Why detect forward muons at a muon collider

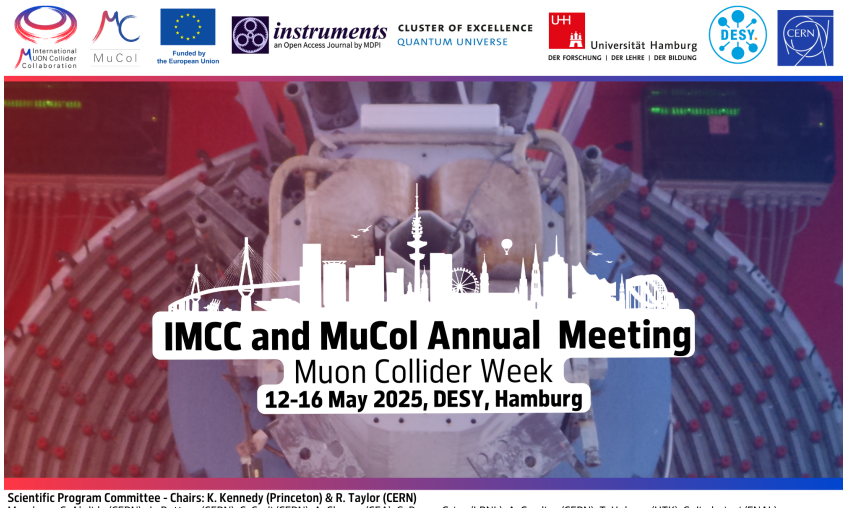
2411.00096 and 2303.14202

with Max Ruhdorfer (Stanford) and Andrea Wulzer (IFAE/ICREA Barcelona)

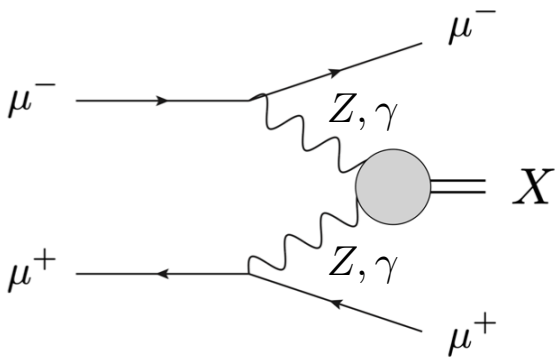
Ennio Salvioni

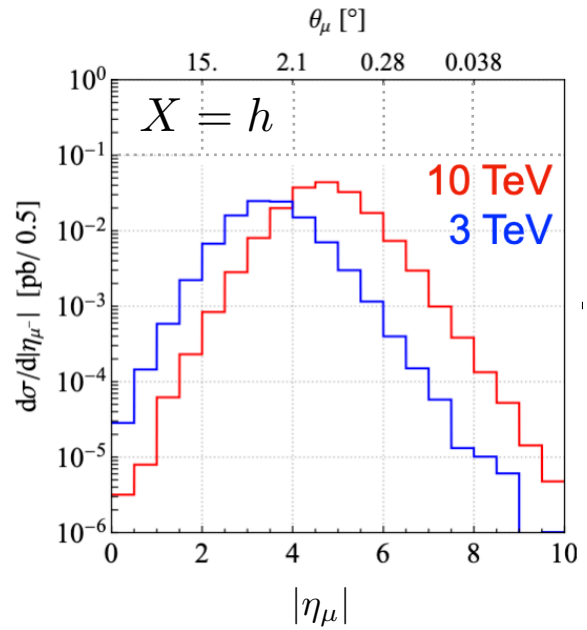
UNIVERSITY OF SUSSEX

Science and Technology Facilities Council



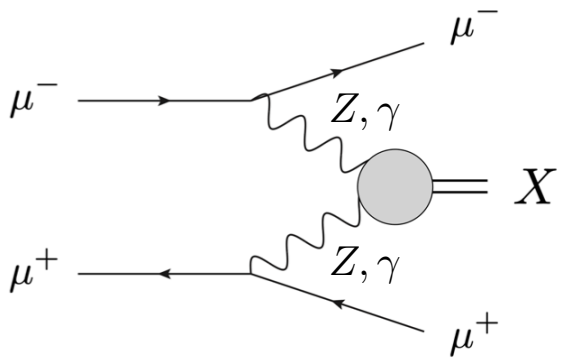
Why detect forward muons?

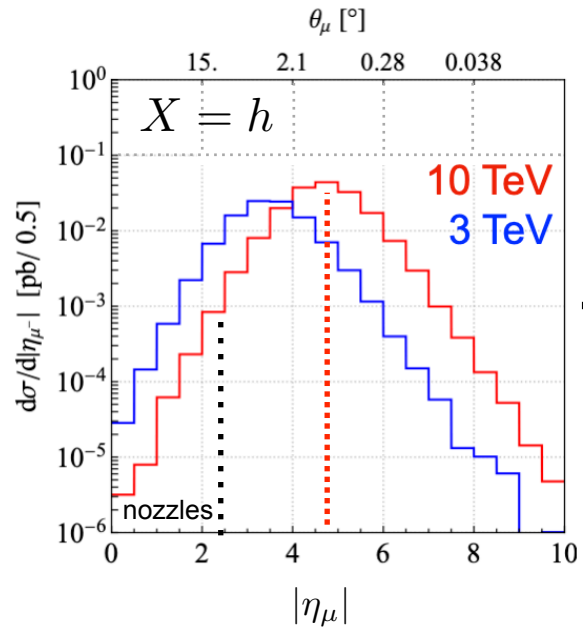




- High-energy MC is vector boson collider
- Neutral gauge boson emissions are associated with high-rapidity muons. Detecting them is:
  - Essential if X is invisible
  - Important for characterisation of VBF / VBS processes

Why detect forward muons?





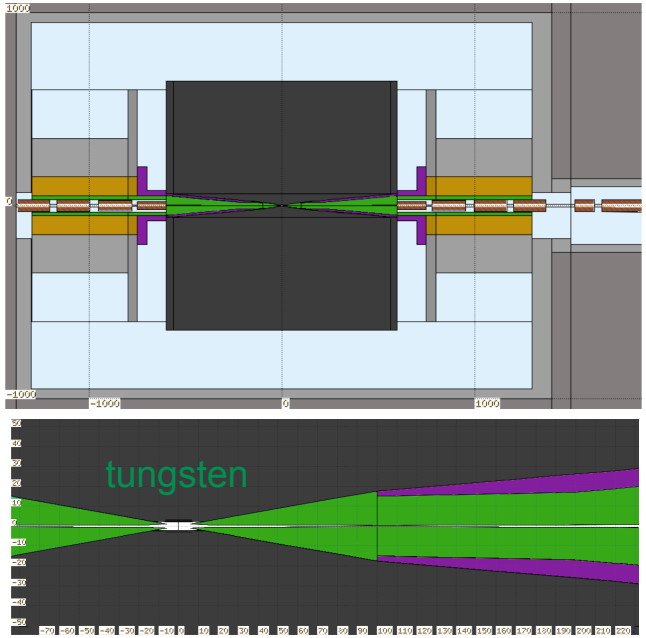
- High-energy MC is vector boson collider
- Neutral gauge boson emissions are associated with high-rapidity muons. Detecting them is:
  - Essential if X is invisible
  - Important for characterisation of VBF / VBS processes
- Z emissions: $p_\perp \sim m_Z$

for $m_X \ll E_\mathrm{b}$ → $\theta_\mu \sim \dfrac{m_Z}{E_\mathrm{b}} \sim 18\ \mathrm{mrad}$ $(|\eta_\mu| \simeq 4.7)$

detecting muons up to $\eta_\mu^{\max} = 6$ would ensure near-complete coverage

How to detect forward muons?

[EPJC report 2303.08533]



- Absorber nozzles that reduce BIB
  cut out $\theta < 10^{\circ}$ with current design $(|\eta| > 2.44)$

- But high-energy muons traverse shielding:
  instrument forward region with dedicated muon detector

- What performance can be achieved?
  Only tagging, measurement of angles,
  measurement of angles + momentum?

Goals of this work:

✓ Identify physics opportunities with forward muons at MC

✓ Evaluate requirements on forward muon detector performance

[Ruhdorfer, Salvioni, Wulzer 2411.00096 and 2303.14202]

Physics opportunities with forward muons

Direct searches for BSM particles

Precision measurements

tagging

angles

angles + momentum

?

EW dark matter

[Han, Liu, Wang, Wang 2021]

new vector bosons

[Airen, Broadberry, Marques-Tavares, Ricci 2024]

…

Higgs portal models

[Ruhdorfer, Salvioni, Wulzer 2024]

Higgs couplings

[Forslund, Meade 2022]

VBS interference resurrection

CP - violating hVV couplings

[Ruhdorfer, Salvioni, Wulzer 2024]

invisible Higgs decays

[Ruhdorfer, Salvioni, Wulzer 2023 + 2024]

[Forslund, Meade 2023]

inclusive Higgs production

[Li, Liu, Lyu 2024]

[Ruhdorfer, Salvioni, Wulzer 2024]

Requirements on detector

[credits: Max Ruhdorfer]

Physics opportunities with forward muons

Direct searches for BSM particles

Precision measurements

tagging

angles

angles + momentum

?

Higgs couplings

[Forslund, Meade 2022]

VBS interference resurrection

CP - violating hVV couplings

[Ruhdorfer, Salvioni, Wulzer 2024]

new vector bosons

[Airen, Broadberry, Marques-Tavares, Ricci 2024]

EW dark matter

[Han, Liu, Wang, Wang 2021]

invisible Higgs decays

[Ruhdorfer, Salvioni, Wulzer 2023 + 2024]

[Forslund, Meade 2023]

Higgs portal models

[Ruhdorfer, Salvioni, Wulzer 2024]

inclusive Higgs production

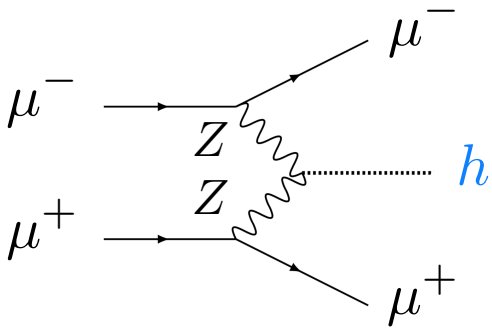
[Li, Liu, Lyu 2024]

[Ruhdorfer, Salvioni, Wulzer 2024]

Requirements on detector

[credits: Max Ruhdorfer]

Invisible Higgs at MC



Produce on-shell Higgs that decays invisibly

Predicted by SM + broad BSM motivations

@ 10 TeV, 10 ab^{-1} : 620 000 Higgses in *ZZ* fusion (VBF cuts)

In SM, $\mathrm{BR}(h \to 4\nu) = 1.2 \times 10^{-3}$ → 750 invisible decays

Relative precision of few percent: in principle could be sensitive to $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}} \sim 10^{-4}$

Bhabha scattering is large background → suppress it with cut on $P_{\perp}^{\mu\mu} = (p_{\mu^+} + p_{\mu^-})_{\perp}$

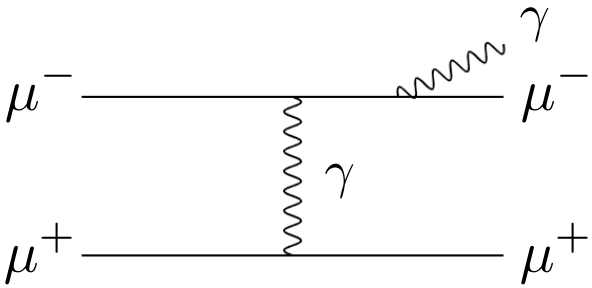
We are left with $\mu^+\mu^- X$ where X is lost (not recorded by main detector)

Invisible Higgs at MC: backgrounds

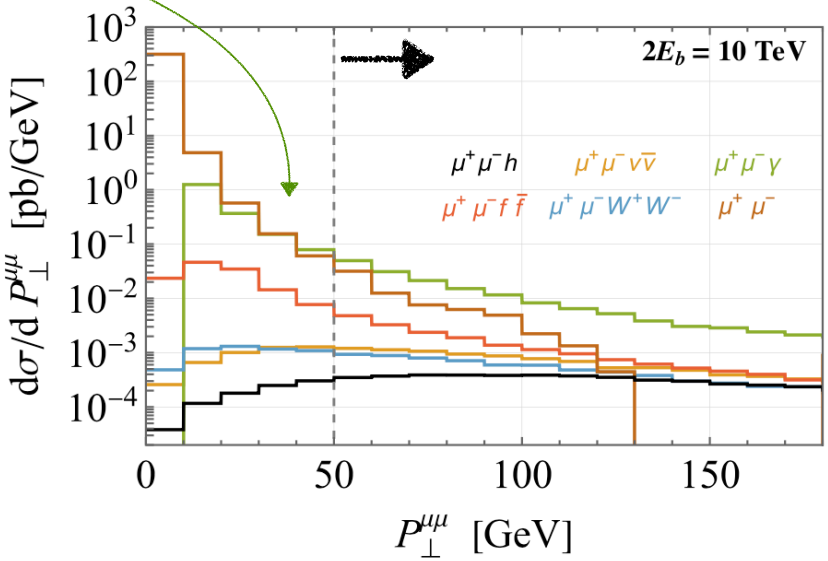
Two muons + lost objects: $\mu^+\mu^- \to \mu^+\mu^- X$

X is outside main detector, $|\eta| > 2.44$

or too soft, $p_\perp < 20$ GeV



Largest contributions from $X = \gamma,\ f\bar{f},\ W^+W^-$

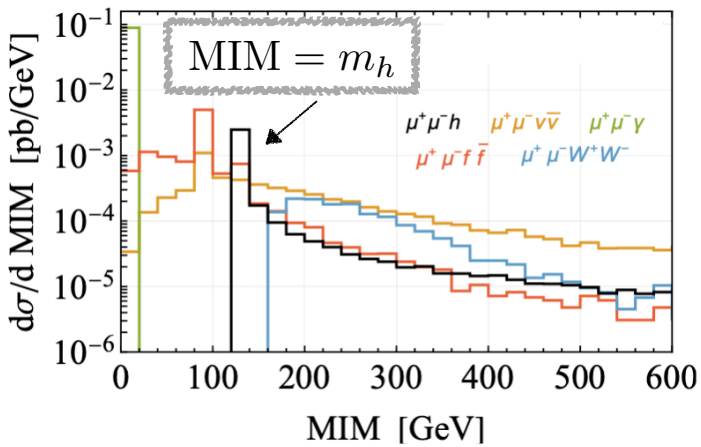


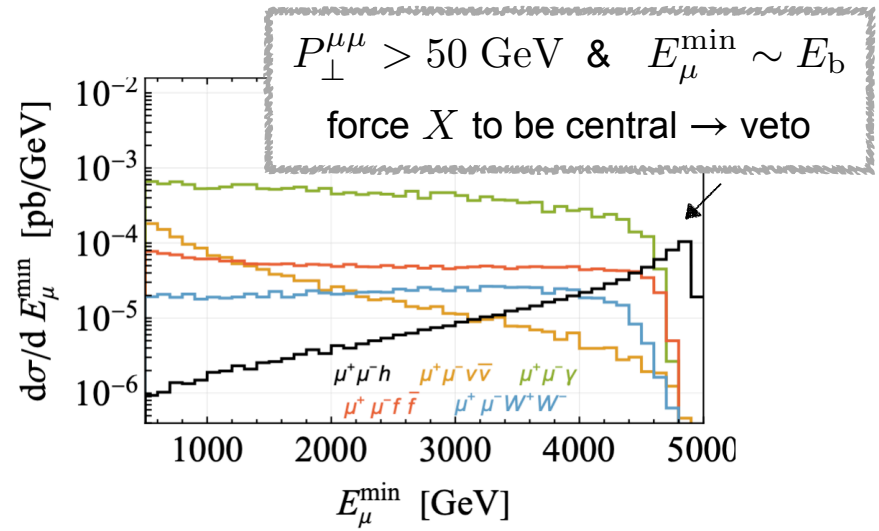
$P_\perp^{\mu\mu} > 50$ GeV

- suppresses background from photon radiation
- has mild impact on signal process $(p_\perp^\mu \sim m_Z)$

Truth-level selection

Near-ideal discrimination of *S* and *B* is possible:

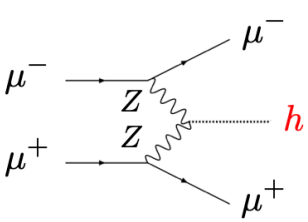


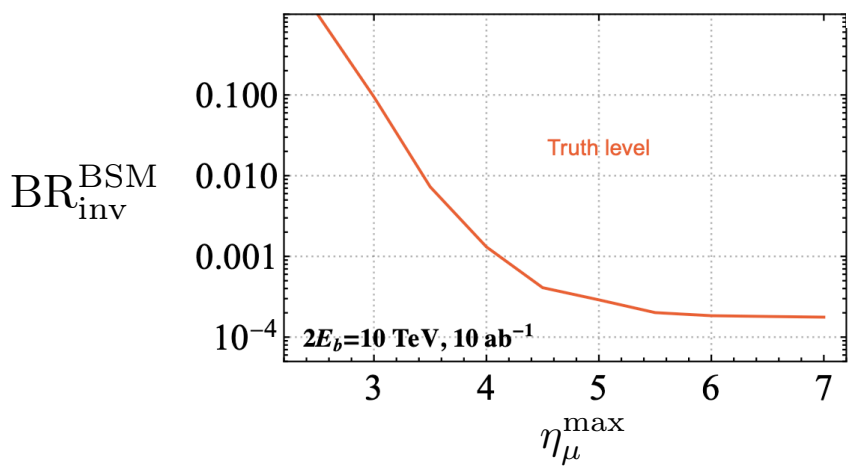


$$\mathrm{MIM} = \sqrt{|(\Delta P)^2|}$$ missing invariant mass

$$\Delta P = (2E_\mathrm{b}, \vec{0}) - p_{\mu^+} - p_{\mu^-}$$

$$E_\mu^{\min} = \min(E_{\mu^+}, E_{\mu^-})$$



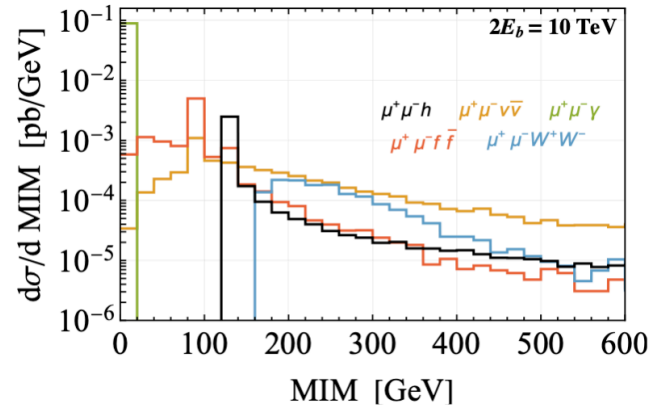


strong degradation if

$$\eta_\mu^{\max} \lesssim 5$$

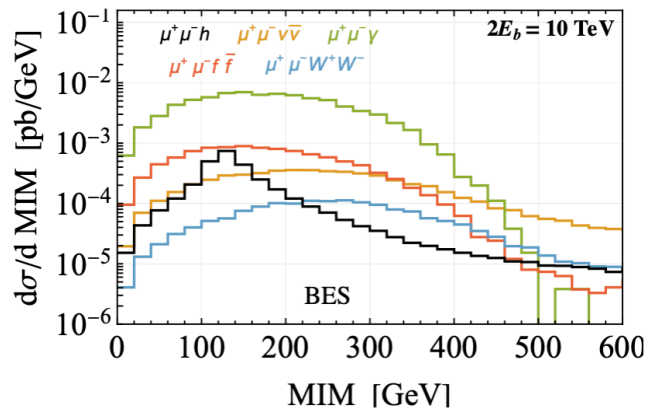
Beam and detector effects

Truth level

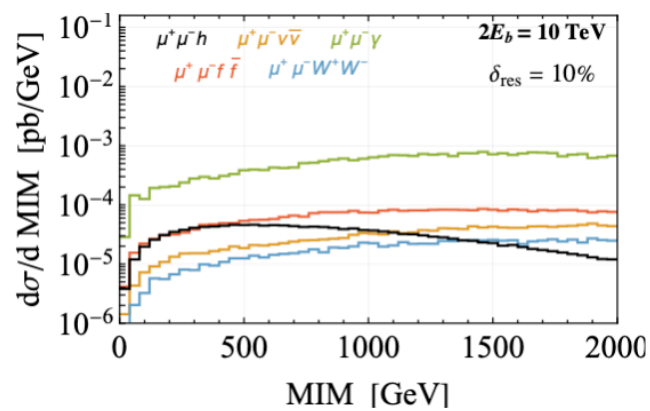


Beam energy spread of 0.1%

(BES spoils large cancellations in MIM)



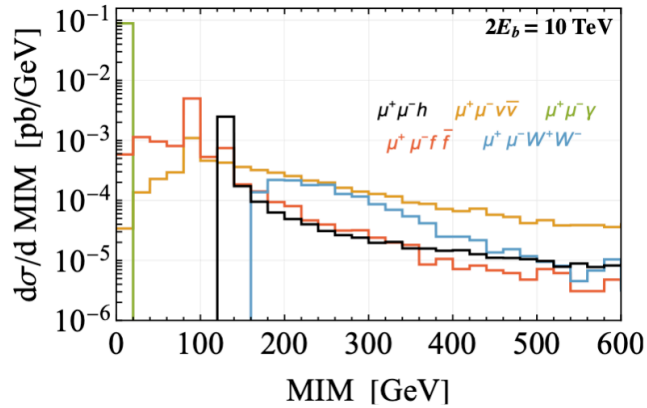
Finite resolution in measurement of muon momentum: Gaussian smearing with $\delta_{\rm res} = 10\%$



MIM does not discriminate anymore

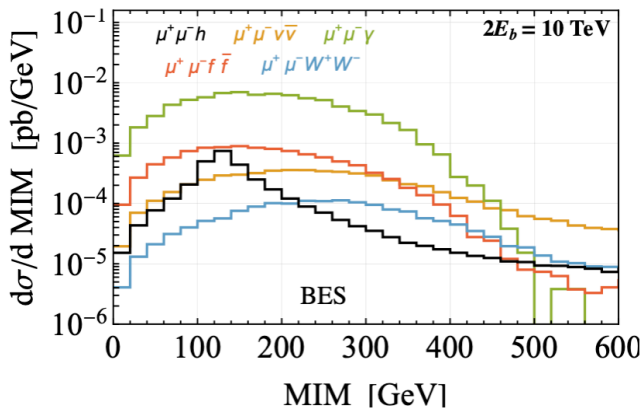
Beam and detector effects

Truth level

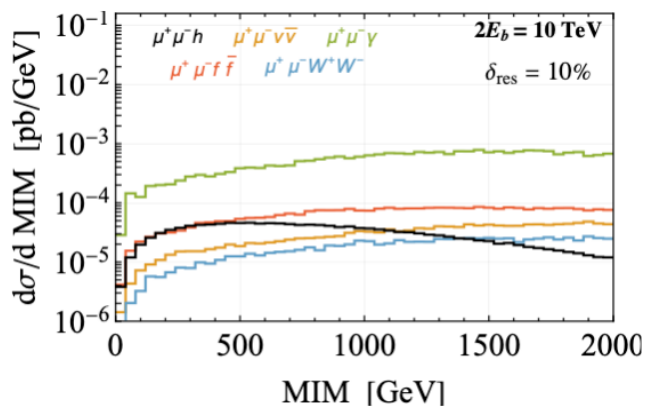


Beam energy spread of 0.1%

(BES spoils large cancellations in MIM)



Finite resolution in measurement of muon momentum: Gaussian smearing with $\delta_{\rm res} = 10\%$

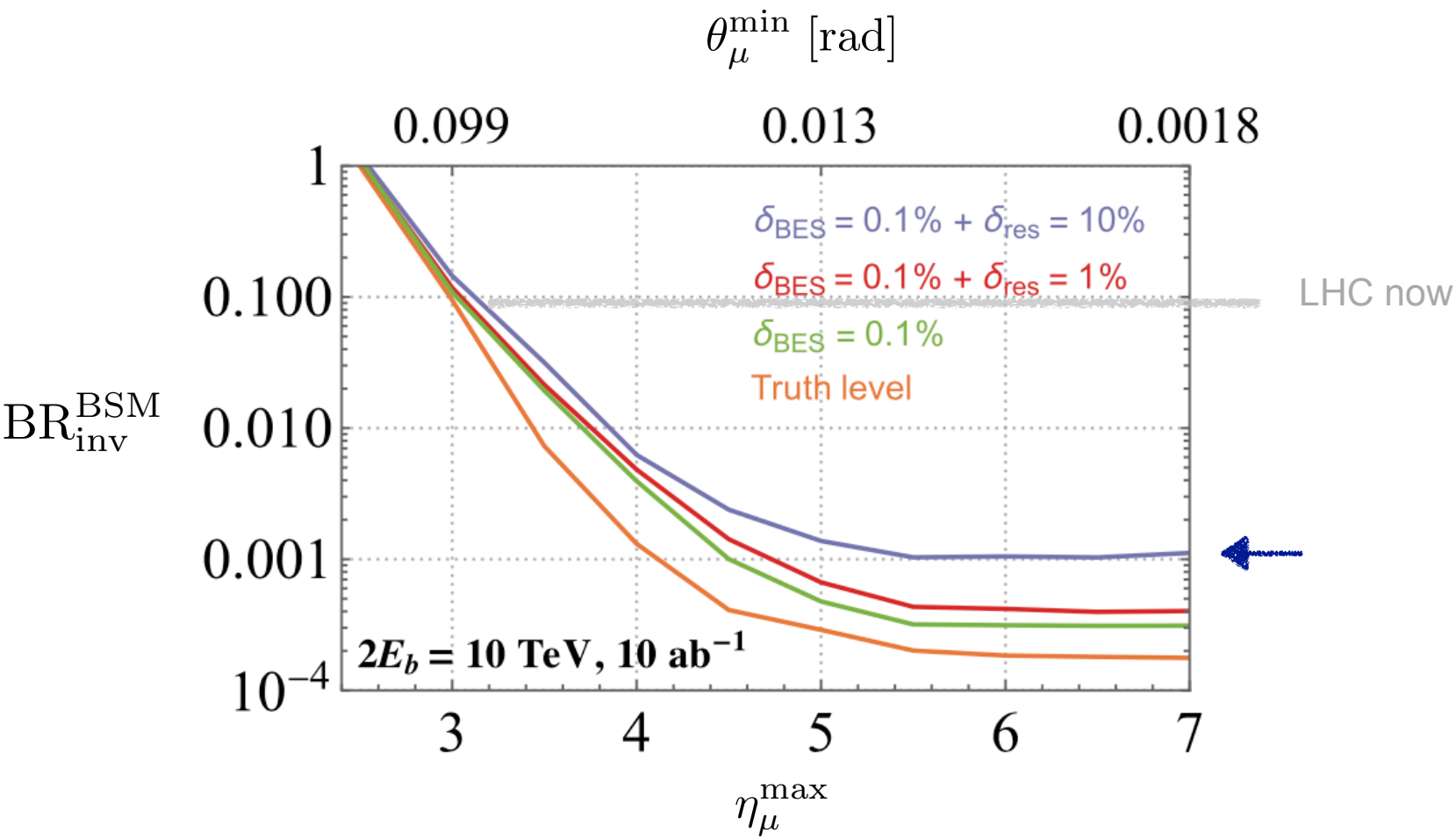


Final selection:

$$|\Delta\eta_{\mu\mu}| > 6.5\,,\ \ |\Delta\phi_{\mu\mu} - \pi| > 1\,,\ \ P_\perp^{\mu\mu} > 180\ \text{GeV}\,,$$
$$M_{\mu\mu} > 8.75\ \text{TeV}\,,\quad E_\mu^{\rm min} > 4.3\ \text{TeV}$$

Invisible Higgs at MC: sensitivity

[Ruhdorfer, Salvioni, Wulzer 2303.14202 + 2411.00096]

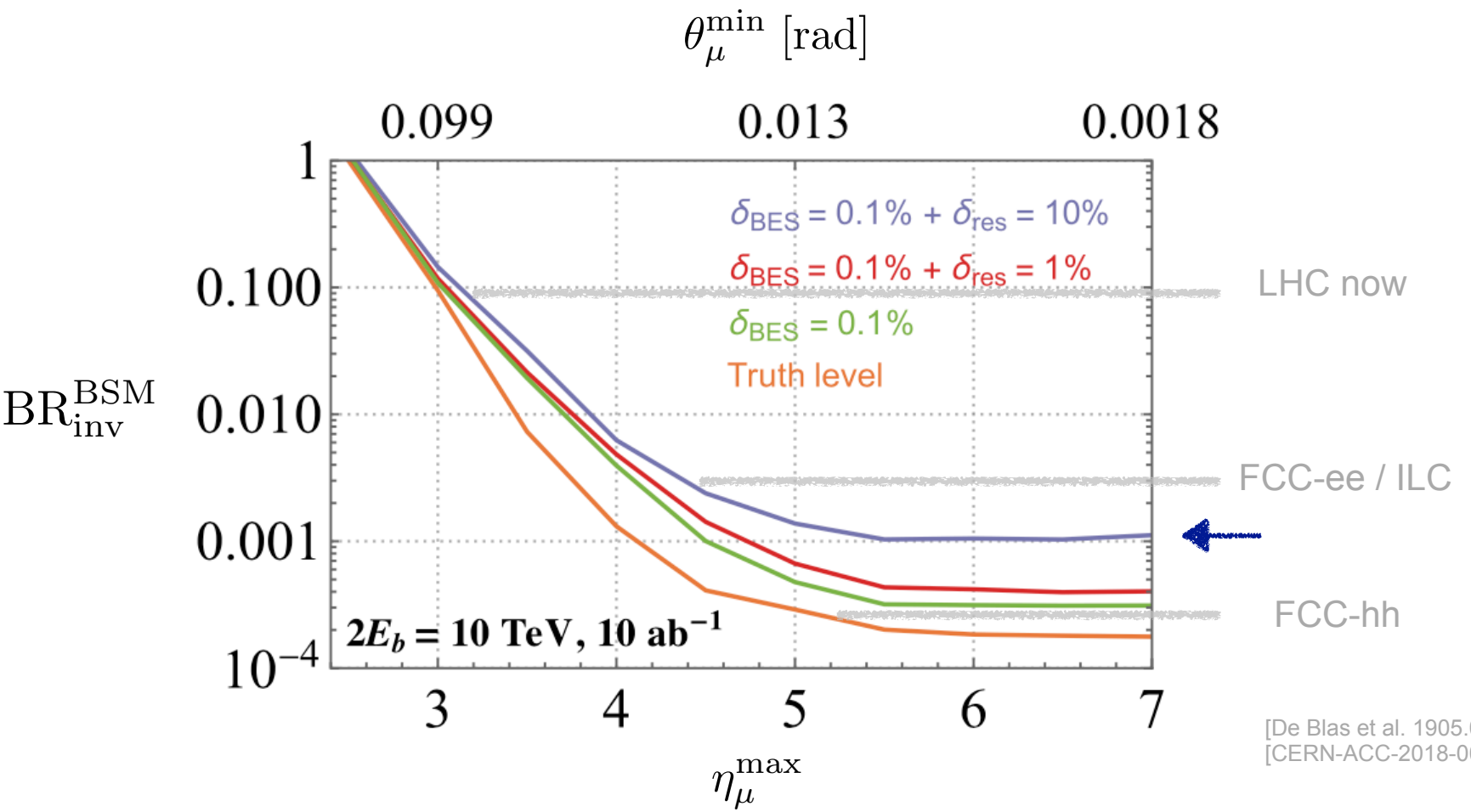


Resolution on muon momentum measurement is limiting factor

For 10% find $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}} < 1.3 \times 10^{-3}$, close to SM prediction

Invisible Higgs at MC: sensitivity

[Ruhdorfer, Salvioni, Wulzer 2303.14202 + 2411.00096]



[De Blas et al. 1905.03764]
[CERN-ACC-2018-0045]

Resolution on muon momentum measurement is limiting factor

For 10% find $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}} < 1.3 \times 10^{-3}$, close to SM prediction

Invisible Higgs portals

- Invisible BSM scalar ϕ coupled to the SM through

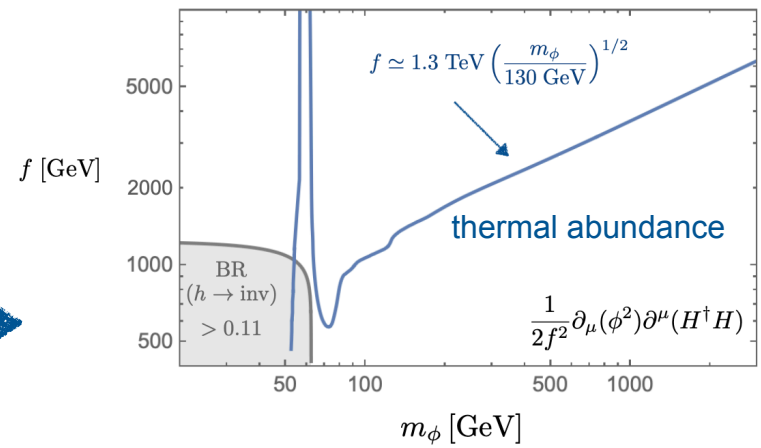
$$\mathcal{L}_{\text{renormalizable}} = -\frac{\lambda}{2}\phi^2 H^\dagger H \qquad \text{or} \qquad \mathcal{L}_{\text{derivative}} = \frac{1}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$

- "Nightmare scenarios" for new physics, notoriously difficult to test

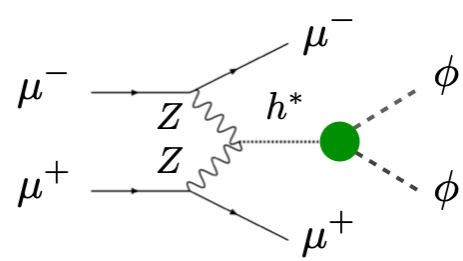
  Yet well motivated: first order electroweak phase transition, neutral naturalness, pseudo-Goldstone dark matter

  …

  [long list of references]

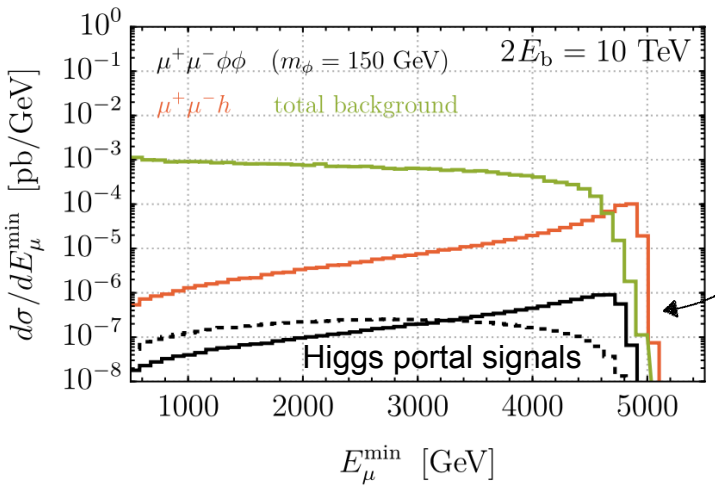


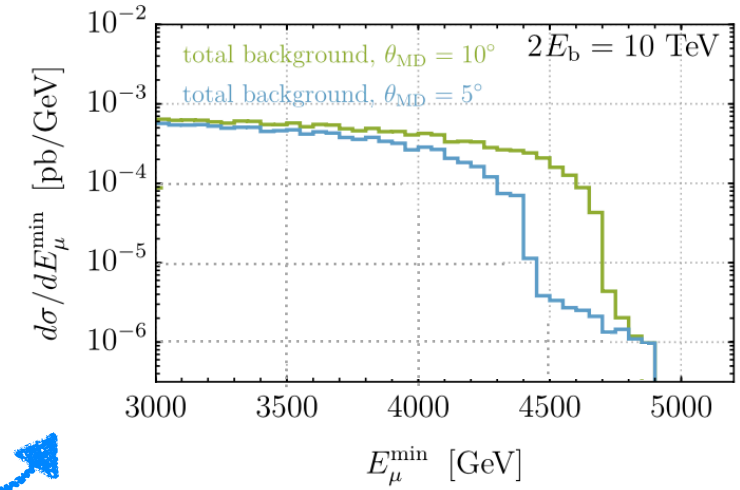
- $2m_\phi < m_h$: invisible Higgs signal
- $2m_\phi > m_h$: same final state, but off-shell kinematics



Invisible Higgs portals: analysis

- Compared to on-shell Higgs decay, the larger invisible mass $2m_\phi > m_h$ reduces $E_\mu^{\rm min}$ $\rightarrow$ reduced *S* vs *B* discrimination





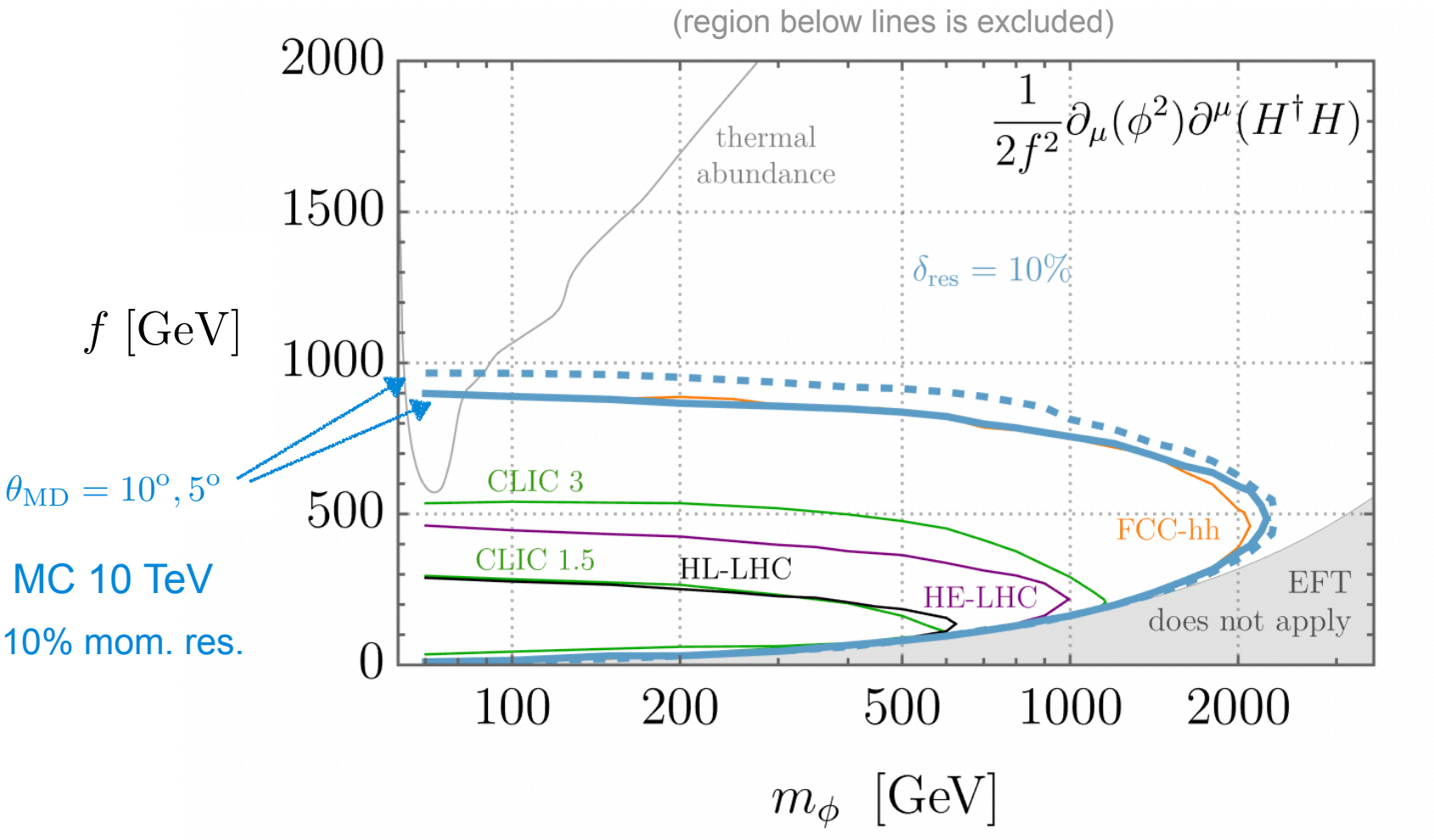
Extending angular coverage of main detector helps: for $\mu^+\mu^- X$ backgrounds can veto less central X $\rightarrow$ remove events with smaller $E_\mu^{\rm min}$

$$\left(E_\mu^{\rm min}\right)_{\rm endpoint} \simeq E_{\rm b} - \frac{P_\perp^{\mu\mu}}{\theta_{\rm MD}}$$

Baseline: $\theta_{\rm MD} = 10^{\rm o}$

Extended: $\theta_{\rm MD} = 5^{\rm o}$

Derivative Higgs portal: results



With ~ 10% momentum resolution, MC would have strongest sensitivity

Probing thermal abundance for $m_\phi \gtrsim 100$ GeV remains a challenge

Physics opportunities with forward muons

Direct searches for BSM particles

Precision measurements

tagging

angles

angles + momentum

?

EW dark matter

[Han, Liu, Wang, Wang 2021]

new vector bosons

[Airen, Broadberry, Marques-Tavares, Ricci 2024]

Higgs portal models

[Ruhdorfer, Salvioni, Wulzer 2024]

invisible Higgs decays

[Ruhdorfer, Salvioni, Wulzer 2023 + 2024]

[Forslund, Meade 2023]

Higgs couplings

[Forslund, Meade 2022]

VBS interference resurrection

CP - violating hVV couplings

[Ruhdorfer, Salvioni, Wulzer 2024]

inclusive Higgs production

[Li, Liu, Lyu 2024]

[Ruhdorfer, Salvioni, Wulzer 2024]

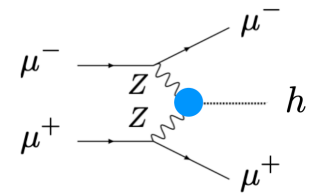
Requirements on detector

[credits: Max Ruhdorfer]

CP-violation and interference resurrection

$$\mathcal{L}_{hZZ} = \frac{m_Z^2}{v}\, h \left[c_z Z_\mu Z^\mu + \frac{\tilde{c}_{zz}}{v^2}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right]$$

CP-violating hZZ coupling



- In inclusive observables, interference effects such as $\mathcal{A}_{c_z}\mathcal{A}^*_{\tilde{c}_{zz}}$ vanish

  For instance, total cross section: $\sigma_h = (c_z^2 + \kappa_0^q \tilde{c}_{zz}^2)\sigma_{h,\mathrm{SM}}$

  only quadratic dependence on (small) $\tilde{c}_{zz}$

- Forward detector enables access to angular information

  → "resurrect" interference effects that vanish upon integration over angles

  linear dependence on $\tilde{c}_{zz}$

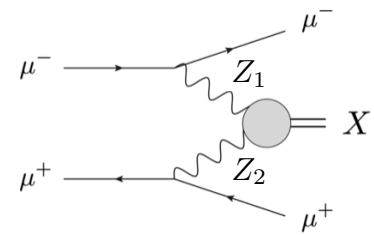
- Access interference of amplitudes with initial *Z* bosons of different helicities

- General strategy applicable to VBF and VBS processes

  Probing CP-violating Higgs couplings illustrates approach: exploit azimuthal angle ϕ of muons (momentum measurement is not necessary)

CP-violation and interference resurrection

- Density matrices in effective Z approximation



$$d\sigma = \sum_{h_{1,2},\, h'_{1,2}} \sum d\rho^{Z_1}_{h_1,h'_1}\, d\rho^{Z_2}_{h_2,h'_2}\, d\rho^{\mathrm{H}}_{h_1,h_2,h'_1,h'_2}$$

splittings

hard scattering

$$d\rho^{Z_1}_{h_1,h'_1} \propto \mathcal{A}(\mu^+ \to \mu^+ Z_1^{h_1})\mathcal{A}^*(\mu^+ \to \mu^+ Z_1^{h'_1})$$

$\ldots$

$$d\rho^{\mathrm{H}}_{h_1,h_2,h'_1,h'_2} \propto \mathcal{A}(Z_1^{h_1} Z_2^{h_2} \to X)\mathcal{A}^*(Z_1^{h'_1} Z_2^{h'_2} \to X)$$

no dependence on muon azimuthal angles

function of muon azimuthal angle and Z helicity

$$d\rho^{Z_1}_{h_1,h'_1} \propto e^{-i\,(h_1 - h'_1)\phi_+}$$

measuring ϕ allows to isolate contribution of individual helicity amplitudes to hard scattering

- For Higgs production, only hard amplitudes with $h_1 = h_2 = h$ are nonzero and

$$d\sigma \propto \sum_{h,h'} e^{-i\Delta h \Delta\phi}\, d\rho^{\mathrm{H}}_{h,h'}$$

$$\Delta\phi = \phi_+ - \phi_-$$

our observable: difference of muon azimuthal angles

$$\Delta h = h - h' = 0, \pm 1, \pm 2$$

$$\frac{d\sigma}{d\Delta\phi} = \text{constant} + f(\Delta\phi) + g(2\Delta\phi)$$

trigonometric functions, vanish upon integration over $\Delta\phi$

CP-violation in the hZZ coupling

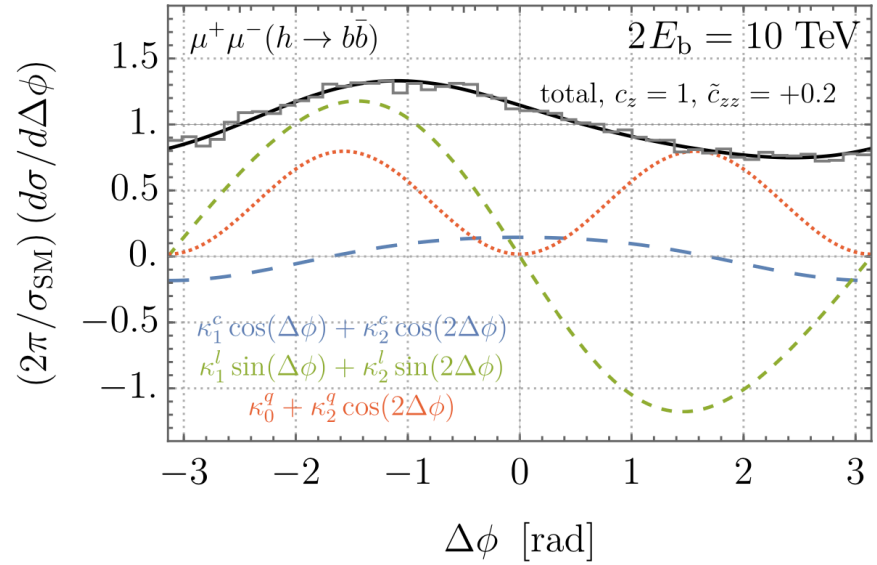
- Viewing $\tilde{c}_{zz}$ as spurion of CP violation fully fixes functional form:

$$\frac{2\pi}{\sigma_{h,\mathrm{SM}}}\frac{d\sigma_h}{d\Delta\phi} = c_z^2\left[1+\kappa_1^c\cos(\Delta\phi)+\kappa_2^c\cos(2\Delta\phi)\right] + c_z\tilde{c}_{zz}\left[\kappa_1^l\sin(\Delta\phi)+\kappa_2^l\sin(2\Delta\phi)\right] + \tilde{c}_{zz}^2\left[\kappa_0^q+\kappa_2^q\cos(2\Delta\phi)\right]$$

provides excellent fit for

$$\mu^+\mu^- \to \mu^+\mu^-(h\to b\bar{b})$$

results for SM couplings consistent with [Forslund, Meade 2203.09425]

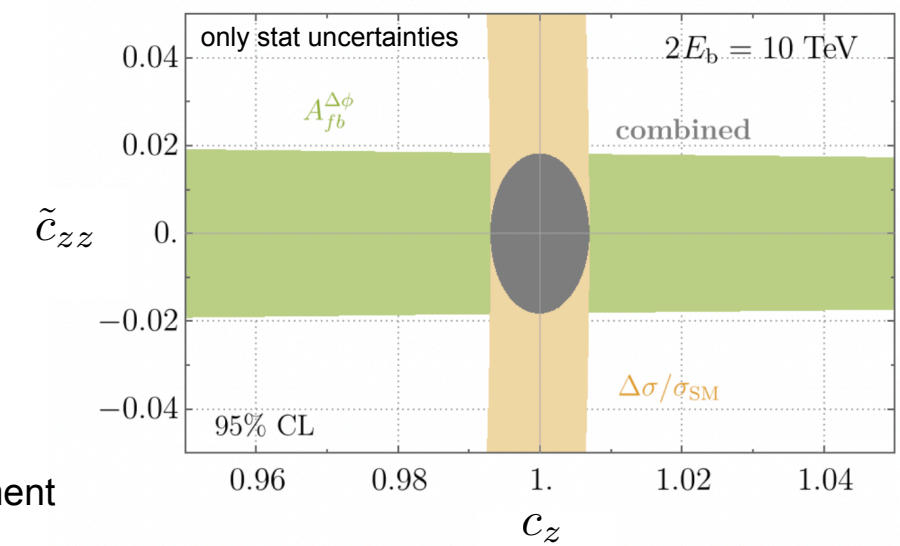


- Extract $\tilde{c}_{zz}$ via forward-backward asymmetry:

$$A_{fb}^{\Delta\phi} \equiv \frac{\sigma_f-\sigma_b}{\sigma_\mathrm{tot}} \propto \kappa_1^l c_z\tilde{c}_{zz}$$

linear dependence on $\tilde{c}_{zz}$

combine with
total cross section measurement



CP-violation in the hZZ coupling

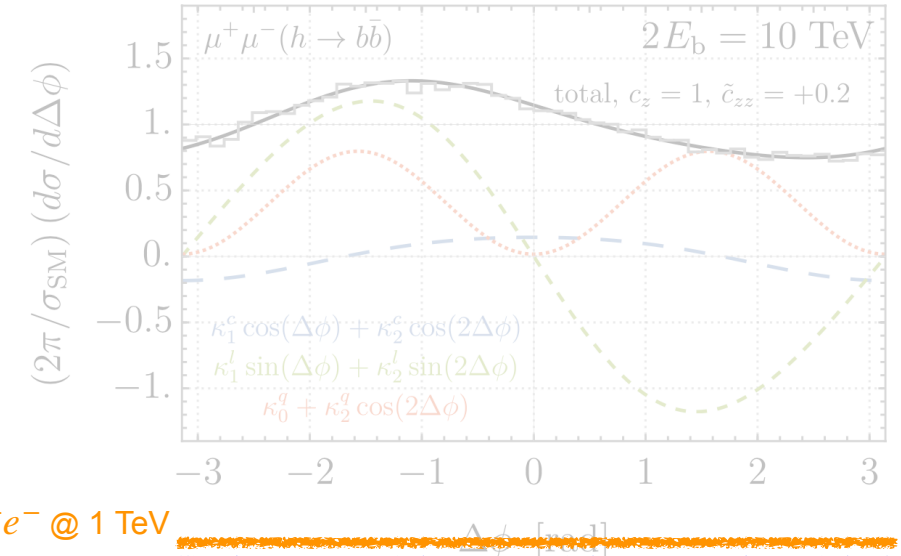
- Viewing $\tilde{c}_{zz}$ as spurion of CP violation fully fixes functional form:

$$\frac{2\pi}{\sigma_{h,\mathrm{SM}}}\frac{d\sigma_h}{d\Delta\phi} = c_z^2\left[1+\kappa_1^c\cos(\Delta\phi)+\kappa_2^c\cos(2\Delta\phi)\right] + c_z\tilde{c}_{zz}\left[\kappa_1^l\sin(\Delta\phi)+\kappa_2^l\sin(2\Delta\phi)\right] + \tilde{c}_{zz}^2\left[\kappa_0^q+\kappa_2^q\cos(2\Delta\phi)\right]$$

provides excellent fit for

$$\mu^+\mu^- \to \mu^+\mu^-(h\to b\bar{b})$$

results for SM couplings consistent with [Forslund, Meade 2203.09425]



e^+e^- @ 1 TeV

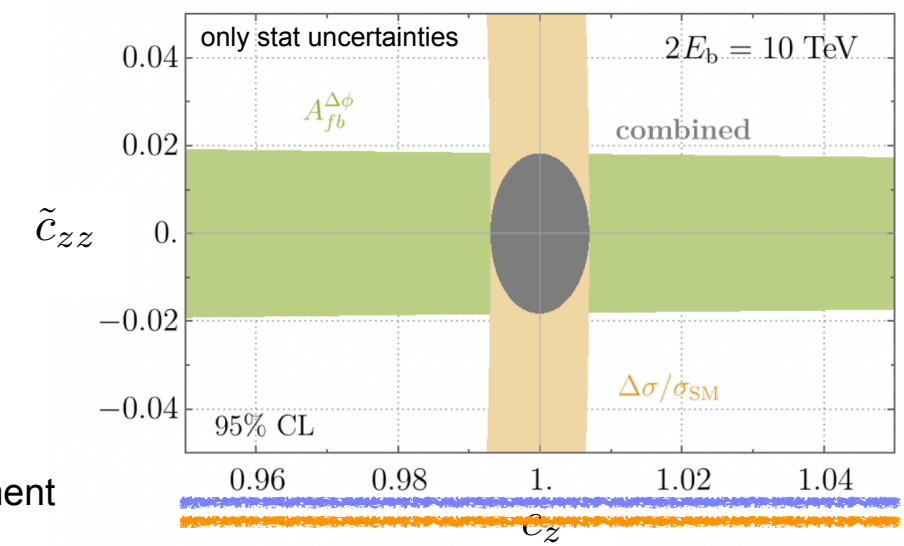
HL-LHC

- Extract $\tilde{c}_{zz}$ via forward-backward asymmetry:

$$A_{fb}^{\Delta\phi} \equiv \frac{\sigma_f - \sigma_b}{\sigma_\mathrm{tot}} \propto \kappa_1^l c_z \tilde{c}_{zz}$$

linear dependence on $\tilde{c}_{zz}$

combine with
total cross section measurement



[CMS 2205.05120]
[Gritsan et al. 2205.07715]

Outlook

- Physics case for forward muon detector is strong.
  Momentum measurement would expand impact significantly

- To do on theory side: explore more opportunities, both in precision measurements and direct searches for BSM particles

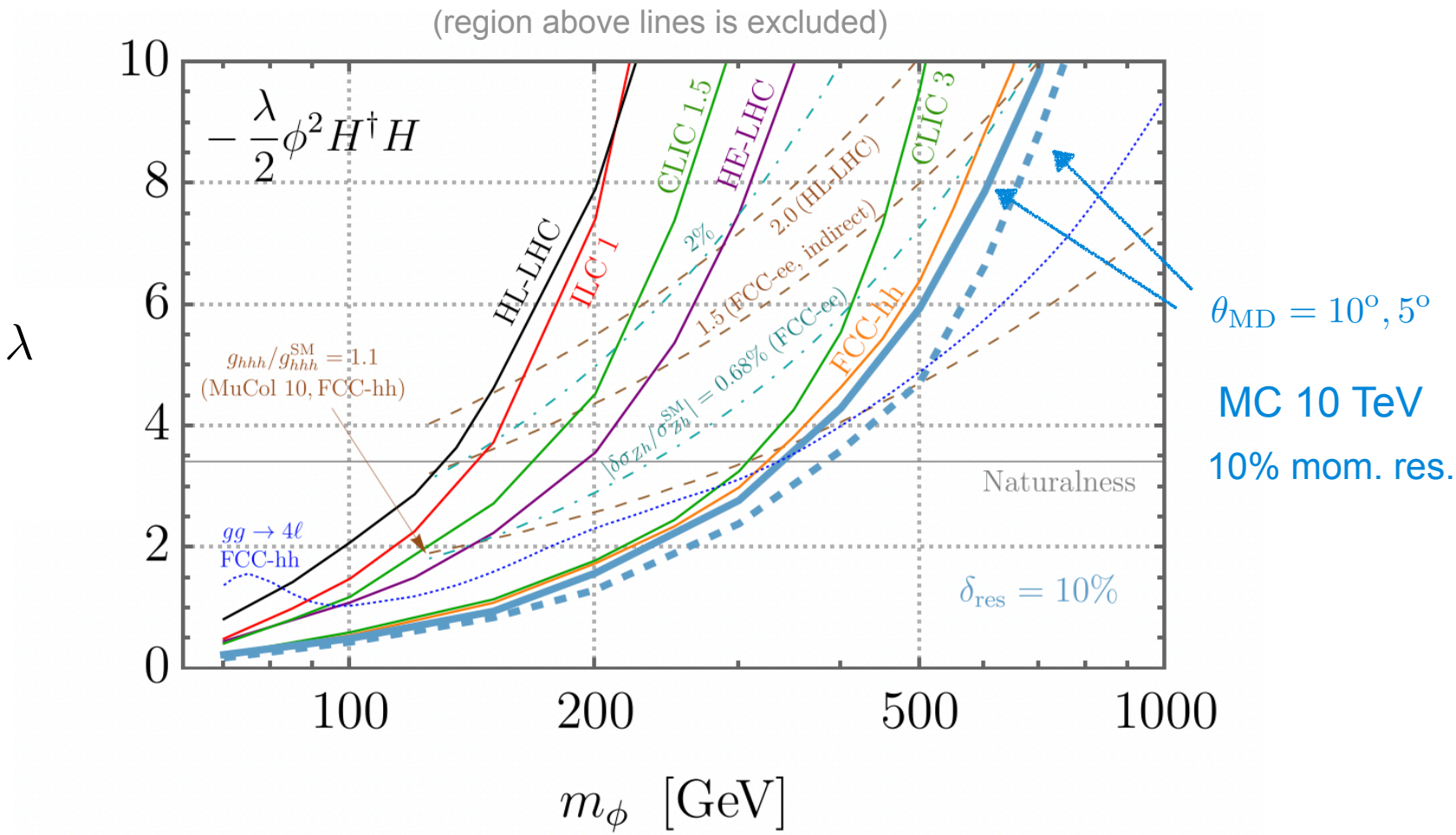
- To do on detector/MDI side: new ideas for detector design

Quoting from the supplementary report to 2026 ESPPU [2504.21417]:

> Any detector in this area needs to be embedded in the nozzle design and sustain fluences up to $\sim 10^{16}$1 MeV n_{eq}/cm^2; in addition it needs to be able to disentangle muons from the interaction point from BIB that are showering in the nozzle. Such a (tracking) device is well beyond current capabilities and requires aggressive research and new ideas to be realised in practice. A momentum measurement based on the amount of multiple scattering in the nozzle appears to be the most straightforward way to achieve the needed precision on momentum resolution but its feasibility will need to be proven once viable technologies are identified.

Backup slides

Renormalizable Higgs portal: results



With ~ 10% momentum resolution, MC would have strongest direct sensitivity

Indirect sensitivity from Higgs self-coupling measurement

Physics opportunities with forward muons

Direct searches for BSM particles

Precision measurements

tagging

angles

angles + momentum

?

EW dark matter

[Han, Liu, Wang, Wang 2021]

new vector bosons

[Airen, Broadberry, Marques-Tavares, Ricci 2024]

Higgs portal models

[Ruhdorfer, Salvioni, Wulzer 2024]

invisible Higgs decays

[Ruhdorfer, Salvioni, Wulzer 2023 + 2024]

[Forslund, Meade 2023]

Higgs couplings

[Forslund, Meade 2022]

VBS interference resurrection

CP - violating hVV couplings

[Ruhdorfer, Salvioni, Wulzer 2024]

inclusive Higgs production

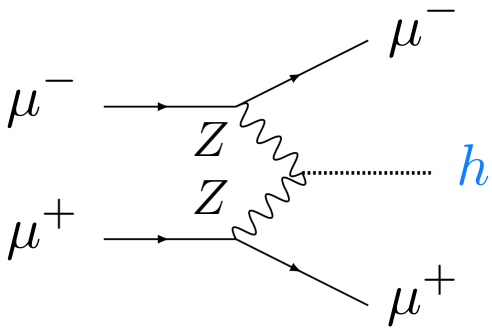
[Li, Liu, Lyu 2024]

[Ruhdorfer, Salvioni, Wulzer 2024]

Requirements on detector

[credits: Max Ruhdorfer]

Inclusive Higgs production at MC



Measure inclusive cross section of Higgs production

Absolute measurement of hZZ coupling
(independent of other Higgs couplings and width)

Analysis:

- no main detector veto
- for $\delta_{\rm res} = 10\%$ momentum resolution, recoil mass loses discriminating power

$$M_{\rm rec} = \sqrt{|(\Delta P)^2|}$$
$$\Delta P = (2E_{\rm b}, \vec{0}) - p_{\mu^+} - p_{\mu^-}$$

[Ruhdorfer, Salvioni, Wulzer 2411.00096]

$\delta_{\rm res} = 10\%$	baseline cuts	$p_\perp^{\mu,\rm min} < 200$ GeV, $E_\mu^{\rm min} > 3.5$ TeV
$\mu^+\mu^- h$	$6.8 \cdot 10^5$	$5.3 \cdot 10^5$
$\mu^+\mu^- \gamma$	$2.9 \cdot 10^7$	$2.7 \cdot 10^6$
$\mu^+\mu^- \nu\bar{\nu}$	$1.3 \cdot 10^6$	$3.6 \cdot 10^4$
$\mu^+\mu^- f\bar{f}$	$3.3 \cdot 10^6$	$1.7 \cdot 10^6$
$\mu^+\mu^- W^+W^-$	$4.6 \cdot 10^6$	$1.9 \cdot 10^6$
$(\Delta\sigma/\sigma_{\rm SM})_{68\%}$		$\boxed{0.50\%}$
$S_{\rm SM}/B$		0.08

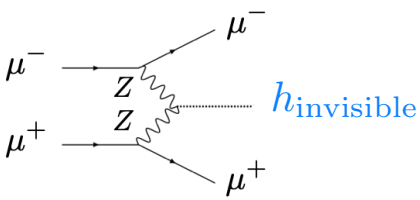
$$|\delta g_{hZZ}/\delta g_{hZZ}^{\rm SM}| < 2.5 \times 10^{-3}$$

similar to FCC-ee: 1.7×10^{-3}

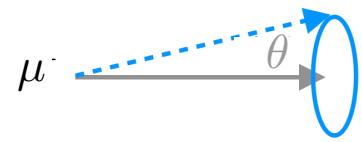
[De Blas et al. 1905.03764]

Results in agreement with first study in [Li, Liu, Lyu 2401.08756]

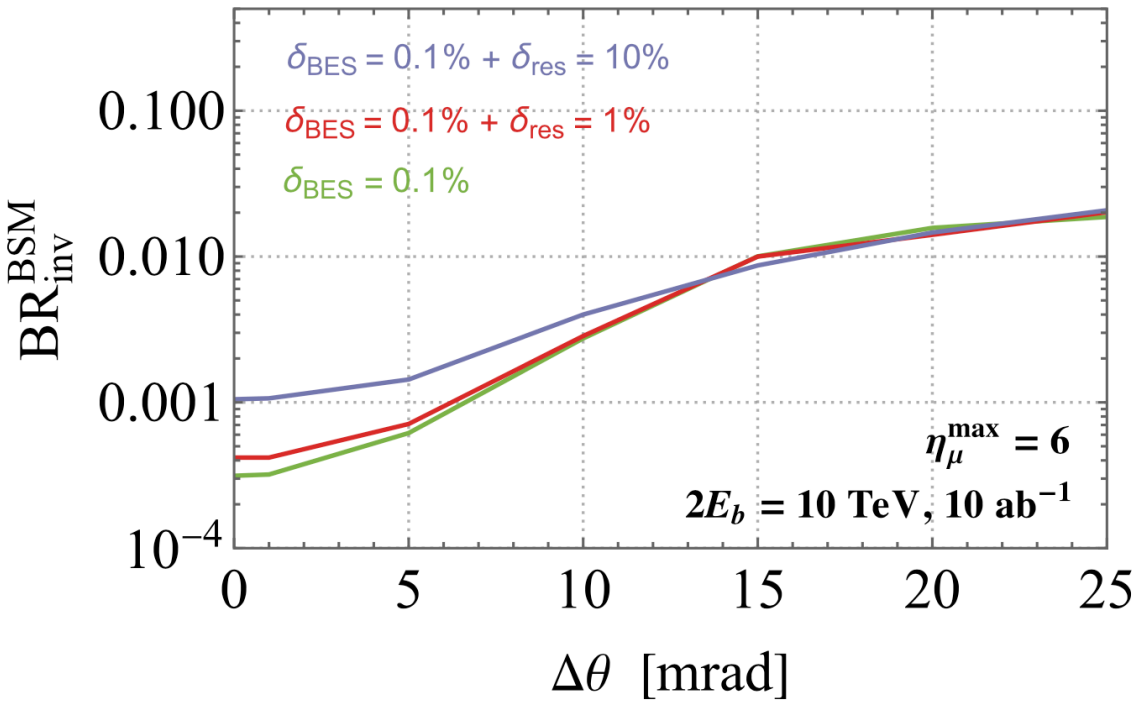
Uncertainty in muon direction measurement



For fixed $\eta_{\max} = 6$:



gaussian with standard deviation $\Delta\theta$



As long as $\Delta\theta \lesssim 5$ mrad , no significant degradation of sensitivity