Detector requirements and current design for a 3 TeV and 10 TeV muon collider

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presenting work of many people, all mistakes mine

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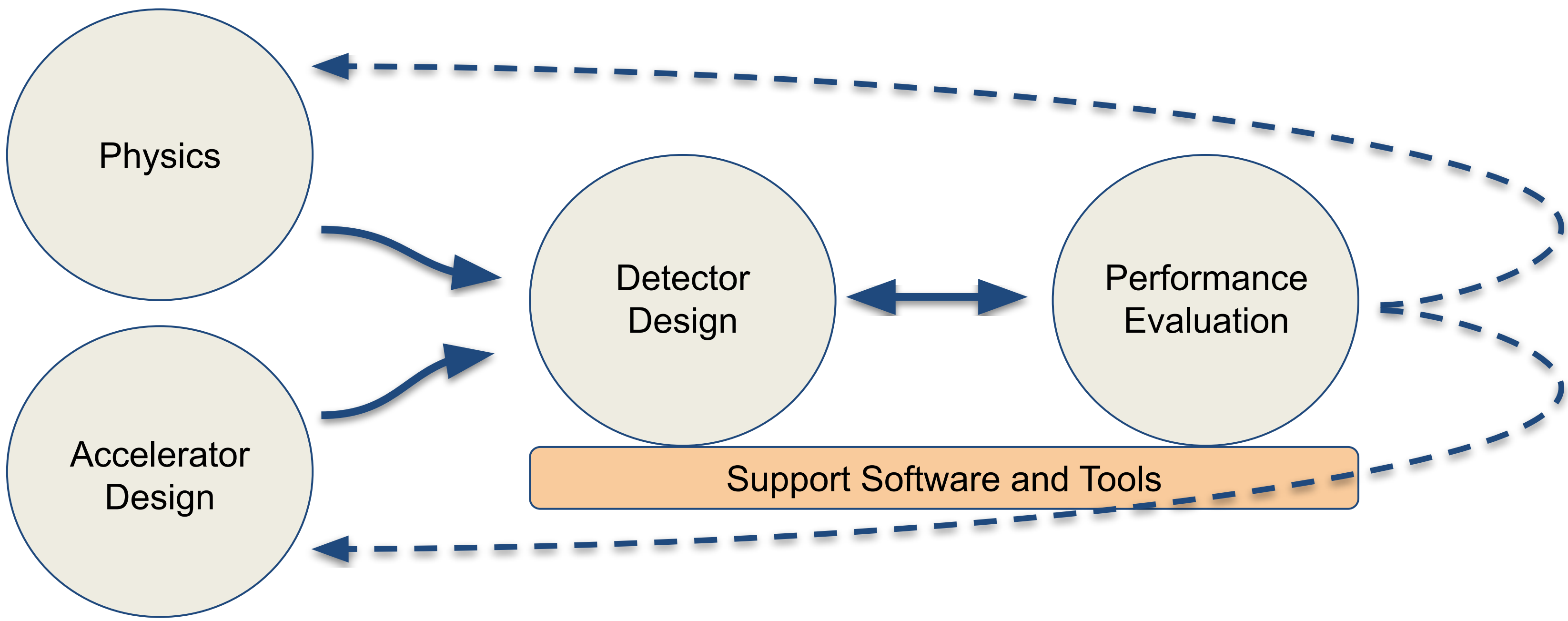
IMCC and MuCol MDI Workshop

BERKELEY LAB
Lawrence Berkeley National Laboratory

Introduction

The detector is our *interface* between collisions and the physics we are after.



Outline:

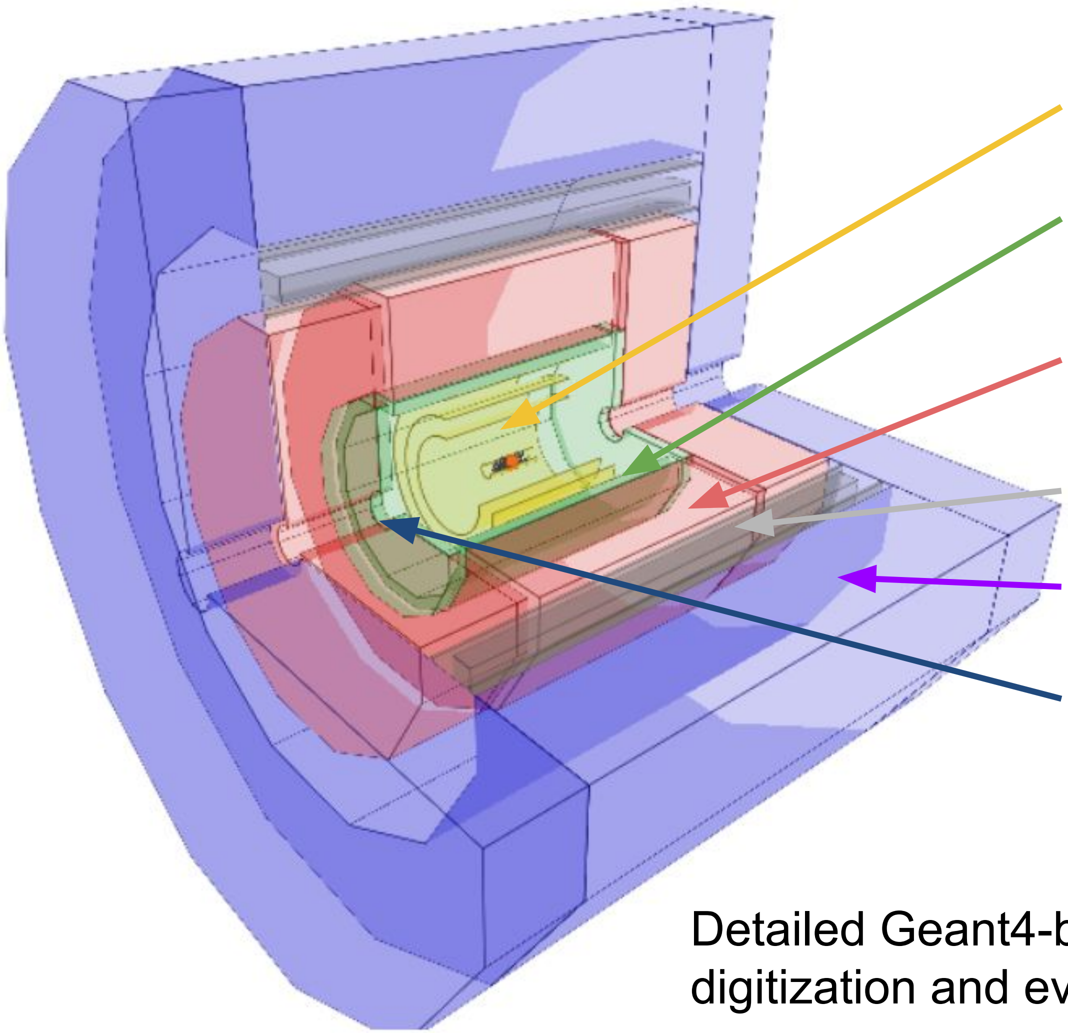
- Brief recap of Detector layout(s)
- General considerations on detector requirements
- System-specific requirements and design choices, focusing on how to further improve what we currently have laid out
    - main ref. IMCC interim report; already updates to be shown this week

Baseline 1 – 3 TeV detector

see Donatella's slides

Multi-purpose detector that targets very broad physics goals.

- many components still inherited from CLIC design and can be further optimized

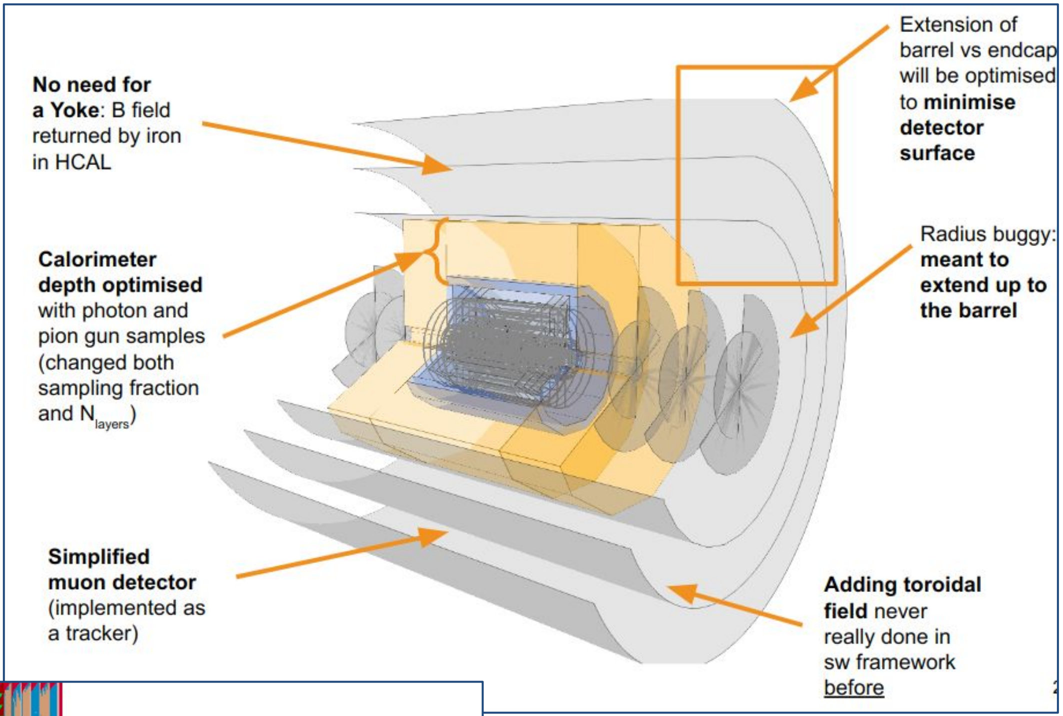


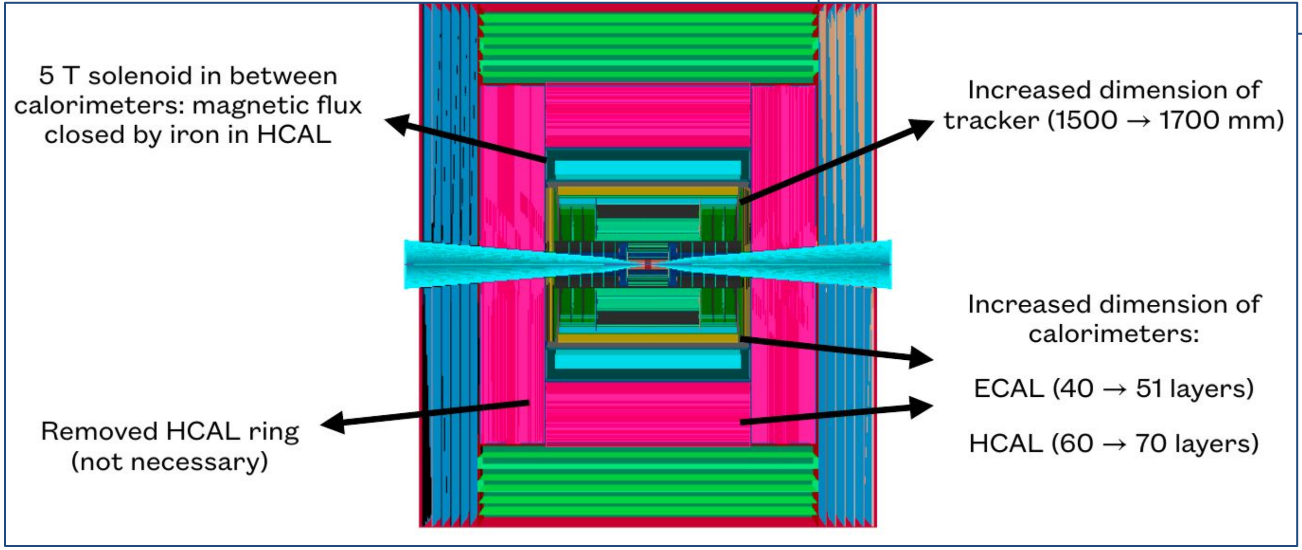
Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

Detector Layouts @ 10 TeV

Lots of proof-of-principle work on new detector layouts

- target 10 TeV
- many lessons apply and should be back-ported to the 1-3 TeV detector as well





Some common points being re-evaluated:

- position and strength of solenoid
- dimension of calorimeters
- tracker layout
- forward muons

Detector requirements

From the IMCC interim report, already a nice initial set of requirements, including a summary table with an initial list of requirements

Requirement	**Baseline**		**Aspirational**
	$\sqrt{s} = 3$ **TeV**	$\sqrt{s} = 10$ **TeV**	
Angular acceptance	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

Baseline: mostly based on current design/ideas and physics benchmark studies
Aspirational: motivated by significantly better physics results achievable
Requirements guide the technology we develop, not all are the same

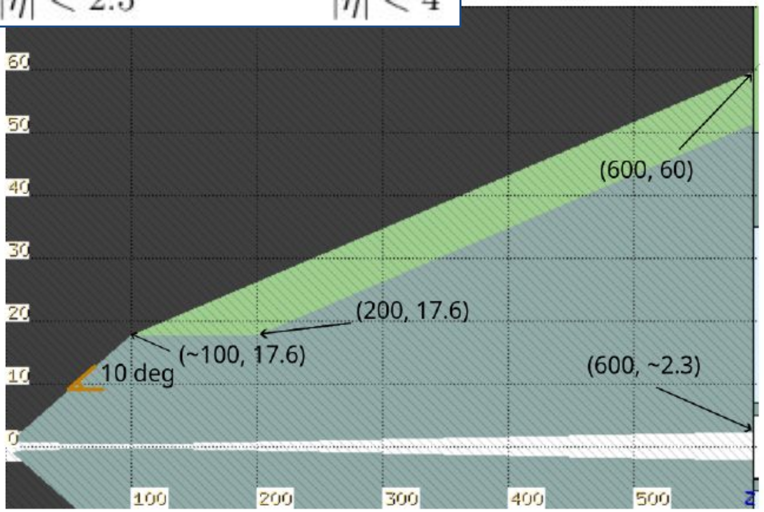
- strict: when they're absolutely necessary or physics would suffer too much
- soft: when meeting or exceeding them has impact on the accuracy achievable but is far from a black&white picture

Some general requirements

Angular acceptance	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$

Angular acceptance

- driven by the kinematic of (central) physics benchmark processes
- currently limited by nozzle design to 10deg. Theory wants more. Nozzle design needs likely more space.
- in principle can differ for tracker and outer-systems (calo, muons)



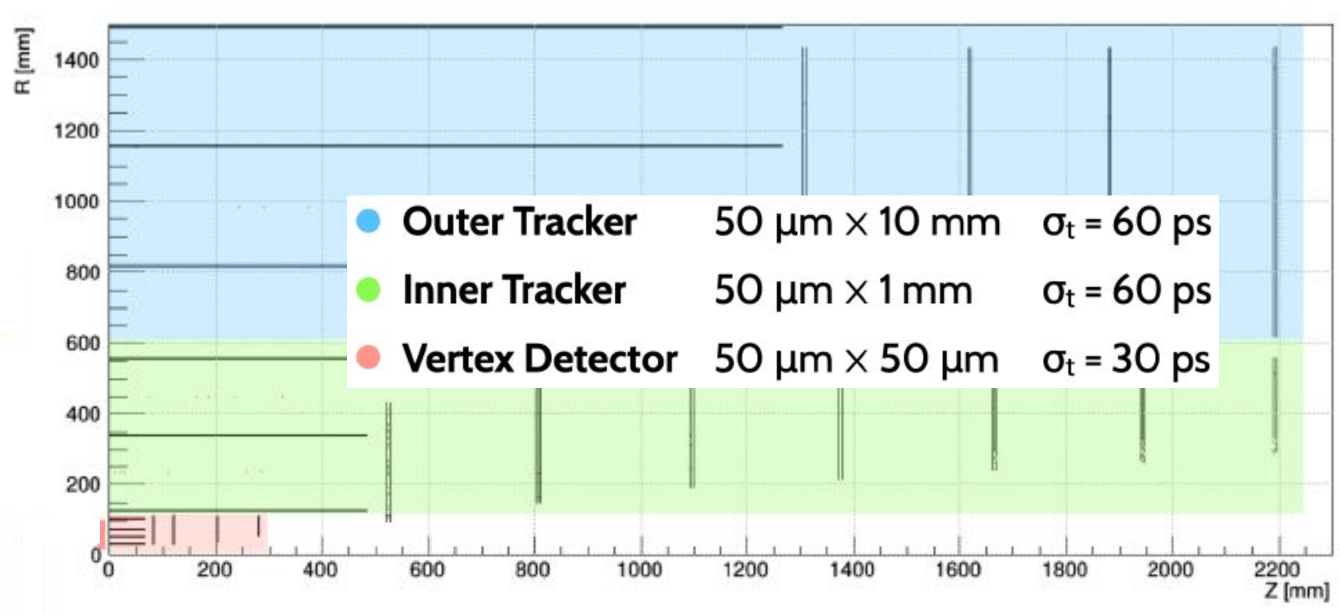
Radiation Hardness

- a good example of a *strict* requirement, e.g. electronics must work/survive
- great progress in validating BIB simulation at multiple c.o.m. energies
- need to specify requirements for full-run / full-program depending on detector
  - for some detector, very steep dependence on radius/placement

1 year of 10 TeV operation, no safety factor

	Dose	1 MeV neutron-equivalent fluence (Si)
Vertex detector	200 kGy	3×10^{14} n/cm^2
Inner tracker	10 kGy	1×10^{15} n/cm^2
ECAL	2 kGy	1×10^{14} n/cm^2

Tracker - current layout



A few key quantities that are *mostly* “bottom-up”: driven by BIB suppression

Granularity

- Occupancy (BIB driven) < 1%, as LHC, how much is LHC “bias”?
- Intrinsic resolution, needed for track parameter resolution ($d_{0/}$,z_0, p_T)

Timing

Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$

- Reduction of out-of-time BIB, some c.o.m. energy dependence (not strong)
- Can be traded-off for other BIB suppression (cluster shape, double-layers)
- Can also be used to determine accurate timing of collision (TOF)

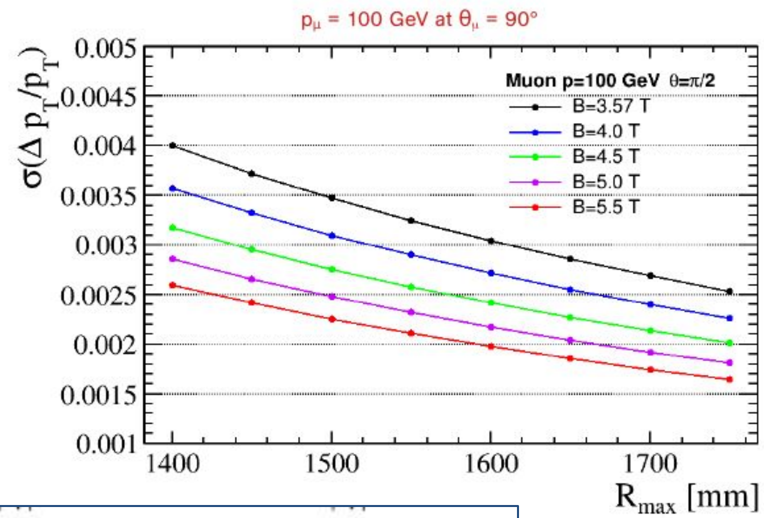
Tracker - II

Other requirements are mostly shaped by the physics we're after

Momentum resolution

Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}

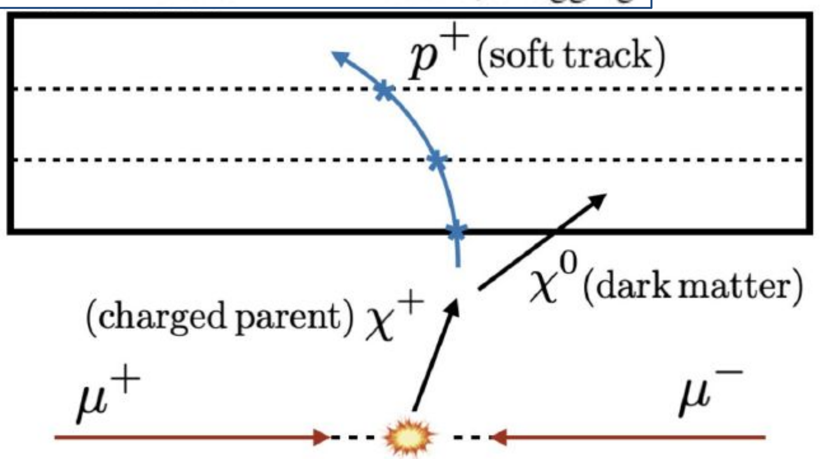
- High-momentum
  - intrinsic resolution of measurements
  - magnetic field strength
  - lever-arm (size of tracker)
- Low-momentum
  - magnetic field strength (not too high!!)
  - (more realistic) material budget



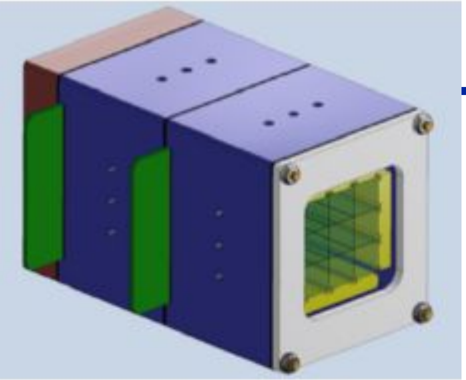
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Flavour tagging	b vs c	b vs c	b vs c, s-tagging

Inner layers radius

- identify b/c hadrons via good d_0/z_0 resolution (extrapolation)
- need a few (~3) measurements close to interaction point to reconstruct short-lived tracks and/or their soft decay products



EM Calorimeter



Baseline inherited by CLIC design

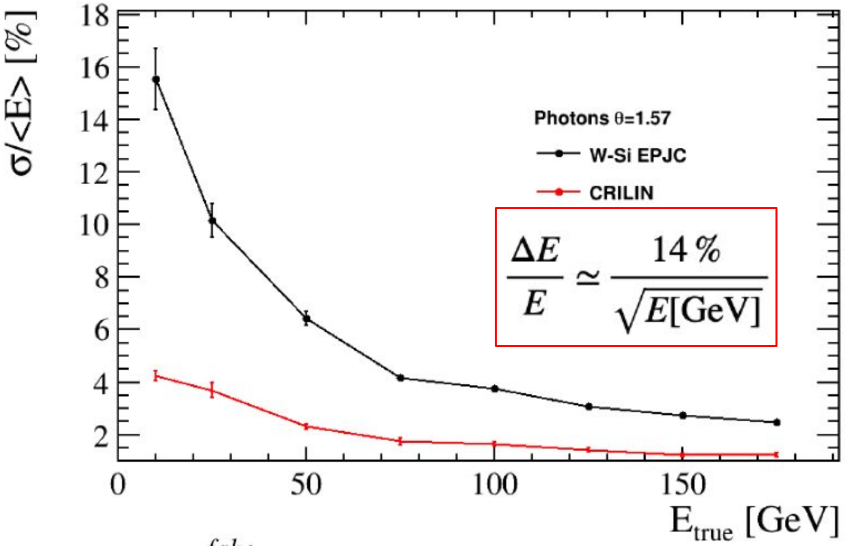
- highly granular Si-W calorimeter
- more recent exploring significantly chapear and more optimized solutions, e.g. Crilin

Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Timing resolution (calorimeters) [ps]	100	100	10

Energy resolution

- needed for good signal (e.g. H to photons) to background ratio
- strongly depends on energy threshold and BIB suppression
- need to include/assess impact of other terms of the resolutions

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



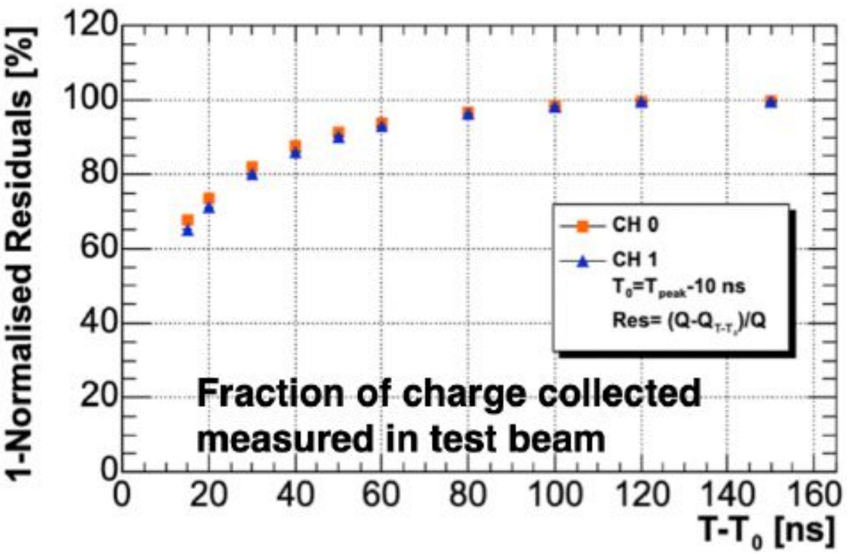
Segmentation

- transverse
  - options considered very finely seg.
- longitudinal
  - strong BIB radial dependence

EM Calorimeter - II

Timing

- <u>time-of-arrival</u> ~ 0.1ns
  - BIB suppression
  - stand-alone capability for ToF
- <u>integration time</u> ~ 100ns
  - critical for energy resolution
  - can be traded off for pulse-shape analysis for BIB subtraction



Shower containment

- dimensions of calorimeter
- do we need to *fully* contain objects from e.g. a 10 TeV Z'?

Solenoid position

- <u>outside/inside EM calorimeter</u> (currently: outside Had Calorimeter)
- affects shower reconstruction and expected occupancy
- both options being studied, affect strongly how we can reach requirements

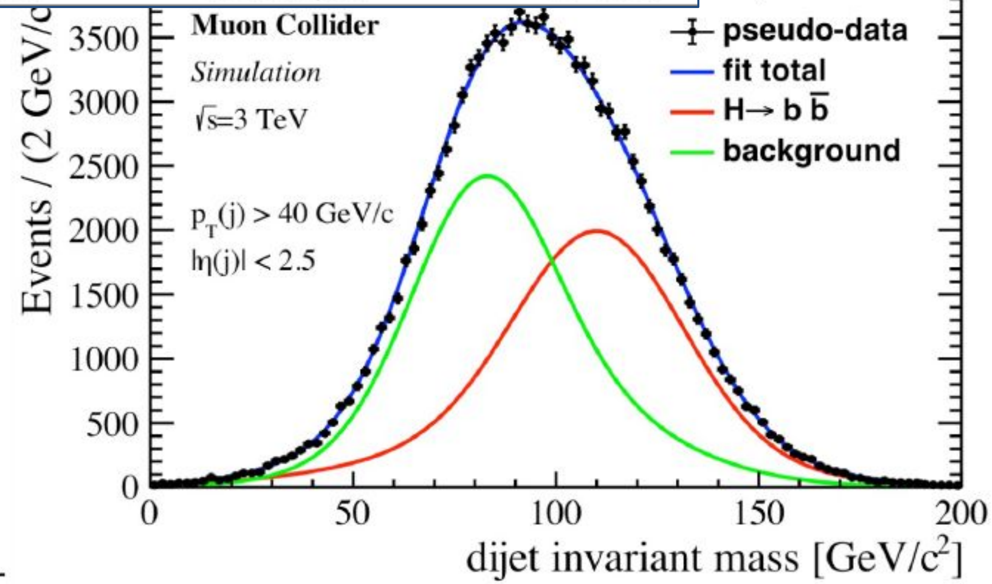
Hadronic Calorimeter

Strongly reduced BIB, even more if moving solenoid inside

Hadronic jet resolution

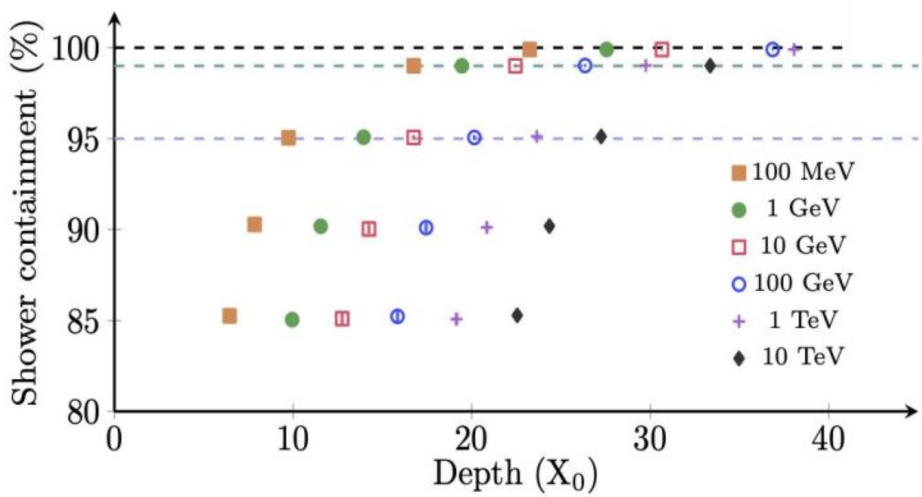
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

- currently set by viability of H measurement
- a great example of soft requirement that should be expanded



Shower containment

- what's the max had. E we aim to really fully contain? what's an acceptable leakage?



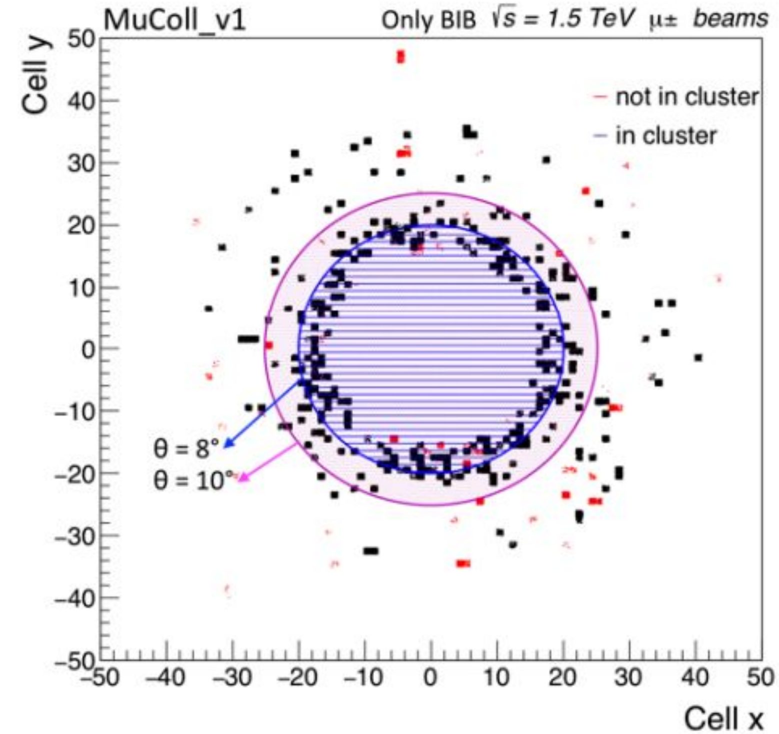
Timing capabilities

- less stringent/needed but useful for ToF measurements of e.g. LLP (large volume preferred)

“”Central” Muon Spectrometer

Standalone muon reconstruction

- momentum accuracy for high-p_T
    - magnetic field, lever-arm
    - appropriate benchmark?
      might not need great resolution to find new multi-TeV objects
- helps for long-lived particle decays



Detector size

- linked to momentum resolution
- a large volume helps in neutral long-lived particles reconstruction

Timing capabilities

Timing resolution (muon system) [ps]	~ 50 for $\lvert\eta\rvert > 2.5$	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert > 2.5$

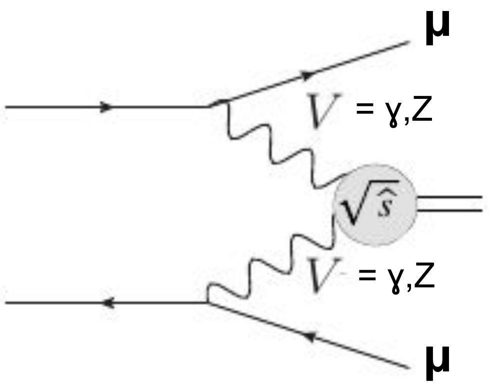
- reduce BIB where needed
- best ToF for particles passing calorimeter
- how *strict* is this requirement?
    - trade-off with higher multiplicity
    - most important use-case might come from long-lived particle ToF

(Very) Forward Muons

see also
Daniele's talk

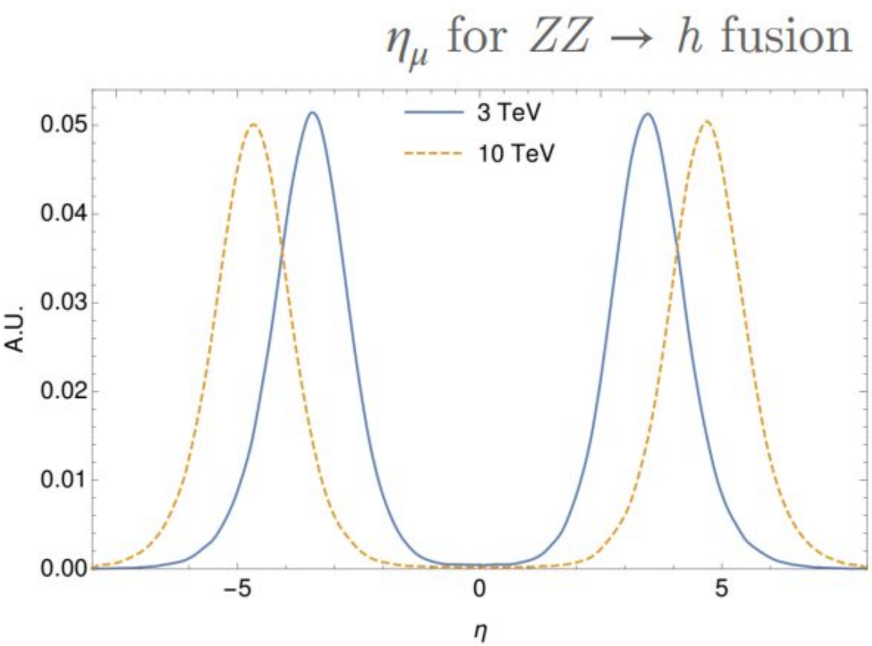
Due to the predominance of VBF processes
- when neutral current, muons in final state
- unfortunately some get “captured” since very close to beam trajectory

Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$



Forward Muon Tagging
- already incredibly useful
  to tag neutral-current interactions
- angular information

Forward Muon Momentum
- ideally some momentum resolution can increase our physics reach, e.g. H->inv
- Very non trivial, a few studies point to ~10% as a great target



Several ideas to instrument the nozzle already being developed.

A few more requirements we'd love to add

Particle Identification

- intrinsic dE/dx and ToF capabilities of existing detectors
- need for dedicated detectors? e.g. cherenkov
- need for a few benchmark cases to assess

Luminosity

- Online, feedback needed from accelerators; assuming ~5%
- Offline, review precision measurements but likely aspire to 0.1-0.5%
    - multiple methods are critical to control systematics
    - other well-predicted processes other than Bhabha scattering?

Data Acquisition System

- roughly expect a rate of data out of the detector not far from HL-LHC
    - possibility of streaming data
- need more accurate estimates to form requirements for DAQ system
- bottom-up: need input from systems (especially tracking) on needed accuracy of information (timing, E, …)
    - some initial studies performed using realistic digitization, need to be expanded

Conclusions

Detector layout concepts evolving from the initial CLIC-like detector

- new results expected this week as well

As stressed already, the tight connection between accelerator, detector and theory is instrumental in defining detector concepts and requirements and a strength of the IMCC organization that we need to leverage at best

An initial set of requirements and performance already shown in the interim report

- still the main objective is to show we can extract at least the physics we need

Several places where we should evolve these requirements, in particular I'd strongly favor

- explicitly labeling any *strict* requirement (not met = fail)
- studying and explicitly showing how the *soft* requirements pay off in terms of physics to further motivate R&D and unique opportunities