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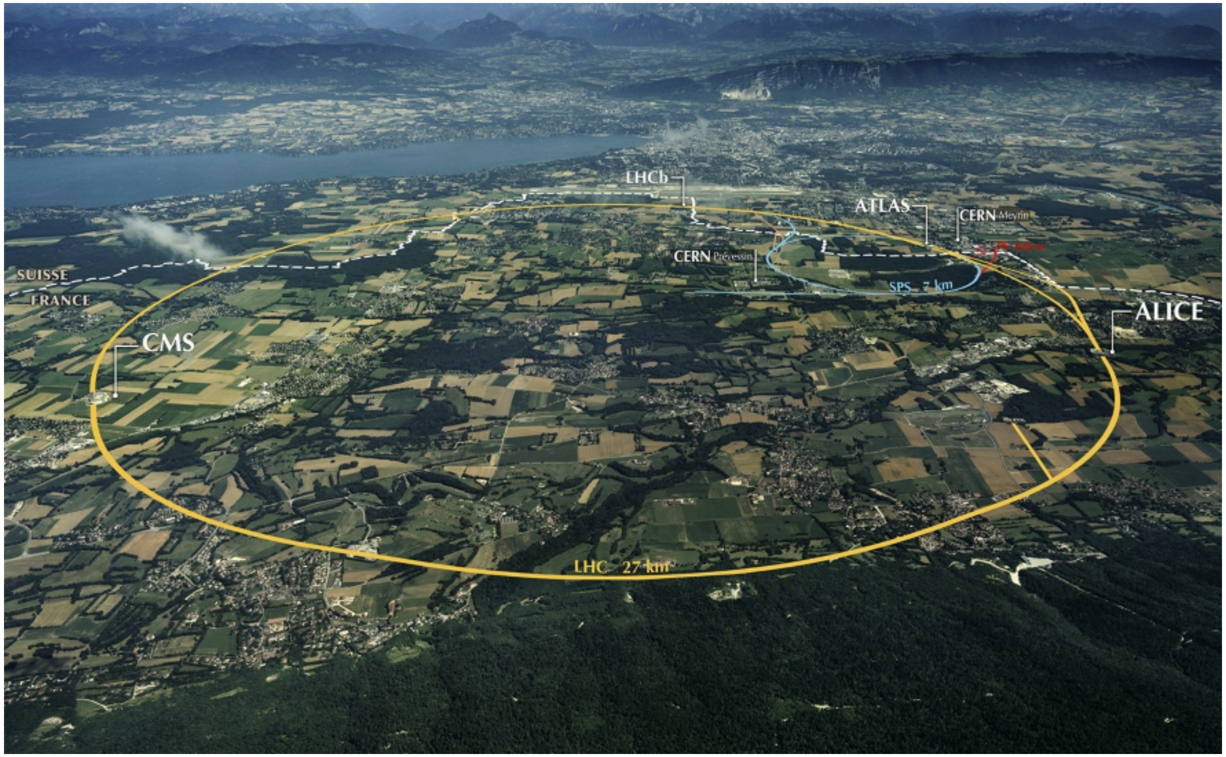
Frontier Colliders

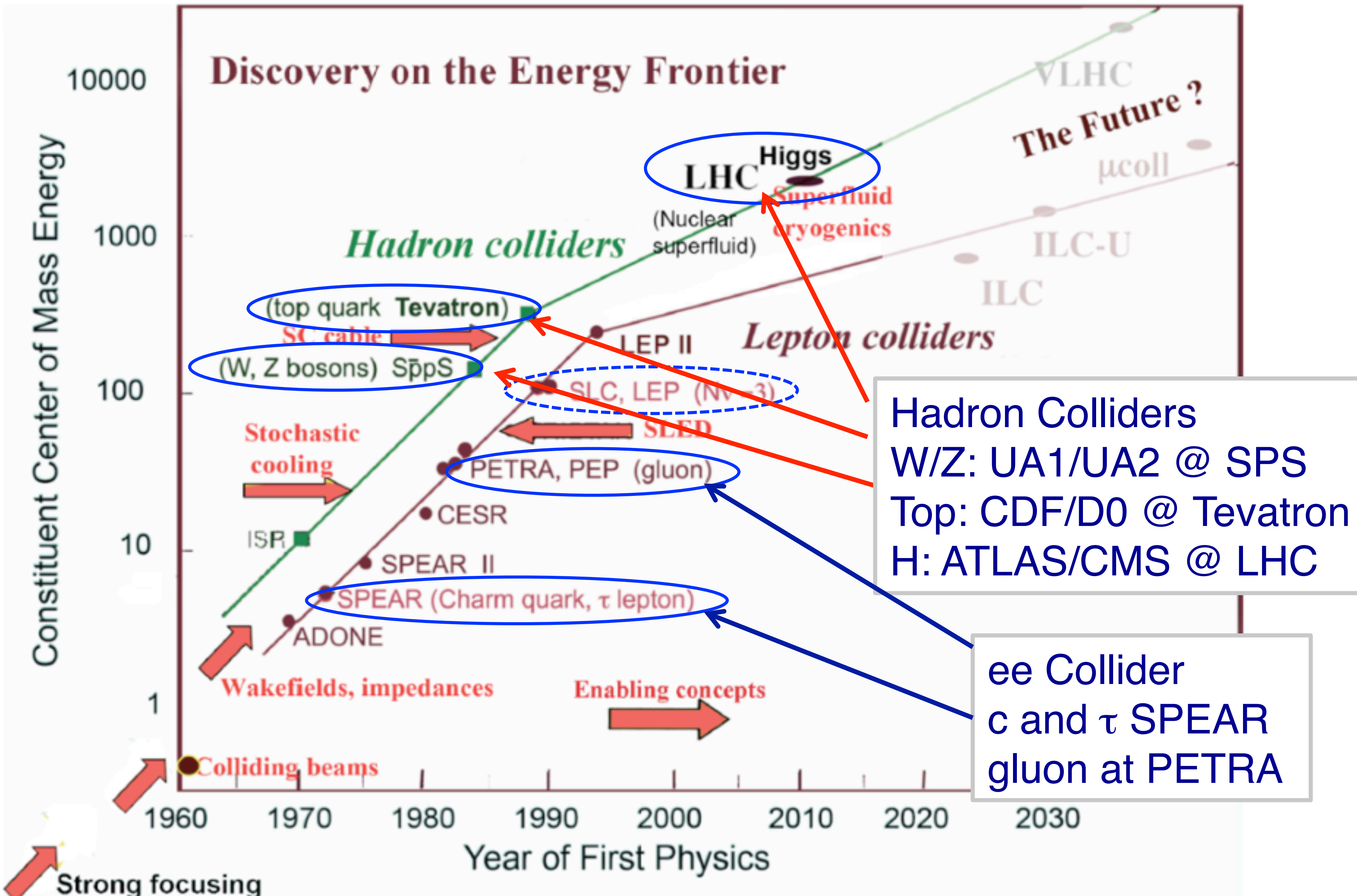
8th April 2019, Imperial College

IOP Institute of Physics



Tejinder S Virdee, Imperial College

Frontier Colliders: Evolution and Discoveries



Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

✓ **2. Clarify the e-w symmetry breaking sector**

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, $M_Z \sim 100{,}000$ MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone: next question is "Why is (Higgs) mass so low"?

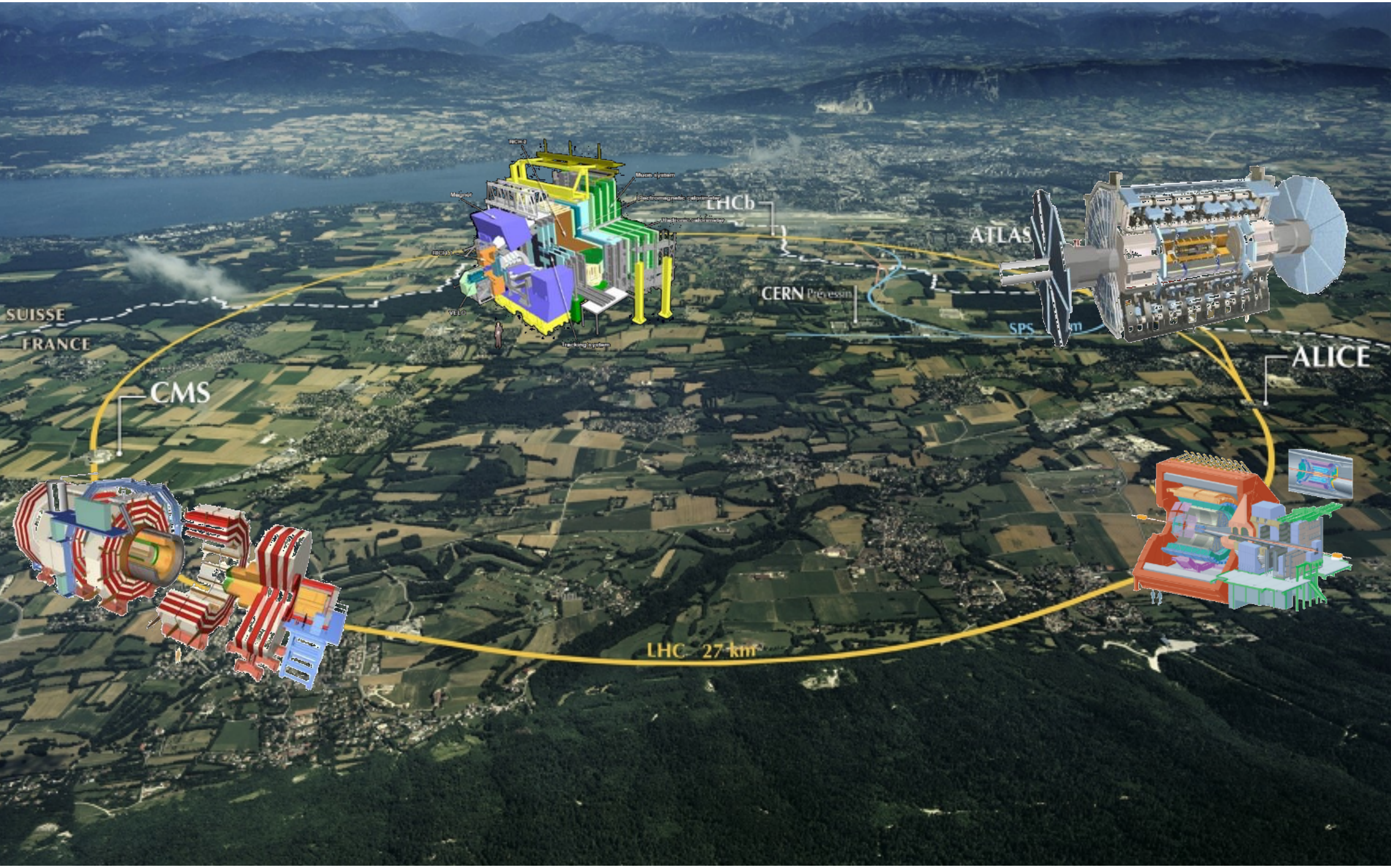
*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

5. Search for new physics at the TeV scale

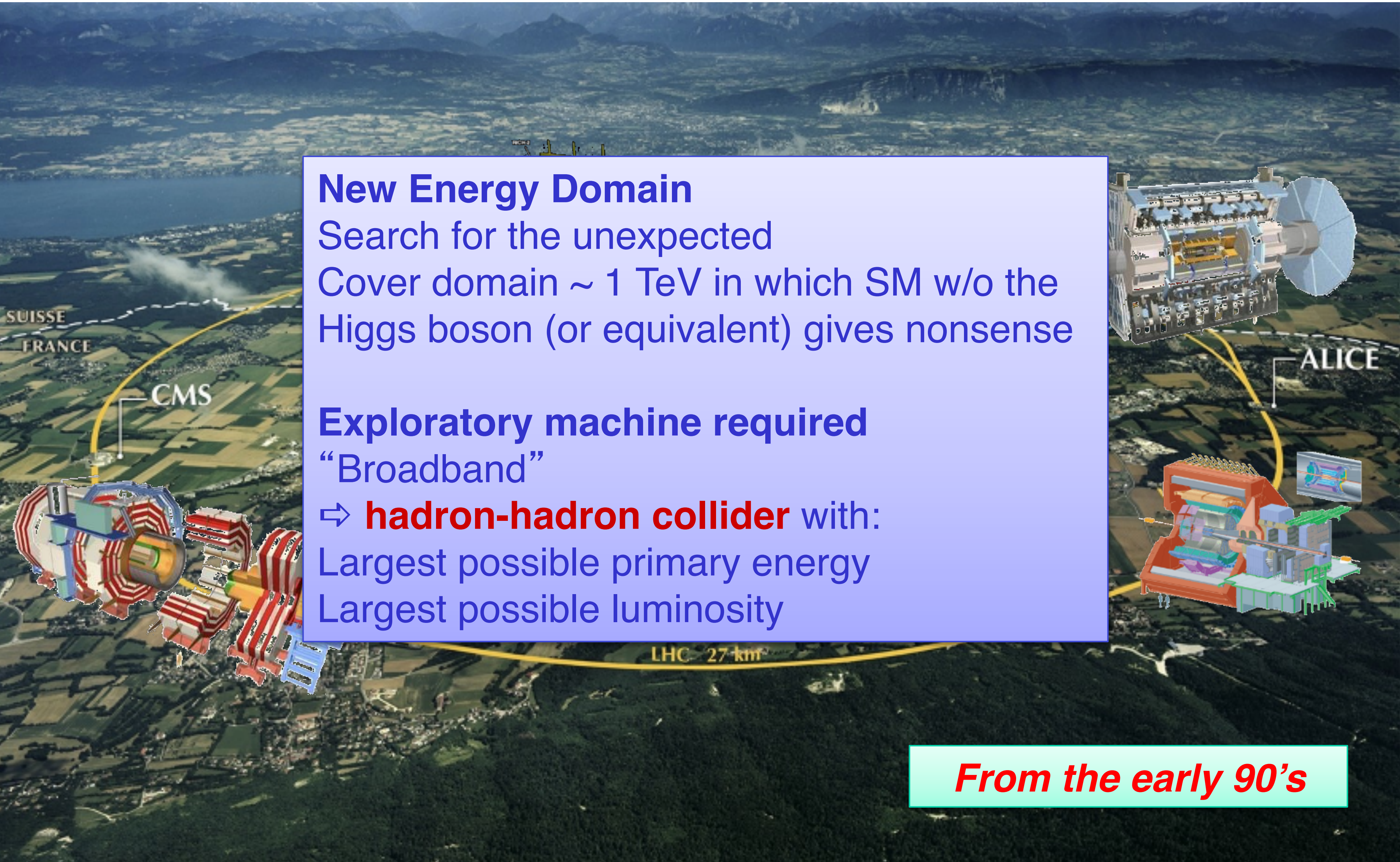
SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

The Large Hadron Collider



The Large Hadron Collider



New Energy Domain
Search for the unexpected
Cover domain ~ 1 TeV in which SM w/o the Higgs boson (or equivalent) gives nonsense

Exploratory machine required
“Broadband”
⇨ **hadron-hadron collider** with:
Largest possible primary energy
Largest possible luminosity

From the early 90’s

Short- to Medium- Term Outlook (briefly)

LHC

What are the expectations for an integrated luminosity of 300 fb^{-1} (original design goal)?

HL-LHC

What are the features/motivations for the upgrades to the experiments?

What are the expectations for an integrated luminosity 3000 fb^{-1}(HL-LHC design goal)?

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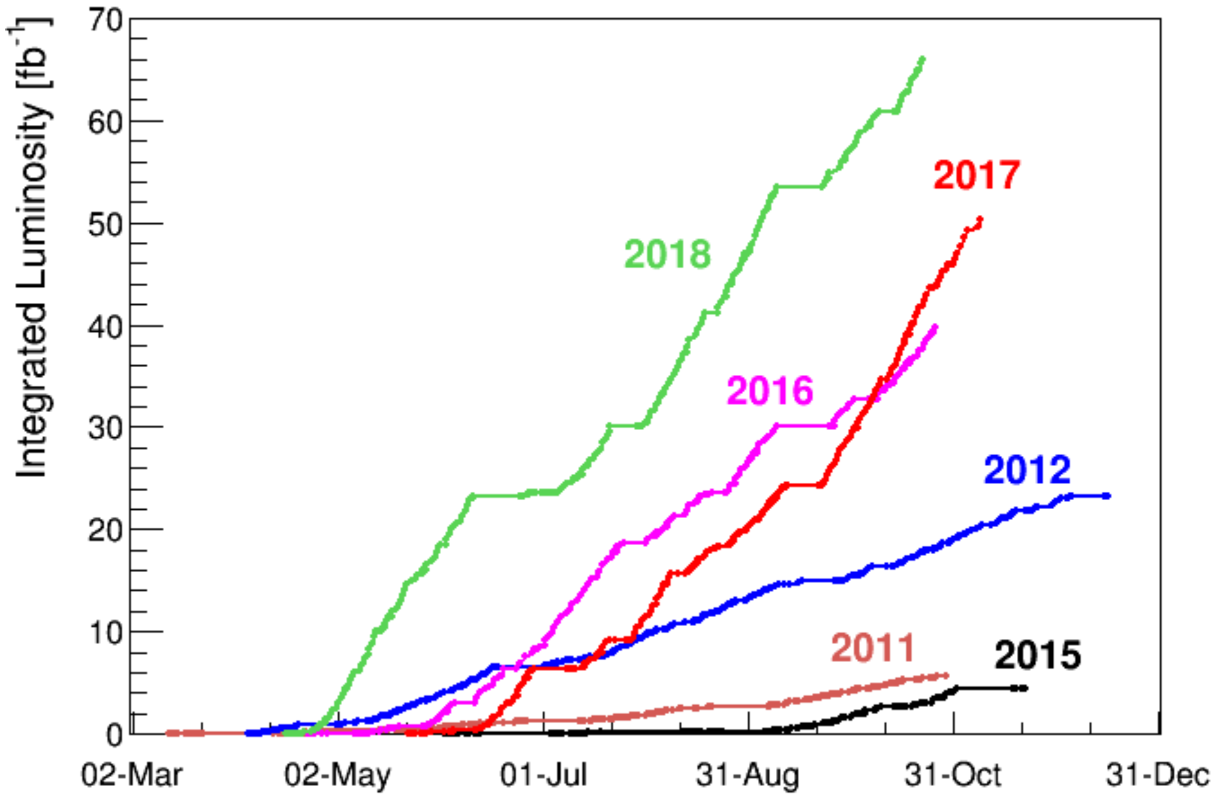
The LHC Accelerator is Operating Superbly

Every year beats the record of the previous one!

Integrated luminosity Run 2: 160 fb^{-1}

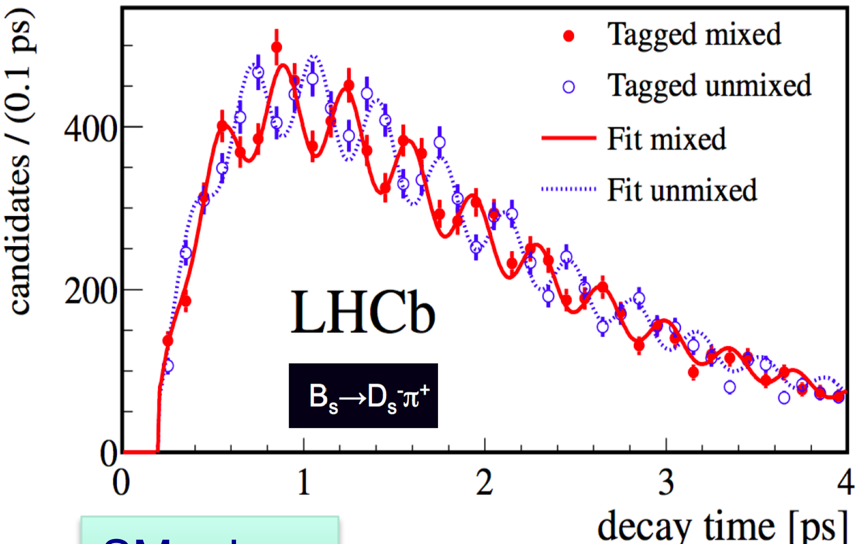
Peak Luminosity ~ 2.10^{34} $cm^{-2}s^{-1}$

LHC total integrated proton-proton luminosity: 189 fb^{-1}

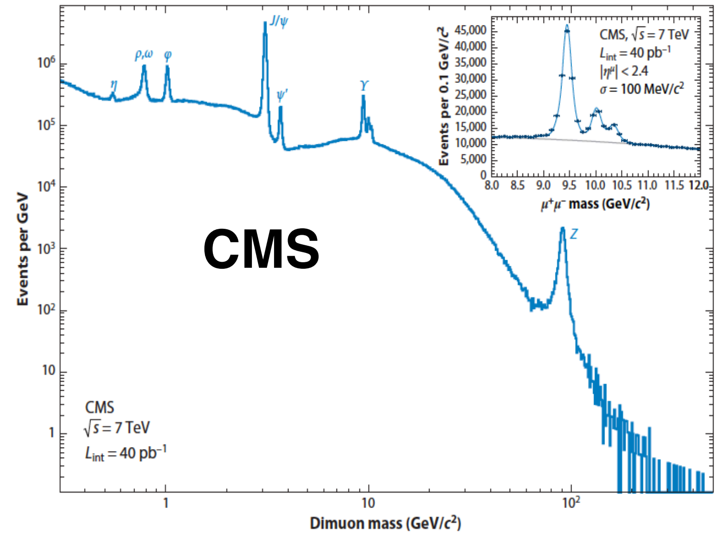


So are the experiments …

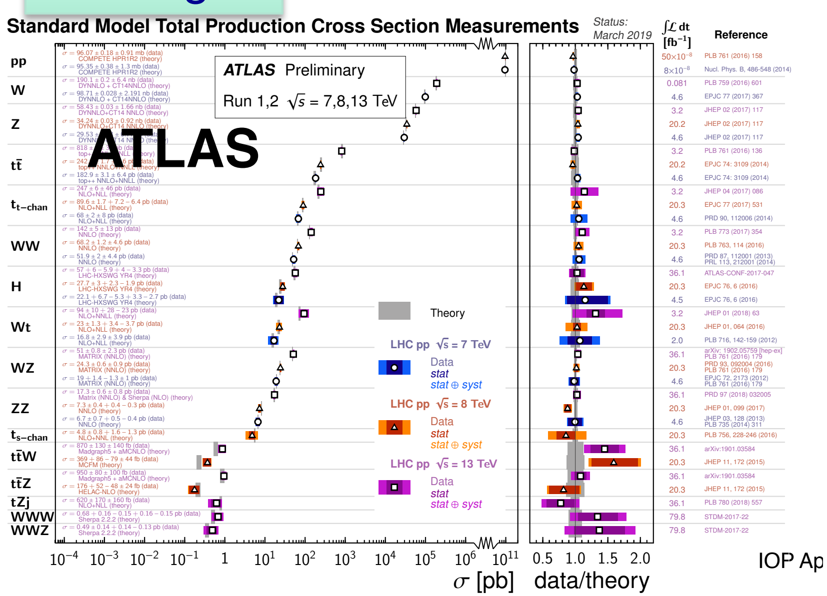
B_s^0–B_s^0 Oscillation frequency



Dimuon Mass Distribution

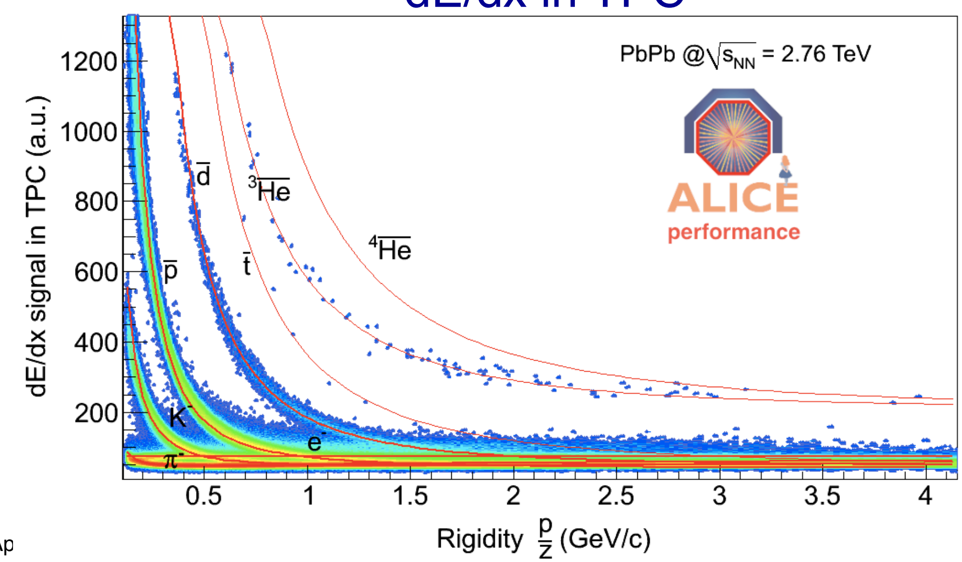


SM reigns

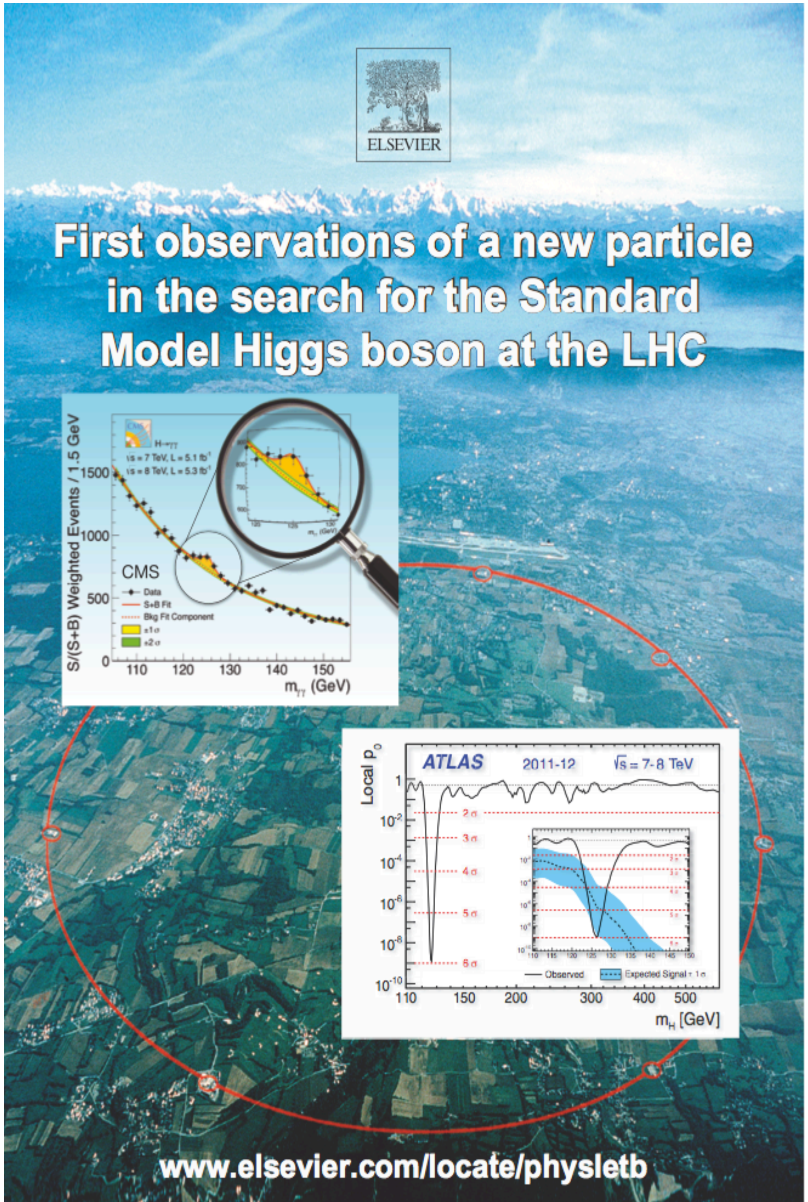


IOP Ap

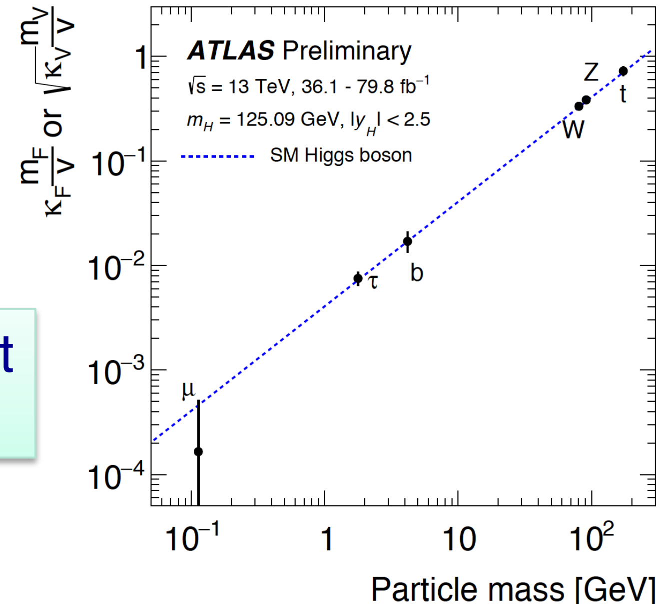
dE/dx in TPC



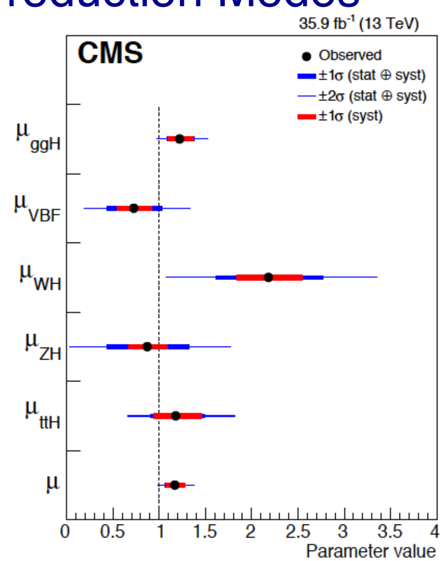
The LHC – Discovery of the Higgs boson



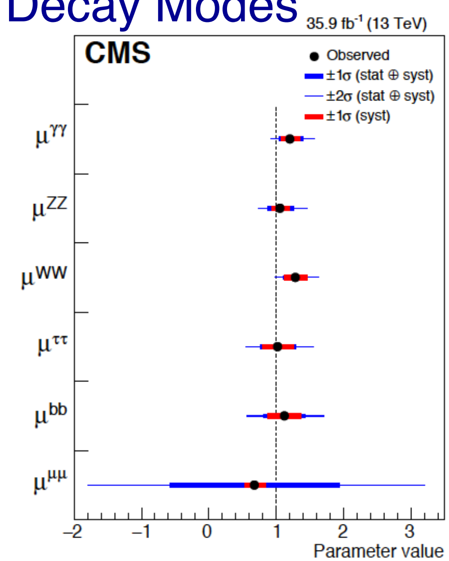
Current Status



Production Modes



Decay Modes



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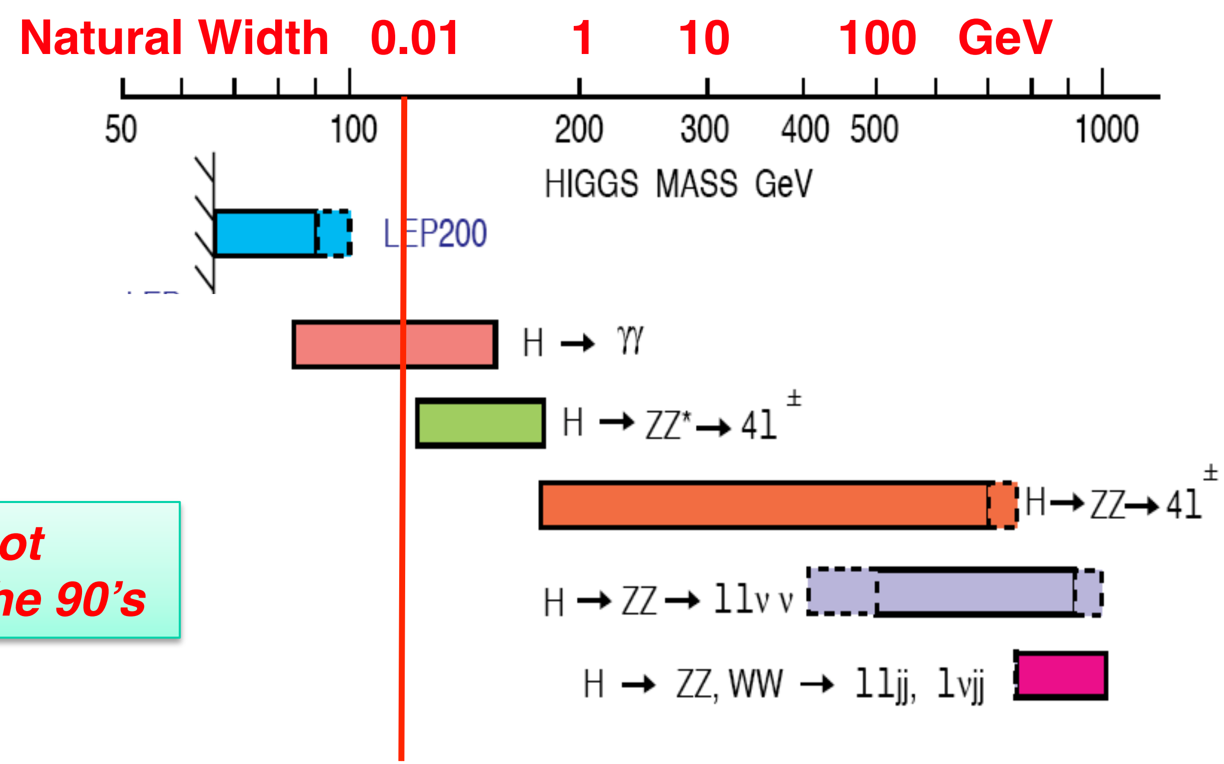
Search for the Standard Model Higgs Boson and LHC Experiment Design

The possibility of detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a crucial role in the conceptual design of the ATLAS and CMS experiments

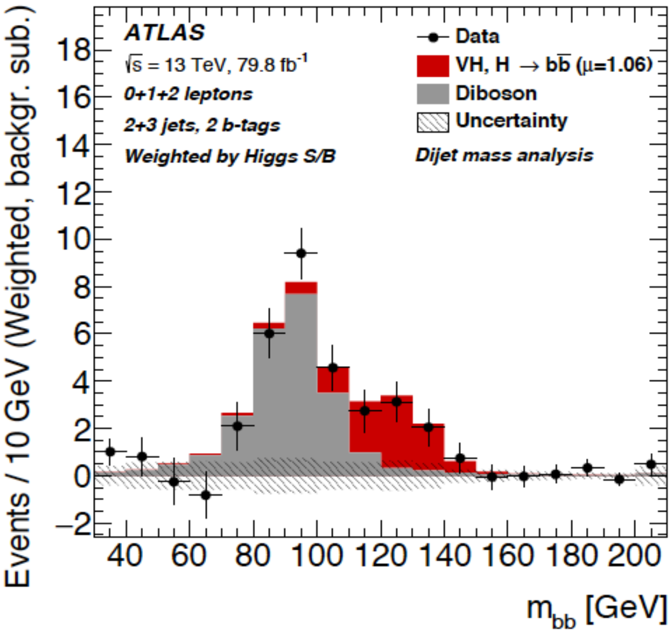


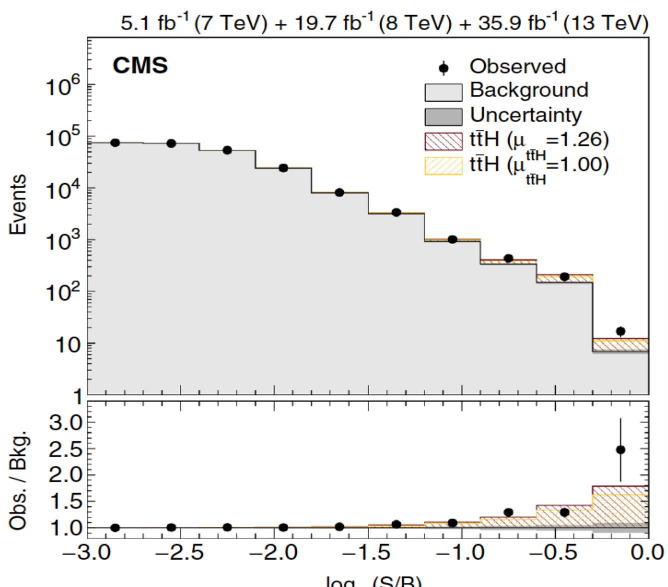
Natural width
$\Gamma \sim h/\tau$

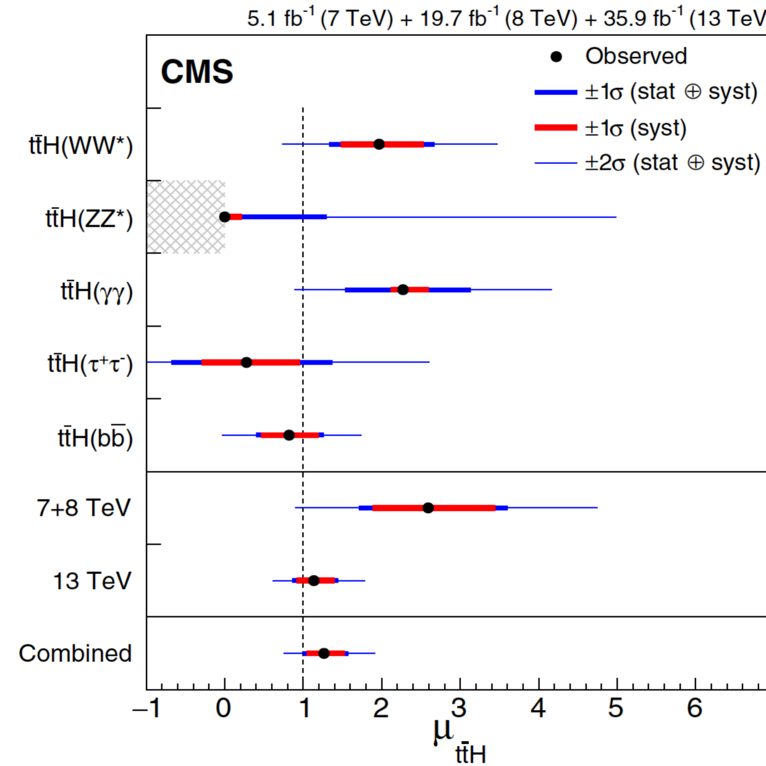
Plot from the 90's

Search for a low mass Higgs boson (e.g. $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$) **placed stringent performance requirements on ATLAS and CMS detectors** (especially Tracker momentum and ECAL energy resolution).

H → bb, pp → ttH







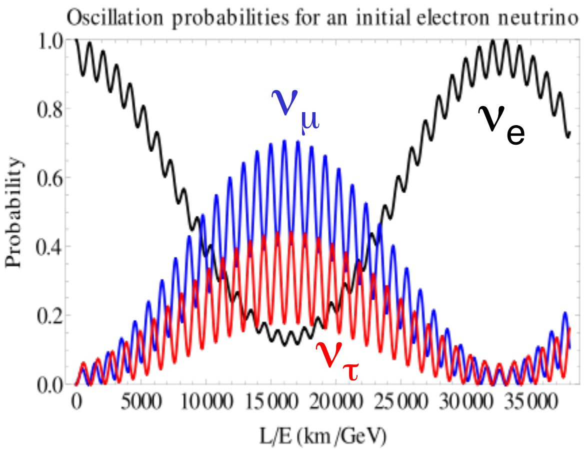
Xpts have performed well: large strides in studying difficult or almost impossible channels – combiing multiple final state analyses regression techniques, b-tagging, jet substructure, MVA, machine learning, …….

Moving Forward
Should we really expect new physics?

Ample Observational Evidence for Physics Beyond the SM

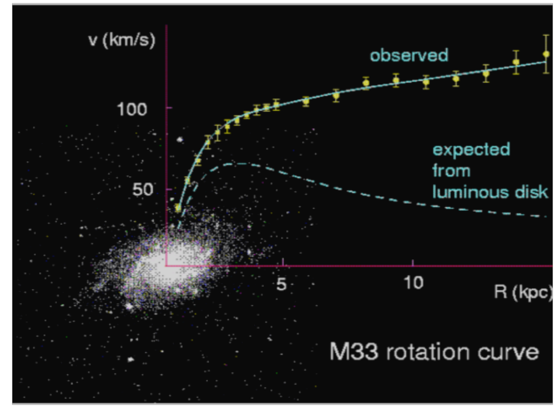
Neutrino mass (oscillations)

a QM phenomenon

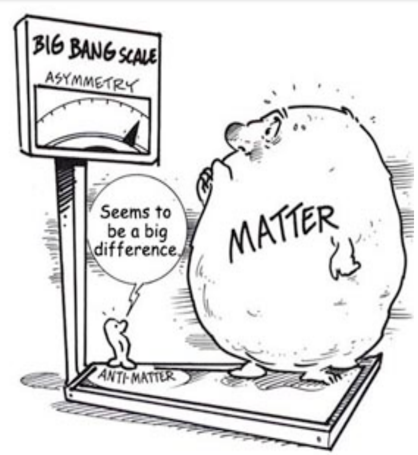


2015

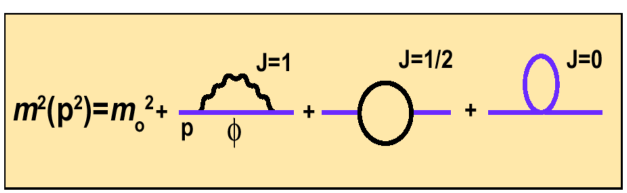
Dark Matter



Matter-antimatter asymmetry



The lightness of the Higgs boson?



$\delta m_H^2 \sim M^2/16\pi^2$

Frontier Colliders: The next 20 Years – HL-LHC

2013 Strategy: World's Topmost Priority in Particle Physics

exploitation of the full potential of the LHC

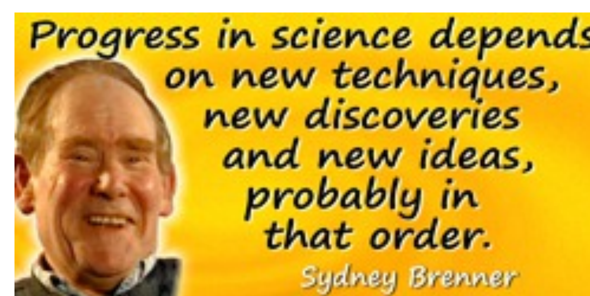
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

What makes it worthwhile to continue physics exploitation of an accelerator?

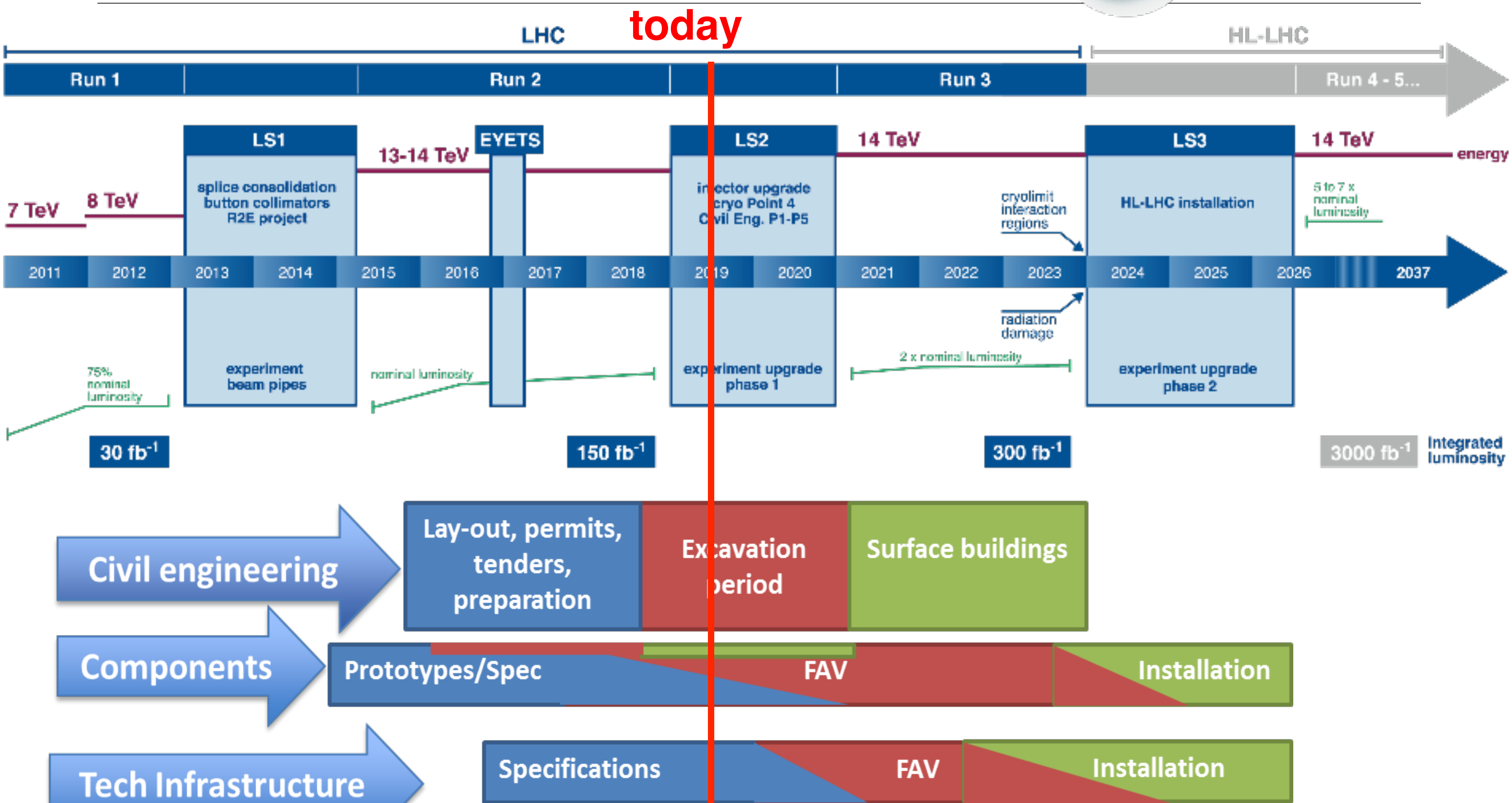
1. **Higher centre-of-mass Energy**
   LHC is now running at 13 TeV (~ twice the energy of Run 1)

2. **Higher Integrated Luminosity**
   From mid-2020s to mid-2030s LHC will aim to examine 10 times the number of p-p collisions examined in Phase 1.

3. **Qualitatively better detectors**



LHC / HL-LHC Plan



FAV = Fabrication, Assembly and Verification

HL-LHC (SLHC) Started a Long Time Ago

Jan 2001

Detector Issues

EP-TH Faculty Meeting

Challenges for pp GPDs

- LHC design luminosity,
- L ~ 10^{35} $cm^{-2}s^{-1}$,
- Higher c.o.m energy

Implications for Detector R&D

- LHC design energy and luminosity - Upgrades (~ 2009)
- L ~ 10^{35} $cm^{-2}s^{-1}$ - Major Upgrades (~ 2012)
- Higher energy – next generation of detectors (20??)

Conclusions

EP-TH Faculty 17 Jan 01 T. S. Virdee

Apr 2002

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtinen [1], K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

EPJC39 (2005) 293

HL-LHC: Optimism bias?

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Physics Should Drive Technical Choices

Physics thrust for HL-LHC

1. **Higgs boson and EWSB physics**

- Experimentally → make precision (sensitive) measurements of the properties (couplings etc.) and self couplings **in a new sector**
- Theoretically → are precise predictions (~1%) possible

2. Search for physics beyond the SM

- Extend mass reach for possible high mas objects predicted by BSM
- Dark matter & weakly interacting BSM phenomena
- Ensure coverage and sensitivity to elusive signatures

3. Precision (sensitive) SM measurements

- Look for (significant) deviation from SM predictions
- Intrinsic value of knowledge acquired independent of discovery

Higgs boson Events in Numbers

Numbers of events at $\sqrt{s}$=14 TeV for 3000 fb^{-1}

Process	No. Evts (M)
gg→ H	150
VBF	13
WH	5
ZH	2.5
ttH	1.8

- Higher statistics allows categorization (selection) of signal regions with higher S/B, regions where the systematics are better controlled,
- The balance between statistical and systematic errors changed

- The precision of theoretical calculations/prediction need improving.
- Is achieving 1% theoretical predictions possible (for a hadron collider)?

What will the LHC (and HL-LHC) Bring?

G. Salam

- Run 2: observation of $H \to bb$ (Yukawa)
- Run 2/3: observation of ttH (Yukawa)
- HL-LHC: observation of $H \to \mu\mu$ (2nd gen Yukawa)

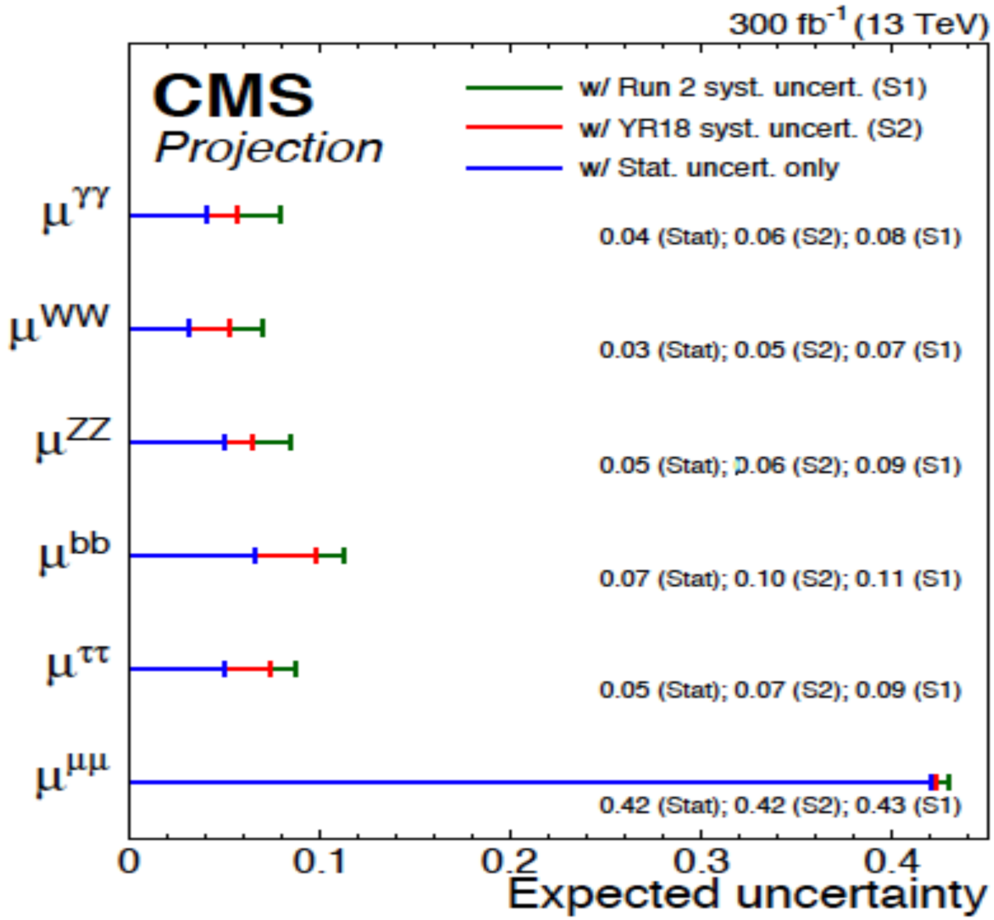
- HL-LHC: Higgs width → SM \pm 50% (BSM constraint)
- HL-LHC: $H \to$ invisible $< 10\%$ (BSM constraint)

- HL-LHC: $gg \to HH$? (Higgs potential)
- HL-LHC: Hcc coupling? (2nd gen Yukawa)

Higgs boson: What will the LHC Bring?

LHC

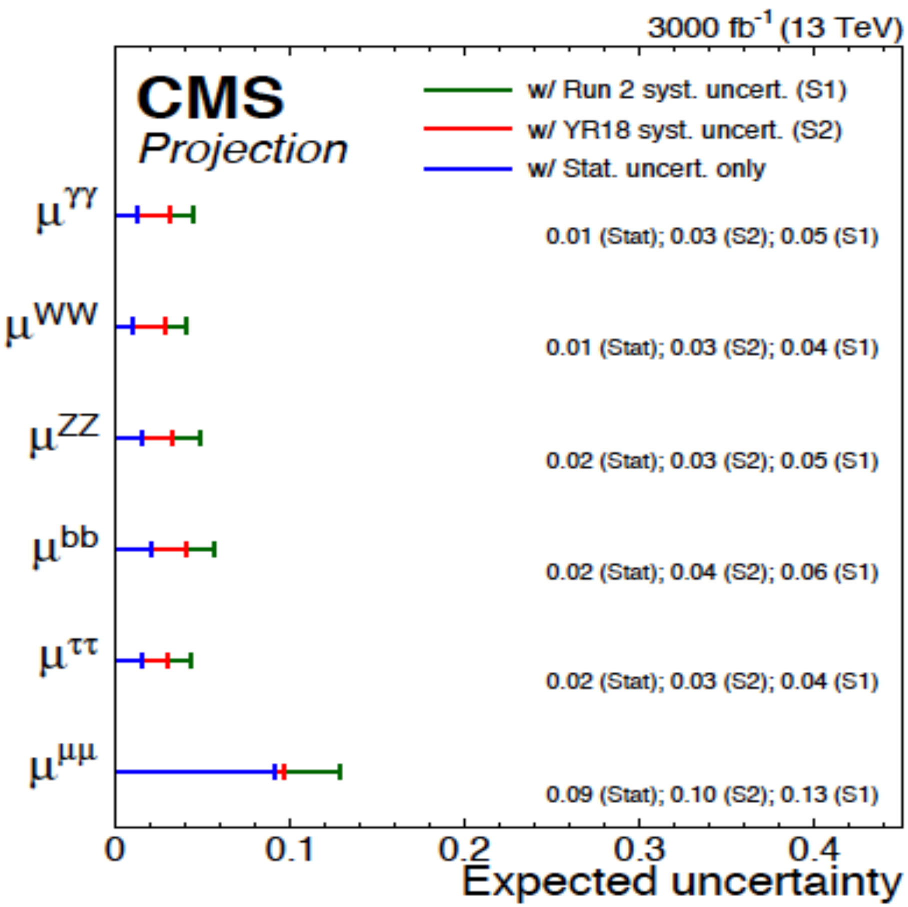
What are the expectations for an integrated luminosity of 300 fb^{-1} (original design goal)?

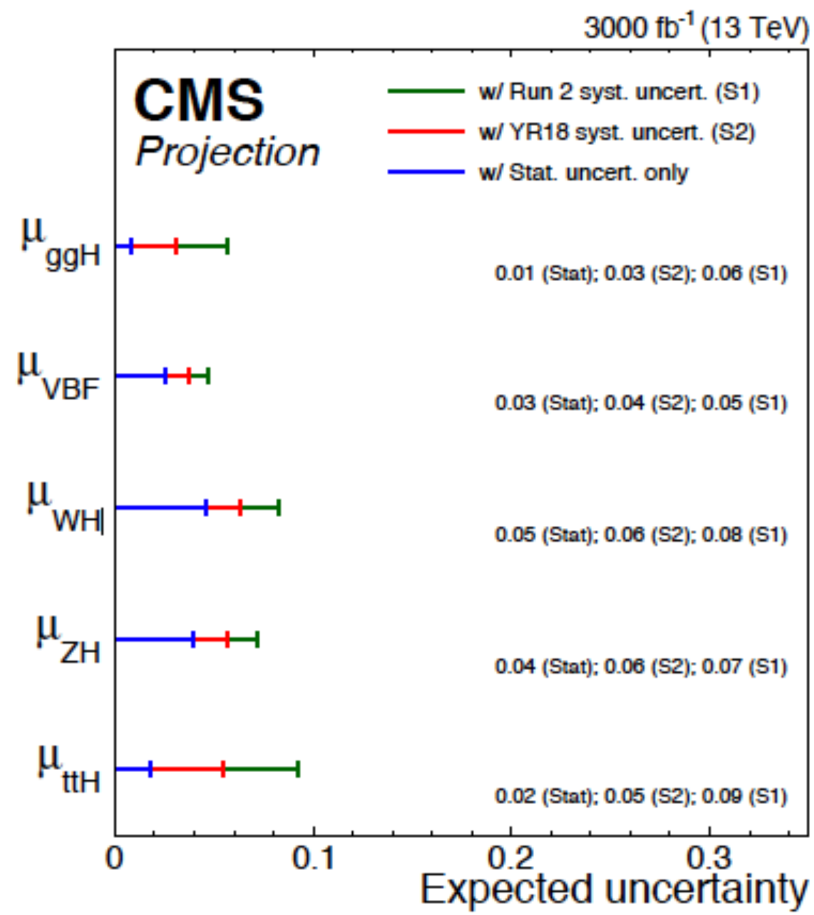


Higgs boson: What will the HL-LHC Bring?

HL-LHC

What are the expectations for an integrated luminosity 3000 fb^{-1}(HL-LHC)?

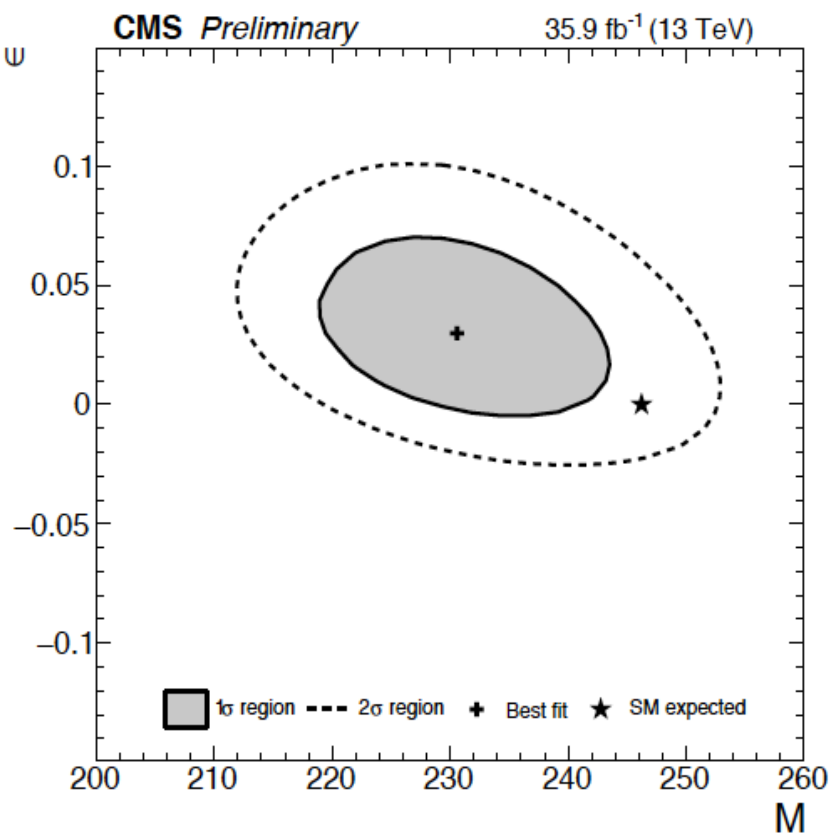


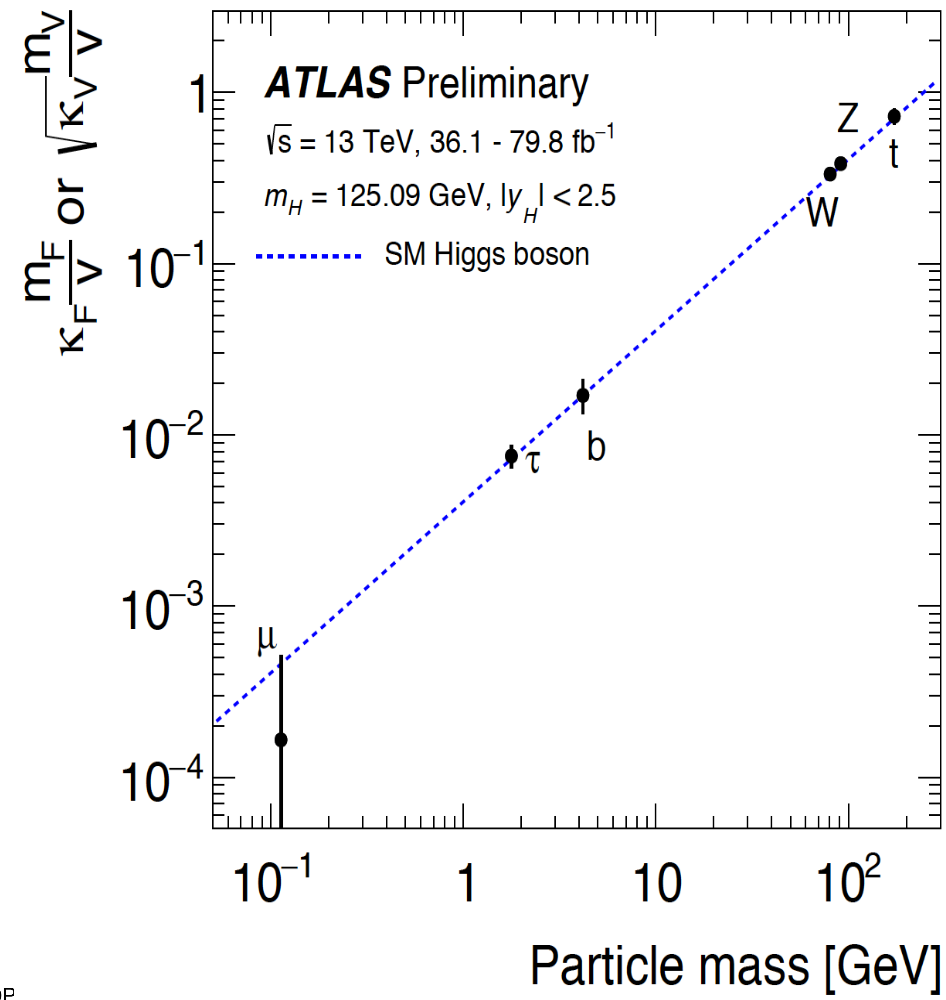


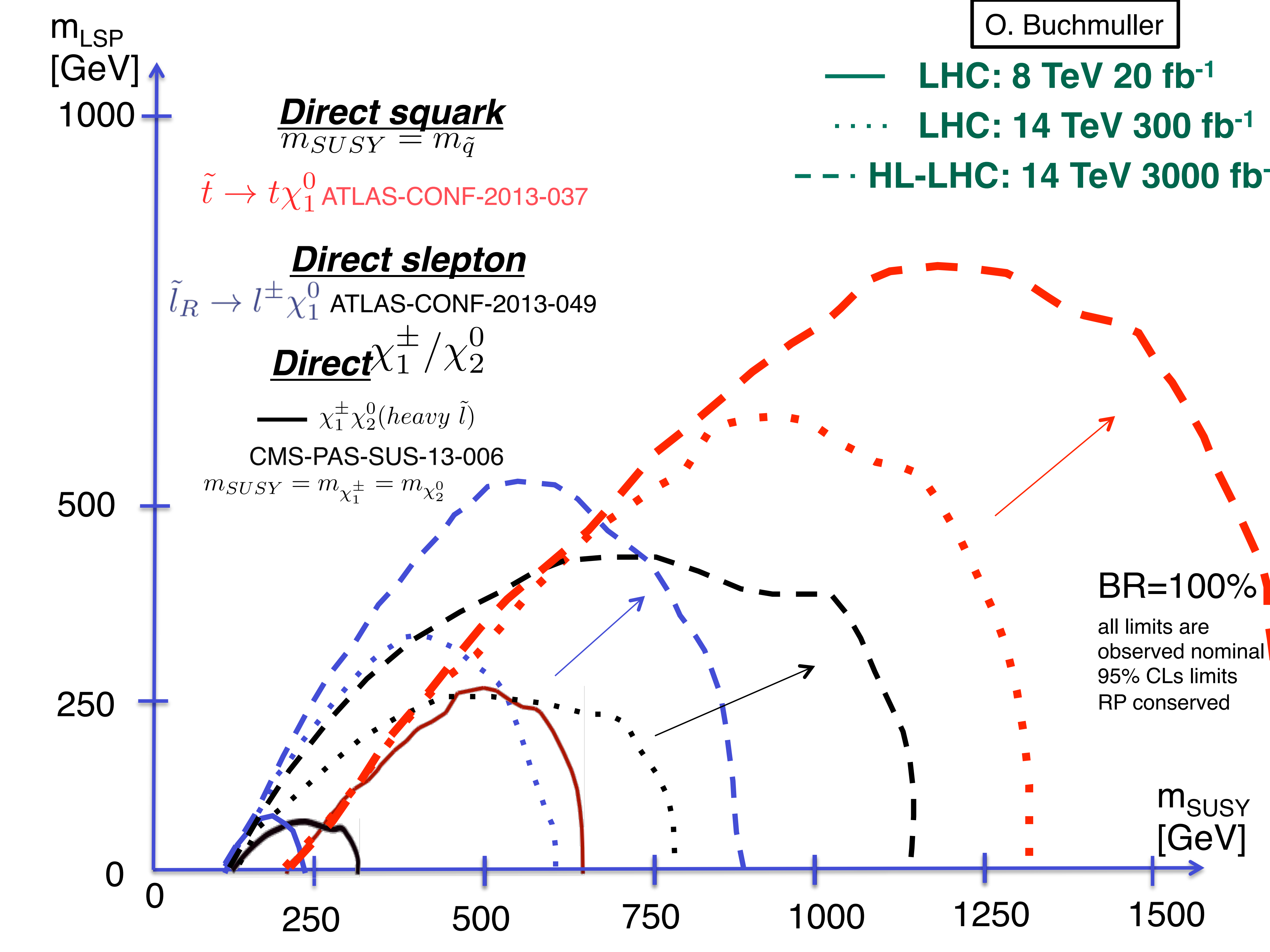
What will the HL-LHC Bring?

HL-LHC

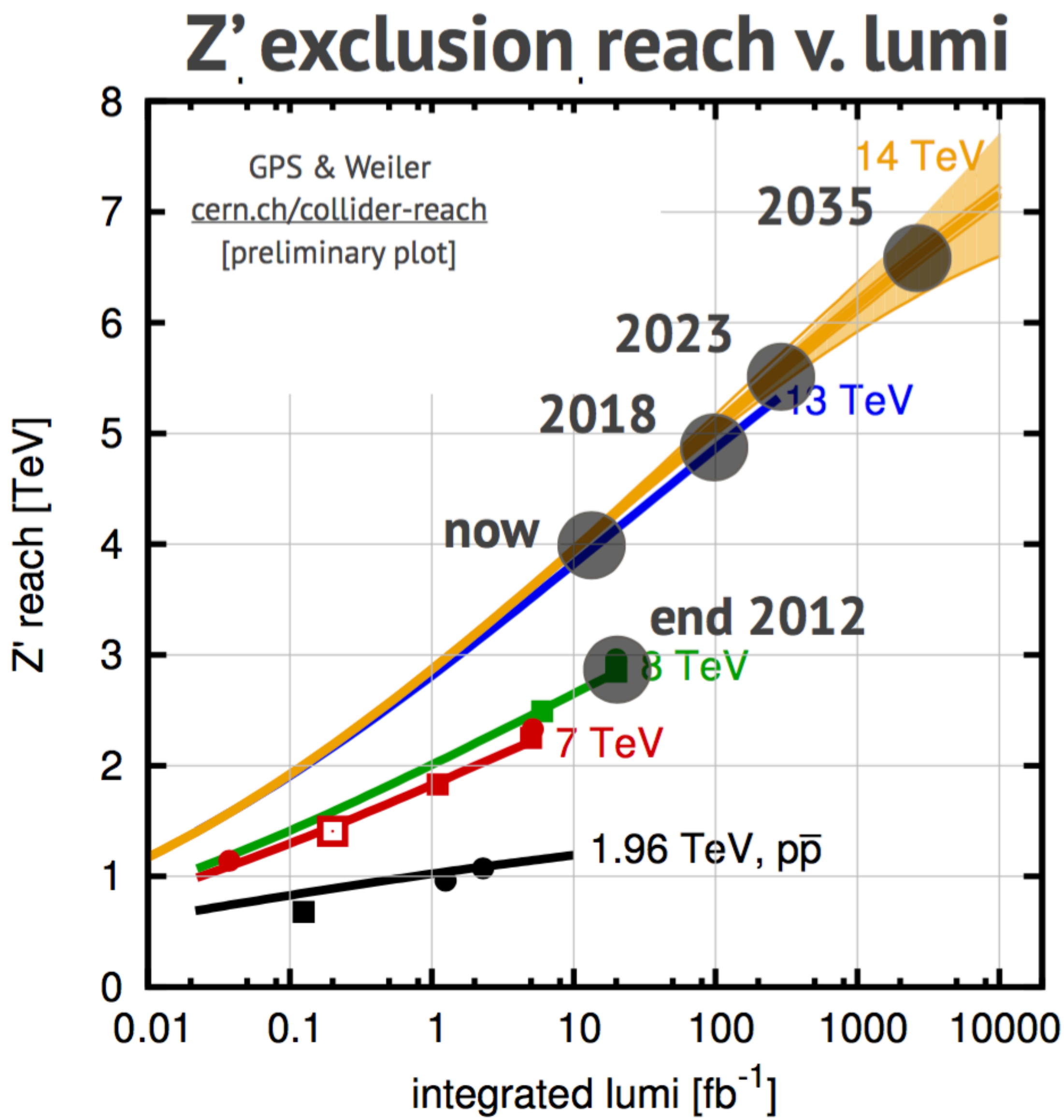
What are the expectations for an integrated luminosity 3000 fb^{-1}(HL-LHC)?






O. Buchmuller
LHC: 8 TeV 20 fb-1
LHC: 14 TeV 300 fb-1
HL-LHC: 14 TeV 3000 fb-1
mLSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
mSUSY [GeV]
0
250
500
750
1000
1250
1500

Heavy Objects: Mass Reach



Future Colliders

Physics Imperatives

- No clear sign of any BSM physics at the LHC yet.
- The situation would obviously change if we did find some significant signs in the HL-LHC phase.
- However, the Higgs boson has been discovered – a quite unusual particle in the zoo of SM particles. Must study it well – also in view of finding clues to BSM physics.

Precision Frontier - Higgs boson, EWSB and SM physics

It is incumbent on us to make precision (sensitive) measurements of the properties and couplings in the Higgs sector, SM measurements – sensitive probe of high mass scales – deviations from SM predictions may give clues to the next interesting scale.

Energy Frontier - Search for Physics Beyond the SM

An exploratory collider with a factor of 10 leap in constituent $\sqrt{s}$ is needed

Observations: Construction of LHC Xpts

A struggle with constant challenges.

- Constant preoccupation was the cost-to-complete, time-to-complete but preserving quality was vital –> the performance of LHC experiments has been very good.
- Develop funding modes (common fund, shared funding, in-kind contributions, metric for evaluating contributions,…)
- Contingency and flexibility

Sobering Plot
Time needed for large projects is long

Role of Host Lab. In Large Projects

What is the guidance from LHC for future large projects?

A well established strong host laboratory is critical and pivotal - operating in partnership with national laboratories and universities. Large projects constructed with **major contributions from national labs and universities** (especially those capable of building large instruments). Critical mass of in-house/field expertise and facilities.

The services provided by host lab (CERN) include legal, contractual (market surveys, tendering, difficulties during production, ….), financial (guarantees, loans, credit, …) , technical, …..

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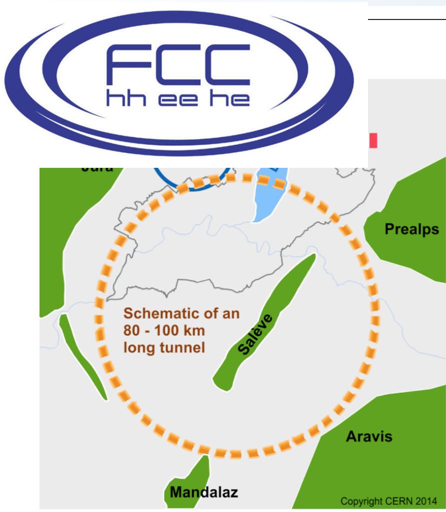
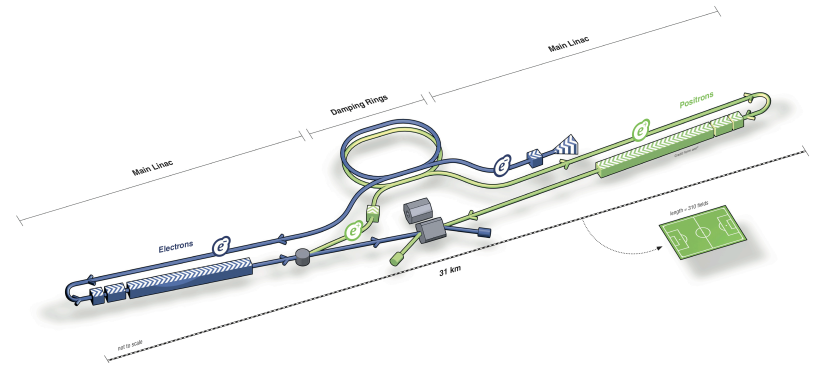
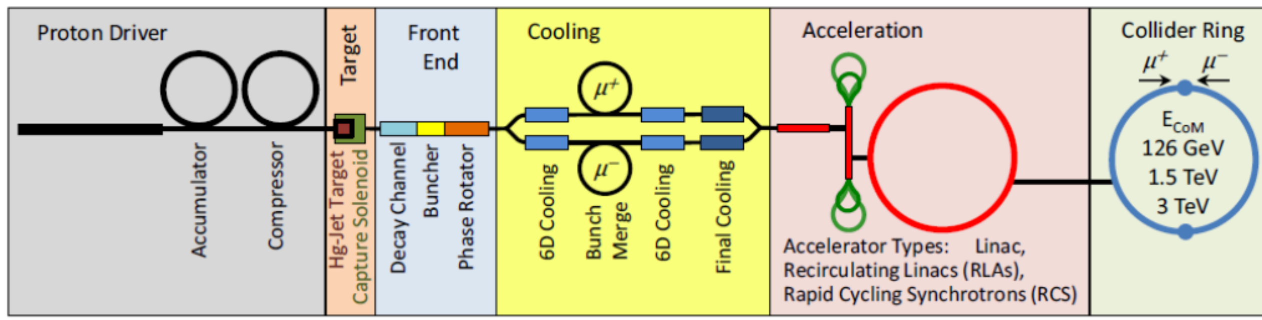
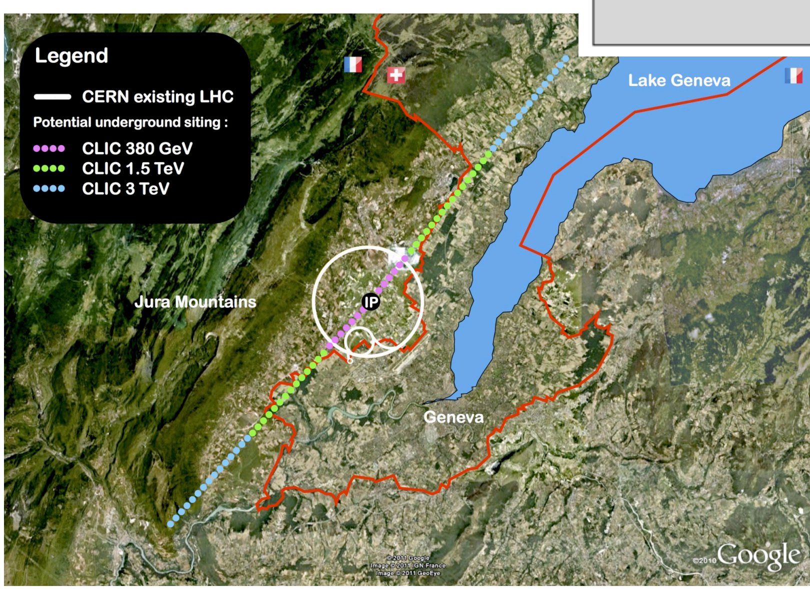
Future Colliders









Future Colliders: European Strategy

Europe's 2nd topmost priority (2013 Update)

To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

Obviously this talk is not going to pre-empt the outcome of discussions during the 2019-2020 European Strategy update (submissions will be discussed at the Granada Meeting in May'19)

Rather present some pointers for the future.

What will the LHC (and HL-LHC) Bring?

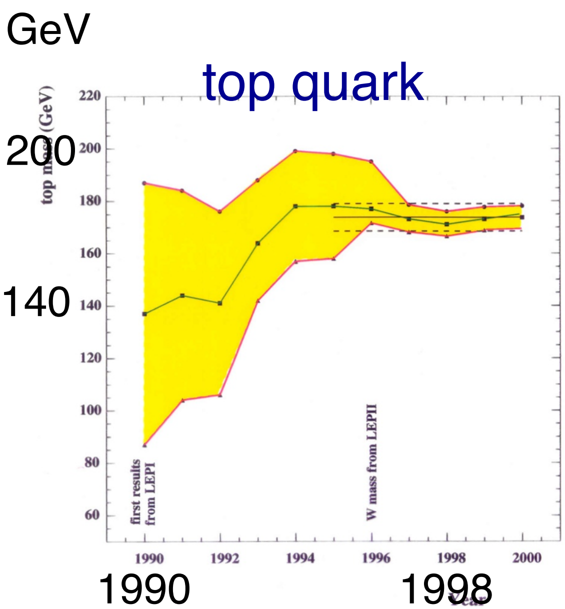
arXiv.1306.6352

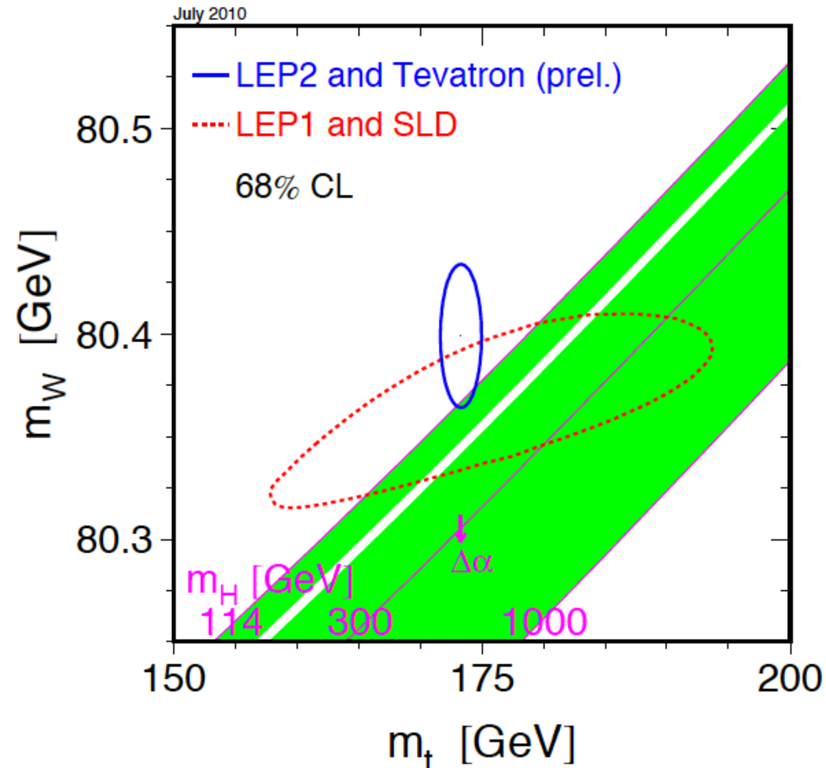
No direct sign of new physics @ LHC from searches

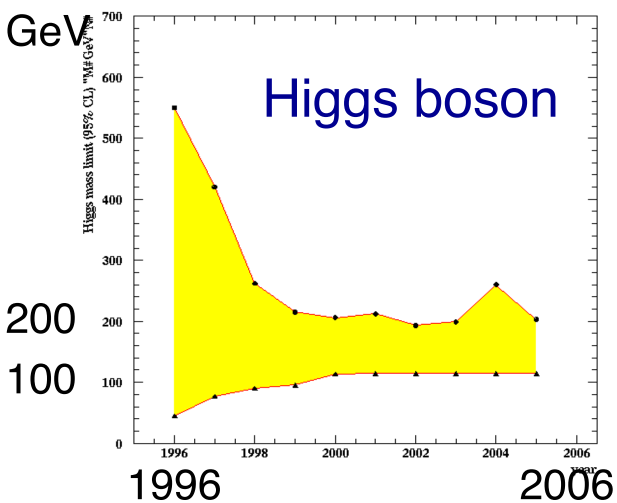
Higgs couplings can provide indirect access to BSM:

- SUSY (tanβ=5): $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$
- Composite Higgs: $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$
- Top partners: $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$

Sensitivity to Higher Energy Scales
Role of Quantum Corrections





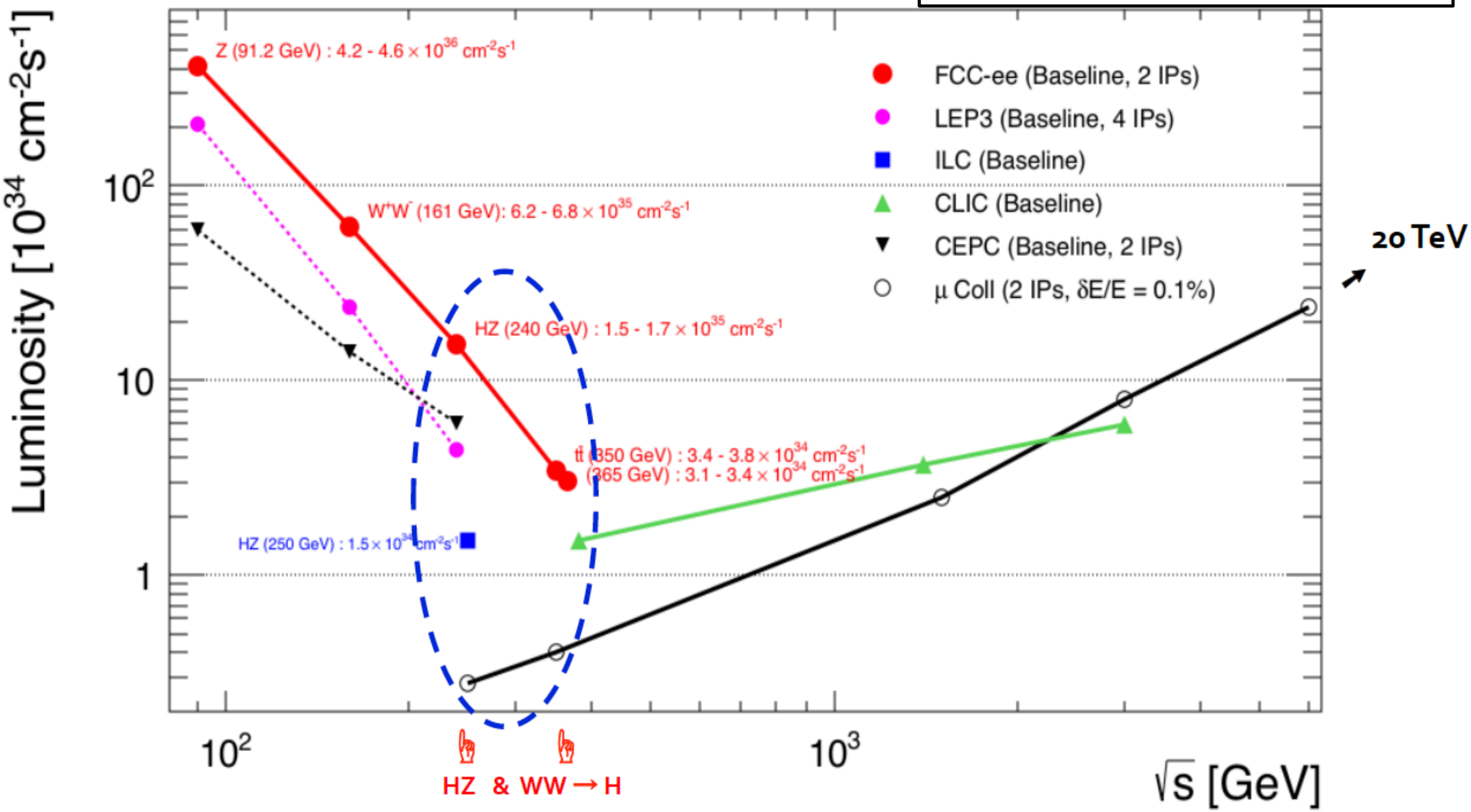


"…. The mass of the top quark could be predicted, using high precision data from LEP, several years before it was discovered in 19915 at Fermilab.
….Similarly comparison of theoretical values of quantum corrections involving the Higgs boson with precision measurements at LEP, SLC and Tevatron gives information on the mas of the as yet undiscovered particle."

C. Jarlskog, 1999 Nobel Prize to Veltmann and t'Hooft.

Future Lepton Colliders

Janot EP Faculty Meeting Jun '18



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Future Lepton Colliders: Higgs boson

Janot EP Faculty Meeting Jun '18

In numbers

(+) With -80%/+30% polarization
(*) Infrastructure exists already

Collider (#IPs)	Lumi (10^{34} $cm^{-2}s^{-1}$) at …		Time (yrs) for …	Length (km)	Energy frontier (TeV)
	240-250 GeV	350-380 GeV	10^6 HZ events		
ILC (1)	1.5	–	20(+)	23	0.35 – 0.5 (ILC?)
CLIC (1)	–	1.5	30(+)	11	3 (CLIC)
LEP3 (4)	4.4	–	10	27(*)	27 (HE-LHC)
CEPC (2)	6.0	–	7	100	70 (SppC)
FCC-ee (2)	17.	3.4	2.5	100	100 (FCC-hh)
μColl (1-2)	0.15	0.20	200	0.6	20 (FCC-μμ?)

Future Lepton Colliders: Higgs boson

Janot & Blondel arXiV: 1809.10041

Table 2: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee running as a Higgs factory for seven years, compared to those from HL-LHC and from the ILC running as a Higgs factory for 15 years. All numbers (in %) indicate 68% C.L. intervals, except for the last line which gives the 95% C.L. sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays.

Collider	HL-LHC	ILC_{250}	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	5_{240}	$\oplus 1.5_{365}$	$\oplus$ HL-LHC
Years	10	15	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	50	3.8	2.8	**1.6**	1.5
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	0.35	0.25	**0.22**	0.22
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	1.7	1.3	**0.47**	0.46
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	1.8	1.4	**0.68**	0.67
$\delta g_{Hcc}/g_{Hcc}$ (%)	**SM**	2.3	1.8	**1.23**	1.20
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	2.2	1.7	**1.03**	0.89
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	1.9	1.4	**0.80**	0.78
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	13	9.6	**8.6**	3.4
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	6.4	4.7	**3.8**	1.4
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	–	–	–	3.3
BR_{EXO} (%)	**SM**	< 1.8	< 1.2	< 1.1	< 1.0

Future Colliders

Physics Imperatives

No clear sign of any BSM physics at the LHC yet. The situation would obviously change if we did find some in the HL-LHC phase.
However, the Higgs boson has been discovered – a quite unusual particle in the zoo of SM particles. Must study it well – also in view of finding clues to BSM physics.

Precision Frontier - Higgs boson, EWSB and SM physics

It is incumbent on us to make precision measurements of the properties and couplings in the Higgs sector – sensitivity to high mass scales – deviations from SM predictions may give clues to the next interesting scale; precision SM measurements.

An e^+e^- collider is the best way to carry out this step.

Energy Frontier - Search for Physics Beyond the SM

An exploratory collider with a factor of 10 leap in constituent $\sqrt{s}$ is needed

A hadron collider with $\sqrt{s}$ ~ 100 TeV is arguably the best way to do this

Future Collider Projects

Projects:

e^+e^-: ILC (Japan), CLIC (CERN), CepC (China), FCC(ee) (CERN)
100 GeV to 3TeV
ep: CERN FCC(ep)
$\mu^+\mu^-$: 100 GeV to 14 TeV
pp: CepC(pp), FCC(pp) – 100 TeV (~10 TeV constituent cms)

Readiness

ILC: green field, TDR, ready to go (250 GeV)
CepC: green field, CDR
CERN: CLIC – CDR, FCC(ee, ep, pp) CDR, R&D on high field magnets

Timeline

ILC: decision to proceed is still pending
CepC: MOST: 3-5 seed projects by '20, 1-2 to be approved for construction.
μμ: still in R&D
CERN: CLIC or FCC(ee) planning to be operational a few years after HL-LHC finishes data taking

Future Collider Projects

Costs (units of 10 BCHF)**:**
ILC : ~ 0.7 for initial stage, one experiment
CLIC: ~ 0.7 for initial stage, one experiment, (+1.2 for upgrade to 3 TeV)
CepC(ee): ~ 1, two experiments
FCC(ee) ~ 1 (2-4 experiments) + 1.5 for FCC(pp)

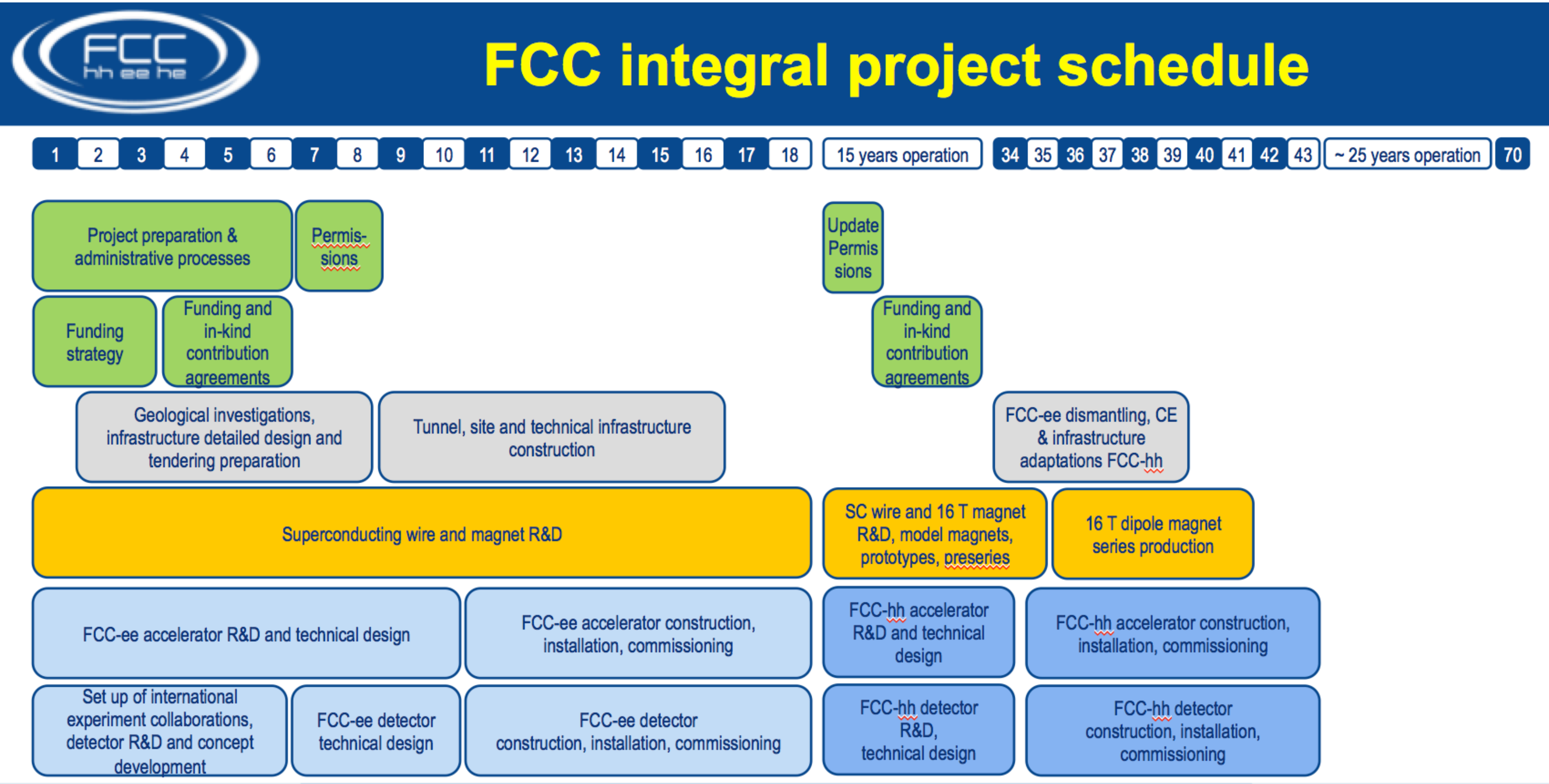
Funding
ILC: no firm commitment yet of the Japanese government
CepC: China to fund the major part but an international project
CERN: "needs to host a frontier accelerator" but has stated that it cannot continue to pursue both CLIC and FCC options beyond this strategy update, funding to be established.

Supposing CEPC Circular Collider

design issues R&D items preCDR	design, funding R&D program Intl. collaboration site study	seek approval, site decision construction during 14th 5-year plan commissioning

- CEPC data-taking starts before the LHC program ends around 2035
- earlier than the FCC(hh, ee)
- possibly con-current, and complimentary to the ILC

Supposing CERN FCC



Summary

LHC and Xpts are performing well. The Higgs boson has been discovered. It is a very unusual particle. Exploration of the TeV scale is continuing but no significant signs of BSM have yet been found.

The SM is highly successful but is a low energy approximation

Our discipline is at a crossroad

Progress in the future has to be made on a wide front, including precision measurements in the Higgs sector and direct exploration of landscape of physics at energy scales a factor 10 larger than possible at the LHC.

Most colliders, at increasing constituent cms energy, have led to discoveries.

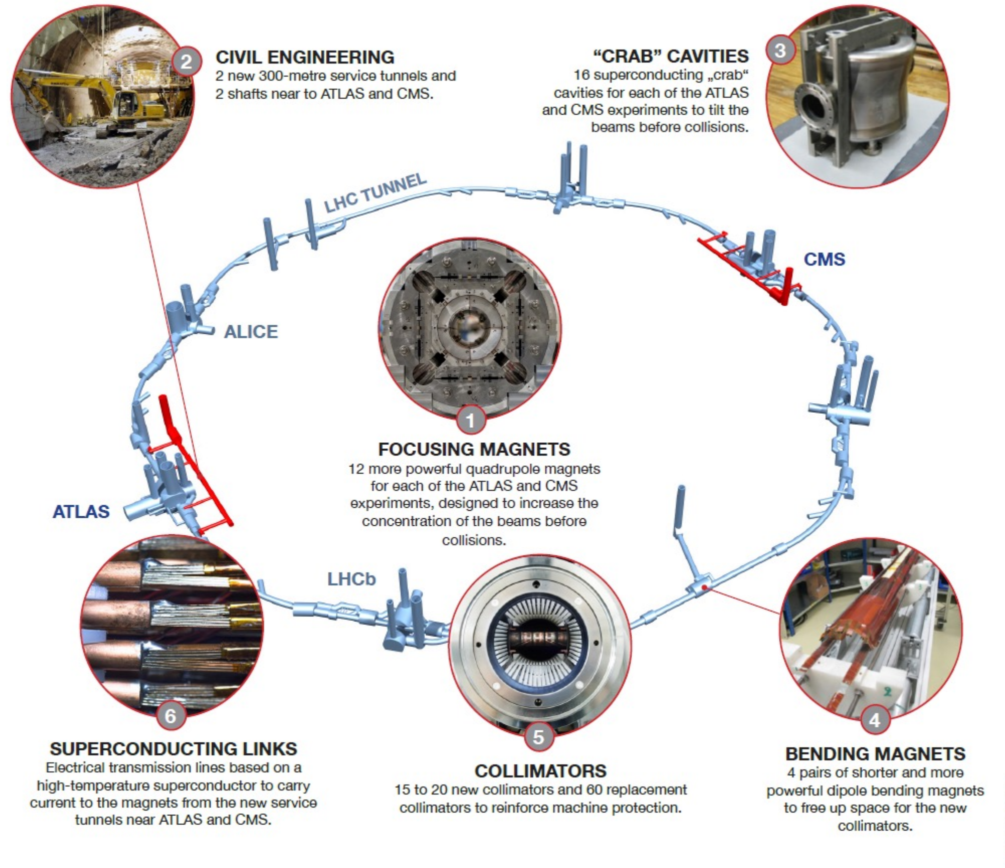
An e^+e^- collider is best way to carry out precision (sensitive) measurements in the Higgs boson (and other SM) physics.

A hadron collider with $\sqrt{s}$ ~ 100 TeV is arguably the best way to directly probe physics at scale a factor ~ 10 times higher than the LHC. (Heavy ions, ep etc programmes are also possible)

A stepwise approach for a particle physics programme that lasts > 2/3rd of a century is possible leading to a bright future for our discipline.

The HL-LHC Project: 300 fb^{-1}→3000 fb^{-1}

- **New IR-quads Nb_3Sn (inner triplets)**
- **New 11 T Nb_3Sn (5.5 m dipoles)**
- **Crab Cavities**
- Collimation upgrade
- Cryogenics upgrade
- Cold powering
- Machine protection
- …



Major intervention on more than 1.2 km of the LHC

LHC Status and Outlook
EPS-HEP 2017 conference
Frédérick Bordry
Venice, Italy, 10th July 2017

Translation to Detector Design

New higher granularity more radiation hard inner trackers

ATLAS & CMS – factor ~10 more channels with sensors and electronics that can withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2

LHCb – new Velo with pixels, new SciFi tracker

ALICE - new pixels detector and new (lower deadtime) readout for TPC

Replacement of components affected by radiation

ATLAS/CMS – endcap calorimeters (CMS' needs replacement – open new physics channel – VBF – **WW initial state** !)

Higher bandwidth L1 triggers and DAQ

Introduce Track Triggers in L1

Higher L1 output rate [e.g. ATLAS/CMS 100→750kHz and latency (>10μs)] – new trigger processors (ASICs → FPGAs).

DAQ recording rate 1000→10k evts/s

Replacement of front-end electronics

Deal with higher rates, longer pipelines (e.g. ATLAS/CMS >10 us),

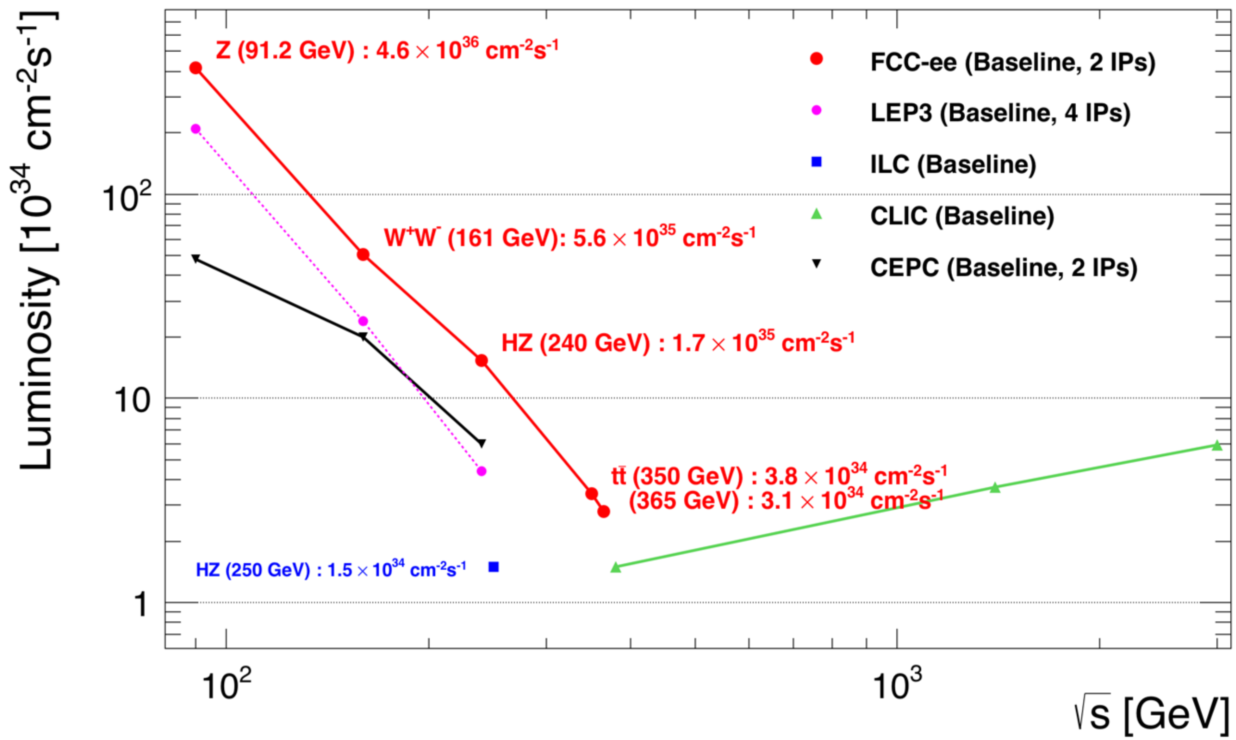
LHCb – deal with 40MHz L1 trigger

Introduction of precision timing

Vertex localization and pileup suppression

FCC-ee

Z WW HZ tt



Event statistics :

					E_{CM} errors
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5	100 keV
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3	300 keV
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done	2 MeV
[?]tt threshold	E_{cm} : 350 GeV	10^6	e+e- → [?]tt	Never done	5 MeV

Great energy range for the heavy particles of the Standard Model.

Observations: Construction of LHC Xpts

A struggle with constant challenges

- LHC Experiments: the first truly global construction projects in our field (ATLAS,CMS each with 150 institutions from 40 countries with > 40 funding agencies)
- time needed was long ~20 years (required stability of resources: human resources and funding), changing technological/economic conditions, (raw material cost fluctuations..)
- **the physics motivation was strong**.

- very challenging design and construction – many phases: R&D, prototyping mostly with industry, worldwide distributed construction, installation at CERN
  - R&D: several technologies studied for one retained (DRDC was vital)
  - Surprises during development
  - Surprises during production
  - Surprises during integration (systems) and installation (services)
  - Surprises in software/computing

Guidance for HL-LHC: Energy Frontier

1. **Higgs boson and EWSB physics**
2. **Search for physics beyond the SM**
3. **Precision (sensitive) SM measurements**

Instantaneous Luminosity x 5 (much higher pileup !!!)

Integrated Luminosity x 10 (higher radiation levels!!!)

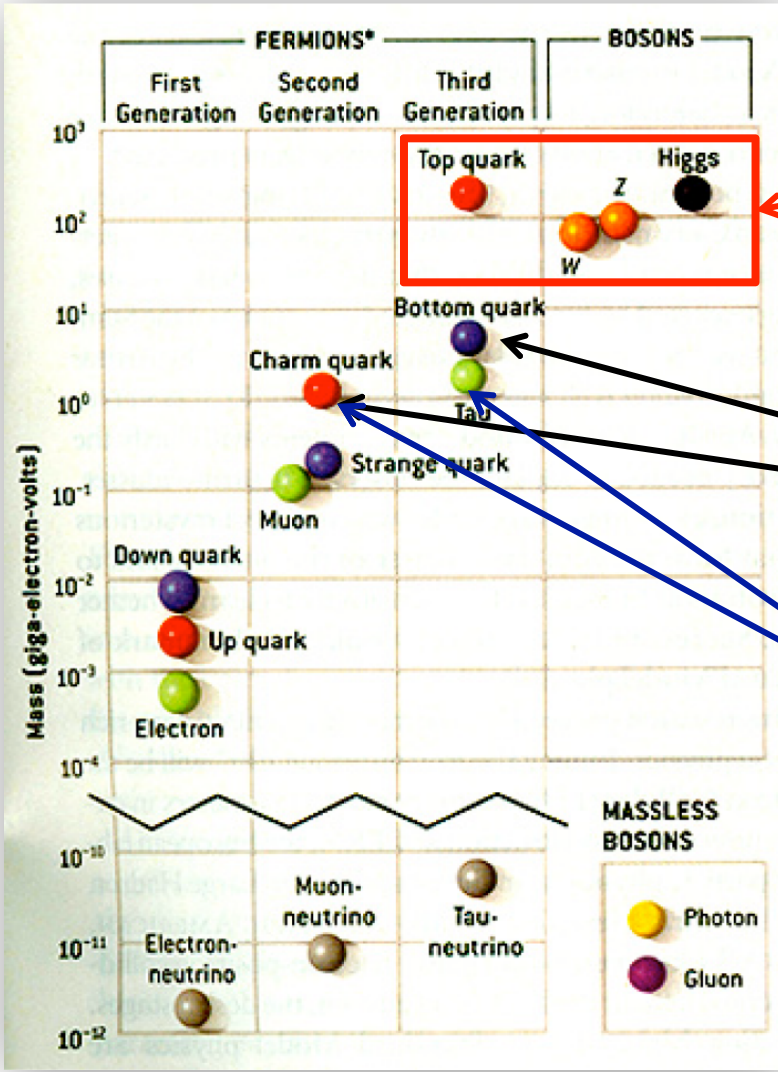
The guidance implies the following:

Preserve (and possibly improve), wrt today's values,

- trigger thresholds
- reconstruction and identification efficiencies (granularity)
- energy/momentum/mass resolutions

All at factor of 5 larger pileup !

Standard Model and Colliders



Hadron Colliders
W/Z: UA1/UA2 @ SPS
Top: CDF/D0 @ Tevatron
H: ATLAS/CMS @ LHC

Hadron Collisions
b quark: E288 @ FNAL
c quark: pBe @ AGS

ee Collider
c and τ SPEAR

Not shown: probing the strong, weak and EM interactions

Alas – SUSY has not turned up yet …

Inclusive Searches

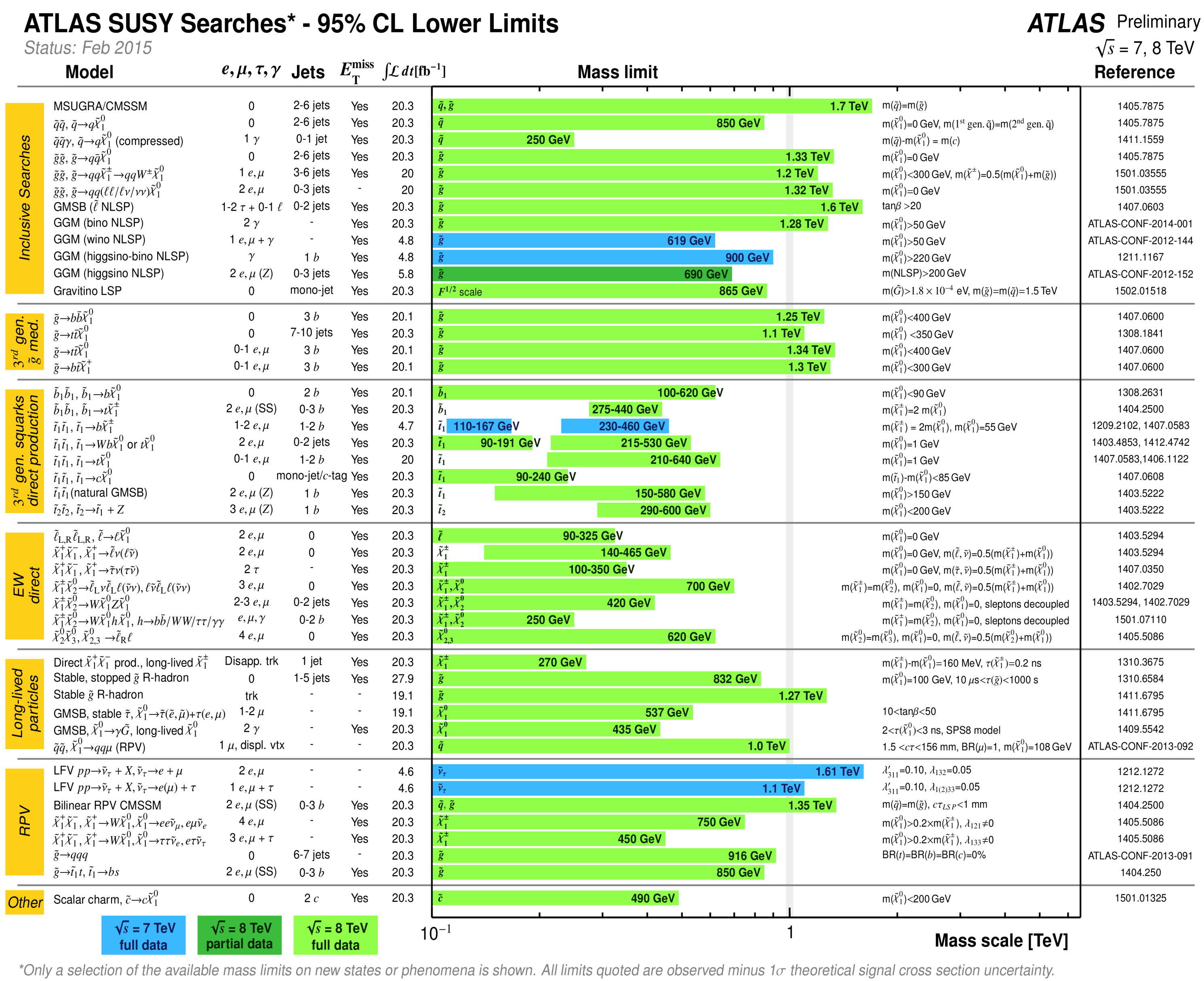
3rd Gen gluino med.

3rd Gen Direct

EW Direct

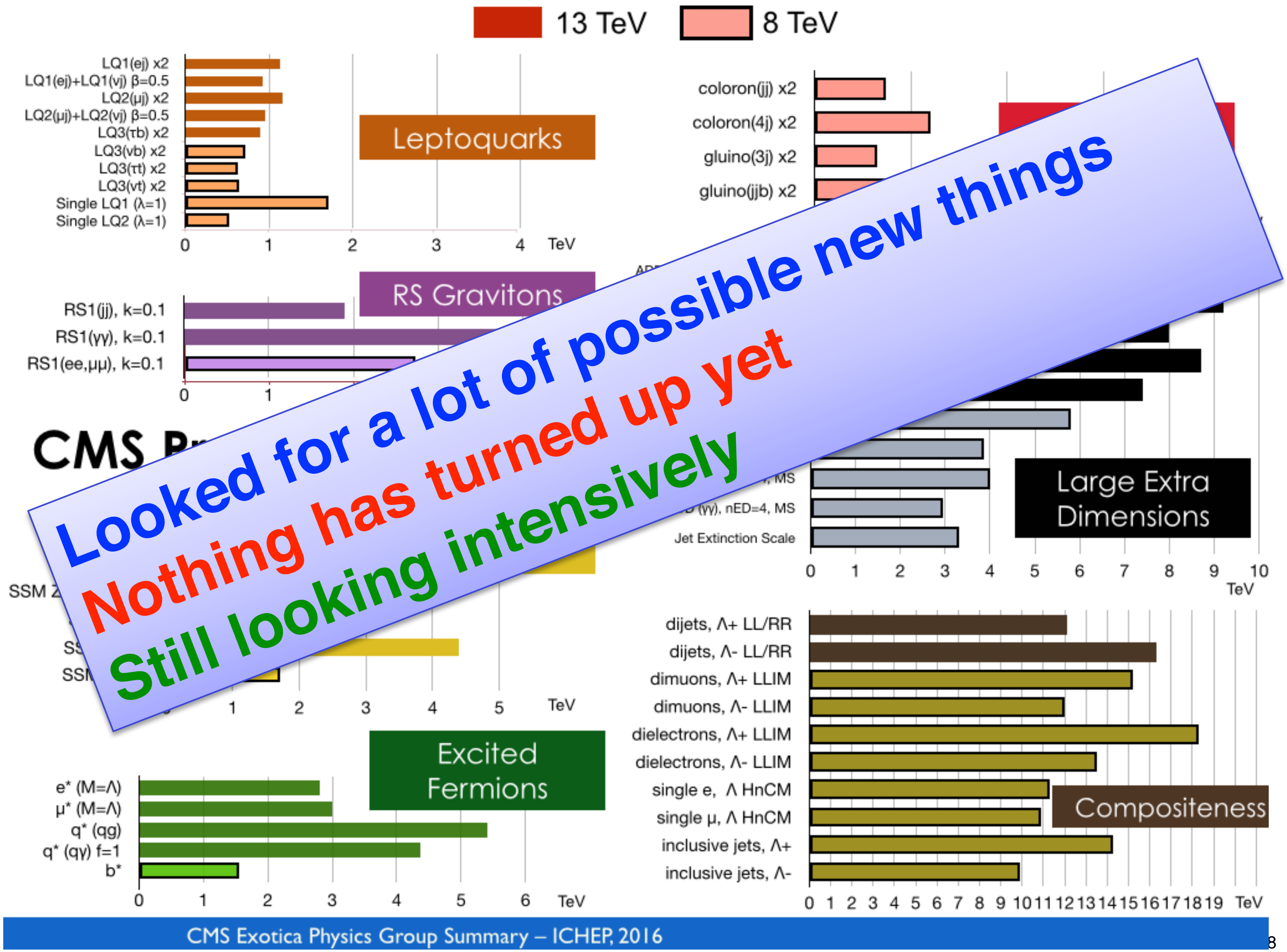
Long-lived

RPV



Imperial College London

Non-SUSY BSM: vast, simply vast ….

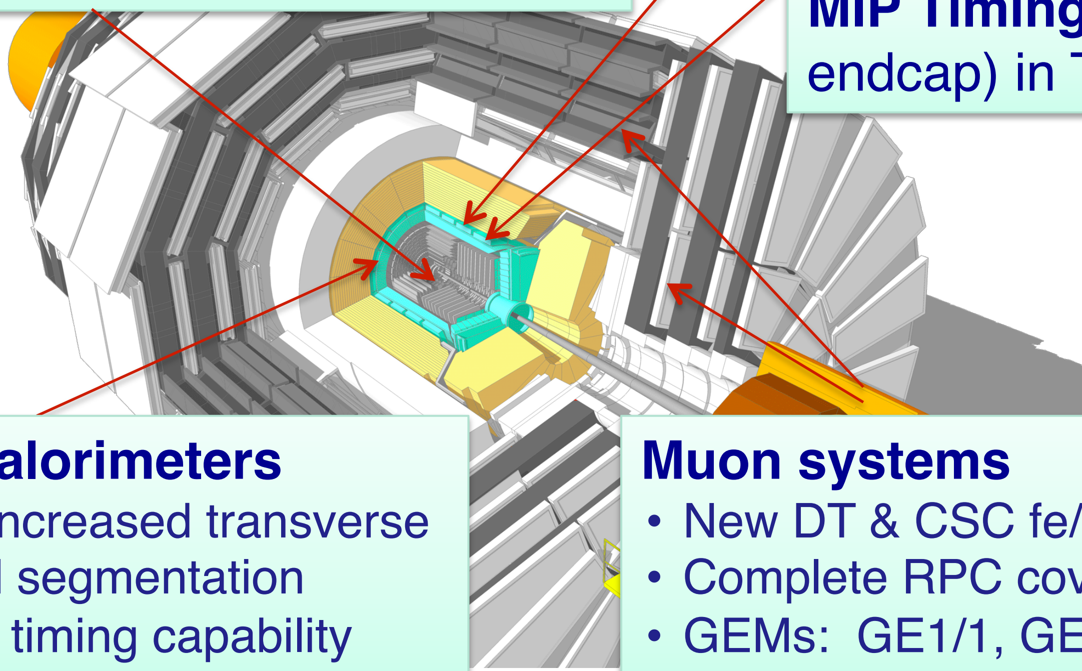


Example: CMS Upgrades for Phase II

New Tracker
- Rad. tolerant - increased granularity - lighter
- Tracks (p_T≥2 GeV) in hardware trigger (L1)
- Extended coverage to η ≃ 4

Barrel EM calorimeter
- New FE/BE electronics
- Lower operating temperature (8°C)

MIP Timing Layer (barrel & endcap) in TP stage



New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation
- intrinsic precise timing capability

Muon systems
- New DT & CSC fe/be electronics
- Complete RPC coverage 1.5<η<2.4
- GEMs: GE1/1, GE2/1, ME0

Trigger/HLT/DAQ
- Tracks (p_T≥2 GeV) in hardware trigger (L1)
- Trigger latency 12.5 μs, output rate 750 kHz
- HLT output 7.5 kHz

Beam radiation and luminosity
Common systems &infrastructure

Calculations: Great progress in recent years

GLUON-FUSION (13 TEV)

G. Salam

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

$$48.58\,\text{pb} \pm 1.89\,\text{pb}\,(3.9\%)\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

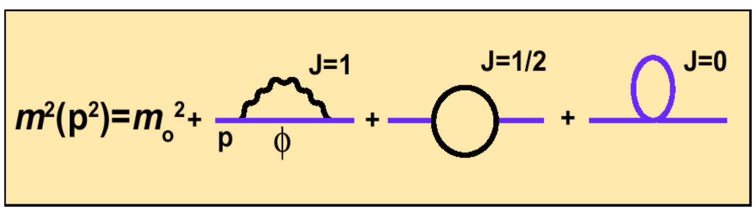
Higgs boson – A Conundrum!

- **A very different type of particle from all other fundamental ones, a point-like scalar?**

- **Is it really the SM Higgs boson?**

The compatibility of the measured and widely differing production and decay modes with those predicted for the SM Higgs boson suggests so – at least it must be a close relative.

- **Why has it shown its face at the LHC? Ascribe it Naturalness??**



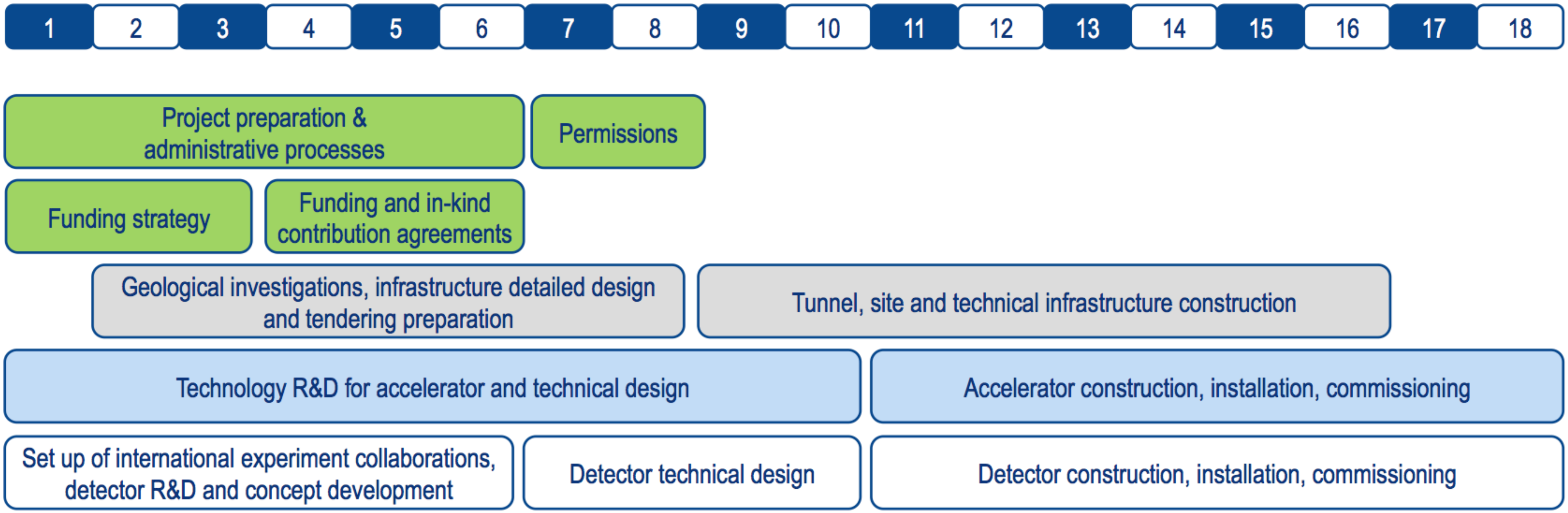
Cancellation of radiative corrections

Fine tuning

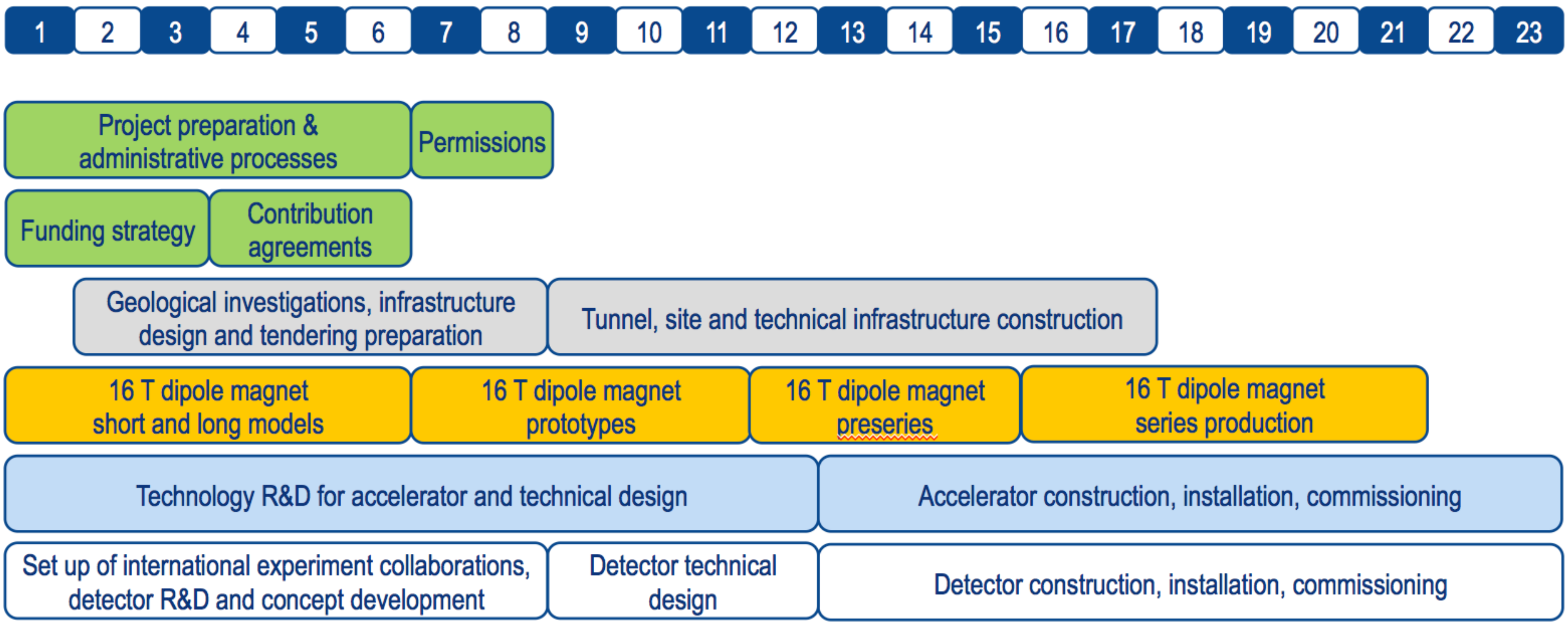
- **Using the Higgs boson as a new tool of discovery:**

  Any small (significant) deviation will be a breakthrough.

Supposing CERN FCC (ee)



Supposing CERN FCC (hh)



- Assumes injection from (adapted) LHC.