Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Energy Frontier Science: Circular Colliders and Muon Collider

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Strategic Group on the Energy Frontier
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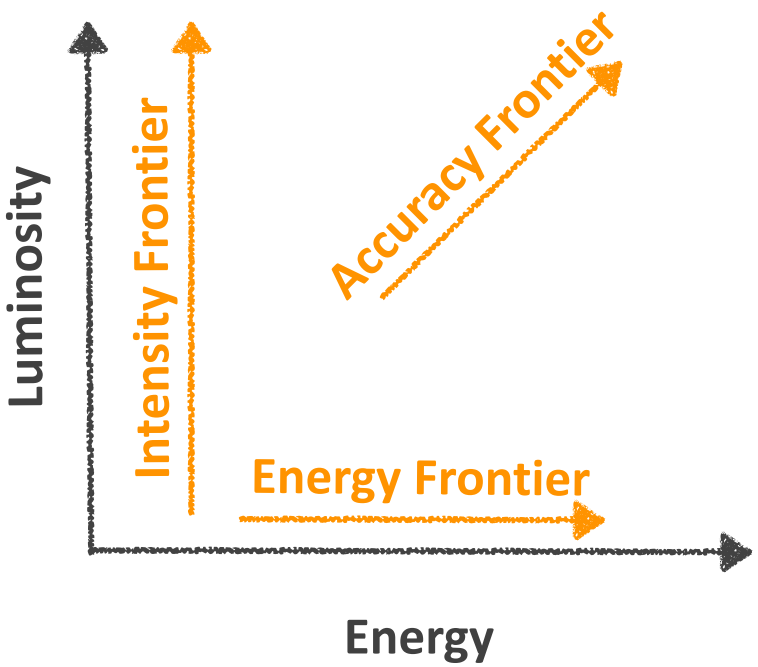
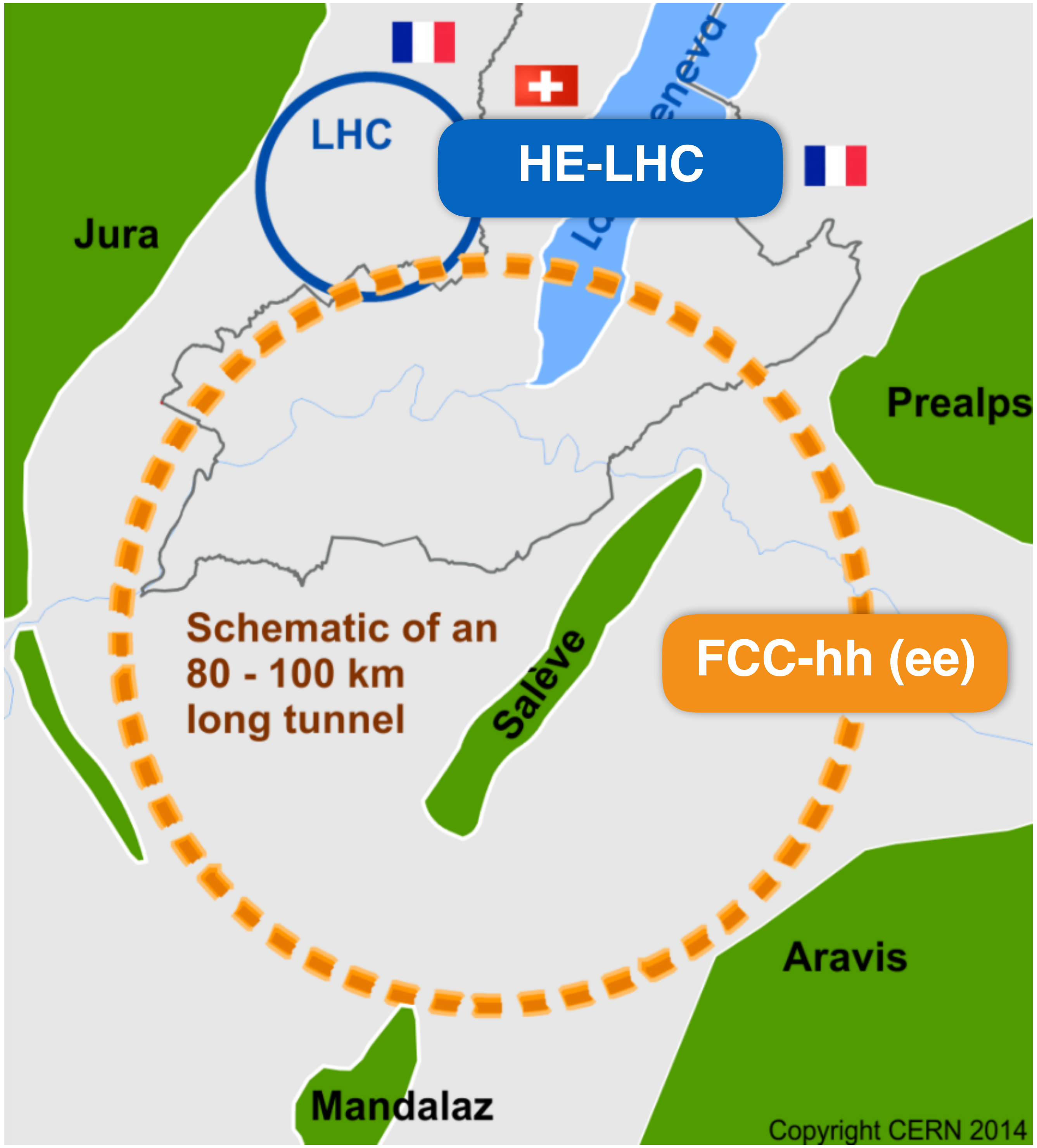
New Era for Fundamental Physics

- **The discovery of the Higgs boson represents a historical moment and remarkable achievement in particle physics**
  - It demonstrates that we have a correct effective theory to describe all known fundamental particles
- **The Higgs discovery is also the dawn of a new era for fundamental physics**
  - when we address fundamental questions related to the dynamics of EWKSB, dark sector, neutrino masses, naturalness, unification , …
- **What are the main paths forward in the exploration of the unknown?**
  - **Continue probing the energy frontier**
    - by extending the mass reach
  - **Exploiting the “Higgs as a tool for discovery”**
    - Since the Higgs boson is a neutral scalar and it can interact with new particles we may not otherwise detect, a precision measurement program of its properties offers a portal to BSM
    - Mapping the Higgs potential can shed light on how the EWK phase transition occurred in the early Universe and the origin of the matter-antimatter asymmetry



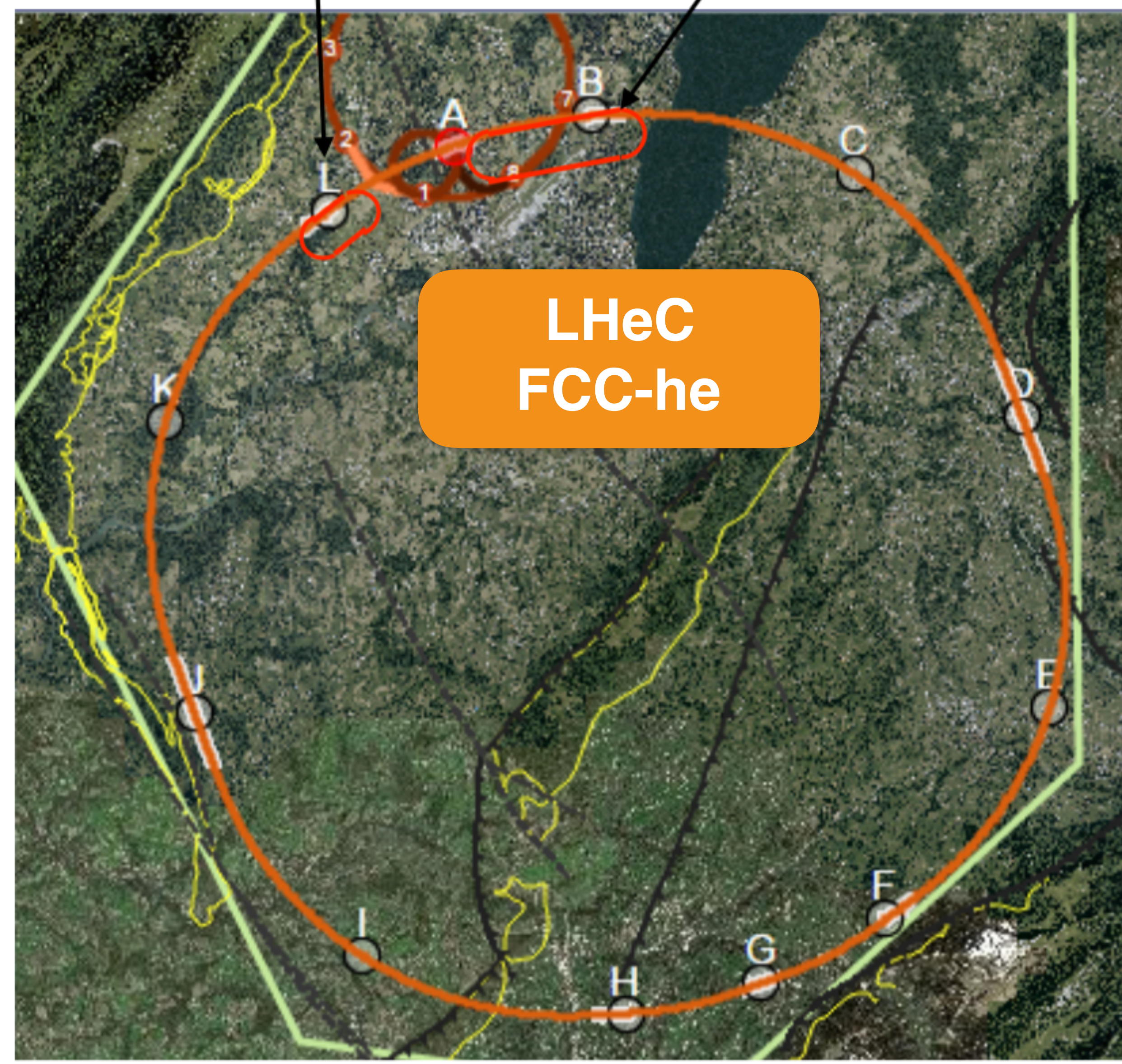
Circular Machines (at CERN)



pp-collider and ee-collider

Independent FCC-he
Point L, F, H or B

LHeC / FCC-he
LHC P8 & FCC PB



ep-collider and eA-collider

Hadron Machines (at CERN): LHC, HL-LHC, FCC-hh

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

Wine and Cheese by Michelangelo Mangano:
https://indico.fnal.gov/event/10682/session/11/contribution/22/material/slides/0.pdf
FCC Weeks: https://indico.cern.ch/category/5225/

Electron-proton Machines (at CERN): LHeC, ep at HL, HE, FCC

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

LHeC and FCC-eh Workshop

https://indico.cern.ch/event/639067

https://arxiv.org/abs/1211.5102

Electron-electron Machines (at CERN): FCC-ee

Parameter	FCC-ee				LEP2
physics working point	Z	WW	ZH	$t\bar{t}$ (tt$_{bar}$)	
energy/beam [GeV]	~45.6	~80.5	~120	~175	~105
bunches/beam	70760	7280	826	64	4
bunch spacing [ns]	3.0	40	400	5000	22000
bunch population [10^{11}]	0.4	0.4	0.7	2.1	4.2
beam current [mA]	1400	150	30	6.4	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	137	16.5	4.9	1.4	0.0012
energy loss/turn [GeV]	0.036	0.34	1.71	7.72	3.34
synchrotron power [MW]	100				22
RF voltage [GV]	0.25	0.8	3.0	9.5	3.5
√s spread SR [%]	0.04	0.07	0.10	0.15	0.11
√s spread SR+BS [%]	0.07	0.07	0.11	0.19	0.11

FCC Weeks
https://indico.cern.ch/category/5225/

Muon Collider

- **Various proposals for a Higgs factory and/or a multi TeV discovery machine**

https://arxiv.org/pdf/1308.6612.pdf

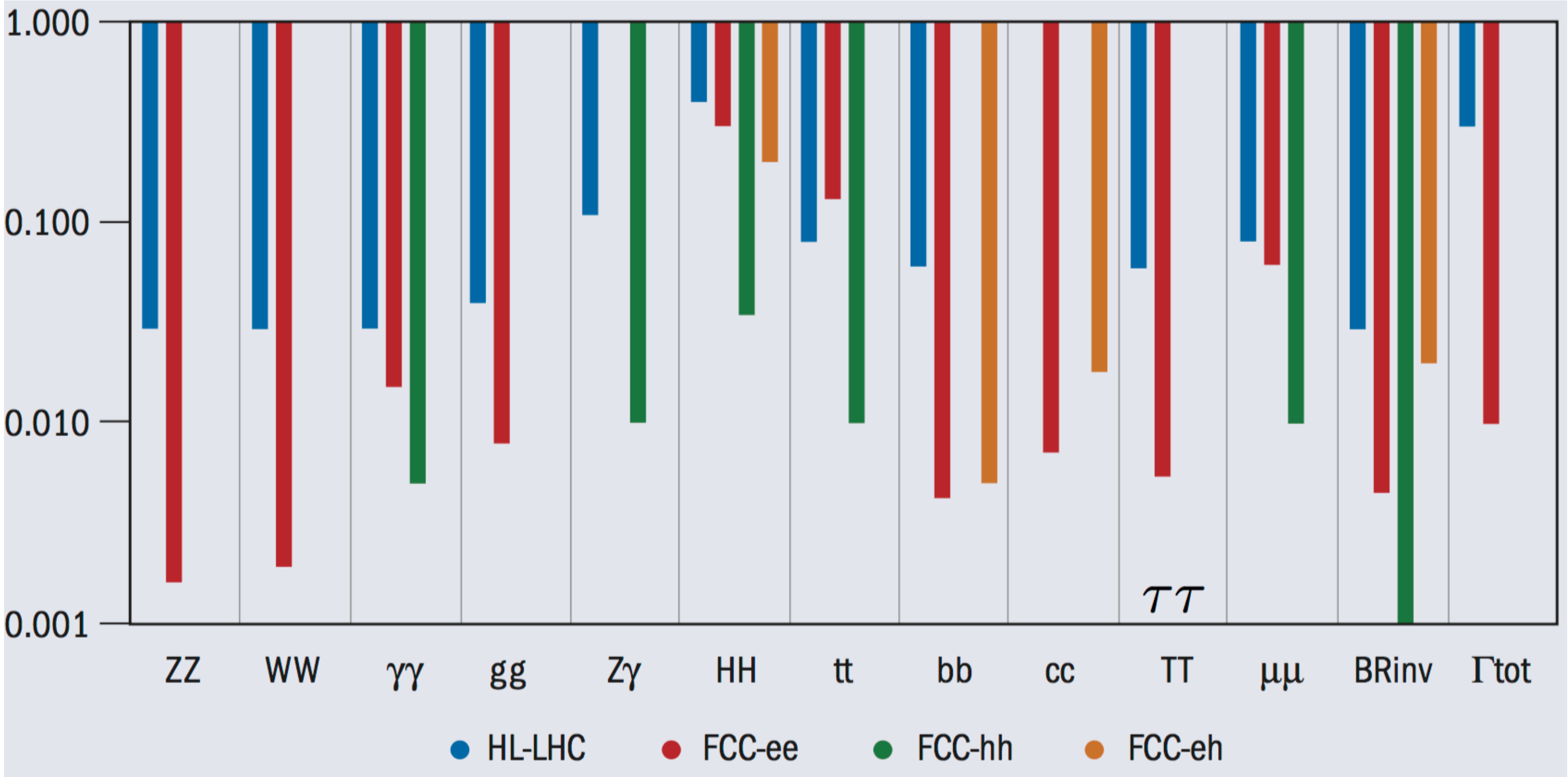
Collider ring		
Circumference	350.0	m
Nominal energy at H_o peak	125	GeV
Nominal muon momentum	62.50	GeV/c
Muons/bunch (each sign)	6 x 10^{12}	μ/bunch
Final lifetime:	1.295	ms
Mu decay length:	388.6	km
Average number of turns:	1110.	
No effective luminosity turns:	555.2	
Crossings/sec: (at 15 hz)	8328.	
Beta value at crossing point	4.0	cm
Indicative performance		
H_o peak cross section	2.00 x 10^{-35}	cm2
Luminosity	0.63 x 10^{32}	cm-2 s-1
H_o events/y (10^7 s)/ each cross:	12500 (*)	
H_o reduction due to finite ΔE/E	0.5	
Bunch transv. rms size	197.5	microns
Beam-beam tune shift	0.071	
Final bunch half-length	2.4	cm
Final Δp muon	2.0	MeV/c
Final Δp/p muon	3.2 x 10^{-5}	
rms ΔE/E at H_o resonance	2.4 x 10^{-5}	

http://iopscience.iop.org/article/10.1088/1748-0221/11/09/P09003/pdf

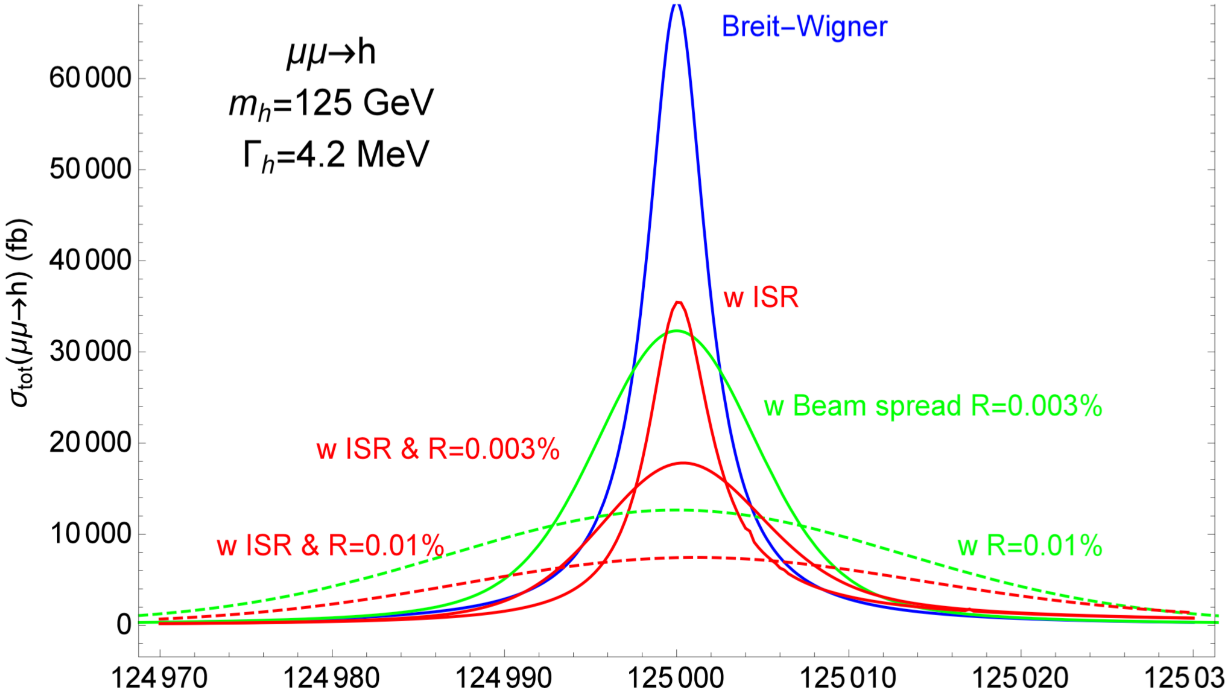
Parameter	Unit	Value
Beam energy	TeV	3.0
Number of IPs		2
Circumference	m	6302
β^*	cm	1
Tune x/y		38.23/40.14
Momentum compaction		−1.22E-3
Normalized emittance	mm·mrad	25
Momentum spread	%	0.1
Bunch length	cm	1
Muons/bunch	10^{12}	2
Repetition rate	Hz	15
Average luminosity	10^{34} cm^{-2}s^{-1}	7.1

http://events.fnal.gov/colloquium/events/event/lucchesi-colloq-2018/
https://indico.fnal.gov/event/7563/session/0/contribution/1/material/slides/1.pdf
https://arxiv.org/abs/1307.6129
https://arxiv.org/pdf/0711.4275.pdf

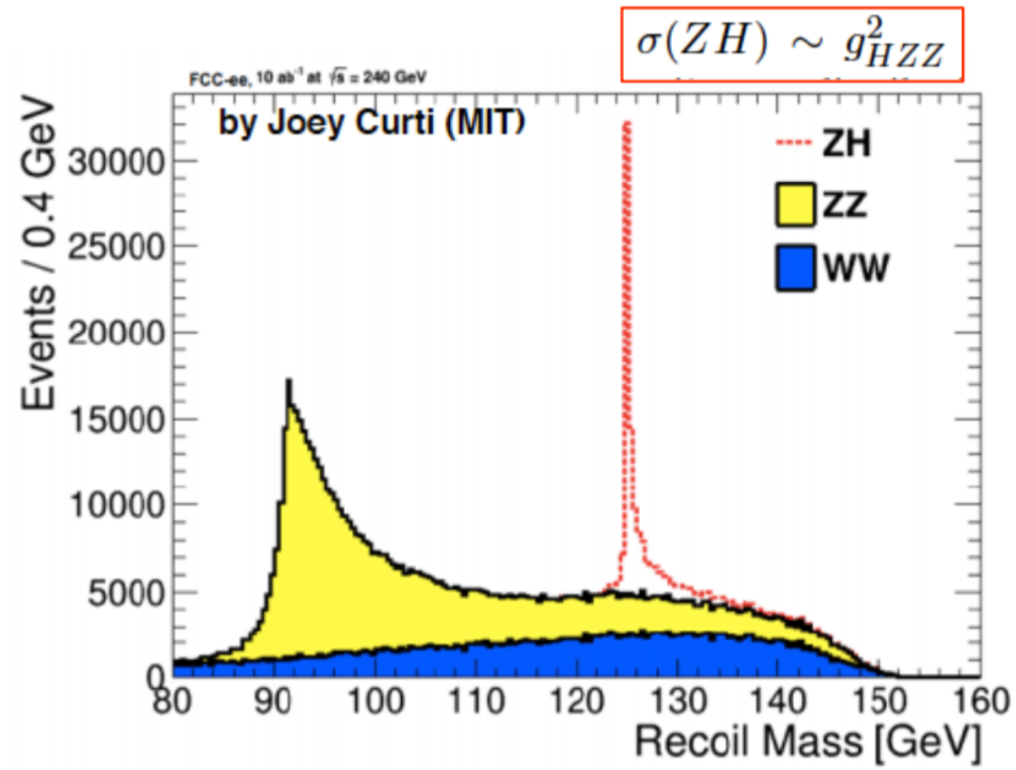
A few examples from the Higgs Precision Program - I

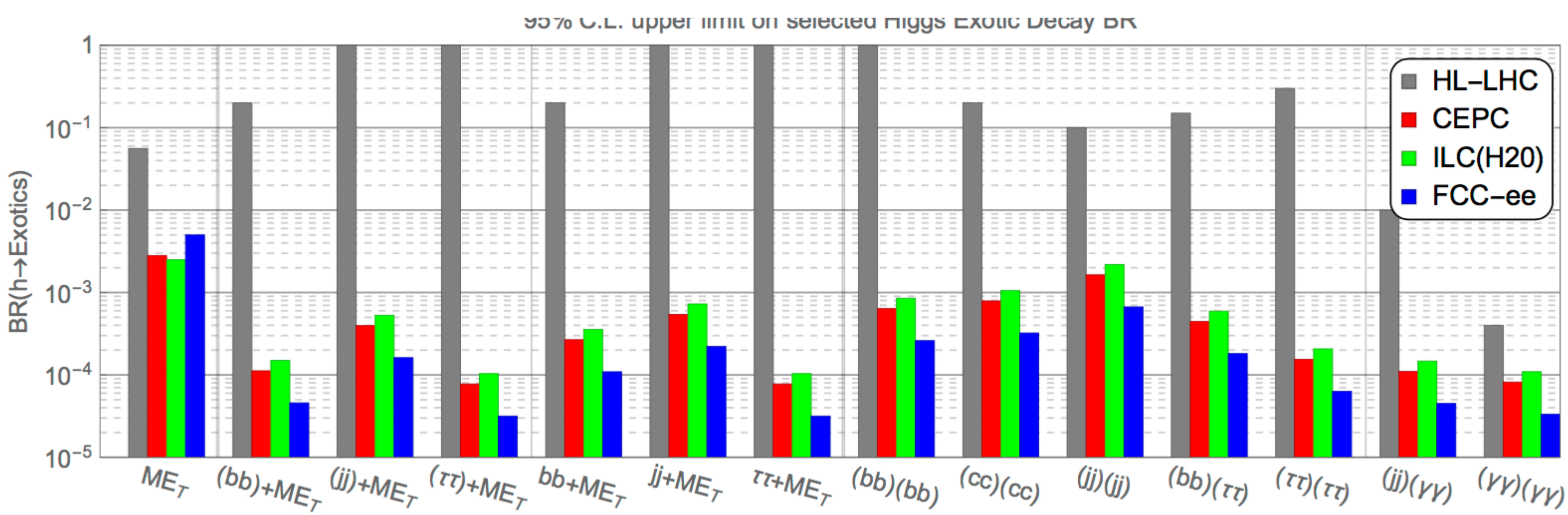


- A ee collider with L > 10^{34}
    - ZH signal cross-section ≈ 200 fb
- A μμ collider at L > 10^{32}
    - H signal cross-section ≈ 20'000 fb in the s-state

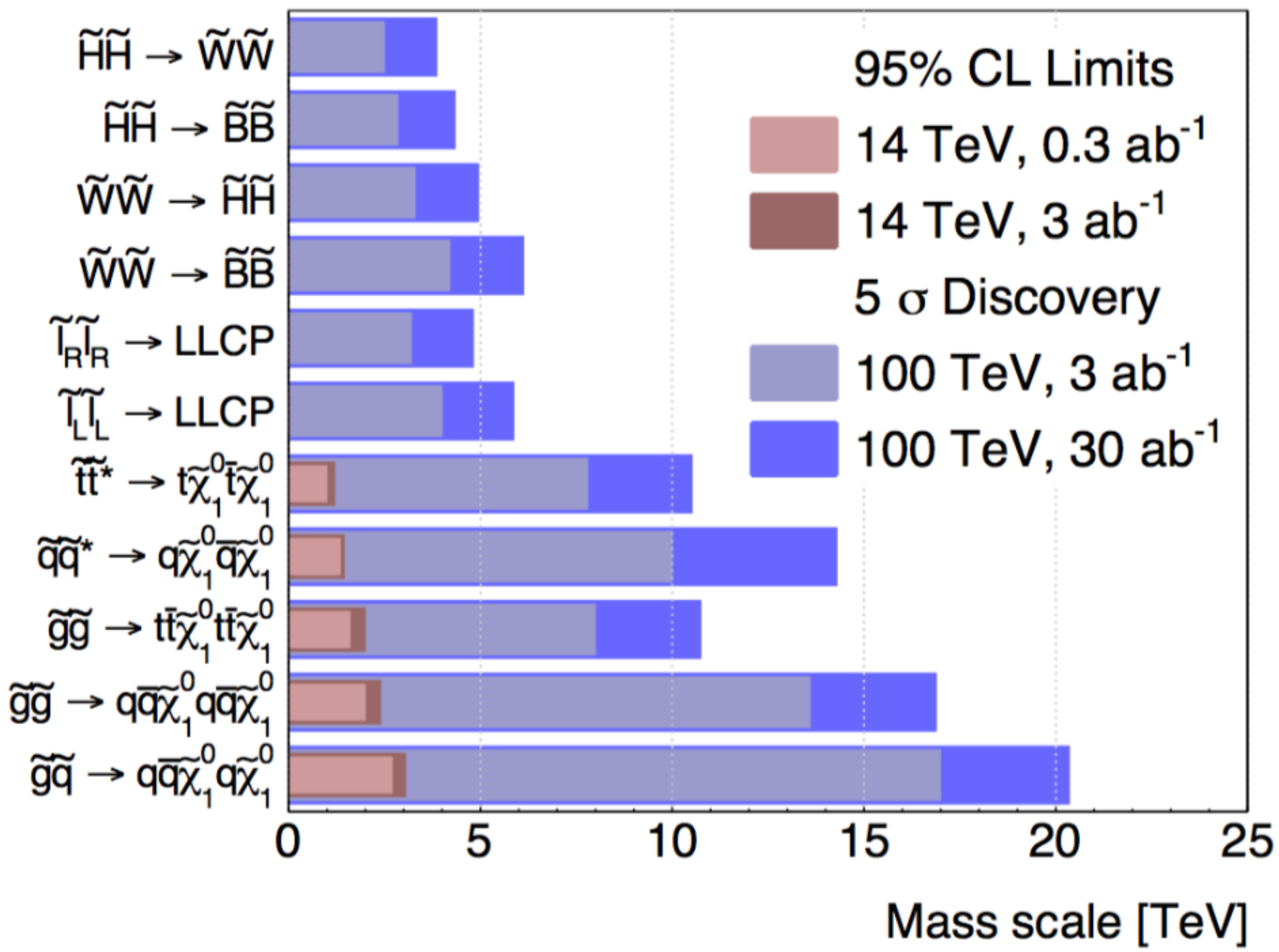


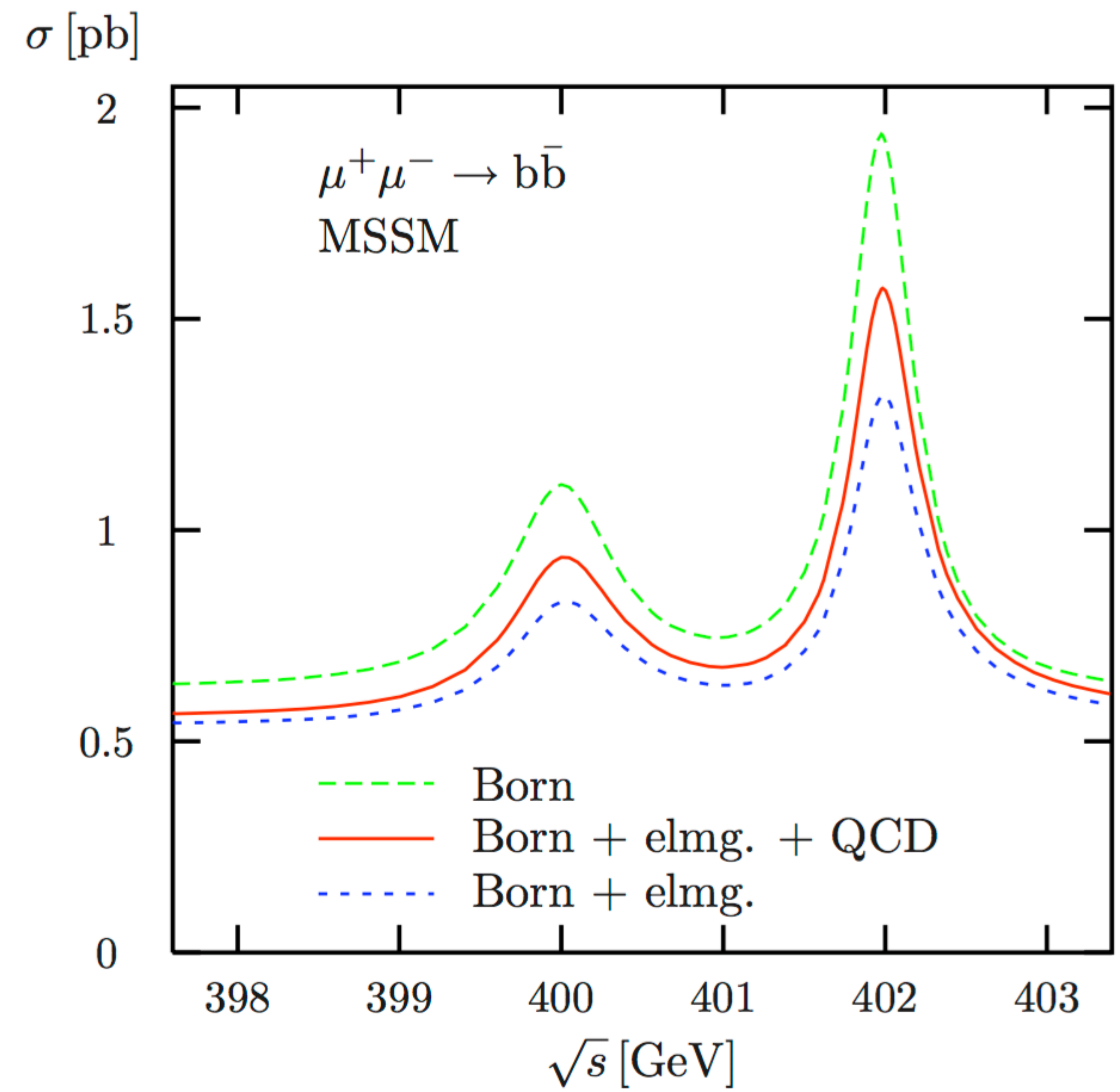
A few examples from the Higgs Precision Program - II





A few examples of Direct Searches for BSM





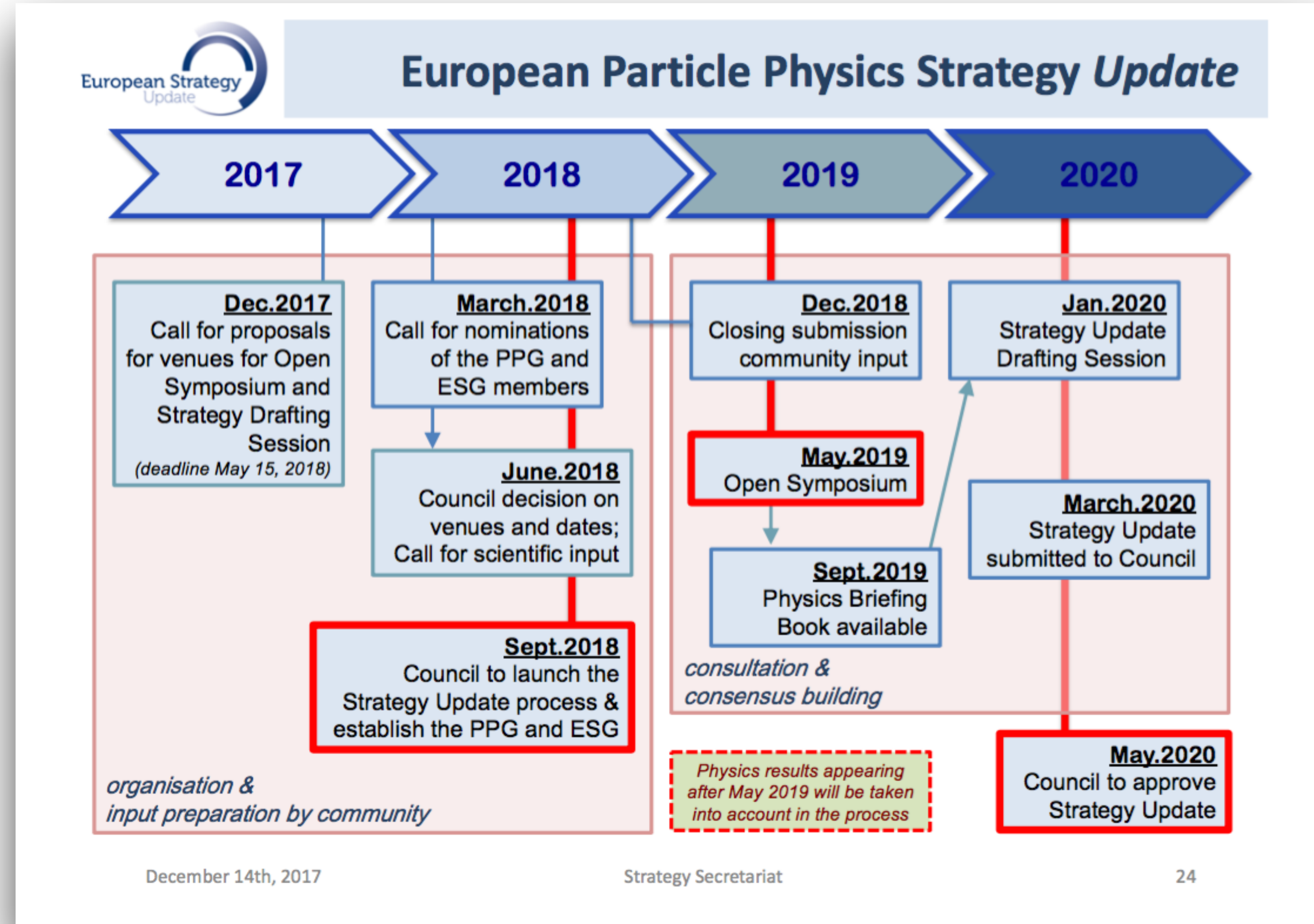
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Organization

- Fermilab scientists are invited to participate in the long range planning for the laboratory research program in the post 2026-period
- The process includes:
  - The All-Scientist retreat on April 26, 2018
  - The submission of contributions to the White Papers foreseen in the context of the European Strategy planning effort (deadline Dec 2018)
  - Initial steps towards developing input to the P5 community planning process
- The Strategic Group for the Energy Frontier planned two meetings to discuss plans for the April 26 retreat
  - **Today**, the group conveners describe the White Papers foreseen and a suggested approach for contributions
  - **April 3rd**, scientists planning to join the studies will express their interest and a coherent plan for contributions from Fermilab is defined
- The group conveners will summarize the plans at the **April 26 retreat**
- A meeting of the strategic group will be held in late **November / early December** to review the results intended for submission to the White Papers Addenda

European PP Strategic Planning

- *Details of the ES in Halina Abramowicz's presentation http://events.fnal.gov/colloquium/events/event/abramowicz-colloq-2018/*

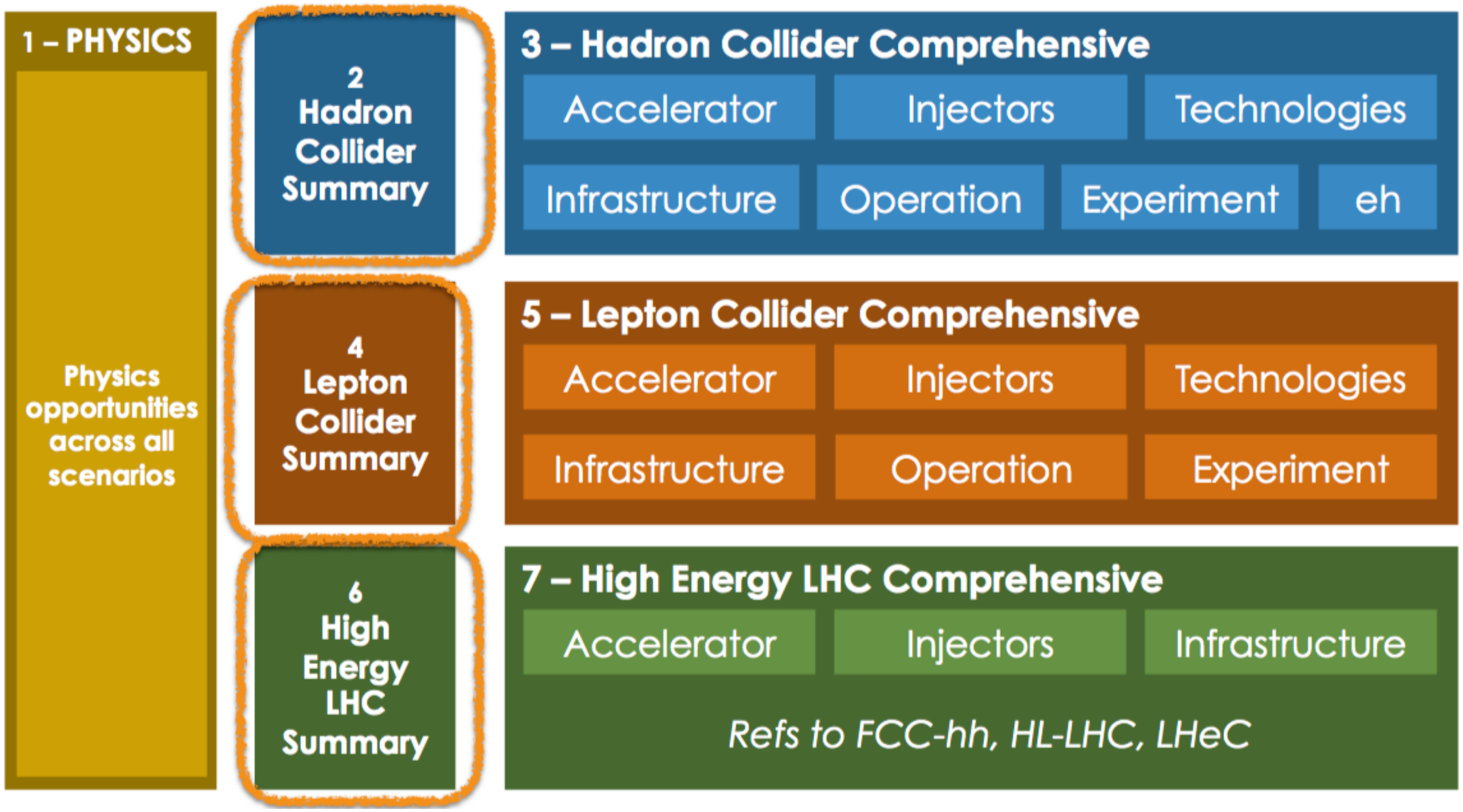


Contributions to the European PP Strategic Planning - I

- The organization is handled by the Strategy Secretariat (chaired by H. Abramowicz)
  - The Strategy Secretariat is the recipient of the proposals
- **US scientist are invited to submit their proposals through European partners (while other channels are still under consideration)**
  - **Studies on High-luminosity and High-Energy LHC are developed within CMS**
    - The CMS Upgrade Performance Group is providing support and Andreas B. Meyer is responsible for editing the Yellow Report
      - (internal link) https://twiki.cern.ch/twiki/bin/viewauth/CMS/HLandHELHCYR
      - subgroups: WG1 SM (Patrizia Azzi); WG2 Higgs (Maria Cepeda); WG3 BSM (Keith Ulmer); WG4 Flavour (Sandra Malvezzi); WG5 Heavy Ions (Yen-Jie Lee)
      - Time scale: June 2018: Plenary meeting, Sept 2018: Full draft chapters (one per WG, 150 pages each), 18 Dec 2018: Submission
  - Studies on High-Energy LHC can also be developed within the FCC Collaboration

Contributions to the European PP Strategic Planning - II

- **Studies on FCC (hh, ee, eh)**
  - Targeted studies have been develop over the course of the past few years in preparation for CDR submission in December 2018
  - Details can be found here: https://indico.cern.ch/event/618254/contributions/2833205/attachments/1582373/2500981/Mangano-WshopIntro.pdf



Contributions to the European PP Strategic Planning - III

- **Studies on FCC (hh, ee, eh)**
  - "The CDR only contains key physics goals and reach for the FCC, it is a selection of the most outstanding and unique selling points, not a global review" (from M. Mangano)
  - Time scale: additional studies can be developed and submitted by December 2018
    - studies available after May 2019 may still be considered
  - Contacts for the ES documentation:
    - accelerators - Michael Benedikt
    - physics/detectors - Michelangelo Mangano
- **Studies on the Muon Collider**
  - Significant interest in the community
  - Potential platform to be created at CERN
  - On-going studies at FNAL and potential collaboration between FNAL scientists and INFN scientists
  - Time scale: studies can be developed and submitted by December 2018
    - studies available after May 2019 may still be considered
  - Contacts for the ES documentation: Nadia Pastrone (TBC)

Summary

- **It is a unique and exciting time for particle physics**
  - **the exploration of the unknown**
- An effective synergy between the intensity and of the energy frontier is essential to maximize our discovery potential
- Fermilab scientists are invited to contribute to the laboratory strategic planning for the decades after 2026 through an active participation in the ES planning and then in the Snowmass/P5 process
- **Several Yellow Reports and White Papers & Addenda are foreseen with the ES**
  - HL-LHC and HE-LHC
  - FCC: FCC-hh, FCC-ee, FCC-eh
  - Muon Collider
  - [See Dmitri Denisov’s presentation for other Reports]
- The Fermilab Strategic Group for Energy Frontier is expected to facilitate the integration of the FNAL Scientists in the ES process
- If you are interested, please do not hesitate to contact us and share your plans at the next meeting on April 3rd

Additional Material

Additional Material

Operation model assumed for the CDR

- Physics goals (see next slides)
  - 150 ab^{-1} around the Z pole (~ 25 ab^{-1} at 88 and 94 GeV, 100 ab^{-1} at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - 5 ab^{-1} at the HZ cross section maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the top threshold (a fraction at ~350 GeV, the rest at ~370 GeV)
  - Benchmark run plan with 2 IP and the baseline optics
    - Numbers of years are soft numbers that can be revised in view of the physics panorama at the time

√s (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	15, then 30	4	1	0.3
Events/year	1.2×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}
Runtime (years)	6	2	5	5

M. Benedikt
May 2017

200 scheduled physics days per years, Hübner factor ~ 0.6

Additional Material

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
gg→H	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	70
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
gg→HH	28 M		280

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\ \text{fb}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC