The physics case of a very forward muon detector

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Cornell University

Muon Collider Collaboration Meeting

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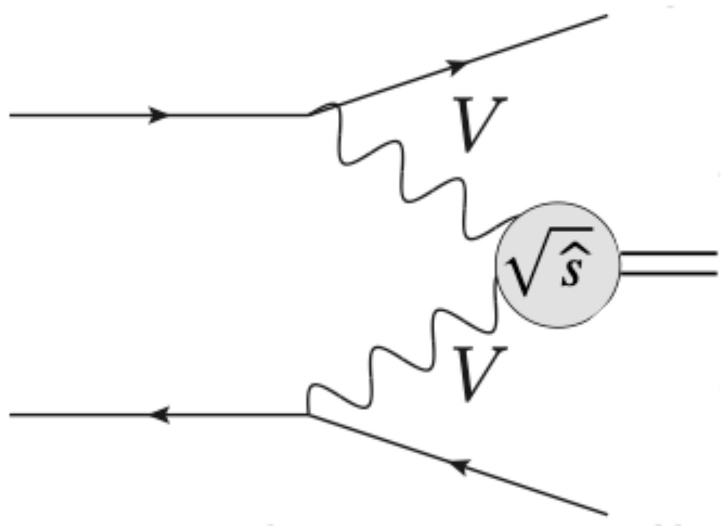
Work in progress

with R. Masarotti, E. Salvioni *and* A. Wulzer

Why Forward Muons?

- HE muon collider is a vector boson collider



Taken from 2203.07256

final state muons are typically very forward

→ with limited detector coverage of $\theta > 10°$ muons are often lost

- Resolving forward muons is essential for:

1. Better BG separation in Higgs coupling measurements (e.g ZZ fusion vs WW fusion)

   See e.g. Forslund, Meade '22

2. Studying signatures with invisible particles (DM, LLPs,…)

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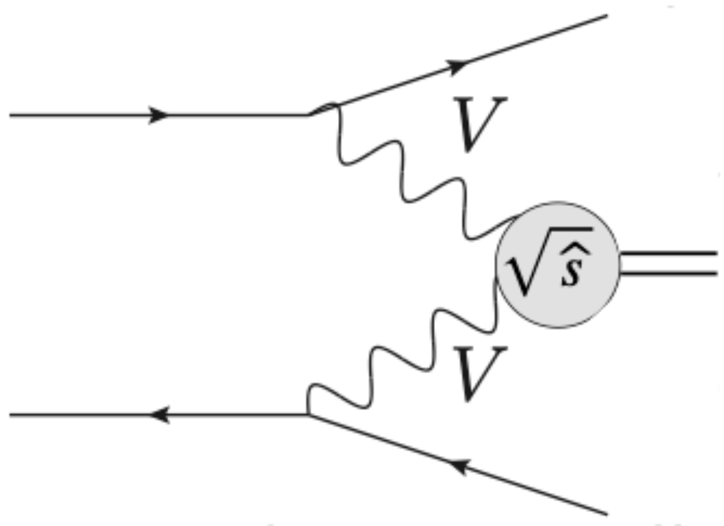

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Our focus in the following

This Talk

1. Physics case for very forward muon detector (idealized)

- Focus on scalar Higgs portal to invisible new physics

$$-\frac{\lambda}{2}\phi^2|H|^2$$

marginal portal

$$\frac{c_d}{2f^2}\partial_\mu\phi^2\partial^\mu|H|^2$$

derivative portal

- Assume perfect resolution of MIM,…

2. Realistic case study: invisible Higgs decays

- Include accelerator and detector effects (beam energy spread,…)
- New BGs become important

Marginal Higgs Portal

Marginal Higgs portal
(aka renormalizable Higgs portal)

$$\mathscr{L}_{\mathrm{BSM}} \supset -\frac{\lambda}{2}\phi^2 H^\dagger H$$

- Scalar DM ϕ

→ minimal version in tension with direct detection, but possible in extended theories

Recent review: 1903.03616

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➡ effective coupling $\lambda = \sqrt{4N_c}\, y_t^2 \approx 3.4$

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Cohen, Craig, Giudice, McCullough 2018

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- First-order electroweak phase transition

  ➡ requires large couplings $\lambda \sim \mathcal{O}(1)$

  For collider tests see e.g. Curtin, Meade, Yu 2014

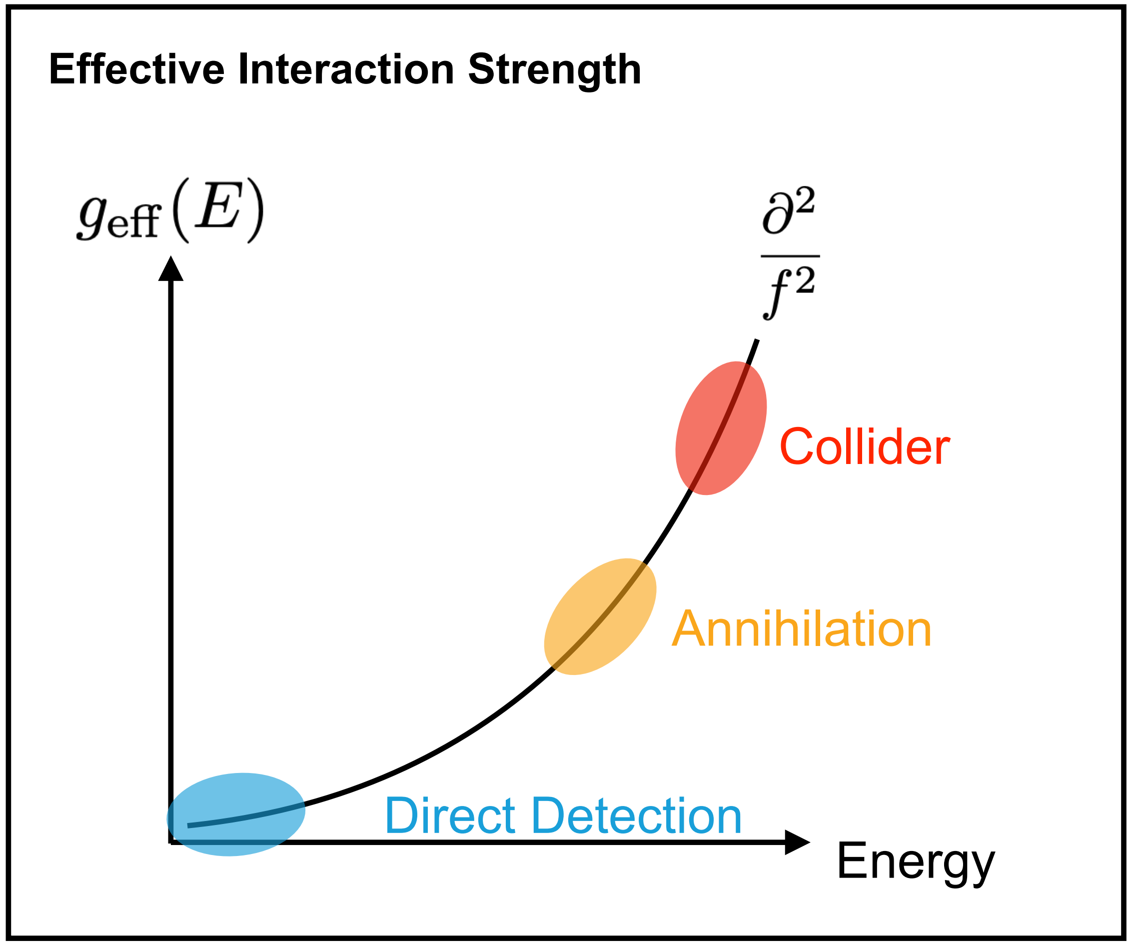
Derivative Higgs Portal

Derivative Higgs portal $$\frac{c_d}{2f^2}\partial_\mu\phi^2\partial^\mu|H|^2$$

Frigerio, Pomarol, Riva, Urbano 2012

- If ϕ is stable: pseudo Nambu-Goldstone Boson dark matter

→ arises naturally in non-minimal Composite Higgs models



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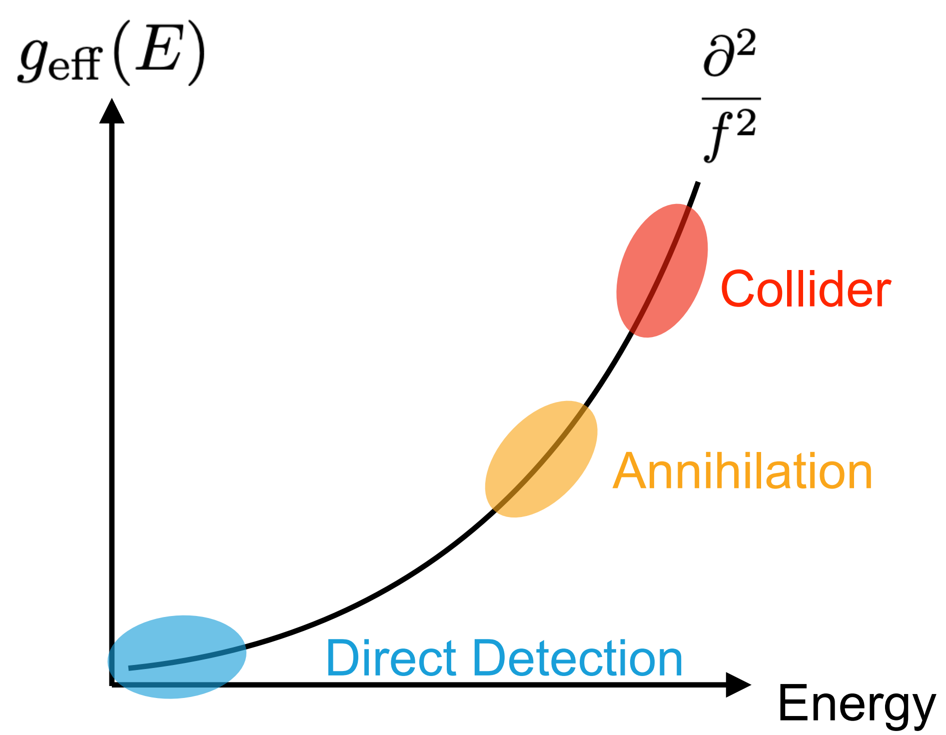
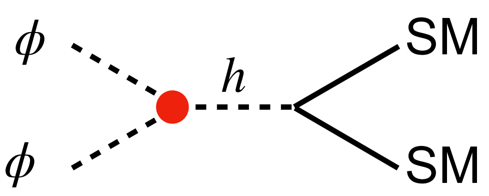
Effective Interaction Strength



Annihilation



$$f/c_d^{1/2} \sim 0.8 \text{ TeV}\left(\frac{m_\phi}{130 \text{ GeV}}\right)^{1/2}$$

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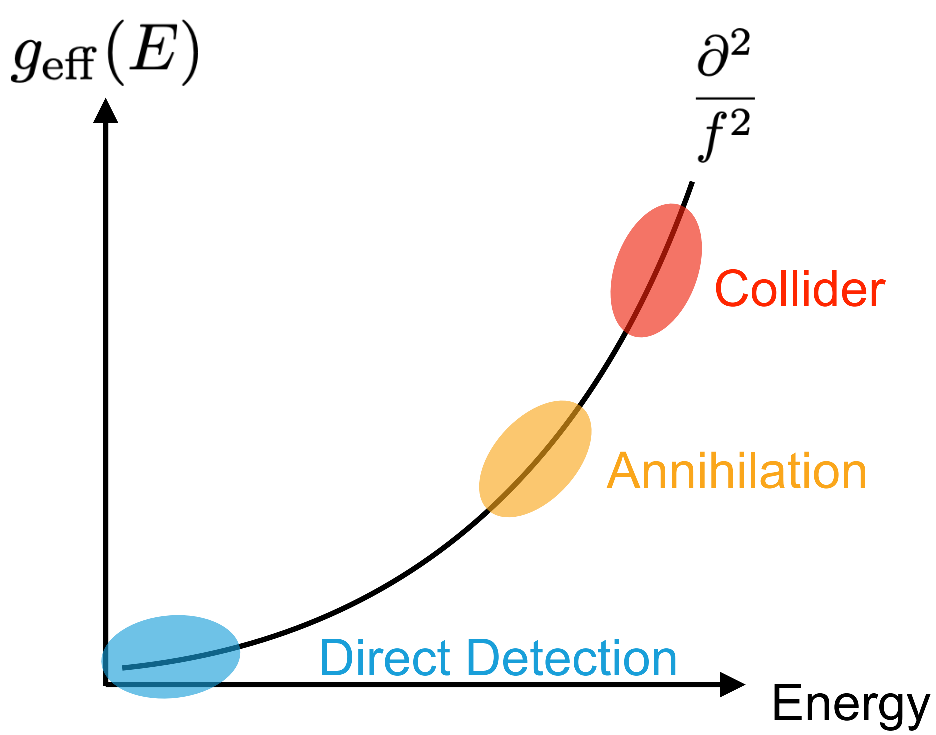

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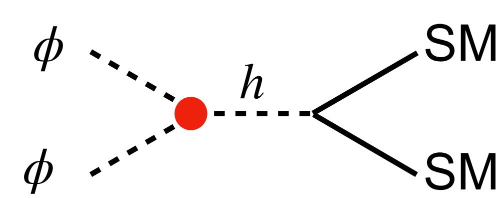

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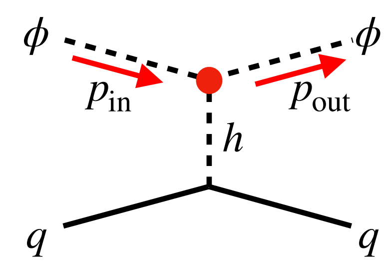
Direct Detection



$$\sim \frac{|t|}{f^2} \leq \frac{(100\text{ MeV})^2}{(1\text{ TeV})^2} \sim 10^{-8}$$

pNGB DM can be practically invisible in Direct Detection

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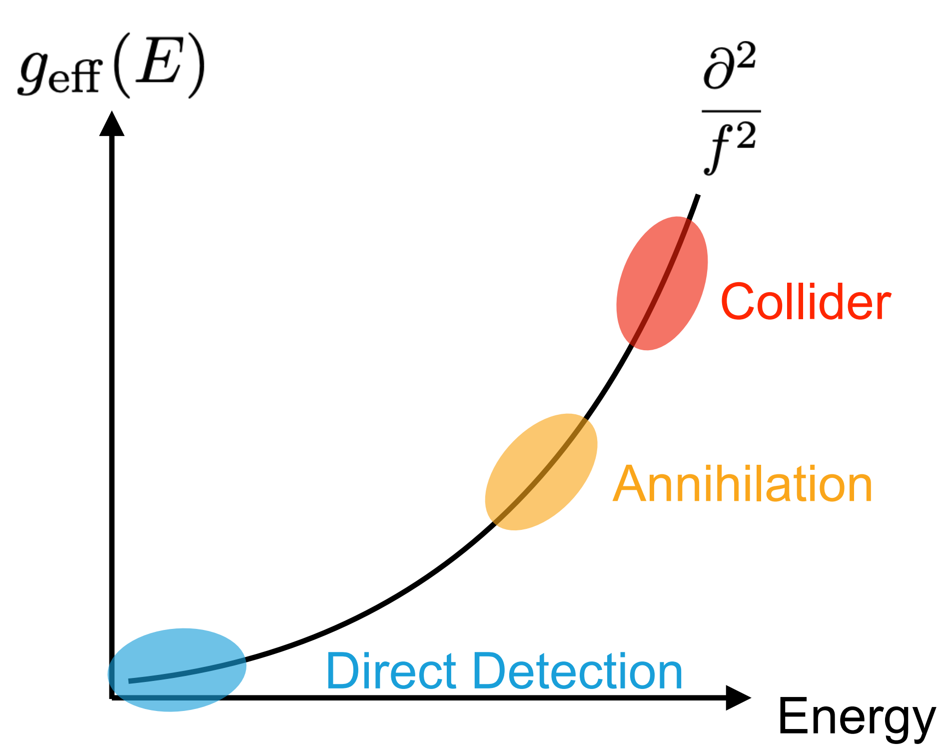

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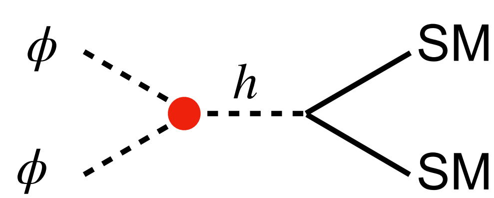

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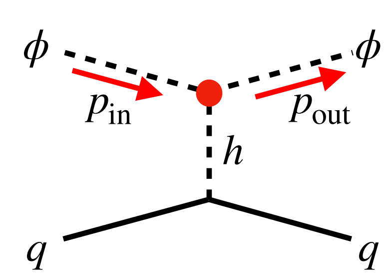

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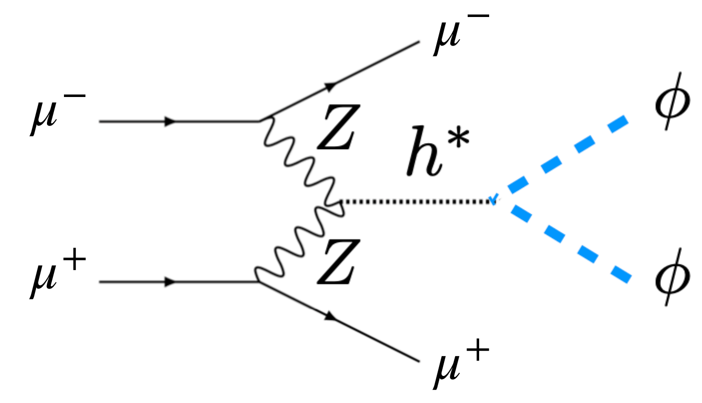
→ Colliders are important **direct** probes, **complementary** to direct detection

Invisible singlets at the muon collider

- Main production channel is VBF for $\sqrt{s} \gtrsim 1$ TeV

  WW fusion is completely invisible, focus on ZZ fusion



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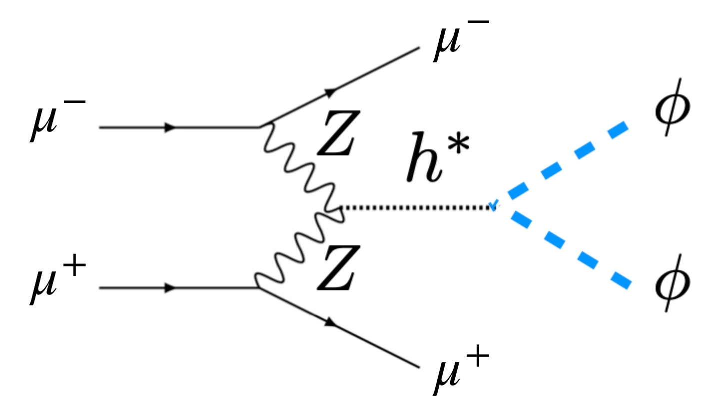

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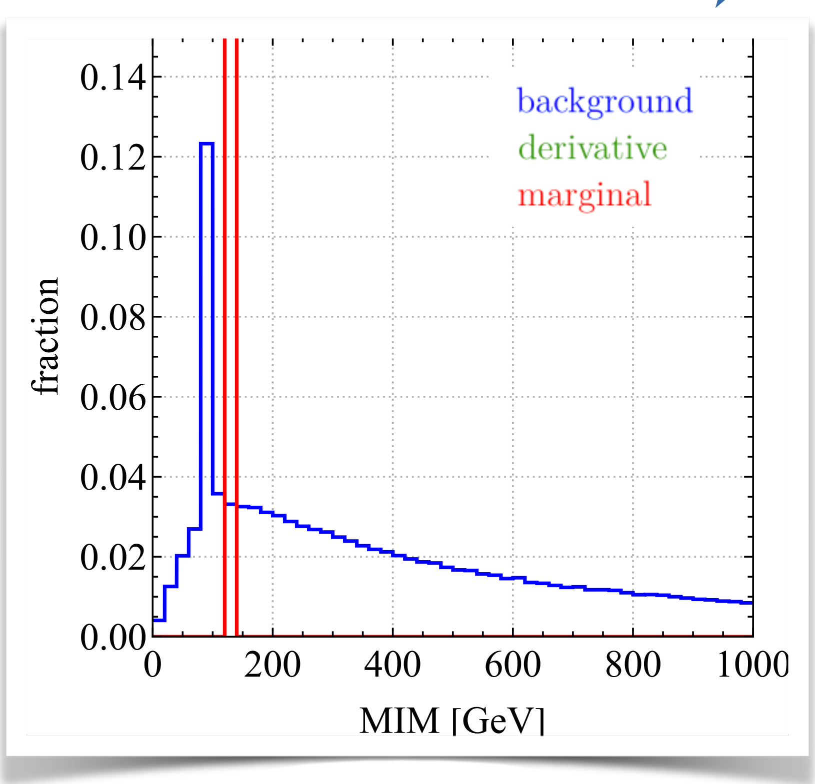

$\sqrt{s} = 6$ TeV

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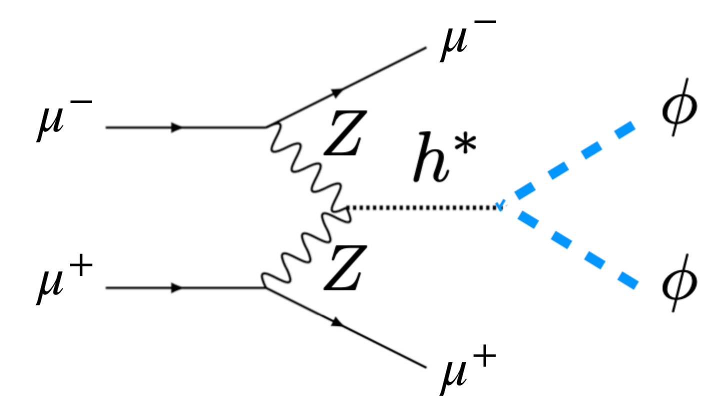

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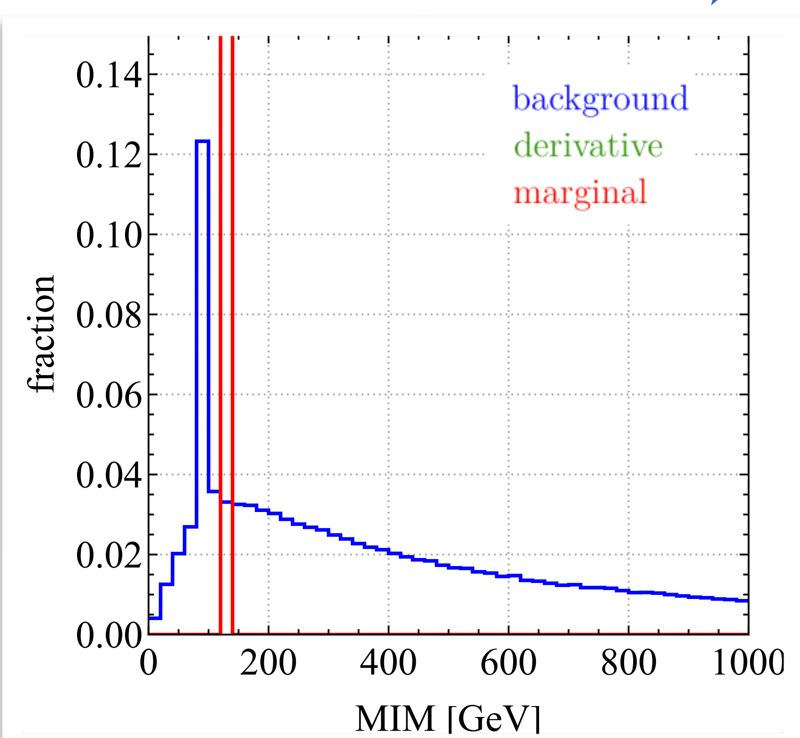

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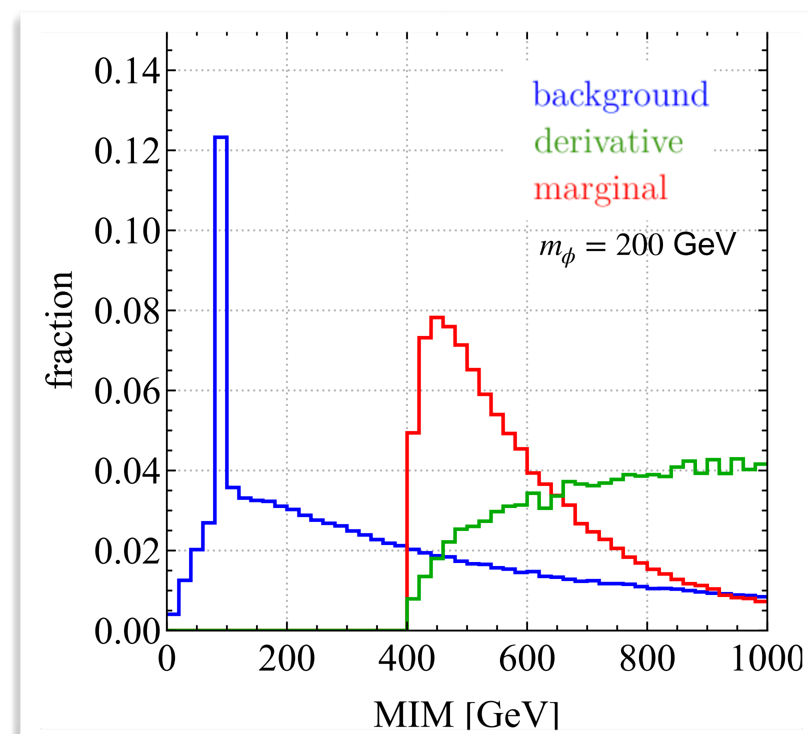
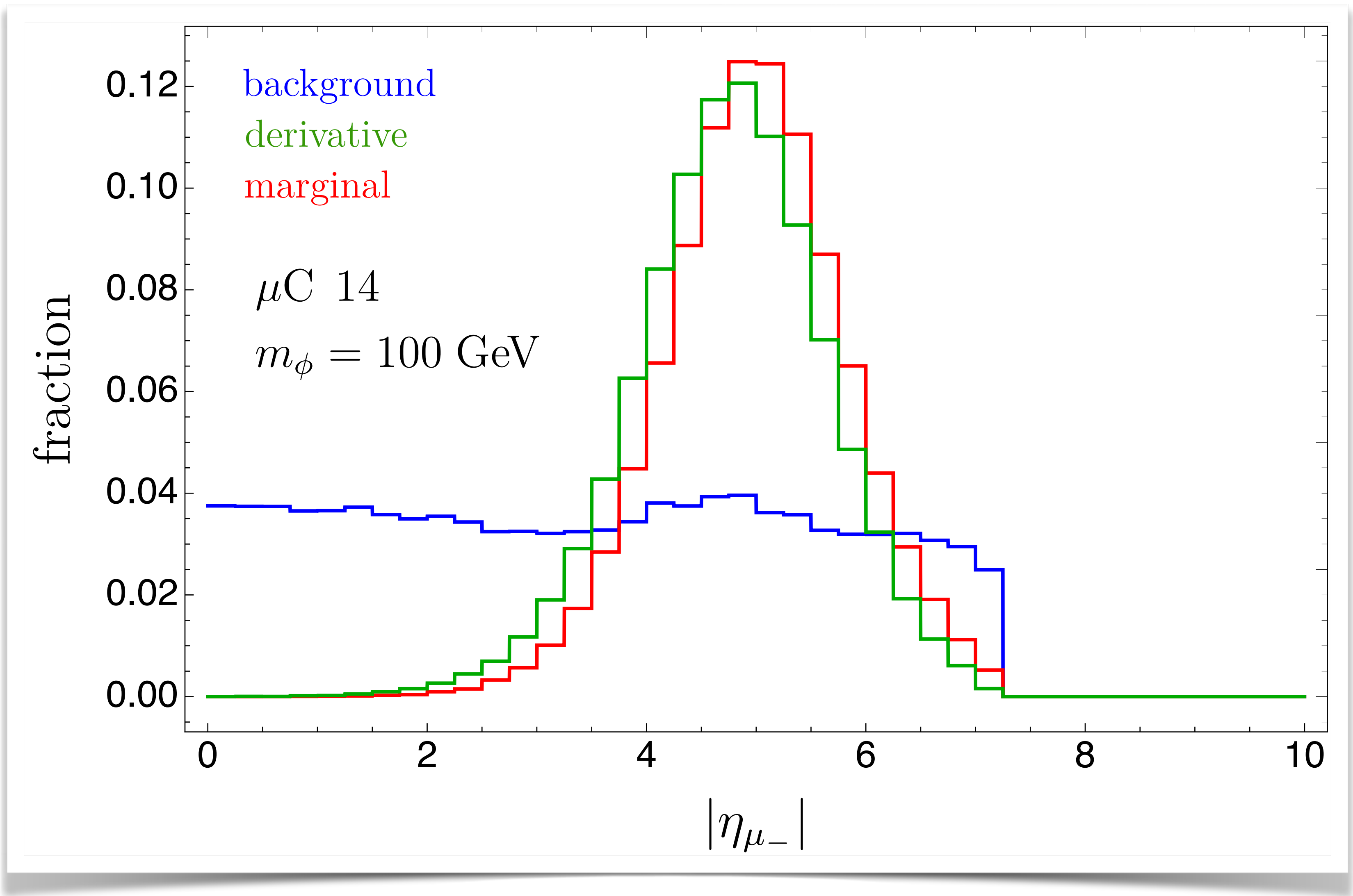


Higgs Portal: forward muons

Caveat: coverage of very forward muons is crucial



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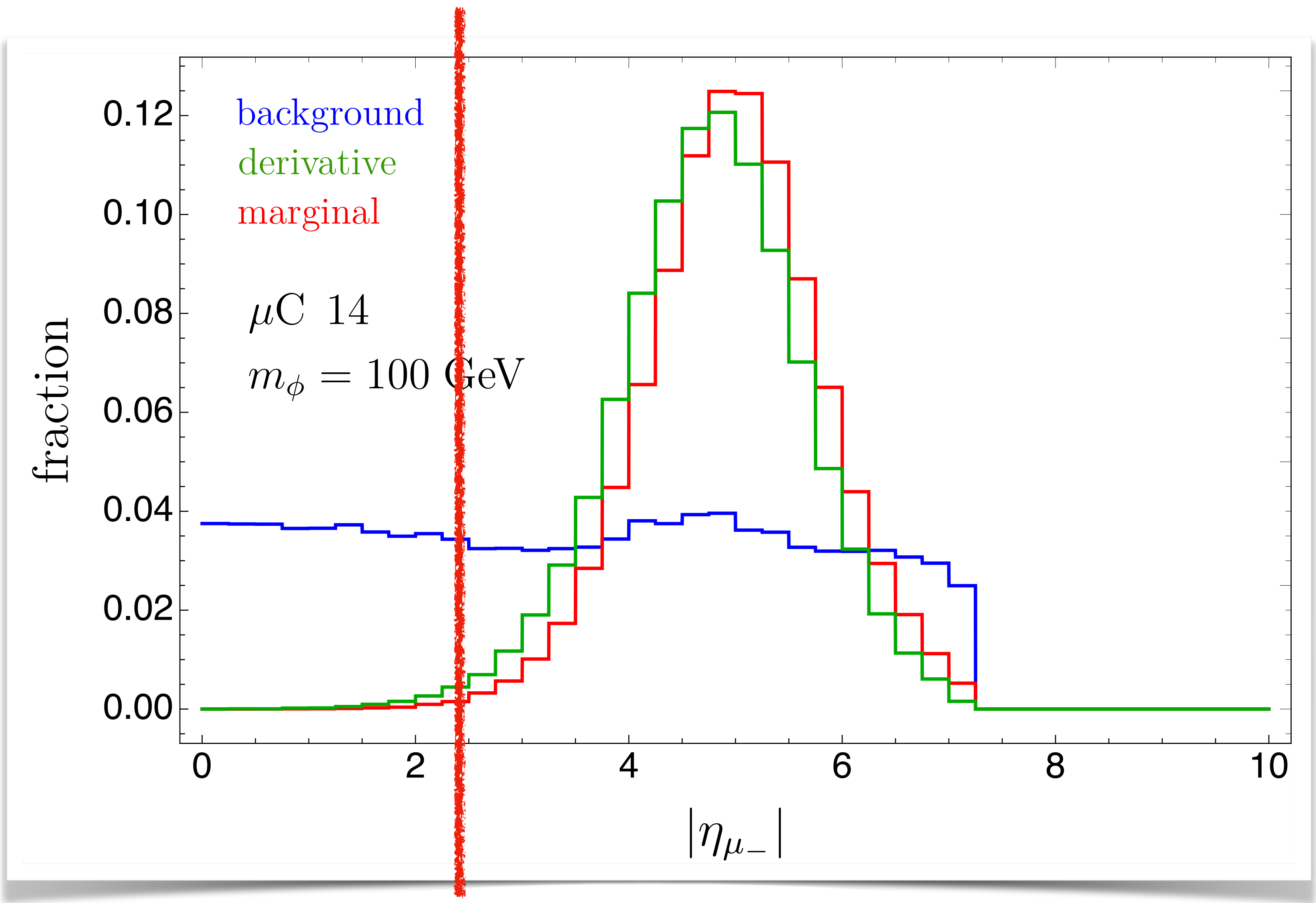

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$|\eta_\mu| < 2.44$ would remove **all** signal

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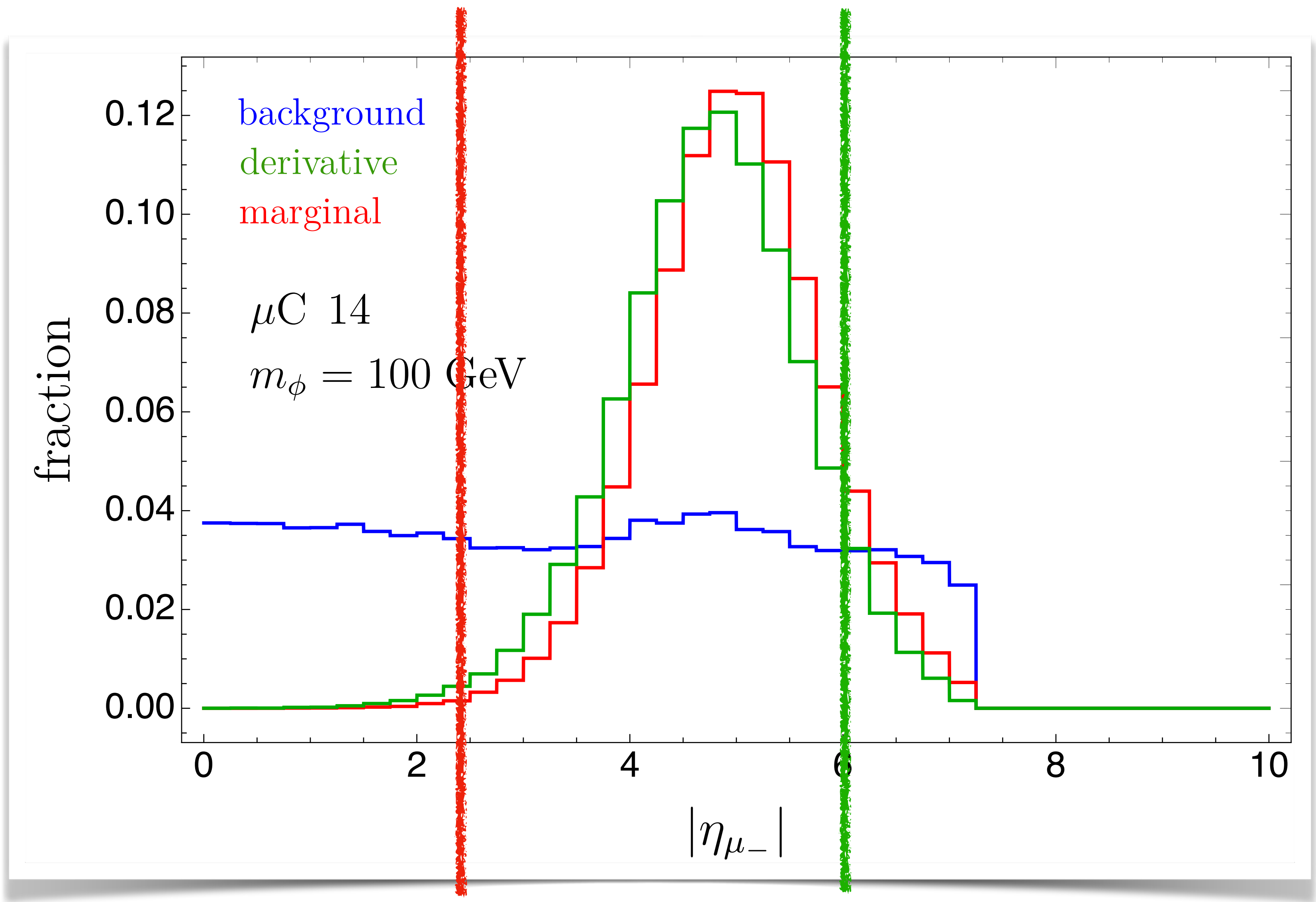
Assume for now coverage of $|\eta_\mu| < 6$



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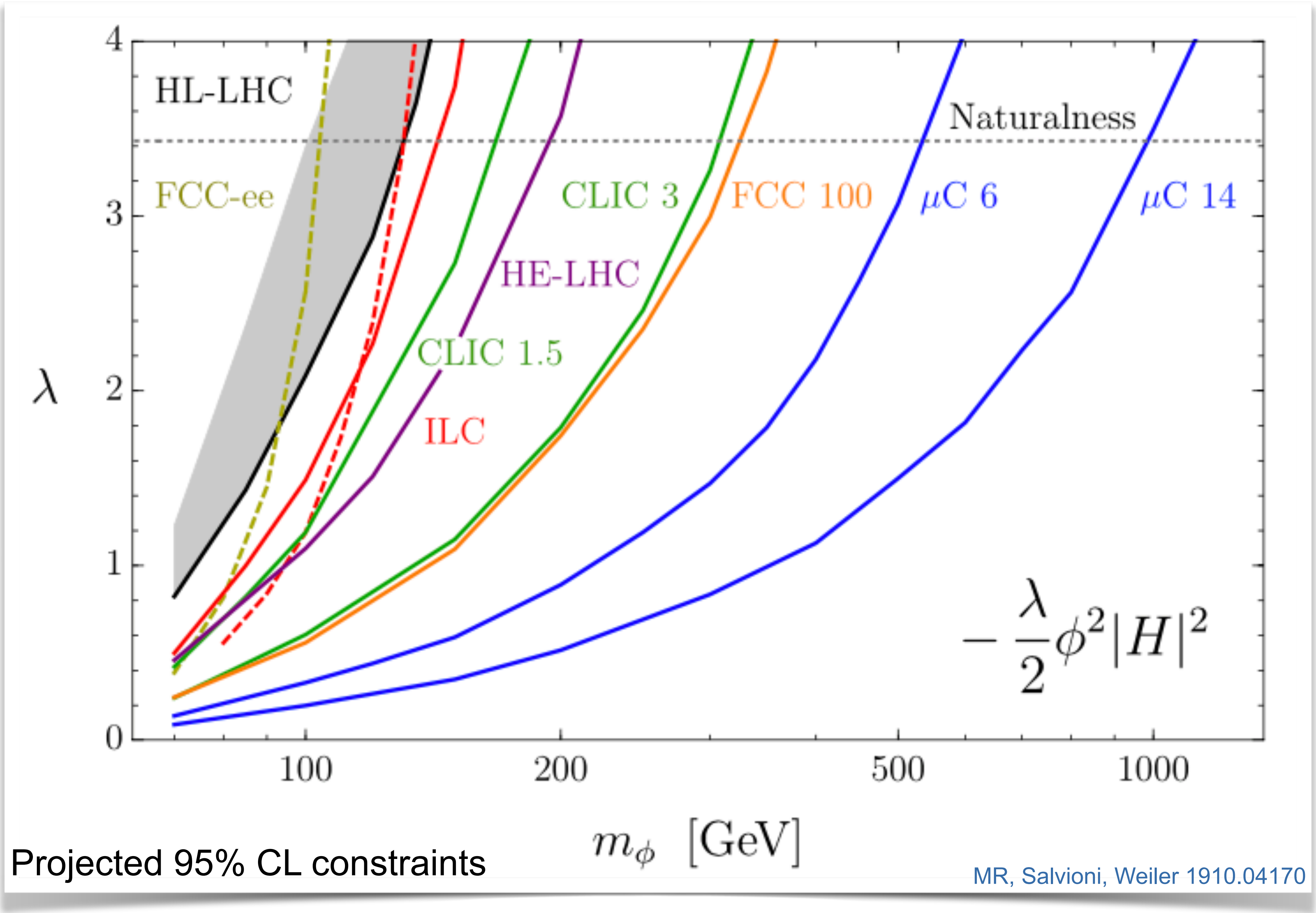

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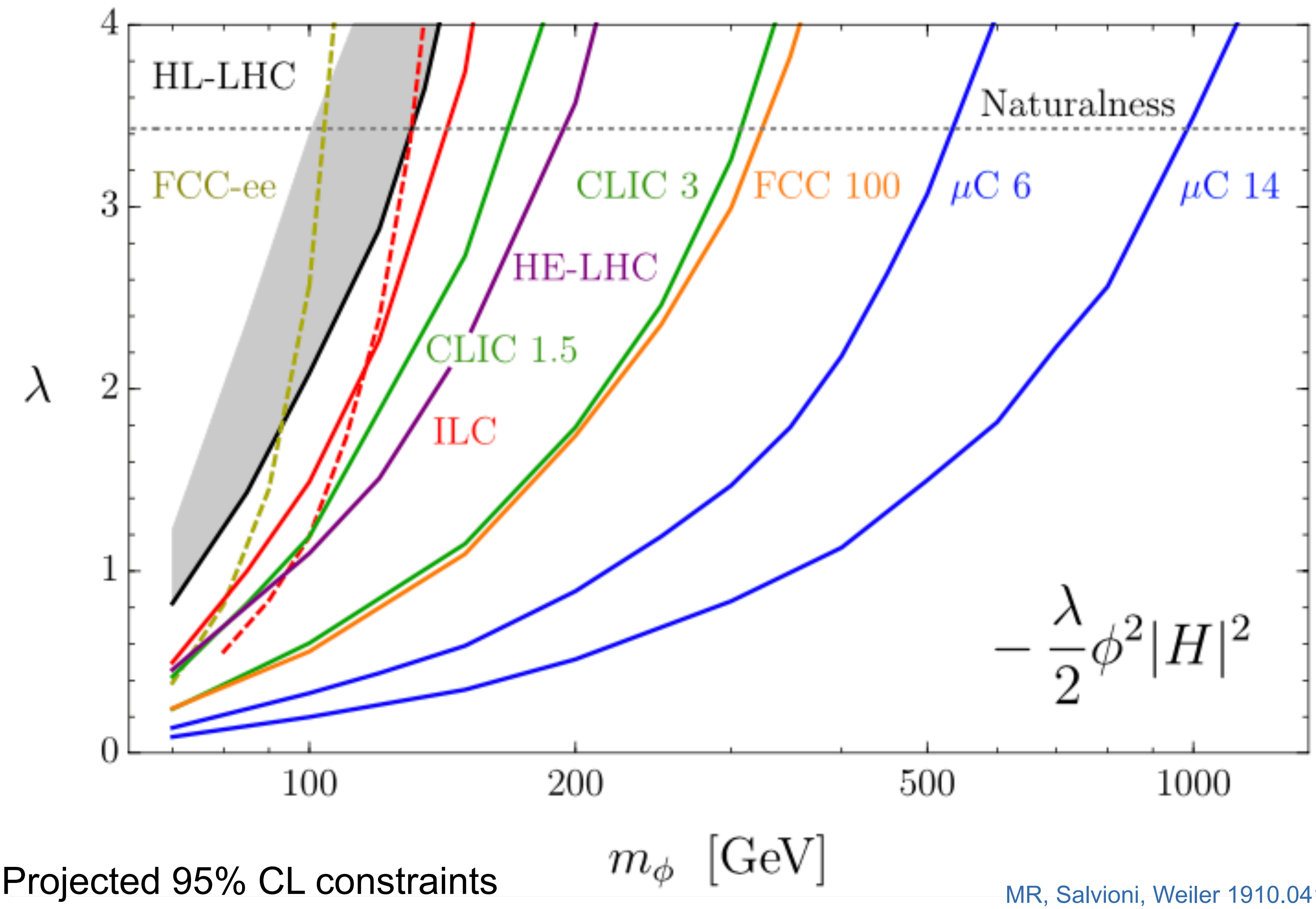
	HL-LHC	CLIC 1.5	HE-LHC	CLIC 3	FCC 100	μC 6	μC 14
m_ϕ [GeV]	130	170	190	310	330	540	990

at $\lambda = \sqrt{4N_c}\, y_t^2 \approx 3.4$

(scalar top partners)

Marginal Higgs Portal



Projected 95% CL constraints

MR, Salvioni, Weiler 1910.04170

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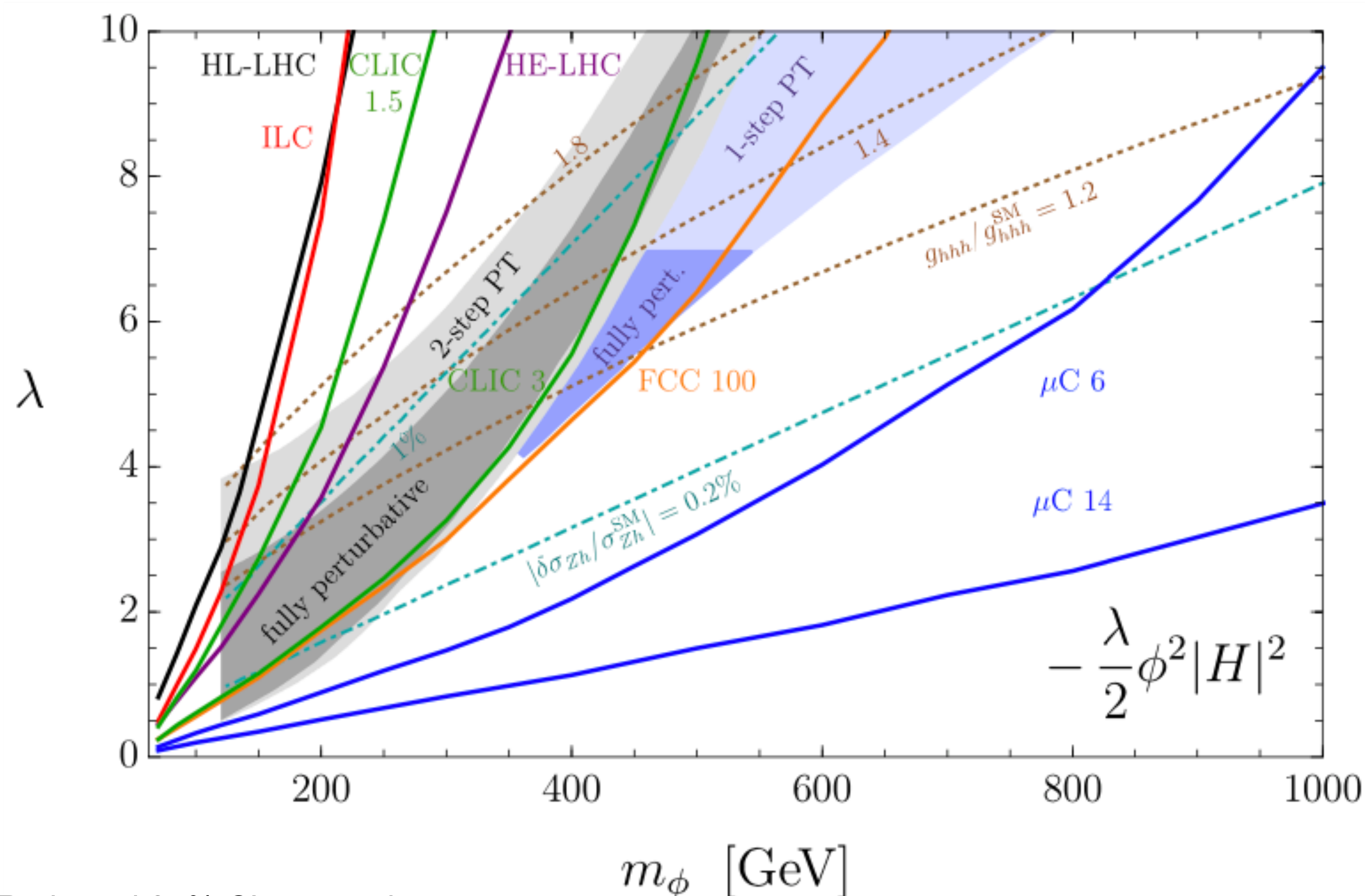
$\sqrt{s} = 6$ TeV muon collider outperforms FCC-hh

Marginal Higgs Portal: 1st order EWPT



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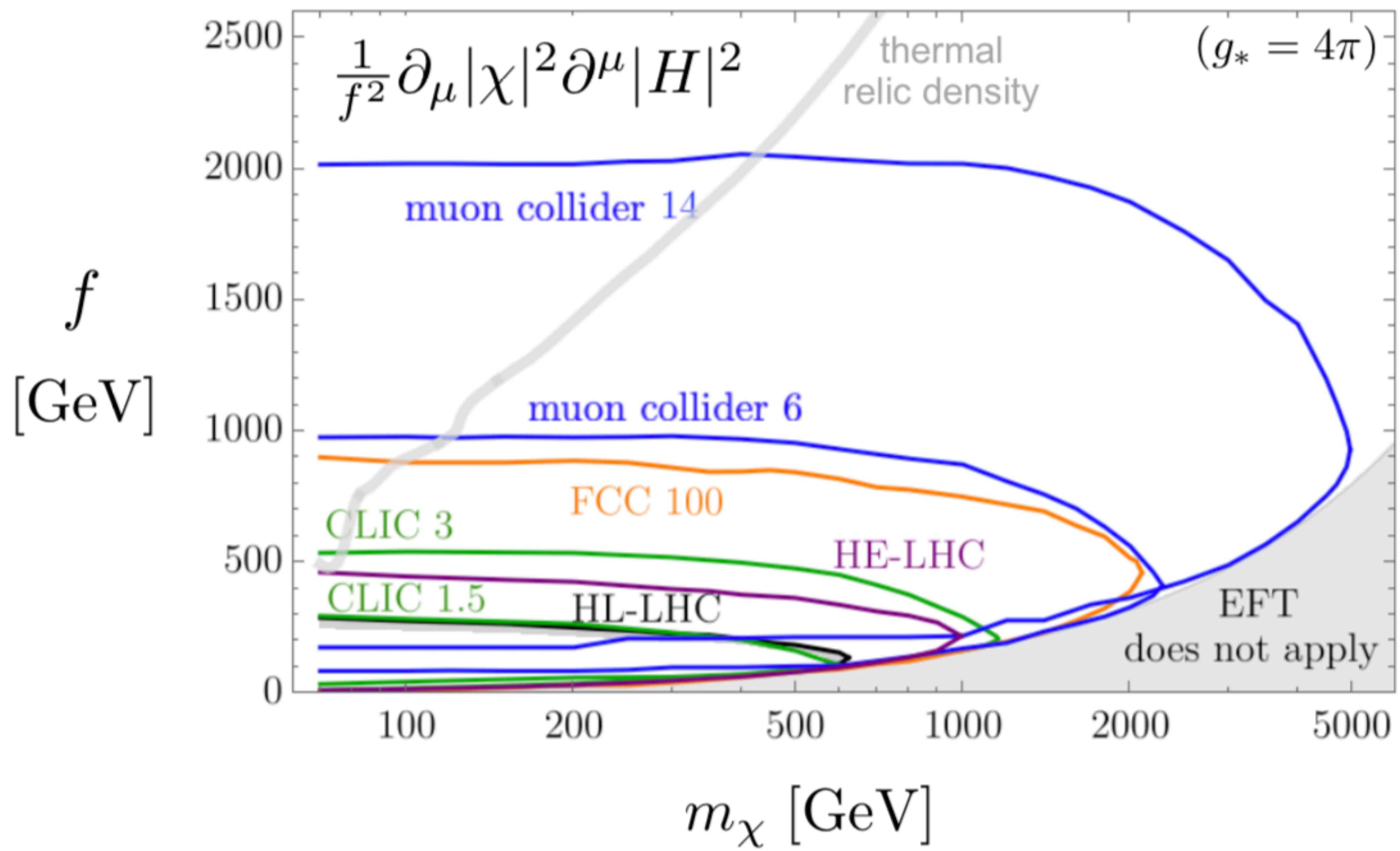
MR, Salvioni, Weiler 1910.04170

Shaded regions: possibility of a first order EW phase transition

Buttazzo, Redigolo, Sala, Tesi 1807.04743

Derivative Higgs Portal



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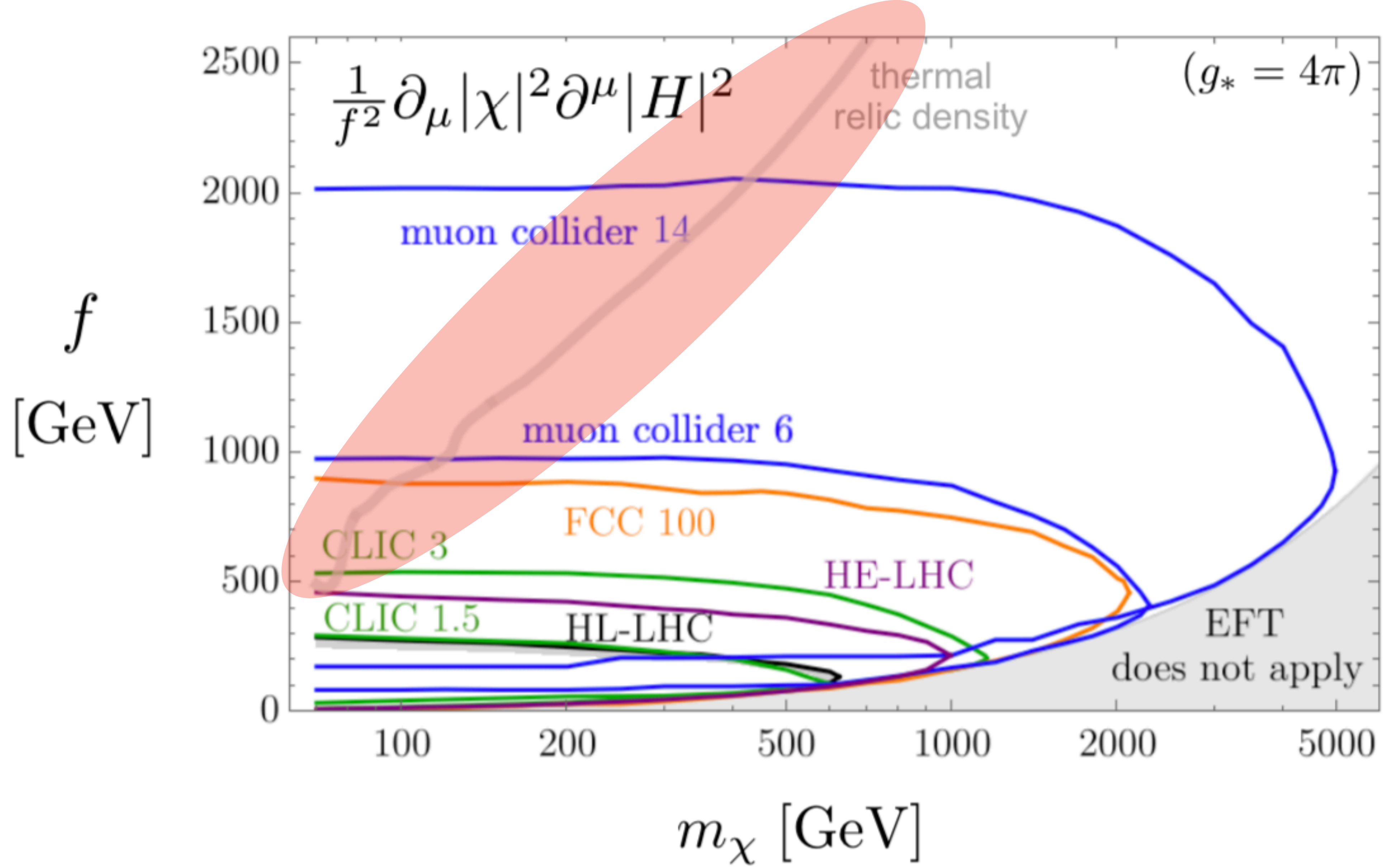

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Only muon collider can truly probe pNGB DM

A realistic benchmark: invisible Higgs decays

- At FCC-hh: $\mathrm{BR}(h \to \mathrm{inv}) < 2.5 \cdot 10^{-4}$ FCC Collaboration '19

How well can we do at a muon collider as a function of the detector coverage?

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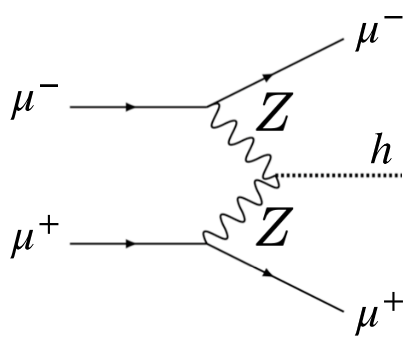

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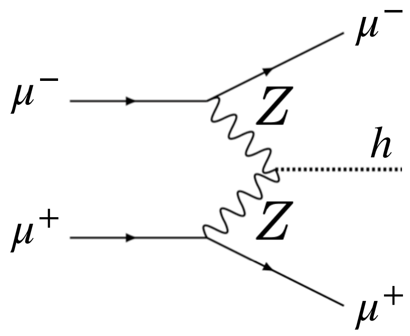

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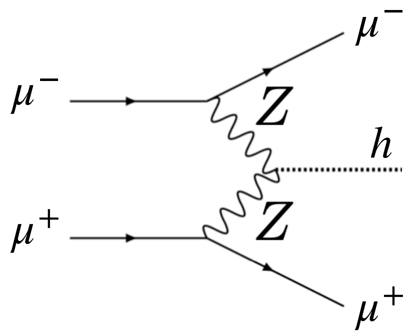

- Consider ZZ-fusion production at $\sqrt{s} = 10$ TeV
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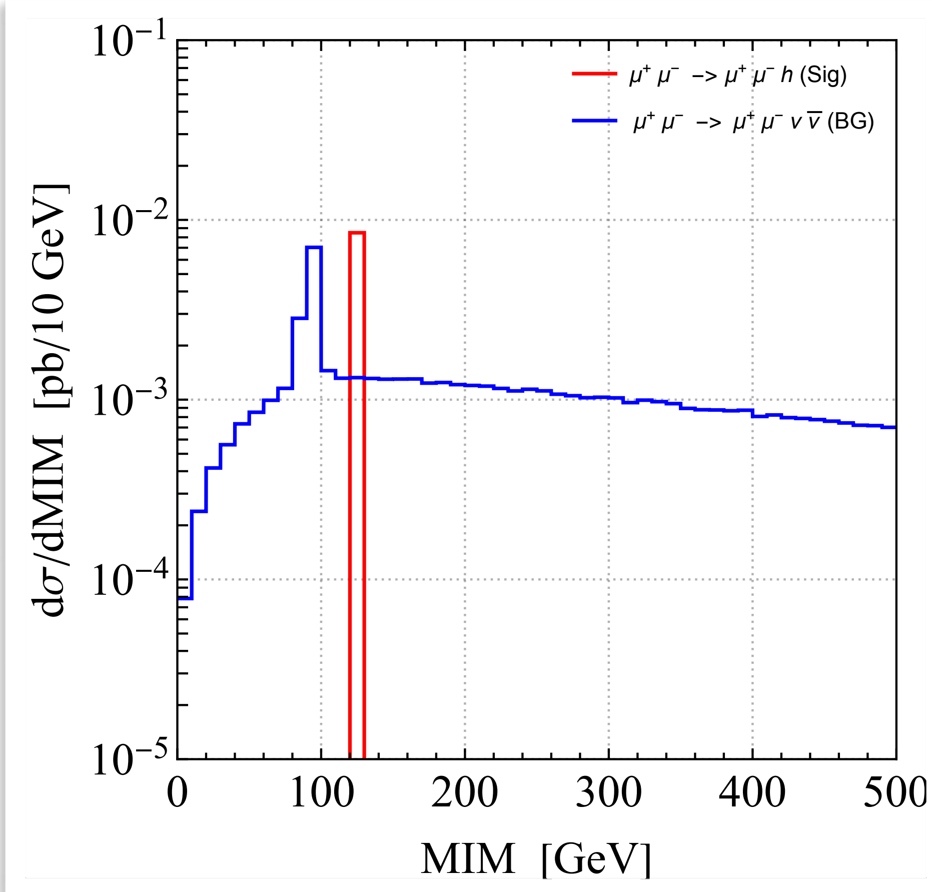
- In contrast to FCC-hh:

  Muon collider is sensitive to MIM

➡ MIM is essential for BG suppression



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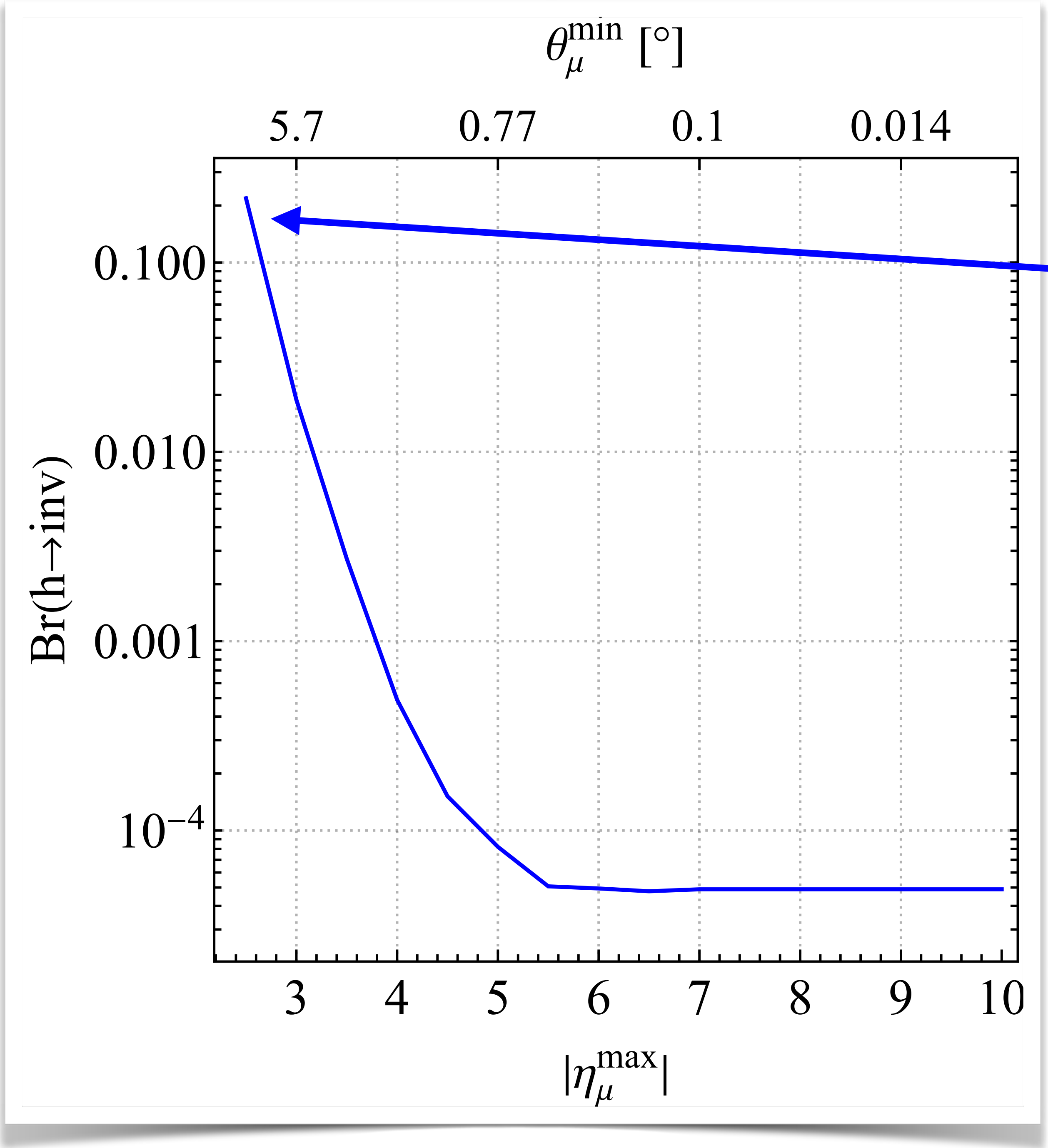
Invisible Higgs Decay: Parton Level

- Cut on $\mathrm{MIM}, M_{\mu\mu}, \Delta\eta_{\mu\mu}, \not{E}_T, \min(E_{\mu^-}, E_{\mu^+})$



→ MIM ∈ [120,130] GeV

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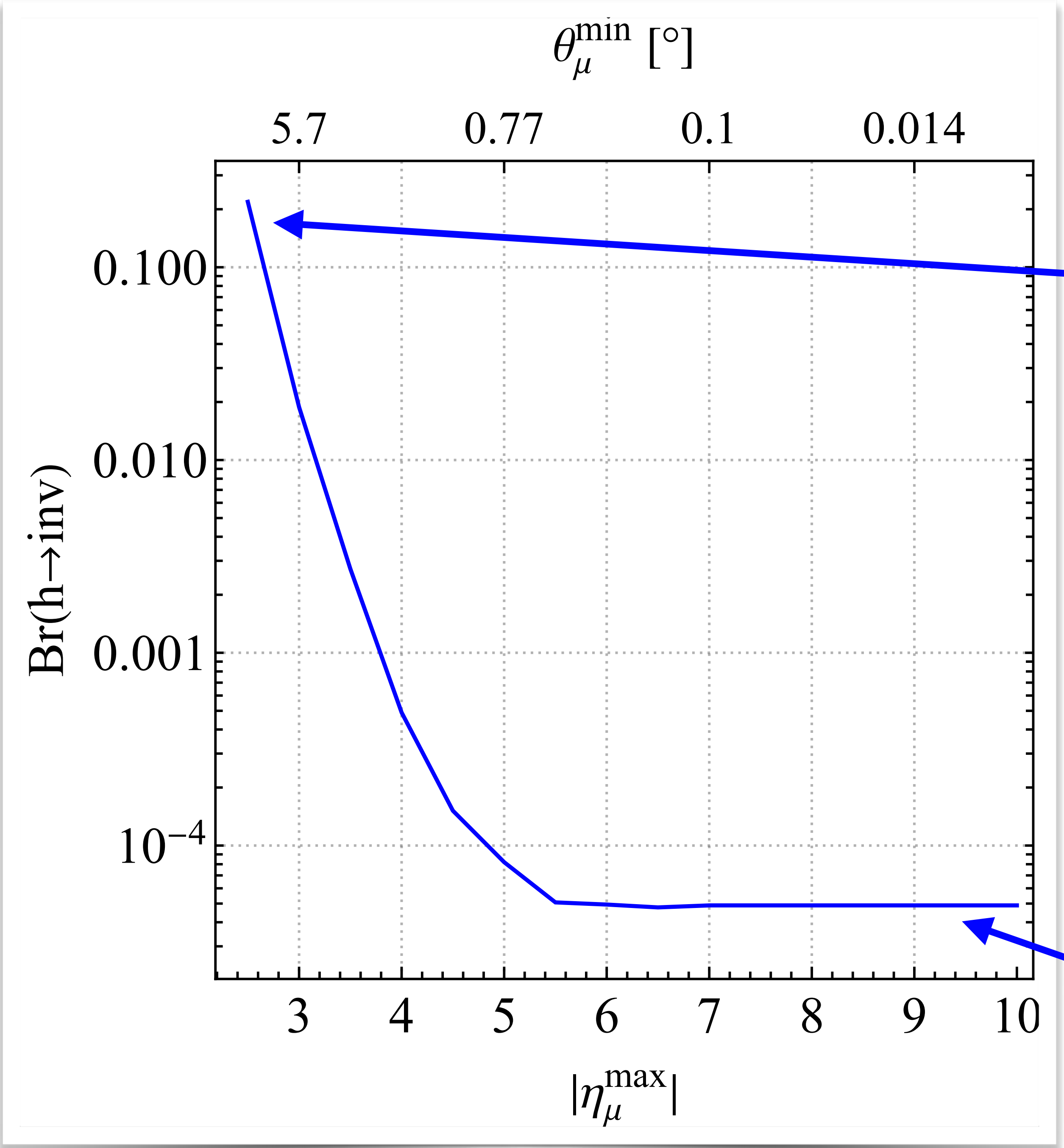

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Bound for $\theta_\mu^{\min} = 10°$:
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Bound asymptotes to $5 \cdot 10^{-5}$

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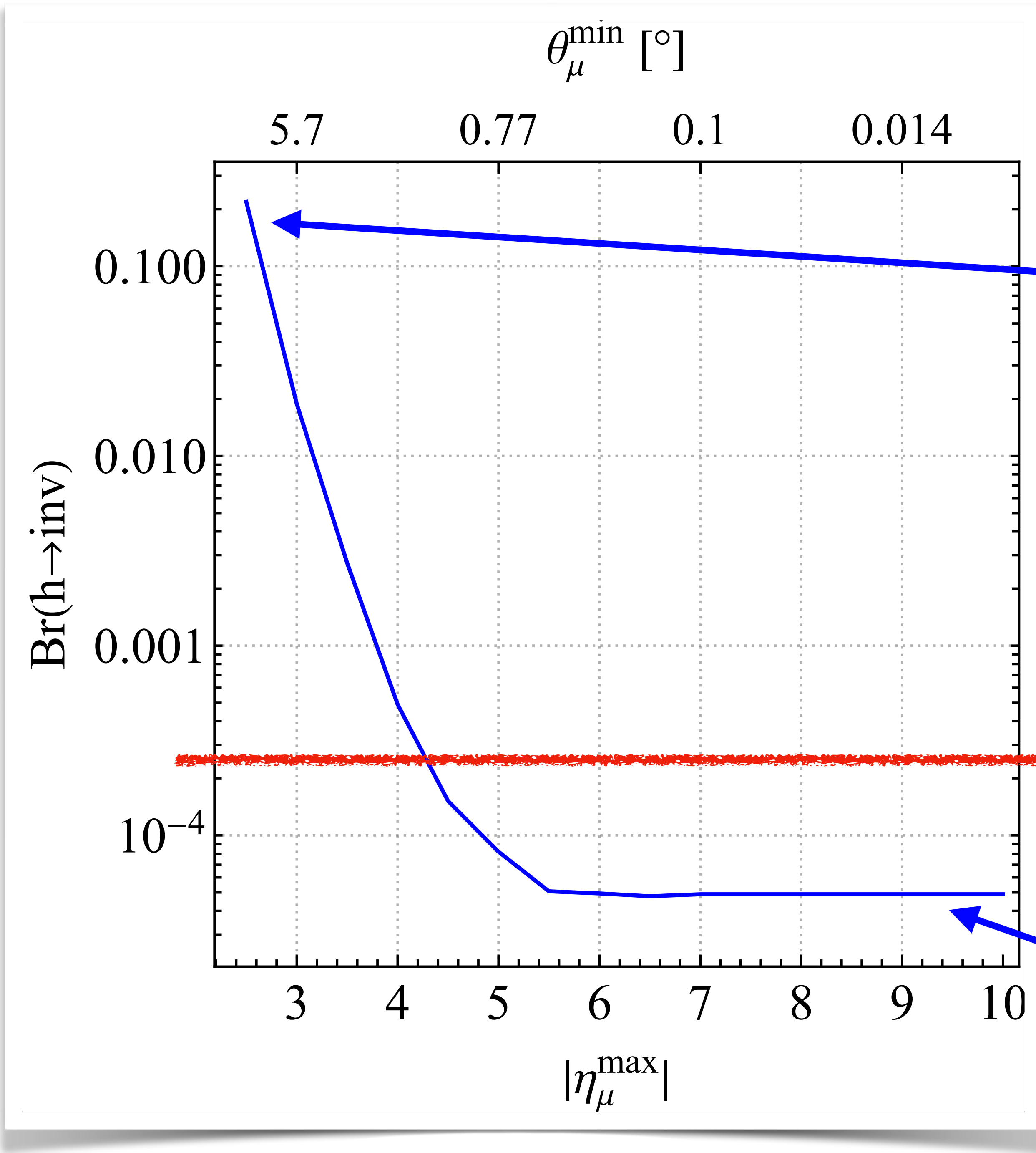

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FCC-hh projection: $2.5 \cdot 10^{-4}$

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MIM measurement - Imperfections

- Irreducible imperfections of MIM measurement

$$\not{p} = (\sqrt{s}, \vec{0}) - p_{\mu^+} - p_{\mu^-}$$

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2. Beam angular spread (BAS)

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4. Lost particles (especially photons)

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- Different definitions for MIM possible $\mathrm{MIM} \equiv \left|\sqrt{\not{p}_\mu \not{p}^\mu}\right|$ or $\mathrm{MIM} \equiv \mathrm{Re}\left(\sqrt{\not{p}_\mu \not{p}^\mu}\right)$

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- High-rate processes become important BGs $\mu^- \mu^+ \to \mu^- \mu^+$

$$\mu^- \mu^+ \to \mu^- \mu^+ \gamma$$

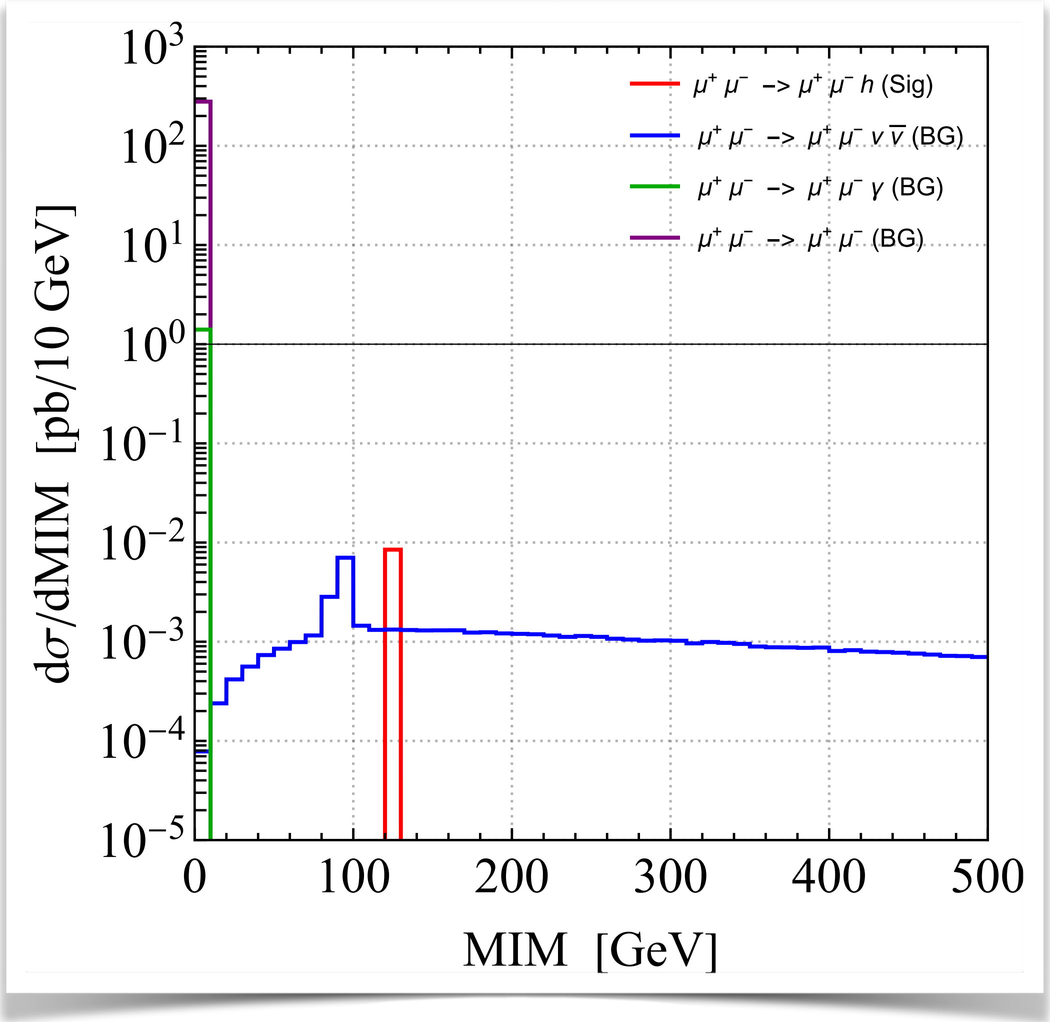
Beam Energy Spread (BES)

$$p_{\mu^-} = (E_1, 0, 0, E_1) \quad \xrightarrow{\mu^-} \quad \xleftarrow{\mu^+} \quad p_{\mu^+} = (E_2, 0, 0, -E_2)$$

- Expected BES is 1 per mille e.g. 2203.07224

➡ Detection frame ≠ COM frame (longitudinal boost)

➡ MIM distribution gets smeared



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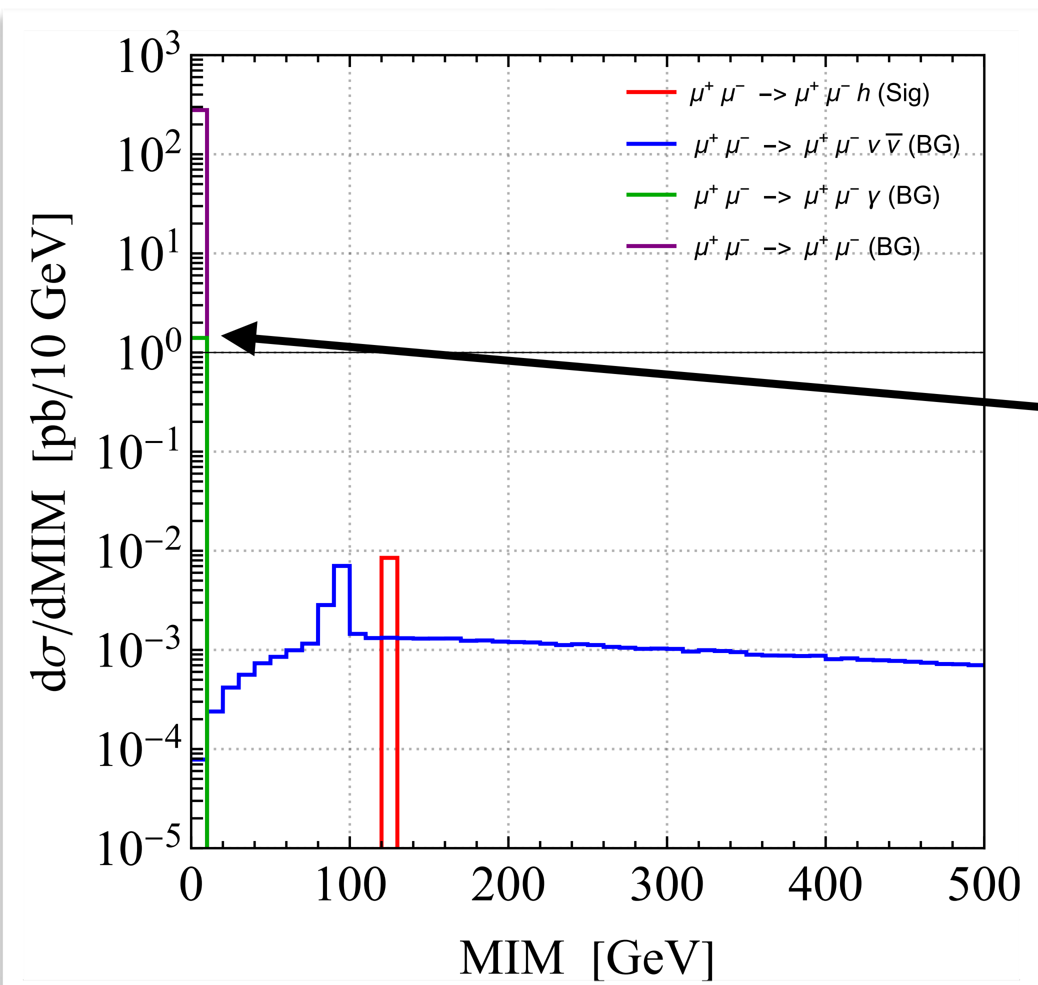

$\mu^+\mu^- \to \mu^+\mu^-$ and $\mu^+\mu^- \to \mu^+\mu^-\gamma$ with lost γ have MIM = 0 if all 4-momenta can be reconstructed

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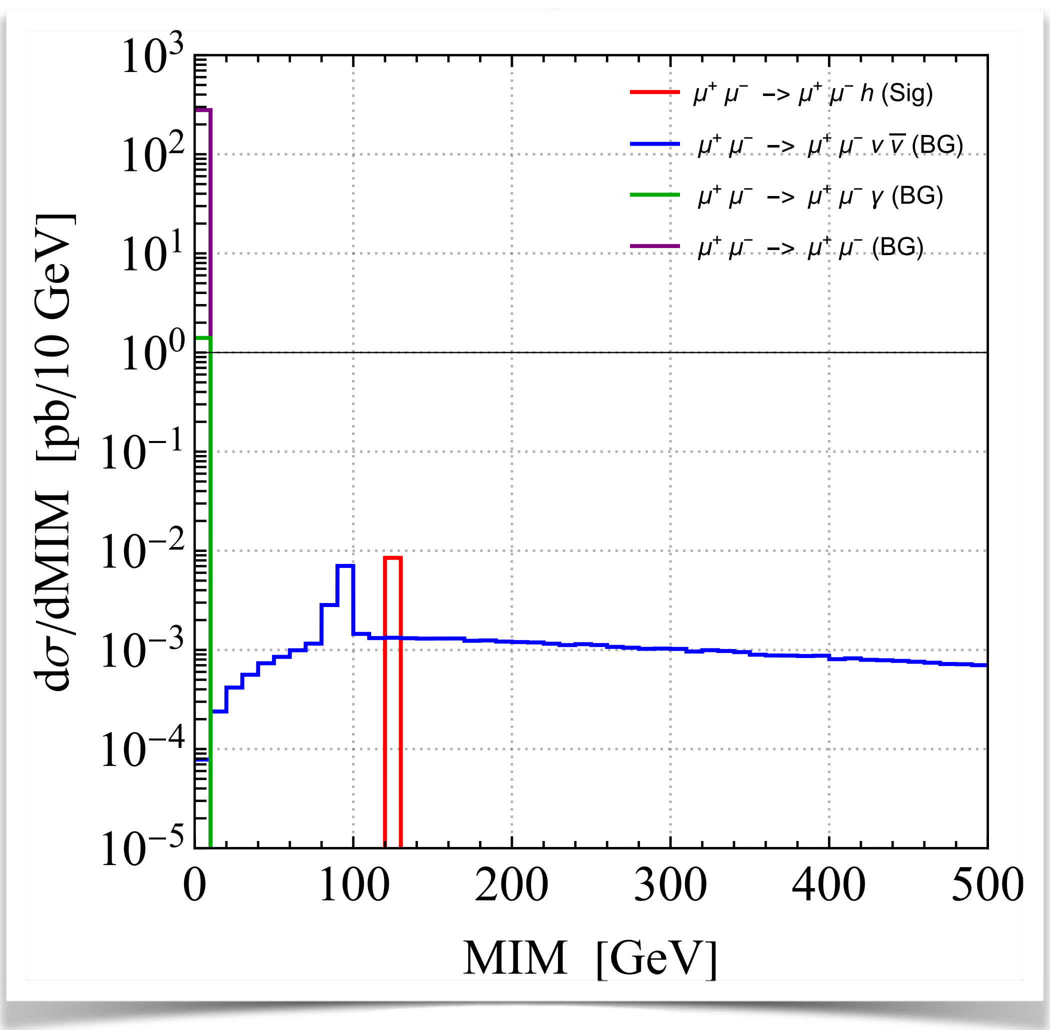
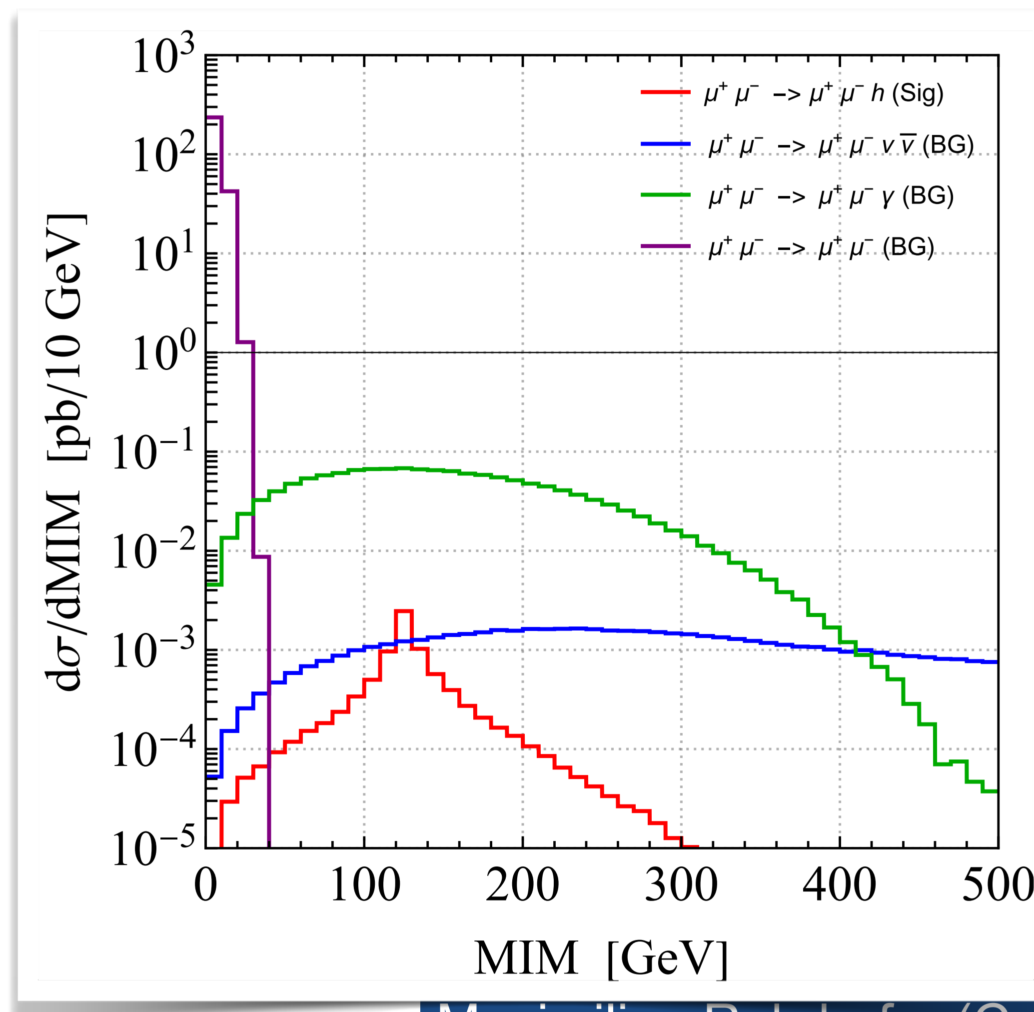
→ Detection frame ≠ COM frame (longitudinal boost)

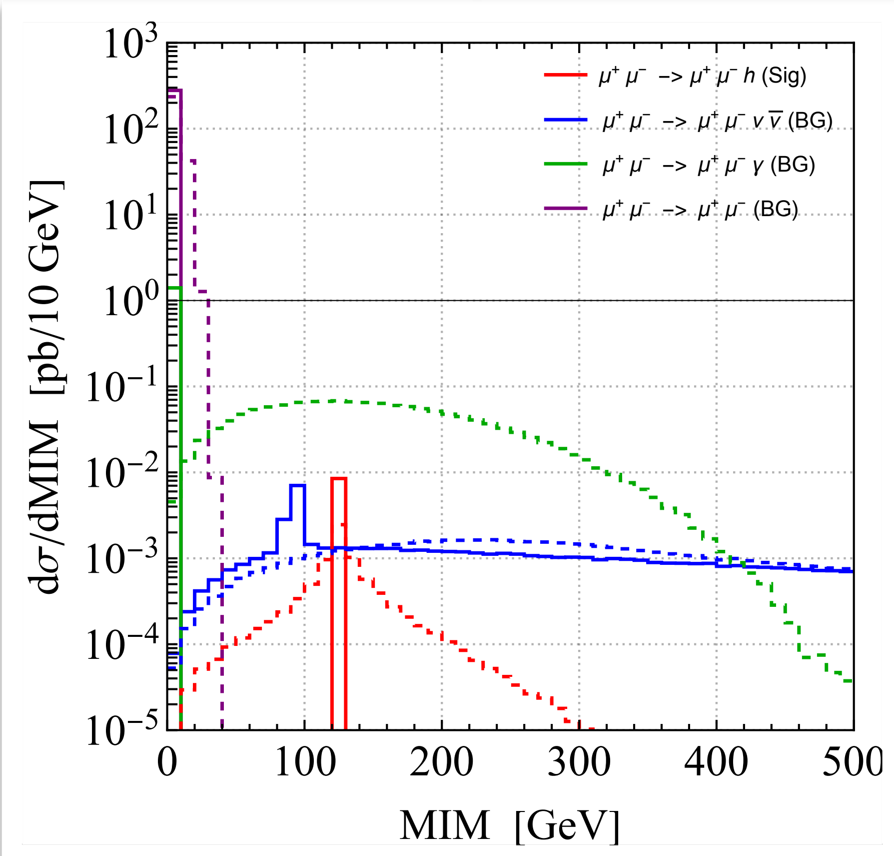
→ MIM distribution gets smeared



0.1% BES →



Beam Energy Spread (BES)



- Higgs peak swamped by photon BG
- Width of photon distribution set by p_γ^z

$$\Delta\text{MIM} \sim 200\ \text{GeV} \left(\frac{\delta_{\text{BES}}}{10^{-3}}\right)^{1/2} \left(\frac{p_\gamma^z}{2\ \text{TeV}}\right)^{1/2}$$

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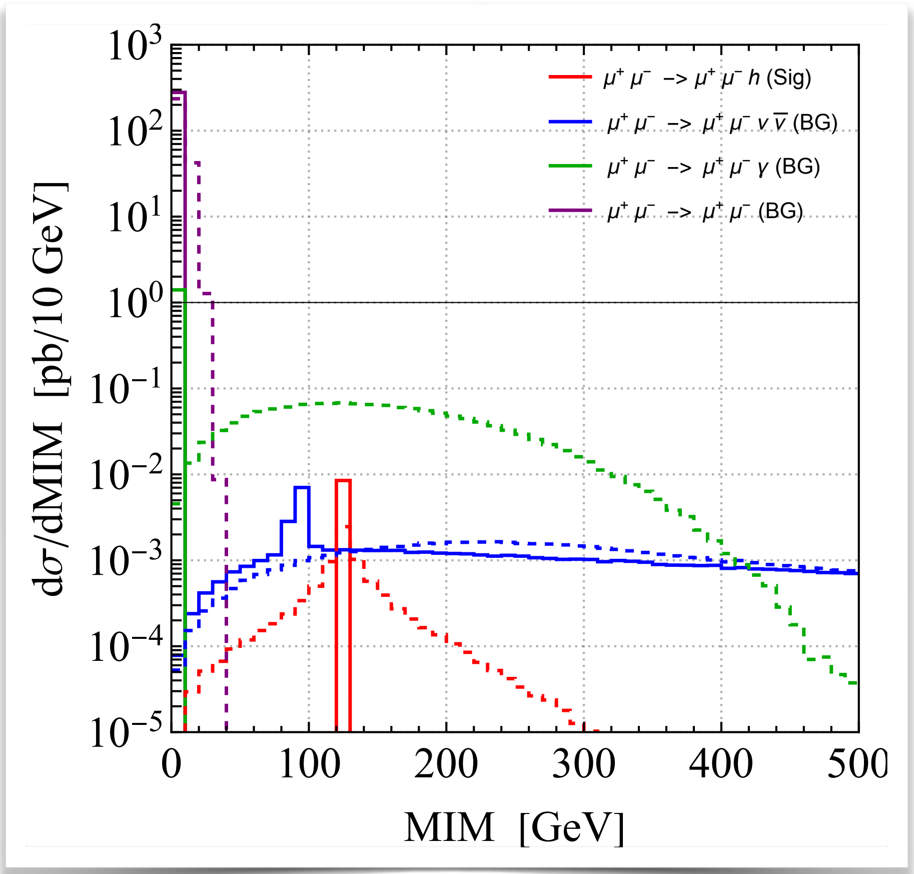

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Hard collinear photon emission is main source of photon BG

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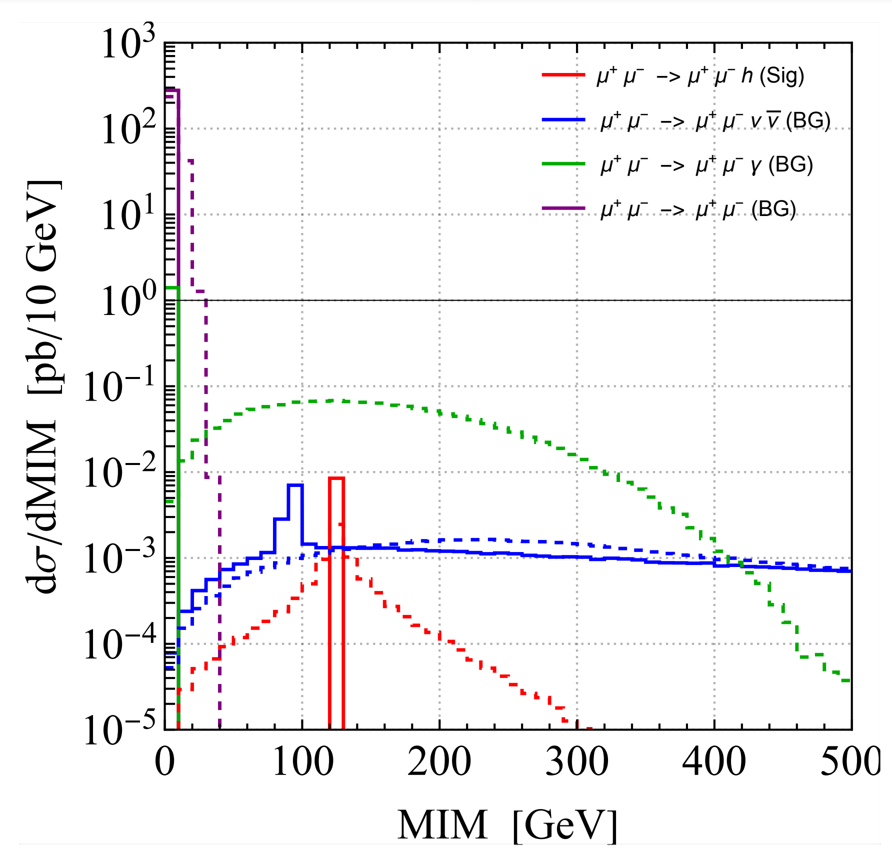

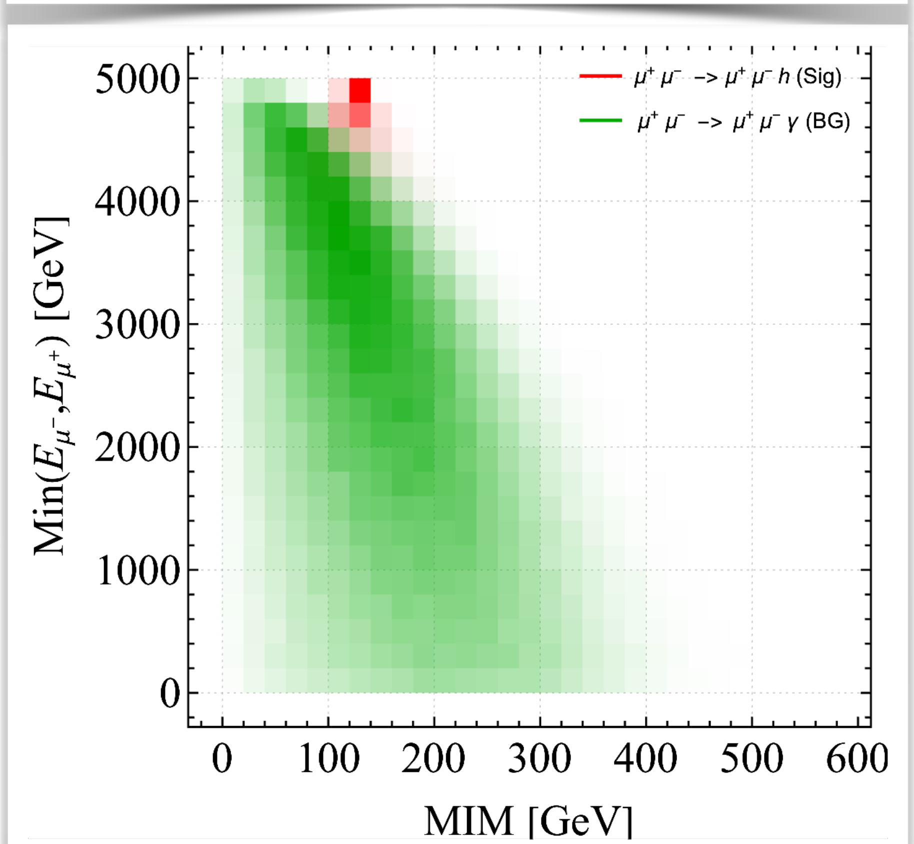

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Hard collinear photon emission is main source of photon BG

↓

One of the muons will be less energetic

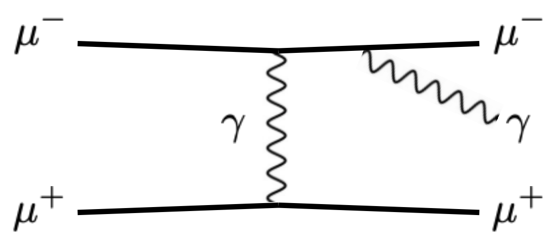
→ Efficient suppression with cut on

$$\mathrm{Min}(E_{\mu^-}, E_{\mu^+})$$

Maximilian Ruhdorfer (Cornell)

Comment on Photon BG

- Photon BG is generated at fixed order in MadGraph



$+ \quad \dots$

- Generator level cuts of $p_T^\gamma > 10$ GeV and $|\eta_\gamma| > 2.44$

→ assume that EM calorimeter only covers $\theta > 10^\circ$ $(|\eta| < 2.44)$

- Including photon radiation from signal and an improved simulation is work in progress

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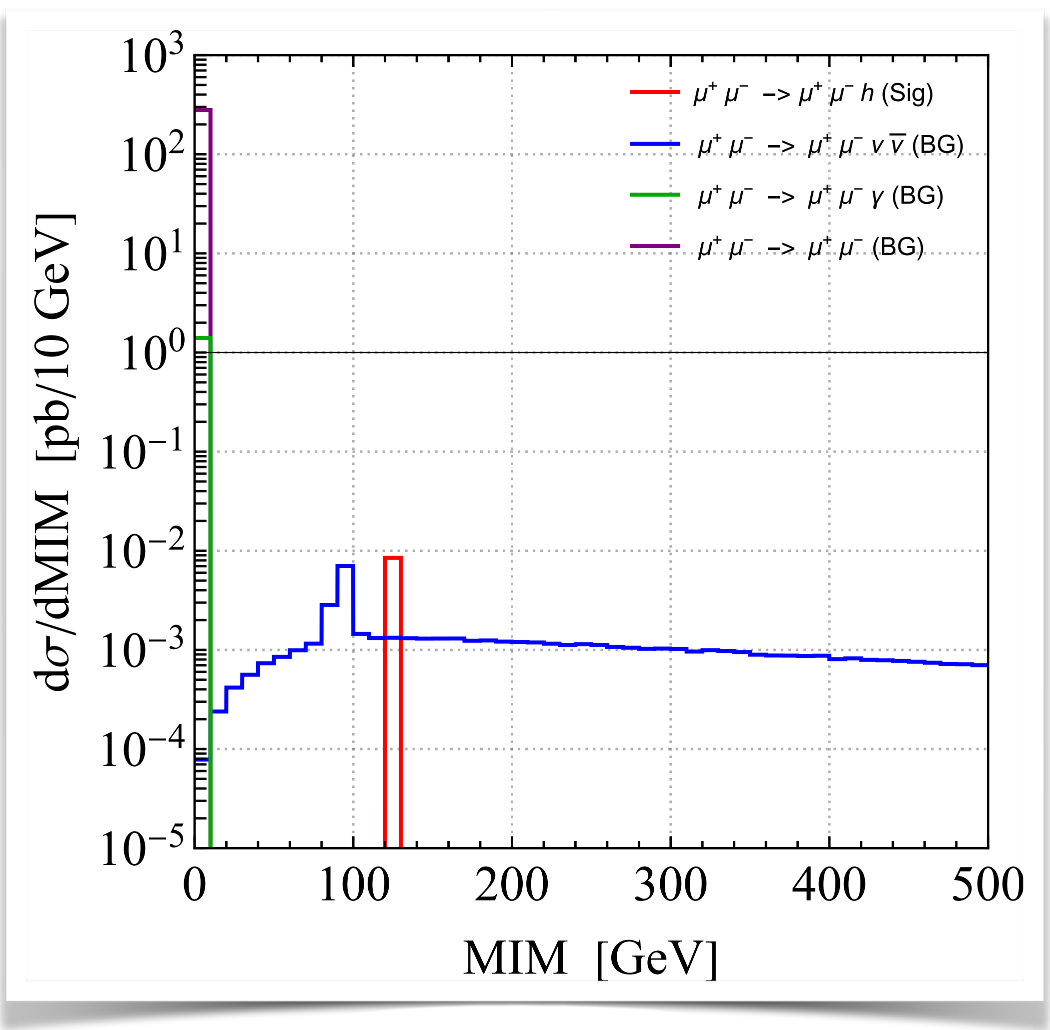
Beam Angular Spread (BAS)

- Average angular spread $\Delta\theta \sim 0.6$ mrad

  ➡ final state muons are boosted w.r.t. collision in COM frame (transverse)

- Seems to have small effect on analysis



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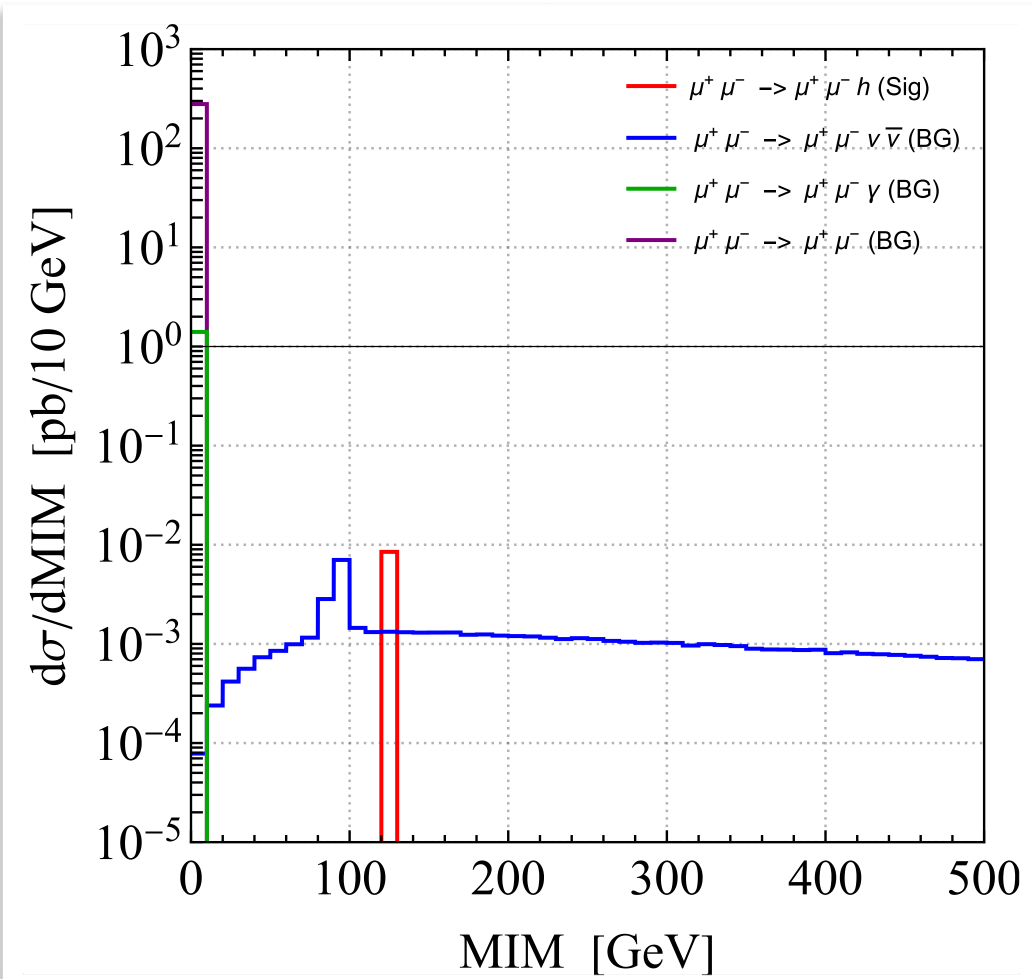
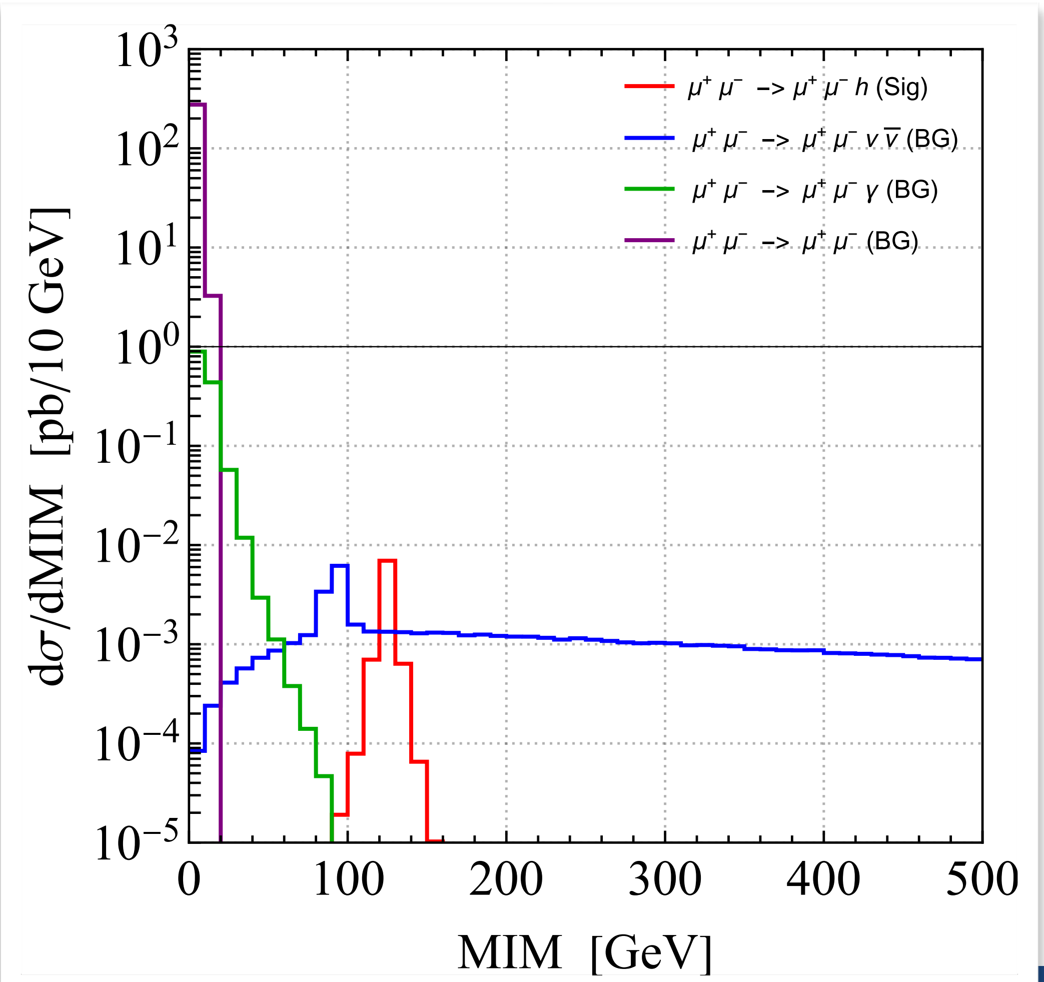
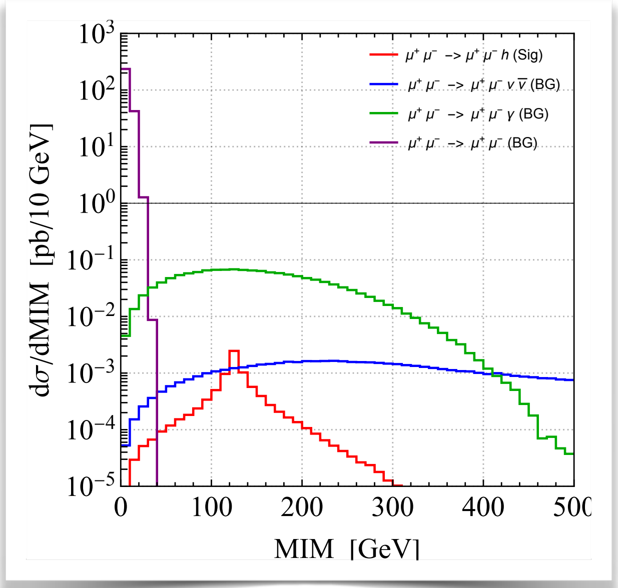


0.6 mrad BAS →



Energy Measurement Uncertainty

- Energy measurement uncertainty of forward muons has large effect on MIM



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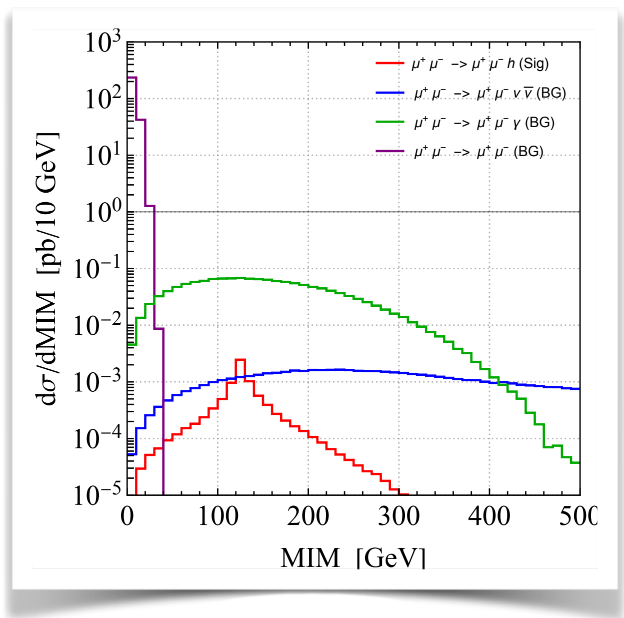
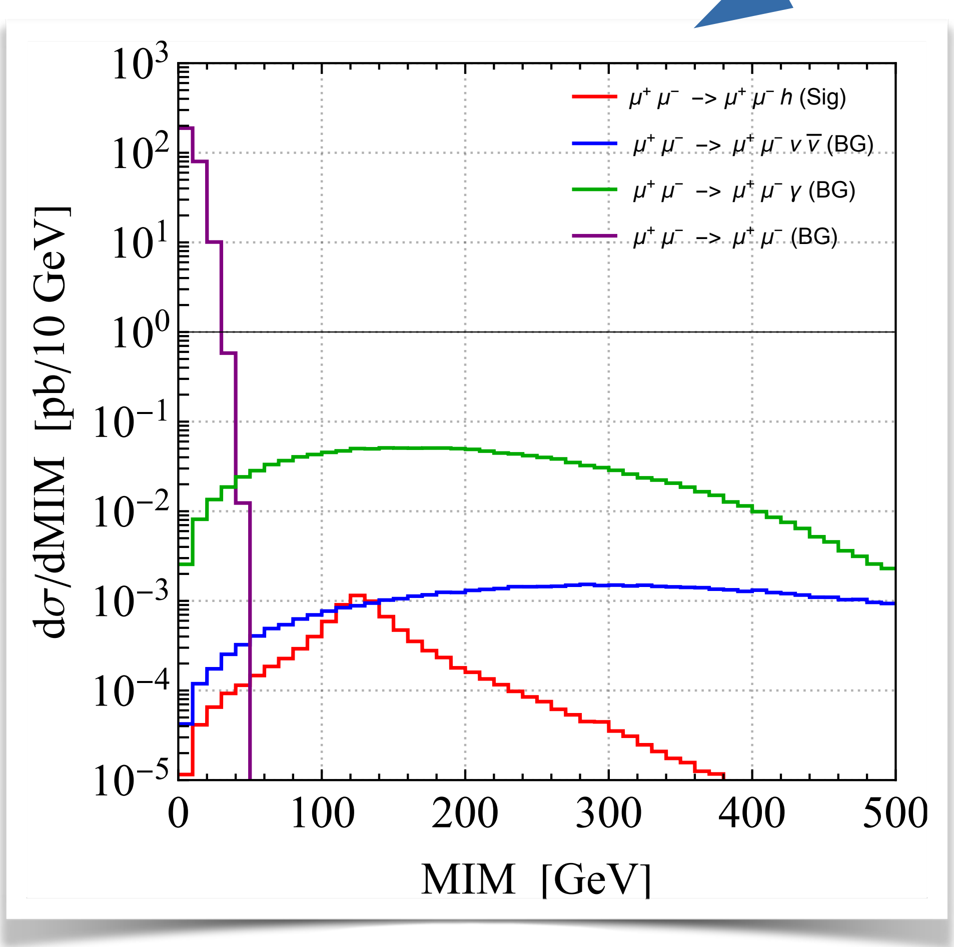


0.1% uncertainty



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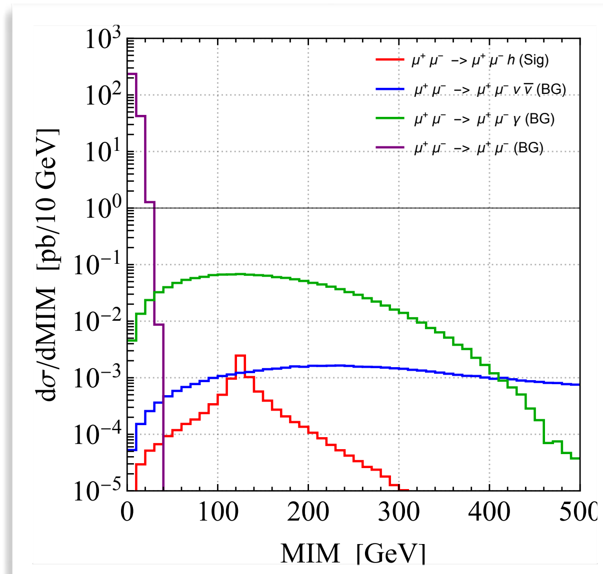

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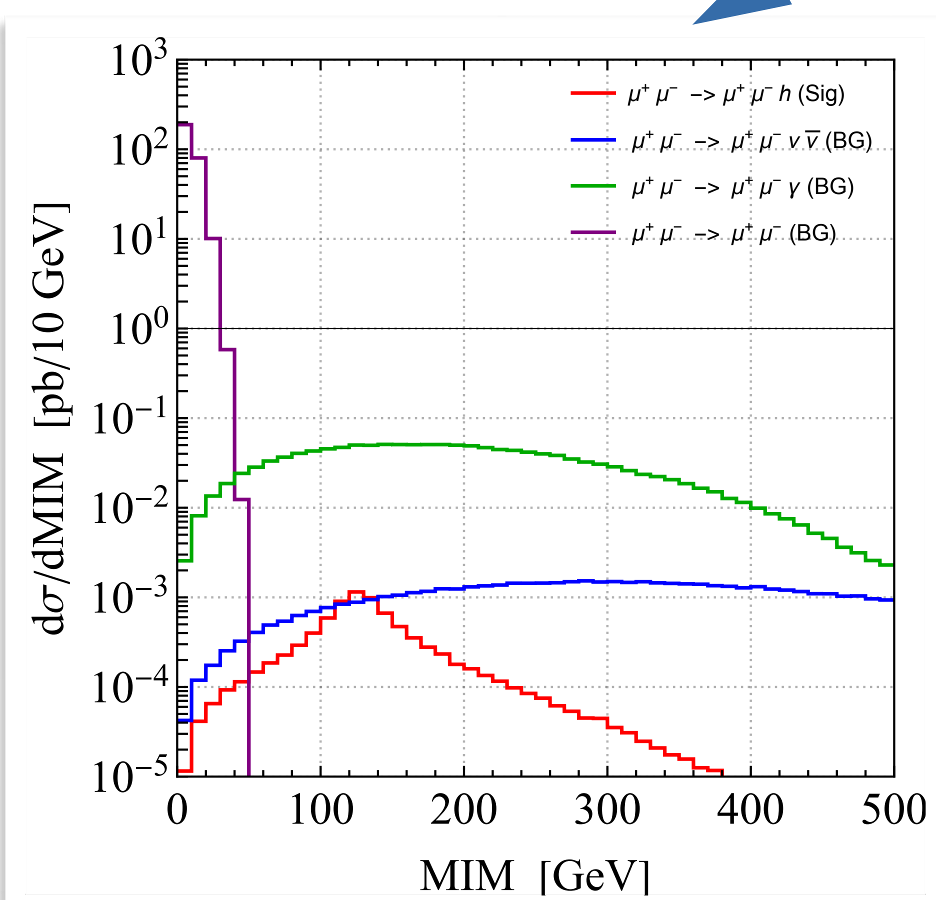
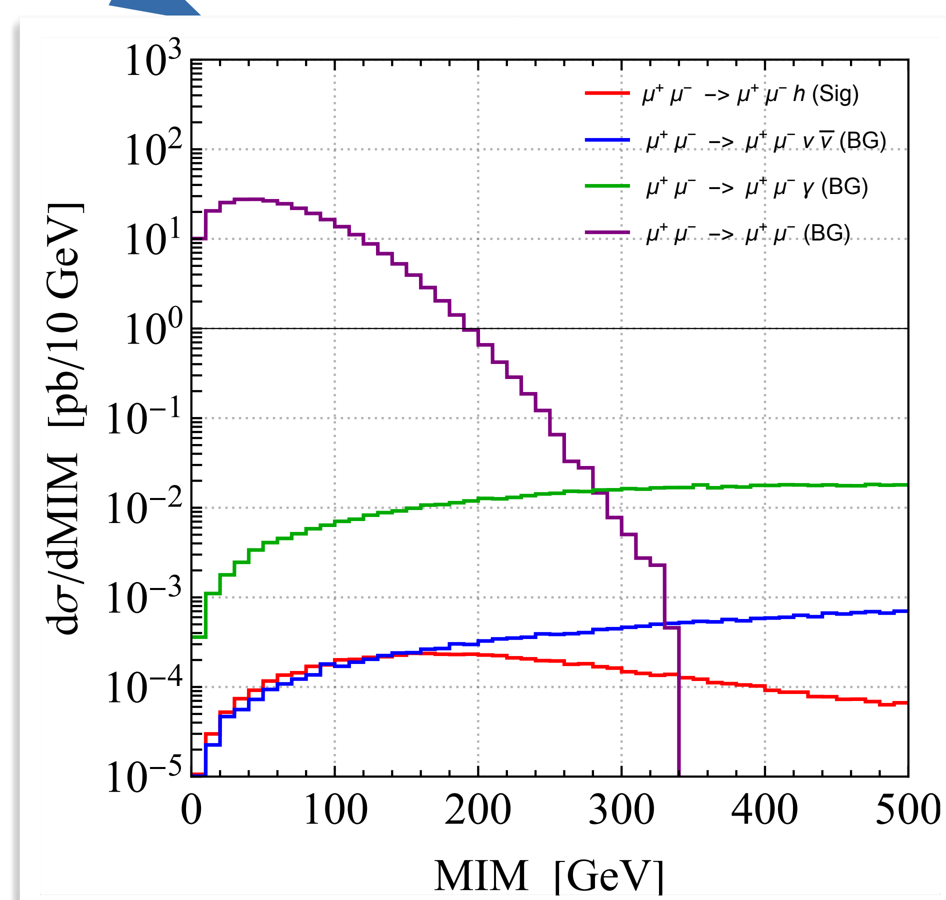


1% uncertainty



Energy Measurement Uncertainty

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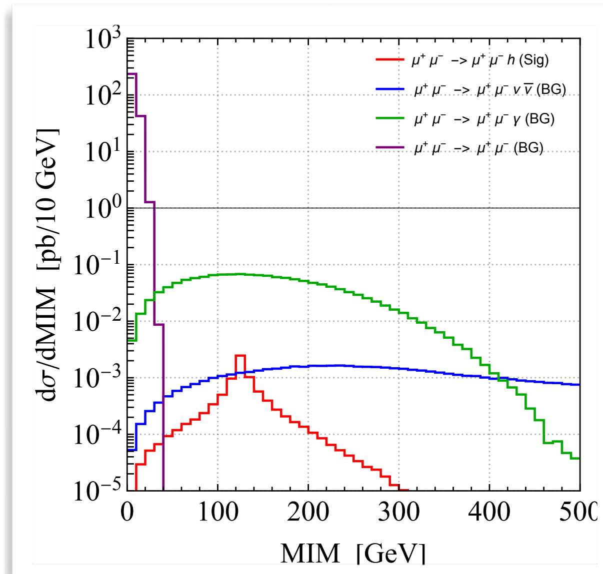
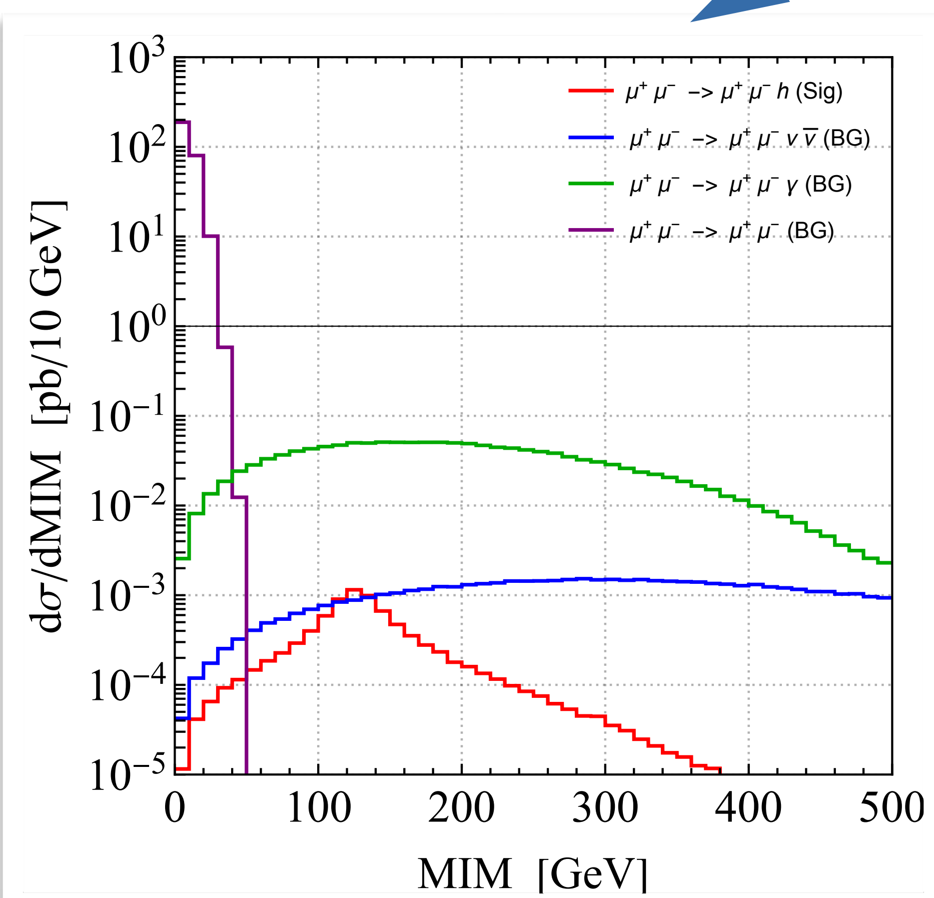


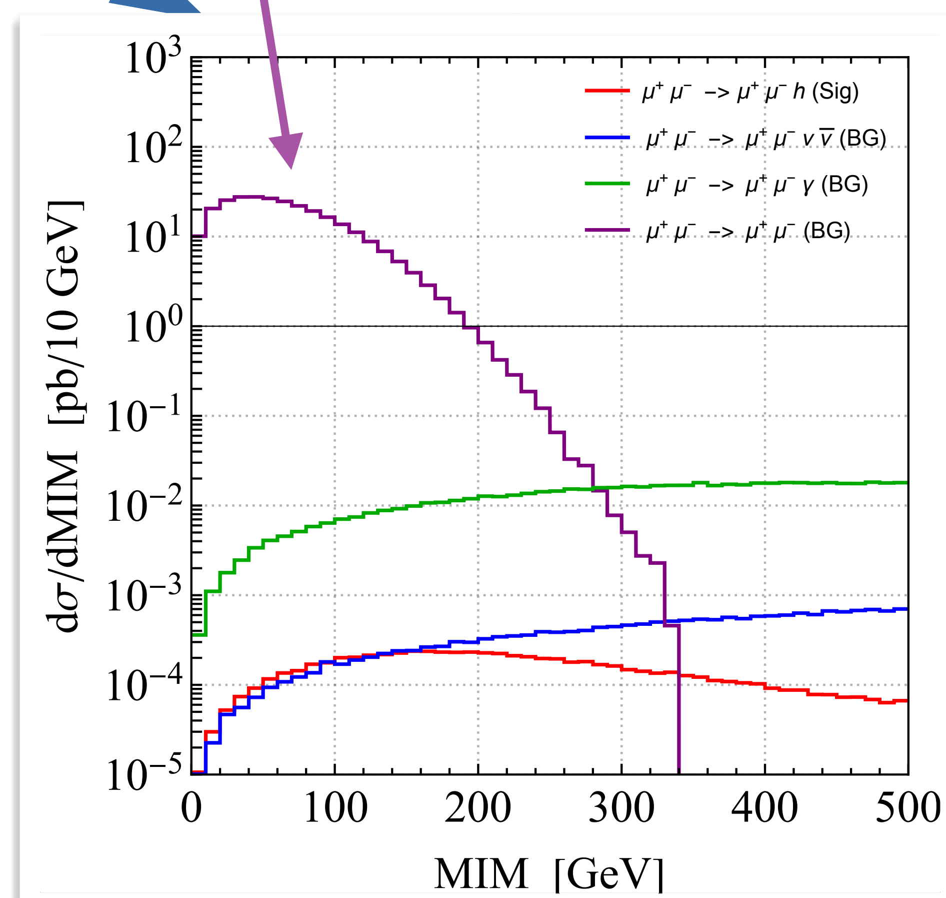
$\mu^+\mu^- \to \mu^+\mu^-$ becomes important

Can be suppressed with MET cut

0.1% uncertainty

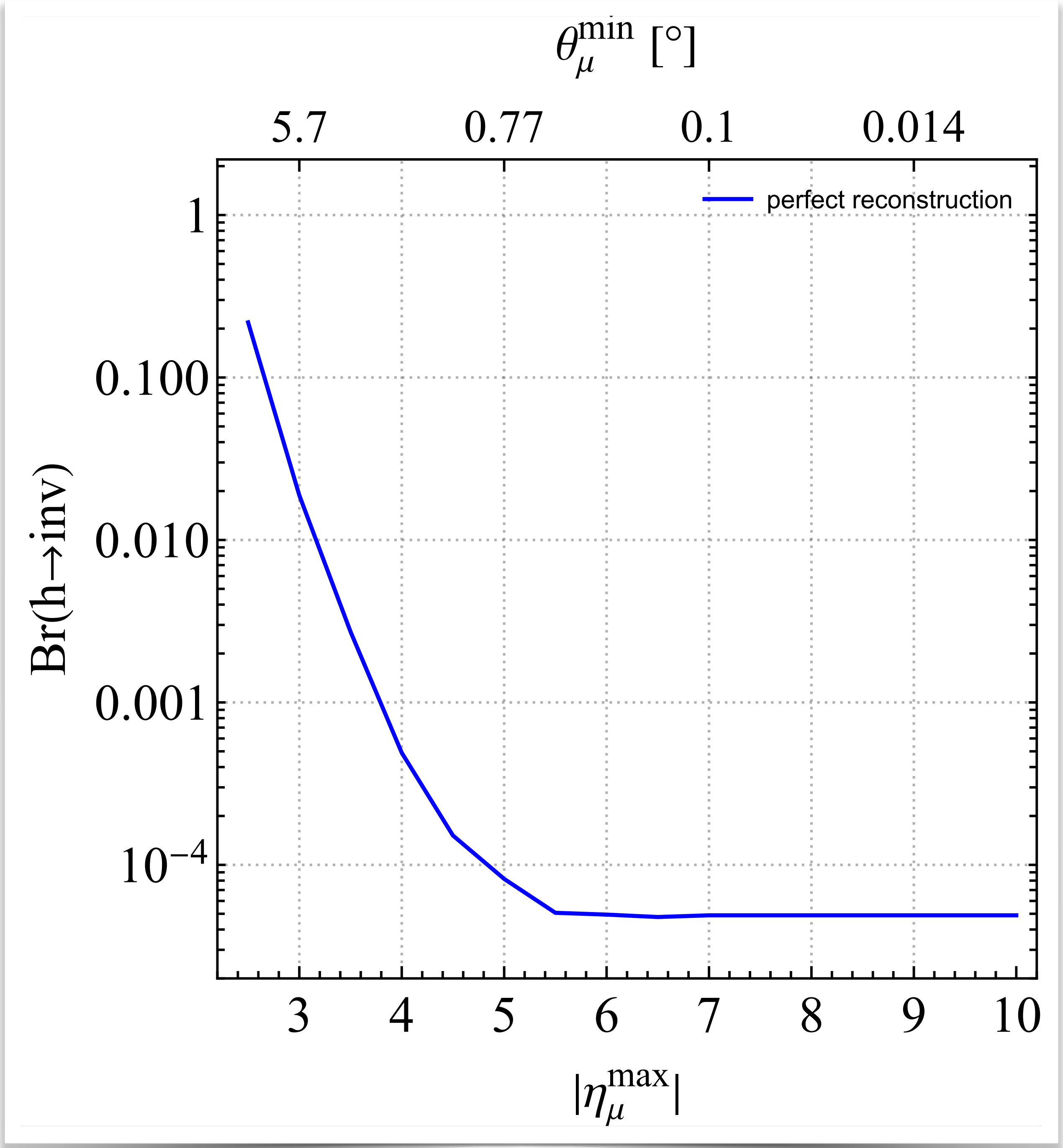


1% uncertainty



Combination

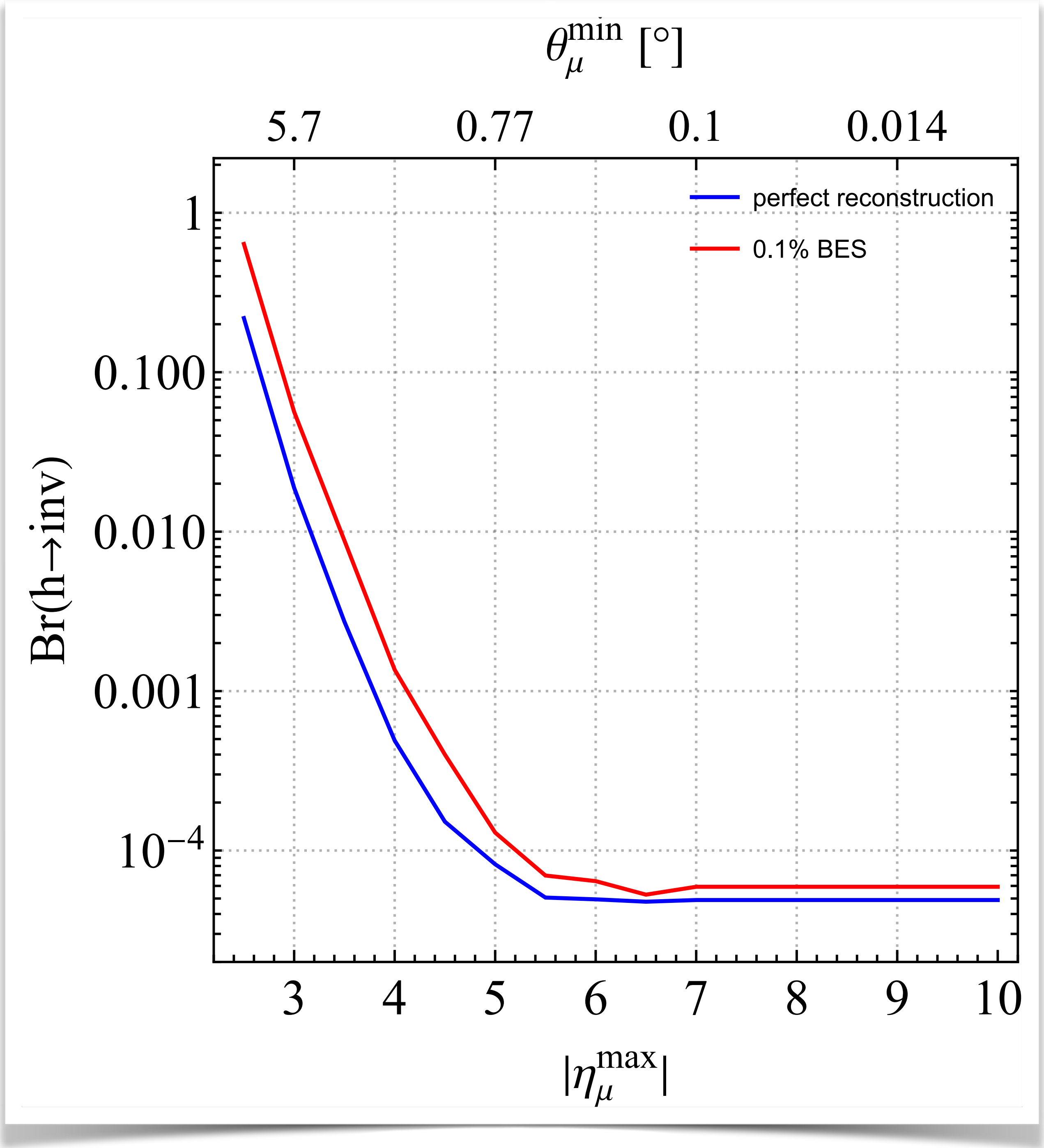
- Sensitivity to BR($h \to$ inv) with all effects combined



1. Perfect 4-momentum reconstruction

Combination

- Sensitivity to BR($h \to$ inv) with all effects combined

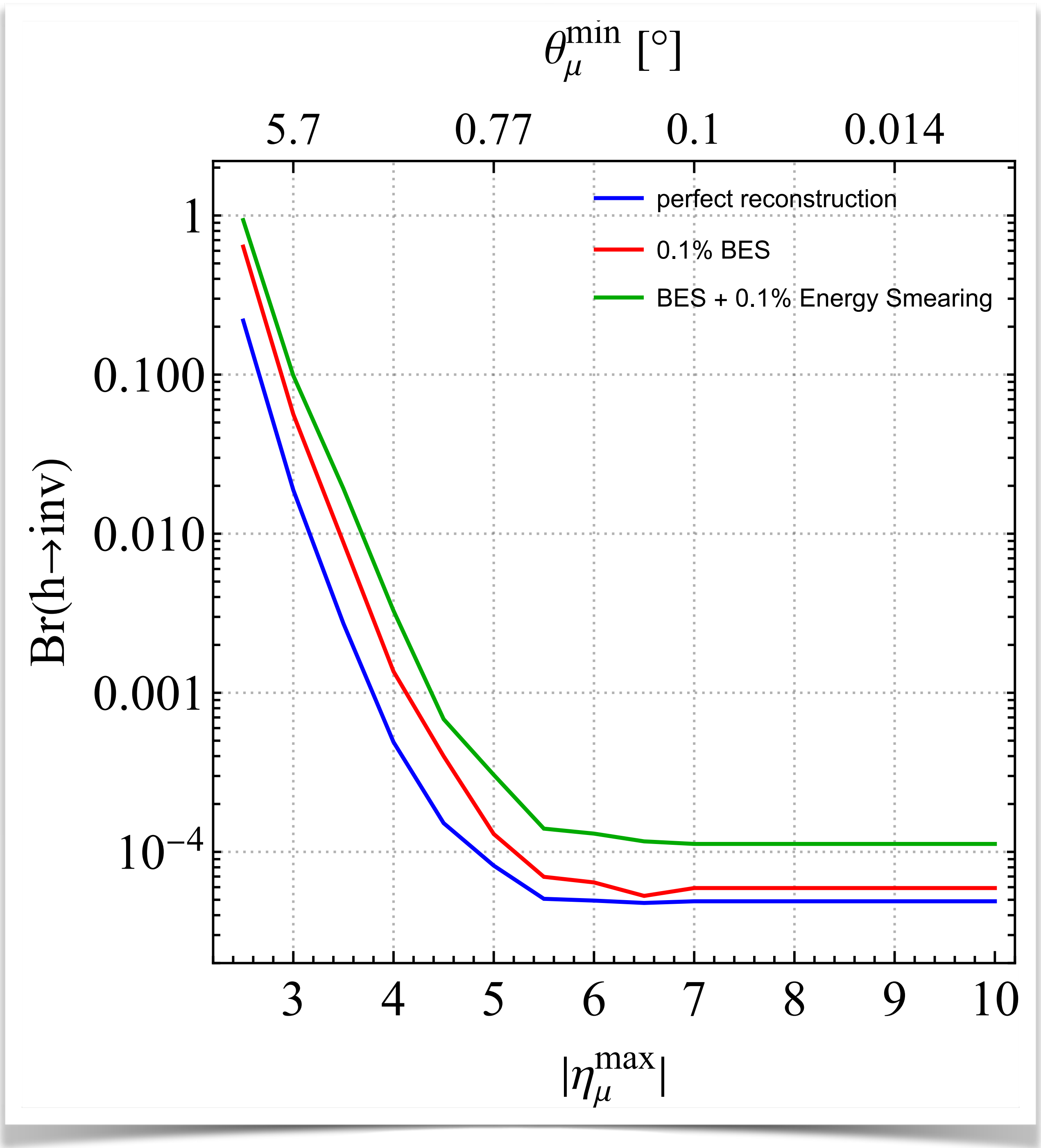


1. Perfect 4-momentum reconstruction

2. 0.1% BES

Combination

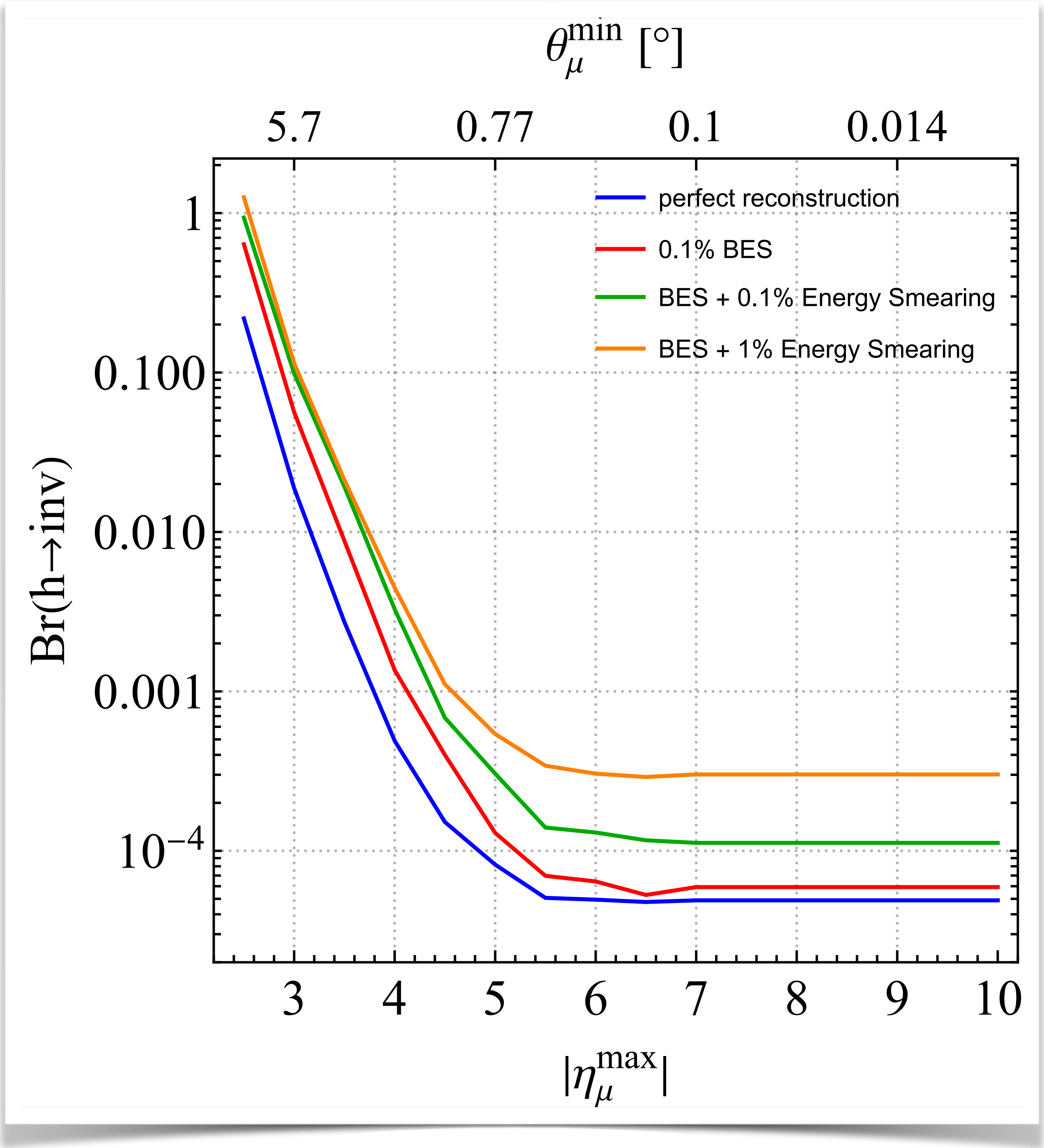
- Sensitivity to BR($h \to$ inv) with all effects combined



1. Perfect 4-momentum reconstruction
2. 0.1% BES
3. 0.1% BES + 0.1% energy uncertainty

Combination

- Sensitivity to BR$(h \to \text{inv})$ with all effects combined



1. Perfect 4-momentum reconstruction

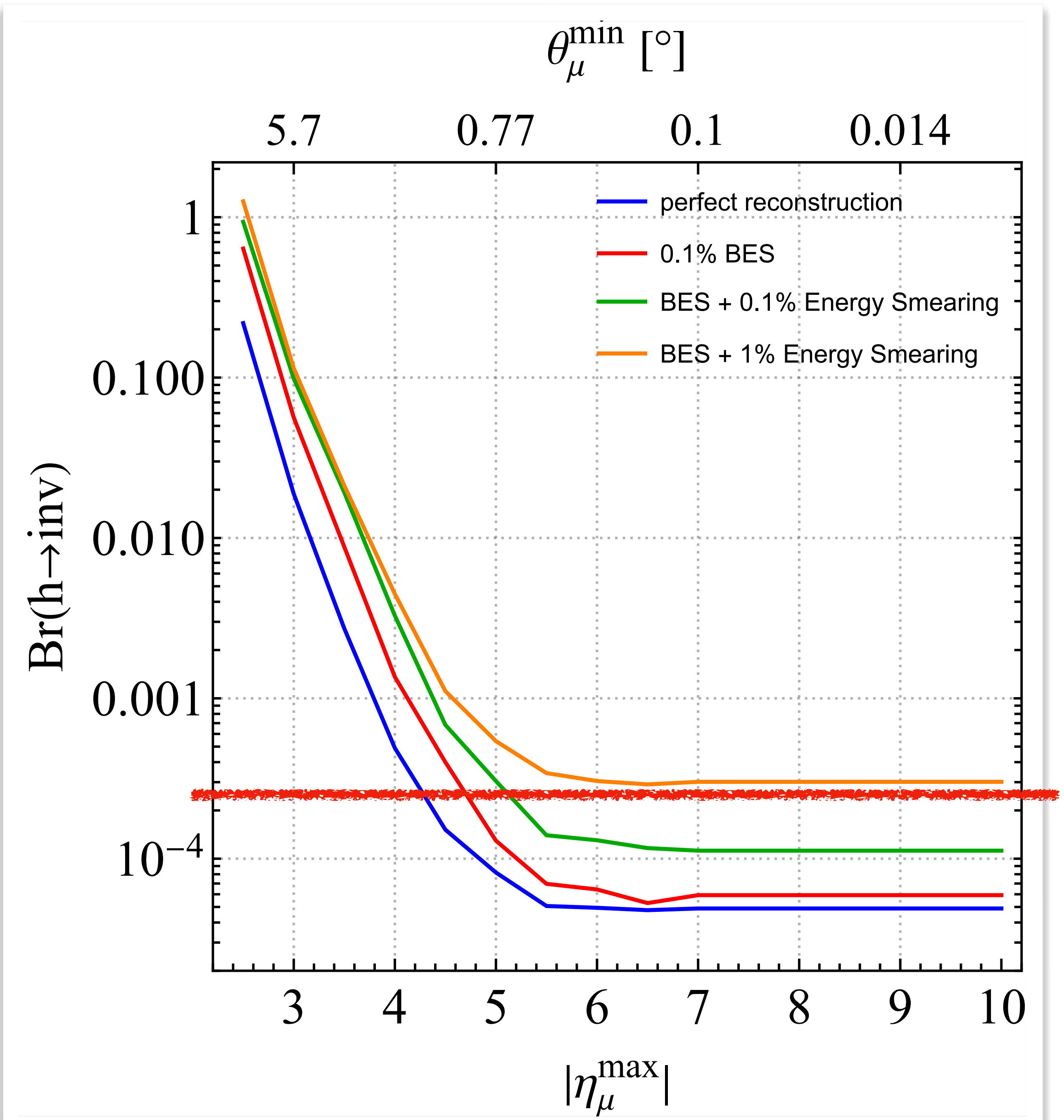
2. 0.1% BES

3. 0.1% BES + 0.1% energy uncertainty

4. 0.1% BES + 1% energy uncertainty

Combination

- Sensitivity to BR($h \to$ inv) with all effects combined



1. Perfect 4-momentum reconstruction

2. 0.1% BES

3. 0.1% BES + 0.1% energy uncertainty

4. 0.1% BES + 1% energy uncertainty

FCC-hh projection: $2.5 \cdot 10^{-4}$

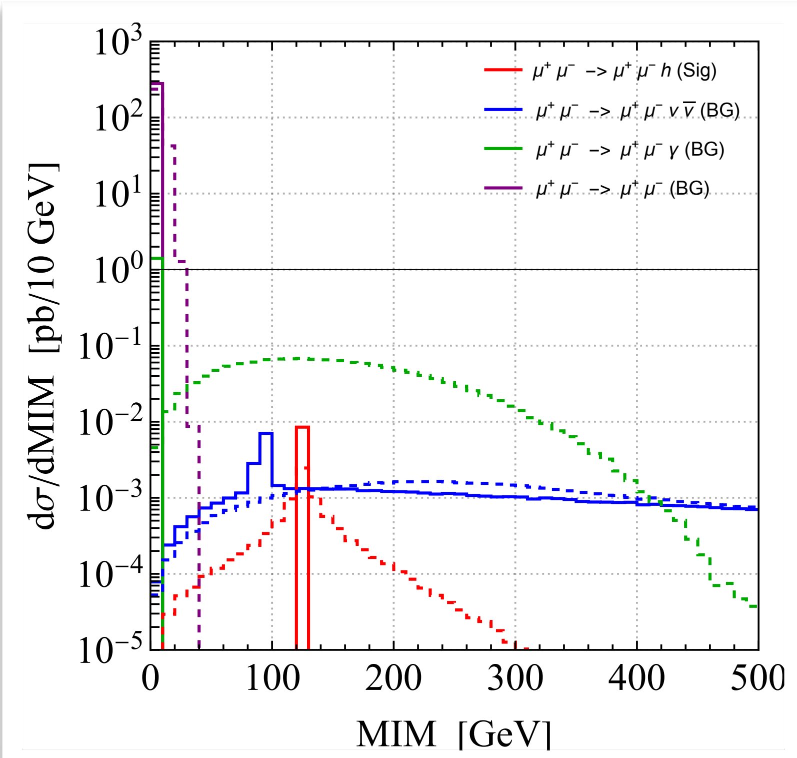
Next Steps

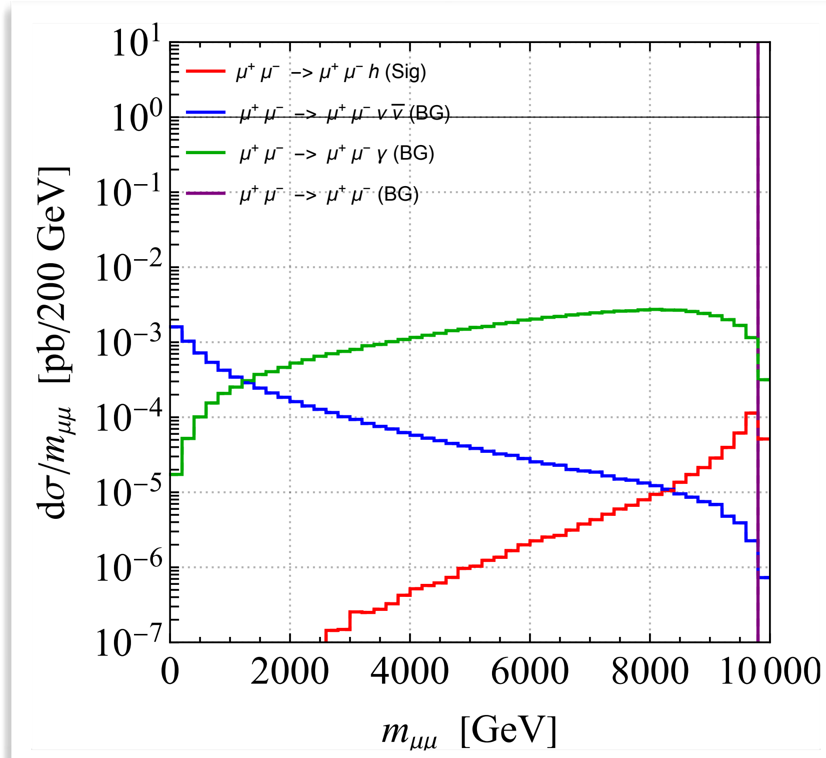
- Improve simulation of photon BG
- Include photon radiation off signal
- Further detector / accelerator effects (displacement of interaction point,…)
- Apply to other scenarios

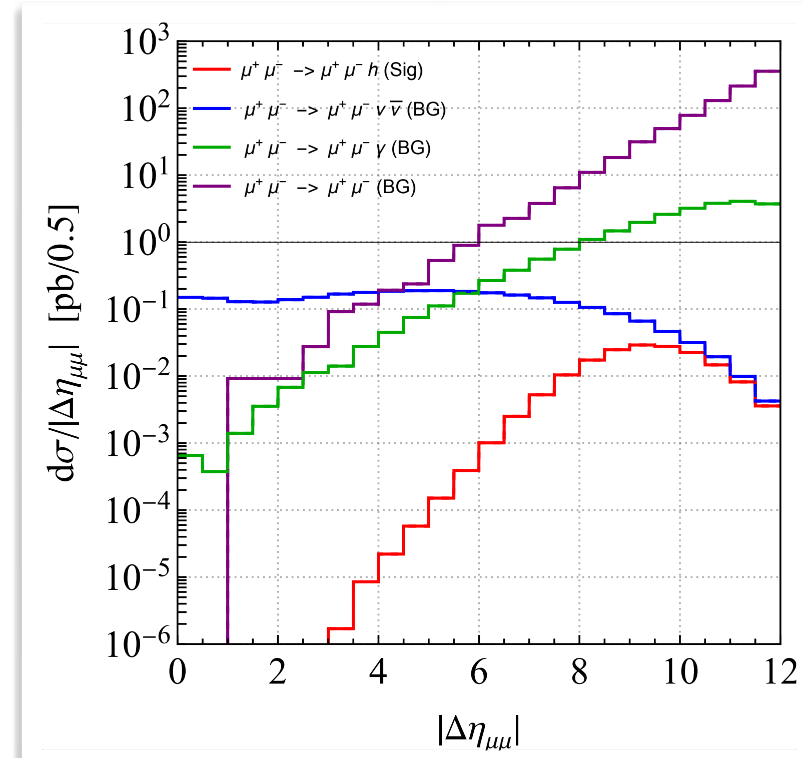
Your suggestions or comments

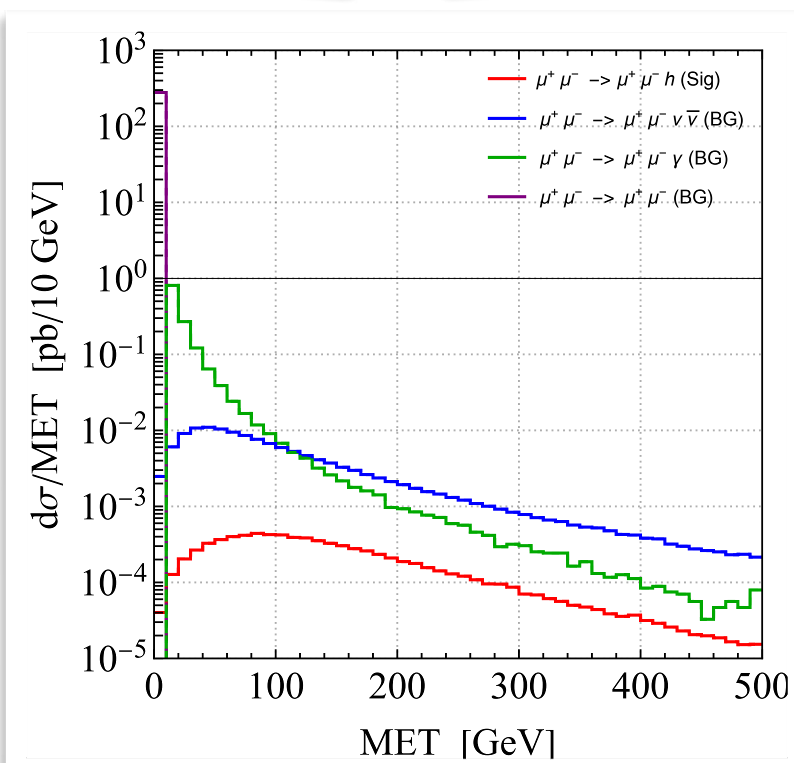
Backup

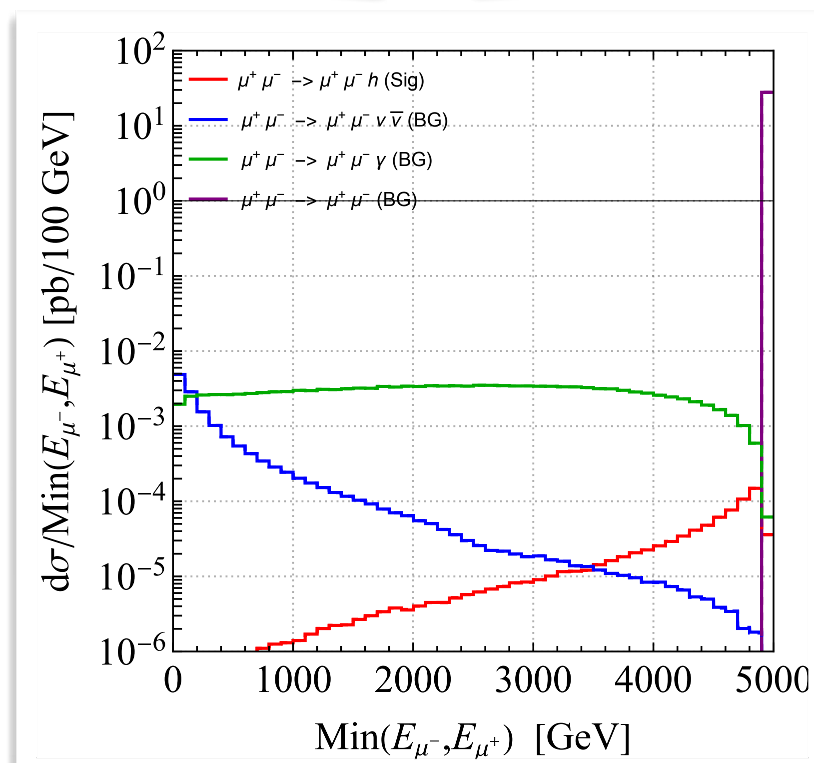
Invisible Higgs Decay Distributions











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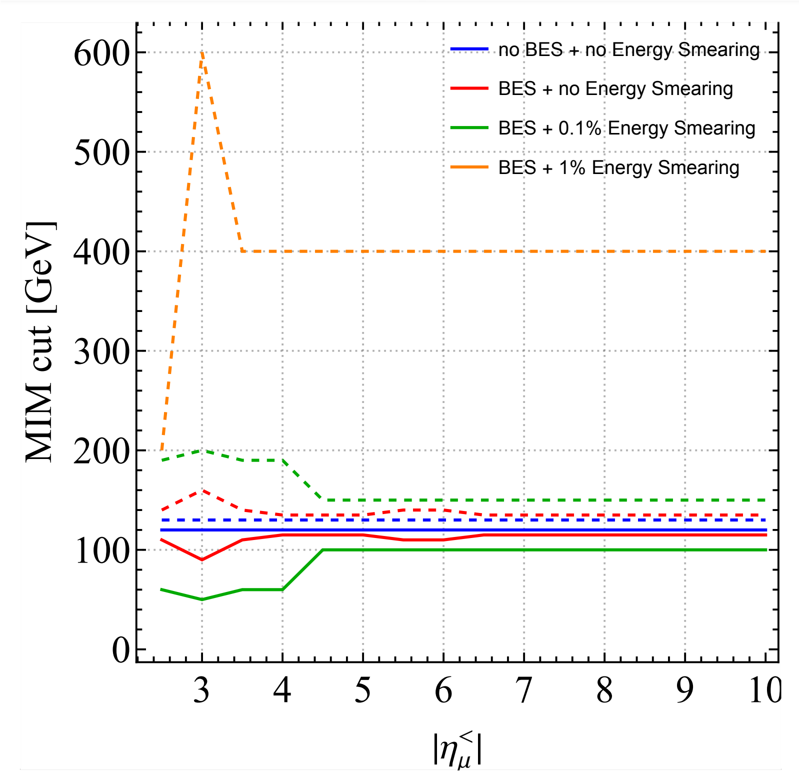
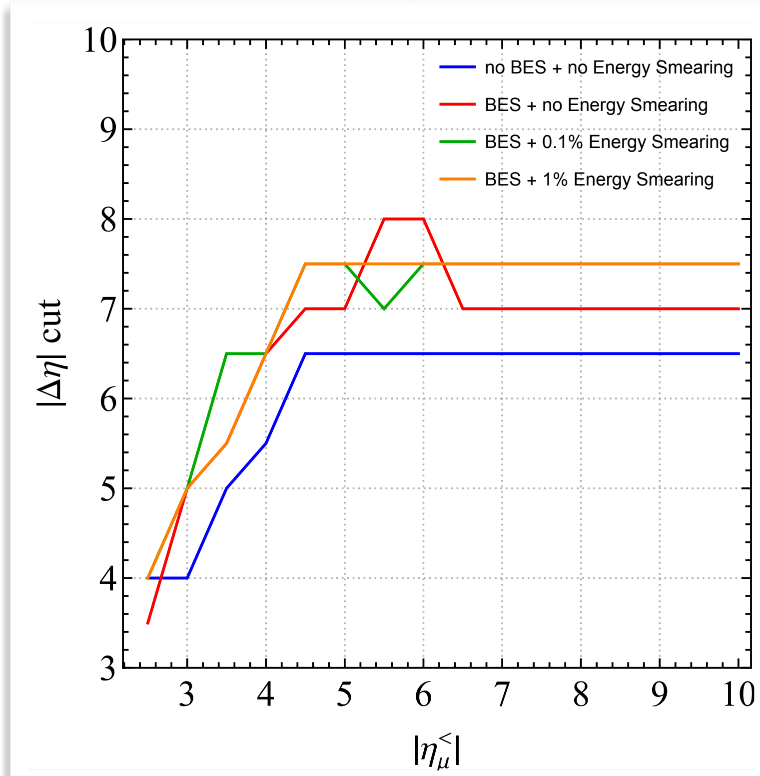
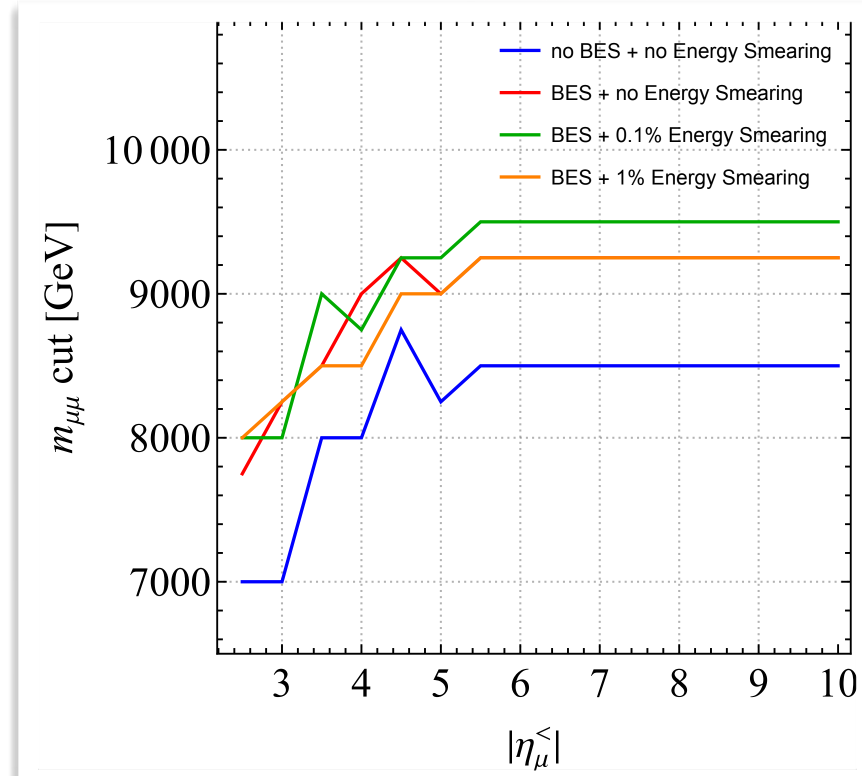
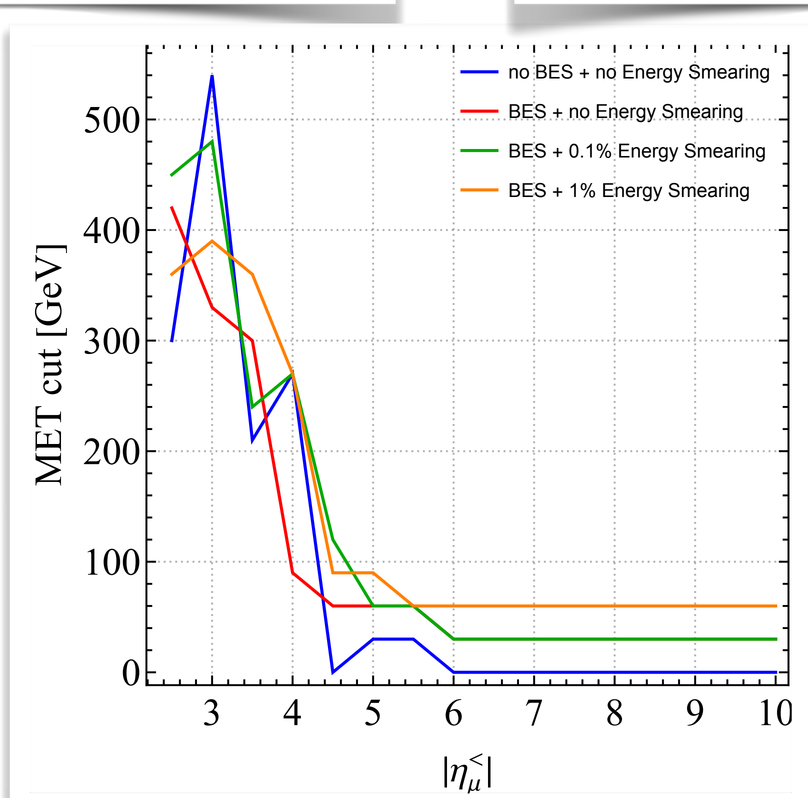
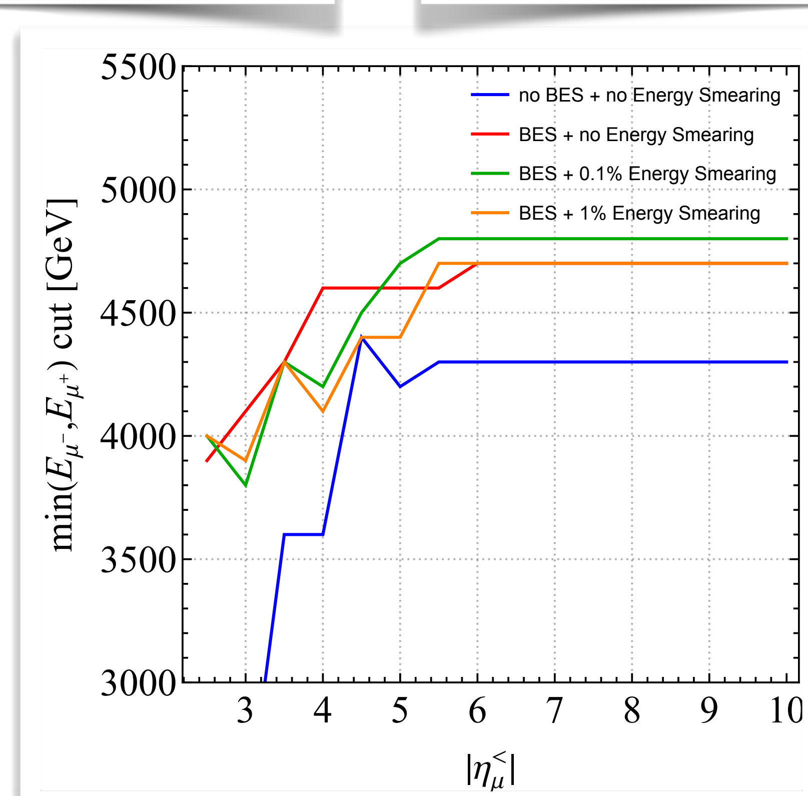
Cut Summary


no BES + no Energy Smearing
BES + no Energy Smearing
BES + 0.1% Energy Smearing
BES + 1% Energy Smearing
MIM cut [GeV]
$|\eta_\mu^<|$


no BES + no Energy Smearing
BES + no Energy Smearing
BES + 0.1% Energy Smearing
BES + 1% Energy Smearing
$|\Delta\eta|$ cut
$|\eta_\mu^<|$


no BES + no Energy Smearing
BES + no Energy Smearing
BES + 0.1% Energy Smearing
BES + 1% Energy Smearing
$m_{\mu\mu}$ cut [GeV]
$|\eta_\mu^<|$


no BES + no Energy Smearing
BES + no Energy Smearing
BES + 0.1% Energy Smearing
BES + 1% Energy Smearing
MET cut [GeV]
$|\eta_\mu^<|$


no BES + no Energy Smearing
BES + no Energy Smearing
BES + 0.1% Energy Smearing
BES + 1% Energy Smearing
$\min(E_{\mu^-}, E_{\mu^+})$ cut [GeV]
$|\eta_\mu^<|$

MIM Scaling with BES

- Consider $\mu^-(p_1)\mu^+(p_2) \to \mu^-(p^{\rm out}_{\mu^-})\mu^+(p^{\rm out}_{\mu^+})\gamma(p_\gamma)$

- True initial 4-vectors $p^\mu_{1/2} = E_{1/2}(1,0,0,\pm 1)$

$$\Rightarrow \quad {\rm MIM}^2 = \left(p_1 + p_2 - p^{\rm out}_{\mu^-} - p^{\rm out}_{\mu^+}\right)^2 = p_\gamma^2 = 0$$

- We do not know initial 4-momenta and assume $\tilde{p}^\mu_{1/2} = \frac{\sqrt{s}}{2}(1,0,0,\pm 1)$

$\Rightarrow$ reconstructed MIM

$${\rm MIM}^2 = (\tilde{p}_1 + \tilde{p}_2 - p^{\rm out}_{\mu^-} - p^{\rm out}_{\mu^+})^2 = (\tilde{p}_1 + \tilde{p}_2 - p_1 - p_2 + p_\gamma)^2$$

- For $E_i = \frac{\sqrt{s}}{2}(1+\delta_i)$

$${\rm MIM}^2 = 2(\tilde{p}_1 + \tilde{p}_2 - p_1 - p_2)\cdot p_\gamma + \mathcal{O}(\delta_i^2) \simeq 2\,|p^z_\gamma|\sqrt{s}\,\delta_i$$

pNGB DM Realizations

- **Complex** scalar DM

$SO(7)/SO(6) \longrightarrow (H, \chi) \sim \mathbf{4}_0 + \mathbf{1}_{\pm 1}$ of $SO(4)_{U(1)_{\rm DM}}$

Balkin, MR, Salvioni, Weiler, 1707.07685

➡ stabilised by exact $U(1)_{\rm DM} \subset SO(6)$

- Controlled Goldstone symmetry-breaking / mass generation by

1. Coupling to top $\lambda \sim \frac{\lambda_h}{2}$ In tension with XENON1T
   Balkin, MR, Salvioni, Weiler, 1707.07685
2. Coupling to bottom (or lighter quarks) $\lambda \propto y_b^2 \ll 1$
   Balkin, MR, Salvioni, Weiler, 1809.09106
3. Weakly gauging $U(1)_{\rm DM}$ $\lambda \propto$ higher-loop $\ll 1$

Non Composite Higgs pNGB DM

- **pNGB DM** can arise from complex scalar with $U(1)$ broken by mass term

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |\partial_\mu S|^2 + \frac{\mu_S^2}{2}|S|^2 - \frac{\lambda_S}{2}|S|^4 - \lambda_{HS}|S|^2|H|^2 + \frac{\mu_S'^2}{4}(S^2 + \text{h.c.})$$

➡ $U(1)$ spontaneously broken $S = \frac{1}{\sqrt{2}}(v_s + \sigma)e^{i\phi/v_s}$

- Integrating out radial mode generates $\frac{c_d}{2f^2}\partial_\mu\phi^2\partial^\mu|H|^2$ with $\frac{c_d}{f^2} \simeq \frac{\lambda_{HS}}{\lambda_S v_S^2}$

➡ note that corrections to Higgs couplings scale as $\frac{c_H}{c_d} \simeq \frac{\lambda_{HS}}{\lambda_S}$

instead of $\frac{c_H}{c_d} \simeq 1$ (typical scaling in Composite Higgs)