Towards a muon collider

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Nikhef colloquium
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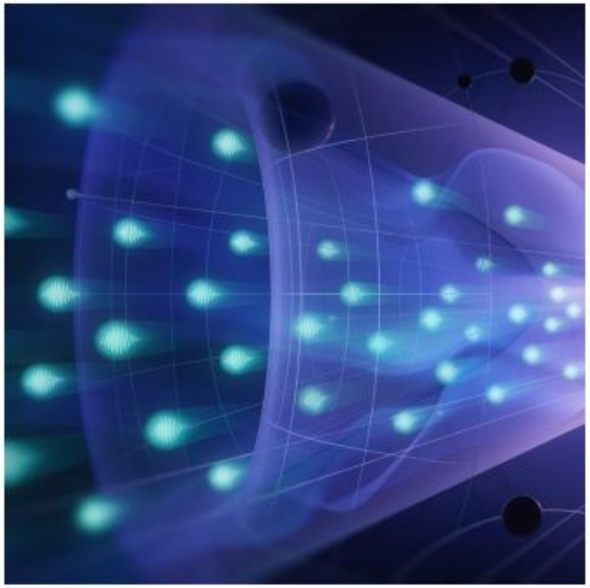
Co-funded by
the European Union

The Muon Shot



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

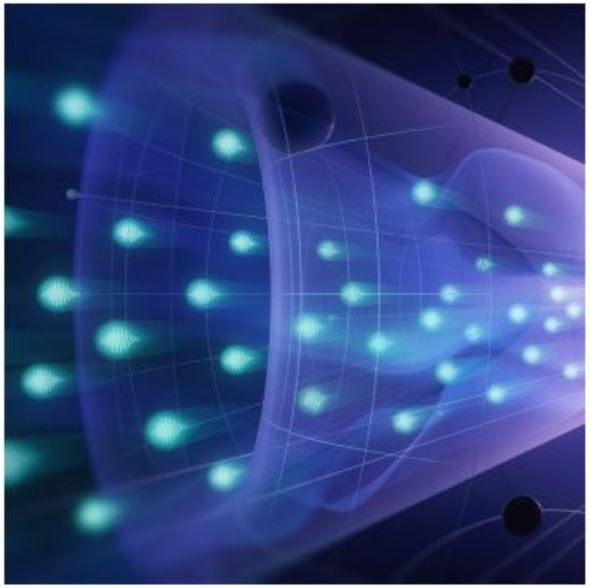
Pursue Quantum Imprints of New Phenomena

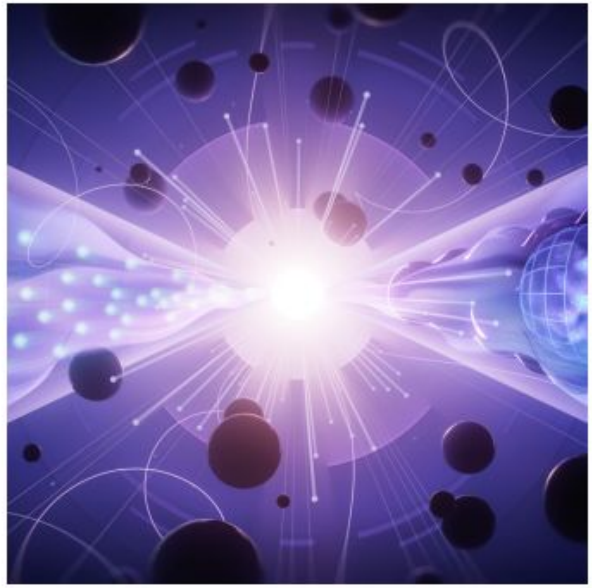
Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

The Muon Shot





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.

physics/9901022

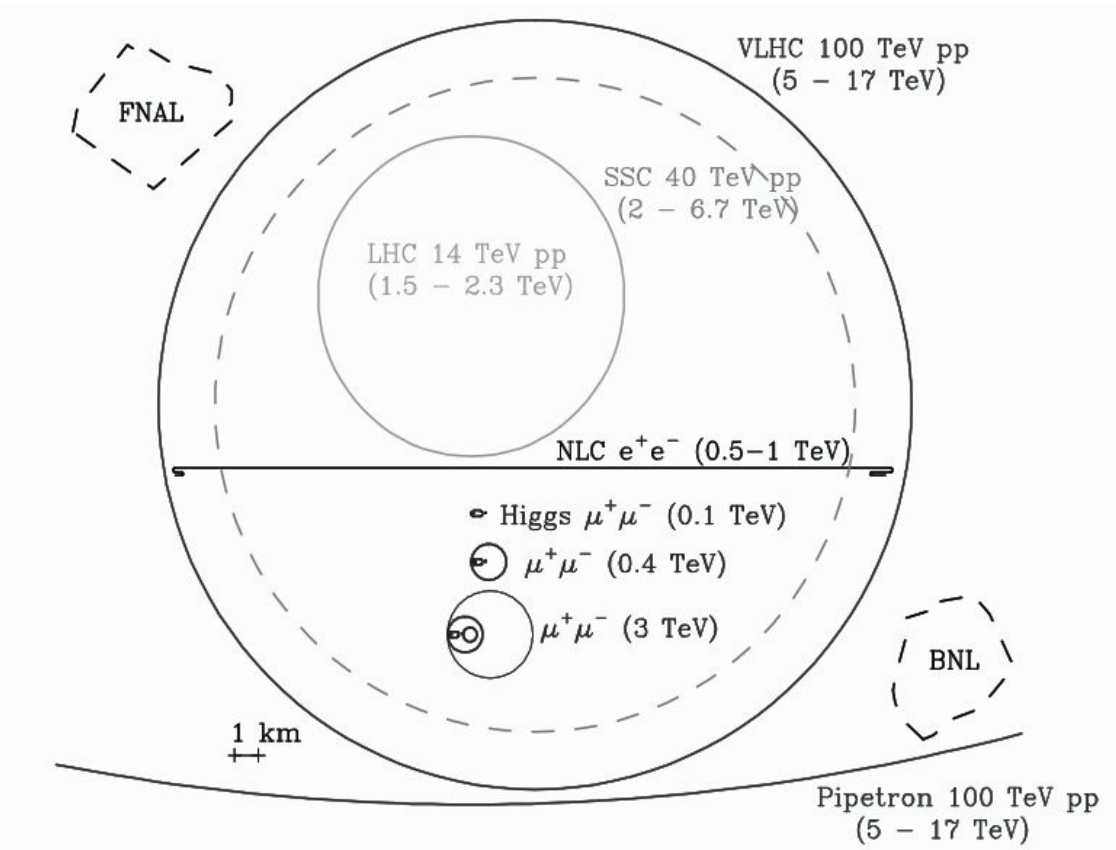
Why muons?

We conventionally probe shorter distances with either precision (indirect) or energy (direct)

Muon colliders blur this dichotomy

The muon mass (105.7 MeV/c^2, 207 x $e^{\pm}$ mass) means:

- Negligible synchrotron radiation emission
- Negligible beamstrahlung at collision



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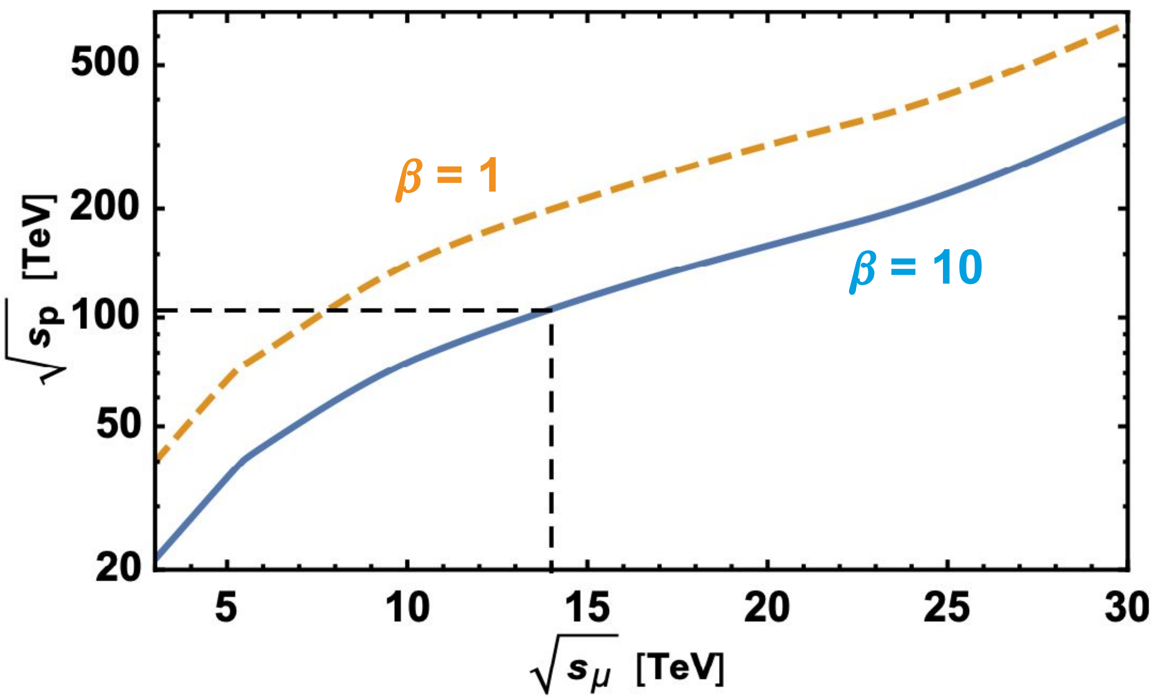
Why muons?

Leptons are the ideal probes of short-distance physics

- All the energy is stored in the colliding particle
- No energy “waste” due to parton distribution functions
- High-energy physics probed with much smaller collider energy

$$\beta \equiv [\hat{\sigma}]_p / [\hat{\sigma}]_\mu$$



A brief history of muon colliders

1970/90 Initial proposal

G.I. Budker, Accelerators and colliding beams, 1969
A.N. Skirnsky, Intersecting storage rings at Novosibirsk, 1971
D. Neuffer, Multi-TeV muon colliders, 1986

2013 - LEMMA

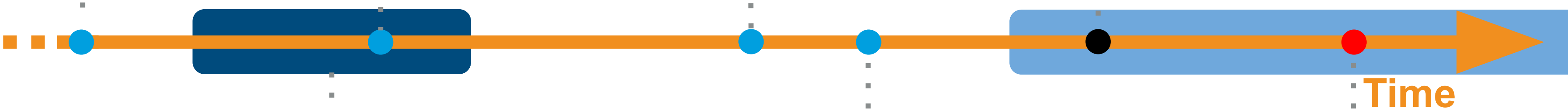
- Propose positron-driven scheme

2019 - MICE

- Demonstrates ionisation cooling

International MUON Collider Collaboration

IMCC



2011 - 2014 US Muon Accelerator Program MAP

- Short- and long-baseline neutrino facilities
- Higgs factory with good energy resolution
- TeV-scale muon collider

Muon Accelerators for Particle Physics

European Strategy for Particle Physics Update 2020

- Set up an international collaboration

2023 P5 process

- The Muon Shot

Why are we excited?

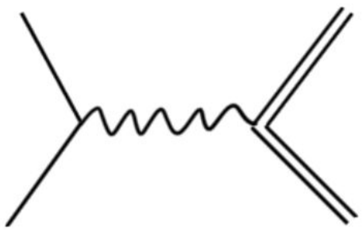
The muon collider combines *pp* and *ee* advantages:

- High available energy for new heavy particles production

Slide design credit: A. Wulzer

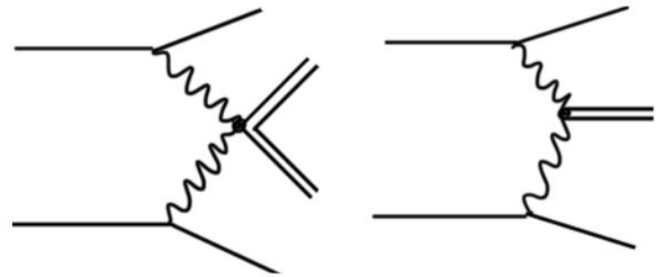
Why are we excited?

Direct searches for new particles



μμ annihilation

EW-charged particles up to $E_{cm}/2$

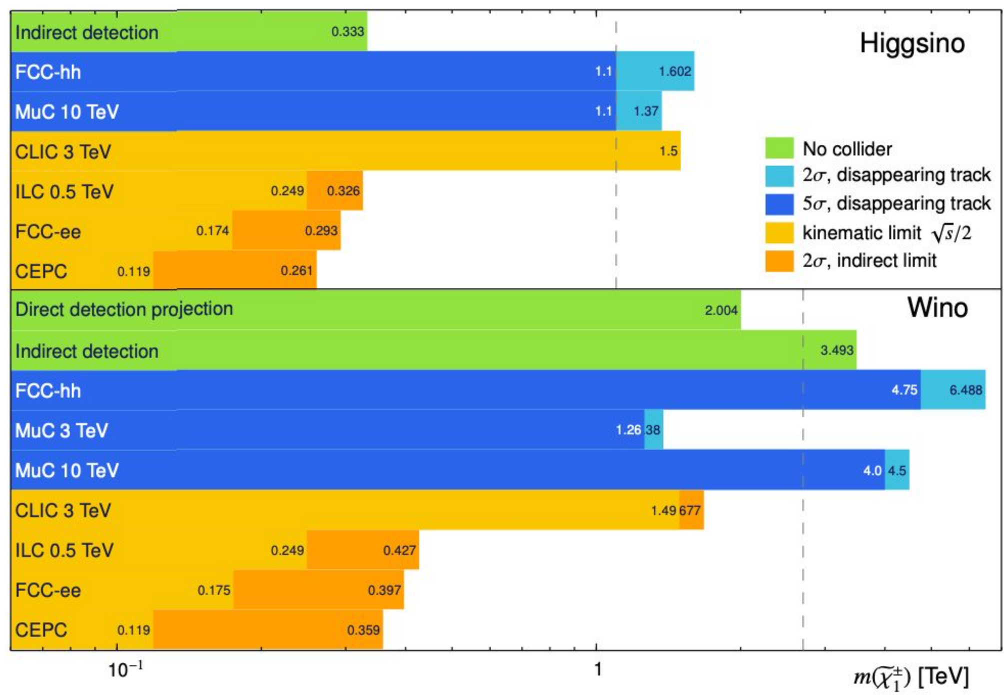


Vector Bosons Fusion

EW-neutral **Higgs-Portal** particles

Amazing **WIMP** or **WIMP-like dark matter** search programme

Thermal Wino and Higgsino discovery



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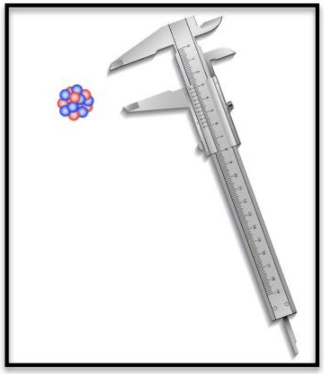
Why are we excited?

The muon collider combines *pp* and *ee* advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD background)

Energy



Precision

Slide design credit: A. Wulzer

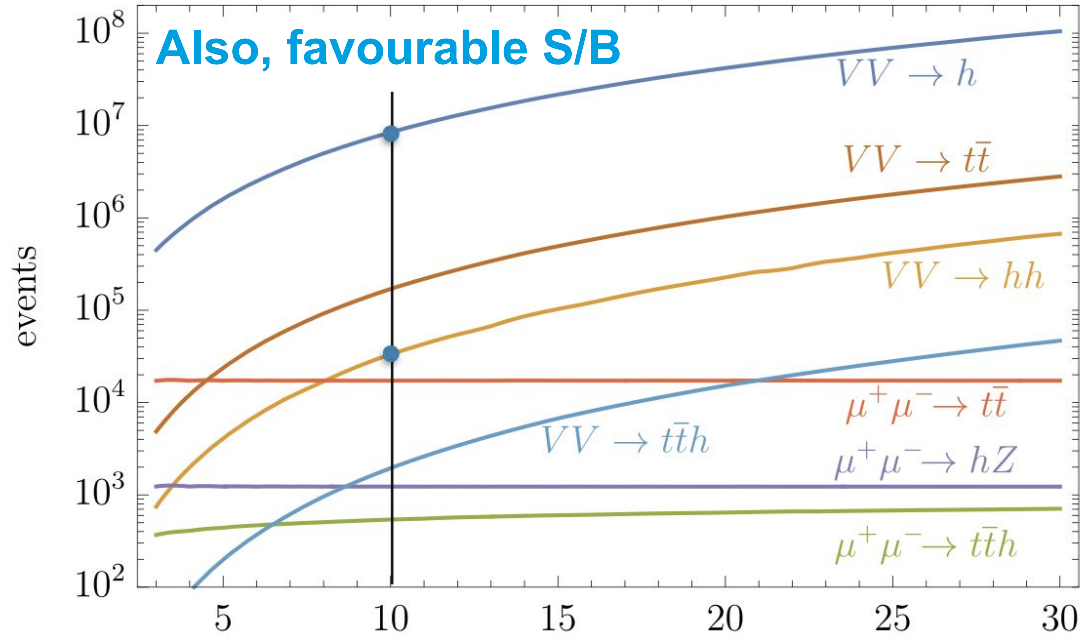
Why are we excited?

High precision indirect probes

The Higgs is revolutionary!

- First manifestation of **massive gauge theories**
- First **elementary scalar?**

Is it the SM Higgs Particle?
What is it made of?



Pictorial view of 3-linear Higgs precision [Nathaniel Craig]

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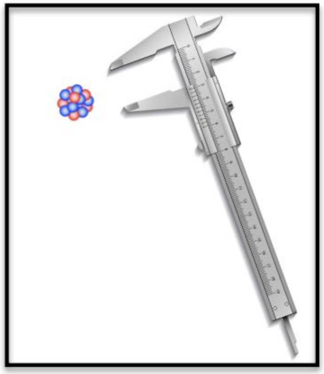
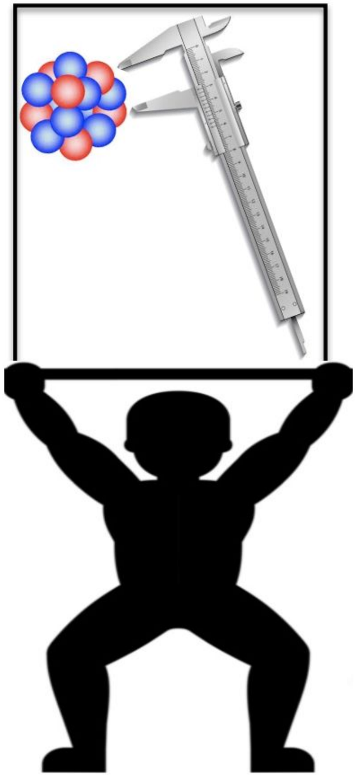
Why are we excited?

The muon collider combines *pp* and *ee* advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD background)
- Can measure processes of very high energy





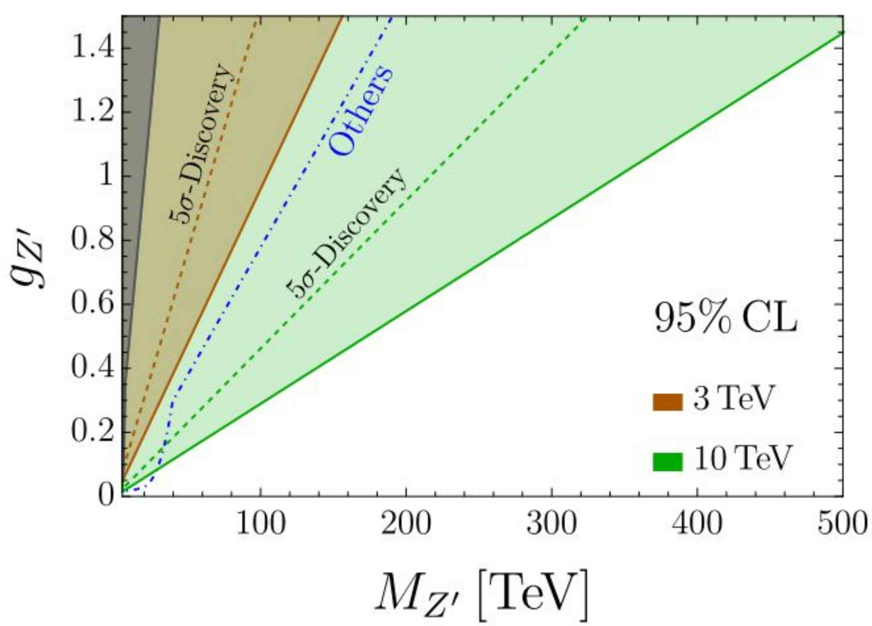
Slide design credit: A. Wulzer

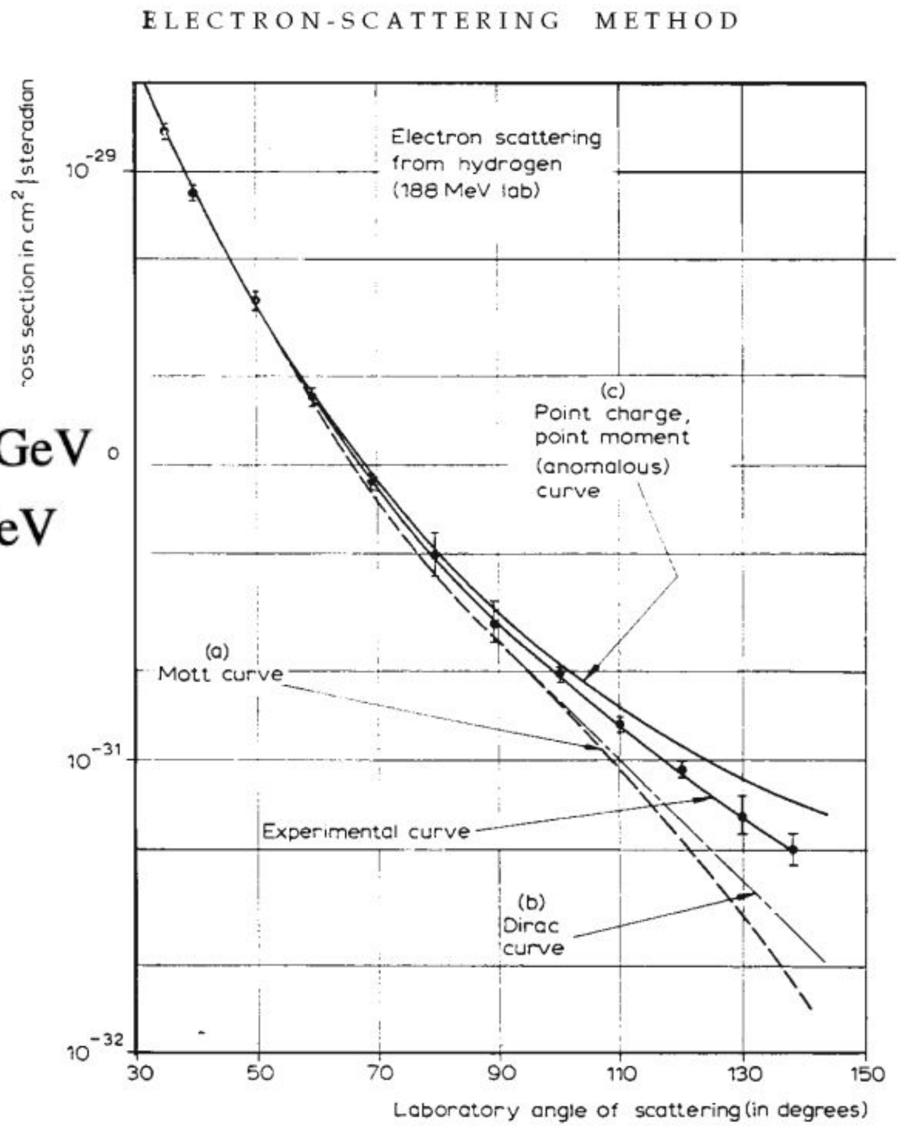
Why are we excited?

Energy helps accuracy

Many discoveries came neither from new particle detection, nor from extreme precision, **but needed energy**

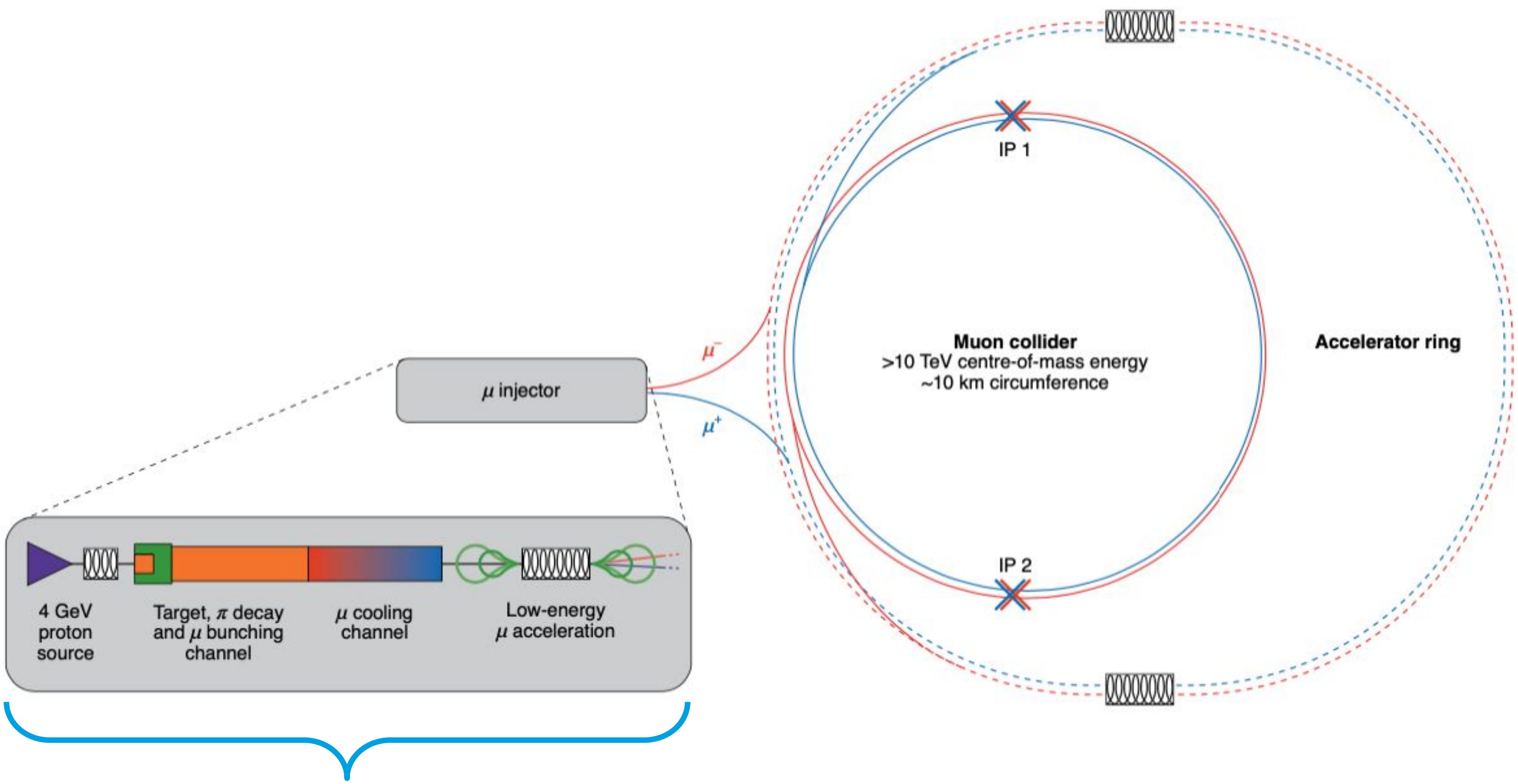
$$\frac{\Delta\sigma(E)}{\sigma_{\mathrm{SM}}(E)} \propto \frac{E^2}{\Lambda^2_{\mathrm{BSM}}} \approx \begin{cases} 10^{-6}, & E \sim 100\,\mathrm{GeV} \\ 10^{-2}, & E \sim 10\,\mathrm{TeV} \end{cases}$$





How do we make it happen?

Collider overview



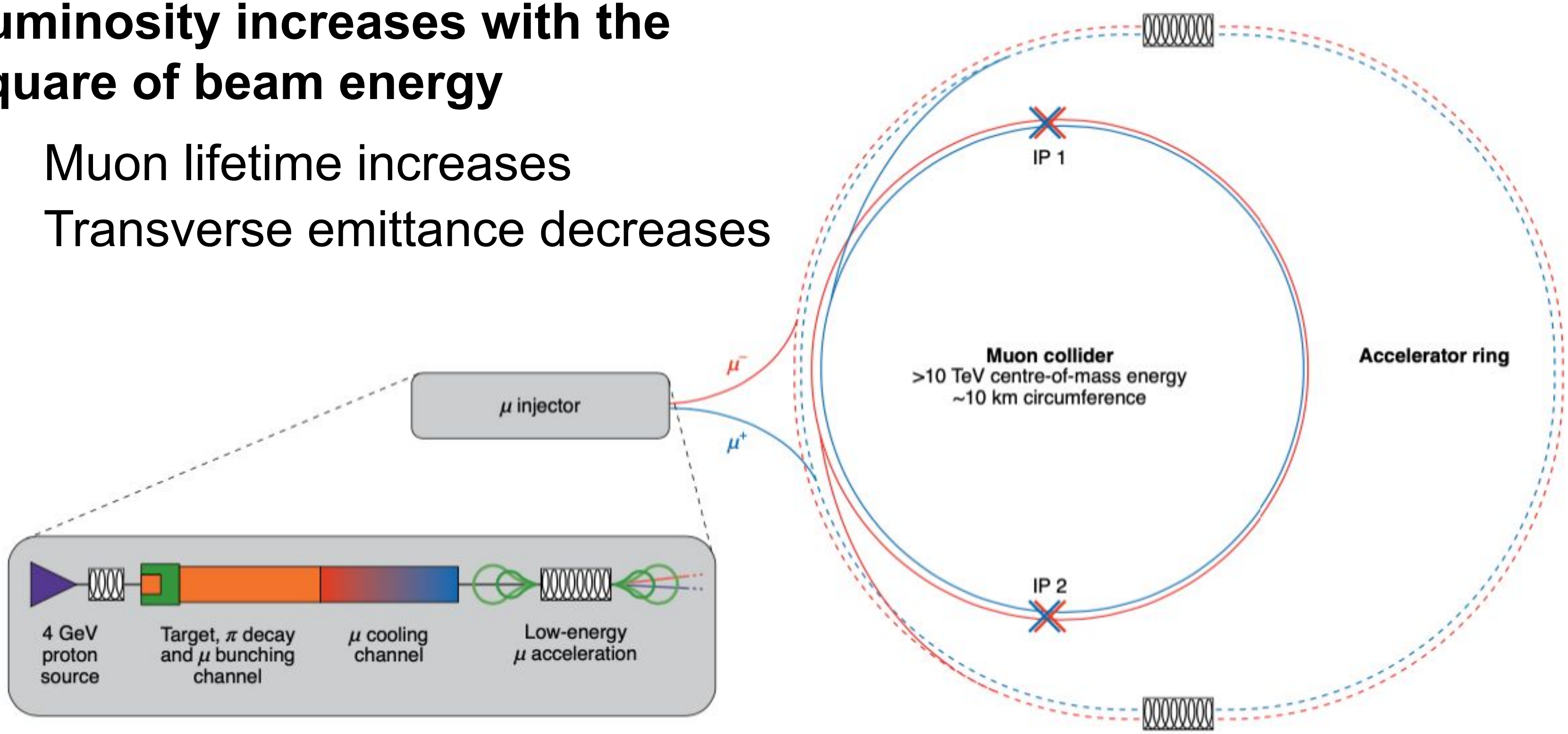
Proton-driven scheme

Collision paradigm

Circulate two bunches and re-fill when they are depleted

Luminosity increases with the square of beam energy

- Muon lifetime increases
- Transverse emittance decreases



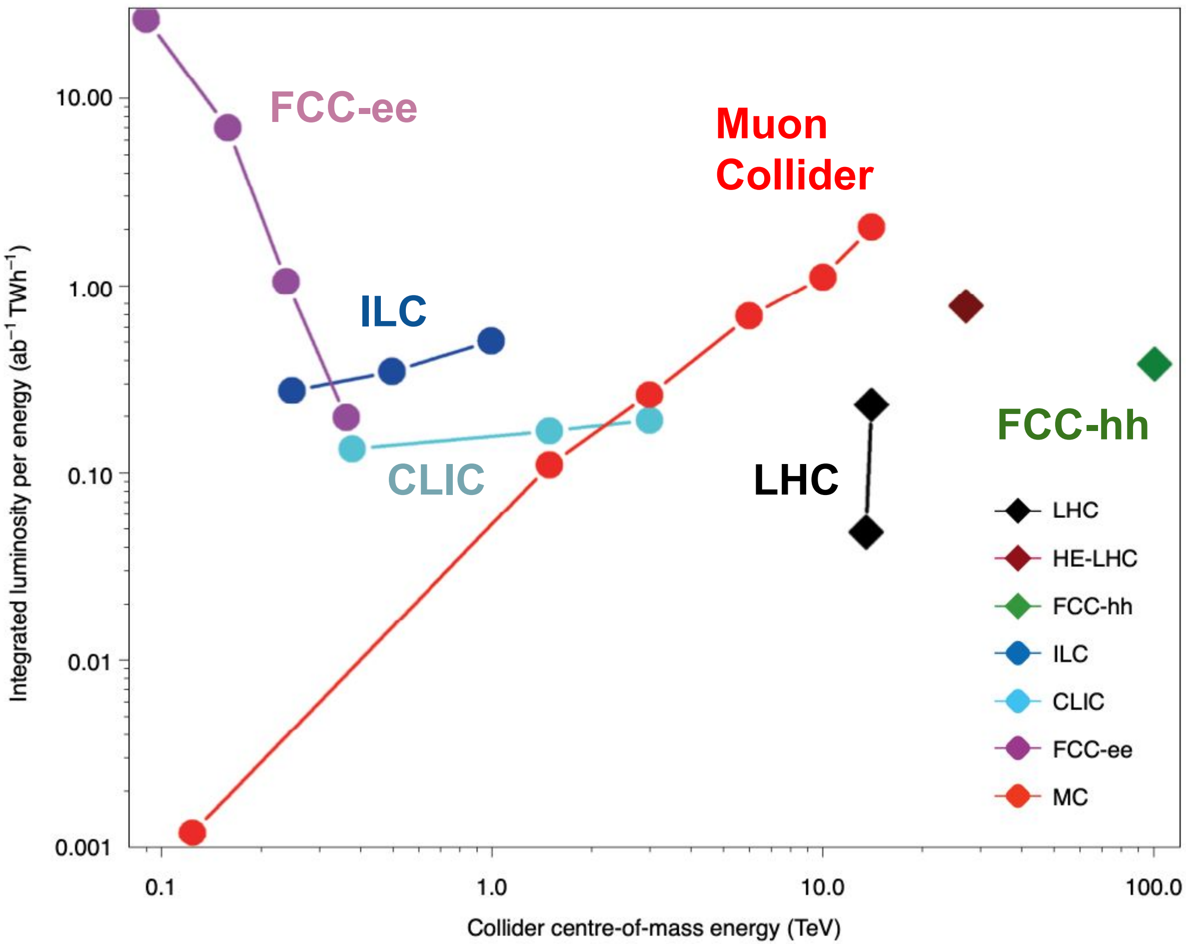
1000 times lower collision rate than LHC!

For the luminosity experts

$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \frac{f_{hg}\sigma_\delta \bar{B}}{\varepsilon_\perp \varepsilon_L n_b f_r} \underbrace{\eta_+\eta_-(\eta_\tau P_p E_\mu)^2}_{P_+P_-}$$

2007.15684
2003.09084

A sustainable collider



ROUGH RULE OF THUMB

Cost ∝ Energy

Power ∝ Luminosity

High luminosity with **reasonable wall plug power** needs (~½ CLIC)

Cost-effective construction and operation

Possible staging / re-use of existing facilities

Muon collider target parameters

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-} + P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^*_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

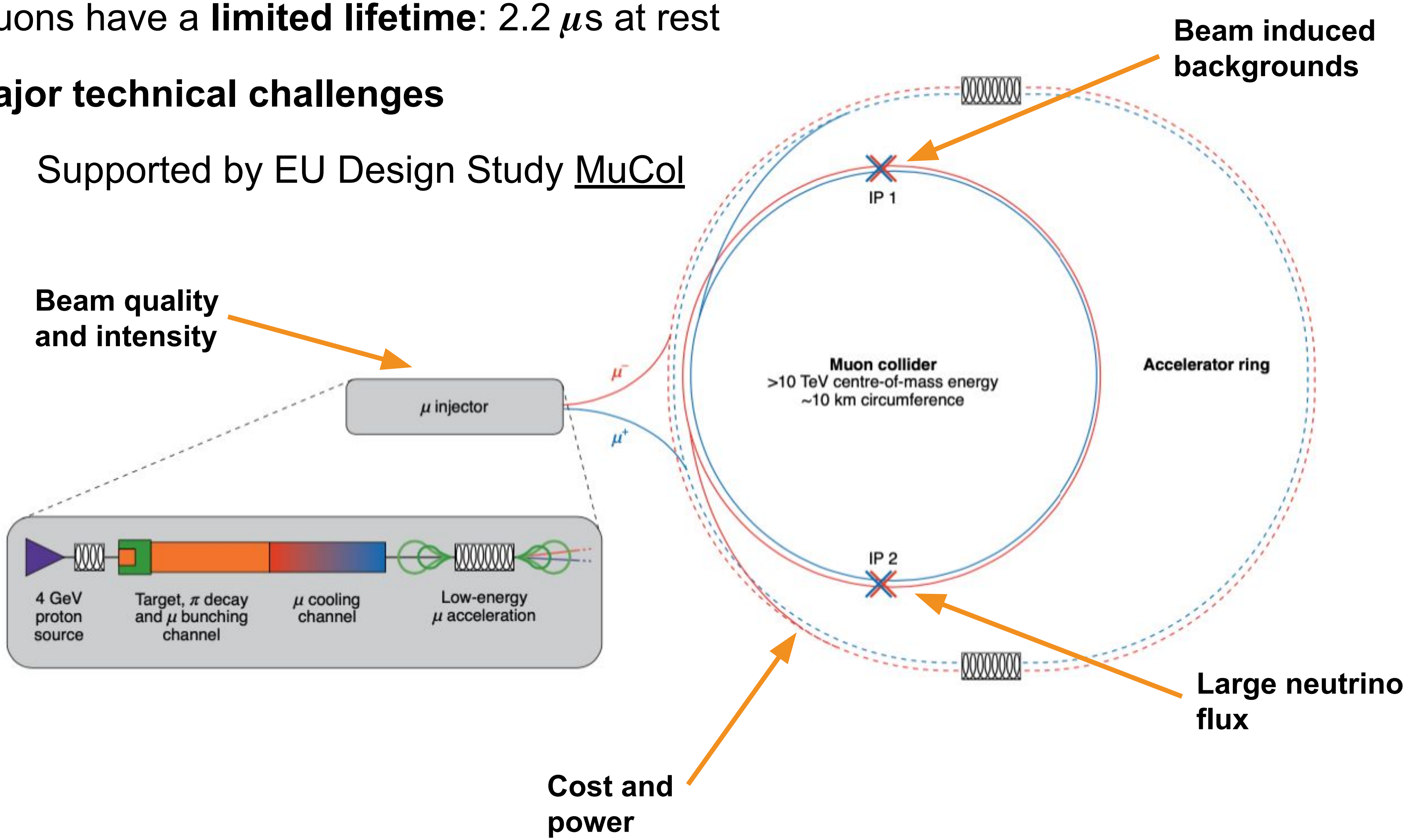
Plan to operate 5-10 years at each centre-of-mass energy
(for reference, FCC-hh to operate for 25 years)

Key challenges

Muons have a **limited lifetime**: 2.2 μs at rest

Major technical challenges

- Supported by EU Design Study <u>MuCol</u>



The 12 ~~miracles~~ challenges

Many thanks to S. Jindariani, D. Schulte, and M. Wing for inputs and useful discussions

	Target	Status	Notes	Future work
Pulse compression	1-3 ns	SPS does O(1) ns	Need higher intensity. O(30) ns loses only factor 2 in the produced muons.	Refine design, including proton acceleration. Accumulation and compression of bunches.
High-power targets	2 MW	2 MW	Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.	Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.
Capture solenoids	15 T	13 T	ITER central solenoid.	Study superconducting cables and validate cooling. Investigate HTS cables.
Cooling solenoids	50 T	30-40 T	30 T leads to a factor 2 worse transverse emittance with respect to design.	Extend designs to the specs of the 6D cooling channel. Demonstrator.
RF in magnetic field	>50 MV/m	65 MV/m	MUCOOL published results. Requires test in non-uniform B.	Design to the specs of 6D cooling. Demonstrator.
6D cooling	10^{-6}	0.9 (1 cell)	MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.	Optimise with higher fields and gradients. Demonstrator.
RCS dynamics	-	-	Simulation. 3 TeV lattice design in place.	Develop lattice design for a 10 TeV accelerator ring.
Rapid cycling magnets	2 T/ms 2 T peak	2.5 T/ms 1.81 T peak	Normal conducting magnets. HTS demonstrated 12 T/ms, 0.24 T peak.	Design and demonstration work. Optimise power management and re-use.
Ring magnets aperture	20 T quads	12-15 T (Nb3Sn)	Need HTS or revise design to lower fields.	Design and develop larger aperture magnets, 12-16 T dipoles and 20 T HTS quads.
Collider dynamics	-	-	3 TeV lattice in place with existing technology.	Develop lattice design for a 10 TeV collider.
Neutrino radiation	10 μSv/year	-	3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.	Study mechanical feasibility of the mover system impact on the accelerator and the beams.
Detector shielding	Negligible	LHC-level	Simulation based on next-gen detectors.	Optimise detector concepts. Technology R&D.

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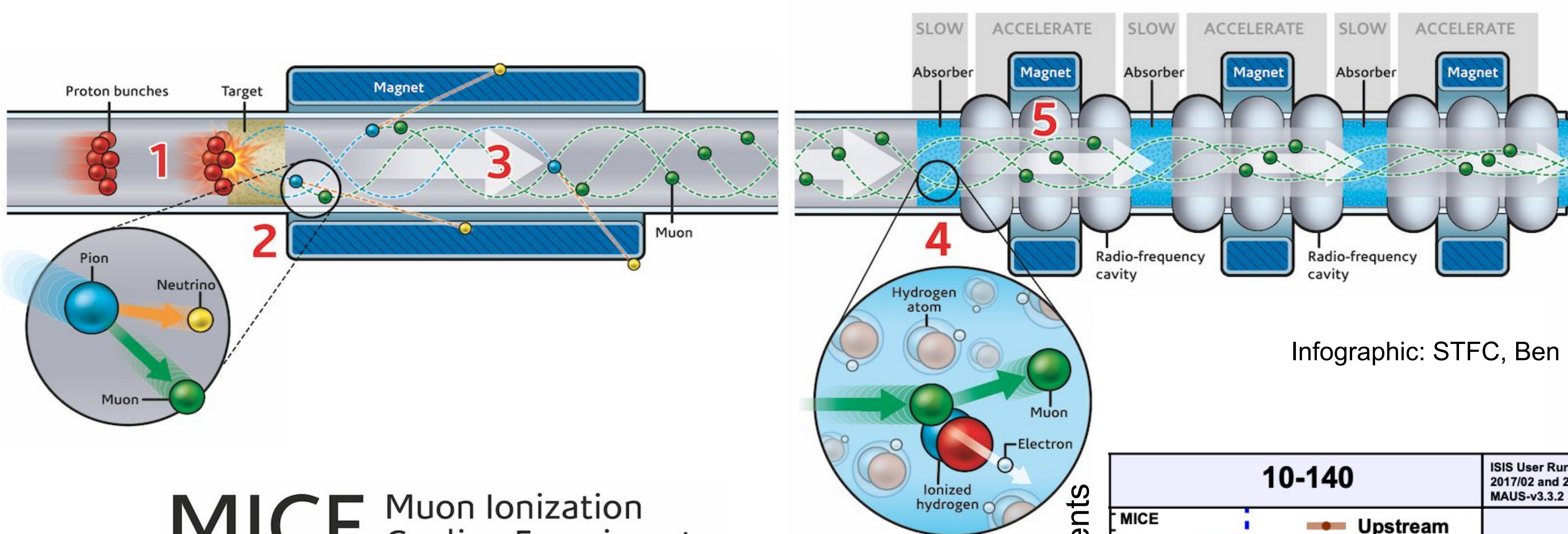
Cooling the beams

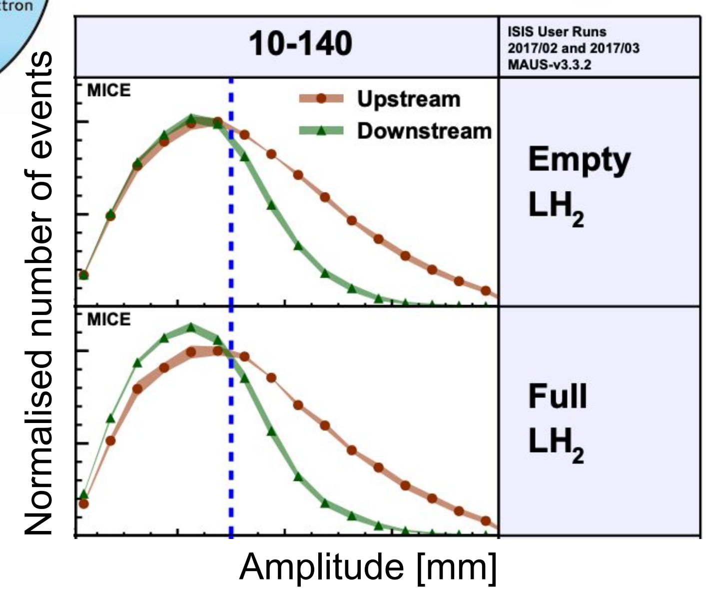


Infographic: STFC, Ben Gilliland

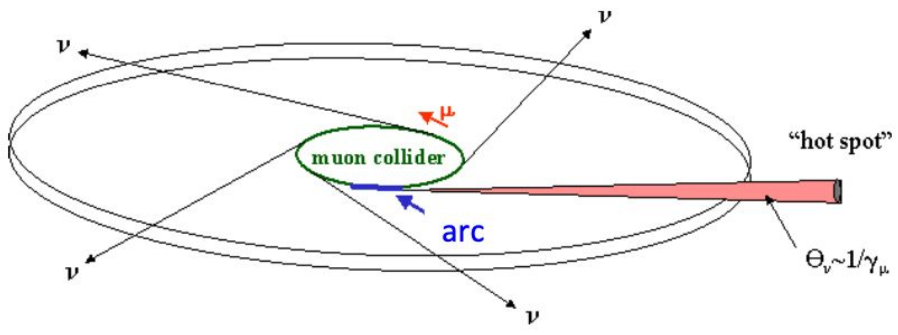
MICE Muon Ionization Cooling Experiment

Need 10^6 emittance reduction!

- Demonstrator with RF and more than one stage required



Neutrino flux



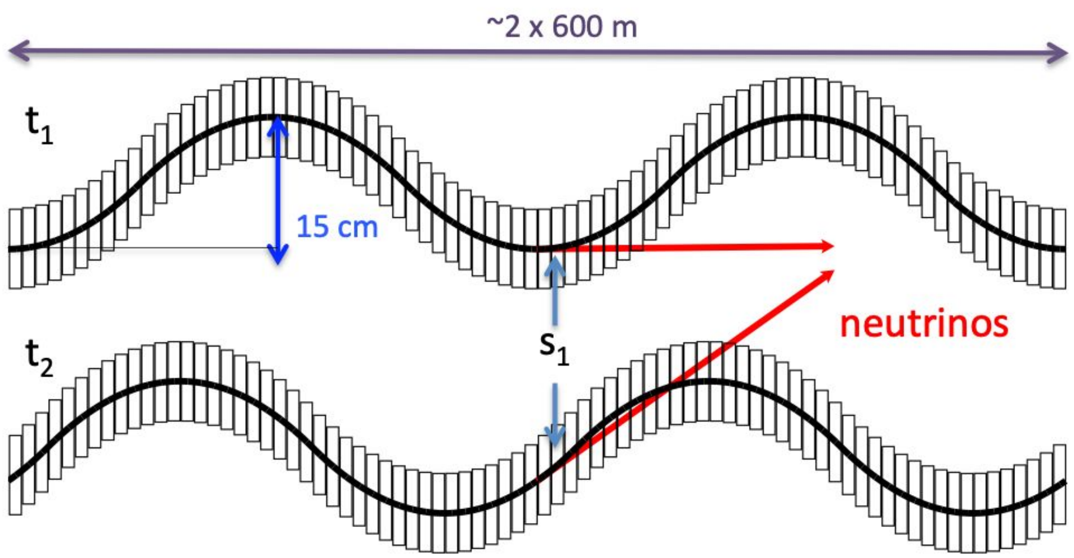
Legal limit: 1 mSv/year
MAP goal: < 0.1 mSv/year

IMCC goal: arcs below threshold for legal procedure < 10μSv/year
LHC achieved: < 5 μSv/year

3 TeV, 200 m deep tunnel ~ OK

Need mitigation in collider arcs at 10+ TeV: move collider ring components

Example: vertical bending

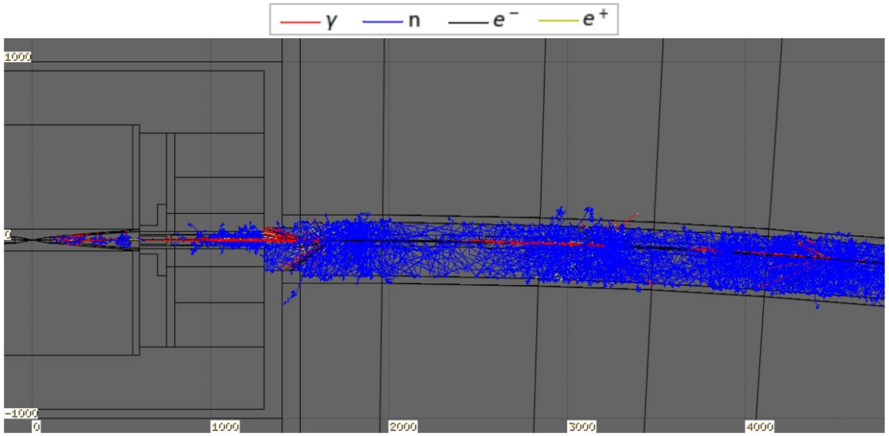


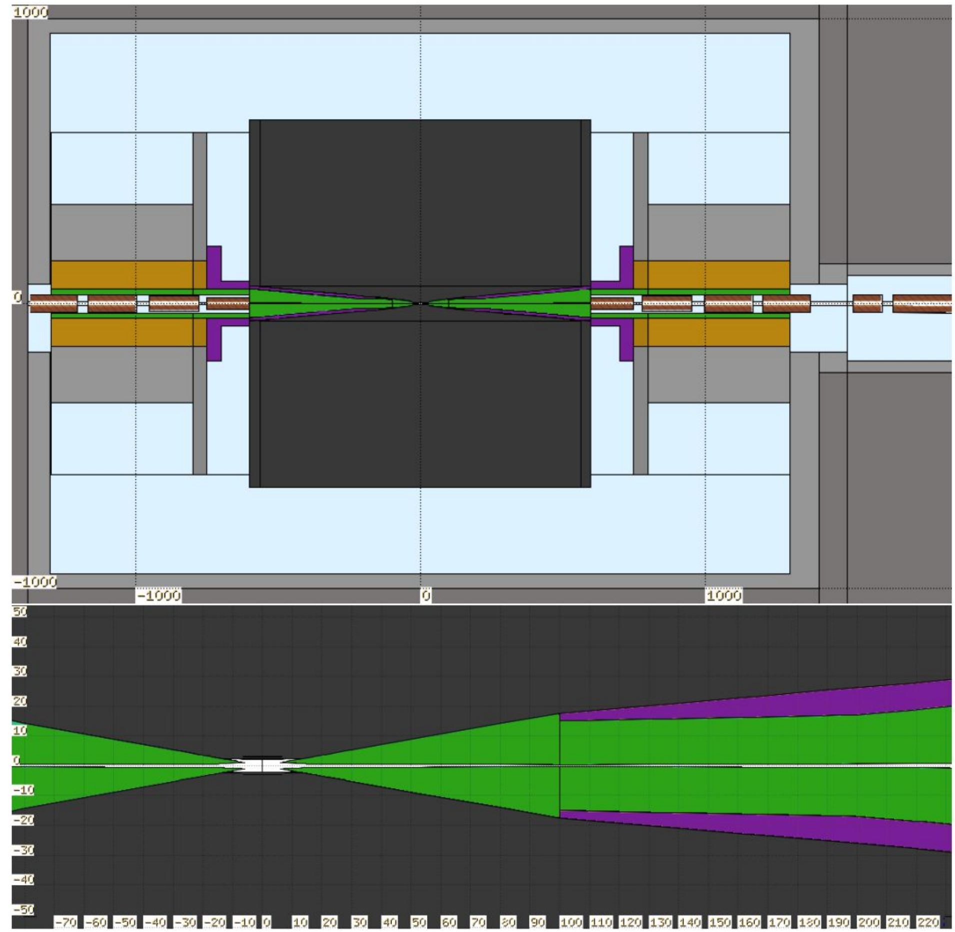
Sketch credit: D. Schulte

Opening angle of 1 mradian makes 14 TeV collider comparable to LHC

Need to engineer mover system and study impact on beams

The beam-induced backgrounds (BIB)





Huge number of particles from muon decays (4×10^5 per metre of lattice) and their byproducts

- Shielding with tungsten nozzles with borated polyethylene (BCH_2) coating

Unique challenge of Muon Colliders

Machine-Detector interface

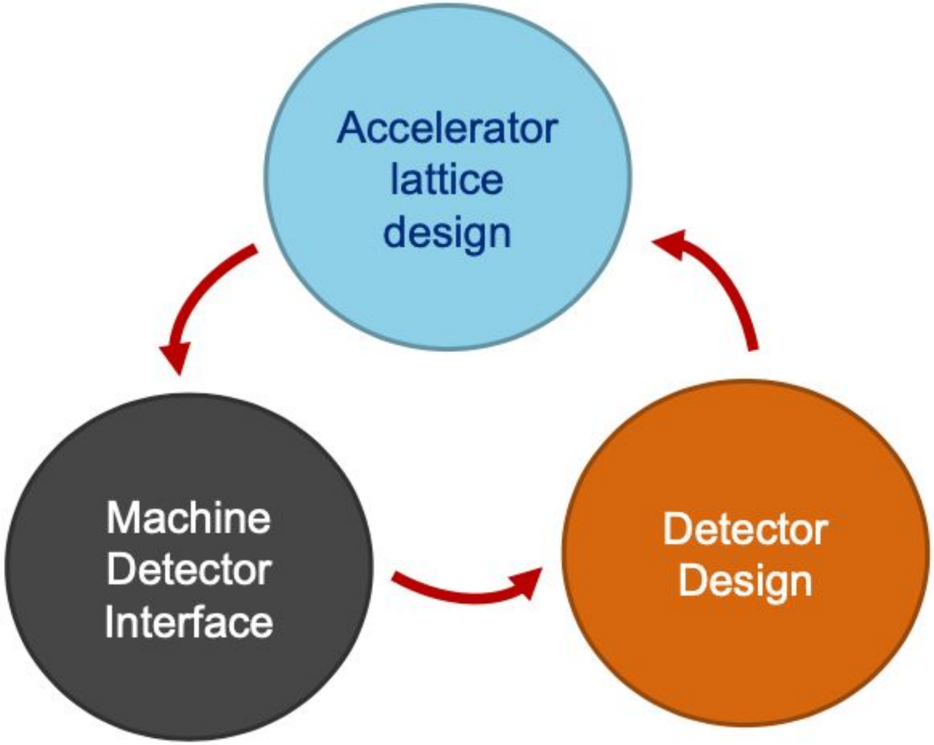


Diagram credit: S. Jindariani

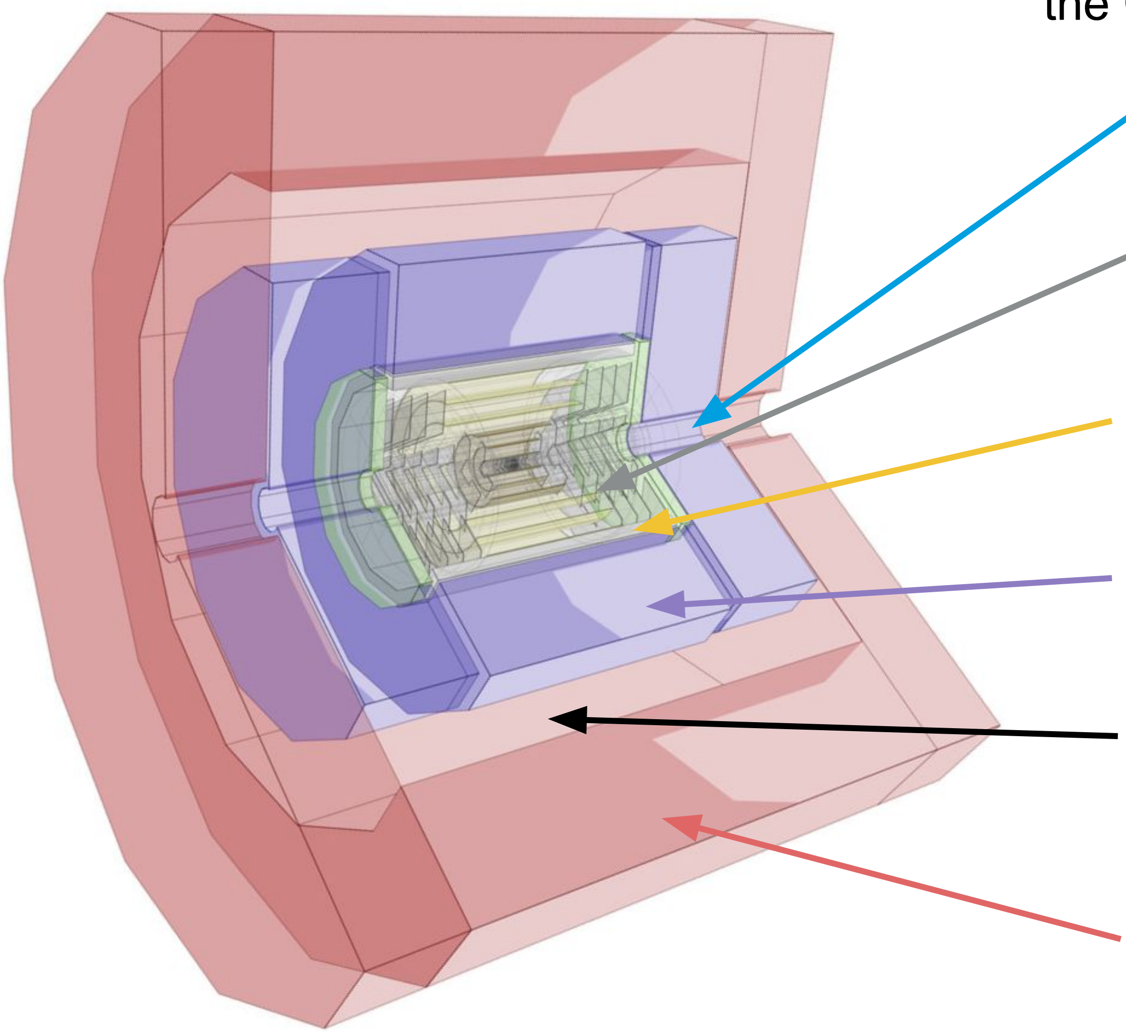
Muon Collider detector design has to be carried out in close collaboration with accelerator and MDI designers!

STATUS

√s	IP design	MDI	Detector
3 TeV	✔	1.5 TeV BIB	✔
10 TeV	ongoing	ongoing	ongoing

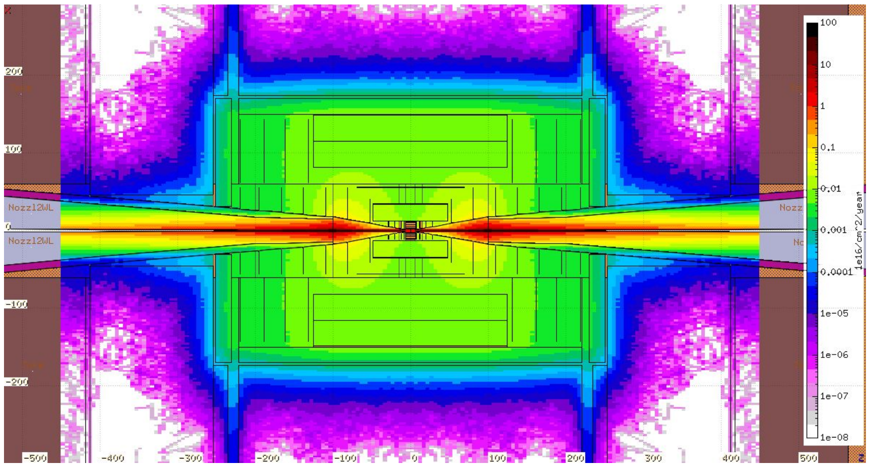
3 TeV detector layout

The detector model is based on the CLIC concept

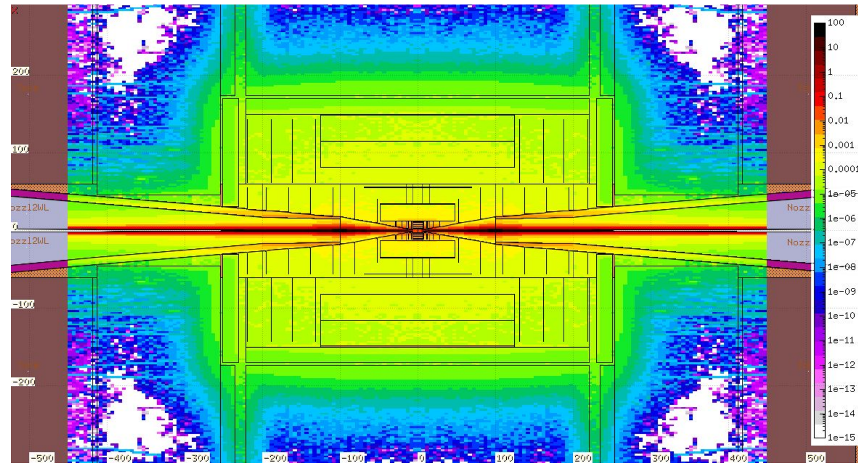


Detection Environment

Predictions from FLUKA with simplified detector geometry



1-MeV-n_{eq}/cm^2 fluence for 200 days of operation



Total Ionising Dose for 200 days of operation

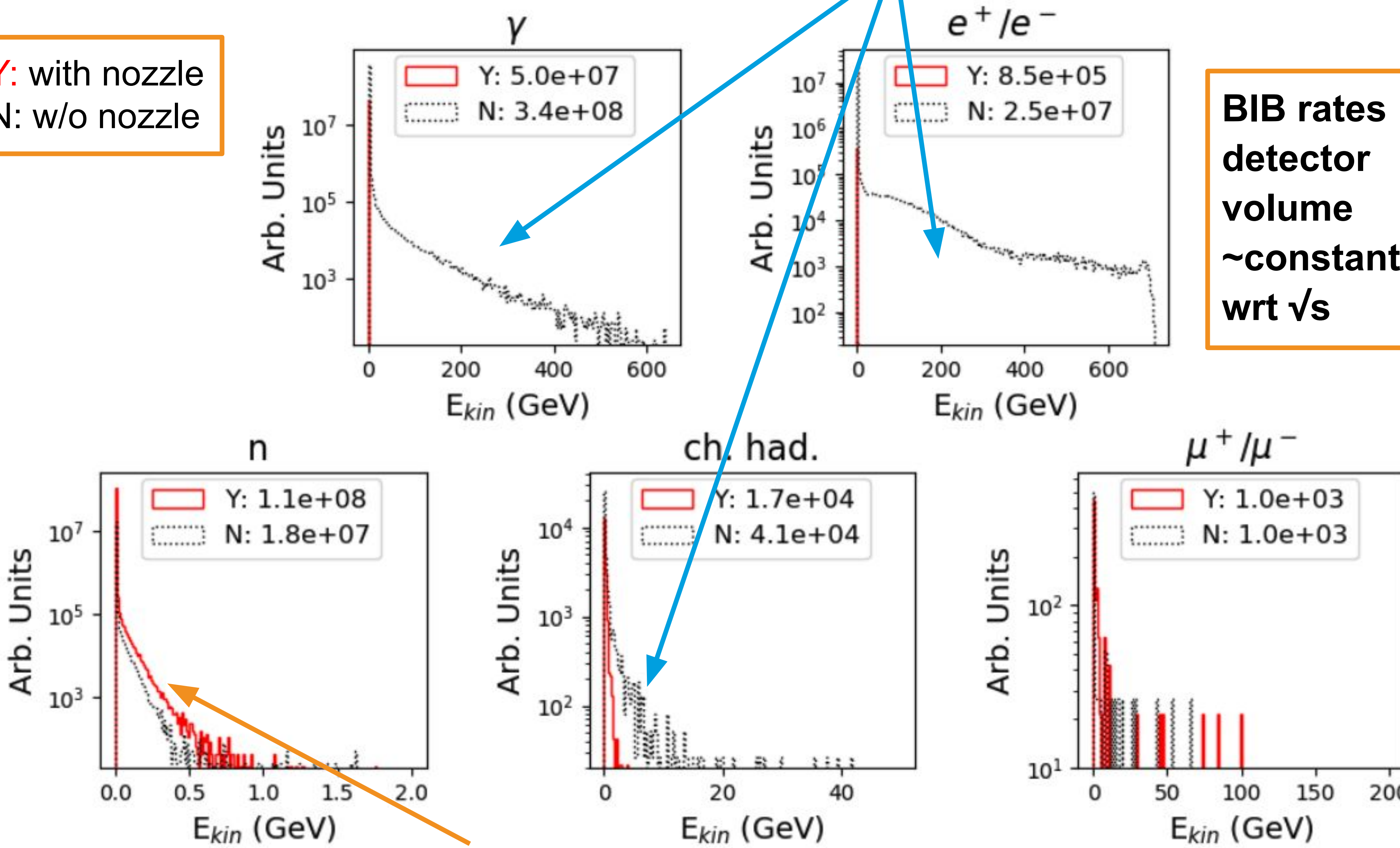
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

FCC-hh requirements
~10^{18} 1 MeV-n_{eq}/cm^2

Impact of nozzles

High-energy component absorbed

Y: with nozzle
N: w/o nozzle



BIB rates in detector volume ~constant wrt √s

Increase in neutron flux

Beam-induced background properties

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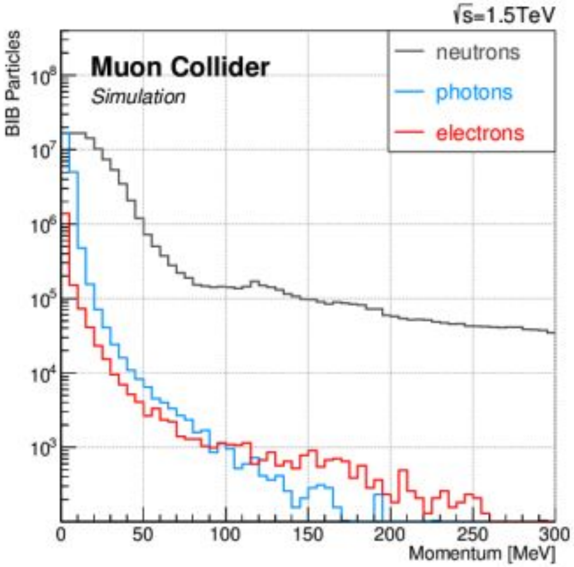
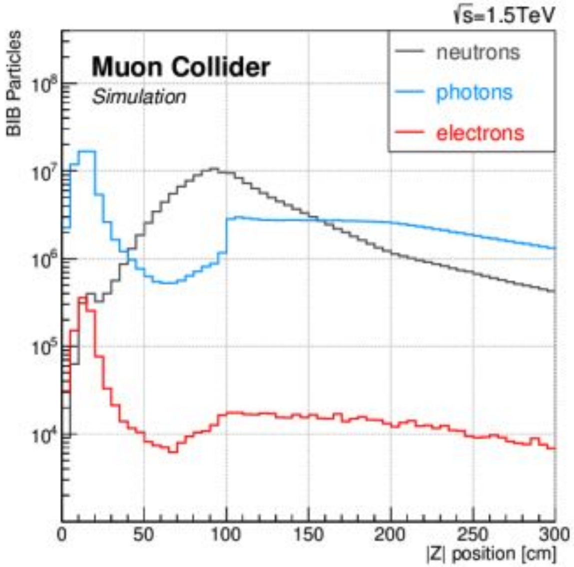
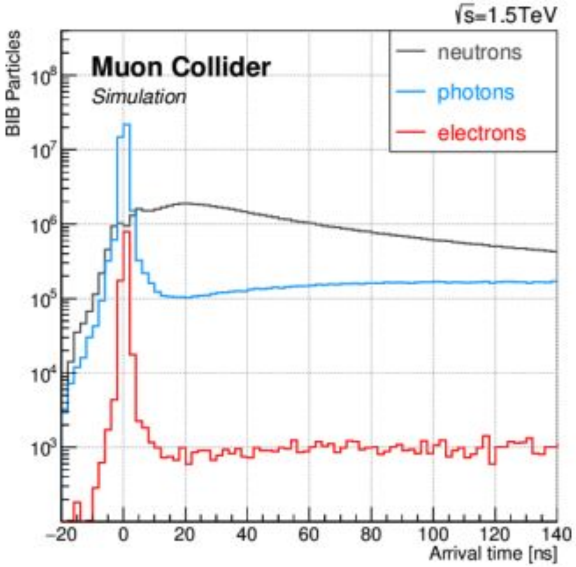
[1905.03725](1905.03725)
[2105.09116](2105.09116)



Low momentum



Origin and direction

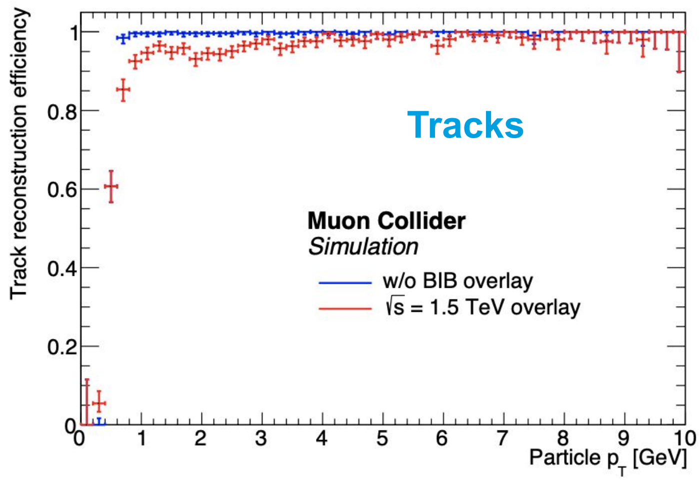


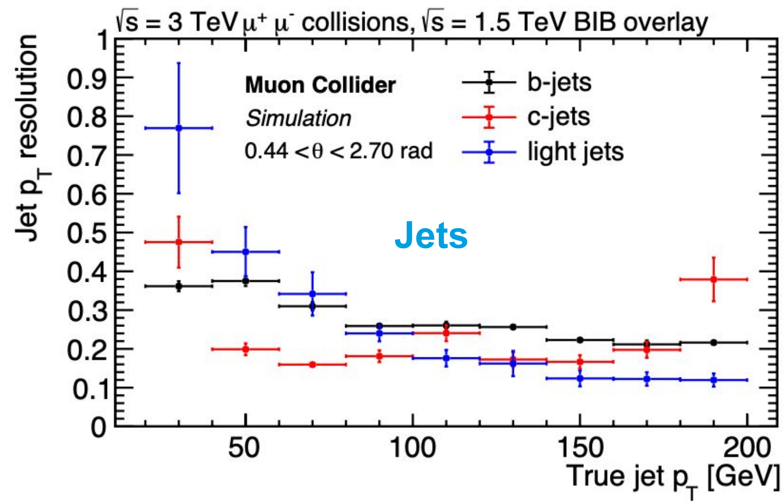
Timing

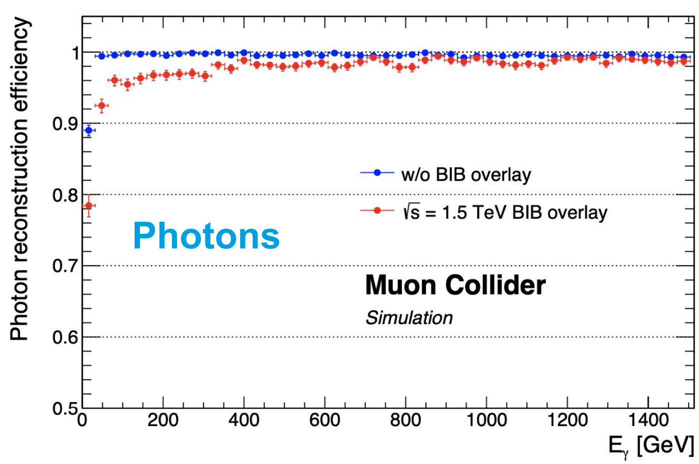
Snapshot of 3 TeV performance

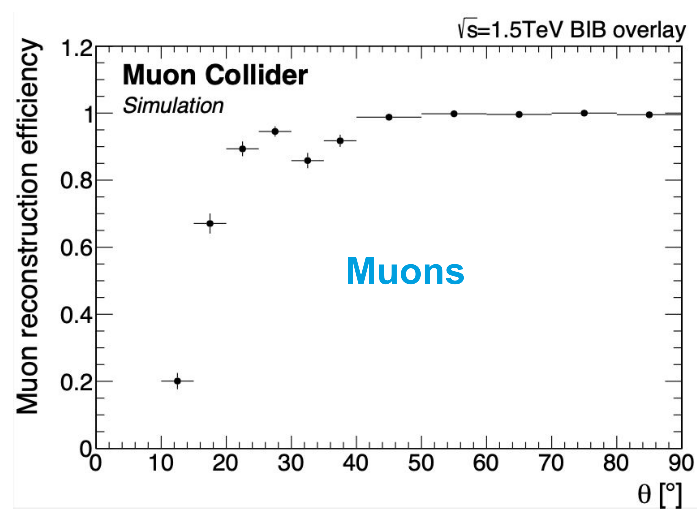
Achieved "LHC-level" performance without using dedicated techniques

- Huge potential to improve further





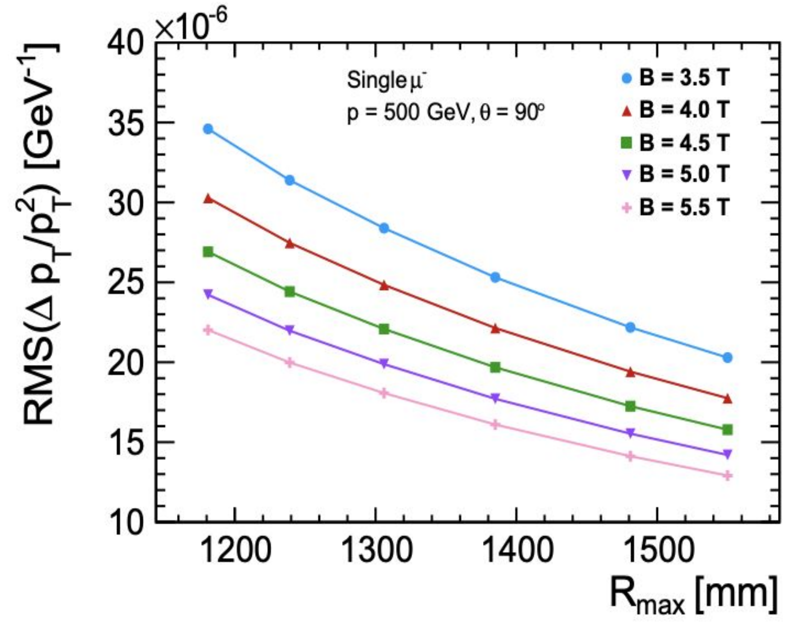




Designing a 10 TeV detector

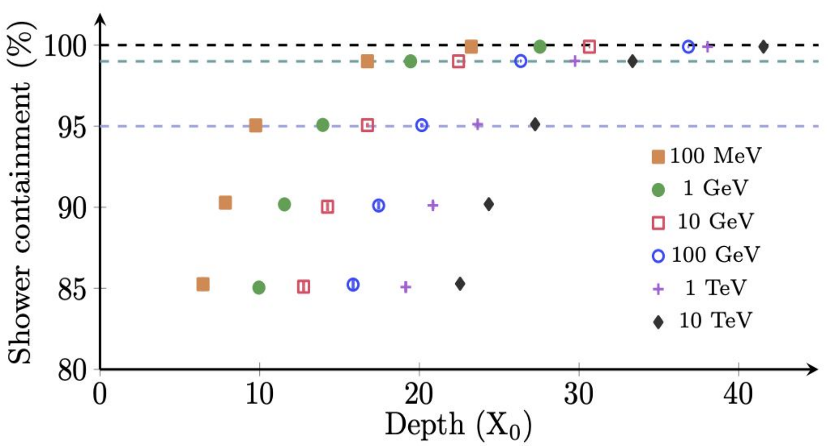
Update the tracker

- Optimise position and granularity
- Reconsider double layers
- Re-design endcap region



Make the calorimeters thicker

- More radiation/interaction-lengths for containment
- Revisit cell energy thresholds, or think about some level of "BIB shielding"

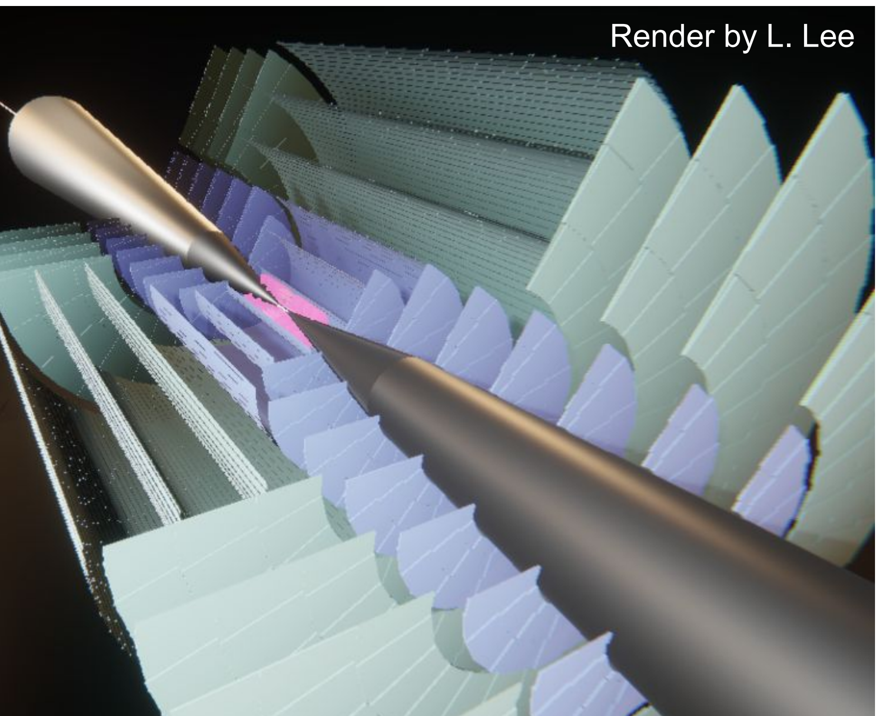


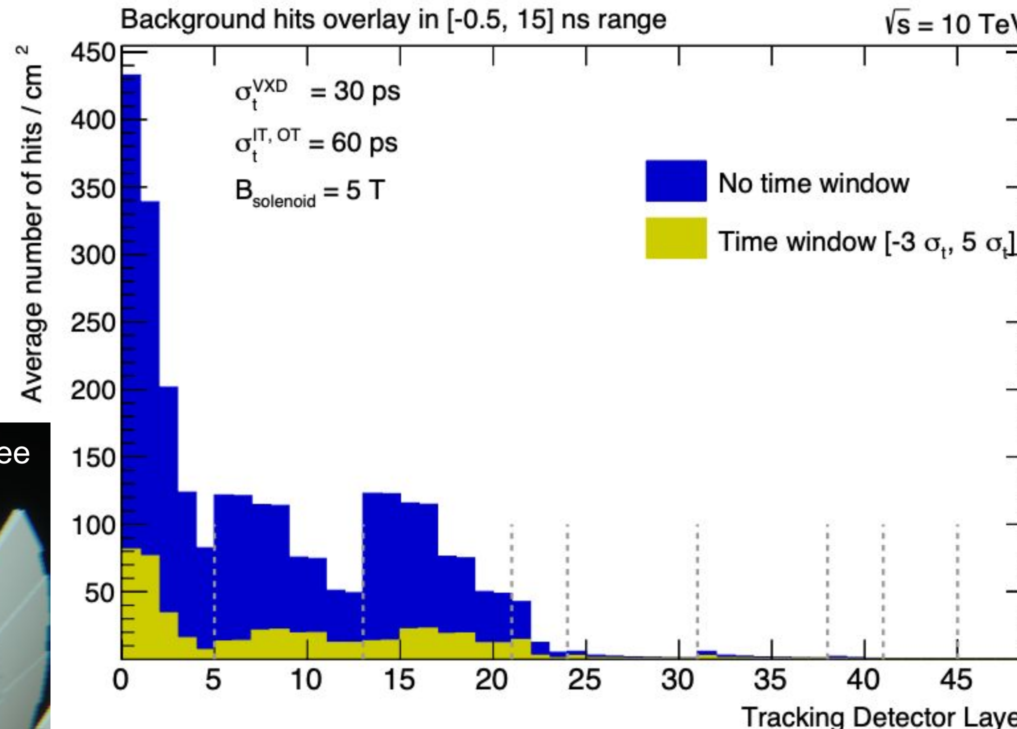
Verify feasibility of streaming operation

Tracking detectors

Goal: tracker occupancy < 1%

- Other requirements are not unique: **low mass/power, radiation tolerance, low noise**





Detector Reference	3 TeV MuC	Hit Density [mm^{-2}] ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

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PoS Vertex2014 (2015) 045

R&D: 4D tracking detectors

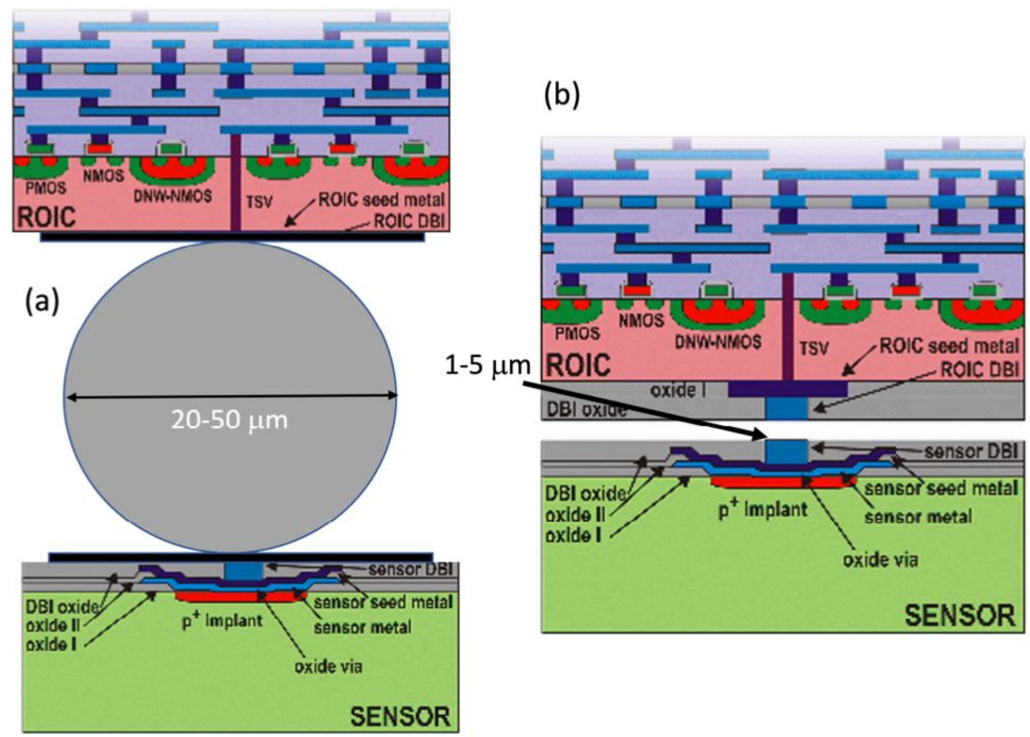
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

R&D efforts crucial

Promising technologies exist

Example: Advanced hybrid bonding tech can give < 5 µm pitch and low input capacitance

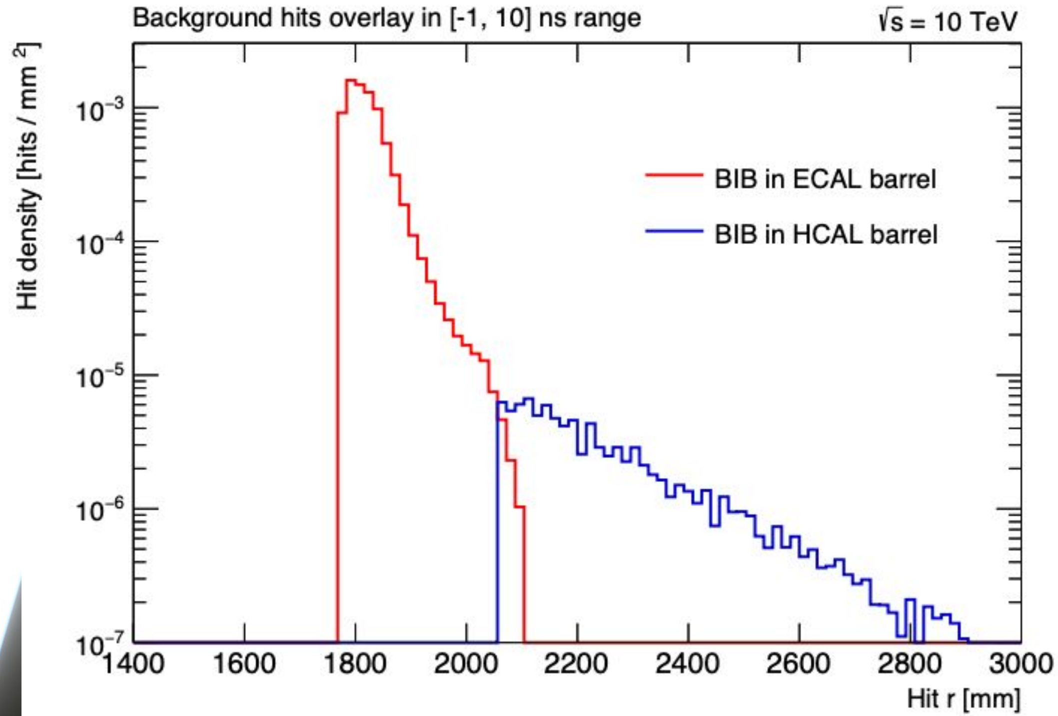
- 20-30 ps time resolution

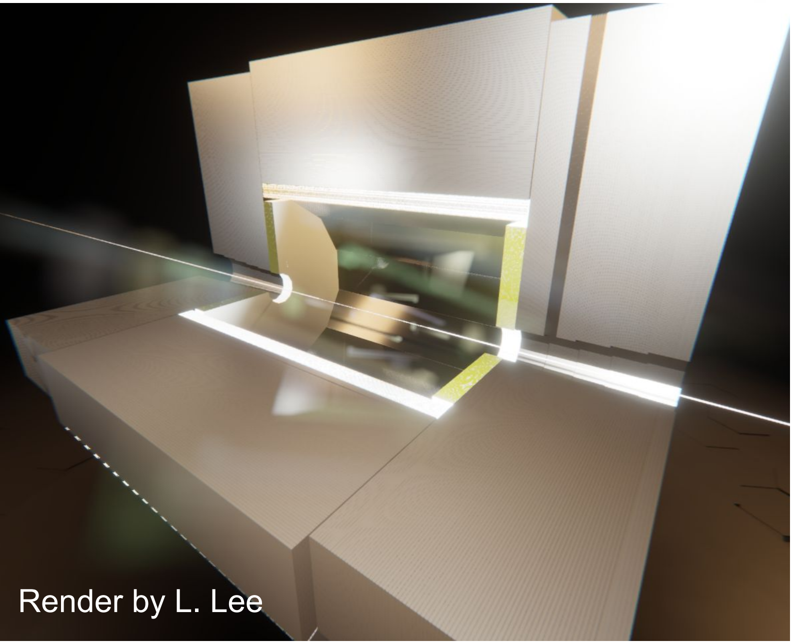


Calorimetry

BIB dominated by neutral particles: photons (96%) and neutrons (4%)

Ambient energy per unit area similar to HL-LHC





- High granularity
- Precise hit time measurement O(100ps)
- Longitudinal segmentation
- Good energy resolution 10%/√E for photons and 35%/√E for jets or better

Fast evolution from concept (March '23) …

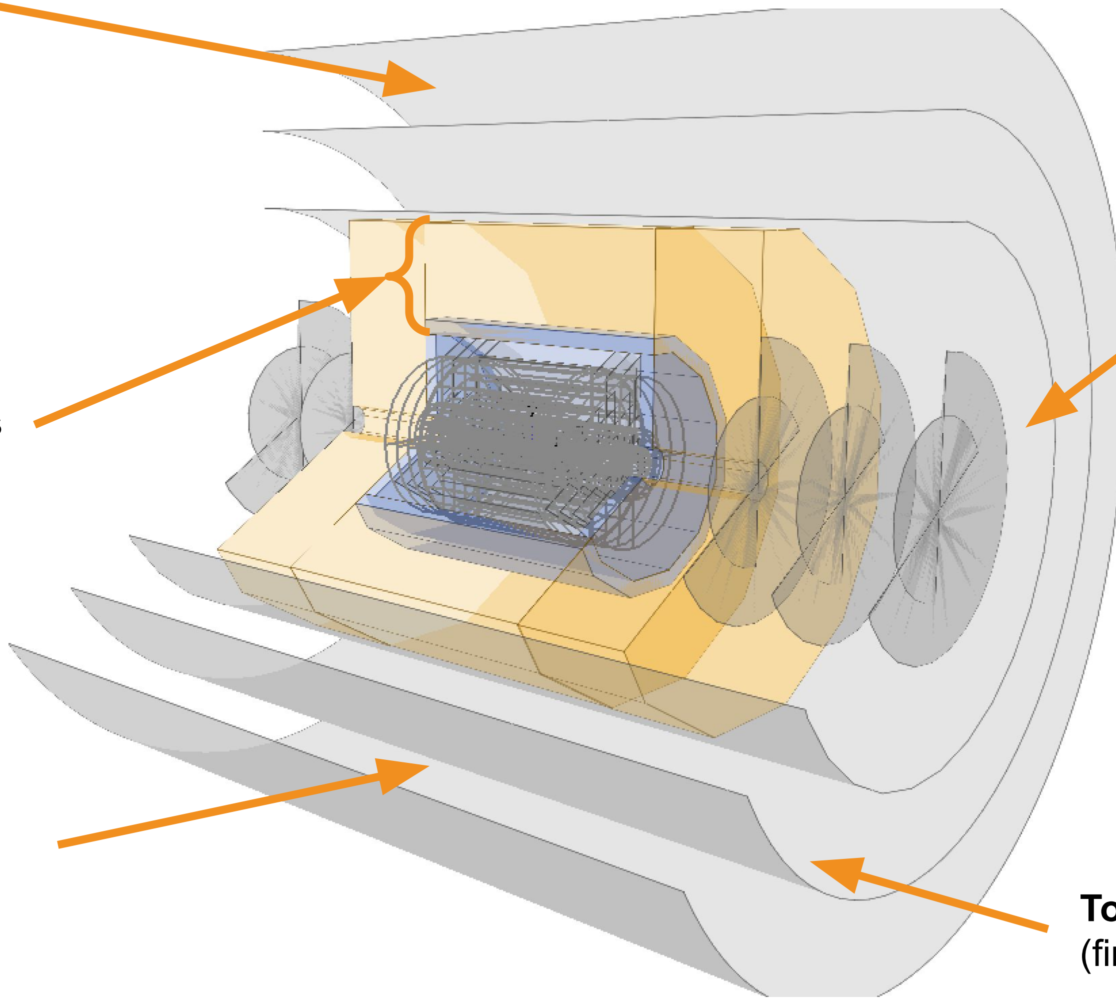
No need for a Yoke

Calorimeter depth optimised with photon and pion gun samples (changed both sampling fraction and N_{layers})

Simplified muon system

Visualisation glitch **(extend up to the barrel)**

Toroidal field (first time in key4hep)



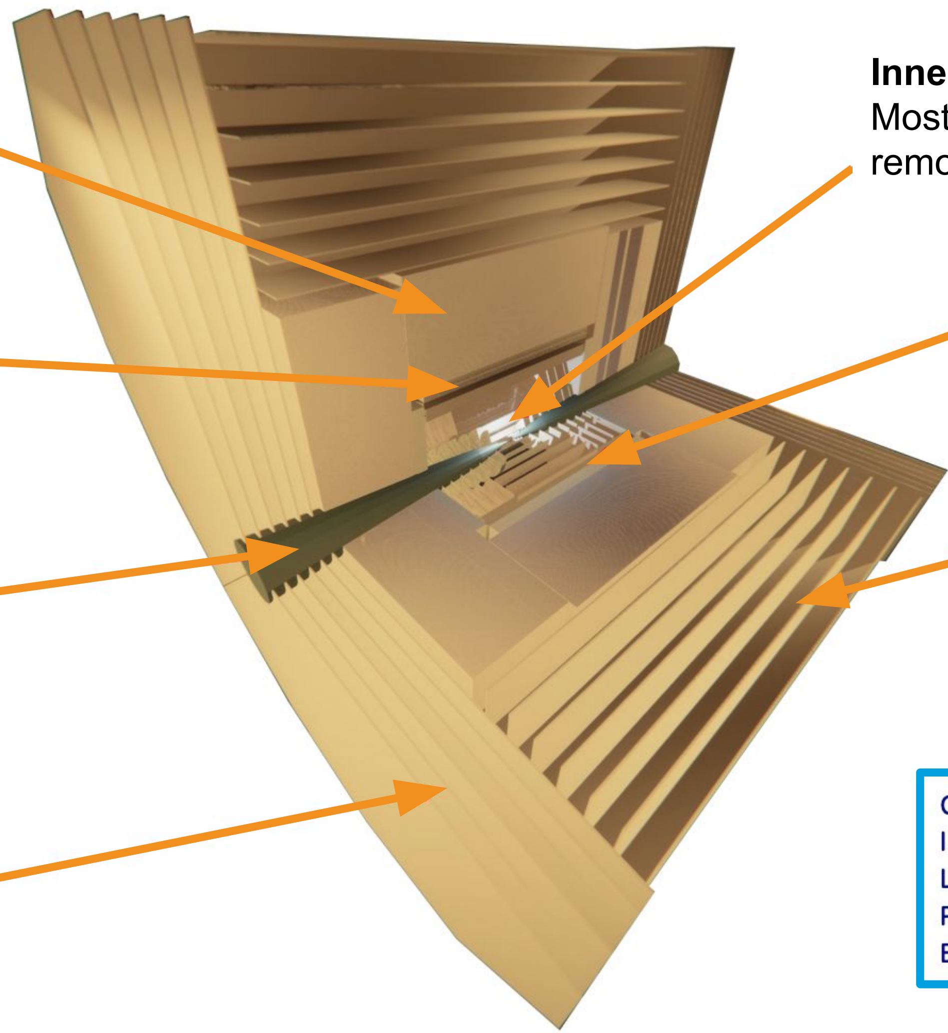
… to design (October ‘23)

HCAL
Fe+Scillator
Return B field

ECAL
Si+W

Shielding nozzle
Dimensions to be optimised

In-air muon system
RPC-based



Inner tracker
Most double layers removed

Solenoid
5 T
3m diameter

Toroidal field could be added

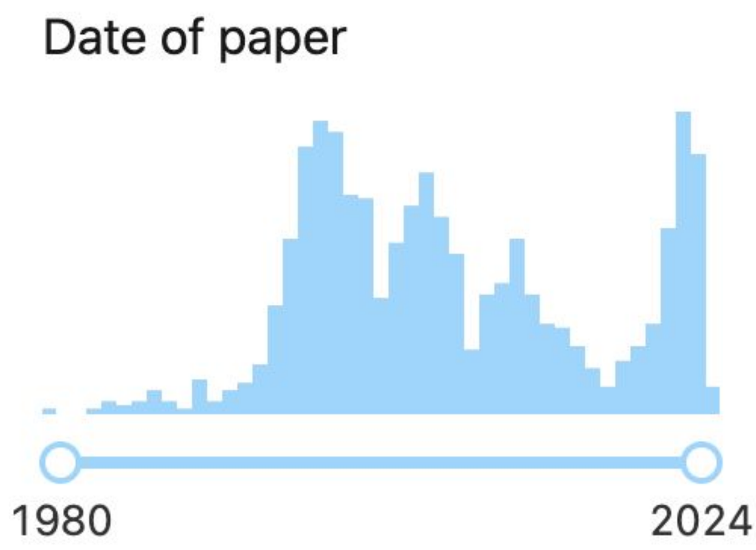
C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

From physics potential to detector design

Bottom-up design supported by studies of physics potential

Direct searches	High-rate measurements	High-energy probes	Muon flavour physics
Pair production, Resonances, VBF, Dark Matter, …	Higgs single and self-couplings, rare decays, top, …	Di-fermion, di-boson, EFT, Higgs compositeness, …	Lepton Flavor Universality, $b \to s\mu\mu$, g-2, …

Tens of papers submitted to the arXiv in the past few months!

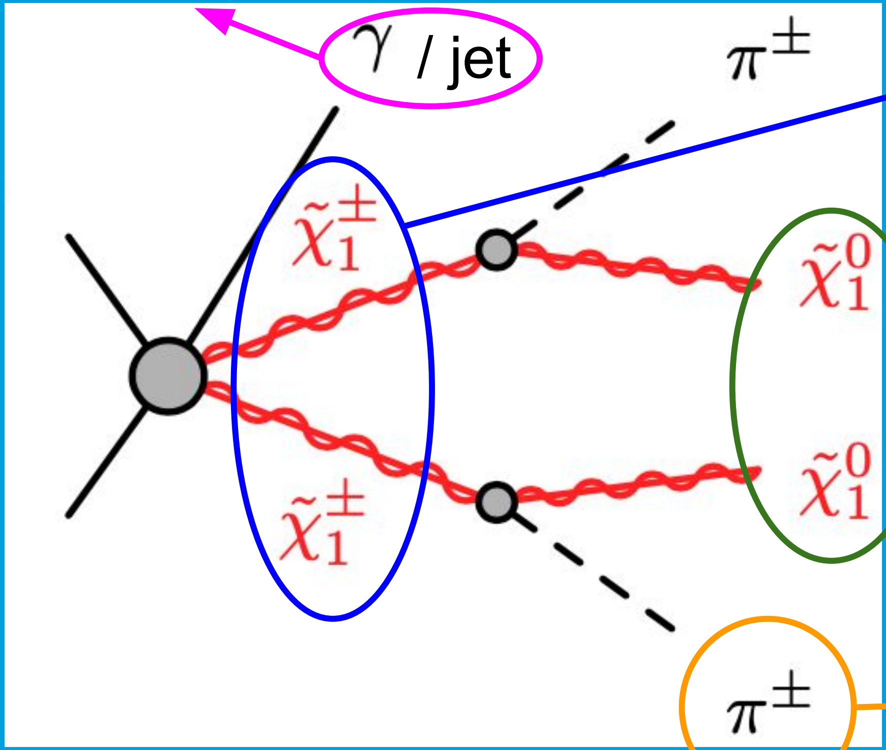


2102.11292

(if time allows) Disappearing tracks

ISR/FSR:

- “Trigger” the event



Charginos:

- Long lived, charged
- Reconstructable as “tracklets”

Neutralinos:

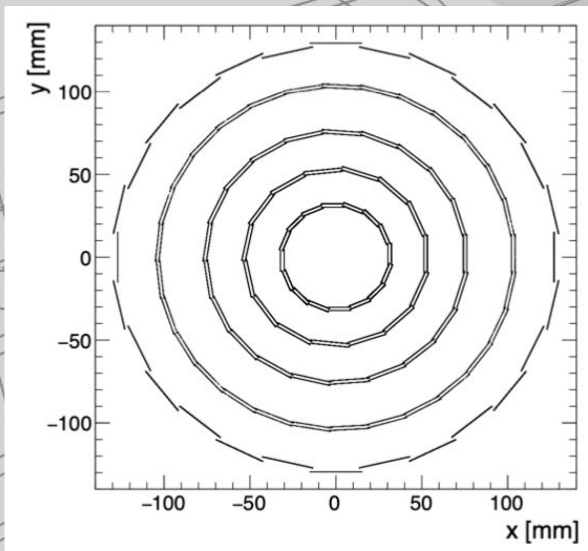
- Stable, neutral
- Invisible

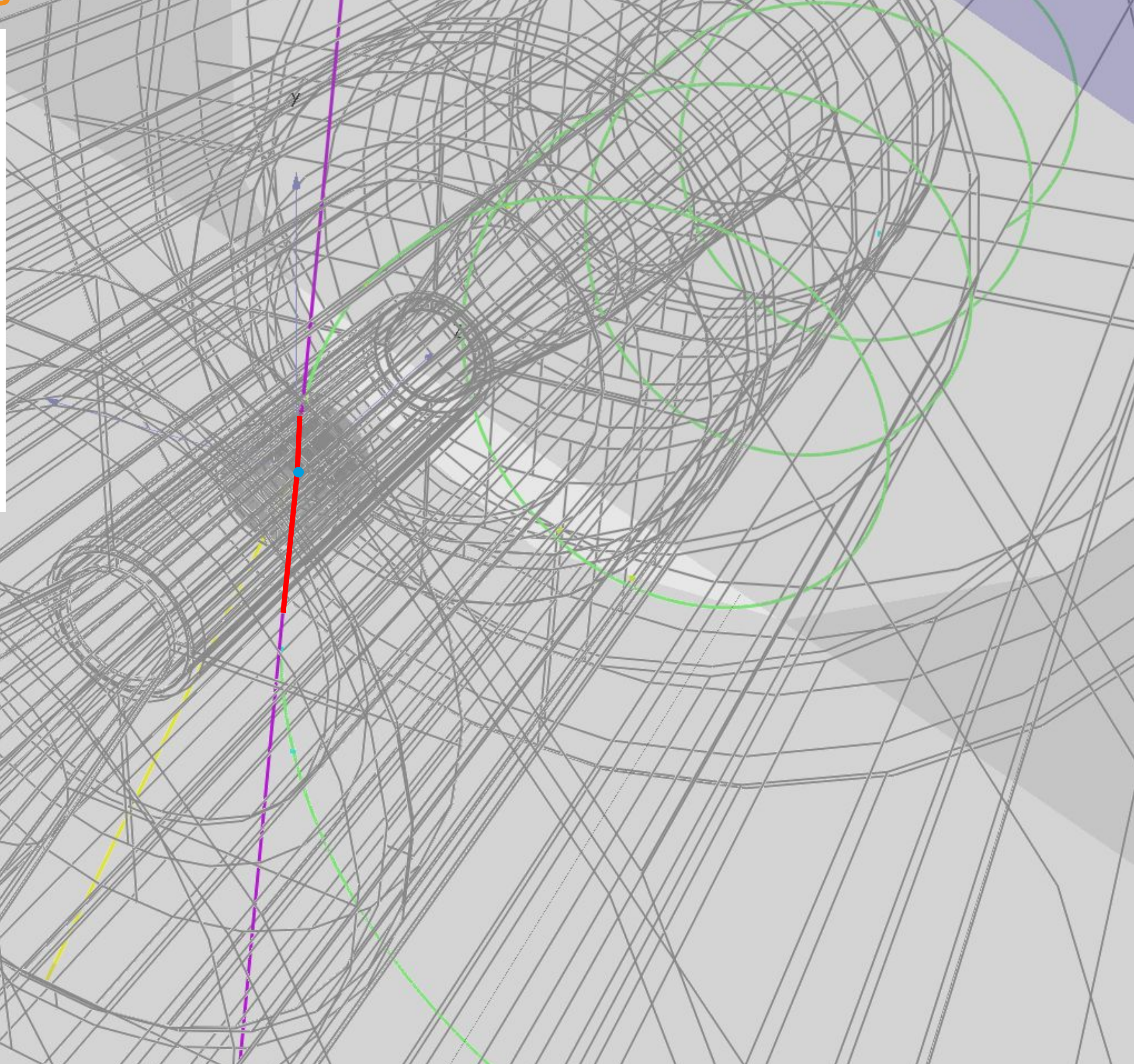
Displaced pions:

- Possibly reconstructable
- Not considered here

Signal event

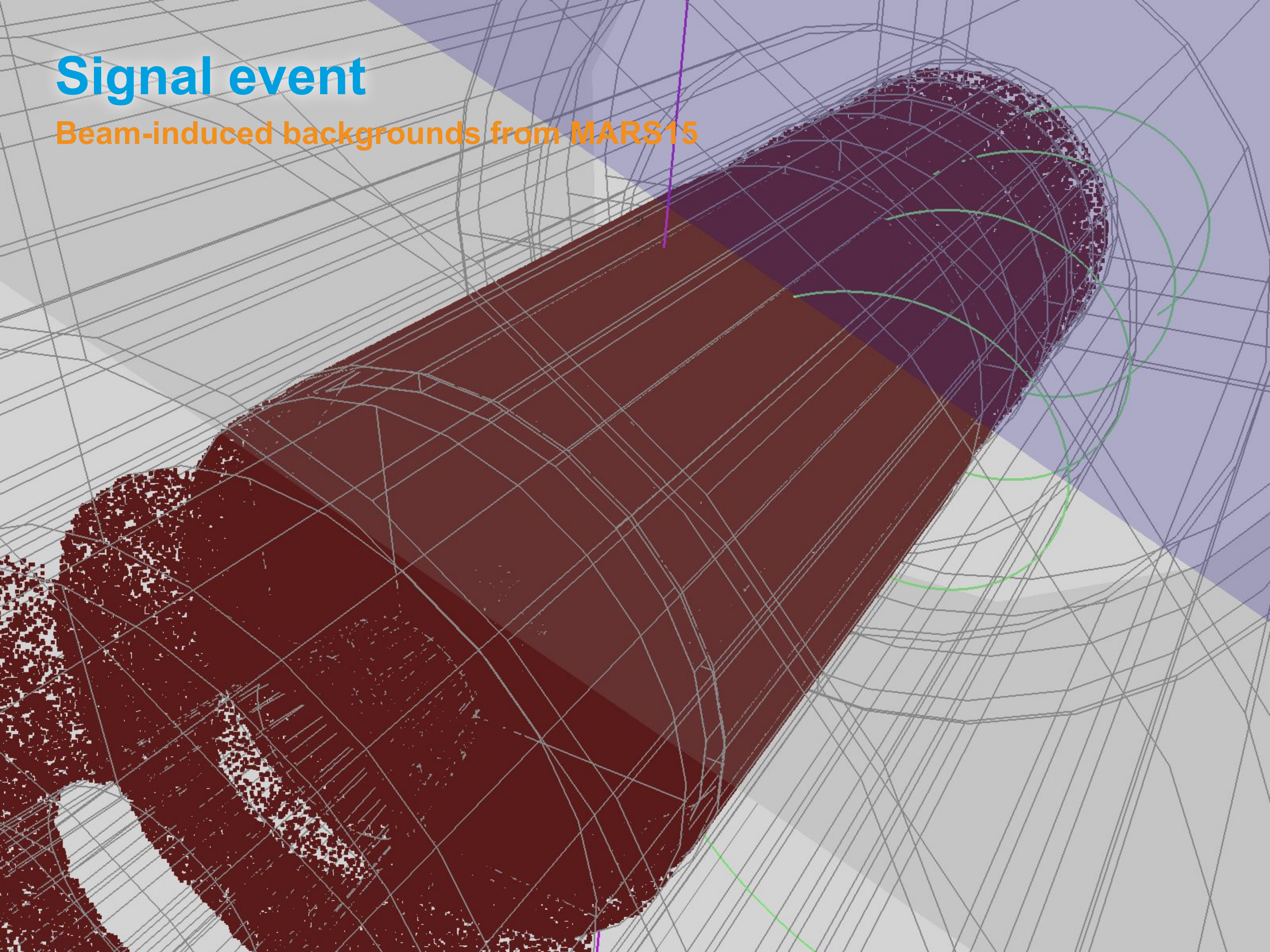
No beam-induced backgrounds





Signal event

Beam-induced backgrounds from MARS15



Tracklet reconstruction

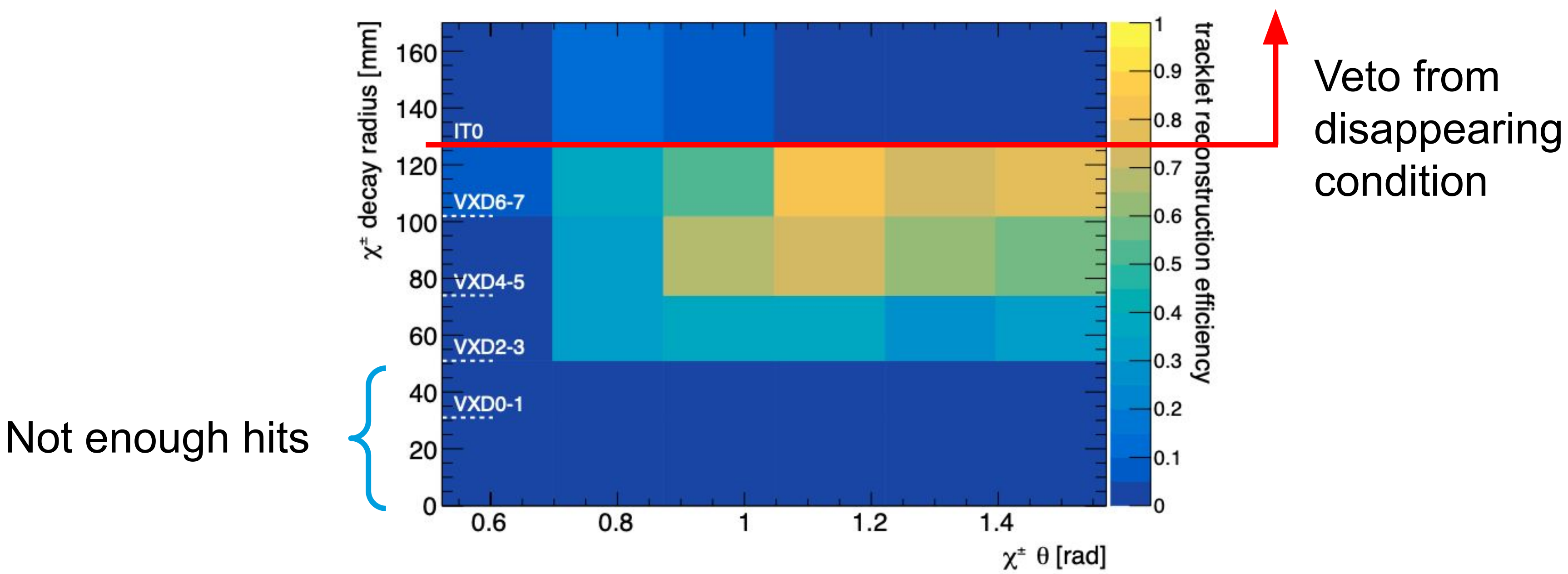
After BIB rejection cuts

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV

Impose a "disappearing condition" (hit veto) at the first layer of the IT (12.7 cm)

Efficiencies evaluated with truth matching to $\chi^{\pm}$

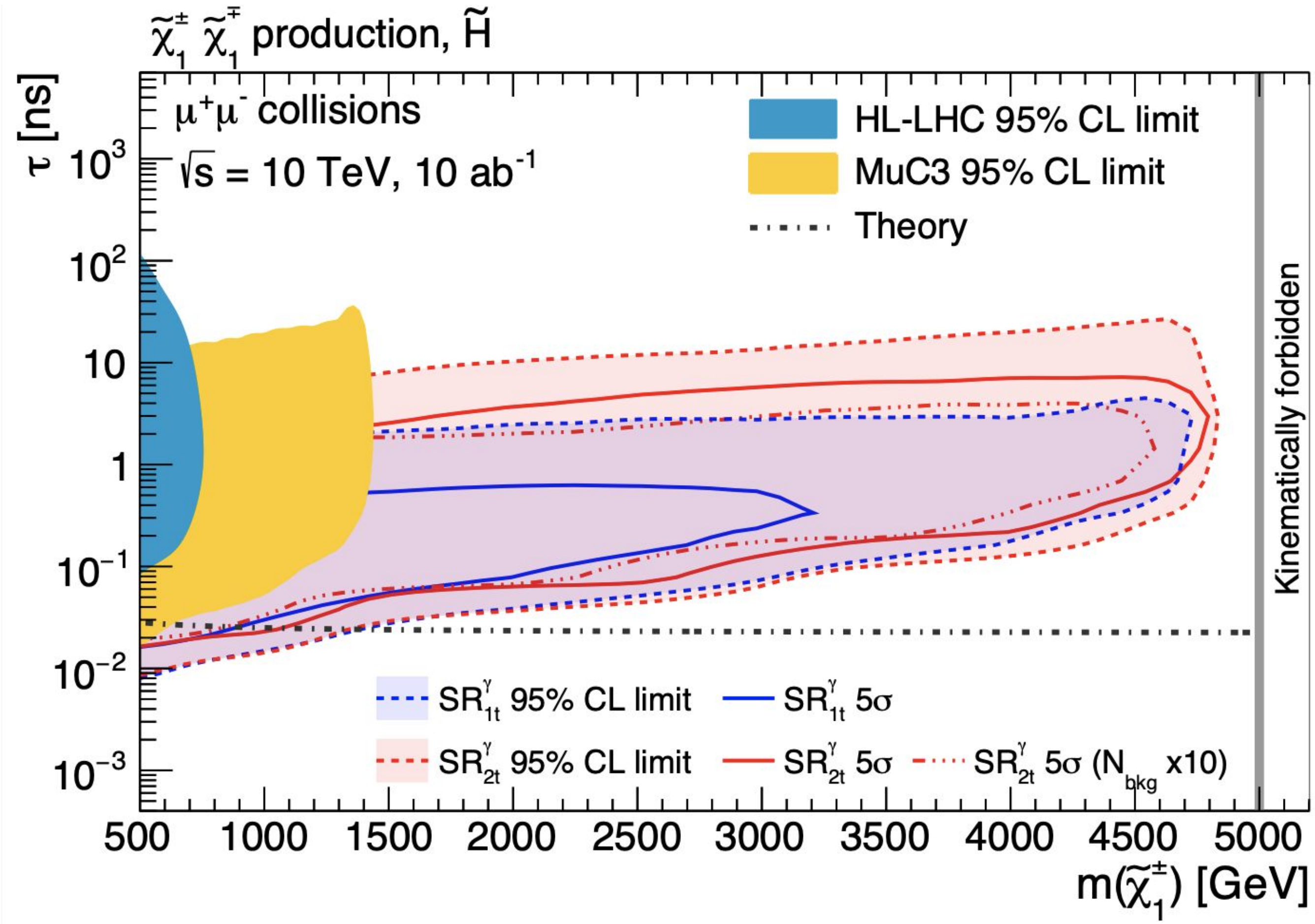
- Evaluated vs the $\chi^{\pm}$ decay radius and polar angle θ



Expected sensitivity

Pure higgsino models at MuC 10

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV



Expected sensitivity

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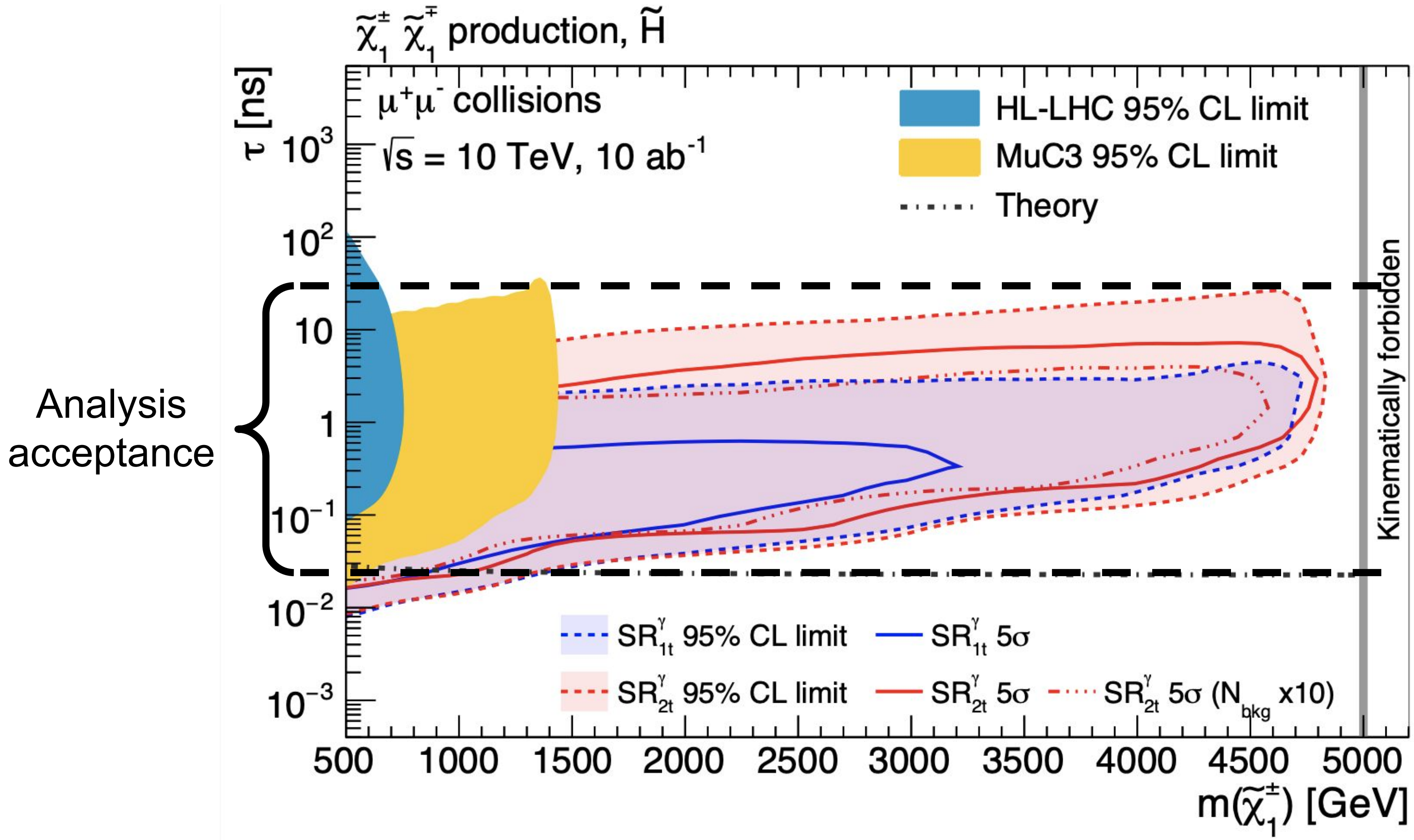


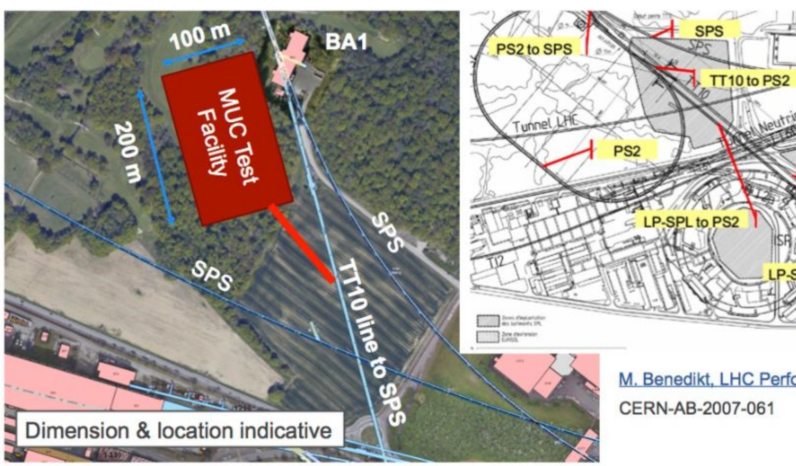
Demonstrators and synergies

Demonstrator programme(s)

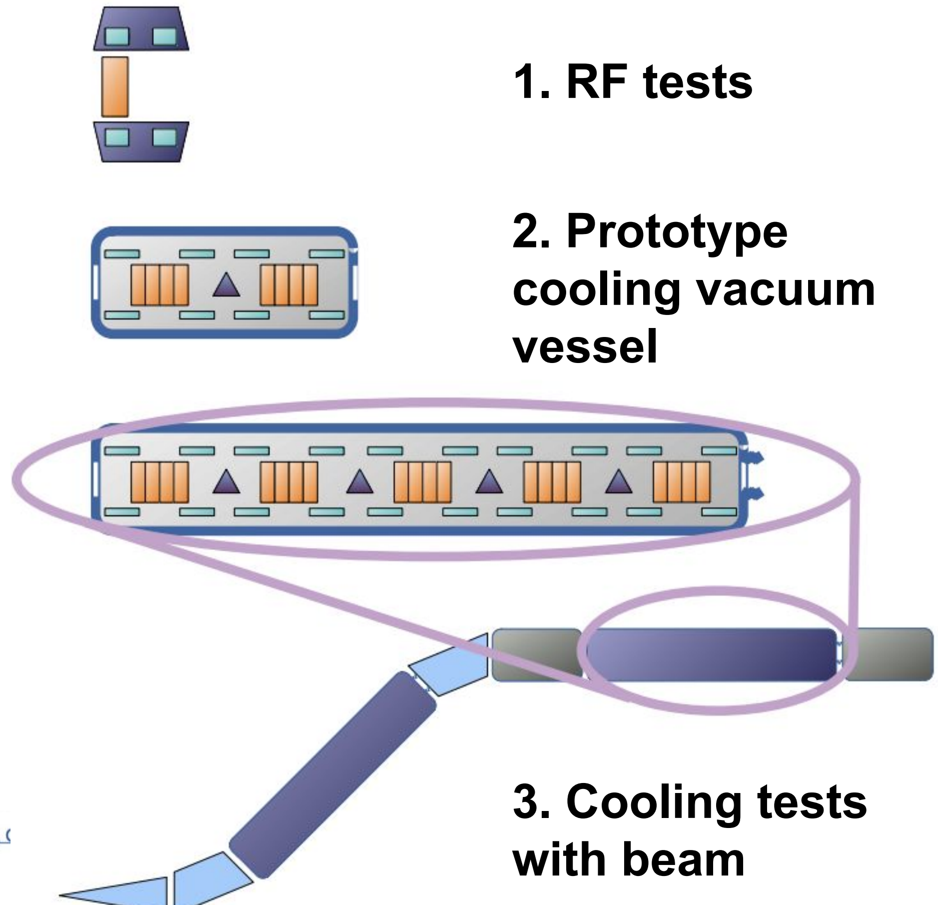
Planning demonstrator facility with muon production target and cooling

- Intensity below real collider (e.g. 10 kW target)

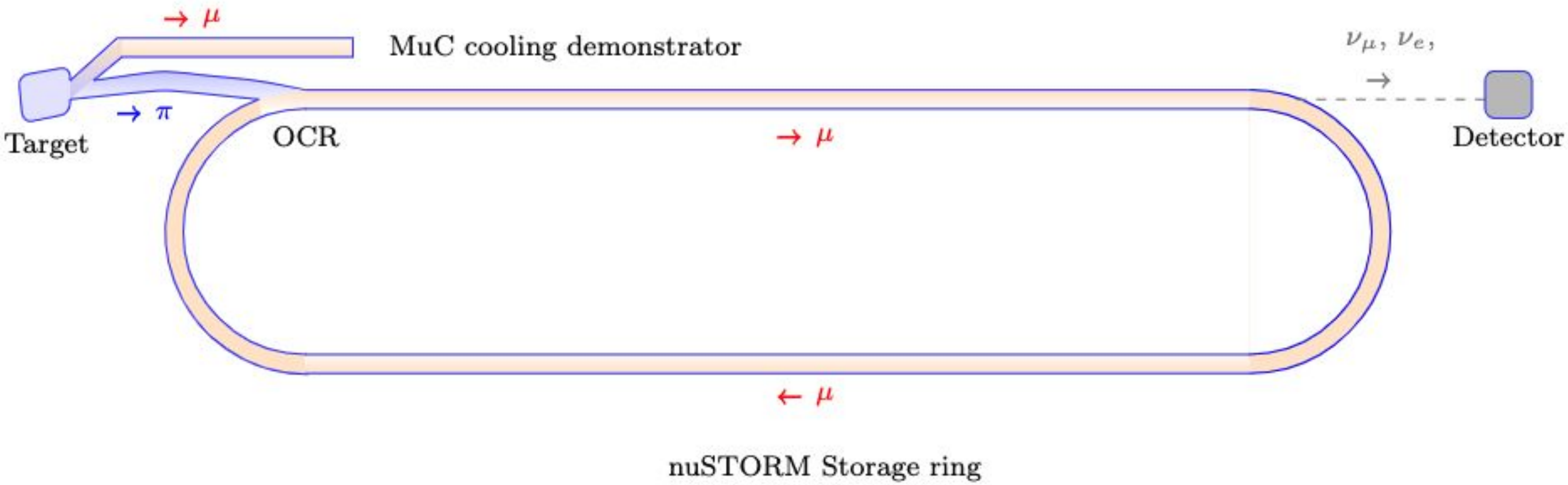
Suitable sites exist on CERN and Fermilab land



M. Benedikt, LHC Performance Workshop, (
CERN-AB-2007-061

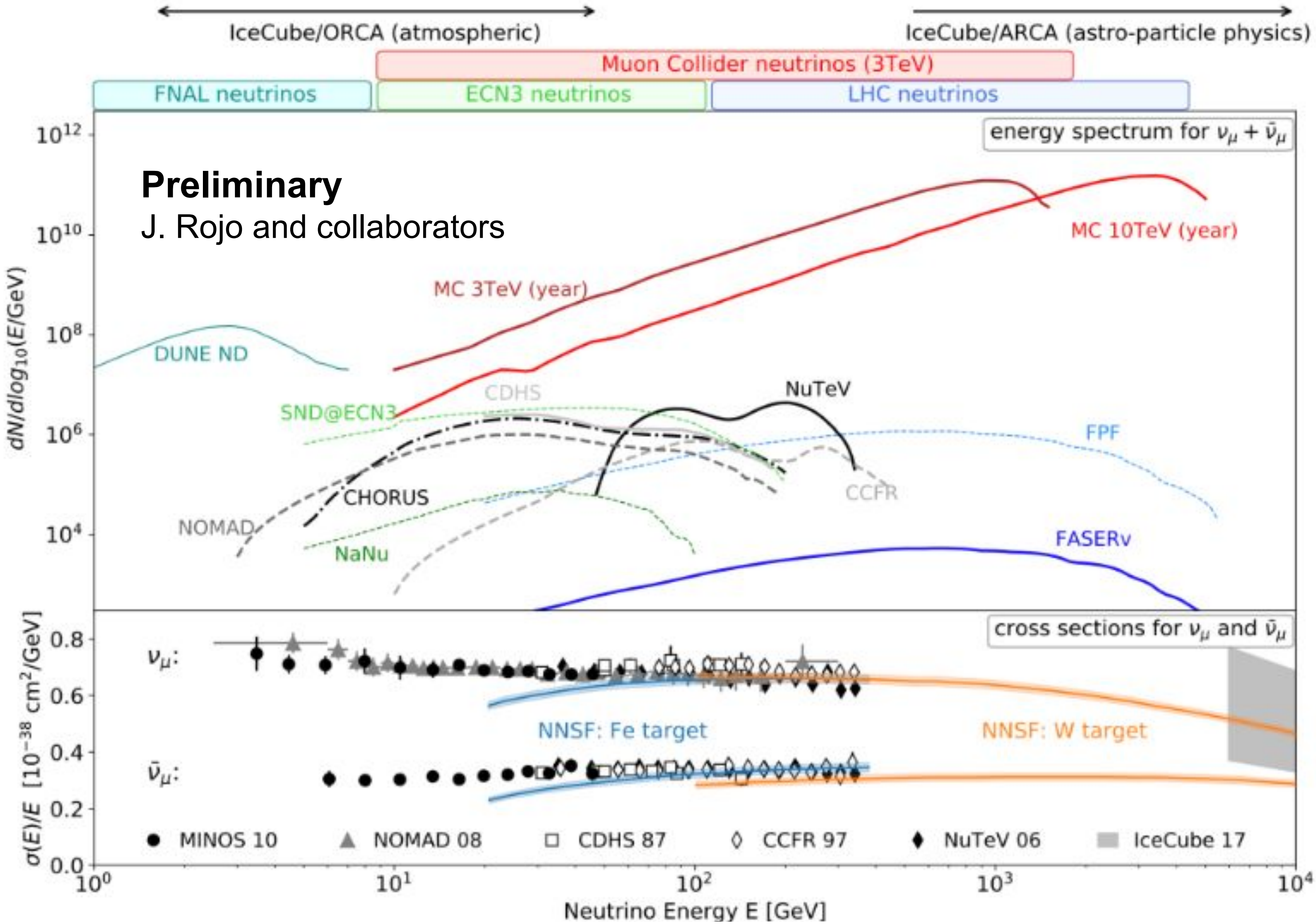


Neutrino synergies I



Facilities such as **nuSTORM** could share infrastructure with a cooling demonstrator from the IMCC Interim report

Neutrino synergies II



Summary

Why waiting for a muon collider?
We are not waiting, but working on it.

- F. Maltoni

The muon collider presents **enormous potential for fundamental physics research** at the energy frontier

The road ahead is filled with challenging and interesting R&D, spanning across **theory, accelerator and experiment!**

Background image credit: L. Lee

Thank you!

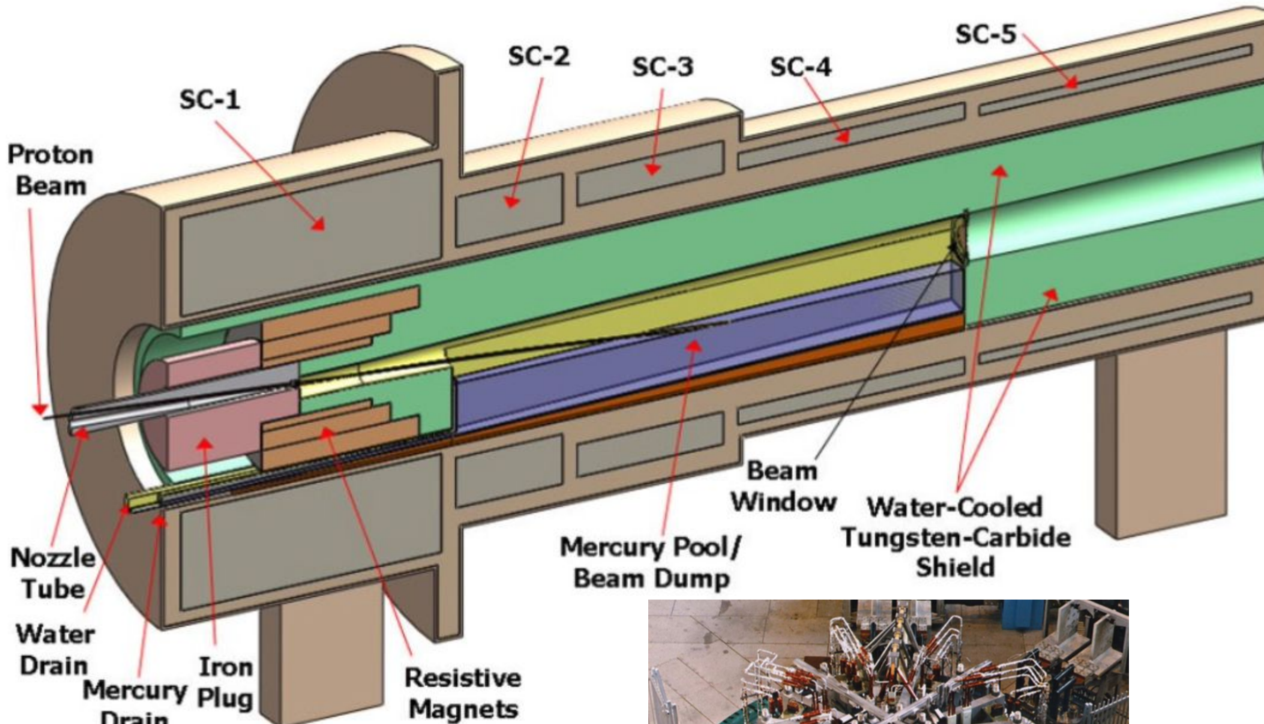
Contact

Federico Meloni
DESY-FH
federico.meloni@desy.de

Background image credit: L. Lee

Proton target

High-field required to efficiency collect pions and muons

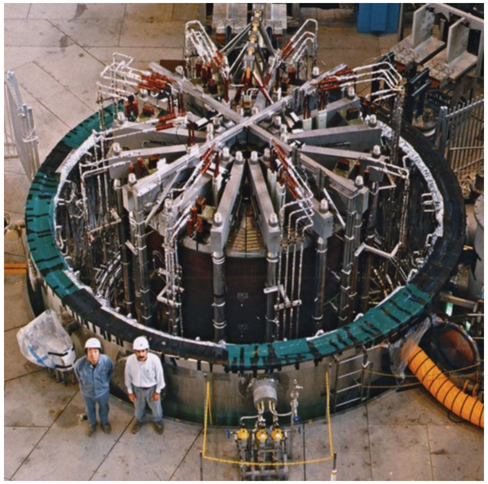


2-4 MW proton beam

- Simulated graphite target ok
- Operation at 2000°C

Large aperture O(1m) to allow shielding

- Synergy with ITER 13 T in 1.7 m



2201.07895
Nature Phys. 8 (2012) 243-247

Accelerator ring

Ramp magnets to follow E_{beam}

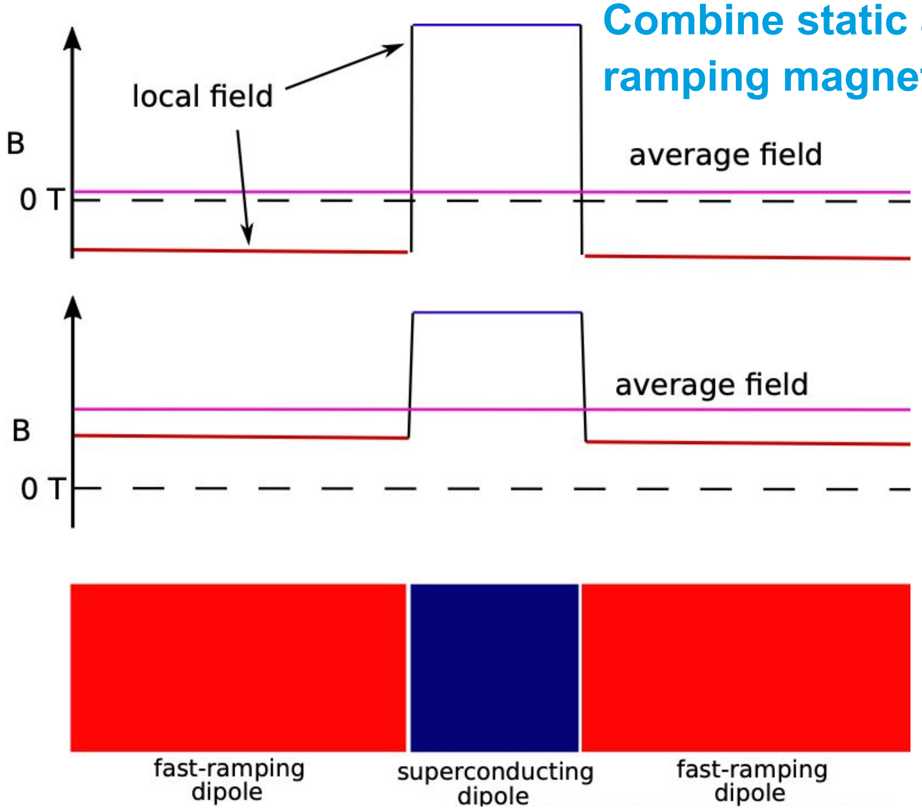
- **Fast-ramping synchrotron magnets** (−2T to 2T in 2 ms)

Demonstrated:

- Normal-conducting magnets (2.5 T/ms with peak of 1.81 T)
- HTS (12 T/ms, peak of 0.24 T)

Need 5 km of 2T magnets per TeV or fast HTS dipoles

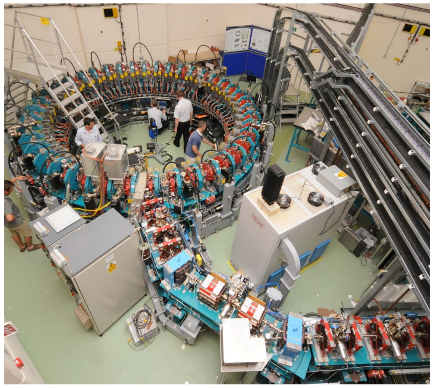
Combine static and ramping magnets



Fixed-Field alternating gradient Accelerator (alternative)

- Complex high-field magnets
- Challenging beam dynamics

EMMA proof of FFA principle



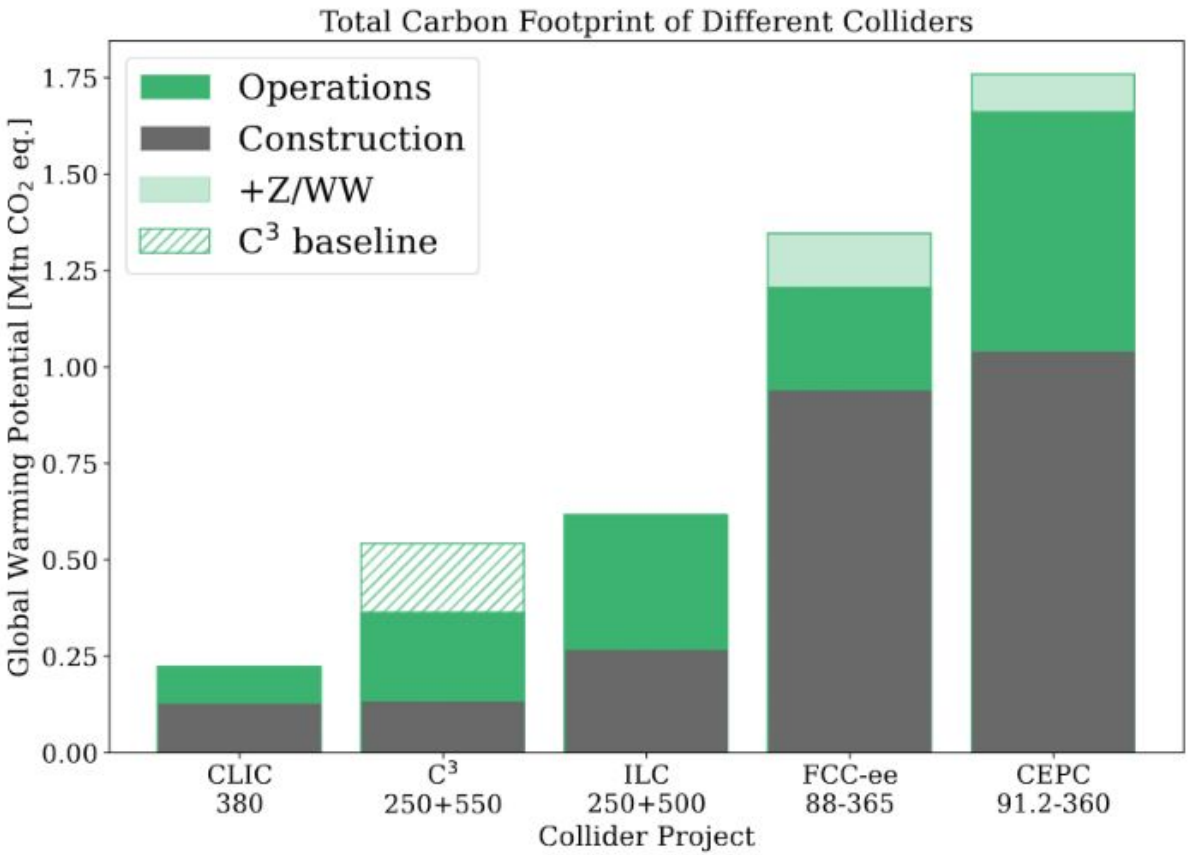
Sustainability

Important aspect for next HEP projects

- Aim to progress in a sustainable way

Life-cycle assessment

- identify leading CO_2 sources



Impact of nozzles

Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadroms ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

The MDI optimised for the centre-of-mass energy of 1.5 TeV is assumed

- Simulation available in MARS15 and FLUKA
- **BIB rates in detector volume approximately constant!**

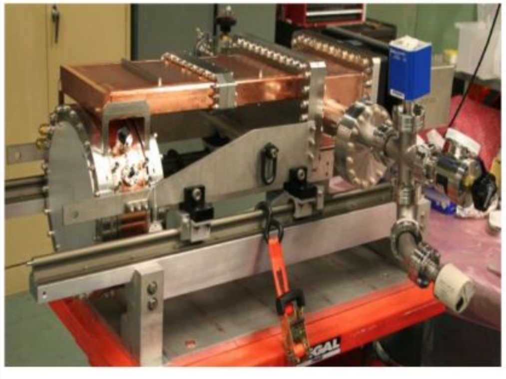
→ higher centre-of-mass energies possible

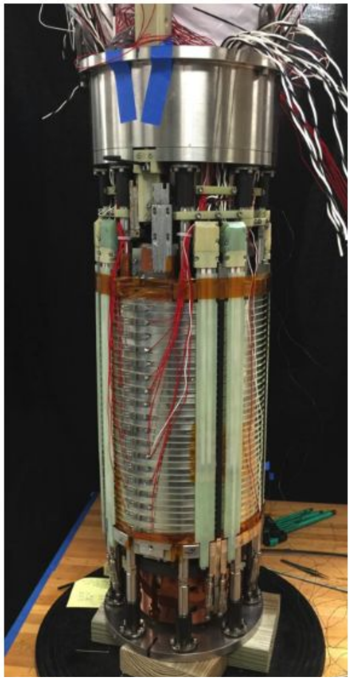
1710.09810
2201.07895

Status of components

MuCool
>50 MV/m, 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps



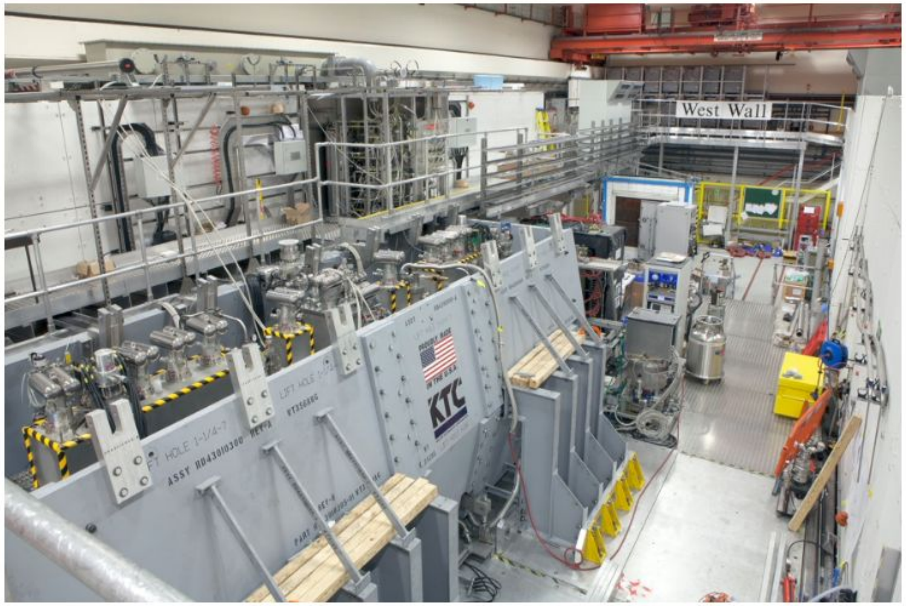


National High Magnetic Field Laboratory
32 T solenoid with HTS

Several developments towards higher fields

Commercial MRI magnets are now available with fields of 28 T

MICE (UK)



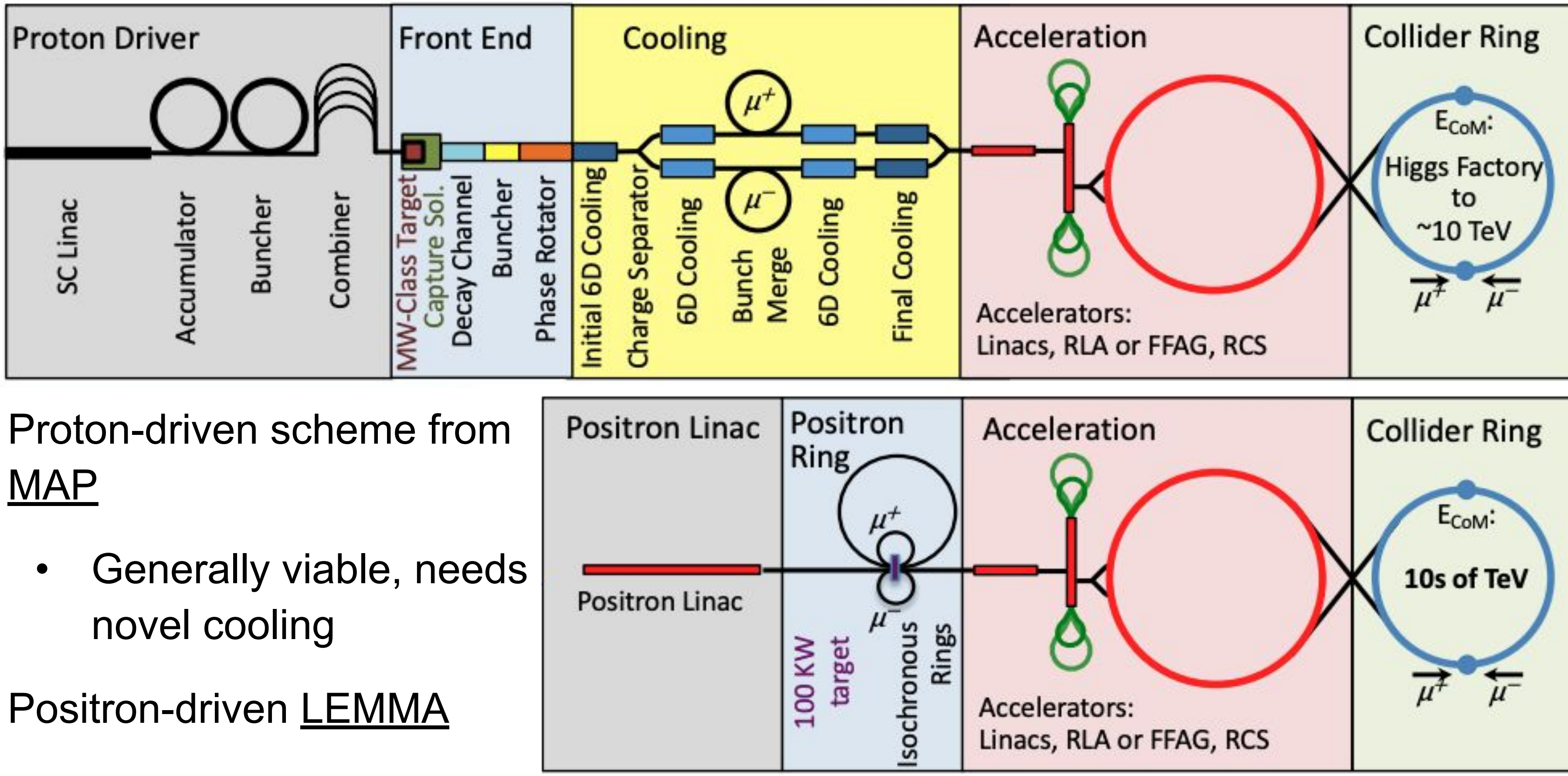
More magnets

Consensus of magnet experts (review panel):

- Anticipated **mature magnet technology in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
  - This corresponds to 3 TeV design
- Still under discussion:
  - Timescale for HTS/hybrid collider ring magnets

Machine designs

Proton or positron-driven sources?



Proton-driven scheme from MAP

- Generally viable, needs novel cooling

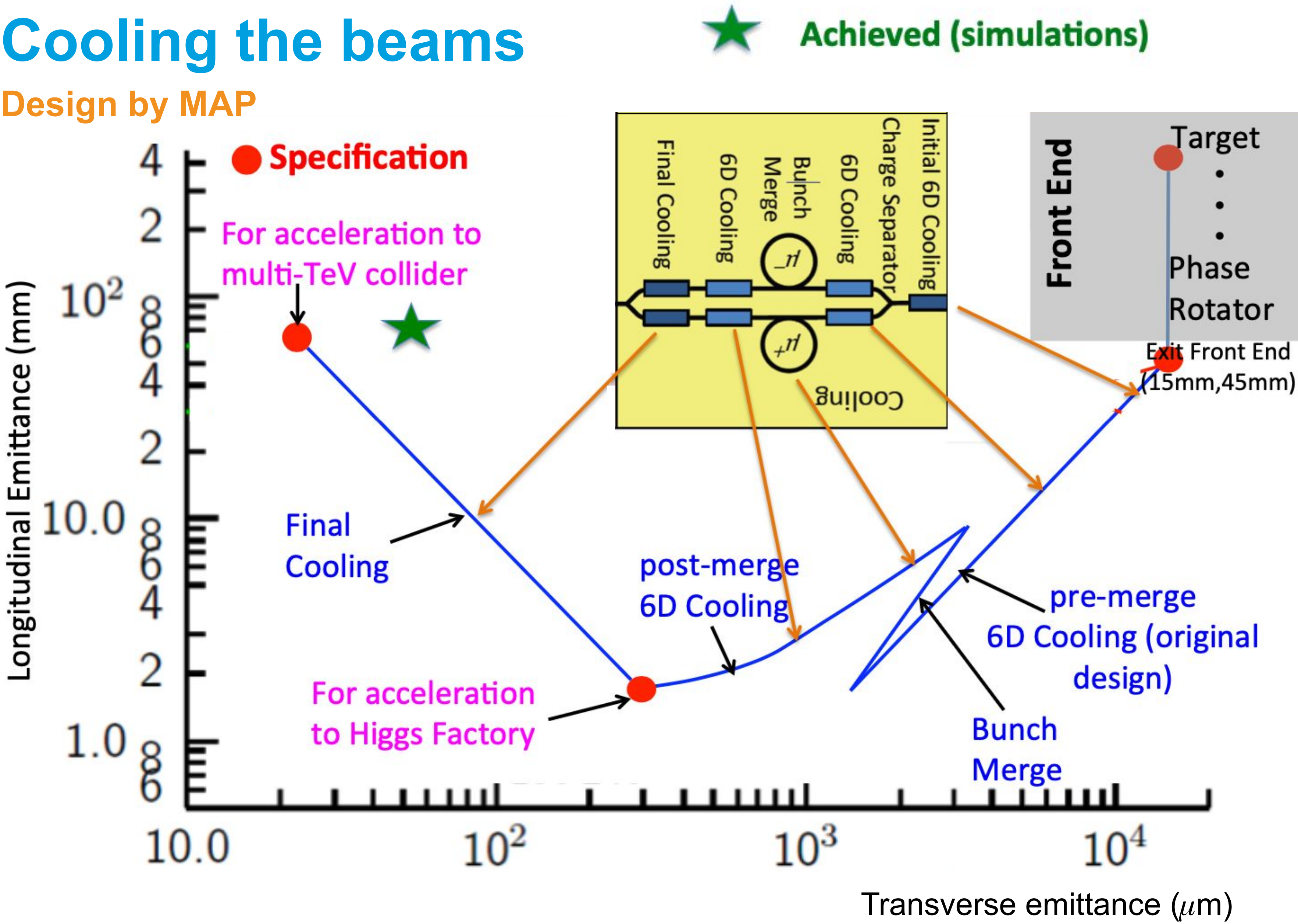
Positron-driven LEMMA

- Requires consolidation for higher muon intensities

Image source

Cooling the beams

Design by MAP

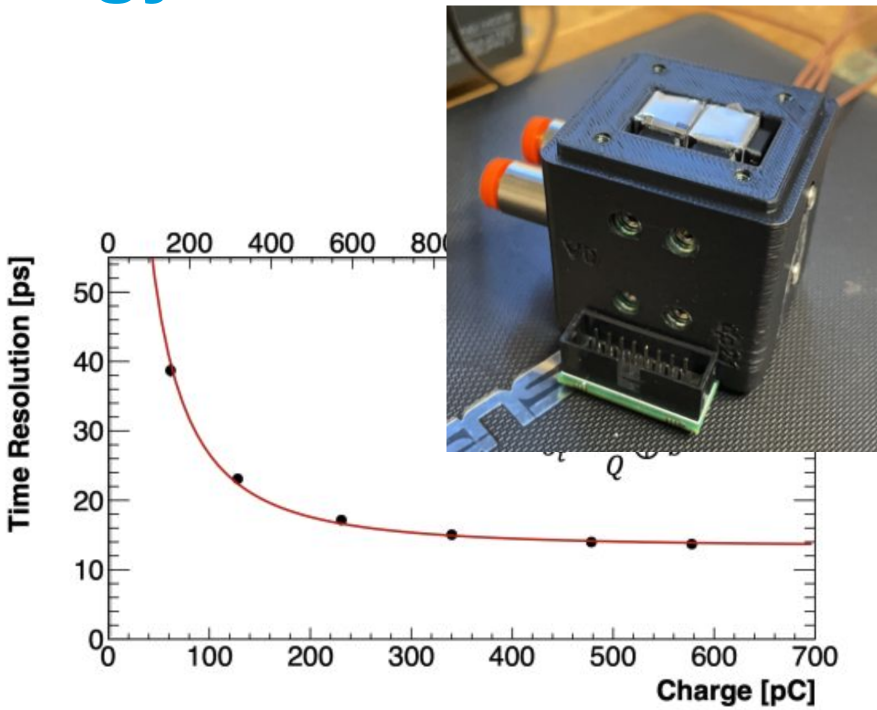


R&D and HL-LHC "technology transfer"

Crilin calorimeter

Semi-homogeneous calorimeter based on Lead Fluoride (PbF_2) crystals

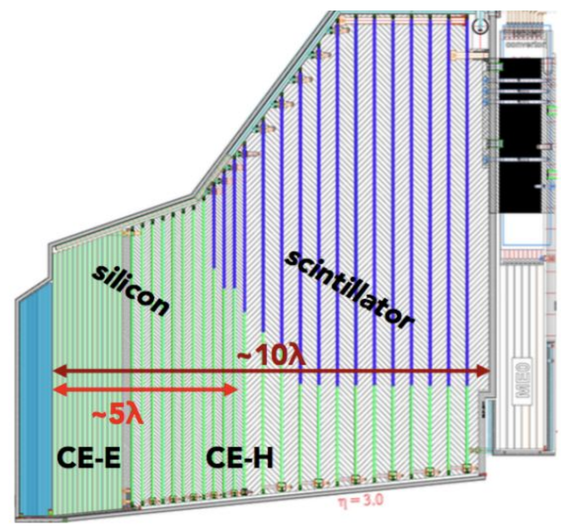
- Segmented longitudinally
- Stackable submodules composed of matrices of crystals



CMS High-granularity Calorimeter

Mix of silicon and scintillator-based high-granularity cells (6.5M channels)

- Large-scale particle flow demonstration
- Achieves O(10) ps time resolution for multi-MIP signals



Readout and DAQ

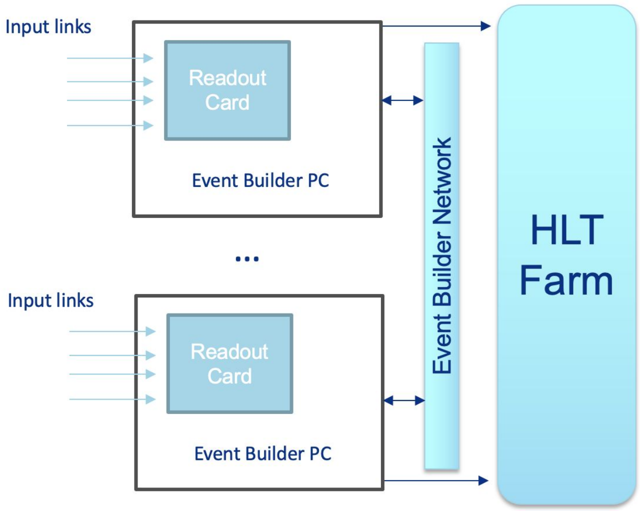
Instantaneous luminosity of **10^{34}-10^{35} cm^{-2}s^{-1}**

Beam crossings **every 10 μs**

Streaming approach: availability of the full event data → better trigger decision, easier maintenance, simplified design of the detector front-end…

	Hit	On-detector filtering	Number of Links (20 Gbps)	Data Rates
Tracker	32-bit	$t-t_0 < 1$ ns	~3,000	30 Tb/s
Calorimeter	20-bit	$t-t_0 < 0.3$ ns E>200 KeV	~3,000	30 Tb/s

Table credit: S. Jindariani

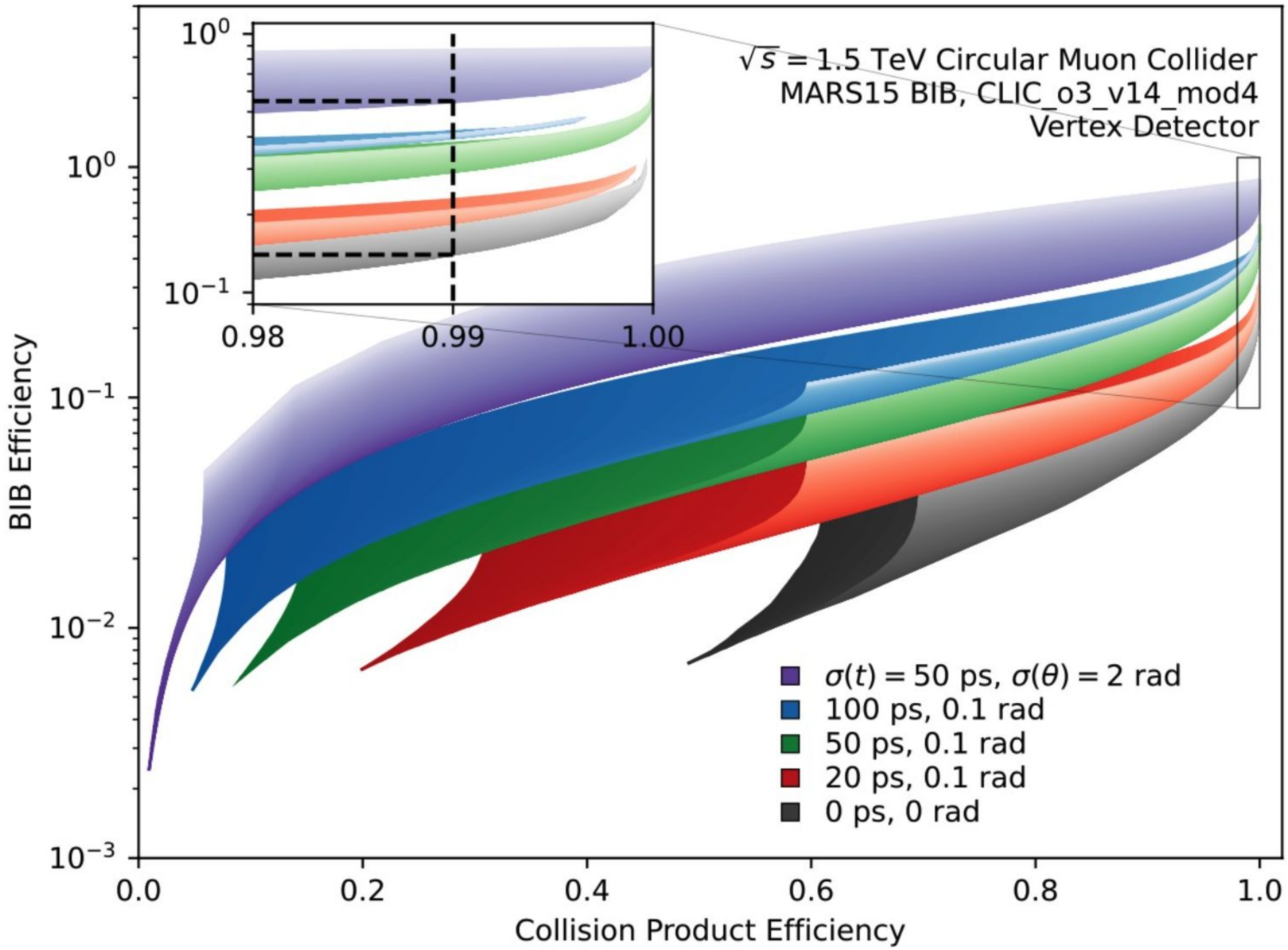


Total data rate similar to HLT at HL-LHC

- **Streaming operation likely feasible**

Beam-induced background rejection

Exploiting timing and pointing in the tracking detectors



Power and space

Estimation of power constraints on vertex detector (assume 25 **μ**m^2 pixels with four barrel layers and eight endcap disks, conventional scaled CMOS electronics and extrapolations of optical-based data transmission).

- 450 W for analog bias
- 100 W for sensor bias
- 1.5 kW for data transmission

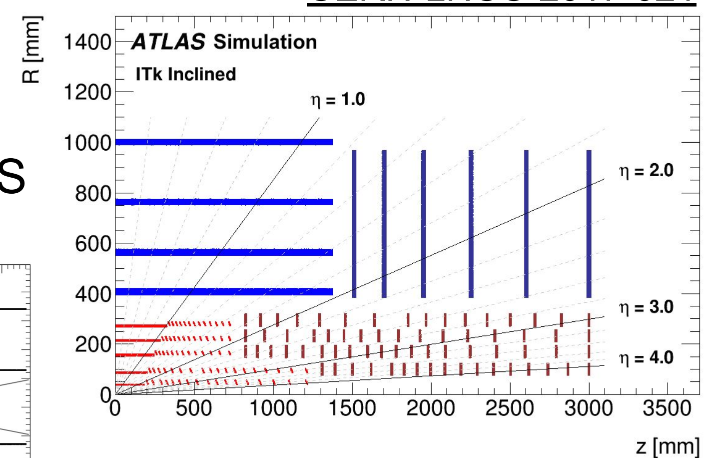
New technologies might change the picture completely.

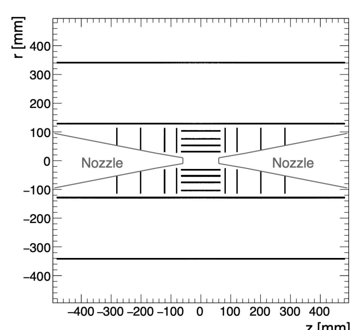
- Extrapolation of current LGAD technology to smaller pixel size would require reduction of O(10^2) to stay in same budget of ATLAS/CMS timing detectors.

Furthermore, the detector is expected to be very compact.

- Need to **minimise space required by services**

CERN-LHCC-2017-021





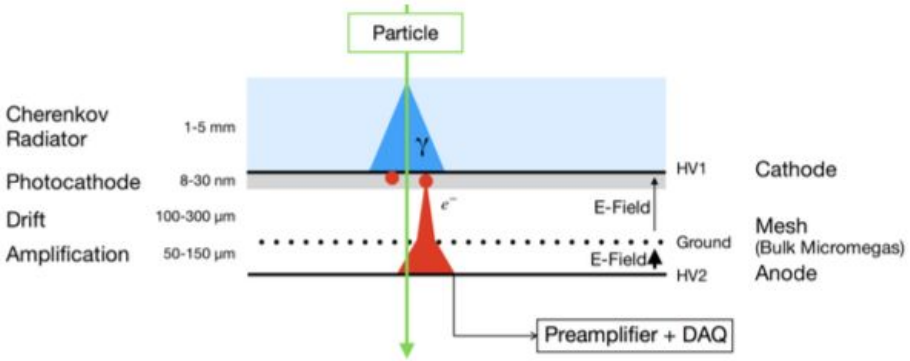
Muon Collider tracker layout

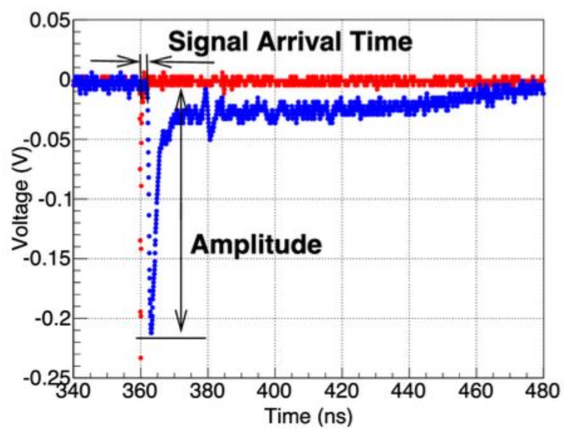
R&D examples: PICOSEC

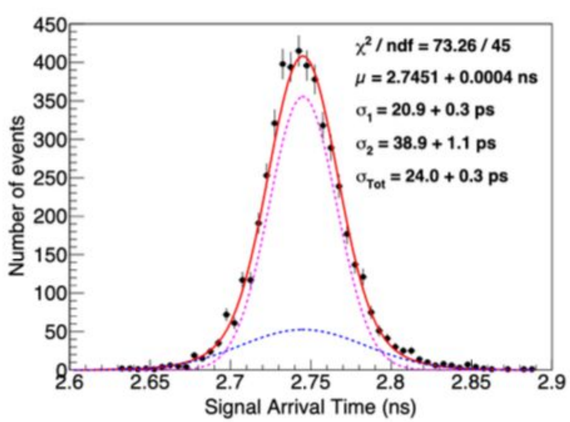
Detect charged particles through **UV Cherenkov photons**.

Absorbed at the photocathode and partially convert into electrons.

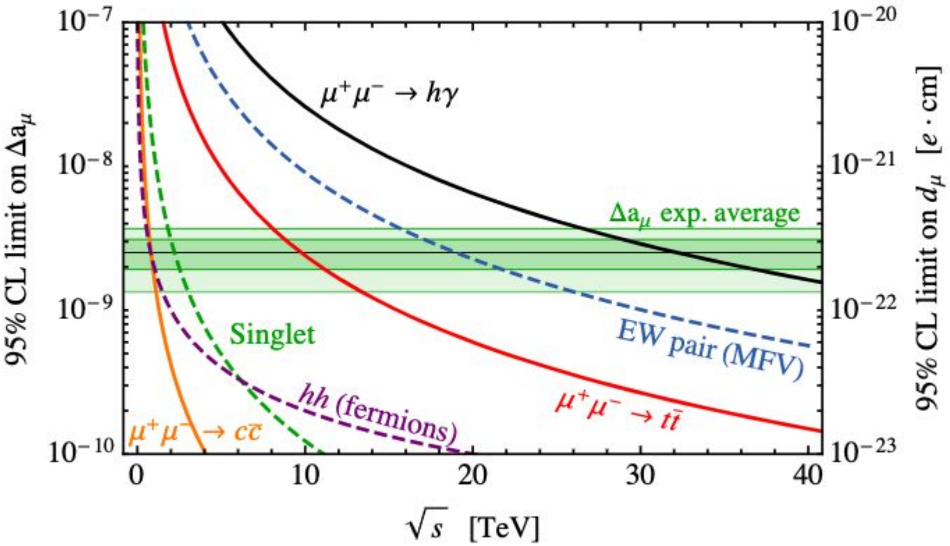
Electrons are then amplified in two high-field drift stages and induce a signal which is measured between the anode and the mesh.







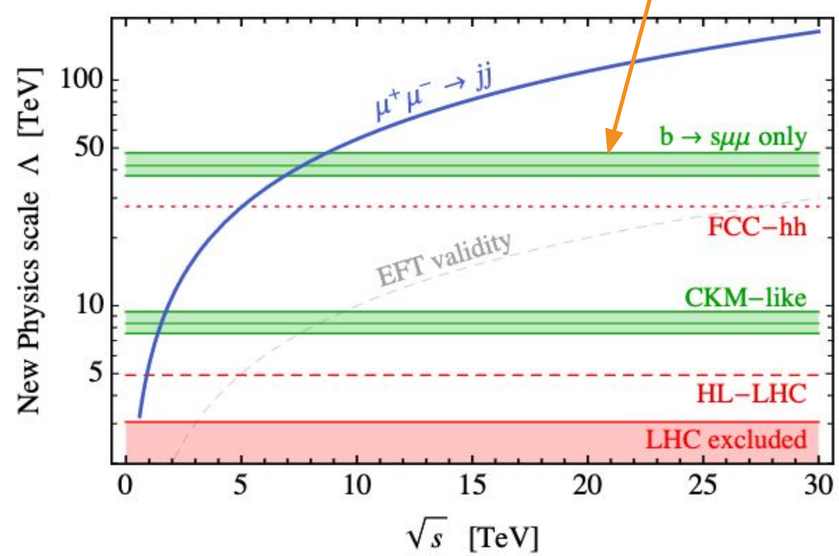
Muon-related anomalies



Model independent test of g-2

- Solid lines correspond to limits on contact interactions
- Dashed lines illustrate the sensitivity to specific classes of models

$R_{K(*)}$ anomaly



Potential to probe flavour anomalies

Assuming EFT validity:

- Better reach than FCC-hh
- Realistic models accessible also at low centre-of-mass energies

The Higgs factory

High-rate measurements

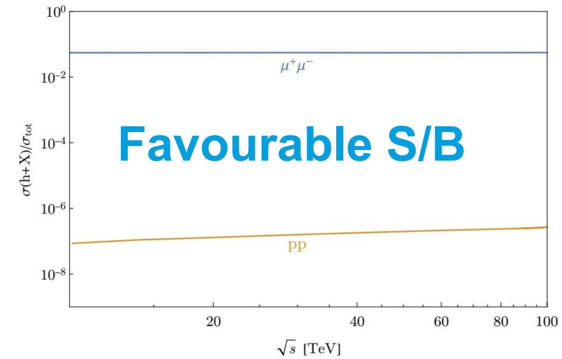
Higgs single and self-couplings, rare decays, top, …

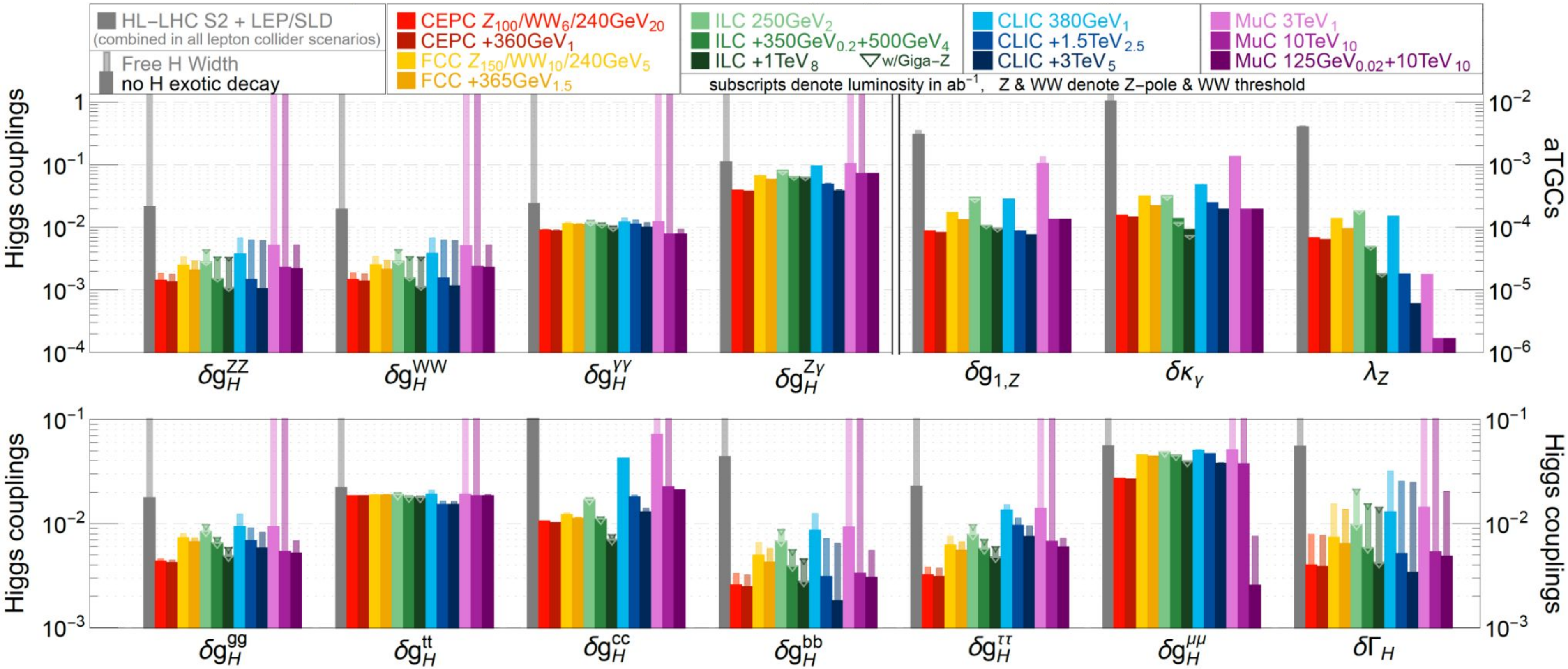
2203.09425

The Higgs itself is key

At 10 TeV, x10 Higgses wrt e^+e^- Higgs factories

- Great potential for exotic decays





Kappas

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

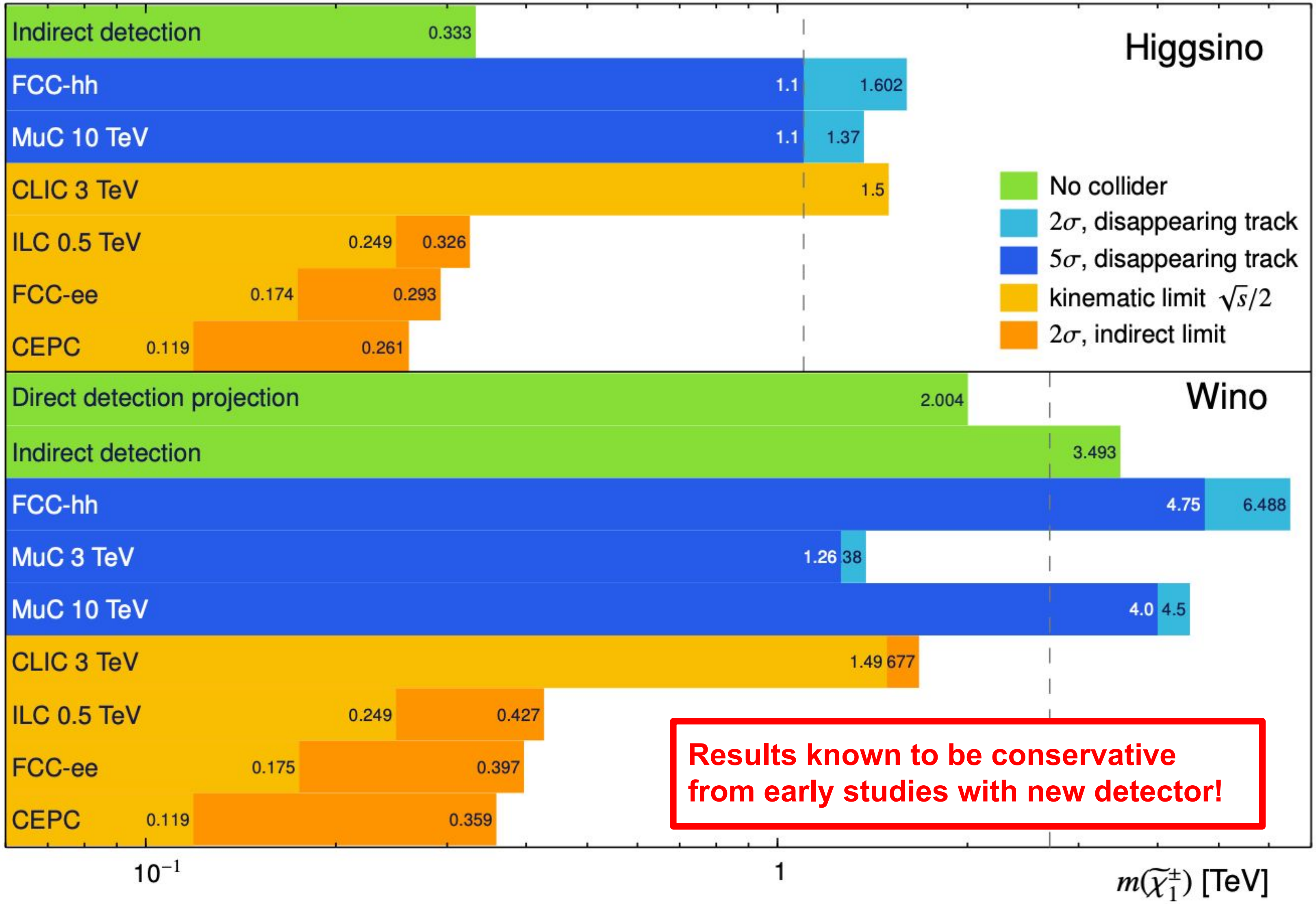
* No input used for the MuC

WIMP dark matter reach

Direct searches

Pair production, Resonances, VBF, Dark Matter, …

2203.07256
2102.11292



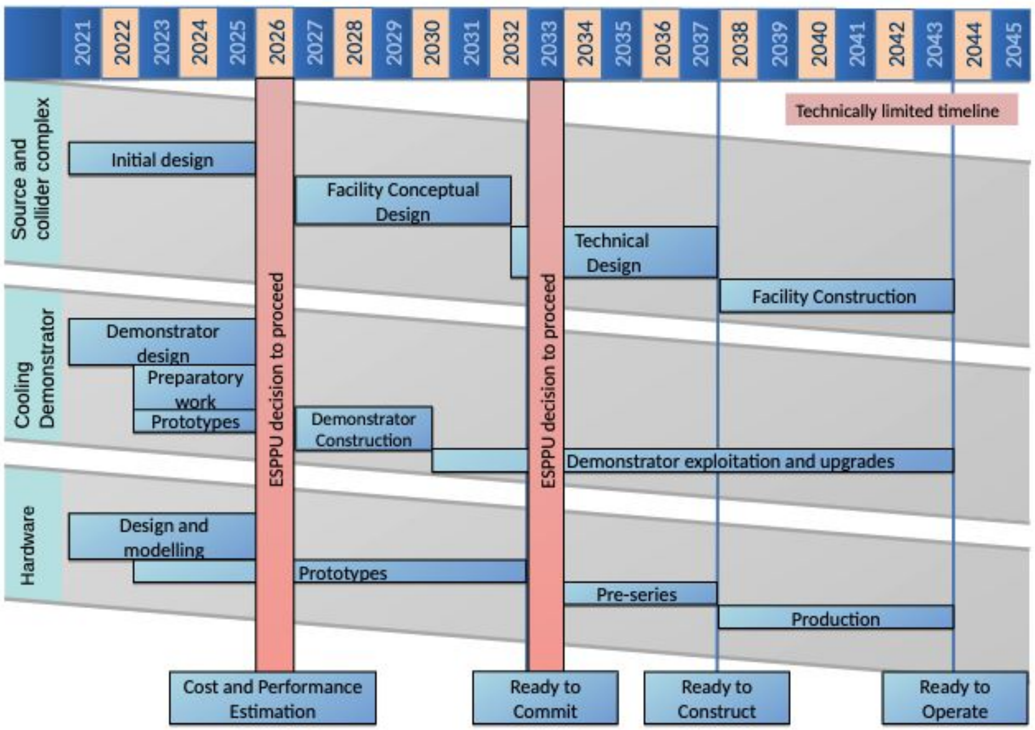
Accelerator roadmap

On request by CERN Council LDG developed R&D Roadmap

- Global community participated
- Estimates of resources

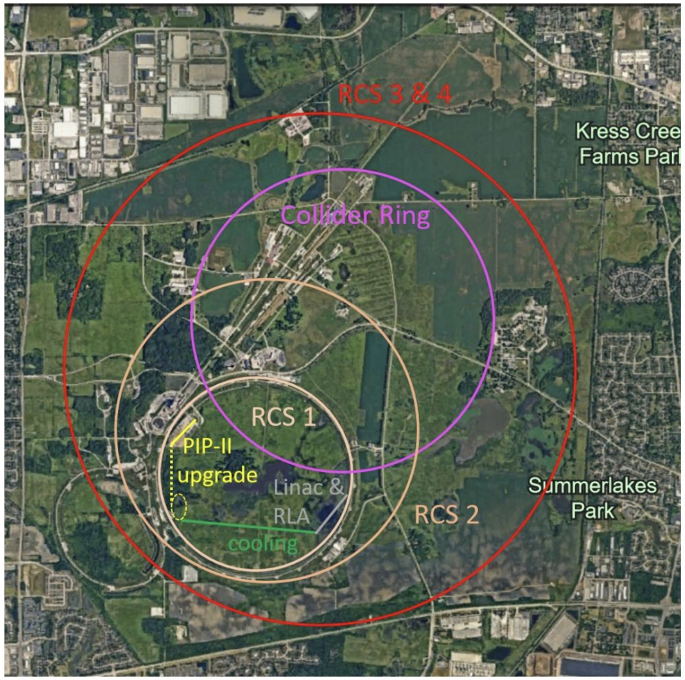
No insurmountable obstacle found for the muon collider

- Important need for R&D
- Implementation plan in the works



Siting

Preliminary Fermilab siting study



Potential site next to CERN identified

- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura