HEP SEMINAR

Muon Collider: a window to the future

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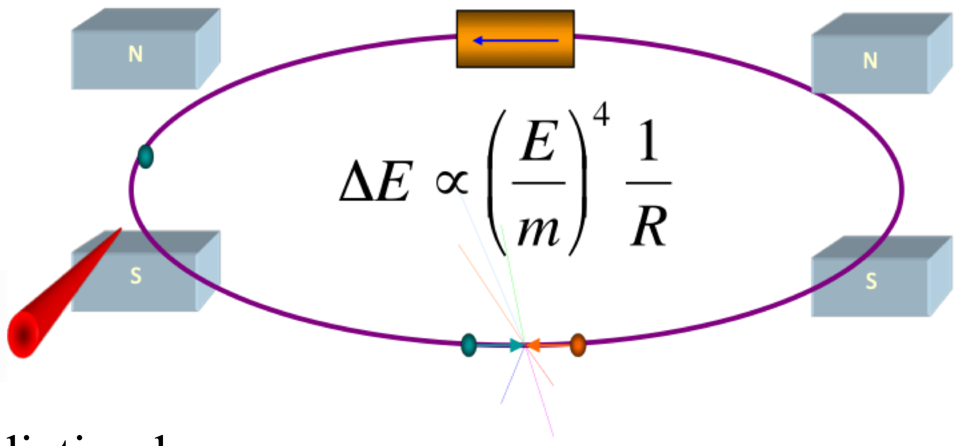
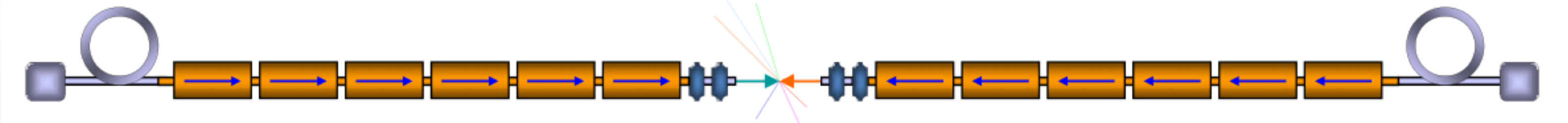
Why do we want to collide muons

- e^+e^- circular colliders are multi-pass, beams can be used many times.
- The energy loss by synchrotron radiation limits their usage: LEP2 lost 2.72 GeV/turn for $E = 105$ GeV.
- That's why proton colliders are considered *energy frontier.*



D. Schulte

- e^+e^- linear colliders do not suffer from synchrotron radiation loss.
- They are single-pass, beams can be used once.



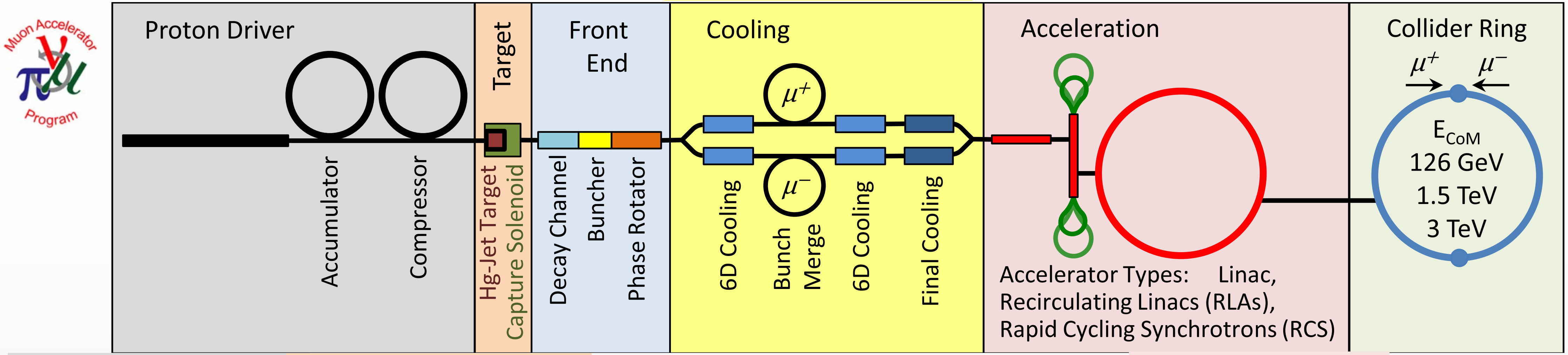
- The achievable center of mass energy and the luminosity are limited by money, CLIC at $\sqrt{s}$=14 TeV costs $\mathcal{O}$(60GCHF)

New approach: collide muons
Heavier than electron ⟹ no synchrotron radiation loss ⟹multi-pass
Lighter than proton ⟹ easier to accelerate
Unfortunately, short lifetime at rest, 2.2 μs

How do we collide muons

$p \rightarrow target \rightarrow \pi \rightarrow \mu\nu$

MICE muon cooling



- Based on 6-8 GeV Linac Source
- H- stripping requirements same as those established for neutrino

- MERIT@CERN studied high power target
- π production in high-field solenoid

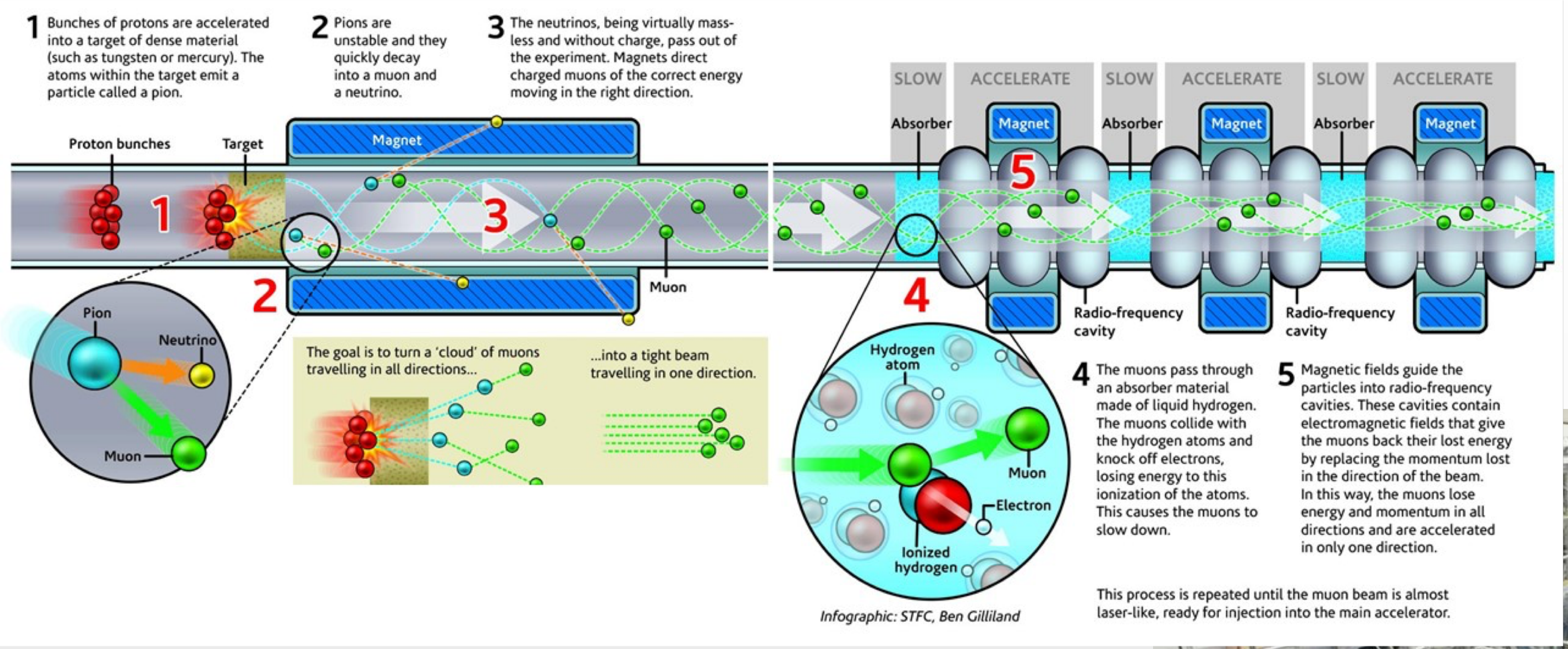
- solenoid π→μ decay channel
- RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Fast ionization 6D cooling ($\tau = 2\mu s$)
- MICE
- Rubbia demonstrator proposal

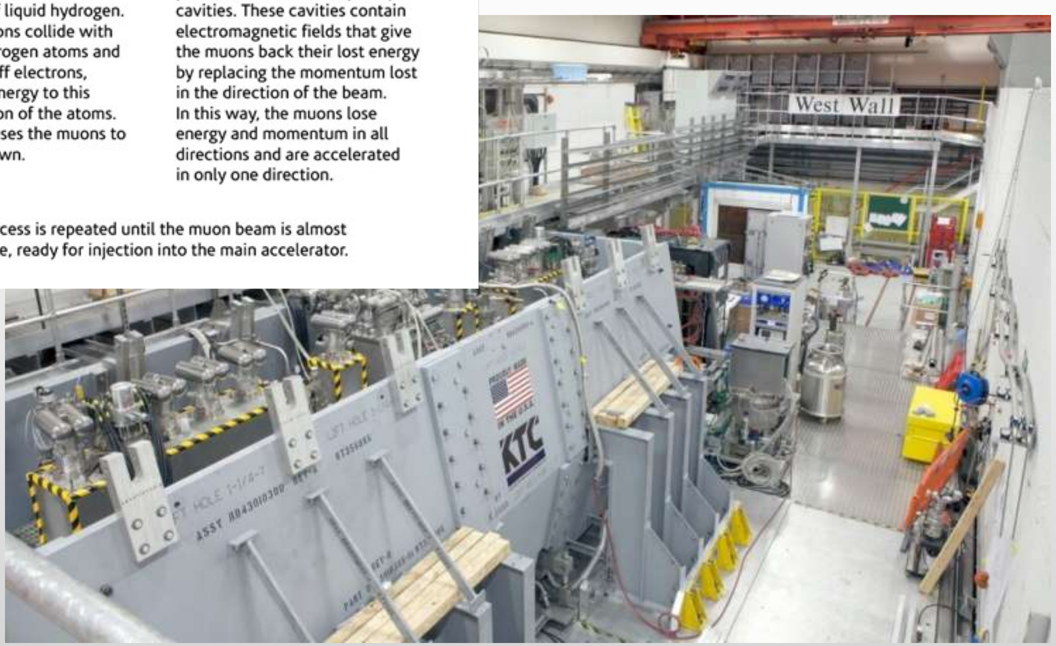
- Fast acceleration
- Use RF and SC

- $\mu^{\pm}$ decay background
- Tungsten shielding or bending magnets to avoid issues from e
- Critical MDI

How to cool muons: Muon Ionization Cooling Experiment, MICE



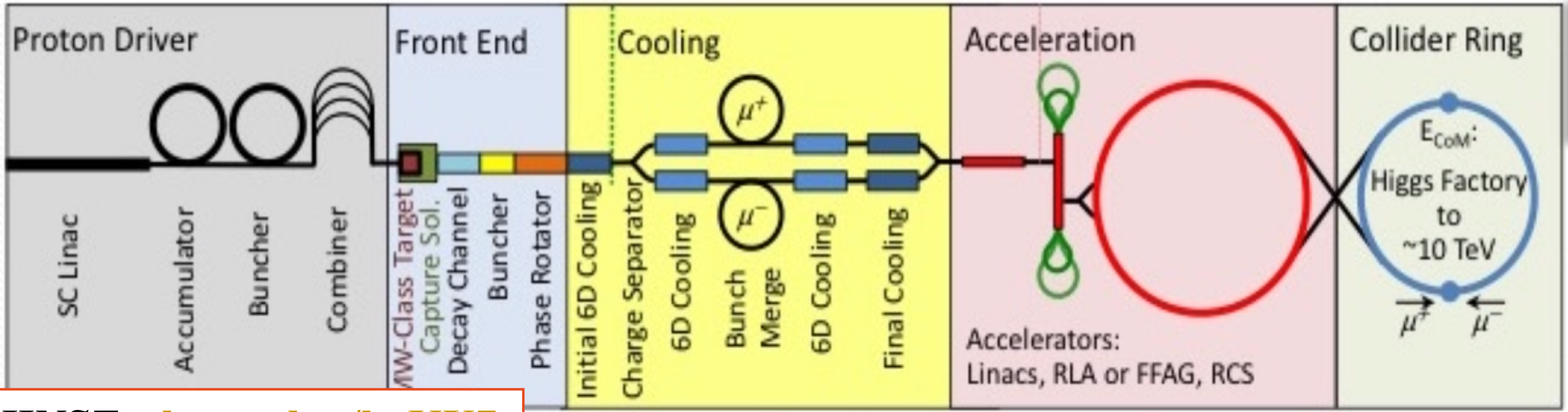
MICE experiment in progress at Rutherford Appleton Laboratory



How do we collide muons – cont'd

$p \rightarrow target \rightarrow \pi \rightarrow \mu\nu$

MAP



Almost ready to go for a CDR.

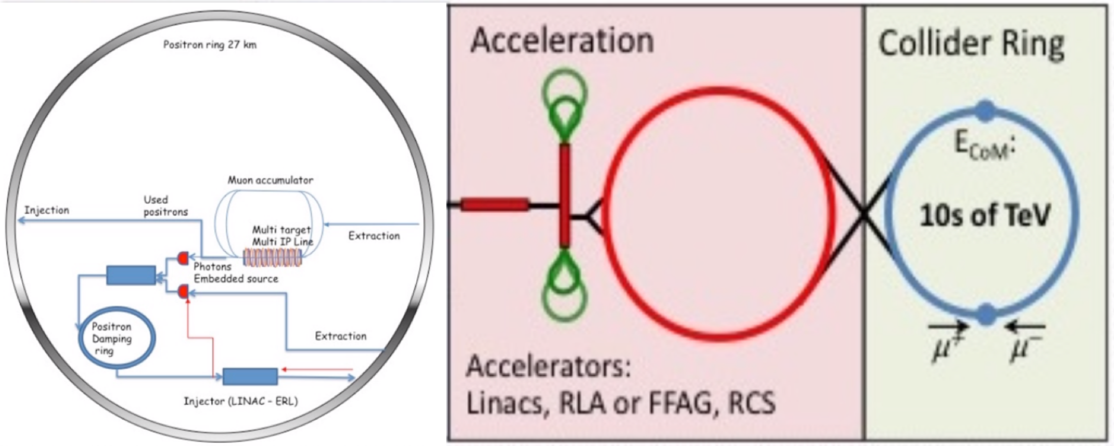
MUON JINST, shorturl.at/kxKU7

$e^+ \rightarrow target \rightarrow e^+e^- \rightarrow \mu\mu$

LEMMA

arXiv:1905.05747v2

e+ source

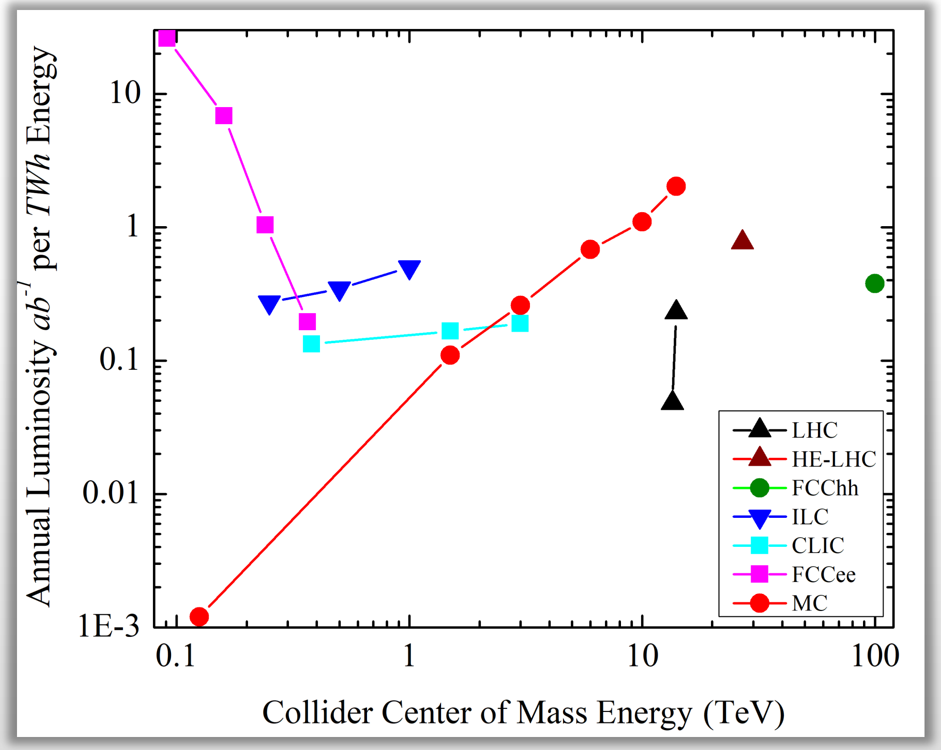


Need consolidation to overcome technical limitation. It can reach very high CM Energies thanks to low emittance beams

Motivations

Economic Motivations

The luminosity per beam power is independent of collision energy in linear lepton colliders, but increases linearly for muon colliders



Cost accounting is not uniform across the projects, estimates for LHeC and muon collider are prorated from the costs of other projects

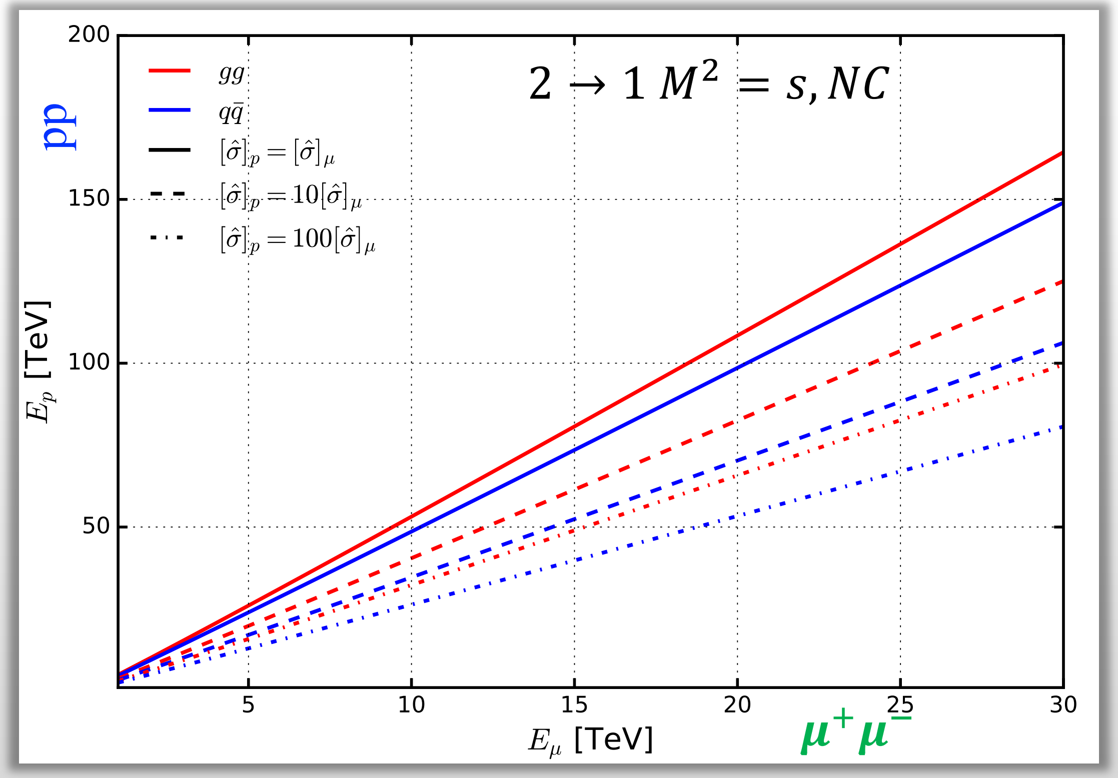
Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{\text{int}}$ (ab^{-1})	Time (years)	Power (MW)	Cost
ILC	e^+e^-	0.25	1	2	11	129	4.8-5.3BILCU
		0.5	1	4	10	163(204)	8.0 BILCU
		1	1			300	+(n/a)
CLIC	e^+e^-	0.38	1	1	8	168	5.9 BCHF
		1.5	1	2.5	7	370	+ 5.1 BCHF
		3	1	5	8	590	+7.3 BCHF
CEPC	e^+e^-	0.091&0.16	2	16+2.6	2+1	149	5 B USD
		0.24	2	5.6	7	266	+(n/a)
FCC-ee	e^+e^-	0.091&0.16	2	150+10	4+1	259	10.5 BCHF
		0.24	2	5	3	282	
		0.365 & 0.35	2	1.5+0.2	4+1	340	+1.1 BCHF
LHeC	ep	1.3	1	1	12	(+100)	1.75* BCHF
HE-LHC	pp	27	2	20	20	220	7.2 BCHF
FCC-hh	pp	100	2	30	25	580	17(+7) BCHF
FCC-eh	ep	3.5	1	2	25	(+100)	1.75 BCHF
Muon Collider	$\mu\mu$	14	2	50	15	290	10.7* BCHF

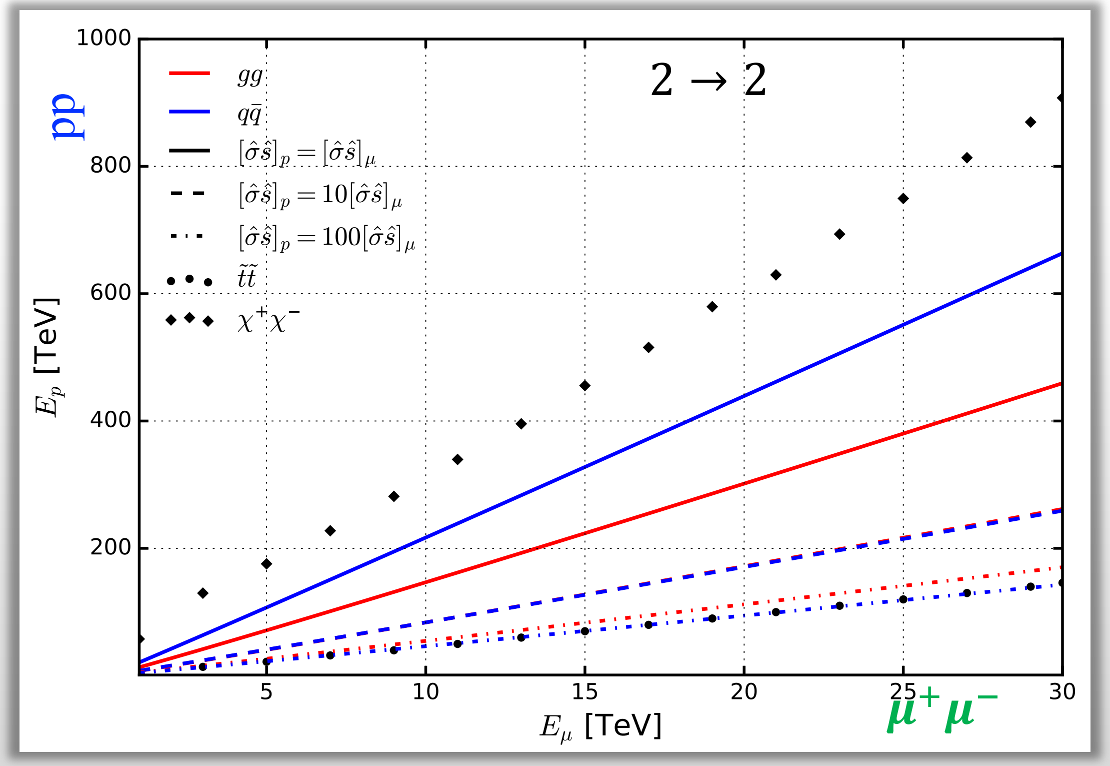
arXiv:2003.09084

Physics Motivations: Discovery Potential

- Muons are elementary particles ⇒ $\sqrt{s_\mu}$ entirely available to produce short-distance reactions.
- Protons are formed by partons ⇒ interactions occur between the proton constituents ⇒ fraction of $\sqrt{s_p}$ enter in the short-distance reactions.

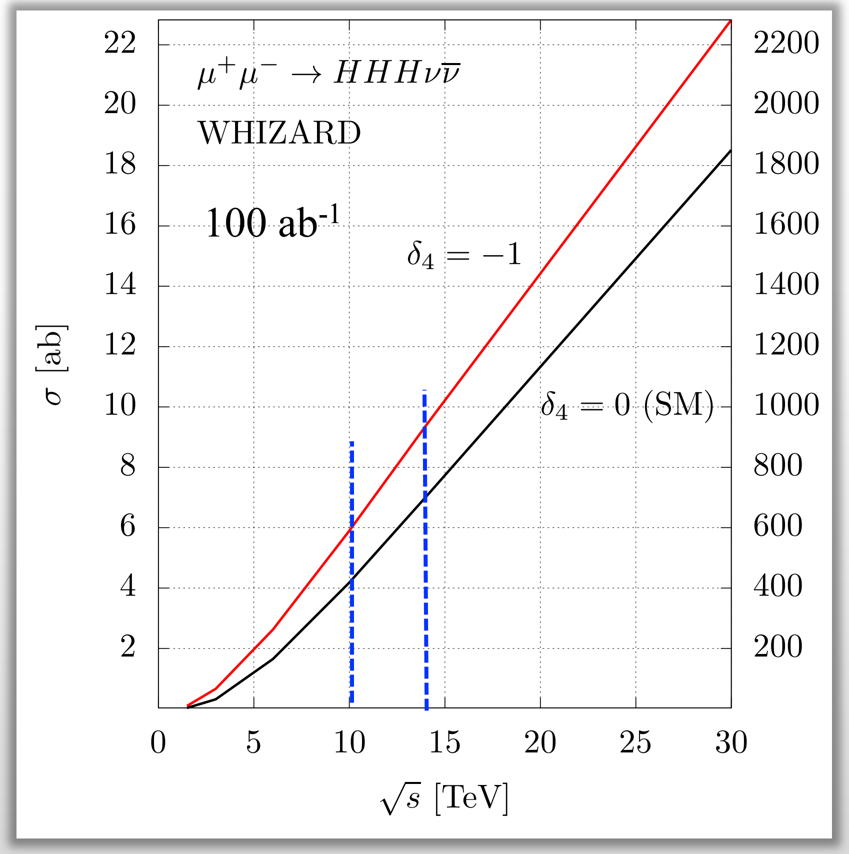
Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





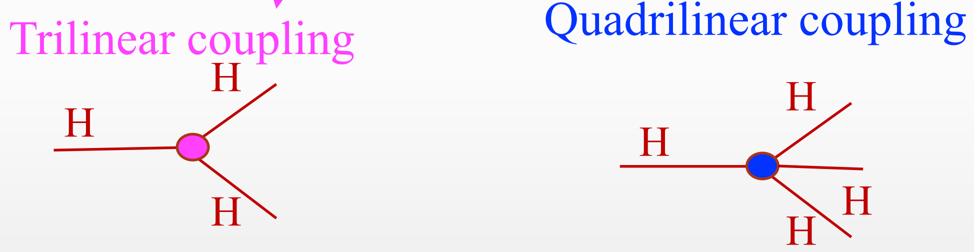
Physics Motivations: Certain Discovery through the Higgs Boson

- Higgs boson couplings to fermions and bosons are expected to be measured with a precision similar or better than e^+e^- .
- Muon collider has the unique possibility to allow the determination of the Higgs potential:



$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$
$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$



Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, M Chiesa *et al*.

Main Issues

The Beam-Induced Background

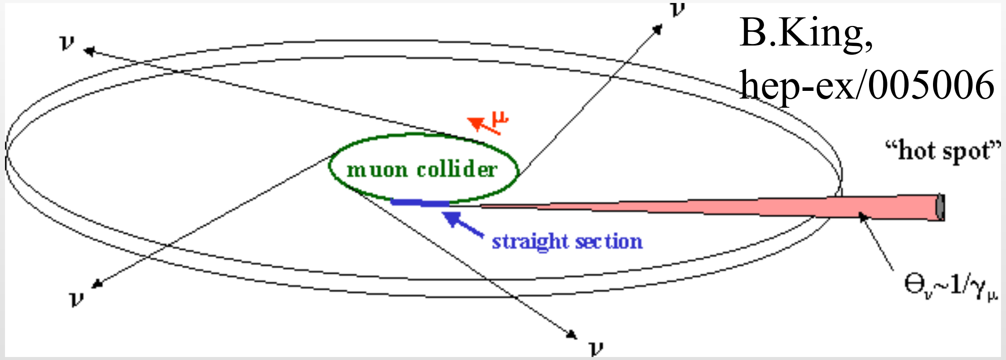
Muon decay… just a back of the envelope calculation:

beam 0.75 TeV $\lambda = 4.8{\times}10^6$m, with $2{\times}10^{12}\mu$/bunch $\Rightarrow 4.1{\times}10^5$decay per meter of lattice.

Muon induced background, if not properly treated, could be critical for:

- Magnets, they need to be protected
- Detector, the performance depends on the rate of background particles arriving to each subdetector
- People due to neutrino induced radiation

- Neutrinos from intense muon beams are very well collimated, $\theta \approx 1/\gamma$. At 1TeV $\theta \approx 10^{-4}$
- Neutrinos beams interact with matter, the products originate the dose when they reach the earth surface



B.King, hep-ex/005006

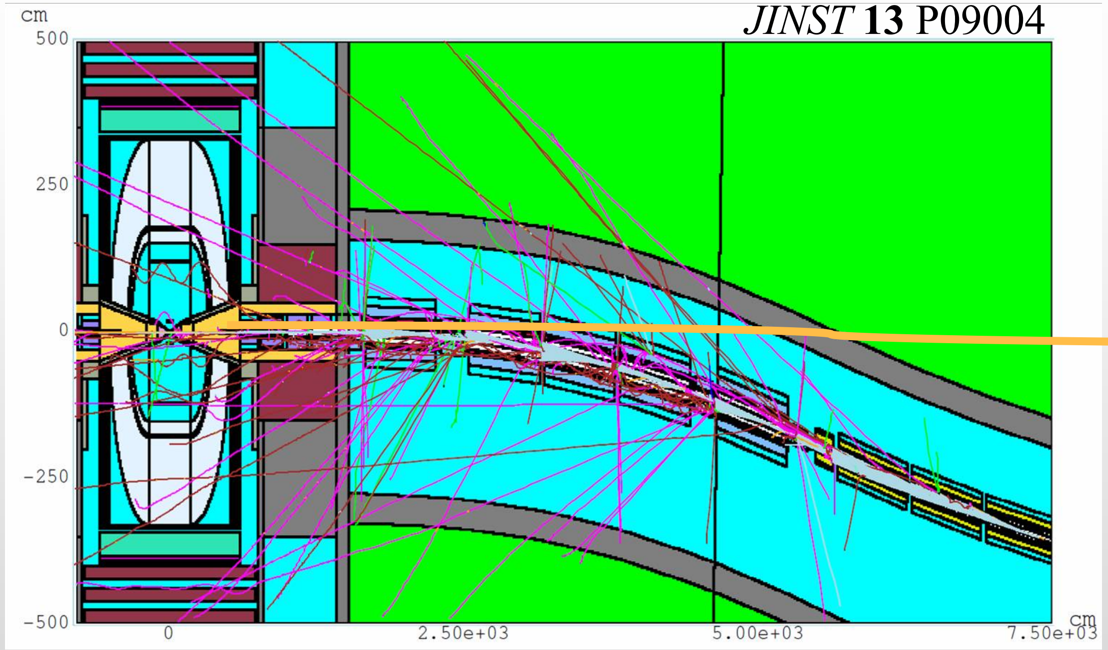
Radiation hazard studied since the beginning MAP:

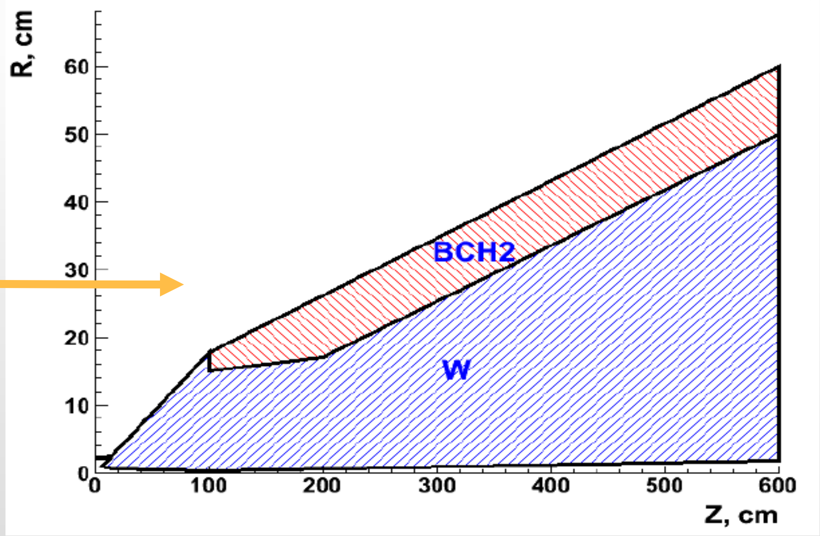
- Muon Collider R.B.Palmer et .al
- N. Mokhov, A. Van Ginneken Neutrino Radiation at Muon Colliders and Storage Rings

New study based on Fluka is starting: careful design of the collider in particular in the straight sections and of the environment is needed.

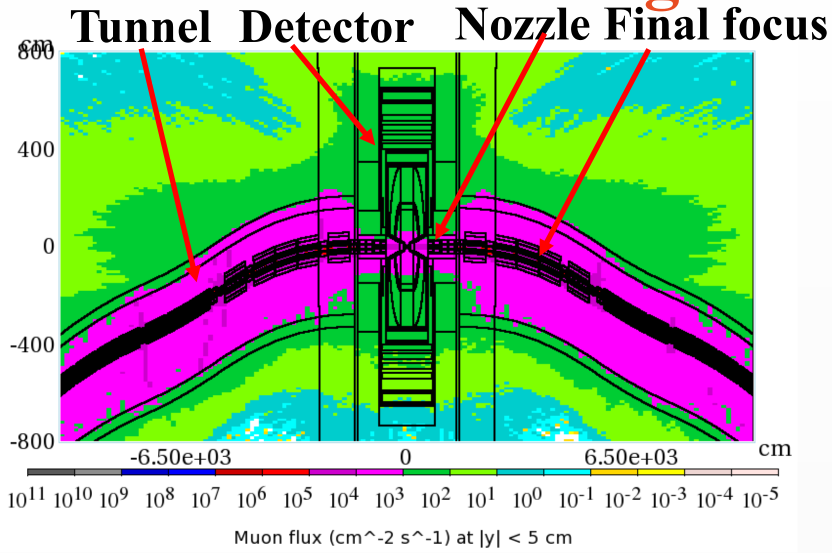
The Beam-Induced Background - BIB

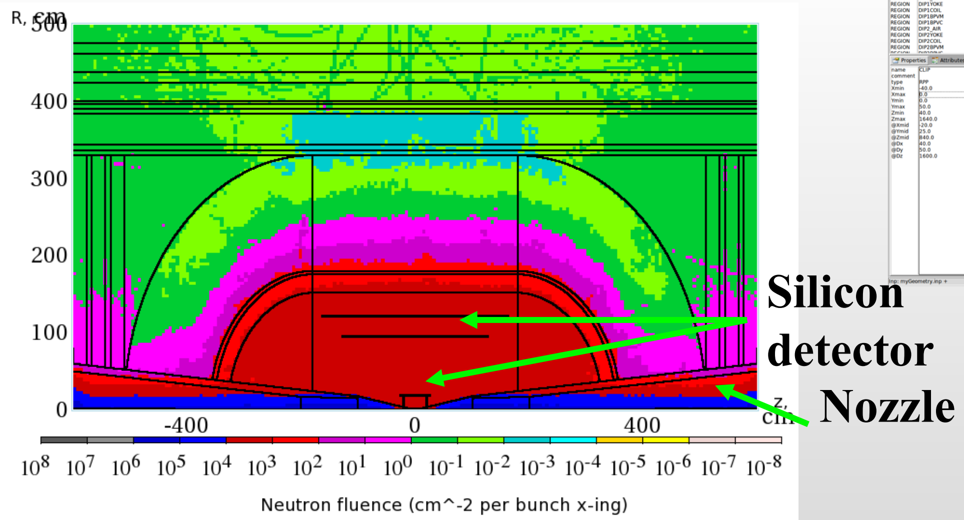
- MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel and the accelerator ±200 m from the interaction point.
- Secondary and tertiary particles from muon decays have been simulated with MARS15 then transported to the detector.
- Two tungsten nozzles play a crucial role in background mitigation inside the detector.





Beam-Induced Background Study



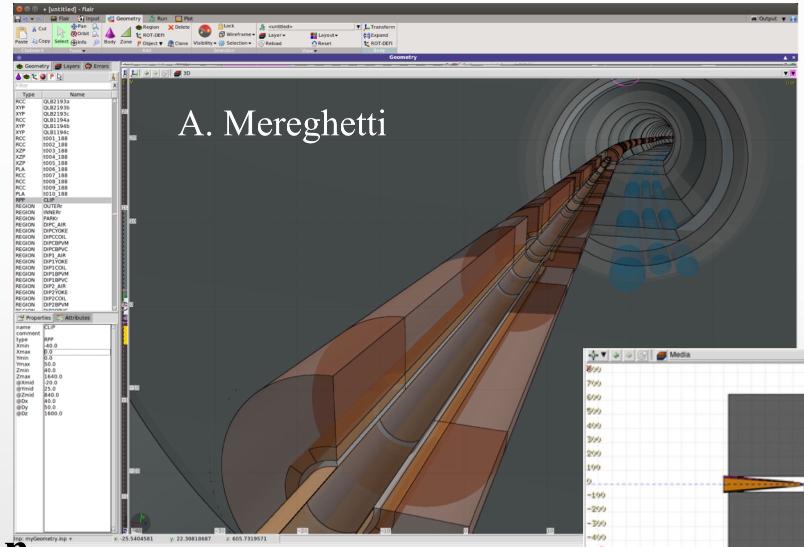


N. Mokhov et al. Fermilab-Conf-11-094-APC-TD

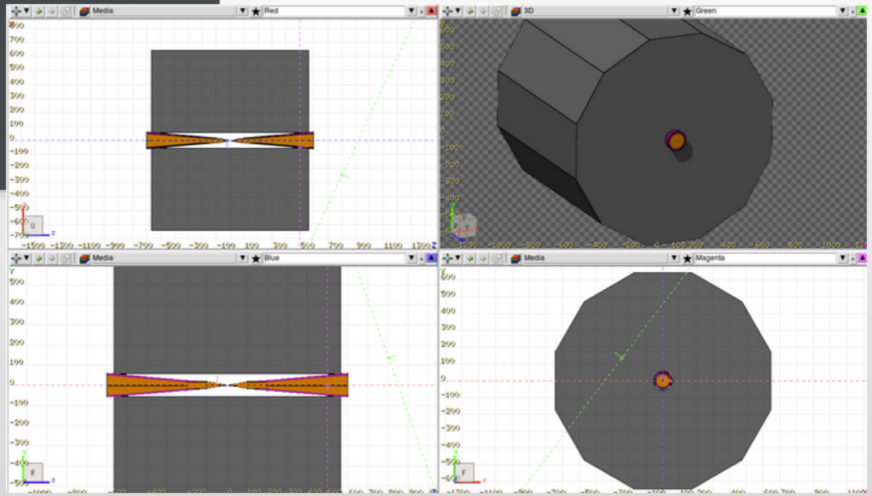
BIB available for $\sqrt{s}$=1.5 TeV and $\sqrt{s}$=125 GeV

Prepare a new tool based on Fluka to generate new BIB:

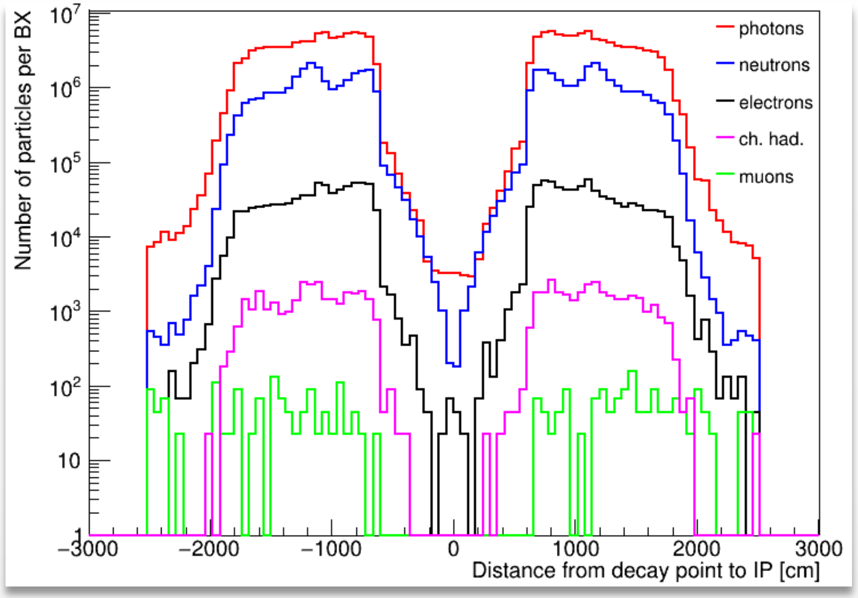
- at different $\sqrt{s}$
- Modifying the detector and the interaction region



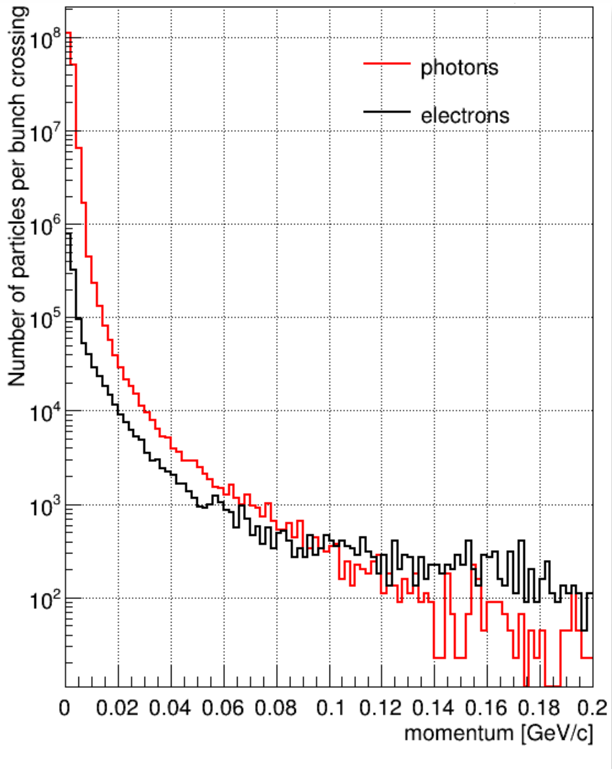
F. Collamati
C. Curatolo

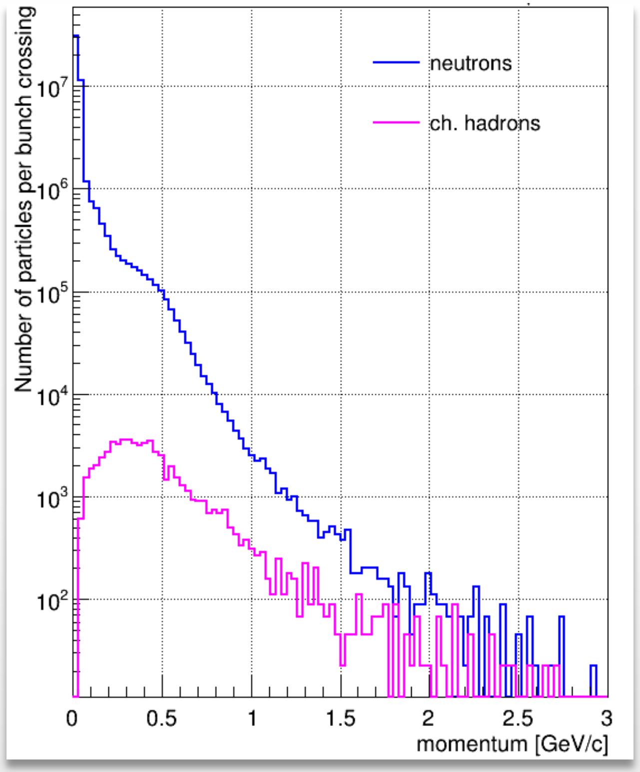


Beam-induced background properties $\sqrt{s}$ =1.5 TeV



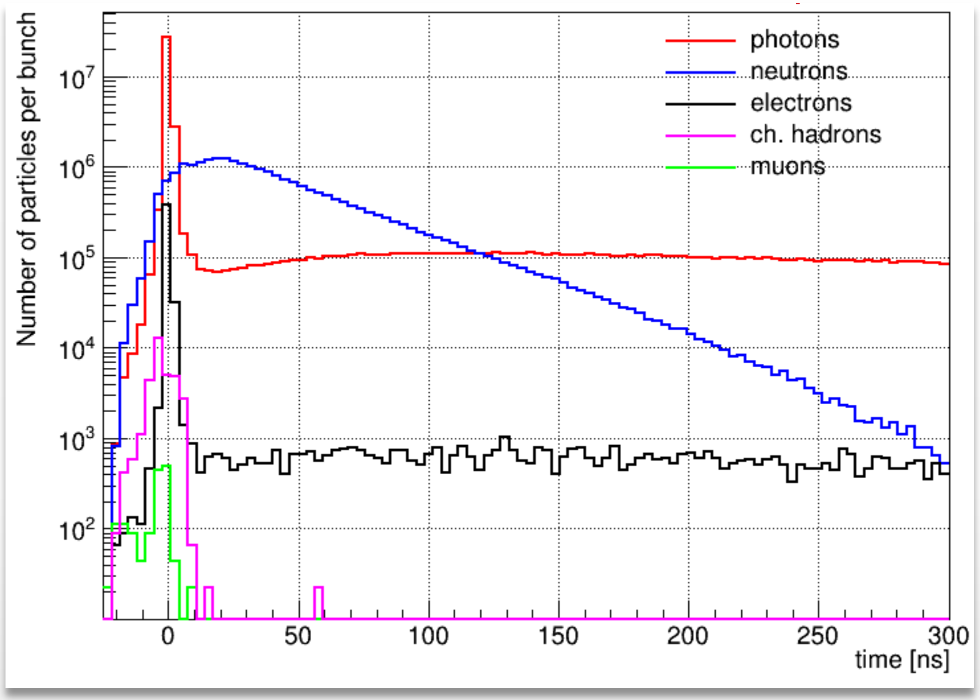
Contributions from μ decays |z| > 25 m become negligible for all background species but Bethe-Heitler muons

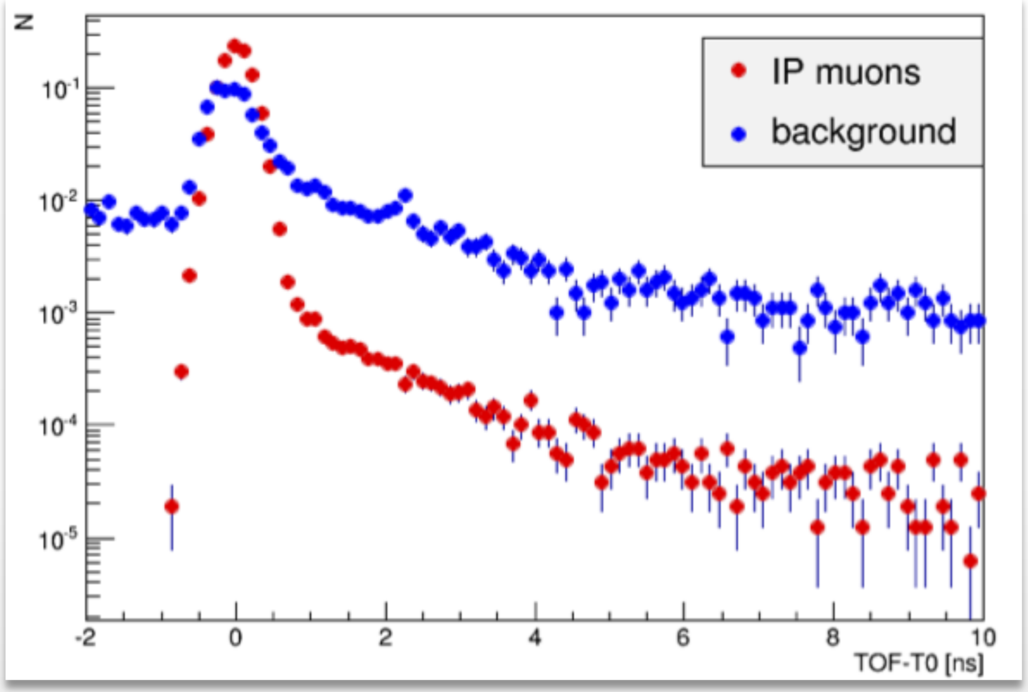




Secondary and tertiary particles have low momentum

Beam-induced background properties $\sqrt{s}$ =1.5 TeV



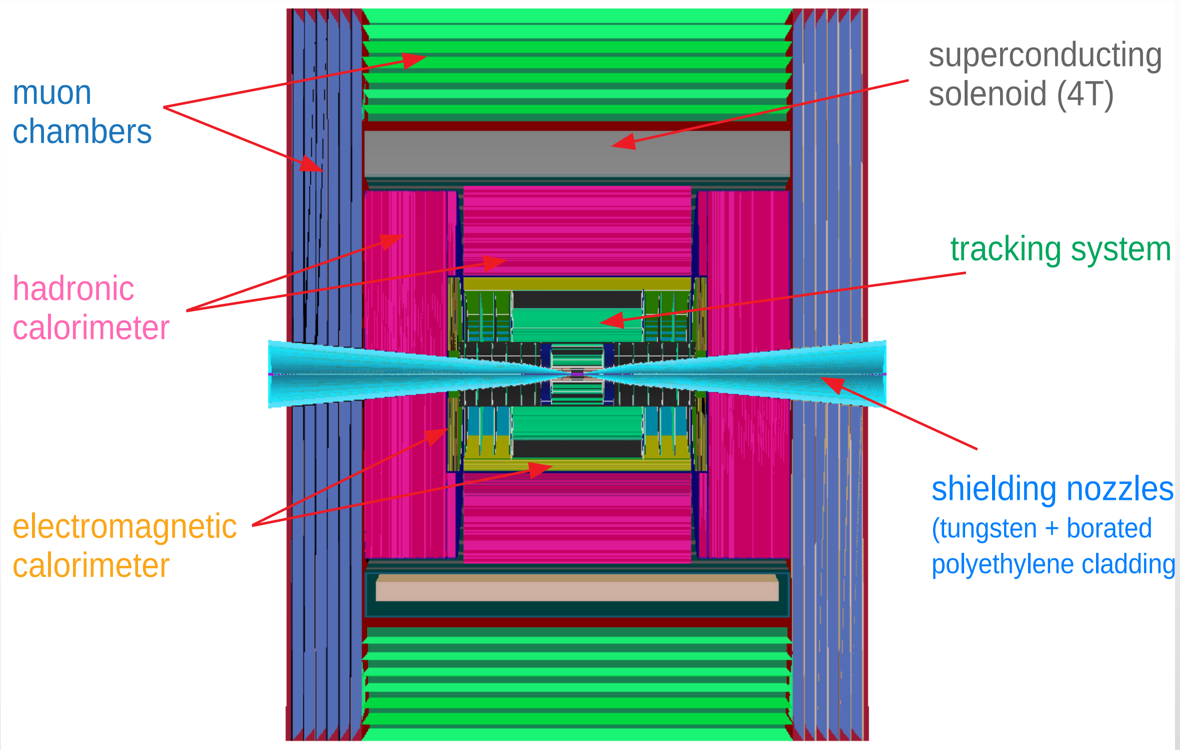


- Time information is important to reduce the beam-induced background at $\sqrt{s}$=1.5 TeV.
- BIB behavior at higher center of mass energies has to be studied.

Detector & Detector Performance at $\sqrt{s}$ =1.5 TeV

Detector for $\sqrt{s}$ =1.5 TeV Collisions

- CLIC Detector adopted with modifications for muon collider needs.
- Detector optimization at $\sqrt{s}$=1.5 (3) TeV is one of the Snowmass goals.



Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)
- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers 50x50μm^2
- 4+4 disks ”

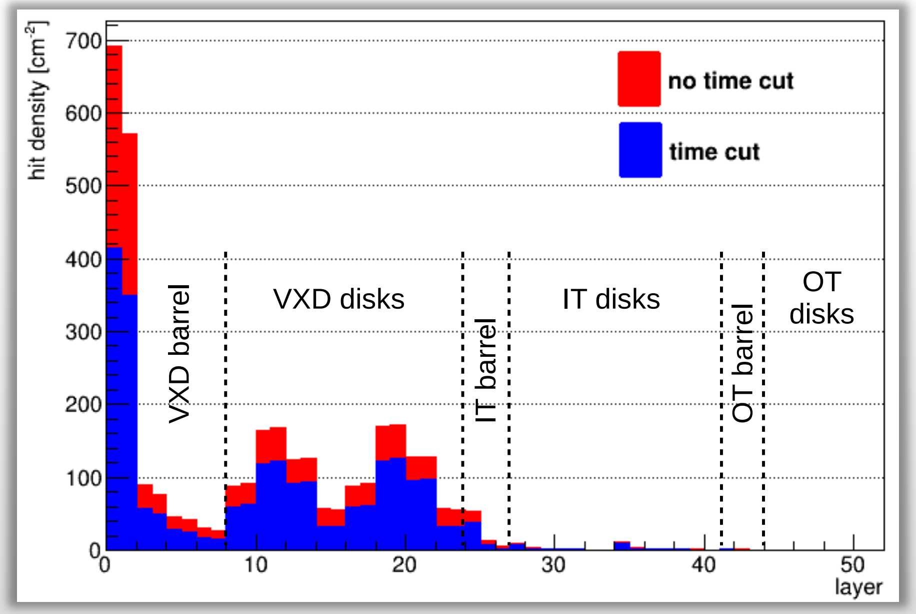
Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

Tracking System at $\sqrt{s}$ =1.5 TeV

Effects of beam-induce background can be mitigated by exploiting "5D" detectors, i.e. including timing.

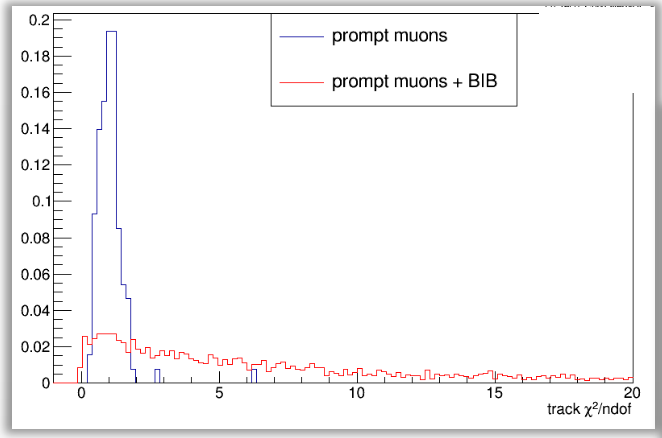
A ±150ps window at 50ps time resolution in the Vertex detector allows to strongly reduce the occupancy.

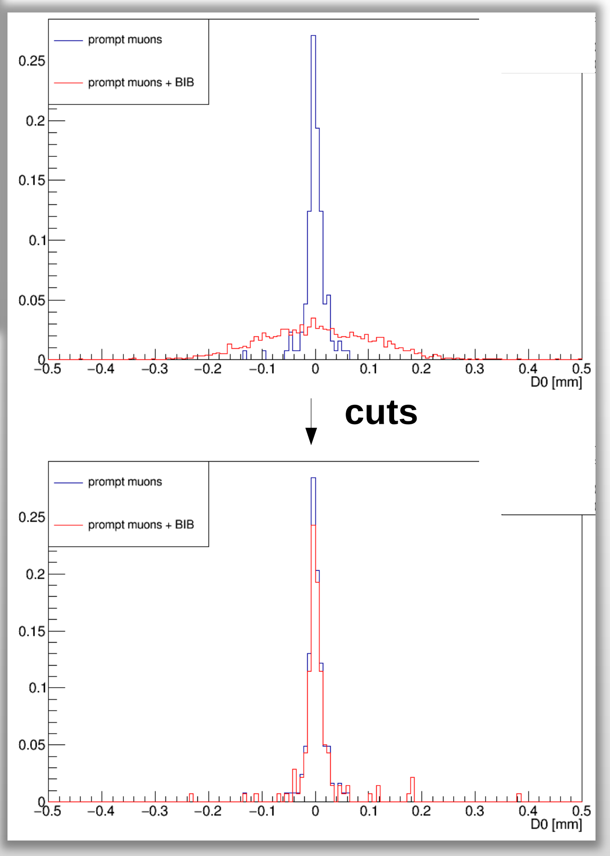


BIB effects can be mitigated at reconstruction time:

Sample of prompt muons: $0 < P_T \leq 10\ GeV$

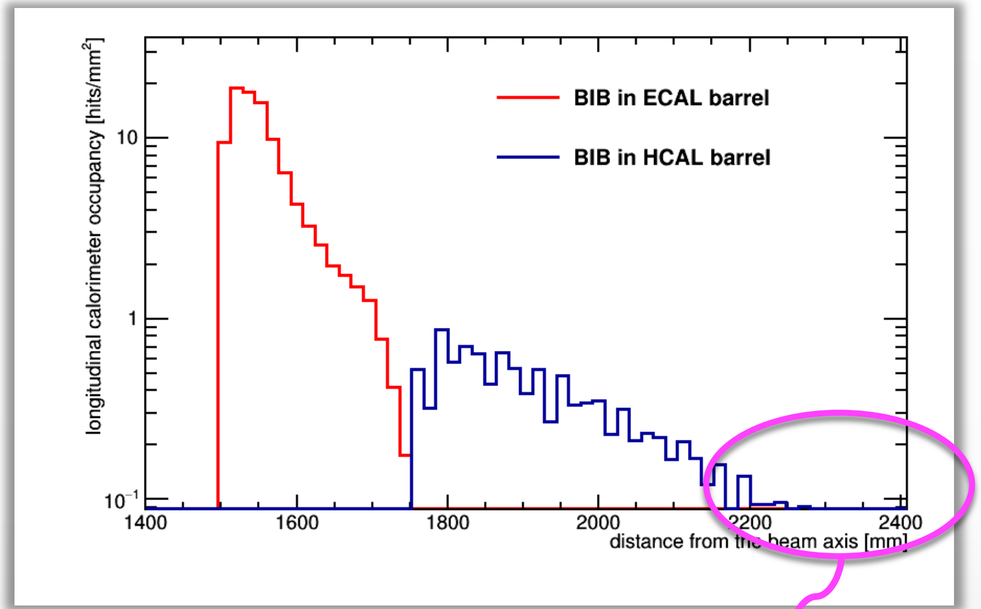
Prompt muons with BIB





Calorimeter System at $\sqrt{s}$ =1.5 TeV

Calorimeter Occupancy

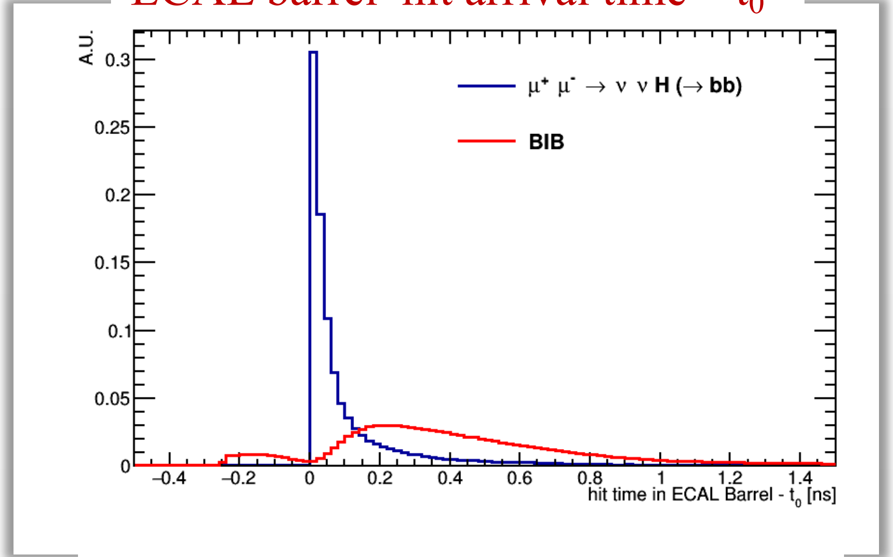


Few BIB hits arrive to the muon detectors

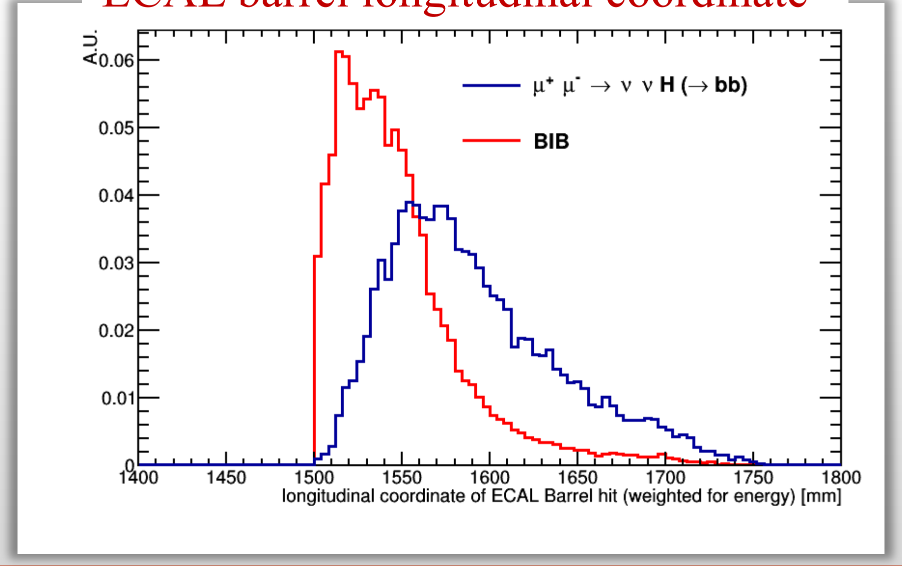
These characteristics need to be exploited in order to:

- Optimize jet reconstruction algorithm.
- Design appropriate algorithm to identify b-jets.
- Propose integrated methods to efficiently reconstruct muons, in particular at very high momentum.

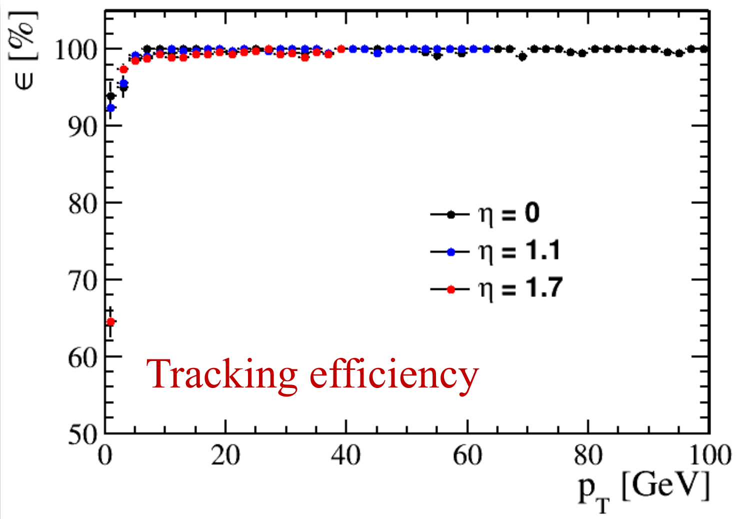
ECAL barrel hit arrival time – t_0

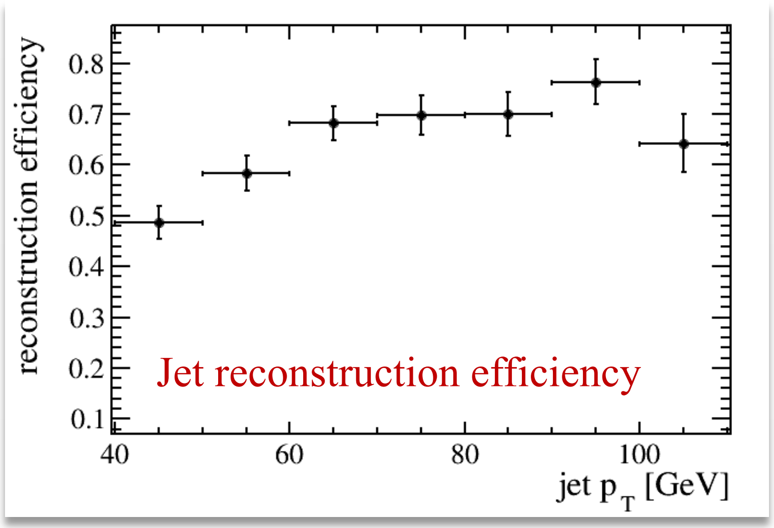


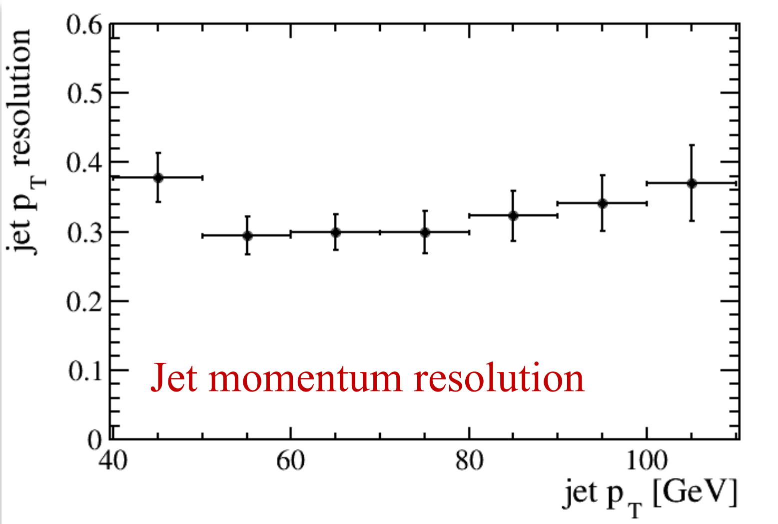
ECAL barrel longitudinal coordinate

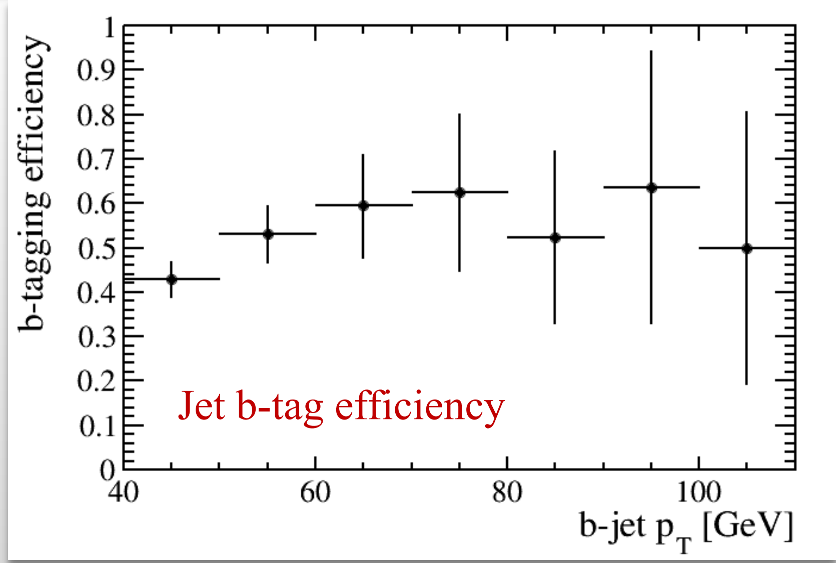


Detector Performance at $\sqrt{s}$ =1.5 TeV









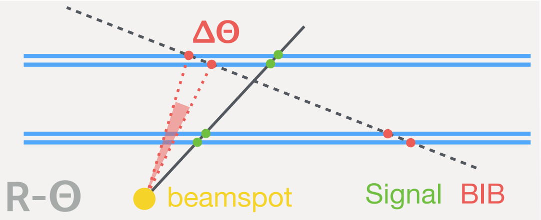
Background tagging:

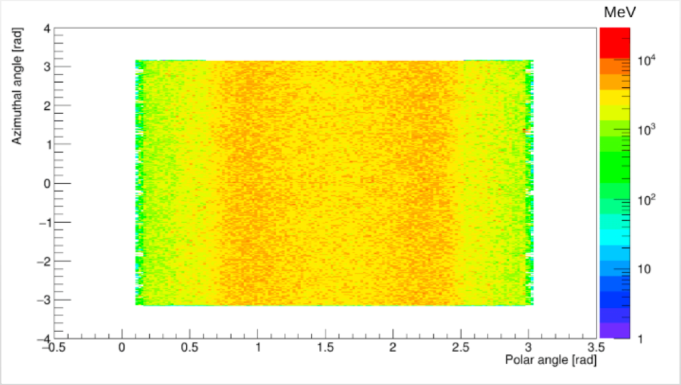
- fake rate: 1 ÷ 3 %
- Studies done so far show fake rate is manageable.

Software Status

- ILCSoft which will be part of the Future Collider Framework, Key4hep, is used.
  The simulation/reconstruction tools support signal + beam-induced background merging.
  Presentation at Snowmass with a tutorial, and Confluence Site.

- Event Full Simulation -> no issues
- Event track reconstruction:
  - It takes a very long time to do it with full BIB
  - Reduce the combinatorial:
    - cutting harder on timing
    - exploit double layer (to be optimized) to remove tracks not coming from primary interaction
- Jet Reconstruction:
  - Subtract “average” energy per tower to remove BIB
  - Optimize ParticleFlow algorithm
- Jet b-tag: to be optimized





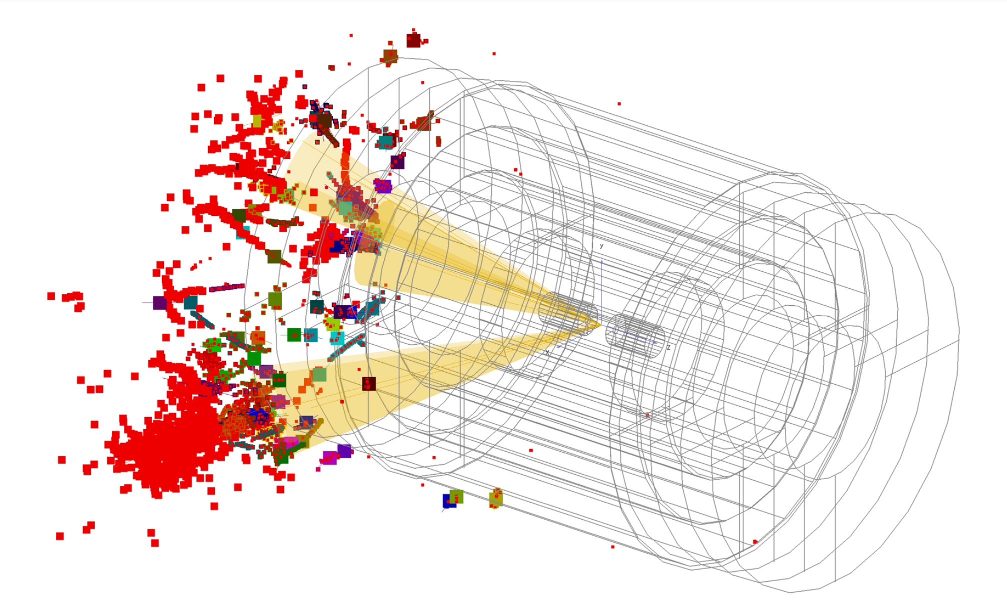
Detailed Physics Studies, so far

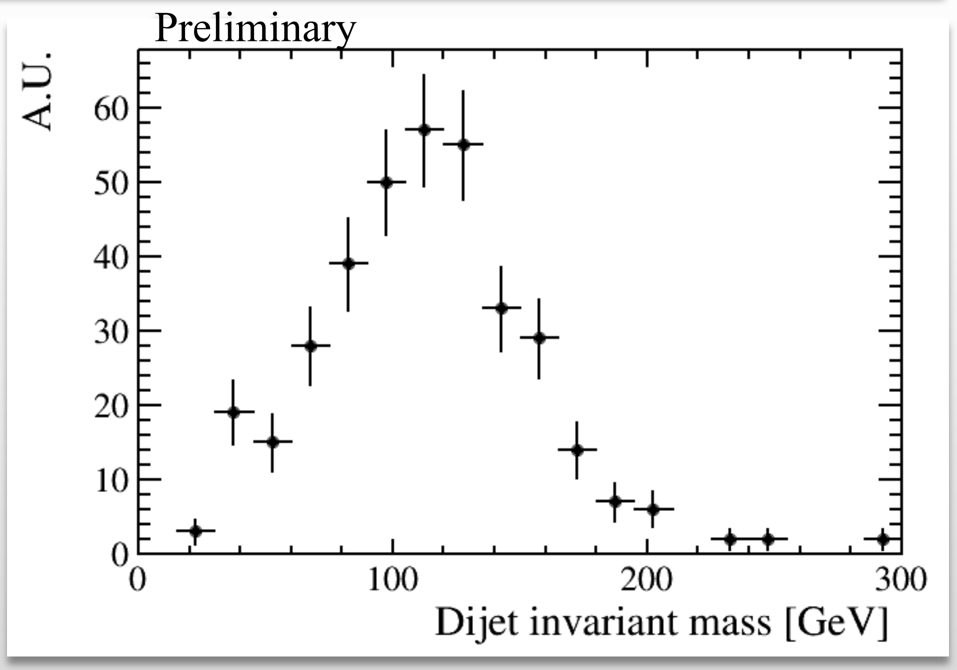
$\mu^+\mu^- \to b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

$\mu^+\mu^- \to HX, H \to b\bar{b}$ and $\mu^+\mu^- \to b\bar{b}X$ generated $@\sqrt{s} = 1.5\ TeV$ with PYTHIA 8

Process	cross section [pb]
$\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$	0.046
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to b\bar{b}$ +X	0.029
$\mu^+\mu^- \to \gamma^*/Z\gamma \to b\bar{b}\gamma$	0.12
$\mu^+\mu^- \to HZ \to b\bar{b}$ +X	0.004
$\mu^+\mu^- \to \mu^+\mu^- H\ H \to b\bar{b}$ (ZZ fusion)	0.018
$\mu^+\mu^- \to \nu_\mu\nu_\mu H\ H \to bb$ (WW fusion)	0.18 Signal

$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated





Higgs $b\bar{b}$ Couplings: Assumptions

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR\left(H \to b\bar{b}\right) = \frac{N_s}{A\varepsilon\mathcal{L}T}$$

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N_s + B}}{N_s}$$

$$4\left(\frac{\Delta g_{Hbb}}{g_{Hbb}}\right)^2 = \left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta(g^2{}_{HWW}/\Gamma_H)}{g^2{}_{HWW}/\Gamma_H}\right)^2$$

Obtained, with several approximations, from e^+e^-:
2% @1.4TeV
1.8% @ 3TeV

N_s : number of signal events.
B: number of background events, $\mu^+\mu^- \to q\bar{q}$ from Pythia + beam-induced background
σ: cross section times BR
A: acceptance; removed nozzle region for $\sqrt{s}$ =1.5 TeV, 2 jets $|\eta| < 2.5$, and $p_T > 40$ GeV
ε: measured with the full simulation at $\sqrt{s}$ =1.5 TeV

Assumptions for Higgs $b\bar{b}$ Couplings at $\sqrt{s} = 3, 10$ TeV

- Nozzles and interaction region are not optimized for these energies, nor is the detector.
- Efficiencies obtained with the full simulation at √s = 1.5 TeV used for the higher center-of-mass energy cases, with the proper scaling to take into account the different kinematic region.
- At higher √s the tracking and the calorimeter detectors are expected to perform significantly better since the yield of the beam-induced background should decrease with √s.
- The uncertainty on $\frac{\Delta(g^2{}_{HWW}/\Gamma_H)}{(g^2{}_{HWW}/\Gamma_H)}$ is taken from the CLIC at √s = 3 TeV and used also at √s = 10 TeV

Conservative Assumptions

Higgs $b\bar{b}$ Couplings Results

- Instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP.
- Acceptance, A, number of signal events, N, and background, B, are determined with simulation.
- Running time $\boldsymbol{t = 4 \cdot 10^7}$ **s ⇒ 4 Snowmass years**
- **Only one detector**

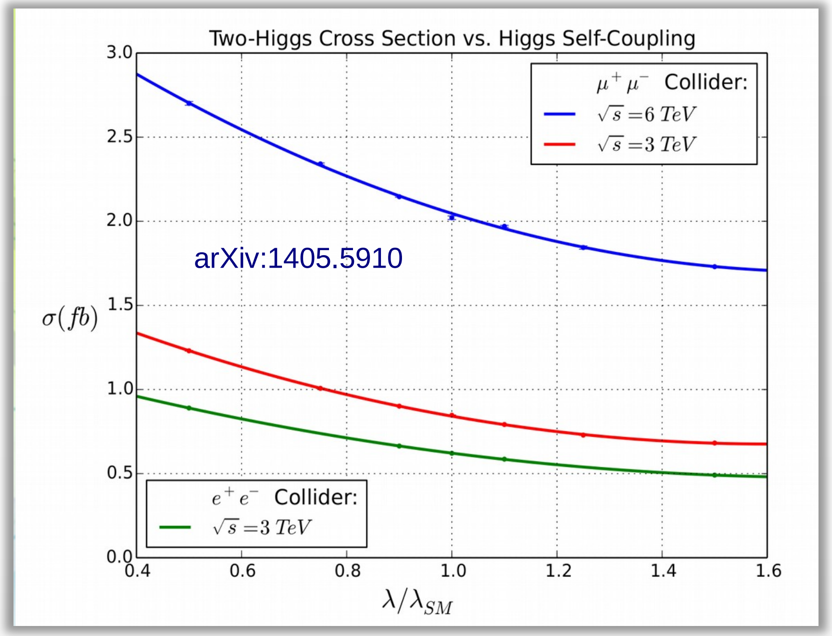
$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

CLIC numbers: obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies.

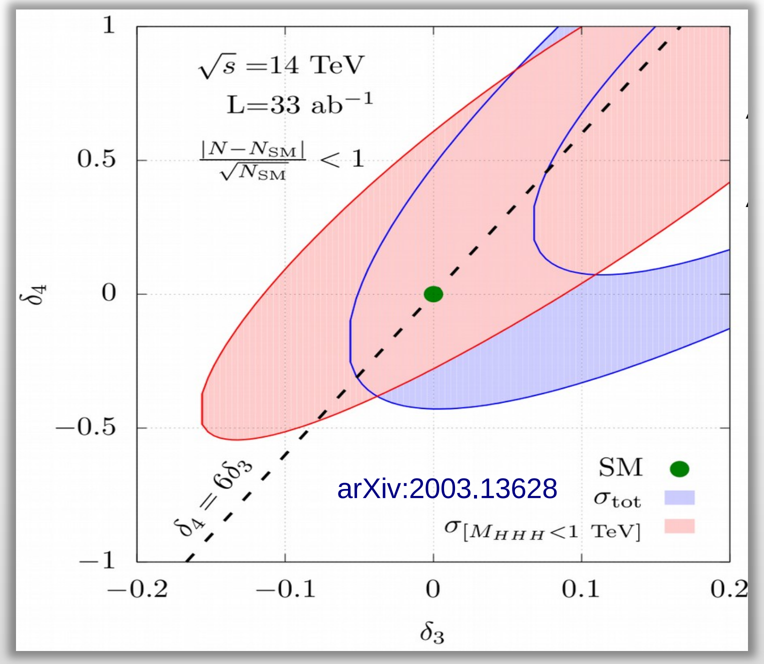
Results published on JINST as Detector and Physics Performance at a Muon Collider

Higgs Boson Potential determination



HH cross section at a muon collider is higher with respect to e^+e^- at the same center-of-mass energy due to different initial state radiation.

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$
$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$



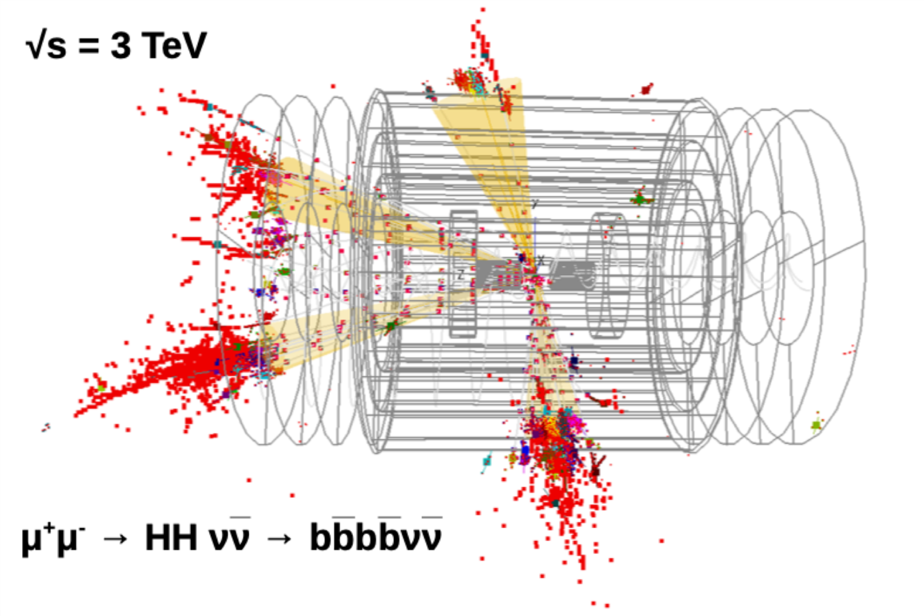
Phenomenological studies show that at 14 TeV, with 33 ab^{-1} it will be possible to achieve an uncertainty of 50% on the quadrilinear coupling.

Double Higgs Boson Studies at $\sqrt{s} = 3$ TeV

Sample used

- ❑ $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$
- ❑ $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$ inclusive

with WHIZARD 2.8.2 at $\sqrt{s} = 3$ TeV



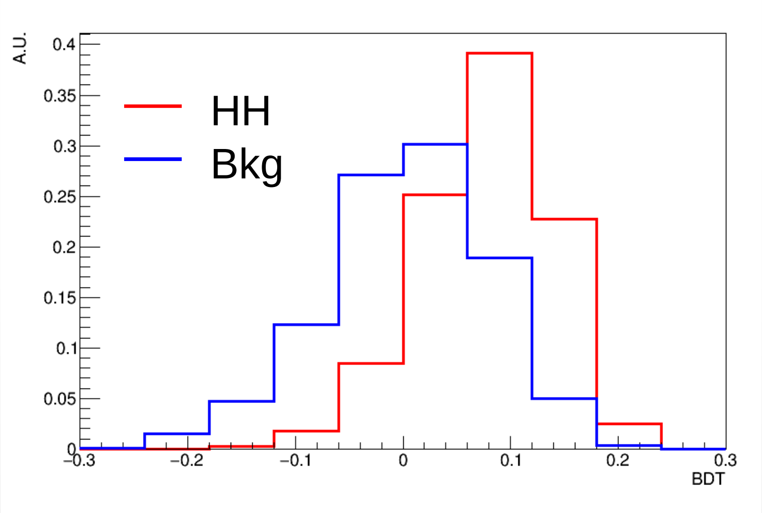
- Detector acceptance and MDI of $\sqrt{s} = 1.5$ TeV
- Detector performance determined at $\sqrt{s} = 1.5$ TeV events weighted to take into account for the different energy

Conservative assumptions

Study of double Higgs production at $\sqrt{s} = 3$ TeV : preliminary results

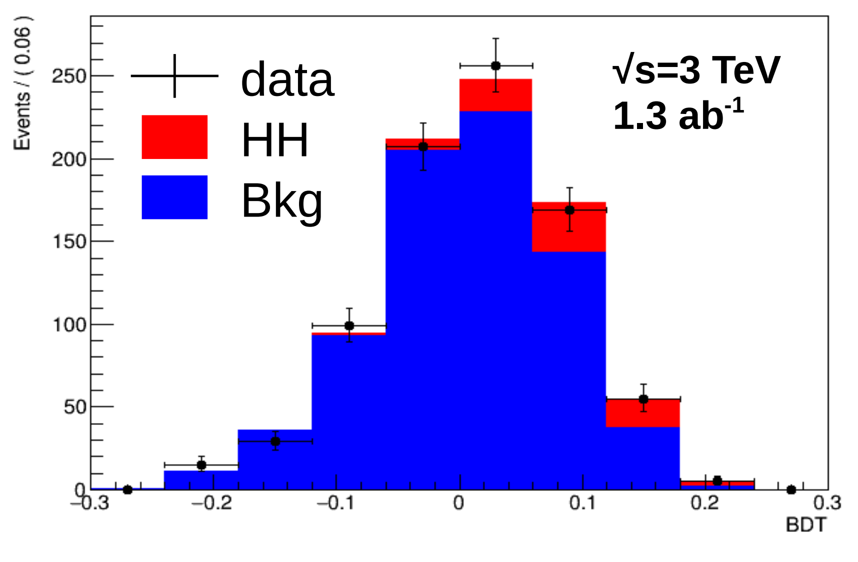
Very preliminary event selection and reconstruction:

- $N_{jets}>3$ with $P_T>20$ GeV, b-tag jets $P_T>40$ GeV
- Jets combined in pairs, one jet per pair is required to be b-tagged
- Separate signal from background using a BDT with 5 input variables.



Assumptions

- $\mathcal{L}_{int} = 1.3\ ab^{-1}$
- Running time = $4 \cdot 10^7$ s
- one detector

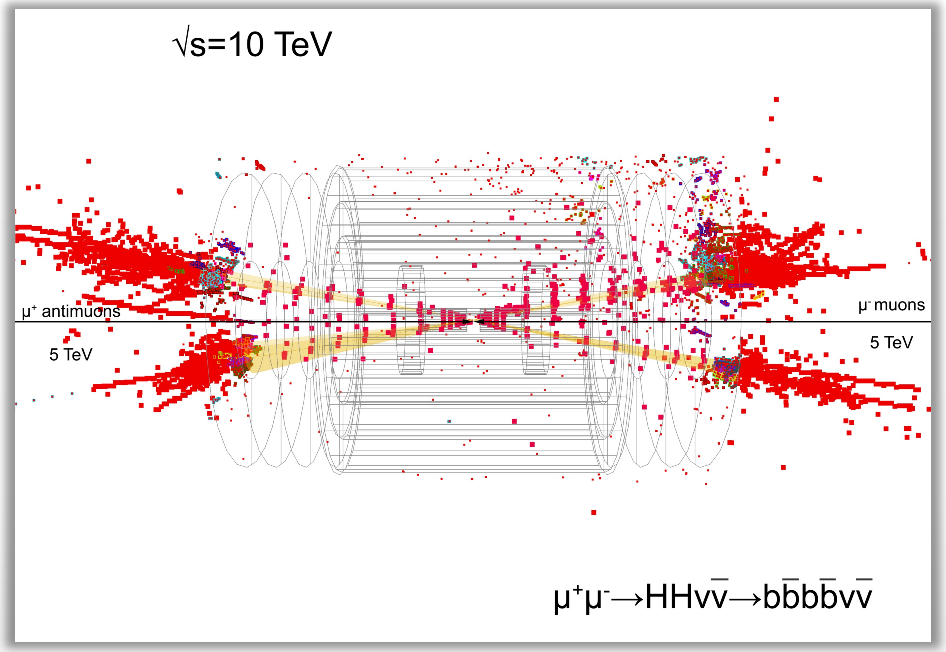


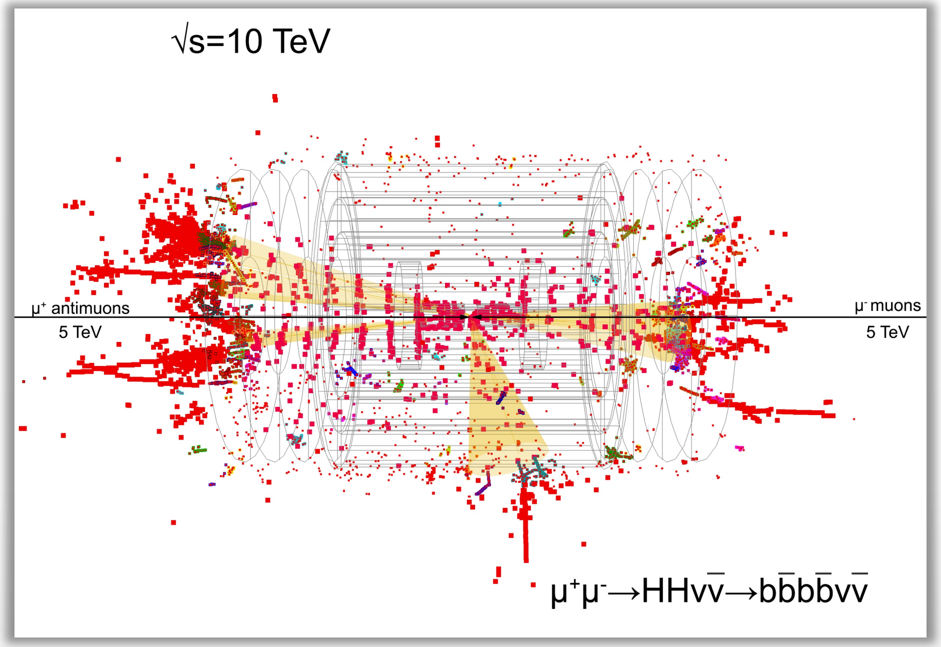
With a simple fit to the BDT output

$$\frac{\Delta\sigma}{\sigma} = 0.33$$

CLIC has 7.5% with $5\ ab^{-1}$ and very refined analysis

How to Study double Higgs production at $\sqrt{s} = 10$ TeV





Simulated for the first time at this energy

- Event topology different with respect to “low” energies.
- Dedicated detector and reconstruction algorithms have to be proposed.
- Signal and background properties and characteristics to be studied

Terra Incognita!!

To conclude

- Muon Collider can be THE future machine
- We need to work together to understand if it is feasible by studying:
  - Machine and Beam-induced background
  - Physics potential:
    - Only a first look at the Higgs in details
    - Plenty of studies to be done, some, maybe even unexpected …

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7 New physics processes at muon colliders: annihilation vs fusion

8 Conclusions

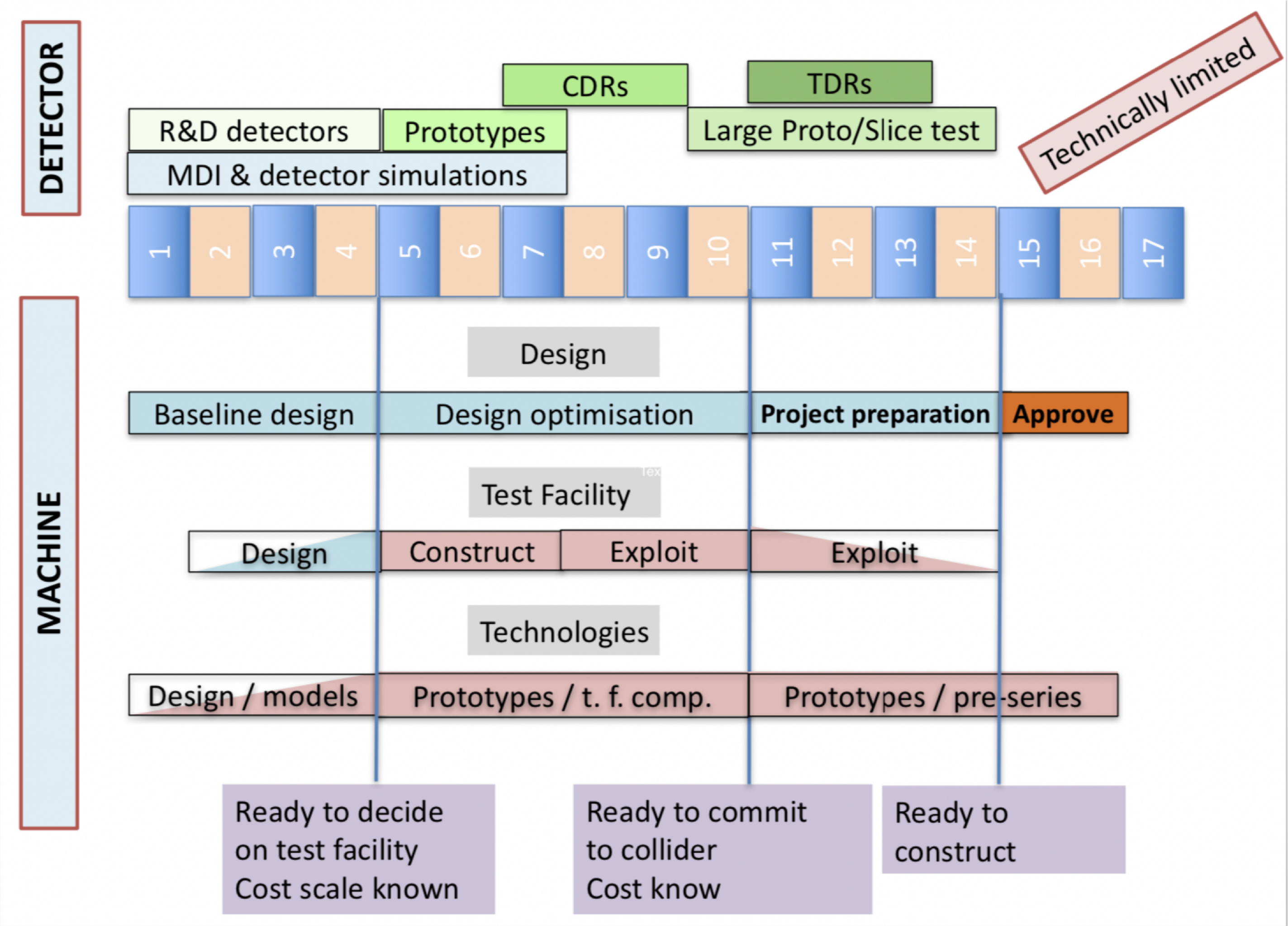
<u>Vector boson fusion at multi-TeV muon colliders</u>, A. Costantini *et al.*

- **An international collaboration is being formed.**

We need to have more courage, and collectively agree on alternatives.

BACKUP

Possible Schedule



Physics Briefing Book
arXiv:1910.11775v2

Briefing Book Tentative Timeline (2019)