Comprehensive Paper:

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

Muon Collider As The Next Generation Particle Physics Facility

Karol Krizka

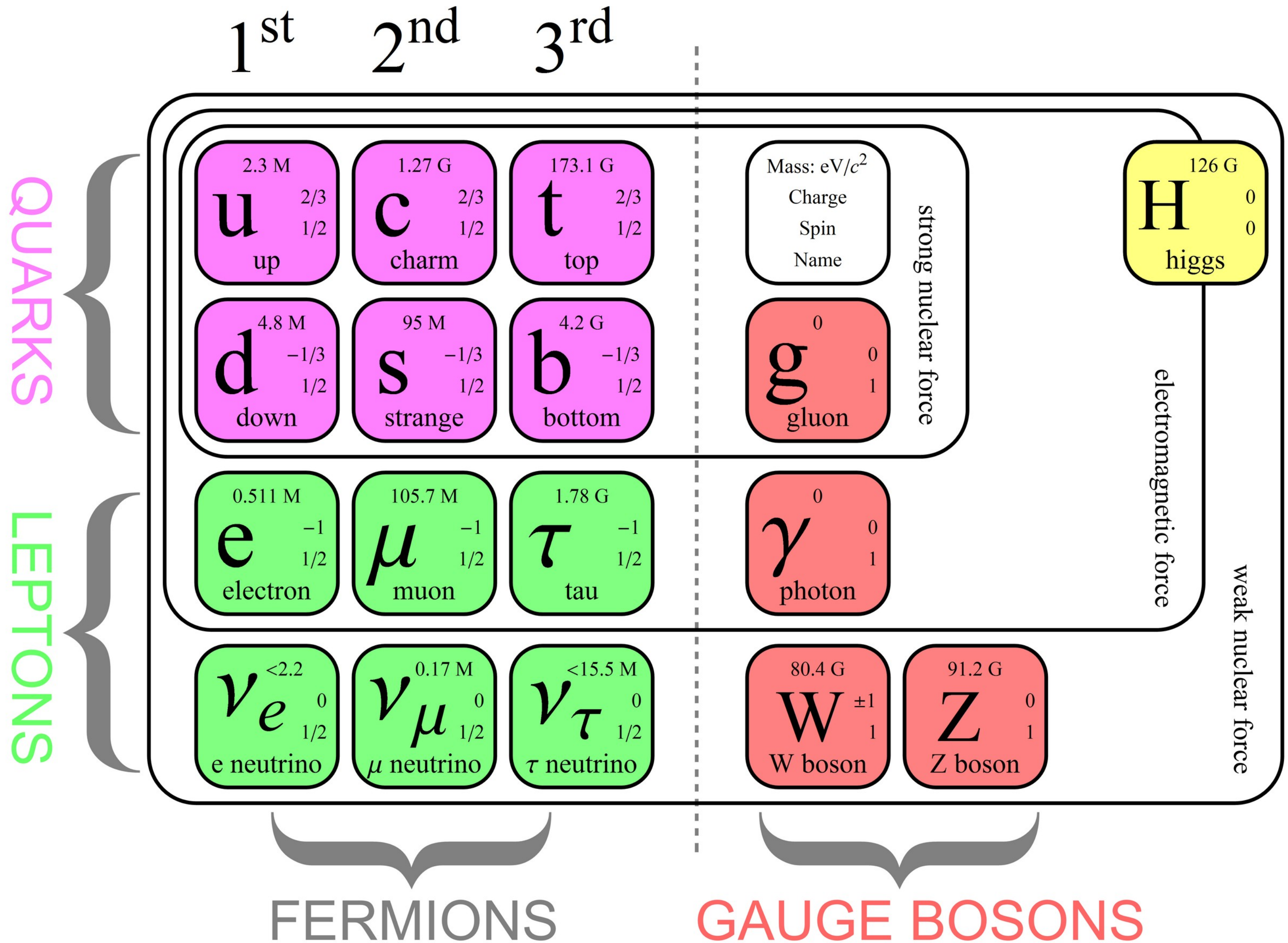
March 20, 2024

International MUON Collider Collaboration

UNIVERSITY OF BIRMINGHAM

RAL PP Seminar

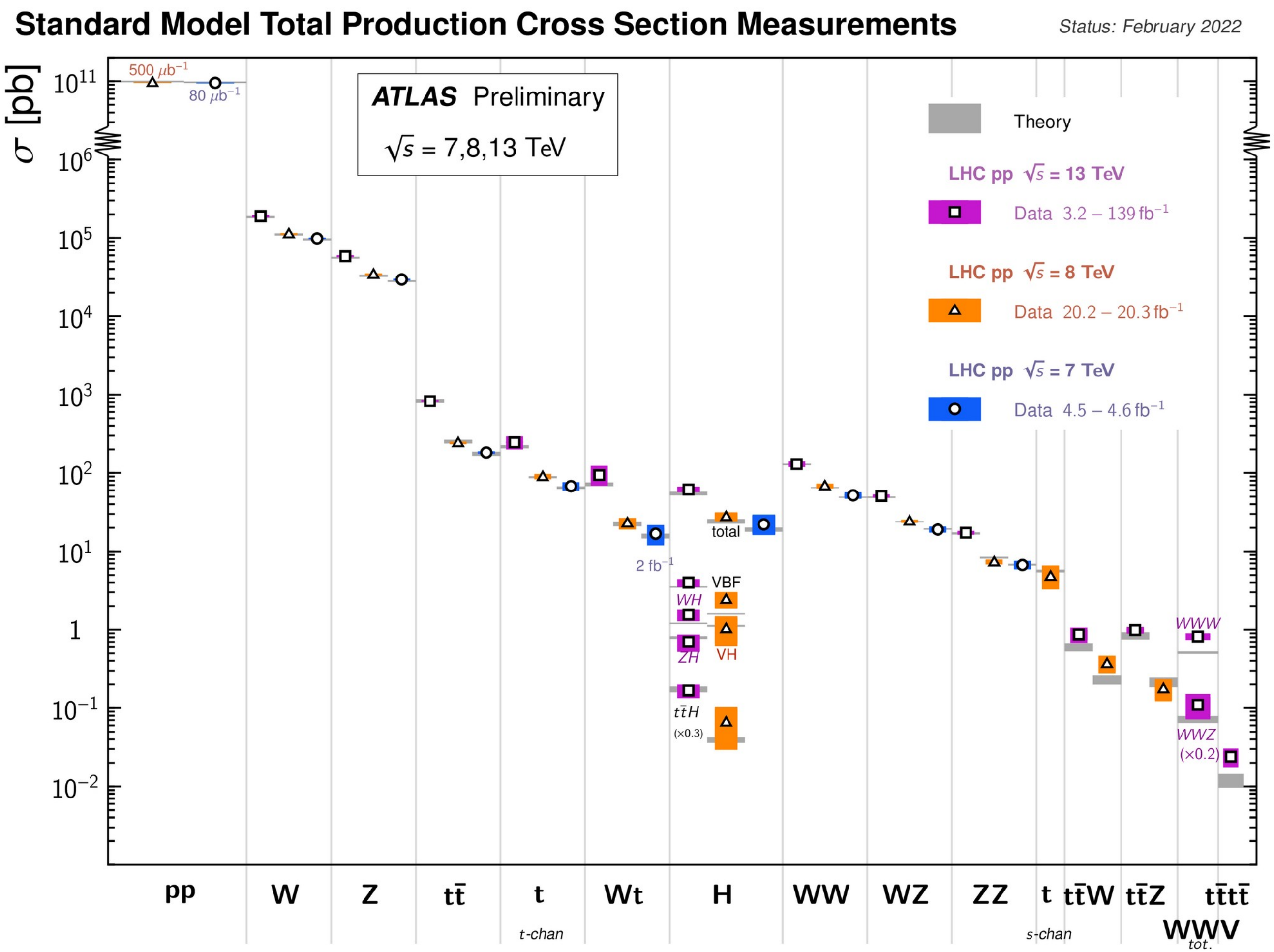
The Standard Model



Our world at the smallest level, as seen experimentally.

The Standard Model Measurements

The Standard Model is working very nicely! HEP experiments give values consistent with theorist's calculations.



But...

The Standard Model Problems

… not consistent with non-HEP observations

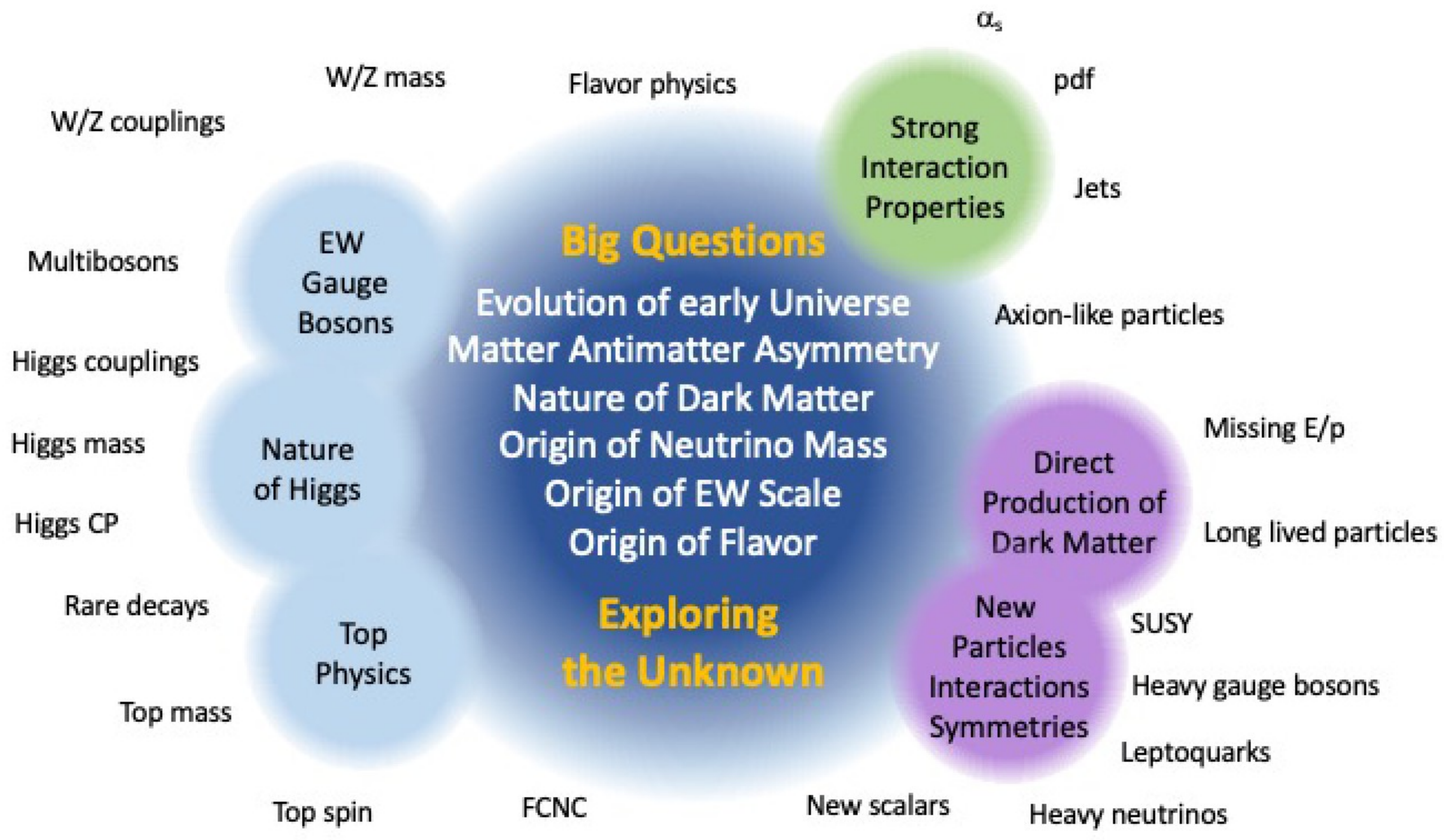
- **Dark Matter**
  - Cosmological observations show large blobs of unseen mass and SM cannot explain them
- **Matter/Antimatter asymmetry**
  - SM says matter/antimatter are almost the same, but world tells us that there is more matter
- **Hierarchy "problem"**
  - Higgs mass only correct if parameters are very precise for cancellations to occur
- **No gravity, Dark Energy, neutrino masses...**

More “solutions” than questions…

Credit: H. Murayama

Why collider experiments?

Collider experiments allow you to sample a **huge space of theories** with **one experimental setup**!

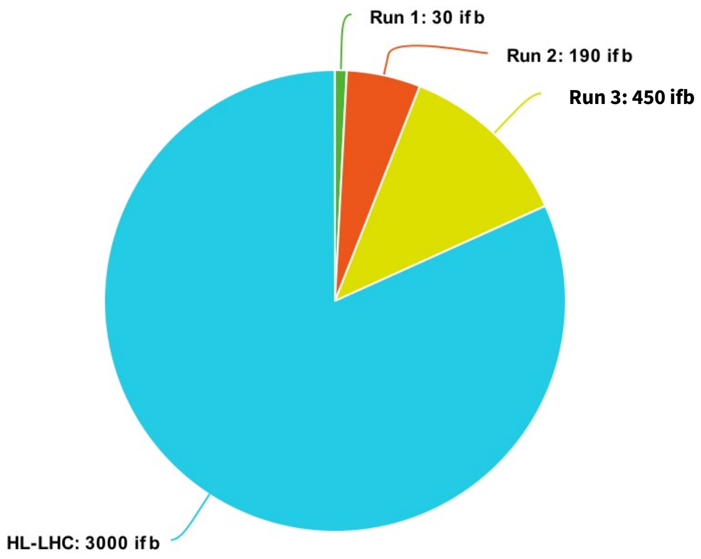


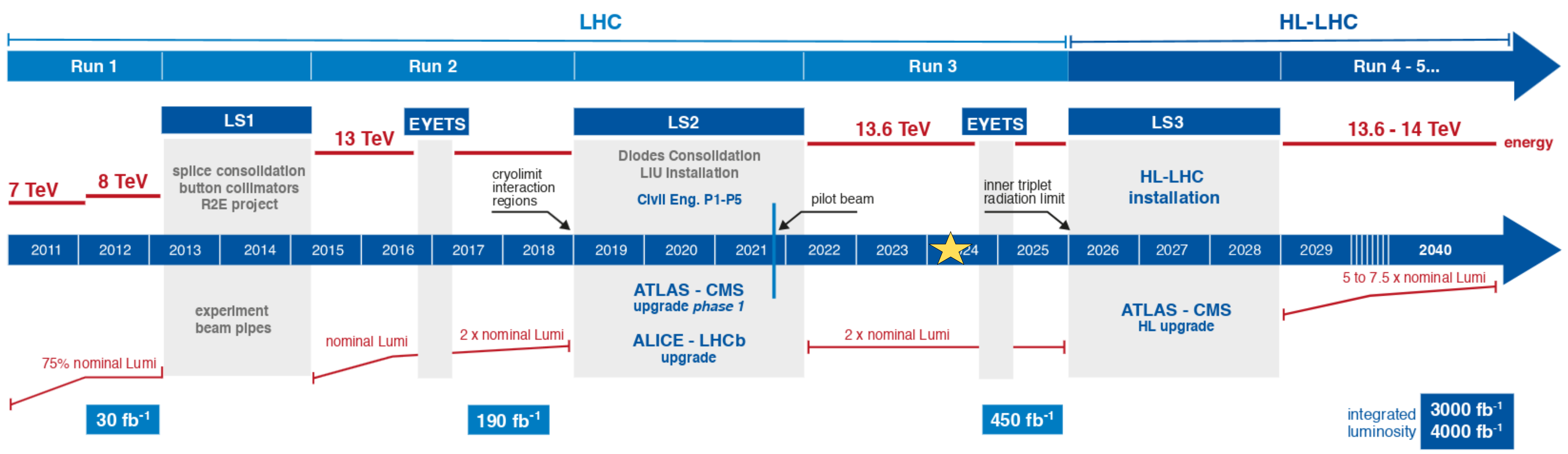
Very useful if you don't know **where to look...**

What About The HL-LHC?

We are not even half-way through the HL-LHC program!!!

both time and data





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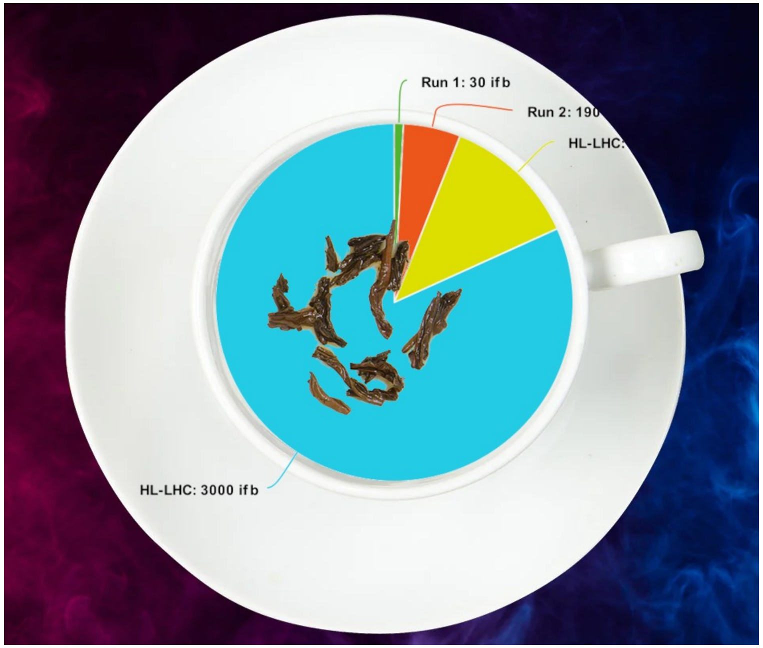
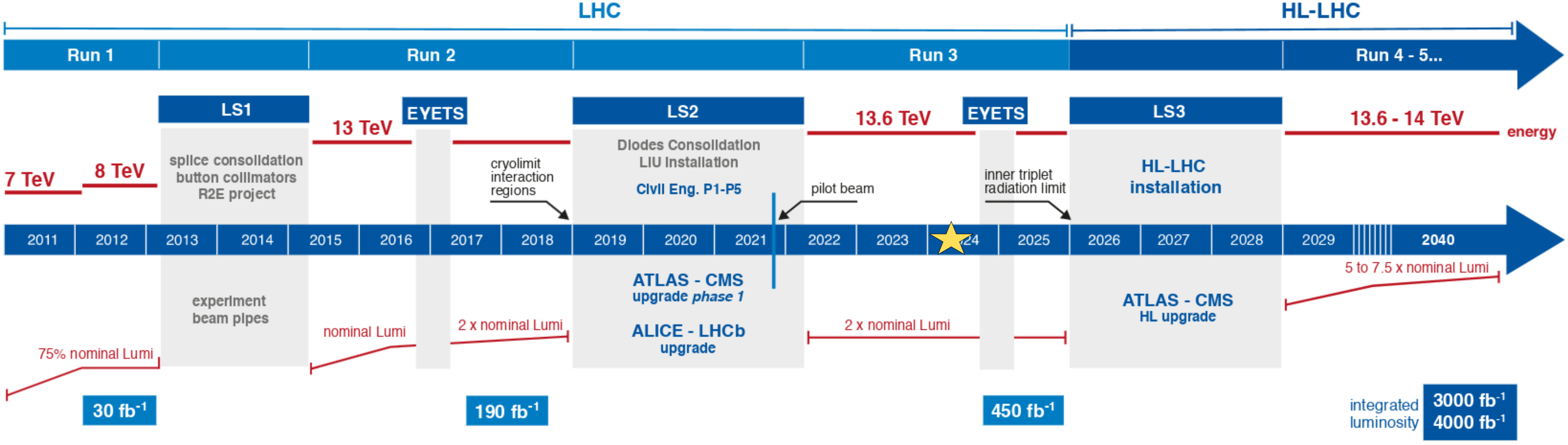
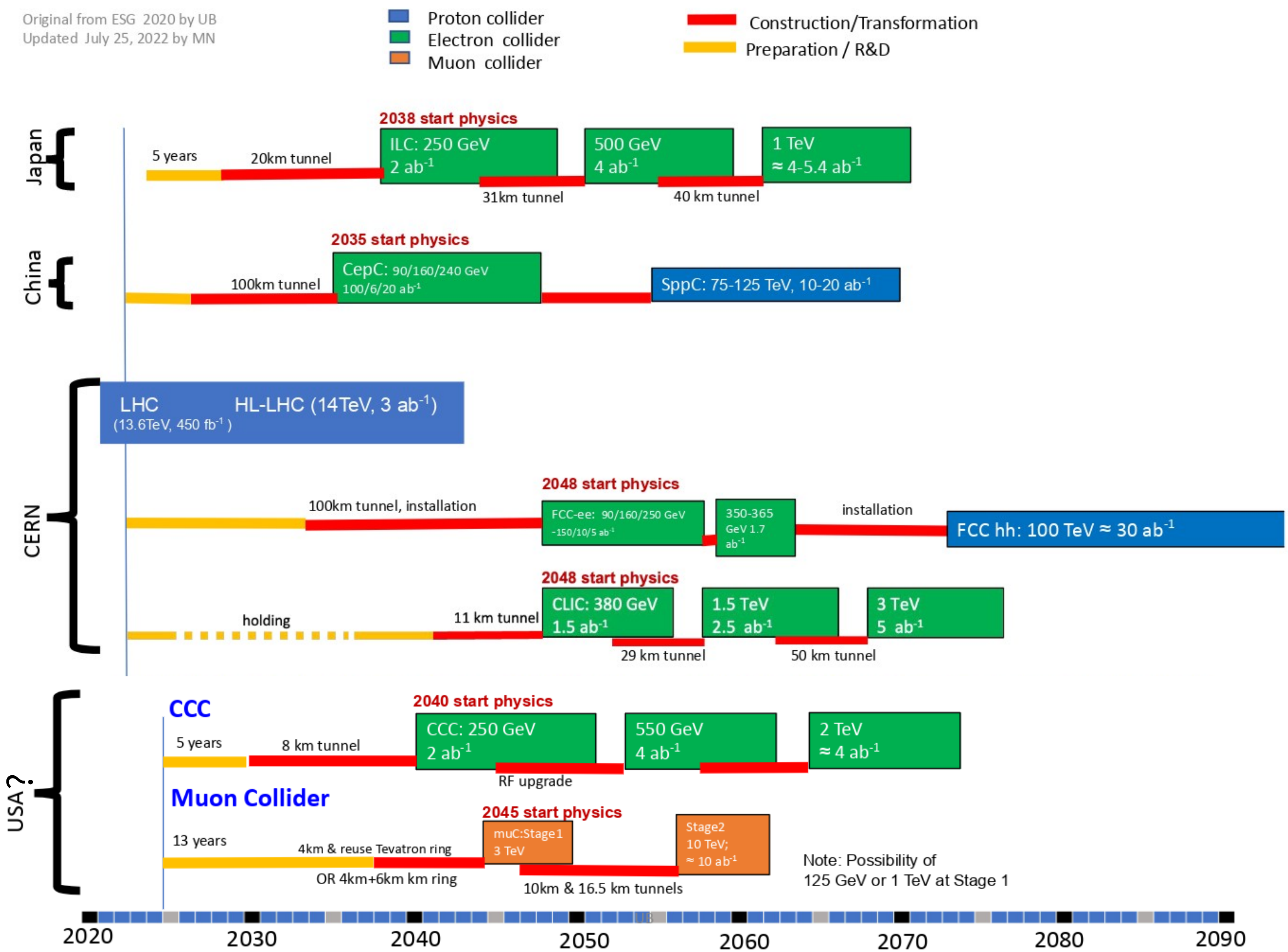




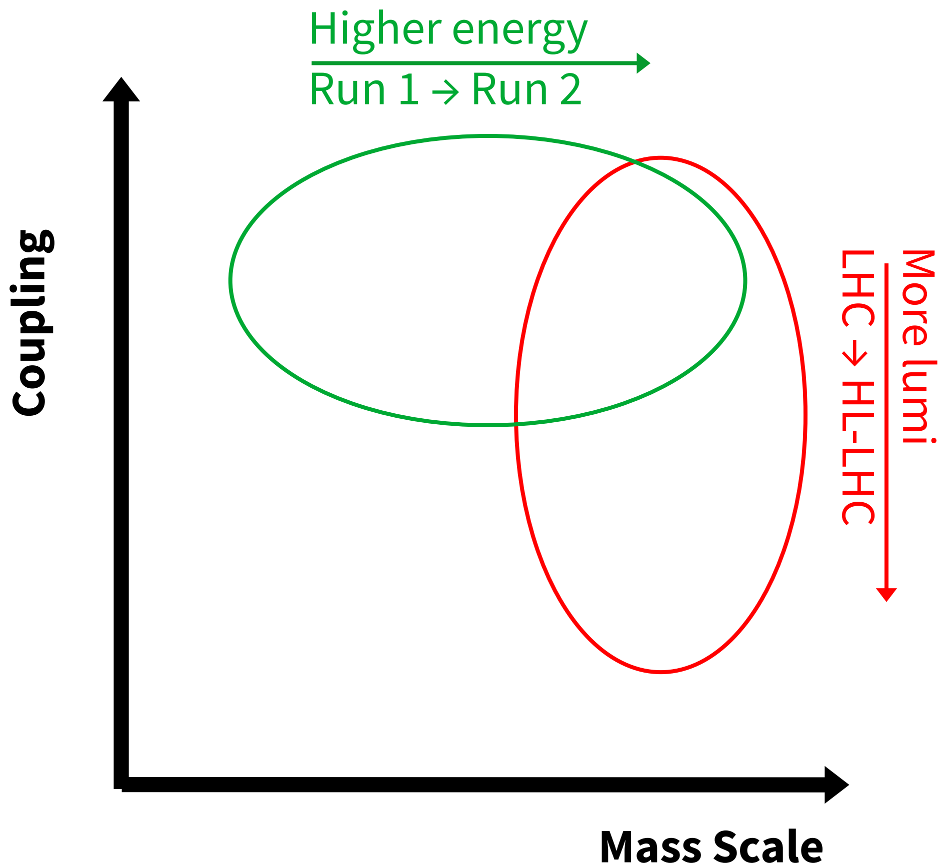
Timelines

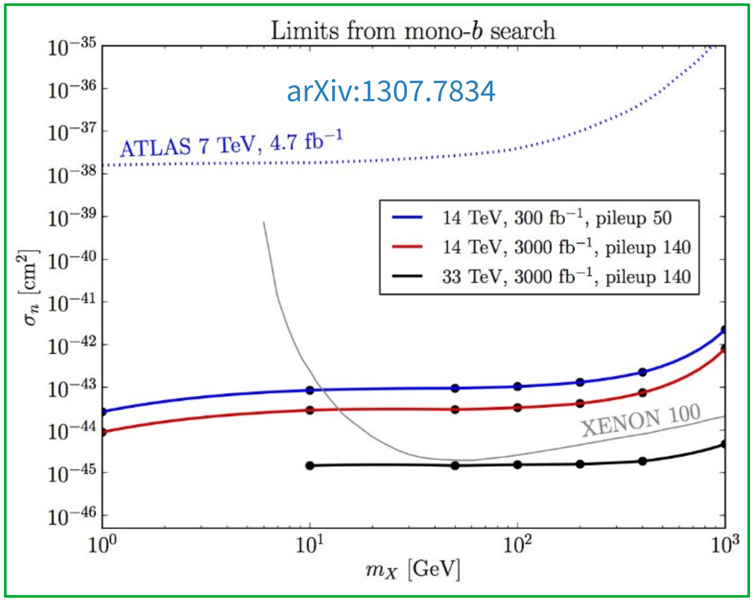
LHC inception was in 1984

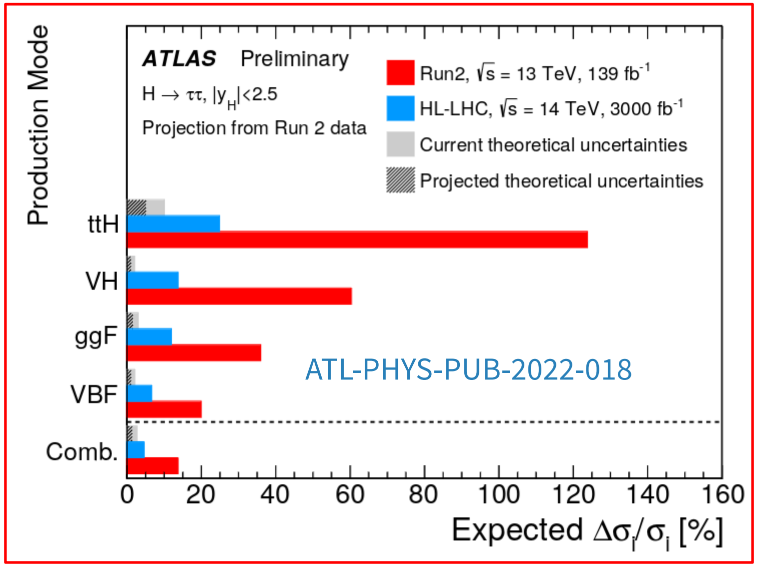
Large Hadron Collider in the LEP tunnel, ECFA 84/85, CERN 84-10



Entering Era of Precision Measurements

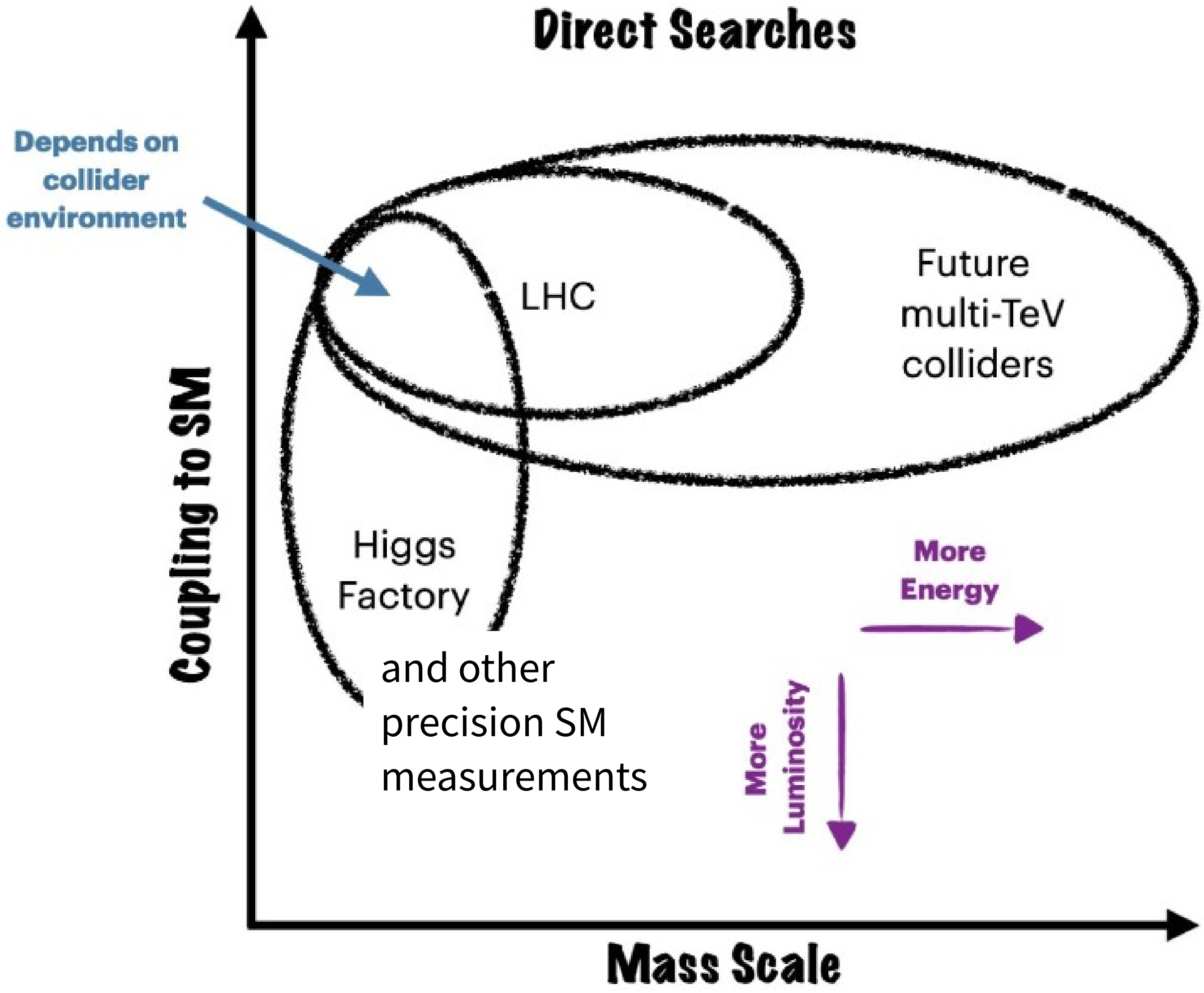




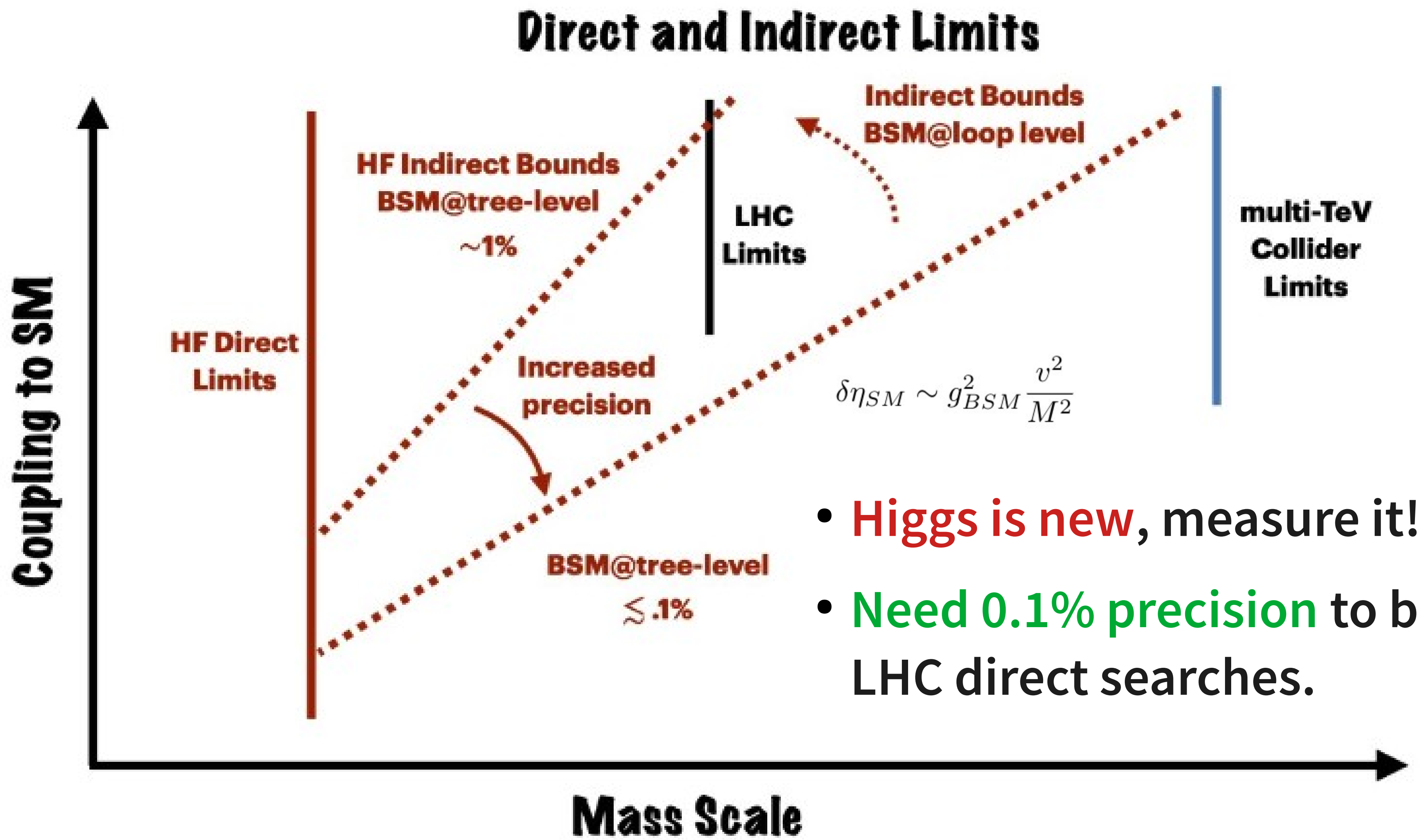


Precision measurements will set limits indirectly, but we need a direct search to explain any deviations.

New Physics at Colliders



Importance of Higgs



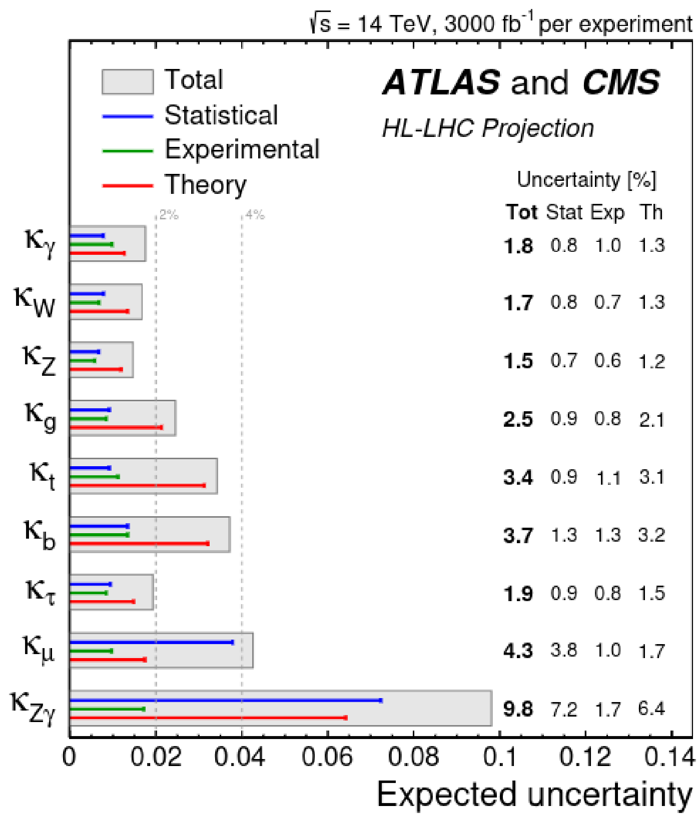
- Higgs is new, measure it!
- Need 0.1% precision to beat LHC direct searches.

Goals at a Future Facility

1)Measurements of the Higgs boson targeting O(0.1%)

1)Couplings, *self-couping* and width

2)Direct searches at high energies to understand any deviations.



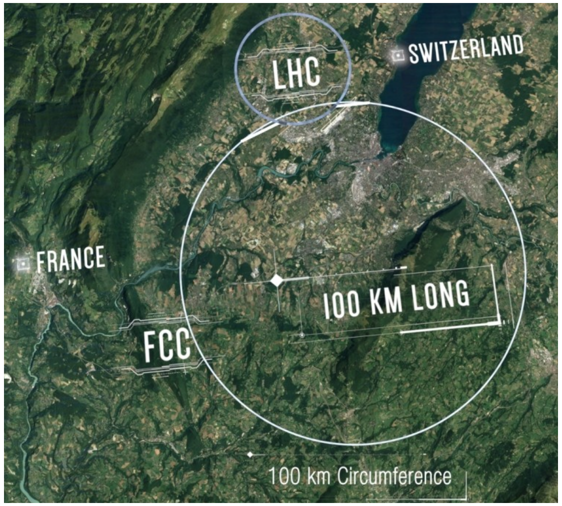
1) HL-LHC Higgs measurements won’t cut it.

Towards Future Colliders

Big Picture: Many comparable proposals with unique problems.

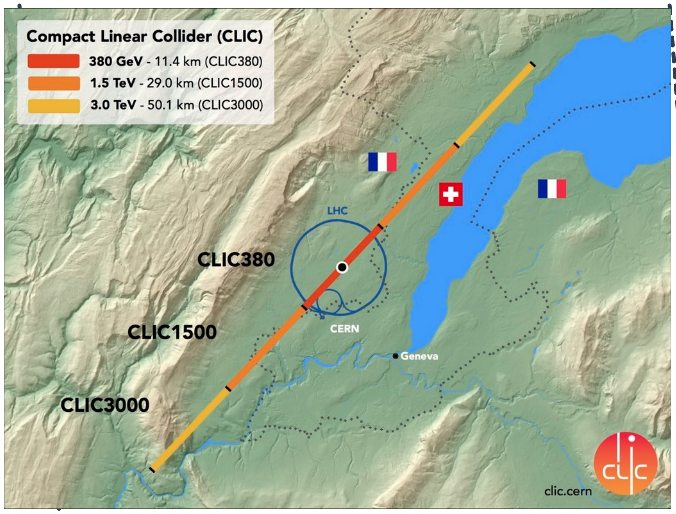
100 TeV Hadron Collider

- Existing technologies in a big (~100 km) tunnel
- e^+e^- collider as *first stage*



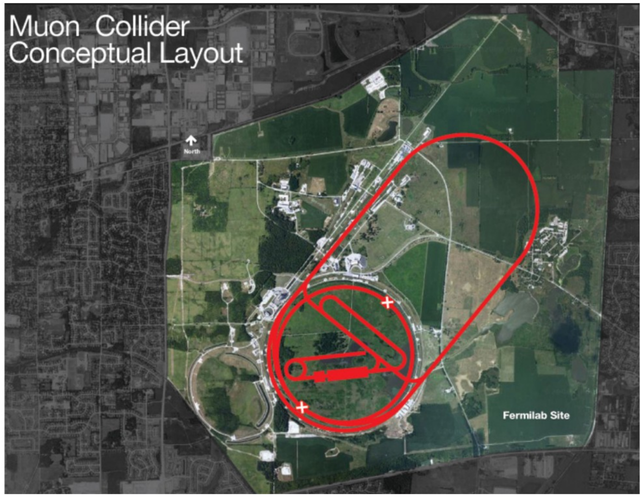
Linear Electron Collider

- Optimized for precision measurements of top quark and Higgs Boson
- ~500 GeV to few TeV stages



3-10 TeV Muon Collider

- Lepton collider
- Higher effective energy reach than *pp*
- R&D needed for muon accelerators



Three Challenges

The Physics

Will a Muon Collider satisfy the physics goals?

- Precision Higgs couplings
- BSM at higher energies

The Accelerator

What technology is required to build a Muon Collider?

- aka muon cooling

The Detector

Is the collision environment clean for precision physics?

- How to deal with Beam Induced Background

Three Challenges

The Physics

Will a Muon Collider satisfy the physics goals?

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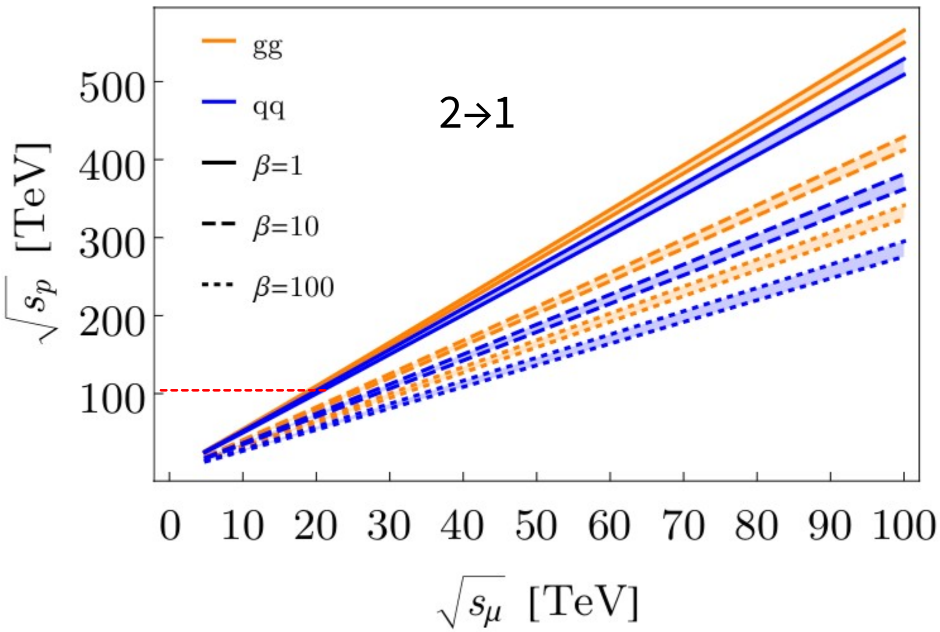
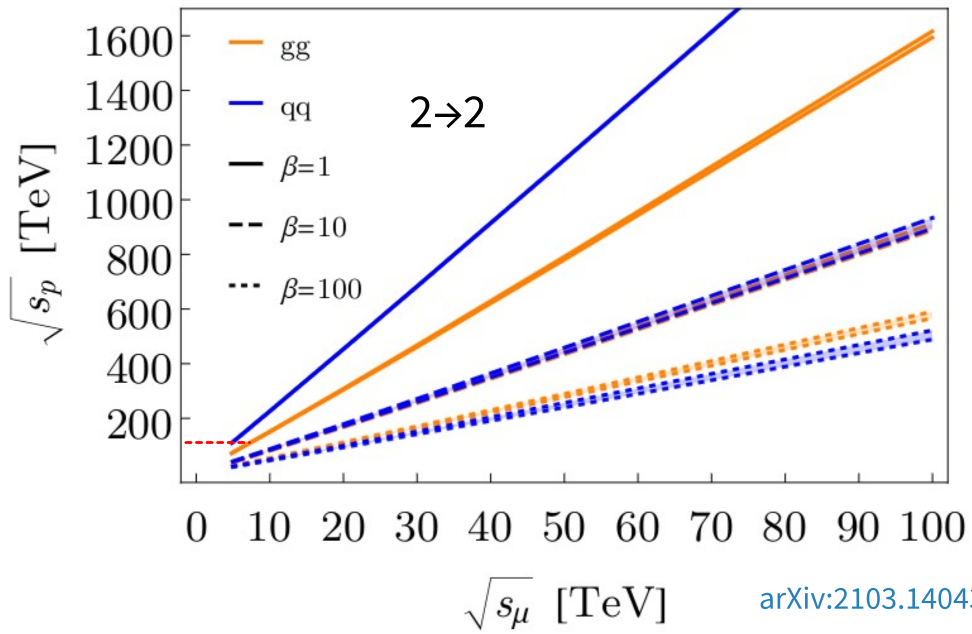
Direct Searches

Muons are elementary = full beam energy used in collision

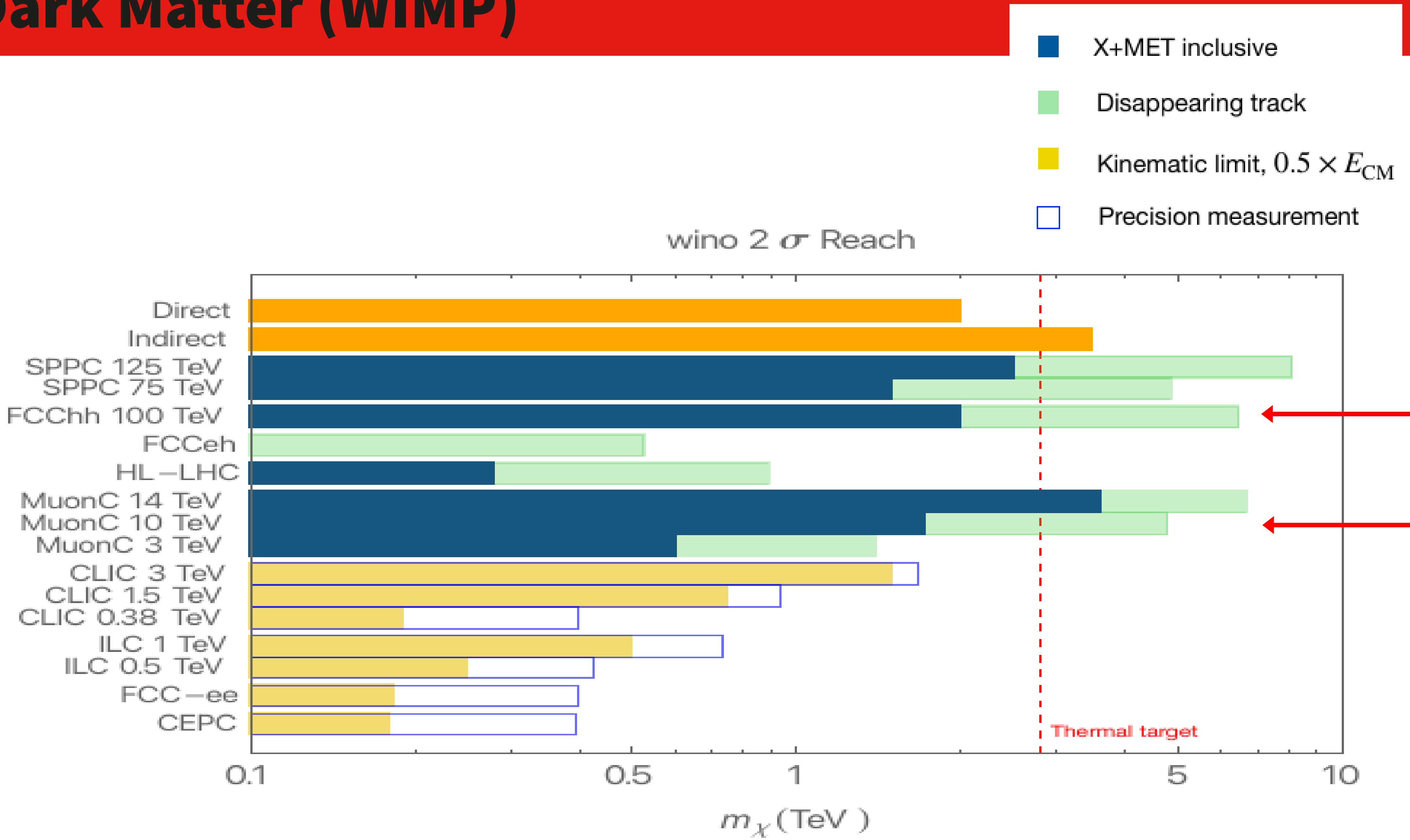




arXiv:2103.14043

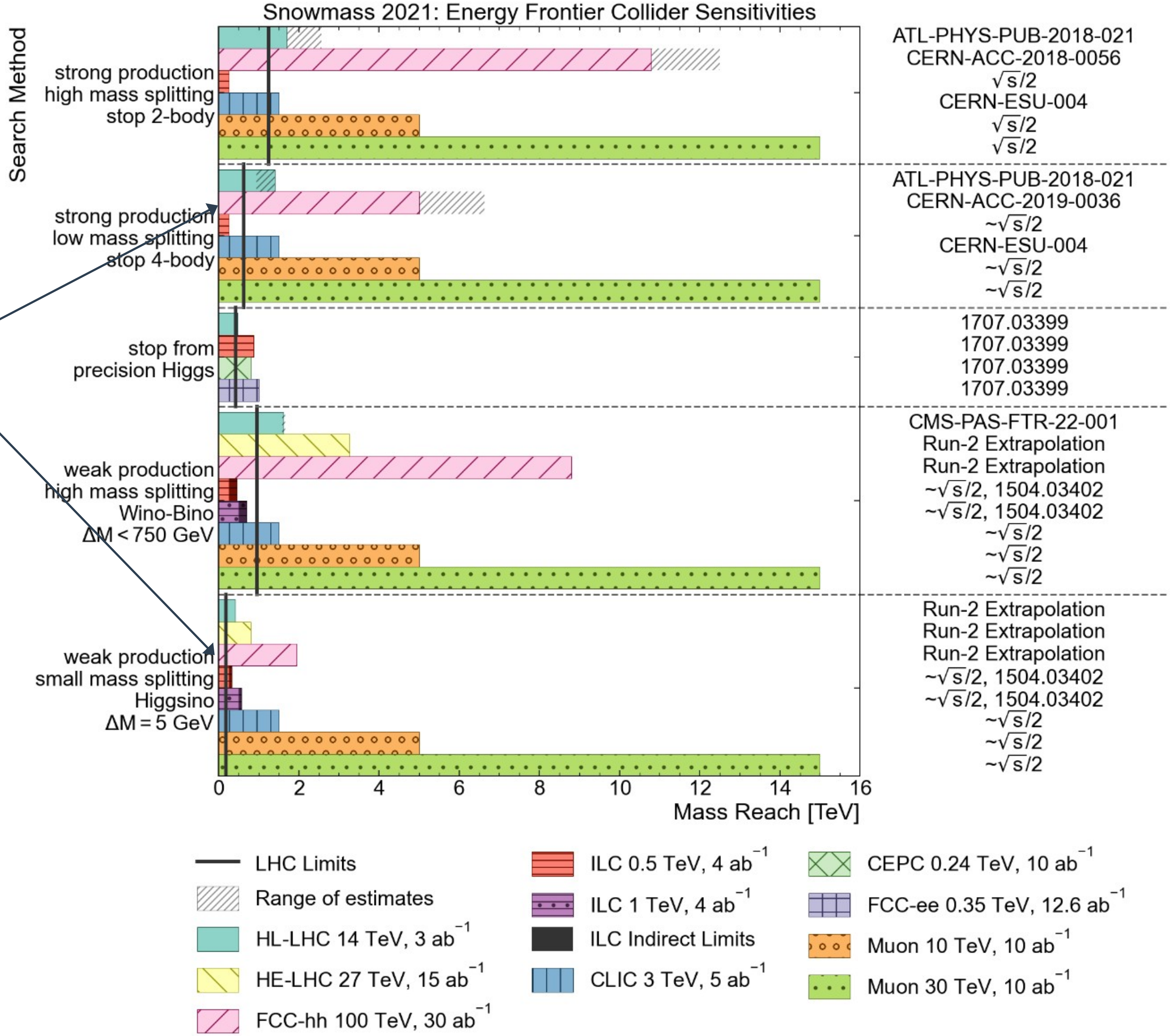
100 TeV pp ≈ 10-20 TeV μμ

Dark Matter (WIMP)

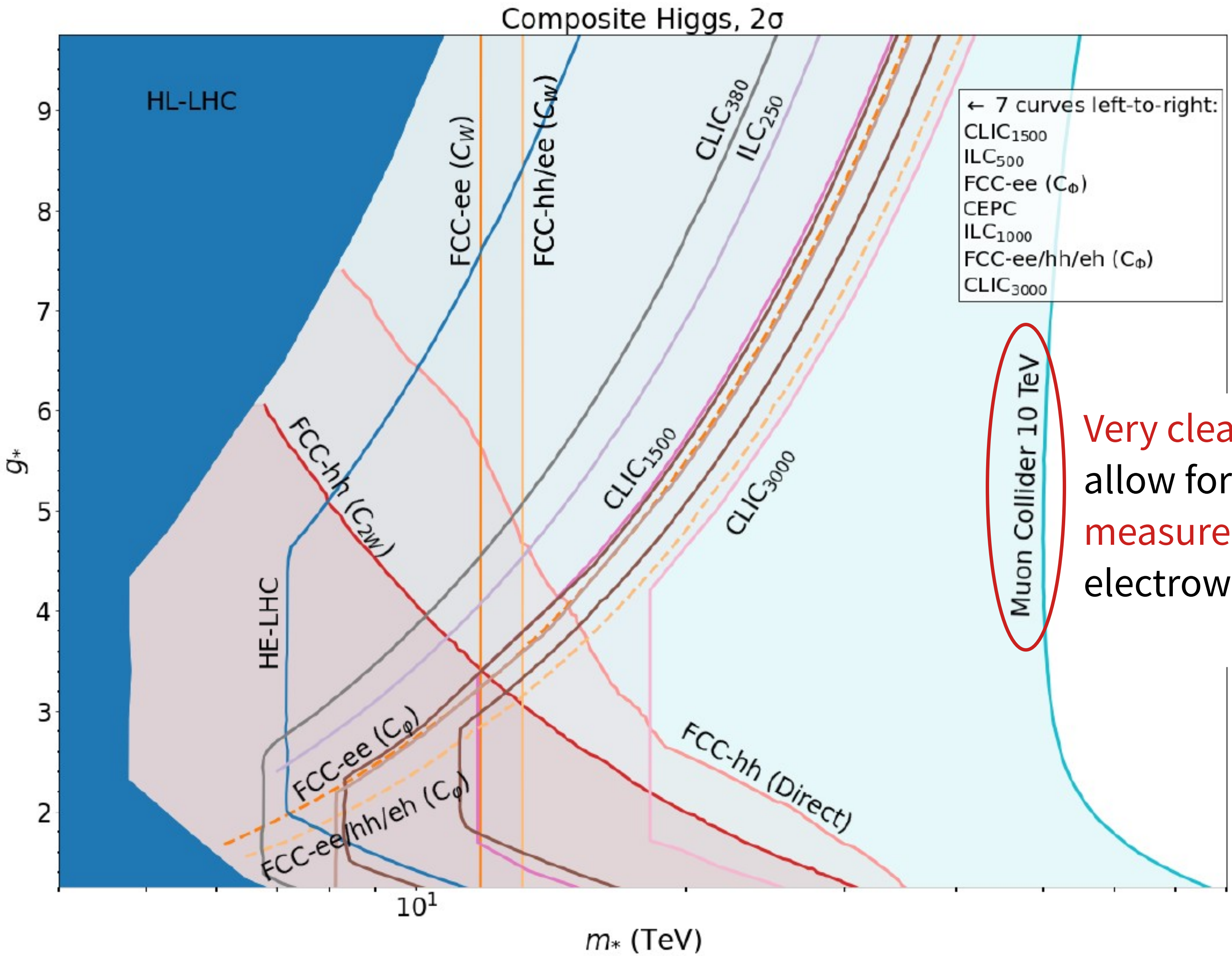


SUSY: Naturalness

Small mass splitting at *hadron colliders* limited by pile-up

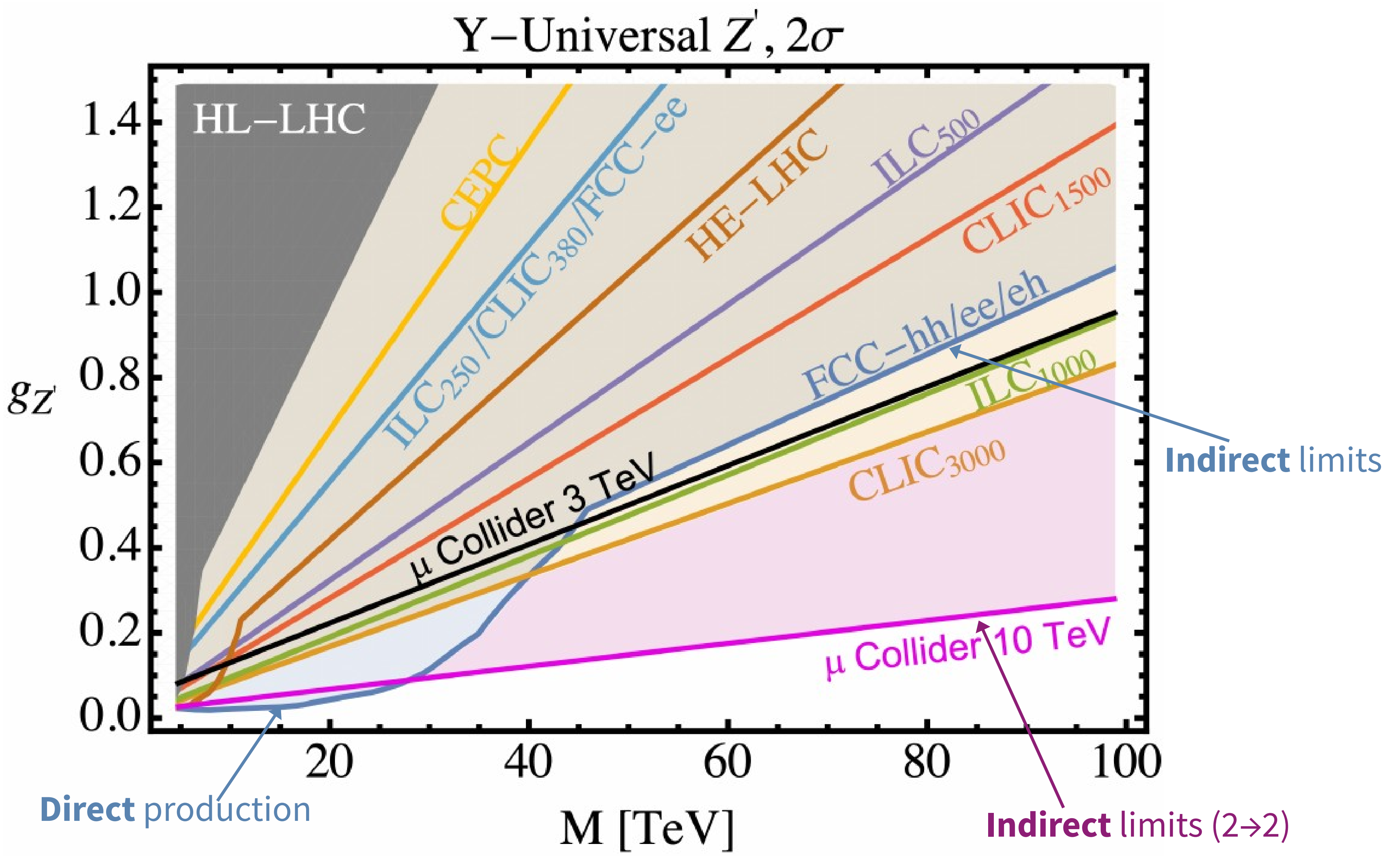


Naturalness: Composite Higgs



Very clean backgrounds allow for precise measurements of electroweak observables

Generic BSM: Z’

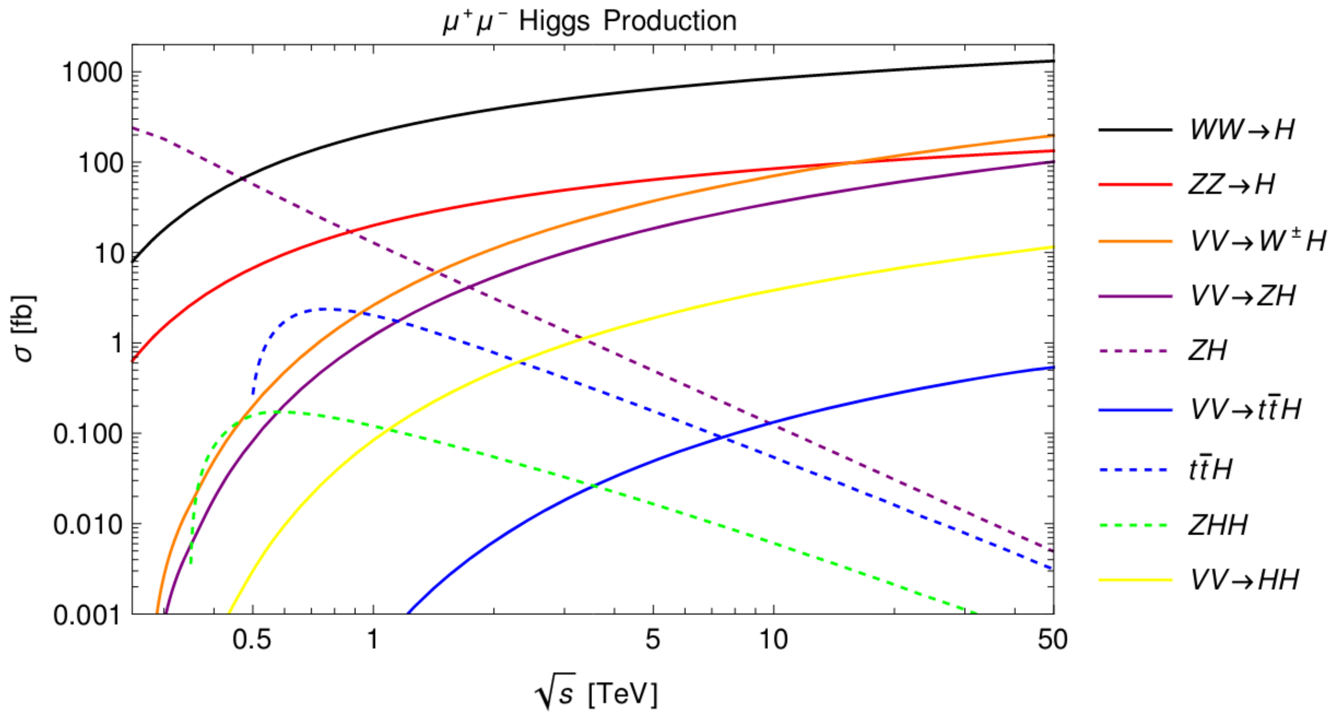


Electroweak Physics: Higgs

μC won't run on the Higgs pole.
or stage it (125 GeV → 10 TeV)?

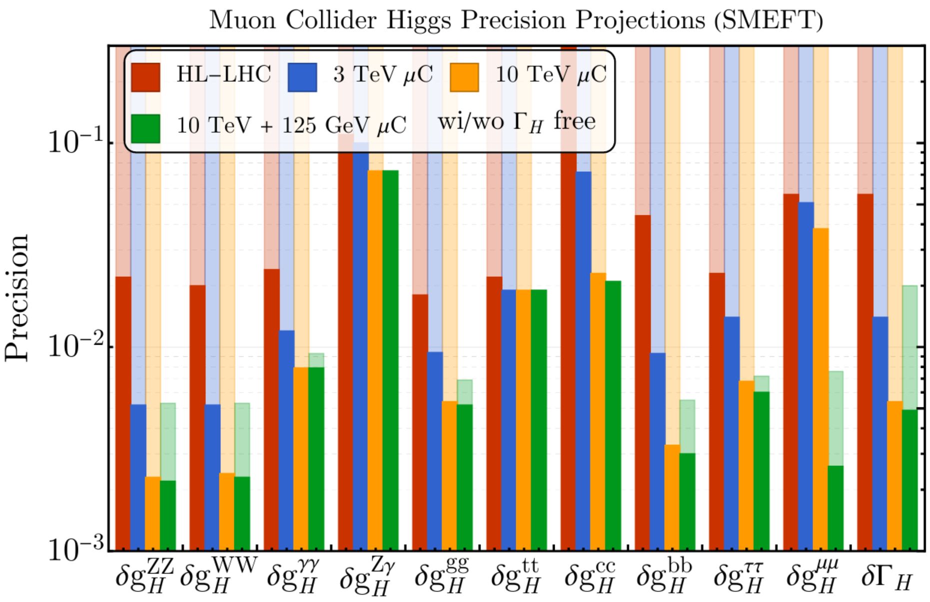
Three key measurements:

- Couplings at O(0.1%)
- Self-coupling
- Higgs width



	HL-LHC	Higgs Factories	l^+l^- @ 3 TeV	l^+l^- @ 10 TeV	pp @ 100 TeV
# Higgs	10^8	10^6	10^6	10^7	10^{10}

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

Three Challenges

The Accelerator

What technology is required to build a Muon Collider?

- aka muon cooling

Collider Specifications

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	$ab^{-}1/year$	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300

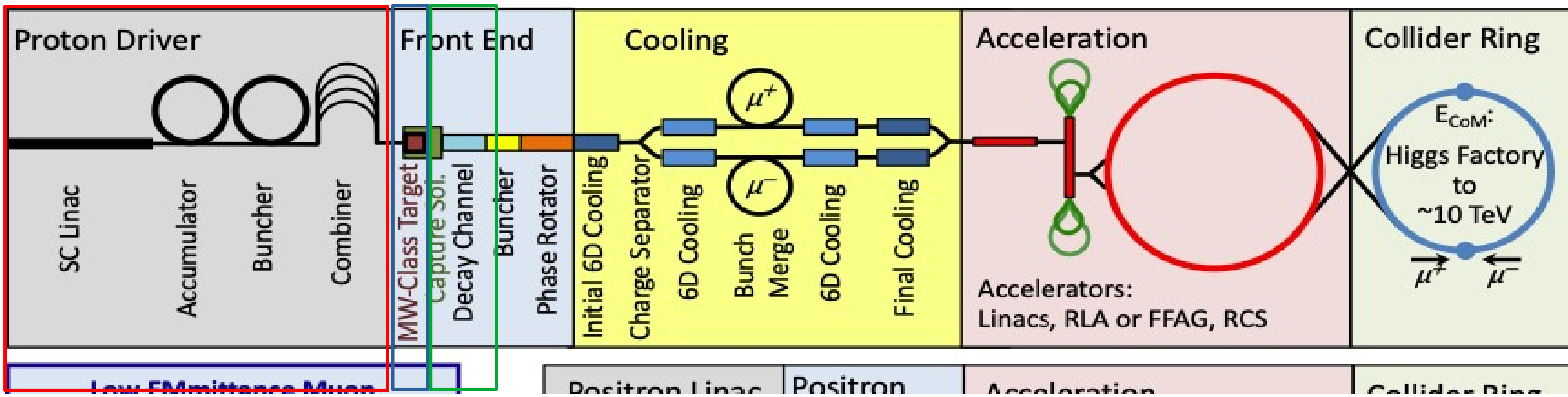
Scale for constant N(2→2)

1/3 of LHC

300 kHz means trigger-less

No pile-up!

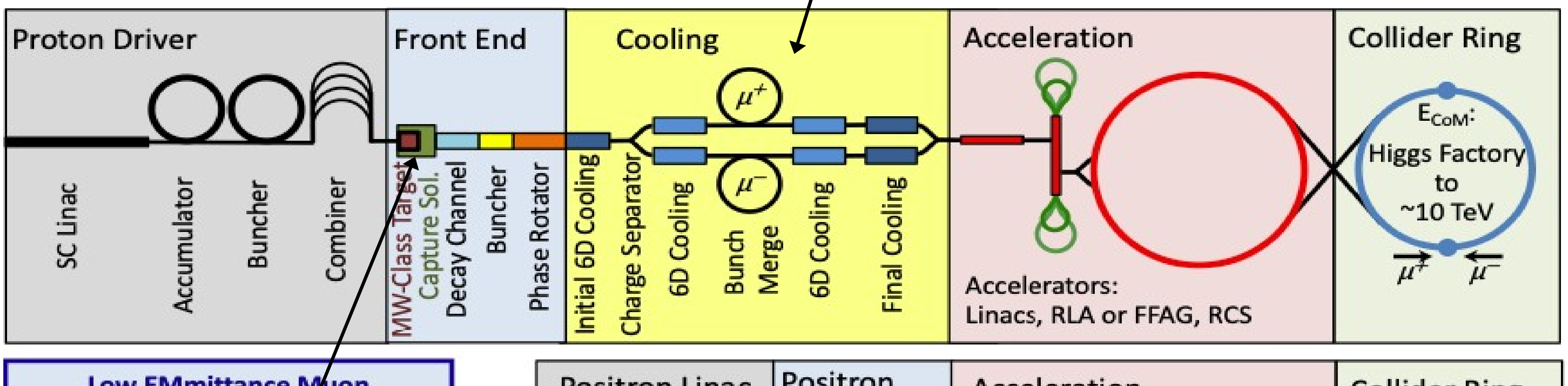
Accelerator Concept



$$p + X \rightarrow \pi^{\pm} + Y \rightarrow \mu^{\pm} + Z$$

Main Challanges

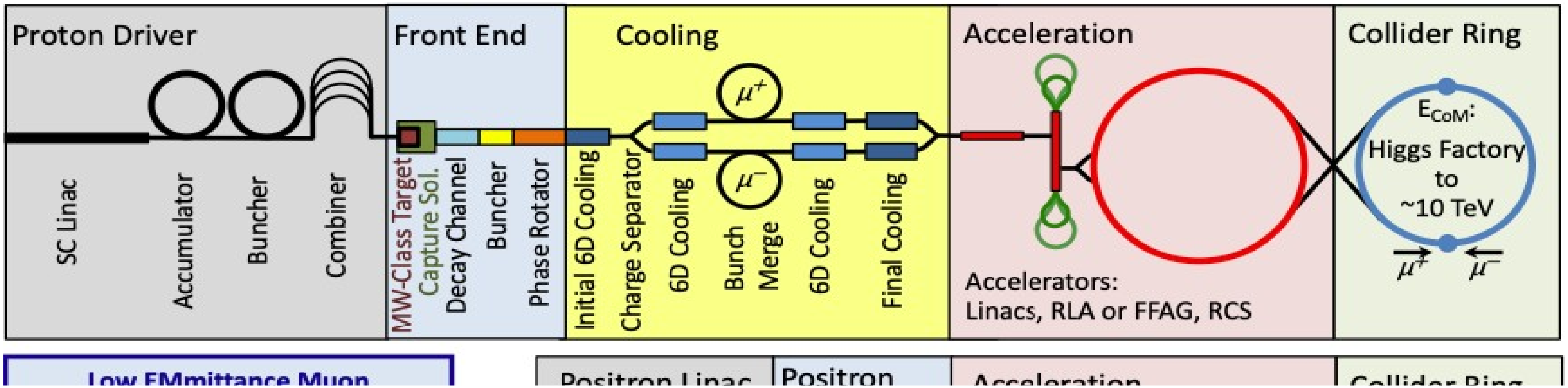
Increase emittance of bunches before muons decay.
Need high RF fields in high B-fields.



Need high-Z materials that can withstand MW proton beams.

Tungsten powder? Liquid metal targets?

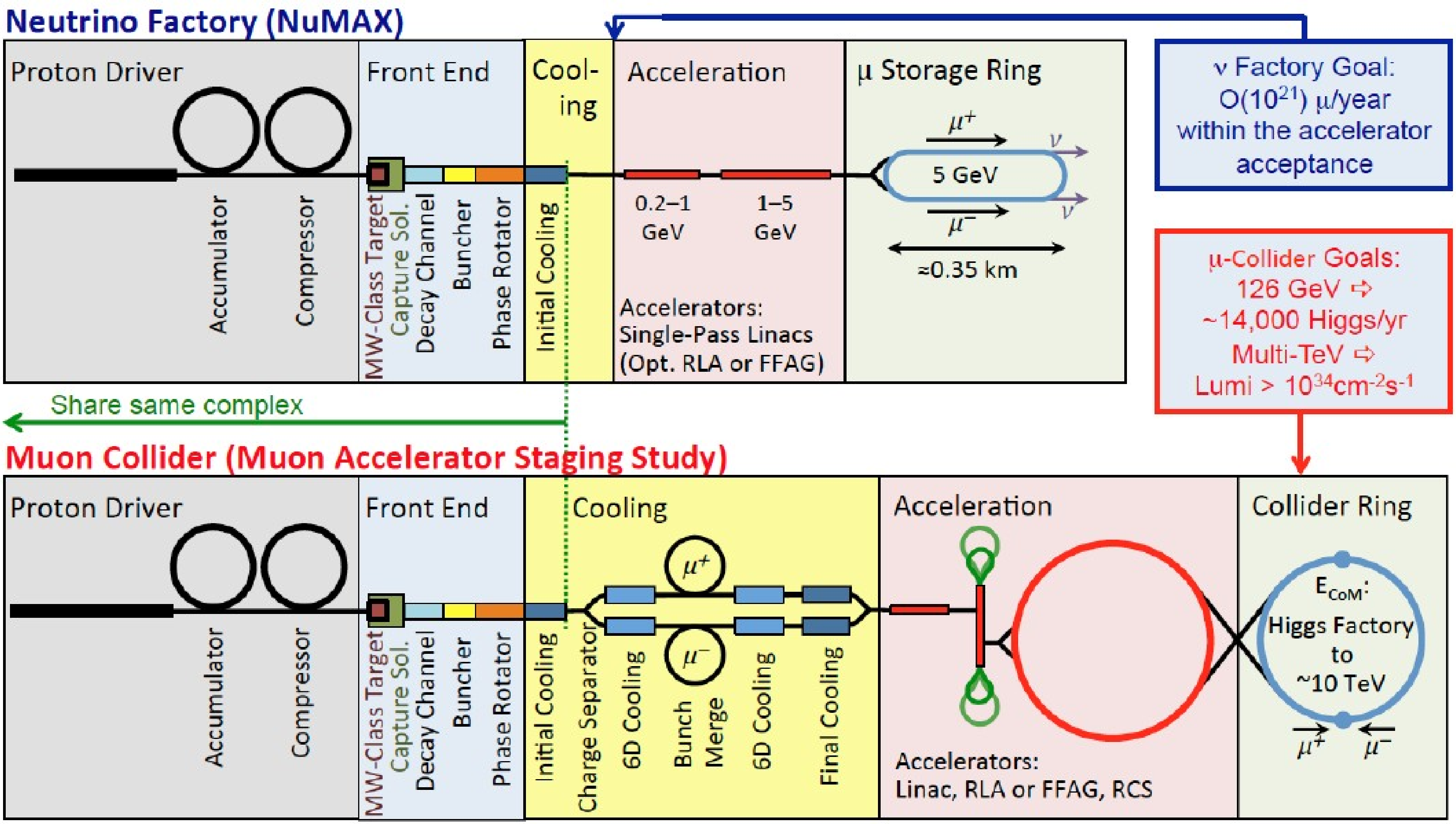
Accelerator Concept: Key Programs



- **Muon Accelator Program @ Fermilab: 2011-2016**
  - Laid the foundation for Muon Collider concepts
- **Muon Ionization Cooling Experiment @ RAL: 2008-…**
  - Demonstrator of most complex part targeting neutrino sources
- **International Muon Collider Collaboration @ CERN: 2022-…**
  - Demonstrator design of most complex part for muon collider

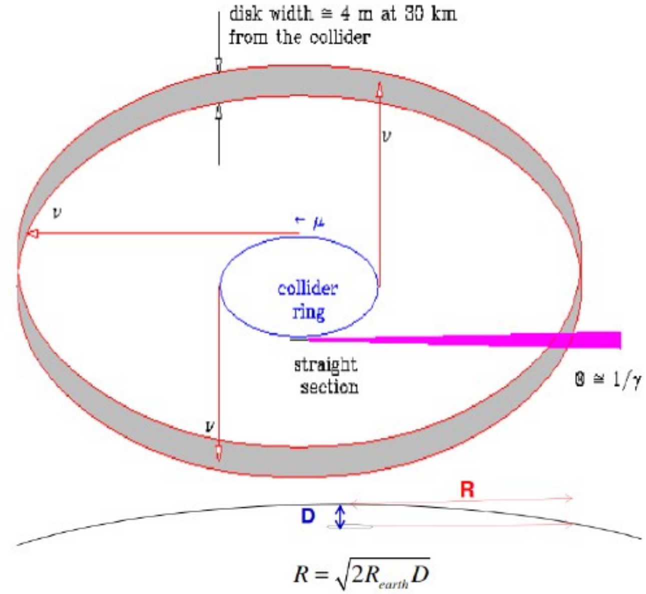
Syngery in Accelerator R&D

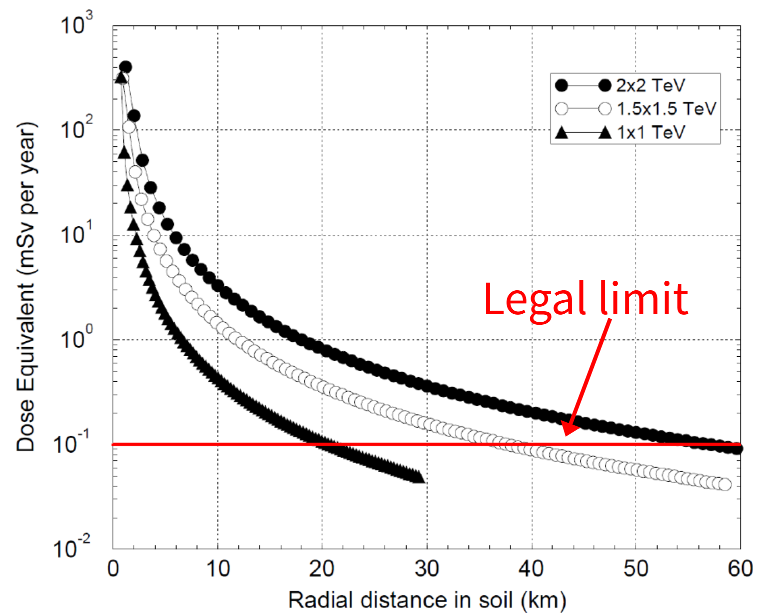
See Muon4Future workshop!



Heath and Safety for Neutrino Beams

- **Intense neutrino beam in collider plane**
  - Muons decay in flight
- **Intense enough to deposit dose?**
  - Charged particles from neutrino interaction
- **Hard to shield! (neutrinos)**
  - And shielding causes neutrino interactions…
- **Mitigation techniques proposed**
  - Build very deep underground (>300m)
  - Build in an isolated place (ie: desert)
  - Wobble beam to disperse neutrinos





Three Challenges

The Detector

Is the collision environment clean for precision physics?

- How to deal with Beam Induced Background

Our (1.5 TeV) Onion Detector

10 TeV concept being developed

heavily based on CLIC detector

hadronic calorimeter

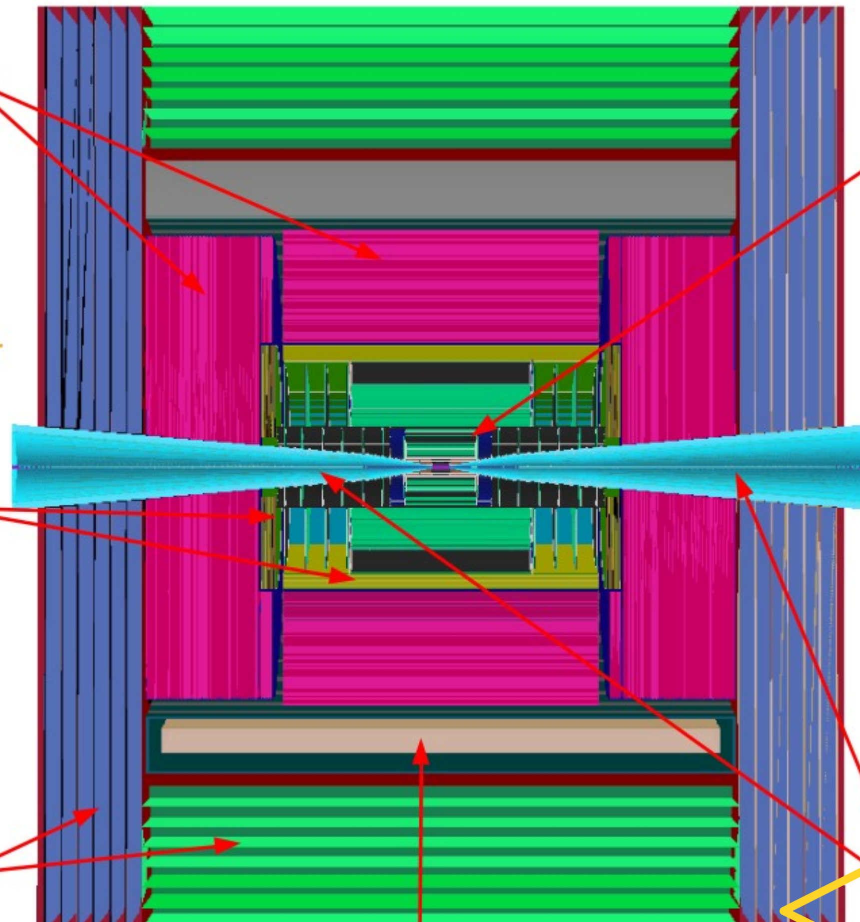
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

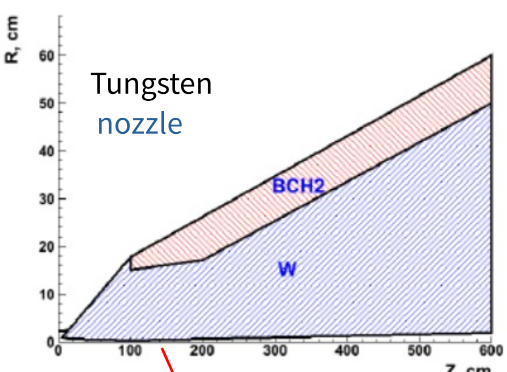
shielding nozzles

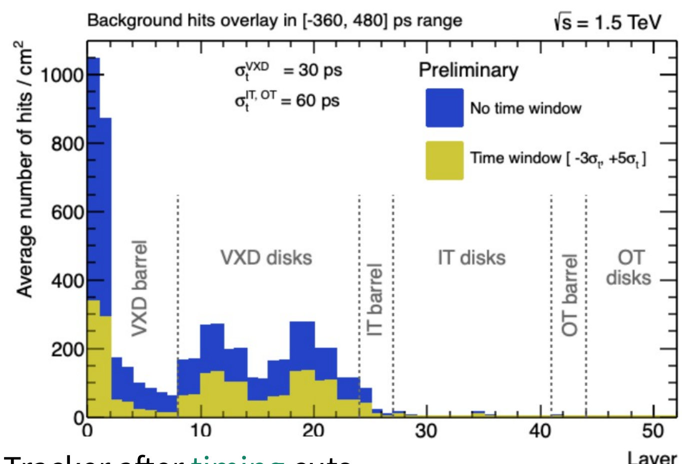
- Tungsten cones + borated polyethylene cladding.

Beam Induced Background

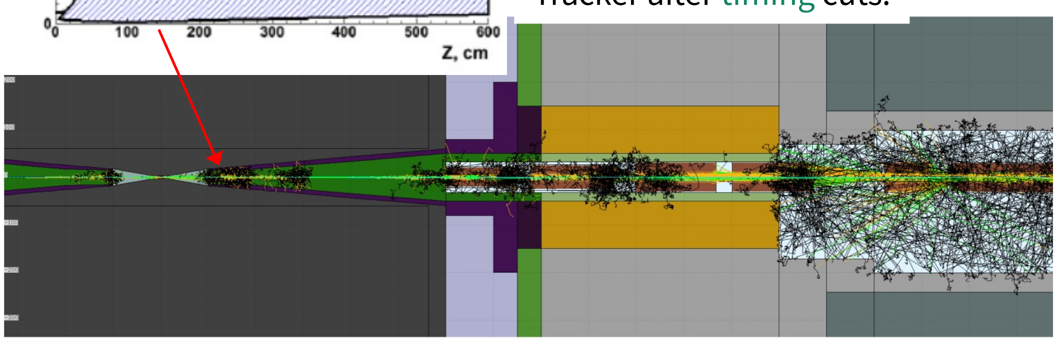
arxiv:2105.09116

- **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

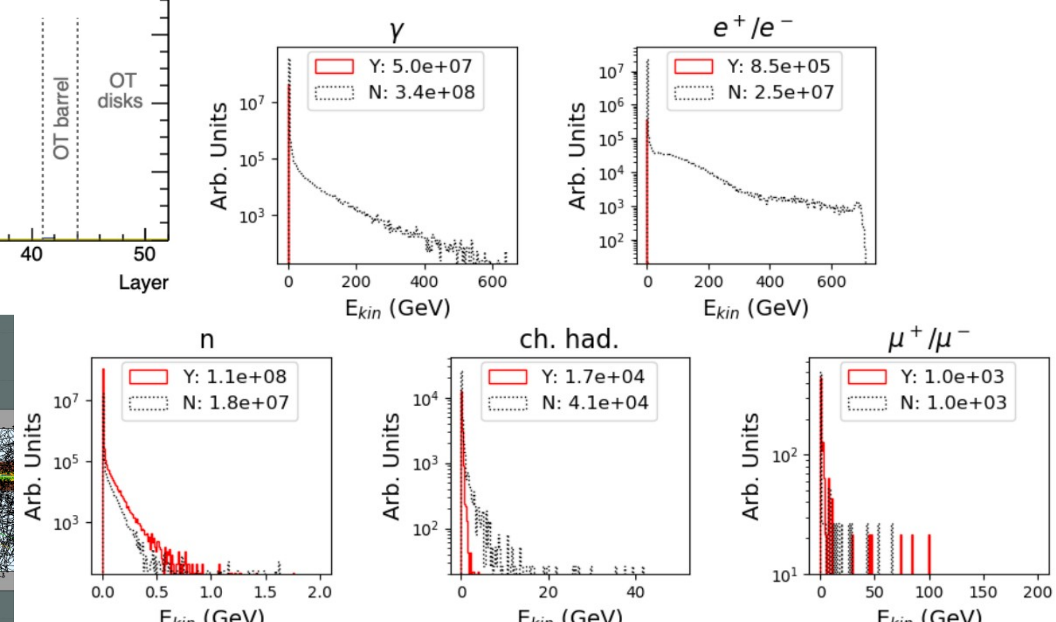




Tracker after timing cuts.



FLUKA simulation of BIB before reaching the detector.



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

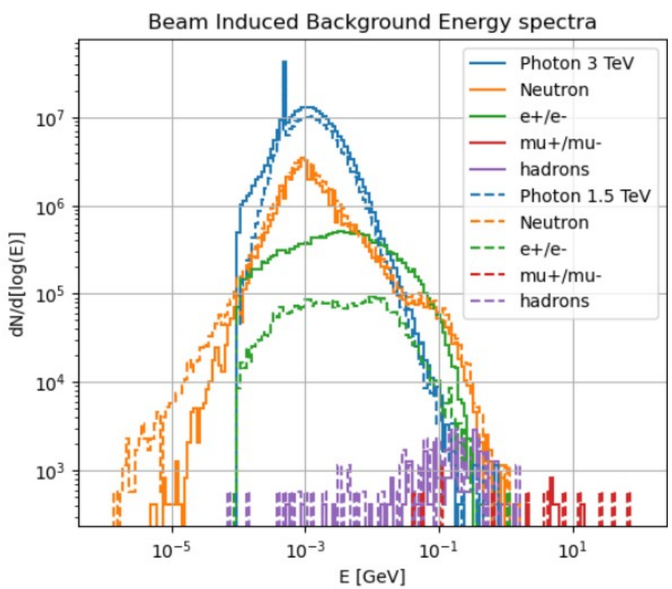
Simulating Beam Induced Background

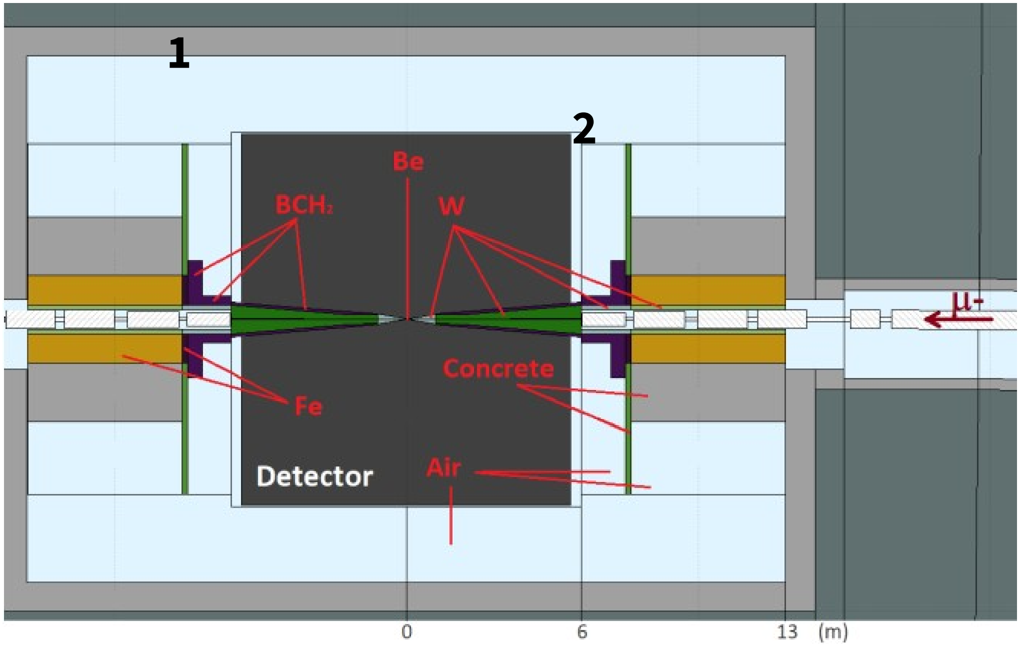
1)Muon trajectory, decay and transport of products via FLUKA*

- Full beam optics present through LineBuilder Interface

2)GEANT simulation of particles entering the detector

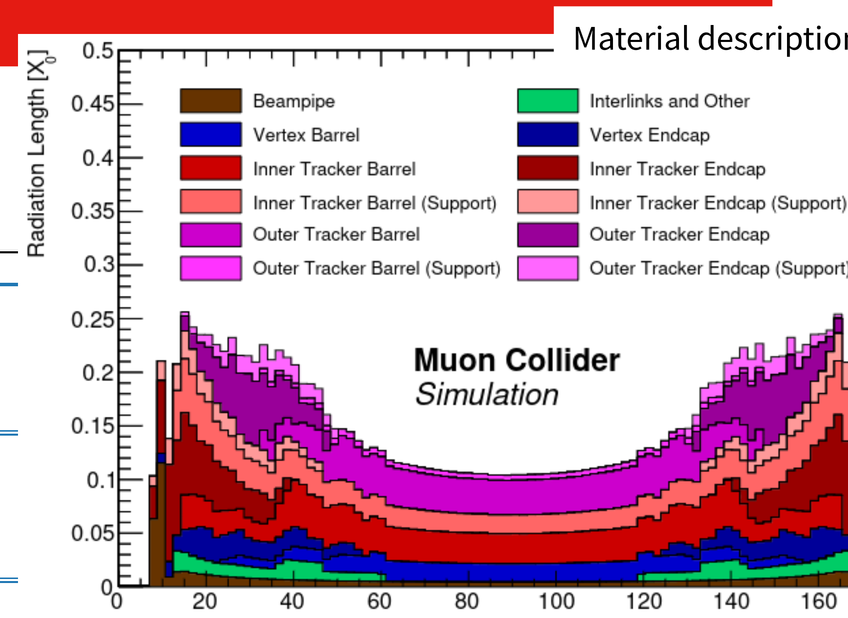
√s=1.5 TeV used to develop setup, more energy points being added.





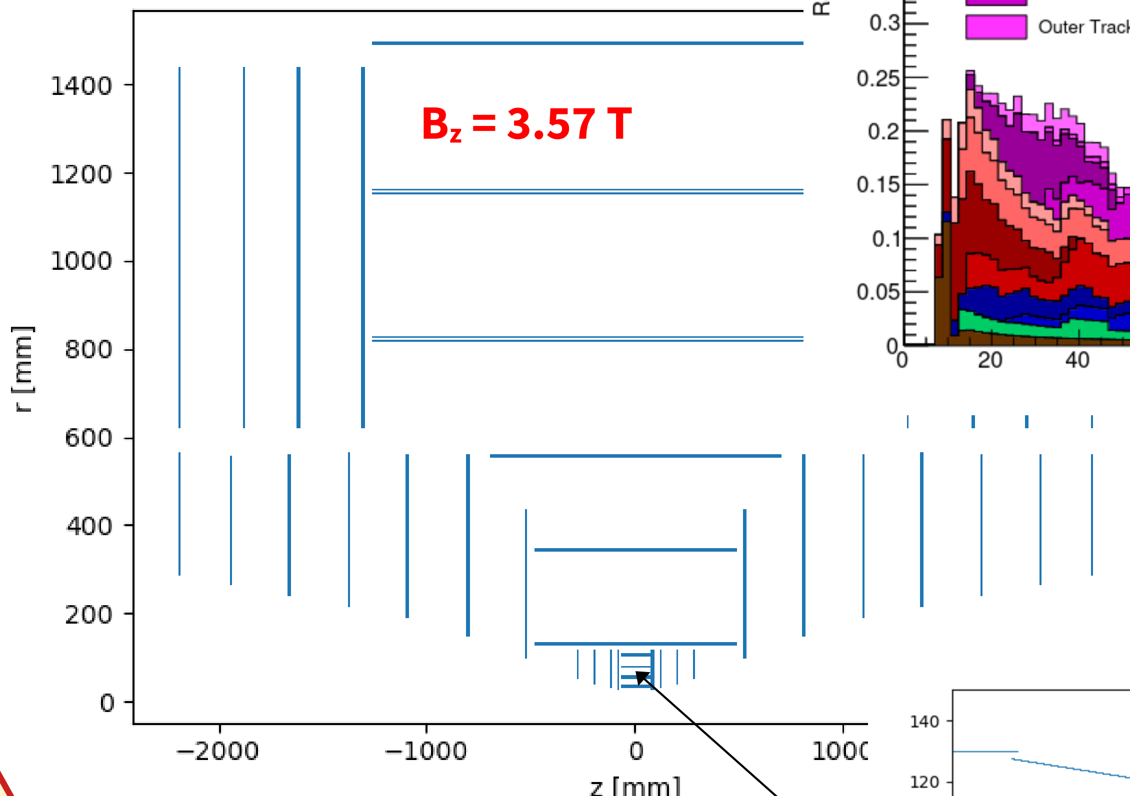
* validating against an older model from MARS15

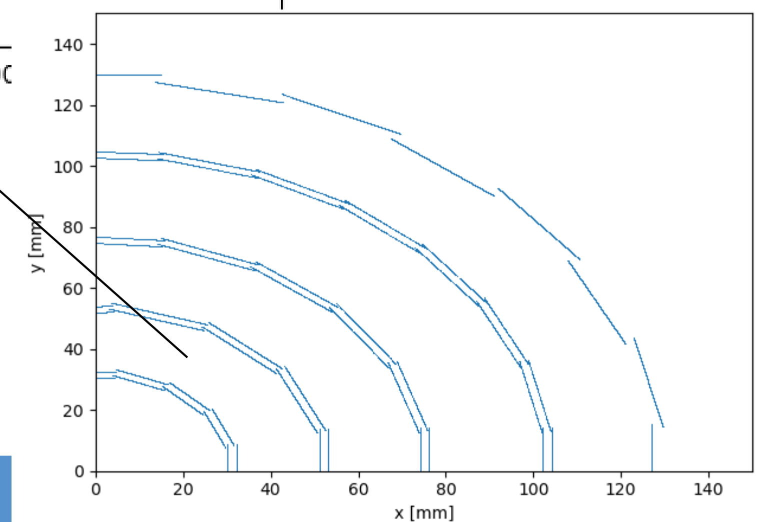
All-Silicon Tracking Detector



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

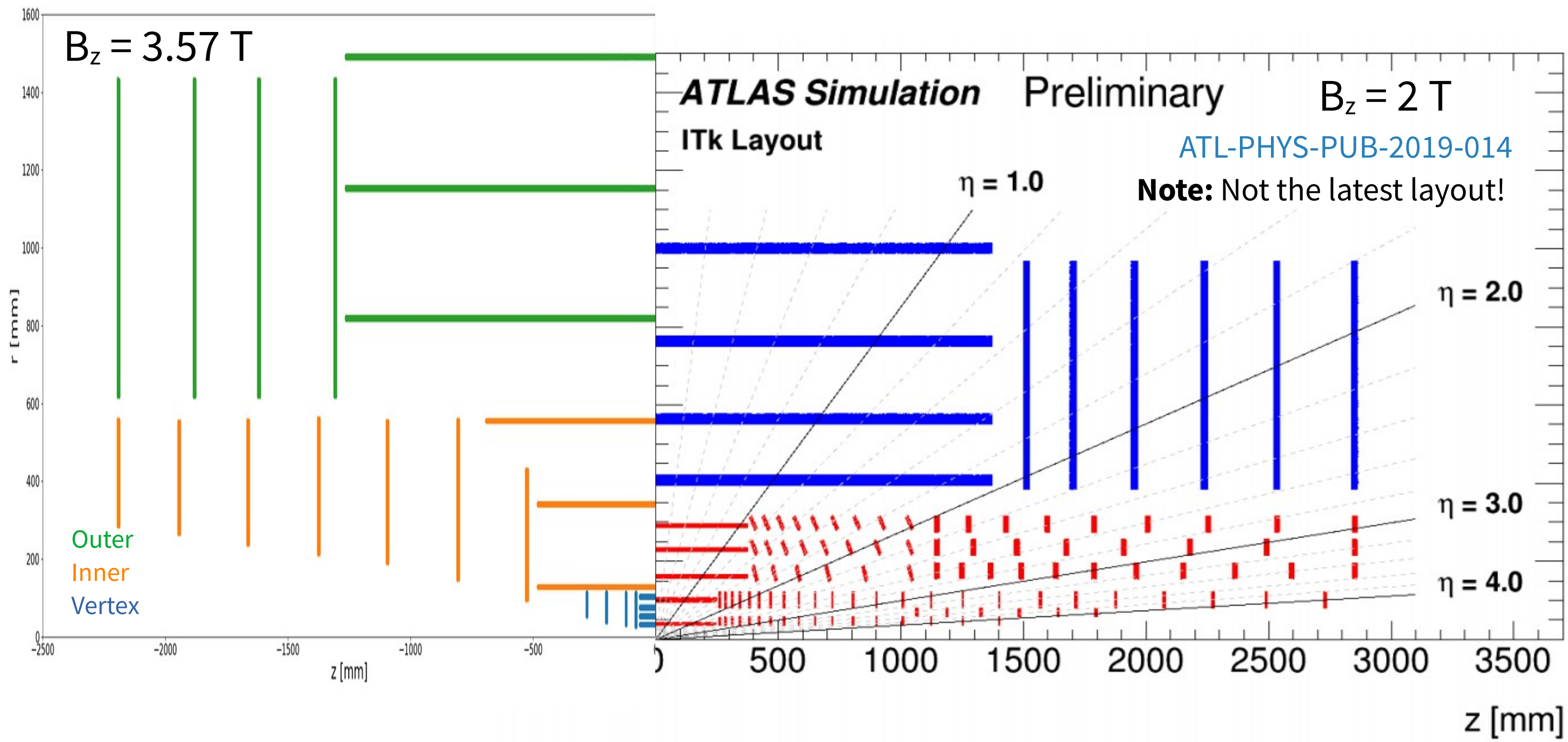




4D tracking critical

Vertex Detector (VXD)
- pixels
- 25 µm x 25 µm
- σ_t = 30 ps
- double layers

The Scale of BIB

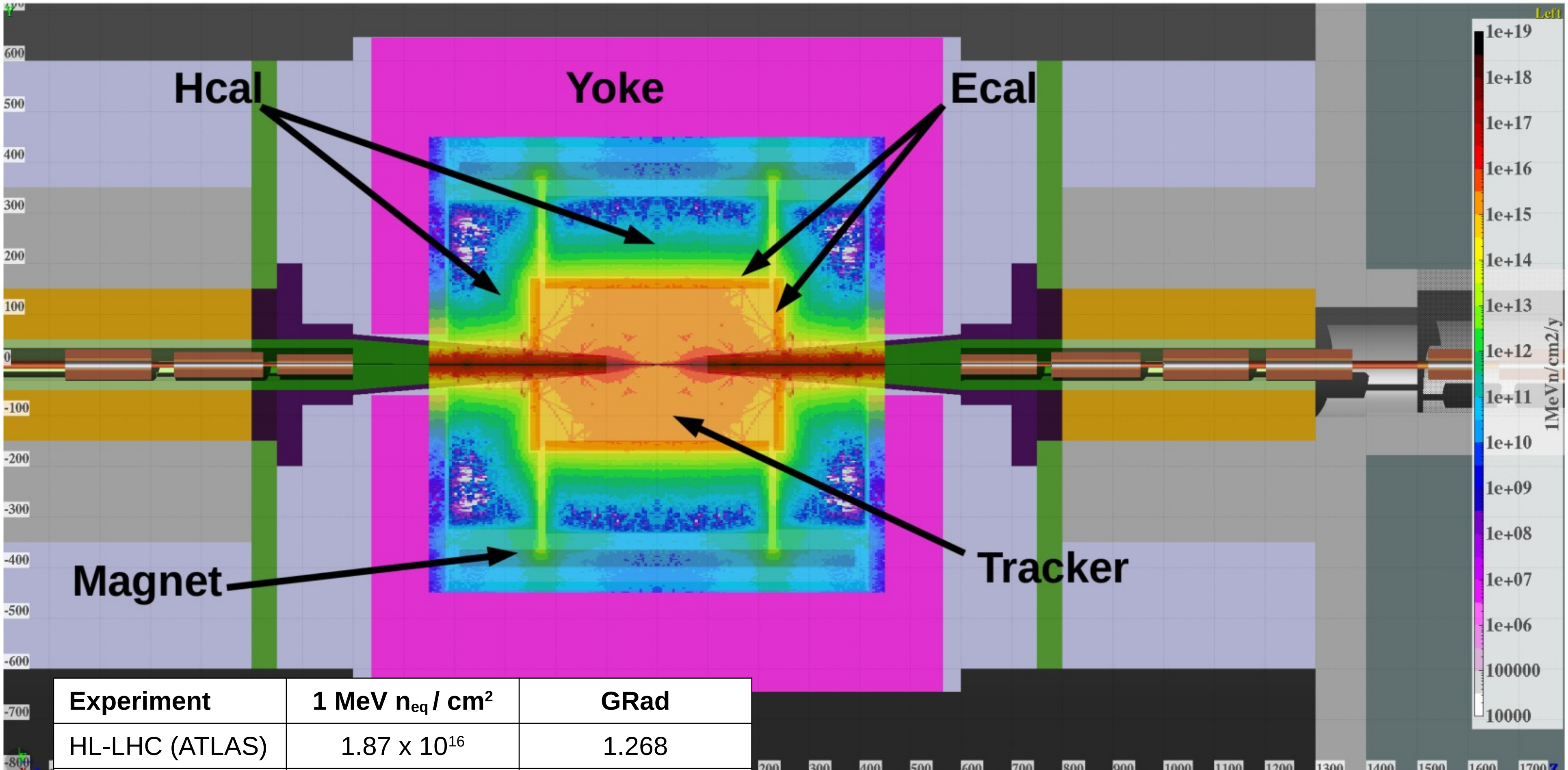


Hit density
after timing cuts
10x HL-LHC

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

ITk Pixels TDR, ITk Strips TDR

Radiation Damage From BIB



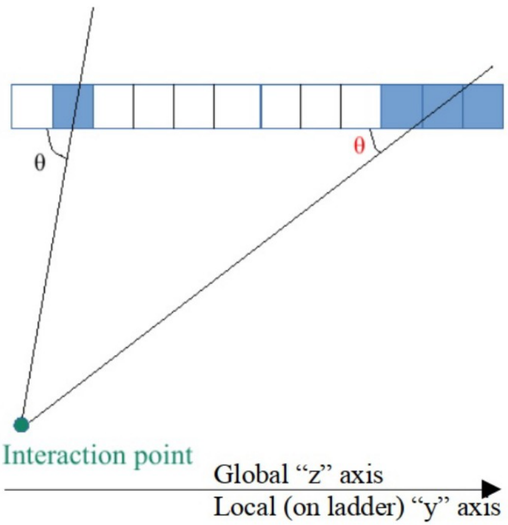
Experiment	1 MeV n_{eq} / cm^2	GRad
HL-LHC (ATLAS)	1.87×10^{16}	1.268
µC (1.5 TeV)	5×10^{15}	0.05
FCChh	8×10^{17}	27
FCCee	? not big ?	? not big ?

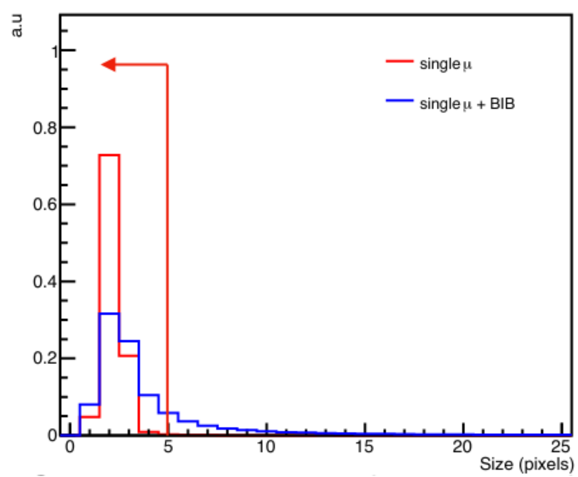
Expected dose in innermost tracking layer.

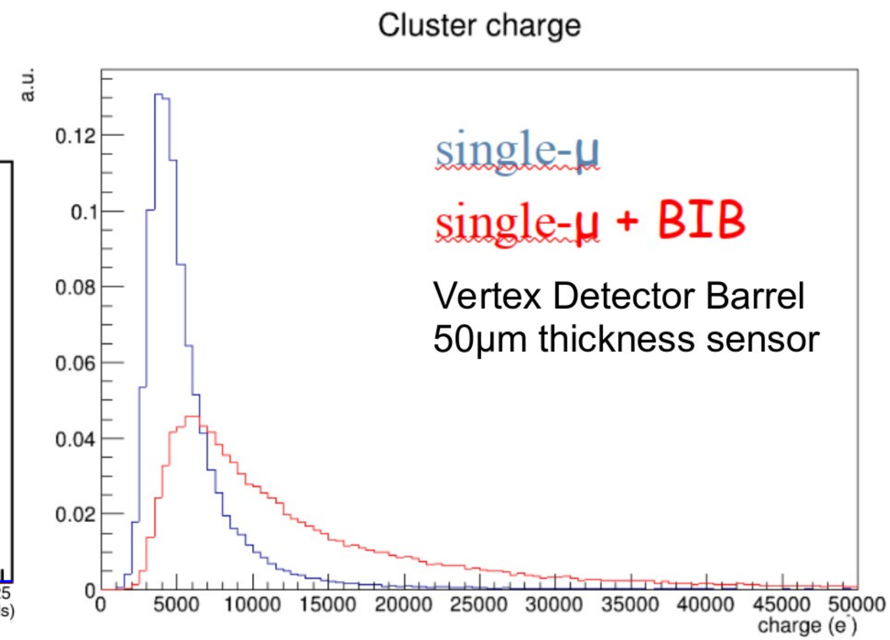
Advantages of Realistic Digitization

Work In Progress: Currently not part of common workflow

- Provides a more accurate description of hit clusters
- Provides a handle on BIB rejection







Requirement	Cut efficiency	Loose	Tight
Size-y cut vs. θ only	Single-μ	99.8 %	99.6 %
	Single-μ and BIB	55.2 %	43.7 %
Adding pixel size-x < 4	Single-μ	99.3 %	99.1 %
	Single-μ and BIB	37.4 %	30.7 %

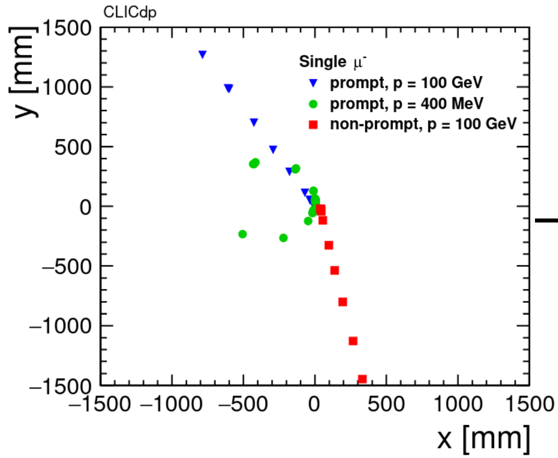
Track Reconstruction Algo #1

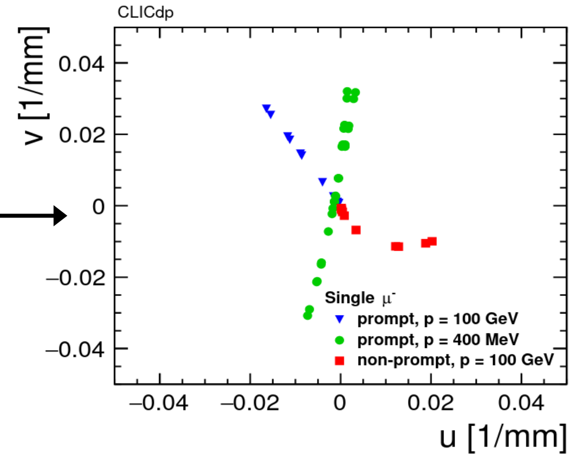
Global Hit Selection
ie: timing or double layers

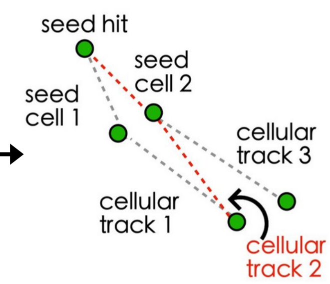
Conformal Transform
circular tracks → straight lines

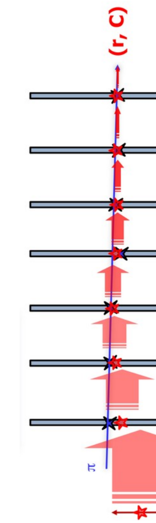
Cellular Automaton
straight "lines" → tracks

Kalman filter
Track fit









Credit: I. Kisel

Remove BIB hits

Pattern Recognition

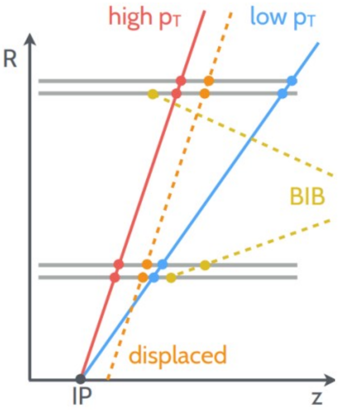
Track Fit

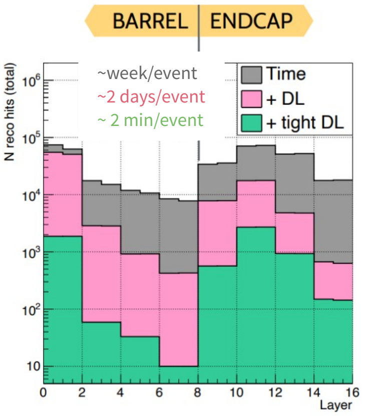
Algorithm + code inherited from CLIC software.

aka optimized for clean e^+e^- environment

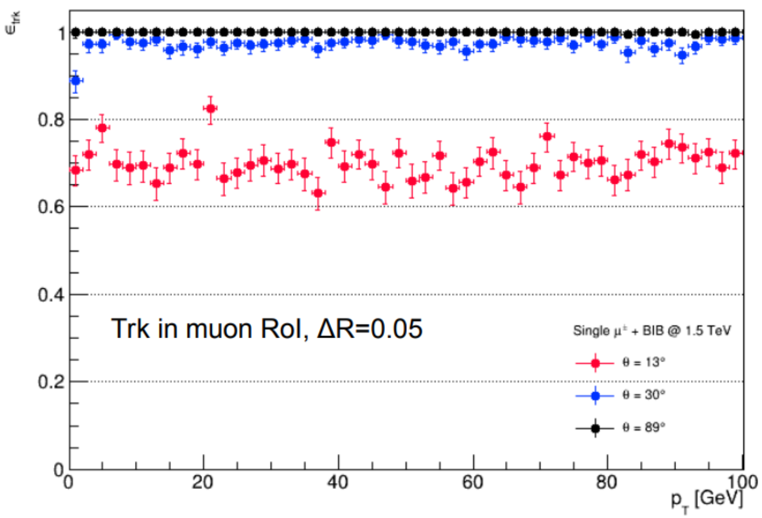
CT Tracking Performance

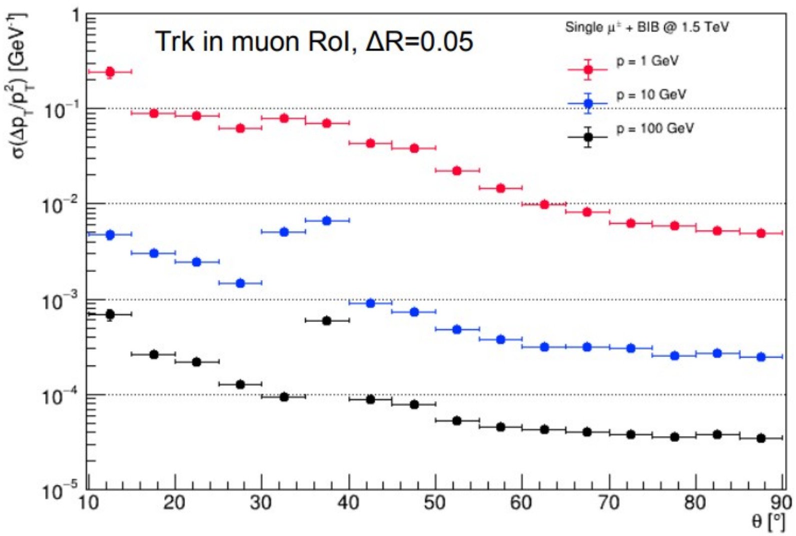
- **Employ hit multiplicity reduction strategies**
  - Region of Interest seeded tracking
  - Directional information from double layers
- **Require tight filtering for practical tracking**





- **Good track reconstruction once algorithm completes**



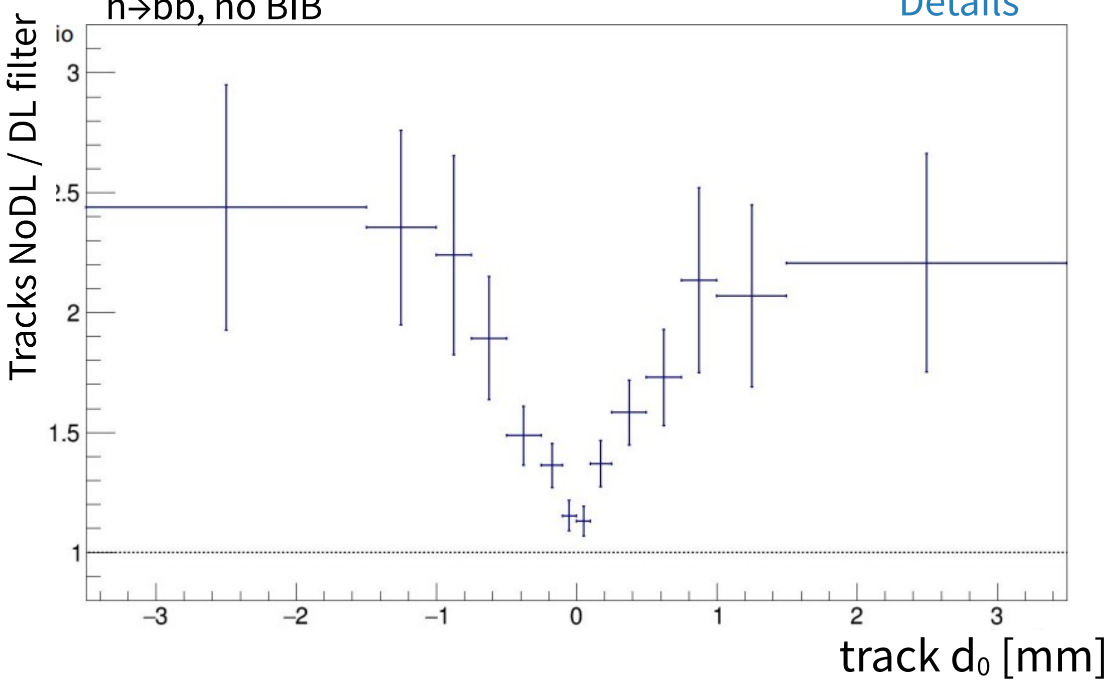


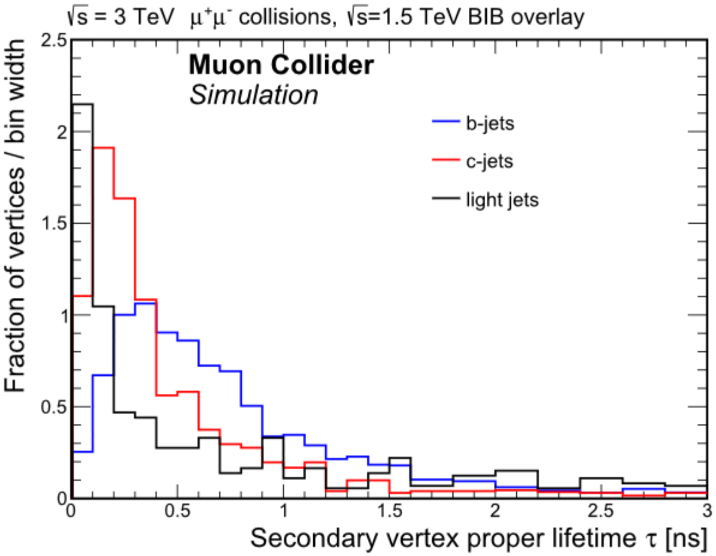
Flavour Tagging

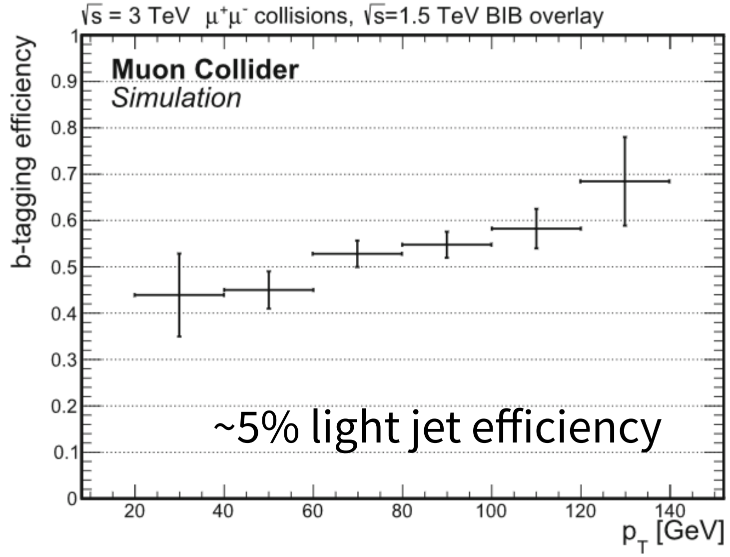
- **Secondary vertex reconstruction possible with BIB**
  - Caveat: using a very loose hit filter
- **Work ongoing on multivariate tagger**
- **Double layer filtering → possible bias**

h→bb, no BIB

Details







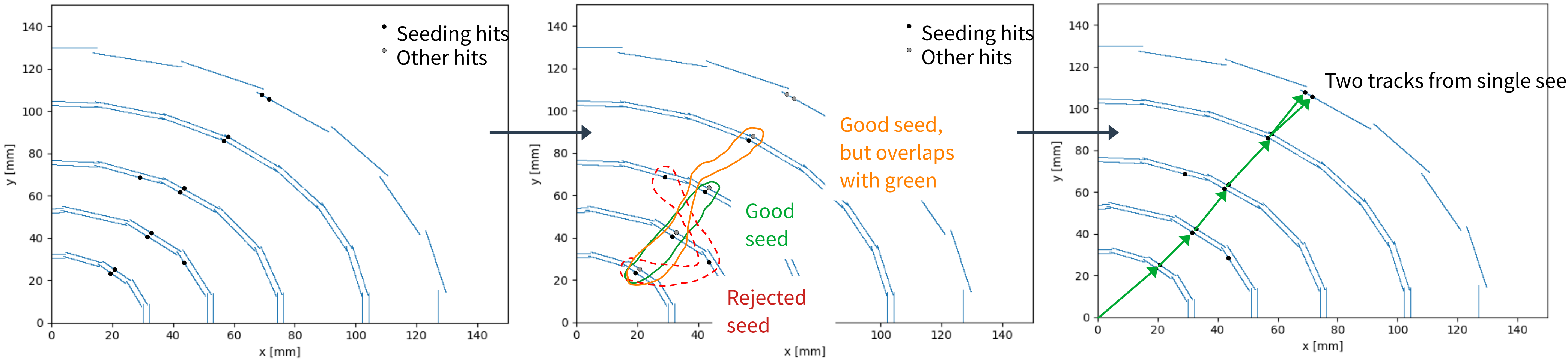
Triplet Seeded CKF

Fit Library	Kalman Filter Execution Time
ACTS	0.5 ms / track
iLCsoft	100 ms / track

Global Hit Selection
ie: timing, *

Seed Finding
Initial parameters for CKF

Combinatorial Kalman filter
Track fit



* Currently not leveraging double layers.

Remove BIB hits

Pattern Recognition

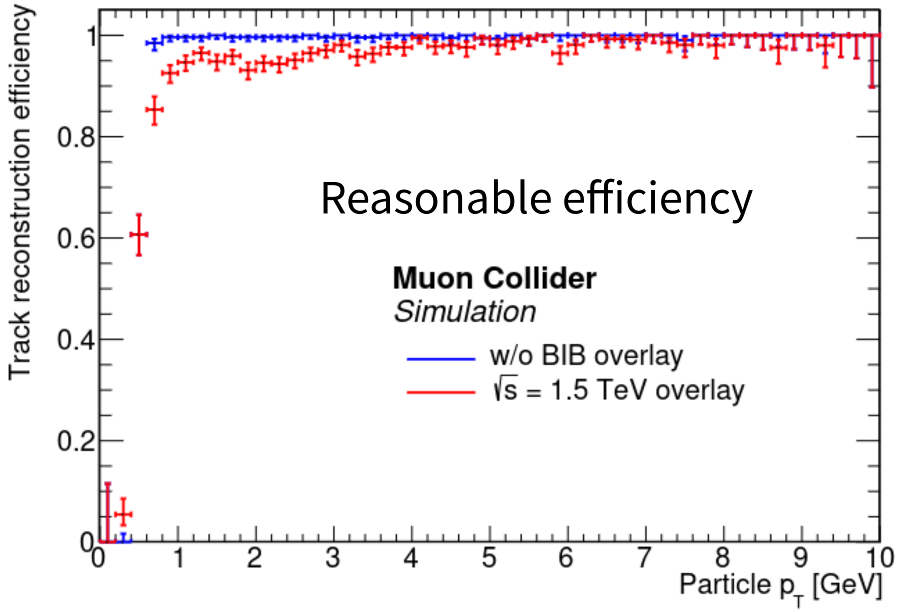
Track Fit

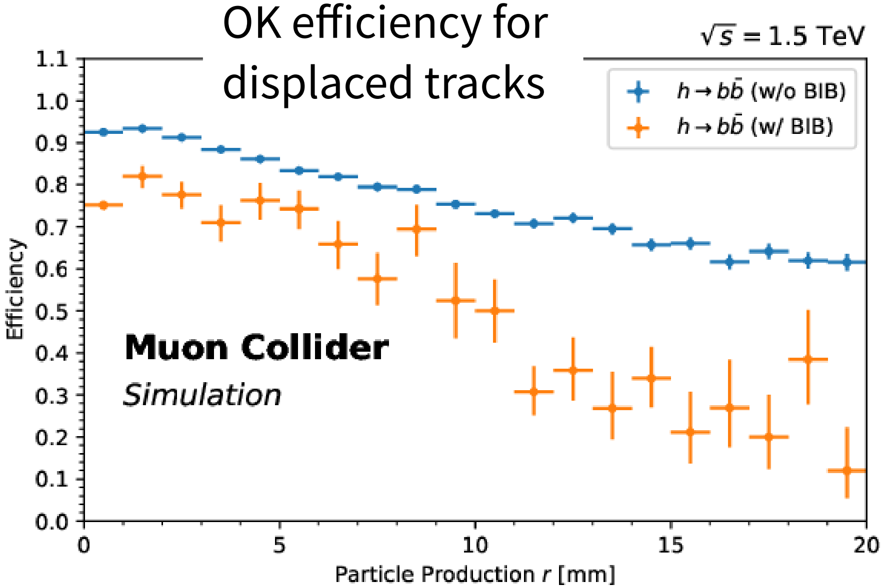
Similar algorithm used by ATLAS.

aka optimized for high hit multiplicity

CKF (ACTS) Tracking Performance

- **Seeded CKF runs in ~4 min / event.**
- **Parameters need to be optimized.**
  - Seeding: *very narrow collision region*
  - CKF: No branching allowed

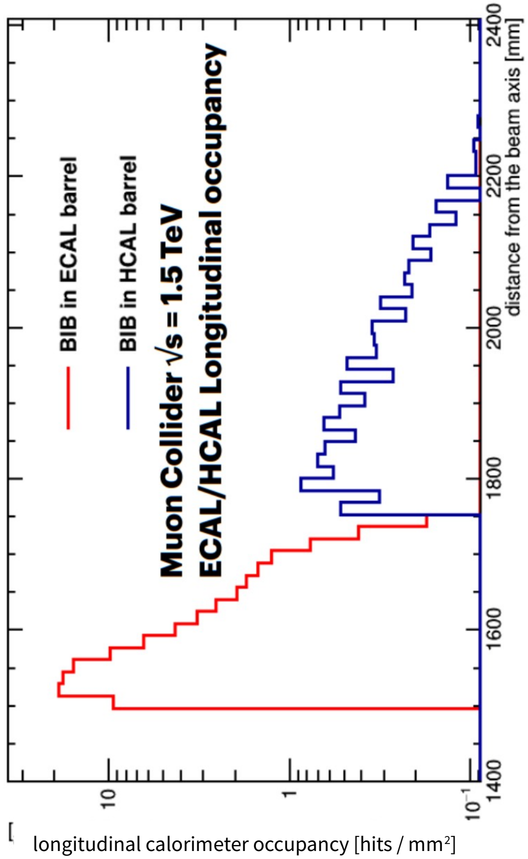




Fake track removal
(optimized with evolutionary algorithms)

Eff WP	Fakes / event
90%	3900
80%	0.13
70%	0.06

Calorimeters



Hadronic Calorimeter

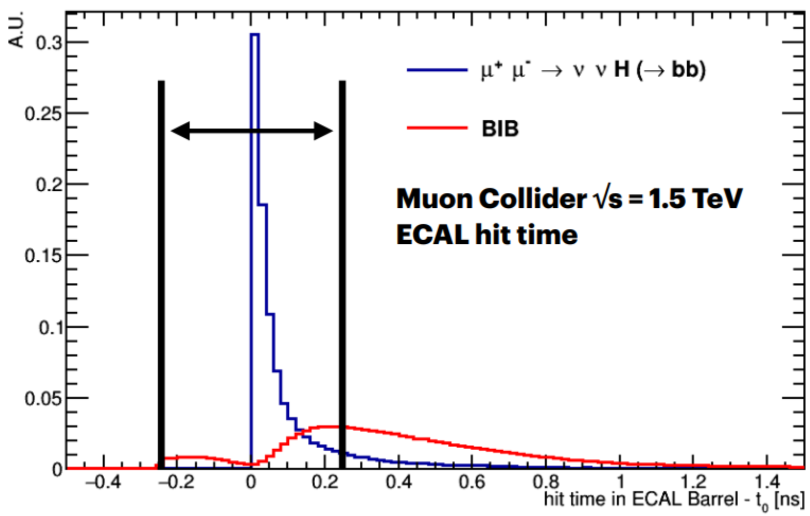
- 40 layers
- W absorber
- Silicon pad sensors, 5x5 mm^2

Electromagnetic Calorimeter

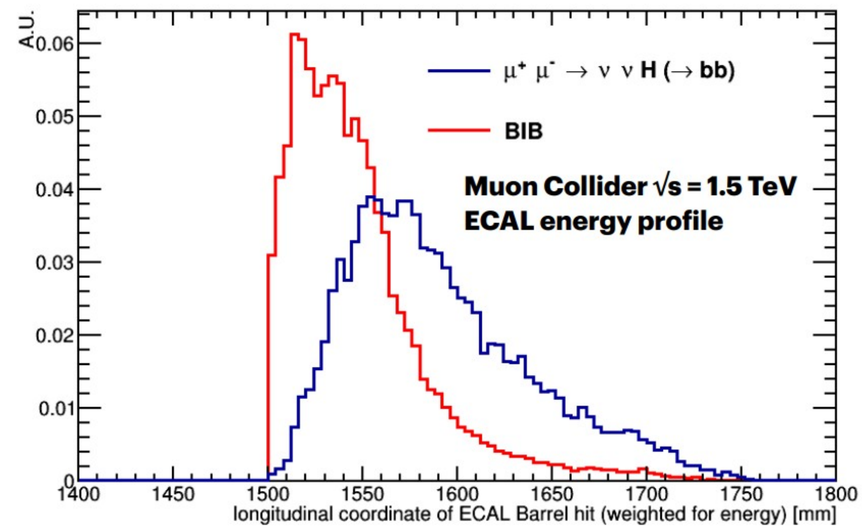
- 60 layers
- steel absorber
- Plastic scintillating tiles, 30x30 mm^2

BIB in Calorimeter

- **Timing is important**



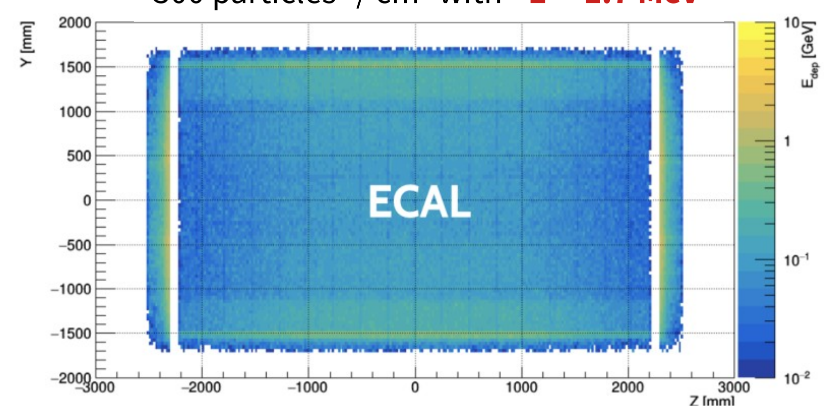
- **Shower shape another handle**



- **Remaining BIB is removed by subtraction**
  - Accept ECal hit if $E_{HIT} > \langle E_{BIB} \rangle + 2\sigma_{BIB}$
  - Correct remaining ECal hits $E_{HIT} \rightarrow E_{HIT} - \langle E_{BIB} \rangle$

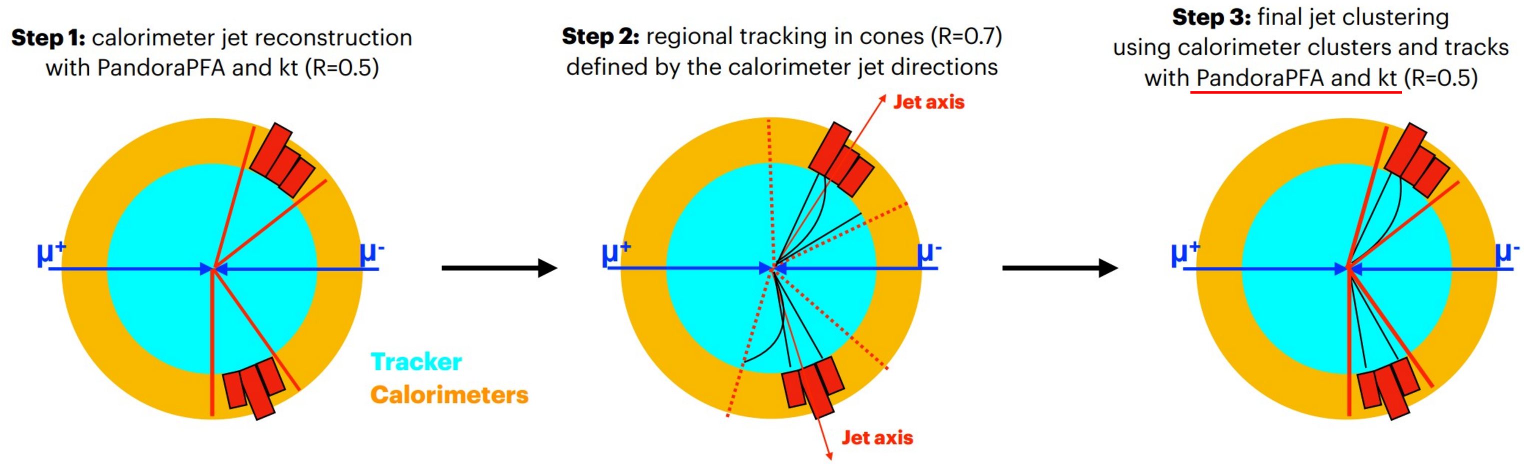
* mostly photons

300 particles* / cm² with **<E>=1.7 MeV**

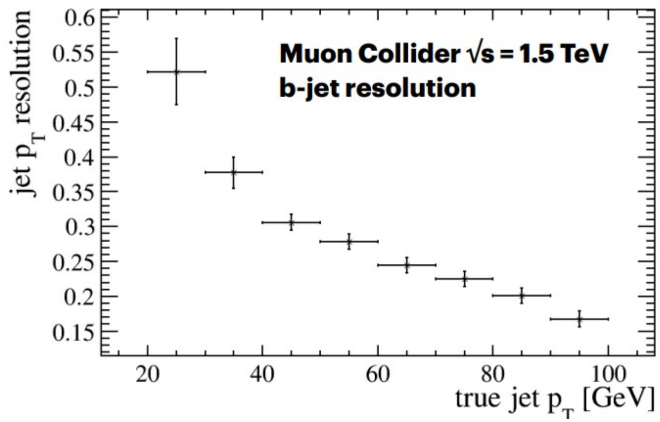


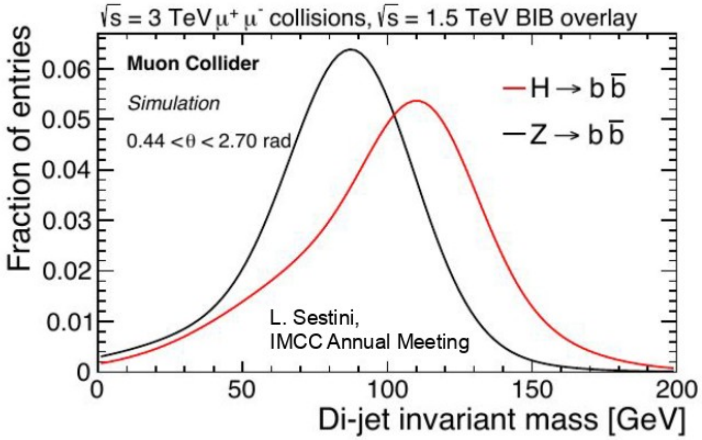
ECal energy deposition in one bunch crossing.

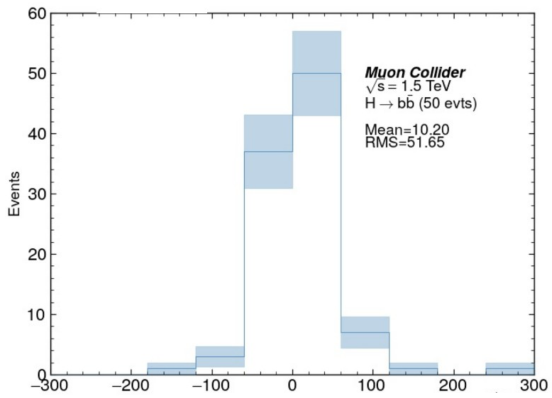
Jet Reconstruction



Fully efficient for p_T>80 GeV with ~20% resolution







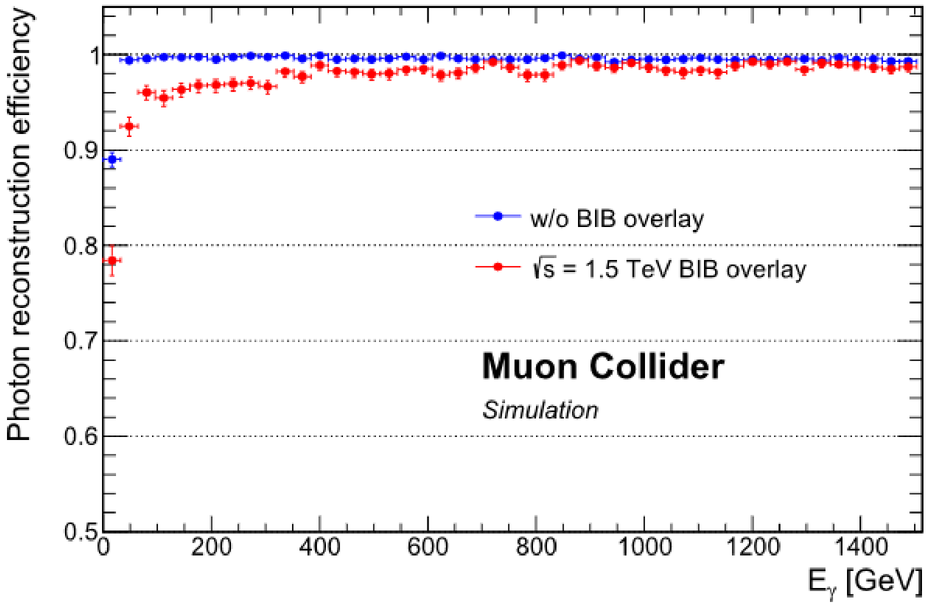
Transverse $H^{miss}_{BIB} - H^{miss}_{noBIB}$ [GeV]

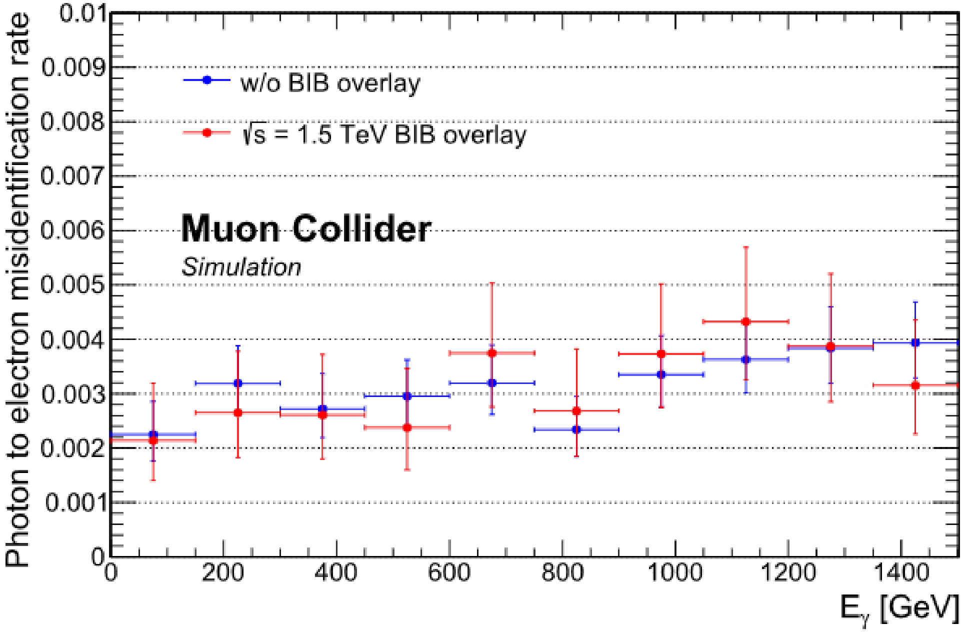
Plenty of room to *optimize* and *innovate*!

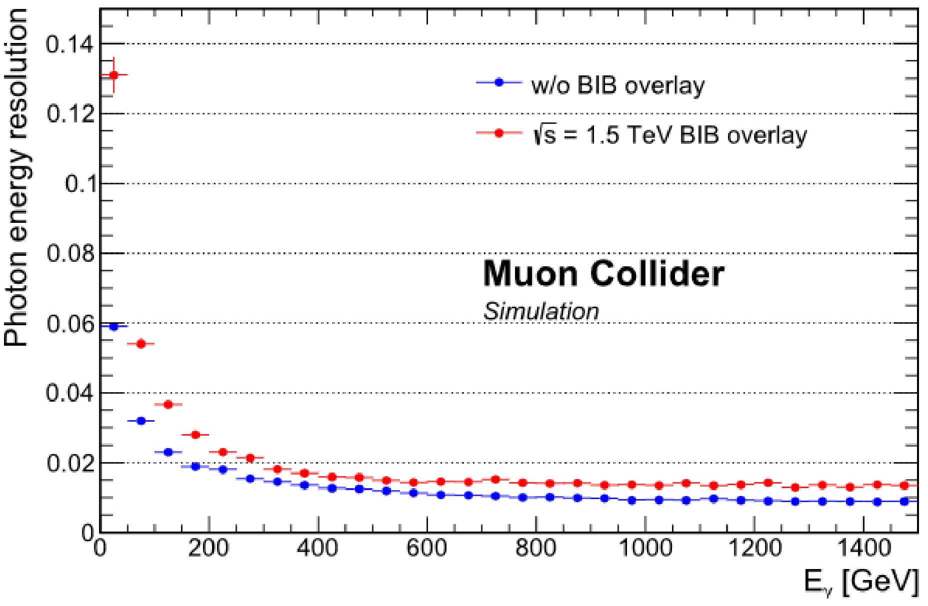
Electrons and Photons

Reconstructed and identified using the Pandora Particle Flow Alg

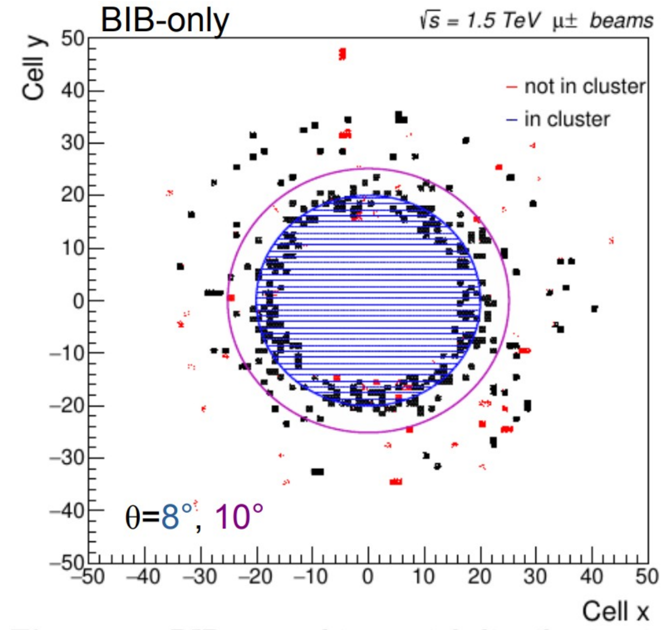
- Electron results similar to photons.



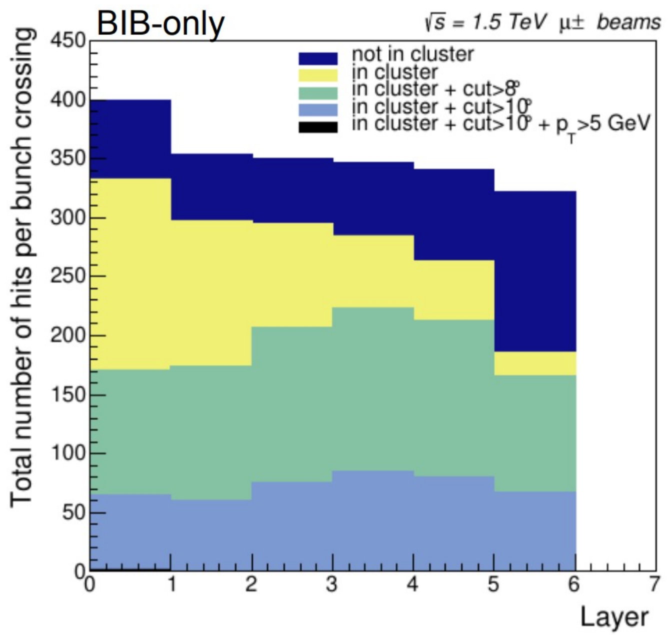




Muon Spectrometer

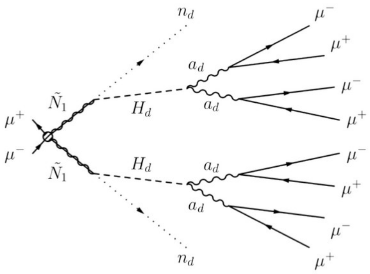


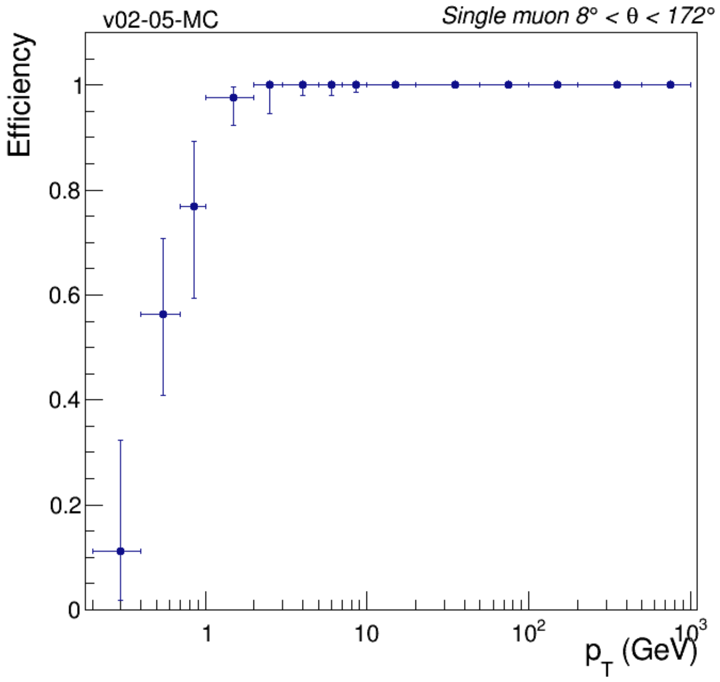
- **RPC cells of 30x30 mm^2**
  - 7 barrel layers, 6 endcap layers
- **BIB not a major problem**
  - Mostly in endcap tips (close to beamline)
  - Suppressed via geometrical cuts (<10°)

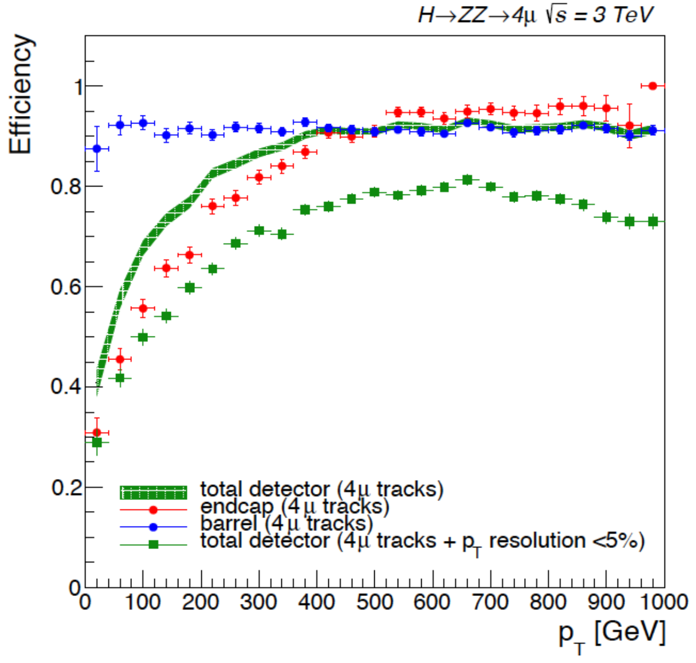


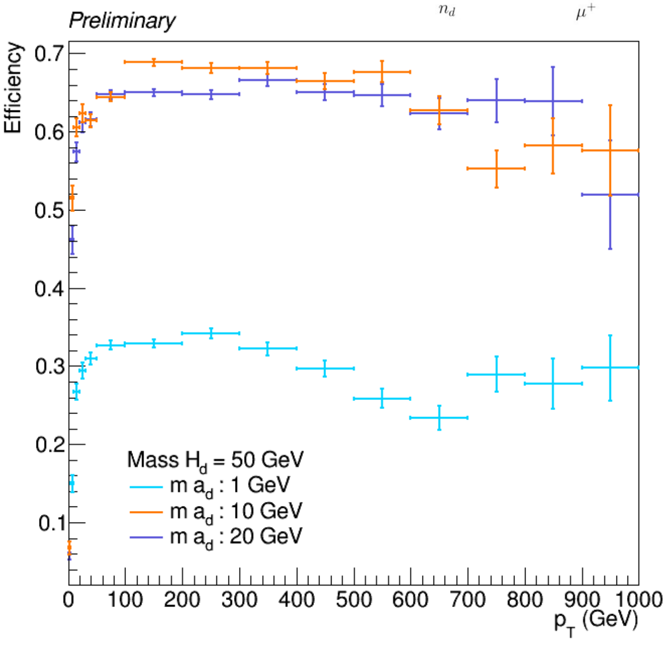
Muon Reconstruction

- Muons reconstructed with high efficiency
- Can seed extension to inner tracker







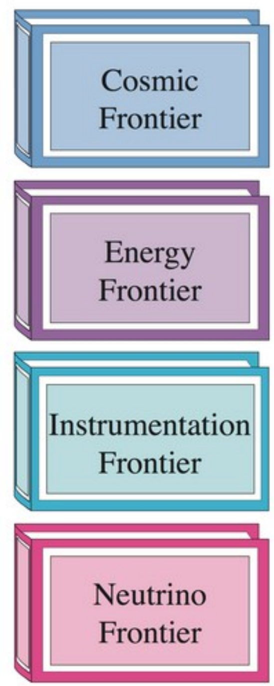


Snowmass Reports

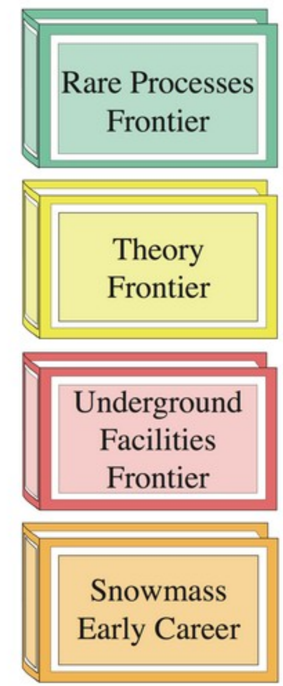
Most plots are from the Snowmass 2021 reports

Latest (March 2023) summary in: https://www.slac.stanford.edu/econf/C210711/

"Towards a Muon Collider" arXiv:2303.08533



40/150 contributed papers **from μC**!



Key Documents

- Frontier Summary Report
- Higgs Boson Physics
- Report of the Snowmass 2021 Muon Collider Forum
- Simulated Detector Performance at the Muon Collider
- A Muon Collider Facility for Physics Discovery

P5 Report on Snowmass Results

Full Report

Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

Not Only American

https://muoncollider.web.cern.ch

International
MUON Collider
Collaboration

- **Resurrected as result of *European Strategy for Particle Physics Update* report**
- **Hosted by CERN**
- **Covers all necessary areas**
  - Accelerator
  - Detector
  - Physics
- **Main driver for the experimental work**
- **Some funding via MuCol project**

Costs

V. Shiltsev

ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	*O*(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Attack Advertisement: FCC-hh

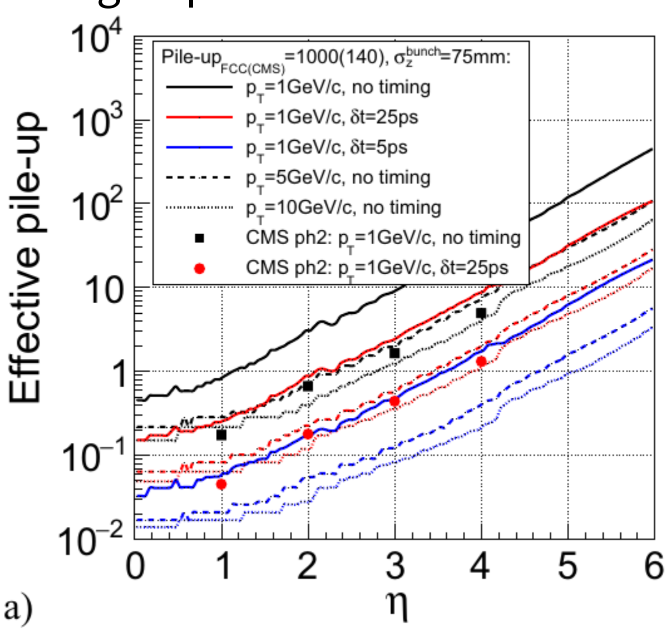
World's longest tunnels (in use) [edit]

Type	Name	Location	Length	Year	Comment
Water supply	Delaware Aqueduct	New York State, United States	137,000 m (85.1 mi)	1945	4.1 m in diameter (13.2 m^2). New York City's main water supply tunnel.
Water supply	Päijänne Water Tunnel	Southern Finland, Finland	120,000 m (74.6 mi)	1982	16 m^2 cross section. Main water supply tunnel for southern Finland, including Helsinki, drilled through solid rock.
Water supply	Dahuofang Water Tunnel	Liaoning, China	85,320 m (53.0 mi)	2009	8 m in diameter[1] (50m^2 cross section)

FCC

World's third longest tunnel!
And longest not filled with water.

5 ps timing requirements for tracker



10x LHC costs!

Conclusions

UK Mailing List: UK-MUON-DETECTOR@JISCMAIL.AC.UK
Catch-ups *first Monday of Month* at 3pm

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

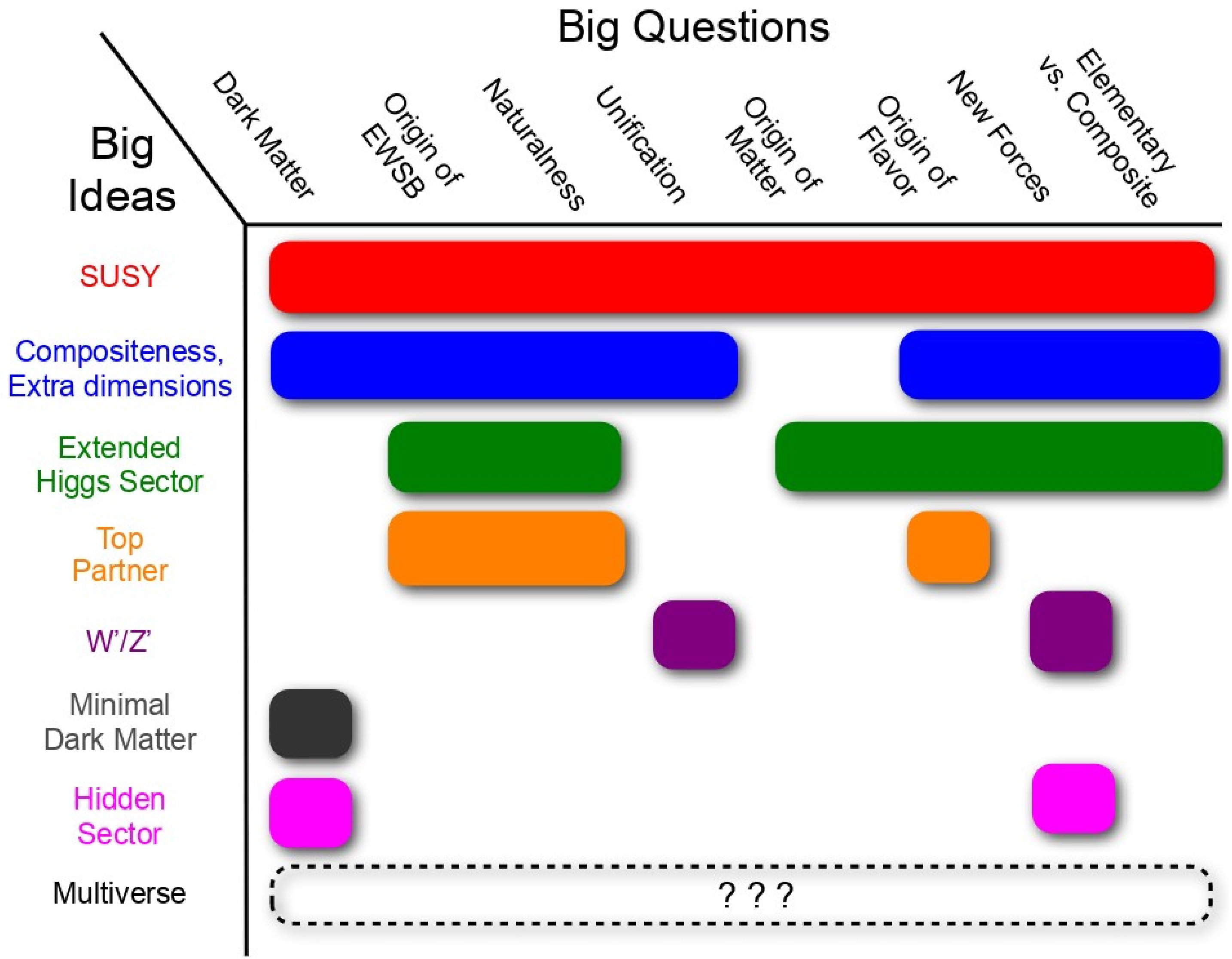
- Key R&D needed for cooling complex
- Work being handled by the IMCC (result of ESPPU)

Detector

- Beam Induced Backgrounds creates a very unclean environment
- *Lots of progress, but still need to understand effect on physics goals*

BACKUP SLIDES

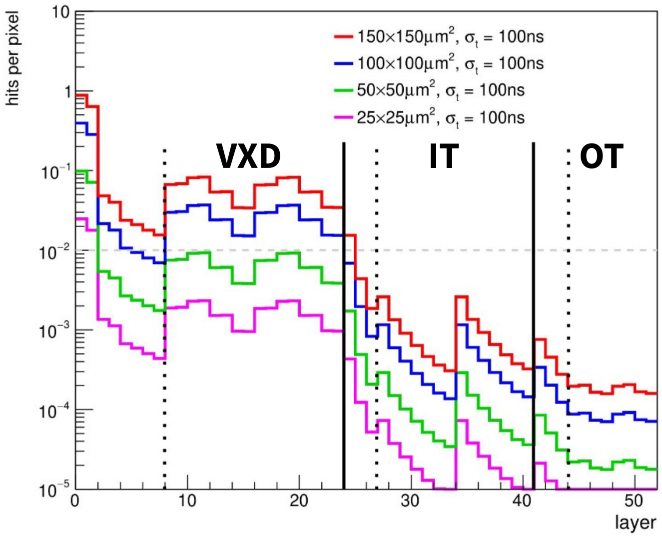
New Physics

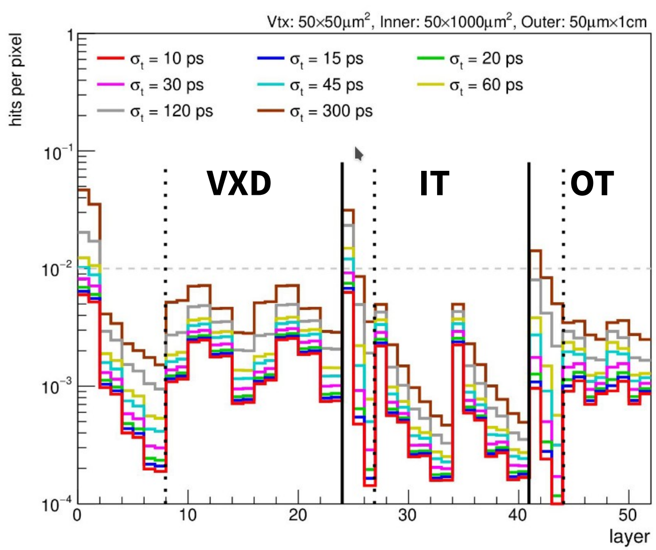


arXiv:1311.0299

Pixel Size and Timing

Details





- **Goal is <1 % occupancy per pixel.**
  - Pixel size optimized to achieve this
  - Precision timing also plays important role
    - Needed for on-detector filtering (for readout)
- **Need to be careful about slow particles**
- **Resolutions are approximated in simulation using Gaussian smearing**

Current Assumptions

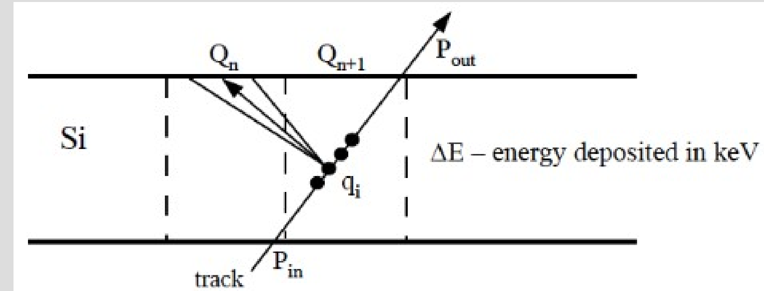
	Cell Size	Sensor Thickness	Time Resolution	Spatial Resolution
VXD	25 µm x 25 µm	50 µm	30 ps	5 µm x 5 µm
IT	50 µm x 1 mm	100 µm	60 ps	7 µm x 90 µm
OT	50 µm x 10 mm	100 µm	60 ps	7 µm x 90 µm

No difference between barrel and endcap.

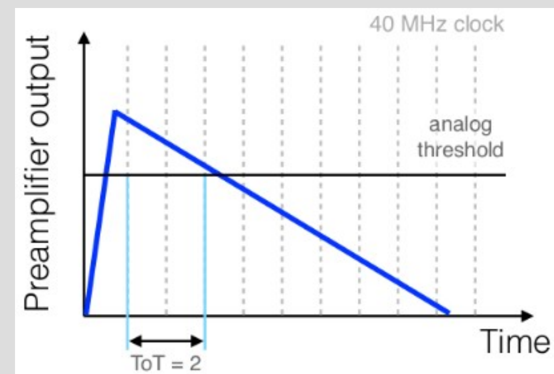
WIP Realistic Digitization

- **Two models for vertex modules**
  - Trivial (collect charge in pixel)
  - RD53A (complete simulation, ref)
- **Hoshen-Kopelman for clustering**
  - Eval alternatives as future development
- **Performance tested with full BIB**
  - Trivial: 100 s / evt
  - RD53A: 5000 s / evt

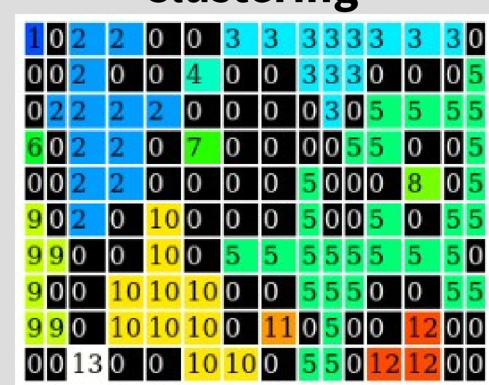
Charge Particle Deposits Details



Sensor Pixelization/Digitization



Clustering



A Common Tracking Software

- **ACTS is a standalone library for tracking algorithms**
- **Dedicated team working on advancing tracking algorithms**
  - Tracking is hard!
- **Allows us explore alternate algorithms**
  - Triplet-based seeding optimized for high multiplicity environments
  - Ongoing work to incorporate ML-based algorithms
- **Code optimization come for free**
  - Good software is even harder than tracking!
  - Also explores modern computing architectures (ie: GPU's)

https://github.com/acts-project/acts

Fit Library	Kalman Filter Execution Time
ACTS	0.5 ms / track
iLCsoft	100 ms / track

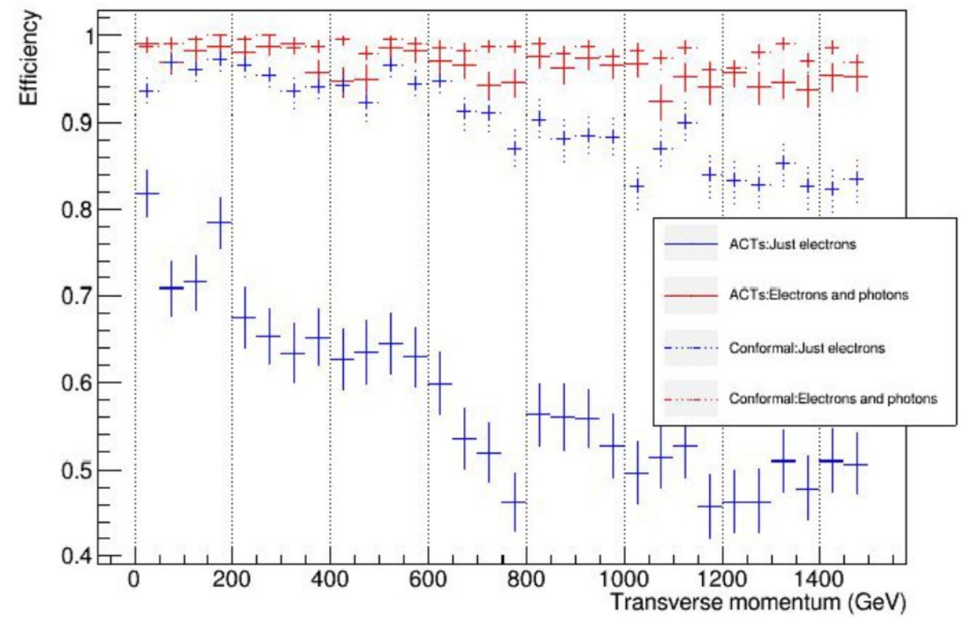
Electrons and Photons

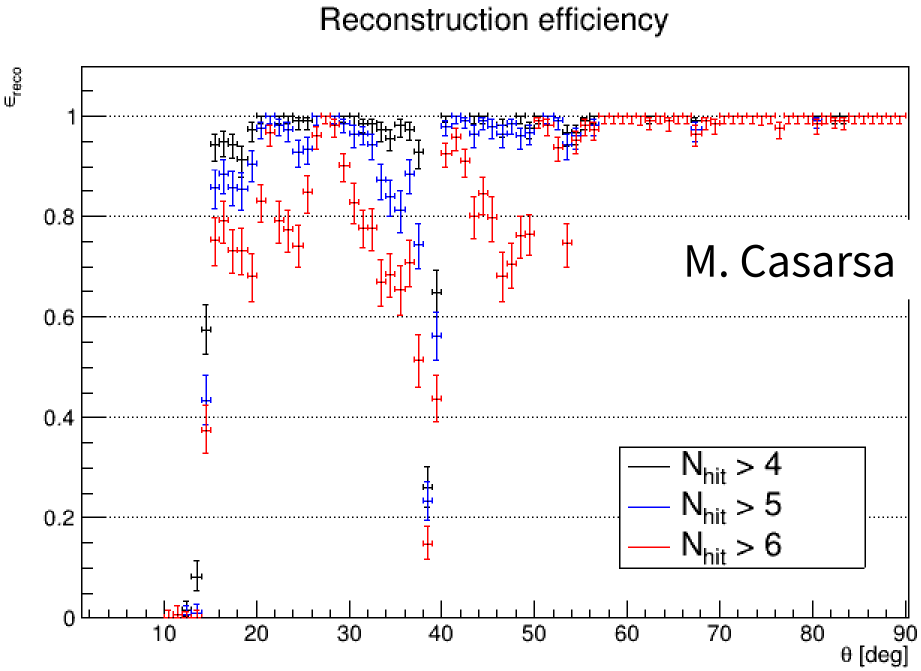
Details

Still need to study impact of ACTS tracking on object identification.

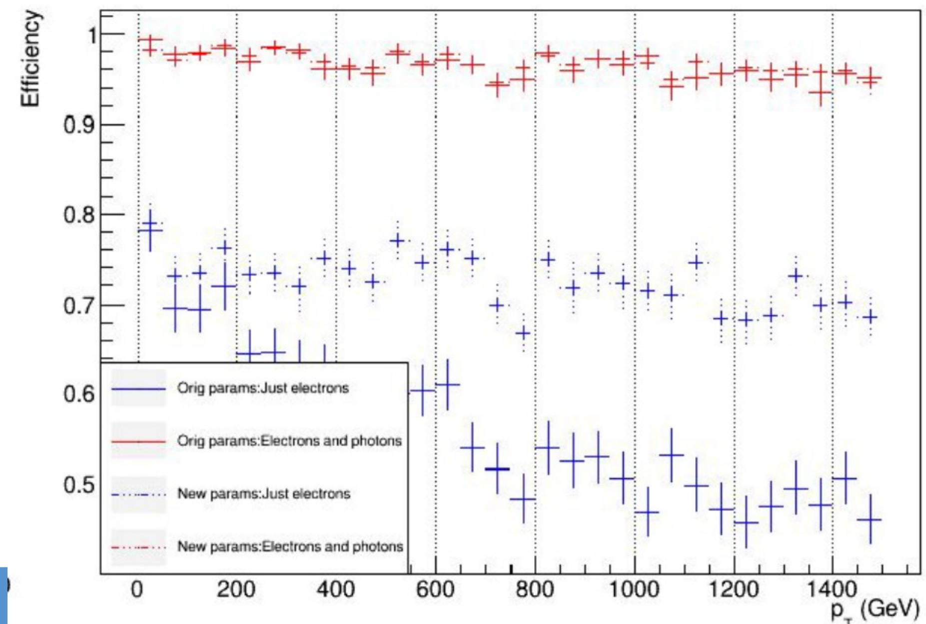
- Electrons reconstructed as photons.
- Sculpting from fake reduction cuts

Electron Reconstruction w/o BIB





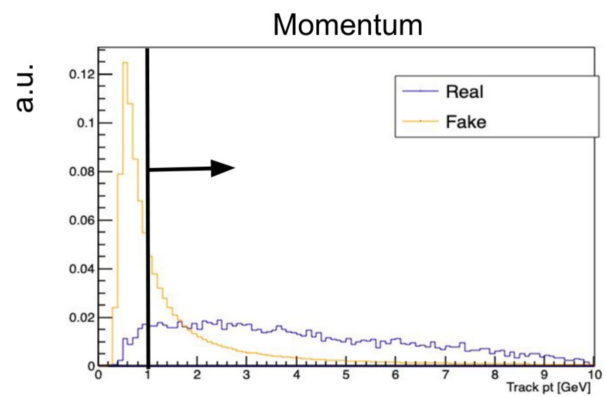
ACTS “Looser” Parameters

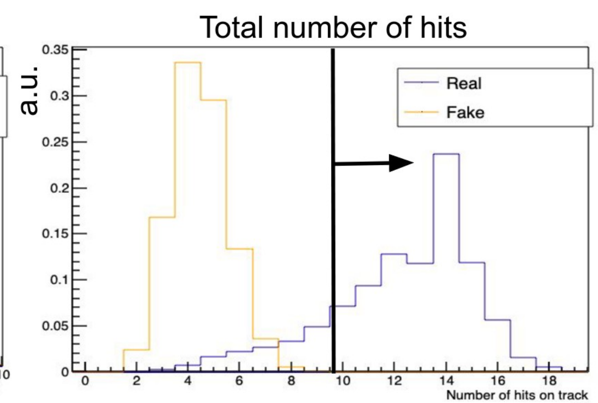


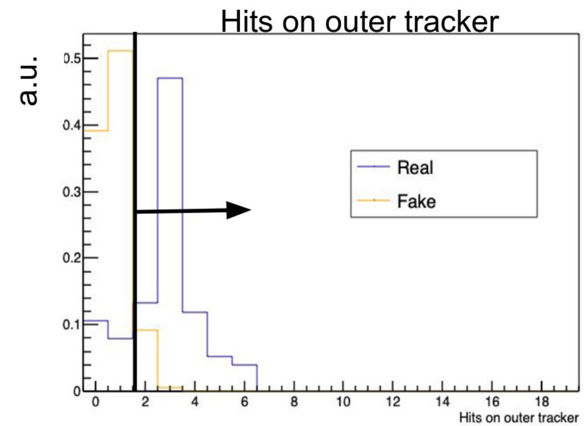
Rejecting Fakes

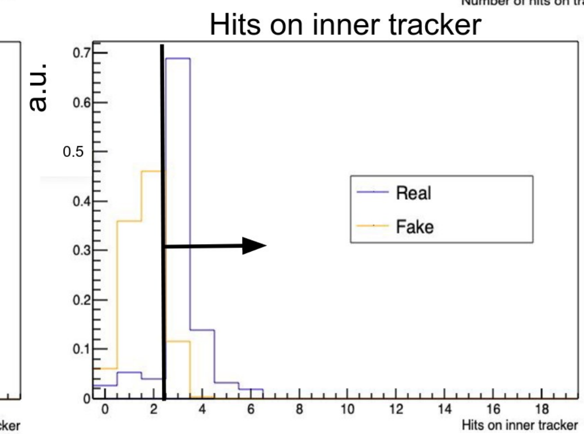
Details

- 100k fake tracks / event
- reduce to < 1 fake / event
- Still missing a few handles
  - χ^2, N_{holes}, timing
- Implemented as an (unreleased) processor

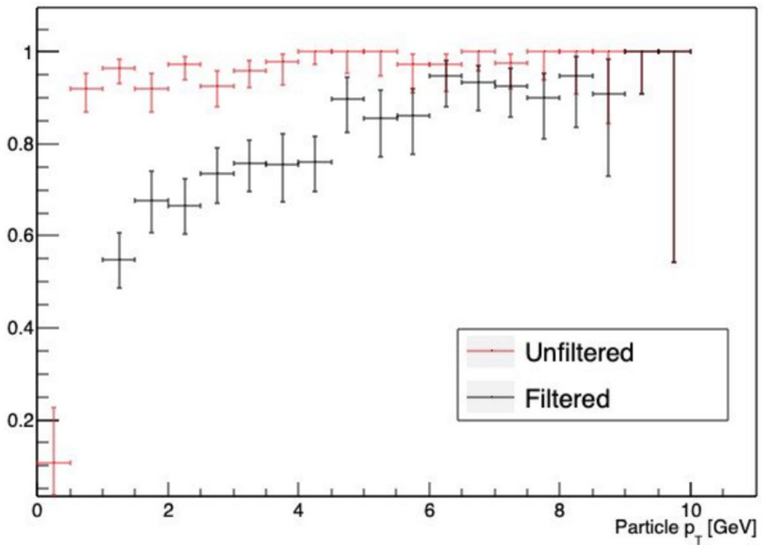


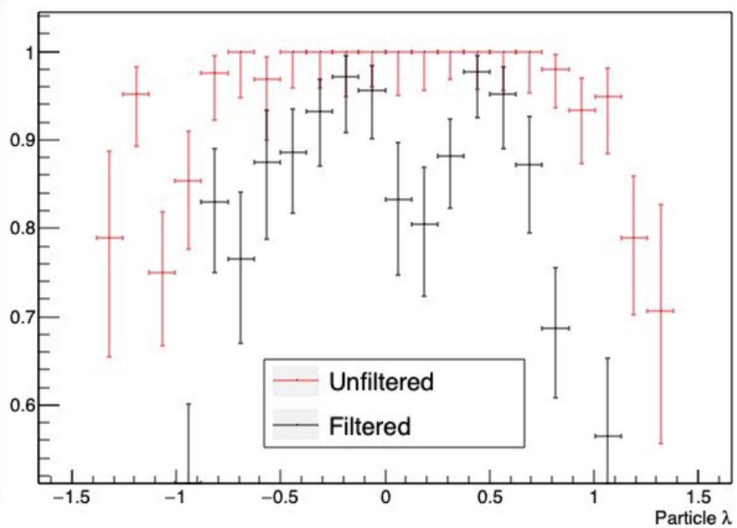


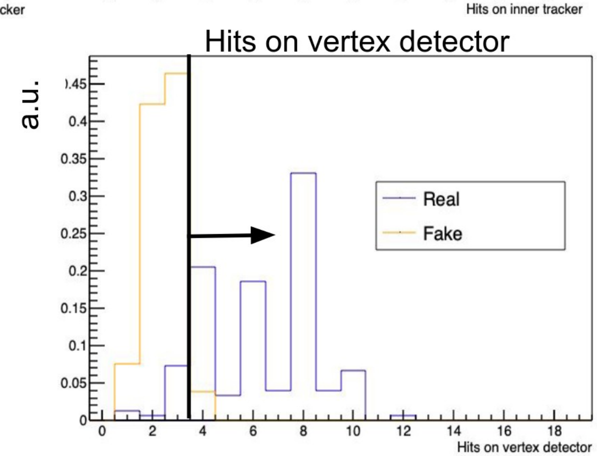




Efficiencies



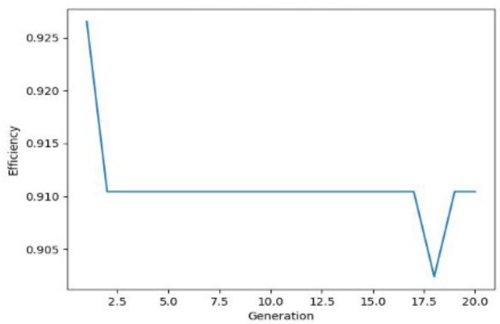
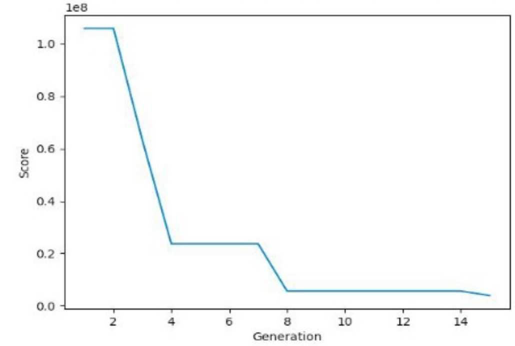
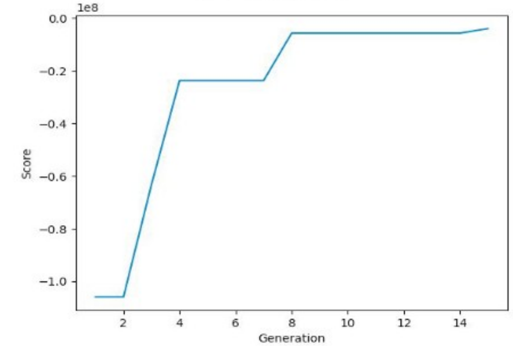




Rejecting Fakes: Optimization

Details

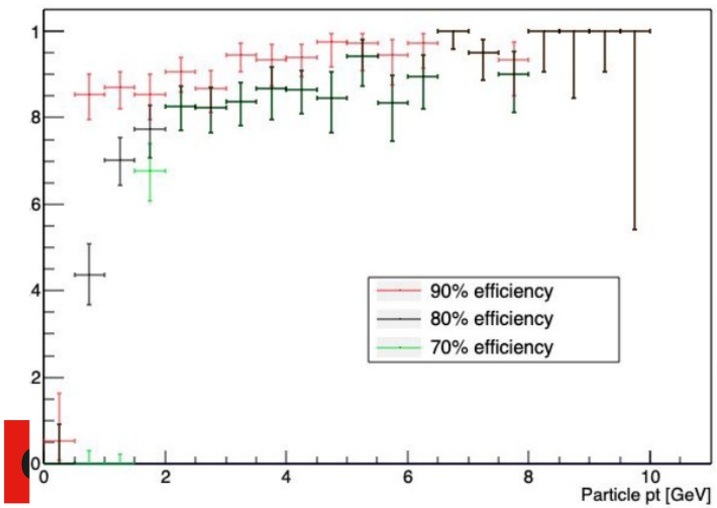
- TrackFilter optimized using evolutionary algorithms

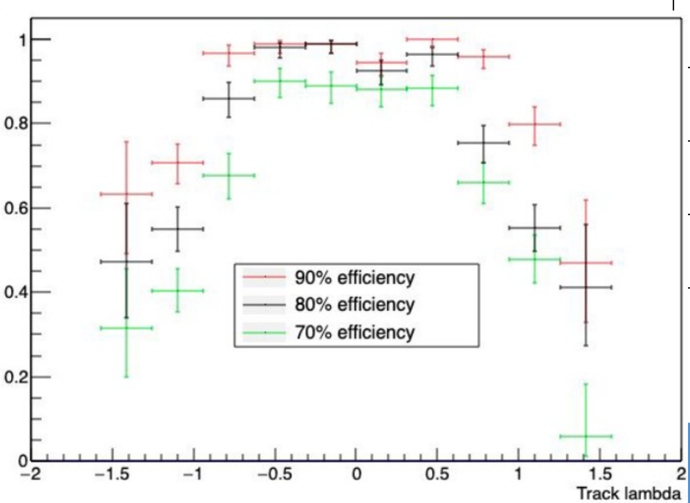
Target efficiency	Efficiency	Number of fakes	Score
90%			

- Studied a few fixed efficiency working points
- For <80% eff, start removing low p_T tracks

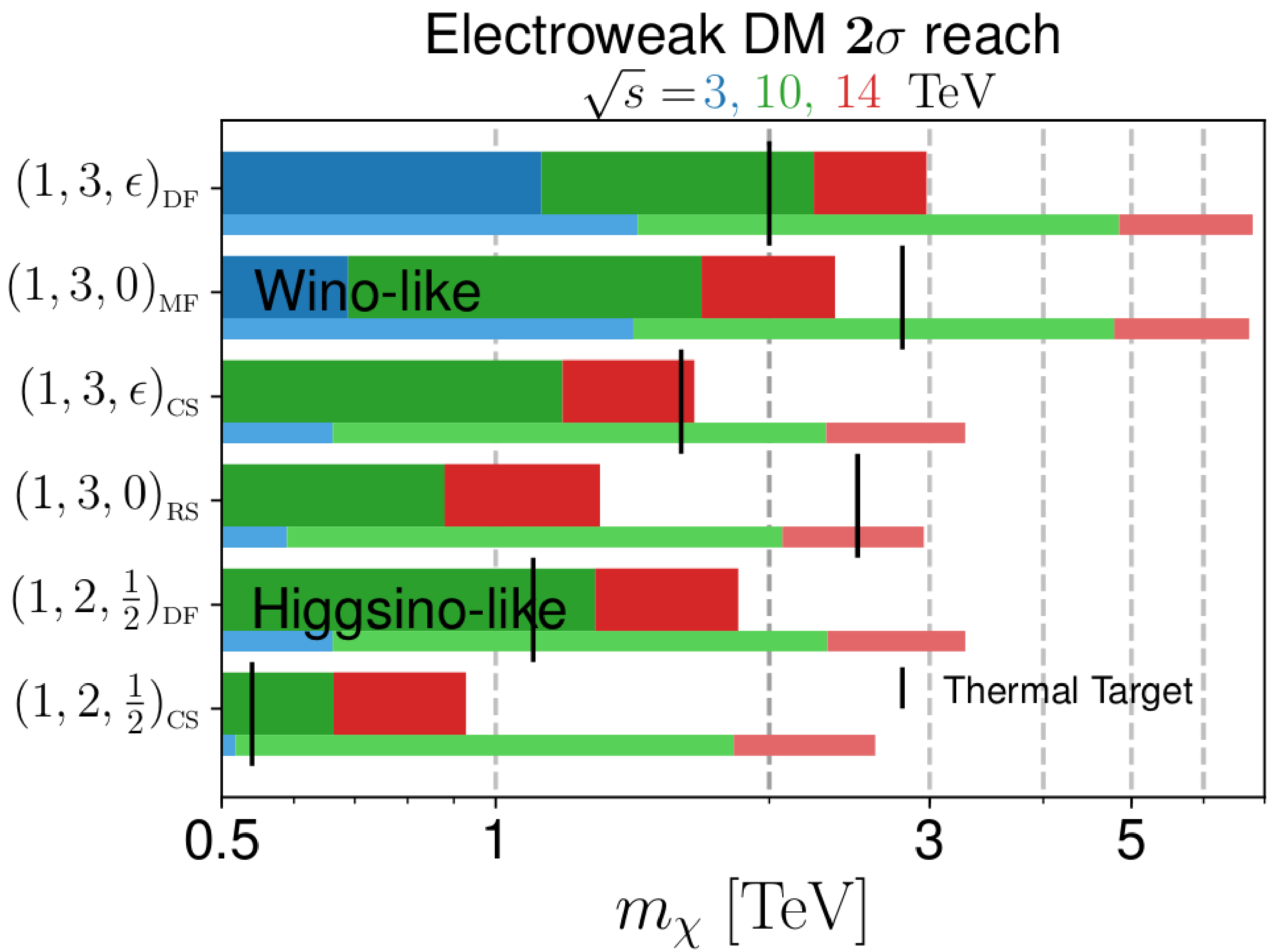
Eff WP	Fakes / event
90%	3900
80%	0.13
70%	0.06
64%*	0.08

* value by hand





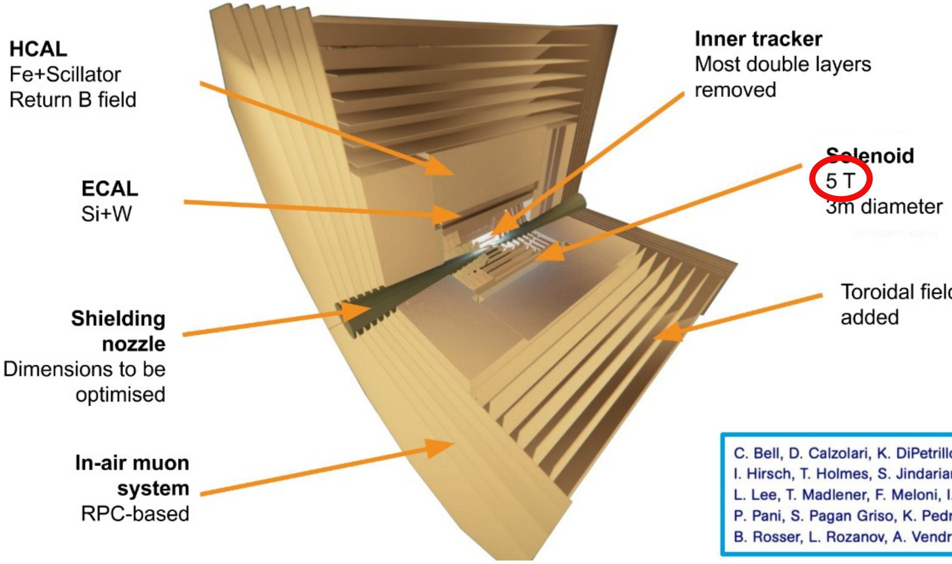
Dark Matter (WIMP)



1.5 TeV vs 10 TeV

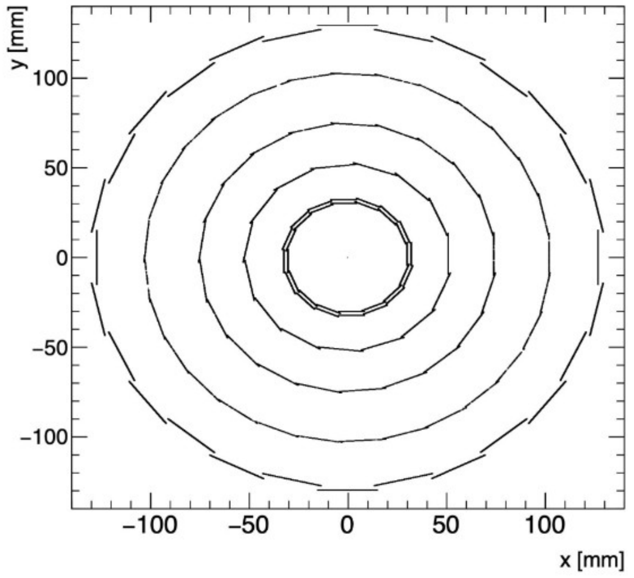
Summary by B. Rosser

Concept developed at KITP workshop at Santa Barbara

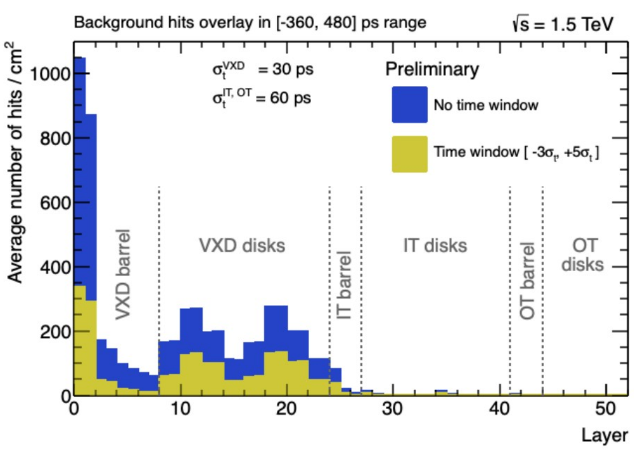


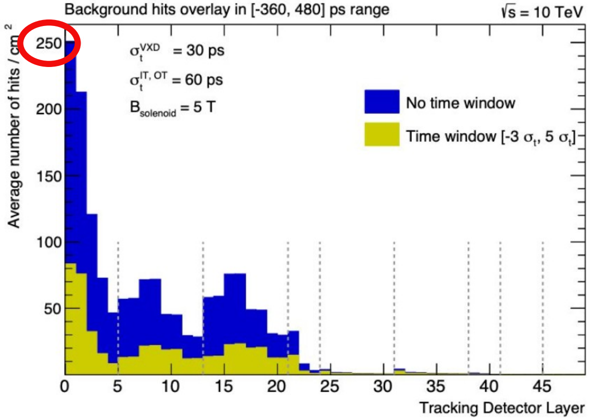
C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

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