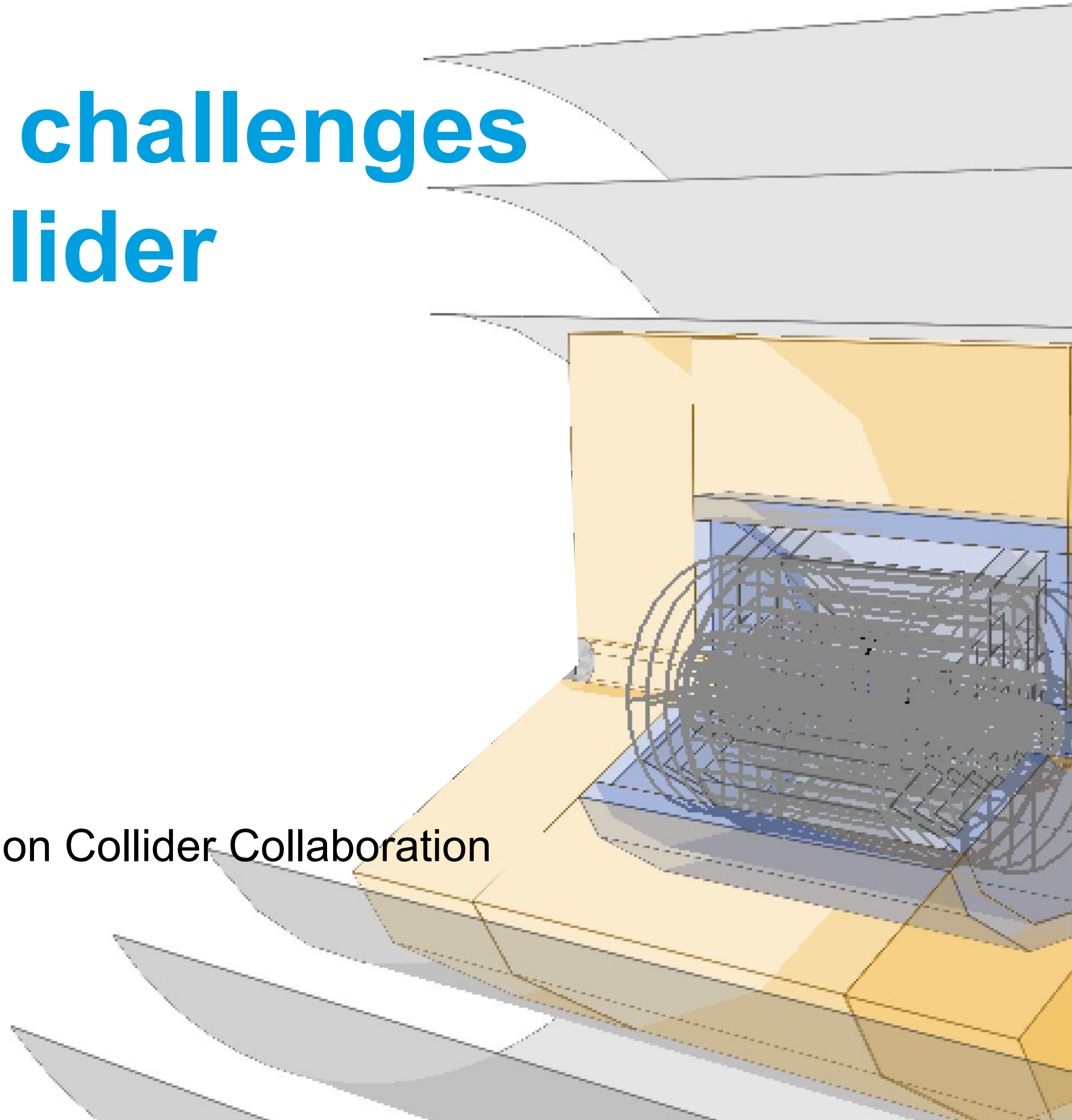
Experimental challenges at a muon collider



LHCP 2023, Belgrade
24/05/2023

Federico Meloni (DESY),
on behalf of the International Muon Collider Collaboration

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES DESY. International MUON Collider Collaboration MuCol physics/9901022

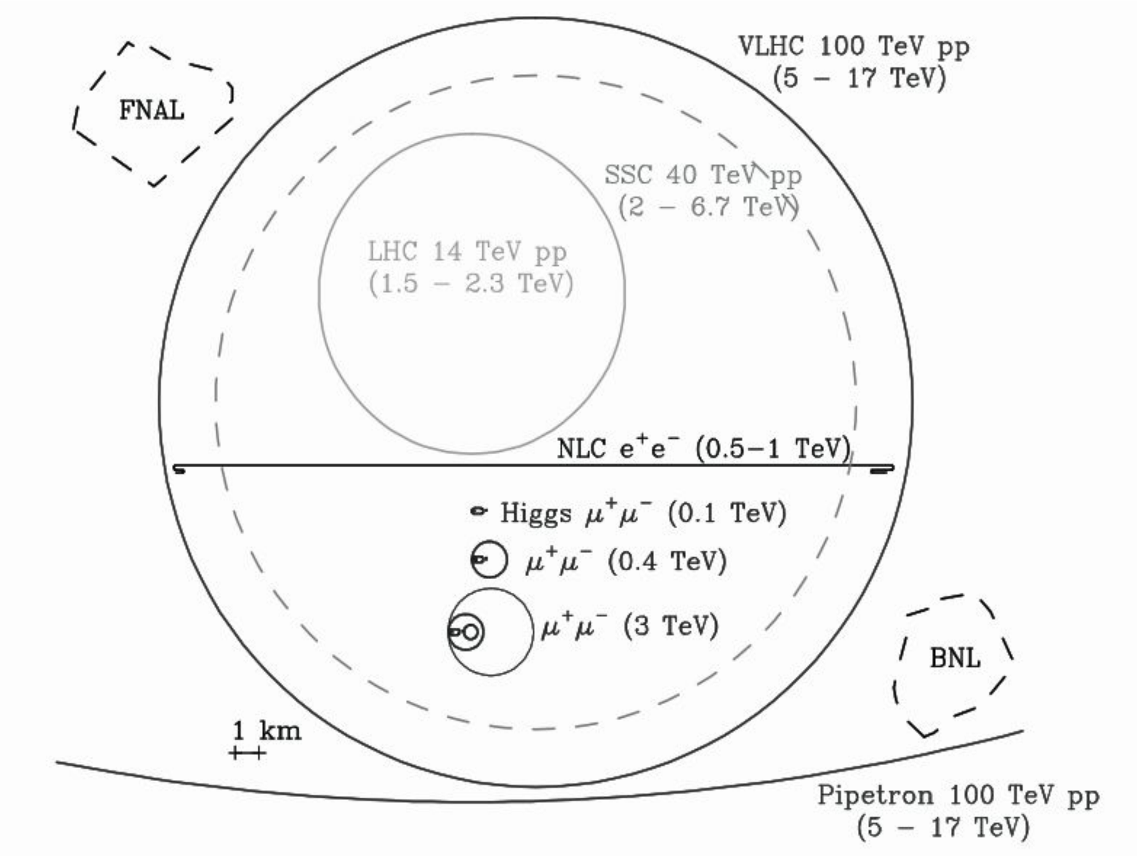
High-energy microscopes

We conventionally pursue HEP research 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

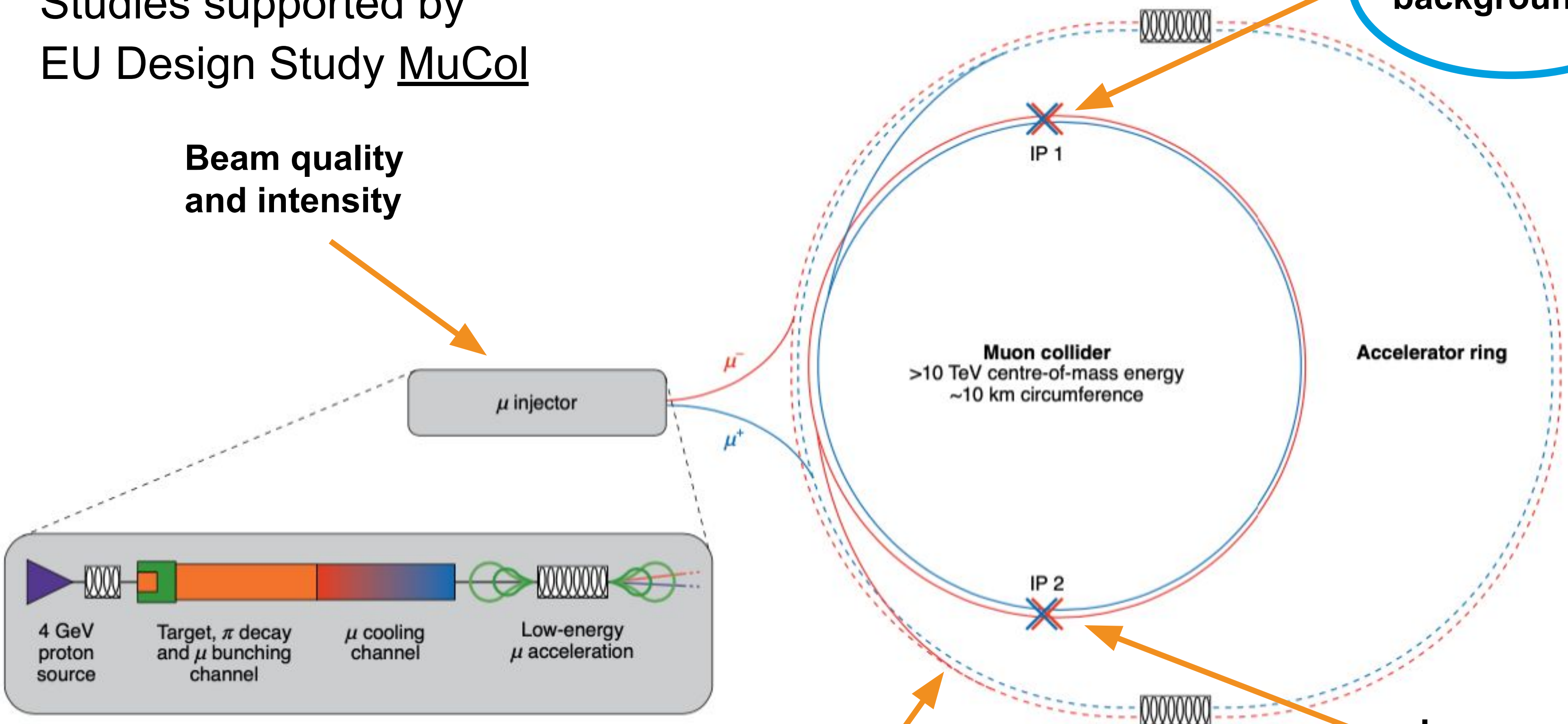
Key challenges

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

- Studies supported by EU Design Study MuCol

Beam quality and intensity

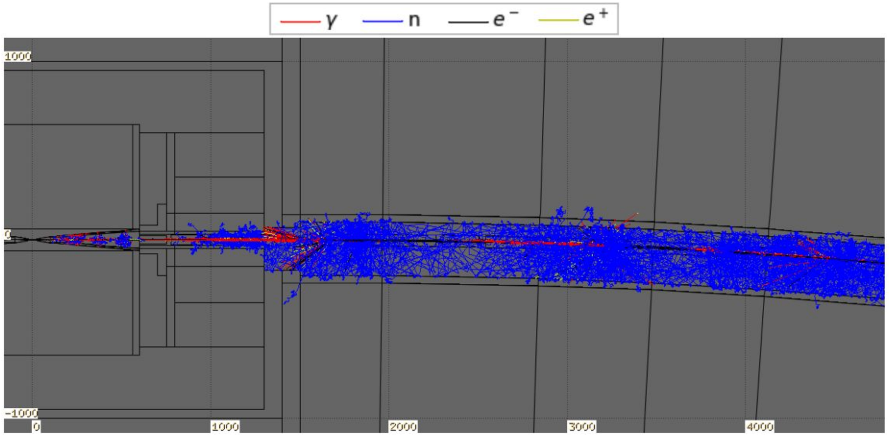
Beam induced backgrounds

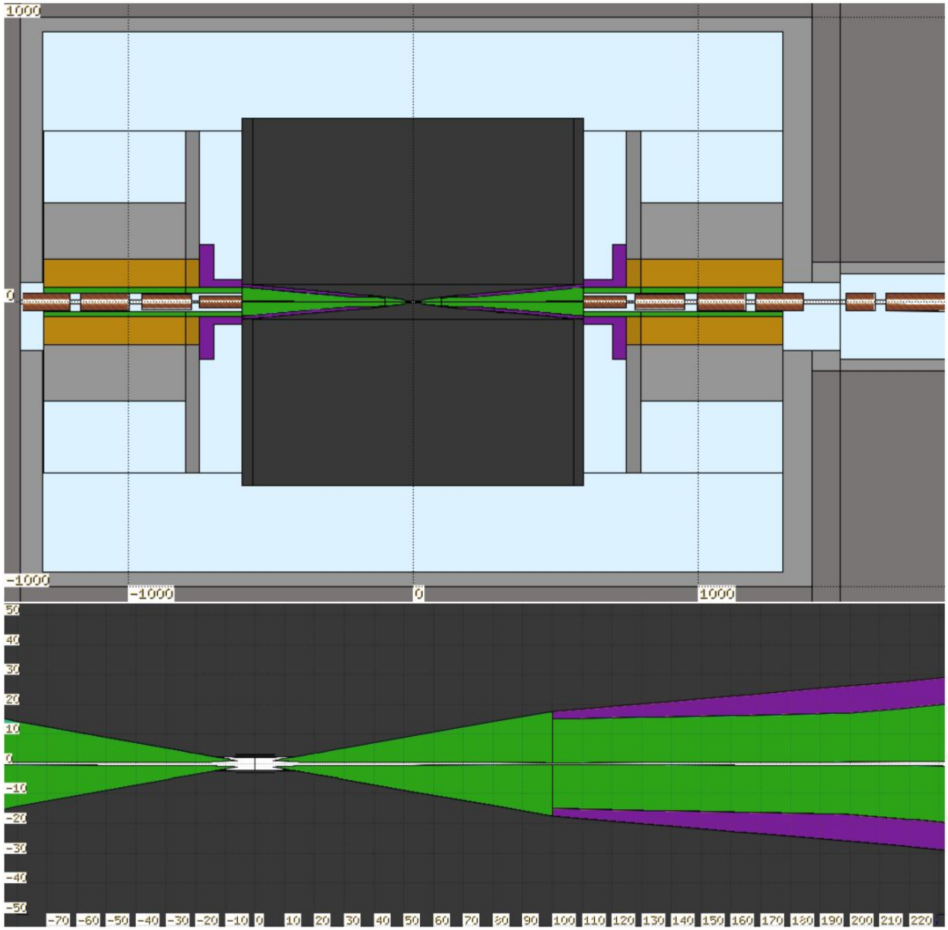


Large neutrino flux

Cost and power

The beam-induced backgrounds (BIB)





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

Need shielding: tungsten nozzles with borated polyethylene (BCH_2) coating

The machine-detector interface is a **unique challenge of Muon Colliders**

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Collision paradigm

Circulate two bunches and re-fill when they are depleted

- 1000 times lower collision rate than LHC
- **Luminosity increases with the square of beam energy**
  - Muon lifetime increases
  - Transverse emittance decreases
- To first approximation, BIB rate does not depend on E

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)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

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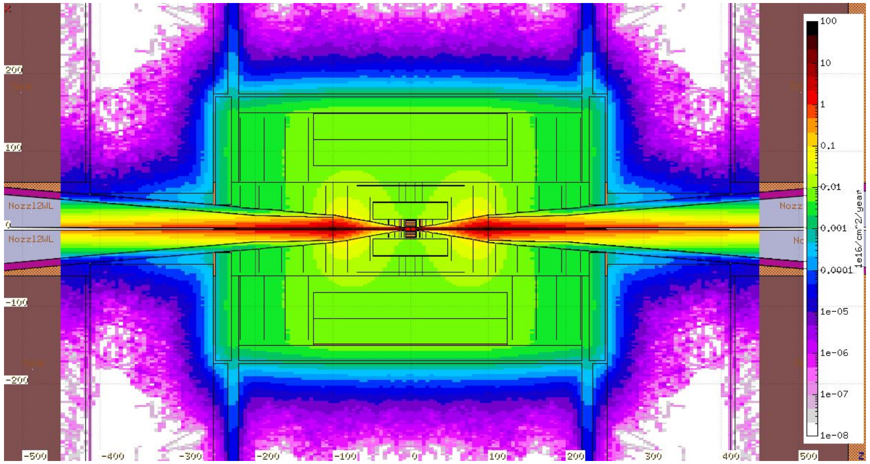
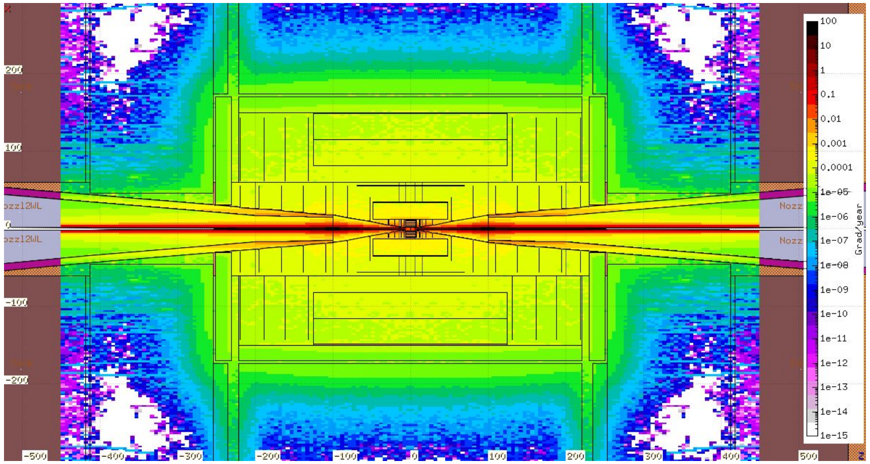
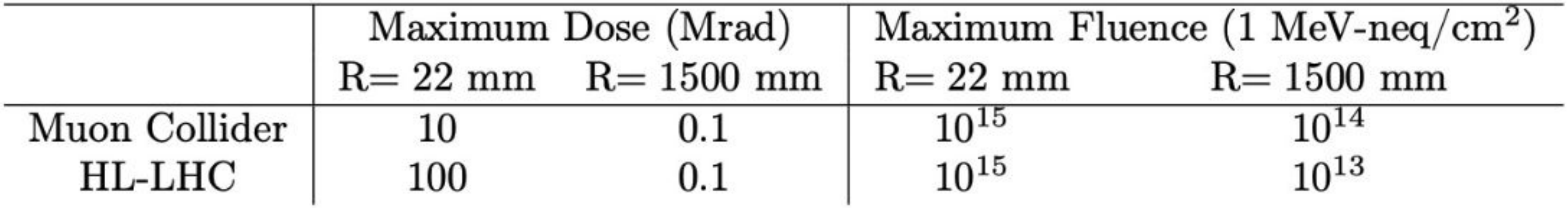
Detection Environment



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



Total Ionising Dose for 200 days of operation



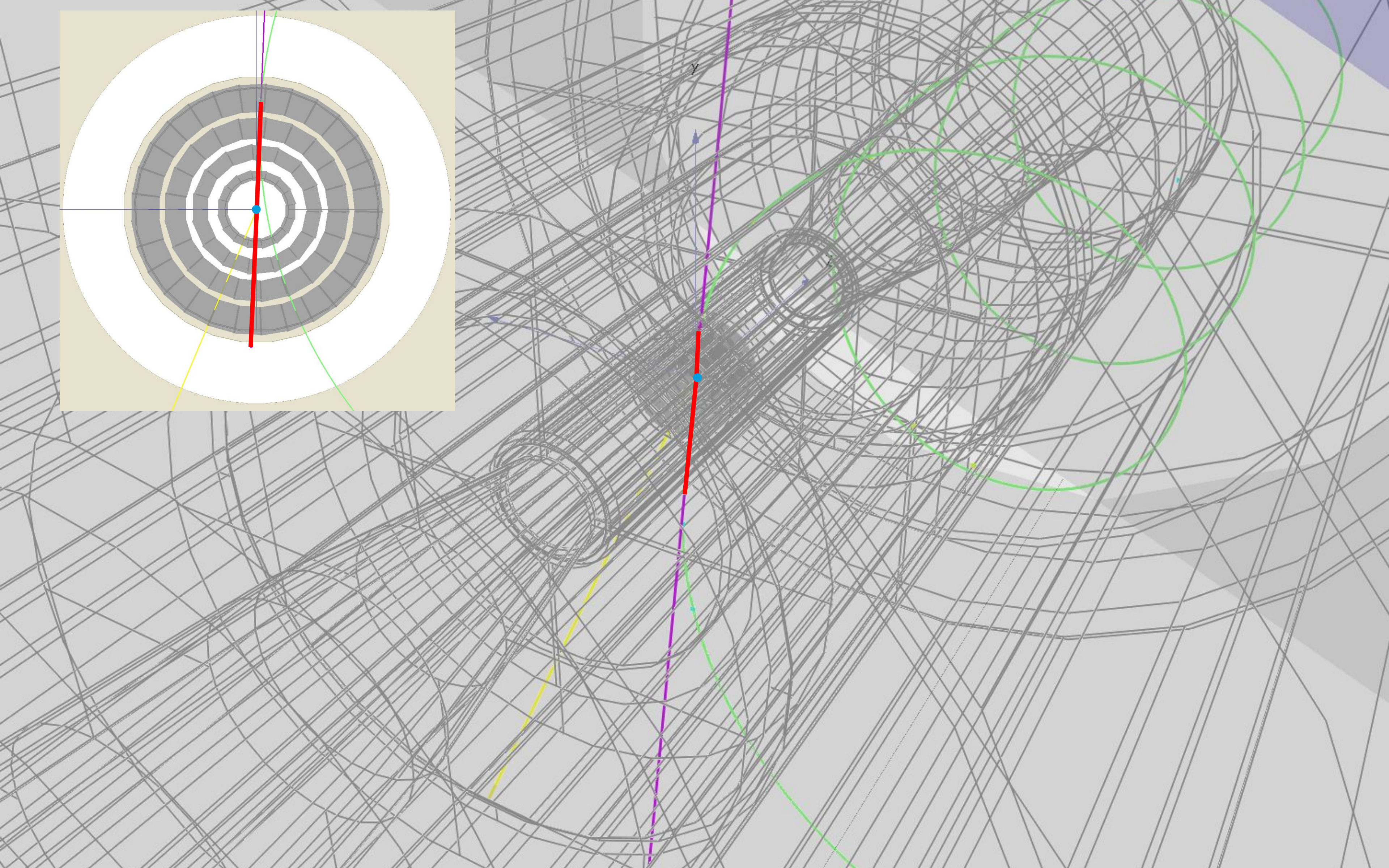
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

FCC-hh requirements

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

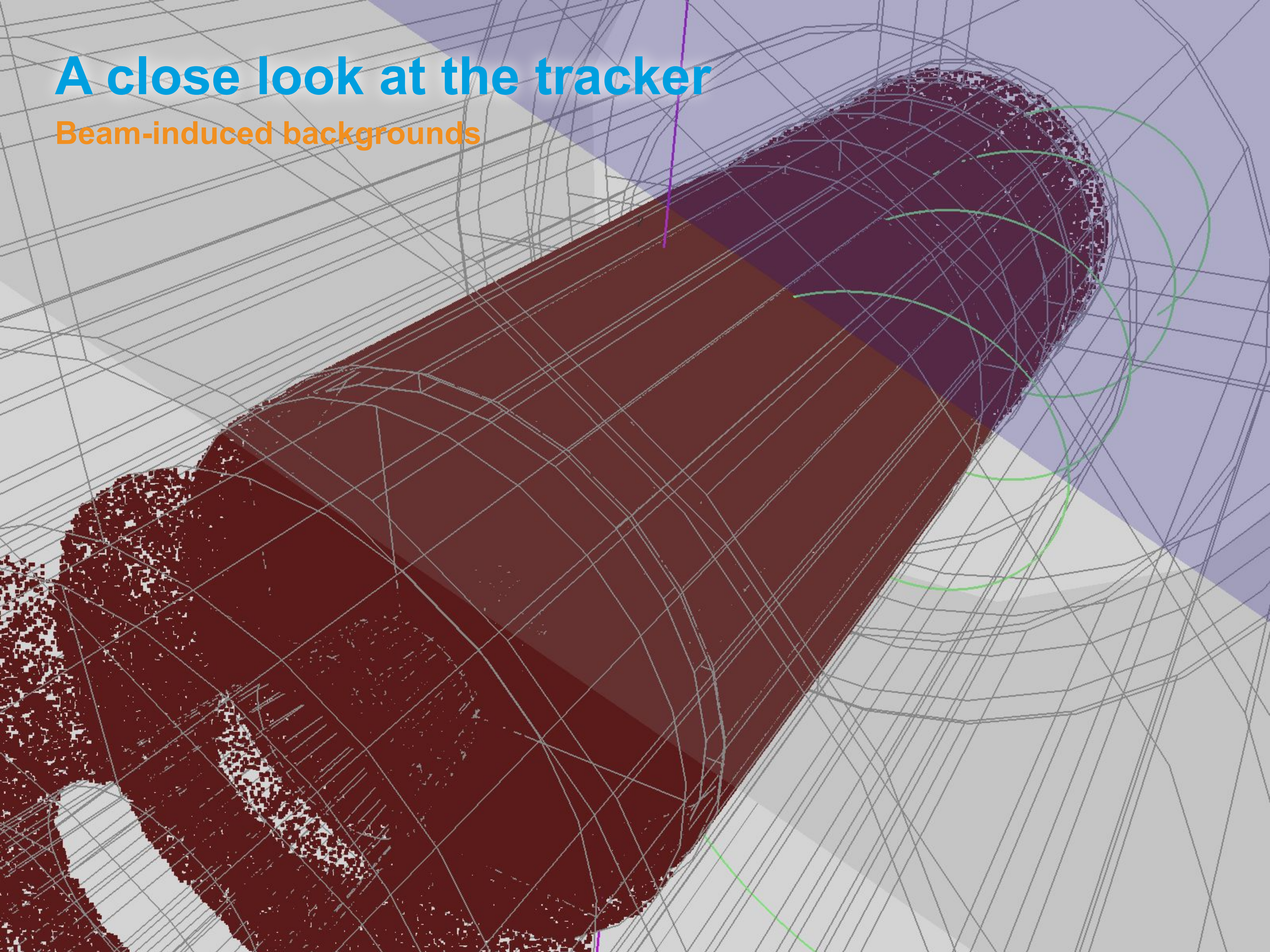
A close look at the tracker

No beam-induced backgrounds



A close look at the tracker

Beam-induced backgrounds



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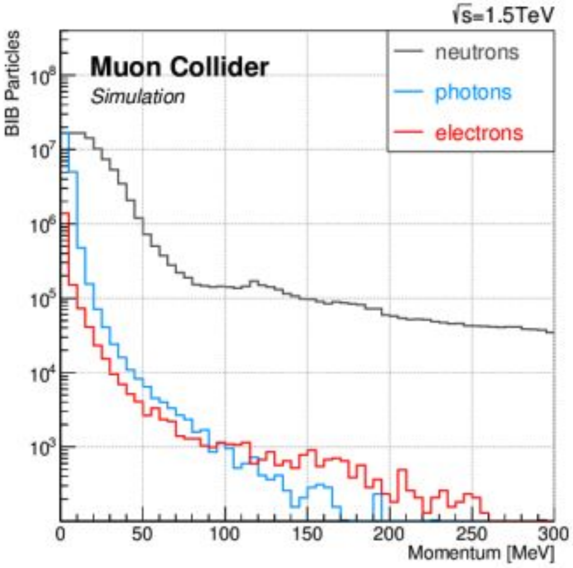
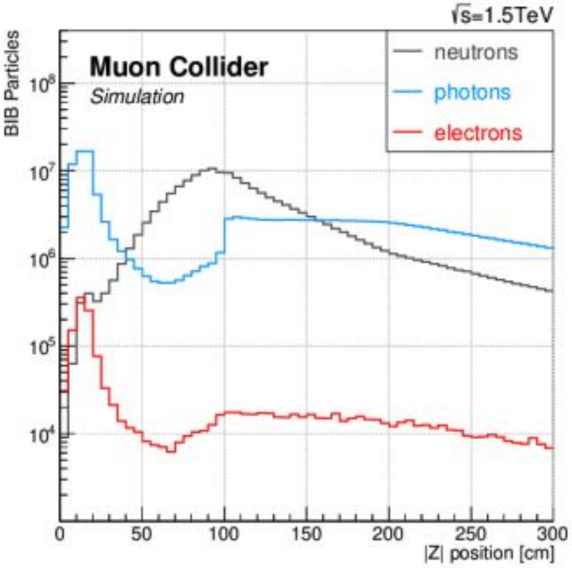
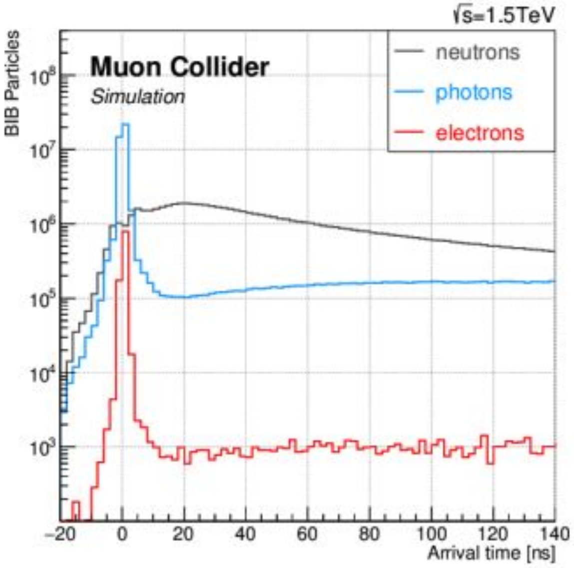
Beam-induced background properties



Low momentum



Origin and direction



Timing

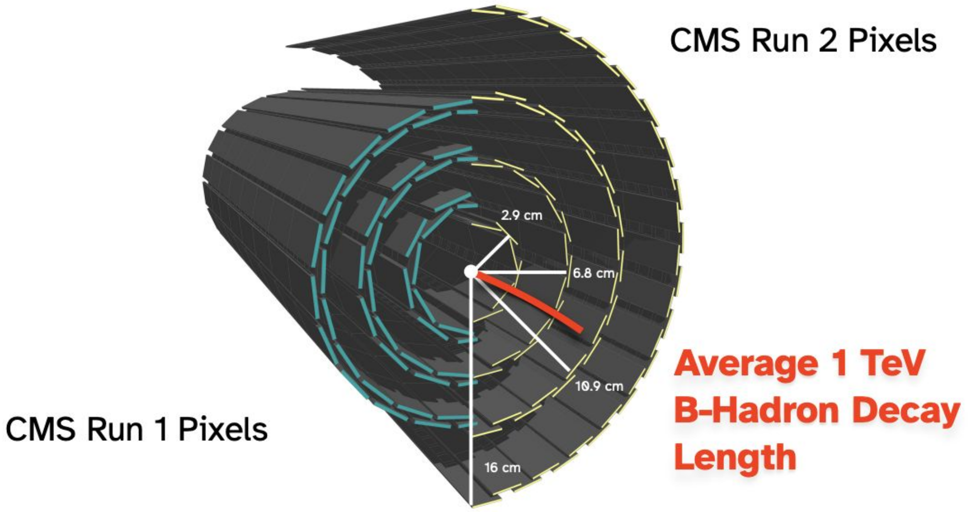
Physics requirements

The detectors need to be ready to **measure both TeV-scale particles** (from s-channel processes) **as well as GeV-scale** (from VBF processes)

- Design a detector which is as “unconventional signature-friendly” as possible

Detector sizes need to grow with energy

- Need thicker calorimeters / bigger trackers with high precision in more places



Sketch: L. Lee

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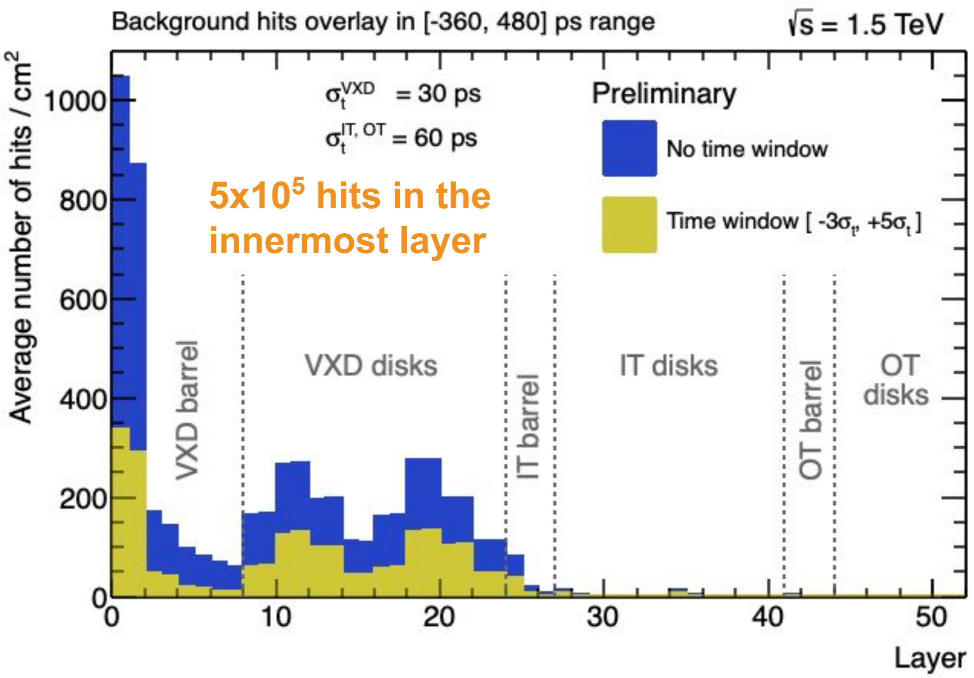
Tracking detectors

Goal: tracker occupancy < 1%

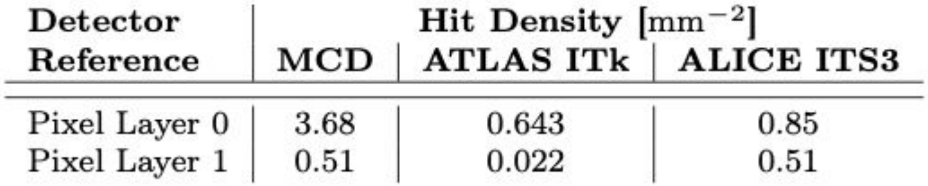
- Other requirements are not unique: **low mass/power, radiation tolerance, low noise**

On- and off-detector filtering:

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



5×10^5 hits in the innermost layer



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

Compared to HL-LHC

~10x hit density

~1/1000 times the bunch crossing rate

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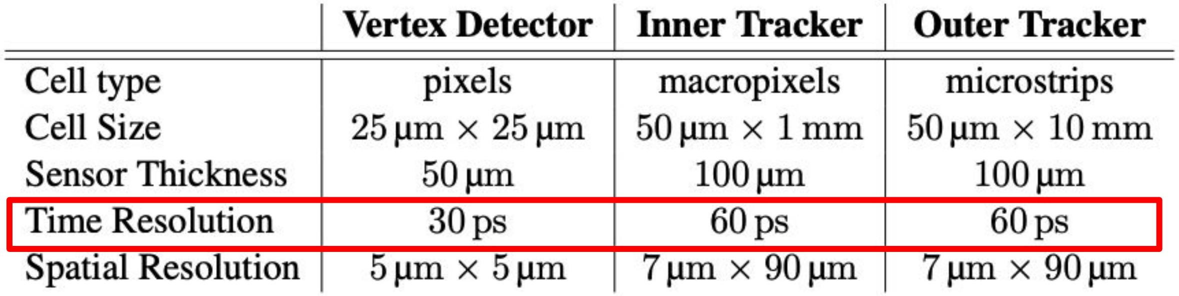
PoS Vertex2014 (2015) 045
2011.02410

4D trackers

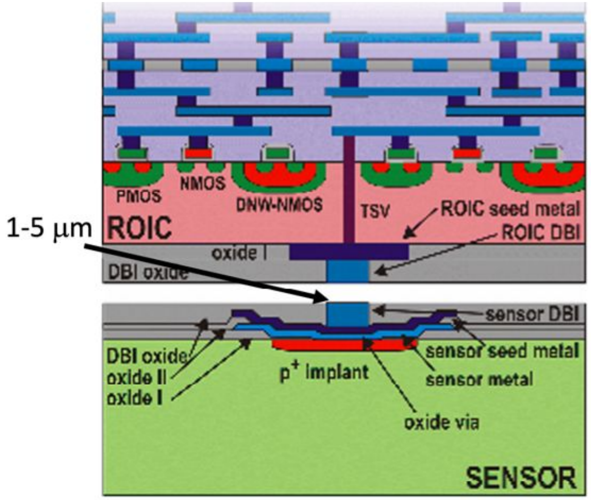


	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

Promising technologies exist

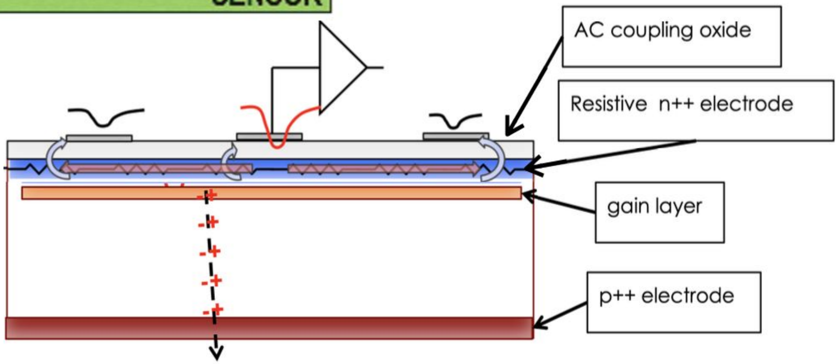
3D-integration: advanced hybrid bonding tech can give < 5 µm pitch and low input capacitance

- 20-30 ps time resolution



Resistive Silicon Detectors/ AC-LGADs
multi-pad signals allow for triangulation

- O(1) µm resolution w/ O(100) µm pitch
- 20 ps resolution w/ 25 µm thickness



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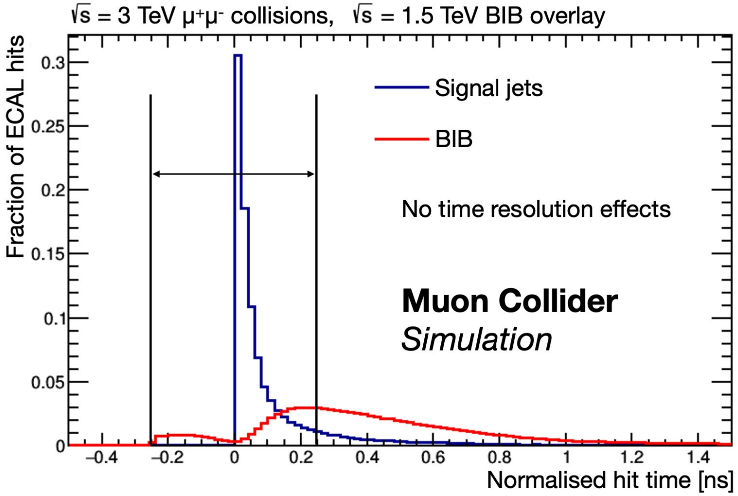
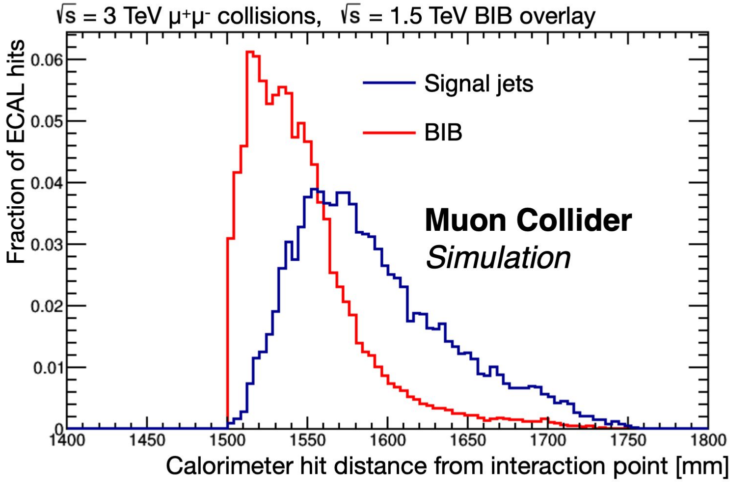
Calorimetry





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

On average 300 particles/cm^2 at the ECAL surface (<E> = 1.7 MeV)

Targets

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

Compared to HL-LHC
25% higher ambient energy per unit area

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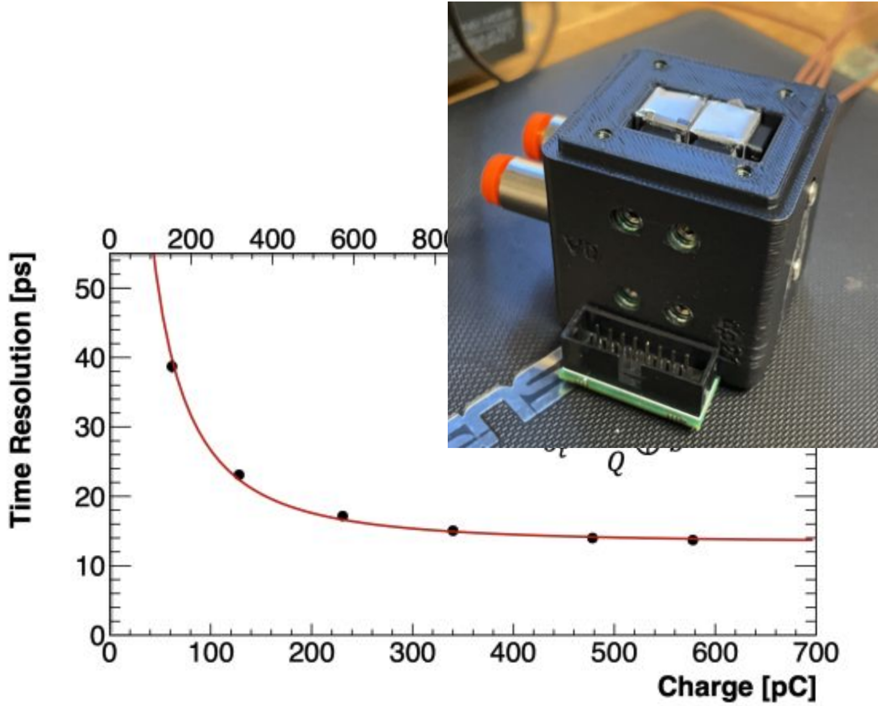
R&D and HL-LHC “technology transfer”

Crilin calorimeter

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

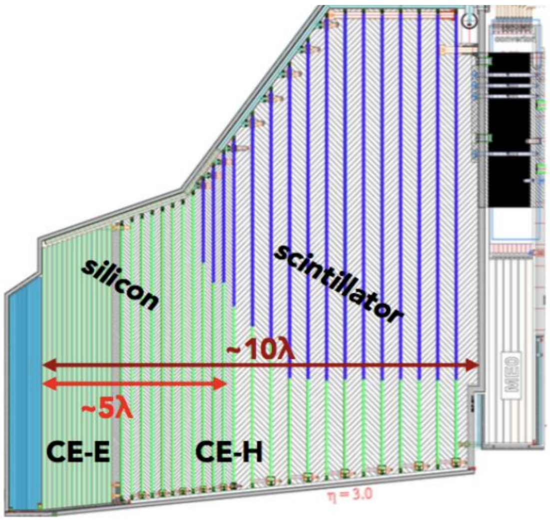
- Segmented longitudinally
- Stackable submodules composed of matrices of crystals



CMS High-granularity Calorimeter

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

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



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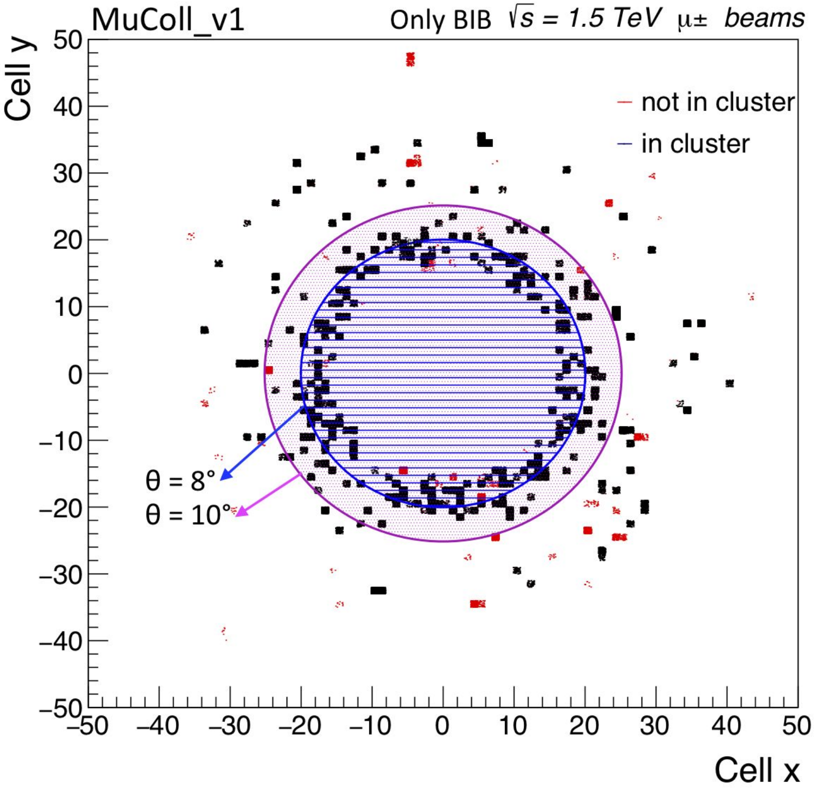
Muon systems

Muon systems are the **least affected by BIB**

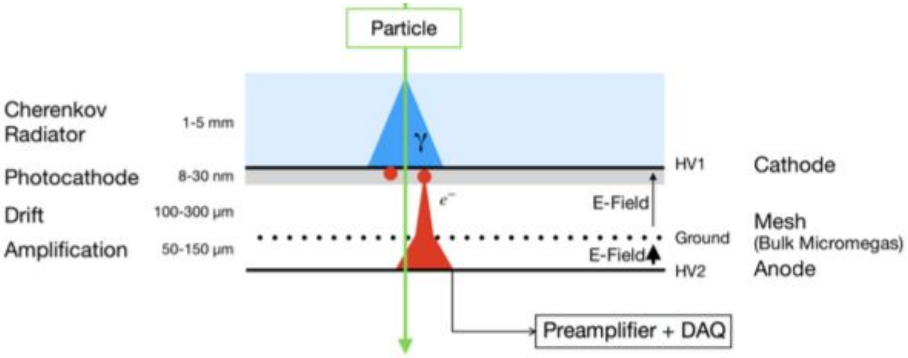
- Most challenging region around the beam axis in the endcaps
- Some technologies (e.g., RPCs), are at the limit of their rate capability

Targets	100 μm	spatial resolution
	< 1 ns	time resolution



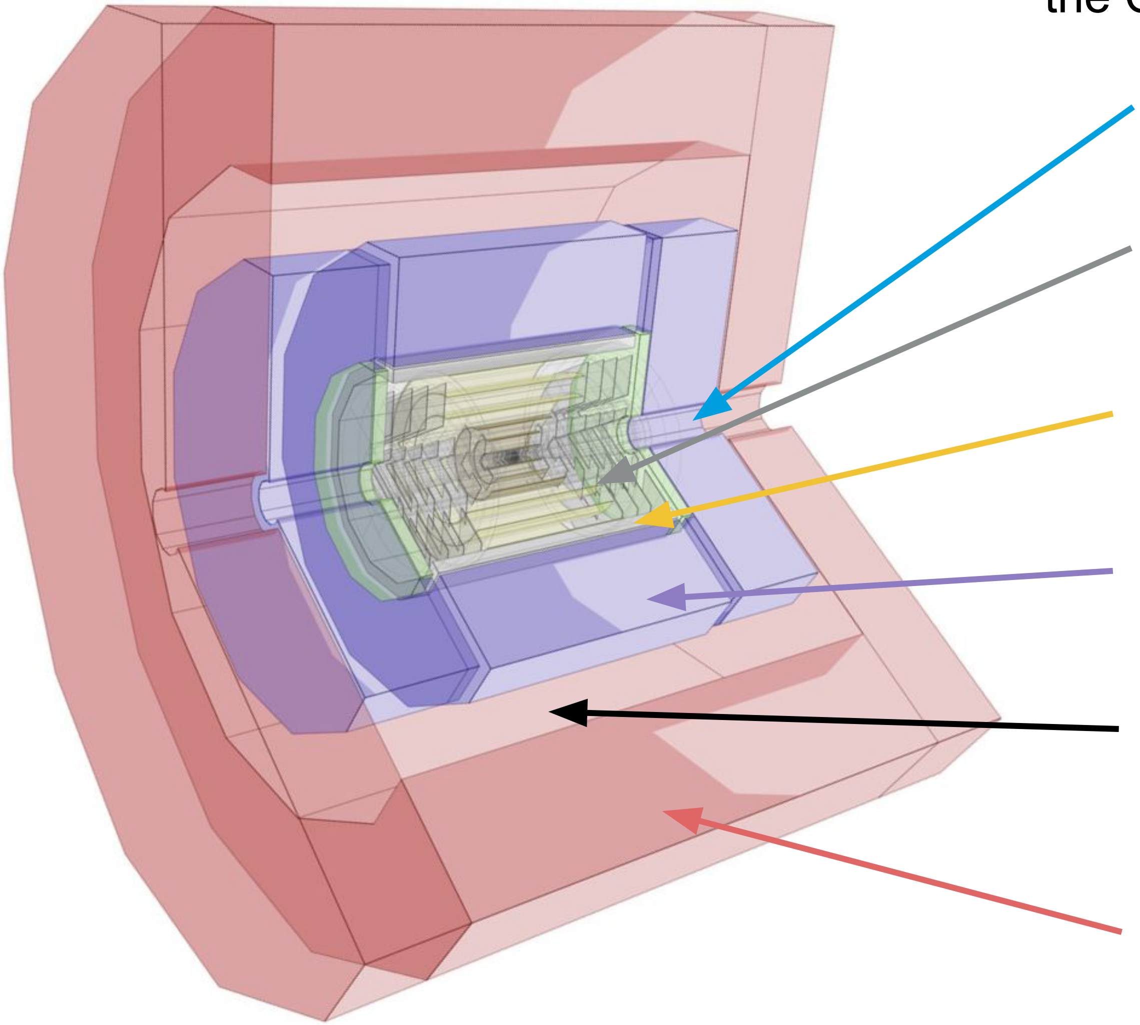
R&D ongoing, e.g.:

- **PicoSec**: hybrid micromegas + cherenkov, reach 25 ps
- **Fast Timing Micropattern** (FTM) use multiple drift and amplification gaps to achieve < 1 ns



Current detector design

The detector model is based on the CLIC concept



Nozzles

All-silicon tracker

ECAL (Tungsten+Silicon)

HCAL (Steel+Scintillators)

3.57 T Solenoid

Muon chambers (RPC) in magnet yoke

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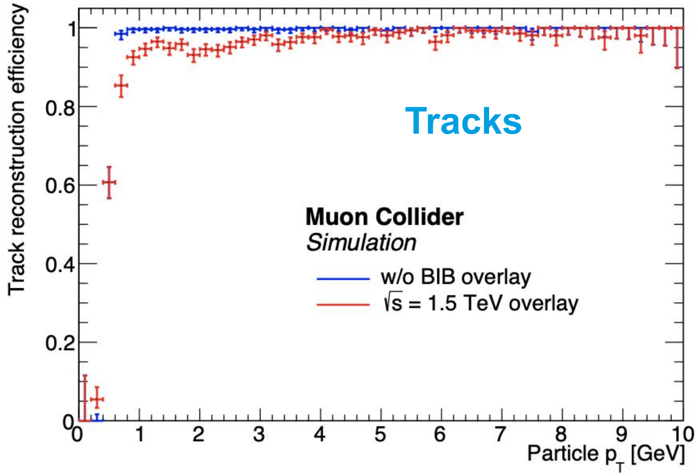
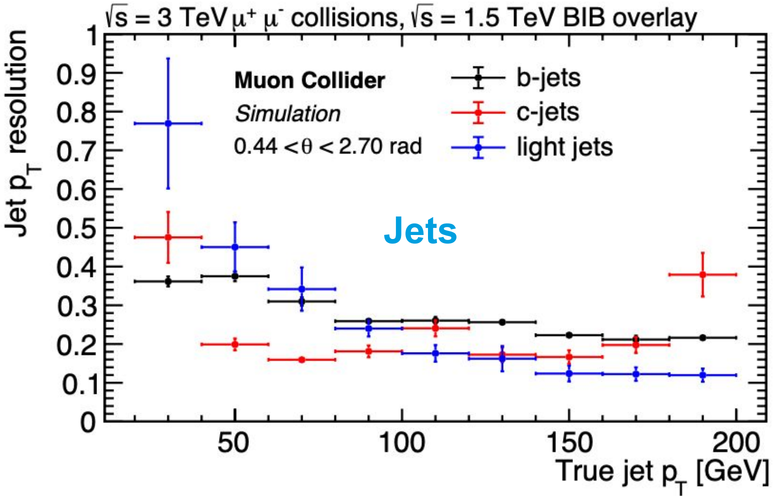
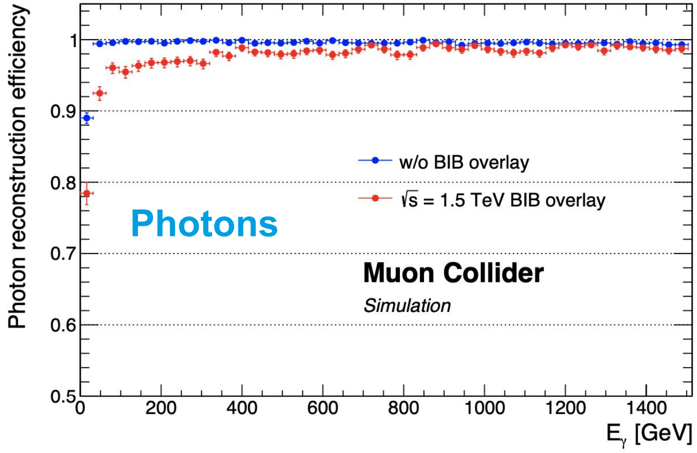
Snapshot of current performance

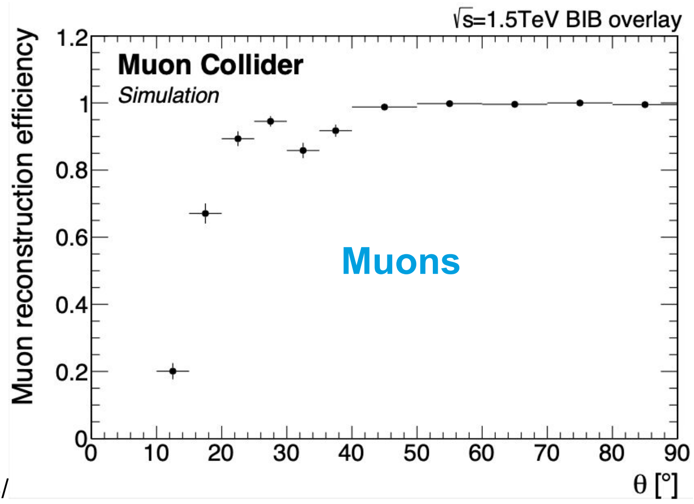
Achieved “LHC-level” performance without using dedicated techniques

- Huge potential to improve further









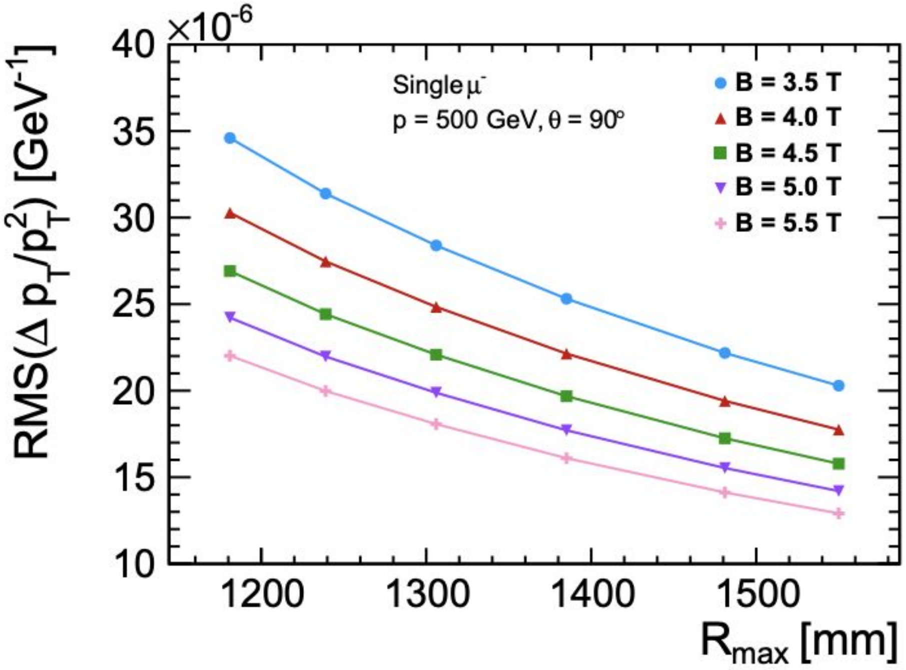
CLICdp-Note-2017-001
CERN-FCC-PHYS-2019-0003

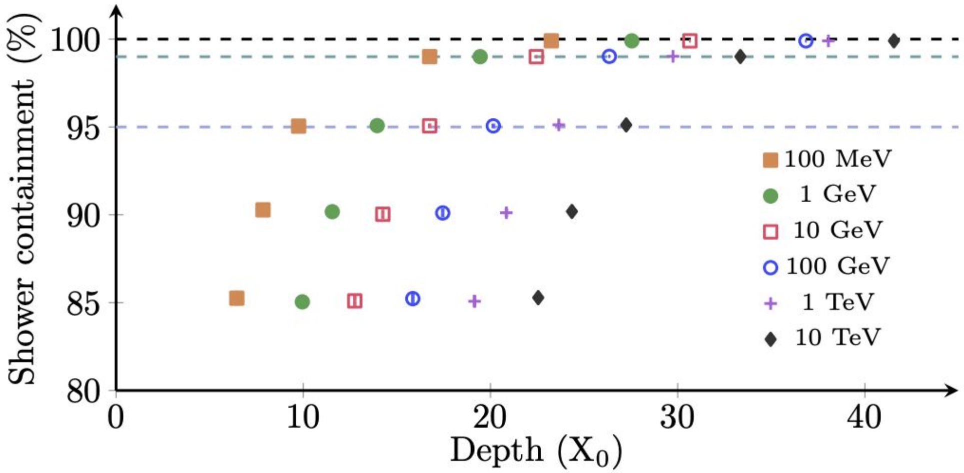
Towards a 10 TeV detector

The **3 TeV CLIC-inspired detector is not suitable for 10 TeV**, beyond the required re-optimisation of the machine-detector interface

Design of 10 TeV detector concept started and progressing vigorously

- Starting from basic aspects
- Many opportunities to experiment with new ideas and explore the potential of your favourite technology

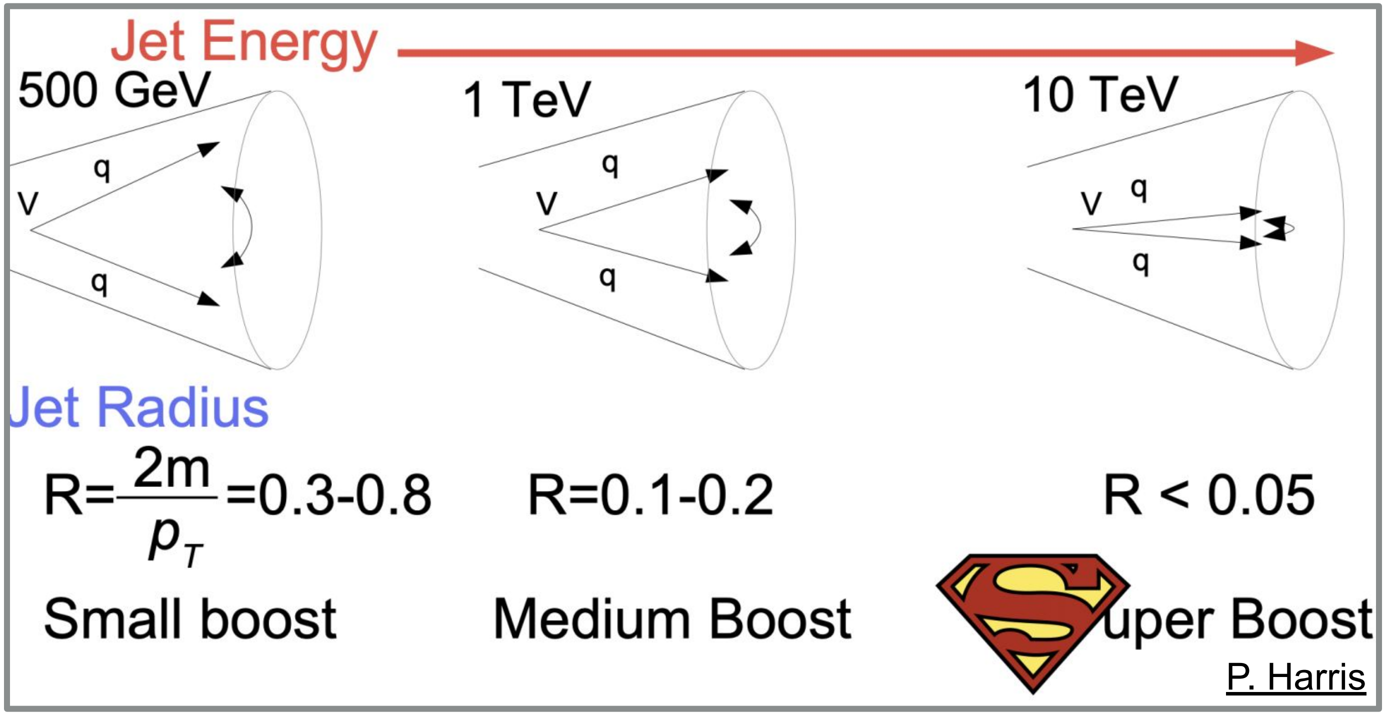




Towards 10 TeV reconstruction

The reconstruction algorithms that were designed at 3 TeV are not guaranteed to work at 10 TeV

- Significantly different energy regime
- Higher detector granularity might require new approaches



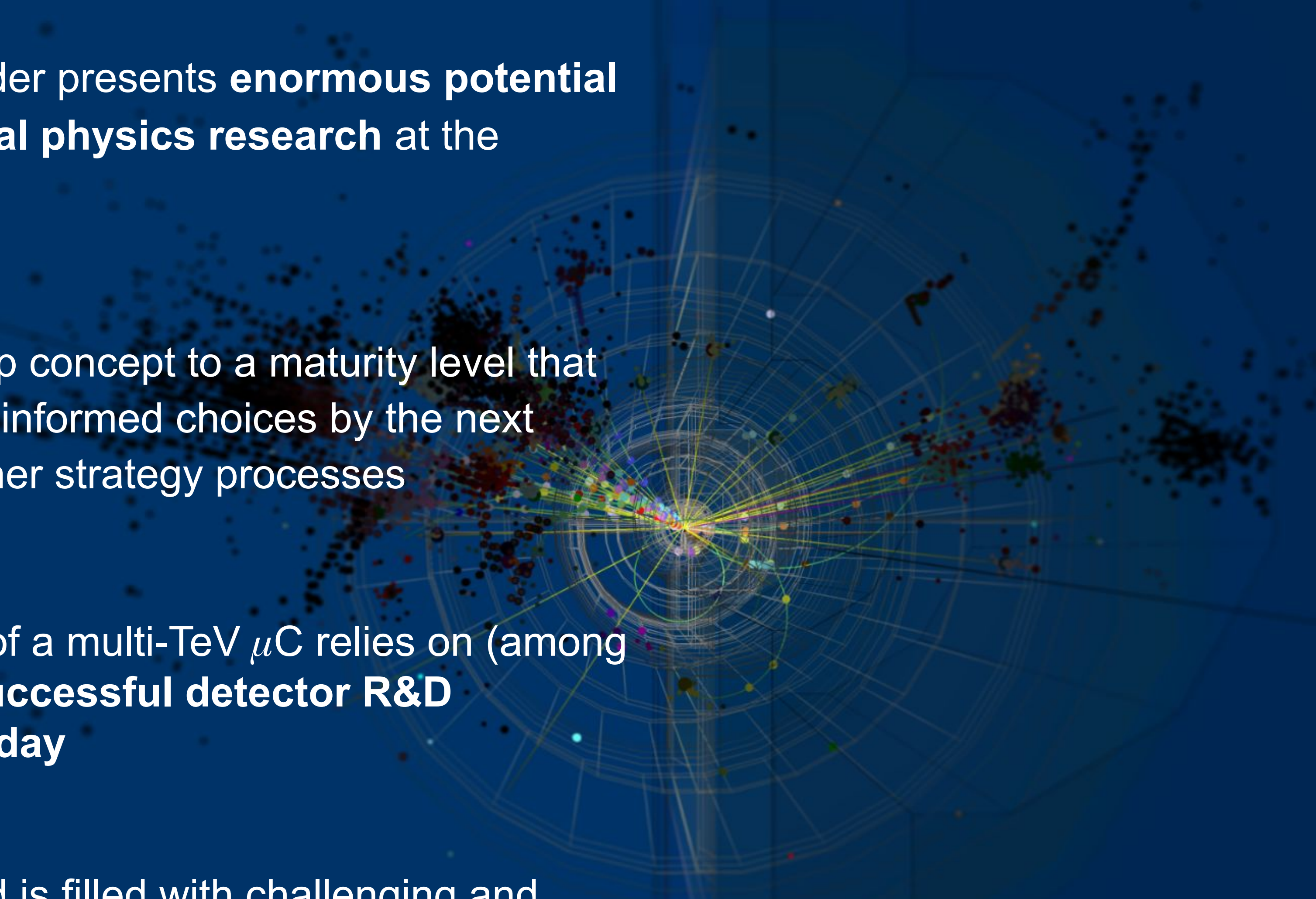
Summary

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

Physics reach of a multi-TeV μC relies on (among other things) **successful detector R&D programme today**

The road ahead is filled with challenging and **interesting R&D**!



Background image credit: L. Lee

Thank you!

Interested?

Join the IMCC physics studies (https://indico.cern.ch/category/12792/)
and Detector and MDI (https://indico.cern.ch/category/13145/) communities!

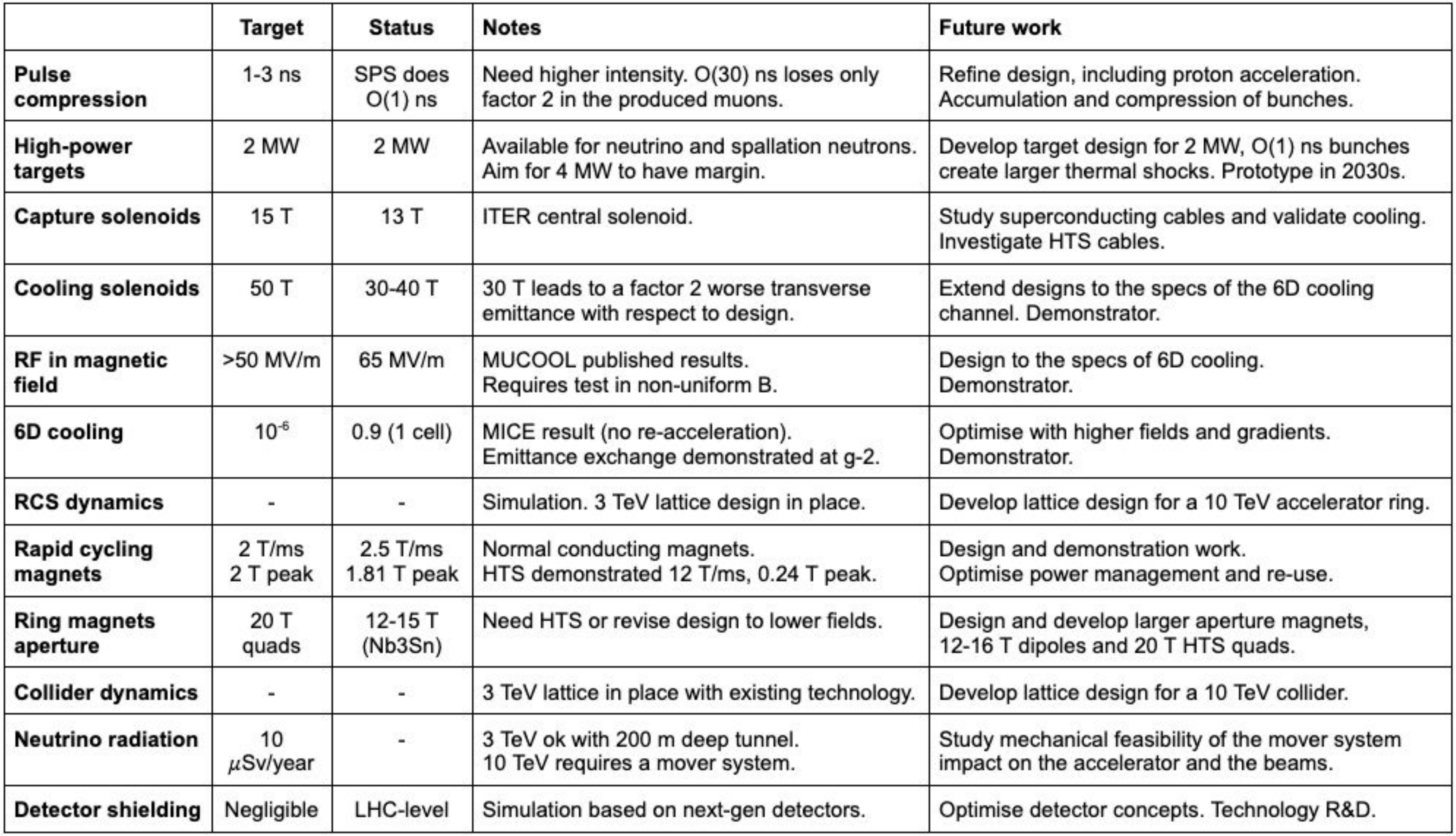
Contact

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

Background image credit: L. Lee

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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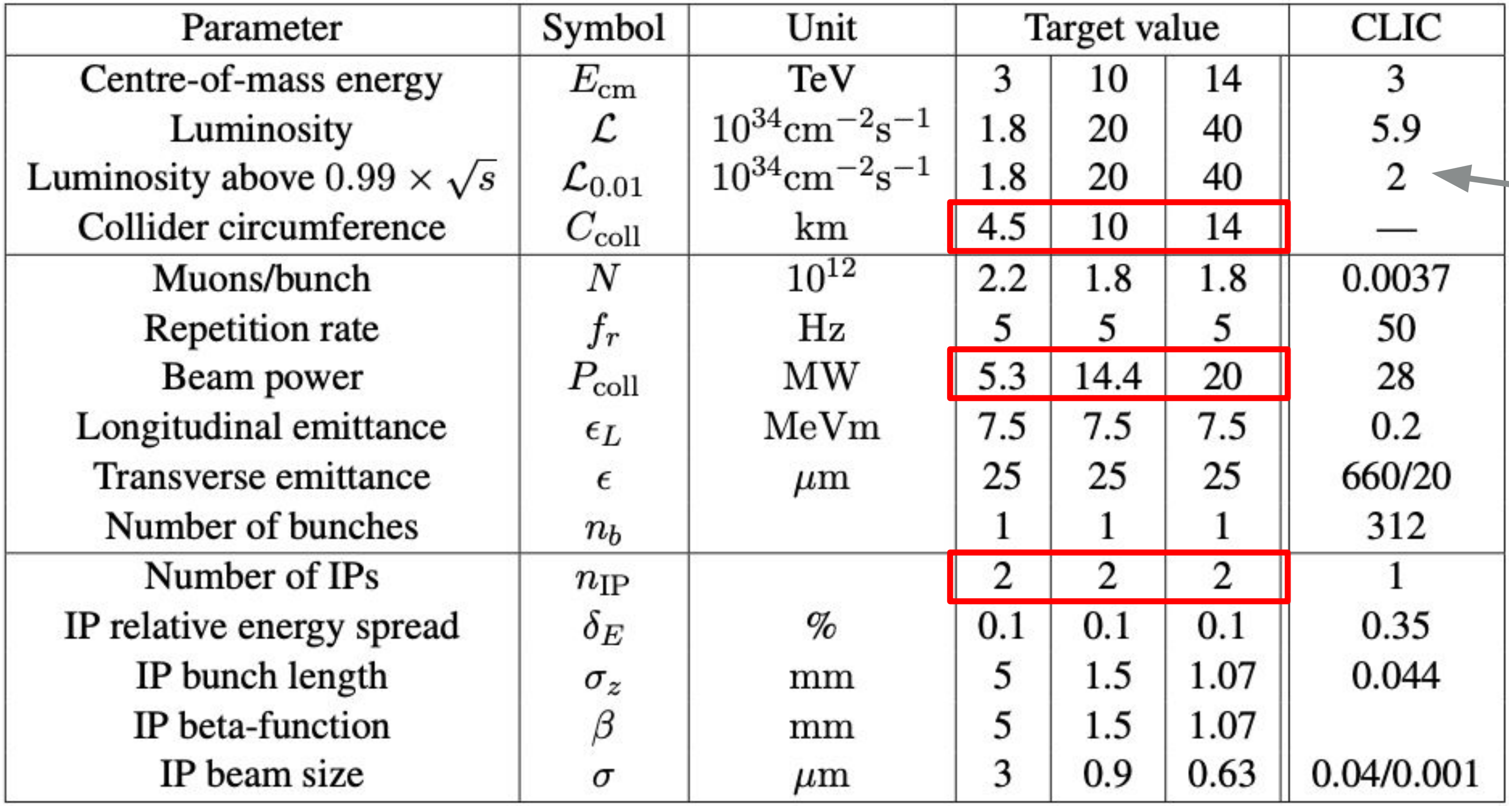
Muon collider target parameters



Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	E_{cm}	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	2
Collider circumference	C_{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_{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_{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)

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

A new collaboration

Objective

In time for the next European Strategy for Particle Physics Update, the study aims to 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. It will also identify an R&D path to demonstrate the feasibility of the collider.

Deliverable

Report assessing muon collider potential and describing R&D path to CDR.

Scope

- Focus on two energy ranges:
  - 3 TeV, with technology ready for construction in 10-20 years
  - 10+ TeV, with more advanced technology
- Explore synergy with other options (neutrino/higgs factory)
- Define R&D path

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Readout and DAQ

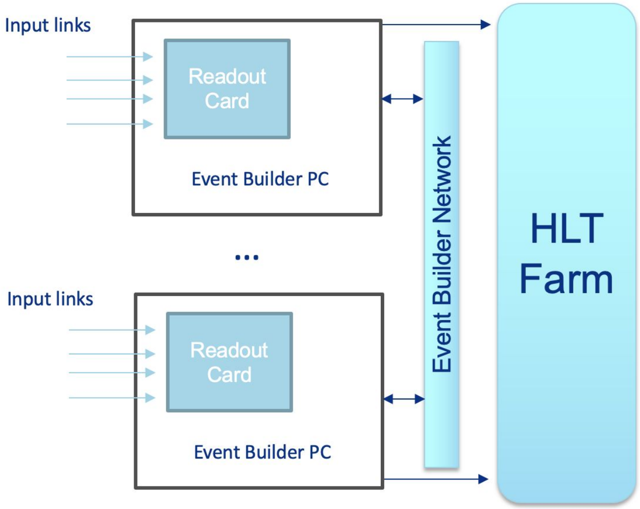
Instantaneous luminosity of **10^{34}-10^{35} cm^{-2}s^{-1}**

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**

Ongoing efforts

Several promising technologies with active R&D:

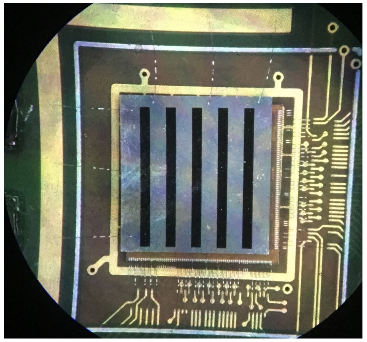
- Monolithic detectors (**HV/HR-CMOS**) - embedded readout
- Low Gain Avalanche Detectors (**LGADs**) - good timing, large pads
- Small “standard” pixels with **3D hybrid bonding** - intrinsically radiation hard
- **Intelligent sensors**

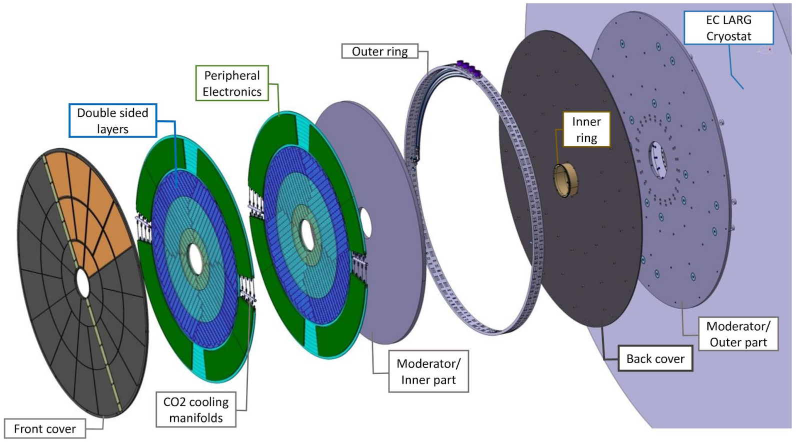
Common challenges for many technologies:

- 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





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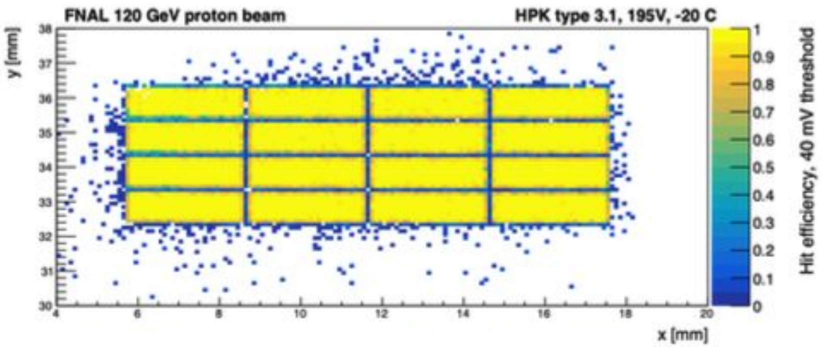
R&D examples

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

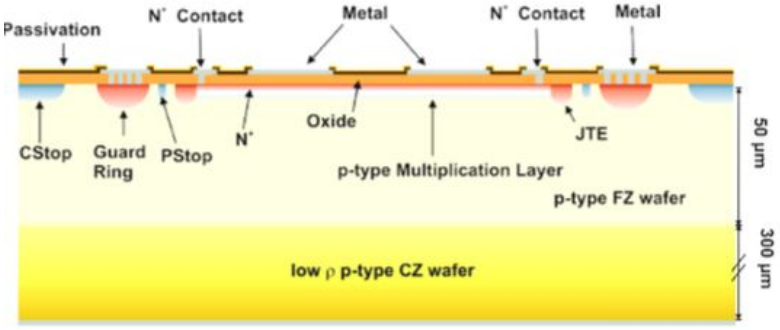


Diagram credit: CNM

R. Lipton, NIM A 945 (2019)

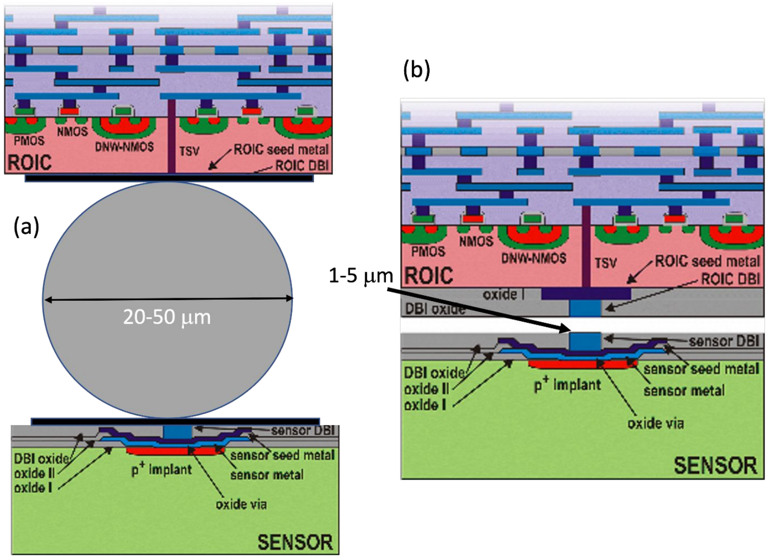
R&D examples

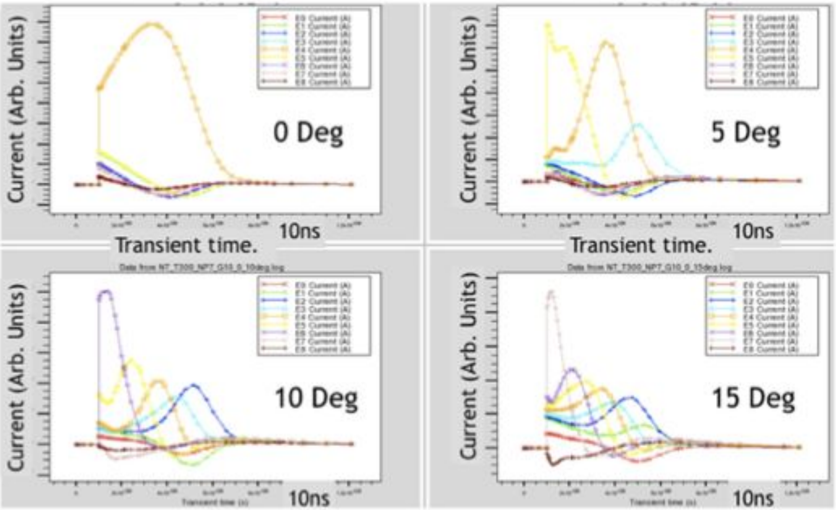
Capabilities enabled by **3D hybrid bonding** provide small pixels with low capacitance

- 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**

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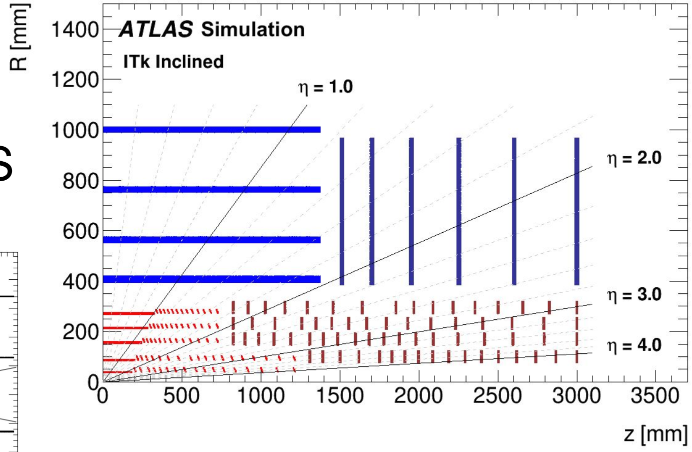
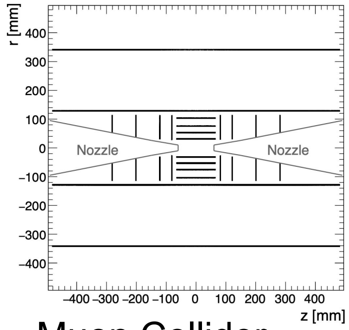




Muon Collider tracker layout

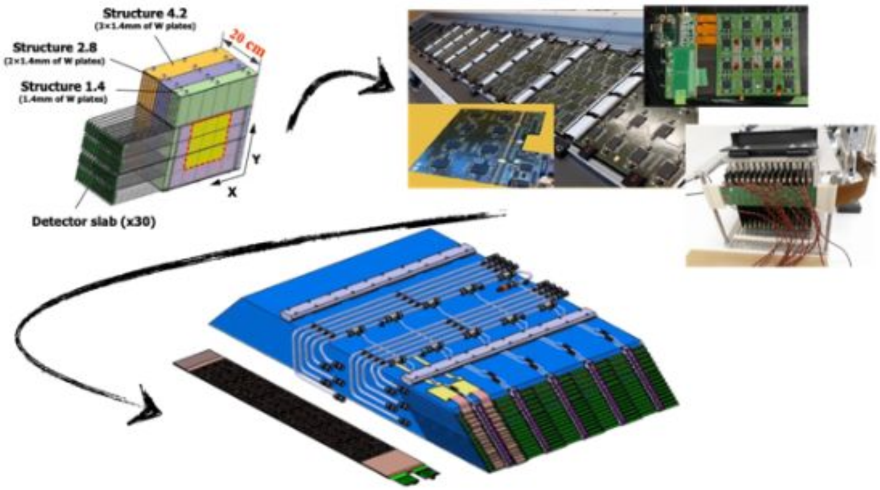
R&D examples: silicon

Main arguments to adopt silicon:

- Fine segmentation
- Robust and stable performance
- High density

Main challenges:

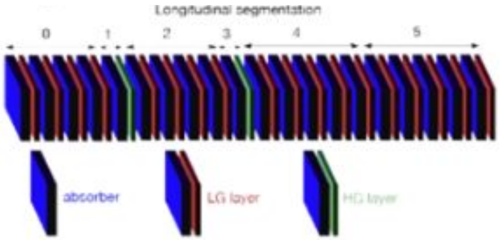
- Cost
- Operation (calibration, monitoring)



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)

ALICE forward calorimeter

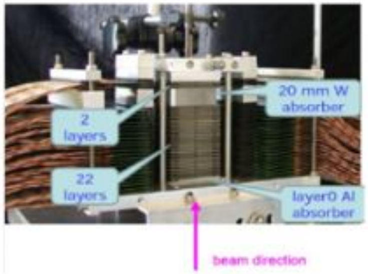


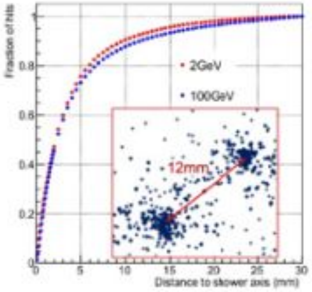
total:

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.

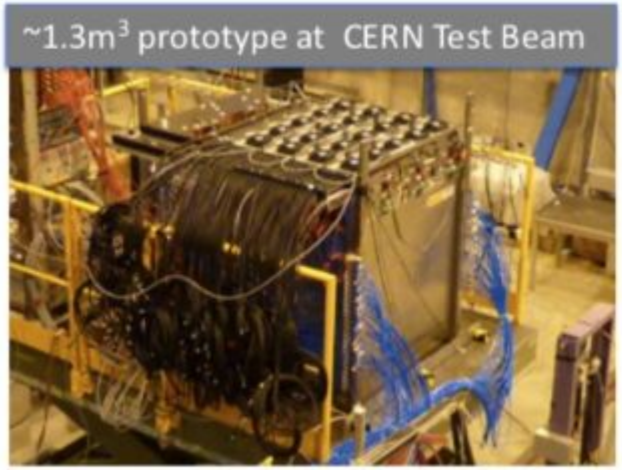
General properties:

- 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

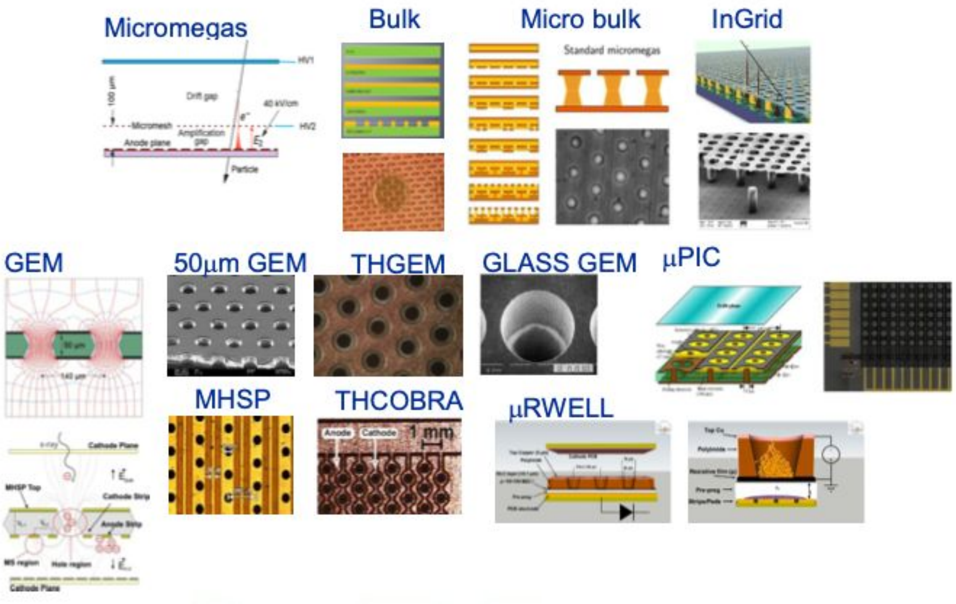
SDHCAL with GRPC



Alternative Micromegas boards

Micromegas prototype of 1x1m2 consisting of six independent Micromegas boards

Ongoing efforts



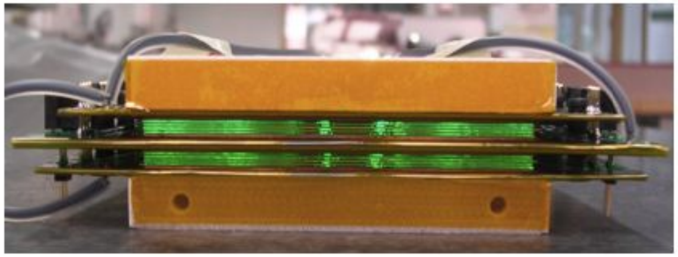
Impressive amount of R&D (and pace of development) for MPGDs.

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

Main challenge:

- Engineering and realization of large area detectors

ALICE-TOF MRPC



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

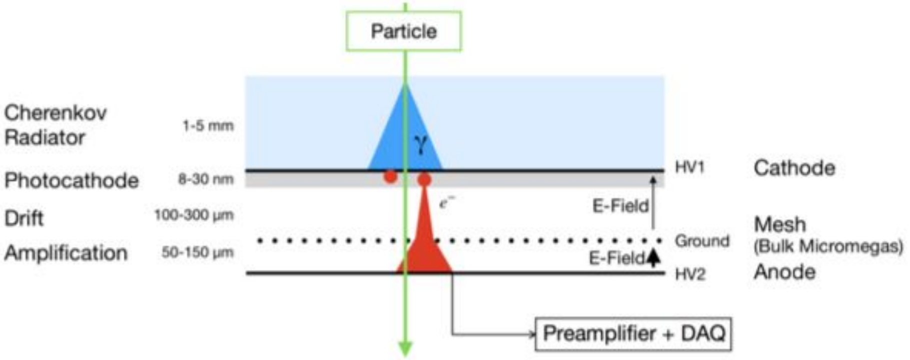
1712.05256

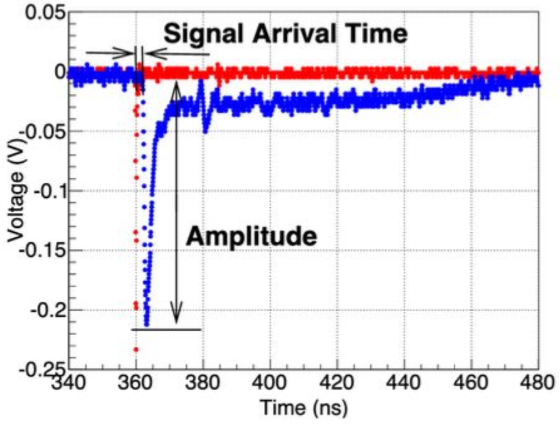
R&D examples: PICOSEC

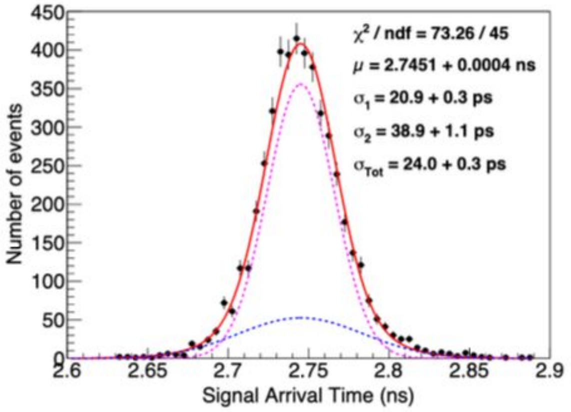
Detect charged particles through **UV Cherenkov photons**.

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.







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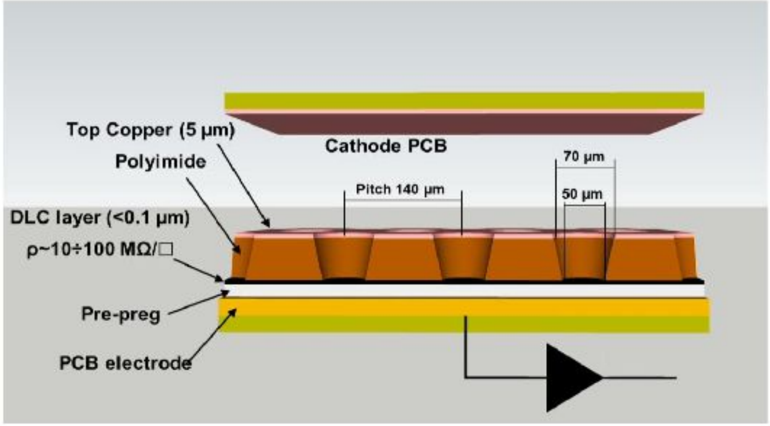
R&D examples: µ-RWELL

Detector composed of two elements:

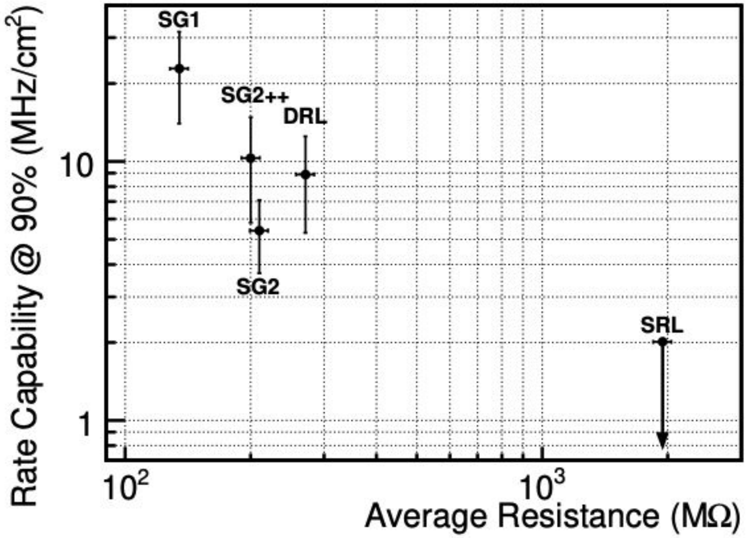
- µ-RWELL_PCB (amplification-stage resistive stage readout PCB)
- drift/cathode PCB defining the gas gap

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



Physics potential

High energy colliders have guaranteed outcomes (SM measurements) but are expensive. Need to prove the ability to make a **great jump** in exploration of **multiple directions**.

The muon collider physics potential is being investigated along three pillars.

Direct search of heavy particles

SUSY-inspired, WIMP, VBF production, 2->1

High rate indirect probes

Higgs single and self-couplings, rare Higgs decays, exotic decays

High energy probes

difermion, diboson, EFT, Higgs compositeness

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