Towards a muon collider

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(DESY)

Experimental Particle and
Astro-particle Physics Seminar

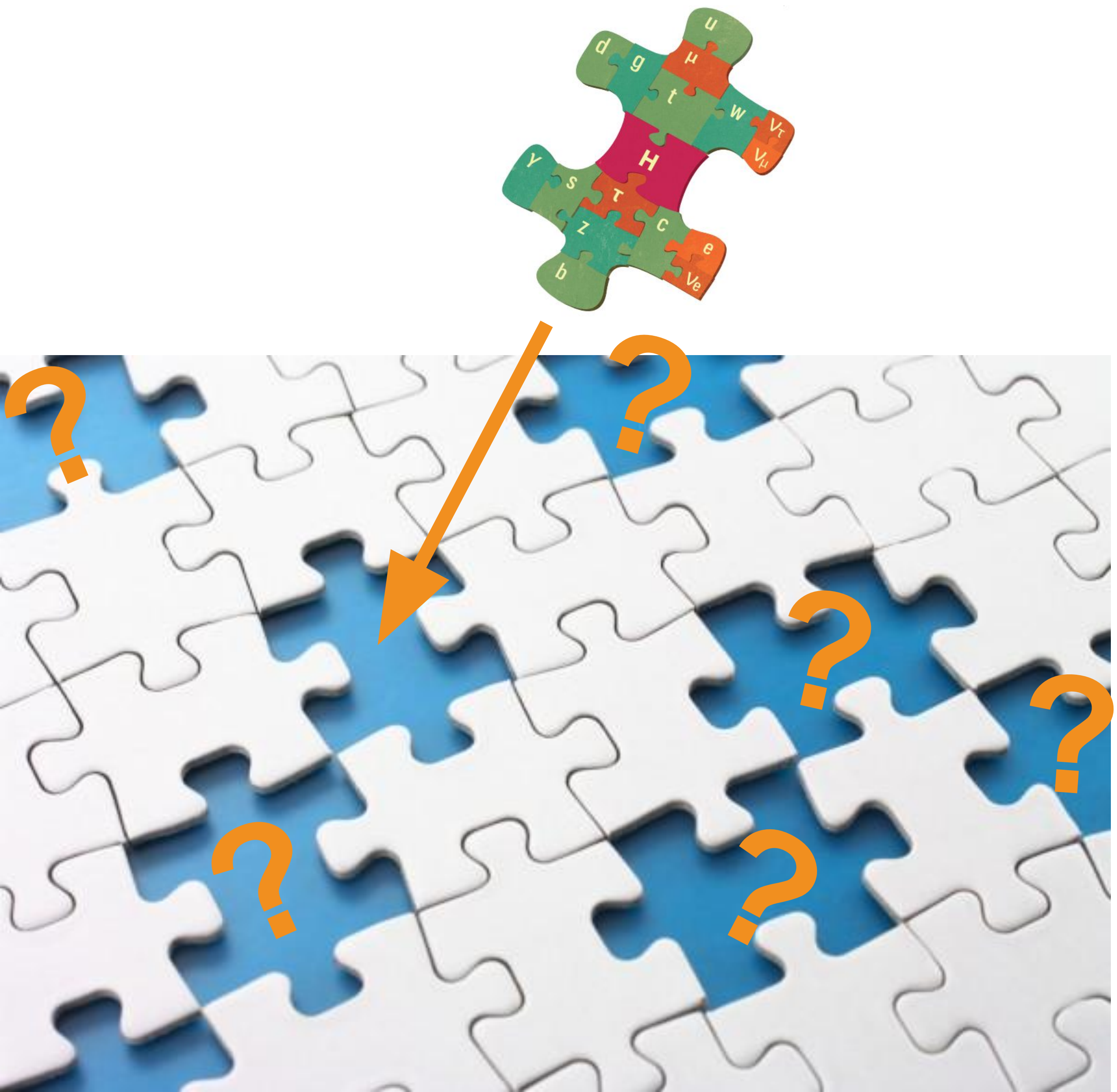
University of Zurich, 10/10/2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Exploring the unknown

The puzzle of nature



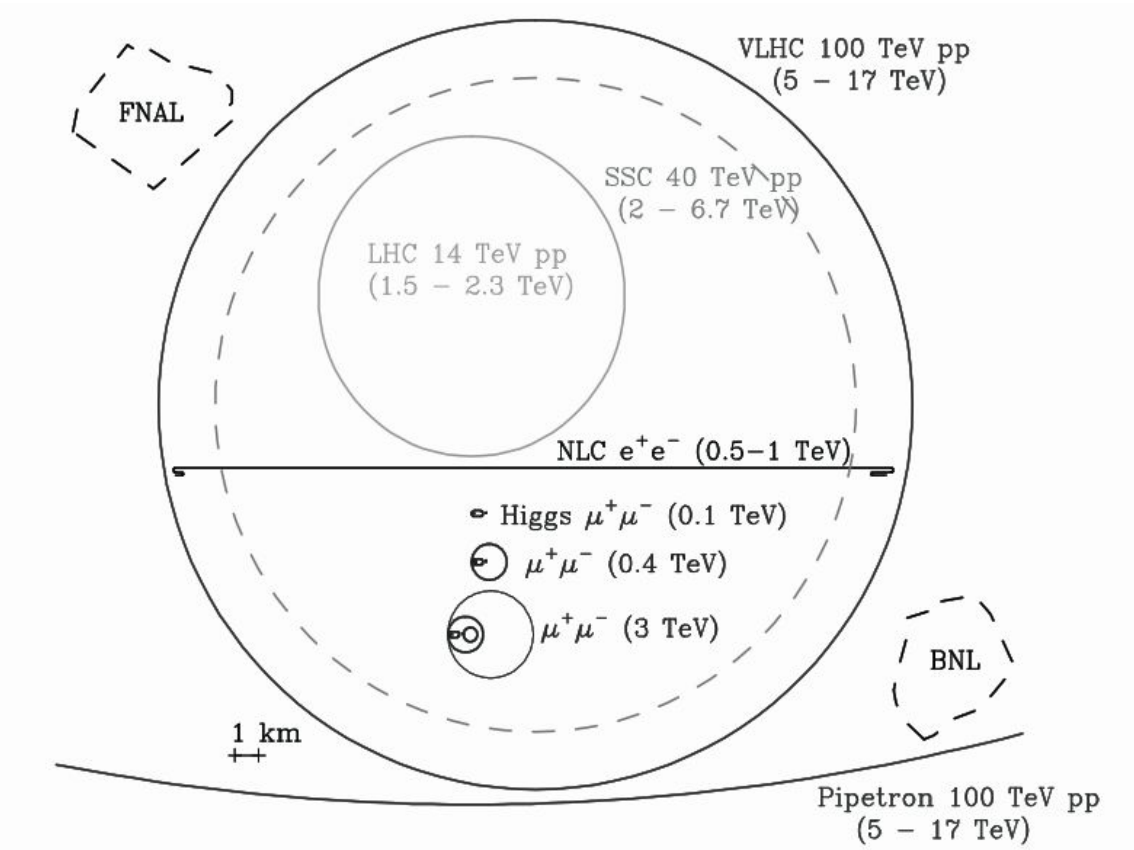
Fundamental open questions:

- Gravity
- Dark matter / energy
- Unification of forces
- Matter-antimatter imbalance
- Is the 125 GeV boson the Standard Model Higgs?
- …

High-energy microscopes

We conventionally pursue these questions by probing 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

Major technical challenges

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

Today
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

The International Muon Collider Collaboration

International
MUON Collider
Collaboration

Link to website

Objective

Establish whether the investment into a full CDR and a demonstrator is scientifically justified

It will provide a baseline concept, well-supported performance expectations, and assess the associated key risks as well as cost and power consumption drivers

Scope

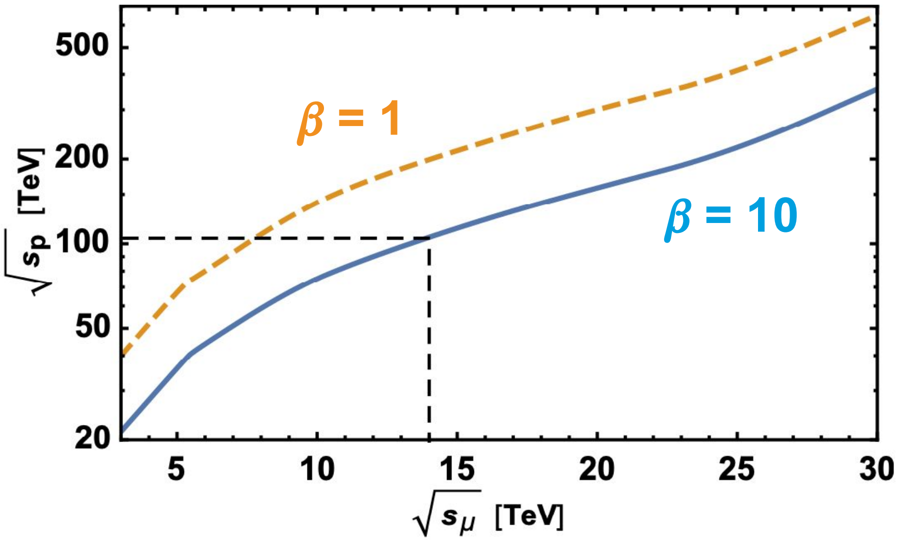
- Focus on two energy ranges:

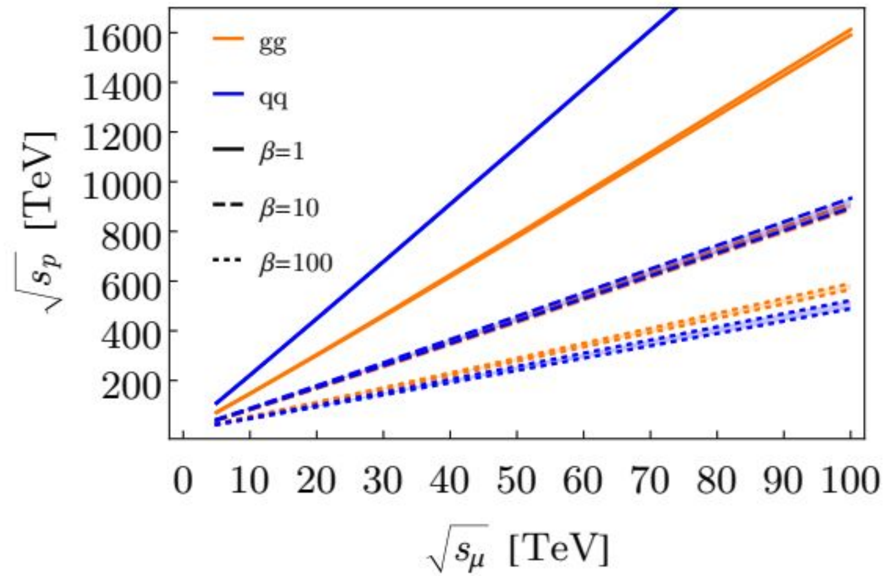
  3 TeV   10+ TeV

- Explore synergy with neutrino/higgs factory
- Define R&D path

Comparison to proton-proton machines

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





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

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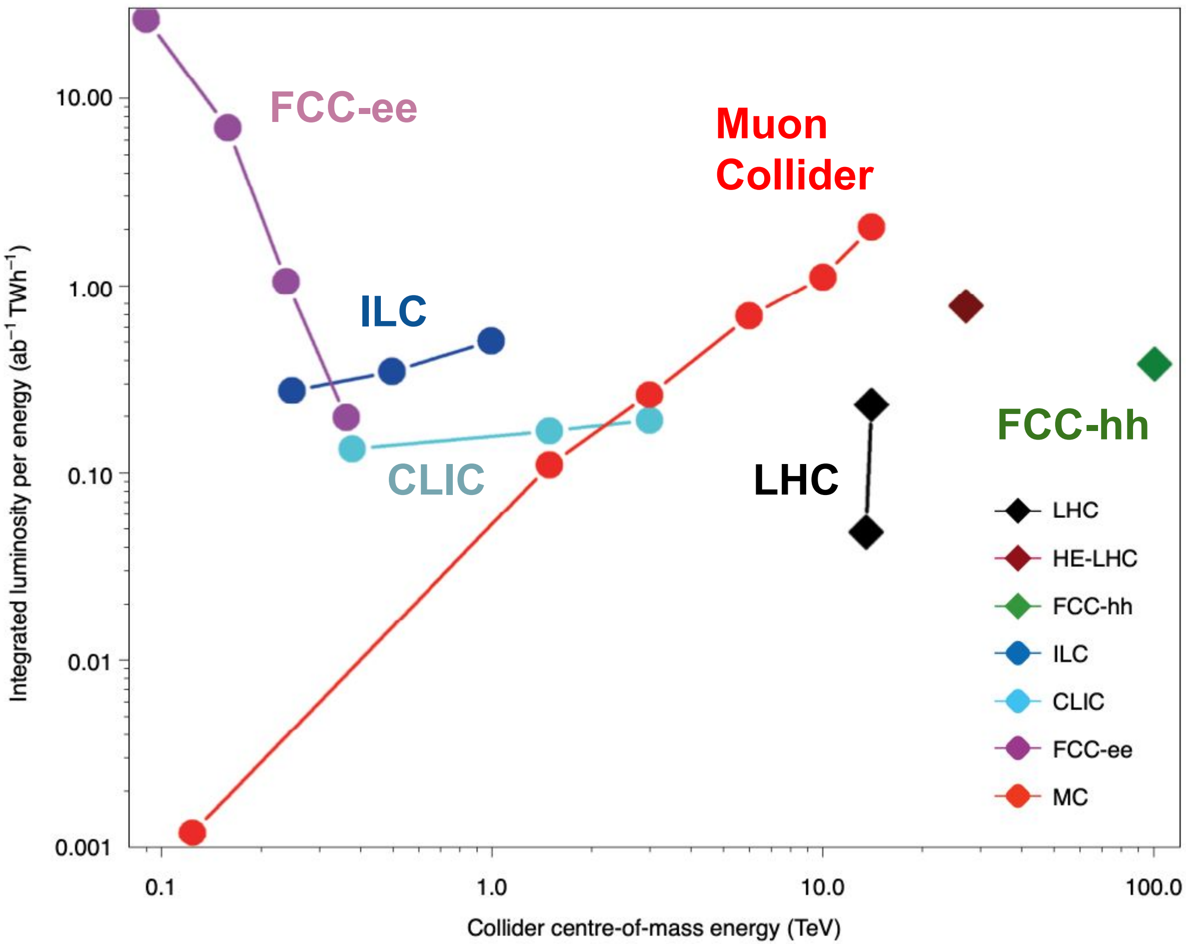
2003.09084

Sustainability



ROUGH RULE OF THUMB

Cost $\propto$ Energy

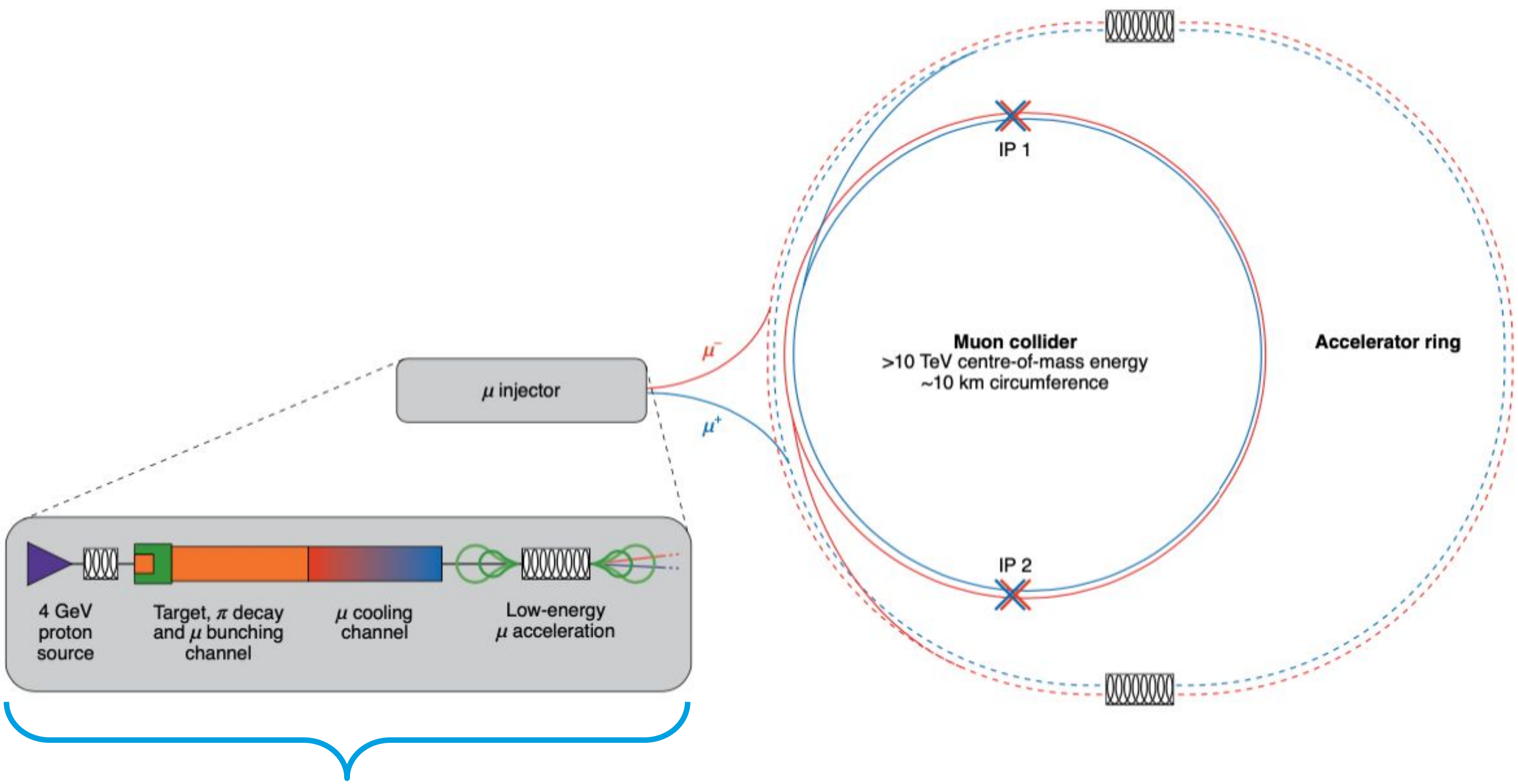
Power $\propto$ Luminosity

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

Cost-effective construction and operation

Possible staging / re-use of existing facilities

Collider overview



Proton-driven scheme
(positron-driven alternative requires additional R&D, not discussed here)

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Muon collider target parameters

Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	$E_{\rm cm}$	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}\rm cm^{-2}s^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\rm cm^{-2}s^{-1}$	1.8	20	40	2
Collider circumference	$C_{\rm coll}$	km	4.5	10	14	—
Muons/bunch	N	10^{12}	2.2	1.8	1.8	0.0037
Repetition rate	f_r	Hz	5	5	5	50
Beam power	$P_{\rm coll}$	MW	5.3	14.4	20	28
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5	0.2
Transverse emittance	ϵ	μm	25	25	25	660/20
Number of bunches	n_b		1	1	1	312
Number of IPs	$n_{\rm IP}$		2	2	2	1
IP relative energy spread	δ_E	%	0.1	0.1	0.1	0.35
IP bunch length	σ_z	mm	5	1.5	1.07	0.044
IP beta-function	β	mm	5	1.5	1.07	
IP beam size	σ	μm	3	0.9	0.63	0.04/0.001

Beamstrahlung

Based on extrapolation of the MAP parameters

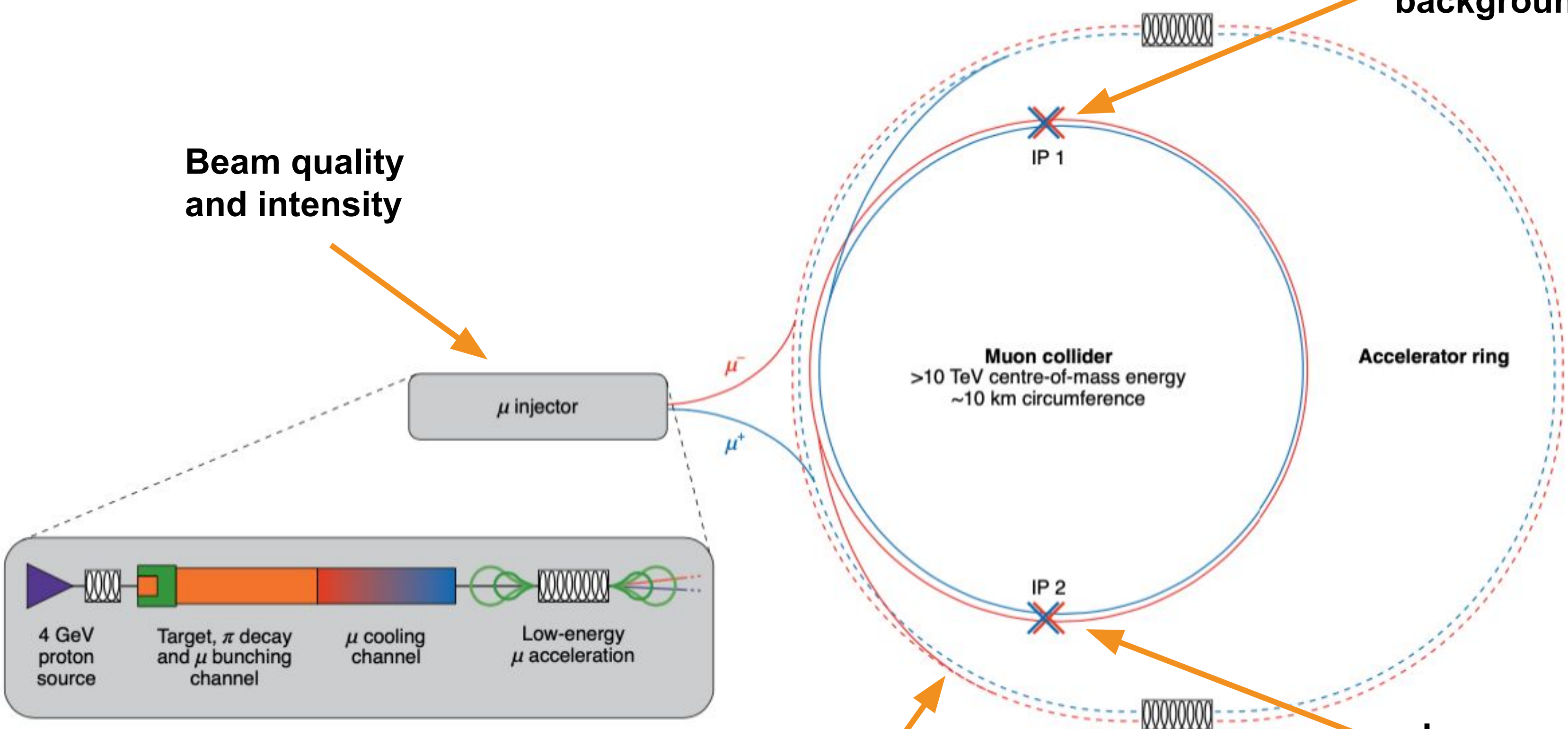
- Plan to operate 5 years at each centre-of-mass energy (FCC-hh to operate for 25 years)

Key challenges

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

Beam induced backgrounds

Beam quality and intensity

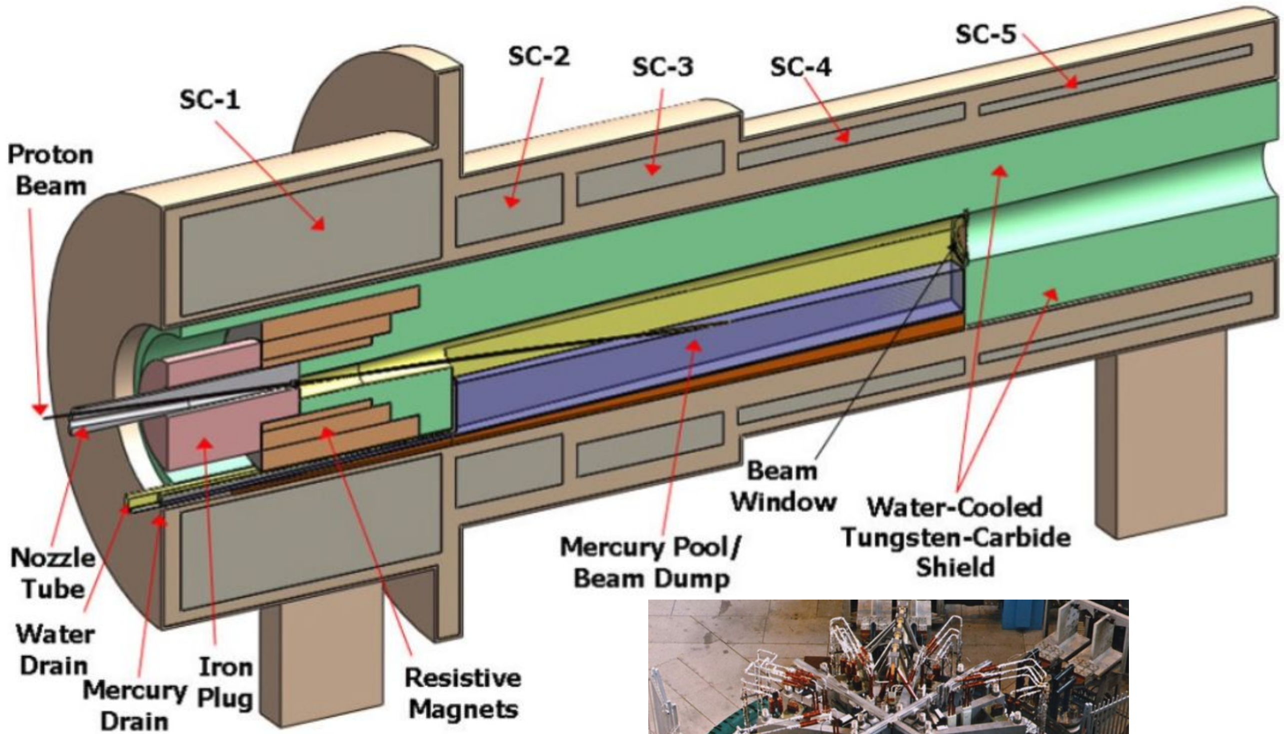


Large neutrino flux

Cost and power

Proton target

High-field required to efficiency collect pions and muons

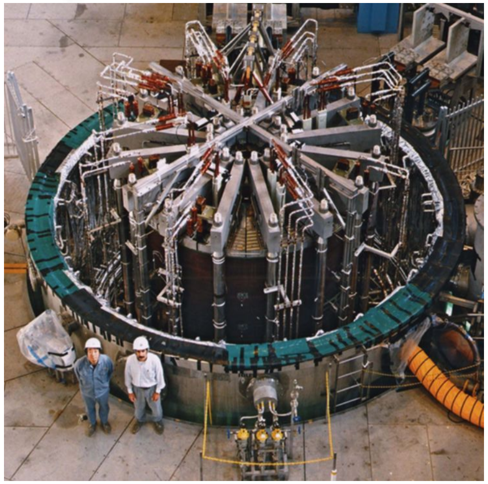


2-4 MW proton beam

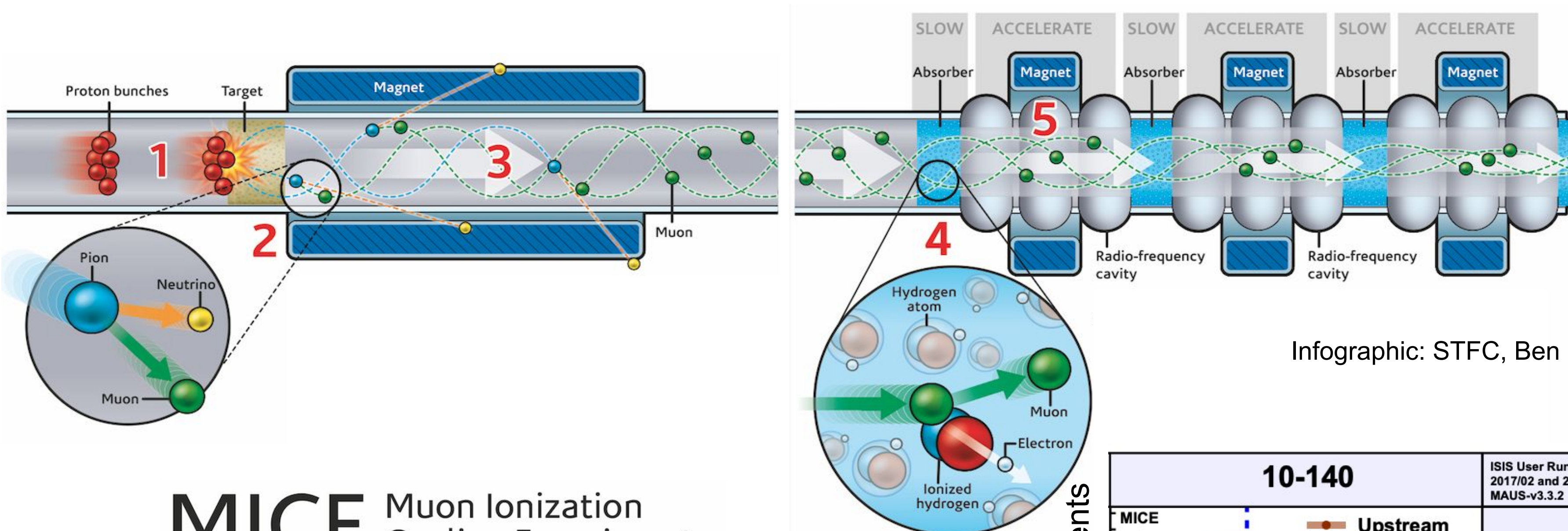
- Simulated graphite target ok
- Operation at 2000°C

Large aperture O(1m) to allow shielding

- Synergy with ITER 13 T in 1.7 m (LTS)



Cooling the beams

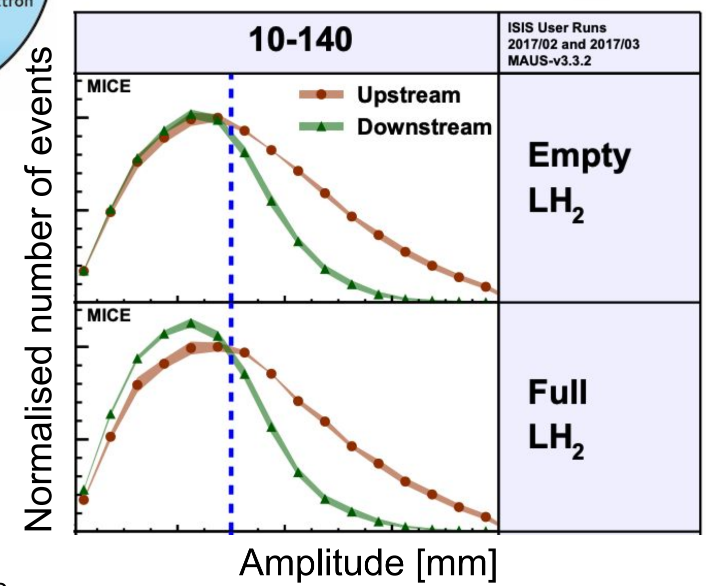


Infographic: STFC, Ben Gilliland

MICE Muon Ionization Cooling Experiment

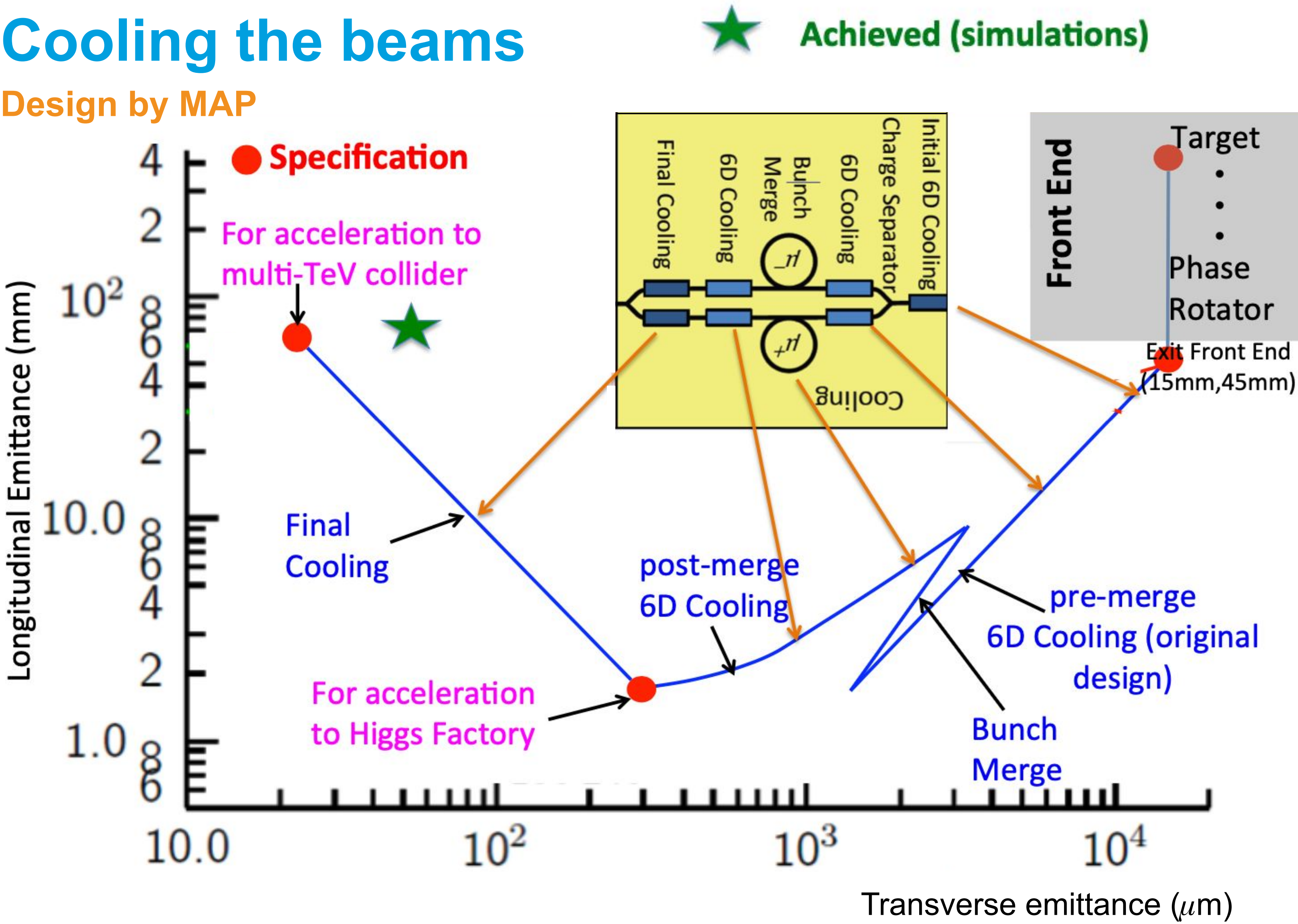
Need 10^6 emittance reduction!

- Demonstrator with RF and more than one stage required



Cooling the beams

Design by MAP



Status of components

Need cavities with **high accelerating gradient** and a **strong magnetic field**

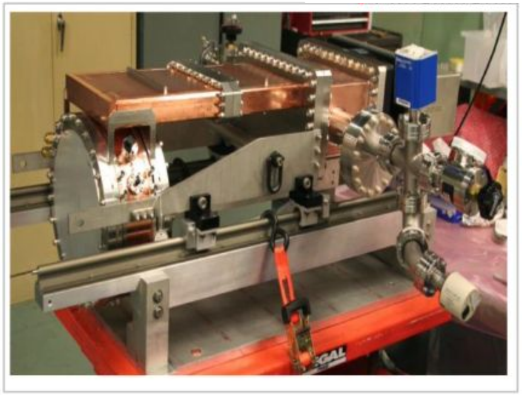
Very strong solenoids required for final cooling

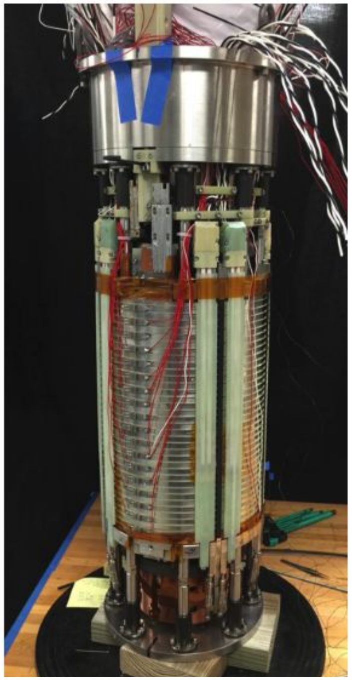
- Luminosity is proportional to the B field

Promising prototypes, need more R&D

MuCool
>50 MV/m, 5 T field

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



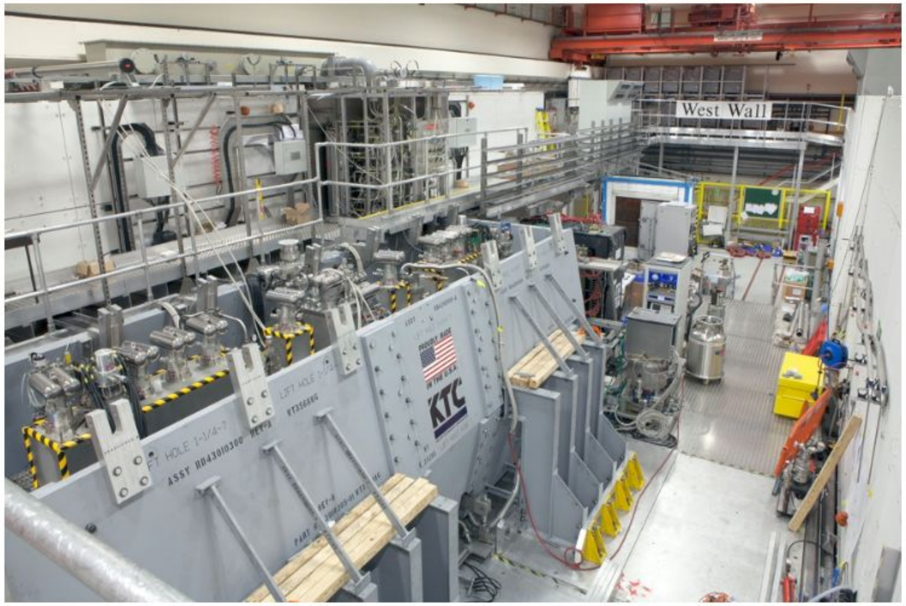


National High Magnetic Field Laboratory
32 T solenoid with HTS

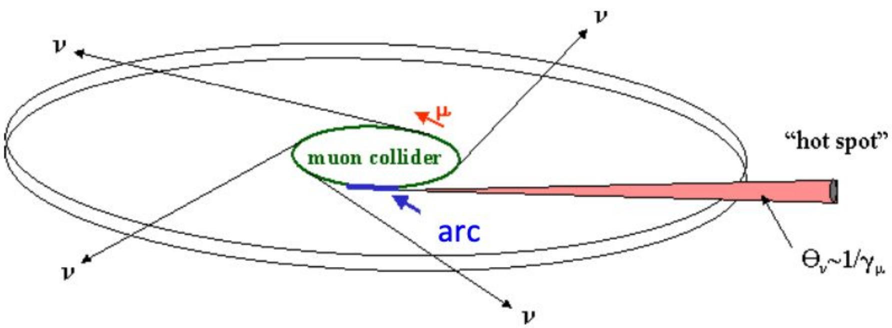
Several developments towards higher fields

Commercial MRI magnets are now available with fields of 28 T

MICE (UK)



Neutrino flux



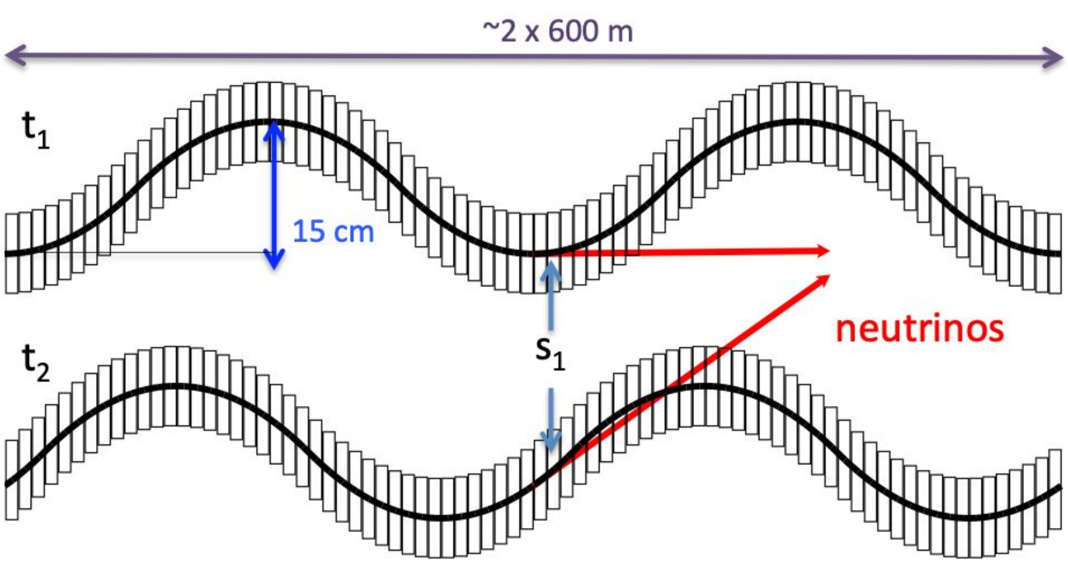
Legal limit: 1 mSv/year
MAP goal: < 0.1 mSv/year

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

2201.07895
Nature Phys. 8 (2012) 243-247

Accelerator ring

Ramp magnets to follow E_{beam}

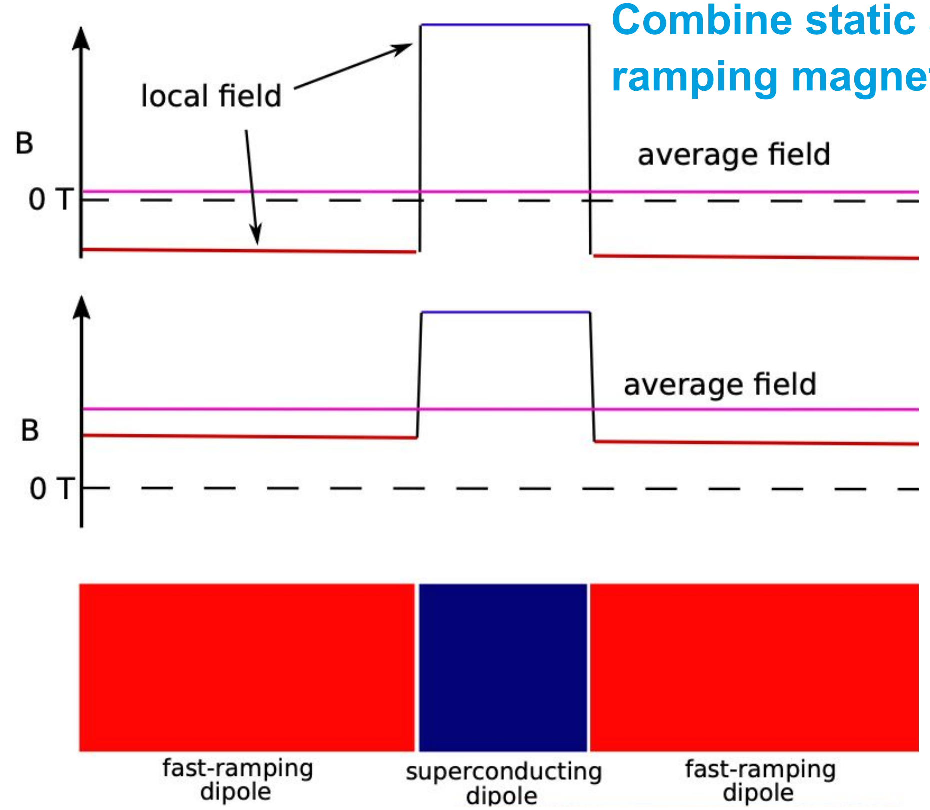
- **Fast-ramping synchrotron magnets** (−2T to 2T in 2 ms)

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

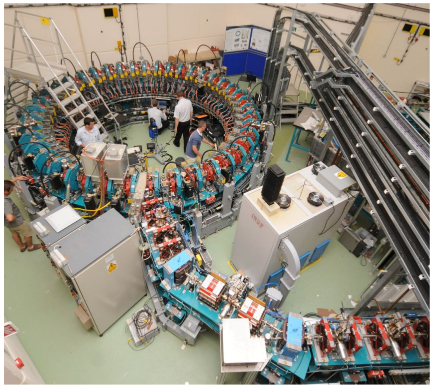
Combine static and ramping magnets



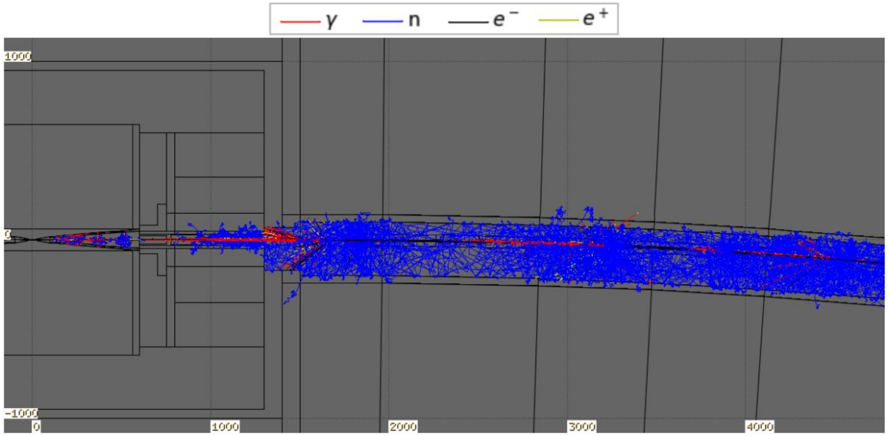
Fixed-Field alternating gradient Accelerator (alternative)

- Complex high-field magnets
- Challenging beam dynamics

EMMA proof of FFA principle

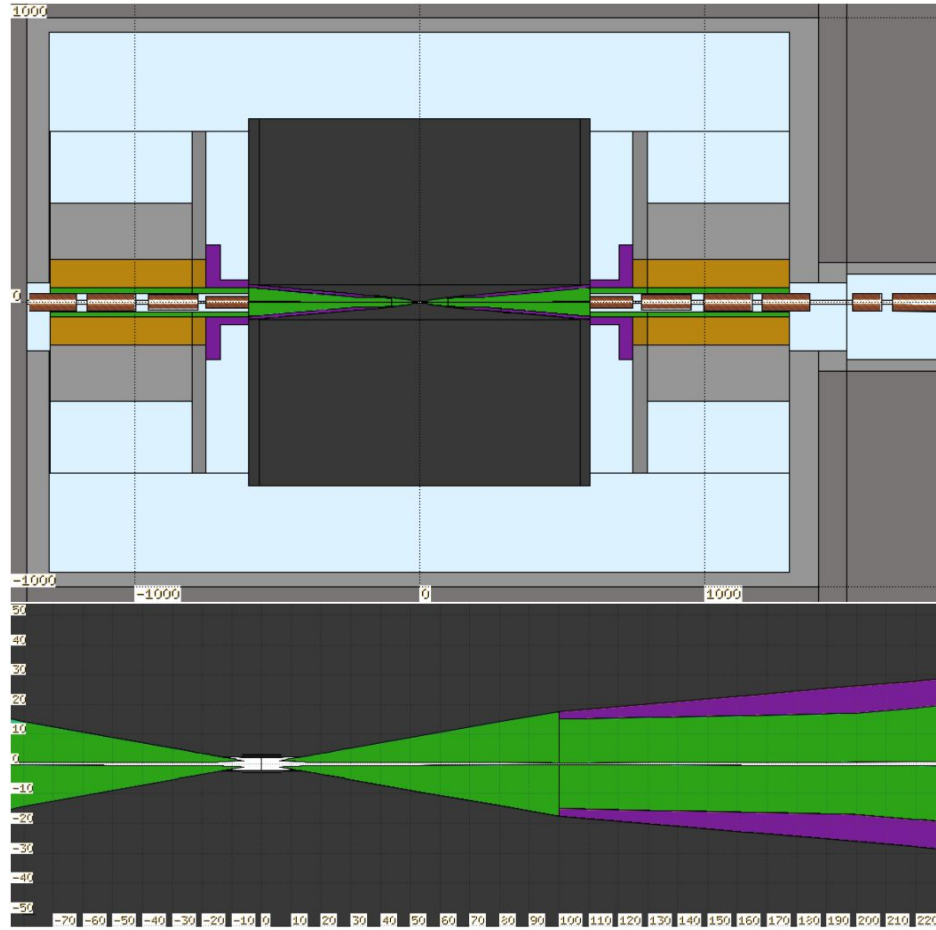


The beam-induced backgrounds (BIB)



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

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



Unique challenge of Muon Colliders

Machine-Detector interface

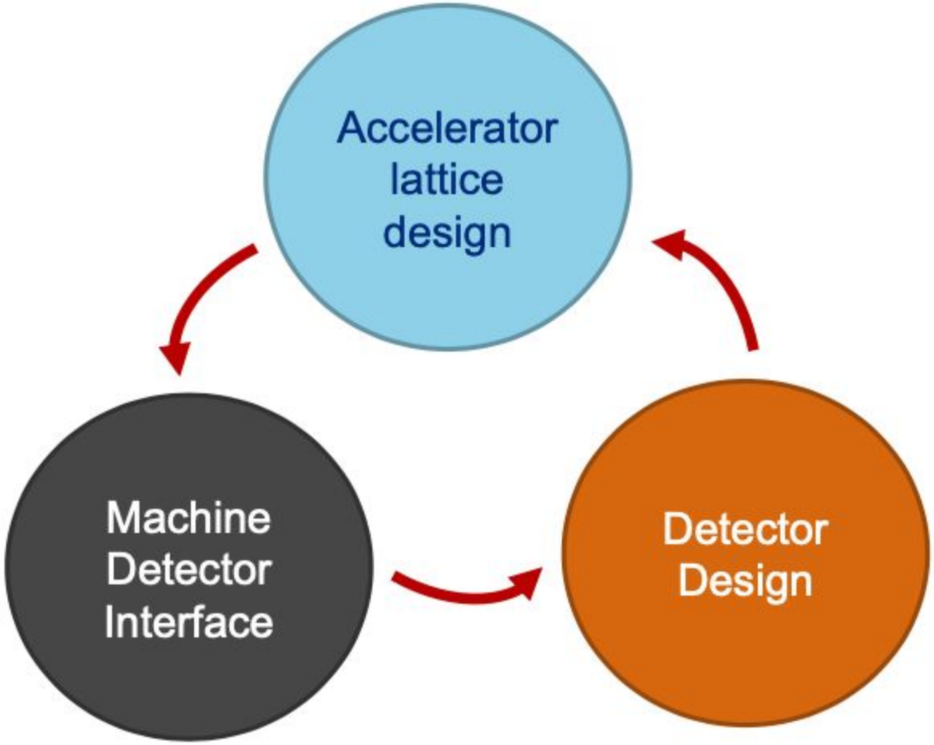


Diagram credit: S. Jindariani

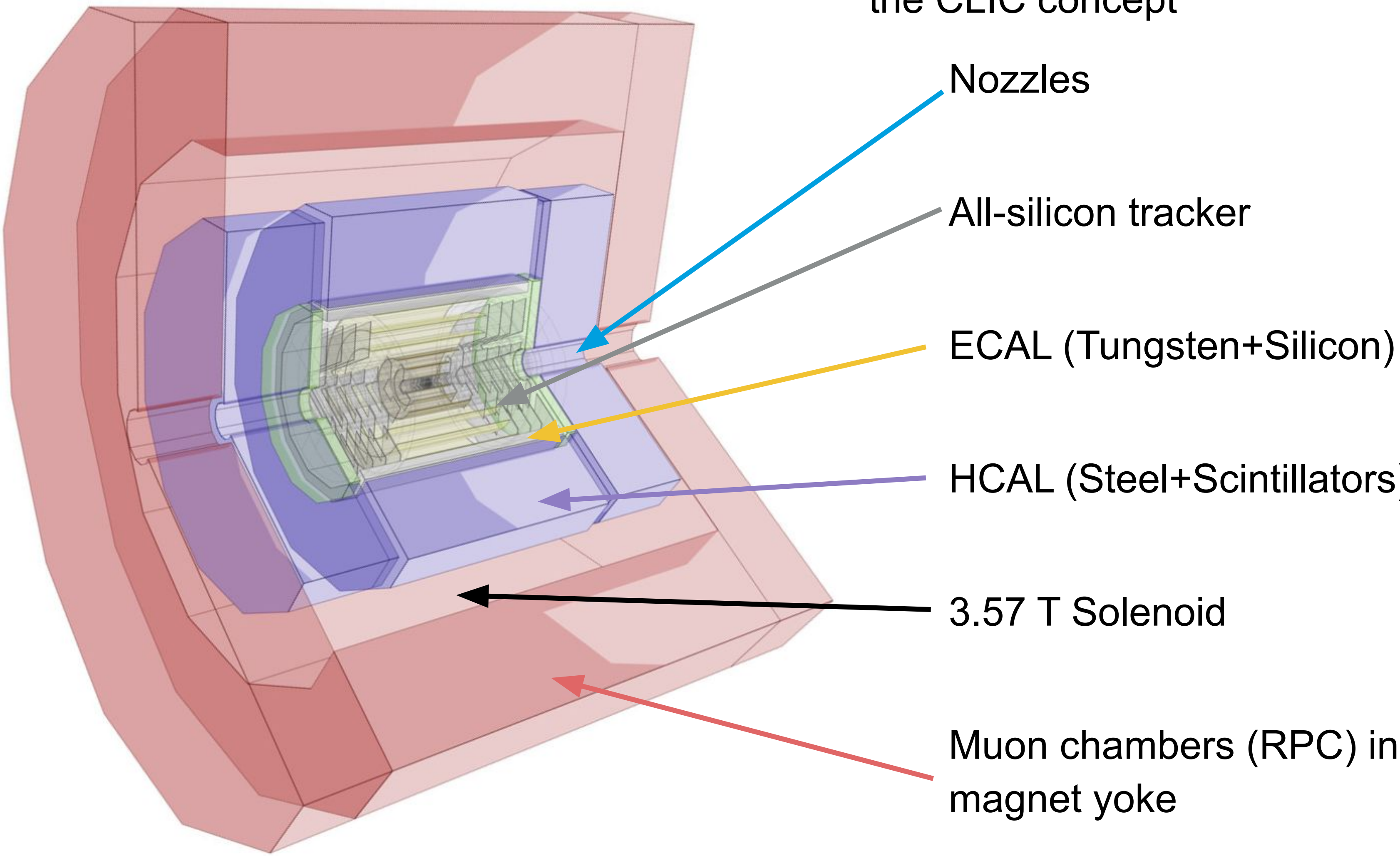
Muon Collider detector design has to be carried out in close collaboration with accelerator and MDI designers!

STATUS

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

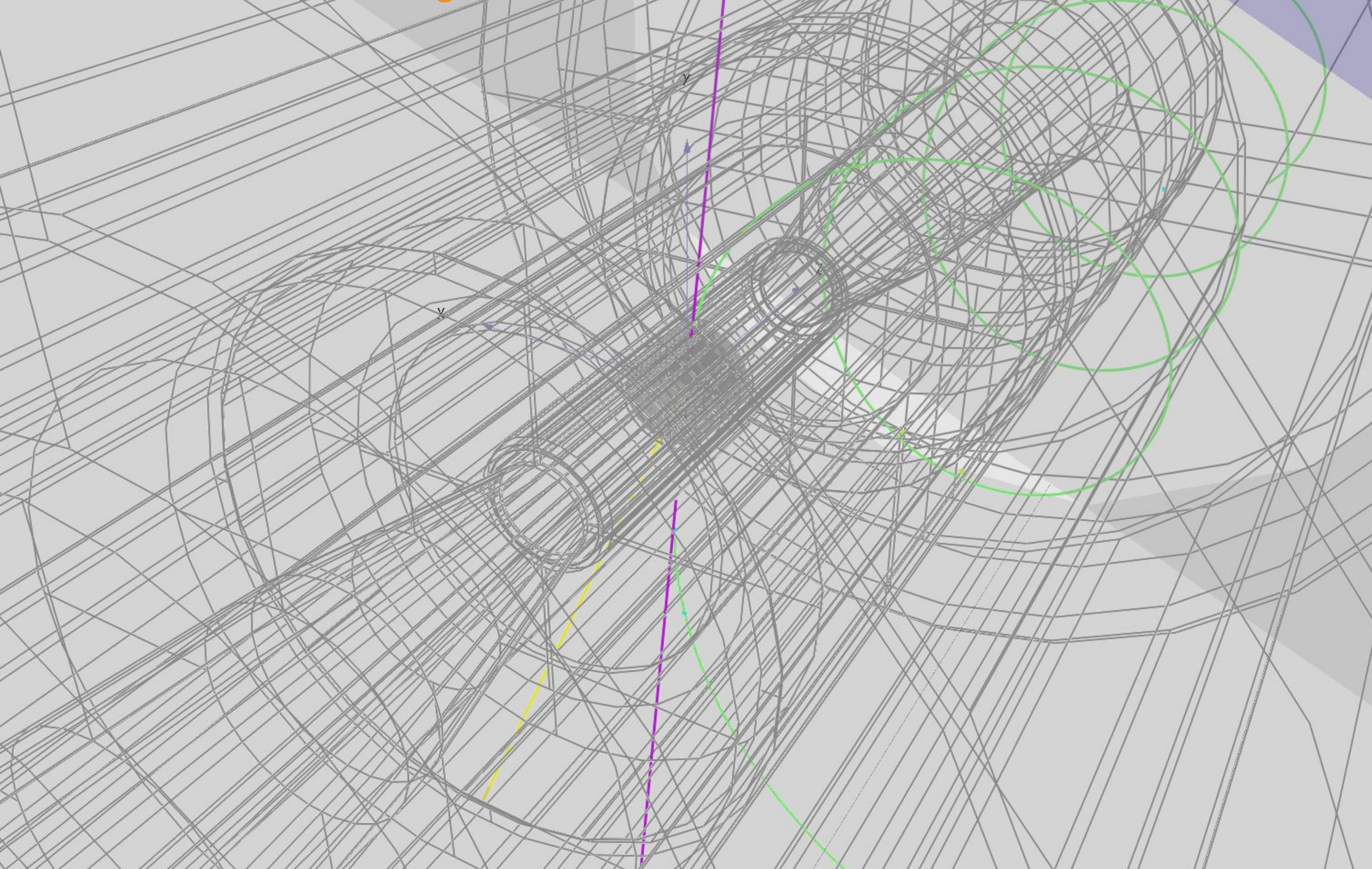
Current Detector layout

The detector model is based on the CLIC concept



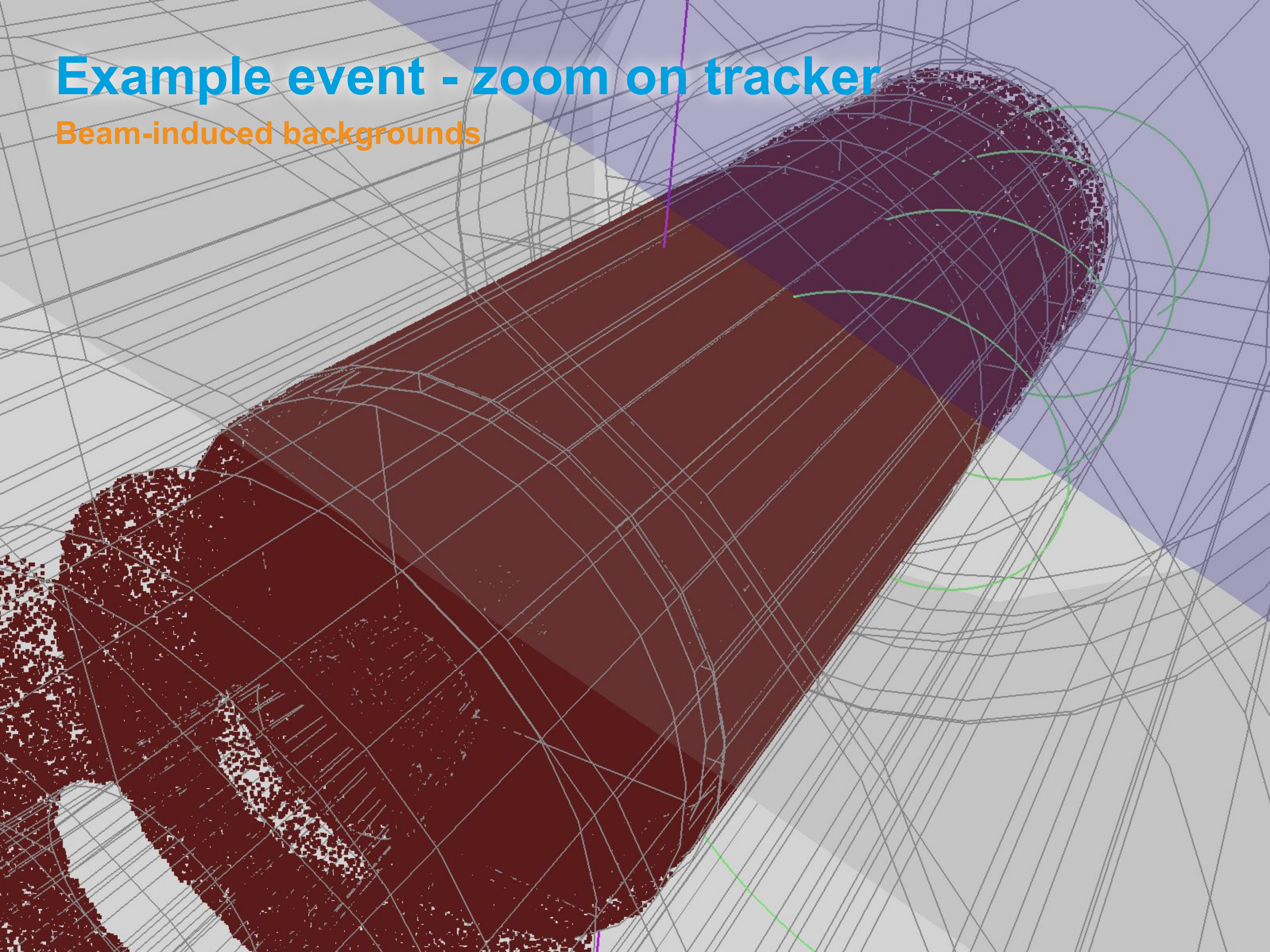
Example event - zoom on tracker

No beam-induced backgrounds

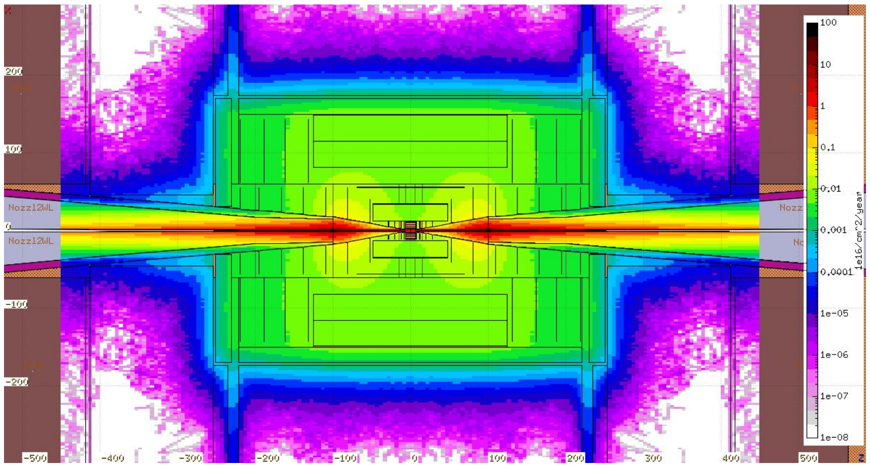


Example event - zoom on tracker

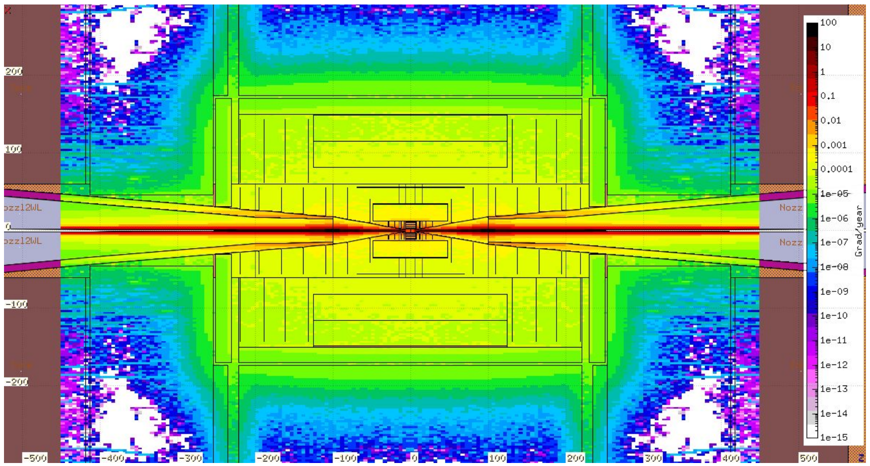
Beam-induced backgrounds



Detection Environment



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	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

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

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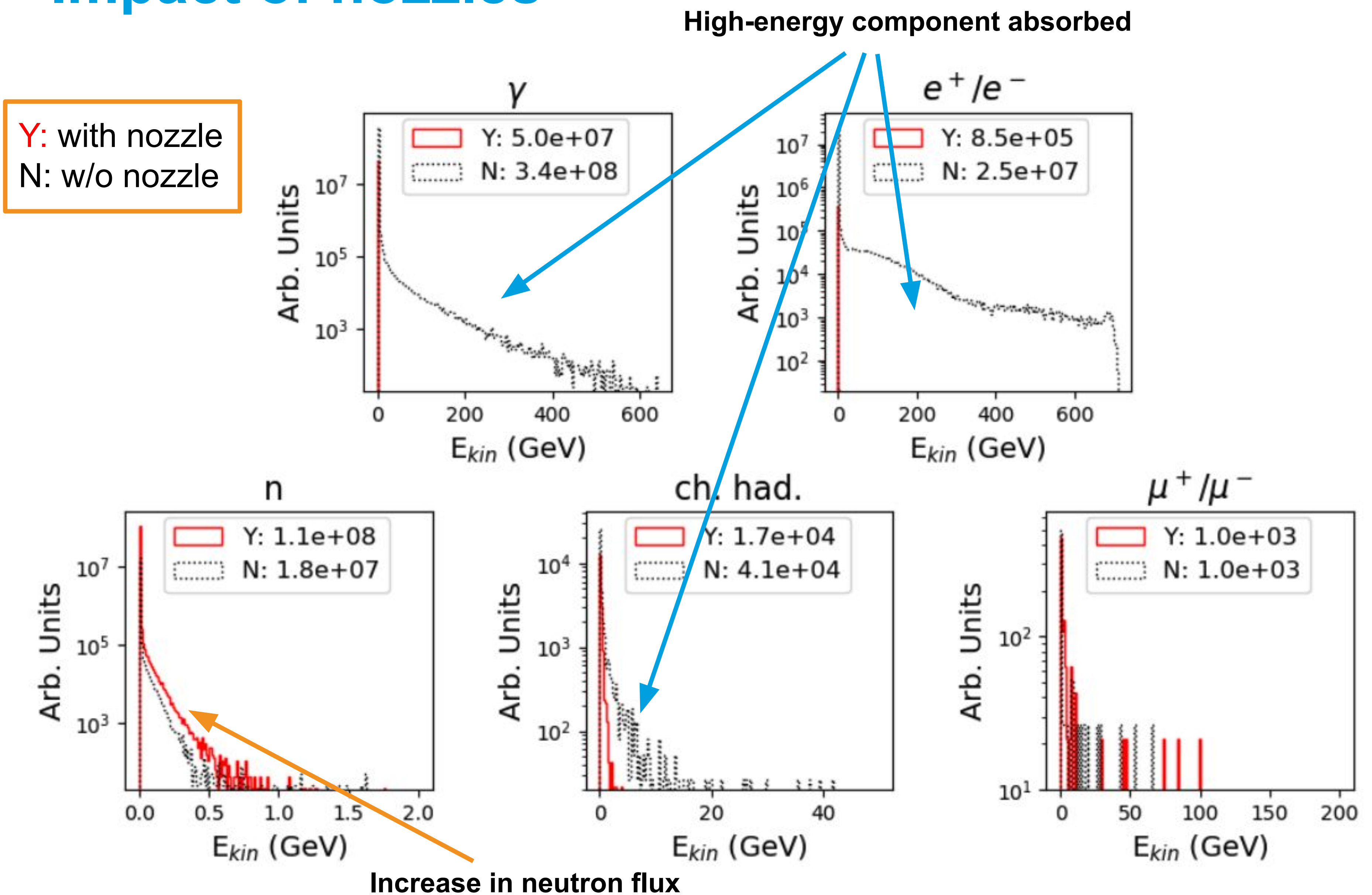
Impact of nozzles



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Impact of nozzles

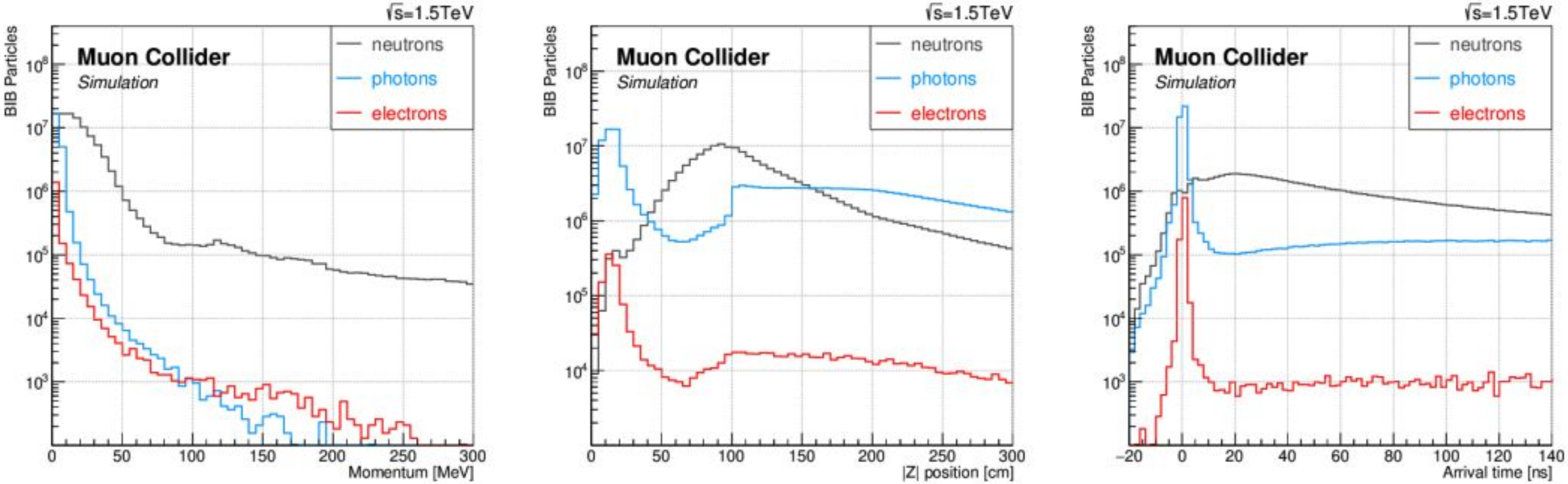
Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
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

Beam-induced background properties

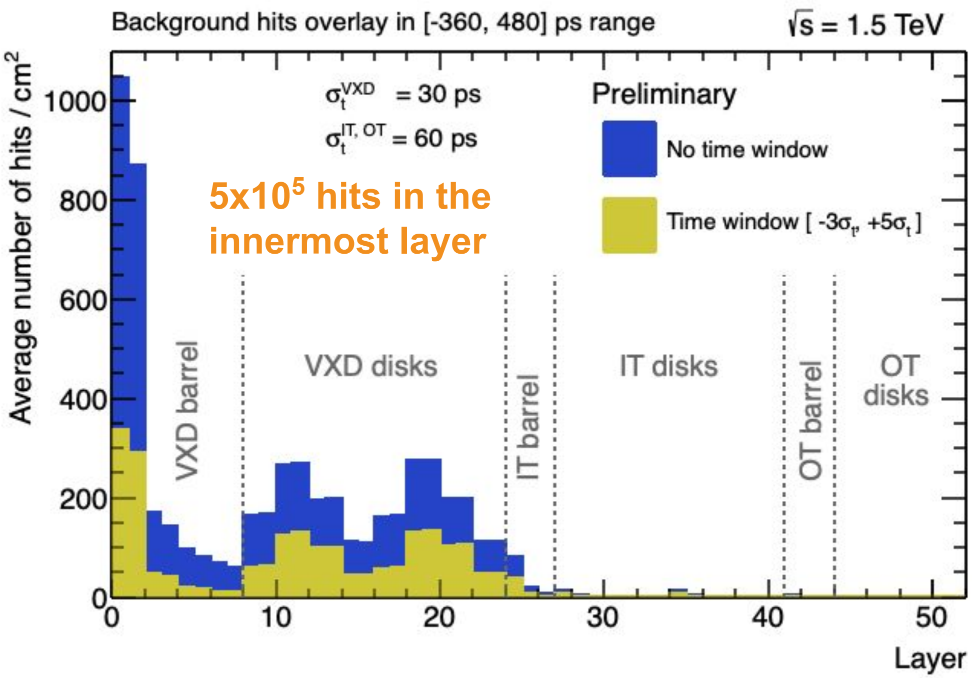


Low momentum **Origin and direction** **Timing**

Tracking detectors

Goal: tracker occupancy < 1%

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



On- and off-detector filtering:

- **Timing**
- Clustering
- Energy deposition
- **Local track angle**
- Pulse shapes

4D tracking detectors

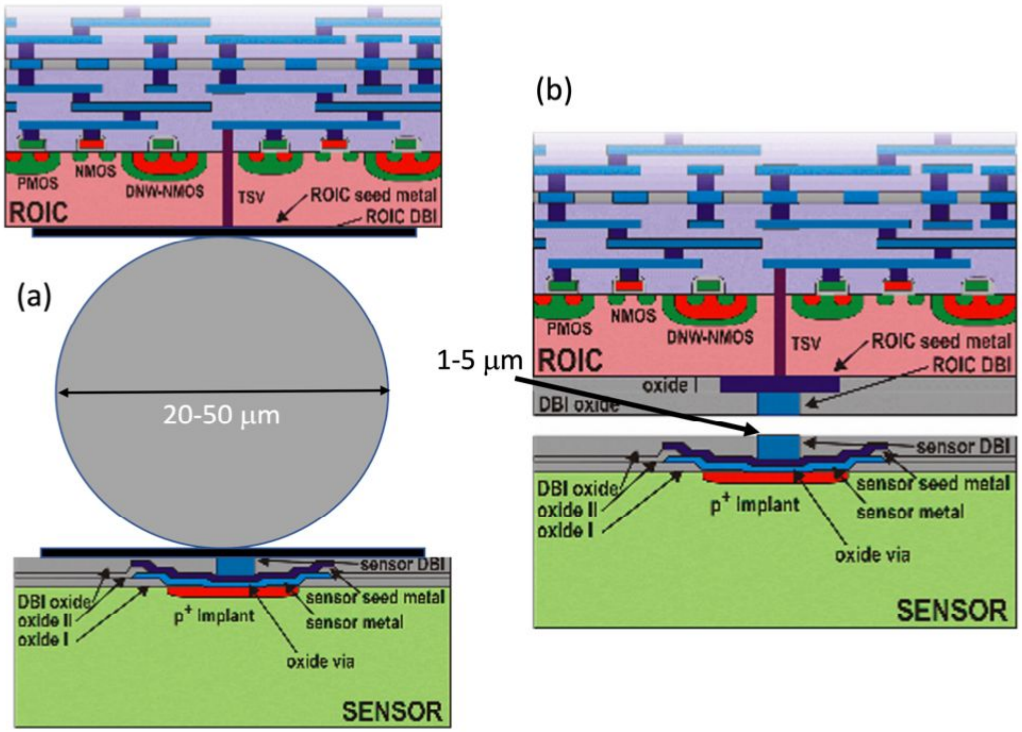
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$

R&D efforts crucial

Promising technologies exist

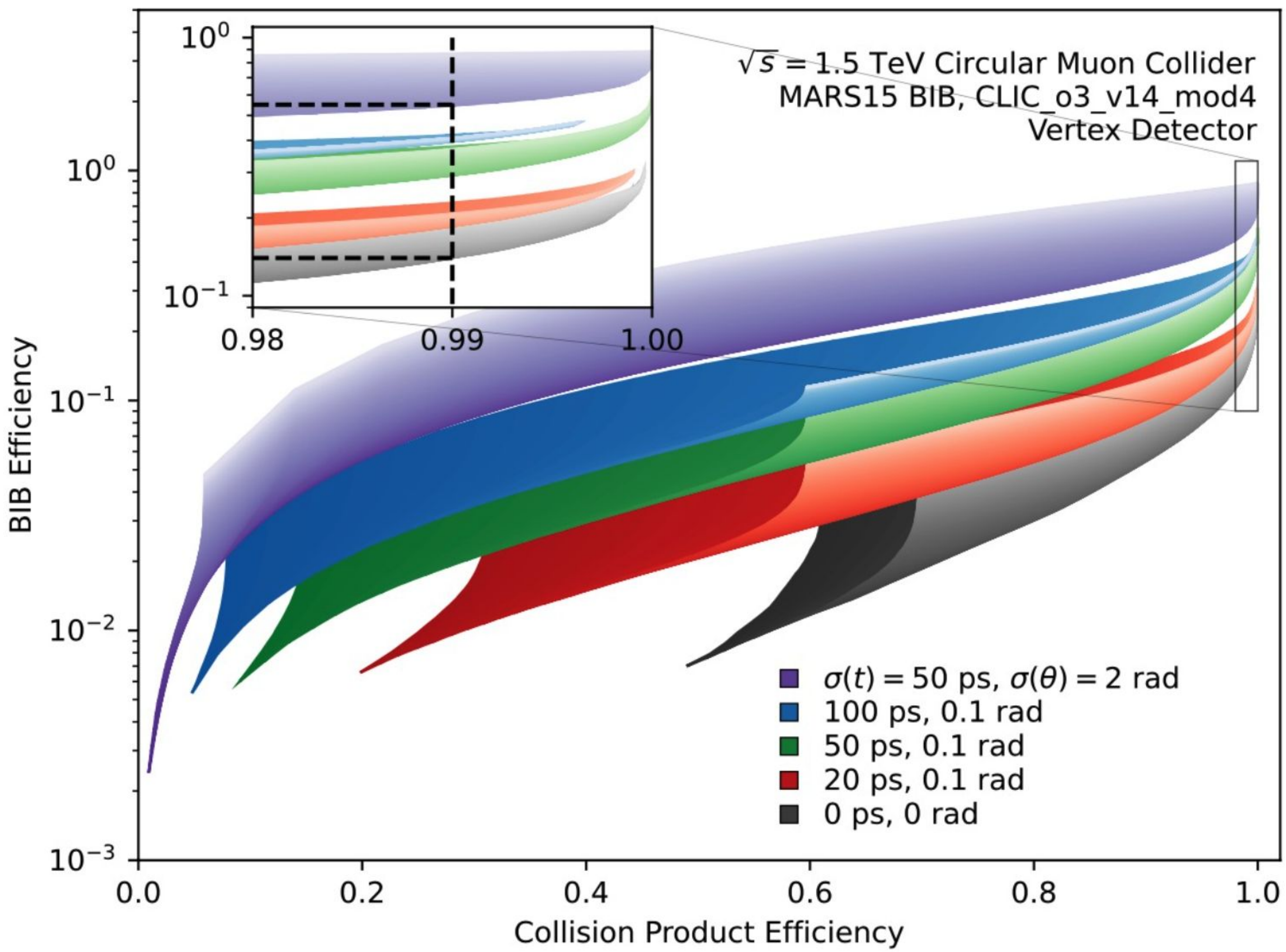
Example: Advanced hybrid bonding tech can give < 5 µm pitch and low input capacitance

- 20-30 ps time resolution

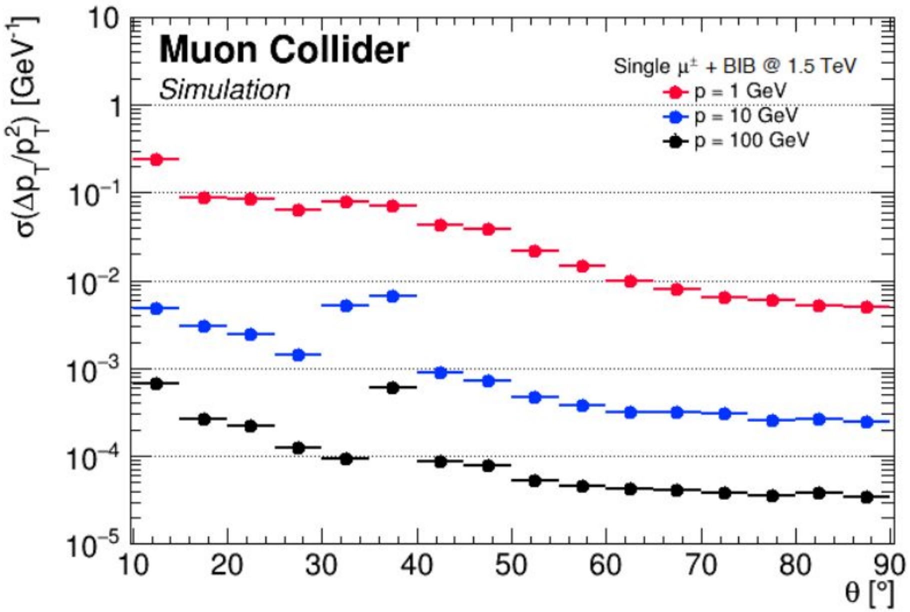


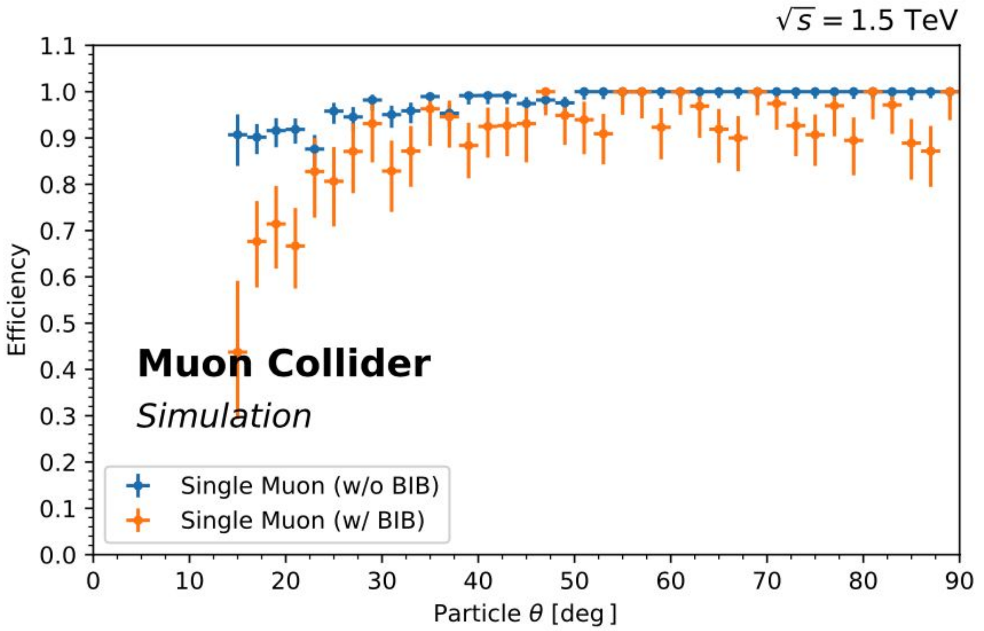
Beam-induced background rejection

Exploiting timing and pointing in the tracking detectors



Track reconstruction





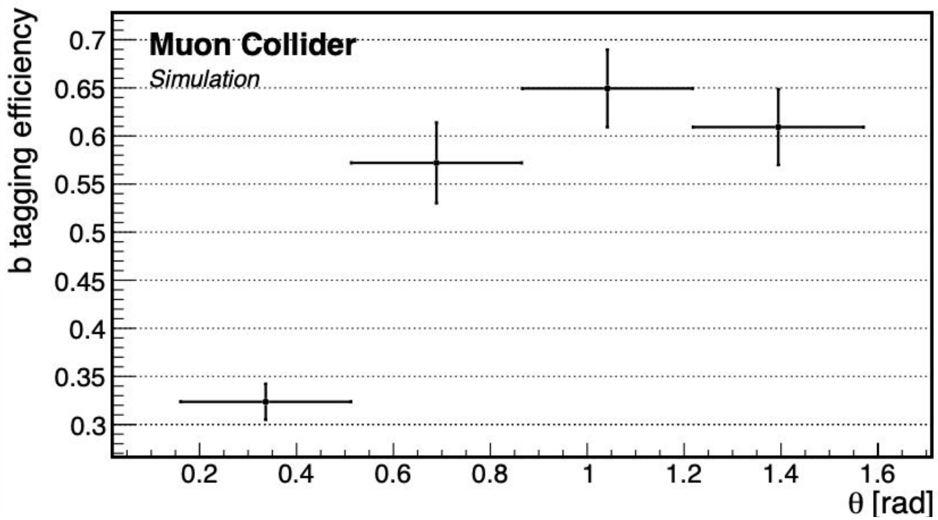
Achieved performance specs in the central region

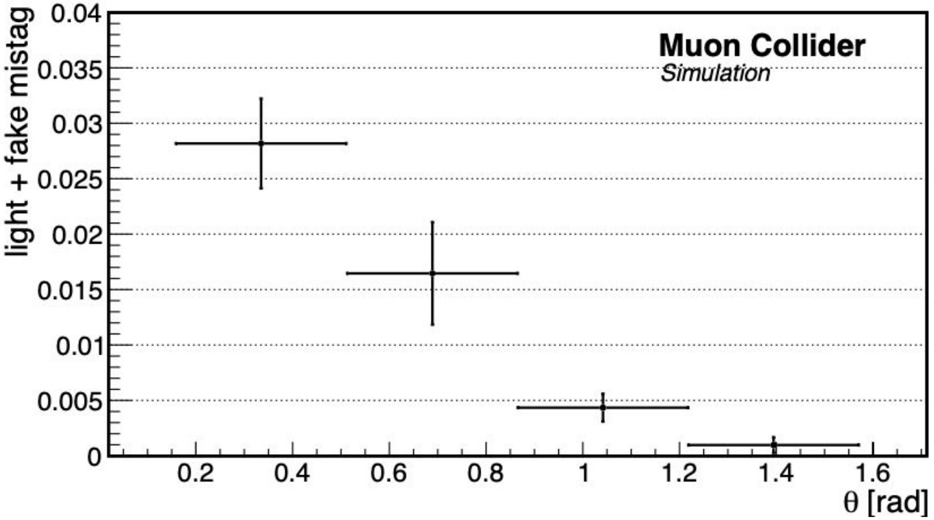
- Needs improvements next to the nozzle

Transitioning from Conformal Tracking → Combinatorial Kalman Filter (ACTS)

- Enormous computational speedup (now ~ 4 min/event)

Flavour tagging

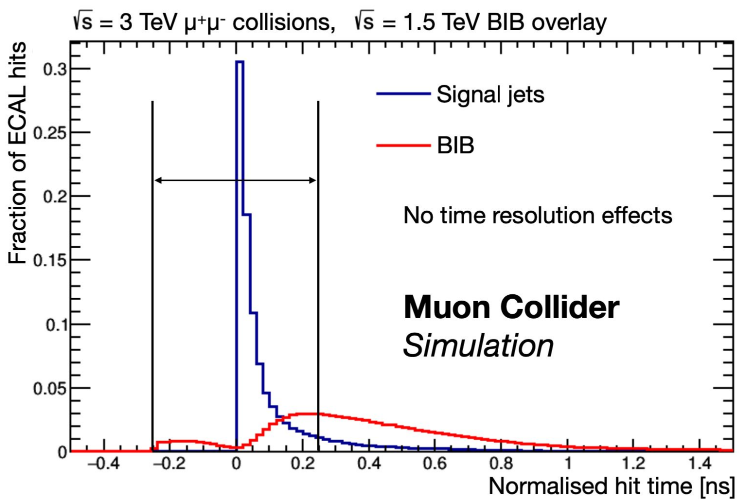


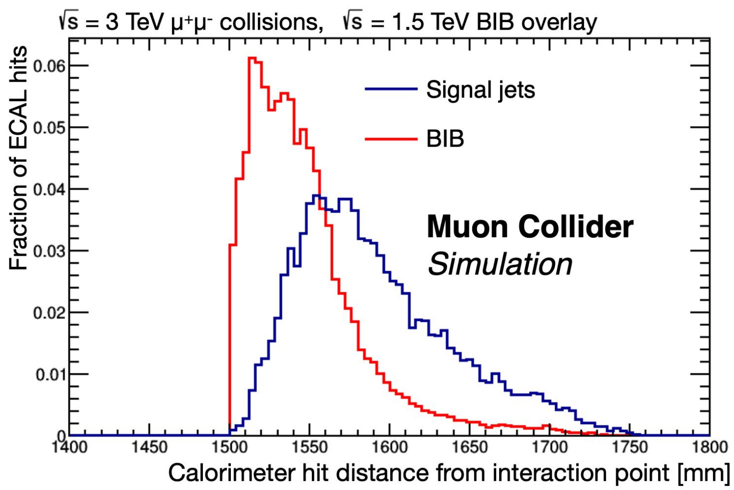


Starting from basic discriminants:

- Secondary vertex-based tagging

Calorimetry





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

Ambient energy about 50 GeV per unit area (~40 GeV in HL-LHC)

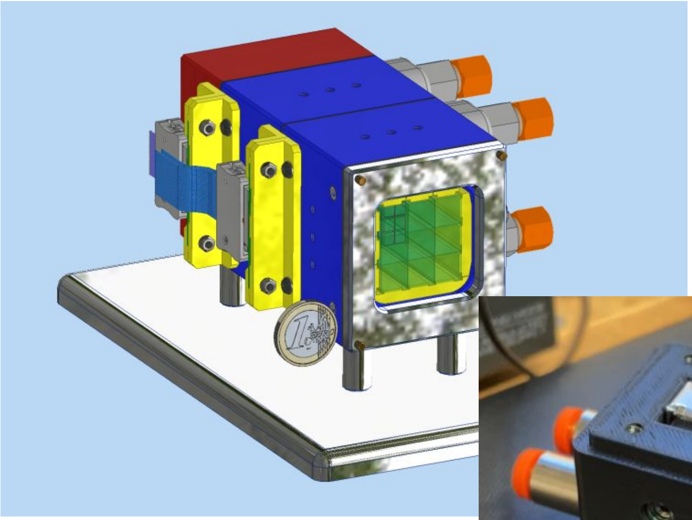
- High granularity
- Precise hit time measurement O(100ps)
- Longitudinal segmentation
- Good energy resolution 10%/√E for photons and 35%/√E for jets or better

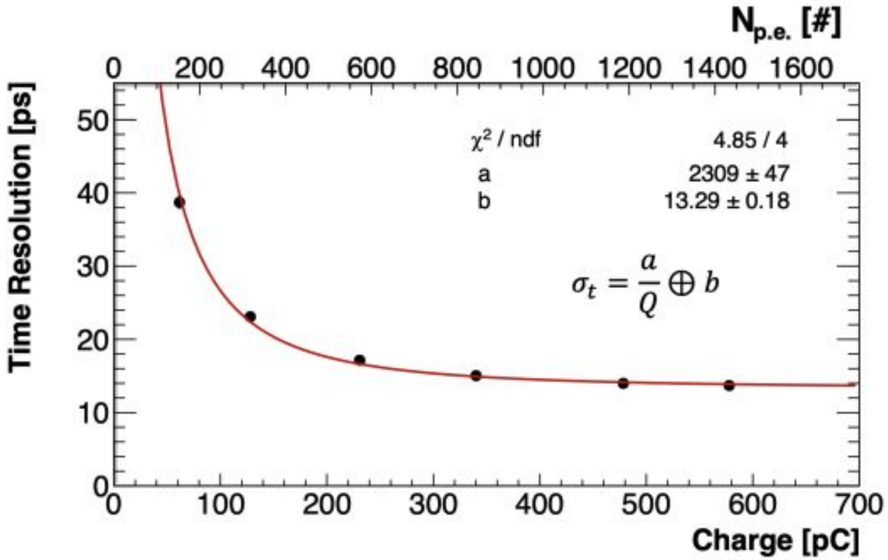
R&D example: crystals

Crilin calorimeter

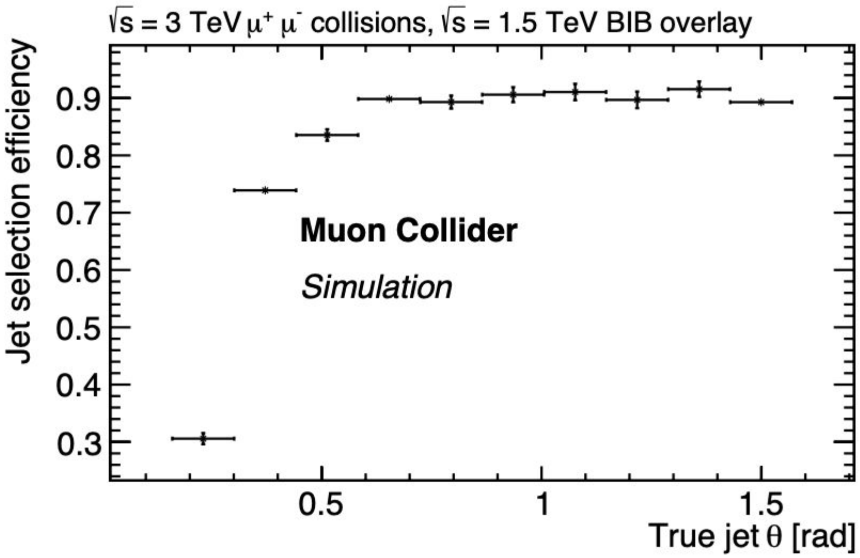
Semi-homogeneous calorimeter based on Lead Fluoride (PbF_2) crystals

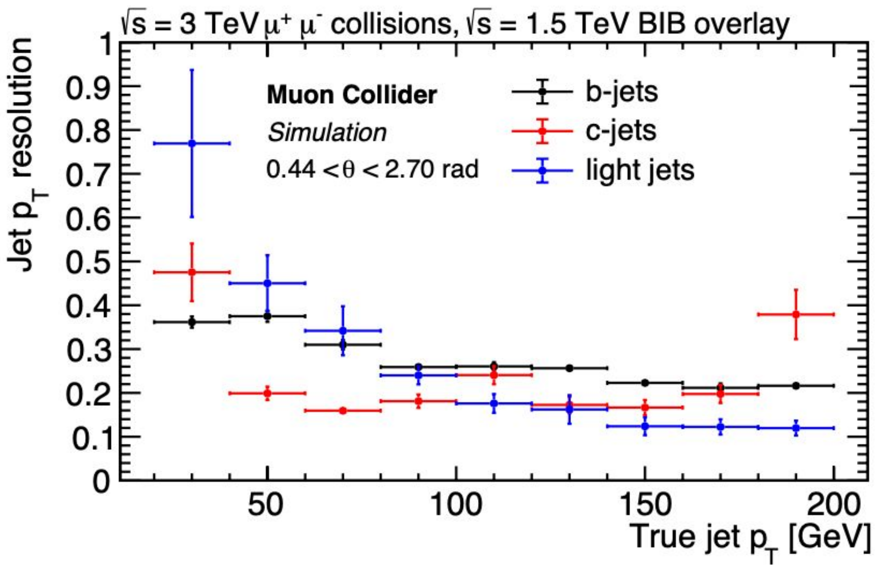
- Segmented longitudinally
- Stackable submodules composed of matrices of crystals
- Crystal individual readout by 2 series of 2 UV-extended surface mount SiPMs





Jet reconstruction





LHC-level resolutions achieved

Further improvements:

- better tracking, calorimeter threshold optimisation, fake jet removal, …

Muon detectors

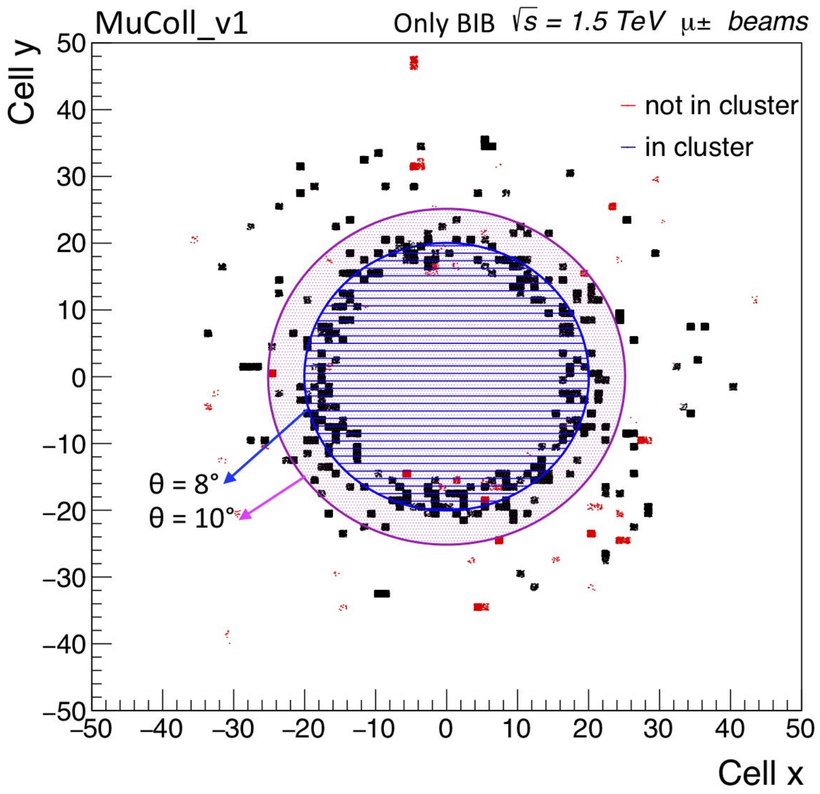
Least affected by BIB:

- Most challenging region around the beam axis in the endcaps
- Some technologies, such as RPCs, are at the limit of their rate capability

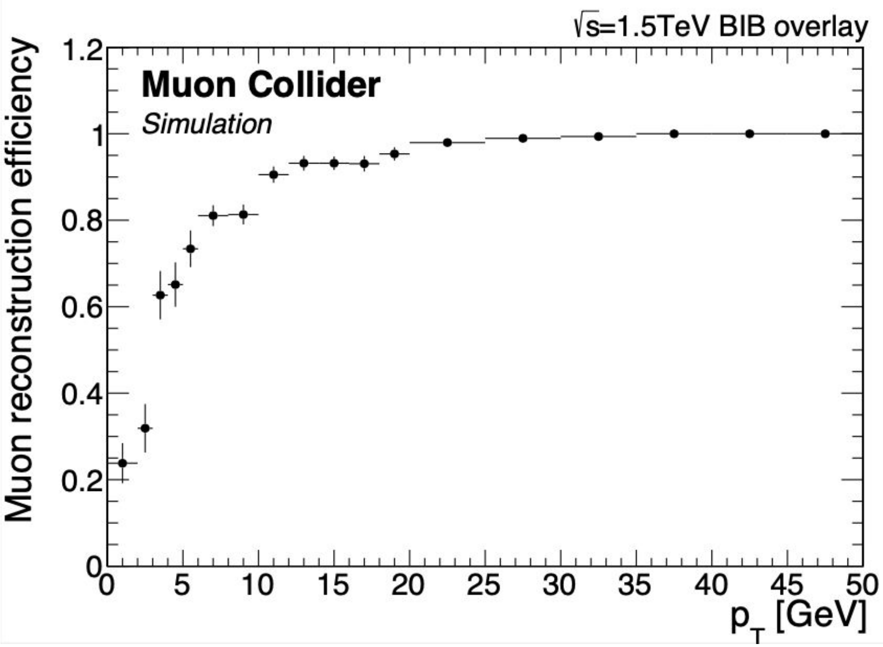
Need R&D work to cope with BIB without loss of acceptance.

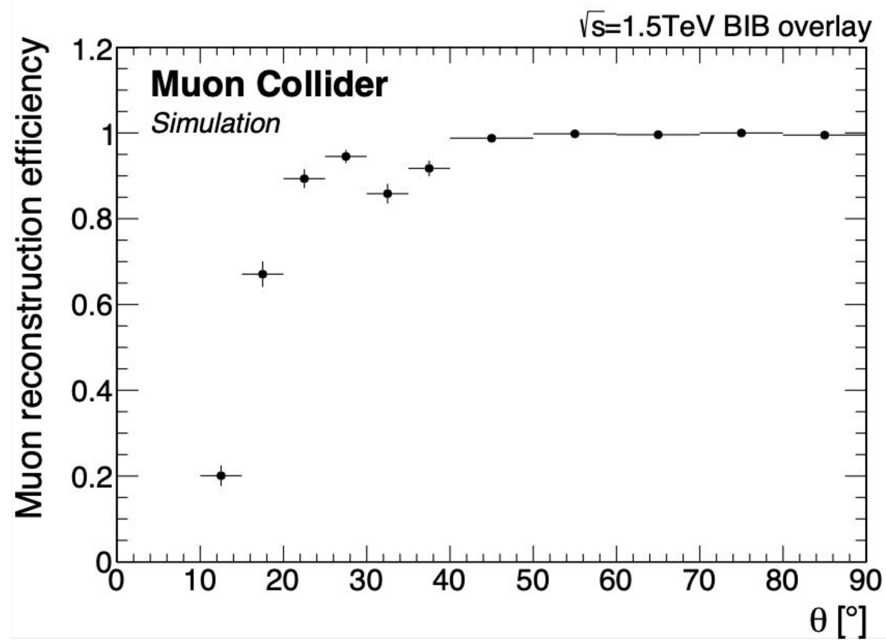
Targets:

- 100 µm spatial resolution
- < 1 ns time resolution



Muon reconstruction





Single muon performance demonstrated in presence of 1.5 TeV BIB

Readout and DAQ

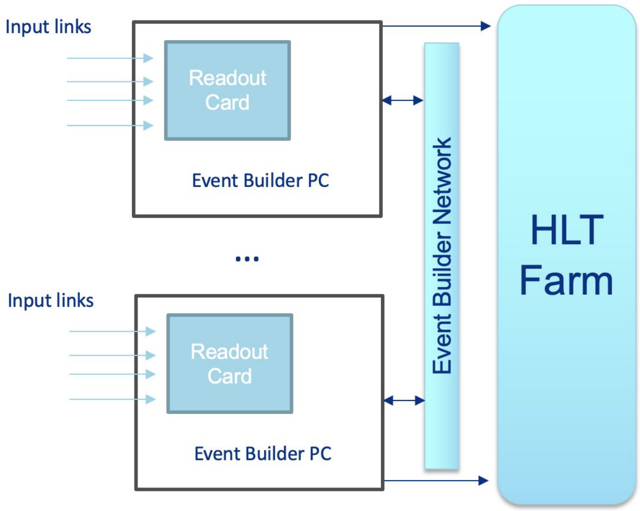
Instantaneous luminosity of **10^{34}-10^{35} cm^{-2}s^{-1}**

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**

Physics potential

A high-energy muon collider is a dream machine:

- Allows to probe unprecedented energy scales, exploring several different directions at once!

Direct searches

Pair production, Resonances, VBF, Dark Matter, …

High-rate measurements

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

High-energy probes

Di-fermion, di-boson, EFT, Higgs compositeness, …

Muon flavour physics

Lepton Flavor Universality, $b \to s\mu\mu$, g-2, …

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

$$\mathscr{L}_{\text{int}} = 10\,\text{ab}^{-1} \times \left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

Required to perform measurements with %-level precision

New heavy particles

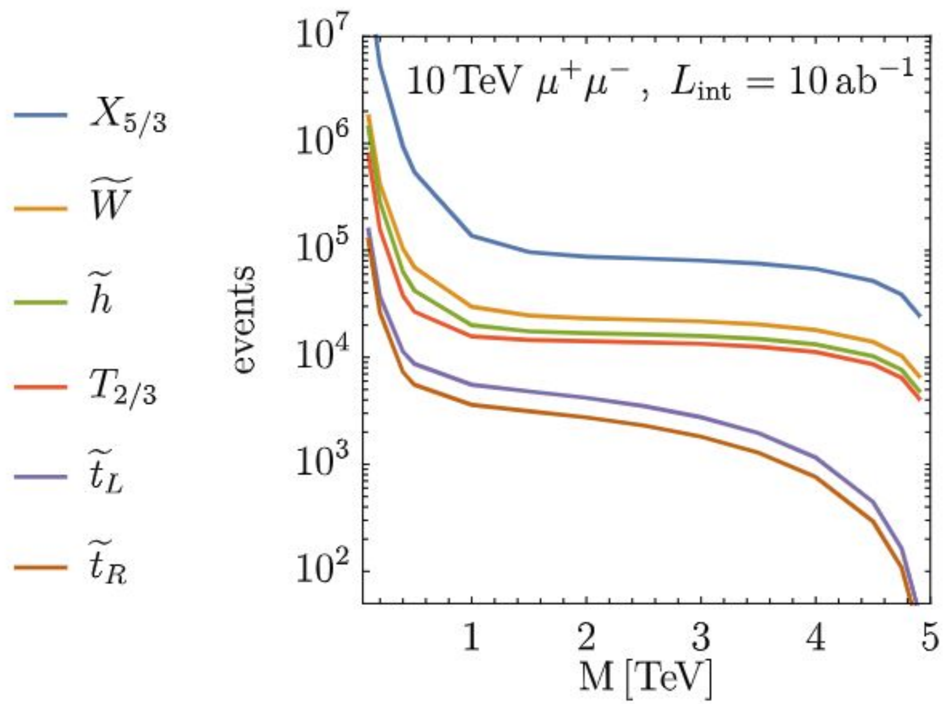
Direct searches

Pair production, Resonances, VBF, Dark Matter, …

Collide elementary particles at very high centre-of-mass energies

- Explore physics at 10+ TeV

Produce pairs of EW particles up to kinematical threshold!

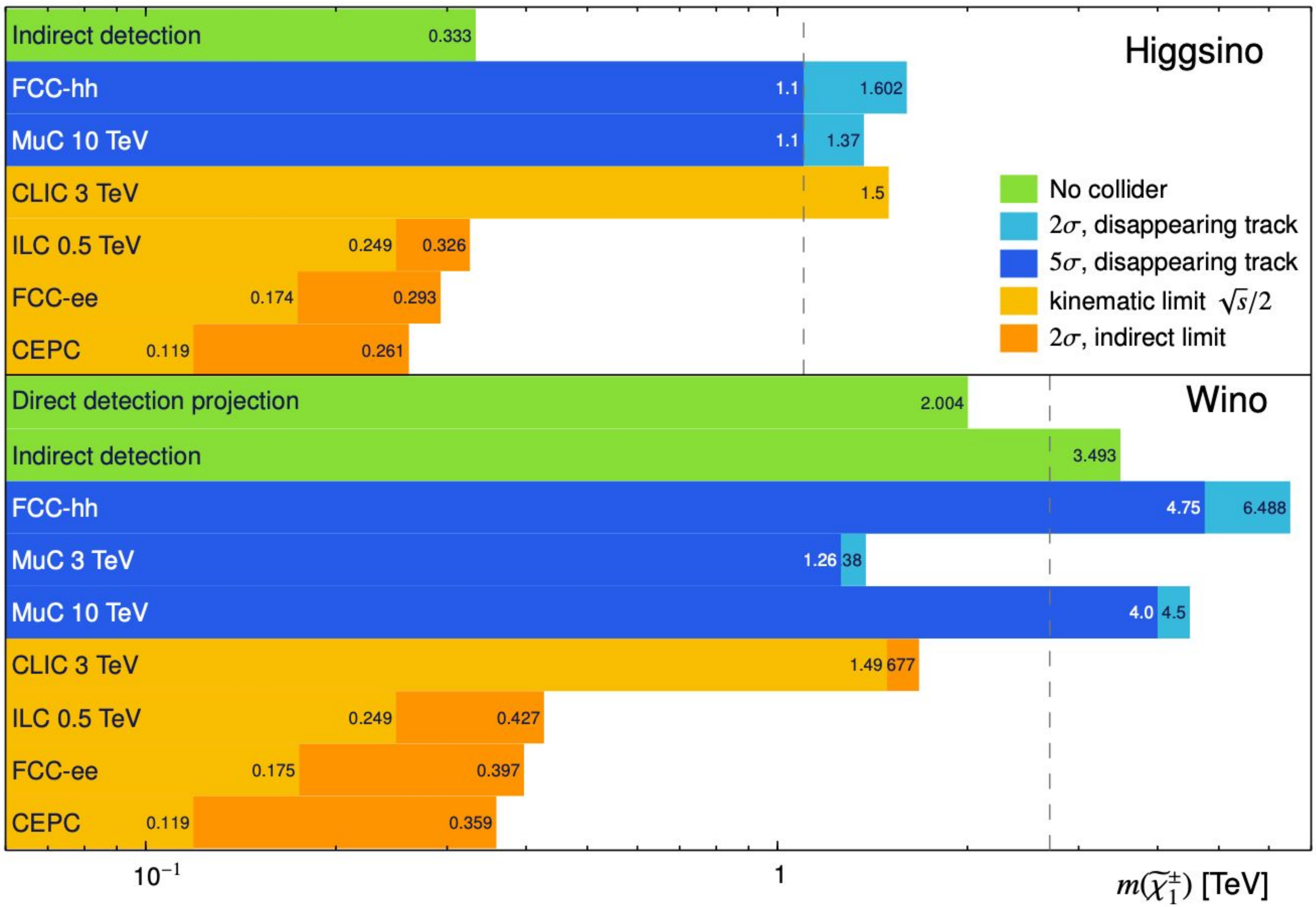


WIMP dark matter reach

Direct searches

Pair production, Resonances, VBF, Dark Matter, …

2203.07256
2102.11292



Higgs boson production

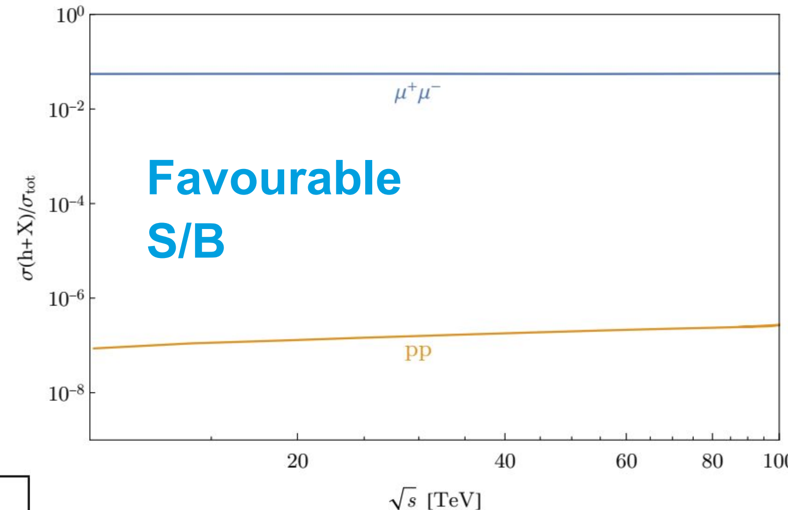
High-rate measurements

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

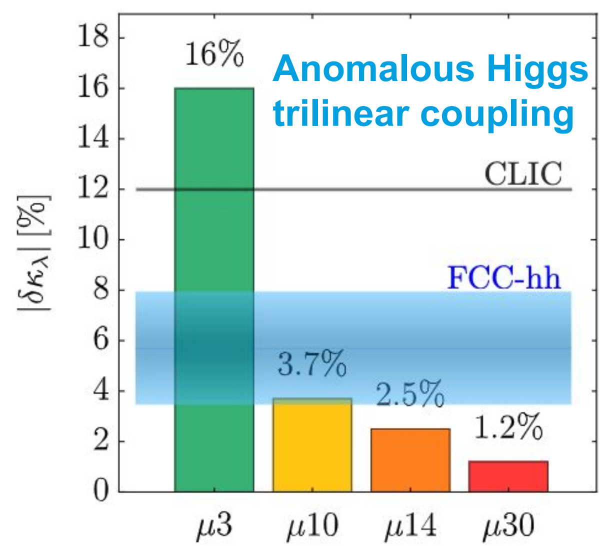
2203.09425

The Higgs itself is key

Any deviation in its properties from SM predictions is a telltale sign of new physics



	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + 250 GeV e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.37	0.10	0.35	0.10	0.31	0.10
κ_Z	1.2	0.34	0.89	0.33	0.12	0.11
κ_g	1.6	0.45	1.3	0.44	0.72	0.39
κ_γ	3.2	0.84	1.3	0.71	1.2	0.69
$\kappa_{Z\gamma}$	21	5.5	22	5.5	4.0	3.3
κ_c	5.8	1.8	5.8	1.8	1.7	1.3
κ_t	34	53	3.2	3.2	3.2	3.2
κ_b	0.84	0.23	0.80	0.23	0.44	0.21
κ_μ	14	2.9	4.7	2.5	4.0	2.4
κ_τ	2.1	0.59	1.2	0.55	0.61	0.40



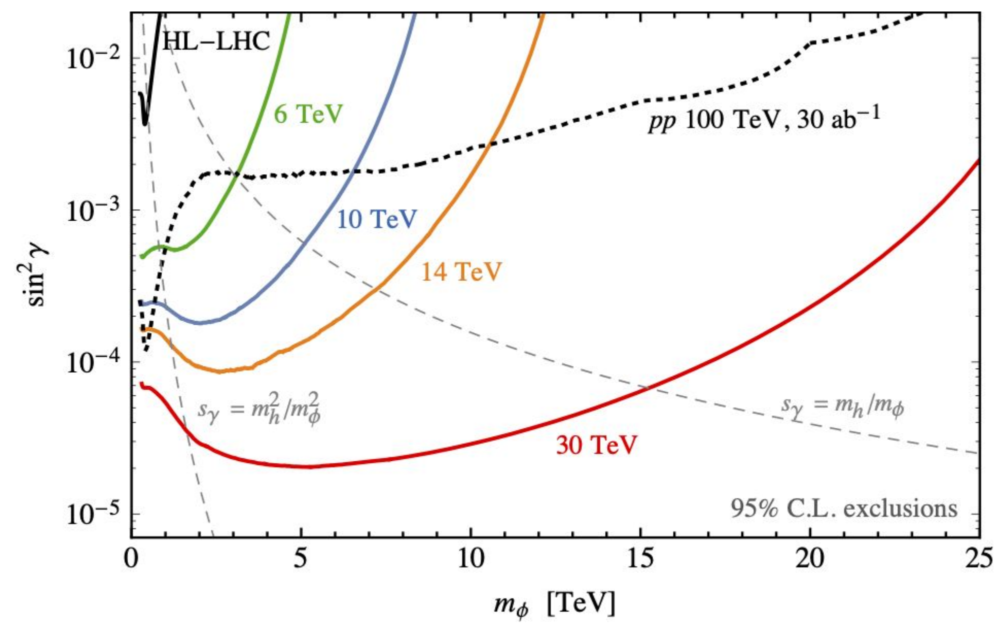
1807.04743

Is the 125 GeV Higgs the only one?

Example extension of scalar sector

- A Standard Model singlet mixing with the Higgs

$$h = h^0 \cos\gamma + S \sin\gamma$$
$$\phi = S\cos\gamma - h^0 \sin\gamma$$



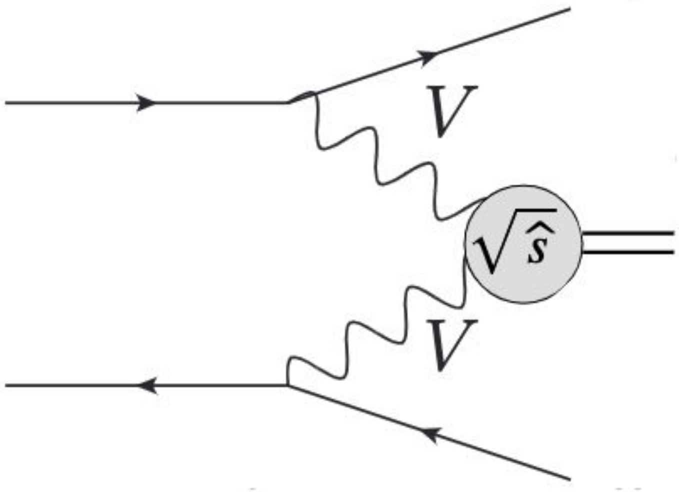
Production:

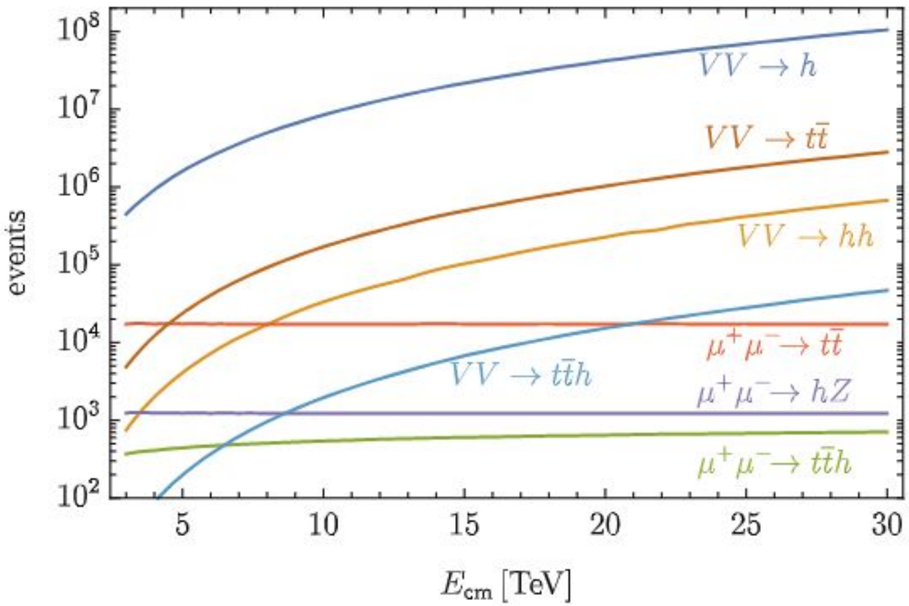
$$\sigma_\phi = \sin^2\gamma \cdot \sigma_h(m_\phi)$$

Decay:

$$\mathrm{BR}_{\phi\to f\bar{f},VV} = \mathrm{BR}_{h\to f\bar{f},VV}(1-\mathrm{BR}_{\phi\to hh})$$
$$\mathrm{BR}_{\phi\to hh} \sim 25\%$$

Muon colliders as vector boson colliders



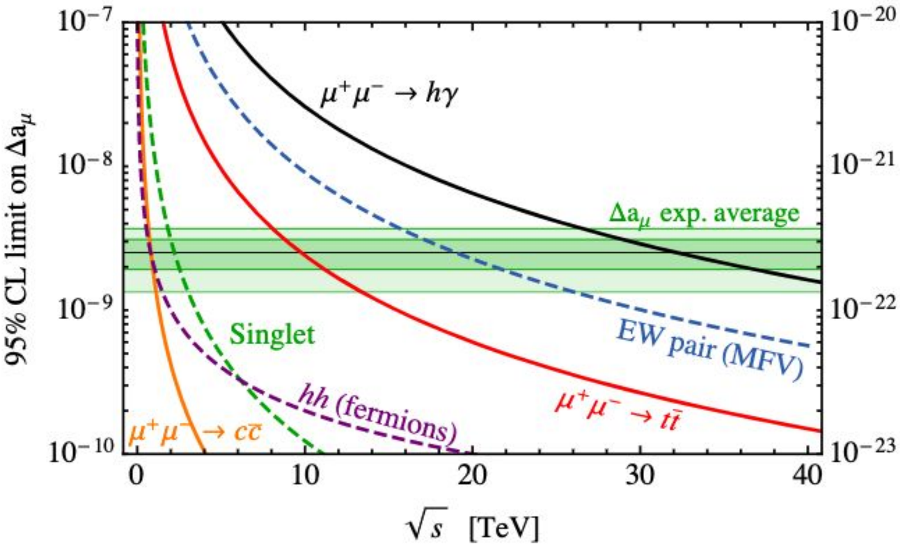


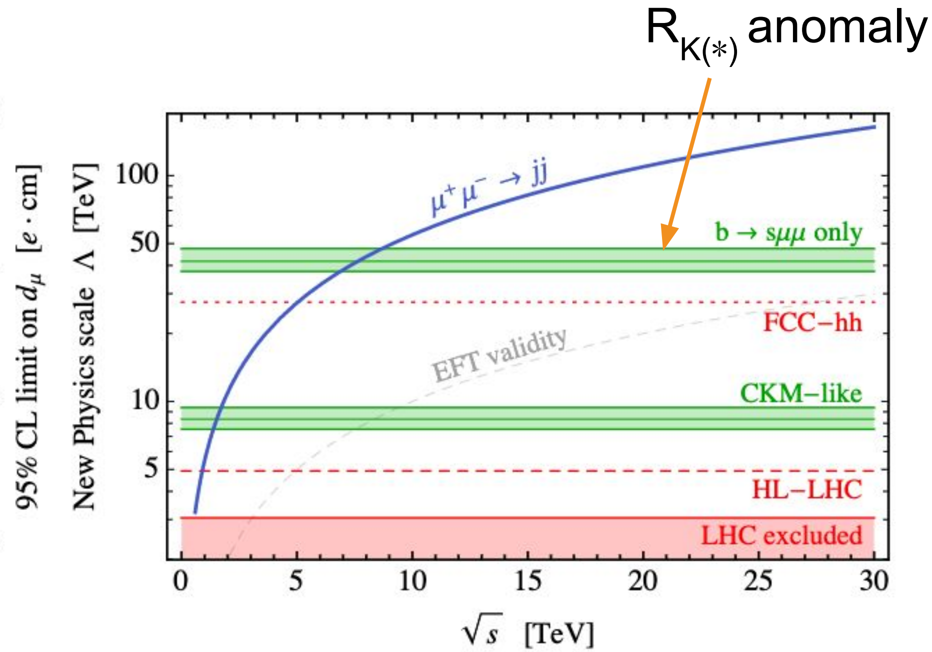
Vector boson fusion dominates well above threshold due to logarithmic growth with centre-of-mass energy

Opportunity to tag forward muons and distinguish between charged and neutral VBF processes is unique at muon colliders

- Requires dedicated detector design!

Muon-related anomalies





Model independent test of g-2

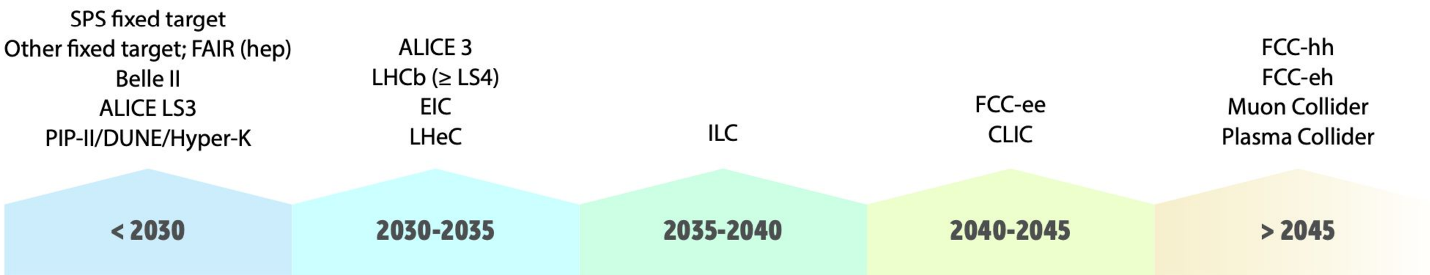
- Solid lines correspond to limits on contact interactions
- Dashed lines illustrate the sensitivity to specific classes of models

Potential to probe flavour anomalies

Assuming EFT validity:

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

Accelerator roadmap

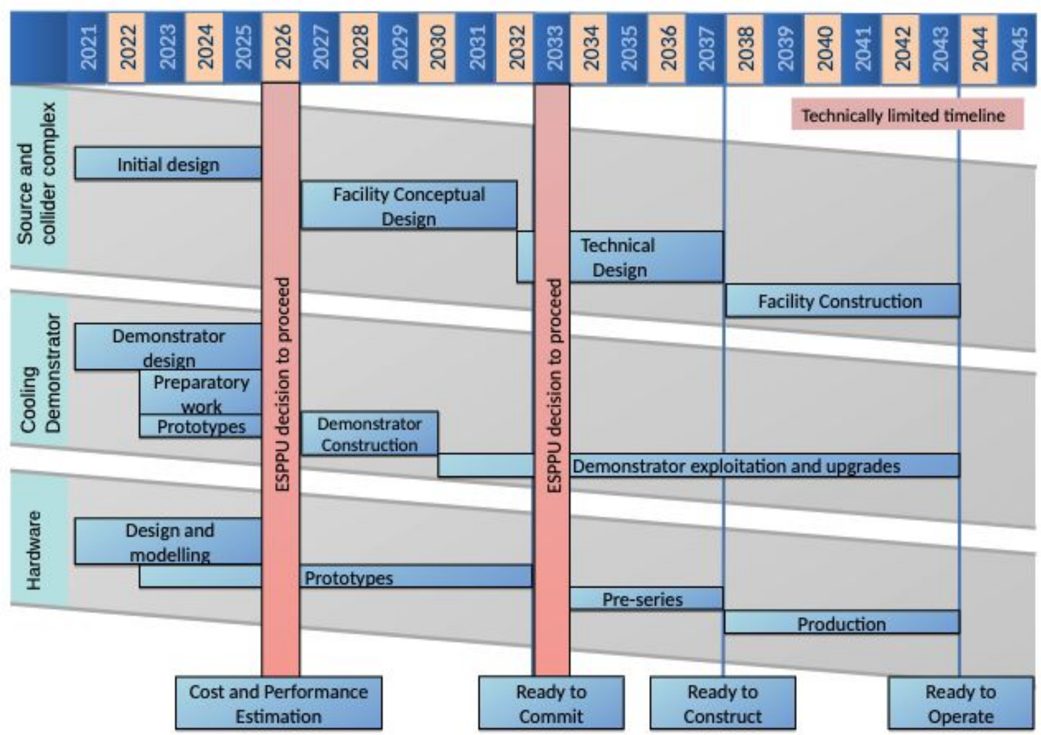


On request by CERN Council LDG developed R&D Roadmap

- Global community participated
- A global roadmap
- Estimates of resources

No insurmountable obstacle found for the muon collider

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

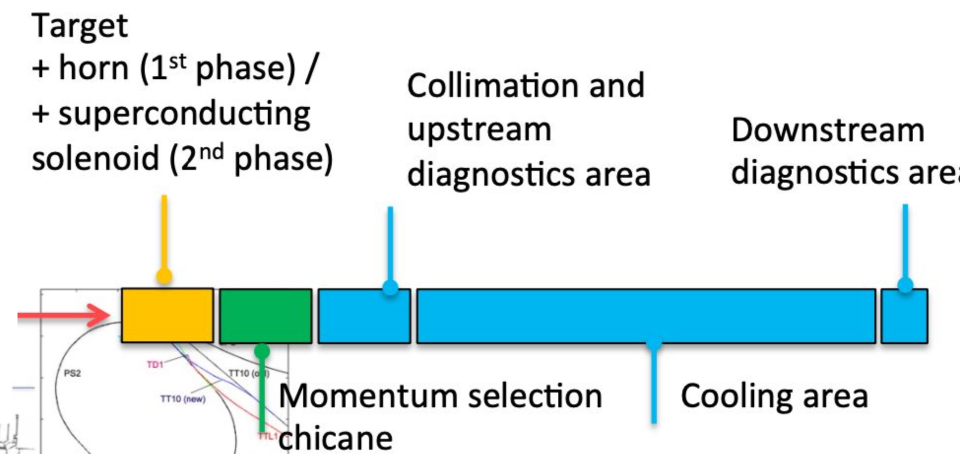


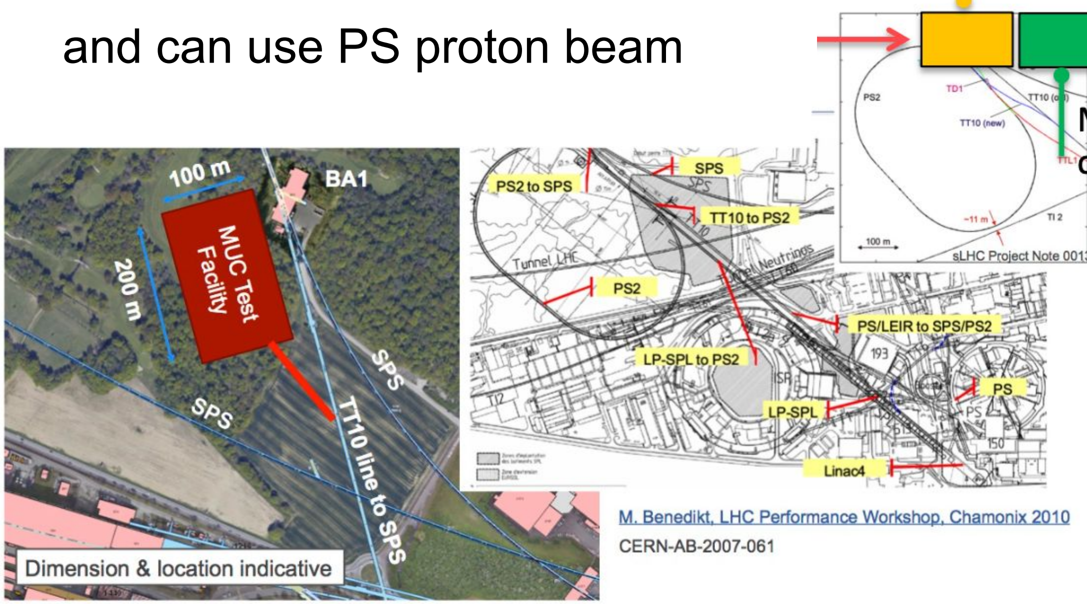
Demonstrator programme

Planning demonstrator facility with muon production target and cooling

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

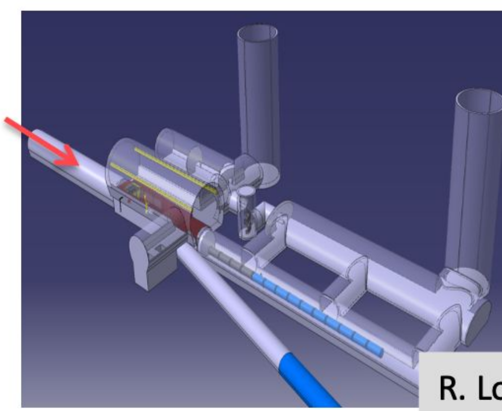
Suitable site exists on CERN land and can use PS proton beam





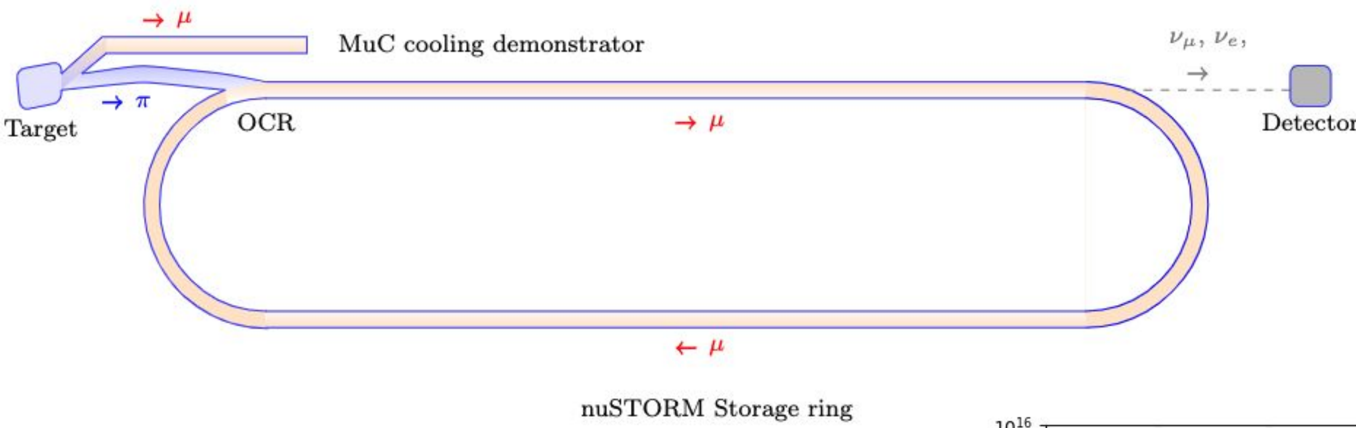
M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



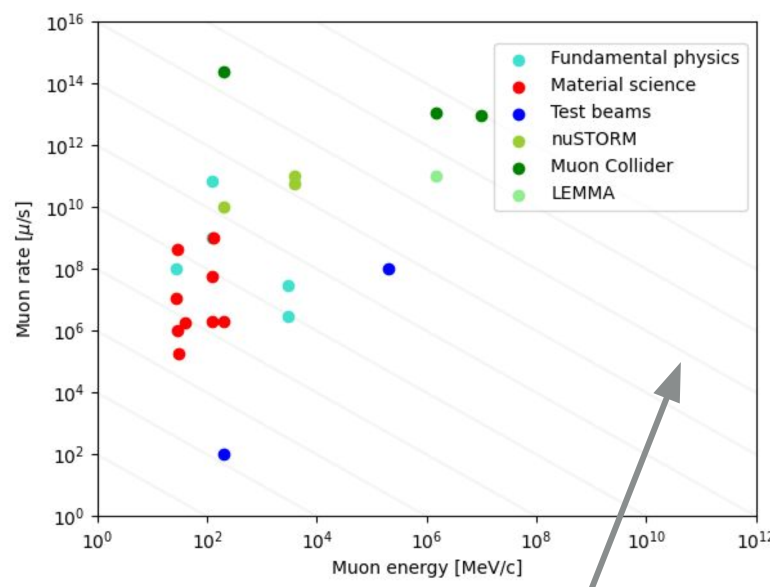
R. Losito et al.

Demonstrator programme - synergies



Bright muon beams are the basis of neutrino physics facilities such as nuSTORM

- Potential to share an important part of the complex with a muon cooling demonstrator



Lines show equal beam power

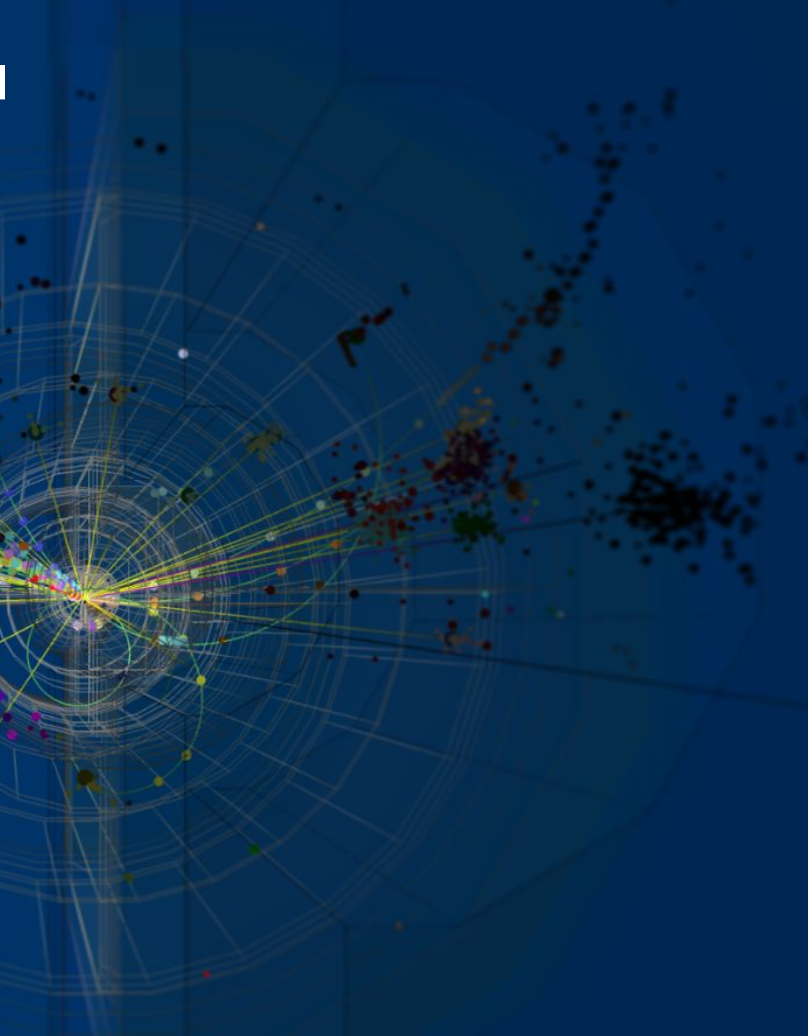
Summary

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

Need to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes

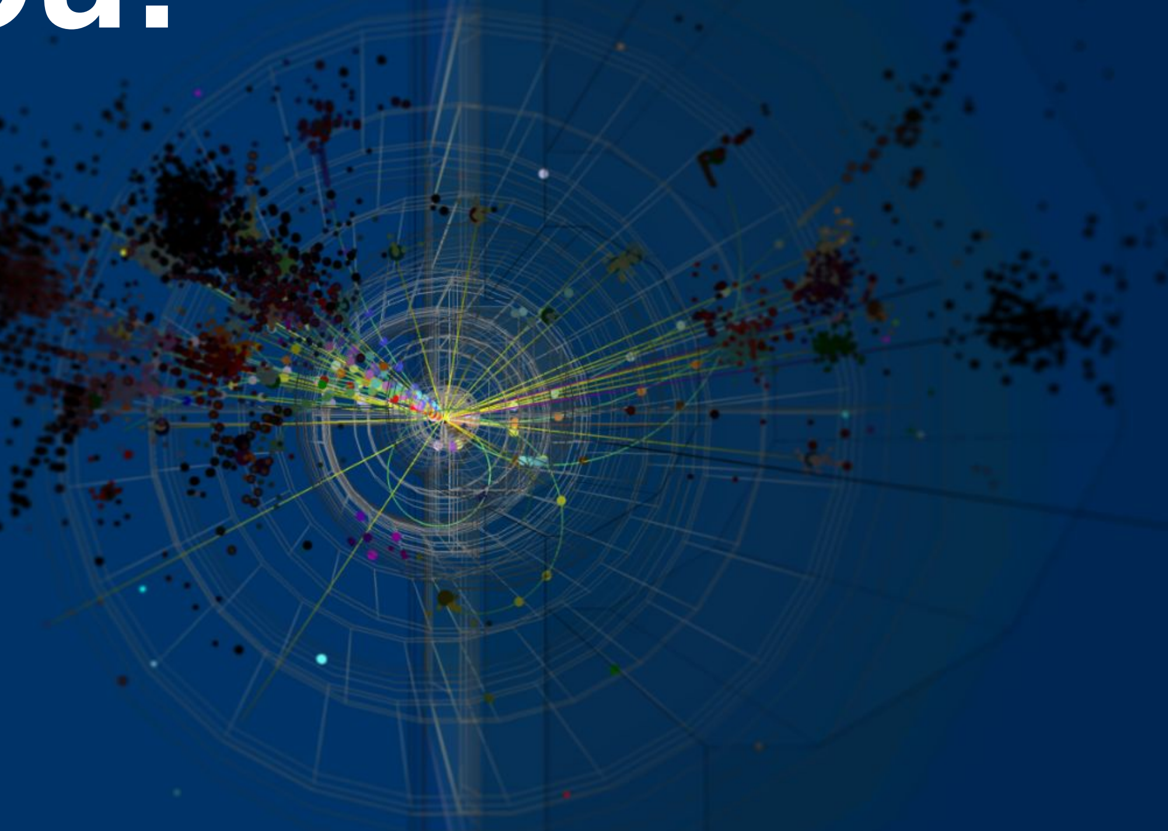
Important progress in development of workplan

Getting there won’t be simple: the road ahead is filled with challenging and interesting R&D!



Background image credit: L. Lee

Thank you!

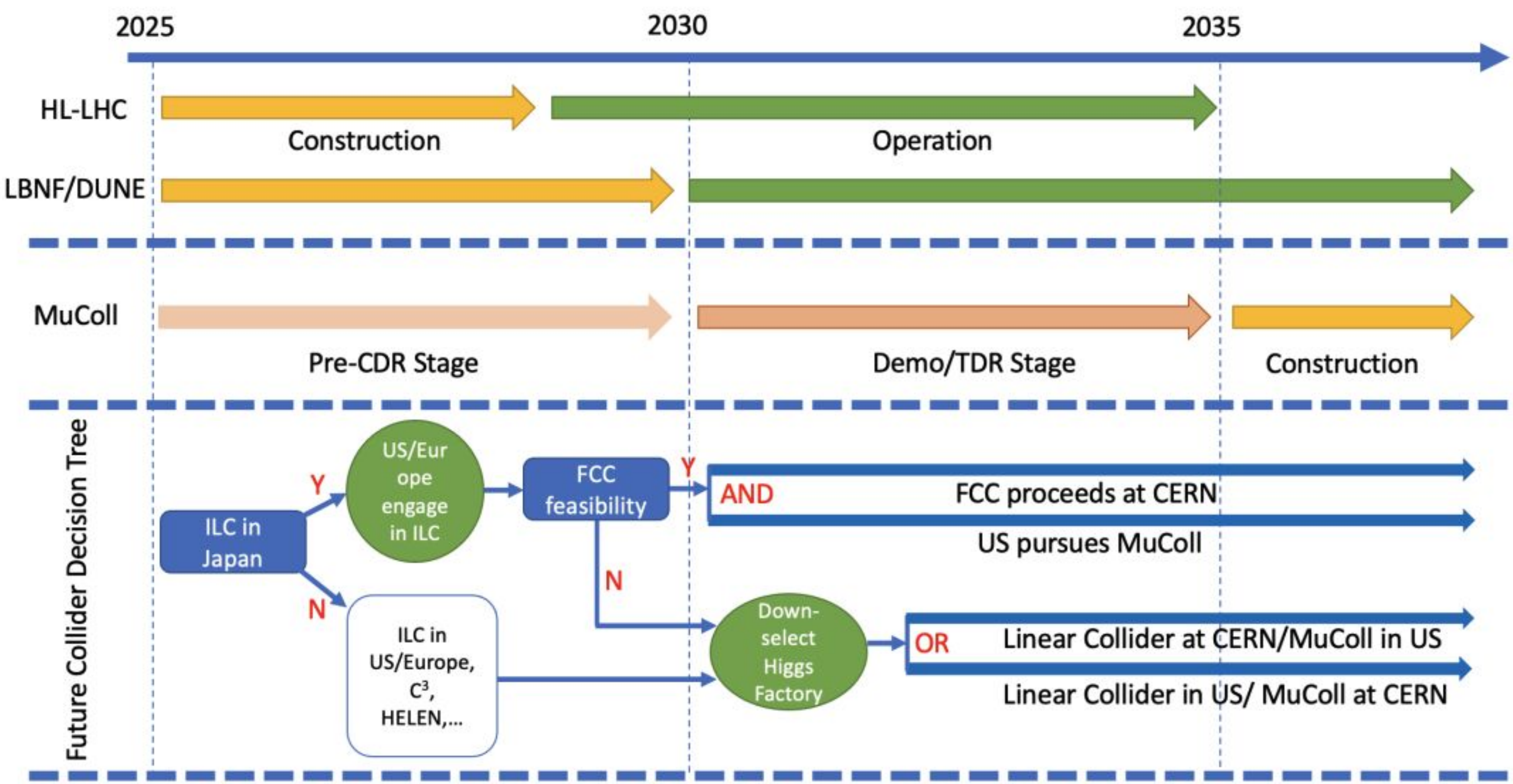


Contact

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

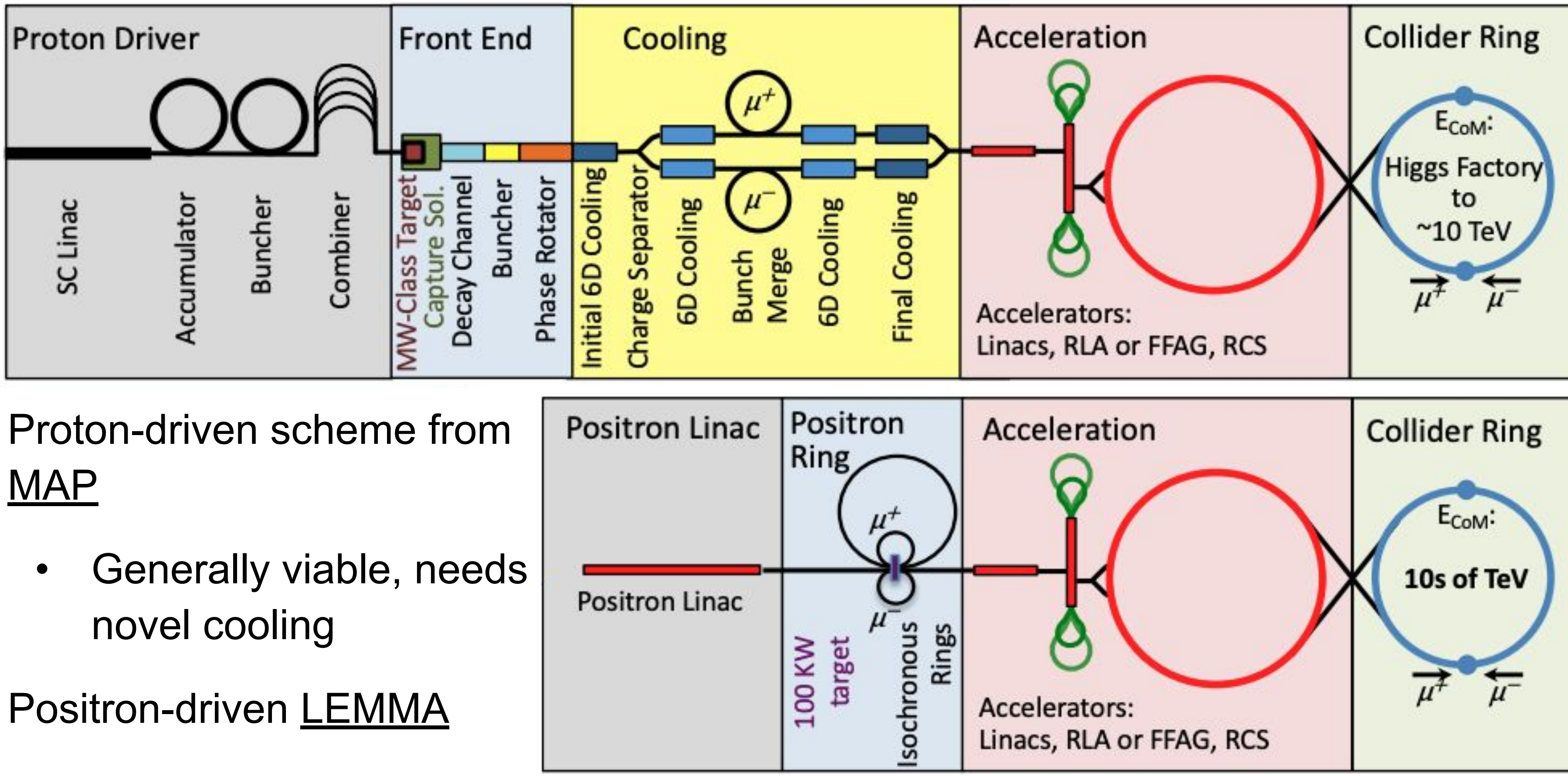
Background image credit: L. Lee

Future decision tree



Machine designs

Proton or positron-driven sources?



Proton-driven scheme from MAP

- Generally viable, needs novel cooling

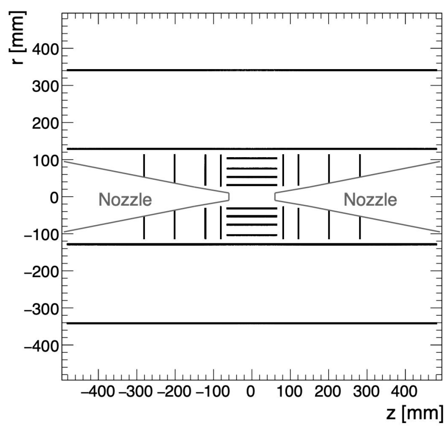
Positron-driven LEMMA

- Requires consolidation for higher muon intensities

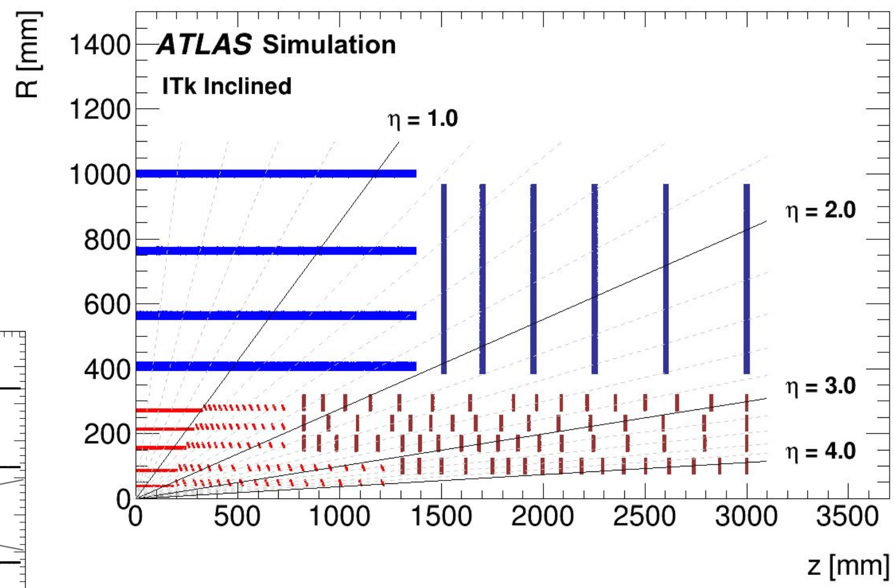
Image source

Space constraints

CERN-LHCC-2017-021



Muon Collider tracker layout



Tracking and trackers

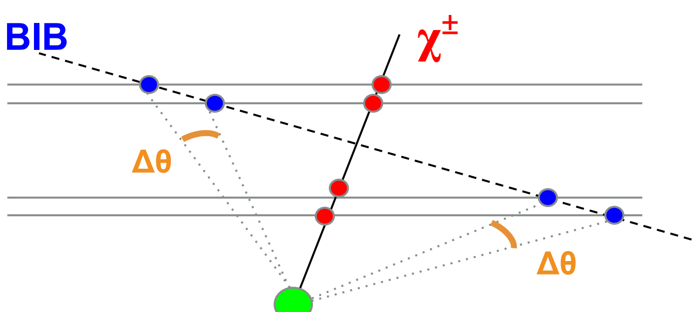
Tracking detector bombarded by huge amount of randomly distributed hits/BX.

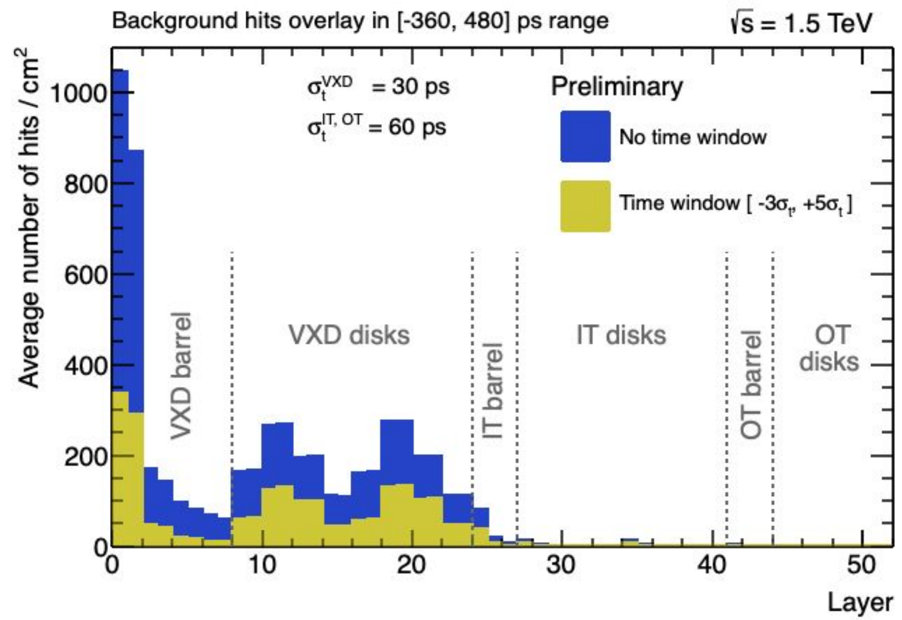
- Extremely challenging track reconstruction

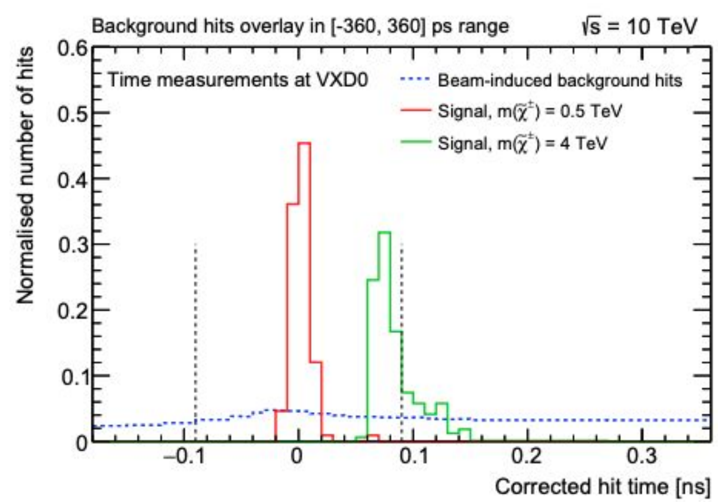
Goal: tracker occupancy < 1%

Need to filter hits:

- Timing (aim for ~30 ps resolution)
- Correlation of hit pairs (similar to CMS pT modules for track trigger)







Ongoing efforts

Several promising technologies with active R&D:

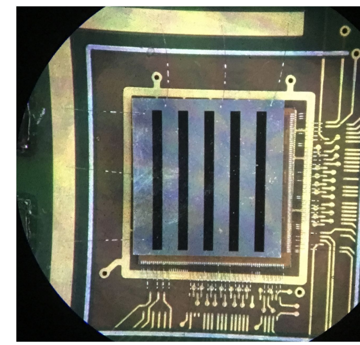
- Monolithic detectors (**HV/HR-CMOS**) - embedded readout
- Low Gain Avalanche Detectors (**LGADs**) - good timing, large pads
- Small “standard” pixels with **3D hybrid bonding** - intrinsically radiation hard
- **Intelligent sensors**

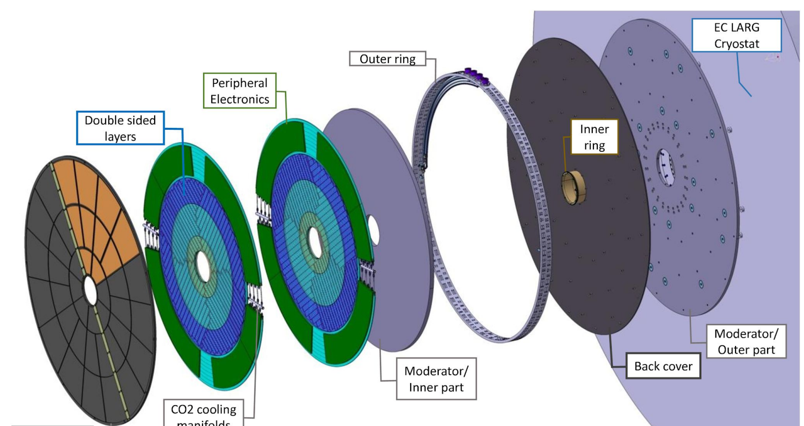
Common challenges for many technologies:

- Services, cooling, low-power ASICs

CMS and ATLAS are building **1st generation 4D-tracking detectors**

- Single or two hits per charged particle, and large pixels
- Next generation detectors will be more sophisticated



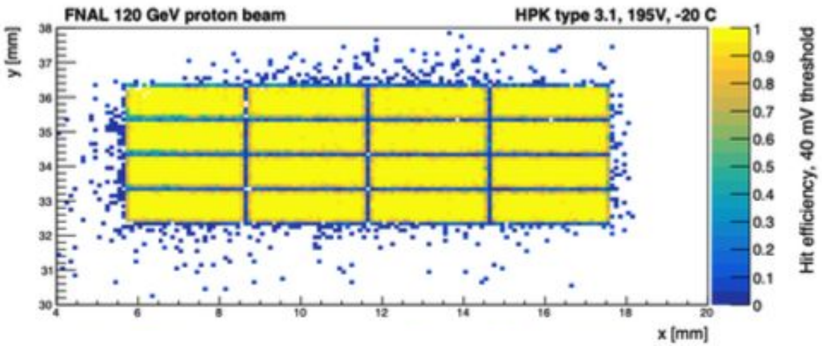


CERN-LHCC-2020-007

R&D examples

Sensors developed for CMS and ATLAS show high degree of uniformity, excellent time resolution, but are rapidly becoming obsolete.

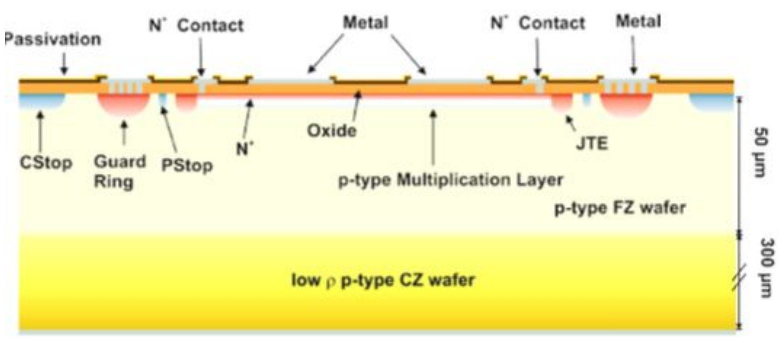
- **Limited fill factor**
- **Moderate radiation hardness**



AC-coupled LGADs

- Remove dead area and improve position resolution via charge sharing
- Fast timing information at per-pixel level
- Signal from drift of multiplied holes into the substrate and AC-coupled through dielectric
- Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge

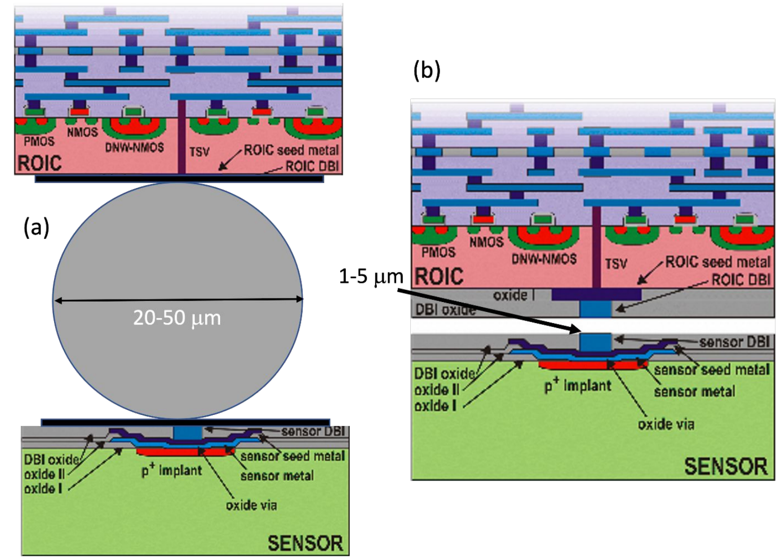
Diagram credit: CNM



R&D examples

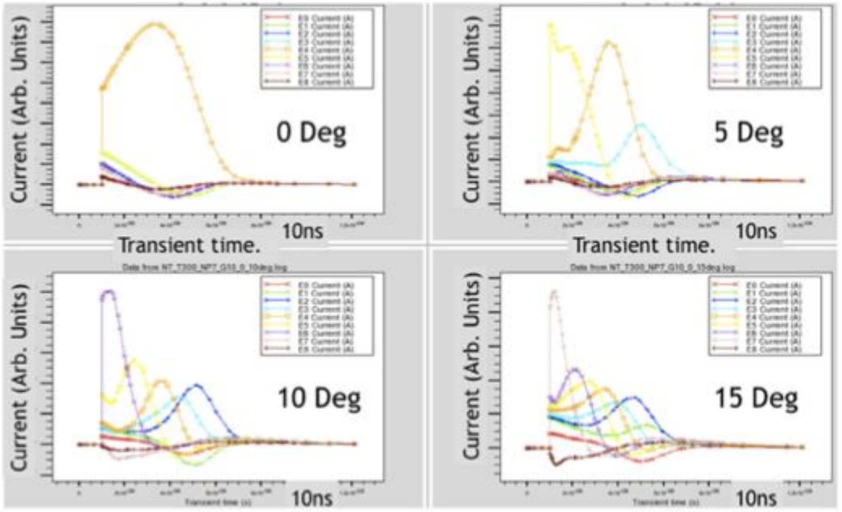
Capabilities enabled by **3D hybrid bonding** provide small pixels with low capacitance

- 3D integration of sensors and electronics provide low C_L, dense interconnects and processing
- Enables **4D tracking detectors + directionality (X,Y,Z,T,θ)**



If the signal/noise is high enough we can use fast induced currents instead of collected charge

- Use the current pulse shape to characterize charge deposit, track angle
- Fast timing, radiation hard, precise, angle resolution



Power and space

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

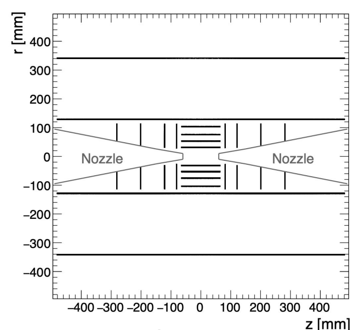
- 450 W for analog bias
- 100 W for sensor bias
- 1.5 kW for data transmission

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.

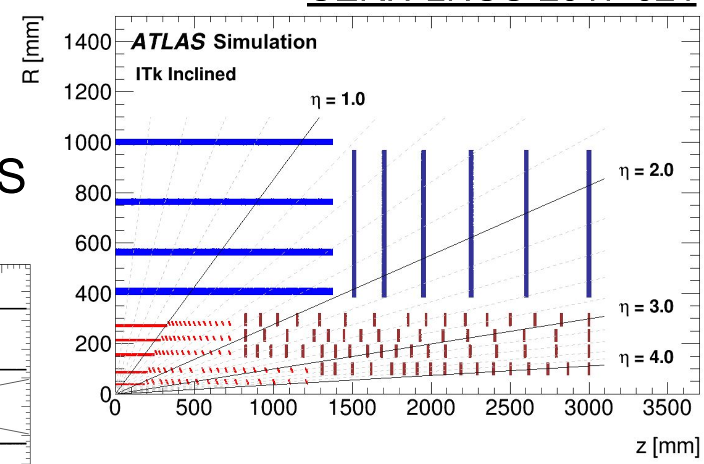
Furthermore, the detector is expected to be very compact.

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



Muon Collider tracker layout

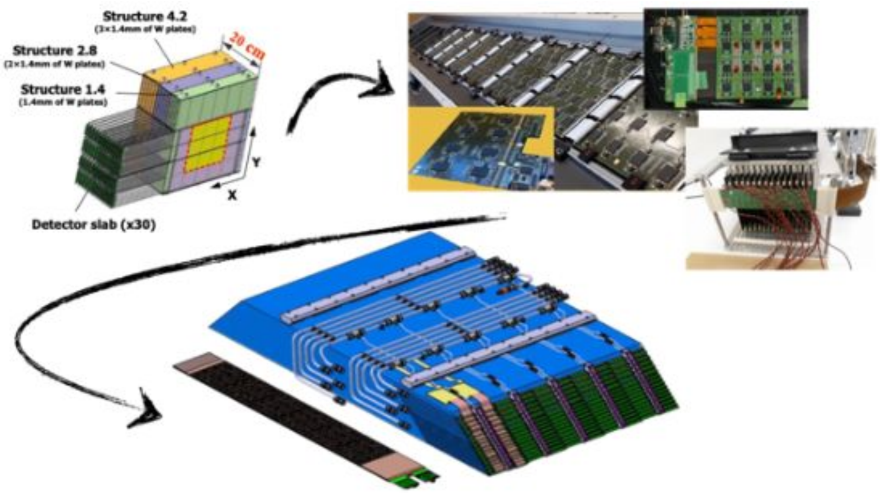
CERN-LHCC-2017-021



R&D examples: silicon

Main arguments to adopt silicon:

- Fine segmentation
- Robust and stable performance
- High density



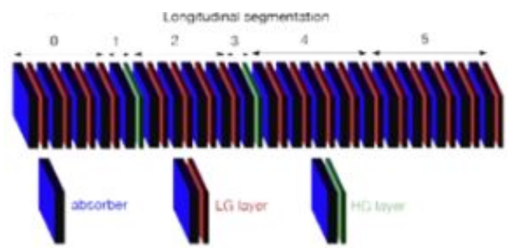
Development by CALICE collaboration

- 1 m^2 area prototypes
- Scale up to 2500 m^2 for full detector
- Could adopt CMOS for digital ECAL (10^4 increase in channel density)

Main challenges:

- Cost
- Operation (calibration, monitoring)

ALICE forward calorimeter

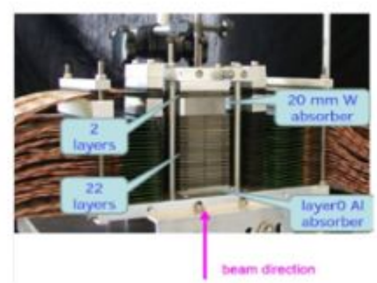


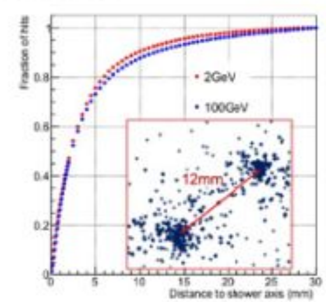
total:

14.5 m^2 Si pads

1.5 m^2 CMOS pixels

Full CMOS prototype of a digital ECAL





R&D examples: gas detectors

Resistive Plate Chambers (RPC) and Micro Pattern Gas Detectors (MPGD) are good candidates as active medium for high granularity sampling calorimeters.

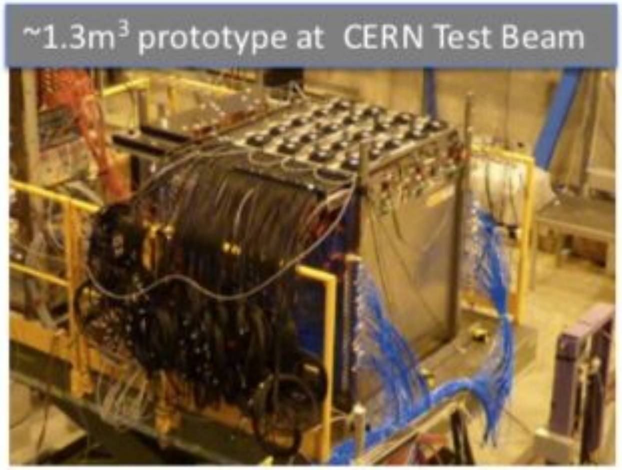
General properties:

- robustness and cost
- can cover large areas
- 50-100 μm space resolution
- are radiaton hard
- can cope with relatively high rates
- good time resoluton

R&D and engineering challenges

- uniformity on large areas
- limits on sizes (dead areas)
- gas homogeneity and time stability
- low sampling fraction

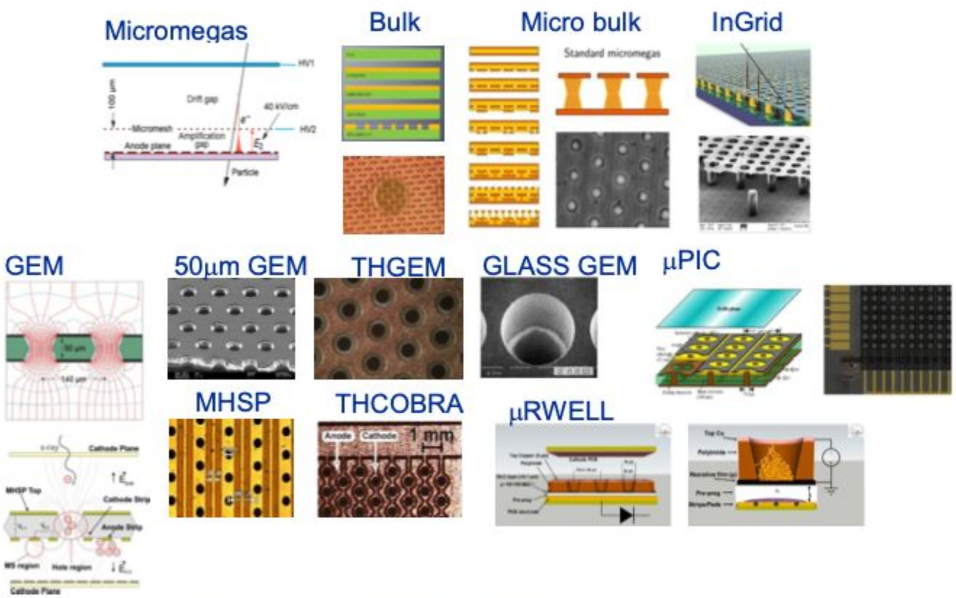
SDHCAL with GRPC



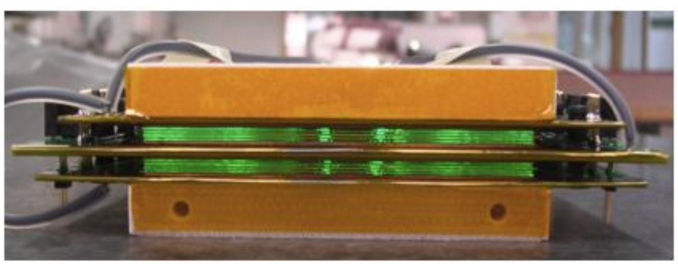
Alternative Micromegas boards

Micromegas prototype of 1x1m2 consisting of six independent Micromegas boards

Ongoing efforts



ALICE-TOF MRPC



Impressive amount of R&D (and pace of development) for MPGDs.

- Still young detectors ~ 10 years
- Most mature technologies being used in LHC phase 2 upgrades

Main challenge:

- Engineering and realization of large area detectors

Multi-gap RPC are a proven option to operate in large particle fluxes.

- 20 ps time resolution achievable

Main challenge:

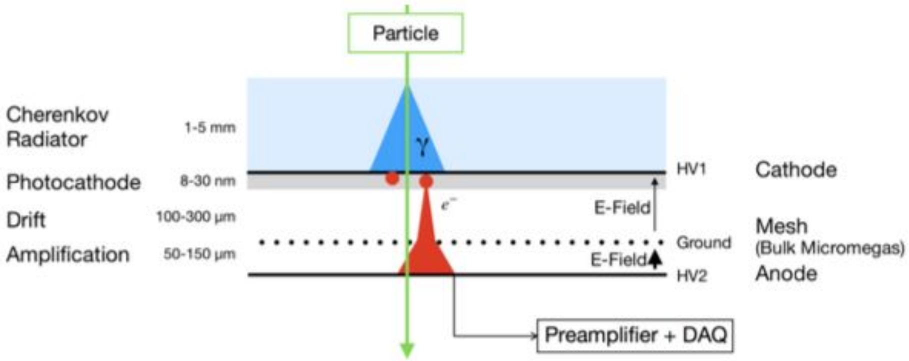
- current gas mixture which has a high Global Warming Potential

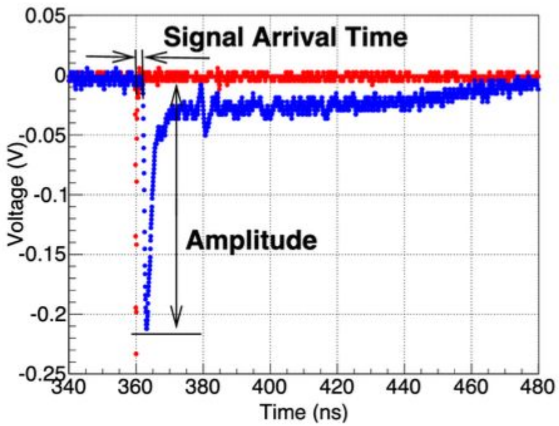
R&D examples: PICOSEC

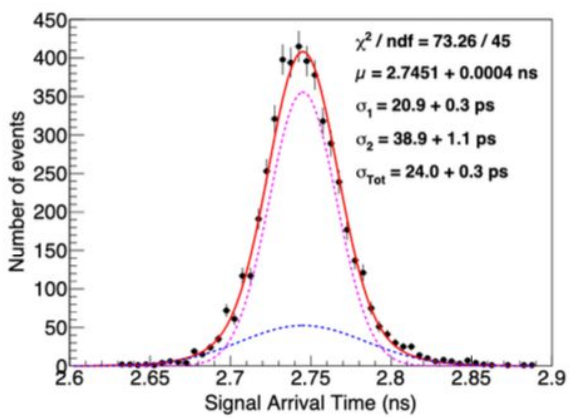
Detect charged particles through **UV Cherenkov photons**.

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.



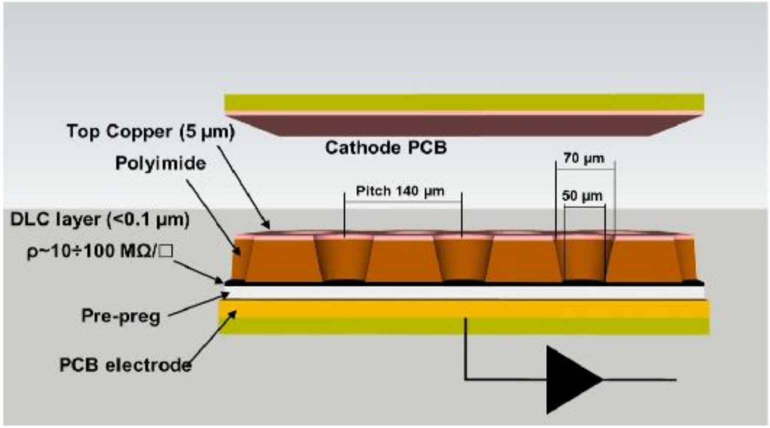




R&D examples: µ-RWELL

Detector composed of two elements:

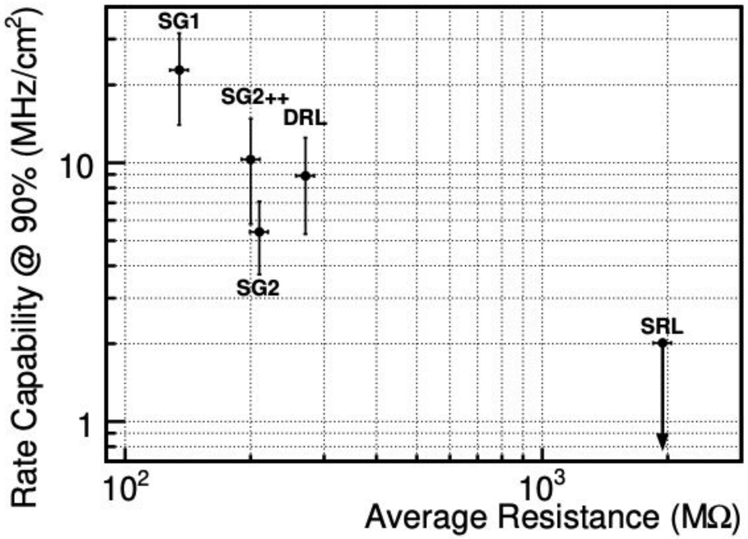
- µ-RWELL_PCB (amplification-stage resistive stage readout PCB)
- drift/cathode PCB defining the gas gap



The "WELL" acts as a multiplication channel for the ionization produced in the gas of the drift gap.
Different high-rate layouts.

General characteristics:

- very reliable
- low discharge rate
- adequate for high particle rates
- space resolution < 60 µm
- time resolution < 6 ns



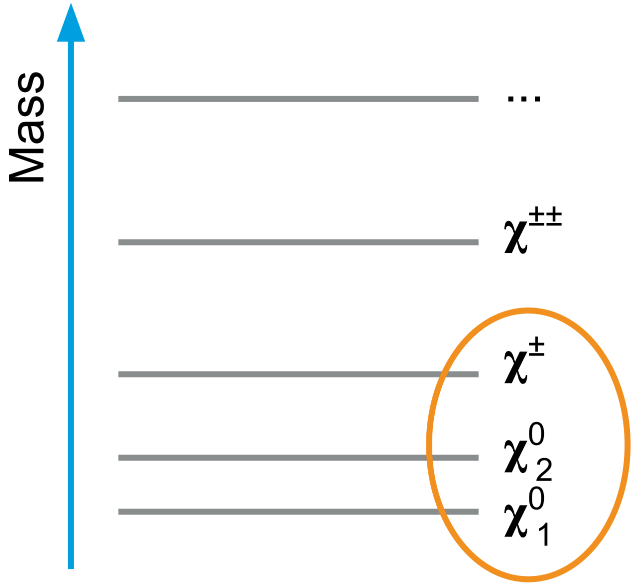
Electroweak multiplets and dark matter

Start from the simplest interpretation of dark matter:
it is the **thermal relic of at least a new stable neutral particle**.

- The SM is extended with *n*-tuplets that predict such neutral state χ^0
- Stability of χ^0 is ensured by the theory, or by an external stabilisation mechanism
- Small mass splitting between the components of the multiplet
- **Heavier states can be long-lived**

Experimental signatures:

- Displaced vertices
- Kinked tracks
- Displaced tracks
- **Disappearing tracks**



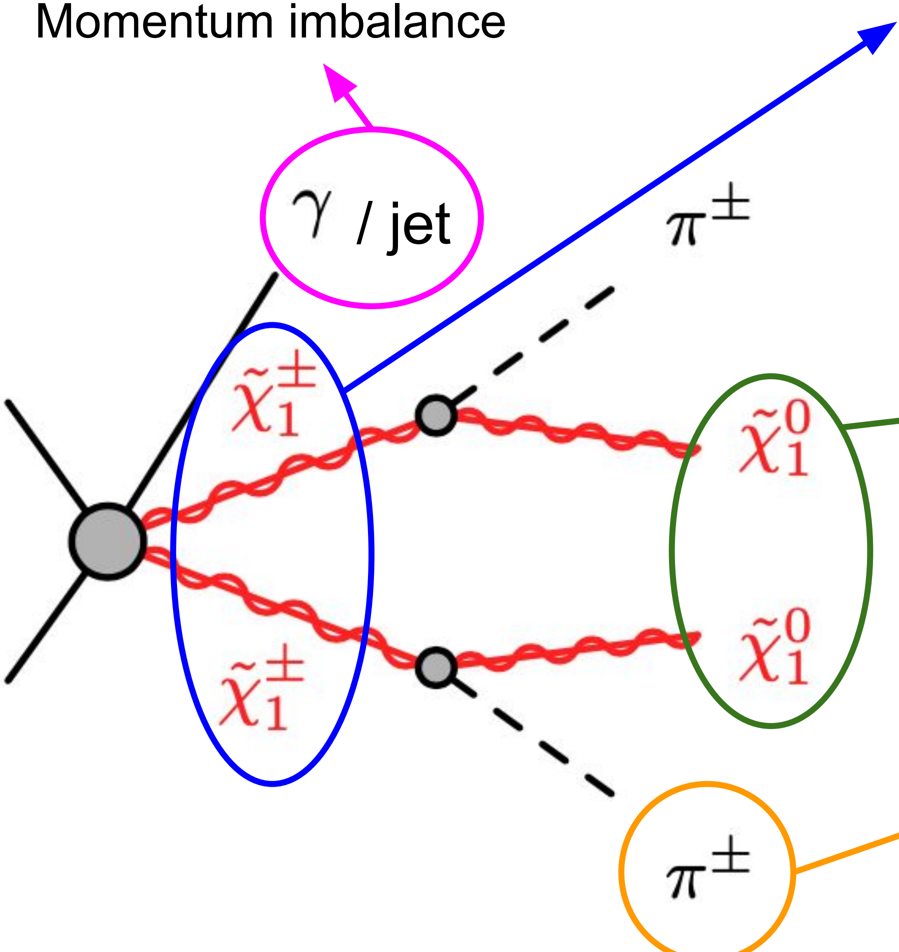
Consider the MSSM case:
doublets (winos) and
triplets (higgsinos)

The search for disappearing tracks

An example from supersymmetry

ISR/FSR:

- “Trigger” the event
- Momentum imbalance



Charginos:

- Long lived, charged
- Reconstructable as “tracklets”

Neutralinos:

- Stable, neutral
- Invisible
- Momentum imbalance, missing mass

Displaced pions:

- Possibly reconstructable
- Not considered here

Where to look for these?

If dark matter is explained by a single particle, we expect this particle to be heavy.

Higgsino ~ 1.1 TeV

Wino ~ 2.7 TeV

Beyond the reach of the LHC!

- To characterise this particle in a lab, a higher energy collider is required.
  - FCC-hh expected to deliver proton-proton collisions at $\sqrt{s}$ = 100 TeV.

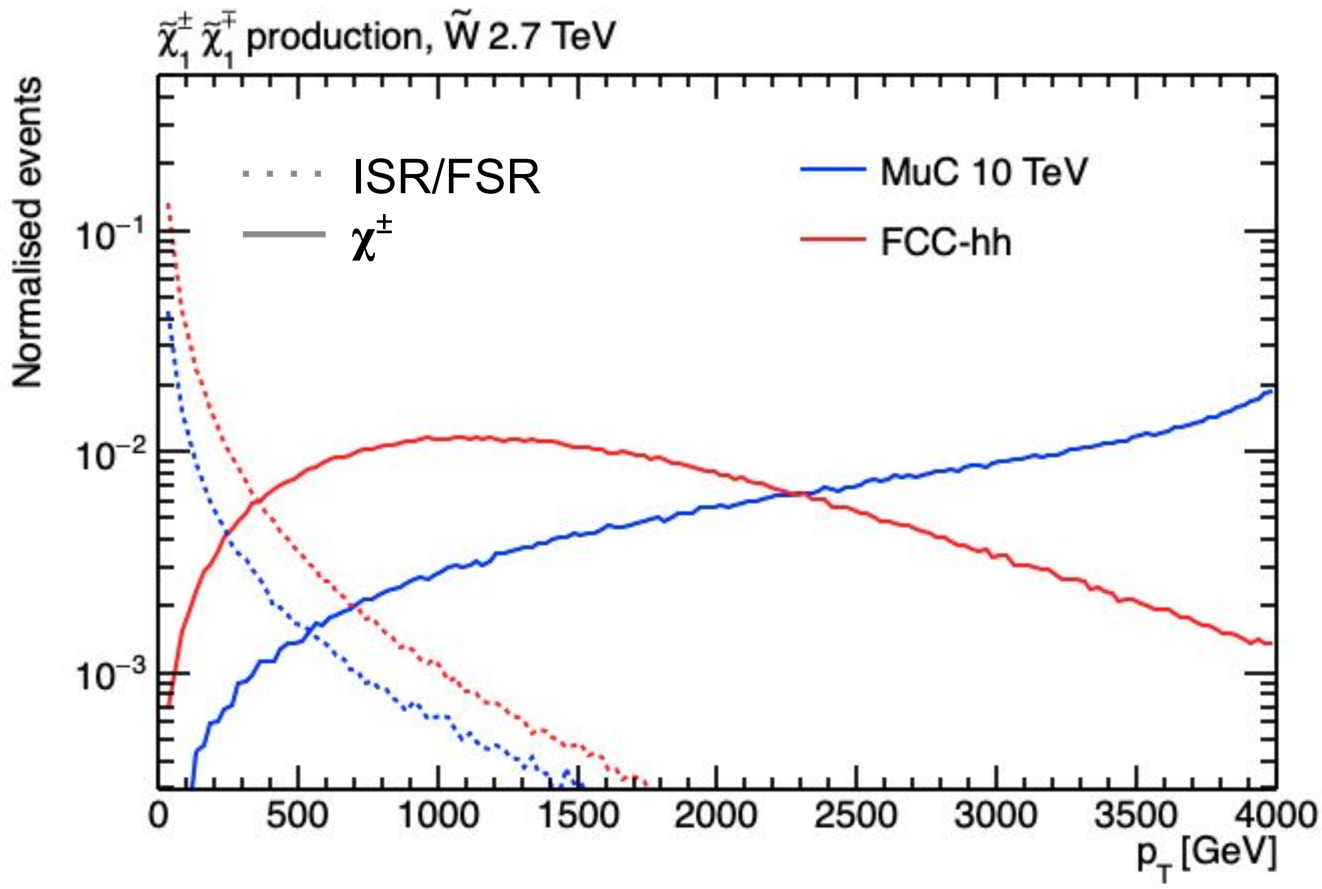
    (M. Saito, R. Sawada, K. Terashi, S. Asai, arXiv: 1901.02987)

  - **A high energy muon collider at $\sqrt{s}$ = 3, 10 TeV (MuC 3, MuC 10).**

    (R. Capdevilla, F. Meloni, R. Simoniello, J. Zurita, arXiv: 2102.11292)

Kinematic expectations

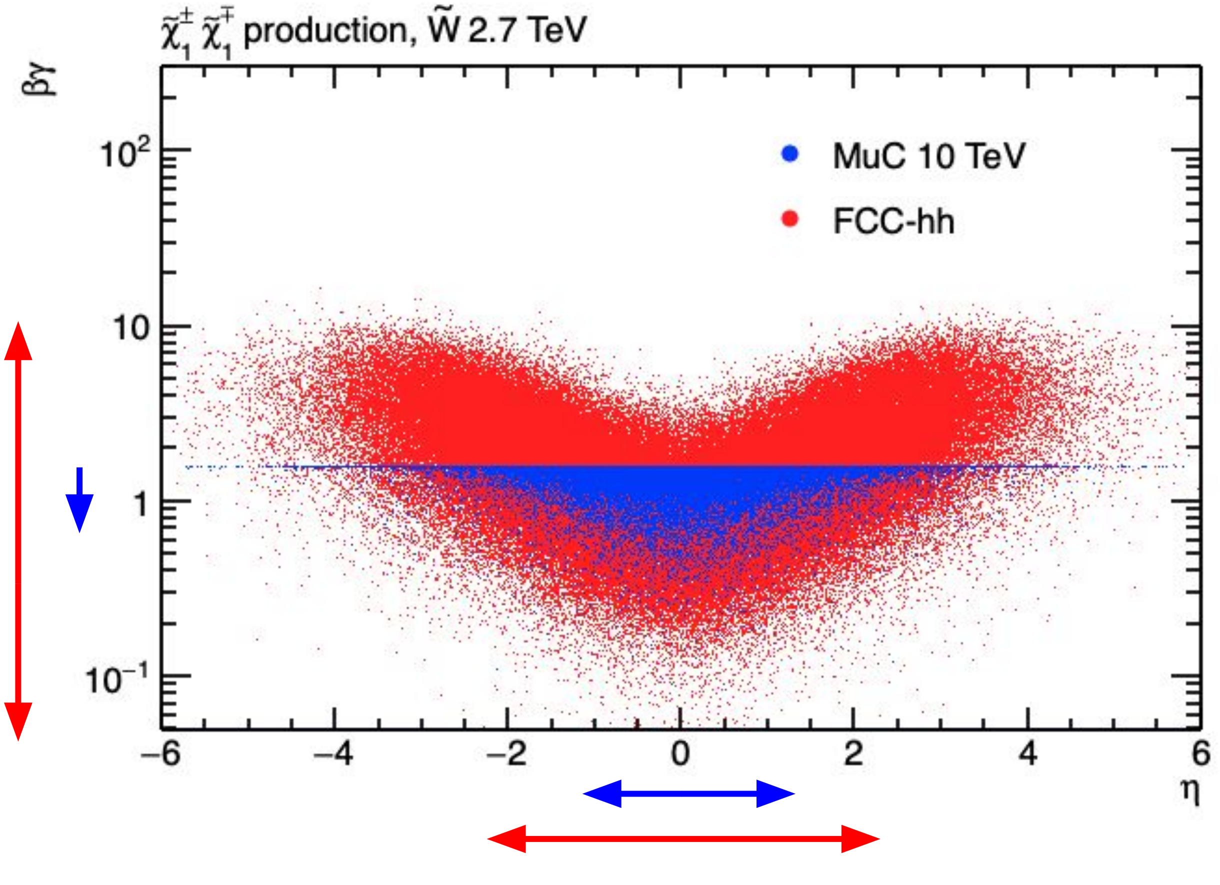
Comparing the FCC-hh and MuC 10



Lorentz boosts

FCC-hh spread over a large interval

MuC much more peaked

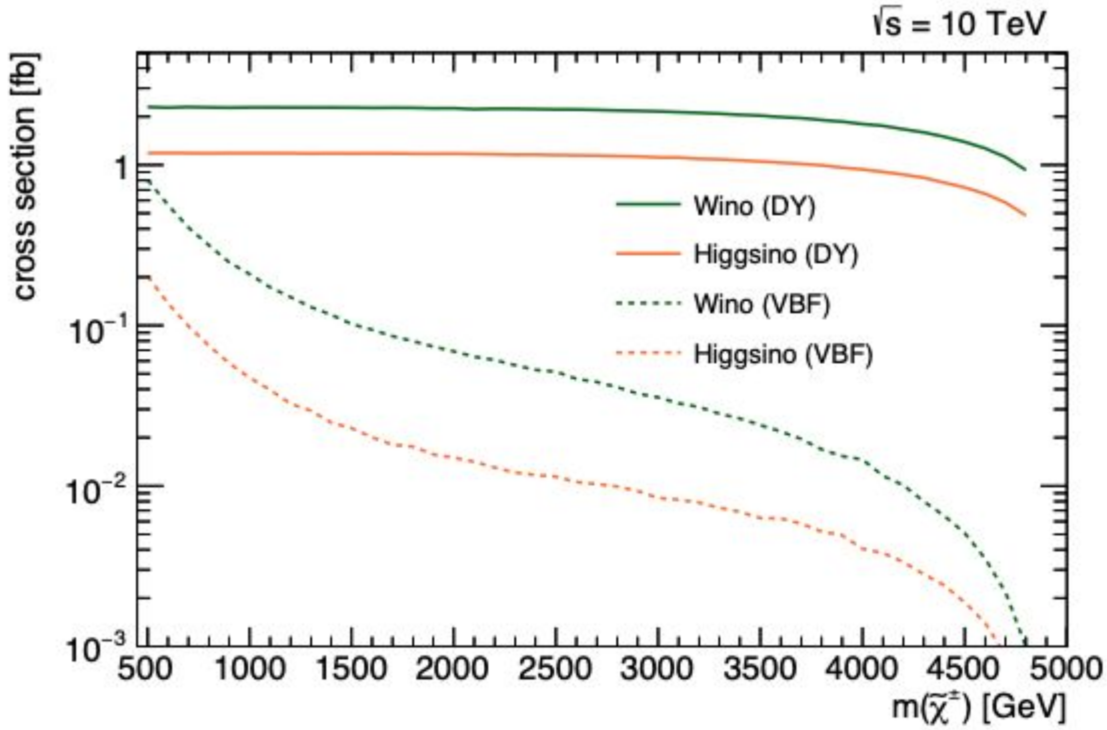


MuC 10 events are in general more central than FCC-hh

Expected production rates

At the MuC 10

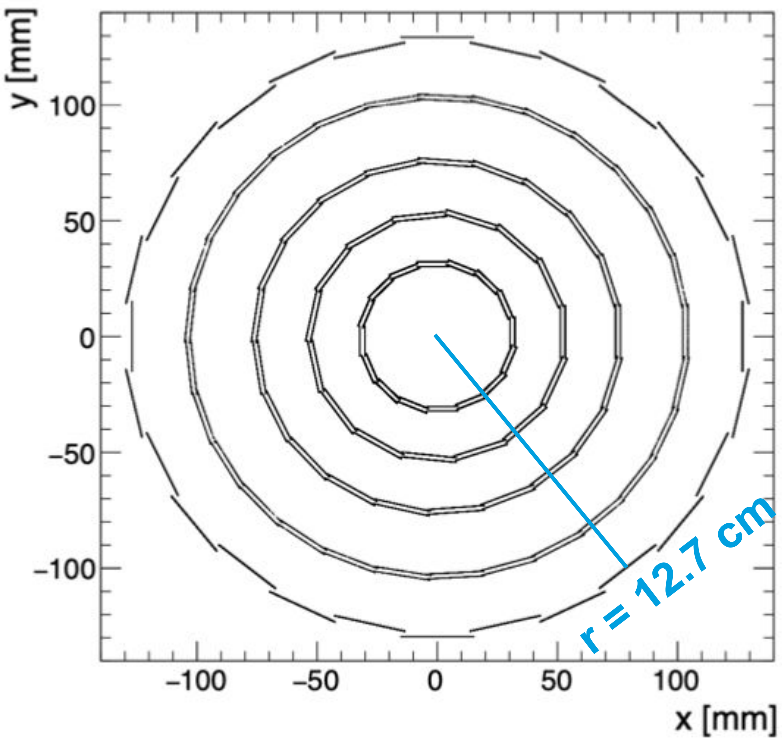
Cross-section predictions from MadGraph5_aMC@NLO 2.8.2

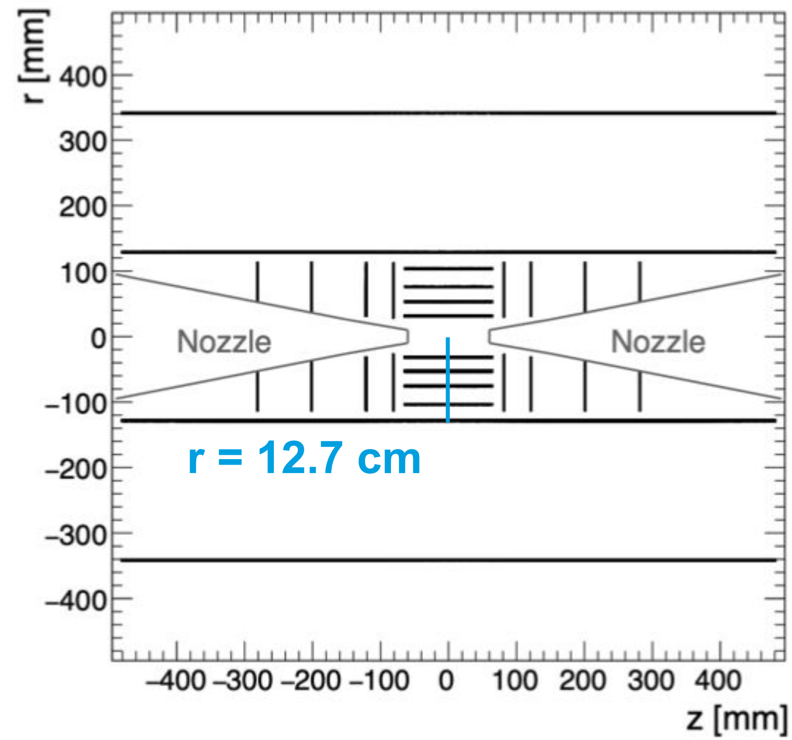


Expect to produce about 10000 $\chi^{\pm}\chi^{\mp}$

- Similar expectation for MuC 3 (1/10 int. luminosity but x10 cross-section)
- s-channel 2→2 "Drell-Yan" dominant in the range of masses considered
- Photon-initiated production possible (arXiv: 2009.11287) but sub-dominant

The tracking detectors





Vertex Detector (VXD)

Double-sensor layers
(4 barrel, 4+4 disks)

Inner Tracker (IT)

Single-sensor layers
(3 barrel, 7+7 disks)

Outer Tracker (OT)

Single-sensor layers
(3 barrel, 4+4 disks)

50 µm thick
5 µm single-point resolution
30 ps time resolution

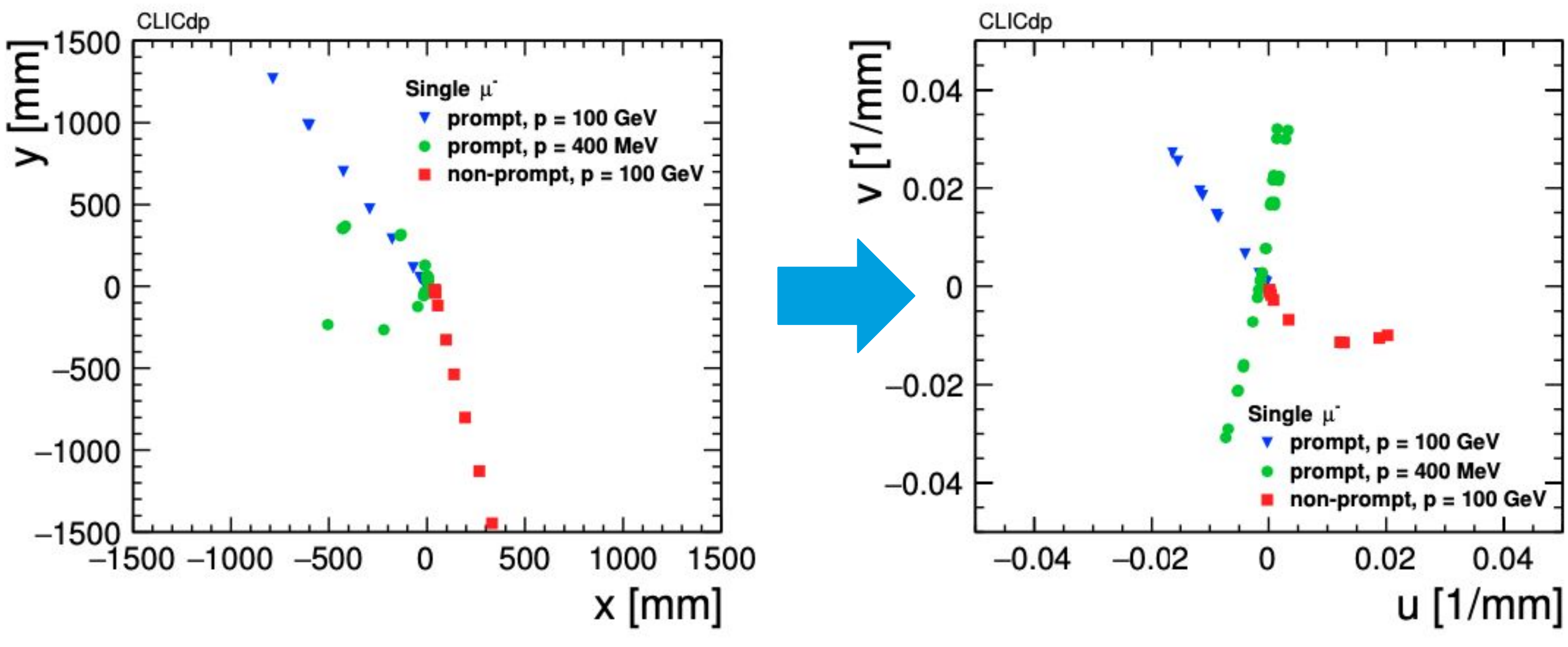
100 µm thick
7 x 90 µm single-point resolution
60 ps time resolution

Track reconstruction

Use conformal tracking algorithm (developed for CLIC, arXiv: 1908.00256):

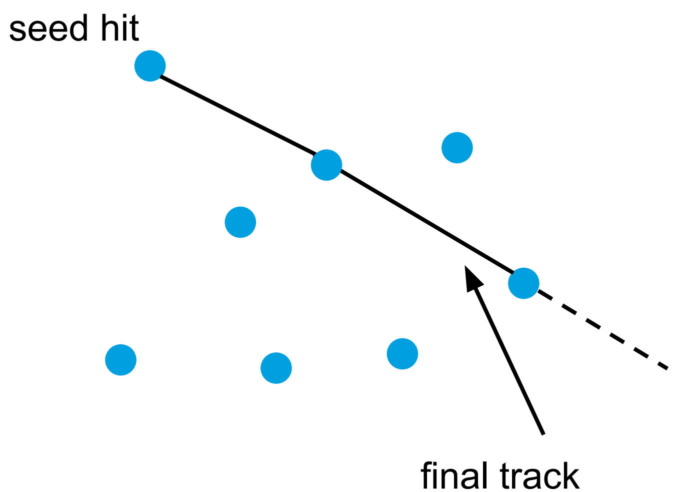
1. Conformal mapping

$$u = \frac{x}{x^2 + y^2} \quad v = \frac{y}{x^2 + y^2}$$



Track reconstruction

2. Cellular automaton-based track finding



- Consider only a **subset of the hits**
- Each hit is used as seed to **look for neighbours**, with cuts on angles and distances
- **Seed cells** are created and the search for neighbours is repeated
- **Cellular tracks** are groups of cells
- The **best tracks** (lowest χ^2/N.d.f.) are **kept**, the hits marked as used and the search repeated
- Seed tracks can be **extended** (e.g. with hits from another sub-detector)

This specific case

We want to reconstruct as short as possible tracks.

- Minimum 4 hits (2 double layers)
  - Minimal reconstructable decay length is 5.1 cm

If we consider all hits, it takes **more than a week** to reconstruct the tracks from a single event.

Need to simplify the problem!

- Regional tracking (in bins of the polar angle θ)
- Tight cuts on cell creation (both in *rφ* and *rz* planes)
- Add hit-level selection requirements

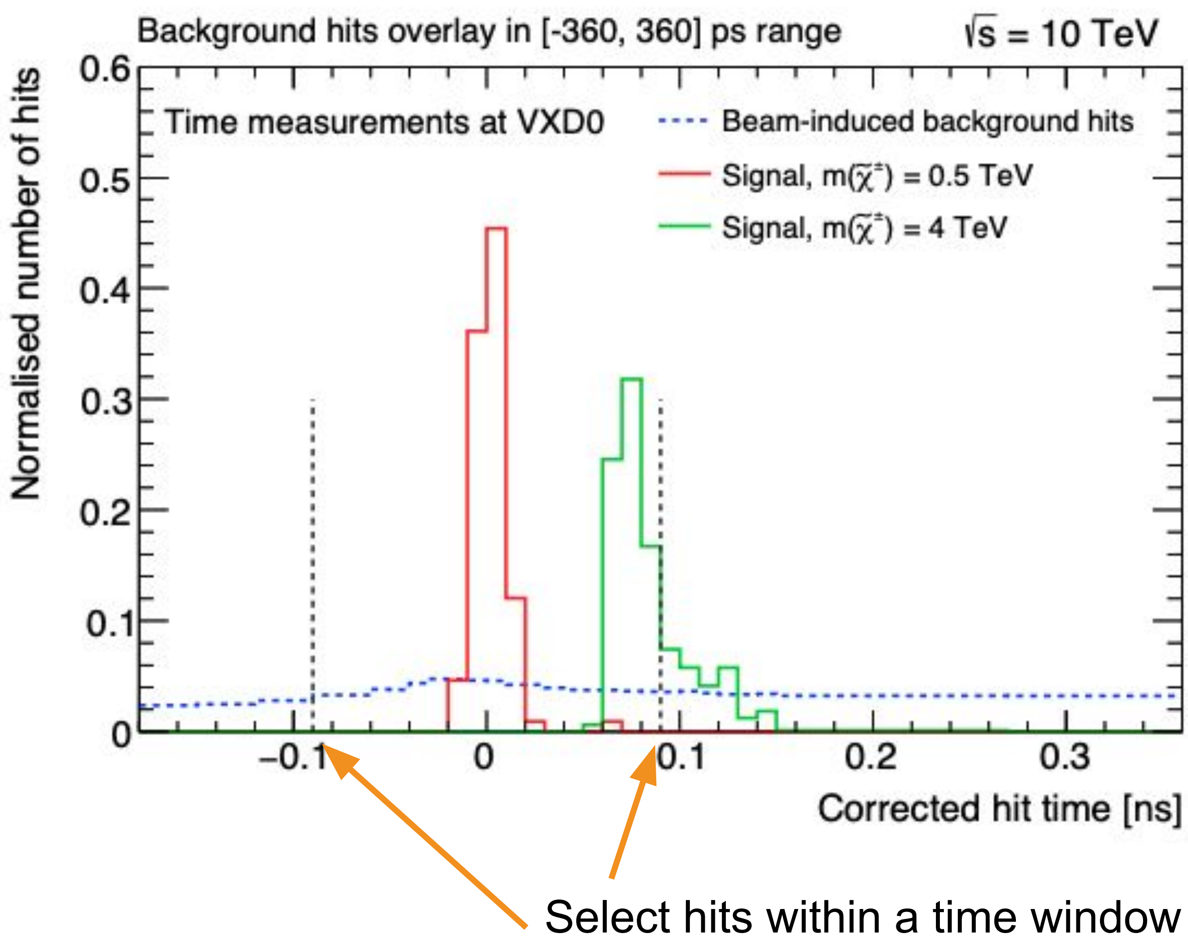
In the future testing more aggressive LHC-like algorithms (ACTS?) could greatly improve the run-time.

BIB rejection: timing

Exploit particle arrival times to reduce BIB

- Correct for time of flight (assuming β=1)

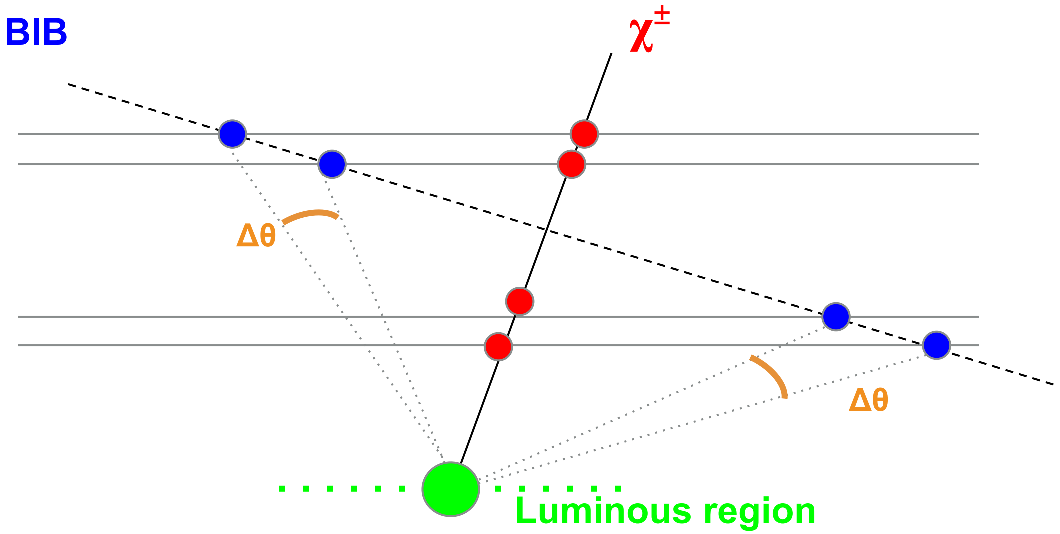
$$\text{Corrected time} = t_{measured} - \frac{|r|}{c}$$



BIB rejection: stub tracks

The double-layer layout of the vertex detector can be exploited to reject hits from BIB particles.

- Look for pairs of hits in neighbouring double-layers forming “stub tracks” that point back to the luminous region.



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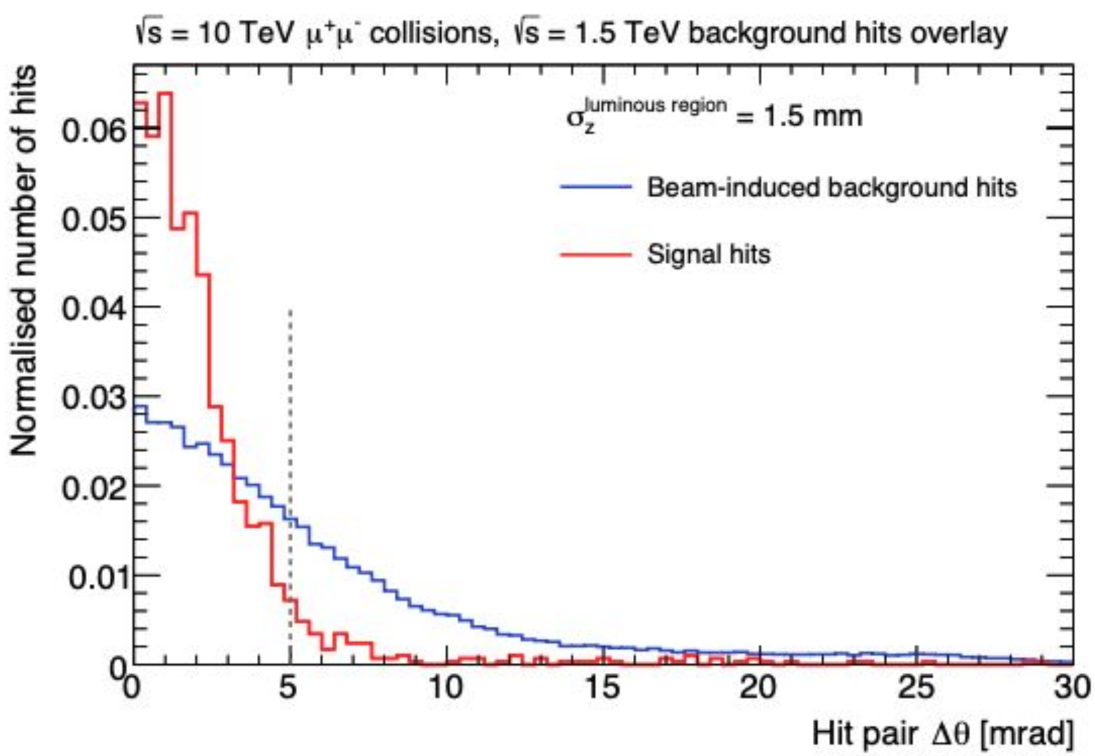


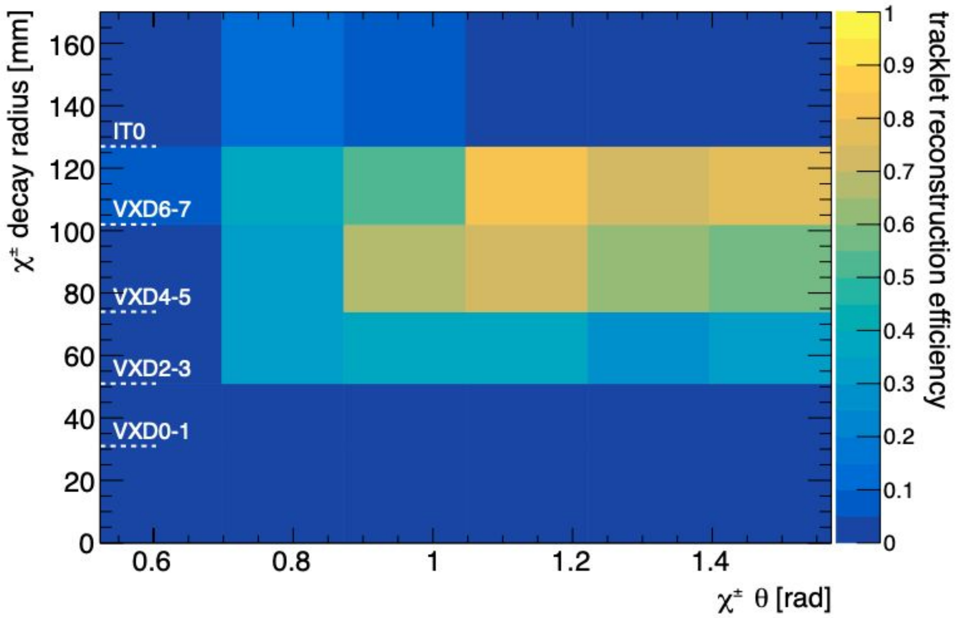
Tracklet reconstruction efficiencies

After BIB rejection cuts

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

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

- Reconstructable tracks are defined as tracks from $\chi^{\pm}$ with at least 4 hits
- Tracks must have at least 70% of hits from a single $\chi^{\pm}$
- Evaluated vs the $\chi^{\pm}$ decay radius and polar angle θ

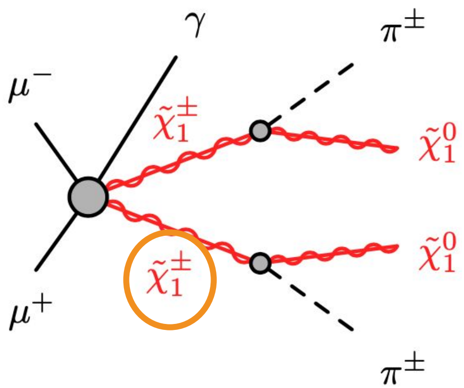


Towards quantifying the sensitivity

- Perform analysis on **smeared truth-level events**
  - Use Delphes card (v0) by M.Selvaggi for high-level reconstructed objects
  - Use tracklet reconstruction our response functions from full simulation
  - Overlay BIB tracklet background from full simulation

- Focus on fake tracklets and assume that hadron and lepton tracks lost to multiple scattering can be made negligible (as in LHC searches)
  - **σ** $(\mu^+\mu^- \rightarrow \nu\nu)$ **~ 60000 fb** (dominated by t-channel W exchange)
  - **σ** $(\mu^+\mu^- \rightarrow \chi^\pm\chi^\mp)$ **~ 1-2 fb**

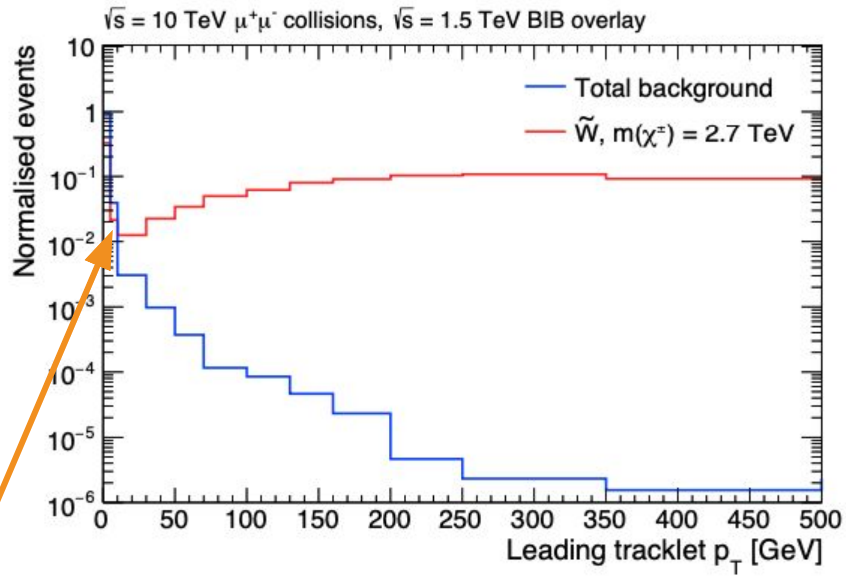
Event selection



Relatively simple event selection:

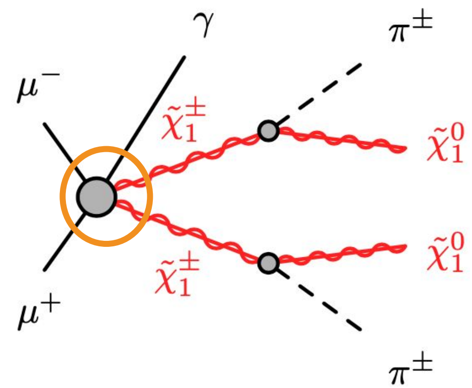
- Tracklet p_T (single most important quantity)

Requirement / Region	SR_{1t}^{γ}	SR_{2t}^{γ}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25



Peak at low p_T in signal events due to BIB overlay

Event selection



Relatively simple event selection:

- The $\chi^{\pm}\chi^{\mp}$ come from the same vertex

Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
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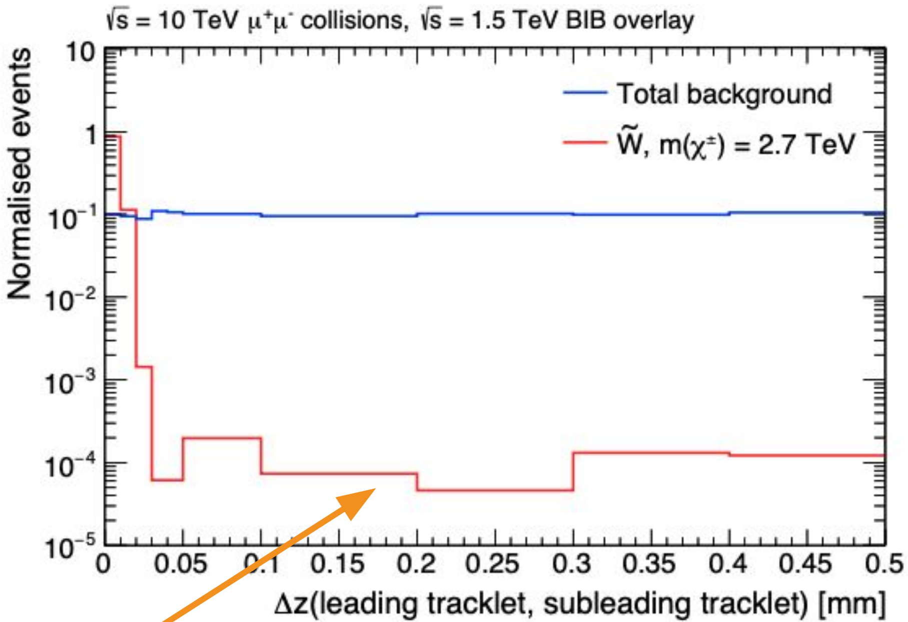
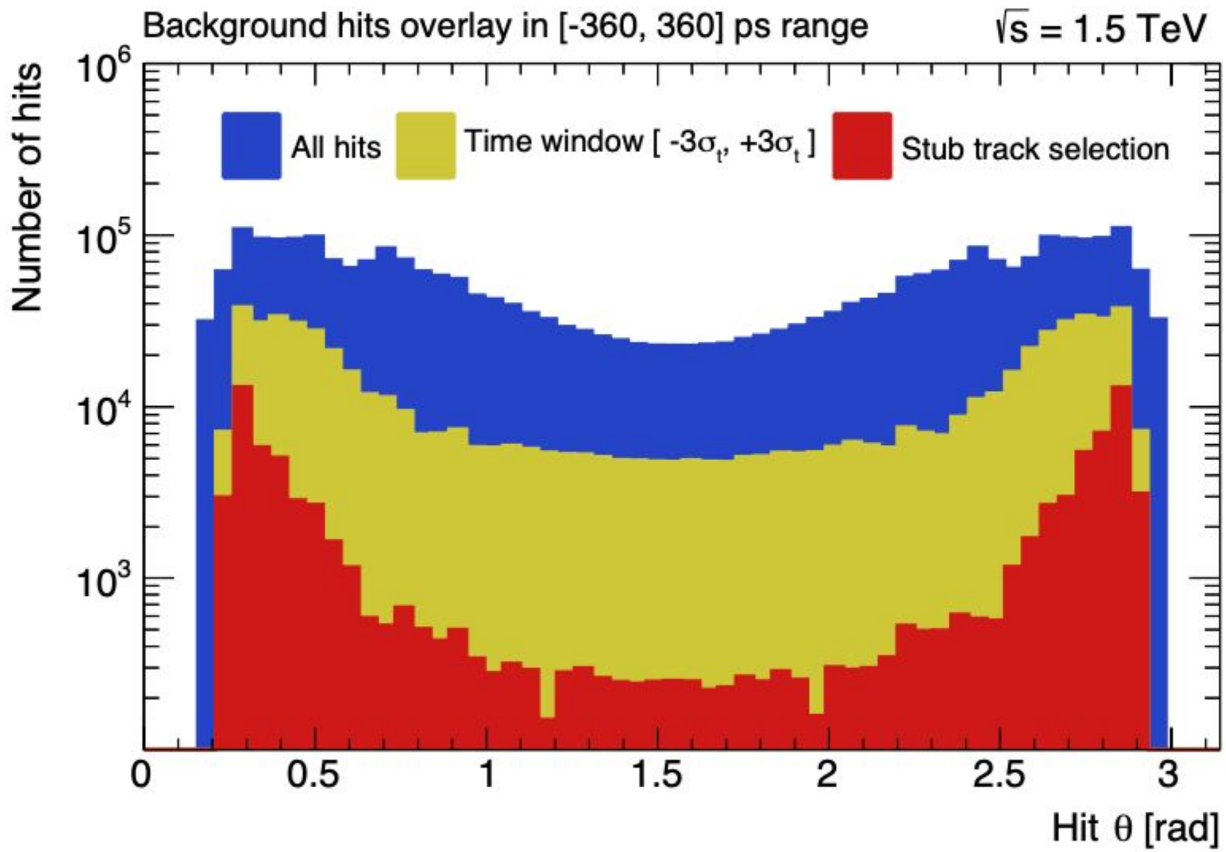


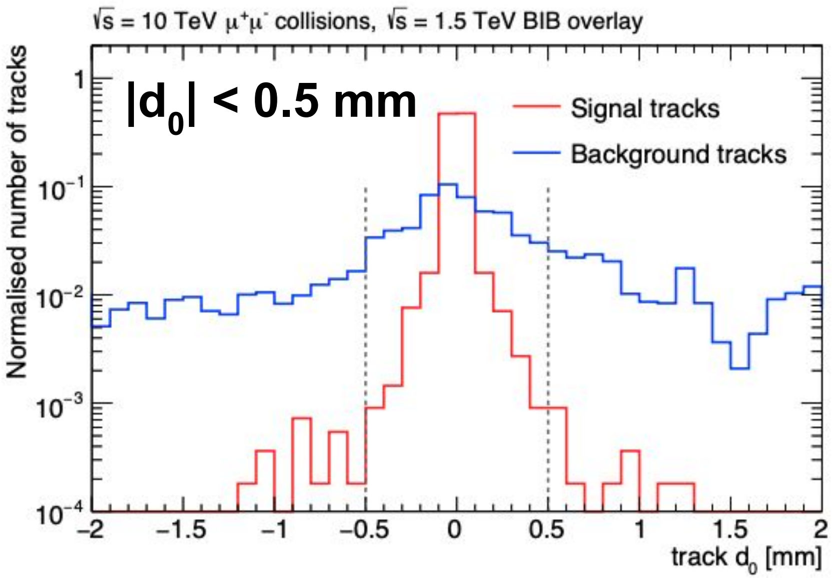
Long tails from events with at least one fake tracklet

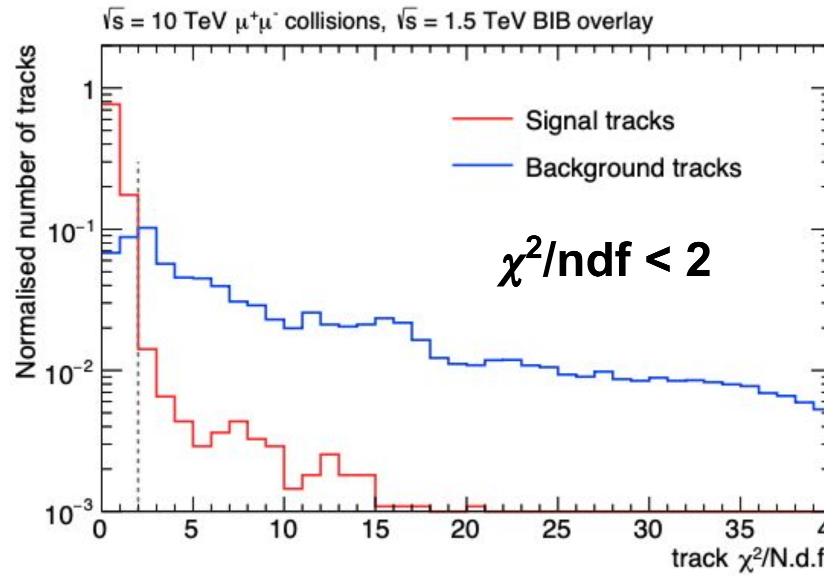
BIB rejection
Angular summary

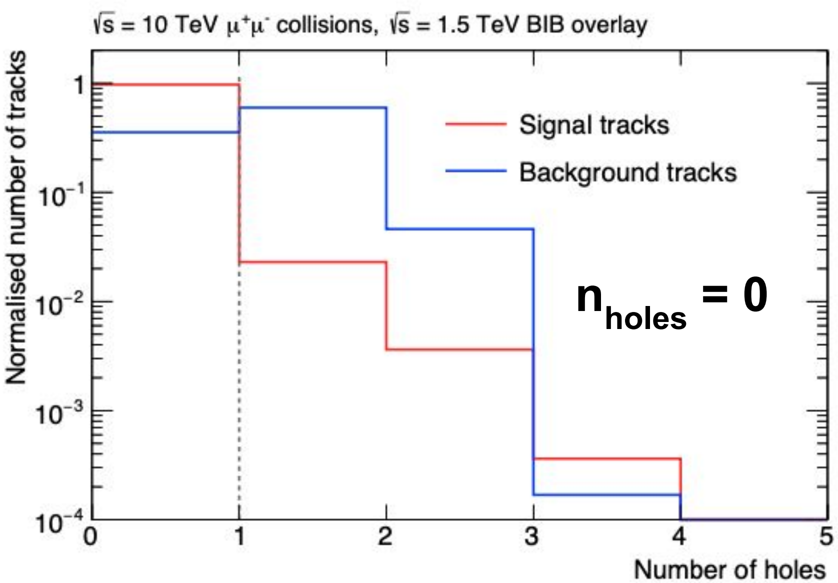


Selections most effective in the central region, which is favoured by signal.

Track-level selections







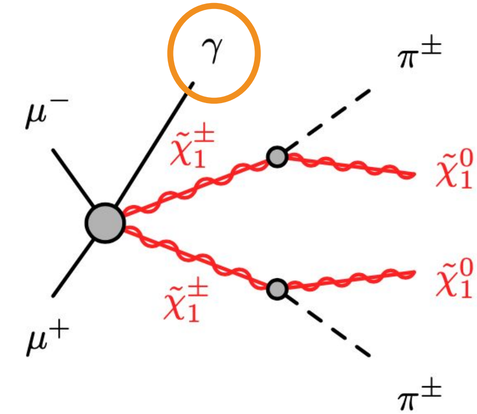
Several selections applied to reduce the number of tracks from BIB particles.

- No cuts on z_0 to reduce dependence on beamspot size

After cuts:

- 0.08 BIB tracks per event
- 90% signal track efficiency

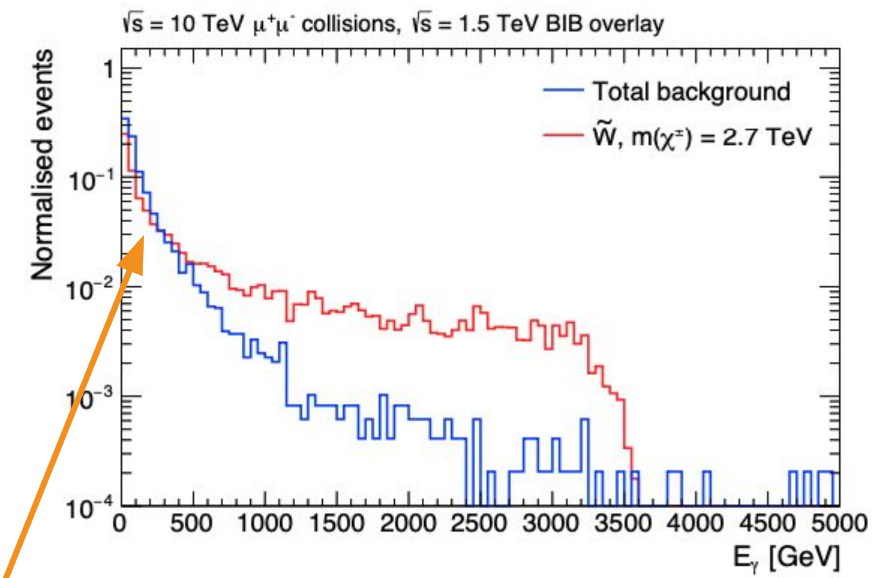
Event selection



Relatively simple event selection:

- ISR/FSR photon

Requirement / Region	SR^γ_{1t}	SR^γ_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25



No strong discrimination, opted for low energy selection (just above the “supported” minimum)

Muon colliders: prospects