APS physics APRIL MEETING 2021
Q2C quarks cosmos
APRIL 17–20 ONLINE

Detector design for a Muon Collider experiment

S. Pagan Griso (LBNL)

on behalf of

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BERKELEY LAB
Lawrence Berkeley National Laboratory

APS April Meeting, Muon Collider Symposium III

Apr 18th, 2021

see N. Craig's talk
B08 (Sat)

Why a Muon Collider?

Provides a versatile and powerful tool for HEP exploration

- access energy frontier also allowing precision measurements

The Muon Smasher's Guide

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dari
Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid E
JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9],
Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Albert

Measuring the quartic Higgs self-coupling at a multi-TeV muon collider

Mauro Chiesa[a], Fabio Maltoni[b,c], Luca Mantani[b,d], Barbara Mele[e], Fulvio Piccinini[f], Xiaoran Zhao[b]

WIMPs at High Energy Muon Colliders

Tao Han,[a] Zhen Liu,[b] Lian-Tao Wang[c] and Xing Wang[d]

A No-Lose Theorem for Discovering the New Physics of $(g-2)_\mu$ at Muon Colliders

Rodolfo Capdevilla,[a,b] David Curtin,[a] Yonatan Kahn,[c,d] Gordan Krnjaic[e,f]

Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider

Tao Han,[a] Da Liu,[b] Ian Low[c,d] and Xing Wang[e]

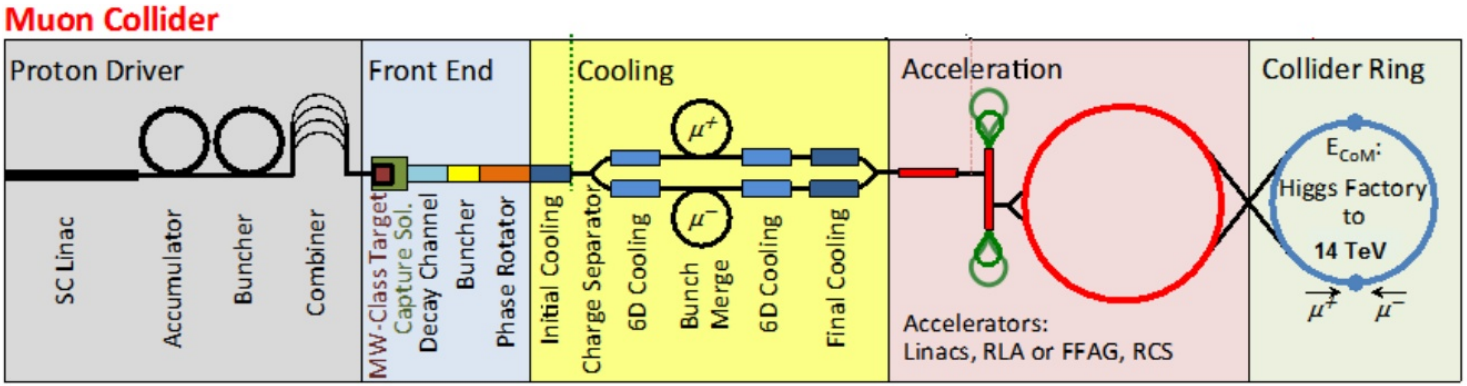
Vector boson fusion at multi-TeV muon colliders

Antonio Costantini,[a] Federico De Lillo,[b] Fabio Maltoni,[b,c] Luca Mantani,[b,d] Olivier Mattelaer,[b] Richard Ruiz[b] and Xiaoran Zhao[b]

… and many more!
>15 papers in 2021, >25 in 2020, ...

see D. Schulte's talk
D14 (Sat)

Muon Collider Accelerator complex

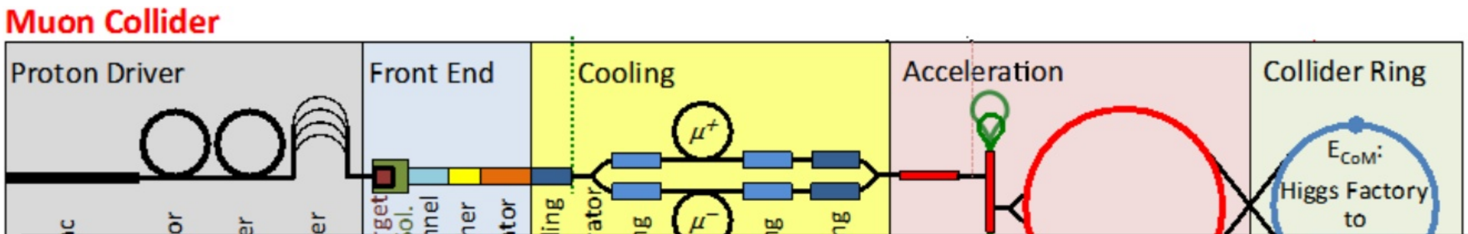


Alternative acceleration concept (positron-based) being also explored

- Potentially "compact" design even for very high energies
- Challenges: design a system (accelerator+detector) that meets physics requirements
- Different stages of design depending on CoM energy
  - Most of the results shown today for $\sqrt{s}$=1.5 TeV
  - Quite advanced designed also for Higgs factory, 3 TeV and 6 TeV
  - In the context of Snowmass, being investigated 10, 14, ... TeV

oversimplified picture

Muon Collider Accelerator complex



Outline

Today I'll focus on the status and challenges of **detector design**:

- Muon collider environment
- Detector overview and software
- Expected performance and challenges
  - Inner Tracker
  - Calorimeters
  - Muon Spectrometer
- Non-conventional detector requirements and Luminosity

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DISCLAIMER: the aim is to show basic performance are achievable
in this environment, huge room for new ideas and optimization!
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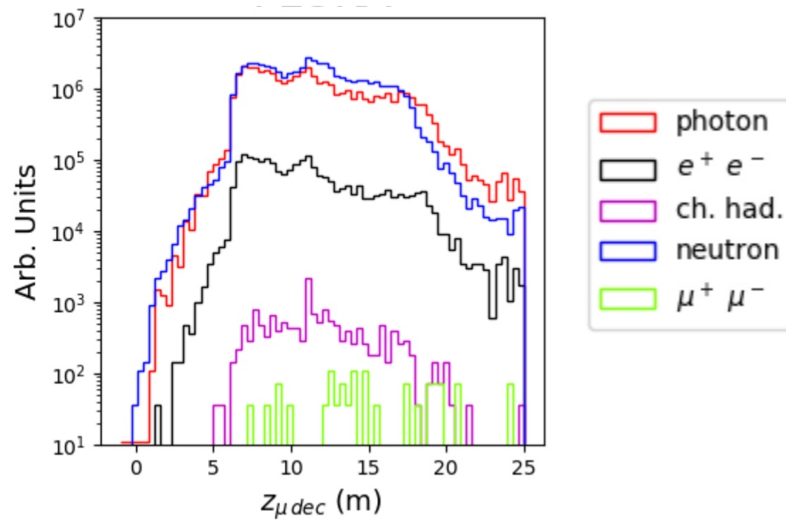
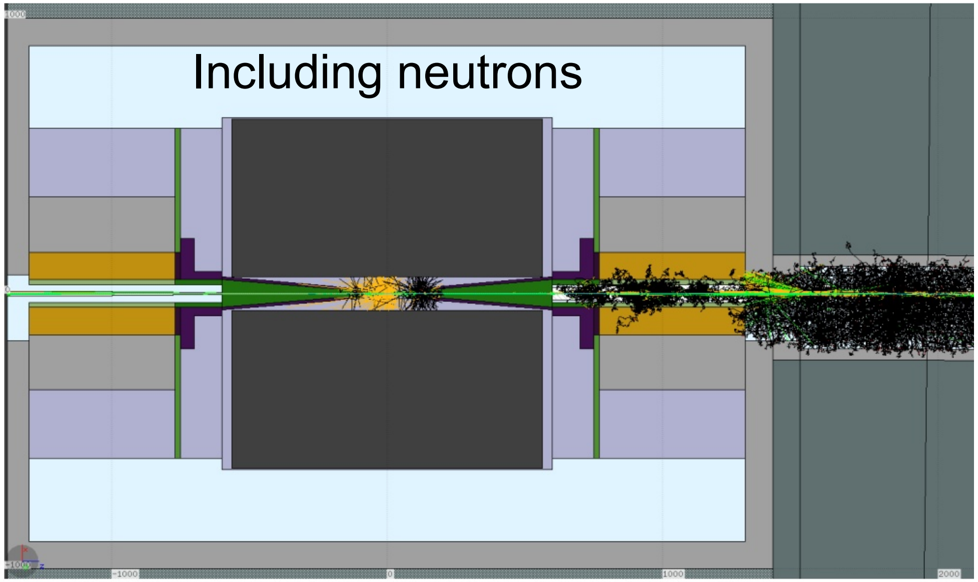
- Po
- Ch ... ics
  rec
- Dif
  - M
  - Q
  - In the context of Snowmass, being investigated 10, 14, ... TeV

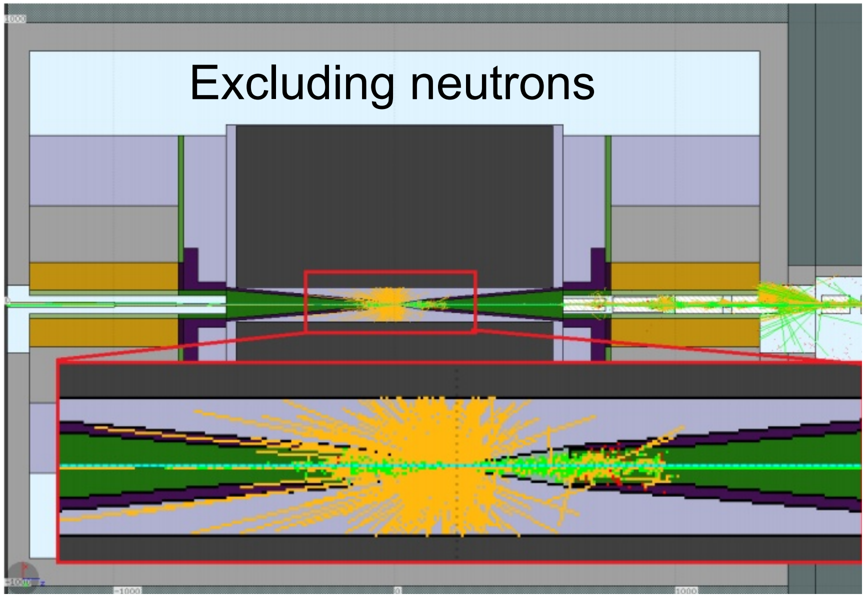
Previous studies e.g. JINST 13 P10024, arxiv:1905.03725, arXiv:1204.6721

Beam-Induced Background (BIB)

- Detailed accelerator design studies are needed to understand the environment around the interaction point
- Dominant BIB source: μ decays
- Dedicated shielding (nozzle) to protect magnets/detector near interaction region





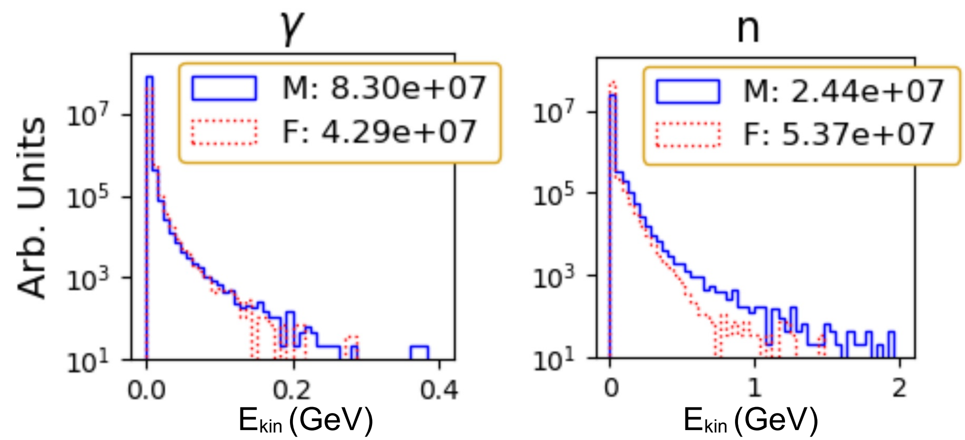


see C. Curatolo's talk
B08 (Sat)

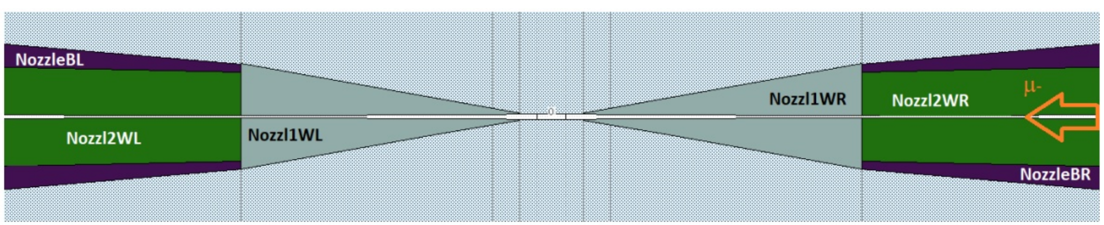
BIB Simulation

- Initial studies by MAP Collaboration (MARS15 simulation)
- Reproduced with reasonable accuracy using a new framework based on LineBuilder+FLUKA

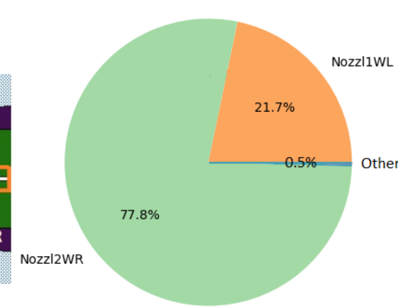
Particle (E_{th}, MeV)	MARS15	FLUKA
Photon (0.2)	$8.3\ 10^7$	$4.29\ 10^7$
Neutron (0.1)	$2.44\ 10^7$	$5.37\ 10^7$
Electron/positron (0.2)	$7.23\ 10^5$	$2.2\ 10^6$
Ch. Hadron (1)	$3.07\ 10^4$	$1.52\ 10^4$
Muon (1)	$1.47\ 10^3$	$1.22\ 10^3$



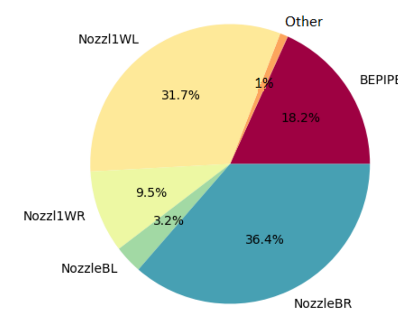
- Allows to study BIB in detail and extend to new designs / energy regimes
- Example: study of where muon decay products first / last interact with shielding



First interaction after μ decay

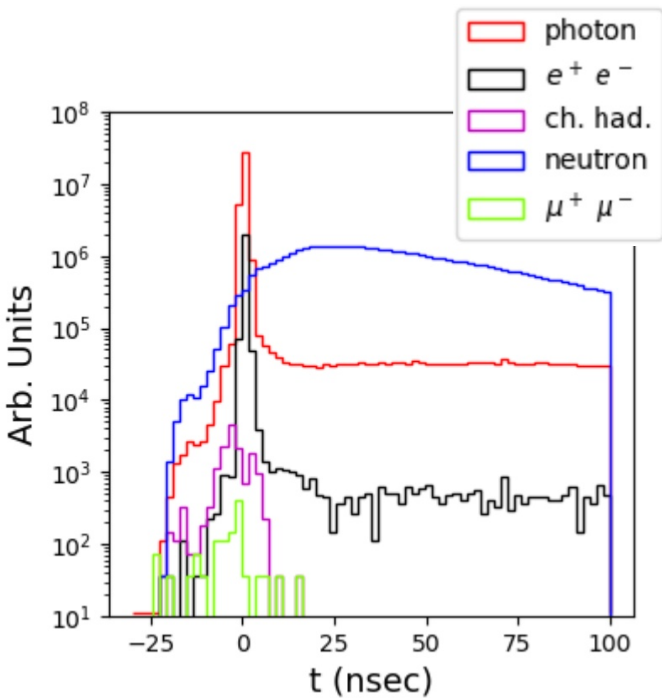


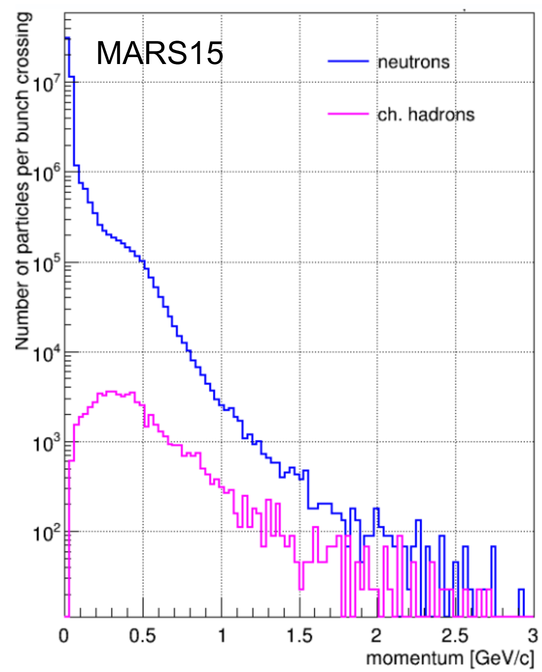
Last interaction when entering the detector

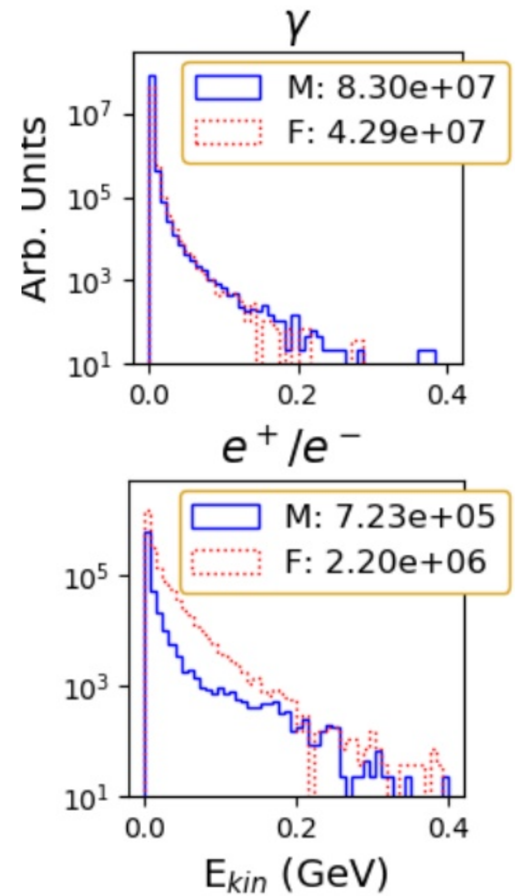


BIB characterization

- Key findings for discrimination:
  - Precise timing and Directional information (not from IP)
  - Energy deposit (especially $\gamma/e^{\pm}$ in Si)
  - Majority of particles with low transverse momentum
- Re-optimization and new handles being explored!

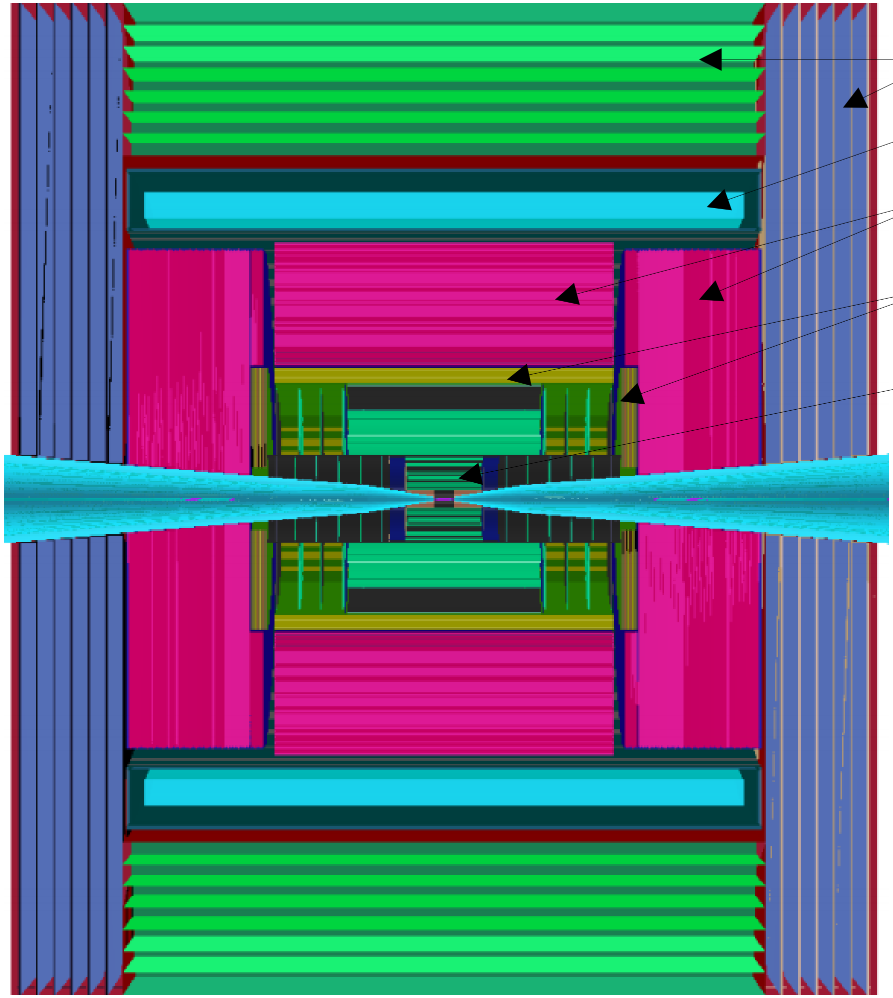




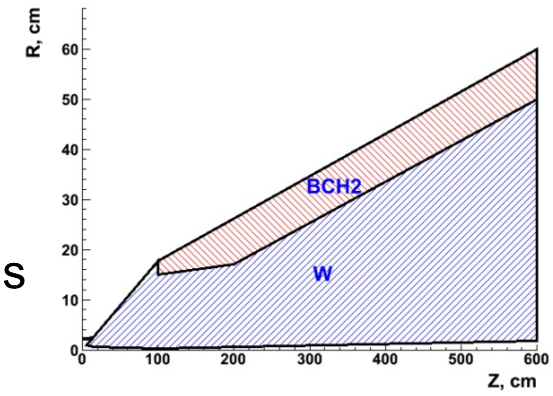


Detector design, √s=1.5 TeV

- Heavily based on CLIC detector, with modification for BIB suppression
- Detector optimization is one of the goals within the Snowmass timescale



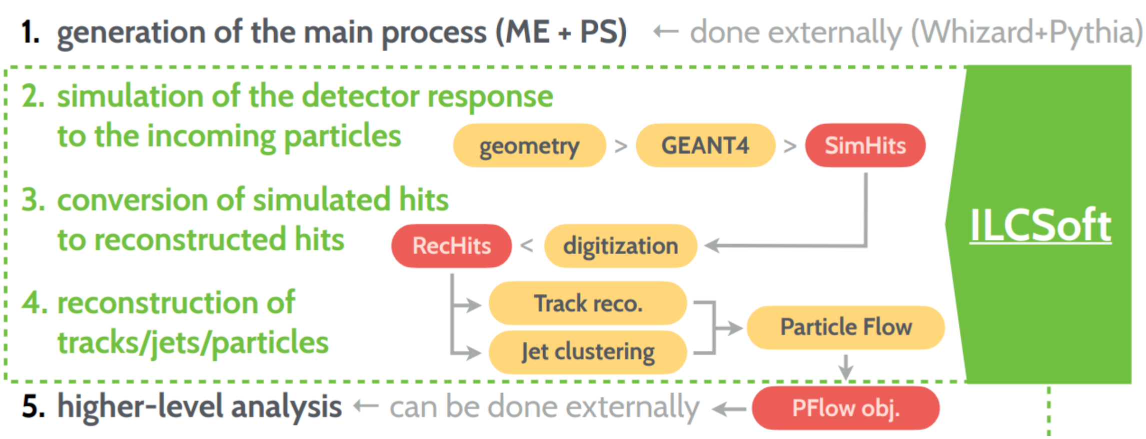
Nozzle design limits acceptance to θ=10° - different √s might allow different designs



Aiming for trigger-less readout of the detector at bunch crossing rate of ~100 kHz

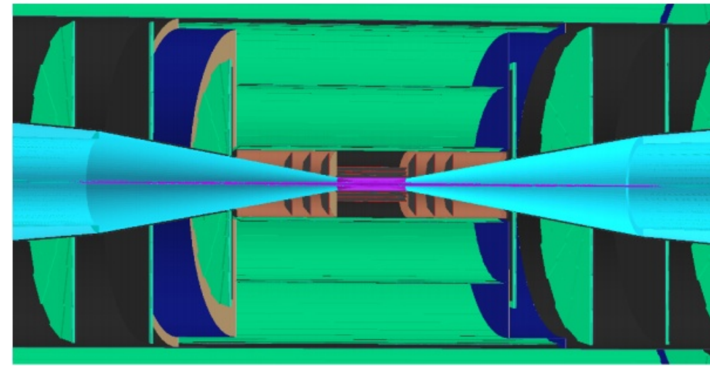
Software

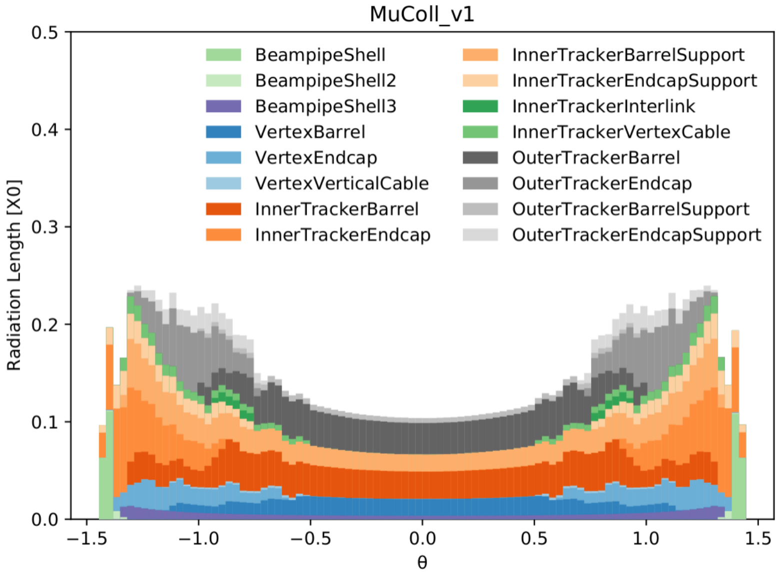
- Need both fast and full simulation to simultaneously meet challenges of a vast physics program exploration and detailed performance assessment
- **Fast simulation**: based on Delphes (card) by M. Selvaggi
  - Currently mostly based on similar assumed performance for FCC-hh and CLIC
  - Goal to progressively validate those assumptions with full simulation
- **Full Simulation/Reconstruction** based on ILCSoft (MuColl github)
  - Includes beam-induced background effects
  - Snowmass tutorial and twiki page
  - Main challenge: large computational time to include BIB effects
- All results shown today use full simulation with BIB (unless specified)

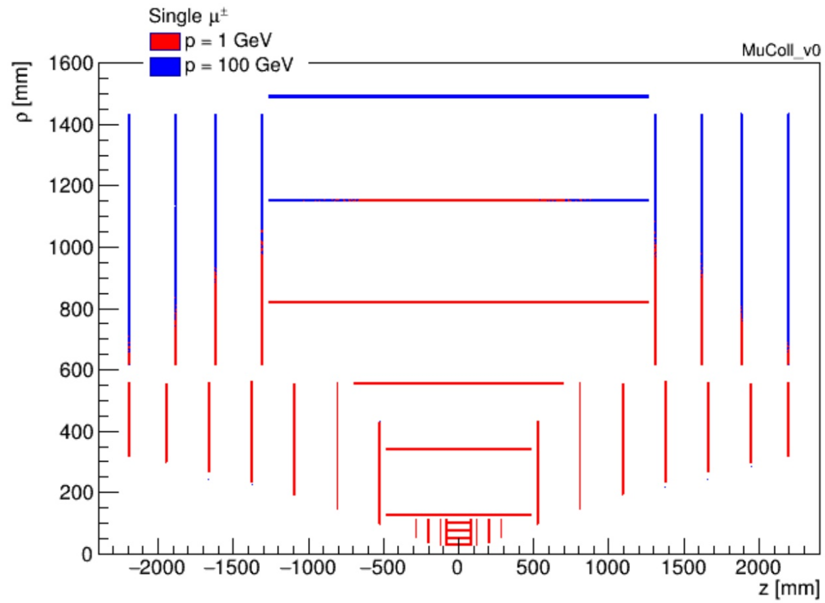


Inner Tracking Detector

- Current design consists of an entirely silicon-based detector
  - Vertex detector: 4 barrels + 4 endcaps / side
    - Each is a double-sensor layer to allow directional information from hits coincidence
  - Inner Tracker: 3 barrels + 7 endcaps / side
  - Outer Tracker: 3 barrels + 4 endcaps / side
- Simulation including estimate of support structures and services





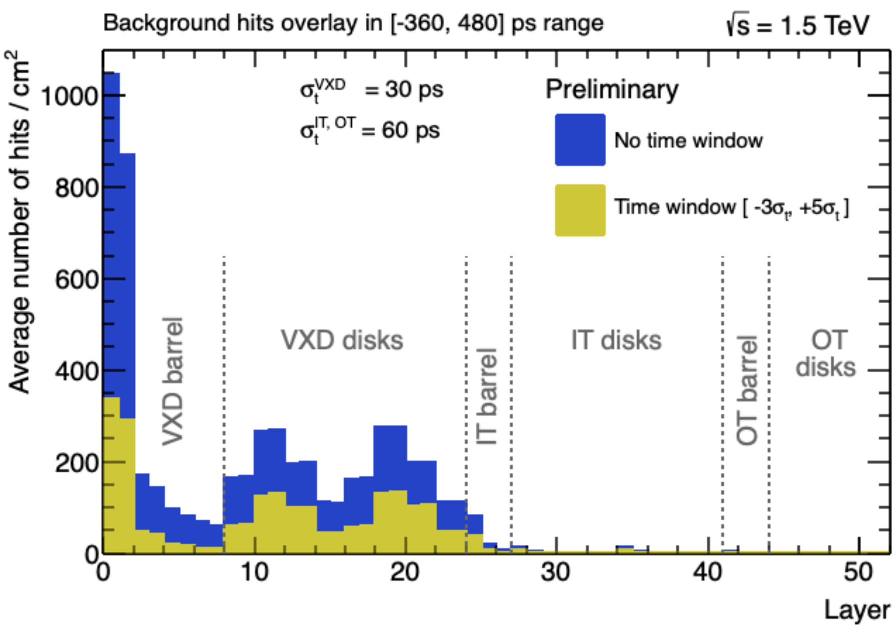


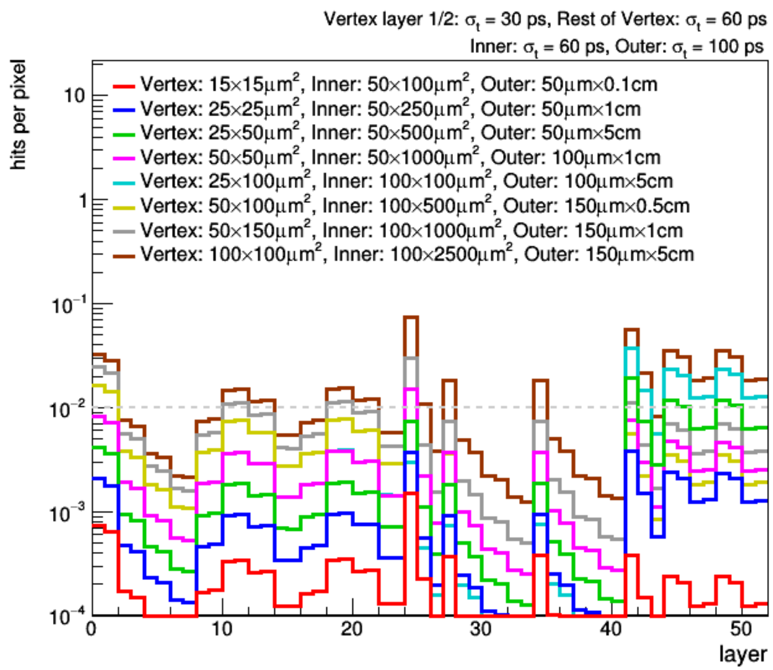
see H. Weber's talk
H08 (today!)

Tracker assumptions

- Parametric digitization, realistic digitization developed for the critical innermost layers
- Applying a timing window to reduce hits from out-of-time BIB
- Granularity optimized to ensure <= 1% occupancy in each layer

		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	729M
	E	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	462M
IT	B	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	164M
	E	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	127M
OT	B	50 μm × 10 mm microstrips	100 μm	60 ps	7 μm × 90 μm	117M
	E	50 μm × 10 mm microstrips	100 μm	60 ps	7 μm × 90 μm	56M





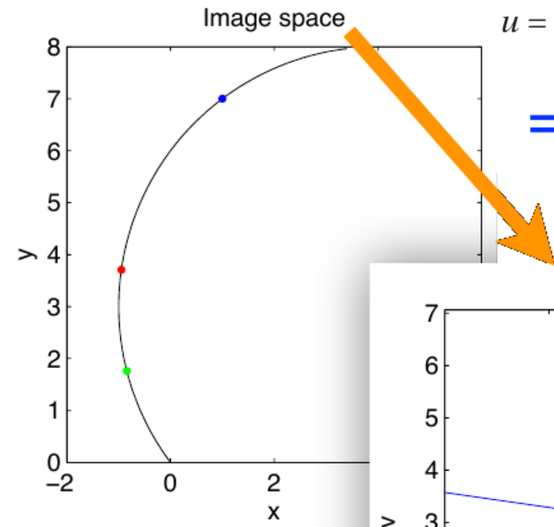
See:
M. Casarsa's talk, D14 (Sat)
K. Krizka's talk, Y07 (Tue)

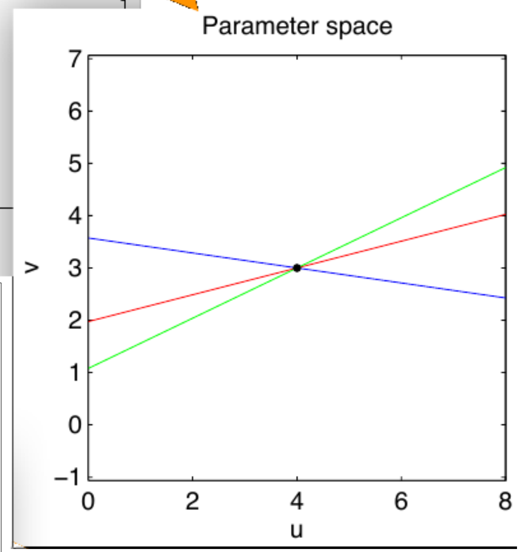
Track reconstruction

- Overall expect O(1M) measurements per event, dominated by BIB
  - Hard combinatorial problems for pattern recognition algorithms!
- Current implementation heavily inherited by CLIC studies: arXiv:1908.00256
  - conformal tracking approach
  - cellular automaton for track finding
- Not designed for large multiplicity
  - efforts to test ACTS tracking with high multiplicity pp-optimized algorithms

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

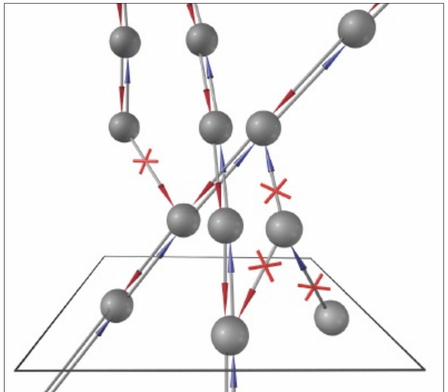
$$\Rightarrow v = -\frac{x}{y}u + \frac{x^2+y^2}{2y}$$





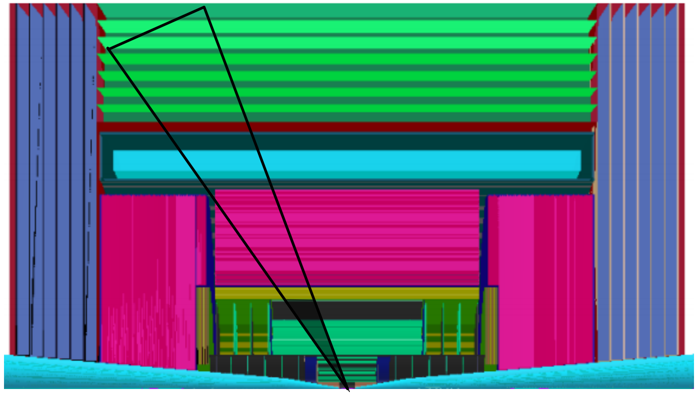
	No BIB	BIB (all)	BIB + timing filter
O(#measurements)	10^2	$10^{7\text{-}9}$	10^6
O(# 3-meas. "sensible" comb.)	10^3	10^{15+}?	10^{12}
O(time/evt)	1 s	∞	days

WARNING: contains rough back-of-the-envelope estimations

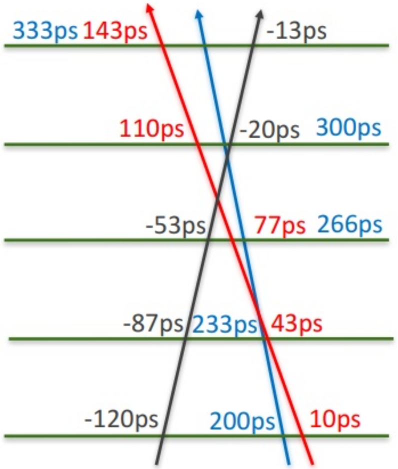

arXiv:1812.08036

Reducing track finding complexity

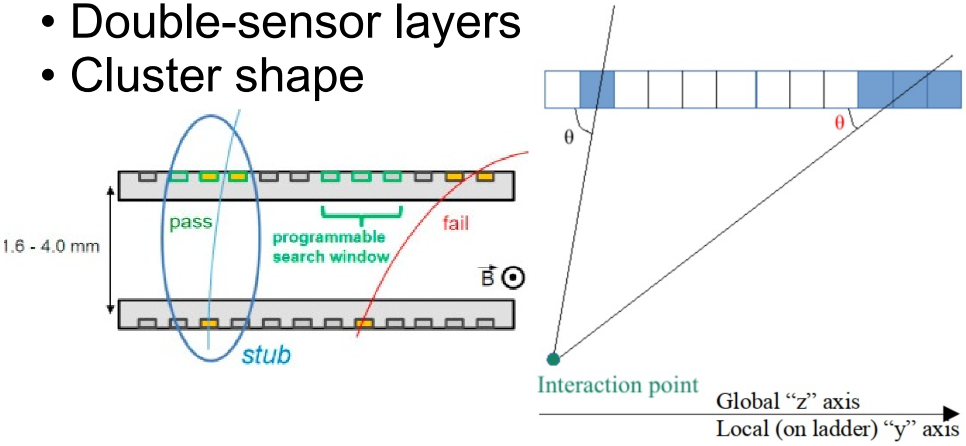
Regions of Interest
- Split detector regions
- Seed from calo/muon systems



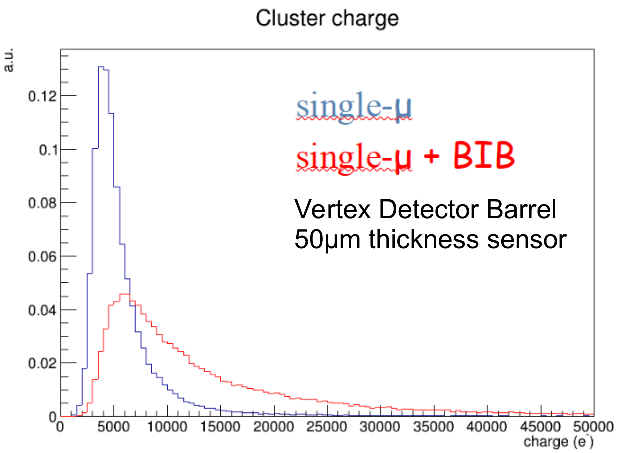
Precision timing
Embedded in track finding algorithms



Directional information
- Double-sensor layers
- Cluster shape

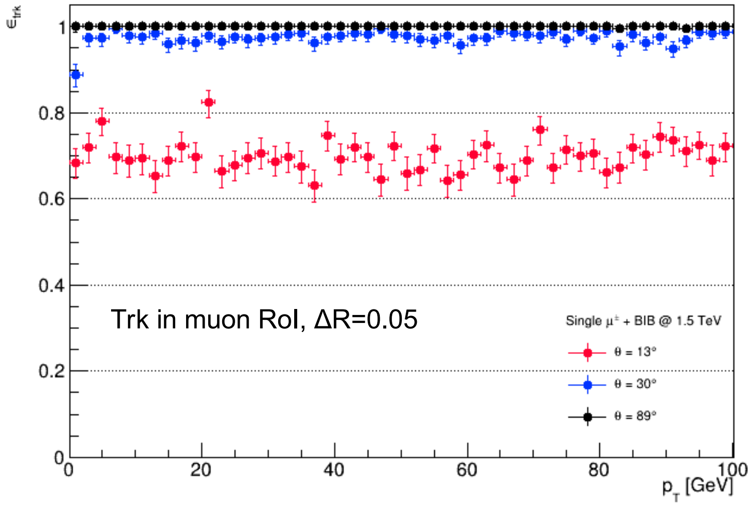


Energy loss in Silicon

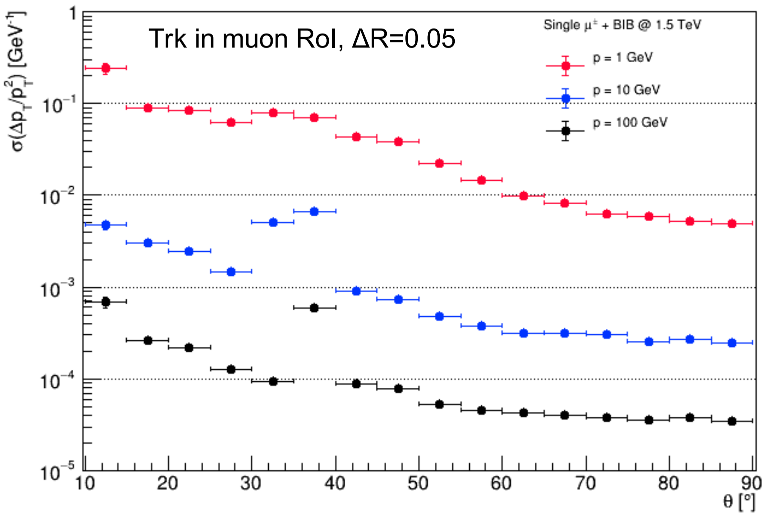


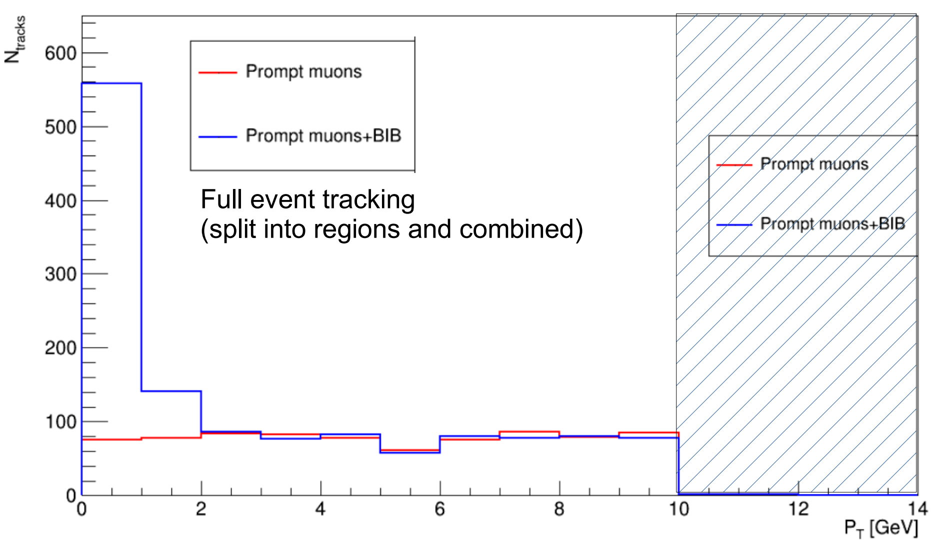
Tracking performance

- Establishing basic performance and ability to reconstruct physics objects in presence of beam-induced background



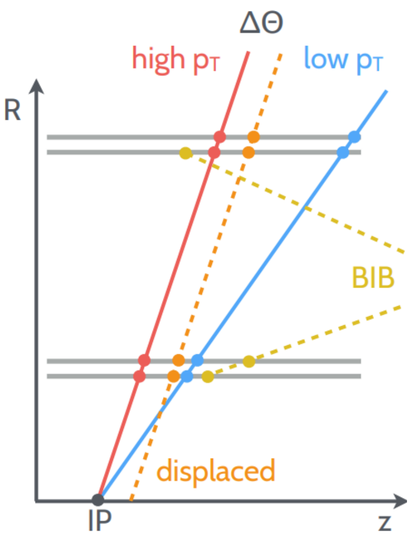
- Can successfully reconstruct muons with high purity of measurements associated to the track
- Further algorithm and geometry tuning needed to ensure high efficiency at all θ and smooth detector resolution

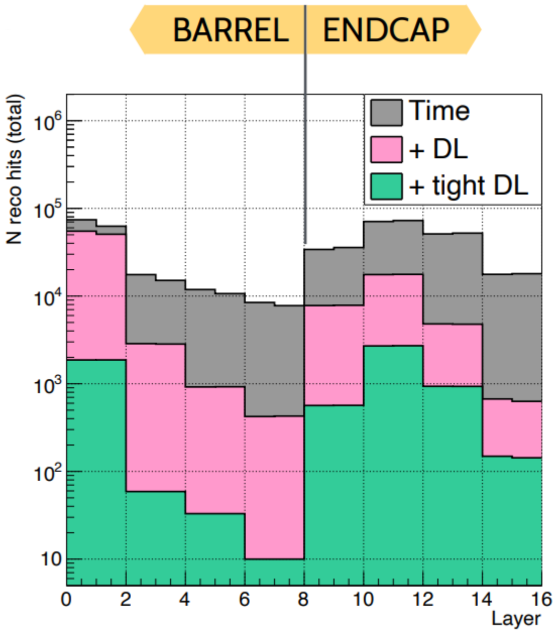




Using directional information

- Double-sensor layers

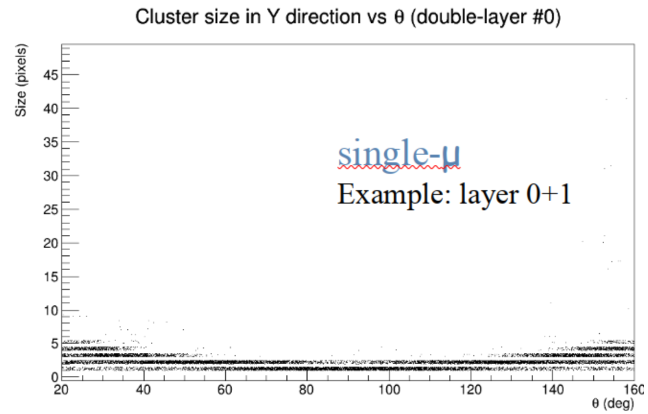


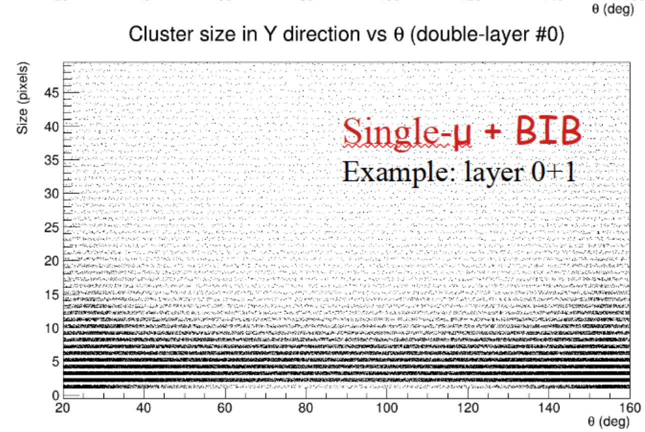


Loose: requires compatiblity with beamspot region within ~10mm
Tight: assumes knowledge of primary vertex position (or secondary-vertex)

Track reconstruction time decreases to hours or ~ 3 minutes per event

- Cluster shape analysis using realistic pixel detector digitization

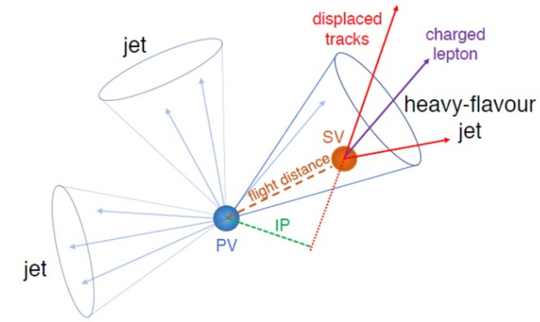


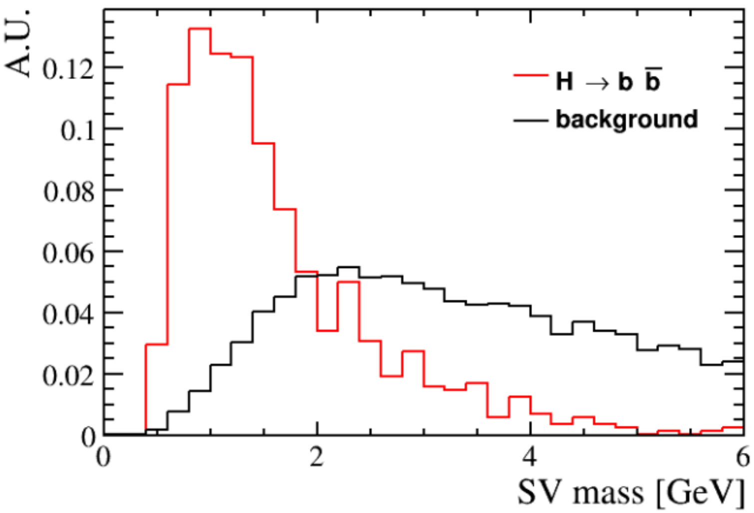


Cut Efficiency	Loose	Tight
Single muon	99.7%	99.6%
Single muon + BIB	55.2%	43.7%

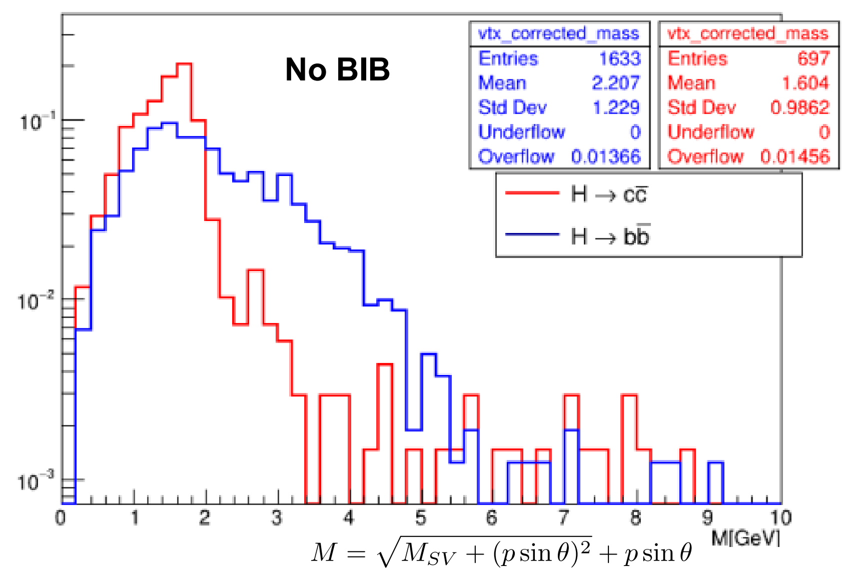
Flavour Tagging

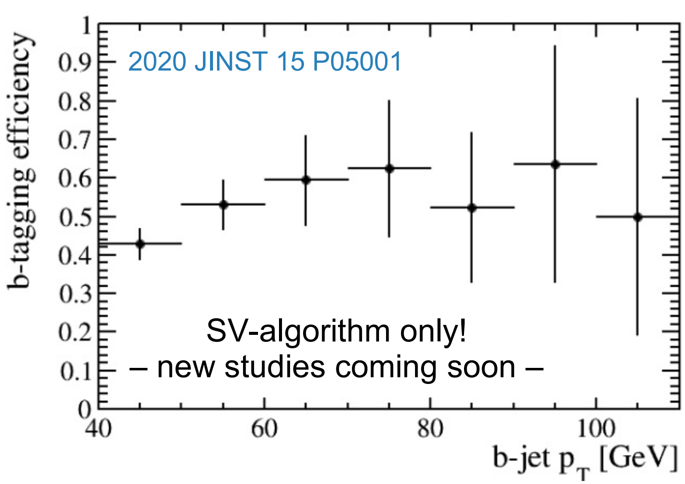
- Exploring secondary vertex reconstruction with BIB
  - Simple vertexing algorithm with optimized track selection





Corrected SV mass (jet-matched only)





- First studies on c-tagging
  - Coming soon: combination with other variables for advanced taggers!

see L. Buonincontri's talk
B08 (Sat)

E.g. Higgs physics with b-jets

- Proof of concept studying HH using realistic performance from full simulation with BIB included
  - Current performance very conservative!
  - Extrpolate at higher energies assuming the same performance as 1.5 TeV

- H → bb

2020 JINST 15 P05001

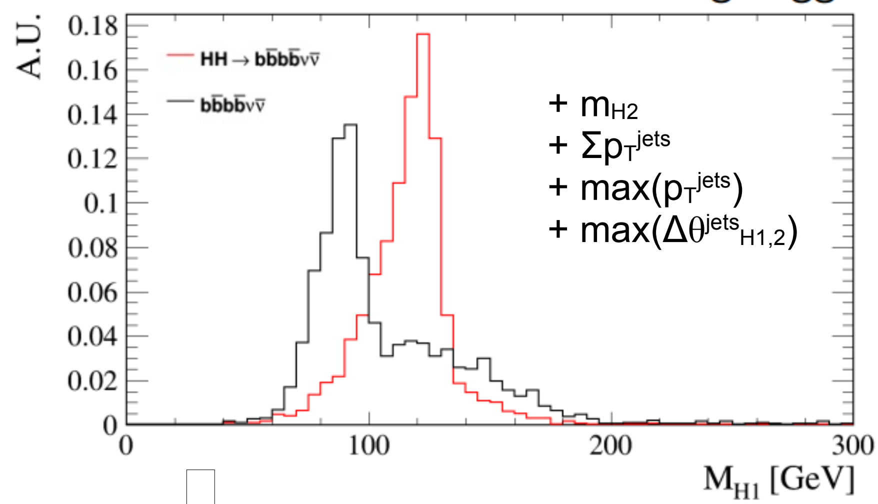
$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	0.20	0.91

- HH → 4b

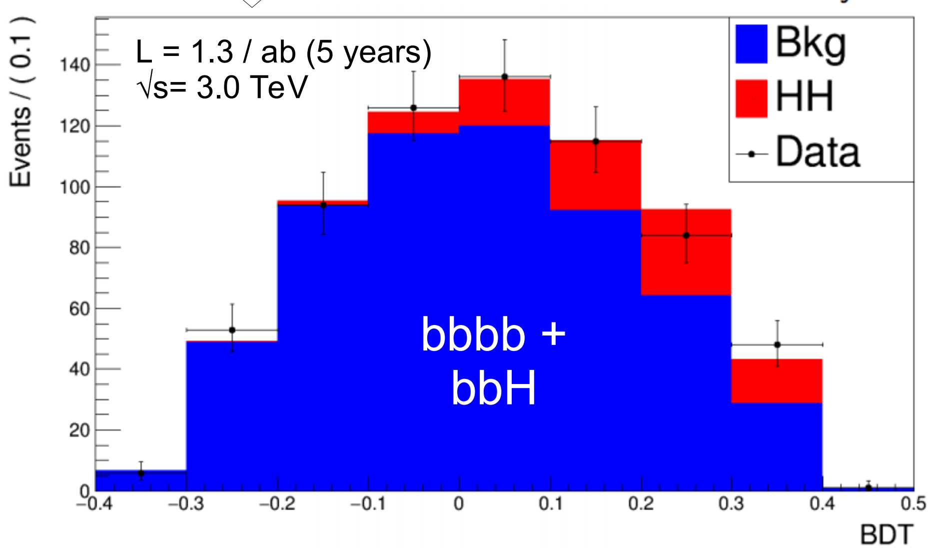
$$\frac{\Delta(\sigma(HH \to 4b))}{\sigma(HH \to 4b)} \sim 30\%$$

- Studies on H → cc also ongoing! Stay tuned!

Invariant mass of the leading Higgs

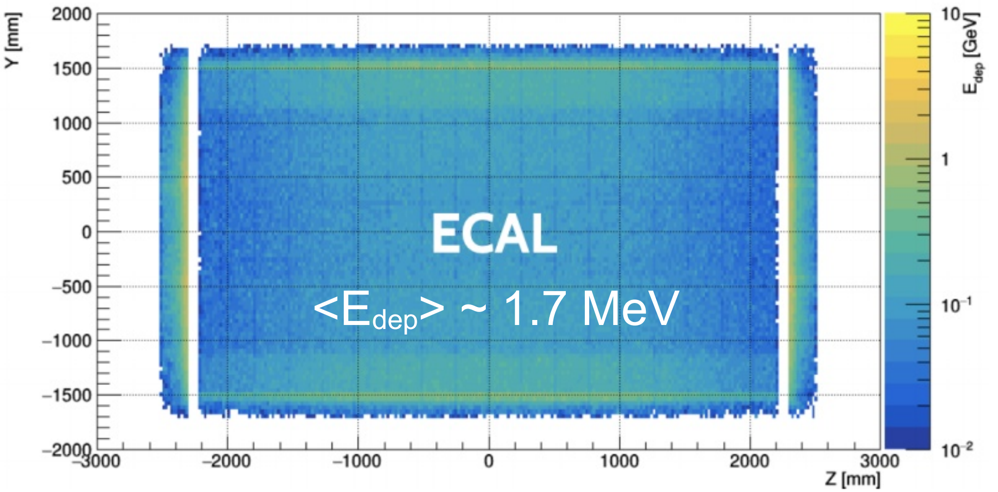


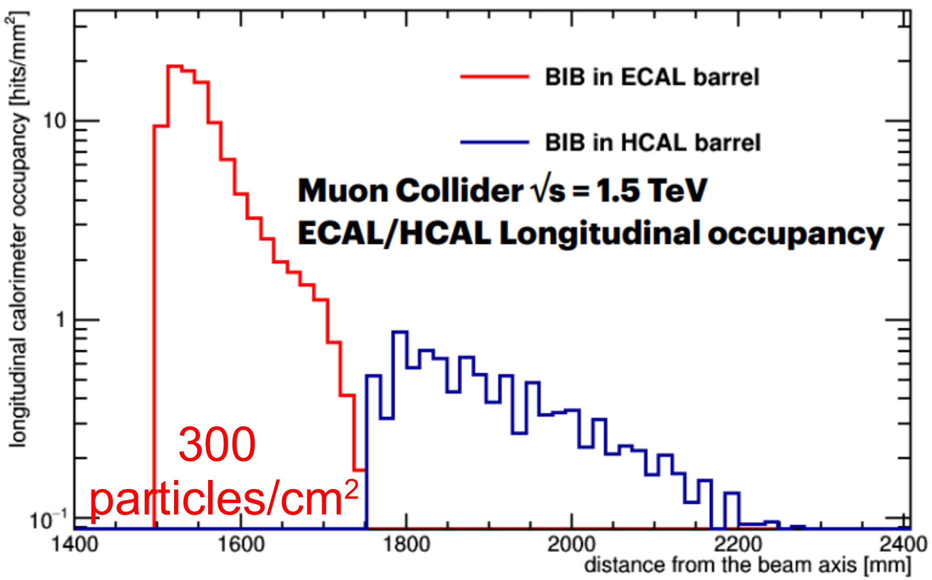
Preliminary



Calorimeters

- **E**lectromagnetic **cal**orimeter
  - 40 layers W absorber and silicon pad sensors, 5x5 mm2
- **H**adronic **cal**orimeter
  - 60 layers steel absorber & plastic scintillating tiles, 30x30 mm2
- BIB characteristics in calorimeters
  - diffuse energy deposits
  - out-of-time





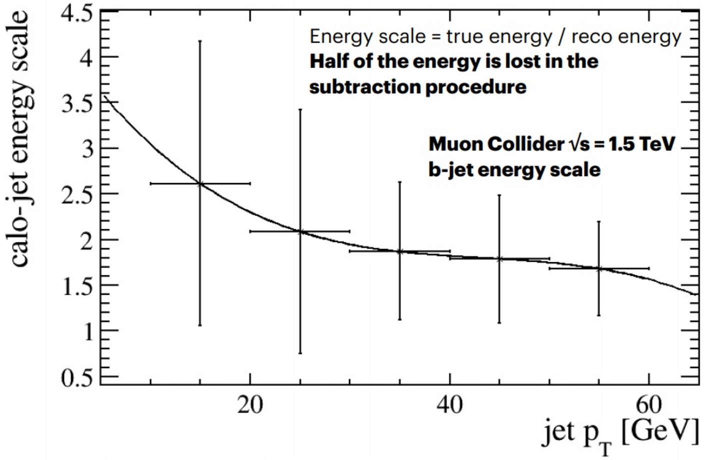
- Time measurements and Longitudinal segmentation play a crucial role in BIB suppression
  - Assuming ±0.25ns readout window
- Estimate average BIB contribution and subtract per-event

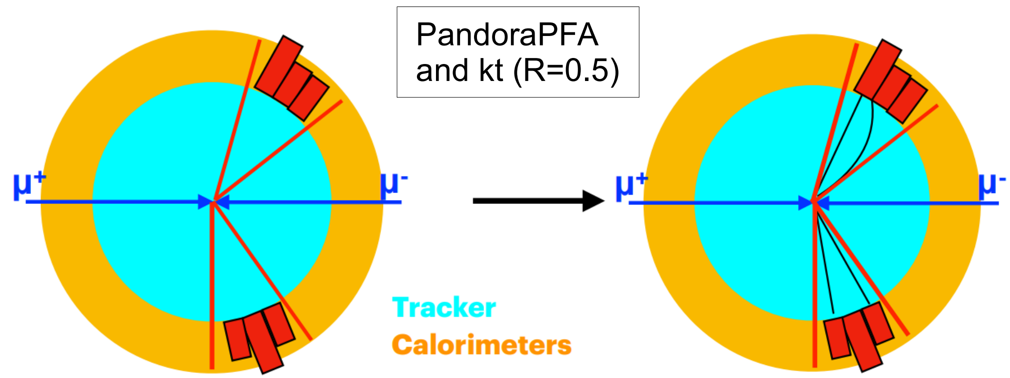
$$E_{HIT} > E_{BIB} + 2\sigma_{BIB}$$
$$E_{HIT} \rightarrow E_{HIT} - E_{BIB}$$

e.g. for ECAL

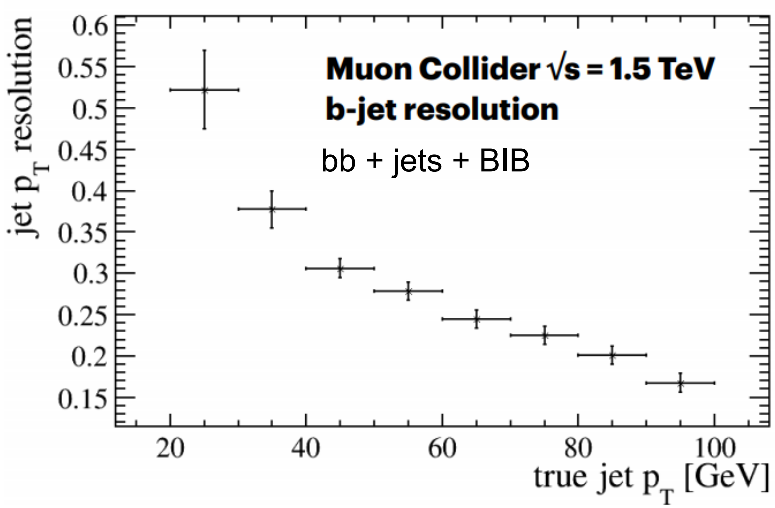
Jet reconstruction

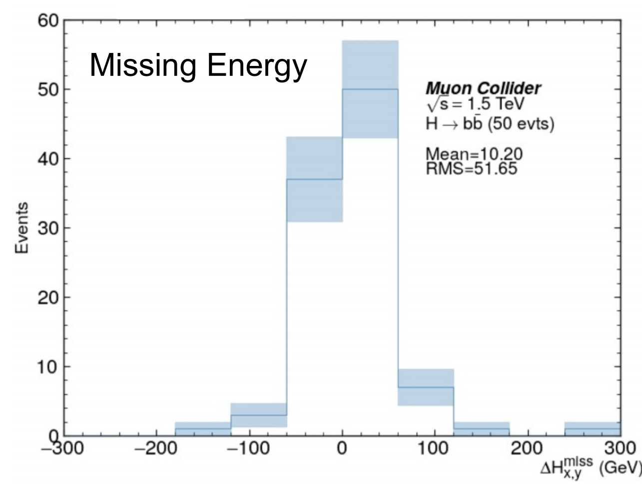
- Particle-flow algorithm with regional tracking around initial clusters





- Jet reconstruction fully efficient for p_T > 80 GeV (50% @ 20 GeV)



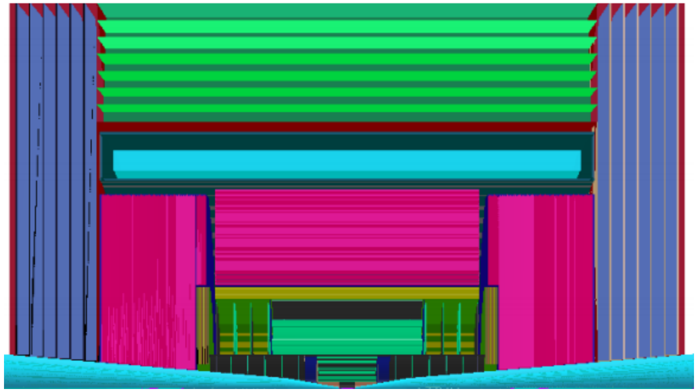


Initial study to prove feasibility of reconstruction with BIB.

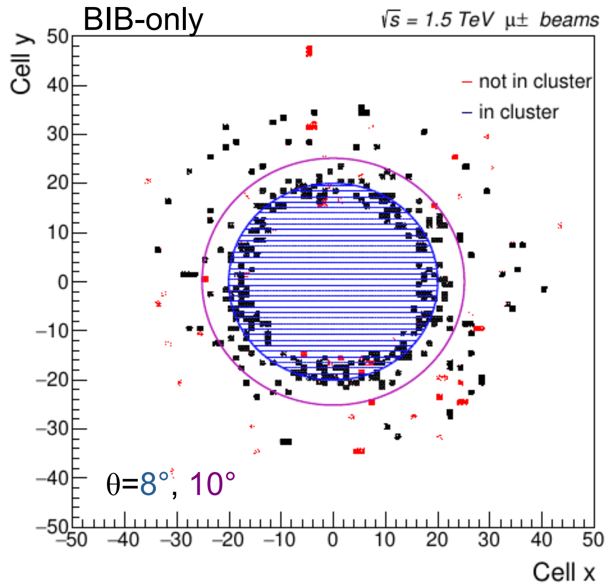
Lots of room for optimization at all stages.

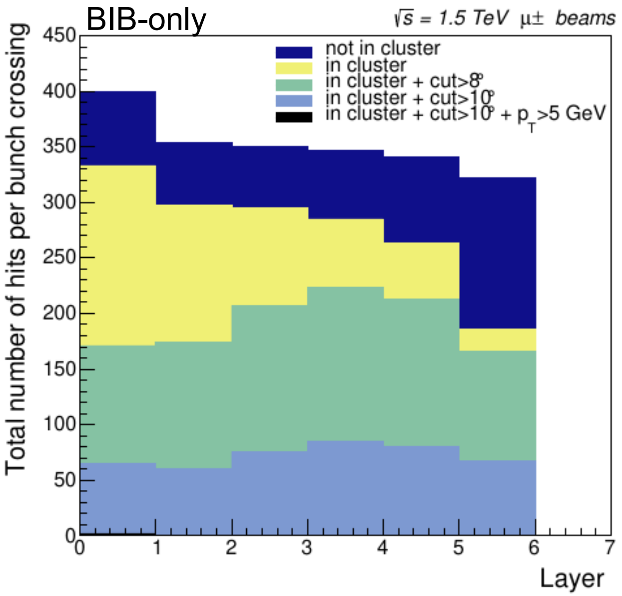
- Coming soon: e/γ and tau reconstruction

- RPC cells of 30x30mm^2
  - 7 barrel layers, 6 endcap layers
- Much reduced BIB contribution compared to tracker and calorimeter (~8% of BIB)
  - concentrated in the low-radius endcap region



- Can be effectively removed with geometrical cut to a level that does not contaminate reconstructed muons

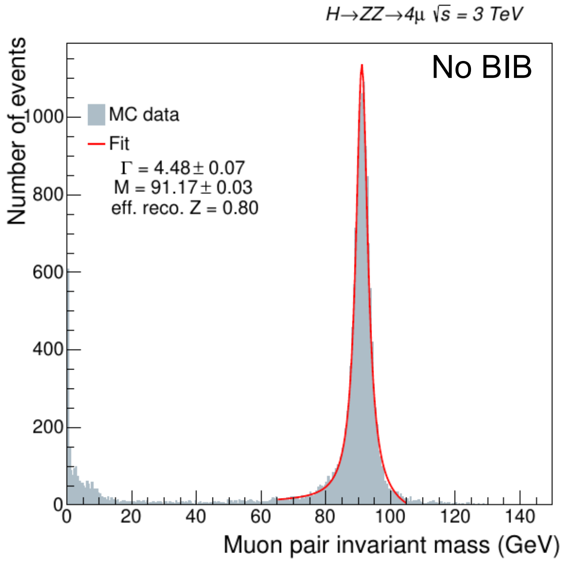




see C. Aimè's talk
B08 (Sat)

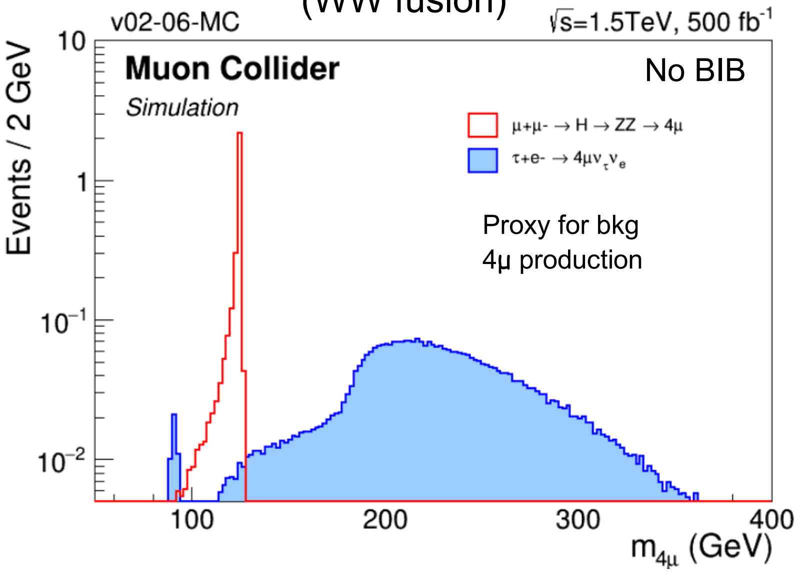
Muon reconstruction

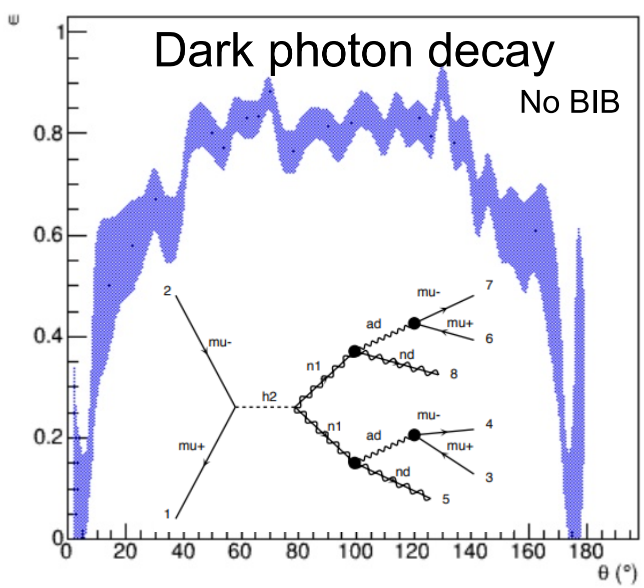
- Muon reconstructed with high efficiency
  - 99% barrel, 92-95% endcap (w.i.p.)
- Can seed inner track reconstruction around clean candidate muons



$$\mu^+\mu^- \to H(\to 4\mu)\nu_\mu\bar{\nu}_\mu$$

(WW fusion)





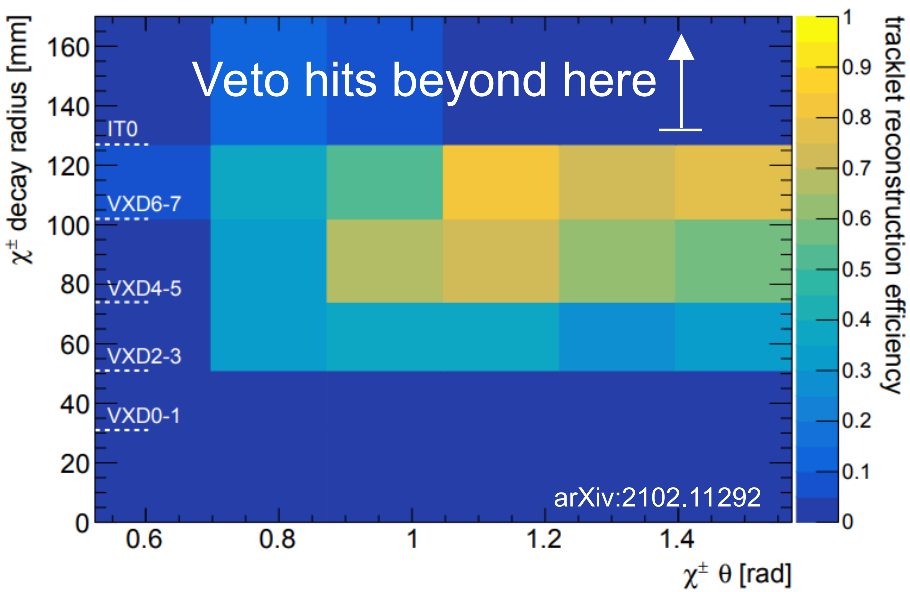
~~Non~~-conventional detector requirements

- Long-lived particles, boosted objects, ..
- Attention to detector design choices, e.g.
  - Granularity
  - Acceptance for slow particles
- e.g. dedicated reconstruction for short-lived “disappearing” tracks

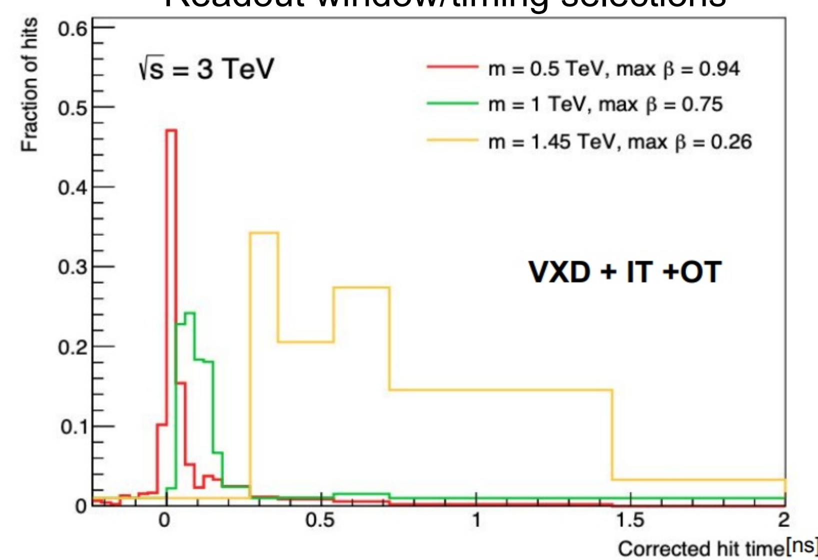
Example slide from Snowmass CPM#131

General Requirements (for LLP)

- Hermiticity
  - Different geometry choices that provide similar hermeticity for prompt particles can differ drastically in their coverage of particles not originating at the interaction point
- Geometry
  - Interplay of geometry choice with hermeticity, trigger-capabilities, and even data-rate reduction need to keep in mind LLP needs
- High granularity at large radius
  - Identifying decays of LLP in various sub-systems away from the interaction point and distinguish them from detector-specific backgrounds (including beam-induced backgrounds)
- Particle ID
  - Measurement of ionization energy loss and timing can boost particle ID capabilities and offer unique handles for LLP direct identification
- Timing (more later)
- Dataflow/software must be defined to not prevent LLP searches
  - Inclusive initial reconstruction and/or nimble re-reconstruction

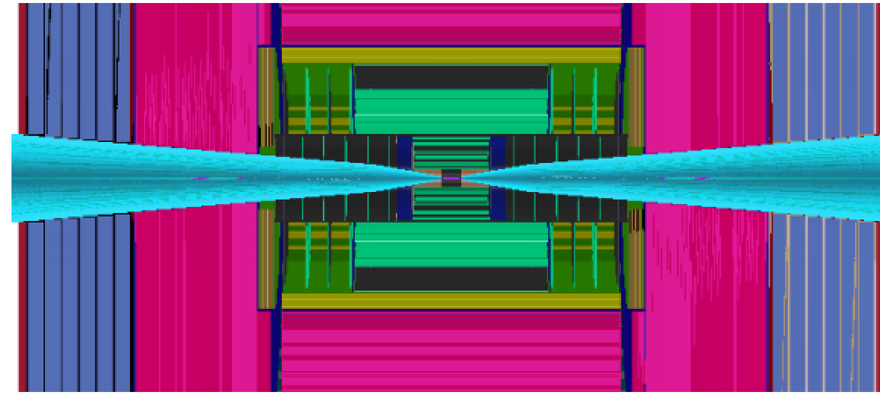


Readout window/timing selections



Luminosity measurement

- Noozle does not leave much space for dedicated forward detectors
- Direct method (e.g. vdM scans) difficult due to the short muon lifetime



- Investigated μμ → μμ scattering as indirect luminometer

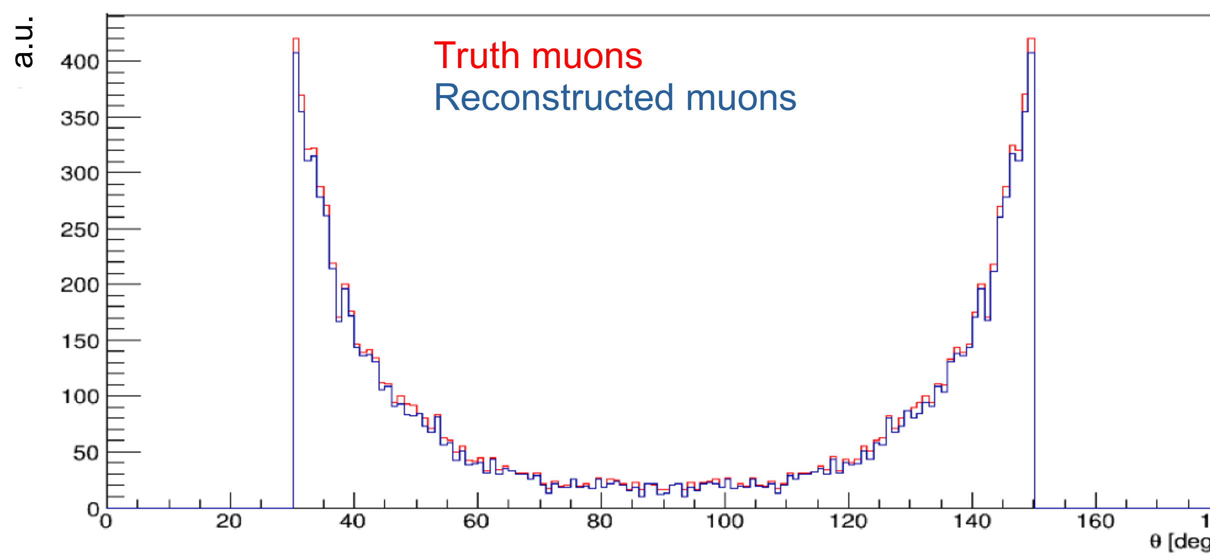
2 opposite-sign muons back-to-back

m(μμ) ~ 1.5 TeV

$\delta L/L \sim 0.2\%$

one year of data-taking - no theory uncertainties

Limited statistics due to detector acceptance



Conclusions

- A Muon Collider offers great opportunities to extend the energy frontier, but its environment exposes unique challenges

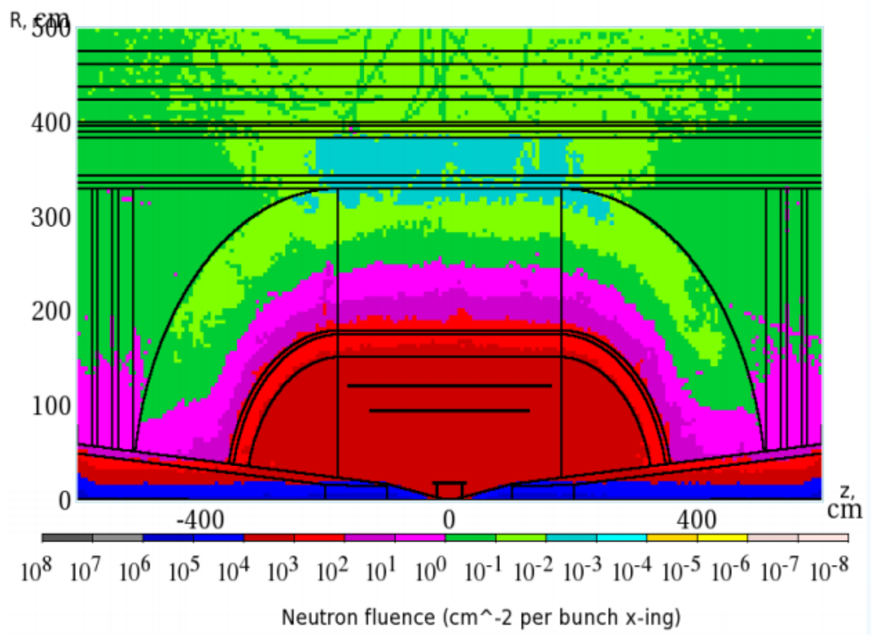
- Ongoing studies to produce a realistic detector design, simulation and reconstruction software
  - Aim to study interplay of needed detector R&D (requirements) and physics reach

- Basic performance are being established
  - Moderately optimistic picture in terms of ability to control effects of beam-induced background on object reconstruction
  - Rapid progress, with a lot of room for creative solutions in such a unique environment

BACKUP

Radiation environment

- Expected fluence < HL-LHC
- HL-LHC < Expected dose < FCC-hh
- Still expecting radiation hardness to play a significant role, but unlikely to be a major problem
- Leaves more flexibility in adapting detector design to such requirements



Trigger and DAQ considerations

- Bunched beam with O(10 μs) bunch spacing → 100 kHz
- A critical item for transferring data is the tracker
  - For the given tracker occupancy → up to O(50Gbps) of data per module
  - About a factor 10 of HL-LHC designs
  - In-chip data reduction through logic might allow to lower this requirement
    - e.g. cluster timing, shape, double-layers logic, energy threshold, etc..
- Total data flux approx (tracker-only, assumed dominant) ~ 30Tbps
- Trigger-less readout is likely a considerable option!

Muon reconstruction