Detectors for Muon Collider

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International MUON Collider Collaboration

UNIVERSITY OF BIRMINGHAM

UK Muon Collider

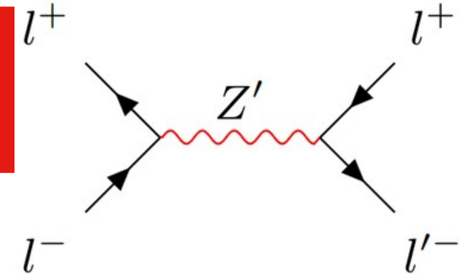
Three Challenges

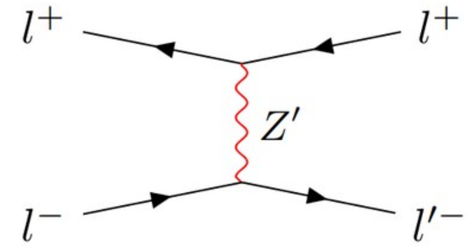
The Physics

Will a Muon Collider satisfy the physics goals?

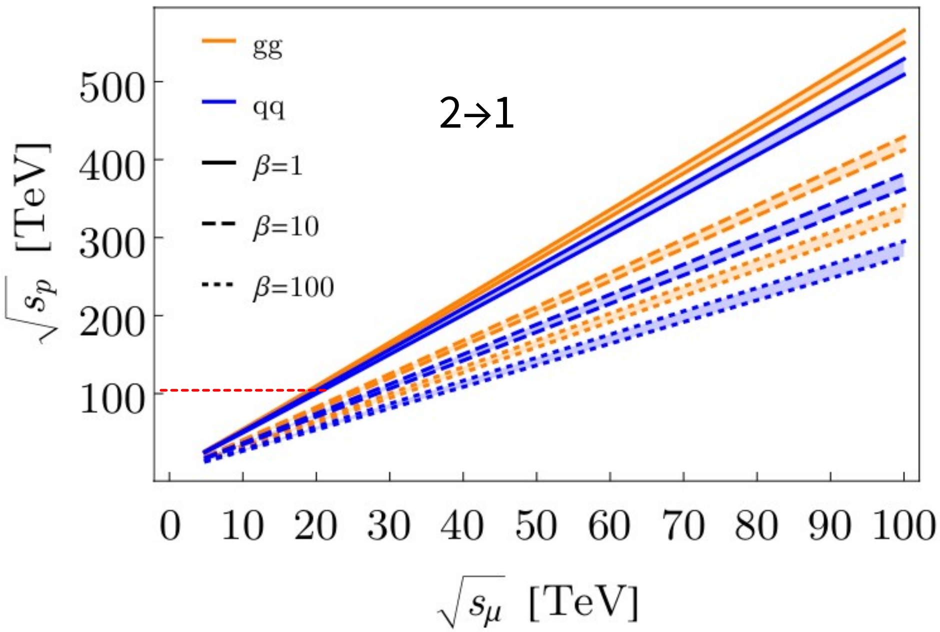
- **Precision Higgs couplings**
- **BSM at higher energies**

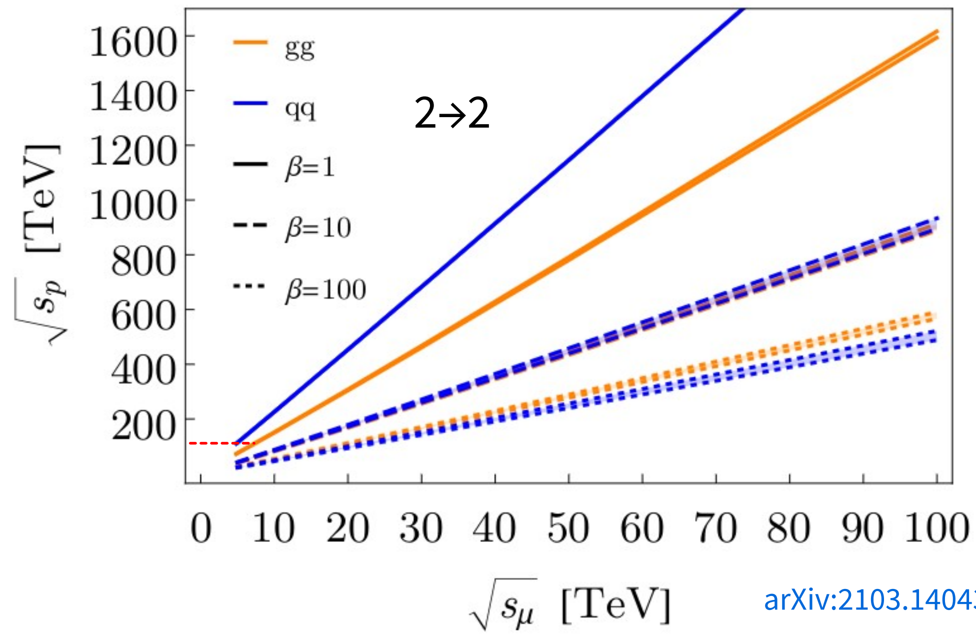
Direct Searches





Muons are elementary = full beam energy used in collision

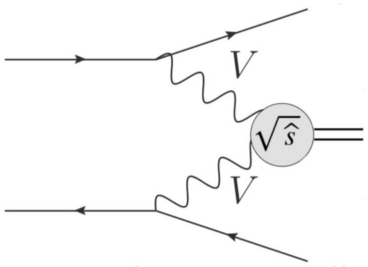




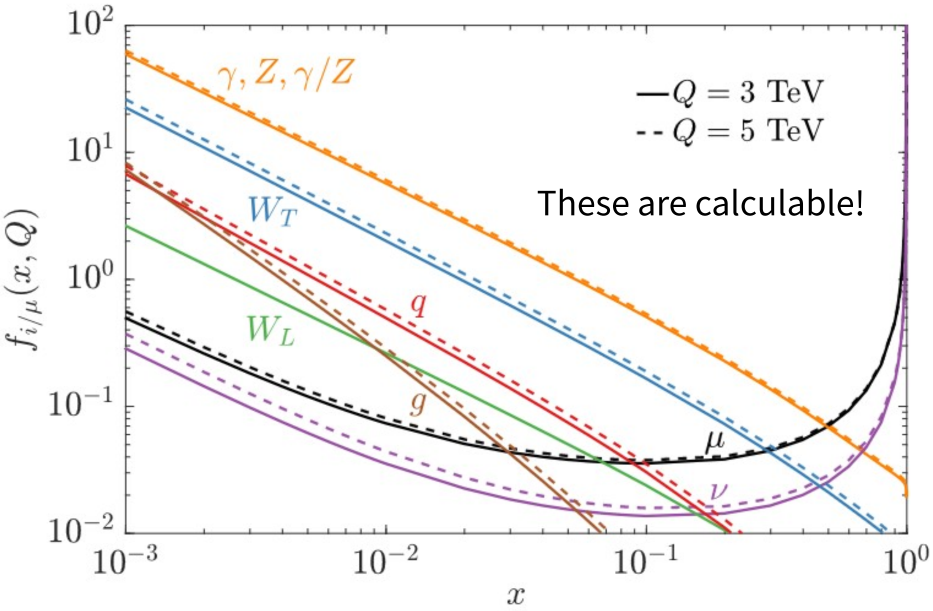
arXiv:2103.14043

100 TeV pp ≈ 10-20 TeV μμ

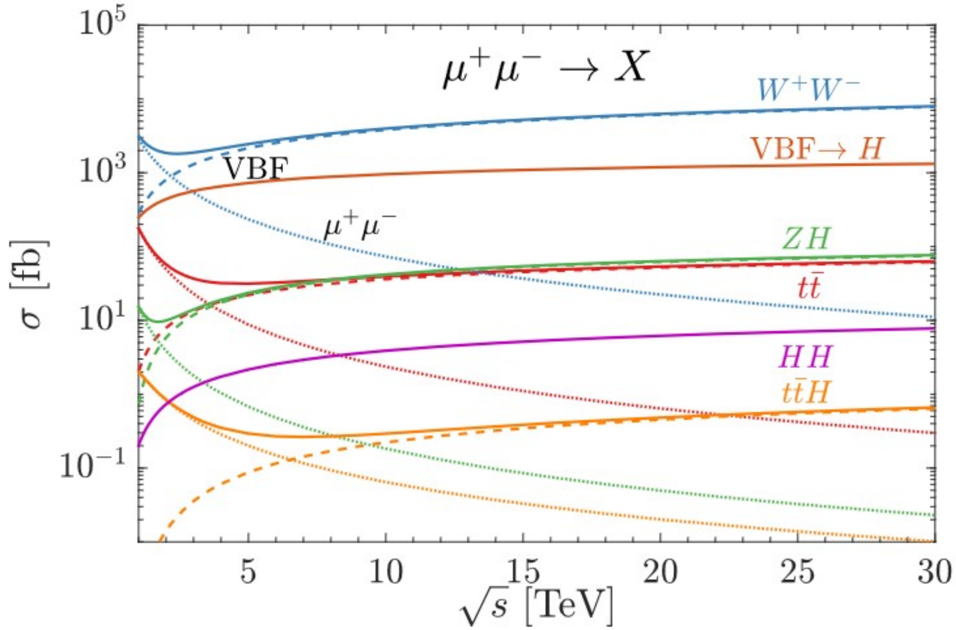
Vector Boson Fusion (x << 1)



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



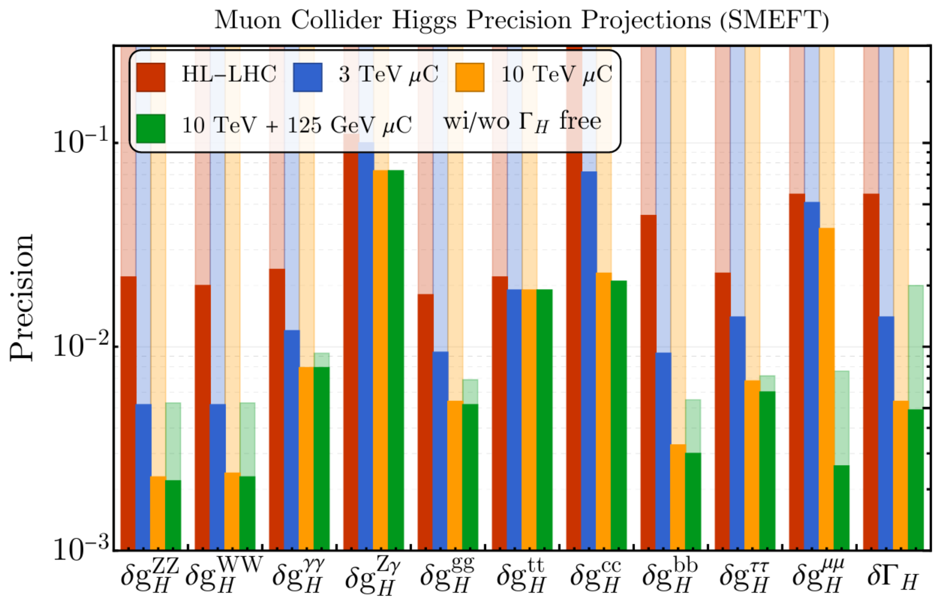
Standard Model (background) cross-sections.
VBF (solid) dominates over annihilation (dashed).



arXiv:2007.14300

Muon collider is a vector-boson collider

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)

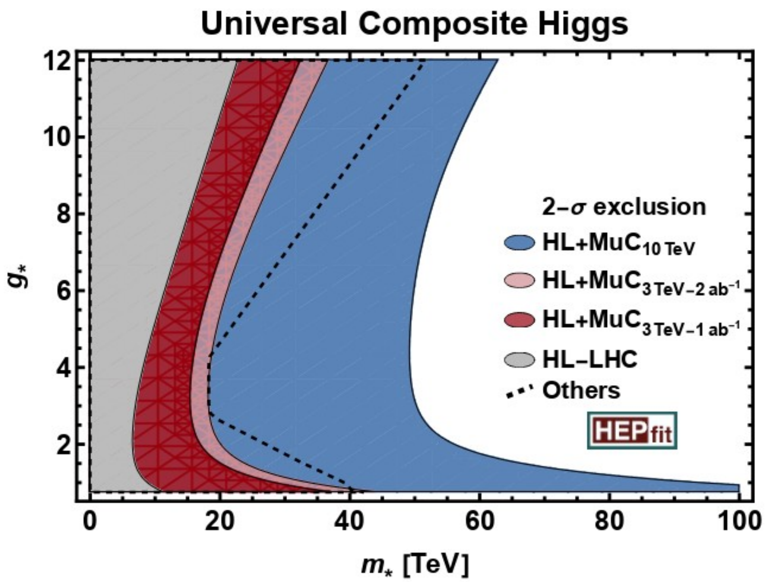
collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%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

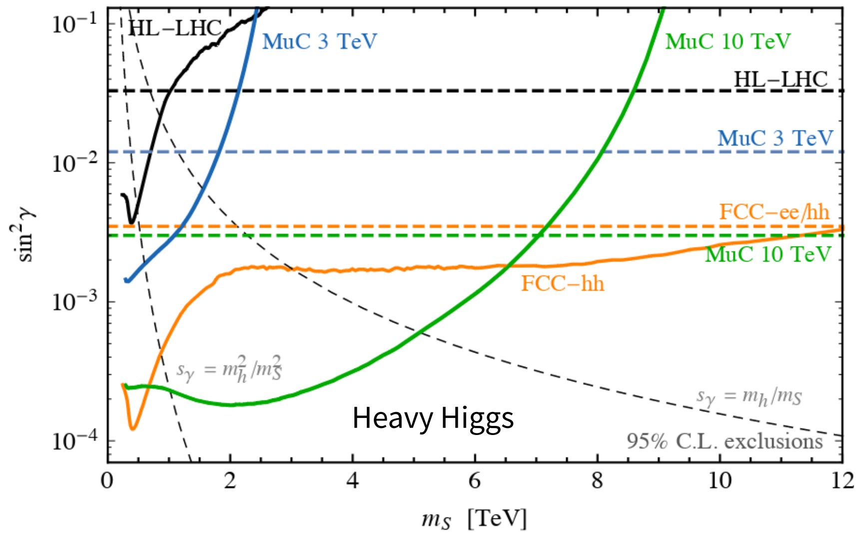
Multi-TeV collider is required for higgs self-coupling

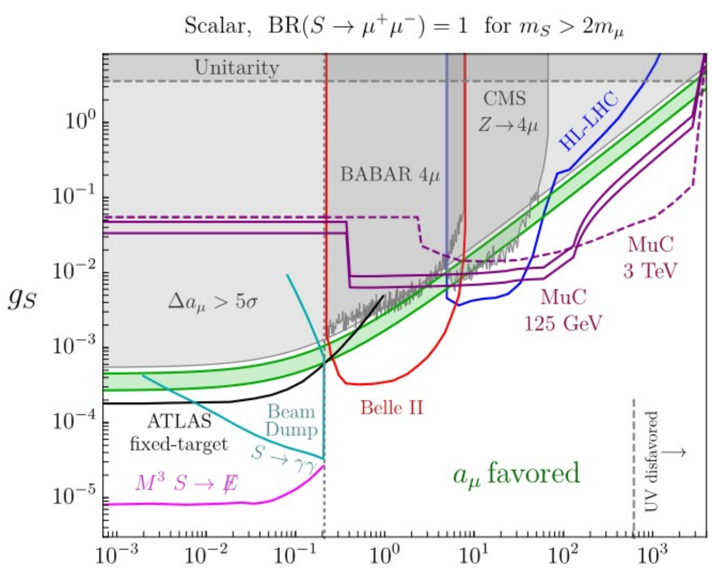
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

Credit: R. Petrossian-Byrne, N. Craig

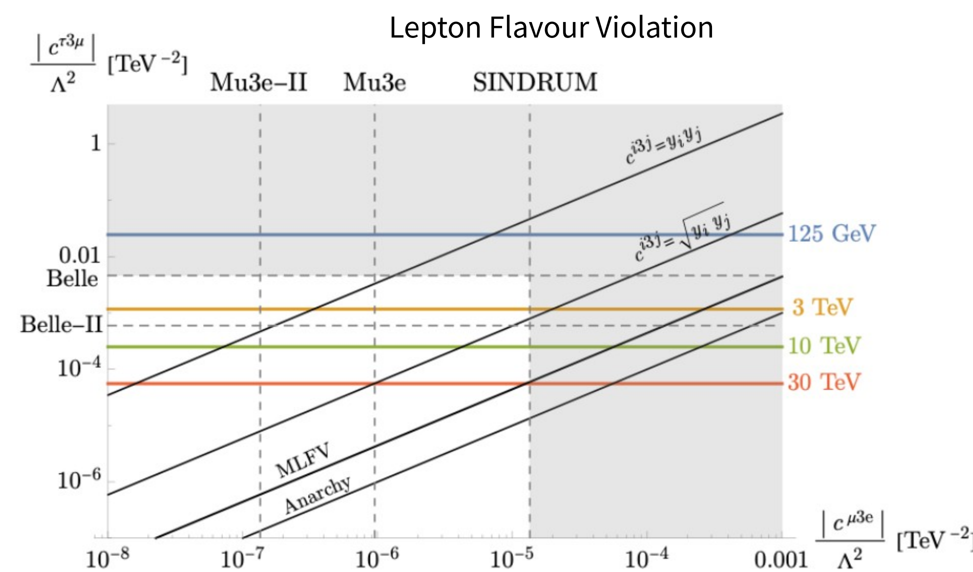
And many more...







g-2 inspired singled models m_S [GeV]



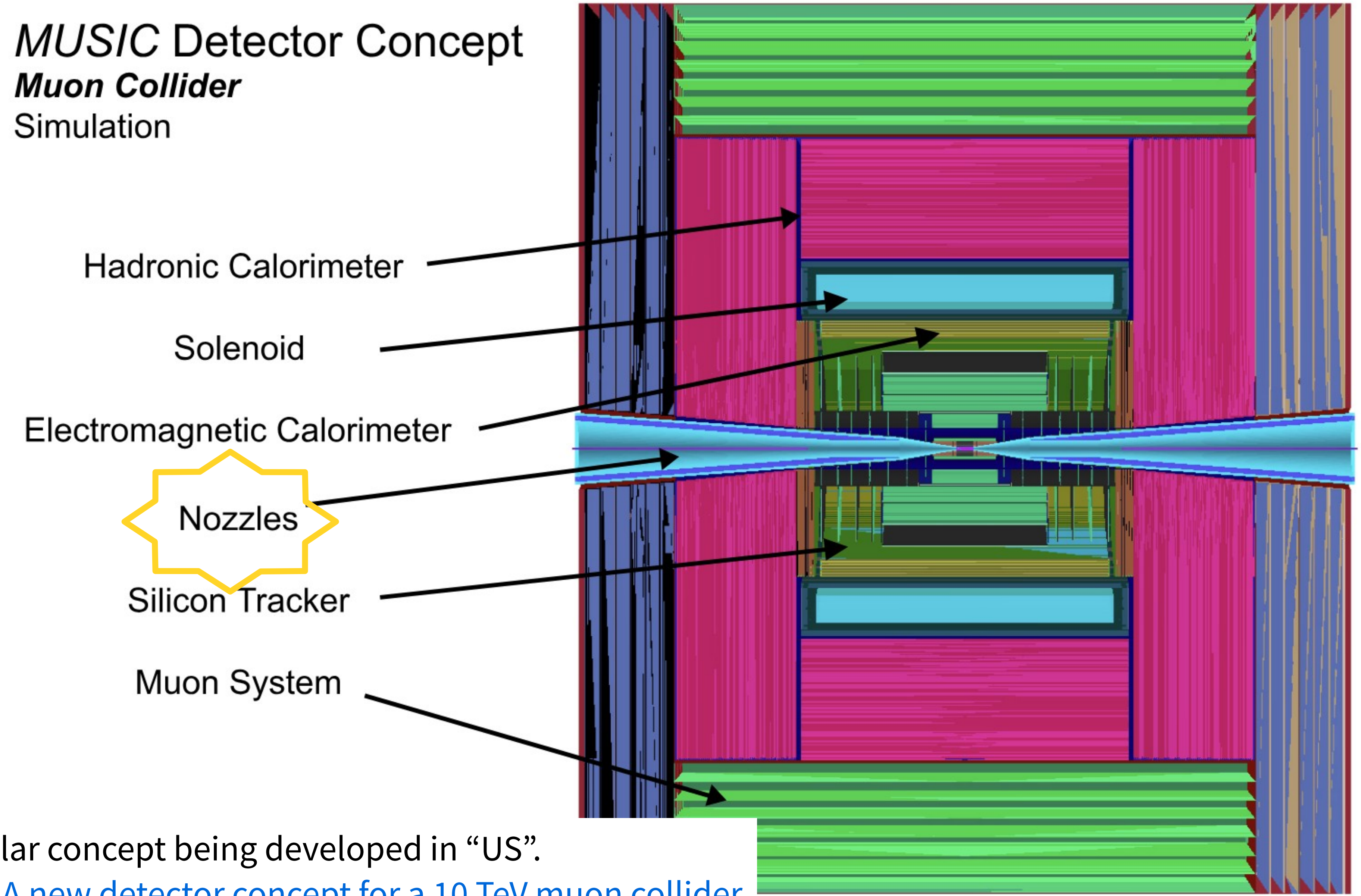
Three Challenges

The Detector

Is the collision environment clean for precision physics?

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

The MUSIC Detector

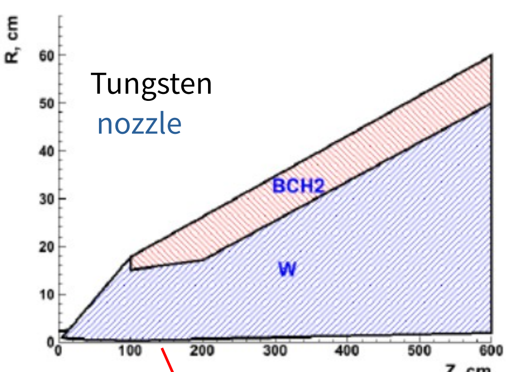


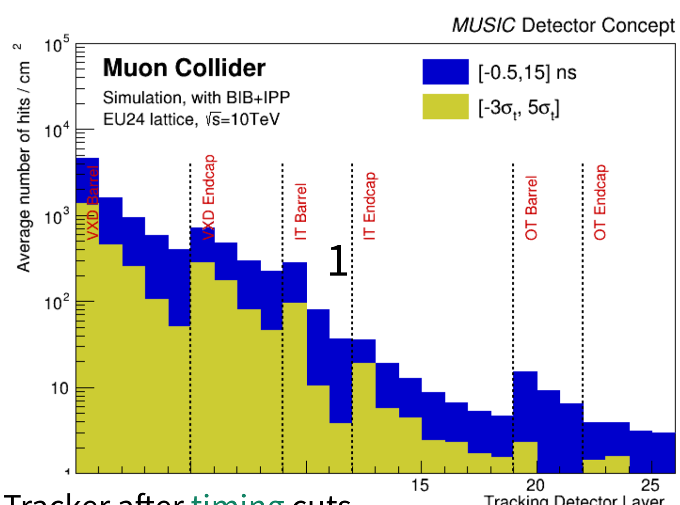
A similar concept being developed in "US".

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

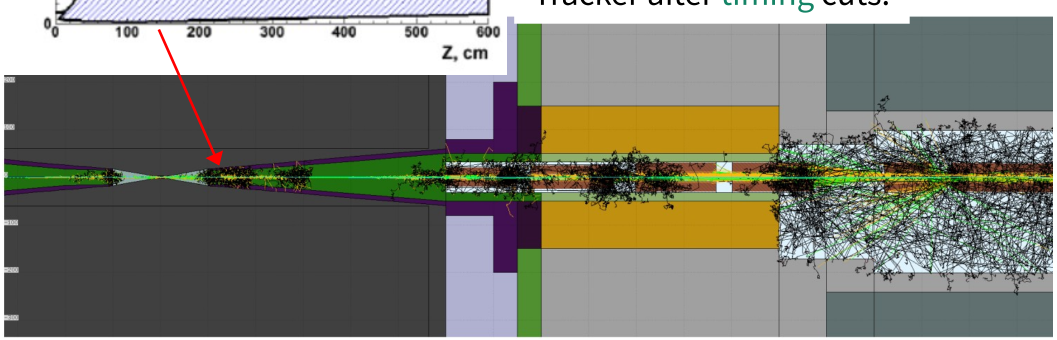
Beam Induced Background

- **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

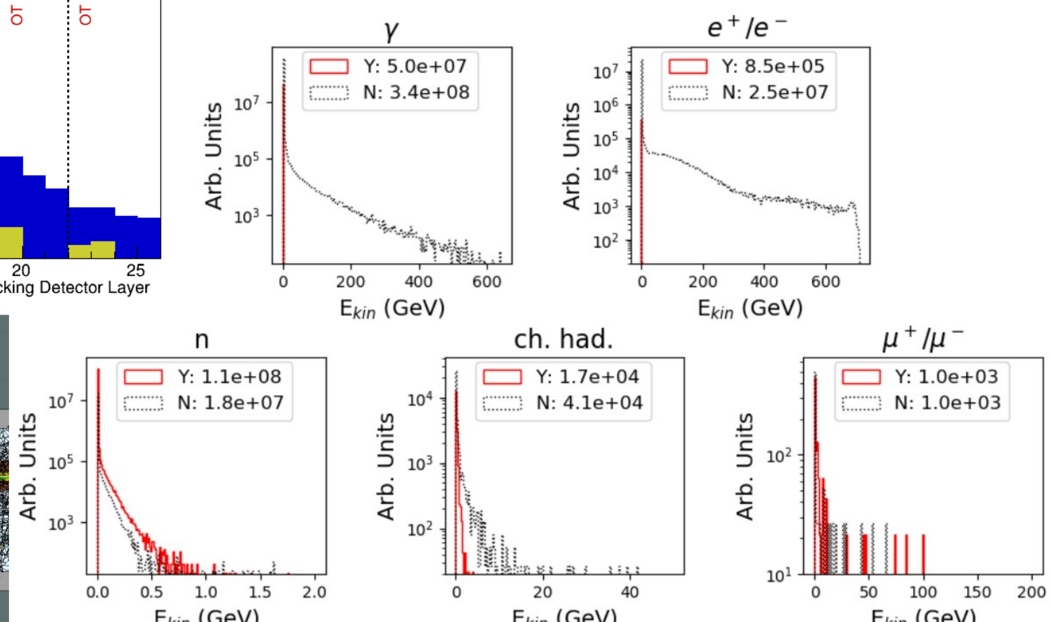




Tracker after timing cuts.



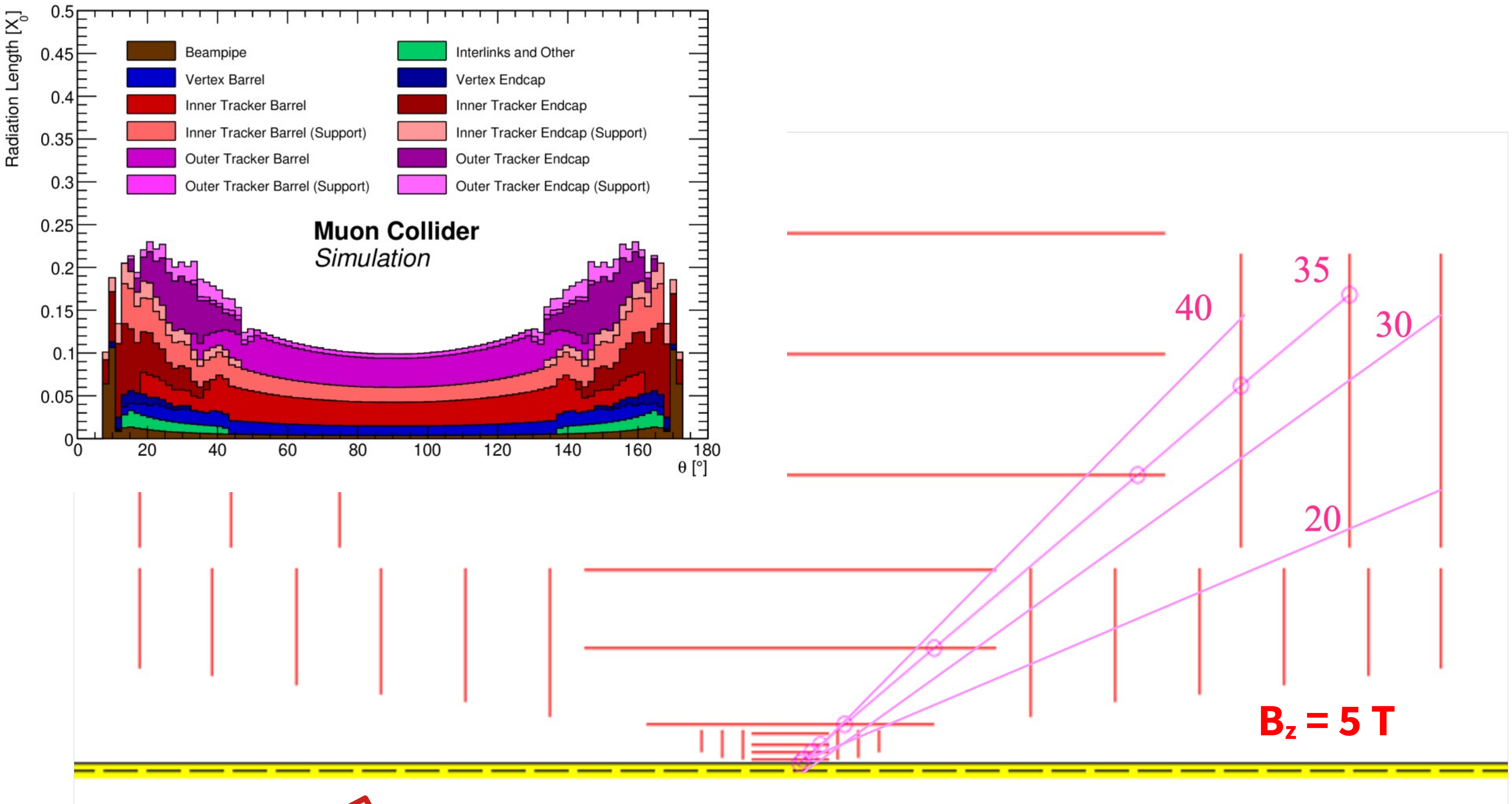
FLUKA simulation of BIB before reaching the detector. (1.5 TeV study)



Particle energy spectra with (Y) and without (N) nozzle. (1.5 TeV study)

All-Silicon Tracking Detector

Material description



Outer Tracker (OT)

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

Inner Tracker (IT)

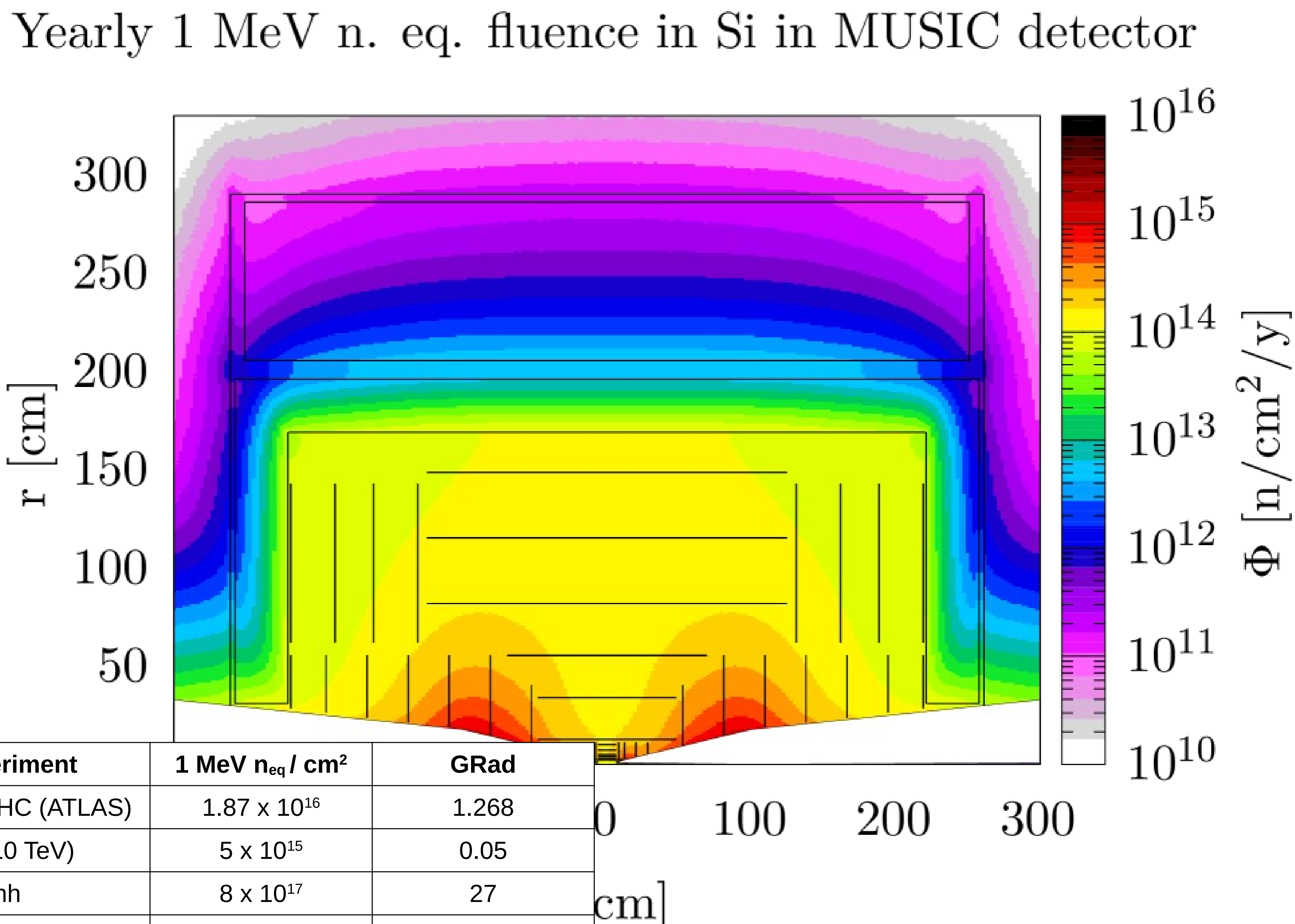
- macro-pixels
- 50 µm x 1 mm
- σ_t = 60 ps

Vertex Detector (VXD)

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

4D tracking critical

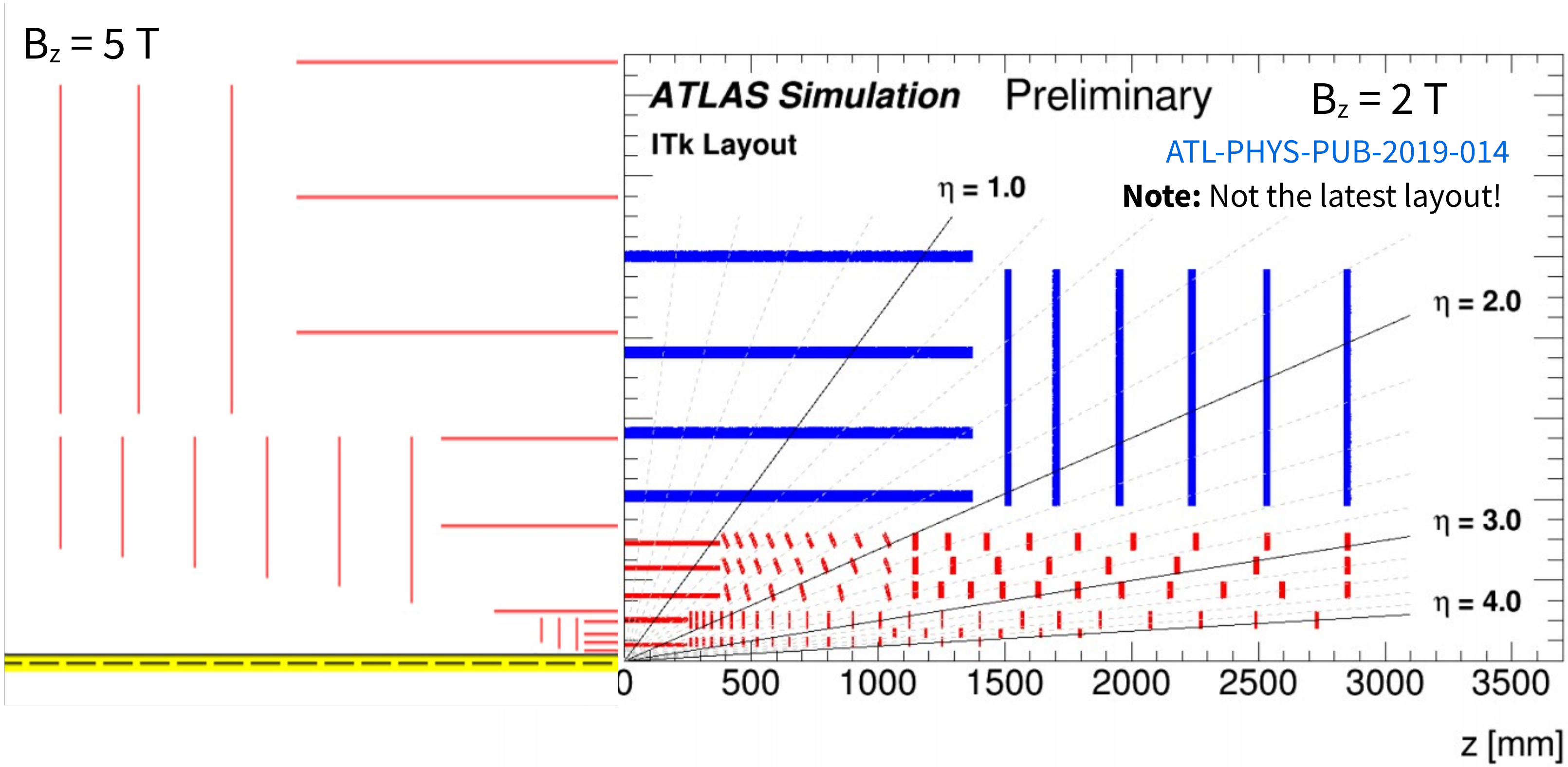
Radiation Damage From BIB



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

Expected total (5 year) dose in innermost tracking layer.

The Scale of BIB



Hit density
after timing cuts
10x HL-LHC

	ITk Hit Density [mm^{-2}]	MCC Equiv. Hit Density [mm^{-2}]
Pix Lay 0	0.643	3
Pix Lay 1	0.022	0.5
Str Lay 1	0.003	0.1

ITk Pixels TDR, ITk Strips TDR

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).

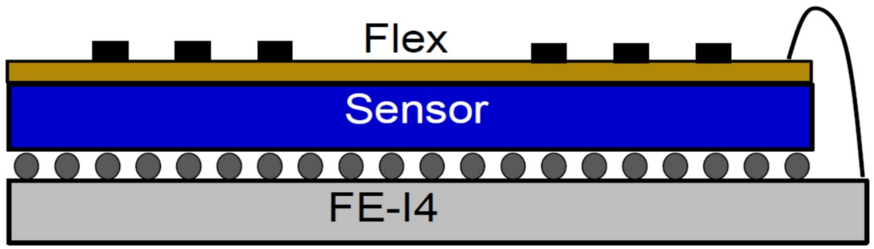
			"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)	< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	HIKE 2030 ☹	Belle II 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 (x 10^{16} neq/cm^2)			1				≃ 6	≃ 2						≃ 10^2		0.5
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		0.05

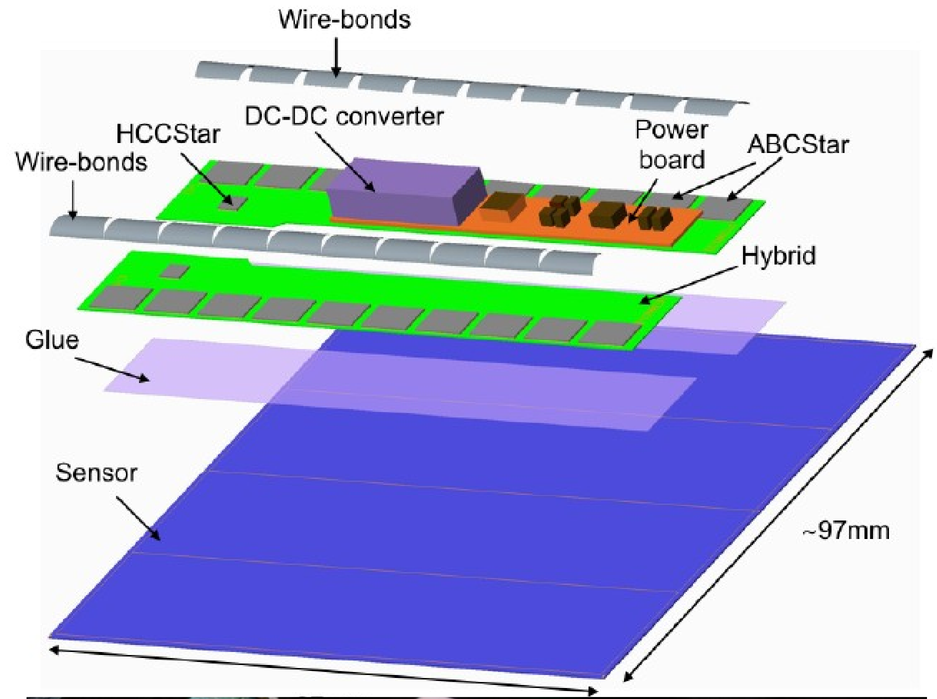
Technology demonstrators?

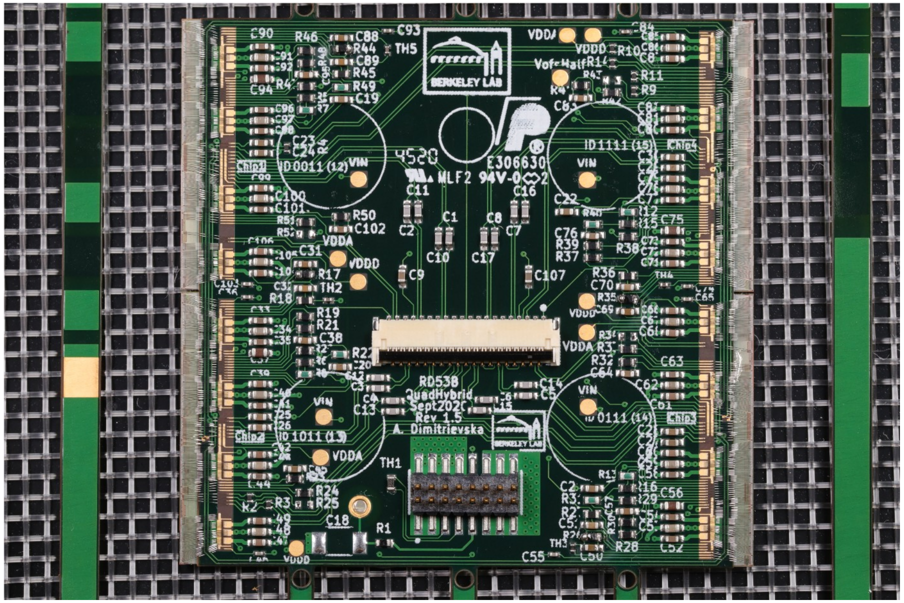
4D tracking, high data rates, rad hard

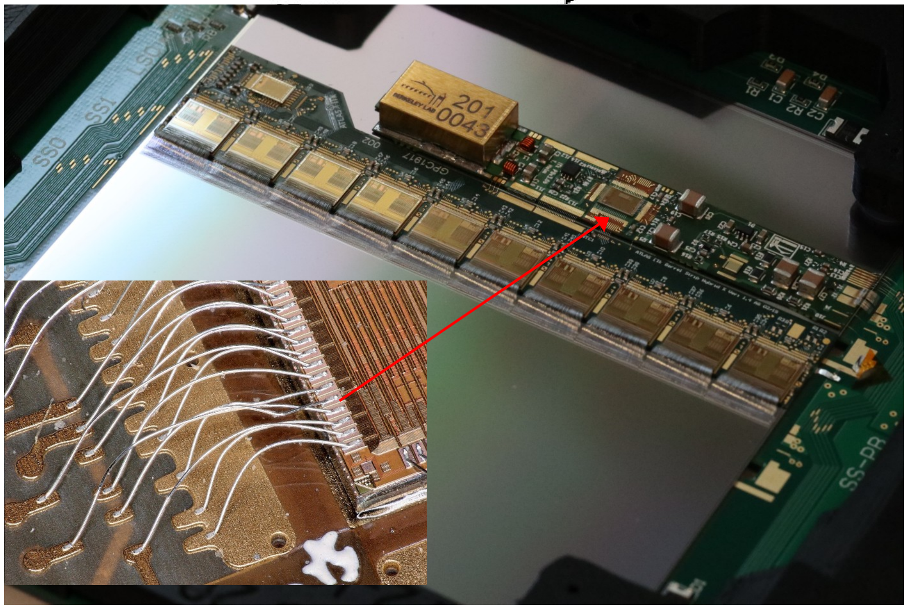
ATLAS ITk: Example of Current Trackers

Neither contain precision timing information!







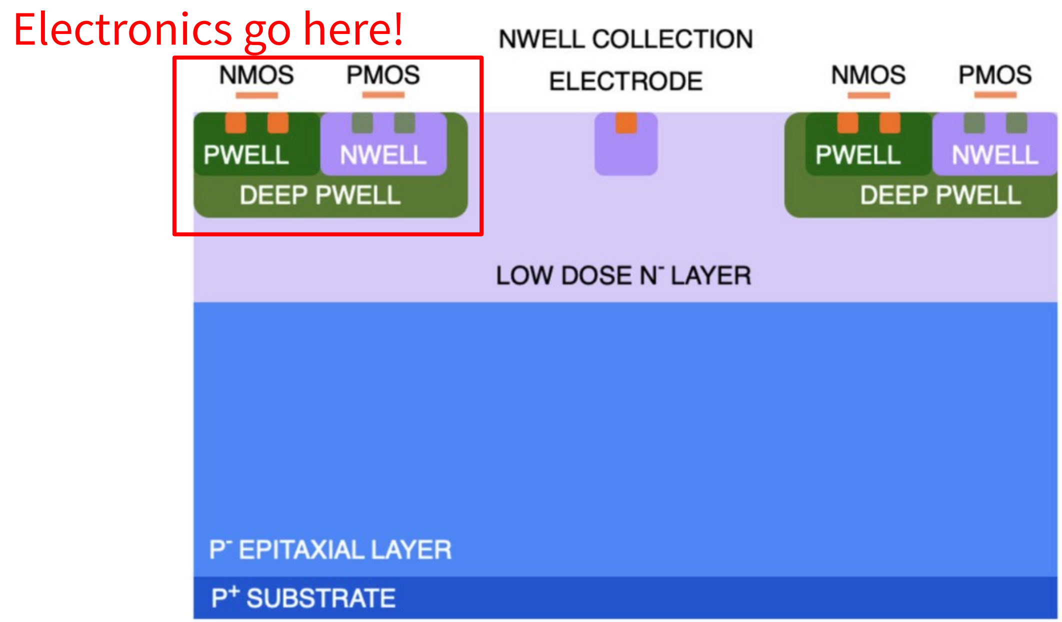


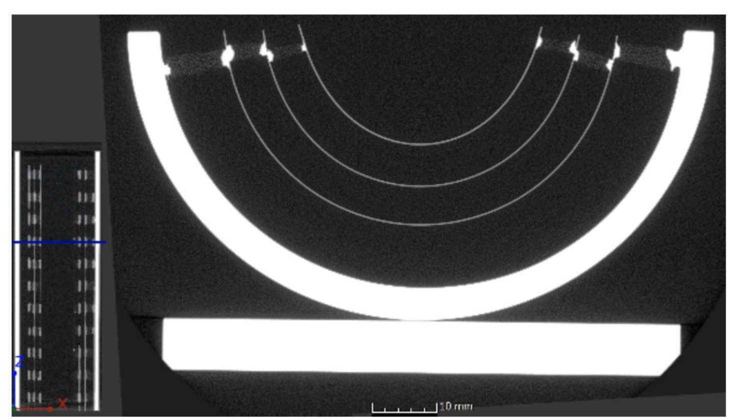
Key Theme in Tracker (Sensor) R&D: Monolithic

- Thin → low scattering → precision
- Fully integrated → “easier” construction

Example Applications:

- ALICE ITS3
- ePIC experiment at EIC
- Pretty much anything that needs a tracker...



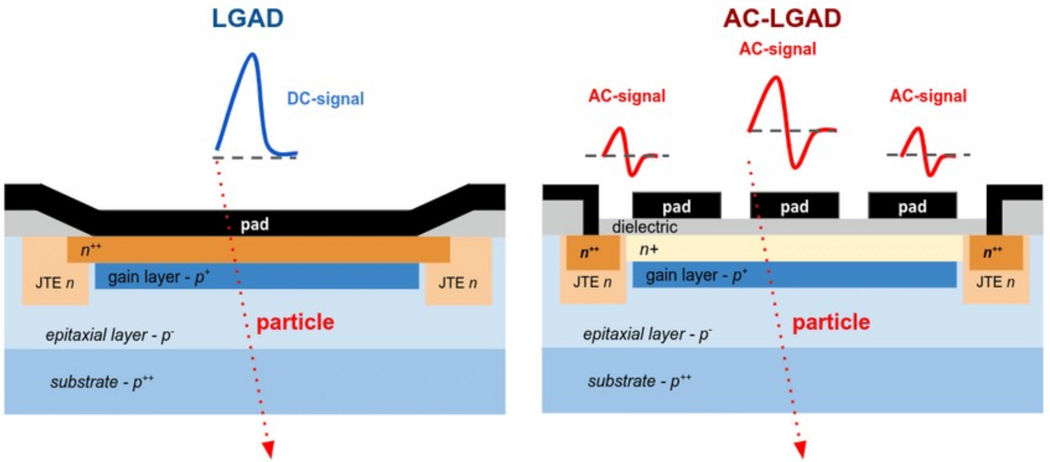


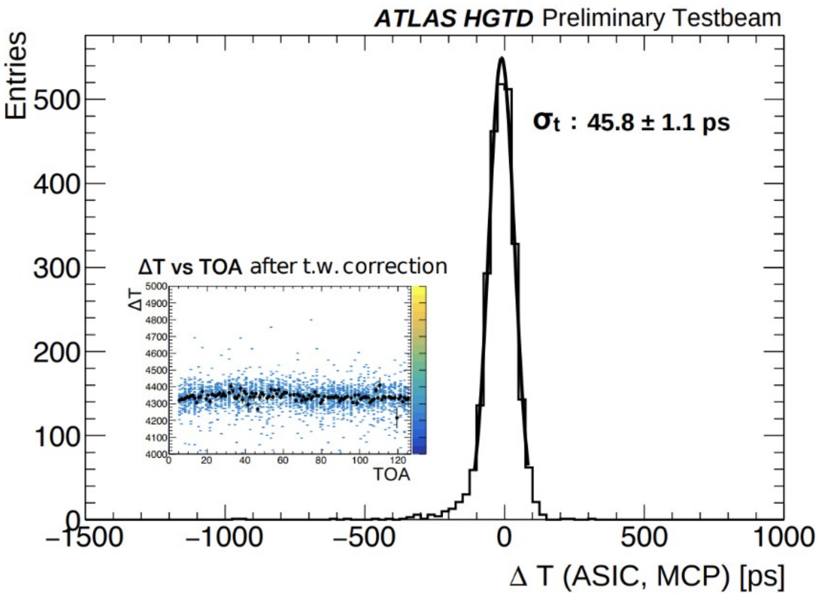
Key Theme in Tracker (Sensor) R&D: Timing

- Need “fast” (thin) sensors.
- Need Time-To-Digital circuitry.

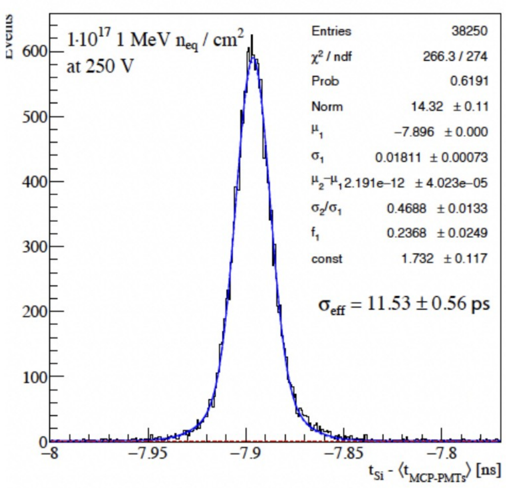
Example Applications:

- NA62 (100ps, 300x300 μm^2)
- LHCb VELO Phase 2 (50ps, 50x50μm^2)
- ATLAS HGTD and CMS ETL (50ps, 1x1 mm^2)





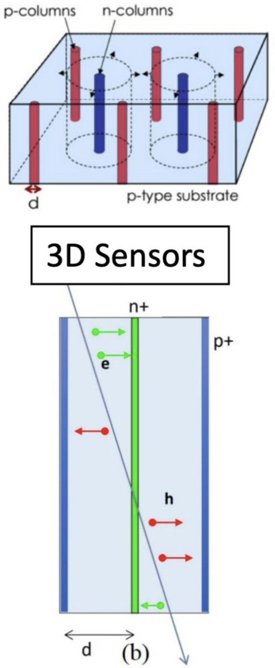
HGTD results from ATLAS HGTD hybrid.



$1{\cdot}10^{17}$ 1 MeV n_{eq}/cm^2

σ_t ≈ 11.5 ps @ −250 Vbias [2]

3D sensor performance from TIMESPOT

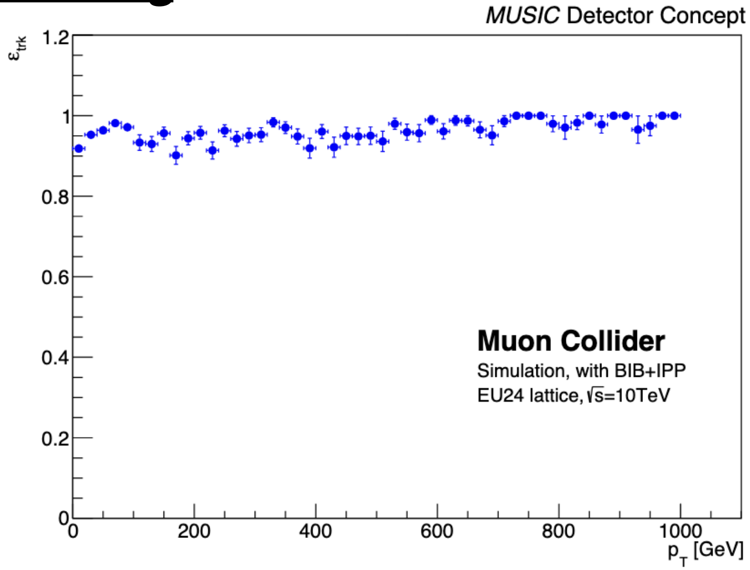


Work ongoing to add timing functionality to monolithic sensors.

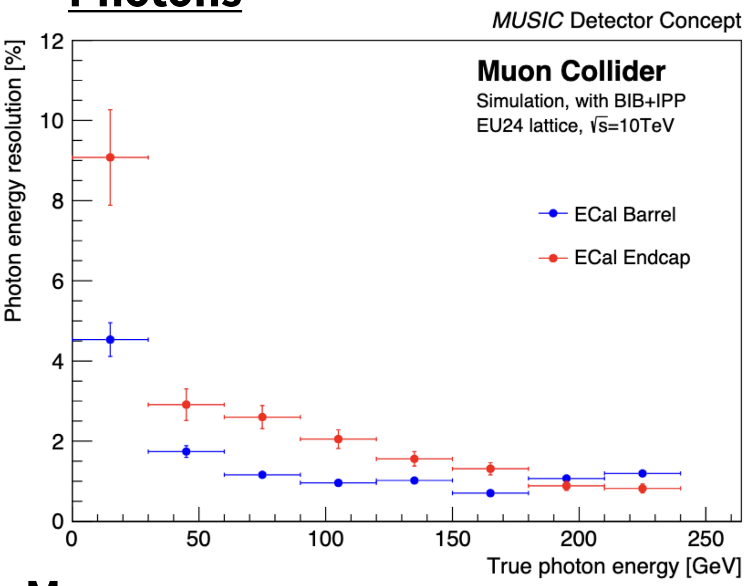
Object Reconstruction

[Similar plots exist for MAIA.]

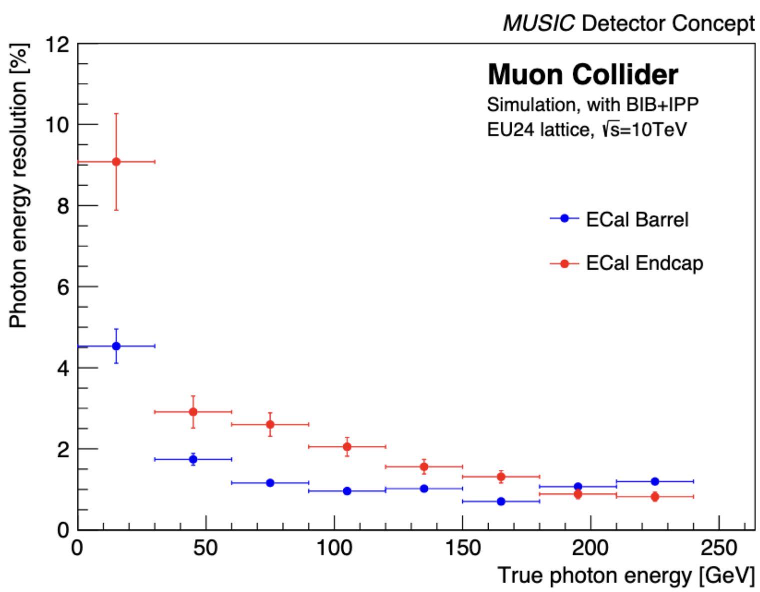
Tracking



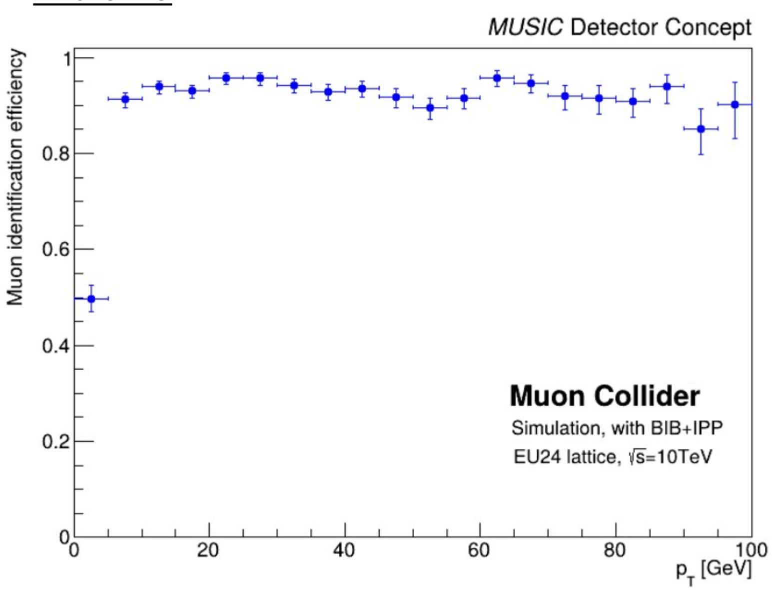
Photons



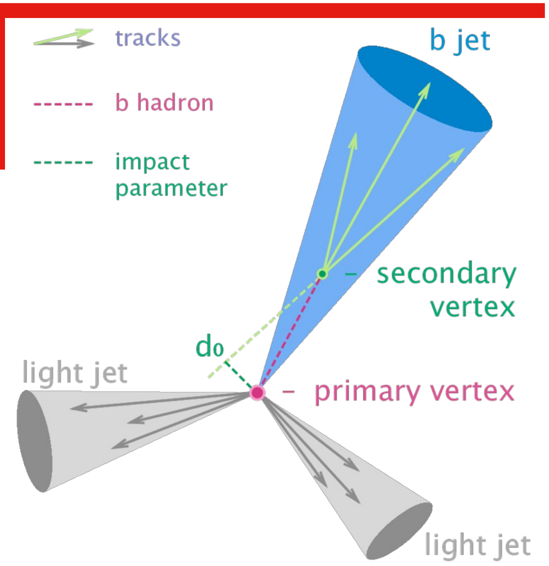
Jets



Muons

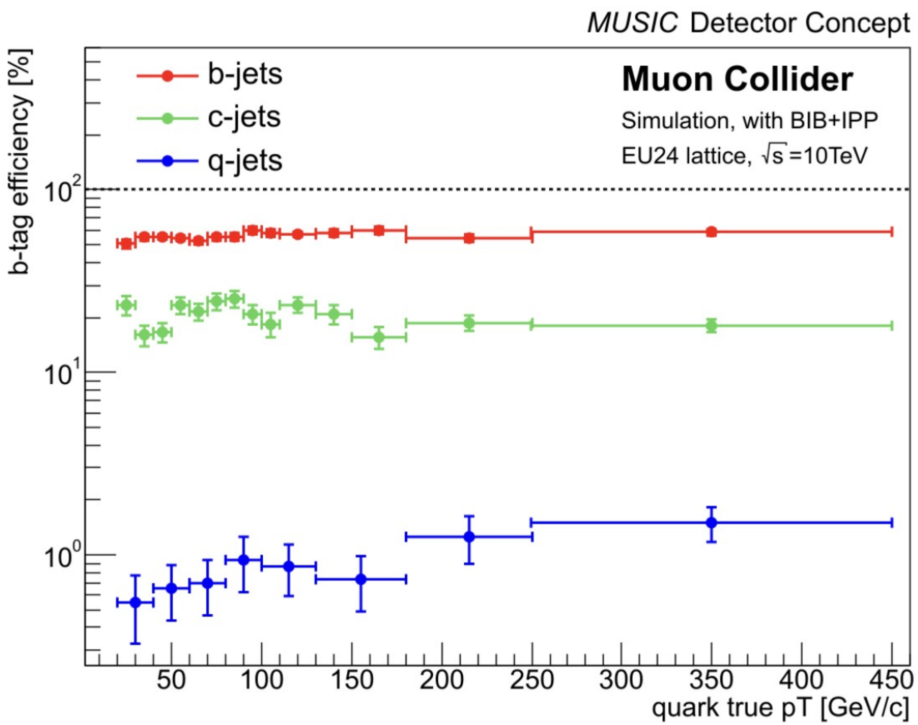


b-jet identification



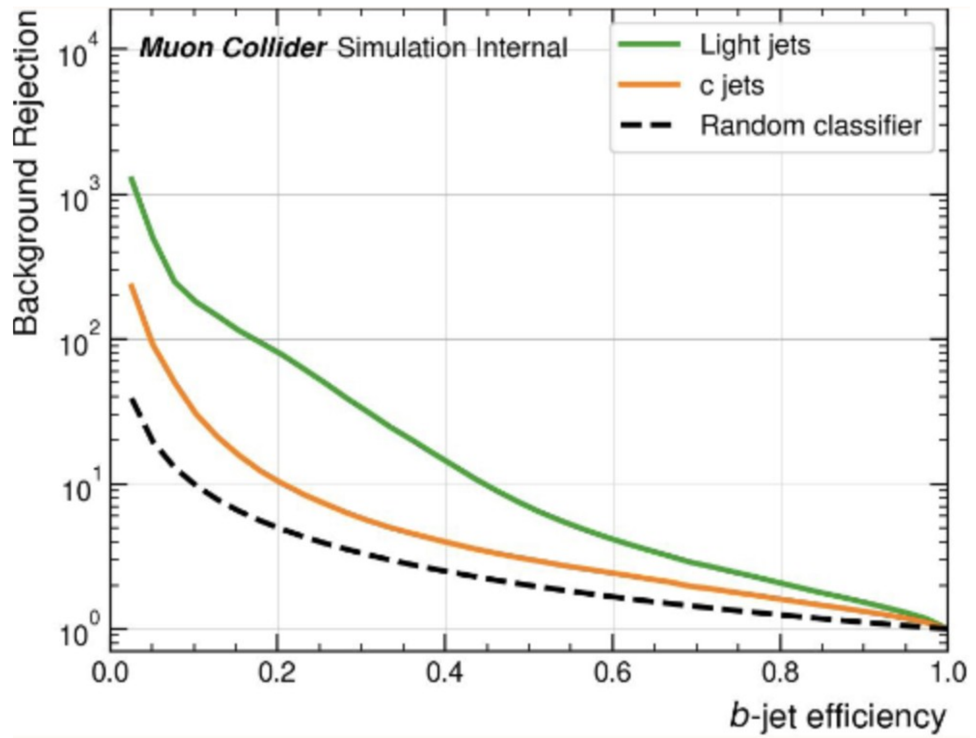
- **Important for Higgs studies.**
  - Most common decays is into two b-quarks.

by explicit secondary vertex reconstruction



by Machine Learning (ATLAS SALT framework)

Prelim work by Saurabh Saini (Sussex) and Abigail McIntosh (Birmingham)



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

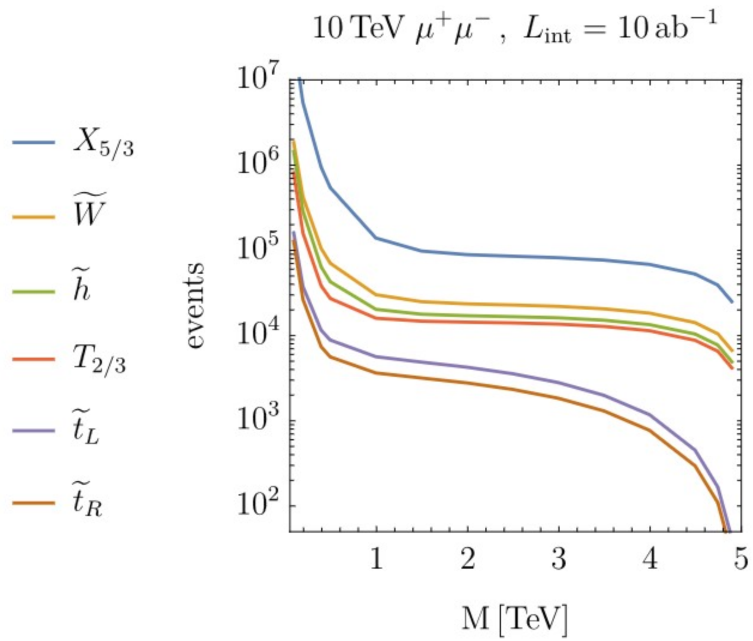
- Beam Induced Backgrounds creates a very unclean environment.
- Two concepts with advanced object reconstruction studies.
  - Created since Snowmass. Shows maturity of framework.
- *Lots of progress, but still need to understand effect on physics goals.*

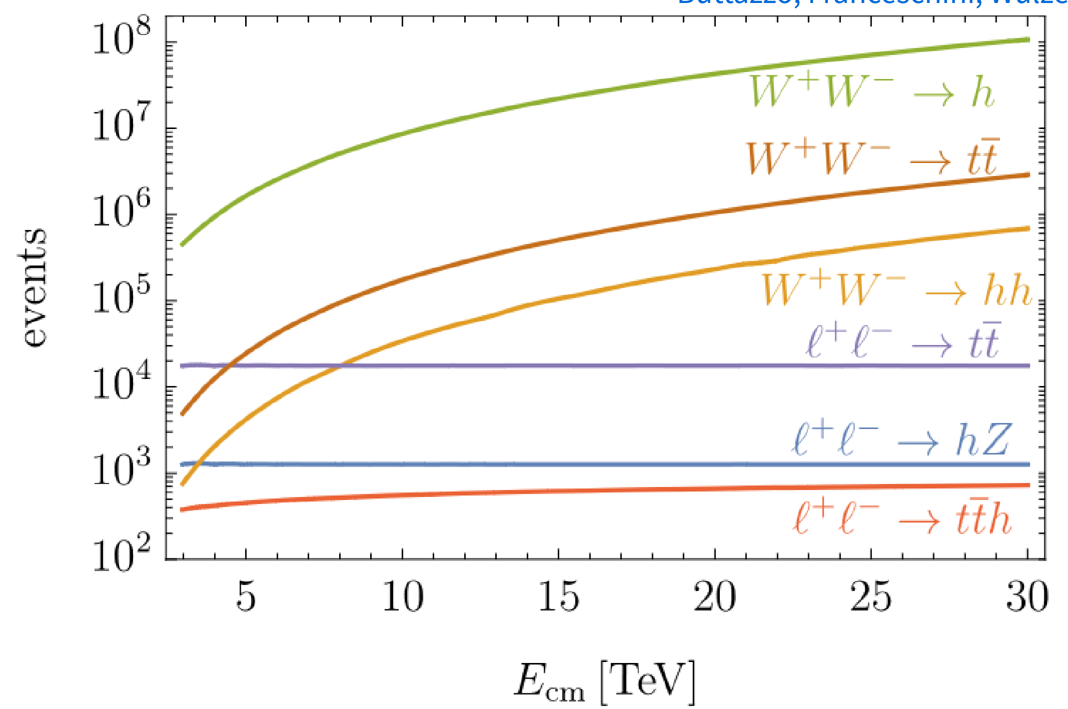
BACKUP SLIDES

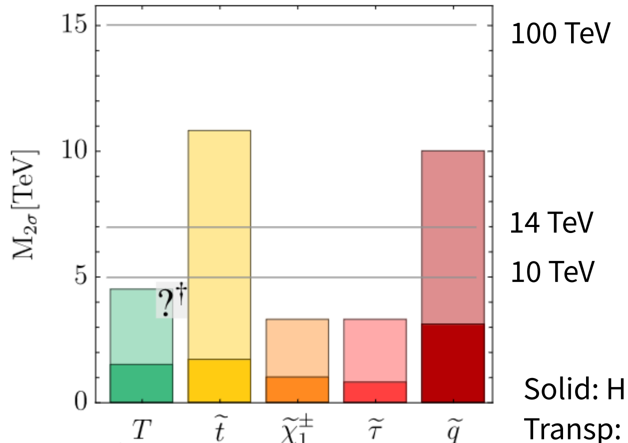
Event Counts

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

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

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

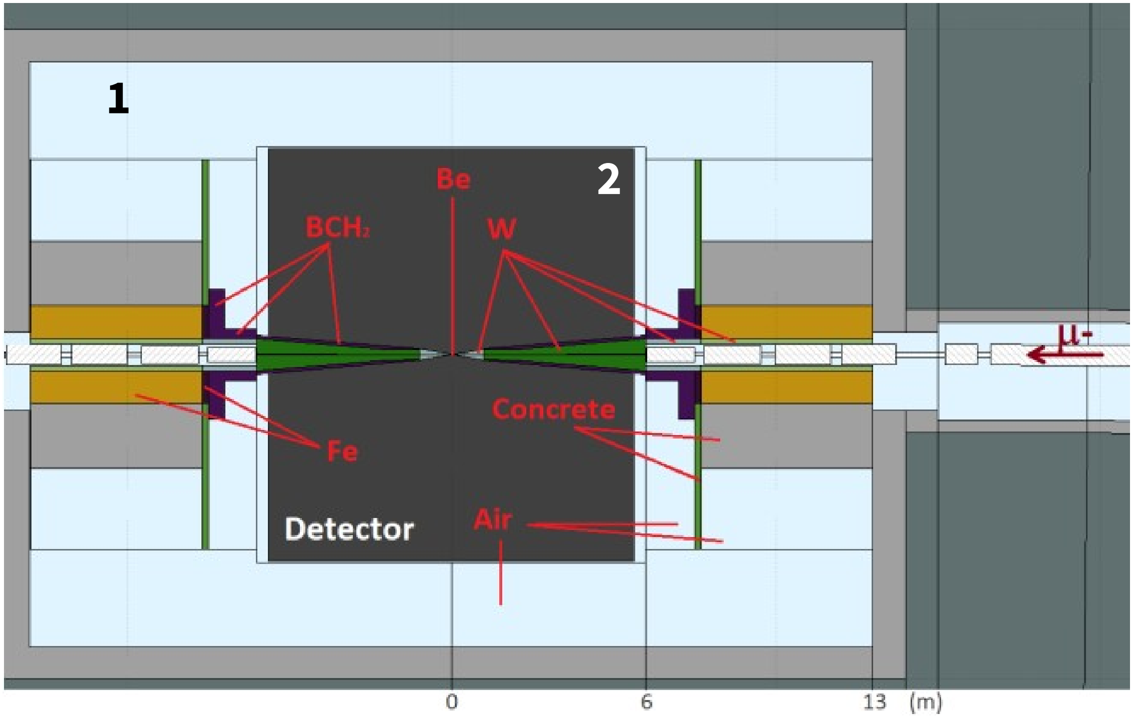
Solid: HL-LHC
Transp: FCChh

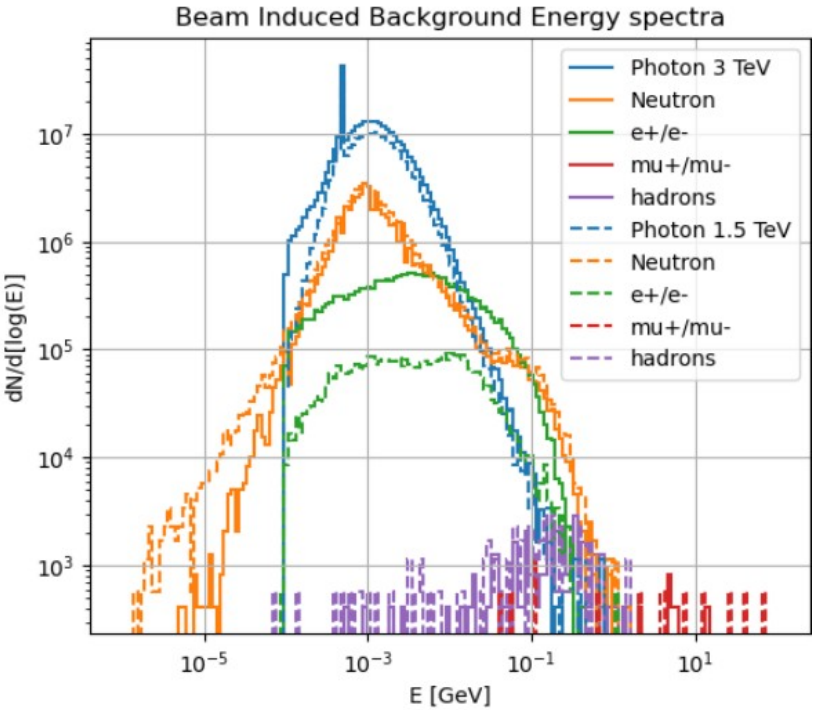
Simulating Beam Induced Background

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

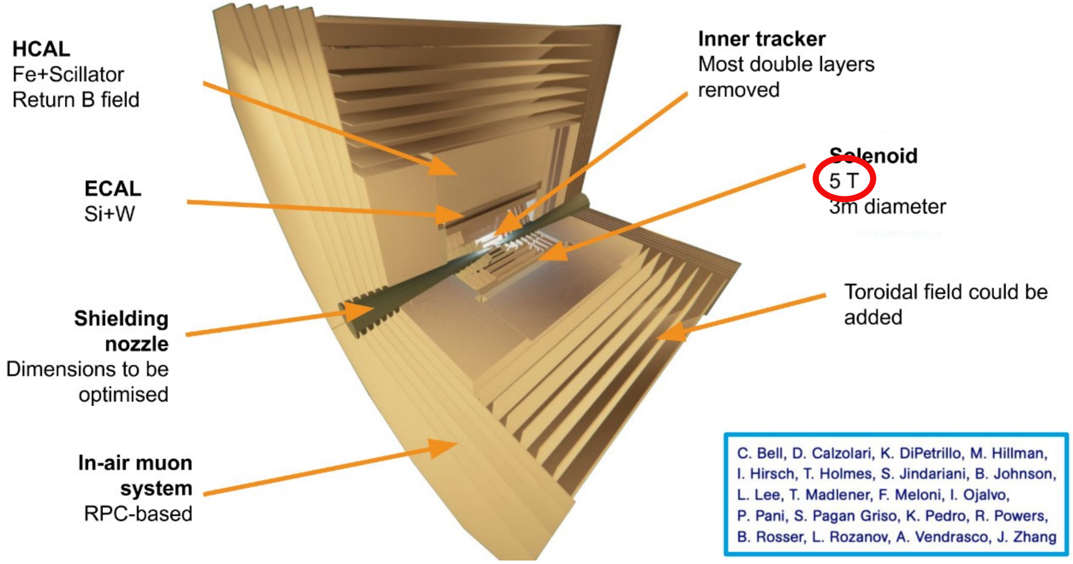




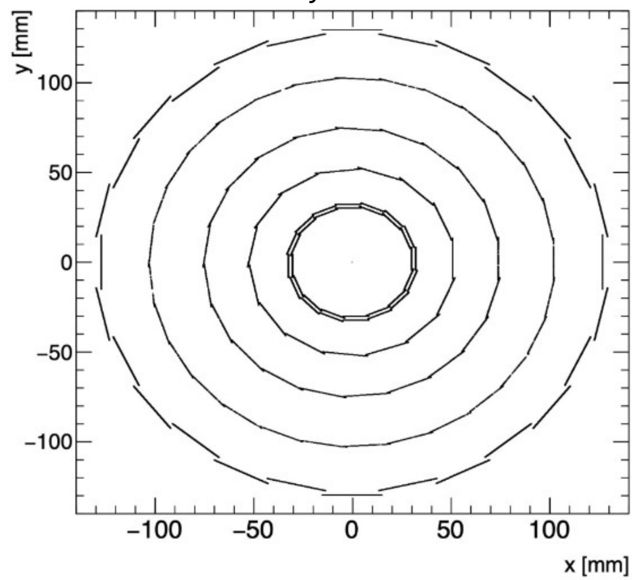
1.5 TeV vs 10 TeV

Summary by B. Rosser

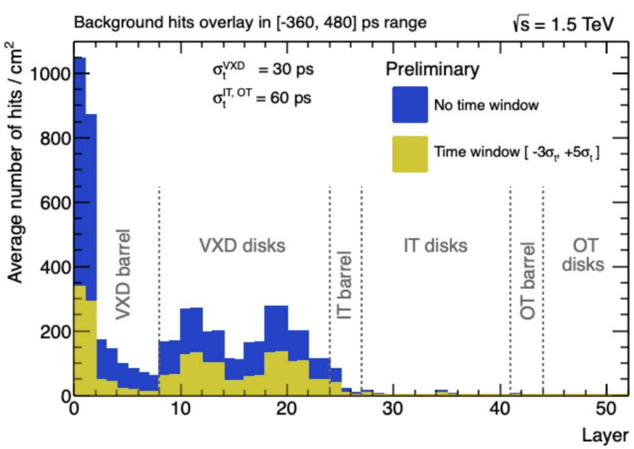
Concept developed at KITP workshop at Santa Barbara

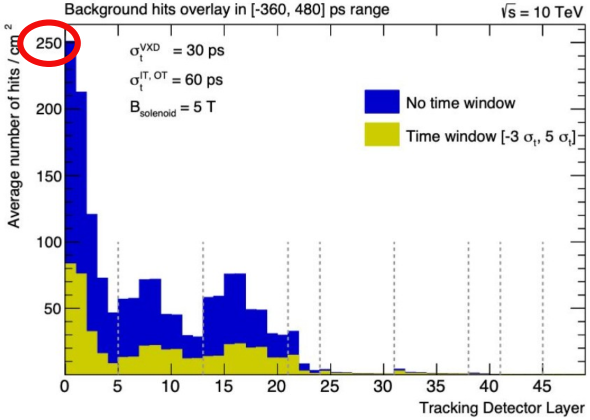


Removed double layers in tracker



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