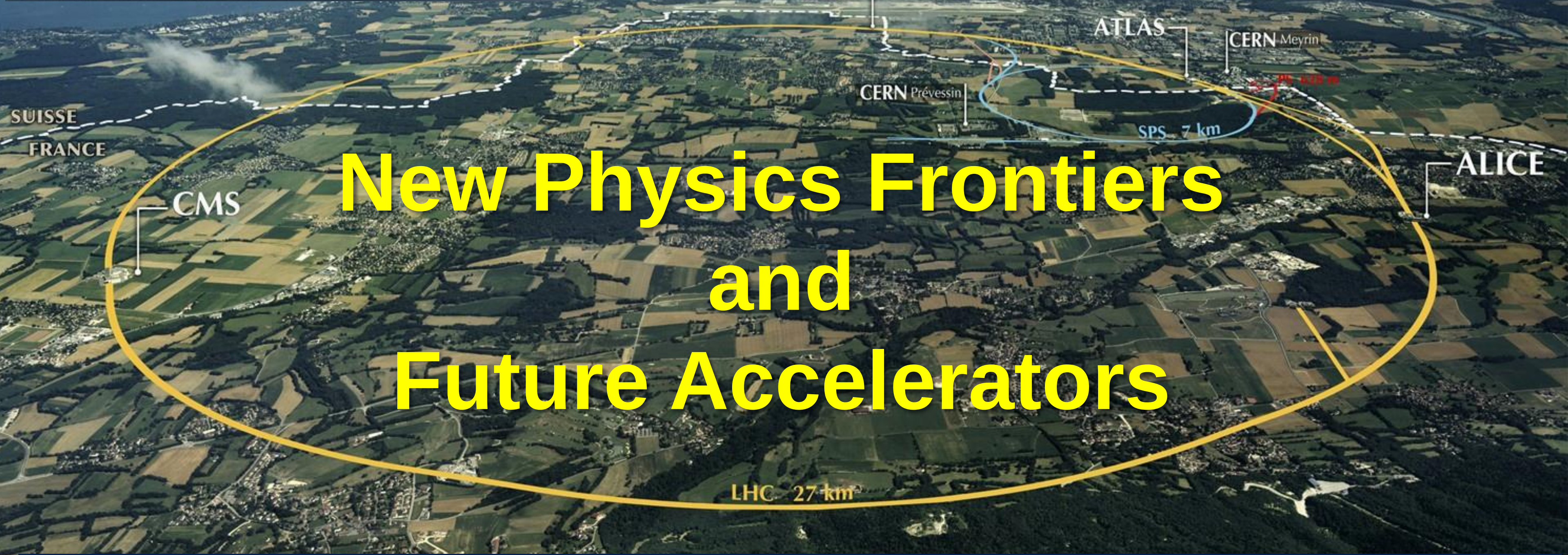



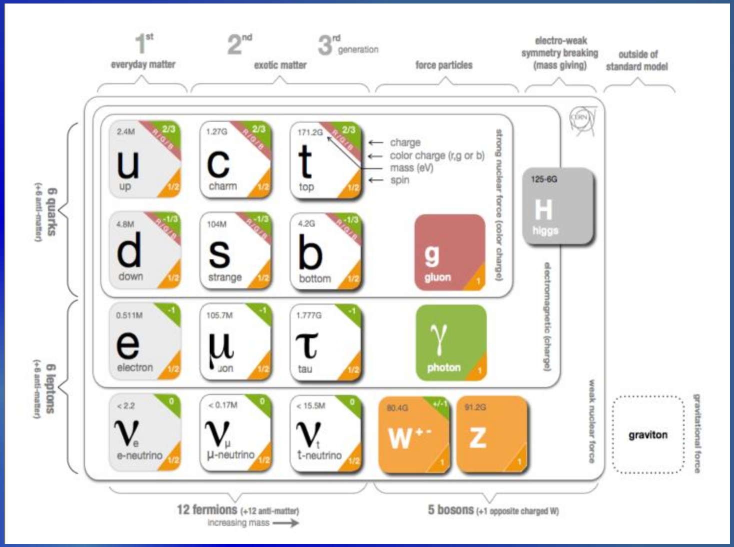

# New Physics Frontiers and Future Accelerators

Maxim TITOV, CEA Saclay, France

6th International Conference on Micro Pattern Gaseous Detectors (MPGD19)
La Rochelle, France, 6-10 May, 2019

# What We have Learned the Last 50 Years or *Status of the Standard Model*

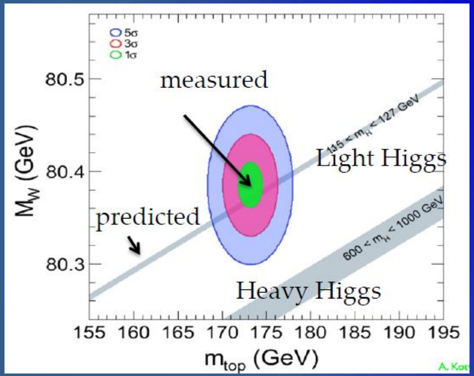
The Standard Model explians all known collider phenomena and almost all particle physics

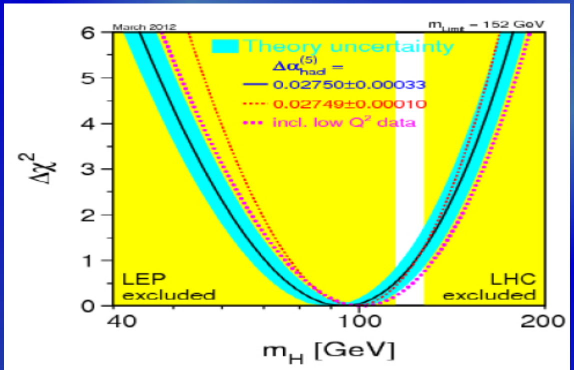


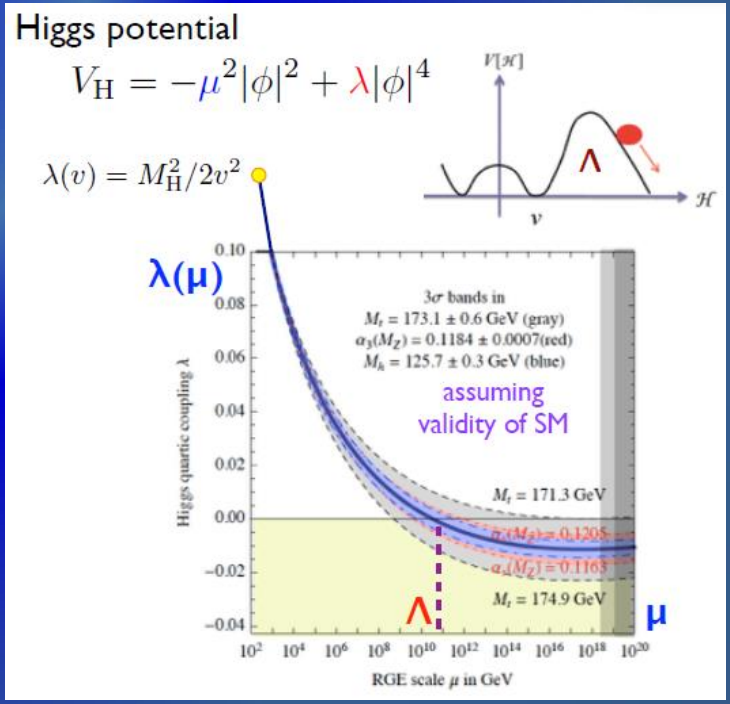

experimental validation down to ~ $10^{-18}$ m up to *O* (100 GeV)

– this was beautifully verified at LEP, SLC, Tevatron and the LHC;

– the EWPO radiative corrections predicted top and Higgs masses, assuming SM *and nothing else;*



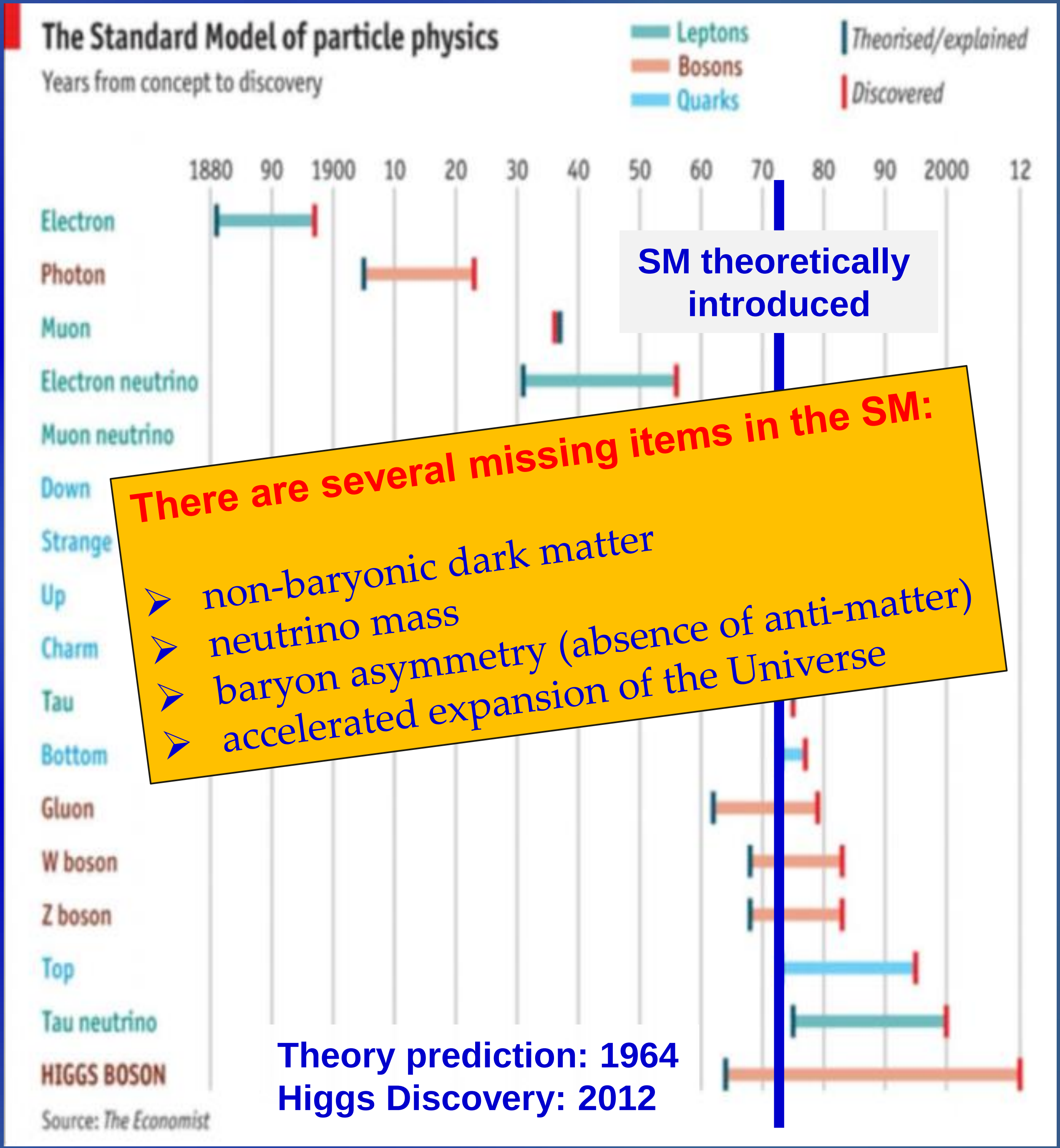




– With $M_H$ ~ 126 GeV, one can even extrapolate the Standard Model all the way to the Plank scale

**Source:**
**The Economist**
**July 4th, 2012**

**With a well-founded theoretical model, precision measurements can be turned into discoveries - and precision measurements can guide the development of new models**




**The clear need for long-term planning in our research field**

# Beyond Standard Model Physics: Solutions

## Technicolor
New (strong) interactions produce EWSB

Extensions of the SM gauge group :
Little Higgs / GUTs / ...


For (most of) proposed solutions:
new particles should appear
at **TeV** scale → **territory of the LHC**

**We are embarking on an entirely new "lucky era" in fundamental physics → No lack of compelling questions !**

## Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
**No new interactions**

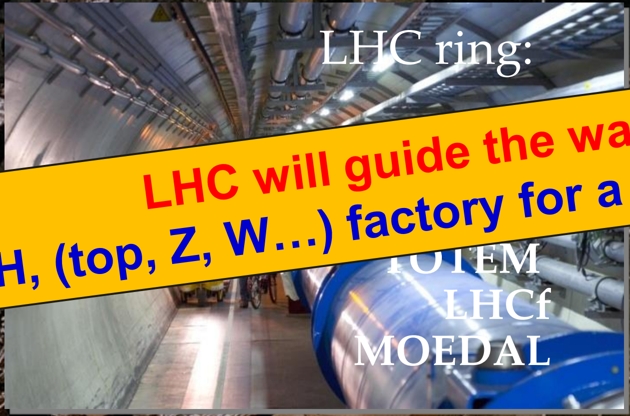
## Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{elw}$ ➲ Hierarchy problem solved
**New particles at ≈ TeV scale**

# New Energy Frontier - Large Hadron Collider (LHC)


**2013: Nobel Prize in Physics for Higgs Boson Discovery**

*'The Large Hadron Collider at CERN is the largest most complex machine in the world, possibly the universe. By smashing particles together at enormous energies, it recreates the conditions of the Big Bang. The recent discovery of what looks like the "Higgs particle" is a triumph of human endeavour and international collaboration. It will change our perception of the world and has the potential to offer insights into a complete theory of everything.' Stephen Hawking*

ATLAS / CMS: Energy Frontier
LHCB: Flavour Physics and CI
ALICE: Heavy Ion Physics


**LHC will guide the way →**
**the only H, (top, Z, W…) factory for a decade(s) to come**

# PARTICLE PHYSICS LANDSCAPE AT CERN

**High Energy Frontier**
*LHC*

**Hadronic Matter**
*deconfinement*
*non-perturbative QCD*
*hadron structure*

**Low Energy**
*heavy flavours / rare decays*
*neutrino oscillations*
*anti-matter*

**Multidisciplinary**
*climate, medicine*

**Non-accelerator**
*dark matter*
*astroparticles*

***Non-LHC Particle Physics = o(1000) physicists / o(20) experiments***

**Physics Beyond Colliders Group set up in 2016:** explore opportunities offered by CERN acc. complex / other scientific infrastr.

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, bending crystals) in ALICE and LHCb

Hidden sector with "beam dump"
NA64++ (e,μ)
NA62++

Rare
KLEV
TauFV
REDT
MUonE
Proton

γ-factory from Partially Stripped Ions; nuSTORM

Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

→ Report submitted to the ESPP

**Some Highlights in 2018:**

- Upgrades of the HIE/ISOLDE and AD/ELENA facilities were completed;
- AWAKE, demonstrated for the first time electron acceleration from plasma wakefields induced by a proton beam;
- The world's largest liquid-argon neutrino detector, the single-phase proto-DUNE, at the CERN Neutrino Platform, reconstructed tracks from incident test-beam particles

**Scientific Diversity at unique facilities**
**(CERN maintains and upgrades them)**

**AD/ELENA:** Antiproton Decelerator for antimatter studies

**CAST, OSQAR**: axions

**CLOUD**: impact of cosmic rays on aeorosols and clouds → implications on climate

**COMPASS**: hadron structure and spectroscopy

...active nuclei

...ions and

...cays

...processes in strong EM fields in crystal targets

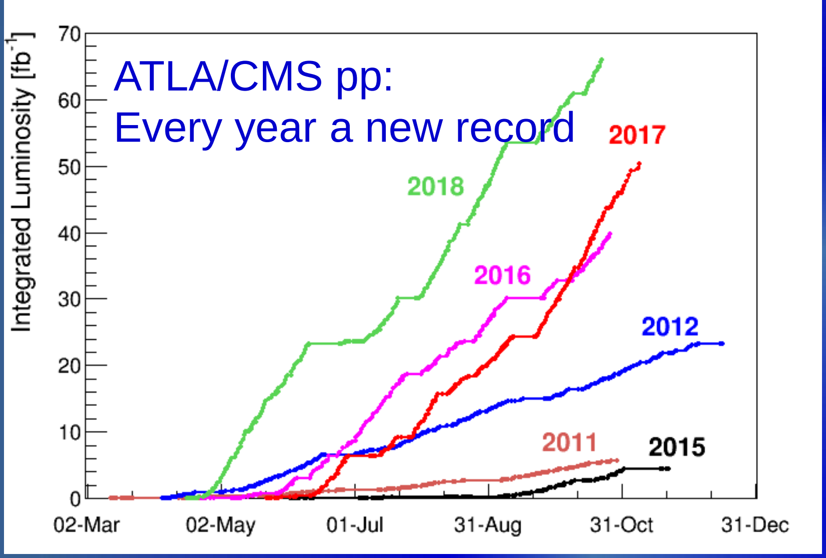
**NA64**: search for dark photons

**Neutrino Platform:** ν detectors R&D for experiments in US, Japan

**n-TOF:** n-induced cross-sections

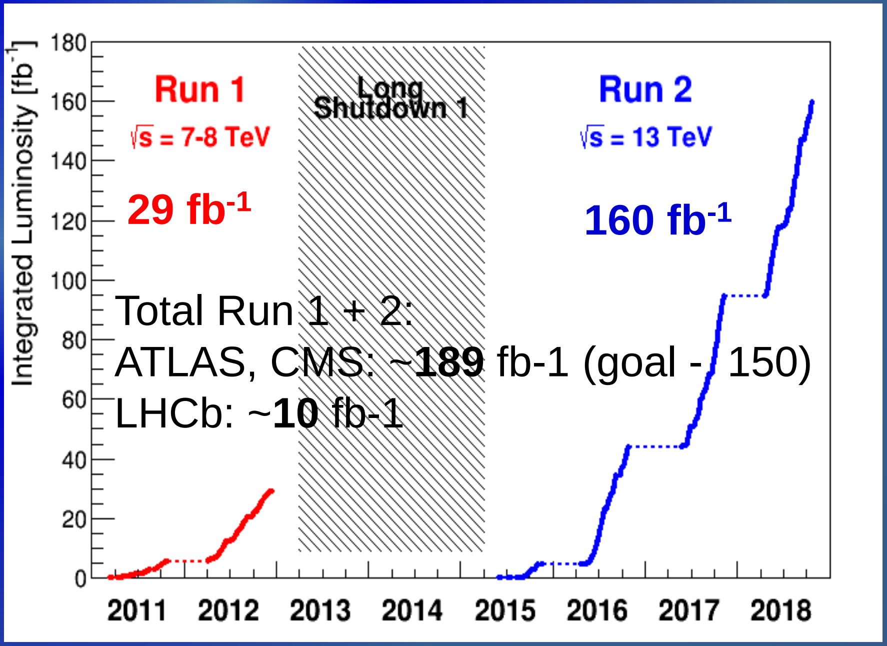
**UA9**: crystal collimation

# LHC Accelerator Complex: Glorious Run 2

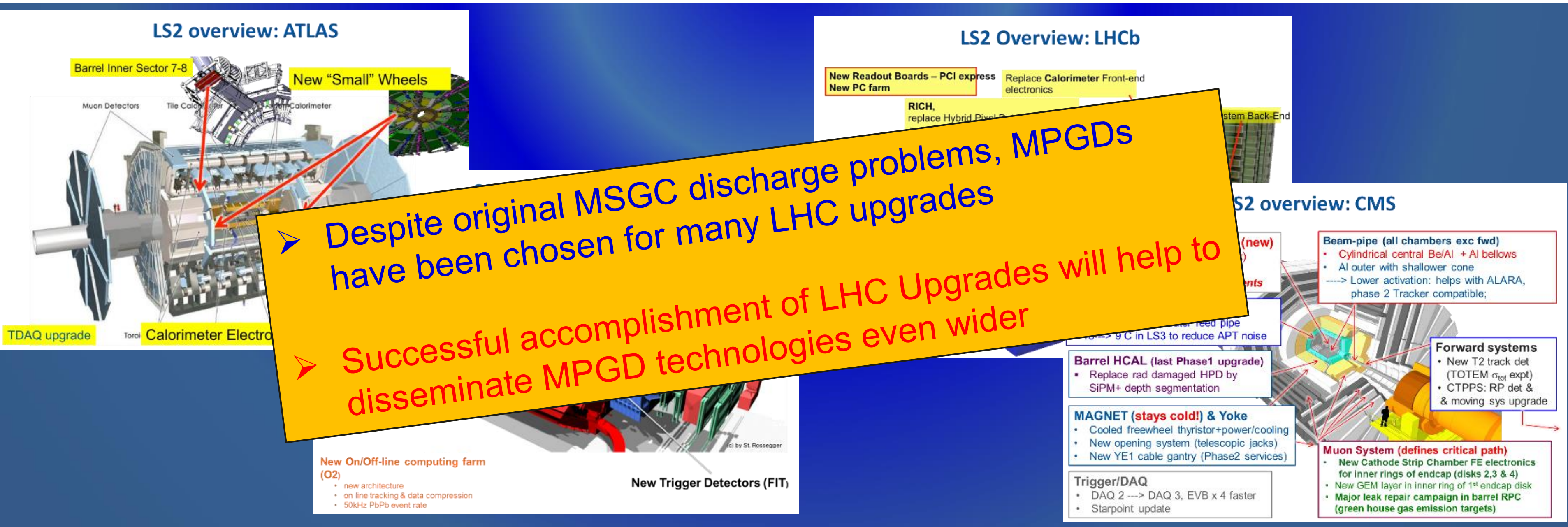



| Parameter | 2018 | Design |
|---|---|---|
| Energy (TeV) | 6.5 | 7.0 |
| No. of bunches | 2556 | 2808 |
| Max. stored energy per beam (MJ) | 312 | 362 |
| β* [cm] | 30 → 25 | 55 |
| p/bunch (typical value) ($10^{11}$) | 1.1 | 1.15 |
| Typical normalized emittance (μm) | ~1.8 | 3.75 |
| Peak luminosity ($10^{34}$ $cm^{-2}s^{-1}$) | 2.1 | 1.0 |

- **LHC peak luminosity: ~2 x $10^{34}$ $cm^{-2}$ $s^{-1}$ (2 x nominal): thanks mainly to brightness of beams from injectors and β* ≤ 30 cm**
- **Fraction of time in physics: ~ 50%**
- **Integrated luminosity in 2018:**
  **~ 66 $fb^{-1}$ ATLAS, CMS (goal was 60 fb-1)**
  **~ 2.5 $fb^{-1}$ LHCb (goal was 2 fb-1)**
  **~ 27 $pb^{-1}$ ALICE**

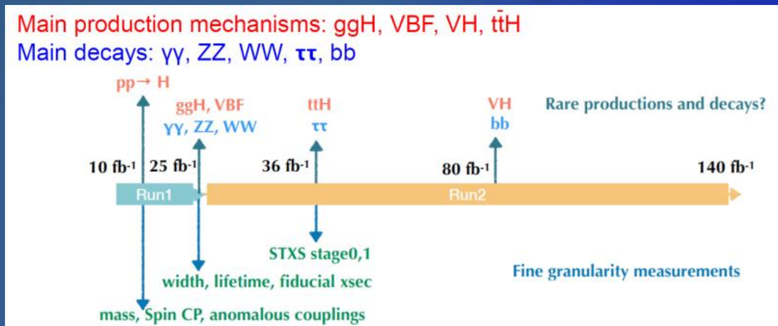


# Run 2 is over, … welcome to LS 2
# Preparation for Run 3 and HL-LHC

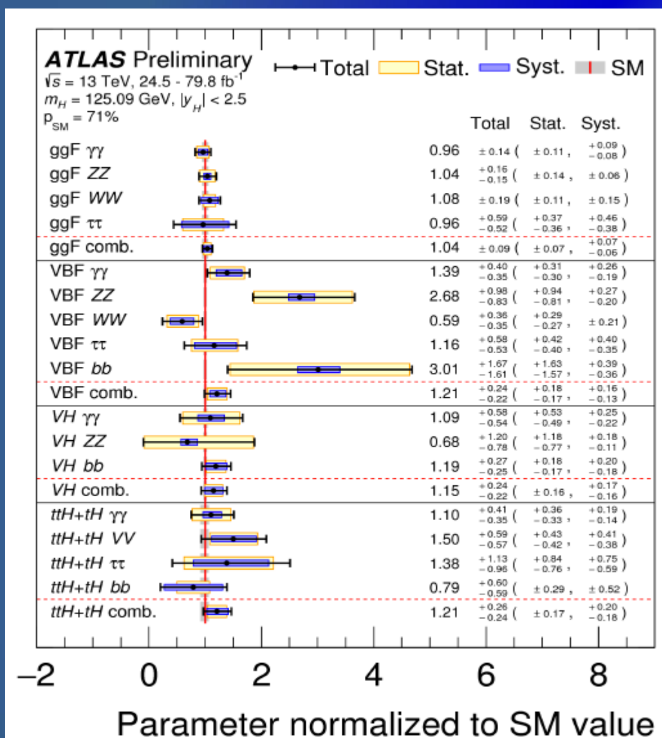




- Despite original MSGC discharge problems, MPGDs have been chosen for many LHC upgrades
- Successful accomplishment of LHC Upgrades will help to disseminate MPGD technologies even wider

# From Discovery to Precision: THE Higgs or A Higgs

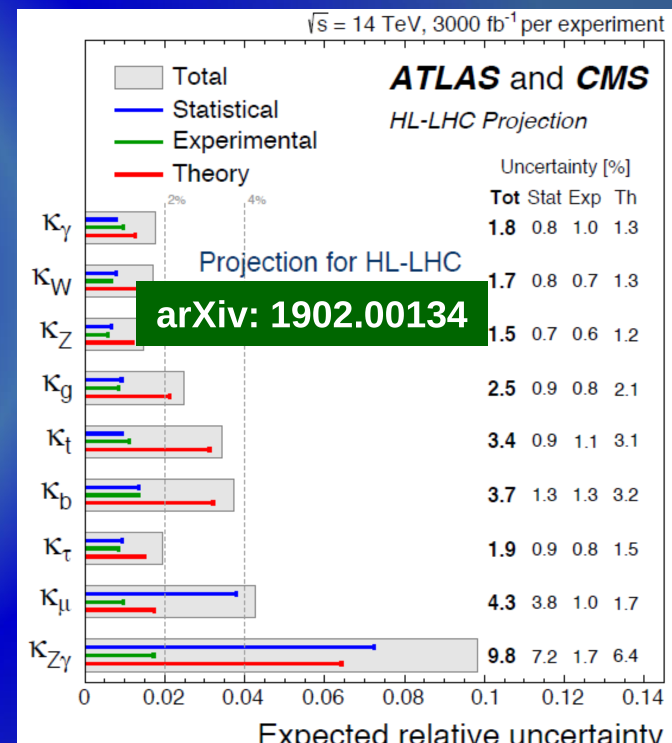



**Measurements of Higgs properties with increasing precision are a formidable tool to look for new-physics manifestations**
→ experimental precision approaching theory precision even before using full Run 2 statistics




← **TODAY:**
consistency so-far with the SM-like Higgs Boson

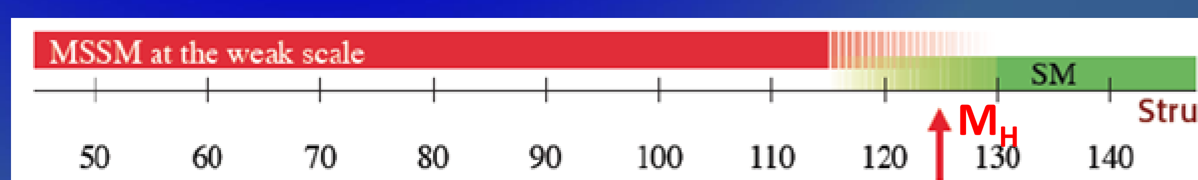
**FUTURE:** →
20x increase in statistics




Projection for HL-LHC

**arXiv: 1902.00134**

**Higgs is so simple and so unnatural**
→ a "malicious choice"

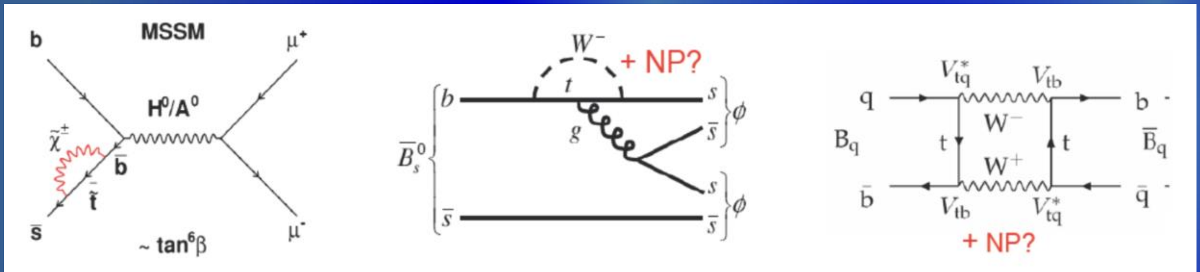


# Energy Frontier vs Flavour Physics Experiments: Complementary Approaches

**Direct searches at the Energy Frontier (ATLAS, CMS)**

probe the scale of New Physics Scale (Λ)

**Limited by available CM energy**



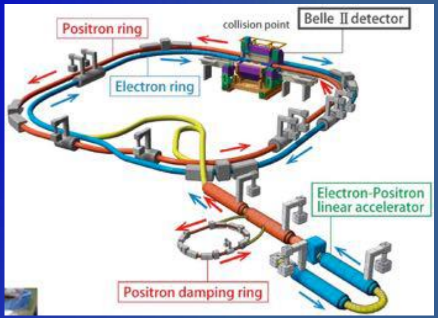

**Flavour physics (LHCb, Belle II,** also ATLAS/CMS)

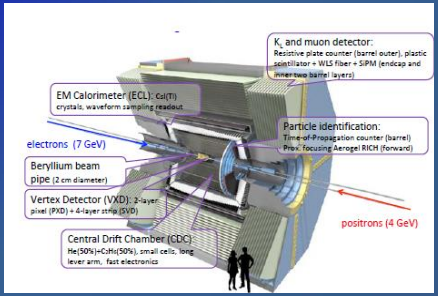
probe NP scale ($10^2$–$10^5$ TeV) indirectly,

through loop effects

**Limited by the size of flavor violation δ and the available statistics/precision**

Belle II at Super KEKB:

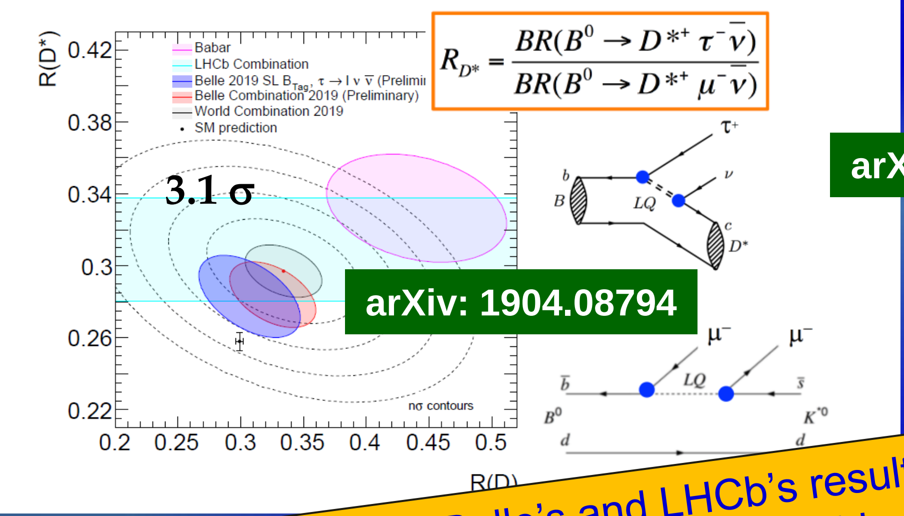


# Lepton Flavour Universality: Intriguing Anomalies

## LFU tests in b → clν transitions

**BSM: Two-Higgs- Doublet Model Type II**

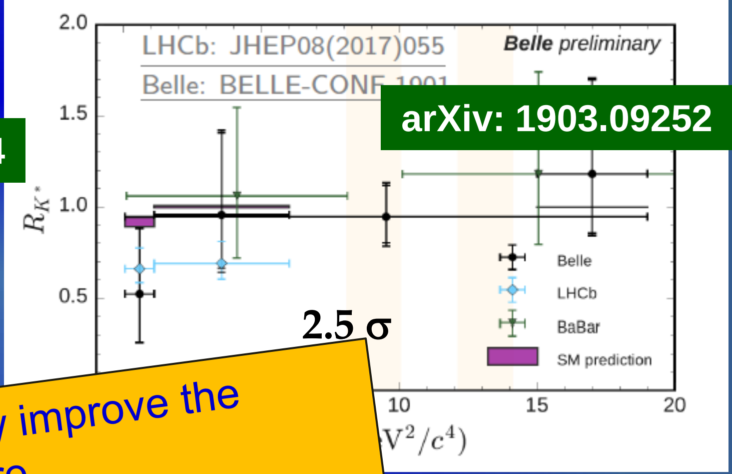



$$R_{D^*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

## LFU test in b → sl+l- transitions

**theoretically very clean → non-LFU sign of NP**

arXiv: 1903.10434

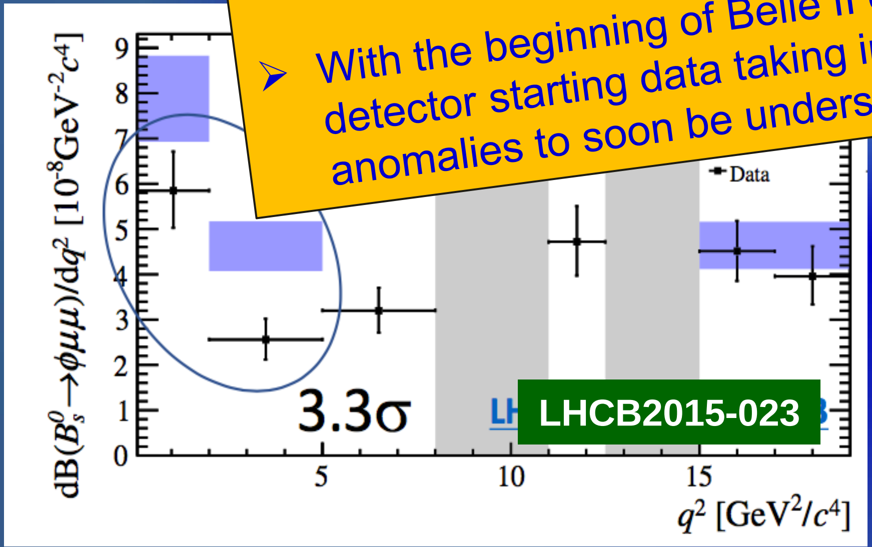



F($B^+ \to K^+ e^+ e^-$)

BF($B^0 \to K^{*0} e^+ e^-$)

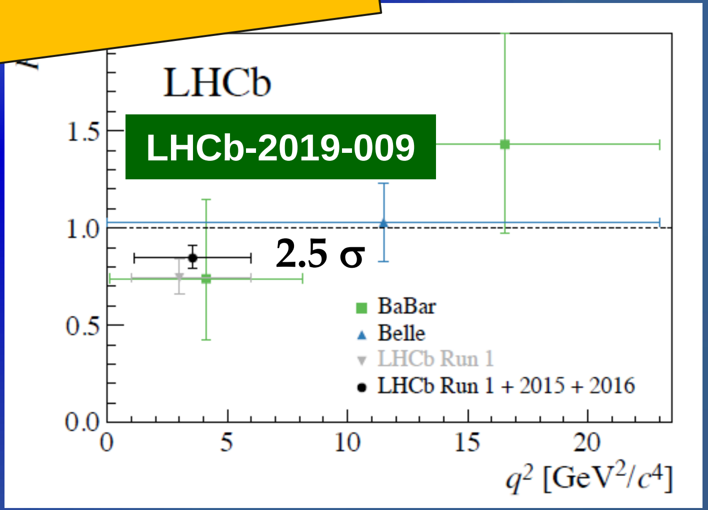
## Non-LFU H…

**leptoquar…**




…pectator quark

Caveat: uncertainties in predictions are matter of theory debate



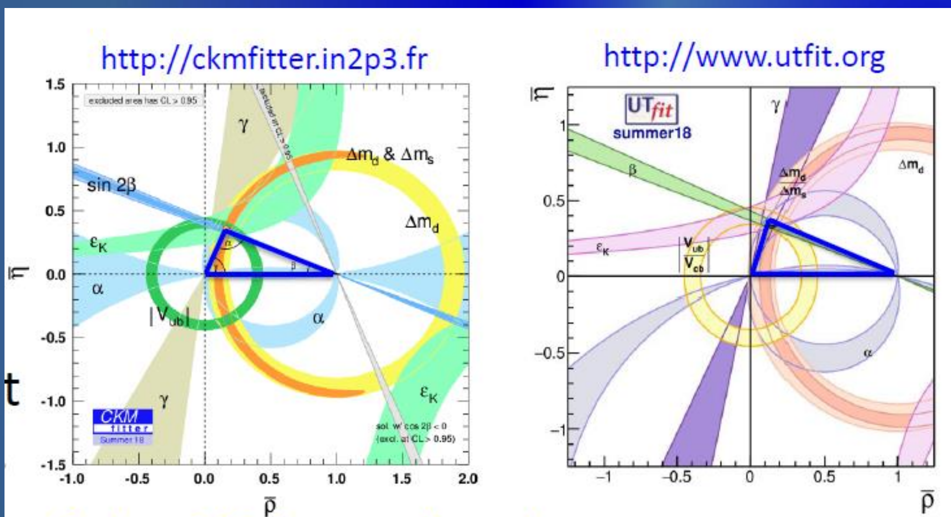

- Recent Belle's and LHCb's results significantly improve the precision, but don't really yield a clearer picture…
- With the beginning of Belle II data taking, and LHCb upgraded detector starting data taking in 2021, we can expect the flavour anomalies to soon be understood.

# The CKM Unitarity Triangle and New Physics

## NP Flavor Problem:

- Most TeV-scales new physics contain new **sources of CP and flavor violation**
- The observed baryon asymmetry of the Universe **requires CPV beyond the SM** (neither necessarily in flavor changing processes, nor necessarily in quark sector)

## *Tremendous success of the CKM paradigm:*

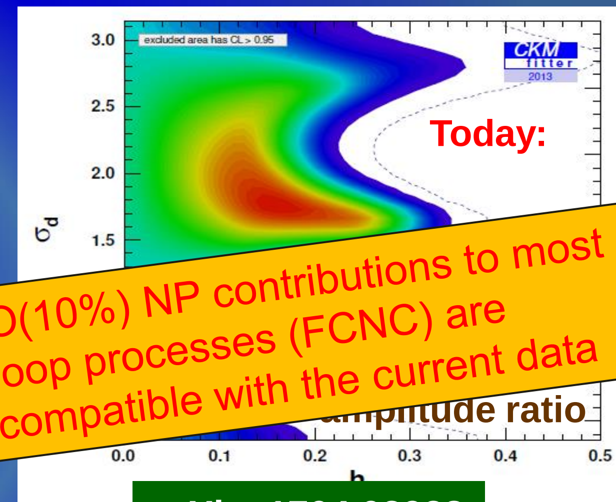



**Crucial for improving sensitivity to BSM → compare tree vs. loop measurements → e.g. $\gamma$ and $|V_{ub}|$ (statistics limited with any currently imagined dataset/experiment)**

**Need experimental precision and theoretical cleanliness to increase NP sensitivity**

$$\frac{(\text{LHCb upgrade})}{(\text{LHCb } 1\,\text{fb}^{-1})} \sim \frac{(\text{Belle II data set})}{(\text{Belle data set})} \sim \frac{(\text{2009 BaBar data set})}{(\text{1999 CLEO data set})} \sim 50$$

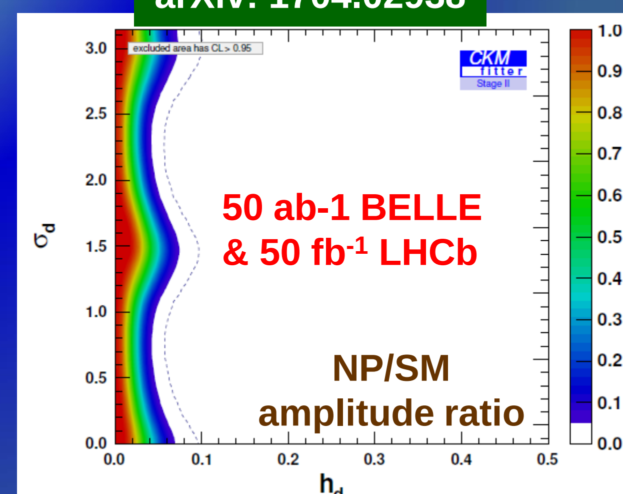
NP Phase



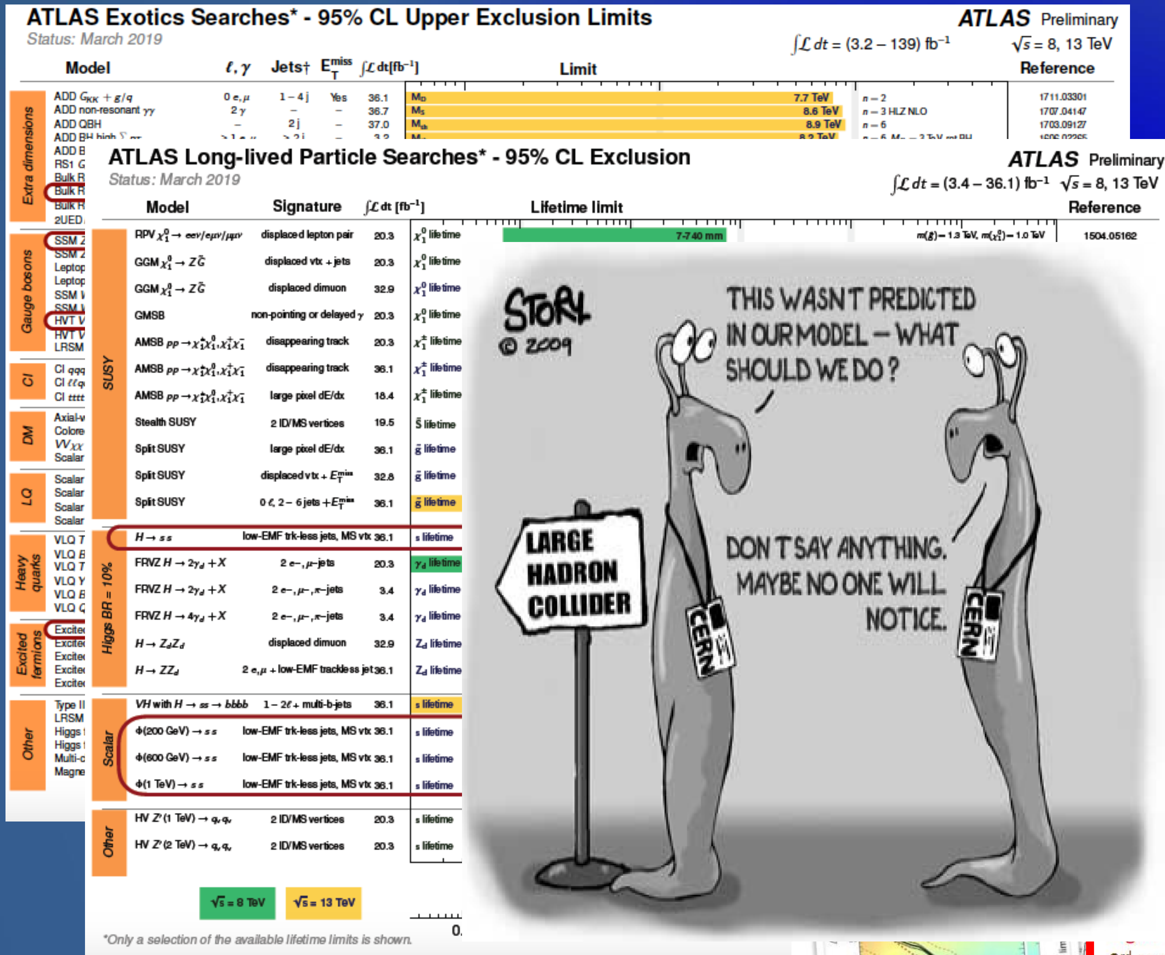

**O(10%) NP contributions to most loop processes (FCNC) are compatible with the current data**

**arXiv: 1704.02938**

NP Phase

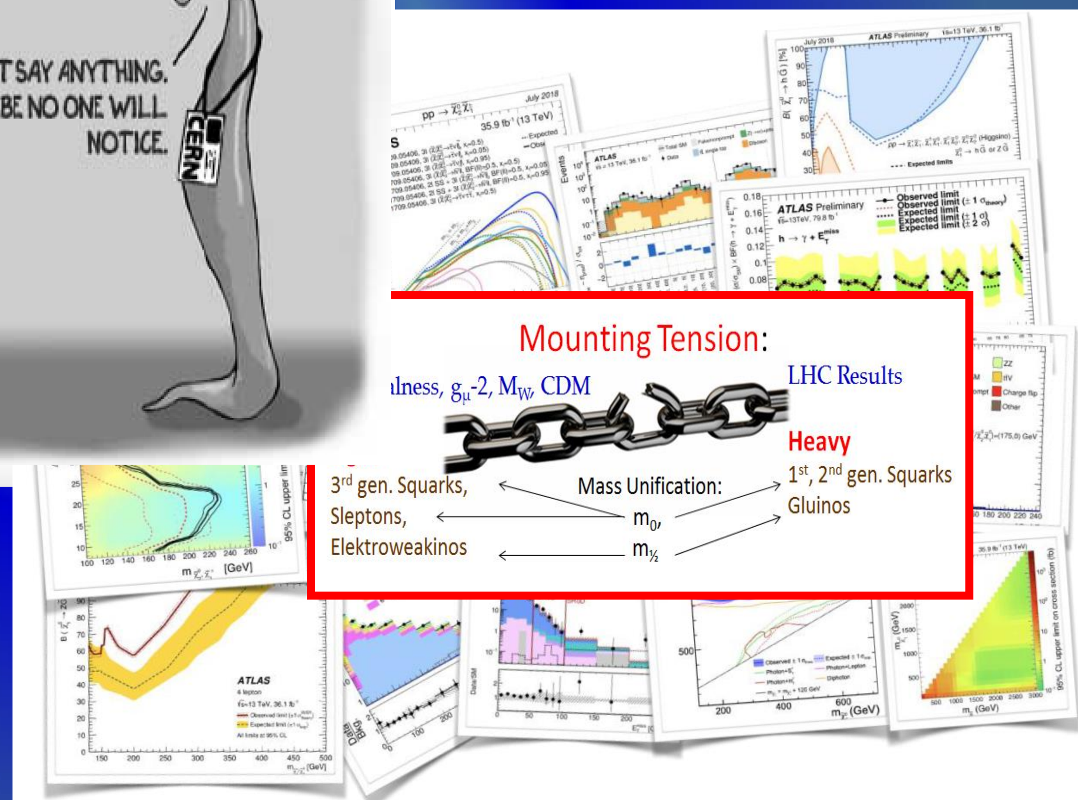


# Direct Searches for the BSM Physics




## *NO EVIDENCE …*

- Yet hierarchy problem remains
- Universe could be fine-tuned
- Or we need a new paradigm
  → widening the horizon "which SUSY" (e.g. CMSSM,PMSSM,)

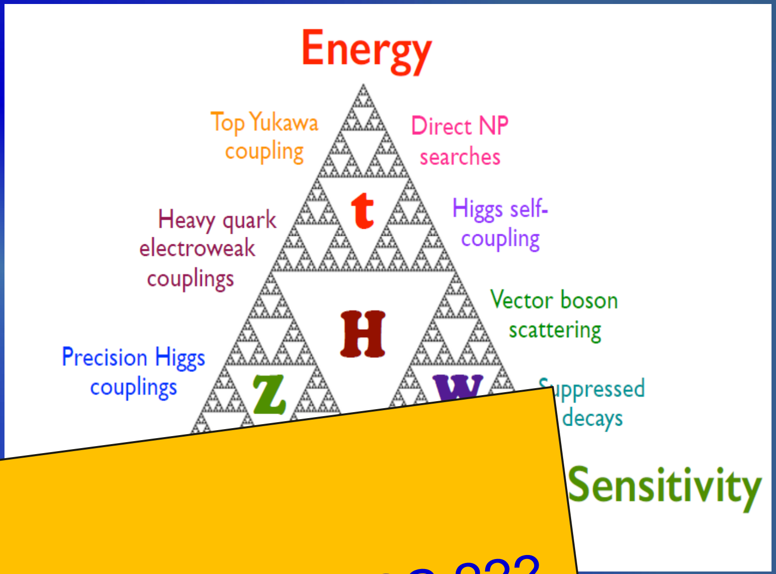



- New particles may have complex signatures (SUSY hiding in some unexplored corner ?)

→ Room for discovery with sophisticated analyses / at future upgrades, colliders

# Four Main Results from LHC Up-to-Now:

❖ **We have consolidated the Standard Model**
(wealth of measurements at 8 / 14 TeV, including flavor physics, rare $B_s \rightarrow \mu\mu$ decay, very sensitive to New Physics)
→ it works BEAUTIFULLY …




2) **We have completed the Standard Model**:
Discovery of the messenger of the BEH fi…
→ the Higgs boson di…

Where is “Everybody” ?

AT HIGHER MASSES ??? – OR AT SMALLER COUPLINGS ???

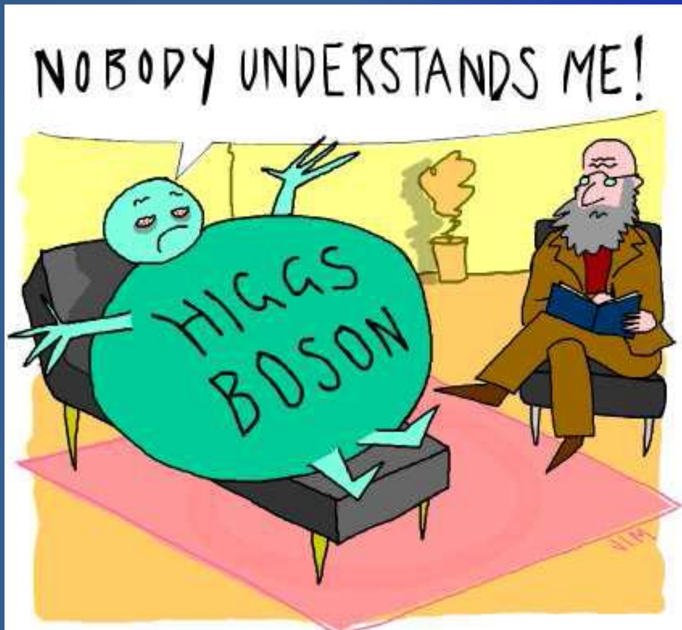
3) W… the hot dense matter

4) We have no evidence of new physics (YET), beyond the Standard Model – it may remain valid up to very high energies

***→ No argument yet for a particular energy scale beyond the SM***

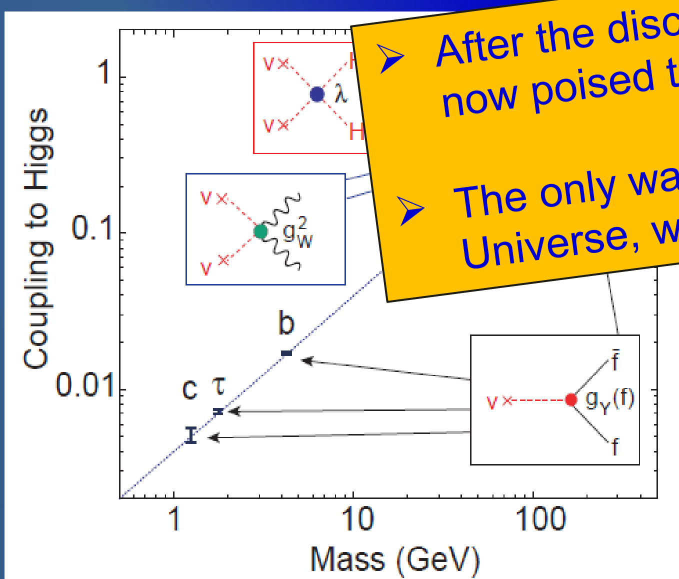
# Is this the End … What’s Next ?

# Put the Higgs Boson Under a Magnifying Glass



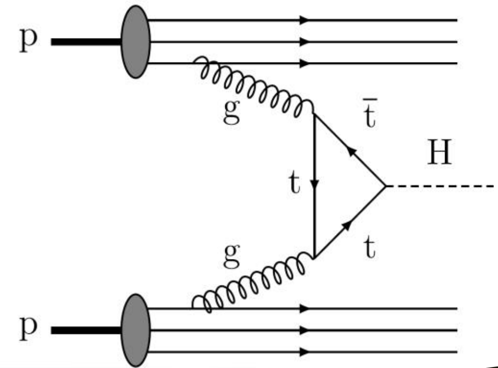

***Higgs boson is the only fundamental scalar particle ever discovered:***

- **Is the Higgs elementary particle or composite?**
- **Is there a single Higgs or more than one Higgs?**
- **Additional sources of CP violati... ...gs sector?**
- **...ector**
- **...neutrino masses?**
- **Does the Higgs couple to Dark Matter?**
- **How is the Higgs mass protected from physics at high scales ("Naturalness problem")**
  **→ Is $m_H$ stabilized by ~TeV scale new physics or is it fine-tuned ?**




- After the discovery of the Higgs Boson fundamental physics is now poised to ask the big, structural questions
- The only way we can hope to understand the origin of the Universe, we live in, is to measure every facet of the Higgs

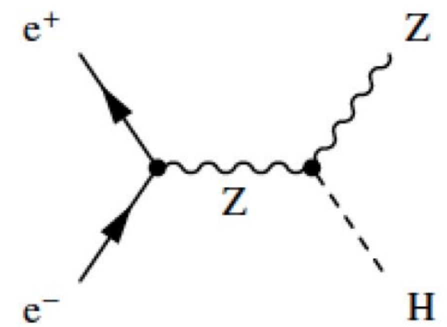
# What's Next? - "Road Beyond the Standard Model"




*At the Energy Frontier:*

*through synergy of:*

- ➢ hadron - hadron colliders
- ➢ lepton - hadron colliders
- ➢ lepton - l… …rs





- ➢ Ambitious Scope
- ➢ **High Costs**
- ➢ Long R&D Times

→ **Global Projects (Politics!)**

| Proton-prot… | …on-positron collisions |
|---|---|
| Proton is compound obj…<br>→ Initial state not known event-by-event<br>→ Limits achievable precision | $e^+/e^-$ are point-like<br>→ Initial state well defined ($\sqrt{s}$ / polarization)<br>→ High-precision measurements |
| High-Energy Circular Colliders feasible | High Energy ($\sqrt{s} > 350$ GeV) requires Linear Colliders (avoid synchrotron radiation) |
| High rates of QCD backgrounds<br>→ Complex triggering schemes<br>→ High levels of radiation | Clean experimental environment<br>→ Trigger-less readout<br>→ Low radiation levels |
| High cross-sections for colored-states | Superior sensitivity for electro-weak states |

# Future Circular Collider (FCC)

| | $\sqrt{s}$ | L /IP ($cm^{-2} s^{-1}$) | Int. L /IP($ab^{-1}$) | Comments |
|---|---|---|---|---|
| $e^+e^-$ FCC-ee | ~90 GeV Z<br>160 WW<br>240 H<br>~365 top | 230 x$10^{34}$<br>28<br>8.5<br>1.5 | 75 $ab^{-1}$<br>5<br>2.5<br>0.8 | 2 experiments<br>Total ~ 15 years of operation |
| pp FCC-hh | 100 TeV | 5 x $10^{34}$<br>30 | 2.5 $ab^{-1}$<br>15 | 2+2 experiments<br>Total ~ 25 years of operation |
| PbPb FCC-hh | $\sqrt{s_{NN}}$ = 39TeV | 3 x $10^{29}$ | 100 $nb^{-1}$/run | [illegible] |
| ep [illegible] | [illegible] | [illegible] | [illegible] | [illegible] GeV e- from ERL<br>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<br>Concurrent operation with PbPb |

**CERN is seeking for its post-LHC future via a new collider**


F. Gianotti, 15/01/2019

**FCC Study: 4-volume CDR released on 15 Jan. 2019**

**Also studied:**
**HE-LHC: $\sqrt{s}$=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6x$10^{35}$ → 15 $ab^{-1}$ for 20 years operation**

## Sequential implementation, FCC-ee followed by FCC-hh, would enable:

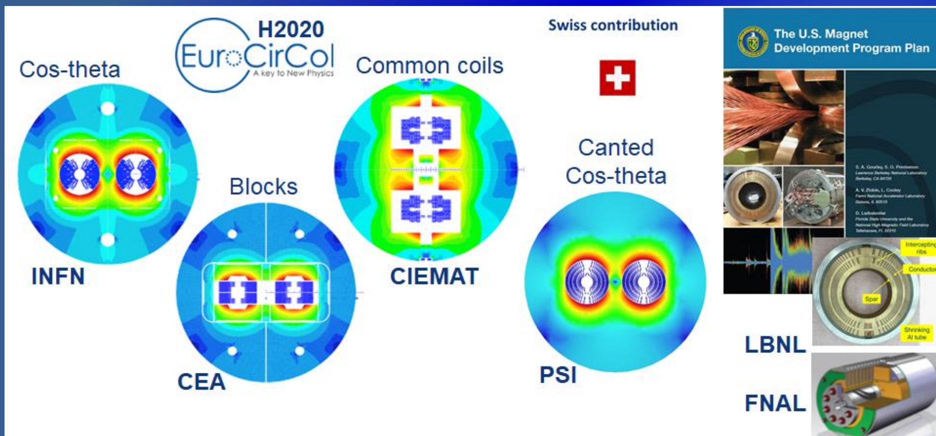
- variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV!)
- building stepwise at each stage on existing accelerator complex and technical infrastructure

**Purely technical schedule**
assuming green light to preparation work in 2020
**A 70 years programme**

| | | | | |
|---|---|---|---|---|
| 8 years preparation | 10 years tunnel and FCC-ee construction | **15 years FCC-ee operation** | 11 years FCC-hh preparation and installation | **25 years FCC-hh operation pp/PbPb/eh** |
| 2020-2028 | | **2038-2053** | | **2064-2090** |

# Accelerator Magnet Technologies: International Collaboration

❖ **Need 16 T** (14.3 m long dipoles) to reach 50 TeV /beam
- move from NbTi (LHC technology) to $Nb_3Sn$
→ $Nb_3Sn$ international R&D programme
→ Several EU countries and US LARP & its successor




- **Magnet is key cost driver** (improve cable performance, reduce cable cost, improve fabrication of magnet, ...)
- **Training quench is still a critical issue →** can we improve training of Nb3Sn magnets ?
- How do we manage the forces and stresses in a 16T accelerator magnet ?
- Can we improve the manufacturing processes ?

**China:** starting the development of HTS high-field magnets (may increase field to 20T) for SppC

Full-size successful (5.5 m)
11 T dipole prototypes
(also 5.5m long coil at $B_c$ > 12 T):

# FCC-hh Collider Parameters & Detector Challenges

| 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 | | 1.27 | 1.1 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 | 2.5 | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 | 25 | 25 | 25 |
| synchr. rad. power / ring [kW] | 2400 | | 101 | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 4.1 | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 1.8 | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.45 | 0.15 (min.) | 0.55 |
| normalized emittance [µm] | 2.2 | | 2.5 | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | 16 | 5 (lev.) | 1 |
| events/bunch crossing | 170 | 1000 | 460 | 132 | 27 |
| stored energy/beam [GJ] | 8.4 | | 1.4 | 0.7 | 0.36 |

HL-LHC and FCC-hh have simiar number of interactions per BX

- **Vertex / Tracker:** neutron fluxes – first layer (2.5 cm ): ~5-6 $10^{17}$ $cm^{-2}$; external part: ~5 $10^{15}$ $cm^{-2}$
- **Barrel ECAL, Endcap ECAL/HCAL, Forward ECAL/HCAL**: LAr technology - intrinsically radiation hard (Silicon ECAL and ideas for digital ECAL with MAPS are also discussed)
- HL-LHC Muon gas detector technology **will work for most of FCC areas → opportunity for MPGDs?**

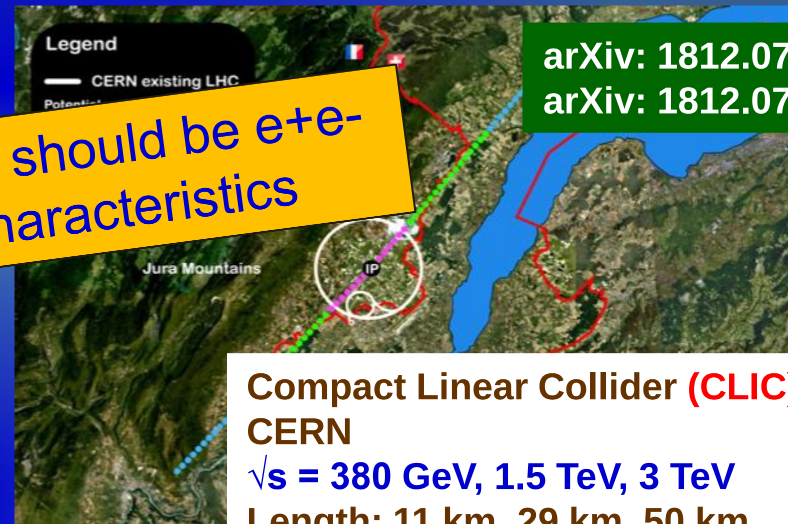
# Future Electron-Positron Colliders: " Higgs Factory"

## Linear colliders: *ILC, CLIC* (technical extendability to TeV regime)

arXiv: 1901.09829
arXiv: 1901.09825

General consensus: next "big machine" should be e+e- collider to scrutinize Higgs boson characteristics

**International Linear Collider (ILC):**
**Japan (Kitakami)**
**$\sqrt{s}$ = 250 - 500 GeV, 1 TeV**
**Length: 21 km - 31 km (50 km)**




arXiv: 1812.07987
arXiv: 1812.07986

**Compact Linear Collider (CLIC):**
**CERN**
**$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV**
**Length: 11 km, 29 km, 50 km**

## Circular colliders: *CEPC, FCC-ee*


arXiv: 1901.03169
arXiv: 1901.03170

**Circular Electron-Positron Collider (CEPC):**
**China**
**$\sqrt{s}$ = 90 - 240 GeV**
**Circumference: 100 km**


http://fcc-cdr.web.cern.ch/

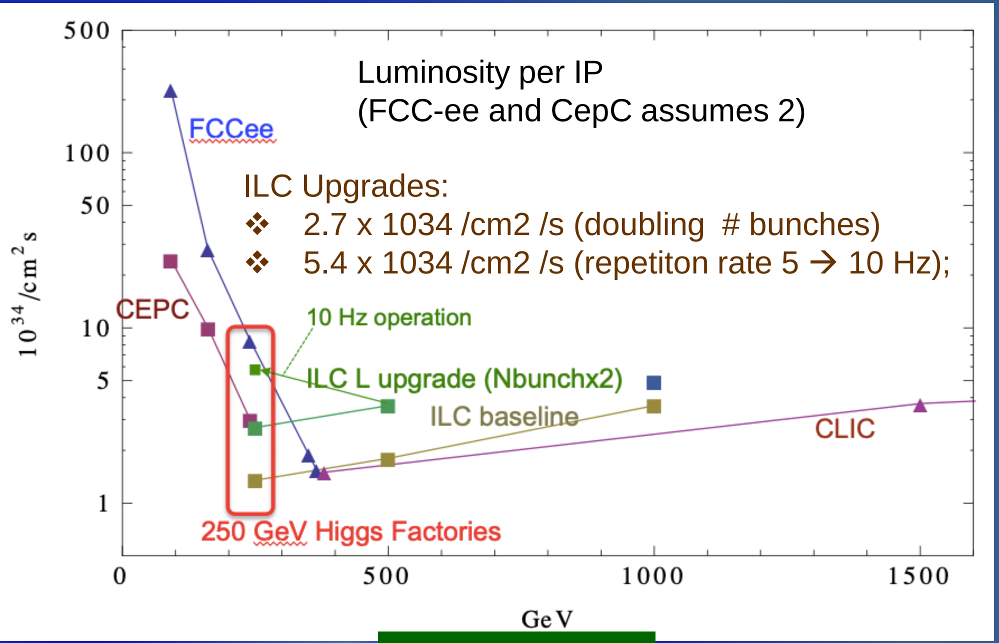
**Future Circular Collider (FCC-ee):**
**CERN**
**$\sqrt{s}$ = 90 - 350 GeV**
**Circumference: ~100 km**

# Storage Rings or Linear Collides for Future e+e- Accelerator

- ❖ **Energy tends to be the cost driver:**
  → hadrons - high-field magnets;
  → e+e- - high-gradient RF

**Circular collider:**
→ high-luminosity from Z peak to top threshold

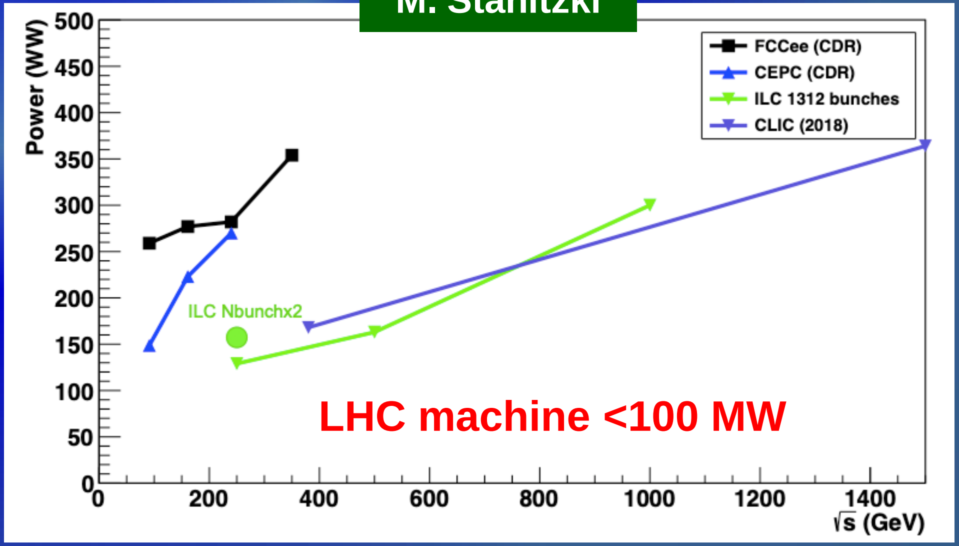
**Linear colliders:**
→ extendability to high energies and beam polarization




**H.Yamamoto, M. Stanitzki**

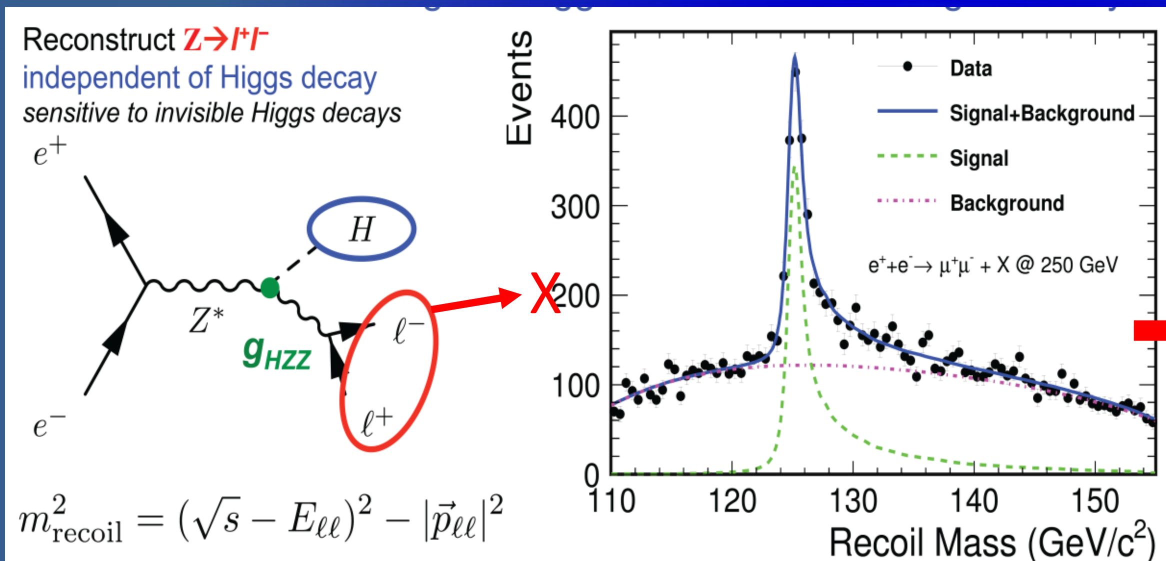
- ❖ **$\mathcal{L} \times E_{CM}$ drives the MWatts (at least for leptons):**
  **→ it's all about COST per GeV | inv fb**

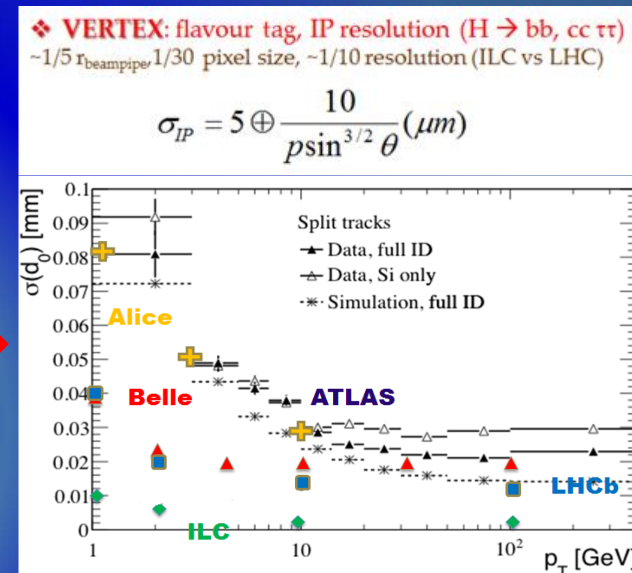
- ➢ Where are the acceptable limits? (not the technical limits)
- ➢ High running costs may need to be shared (global project)
- ➢ R&D needed in increasing efficiencies and/or recovering the energy



# Higgs “Golden Channel” at 250 GeV e+e- Collider

**Recoil mass measurement: detecting the Higgs boson *without using its decay !***




❖ This method yields absolute measurements of all σ(ZH) x BR and model-independent determination of the total Higgs width / cross section (e.g. invisible Higgs, H → cc, modes undetectable at LHC) and Higgs couplings

❖ This would be a boon to entire Higgs effort, as it feeds into hadron-collider Higgs measurements to break redundancies and maximise impact
→ Large quantitative and qualitative improvement over the HL-LHC

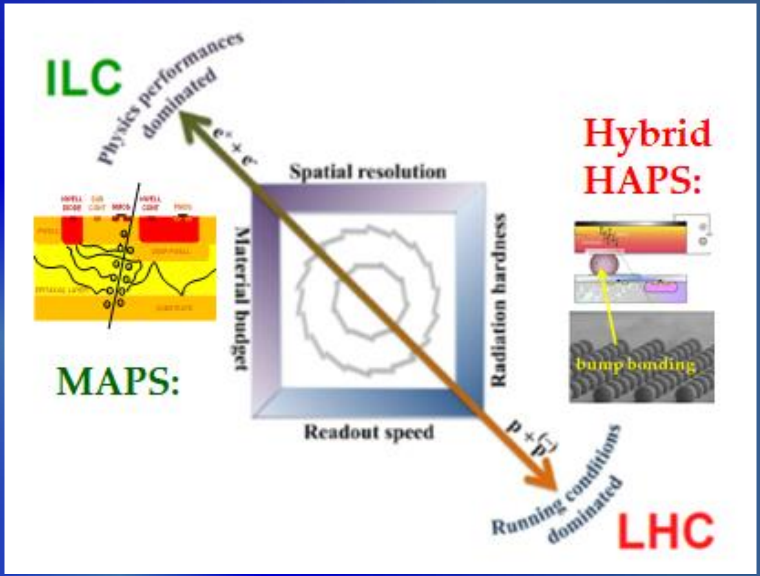
# Si-Vertex and Tracking Detectors in HEP: State-of-the-Art

Low mass, pixelated, radiation hard vertex detectors are needed for the LHC ILC, CLIC, FCC, B-factories, …:

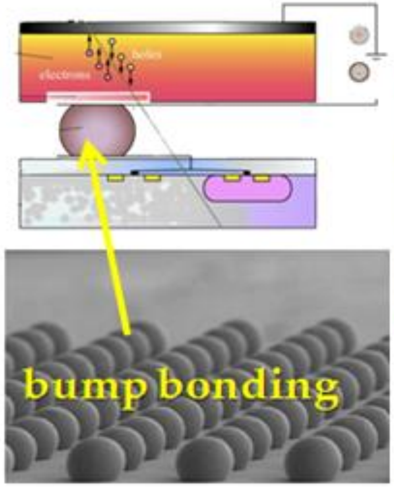
→ Going to smaller node sizes (65nm) does not necessarily guarantee radiation hardness improvement

→ The impact of "digital" is still very small in HEP, replace "quantity" of data with "quality" of data

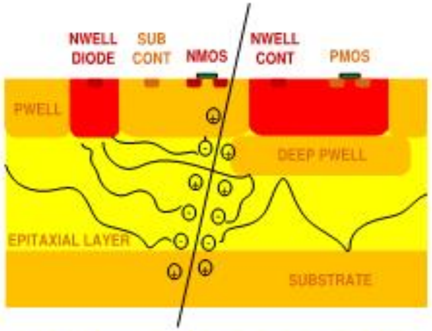
→ More exotic technologies (TSVs, wafer stacking, adv. packaging...) may become available also for low-volume, but history teaches one should bet on mainstream opportunities




**Hybrid:**
50 – 100s μm

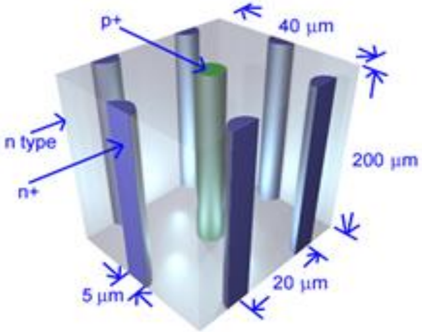



**Monolithic (CMOS-MAPS): 25 – 50 μm**



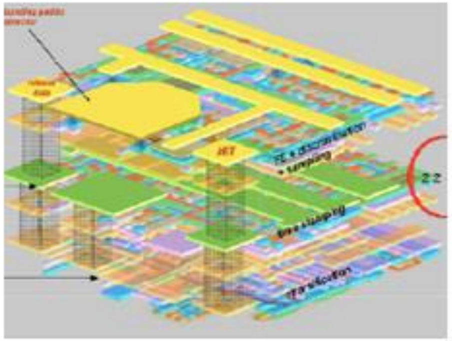

Integrated sensor & electronics: Less X0, no bonding, low noise

**3D-Detectors**
25–50 μm




Lower $V_{dep}$ (power)
Faster charge collection

**3D TSV:**
< 20 μm



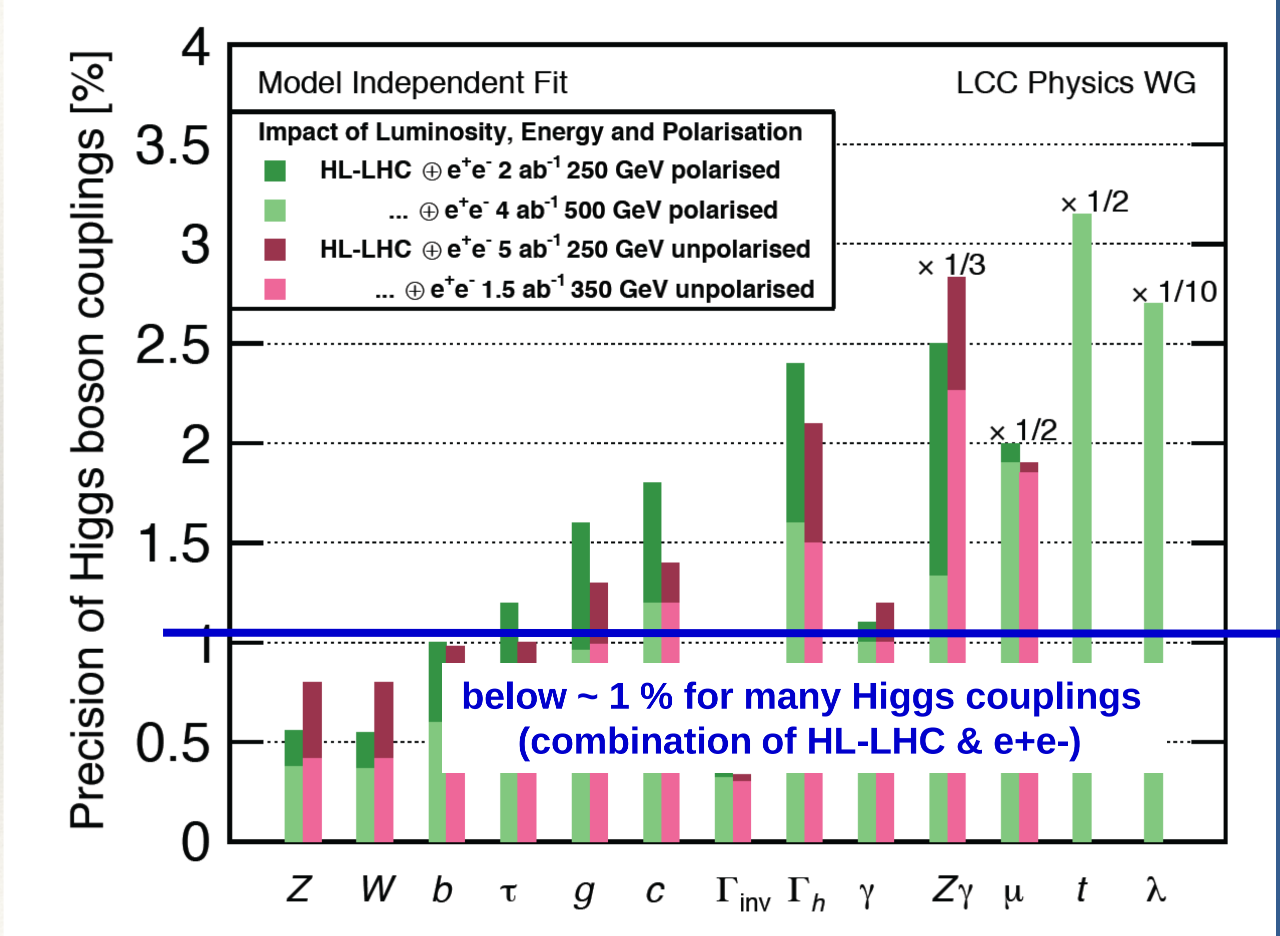
3D vertical Integration (TSV)

# Linear vs Circular Colliders: Impact of Beam Polarization

**Beam polarization is a powerfull tool:**

- Measurement of helicity-dependent electroweak couplings; determine quantum numbers of new particles
- Suppression of backgrounds / enhancement of signals;
- Control of systematic uncertainties;
- Increased sensitivity relative to unpolarized collisions;

arXiv: 1903.01629

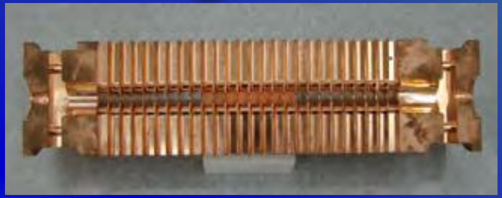



**For Higgs coupling measurements, polarization compensates for ILC's lower than FCC-ee 250 GeV integrated luminosity (2 vs 5 ab-1) by:**

1) Increased rates
2) Removing some correlations between different EFT operators

# ILC vs CLIC: Superconducting vs Normal RF

ILC:



CLIC:

**ILC:**

- **Higher Power Efficiency (31-35 MV/m)**
- Lower RF Frequency (1.3 GHz)

→ relaxed tolerances & smaller emittance dilution

- High-Q ($Q_0$ =$10^{10}$):
- Larger aperture / better beam quality
- **Long beam pulses (~ 1 ms or CW)**
- Cryogenics

**CLIC:**

- **Higher Gradient (70-100 MV/m)**
- Higher RF Frequency (12 GHz):

  → more accuracy required
- Ordinal-$Q_0$
- Smaller aperture / better accuracy
- **Short beam pulses (μs pulse)**
- Water cooling

ILC250 Higgs Factory

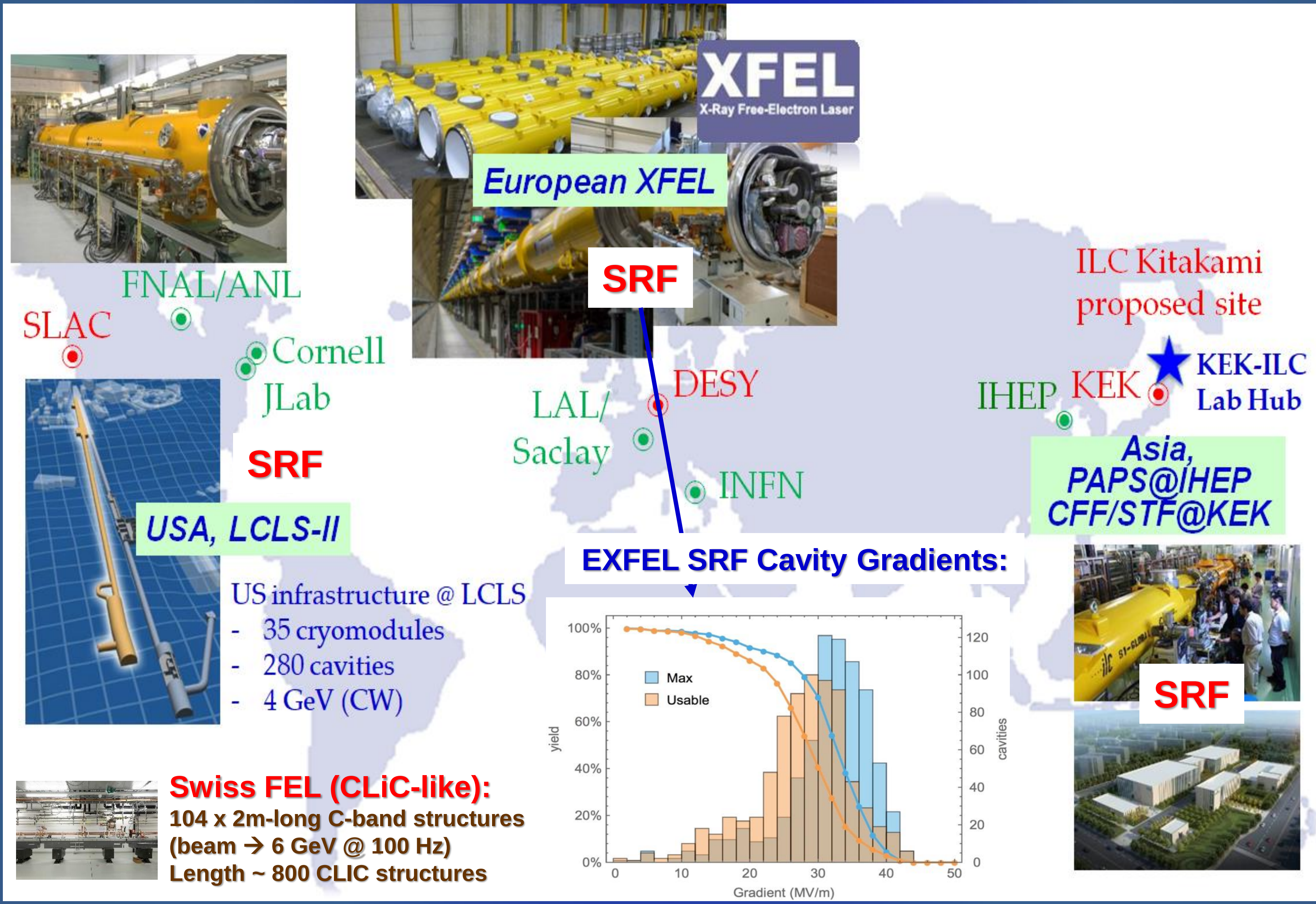
| Quantity | Symbol | Unit | Initial | $\mathcal{L}$ Upgrade | TDR | Upgrades | |
|---|---|---|---|---|---|---|---|
| Centre of mass energy | $\sqrt{s}$ | GeV | 250 | 250 | 250 | 500 | 1000 |
| Luminosity | $\mathcal{L}$ | $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 1.35 | 2.7 | 0.82 | 1.8/3.6 | 4.9 |
| Polarisation for $e^-(e^+)$ | $P_-(P_+)$ | | 80 % (30 %) | 80 % (30 %) | 80 % (30 %) | 80 % (30 %) | 80 % (20 %) |
| Repetition frequency | $f_{\mathrm{rep}}$ | Hz | 5 | 5 | 5 | 5 | 4 |
| Bunches per pulse | $n_{\mathrm{bunch}}$ | 1 | 1312 | 2625 | 1312 | 1312/2625 | 2450 |
| Bunch population | $N_{\mathrm{e}}$ | $10^{10}$ | 2 | 2 | 2 | 2 | 1.74 |
| Linac bunch interval | $\Delta t_{\mathrm{b}}$ | ns | 554 | 366 | 554 | 554/366 | 366 |
| Beam current in pulse | $I_{\mathrm{pulse}}$ | mA | 5.8 | 5.8 | 8.8 | 5.8 | 7.6 |
| Beam pulse duration | $t_{\mathrm{pulse}}$ | μs | 727 | 961 | 727 | 727/961 | 897 |
| Average beam power | $P_{\mathrm{ave}}$ | MW | 5.3 | 10.5 | 10.5 | 10.5/21 | 27.2 |
| Norm. hor. emitt. at IP | $\gamma\epsilon_{\mathrm{x}}$ | μm | 5 | 5 | 10 | 10 | 10 |
| Norm. vert. emitt. at IP | $\gamma\epsilon_{\mathrm{y}}$ | nm | 35 | 35 | 35 | 35 | 30 |
| RMS hor. beam size at IP | $\sigma^*_{\mathrm{x}}$ | nm | 516 | 516 | 729 | 474 | 335 |
| RMS vert. beam size at IP | $\sigma^*_{\mathrm{y}}$ | nm | 7.7 | 7.7 | 7.7 | 5.9 | 2.7 |
| Luminosity in top 1 % | $\mathcal{L}_{0.01}/\mathcal{L}$ | | 73 % | 73 % | 87.1 % | 58.3 % | 44.5 % |
| Energy loss from beamstrahlung | $\delta_{\mathrm{BS}}$ | | 2.6 % | 2.6 % | 0.97 % | 4.5 % | 10.5 % |
| Site AC power | $P_{\mathrm{site}}$ | MW | 129 | | 122 | 163 | 300 |
| Site length | $L_{\mathrm{site}}$ | km | 20.5 | 20.5 | 31 | 31 | 40 |

| Parameter | Symbol | Unit | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|---|---|
| Centre-of-mass energy | $\sqrt{s}$ | GeV | 380 | 1500 | 3000 |
| Repetition frequency | $f_{\mathrm{rep}}$ | Hz | 50 | 50 | 50 |
| Number of bunches per train | $n_b$ | | 352 | 312 | 312 |
| Bunch separation | $\Delta t$ | ns | 0.5 | 0.5 | 0.5 |
| Pulse length | $\tau_{\mathrm{RF}}$ | ns | 244 | 244 | 244 |
| Accelerating gradient | $G$ | MV/m | 72 | 72/100 | 72/100 |
| Total luminosity | $\mathscr{L}$ | $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ | 1.5 | 3.7 | 5.9 |
| Luminosity above 99% of $\sqrt{s}$ | $\mathscr{L}_{0.01}$ | $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ | 0.9 | 1.4 | 2 |
| Total integrated luminosity per year | $\mathscr{L}_{\mathrm{int}}$ | $\mathrm{fb}^{-1}$ | 180 | 444 | 708 |
| Main linac tunnel length | | km | 11.4 | 29.0 | 50.1 |
| Number of particles per bunch | $N$ | $10^9$ | 5.2 | 3.7 | 3.7 |
| Bunch length | $\sigma_z$ | μm | 70 | 44 | 44 |
| IP beam size | $\sigma_x/\sigma_y$ | nm | 149/2.9 | ~ 60/1.5 | ~ 40/1 |
| Normalised emittance (end of linac) | $\varepsilon_x/\varepsilon_y$ | nm | 900/20 | 660/20 | 660/20 |
| Final RMS energy spread | | % | 0.35 | 0.35 | 0.35 |
| Crossing angle (at IP) | | mrad | 16.5 | 20 | 20 |

**The LC (ILC/CLIC)** can be pursued for construction starting-up in about 5 years

**→ aiming for operation by ~ 2030-2035**

# A World-Wide Infrastructure for Linear Colliders



# EXFEL @ DESY: an Ultimate Integrated System Test (10%) for ILC

## The currently longest super-conducting accelerator in the world


**Largest deployment of SRF technology to date:**
- **100 cryomodules**
- **800 cavities**
- **17.5 GeV (pulsed)**

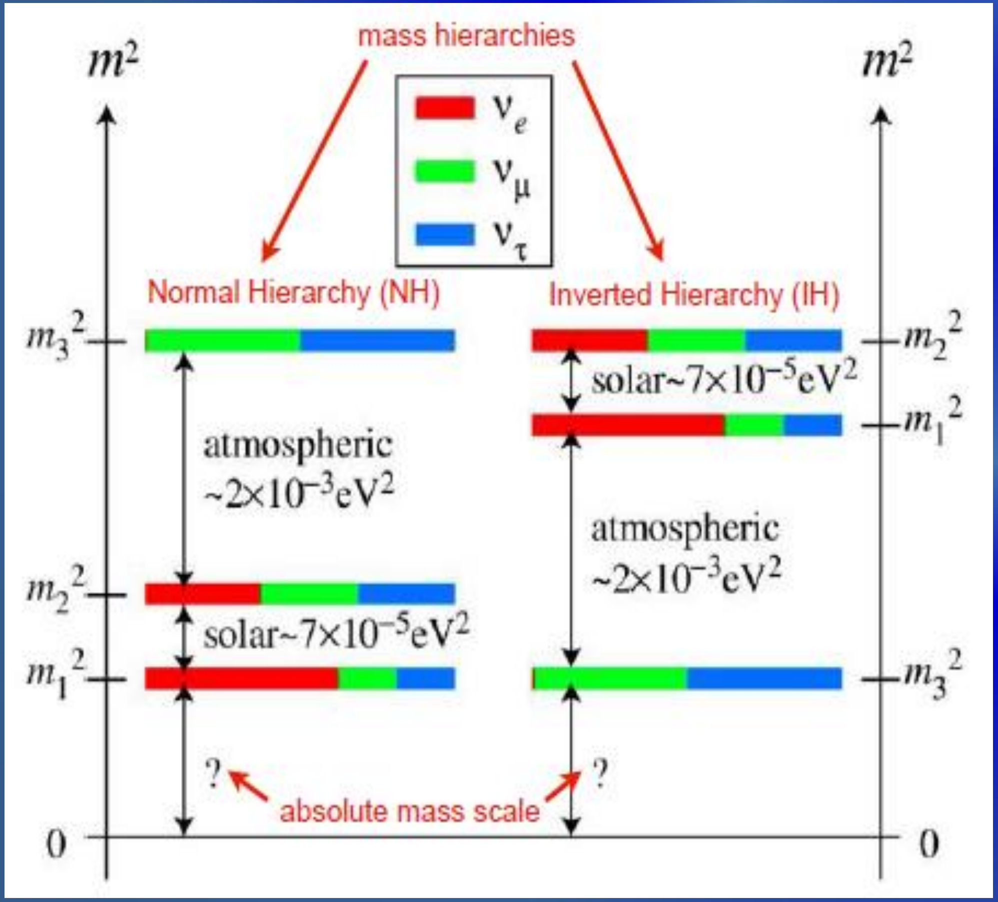
**Personal remark - ILC remains:**

➢ The most advanced of all e+e- collider projects
➢ The less expensive option for European budget (also new money for HEP)
→ an opportunity for European expertise and high-tech industry

**Acknowledging the efforts of the Tesla Technology Collaboration (TTC)**

# Neutrinos are Messengers of New Physics

- ❖ Flavour mixing & $\Delta m^2$ are well known - O(10%);
  → very different in quark and leptons
- ❖ Neutrino masses: what is the absolute scale and the hierarchy (normal or inverse) ?
- ❖ How large is CPV phase $\delta_{CP}$ ?
- ❖ Is $N\nu = 3$ or there are more (sterile) neutrinos ?
- ❖ Is neutrino Dirac of Majorana fermion ?




Do neutrino oscillations violate CP ( $\delta_{CP}$)?

→ Necessary condition for successful baryogenesis (matter-antimatter asymmetry of the universe)

CP violation requires genuine 3ν oscillations, distinct from 2ν limits...

PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*

*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation. CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar\nu_\mu \leftrightarrow \bar\nu_e$ oscillations to be equal. Time reversal invariance requires the oscillation probability to be an even function of time. Both conditions can be violated, even drastically, if more than two neutrinos exist.

- ❖ 3 mixing angles should be nonvanishing ✓
- ❖ 2 mass gaps should be nonvanishing ✓
- ❖ 1 phase should be nonvanishing

⬇

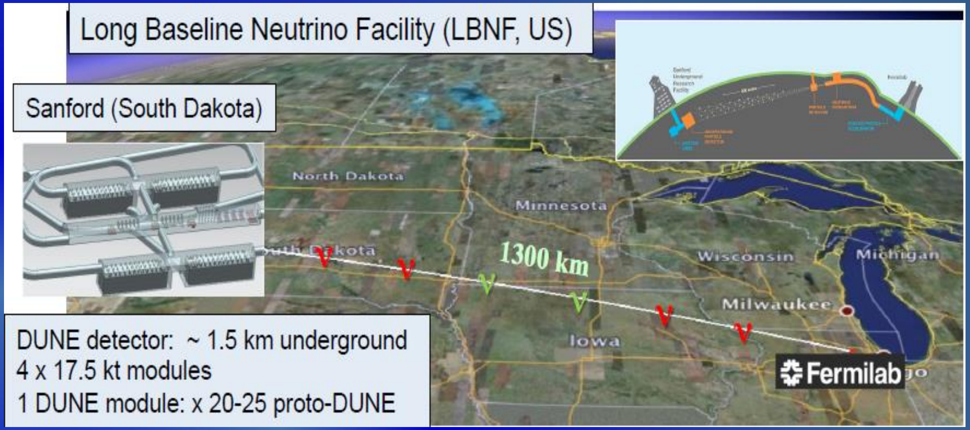
Nature has already provided us with 5 favorable conditions at terrestrial scales ...

Let us hope that the 6th is also realized !

# Long-Baseline Neutrino Oscillation Programme

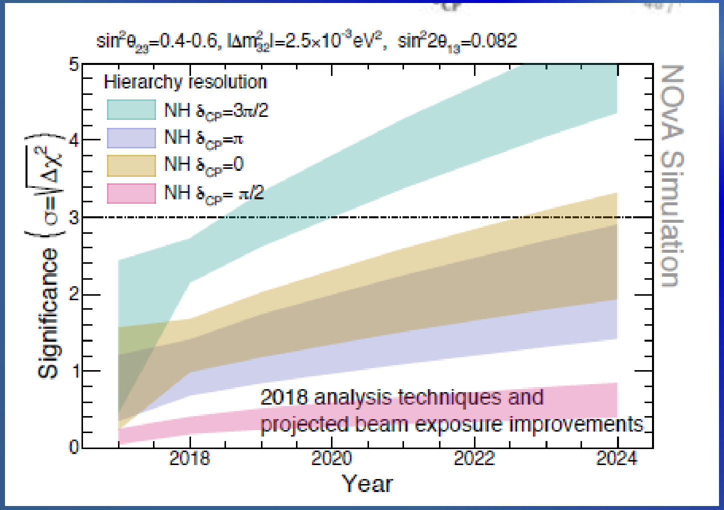
**Present / Recent:**
- Europe: OPERA, ICARUS (complete)
- Japan: T2K
- US: MINOS, MINOS+ (data analysis)
  NOvA

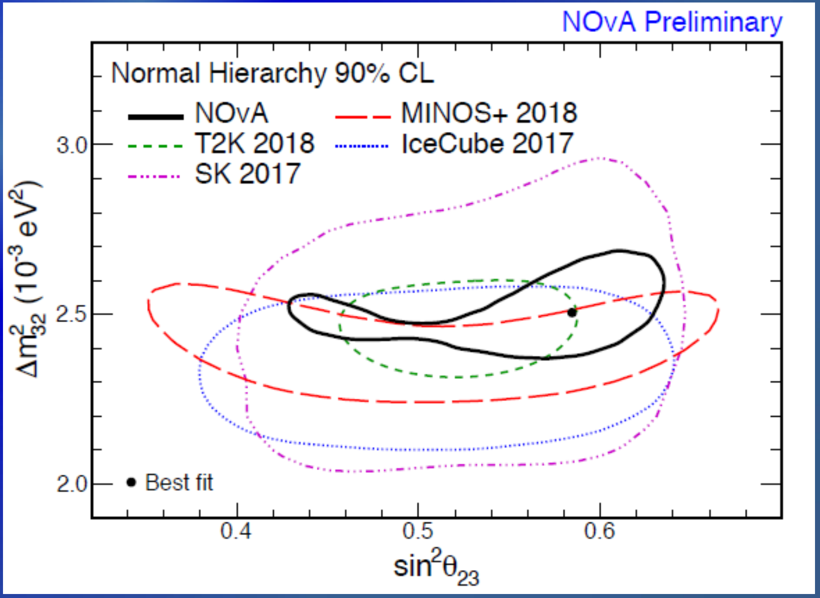
**Near Future**
- Japan: T2K, T2HK, T2HKKK
- US: DUNE



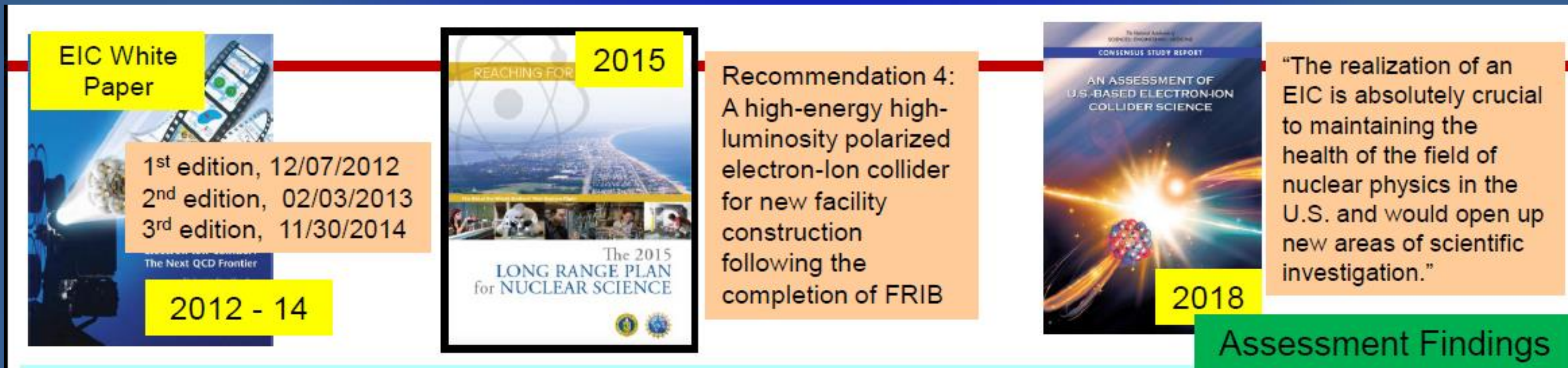

→ Both (NOvA and T2K) favor maximal mixing for neutrinos and Normal hierarchy (also slight preference by IceCube)

❖ 2 σ sensitivity to CP violation for favourable parameters by 2024
❖ Possible hierarchy determination at 3σ in 2020



# Electron – Ion Collider (EIC) in US: Milestones




***Finding 1 (Science):*** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms: How does the mass of the nucleon arise? How does the spin of the nucleon arise? What are the emergent properties of dense systems of gluons?

***Finding 2 (Accelerator):*** These three high-priority science questio… an EIC with highly polarized beams of electrons and ions, with suffi… ariable center-of-mass energy.

All proposed EIC detector concepts feature a form of large GEM tracker at forward and backward rapidities

***Finding 3:*** An EIC … ity in the world, and would maintain U.S. leadership in nuclear physics.

***Finding 4:*** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.

***Finding 5:*** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

***Finding 9:*** The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

# The European Strategy for Particle Physics

…executing the ongoing European Strategy for Particle Physics


→ Need to present and discuss new large scale projects in an international context before making choices

→ Need to present physics case(s) always taking into account latest results at existing facilities

→ Need to present (additional) benefits to society from the very beginning of the project

→ Need to have excellent communication and outreach accompanying all projects

*Energy Frontier*

- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the in… sign, by around 2030. This upgrade programme will also pro… citing opportunities for the study of flavour physics and the quan…*

**Done**

*Energy Frontier*

- 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.

*CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton an… itron high-energy frontier machines. These design studies sho… to a vigorous accelerator R&D programme, including high-… magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

**Done**

*$e^+e^-$ collider*

- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unpr… on and whose energy can be upgraded. The Technic… nternational Linear Collider (ILC) has been complete… uropean participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

*Europe looks forward to a proposal from Japan to discuss a possible participation.*

**Not yet …**

*ν-physics*

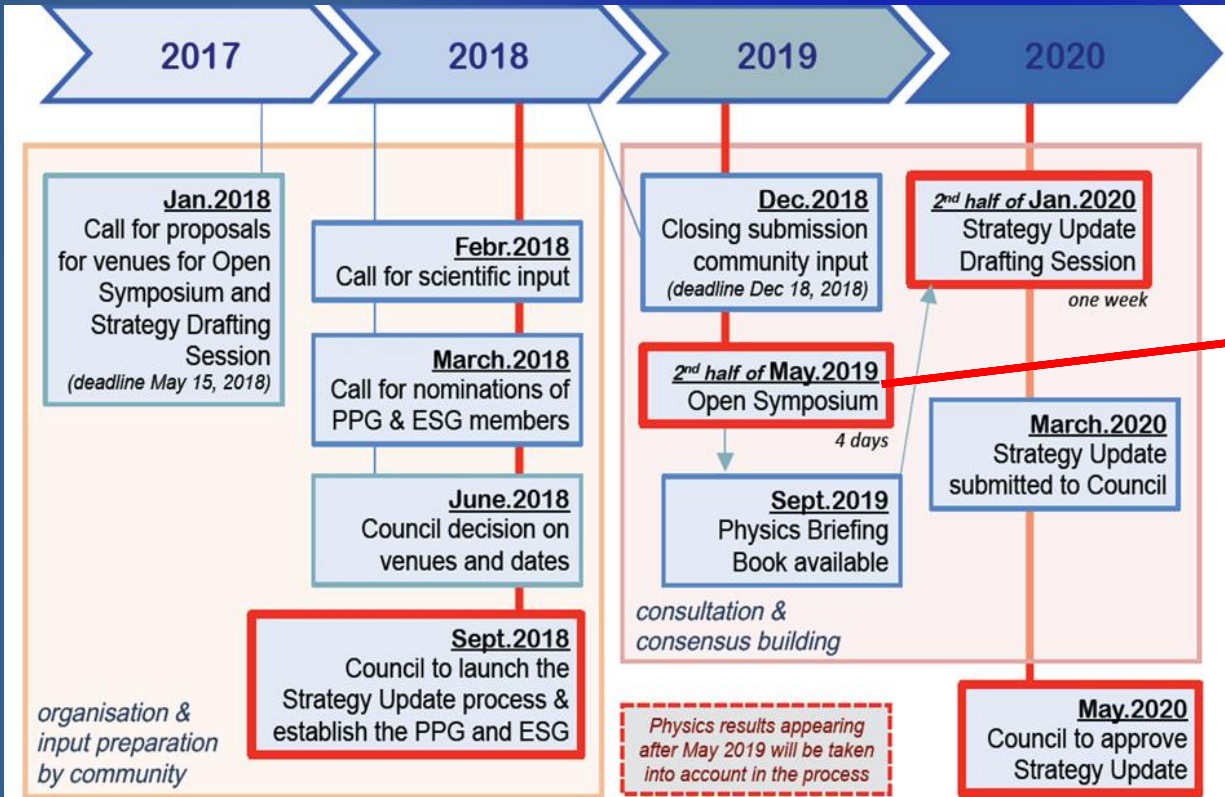
- Rapid progress in neutrino oscillation physics, with significant European involvement, has established a stro… cientific case for a long-baseline neutrino programme exp… on and the mass hierarchy in the neutrino sector. CERN sh… neutrino programme to pave the way for a substantial European role in future long-baseline experiments.

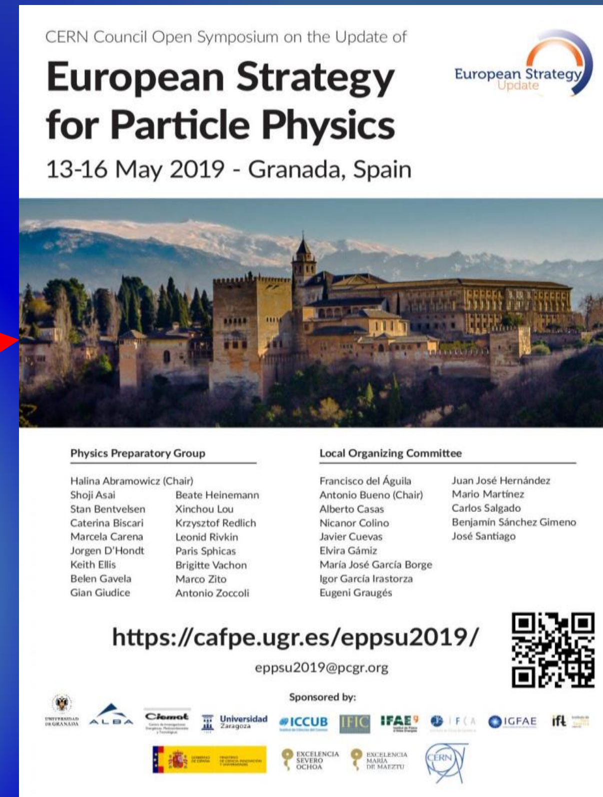
*Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

**Done**

- **Global vision for our field going beyond regional boundaries**
- **CERN is playing a major role in this global endeavour**

# Towards 2020 Update of European Strategy for Particle Physics




**ESPP Symposium:** https://indico.cern.ch/event/808335/timetable/#all.detailed

**Preparing Update of the European Strategy for Particle Physics:**

- LHC and HL-LHC Exploitation
- Next Step at the Energy Frontier (FCC / ILC / CLIC) and R&D beyond
- Accelerator-based Neutrino Programme (US & Japan) via Neutrino Platform
- Rich Diversity Physics Programme Beyond Colliders


BACK-UP SLIDES