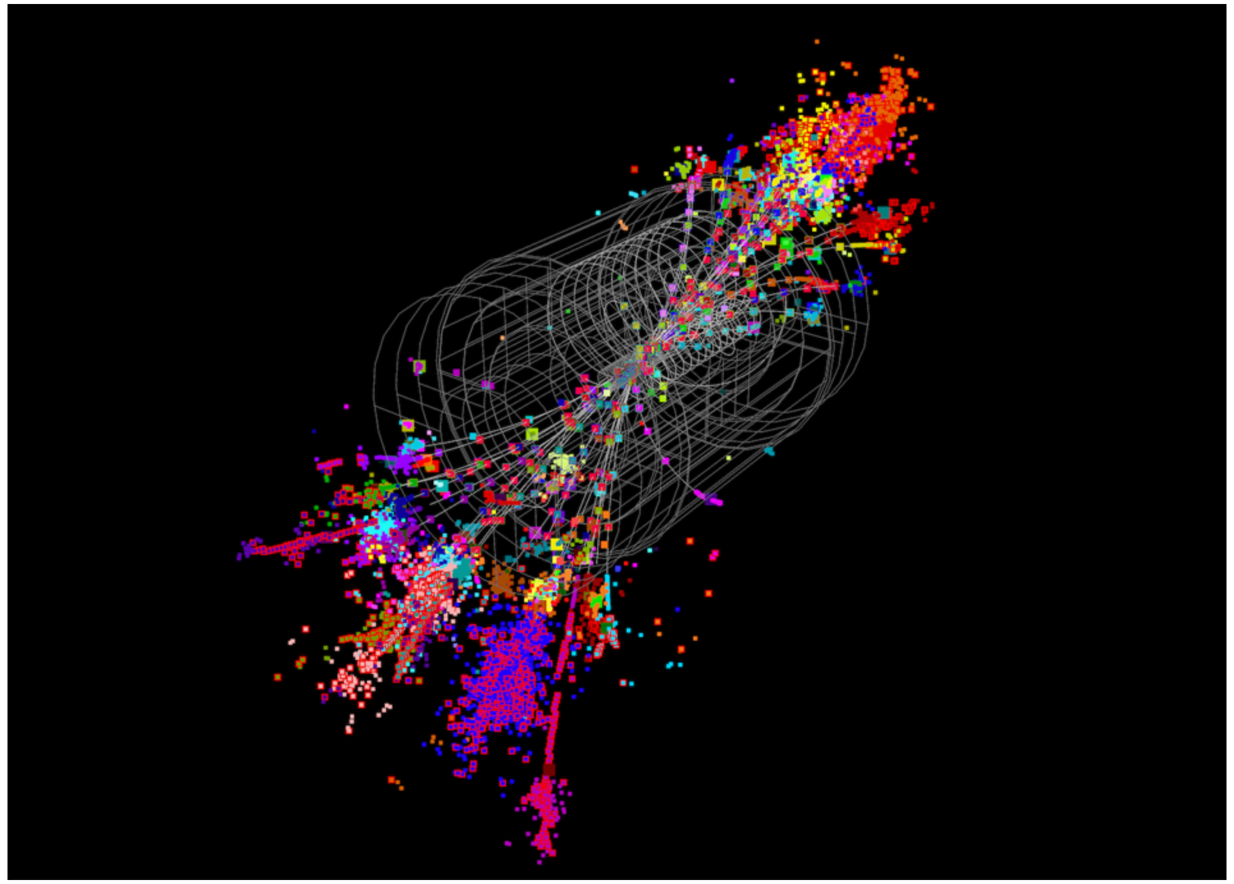
Muon Collider: the dream machine

(a personal perspective with input from many others)

Sergo Jindariani (Fermilab)

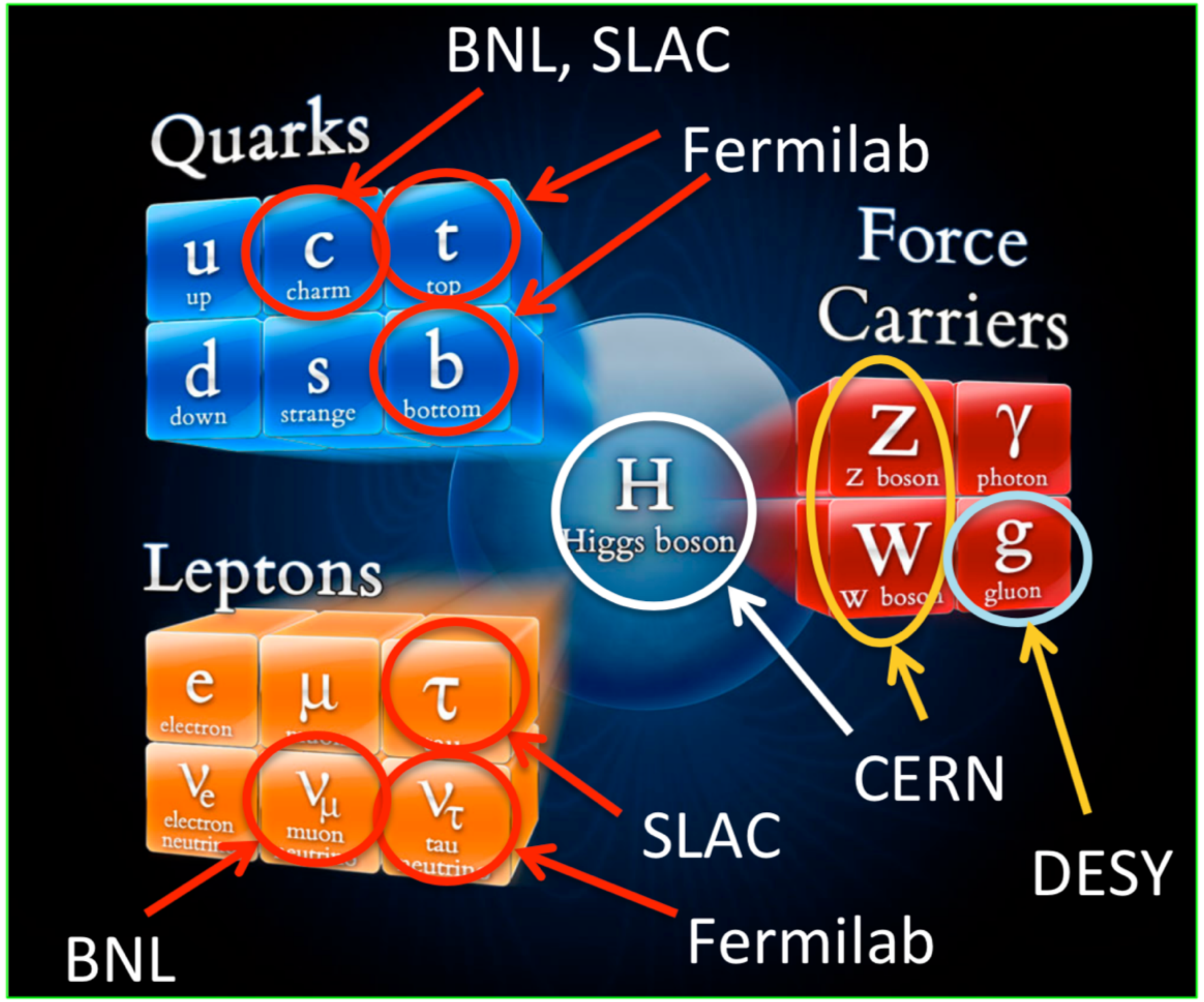
With input from P.Bhat, M.Casarsa, Z.Liu,
D.Lucchesi, M.Palmer, N.Pastrone,
V.Shiltsev, and others



Energy Frontier Snowmass Early Career Meeting
September 2020

The breadth of Collider Physics

The Triumph of
The Standard Model



- Charm quark (1974) e+e-, pN
- Tau lepton (1975) e+e-
- bottom quark (1977) pN
- Gluon (1978/79) e+e-
- W,Z bosons (1983) **p-pbar**
- Top quark (1995) **p-pbar**
- Tau neutrino (2000) pN
- Higgs boson (2012) **pp**

Where is BSM?

CMS Exotica example

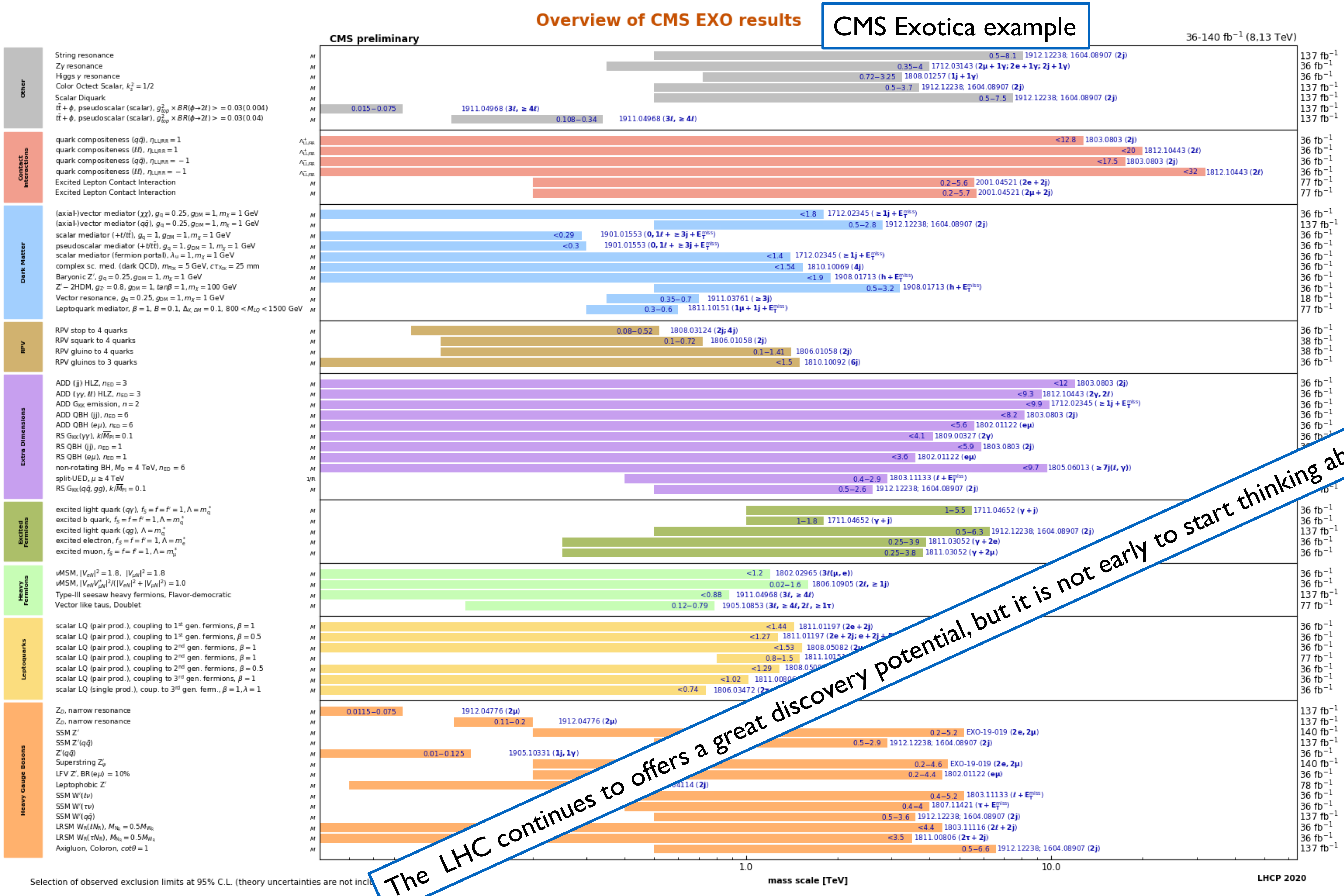
Contact Interactions

Dark Matter

Extra Dimensions

Leptoquarks

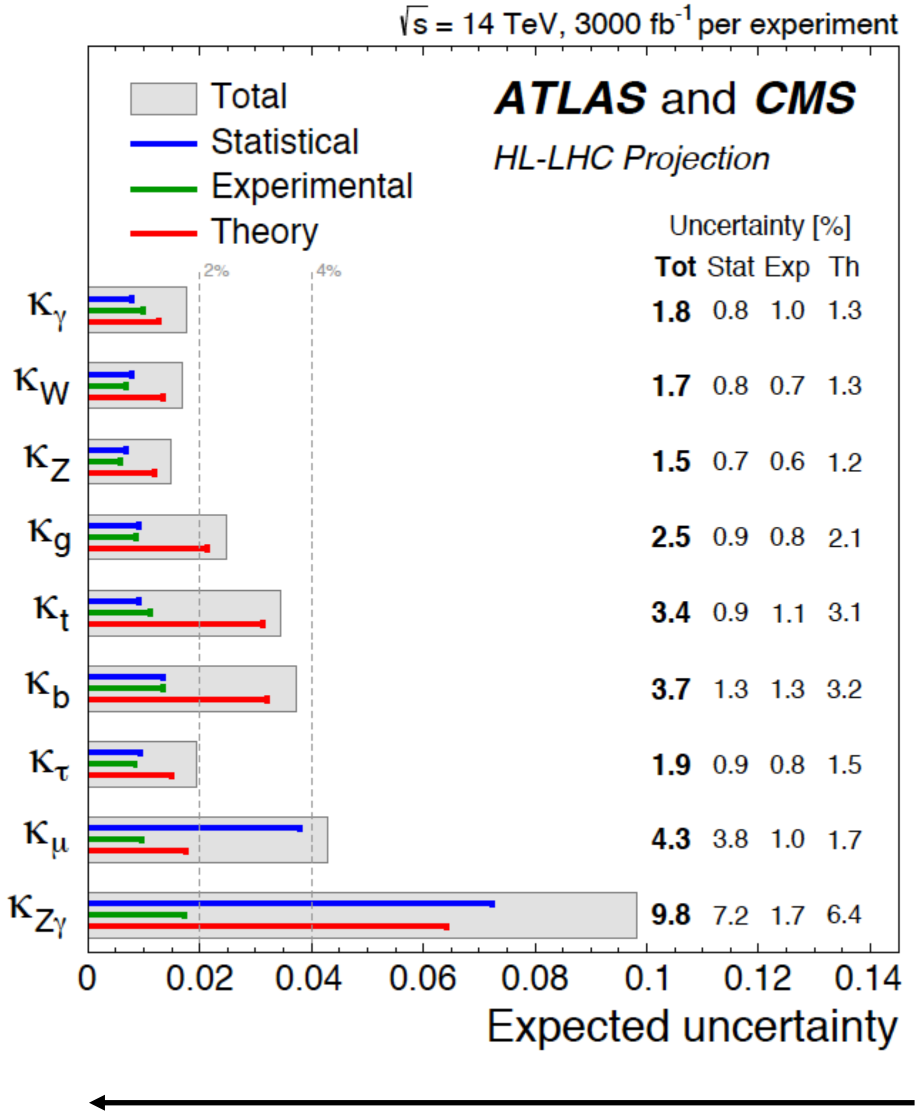
Heavy Vector Bosons



The LHC continues to offers a great discovery potential, but it is not early to start thinking about future machines

Some Physics Questions

Precision Measurements of Higgs Couplings and width

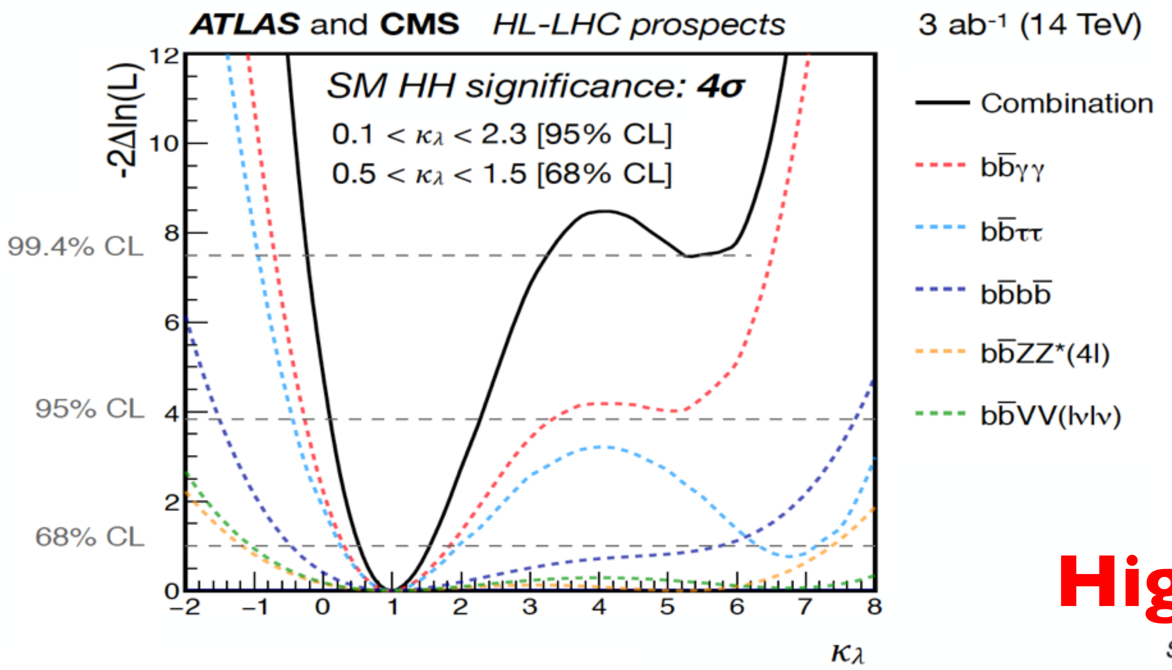


Future colliders target under 1% precision

Higgs

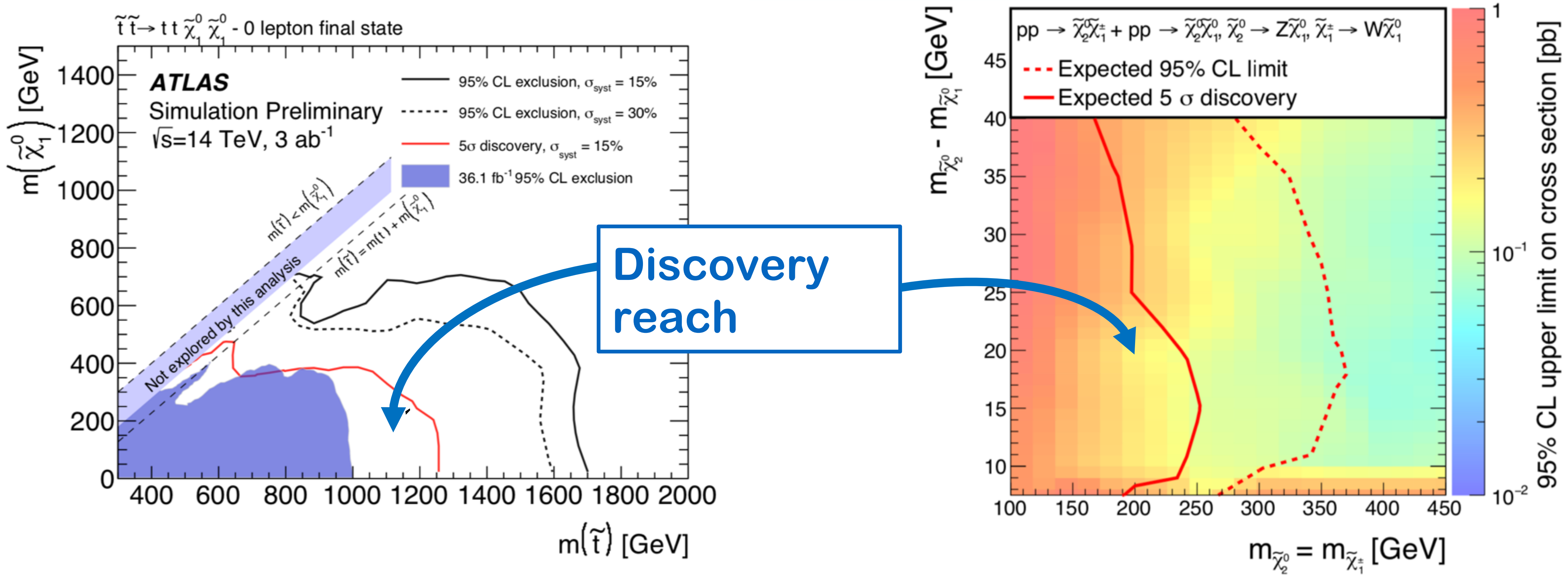
Higgs trilinear and quartic coupling: an insight into the Higgs potential

$$V_h = \frac{m_h^2}{2}h^2 + (1+\boxed{\kappa_3})\lambda^{SM}_{hhh}vh^3 + \frac{1}{4}(1+\boxed{\kappa_4})\lambda^{SM}_{hhhh}h^4$$



Stops

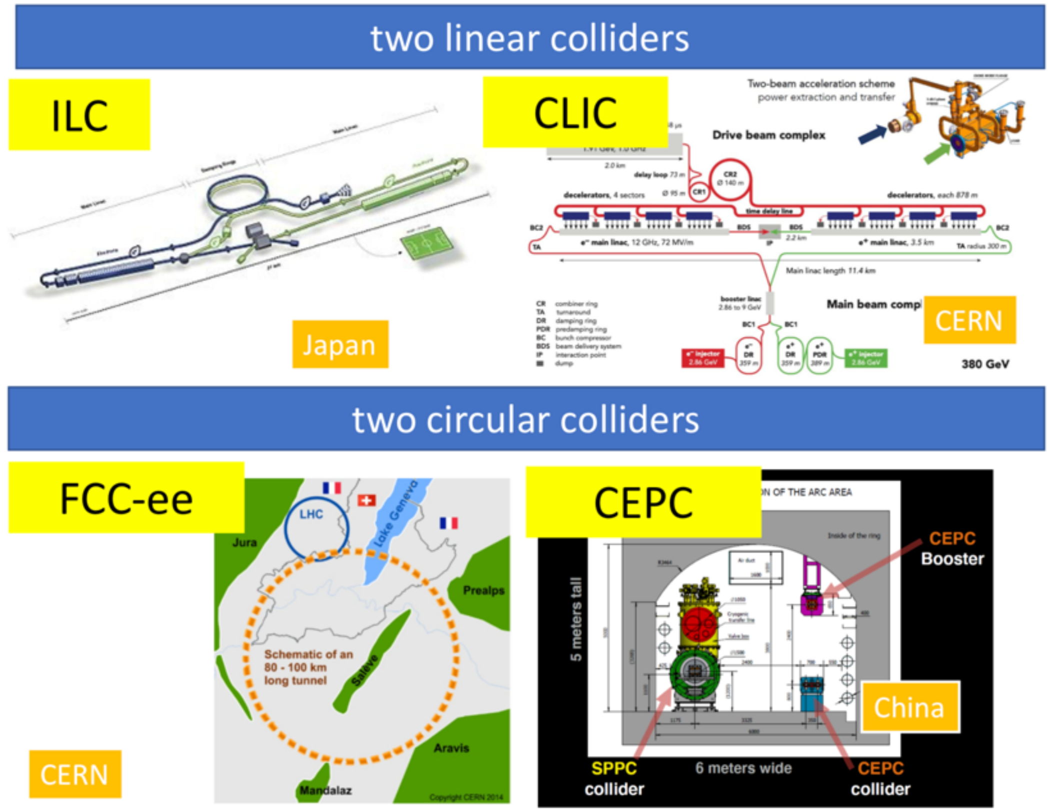
Higgsinos



Discovery reach

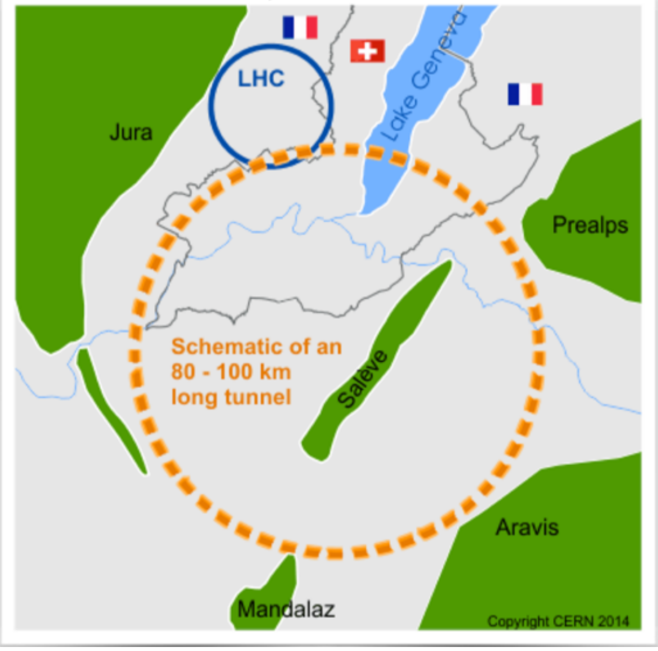
Future e+e- and pp machines

e^+e^- colliders with a center of mass energy of ~240 GeV or above to make precision measurements in the Electroweak sector



pp collider with ~100 TeV energy for direct searches of new physics beyond the Standard Model, and exploration of the energy frontier

Geneva, Switzerland



SppC, various sites in China

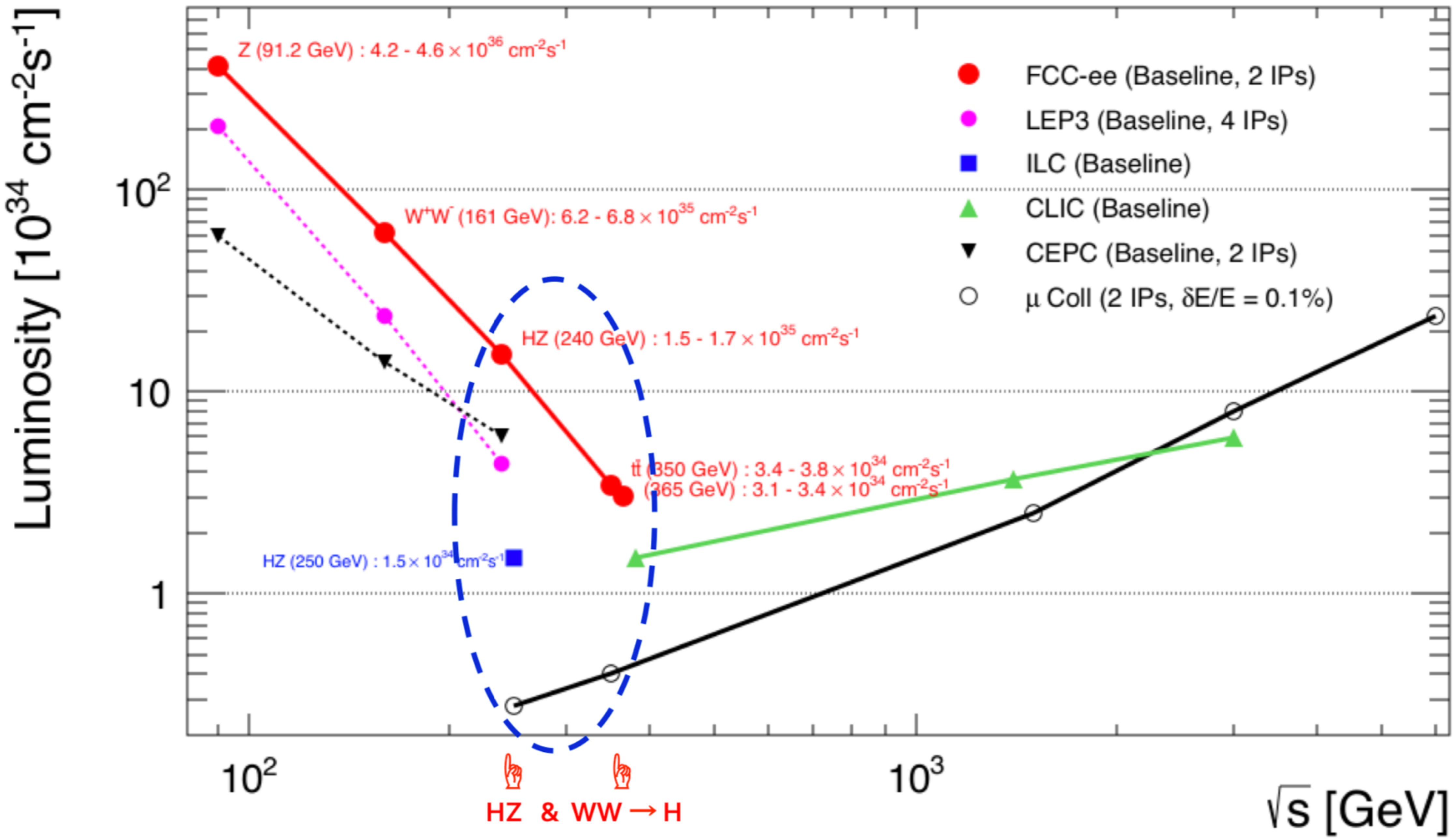
Why Muons? Energy reach

As the trajectory of a charged particle is deflected, it emits “synchrotron radiation”

$$\text{Radiated Power} \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

Radius of curvature

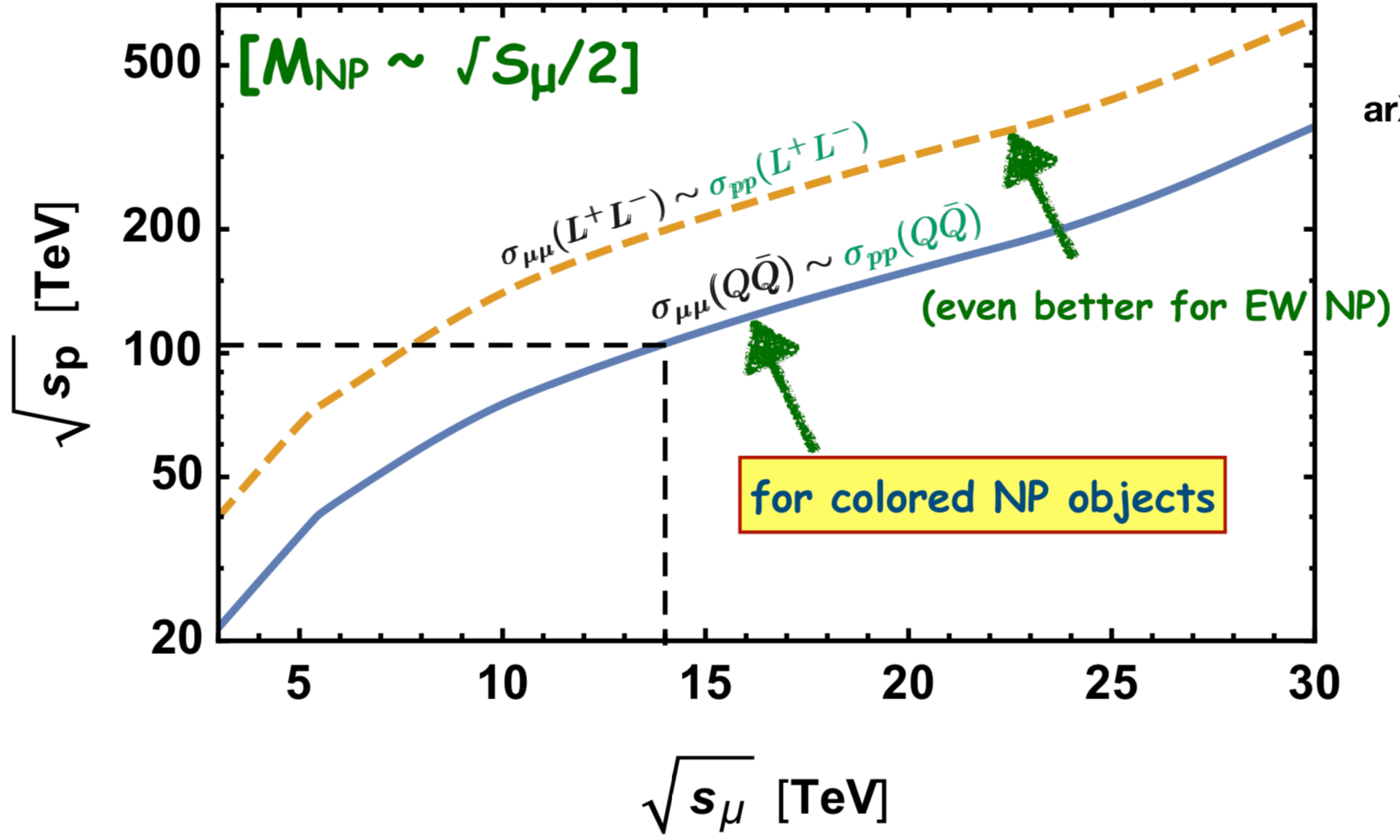
An electron will radiate about 10^9 times more power than a muon of the same energy



30 TeV ?

Note logarithmic scale

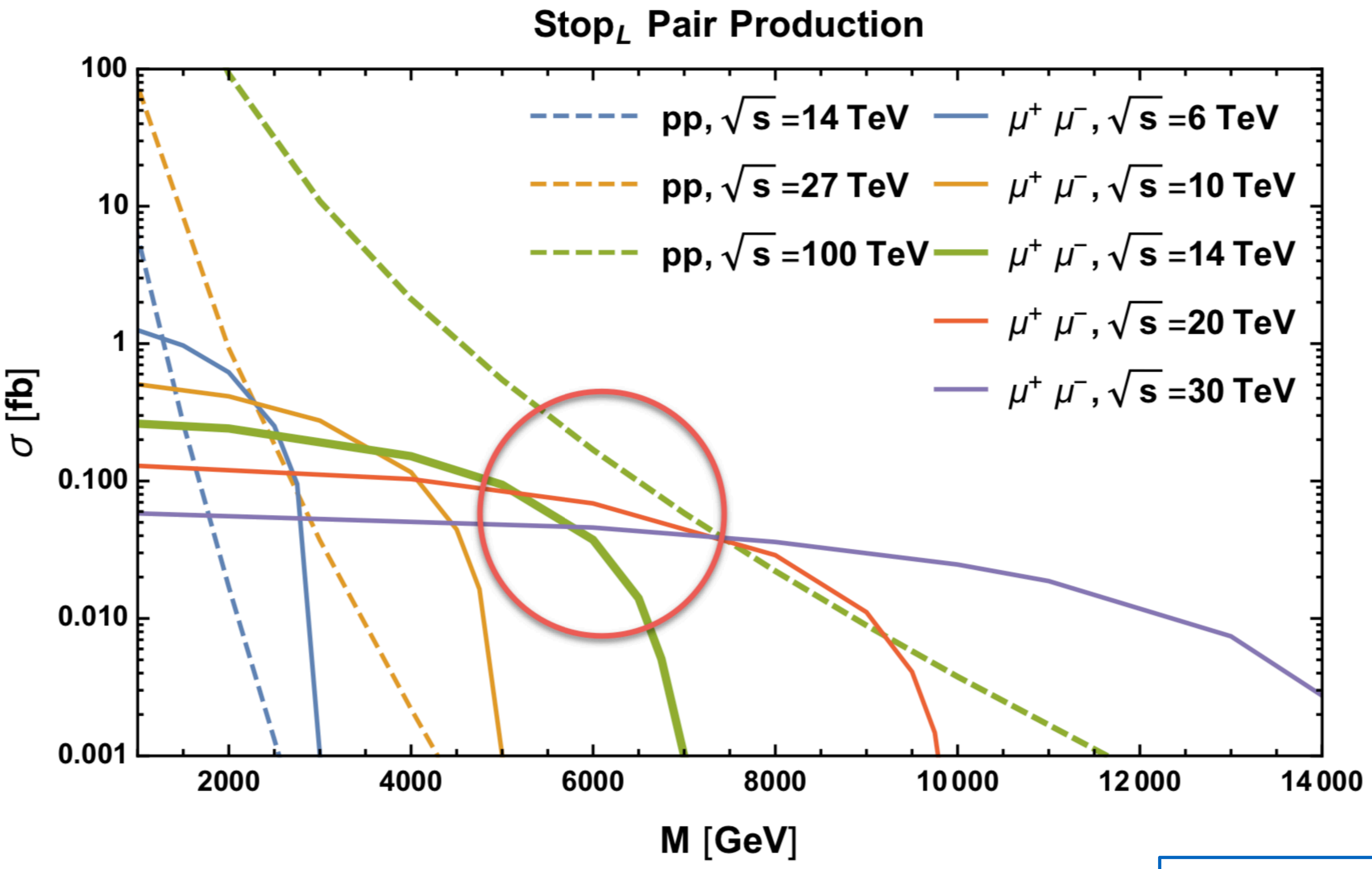
Why Muons? Physics reach



arXiv:1901.06150

Stops

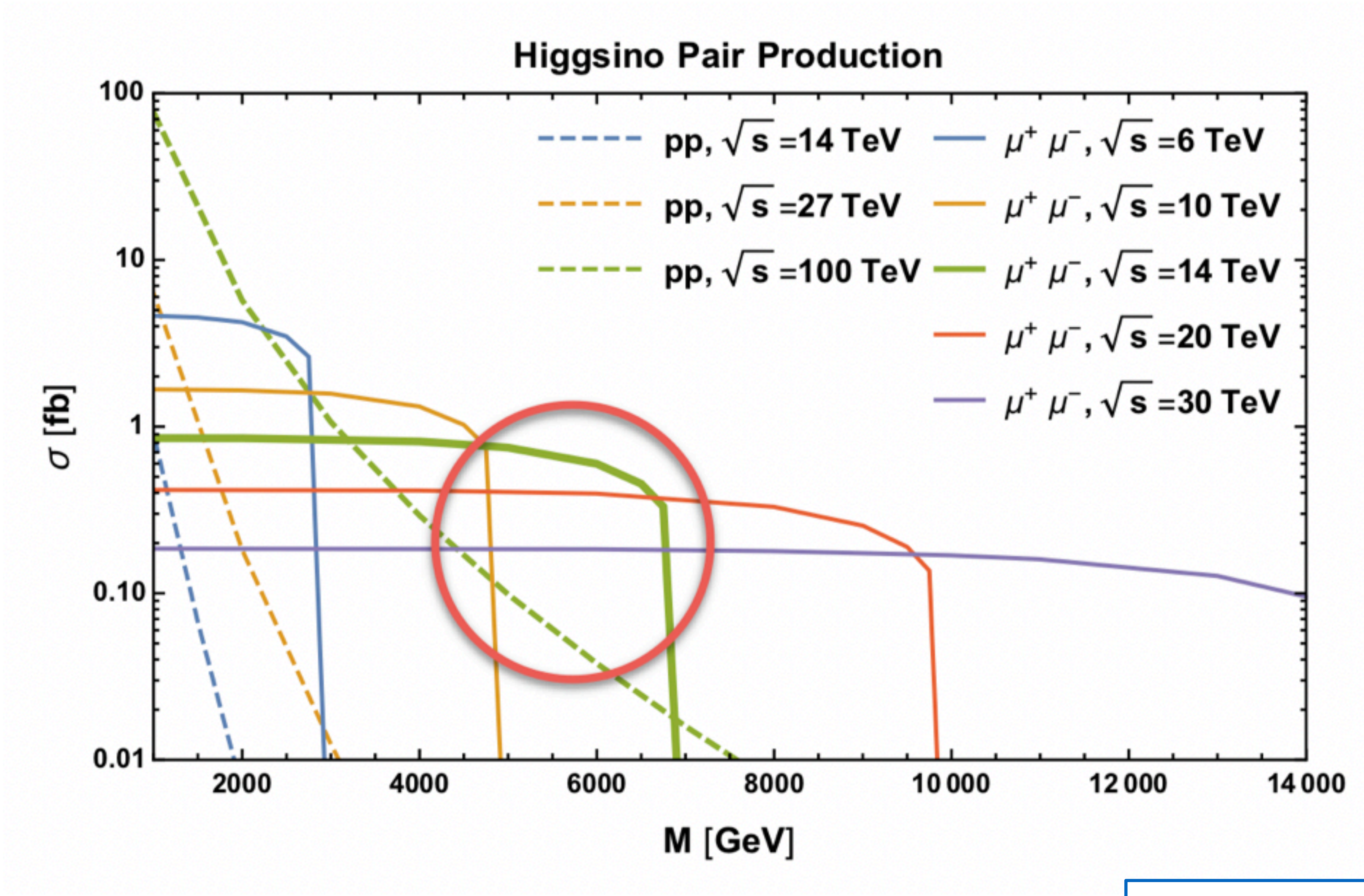
A. Wulzer et al.



Recall HL-LHC reach ~1.2-1.5 TeV

Higgsinos

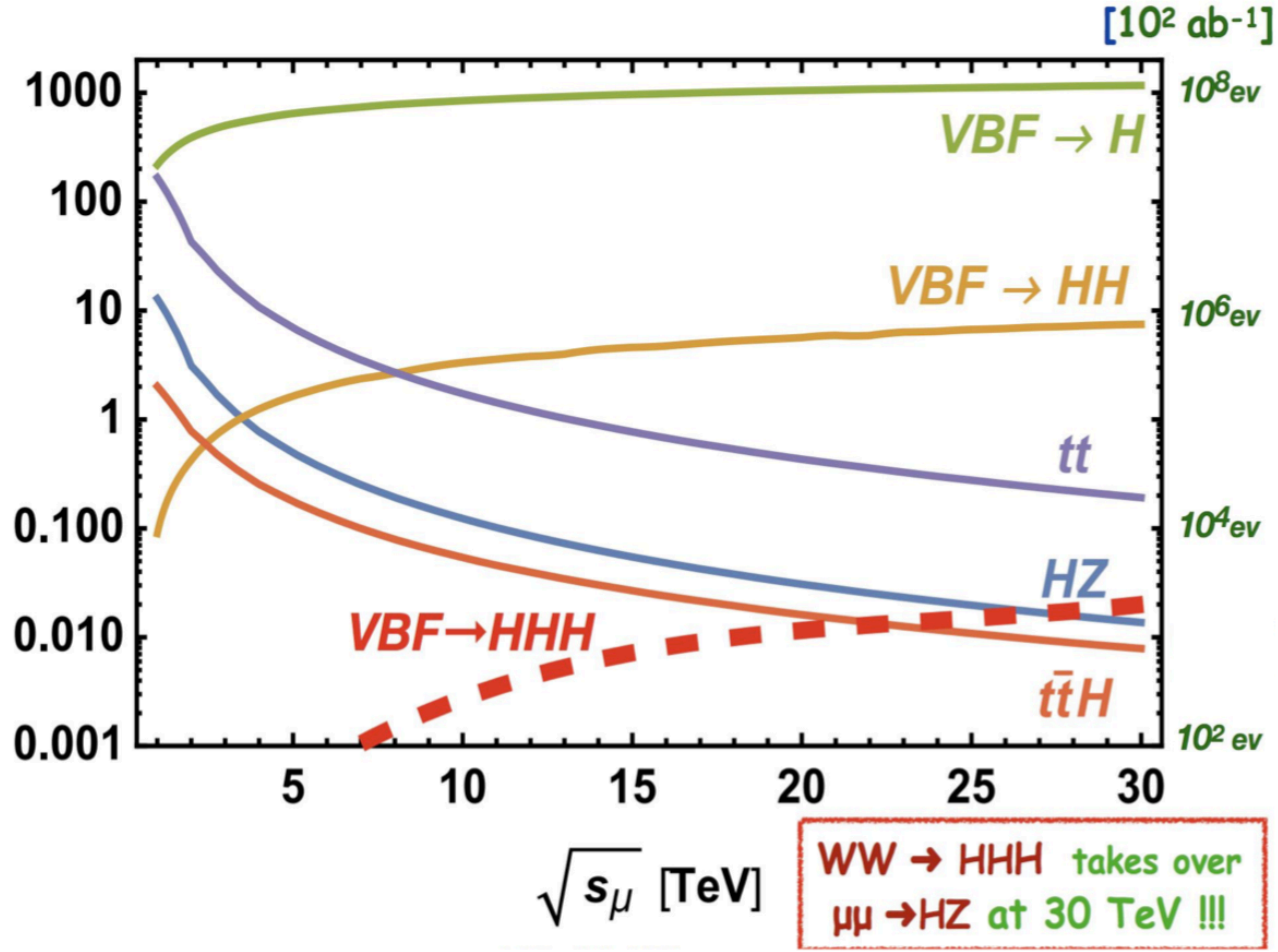
A. Wulzer et al.



Recall HL-LHC reach O(100) GeV

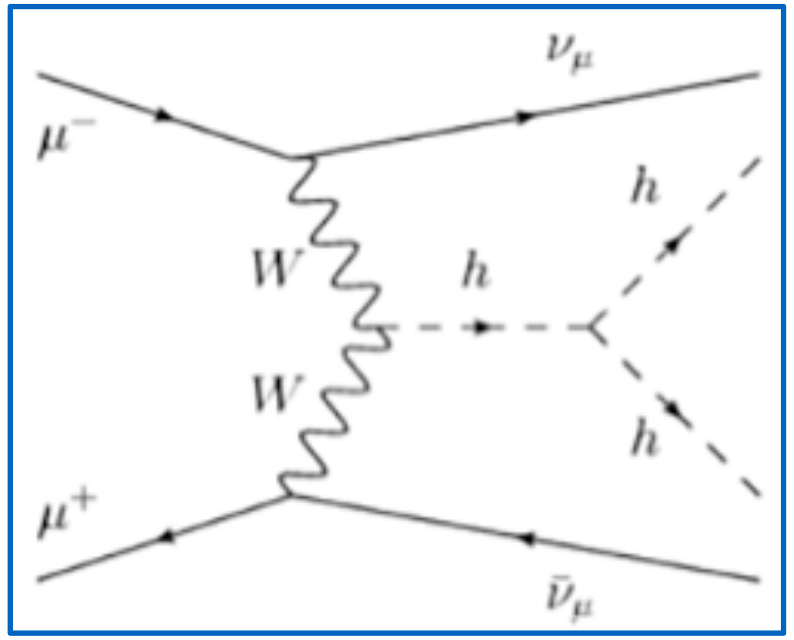
Higgs at the Muon Collider

A. Wulzer et al.



at

WW → HHH takes over μμ →HZ at 30 TeV !!!



Recall HL-LHC 50% precision for $k_{3,}$ no prospects for k_4

125 GeV Higgs factory

Z.Liu et al

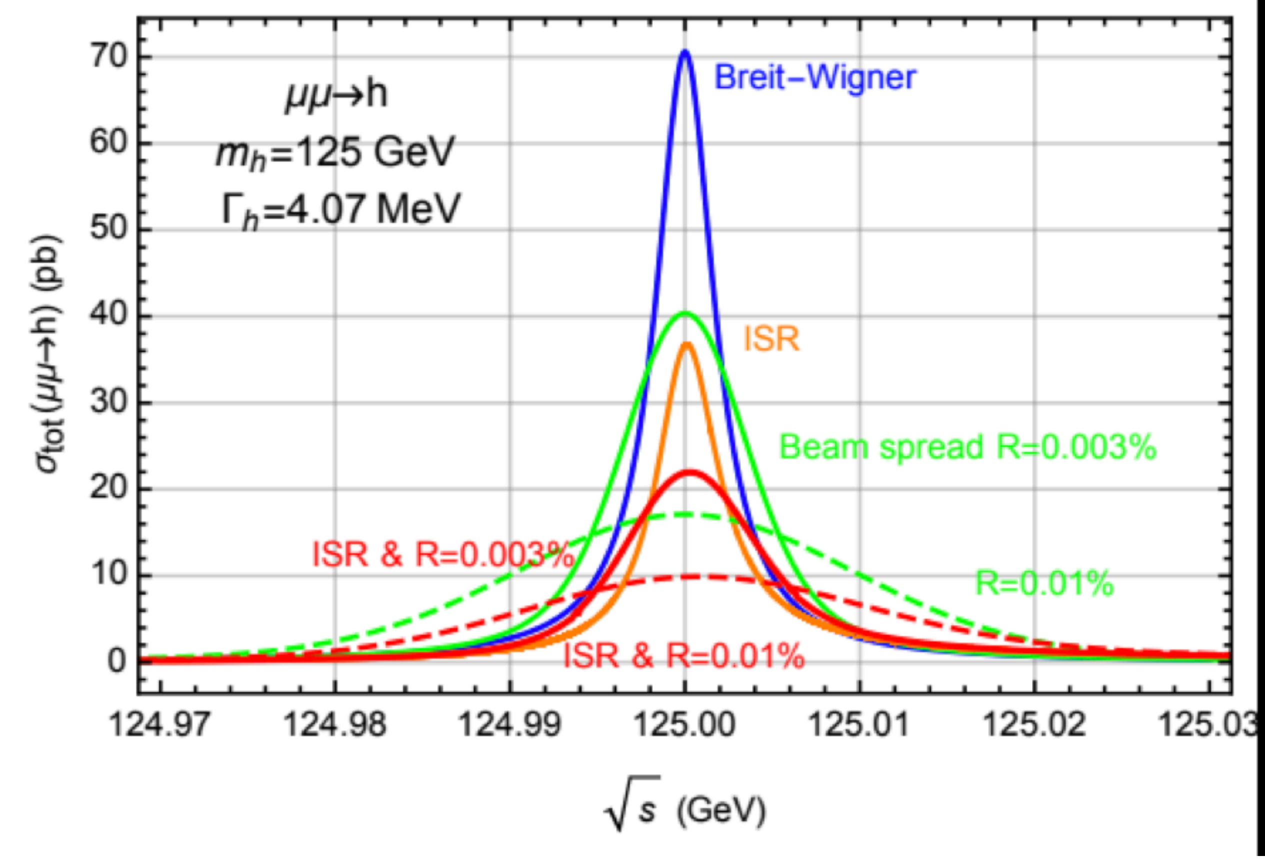
Higgs production in annihilation much larger for $\mu^+\mu^-$ than e^+e^-

$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

- Model independent , precise determination of total Higgs width (~1-2%)
- Very precise measurement of the Higgs mass (~0.05 MeV)
- Excellent measurement of the muon Yukawa coupling (~2%)

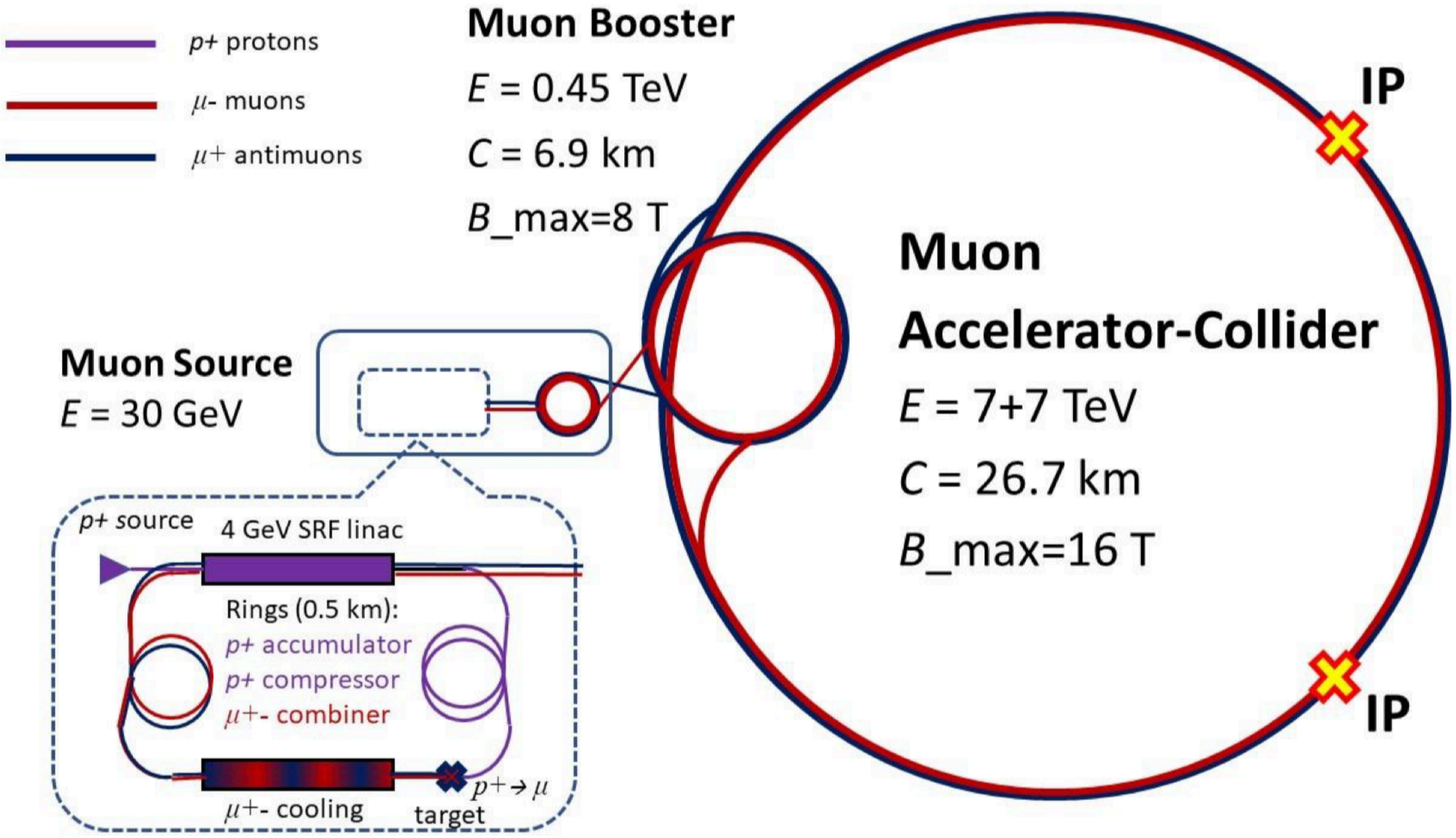
Han, ZL, 1210.7803; also see Conway, Wenzel 1304.5270

$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03



Greco, Han, ZL, 1607.03210
Resolving interferences,
ZL, et al, arXiv:1308.2143

Sketch of a Muon Collider



$p+$ protons

$\mu-$ muons

$\mu+$ antimuons

Muon Booster

E = 0.45 TeV

C = 6.9 km

B_max=8 T

Muon Accelerator-Collider

E = 7+7 TeV

C = 26.7 km

B_max=16 T

Muon Source

E = 30 GeV

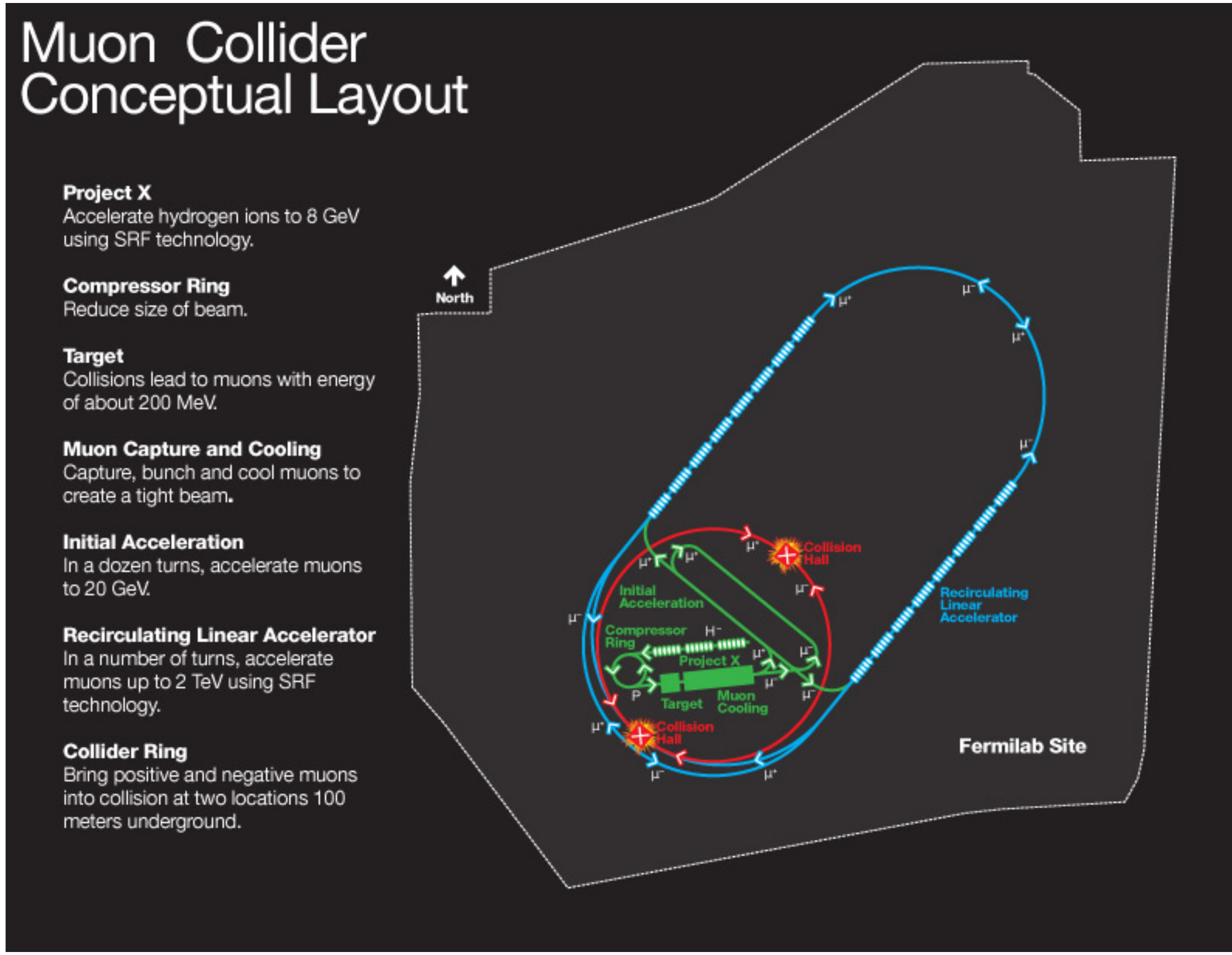
US Muon Accelerator Program (MAP)

https://map.fnal.gov

AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

- Short-baseline neutrino facilities (nuSTORM)
- Long-baseline neutrino factory (nuMAX) with energy flexibility
- Higgs factory with good energy resolution to probe reonance structure
- TeV-scale muon collider

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014



Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

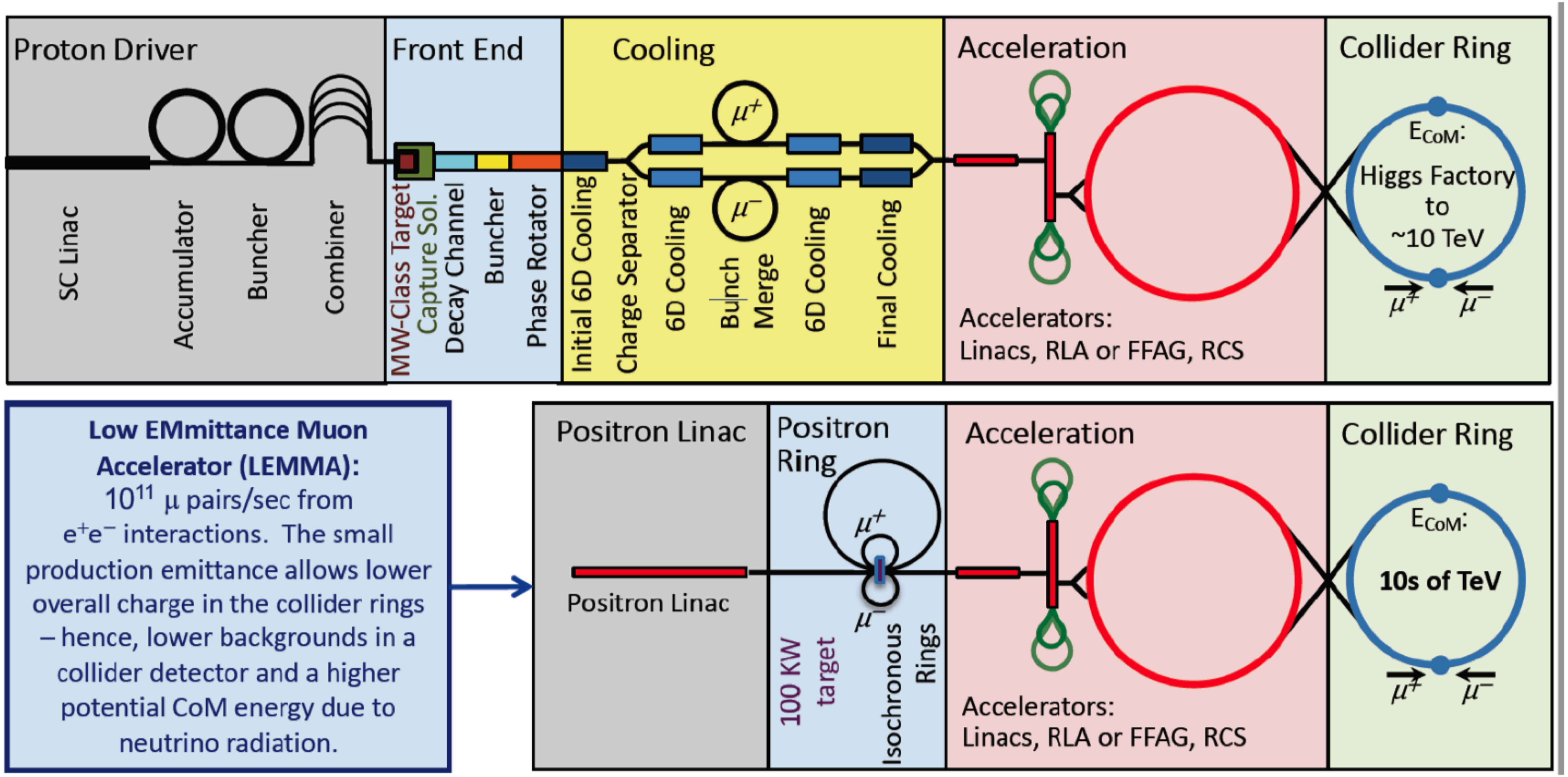
Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.

A more detailed look

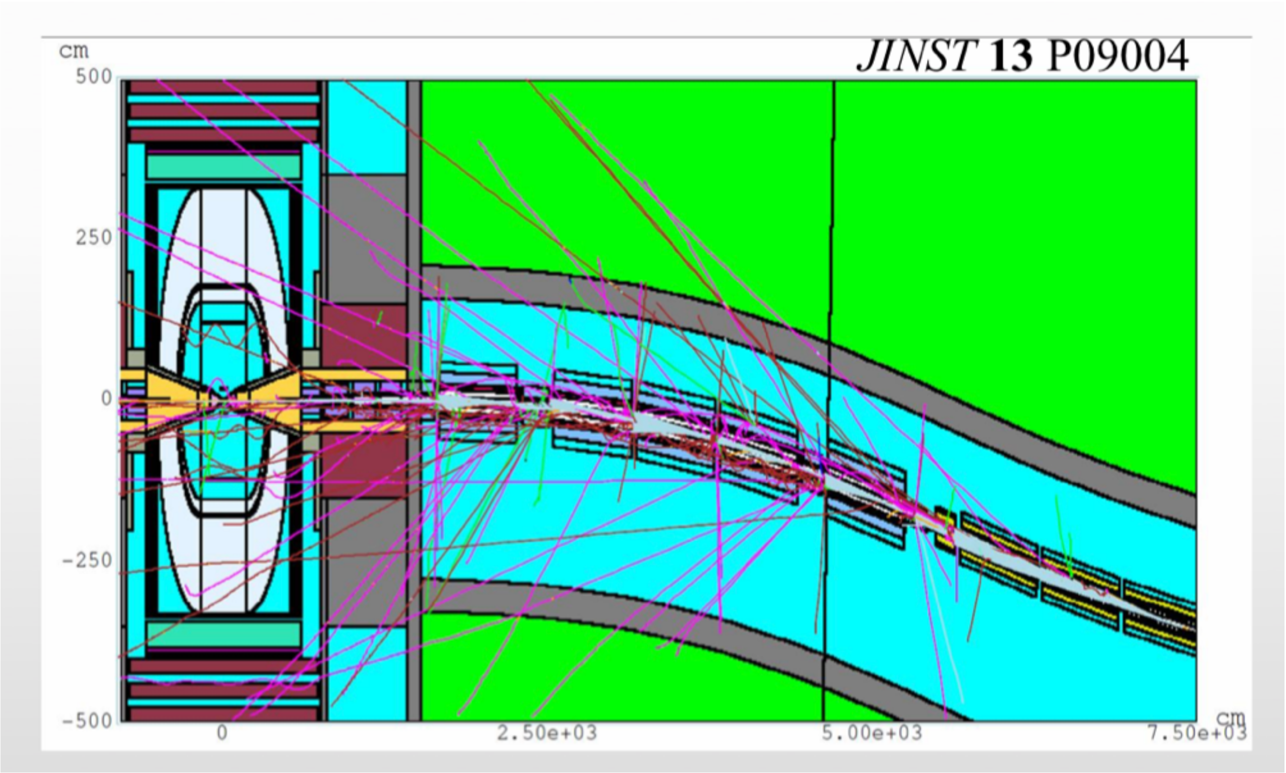


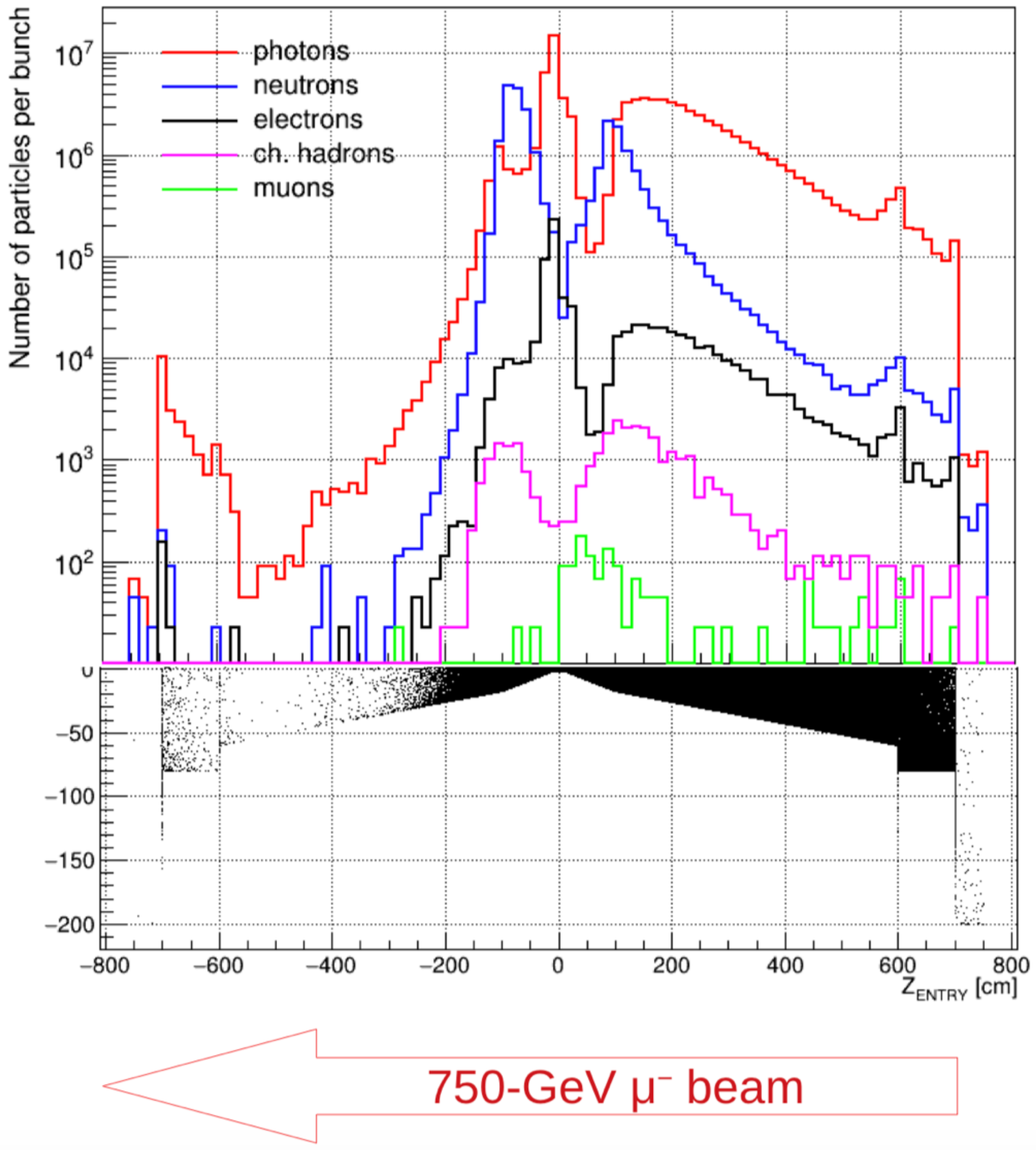
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Beam Induced Background (BIB)

Casarsa et al

- Muons are great particles, except they decay…
- 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.
- More studies performed recently by INFN colleagues

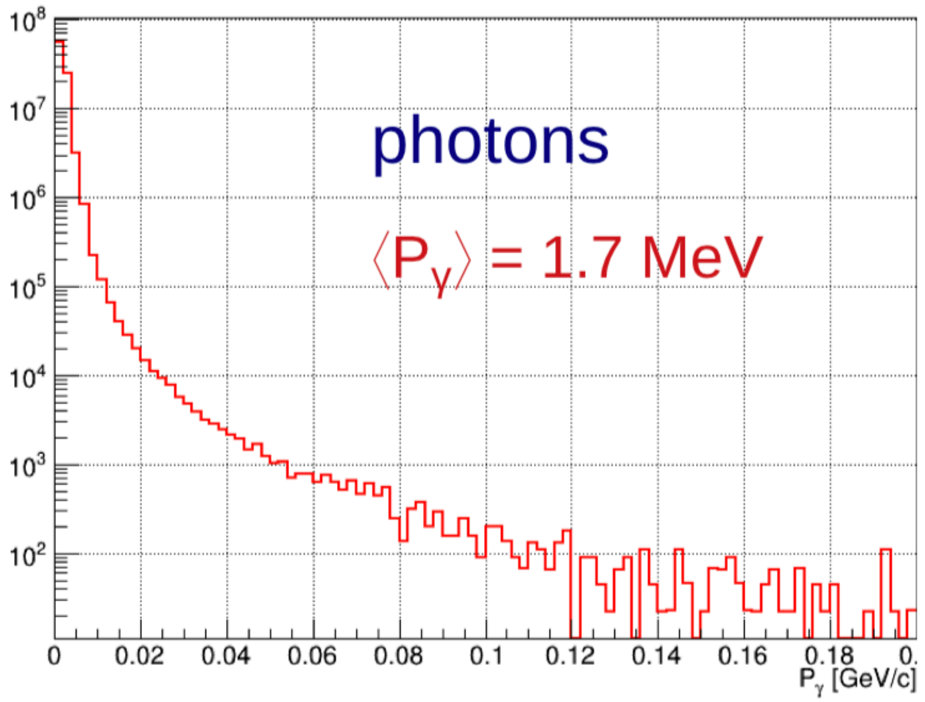


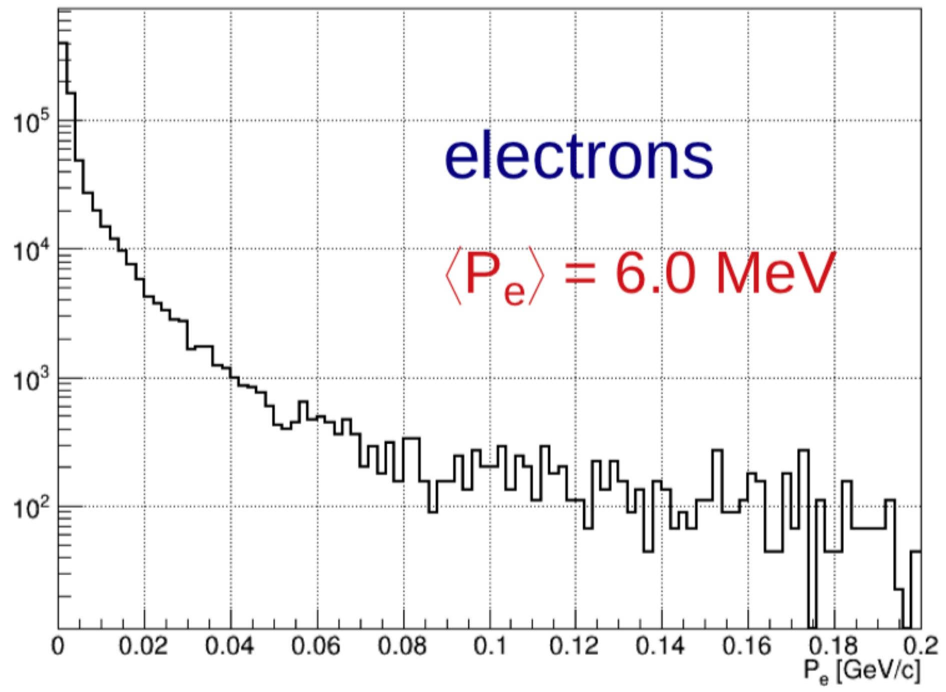


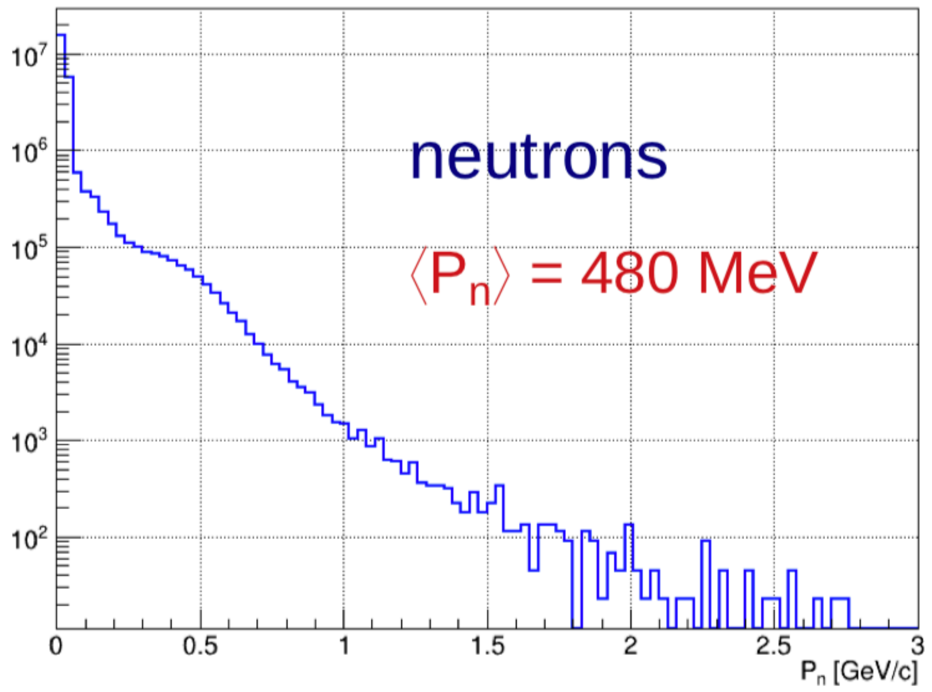
- 0.75 TeV and 2×10^{12} μ/bunch ⇒ 4.1×10^{5} decay/m
- Accelerator components need to be protected
- Detector performance may suffer

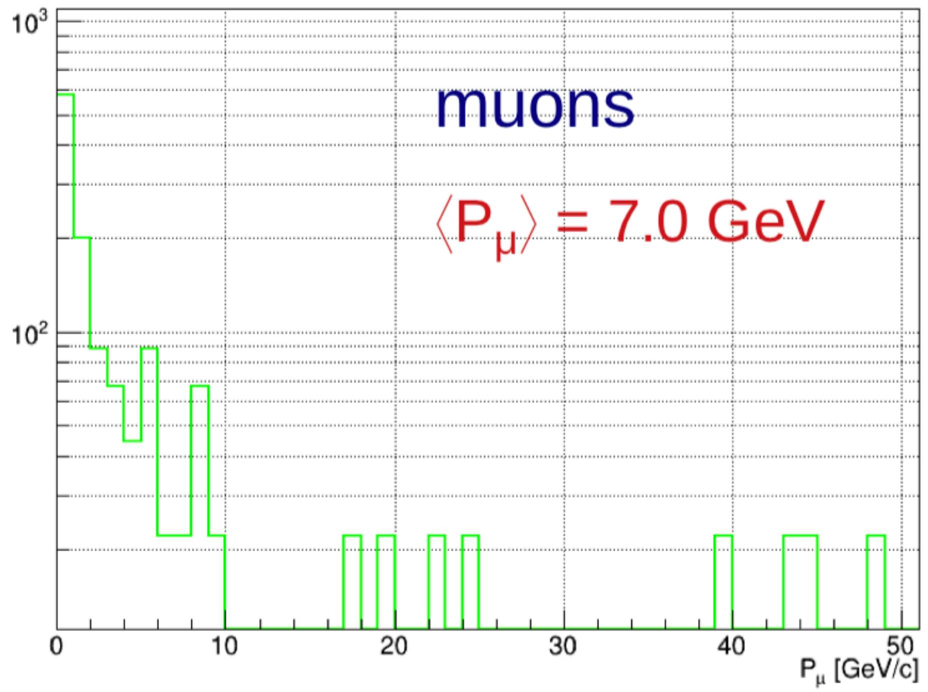
More About the BIB

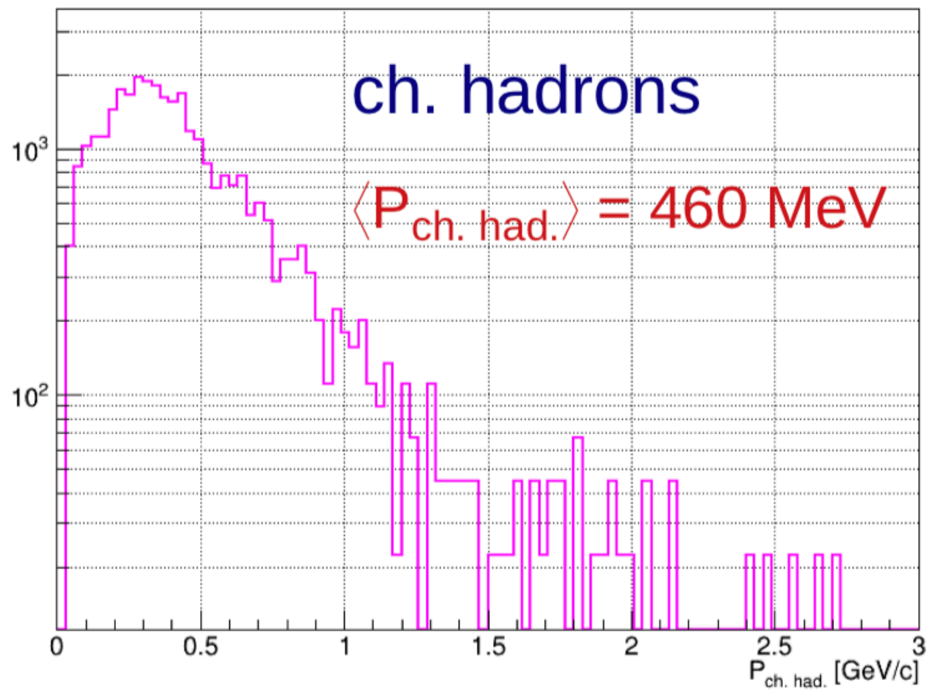
Casarsa et al





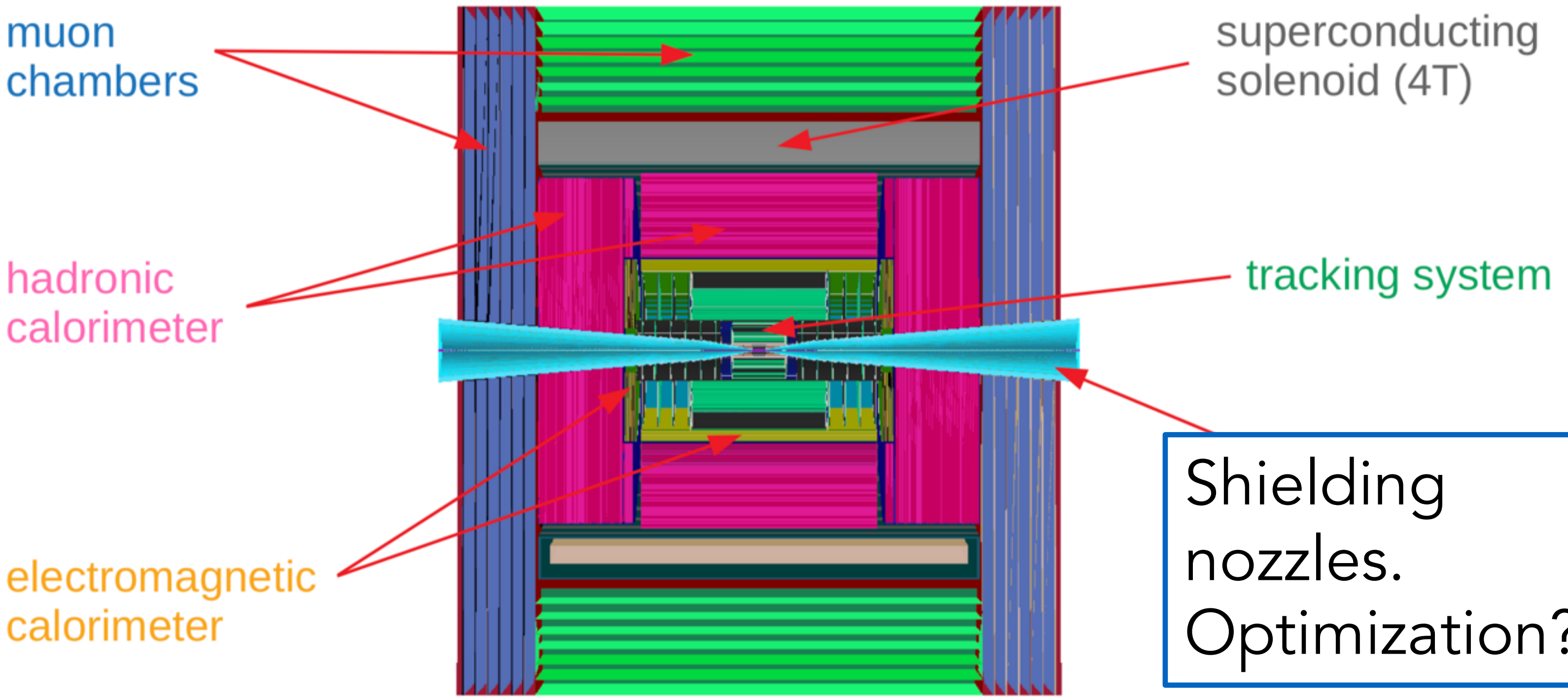






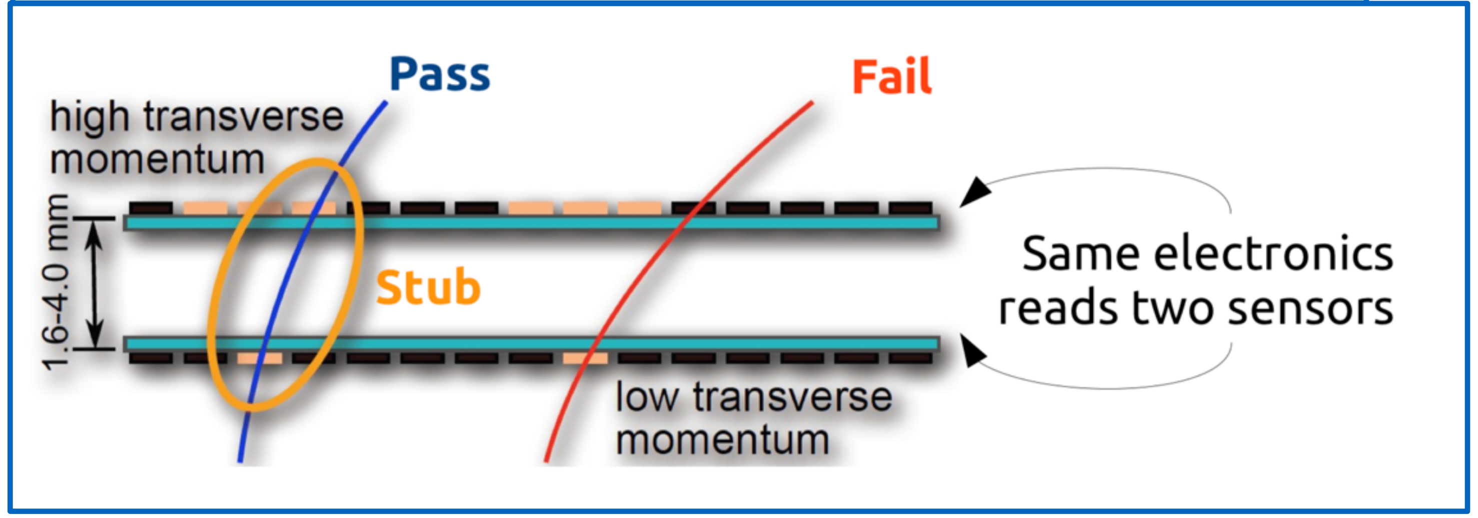
Most Beam Induced Background particles are soft

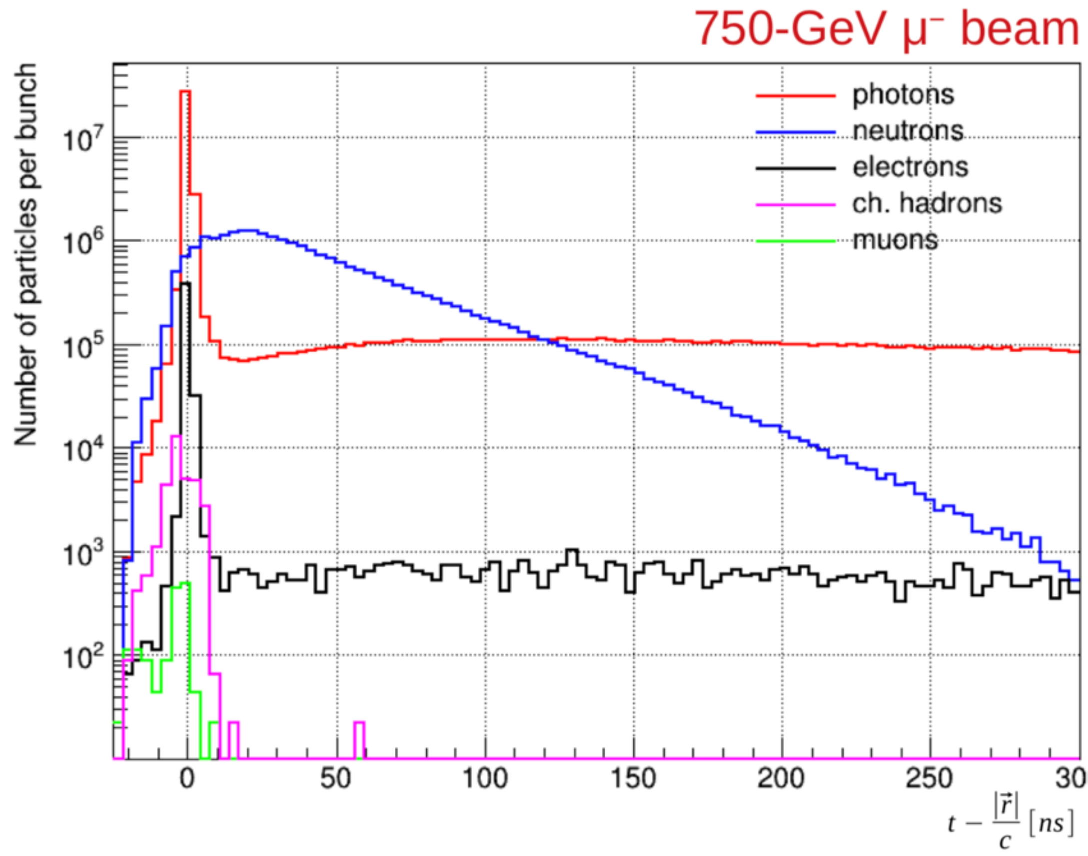
BIB Suppression

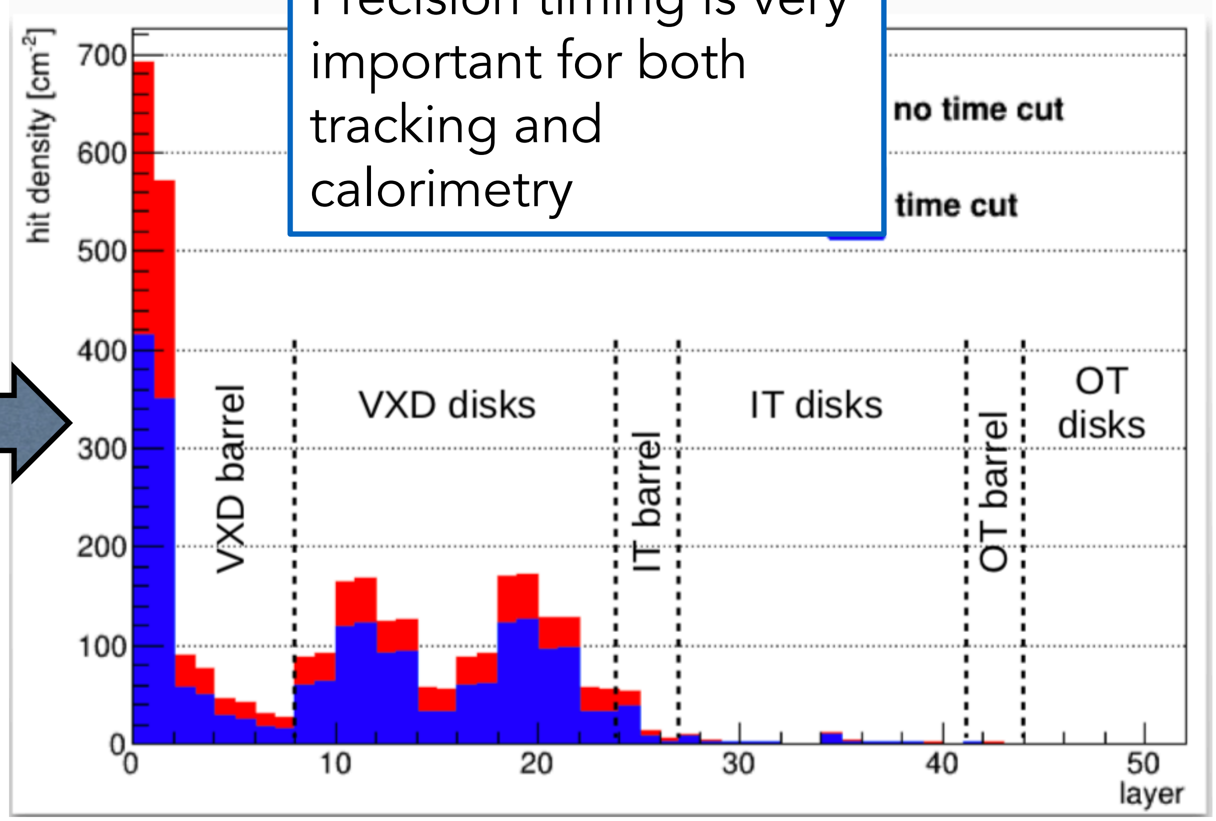


Shielding nozzles. Optimization?

pT modules a la CMS Phase-2 tracker







Precision timing is very important for both tracking and calorimetry

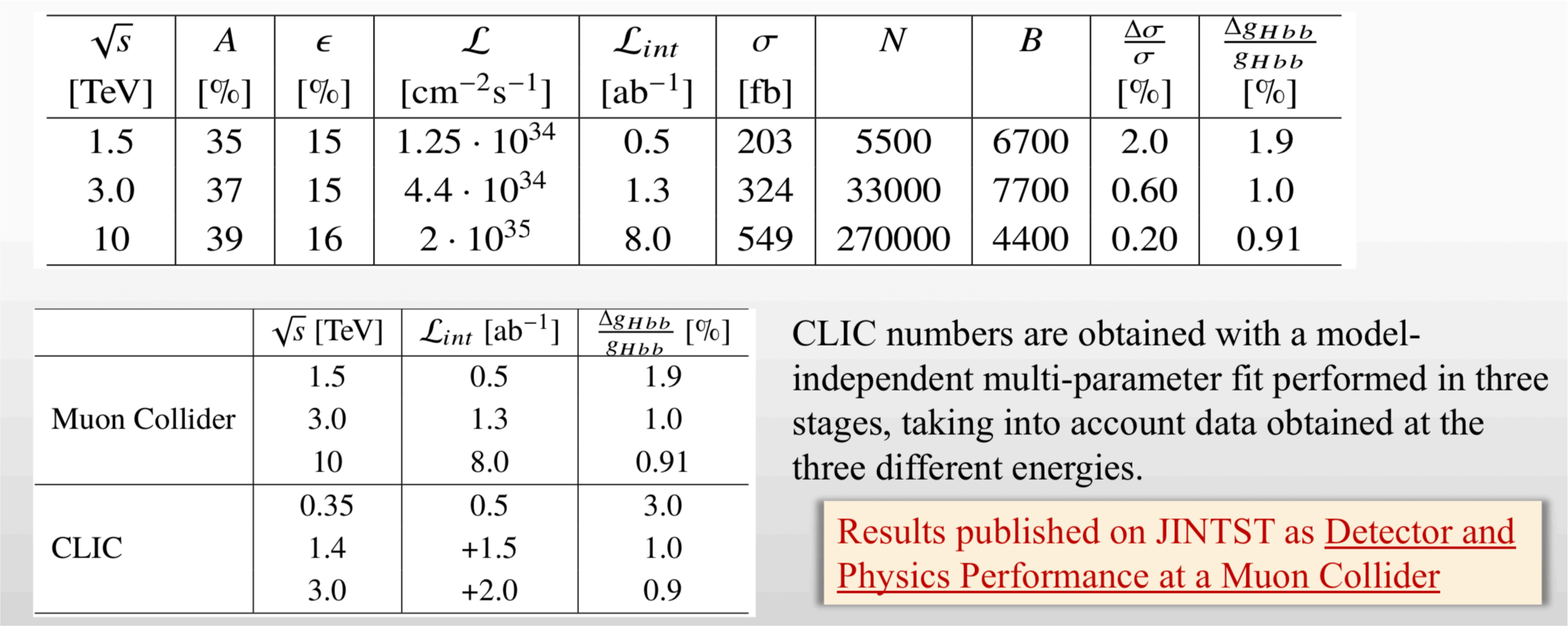
Many other questions:

- Trigger or trigger-less
- Advanced reconstruction (Machine Learning?)
- Simulation is not trivial, acceleration with heterogeneous platforms

H→bb study

https://arxiv.org/pdf/2001.04431.pdf

$\mu^+ \mu^- \to H(\to b\bar{b})\nu\bar{\nu}$



$\sqrt{s}$ [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 are 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 JINTST as Detector and Physics Performance at a Muon Collider

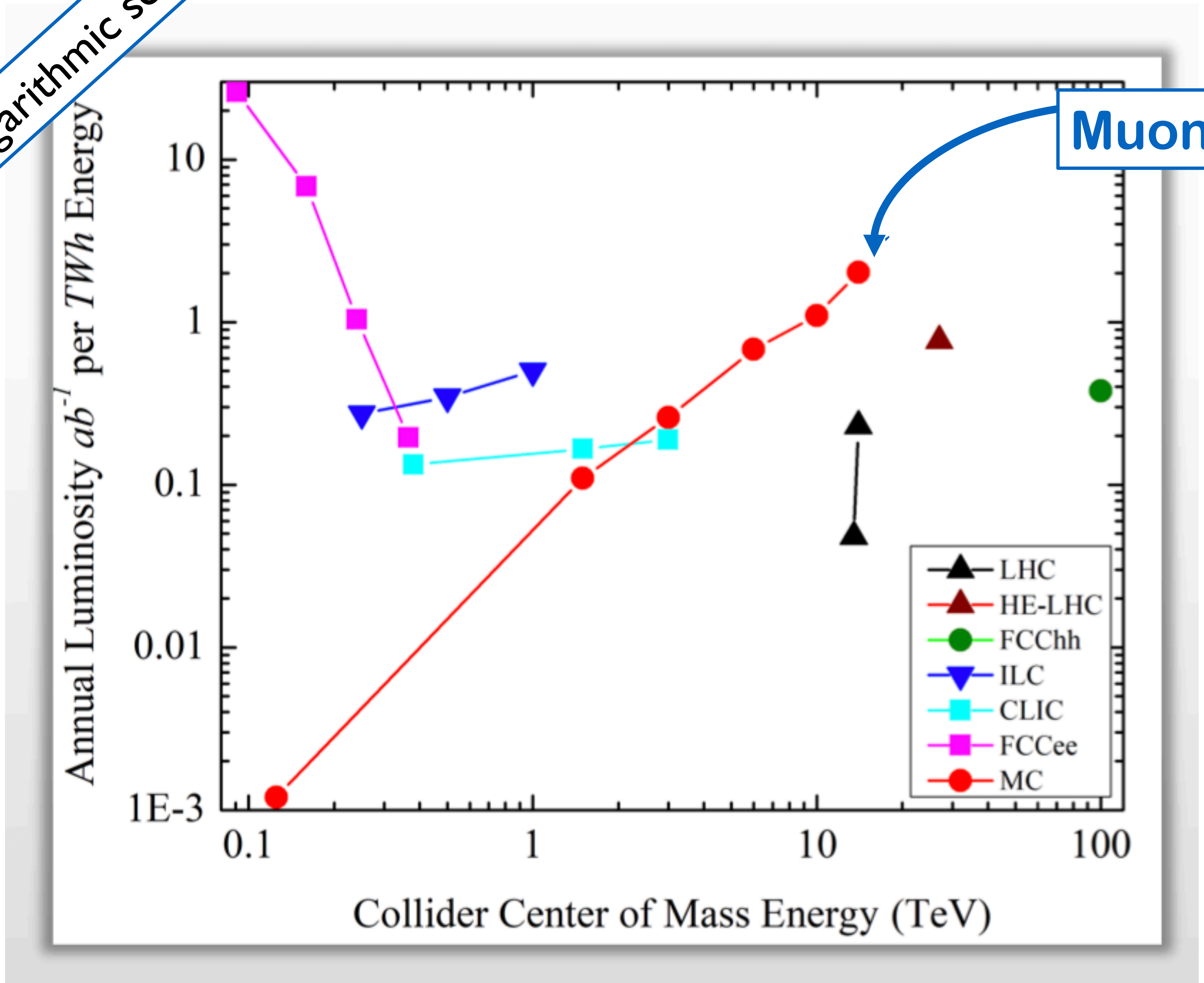
Can definitely do competitive physics

More studies and optimization necessary!

Power Efficiency

https://arxiv.org/abs/2003.09084

Note logarithmic scale

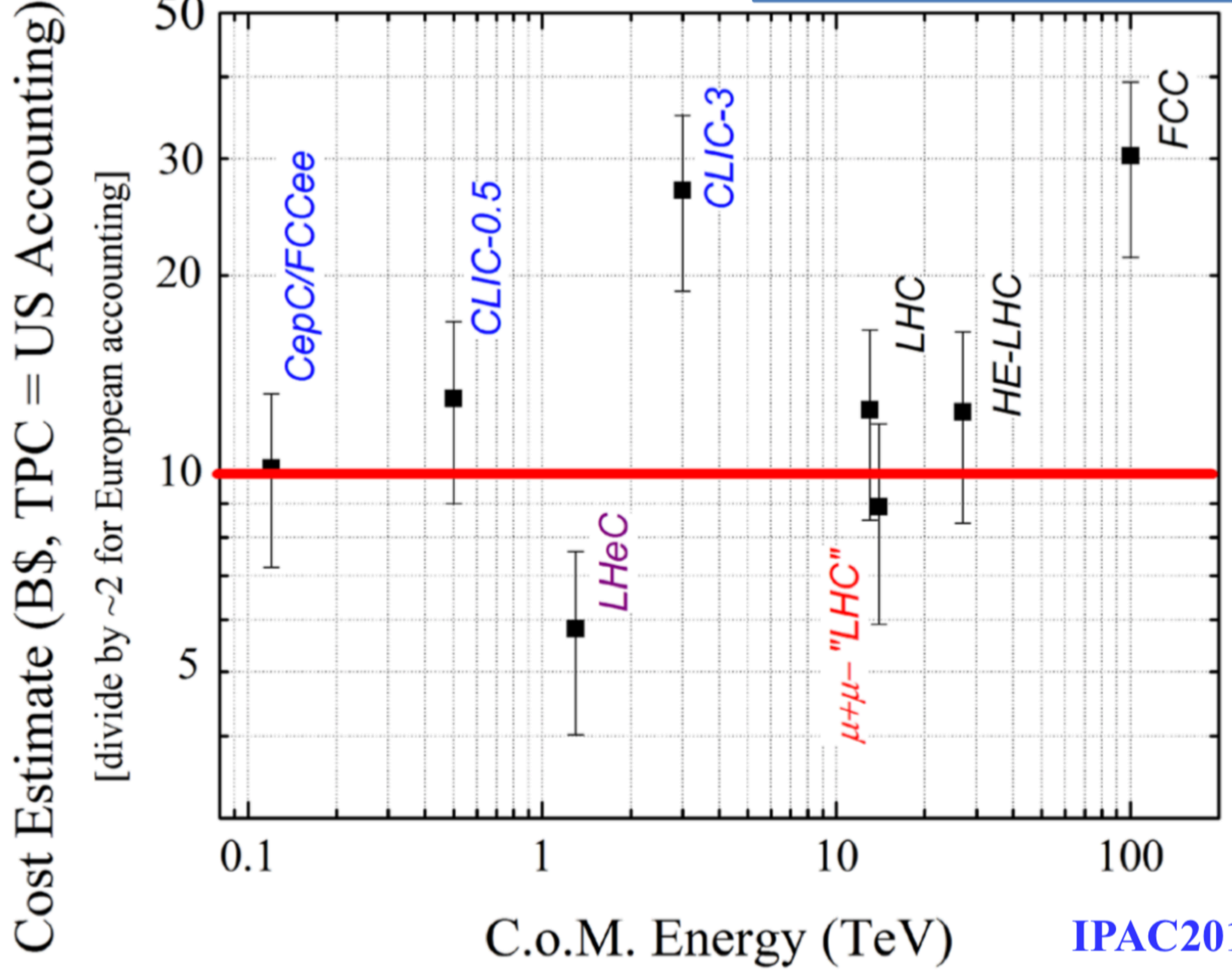


Muon Collider

Cost Estimates

NB: all $$ - "US Accounting" (divide by 2-2.4 at CERN)

Vladimir SHILTSEV,David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

Muons: Particles of the Future

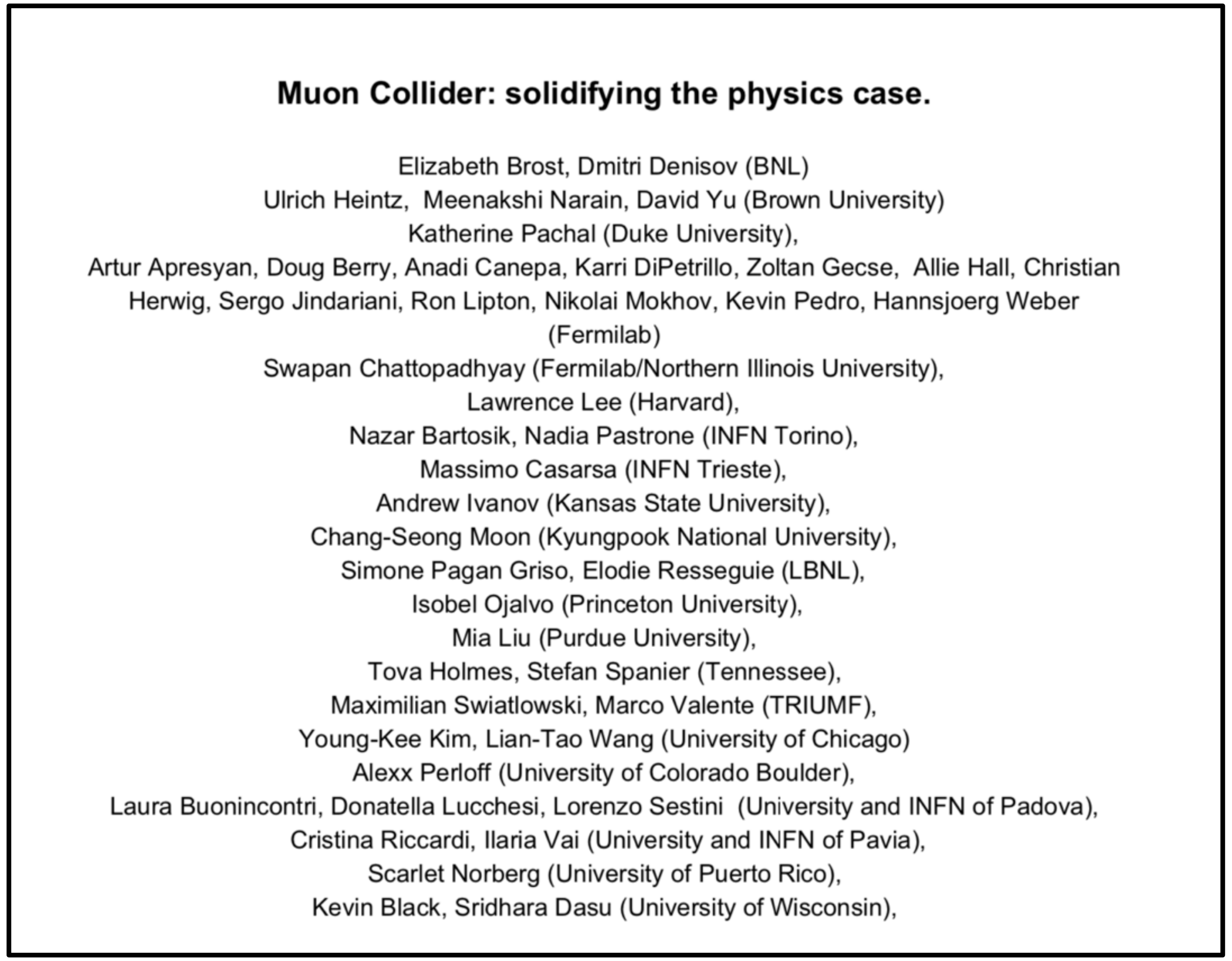
Muons provide a potential solution for very high energy colliders.

- At very high energies acceleration is circles becomes prohibitively expensive
- Linear accelerators => Need very high fields or very long accelerator chains
- Advanced acceleration schemes with plasma can provide high fields. Protons can break while propagating through plasma, but muons won’t

Muon Collider Snowmass LOIs

Strong Interest in the Muon Collider. Several physics LOIs have been submitted.

- Develop improved detector design concepts, reconstruction algorithms, and allow corner specifications for the future muon collider detectors.
- Make simulation tools more efficient and streamlined
- Derived parametrizations will be used for creating DELPHES cards necessary to benchmark physics scenarios for Snowmass
- Pave the way to the development the Muon Collider Physics TDR
- Muon Collider Simulation Tutorial is coming up at the end of September



Muon Collider: solidifying the physics case.

Elizabeth Brost, Dmitri Denisov (BNL)
Ulrich Heintz, Meenakshi Narain, David Yu (Brown University)
Katherine Pachal (Duke University),
Artur Apresyan, Doug Berry, Anadi Canepa, Karri DiPetrillo, Zoltan Gecse, Allie Hall, Christian Herwig, Sergo Jindariani, Ron Lipton, Nikolai Mokhov, Kevin Pedro, Hannsjoerg Weber (Fermilab)
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Lawrence Lee (Harvard),
Nazar Bartosik, Nadia Pastrone (INFN Torino),
Massimo Casarsa (INFN Trieste),
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Mia Liu (Purdue University),
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Alexx Perloff (University of Colorado Boulder),
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Cristina Riccardi, Ilaria Vai (University and INFN of Pavia),
Scarlet Norberg (University of Puerto Rico),
Kevin Black, Sridhara Dasu (University of Wisconsin),

Muon Collider Snowmass LOIs (2)

Physics LOIs:

- Higgs and Electroweak Physics at the Muon Collider: Aiming for Precision at the Highest Energies
  Higgs couplings, width, mass, self-coupling, vector boson scattering
- Muon Collider: a Window to New Physics
  New resonances, Dark Matter, Ewlectroweak SUSY, Long-lived particles

  Not constrained to just these topics – new ideas and interest is welcome

Mailing list on listserv: muoncolliderphysics@fnal.gov
We also have a CERN Mattermost channel

Collaborating closely with people in Europe

Conclusions

- Muon Collider is a very intriguing future collider option. A machine that can potentially provide a lepton collider environment and discovery reach of a hadron machine.

- It is a responsibility of our community to firmly establish its physics potential

- Requires new ideas in the accelerator and detector design, reconstruction, triggering, simulation and computing

- Strong expertise and interest in the US

- A great place for Early Career Scientists to contribute. This can be a discovery machine for your generation to build!

Acknowledgements

- I appreciate the material and input provided by0 P.Bhat, M.Casarsa, Z.Liu, D.Lucchesi, M.Palmer, N.Pastrone, V.Shiltsev, and others

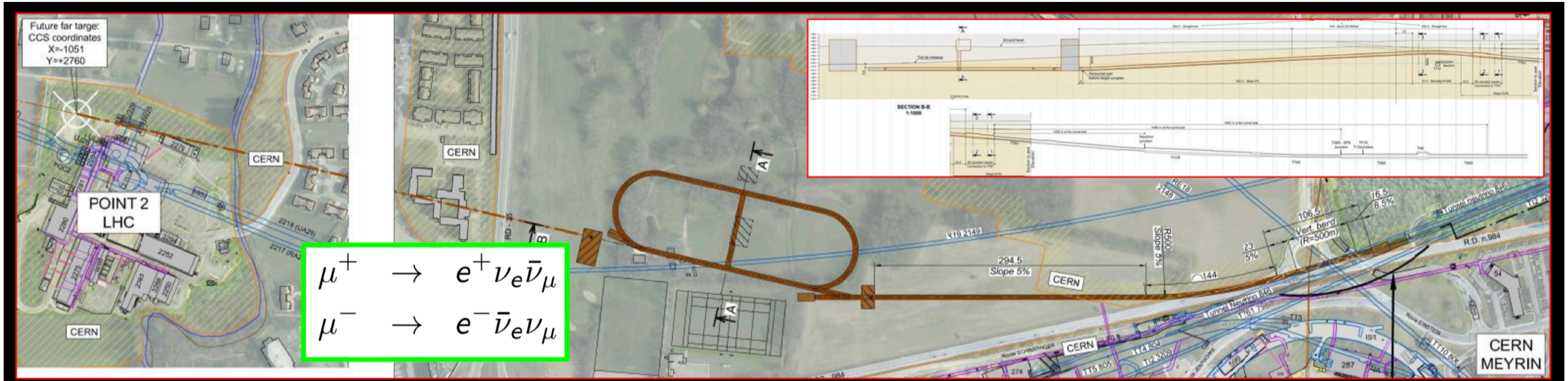
- And from the International Muon Collider Collaboration

Backup

P5 Science Drivers

- **Use the Higgs boson as a new tool for discovery**
- **Pursue the physics associated with neutrino mass**
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation**
- **Explore the unknown: new particles, interactions, and physical principles.**

NuStorm

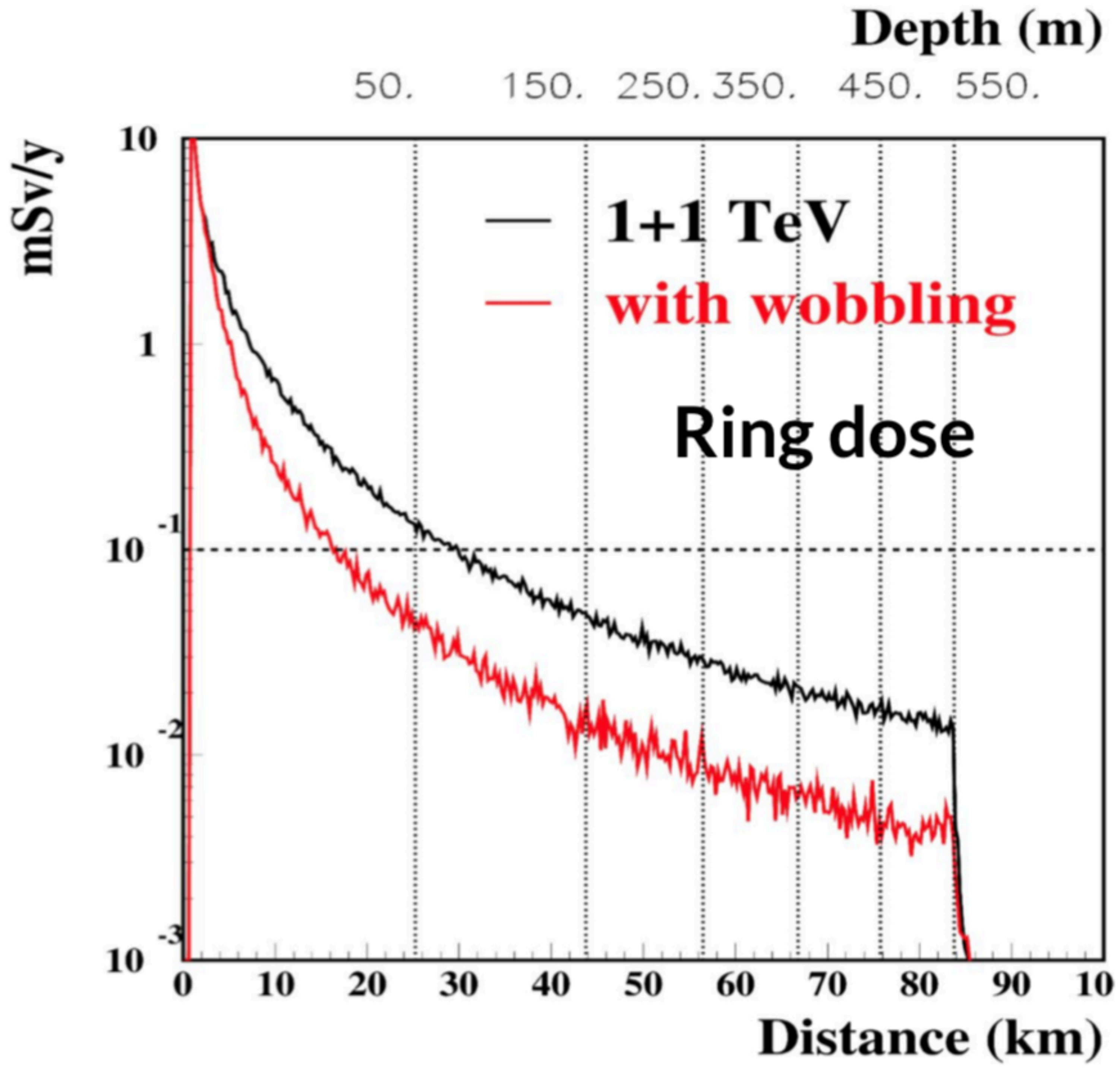


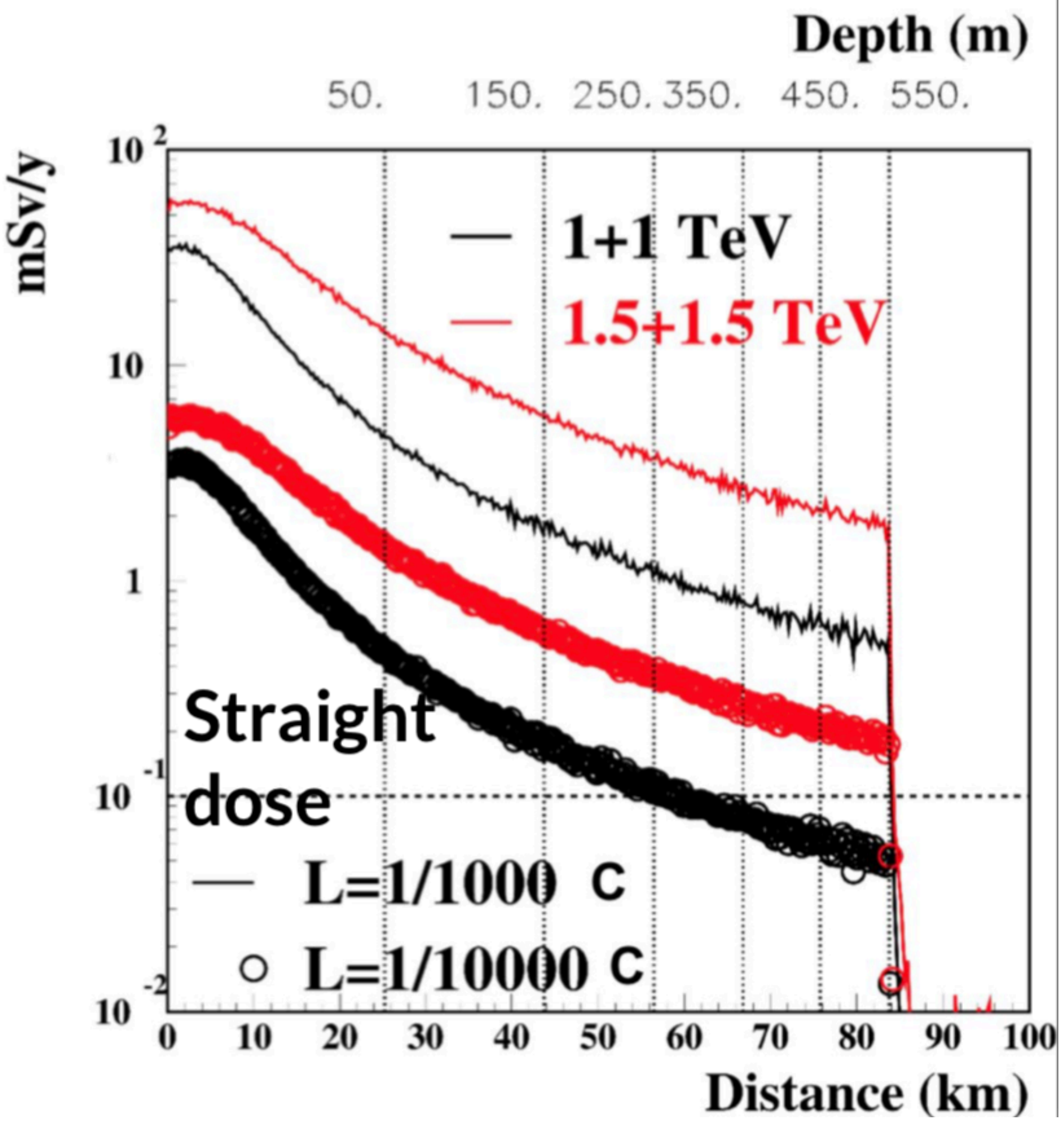
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- **Scientific objectives:**
  1. %-level ($\nu_e N$)cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

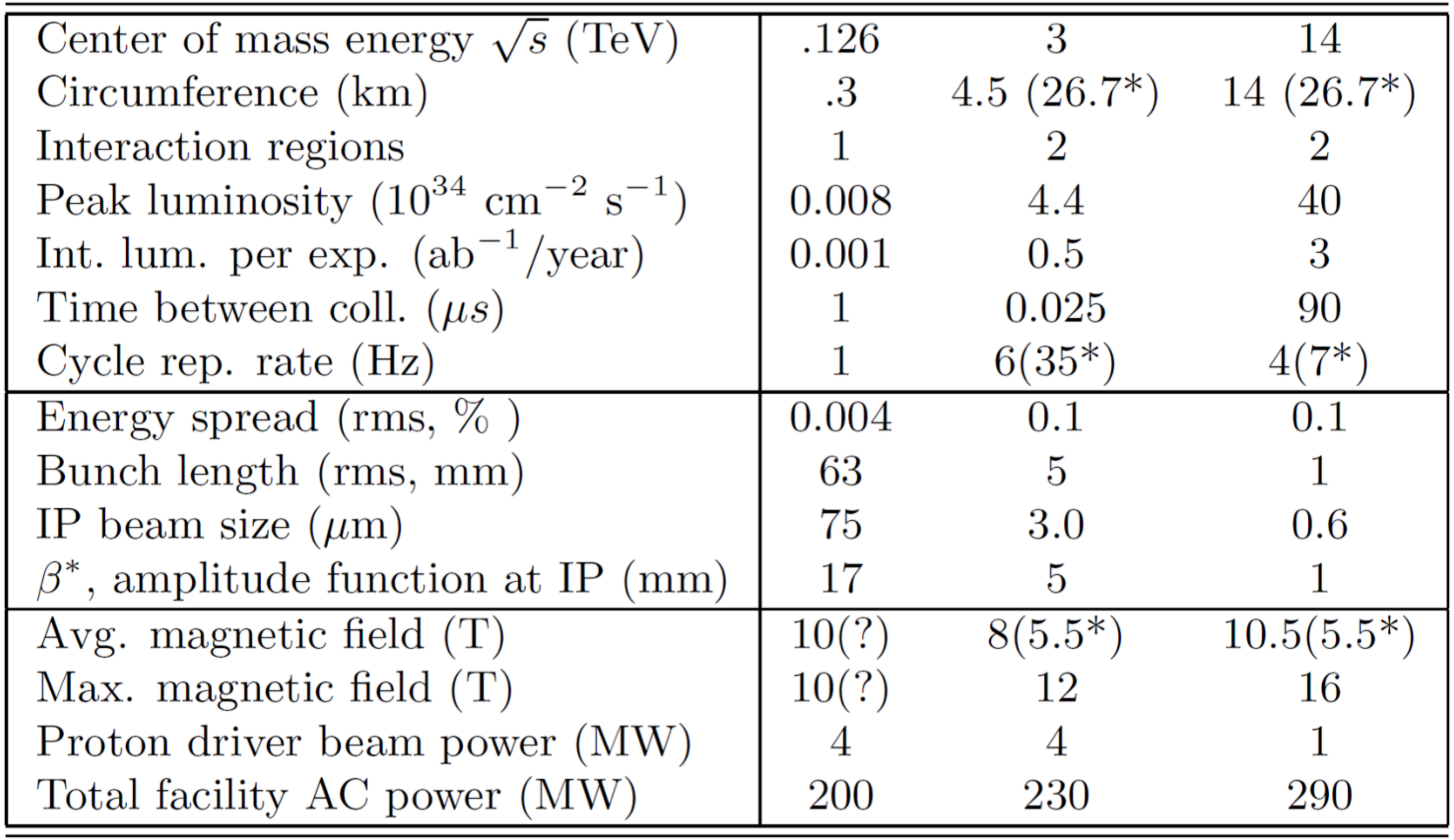
- Precise neutrino flux:
  - Normalisation: < 1%
  - Energy (and flavour) precise
- π ®μ injection pass:
  - “Flash” of muon neutrinos

Neutrino Radiation



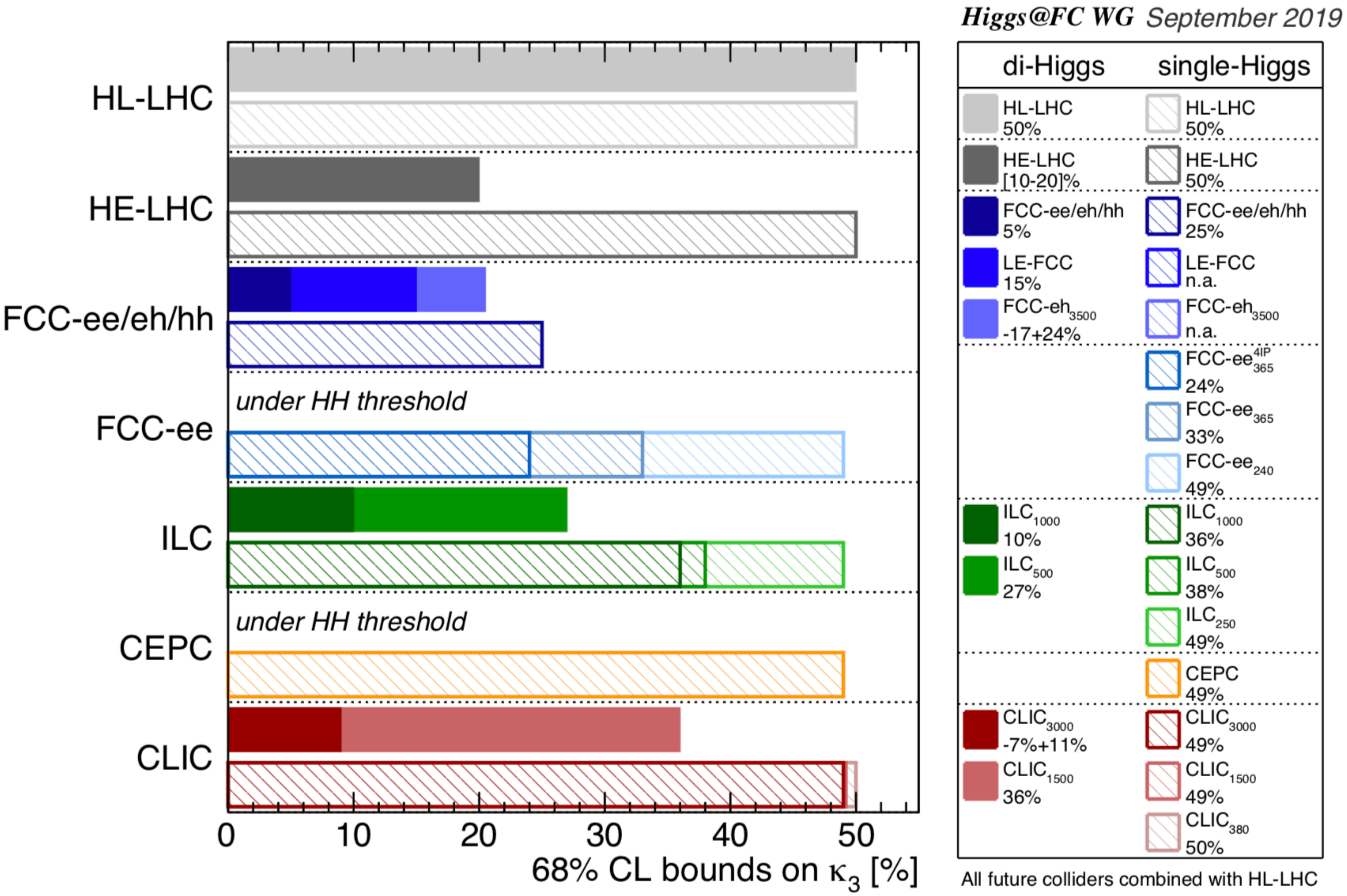


Collider Parameters



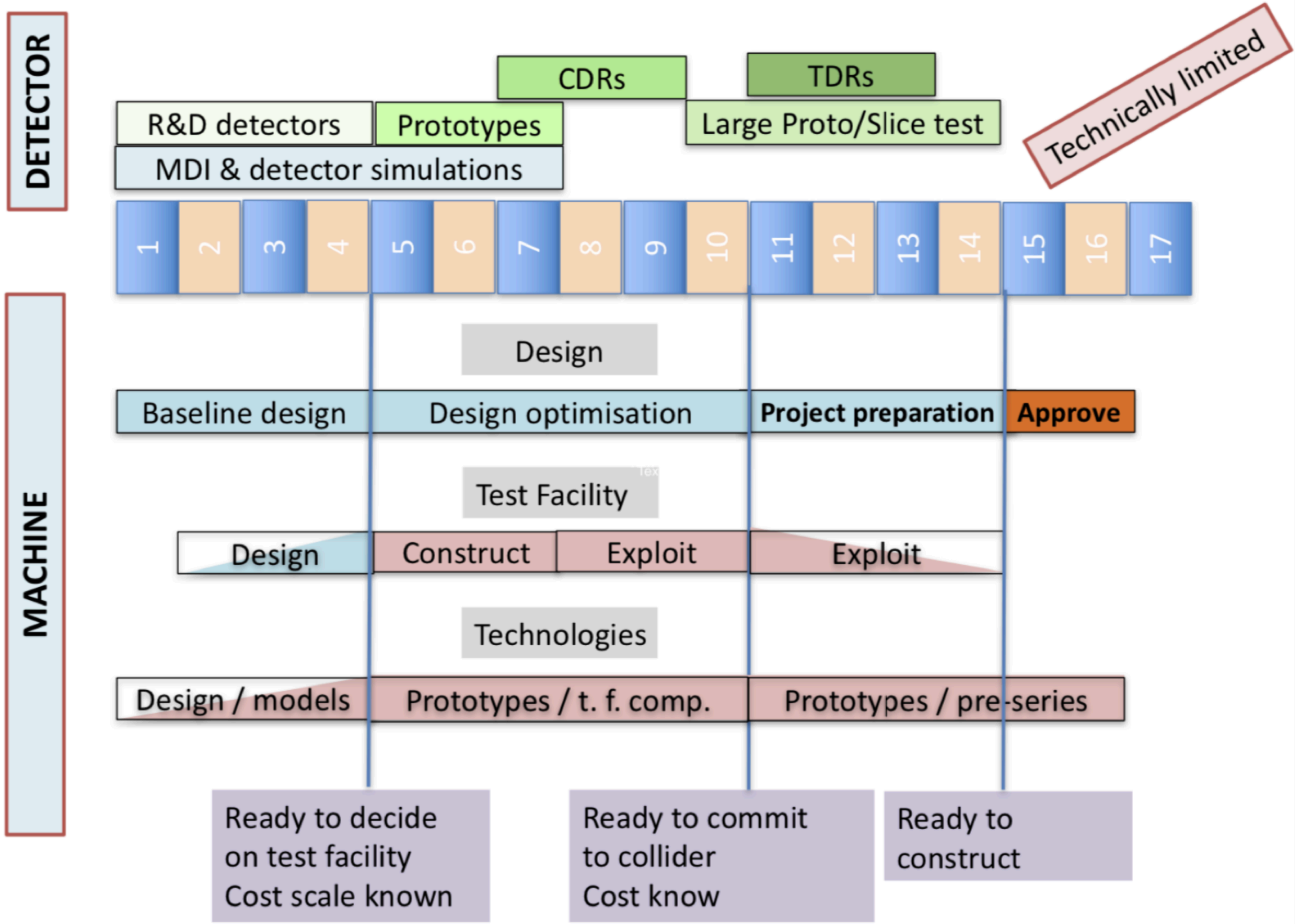
Center of mass energy $\sqrt{s}$ (TeV)	.126	3	14
Circumference (km)	.3	4.5 (26.7*)	14 (26.7*)
Interaction regions	1	2	2
Peak luminosity (10^{34} cm^{-2} s^{-1})	0.008	4.4	40
Int. lum. per exp. (ab^{-1}/year)	0.001	0.5	3
Time between coll. (μs)	1	0.025	90
Cycle rep. rate (Hz)	1	6(35*)	4(7*)
Energy spread (rms, %)	0.004	0.1	0.1
Bunch length (rms, mm)	63	5	1
IP beam size (μm)	75	3.0	0.6
β^*, amplitude function at IP (mm)	17	5	1
Avg. magnetic field (T)	10(?)	8(5.5*)	10.5(5.5*)
Max. magnetic field (T)	10(?)	12	16
Proton driver beam power (MW)	4	4	1
Total facility AC power (MW)	200	230	290

Higgs Self Coupling



Potential Timeline

Physics Briefing Book



DETECTOR

R&D detectors

Prototypes

MDI & detector simulations

CDRs

Large Proto/Slice test

TDRs

Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

MACHINE

Design

Baseline design

Design optimisation

Project preparation

Approve

Test Facility

Design

Construct

Exploit

Exploit

Technologies

Design / models

Prototypes / t. f. comp.

Prototypes / pre-series

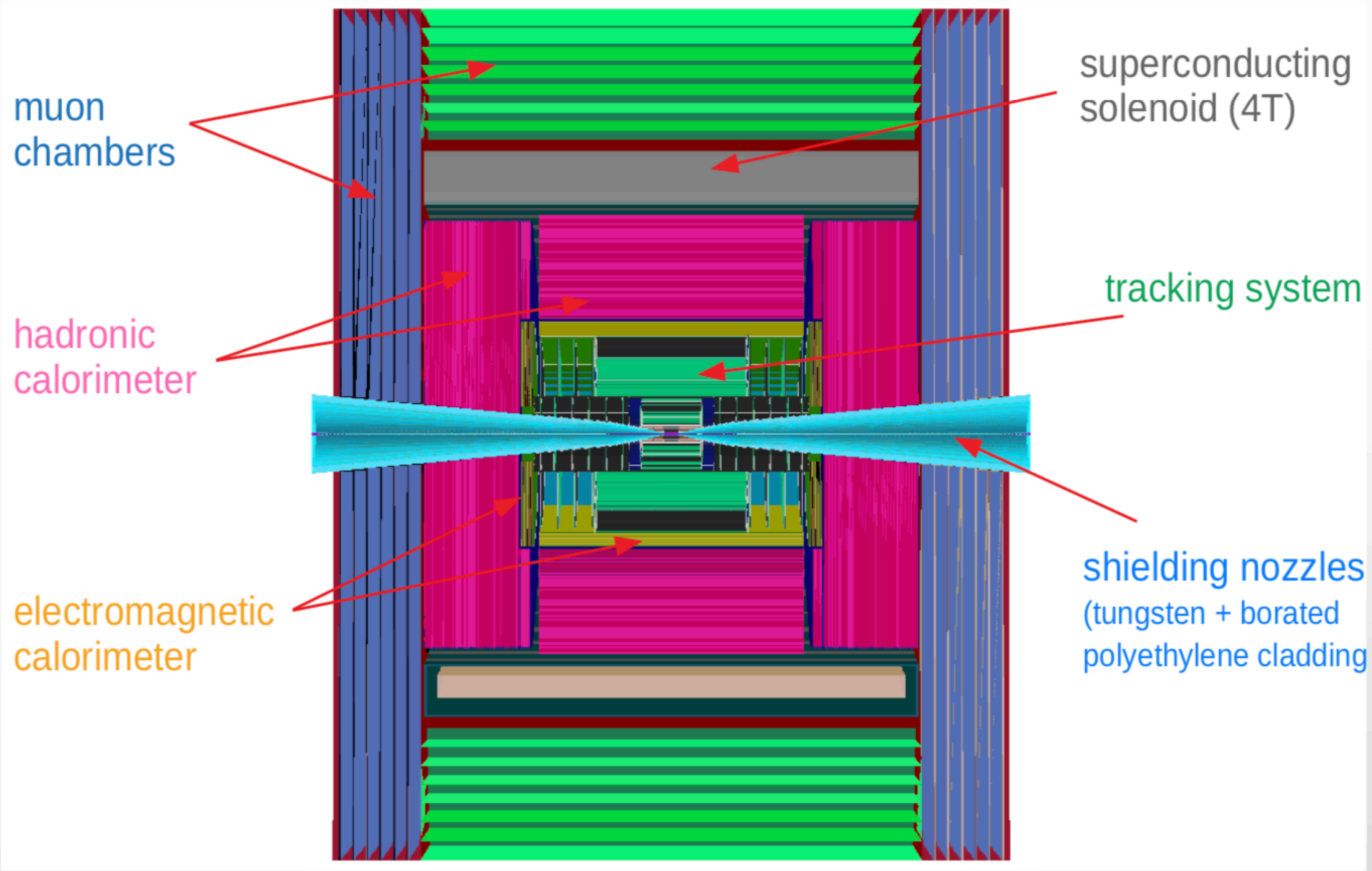
Ready to decide
on test facility
Cost scale known

Ready to commit
to collider
Cost know

Ready to
construct

Detector

The simulation/reconstruction tools supports signal + beam-induced background merging



CLIC Detector adopted with modifications for muon collider needs.
Detector optimization is one of the future goal.

Vertex Detector (VXD)

- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks ”

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