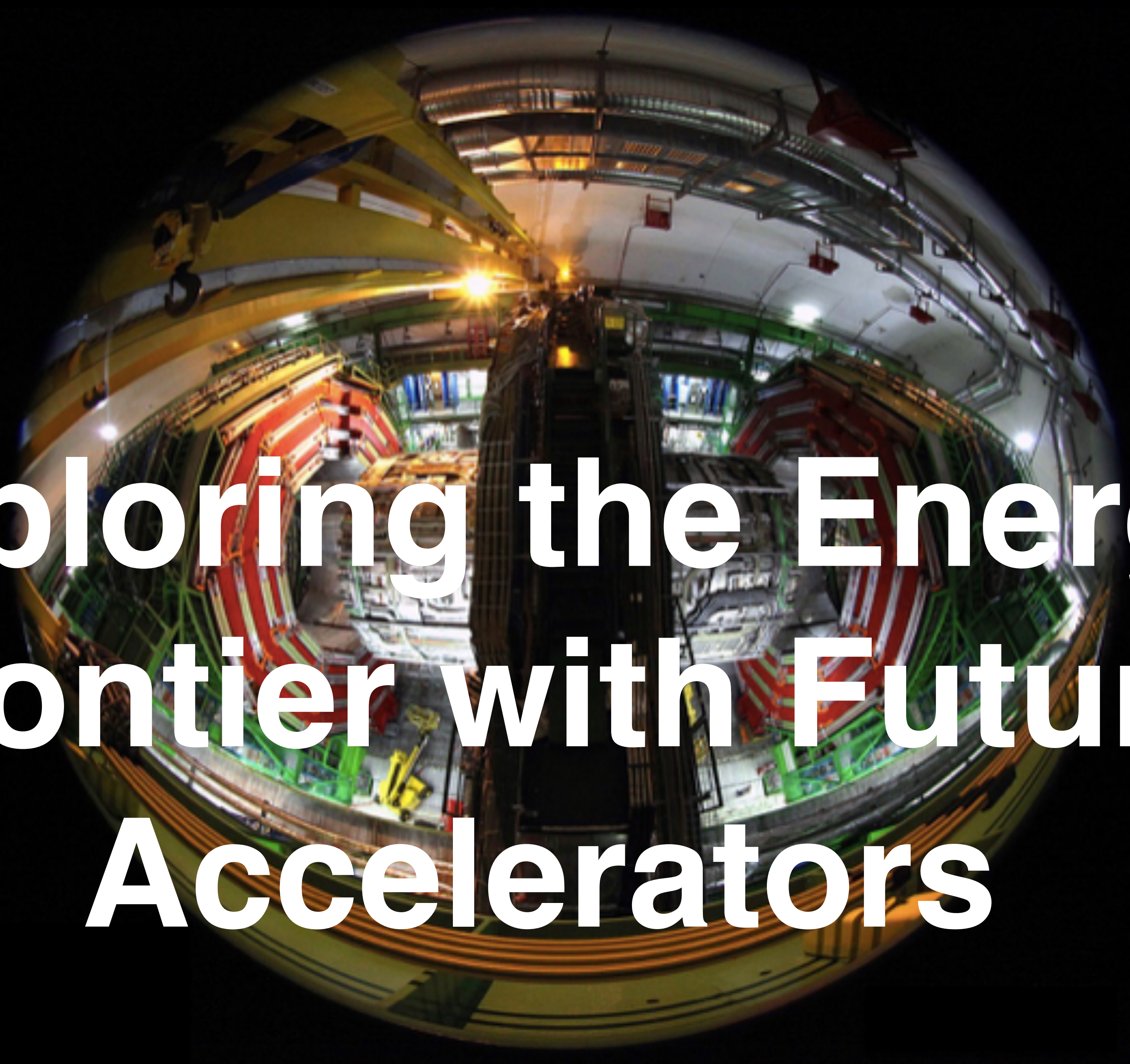
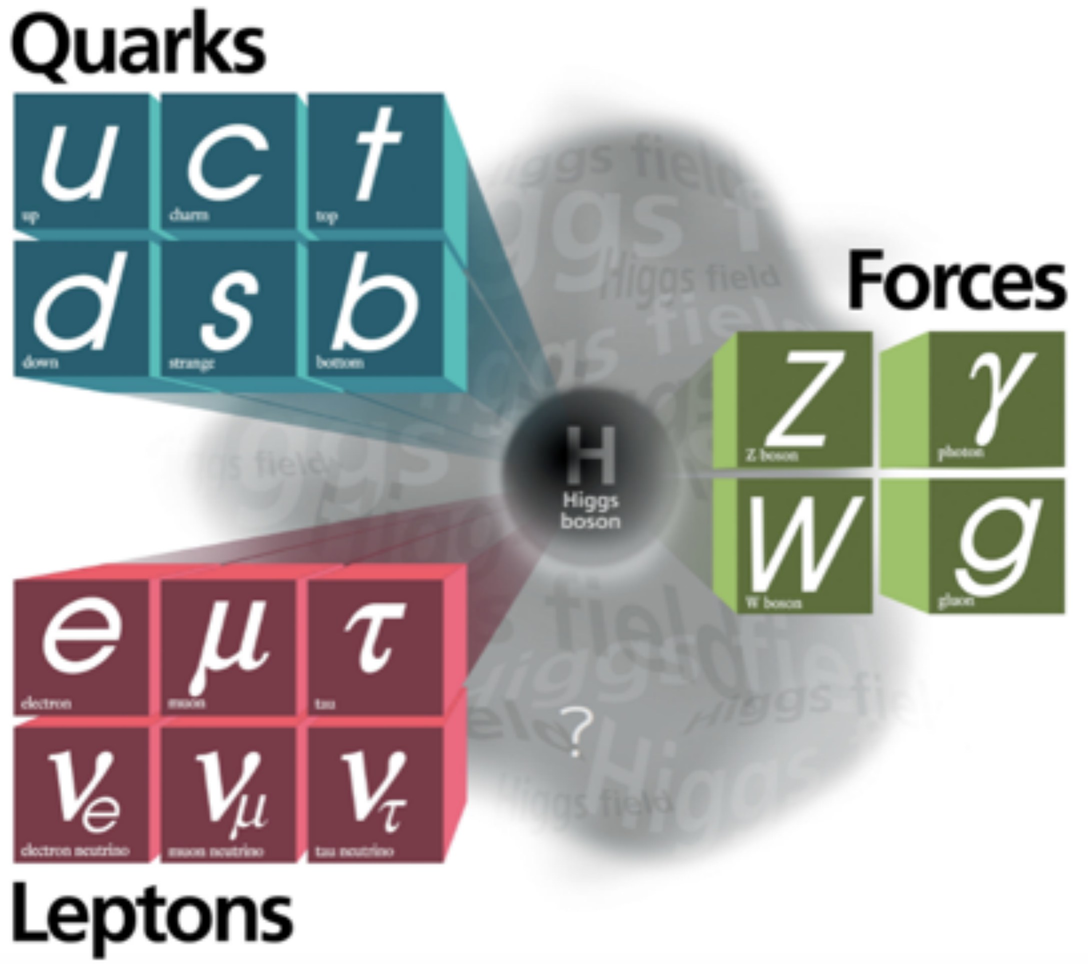


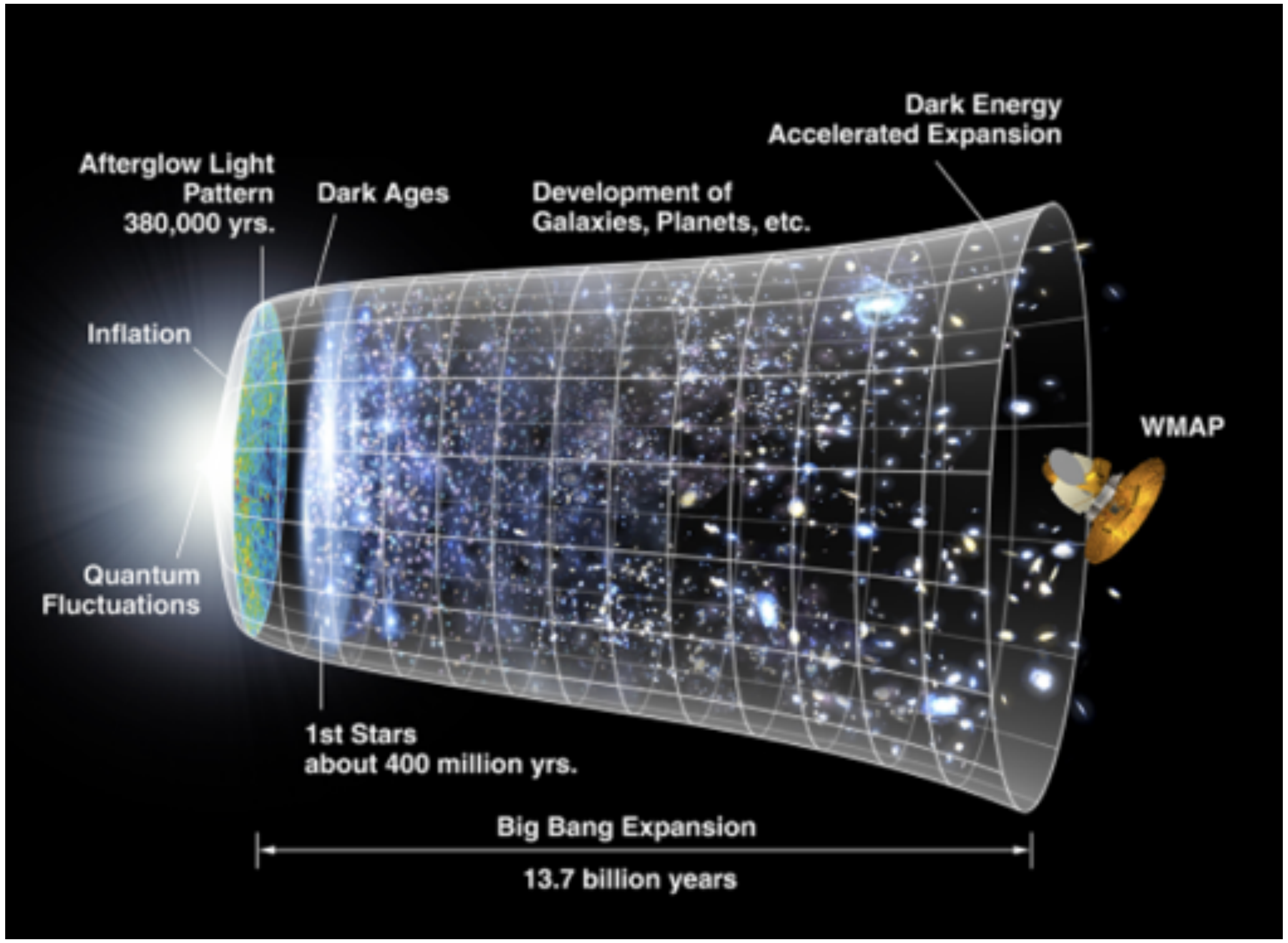
Exploring the Energy Frontier with Future Accelerators

Seminar - Dresden
June 1st, 2017
Markus Klute (MIT)

Fundamental Physics Today

Complete theory valid to very high energies





... but it is not enough

High Energy Physics Today

Is this the end? **Of course not!**
Is there anything new to be discovered? **Of course!**

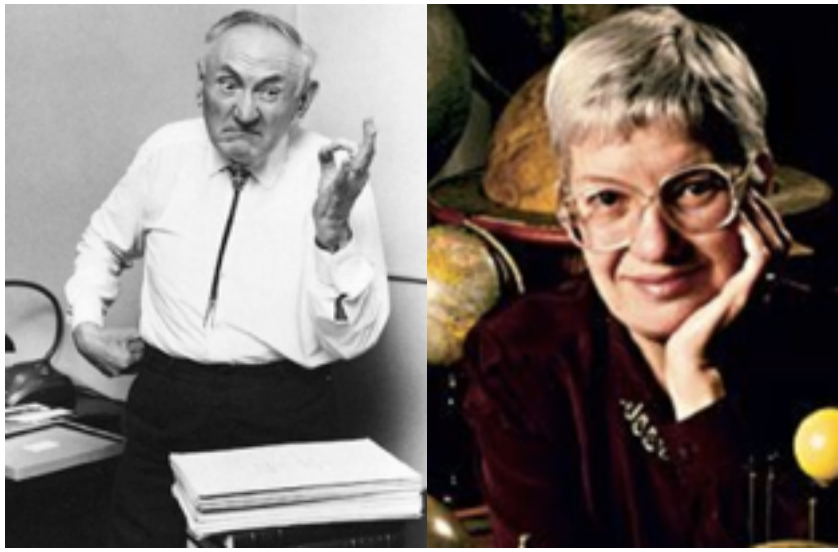
➡ **The SM fails to explain important observations - experimental proof for physics beyond the SM**

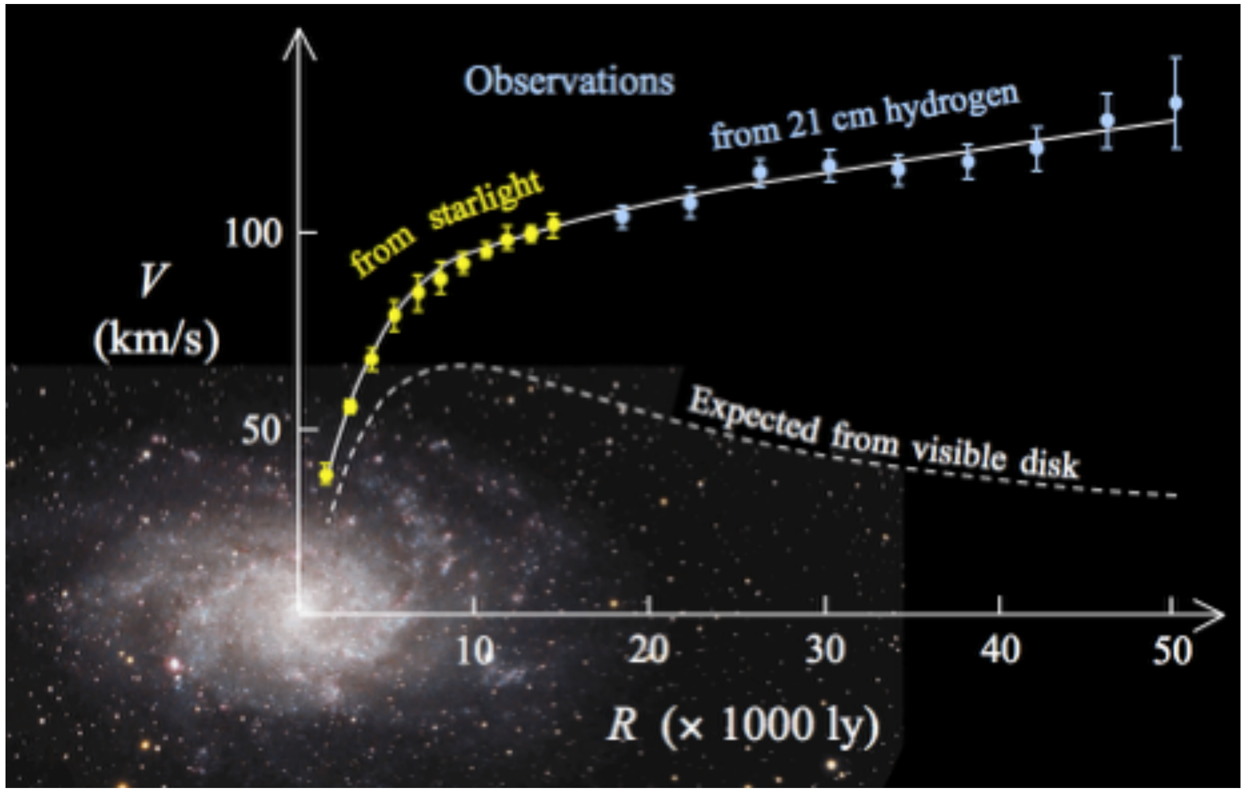
- Cosmological dark matter (DM)
- Baryon asymmetry
- Non-zero, but very small neutrino mass
- A hint: the small Higgs boson mass is rather unnatural

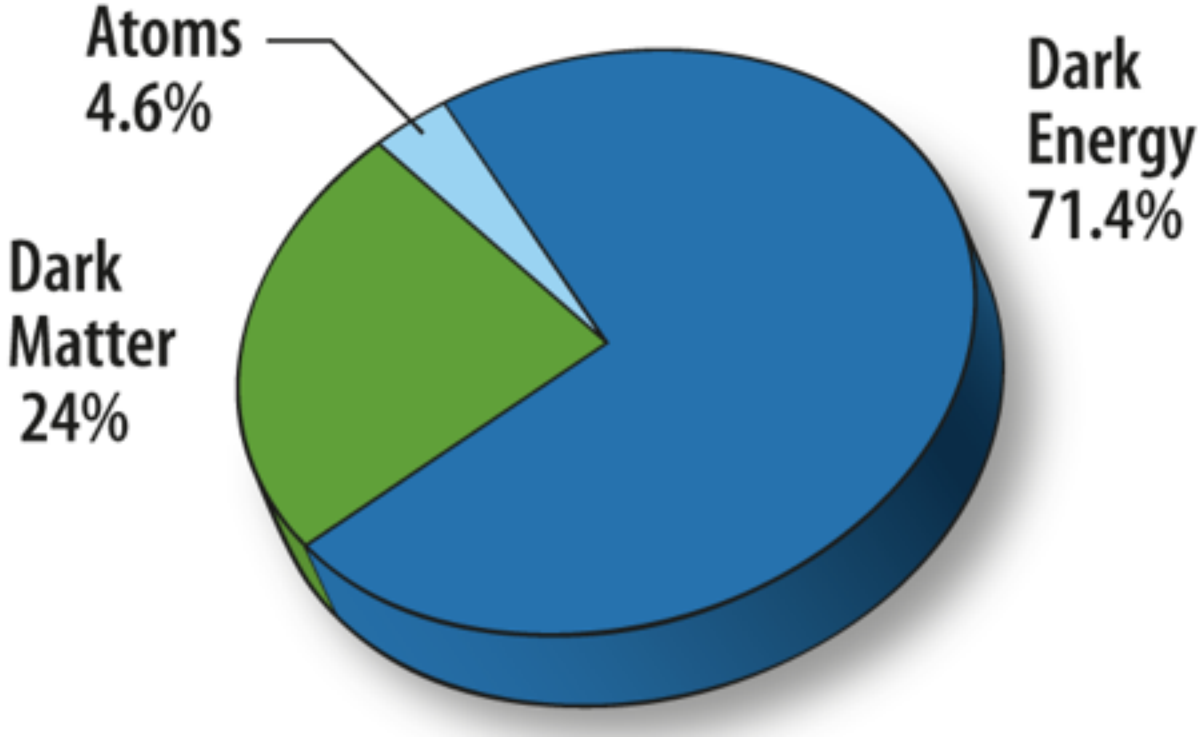
Fundamental Physics Today

➡ **Dark Matter: the matter we can not see**

- first proposed as a concept by Oort and Zwicky in the ~1930th
- confirmed by Rubin and Ford in galaxy rotation curves ~1960-70th
- evidence through gravitational effects only
- leading candidate: weakly interacting massive particle





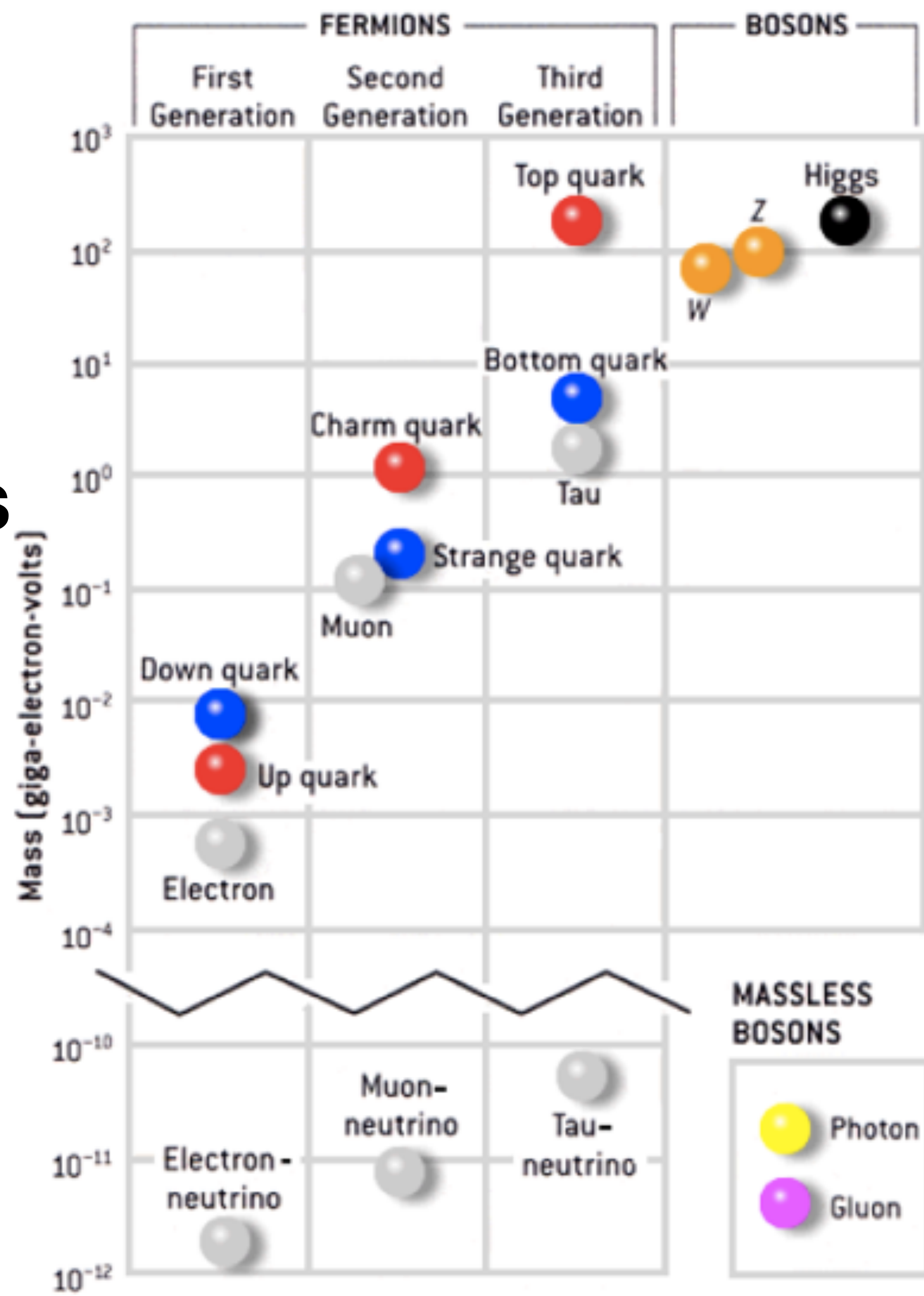


Fundamental Physics Today

➡ **Baryon matter asymmetry**

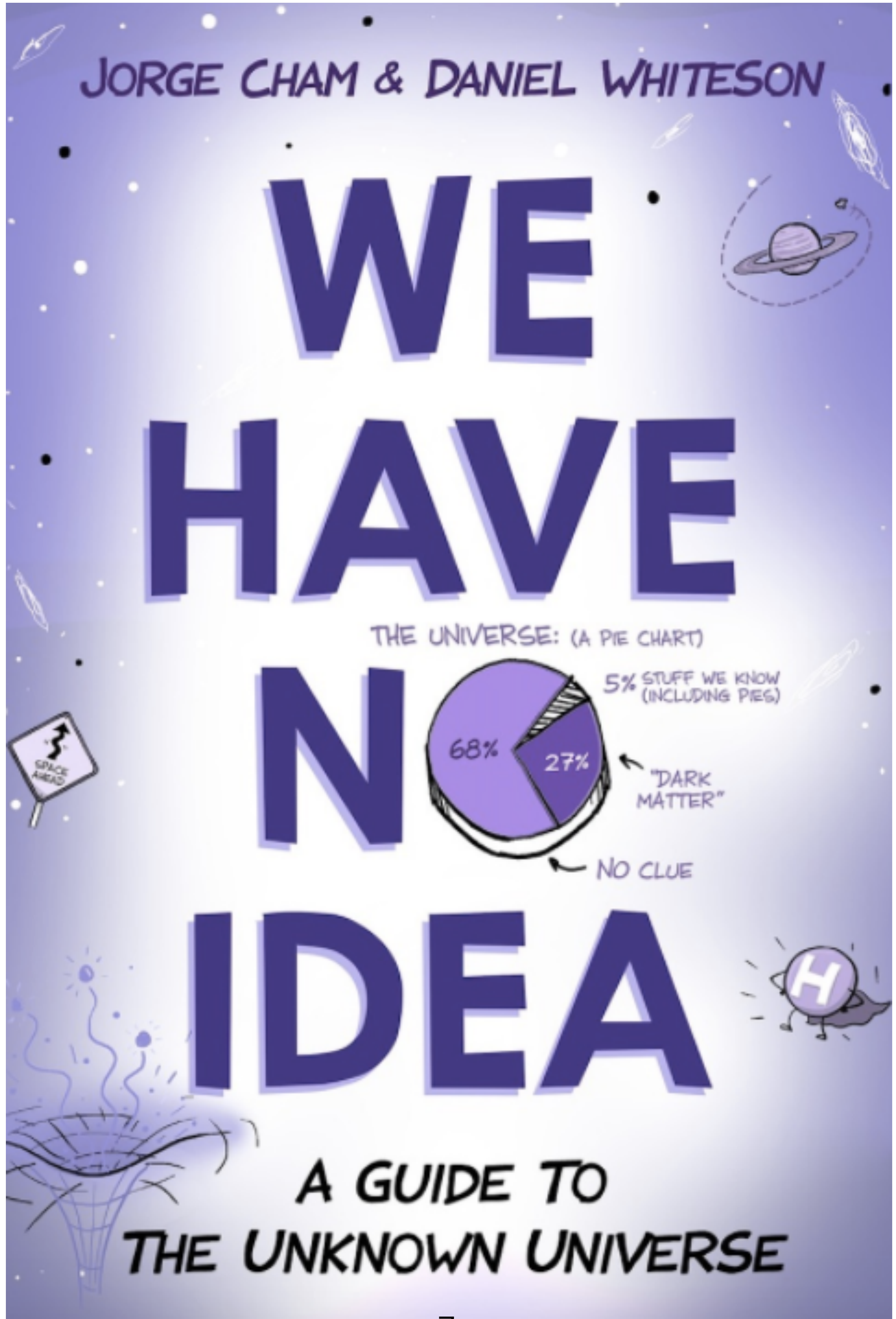
Fundamental Physics Today

How do particles acquire mass?



Why do they have these masses?

Why are neutrino masses tiny?

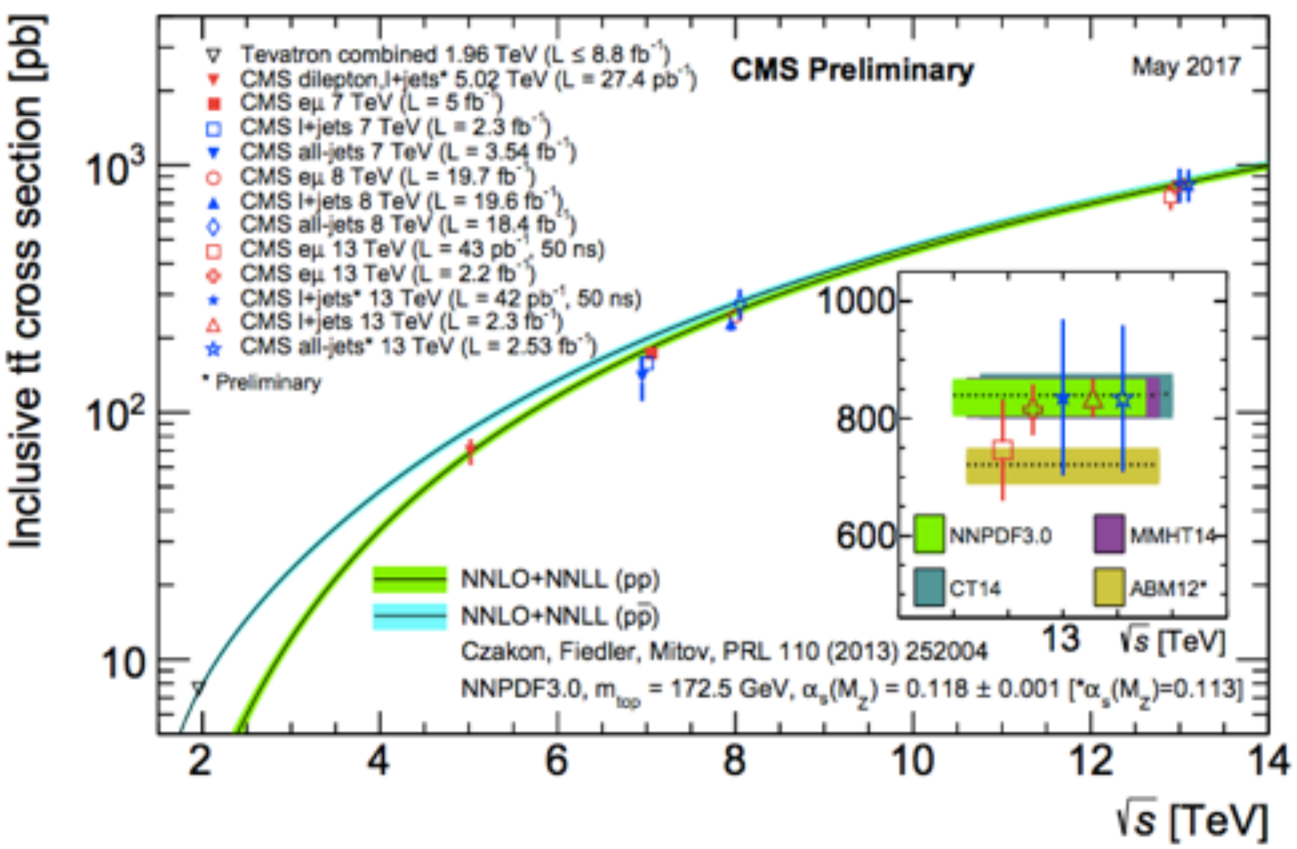

JORGE CHAM & DANIEL WHITESON
WE HAVE NO IDEA
THE UNIVERSE: (A PIE CHART)
5% STUFF WE KNOW (INCLUDING PIES)
68%
27%
"DARK MATTER"
NO CLUE
A GUIDE TO THE UNKNOWN UNIVERSE

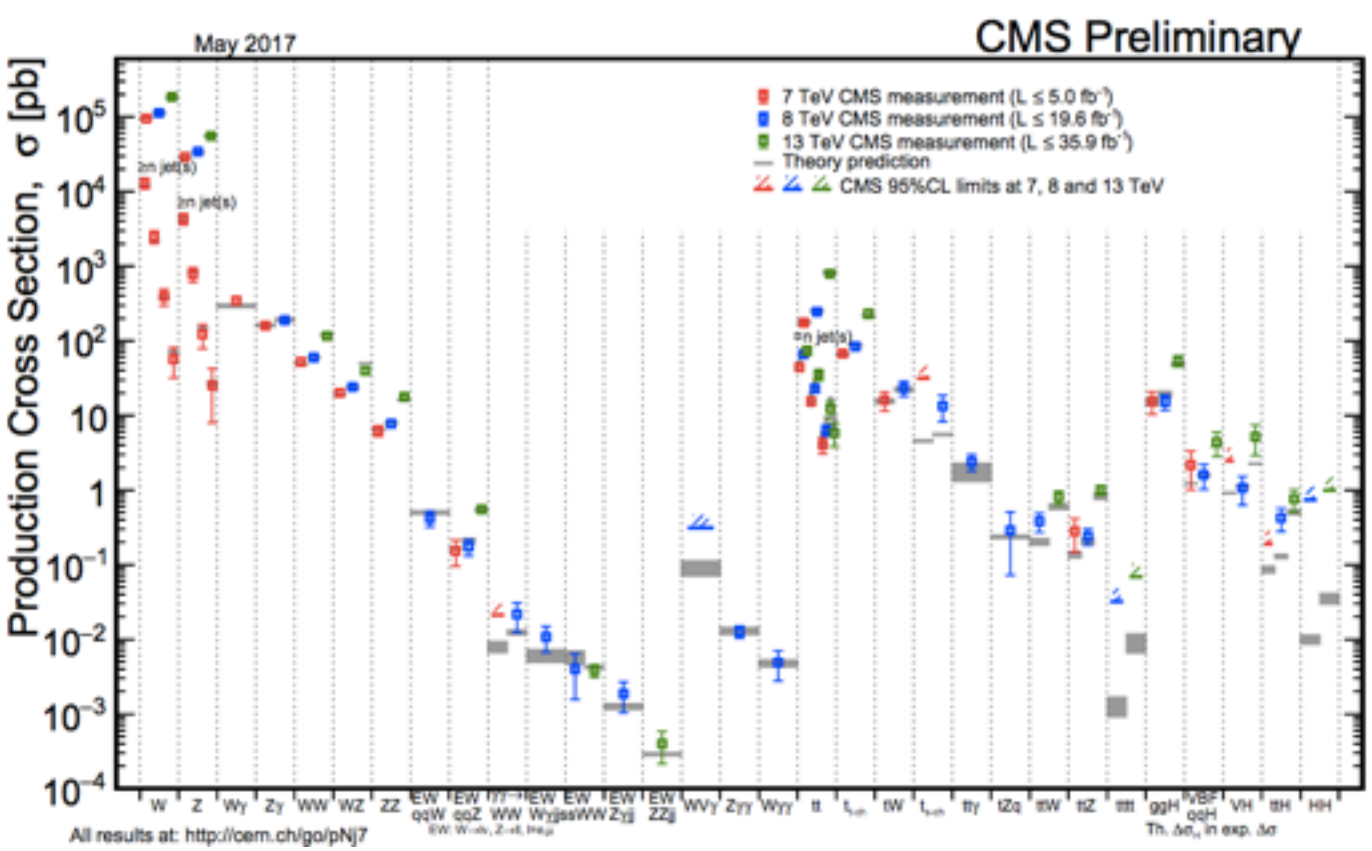
Fundamental Physics Today

➡ **… wait a minute**

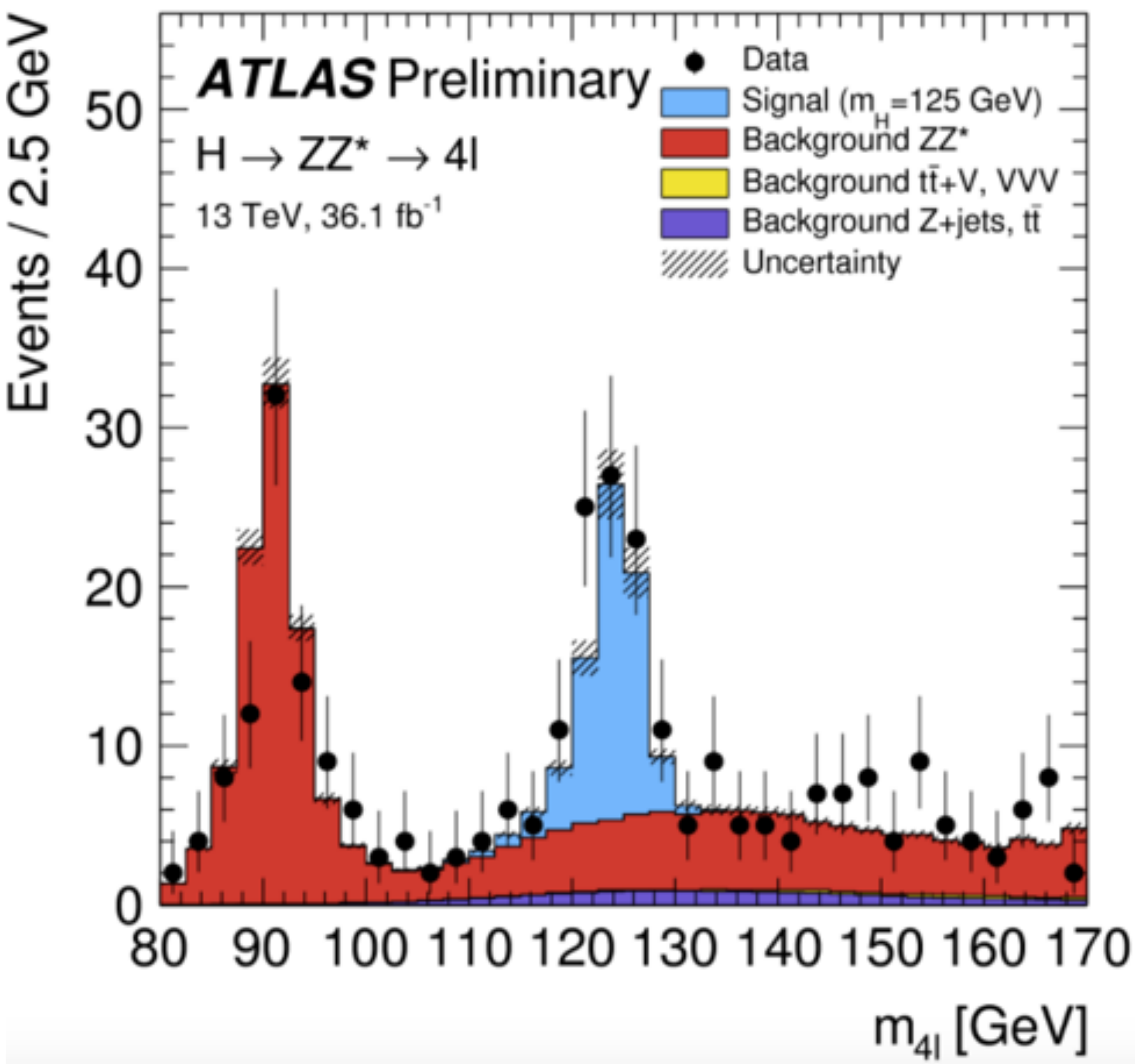
➡ Standard Model of Particle Physics is very predictive

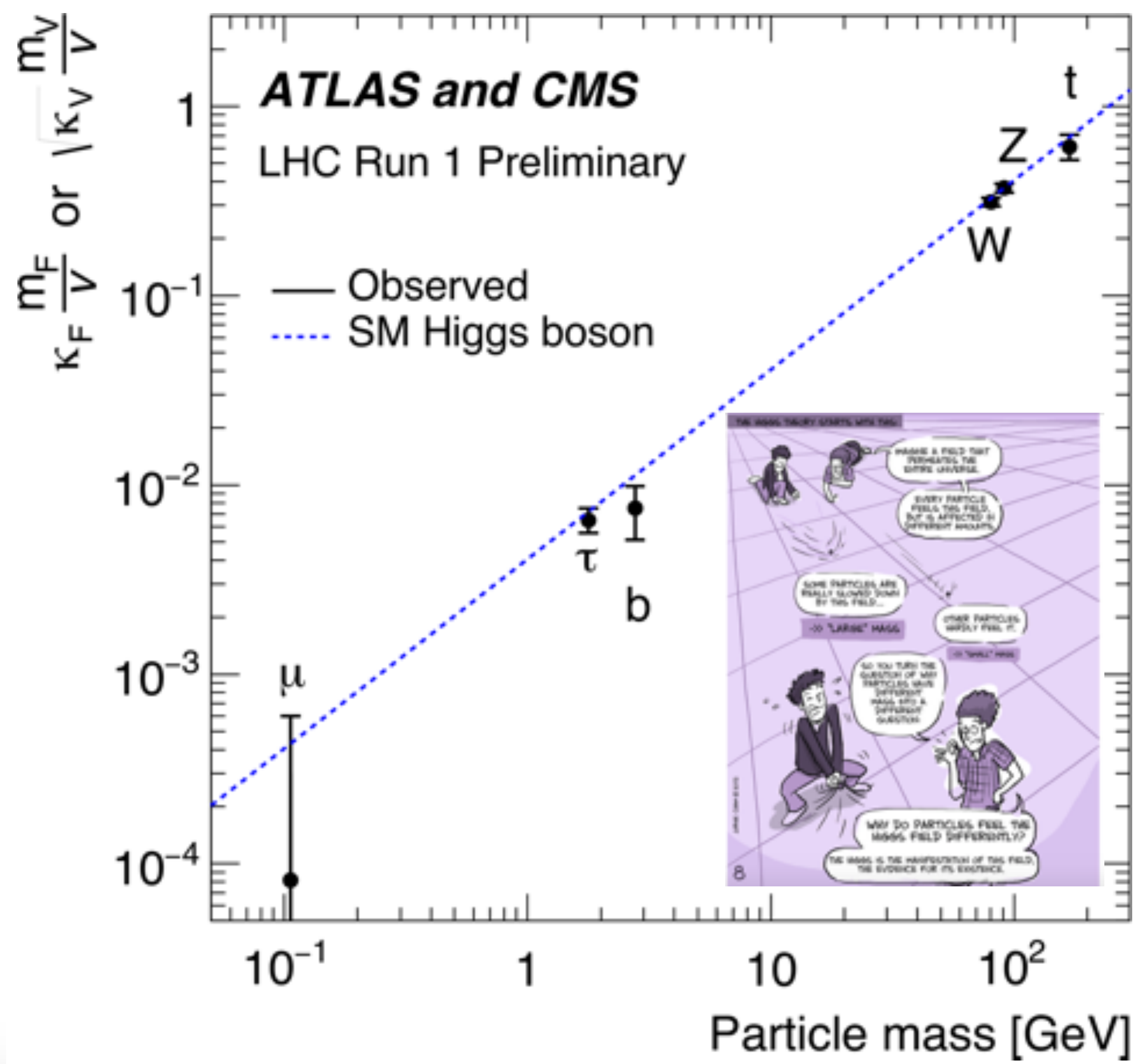
- there are a finite number of free parameter
- “infinite” number of measurements are in excellent agreement





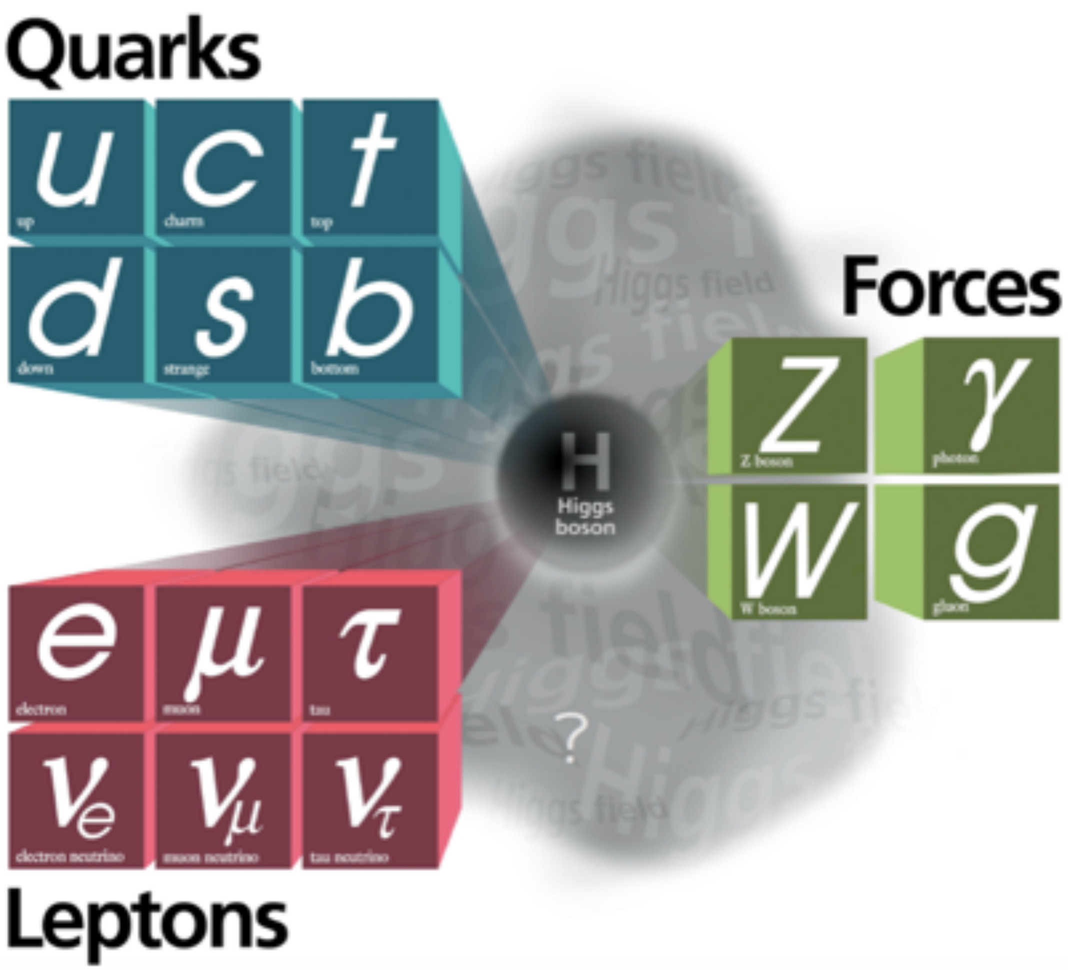
➡ Standard model did not only predict the outcome of scattering experiments, but also the existence of a new particle and it’s properties - **the Higgs boson**

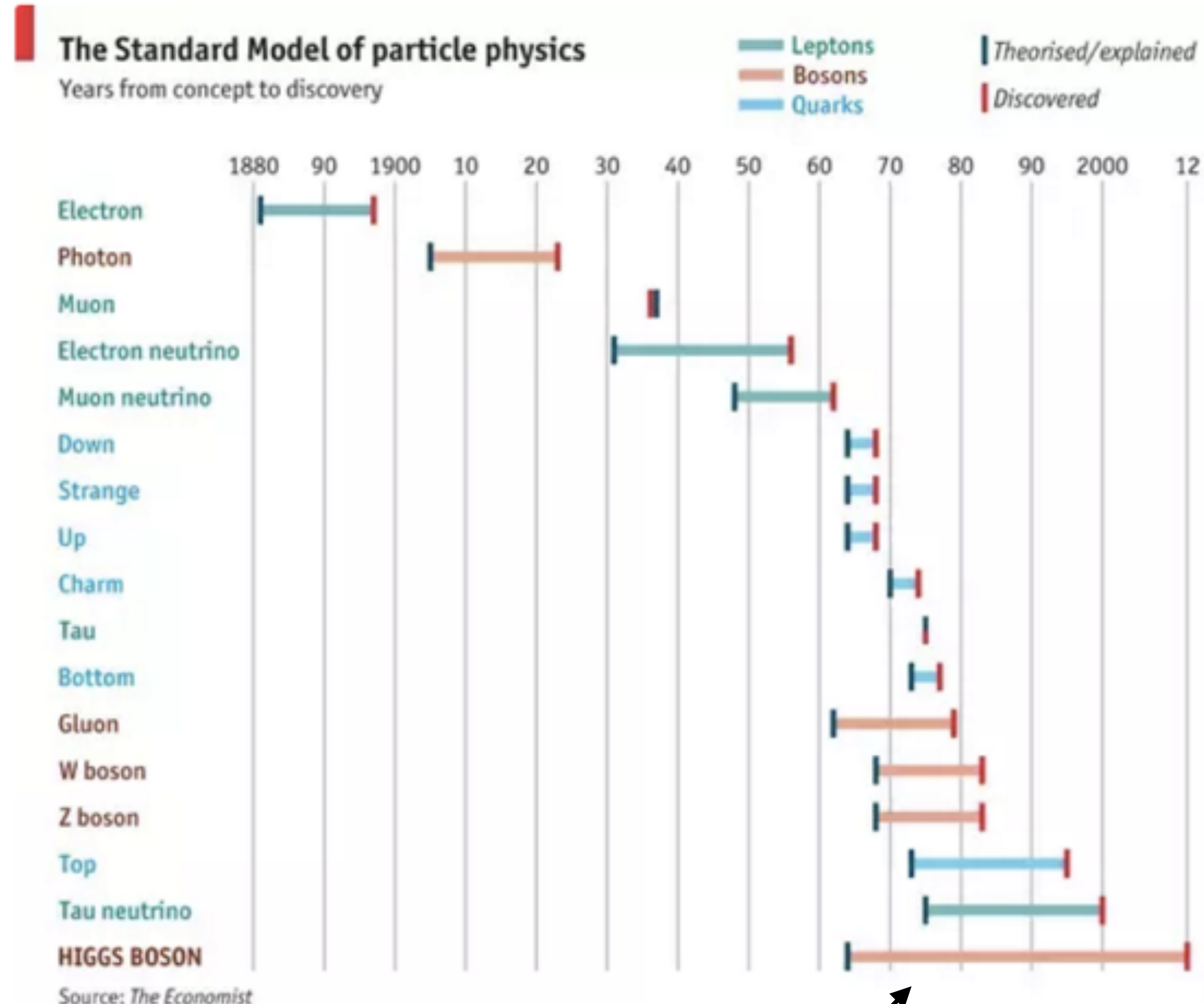




High Energy Physics Today

Complete theory valid to very high energies





SM

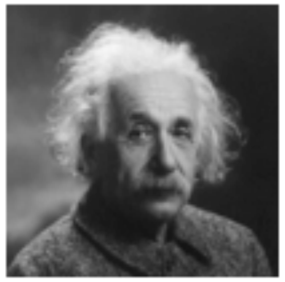
Experimental Approach

Study particle interaction, resulting reaction products and features
Measure energy, direction and identity of collision products

➡ **The highest energies allows us to**

- look deep into matter "powerful microscope": E ~ 1/size
- produce heavy particles: $E = mc^2$
- probe conditions of the early universe: $E = kT$

de Broglie



Einstein

Boltzmann

Experimental Approach

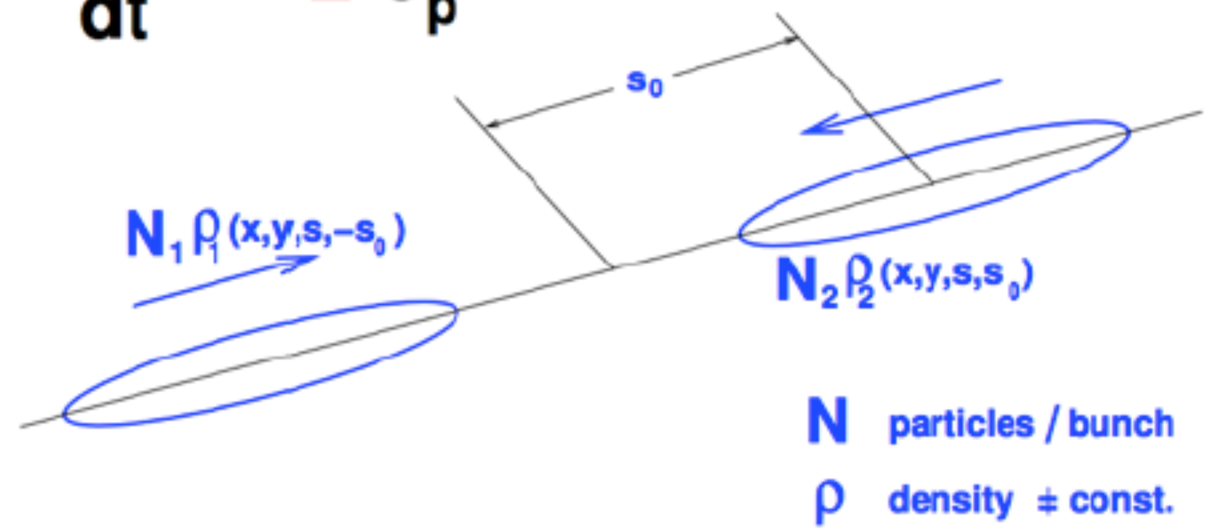
➡ **Elements of collider**

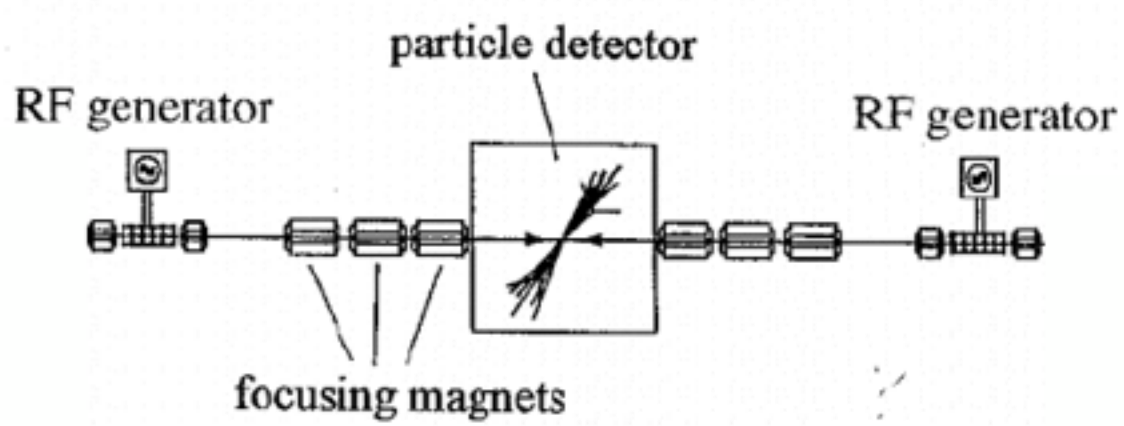
Key collider parameter

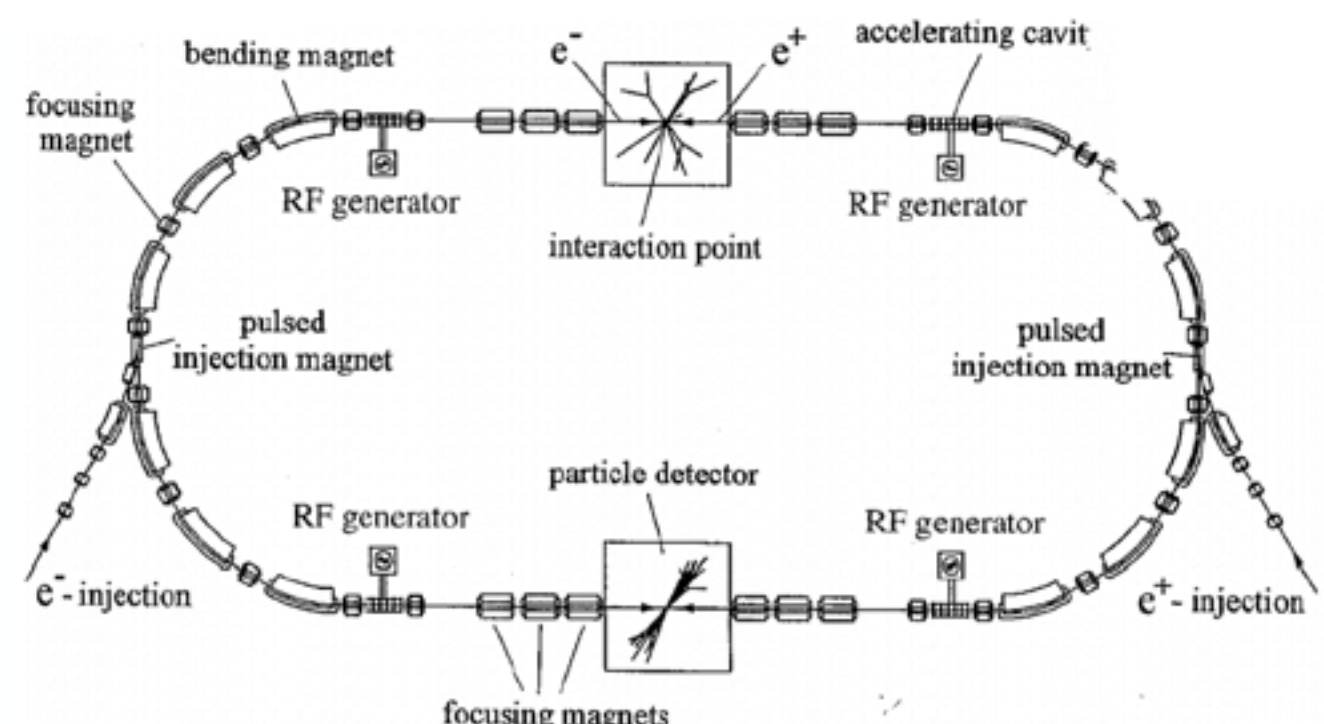
$$E_{\rm cm}^2 = (E_1 + E_2)^2$$

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

$$\frac{dR}{dt} = L\,\sigma_p$$







Experimental Approach

➡ **Hadron vs Lepton Collider**

"Every event at a lepton collider is physics, every event at a hadron collider is background."
- Sam Ting.

"All events (background) are equal but some events are more equal than others."
- George Orwell (Klute-fied)

Experimental Approach

➡ **Linear** vs **Circular**

- no synchrotron radiation
- no bending magnets
- currents and focusing are limiting L
- gradients are limiting E
- limited to one experiment

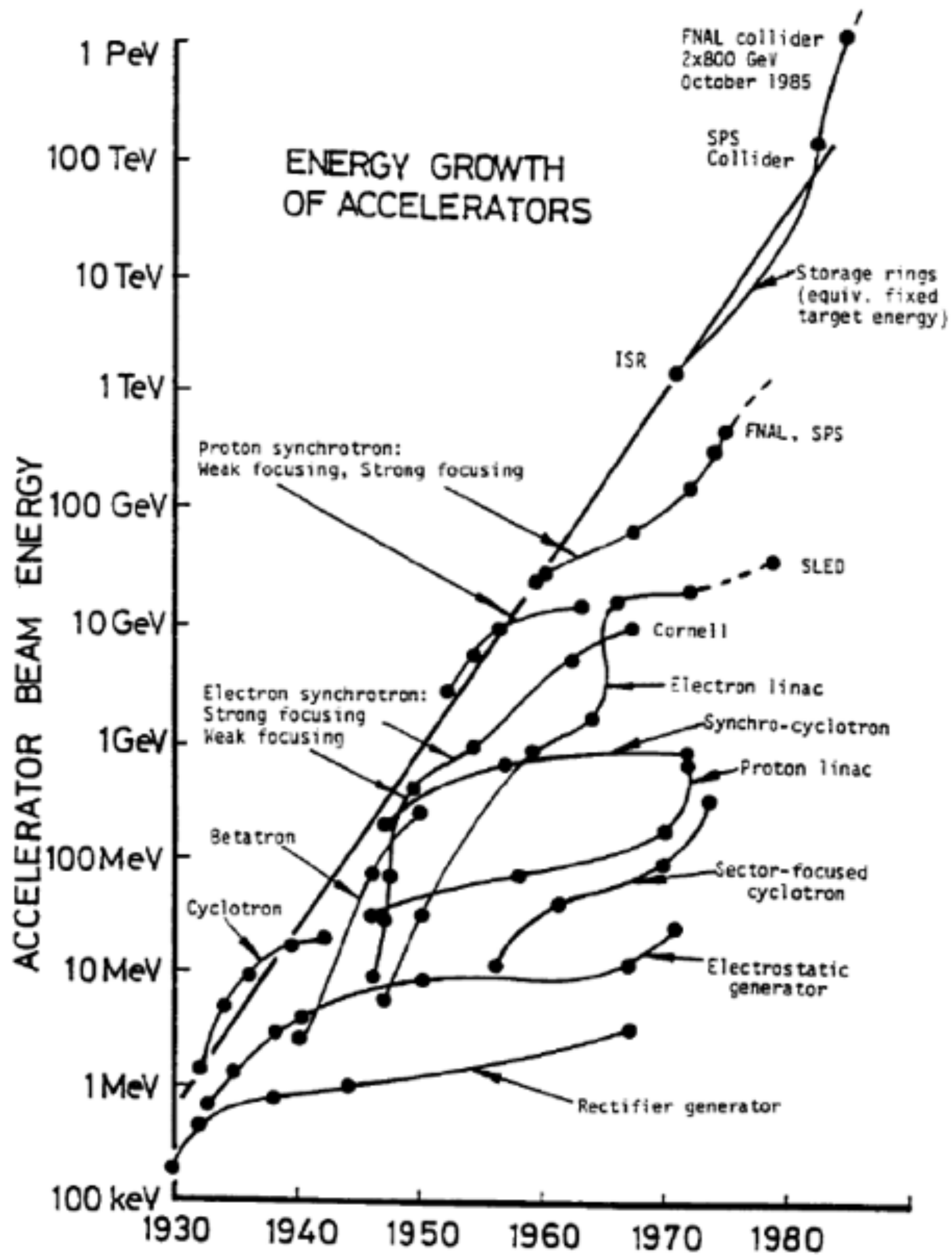
- accelerate over long distance by repetition
- recycle particles not used in collisions
- in principle, this leads to larger L and E

$$P_{radiation} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate
Radiation becomes too large

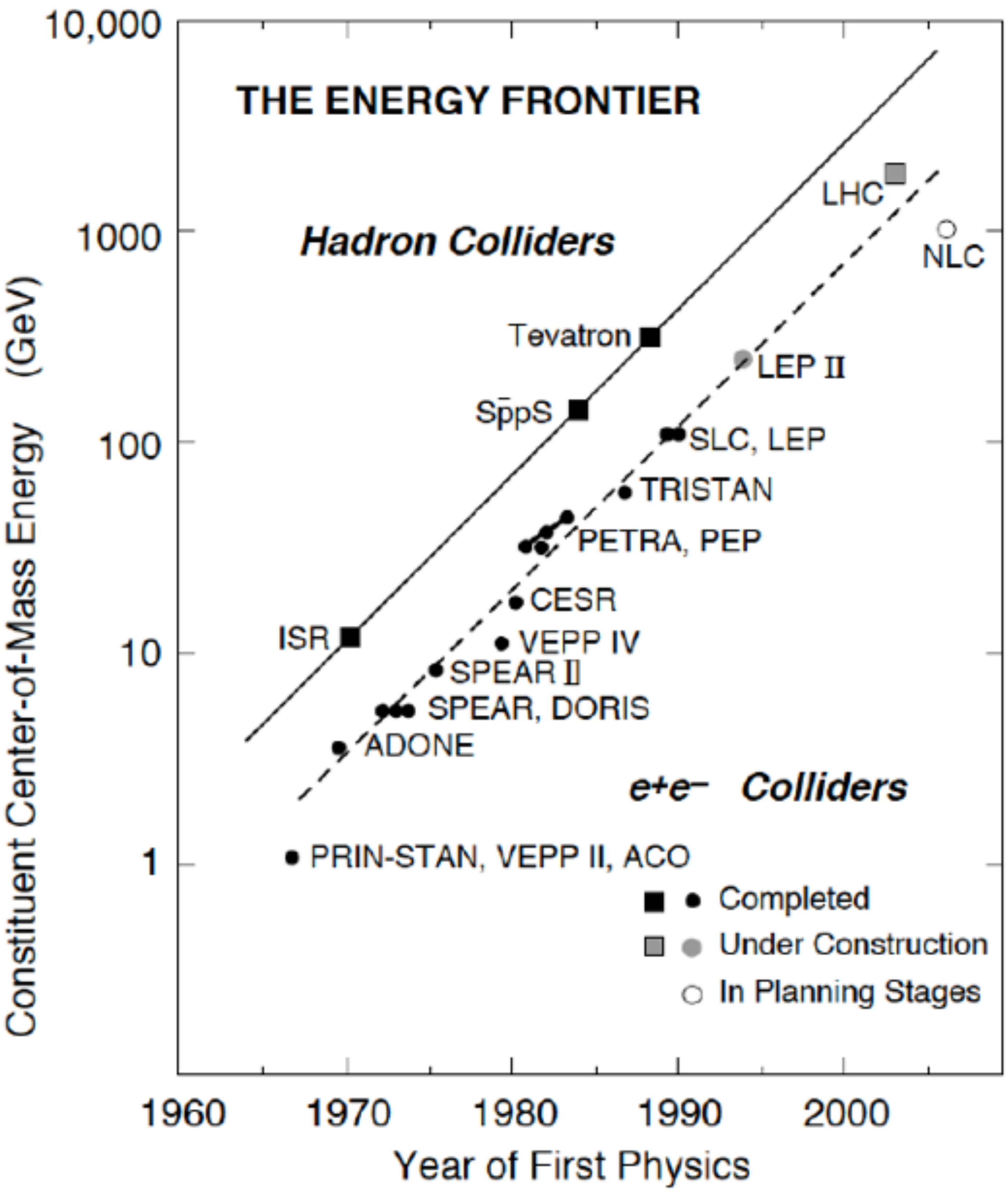
$$\rho = \frac{p}{qB} \quad \Rightarrow$$ The rings become too long

Roadmap for Particle Physics



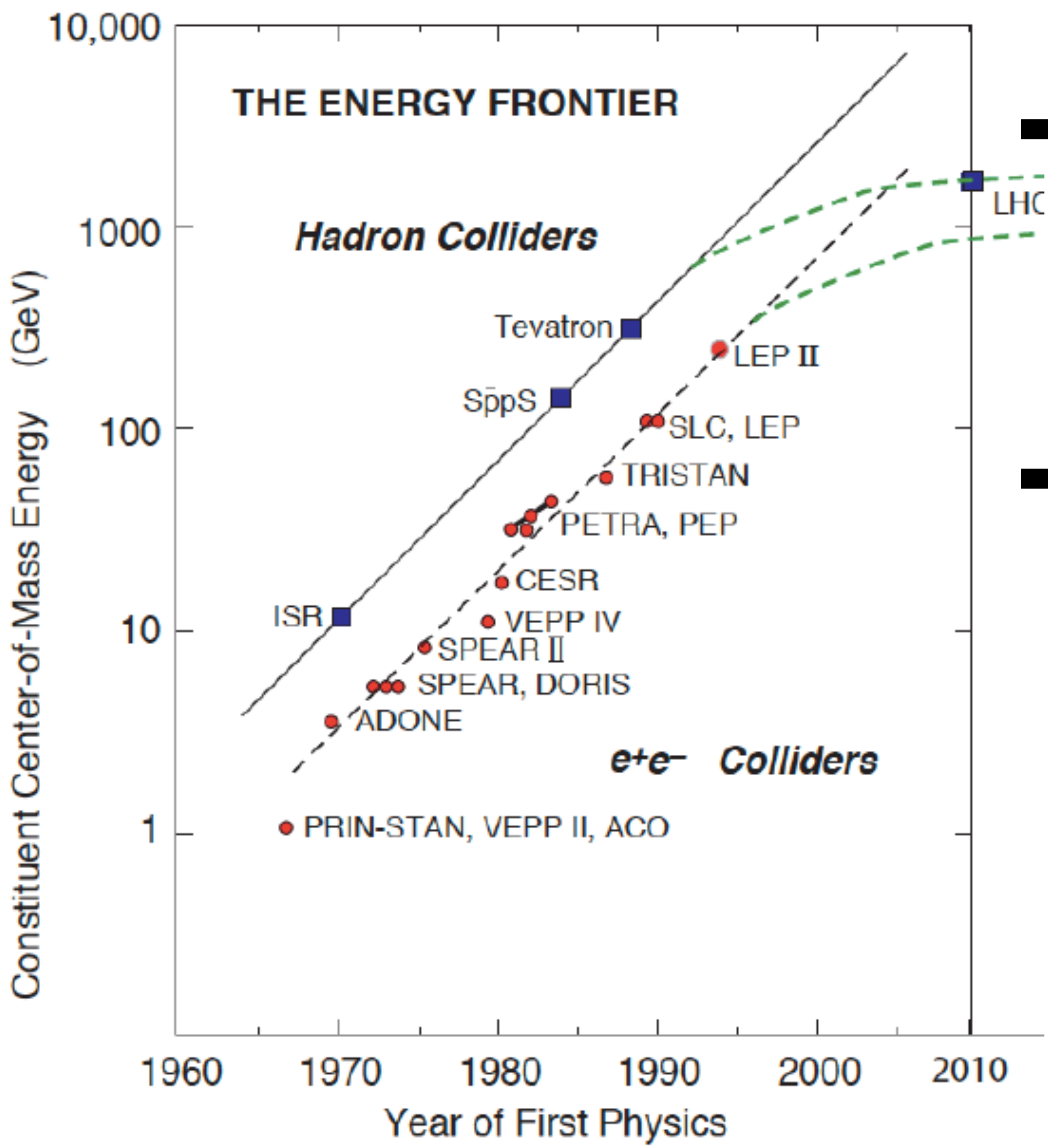
- ➡ Using history as a guide for the future
  - The last ~100 year in particle physics with collider
- ➡ Livingston Plot ~1985
  - nearly 6 decades of growth
  - driven by continuous innovation
  - pushing energy (discovery) frontier

Roadmap for Particle Physics



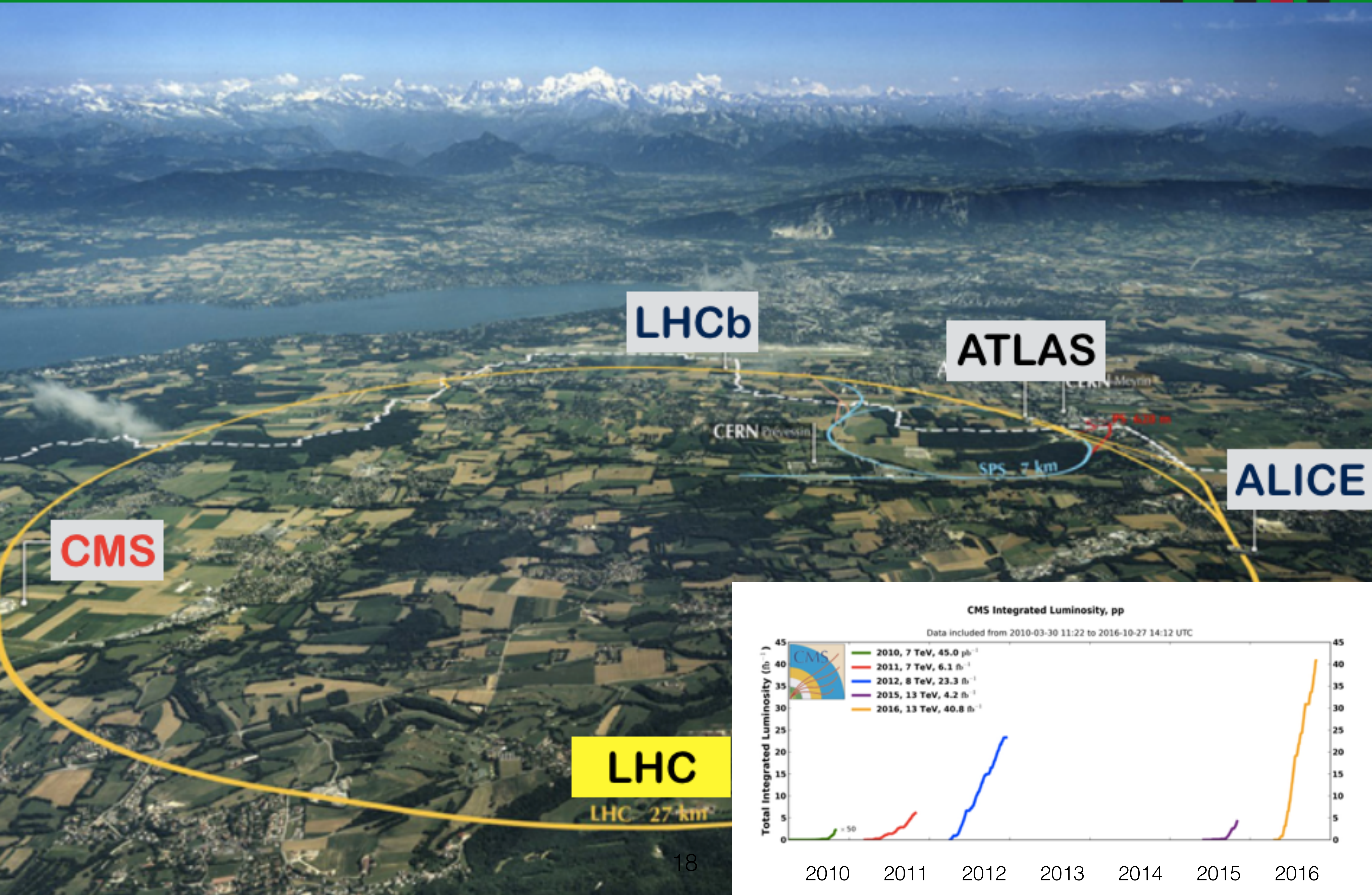
- ➡ Using history as a guide for the future
  - The last ~100 year in particle physics with collider
- ➡ Livingston Plot ~1996
  - It was clear that trend can not be continued into the 21st century
  - SSC was meant to fall on the line!
  - Two directions
    - electron-positron collider for precision measurements
    - energy frontier hadron collider

Roadmap for Particle Physics

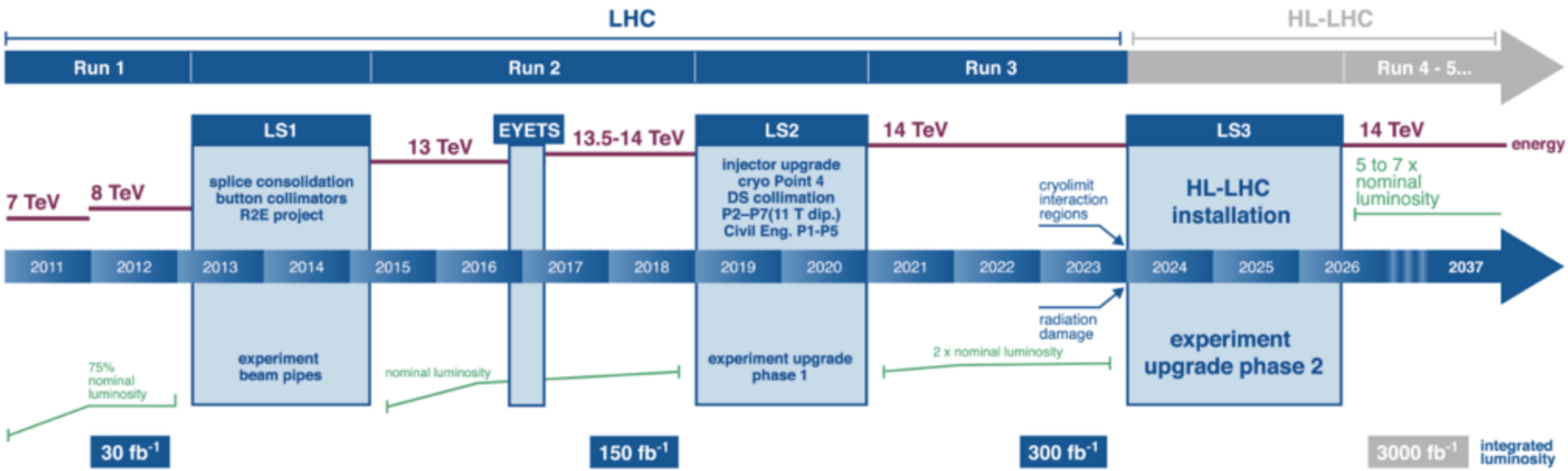


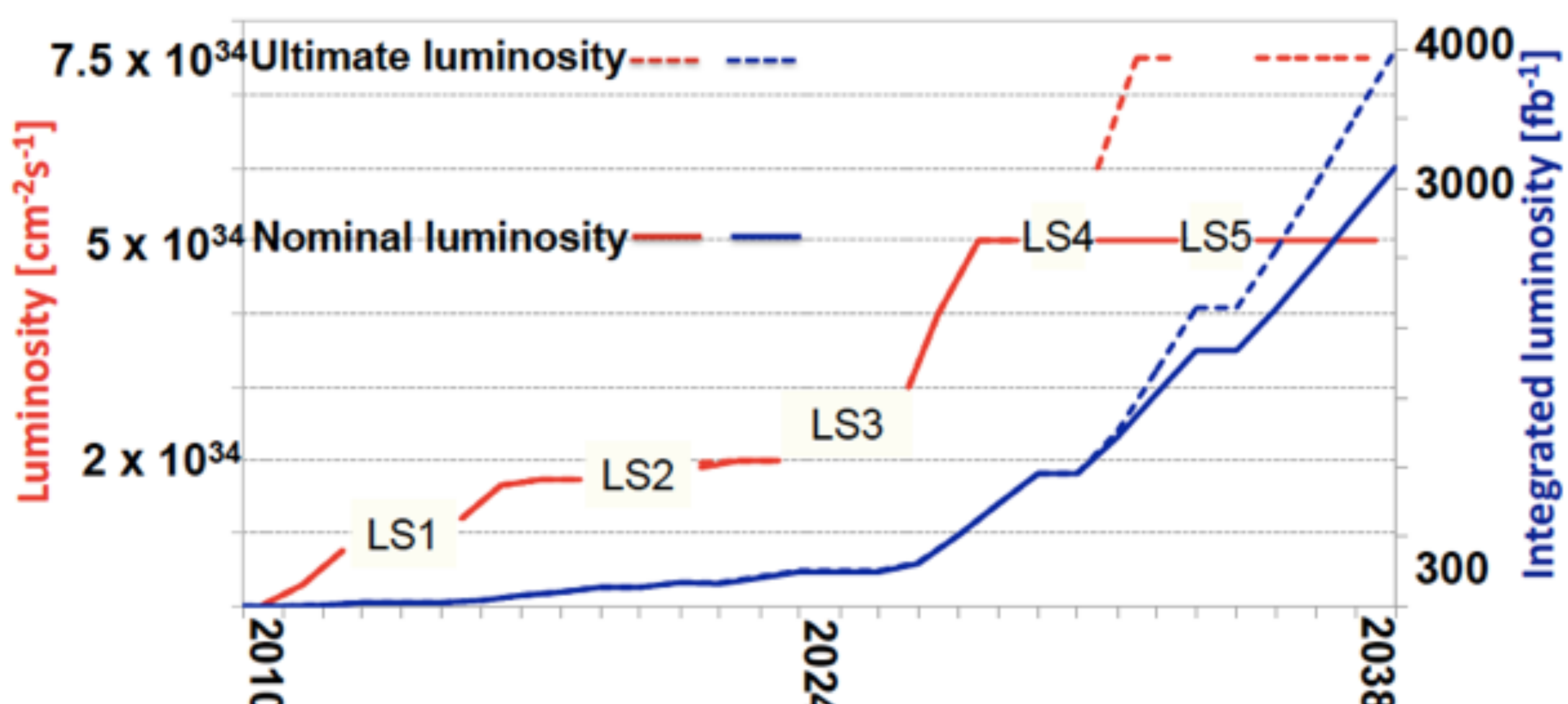
- ➡ Using history as a guide for the future
  - The last ~100 year in particle physics with collider
- ➡ Livingston Plot ~2010
  - Progress slowed down considerably
  - Investment in accelerator technology is still large, but directed towards tools like light sources
  - Limiting factor → cost (size)!

Large Hadron Collider

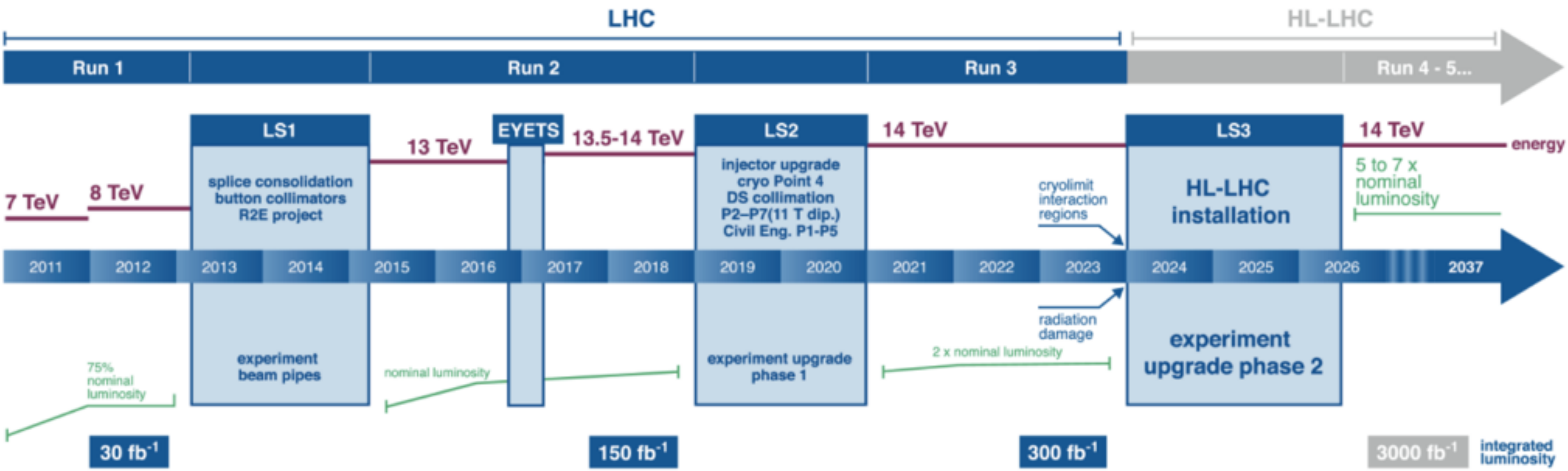


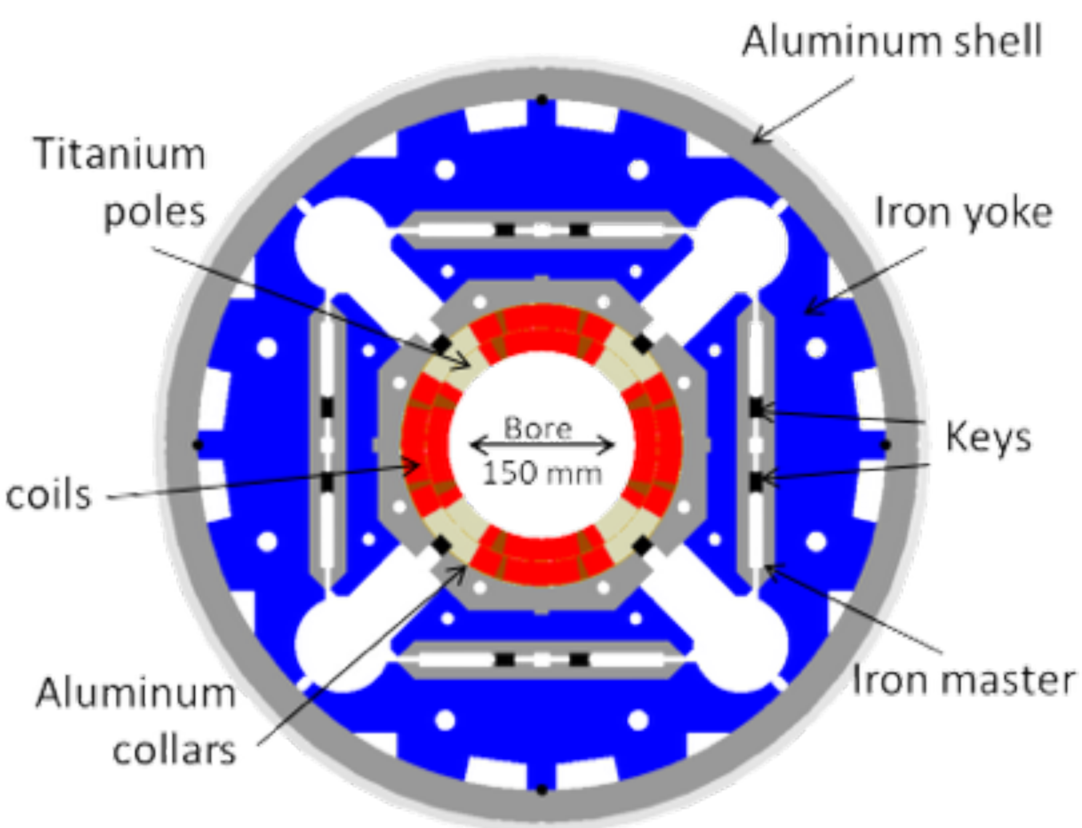
High Luminosity LHC





High Luminosity LHC





- ➡ **LHC dipoles stretched NbTi technology to its limit**
  - 8.3T in central region via operation at 1.8k
- ➡ **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β*
- ➡ **Operating and upgrading the LHC is a very significant investment**

Physics Case

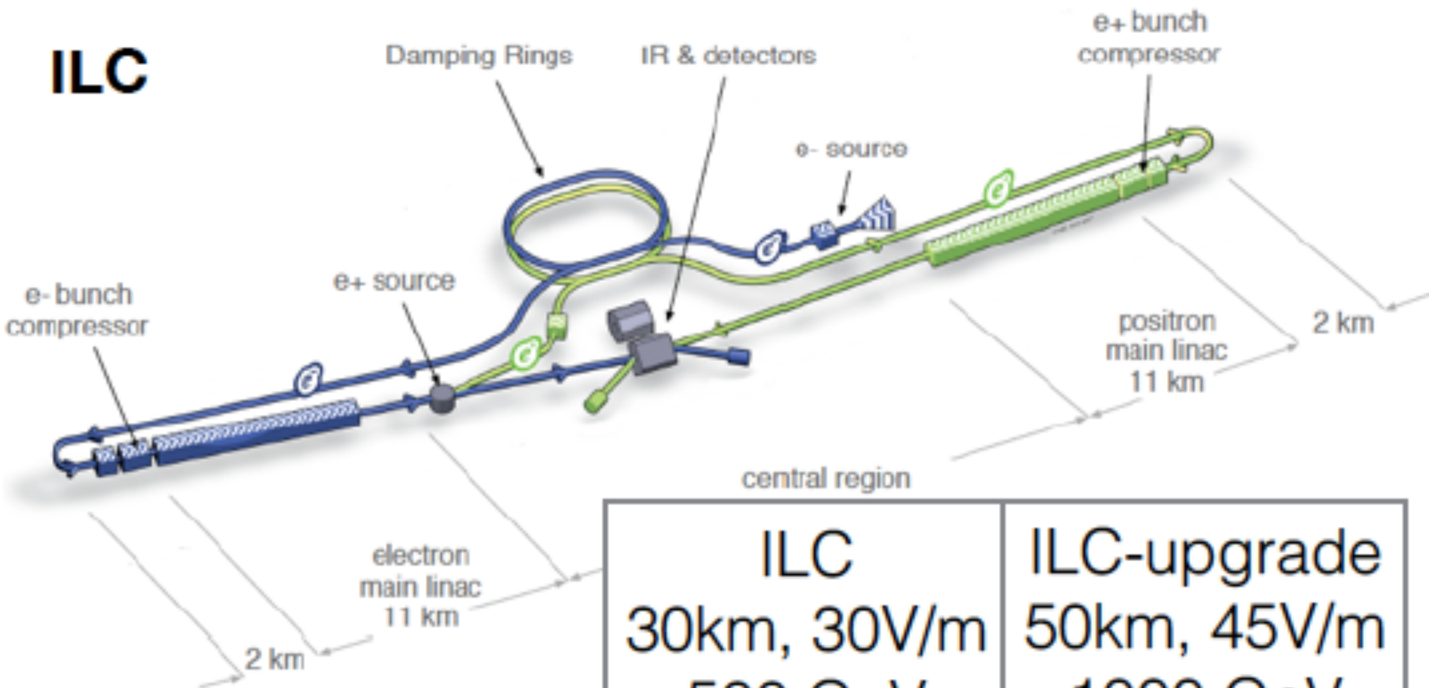
- ➡ **Higgs case at the start of the LHC was exceptional**
  - something to built on, not the reference
- ➡ **Goal for the future LHC and HL-LHC program**
  - **Explore the energy frontier**

- ➡ **Precision measurements of SM parameters (including the Higgs boson)**
- ➡ **Sensitivity to rare SM & rare BSM processes**
- ➡ **Extension of discovery reach in high-mass region**
- ➡ **Determination of BSM parameter**

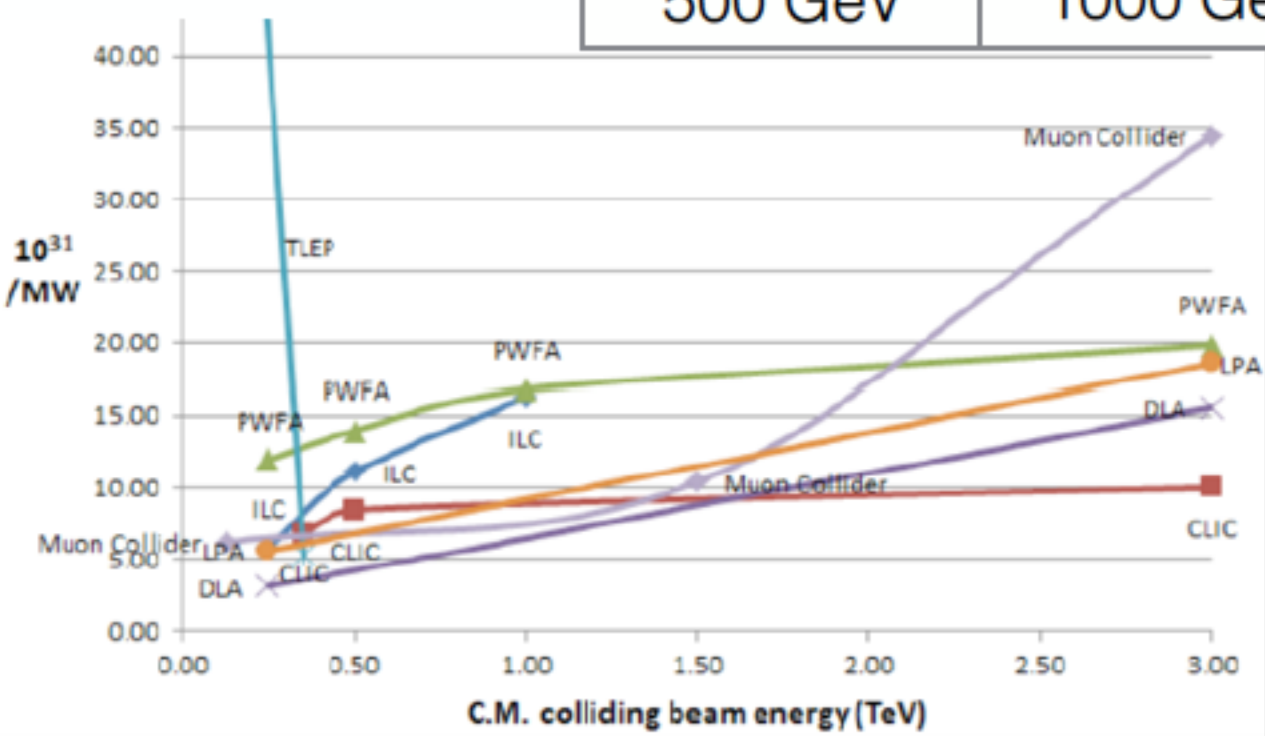
- ➡ **Actively working on "no-lose" theorem for future collider**

Lepton Collider

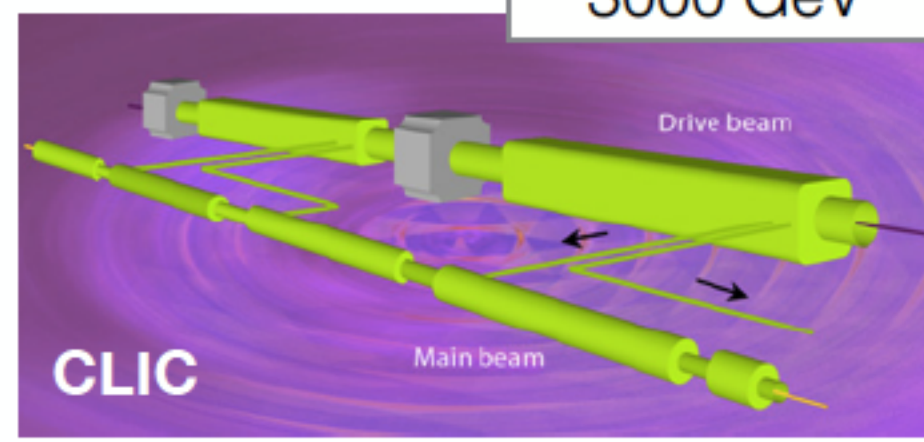
➡ Future Lepton Collider



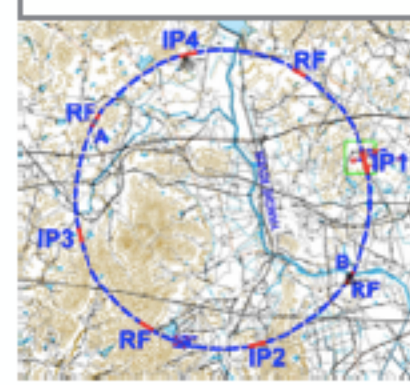
ILC	ILC-upgrade
30km, 30V/m 500 GeV	50km, 45V/m 1000 GeV



CLIC
50km, 100V/m 3000 GeV



CEPC	FCC-ee
50km 240 GeV	100km, 200MV 350 GeV

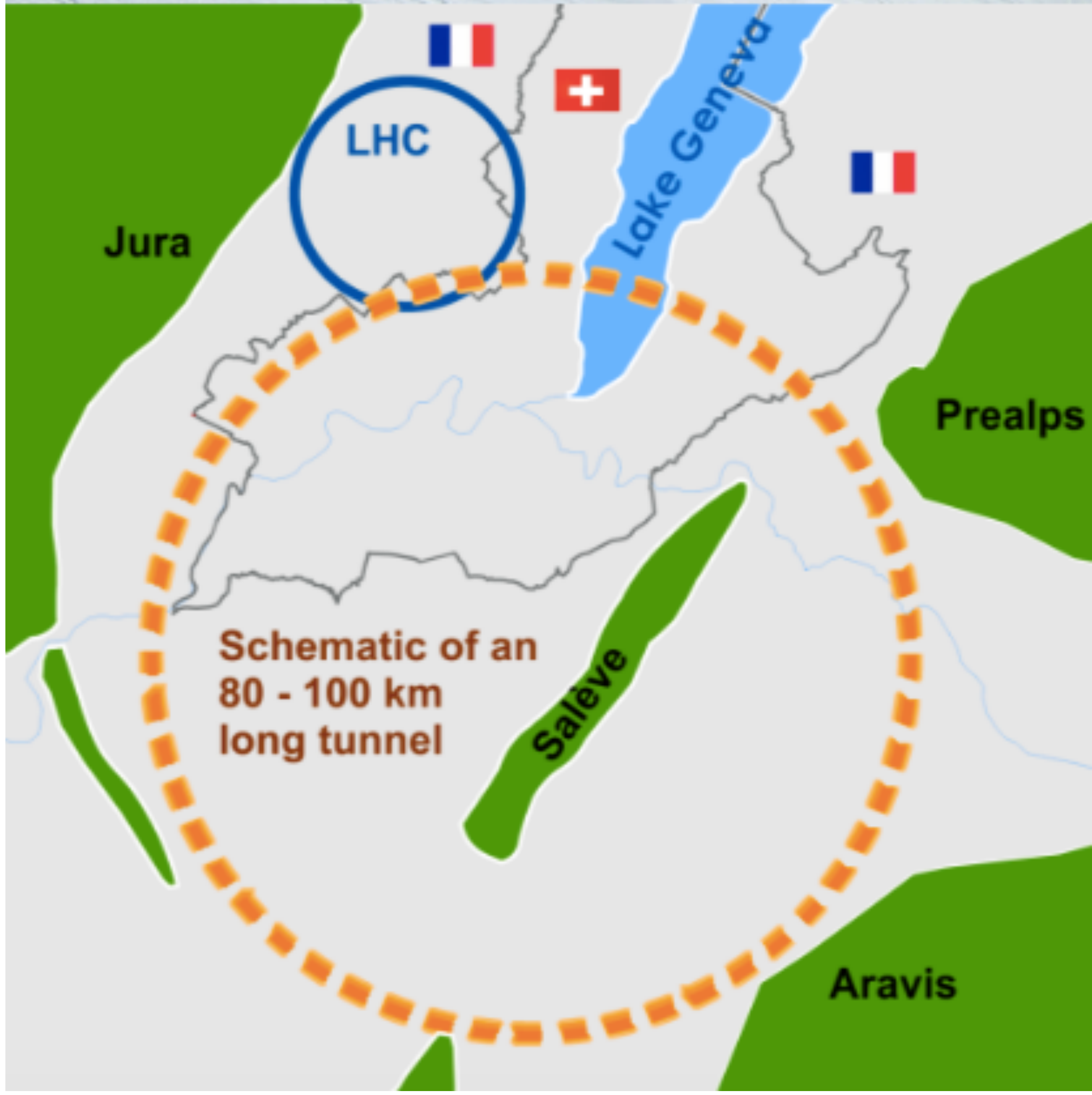


Future Circular Collider (FCC-ee)

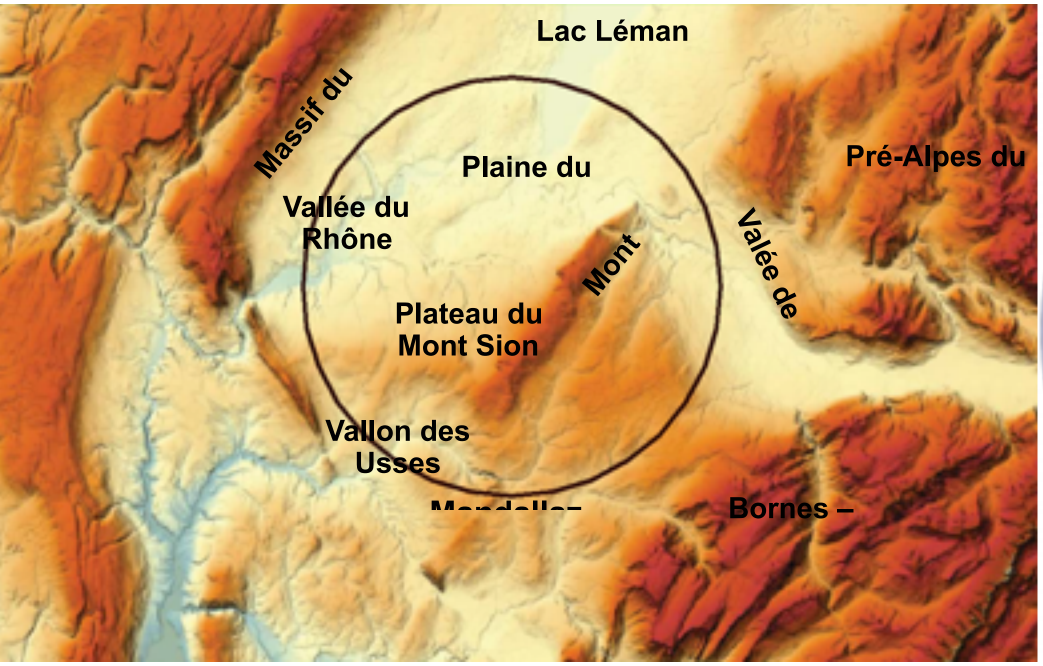
Circular Electron Position Collider (CEPC)

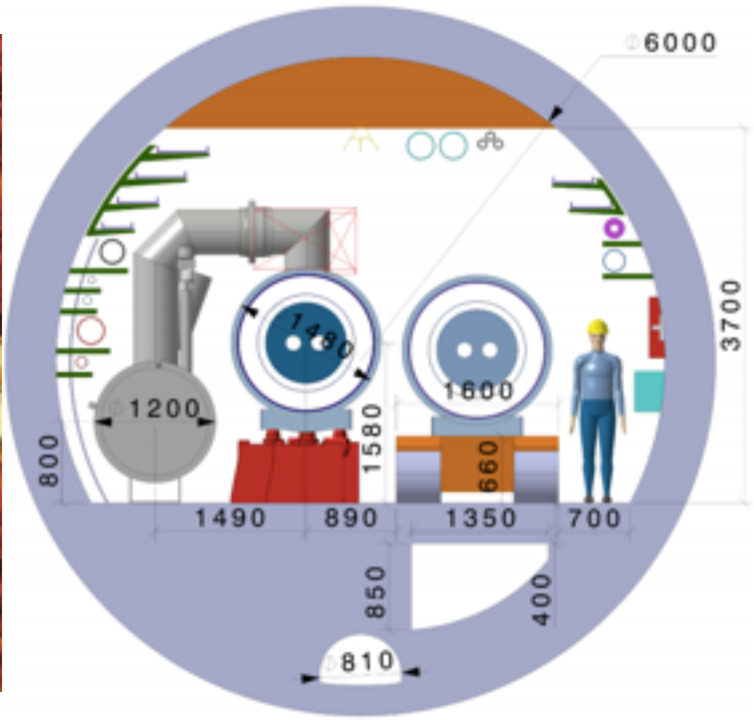
Future Circular Collider

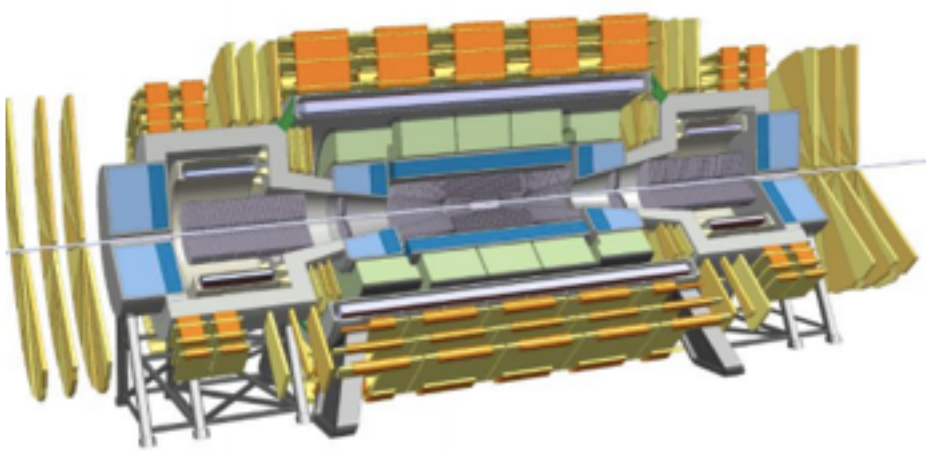
- **International FCC collaboration to study**
  - pp collider (FCC-hh)
  - e^+e^- collider (FCC-ee)
  - p-e (FCC-he)
- 80-100 km infrastructure in Geneva area
- **Goal:** CDR and cost review by 2018
- Similar studies in China (50-100 km infrastructure)
  - pp collider (SppS)
  - e^+e^- collider (CepC)

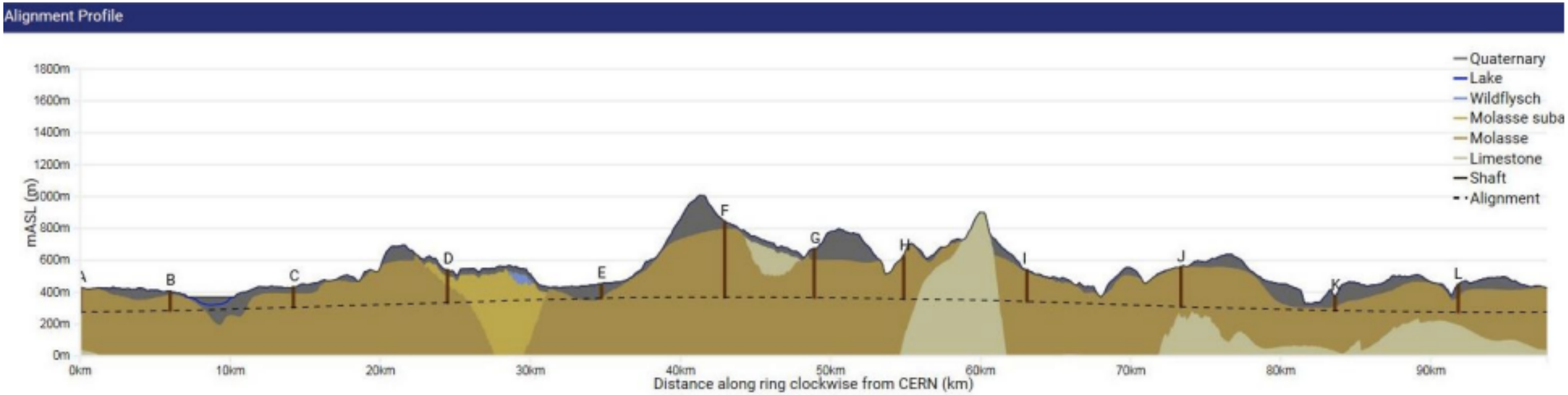


Future Circular Collider







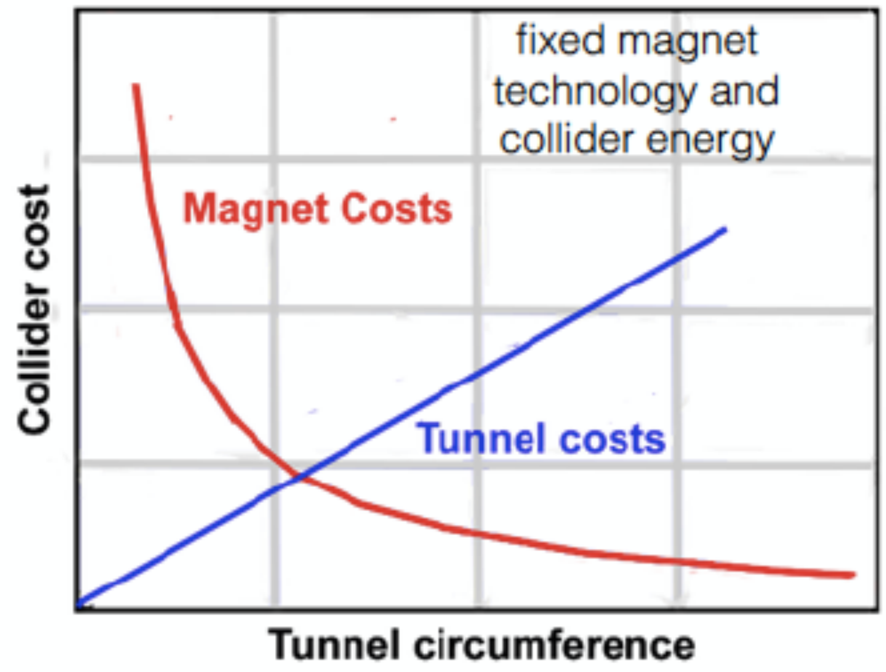


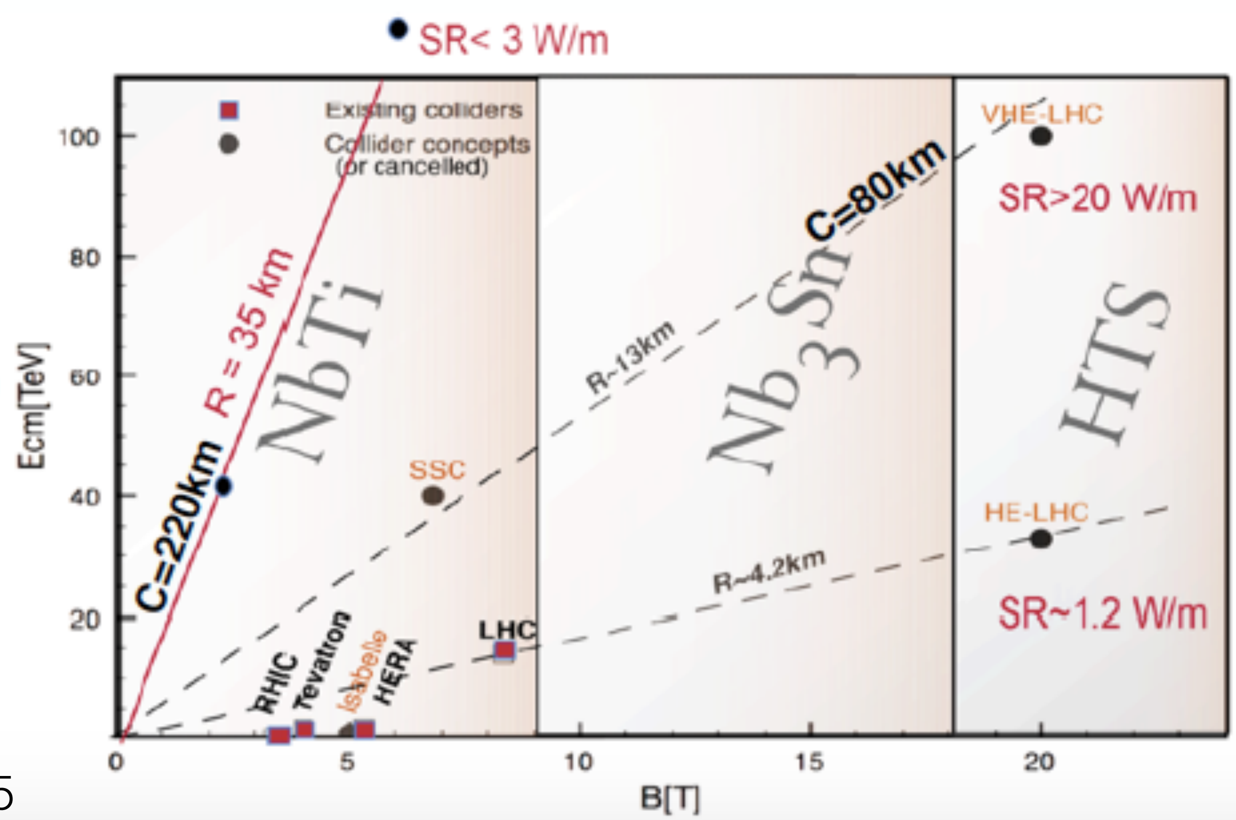
Michael Benedikt at FCC week in Berlin

Future Circular Collider

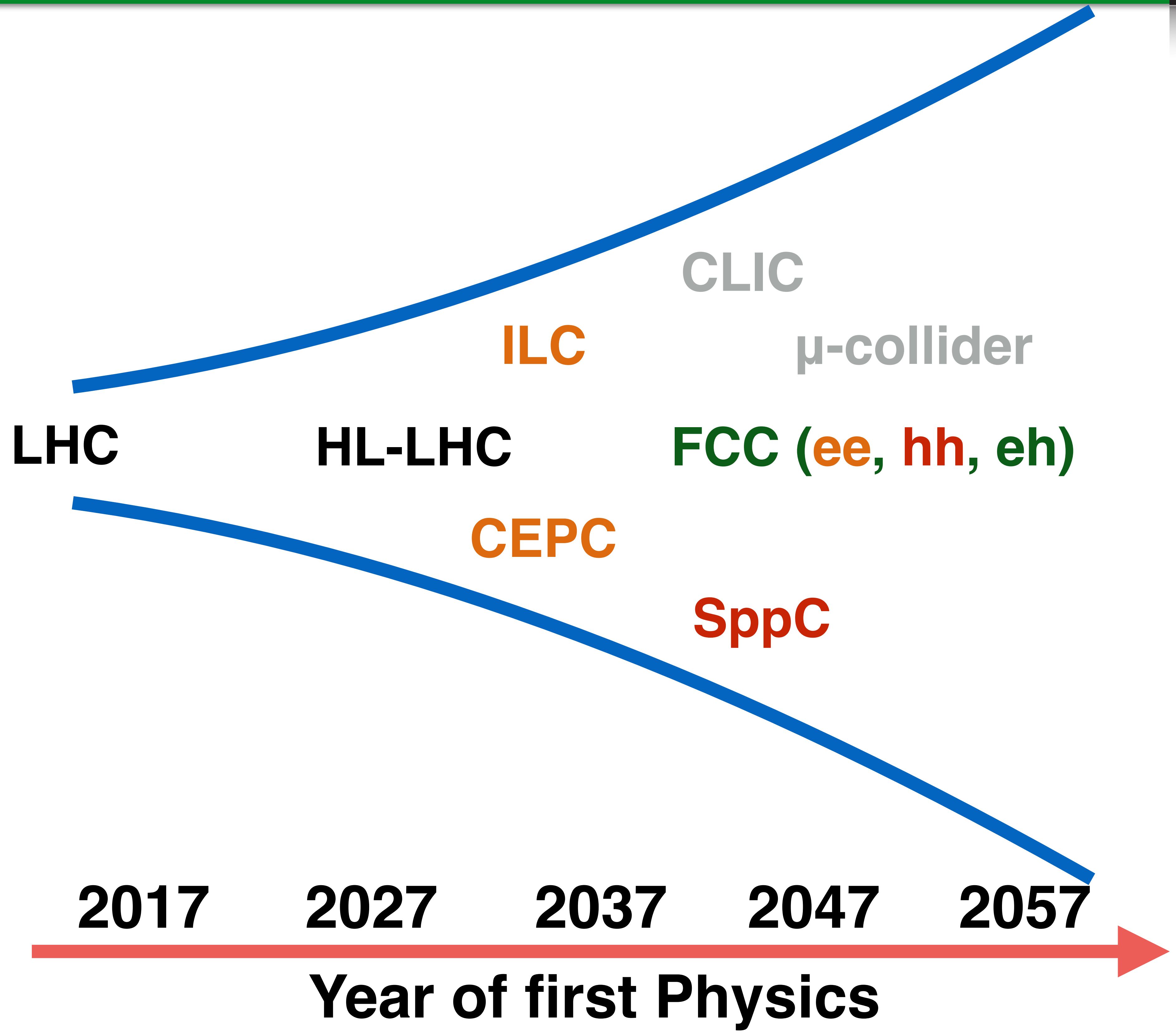
➡ Future Hadron Collider Challenges

- **Overall construction cost**
  - cost driver are magnets and the tunnel
  - depend on magnet technology
  - tunnel cost highly geology dependent
- **Magnet technology**
  - Nb_3SN foreseen for HL-LHC
- **Total energy stored**
  - for 100km, 20T machine
    - ~200 GJ in magnet
    - ~10 GJ in beam,
  - both are very challenging (~20*LHC)
- **Proton synchrotron radiation**

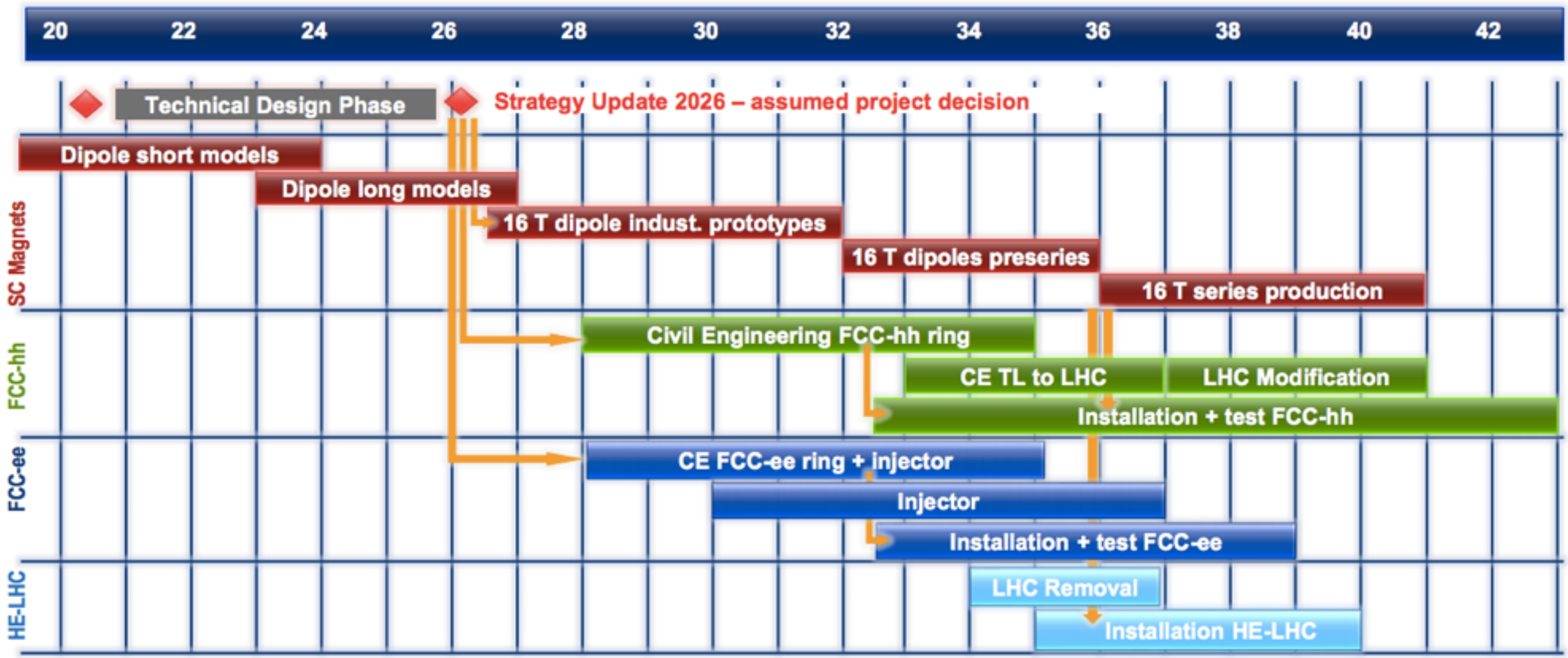




Roadmap for Particle Physics



Roadmap for CERN



Michael Benedikt at FCC week in Berlin

Priorities in HEP today

➡ **Explore the physics of electroweak symmetry breaking**

- measurements of Higgs properties, couplings of gauge bosons, flavor phenomena, …

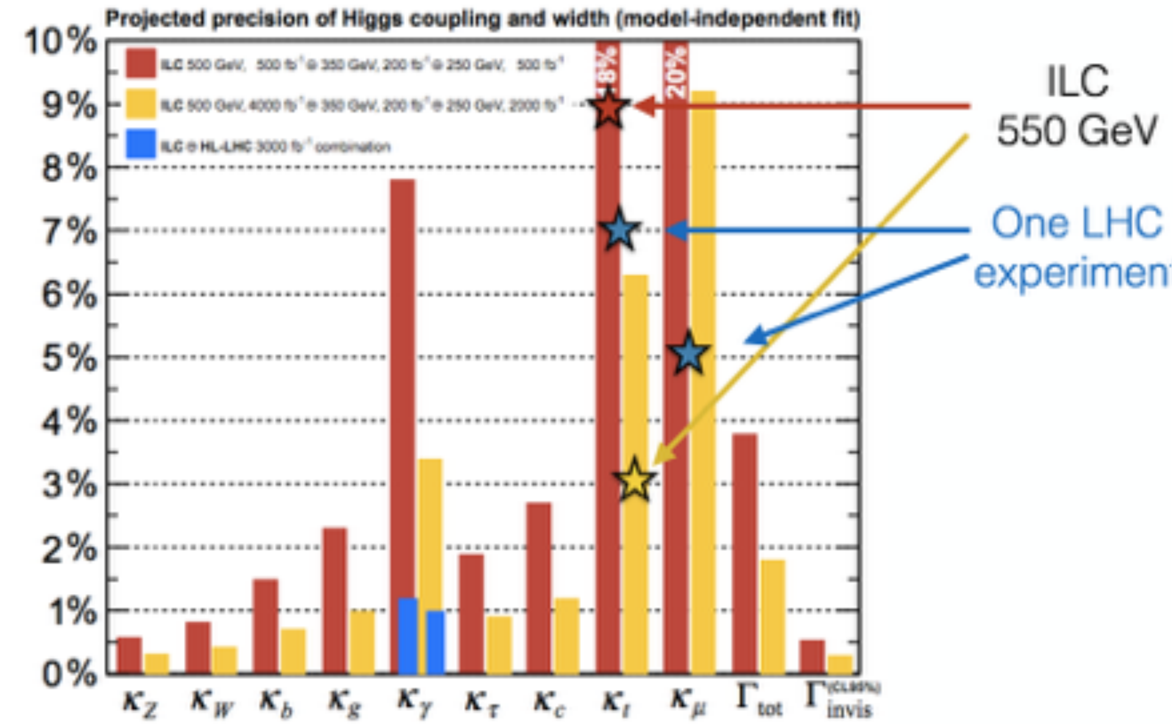
➡ **Investigate known departures from the SM**

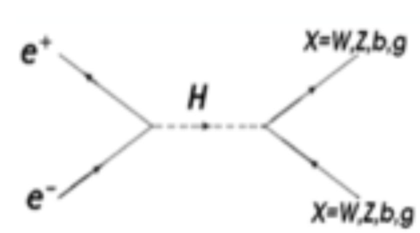
- Dark Matter, neutrino masses, baryon asymmetry of the universe, …

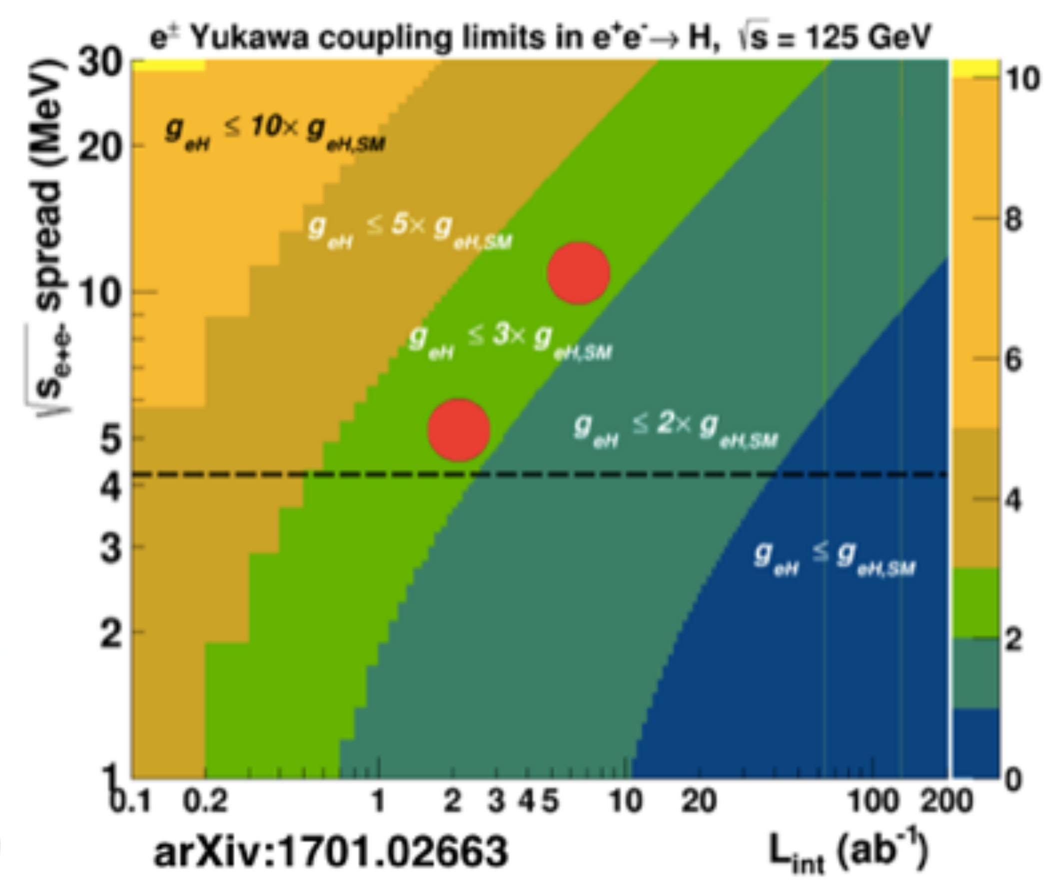
Prospects on Higgs Physics

➡ **Example: the Higgs boson (mechanism)**

- predicted in 1964
- discovered in 2012
- today's knowledge
  - consistent with SM prediction ~20% level
  - Spin-0
  - gives mass to W and Z bosons
  - gives mass to 3 generation fermions
- **with today's technology**
  - consistent (or not) with SM prediction ~0.1% level
  - gives mass to 2 and 1 generation fermions
  - whether there is more than one Higgs boson







Case for Higgs precision

➡**How well do we need to measure Higgs couplings?**

- to be sensitive to a deviation δ, the measurement needs a precision of at least δ/3, better δ/5
- implications of new physics scale on couplings from heavy states or through mixing

➡**How large are potential deviations from BSM physics?**

$$g = g_{\rm SM}\,[1+\Delta] \;\;:\;\; \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\frac{\Gamma_{\rm 2HDM}[h^0\to X]}{\Gamma_{\rm SM}[h\to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

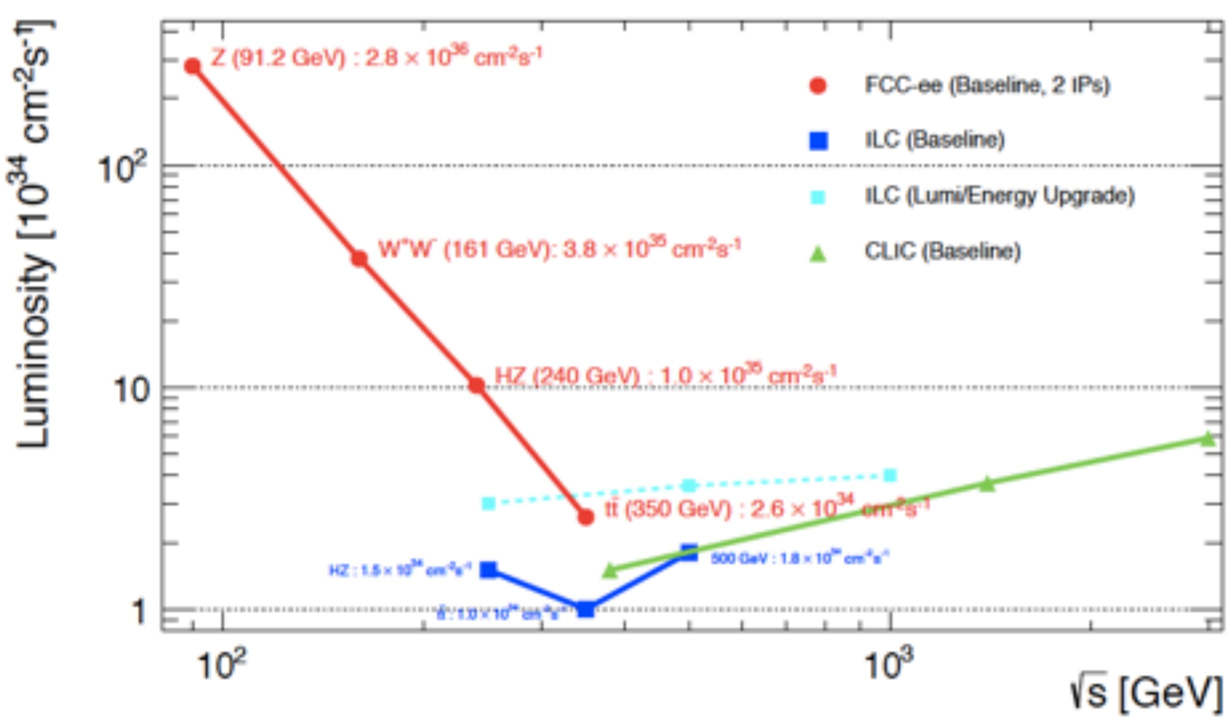
➡**Testing multi-TeV scale with sub-percent level measurements**

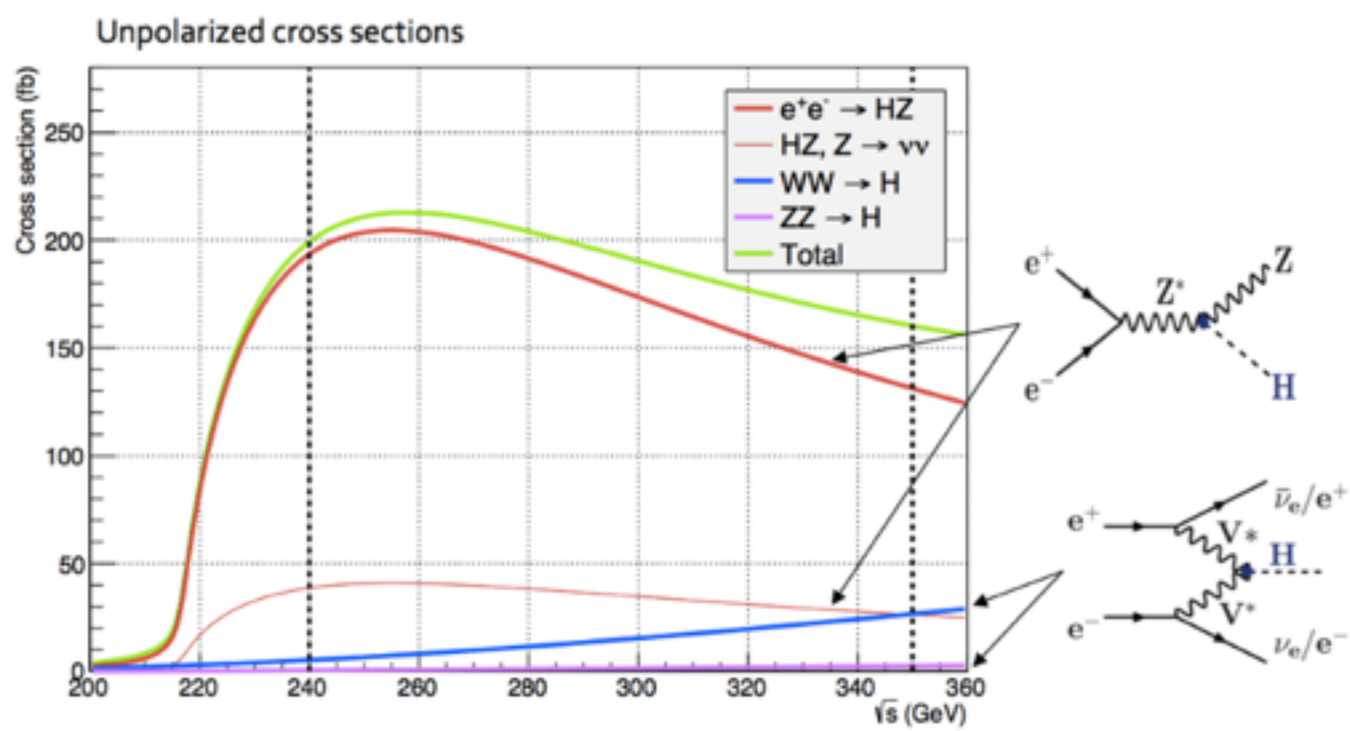
arXiv:1310.8361

➡**There is no strict limit to the precision needed!**

Lepton Collider Higgs Program

➡ **Exploiting a very large Higgs boson sample, produced under clean experimental conditions, and collected with superb precision detectors**



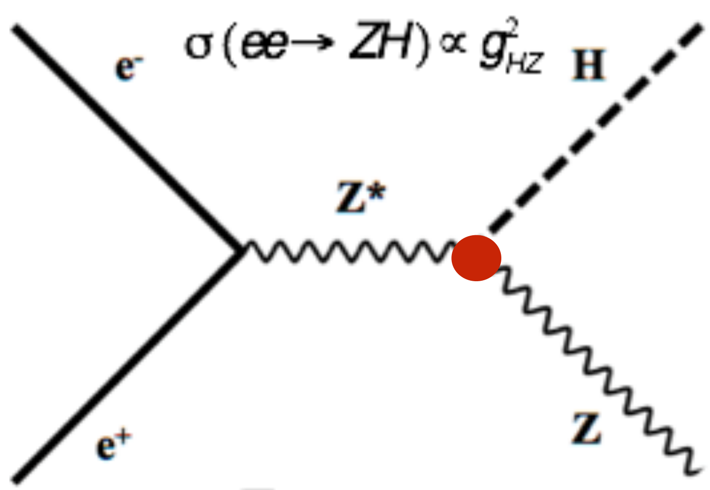


	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	**5**	**1.5**
Number of Higgs bosons from $e^+e^- \to HZ$	**1,000,000**	**200,000**
Number of Higgs bosons form fusion process	**25,000**	**40,000**

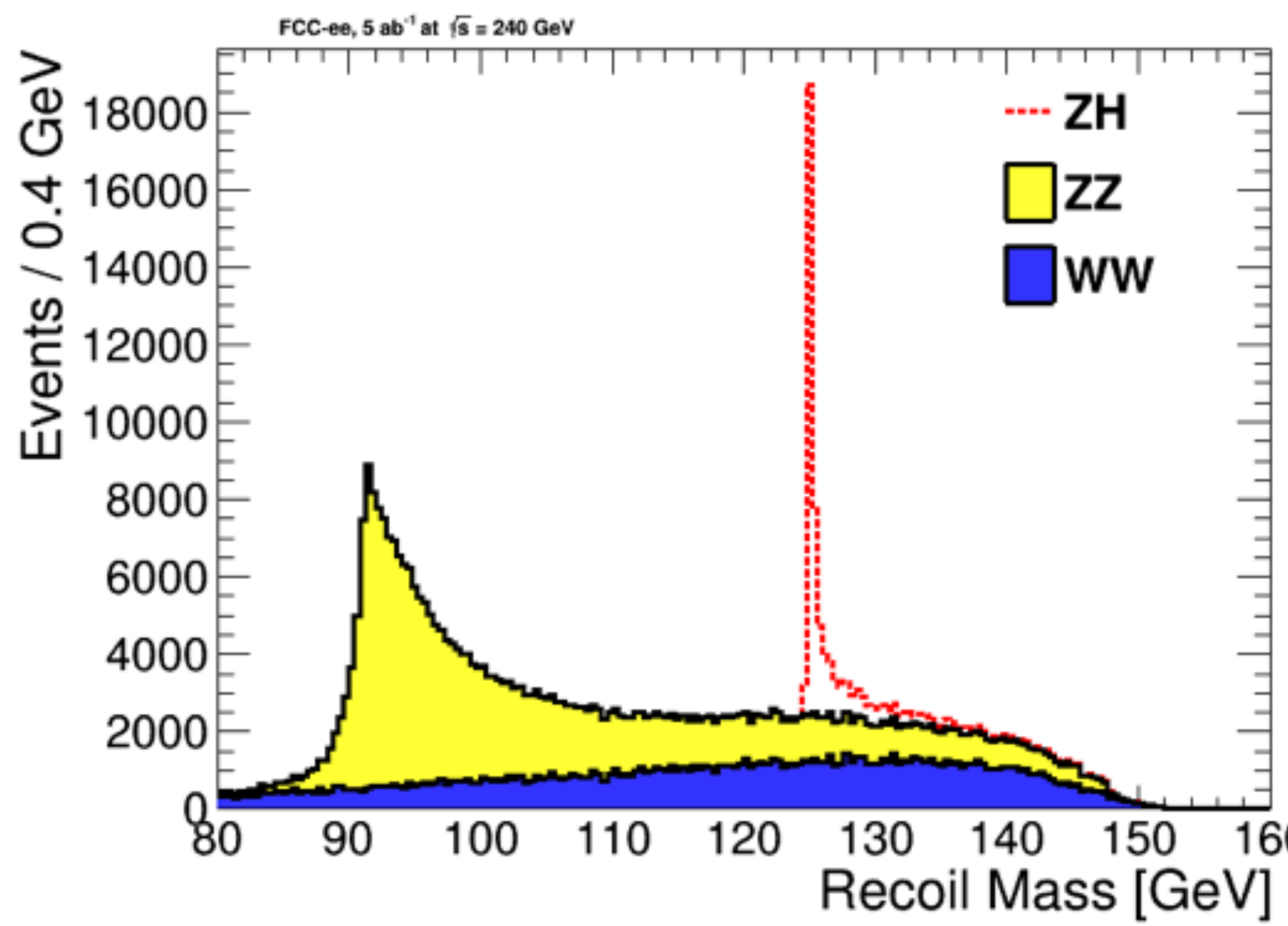
Higgs coupling to Z bosons

➡ **Recoil method provides unique opportunity for model independent measurement of HZ coupling**

- Higgs events are tagged Higgs decay mode independent
- expected precision ~0.5% on ZH cross section at FCC-ee
- using only leptonic Z decays and only measurement at 240 GeV so far



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



- Total width from

$$\sigma(ee \rightarrow ZH) \cdot BR(H \rightarrow ZZ) \propto \frac{g_{HZ}^4}{\Gamma_H}$$

Higgs Boson Couplings

➡ **Precision Higgs coupling measurements**

- absolute coupling measurements enabled by HZ cross section measurement
    - only leptonic modes used so far
- tagging individual Higgs final states
- data at 350 GeV constrain total width
    - only used H→bb in fusion production so far
- couplings extracted from model-independent fit
- statistical uncertainties are shown for $5ab^{-1}$@240 GeV and $1.5ab^{-1}$@350GeV (from arXiv:1308.6176)
    - all measurements are under review / are being redone
    - most result use CMS detector performance and will be improved
- optimization of relative size of datasets (240 GeV and 350 GeV) to be done

in %	FCC-ee 240 GeV	+FCC-ee 350 GeV
g_{HZ}	0.21	0.21
g_{HW}	1.25	0.43
g_{Hb}	1.25	0.64
g_{Hc}	1.49	1.04
g_{Hg}	1.59	1.18
$g_{H\tau}$	1.34	0.81
$g_{H\mu}$	8.85	8.79
$g_{H\gamma}$	2.37	2.12
Γ_H	2.61	1.55

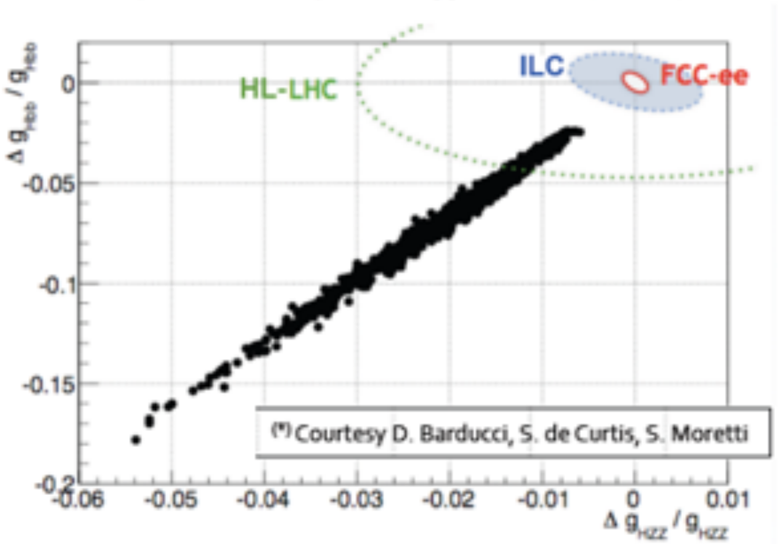
Higgs Boson Couplings

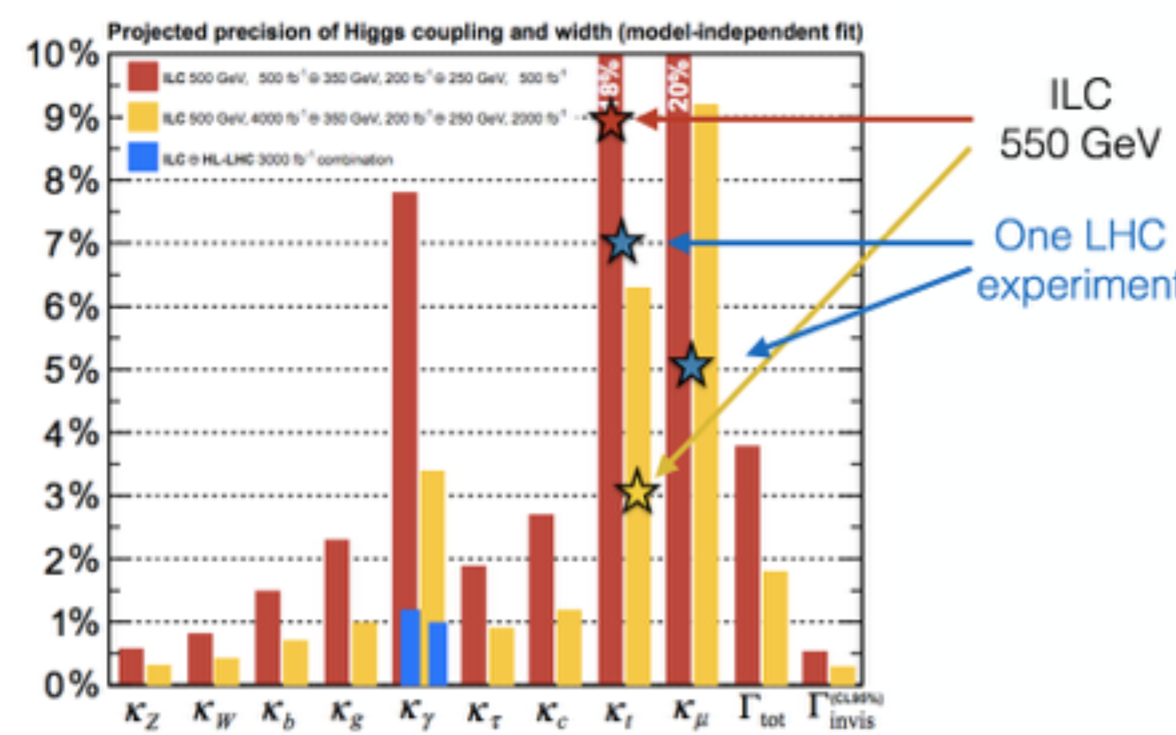
- ➡ **Comparison with (HL-LHC)**
  - model dependent fit shown for HL-LHC results
  - results shown for one LHC experiment
- ➡ **Factor ~10 improvement for most couplings**
  - FCC-ee measurements turn hadron collider Higgs measurements into absolute coupling measurements (synergy)
  - rare decays favored by hadron collider searches (complementarity)
- ➡ **Testing new physics at multi-TeV scale**
  - start probing quantum structure

in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

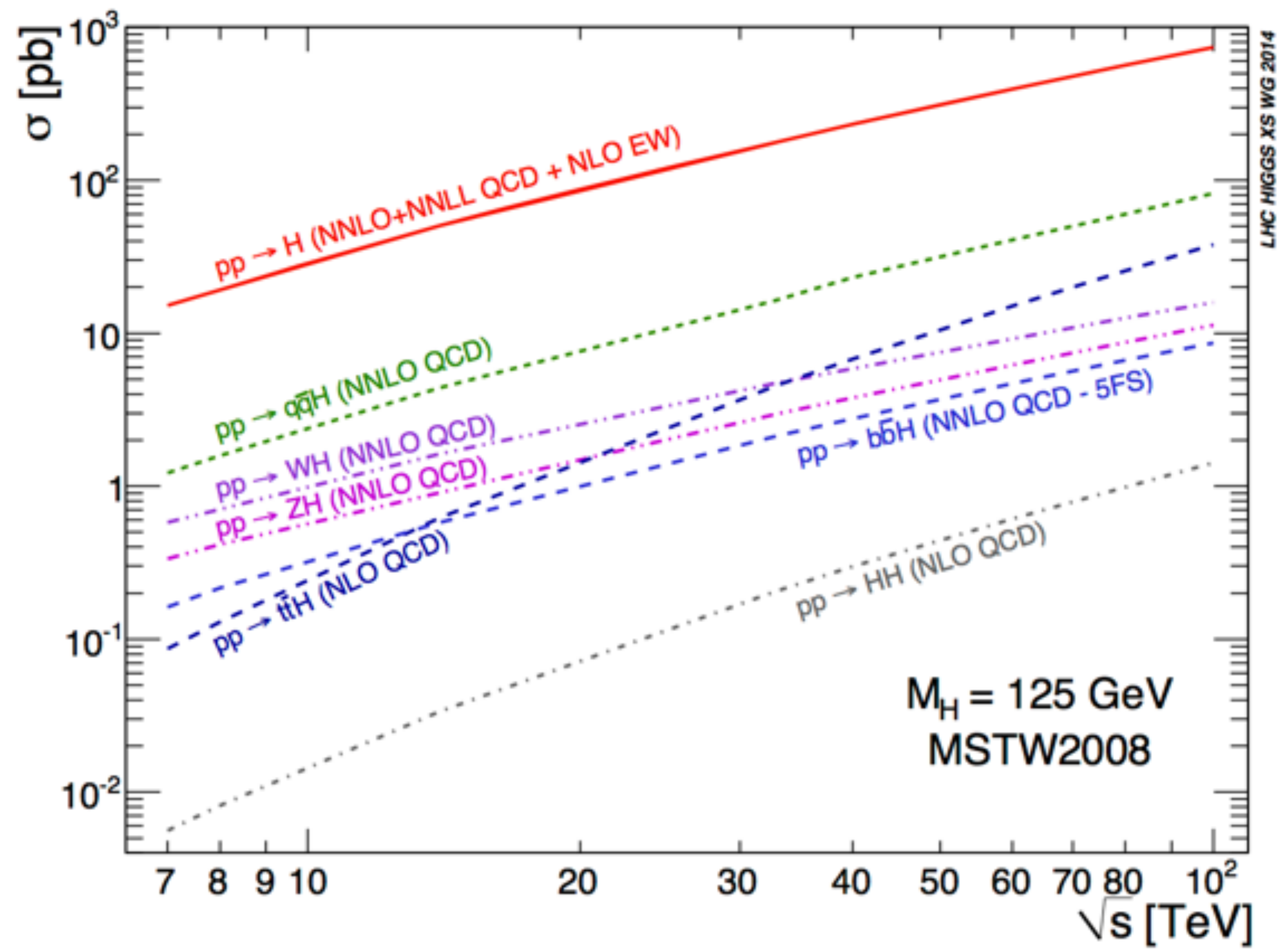
Example from Composite Higgs Models (4HDM)





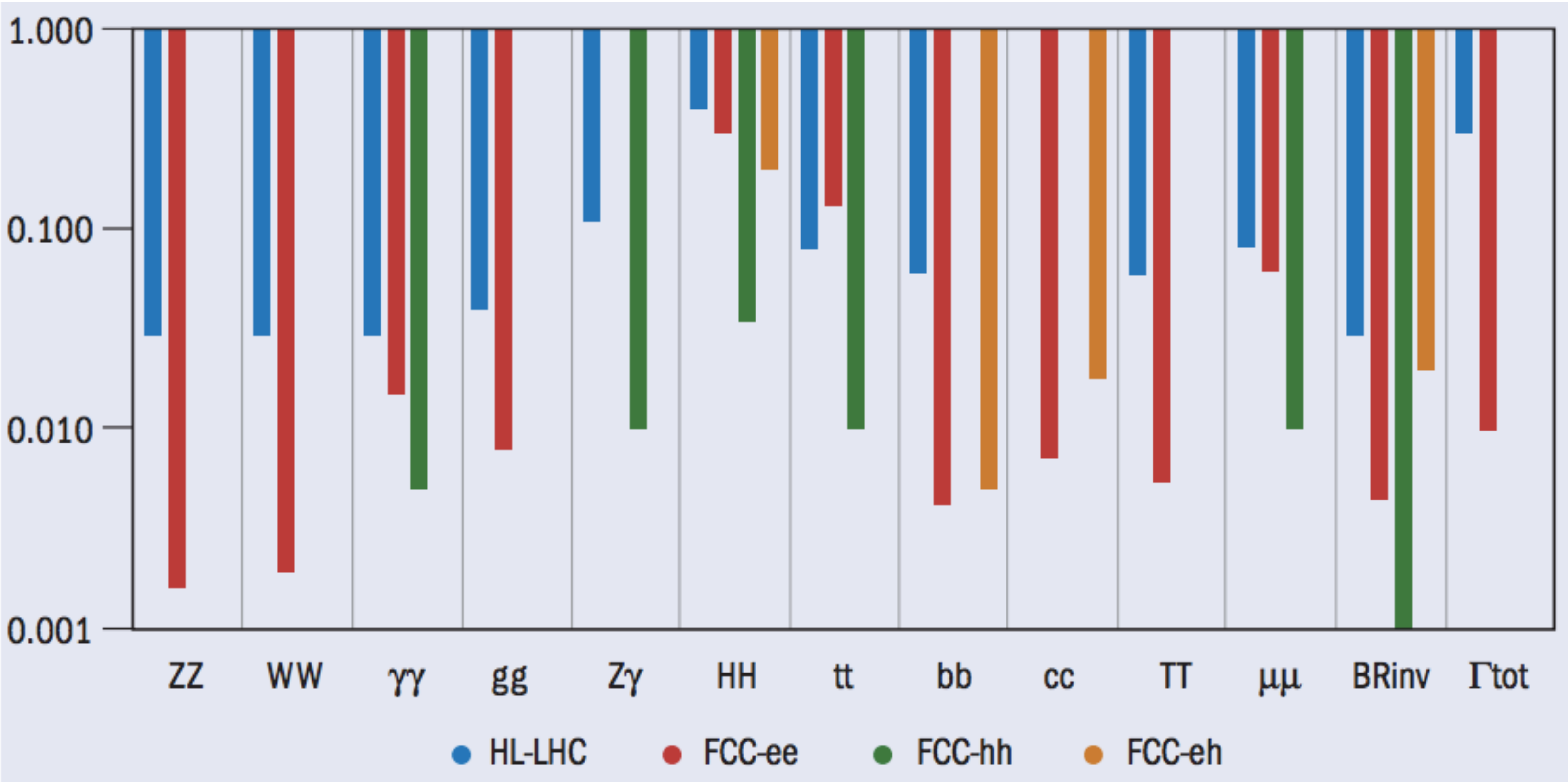
Higgs Boson Couplings

Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Higgs Boson Couplings

Summary from CERN Courier

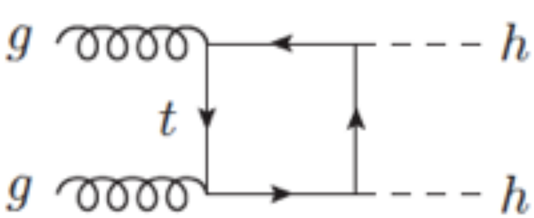


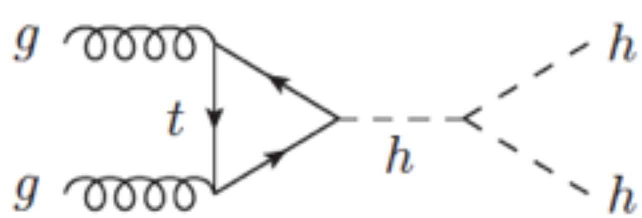
Sensitivity to new physics beyond inclusive measurements!

Higgs Boson Couplings

➡ **Probing triple-Higgs coupling with double Higgs production**

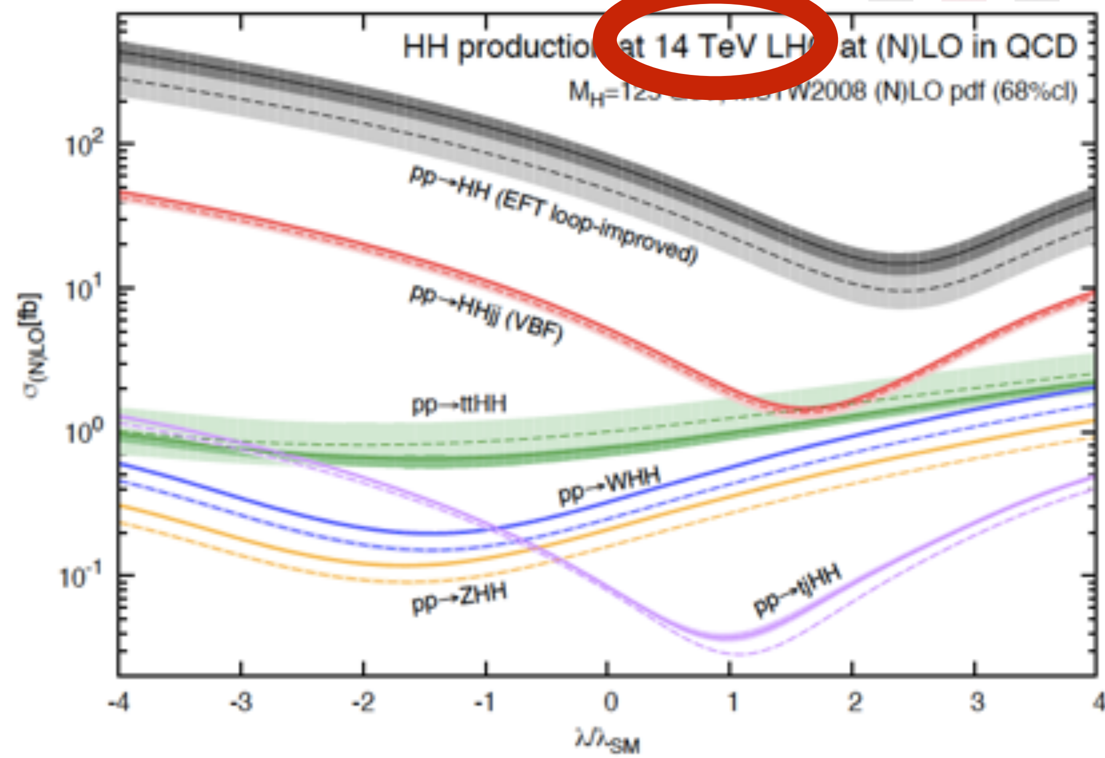
- Consistency of check of EWSB
- Reconstructing the Higgs potential
- Sensitivity through yields and kinematics
- Large enhancement through BSM possible
- Exhaustive program at the (HL-)LHC

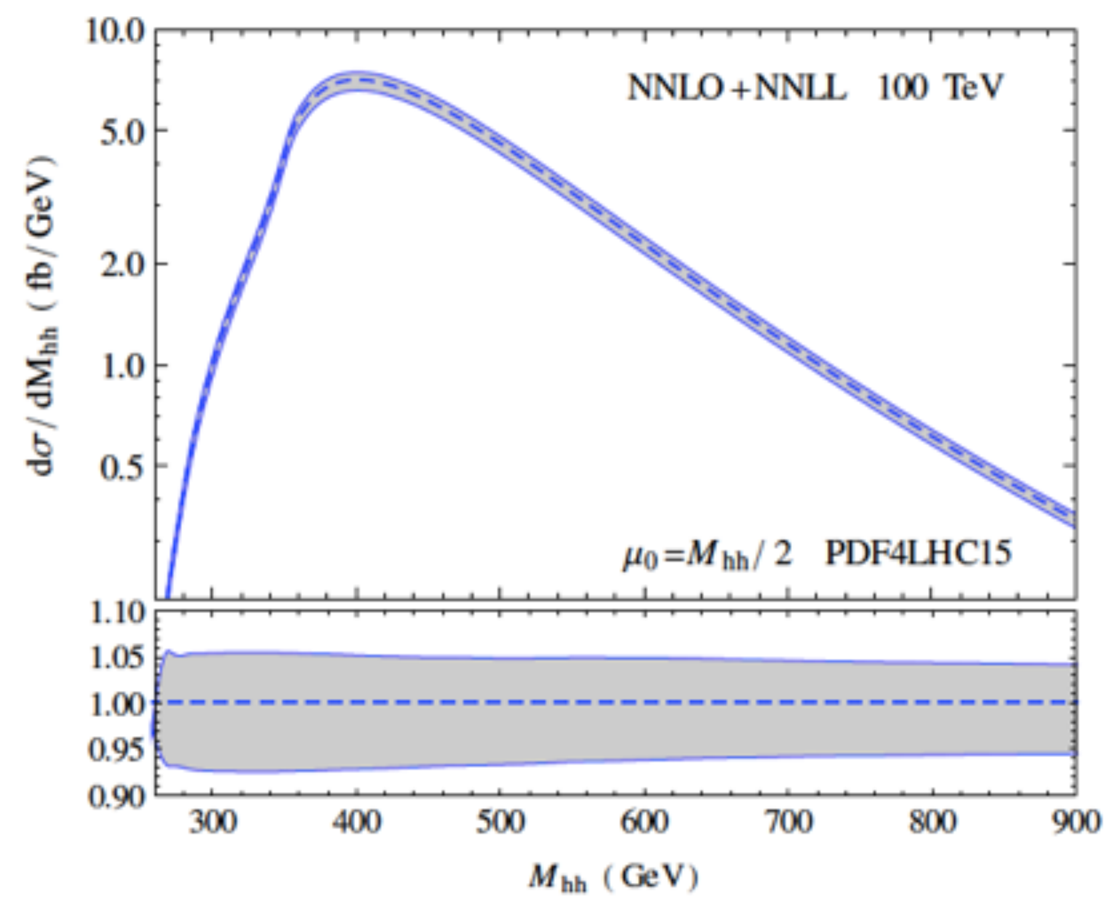




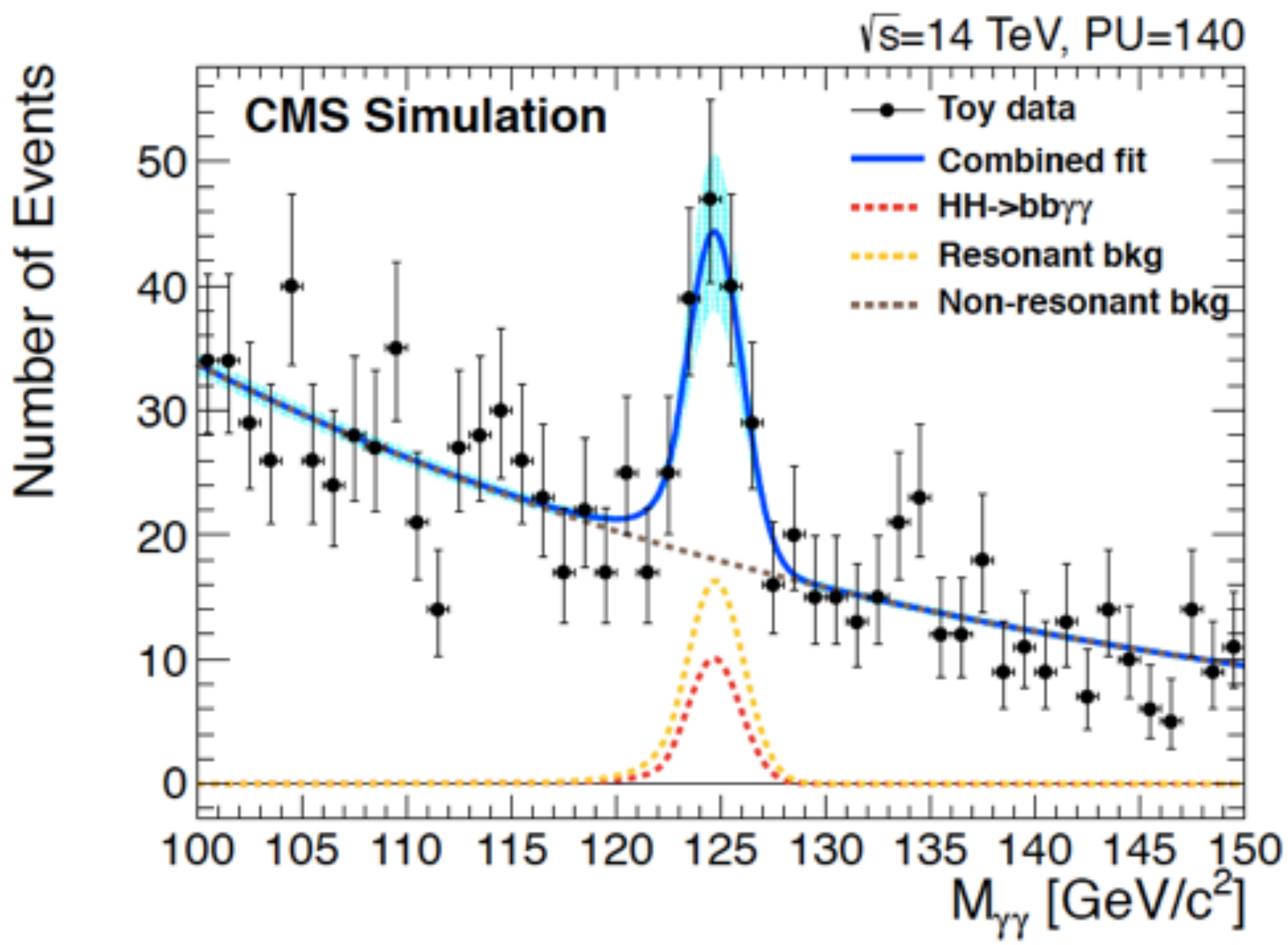
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

EFT Lagrangian





Higgs Boson Couplings



➡ **Comparing FCC-hh with HL-LHC results**

- similar S/B
- ~10 signal events at HL-LHC
- FCC has larger cross section and luminosity
- FCC has larger acceptance and selection efficiency

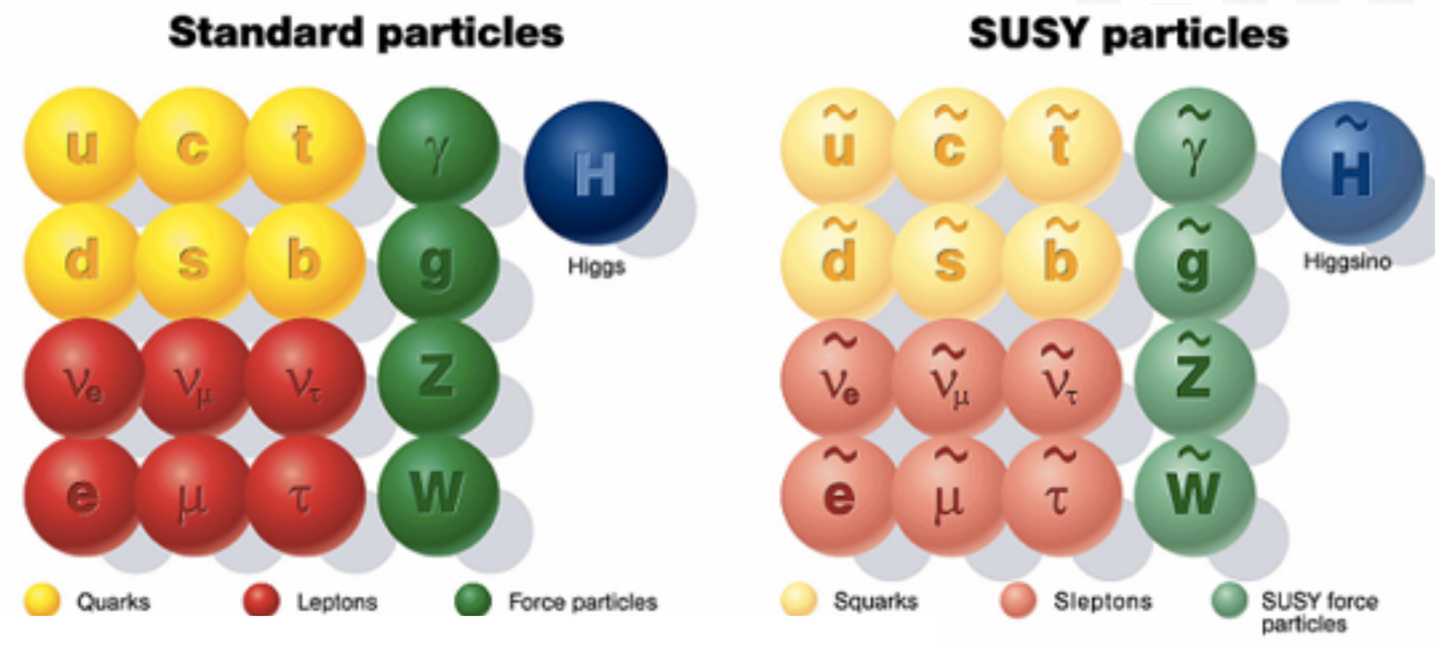
Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.76	0.44	13200
$bbj\gamma$	147	0.203	6110
$t\bar{t}h(\gamma\gamma)$	1.9	0.164	4930
$jj\gamma\gamma$	83	0.082	2460
$b\bar{b}\gamma\gamma$	14.7	0.074	2220
$b\bar{b}h(\gamma\gamma)$	0.10	8.1×10^{-3}	240
Total background	247	0.53	15960

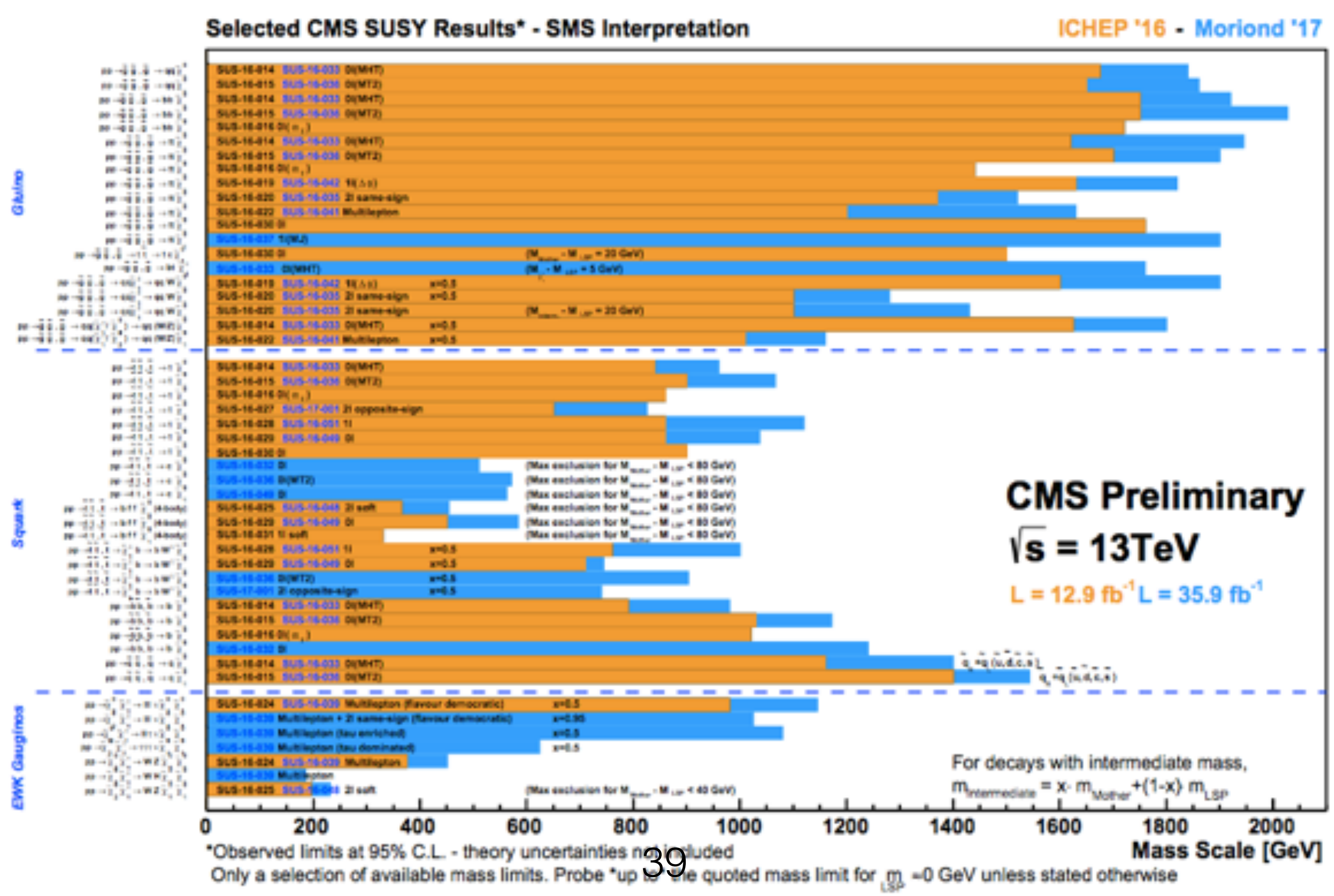
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–

Prospects for SUSY

➡ **Example: Supersymmetry**

- proposed in ~1974 (by Wess & Zumino)
- **today's knowledge**
  - **Supersymmetry must be broken**
- discovery in …





Prospects for SUSY

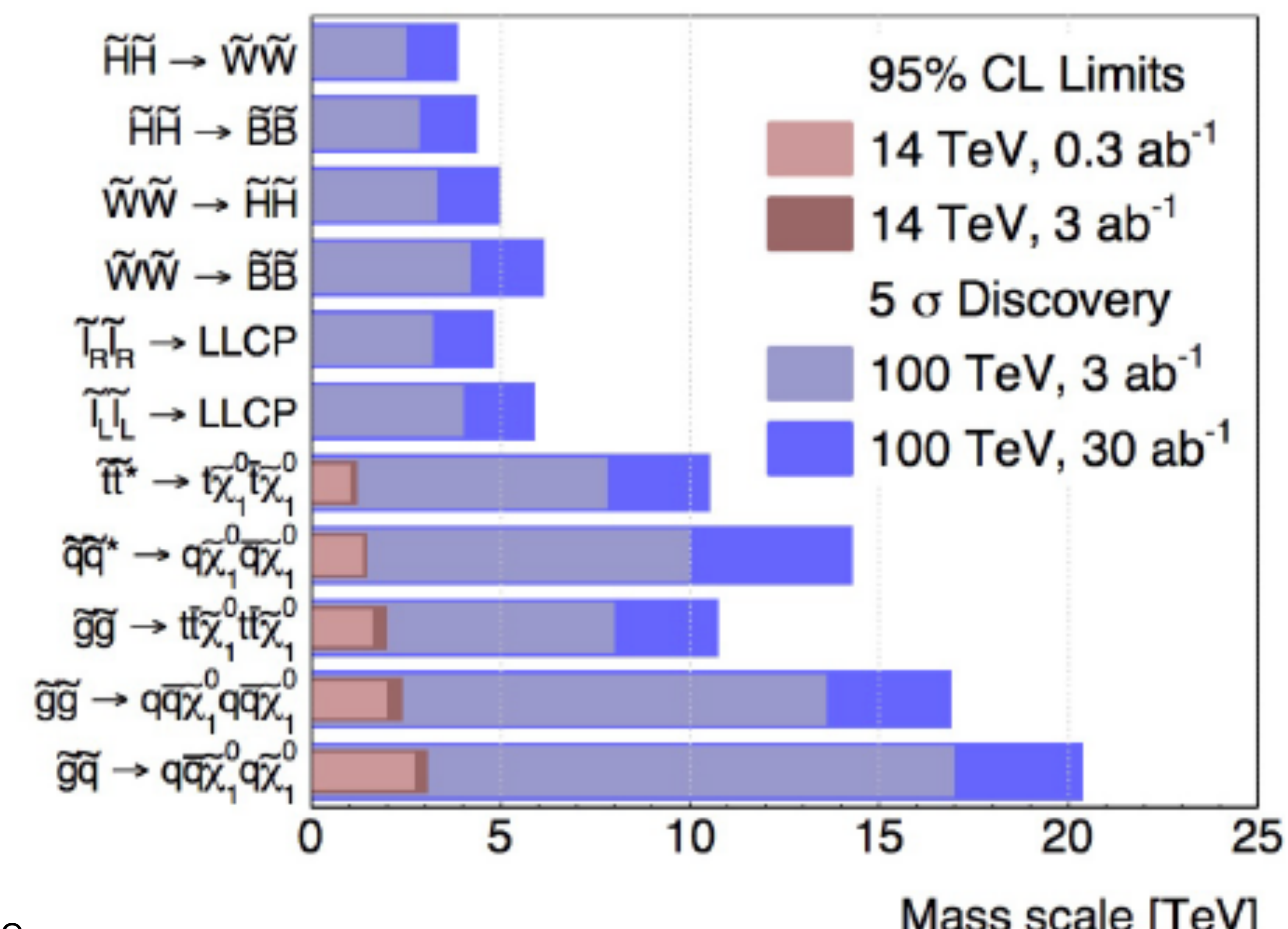
➡ **Example: Supersymmetry**

- proposed in ~1974 (by Wess & Zumino)
- today's knowledge
- **discovery in …**

HL-LHC

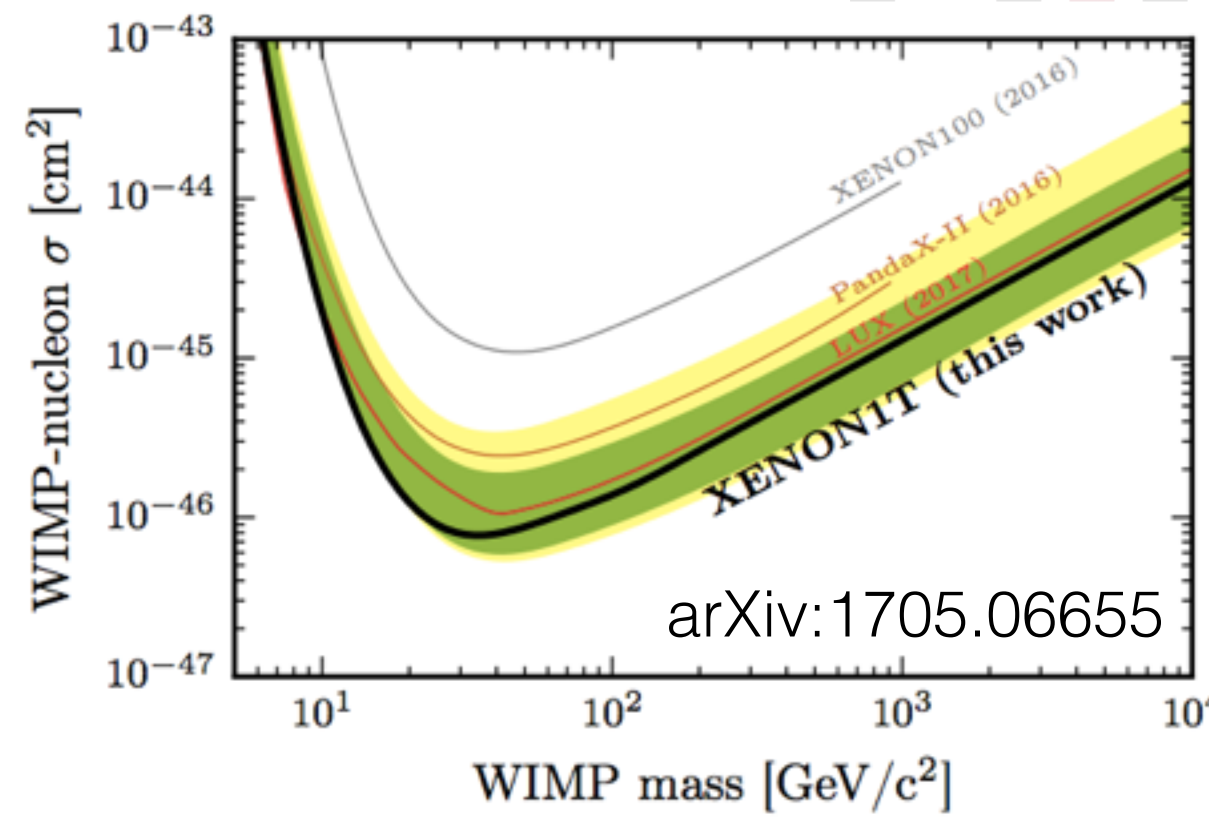
Analysis	Luminosity (fb^{-1})	Model NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300				< 3σ	3 – 5σ
	3000				3 – 5σ	> 5σ
all-hadronic (MT2) search	300	3 – 5σ	> 5σ	> 5σ		
	3000	> 5σ	> 5σ	> 5σ		
all-hadronic b_1 search	300	< 3σ	< 3σ	< 3σ	3 – 5σ	< 3σ
	3000	< 3σ	< 3σ	< 3σ	> 5σ	< 3σ
1-lepton t_1 search	300	> 5σ	> 5σ	> 5σ	3 – 5σ	< 3σ
	3000	> 5σ	> 5σ	> 5σ	> 5σ	> 5σ
monojet $\tilde{t}_1$ search	300					3 – 5σ
	3000					3 – 5σ
$m_{\ell^+\ell^-}$ kinematic edge	300	< 3σ	< 3σ	< 3σ		
	3000	> 5σ	< 3σ	< 3σ		
multilepton + b-tag search	300	> 5σ	> 5σ	> 5σ	3 – 5σ	
	3000	> 5σ	> 5σ	> 5σ	> 5σ	
multilepton search	300	< 3σ	< 3σ	< 3σ	< 3σ	
	3000	3 – 5σ	3 – 5σ	< 3σ	3 – 5σ	
ewkino WH search	300		< 3σ			
	3000		3 – 5σ			

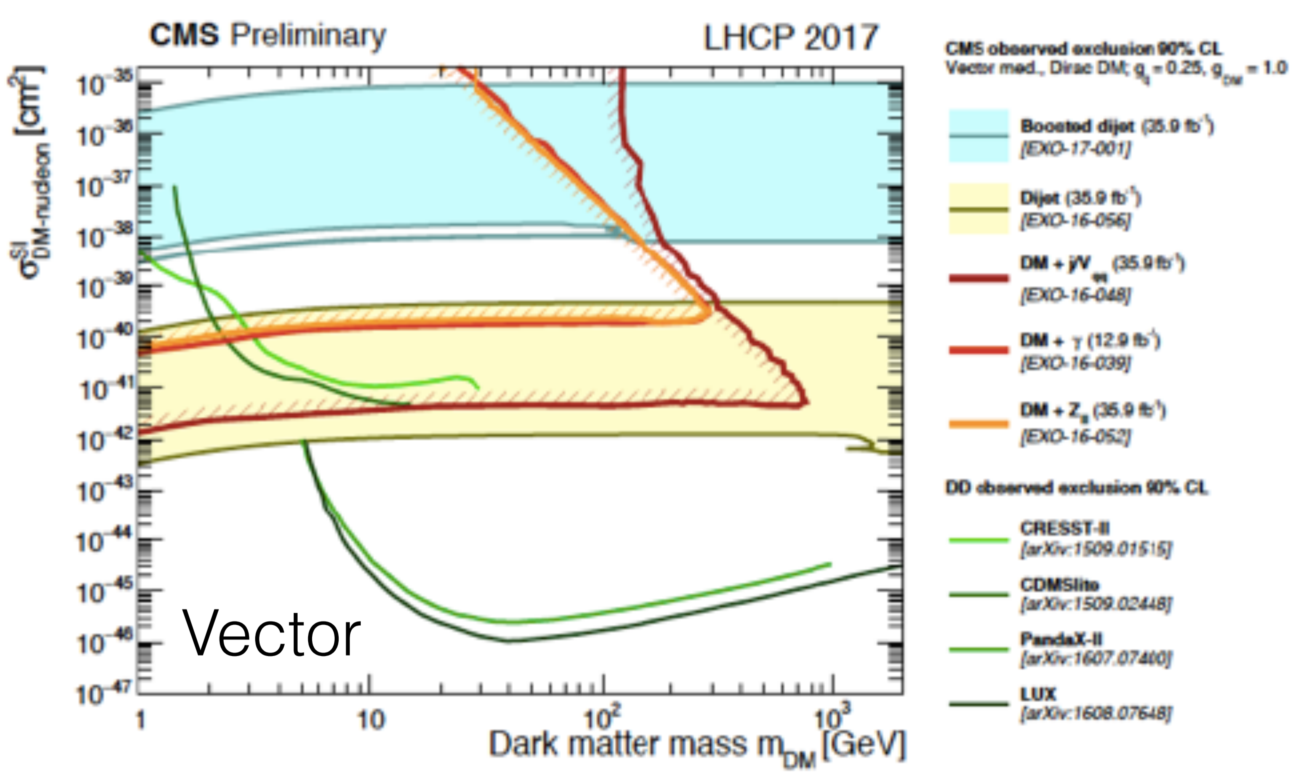
< 3σ | 3 – 5σ | > 5σ

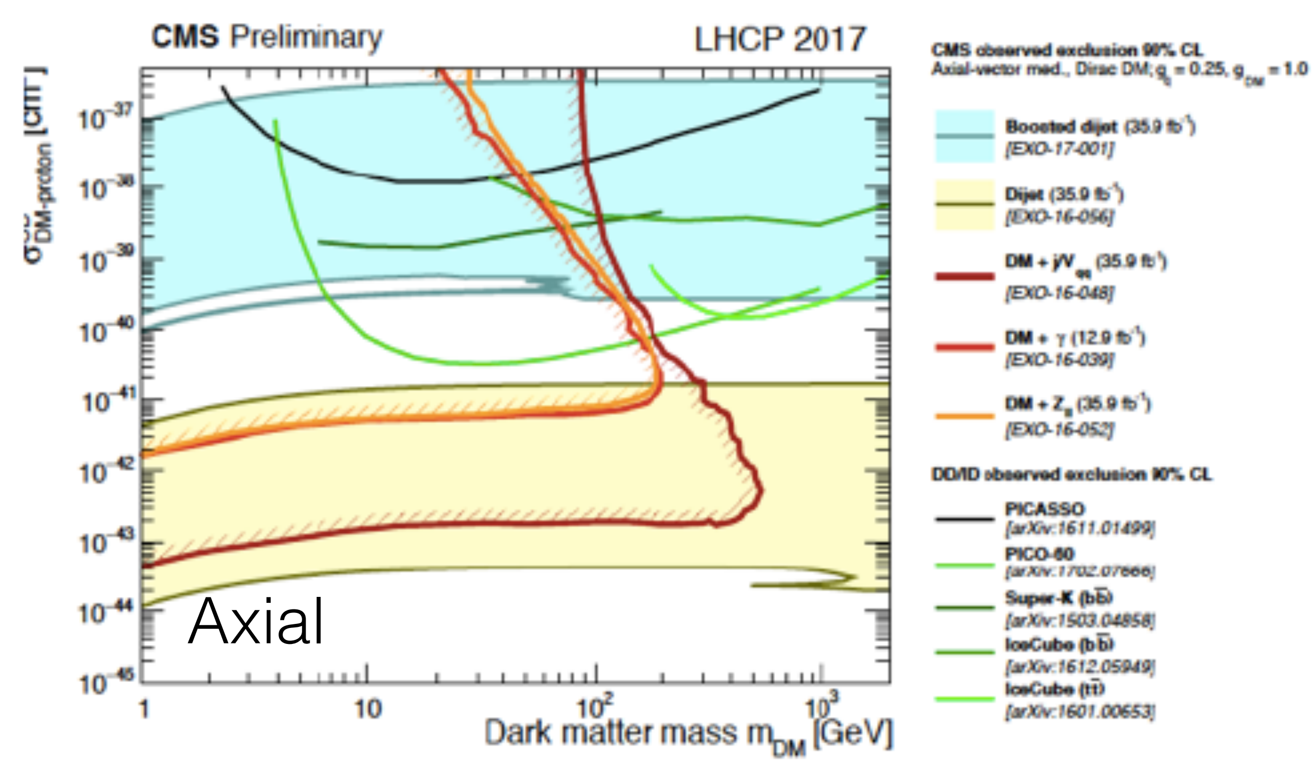


Prospects for Dark Matter

- **Example: dark matter**
  - proposed in ~1930
  - confirmed in ~1970
  - **today's knowledge**
    - **dark matter is very very weakly interacting**
  - discovery in …



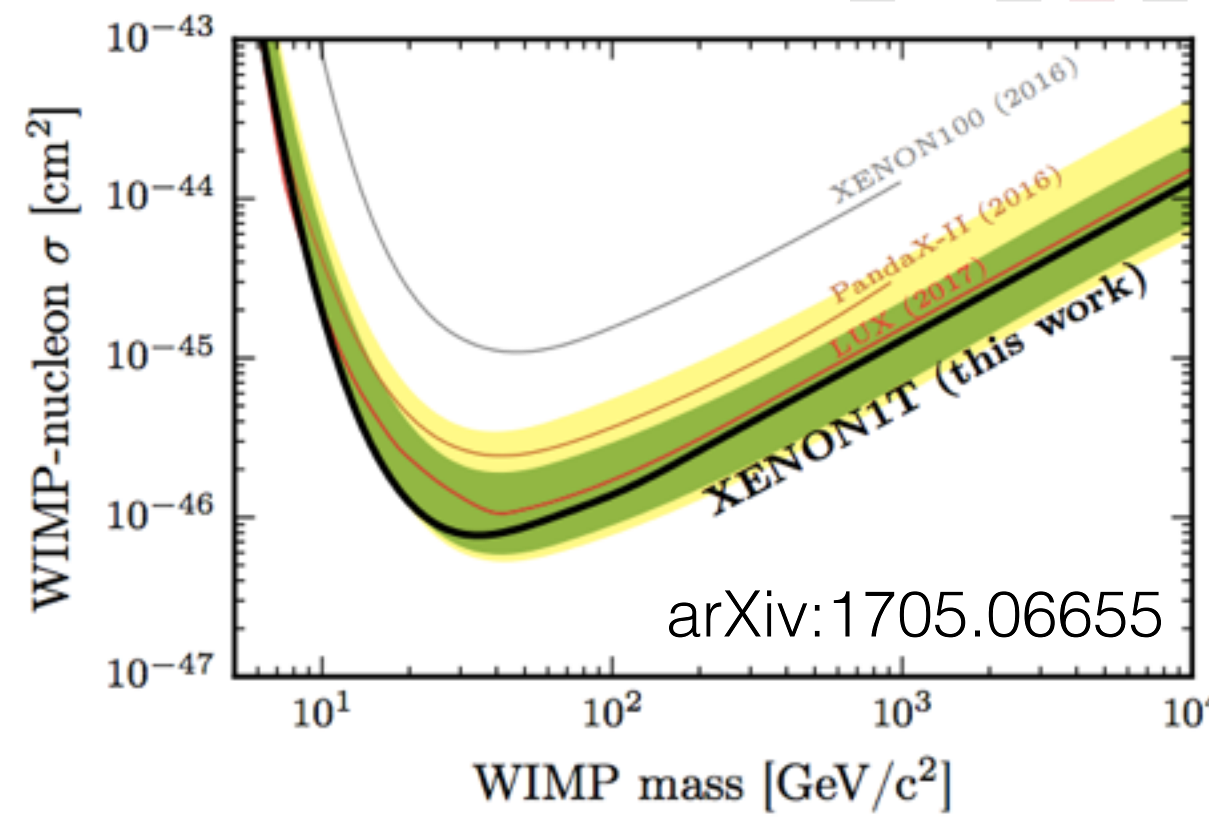


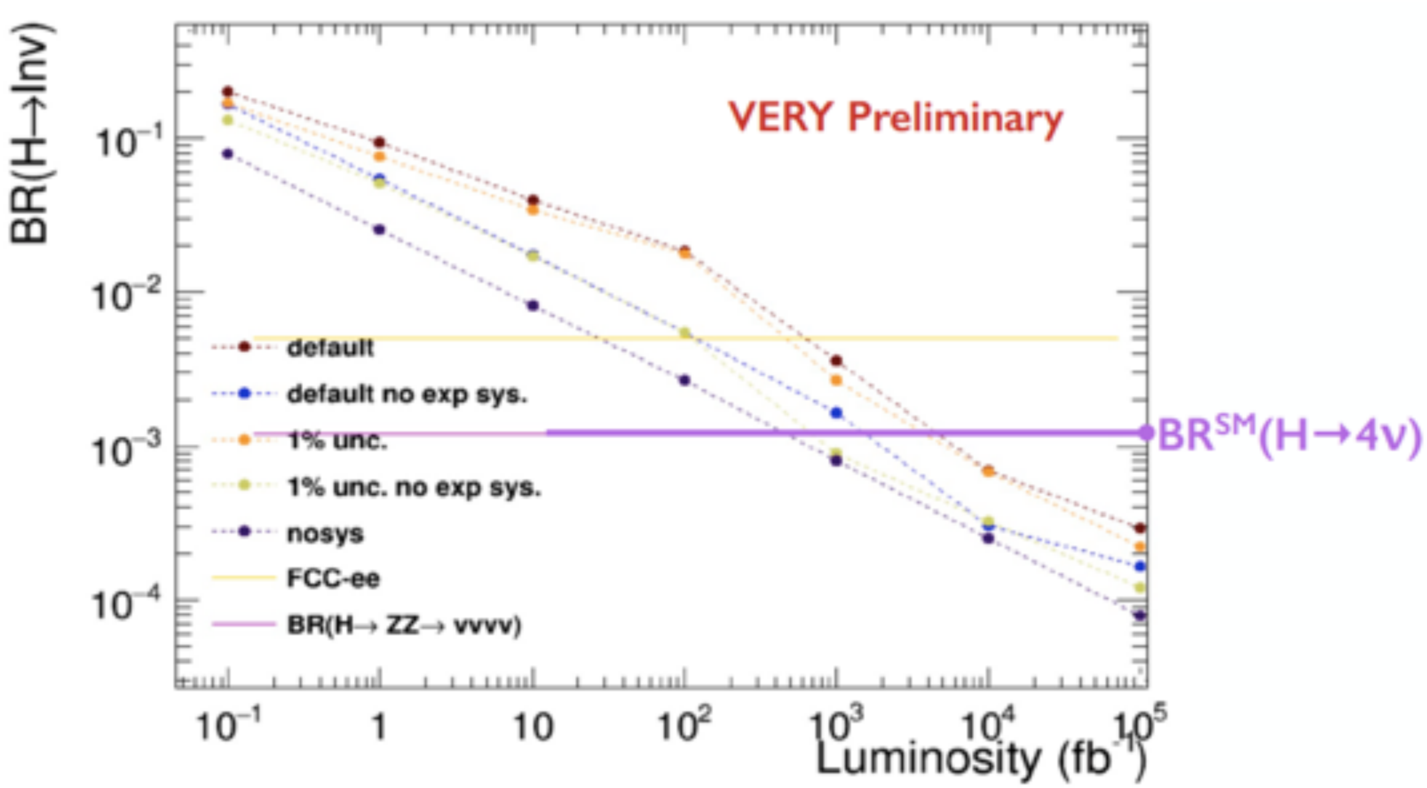


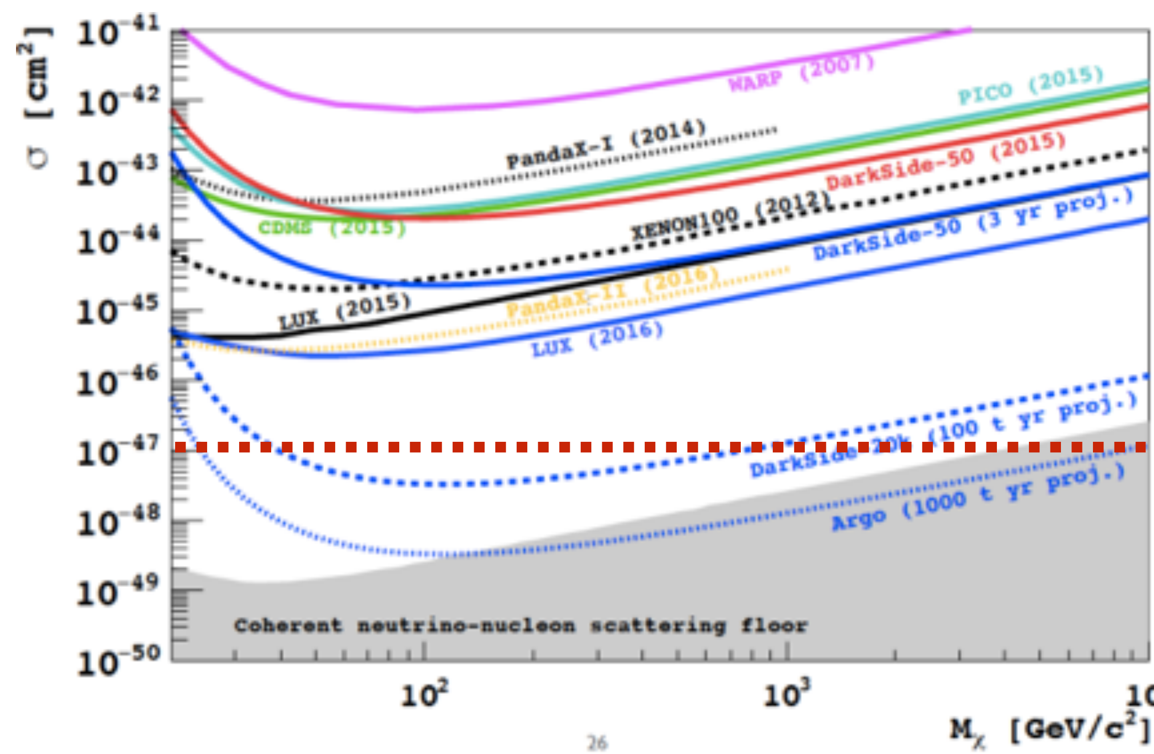
Prospects for Dark Matter

➡ **Example: dark matter**

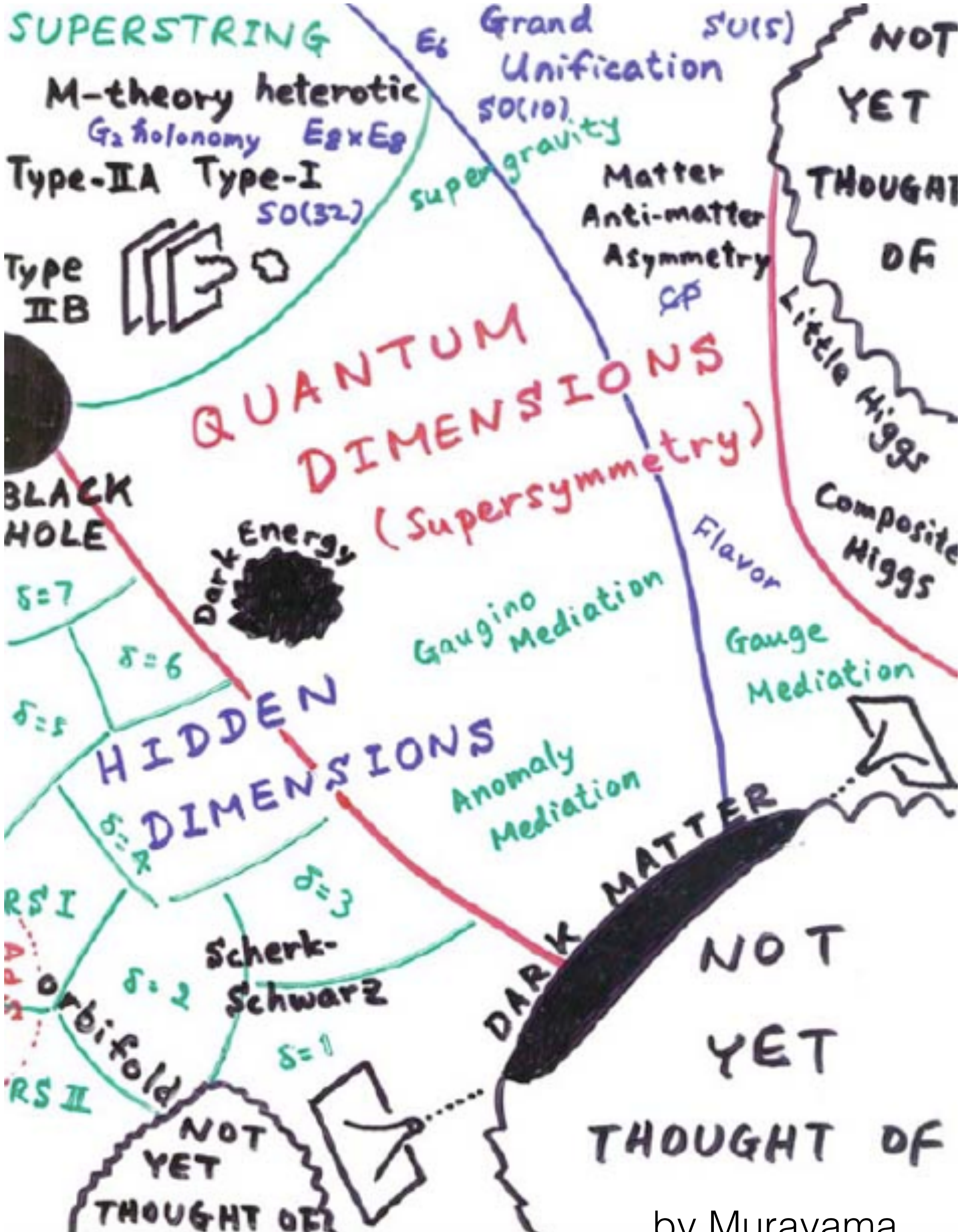
- proposed in ~1930
- confirmed in ~1970
- today's knowledge
- discovery in …
- **FCC-hh will answer**
  - **whether (or not) WIMPs exist**
  - **and have answers for alternative ideas**



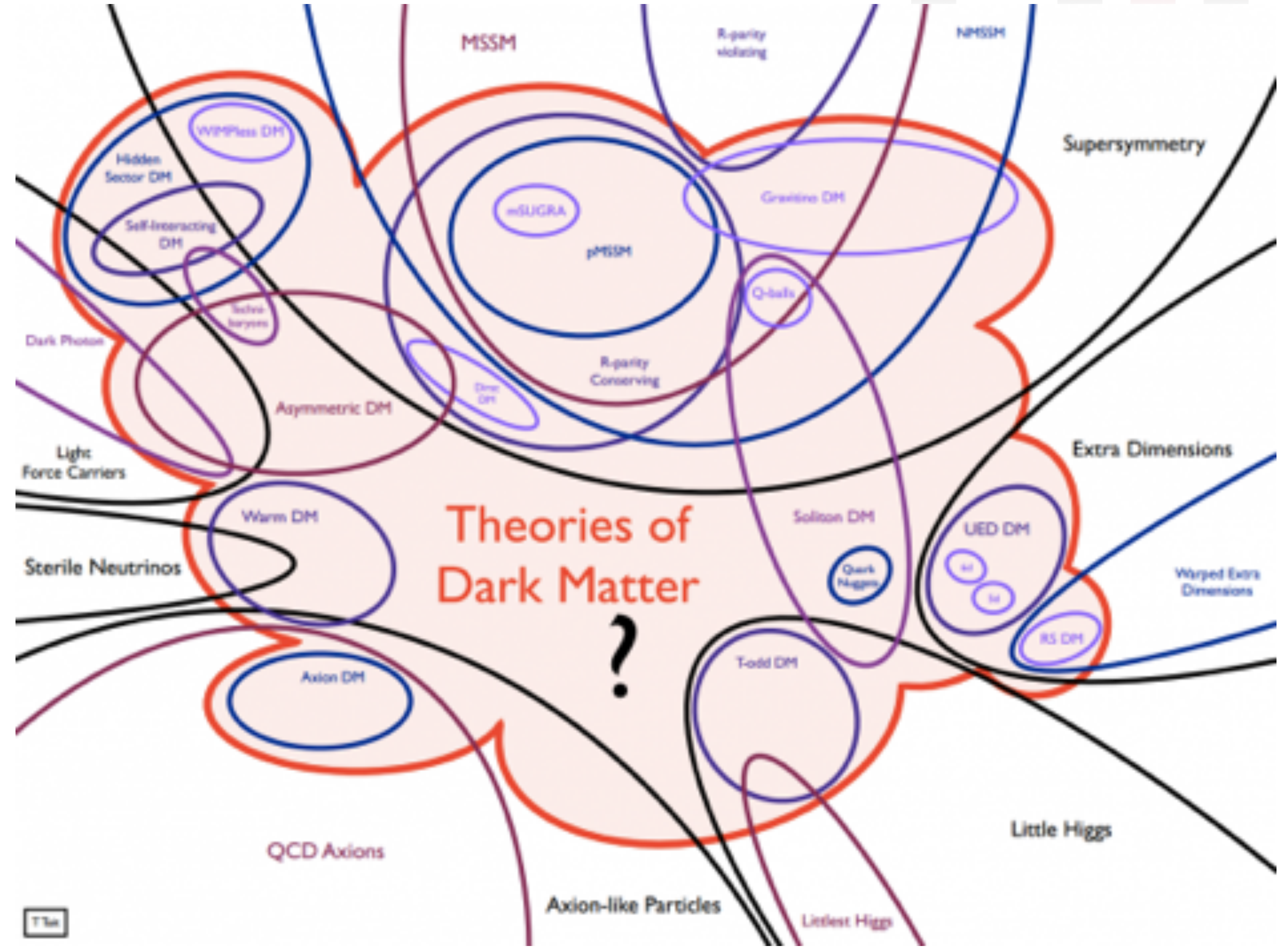




Theoretical Landscape



by Murayama



by Tait

Large space of
"Not Yet Thought Of"

Conclusion

➡ **Important and open questions in fundamental physics**

- we have or are developing the tools to find answers

➡ **Priorities in high energy physics**

- exploration of EWSB (the Higgs boson)
- investigation of known shortcomings (DM, baryon asym., neutrino masses, etc)

➡ **Future accelerators**

- next generation lepton and hadron colliders provide keys to unlock mysteries in particle physics
- important synergies and complementarities

Concluding Remarks

➡ **Prediction**

- Niels Bohr: “it is very difficult to predict - especially the future”

➡ **Progress through technology and new ideas**

- Continuous innovation (investment) is crucial

➡ **Spirit of exploration**

- It is in the nature of fundamental research that we do not know what’s beyond our current knowledge