Collider Physics

... at the energy frontier

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9th KSETA Plenary Workshop 2022

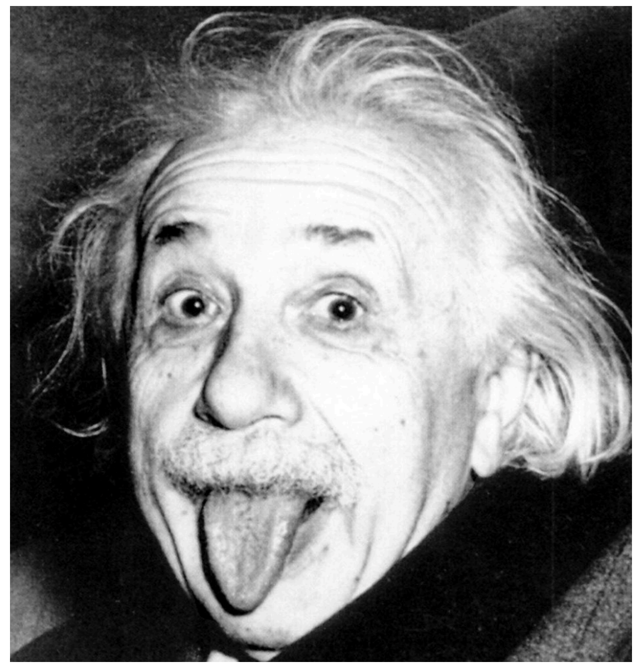
Collider Physics

… Experimental Approach

- Accelerate and collide particles at high energies
- Study particle interactions, resulting products, and features
- Measure energies, directions and identity of collision products
- Higher energies allow us
  - E ~ 1/size To look deeper into matter
  - E = kT To probe conditions of the early universe
  - $E = mc^2$ To discover new heavier particle
- All this in a controlled way in a laboratory

Louis de Broglie

Ludwig Boltzmann



Albert Einstein

Collider Physics

… Requirements

- Accelerator: powerful machine to accelerate particles to extreme high energy and collide them
- Detector: gigantic instruments to record collisions and resulting particles
- Computing: infrastructure to collect, distribute, and analyse the vast amount of data produced
- People: scientists and engineers to design, build, and operate the complex machines and to extract physics

People

… of CMS

3103	1031	269	241	54
PHYSICISTS (1050 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

The Details

The CMS collaboration has around:

5494

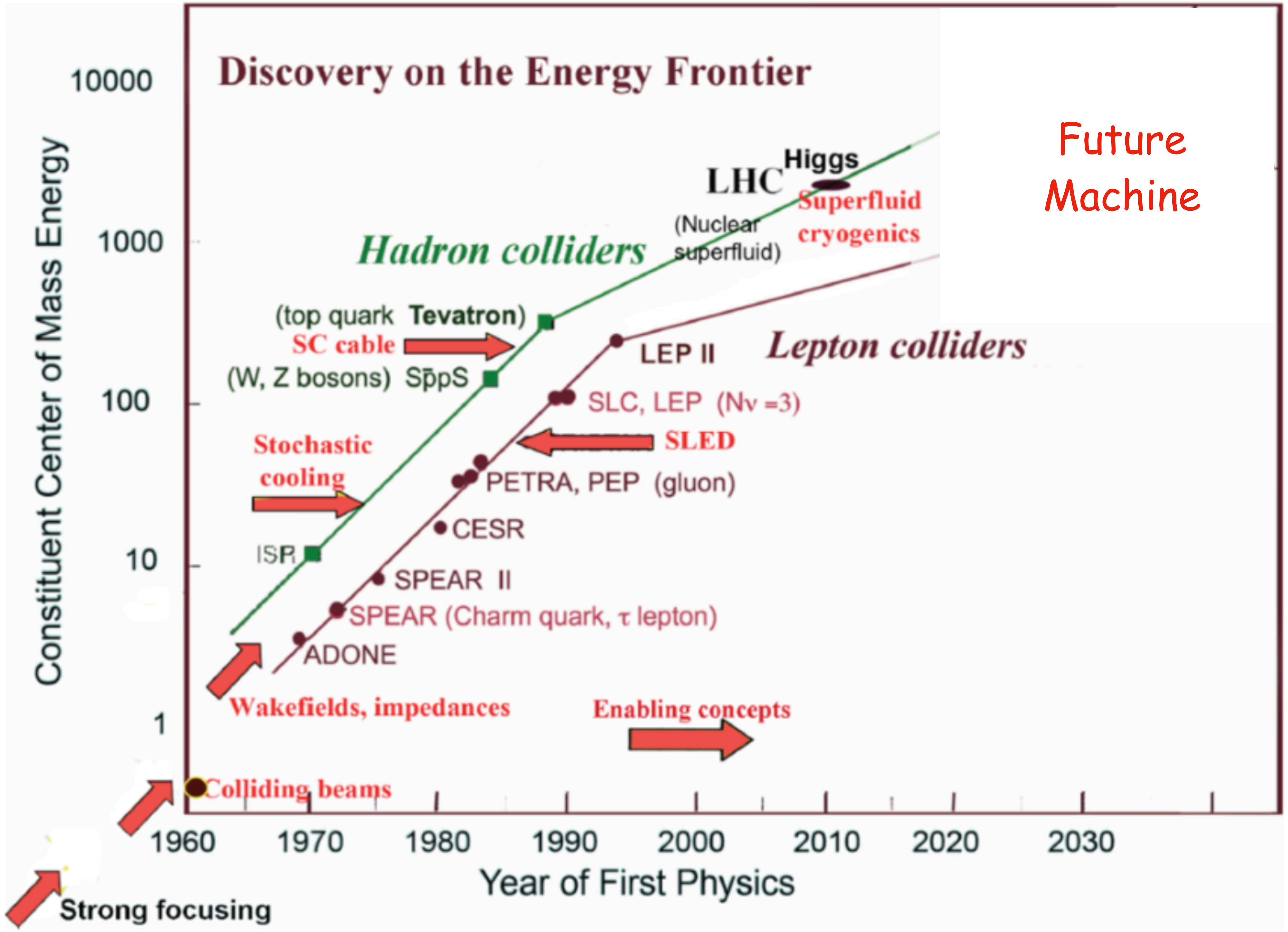
ACTIVE PEOPLE
(PHYSICISTS, ENGINEERS, TECHNICAL, ADMINISTRATIVE, STUDENTS, ETC.)

Of these members there are about:

2053	1050	1031	978
PHD PHYSICISTS (1689 MEN, 364 WOMEN)	PHYSICS DOCTORAL STUDENTS (792 MEN, 258 WOMEN)	ENGINEERS (895 MEN, 136 WOMEN)	UNDERGRADUATES (708 MEN, 270 WOMEN)

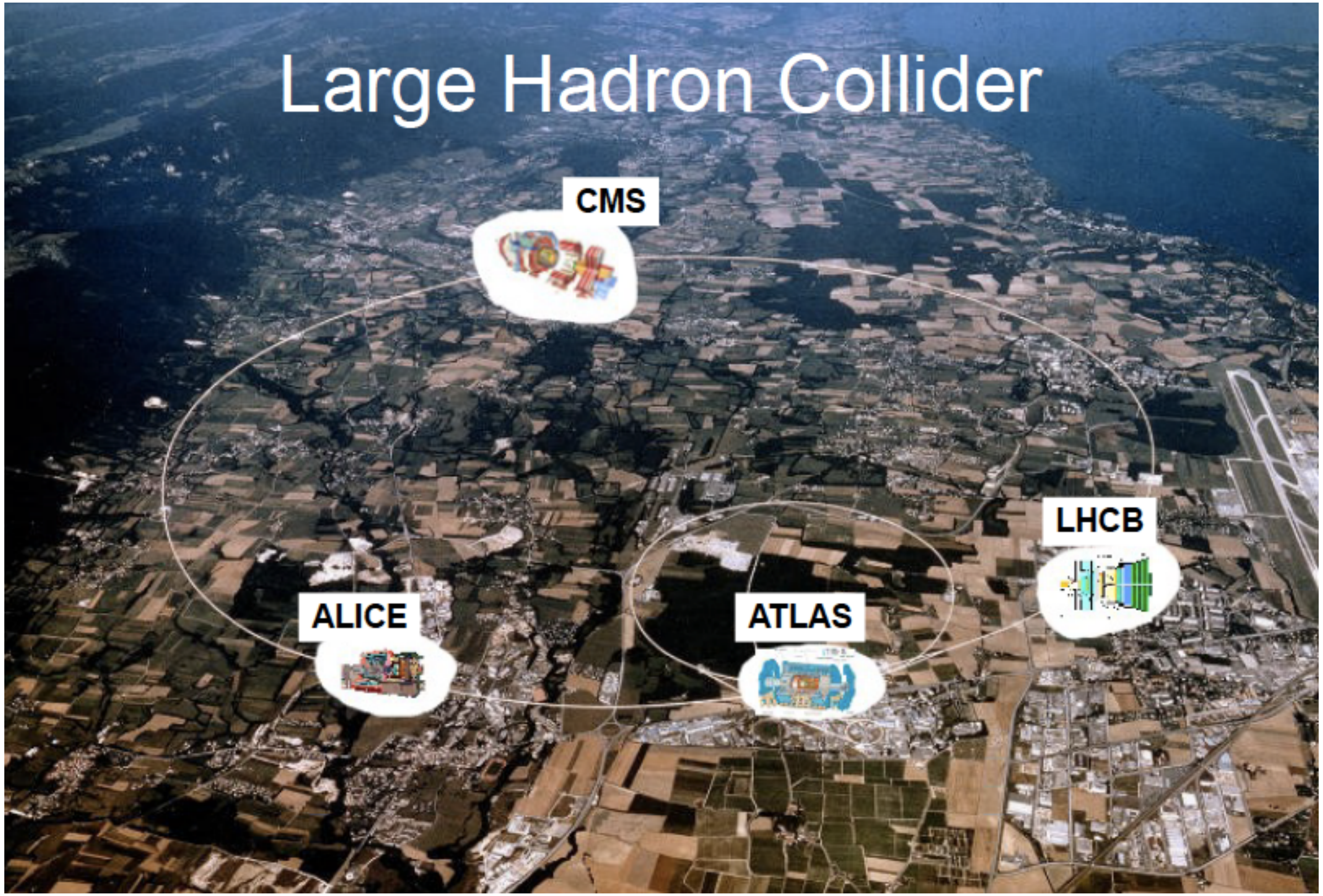
Accelerators

… Livingston plot



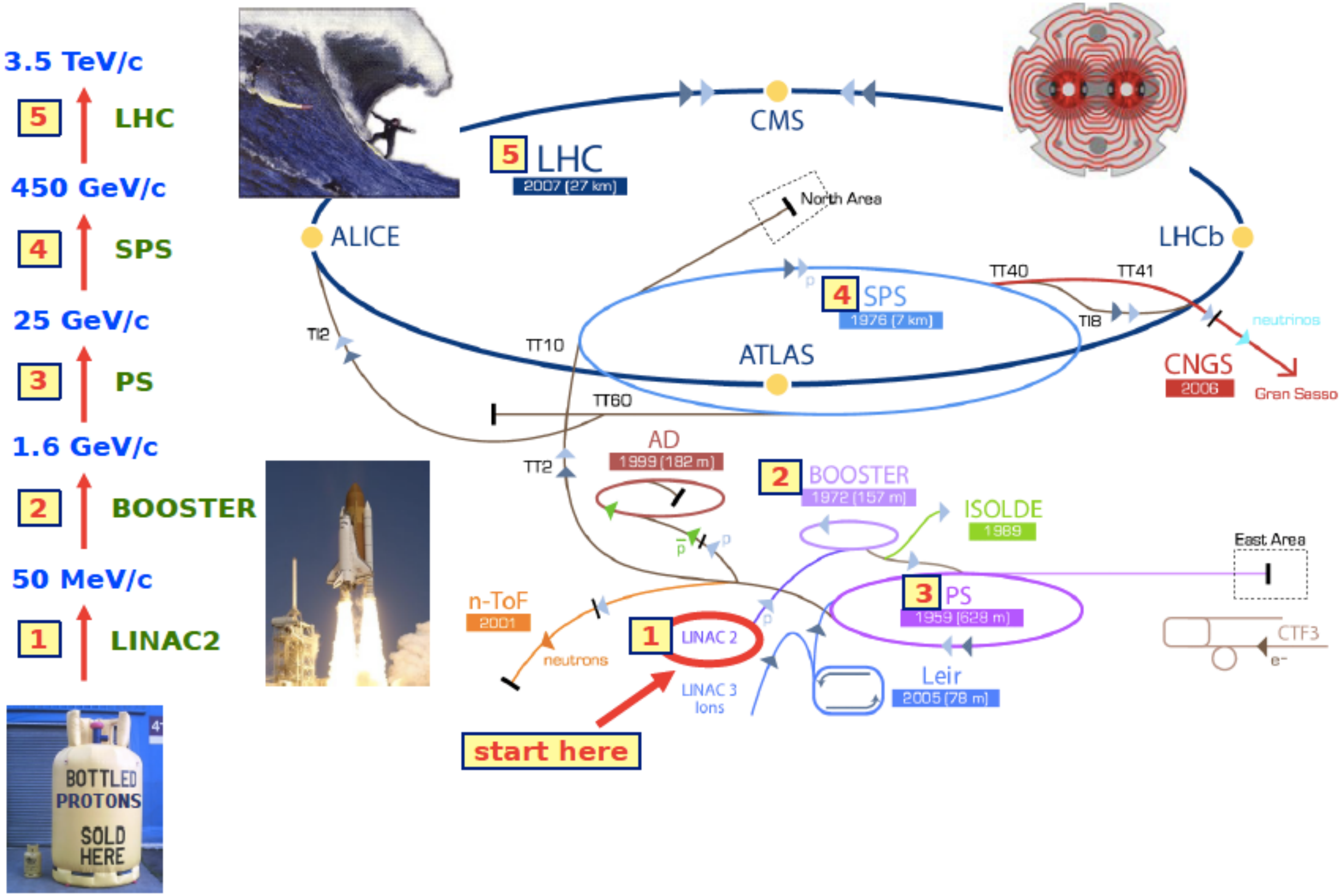
Accelerators

… LHC at the Energy Frontier



Accelerators

… LHC at the Energy Frontier



Accelerators

… LHC at the Energy Frontier

1984 Workshop on installing a Large Hadron Collider (LHC) in the LEP tunnel

1987 CERN's long-range planning committee chaired by Carlo Rubbia recommends Large Hadron Collider as the right choice for CERN's future

1989 **LEP collider starts operation**

1992 First concepts for LHC Experiments, Evian les Bains

1994 LHC Approved, ATLAS and CMS approved (Technical Proposals)

1998 Construction begins

2000 CMS assembly begins above ground; **LEP Collider closes**

2003 ATLAS underground cavern delivered and assembly underground begins

2005 CMS experiment cavern delivered

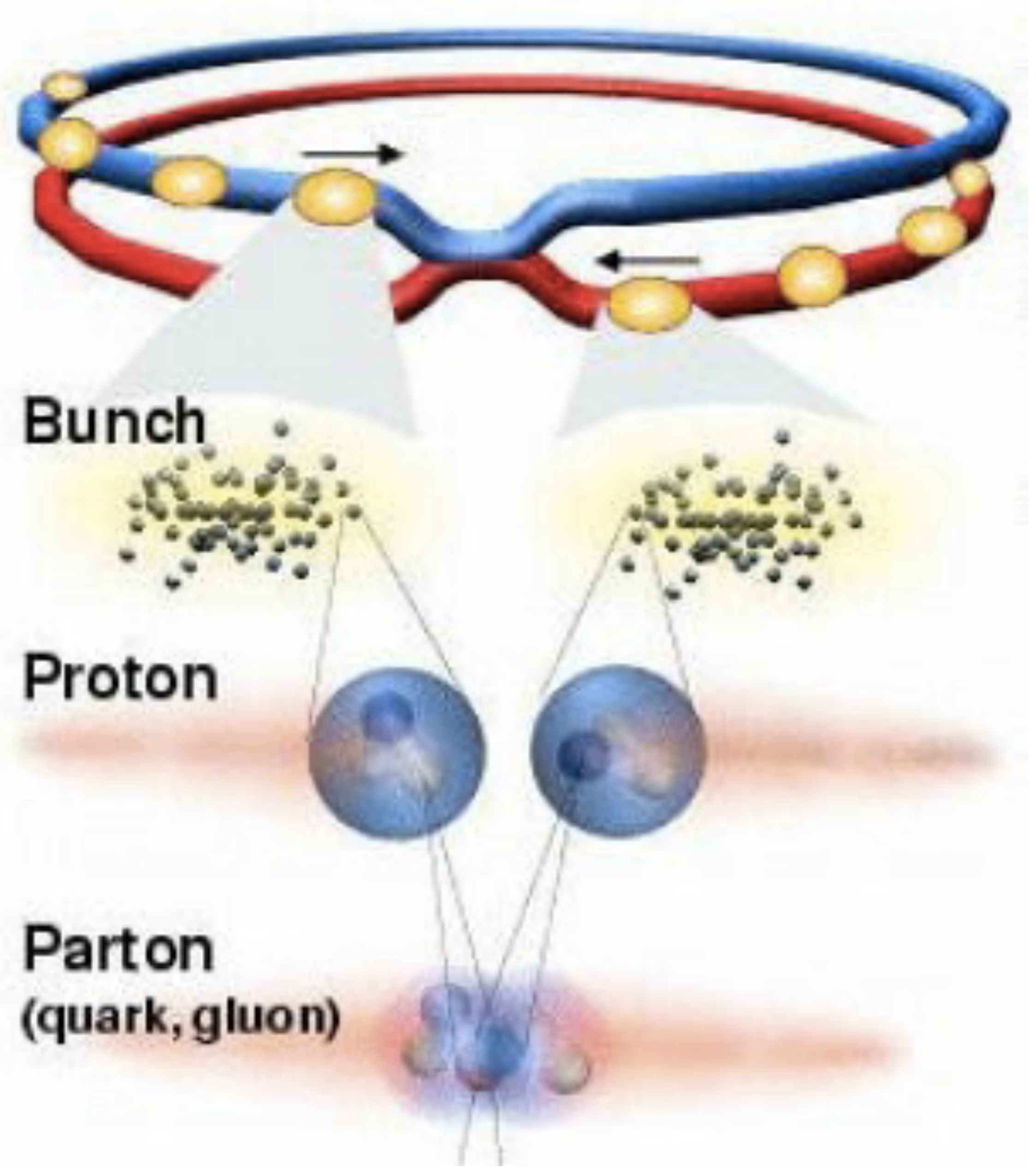
2008 LHC & Experiments ready for Beam. September incident.

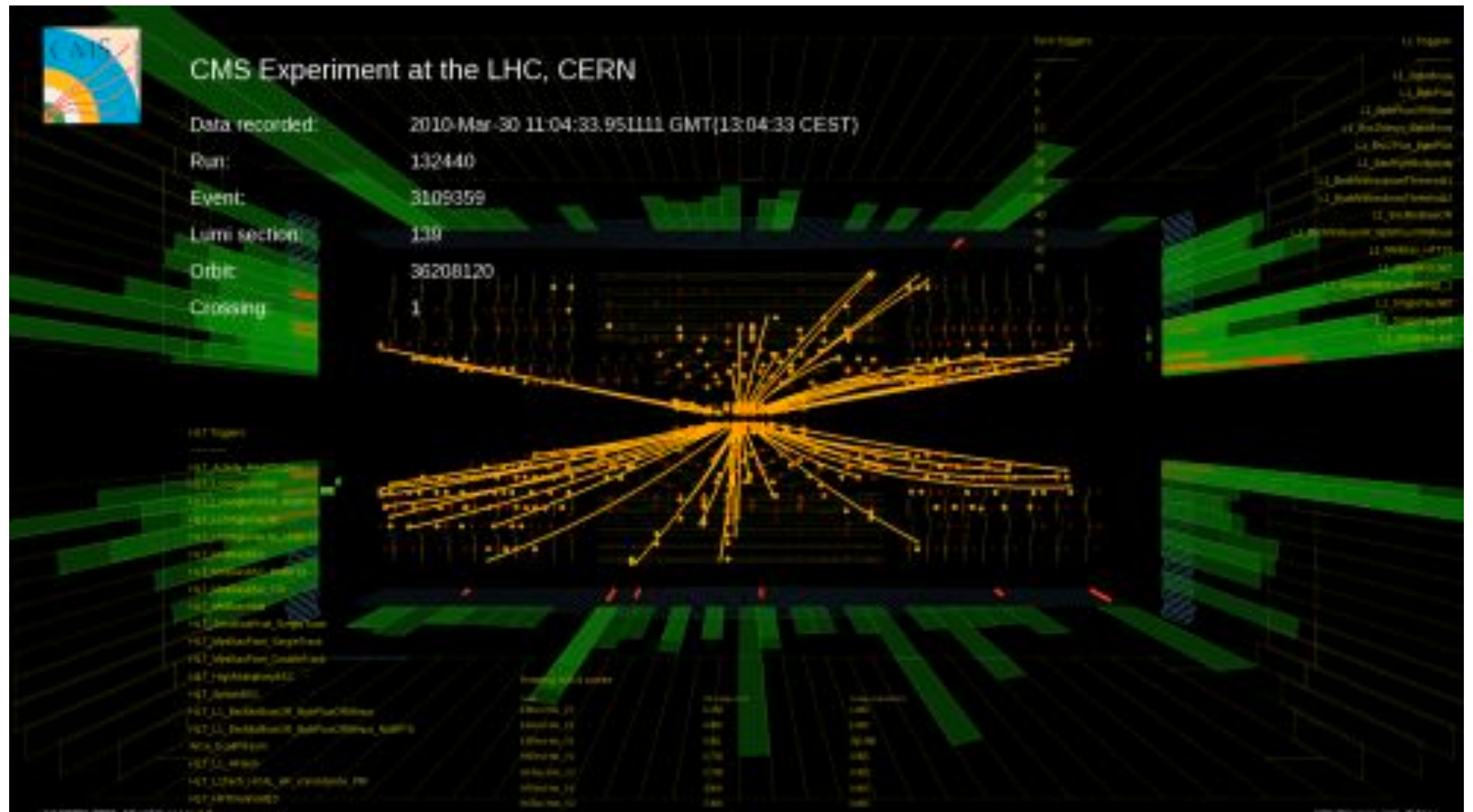
2009 LHC & Experiments ready for Beam.

First proton-proton Collisions !!!

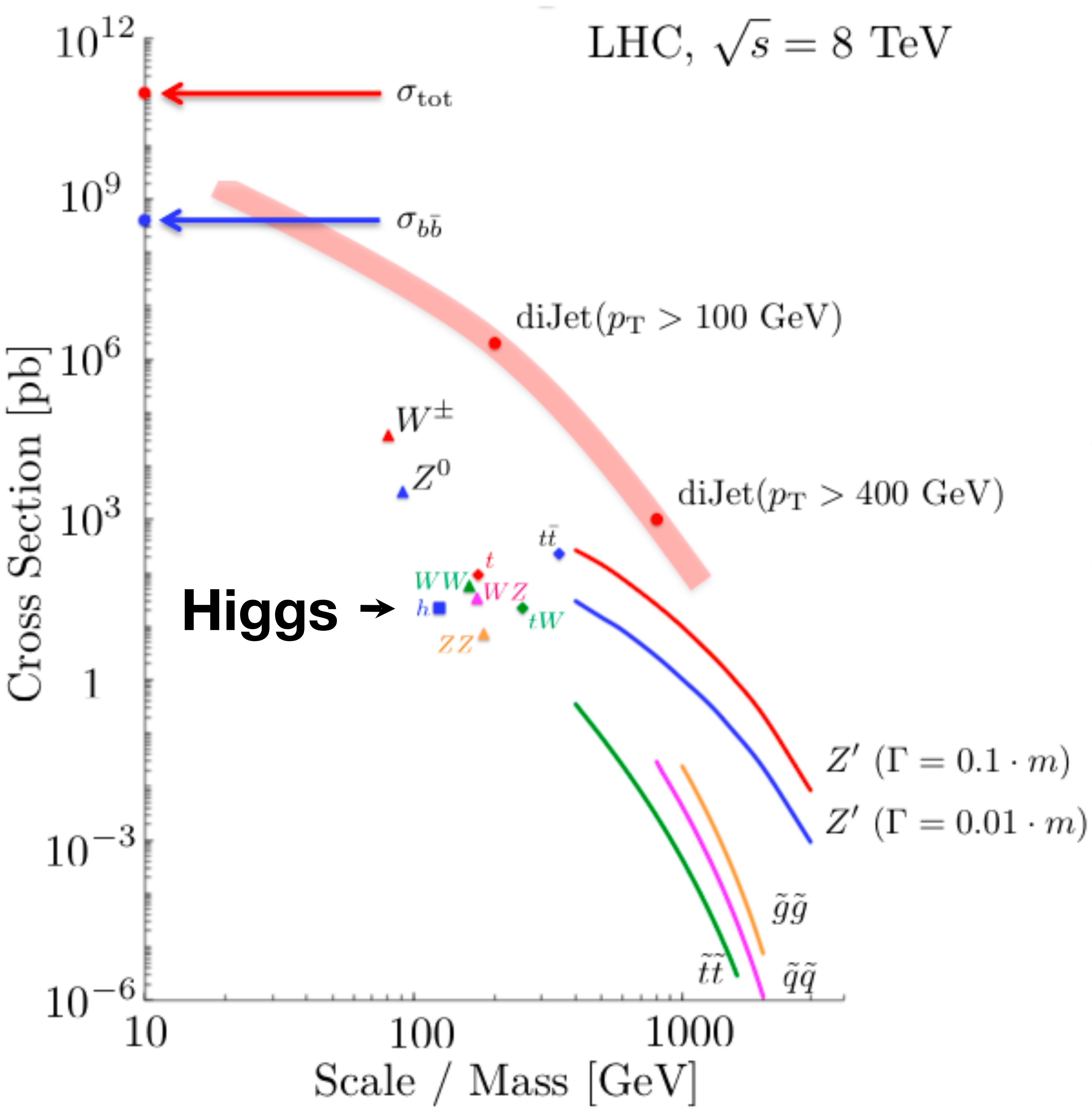
Accelerators

… LHC Collisions



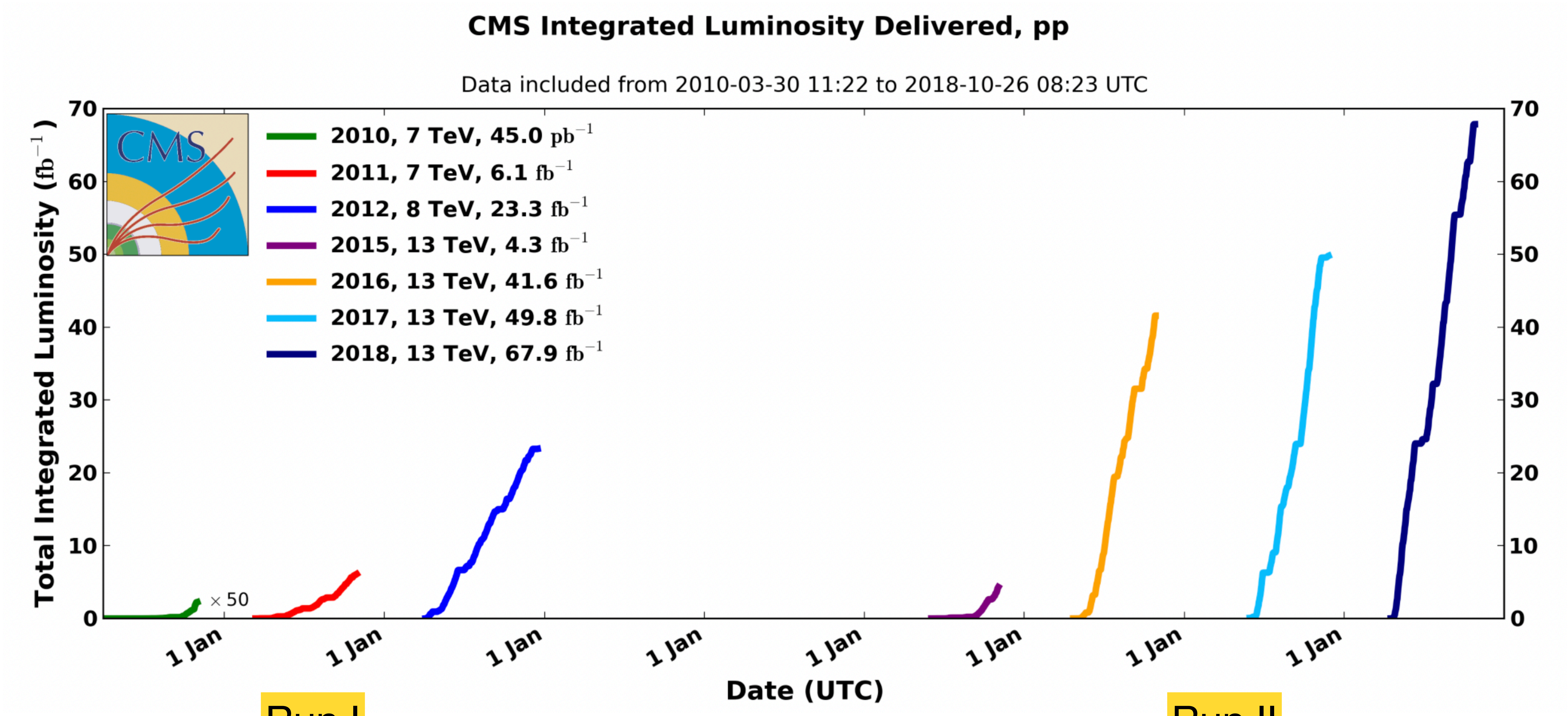


1 barn = 10^{-24} cm^2



Accelerators

… LHC Collisions



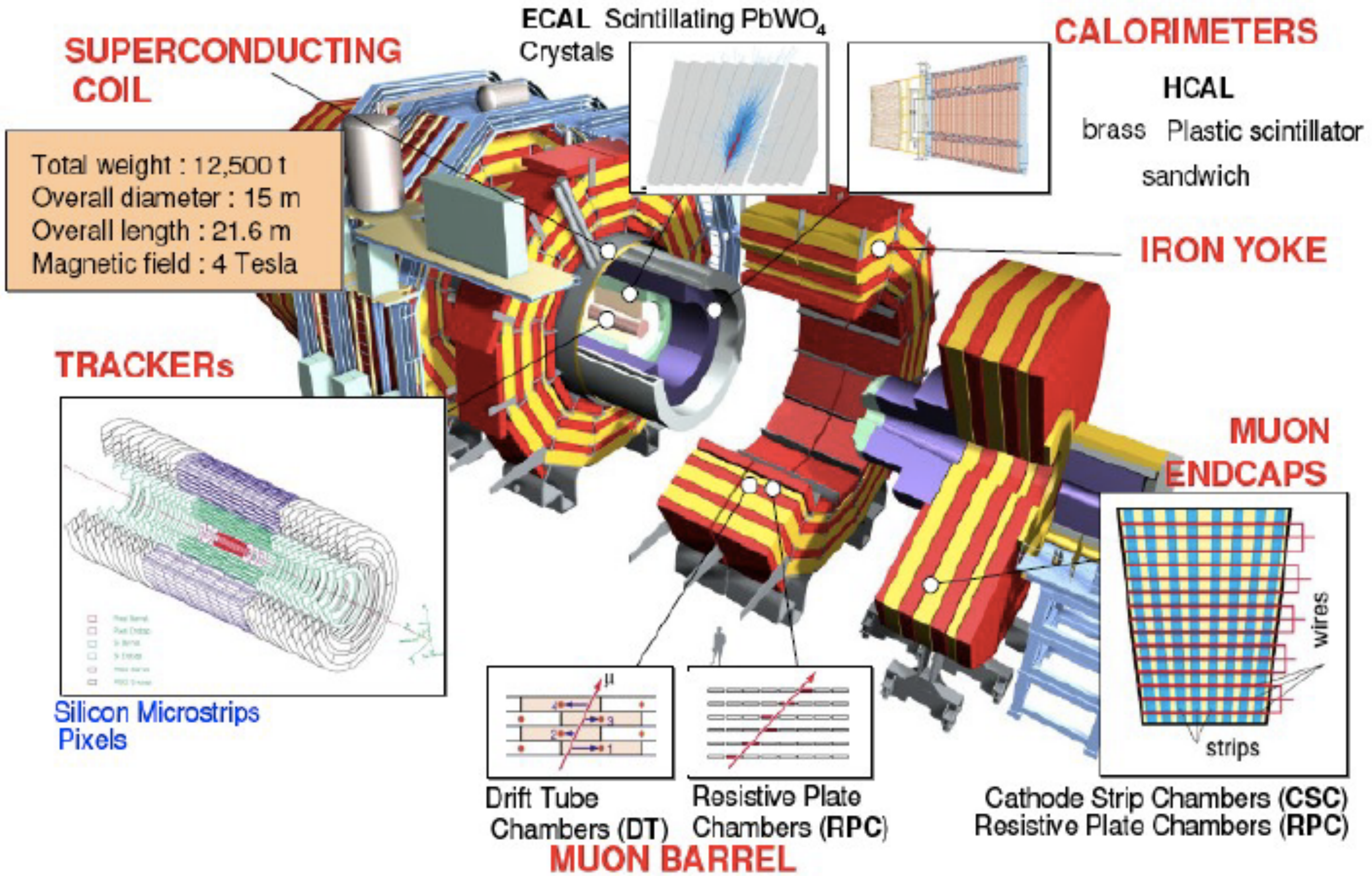
Run I

Run II

Particle Detectors

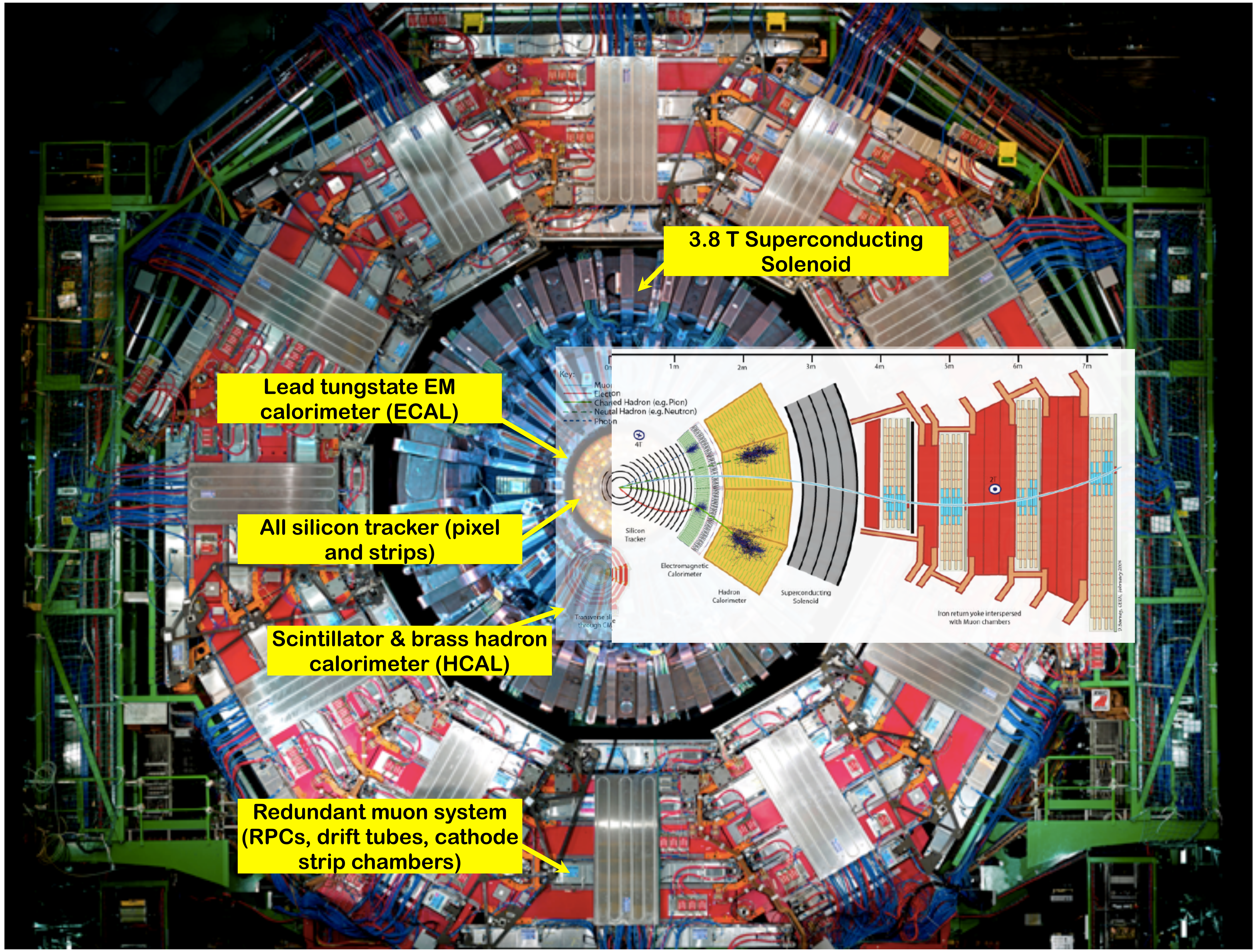
… CMS at the LHC

- Many synchronous cameras
- Order of 100 million channels
- 40 MHz shutter speed
- Real time filtering (trigger)



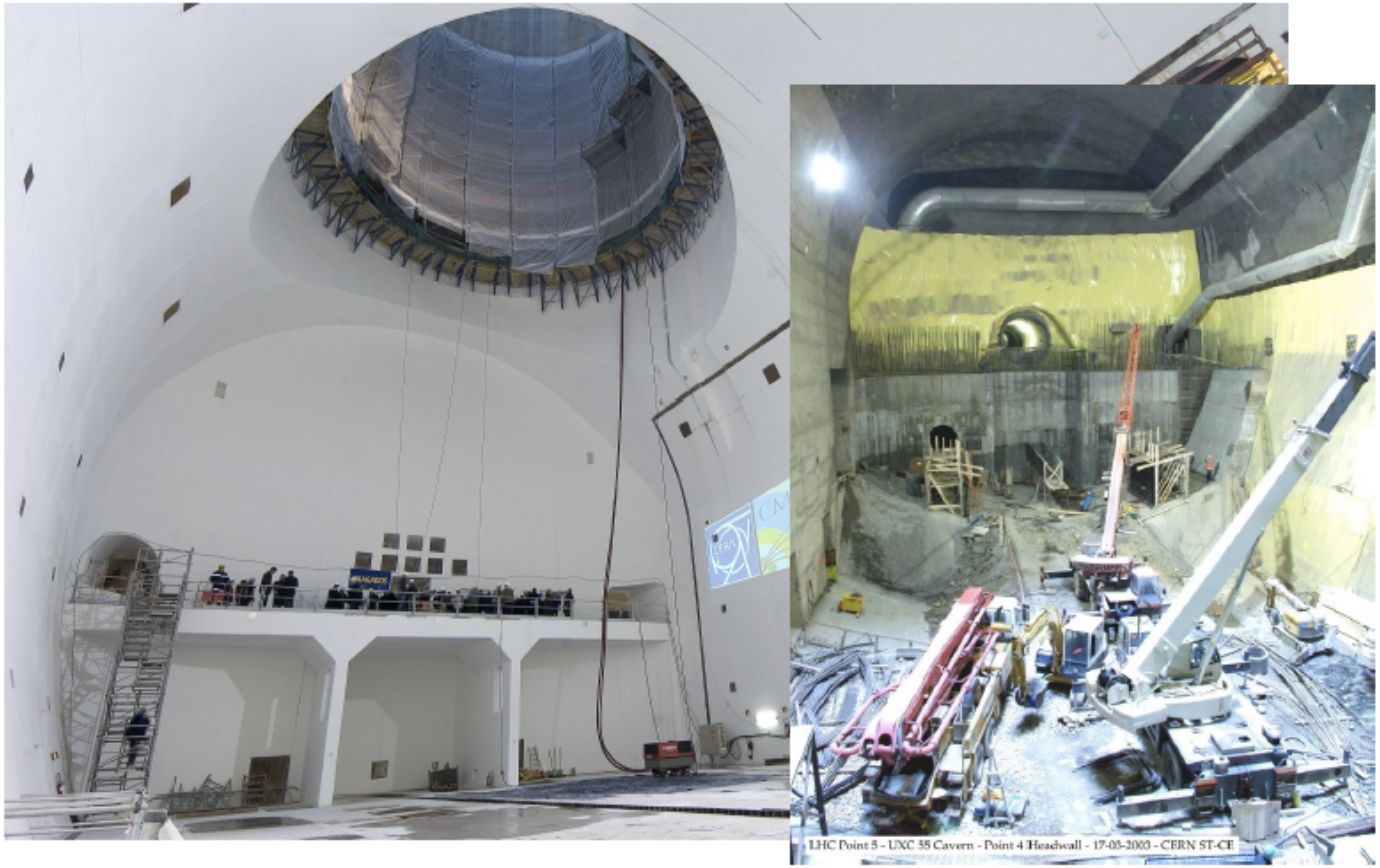
Particle Detectors

… CMS at the LHC



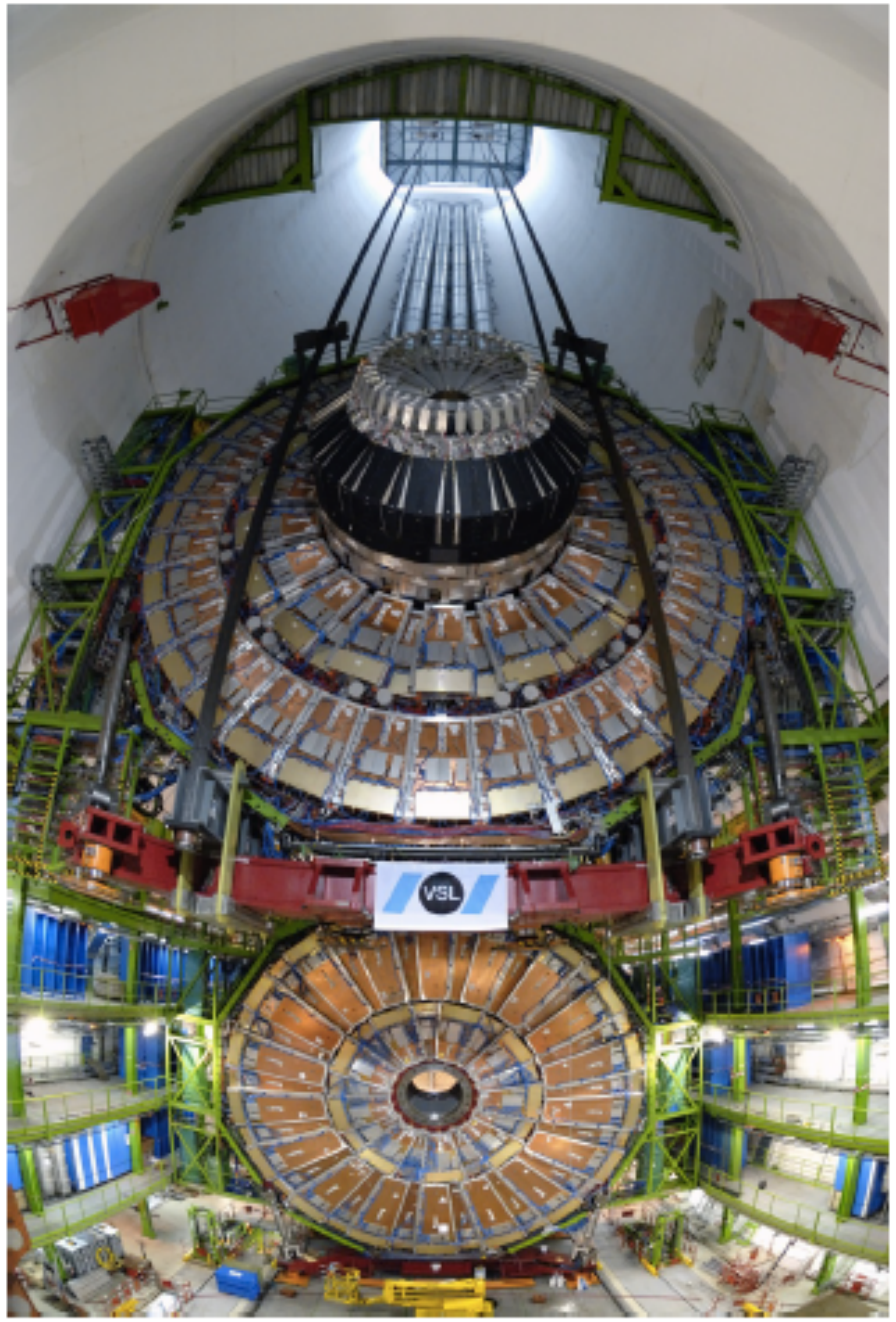
Particle Detectors

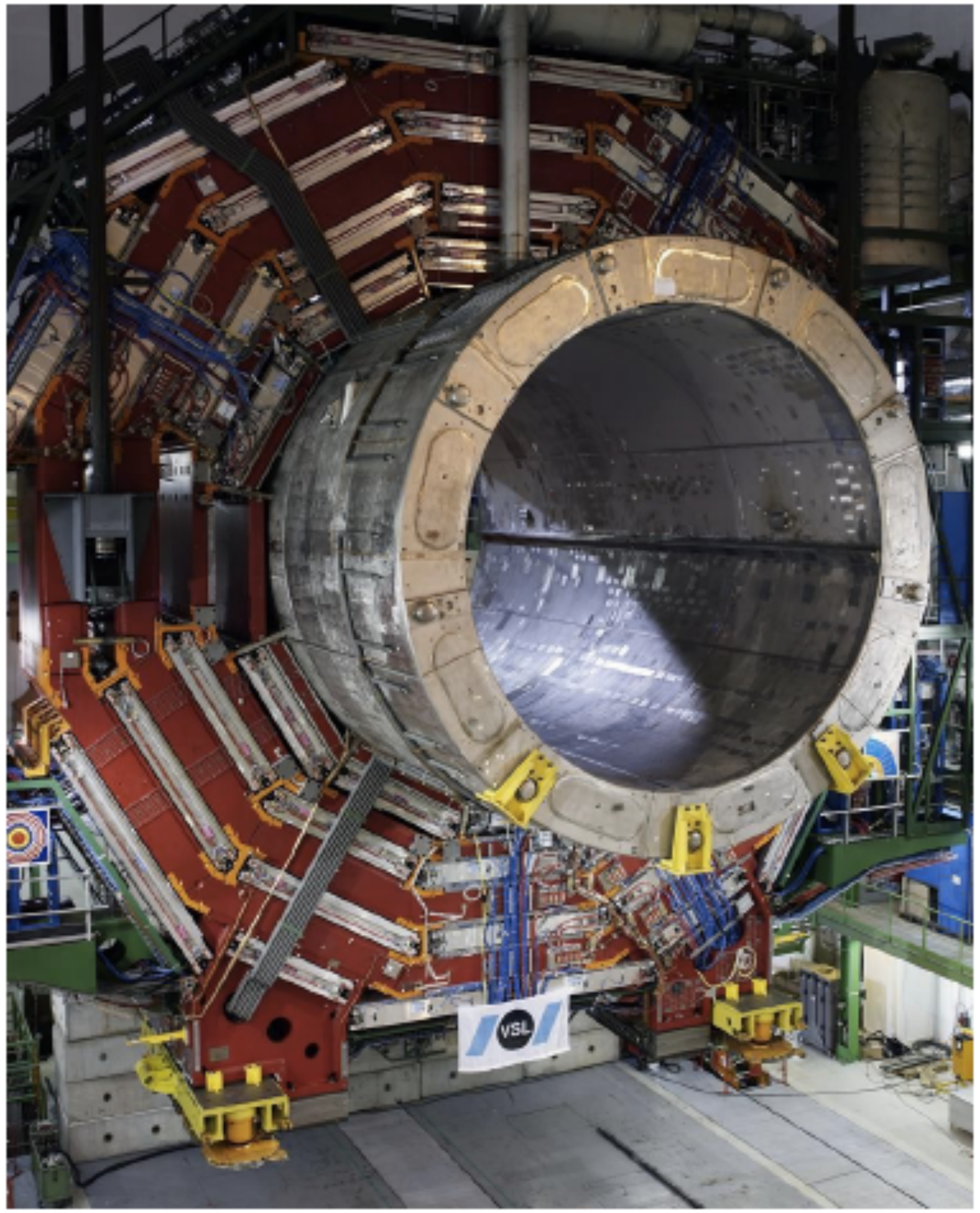
… CMS in 2004



Particle Detectors

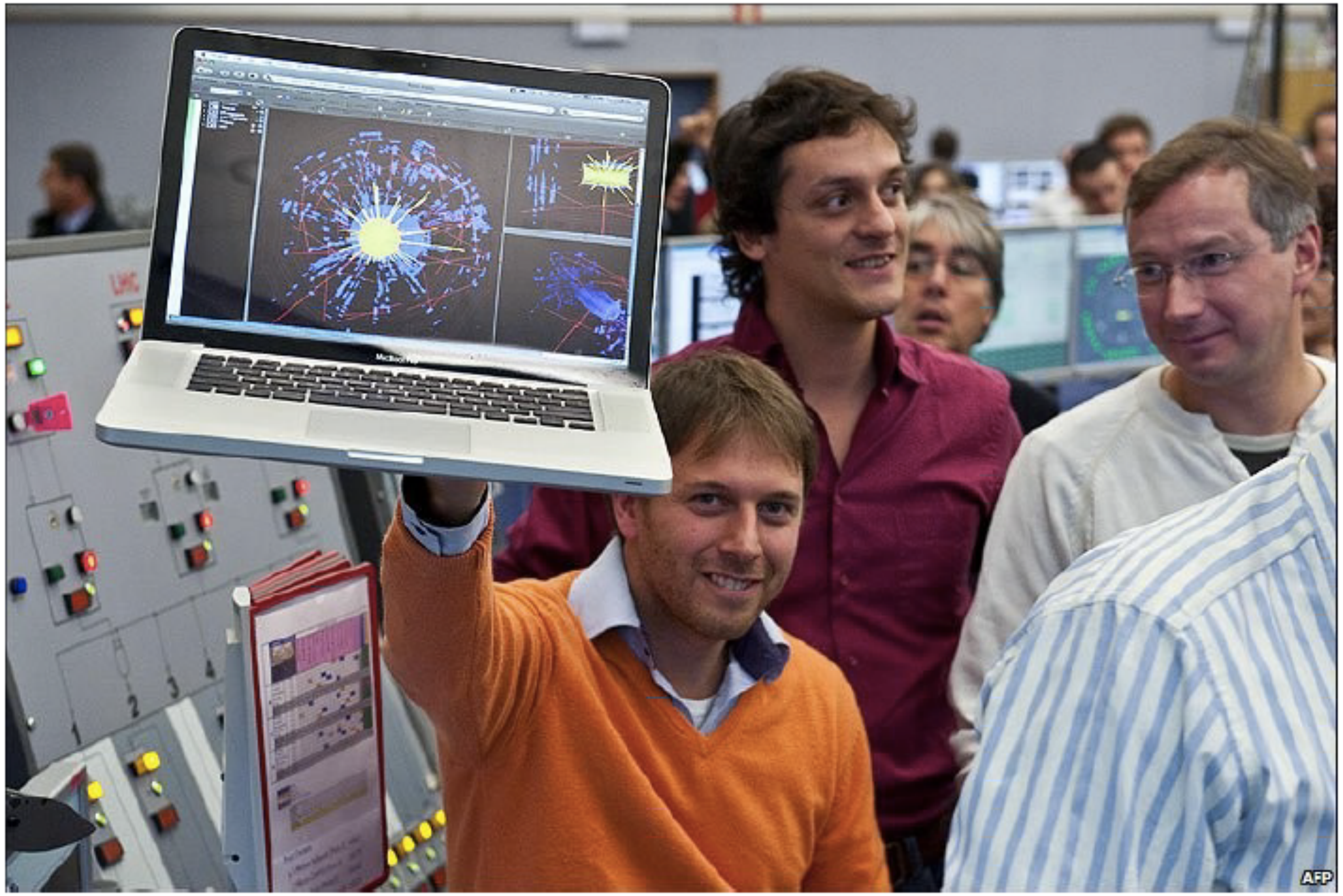
… CMS in 2007





Particle Detectors

… CMS in 2009

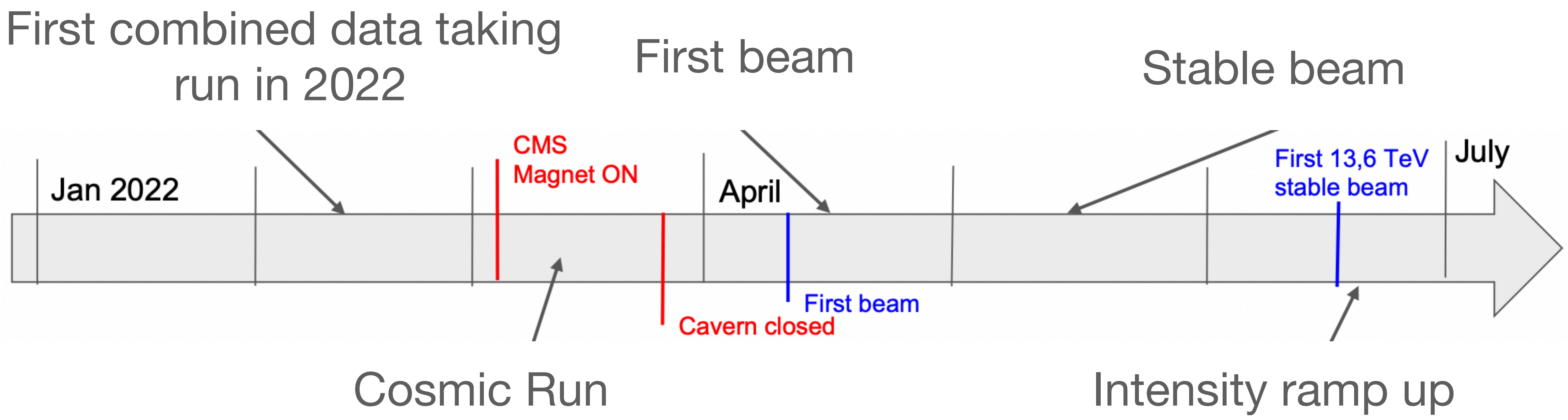


Particle Detectors

… CMS in 2012

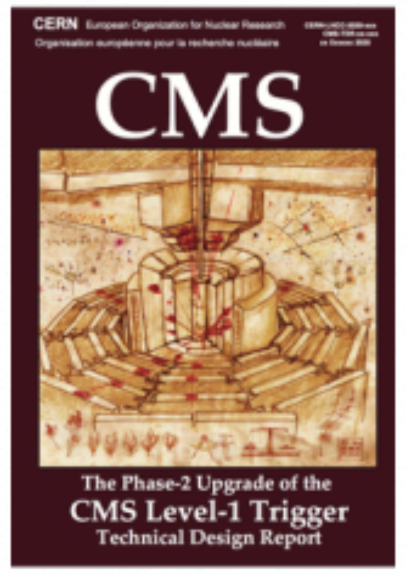
Particle Detectors

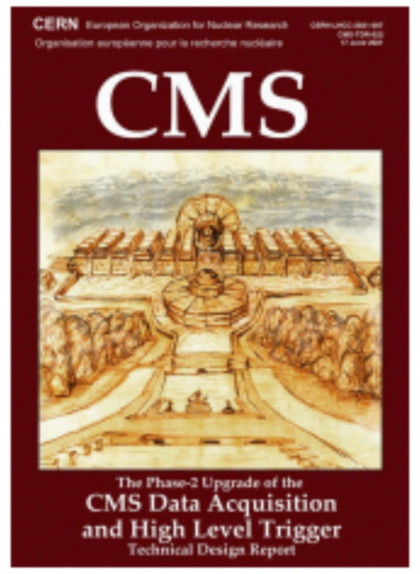
… CMS in 2022



Particle Detectors

… CMS in 2028





L1-Trigger HLT/DAQ

https://cds.cern.ch/record/2714892

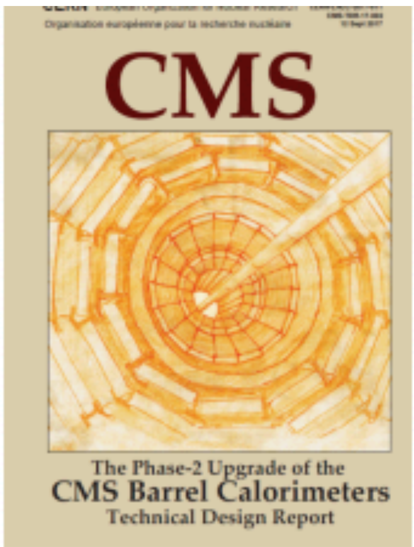
https://cds.cern.ch/record/2759072

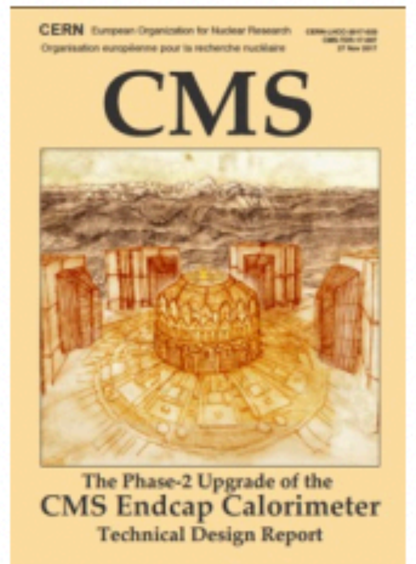
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

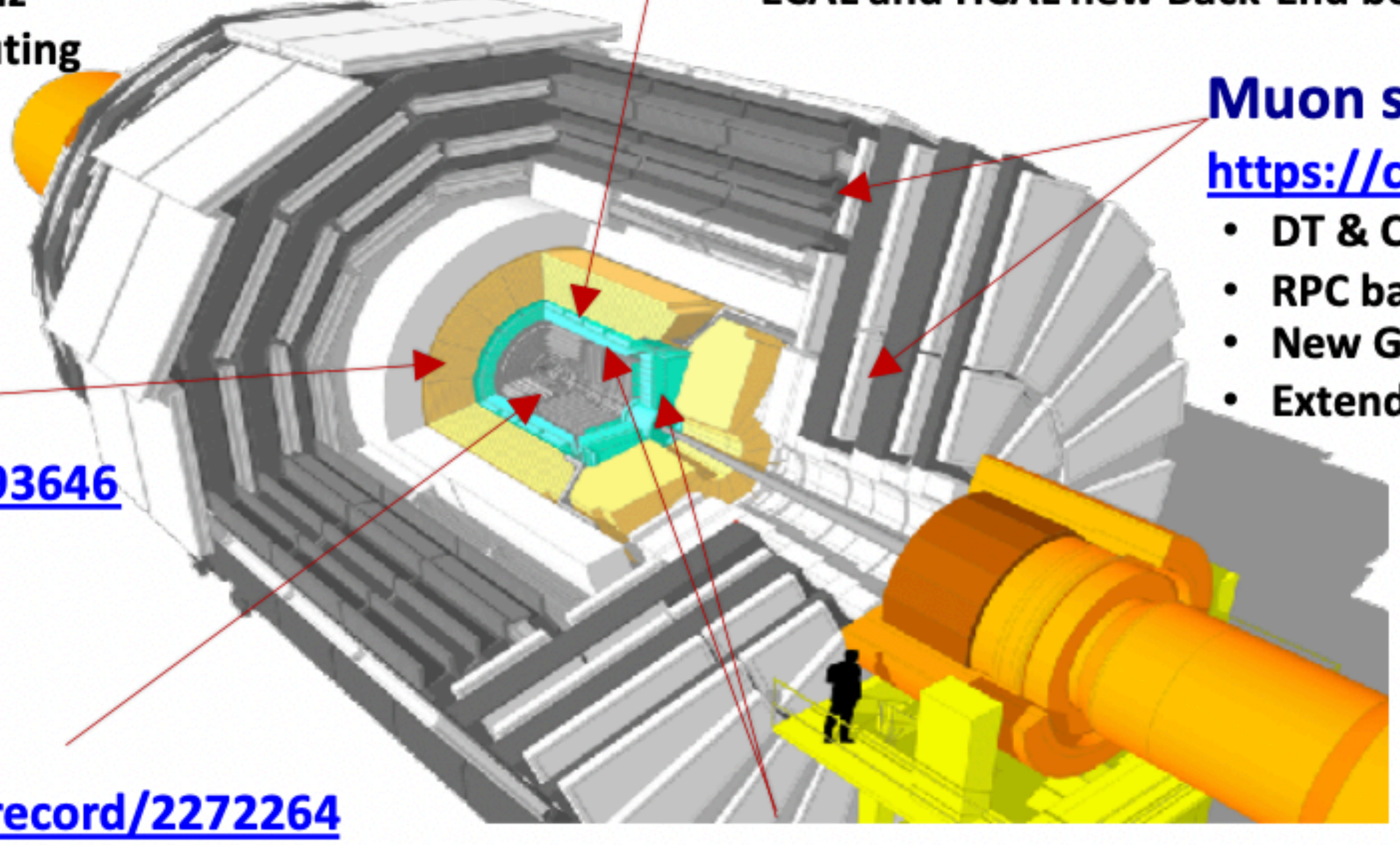
Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



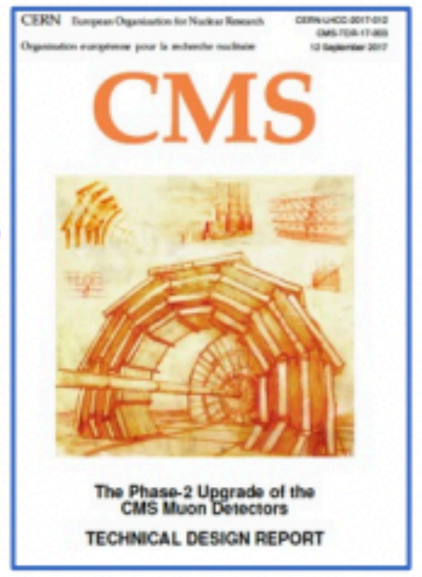




Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap

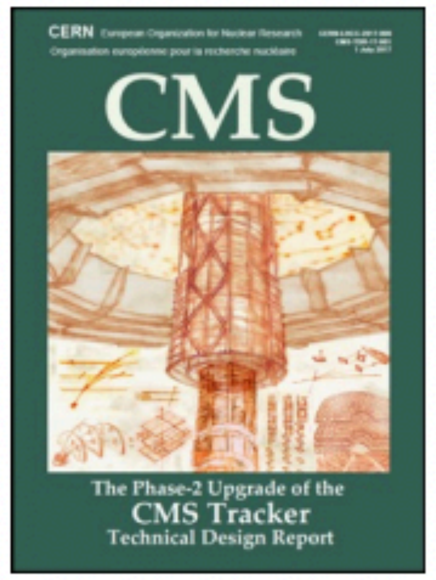
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264

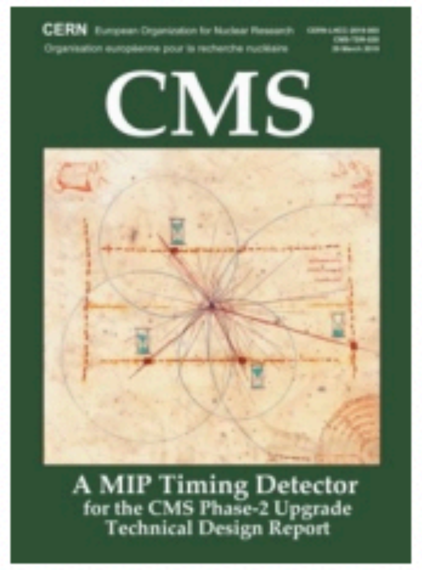
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

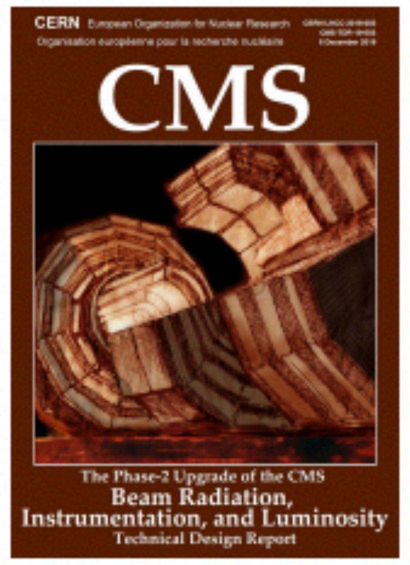
MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





Overview of LHC Physics

… the success story of the Standard Model

Electroweak

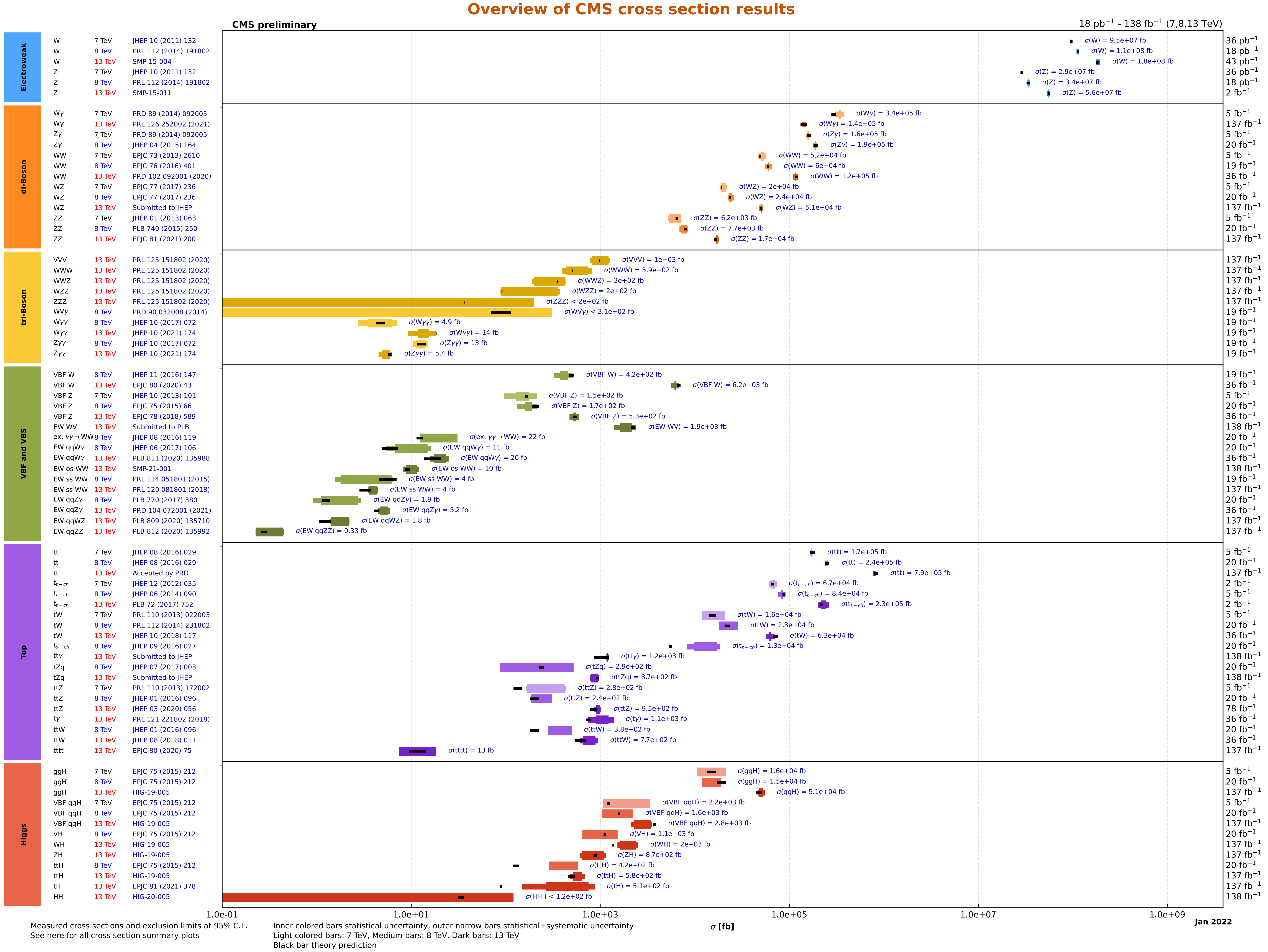
di-Boson

tri-Boson

VBF and VBS

Top

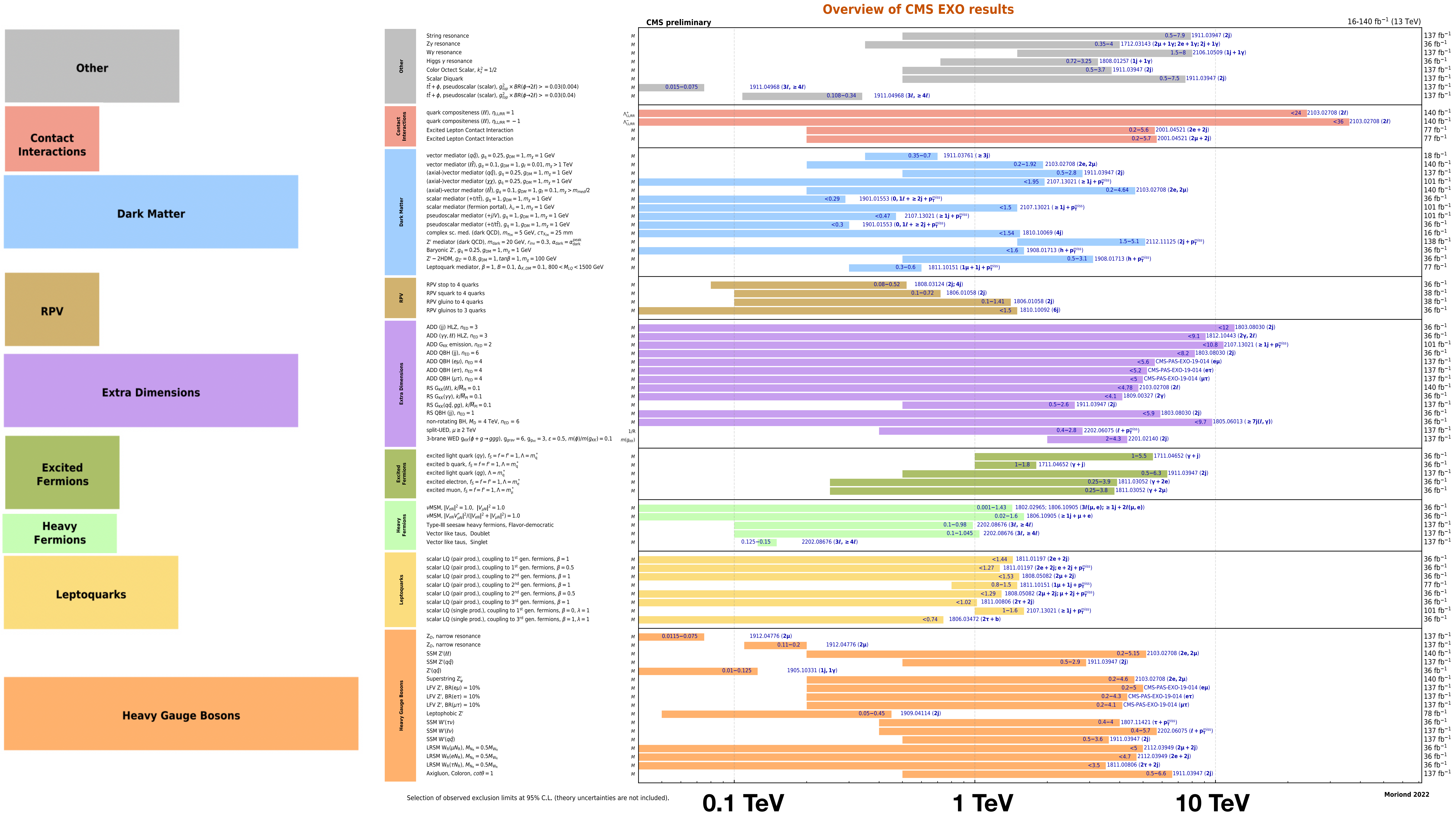
Higgs



Karlsruhe Institute of Technology

Overview of LHC New Physics Searches

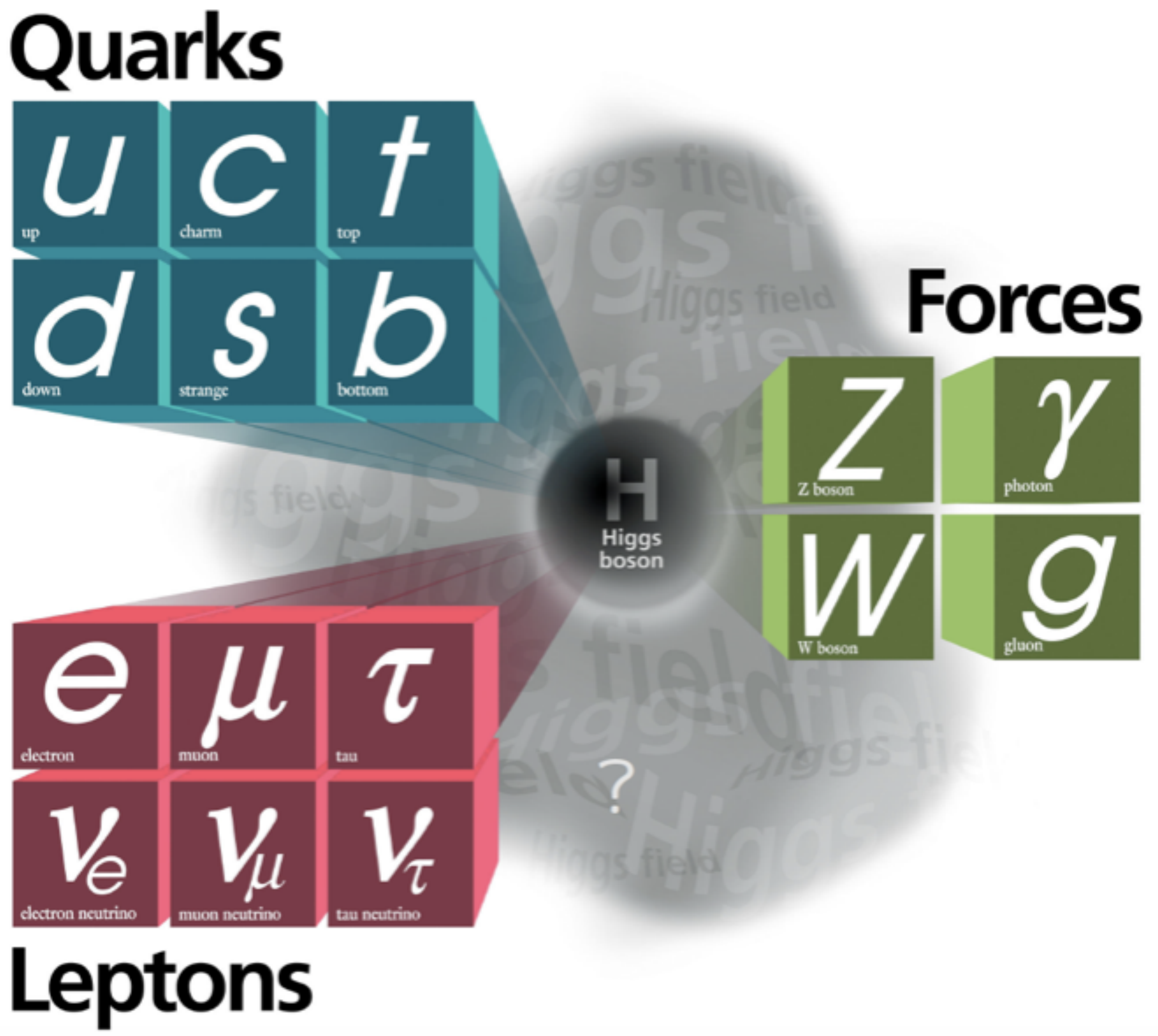
… example: CMS Exotic Searches



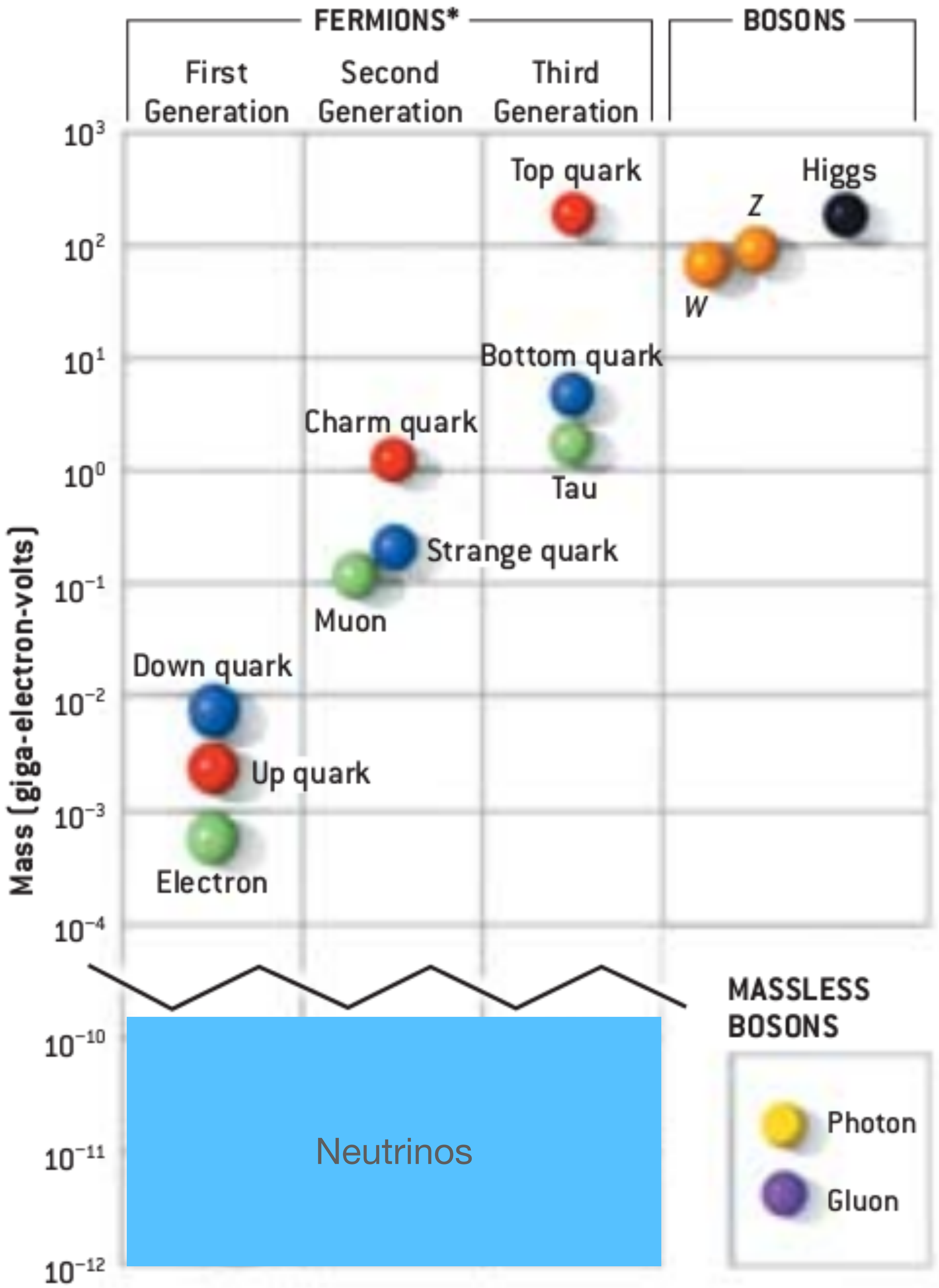
Energy Frontier Today

… where is everybody else?

Complete theory valid to very high energies

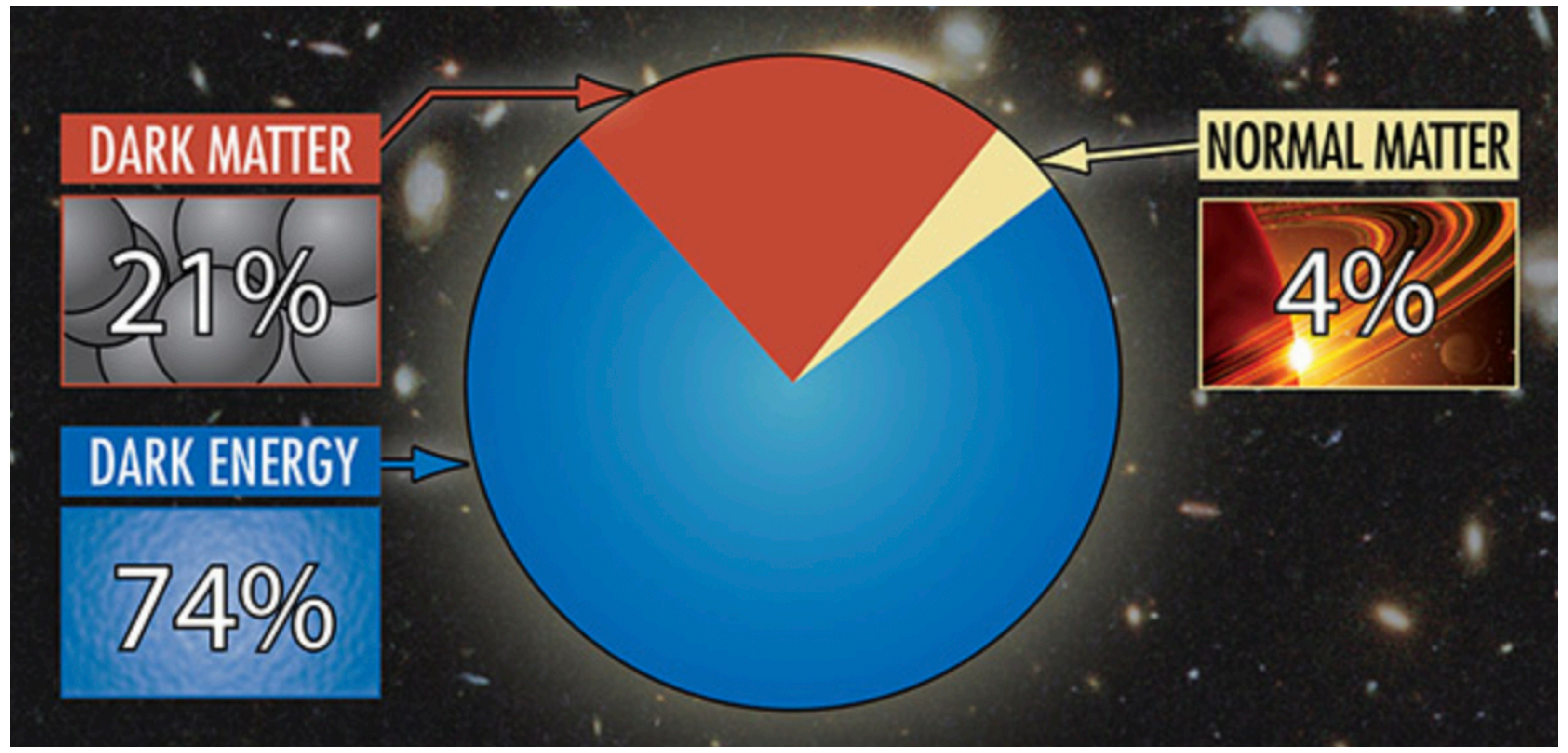


… but it is not enough



Mass and the Universe

… the big picture

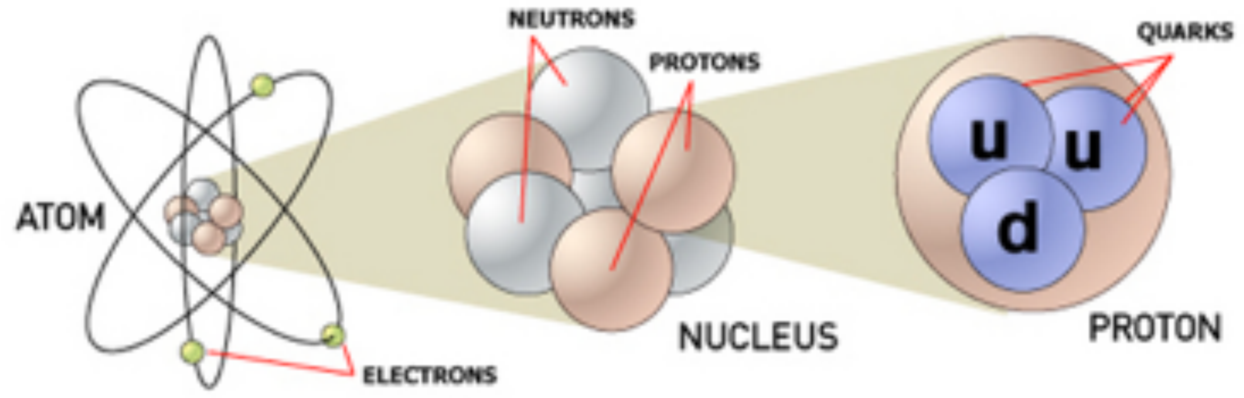


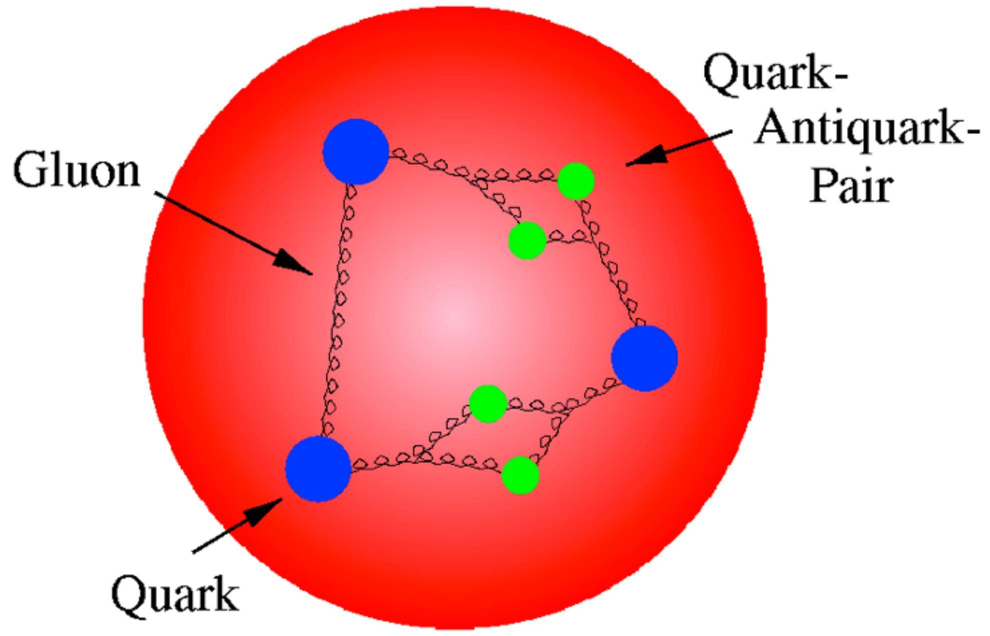
Ten most common elements in the Milky Way Galaxy estimated spectroscopically[3]

Z	Element	Mass fraction (ppm)
1	Hydrogen	739,000
2	Helium	240,000
8	Oxygen	10,400
6	Carbon	4,600
10	Neon	1,340
26	Iron	1,090
7	Nitrogen	960
14	Silicon	650
12	Magnesium	580
16	Sulfur	440
	Total	999,060

Most abundant nuclides in the Solar System[8]

Nuclide	A	Mass fraction in parts per million	Atom fraction in parts per million
Hydrogen-1	1	705,700	909,964
Helium-4	4	275,200	88,714
Oxygen-16	16	9,592	477
Carbon-12	12	3,032	326
Nitrogen-14	14	1,105	102
Neon-20	20	1,548	100

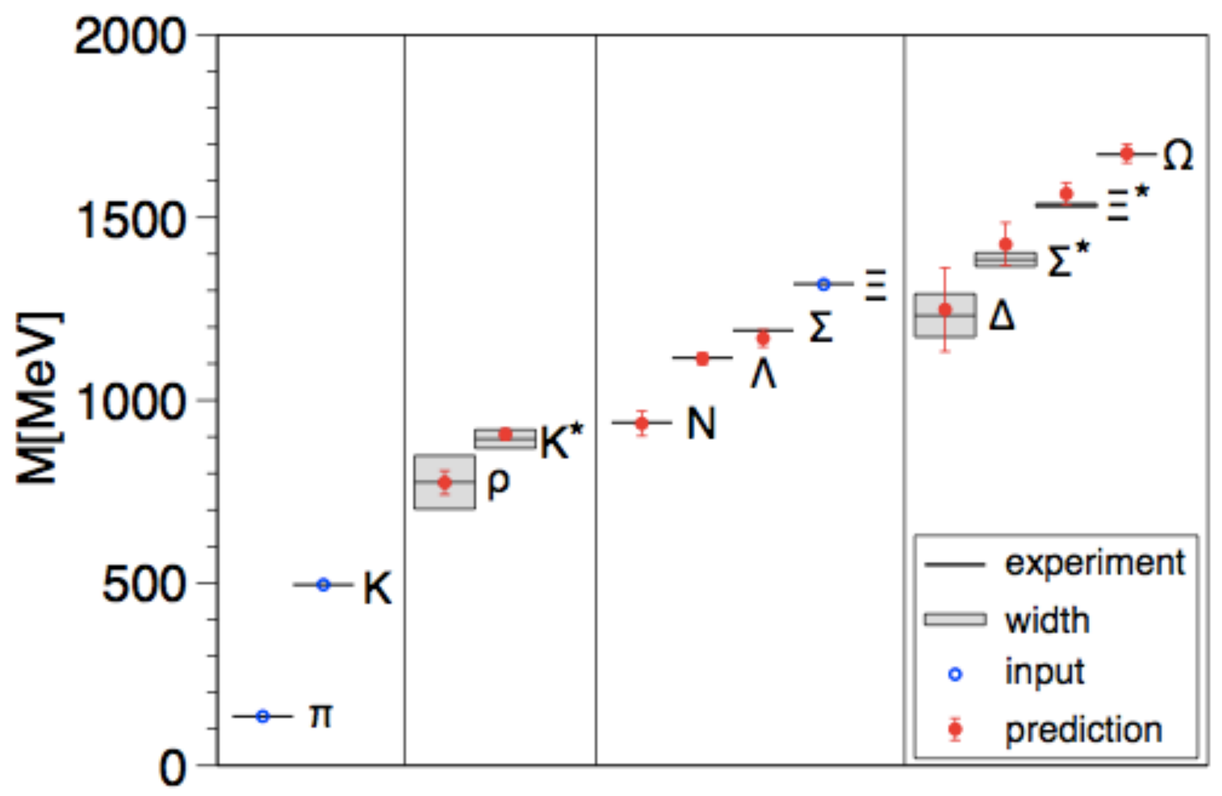




Proton mass
m_P = 938 MeV

Quark masses
m_u = 1.5-4.5 MeV
m_d = 5.0-8.5 MeV

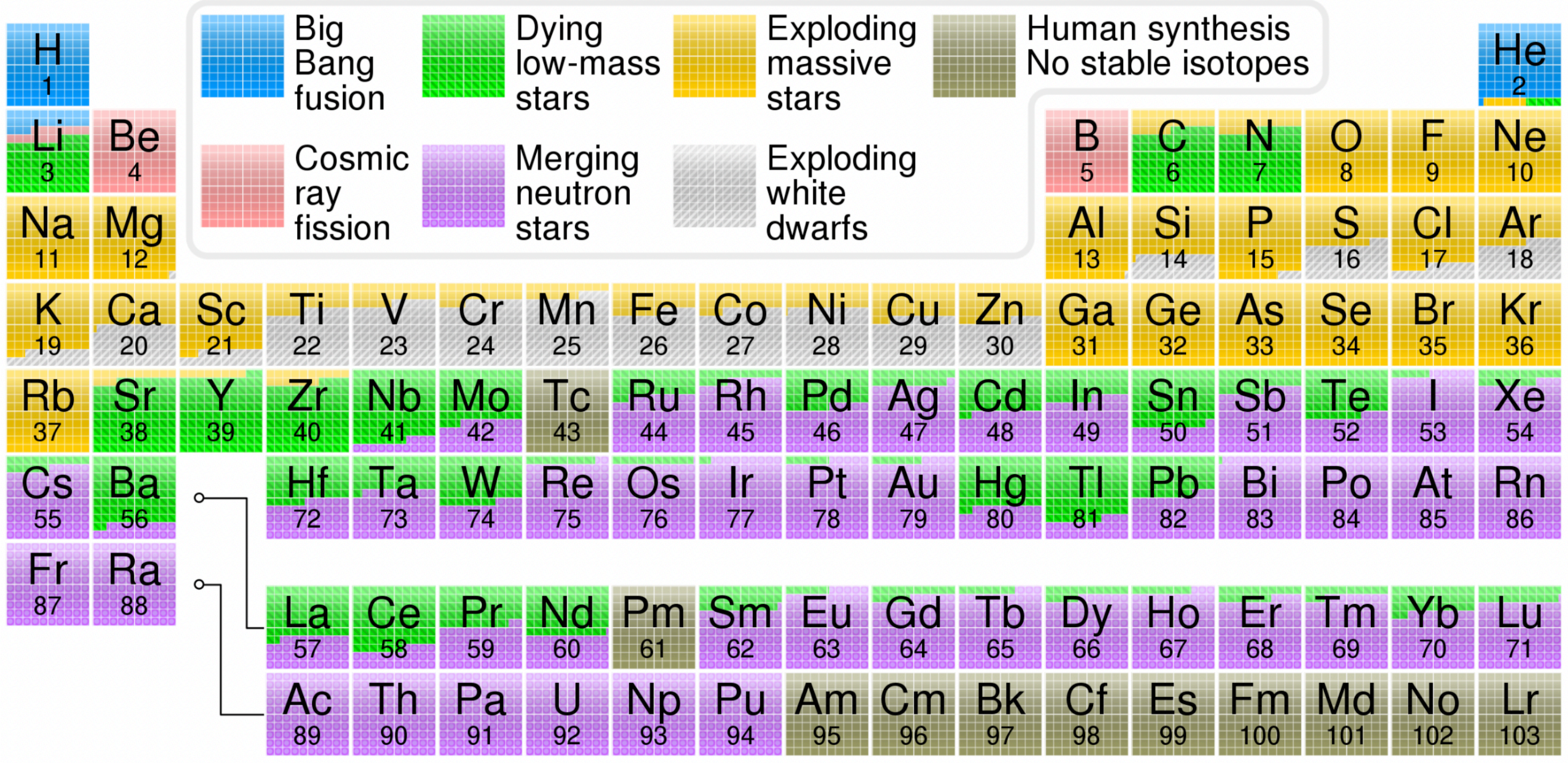
Inertial mass
mostly QCD effects



Higgs Boson Properties

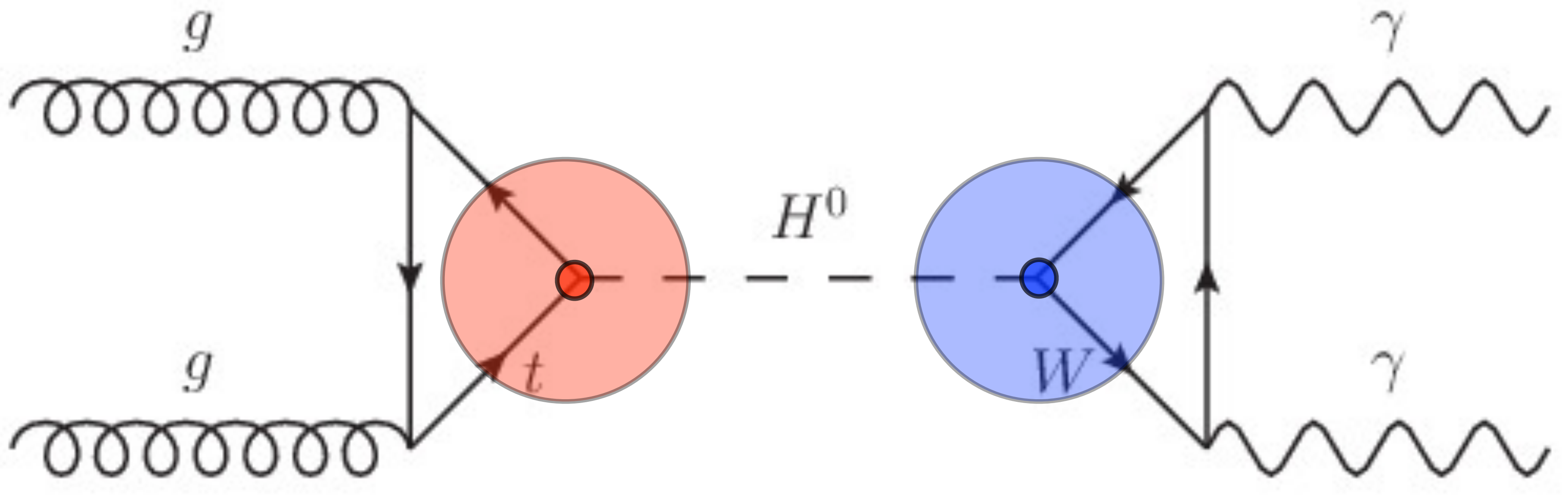
… a universe with modified Higgs Yukawa couplings

- Quarks: modified quark masses would have profound consequences for nucleosynthesis;
- Electrons: a massless electron would not be trapped by a protons to form a hydrogen atom; a modified electron mass would have profound consequences for chemistry

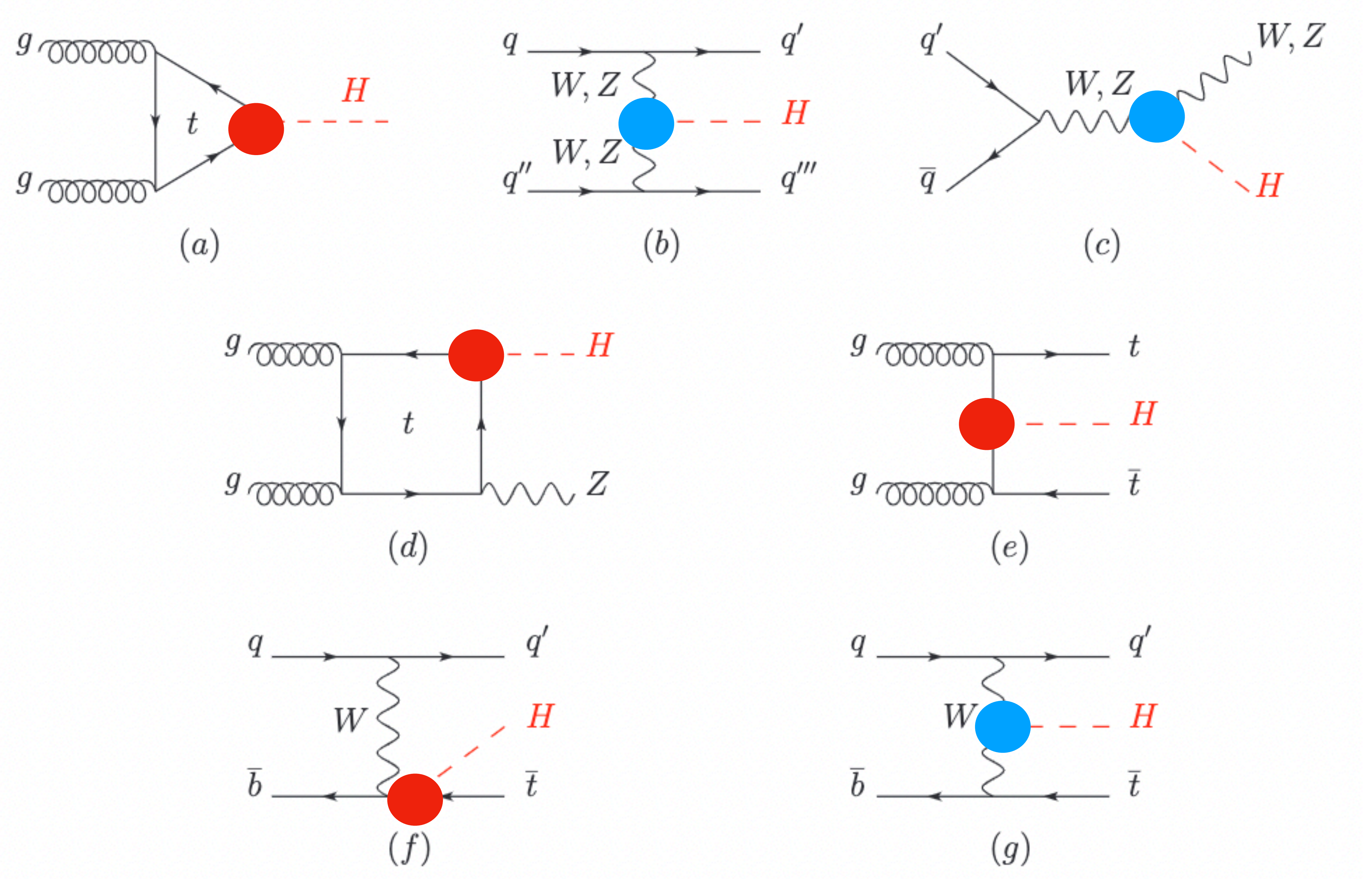


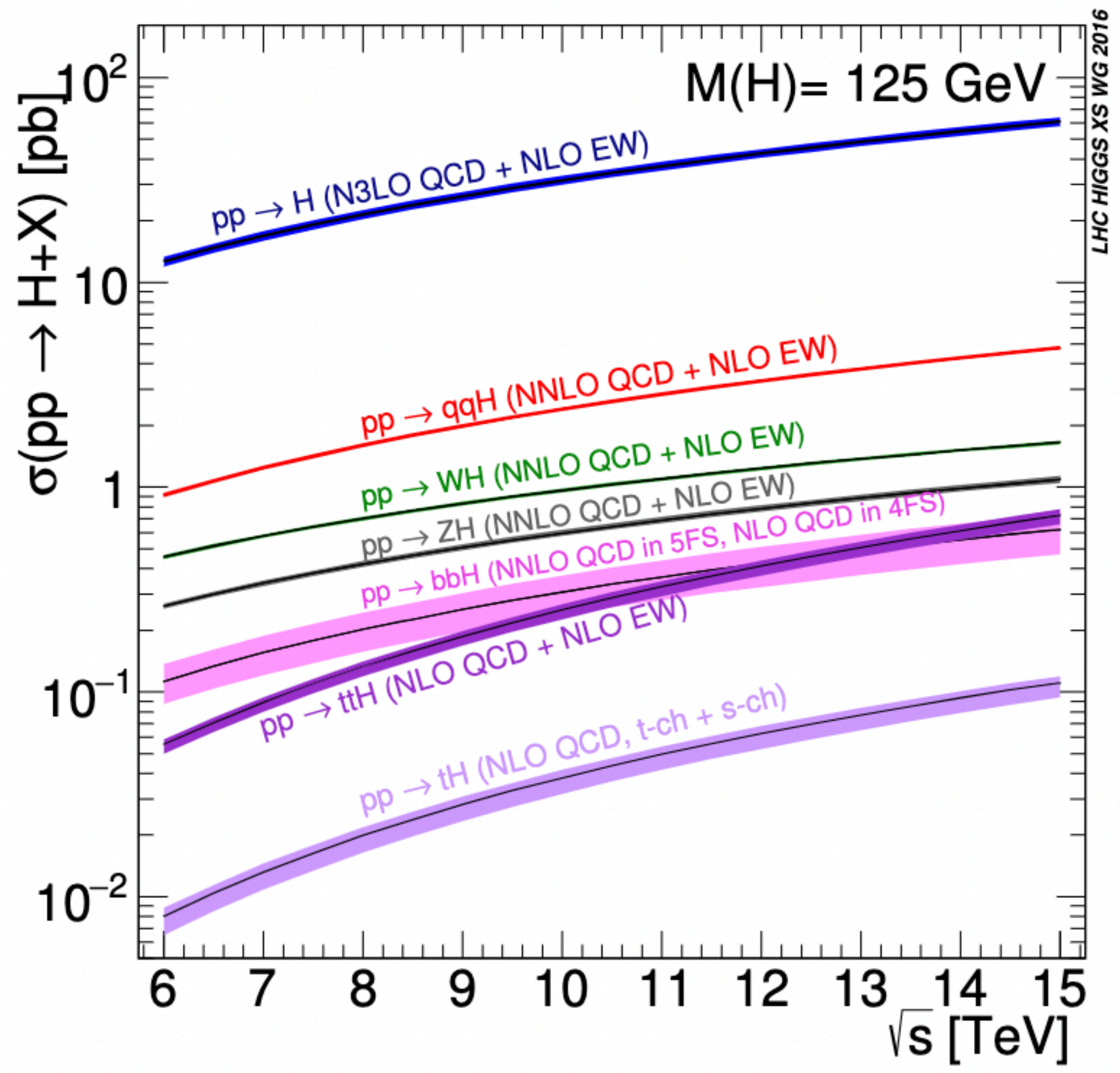
Higgs Physics

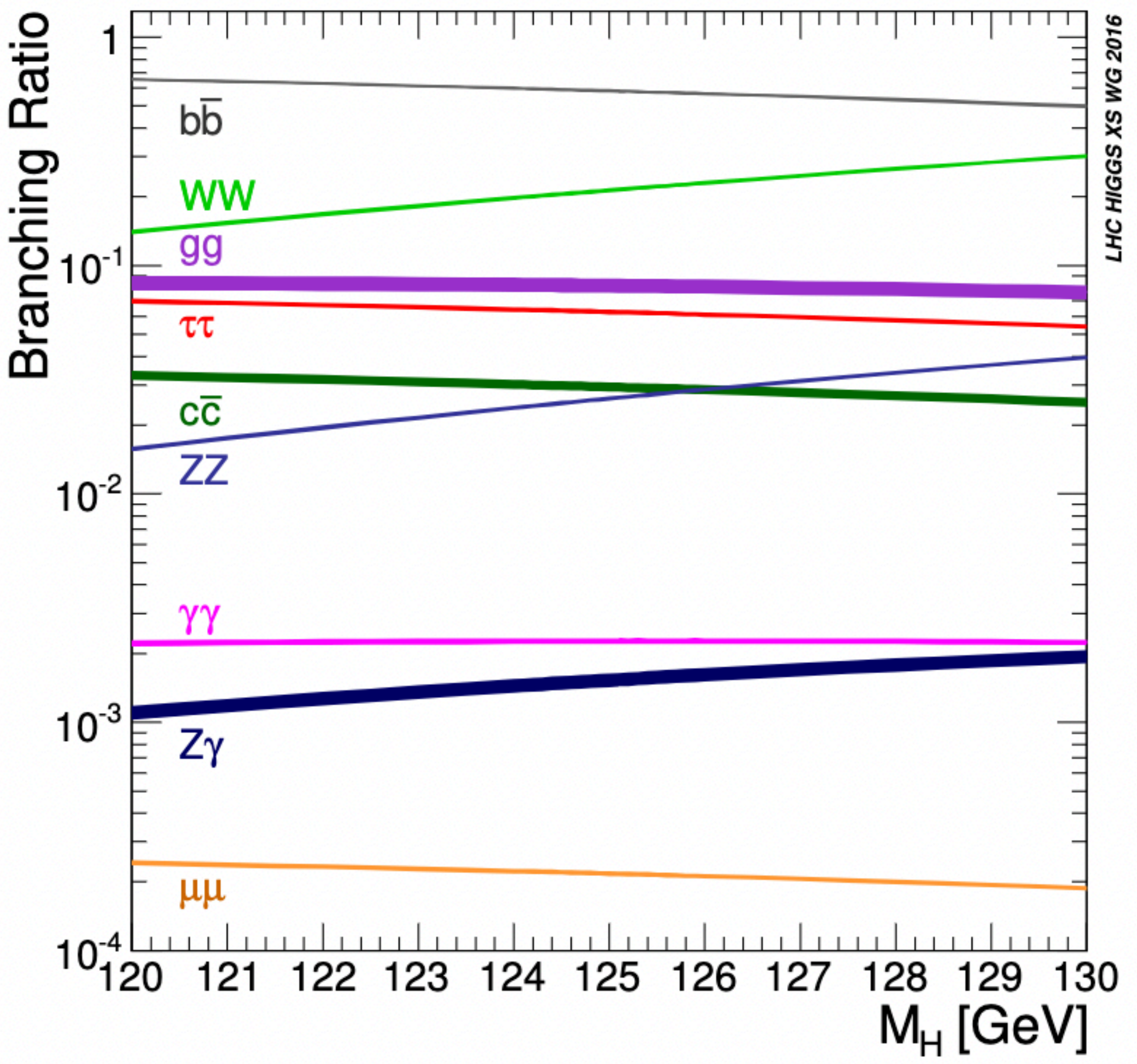
… Production and decay at the LHC



$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

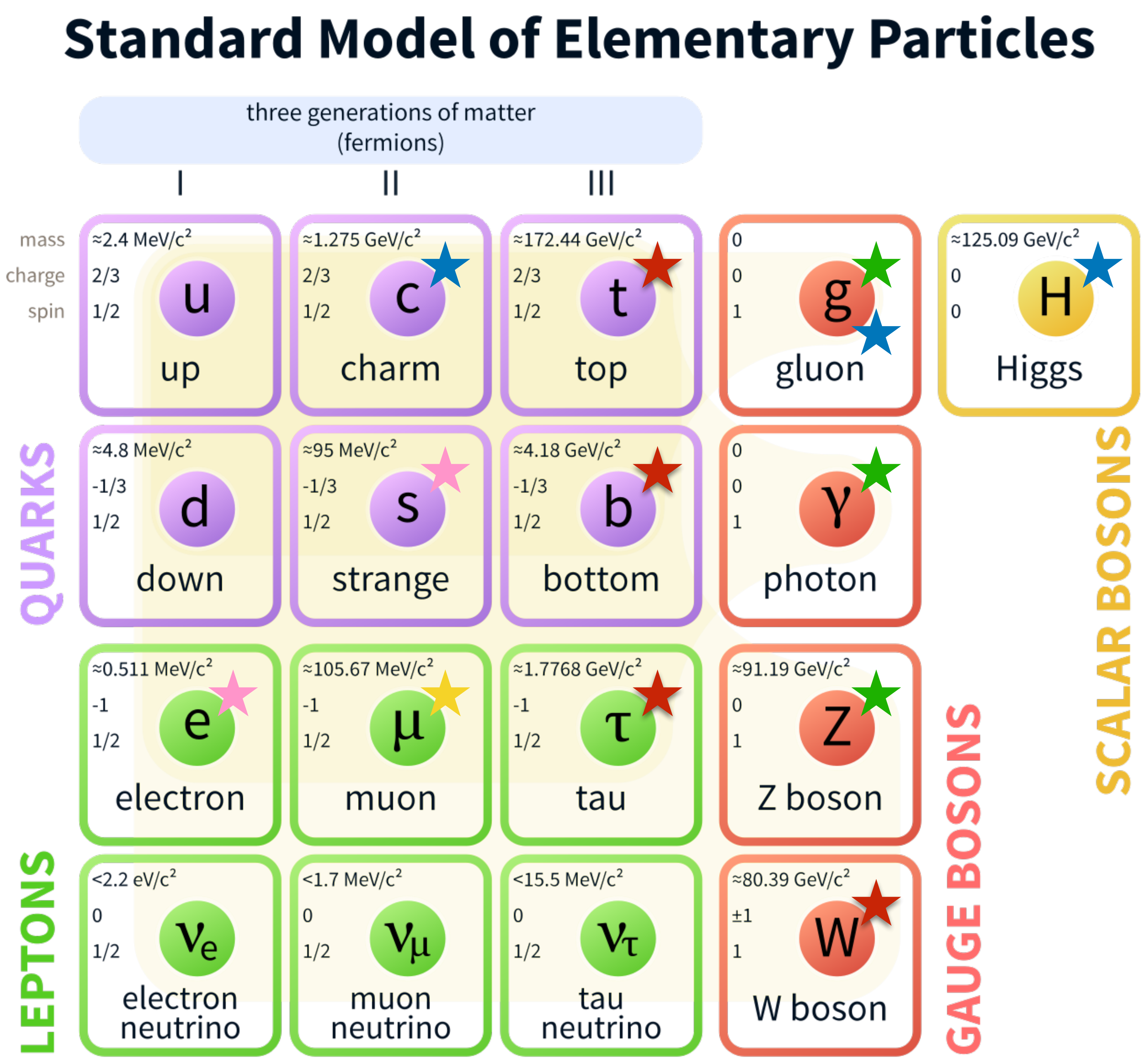






Higgs Physics

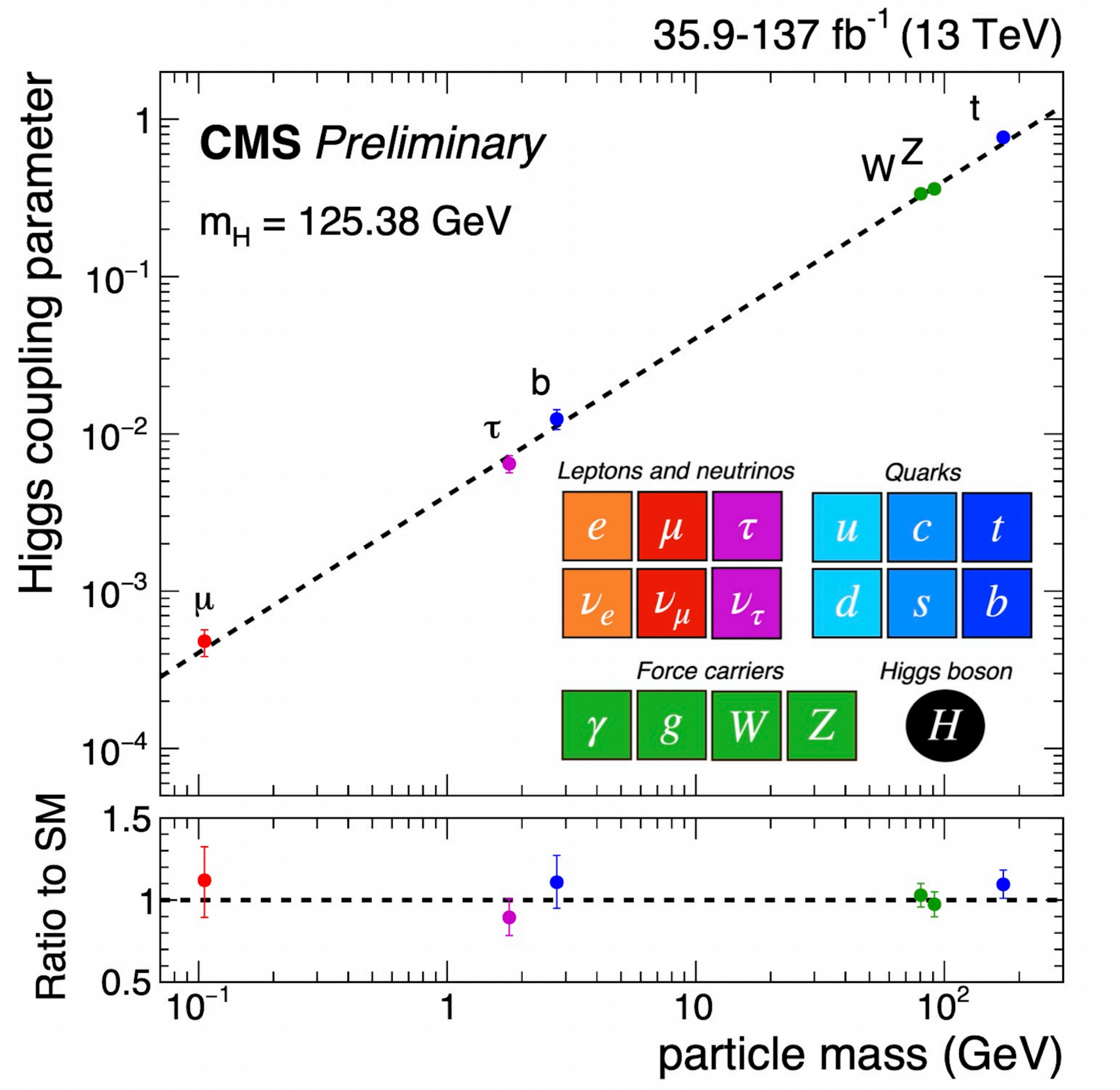
… Status of Higgs Coupling Measurements

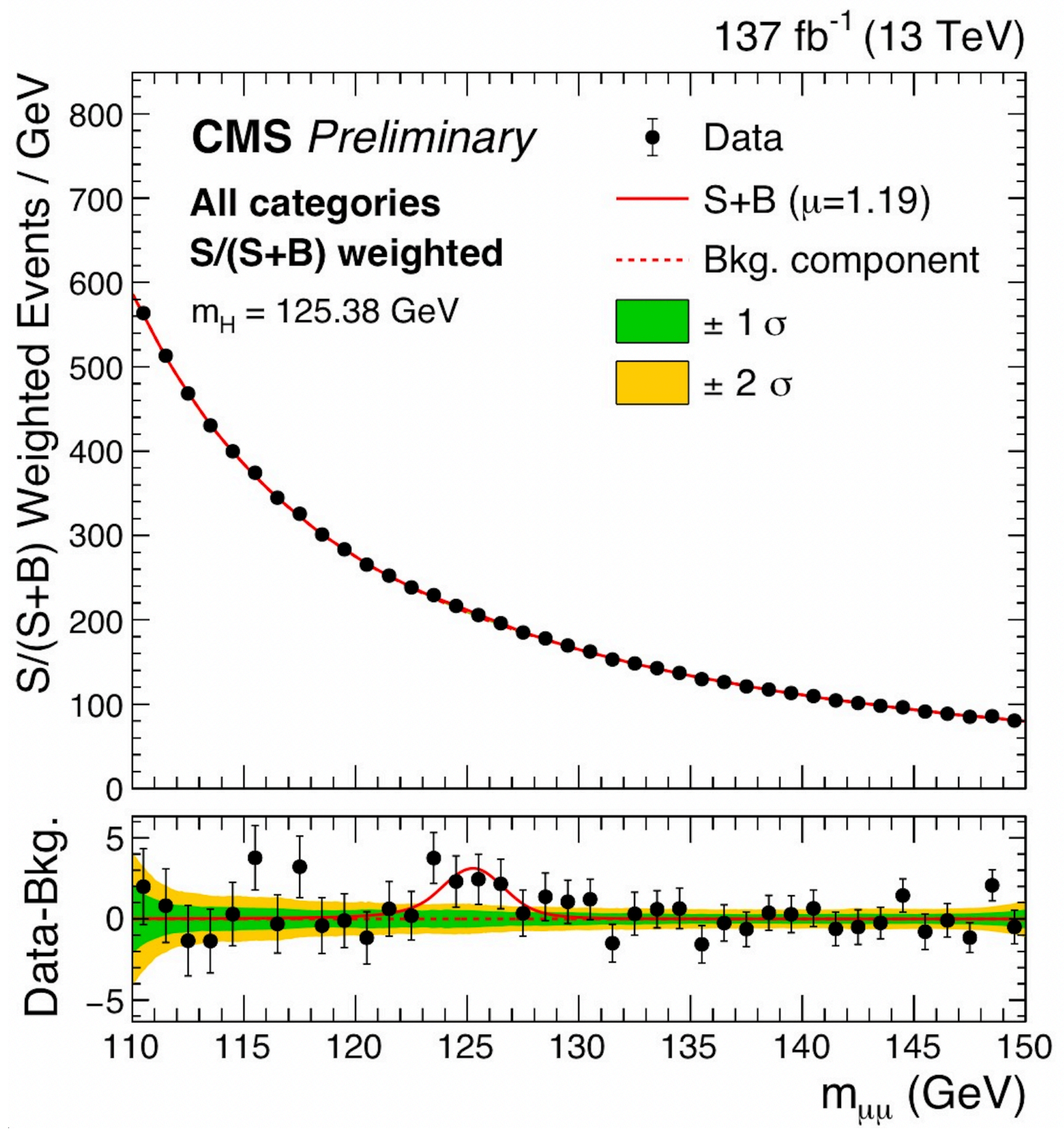


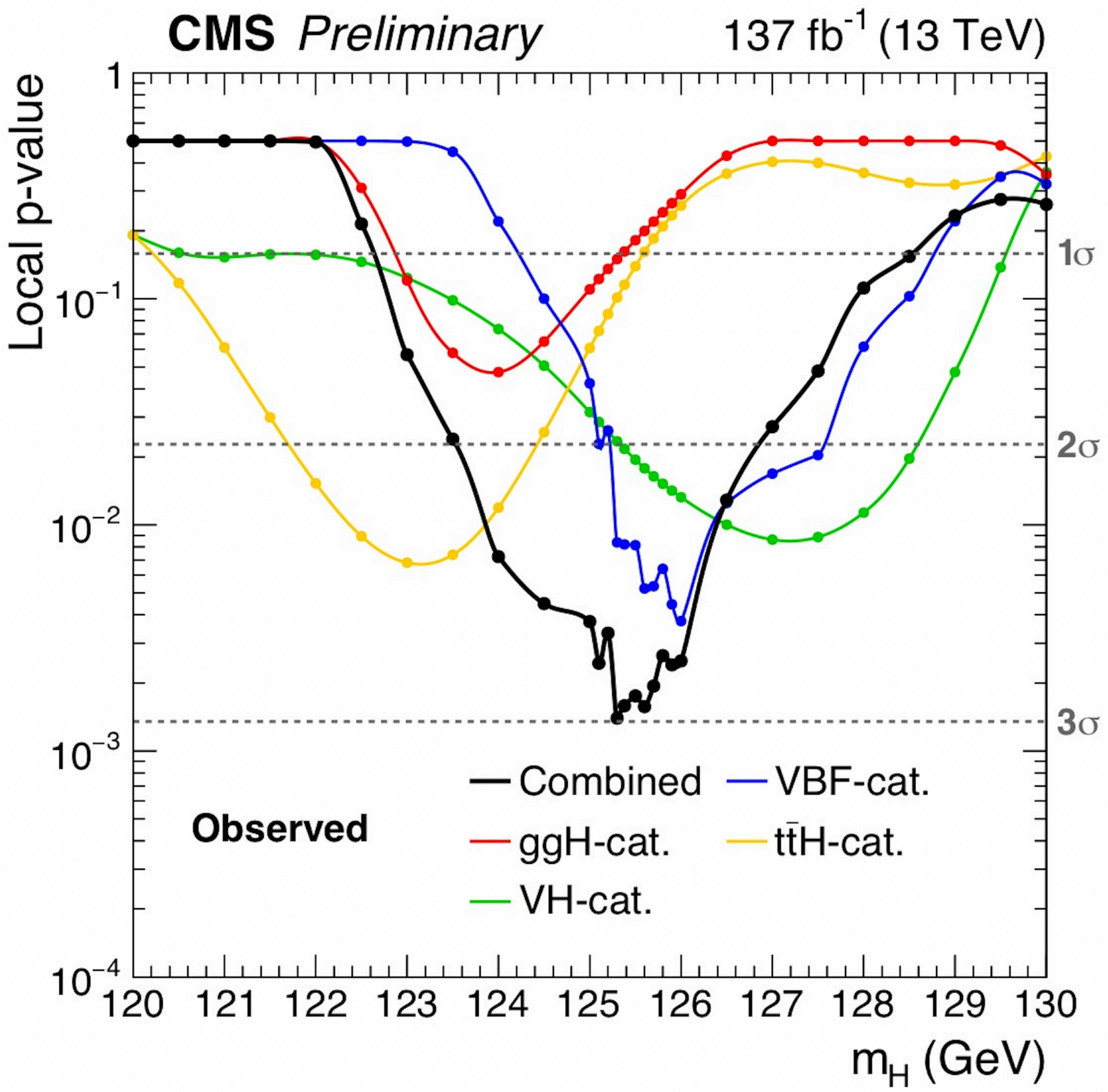
- ★ Observed in 2012
- ★ Observed
- ★ Evidence today
- ★ Getting there with the LHC
- ★ Studies with e^+e^- Higgs Factory

Higgs Physics

… latest results





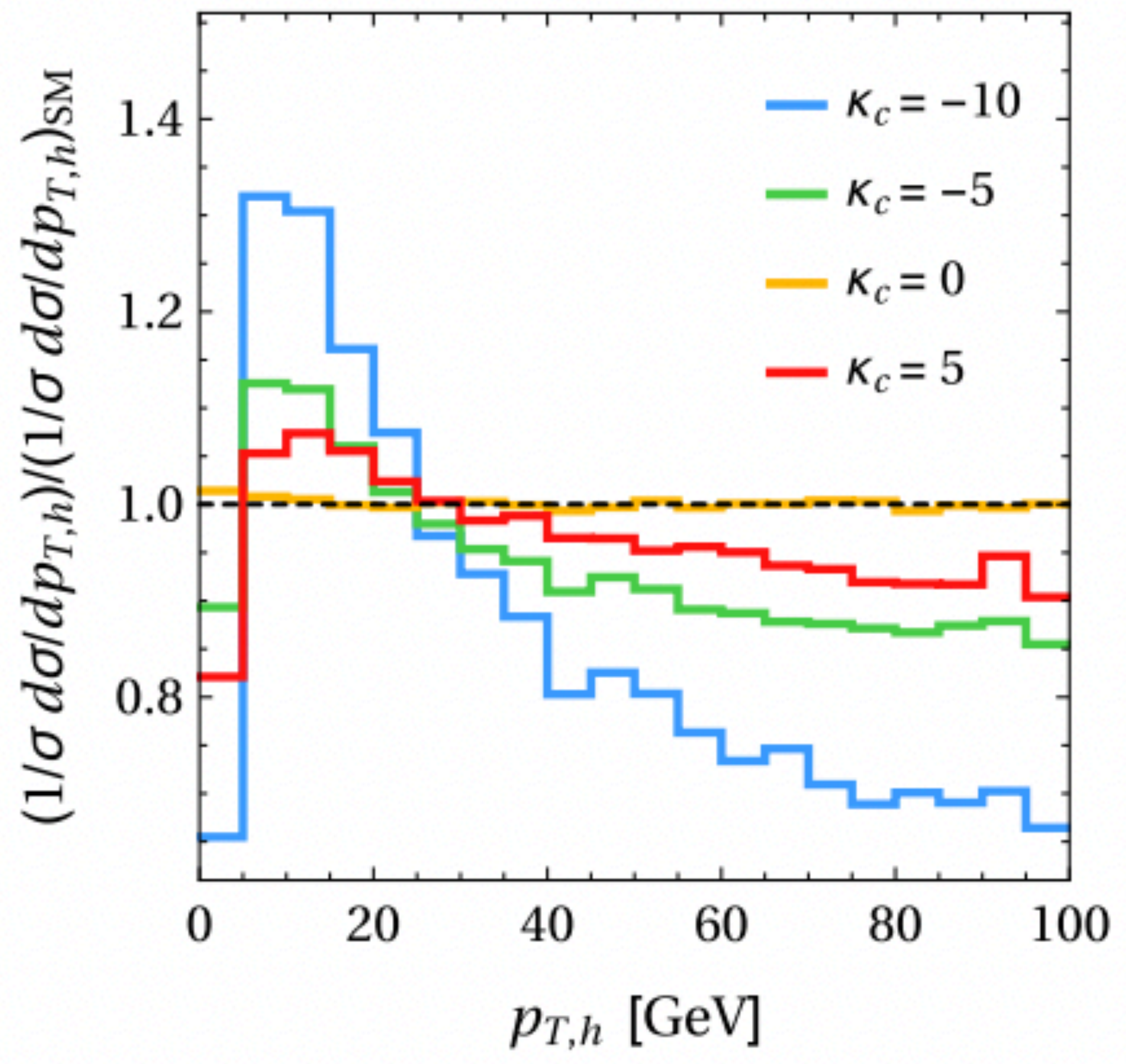


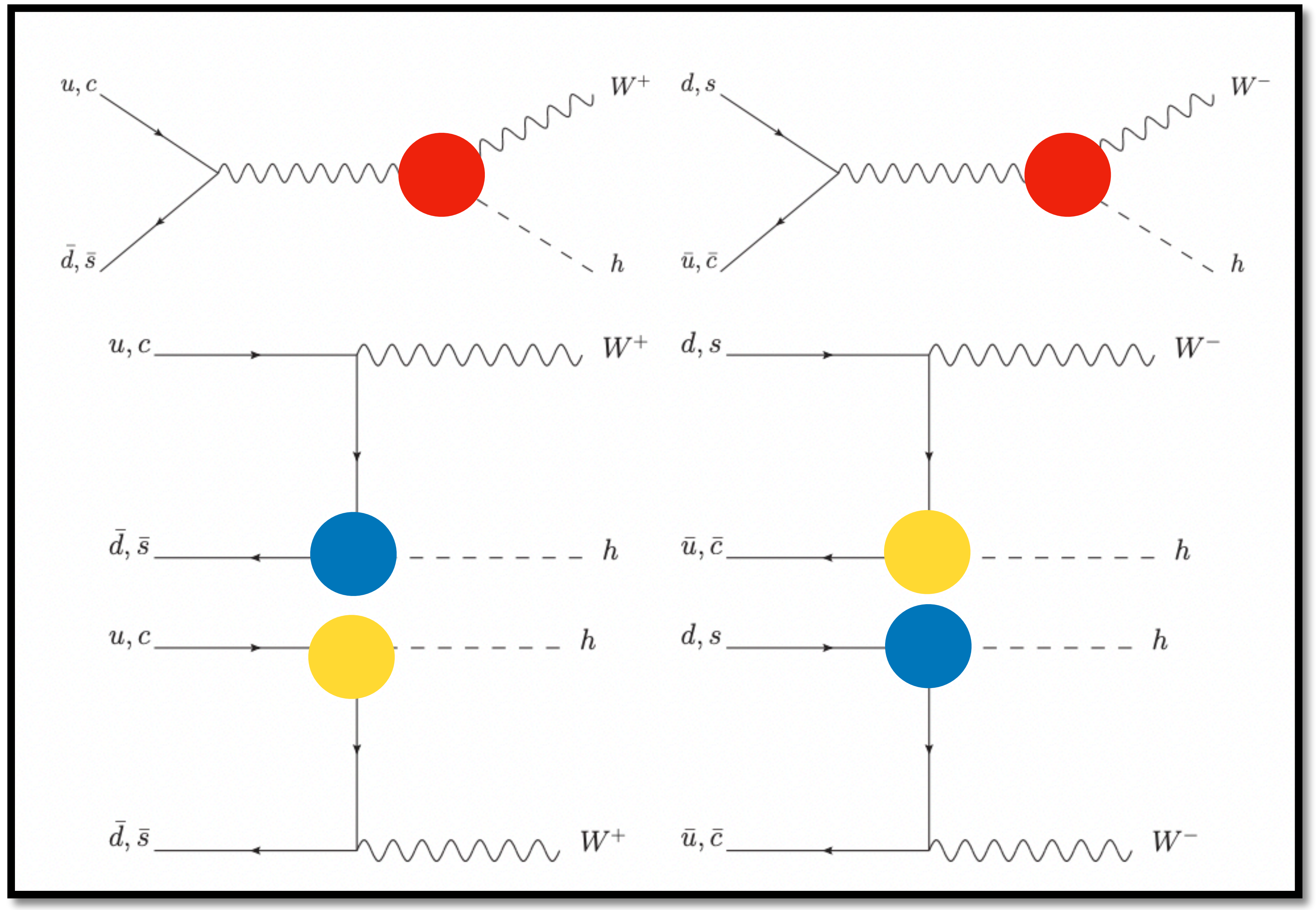
Higgs Physics

… how charming is the Higgs Boson?

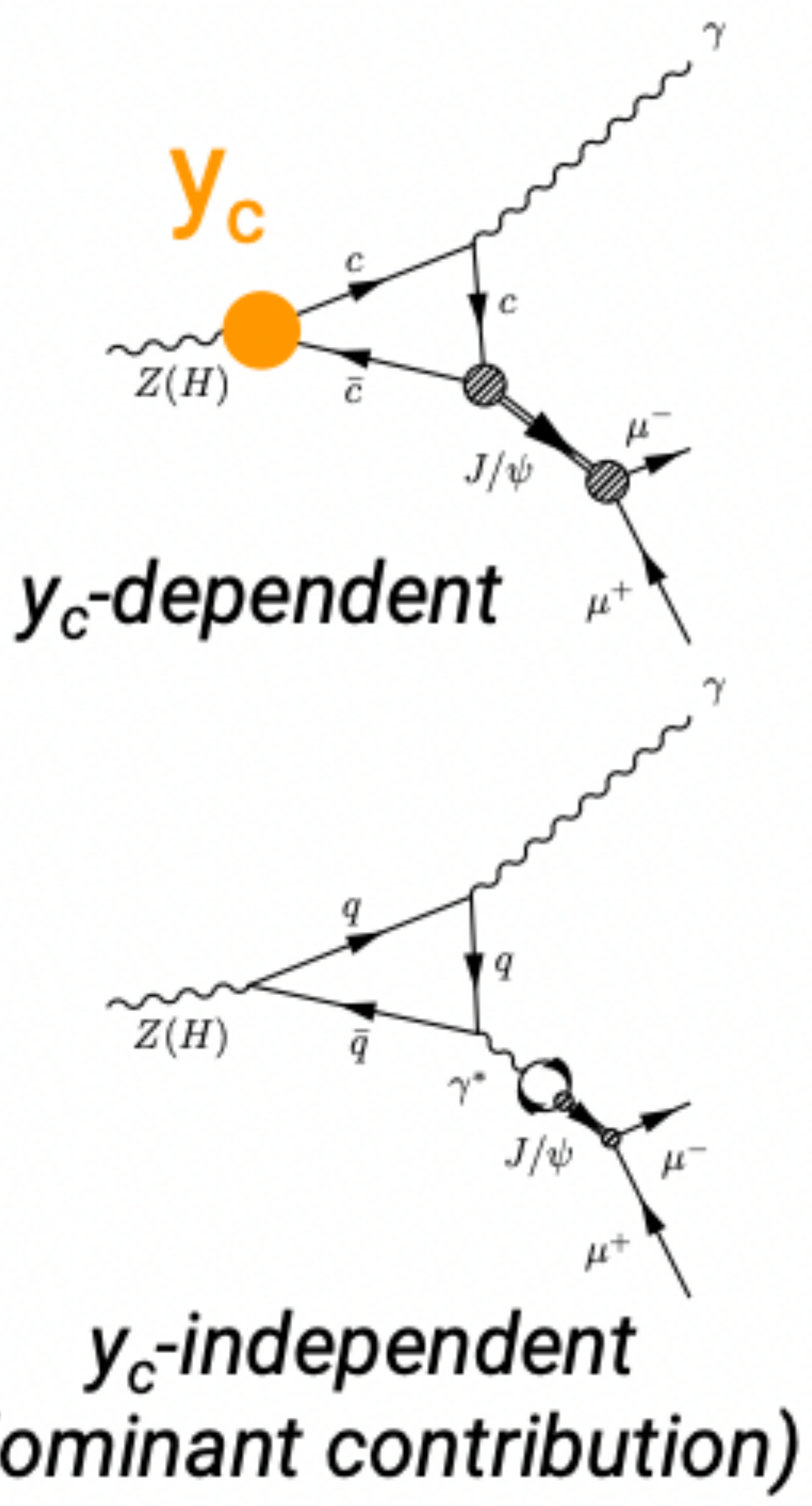
- Several methods to explore light quark (charm) Higgs Yukawa couplings
    - Indirect constraint from Higgs kinematics
    - Search for exclusive Higgs decays (H →J/ψ γ)
    - Study of charge asymmetry in WH production
    - Direct search for Higgs decays

Phys. Rev. Lett. 118, 121801



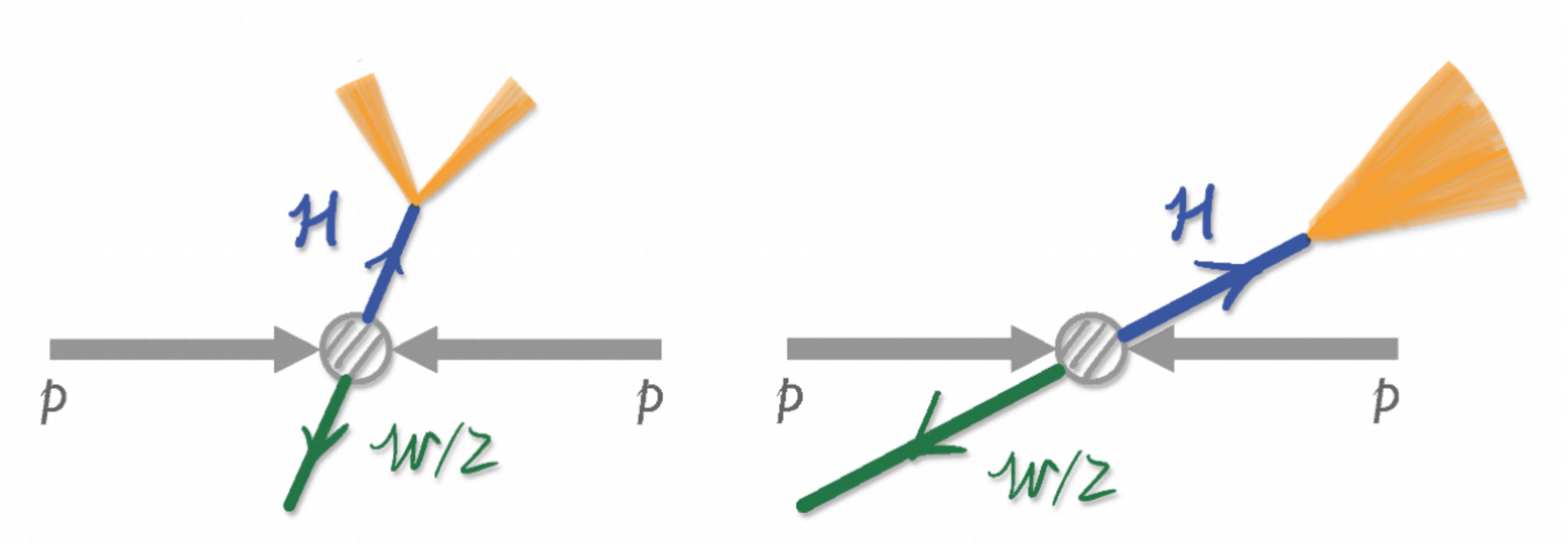


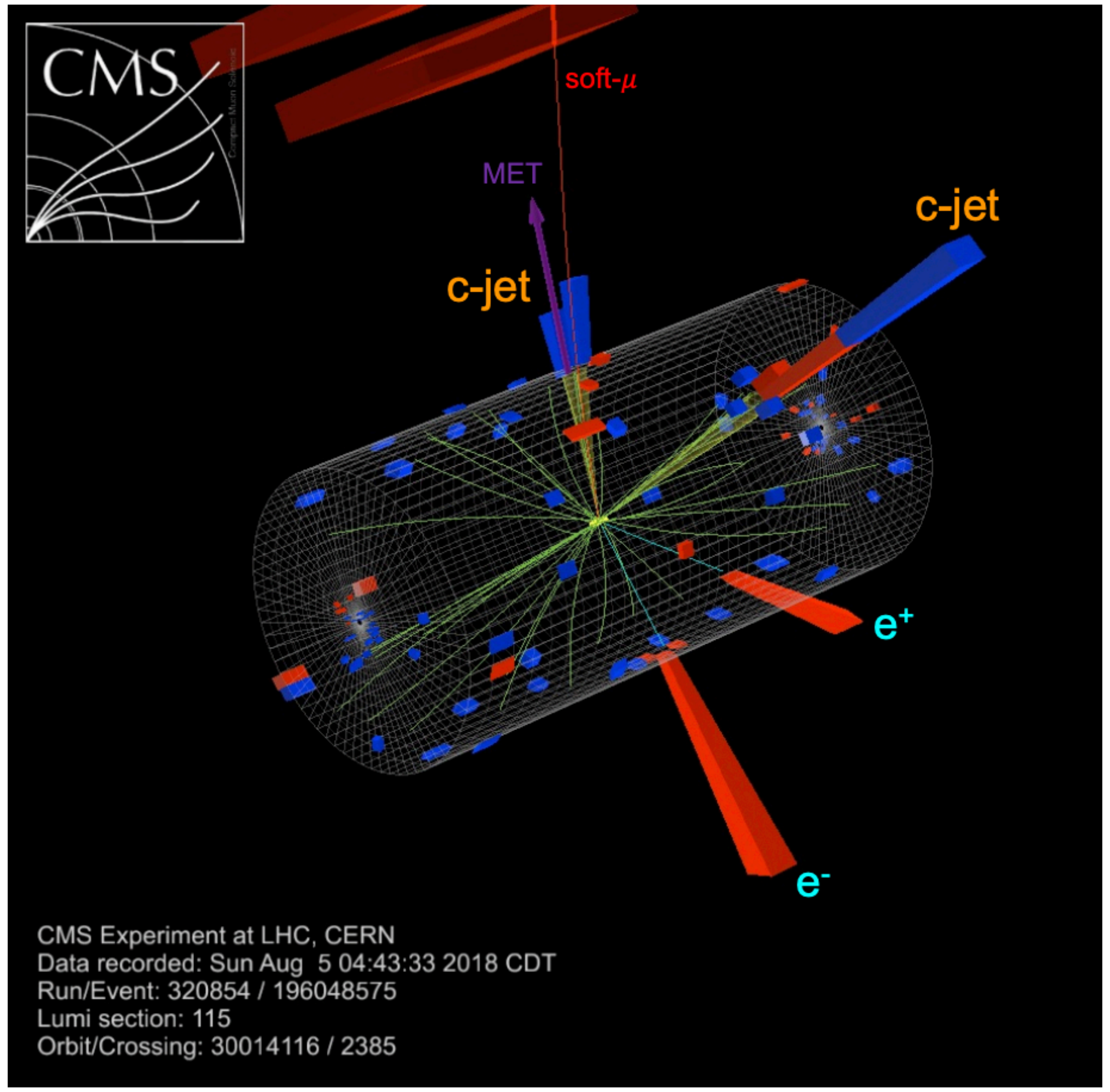
Eur. Phys. J. C 79 (2019) 94

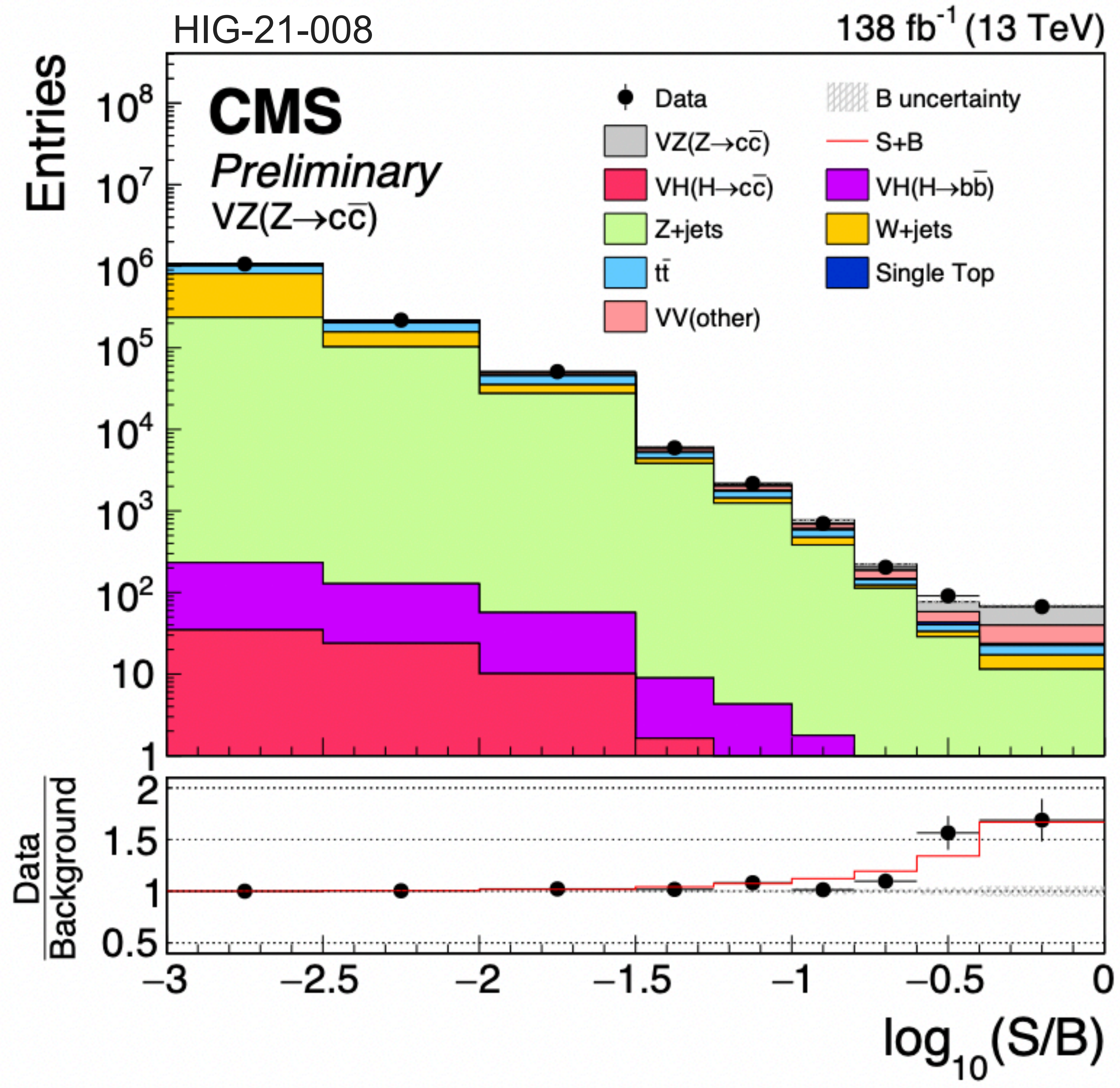


Higgs Physics

… how charming is the Higgs Boson?





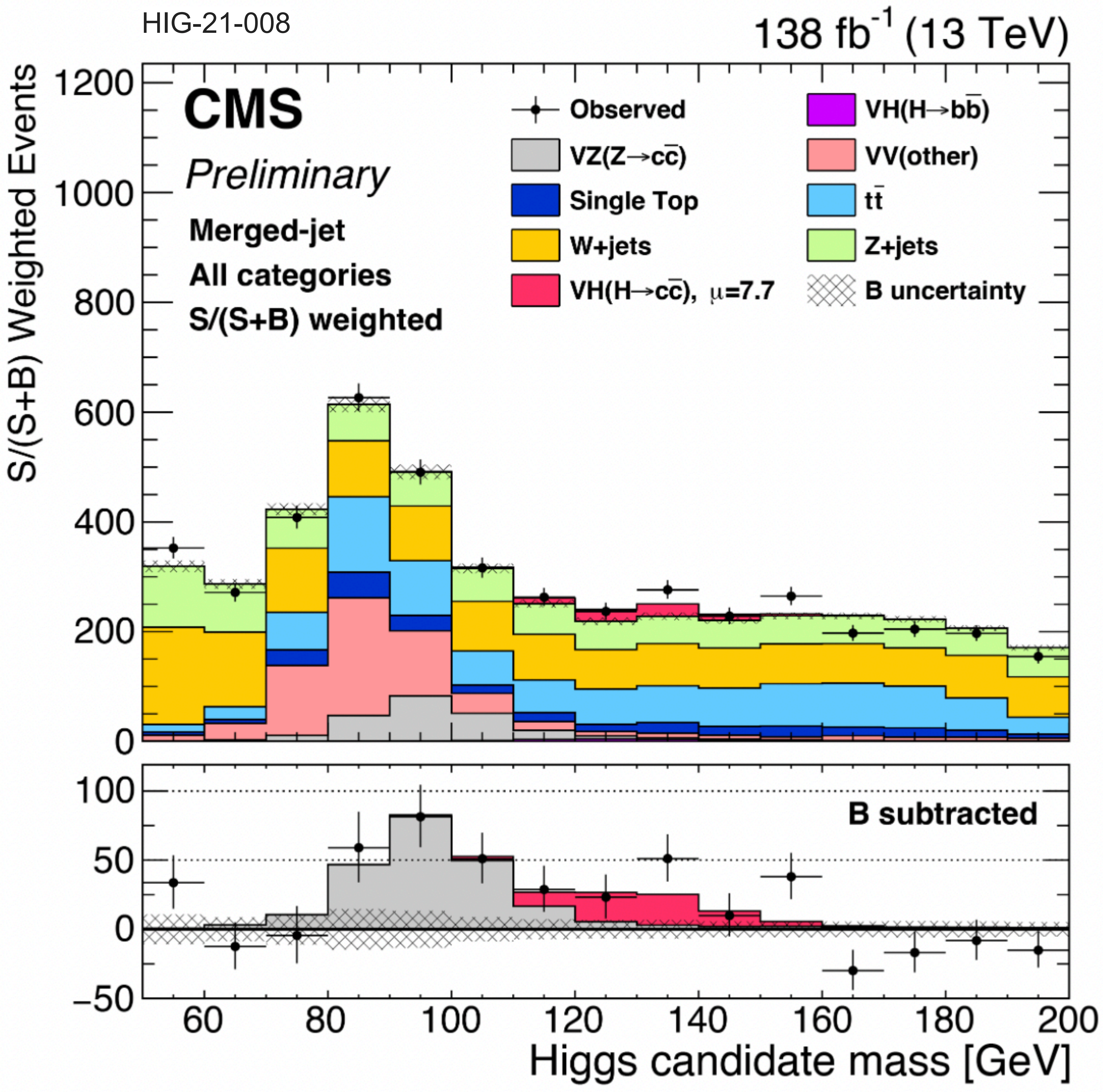


- Measured VZ (Z → cc) production
  - Cross section consistent with SM expectation ~20% uncertainty
  - First observation (5.7σ) of Z → cc at a hadrons collider

Higgs Physics

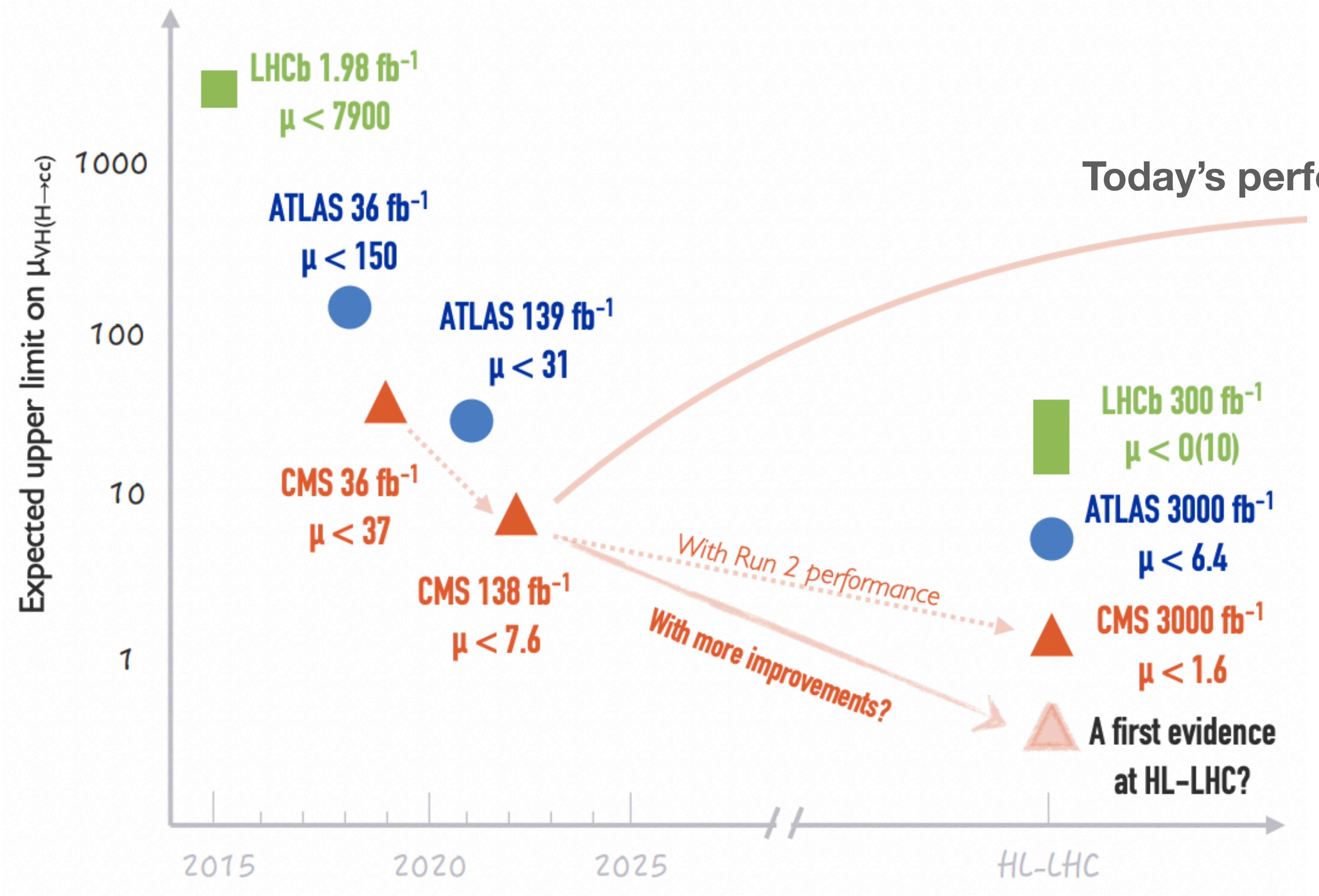
… how charming is the Higgs Boson?

- Upper limits on VH (H → cc) production
  - Excluding cross section 14 times SM expectation (7.6 exp. limit)
  - Constraints on Higgs-charm coupling 1.1< | κ_c | < 5.5 (| κ_c | < 3.4 exp. limit)



Higgs Physics

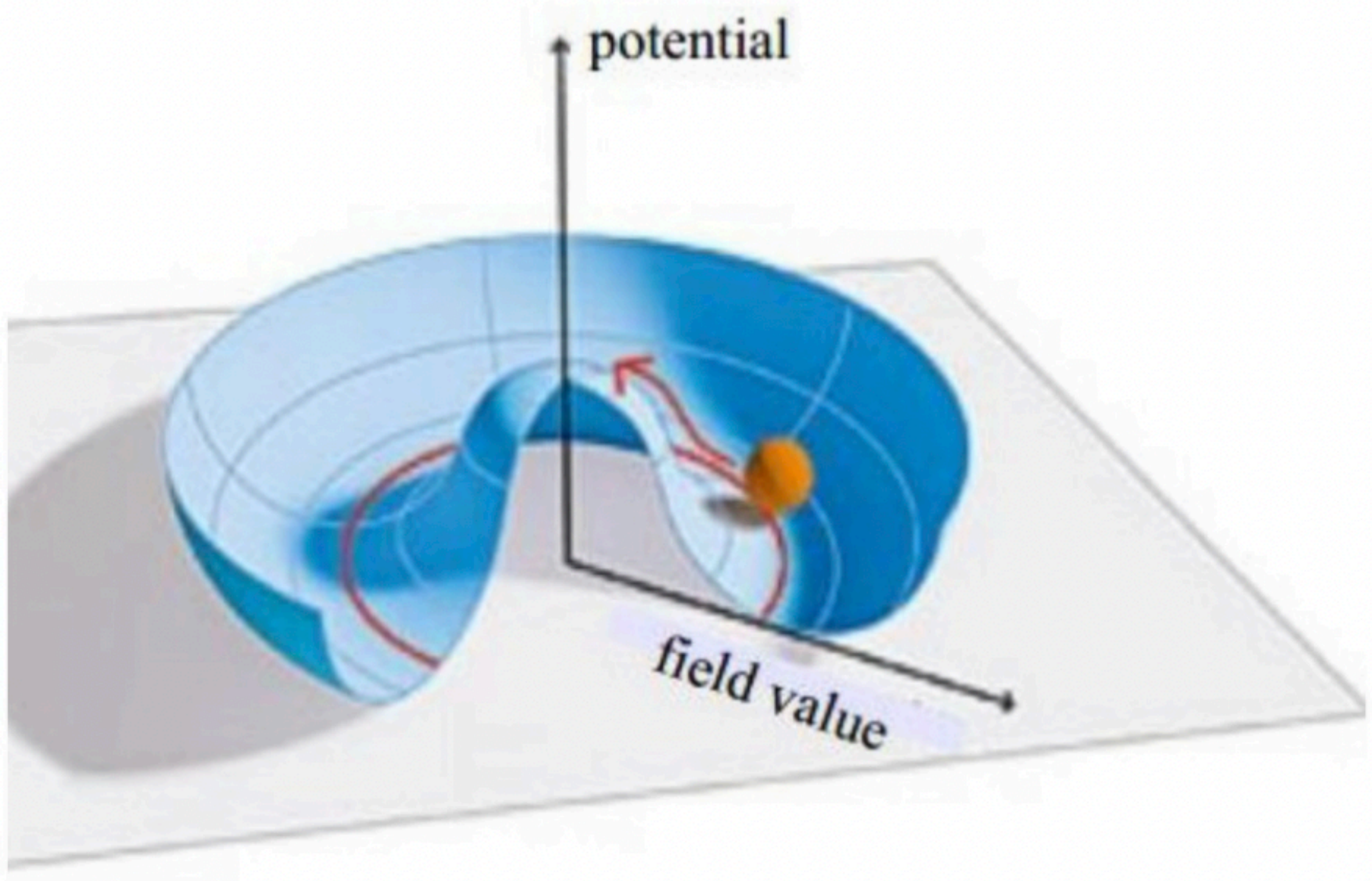
… how charming is the Higgs Boson?



Today's performance

Higgs Physics

… study of the Higgs potential

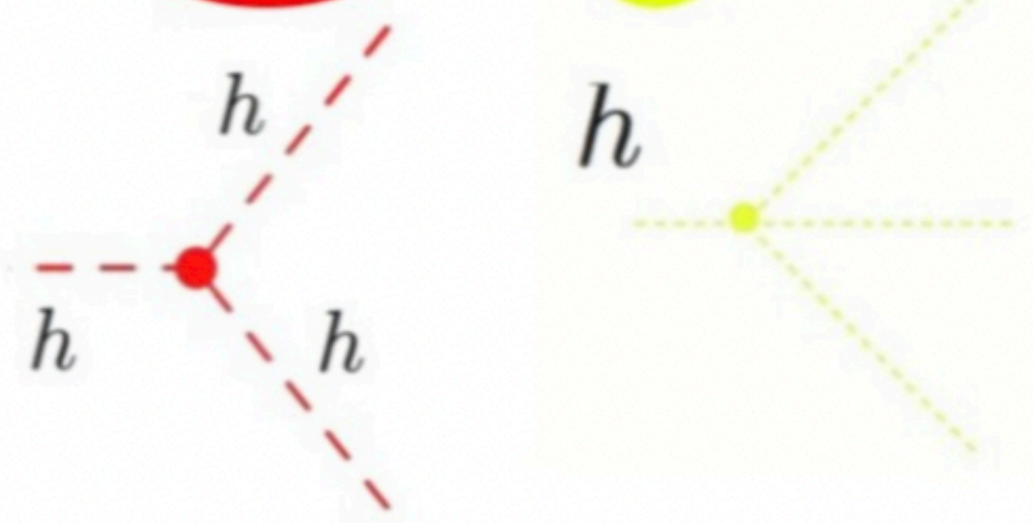


Higgs potential in the standard model:

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2$$

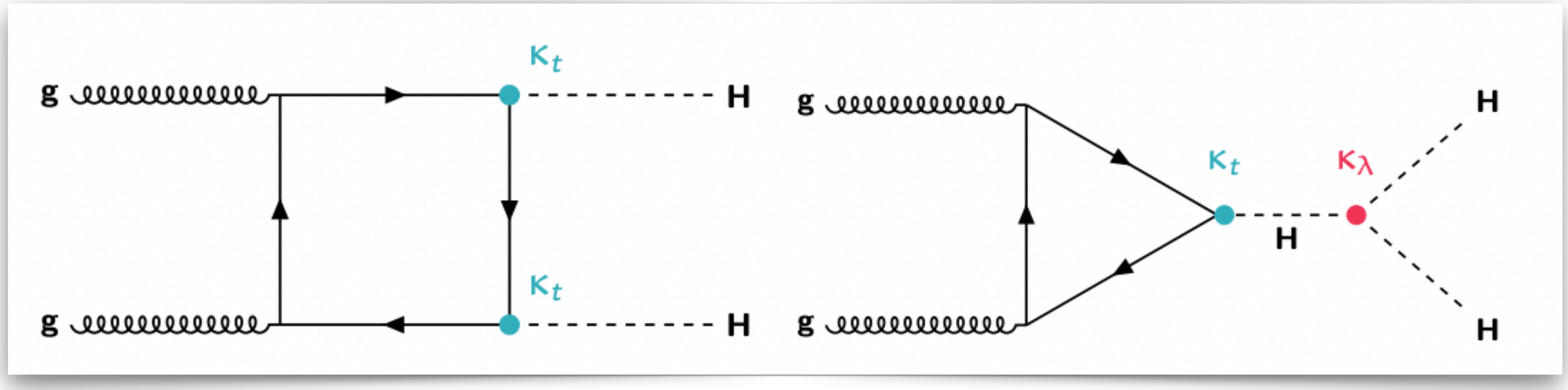
expansion around the minimum

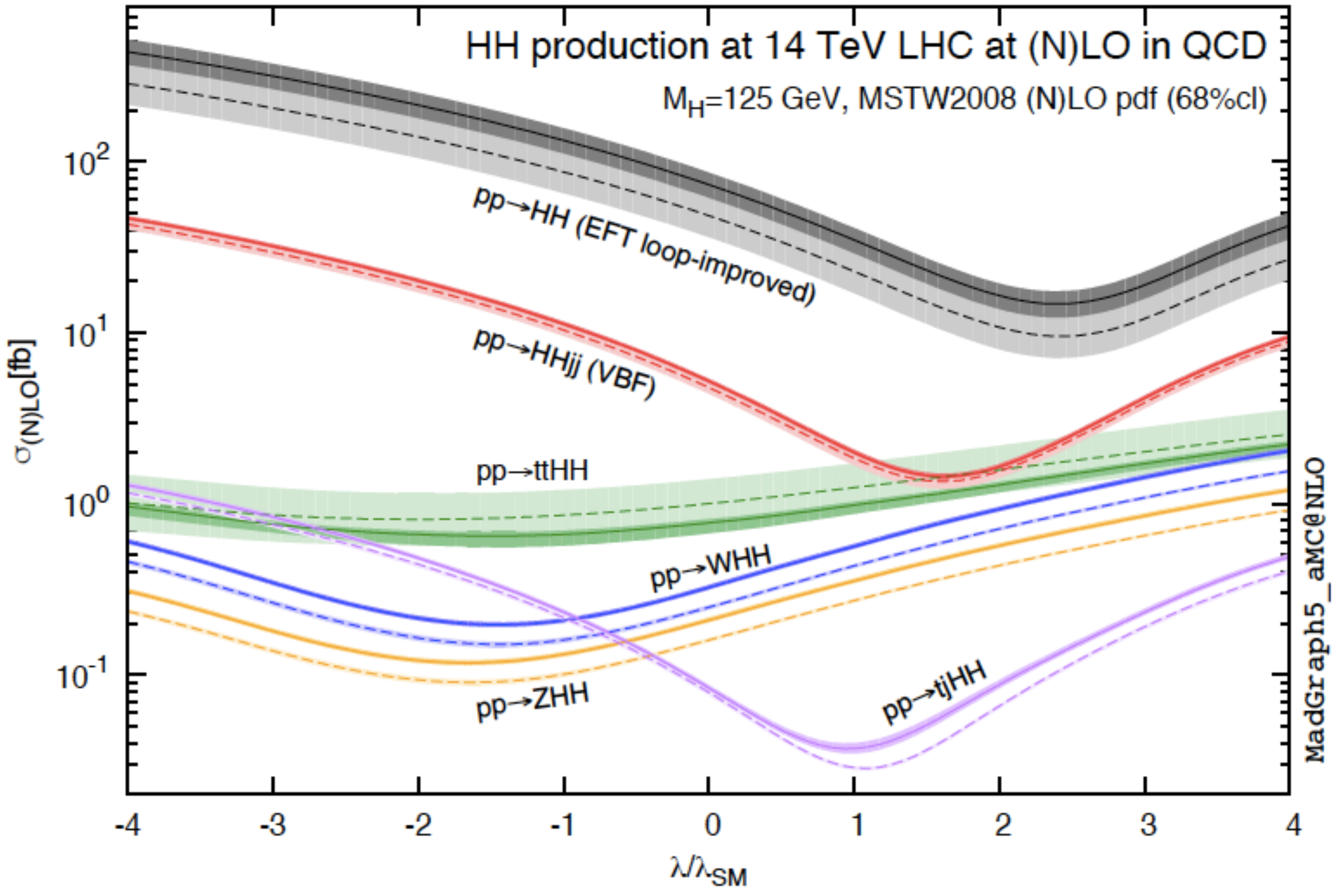
$$\frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4$$



Higgs Physics

… study of the Higgs potential



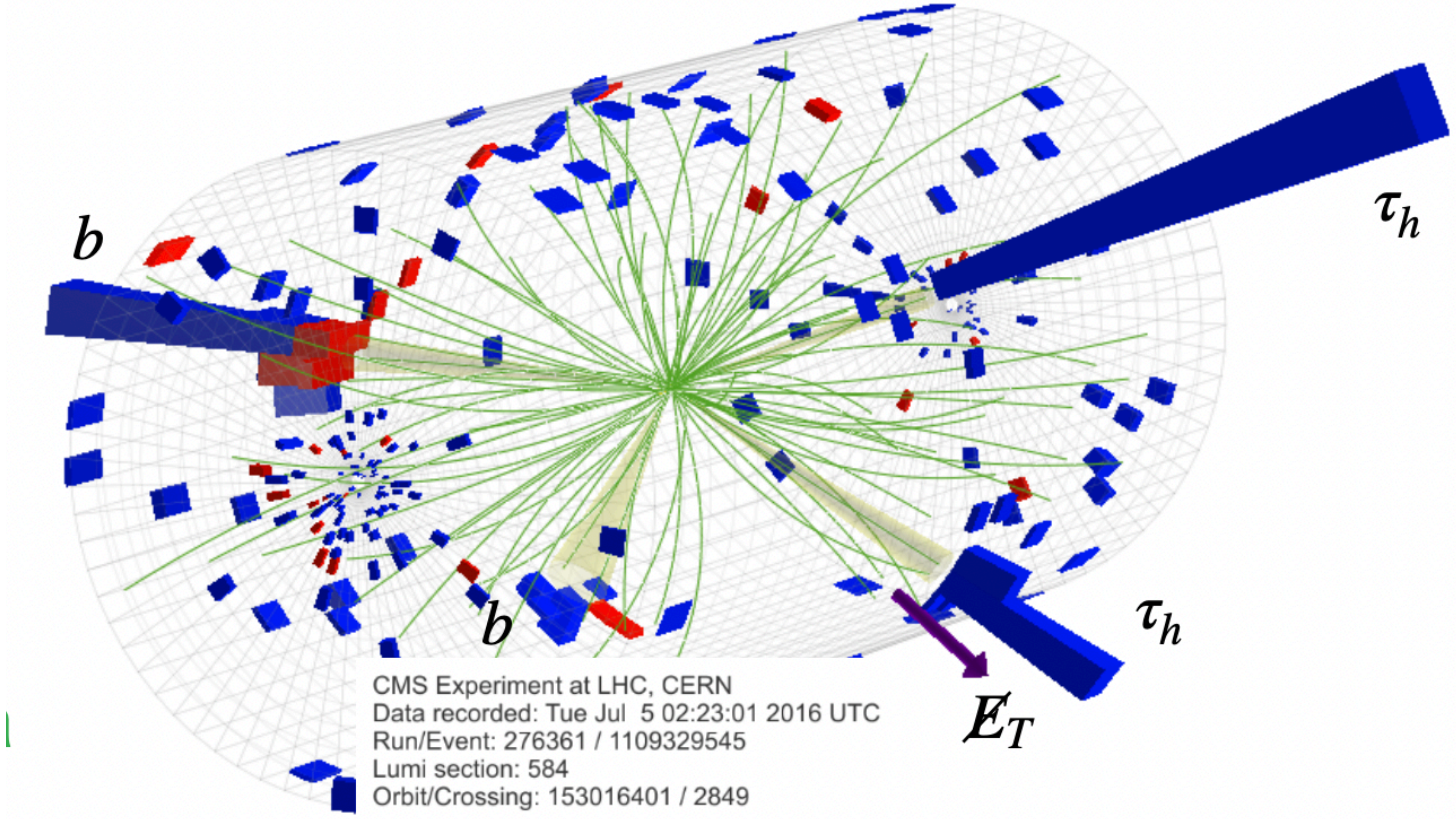


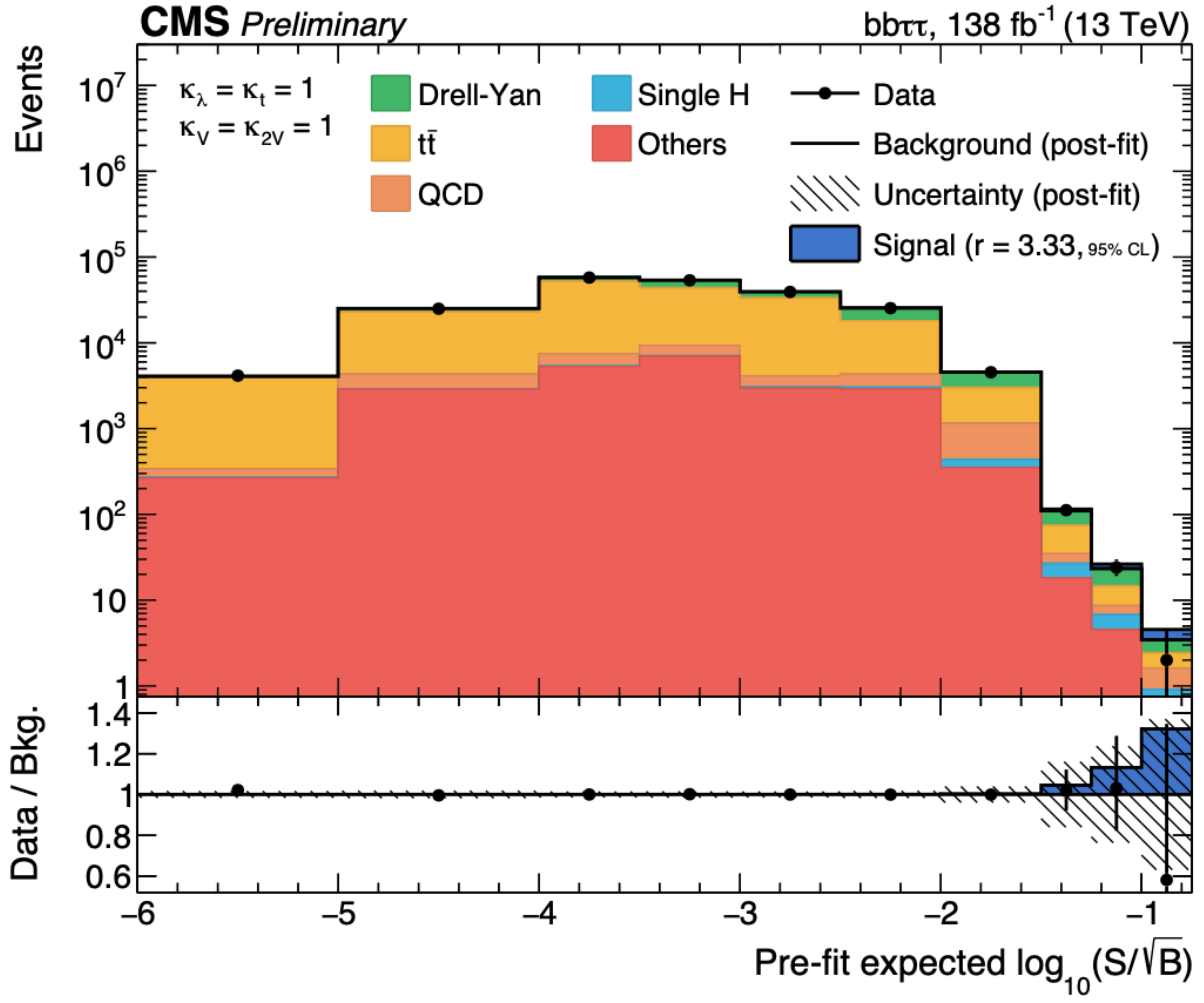
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Higgs Physics

… study of the Higgs potential

- HH → bb ττ





CMS-HIG-20-010

$$\sigma(pp \to HH) = 3.3(5.2) \times \sigma^{SM}_{ggF+VBF}$$

Higgs Physics

… study of the Higgs potential

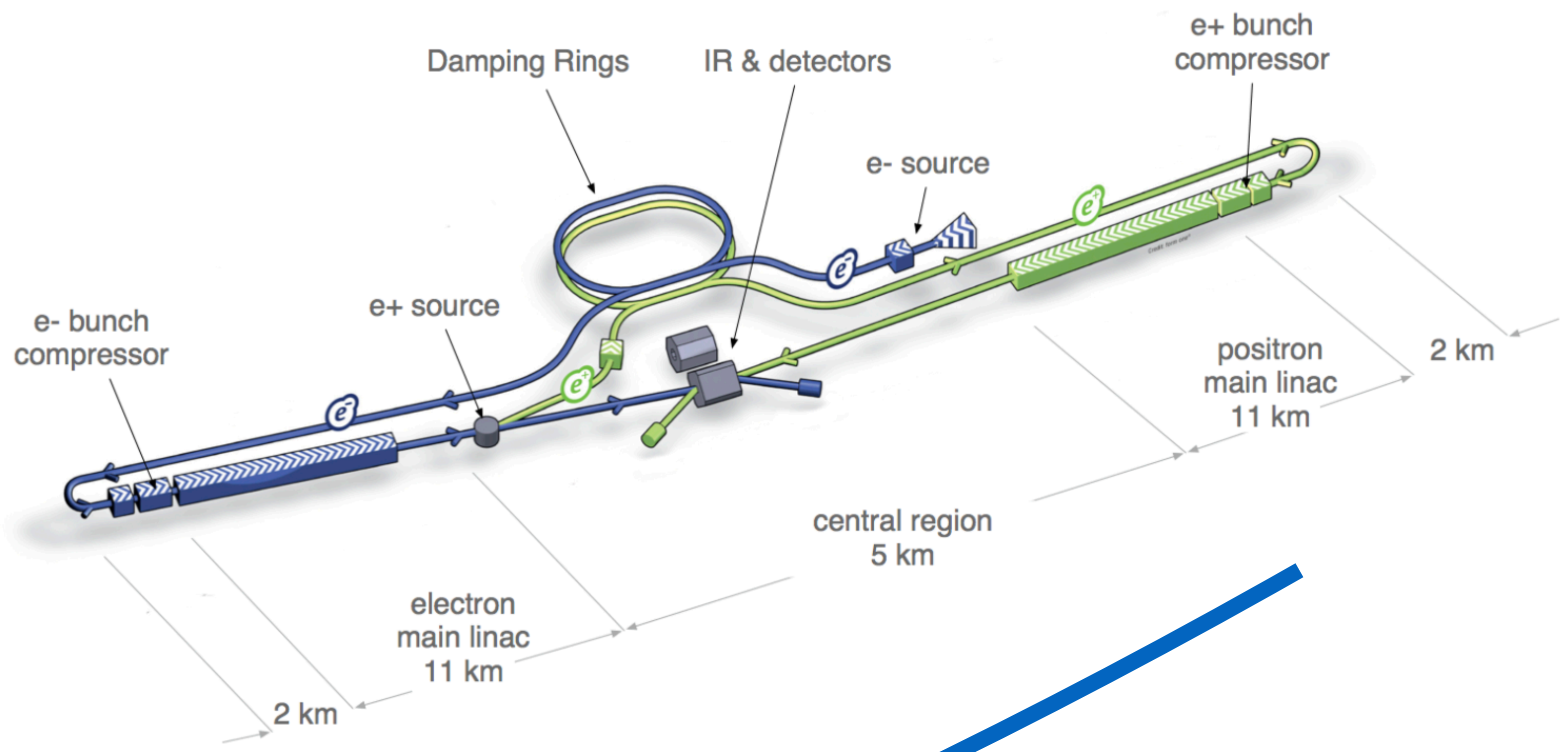
		$\sigma_{HH}/\sigma_{HH}^{SM}$ 95% CL Obs.	Exp.	Improvement wrt. 36 fb^{-1} tot. (w/o lumi)	κ_λ 95% CL Obs.	Exp.
$HH \to bb\gamma\gamma$	ATLAS	4.1	5.5	×5.1 (2.5)	[-1.5, 6.7]	[-2.4, 7.7]
	CMS	7.7	5.2	×3.9 (2)	[-3.3, 8.5]	[-2.5, 8.2]
$HH \to bb\tau\tau$	ATLAS	4.7	3.9	×3.8 (2)	[-2.4, 9.2]	[-2.0, 9.0]
	CMS	3.3	5.2	—	—	—
$HH \to bbbb$	ATLAS	—	—	—	—	—
	CMS	3.9	7.8	×5.1 (2.6)	[-2.3, 9.4]	[-5.0, 12.0]
$HH \to bbZZ$	ATLAS	—	—	—	—	—
	CMS	30	37	—	[-9.0, 14.0]	[-10.5, 15.5]
Multilepton	ATLAS	—	—	—	—	—
	CMS	21.8	19.6	—	[-7.0, 11.7]	[-7.0, 11.2]
Combination ($bb\gamma\gamma$+$bb\tau\tau$)	ATLAS	3.1	3.1	×3.5 (1.8)[a]	[-1.0, 6.6]	[-1.2, 7.2]
	CMS	—	—	—	—	—

$\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment

	Statistical-only ATLAS	CMS	Statistical + Systematic ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

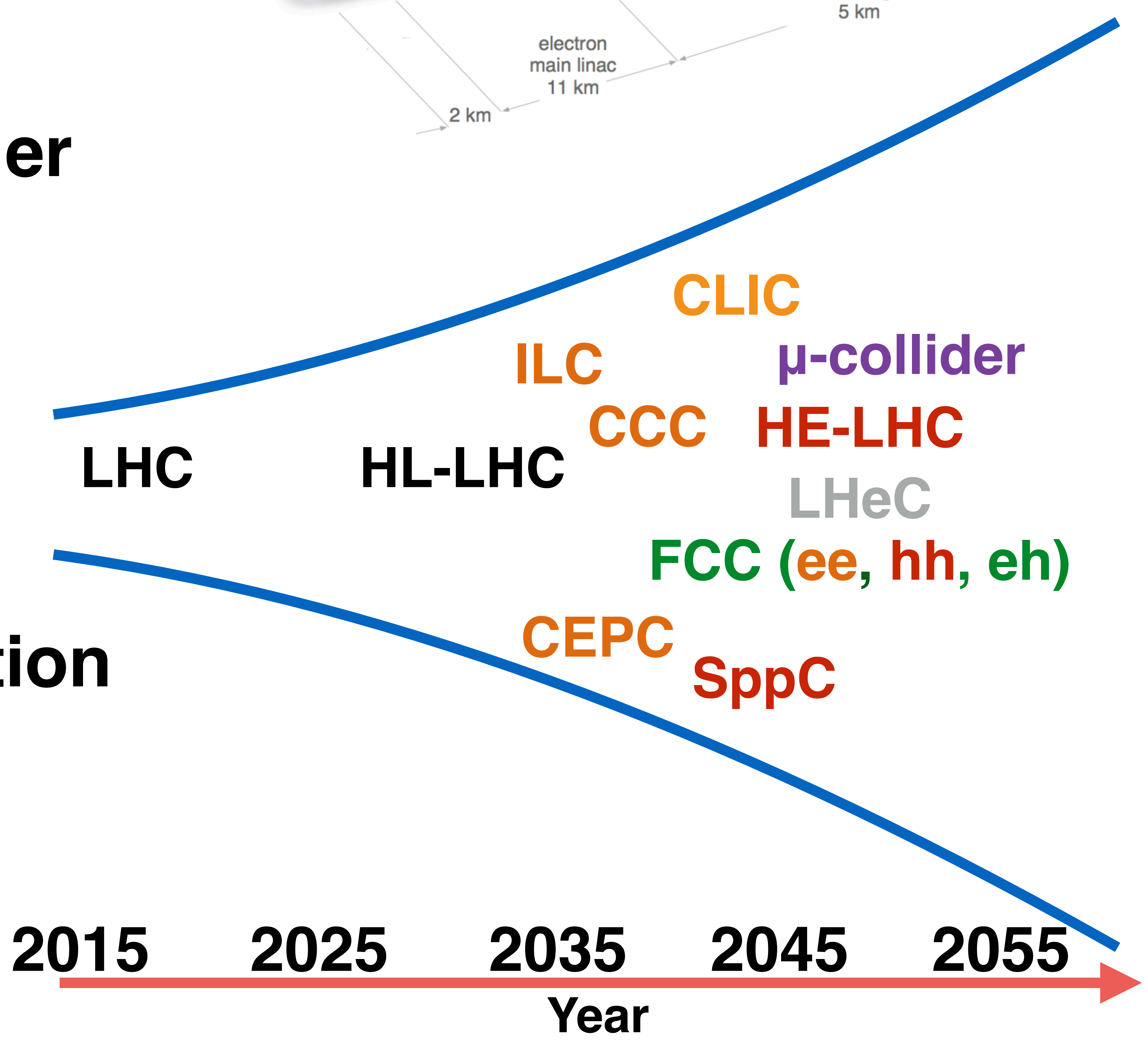
Higgs Physics

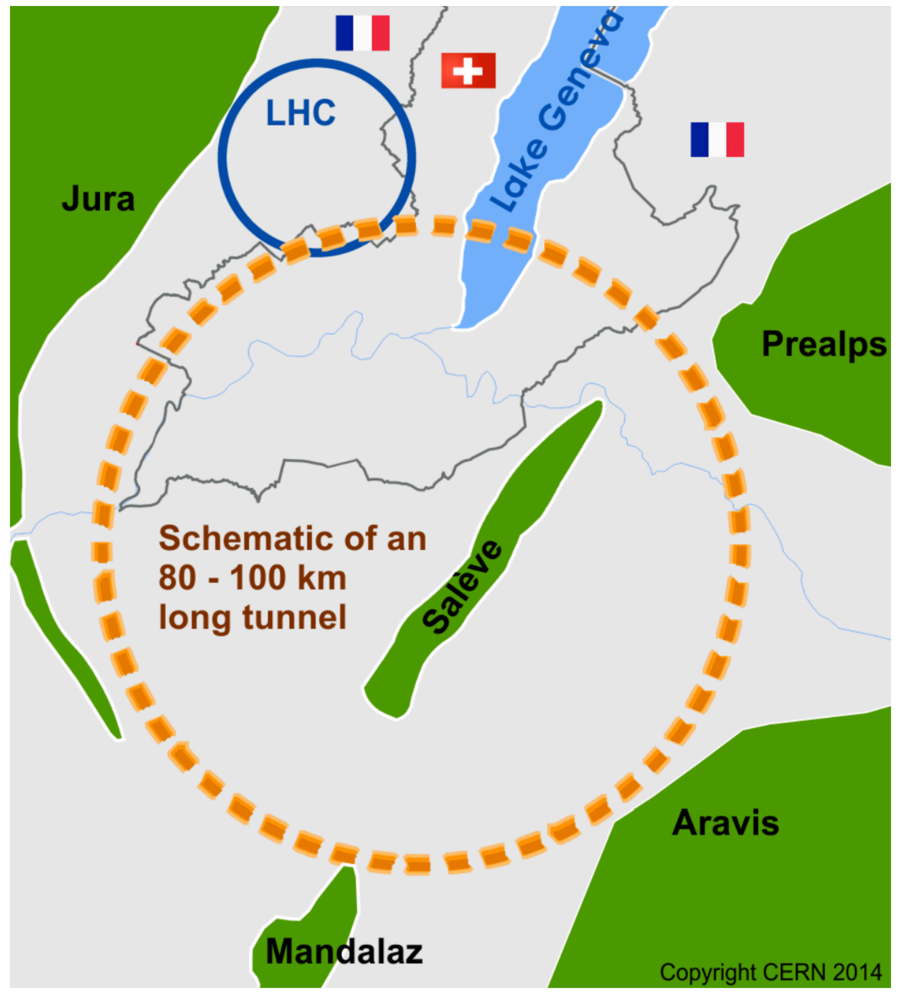
… beyond the LHC



LHC (and HL-LHC) is the energy frontier for foreseeable future

- Fantastic opportunity for great physics



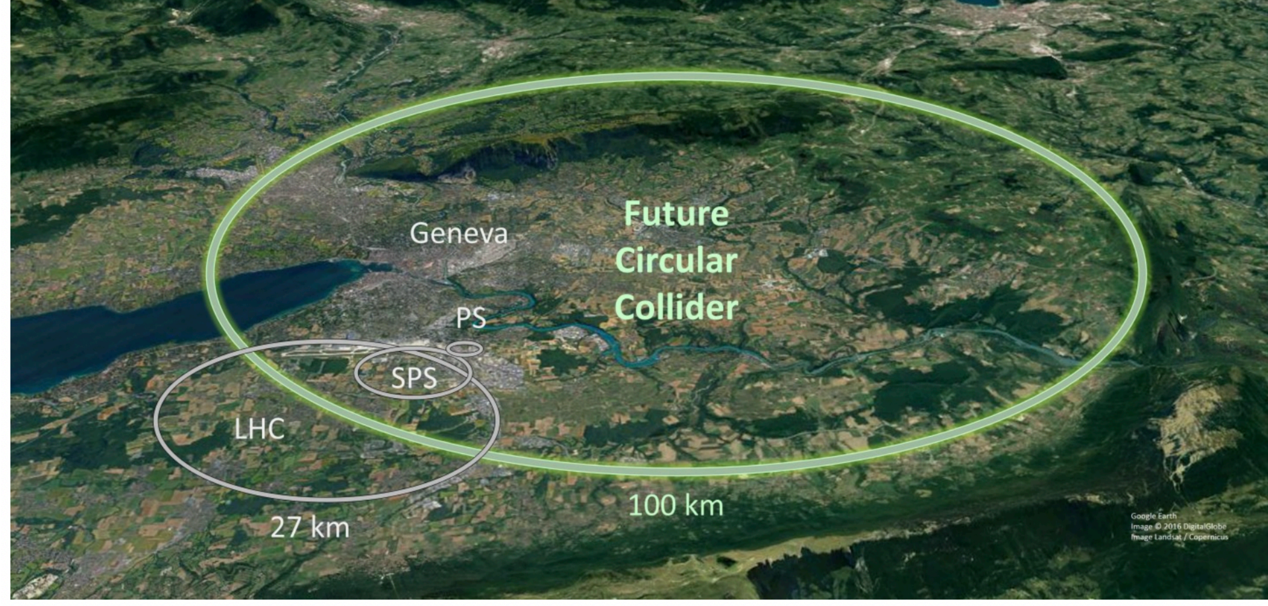


Exploring / preparing the next generation of machines

- Lepton collider for ultimate Higgs measurements and much more
- Future high energy hadron collider

Future Circular Collider

… a roadmap for particle physics at the energy frontier



Technical schedule

1 2 3 4 5 6 7 8 9 10 11 ………………… 19 20 | FCC-ee ~ 15 years operation | 10 years | FCC-hh ~ 25 years operation | 70

Feasibility Study | ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

F. Gianotti

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

Future Circular Collider

… a roadmap for particle physics at the energy frontier

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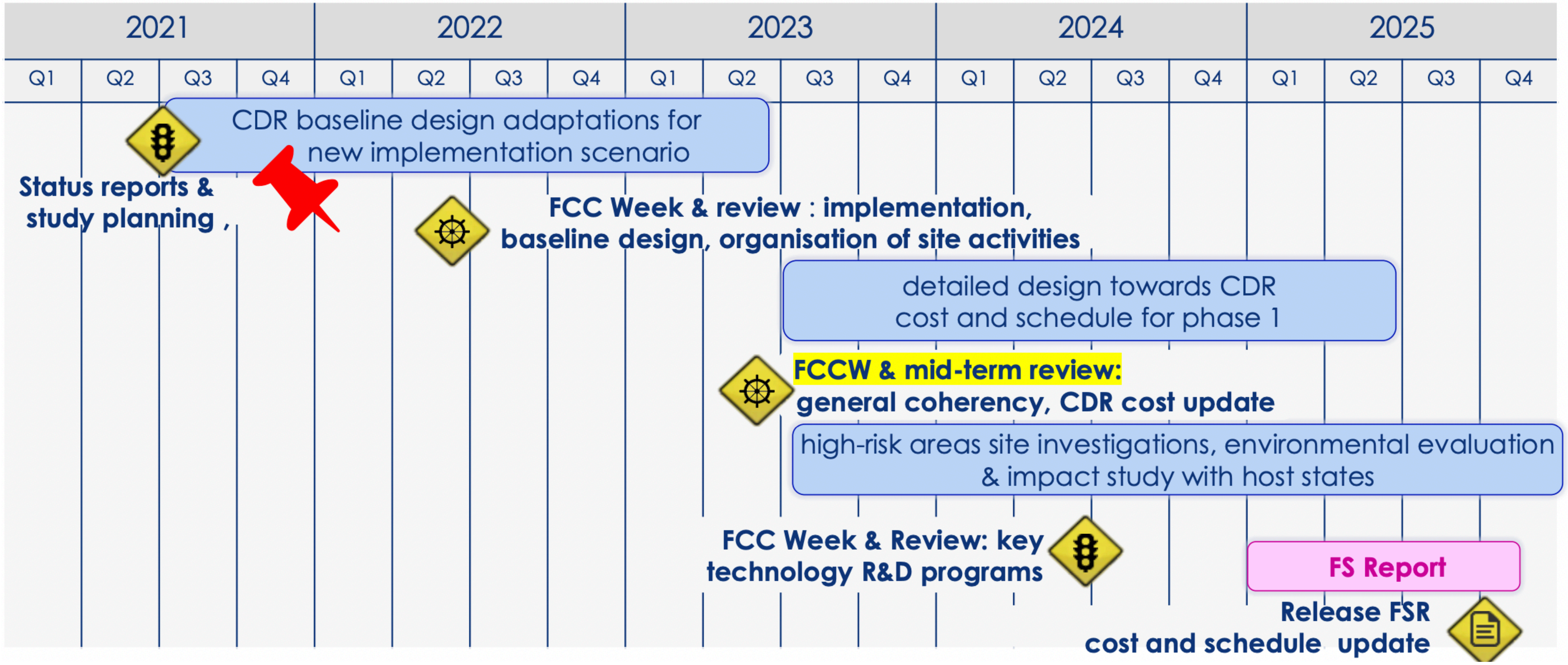
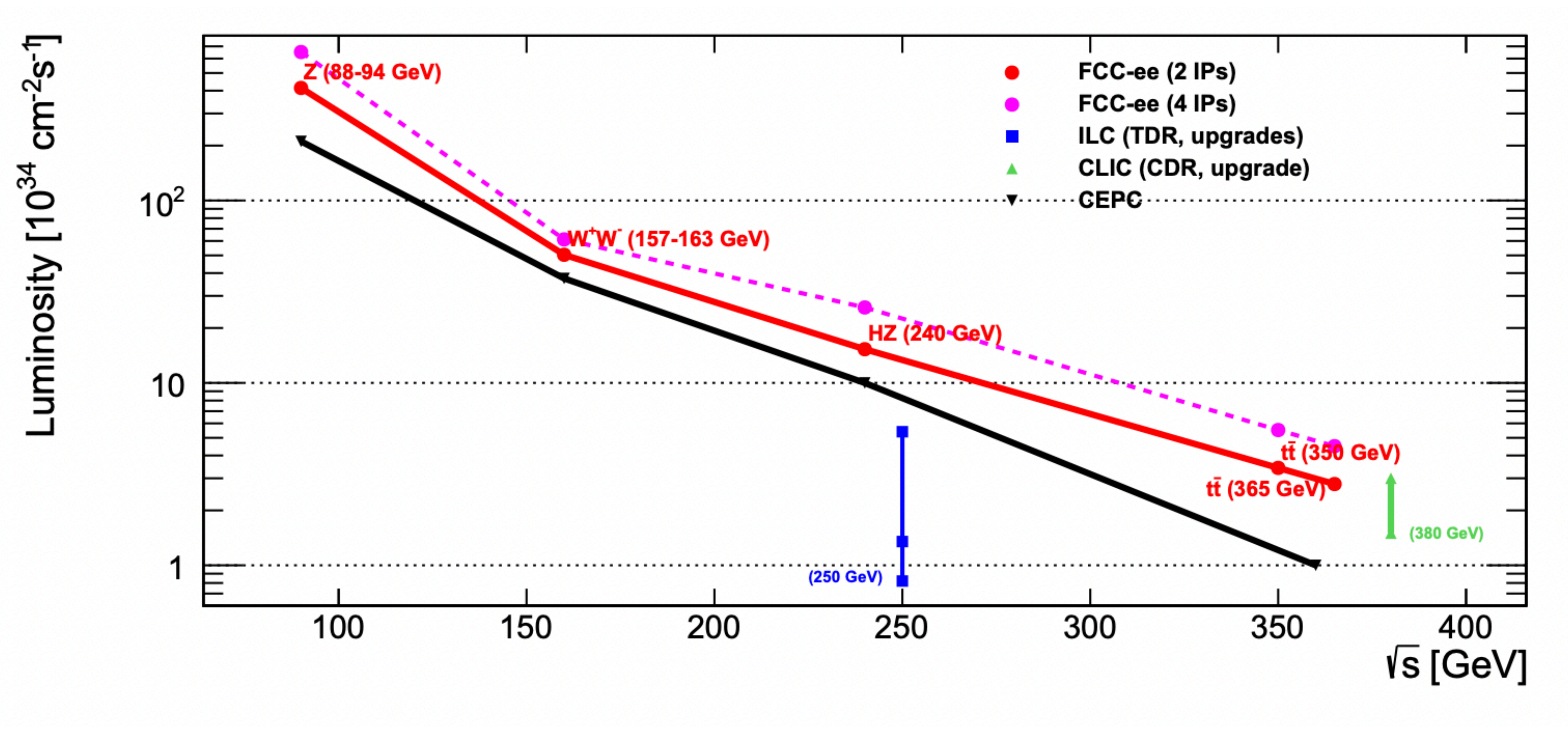


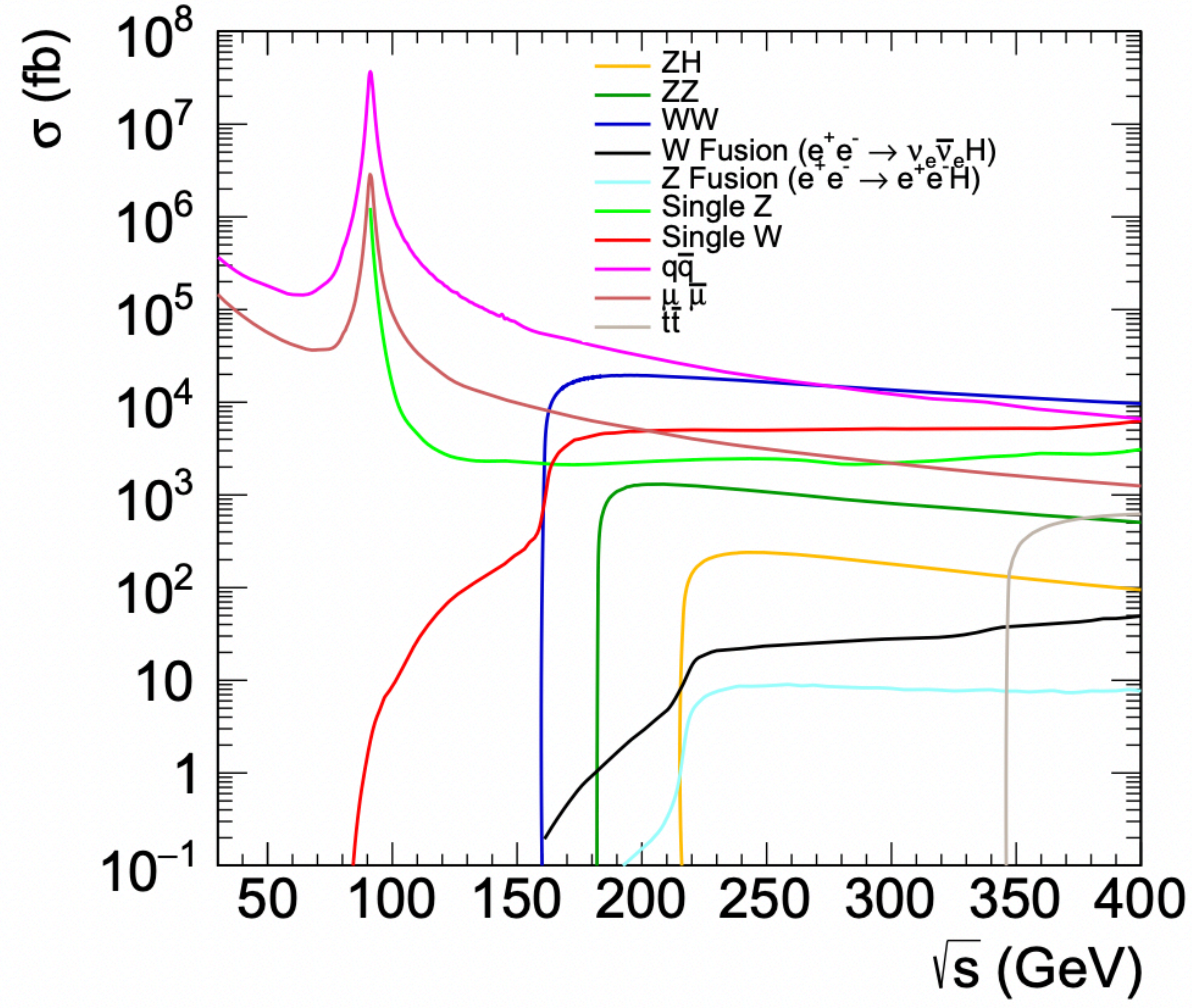
Michael Benedikt, FCC week 2/22

Future Circular Collider

… a roadmap for particle physics at the energy frontier

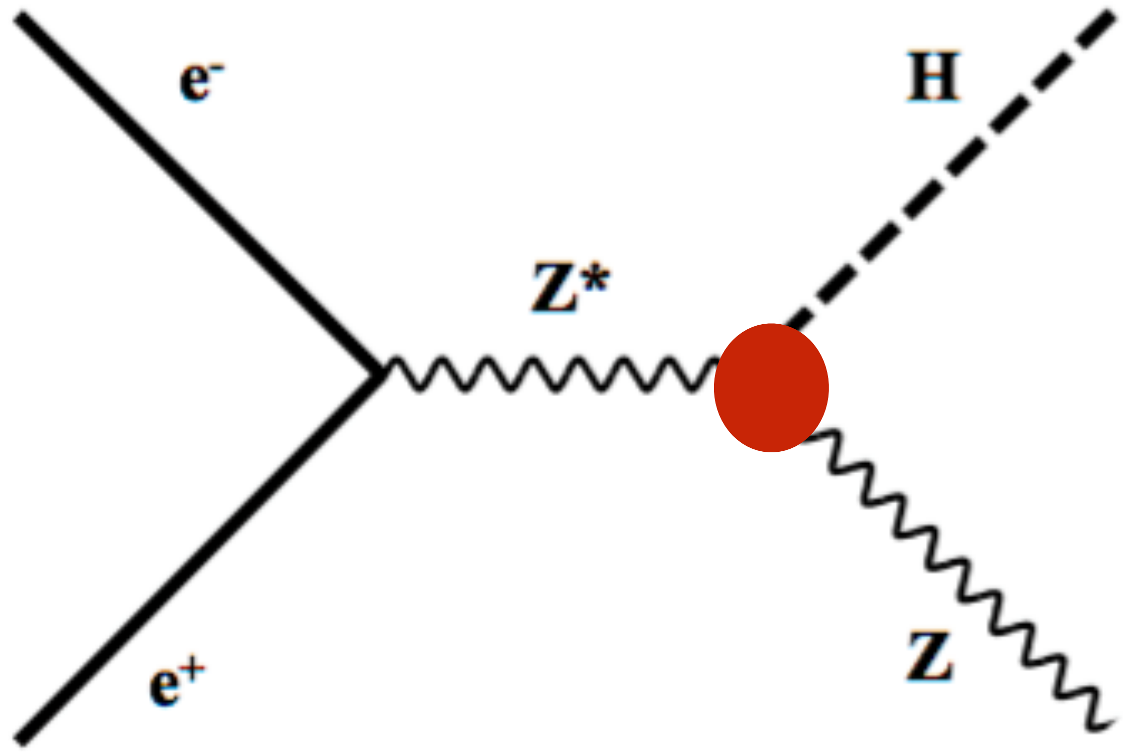
arXiv:2203.06520



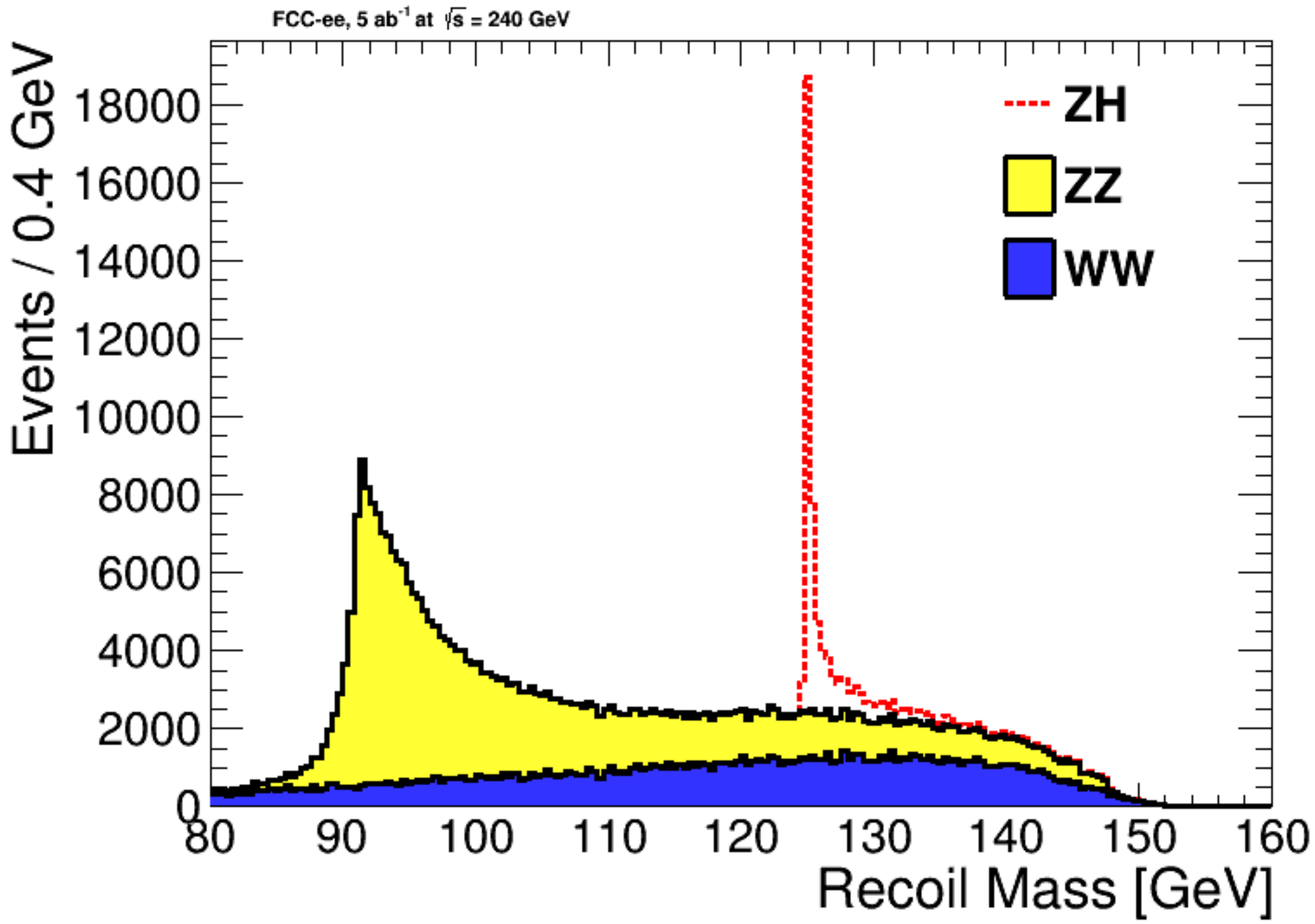


Higgs Physics
… at Lepton Collider

- ➡**Recoil method provides unique opportunity for model independent measurement of HZ coupling**
  - Higgs events are tagged Higgs decay mode independent
- ➡**Total width can be extracted from a combination of measurements**



$$m_R^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Higgs Physics

… with the HL-LHC and Beyond

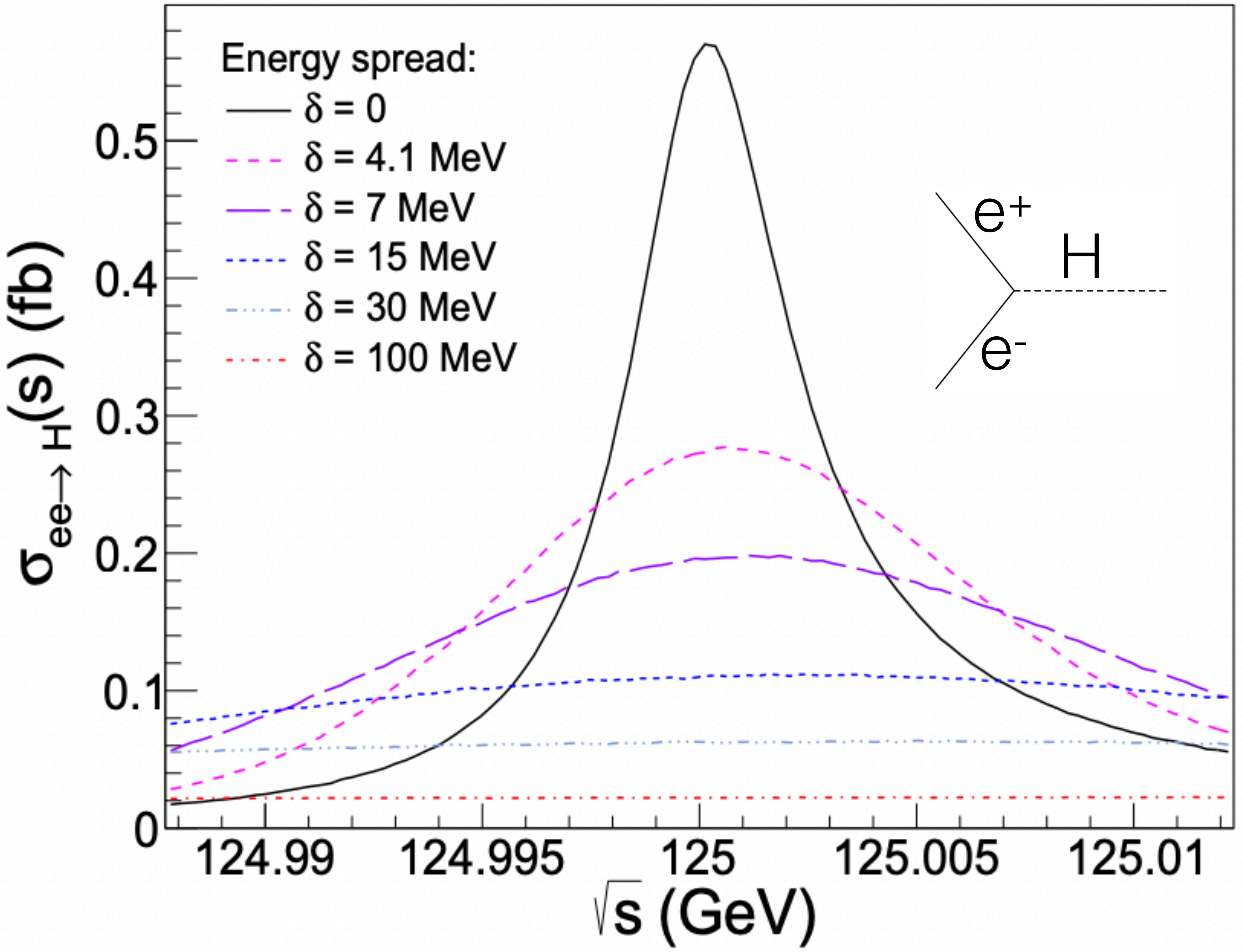
Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-ee + HL-LHC	FCC-INT
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–	30
Years	10	3 + 1 + 4	–	25
g_{HZZ} (%)	1.5	0.18	0.17	0.17
g_{HWW} (%)	1.7	0.44	0.41	0.20
g_{Hbb} (%)	5.1	0.69	0.64	0.48
g_{Hcc} (%)	SM	1.3	1.3	0.96
g_{Hgg} (%)	2.5	1.0	0.89	0.52
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74	0.66	0.49
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32
$g_{\mathrm{HZ}\gamma}$ (%)	11.	–	10.	0.71
g_{Htt} (%)	3.4	–	3.1	1.0
g_{HHH} (%)	50.	44.	33.	3–4
Γ_{H} (%)	SM	1.1	1.1	0.91

Higgs Physics

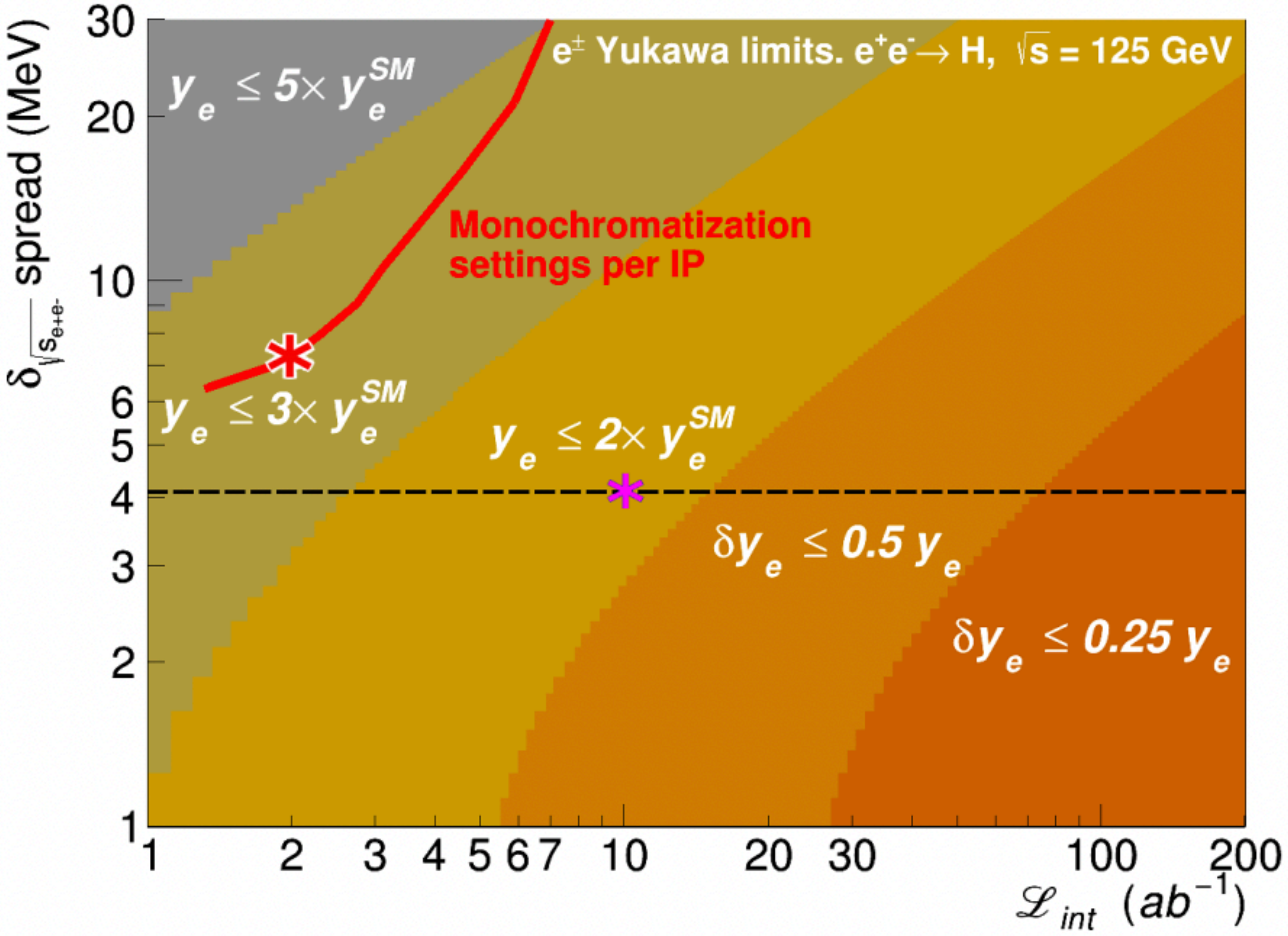
… with the HL-LHC and Beyond

➡ First generation Higgs couplings

- **Not part of baseline** run plan but a few years at $\sqrt{s}$ = mH with high luminosity and **monochromatization** is an interesting add-on



Results per year and interaction point



Higgs Factories

… with rich physics program beyond the Higgs boson

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

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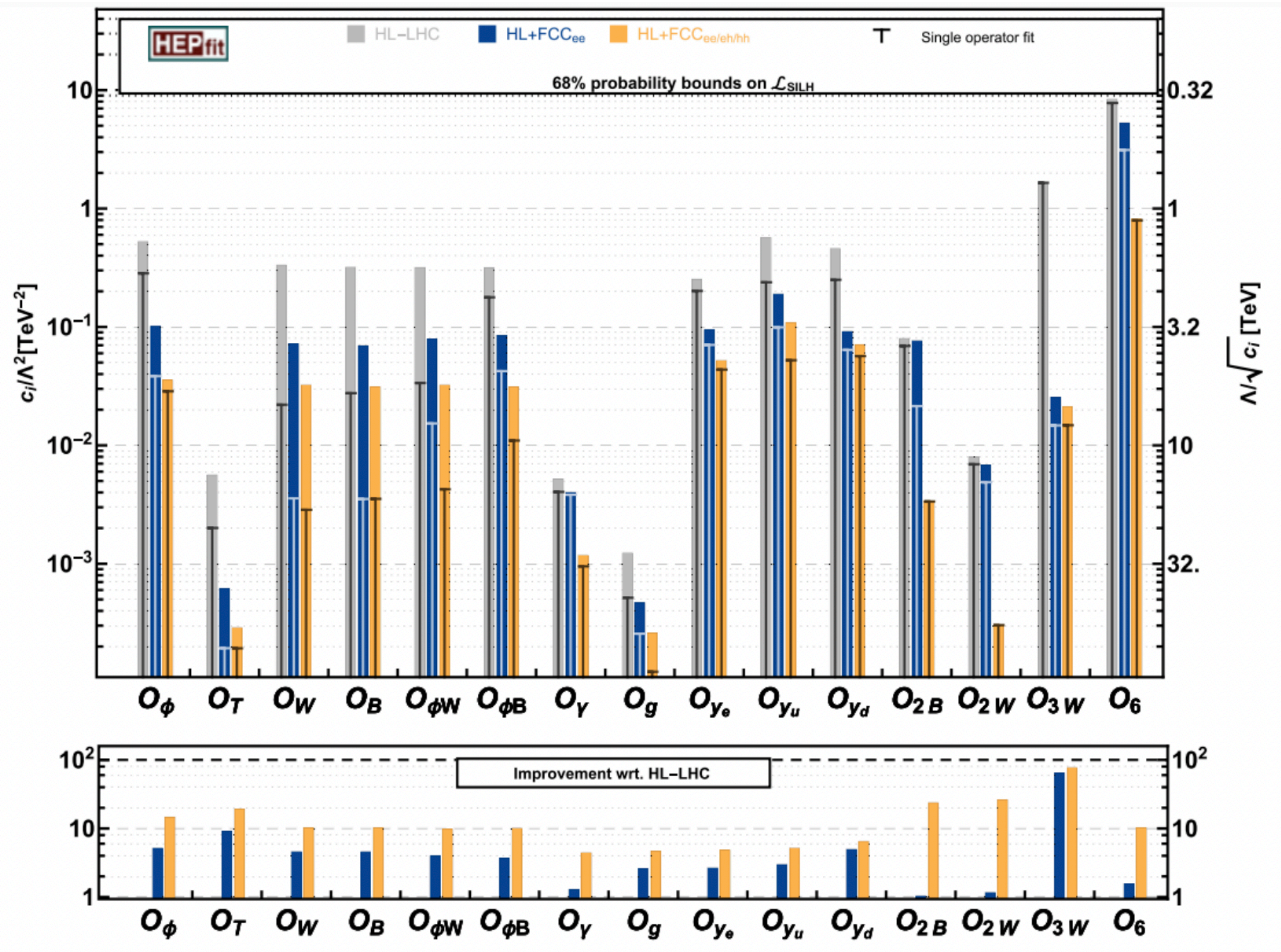
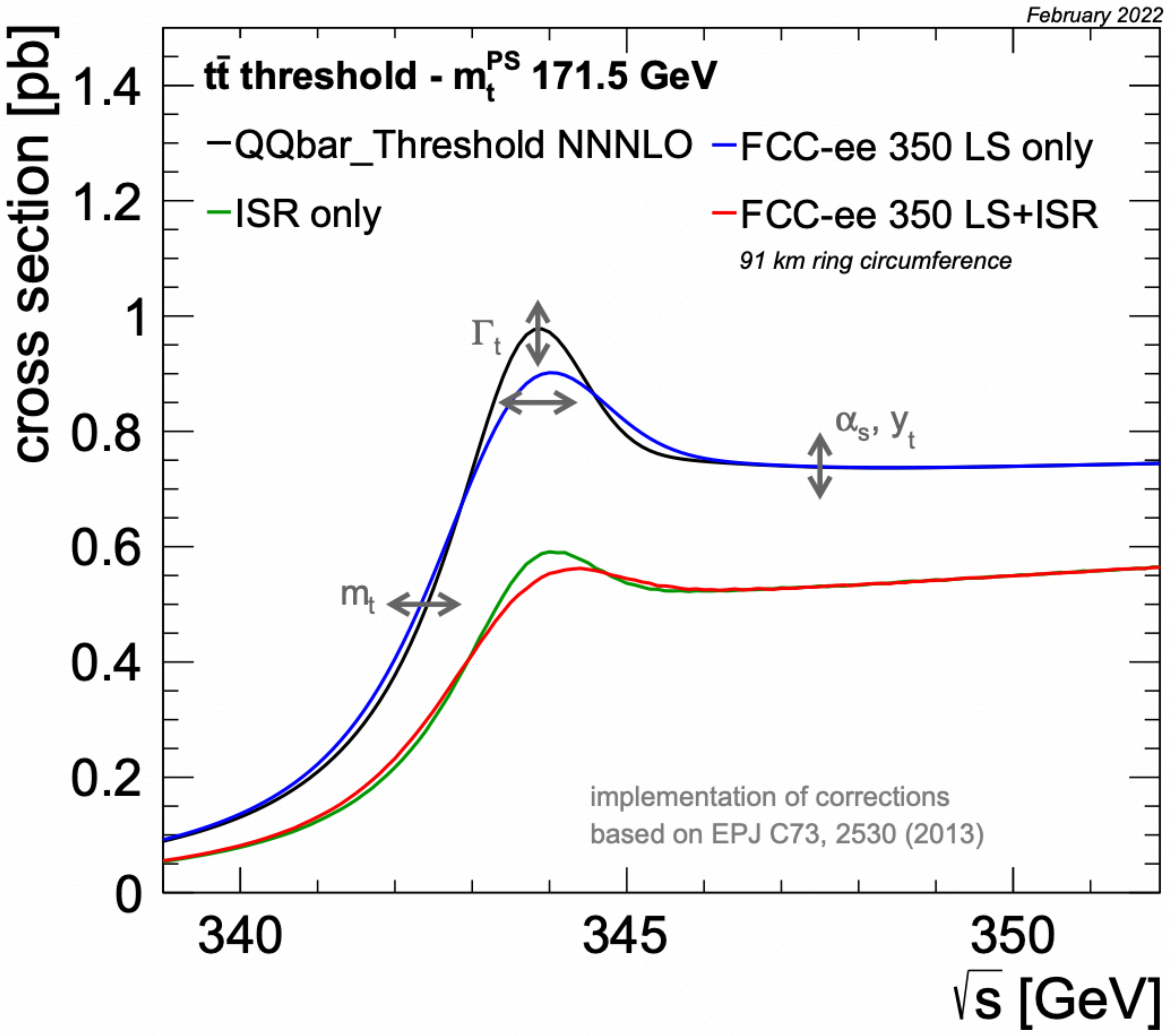
Higgs Factories

… with rich physics program beyond the Higgs boson





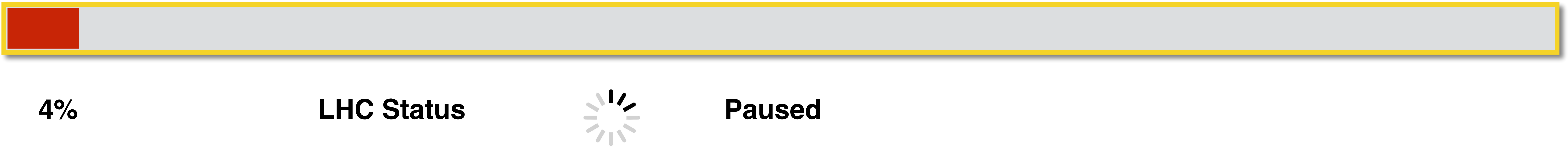
Summary and Outlook

… only discussed the tip of the iceberg

➡ **The Higgs Boson is cornerstone of the LHC physics program**

- Precision measurement probing SM - no significant deviation so far
- 2nd generation and Higgs self coupling are work in progress

➡ **(HL-) LHC datasets will start growing again this summer**



- **Extensive work, challenges & opportunities ahead to collect quality data**

➡ **Fantastic prospects to probe the Higgs sector and much more with future lepton collider**

- Unique measurements of g_{HZ} and total width
- Precision measurements of the Higgs boson and more

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