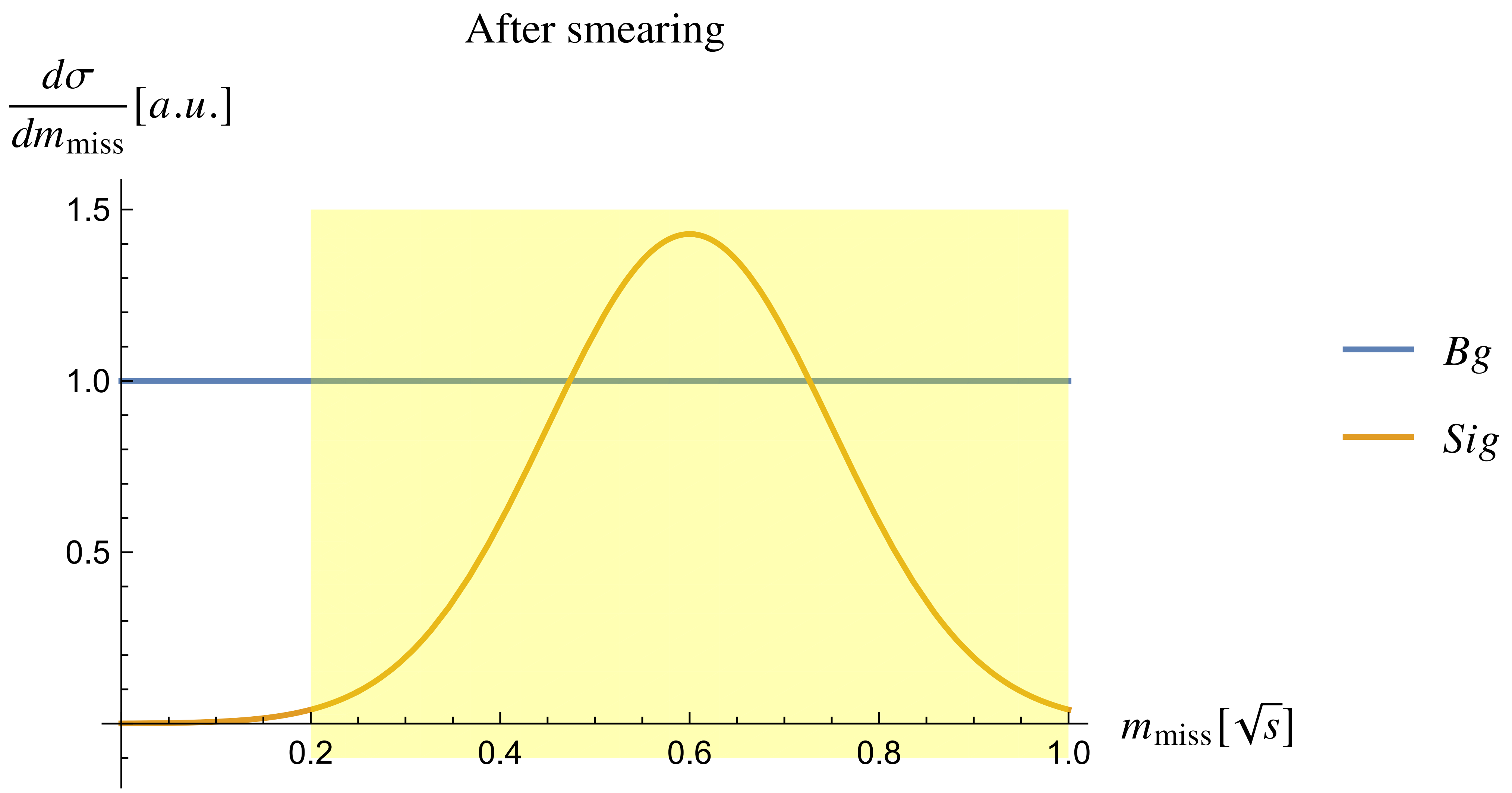

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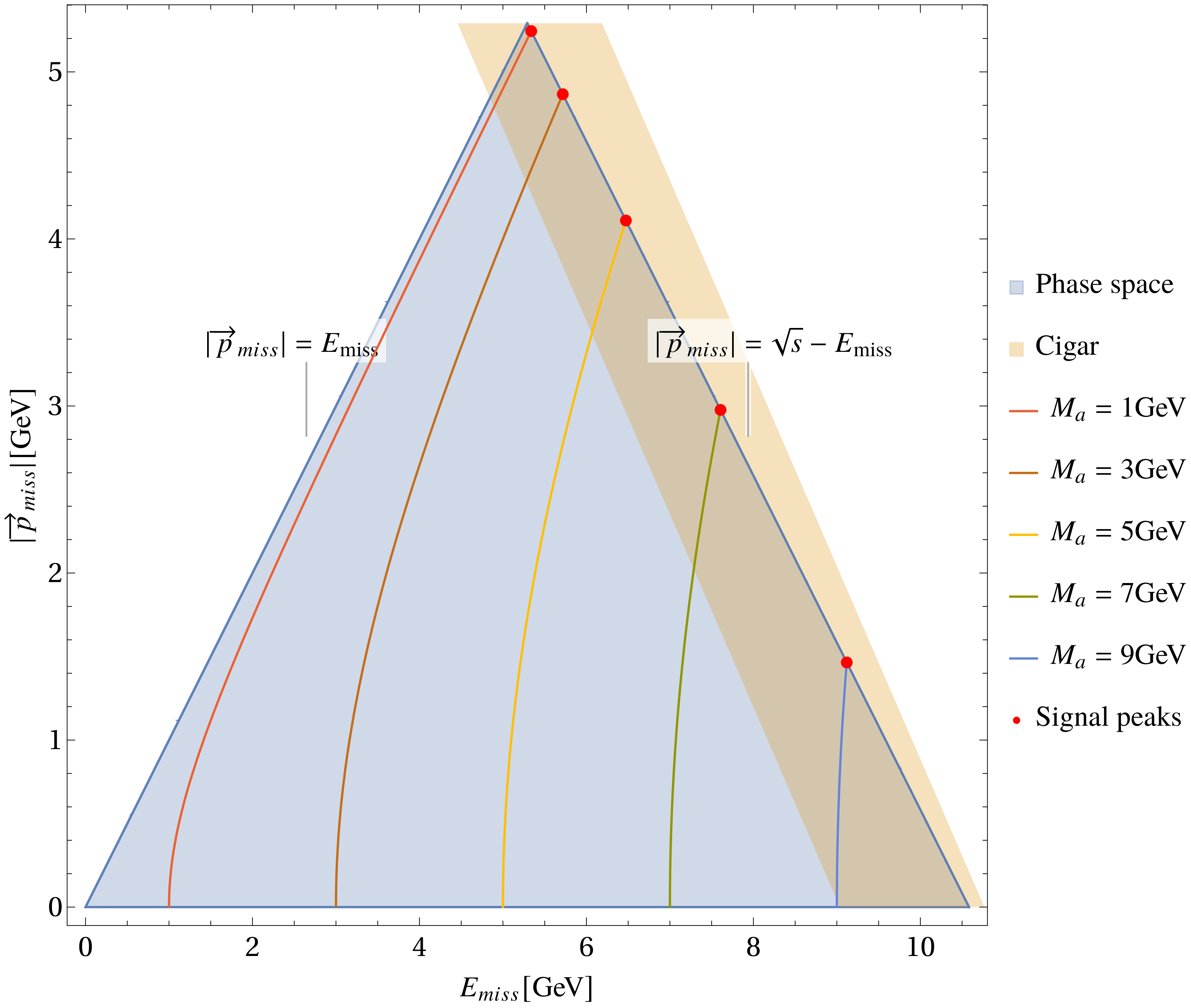
WHAT NOW?

CIGAR CUT

$$e^+e^- \to e^+e^- a$$



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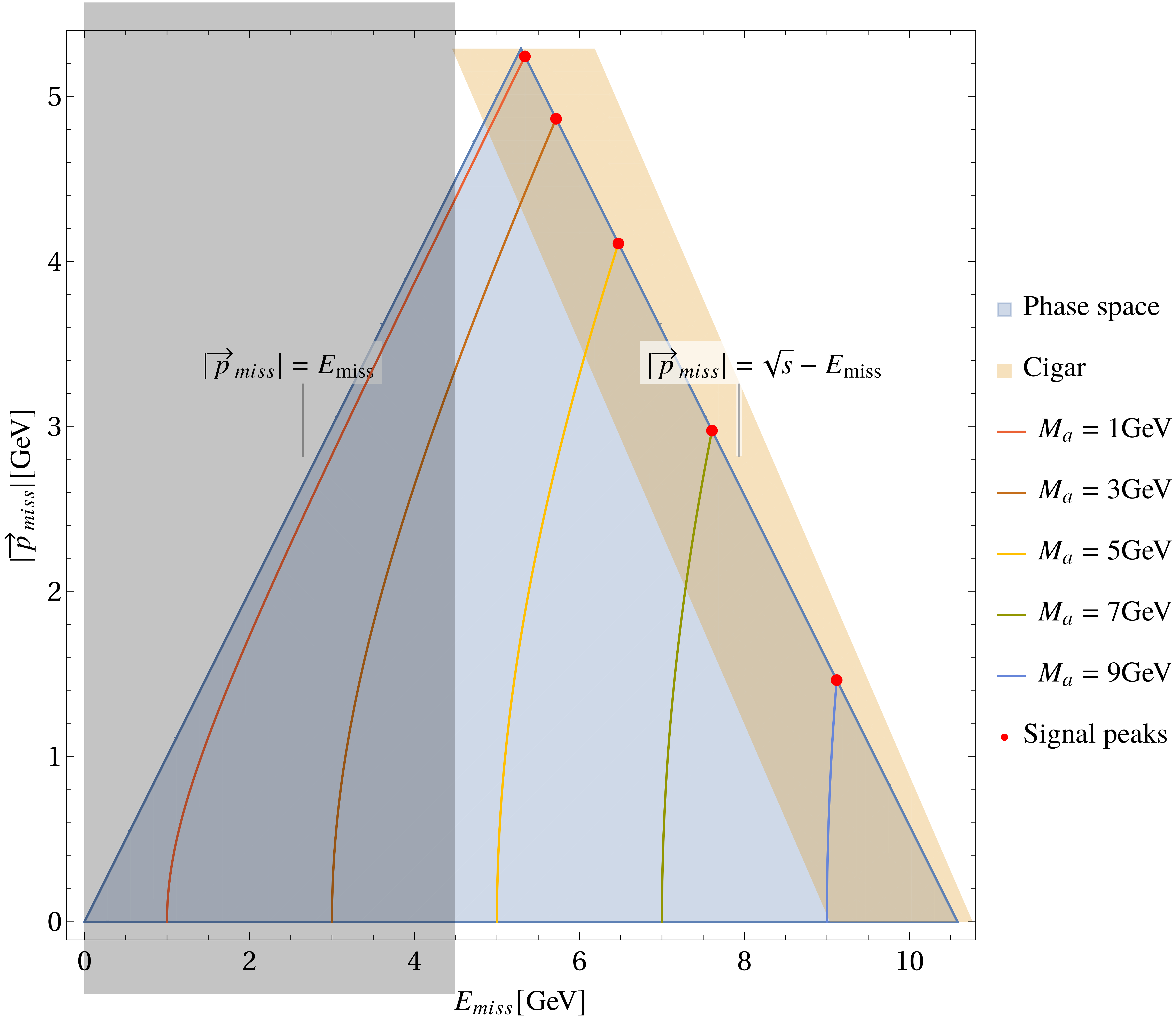
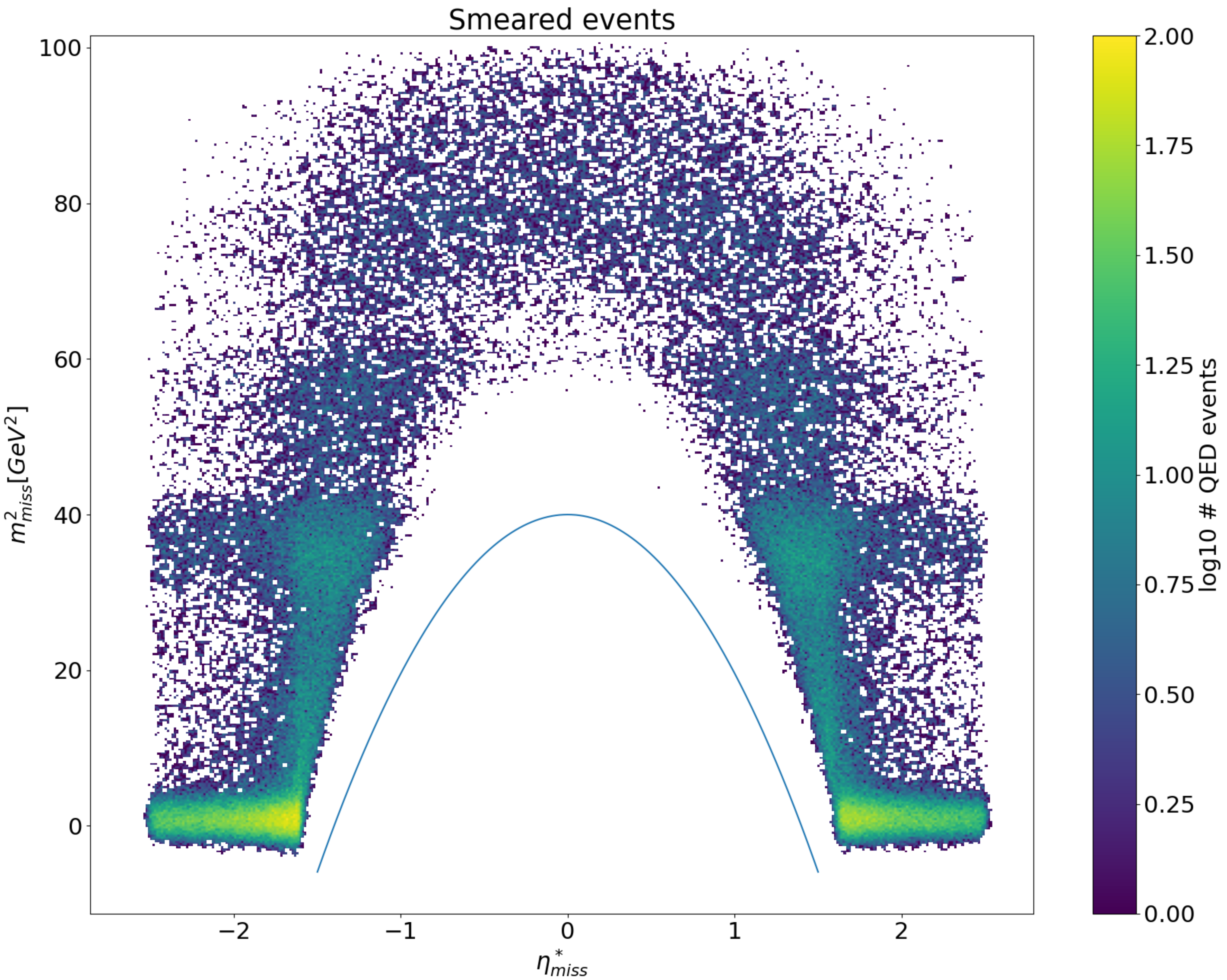


EMPTY REGION IN $(m_{\text{miss}}, \eta_{\text{miss}})$ PLANE FOR QED BG

$e^+e^- \to e^+e^-2\gamma_{\text{inv}}$



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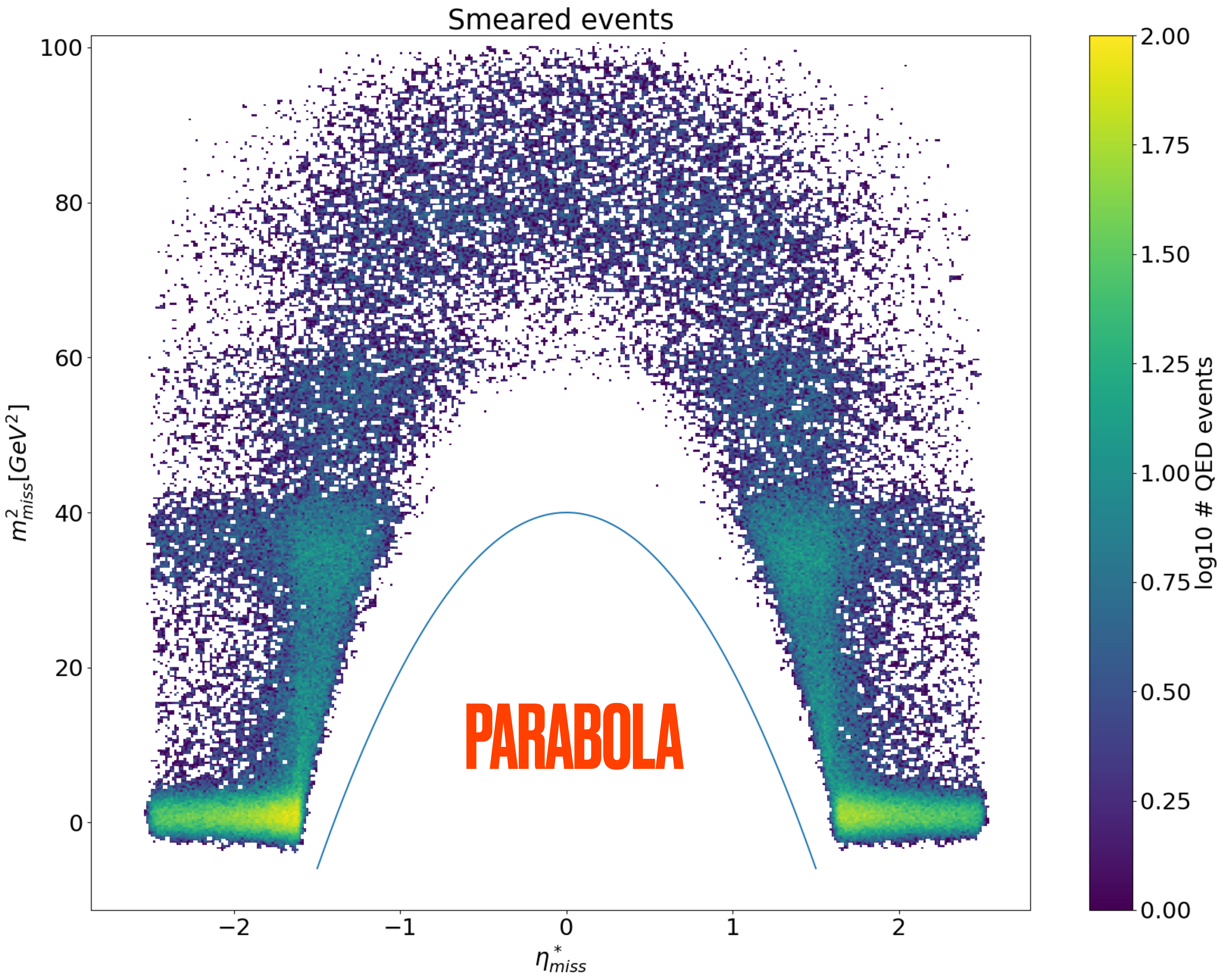

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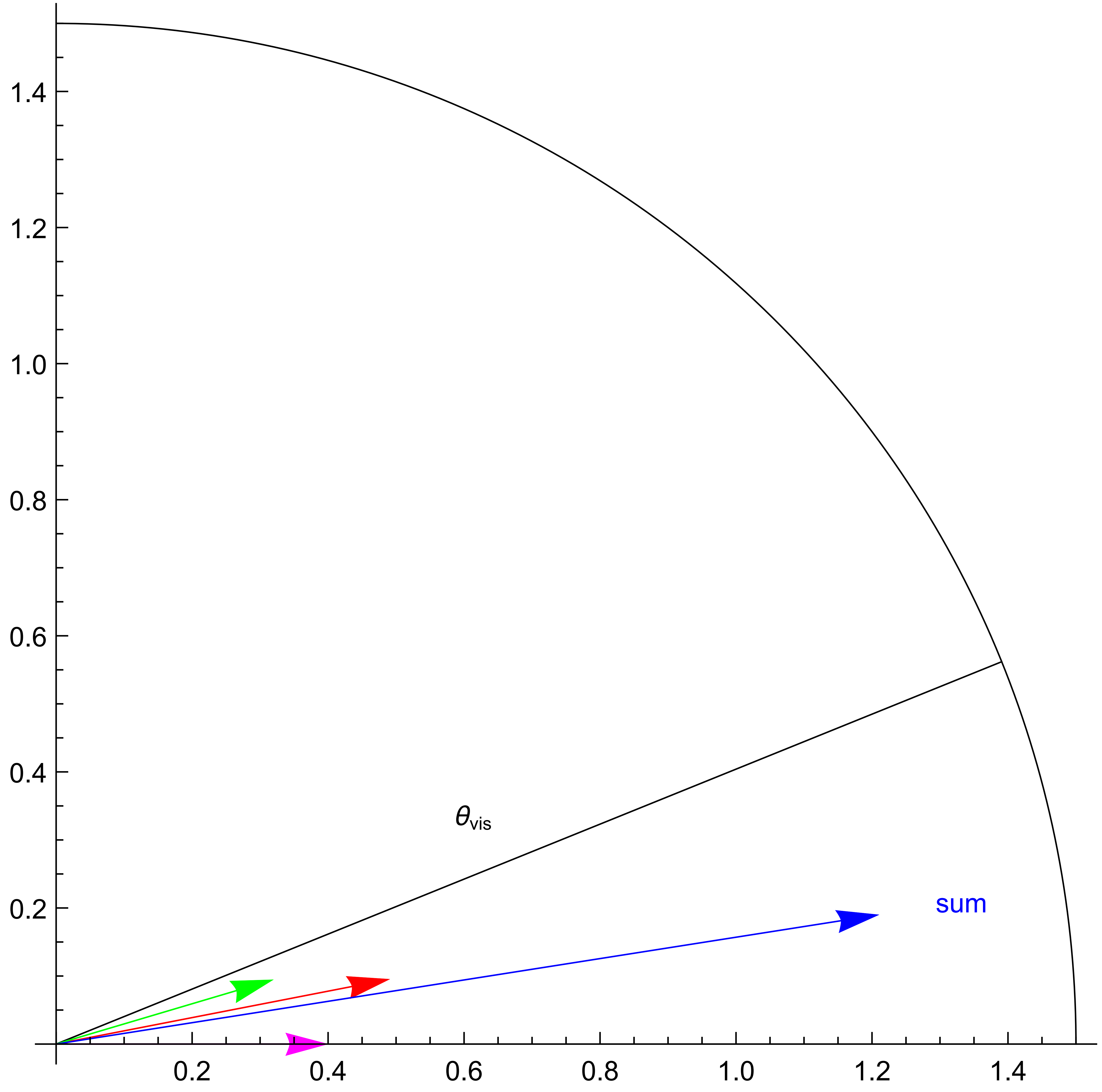

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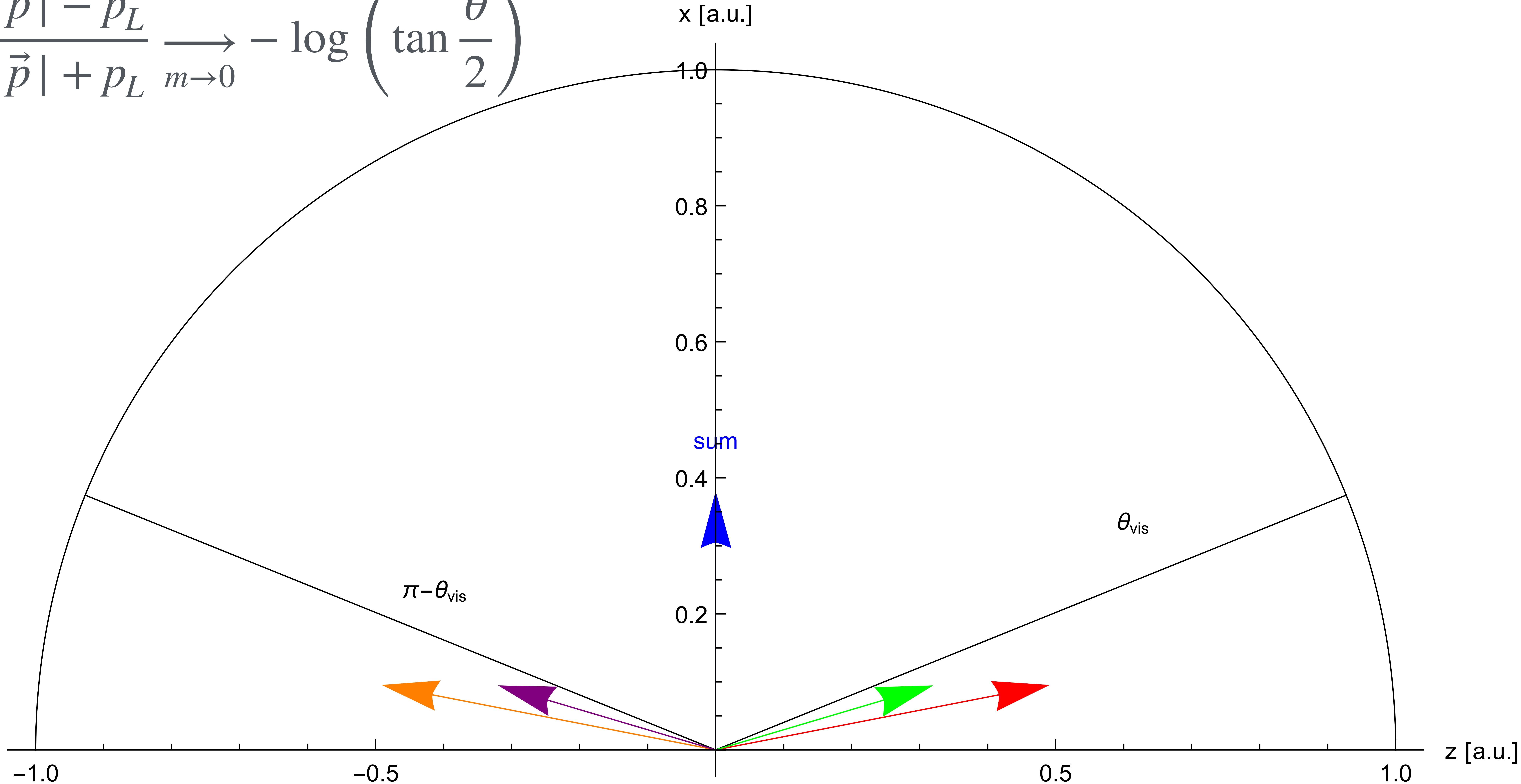

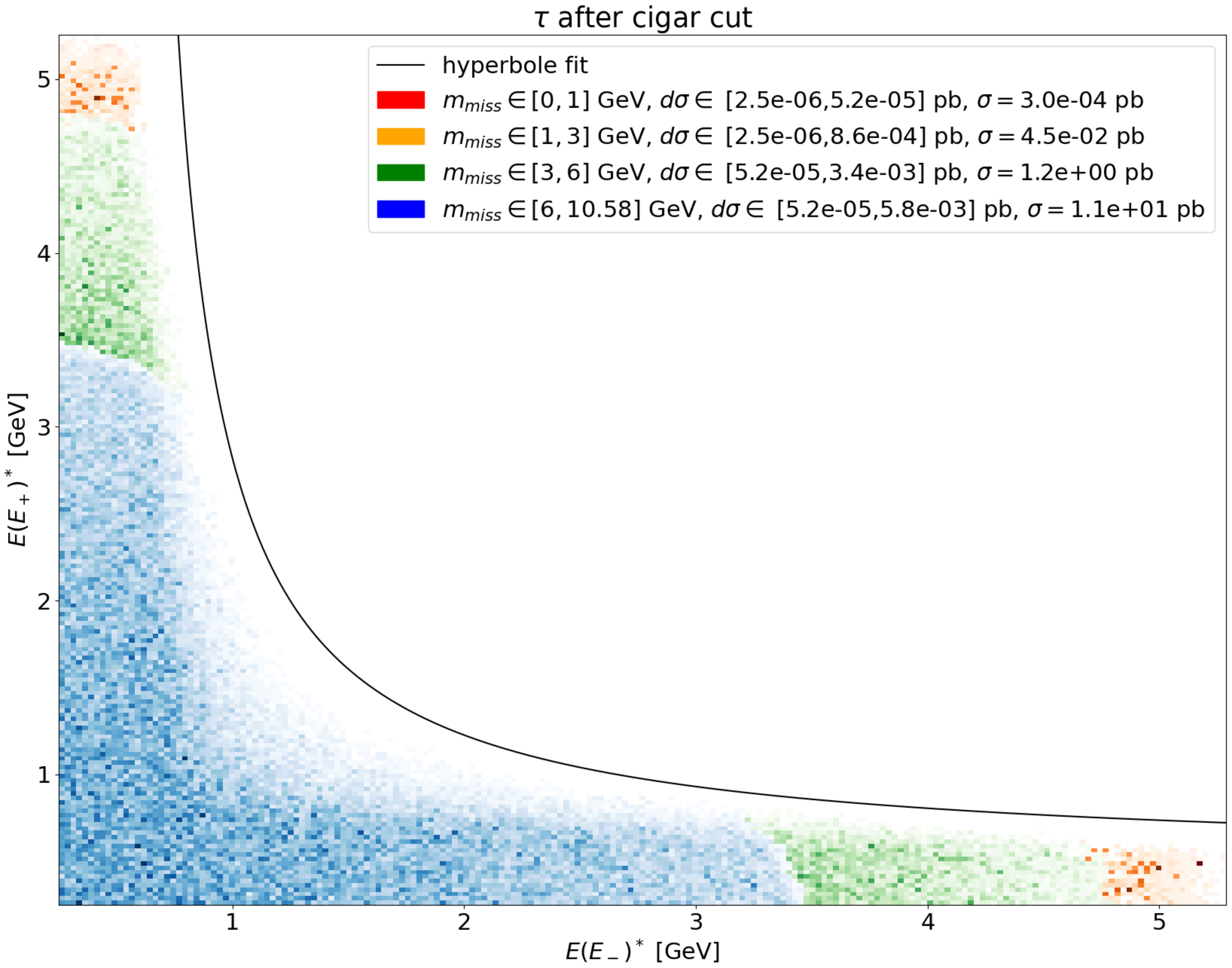

EMPTY REGION IN $(E(e^-), E(e^+))$ PLANE FOR $\tau\tau$ BG

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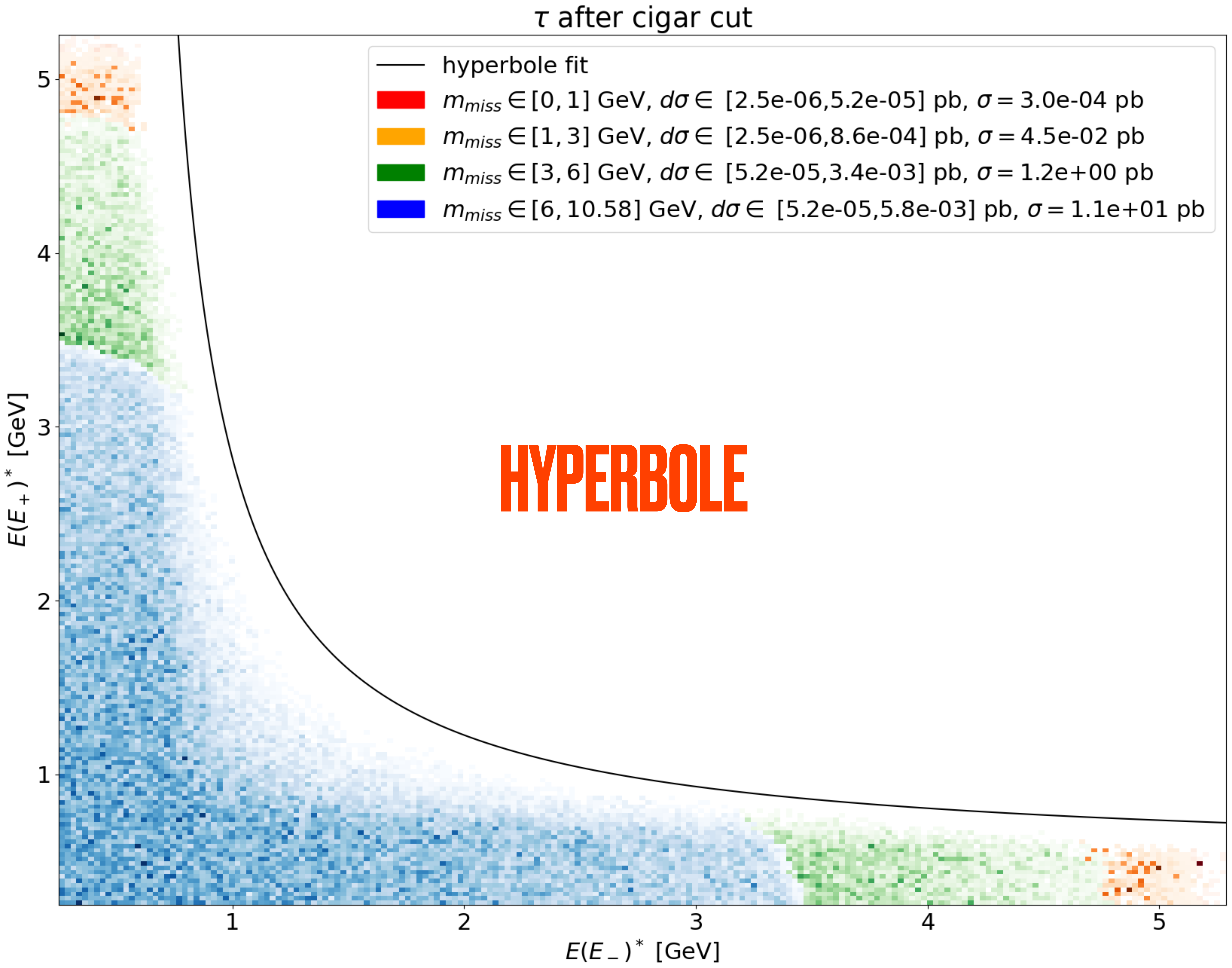

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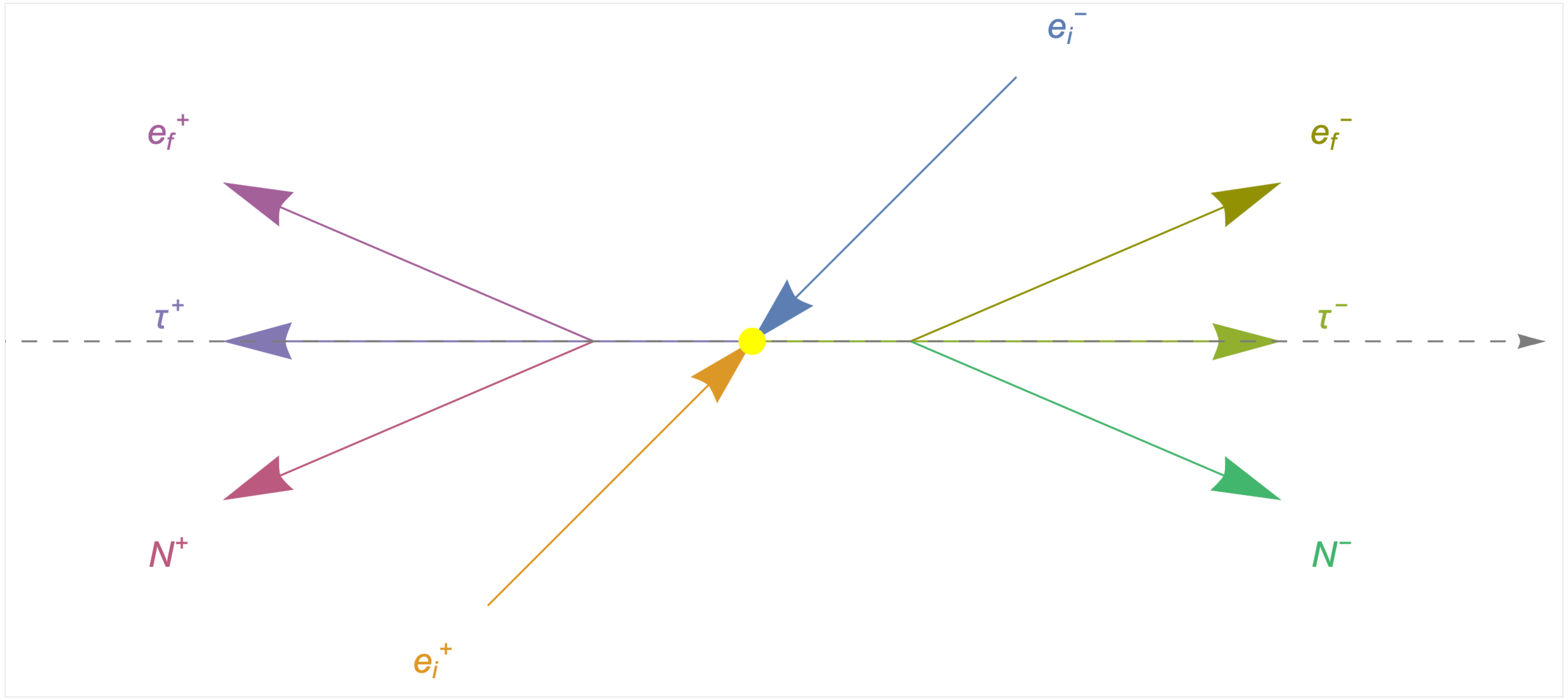
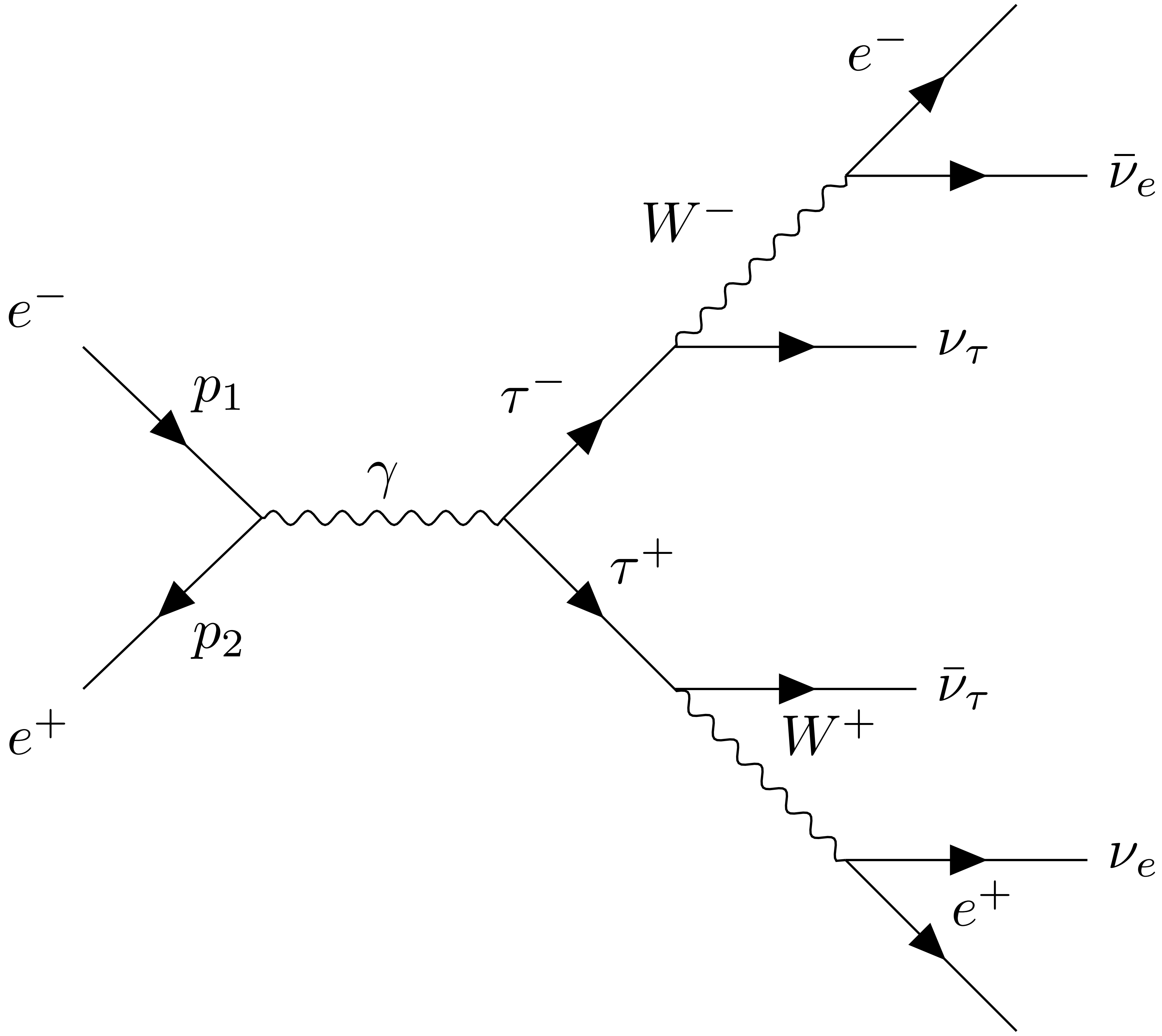
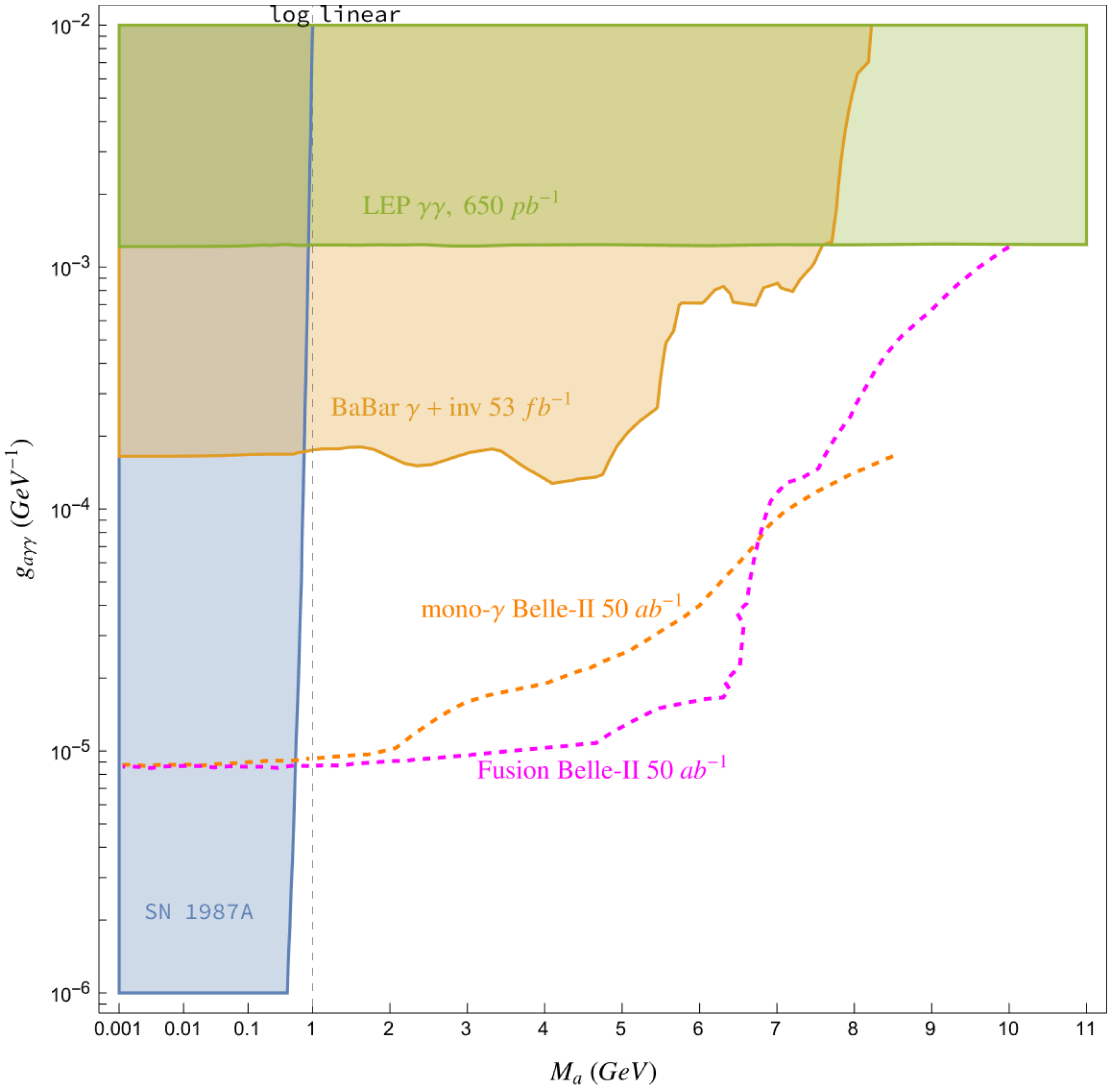

e_i^-
e_f^+
e_f^-
τ^+
τ^-
N^+
N^-
e_i^+

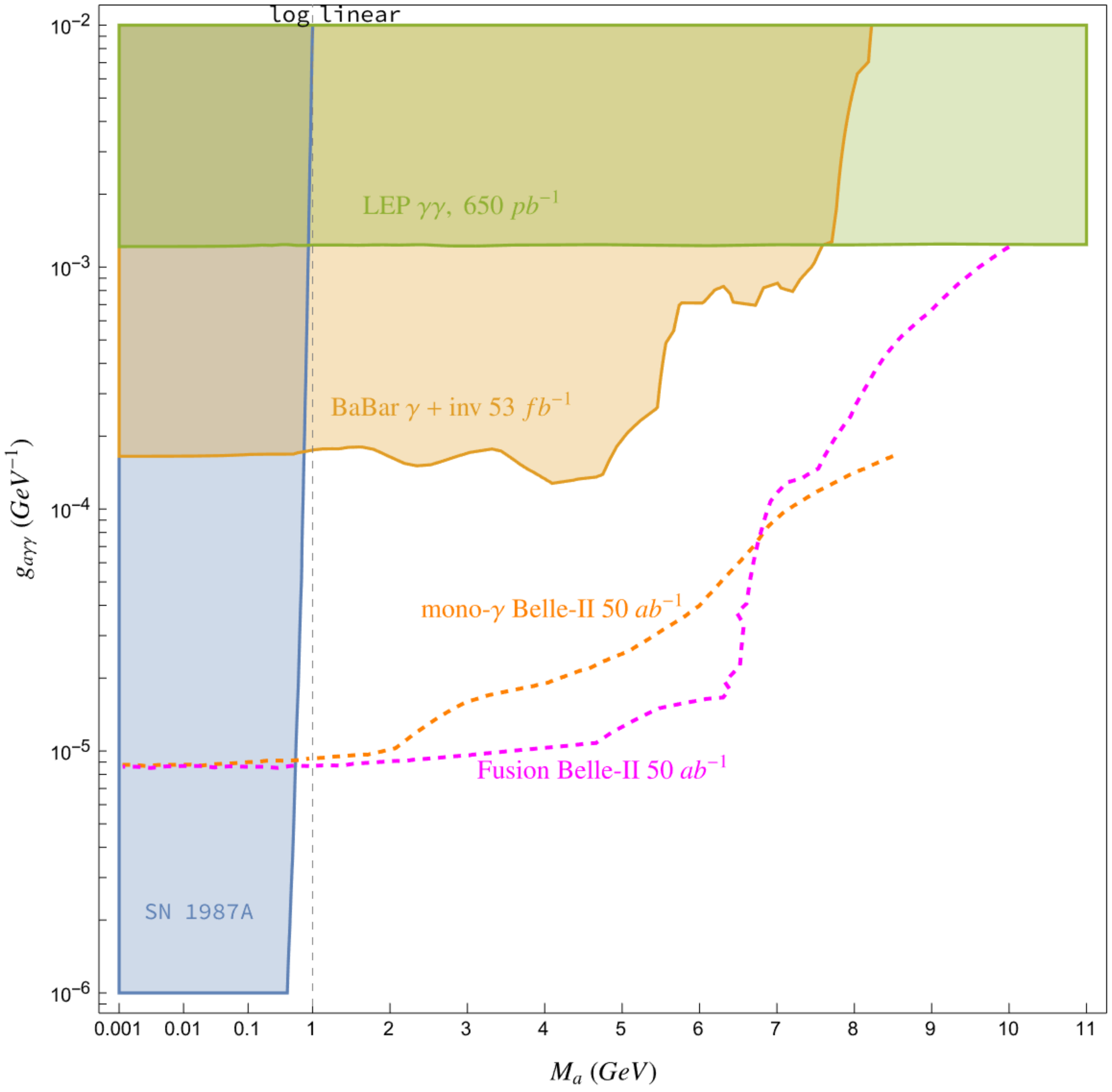

e^-
$\bar{\nu}_e$
W^-
e^-
ν_τ
p_1
τ^-
γ
τ^+
p_2
$\bar{\nu}_\tau$
e^+
W^+
ν_e
e^+

RESULTS

REACH


log linear
LEP $\gamma\gamma$, 650 pb^{-1}
BaBar γ + inv 53 fb^{-1}
mono-γ Belle-II 50 ab^{-1}
Fusion Belle-II 50 ab^{-1}
SN 1987A
$g_{a\gamma\gamma}$ (GeV^{-1})
M_a (GeV)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.001 0.01 0.1 1 2 3 4 5 6 7 8 9 10 11

REACH



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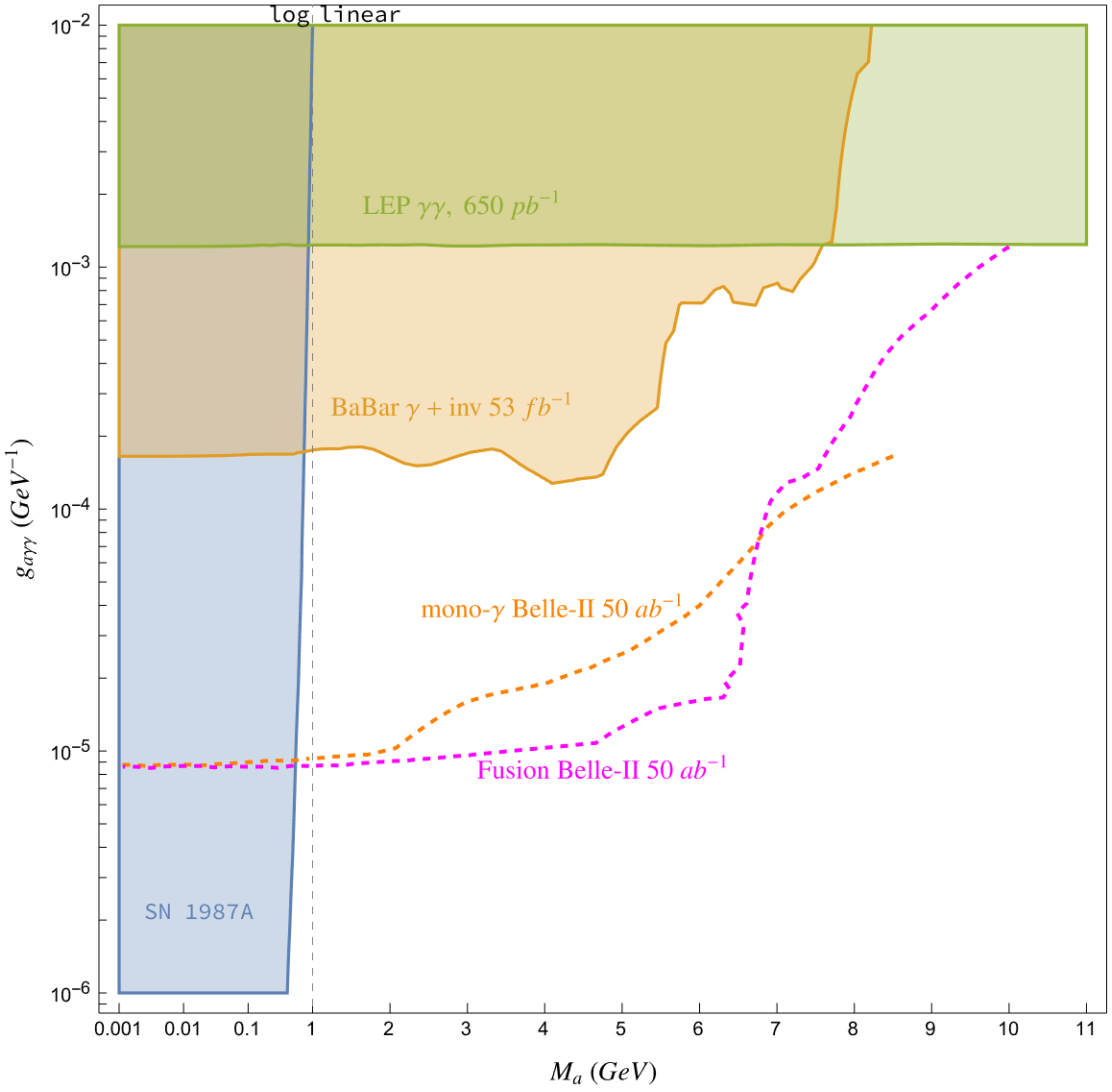
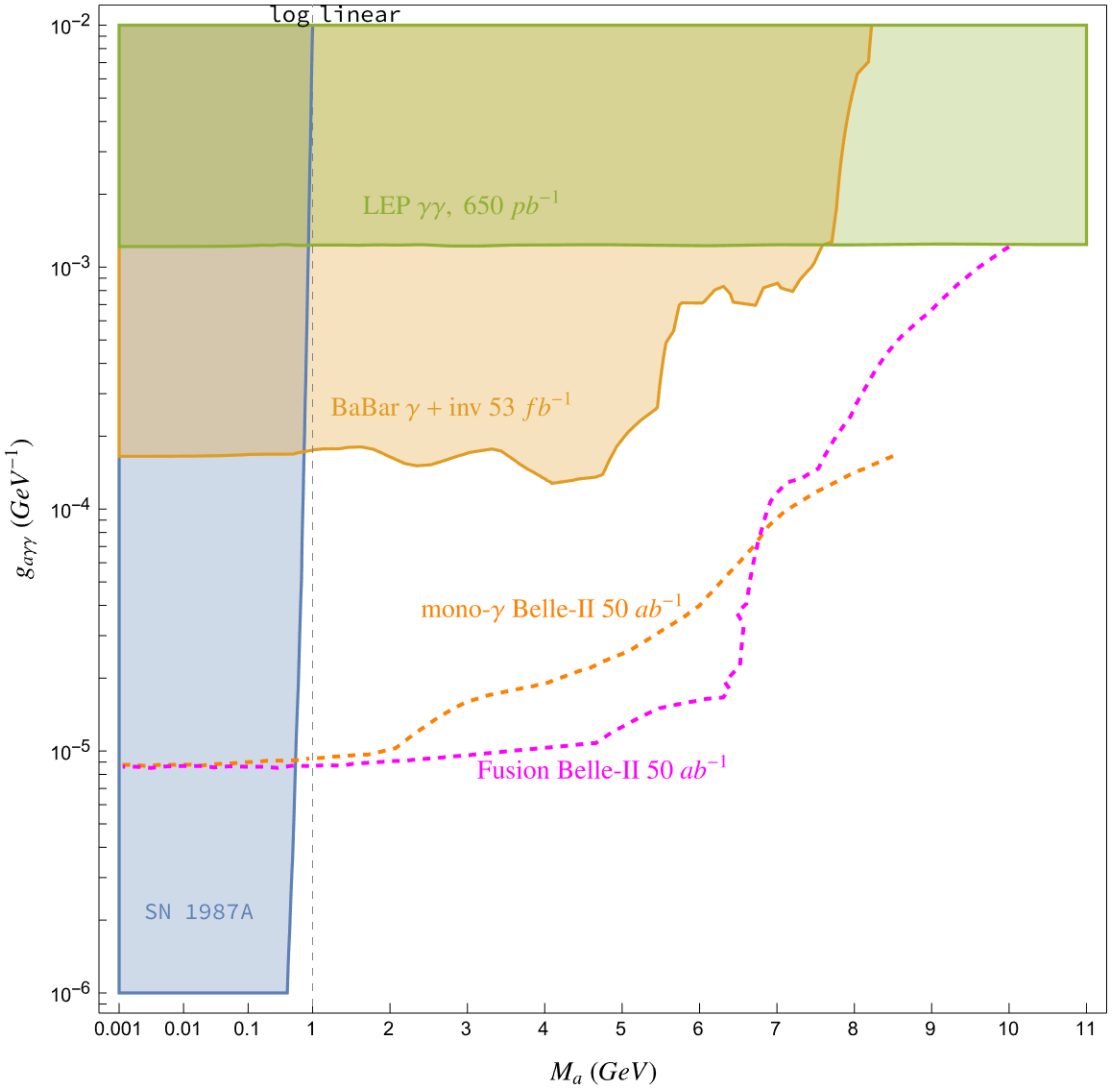
- Cigar

REACH



- Cigar
- Parabola

REACH



- Cigar
- Parabola
- Hyperbole

CONCLUSIONS

- **The VBF was** worth **it and proved better than the strahlung**
- **Original** selections **were proposed:**
  - **High** purity **search**
  - **Depend on signal and bg** topology **only:**
    - **Detector-independent**
    - **Theory-independent**
- **Future work:**
  - **Apply to other colliders**
  - **Apply to other BSM searches**

THANK YOU

BACKUP SLIDES

ALPS MILESTONES

- Peccei-Quinn symmetry PhysRevLett.38.1440
- Wilczeck PhysRevLett.40.279 and Weinberg PhysRevLett.40.223
- KSVZ ITEP-64-1979 and DFSZ models Print-81-0320 (IAS,PRINCETON)

ALPS COUPLED TO GAUGE BOSONS

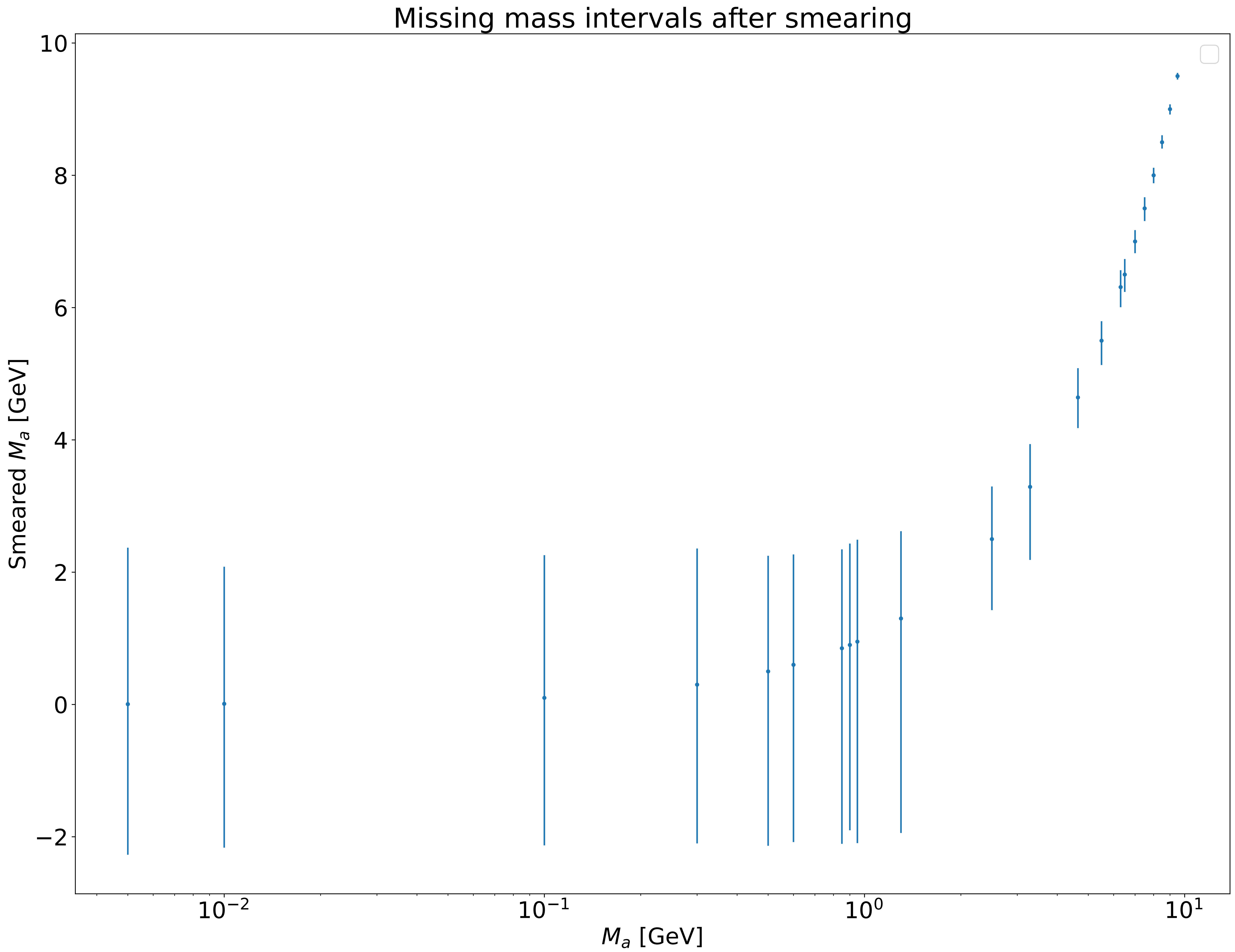
$$\mathscr{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{c_B}{4f_a} a B^{\mu\nu}\tilde{B}_{\mu\nu} - \frac{c_W}{4f_a} a W^{i,\mu\nu}\tilde{W}^i_{\mu\nu}$$

- $\tilde{B}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}B^{\rho\sigma}$.

$$\mathscr{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu},$$

- $g_{a\gamma\gamma} = \dfrac{c_B \cos^2\theta_W + c_W \sin^2\theta_W}{f_a}, \quad g_{a\gamma Z} = \dfrac{\sin 2\theta_W \left(c_W - c_B\right)}{f_a}$

EFFECT OF SMEARING ON MISSING MASS



QED PROOF SKETCH

Claim: can not do $m_{\text{miss}} \sim 0,\, \eta_{\text{miss}} \sim 0$ with:

- Low mass
- High missing energy
- Few invisible photons

1. A small mass needs all coplanar photons
2. High missing energy needs photons along the beam pipe
3. $\eta_{\text{miss}} = 0$ needs forward and backward photons
4. There is missing mass lower bound

$\tau\tau$ PROOF SKETCH

- The $e^+e^- \to \tau^+\tau^-$ dynamics has one angular degree of freedom θ. Irrelevant for our aim.
- The $\tau \to e\nu\bar{\nu}$ dynamics has the $(\nu\bar{\nu})$ body mass $M(N^{\pm})$ and one angular degree of freedom $\theta^{\pm}$
- Without loss of generality $M(N^{\pm}) = 0$
- Then $E(e^{\pm})$ only depend on $\theta^{\pm}$
- $\tau^{\pm}$ are boosted $\to$ $e^{\pm}$ collinear to parent $\tau \to |\theta^+ - \theta^-| \sim \pi$ in CoM
- Cigar asks for maximal $|\vec{p}_{\text{miss}}|$ $\to$ at most one hard electron at a time

SELECTIONS MORE EXPLICITLY: LOW MASS

- **Cigar**: $10.437GeV - 1.155E_{\text{miss}} \leq |\vec{p}_{\text{miss}}| \leq 12.437GeV - 1.155E_{\text{miss}}$

- **Hyperbole**: $E_+^* > 0.50GeV + \dfrac{1.06GeV^2}{-0.54GeV + E_-^*}$.

- **Parabola**: $m^2_{\text{miss}} < -20.41(\eta_{\text{miss}} - 1.4)(\eta_{\text{miss}} + 1.4)GeV^2$.

SELECTIONS MORE EXPLICITLY: HIGH MASS

- **Missing mass**
- $\cos\theta(e^-, e^+)^* \geq 0.4$
- $-0.5 \leq \eta^*_{\textbf{miss}} \leq 0.5$

SIMULATIONS DETAILS

- MG5_aMC (MadGraph) to simulate signal and backgrounds
- Python analysis
- QED bg cross section:
  - Before cigar selection = 29.84 pb
  - After= 14.76 pb
- $\tau\tau$ bg cross section:
  - Before cigar selection = 19.86 pb
  - After= 7.84 pb
- Signal cross section on $M_a = 4.35 \cdot 10^{-5}$ pb