Probing invisible physics at a muon collider: Opportunities and Challenges

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PPMC at IFT Madrid
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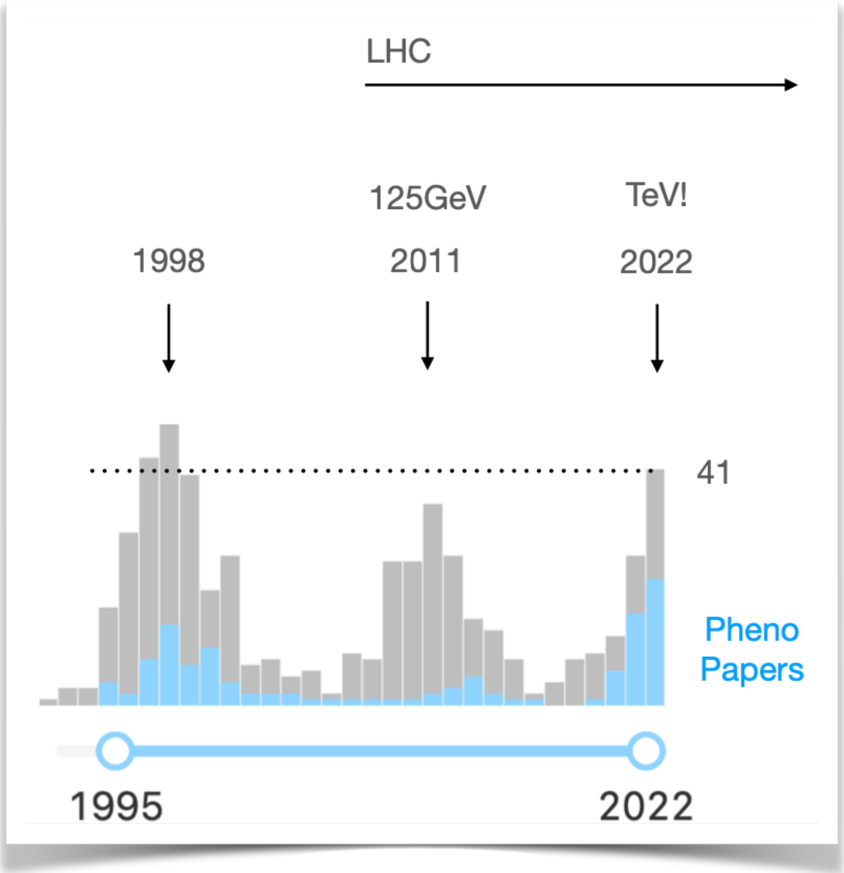
Based on work in progress
with R. Masarotti, E. Salvioni *and* A. Wulzer

Muon Colliders

- There has been a renewed interest in muon colliders



Taken from Fabio Maltoni's talk at
Muon Collider Collaboration Meeting '22

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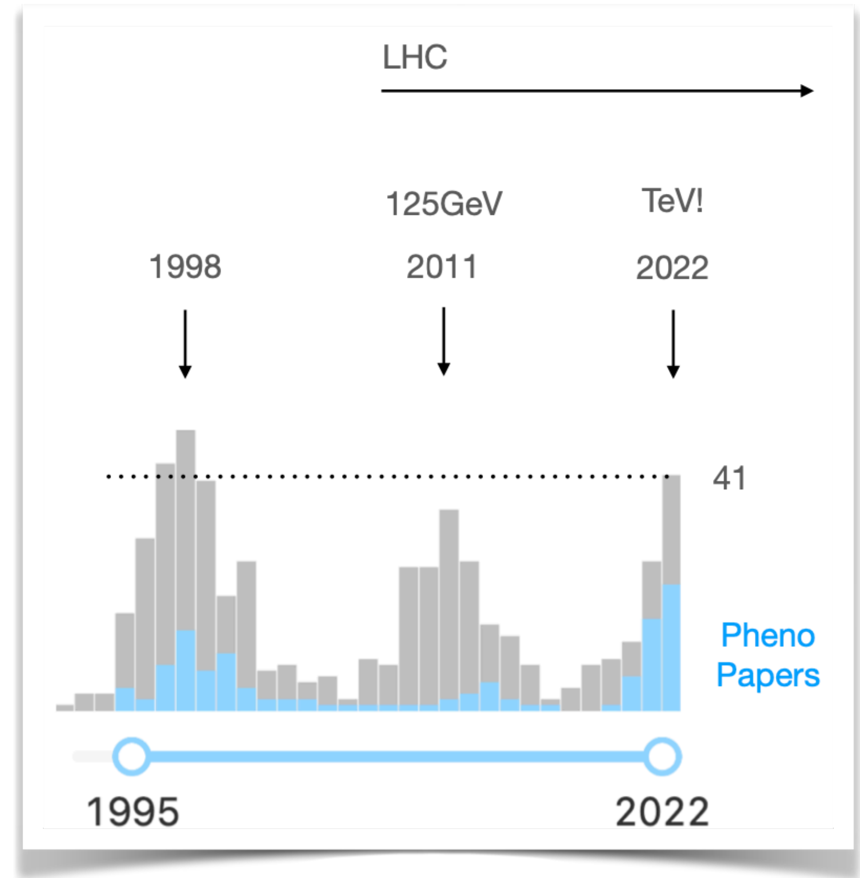
- Considerable R&D effort

International MUON Collider Collaboration

→ first annual meeting was this October

→ EU design study proposal accepted



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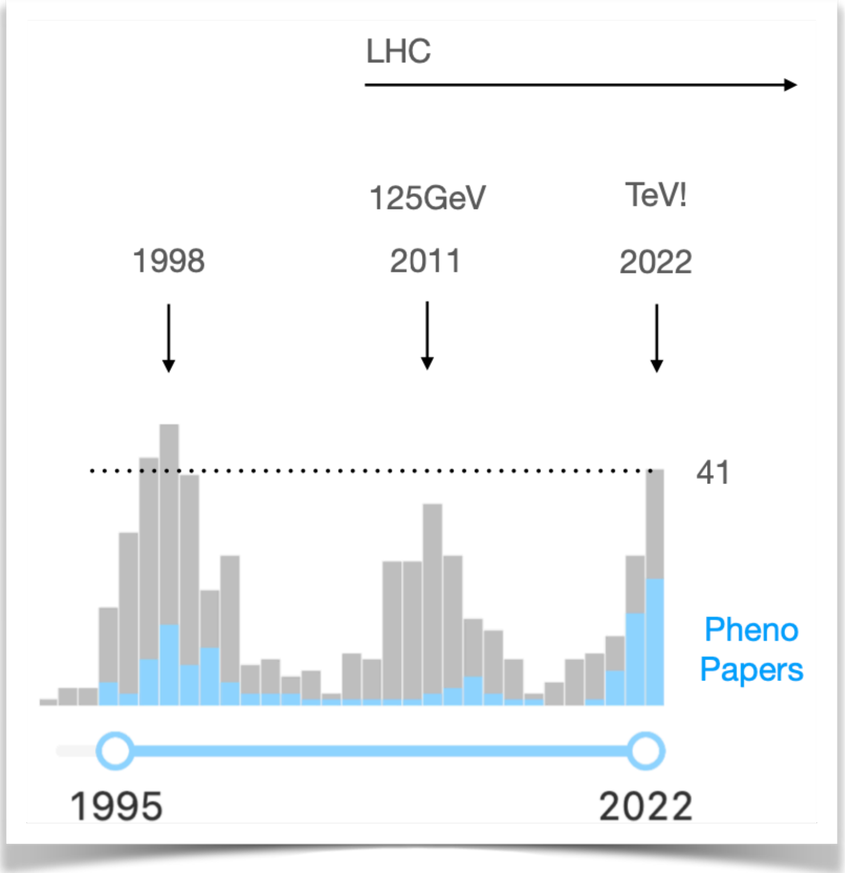

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What is the physics potential of a muon collider?

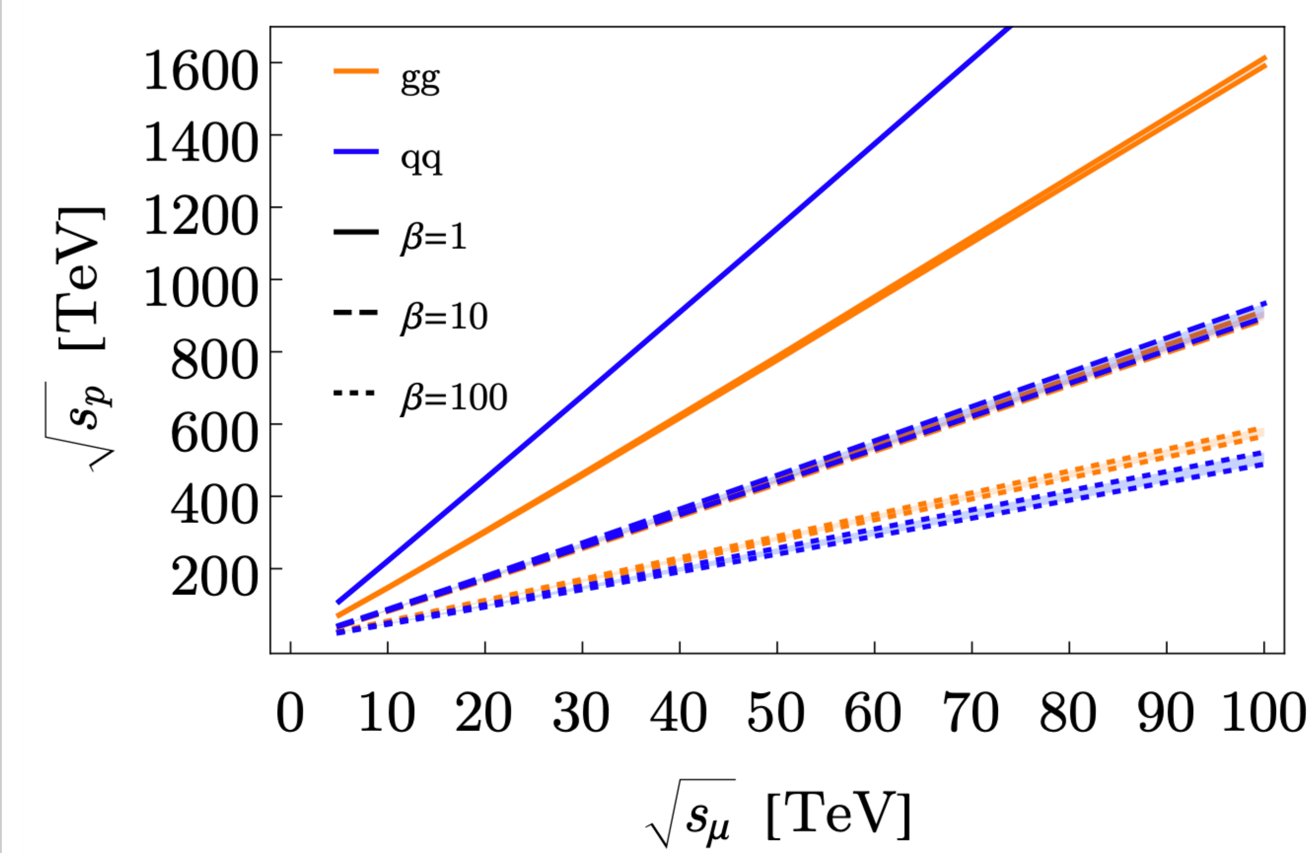
Advantages of a Muon Collider

- Energy Reach

$2 \to 2$ scattering

EW: $\beta \sim 1$

QCD: $\beta \sim \left(\frac{\alpha_s}{\alpha_2}\right)^2 \sim 100$



arXiv: 2103.14043

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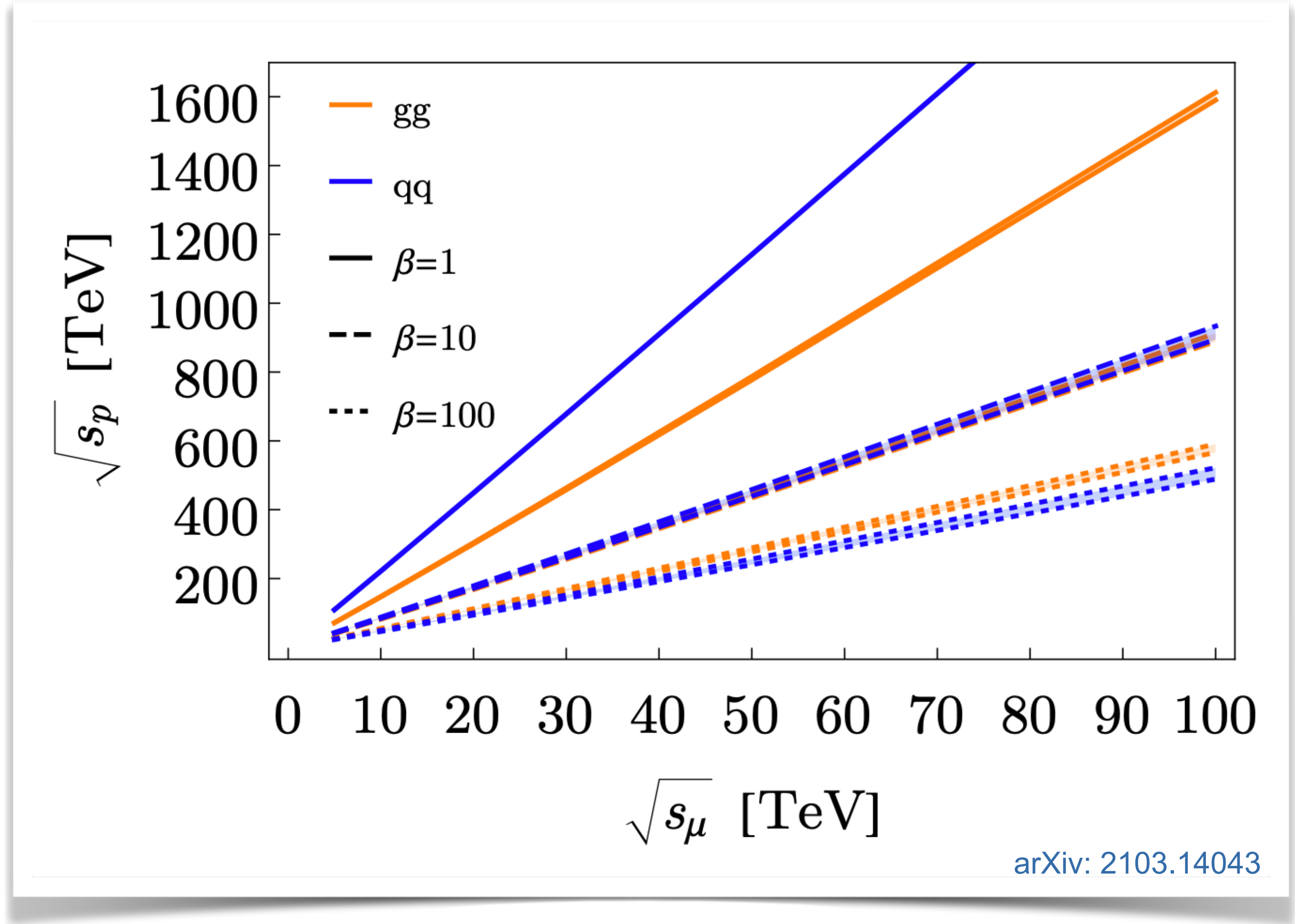

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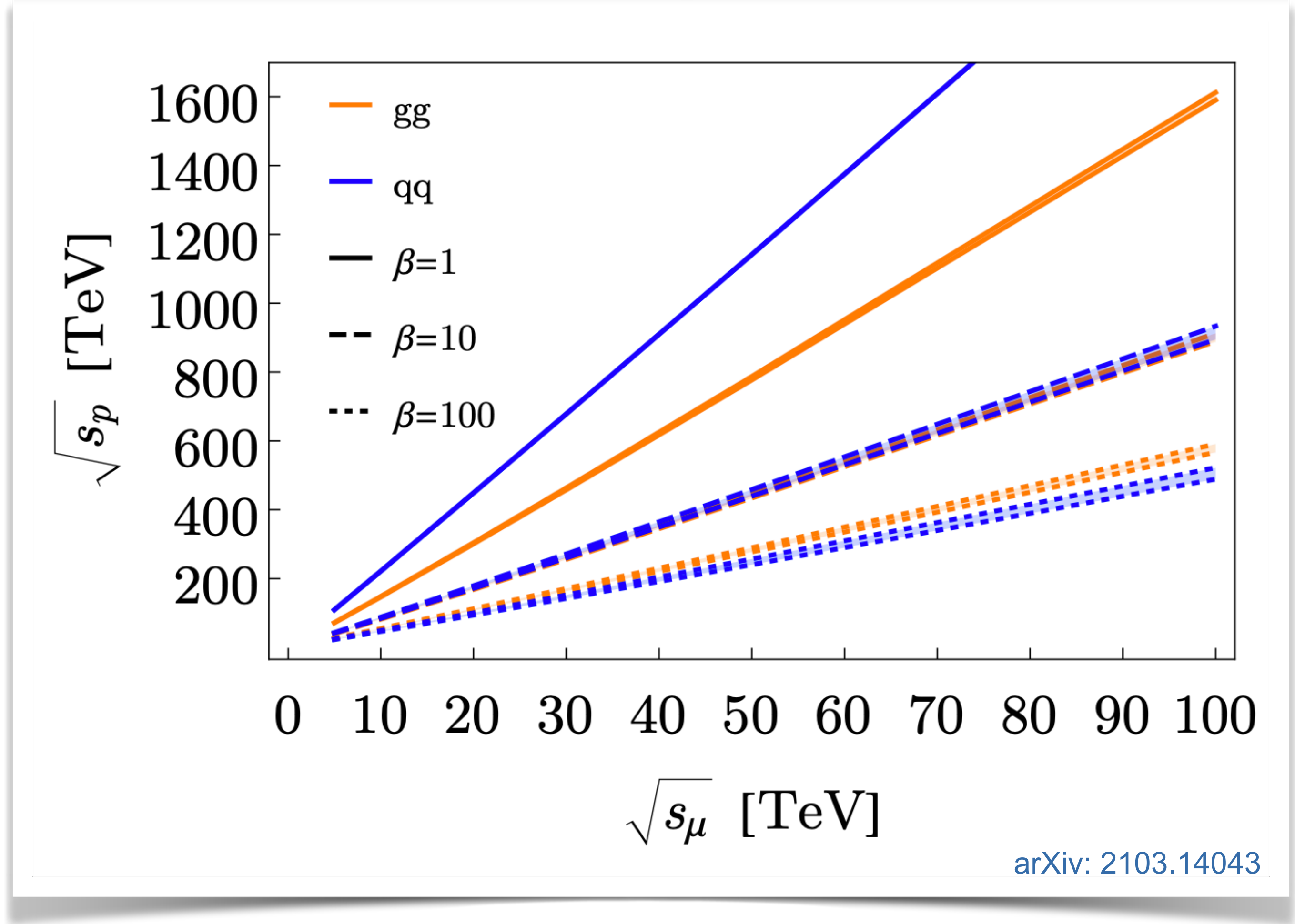

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Perfect machine for studying invisible physics (DM, LLPs,…)

Probing invisible physics at a muon collider

1. Opportunities:

- Focus on scalar Higgs portal to invisible new physics:
  1. Higgs portal scalar
  2. pNGB dark matter
  3. invisible Higgs decays

2. Challenges:

- Realistic limitations of muon collider / detector
- Accelerator and detector effects (beam energy spread,…) are important
- Study invisible Higgs decays as realistic benchmark

1. Opportunities

Higgs Portal Scalar

- SM singlet scalar ϕ coupled to SM through **renormalizable** Higgs portal

Marginal Higgs portal
(aka renormalizable Higgs portal)

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

- Assume that ϕ is stable or long-lived on detector scales

→ "Nightmare Scenario" for BSM physics: extremely hard to probe (especially for $m_\phi > m_h/2$)

- Well motivated; relevant for many BSM scenarios

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- Scalar DM ϕ

➡ observed relic abundance requires $\lambda \sim \mathcal{O}(10^{-2} - 10^{-1})$

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

Cheng, Li, Salvioni, Verhaaren 2018
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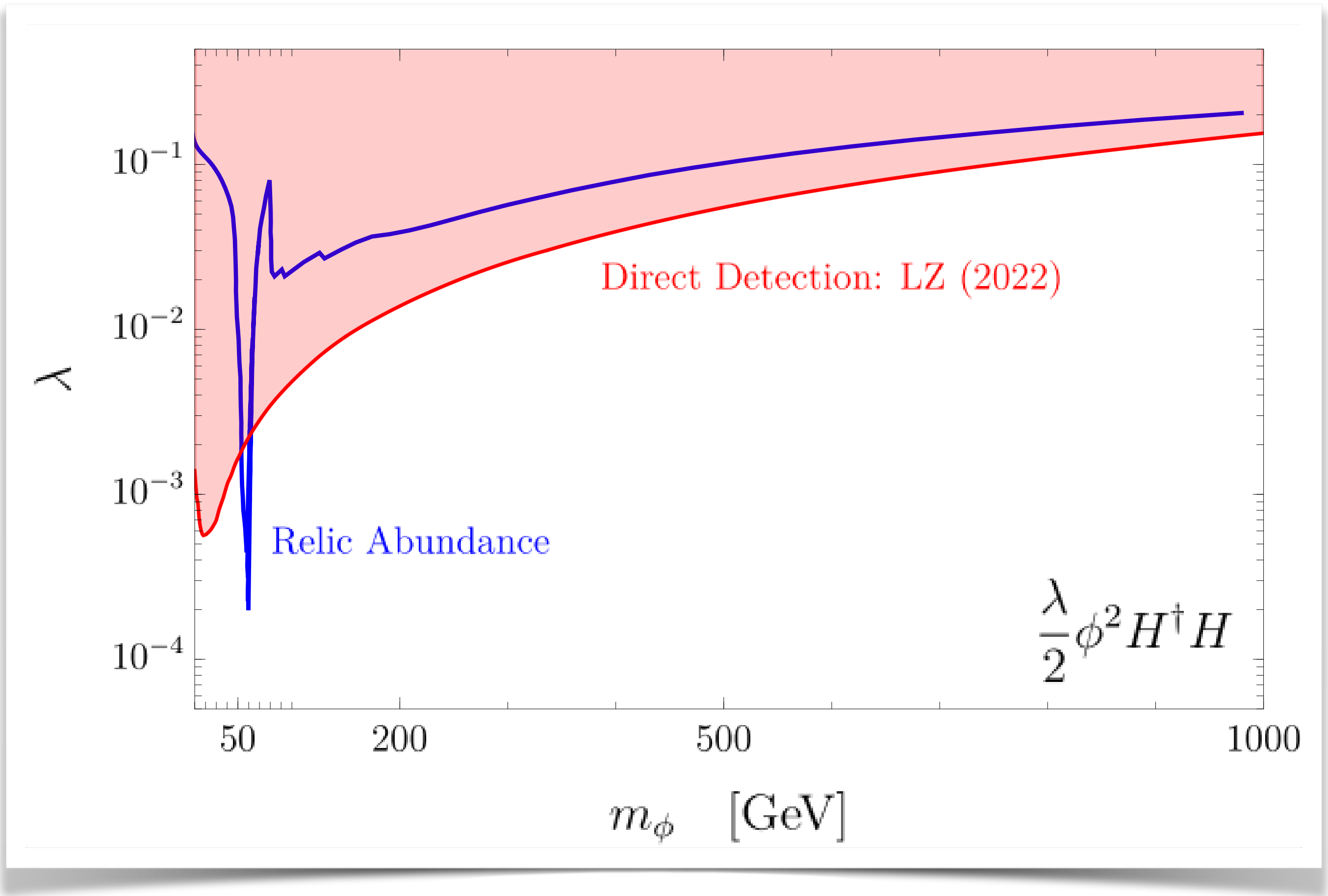
- First-order electroweak phase transition

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

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

Higgs Portal Scalar DM

- Minimal model in tension with direct detection experiments



$$\sigma_{\phi N \to \phi N} \simeq 5 \cdot 10^{-47}\ \text{cm}^2 \left(\frac{\lambda}{0.007}\right)^2 \left(\frac{100\ \text{GeV}}{m_\phi}\right)^2$$

- Still possible in extended theories (extra scalars, non-standard cosmology,…)

See e.g. 1903.03616

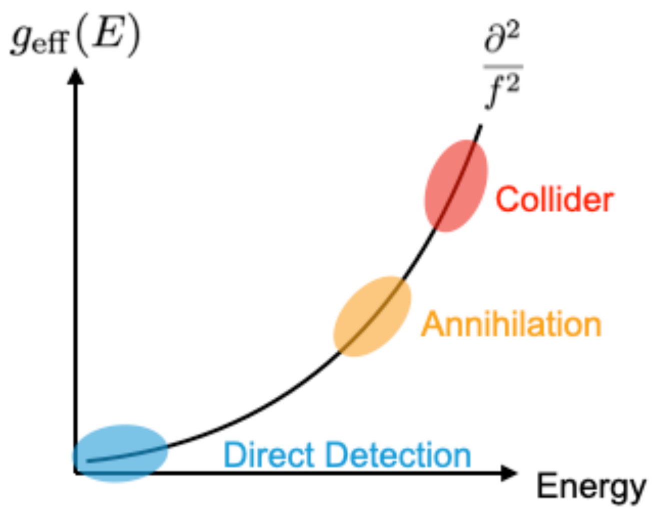
Derivative Higgs Portal: pNGB DM

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

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

Frigerio, Pomarol, Riva, Urbano 2012

Effective Interaction Strength



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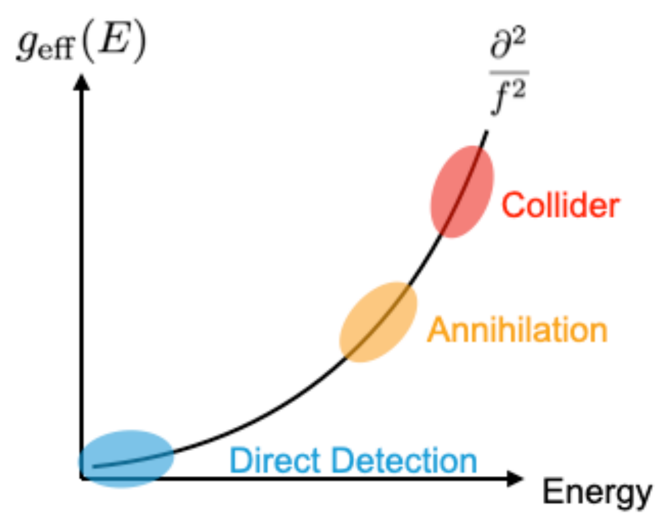
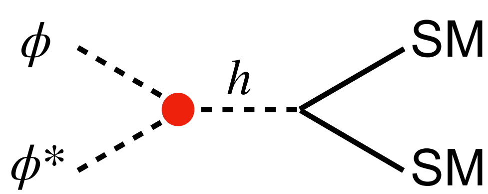
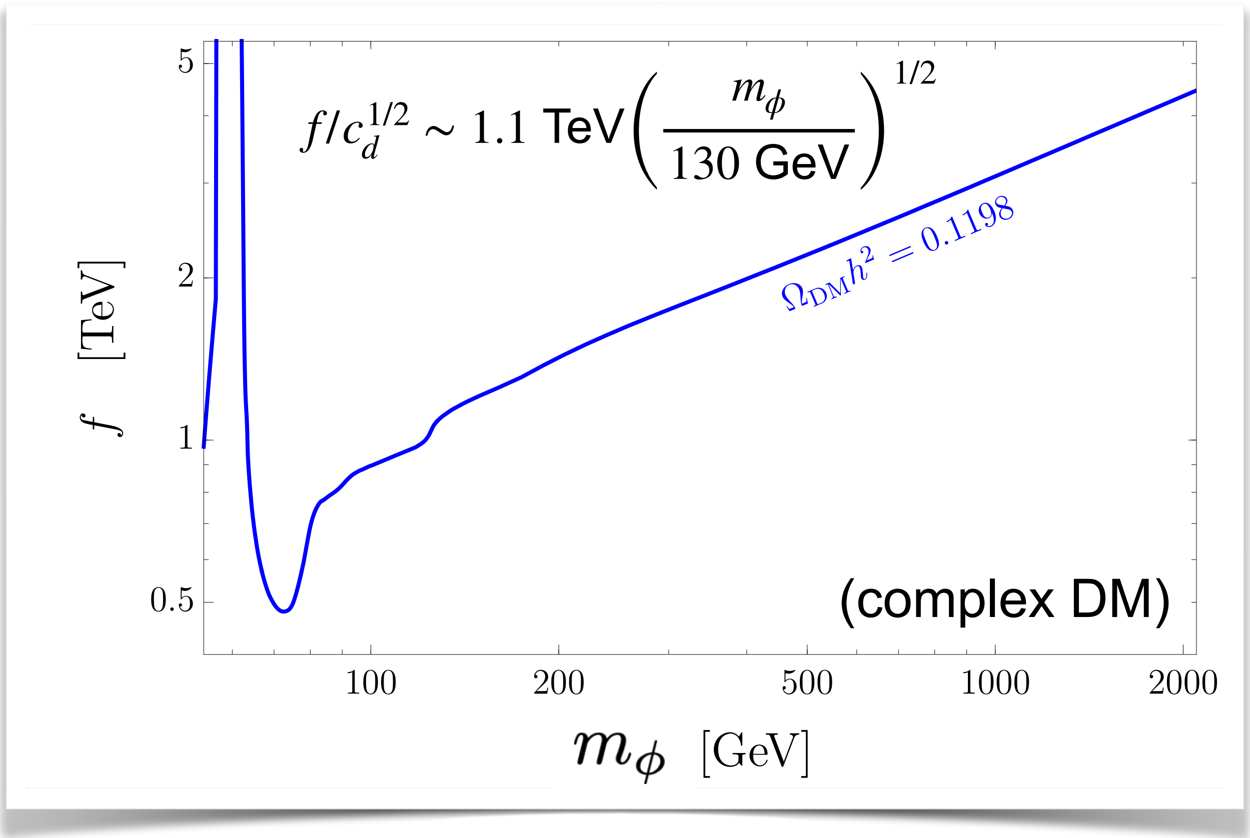


Relic Abundance



$\propto \frac{s}{f^2} \simeq \frac{4m_\phi^2}{f^2}$



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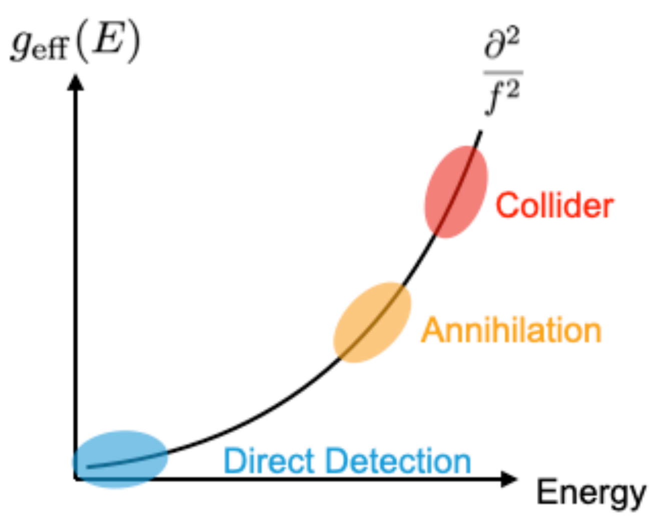

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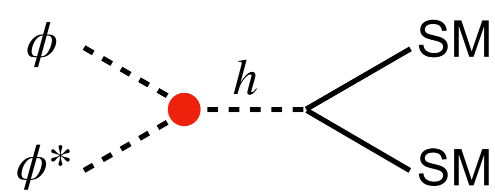
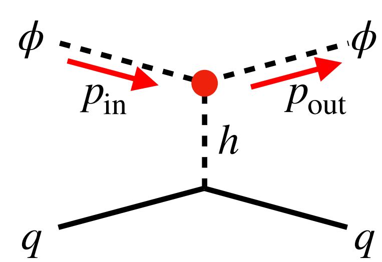


$$\propto \frac{s}{f^2} \simeq \frac{4m_\phi^2}{f^2}$$

$$f/c_d^{1/2} \sim 1.1 \text{ TeV}\left(\frac{m_\phi}{130 \text{ GeV}}\right)^{1/2}$$

Direct Detection



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

pNGB DM is practically **invisible** in direct detection

pNGB DM in Composite Higgs

- pNGB DM arises naturally in non-minimal composite Higgs models

- **Minimal** model

$$SO(6)/SO(5) \longrightarrow (H, \phi) \sim \mathbf{4} + \mathbf{1} \quad \text{of } SO(4)$$

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e.g. unbroken $U(1) \subset SO(6)$ in $SO(7)/SO(6)$

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has to be suppressed!

Non Composite Higgs pNGB DM

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

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

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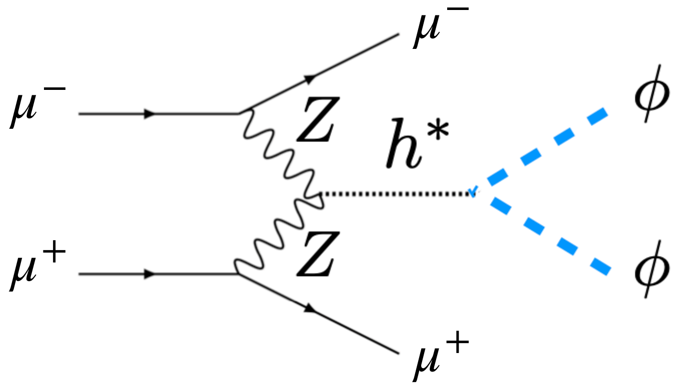
Collider probes are even more important!

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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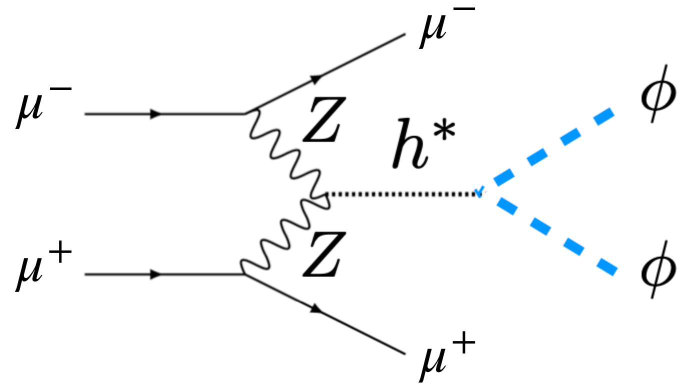

- Very different scaling of cross-section with m_ϕ and s

$$\sigma^{\text{der}}_{\mu^-\mu^+\to\mu^-\mu^+\phi\phi} \sim \frac{c_d^2 s}{f^4}$$

approximately independent of m_ϕ
limited by $\sqrt{s}$

$$\sigma^{\text{marg}}_{\mu^-\mu^+\to\mu^-\mu^+\phi\phi} \sim \frac{\lambda^2}{m_\phi^2} \log \frac{s}{m_\phi^2}$$

(for $s \gg m_h^2, m_V^2$)

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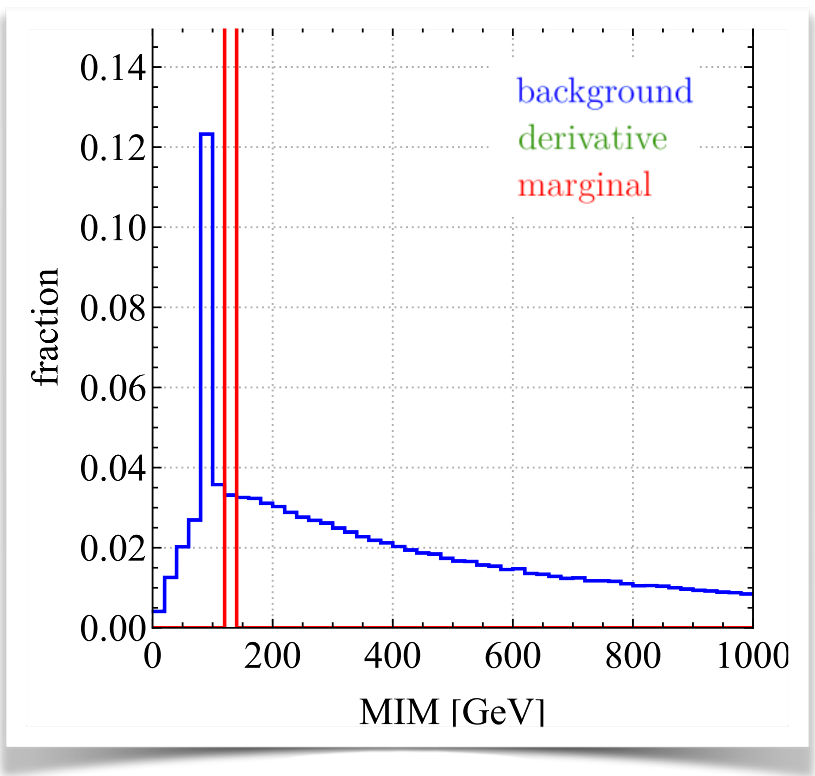

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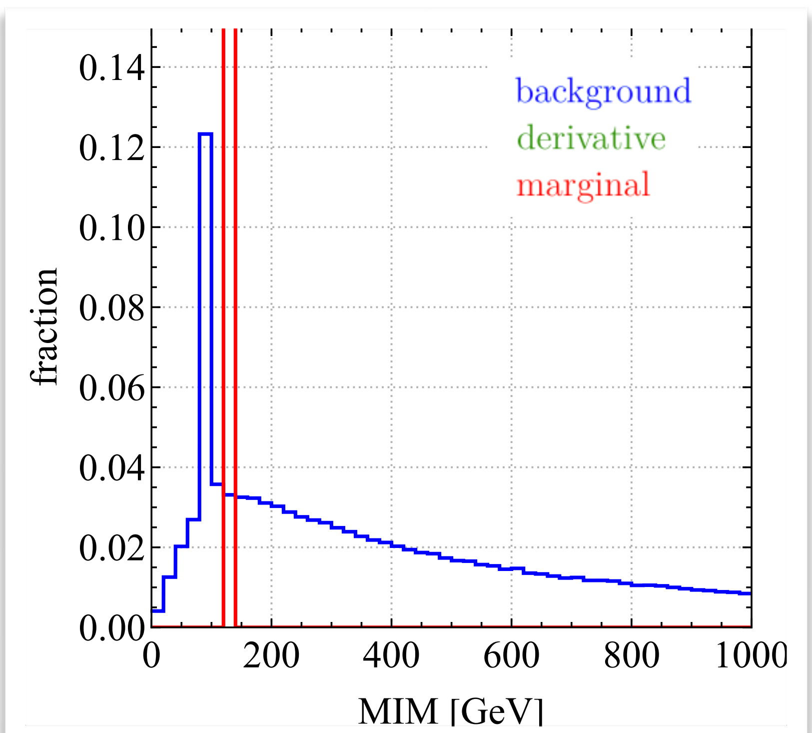

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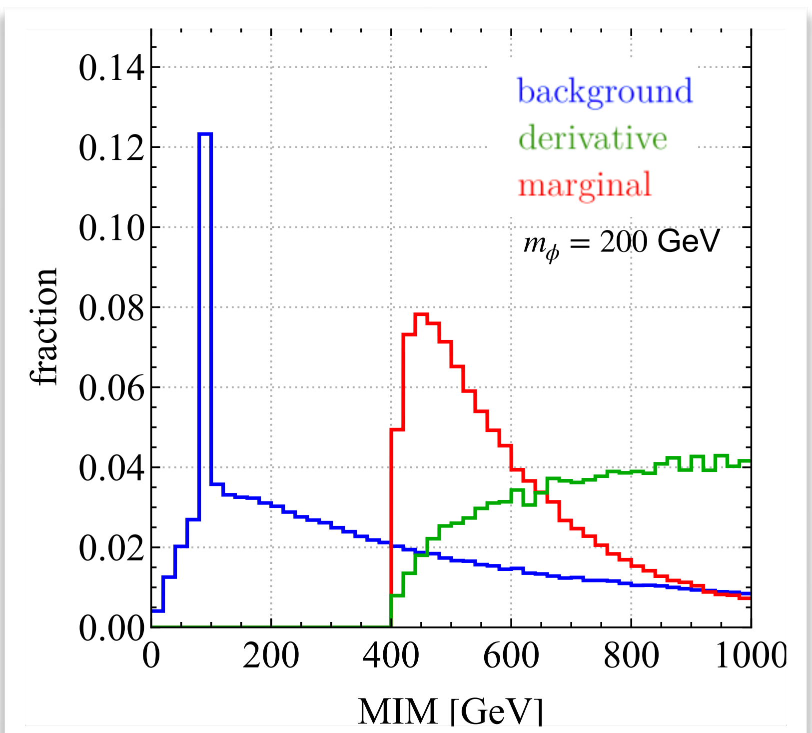

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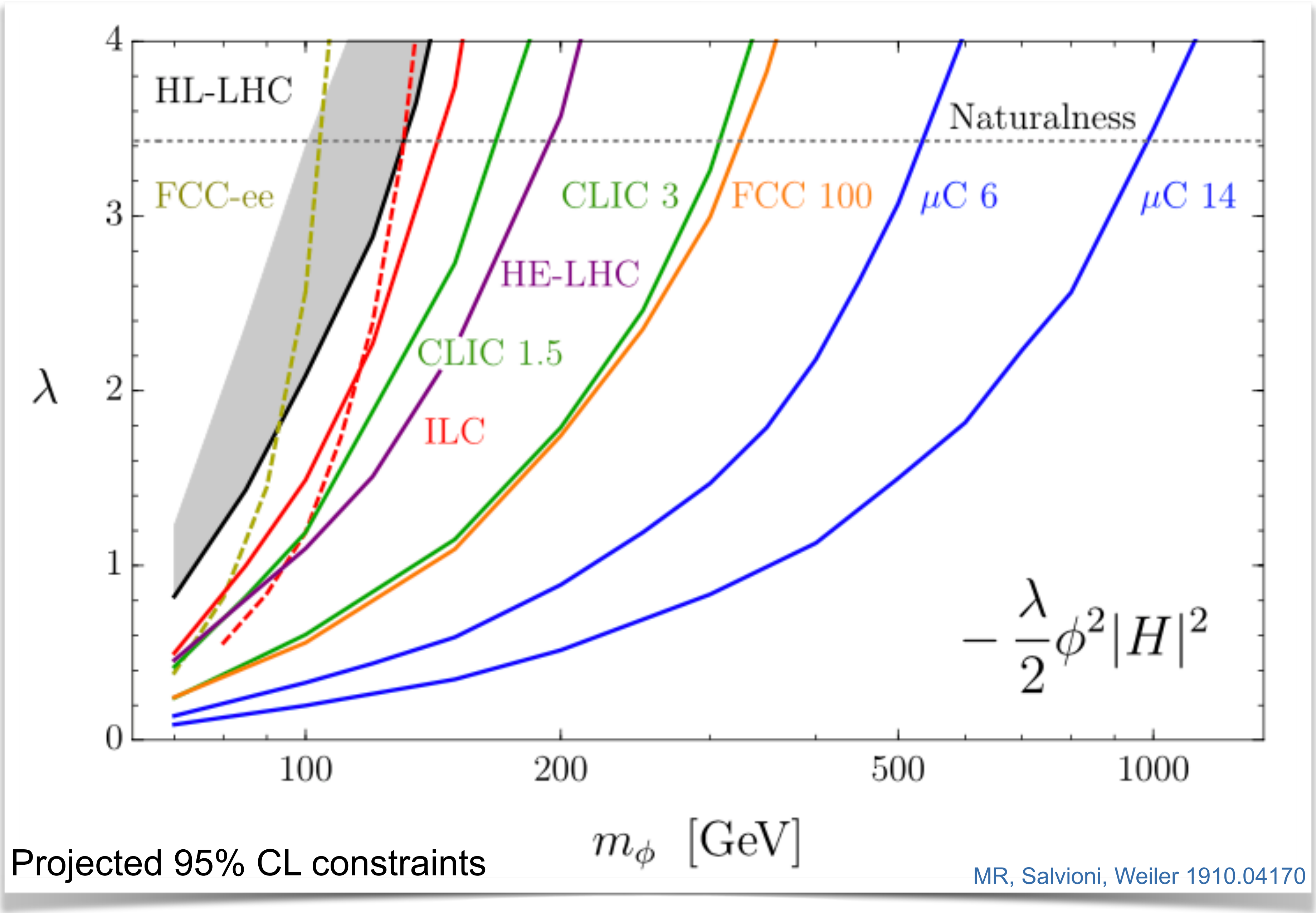
Marginal Higgs Portal



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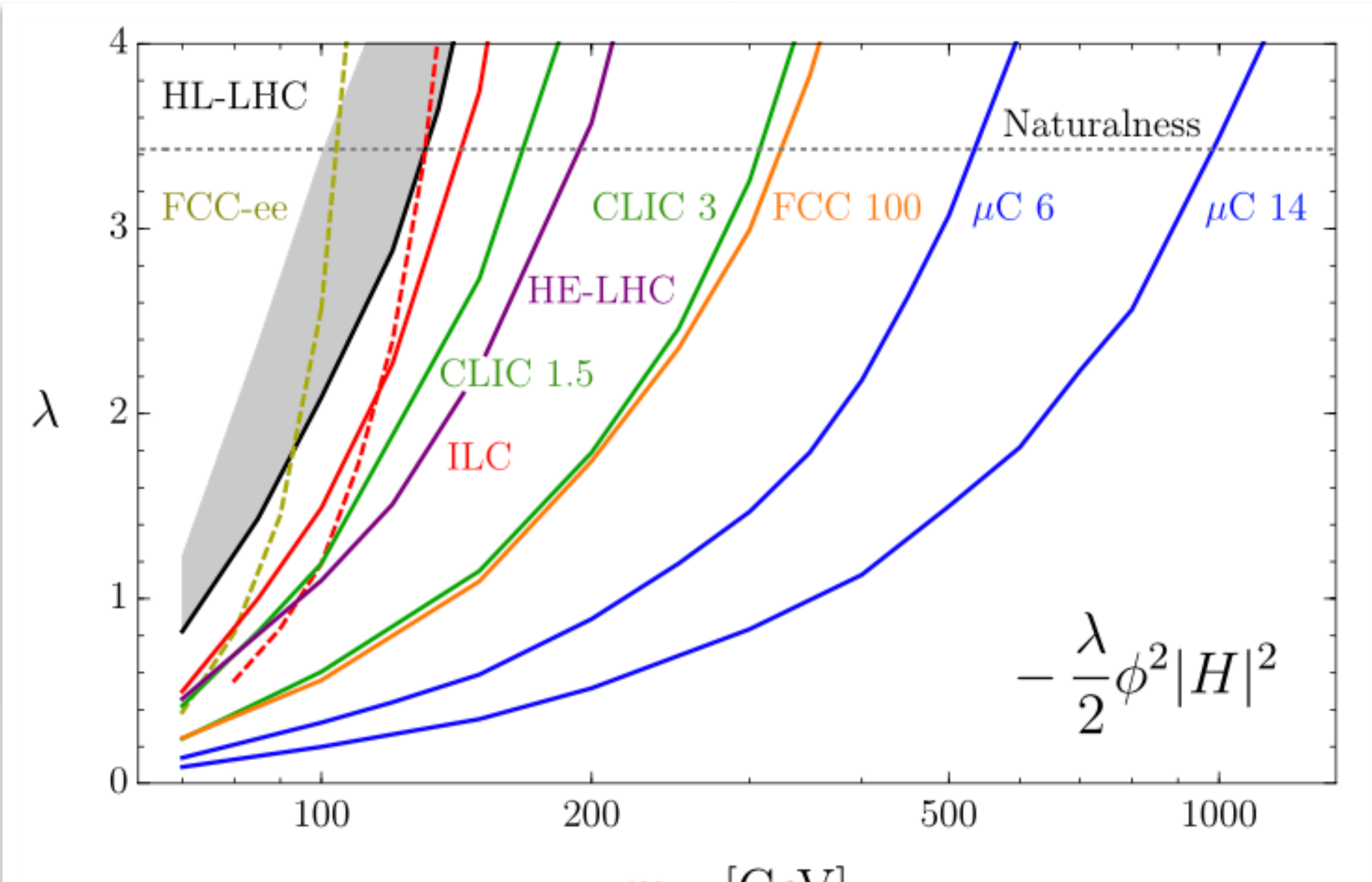

Projected 95% CL constraints

MR, Salvioni, Weiler 1910.04170

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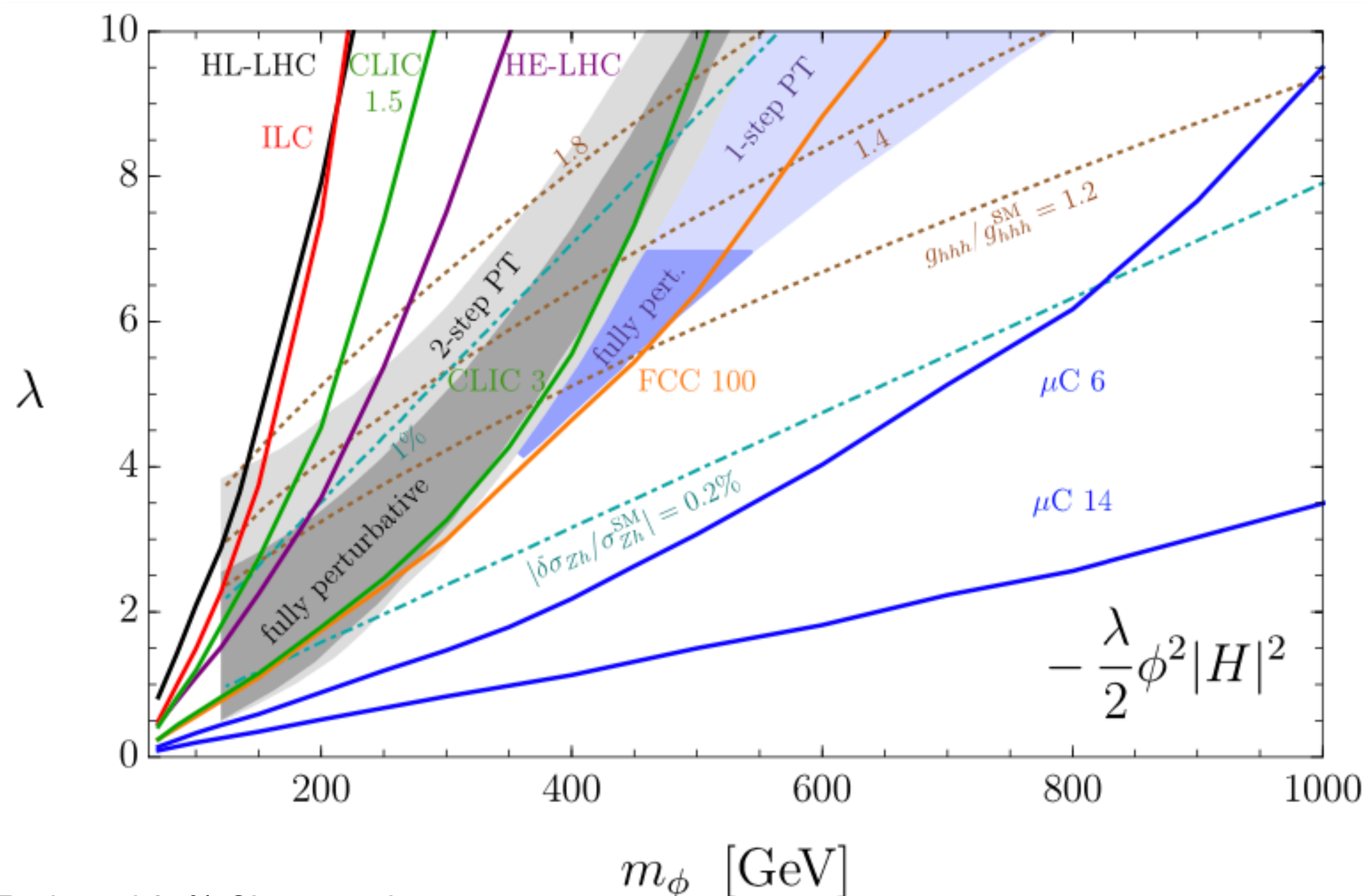
$\sqrt{s} = 6$ TeV muon collider outperforms FCC-hh

Marginal Higgs Portal: 1st order EWPT



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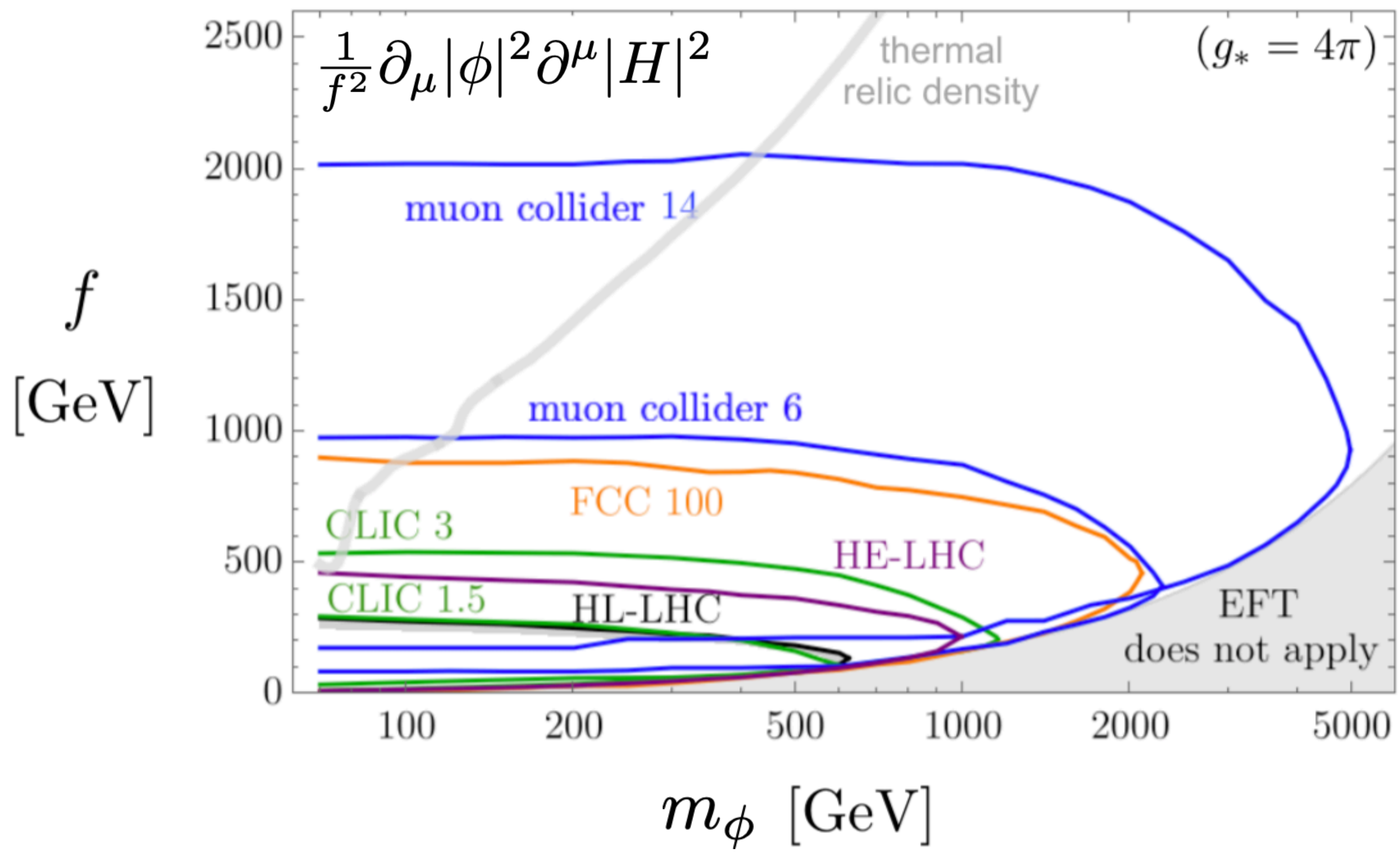
Shaded regions: possibility of a first order EW phase transition

Buttazzo, Redigolo, Sala, Tesi 1807.04743

Derivative Higgs Portal



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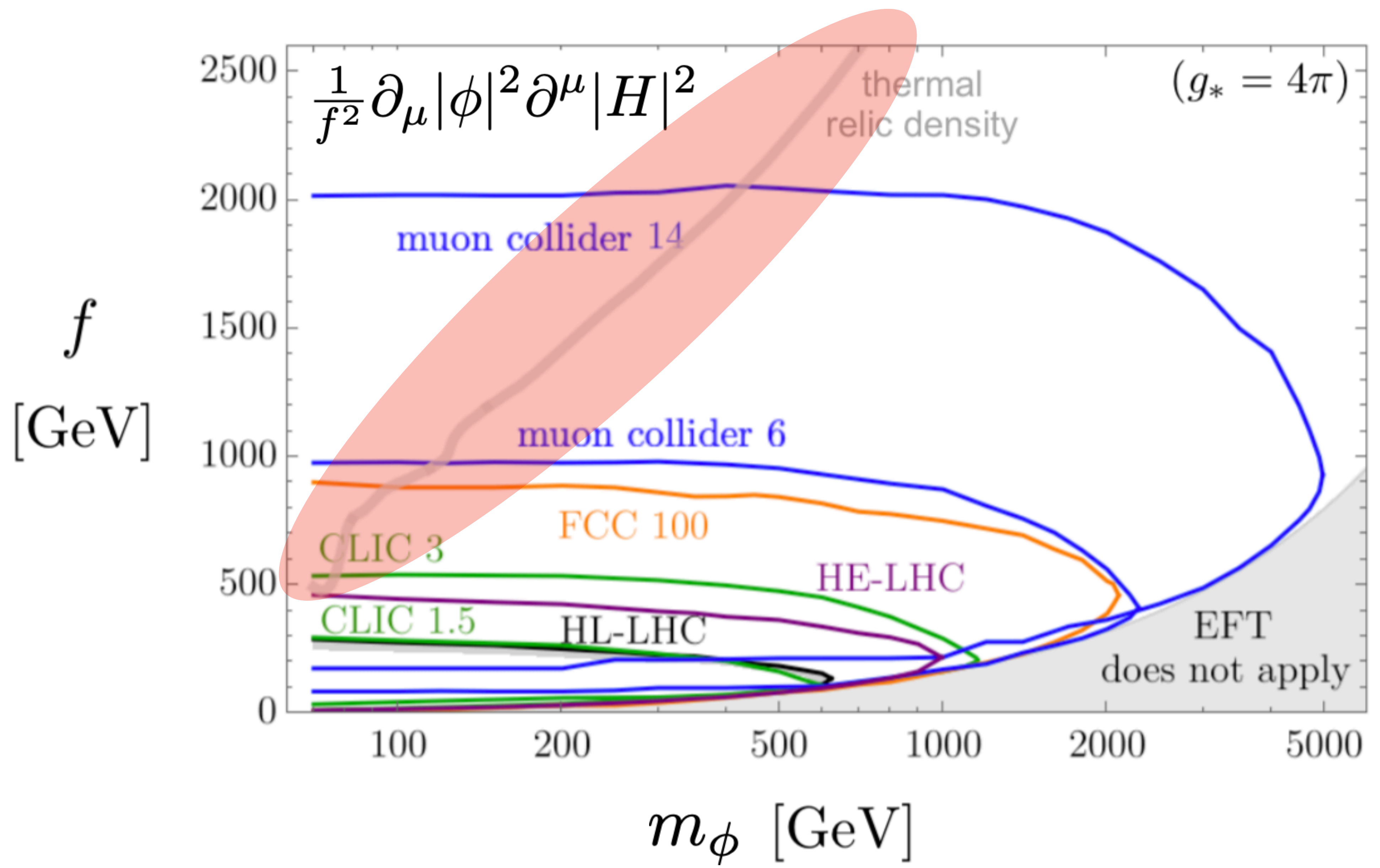

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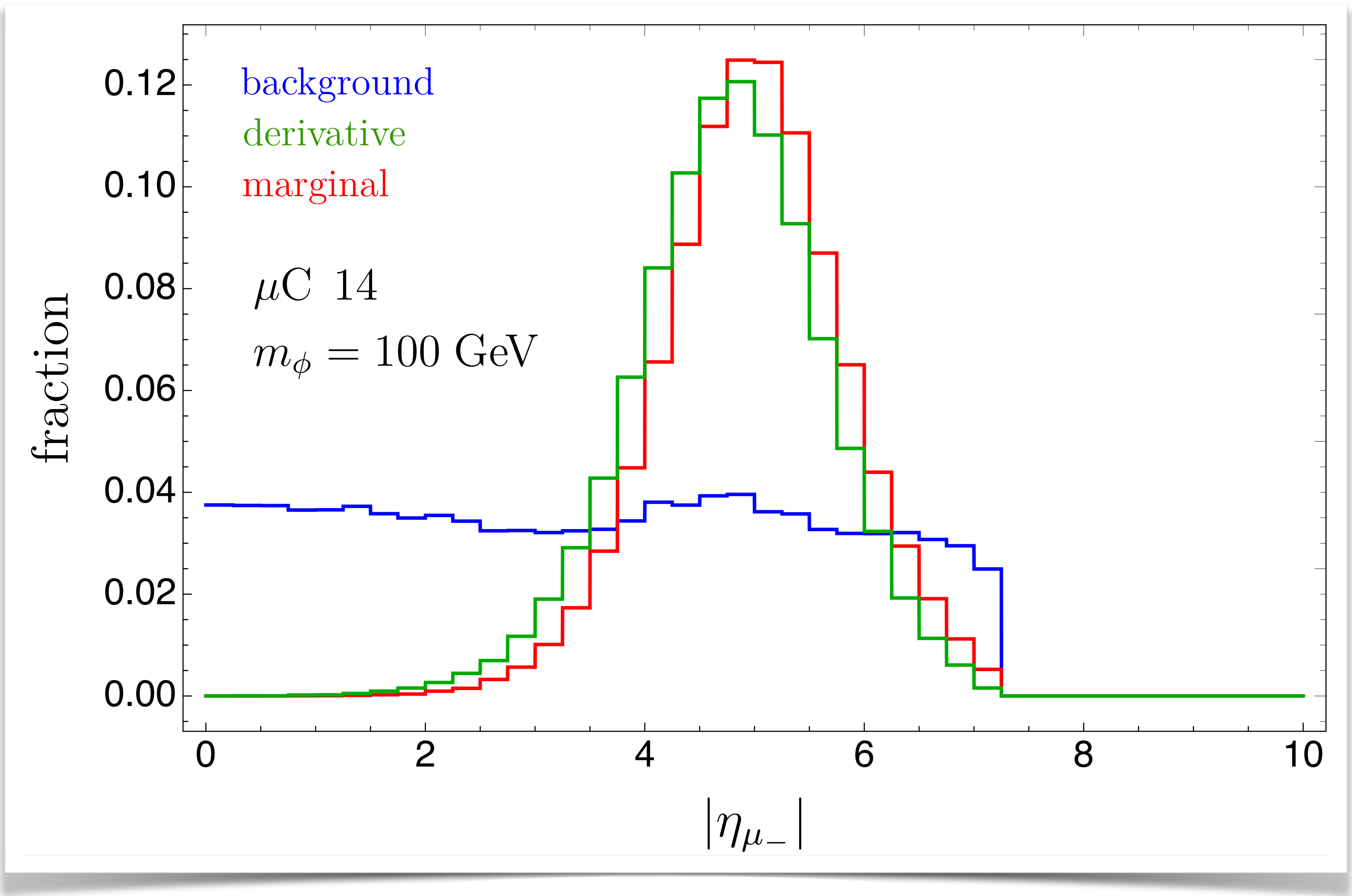
Only muon collider can truly probe pNGB DM

2. Challenges

Higgs Portal: forward muons

Caveat: coverage of very forward muons is crucial

→ current design: detector coverage of $|\eta_\mu| < 2.44$



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2°	4.05
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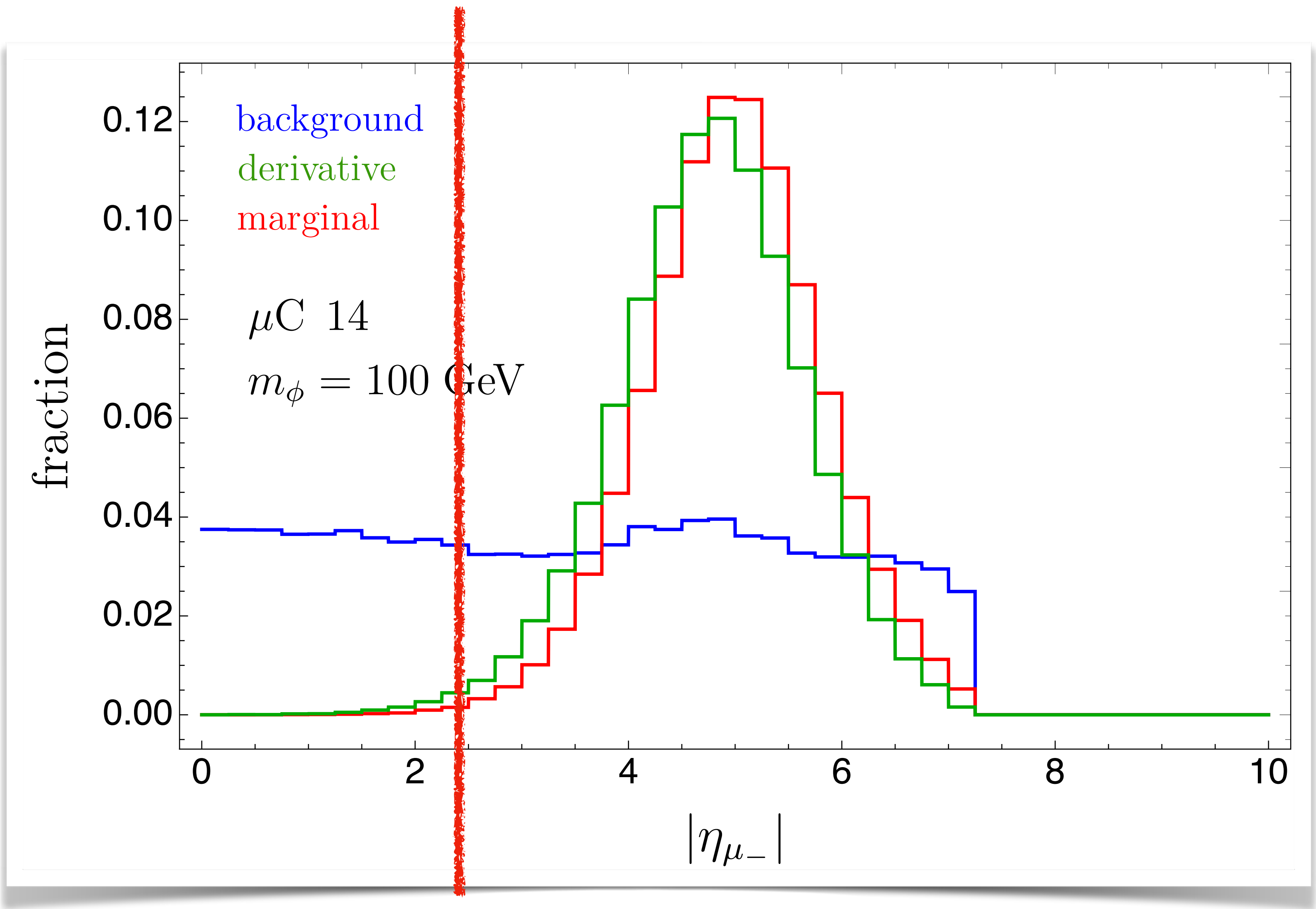

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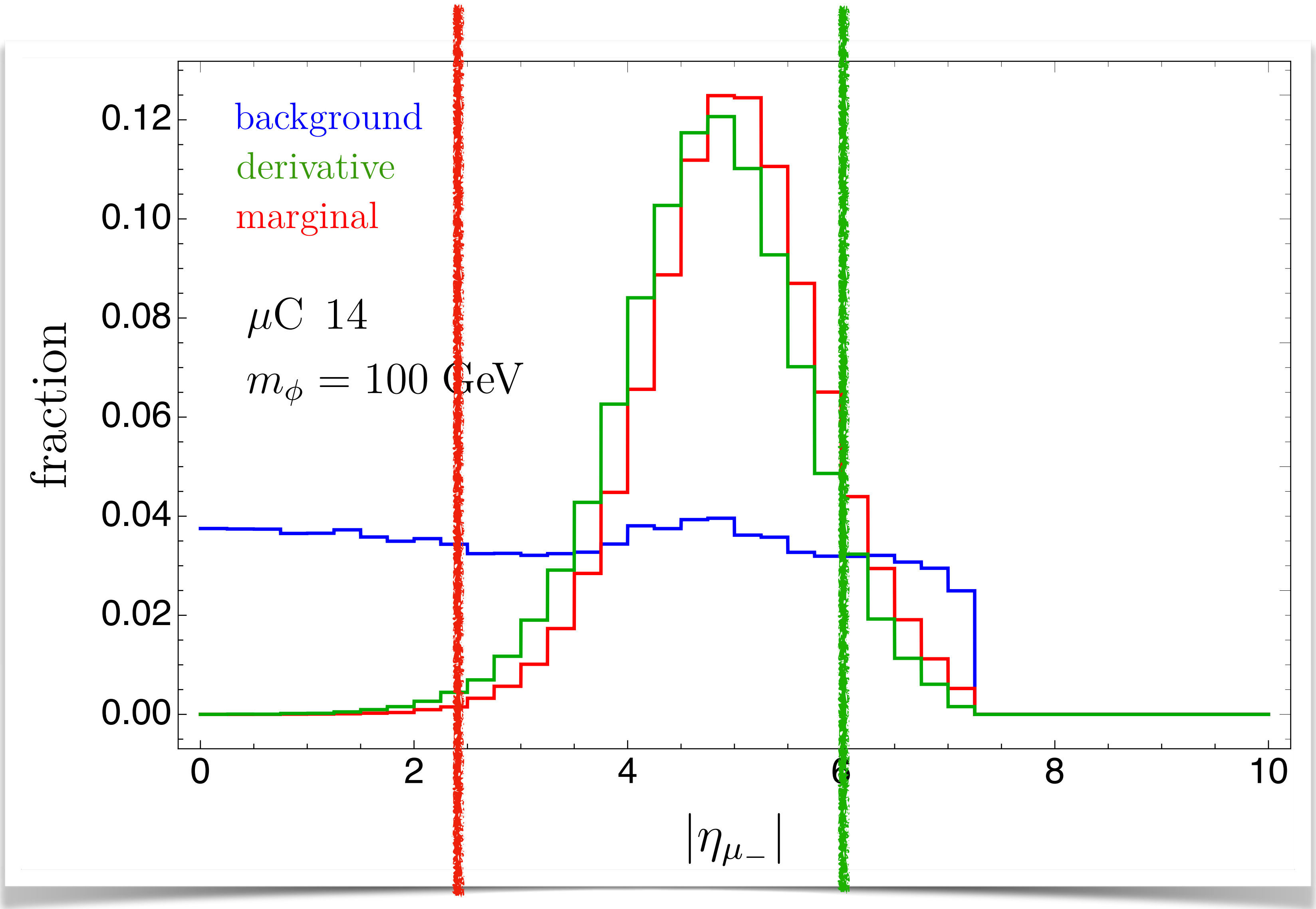
Previous results assumed coverage of $|\eta_\mu| < 6$



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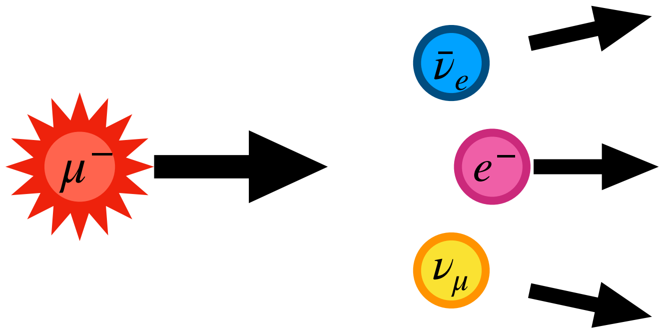
Maximilian Ruhdorfer (Cornell)

Challenges

- Large beam induced background (BIB) in forward region

→ muons decay along the beam



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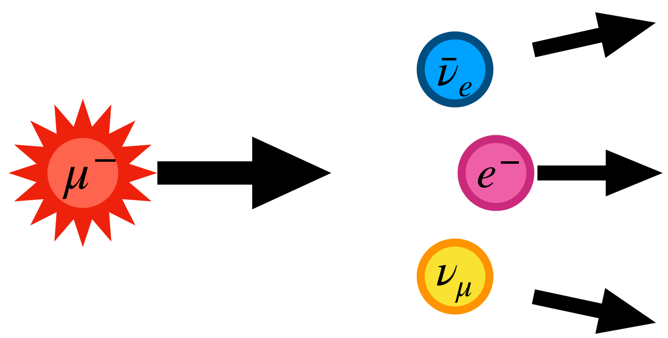

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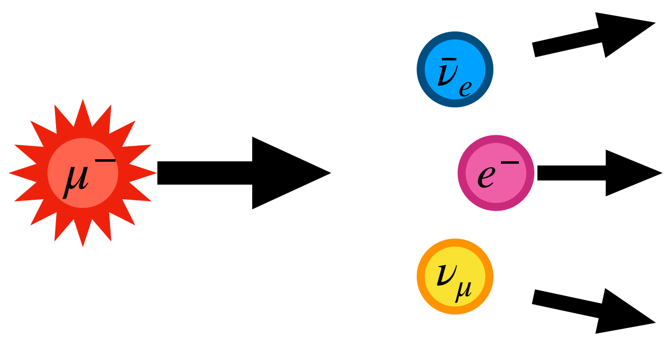

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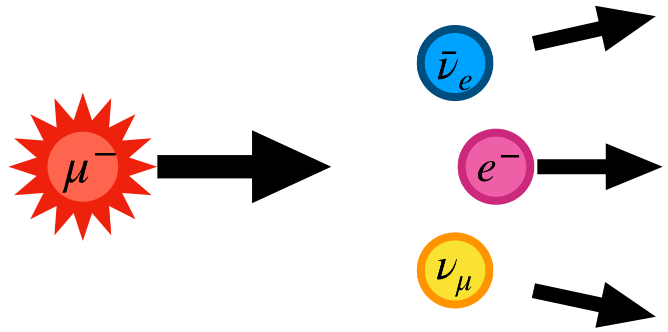

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A more realistic study is needed
to make the case for a forward muon detector

A realistic benchmark: invisible Higgs decays

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

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

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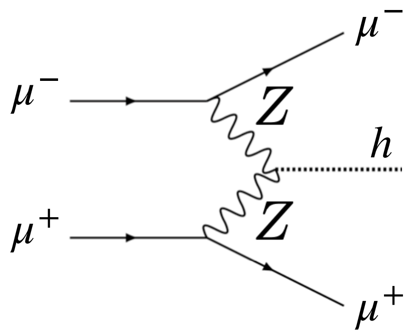

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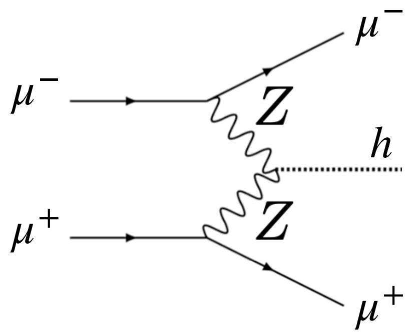

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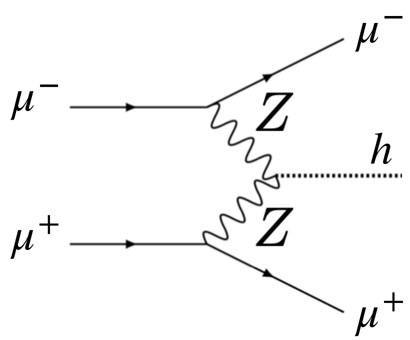


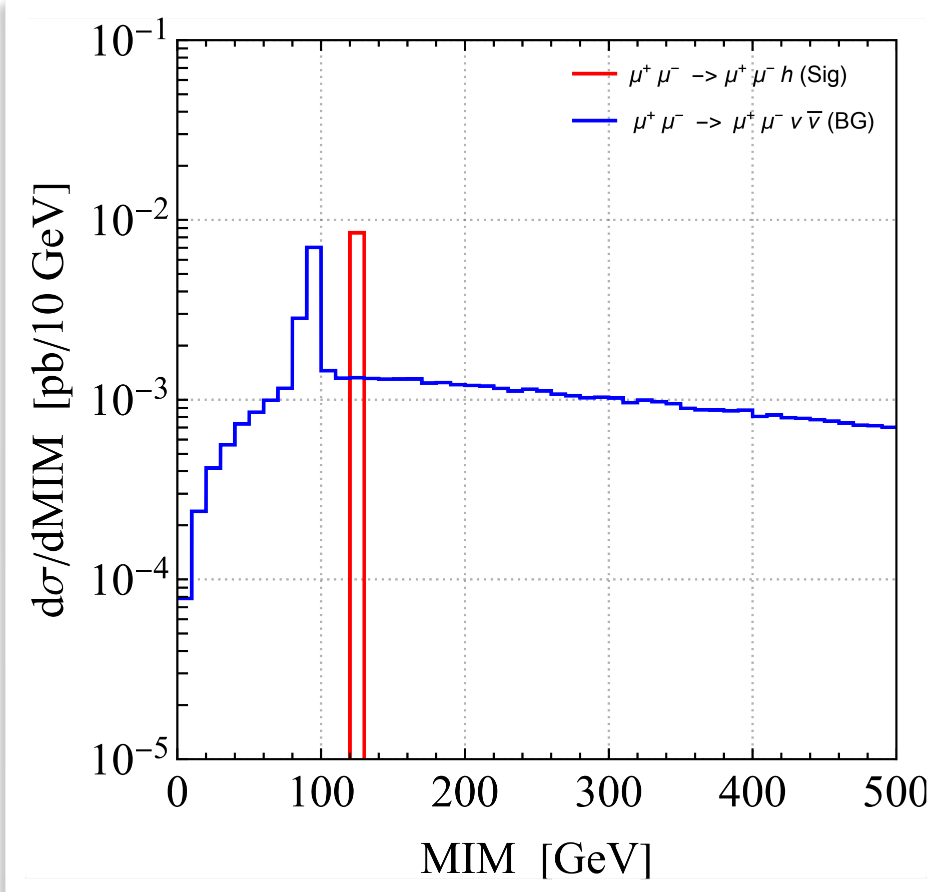
- Consider ZZ-fusion production at $\sqrt{s} = 10$ TeV

- Main BG: $\mu^-\mu^+ \to \mu^-\mu^+\nu\bar{\nu}$

- In contrast to FCC-hh:

  Muon collider is sensitive to MIM

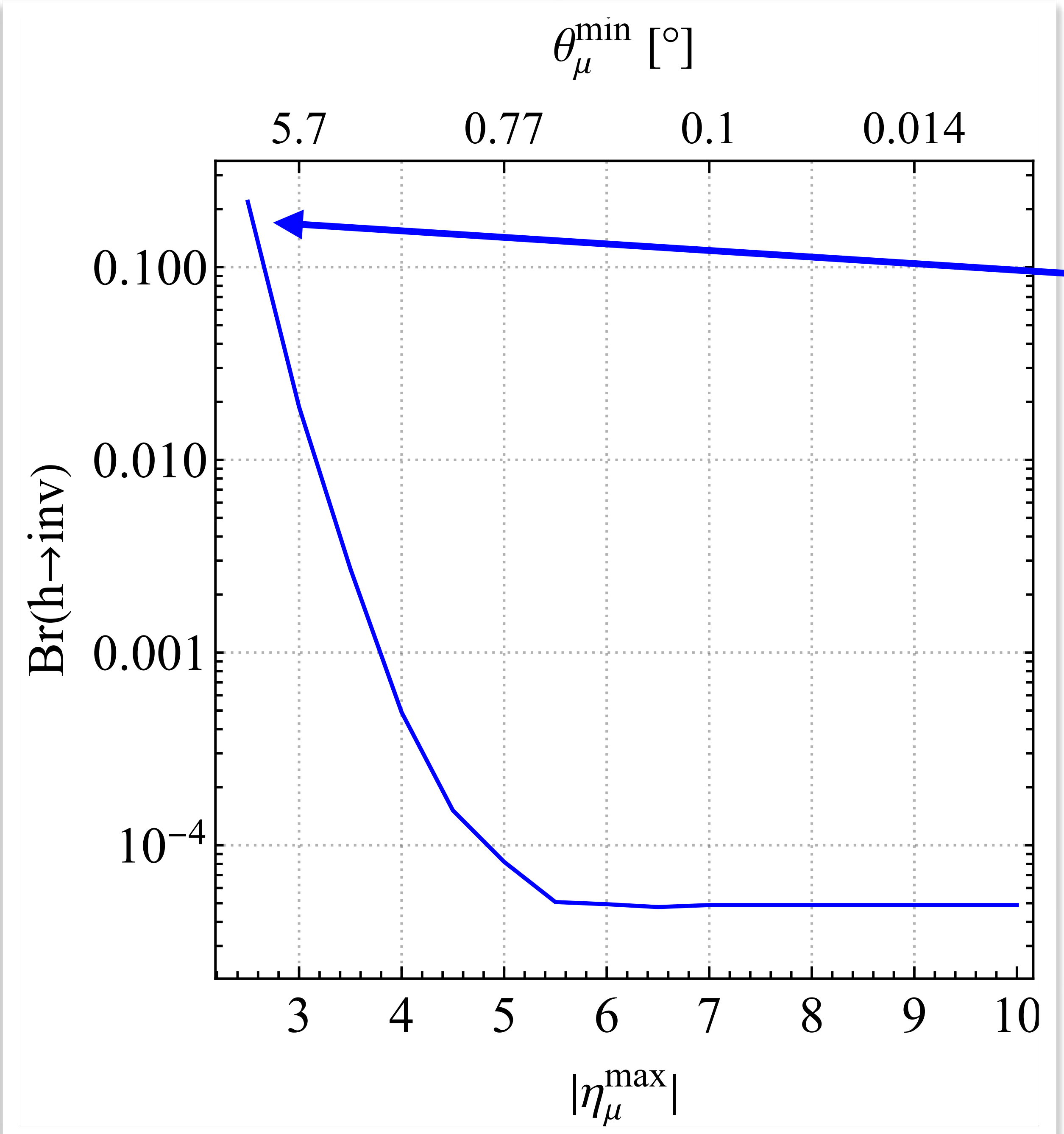
→ MIM is essential for BG suppression



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

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

Bound for $\theta_\mu^{\min} = 10°$:
$2.2 \cdot 10^{-1}$

Projected 95% CL constraints

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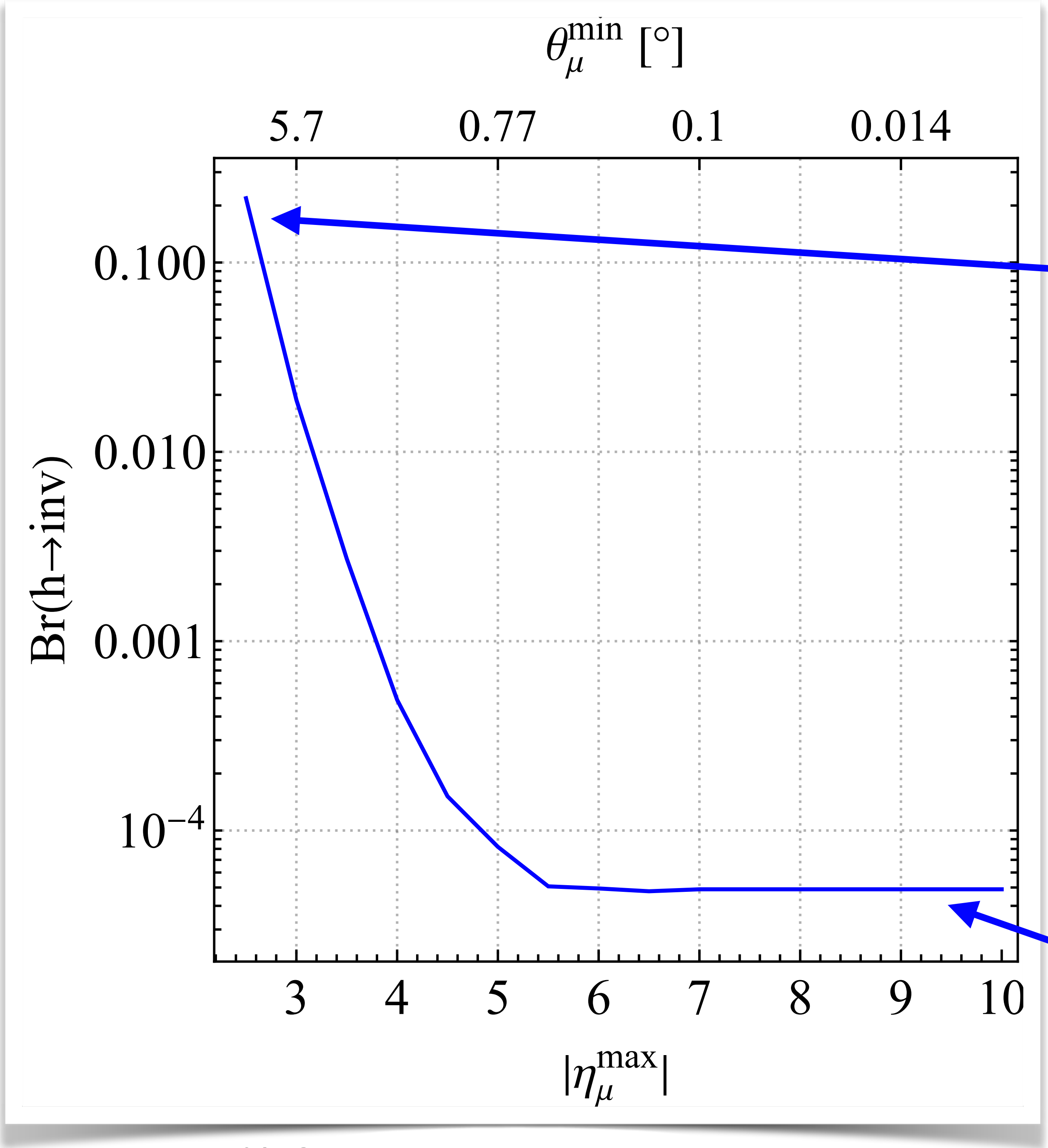

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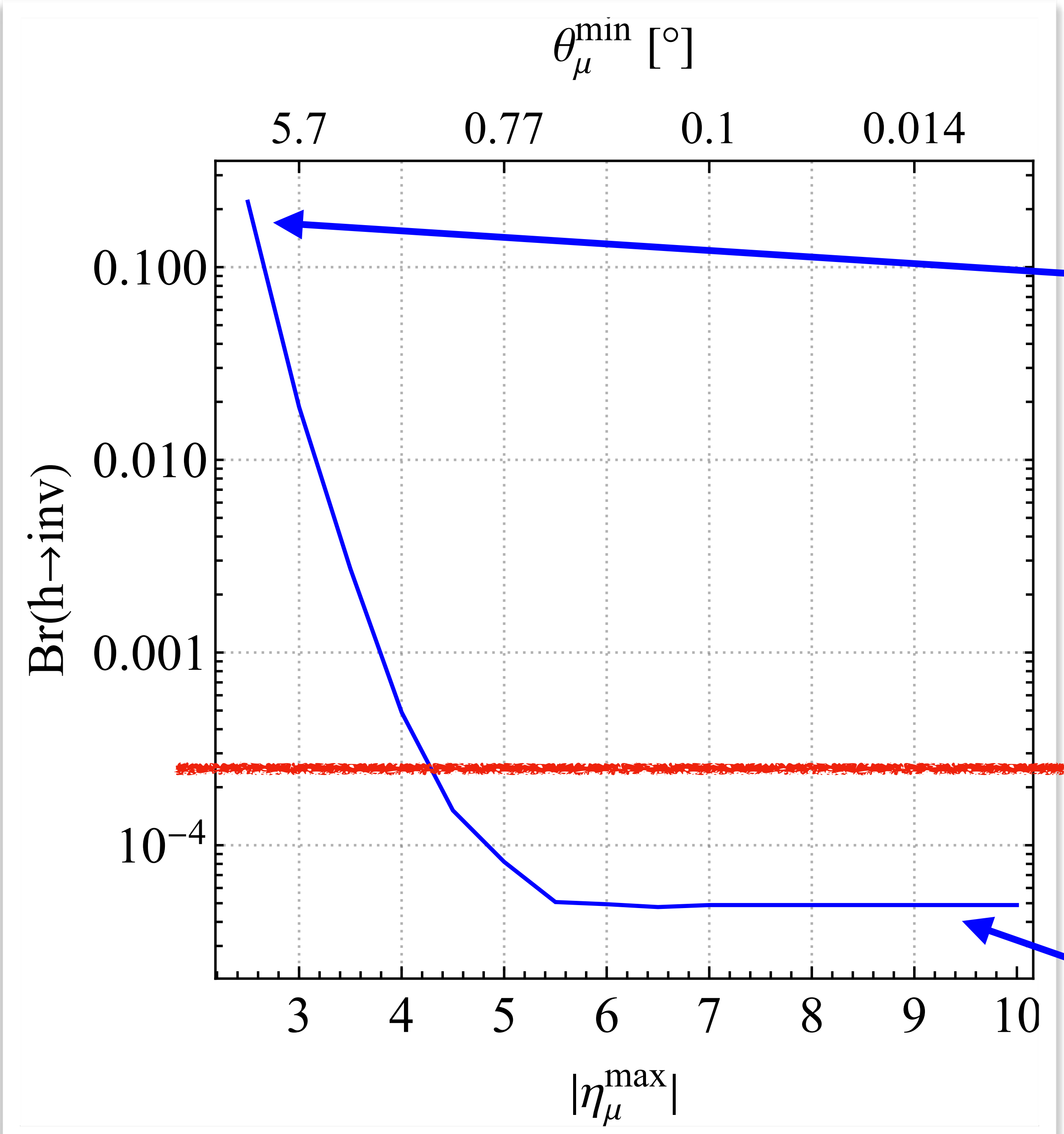

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MIM measurement - Imperfections

- Irreducible imperfections of MIM measurement

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

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MIM measurement - Imperfections

- Irreducible imperfections of MIM measurement

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

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

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

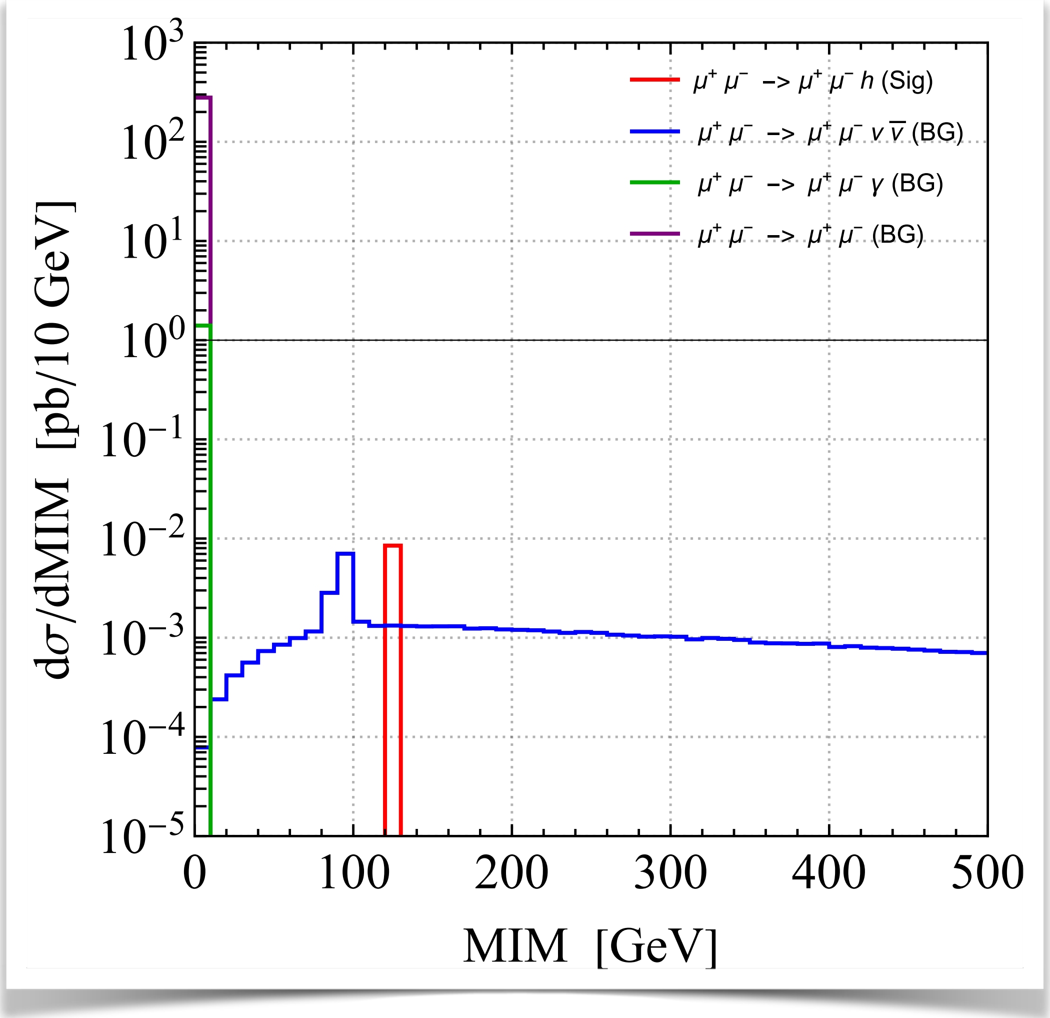
Beam Energy Spread (BES)

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

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

➡ Detection frame $\neq$ COM frame (longitudinal boost)

➡ MIM distribution gets smeared



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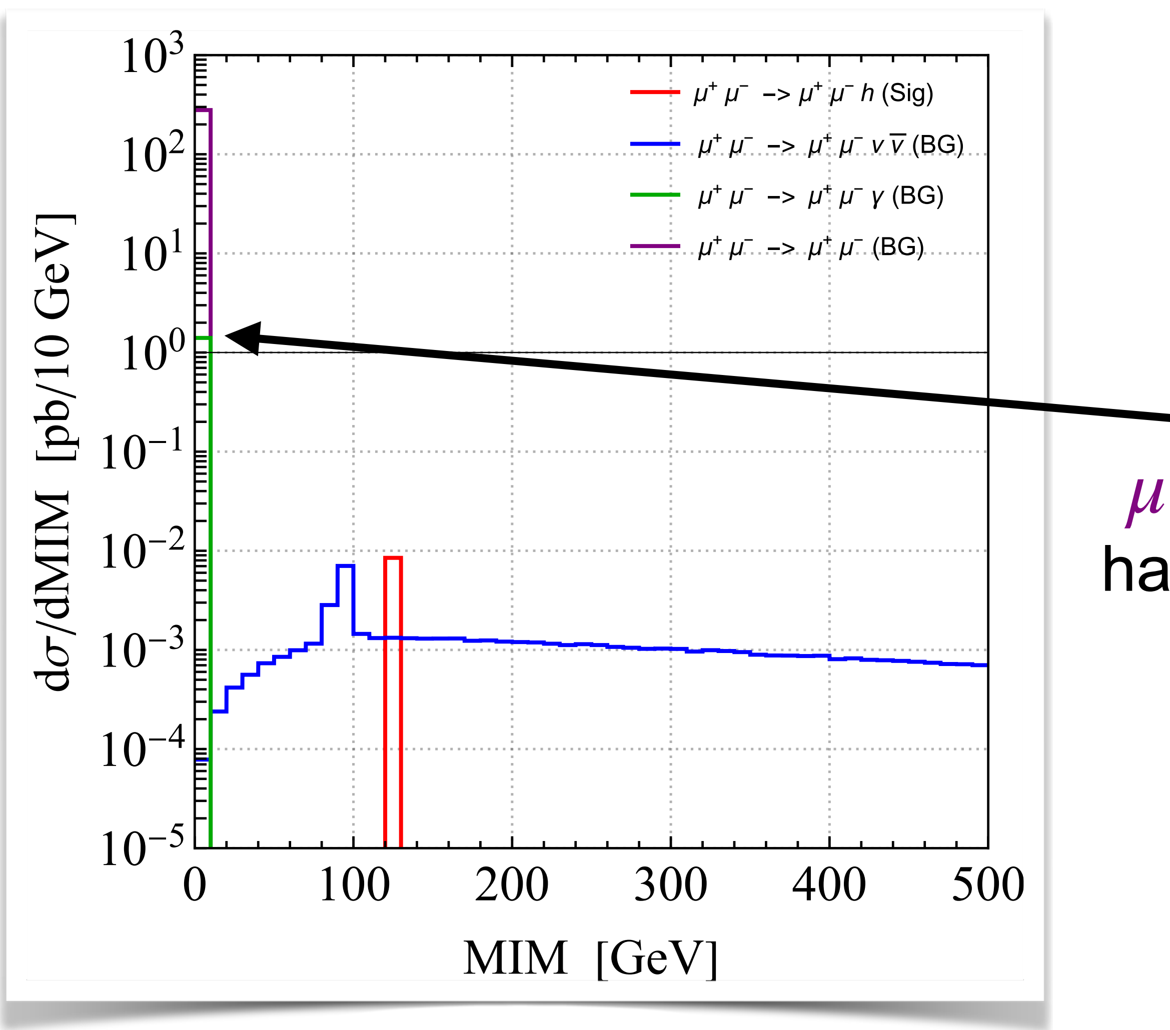

$\mu^+\mu^- \to \mu^+\mu^-$ and $\mu^+\mu^- \to \mu^+\mu^-\gamma$ with lost γ
have MIM = 0 if all 4-momenta can be reconstructed

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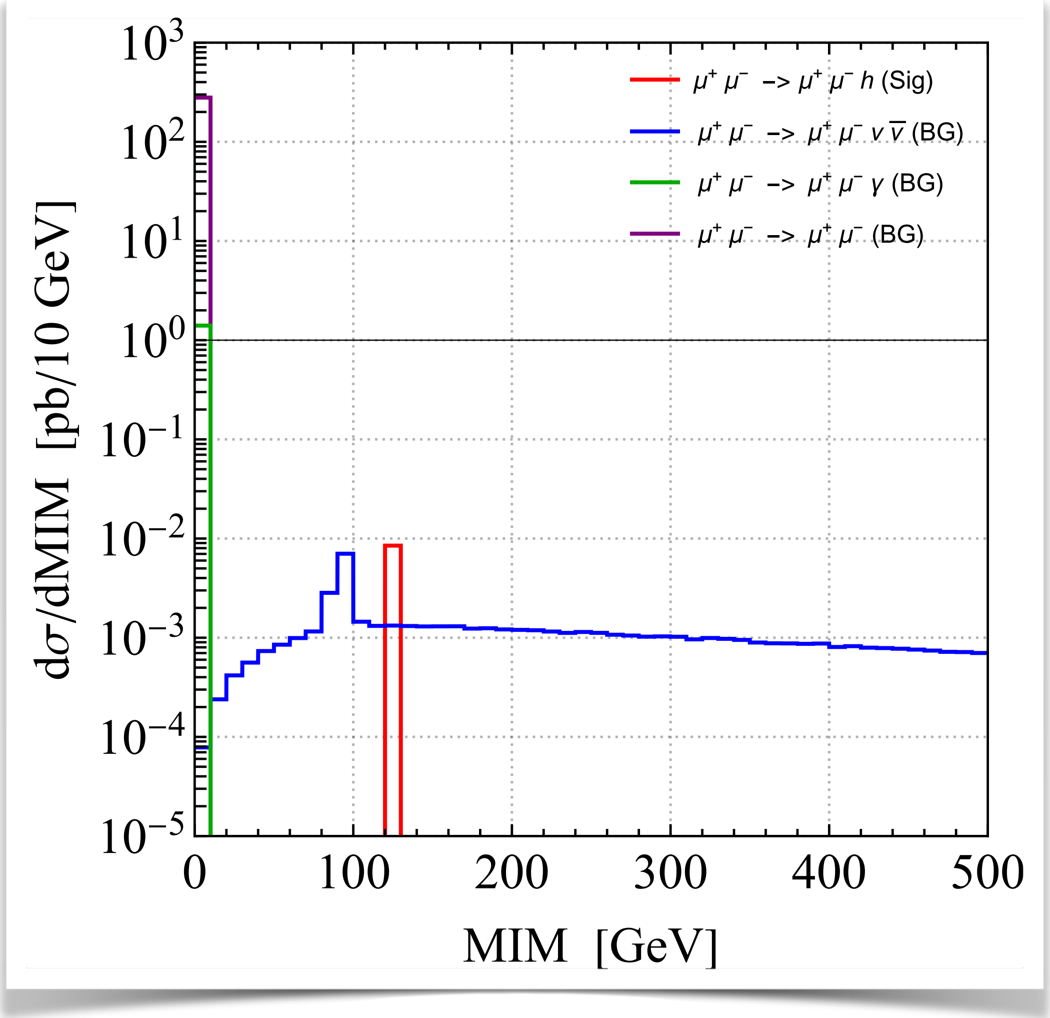
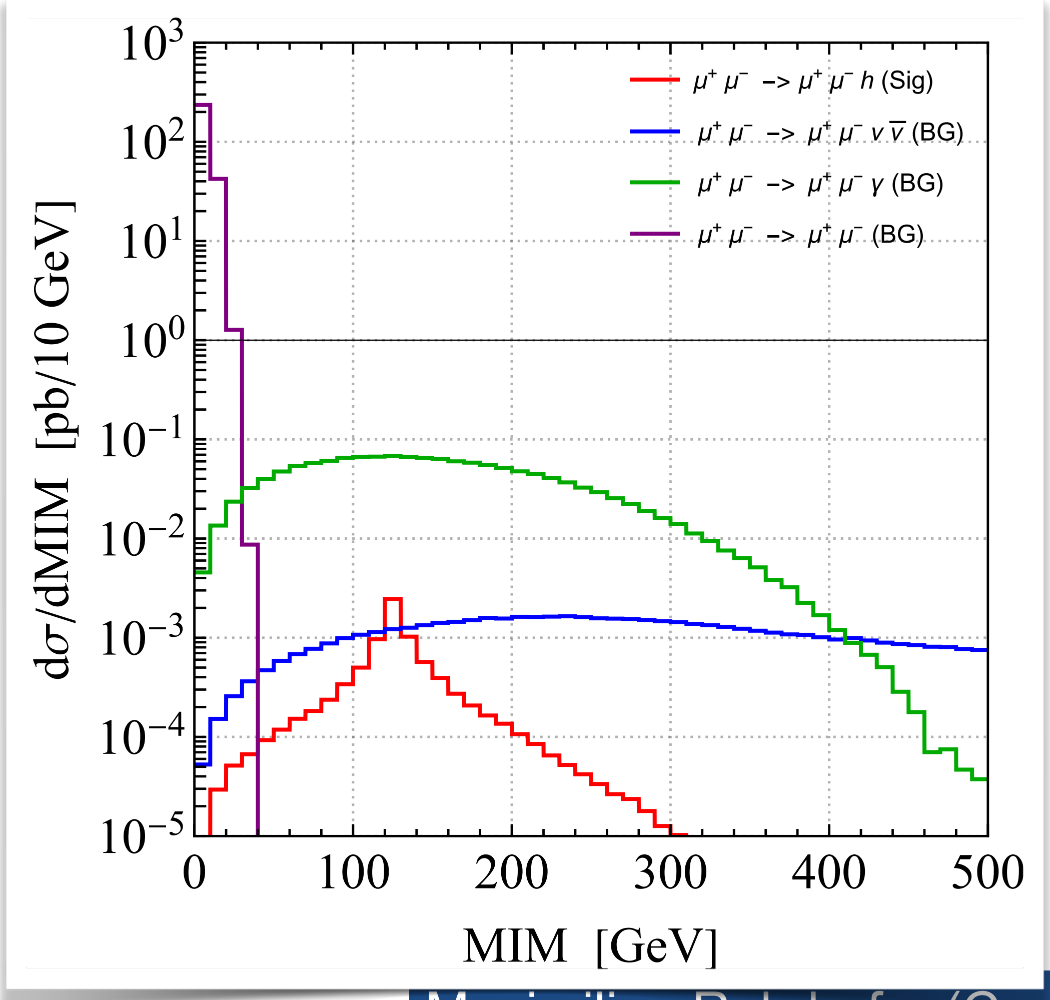


0.1% BES ➡



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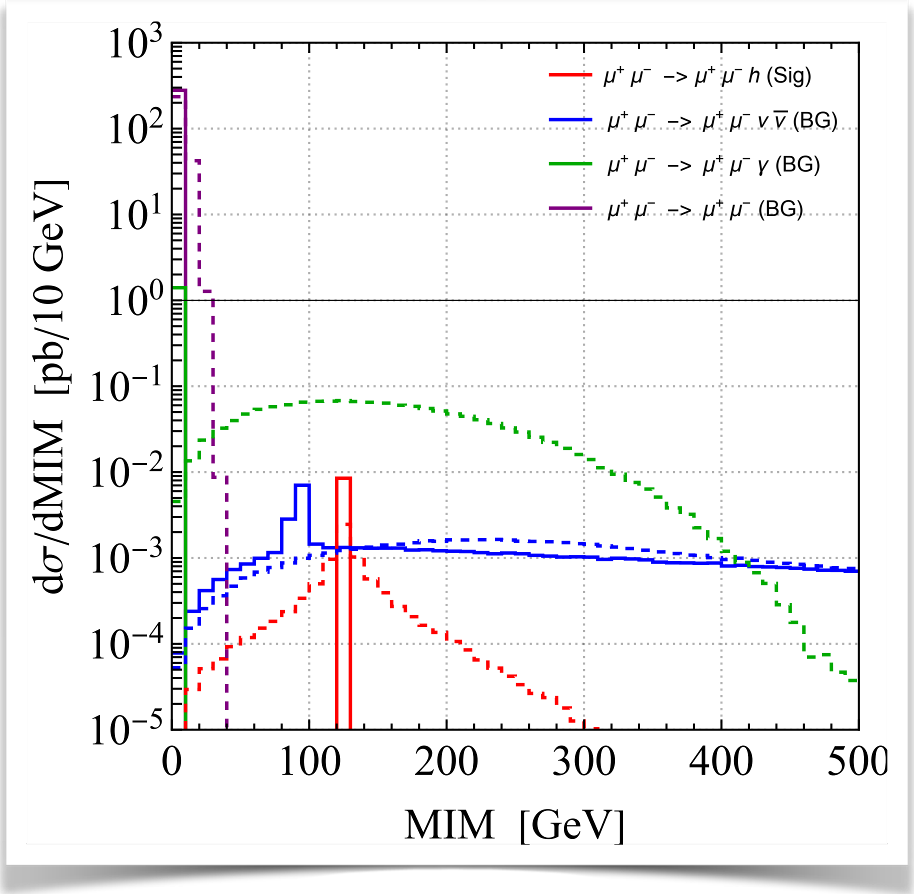

- Higgs peak swamped by photon BG

- 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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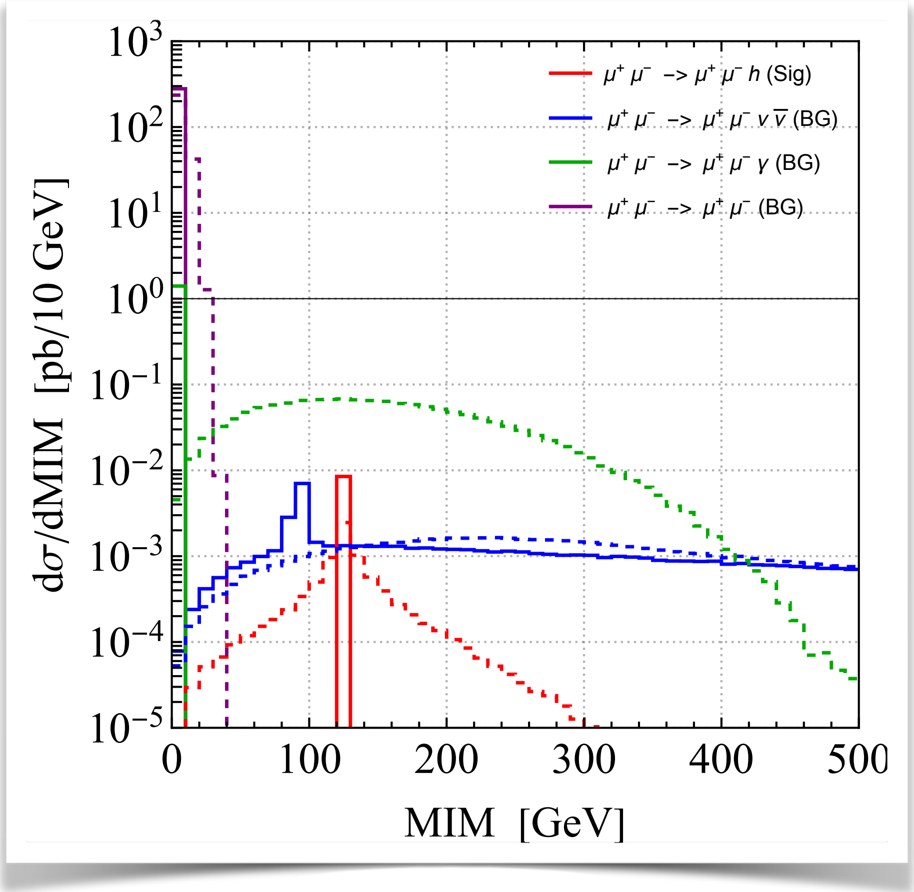

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Hard collinear photon emission
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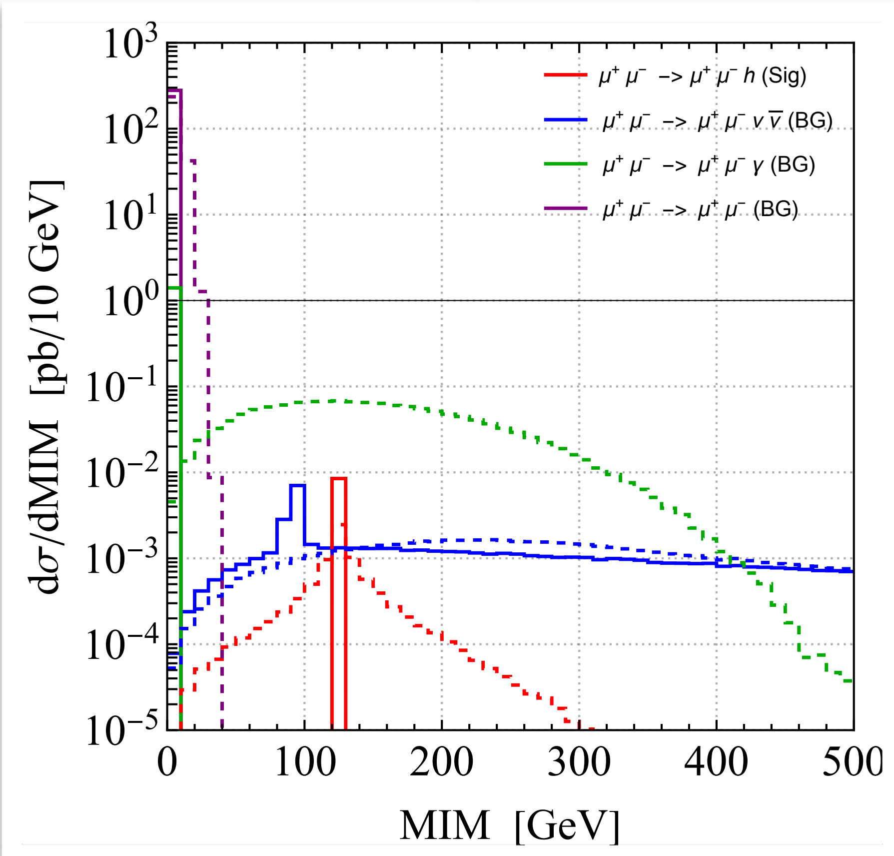

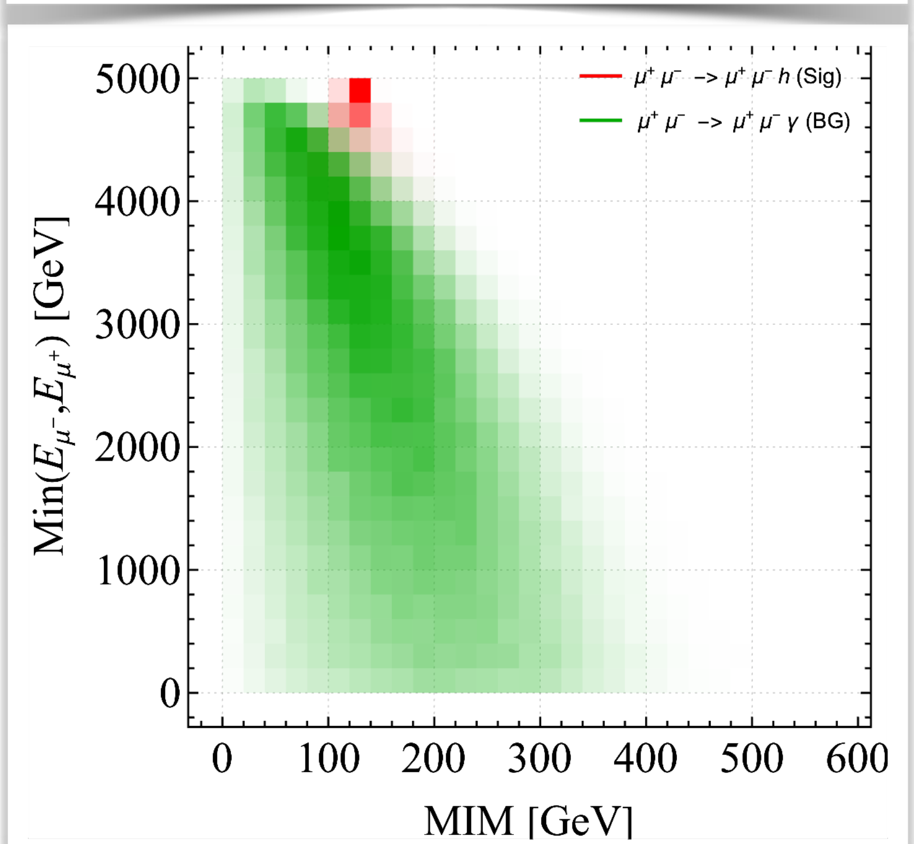

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Hard collinear photon emission is main source of photon BG

One of the muons will be less energetic

→ Efficient suppression with cut on

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

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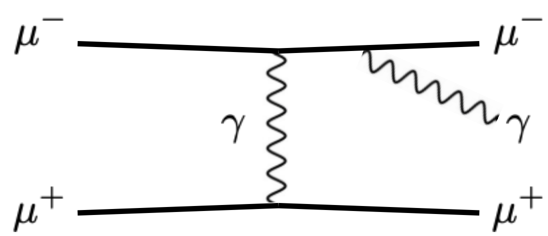
Comment on Photon BG

- Photon BG is generated at fixed order in MadGraph



$+ \quad \ldots$

- 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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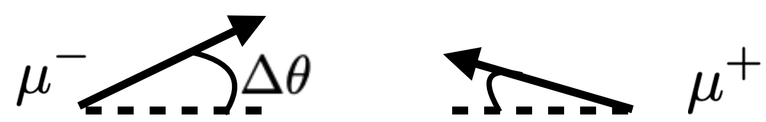
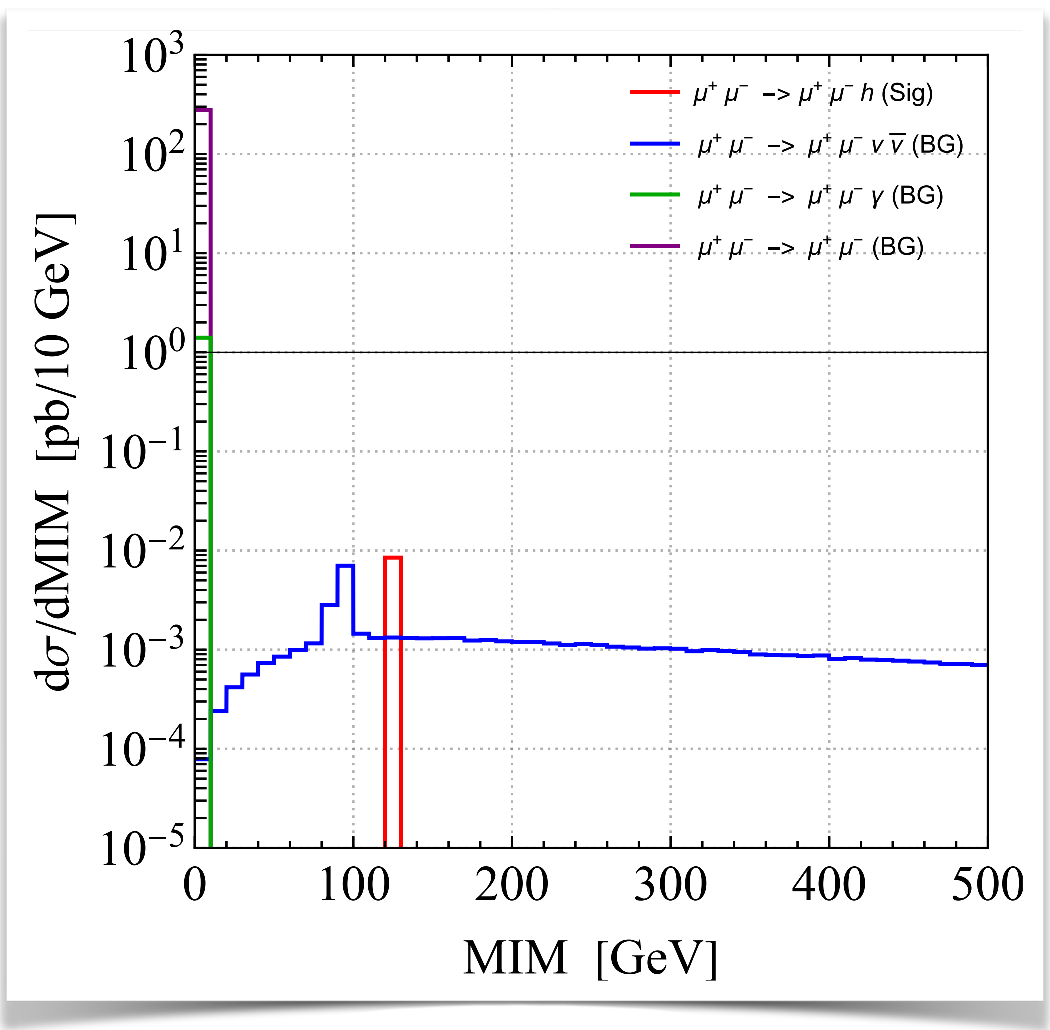
Beam Angular Spread (BAS)



- 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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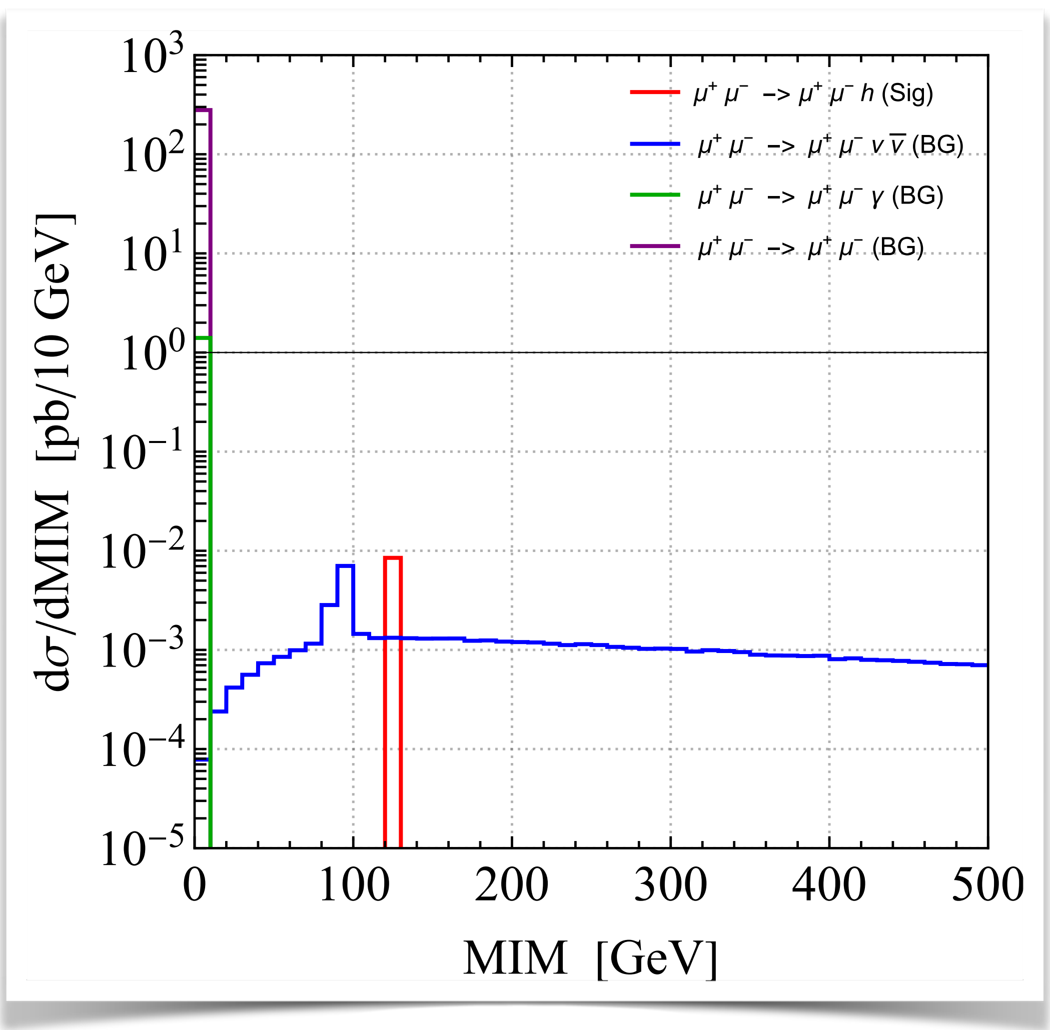
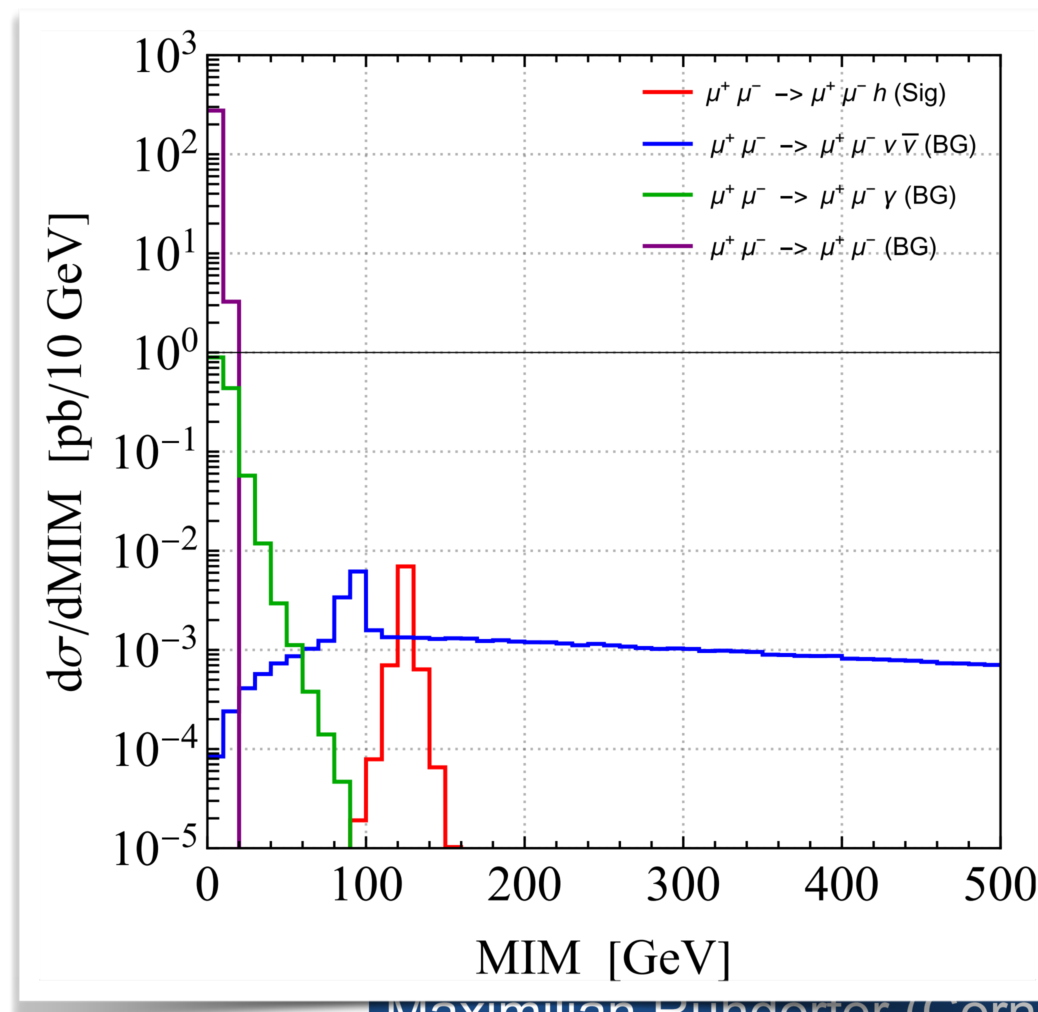
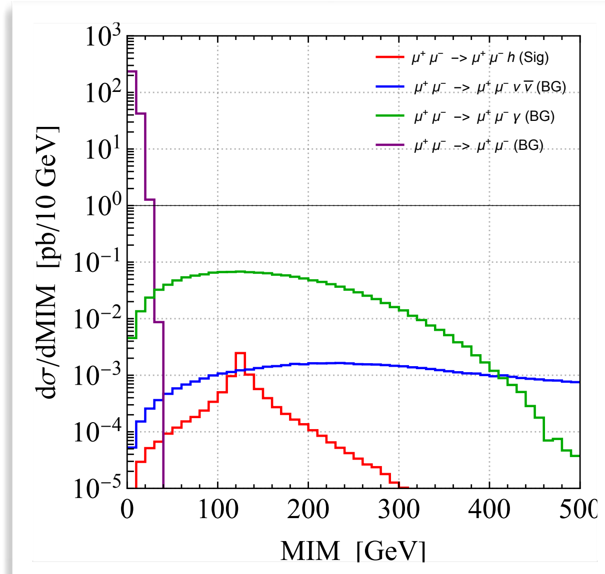


0.6 mrad BAS →



Energy Measurement Uncertainty

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



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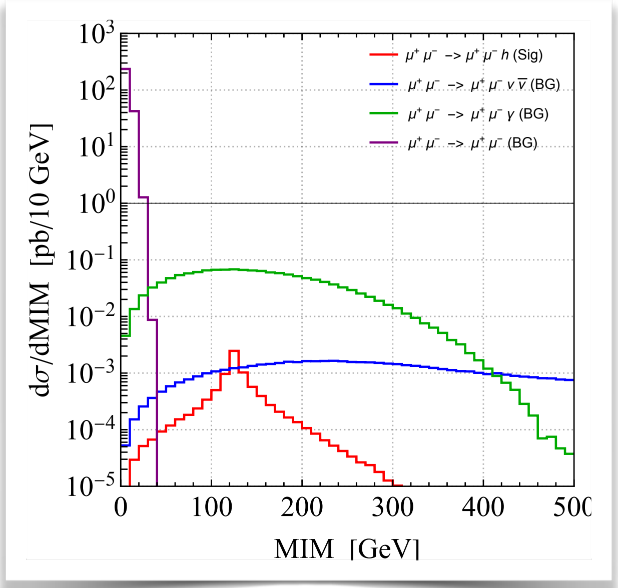
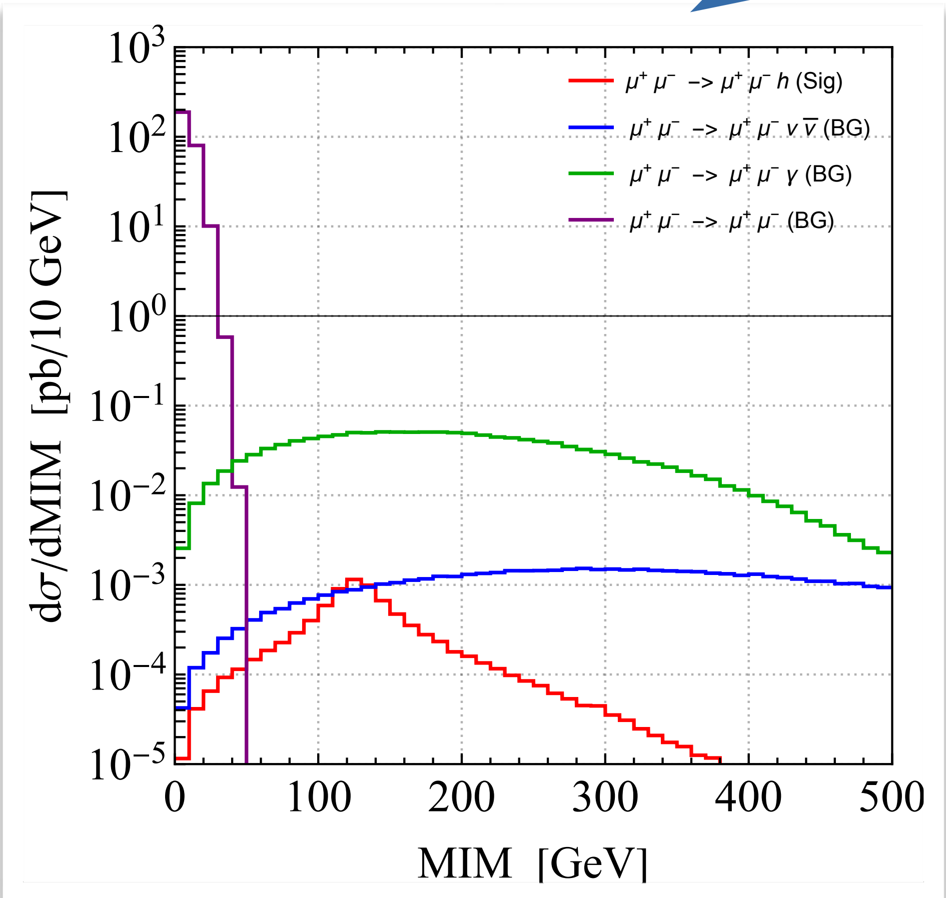


0.1% uncertainty



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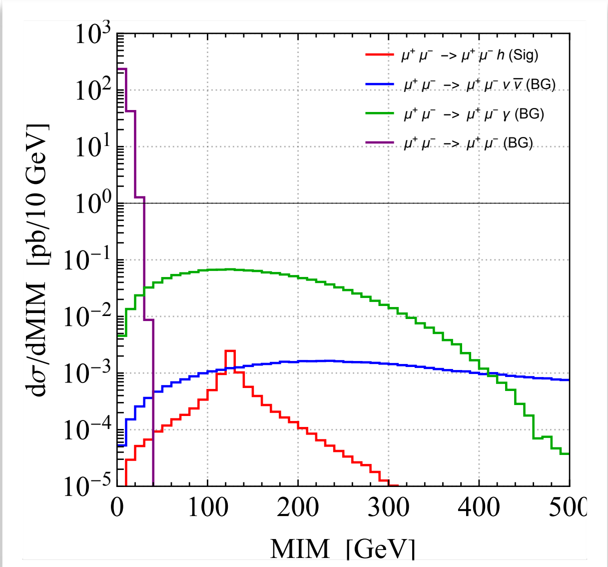

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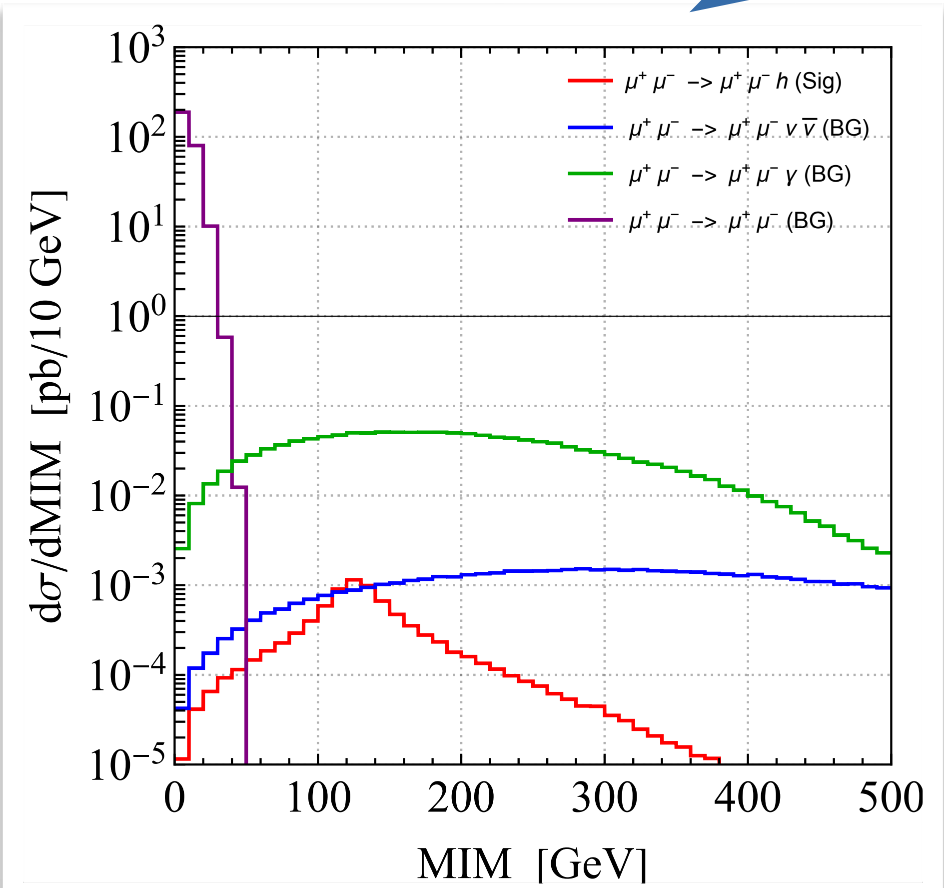
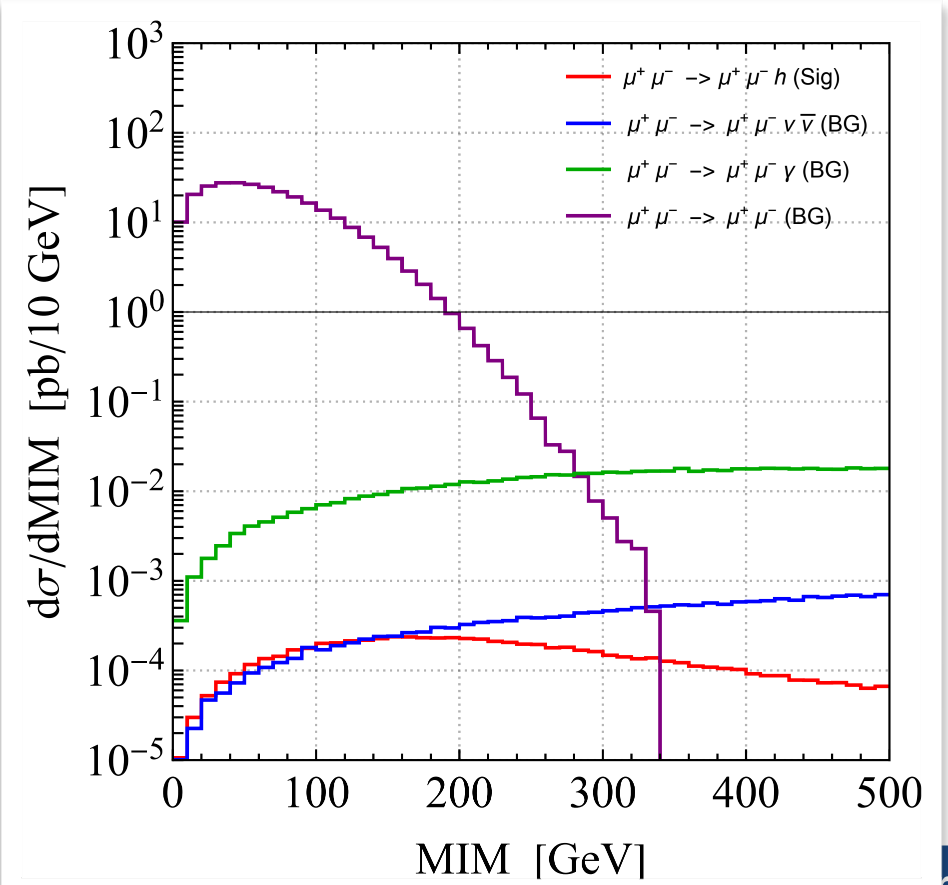


1% uncertainty



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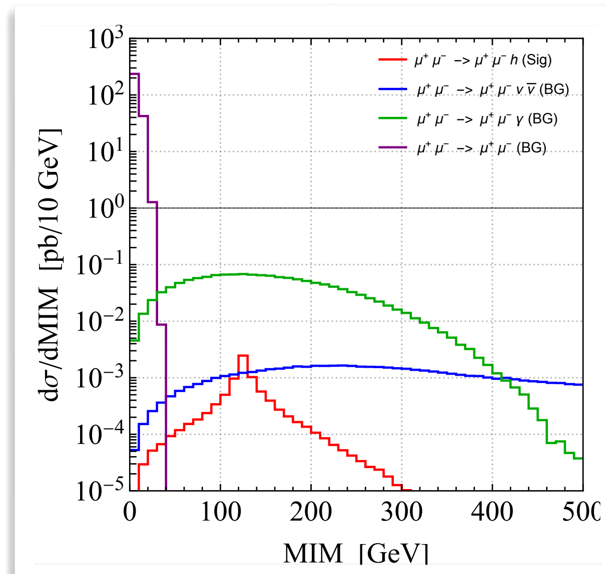
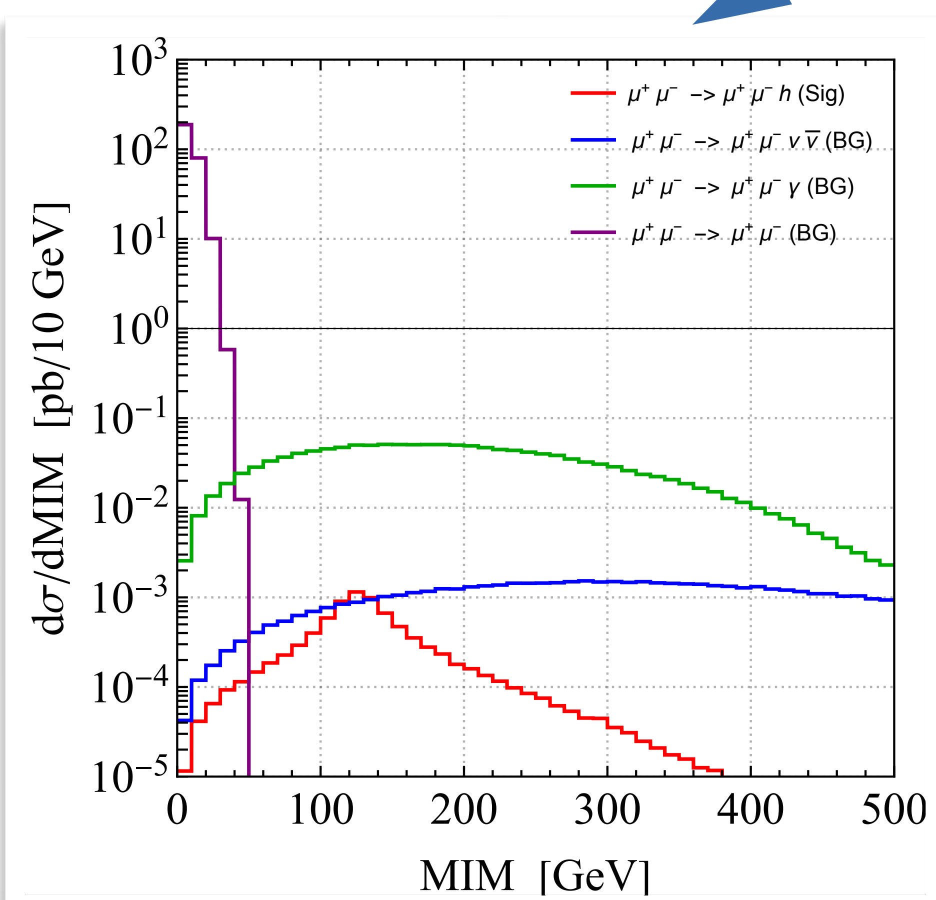


$\mu^+\mu^- \to \mu^+\mu^-$ becomes important

Can be suppressed with MET cut

0.1% uncertainty



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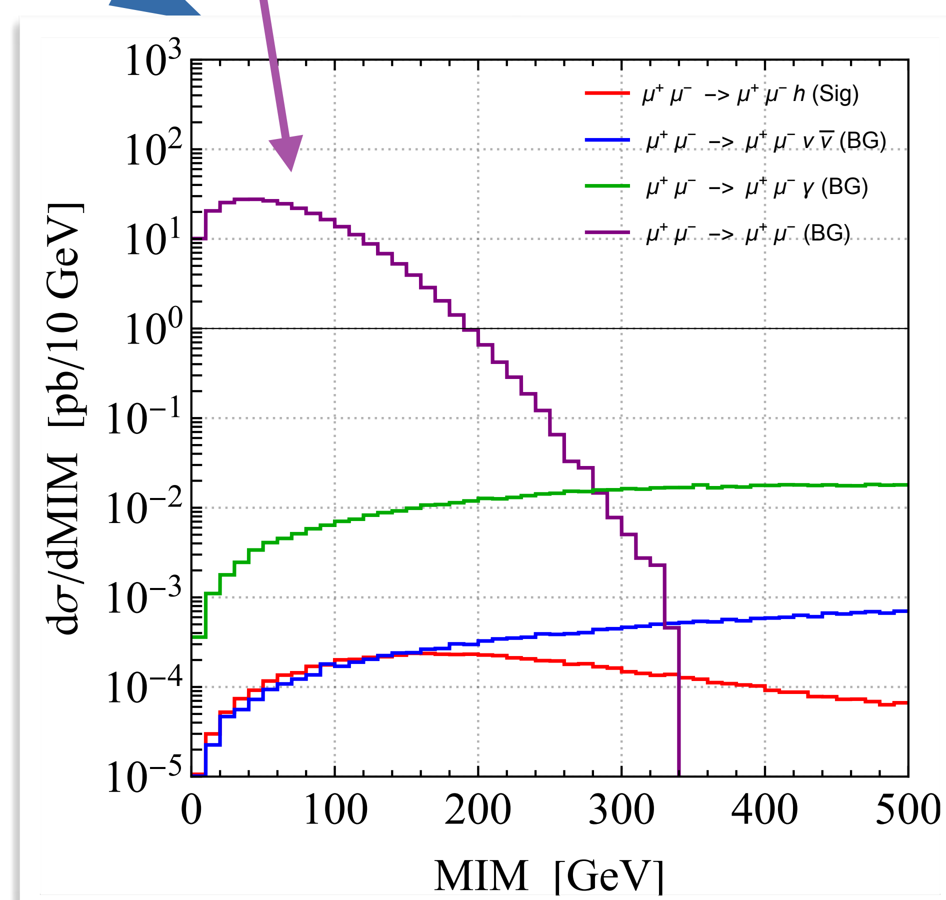
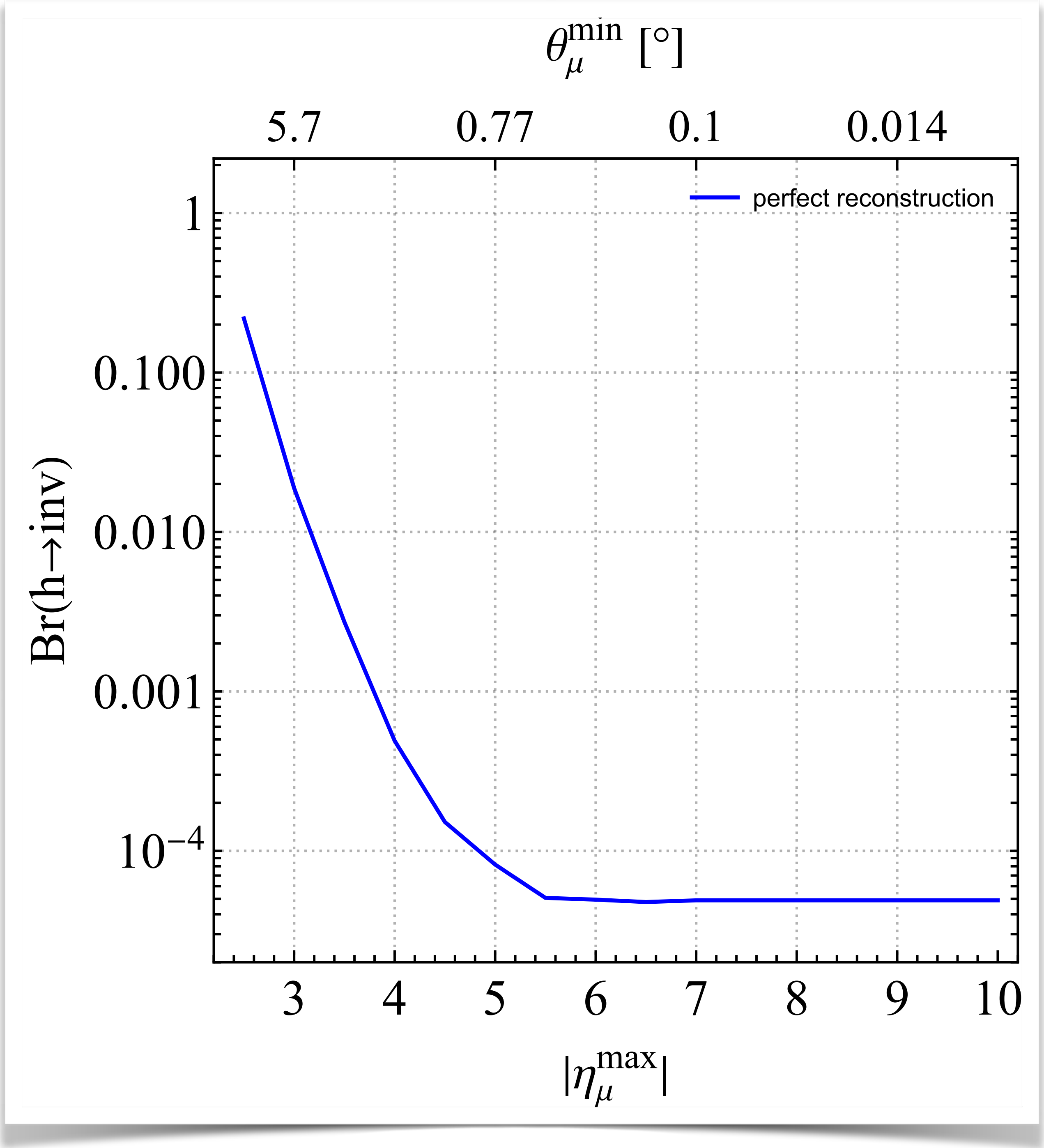


Combination

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



1. Perfect 4-momentum reconstruction

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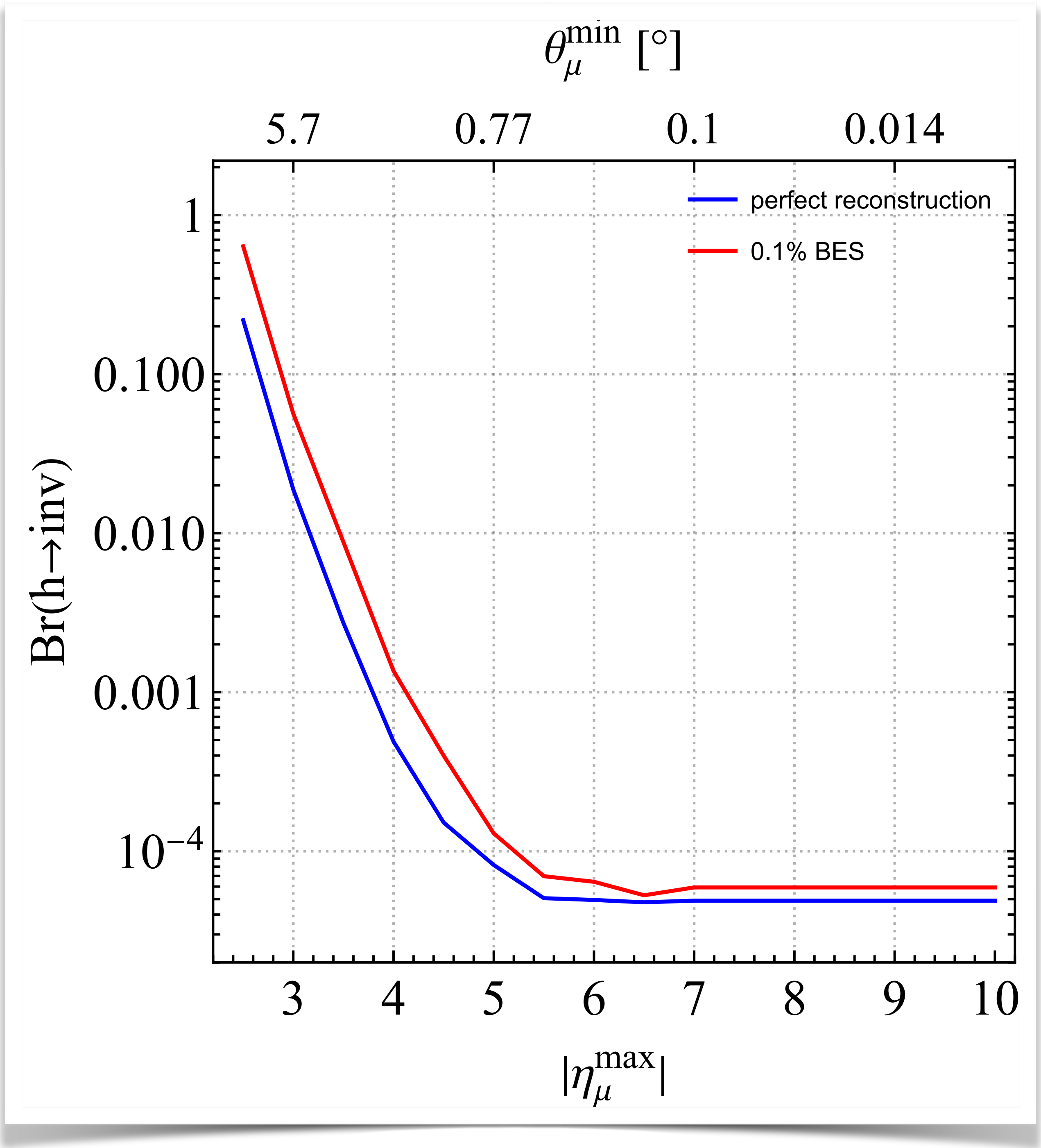

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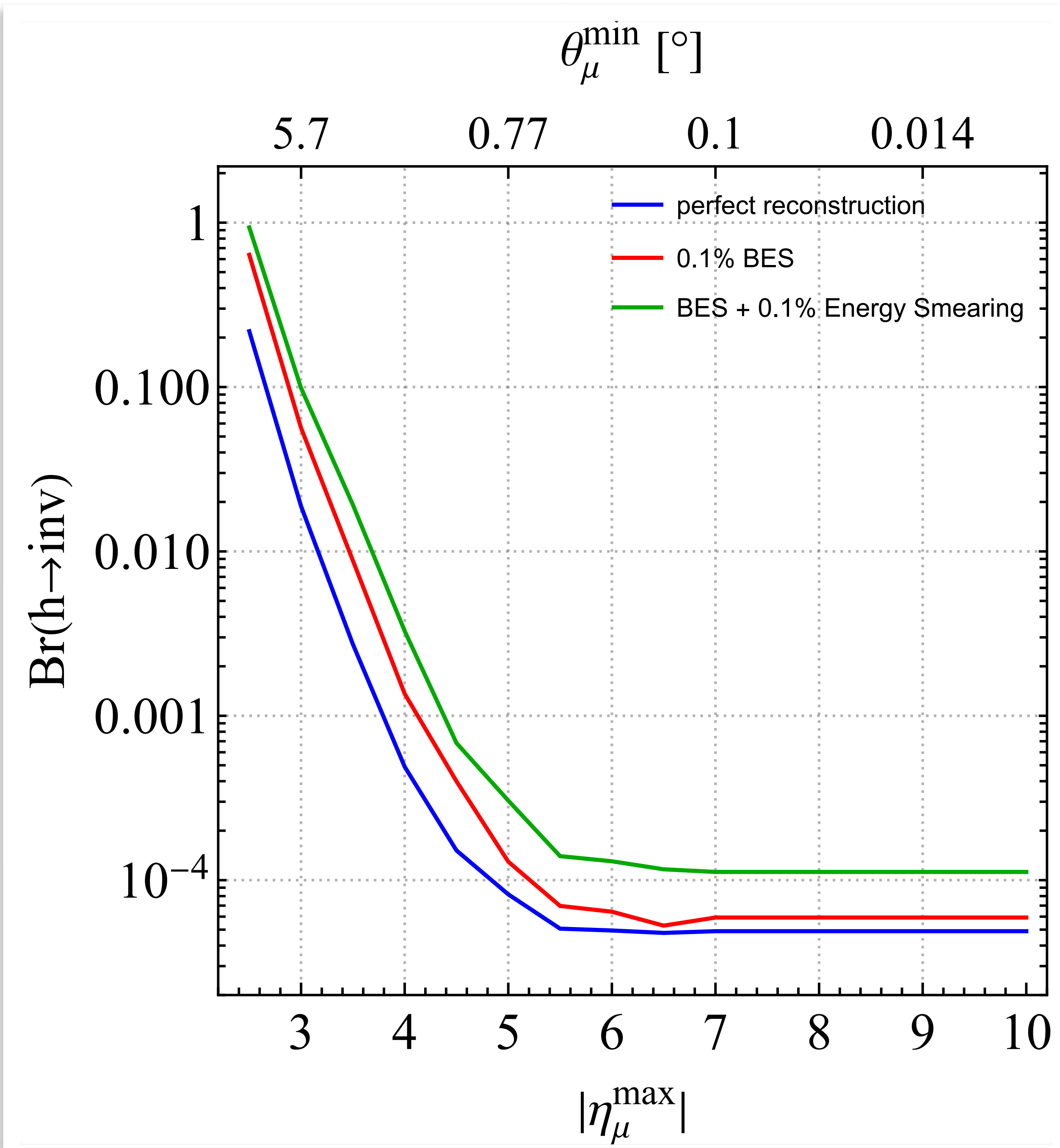

1. Perfect 4-momentum reconstruction
2. 0.1% BES
3. 0.1% BES + 0.1% energy uncertainty

Combination

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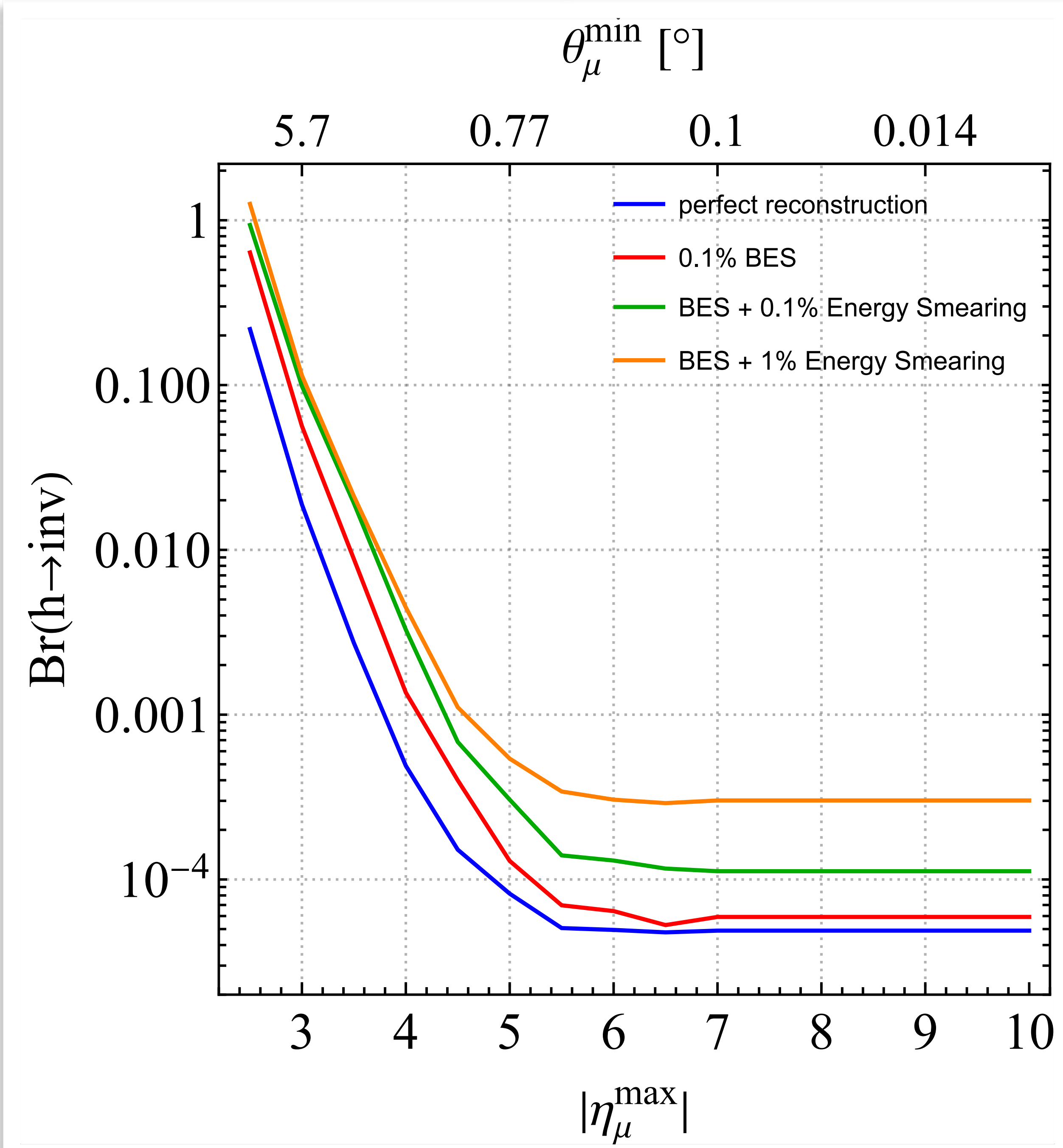

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4. 0.1% BES + 1% energy uncertainty

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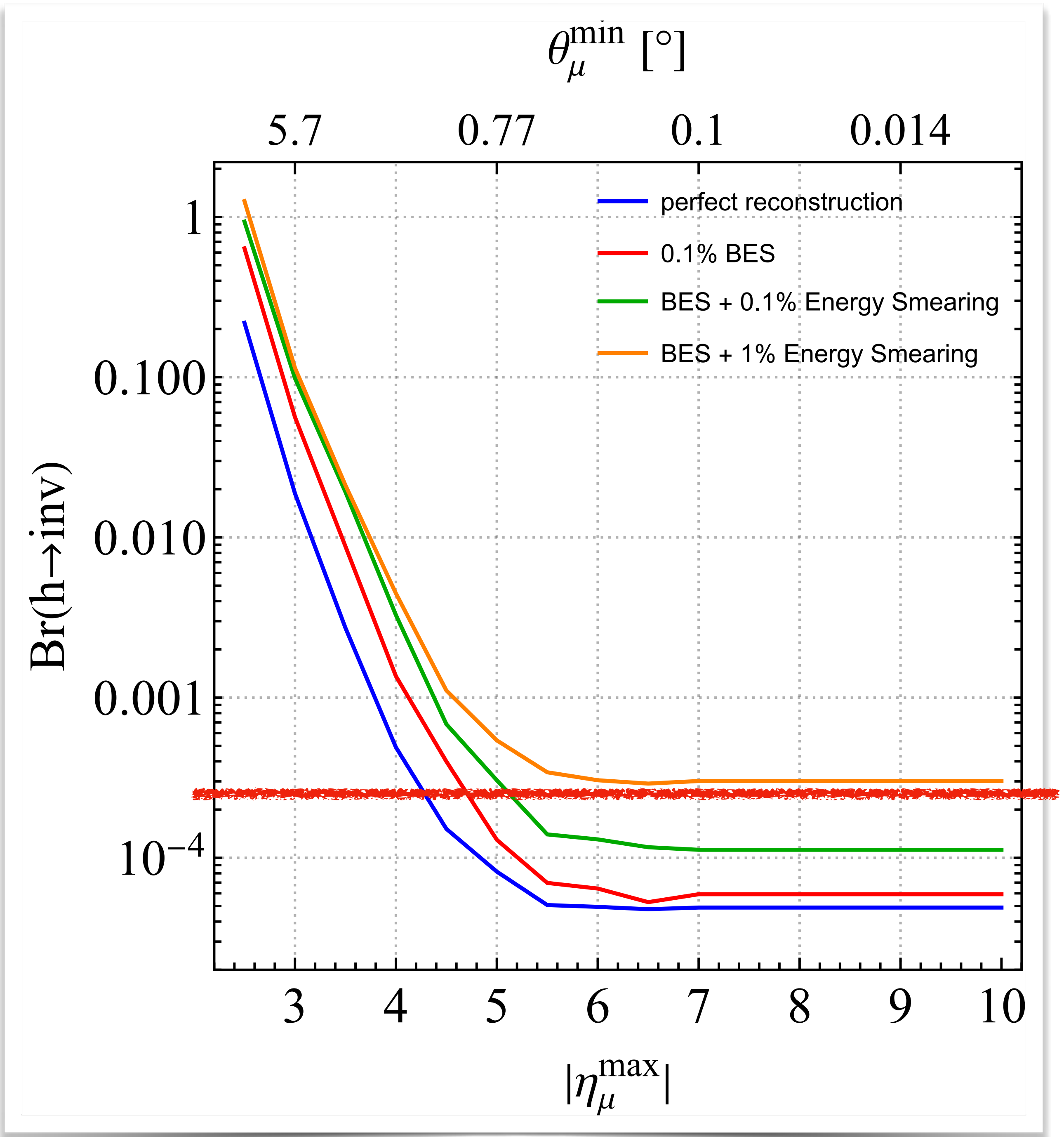
Combination

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



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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

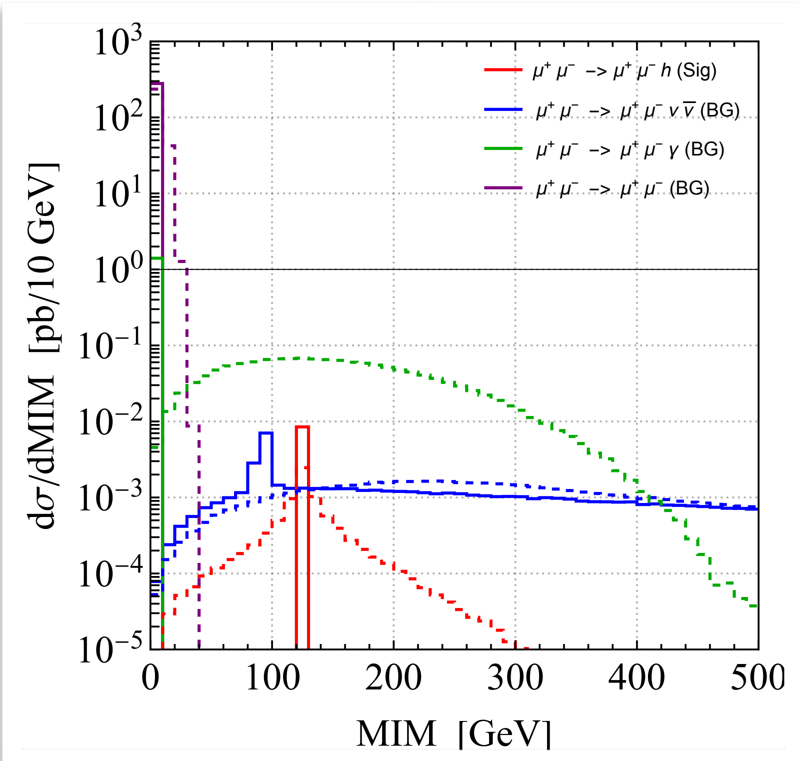
Conclusions

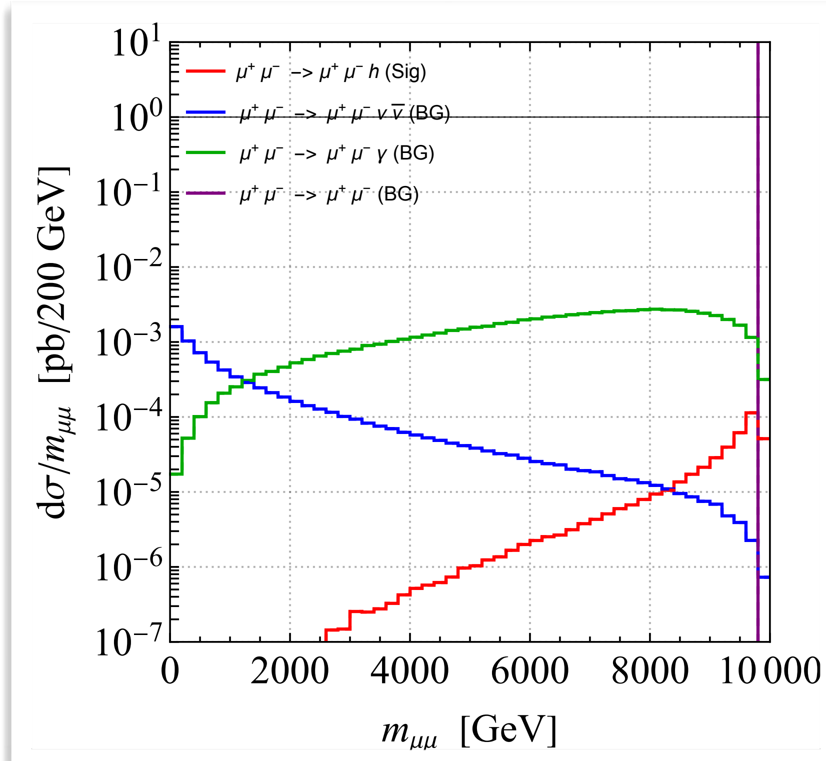
- A **high-energy** μ-collider can be the perfect machine to study invisible physics
- Accurate reconstruction of MIM requires **forward** muon detector
- **Detector** and **accelerator** effects not negligible for forward muons

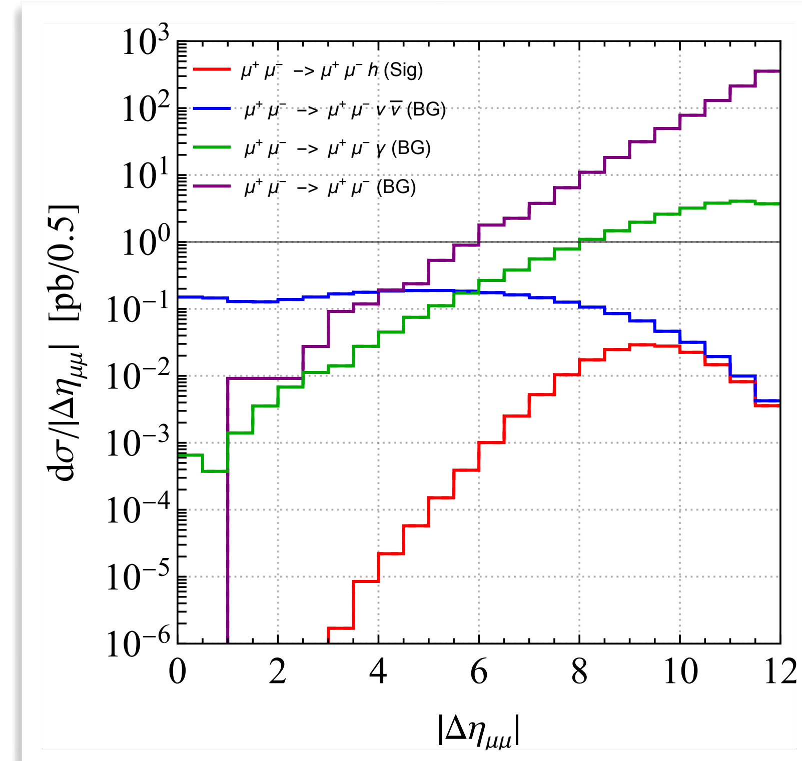
A realistic study of these effects is needed
to make the case for a forward muon detector

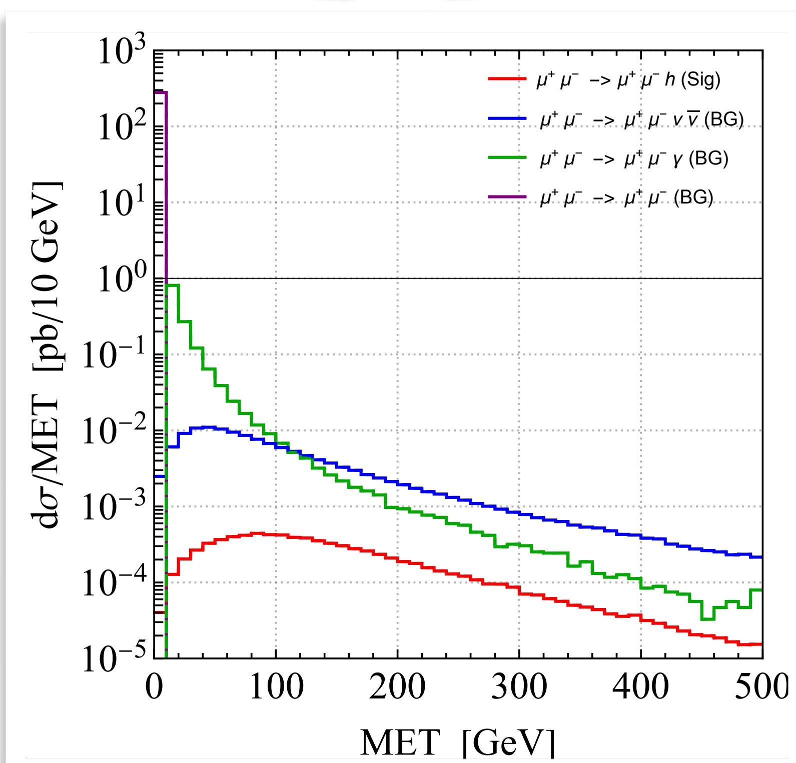
Backup

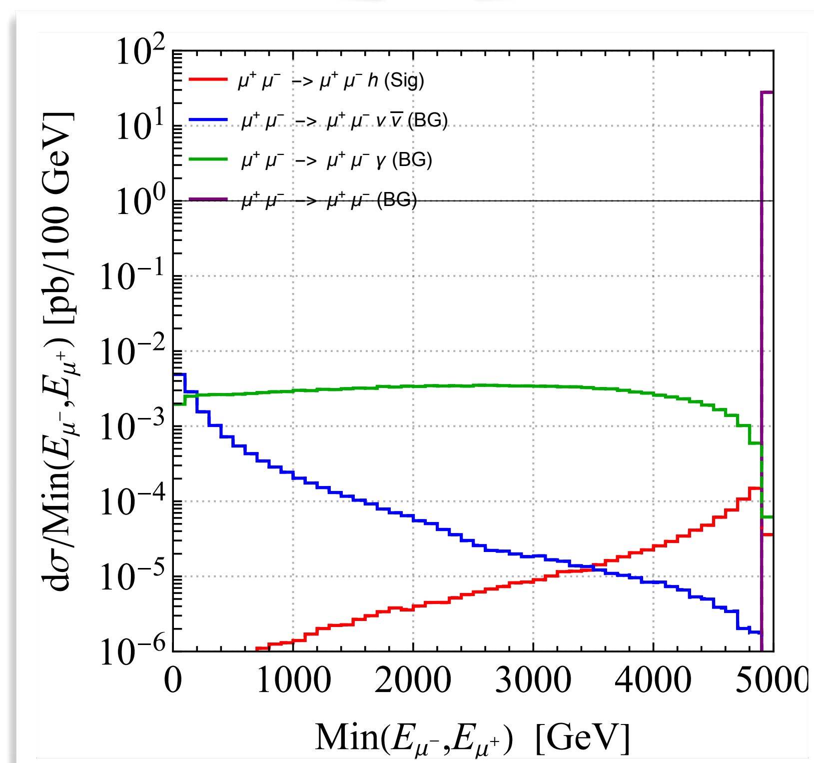
Invisible Higgs Decay Distributions











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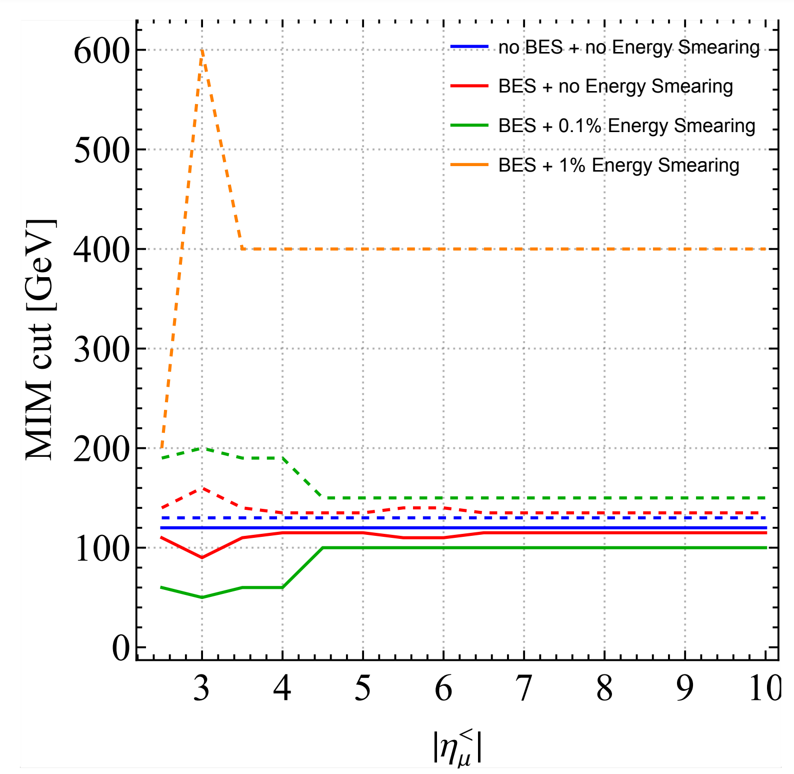
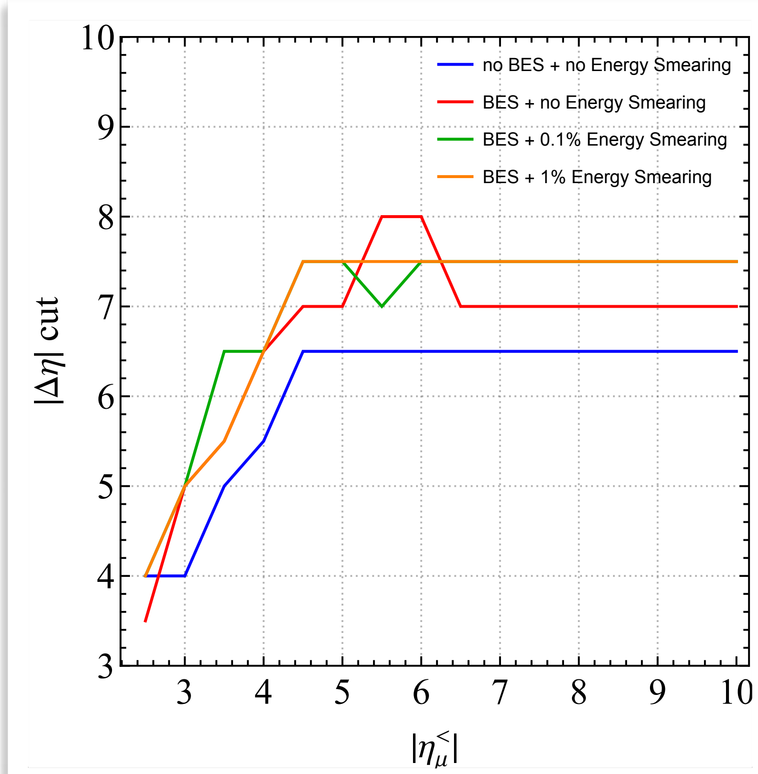
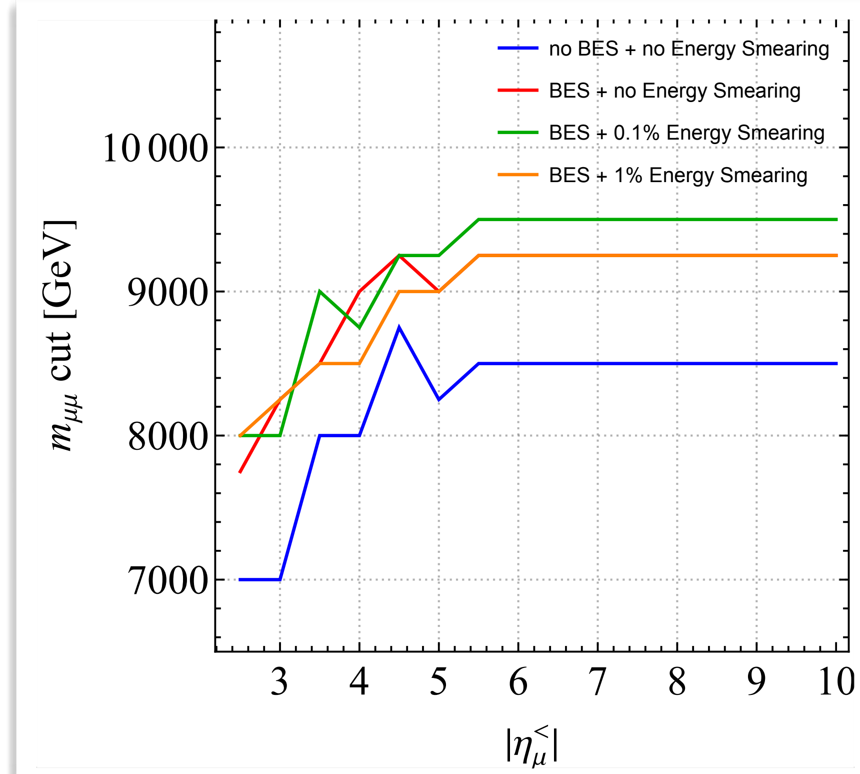
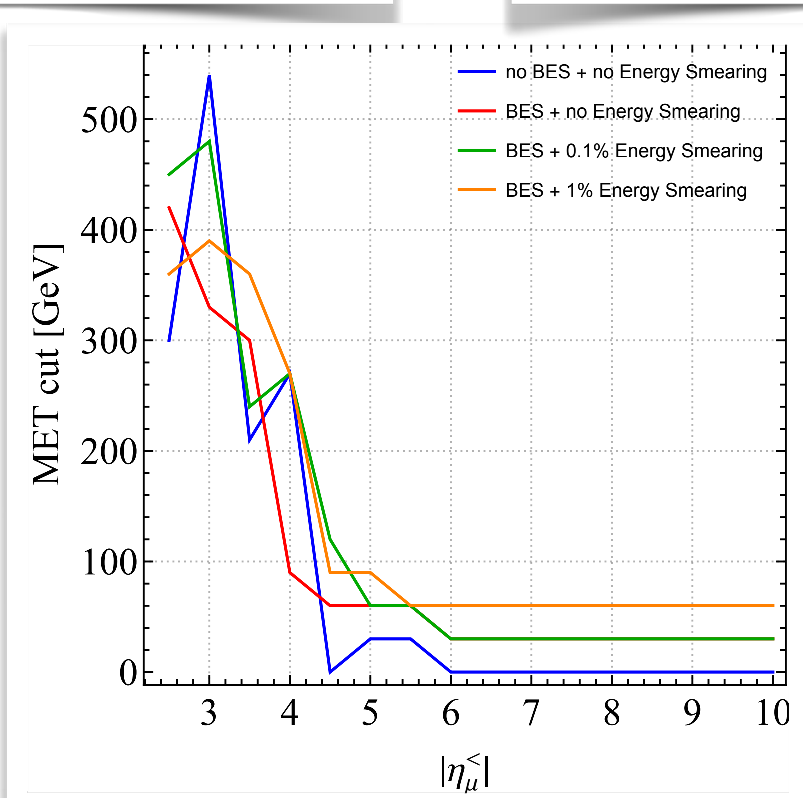
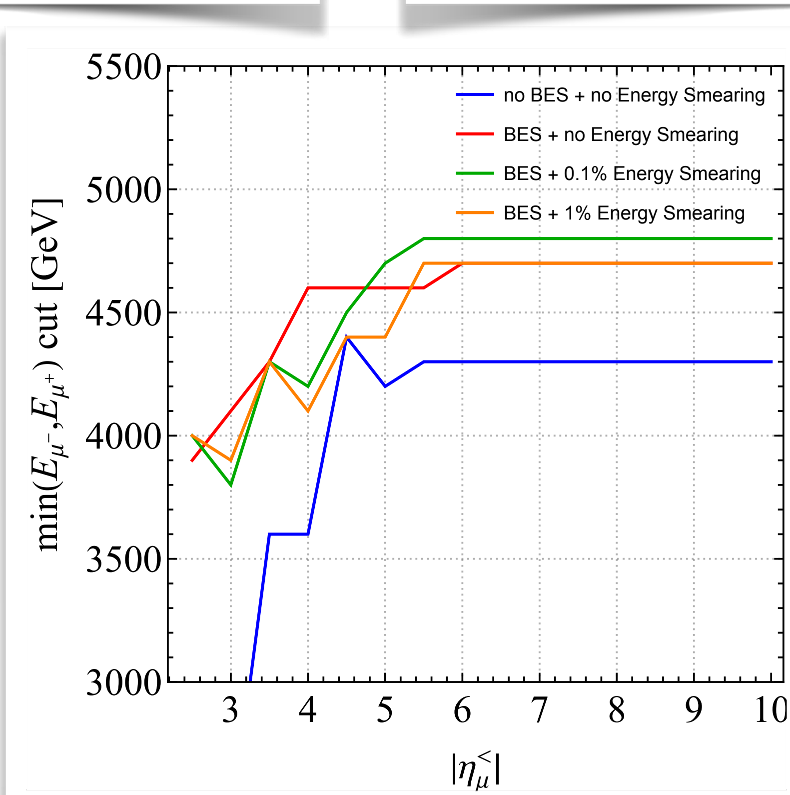
Cut Summary











Maximilian Ruhdorfer (Cornell)

Invisible Higgs Decay Projections

	LHC current [52] (VBF)	HL-LHC VBF [53] [Zh] [54]	ILC 250 [44] (Zh)	FCC-ee 240 [44] (Zh)	FCC-hh [55] (inclusive)
BR($h \to$ inv)	0.13	0.035 [0.08]	$1.3 \cdot 10^{-3}$	$8 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$

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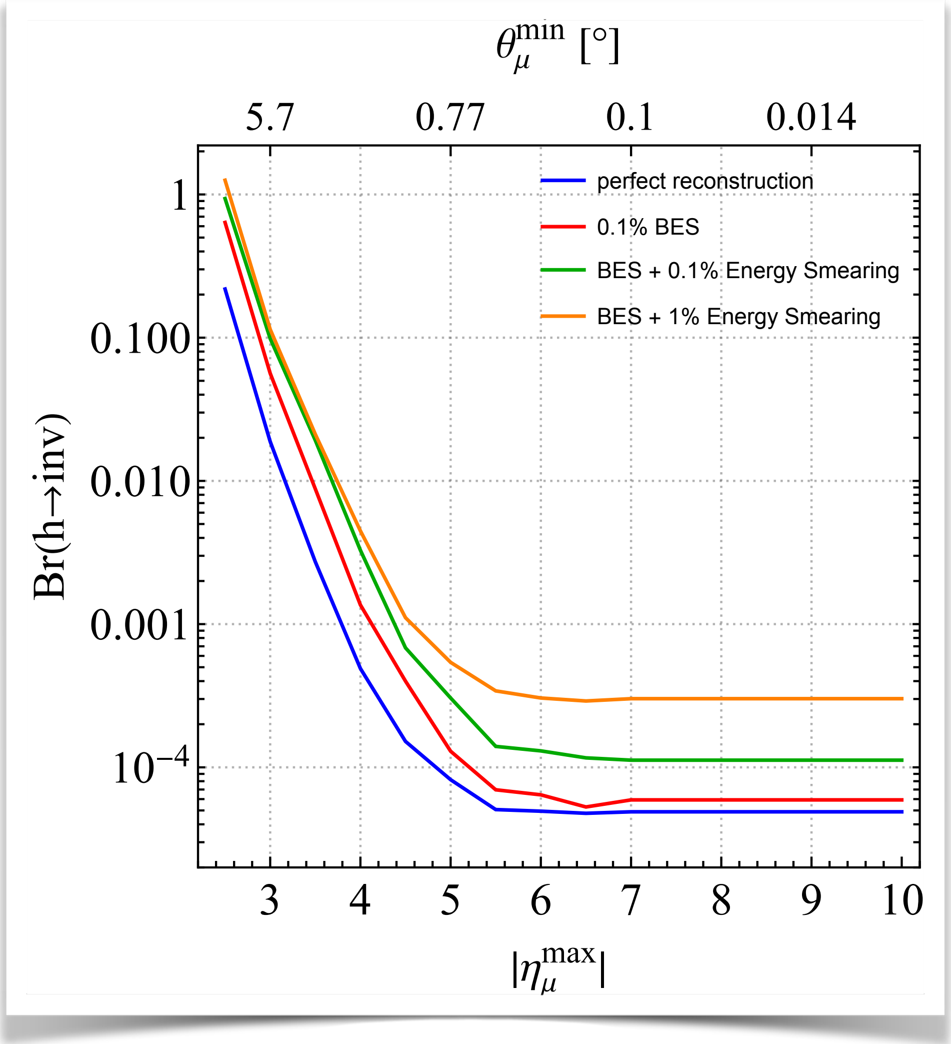

MIM Scaling with BES

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

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

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

→ reconstructed MIM

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

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

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

pNGB DM Realizations

- **Complex** scalar DM

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

Balkin, MR, Salvioni, Weiler, 1707.07685

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

- 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 $U(1)_{\mathrm{DM}}$ $\lambda \propto$ higher-loop $\ll 1$