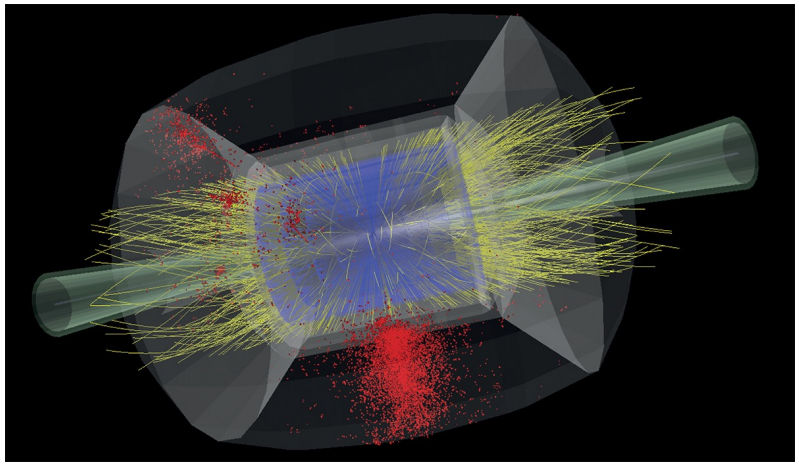


Status of Muon Collider Higgs Studies

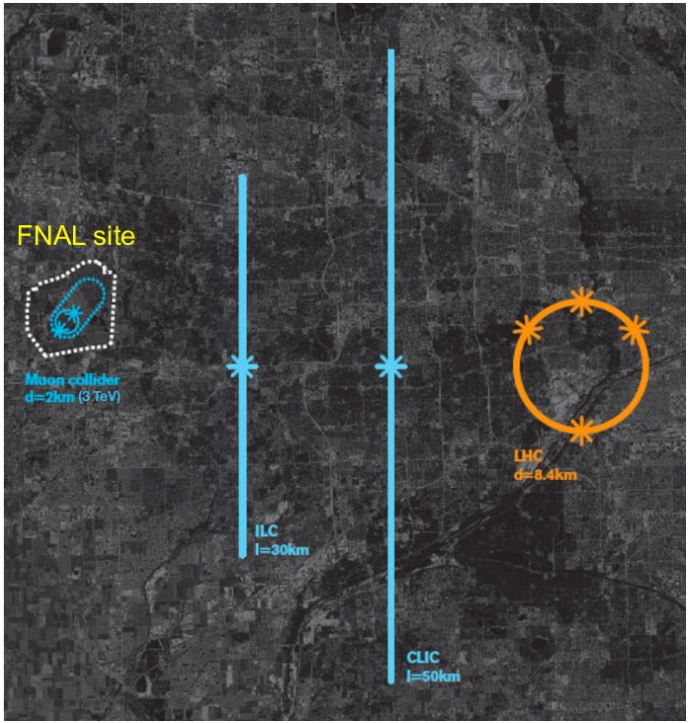
(with input from Snowmass Muon Collider Forum, Muon Collider Physics and Detector group, Muon Smashers Guide, and more)

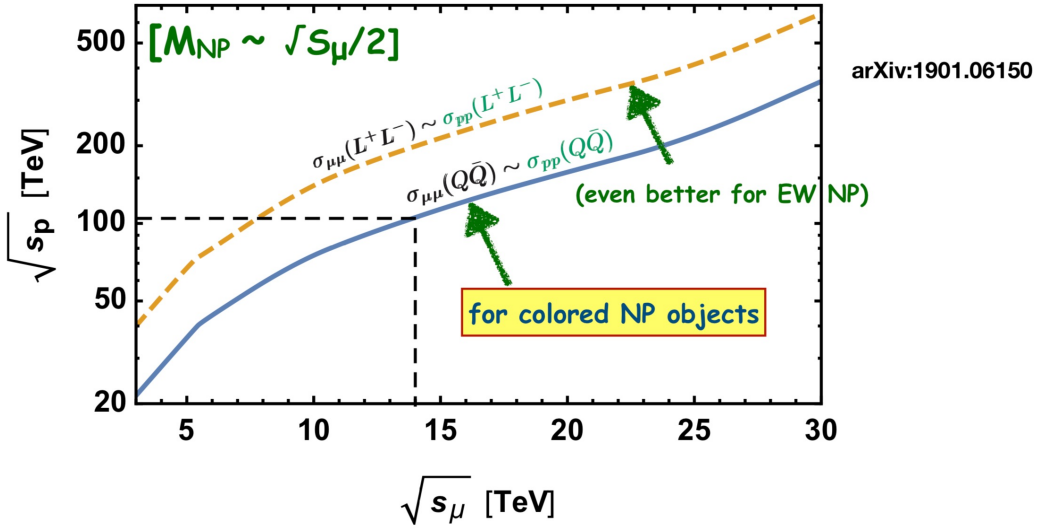
Sergo Jindariani (Fermilab)

Nov 2nd, 2021

Muon Collider

A compact machine with an incredible BSM potential





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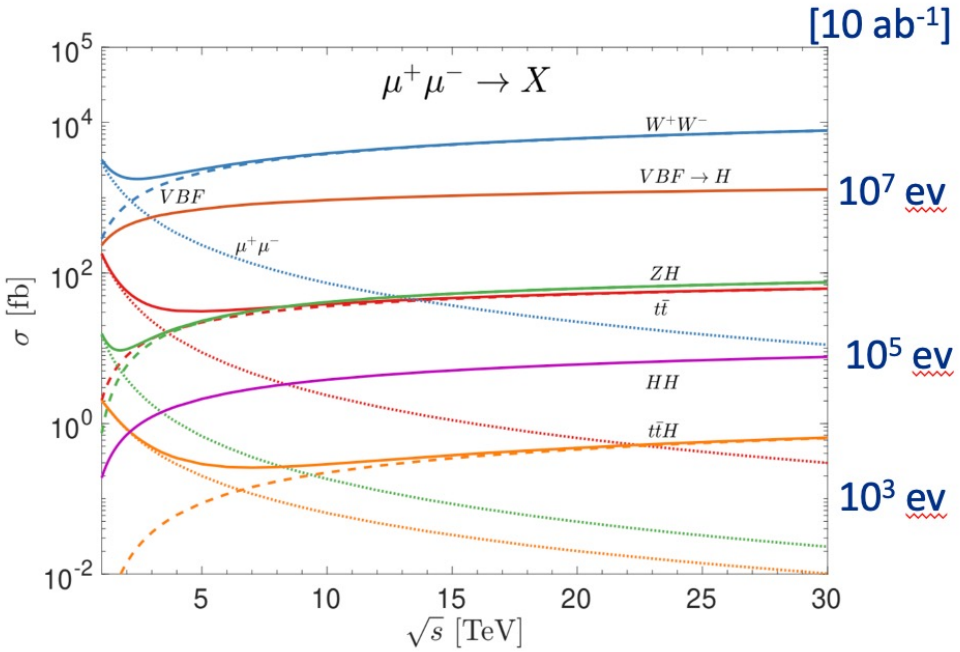
Muon Collider

And an excellent “Higgs” program



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Snowmass Muon Collider Forum

Charge from AF+EF+TF:

"The intent of this Forum is to create a venue where people participating in Snowmass who are also interested in the muon collider can freely share ideas and studies across frontiers, learn from each other, in harmony with the wider muon collider community. We envision that this Forum may also organize general seminars focused on various aspects of muon collider physics potential and feasibility, and possibly host workshops etc. depending on the interest of the community. "

Mailing list: Snowmass-Muon-Collider-Forum@FNAL.GOV

Slack channel: #muon-collider-forum

Wiki page: https://snowmass21.org/energy/muon_forum

Forum Meetings this Year

Past Muon Forum Meetings and their Focus Areas (with recordings)

Upcoming: Nov 30th: Discussion of the White Paper

- Synergies with precision muon. Comparison of BiB at different energies 10/12/2021
- Synergies with neutrinos and muon-ion collider 9/21/2021
- Physics and technology of 125 GeV Higgs Factory 08/24/2021
- R&D for high energy muon colliders 05/19/2021
- Physics and technology of high energy muon colliders 04/14/2021
- Forum Kickoff Meeting 01/27/2021

Recommended Parameters for Studies

Points shown in **RED** to be included into the Snowmass Summary plots/tables. Additional points (in black) are optional, but can be used to demonstrate performance in the presence of realistic beam background connditions.

COM Energy	**125 GeV**	1.5 TeV	**3 TeV**	6 TeV	**10 TeV**	14 TeV	**30 TeV**
Total Luminosity (ab-1)	0.010 (conserv.) - 0.025 (optim.)	0.25	1.0	4.0	10	10	10

Comments:

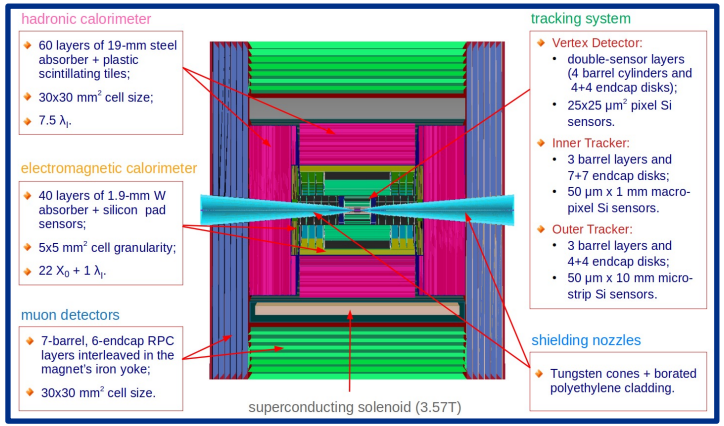
- Total luminosity is per interaction point and assumes 5 years of datataking.
- Higgs Factory 125 GeV luminosity projections correspond to conservative and optimistic scenarios. The projections assume very narrow energy spread of the beam, which is beneficial for Higgs production and width measurements.
- Two detectors can be planned (except for 125 GeV), which will further increase luminosity by a factor of 2.
- Please contact us for configurations not included in the table or with any other questions.
- Note that we are still finalizing parameters for the muon-ion collider studies.

A combination of 125 GeV+3 TeV and 125 GeV+10 TeV may be interesting

Tools available

- Full Simulation Framework (link)
  - Detector concept taken from CLIC and adapted to the Muon Collider environment
  - Allows to overlay Beam-Induced-Background (BIB)
  - Simulation of BIB demands high CPU/RAM

- DELPHES fast simulation Card (link):
  - Inspired by CLIC and FCC-hh performance
  - Accounts for limited acceptance due to the forward shielding “nozzles”
  - Assumes that the remaining impact of the BIB is mostly mitigated with novel technology and reconstruction



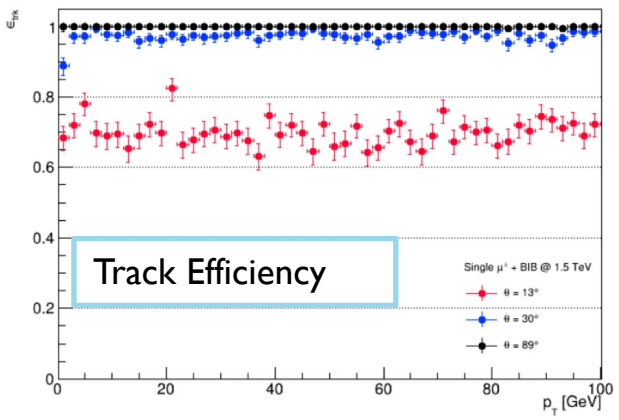
Methodology of Snowmass Physics Studies

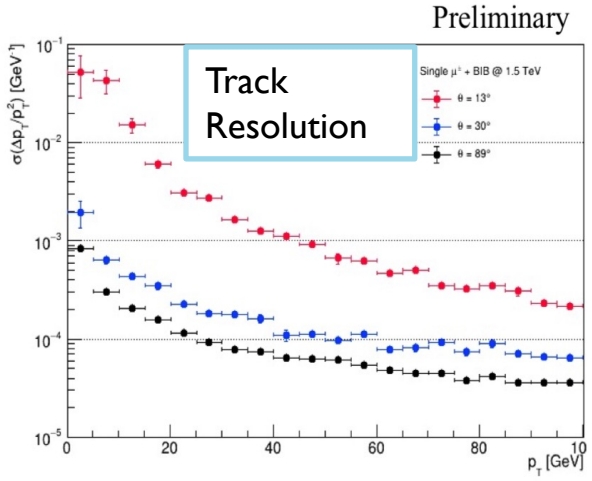
- Compare physics objects performance in DELPHES simulation against FullSim at 3 TeV to identify areas of improvements
- Perform select set of FullSim+BIB physics studies at 3 TeV
- Evaluate and understand BIB evolution with energy
- Produce a broad set of physics projections at different energies using DELPHES simulation

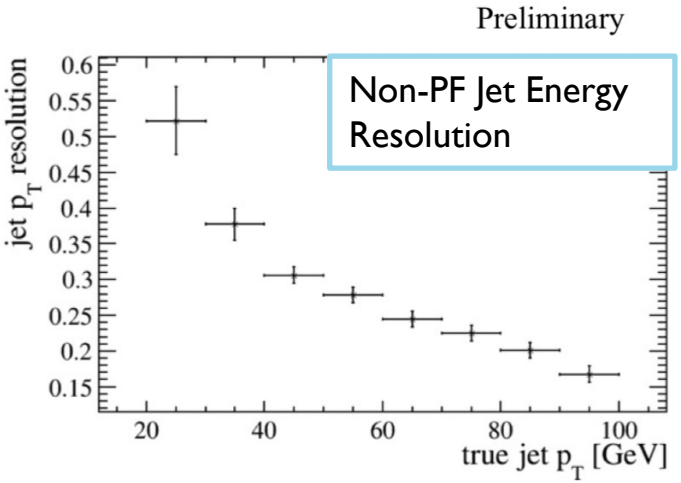
Fullsim + BIB @ 1.5 TeV

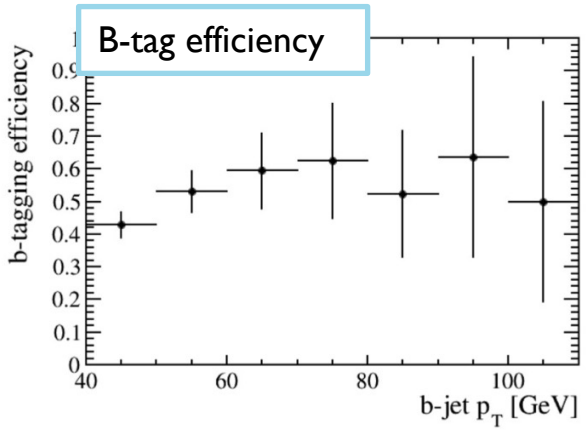
K.Krizka et al

- Achieved or approaching DELPHES performance
- A lot of room for further improvements





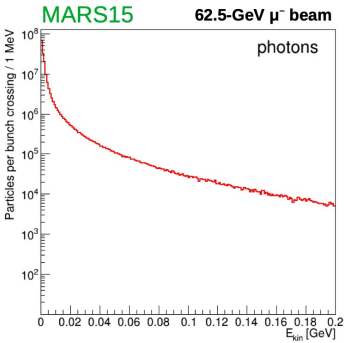


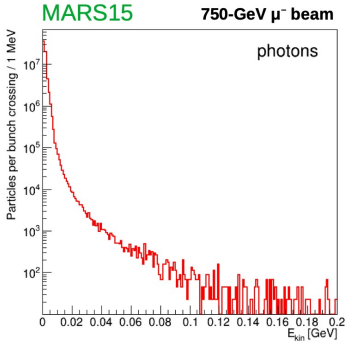


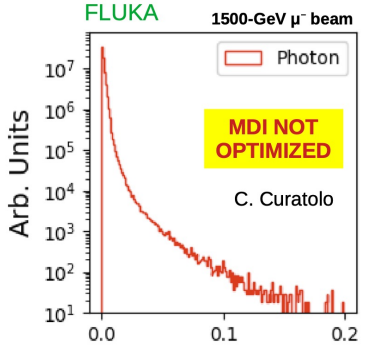
Evolution of BIB with Energy

M.Casarsa et al

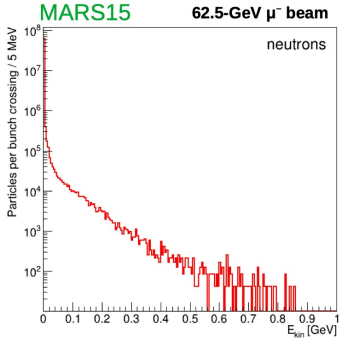
Photons

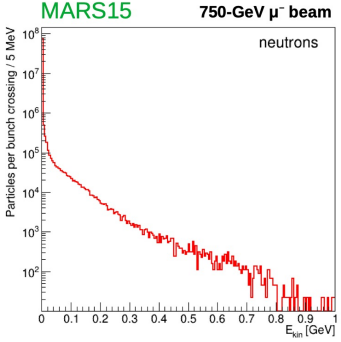


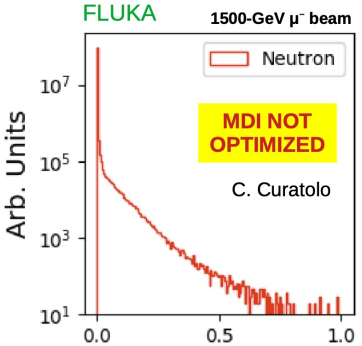




Neutrons







Even without MDI optimization, the BIB appears to fall at higher energies

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Higgs Couplings

Smasher's Guide

Start with 10 TeV signal-only DELPHES studies

- Sets the lower bound for the couplings
- 3 TeV results will come very soon

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

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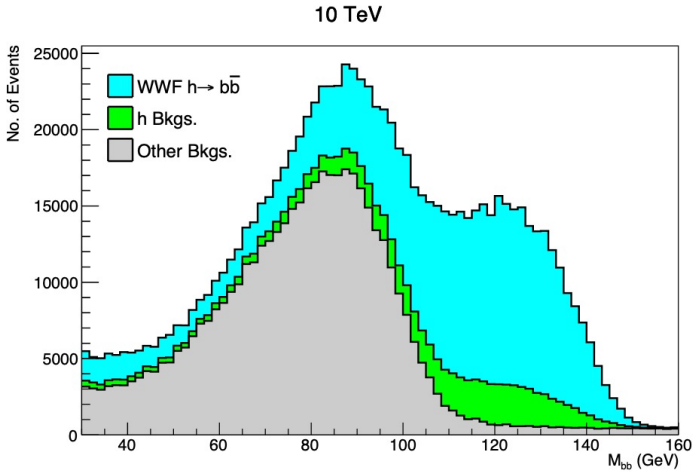
What about Physics Backgrounds?

M.Forslund, P.Meade

- H→bb used as an example here
- Reported at Higgs'21:



Cross section precision %

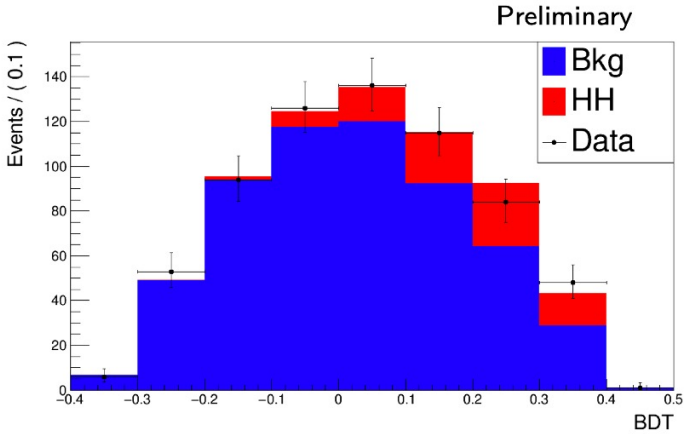
Energy	*WWF*	*ZZF*	*ZZF* ($N_\mu \geq 2$)
3 TeV	0.84	7.9	2.5
10 TeV	0.23	2.1	0.71
30 TeV	0.23	2.1	0.72
	Smasher's guide (signal only):		
10 TeV	0.17	0.49	-

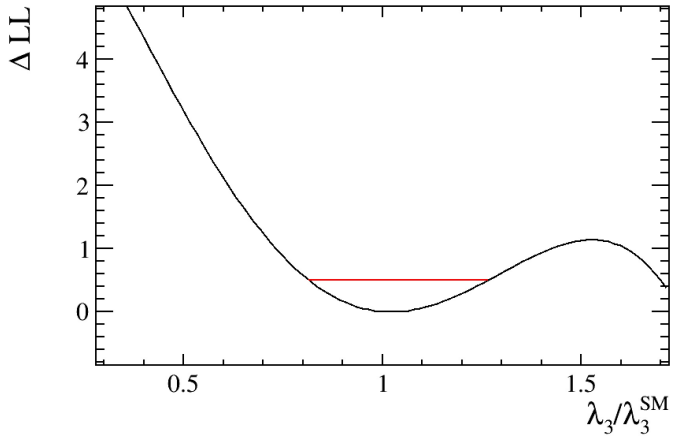
- Signal-only study not too far off (at least for H→bb). Other channels are being studied.
- Comparison with FullSim is ongoing

Di-Higgs FullSim Study

L. Sestini et al

- 4b final state (interest in exploring others)
- 50 HH and 432 background events are expected with 1 ab^{-1} at 3 TeV
- A preliminary statistical uncertainty on **$\sigma(\mu\mu \rightarrow HH\nu\nu) \cdot BR(HH \rightarrow b\bar{b}b\bar{b})$** of about **30%** is found
- The preliminary result **on the λ_3 statistical uncertainty is** of about **20% at 1.0 ab^{-1}** (at 68% CL)
- Agrees with CLIC after luminosity scaling





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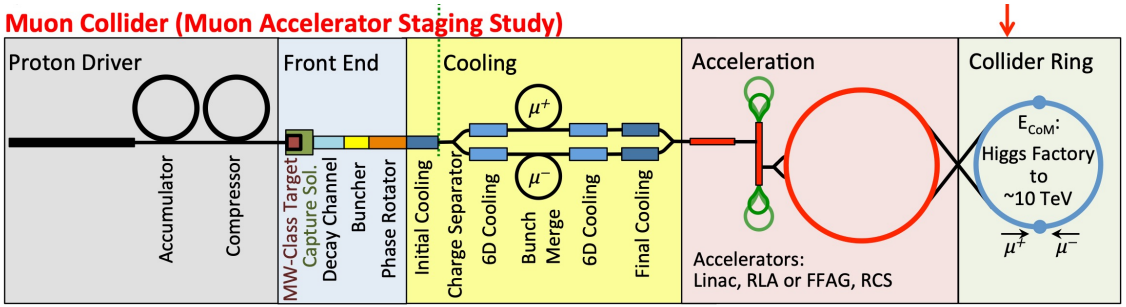
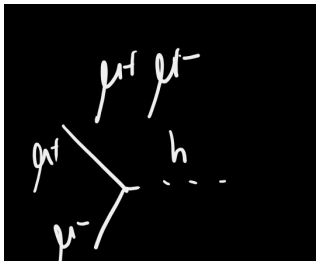
A word on 125 GeV Higgs Factory

A 125 GeV Higgs factory on the way to multi-TeV Muon Collider?

- demonstration of technology
- unique Higgs physics to complement e+e- and pp

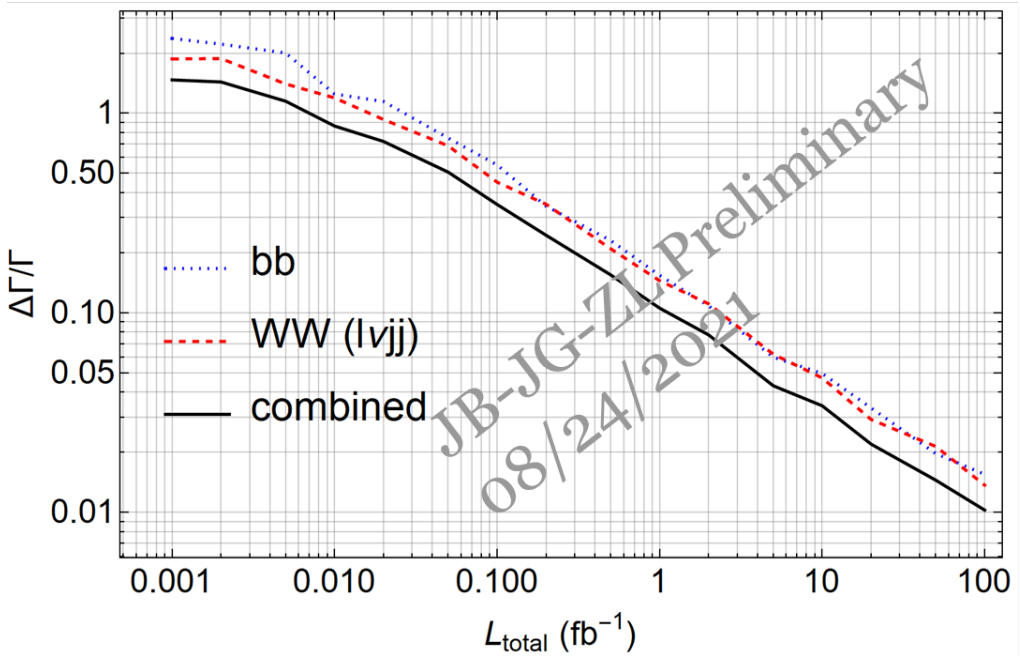


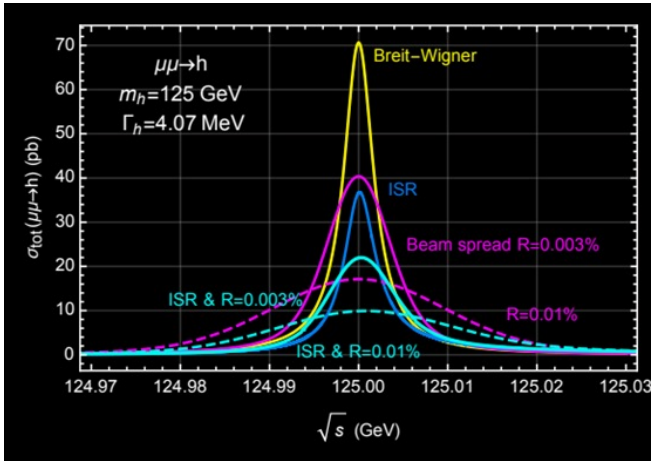


15 pb * 10 fb^{-1}= 0.15M Higgs events compared to 1M+ at e+e-

Higgs Total Width

Z.Liu et al





- Width precision basically scales as 1/Sqrt[L] → large gains with luminosity
- A precise measurement, uncorrelated with all the other parameters

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Impact on Couplings Precision

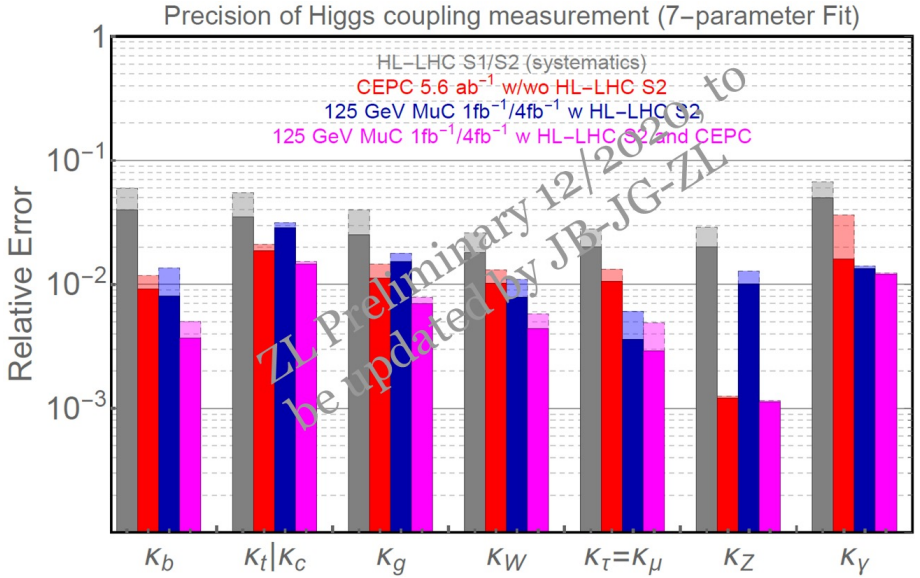
Z.Liu et al

New Insight: the total width sets floor for the individual coupling extraction as:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma} \Rightarrow$$

$$\Delta\kappa_j = 1/2(\Delta\kappa_j^2)$$

$$= 1/2(\Delta\kappa_\Gamma \oplus \Delta\sigma(i \to H \to j) \oplus \Delta\kappa_i^2)$$



- Another unique MHF125 aspect: sub-percent muon Yukawa measurement

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What to expect:

- Couplings:
  - All couplings using DELPHES at 125 GeV, 3, 10, 30 TeV
  - Select couplings using FullSim at 3 TeV (bb, WW, mm, ..)

- HH Production:
  - using DELPHES at 3, 10, 30 TeV
  - using FullSim at 3 TeV

- Higgs Width:
  - Using BW shape at 125 GeV and evaluate impact on couplings precision
  - Indirectly at high energy (3, 10, 30 TeV)

Summary

- Strong resurgence of interest in Muon Colliders within Snowmass and Globally. Program for realization of such machine developed by IMCC.

- Active engagement of the community in the Muon Collider Forum established in 2021. White Paper discussions in progress.

- Many physics studies at DELPHES and FullSim levels, including an exciting Higgs program

- Expect to converge by early 2022, followed by preparation of the White papers