Interplay Between Theory and Experiment

Inaugural US Muon Collider Meeting

Fermilab

Aug 8, 2024

Rodolfo Capdevilla
Fermilab

Many thanks to my colleagues for their input:

Federico Meloni, Nazar Bartosik, Danielle Calzolari, Zhen Liu, Donatella Lucchesi, Massimo Casarsa, Tova Holmes, Patrick Meade…

Outline

Theory Target ⟷ ***Experimental Target***

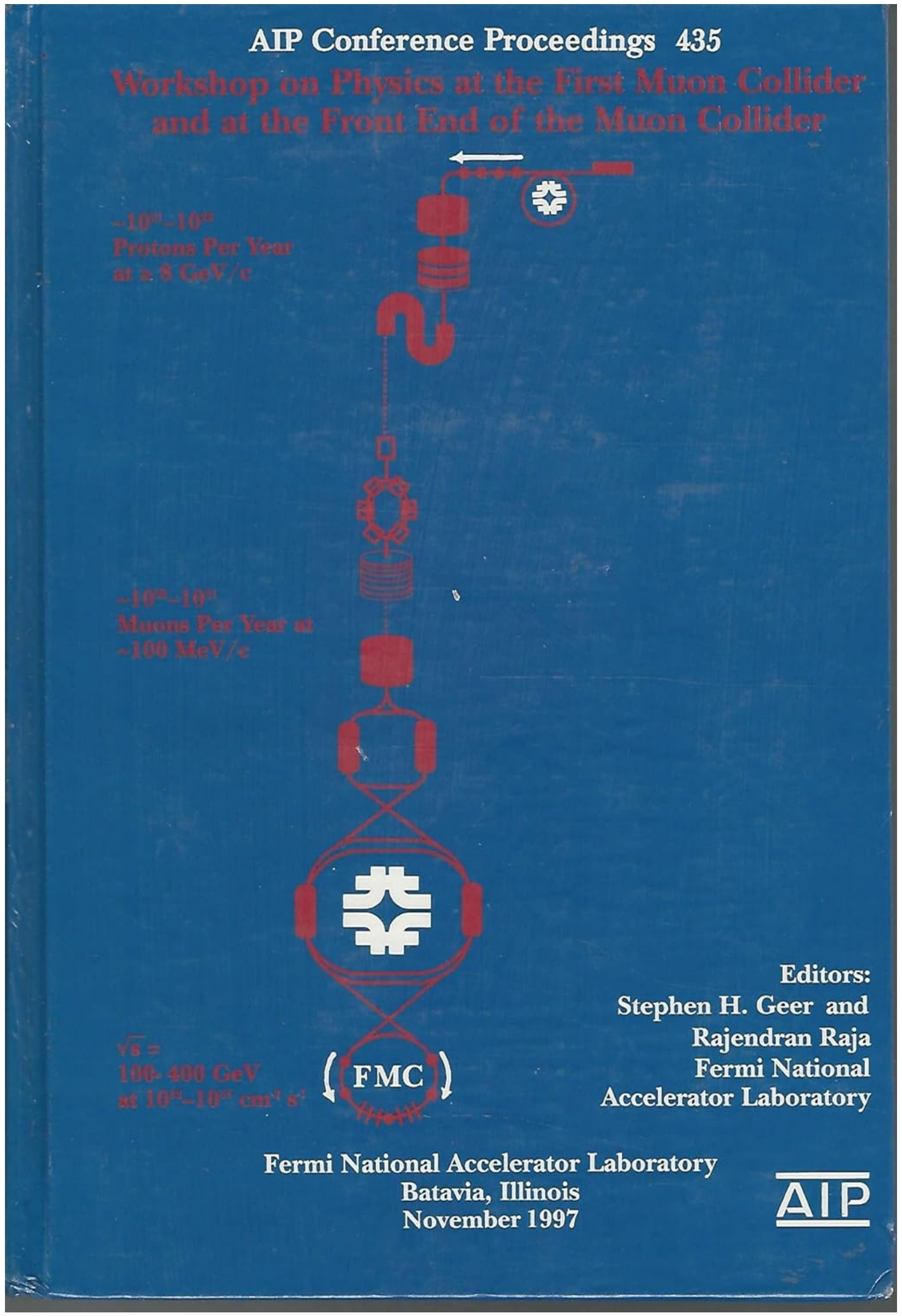
Theory Target

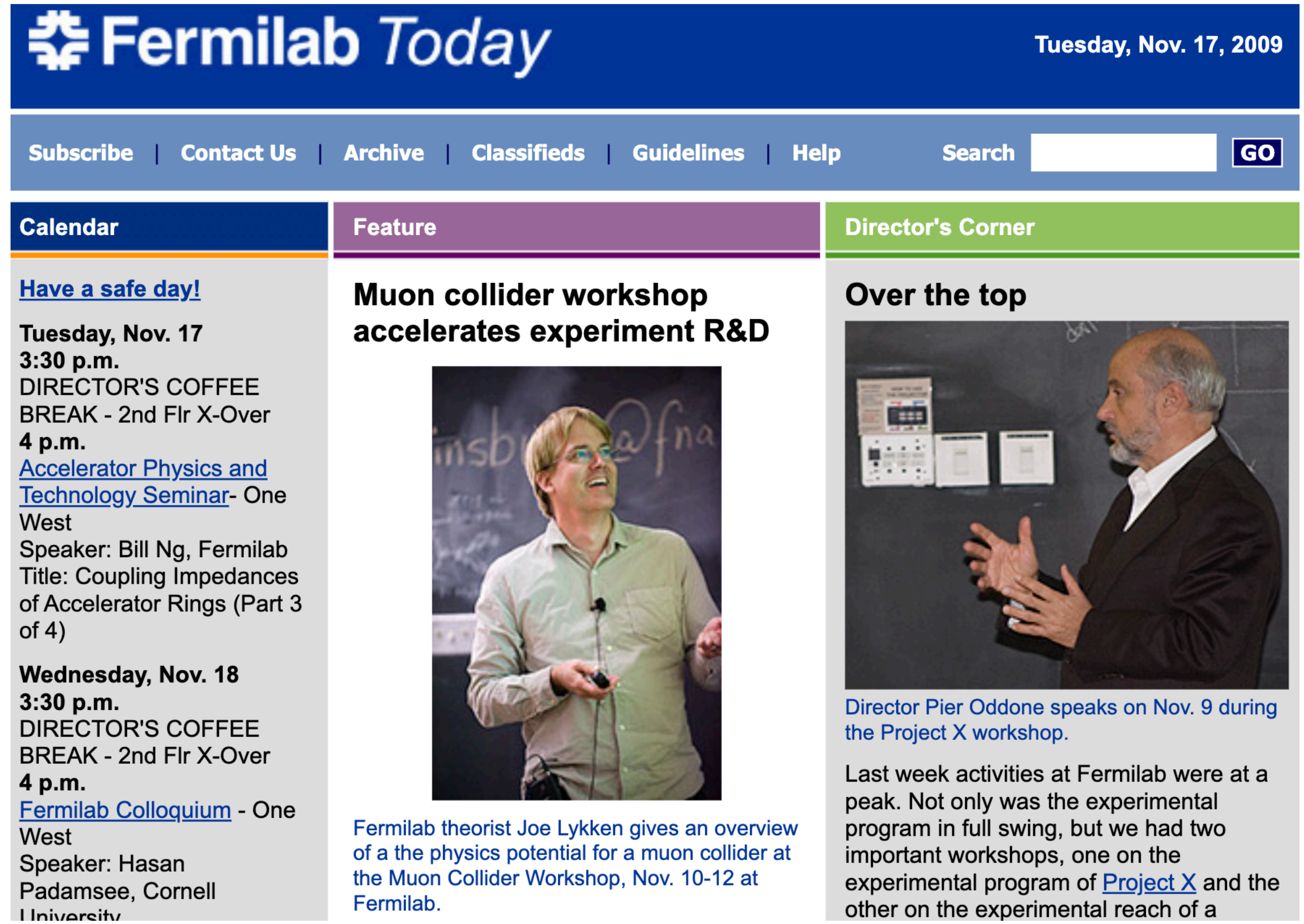
- Higgs Precision
- Heavy resonances
- Forward Physics
- Long-Lived Particles
- …

Experimental Target

- Object Reconstruction
- High pT
- Forward Tagger
- Disappearing+Soft Tracks
- Displaced Vertices
- Detector Acceptance
- …

Memories worth reviving!





Fermilab *Today* — Tuesday, Nov. 17, 2009

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Calendar

Have a safe day!

Tuesday, Nov. 17
3:30 p.m.
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
4 p.m.
Accelerator Physics and Technology Seminar- One West
Speaker: Bill Ng, Fermilab
Title: Coupling Impedances of Accelerator Rings (Part 3 of 4)

Wednesday, Nov. 18
3:30 p.m.
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
4 p.m.
Fermilab Colloquium - One West
Speaker: Hasan Padamsee, Cornell University

Feature

Muon collider workshop accelerates experiment R&D

Fermilab theorist Joe Lykken gives an overview of a the physics potential for a muon collider at the Muon Collider Workshop, Nov. 10-12 at Fermilab.

Director's Corner

Over the top

Director Pier Oddone speaks on Nov. 9 during the Project X workshop.

Last week activities at Fermilab were at a peak. Not only was the experimental program in full swing, but we had two important workshops, one on the experimental program of Project X and the other on the experimental reach of a

Memories worth reviving!

Question: How many U.S. Congressmen does it take to build a muon collider?

Answer: One

Fermi National Accelerator Laboratory

FERMILAB-Conf-95/037

Backgrounds and Detector Performance at a 2 x 2 TeV $\mu^+\mu^-$ Collider

G. William Foster and Nikolai V. Mokhov

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Short version of this talk

Question: Is it possible to identify the physics targets of the post-LHC energy frontier collider before we have any LHC results?

Answer: No

How we proceed:

Theory Target

↓

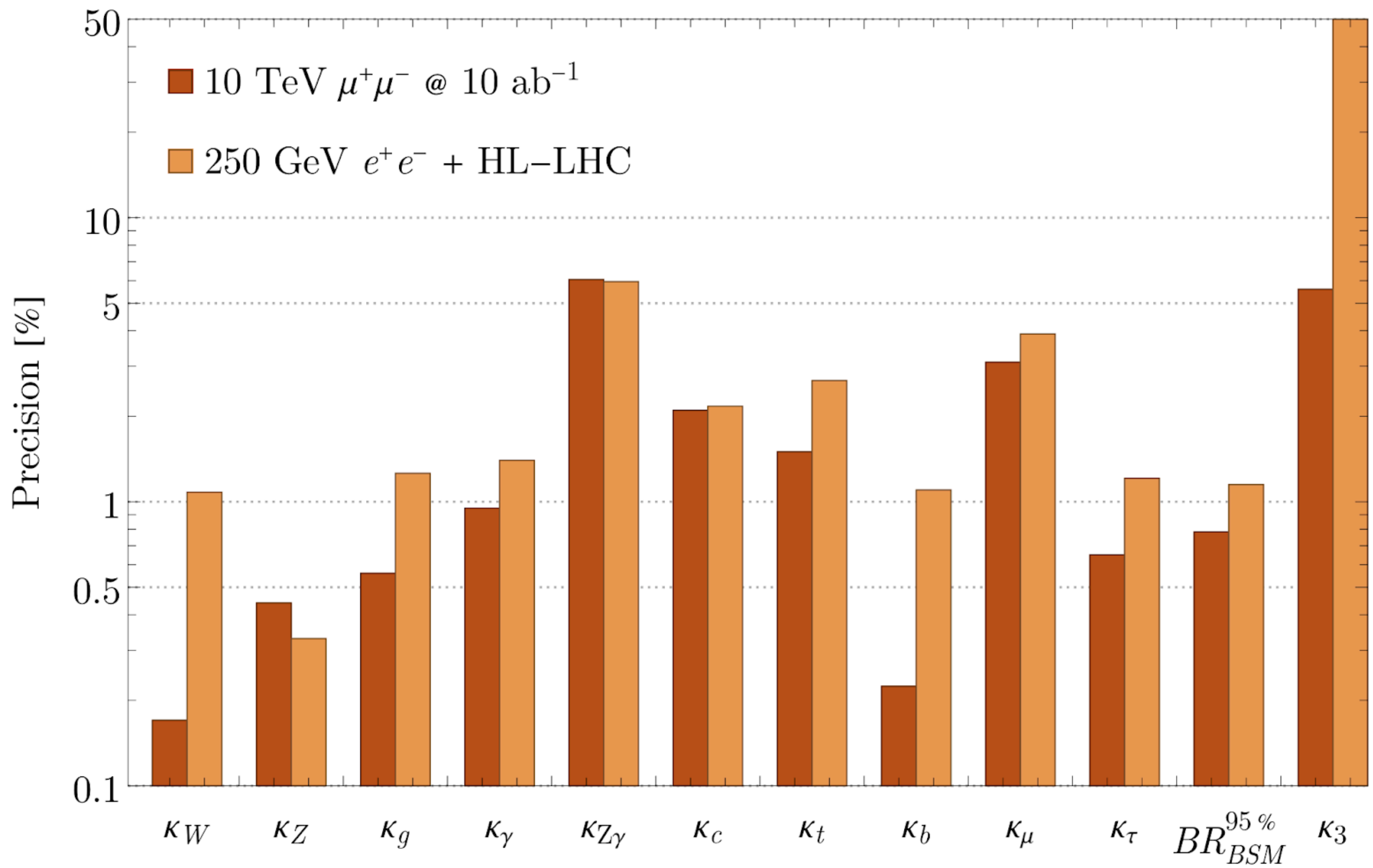
Experimental Target (According to Theory)

↓

Experimental Status (and prospect)

1. Higgs Precision

- Theory Target: Percent Level Higgs couplings!

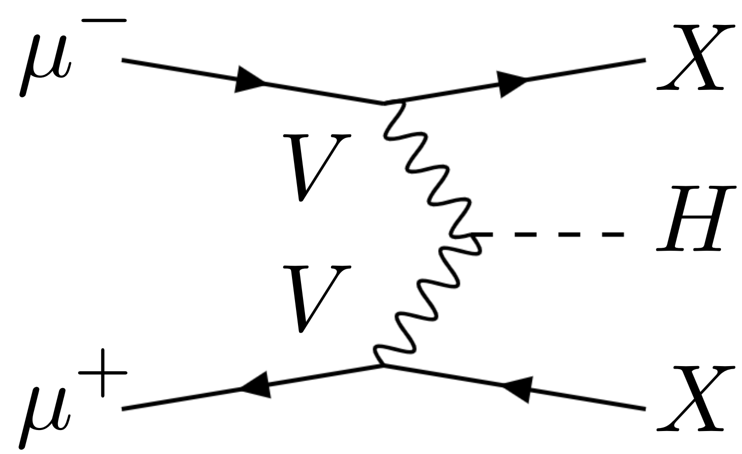


Han, Liu, Low, Wang, Phys. Rev. D 103 (2021) 1, 013002
Buttazzo, Franceschini, Wulzer, JHEP 05 (2021) 219
Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185
C. Accettura et al., Eur. Phys. J. C 83 (2023) 9, 864
Matthew Forslund, Patrick Meade, JHEP 01 (2024) 182 *
P. Andreetto et al, arXiv:2405.19314

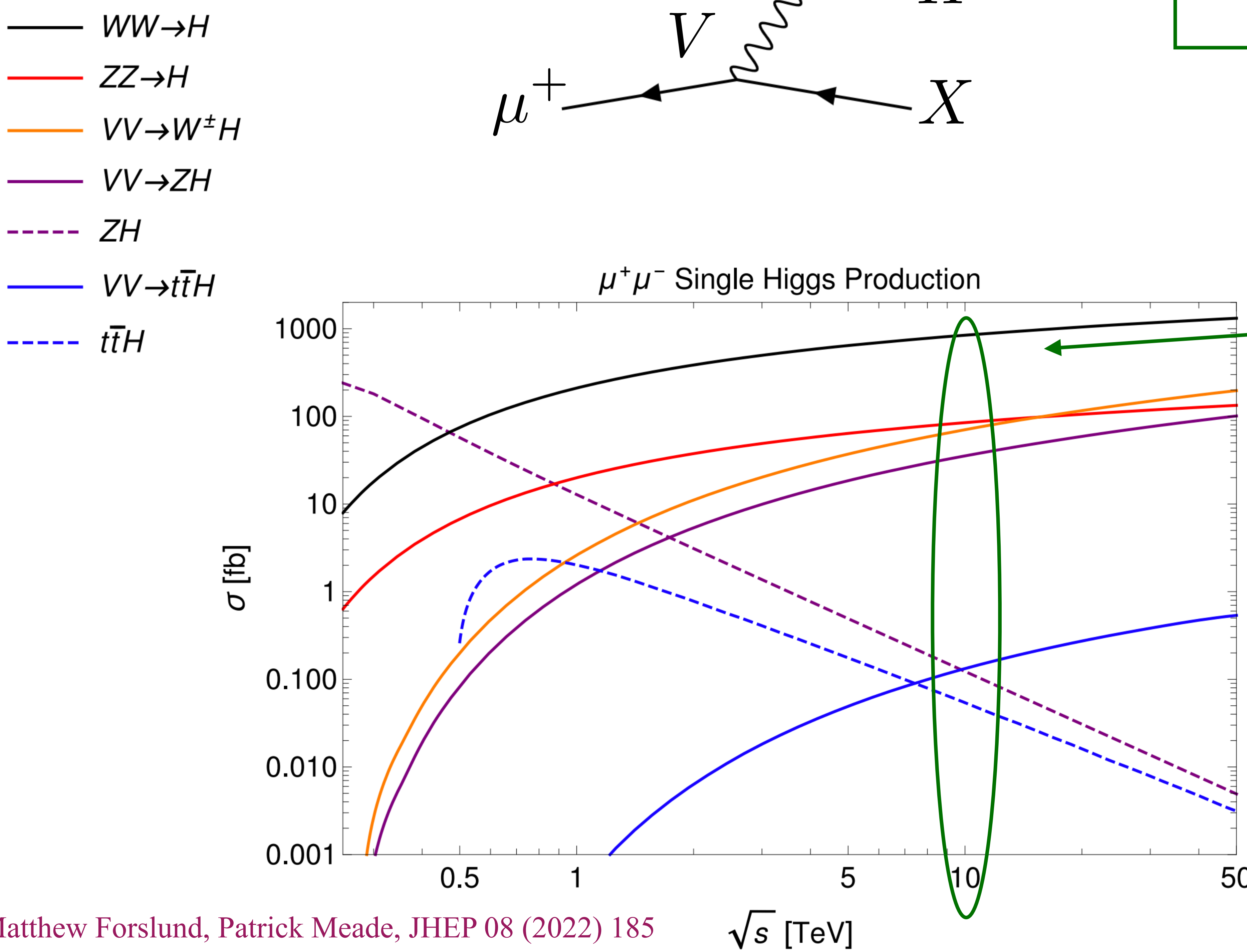
Higgs precision program COMPLIMENTARY to that of a Higgs factory!

1. Higgs Precision

- A key feature:



Vector Boson Fusion (VBF) produces a large number of Higgs bosons!



$\sim 1\,\mathrm{pb}$

$\sim 10\,\mathrm{M}$

Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185

Remember:

$10\,\mathrm{TeV\ MuC}$

$10\,\mathrm{ab}^{-1}\ (5\,\mathrm{years})$

Public thanks to Vladimir Shiltsev for reporting luminosity in units of ab^-1/year (so the theorists can understand!)

1. Higgs Precision

- Experimental Target:

P. Andreetto et al, arXiv:2405.19314

3 TeV Study

Object	Requirements
muons	$\frac{\Delta p_T}{p_T} = 0.4\%$
photons	$\frac{\Delta E}{E} = 3\%$
jets	$\frac{\Delta p_T}{p_T} = 15\%$
b-jets	$\frac{\Delta p_T}{p_T} = 15\%$ b efficiency $= 60$ % c mistag $= 20$ %
b-jets (for λ_3)	$\frac{\Delta p_T}{p_T} = 10\%$ b efficiency $= 76$ % c mistag $= 20\%$

Timing:

30-60 ps VXD
100 ps XCALs

(comparable to HL-LHC)

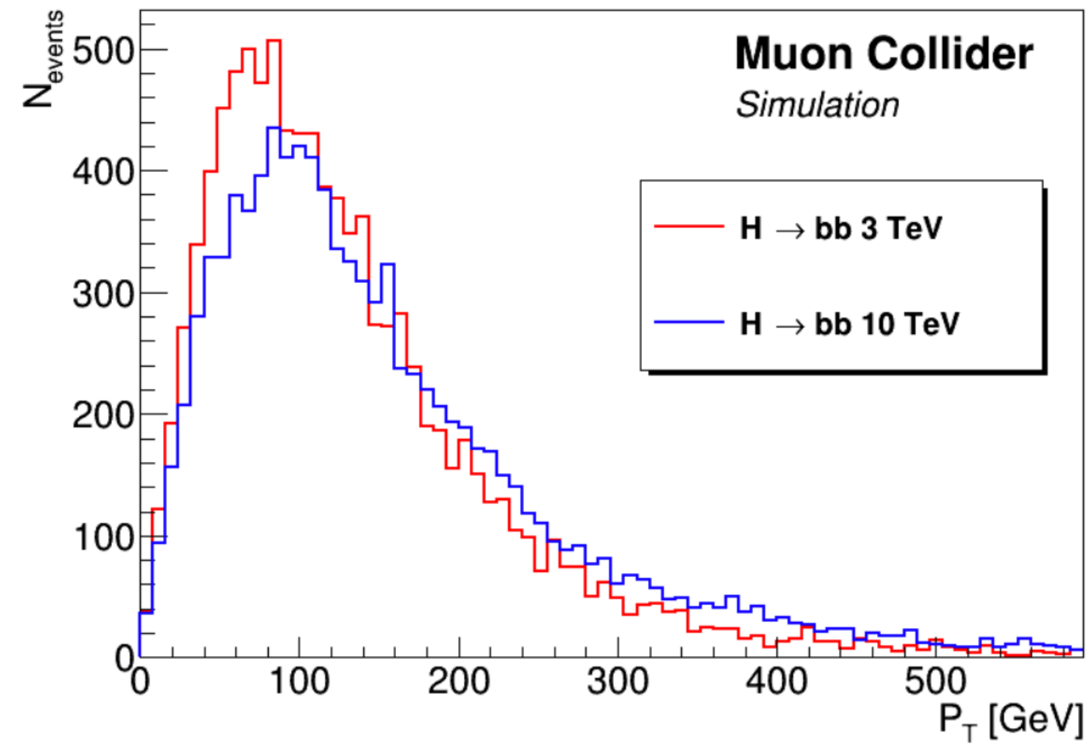


Figure 16 Transverse momenta of b-quarks from the $H \to b\bar{b}$ decay, at $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV muon-muon collisions, determined with Madgraph [58].

Ongoing 10 TeV Studies. Similar requirements expected due to similar kinematics.

1. Higgs Precision

- Status:

P. Andreetto et al, arXiv:2405.19314

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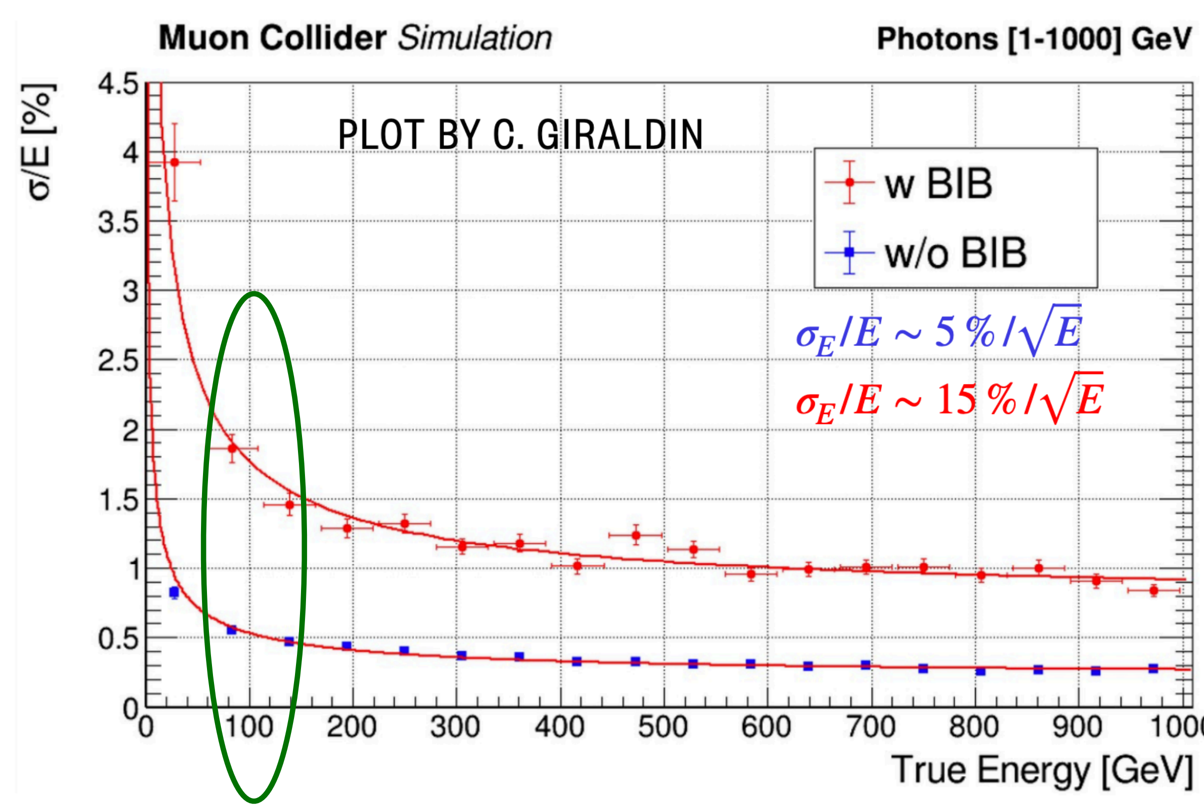
Photon reconstruction better than the target by a factor of ~2



1. Higgs Precision

- Status:

Jet reconstruction does not look as good

P. Andreetto et al, arXiv:2405.19314

3 TeV Study

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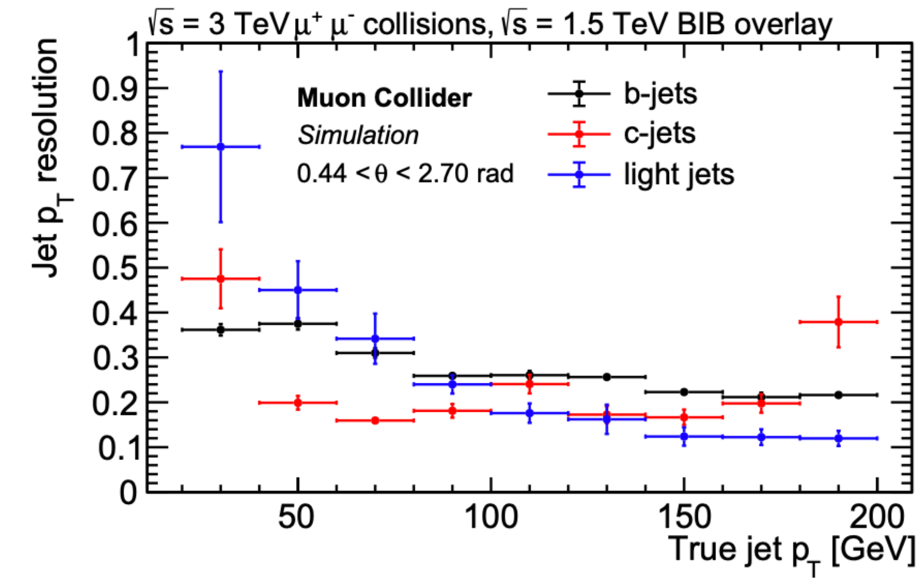
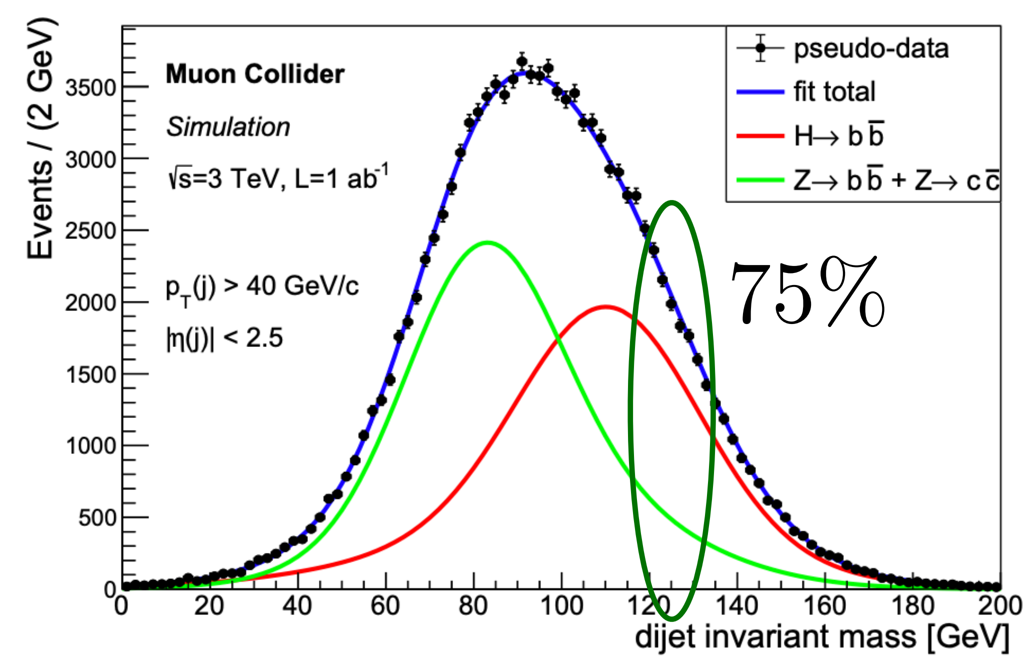


Fig. 58 Jet p_T resolution as a function jet p_T for b-jets, c-jets and light jets in the central region $0.44 < \theta < 2.70$. The differences between the jet flavours are mainly due to different jet θ distributions in the three samples.



C. Accettura et al., Eur. Phys. J. C 83 (2023) 9, 864

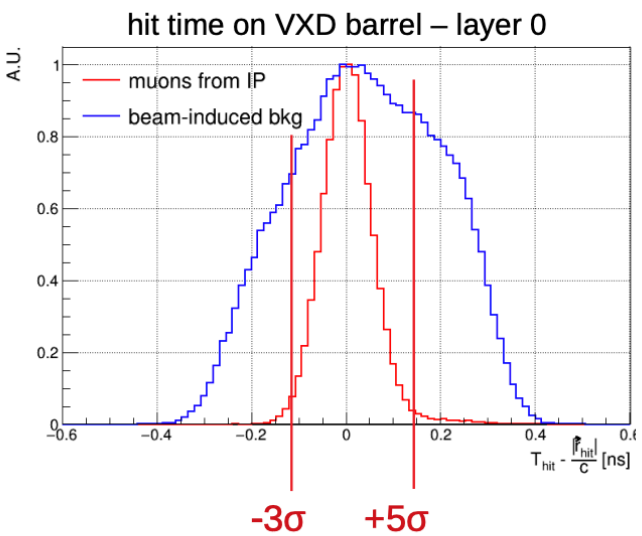
1. Higgs Precision

- Prospects:

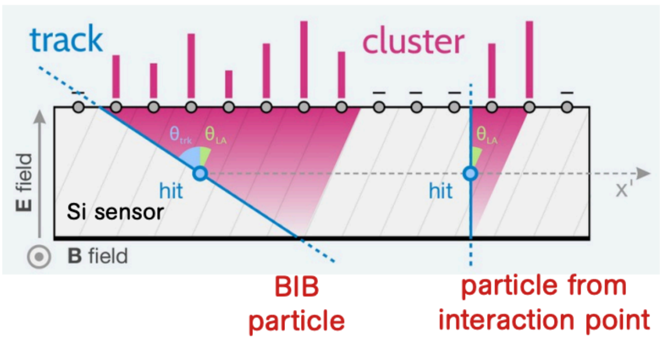
Keys for improvement

Tracker

high-precision timing

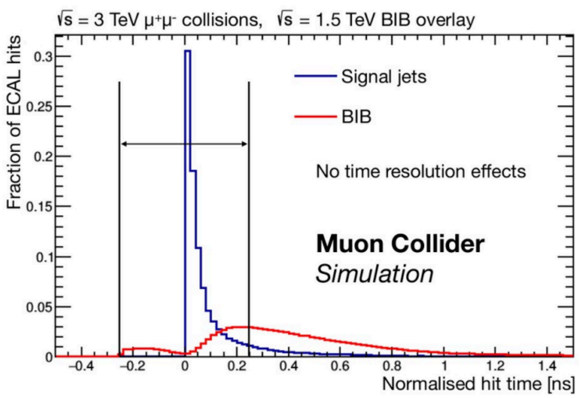


shape and size of pixel clusters

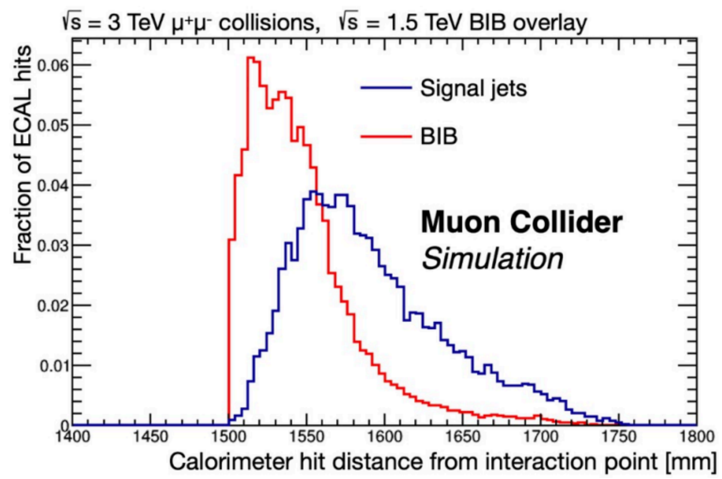


Calorimeter

time of ECAL barrel hits



shower profile of signal jets vs bkg



Ongoing R&D (DRD3)

- Silicon LGAD sensors for 4D tracking up to very high fluence:
  - V. Sola et al., Nucl. Instrum. Meth. A 1040 (2022) 167232.

prototype with new LGAD design funded by INFN-CSN5 and AIDAinnova grants

Project funded also by an EU ERC Consolidator Grant.

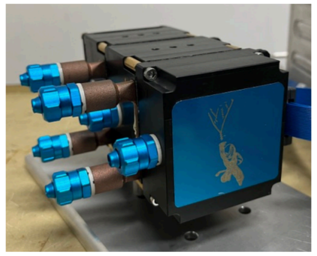
C. Accettura et al., Eur. Phys. J. C 83 (2023) 9, 864

M. Casarsa Detector concepts/ requirements for a Muon Collider - L'INFN e la Strategia Europea per la Fisica delle Particelle - May 7, 2023

More info: Weekly MDI meetings
(Contact Donatella Luchesi)

Ongoing R&D (DRD6)

- Semi-homogeneous electromagnetic calorimeter based on lead fluoride crystals (CRILIN):
  - S. Ceravolo et al., Nucl. Instrum. Meth. A 1047 (2023) 167817.



2-layer 3x3-crystal CRILIN prototype funded by INFN

- Hadronic calorimeter based on Micro-Pattern Gaseous Detectors:
  - C. Aruta et al., Nucl. Instrum. Meth. A 1047 (2023) 167731.

Funding from the Italian Ministry for Universities and Research ("PRIN") to build an integrated ECAL-HCAL prototype.

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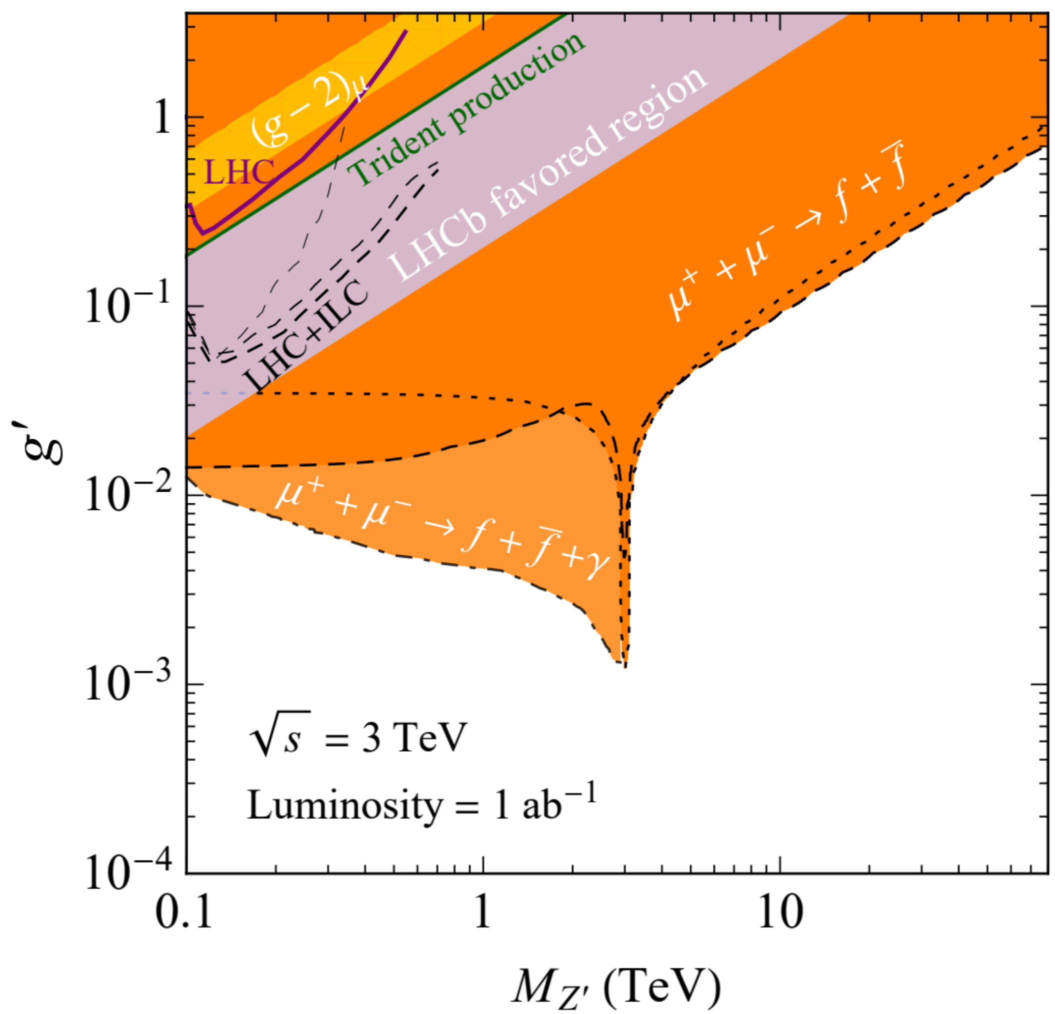
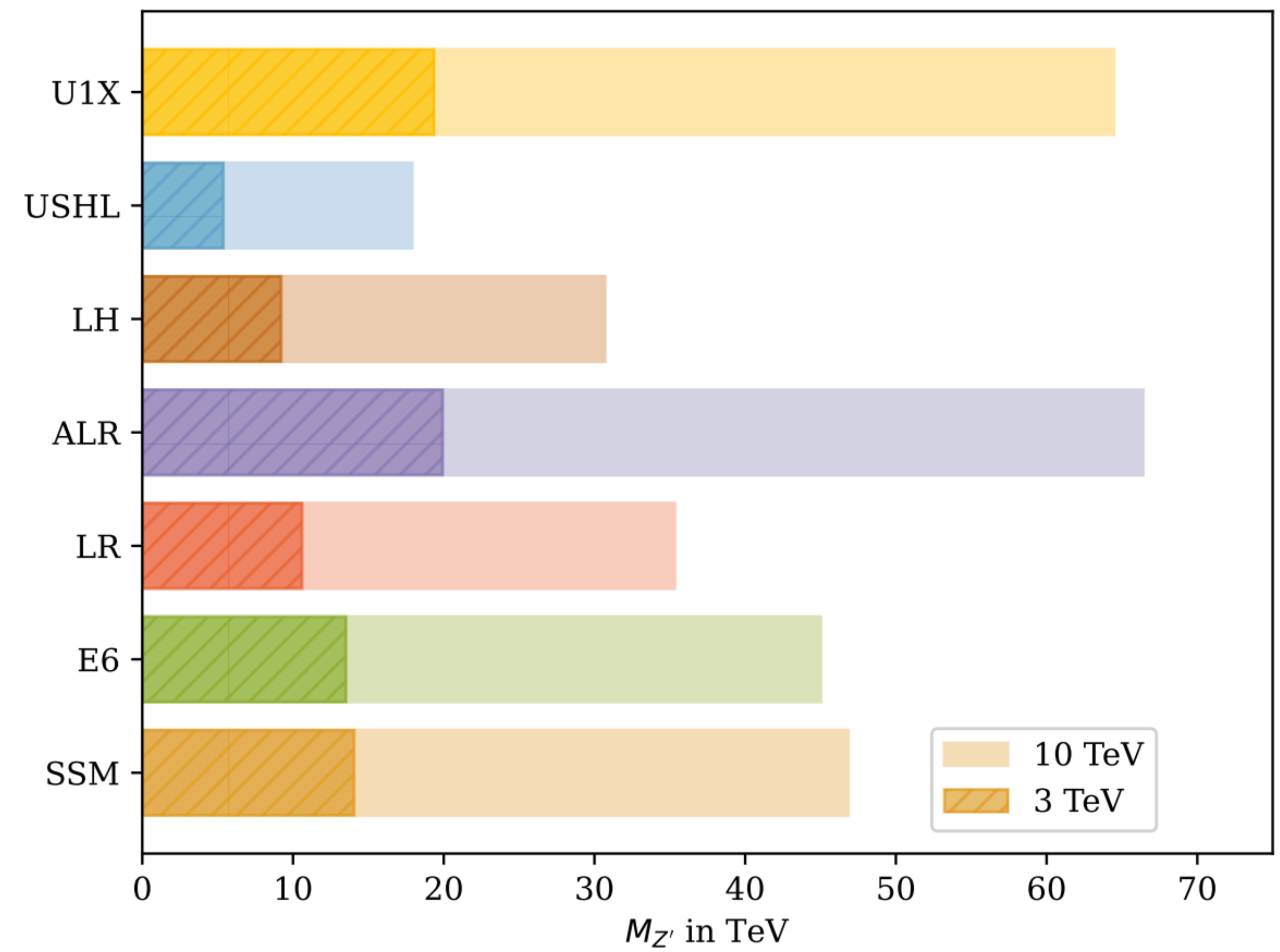
2. Heavy Resonances

- Theory Target: Heavy Resonances





Huang, Queiroz, Rodejohann, Phys. Rev. D 103 (2021) 9, 095005
Korshynska et al., Eur. Phys. J. C 84 (2024) 6, 568
Davide Zuliani, Detector concept at 10 TeV,
Accelerator design meeting

- Direct Z' searches up to M~Ecm.
- Indirect Z' searches up to M ~ 2-6 Ecm.

2. Heavy Resonances

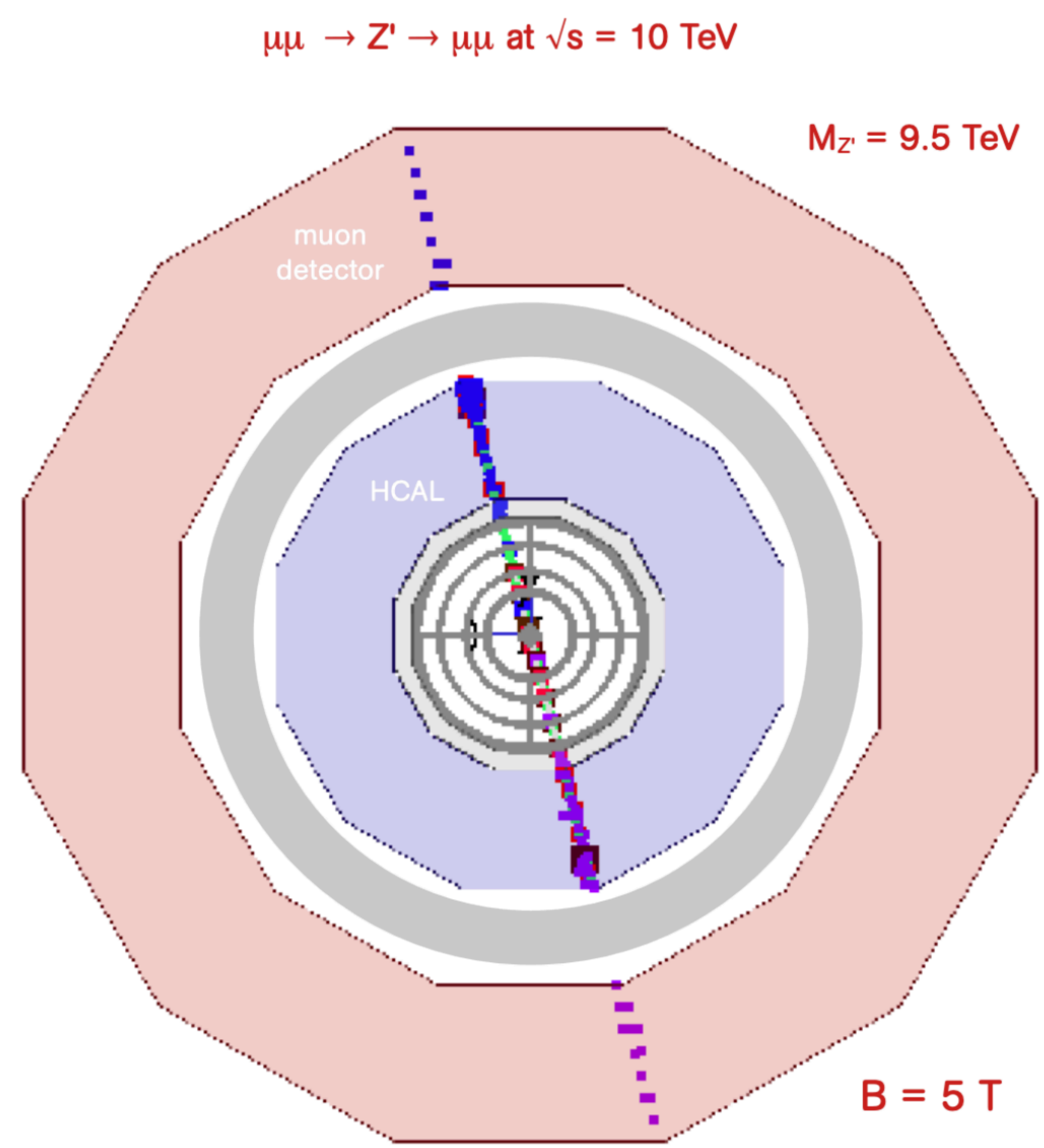
- Experimental Target:

Tracking

$$R \sim \frac{p_T}{0.3B}$$

$$R(p_T = 0.2\,\mathrm{GeV},\ B = 4T) \sim 16\,\mathrm{cm}$$
$$R(p_T = 10\,\mathrm{GeV},\ B = 4T) \sim 8.4\,\mathrm{m}$$
$$R(p_T = 5.0\,\mathrm{TeV},\ B = 4T) \sim 4.2\,\mathrm{km}$$

We need to be able to bend ~3-5 TeV particles to measure their momentum with high precision



Davide Zuliani, Detector concept at 10 TeV, Accelerator design meeting

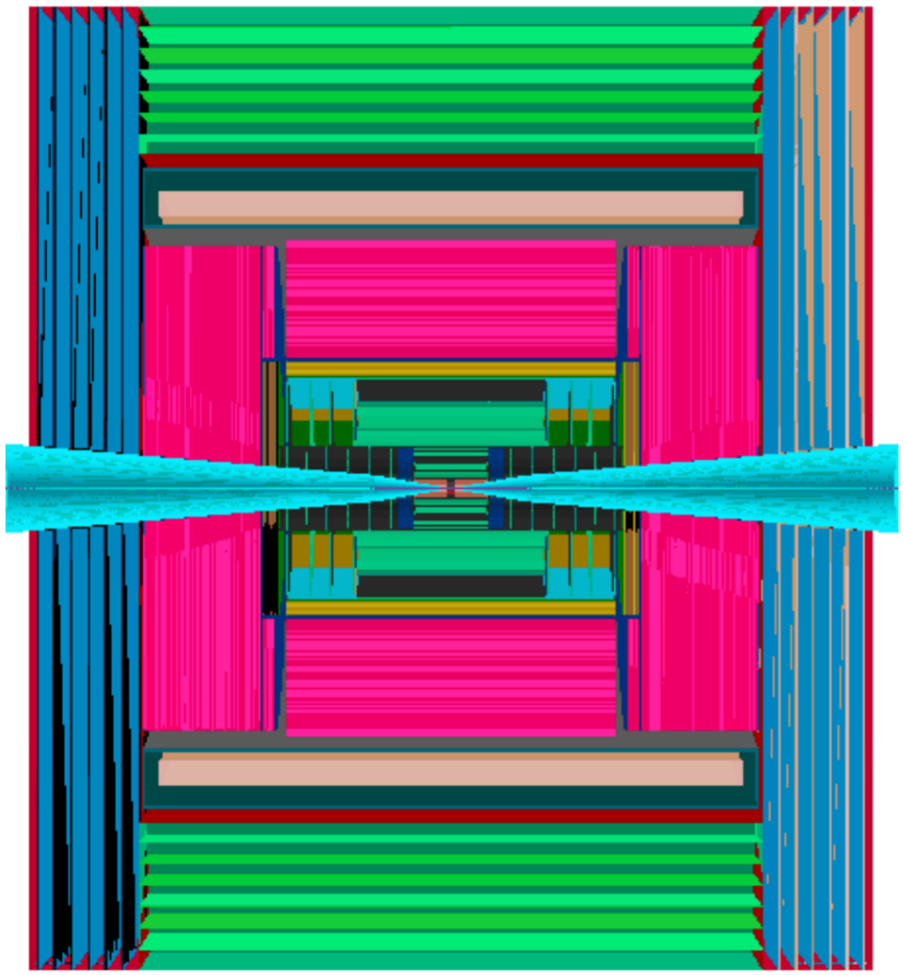
Rodolfo Capdevilla, Fermilab

2. Heavy Resonances

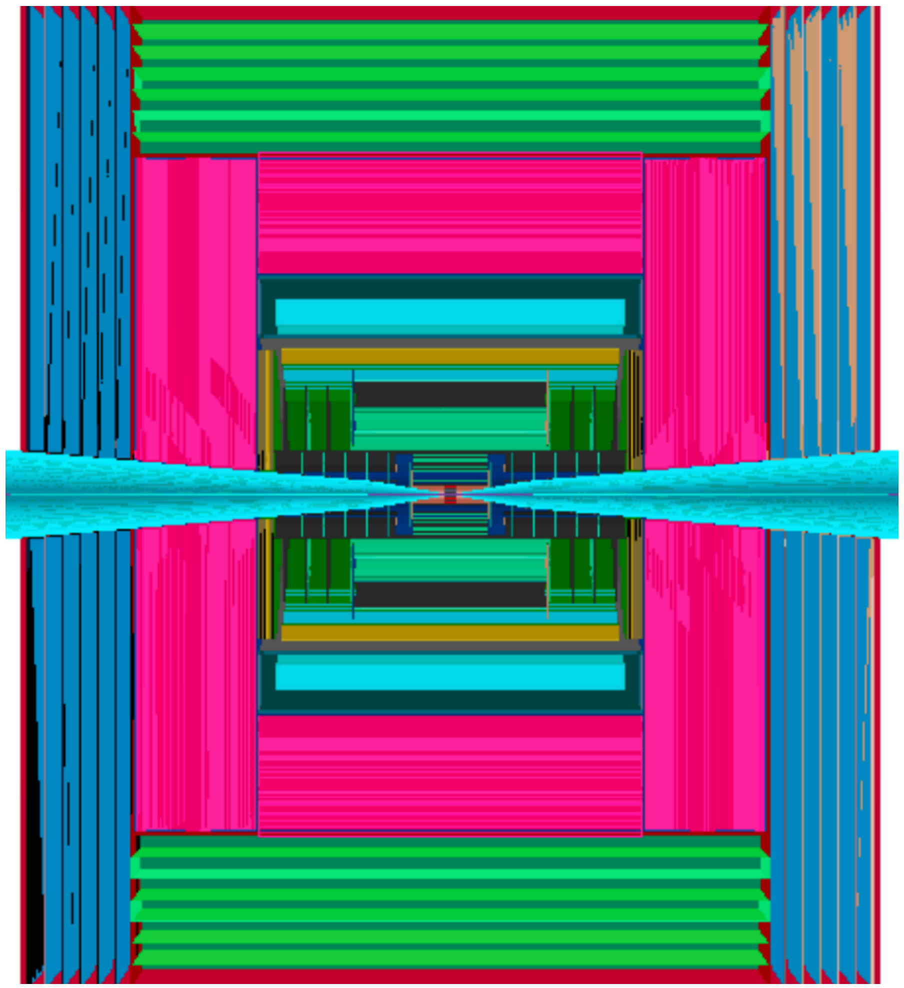
- Status:

Where to place the solenoid?

MuColl_v1 (3 TeV configuration)



MUSIC



Davide Zuliani, Detector concept at 10 TeV, Accelerator design meeting

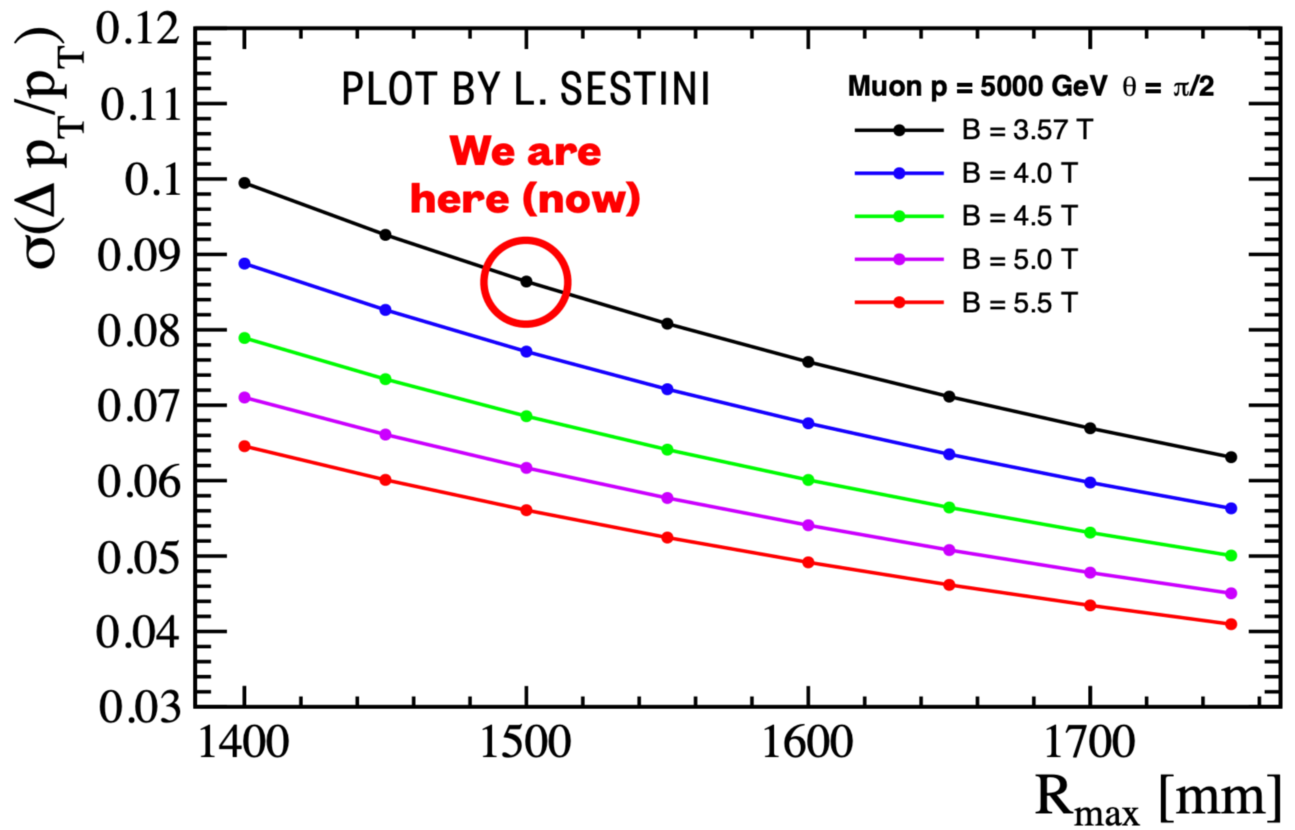
New detector concepts **MUSIC** and **MAIA** place the solenoid before the calorimeters for better resolution of multi-TeV tracks

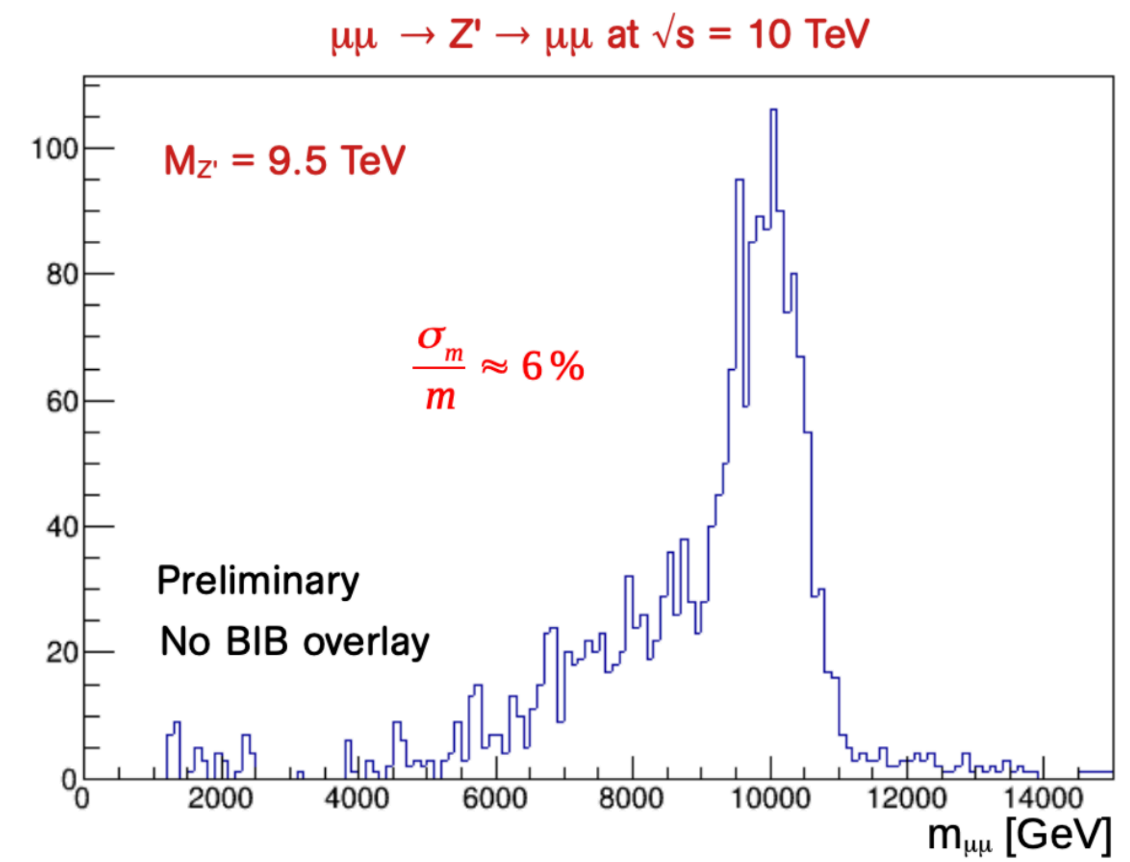
More info: Larry's and Kiley's talks (Contact them, or Tova)

2. Heavy Resonances

- Status:

Tracking





Davide Zuliani, Detector concept at 10 TeV, Accelerator design meeting

- Momentum resolution ~9%
- Mass resolution ~6%

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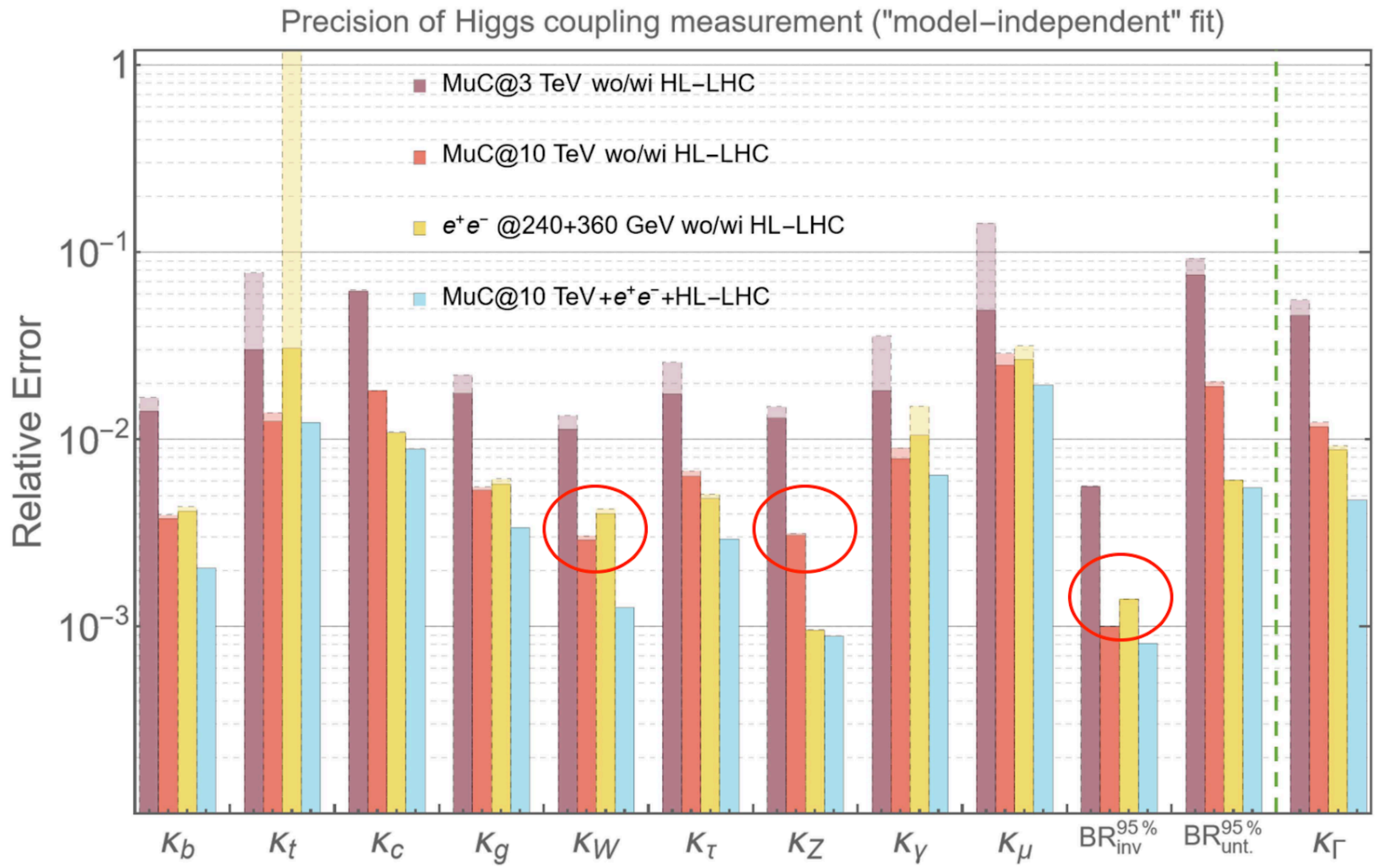
3. Forward Physics

- Theory Target: Invisible Higgs and ZZH/WWH couplings

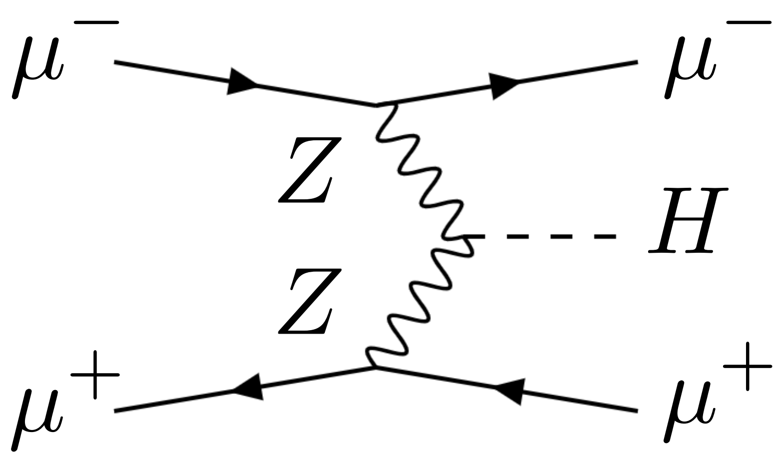


Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185
Ruhdorfer, Salvioni, Wulzer, PRD 107 (2023) 9, 095038
Matthew Forslund, Patrick Meade, JHEP 01 (2024) 182
Li, Liu, Lyu, PRD 109 (2024) 7, 073009

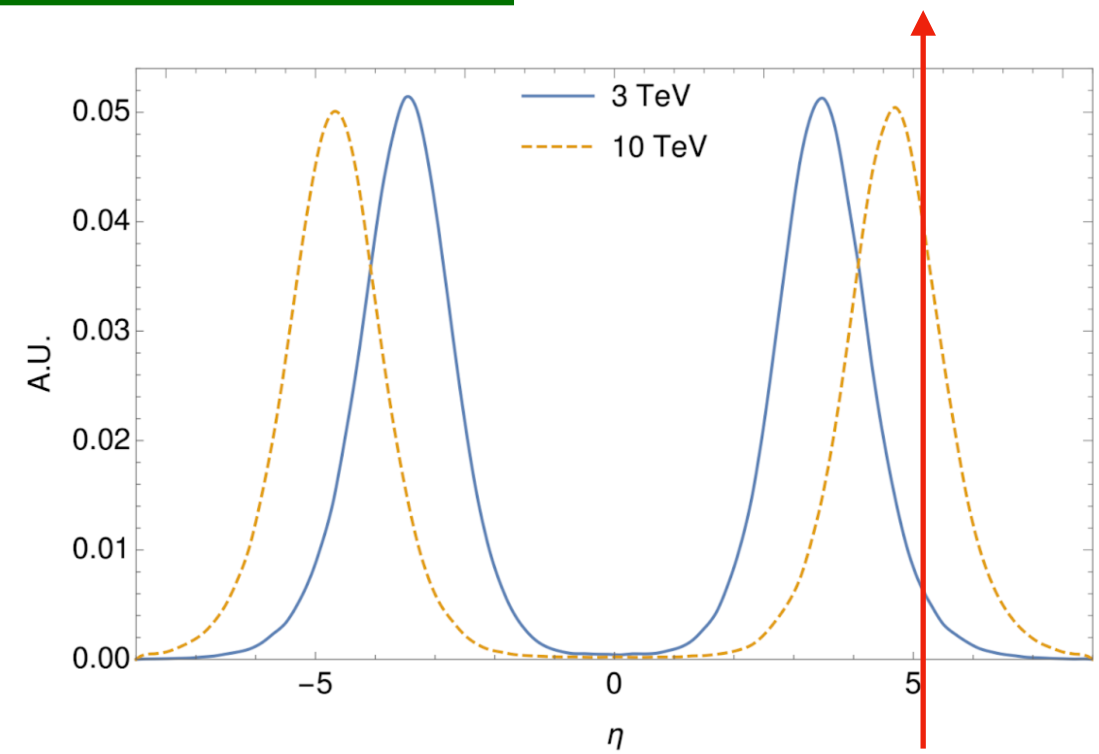
- BR(inv) comparable to a Higgs factory!
- ZZH coupling comparable to WWH

3. Forward Physics

- Experimental Target:

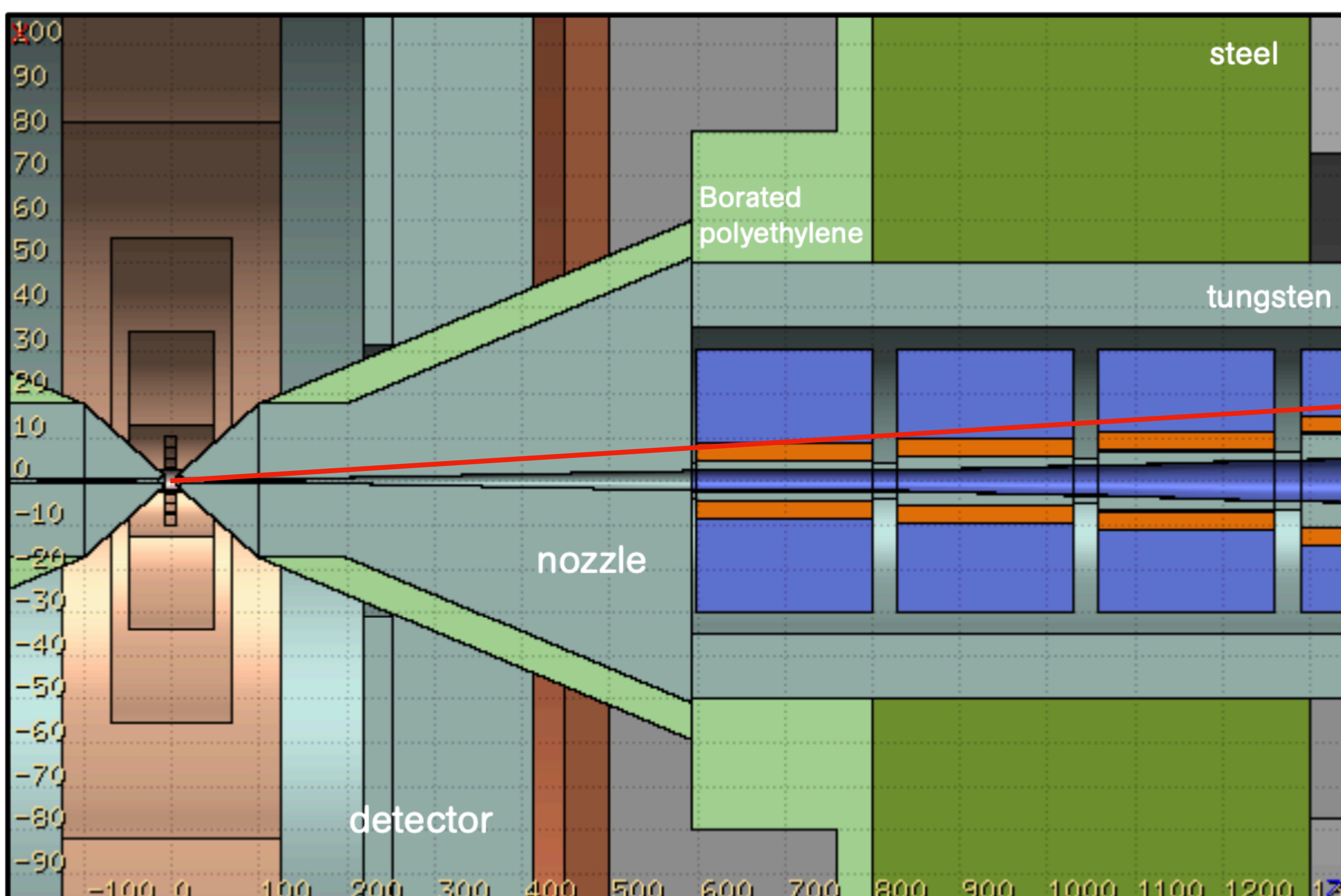


Detector coverage



Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185

Challenging target!



$$\sim 13\,\mathrm{mrad}$$

$$\eta \sim 5.036$$

Rodolfo Capdevilla, Fermilab

3. Forward Physics

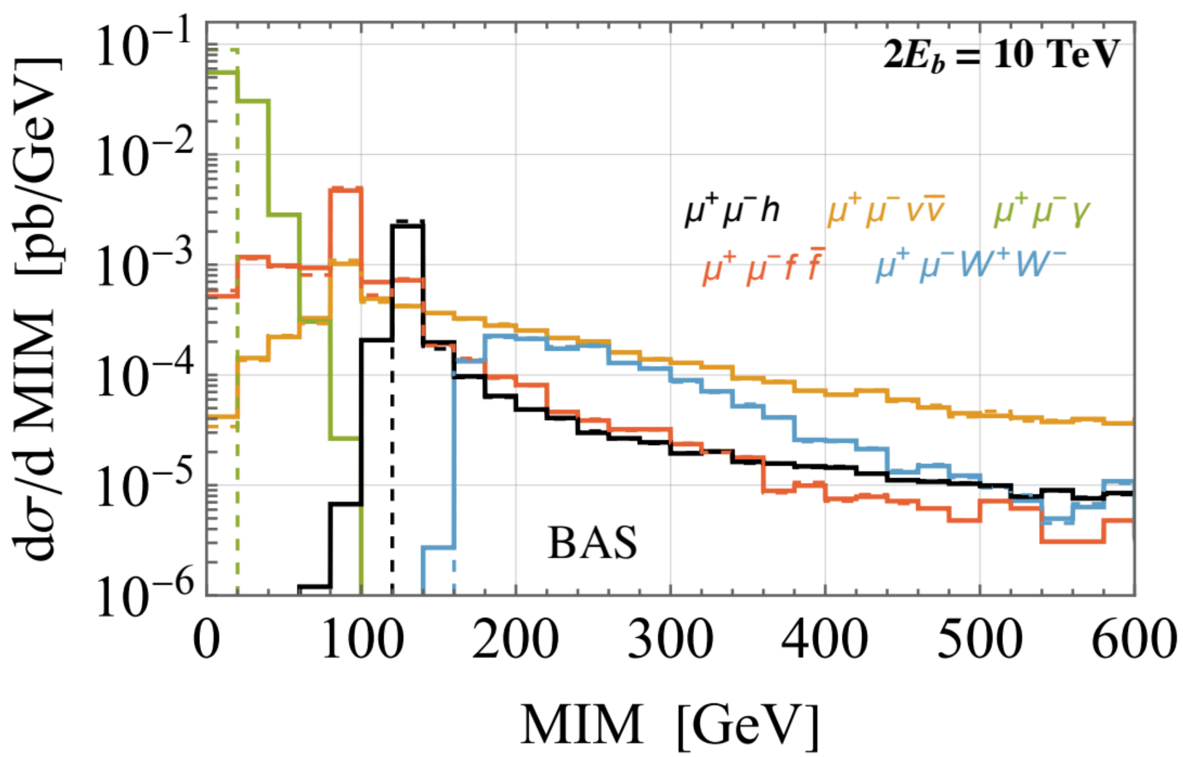
- Experimental Target:

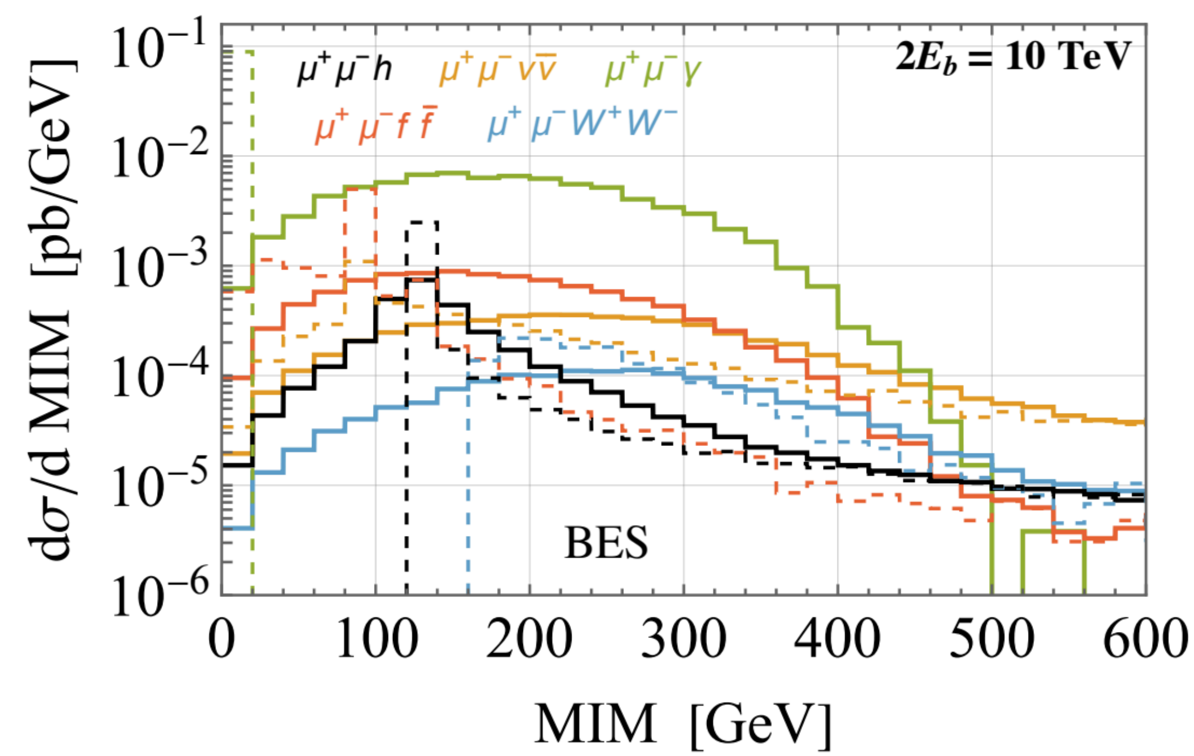
Beam parameters

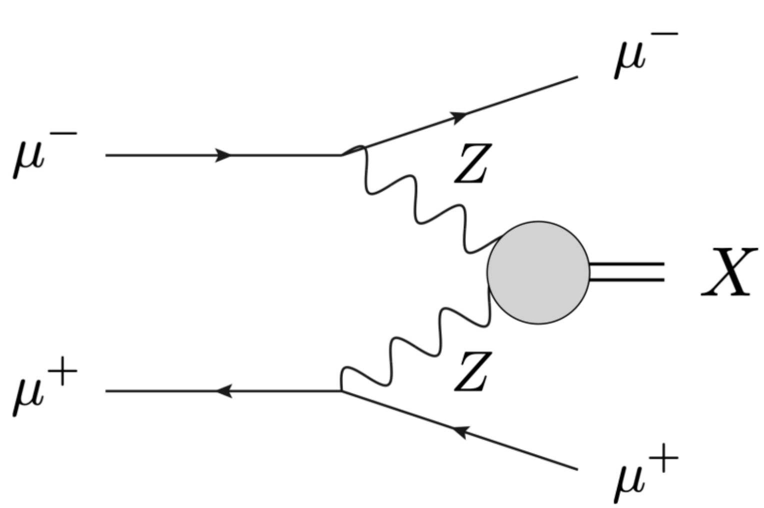
Ruhdorfer, Salvioni, Wulzer, Phys. Rev. D 107 (2023) 9, 095038

Beam Angular Spread: $0.6\,\mathrm{mrad}$

Beam Energy Spread: $0.1\,\%$







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

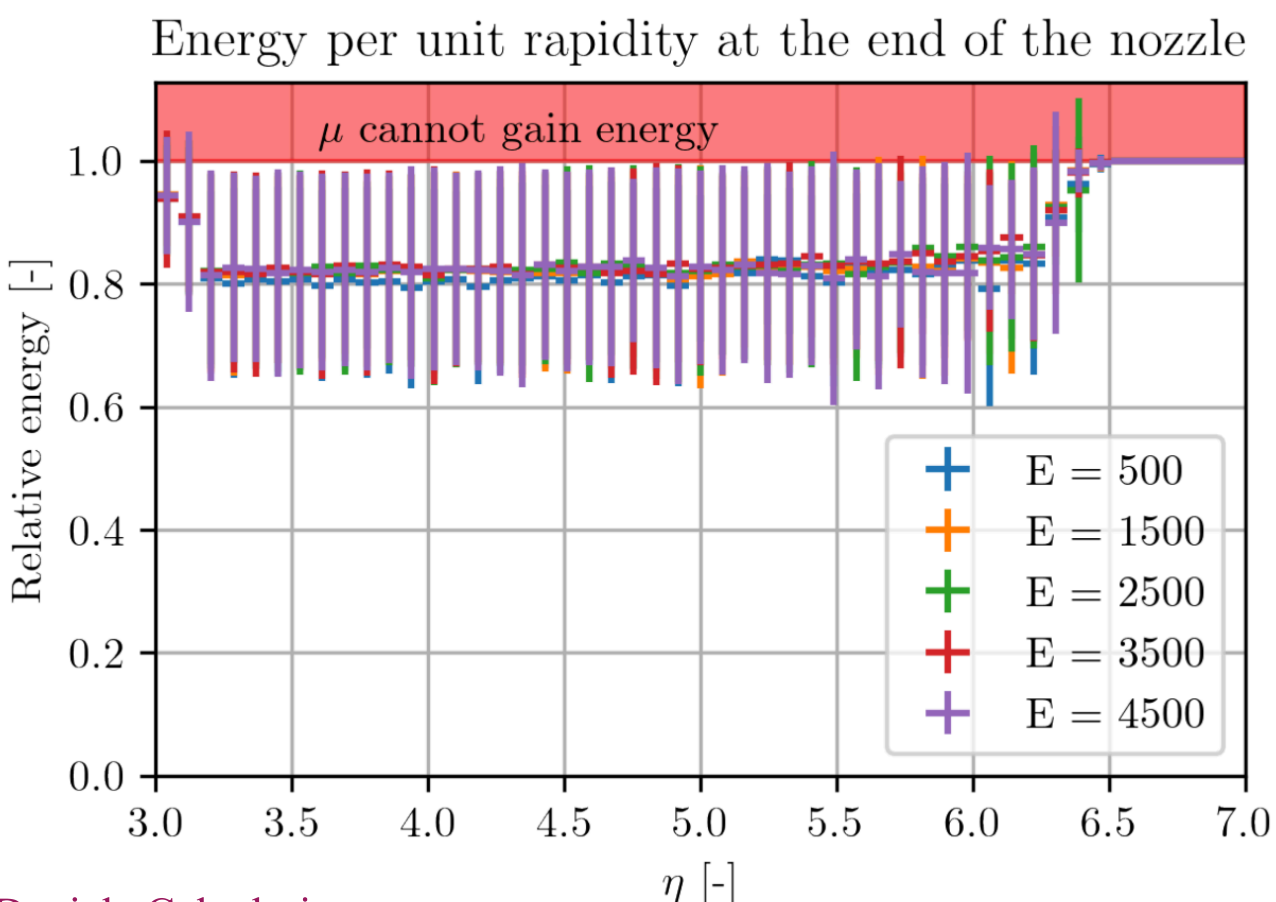
$$\Delta P = (2E_{\mathrm{b}}, \vec{0}\,) - p_{\mu^+} - p_{\mu^-}$$

Need to maintain reasonable energy spread

- Status:

Forward muon parameters

Muon Energy Resolution:



Daniele Calzolari

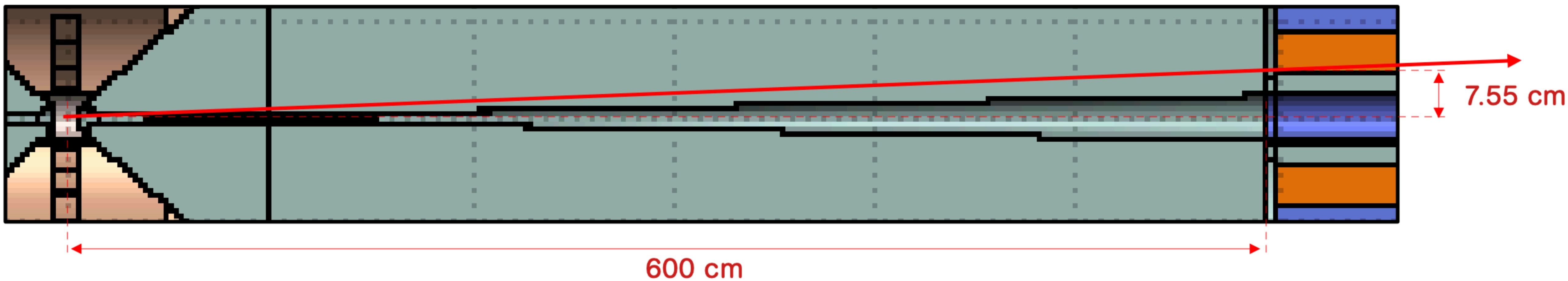
M. Casarsa Forward detector and nozzle instrumentation - IMCC and MuCol MDI Workshop 2024 - March 12, 2024

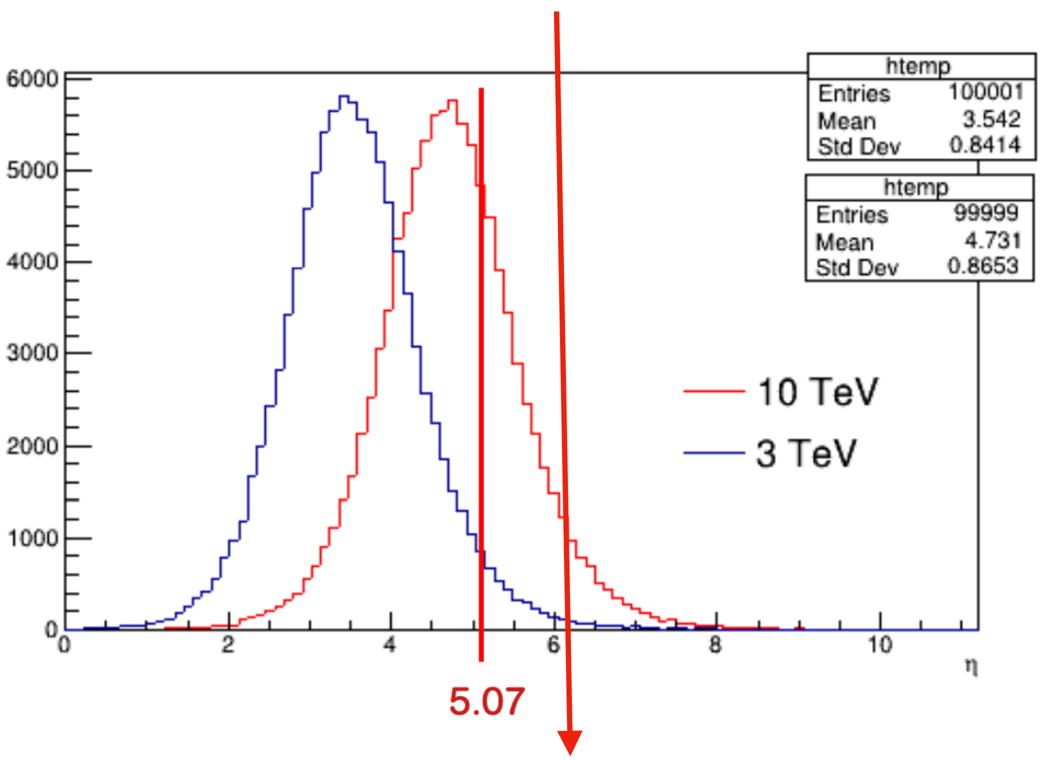
Muons entering the nozzles pass through ~6 m of tungsten and lose on average ~20% of their energy.

3. Forward Physics

- Status:

Detector coverage





Back inside the pipe?

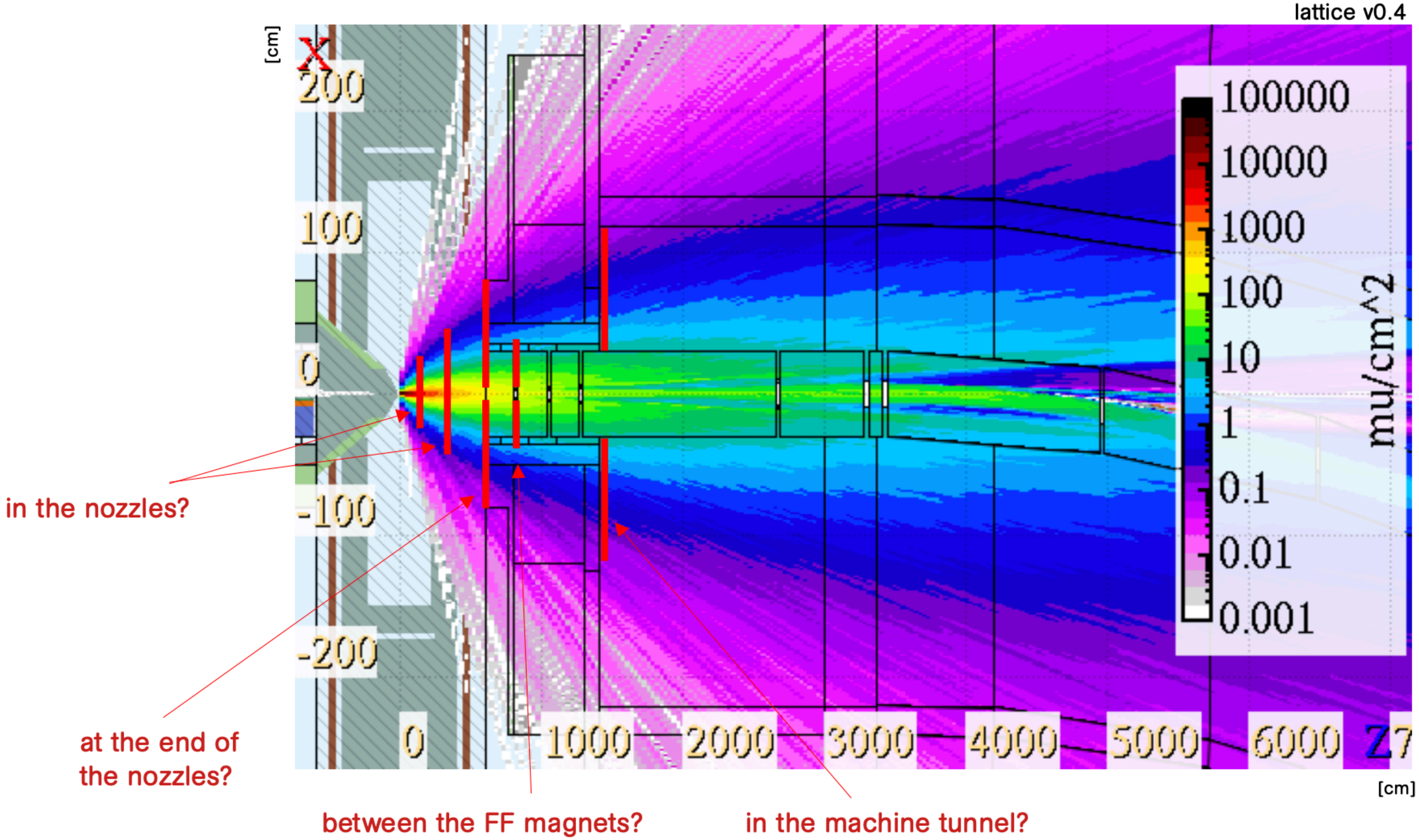
M. Casarsa Forward detector and nozzle instrumentation - IMCC and MuCol MDI Workshop 2024 - March 12, 2024

Muons above eta~6.2 will end up back inside the pipe

3. Forward Physics

- Prospects:

Nozzle instrumentation?



Explore the possibility of instrumenting the nozzle or even components in the machine tunnel!

M. Casarsa Forward detector and nozzle instrumentation - IMCC and MuCol MDI Workshop 2024 - March 12, 2024

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4. Long-Lived Particles

- TheoryTarget: LLP (Minimal Dark Matter et al.)

EW multiplets $SU(3)_c \times SU(2)_L \times U(1)_Y$

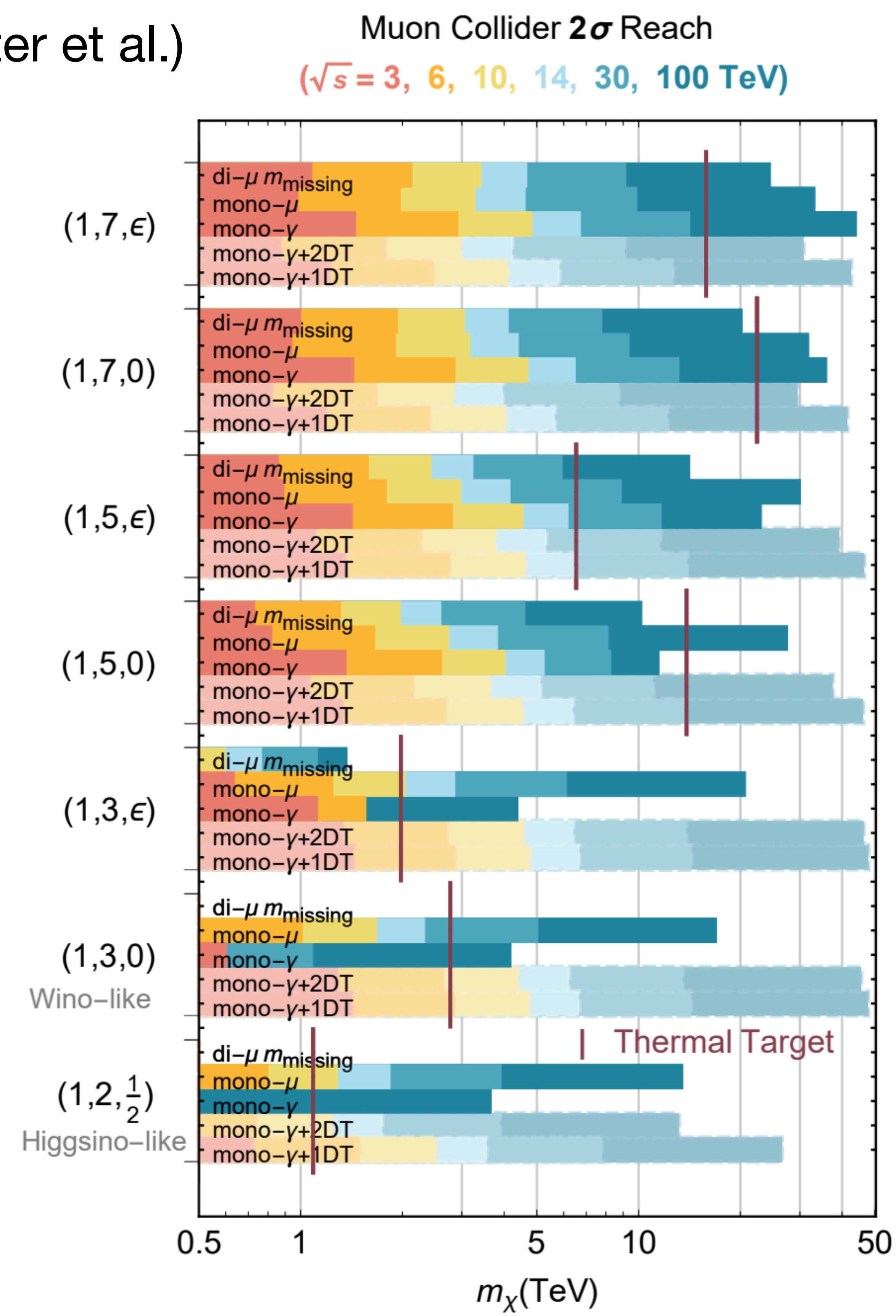
$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^{+}_{\tilde{H}} \\ \chi^{0}_{\tilde{H}} \end{pmatrix}$$

$(\mathbf{1}, \mathbf{2}, 1/2)$
Higgsino-like

$$\chi_{\tilde{W}} = \begin{pmatrix} \chi^{+}_{\tilde{W}} \\ \chi^{0}_{\tilde{W}} \\ \chi^{-}_{\tilde{W}} \end{pmatrix}$$

$(\mathbf{1}, \mathbf{3}, 0)$
Wino-like

- Doubletsand triplets have a thermal mass within the kinematic reach of the collider.
- Larger multiplets that account for a fraction of the total DM in the Universe can be reached as well.



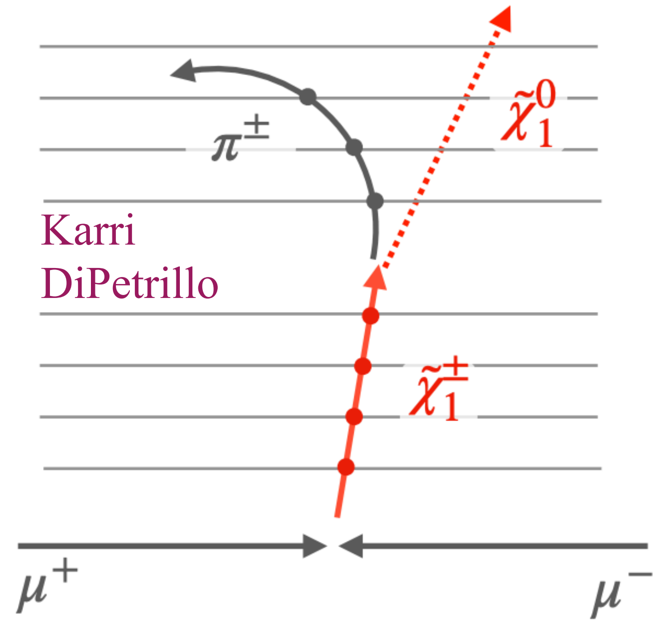
Han, Liu, Wang, Wang, PRD 103 (2021) 7, 075004
RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
Bottaro et al., Eur. Phys. J. C 82 (2022) 1, 31
Bottaro et al., Eur. Phys. J. C 82 (2022) 11, 992
RC, Meloni, Zurita, arXiv:2405.08858

4. Long-Lived Particles

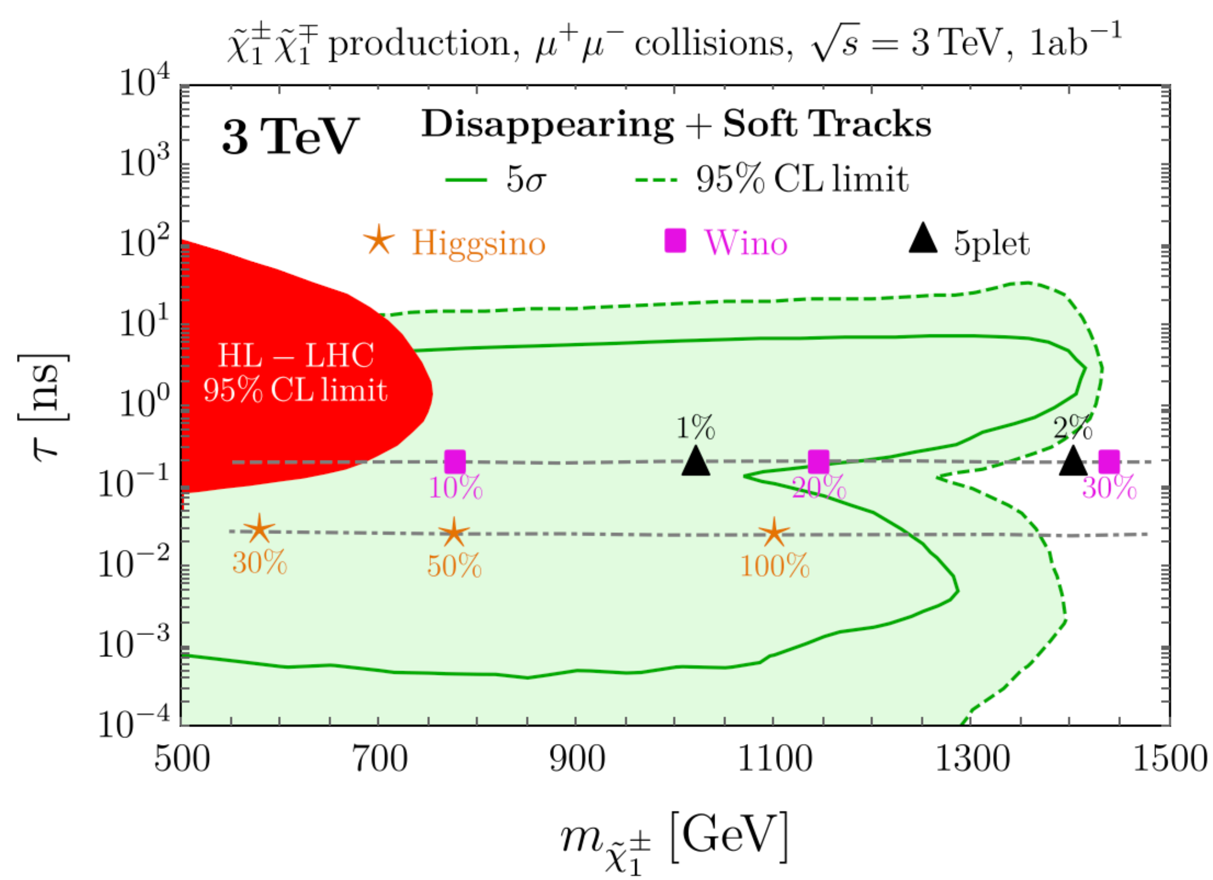
- Theory Target:

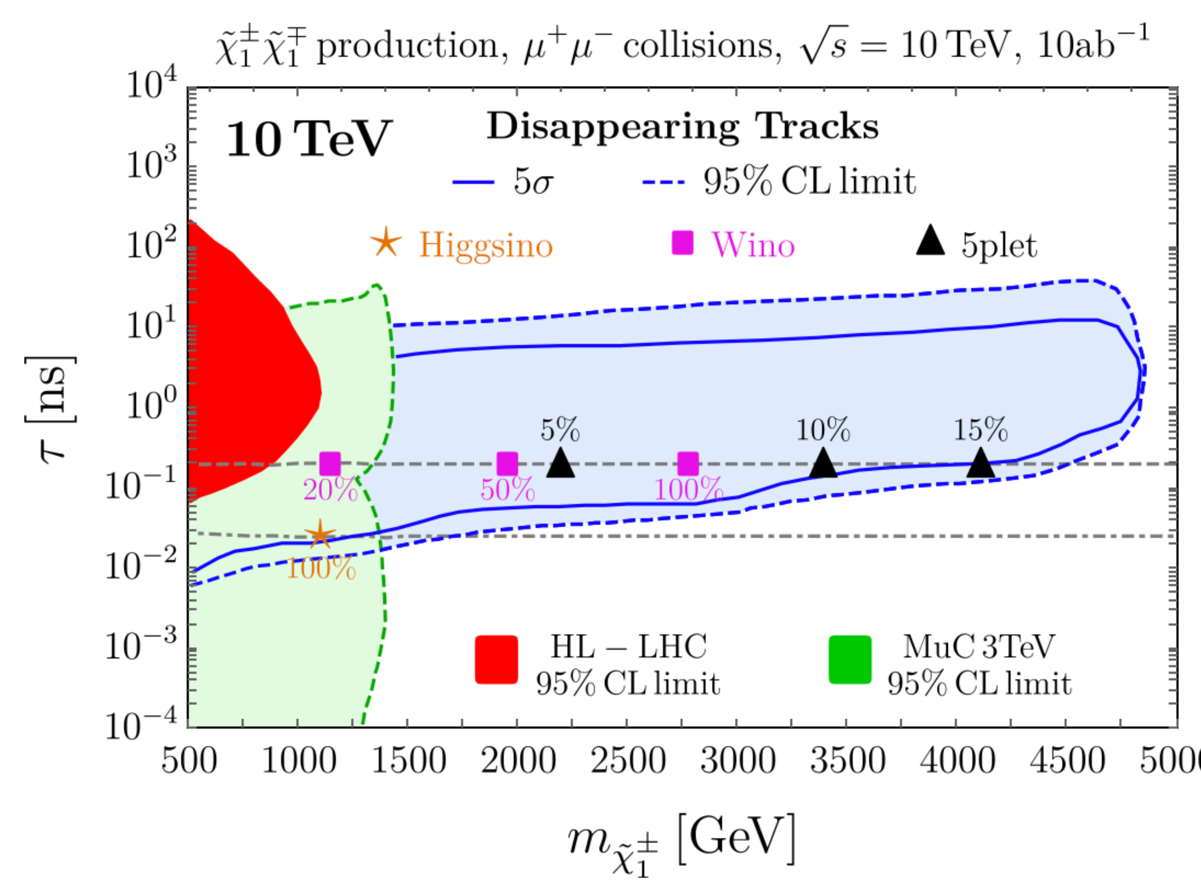
Doublet, Triplets, Fiveplets (10%)

The 3 TeV collider will be able to discover Doublets up to the thermal mass as well as Triplet (20%) and Fiveplet (1%) states.



The 10 TeV collider will be able to discover Triplets up to the thermal mass as well as Fiveplet (12%) states.





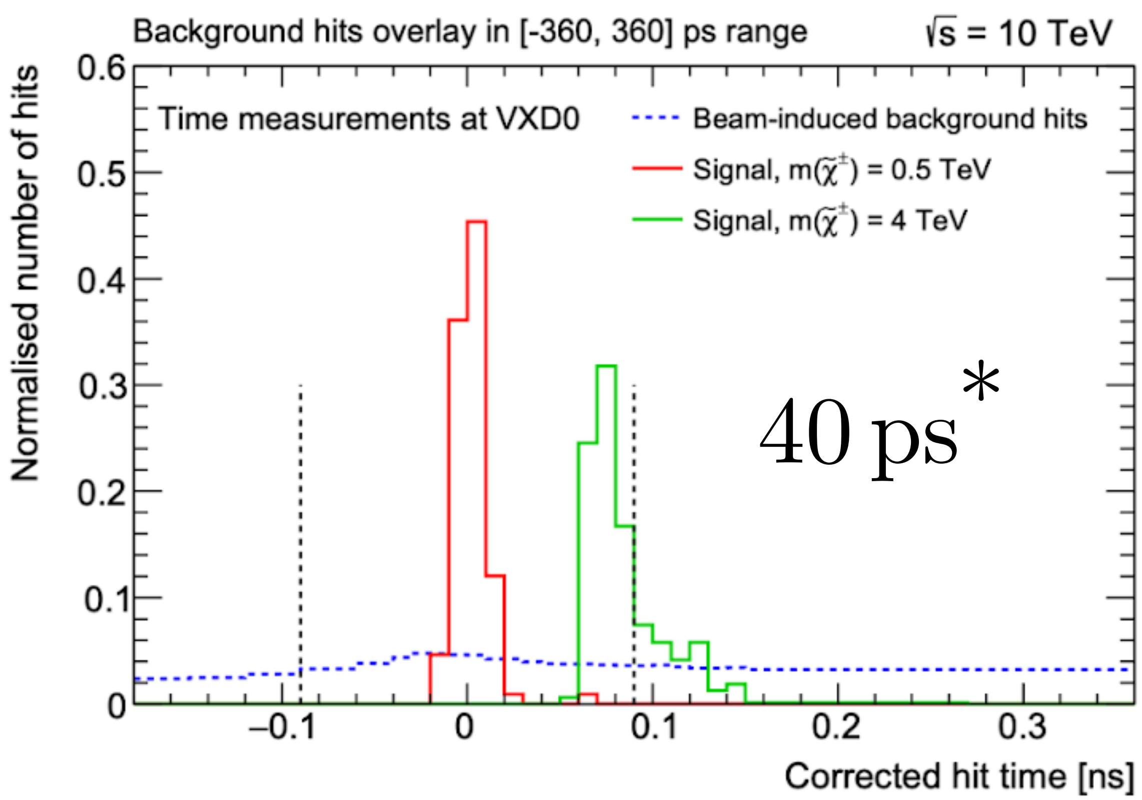
RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
RC, Meloni, Zurita, arXiv:2405.08858

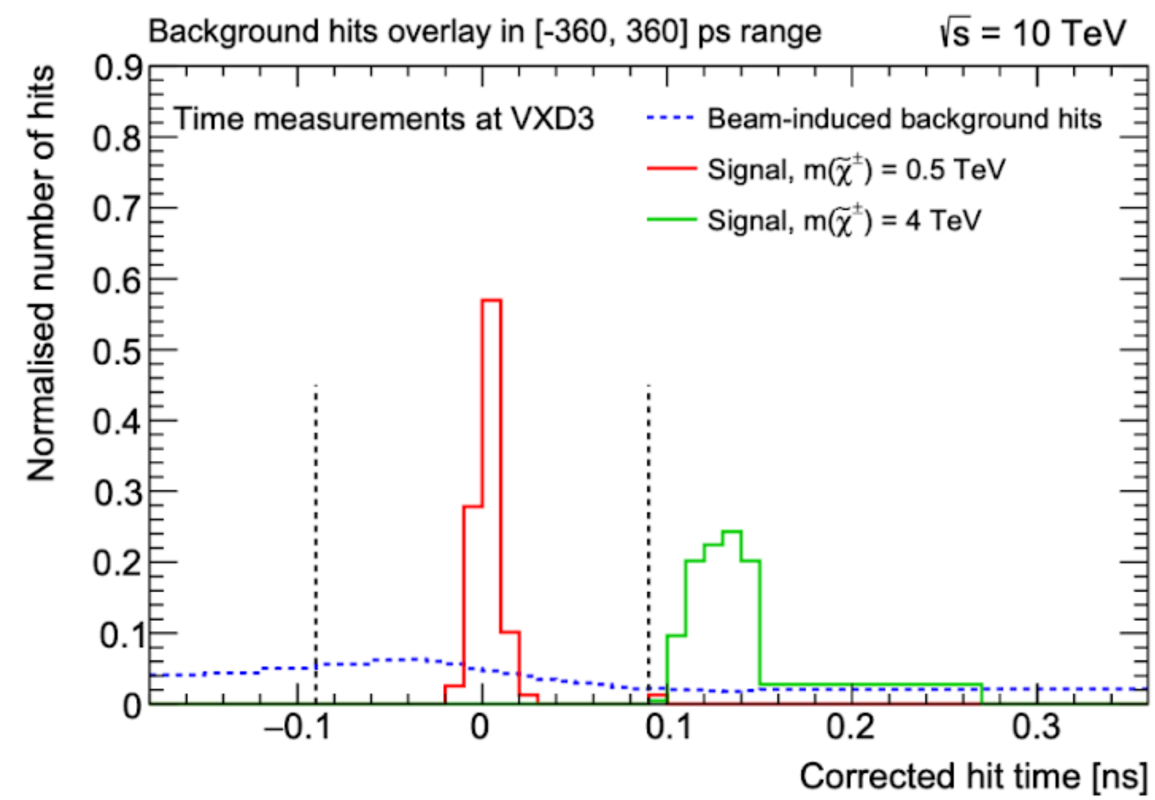
4. Long-Lived Particles

- Experimental Target:

Timing

RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133





Mass-dependent algorithm; time window defined as a function of the mass

Note: Can high timing resolution help to identify the parent particle mass?

$\ast$ Higgs studies assume 30-60 ps

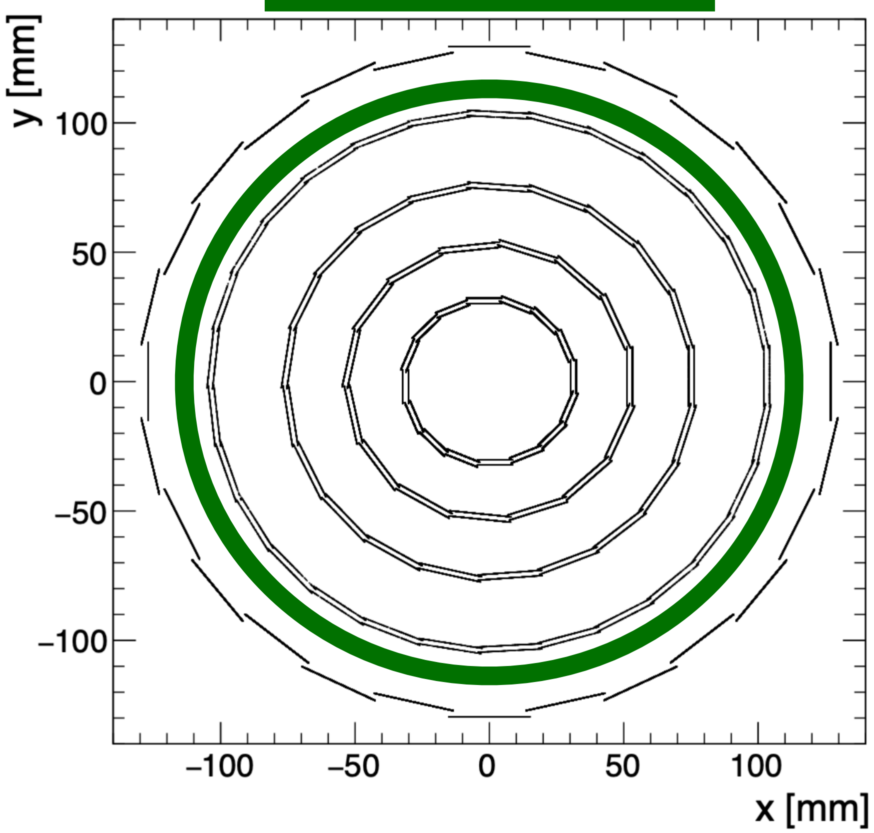
4. Long-Lived Particles

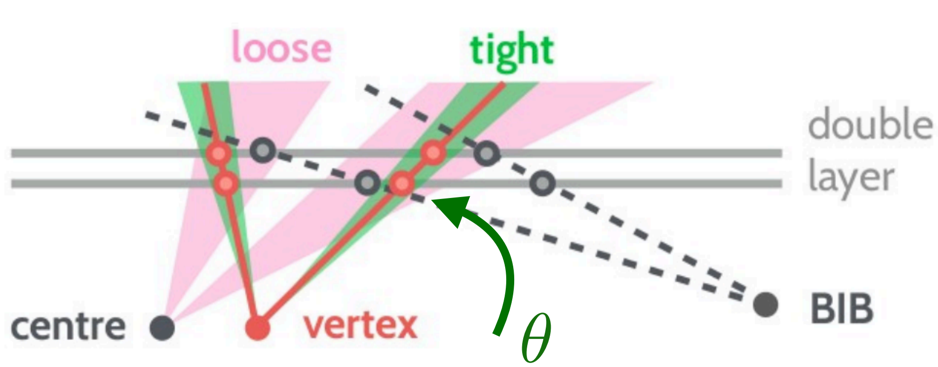
- Experimental Target:

Tracking: angular resolution

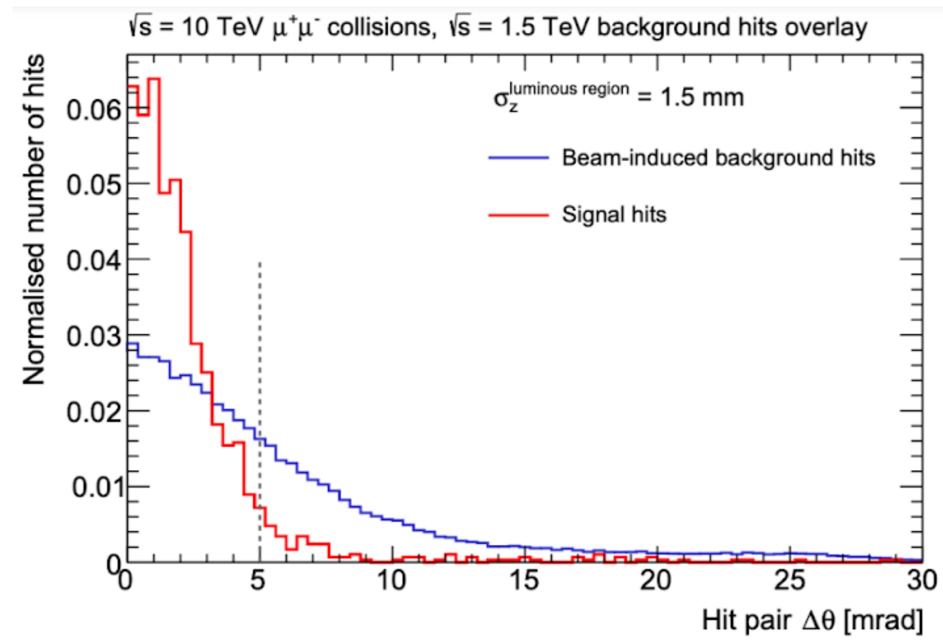
RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133

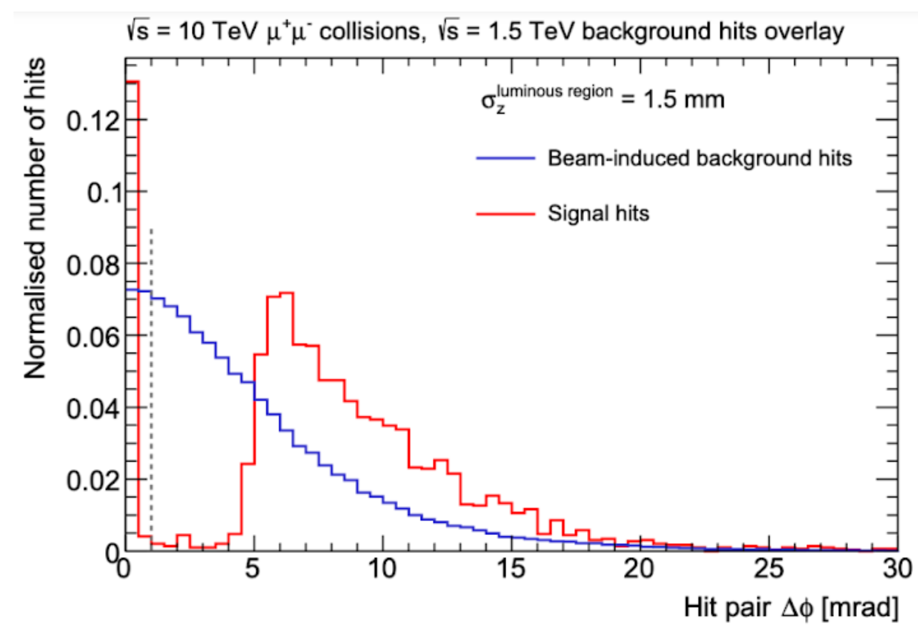
Vertex Detector





Old detector concepts with four double layers and more recent concepts with only one double layer show required performance!



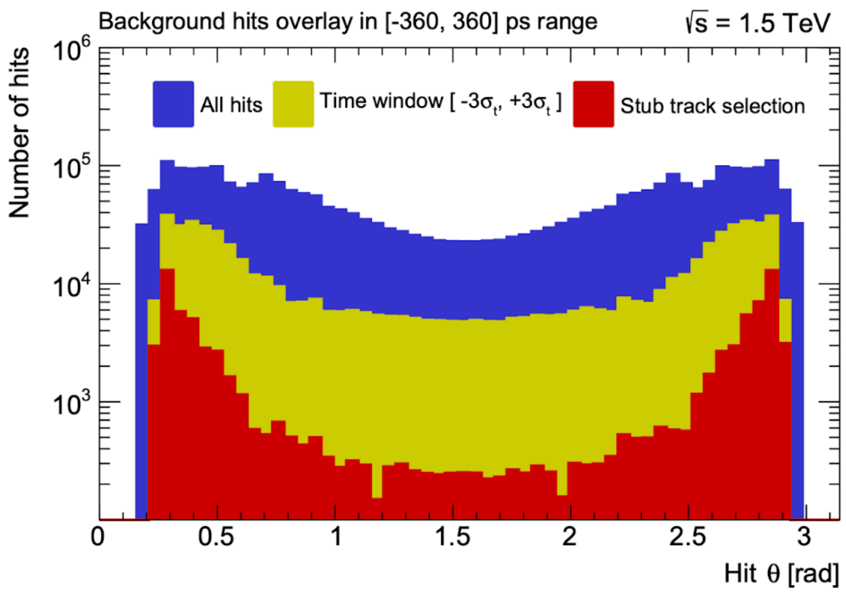


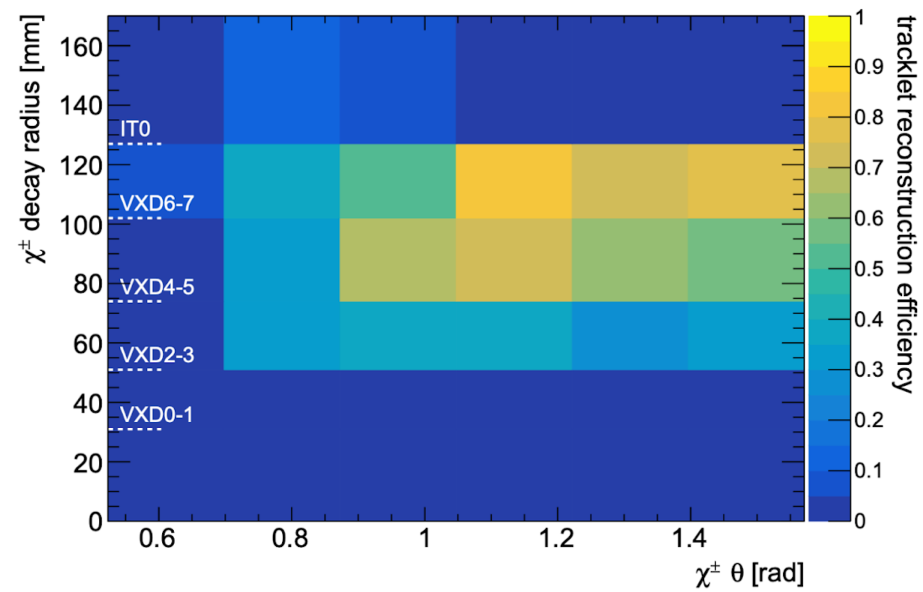
4. Long-Lived Particles

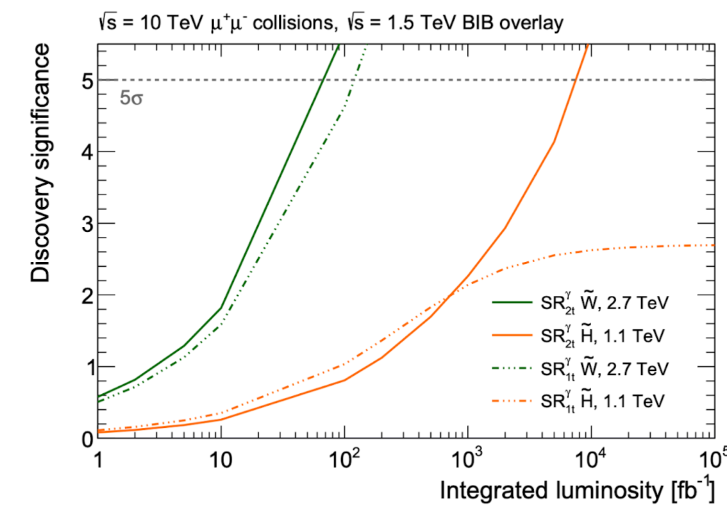
- Experimental Target:

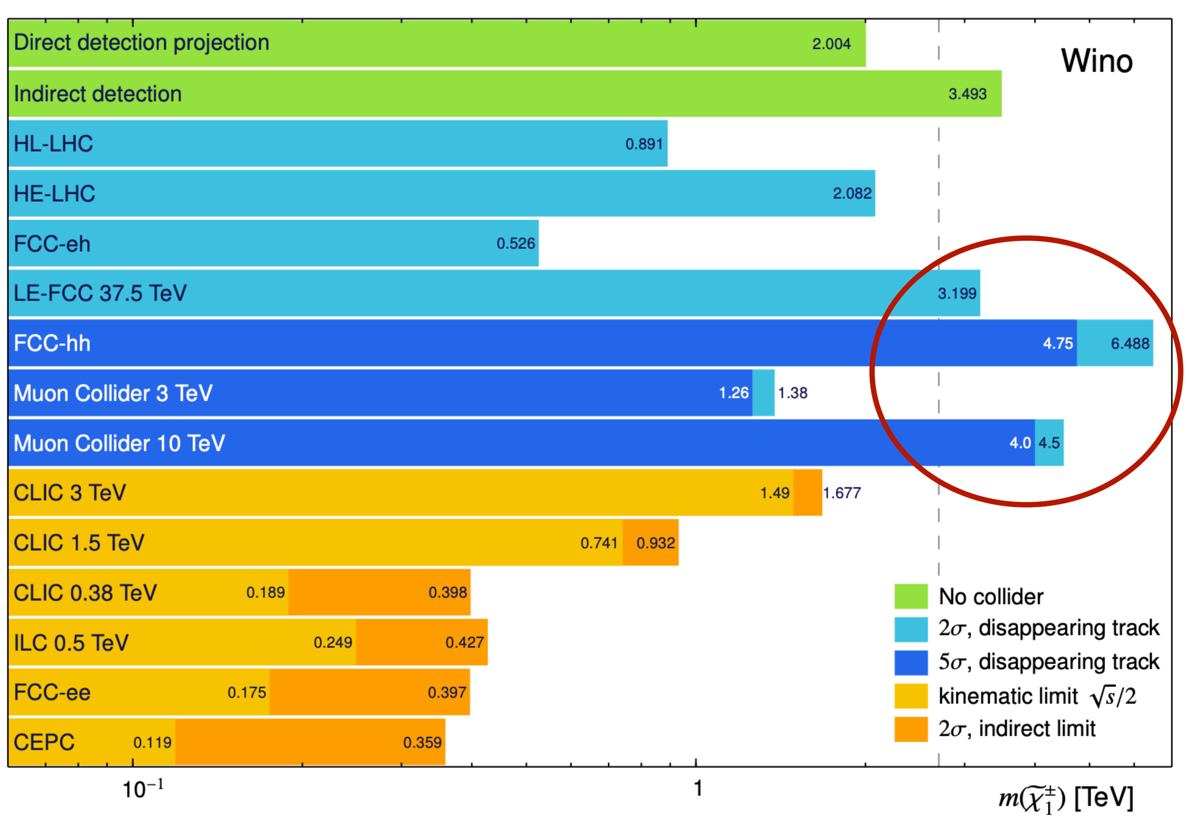
The power of timing + tracking

RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133









Wino is good: Long lifetime

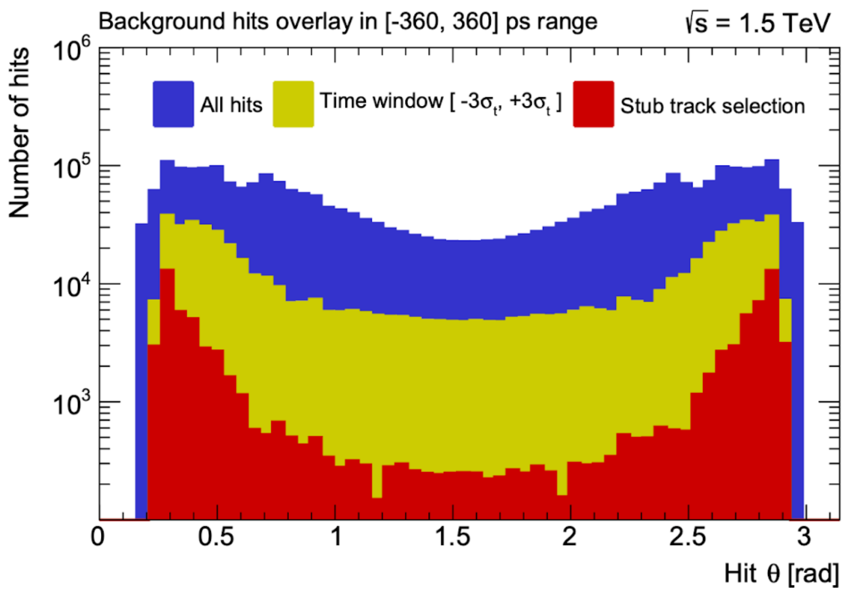
Easily identifiable disappearing tracks!

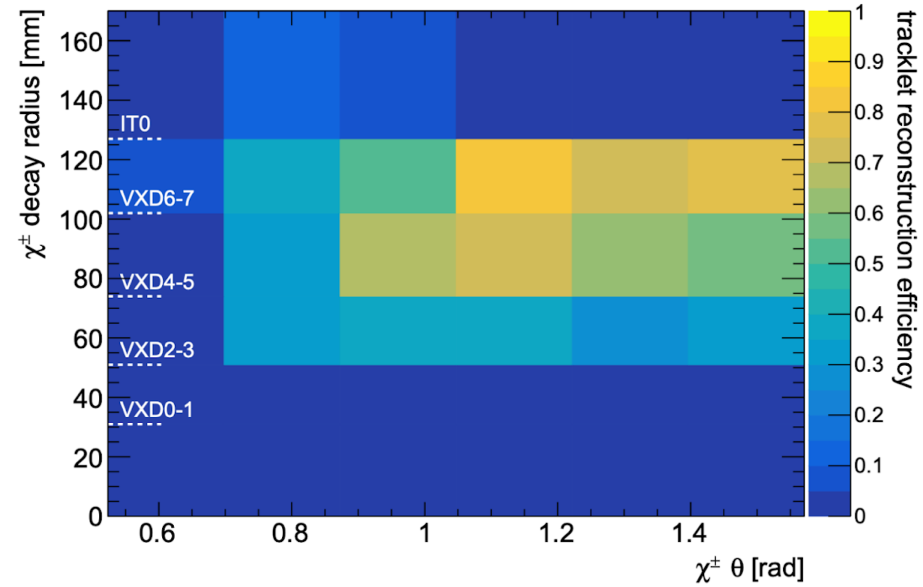
4. Long-Lived Particles

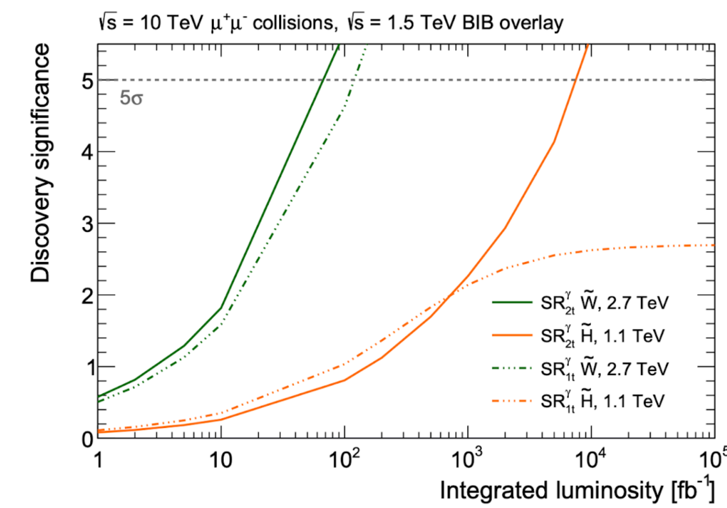
- Experimental Target:

The power of timing + tracking

RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133



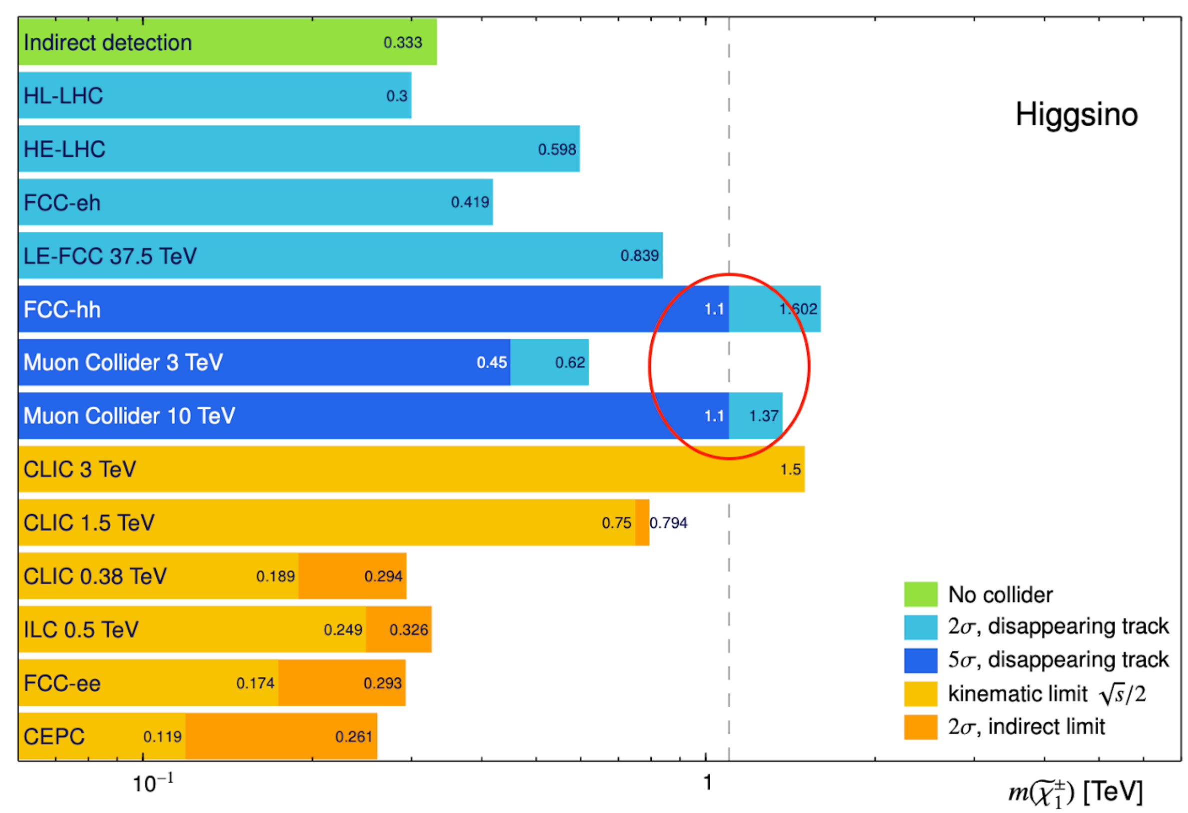




Higgsino is challenging: Short lifetime

Is it possible to extend acceptance below the second double layer?

Update: Smart time selection indicates that the 10 TeV collider can discover the Higgsino (F. Meloni et al)



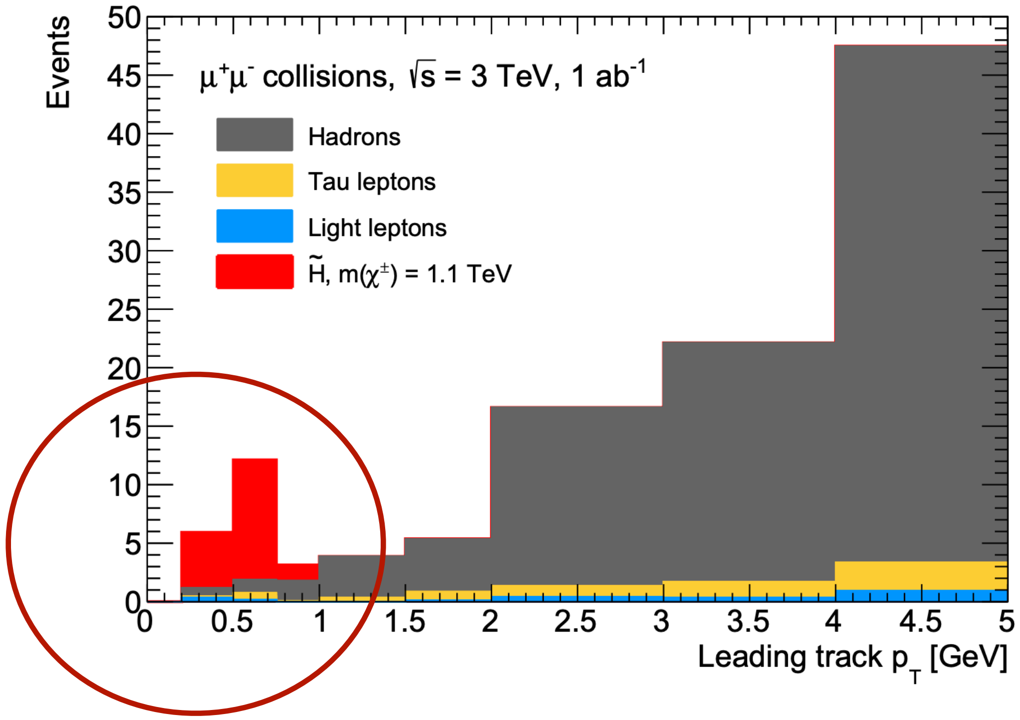
Rodolfo Capdevilla, Fermilab

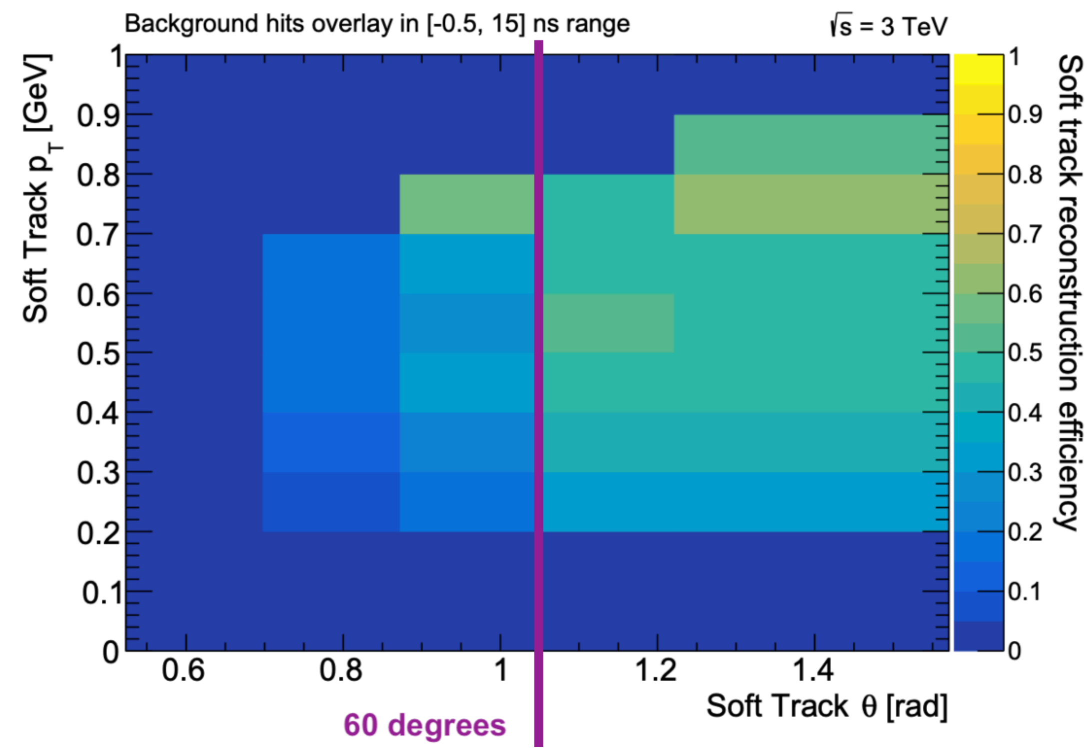
4. Long-Lived Particles

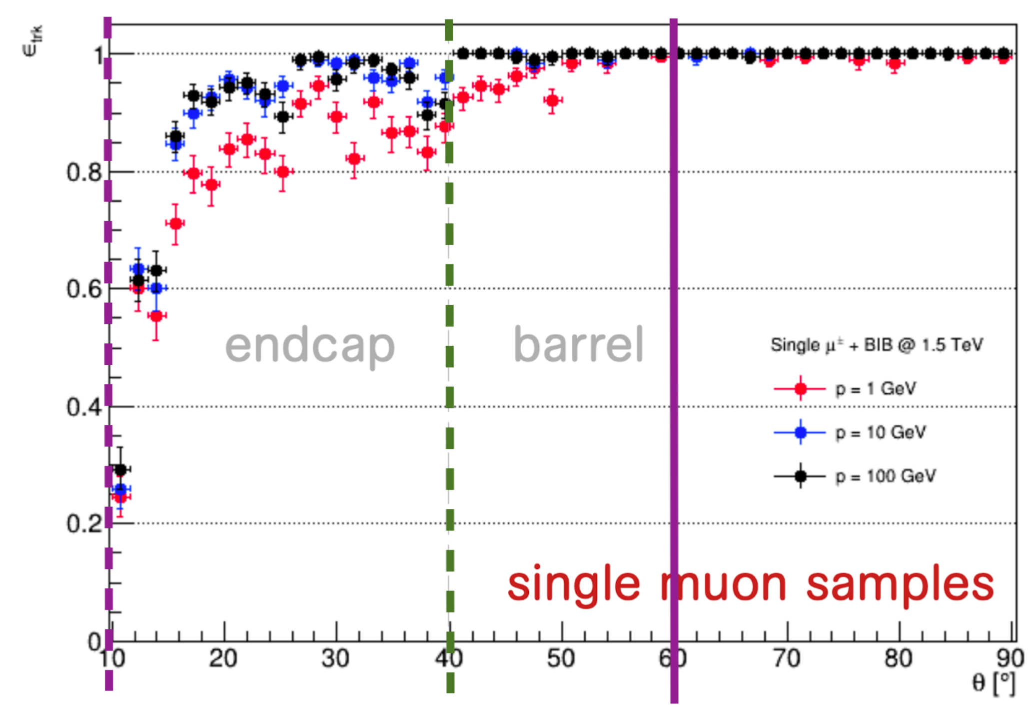
- Experimental Target:

Soft Tracks

RC, Meloni, Zurita,
arXiv:2405.08858







Need 50% tracking reconstruction efficiency for sub-GeV tracks in the central 60 degree acceptance

Outline

Theory Target	⟷	***Experimental Target***

Theory Target

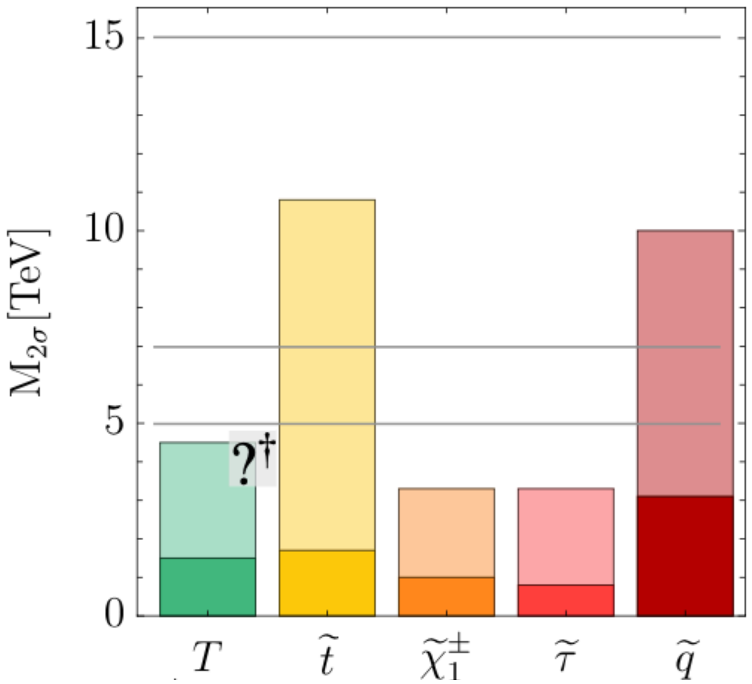
- Higgs Precision
- Heavy resonances
- Forward Physics
- Long-Lived Particles
- …

Experimental Target

- Object Reconstruction
- High pT
- Forward Tagger
- Disappearing+Soft Tracks
- Displaced Vertices
- Detector Acceptance
- …

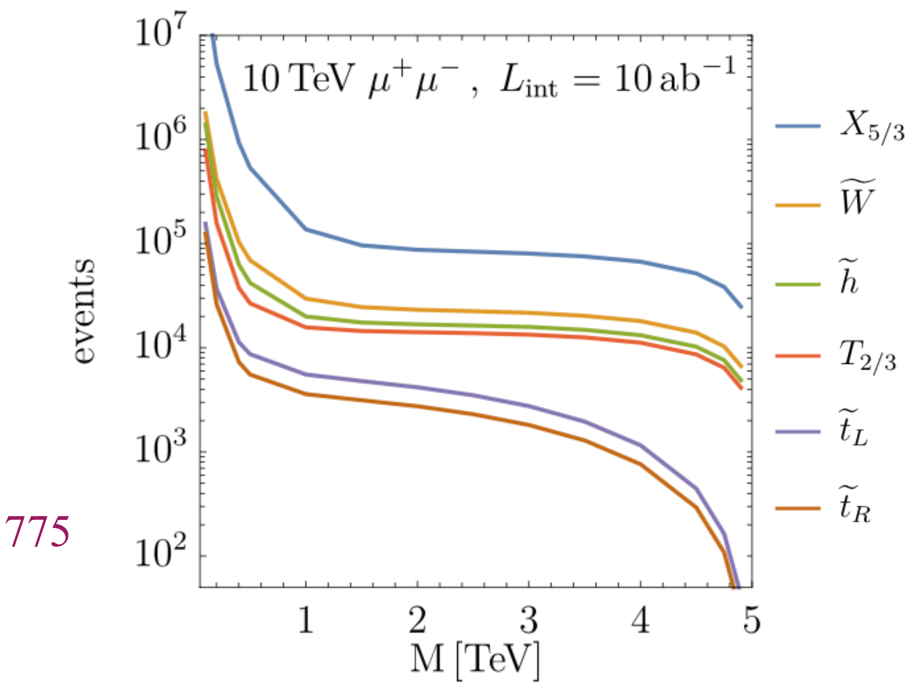
5. Other Targets

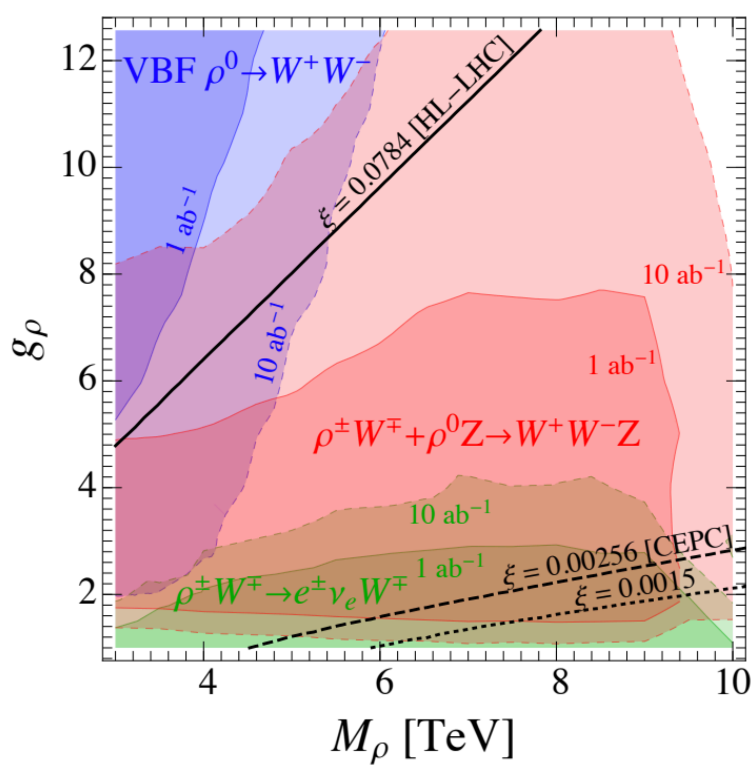
Heavy Resonances



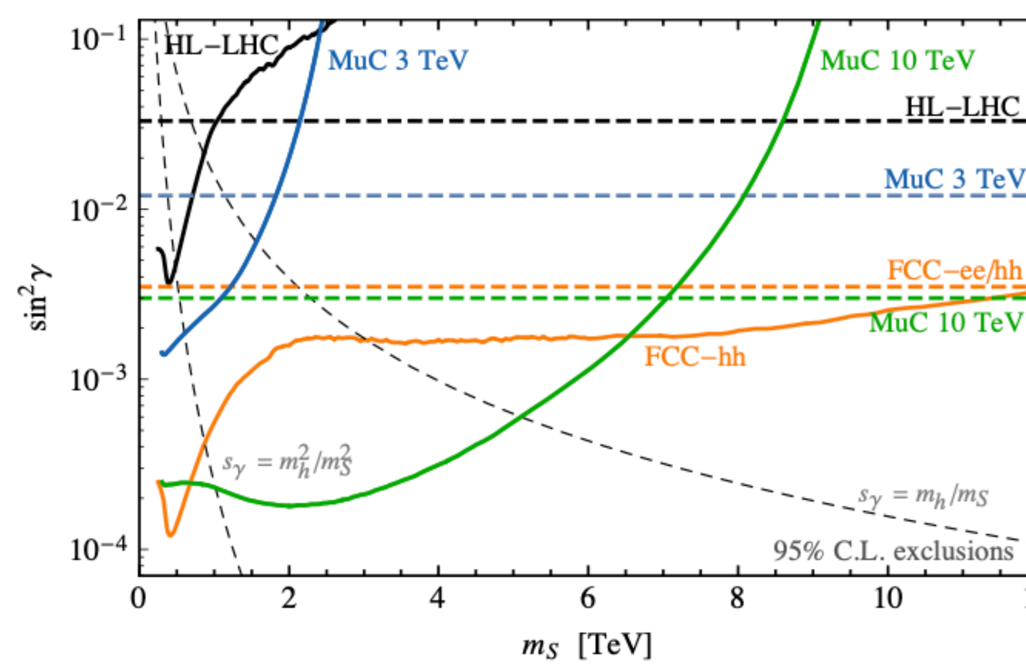
D. Buttazzo, R. Franceschini, A. Wulzer, JHEP 05 (2021) 219

R. K. Ellis et al., arXiv:1910.11775





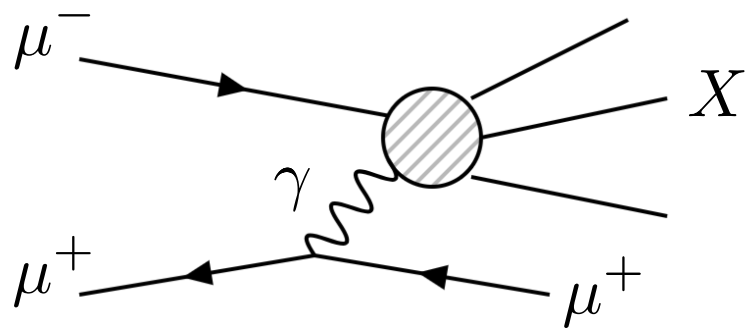
Da Liu, Lian-Tao Wang, Ke-Pan Xie, JHEP 04 (2024) 084



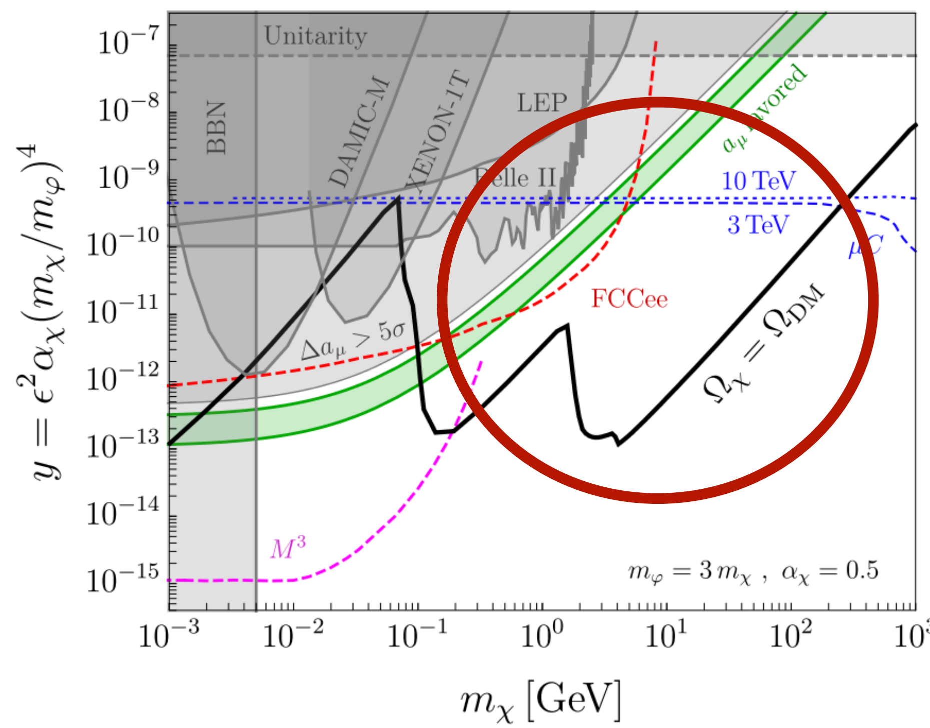
Hind Al Ali et al., Rept. Prog. Phys. 85 (2022) 8, 084201

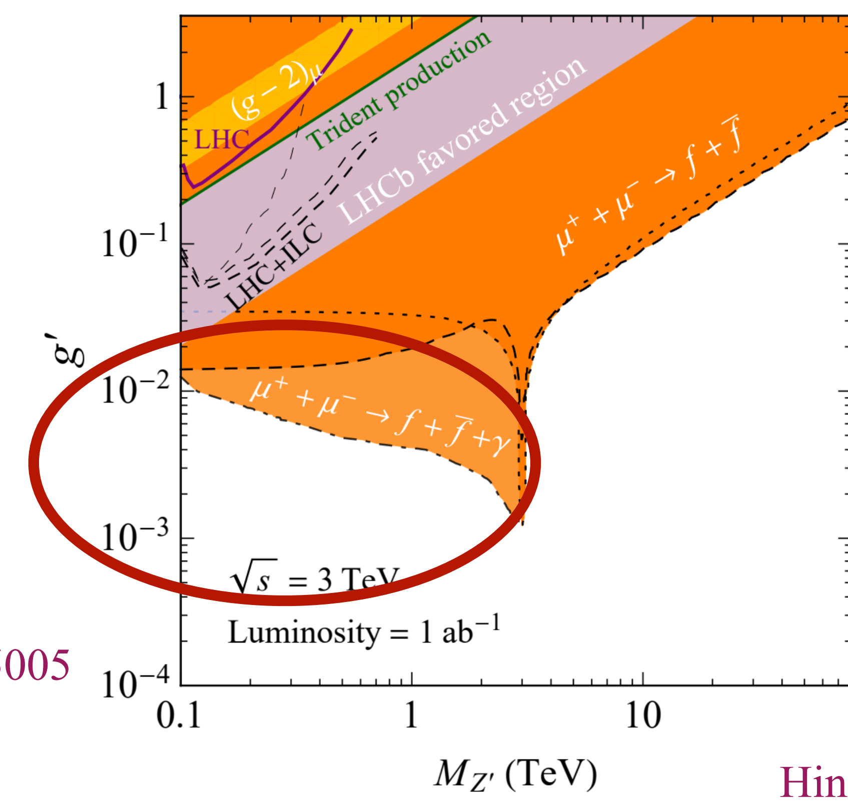
5. Other Targets

Forward Physics



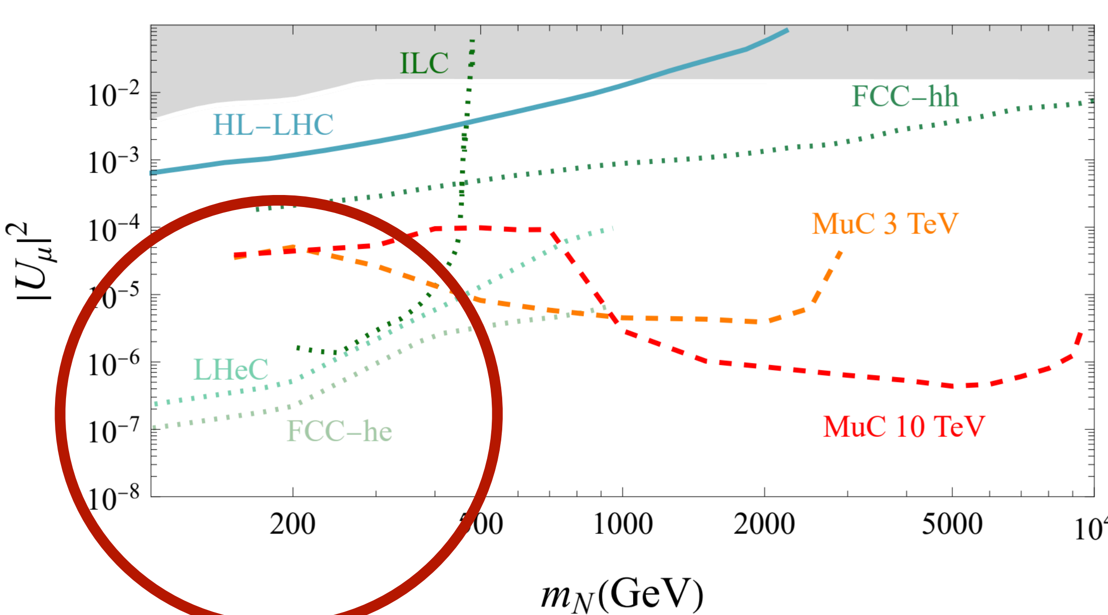
Cari Cesarotti, Gordan Krnjaic, arXiv:2404.02906

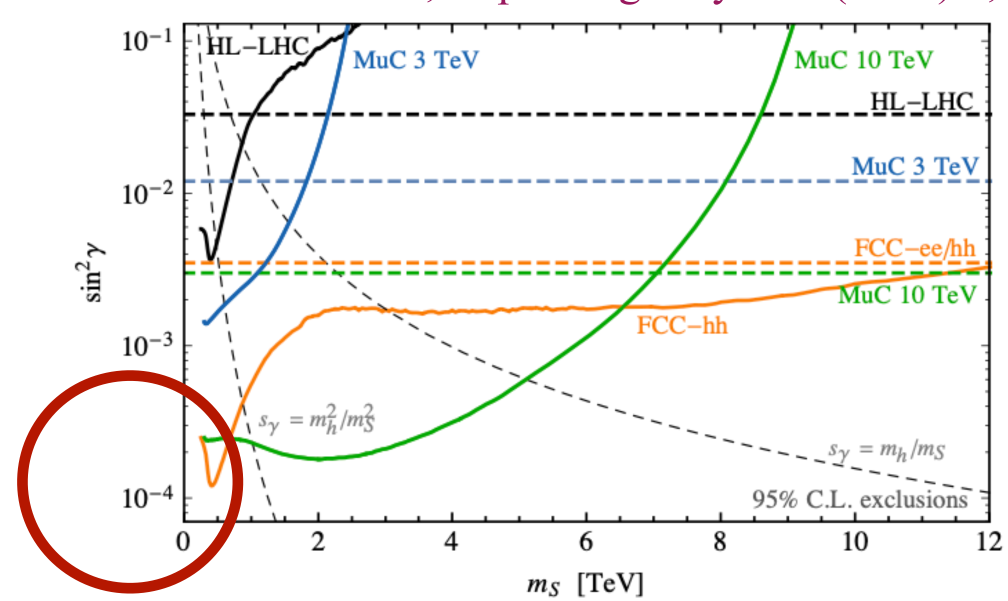




Huang, Queiroz, Rodejohann, Phys. Rev. D 103 (2021) 9, 095005

Hind Al Ali et al., Rept. Prog. Phys. 85 (2022) 8, 084201



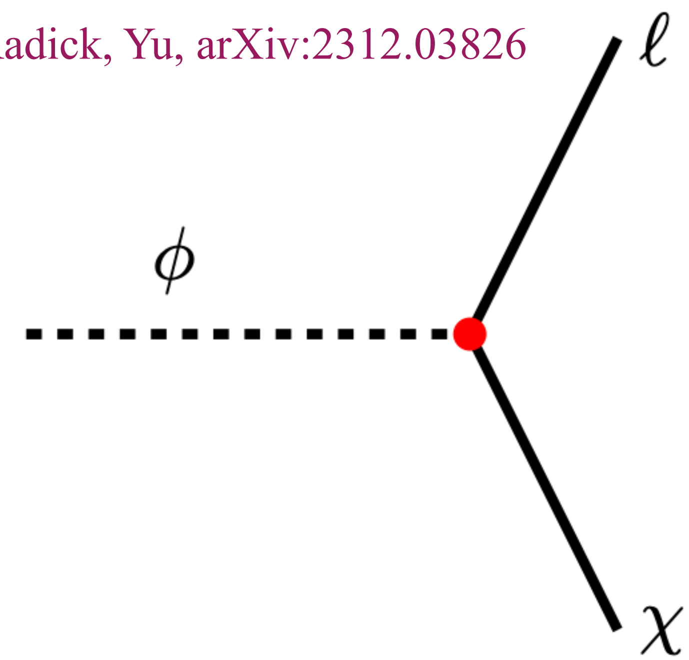


Peiran Li, Zhen Liu, Kun-Feng Lyu, JHEP 03 (2023) 231

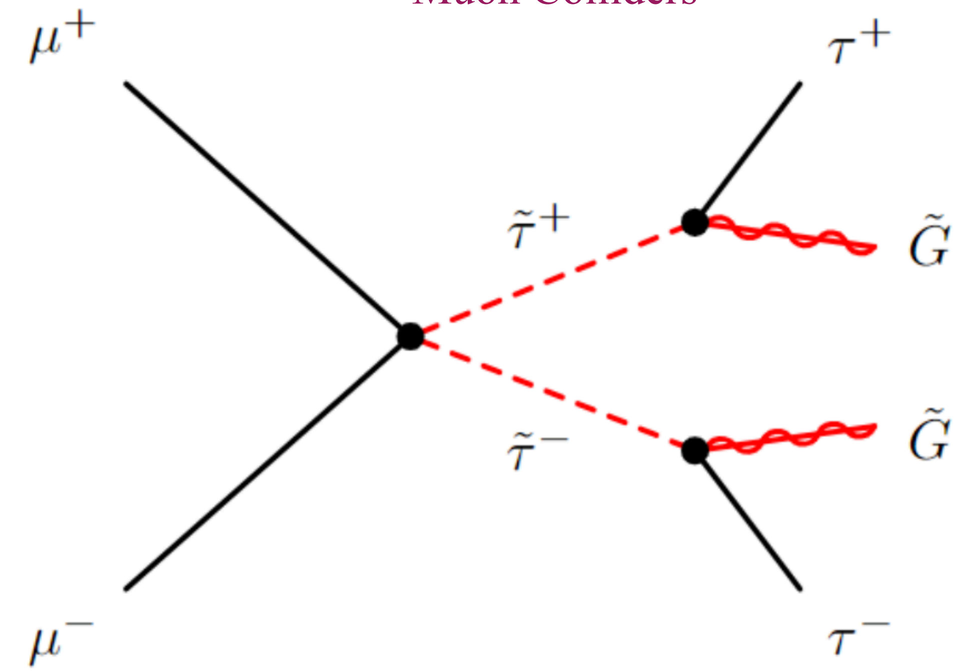
5. Other Targets

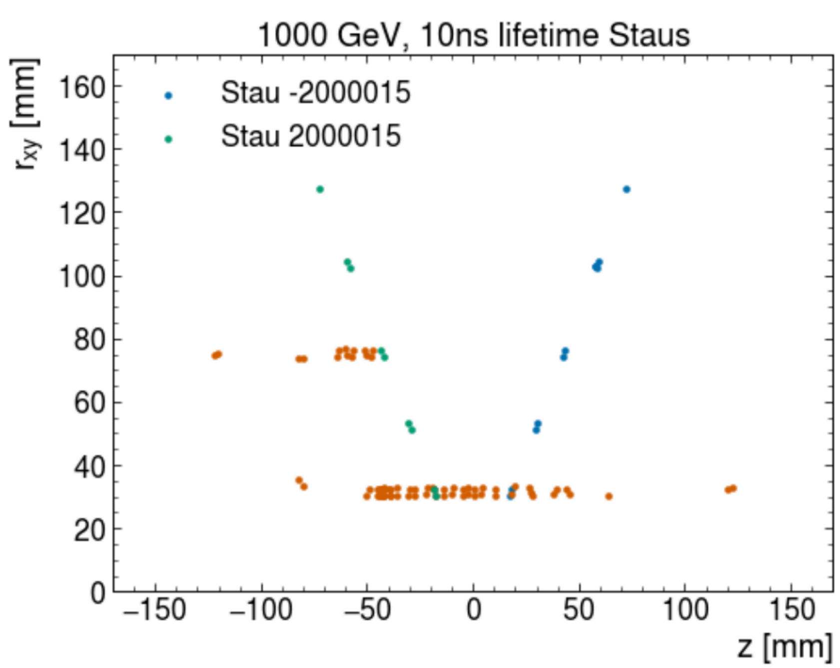
Other Dark Sectors

Asadi, Radick, Yu, arXiv:2312.03826

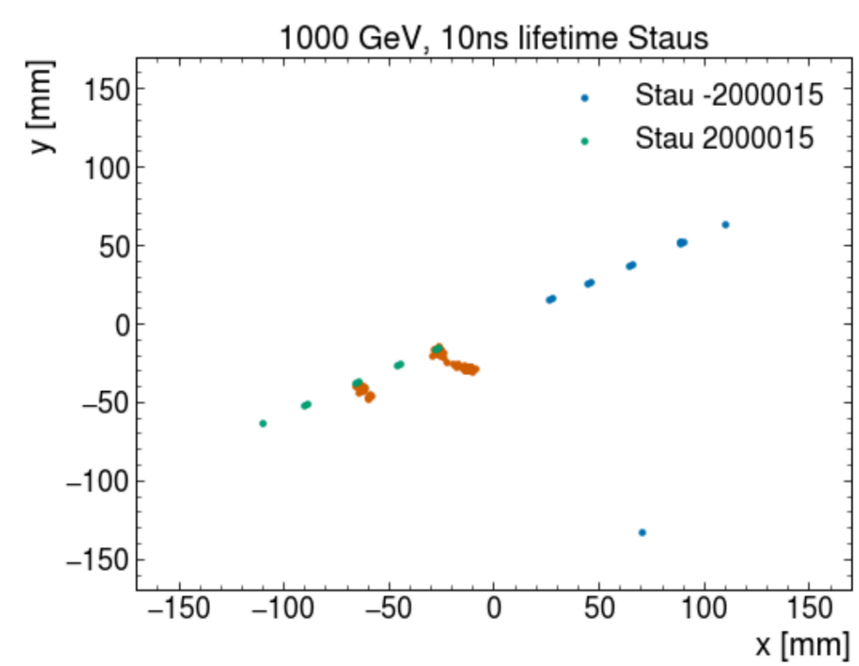


Leo Rozanov, Unconventional Track Signatures at a 10 TeV Muon Collider, KDP Lab | University of Chicago | Muon Colliders





Progress on Stau displaced vertices



Summary

We have discussed a few theory targets, the experimental targets, the status of some experimental searches and the prospects for improvements. We saw:

1. Higgs precision: Object reconstruction requirements for percent level measurements of the Higgs couplings seem possible under current detector simulations. Prospects for improvement in tracking, timing, calorimetry, etc. look promising!

2. Heavy resonances: New detector concepts show high efficiency and mass resolution in the reconstruction of multi-TeV resonances.

3. Forward Physics: Challenging! We need to keep trying! Instrumenting new components of the machine?

4. Long-Lived particles: Disappearing track searches look promising. The muon collider will probe electroweak multiplets whose neutral component is dark matter. As energy increases 3->10, the collider will probe, Doublets (Higgsinos, 100% of DM) via Soft Tracks -> Triplets (Winos, 100% of DM) and Fiveplets (10% of DM) via Disappearing Tracks.

5. More targets…

Thank You!