IMCC Annual meeting highlights

International MUON Collider Collaboration

– Physics and Detector –

(Material taken heavily from the original talks)

Angira Rastogi, postdoc, ATLAS

LBL Future Collider Forum, May 29th
https://indico.physics.lbl.gov/event/2855/

MDI workshop (Mar 11-12, 2024): https://indico.cern.ch/event/1353612/
Annual meeting (Mar 12-15, 2024): https://indico.cern.ch/event/1325963/

BERKELEY LAB

2-part workshop

- Machine-Detector Interface (MDI)
  - Focusing on detector design for 3 TeV and 10 TeV

- IMCC Annual meeting
  - More topical discussions on detector developments, accelerators, magnets, physics-case and so on…

Today's focus!

Machine-Detector Interface (MDI) studies

First detector concept for √s=3 TeV

Modified CLIC"s detector concept:

- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background

Used in Snowmass 2021 studies!

hadronic calorimeter

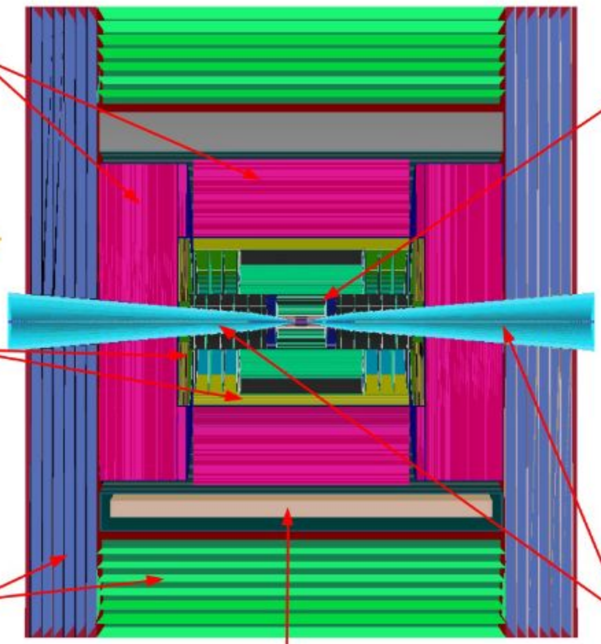
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

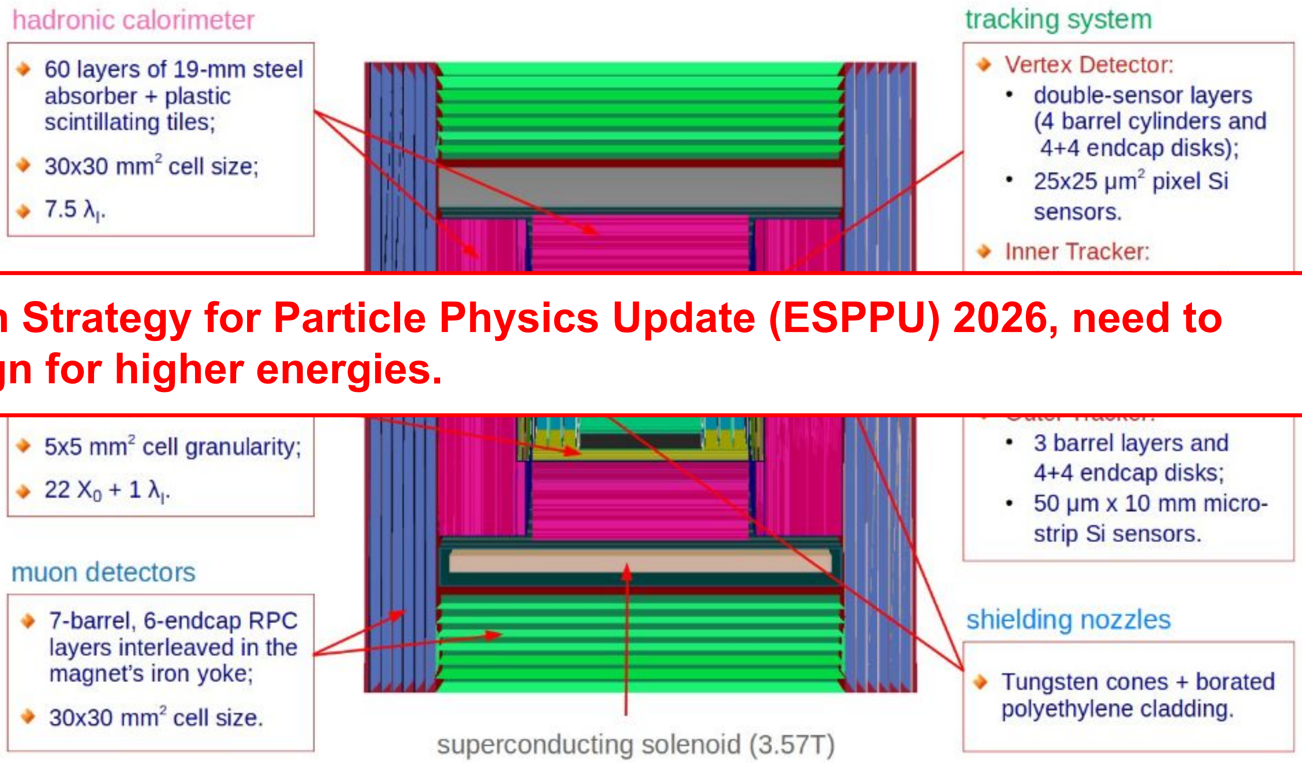
- Tungsten cones + borated polyethylene cladding.

First detector concept for √s=3 TeV

Modified CLIC"s detector concept:

- Removed forward luminosity detectors
- Inserted nozzles

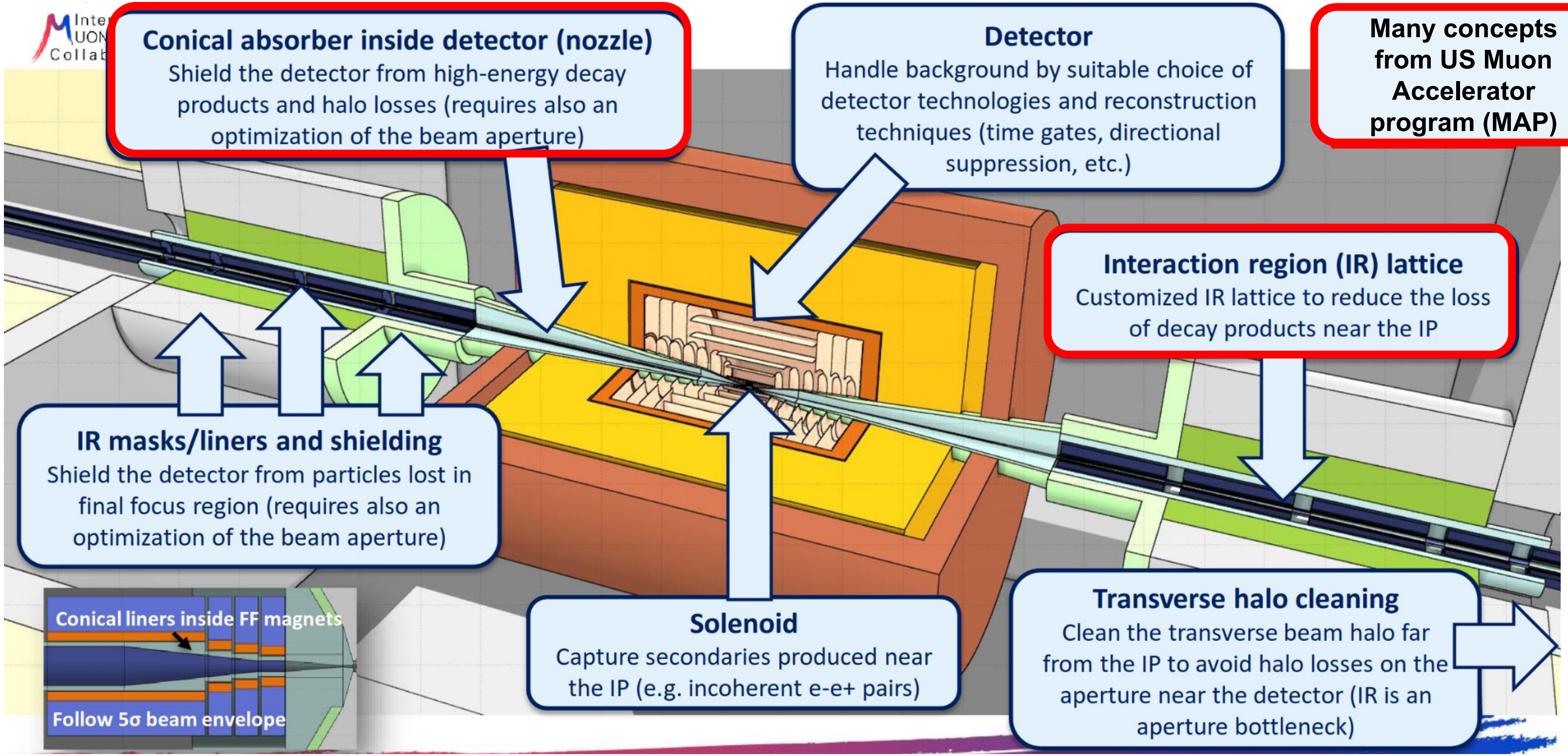
to cope with available beam-induced background



Next target is European Strategy for Particle Physics Update (ESPPU) 2026, need to optimize detector design for higher energies.

Used in Snowmass 2021 studies!

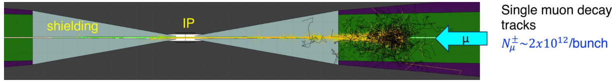
Mitigating beam-induced background (BIB)



Many concepts from US Muon Accelerator program (MAP)

Background is a significant driver of the MDI design.

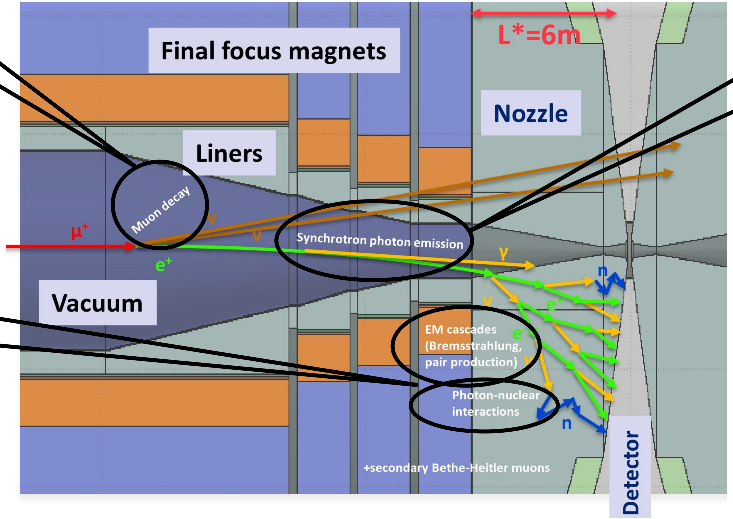
Shielding nozzles



Dominating source

Emission in magnets near the IP, small contribution

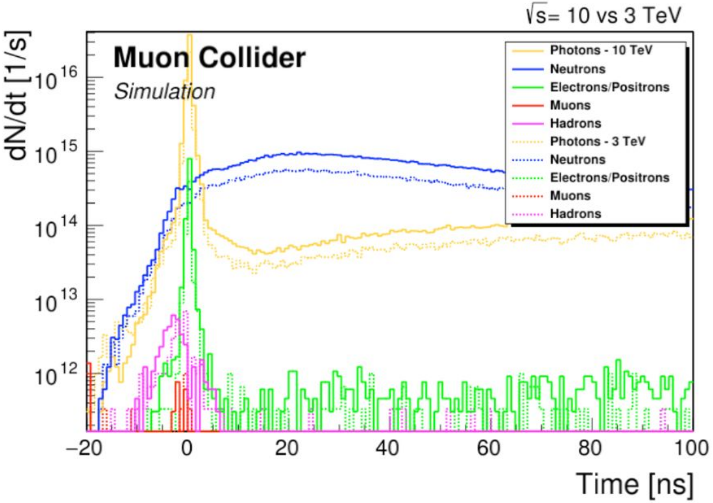
Expected to be small, but will be quantified



Main BIB sources:

- Muon decay (dominant)
- Beam halo losses
- Beam-beam interactions

Time distribution of particles

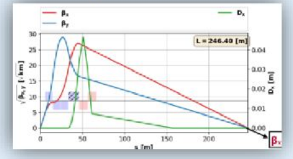


Background particles entering detector per bunch crossing (with time window cut [-1:15]ns):

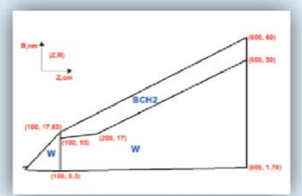
- $O(10^8)$ γ (>100 keV)
- $O(10^7)$ n (>10^{-5} eV)
- $O(10^6)$ e+ & e- (>100 keV)

Iterative optimization with BIB simulation

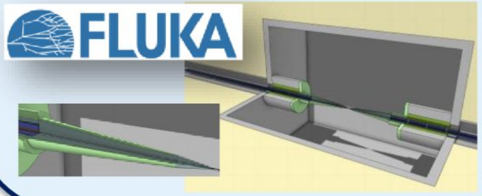
IR layout
Optics (lattice) and apertures



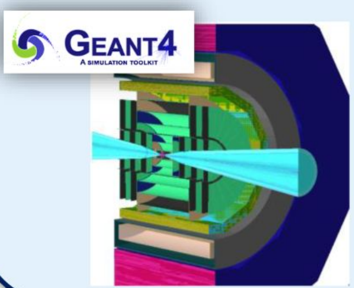
Nozzle & absorber configuration



Background simulations (FLUKA)
*) Realistic geometry model of beam line (magnets), absorbers, nozzle, etc.
*) Sampling of source terms (e.g. muon decay sampling from matched beam phase space distribution)
*) Store distribution of **BIB* particles entering the detector envelope**



Detector simulations (Geant4)
*) Simulation of background hits
*) Overlay with physics collision events

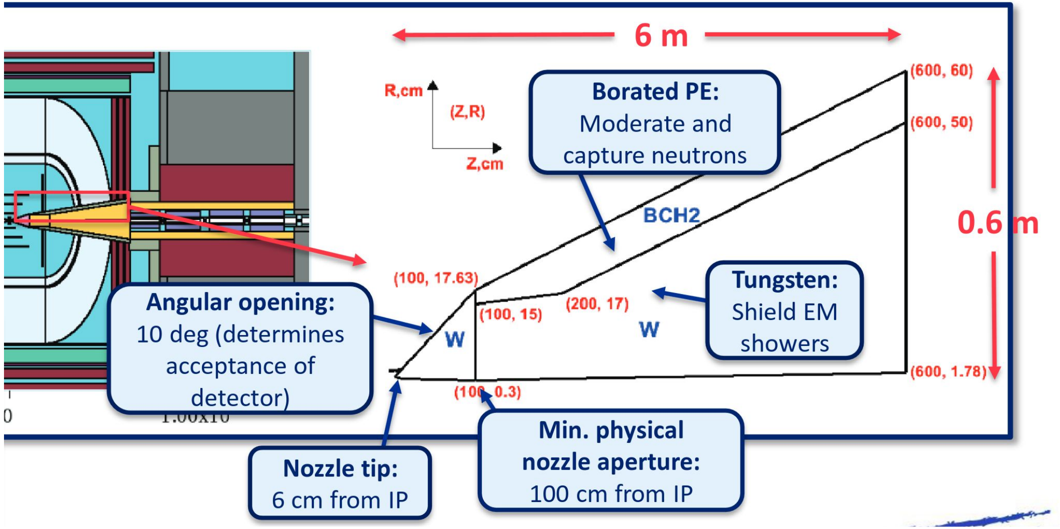


This is of course an **iterative process** to optimize the IR & MDI design!

By looking at particles fluxes, hit occupancy, energy deposits and detector performance.

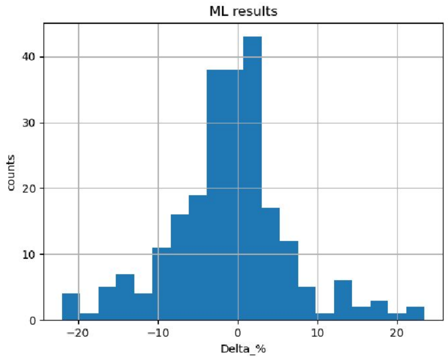
Nozzle design optimization

- Starting from 10° nozzle US MAP design for $\sqrt{s}$=1.5 TeV, and optimizing the shape, material & aperture for 3 & 10 TeV.
- Also, need to consider about nozzle integration inside detector and general technical aspects.



Generating one μ-beam with threshold energy of particles produced at 100 KeV and propagating through the nozzle.

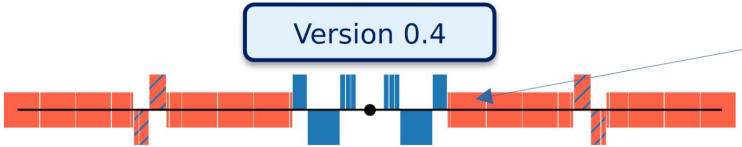
~1.6 % of one BIB event (i.e. bunch crossing) for one beam = 4 days per simulation.
Time consuming and computationally heavy simulation.



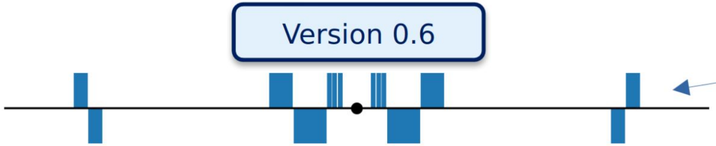
Using **ML-approach** with low statistics BIB simulation (~0.02%) for 1 bunch crossing and scanning over nozzle parameters.
Training XGBoost regressor and evaluating difference between predicted and truth flux.
Choosing the best geometry and then generating full-stat sample for comparison with MAP-like design.

IR lattices for 10 TeV

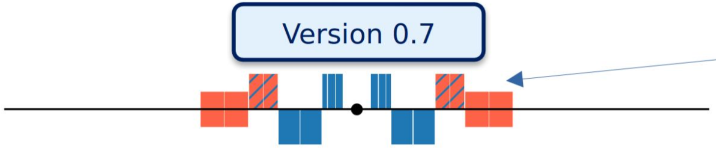
Can decay induced background be reduced by adjusting lattice design?



Dipolar component suppress BIB outside of the final focus. The BIB sample distributed (and considered baseline)

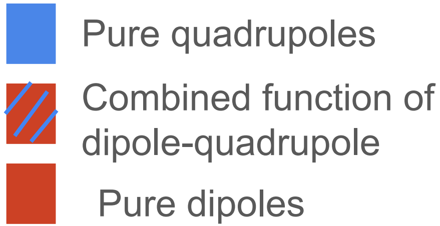


All the muon decays in ~200 meters from the IP give a non negligible contribution to the BIB



A chicane is added to partially clean the line from the secondary electrons before they reach the nozzle

Latest 10 TeV lattice version.

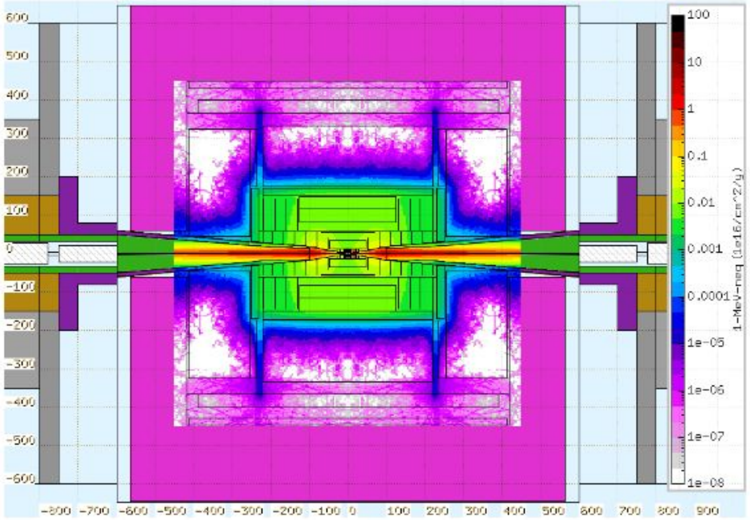


	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	US MAP [1]	IMCC (present vers 0.7) [2]
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

Challenges: small □*, large □ fluctuations in FF, strong chromatic effects

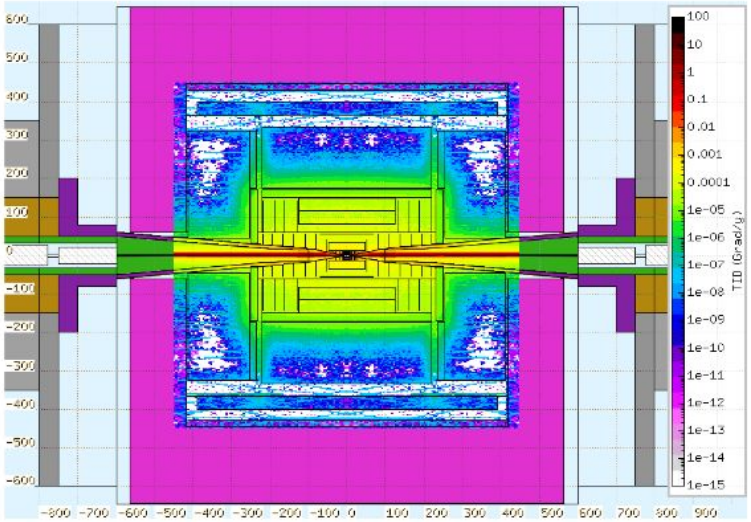
Radiation environment

1-MeV neutron equivalent fluence per year



Assumptions:
Collision energy = 1.5 TeV and days of operation/year = 200

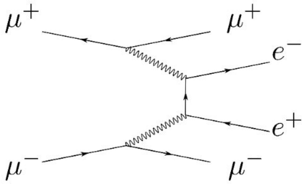
Total ionizing dose per year



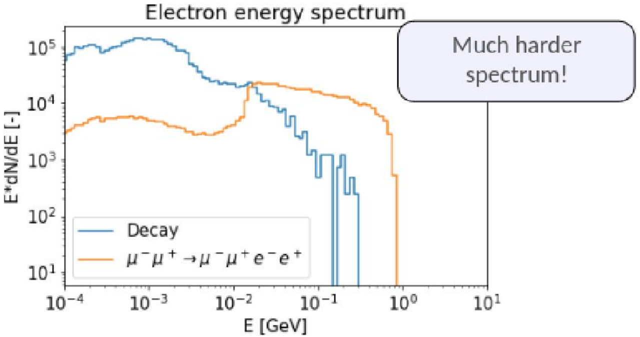
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Modeling other beam effects at 10 TeV

Incoherent e+e- pair production

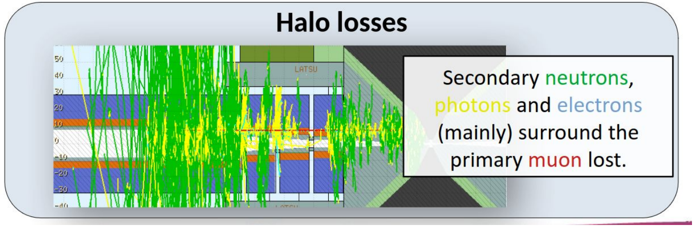


- Only 10% as compared to muon decay background.
- But, overall more energetic and impact directly on the detector since generated in the IR.

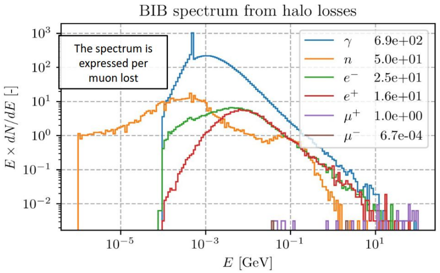


Obtained by GUINEA-PIG event generator.
Need to make sure the modeling is correct and this is not dominating source of background.

Muon halo losses



- Due to muon interaction with the nozzle or liners in magnets
- Results in muon losses on the aperture and many secondary particles (less than muon decay) generated close to the IR.



Refine shower simulations for generic halo losses in the IR.

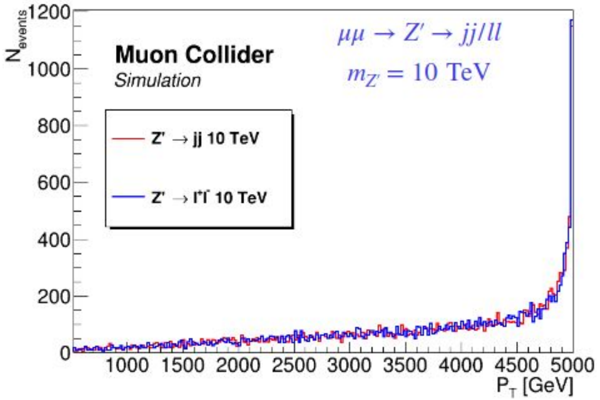
Derive maximum allowed halo loss rate in the IR, should stay below muon decay-background (provides specifications for halo cleaning system).

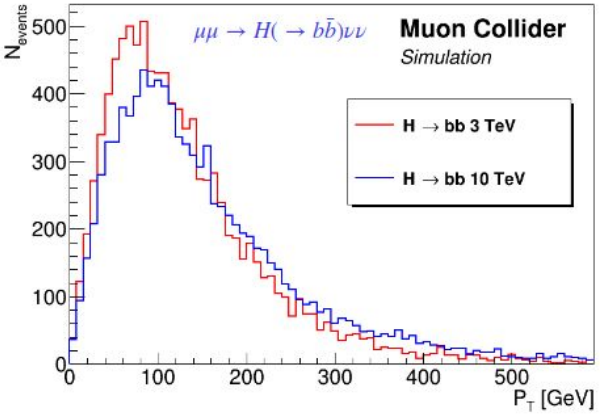
From MDI to detector technologies & performance

Detector optimization for 10 TeV

Physics cases:

- “Low” energy physics processes (EW, Higgs production) ~ hundreds of GeVs
- “High energy physics processes (New Physics, resonance production) ~ order of TeVs
- Unconventional signatures (long-lived particles, emerging jets …)
- Detector concepts should be able to handle large BIB.

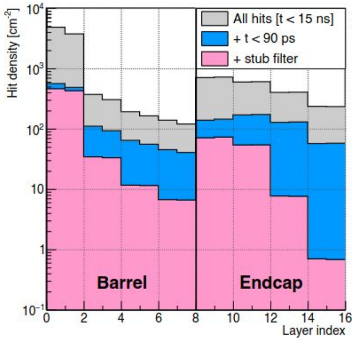




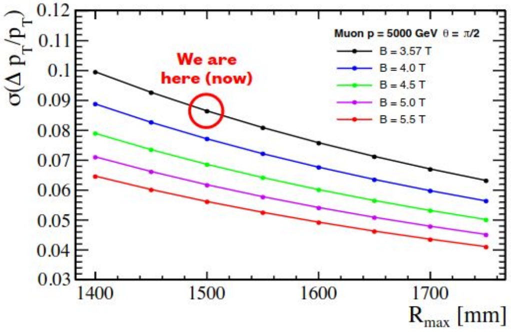
Detector optimization for 10 TeV

For tracker:

1. Hit occupancy (BIB driven) < 1% of LHC, with realistic material budget.
2. Momentum resolution - driven by magnetic field strength and size of tracker for high momentum.
3. Good transverse & longitudinal resolution for b/c hadrons identification. Also, need a few (~3) measurements close to IP to reconstruct short-lived tracks and their soft decay products.
4. Timing resolution for out-of-time BIB reduction and accurate time of collision measurement.



1.



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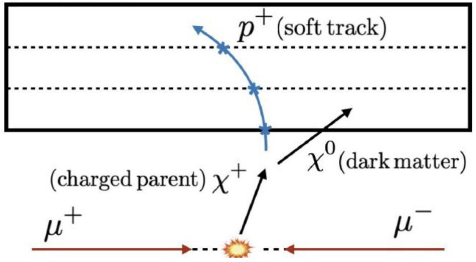

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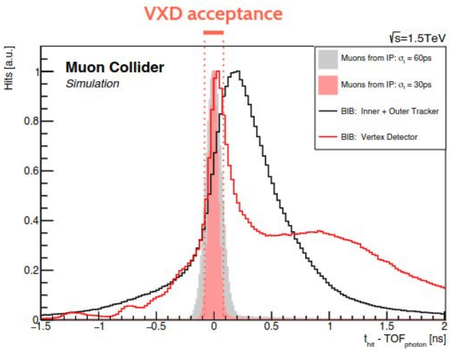
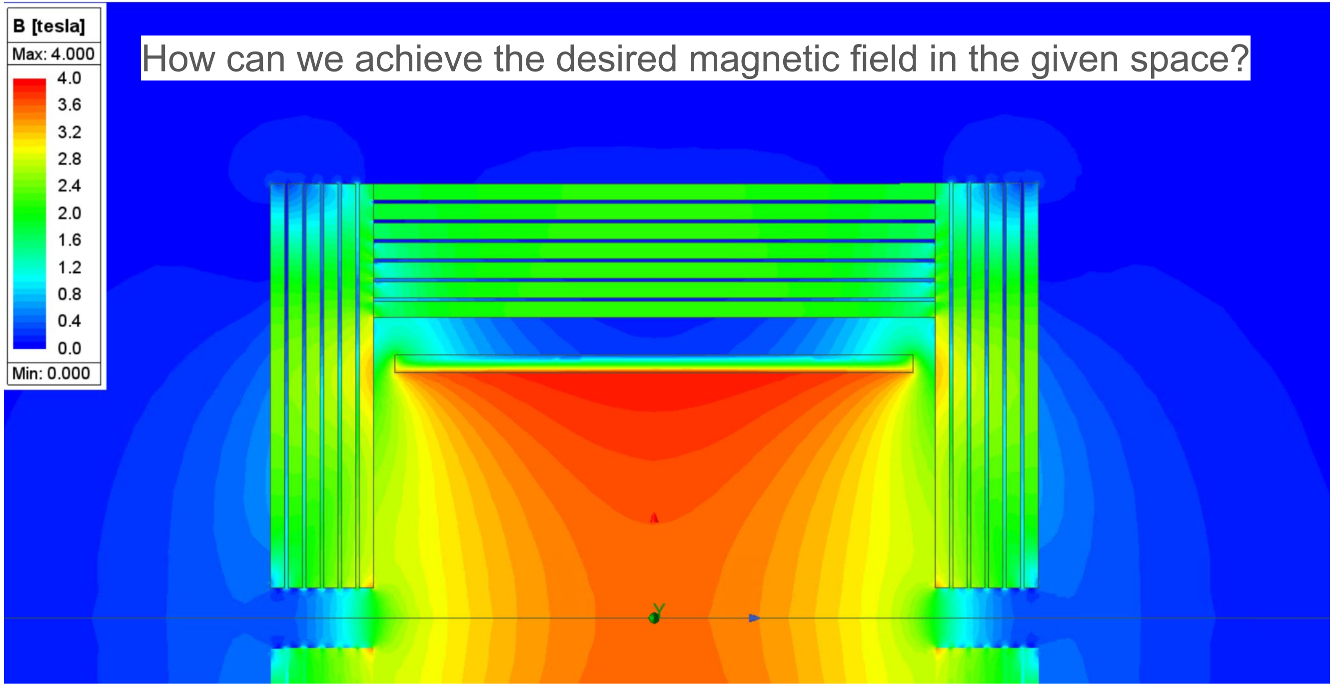


4.

Designing and optimizing magnets



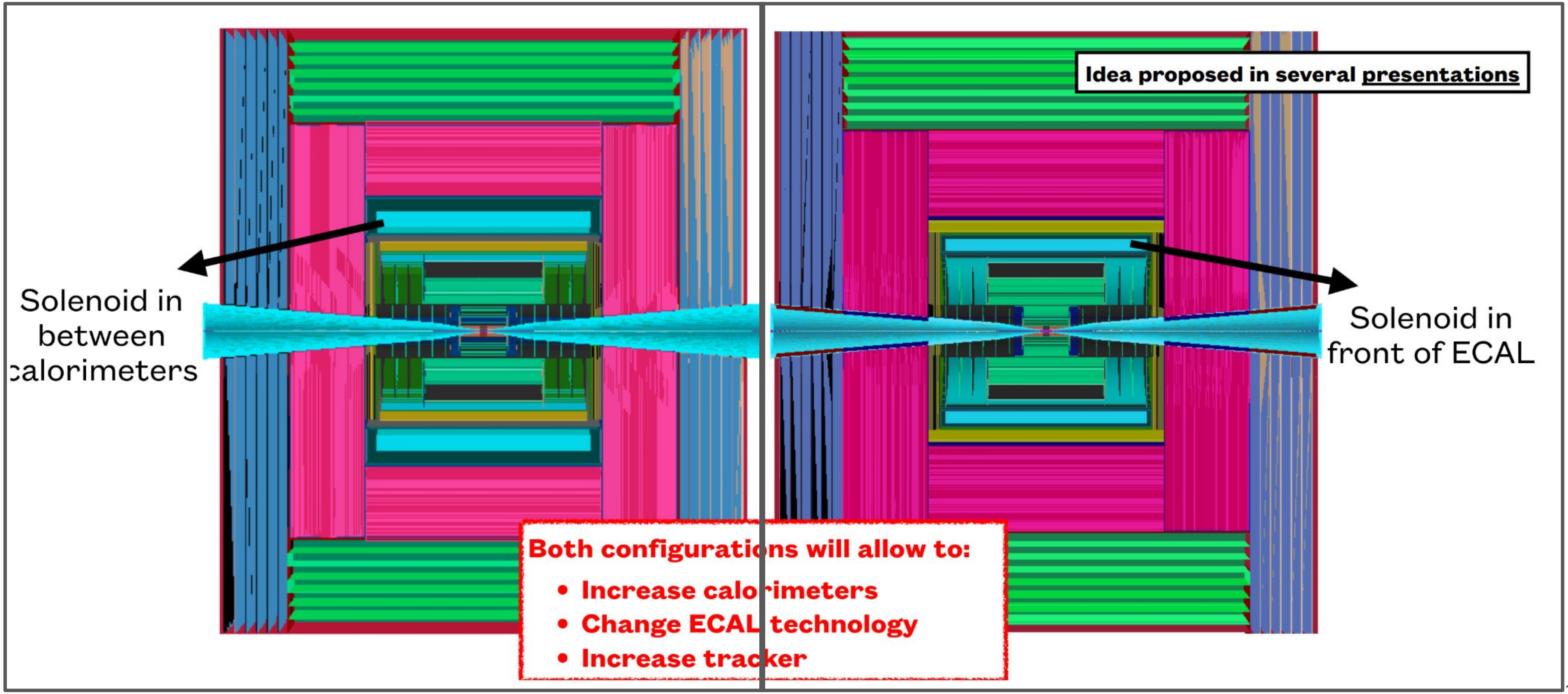
Starting from CLIC-based design, with traditional aluminium stabilized NbTi based Rutherford cable:

- Consider different SC, cable protection and geometries.
- Dimensions of magnet under study
- Number of layers under study
- Forces on the coil to be studied
- Maintain a good field uniformity, keeping the same form factor (length~diameter)

Integration of detector magnet with tungsten cones (nozzle) and other support structures needs to be solved trivially.

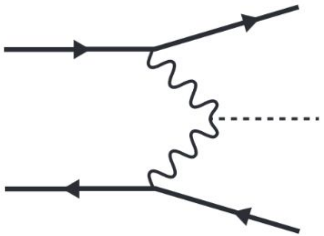
Realistic magnetic field map to be used in BIB generation and detector studies.

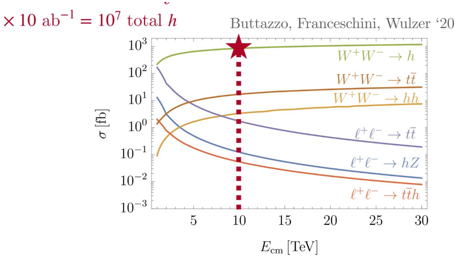
Detector design for 10 TeV – 2 approaches



Physics Goals

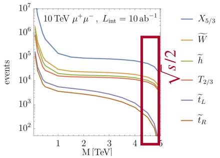
Precision EW & Higgs

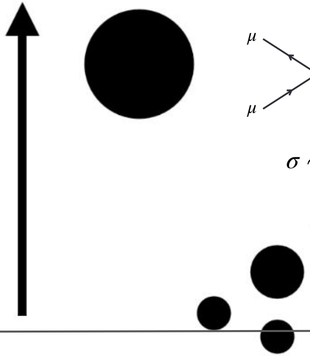




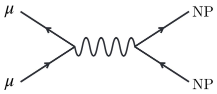
Heavy Particles

$\Lambda_{NP} \geq$ TeV





$m_{W,Z,h}$



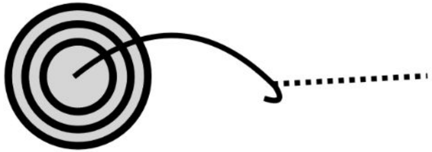
$$\sigma \sim \frac{1}{s} = \frac{1}{E^2}$$

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

Flavor Tagging

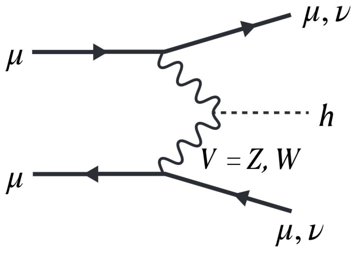
Novel Signatures (e.g. Disappearing tracks, LLPs, SUEPs, etc.)

Can be studied by looking at track properties or global properties of event radiation pattern.

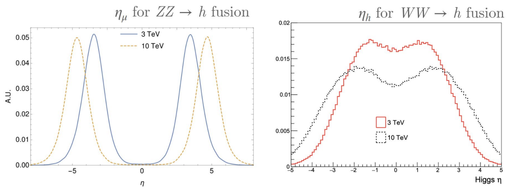


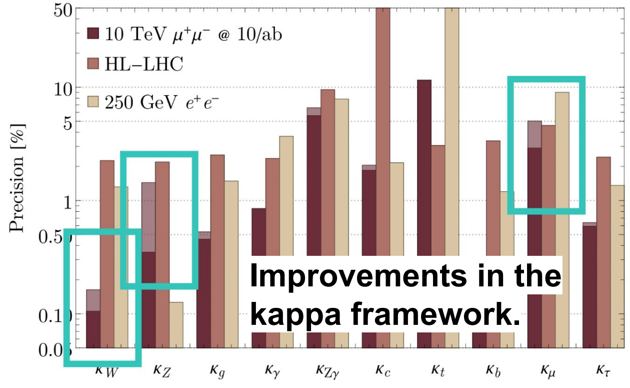
Precision EW & Higgs

VBF higgs production has very forward kinematics.



$\eta_\mu \sim 3.5$ at 3 TeV $\quad$ $\eta_\mu \sim 5$ at 10 TeV

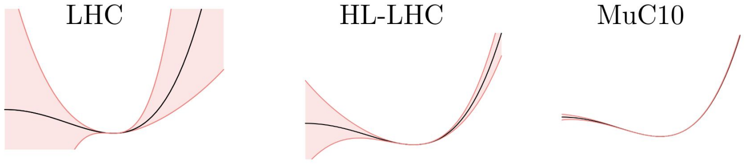




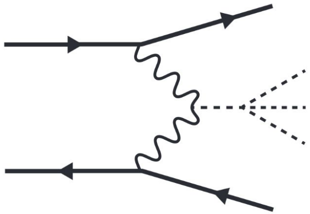
Variety of guaranteed new measurements!

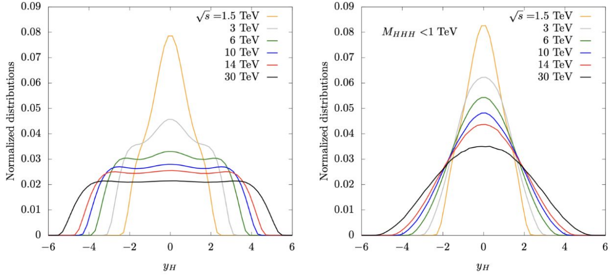
$$V(H) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 = \frac{m_h^2}{2v}(1 + \delta\kappa_3) h^3 + \frac{m_h^2}{8v^2}(1 + \delta\kappa_4) h^4$$

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



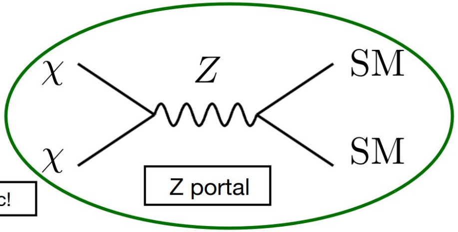
Quartic coupling





Soft & disappearing tracks for Higgsino discovery

- The Model:



Inelastic!

Z portal

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

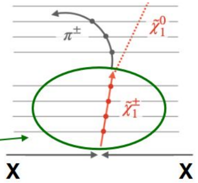
Neutral component = DM

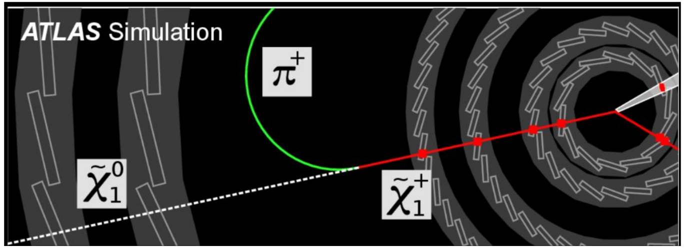
Minimal Dark Matter (MDM)

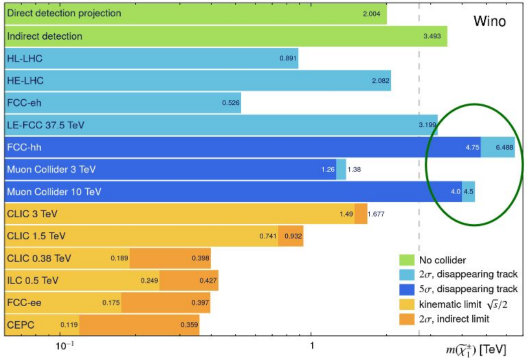
- Lifetime:

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

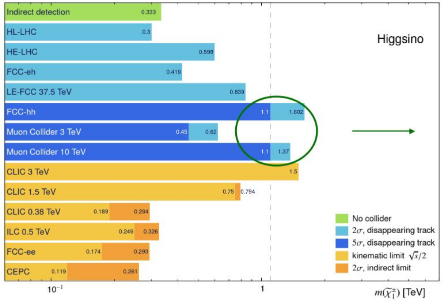
Small mass splitting (from loops) → *Long lifetime Disappearing Tracks (DT)*







Discovery potential from DT



Not clear discovery potential…

Soft & disappearing tracks for Higgsino discovery

EW multiplets

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

$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix} \qquad (\mathbf{1}, \mathbf{2}, 1/2)$$

Higgsino-like

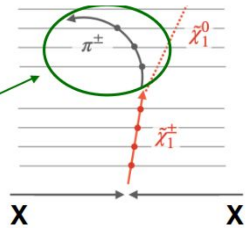
$$\chi_{\tilde{W}} = \begin{pmatrix} \chi^+_{\tilde{W}} \\ \chi^0_{\tilde{W}} \\ \chi^-_{\tilde{W}} \end{pmatrix} \qquad (\mathbf{1}, \mathbf{3}, 0)$$

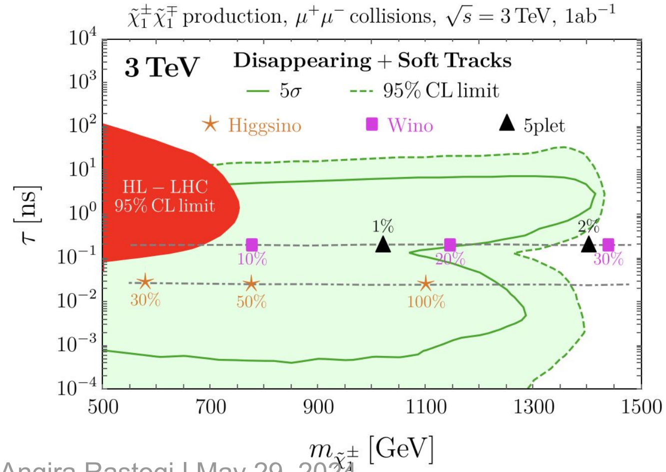
Wino-like

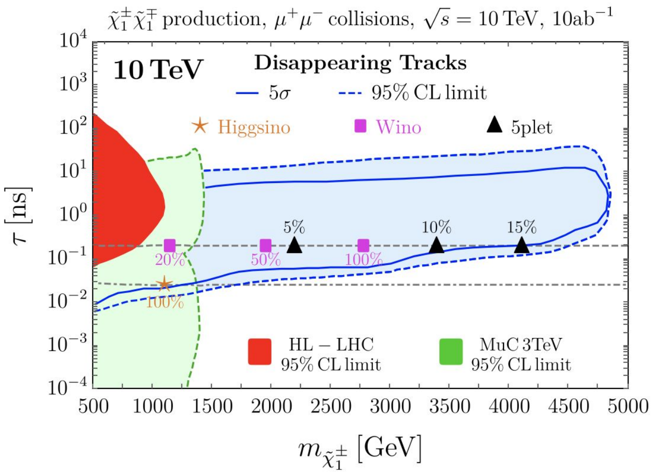
Neutral component = DM

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

Small mass splitting (from loops) → *Long lifetime Disappearing Tracks Soft Tracks (ST)*





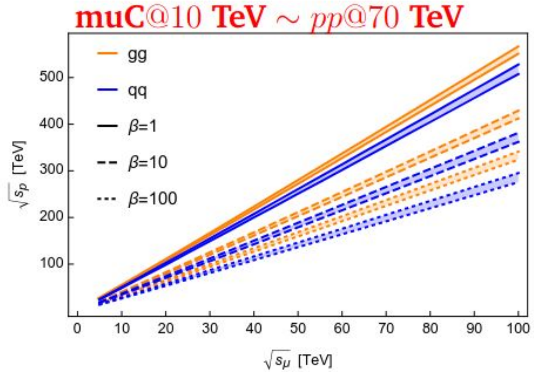


The **3 TeV** muon collider can discover **thermal Higgsinos** as well as Wino(5plet) states that account for ~20%(1%) of DM.

The **10 TeV** muon collider can discover **thermal Winos** as well as 5plet states that account for ~10% of DM.

A “multi-TeV” lepton collider or “electroweak LHC”

- Probe TeV scale directly via l+l- annihilation
- Probe full energy spectrum via VBF physics, up to 2 orders of magnitude above EW scale
- Factory for SM precision test
- “EW-jet” factory, since in addition to QCD jets there are W/Z jet, H jet, t jet, neutrino jet
- Even neutrino collision!



$\mu^+\mu^-$ annihilations

H \ V	0	1	2	3	4	5
0	-	Z	Z^2,W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5,W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

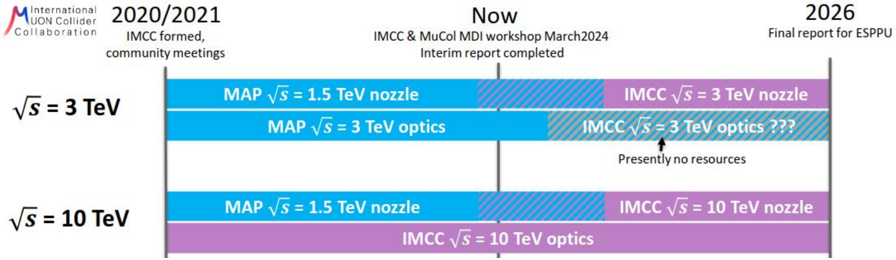
Multi-boson final states and muon-higgs coupling

Challenges:

- Radiation levels
- EW NLO shall be necessary, just like NLO QCD at LHC

Summary

- A lot of work has been going on in the IMCC community, with heavy participation from the US.

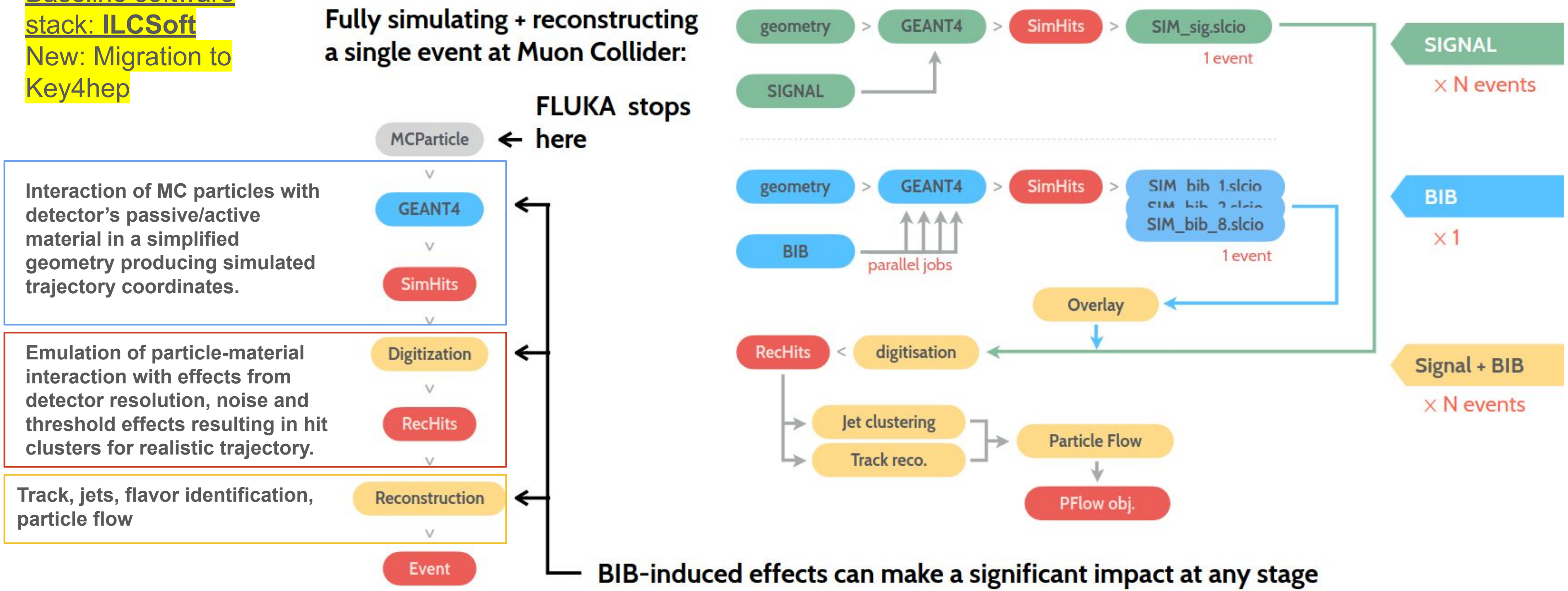


- An initial set of requirements and performance already shown in the interim report, but still much more exciting work needs to be done.
- The US P5 report has already endorsed the muon collider R&D, and we want similar support in ESPPU.
- Therefore, it is essentially to have **well-defined accelerator, experimental and theoretical benchmarks** to demonstrate feasibility of physics potential and confidence in a MuC.

Extra

Simulation framework

Baseline software stack: **ILCSoft**
New: Migration to Key4hep



Impact of IR lattice choices