# Wishlist from the Physics Side

Cari Cesarotti, MIT CTP Postdoc Fellow

**IMCC** MDI Workshop, March 11, 2024

*Image by DallE 3*

# With thanks to many for their input

*Especially D. Buttazzo, K. DiPetrillo, R. Franceschini, P. Meade, F. Meloni, P. Meade, M. Reece, A. Wulzer*

# The US P5 report has endorsed muon collider R&D

Money is **explicitly allocated** for 10 TeV pCOM machines, which includes FCC-hh R&D, for $\mathcal{O}(\mathbf{50}\text{M})$ per year

We want similar support in the ESPPU, and maintained US support

It is essential that we have **well-defined accelerator, experimental, and theoretical** benchmarks to demonstrate feasibility & confidence

# With so many design uncertainties, we get into a feedback loop

Experimental or Accelerator parameters are assumed ⇄ Physics benchmarks are set

Let's set straight what we need from MDI to reach our physics benchmarks

# Goal of this talk:

Establish what is needed for detector technology to achieve our physics benchmarks

(Define what our physics benchmarks are)

# Goal of this ~~Talk~~: Workshop

Establish what is needed for detector technology to achieve our physics benchmarks

(Define what our physics benchmarks are)

Both theorists & experimentalists will have *to-do's* to better inform the physics projections

# Setting the Physics Benchmarks

What are the measurements that we need to justify the construction of a muon collider?

What do we need of MDI to make these measurements?

# Setting the Physics Benchmarks

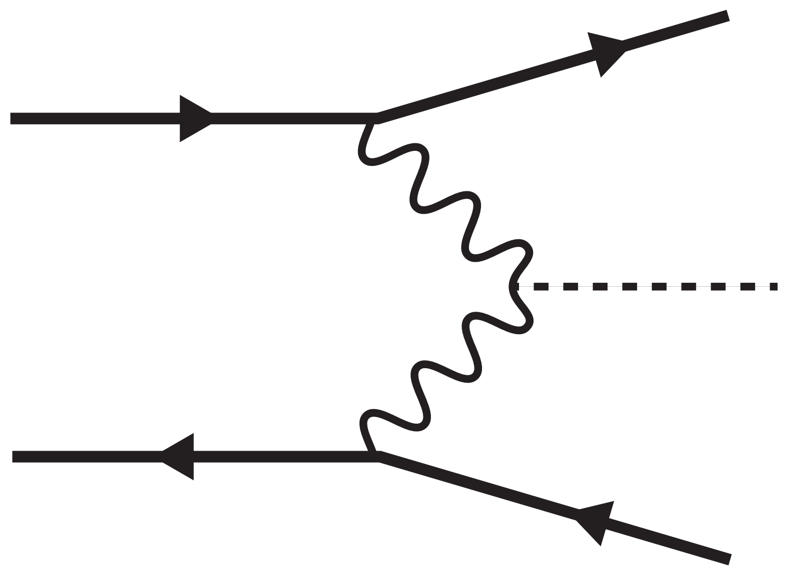
{ What are the measurements that we need to justify the construction of a muon collider?

What do we need of MDI to make these measurements? }

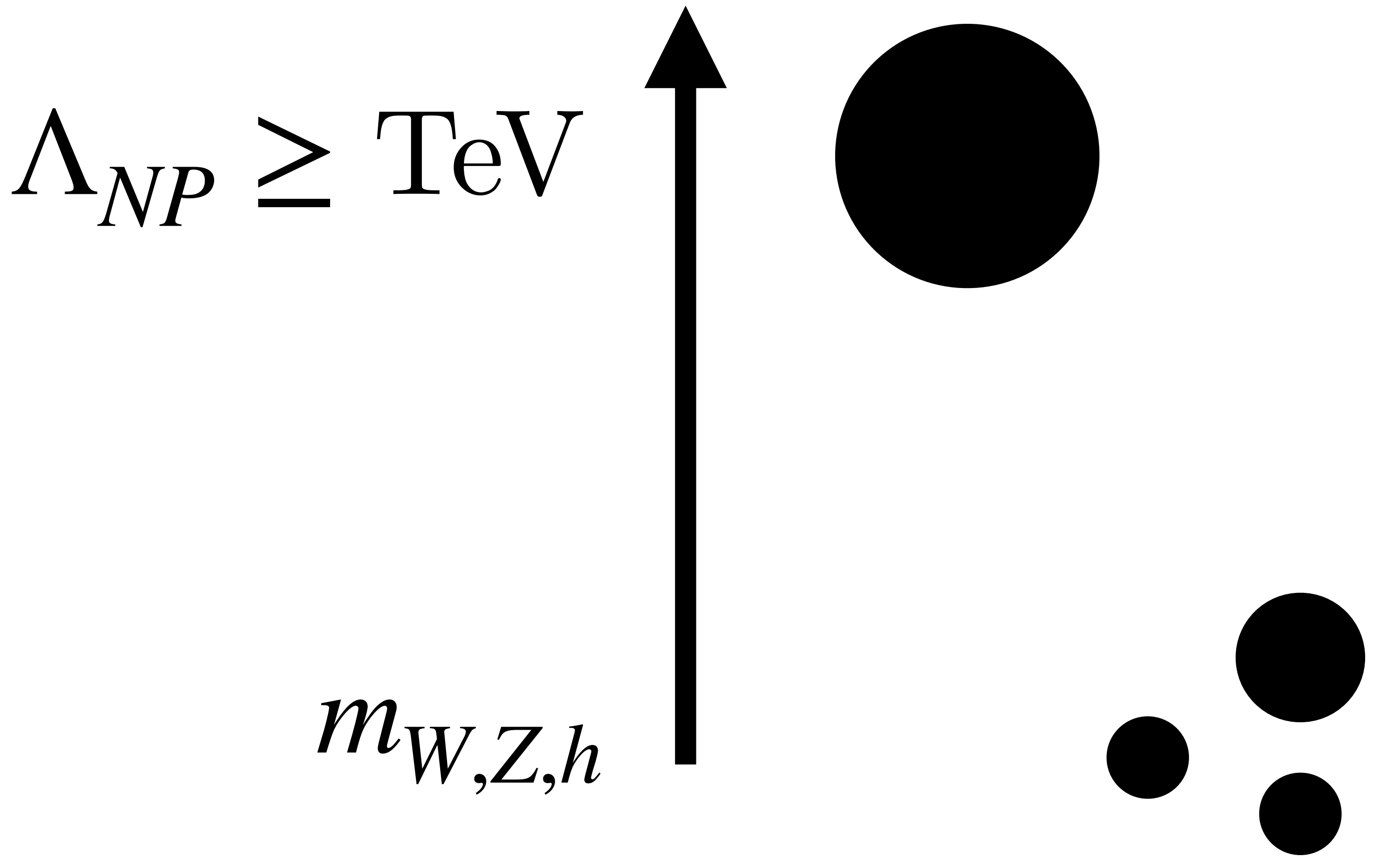
*How will these evolve depending on the status of other future colliders?*

# Physics Goals

Precision EW & Higgs



Heavy Particles

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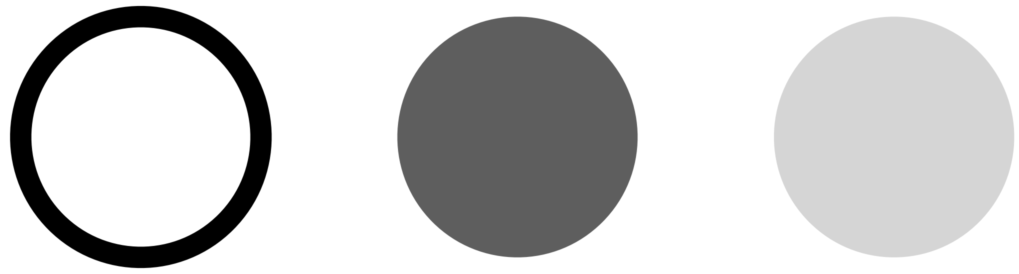

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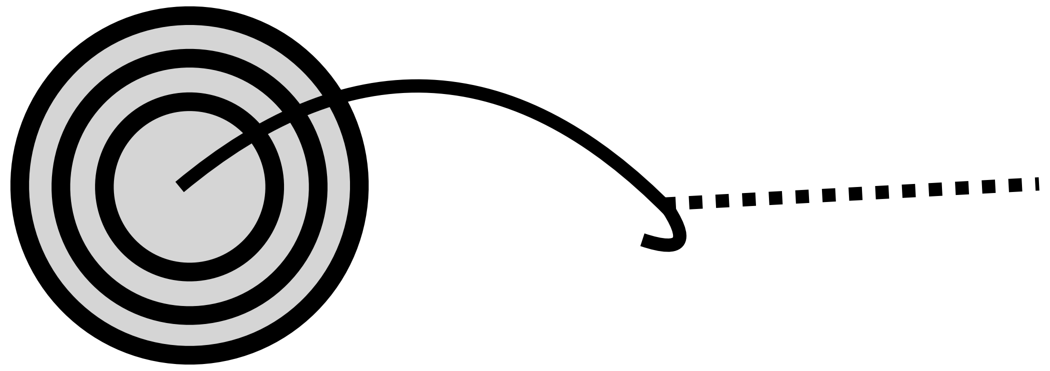
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)



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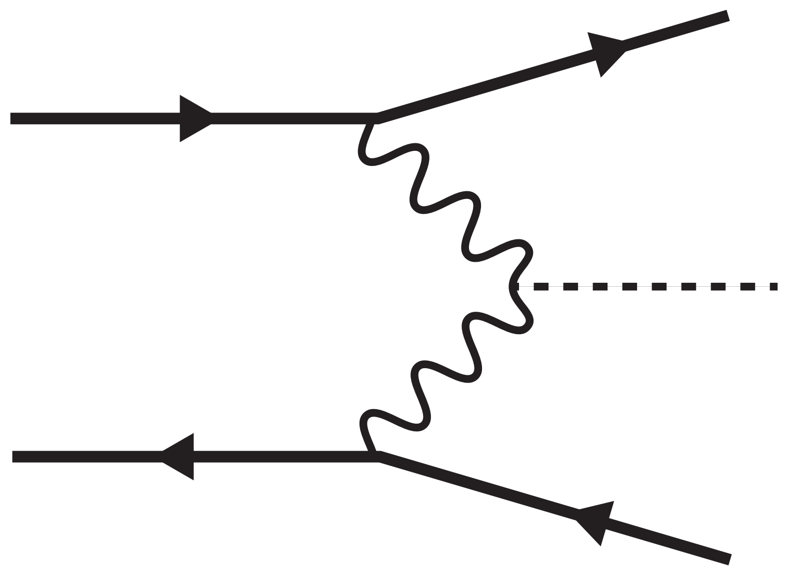

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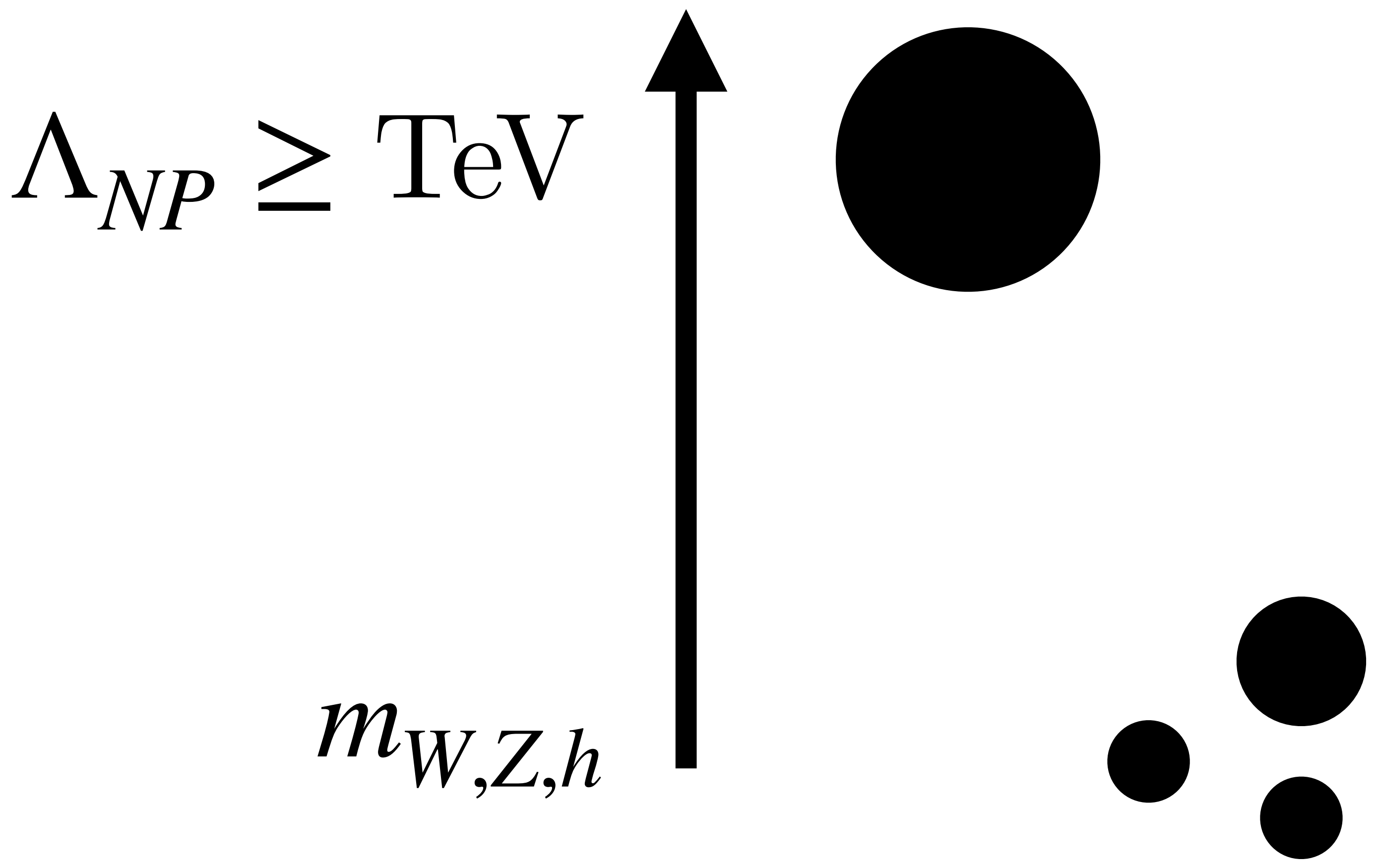


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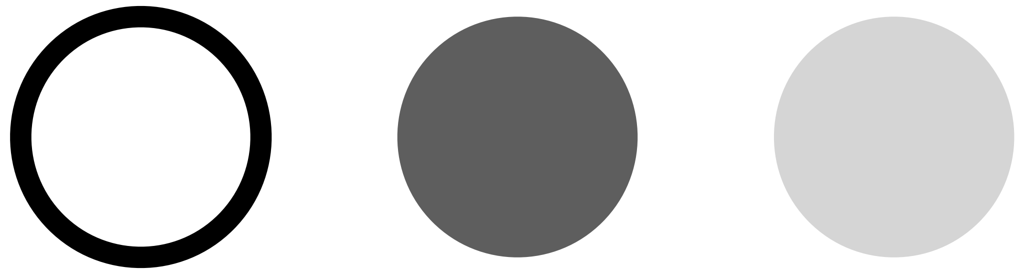

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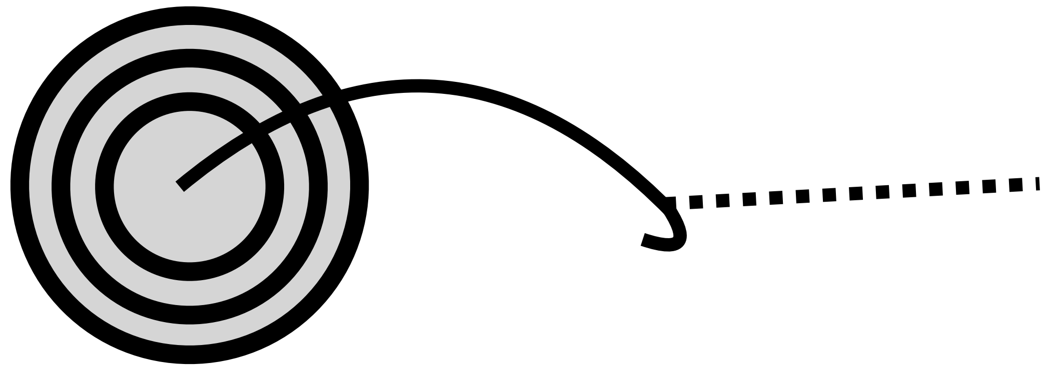
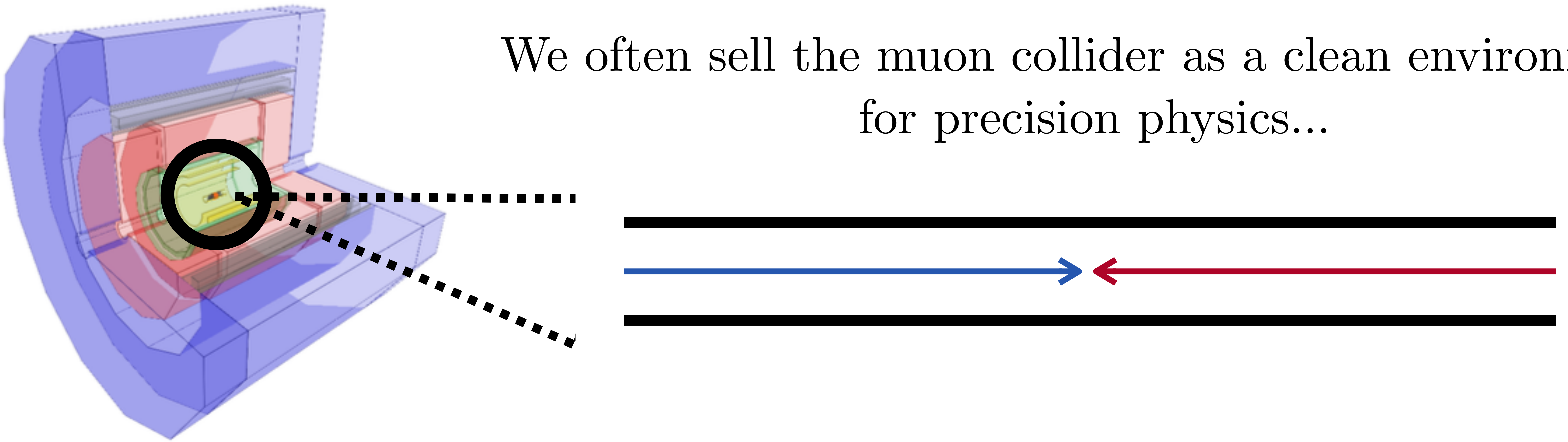


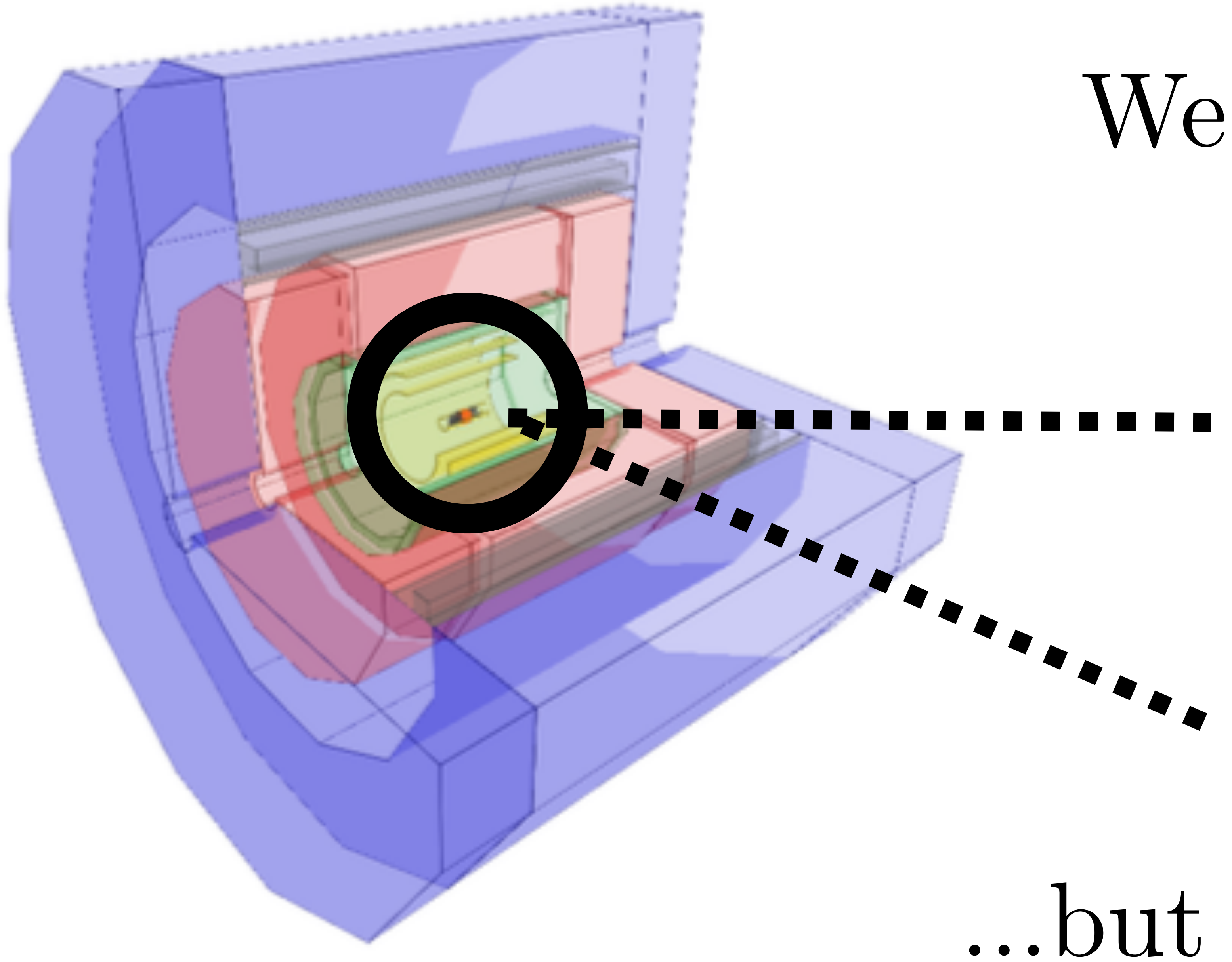
A primary challenge for maintaining sensitivity to these is *mitigating the BIB*

# Primary Challenge:
# The Beam Induced Background (BIB)



We often sell the muon collider as a clean environment for precision physics...

# PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)



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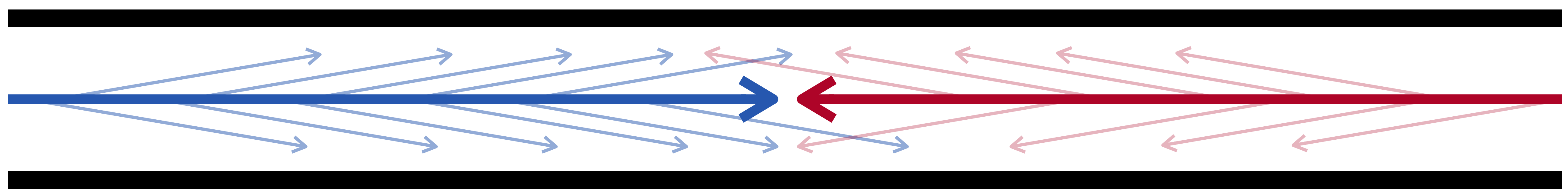
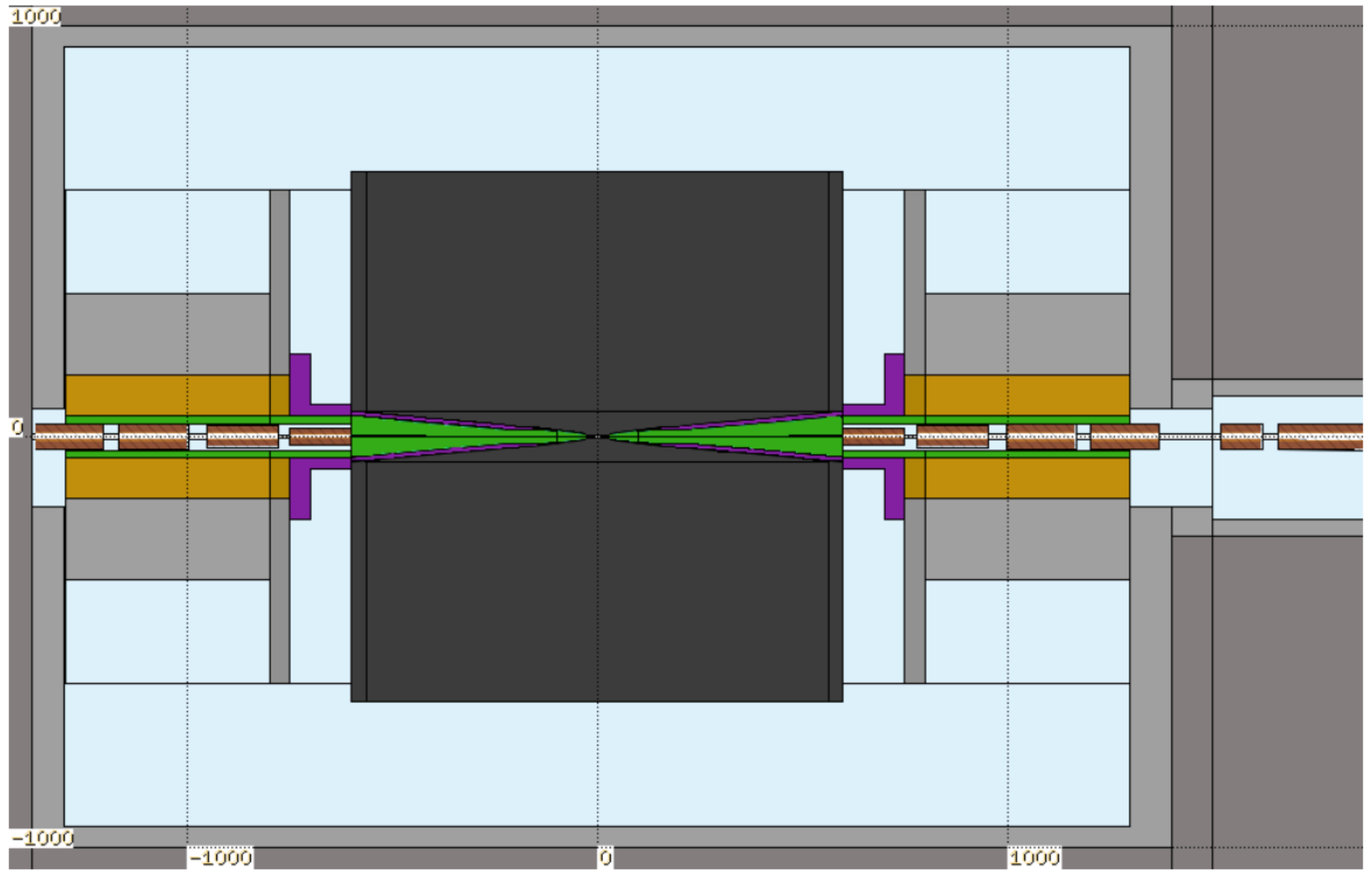
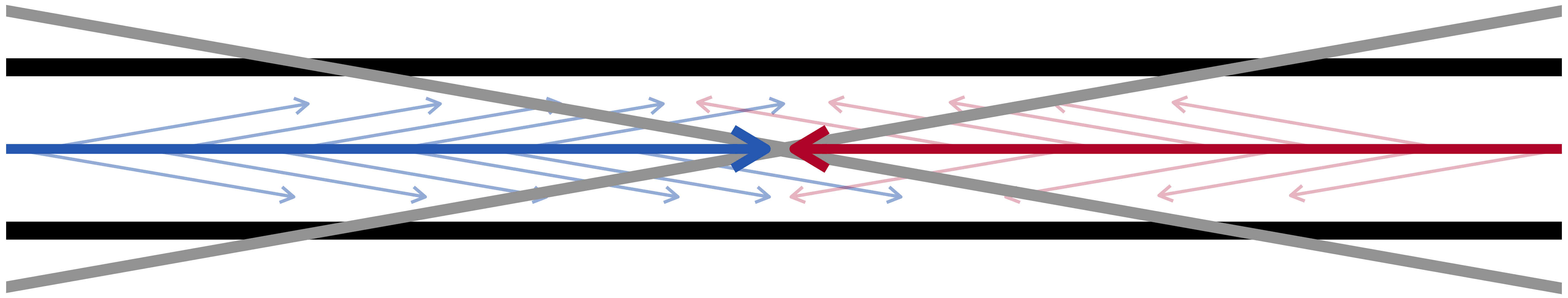


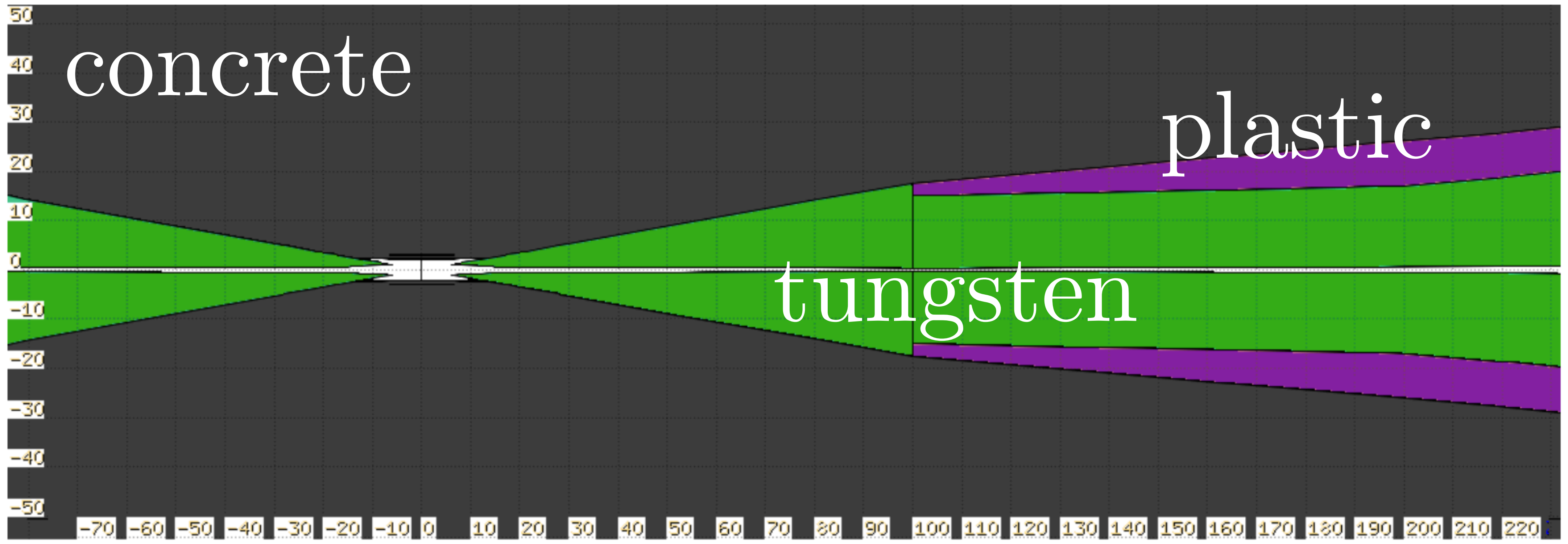
...but to mitigate the effects from beam decay, sensitivity to **forward** and **soft** particles is degraded

# Primary Challenge: The Beam Induced Background (BIB)



Tungsten nozzles can diffuse **hard** BIB objects into **many low-energy** particles






**Zeroth order task:**

Make physics possible in the face of the BIB

# Primary Challenge: The Beam Induced Background (BIB)

For a *single* bunch crossing ($2 \times 10^{12} \mu$)

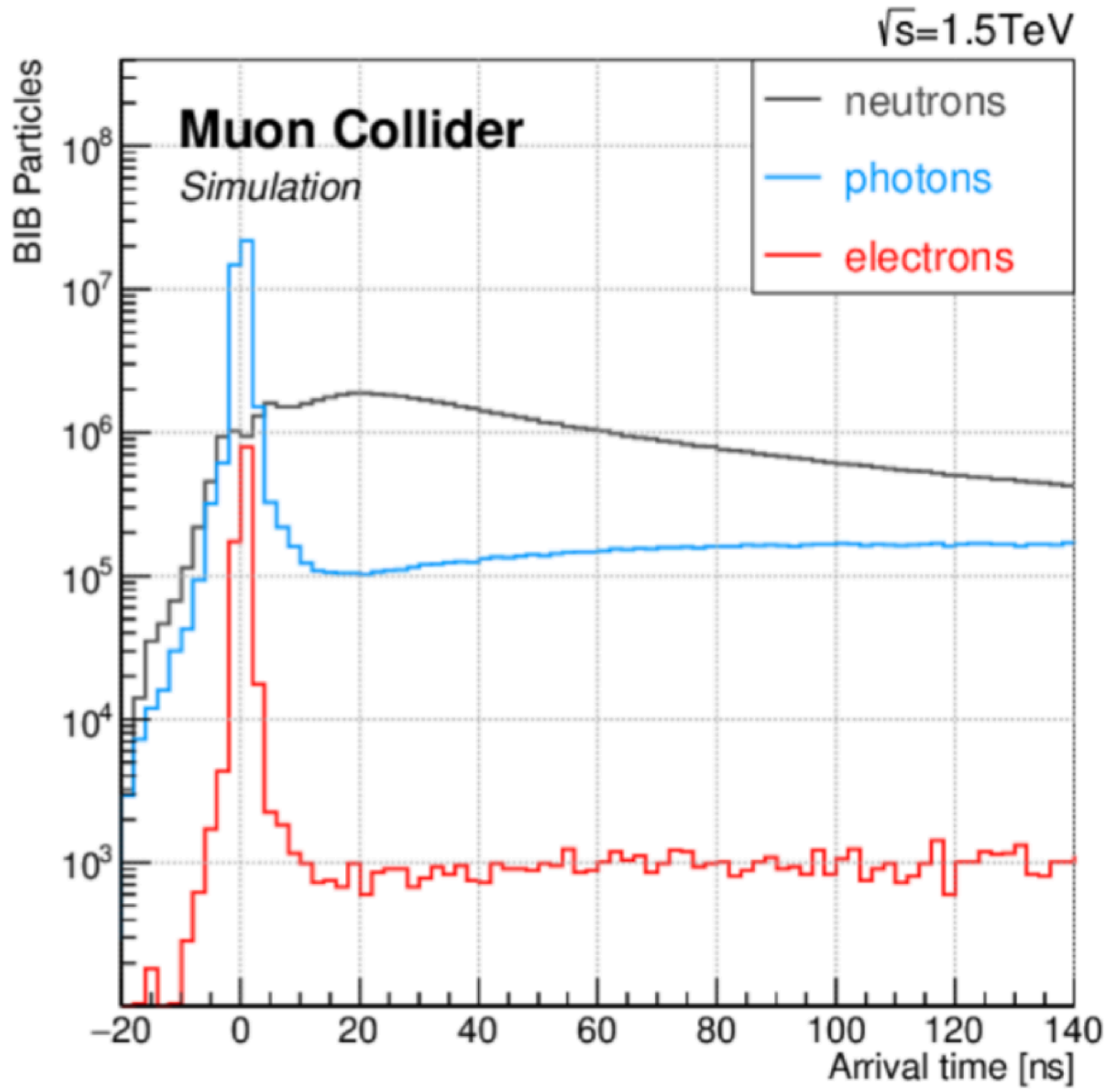
| Monte Carlo simulator | MARS15 | MARS15 | FLUKA | FLUKA | FLUKA |
|---|---|---|---|---|---|
| Beam energy [GeV] | 62.5 | 750 | 750 | 1500 | 5000 |
| $\mu$ decay length [m] | $3.9 \cdot 10^5$ | $46.7 \cdot 10^5$ | $46.7 \cdot 10^5$ | $93.5 \cdot 10^5$ | $311.7 \cdot 10^5$ |
| $\mu$ decay/m/bunch | $51.3 \cdot 10^5$ | $4.3 \cdot 10^5$ | $4.3 \cdot 10^5$ | $2.1 \cdot 10^5$ | $0.64 \cdot 10^5$ |
| Photons ($E_\gamma > 0.1$ MeV) | $170 \cdot 10^6$ | $86 \cdot 10^6$ | $51 \cdot 10^6$ | $70 \cdot 10^6$ | $107 \cdot 10^6$ |
| Neutrons ($E_n > 1$ MeV) | $65 \cdot 10^6$ | $76 \cdot 10^6$ | $110 \cdot 10^6$ | $91 \cdot 10^6$ | $101 \cdot 10^6$ |
| Electrons & positrons ($E_{e^\pm} > 0.1$ MeV) | $1.3 \cdot 10^6$ | $0.75 \cdot 10^6$ | $0.86 \cdot 10^6$ | $1.1 \cdot 10^6$ | $0.92 \cdot 10^6$ |
| Charged hadrons ($E_{h^\pm} > 0.1$ MeV) | $0.011 \cdot 10^6$ | $0.032 \cdot 10^6$ | $0.017 \cdot 10^6$ | $0.020 \cdot 10^6$ | $0.044 \cdot 10^6$ |
| Muons ($E_{\mu^\pm} > 0.1$ MeV) | $0.0012 \cdot 10^6$ | $0.0015 \cdot 10^6$ | $0.0031 \cdot 10^6$ | $0.0033 \cdot 10^6$ | $0.0048 \cdot 10^6$ |

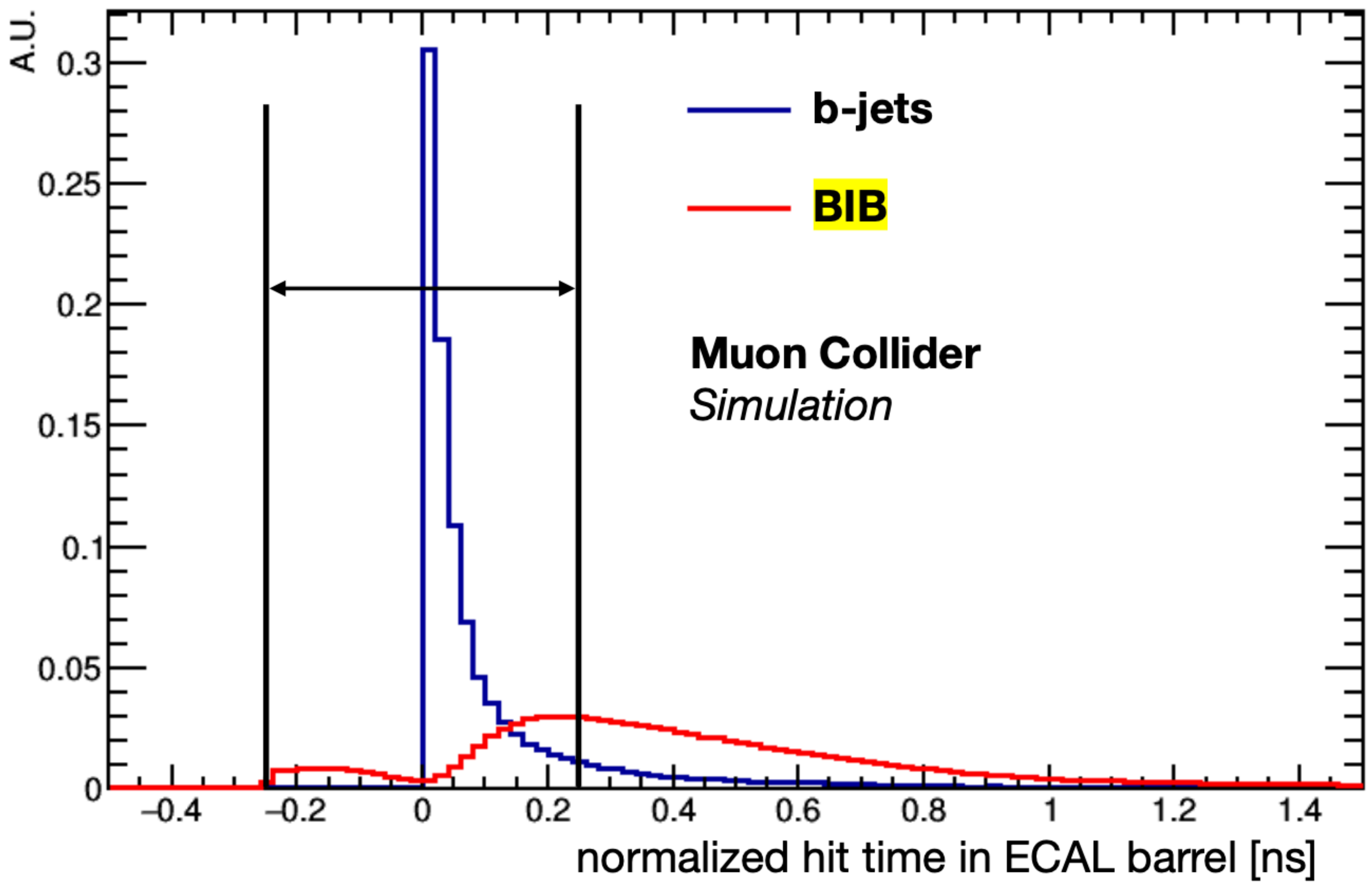


Read more in *Towards a Future Muon Collider*

# Primary Challenge: The Beam Induced Background (BIB)

But not *exactly* in time with bunch crossings



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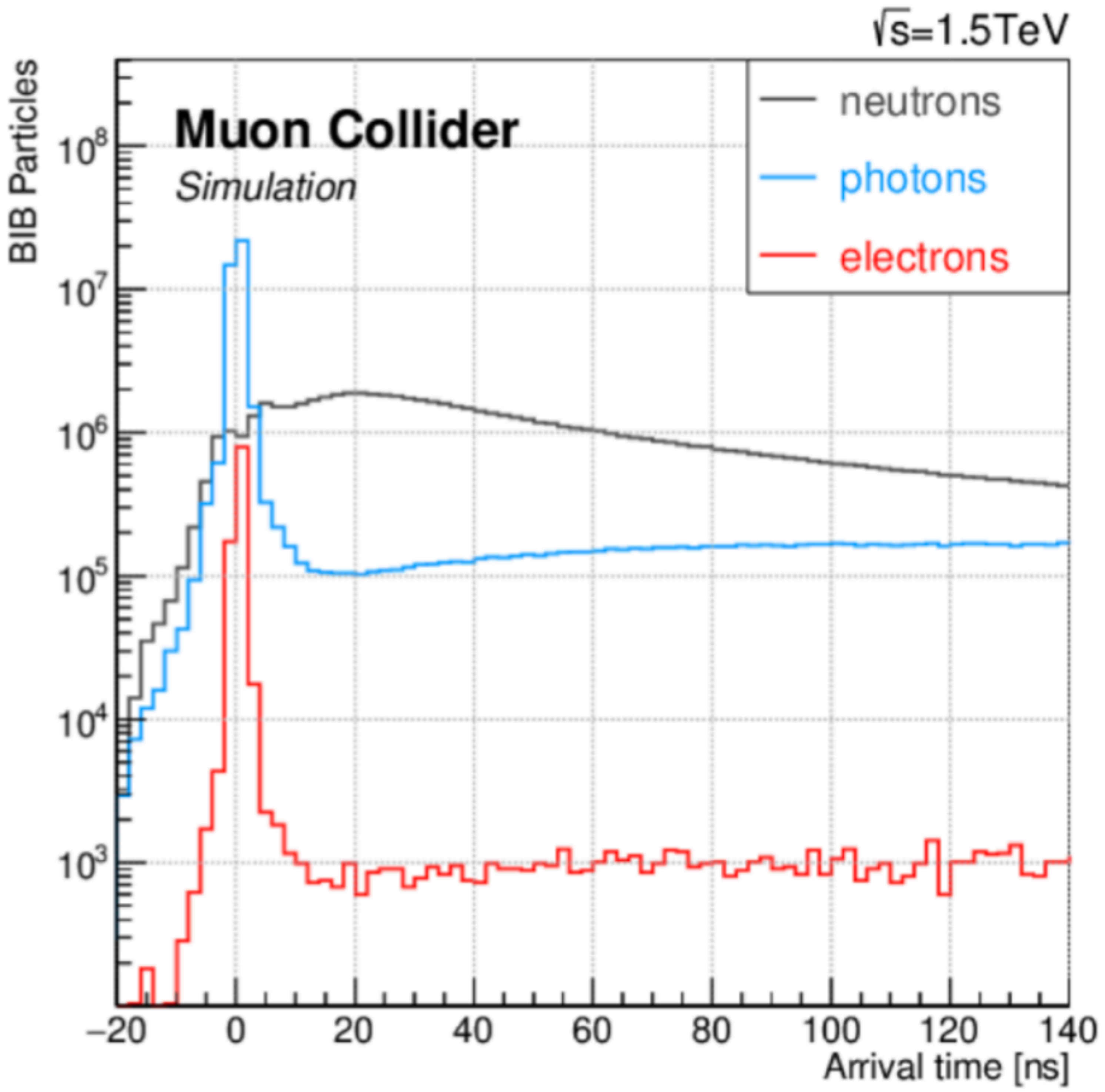
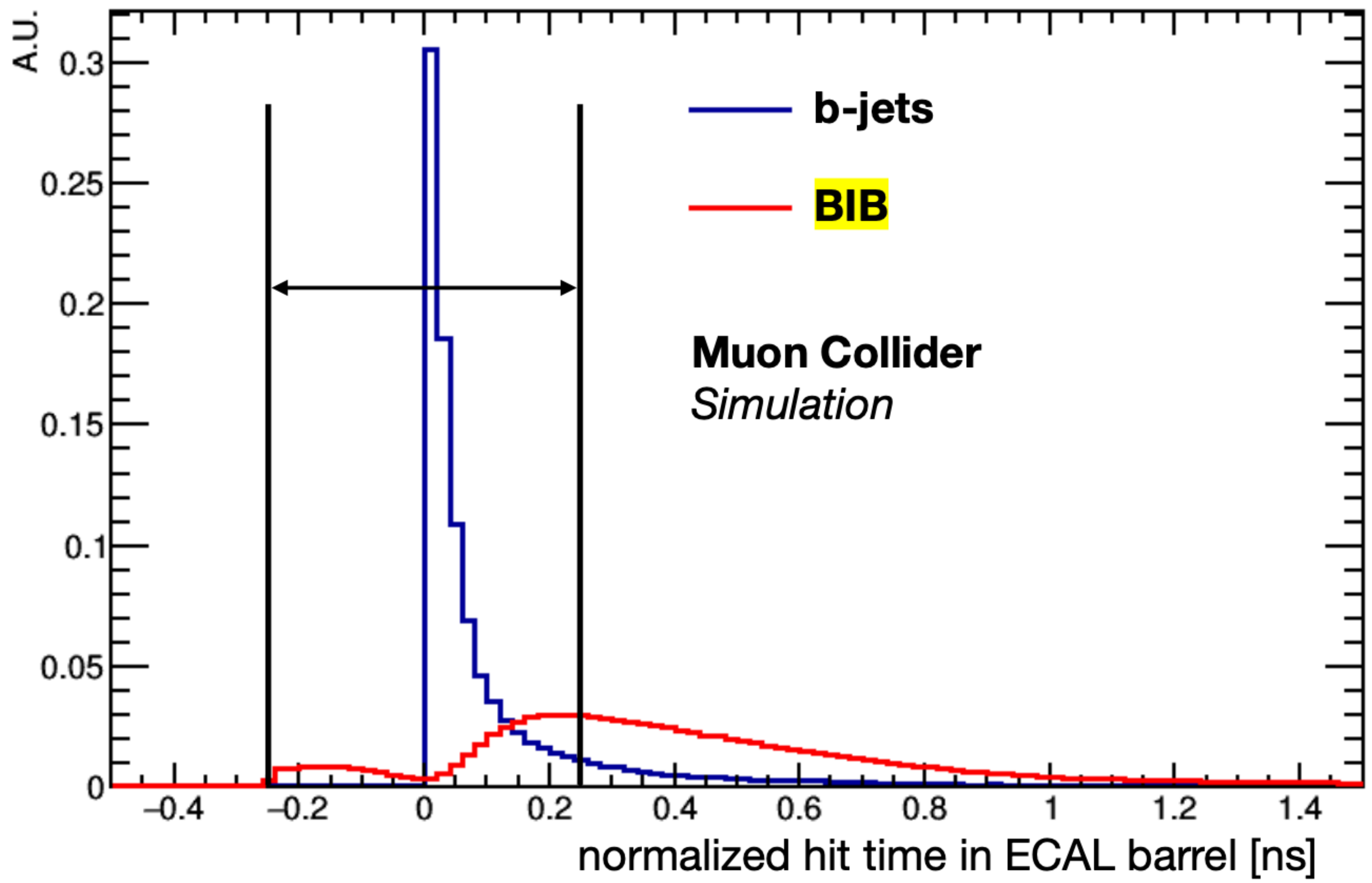
# Wishlist

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns



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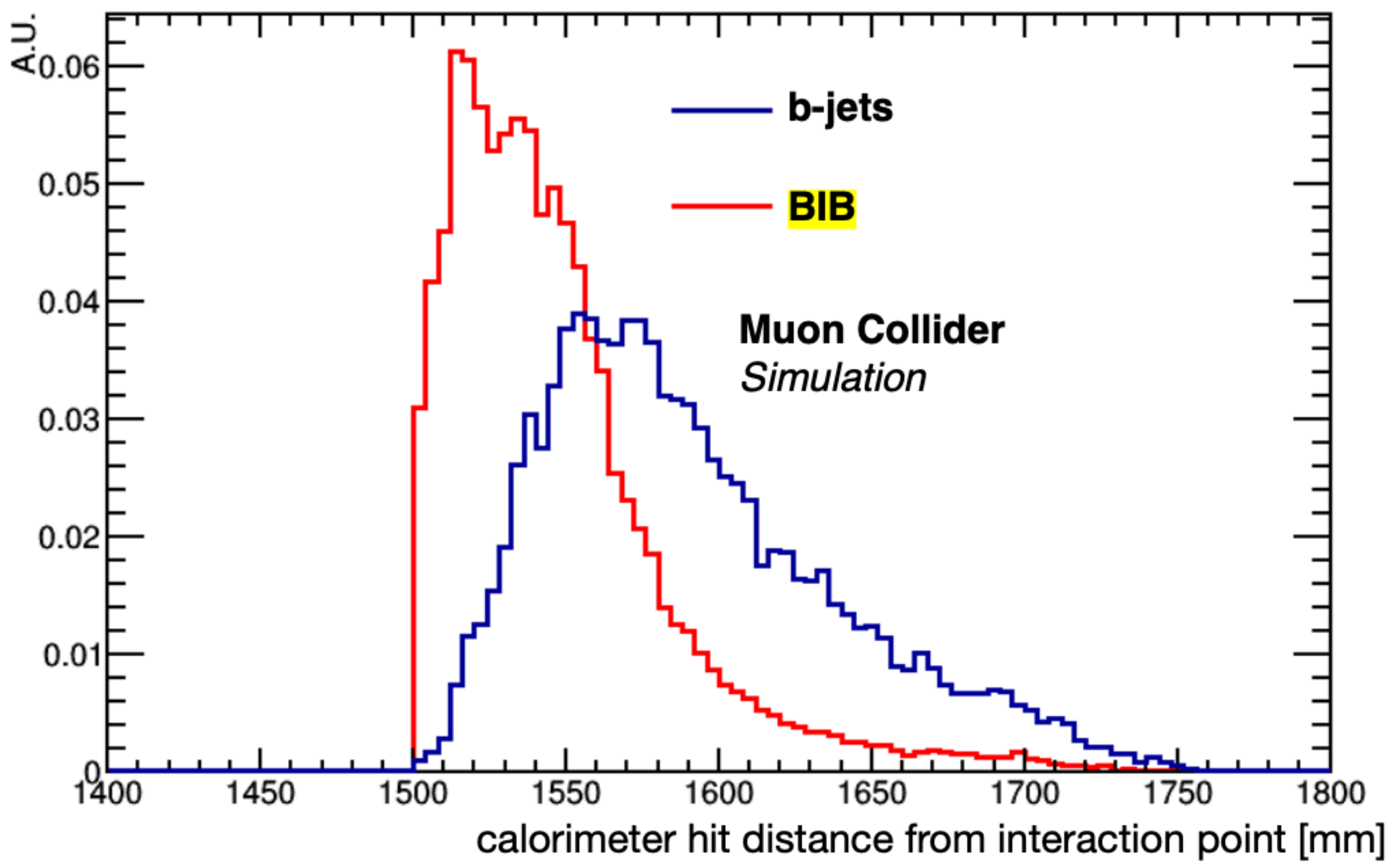
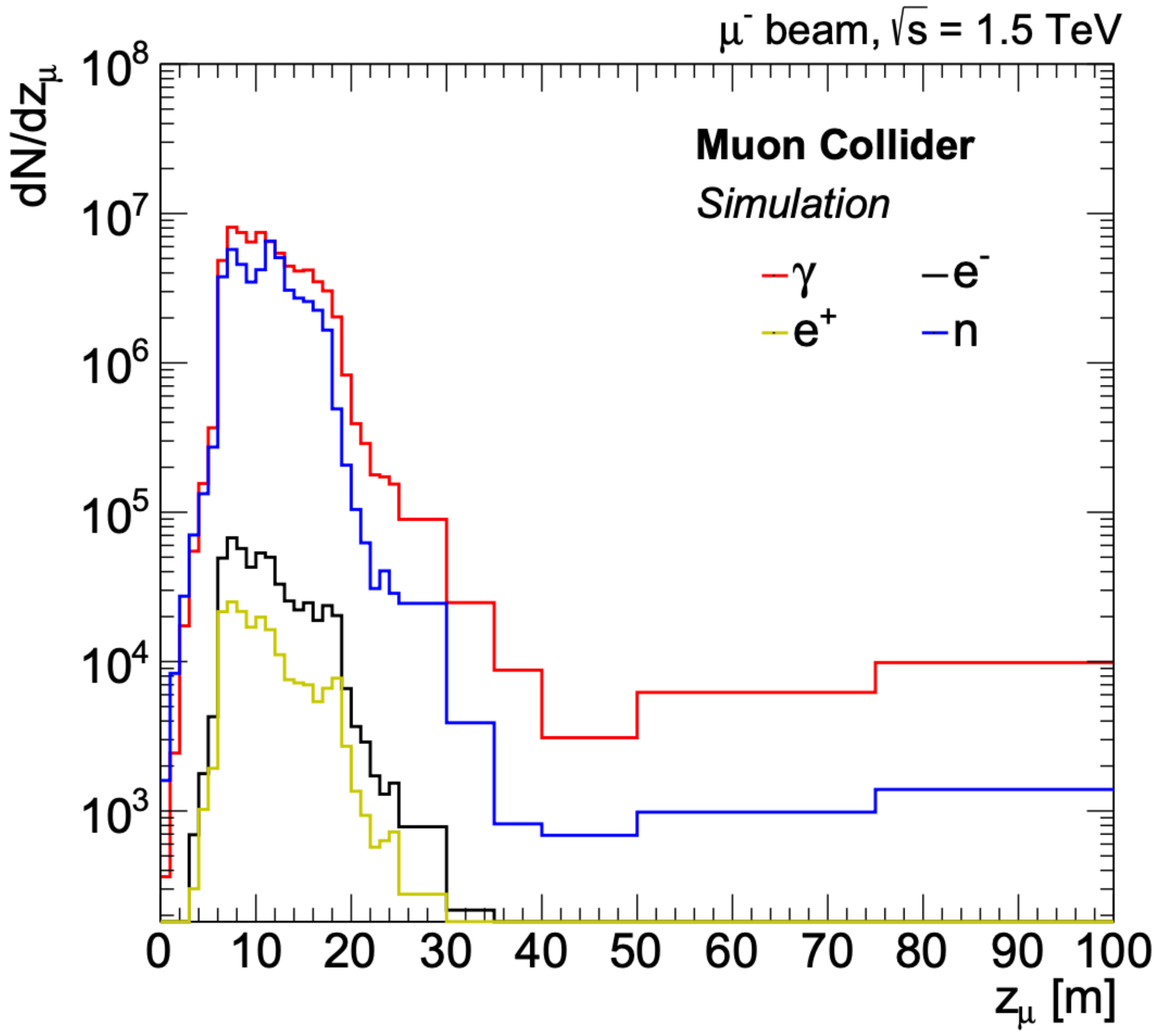
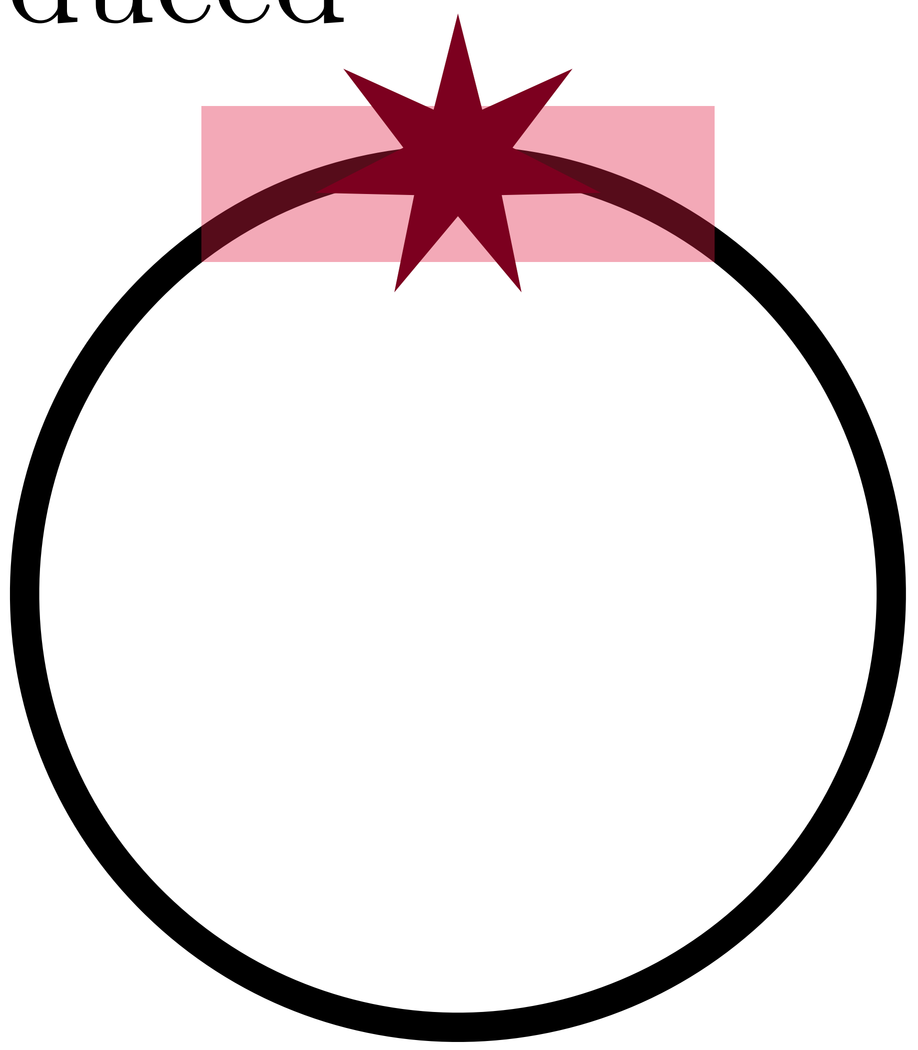
# PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

Similarly, where the BIB hits is also distinct from particles produced at the interaction point





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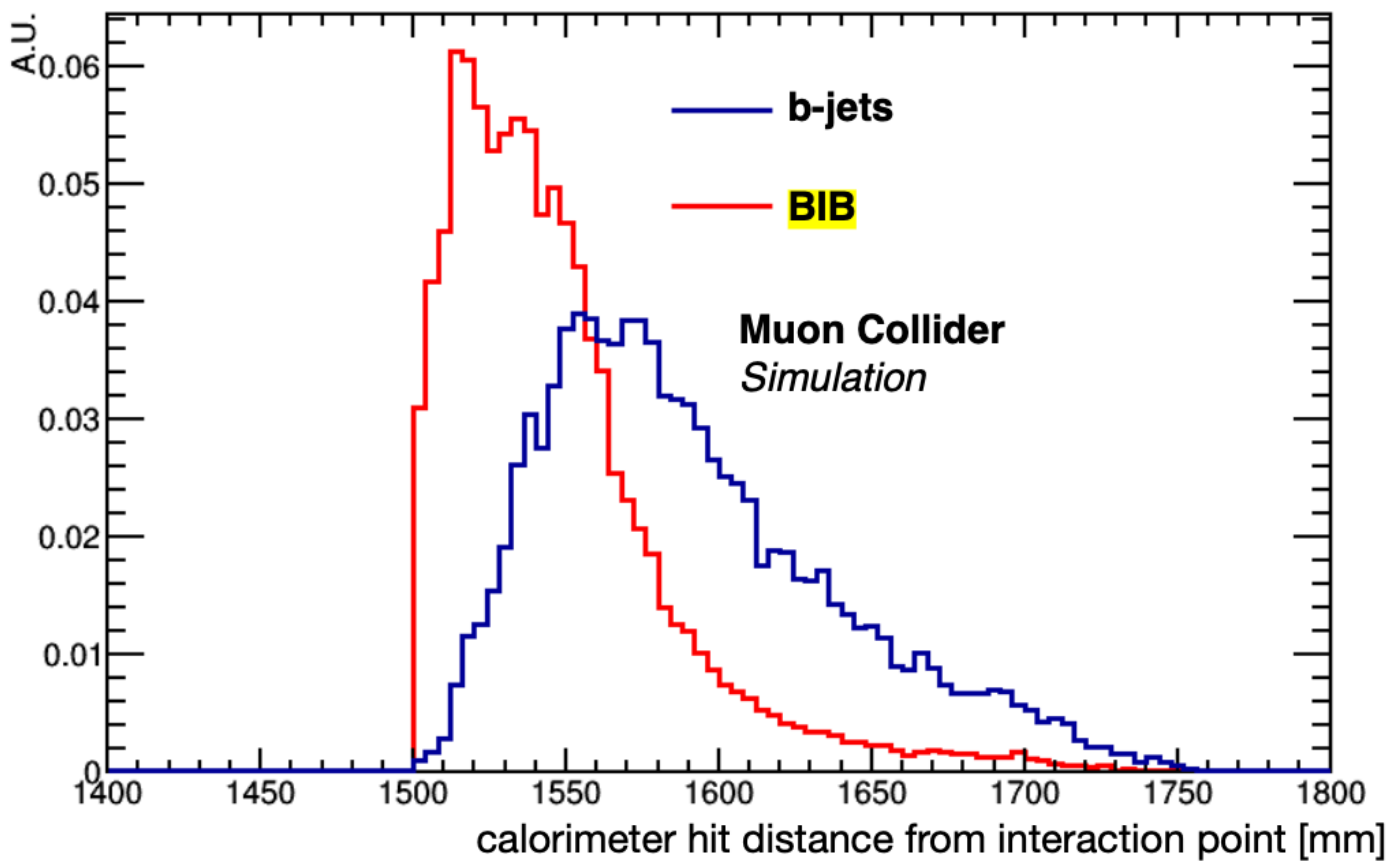
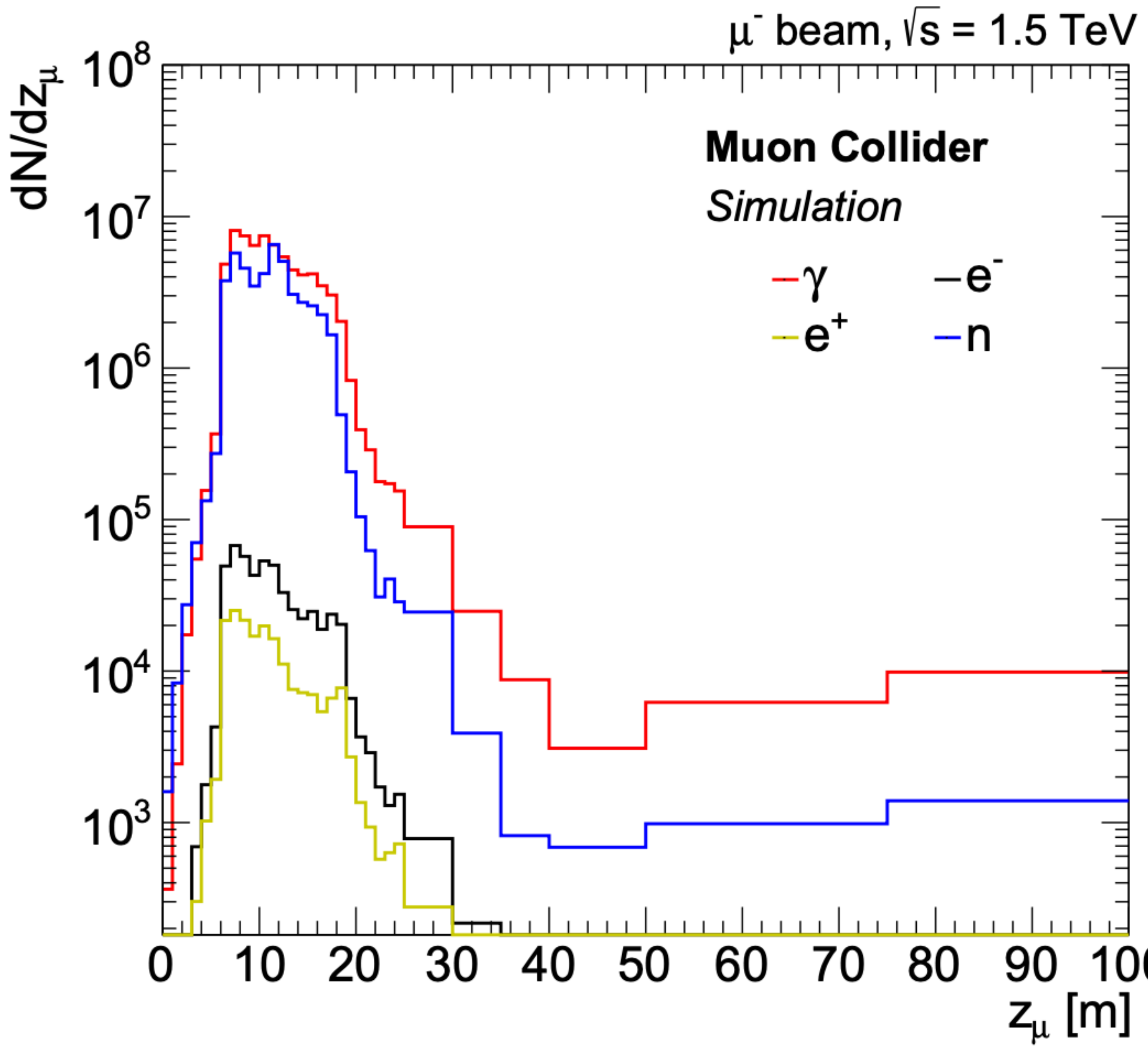
# Wishlist

- Timing resolution on hits to $\mathcal{O}(<0.1)$ ns
- Good granularity of detector



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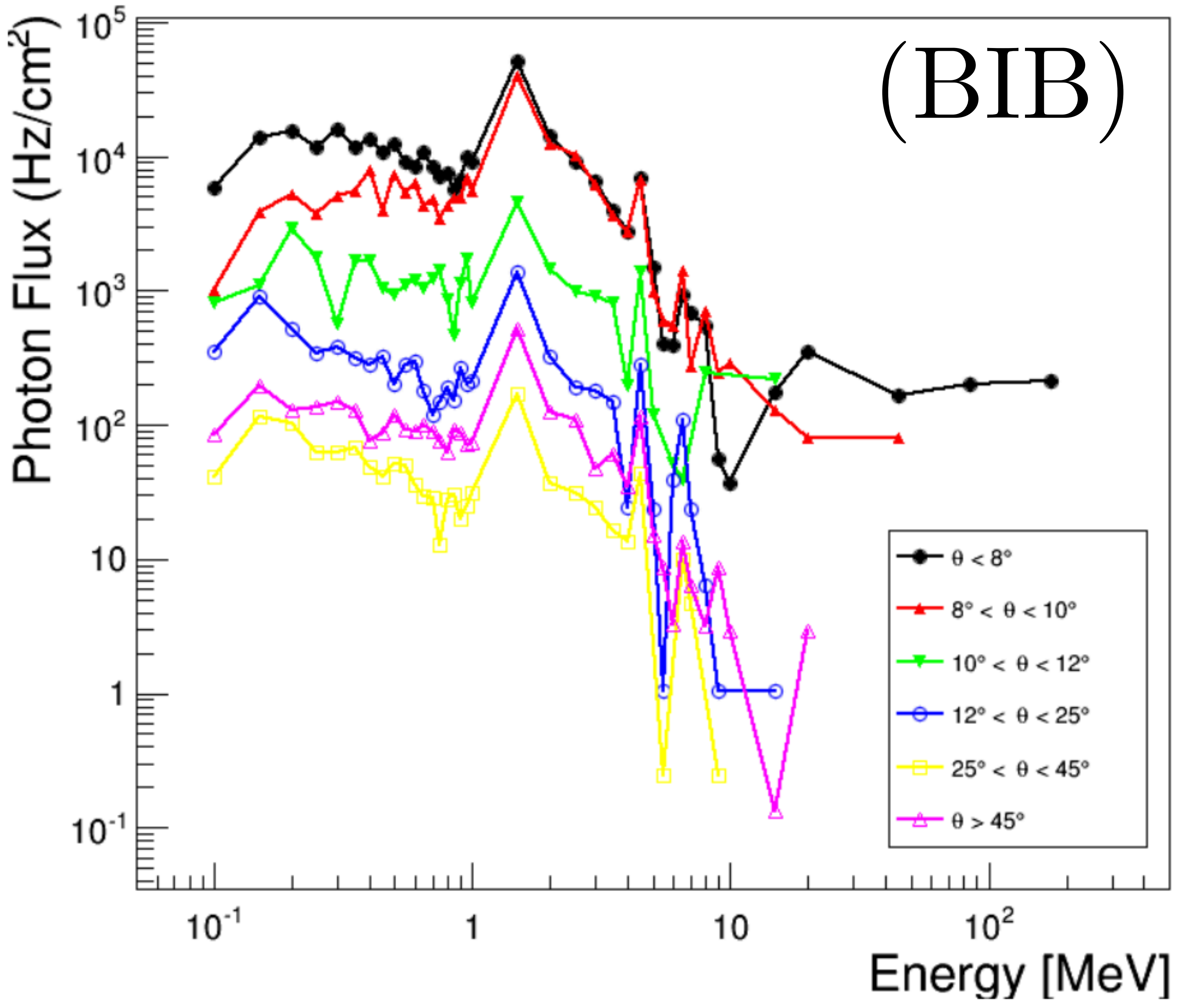
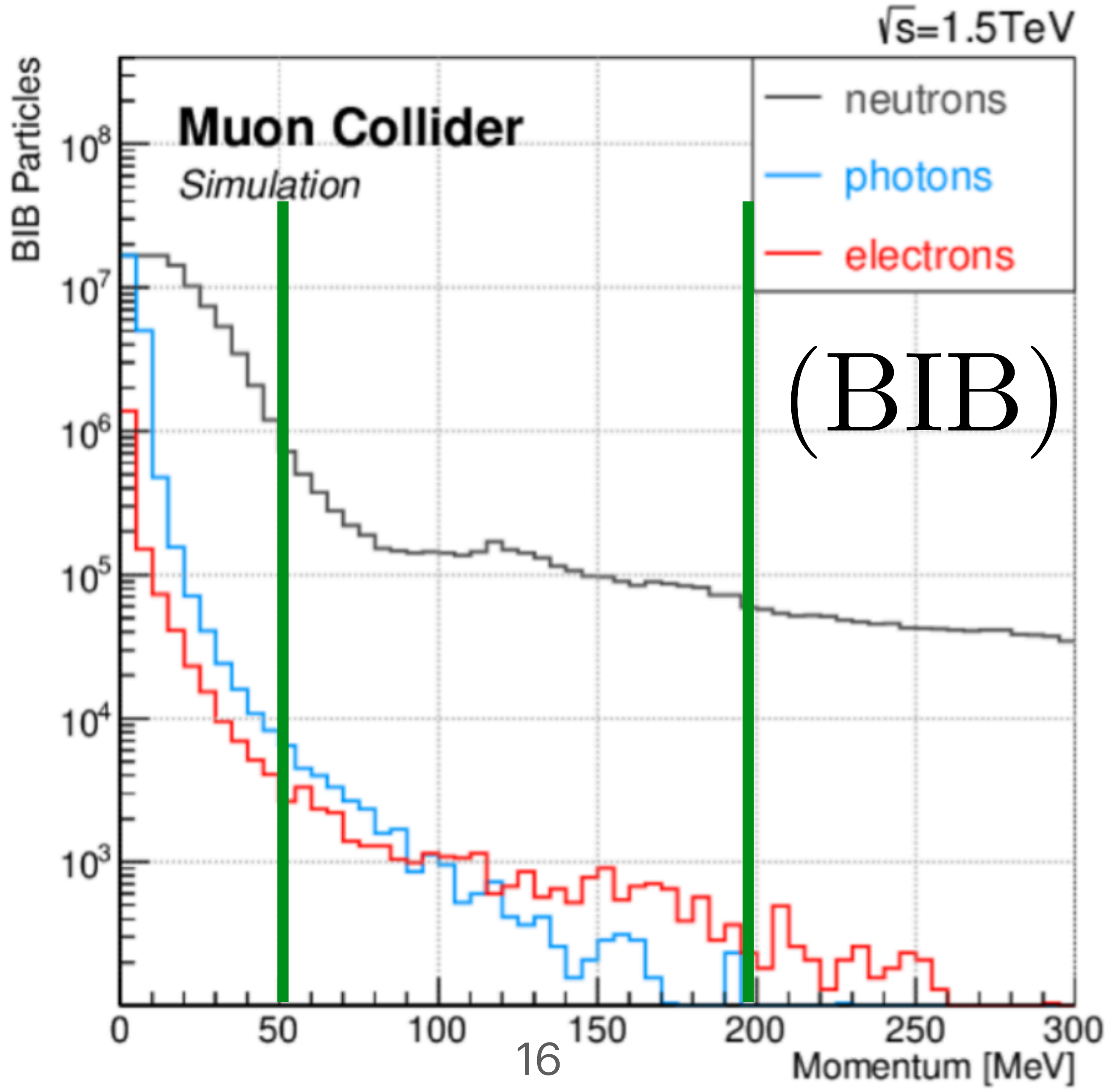
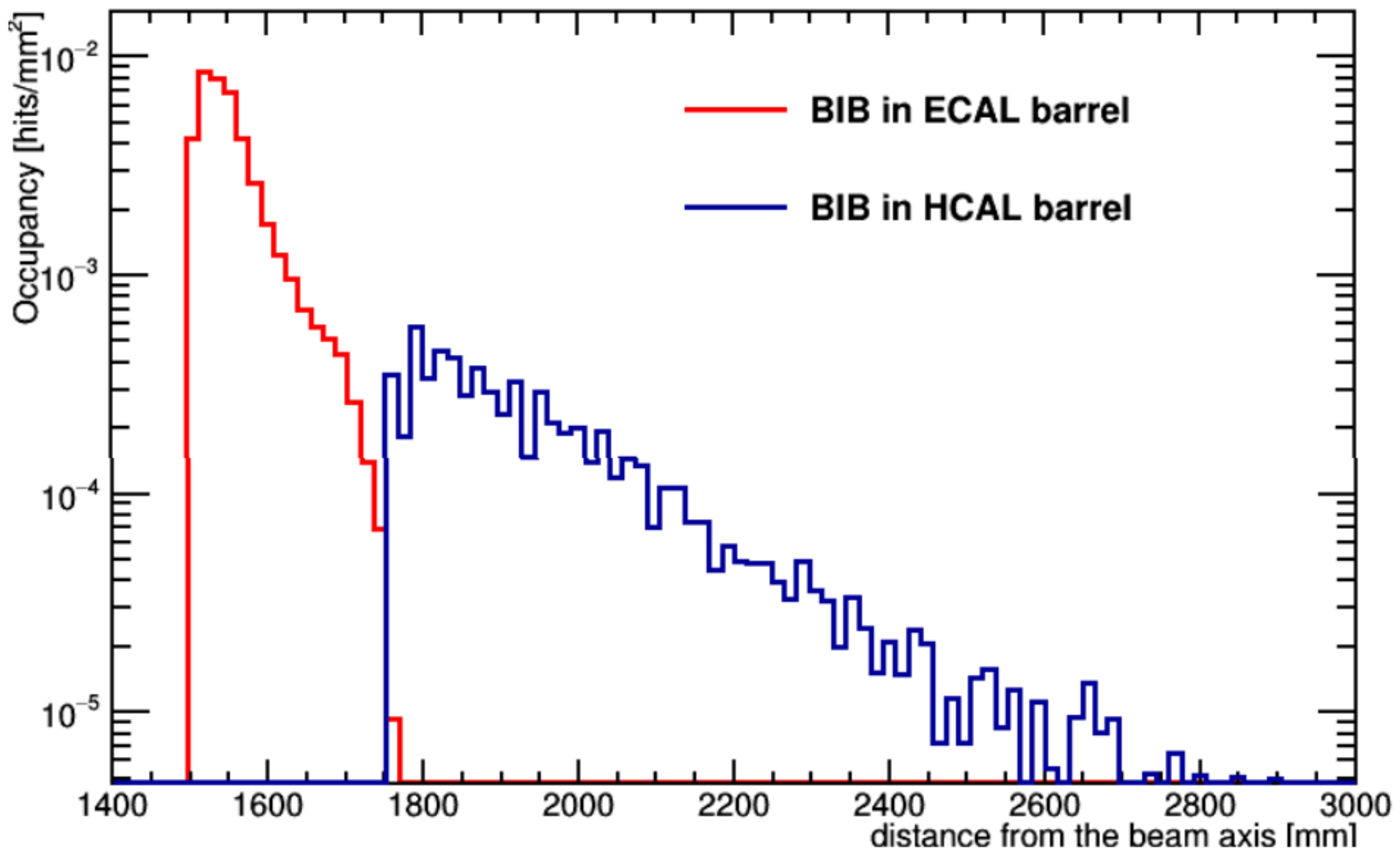
# Primary Challenge: The Beam Induced Background (BIB)

BIB particles are mainly very low energy, but we can imagine NP scenarios that also give lots of low energy tracks (SUEPs)



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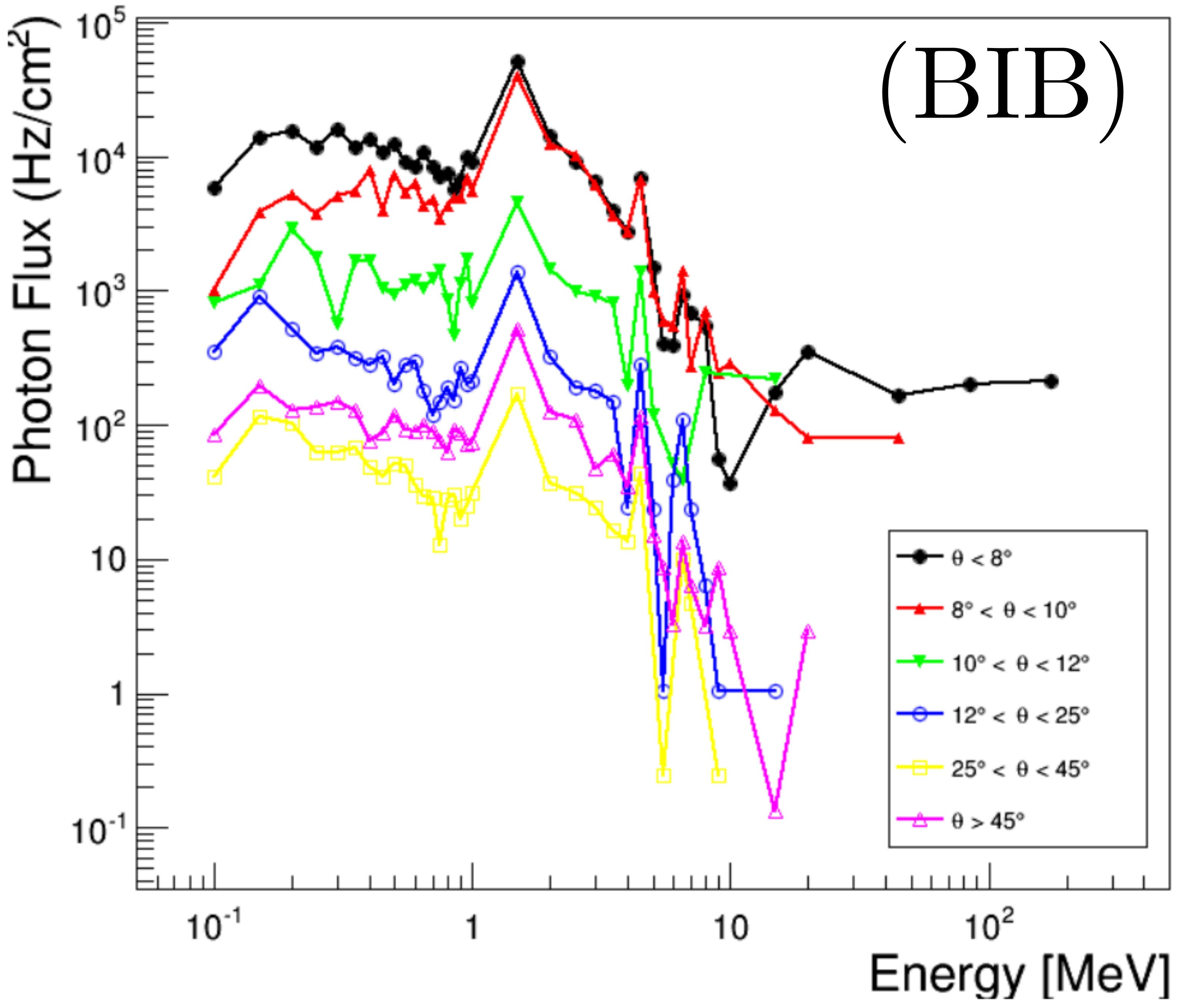
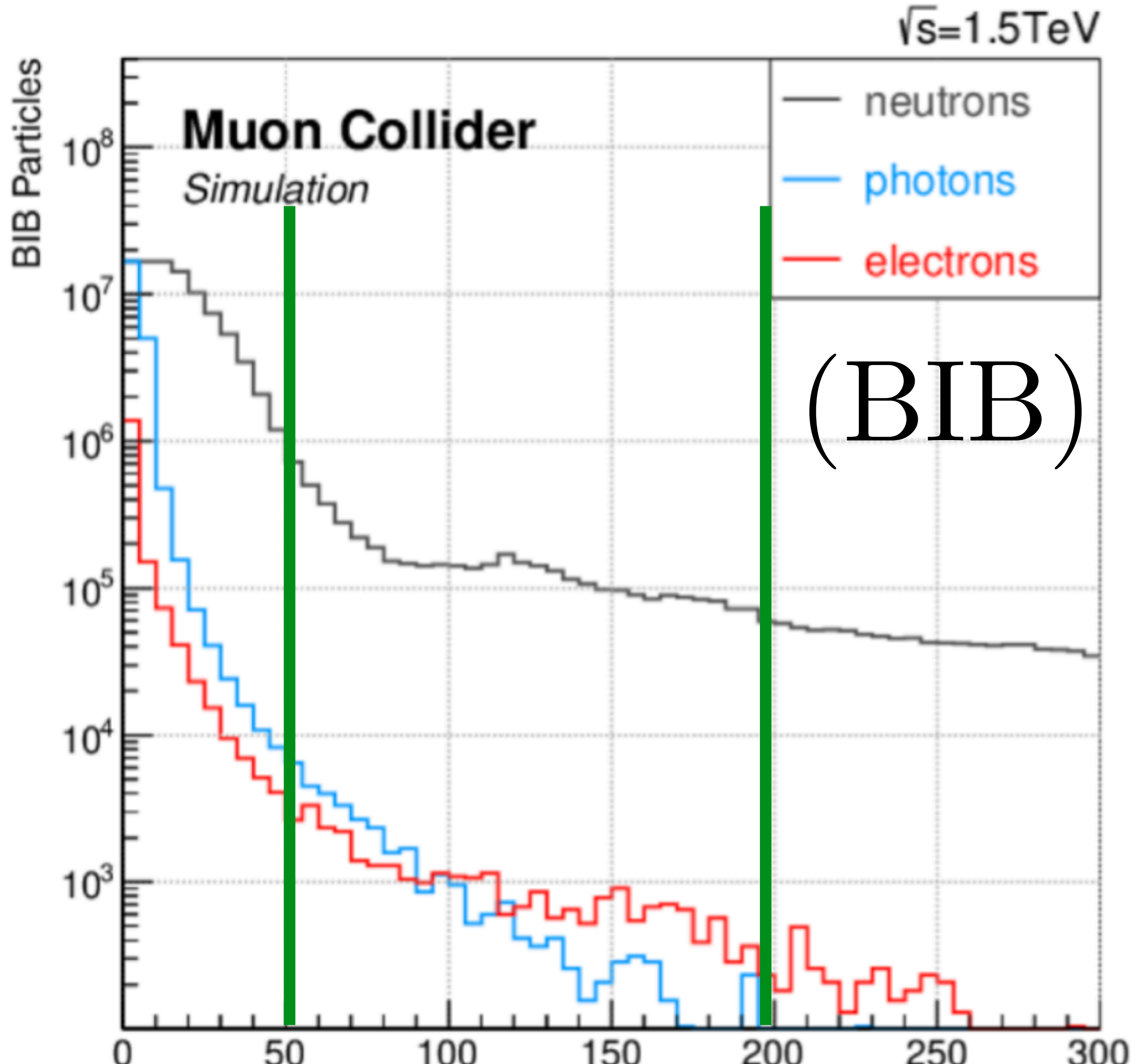
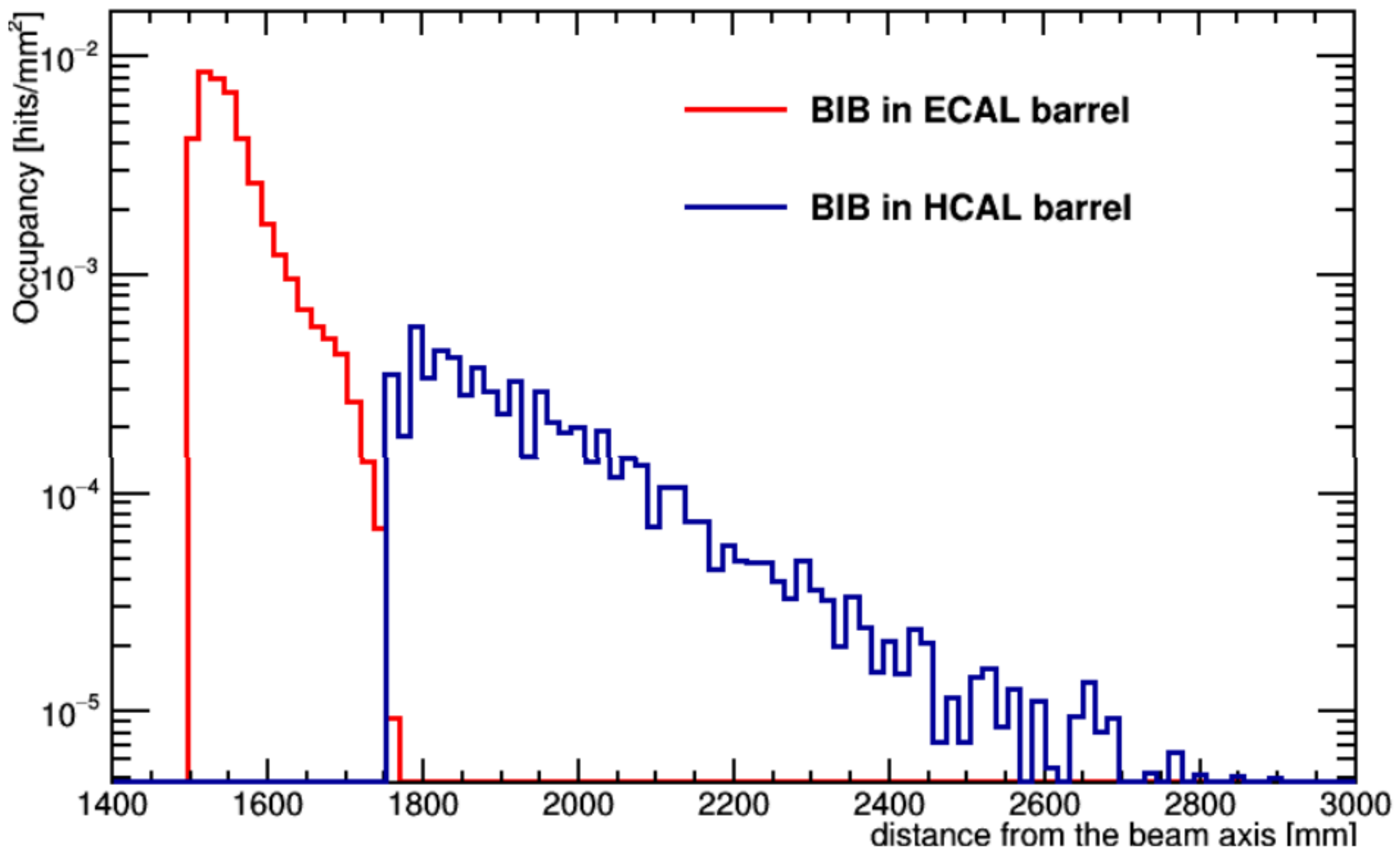
# Wishlist

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
- Good granularity of detector
- Analysis strategies to see sub-GeV particles



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  - High-quality simulation samples of BIB for theorists/experimentalists to study?

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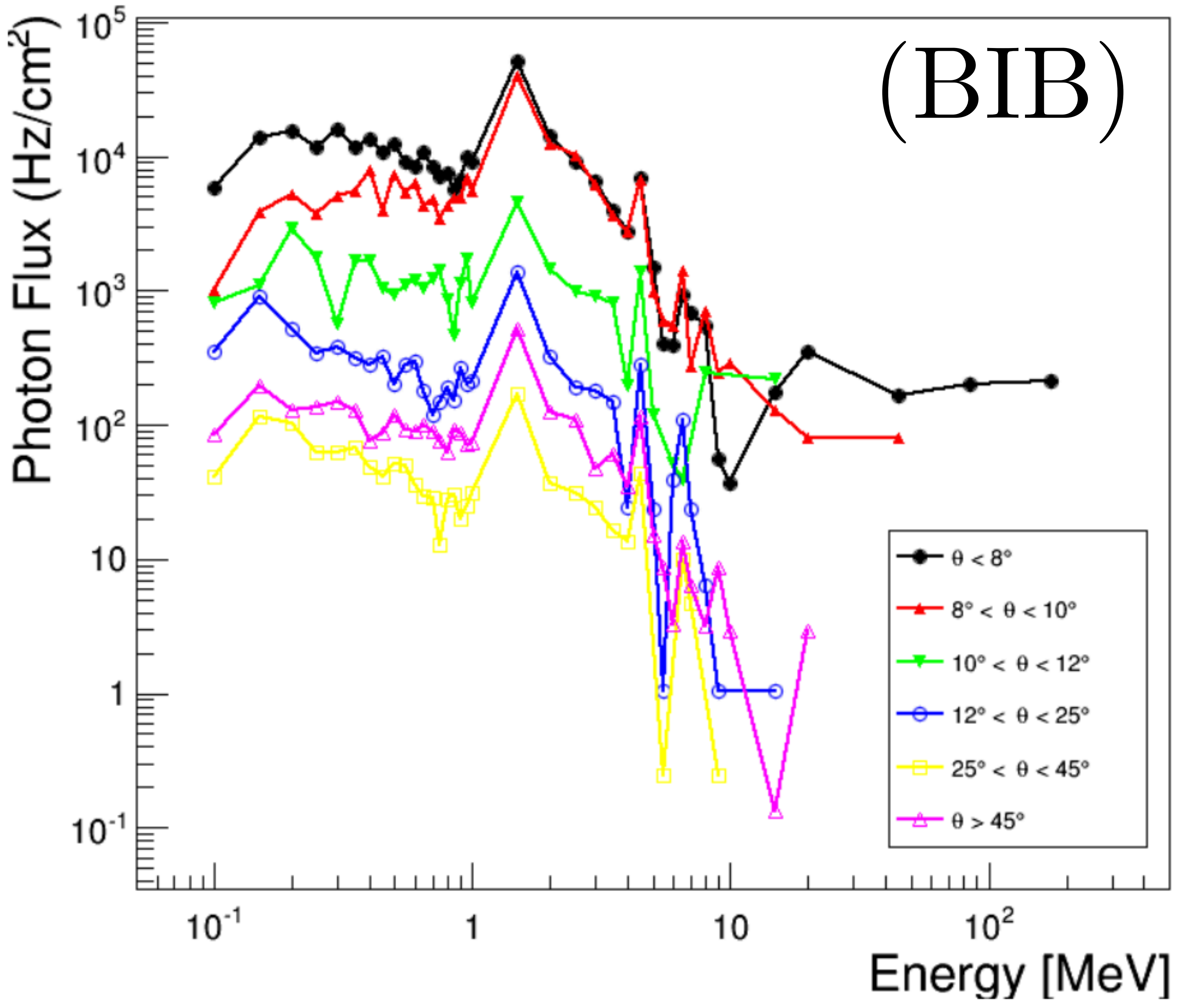


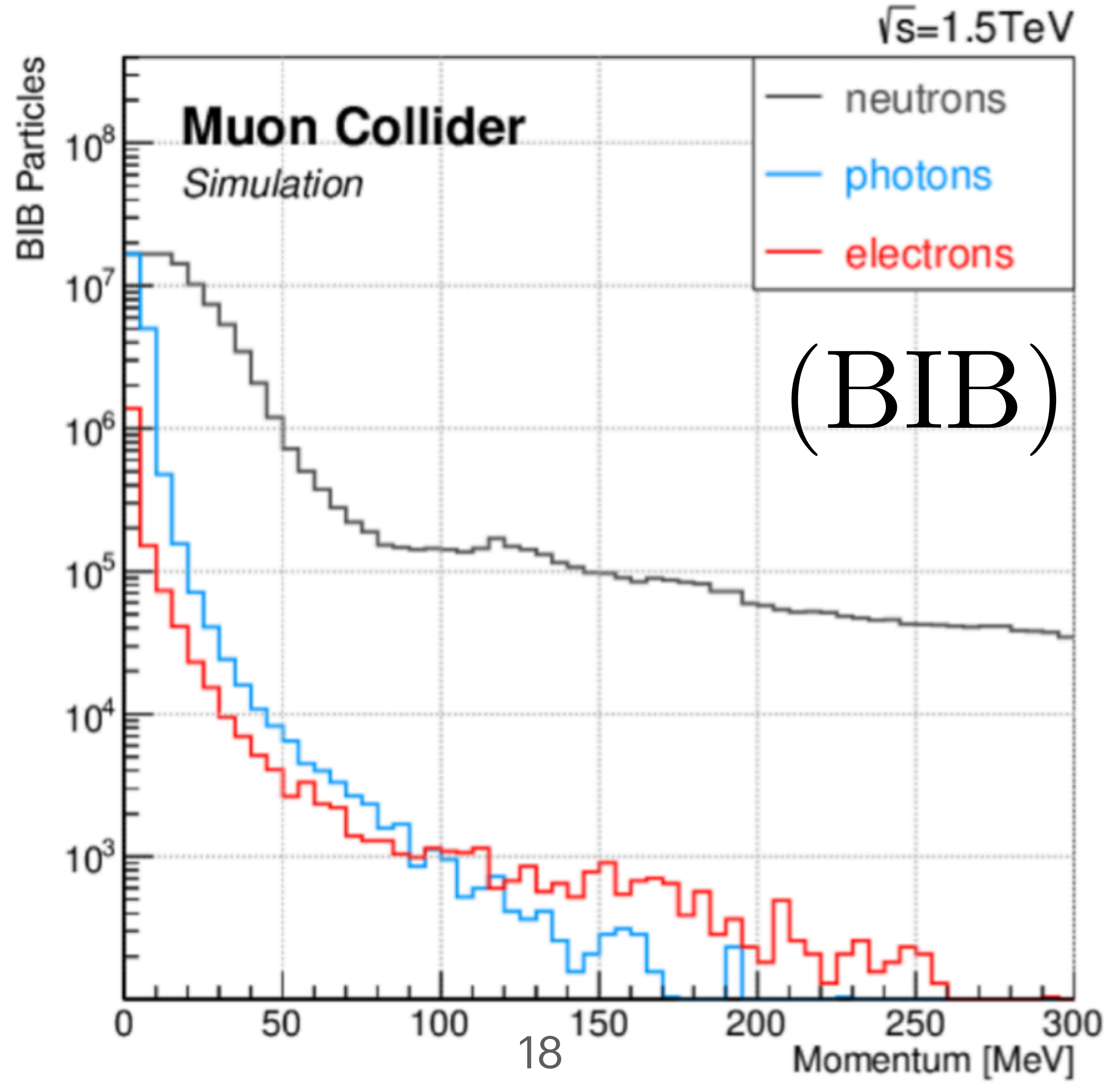


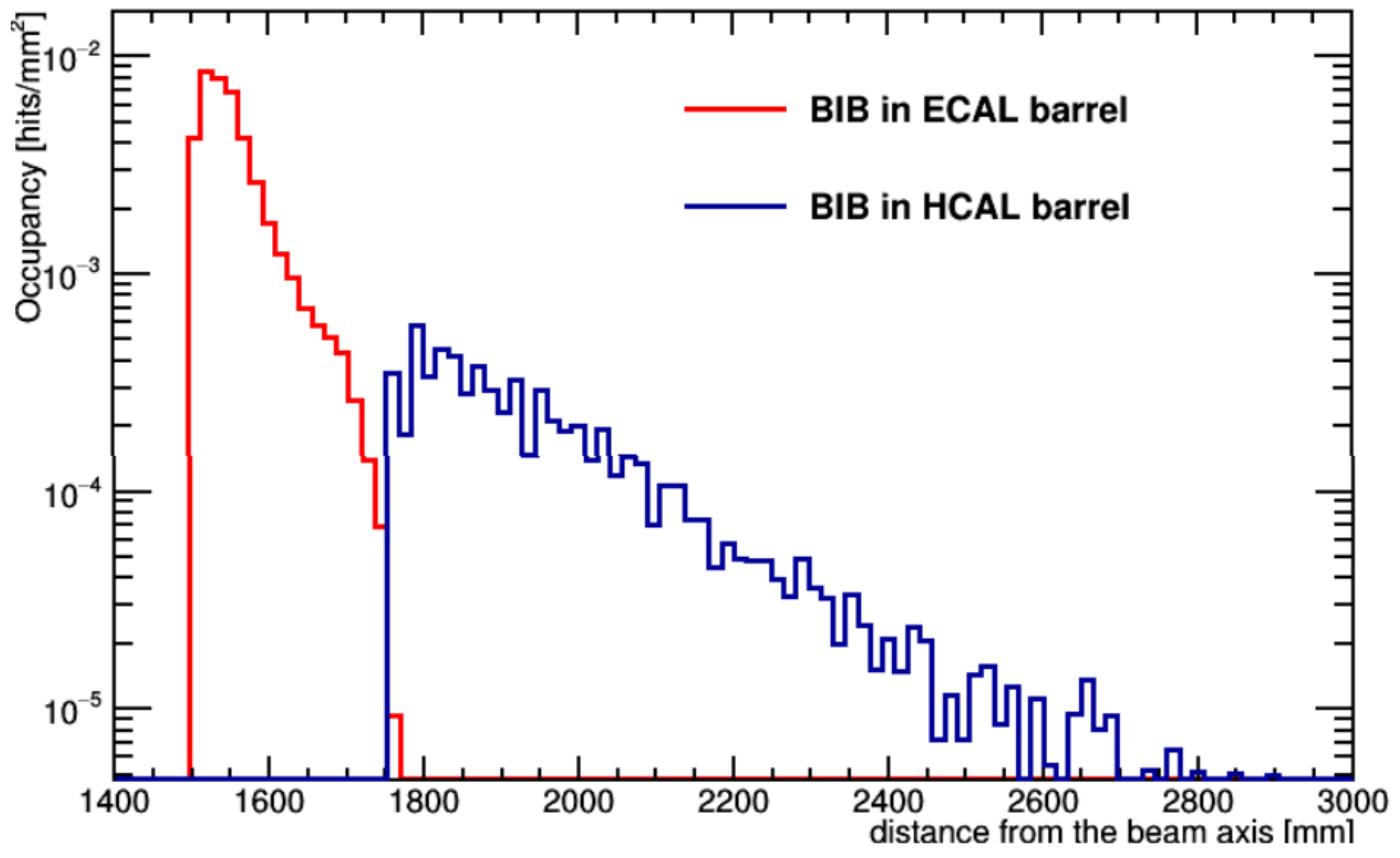


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*One more preliminary*

- Excellent energy resolution (>90%)

$\Gamma \sim \sigma_E \times E \rightarrow$ abandon hope

*IMCC Interim Report*

| Requirement | Baseline | | Aspirational |
|---|---|---|---|
| | $\sqrt{s} = 3$ **TeV** | $\sqrt{s} = 10$ **TeV** | |
| Track $\sigma_{p_T}/p_T^2$ [GeV$^{-1}$] | $4 \times 10^{-5}$ | $4 \times 10^{-5}$ | $1 \times 10^{-5}$ |
| Photon energy resolution | $0.2/\sqrt{E}$ | $0.2/\sqrt{E}$ | $0.1/\sqrt{E}$ |
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# WISHLIST

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
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  - High-quality simulation samples of BIB for theorists/experimentalists to study?

*One more preliminary*

- Excellent energy resolution (>90%)
  - Some document that summarizes reasonable choices for experimental efficiencies?

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| **Requirement** | **Baseline** | | **Aspirational** |
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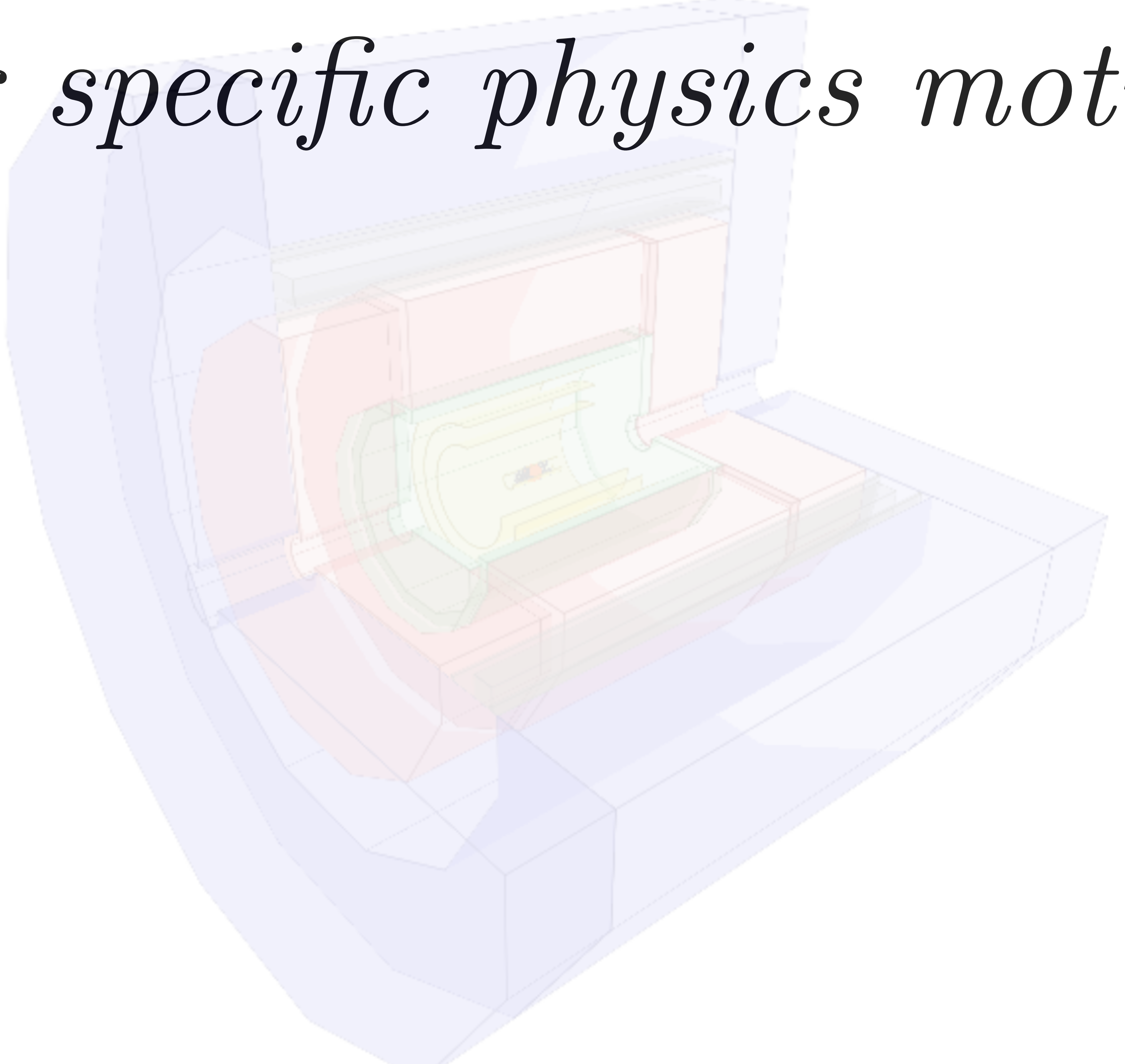
*Assuming we have the BIB under control, let's consider specific physics motivations*



# Physics Goals

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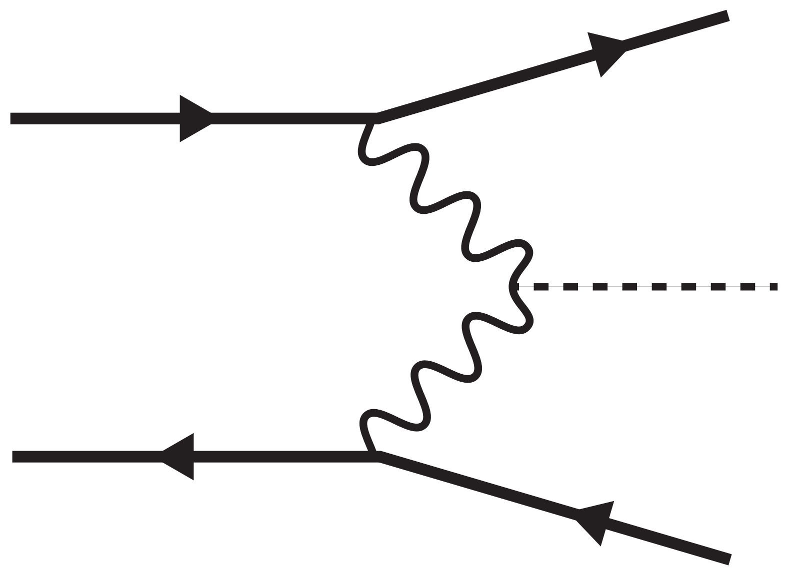

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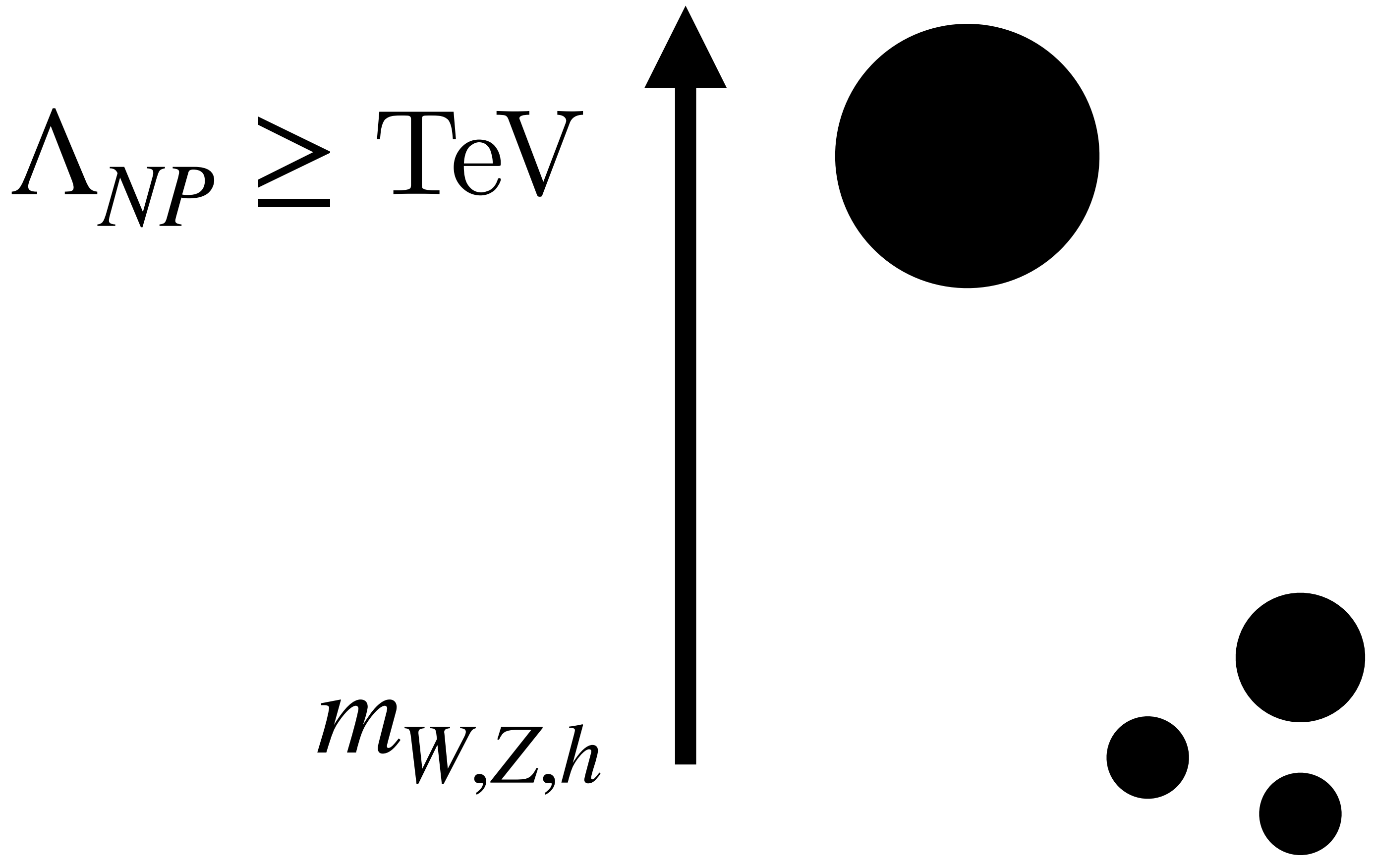


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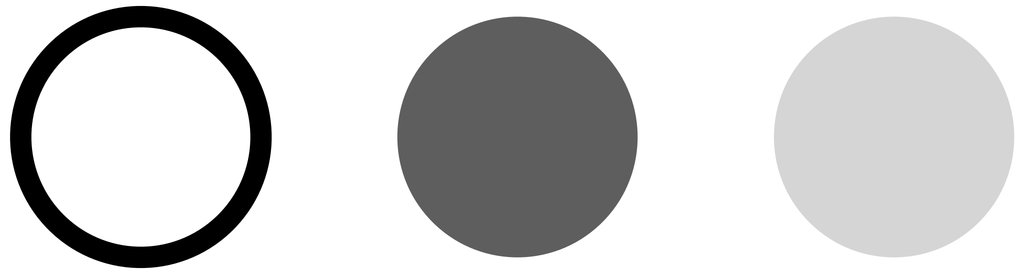

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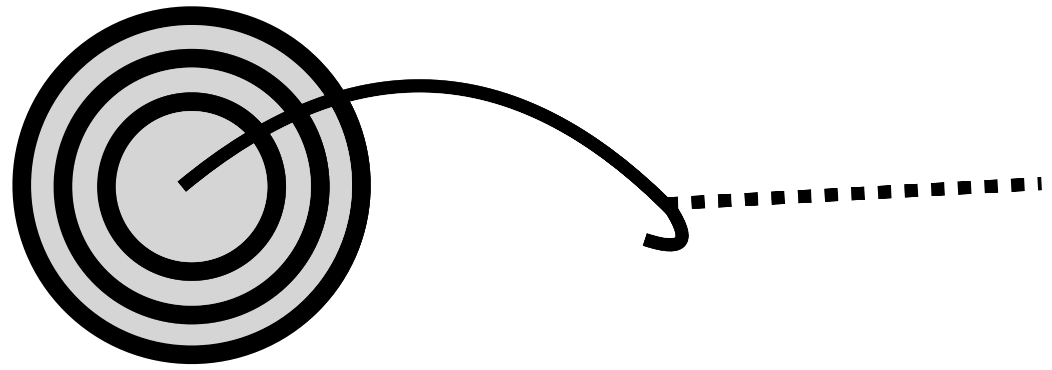

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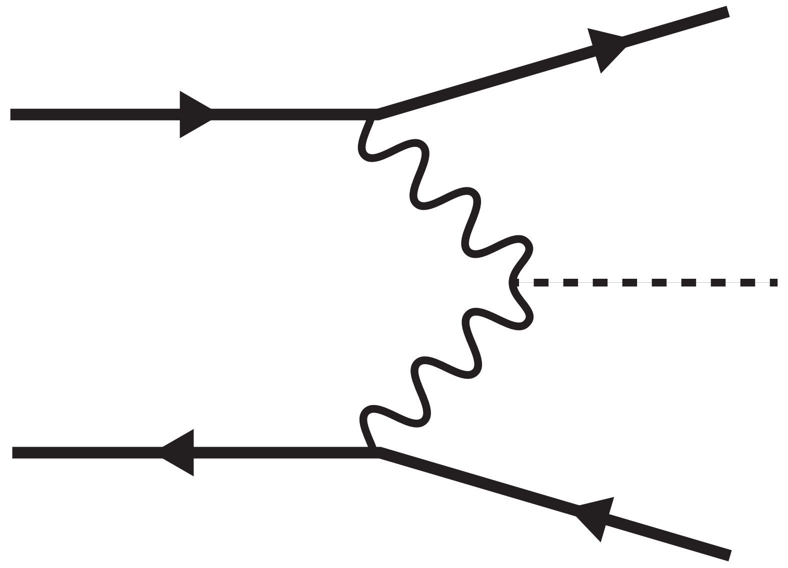

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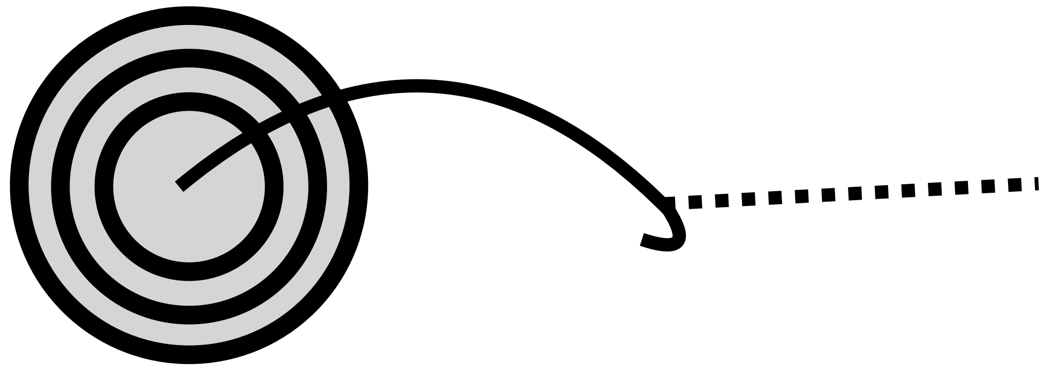
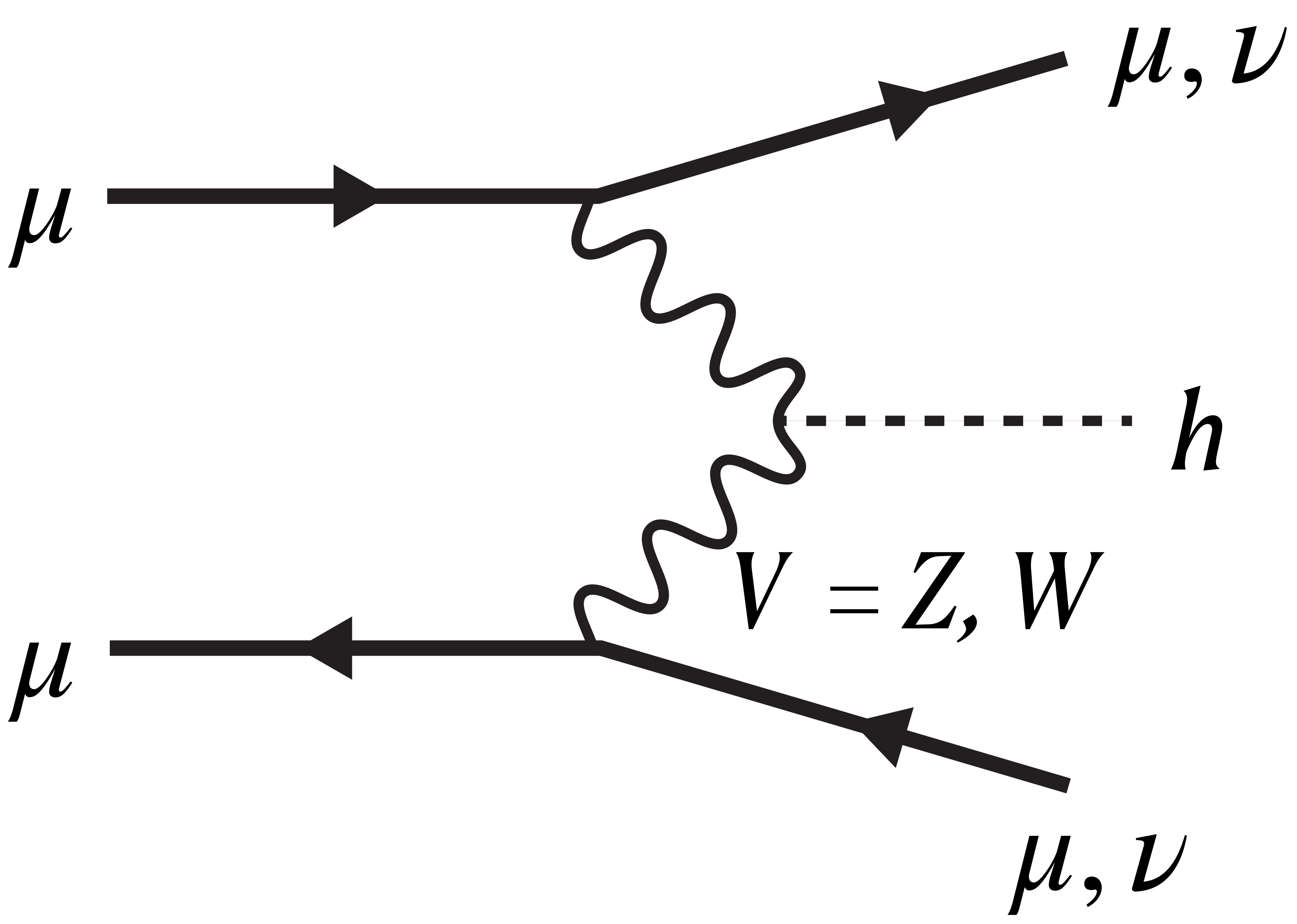
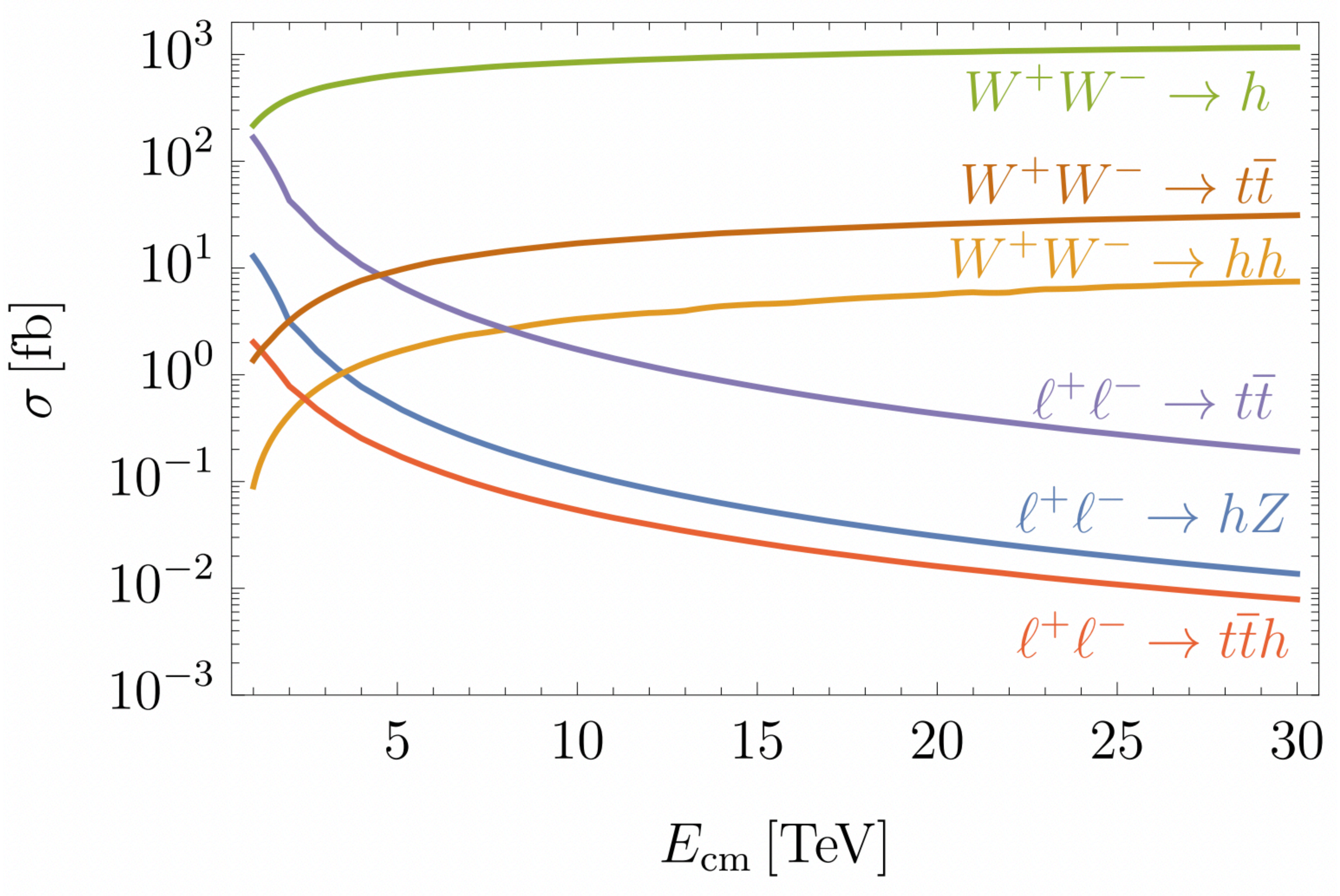


# Precision Higgs & EW

Precision measurements of the Higgs is often presented as a primary motivation for a MuC, and we produce them with VBF




Buttazzo, Franceschini, Wulzer '20



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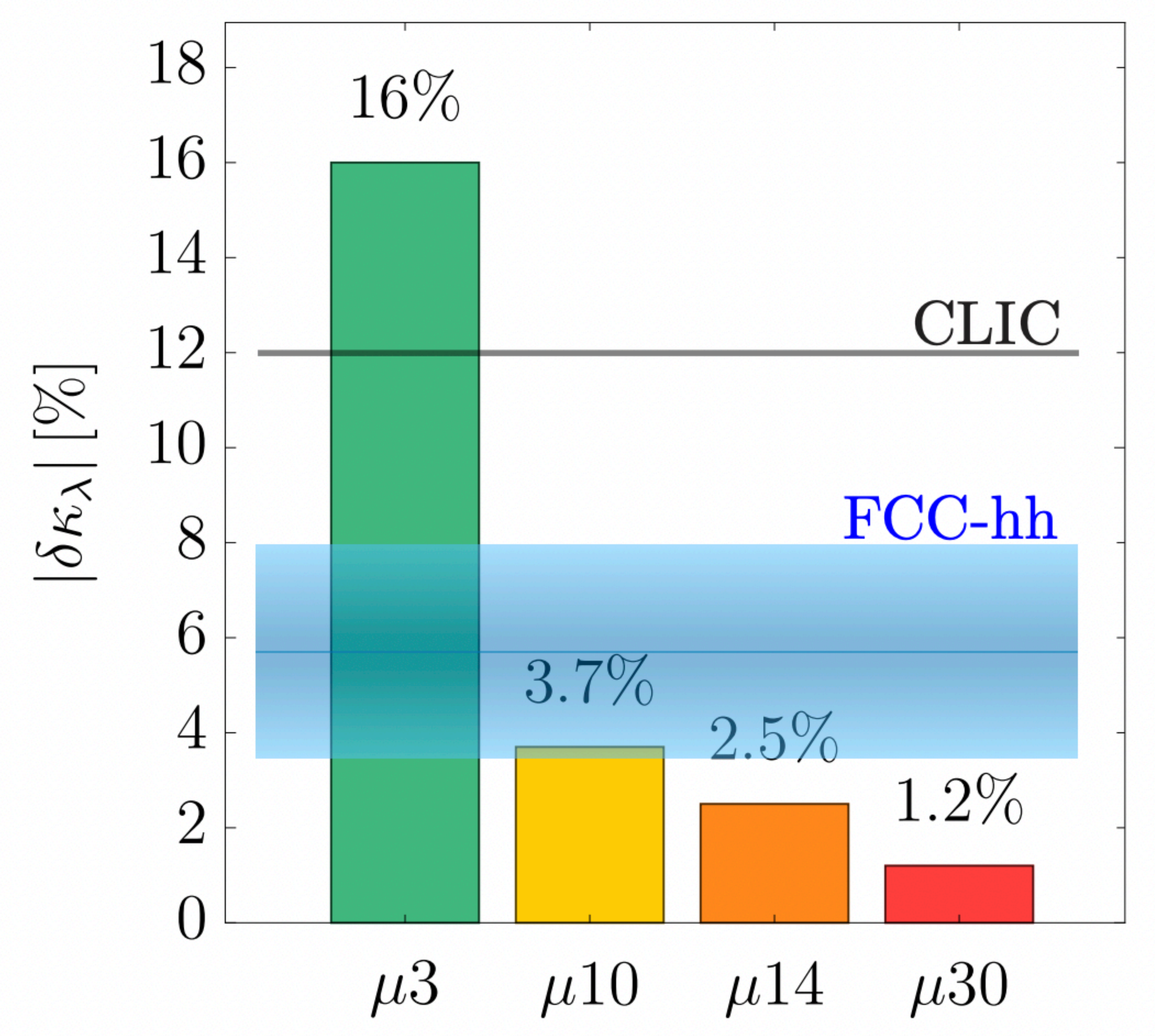
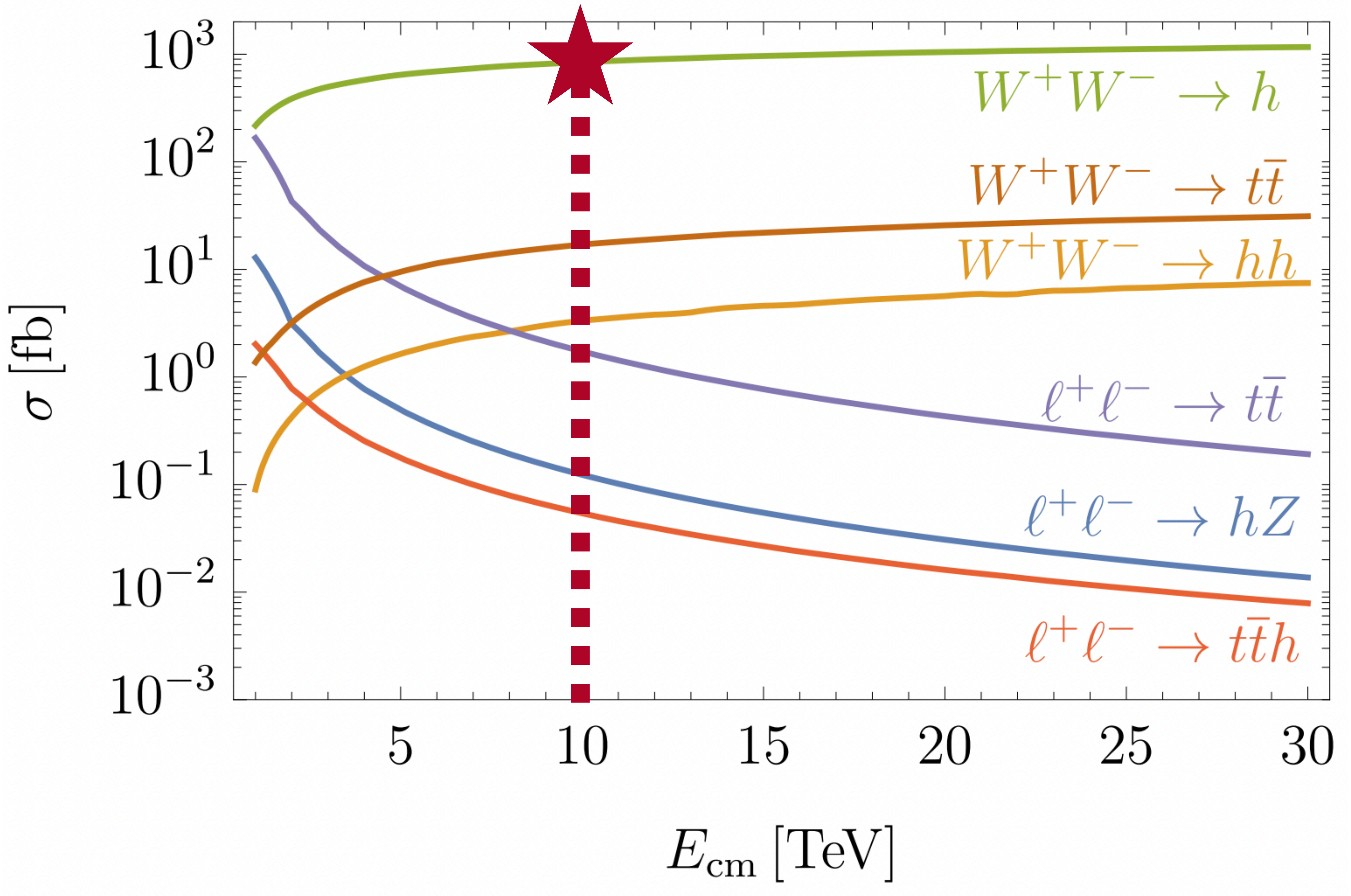



Luminosity Benchmark

$\times\, 10\ \mathrm{ab}^{-1} = 10^7$ total $h$

Buttazzo, Franceschini, Wulzer '20



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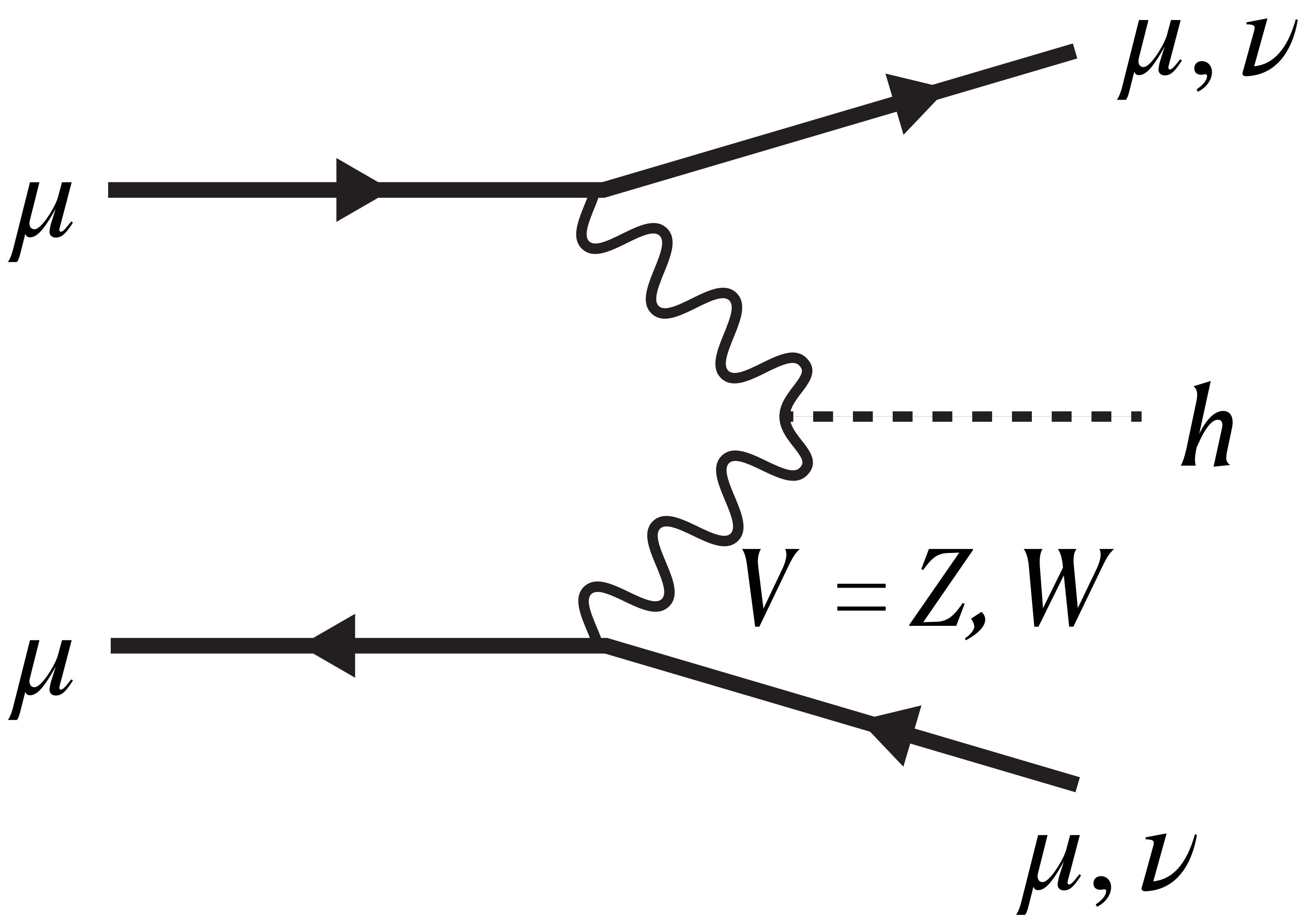
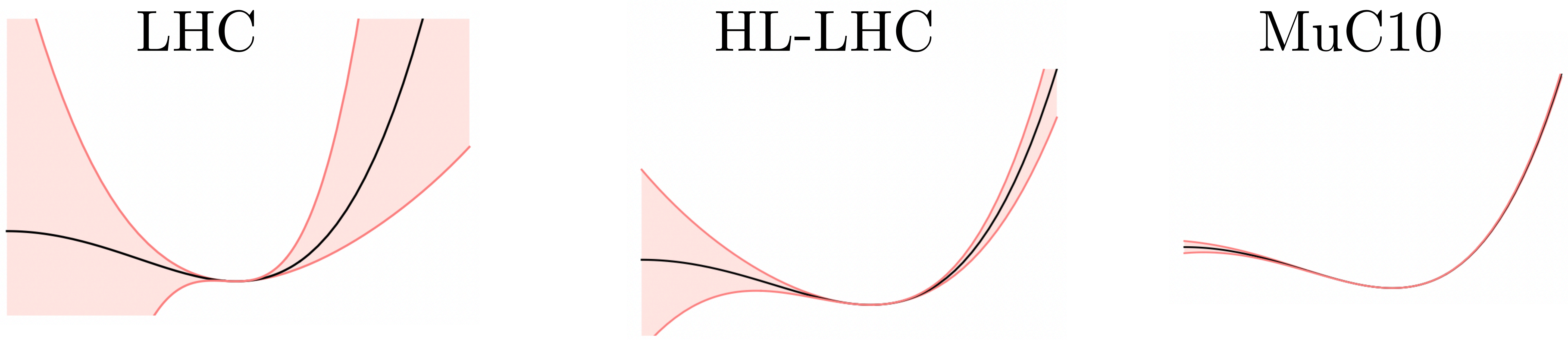



Variety of *guaranteed* new measurements

$$V(h) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

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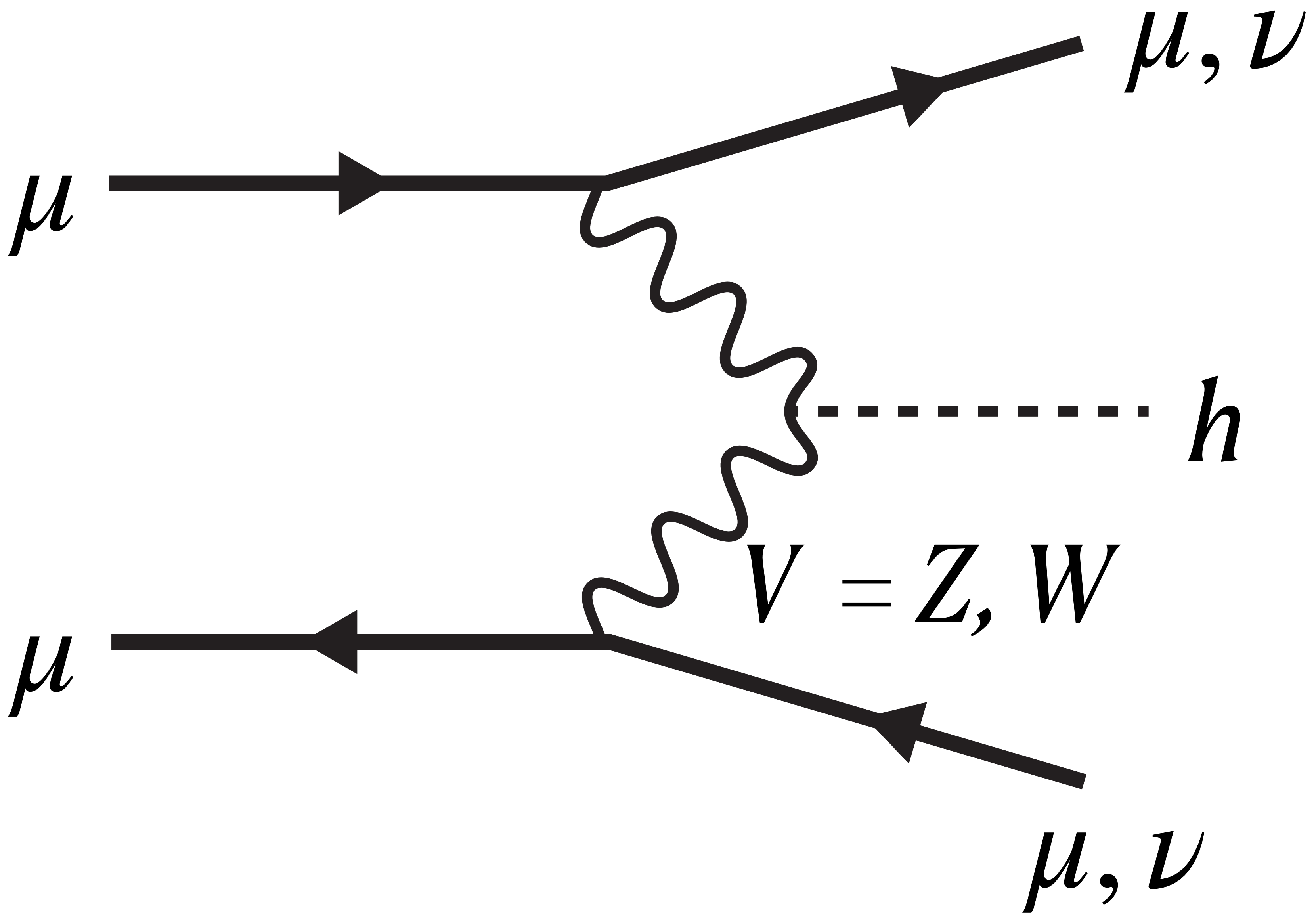


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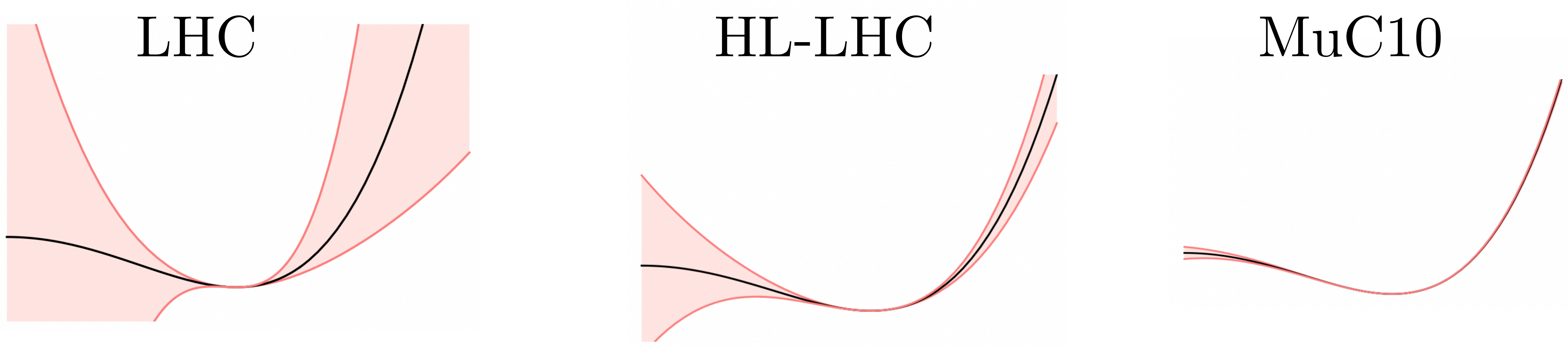
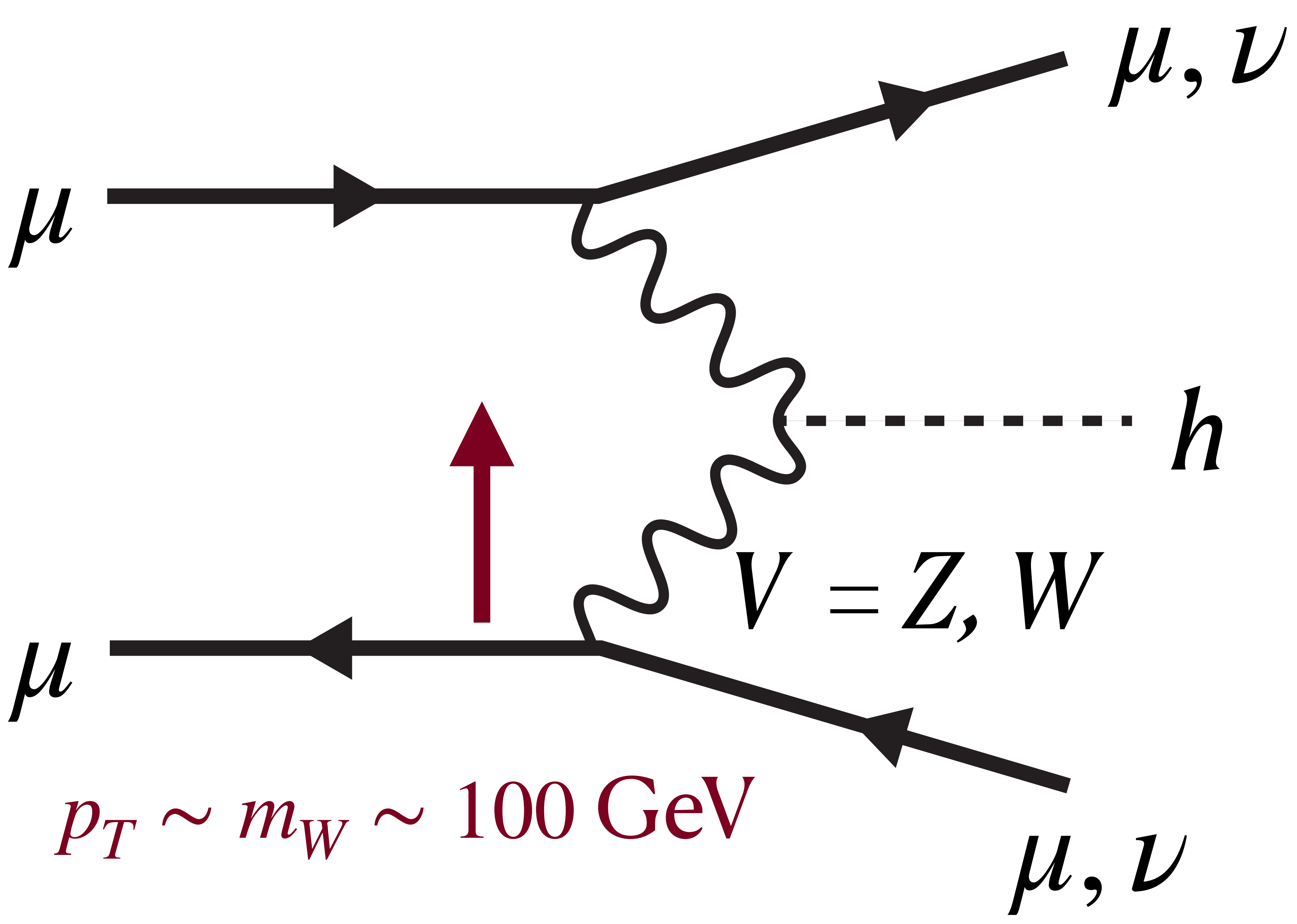



plus improvements shown by $\kappa$ framework

*Assuming* we can reliably identify Higgs events

# Precision Higgs & EW

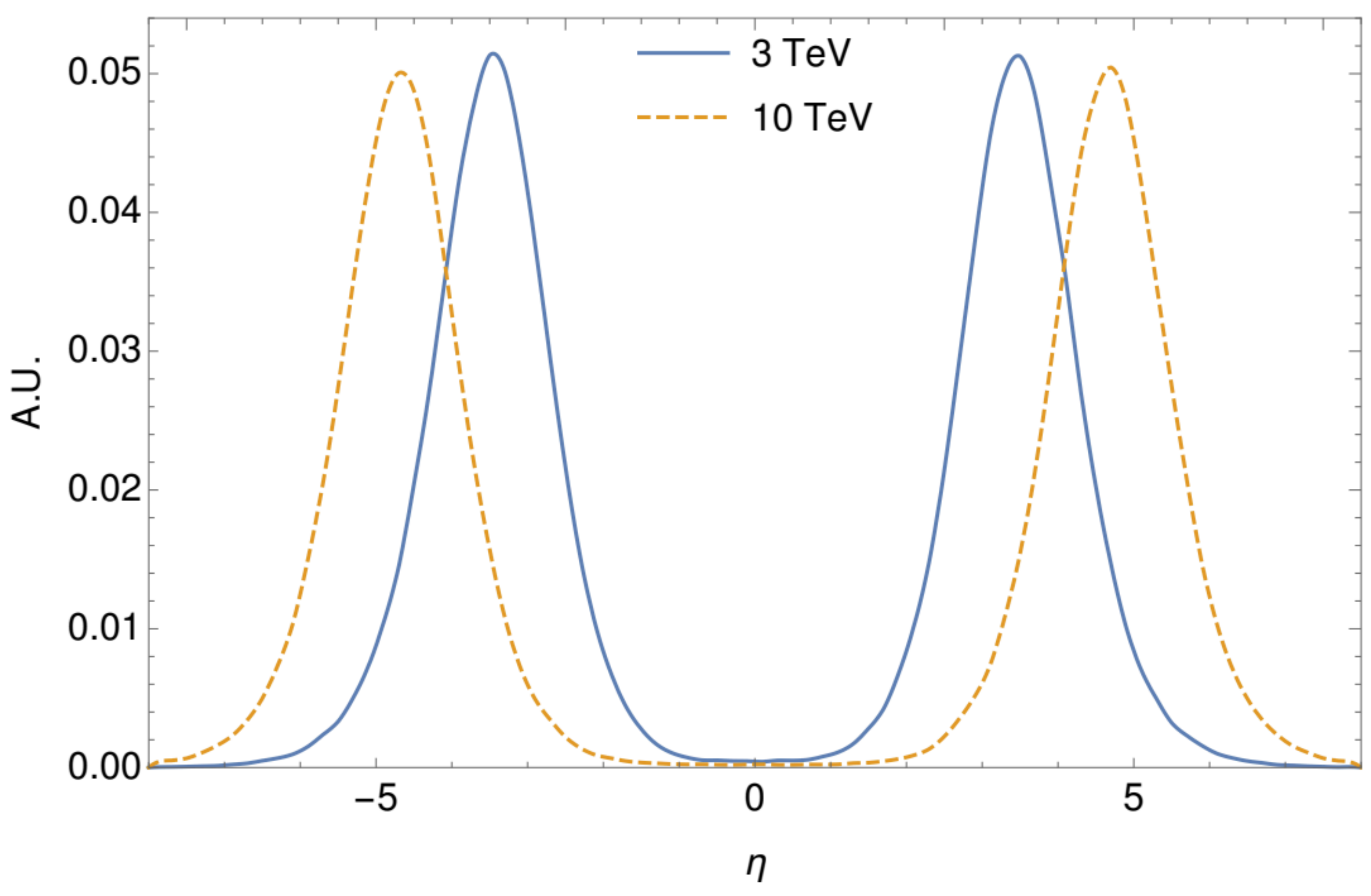
VBF Higgs production has very forward kinematics (for all)



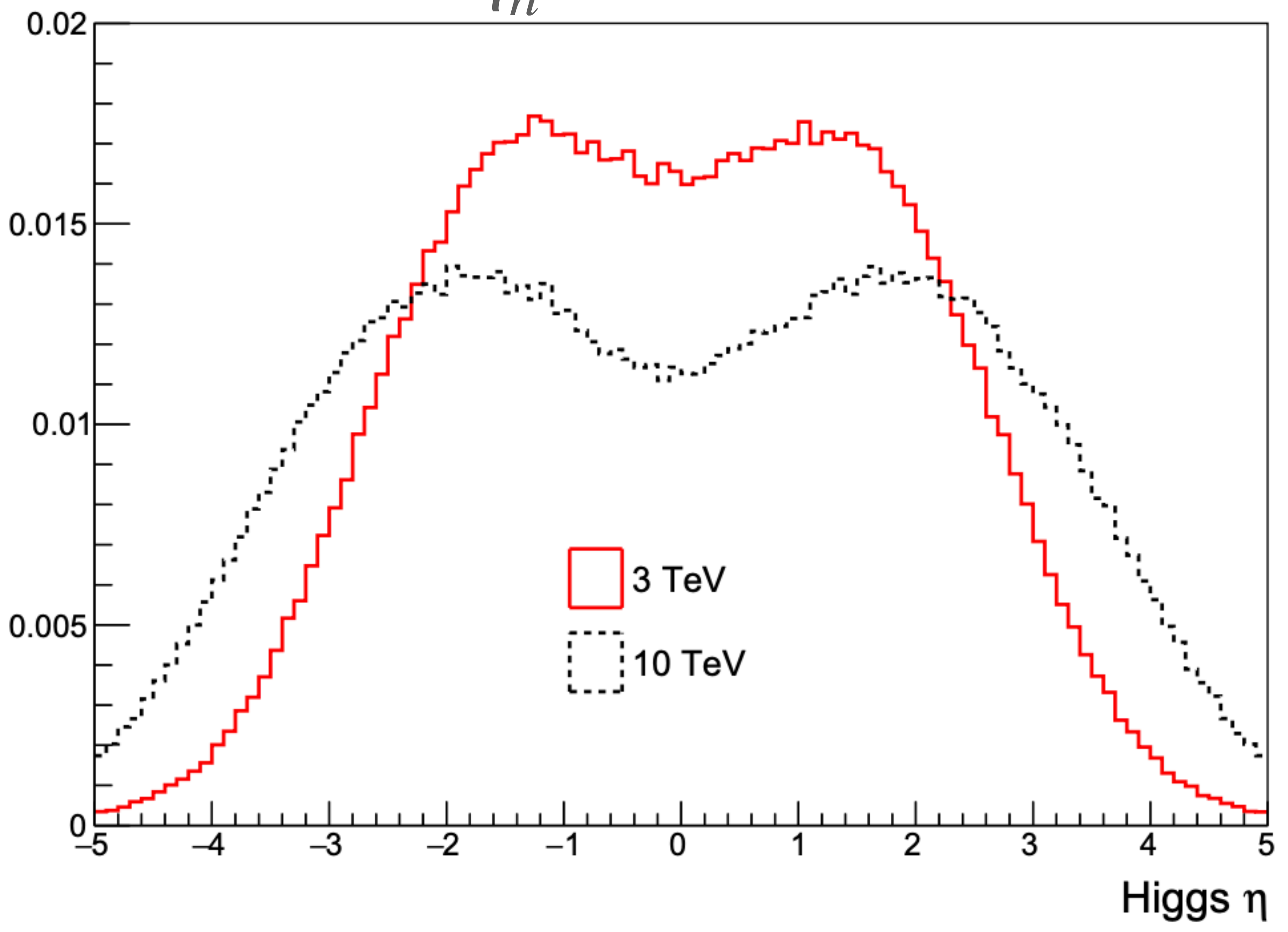

$\eta_\mu \sim 3.5$ at 3 TeV

$\eta_\mu \sim 5$ at 10 TeV

$\eta_\mu$ for $ZZ \to h$ fusion



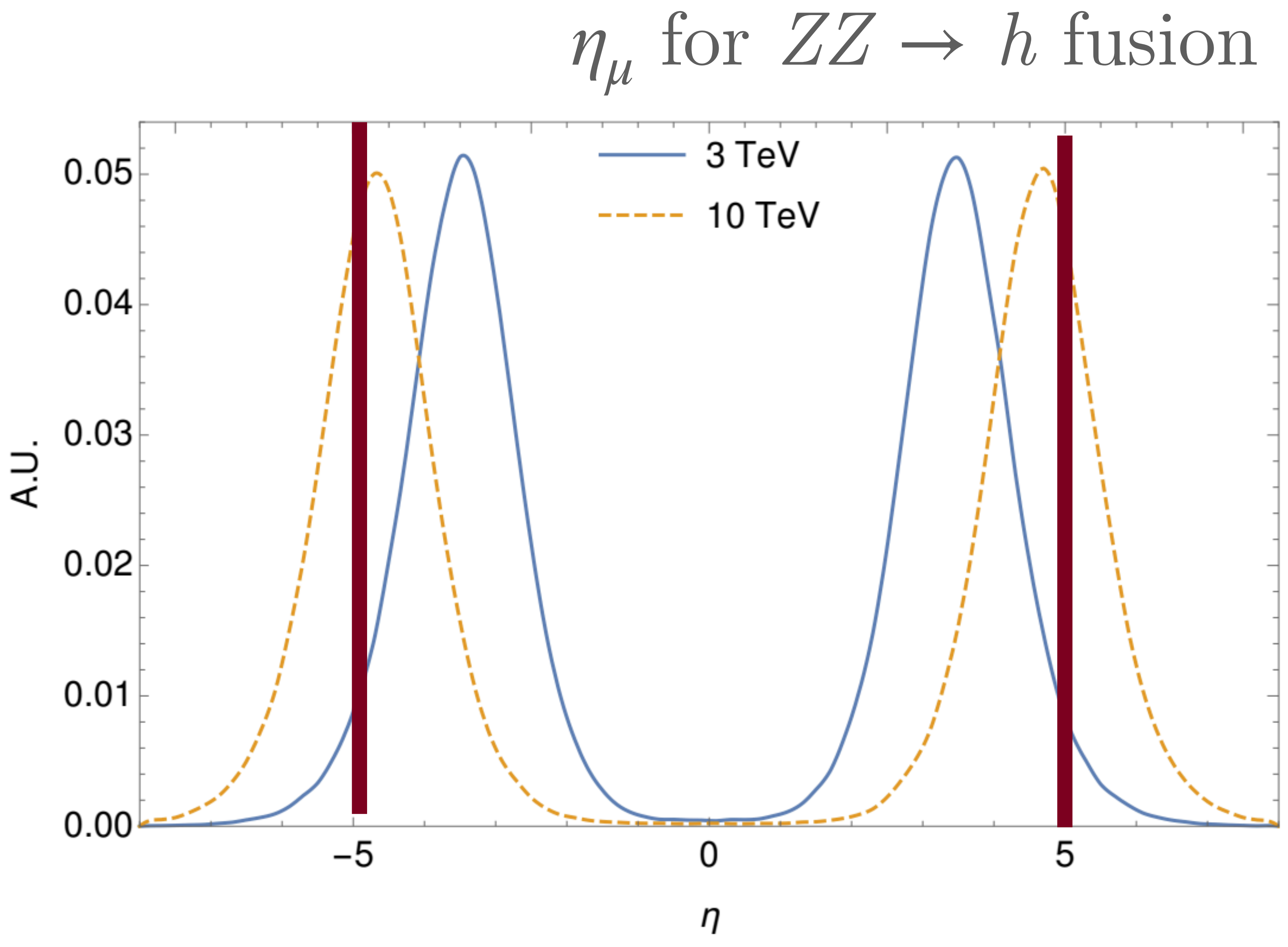

$\eta_h$ for $WW \to h$ fusion

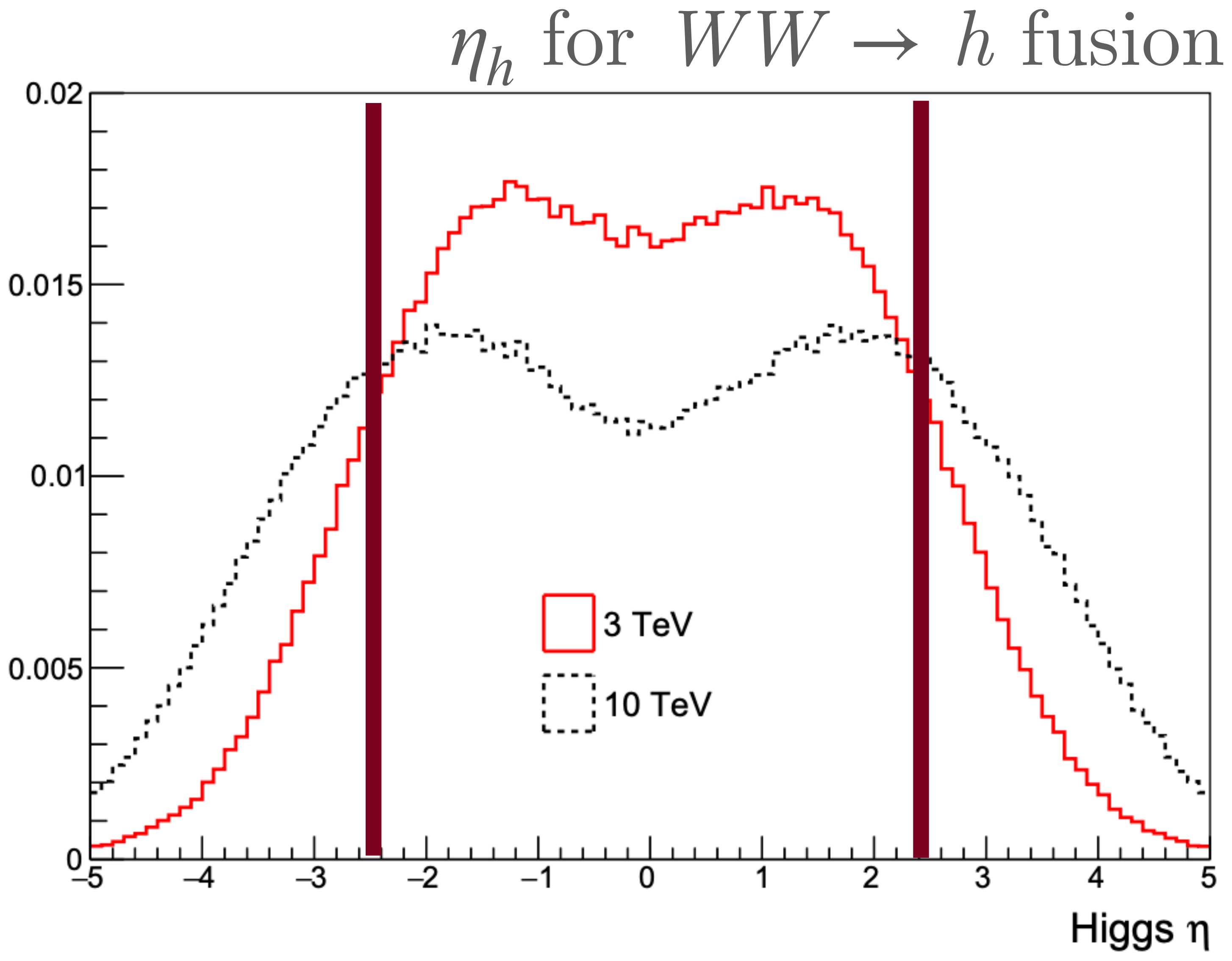



Forslund & Meade '22

# Wishlist

- Sensitivity of $|\eta| \sim 2.5$ - 3 (for high Higgs acceptance )
- Forward muon tagging up to $\eta \sim 5$ at 10 TeV (ZZ vs. WW VBF discrimination)




Forslund & Meade '22

# Precision Higgs & EW

What Higgs processes in specific do we want to see?



Forslund & Meade '23

# PRECISION HIGGS & EW

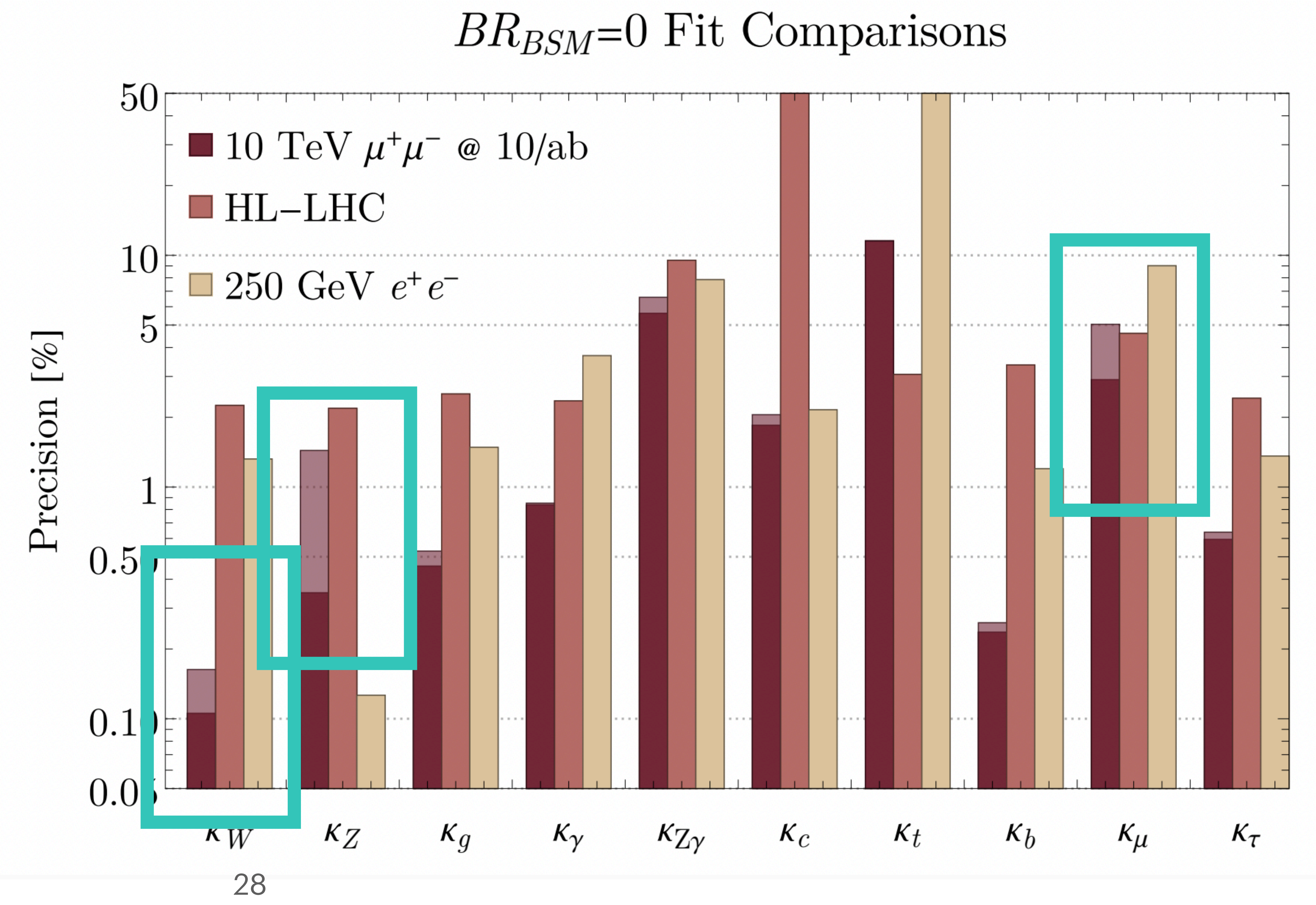
What Higgs processes in specific do we want to see?

| CLIC | | | CEPC | FCC-ee | | FCC-ee/eh/hh |
|---|---|---|---|---|---|---|
| 380 | 15000 | 3000 | | 240 | 365 | |
| 0.86 | 0.16 | 0.11 | 1.3 | 1.3 | 0.43 | 0.14 |
| 0.5 | 0.26 | 0.23 | 0.14 | 0.20 | 0.17 | 0.12 |
| 2.5 | 1.3 | 0.9 | 1.5 | 1.7 | 1.0 | 0.49 |
| 98⋆ | 5.0 | 2.2 | 3.7 | 4.7 | 3.9 | 0.29 |
| 120⋆ | 15 | 6.9 | 8.2 | 81⋆ | 75⋆ | 0.69 |
| 4.3 | 1.8 | 1.4 | 2.2 | 1.8 | 1.3 | 0.95 |
| – | – | 2.7 | – | – | – | 1.0 |
| 1.9 | 0.46 | 0.37 | 1.2 | 1.3 | 0.67 | 0.43 |
| 320⋆ | 13 | 5.8 | 8.9 | 10 | 8.9 | 0.41 |
| 3.0 | 1.3 | 0.88 | 1.3 | 1.4 | 0.73 | 0.44 |

1905.03764

Precision for "standard" assumption ($|\eta| < 2.5$)
vs. forward tagging ($|\eta| < 6$)

Consider Higgs couplings in the $\kappa$ framework




Forslund & Meade '23

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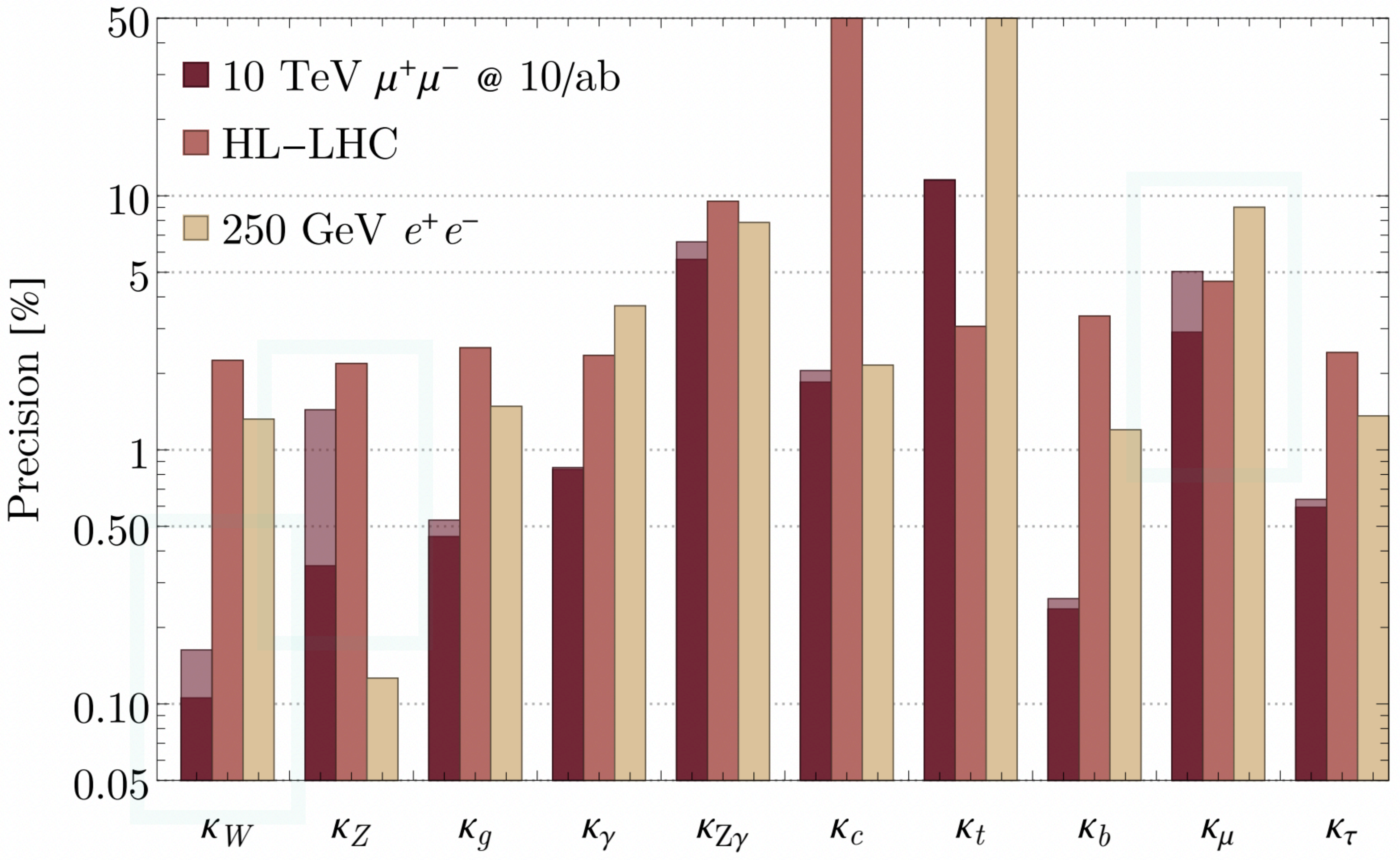

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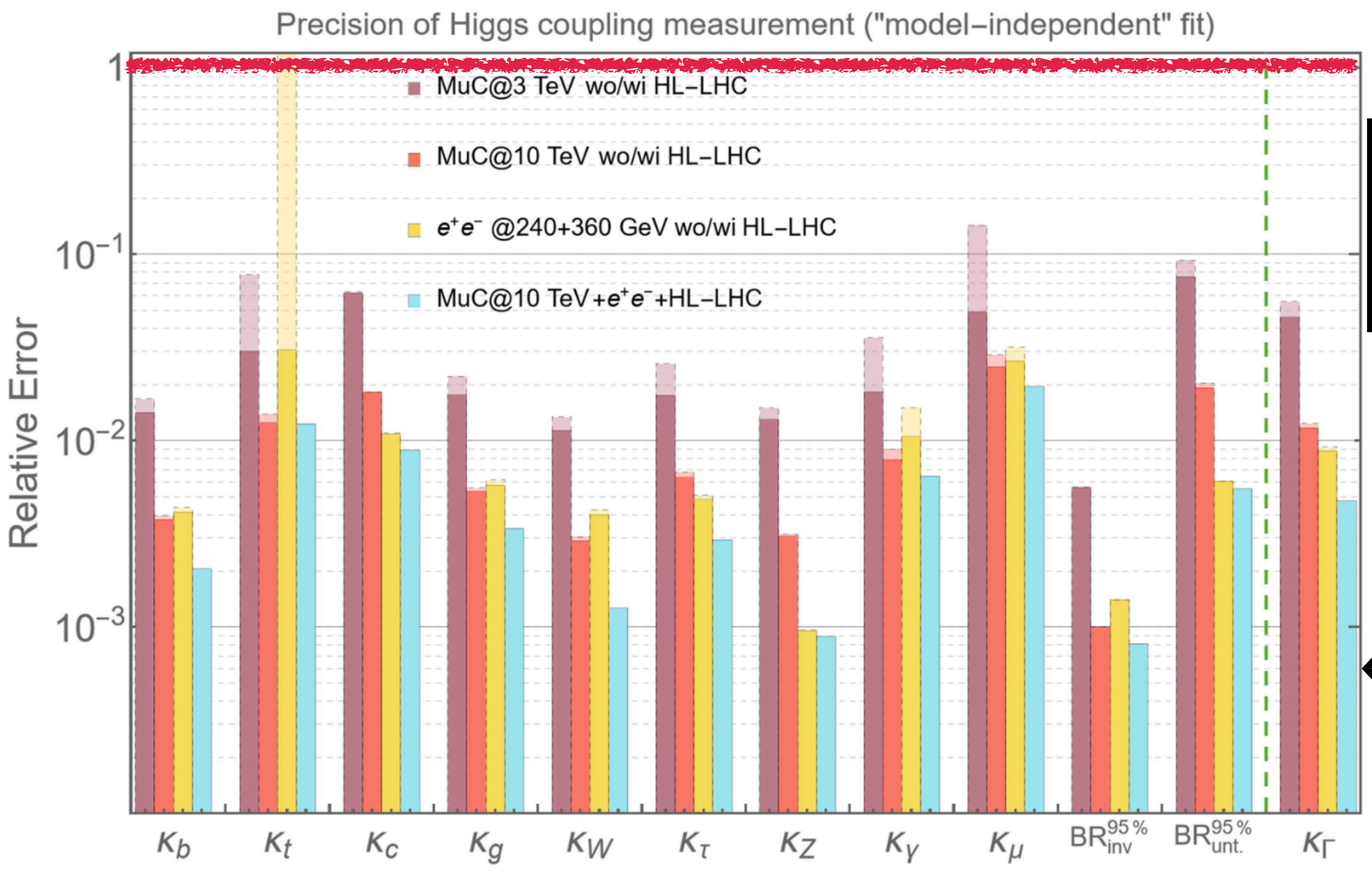


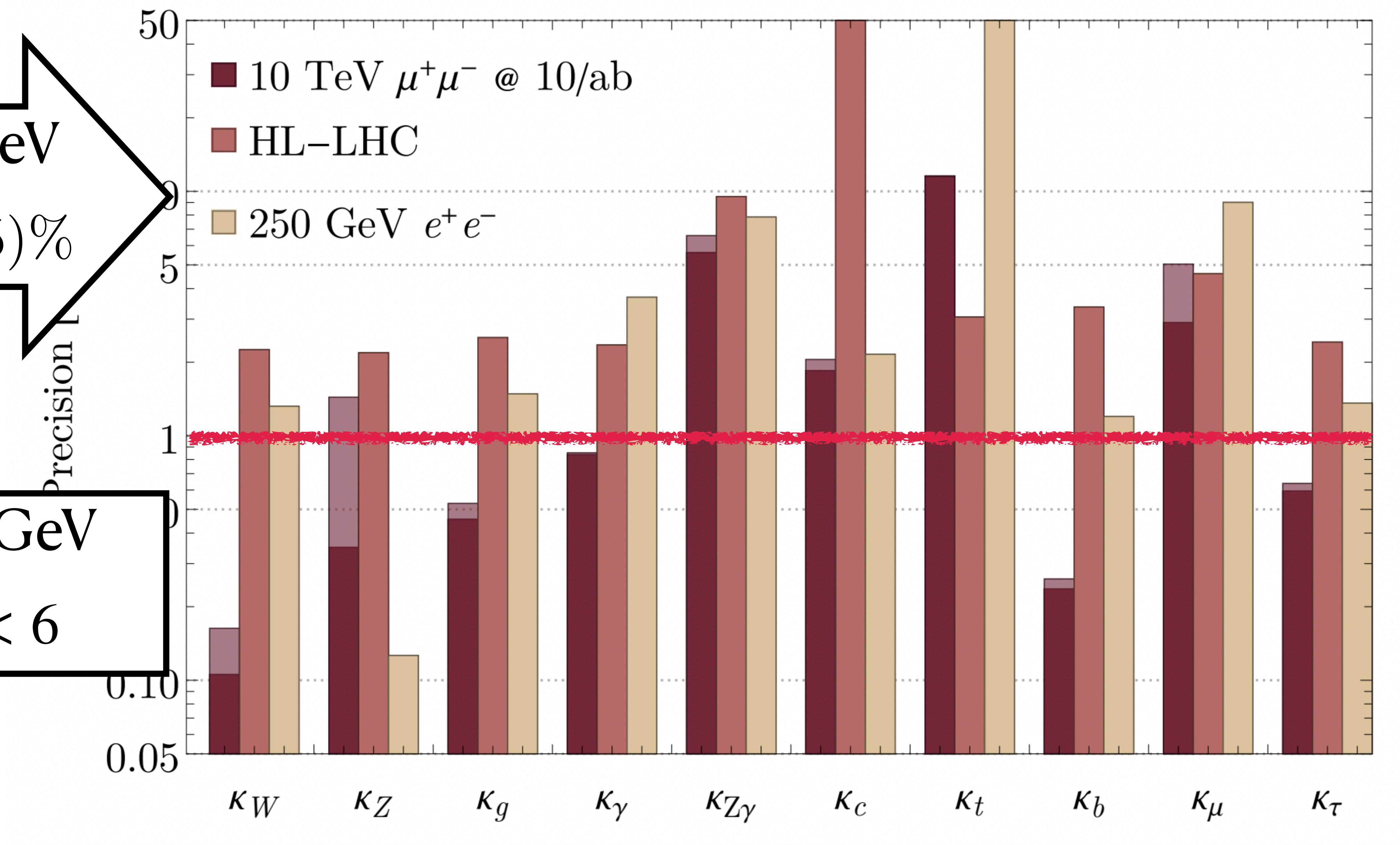

Li, Liu, Lyu ‘23

$p_{T\mu} > 10$ GeV

$\Delta p \sim 90(95)\%$

$p_{T\mu} > 20$ GeV

$|\eta| < 6$






Forslund & Meade ‘23

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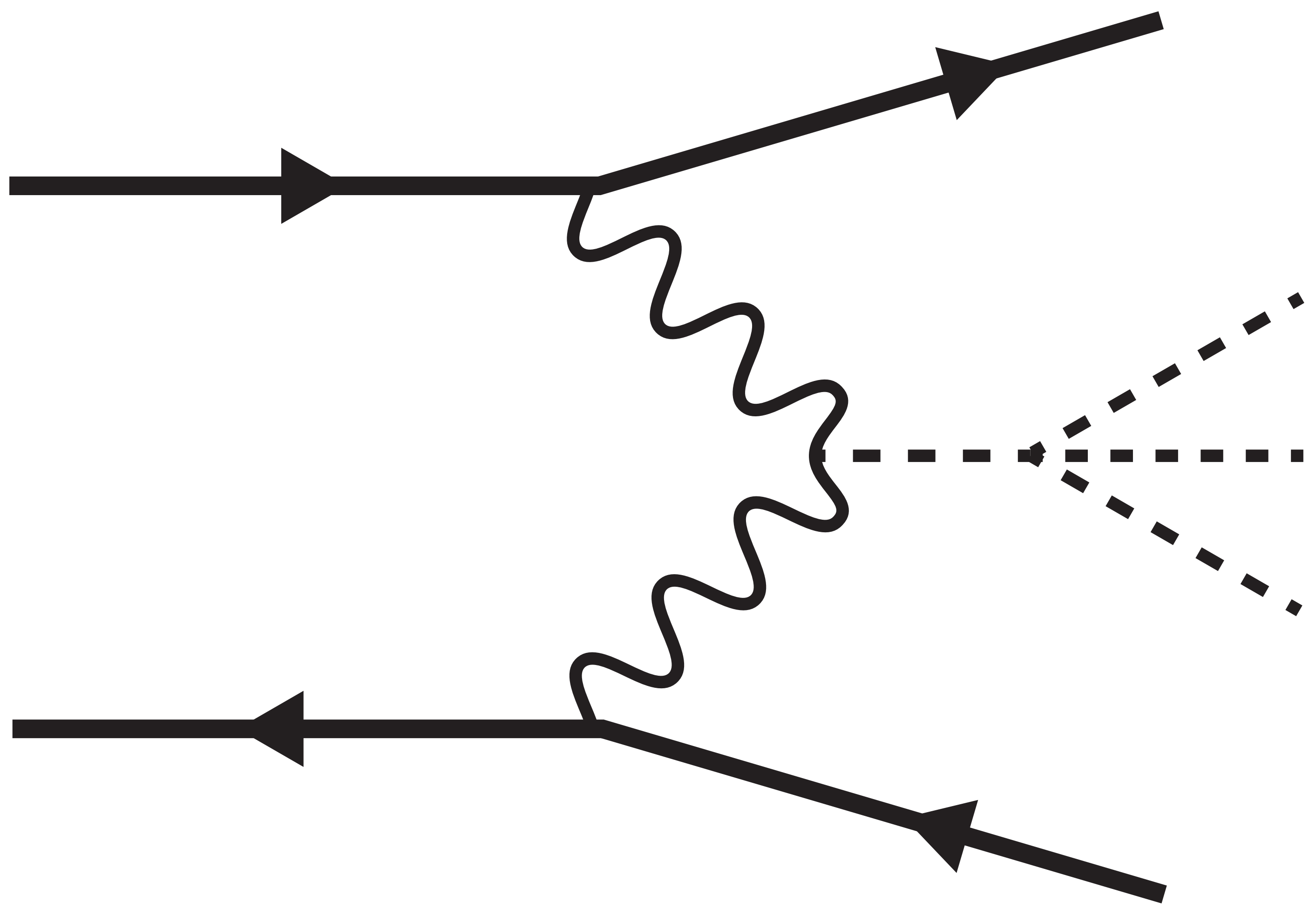
What Higgs processes in specific do we want to see?

$$V(H) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 = \frac{m_h^2}{2v}(1+\delta\kappa_3)h^3 + \frac{m_h^2}{8v^2}(1+\delta\kappa_4)h^4$$

*Quartic coupling*



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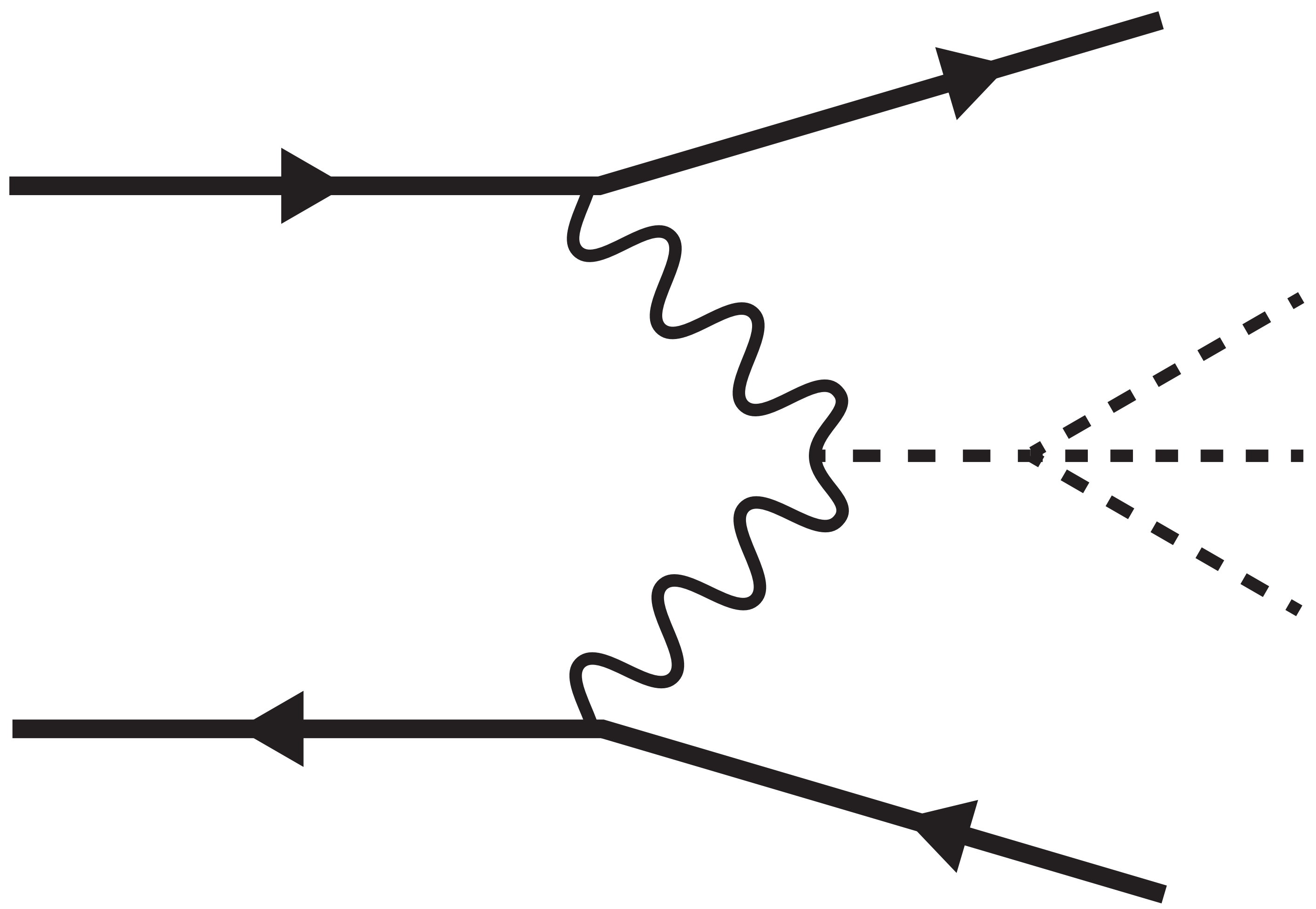
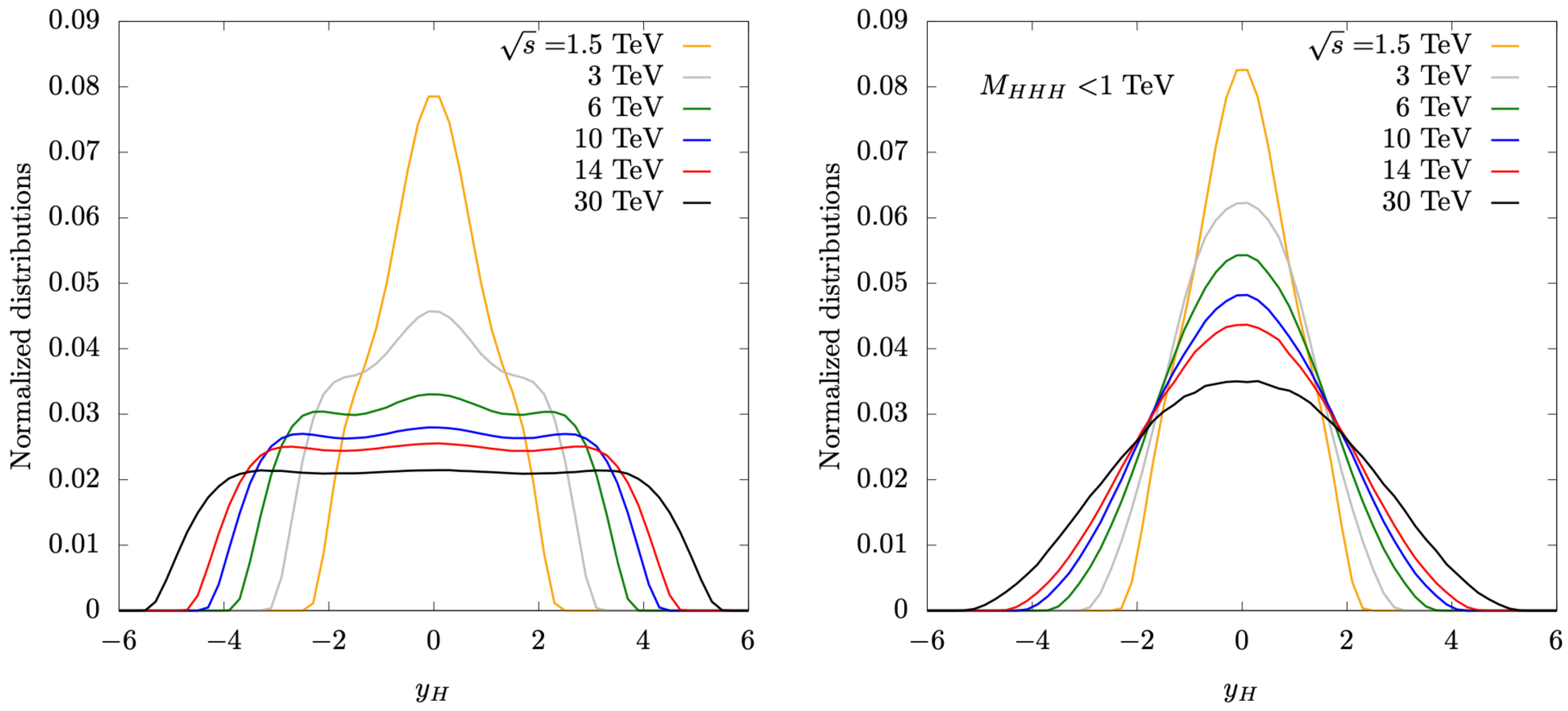
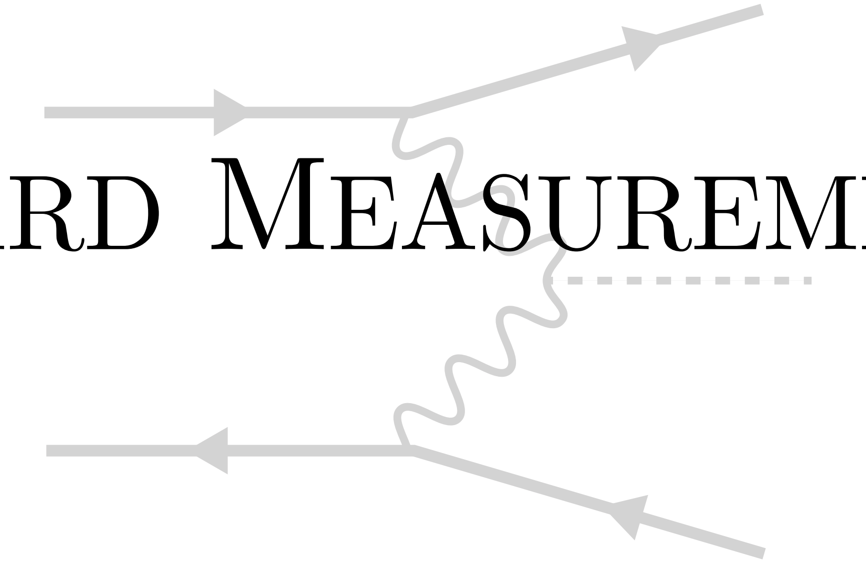




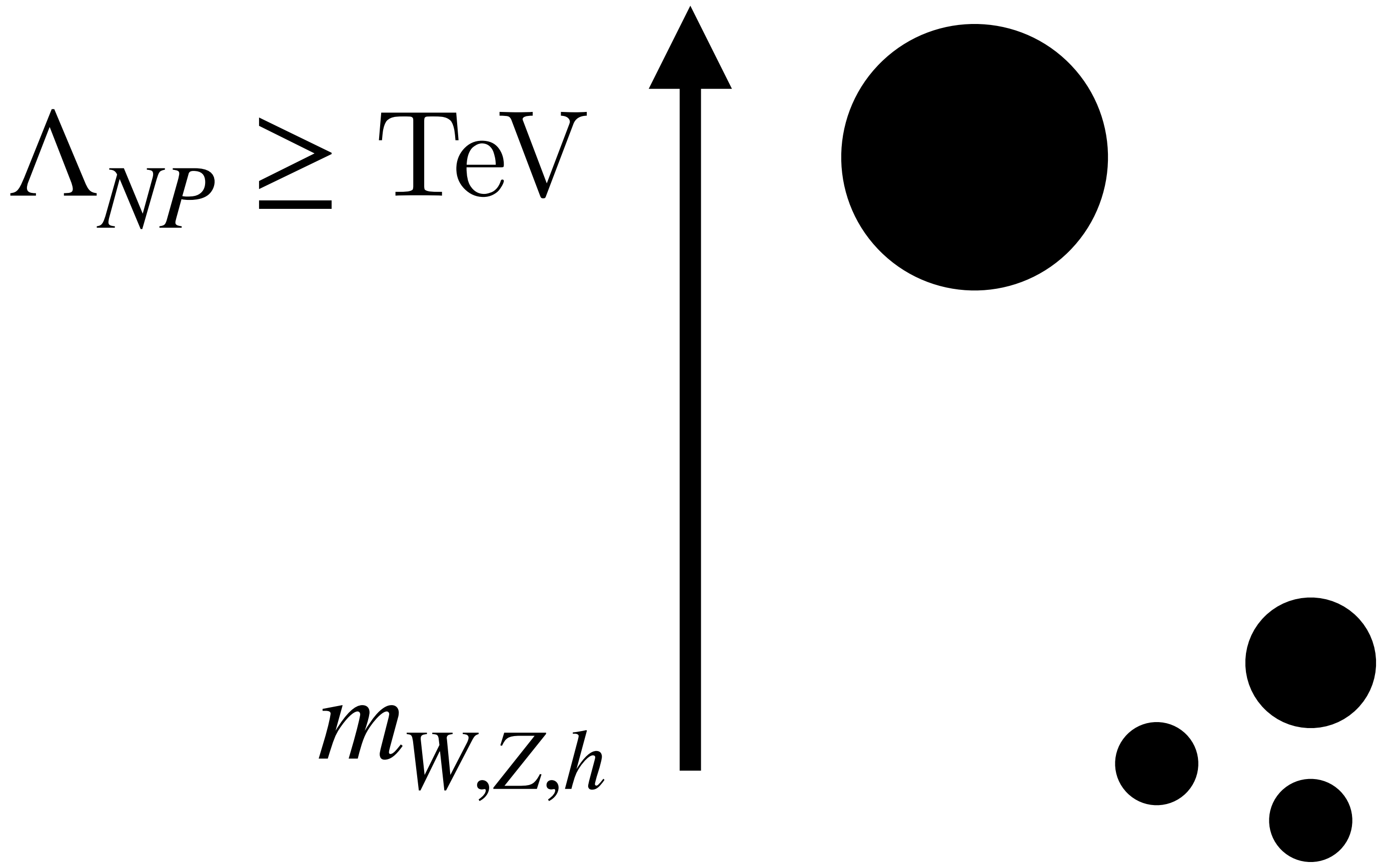

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao 20

Precision EW & Higgs



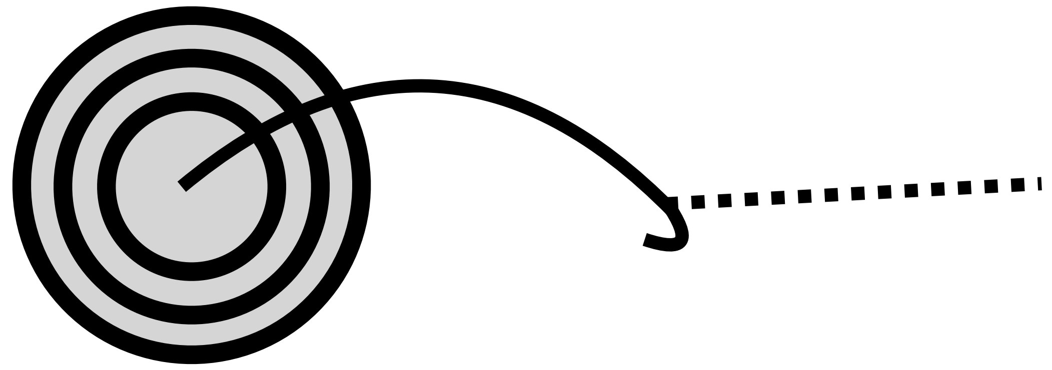
Forward Measurements

Heavy Particles

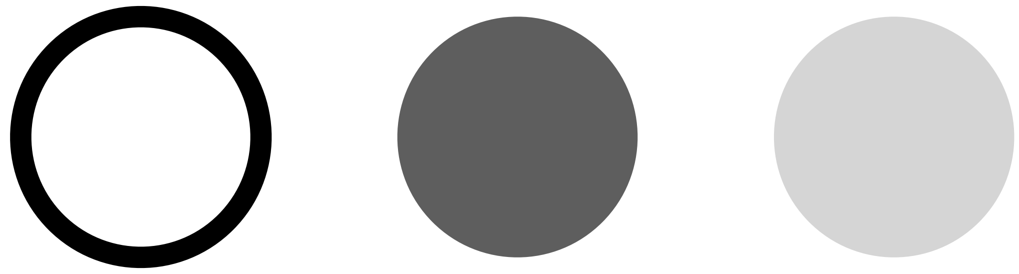



# Physics Goals

Novel Signatures
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)



Flavor Tagging



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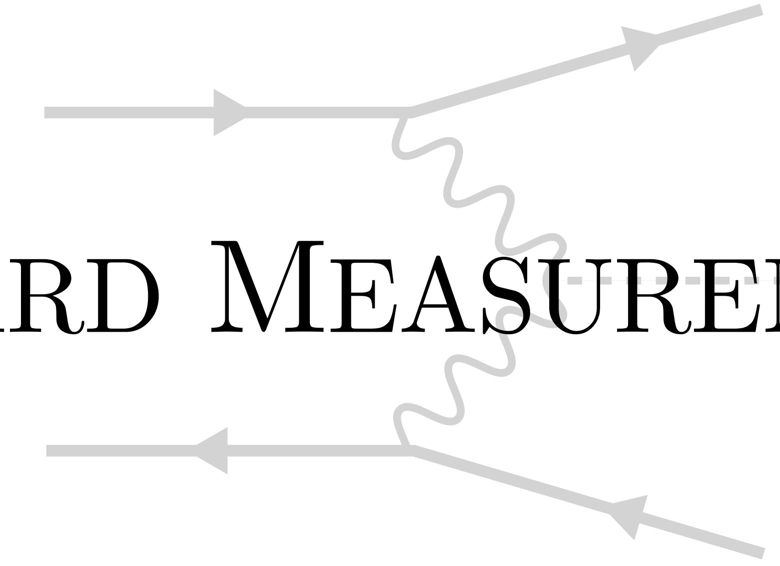
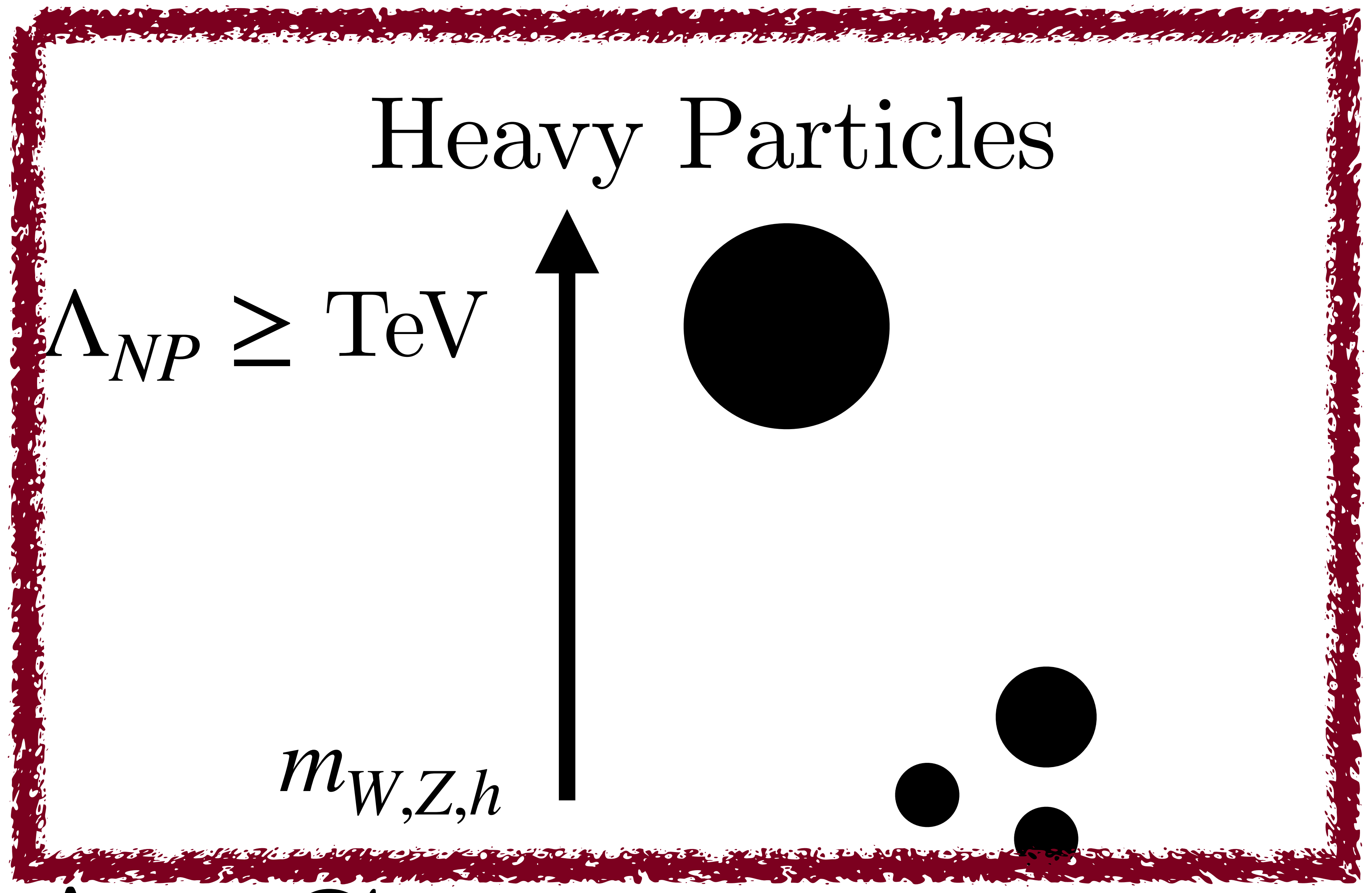


FORWARD MEASUREMENTS




# PHYSICS GOALS

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Flavor Tagging

# Heavy Particles

With a machine like the MuC that can take us to the energy frontier quickly*, searching for new heavy states is a quintessential pillar of the physics program



*hopefully

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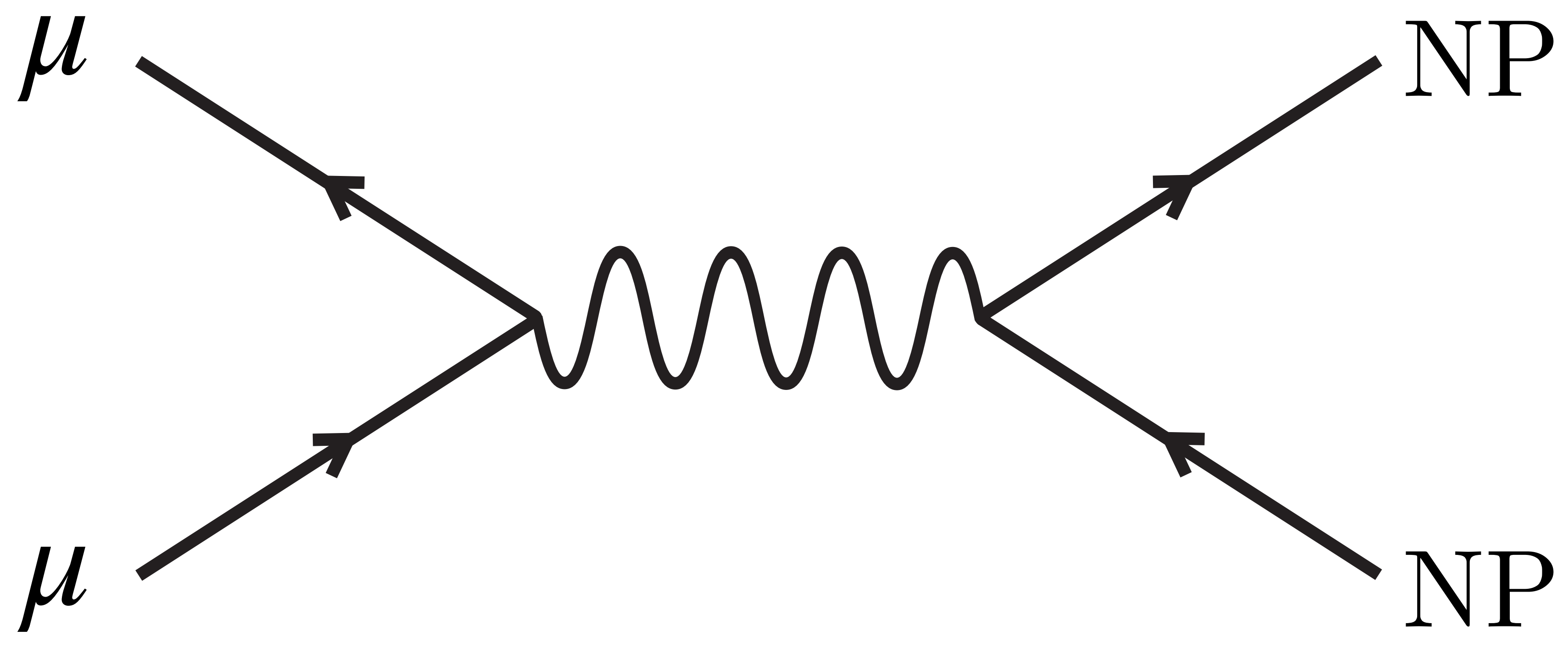


Very different kinematics from primarily $s$-channel pair production

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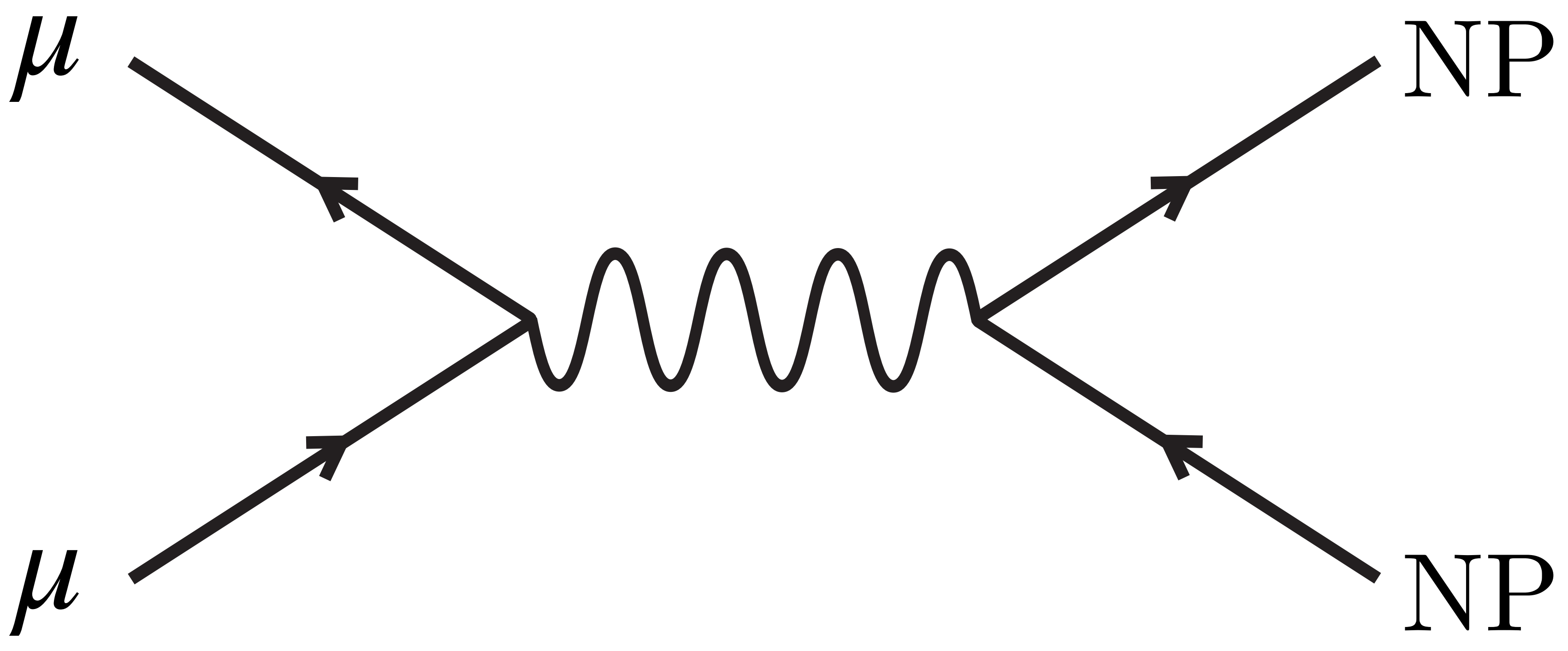


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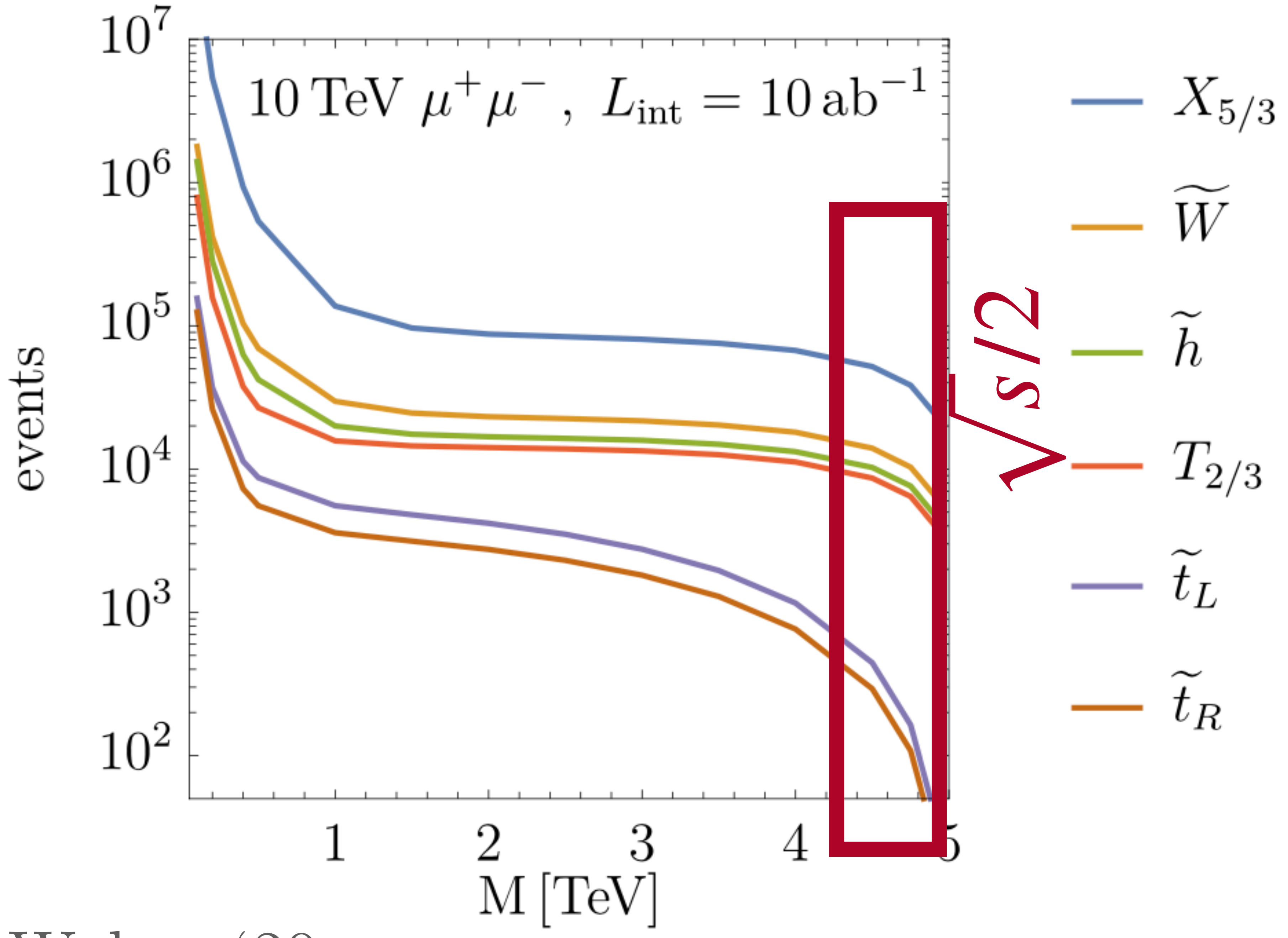




Buttazzo, Franceschini, Wulzer '20

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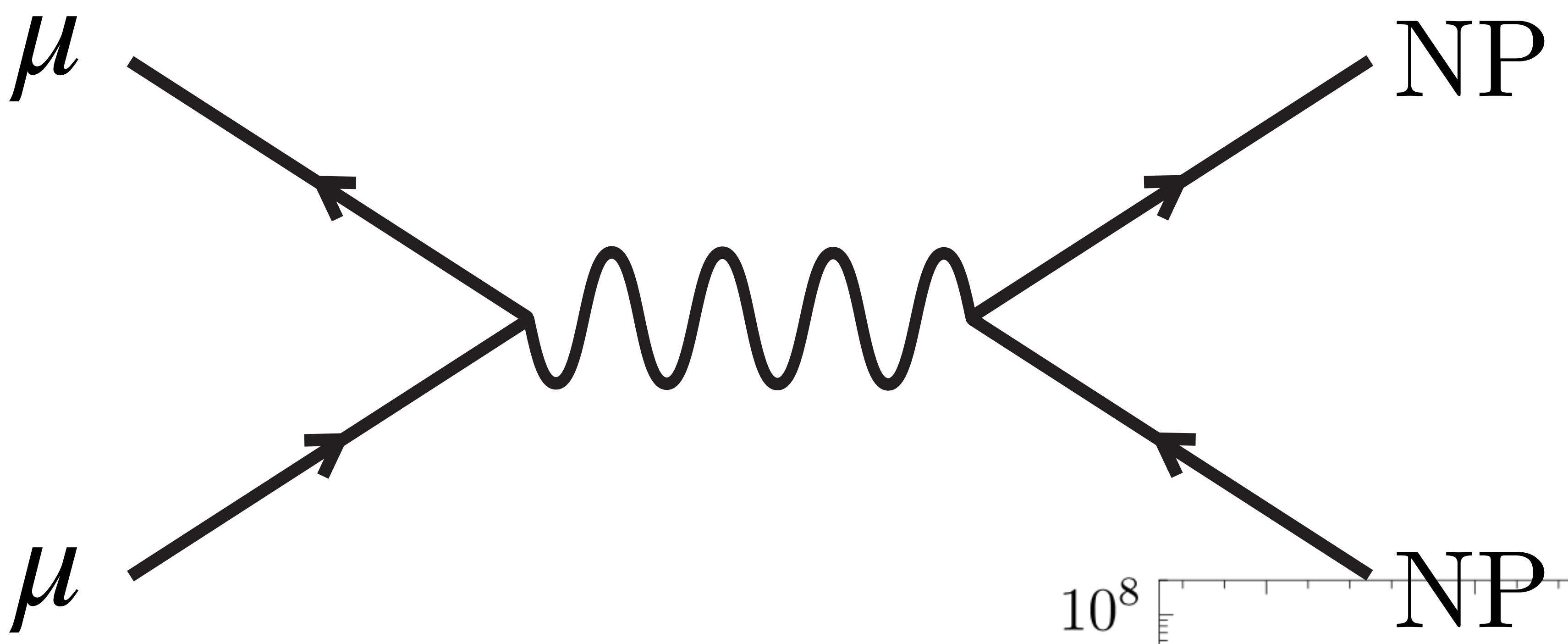
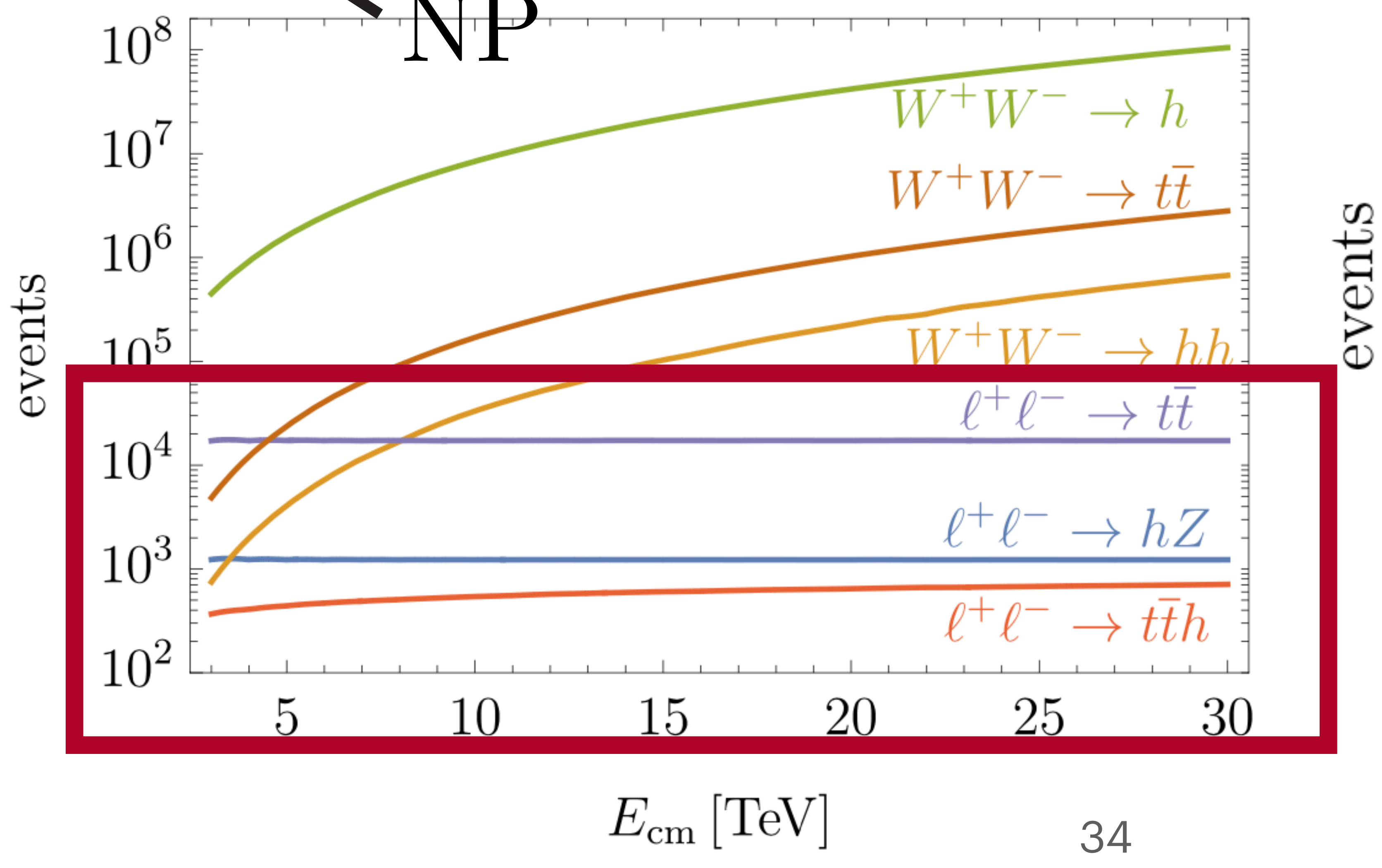
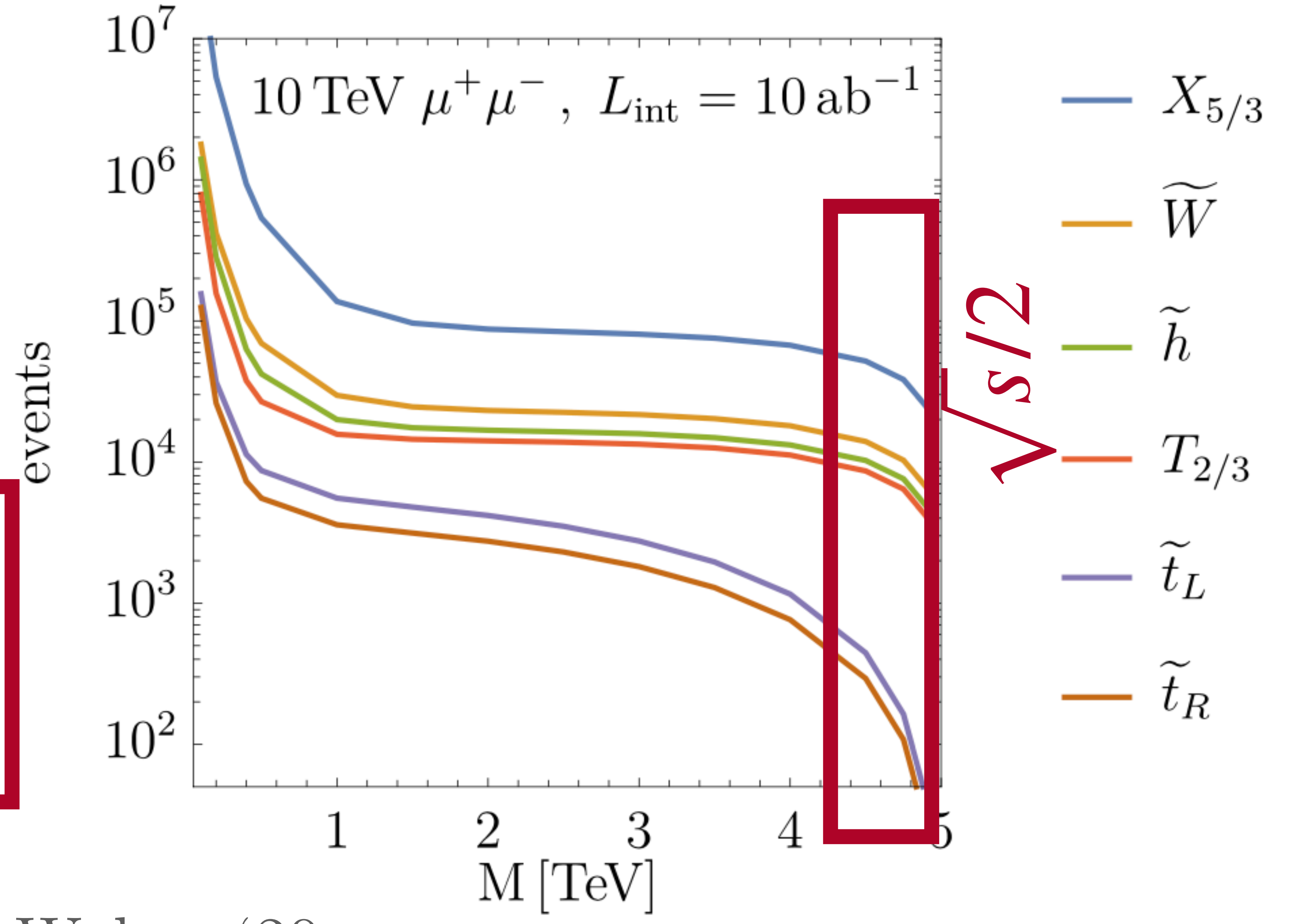



$$\sigma \sim \frac{1}{s} = \frac{1}{E^2}$$

$$\mathscr{L} \sim E^2$$

Very different kinematics from primarily $s$-channel pair production



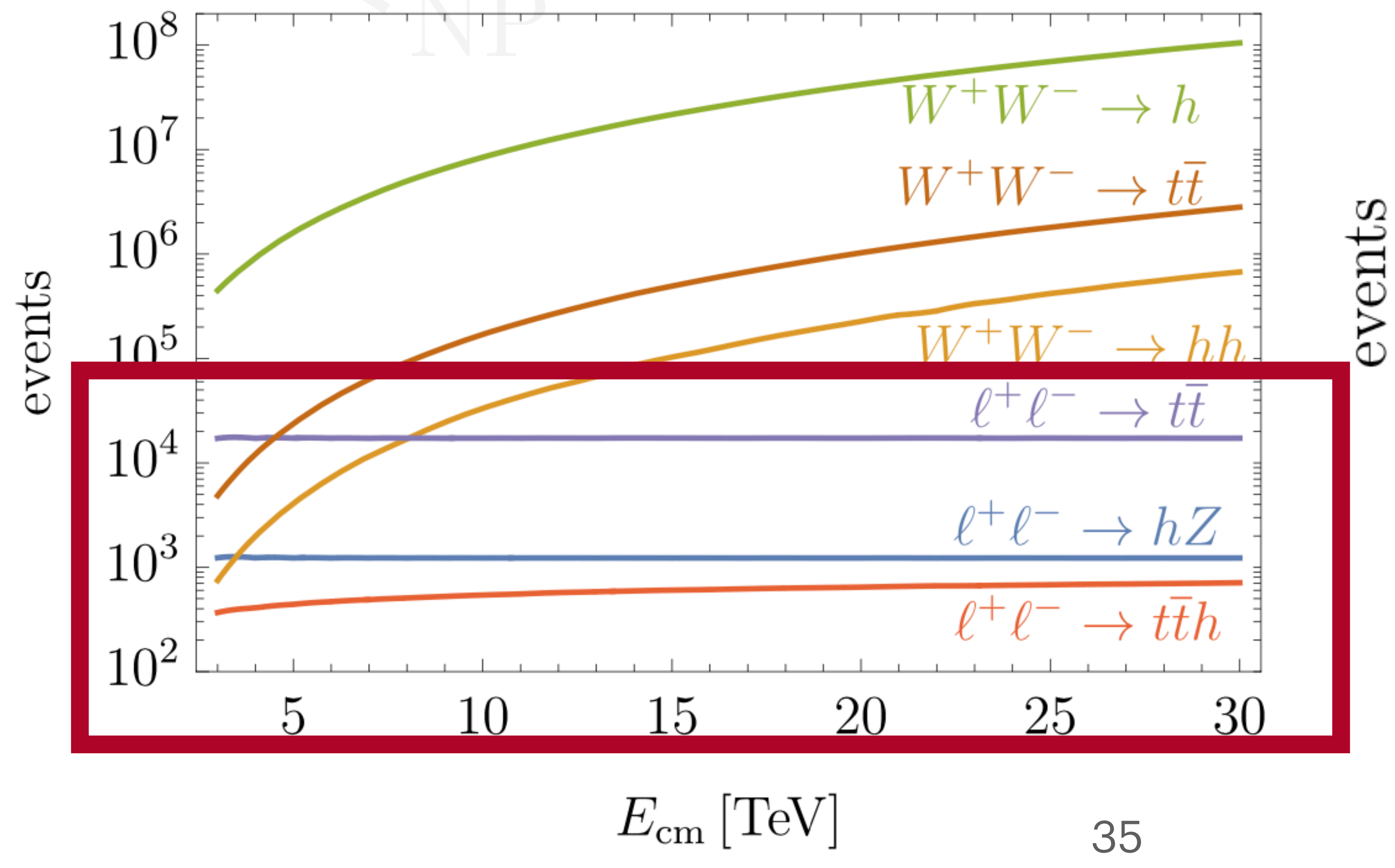



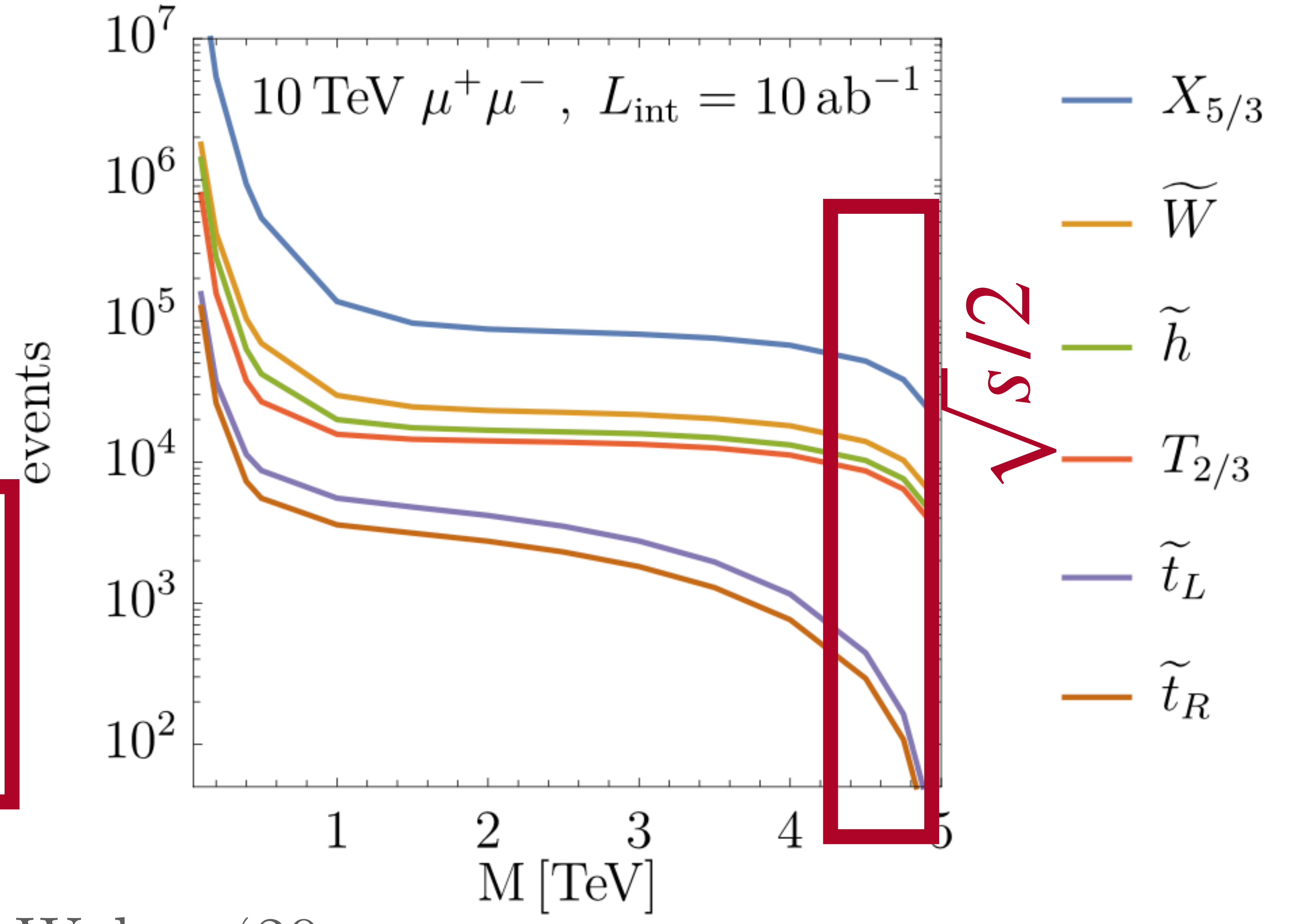



Buttazzo, Franceschini, Wulzer '20

# Wishlist

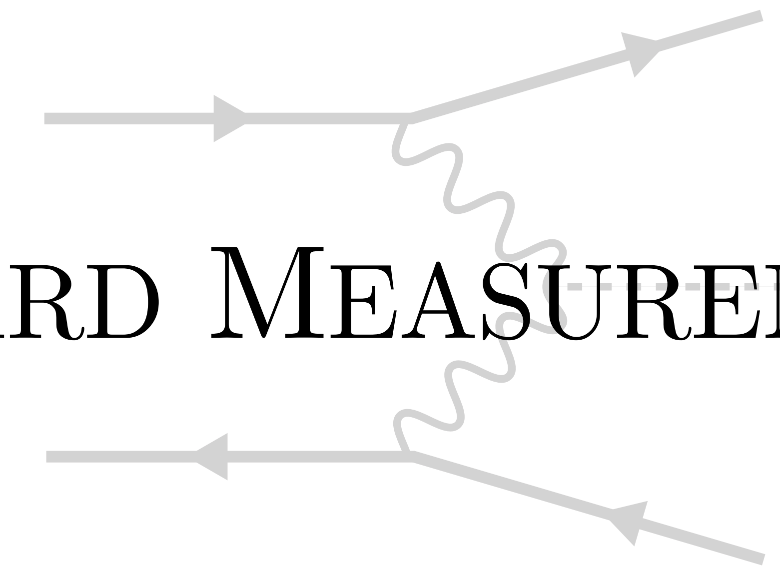
- Let's explode into the energy frontier (what better way of testing UV physics?)
- High resolution (big difference in mass scales)
- Timing to see non-relativistic quasi-stable states?
- Maintain a luminosity that scales like $\mathscr{L} \sim E^2$ (to maintain production of heavy NP)



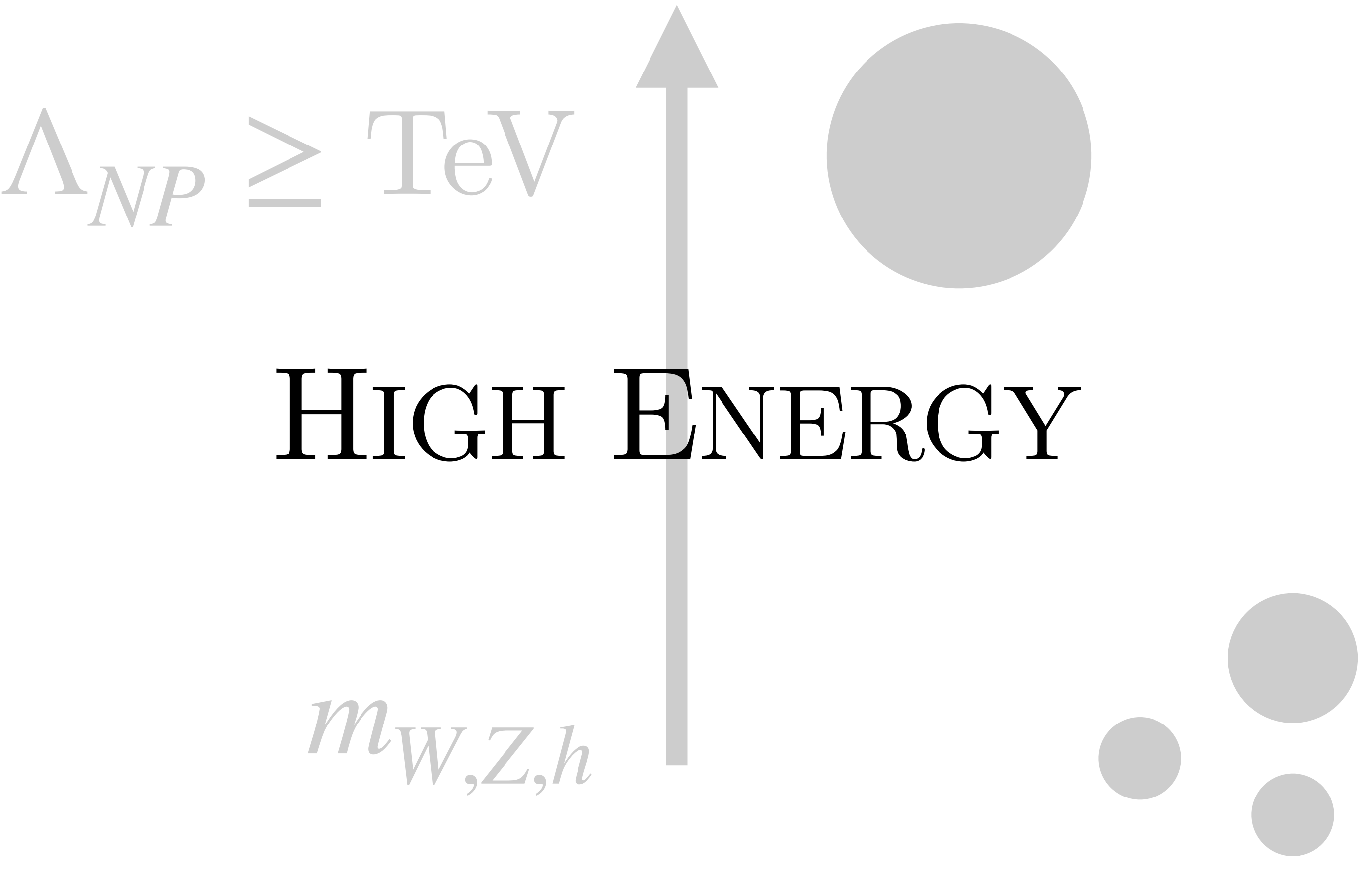

Buttazzo, Franceschini, Wulzer '20

Precision EW & Higgs



FORWARD MEASUREMENTS

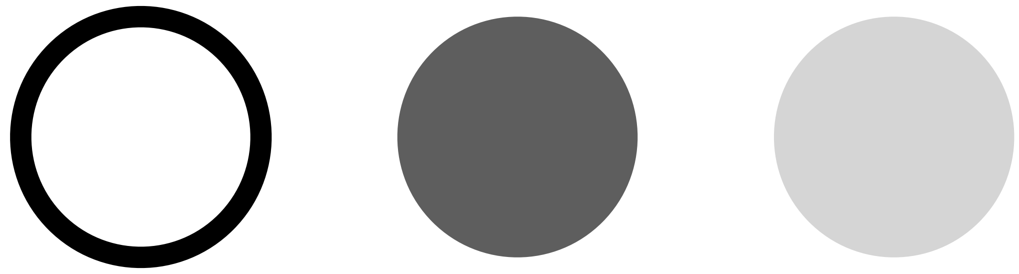
Heavy Particles




HIGH ENERGY

# PHYSICS GOALS

Flavor Tagging



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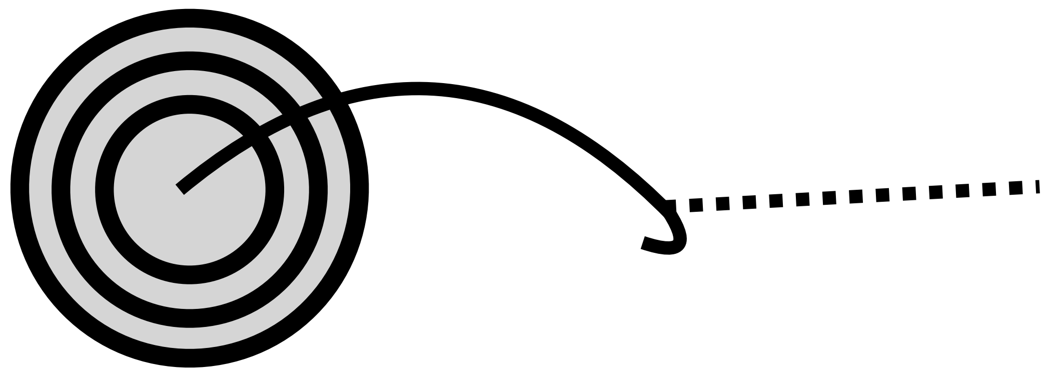

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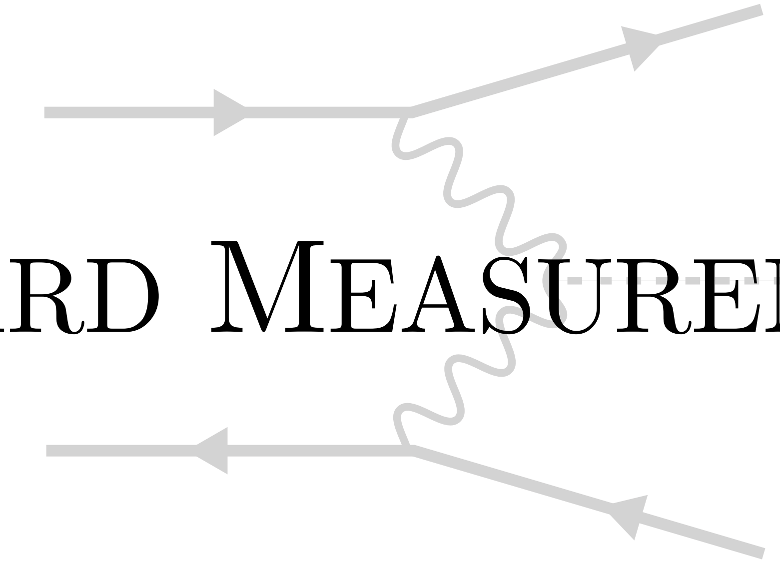

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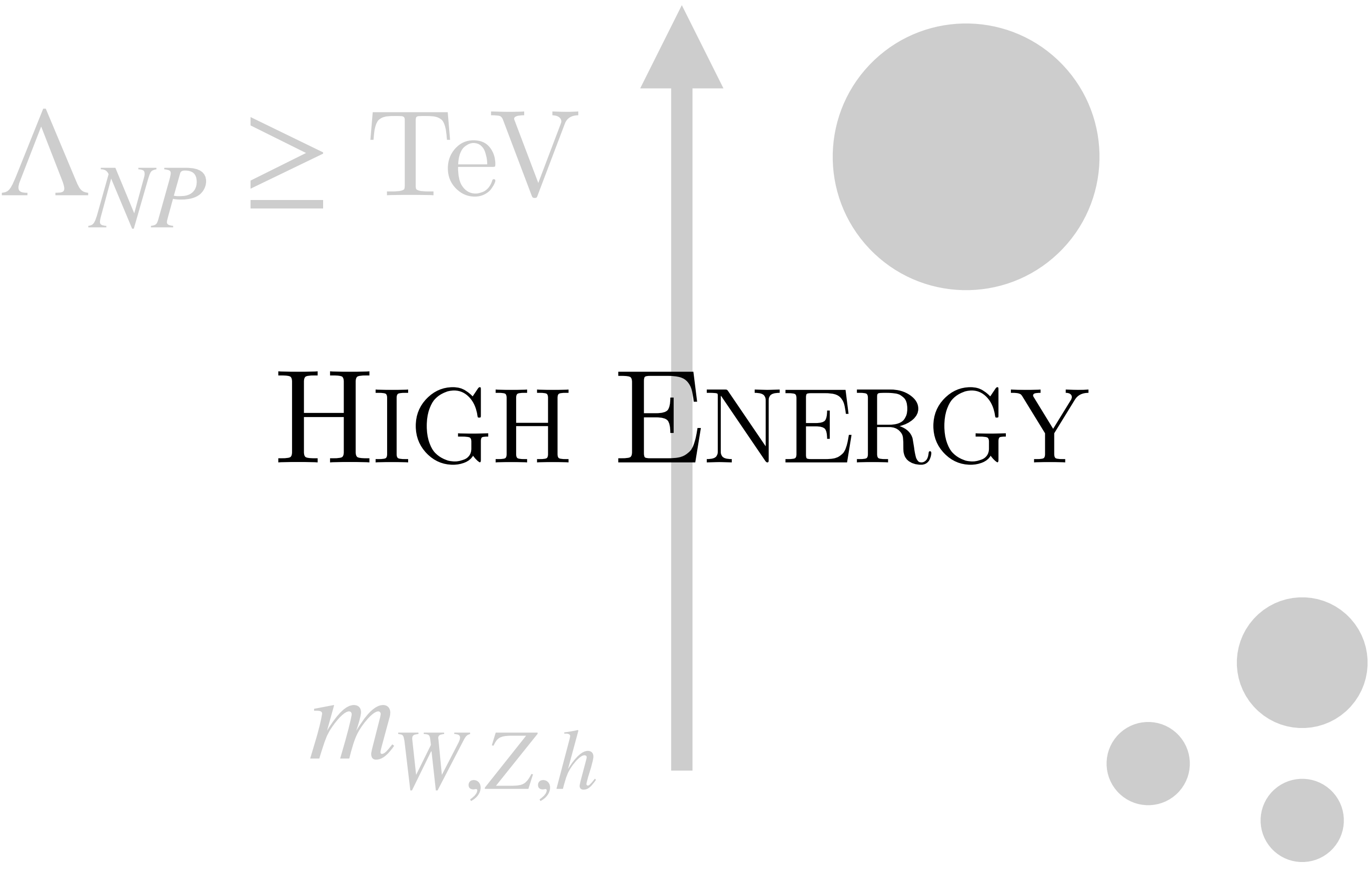


HIGH ENERGY

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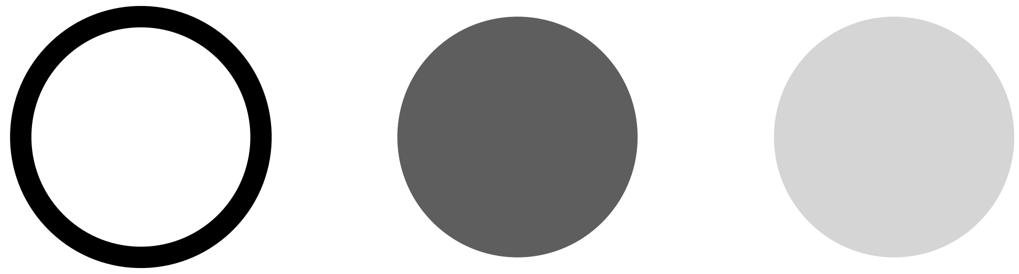

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We can make more **precise measurements** and further **mitigate backgrounds** with reliable particle identification

Discrimination of $b$'s from $c$'s (from light quarks) $\longleftrightarrow$ Discrimination of $h/\mathrm{W}/\mathrm{Z}$

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$$\left.\begin{array}{c} Z \to b\bar{b} \\ h \to b\bar{b} \\ W \to c\bar{b} \end{array}\right\}$$

Remarkably different physics processes...

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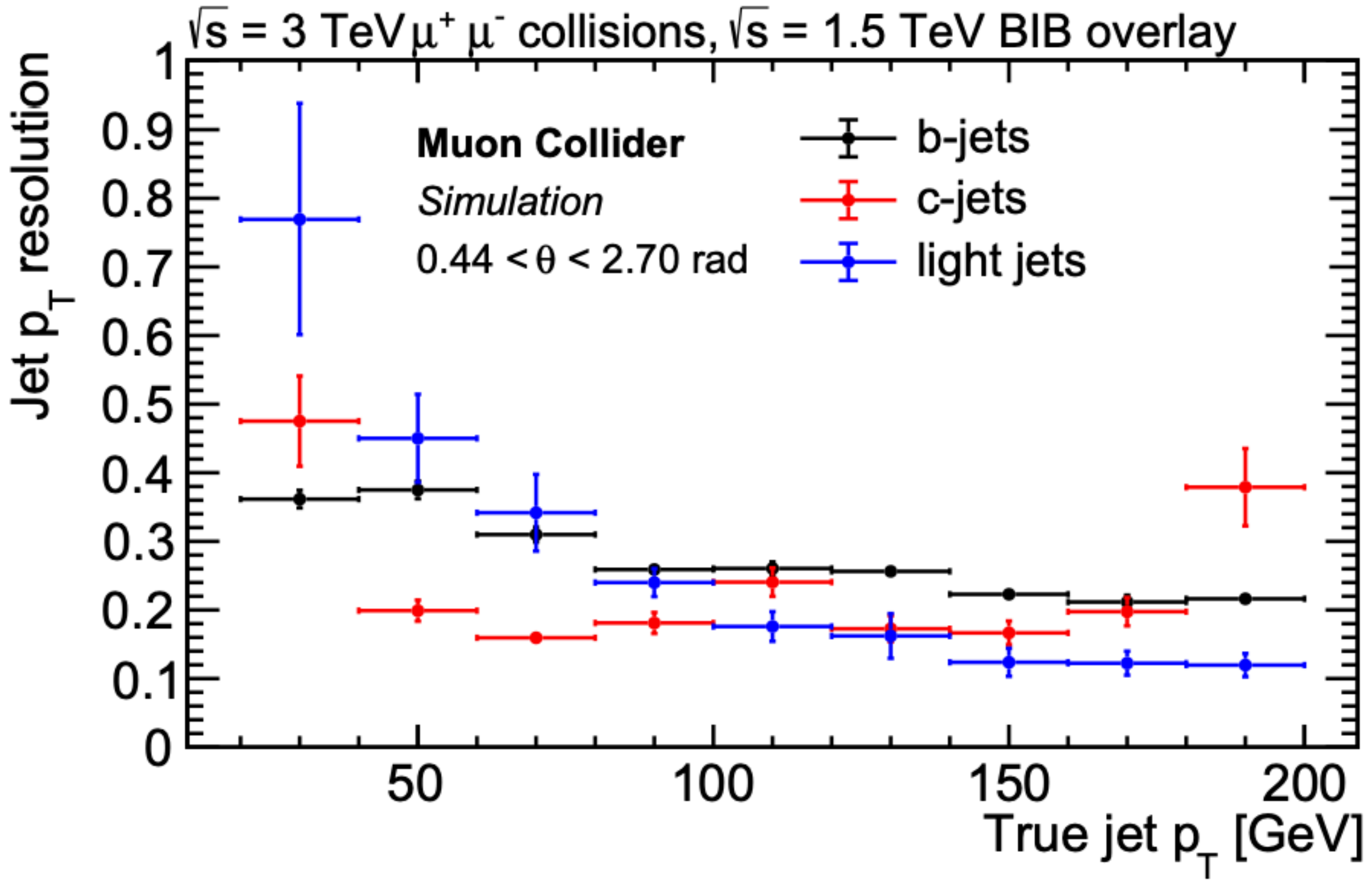


$$Z \to b\bar{b}$$
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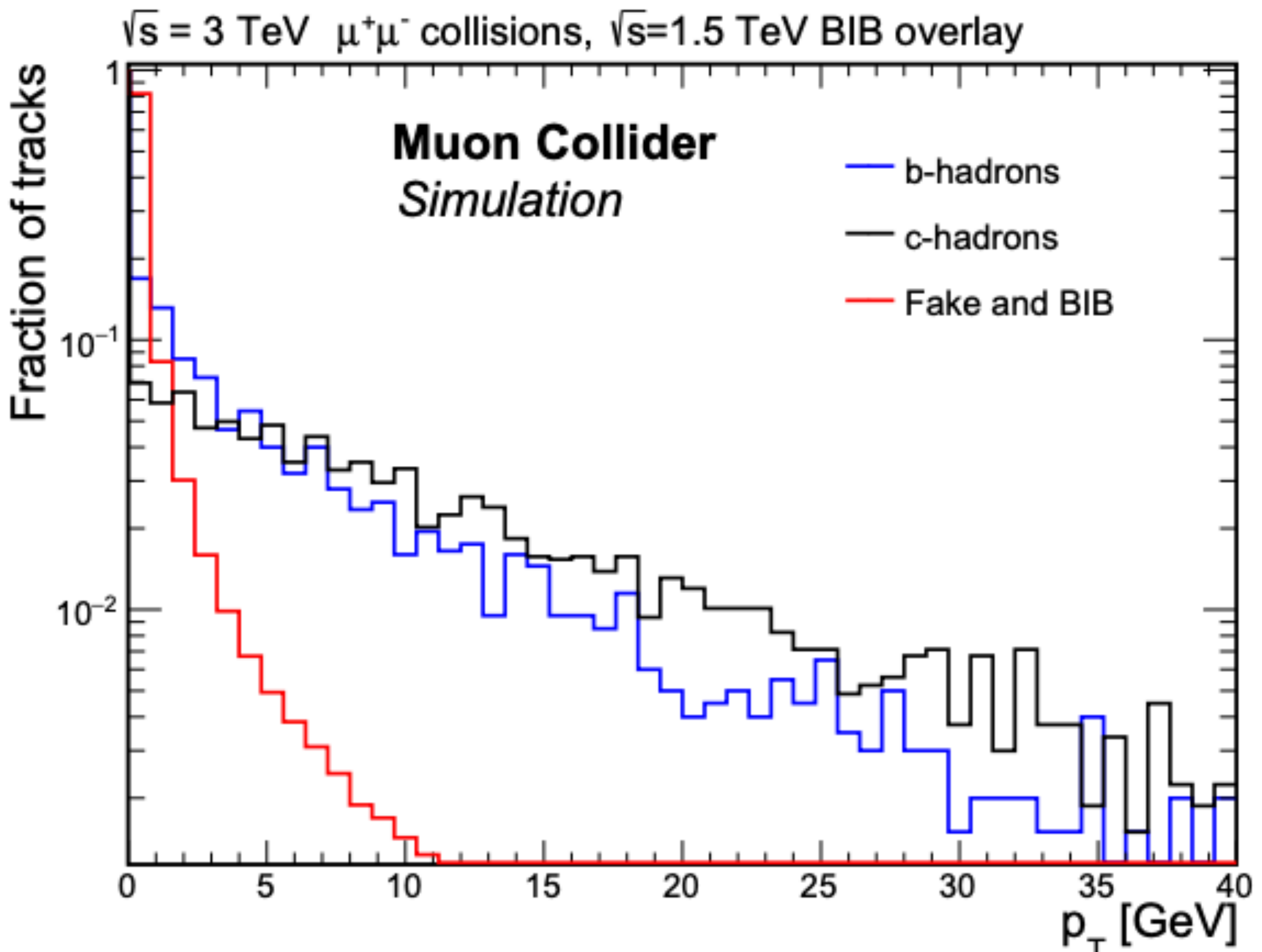
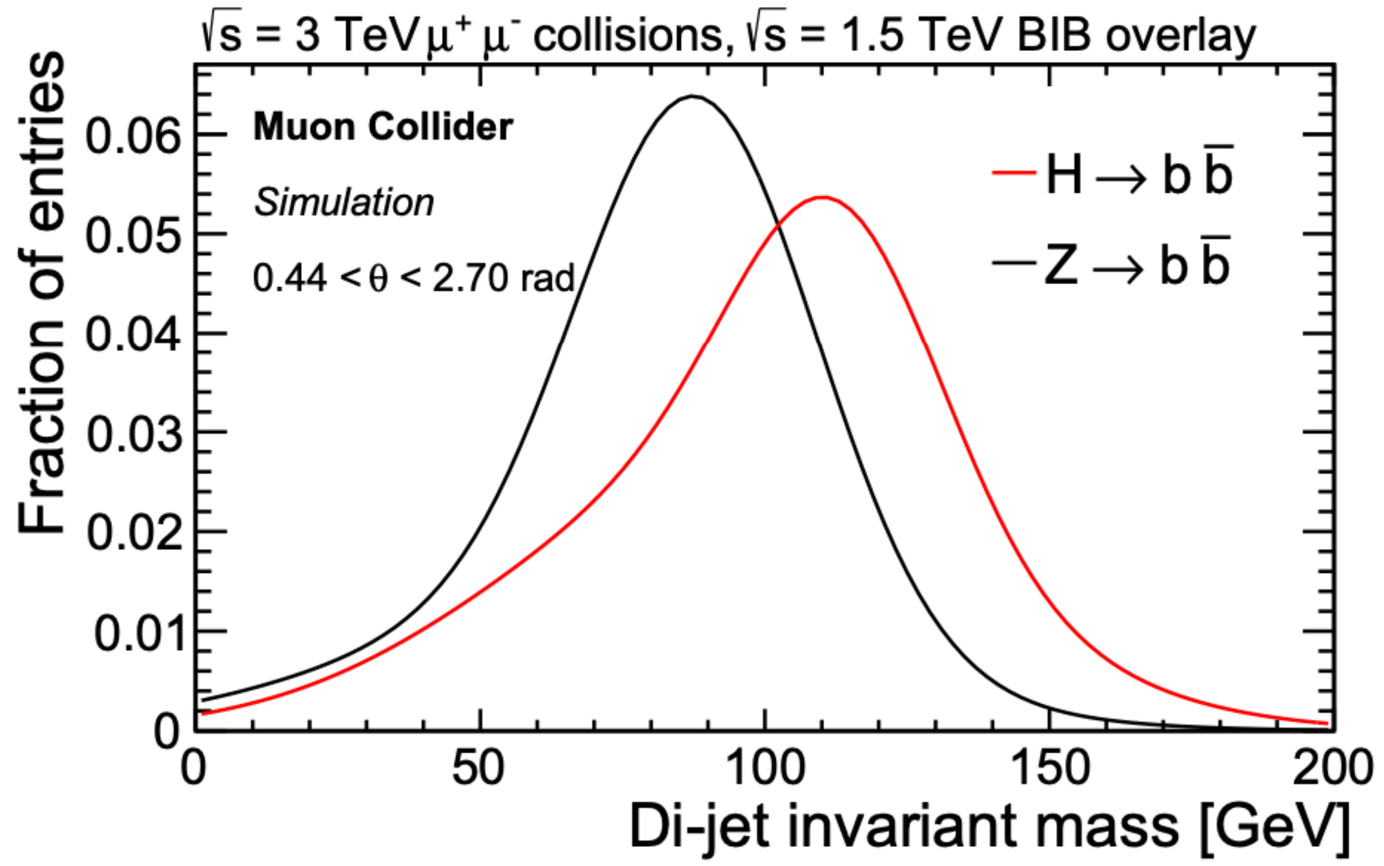
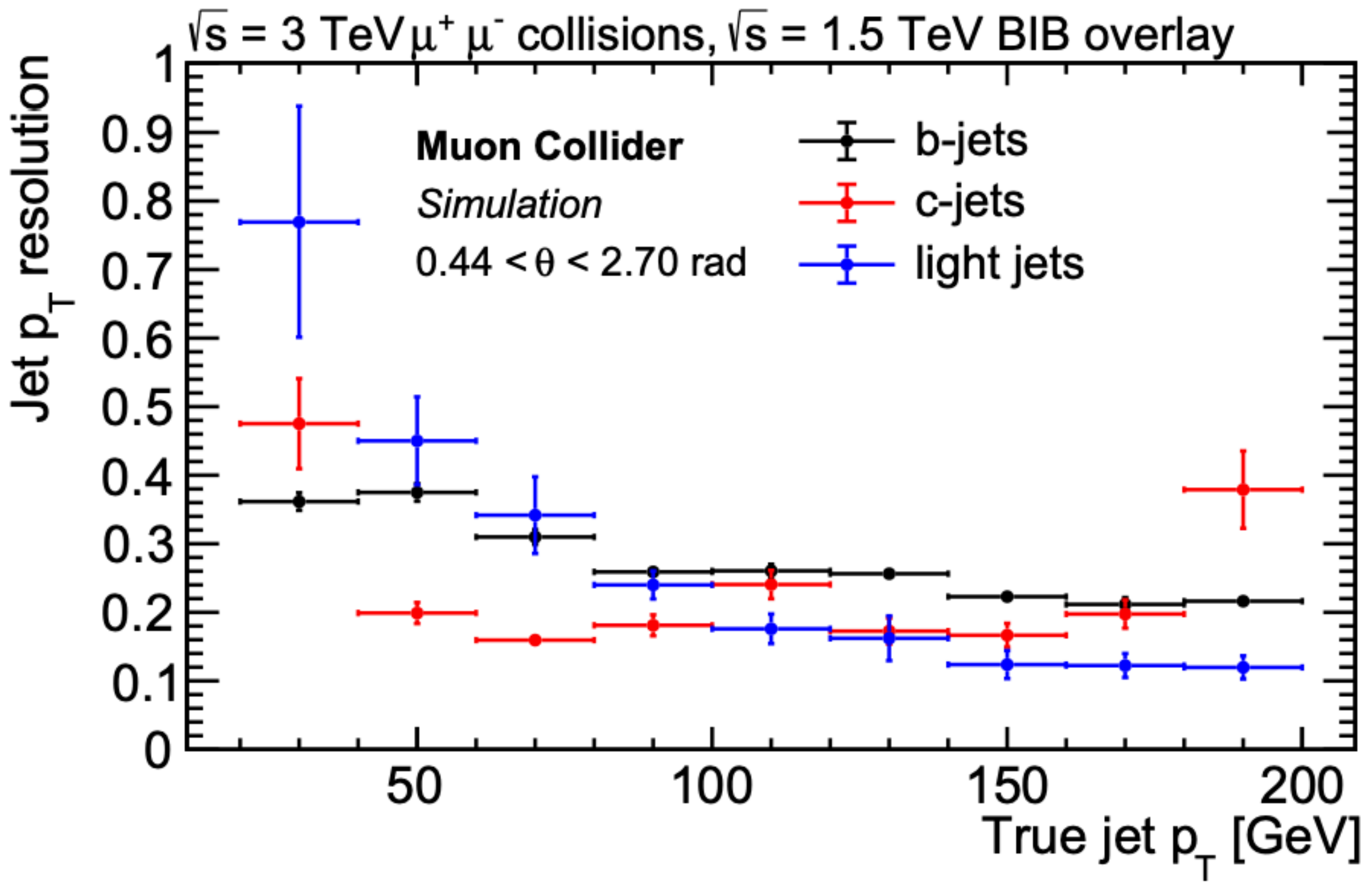


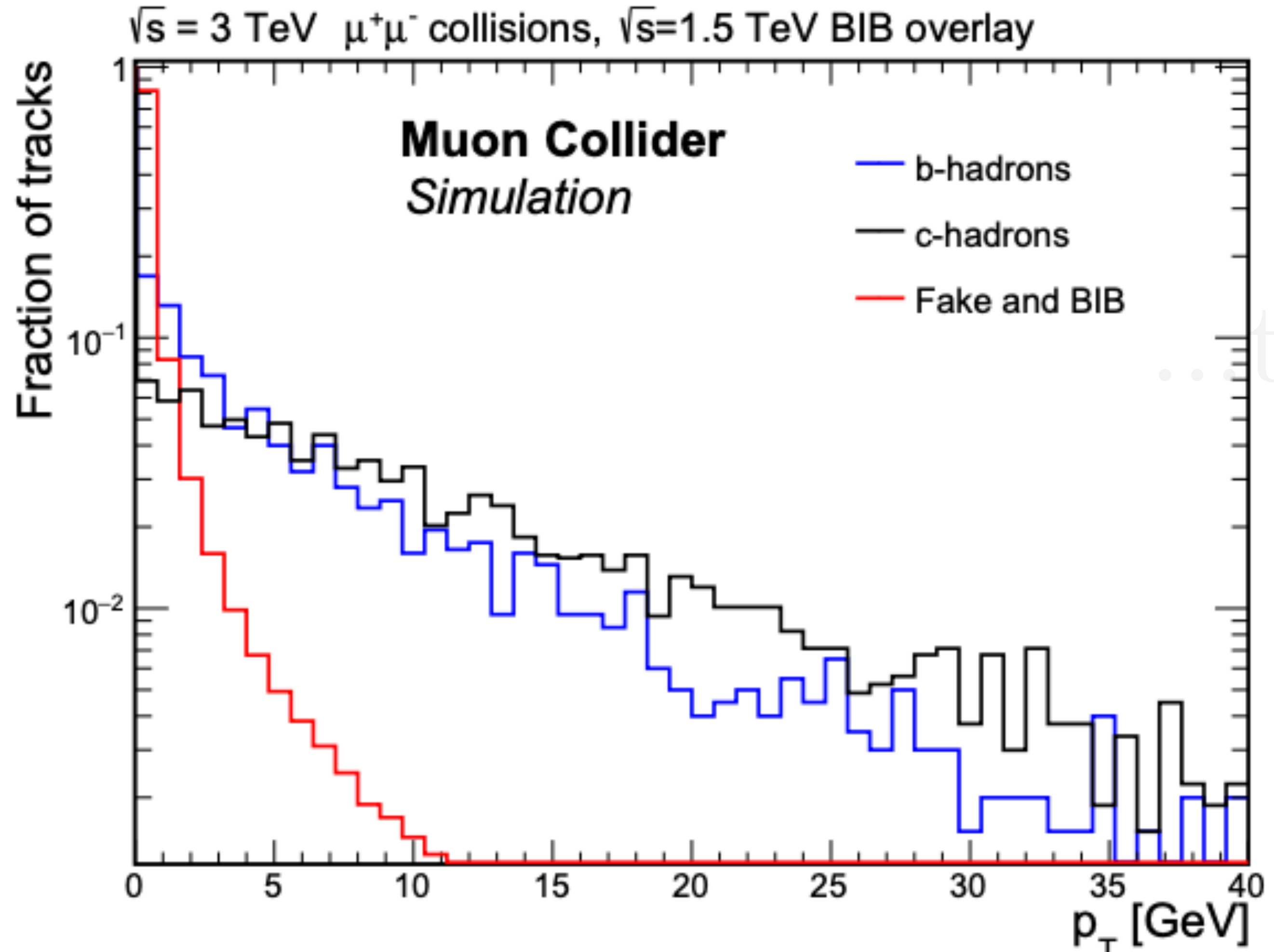



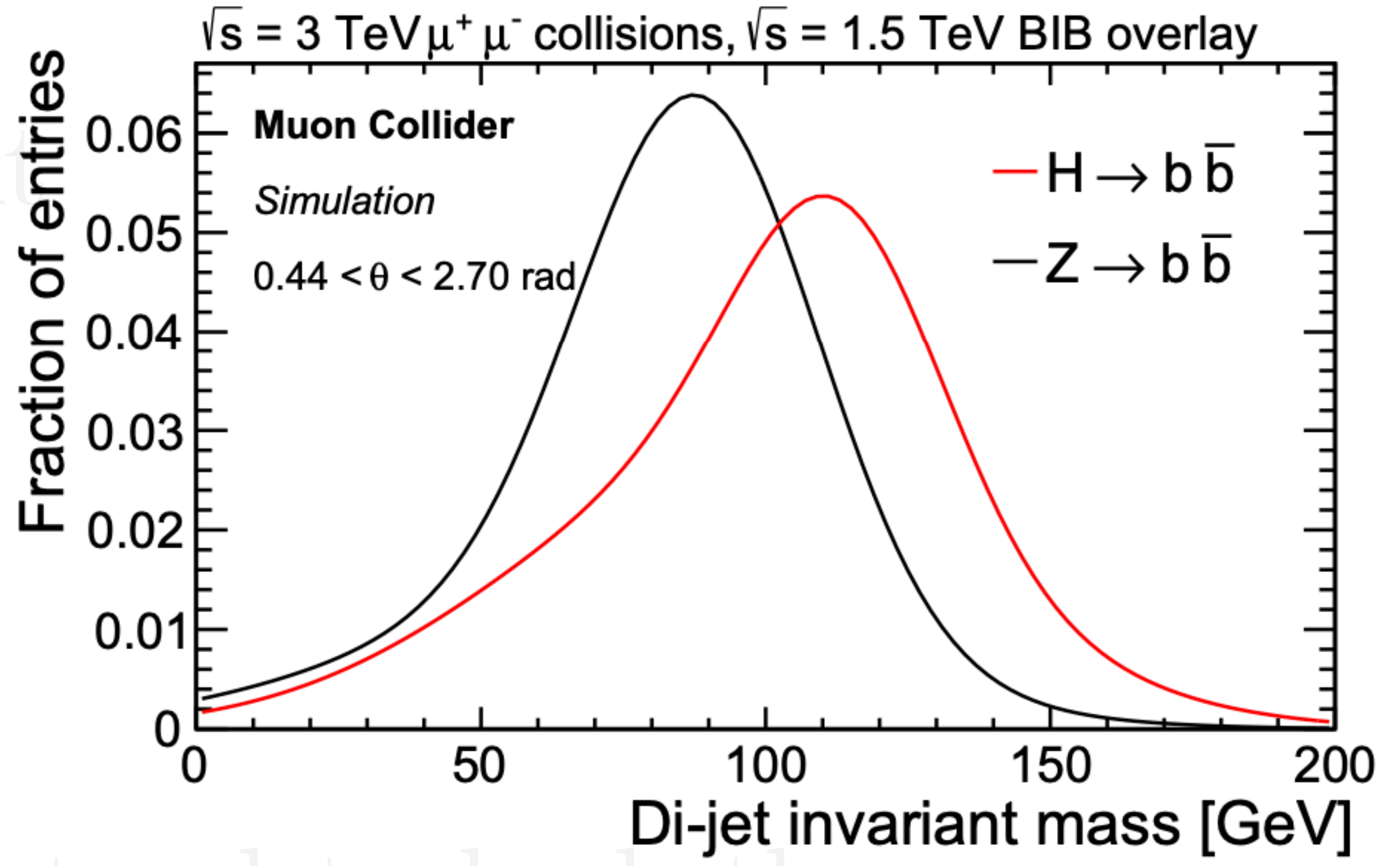

...that tend to look the same

# Wishlist

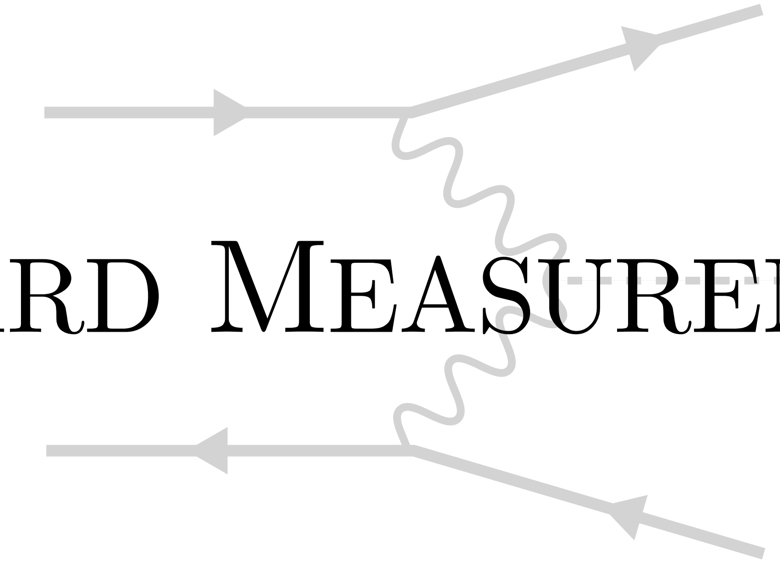
- Tagging for $b$ vs. $c$ (vs. light quarks)
- Separation of gauge bosons ($W$, $Z$) from Higgs
  - Separation of gauge bosons from each other
- Decent resolution on hadronic decays of $W$ and $Z$



Precision EW & Higgs



FORWARD MEASUREMENTS

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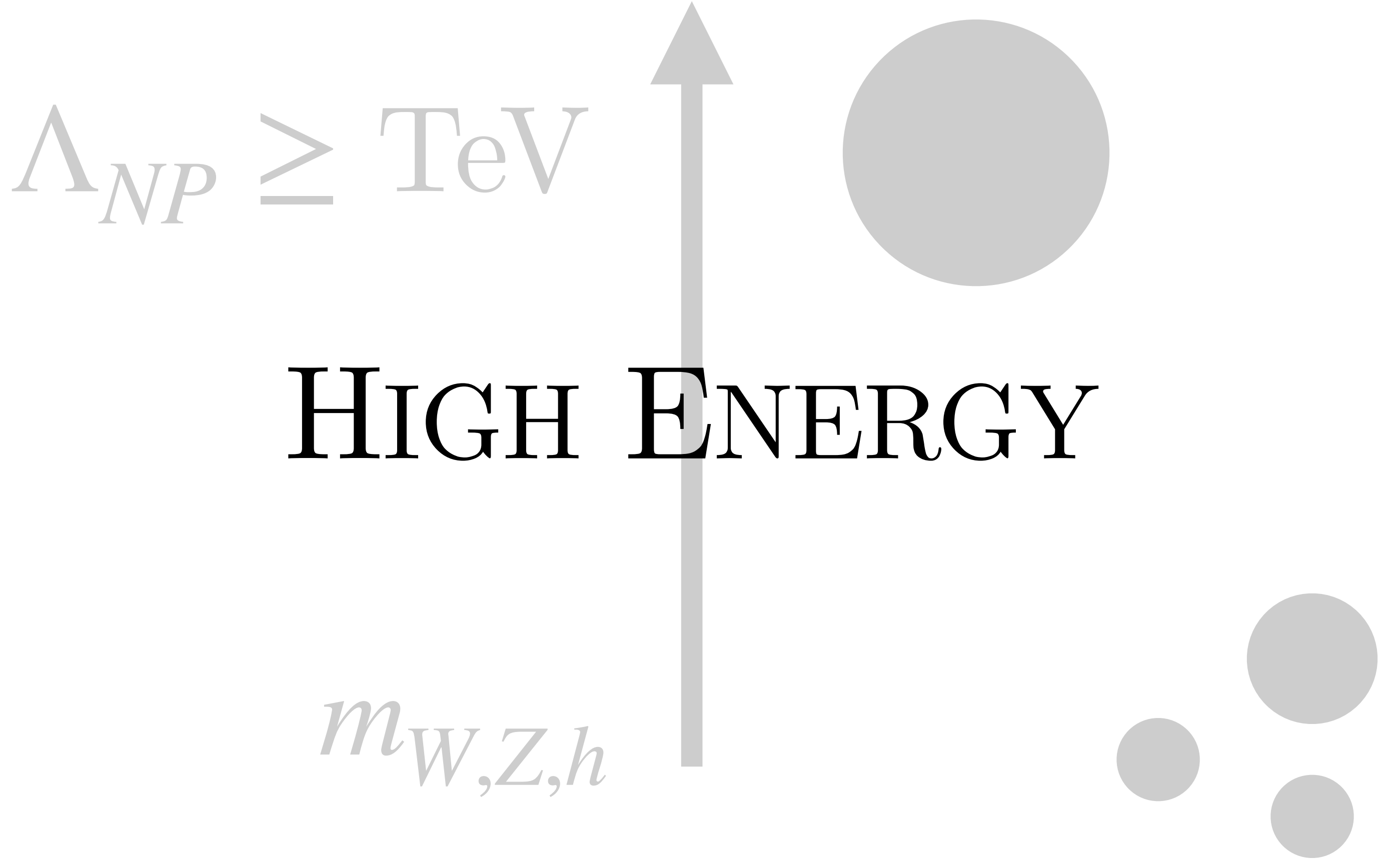


HIGH ENERGY

# PHYSICS GOALS

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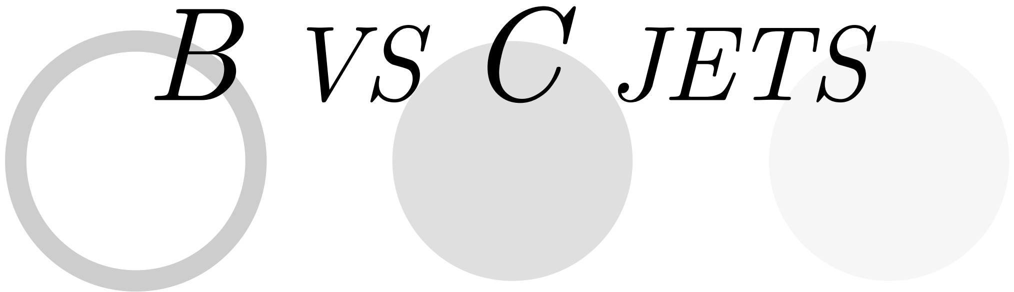
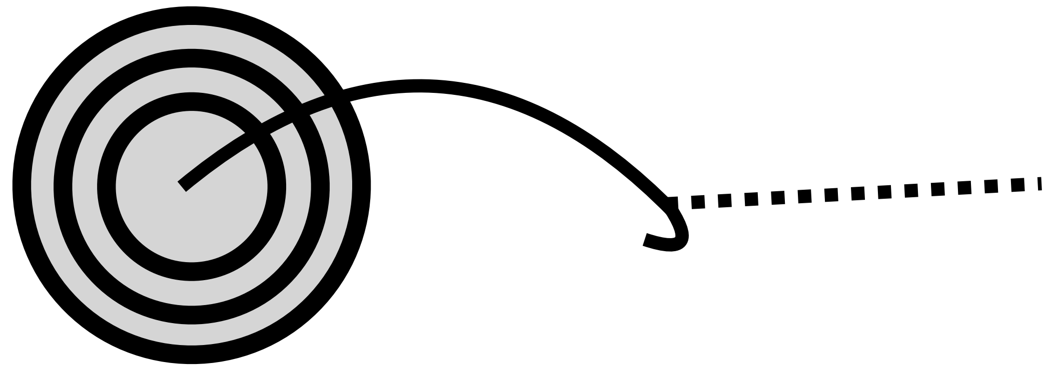
Flavor Tagging

*B* VS *C* JETS

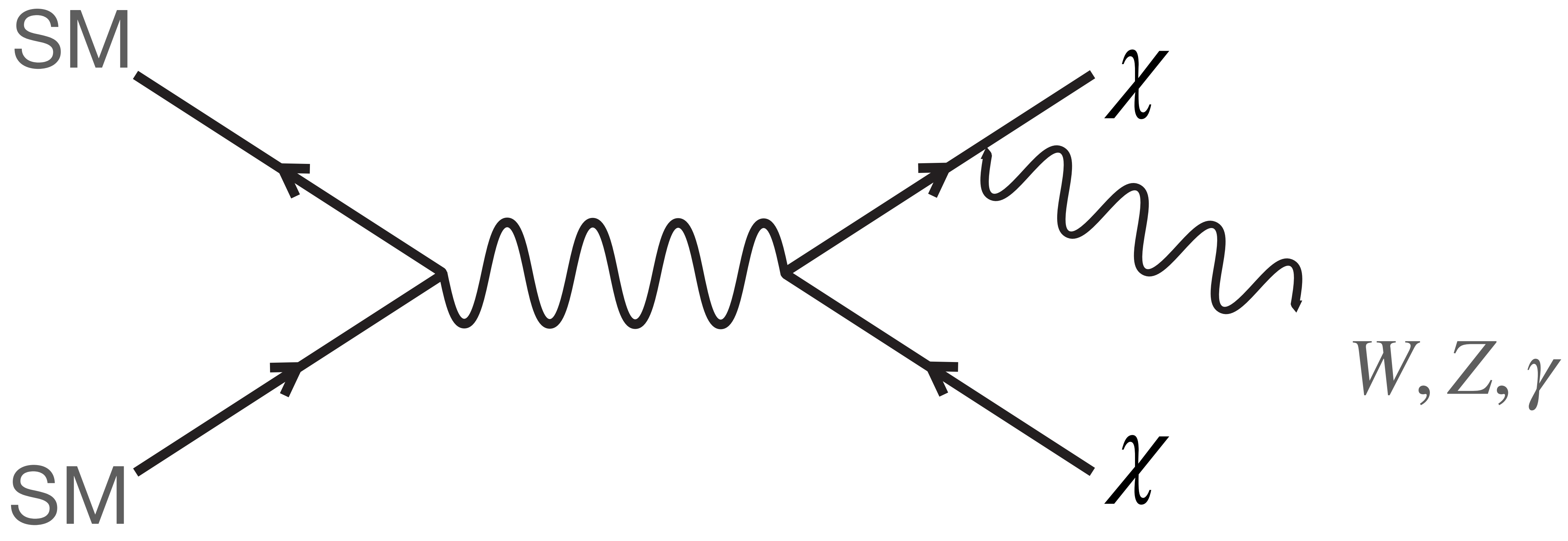




# Novel Signatures

Further studies and sensitivity can be gained by looking at further features of tracks or global properties of the events radiation pattern

E.g. *disappearing tracks & WIMPS*




$\chi$ stable or long lived $\quad \chi^+ \to \pi^+ \chi^0$

Signal

mono-$\gamma$: $\ell^+\ell^- \to \chi^i \chi^{-i} + \gamma$ ,

mono-$Z$: $\ell^+\ell^- \to \chi^i \chi^{-i} + Z$ ,

mono-$W$: $\ell^+\ell^- \to \chi^i \chi^{-i\mp 1} + W^\pm$

Background

mono-$\gamma$ bkg: $\ell^+\ell^- \to \gamma\nu\bar{\nu}$ ,

mono-$Z$ bkg: $\ell^+\ell^- \to Z\nu\bar{\nu}$ ,

mono-$W$ bkg: $\ell^+\ell^- \to W^\mp \nu \; + \; \ell^\pm$(lost)



Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

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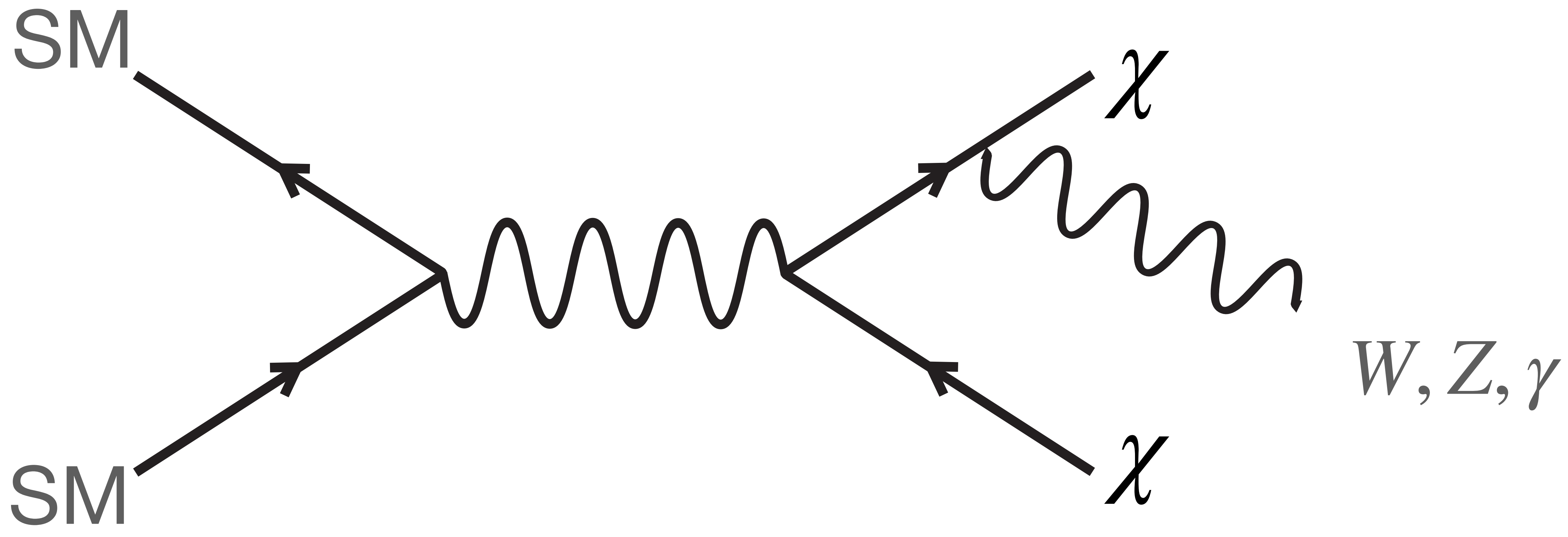


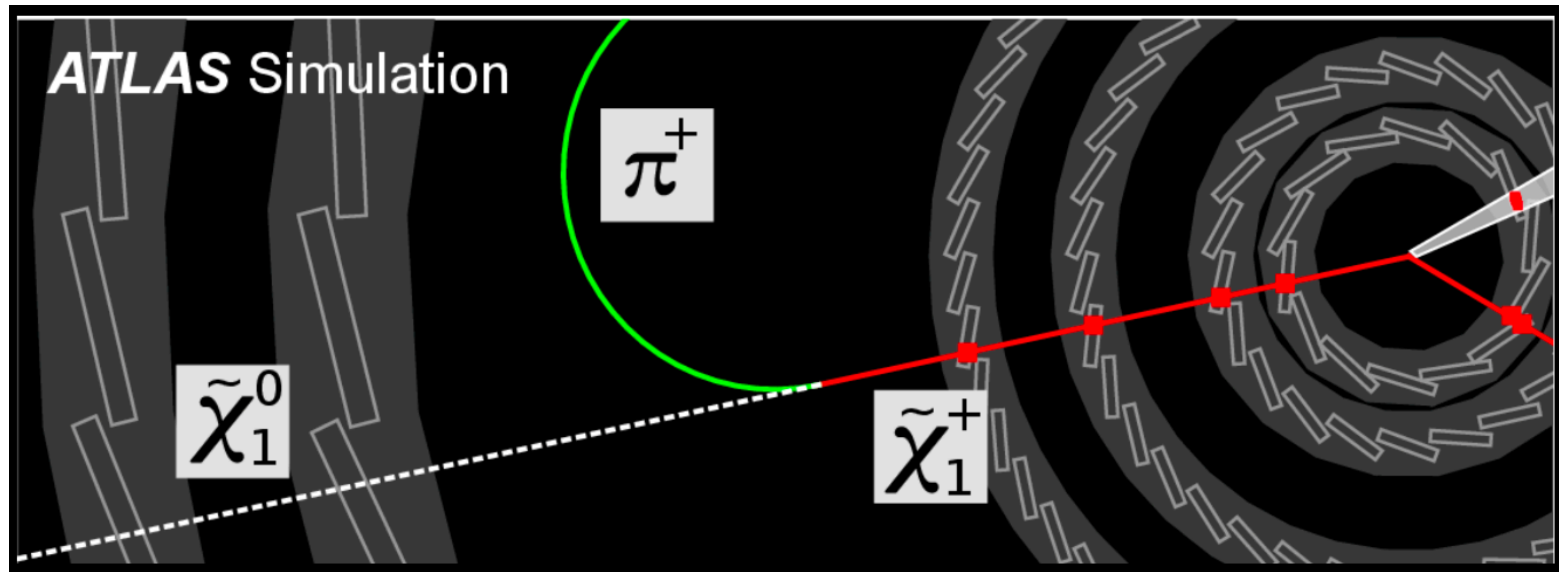


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*Improve sensitivity by requiring a disappearing track*

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio ’21, ’22

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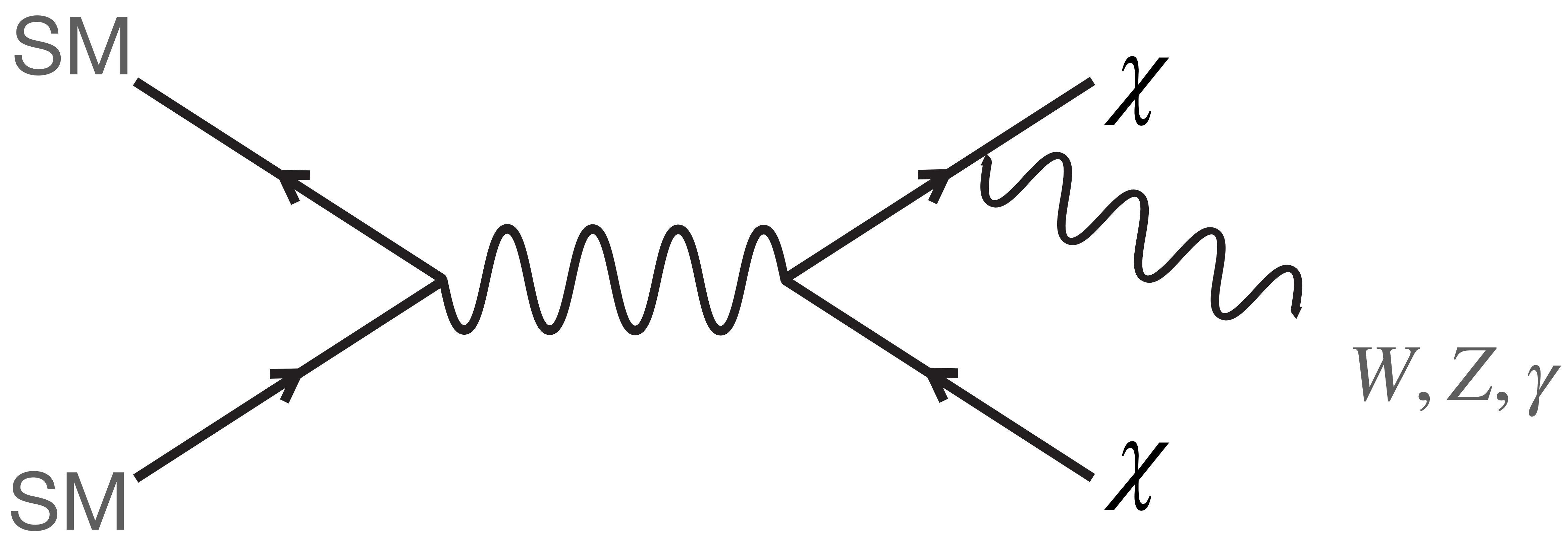
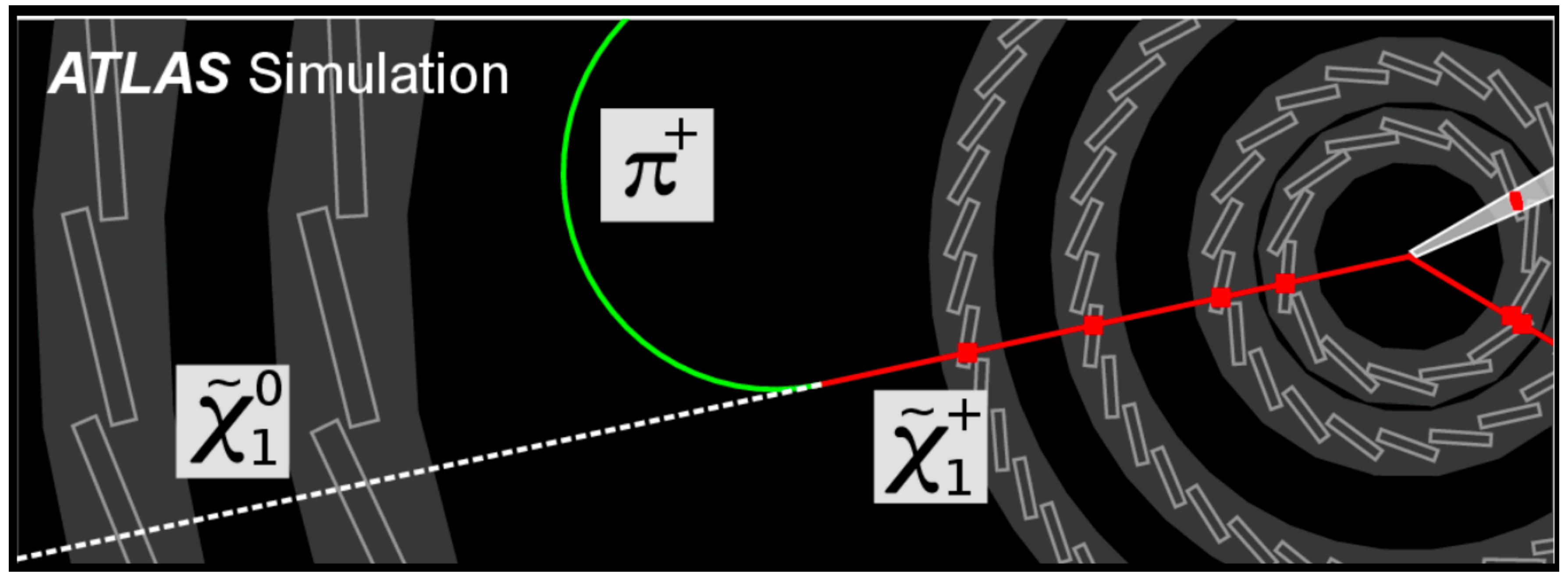
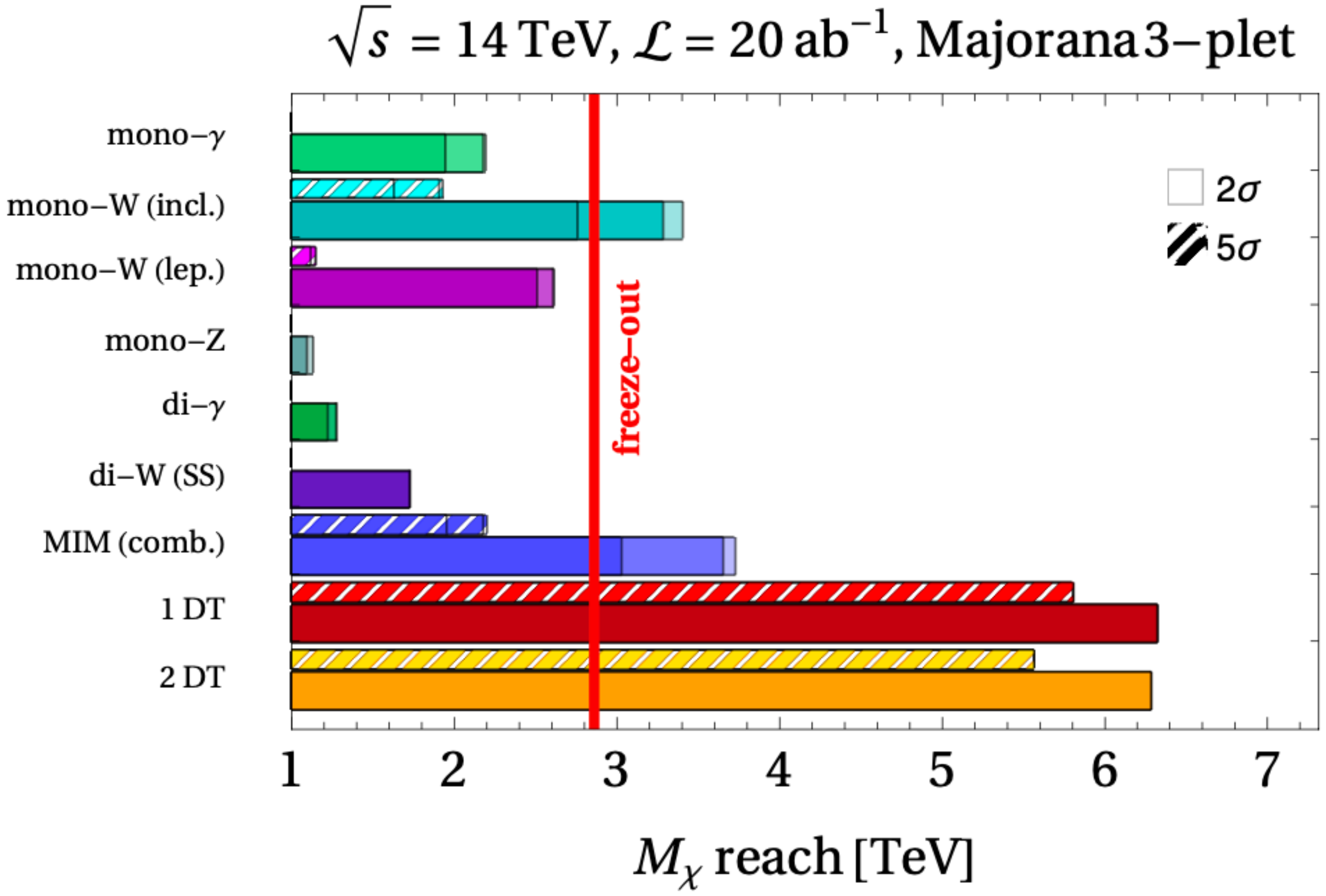


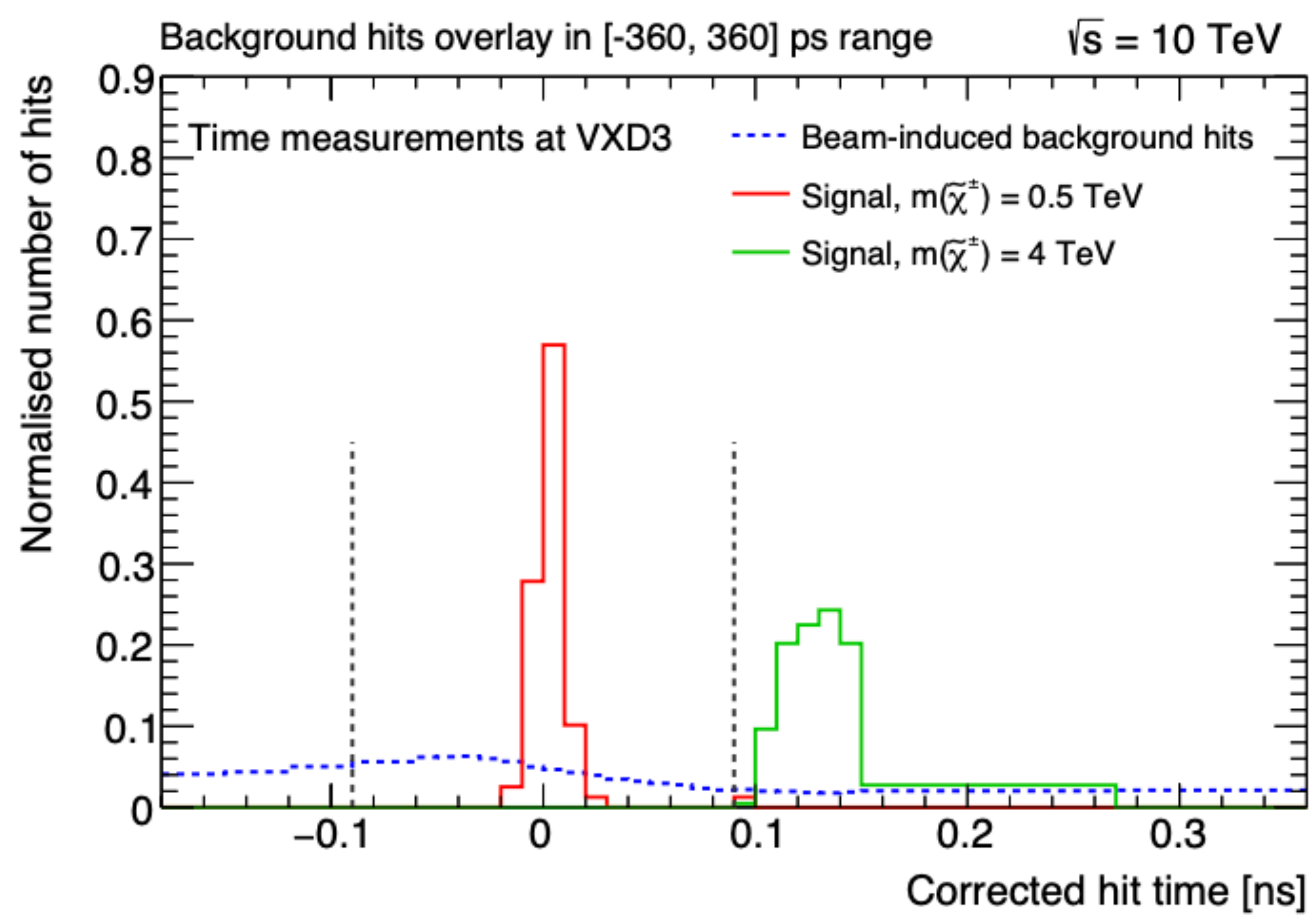

*Improve sensitivity by requiring a disappearing track*

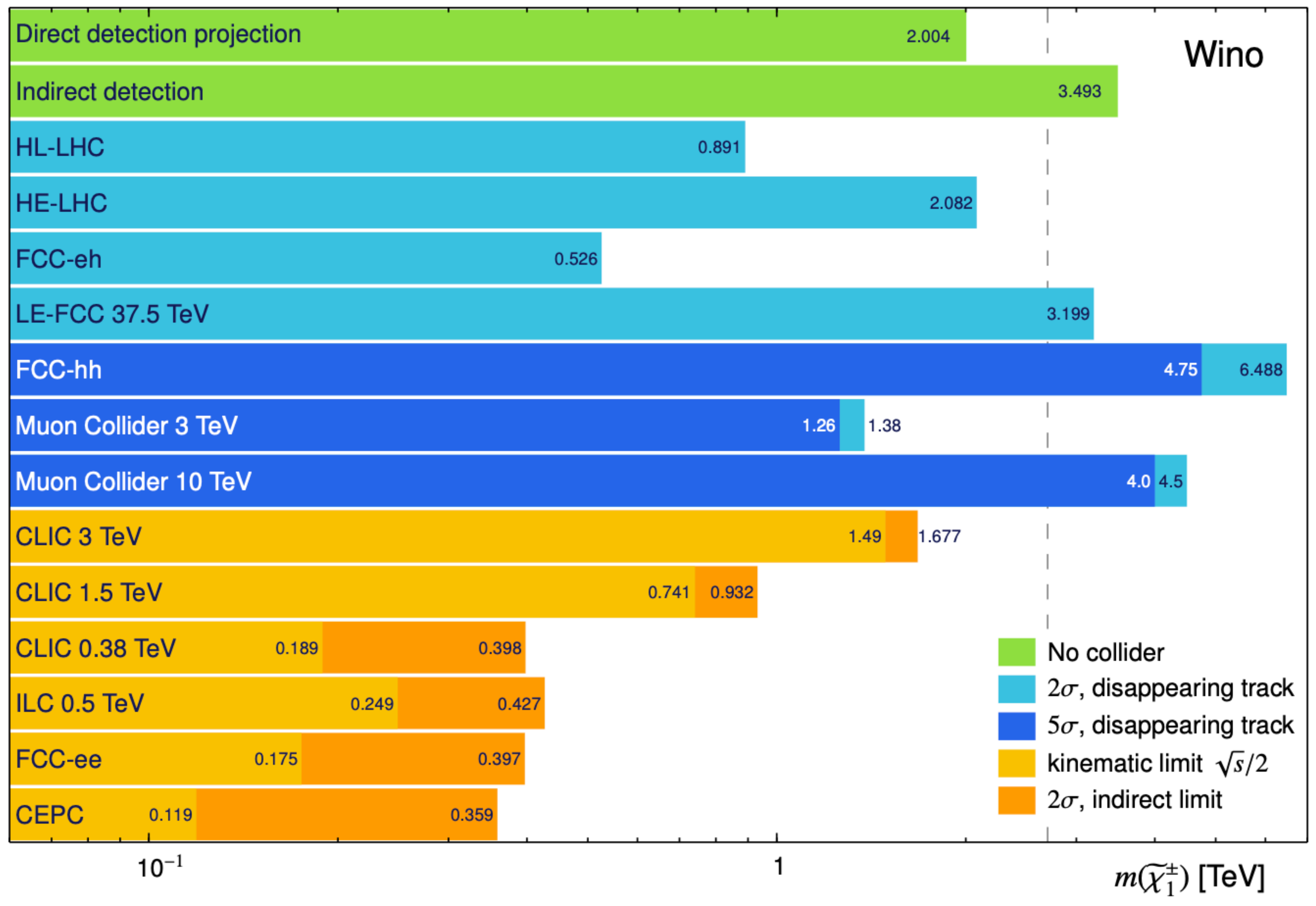


Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

# Wishlist

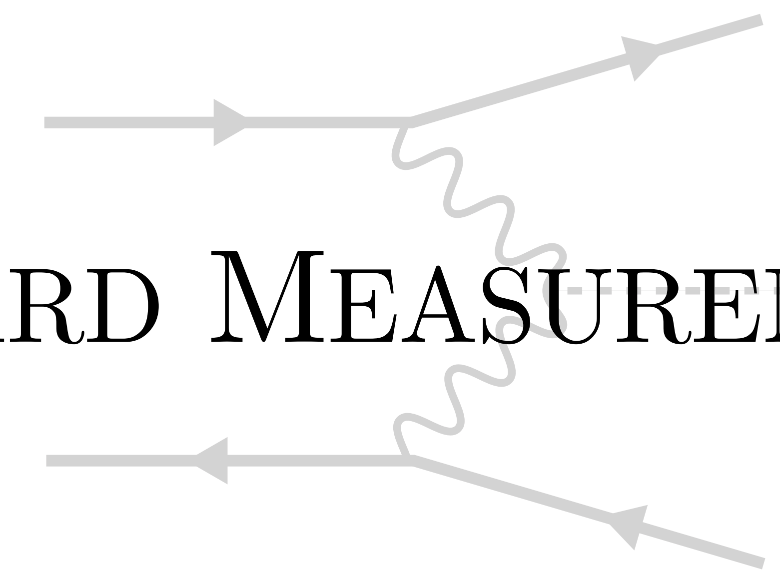
- Disappearing track sensitivity (distinct from BIB)
- Timing and hit-to-hit correlations
  - Algorithms can be useful for all kinds of LLP, DV scenarios, what else is there?




Capdevilla, Meloni, Simoniello, Zurita 23

Precision EW & Higgs



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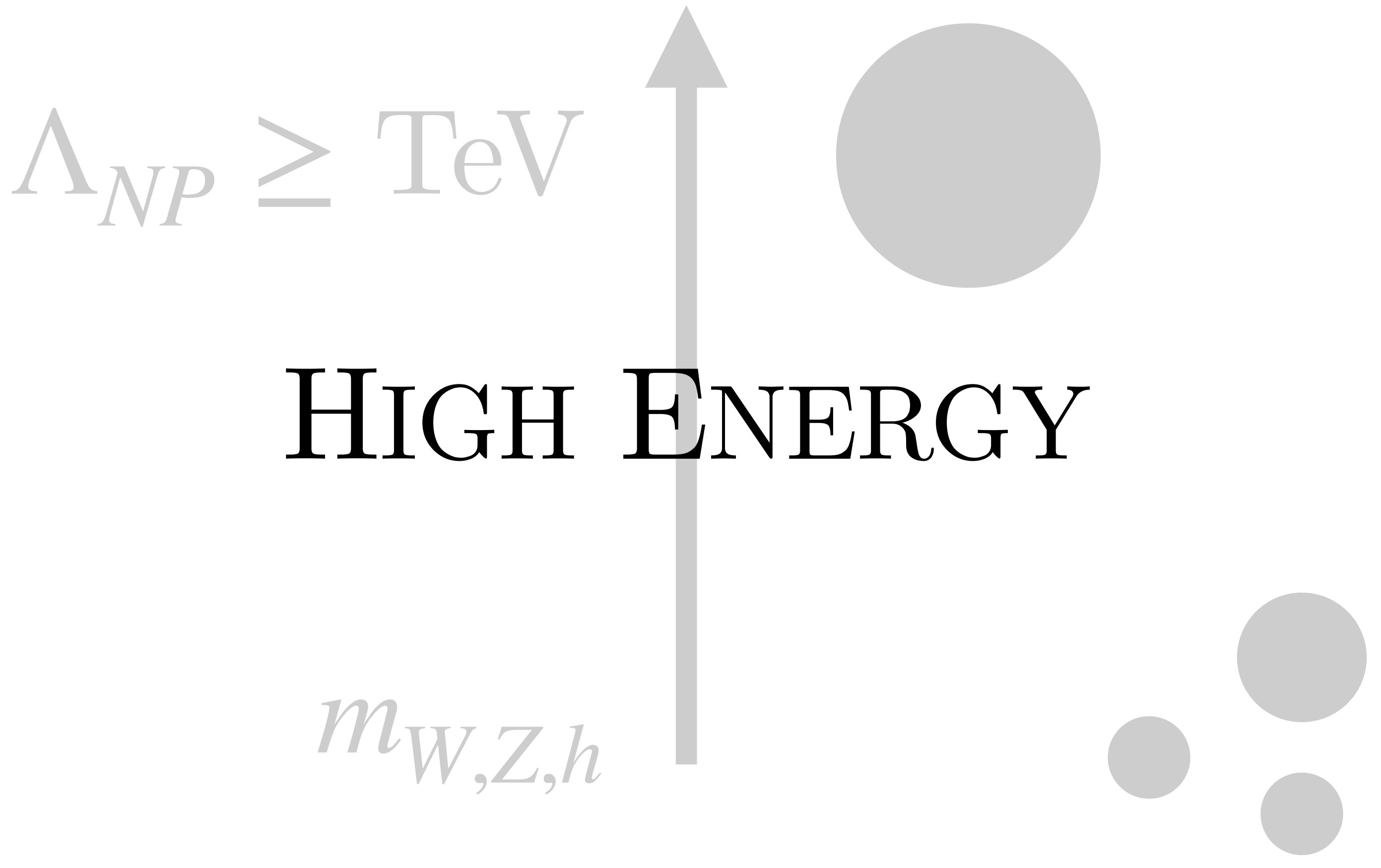
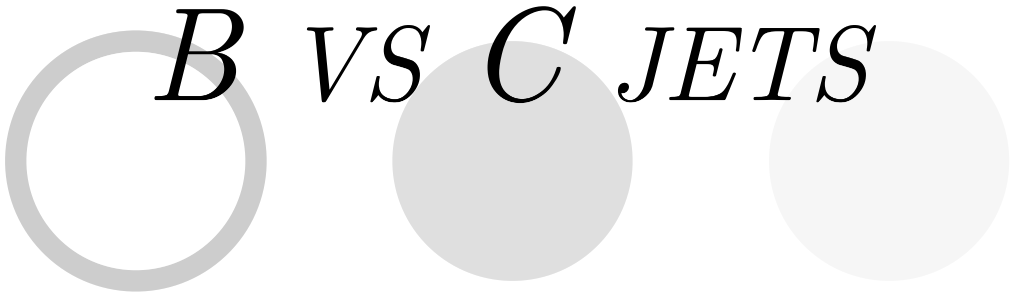



High Energy

# Physics Goals

Flavor Tagging

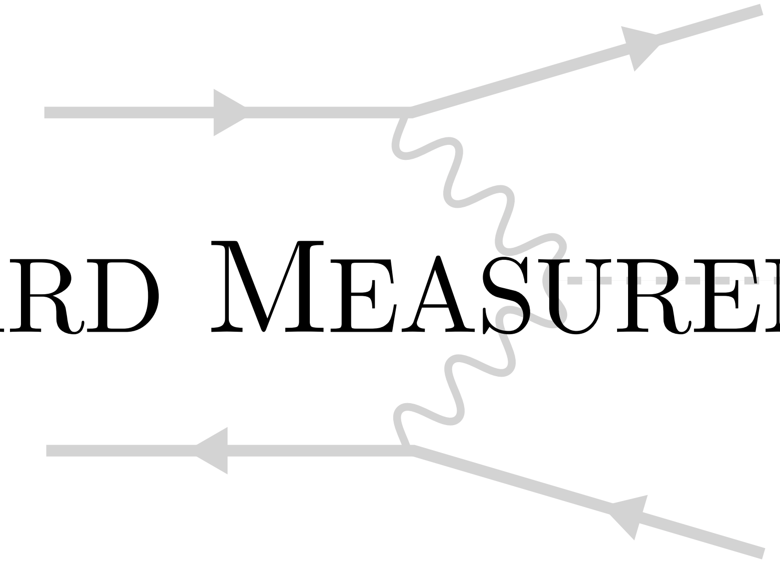
*b* vs *c* jets



Novel Signatures
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)

*Mitigate the BIB with hits and timing*

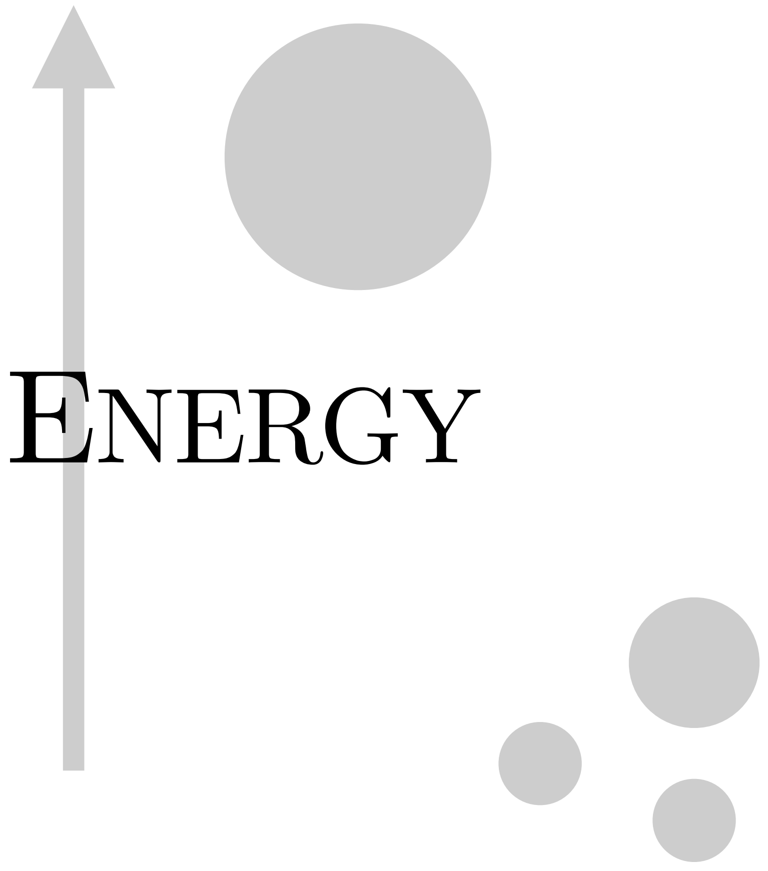
Precision EW & Higgs



FORWARD MEASUREMENTS

Heavy Particles

$\Lambda_{NP} \geq \text{TeV}$



HIGH ENERGY

$m_{W,Z,h}$

# PHYSICS GOALS

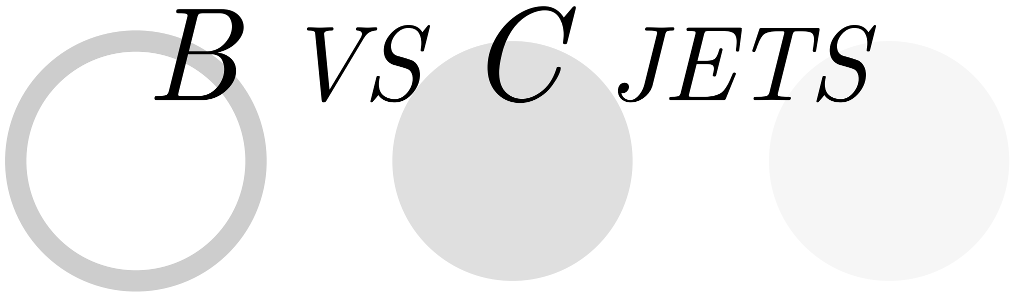
Novel Signatures
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)

*MITIGATE THE BIB WITH HITS AND TIMING*



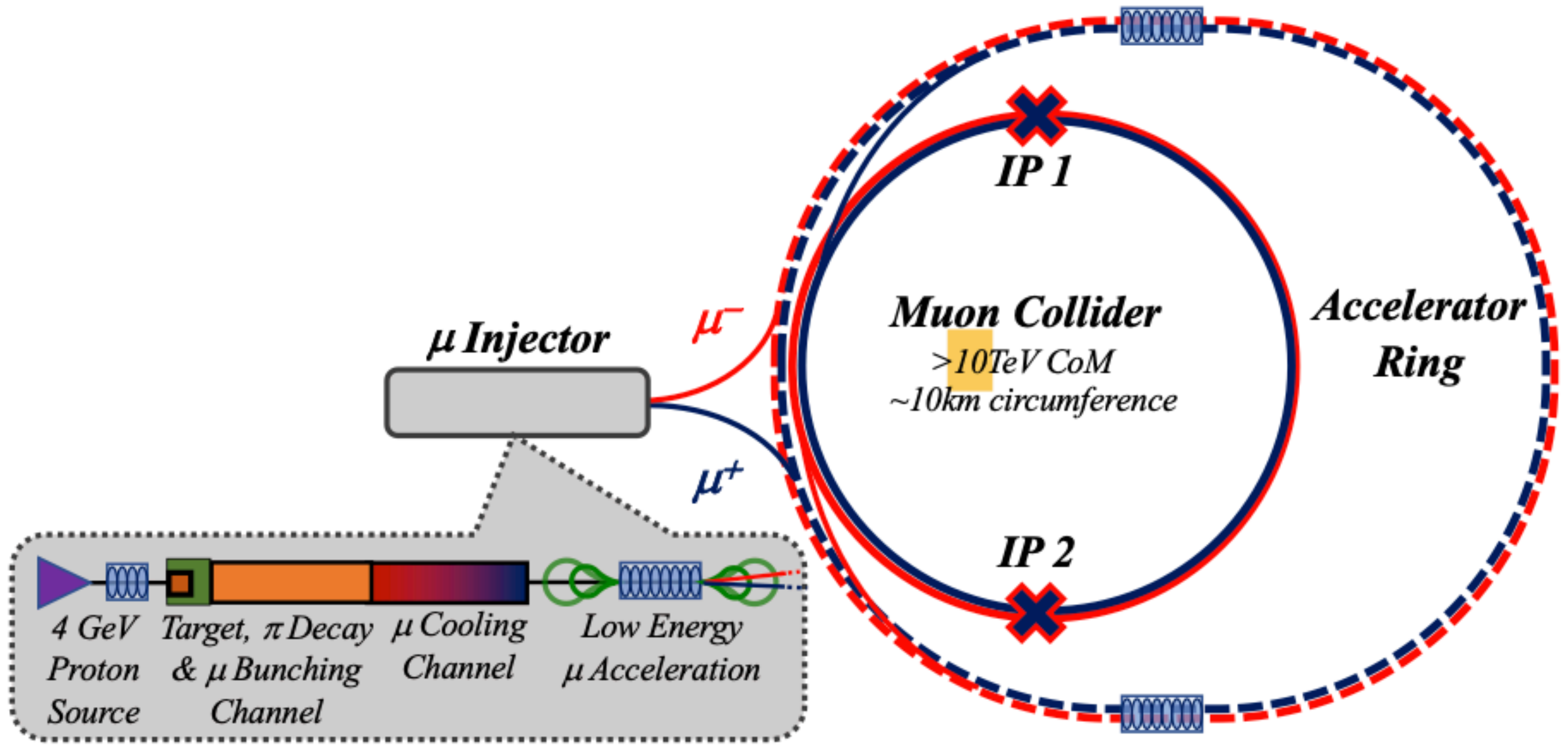
Flavor Tagging

*B VS C JETS*



*And what about auxiliary experiments….*

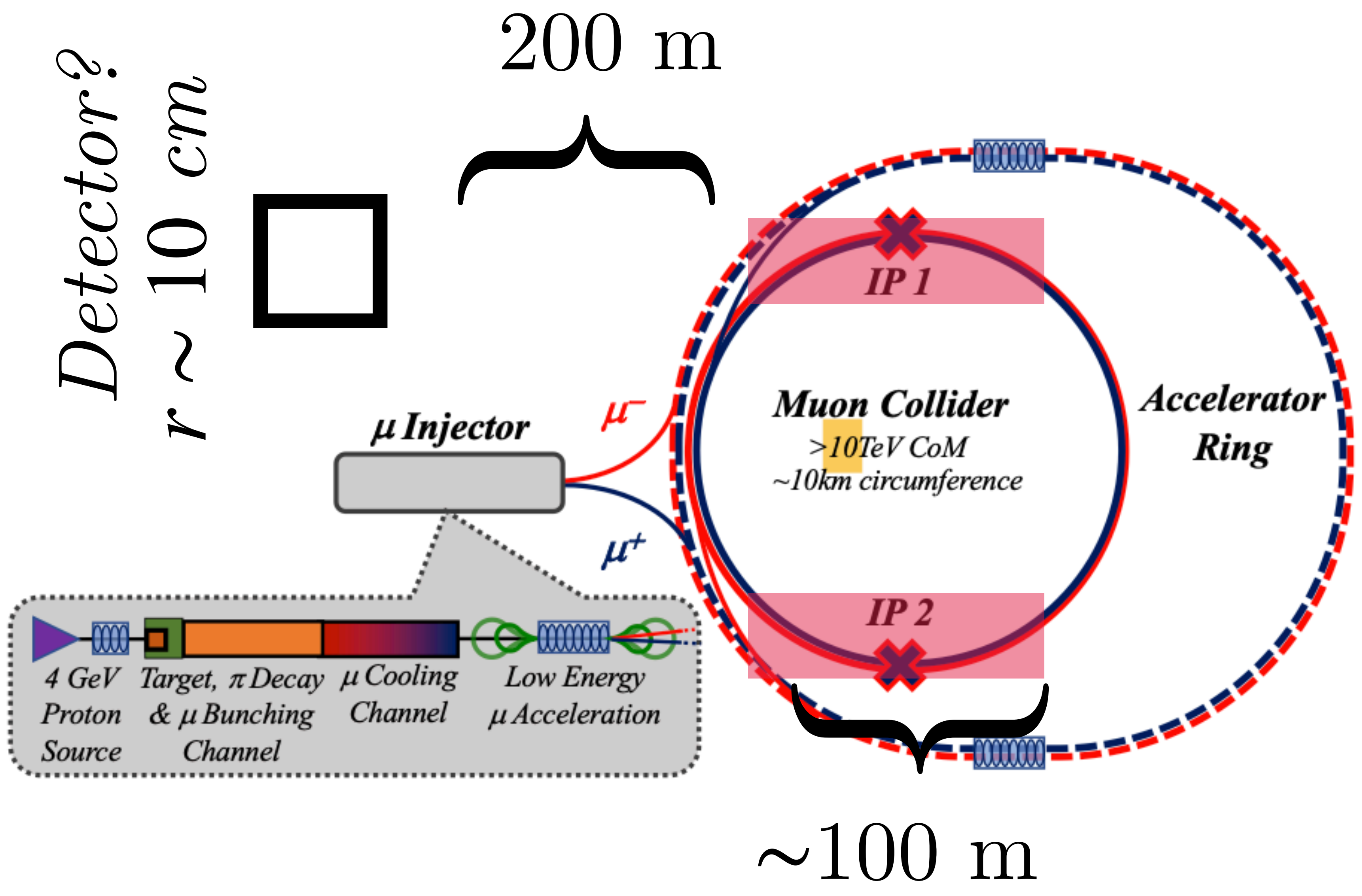
# Auxiliary Experiments




We can be sensitive to interesting physics if we instrument beyond the interaction points

# Auxiliary Experiments

30%

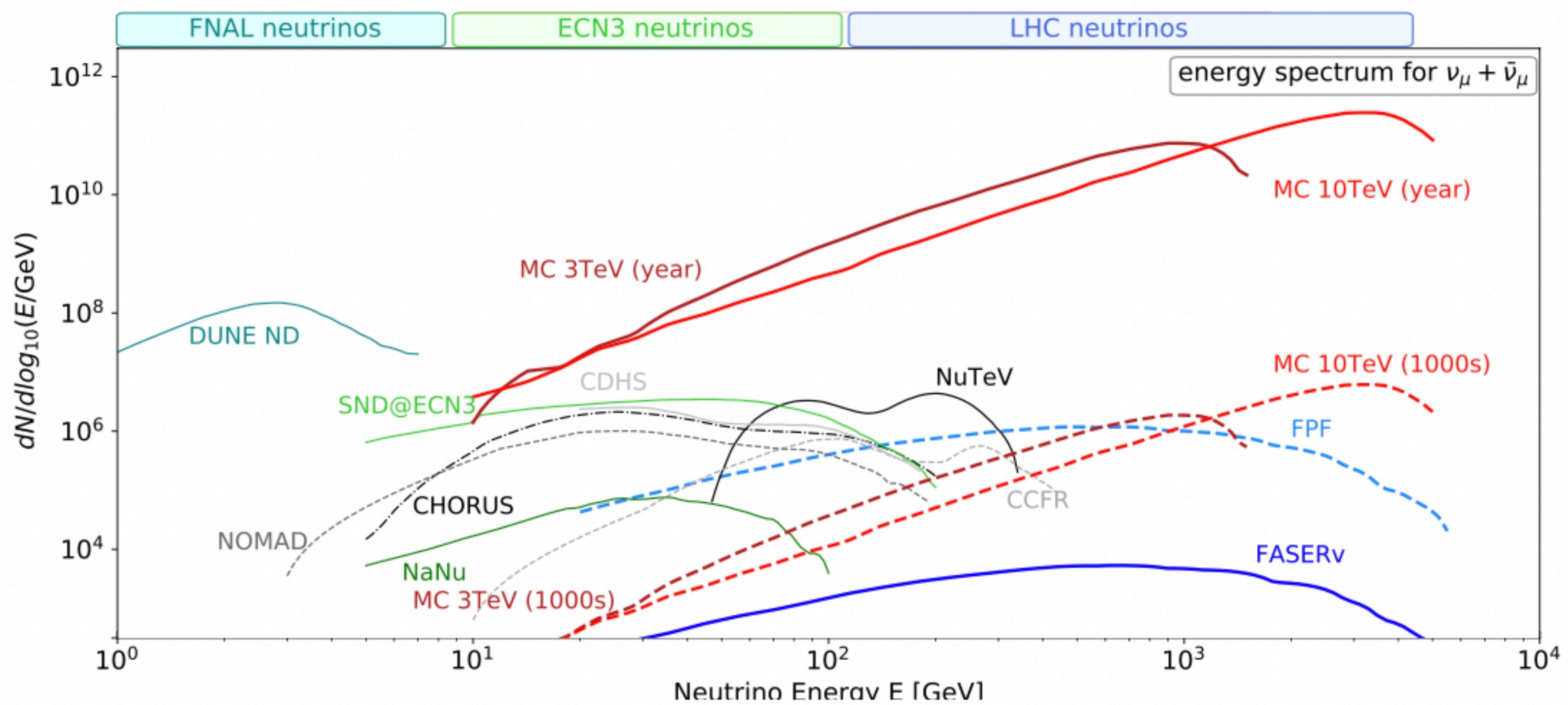



We can be sensitive to interesting physics if we instrument beyond the interaction points

Lattice design has *flat* sections

$10^{20}\mu$ / year $\rightarrow$ $> 10^{16}\nu$ / year

For variety of short-baseline $\nu$ measurements



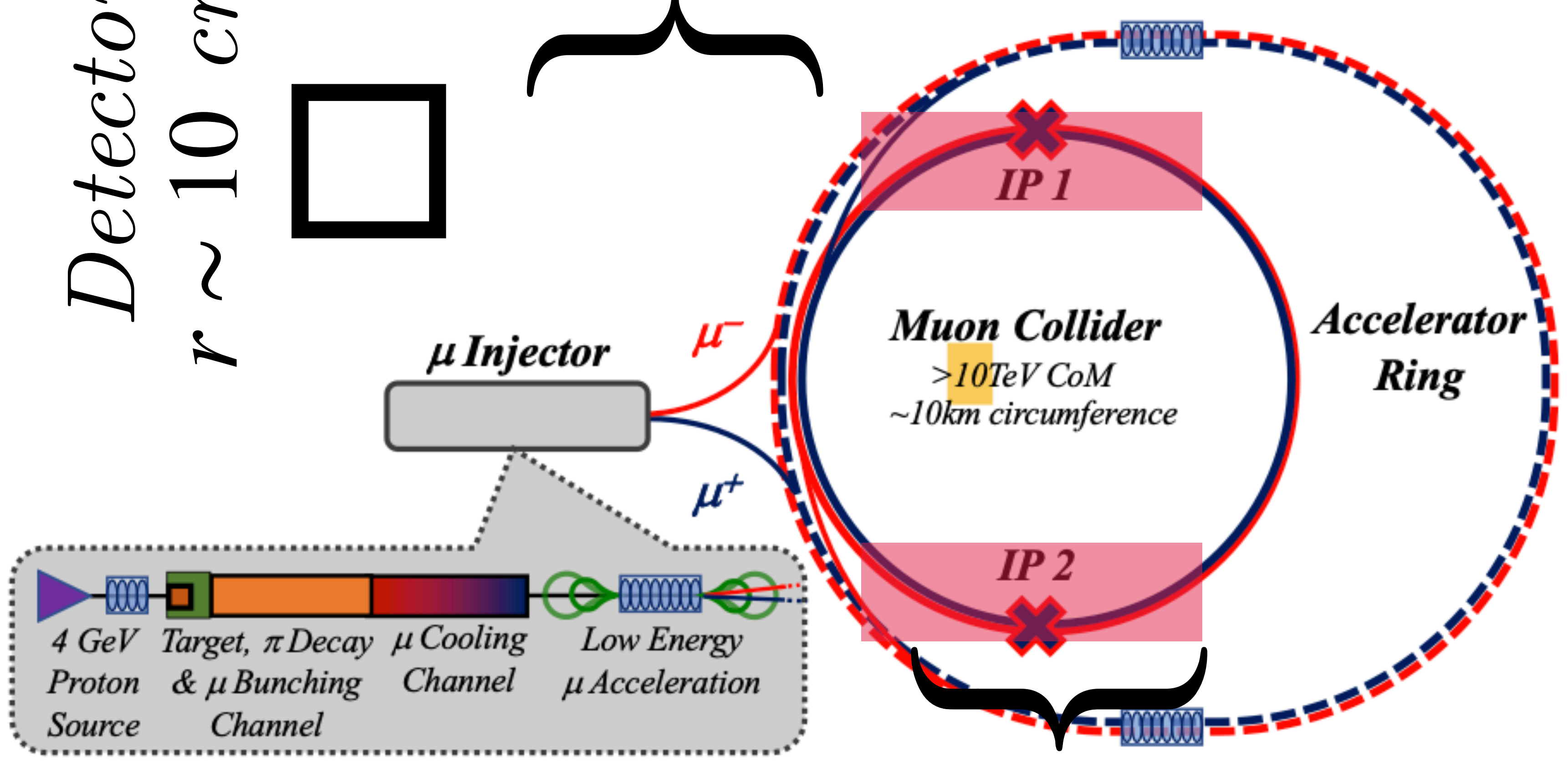
# Auxiliary Experiments

30%

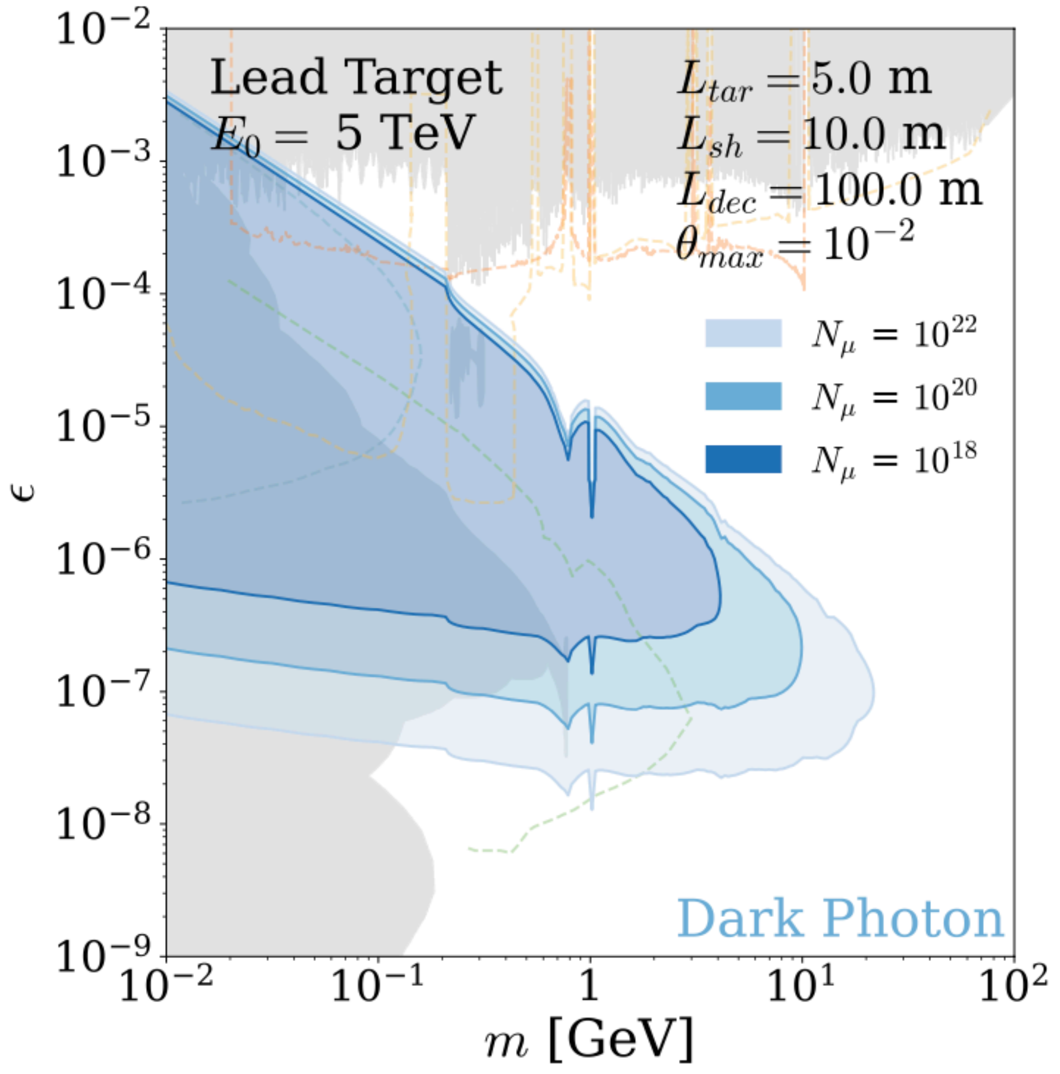
*Detector?*

$r \sim 10$ *cm*

200 m




$\sim$100 m




We can be sensitive to interesting physics if we instrument beyond the interaction points

Lattice design has *flat* sections

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*But maybe also an e beam dump-like experiment?*

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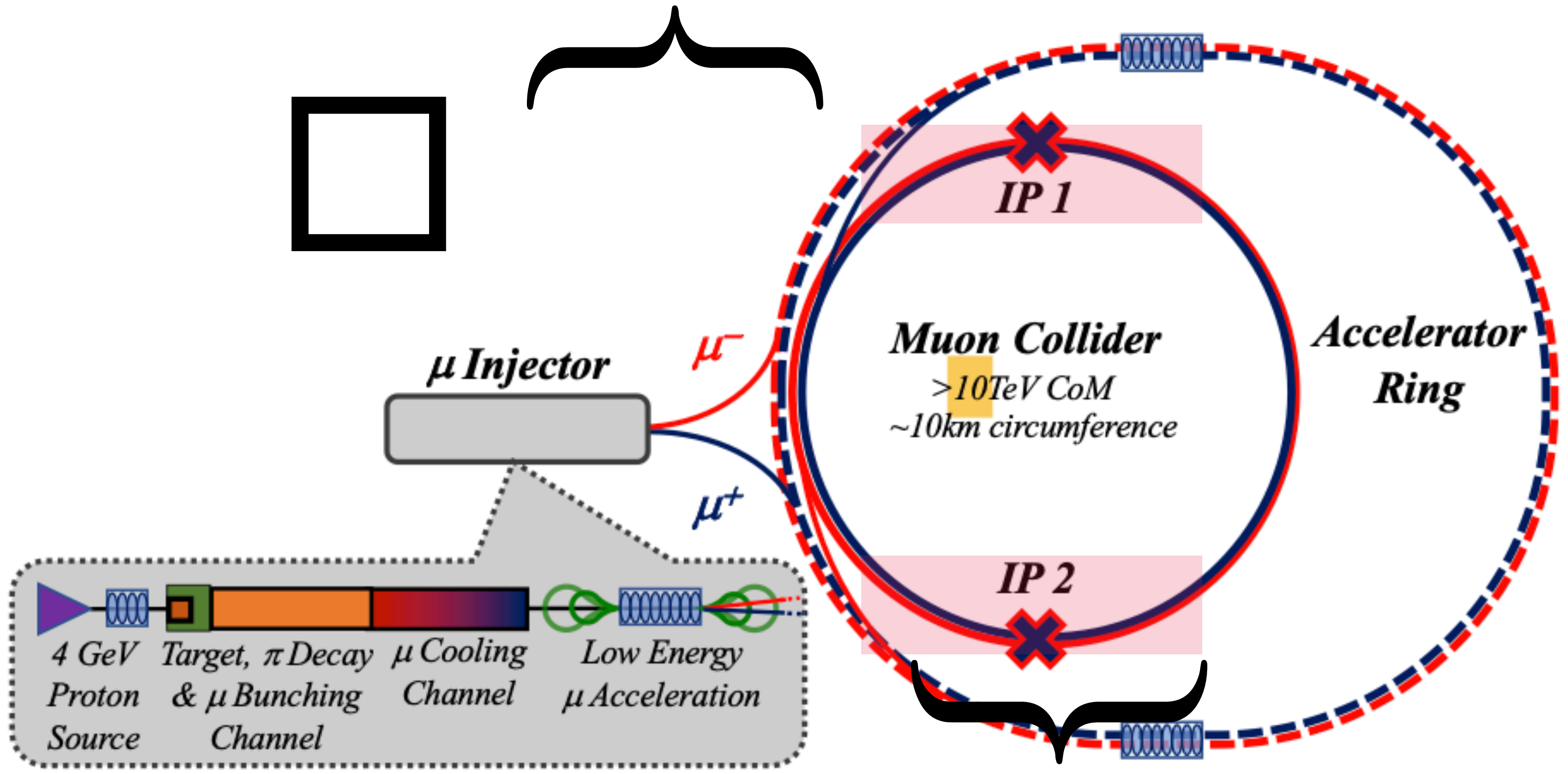
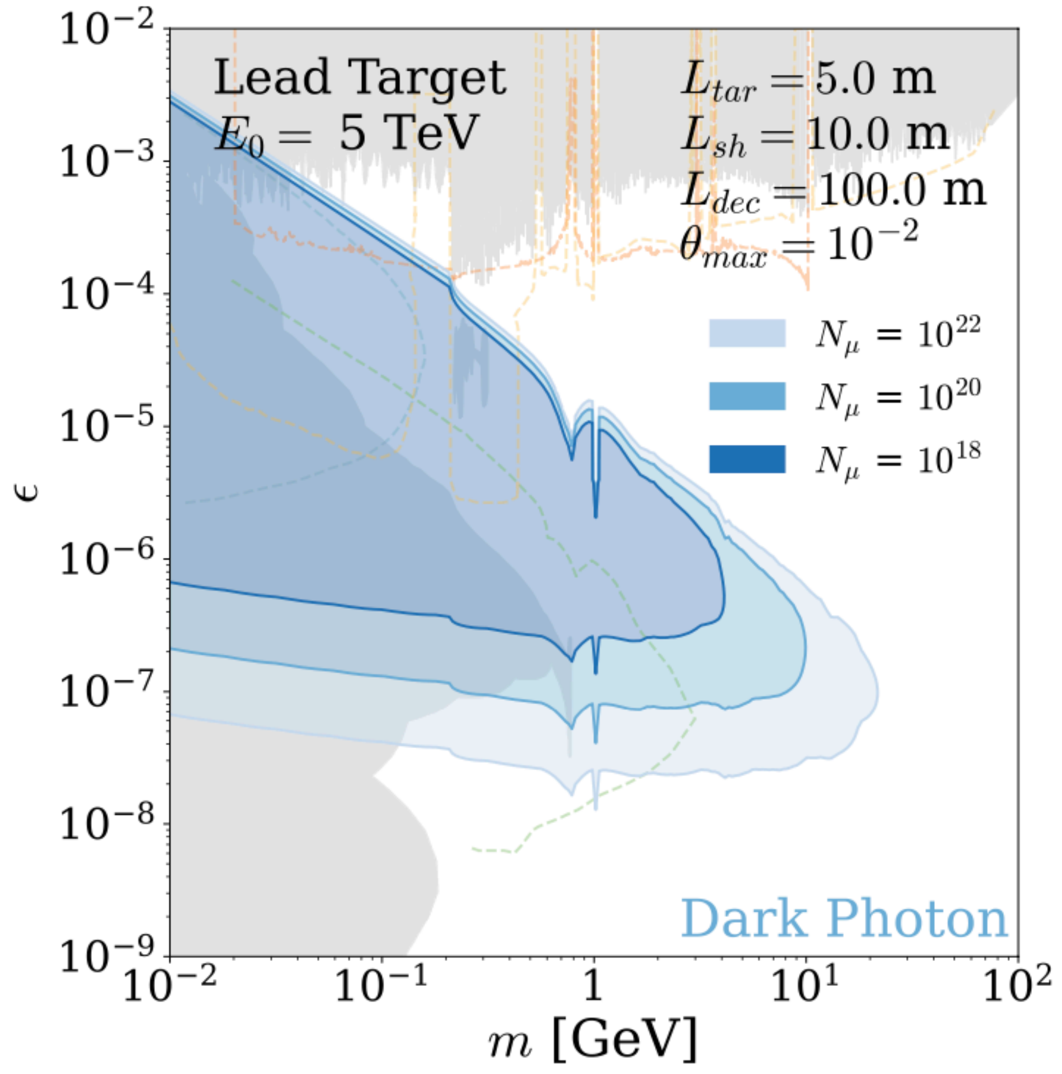
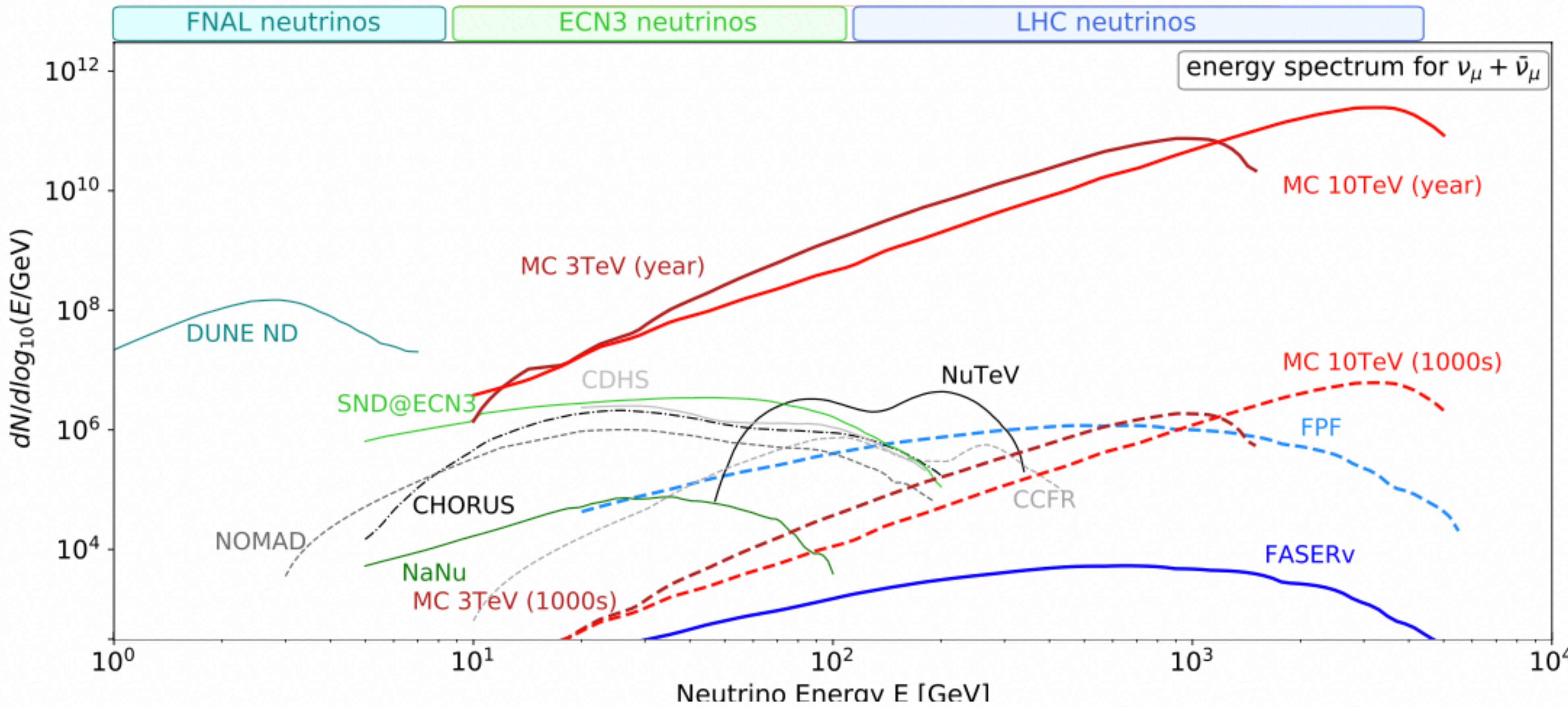
# Wishlist

- Modest calorimetry and tracking for the muon decay products?




~100 m

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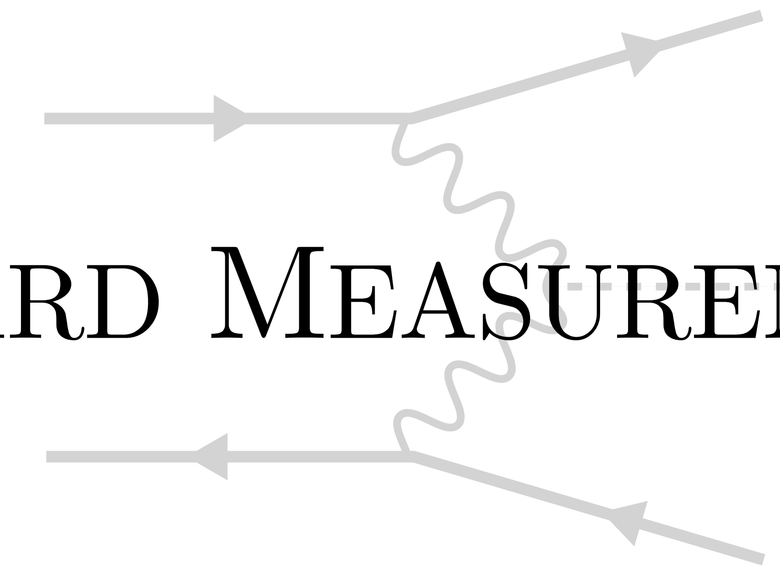
Precision EW & Higgs



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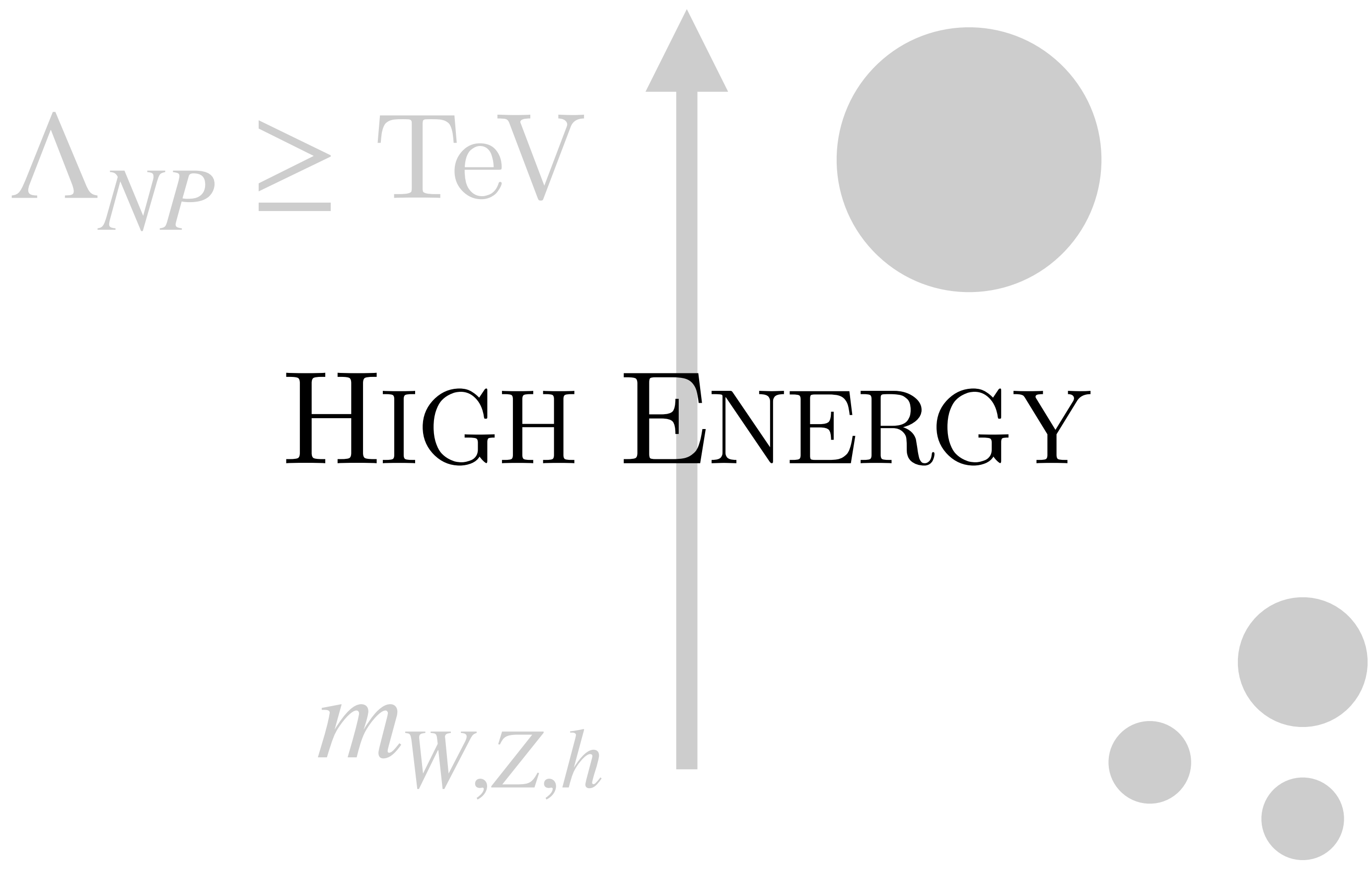
Heavy Particles




High Energy

# Physics Goals

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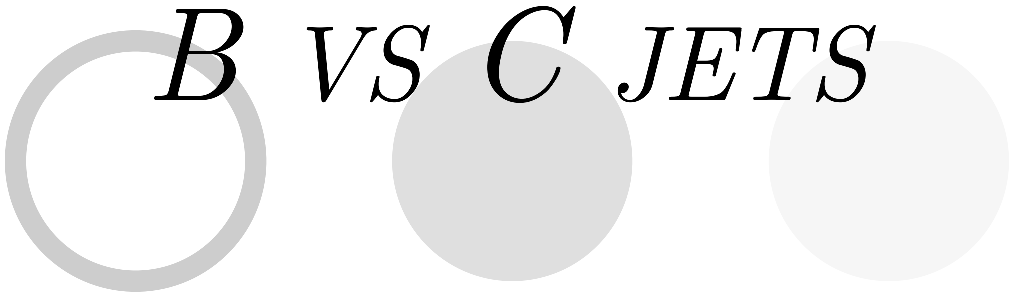
Flavor Tagging

*B vs C jets*



*Mitigate the BIB with hits and timing*



*And auxiliary experiments just needing instrumentation*

# Let's take a step back: What makes the muon collider so special?

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## 10 TeV and Beyond in 205x

# A World with Two Colliders

## FCCee & FCChh

*Precision SM Measurements*

## MuC

*Sprint to 10 TeV Frontier and beyond as fast as we can?*

This comes at the cost of luminosity, but if another experiment is covering that physics program, why not aim for complementary physics goals?

# A World with Two Colliders

## FCCee & FCChh

*Precision SM Measurements*

## MuC

*Sprint to 10 TeV Frontier and beyond as fast as we can?*

This comes at the cost of luminosity, but if another experiment is covering that physics program, why not aim for complementary physics goals?

## Final Wish

How much will luminosity suffer if we use *current* technology to build 10, 14, 30 TeV MuC?

What kinds of new heavy states can we still see with low luminosity but high energy?

# Wishlist Summary

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
- Good granularity of detector
- Sensitivity to low energy tracks
- Excellent energy resolution (>90%)
- Forward tagging and $p$ resolution for $|\eta| < 2.5$ at *least*
- Luminosity should keep up with $s$ channel production
- Discriminate $b$, $c$, and light quarks to discriminate $Z$, $W$, and $h$ bosons
- Find physics applications of the BIB
- *Hitting the energy frontier should be (the highest?) priority*

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- Find physics applications of the BIB
- *Hitting the energy frontier should be (the highest?) priority*

There is much work to be done by **everyone**.

Let's spend this week discussing *what* physics benchmarks are truly a priority (not just a consequence) and *how* we continue to motivate and demonstrate the full physics potential of a MuC