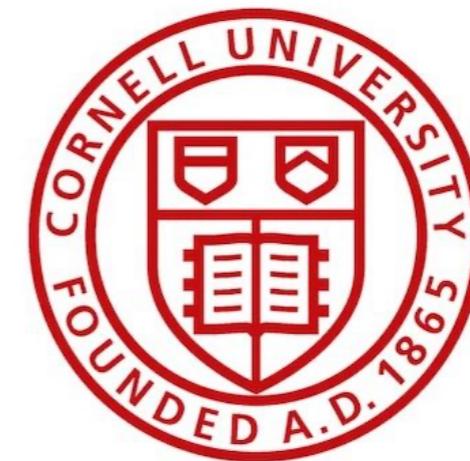


Invisible Higgs from forward muons at a muon collider

Maximilian Ruhdorfer
Cornell University

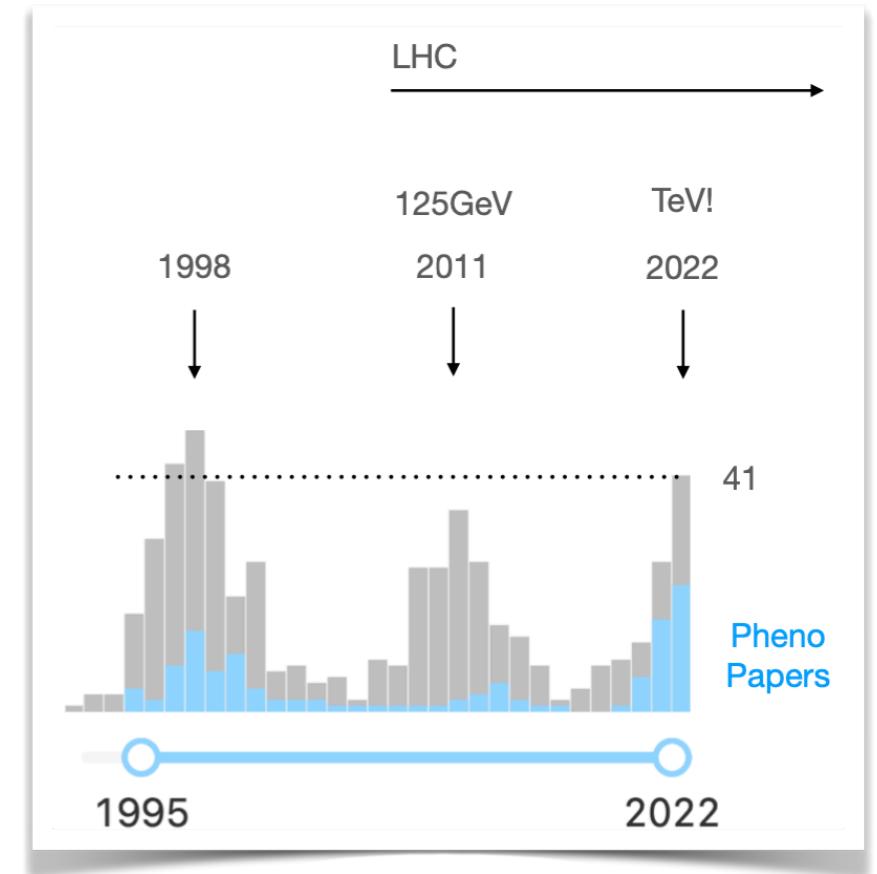


PHENO 2023 at University of Pittsburgh
May 8, 2023

*based on 2303.14202
with E. Salvioni and A. Wulzer*

Muon Colliders

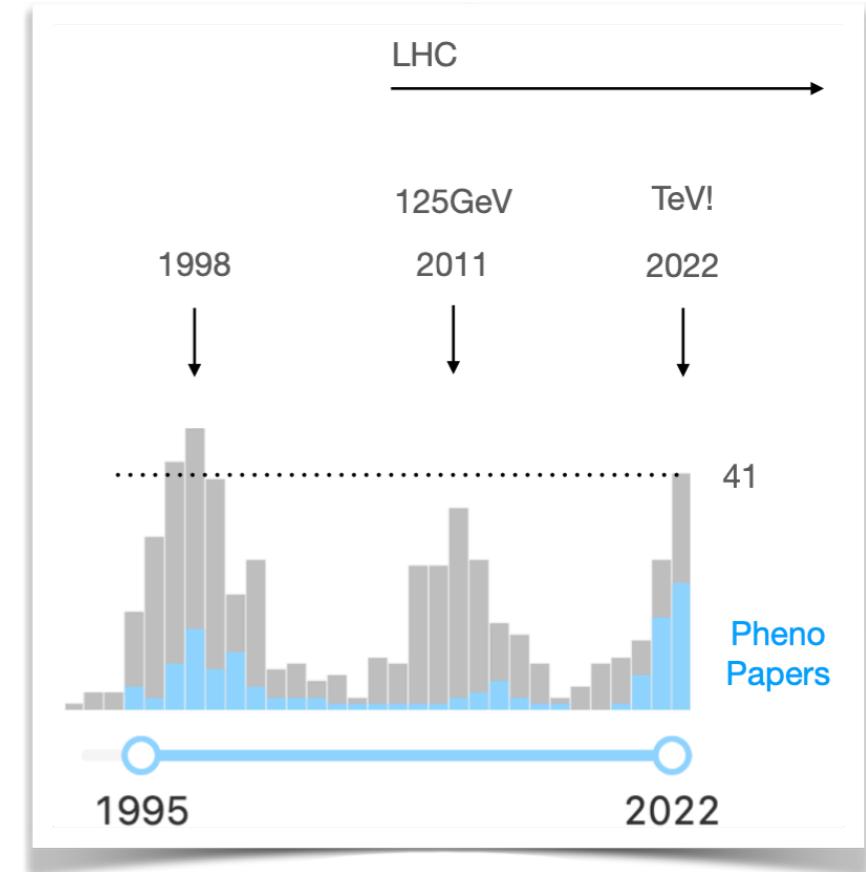
- There has been a renewed interest in muon colliders



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

Muon Colliders

- There has been a renewed interest in muon colliders
 - Considerable R&D effort
- EU design study proposal accepted



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

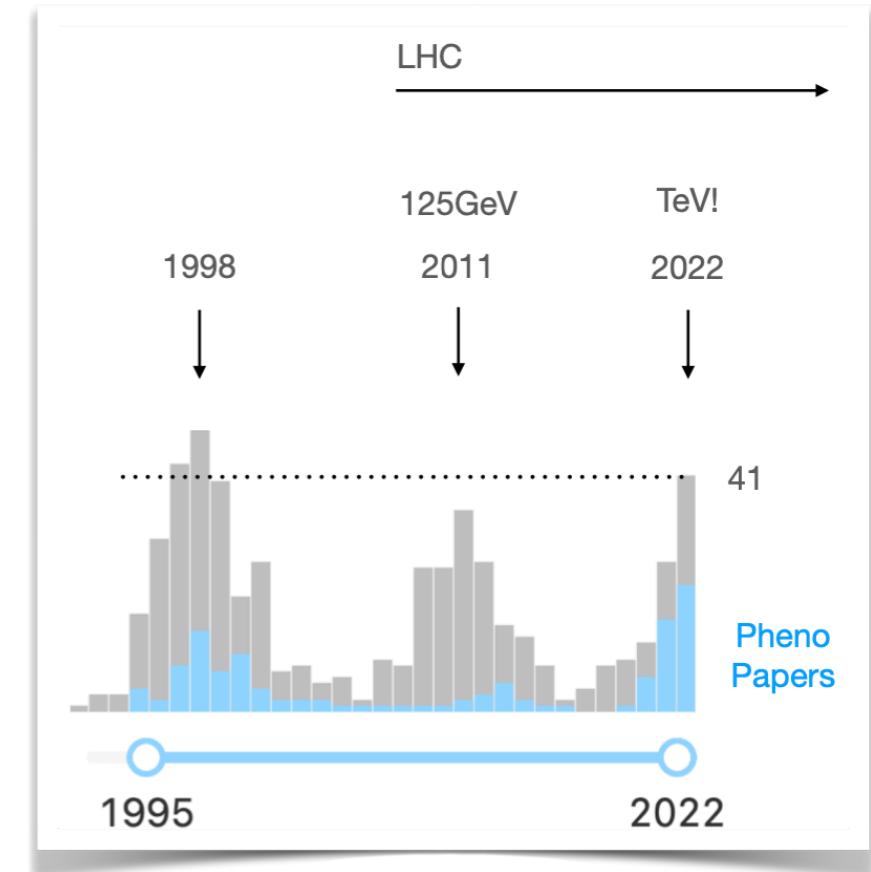
Muon Colliders

- There has been a renewed interest in muon colliders

- Considerable R&D effort



→ EU design study proposal accepted



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

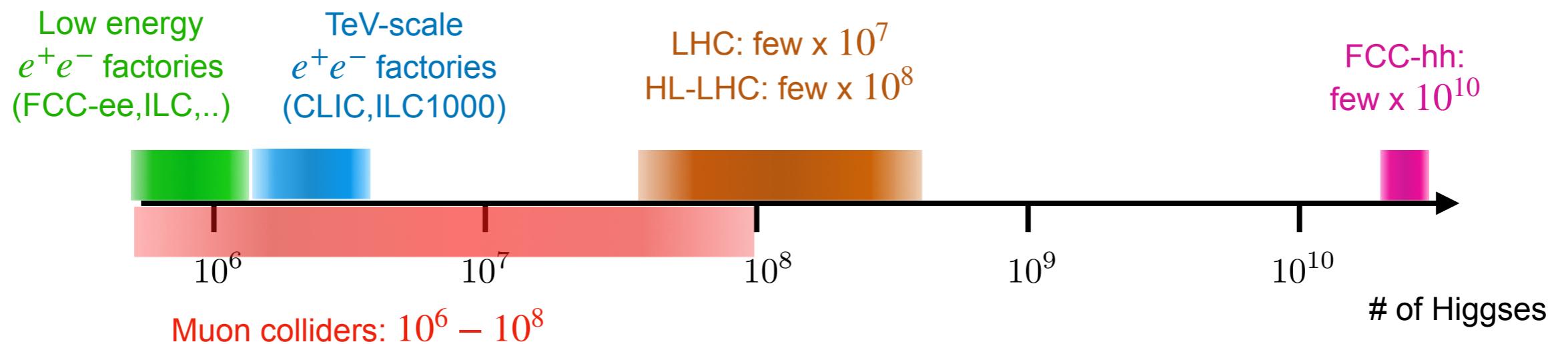
Now is the time to study physics potential of a muon collider!

Important input to experimentalists: what detector specifications are needed?

Physics Potential Meetings every 3 weeks (<https://indico.cern.ch/category/12792/>)

Muon Collider as Higgs Factory

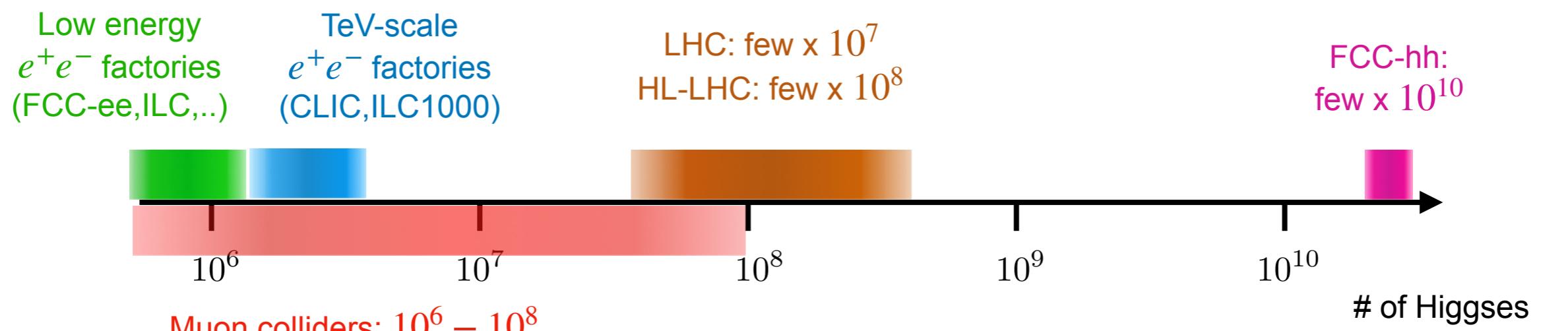
- High-energy muon collider is an ideal Higgs factory



Taken from Dario Buttazzo's talk at
Muon Collider KITP workshop

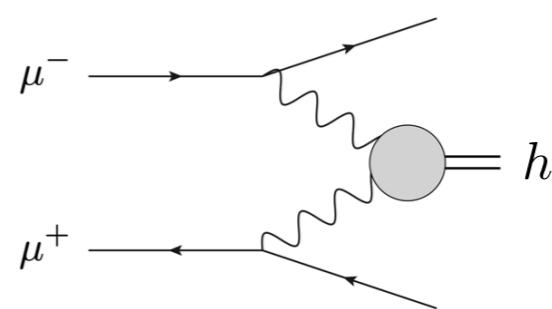
Muon Collider as Higgs Factory

- High-energy muon collider is an ideal Higgs factory



Taken from Dario Buttazzo's talk at
Muon Collider KITP workshop

- At $\sqrt{s} = 10 \text{ TeV}, L = 10 \text{ ab}^{-1}$: 10 million Higgs bosons are produced through VBF



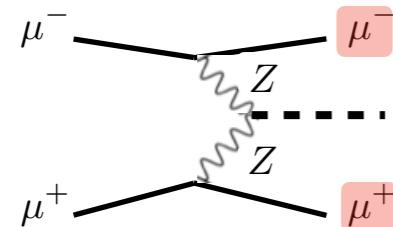
- can test rare Higgs decays
- challenging benchmark:
invisible Higgs decays

Invisible Higgs Decays

- Current best bound at LHC (ATLAS): $\text{BR}(h \rightarrow \text{inv}) < 0.15$

Invisible Higgs Decays

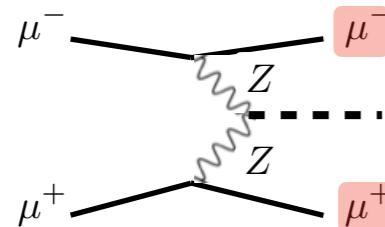
- Current best bound at LHC (ATLAS): $\text{BR}(h \rightarrow \text{inv}) < 0.15$
- At 10 TeV muon collider Higgs is produced in ZZ fusion
→ WW fusion has completely invisible final state



~ 620'000 Higgses in ZZ fusion (after VBF baseline cuts)

Invisible Higgs Decays

- Current best bound at LHC (ATLAS): $\text{BR}(h \rightarrow \text{inv}) < 0.15$
- At 10 TeV muon collider Higgs is produced in ZZ fusion
 - WW fusion has completely invisible final state

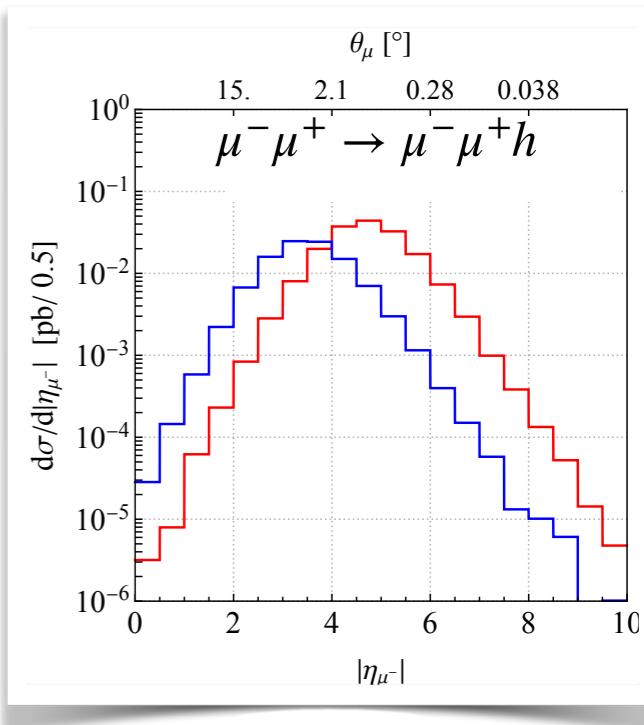


~ 620'000 Higgses in ZZ fusion (after VBF baseline cuts)

- In SM: $\text{BR}(h \rightarrow ZZ^* \rightarrow 4\nu) = 1.2 \cdot 10^{-3}$
 - ~ 1'000 invisible decays can be observed
 - percent-level relative accuracy possible for
- BR_{inv} = BR_{inv}SM + BR_{inv}^{BSM}
- can theoretically probe BR_{inv}^{BSM} $\sim 10^{-4}$

Forward Muons

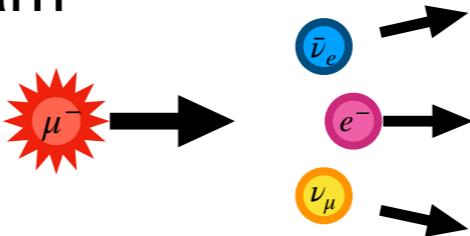
- **Caveat:** Muons are extremely forward



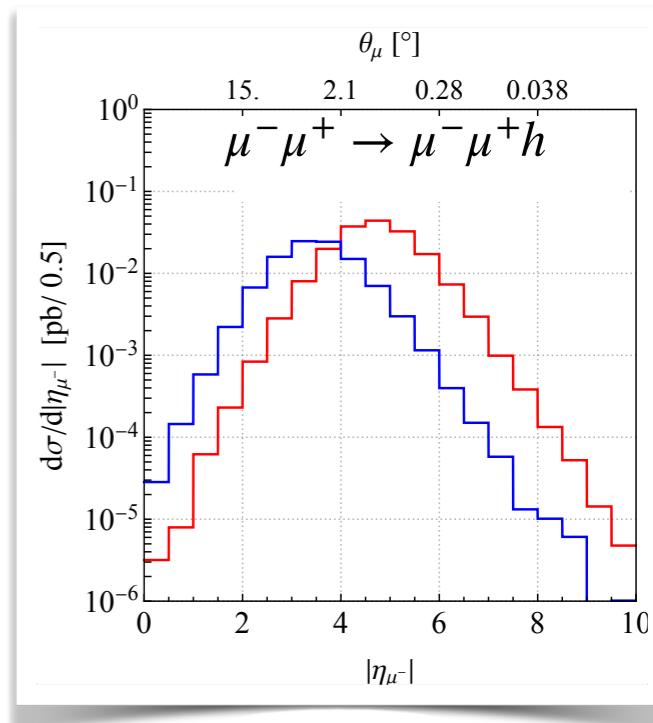
Forward Muons

- **Caveat:** Muons are extremely forward
- Tungsten nozzle shields detector from beam induced BG

→ muons decay along the beam



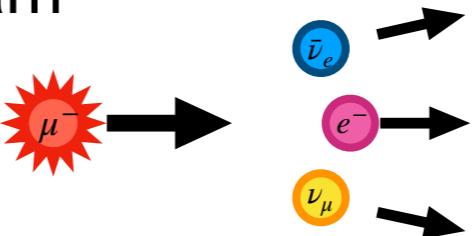
→ limits main detector coverage to $\theta > 10^\circ$



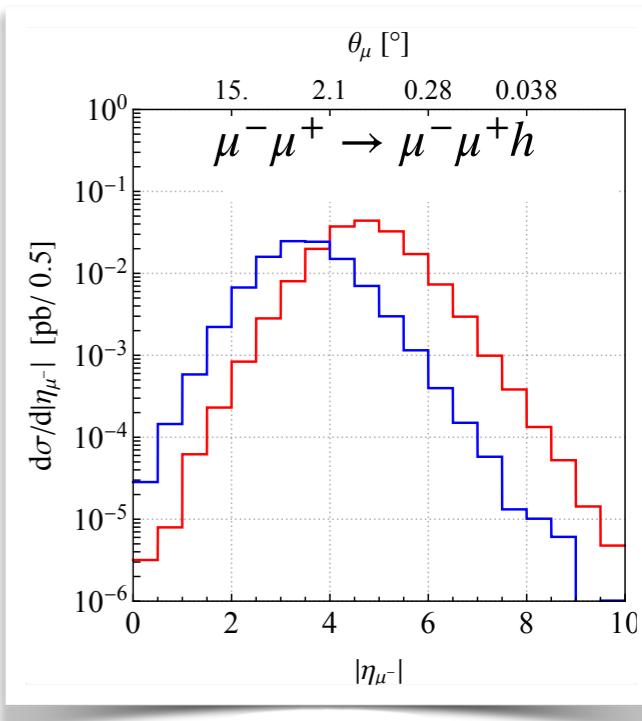
Forward Muons

- **Caveat:** Muons are extremely forward
- Tungsten nozzle shields detector from beam induced BG

→ muons decay along the beam



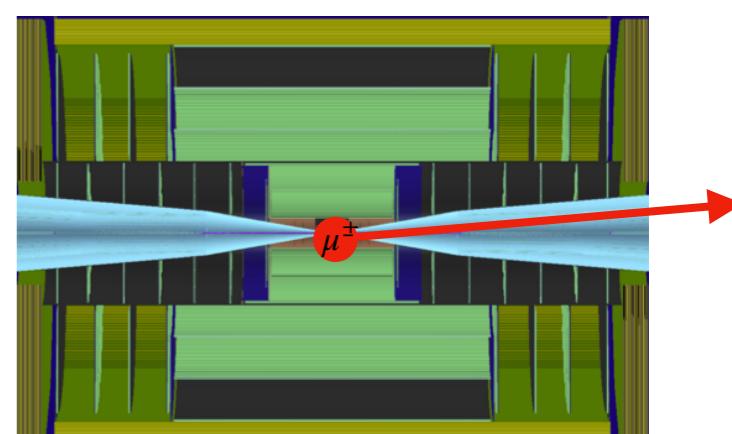
→ limits main detector coverage to $\theta > 10^\circ$



- **But:** high-energy muons are penetrating particles

→ one could imagine a detector some distance after interaction point

invisible Higgs decays are benchmark for study of forward muon detector physics potential



Backgrounds

Backgrounds:

1. Irreducible BG $\mu^-\mu^+ \rightarrow \mu^-\mu^+\bar{\nu}\nu$
2. SM BG $\mu^-\mu^+ \rightarrow \mu^-\mu^+(h \rightarrow 4\nu)$
3. Lost particles $\mu^-\mu^+ \rightarrow \mu^-\mu^+ + X$
 - outside central detector ($|\eta| > 2.44$)
or too soft ($p_\perp < 20$ GeV)
 - largest contributions $X = \gamma, f\bar{f}, W^+W^-$

Backgrounds

Backgrounds:

1. Irreducible BG $\mu^-\mu^+ \rightarrow \mu^-\mu^+\bar{\nu}\nu$
2. SM BG $\mu^-\mu^+ \rightarrow \mu^-\mu^+(h \rightarrow 4\nu)$
3. Lost particles $\mu^-\mu^+ \rightarrow \mu^-\mu^+ + X$

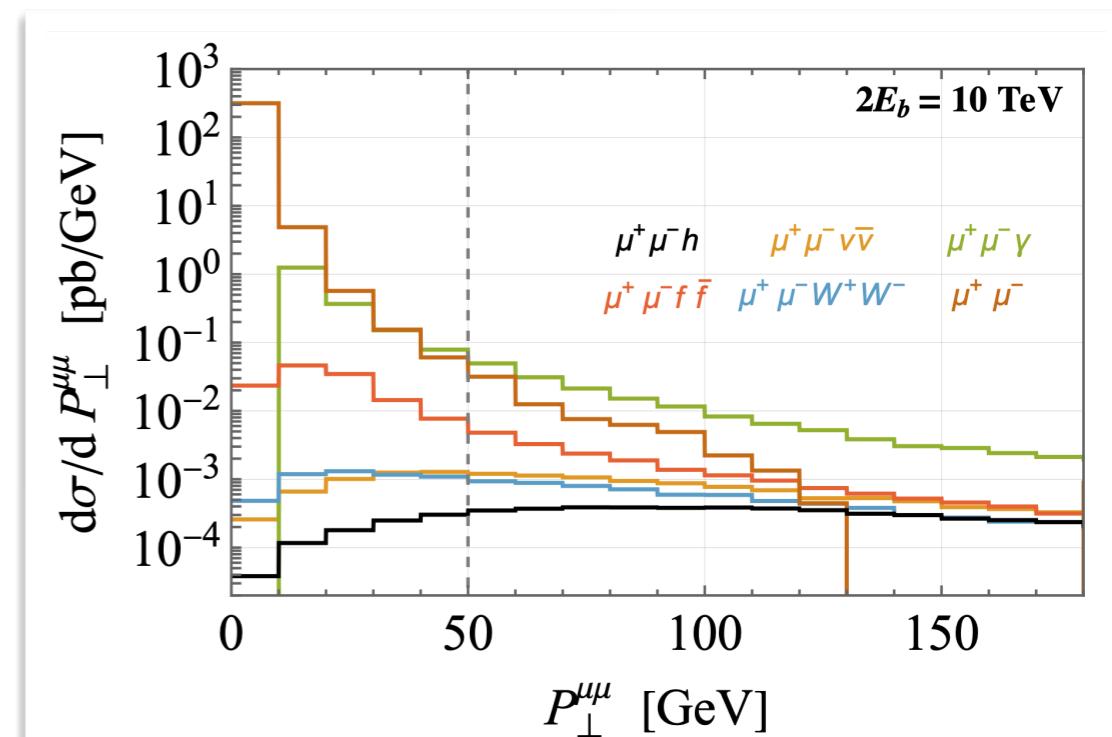
- outside central detector ($|\eta| > 2.44$)
or too soft ($p_\perp < 20$ GeV)
- largest contributions $X = \gamma, f\bar{f}, W^+W^-$

We include QED radiation for signal and some BGs

→ cut on $P_\perp^{\mu\mu} = (p_{\mu^+} + p_{\mu^-})_\perp > 50$ GeV

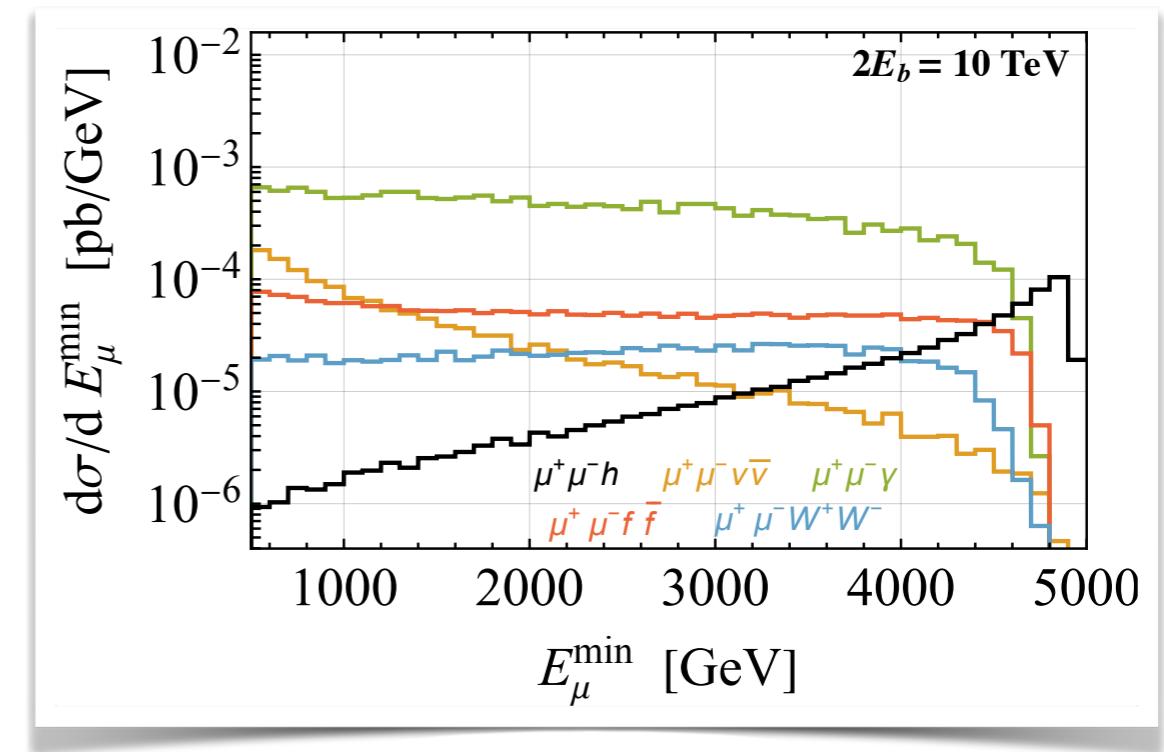
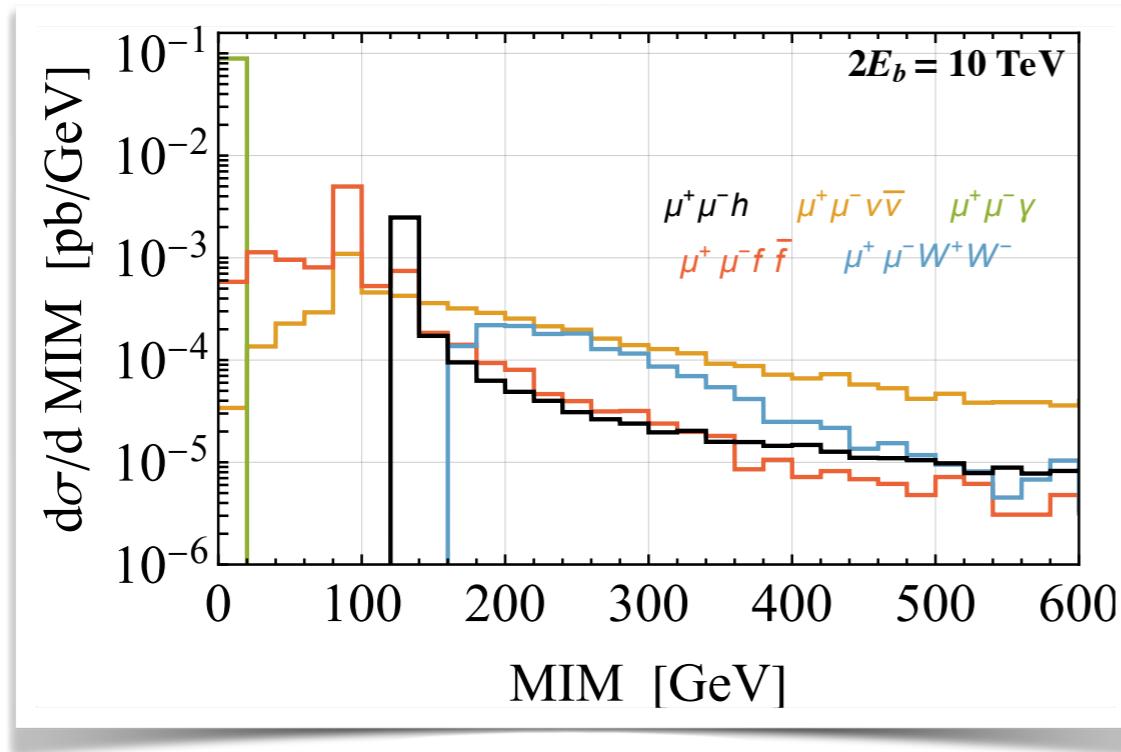
to reduce large QCD BG of soft
and collinear photon radiation

$\mu^-\mu^+ \rightarrow \mu^-\mu^+ + \text{photons}$



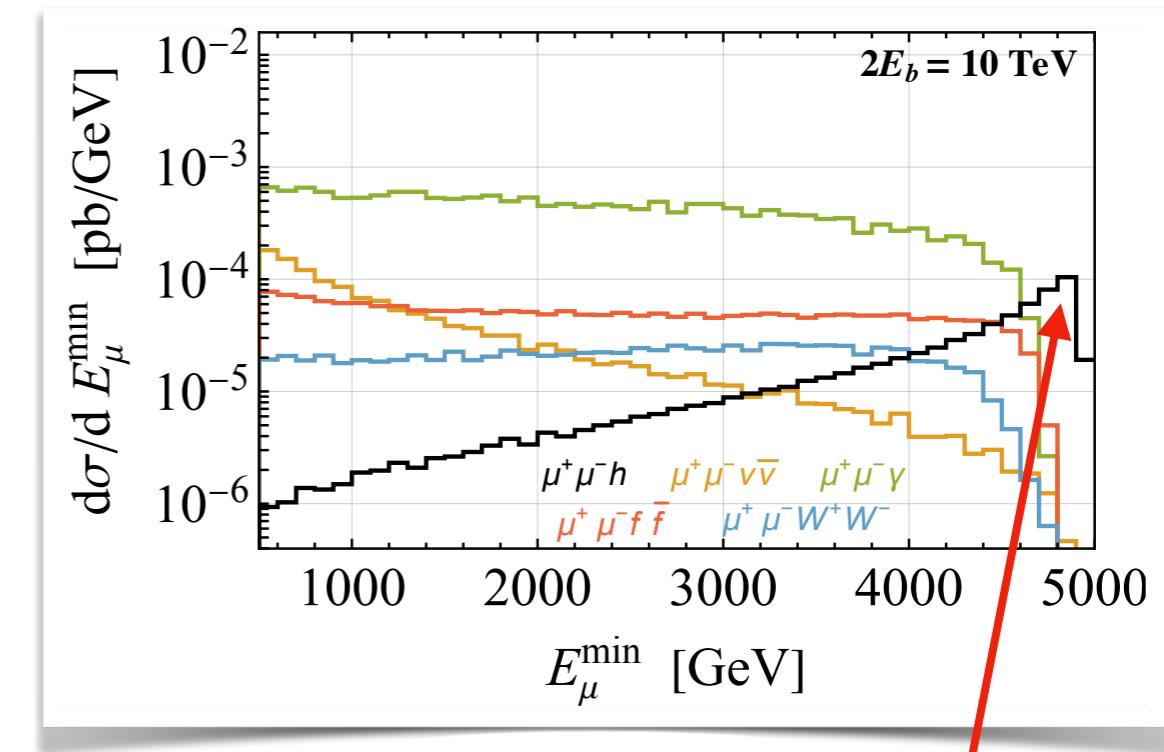
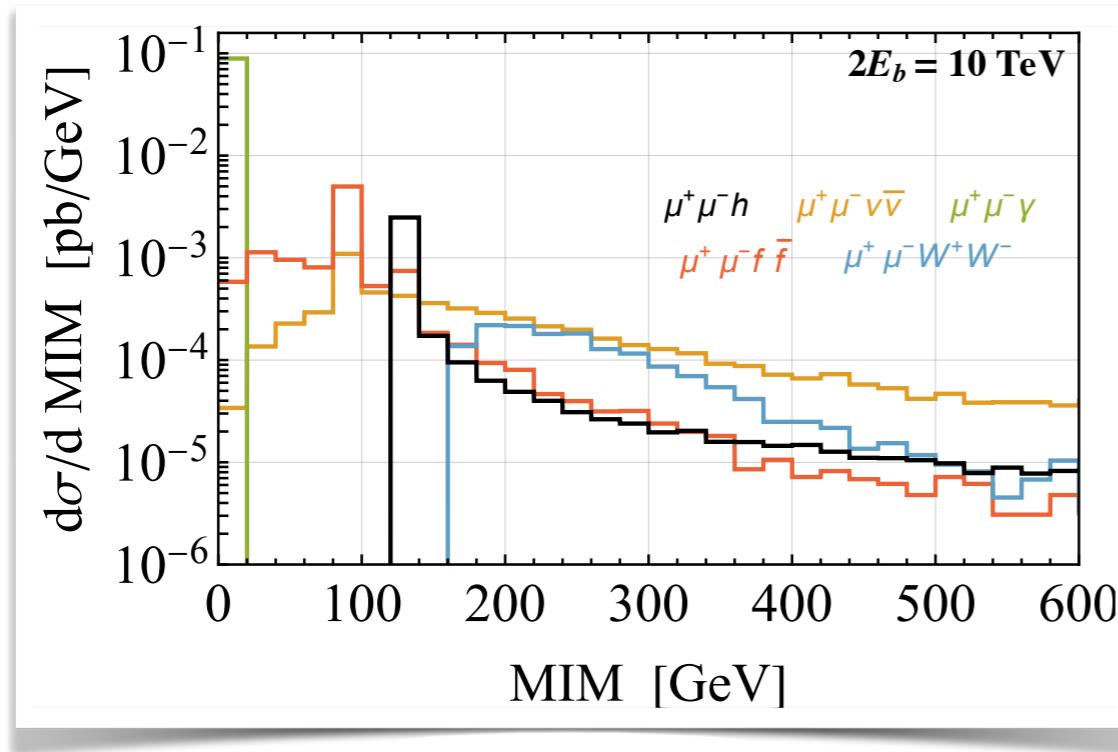
Kinematic Variables

- Efficient BG suppression possible using MIM and E_μ^{\min}



Kinematic Variables

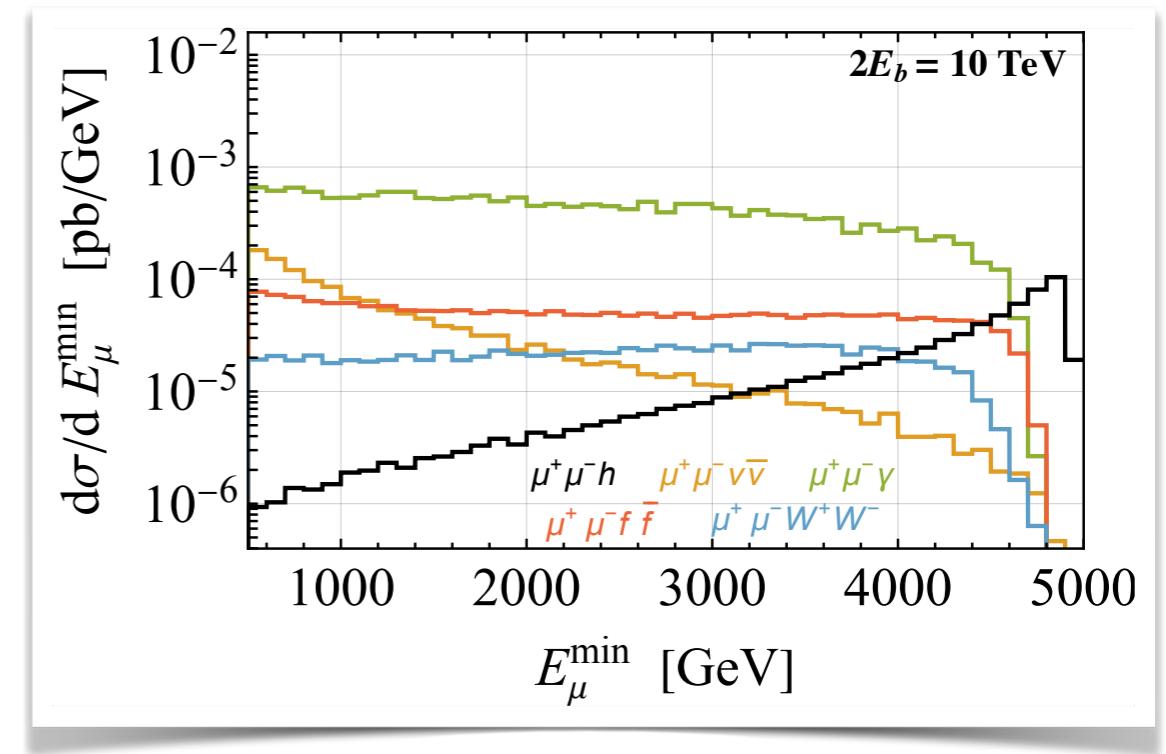
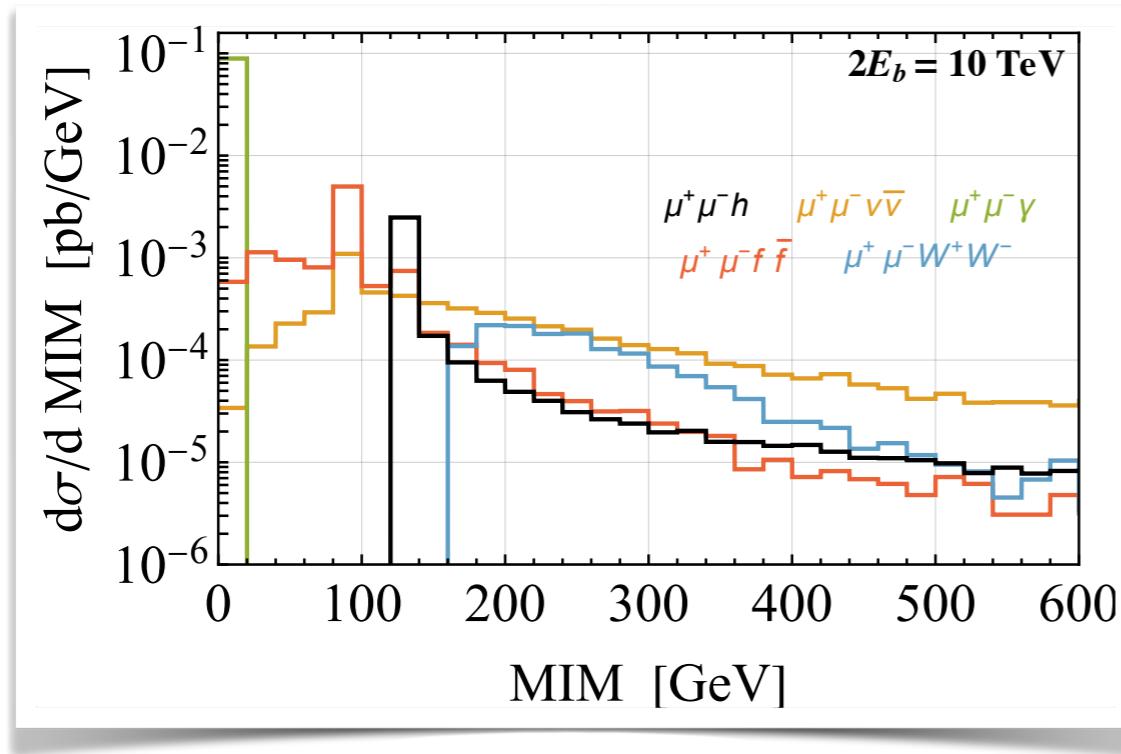
- Efficient BG suppression possible using MIM and E_μ^{\min}



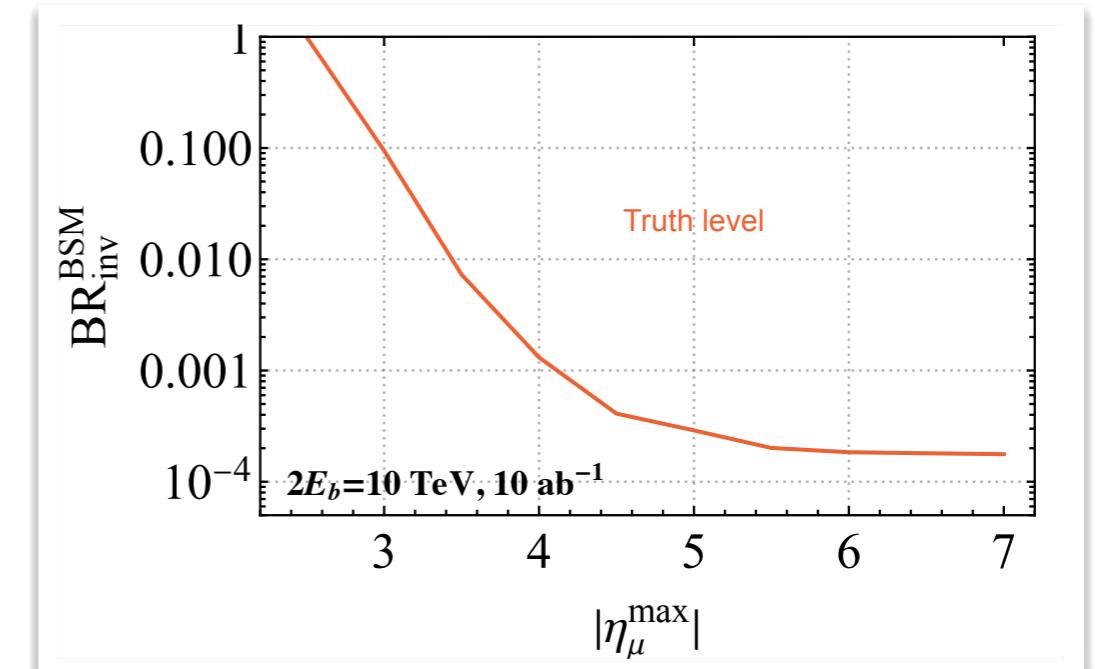
large E_μ^{\min} and $P_{\perp}^{\mu\mu} > 50 \text{ GeV}$ forces “lost” particle to be central
 → can be vetoed

Kinematic Variables

- Efficient BG suppression possible using MIM and E_μ^{\min}

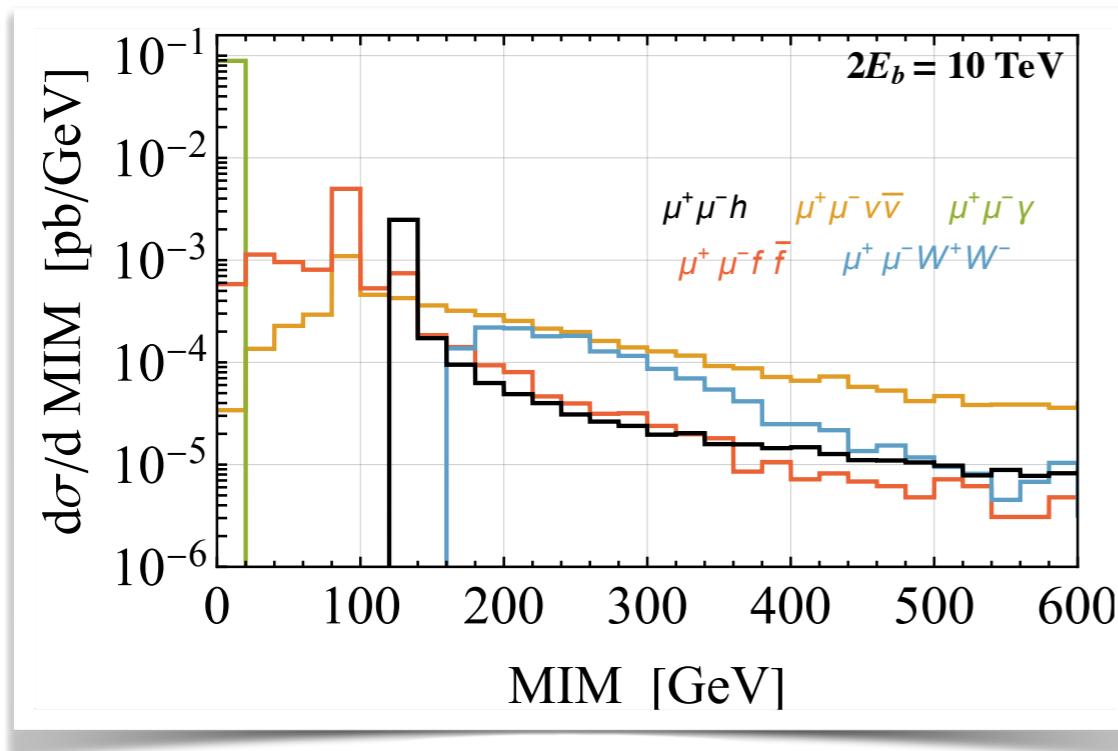


**nearly optimal sensitivity
is achievable at truth level**



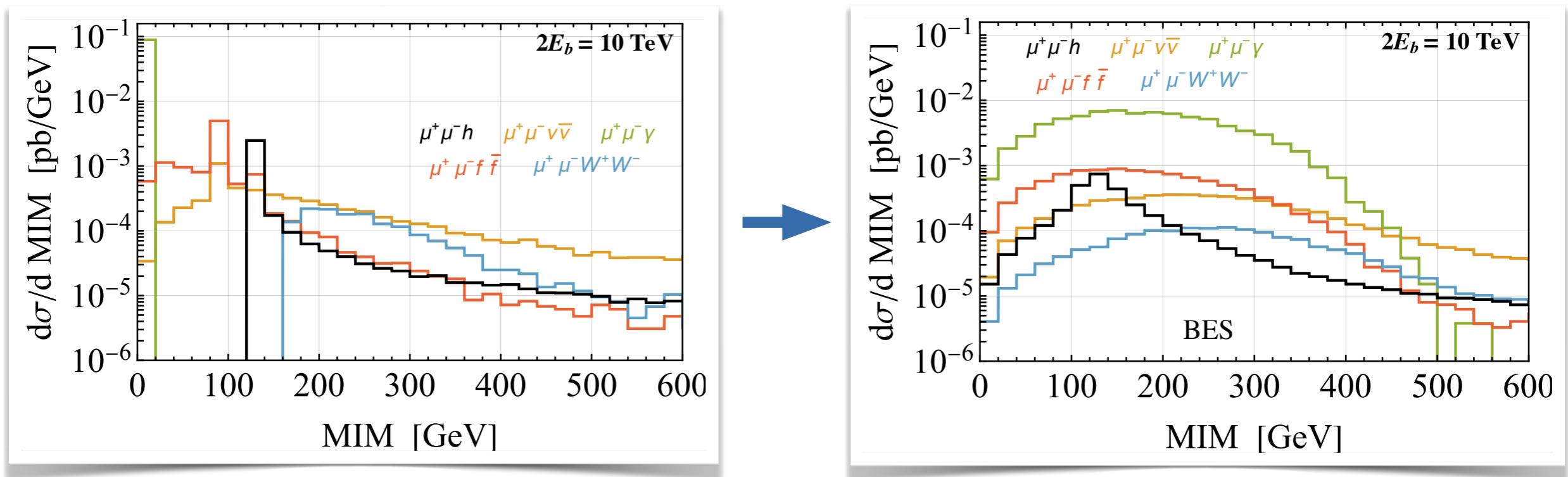
Accelerator Effects

- But: MIM loses discriminatory power with accelerator + detector effects



Accelerator Effects

- But: MIM loses discriminatory power with accelerator + detector effects



0.1% beam energy spread

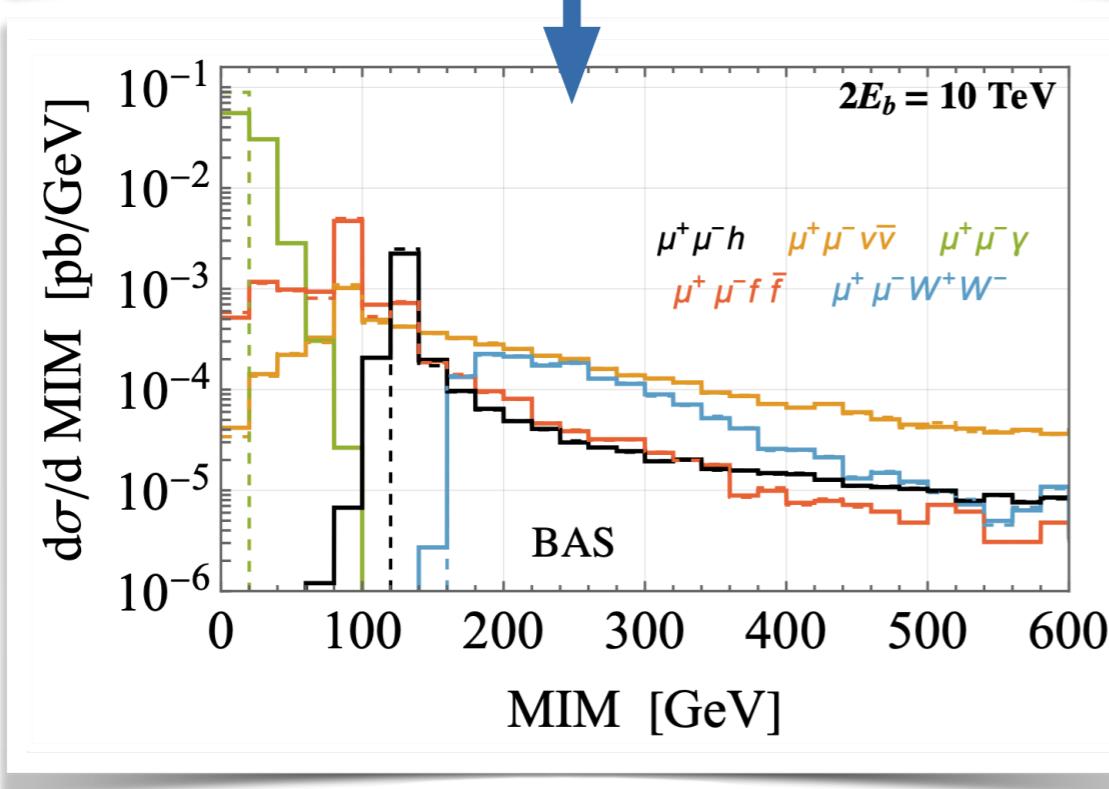
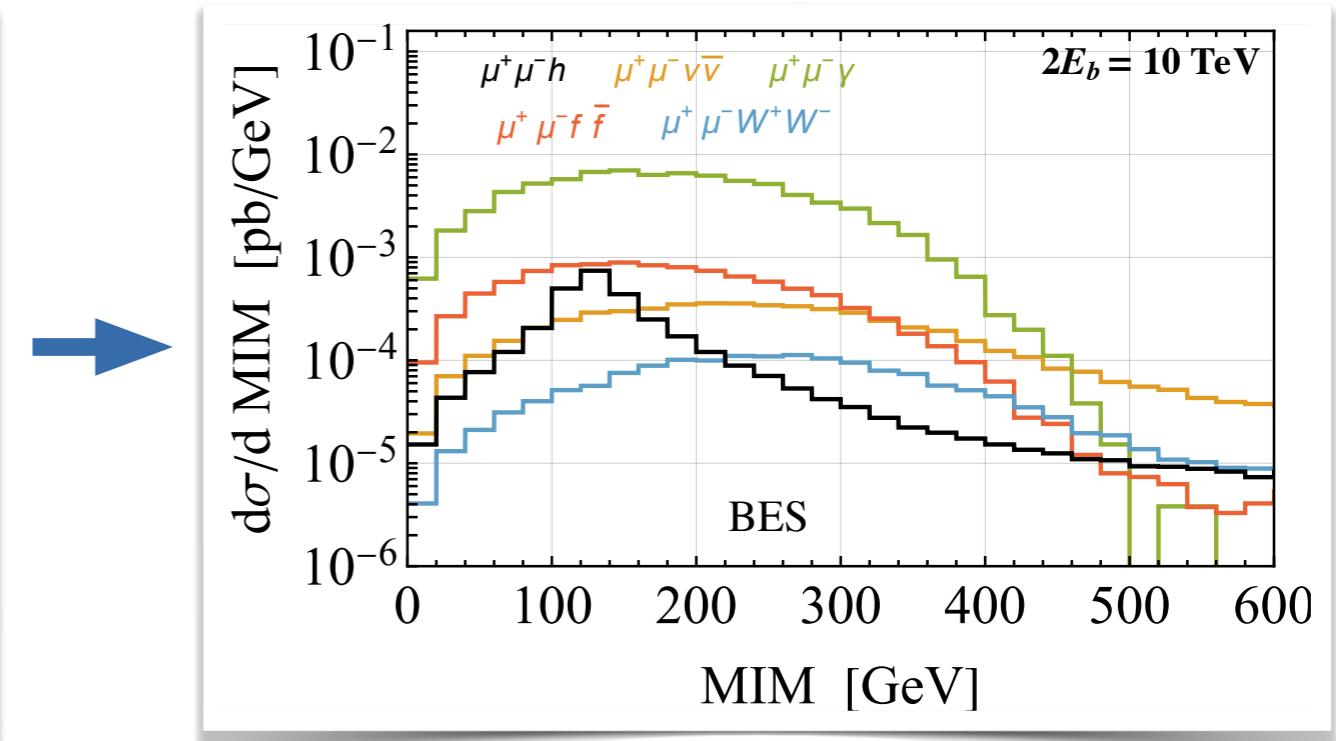
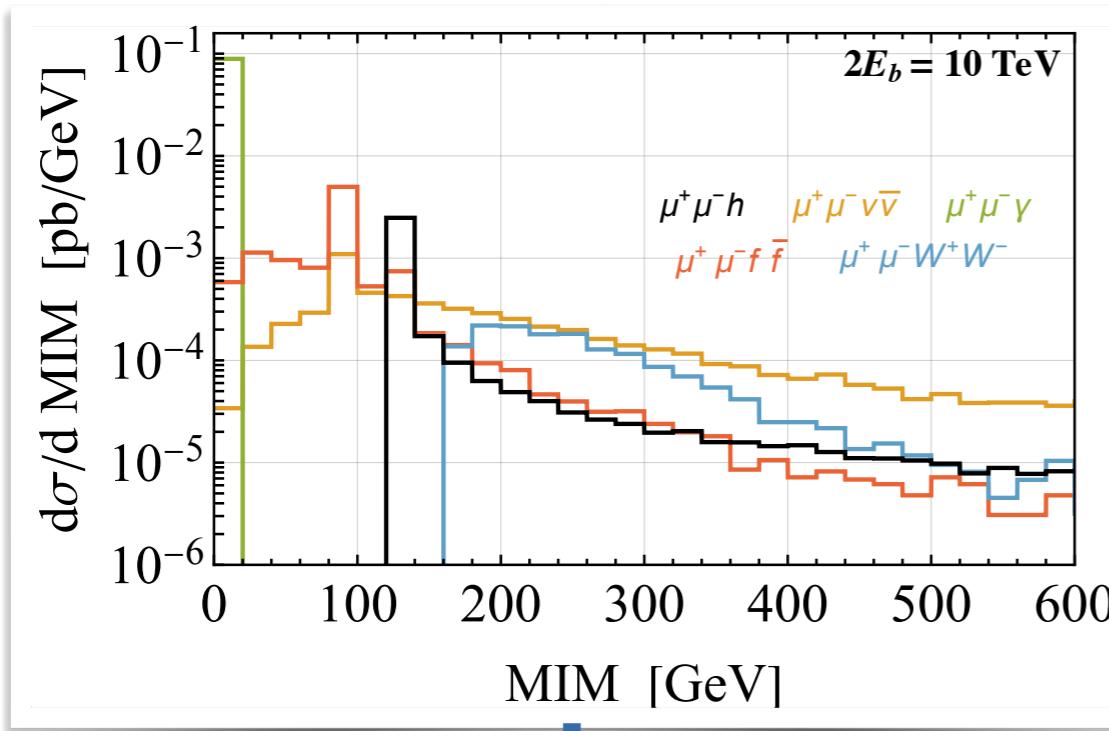
$$\mu^- \quad \mu^+$$

$$p_{\mu^-} = (E_1, 0, 0, E_1)$$

$$p_{\mu^+} = (E_2, 0, 0, -E_2)$$

Accelerator Effects

- But: MIM loses discriminatory power with accelerator + detector effects



$\Delta\theta \sim 0.6 \text{ mrad beam angular spread}$



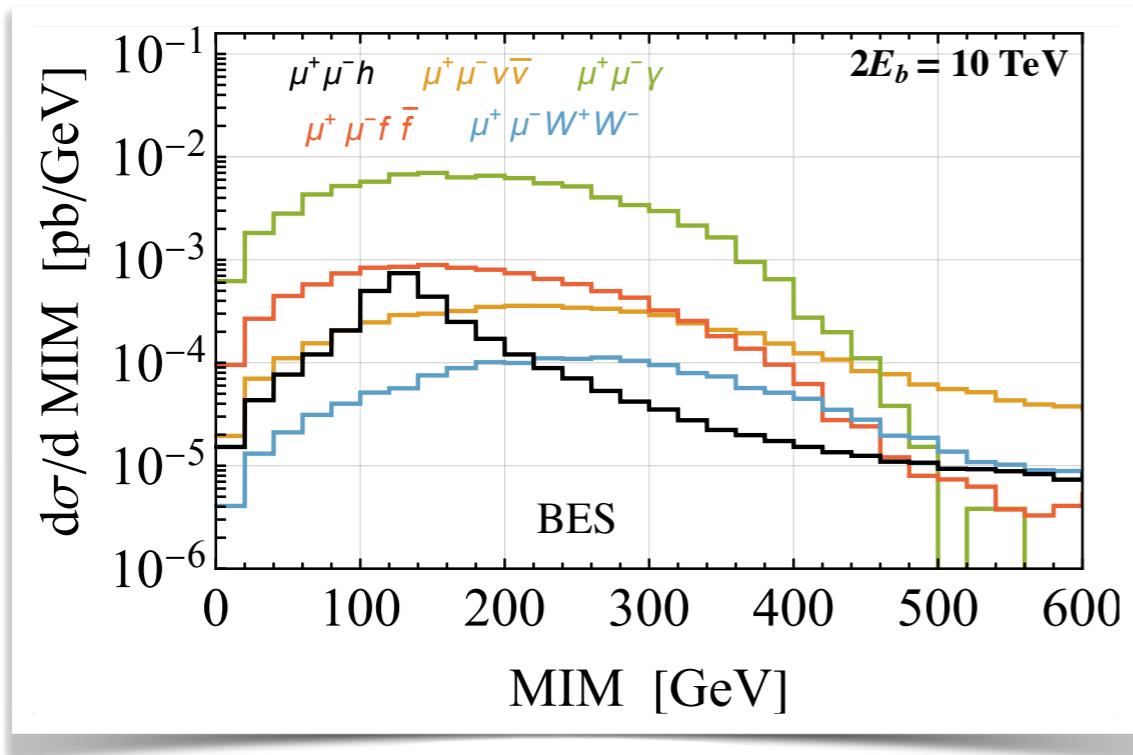
has negligible effect

Detector / Propagation Effects

- Muon energy gets **smeared** when traversing nozzle

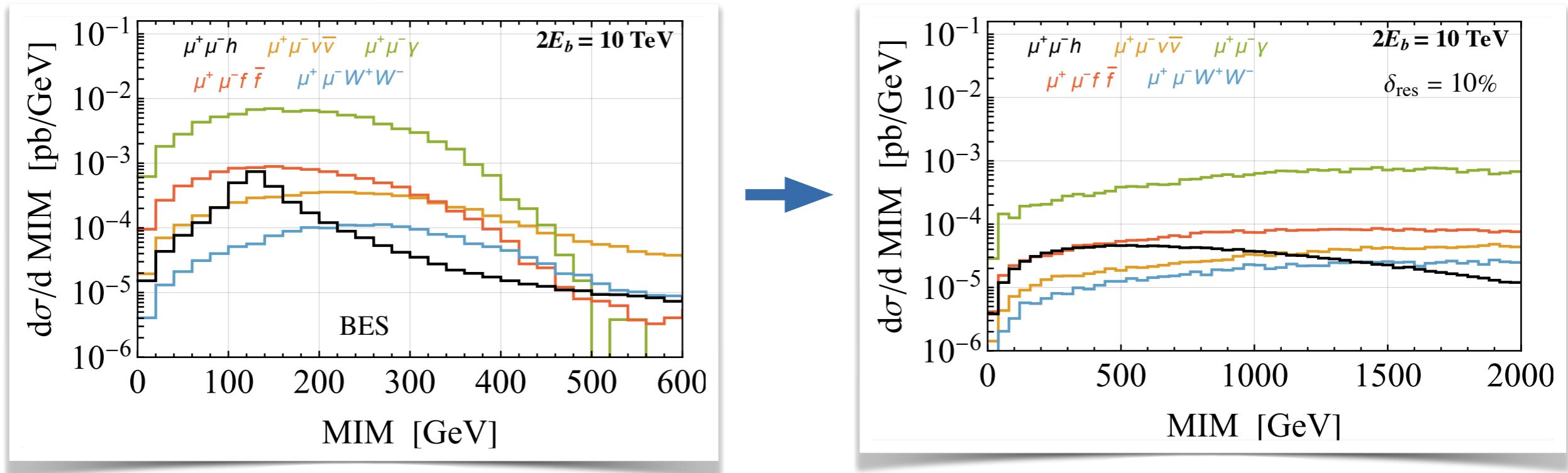
Detector / Propagation Effects

- Muon energy gets **smeared** when traversing nozzle



Detector / Propagation Effects

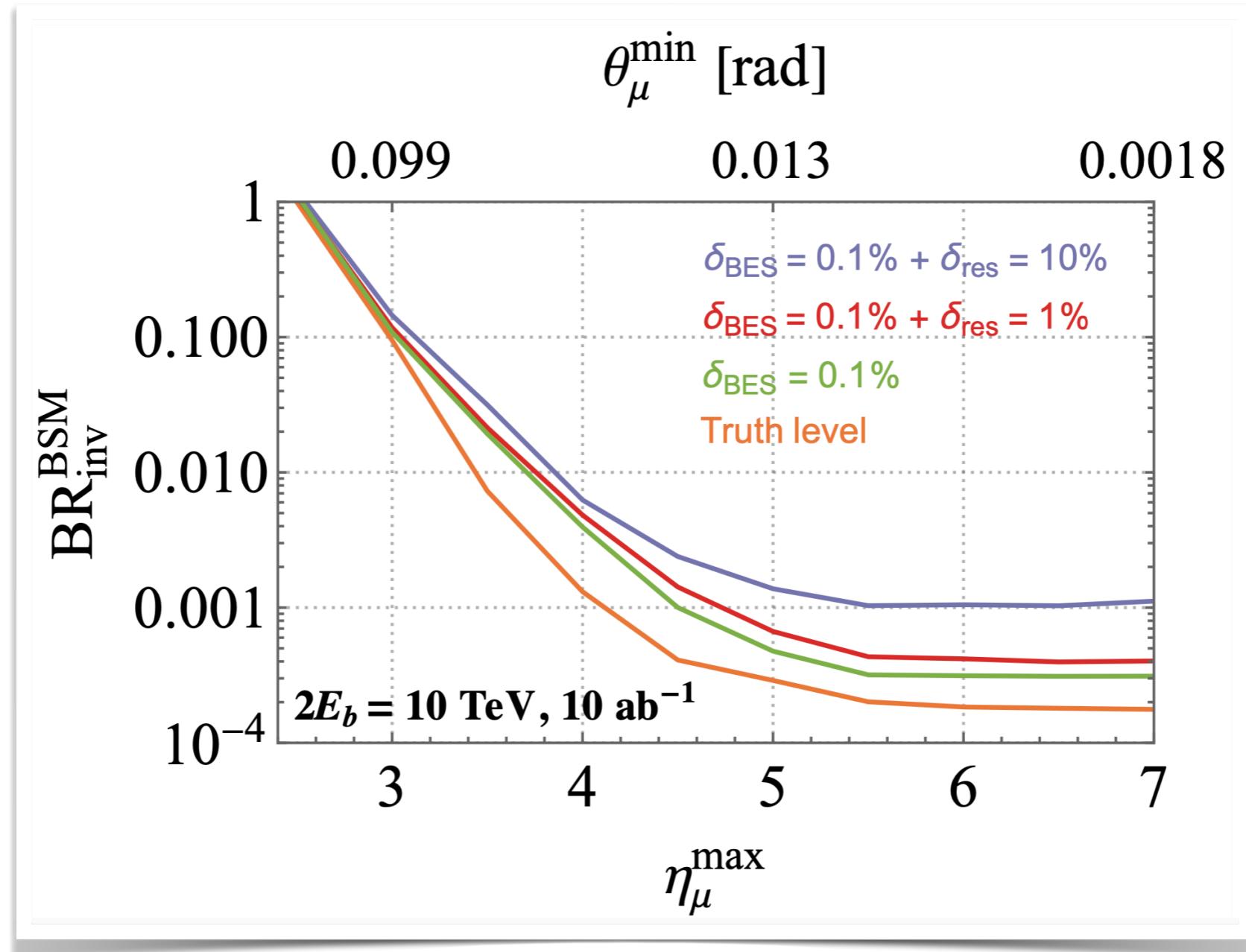
- Muon energy gets **smeared** when traversing nozzle



→ for 10% smearing MIM is almost flat

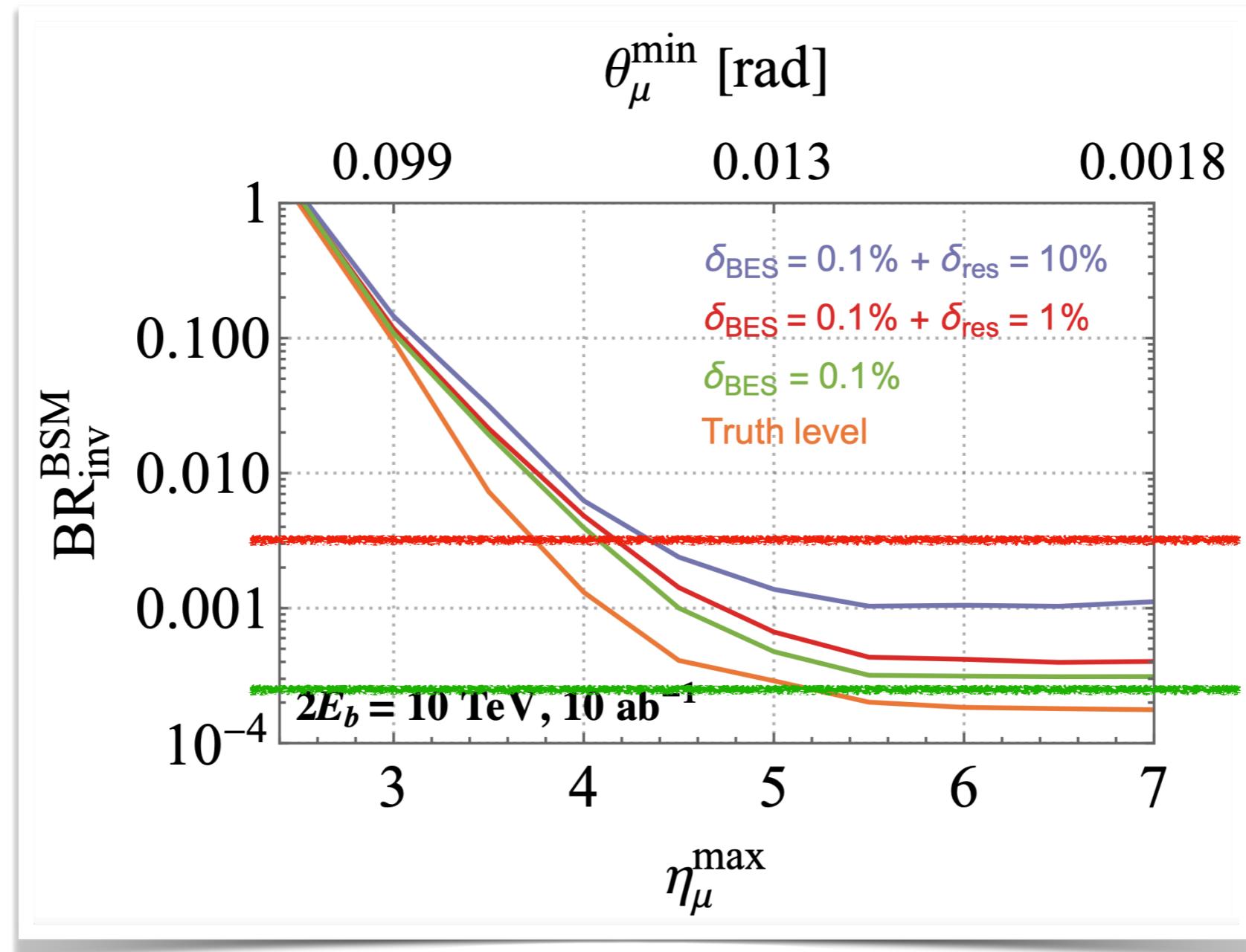
10% smearing is inspired by preliminary
simulation results by Daniele Calzolari
see: [KITP talk](#)

Results



coverage up to pseudorapidity of 5-6 needed for ultimate sensitivity

Results



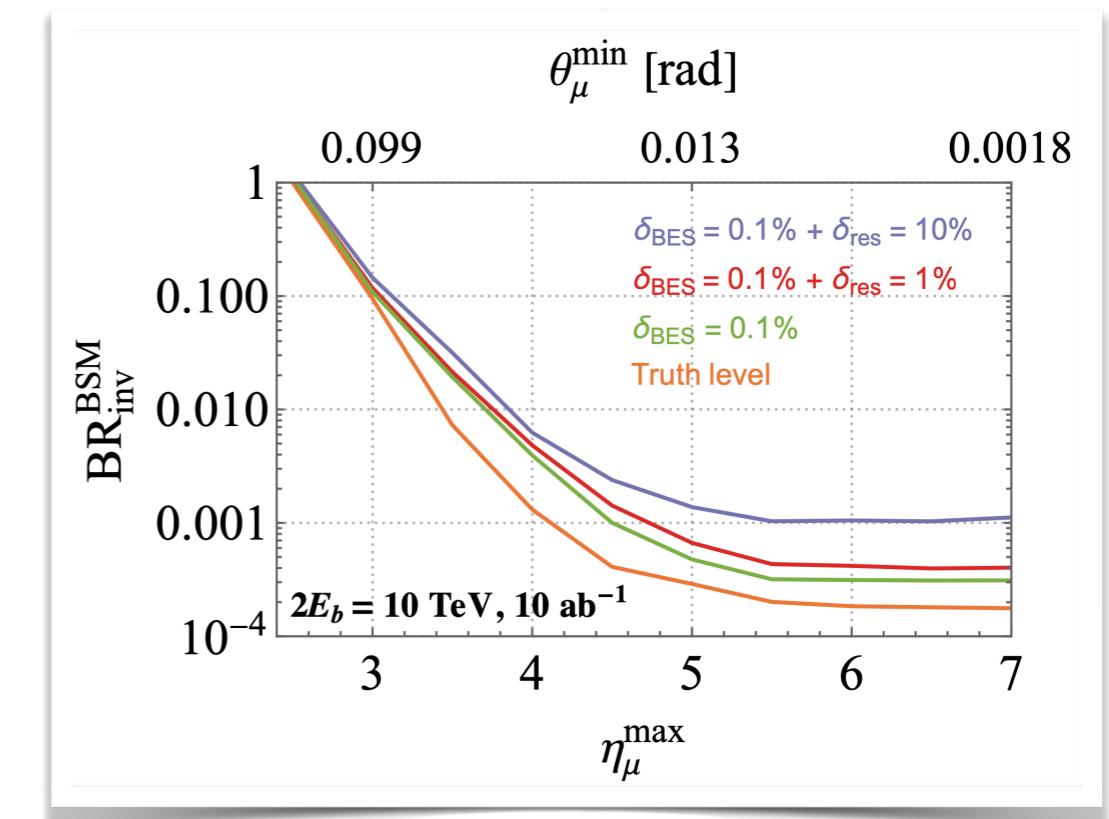
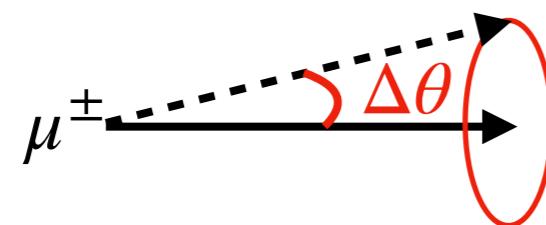
FCC-ee, ILC
1905.03764

FCC-hh
CERN-ACC-2018-0045

coverage up to pseudorapidity of 5-6 needed for ultimate sensitivity

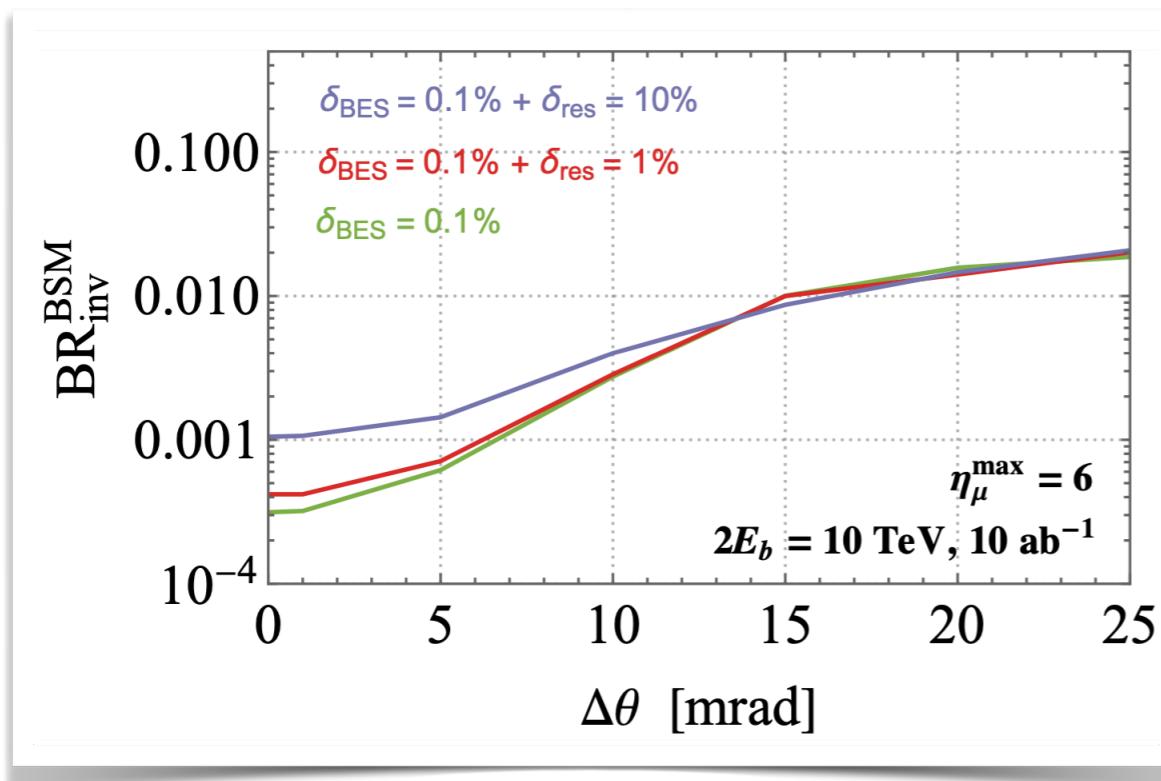
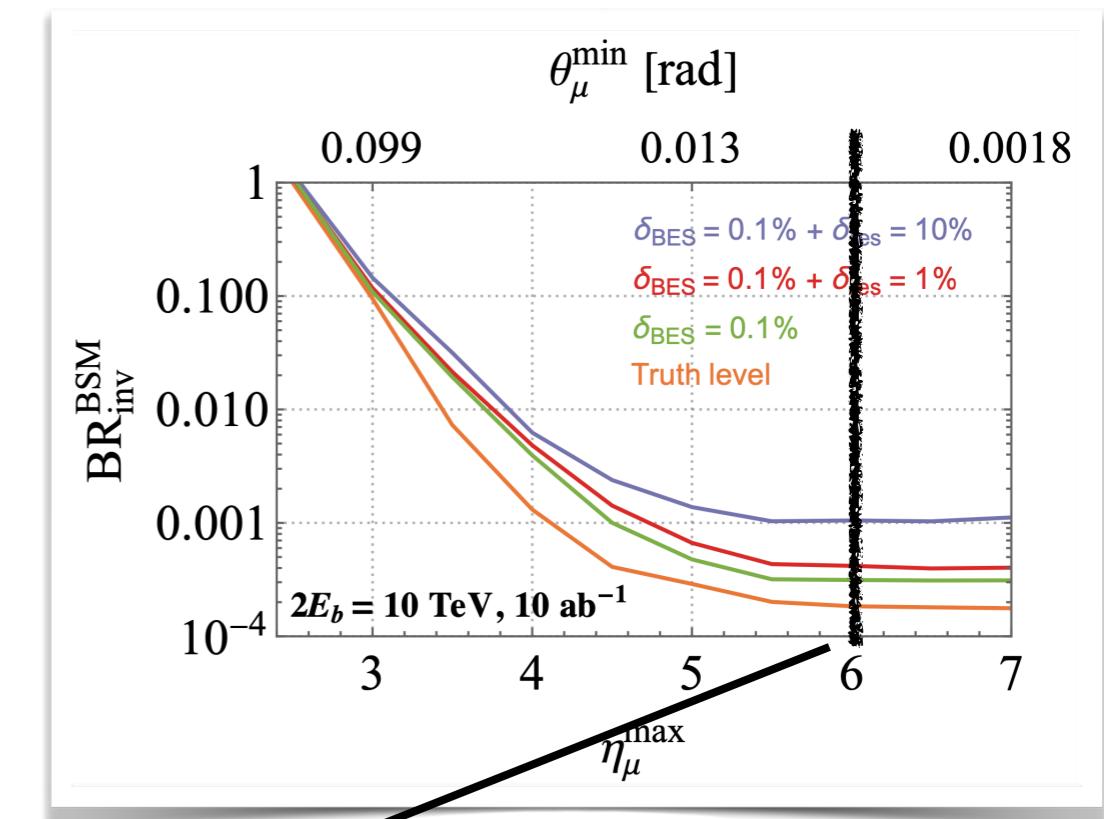
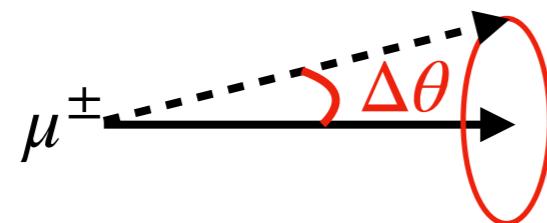
Angular Resolution

Effect of finite angular resolution



Angular Resolution

Effect of finite angular resolution



along this slice

no significant loss in sensitivity
for $\Delta\theta < 5 \text{ mrad}$

Conclusions

- A forward muon detector would ideally allow a sensitivity of
$$\text{BR}(h \rightarrow \text{inv}) \sim 10^{-4}$$

→ ultimate sensitivity is reached for $\eta_\mu^{\max} = 5 - 6$
- Realistic sensitivity is limited by muon energy uncertainty / detector resolution
$$\delta_{\text{res}} = 10\% : \quad \text{BR}(h \rightarrow \text{inv}) \lesssim 10^{-3}$$

Conclusions

- A forward muon detector would ideally allow a sensitivity of
$$\text{BR}(h \rightarrow \text{inv}) \sim 10^{-4}$$

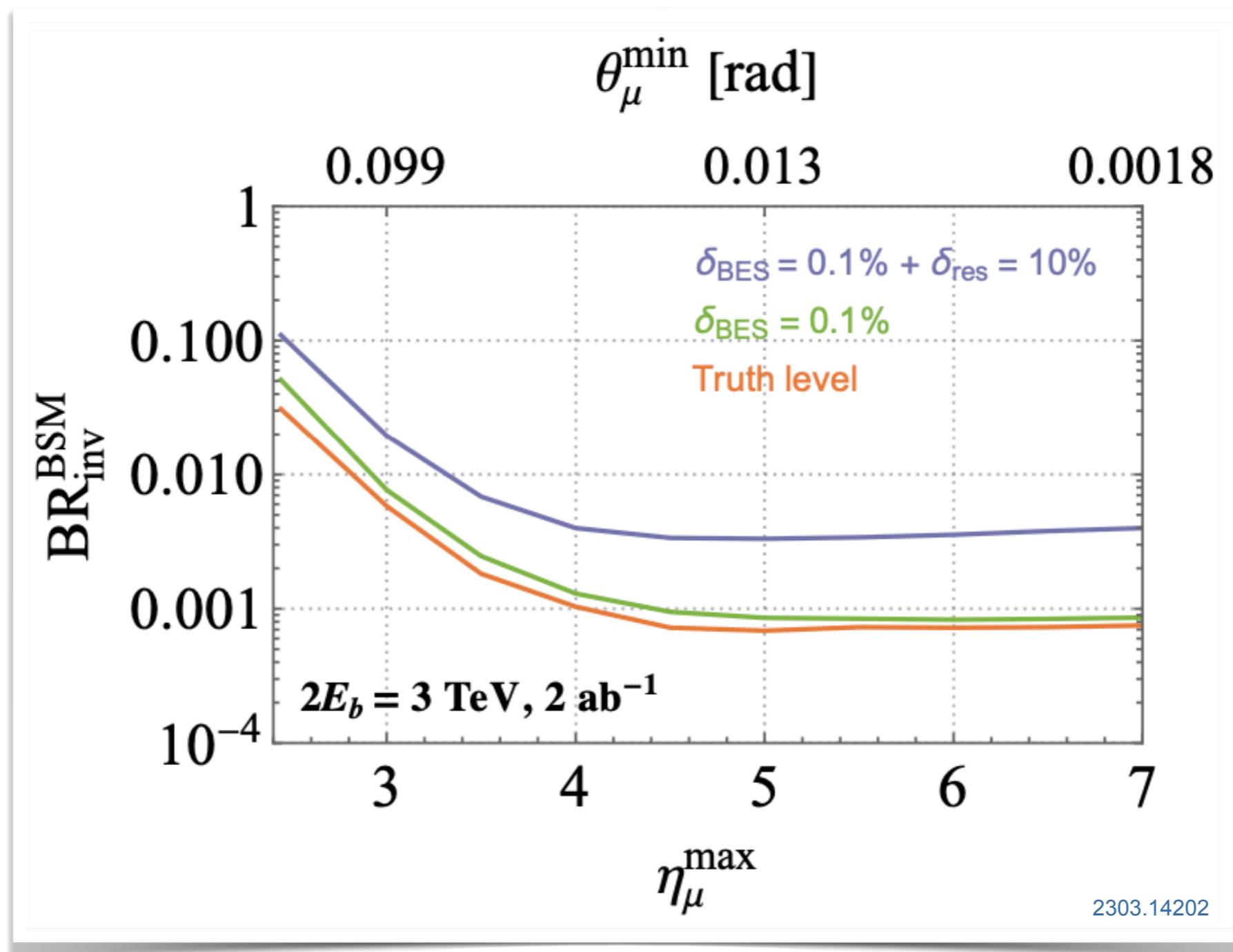
→ ultimate sensitivity is reached for $\eta_\mu^{\max} = 5 - 6$
- Realistic sensitivity is limited by muon energy uncertainty / detector resolution
$$\delta_{\text{res}} = 10\% : \quad \text{BR}(h \rightarrow \text{inv}) \lesssim 10^{-3}$$

Outlook: forward muon detector has bigger physics potential
(Higgs coupling measurements, Higgs portal models,...)

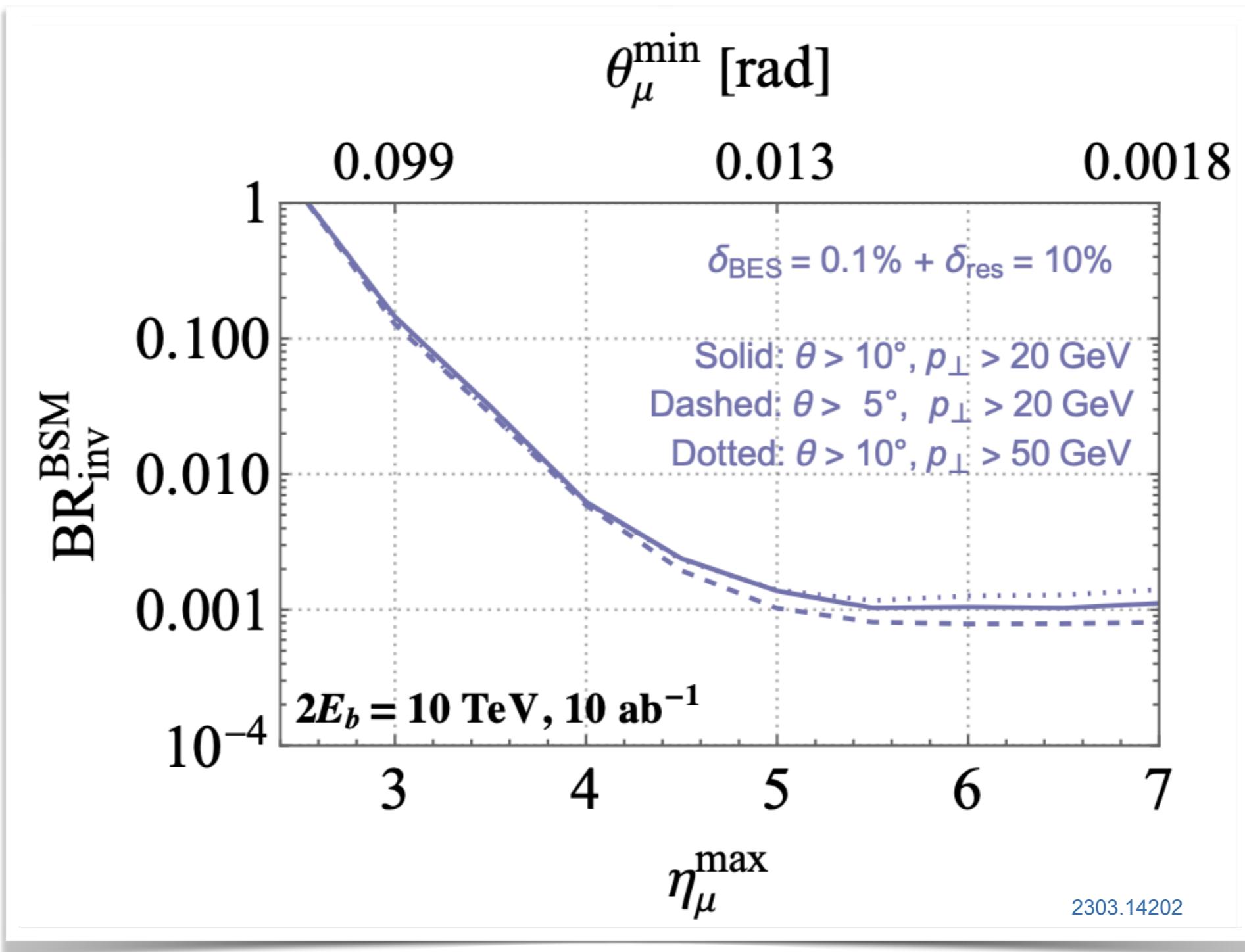
**Detailed study on physics potential of forward
muon detector is currently in work**

Backup

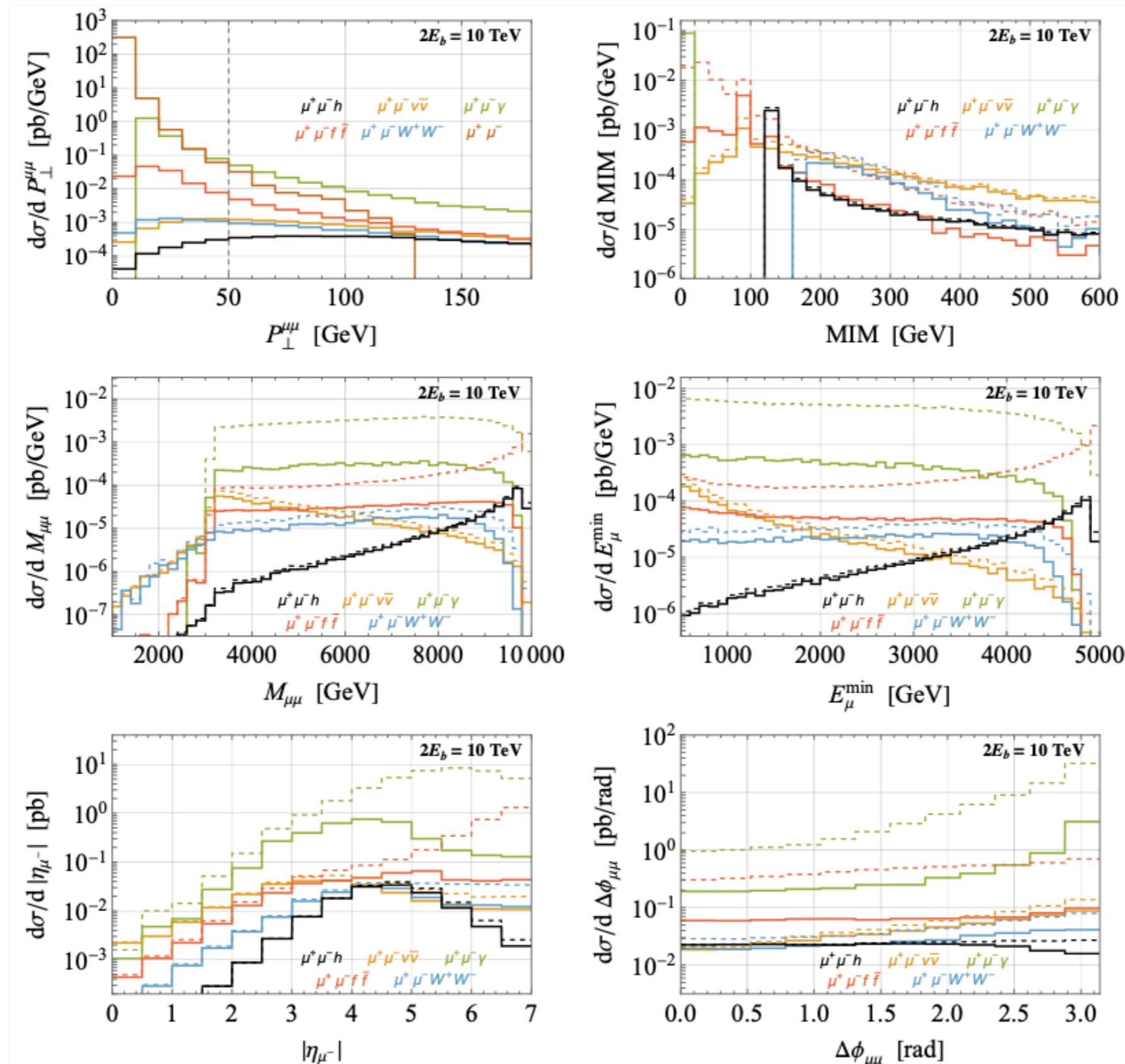
Invisible Higgs Decays 3 TeV



Effects of Main Detector



Parton Level Distributions



Distributions after 1% and 10% Energy Smearing

