Comprehensive Paper: Accettura, C. et al. Towards a muon collider. Eur. Phys. J. C 83, 864 (2023).

Detectors for Muon Collider

Karol Krizka

April 30, 2025

International MUON Collider Collaboration

UNIVERSITY OF BIRMINGHAM

PER ARDUA AD ALTA

UK Muon Collider

Three Challenges

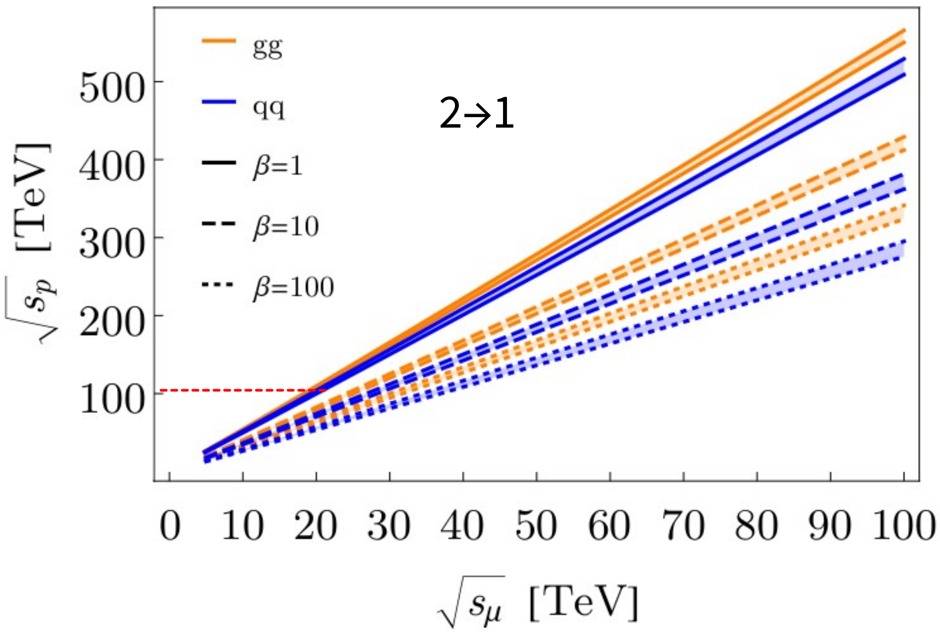
The Physics

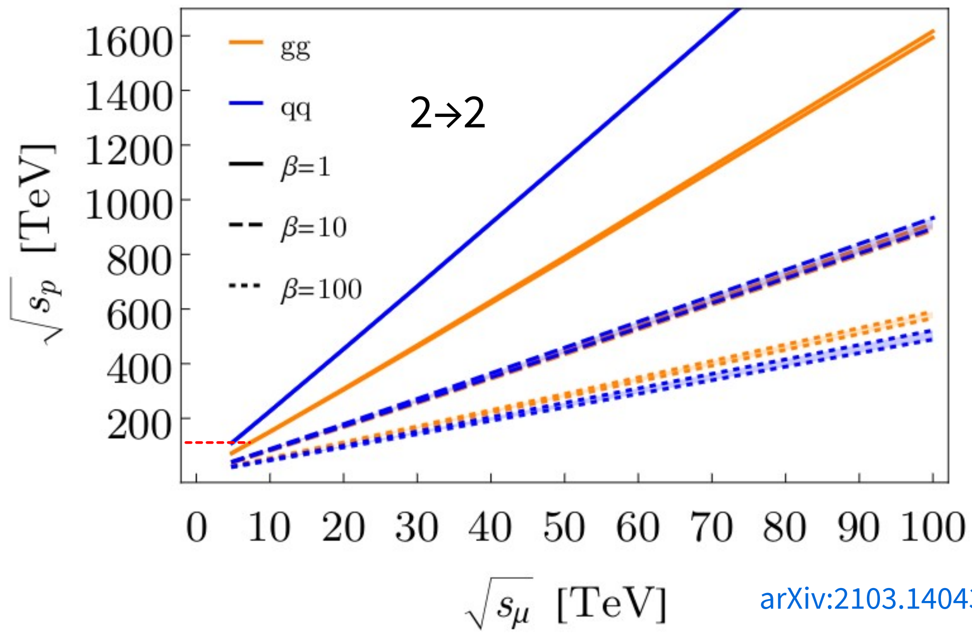
Will a Muon Collider satisfy the physics goals?

- **Precision Higgs couplings**
- **BSM at higher energies**

Direct Searches

Muons are elementary = full beam energy used in collision

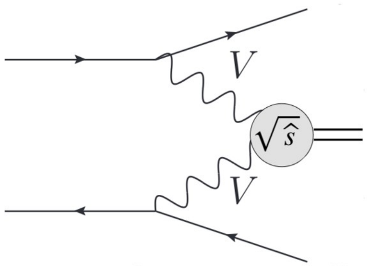




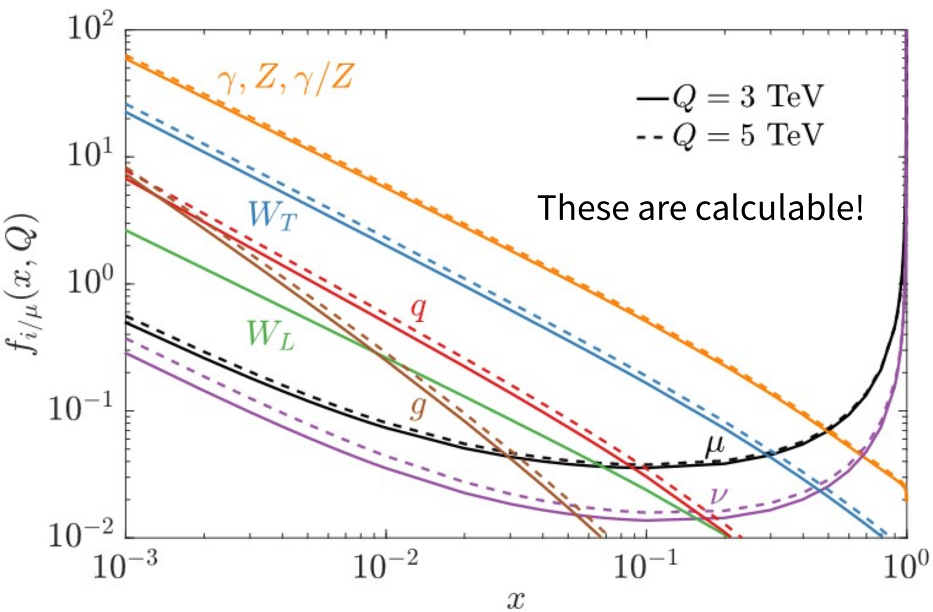
arXiv:2103.14043

100 TeV pp ≈ 10-20 TeV μμ

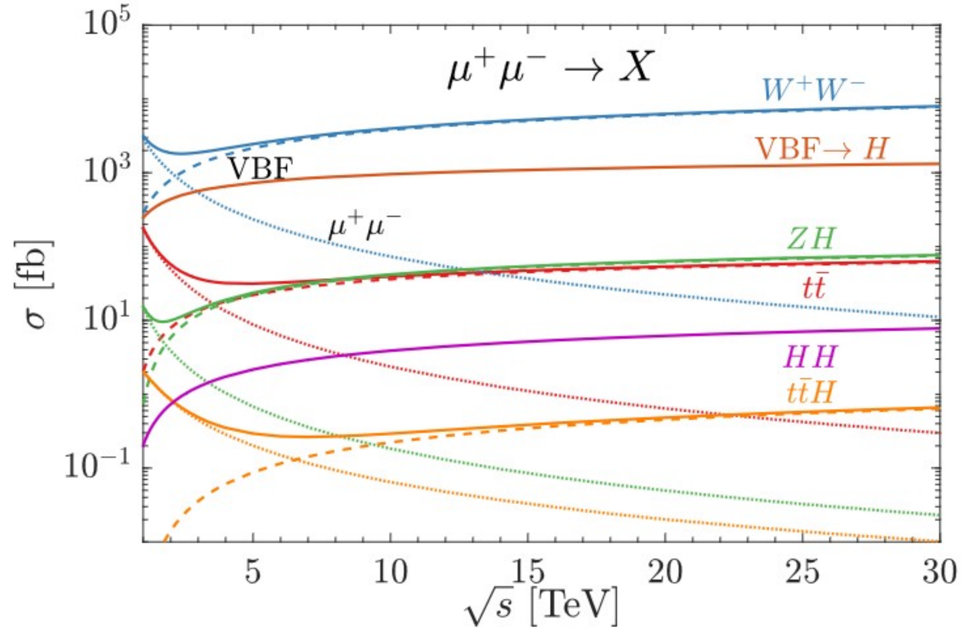
Vector Boson Fusion (x << 1)



Concept of **EW PDFs** useful for parametrizing productions.



Standard Model (background) cross-sections.
VBF (solid) dominates over annihilation (dashed).



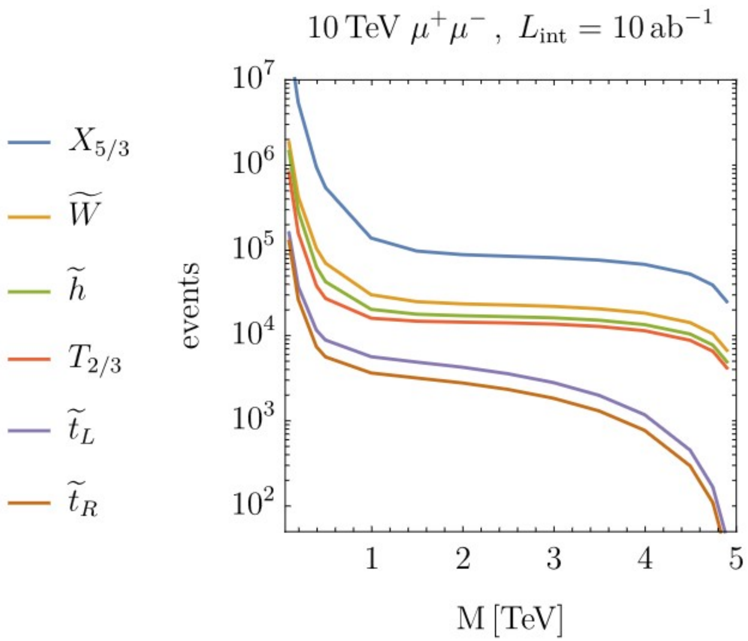
arXiv:2007.14300

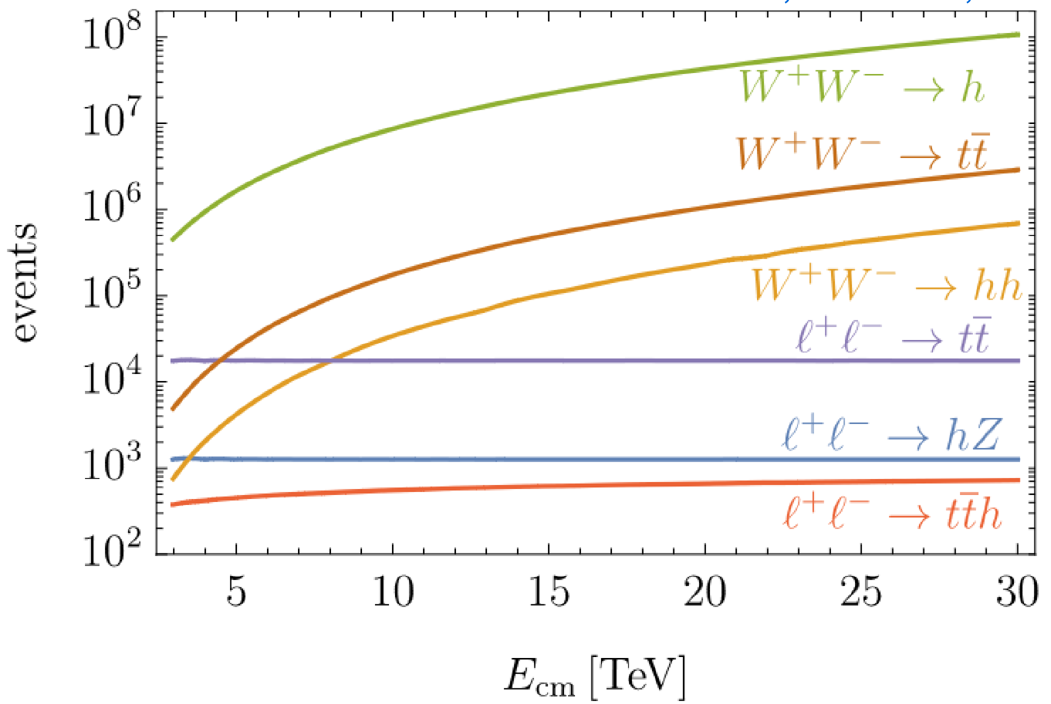
Muon collider is a vector-boson collider

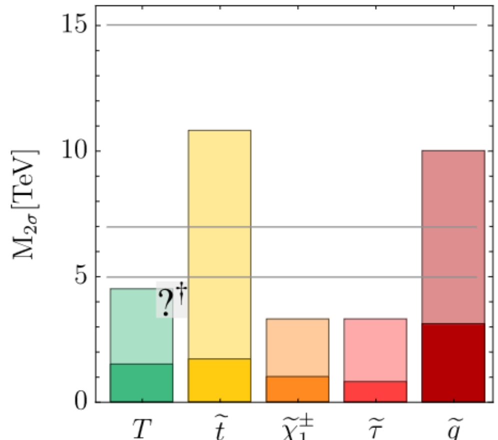
Event Counts

A few common BSM signals (left) and backgrounds (right).

Buttazzo, Franceschini, Wulzer







† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

100 TeV

14 TeV

10 TeV

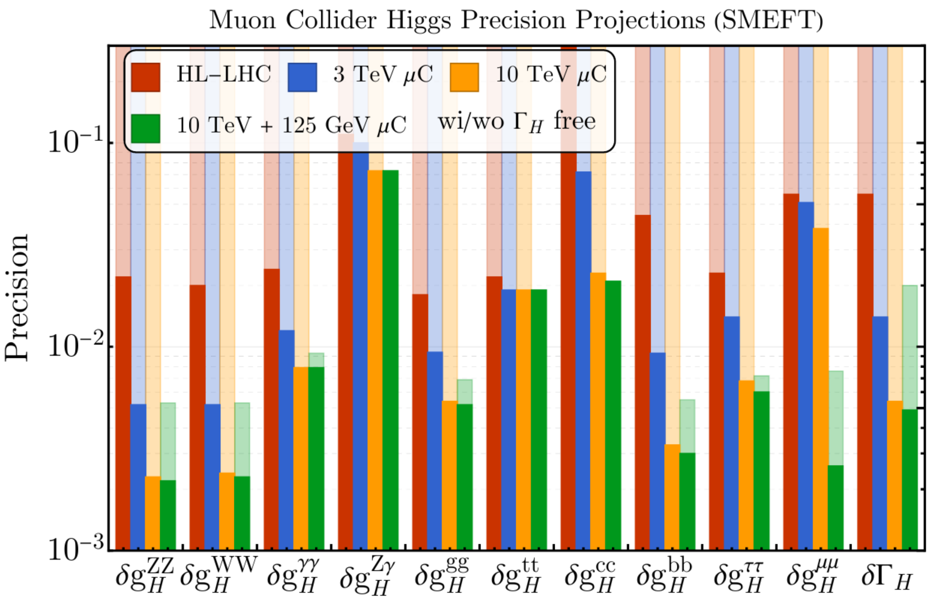
Tentative event reach *competitive* with FCChh for **EW states**.

Reach is tentative as detector effects and more detailed analysis needed.

Solid: HL-LHC

Transp: FCChh

Couplings and Higgs Width



	HL-LHC	ILC (500)	FCC-ee/hh	μC (10 TeV)
hZZ	1.5	0.17	**0.12**	0.33
hWW	1.7	0.20	0.14	**0.10**
hbb	3.7	0.50	0.43	**0.23**
hγγ	3.4	0.58	**0.44**	0.55
hgg	2.5	0.82	0.49	**0.44**
hcc	-	1.22	**0.95**	1.8
hττ	1.8	1.22	**0.29**	0.71
hγZ	9.8	10.2	**0.69**	5.5
hμμ	4.3	3.9	**0.41**	2.5
htt	3.4	2.82	1.0	3.2
Γ_{tot}	5.3	0.63	1.1	**0.5**

- **>10 TeV μC required for Higgs physics**
- **Precision competitive with FCC-ee/hh**
  - Except couplings with small BR's

Higgs Self-Coupling (SM DiHiggs)

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [51, 52]	49%	–	49%
ILC$_{500}$/C^3-550 [51, 52]	38%	20%	20%
CLIC$_{380}$ [54]	50%	–	50%
CLIC$_{1500}$ [54]	49%	36%	29%
CLIC$_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

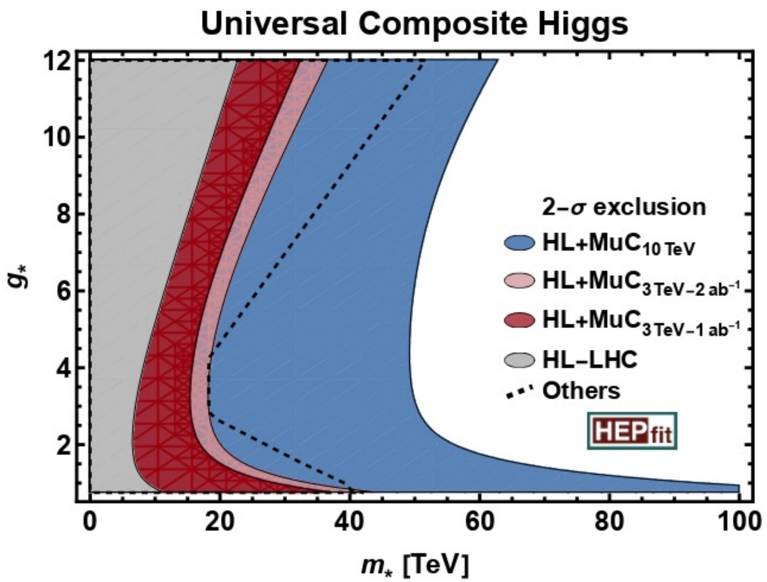
Multi-TeV collider is required for higgs self-coupling

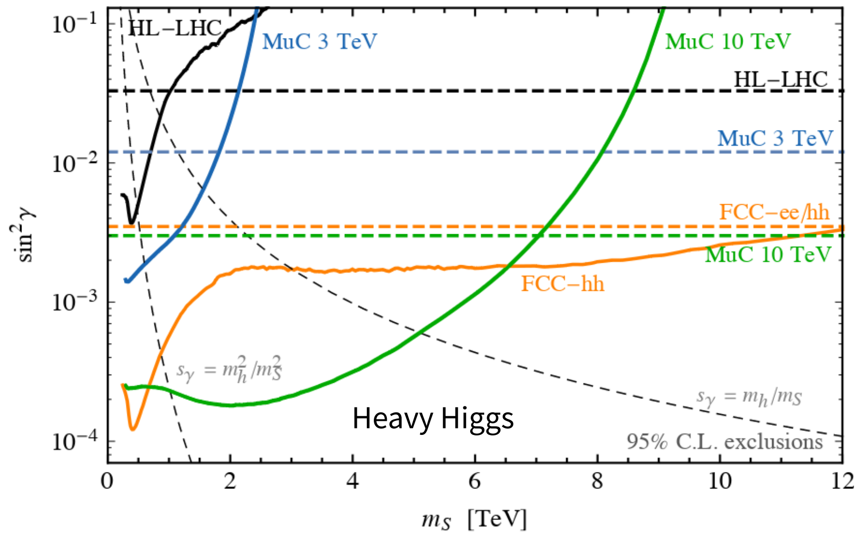
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

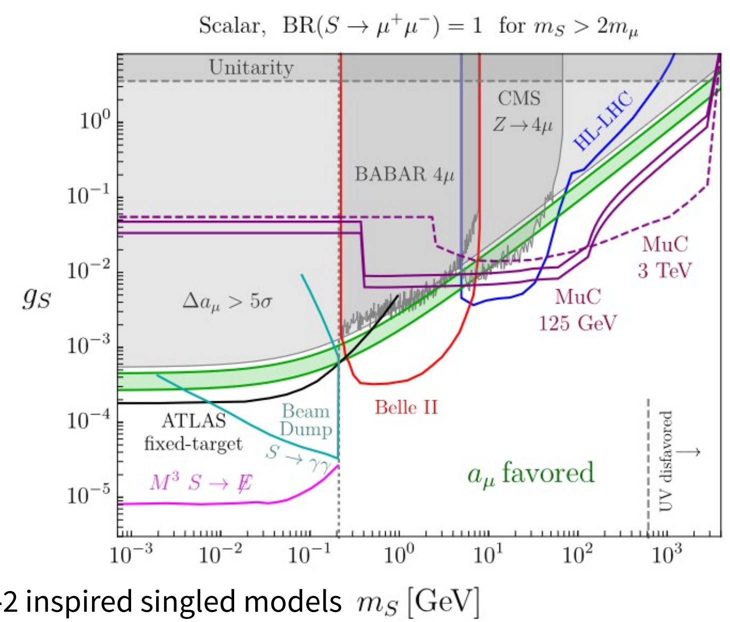
Credit: R. Petrossian-Byrne, N. Craig

And many more...

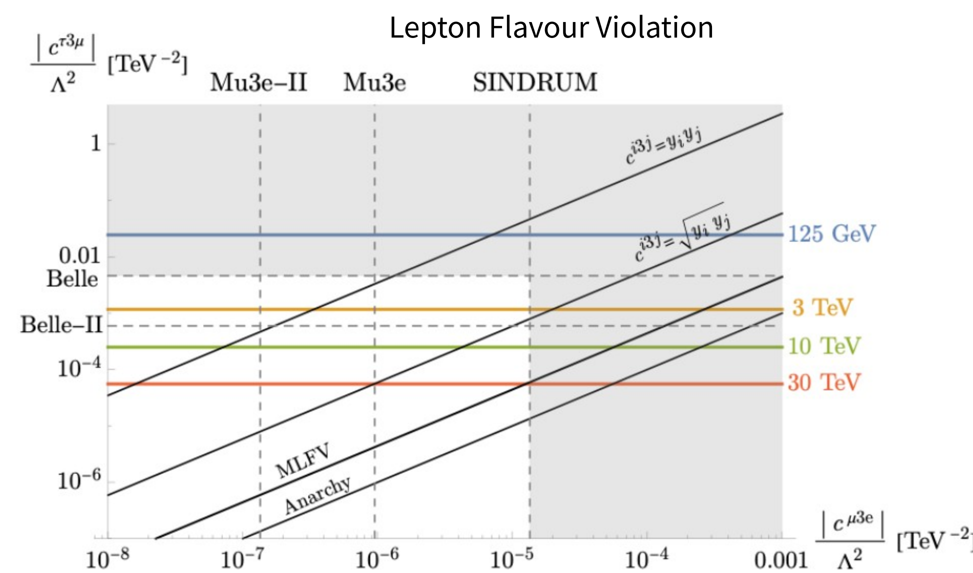
Towards a muon collider







g-2 inspired singled models



Three Challenges

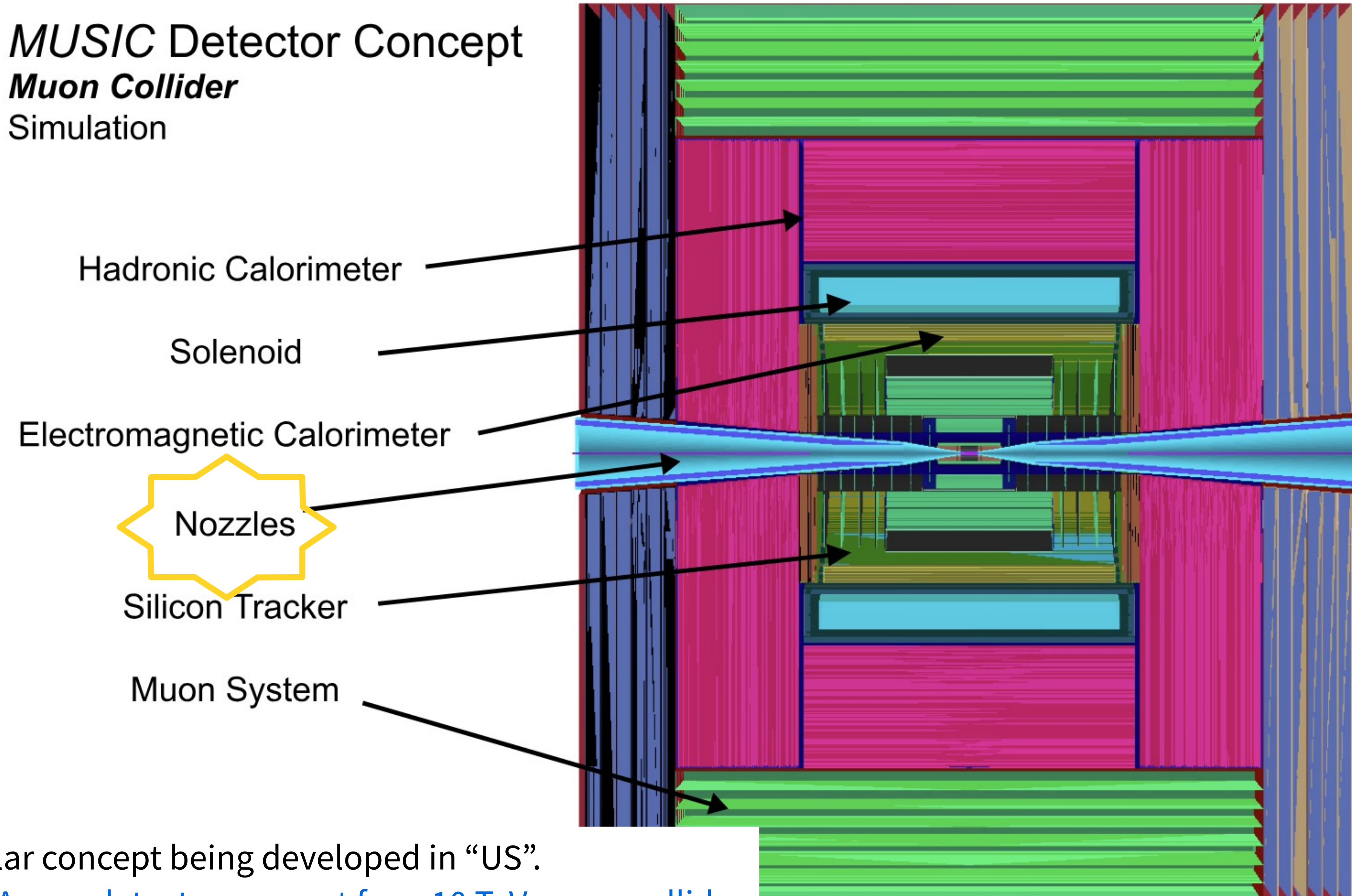
The Detector

Is the collision environment clean for precision physics?

- **How to deal with Beam Induced Background**

The MUSIC Detector

10 TeV concept developed for EPSSU



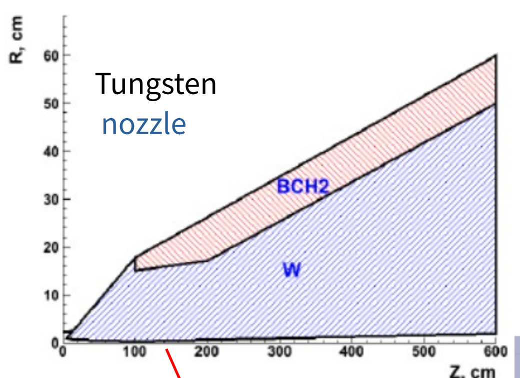
A similar concept being developed in "US".

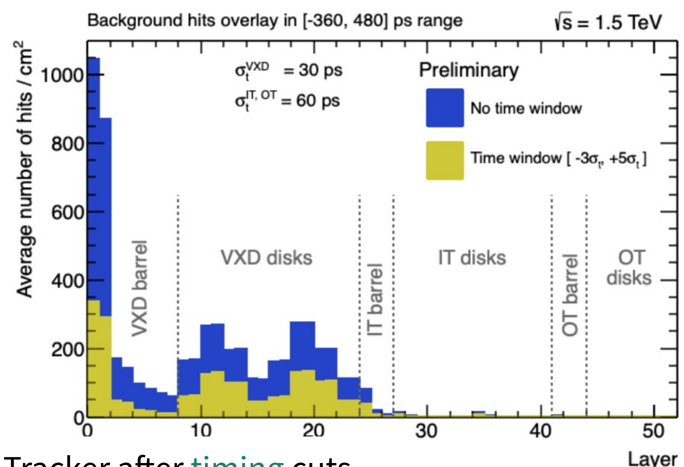
MAIA: A new detector concept for a 10 TeV muon collider

Beam Induced Background

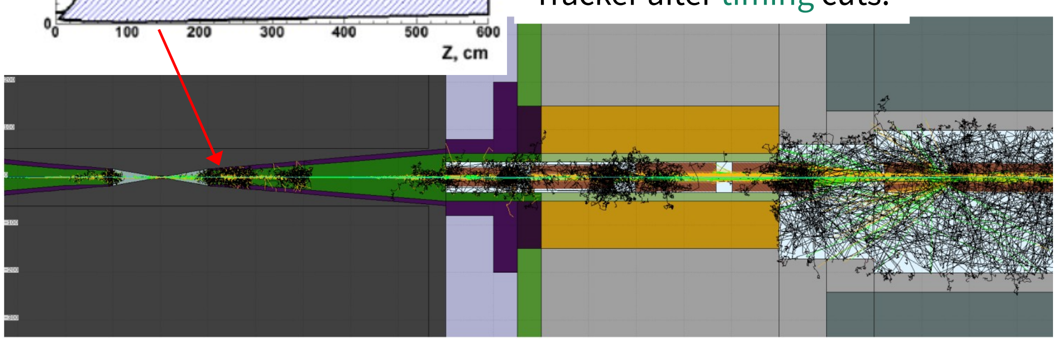
arxiv:2105.09116

- **BIB = muon beam decays and strike the detector**
- **Several main mitigation**
  - 10° tungsten nozzle to shield from beam decay products
  - Precision timing information from detectors

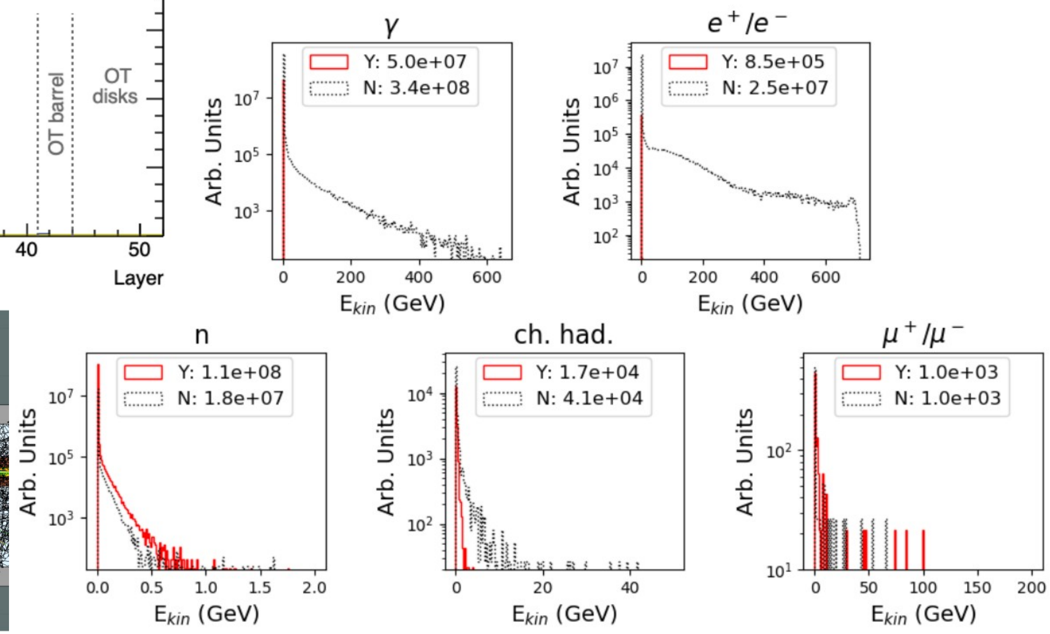




Tracker after timing cuts.



FLUKA simulation of BIB before reaching the detector.



Particle energy spectra with (Y) and without (N) nozzle.

All-Silicon Tracking Detector

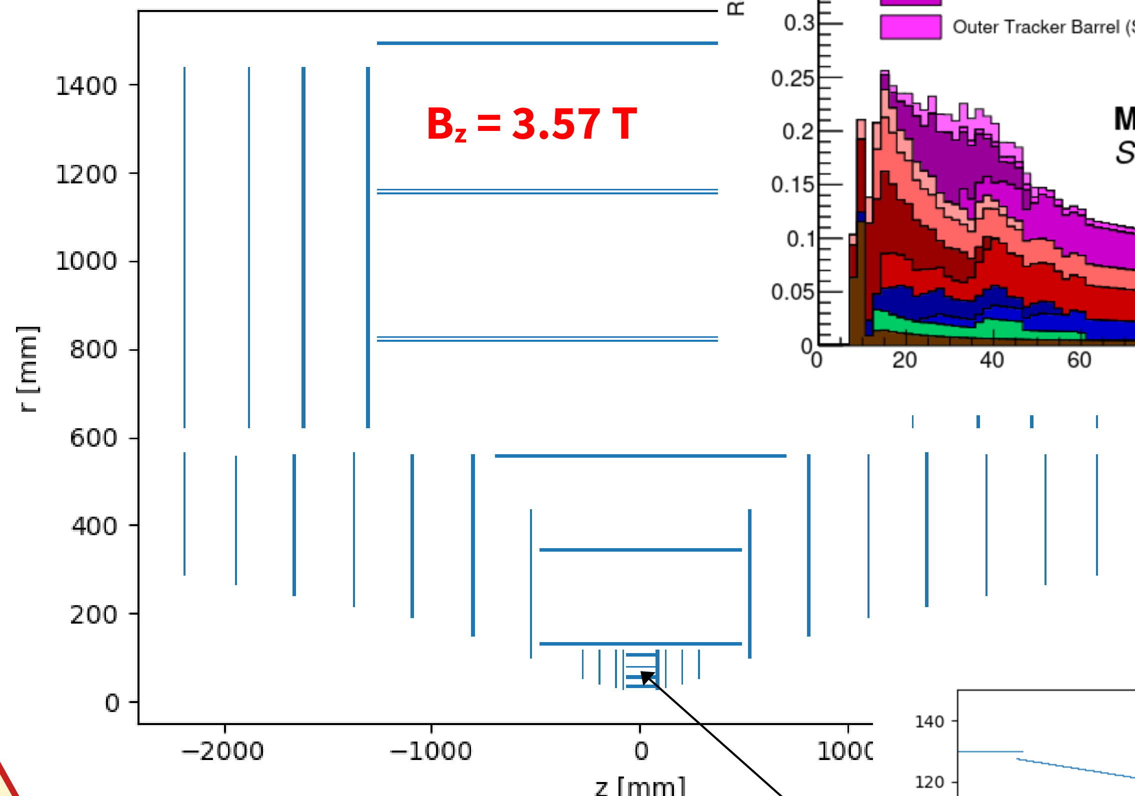
Plots from 1.5 TeV detector concept.

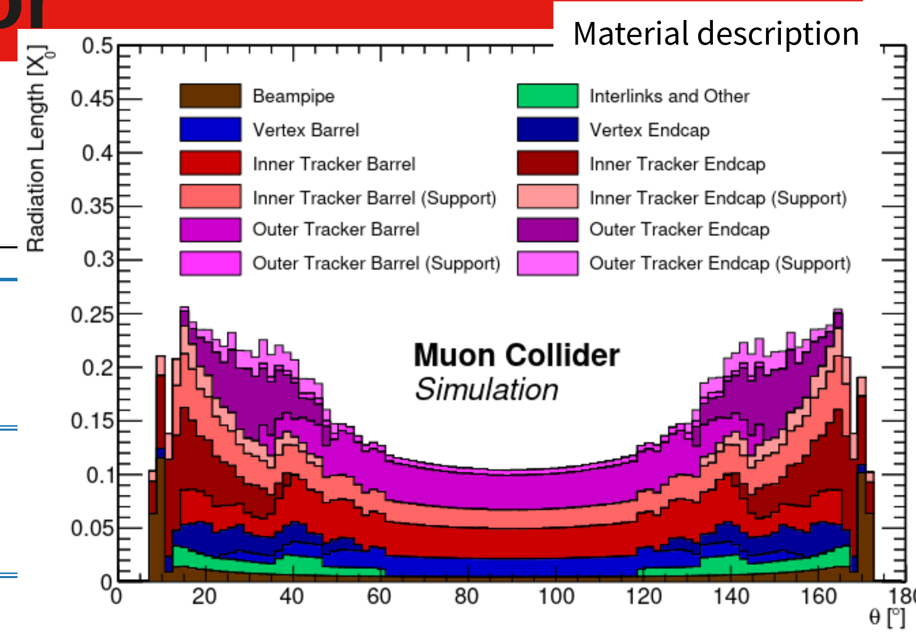
Outer Tracker (OT)

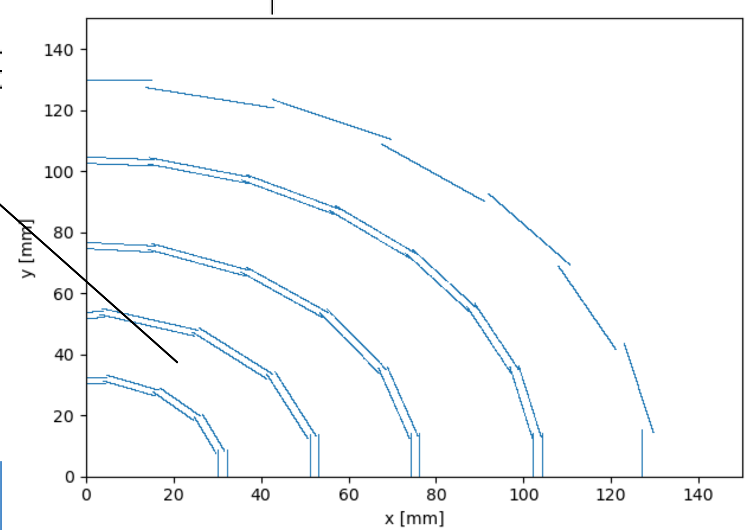
- micro-strips
- 50 µm x 10 mm
- σ_t = 60 ps

Inner Tracker (IT)

- macro-pixels
- 50 µm x 1 mm
- σ_t = 60 ps





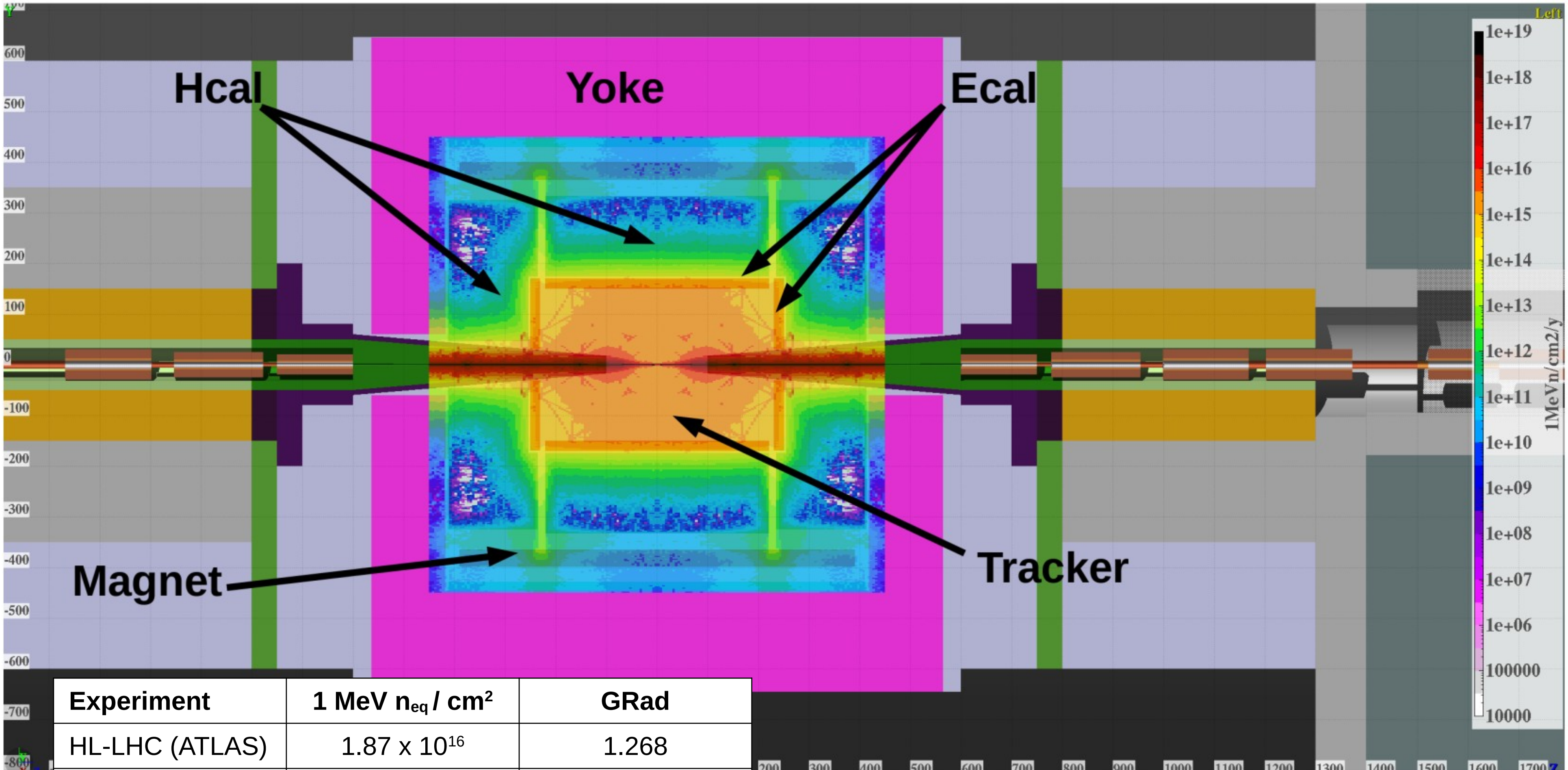


Vertex Detector (VXD)

- pixels
- 25 µm x 25 µm
- σ_t = 30 ps
- double layers

4D tracking critical

Plots from 1.5 TeV detector concept.

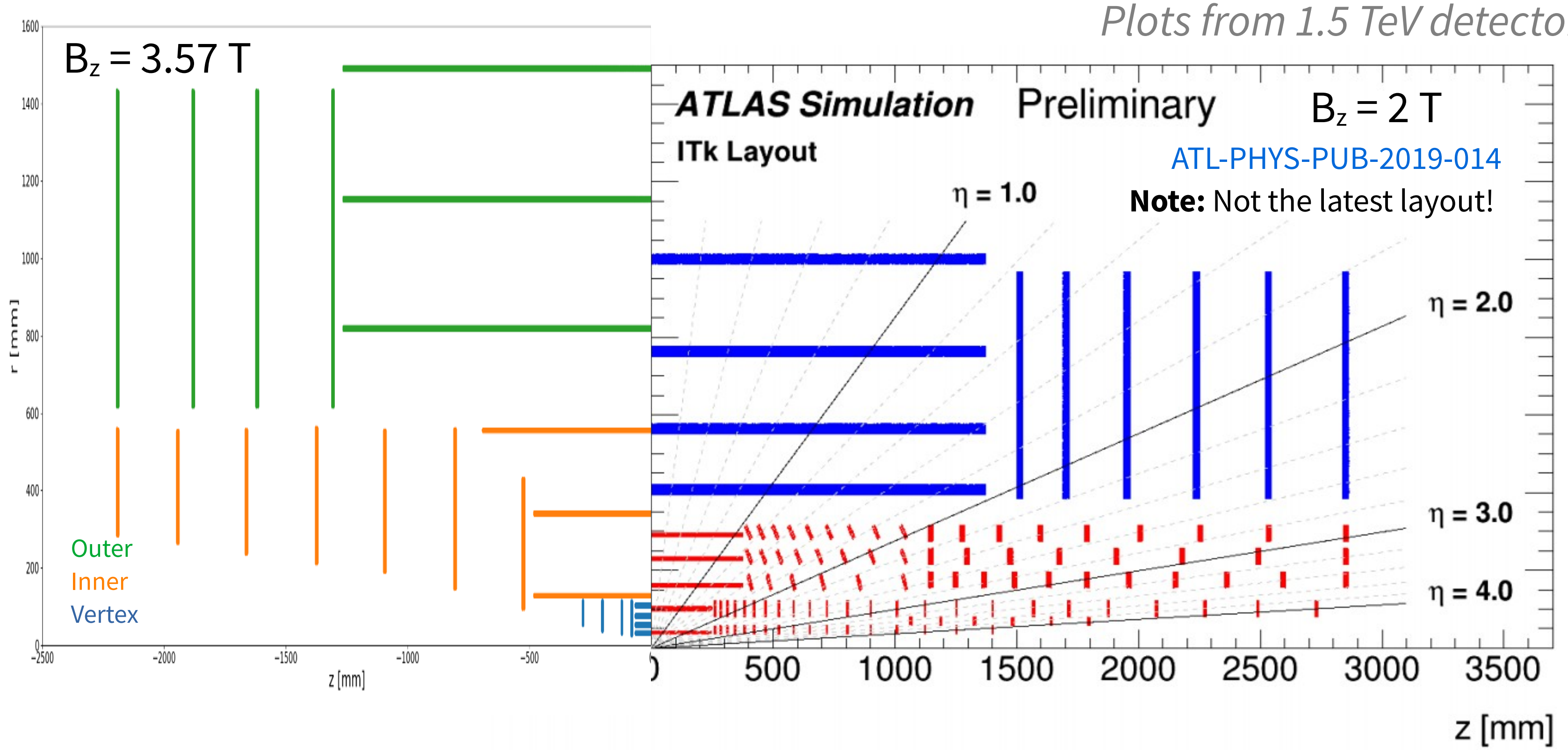


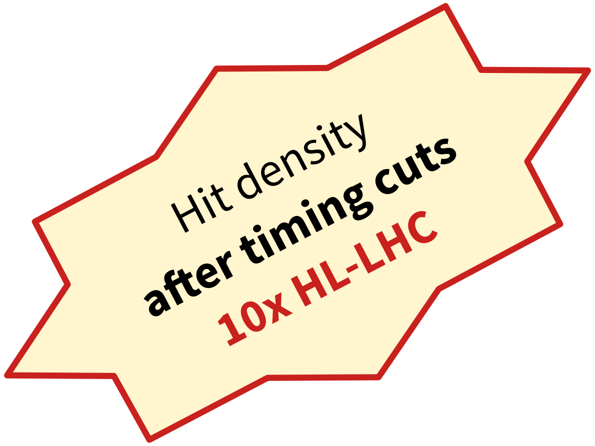
Experiment	1 MeV n_{eq} / cm^2	GRad
HL-LHC (ATLAS)	1.87×10^{16}	1.268
µC (1.5 TeV)	5×10^{15}	0.05
FCChh	8×10^{17}	27
FCCee	? not big ?	? not big ?

Expected dose in innermost tracking layer.

The Scale of BIB

Plots from 1.5 TeV detector concept.





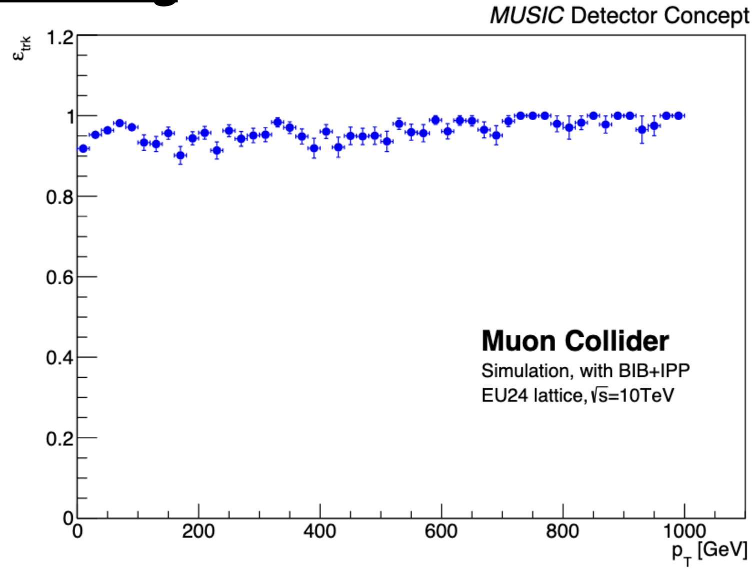
	ITk Hit Density [mm^{-2}]	MCC Equiv. Hit Density [mm^{-2}]
Pix Lay 0	0.643	3.68
Pix Lay 1	0.022	0.51
Str Lay 1	0.003	0.03

ITk Pixels TDR, ITk Strips TDR

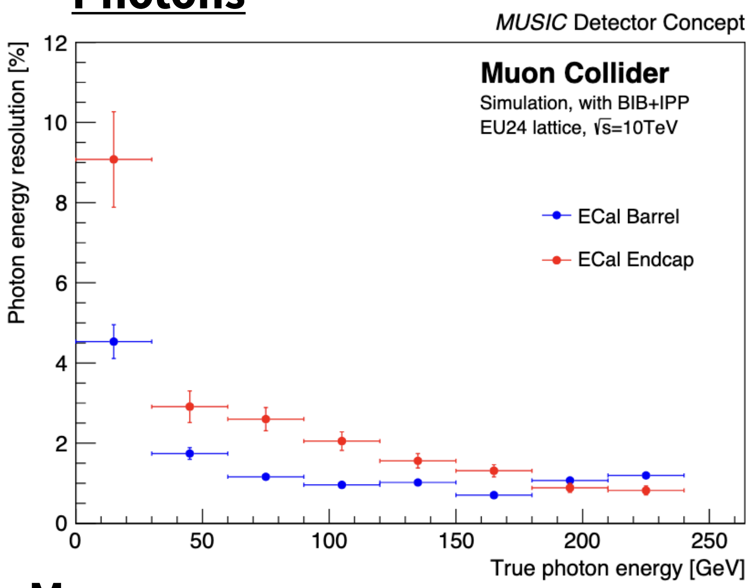
Object Reconstruction

[Similar plots exist for MAIA.]

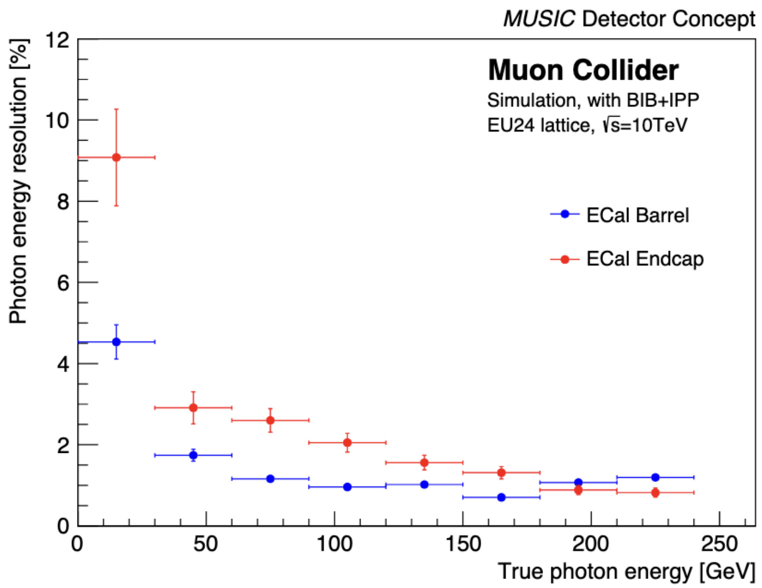
Tracking



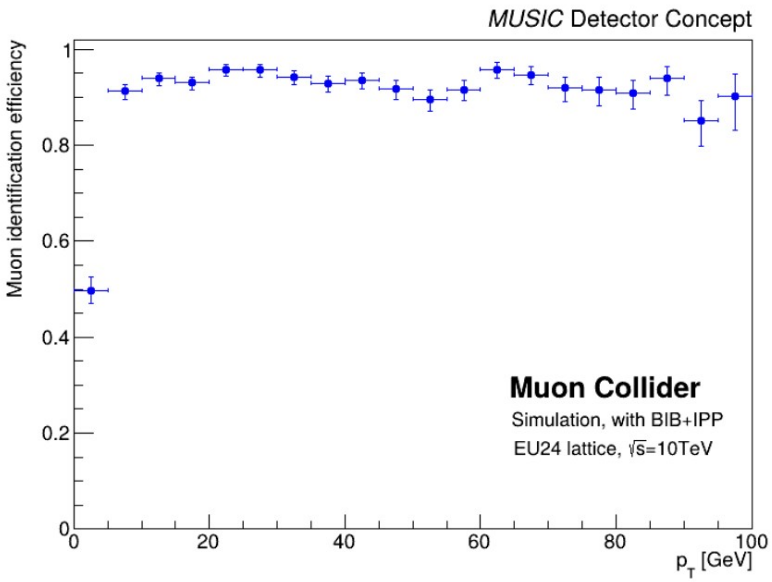
Photons



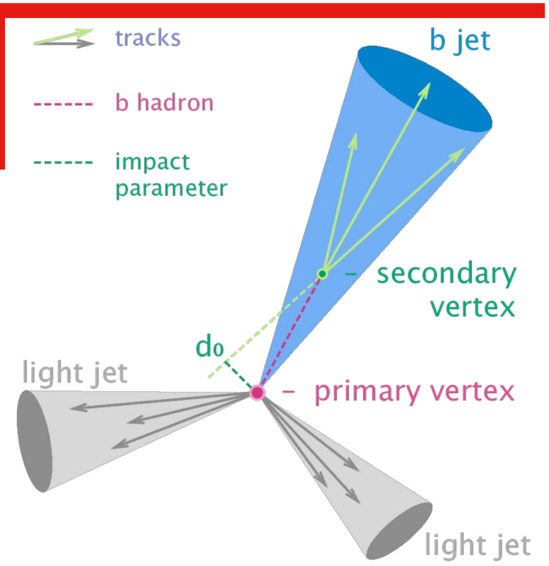
Jets



Muons

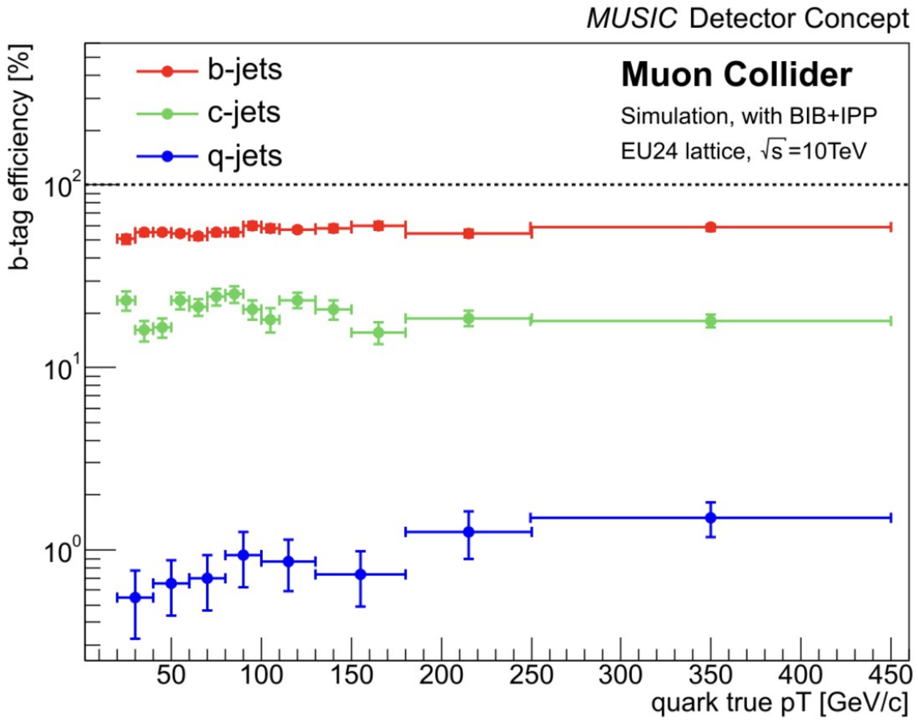


b-jet identification

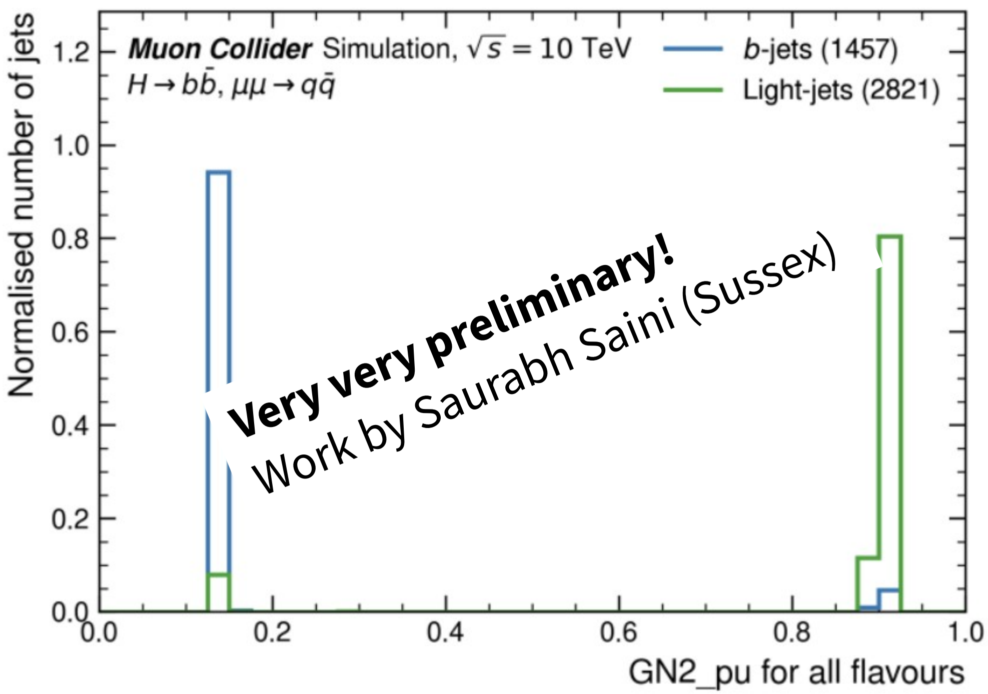


- **Important for Higgs studies.**
  - Most common decays is into two b-quarks.

by explicit secondary vertex reconstruction



by Machine Learning (ATLAS SALT framework)



Detector R&D

Similar challenges at FCChh and μC, but μC is easier.

** Sorry for tracking bias.

Source: The 2021 ECFA detector research and development roadmap (with updates).

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	HIKE 2030 ☹	Belle II 2026	ALICE LS3 [1]	ALICE 3	LHCb (≳LS4)[1]	ATLAS/CMS (≳ LS4)[1]	EIC	LHeC	ILC [2]	FCC-ee	CLIC [2]	FCC-hh ~2070	FCC-eh	Muon Collider ~2045
Vertex Detector[3]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	50
			Wafers area (")[4]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns)[5]	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL ($\times 10^{16}$ neq/cm^2)			1				≃ 6	≃ 2						≃ 10^2		0.5
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		0.05

Technology demonstrators?

4D tracking, high data rates, rad hard

Conclusions

Muon Collider is competitive with FCC, but "simpler".

Physics

- Increase in activity as part of ESPPU/Snowmass studies.
- 10 TeV collider meets the necessary goals.

Accelerator

- See all other talks today!

Detector

- Beam Induced Backgrounds creates a very unclean environment.
- Two concepts with advanced object reconstruction studies.
  - Created since Snowmass. Shows maturity of framework.
- *Lots of progress, but still need to understand effect on physics goals.*

BACKUP SLIDES

Our (1.5 TeV) Onion Detector

10 TeV concept developed for EPSSU

heavily based on CLIC detector

hadronic calorimeter

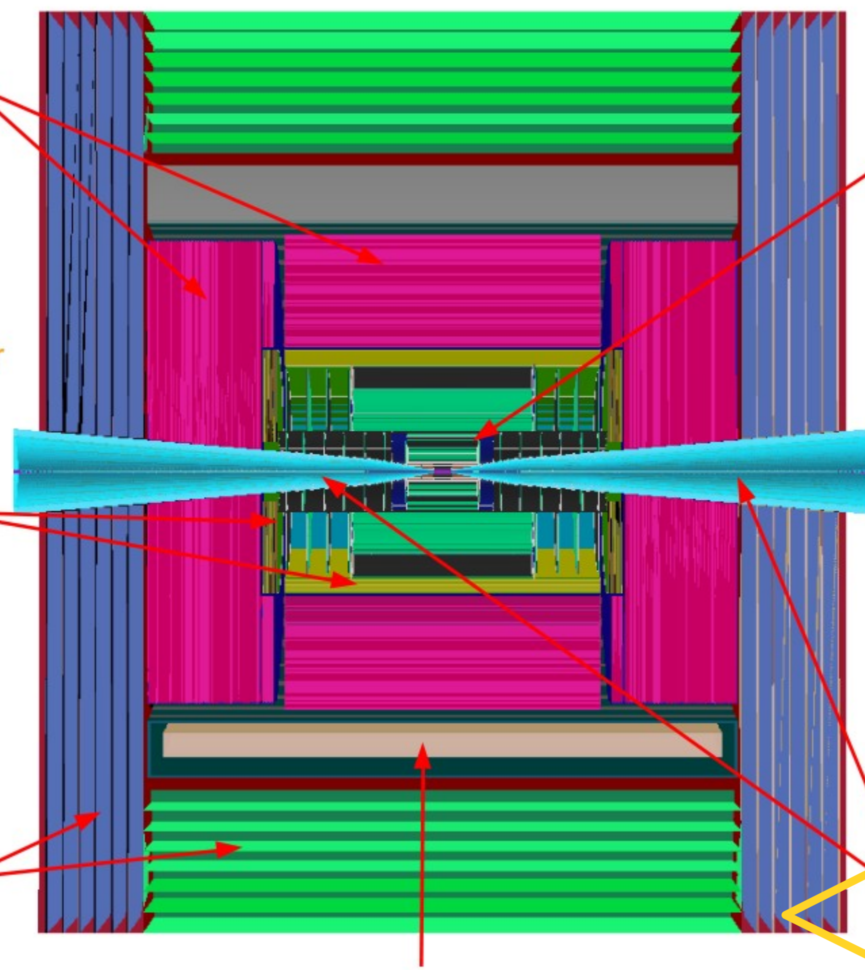
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.



superconducting solenoid (3.57T)

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

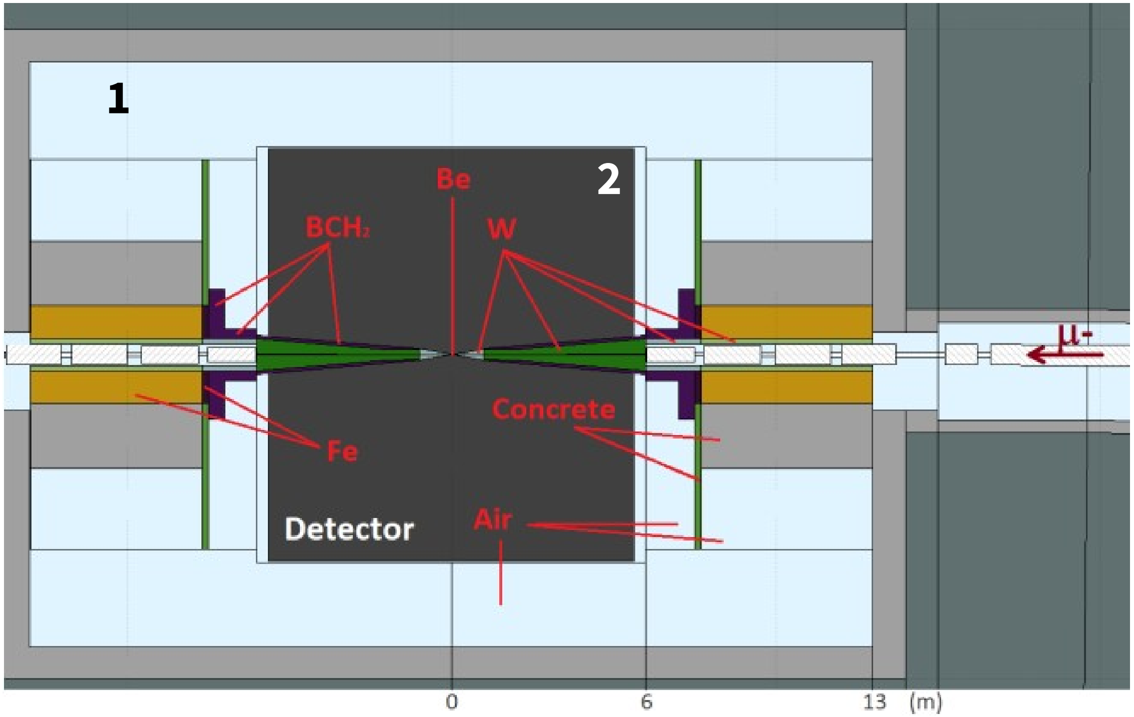
- Tungsten cones + borated polyethylene cladding.

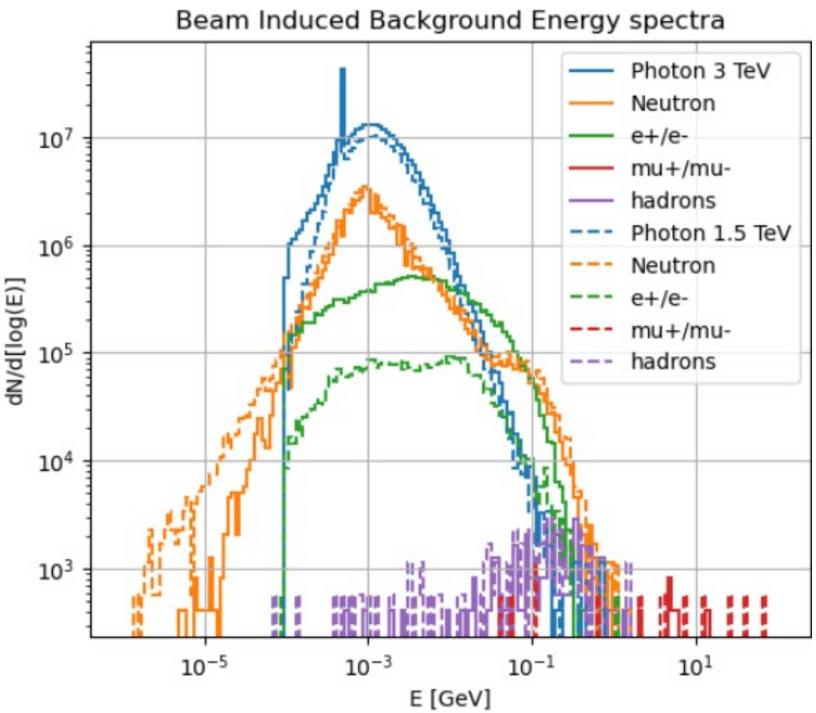
Simulating Beam Induced Background

1) Muon trajectory, decay and transport of products via FLUKA

- Full beam optics present through LineBuilder Interface

2) GEANT simulation of particles entering the detector

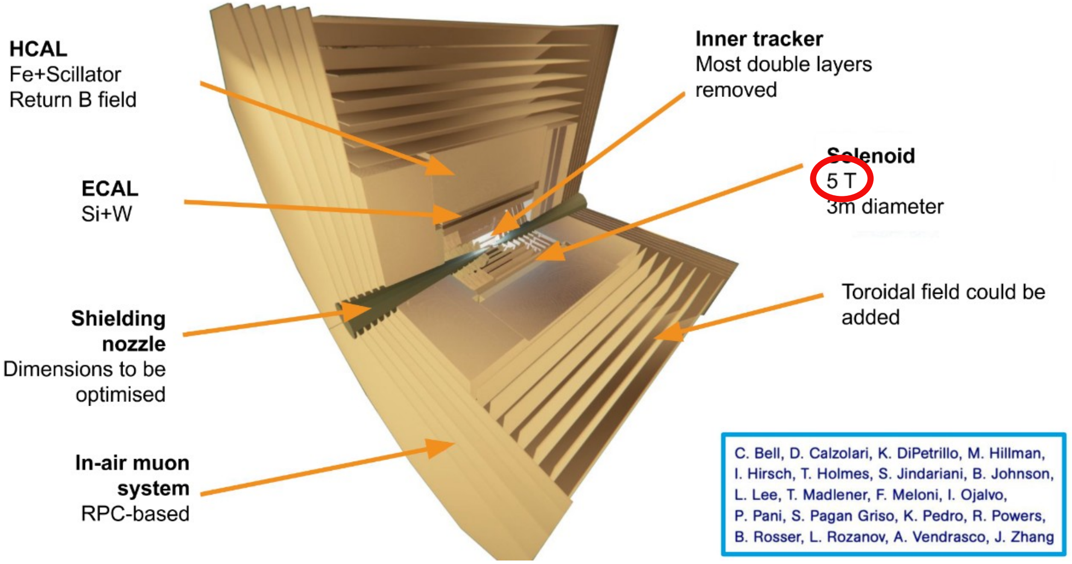




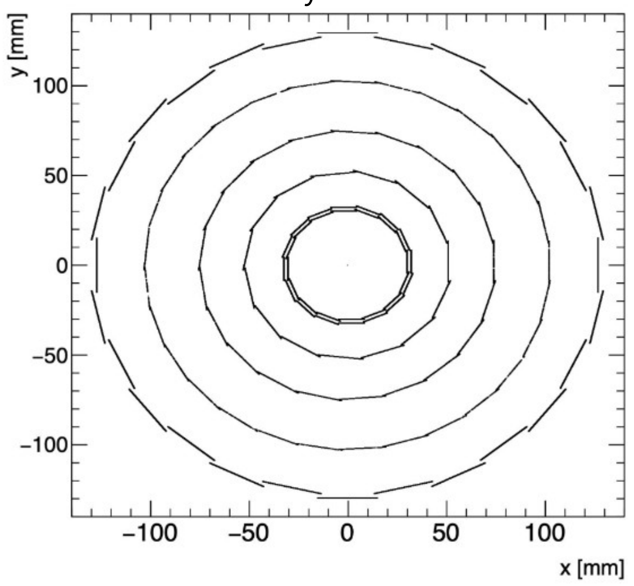
1.5 TeV vs 10 TeV

Summary by B. Rosser

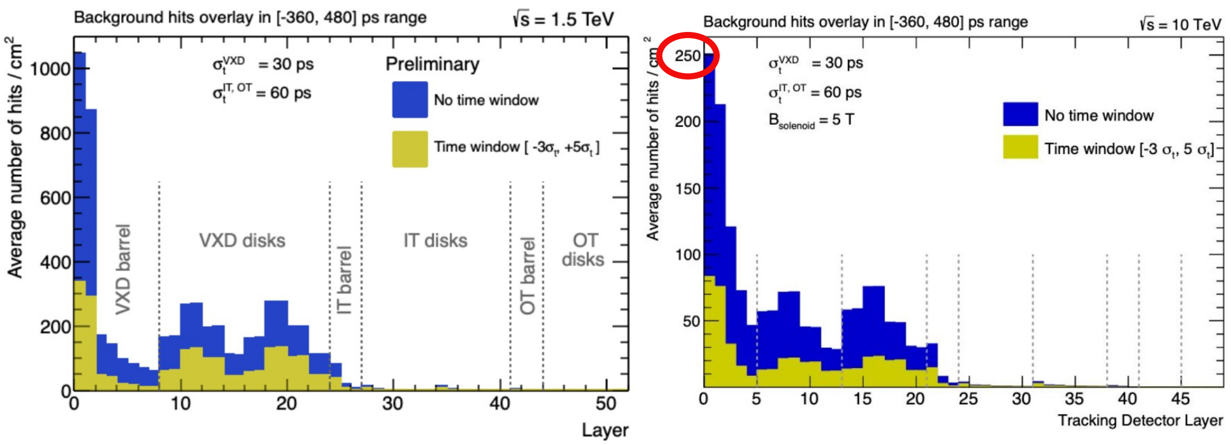
Concept developed at KITP workshop at Santa Barbara



Removed double layers in tracker



BIB is less of an issue.



But scattered muons from ZZh are more forward (nozzle)

M. Forslund, Muon Collider Workshop at FNAL, Dec. 15, 2022