LHC & Co.
Some opportunities for accelerator-based physics

Biennale – Tirrenia, 4-6 October 2016

Francesco Forti

INFN and University, Pisa

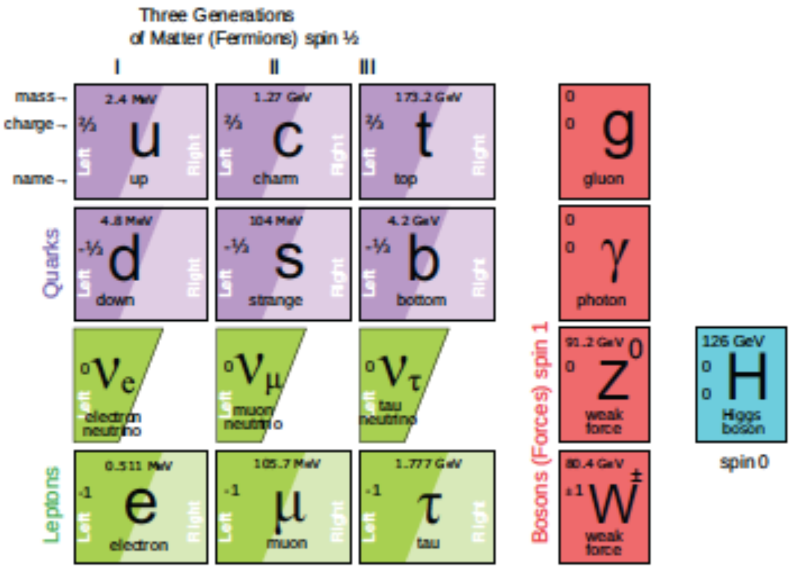
Outline

1. Mysteries of the Standard Model
2. At the energy frontier: LHC, the mountain top.
3. At the intensity frontier: SuperKEKB, the waterfall.
4. Other opportunities: CERN Beyond Colliders, FNAL Muon Campus
5. Future machines: ILC, CLIC, CEPC, FCC
6. Tool-driven scientific revolutions

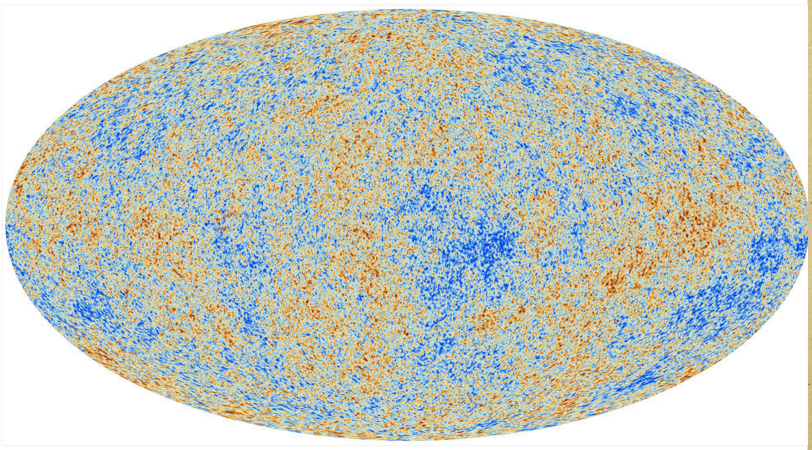
Mysteries of the Standard Model

2013: the triumph of the STANDARD

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION

$\Omega_\Lambda = 0.686 \pm 0.020$

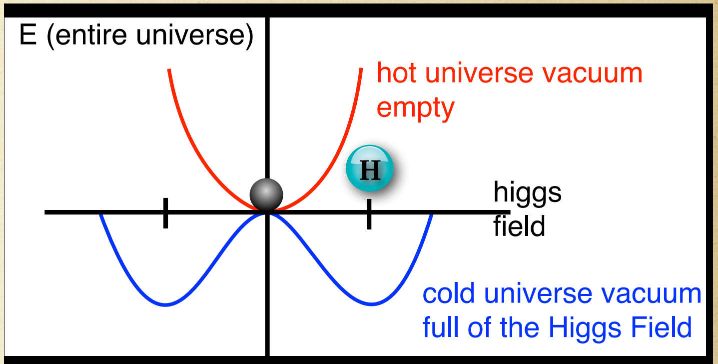
$\Omega_m = 0.314 \pm 0.020$

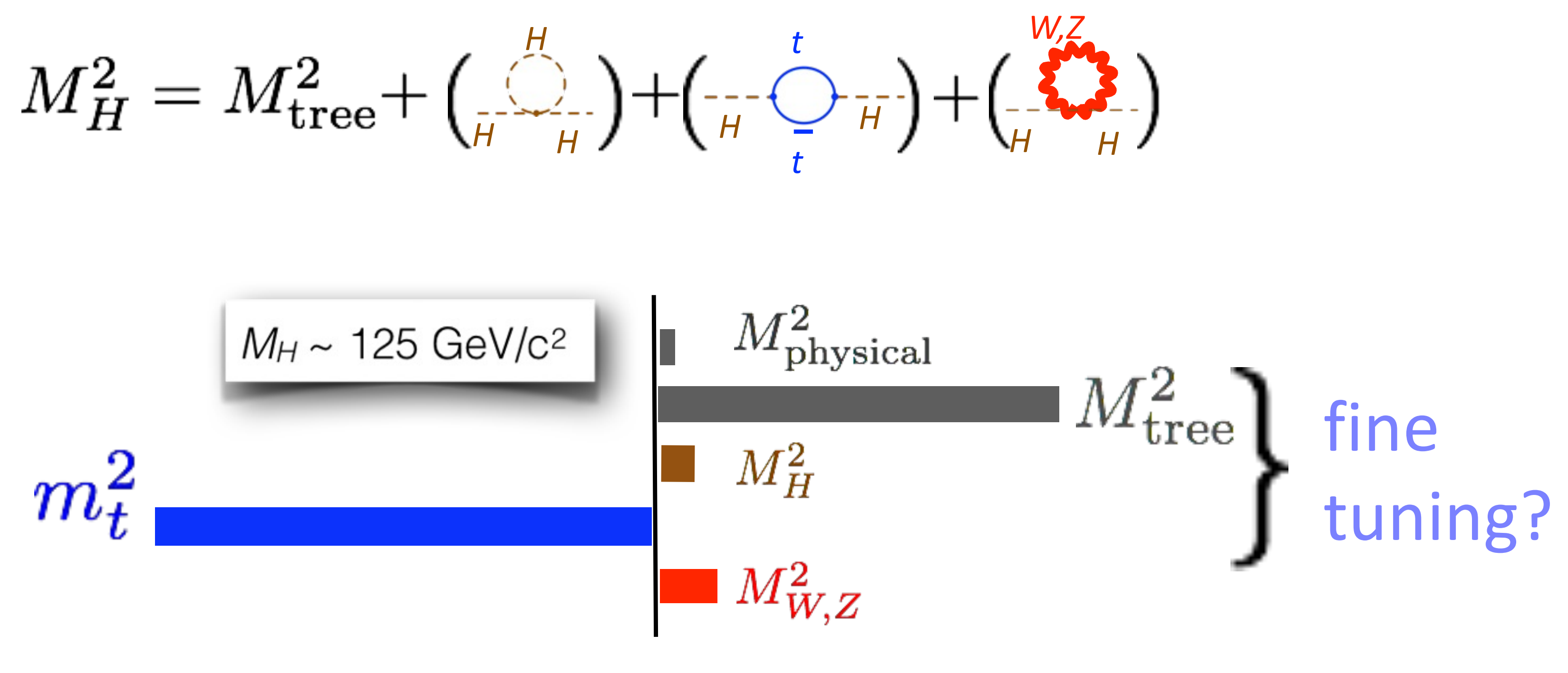
$\Omega_b h^2 = 0.02207 \pm 0.00033$

$h = 0.674 \pm 0.014$

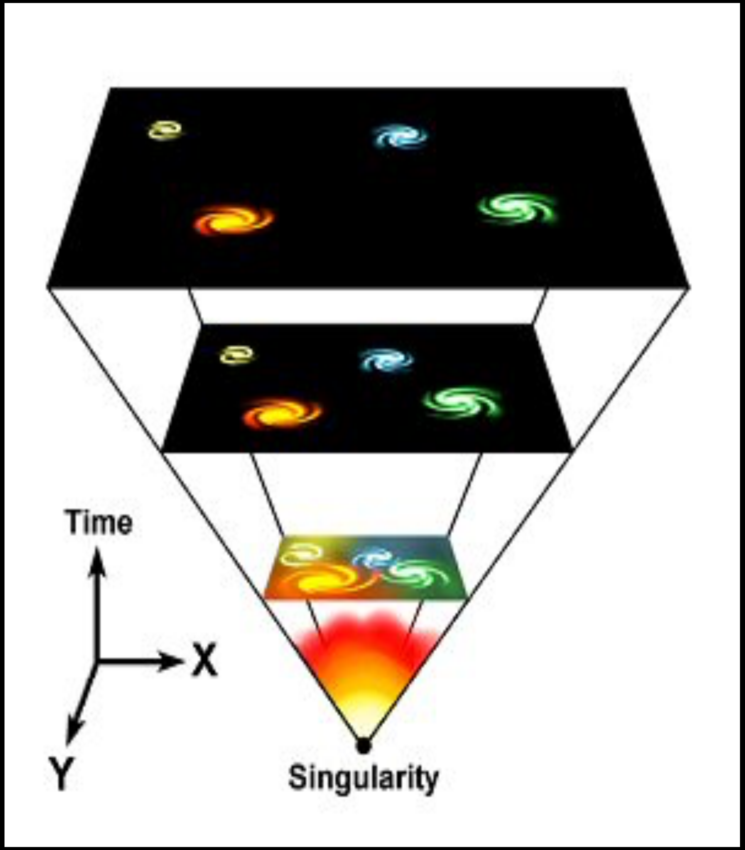
Higgs

- Why that single scalar ?
- Why that mass ?





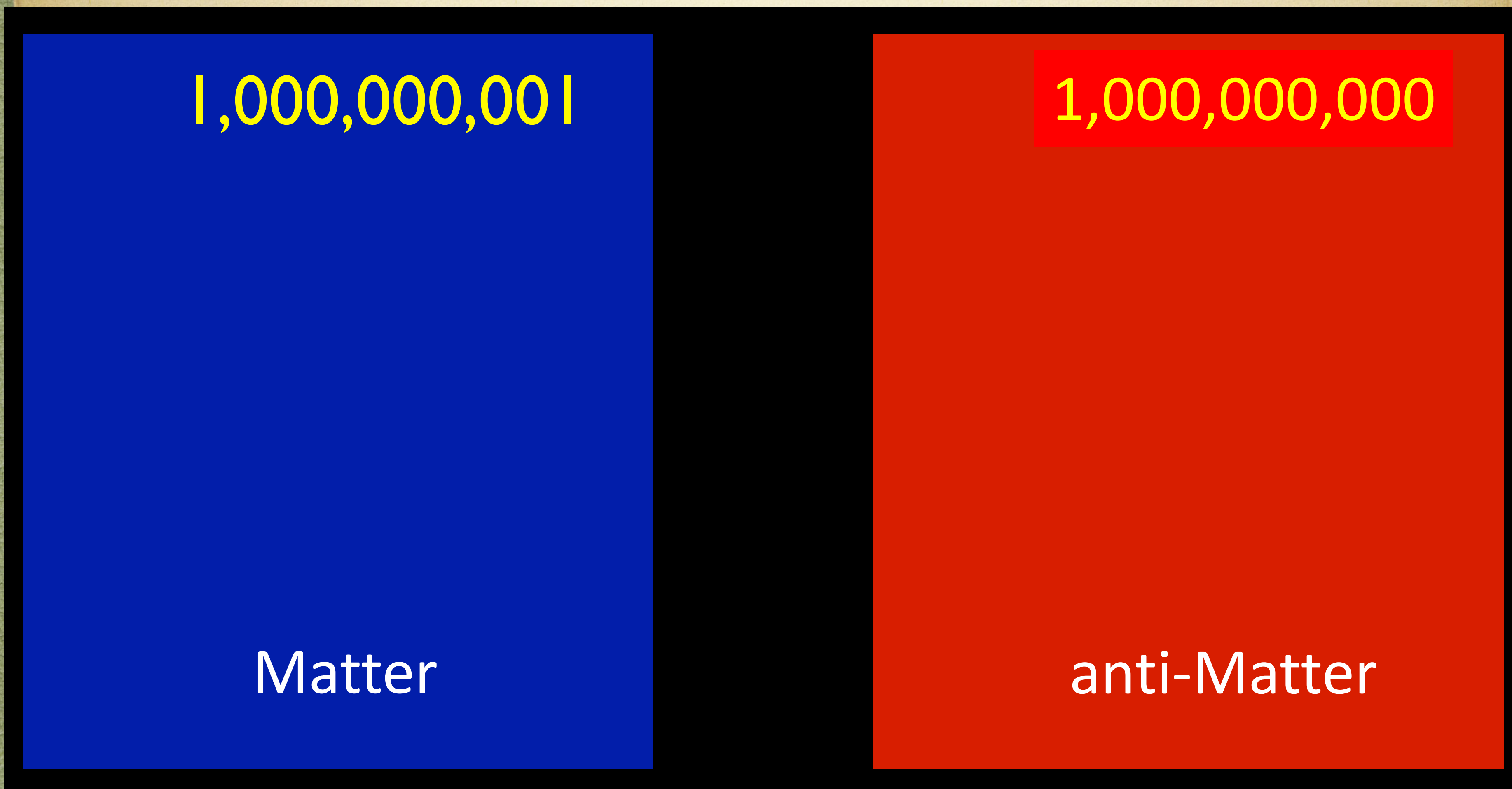
Dark Matter/Dark Energy



What we know: just the tip of the iceberg.

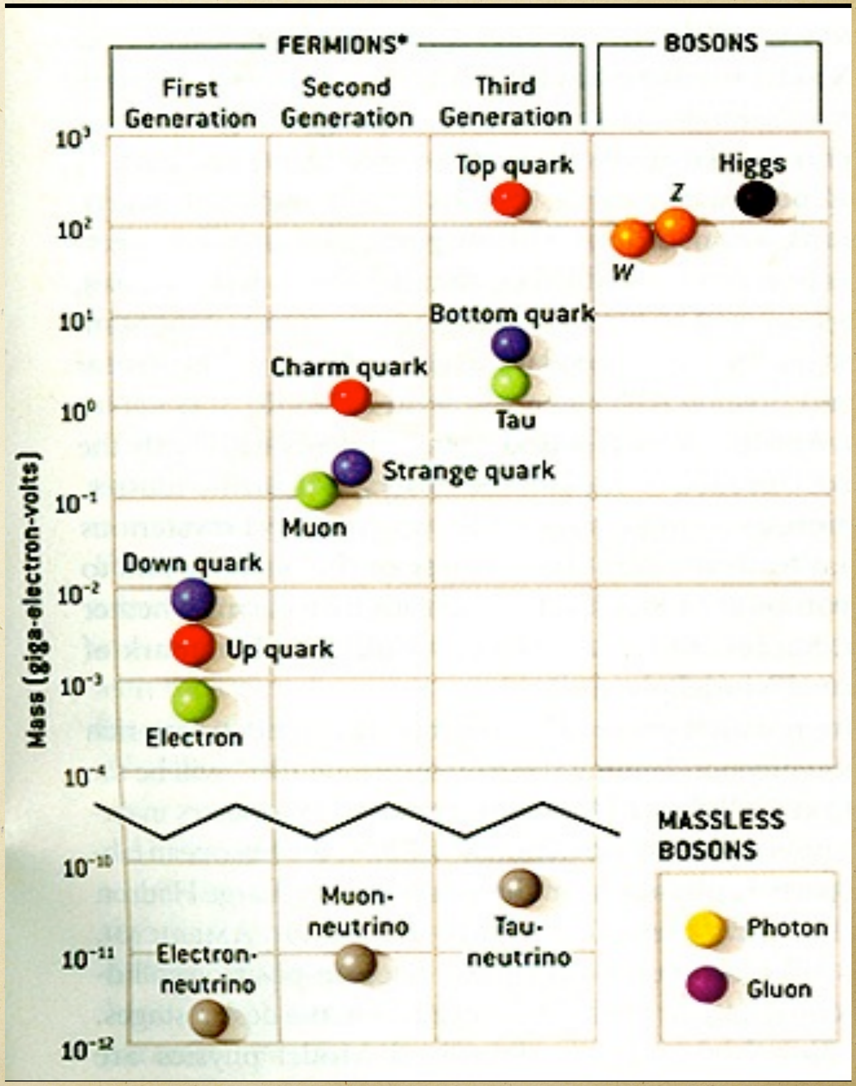
Baryon Asymmetry

- How did matter survive ?

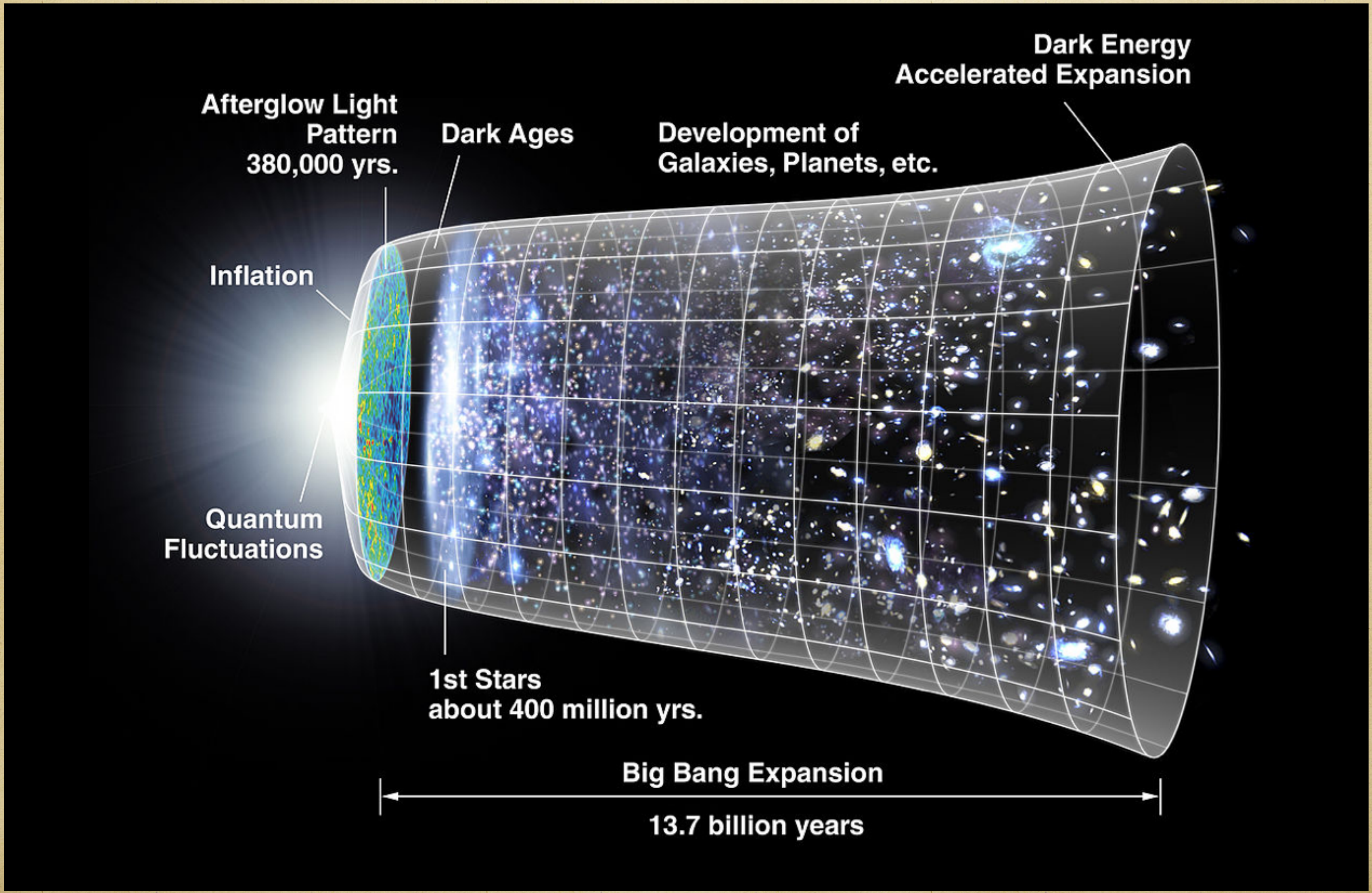


Three Generations

- Why do the particles have such a large range of masses?
- Why does the pattern of particles repeat three times?
- Why do neutrinos have mass at all ?



What powered inflation ?



Multiple approaches

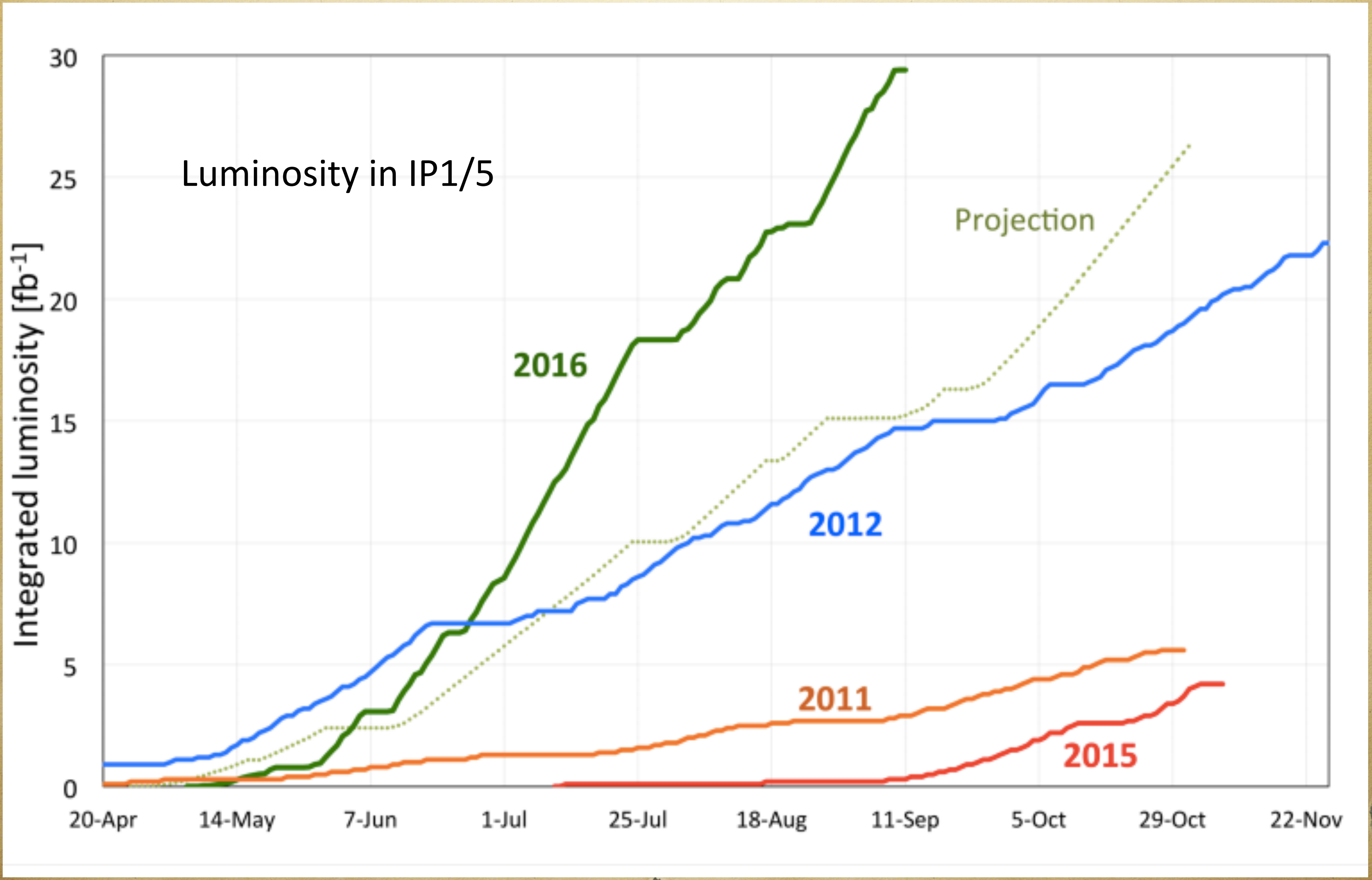
Main questions and main approaches to address them

	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos			x	x	x
Dark Matter	x			x	x
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

At the energy frontier

LHC, the mountain top

Spectacular LHC performance



LHC: the flagship

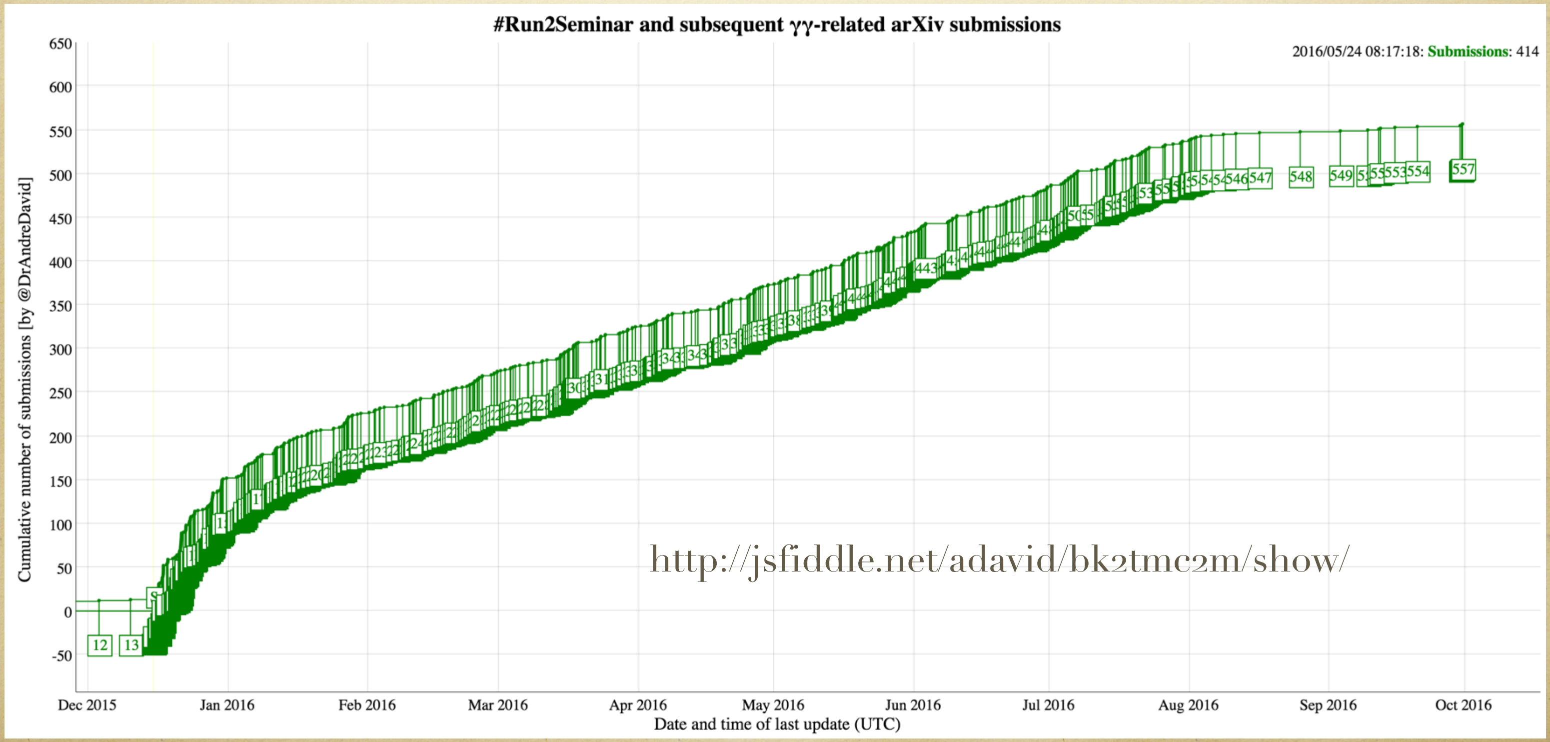
- Fantastic physics program and wealth of results
- Marvelous experiments: ALICE, ATLAS, CMS, LHCb, but also: TOTEM, LHCf, Moedal
- Confirmation of all Standard Model predictions so far…. boring ?

Not really

- Only a small fraction of total luminosity collected
- Many areas still to explore and many questions to be answered
- Expect the unexpected…but not too soon

Theorists are eagerly waiting

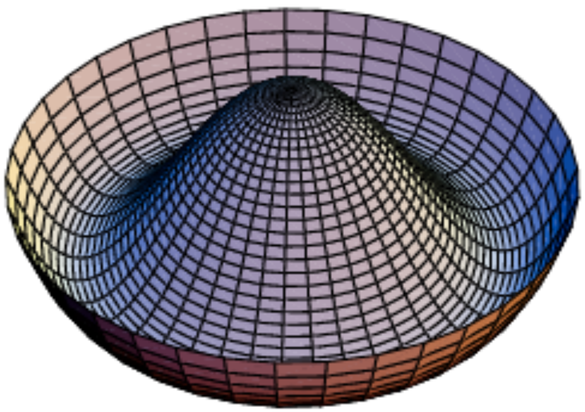
- ArXiv submission after CERN seminar showing the 750 GeV bump
- Need to apply extreme care in how we present preliminary results, especially to the general public

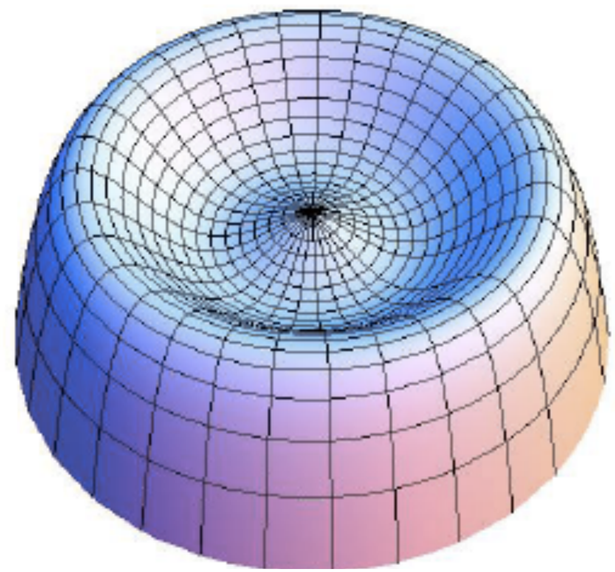


http://jsfiddle.net/adavid/bk2tmc2m/show/

Precision measurements

STABILITY ⟷ **INSTABILITY**



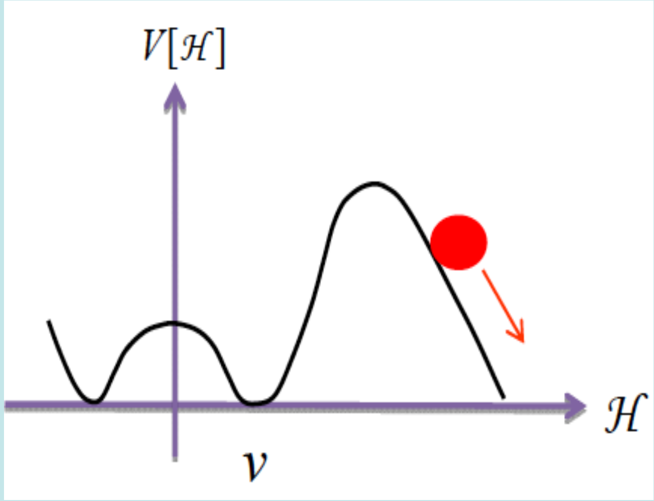


The values of the **TOP and HIGGS masses** are crucial to establish the stability of the

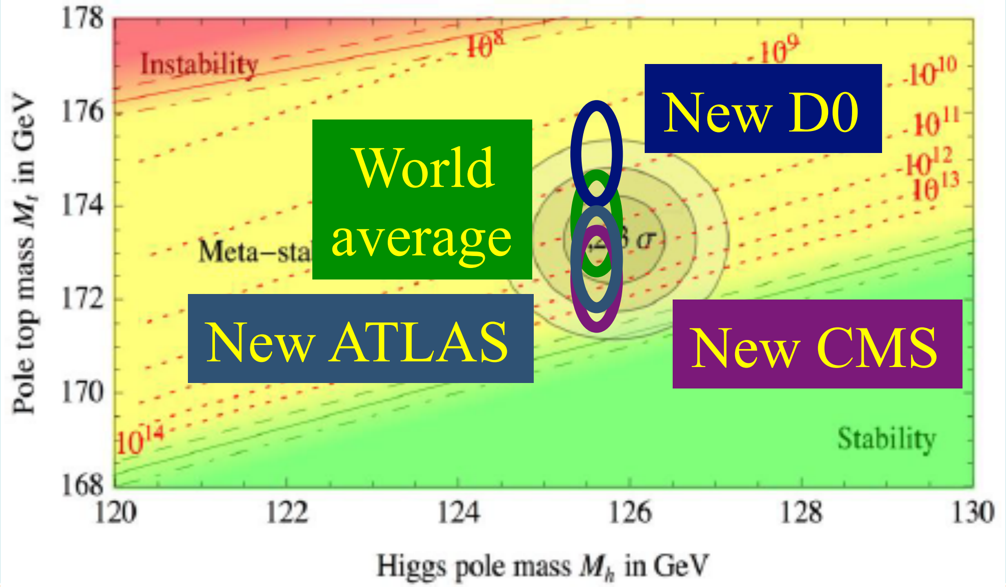
ELECTROWEAK VACUUM

Vacuum instability in the SM

- Very sensitive to m_t as well as M_H



J. Ellis, LP 2015



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

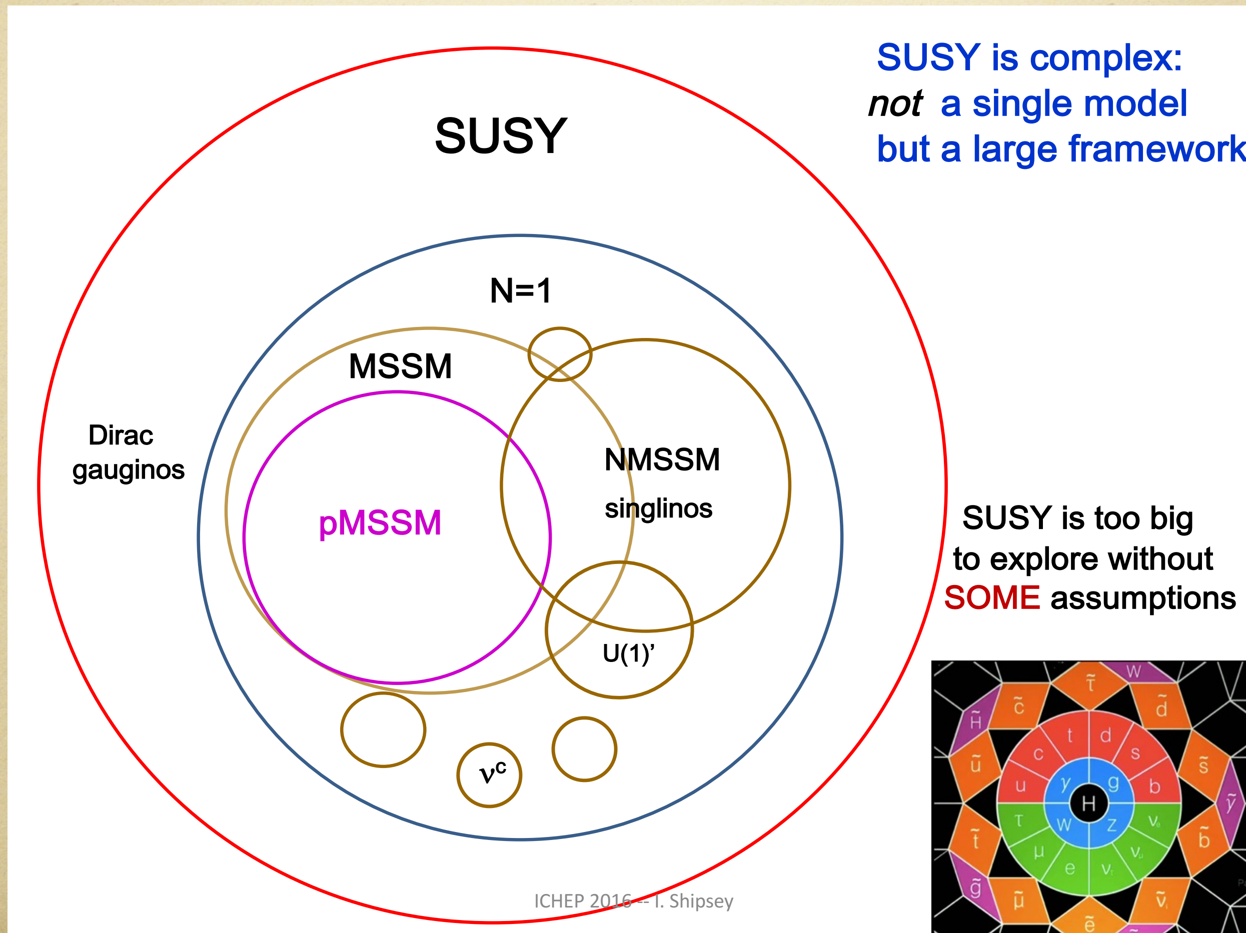
- Instability scale:

$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

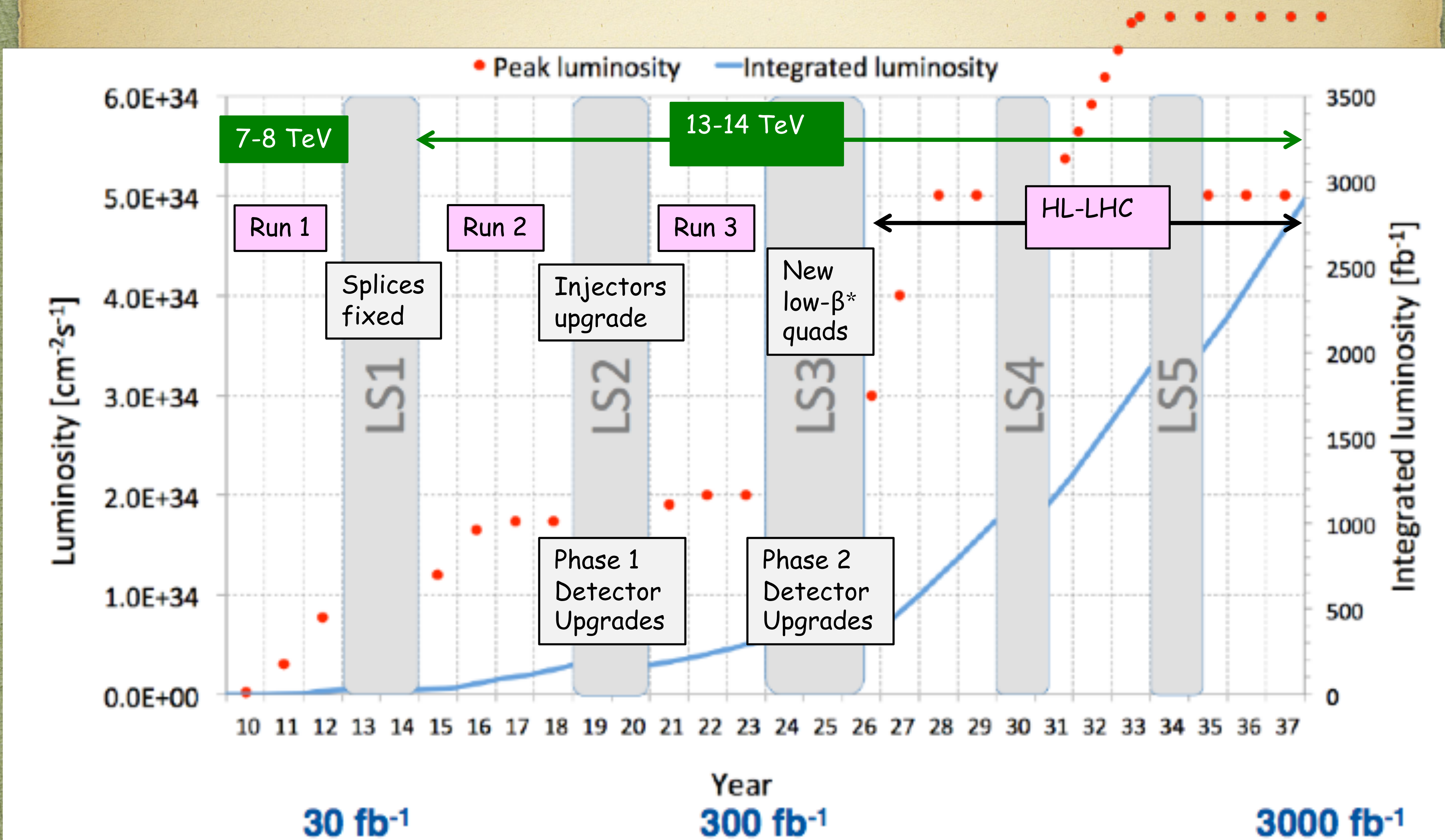
$m_t = 173.3 \pm 1.0$ GeV ➔ $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$

SUSY

- Still many open questions and important searches



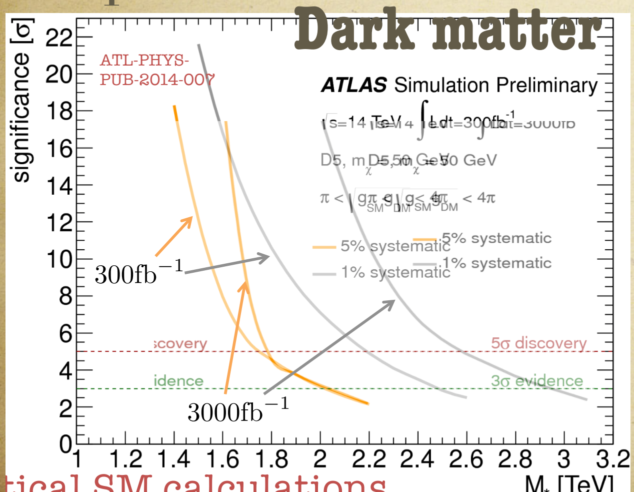
HL-LHC 20 years plan



The known and the unknown

- Many expected measurements can be performed at HL-LHC
- But exploration of uncharted territory is also possible

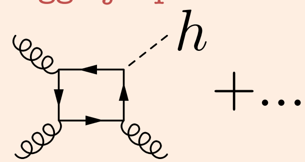
Dark matter



tical SM calculations

Higgs Production

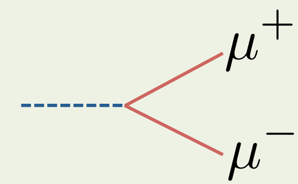
Higgs+jet production



Would occur at Higgs p_T's as large as 1.9 TeV!

Higgs Decays

Higgs coupling to muons

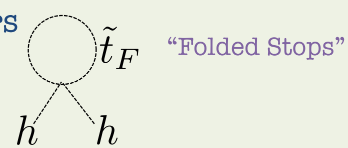


Would be measured to 7%.

Folded SUSY

hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

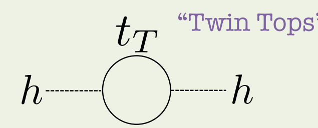


…but they must be charged under new hidden QCD'.

Twin Higgs

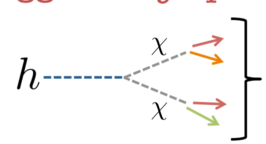
hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



…but they must be charged under new hidden QCD'.

Exotic Higgs decays provide a signature "standard candle"



$m_\chi = 10, 25, 40.$ GeV

HL-LHC status

- HL-LHC program has been formally approved by CERN council
  - Funding for machine included in budget
  - Line of credit authorized to cover peak spending during construction time
- ATLAS and CMS have prepared scoping document for their upgrades
  - Range 200—270 MCHF each
  - Positive perspective in terms of fund availability
  - TDRs in preparation, will come in 2017-2018

Not only high luminosity

- Boost of activity in high field magnets
- Every TeV counts to extend reach and explore new territory
- Limited by technology

F. Gianotti

A working group put in place to explore the technical feasibility of pushing the LHC energy to:

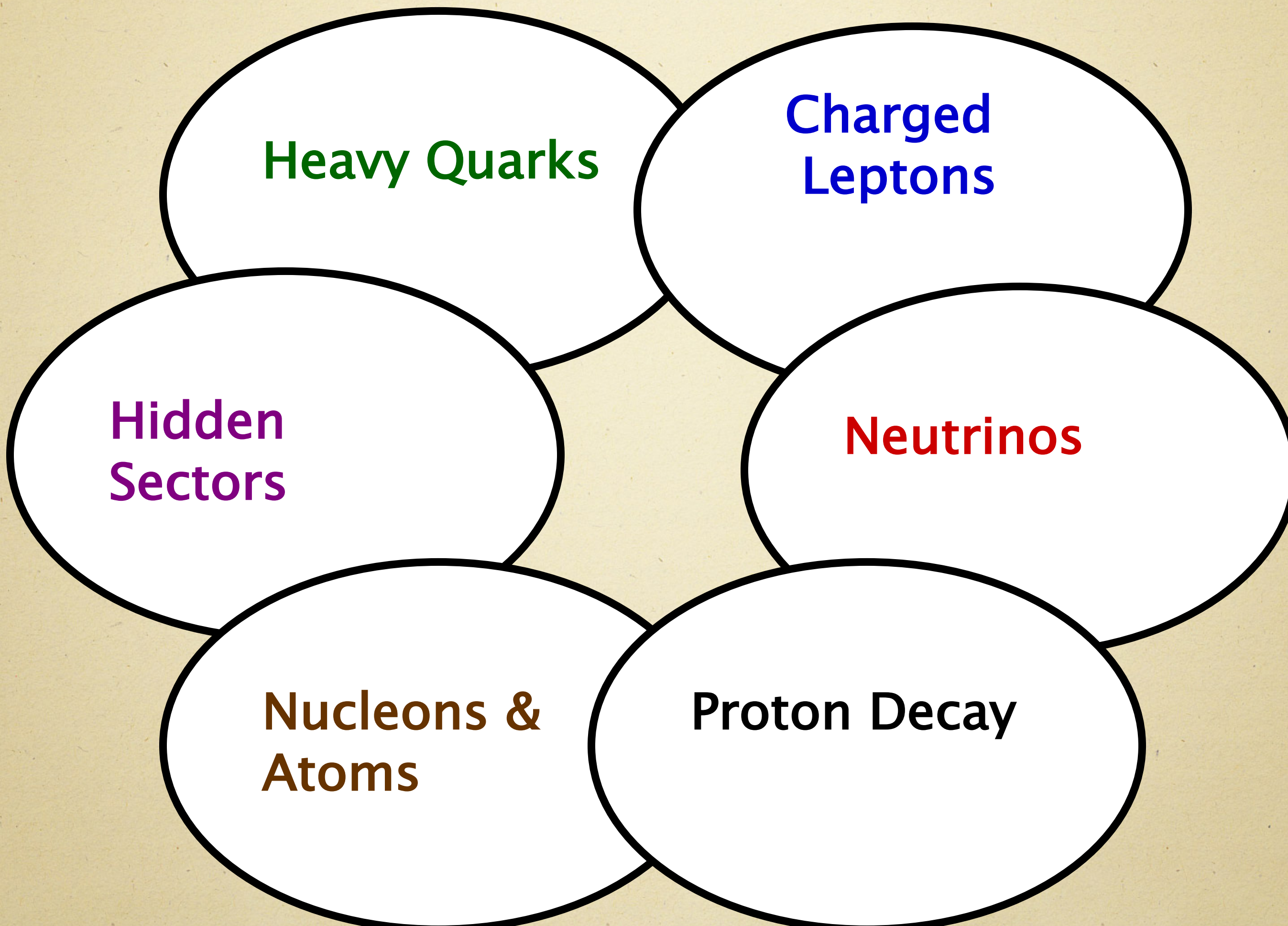
1) design value of 14 TeV
2) ultimate value of 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (by replacing 1/3 of the dipoles with high-field Nb_3Sn magnets)

→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) by end 2016, 2) by end 2017, 3) by end 2018 (preliminary report in time for ES)

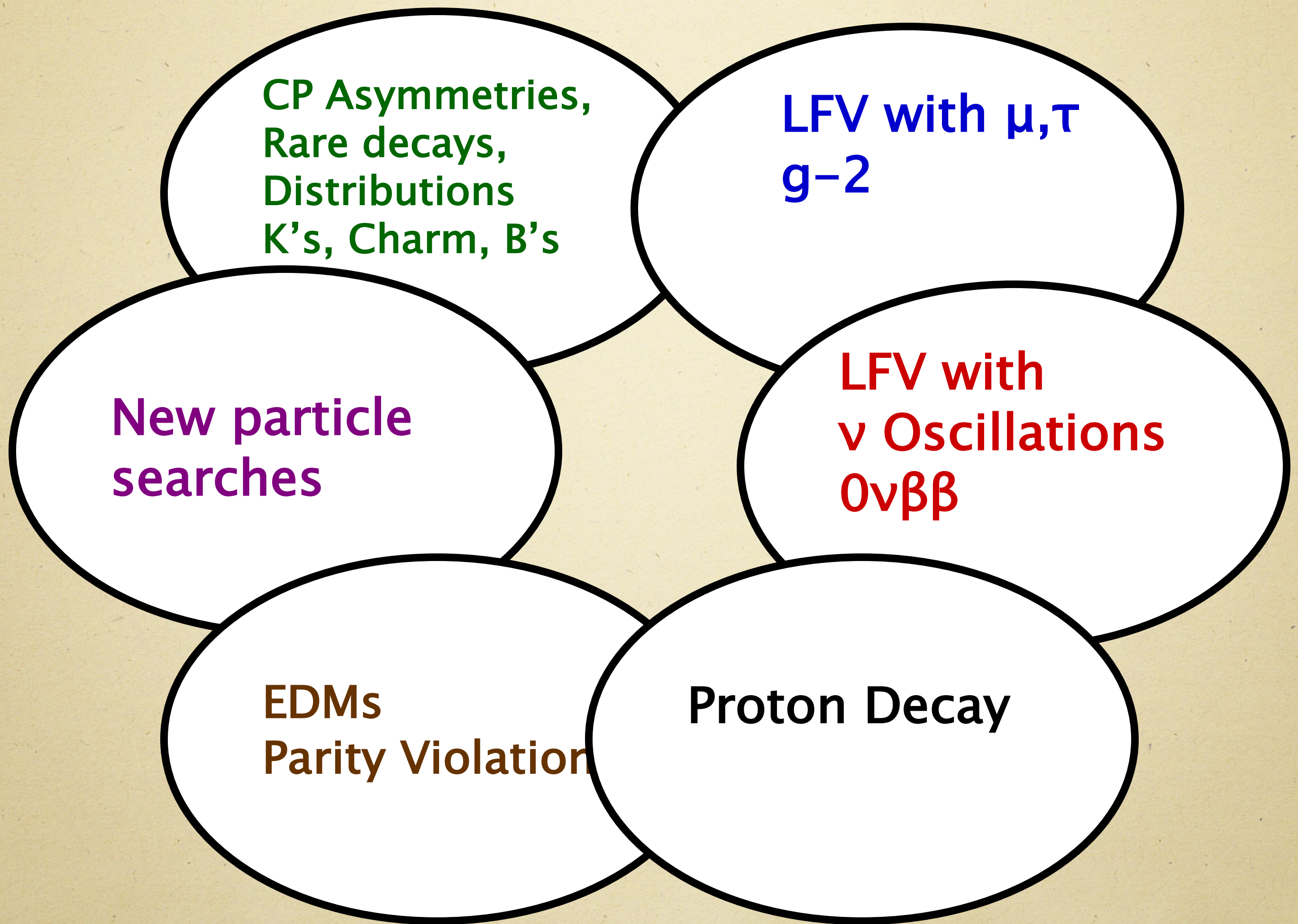
At the intensity frontier

SuperKEKB, the waterfall

Many opportunies at the intensity frontier



Many experimental methods



Large discovery potential

New sources of CPV – Indirect new Physics Search

New sources of CPV – Indirect new Physics Search

Explore DM and other weakly coupled sectors

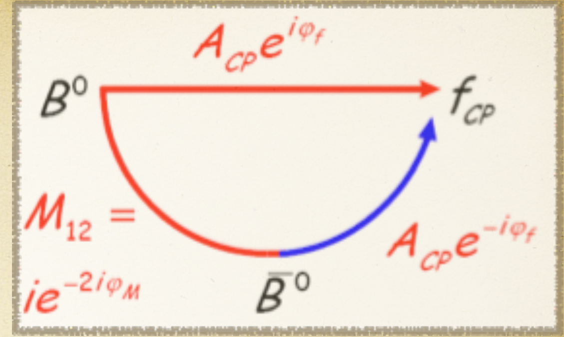
Fundamental Properties: CPV Dirac/Majorana Hierarchy

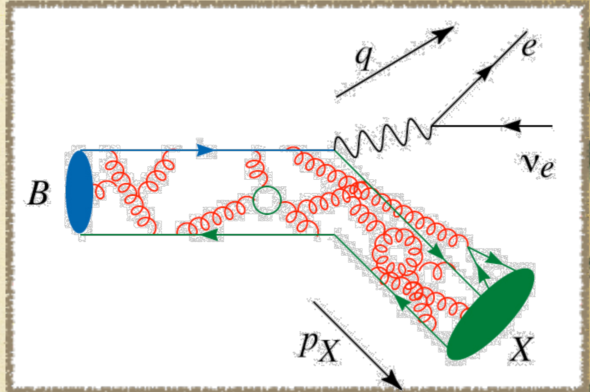
New sources of CPV – Indirect new Physics Search – Fundamental measurements

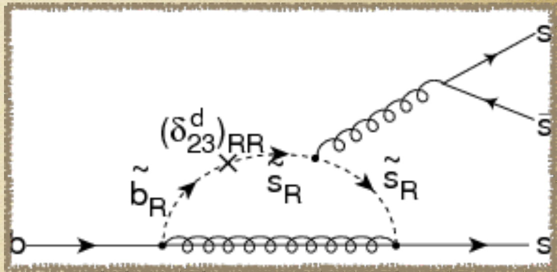
Test of unification

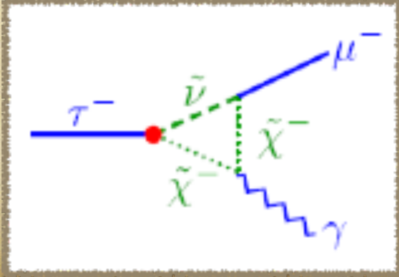
The power of flavor

1. **Explore the origin of CP violation**
    - Key element for understanding the matter content of our present universe
    - Established in the B meson in 2001
    - Direct CPV established in B mesons in 2004
2. **Precisely measure parameters of the standard model**
    - For example the elements of the CKM quark mixing matrix
    - Disentangle the complicated interplay between weak processes and strong interaction effects
3. **Search for the effects of physics beyond the standard model in loop diagrams**
    - Potentially large effects on rates of rare decays, time dependent asymmetries, lepton flav. viol.
    - Sensitive to large New Physics scale, as well as to phases and size of NP coupling constants

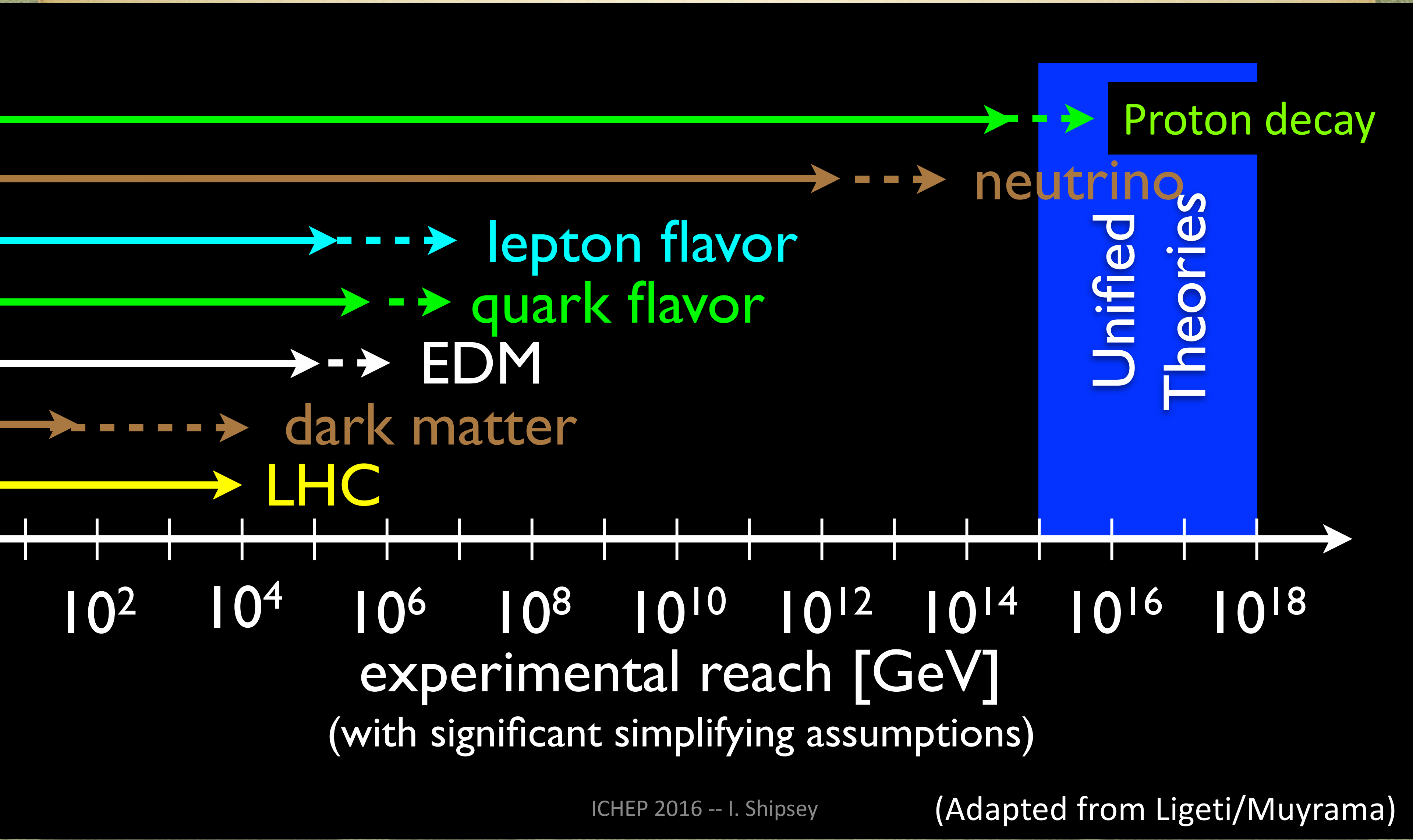




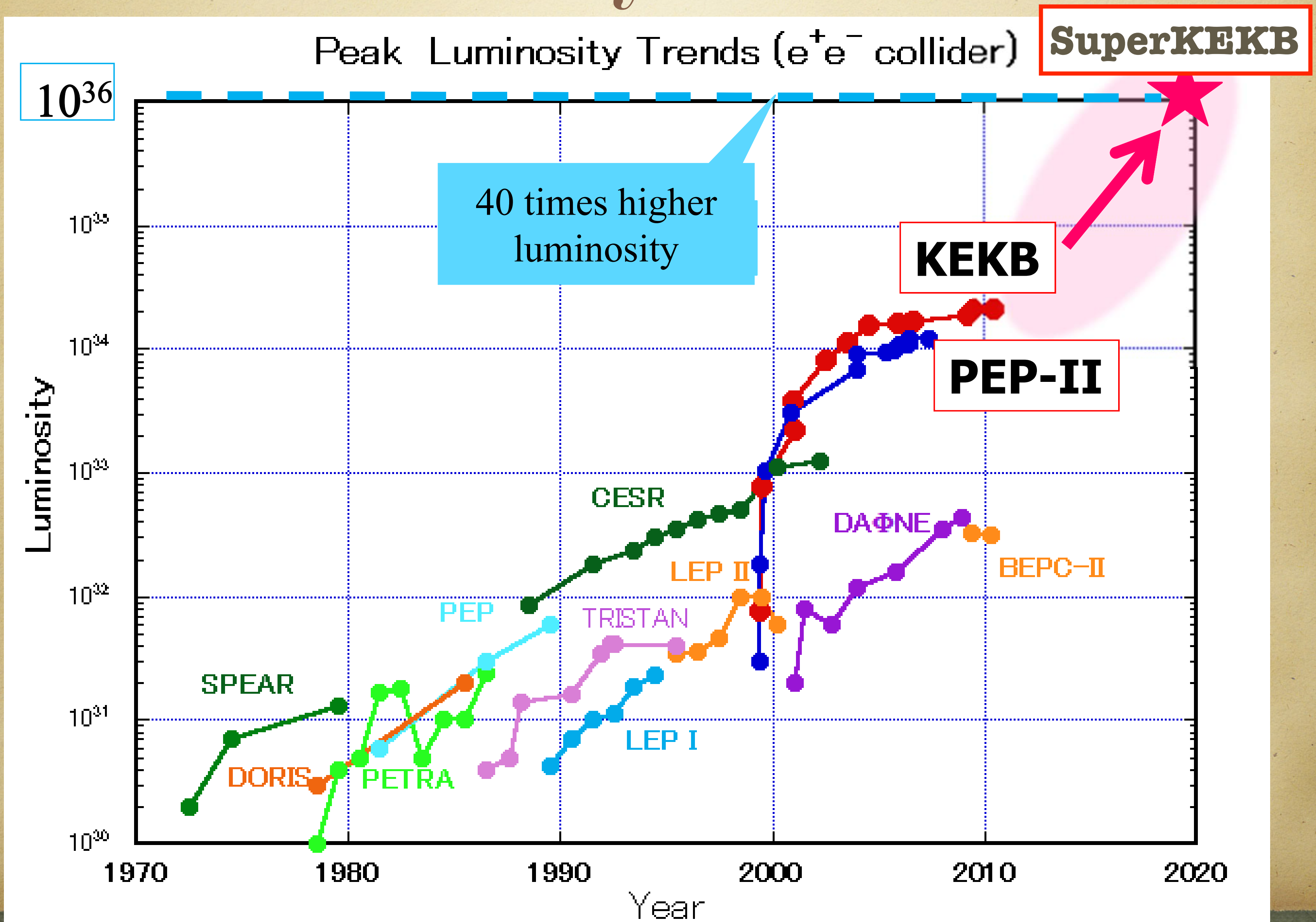




The power of quantum loops



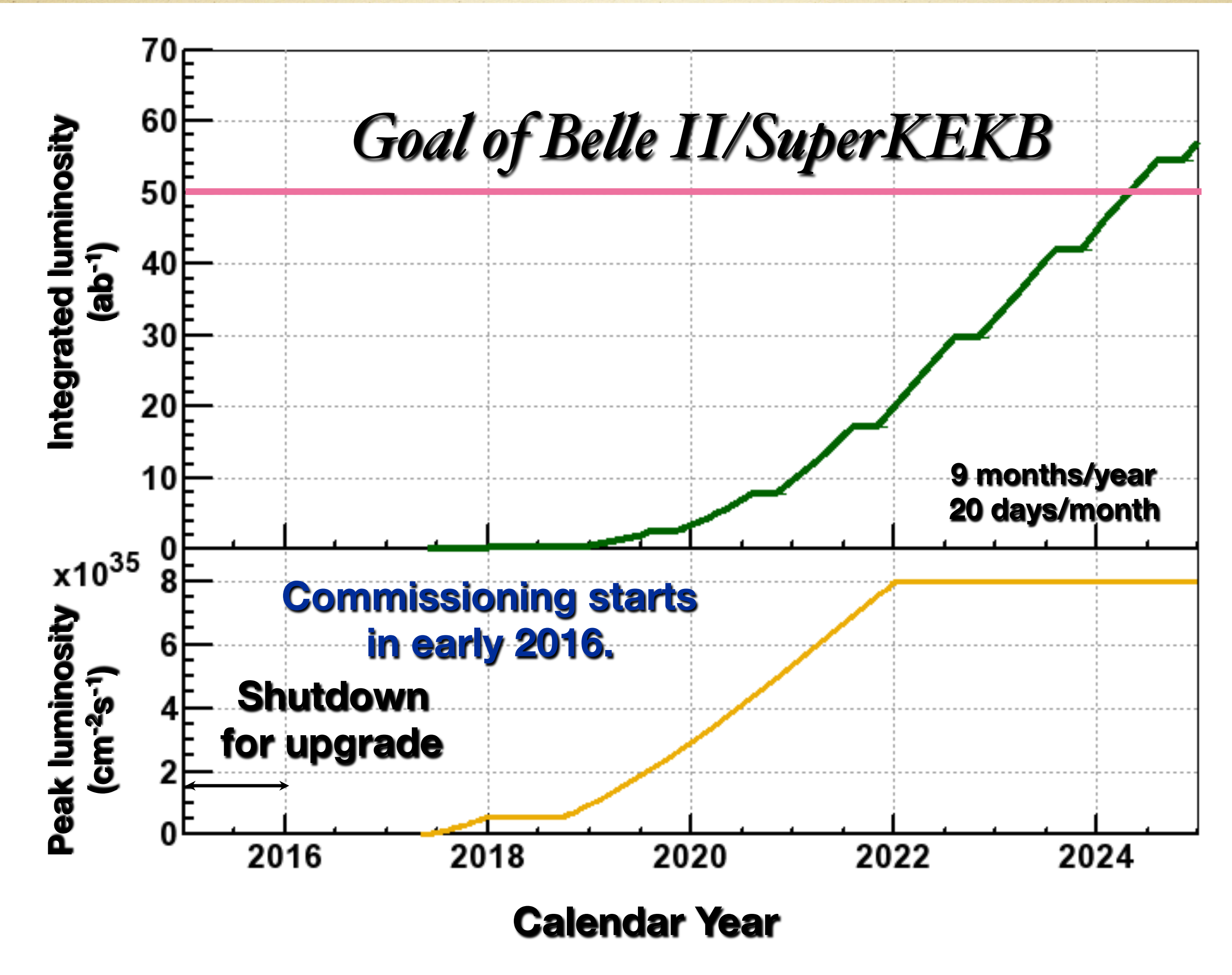
Intensity frontier



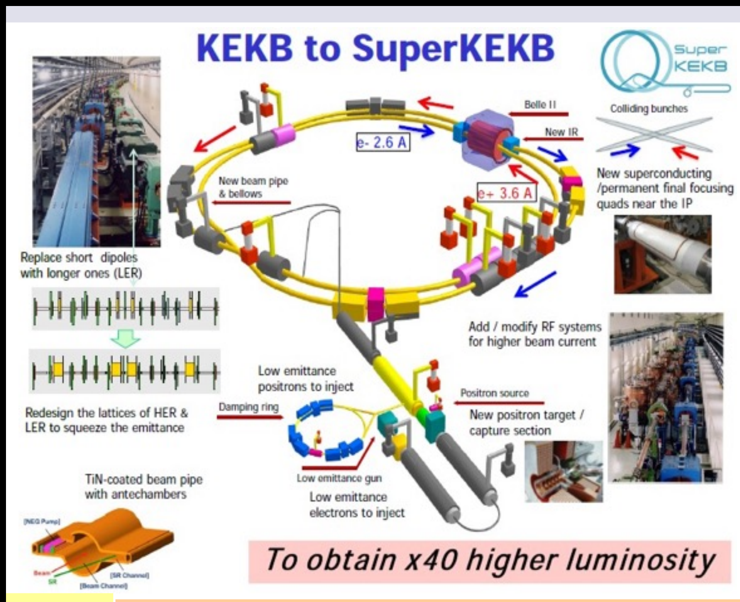
Flavour perspective

- **Babar and Belle** data samples have proven a treasure chest of beautiful physics results
  - Still scratching the bottom of the cask
- **LHCb** has demonstrated unbelievable ability to perform analyses on very difficult channels
  - Will continue to take data in 2016-18 (Run2) 1MHz L0 readout
  - Install upgrade in 2019-20 to restart in 2021 (Run3) at 40MHz readout and improved hadron trigger efficiency
- **Belle-II at SuperKEKB** is on track to start in 2018 with the goal of reaching $L=8x10^{35}cm^{-2}s^{-1}$.
- Competition fiercer than ever

SuperKEKB Luminosity



Physics reach of LHCb and Belle II upgrades



Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi\ell\nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c\ell\nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		$1.5°$	Belle II
ϕ_3	***	$3°$	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	$1.5°$	Belle II

ICHEP 2016 -- I. Shipsey

La pub: Belle II

599 members, 97 institutions, 23 countries

Other opportunities

CERN Beyond Colliders, FNAL Muon Campus

"Physics Beyond Colliders" Study Group established in March 2016

Mandate
Explore opportunities offered by the (very rich) CERN accelerator complex to address outstanding questions in particle physics through projects:

- ❑ complementary to high-energy colliders (studied at CERN: HE-LHC, CLIC, FCC)
  → we know there is new physics, we don't know where it is → we need to be as broad as possible in our exploratory approach
- ❑ exploiting the unique capabilities of CERN accelerator complex and infrastructure and complementary to other efforts in the world:
  → optimise the resources of the discipline globally

⬇

Enrich and diversify CERN's future scientific programme

Goal is to involve interested worldwide community, and to create synergies with other laboratories and institutions in Europe (and beyond).
Note: interesting ideas may emerge from these studies which do not need to be realised at CERN.

- ❑ Overall coordinators: Joerg Jaeckel (Heidelberg; theory), Mike Lamont (CERN; accelerator), Claude Vallée (CPPM and DESY; experimental physics)
- ❑ Kick-off meeting 6-7 September 2016
- ❑ Final report by end 2018 → in time for update of European Strategy

Many proposals from kickoff meeting

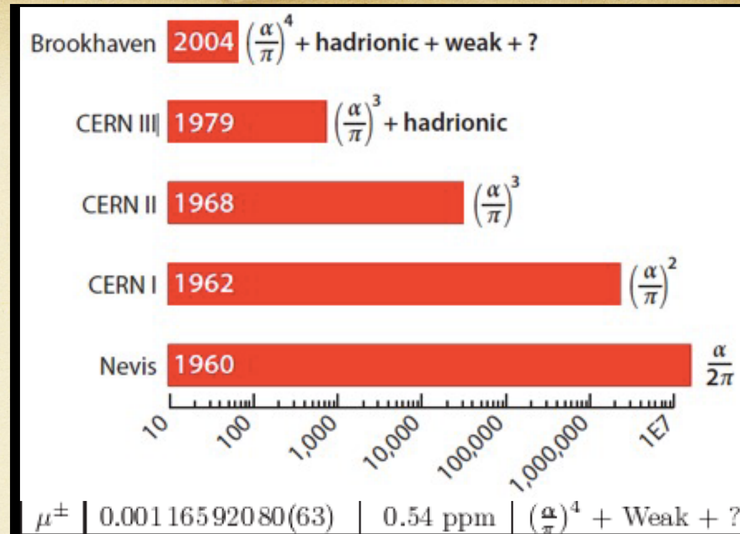
- **Extension of current programs**
  - NA61/Shine (QCD), Compass (spin), NA62 (K→pi nu nu)
- **New fixed target facilities**
  - SHIP (beam dump), LHC extracted beams
- **New facilities (other)**
  - Storage rings for proton EDM, Gamma factory, nu beam
- **Non accelerator**
  - IAXO (Axions), Darkside (DM)

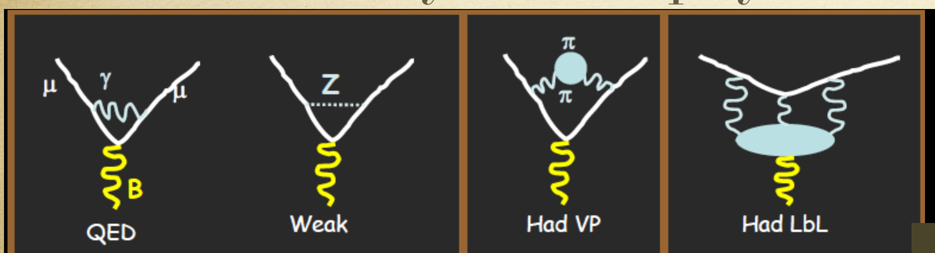
- Need input from the community to define the future strategies

https://indico.cern.ch/event/523655/

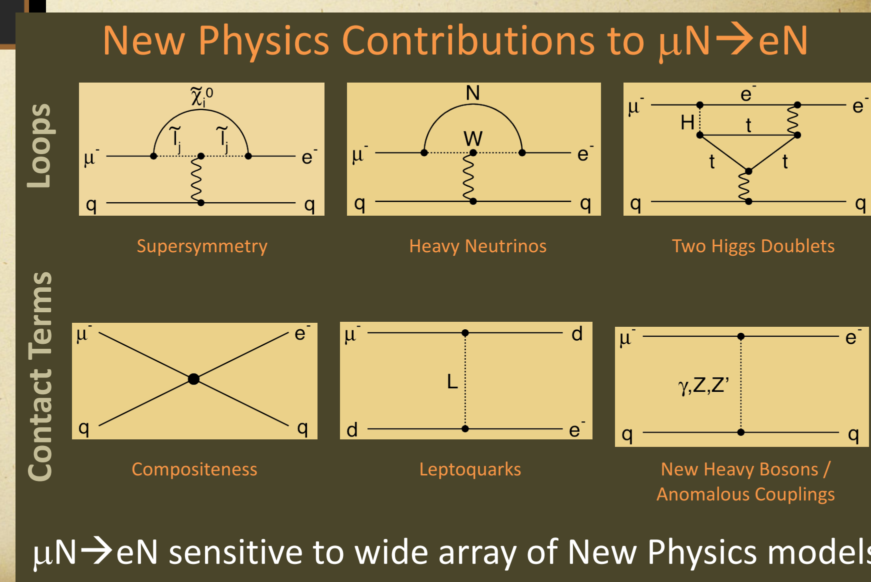
FNAL Muon Campus

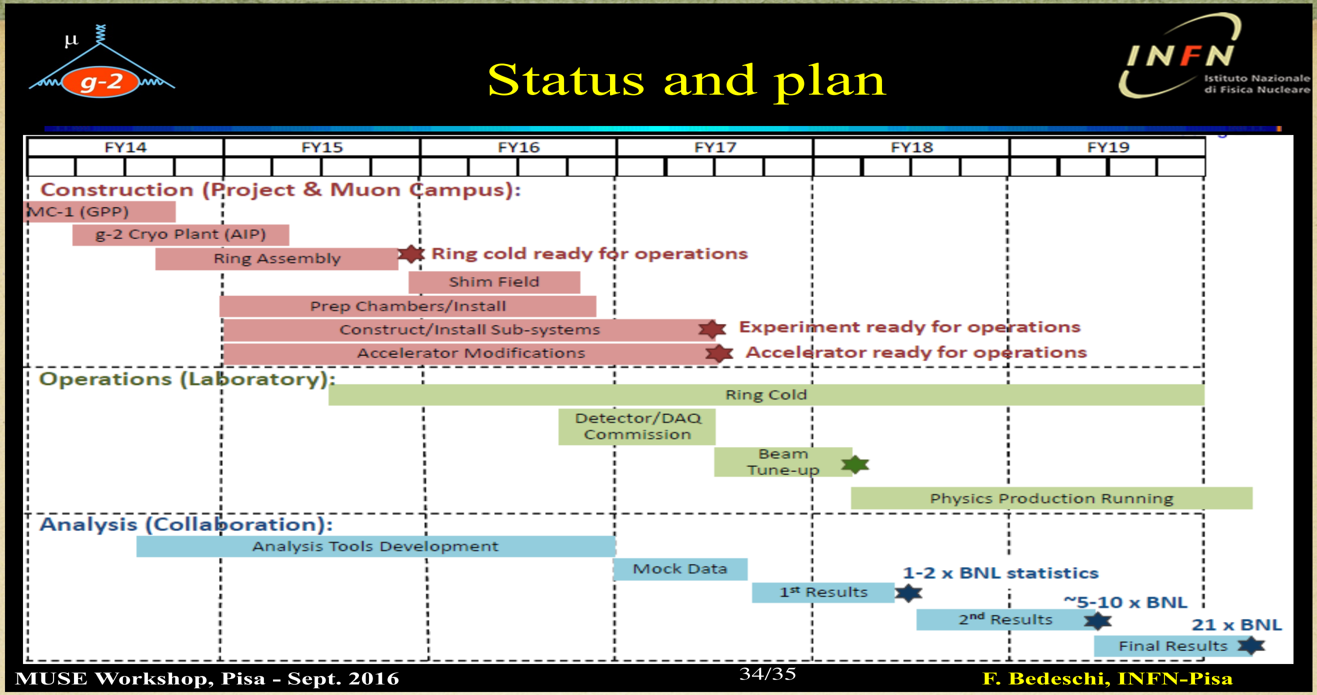
- g-2 experiment
  - Improve precision to 0.14ppm (x4 better)
  - Sensitivity to new physics

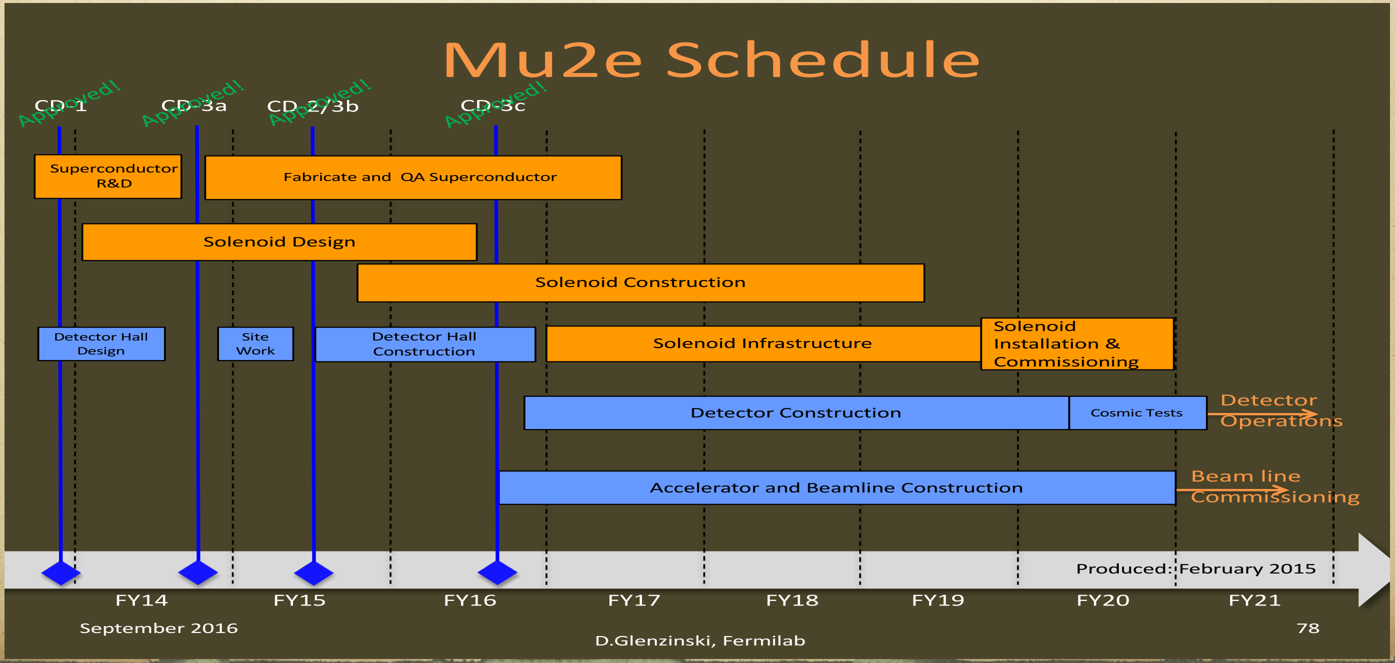




- MU2E experiment
  - Lepton Flavor Violation is the Holy Grail of new physics searches
  - Look for $\mu^- N \rightarrow e^- N$




Status and plan
INFN Istituto Nazionale di Fisica Nucleare
g-2
FY14 FY15 FY16 FY17 FY18 FY19
Construction (Project & Muon Campus):
MC-1 (GPP)
g-2 Cryo Plant (AIP)
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Operations (Laboratory):
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Physics Production Running
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1-2 x BNL statistics
1st Results
~5-10 x BNL
2nd Results
21 x BNL
Final Results
MUSE Workshop, Pisa - Sept. 2016
34/35
F. Bedeschi, INFN-Pisa


Mu2e Schedule
CD-1 Approved!
CD-3a Approved!
CD-2/3b Approved!
CD-3c Approved!
Superconductor R&D
Fabricate and QA Superconductor
Solenoid Design
Solenoid Construction
Detector Hall Design
Site Work
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation & Commissioning
Detector Construction
Cosmic Tests
Detector Operations
Accelerator and Beamline Construction
Beam line Commissioning
Produced: February 2015
FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21
September 2016
78
D.Glenzinski, Fermilab

Future machines

ILC, CLIC, CEPC, FCC

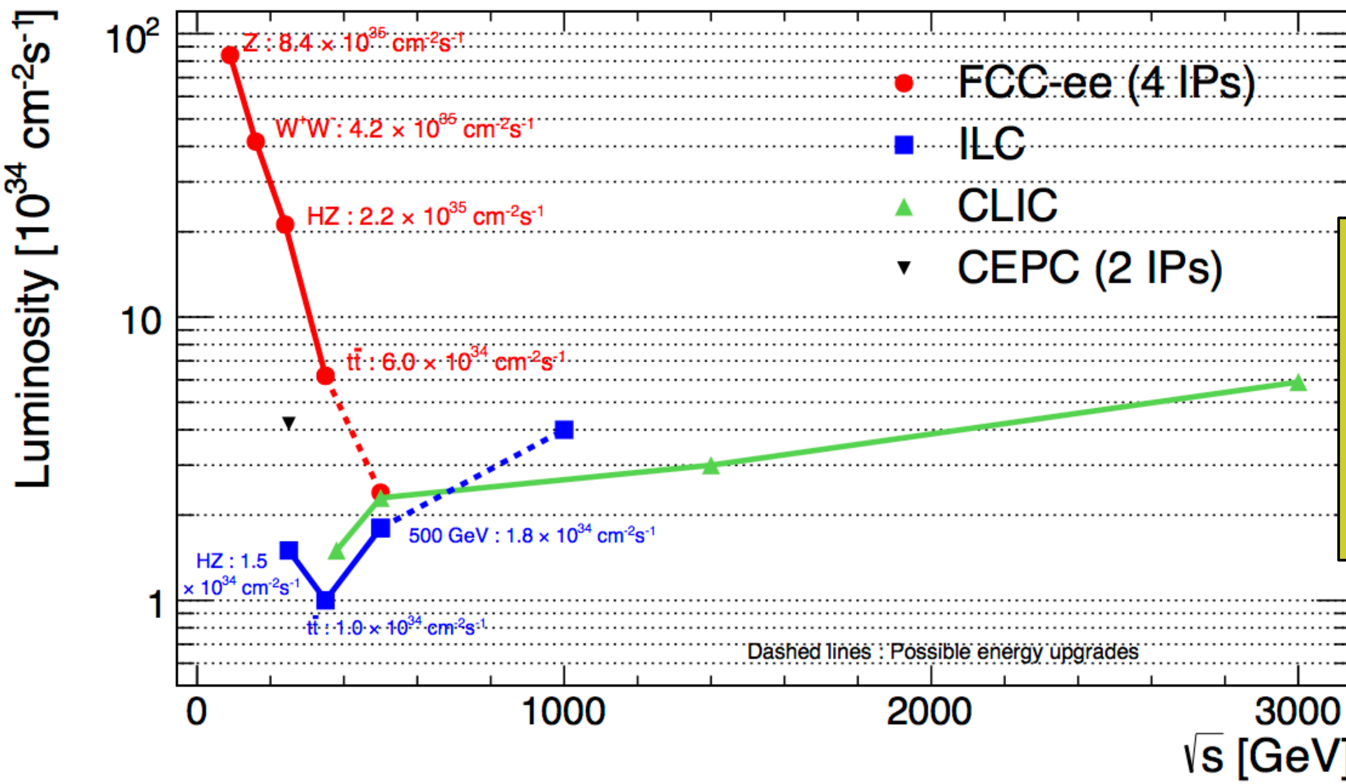
Many ideas on the table

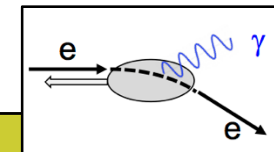
- High energy and luminosity e+e- colliders
  - Linear: CLIC, ILC
  - Circular: FCCee, CEPC
- High energy pp colliders (circular)
  - HE-LHC
  - SppC
  - FCC-hh
- Muon colliders
  - Could reach multi-TeV (if you can make it)

Not cheap

Future
e^+e^-
colliders

$\sqrt{s}$ (GeV)	Main physics goals
90	Z-pole precision EW measurements beyond LEP, SLC
160	WW precision physics (mass at threshold)
250	H precision physics (HZ)
~350	H (HZ, Hνν) and top (mass, couplings) precision physics
500-3000	ttH, HH (self-couplings), direct searches for new physics





Linear:
- ❑ Larger $\sqrt{s}$ reach
- ❑ Low repetition rate
  - → L from nm size beams
  - → large beamstrahlung
  - → larger E-spread
- ❑ Long. polarization easier

Circular:
- ❑ $\sqrt{s}$ limited by SR ~ E^4_{beam}/R
- ❑ Large number of circulating bunches → high L (increases at lower $\sqrt{s}$ as less SR → spare RF power used to accelerate more bunches). Note: need top-up injection ring to compensate fast L burn-off (lifetime ~ 30')
- ❑ Several interaction regions possible
- ❑ Precise E-beam measurement from resonant depolarization

Future pp colliders

Pioneering work started in the US in 1998 with VLHC: http://vlhc.org/vlhc/

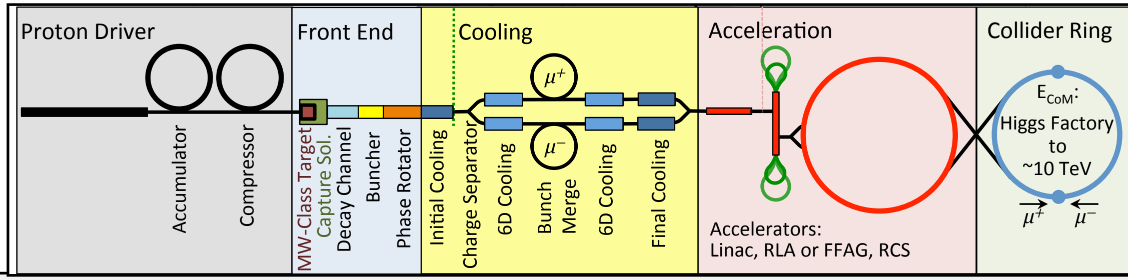
	Ring (km)	$\sqrt{s}$ (TeV)	Field (T)	Magnet technology	L (10^{34})
LHC (for comparison)	27	14	8.3	NbTi	up to 5
HE-LHC	27	26-33	16-20		~5
SppC If enough funds	54 100	70 100-140	20	Nb_3Sn with HTS inserts	12
FCC-hh	100	100	16	Nb_3Sn (with NbTi)	5-20

5×10^{34} operation	HL-LHC	FCC-hh
Bunch spacing	25	25*
N. of bunches	2808	10600
Pile-up.x-ing	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

Many big technical challenges: technology of bending dipoles (Nb_3Sn ok up to ~16T, HTS needed for 20T), SR and beam screen, stored beam energy, radiation, …

* 5 ns considered for $L=2\times10^{35}$ to mitigate pile-up

Muon colliders



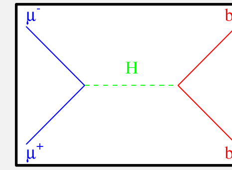
Synergies with neutrino factories

Main advantage compared to e^+e^- colliders: $m_\mu \sim 200\ m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

→ $\sigma(\mu\mu \to H) \sim 20$ pb (s-channel resonant production) → H factory

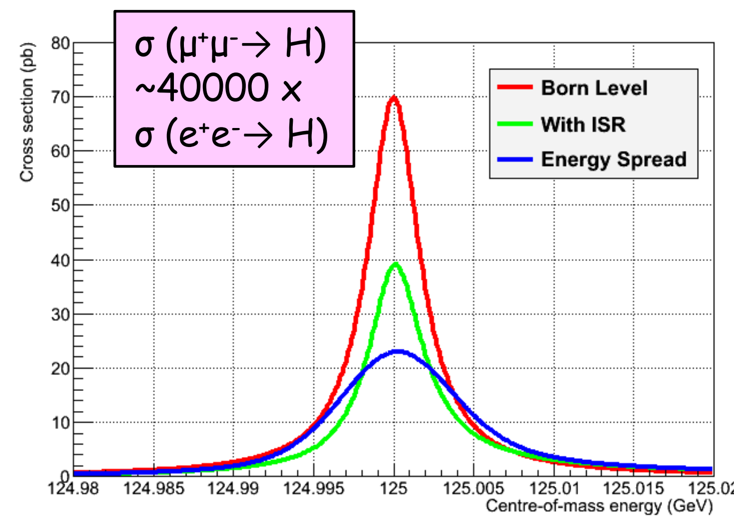


Main challenge: produce high-intensity, low E-spread beams:

- ❑ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of ~ 3×10^{-5} (for precise line shape studies) and high L
- ❑ $\tau_\mu \sim 2.2\ \mu s$ → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of ~ 3×10^{-5} would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances

However, with currently projected L (~10^{32}): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)



More R&D needed to demonstrated feasibility, in particular cooling: linear systems (MICE at RAL), rings (recently re-ignited by C.Rubbia)

Physics motivation

- **Strong**....
  - Higgs boson precision measurement
    - Couplings, rare decays, self coupling
  - Top quark mass measurement
  - Sensitivity to new physics
    - Direct discovery of new states
    - Indirect sensitivity to higher energy particles
    - WIMP / Dark matter
  - Elucidate mechanism of SM
    - Explore energy where EW symmetry is restores
    - Understand EW phase transition
    - Naturalness and fine tuning
- ...**but weak**
  - No specific smoking gun easy to explain
  - Hard to beat skepticisim of politicians, general public **AND** colleagues (remember SSC ?)

Particle Physics is Global

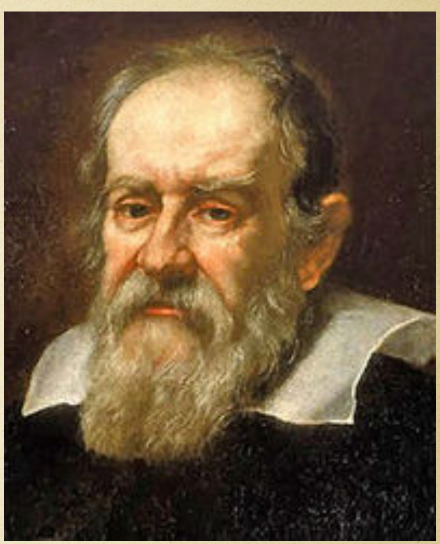
- Reliable partnerships are essential for the success of international projects. This global perspective is finding worldwide resonance in an historically competitive field.
  - The 2013 *European Strategy for Particle Physics* report focuses at CERN on the Large Hadron Collider (LHC) program and envisions substantial participation at facilities in other regions.
  - Japan, following its 2012 *Report of the Subcommittee on Future Projects of High Energy Physics*, expresses interest in hosting the International Linear Collider (ILC), pursuing the Hyper-Kamiokande experiment, and collaborating on several other domestic and international projects.
  - The 2014 U.S *P5 Report* highlights collaboration on the most important scientific opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community including DUNE and cosmic frontier experiments.

ICHEP 2016 -- I. Shipsey

- By the next European Strategy update (2018-2020) hopefully things will be clearer

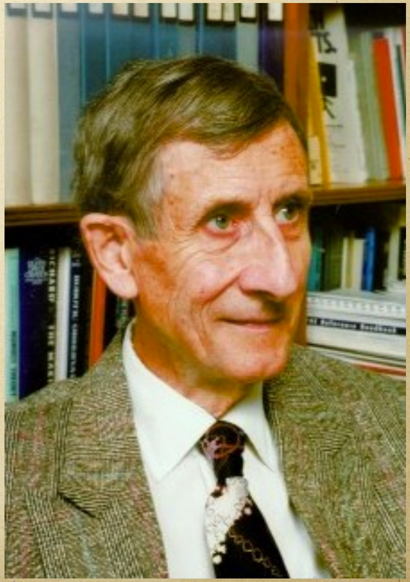
Tool driven scientific revolutions

Quotes



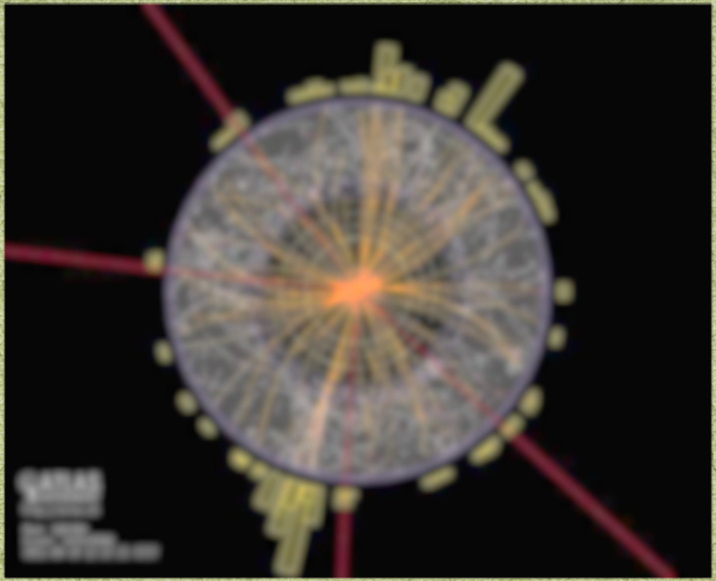
Galileo Galilei

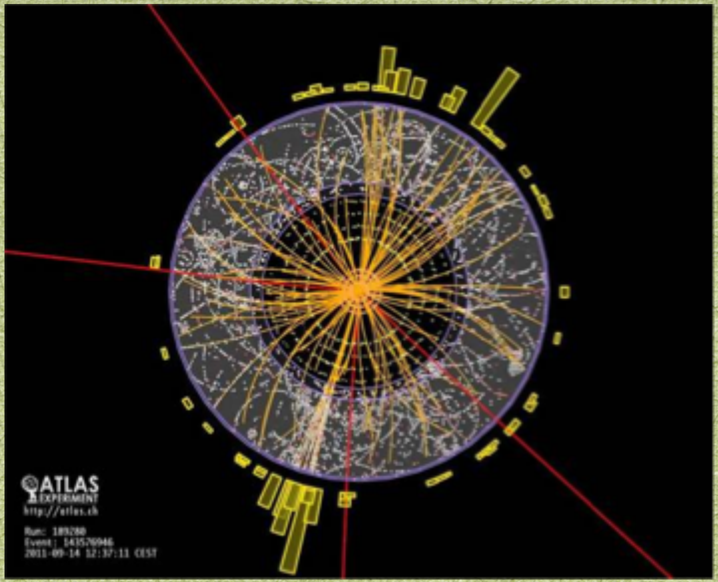
- Measure what can be measured, and make measurable what cannot be measured.

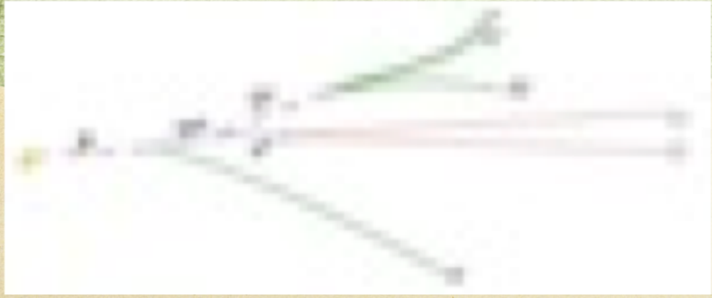


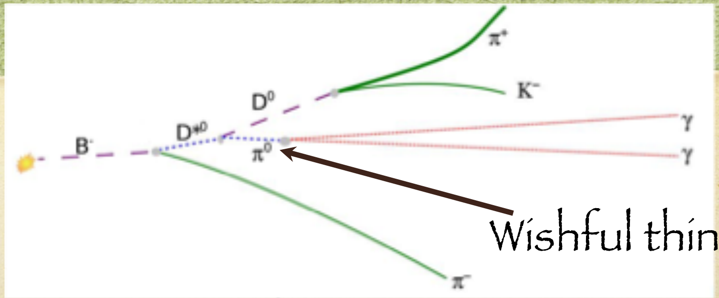
Freeman Dyson

- The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained.







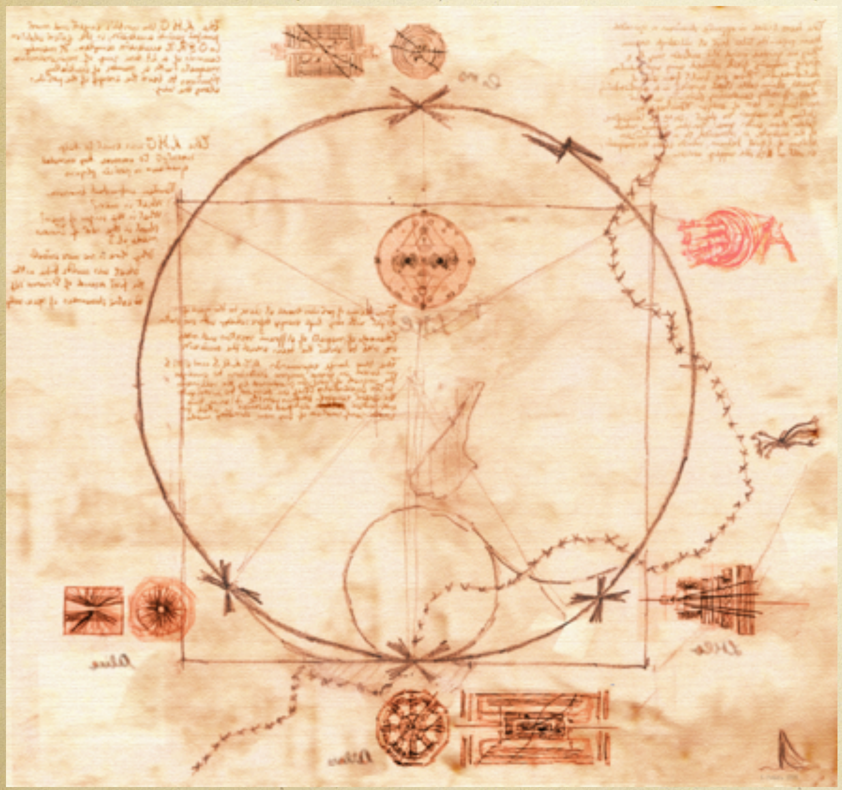


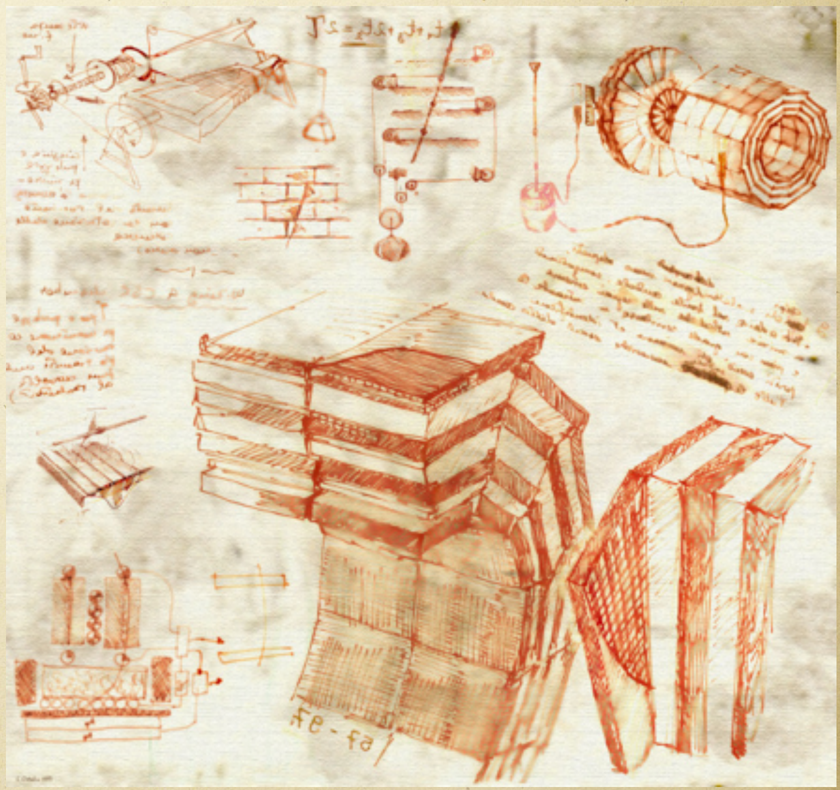
Wishful thinking

We need eyes to see

Long R&D process

LHC ca. 1515 A.D.





S. Cittolin

Detectors are our eyes

- We as a field need to maintain and develop detector expertise. Today's detector marvels are not automatically reproducible by the next generation. Three essential elements:

1. Training, organizing and stimulating participation in instrumentation schools
2. Experimenting, encouraging young experimentalists to do hands-on detector work especially in smaller, shorter scale experiments
3. Rewarding, giving proper recognition of excellence in instrumentation development in careers at universities and research institutions.

Conclusions

- Accelerators provide unique tools to explore fundamental physics
- The current and near term program is strong and providing a wealth of important results
- For the longer term program a coherent global effort is needed to implement effective and affordable future machines

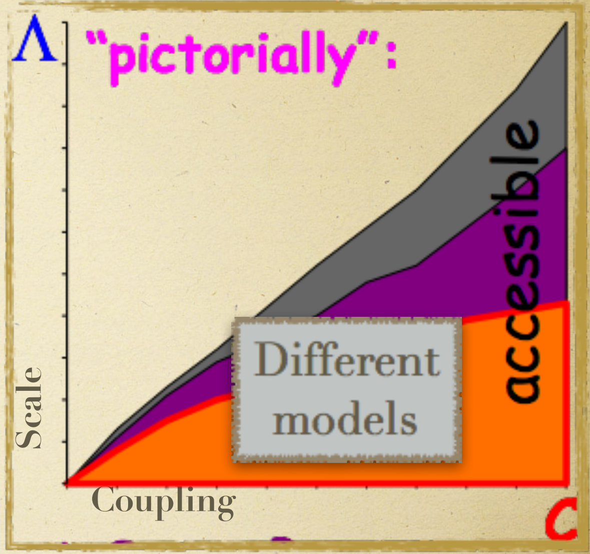
Sources

- I.Shipsey, Vision talk at ICHEP 2016.
- J.Hewett, Physics at the intensity frontier, Phenomelogy 2012 Symposium
- A.Masiero, Dove siamo e dove andiamo, Giornate del piano triennale 2015 INFN
- M.P.Mccullough, The new-physics landscape of HL-LHC, ECFA Workshop 2016
- F.Gianotti, Outlook: physics prospects at high-energy colliders, EPS 2015

Extras

Power of Intensity

- Precision measurements in the flavor sector are sensitive to New Physics (NP)
  - Interference effects in known processes
  - SM Rare or forbidden decays
- NP effects are controlled by
  - NP scale Λ and effective couplings: C
    - Different coupling intensity (different interactions)
    - Differente patterns (e.g. because of simmetries)
- With 5 to 10 x 10^{10} bb, cc, ττ pairs (50-100 ab^{-1}) one can:



LHC finds NP(Λ)

- Determine detailed structure of couplings of NP
- Look for heavier states
- Study NP flavour structure

LHC does not find NP(Λ)

- Look for indirect NP signals
- Connect them to models
- Exclude regions in parameters space

Some channels, such as the LFV decays of τ are unambiguous signals of NP

$L \sim 10^{34}\ cm^{-2}\ s^{-1} \leftrightarrow$ EW scale ~100GeV

$L \sim 10^{36}\ cm^{-2}\ s^{-1} \leftrightarrow$ TeV scale

7 NP physics questions

(See Youngjoon Kwon talk at Beauty 2014)

(1) Are there any new CPV phases?

(2) Any right-handed currents from NP?

(3) Quark FCNC beyond the SM? New operators with quarks enhanced by NP?

(4) Sources of LFV from NP?

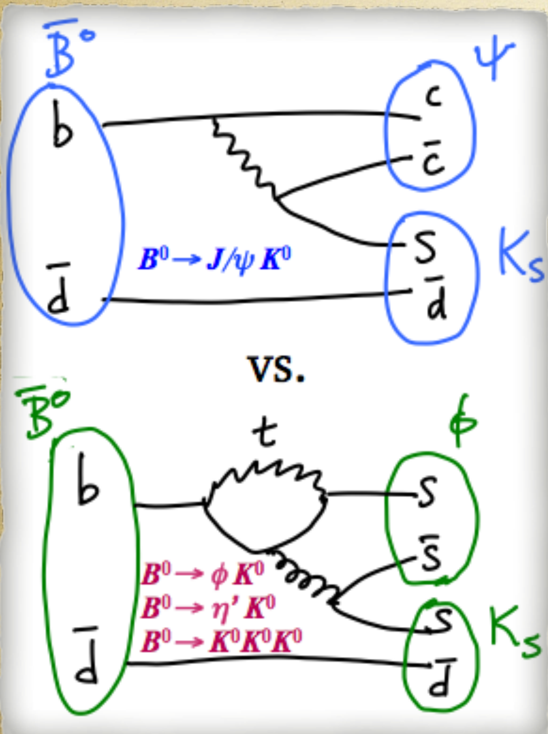
(5) Any more higgses? (e.g. H+)?

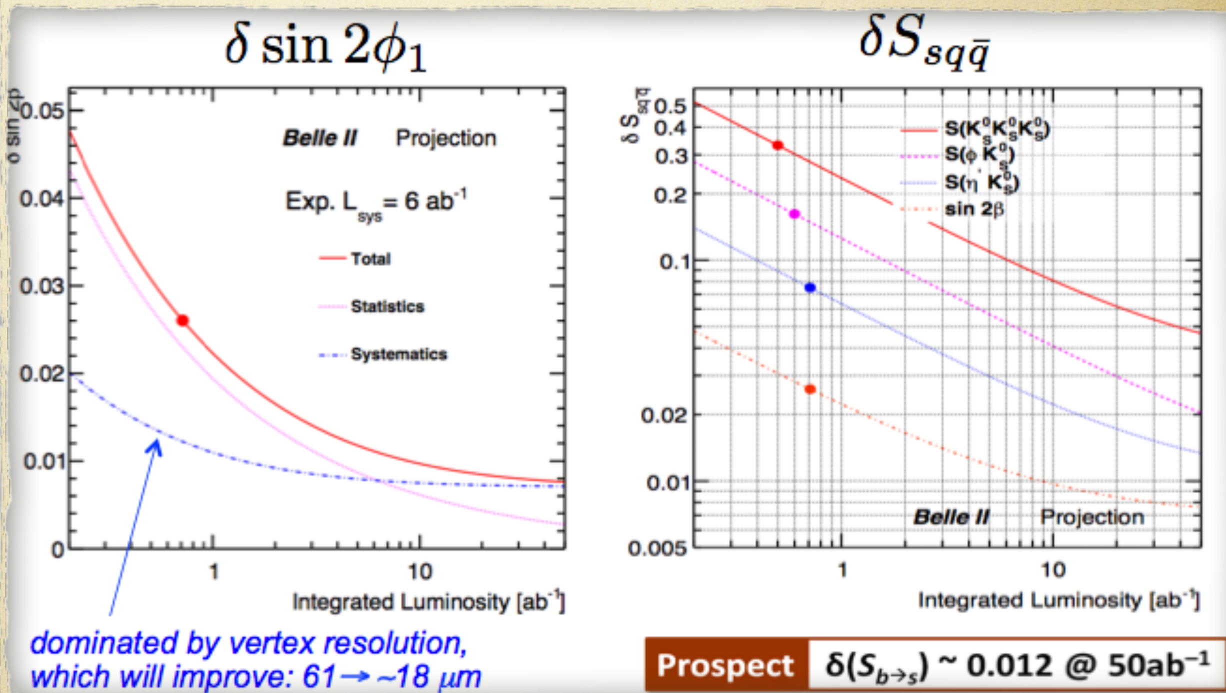
(6) Understanding exotic QCD states?

(7) Hidden dark sector?

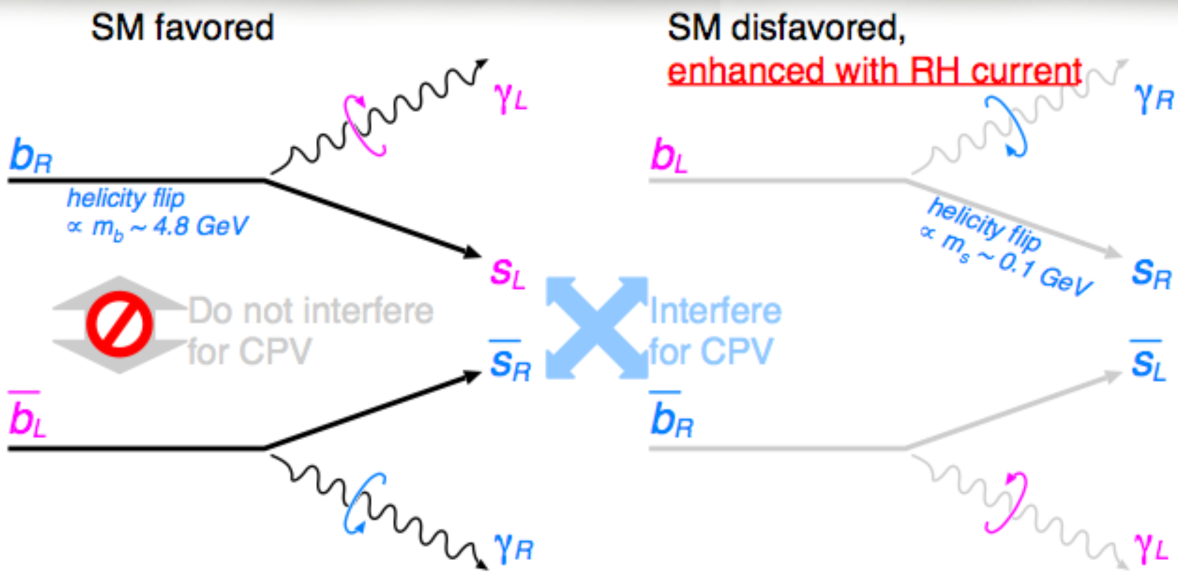
(1) Are there any new CPV phases?

$$\Delta S \equiv \sin 2\phi_{1,\mathrm{eff}}(b \to s\bar{s}s) - \sin 2\phi_1(b \to c\bar{c}s)$$





(2) Any right-handed currents from NP?



can be probed by t-dep. CP asymmetry with $B^0 \to K_S^0 \pi^0 \gamma$

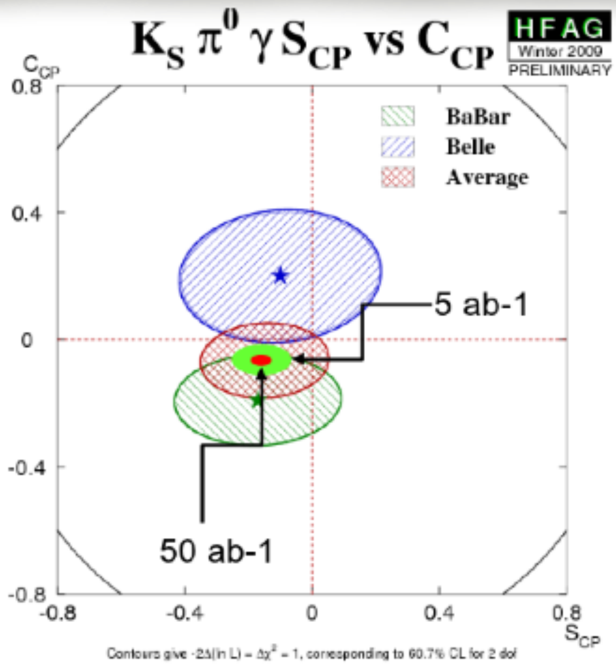
In SM, one naively expects:

$$S_{K_S^0\pi^0\gamma} = -2\frac{m_s}{m_b}\sin 2\phi_1 \sim -0.03$$

In a L-R symmetric model,

$$S_{K_S^0\pi^0\gamma} \sim 0.5$$

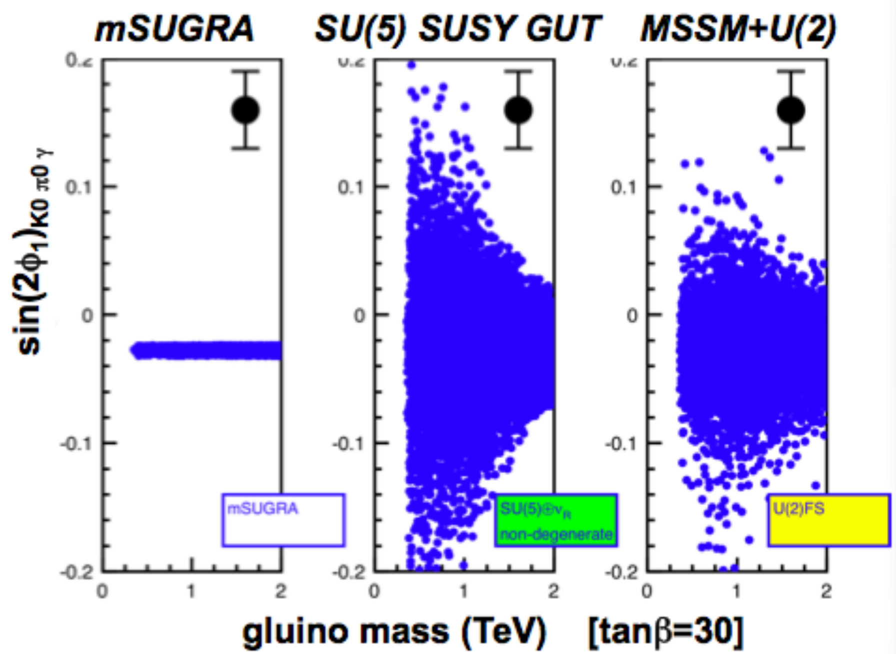
(2) Measure TDCP asymmetry in $B \to K_S \pi^0 \gamma$



$$S = -0.16 \pm 0.22, \quad C = -0.04 \pm 0.14$$

mostly statistics limited

$$\sigma(S_{K^*\gamma}) \sim 0.09 \text{ @ } 5\ \mathrm{ab}^{-1}$$
$$\sim 0.03 \text{ @ } 50\ \mathrm{ab}^{-1}$$



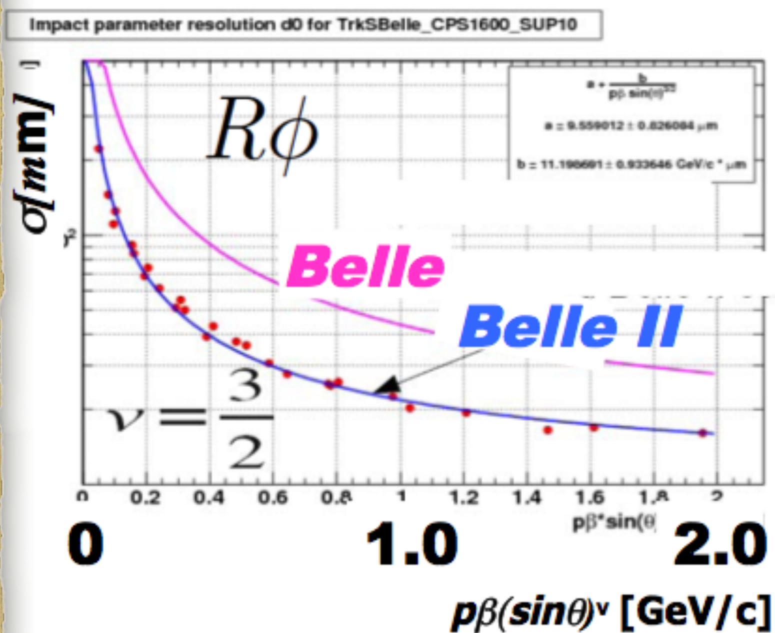
value of S can discriminate among SUSY-breaking mechanisms

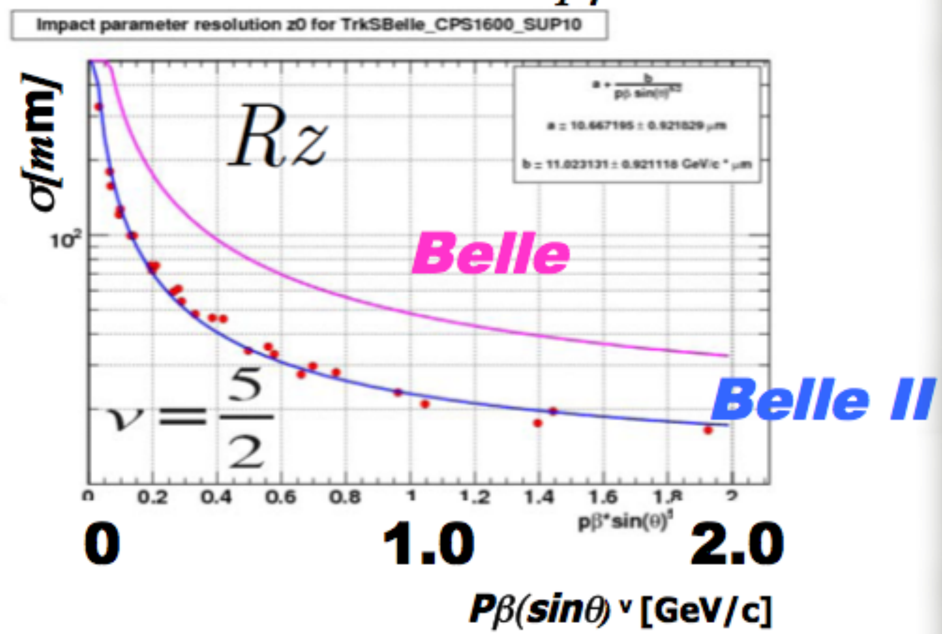
G. Buchalla et al., EPJC 57, 309 (2008)

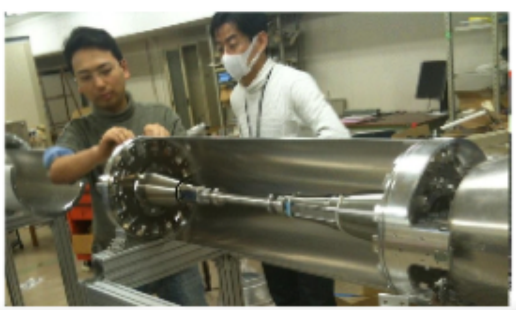
(2) Resolution improvements

Significant improvement in IP resolution:

$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$







Will improve analyses such as $B \rightarrow K_S \pi^0 \gamma$ (decay vertex determined by K_S and IP)

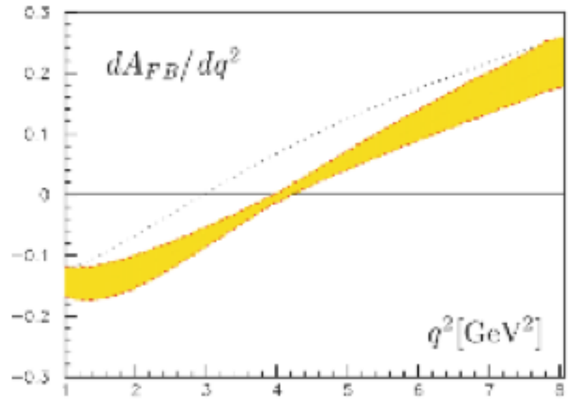
$C_{CP}(K_s\, \pi^0\gamma)$ = -0.07 ±0.12
$S_{CP}(K_s\, \pi^0\gamma)$ = -0.15 ±0.20 → 0.10 (5 fb^{-1})
→ 0.04 (50 fb^{-1})

(3) Quark FCNC beyond the SM? New operators with quarks enhanced by NP?

$b \to s\ell^+\ell^-$

$K^*\ell^+\ell^-$

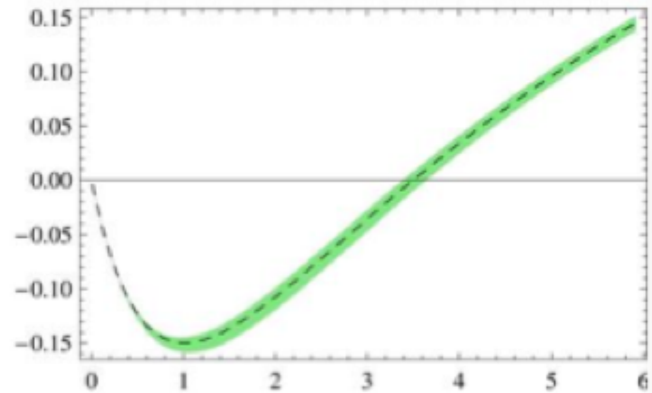
[Ali et al.,EPJ,C47(2006) 625]



$$q_0^2 = \left(4.07^{+0.16}_{-0.13}\right)\ \text{GeV}^2$$

$X_s\ell^+\ell^-$

[Huber et al., NPB 802 (2008) 40]



$$(q_0^2)_{\mu\mu} = (3.50 \pm 0.12)\ \text{GeV}^2$$

$$(q_0^2)_{ee} = (3.38 \pm 0.11)\ \text{GeV}^2$$

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$$

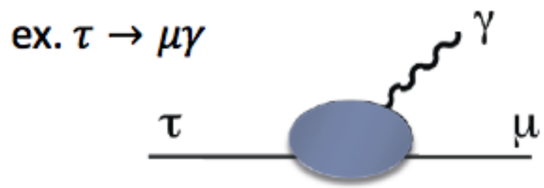
"×5 less signal (for e+e- mode) mainly due to low trigger and recon eff"

from M. D. Cian @ LHCP 2014

- With 'inclusive', theory band is much narrower ➔ **unique for Belle II**
- Belle II can be competitive for R_K, R_{K^*} with excellent electron ID

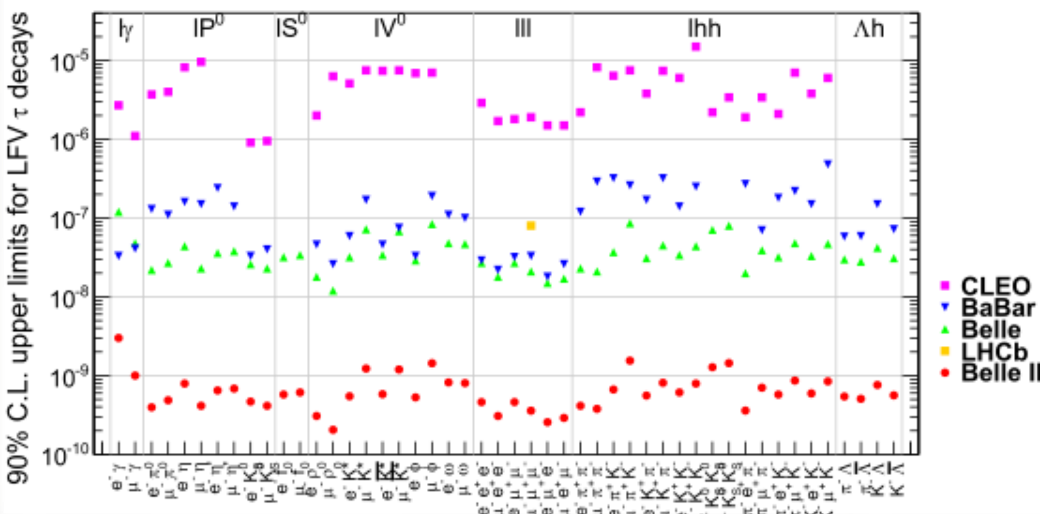
(4) Sources of LFV from NP?

ex. $\tau \to \mu\gamma$

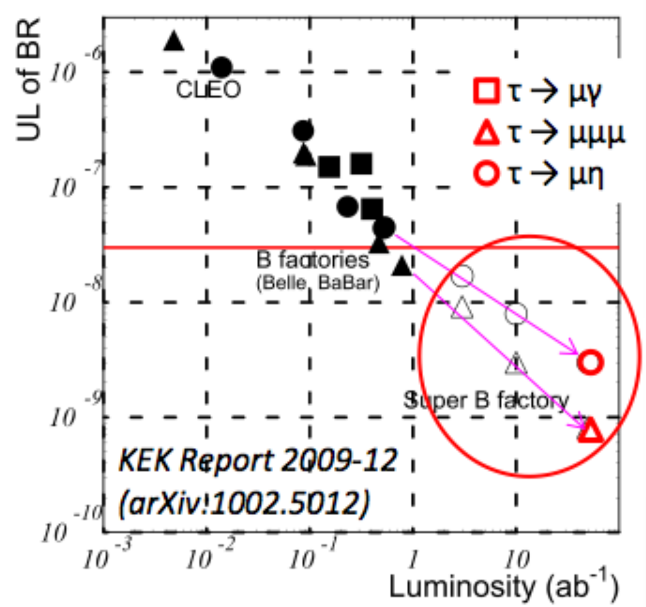


model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z′	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

- Suppressed LFV through ν mixing ~ 10^{-53} - 10^{-49}
- New Physics models generates LFV ~ 10^{-9} - 10^{-7}
  - Enhances in the loop diagram
- Belle II has sensitivity on the τ decays



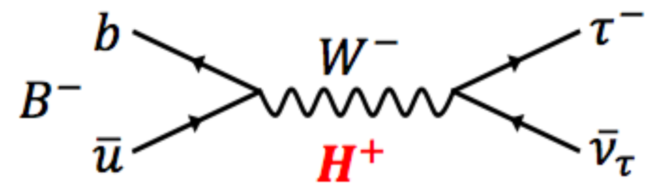
KEK Report 2009-12 (arXiv:1002.5012)



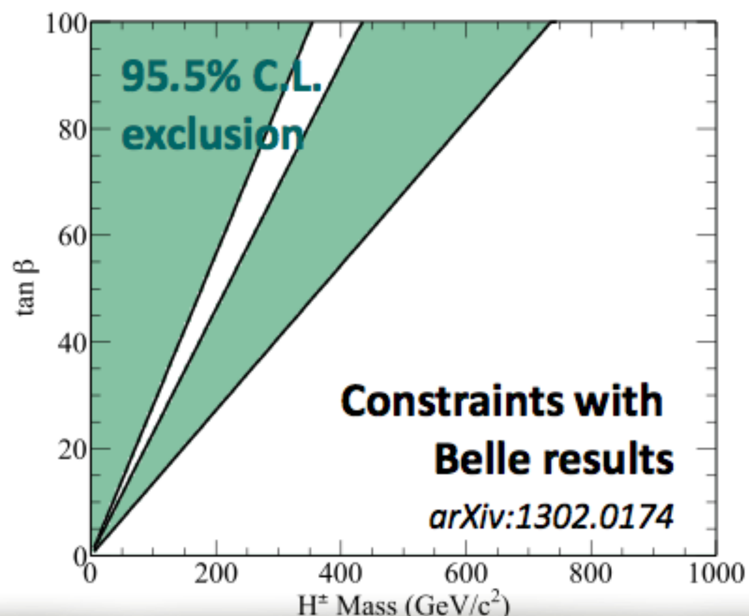
(5) Any more higgses? (e.g. H+)?

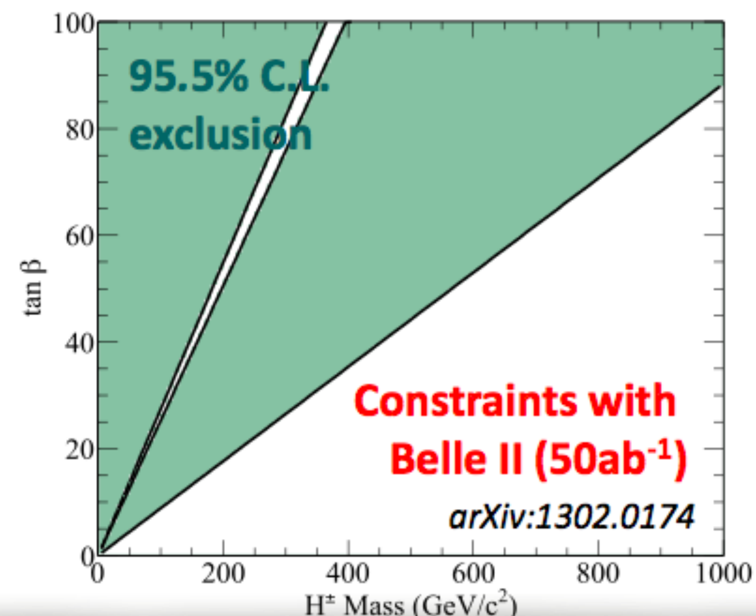
- Two Higgs Doublet Model (THDM) Type II modifies $Br(B \to \tau\nu)$

$$r_H = \frac{Br(B \to \tau\nu)}{Br(B \to \tau\nu)_{SM}} = \boxed{\left(1 - \frac{m_B^2}{m_{H_\pm}^2}\tan^2\beta\right)^2}$$

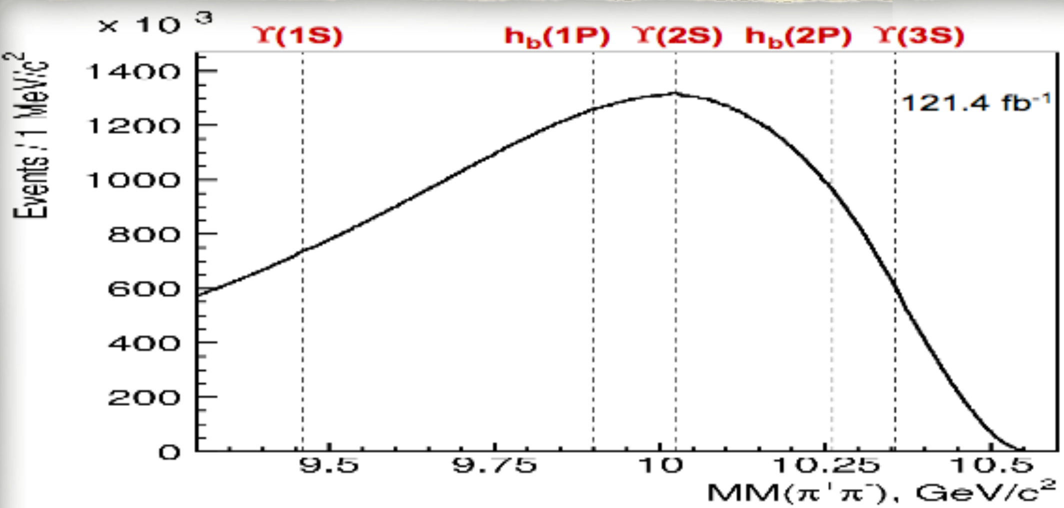


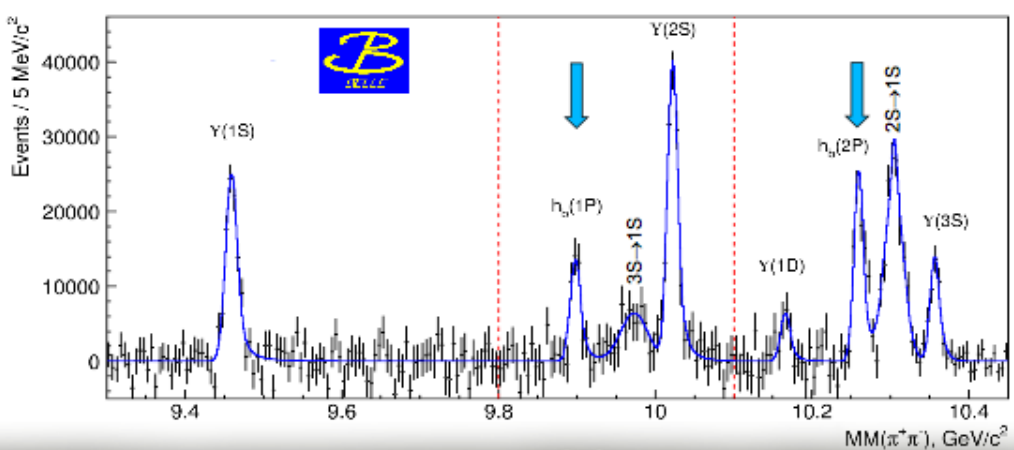
- Strong constraints on m_H and $\tan\beta$ is expected at 50 ab^{-1}





(6) Understanding exotic QCD states?



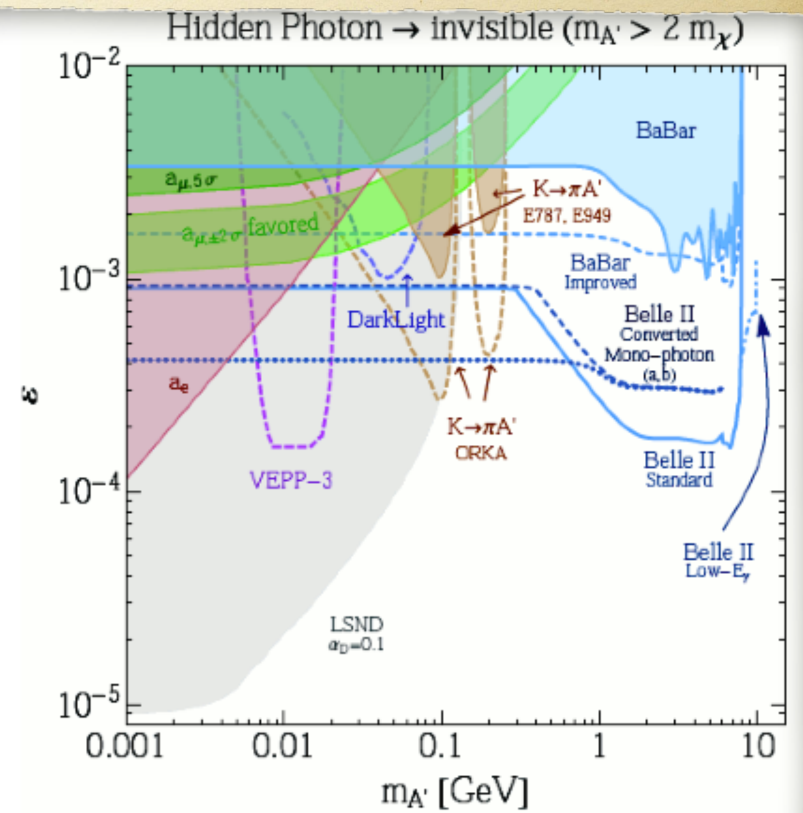


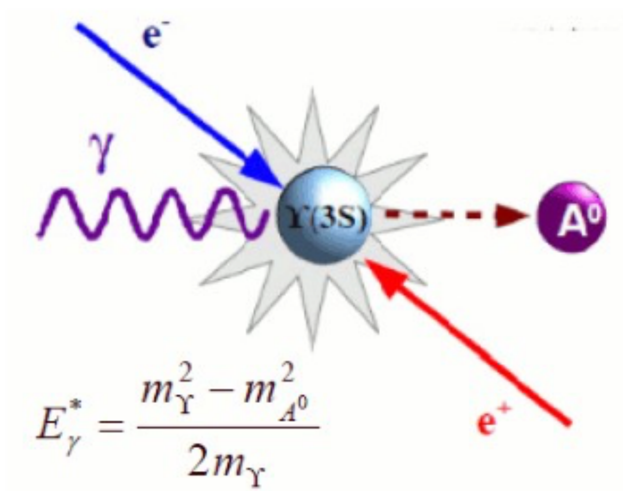
- look for signals in the missing (recoil) mass against $\pi^+\pi^-$ $\Upsilon(5S) \to (\cdots)\pi^+\pi^-$
- lead to discoveries of $h_b(1P)$ and $h_b(2P)$
- and, consequent discoveries of exotic Z_b^+ states in $h_b(1,2P)\pi^+$

* **hermeticity** of Belle II gives a great potential to discover and understand exotic QCD states

(7) Hidden dark sector?

- **Hidden dark sector?**
  - low-mass Higgs in Υ(nS) decays
    (NMSSM models w/ light CP-odd Higgs)
  - U(1) gauge boson in the dark sector ("dark forces")





$$e^+e^- \to \Upsilon(nS) \to \gamma A^0$$

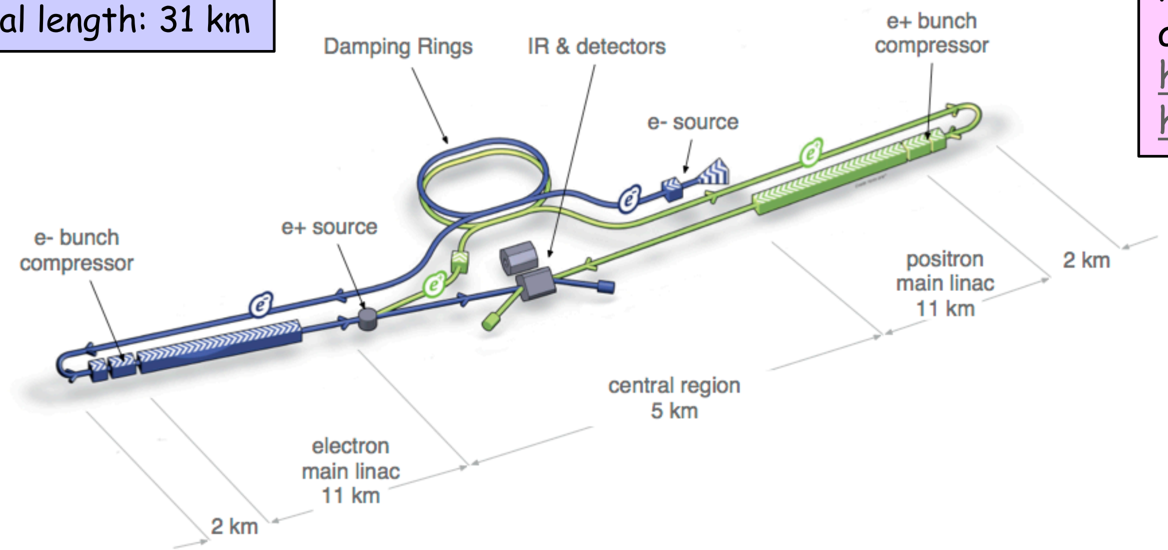
- Trigger can be an outstanding concern:
  * 1 photon + missing-E
  * low mass $\pi^+\pi^-$
  * 1 photon + 2 tracks + missing-E

International Linear Collider (ILC)

Technical Design Report June 2013

Most recent operating scenarios and physics results:
http://arxiv.org/abs/1506.07830
http://arxiv.org/abs/1506.05992

Total length: 31 km



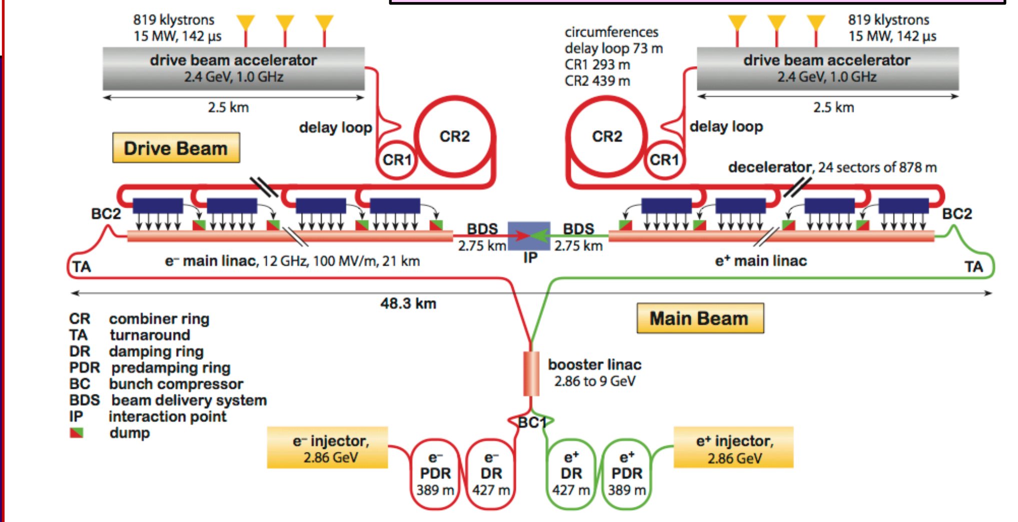
Most recent operating scenarios (~ 20 year programme):
- start at $\sqrt{s}$= 500 GeV (500 fb^{-1}), then 350 GeV (200 fb^{-1}), then 250 GeV (500 fb^{-1})
- L upgrade (double # of bunches): add 3500 (1500) fb^{-1} at 500 (250) GeV

- 500 GeV machine: ~ 15000 SCRF cavities, 31.5 MV/m
  Mature technology (20 years of R&D experience worldwide). European xFEL at DESY is 5% -scale "ILC prototype" (needed gradient 24 MV/m, several cavities reach 30 MV/m)
- 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- Challenges: positron source; final focus (squeeze and collide nm-size beams)

- Japan interested to host → decision based also on ongoing international discussions
- Construction could technically start as soon as decision taken, duration ~10 years
  → physics could start ~2030

Compact Linear Collider (CLIC)

Conceptual Design Report end 2012



Main challenges:

- 100 MV/m accelerating gradient needed for compact (50 km) multi-TeV (up to 3 TeV) collider
- Keep RF breakdown rate small
- Short (156 ns) beam trains → bunch spacing 0.5 ns to maximize luminosity
- 2-beam acceleration (new concept): efficient RF power transfer from low-E high-intensity drive beam to (warm) accelerating structures for main beam
- Power consumption (600 MW at 3 TeV): reduction under investigation
- nm size beams; final focus
- Detectors: huge beamstrahlung (20 TeV per train in calorimeters at 3 TeV) → 1-10 ns time stamps needed

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

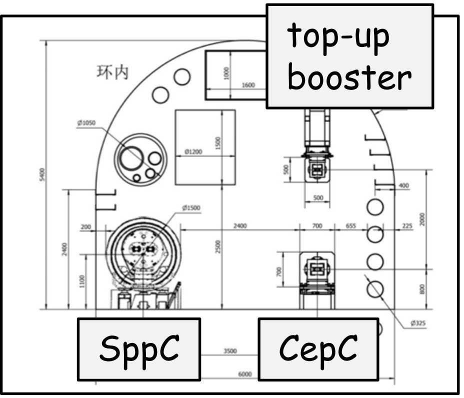
- Most recent operating scenario: start at √s=380 GeV for H and top physics
- If decision to proceed in ~ 2019 → construction could technically start ~2025, duration ~6 years for √s ~ 380 GeV (11 km Linac) → physics could start before 2035

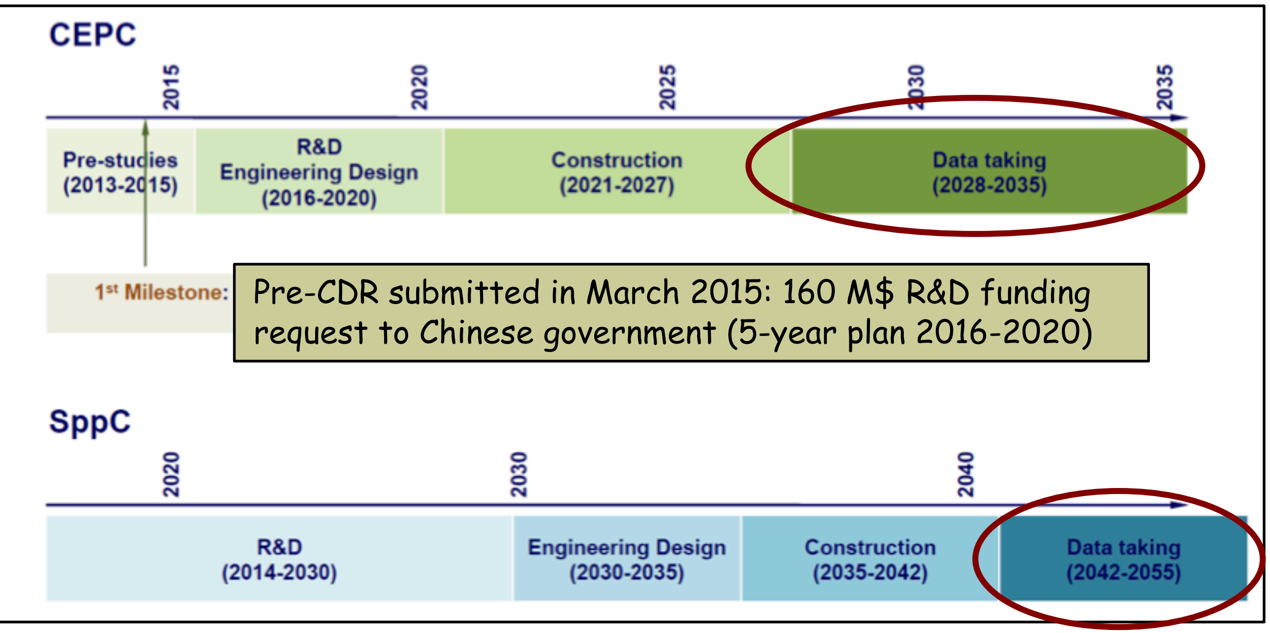
Circular colliders: the Chinese CepC, SppC

http://cepc.ihep.ac.cn/preCDR/volume.html

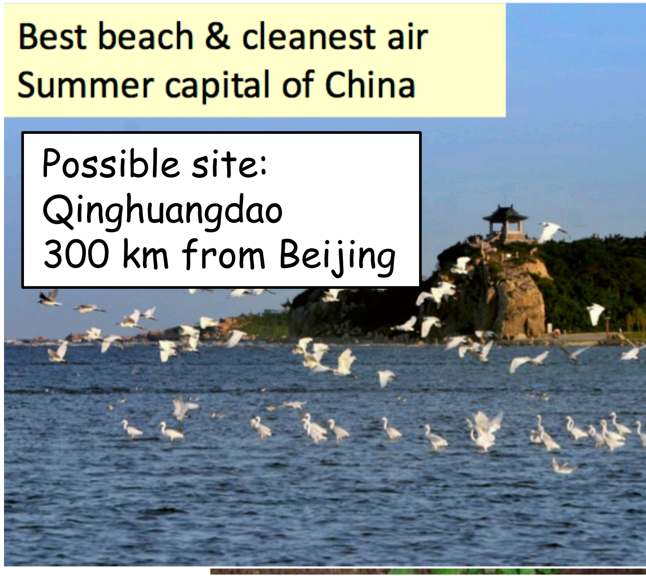
Baseline: 54 km ring
- CepC: $\sqrt{s}$=240 GeV e^+e^- ; L=2x10^{34}; 2 IP
- SppC: $\sqrt{s}$ = 70 TeV pp collider; L=1.2x10^{35}; 2 IP

If more funding: 100 km ring (→ 100-140 TeV pp) and/or separate pipes for e^+/e^- beams (→ not limited to 50 bunches/beam → higher L)





Pre-CDR submitted in March 2015: 160 M$ R&D funding request to Chinese government (5-year plan 2016-2020)



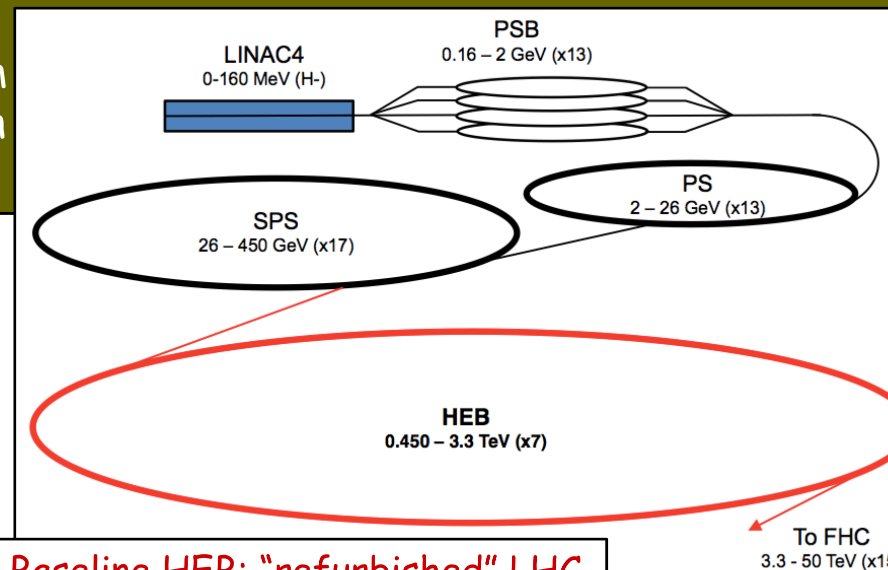
Circular colliders: the CERN FCC project

International conceptual design study for Future Circular Colliders in a ~100 km ring:

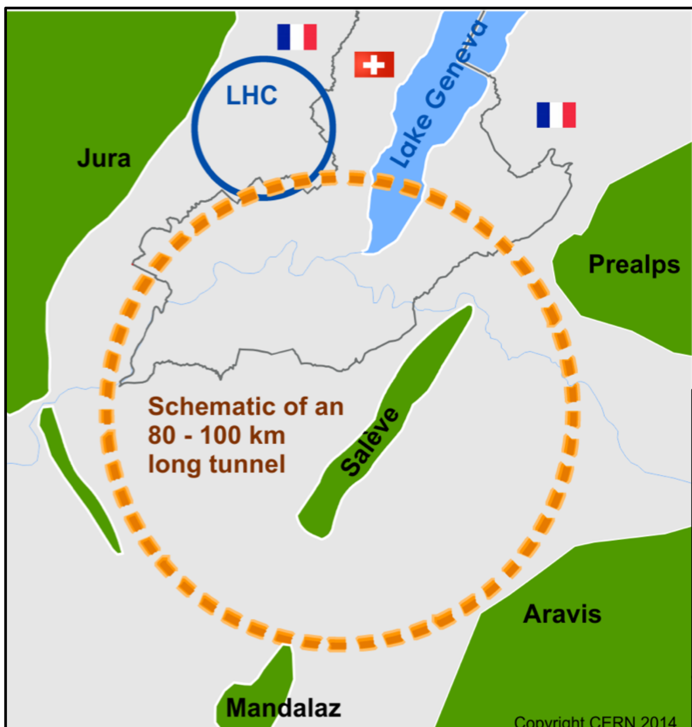
- ❑ goal: pp, $\sqrt{s}$ = 100 TeV (FCC-hh), L~2.5x10^{35}; 4 IP (some general-purpose, some specific)
- ❑ possible intermediate step: e^+e^-, $\sqrt{s}$=90-350 GeV (FCC-ee), L=2x10^{36}-2x10^{34}, 2-4 IP
- ❑ option: ep, $\sqrt{s}$= 3.5 TeV (FCC-eh), L~10^{34}

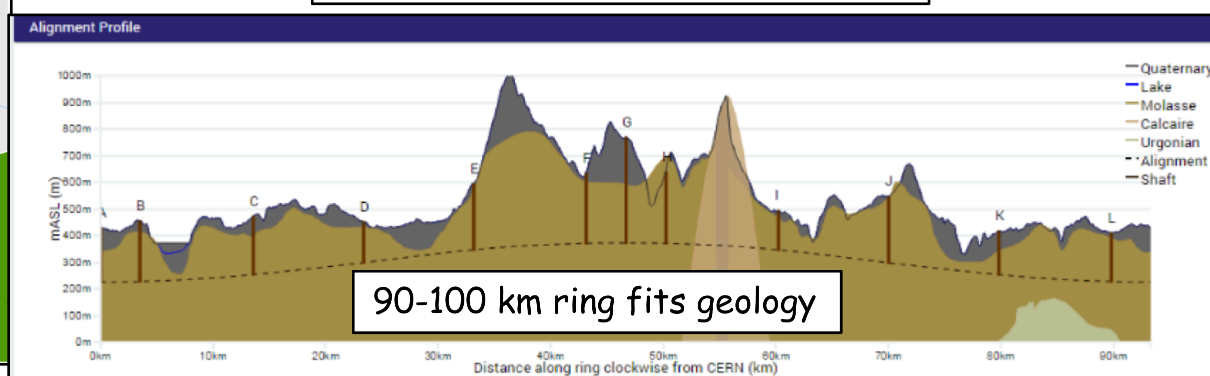
Goal of the study: CDR in ~2018

Machine studies are site-neutral.
However, FCC at CERN would greatly benefit from existing infrastructure (e.g. FCC-hh injector chain would be based on existing accelerator complex)



Baseline HEB: “refurbished” LHC





90-100 km ring fits geology

Future pp colliders

Pioneering work started in the US in 1998 with VLHC: http://vlhc.org/vlhc/

	Ring (km)	$\sqrt{s}$ (TeV)	Field (T)	Magnet technology	L (10^{34})
LHC (for comparison)	27	14	8.3	NbTi	up to 5
HE-LHC	27	26-33	16-20		~5
SppC If enough funds	54 100	70 100-140	20	Nb_3Sn with HTS inserts	12
FCC-hh	100	100	16	Nb_3Sn (with NbTi)	5-20

$5\text{x}10^{34}$ operation	HL-LHC	FCC-hh
Bunch spacing	25	25*
N. of bunches	2808	10600
Pile-up.x-ing	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

Many big technical challenges: technology of bending dipoles (Nb_3Sn ok up to ~16T, HTS needed for 20T), SR and beam screen, stored beam energy, radiation, …

* 5 ns considered for $L=2\text{x}10^{35}$ to mitigate pile-up

Projected integrated luminosities for current operating scenarios

Integrated luminosities (ab^{-1})

$\sqrt{s}$	90	~240	350-380	500	1.4	3	70	100	Total $\int L dt$ at $\sqrt{s}$>240 GeV	# of years	# H events at production
	GeV				TeV						
FCC-ee	90(*)	10	3						13	~7-15	2 M
CepC		5							5	~10	1 M
ILC		2	0.2	4					6.2	~20	1.6 M
CLIC			0.5		1.5	2			4	~20	1.5 M
SppC							30		30	~10	30 B
FCC-hh								40	40	~25	40 B

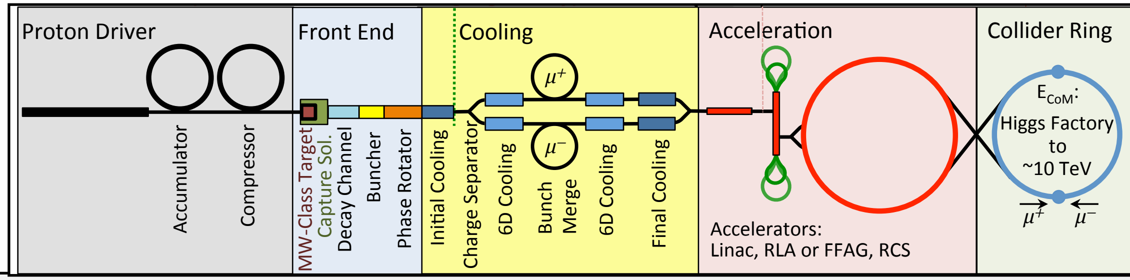
(*) 4×10^{12} Z

2 experiments assumed for CepC, SppC and FCC-hh, 2-4 for FCC-ee
L upgrade assumed for ILC and crab waist option for FCC-ee
FCC-ee run at 160 GeV not included

Note:

- Scenarios (revised after H discovery) will evolve based also on future LHC results
- Different definitions of "year" across projects: assumed physics data-taking time varies over 0.5-1.6x10^7 s/year
  Note: LHC 2012: 0.6x10^7 s of machine operation in physics with stable beams
- pp colliders: usable H events are ~ 10% of total cross-section due to large backgrounds
- H studies are only one of several physics goals

Muon colliders



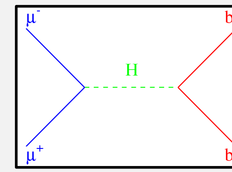
Synergies with neutrino factories

Main advantage compared to e^+e^- colliders: $m_\mu \sim 200\ m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

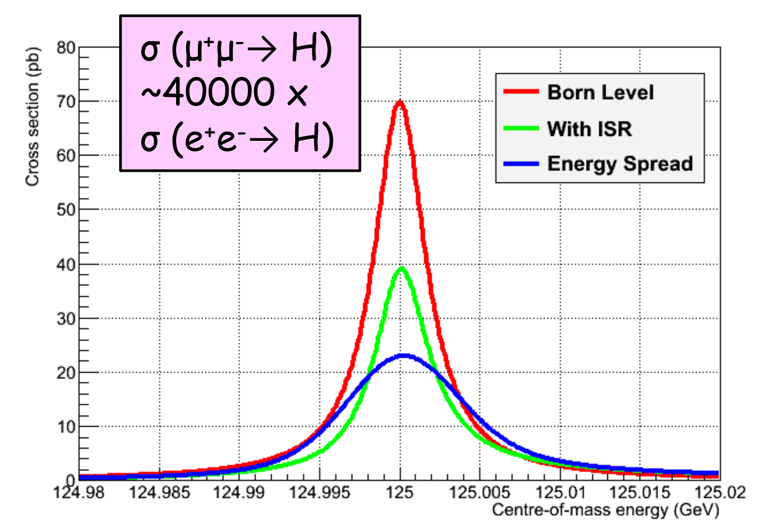
→ $\sigma(\mu\mu \to H) \sim 20$ pb (s-channel resonant production) → H factory



Main challenge: produce high-intensity, low E-spread beams:

- ❑ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of $\sim 3\times10^{-5}$ (for precise line shape studies) and high L
- ❑ $\tau_\mu \sim 2.2\ \mu s$ → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of $\sim 3\times10^{-5}$ would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances



However, with currently projected L (~10^{32}): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)

More R&D needed to demonstrated feasibility, in particular cooling: linear systems (MICE at RAL), rings (recently re-ignited by C.Rubbia)