Muon Collider Detector

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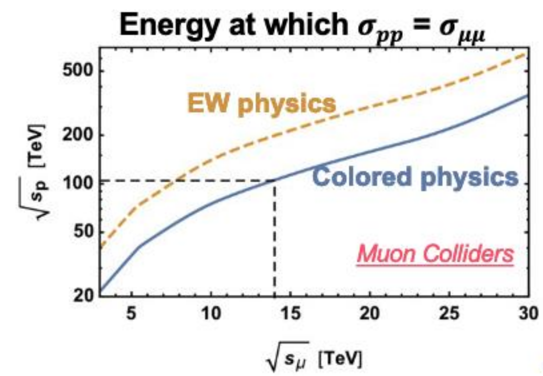
Physics Motivation

HE Muon collider described as “simply a dream machine”:

- Direct searches (pair production, VBF, resonances, DM, …)
- High-rate measurements (single H, self coupling, rare H decays, top, ….)
- High energy probes (di- and tri-boson, di-fermion, EFT, compositeness…)
- Muon physics (LFU, b→sμμ, g-2, …)



Exciting new perspective in the collider landscape, and great interest from the theory community!

307.04743	2005.10289	2008.12204	2012.11555	2102.11292	2104.05720
301.06150	2006.16277	2009.11287	2101.10334	2103.01617	etc …
003.13628	2007.14300	2012.02769	2102.08386	2103.14043	

Iit's Competitive:

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

arXiv 2103.14043

…and complementary!

The Muon Smasher's Guide

Abstract
We lay out a comprehensive physics case for a future high-energy muon collider, exploring a range of collision energies (from 1 to 100 TeV) and luminosities. We highlight the advantages of such a collider over proposed alternatives. We show how one can leverage both the point-like nature of the muons themselves as well as the cloud of electroweak radiation that surrounds the beam to blur the dichotomy between energy and precision in the search for new physics. The physics case is buttressed by a range of studies with applications to electroweak symmetry breaking, dark matter, and the naturalness of the weak scale. Furthermore, we make sharp connections with complementary experiments that are probing new physics effects using electric dipole moments, flavor violation, and gravitational waves. An extensive appendix provides cross section predictions as a function of the center-of-mass energy for many canonical simplified models.

arXiv 2103.14043

Muon collider as potential direct probe of indirect signals from EDM, Flavour, Gravitational Waves…

	$N_{\text{post-cuts}}$		
$\sqrt{s}$ (TeV)	$\mu^+\mu^- \to \mu\,\tau$	$\mu^+\mu^- \to \mu\,\tau\,\nu_\mu\,\nu_\tau$	$\mu^+\mu^- \to \tau^+\tau^-$
.125	0.0948	30.8	3.42×10^4
3	53.3	6.32×10^3	40.4
6	212	3.26×10^3	9.52
14	1.14×10^3	1.14×10^3	0.138
100	5.73×10^4	60.9	0.0312

arXiv 2103.14043

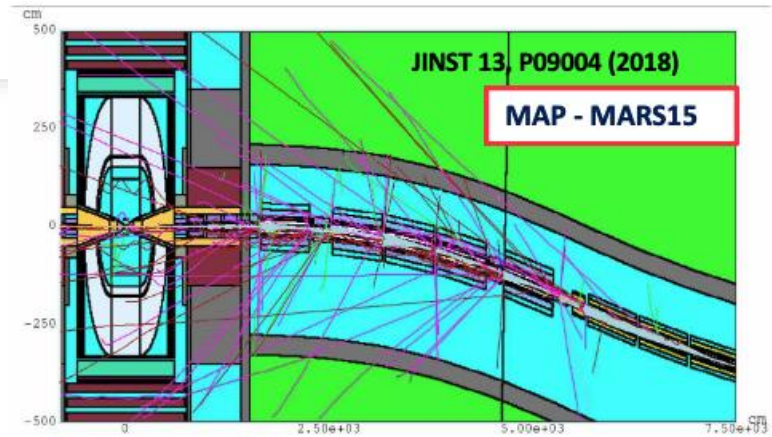
Table 5: Number of signal and background events after kinematic cuts and estimating the loss of signal efficiency due to initial state radiation for 1 ab^{-1} of data and $c^{\tau 3\mu}/\Lambda^2 = 1/(50\ \text{TeV})^2$.

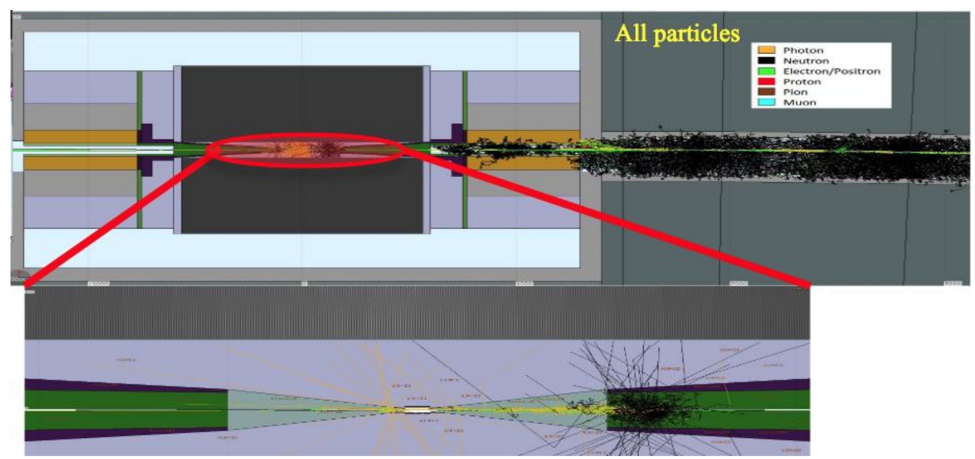
Challenges for a Muon Collider Detector

Prototypical machine design to deliver:

- 1 bunch/beam
- Collision spacing: 10 / 15 μs @ 1.5 / 3 TeV
- σ_z~10 / 5 mm @ 1.5 / 3 TeV

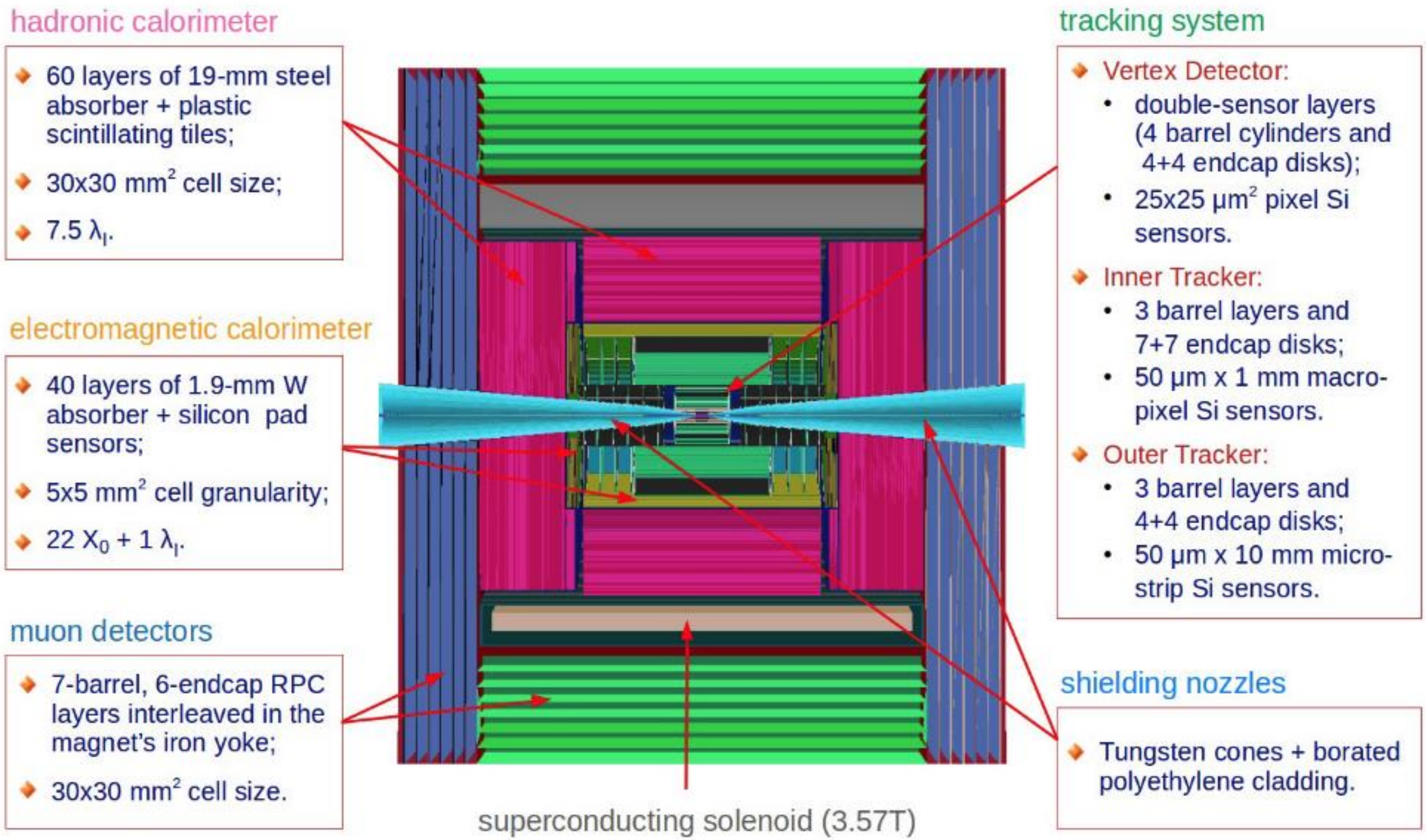
- Beam Induced Background:
  - Muon decays 4E5 decays/m/crossing at 3 TeV
  - Tertiary muons produced far from collision points
  - Showers from final triplets





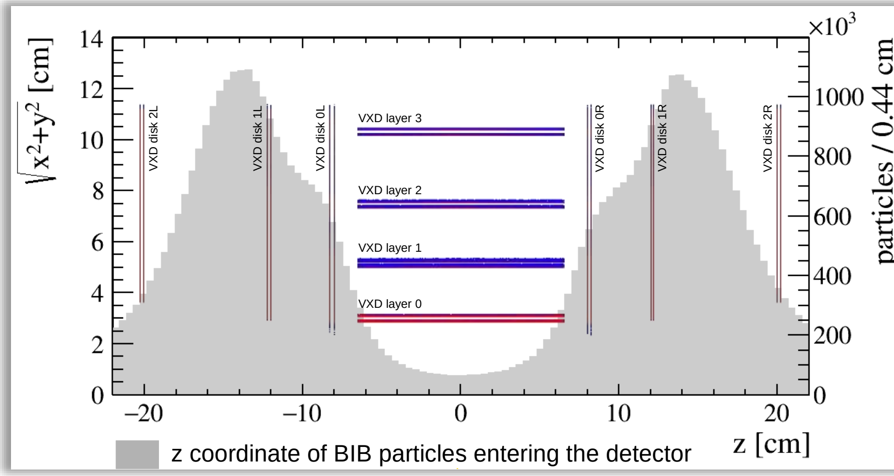
Baseline Detector Model

optimization @1.5 [3] TeV



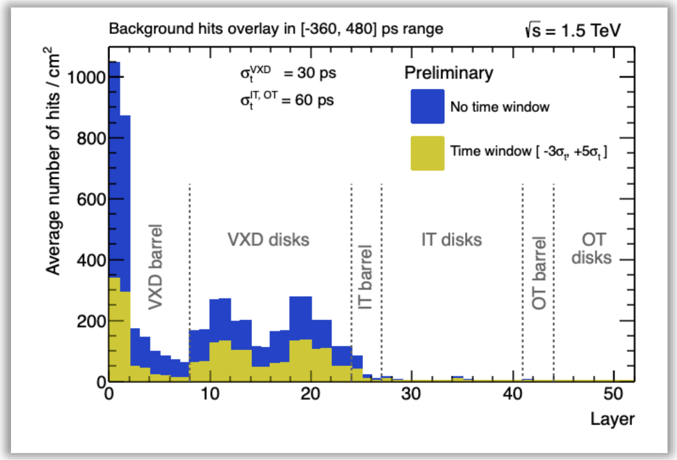
- CLIC baseline detector model model
- MAP-designed MDI and vertex detector

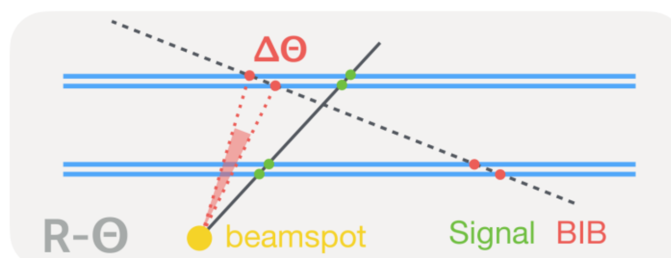
Tracker [1.5 TeV]



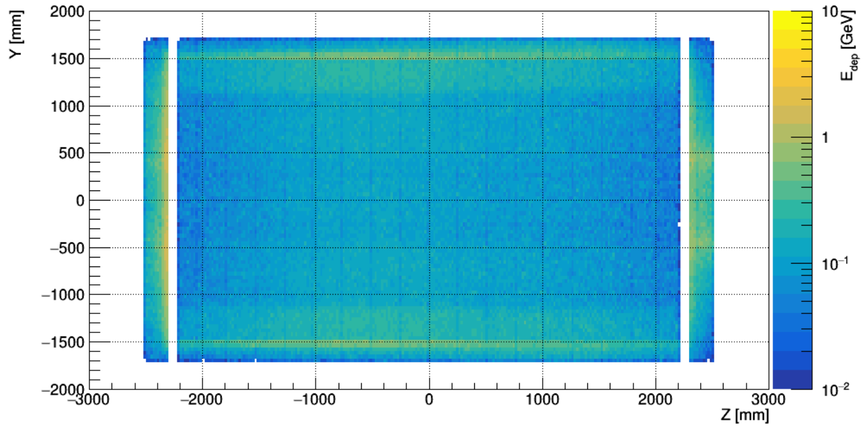
Main focus on BIB effects:

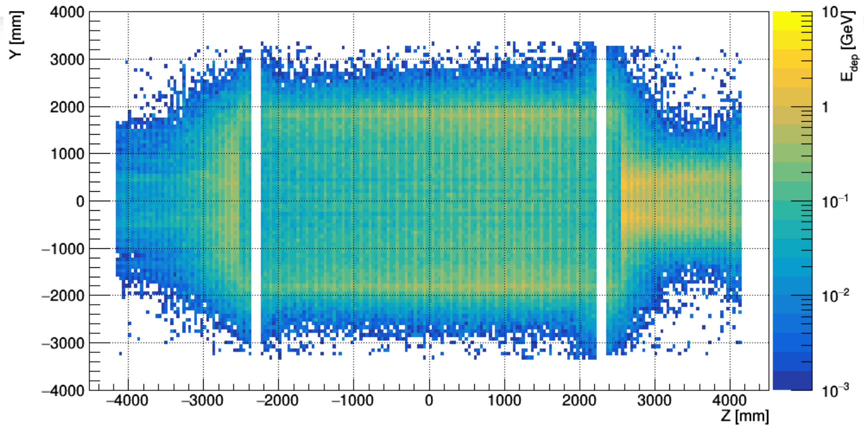
- Design avoids "hottest" BIB regions
- Readout timing window tuned to exclude out of time BIB
- Granularity tuned to ≲1% occupancy
- Additional expedients under study against BIB:
  - Cluster shape
  - Use of PV for angular matching of doublets
- What about secondary vertices and LLP?





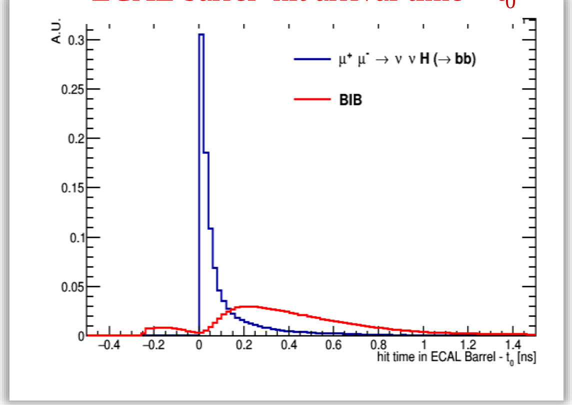
Calorimeters

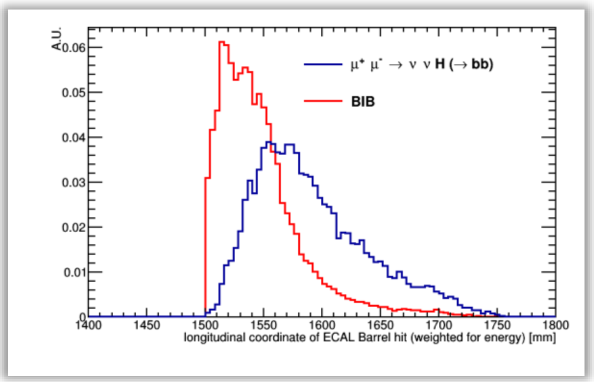




- BIB deposits large amounts of energy both in EM and Hadr. Calorimeters
- Timing and shower profile allow in principle to distinguish:

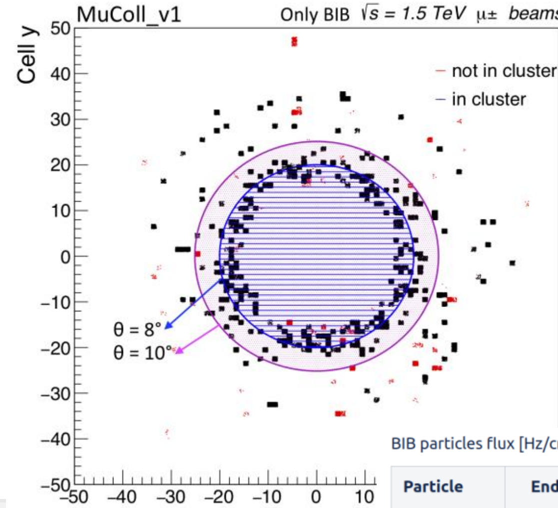
ECAL barrel hit arrival time – t_0





Computational (& DAQ?) challenge in efficient separation from BIB background!

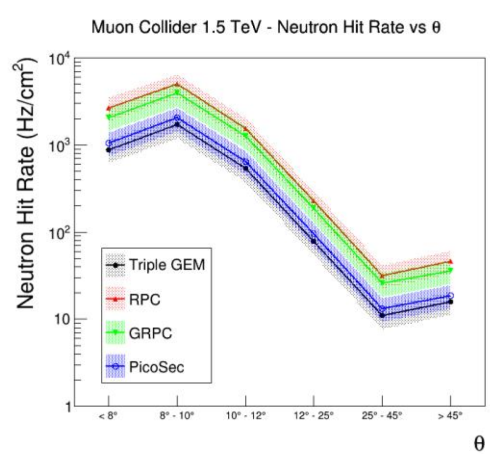
Muon Detectors

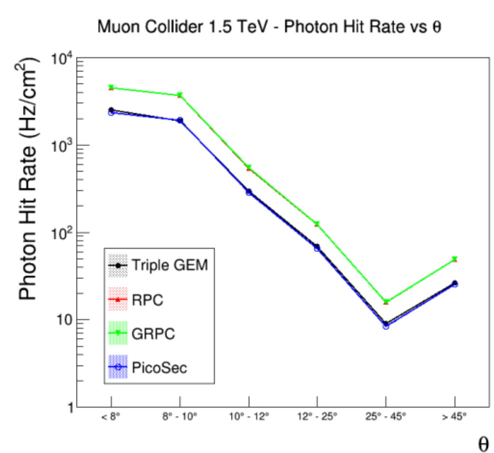


- Several detector technologies explored
- BIB not a performance issue of properly handled

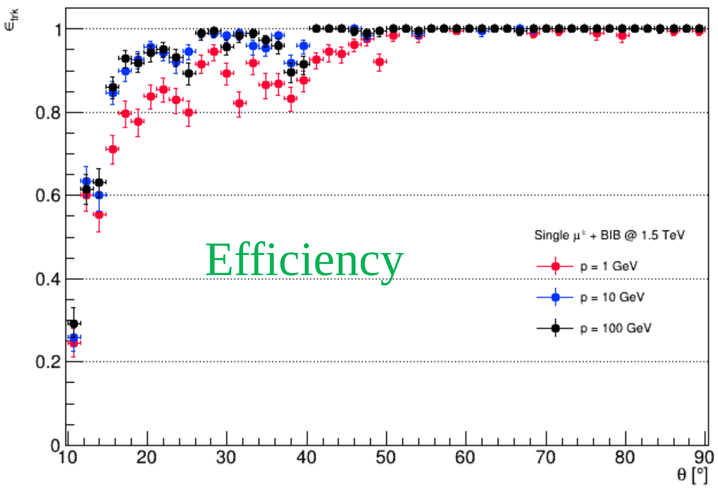
BIB particles flux [Hz/cm^2] in different regions (bunch crossing time 10 μs):

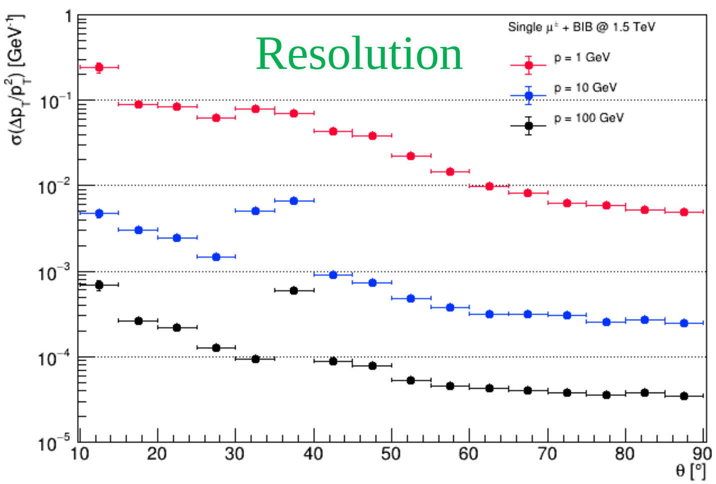
Particle	Endcap (θ >12°)	Endcap (8° < θ < 12°)	Endcap (θ < 8°)	Barrel
neutrons	$1.2 \cdot 10^3$	$5 \cdot 10^4$	$1.2 \cdot 10^6$	$1.4 \cdot 10^2$
photons	$6.2 \cdot 10^2$	$1 \cdot 10^4$	$7.2 \cdot 10^5$	5
protons	16	$3 \cdot 10^2$	$2.4 \cdot 10^4$	----
μ+ μ-	3	$3.7 \cdot 10^2$	$1.2 \cdot 10^4$	----
pions, kaons	< 1	70	$1 \cdot 10^3$	----
e+ e-	3	$3.3 \cdot 10^2$	$5 \cdot 10^3$	< 1
Total	≈ 2 kHz/cm^2	≈ 60 kHz/cm^2	≈ 2 MHz/cm^2	≈ 200 Hz/cm^2





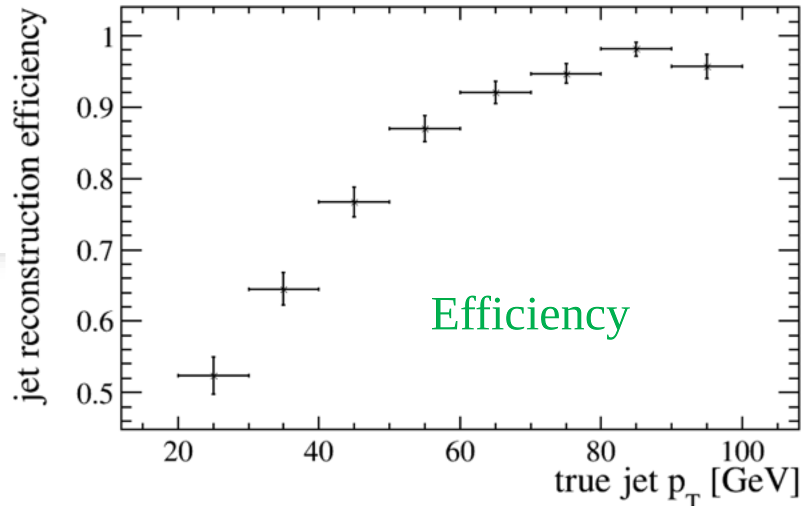
Tracking and Jet reconstruction performance

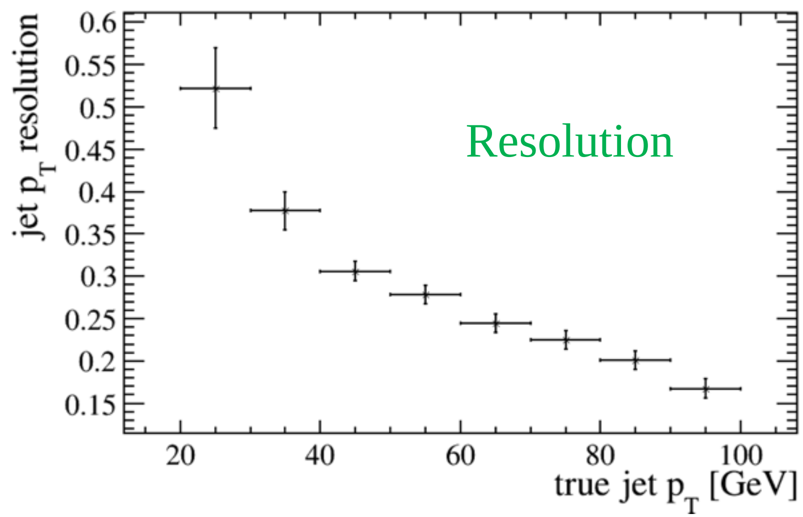




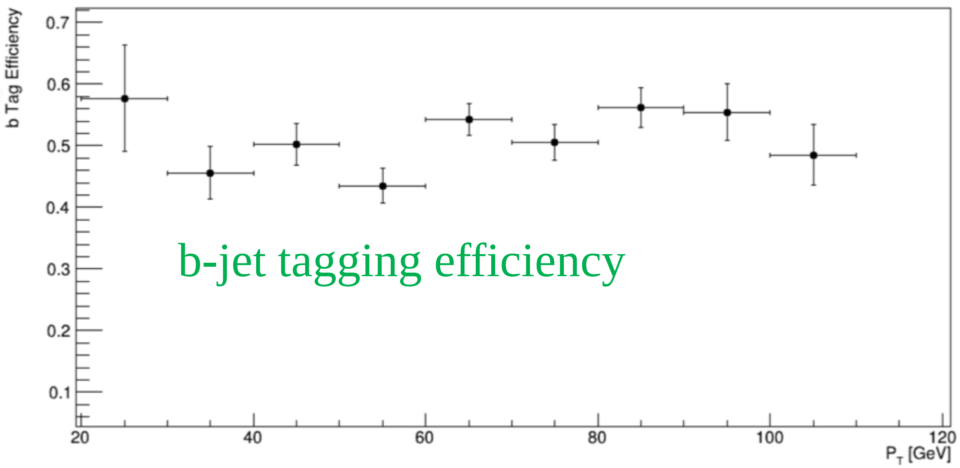
- Efficiency drops in nozzle region
- Resolution degrades too

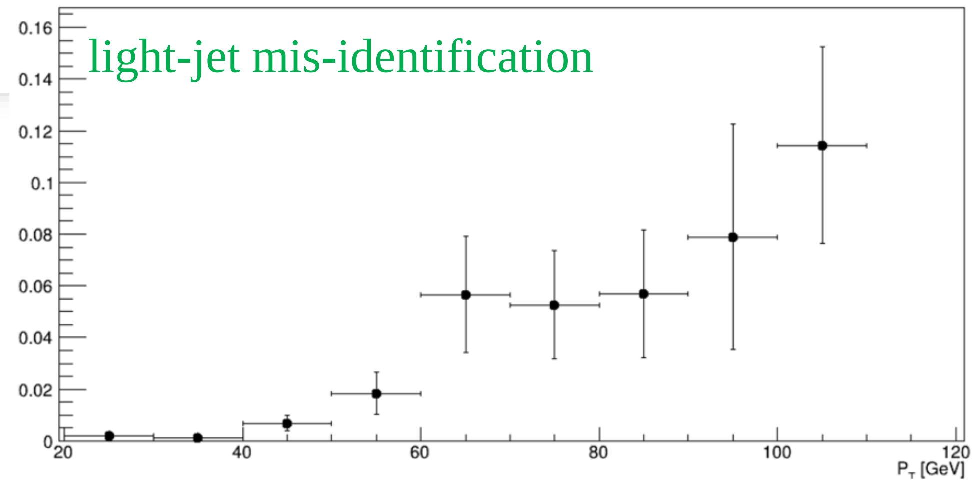
Need further optimization of detectors and algorithms!





B-jets and Secondary Vertex Reconstruction

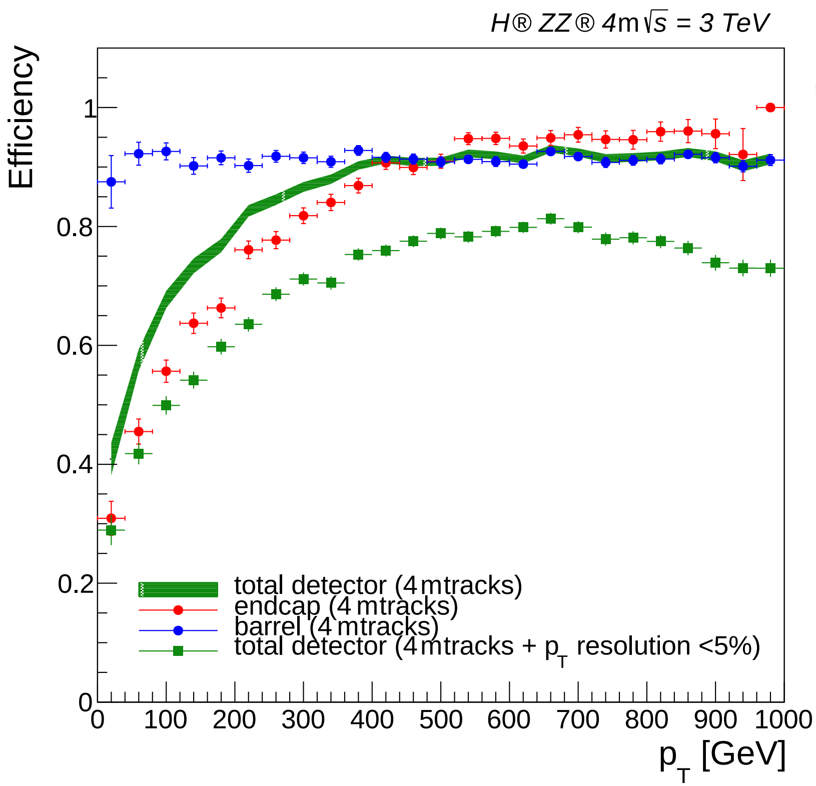


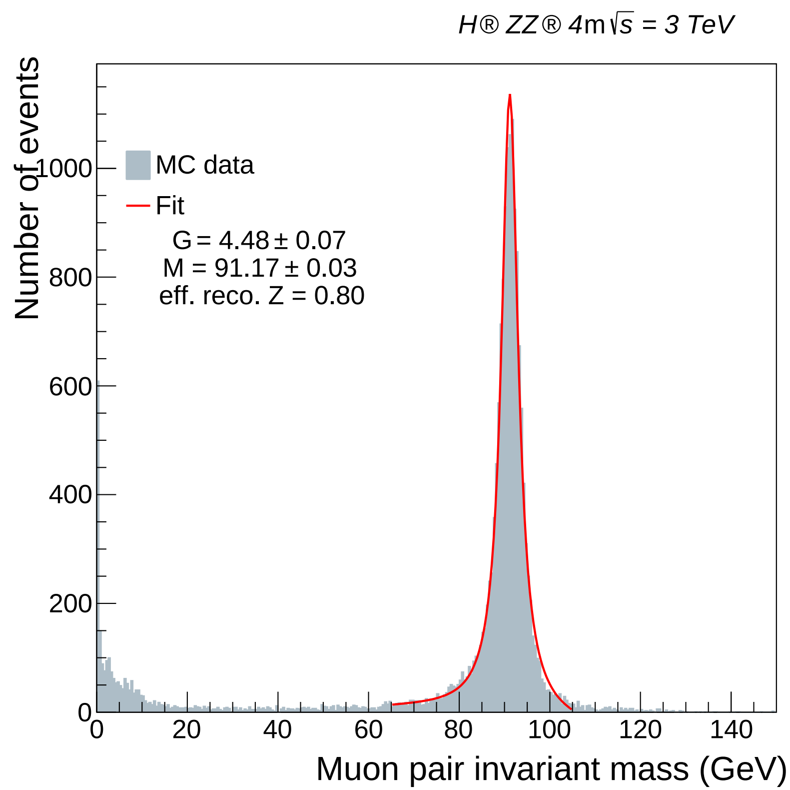


B-jet ID

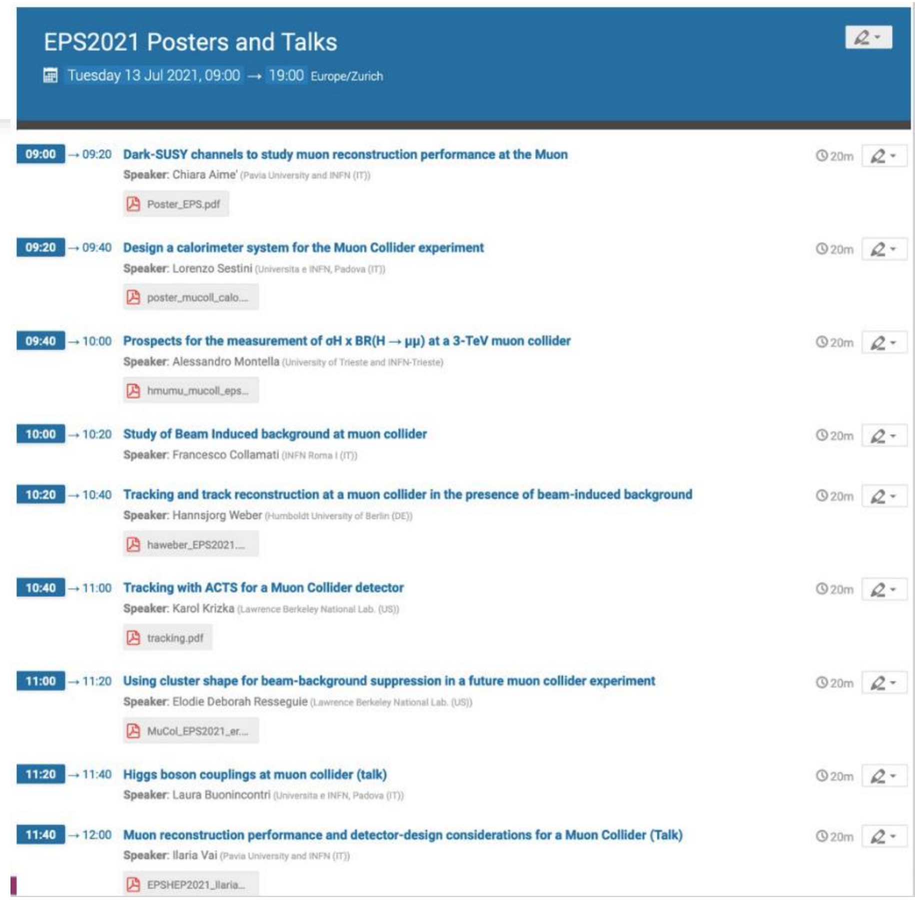
- Regional-tracking selected tracks
- Early steps towards b-tagging *work*in*progress*
  - ML approach under study

Muon Reconstruction



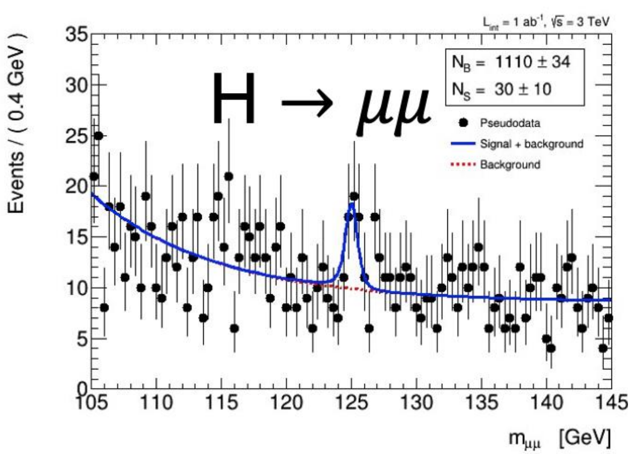


Beyond “detector performance”

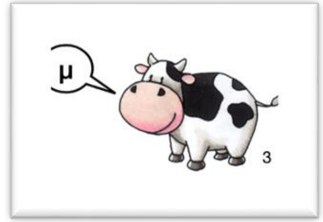


As detector design and simulation mature, detailed physics studies become possible

- Growing engagement within the Snowmass process



Summary



The Muon Collider appeal:

- Exciting physics potential
- Novelty of approach
- Complementarity to other future technologies

…but also an exciting detector and DAQ R&D challenge!

Early detector design under study:

- CLIC inspired
- BIB driven

- Exciting challenge:
  - Detector technology
  - DAQ and data handling
  - Computing