Future Directions in Experimental High Energy Physics

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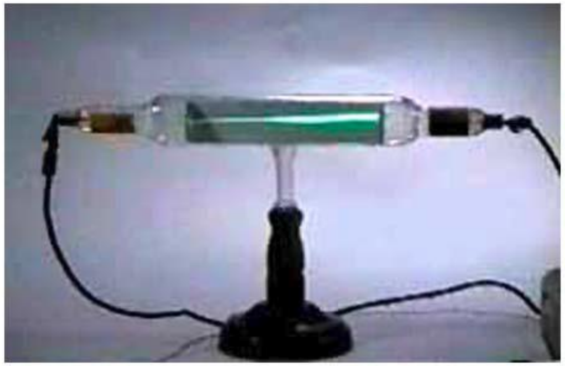
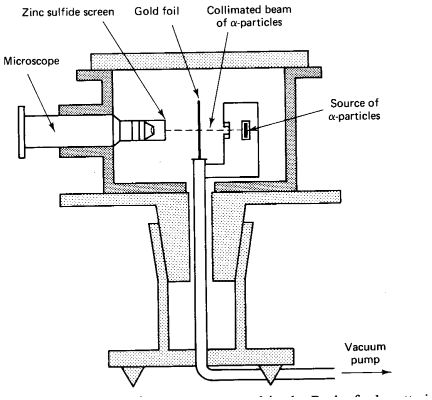
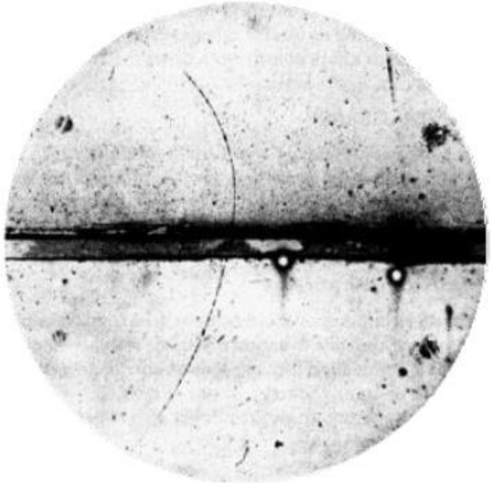
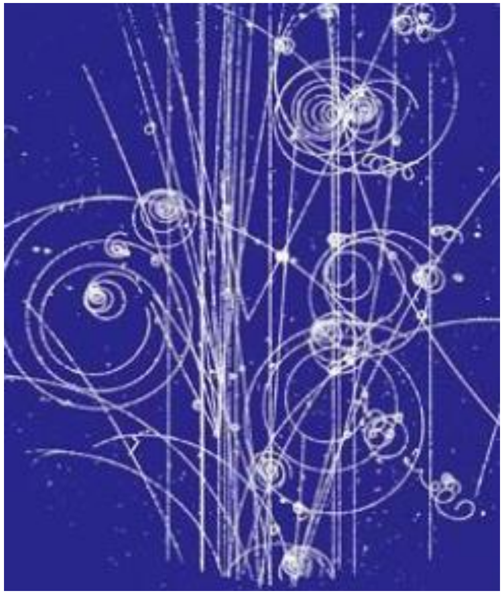
Candles of Darkness, Discussion Meeting
9 June, 2017, ICTS-TIFR, Bengaluru

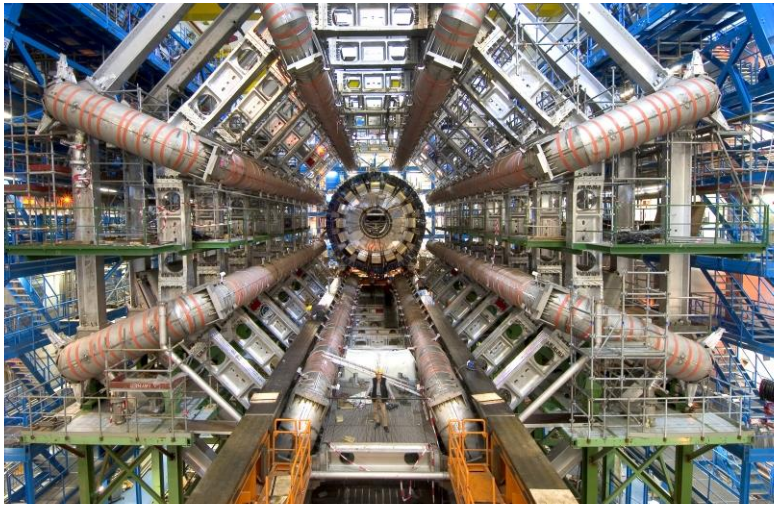
Evolution of our tools for discovery (Detectors)



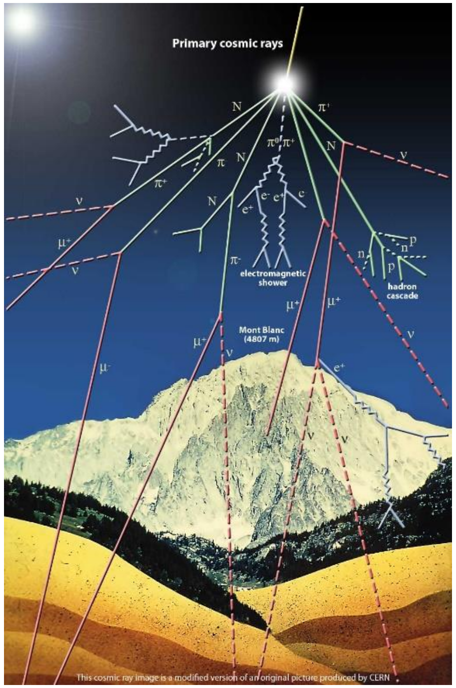




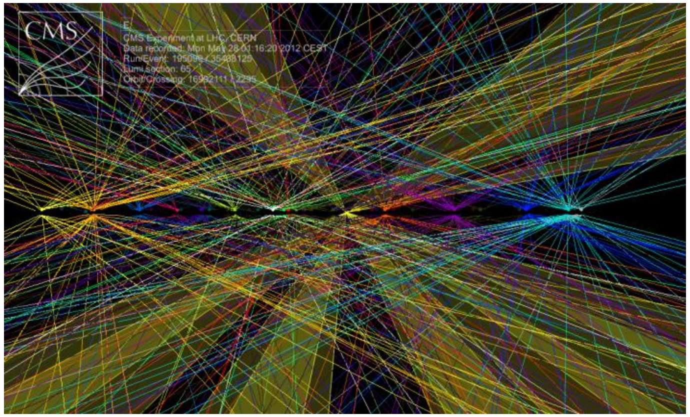




Evolution of our tools for discovery (Accelerators)



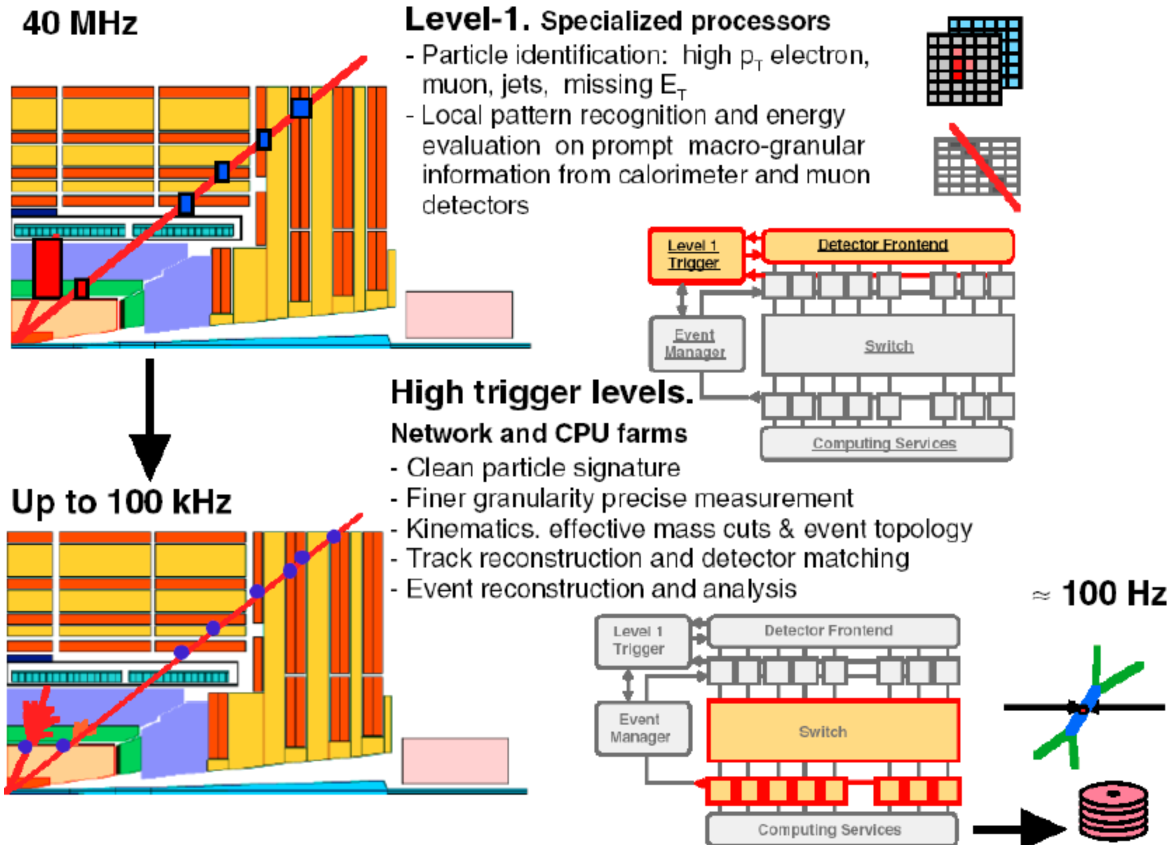
Evolution of our tools for discovery (Data collection)



Bubble Chambers, Cloud Chambers, etc.

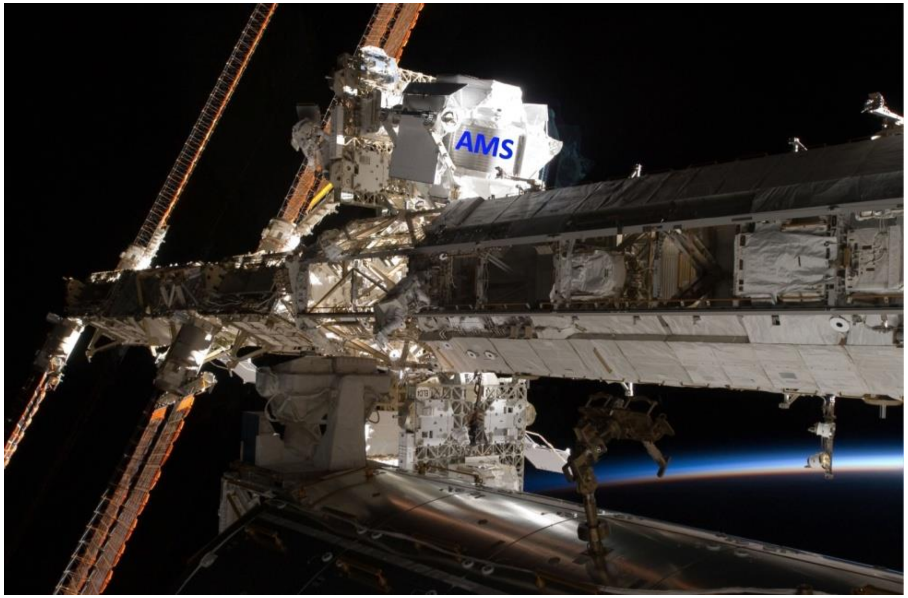
– DAQ was a stereo photograph!

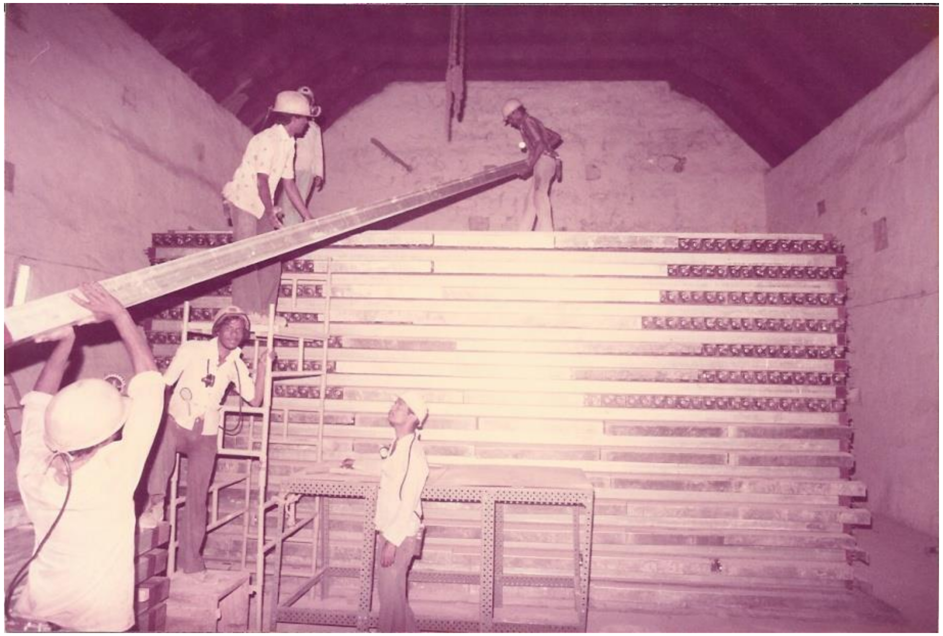
– Effectively no Trigger:



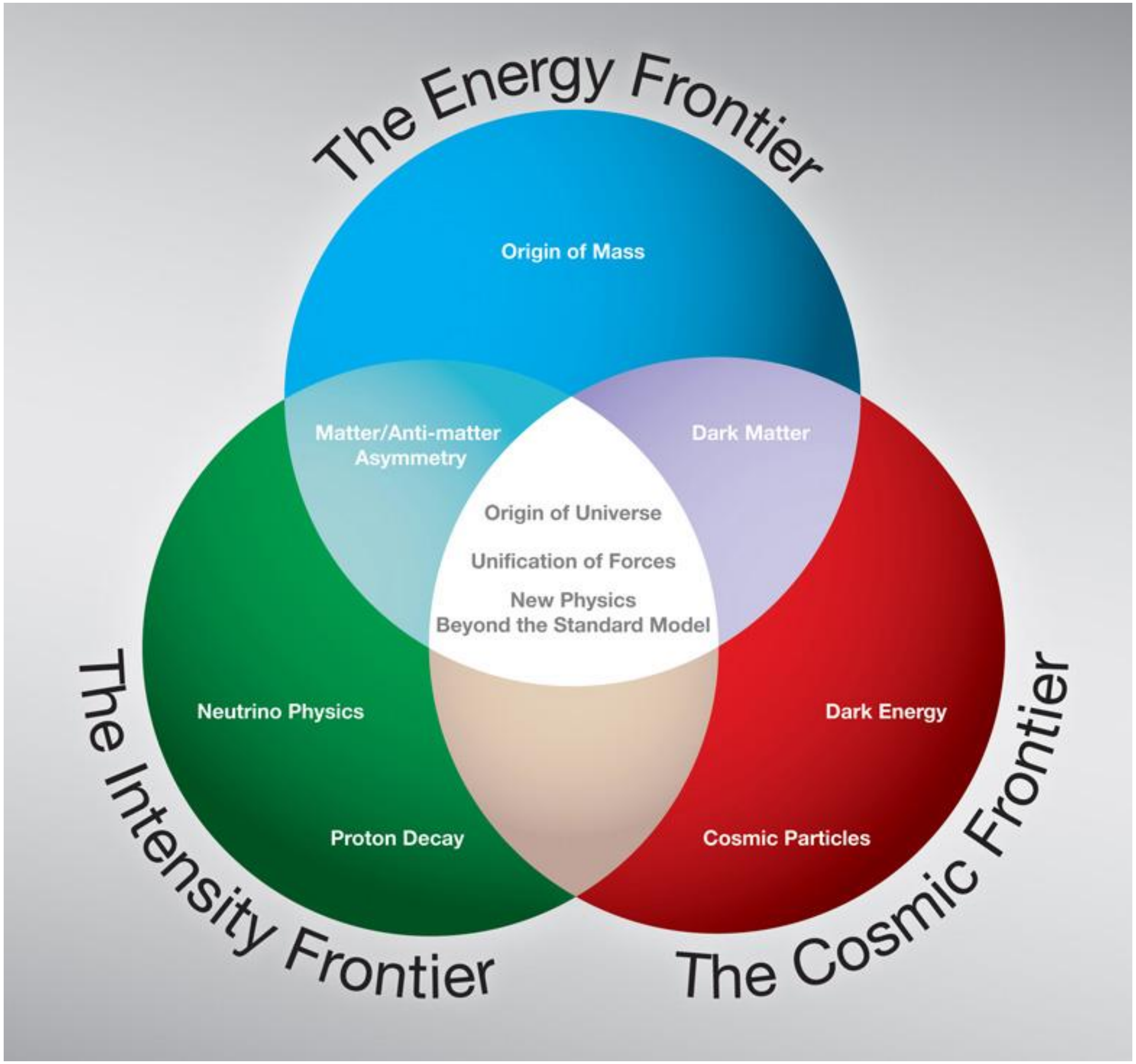
From individual efforts to global enterprises

From Space to Deep Underground

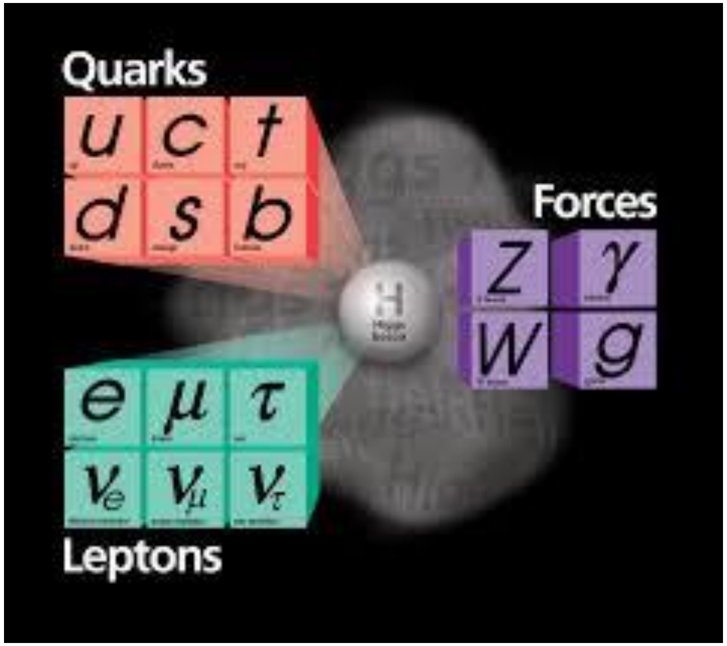


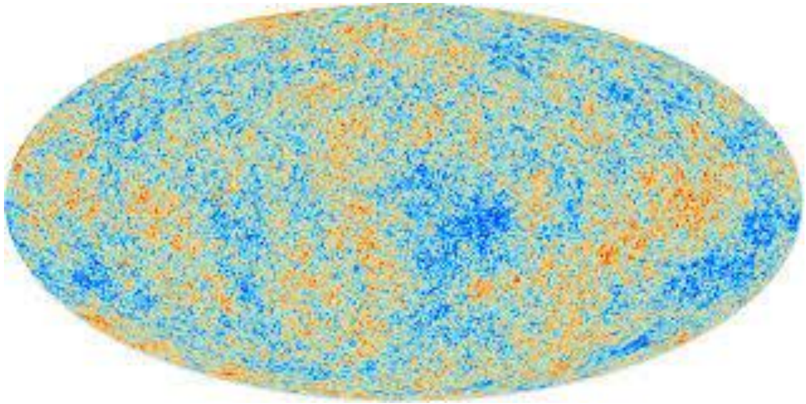


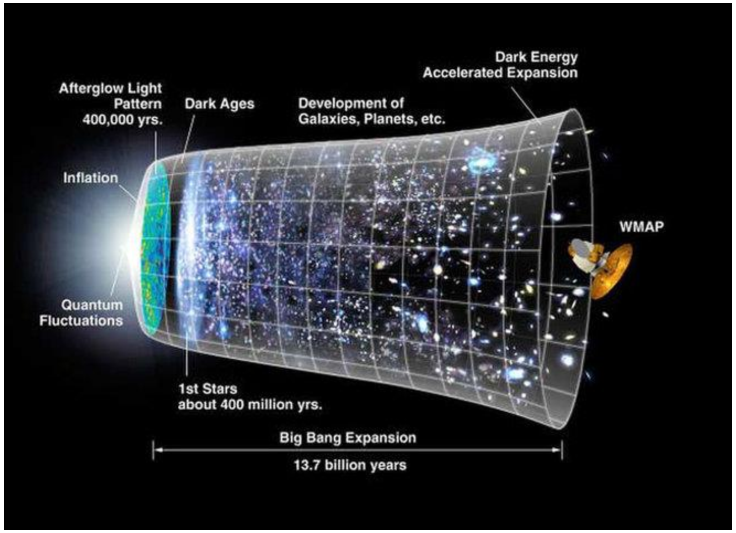
Three Frontiers of Particle Physics

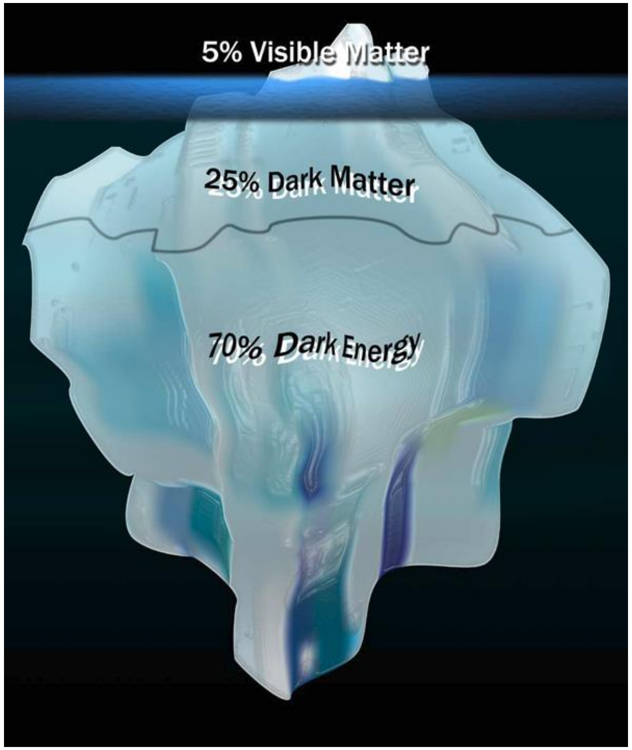


Understanding building blocks of matter to understand our Universe









Benefits of particle physics research for society

Bob Wilson (first Director of Fermilab) who, when asked by a Congressional Committee "What will your lab contribute to the defense of the US?", replied "Nothing, but it will make it worth defending".

Bob Wilson is known as the father of proton therapy for his 1946 paper on "Radiological use of fast Protons" which first suggested the idea of using protons for medical treatment.

Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University

Cambridge, Massachusetts

EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has in

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate intensely a strictly localized

The Neutron therapy facility at Fermi lab treated its first patient on September 7, 1976. In 1989 Fermilab designed and built a Proton Accelerator for Loma Linda University Medical Centre – the first hospital based proton therapy centre

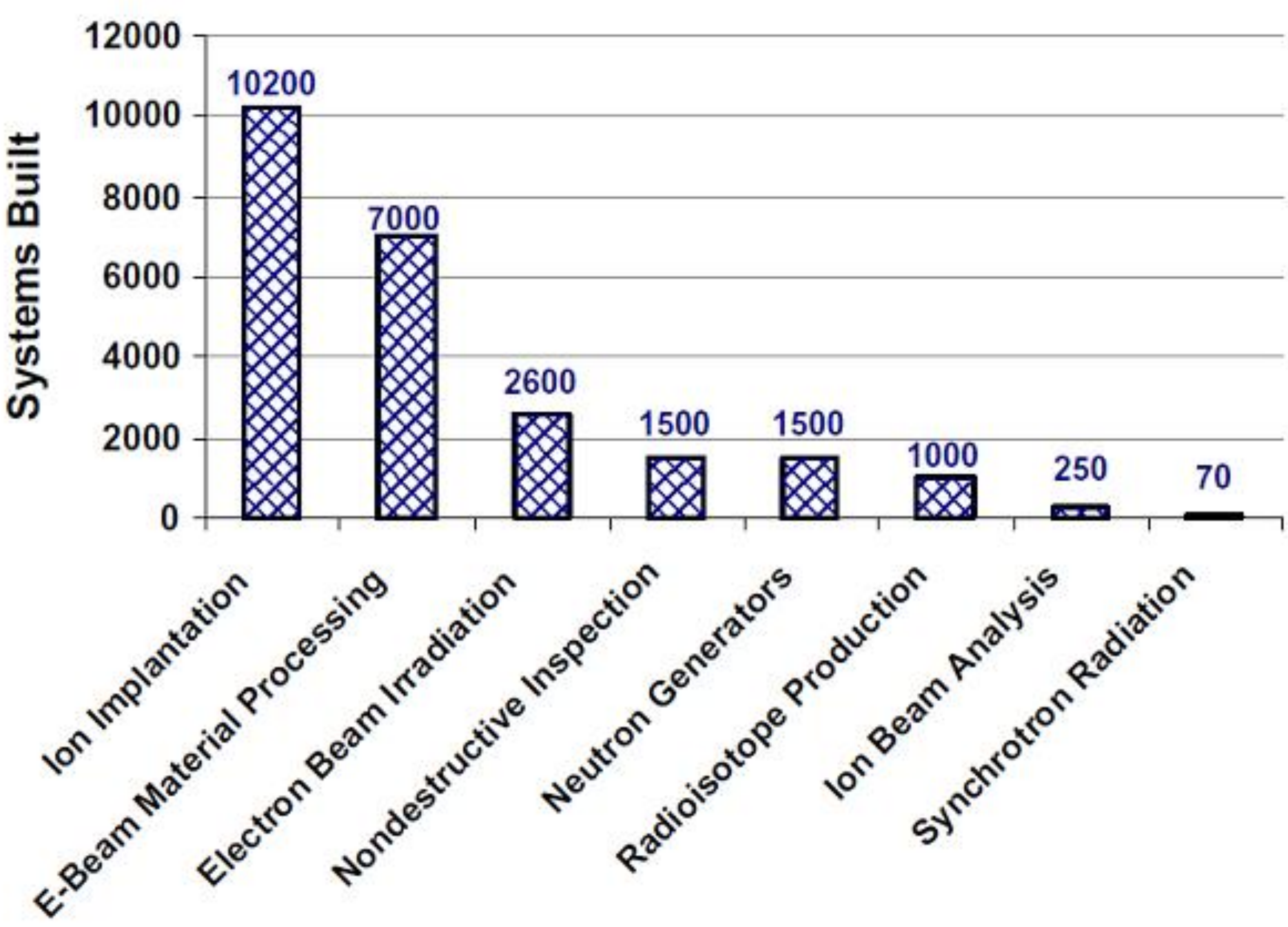
Current : 58 Under construction : 52

Societal application

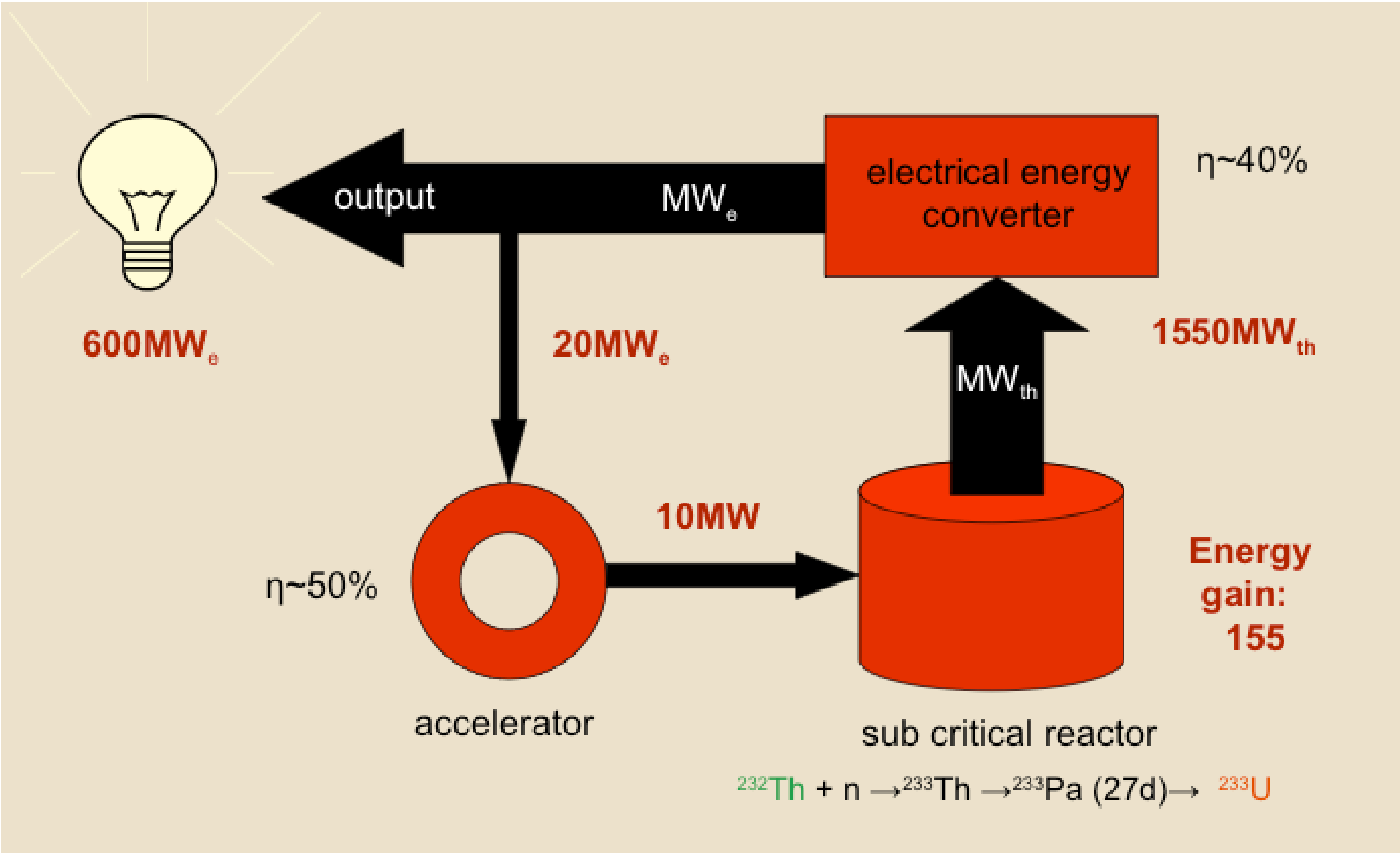
Now there are over 20,000 accelerators in the world :

- *Generating radio-isotopes for medical imaging*
- *Generating X-rays for medical and material imaging*
- *Generating electrons to strengthen heat-shrink tubing*
- *Generating X-rays for food sterilisation*
- *Accelerating ions to implant semi-conductors*
- *Accelerating ions to silver-coat heart valves*
- *High intensity super-conducting X-ray synchrotrons for material/medical research*

Non-particle physics application of accelerators

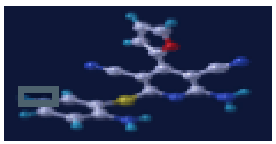


Thorium Reactor

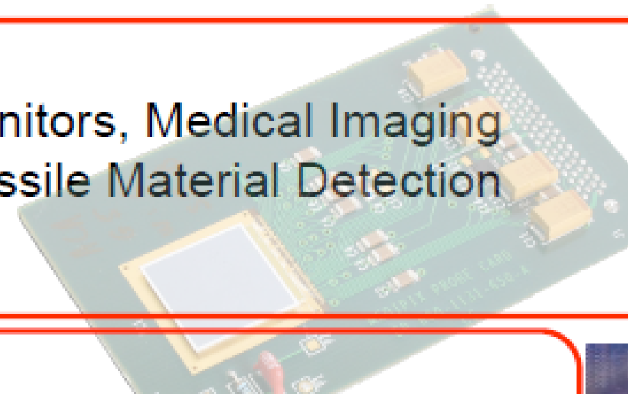


Technological Application

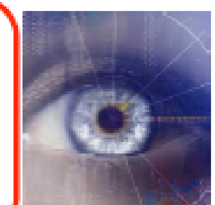
Accelerators →
- Cancer Therapy; Pharmaceutical Imaging
- Food Sterilisation; Nuclear Waste Transmutation
- Nuclear Thorium Reactors
- Ion Doping of Semiconductors



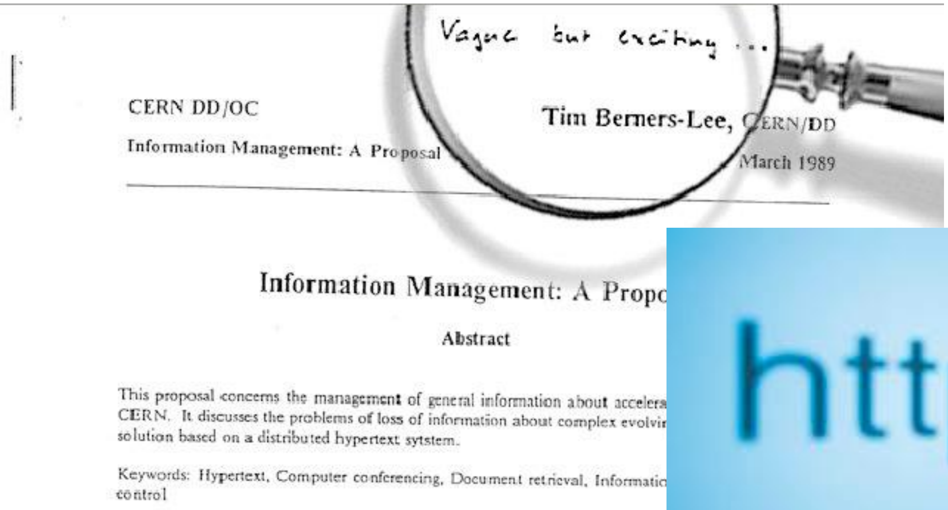
Radiation Detectors →
- Radiation Dose Monitors, Medical Imaging
- Cargo scanners, Fissile Material Detection



MicroElectronics →
- Eye Implants, Radiation tolerant PCBs
- Pixel medical detectors



Advanced Computing →
- New drug simulations
- Design of new medical treatments



Vague but exciting ...

CERN DD/OC

Information Management: A Proposal

Tim Berners-Lee, CERN/DD

March 1989

Information Management: A Propo

Abstract

This proposal concerns the management of general information about accelera
CERN. It discusses the problems of loss of information about complex evolvi
solution based on a distributed hypertext sytstem.

Keywords: Hypertext, Computer conferencing, Document retrieval, Informatic
control

"The quest for fundamental knowledge as embodied by particle physics is the hallmark of a civilised nation. Difficult questions in basic science require innovative technical solutions and a wide range of science disciplines have benefited from the technological advances generated by studies in particle physics."

Sir Paul Nurse: Nobel Laureate (2001) in Physiology or Medicine

Outstanding questions in particle physics today

Higgs boson and EWSB
- m_H natural or fine-tuned ?
- ->if natural: what new physics/symmetry?
- does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? or is there a new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition

Dark matter:
- composition: WIMP, sterile neutrinos,
- axions, other hidden sector particles, one type or more ?
- only gravitational or other interactions ?

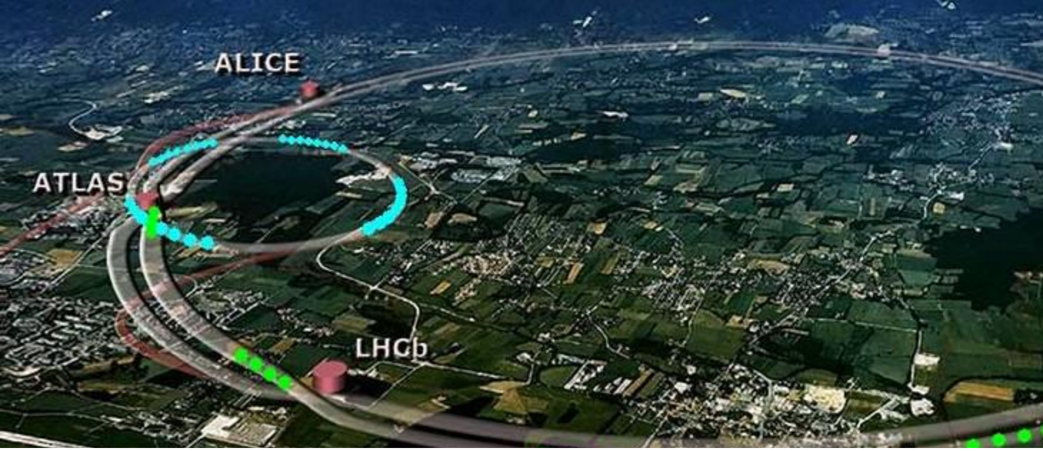
The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

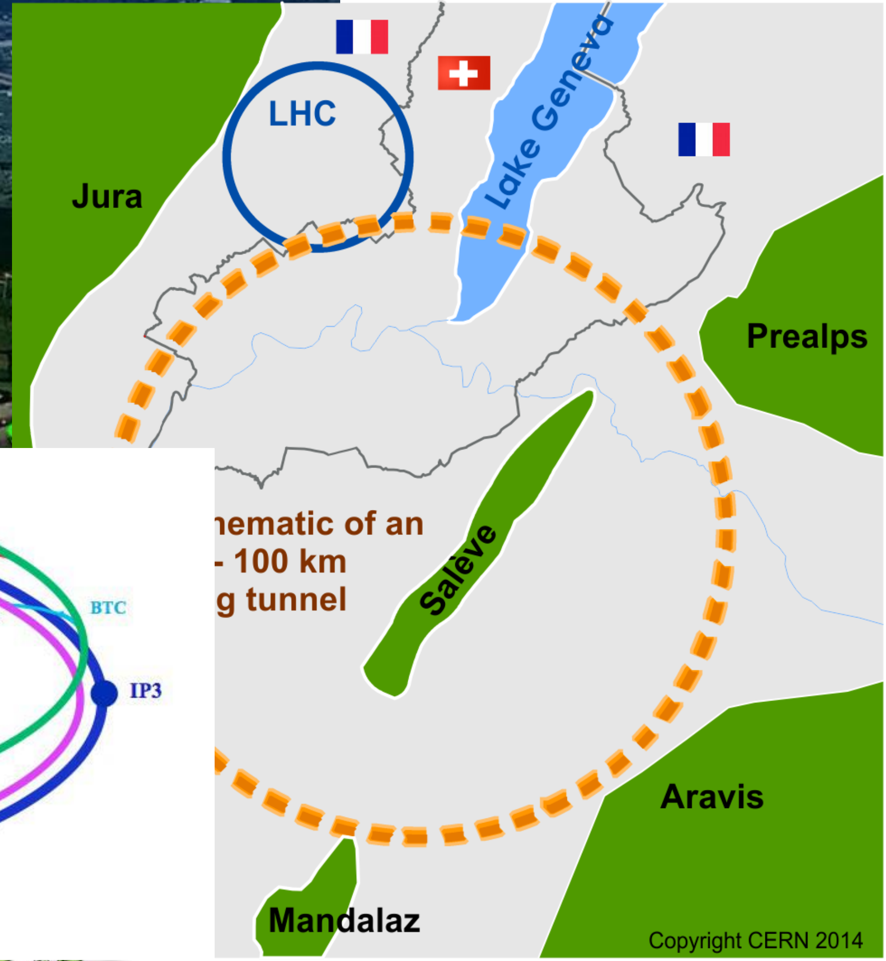
Quarks and leptons:
- why 3 families ?
- masses and mixing
- *CP violation in the lepton sector*
- matter and antimatter asymmetry
- baryon and charged lepton number violation

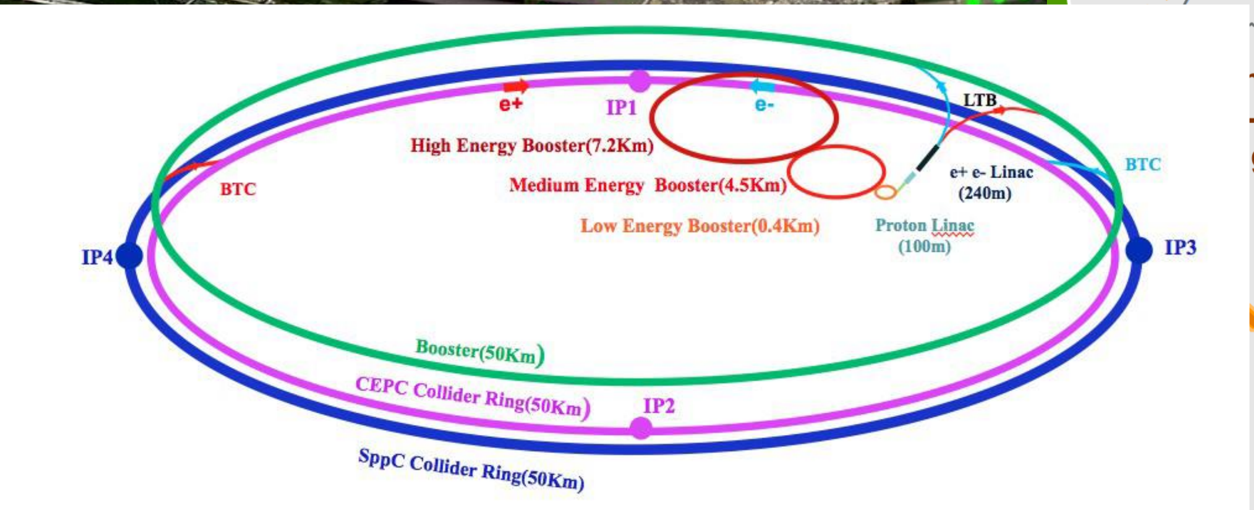
Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

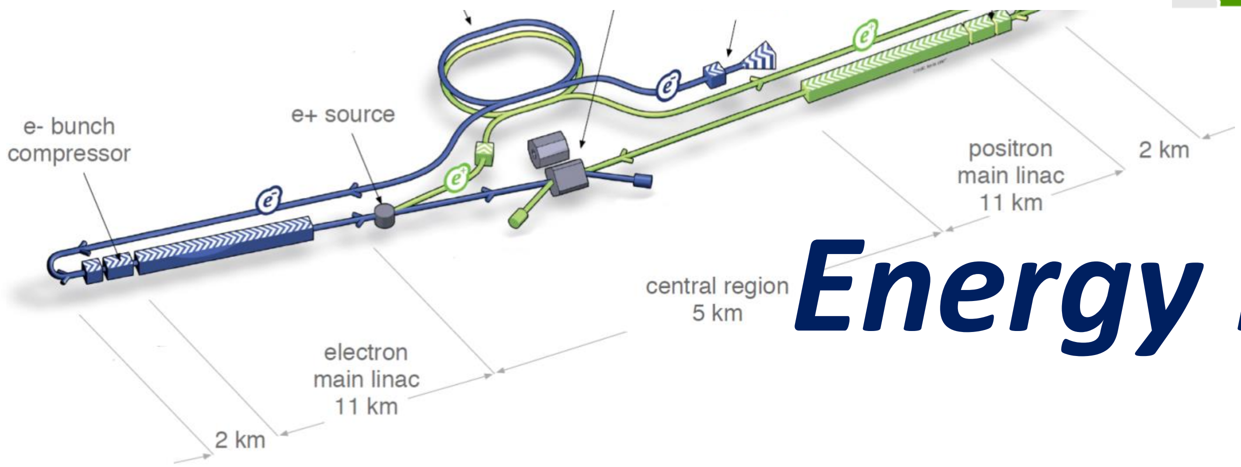
Neutrinos:
- *ν masses and and their origin*
- what is the role of *H(125) ?*
- Majorana or Dirac ?
- *CP violation*
- additional species →sterile *ν ?*

Ian Shipsey's slide at ICHEP-2016



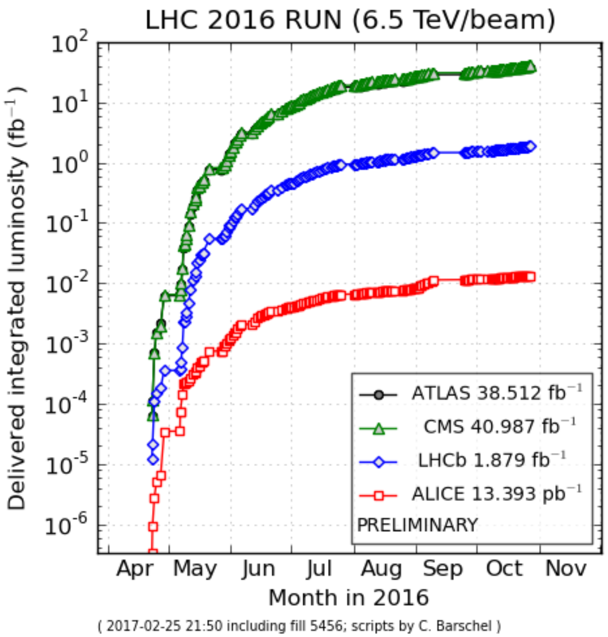


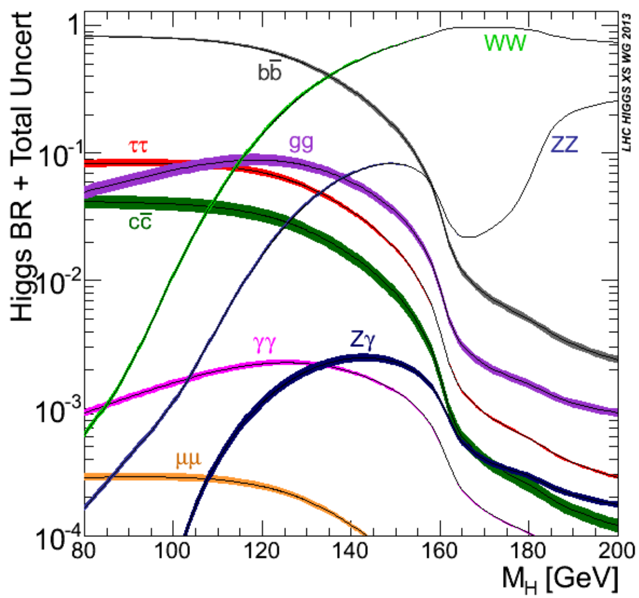


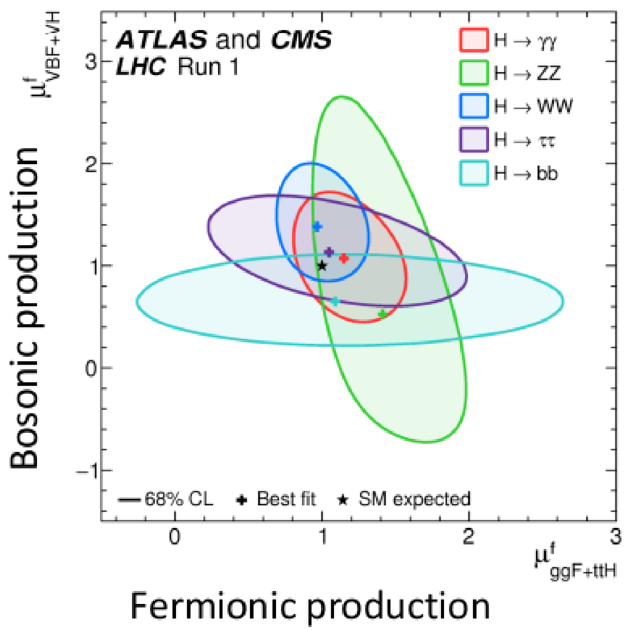


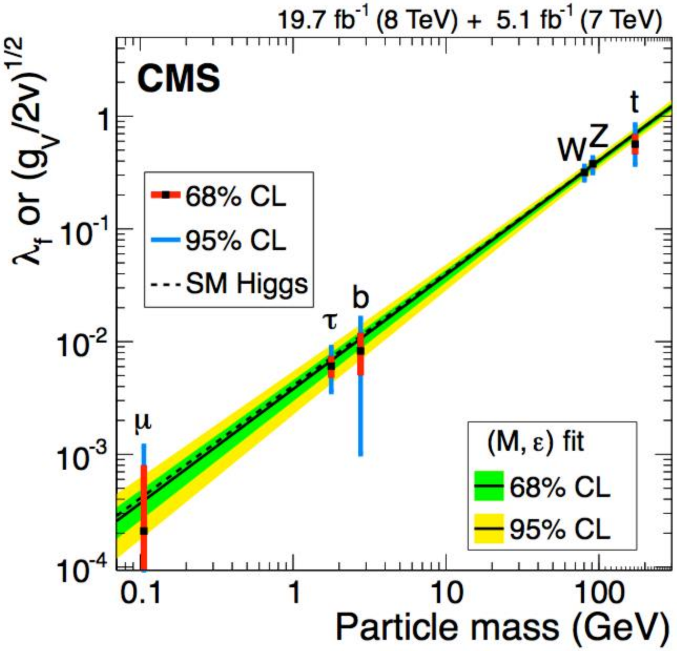
Energy Frontier

The spectacular success of the LHC









LHC & Beyond

- *So far the picture is that Higgs behave like a standard model particle within a large uncertainty.*
- *Unfortunately LHC will continue to provide a fuzzy picture of Higgs.*

Questions remains--

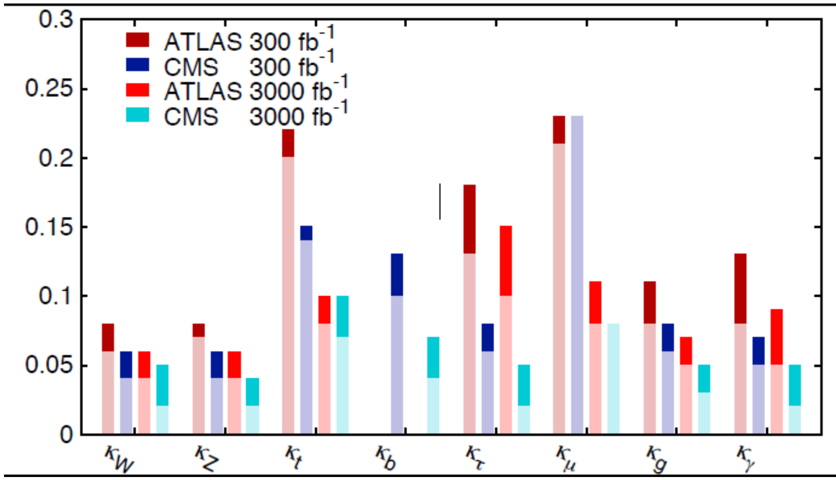
•Is it truly elementary ?

•Self interaction of Higgs.

•What is the shape of the electroweak symmetry breaking potential ? And how it is restored at high scale ?

•Is there more than one fundamental Higgs field ?

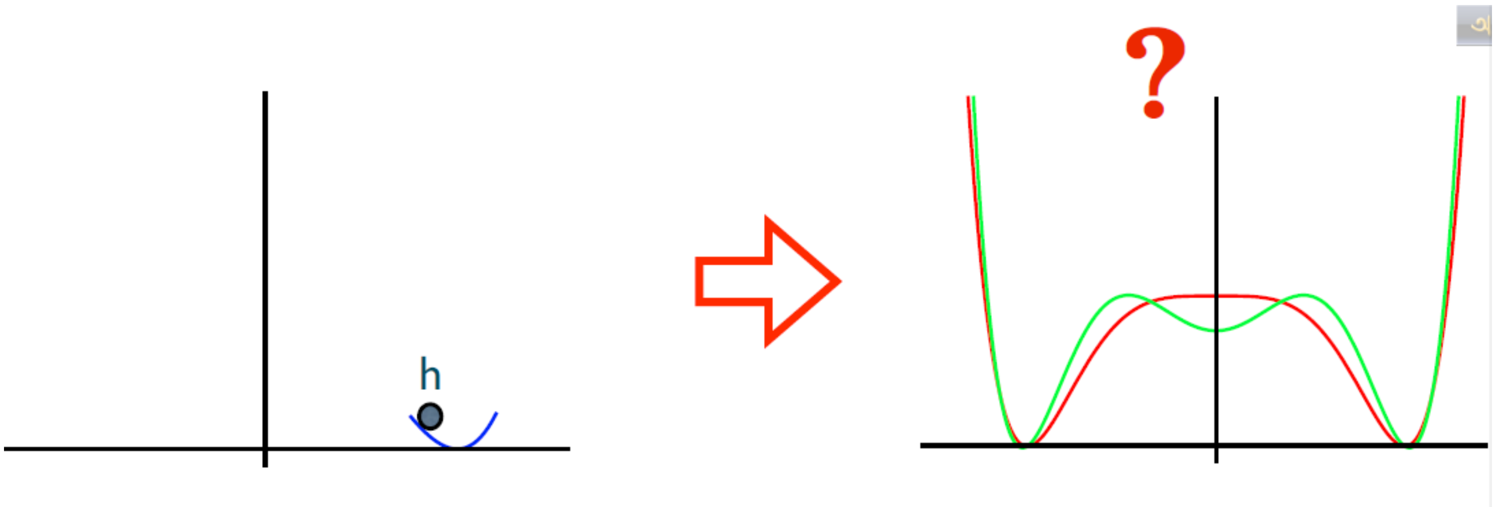
•Higgs decay to invisible or exotic modes.



- *A program focused on Higgs couplings to fermions and vector bosons to a precision of a few percent or less is needed to answer these questions.*

- *Need to put it under a more powerful microscope.*

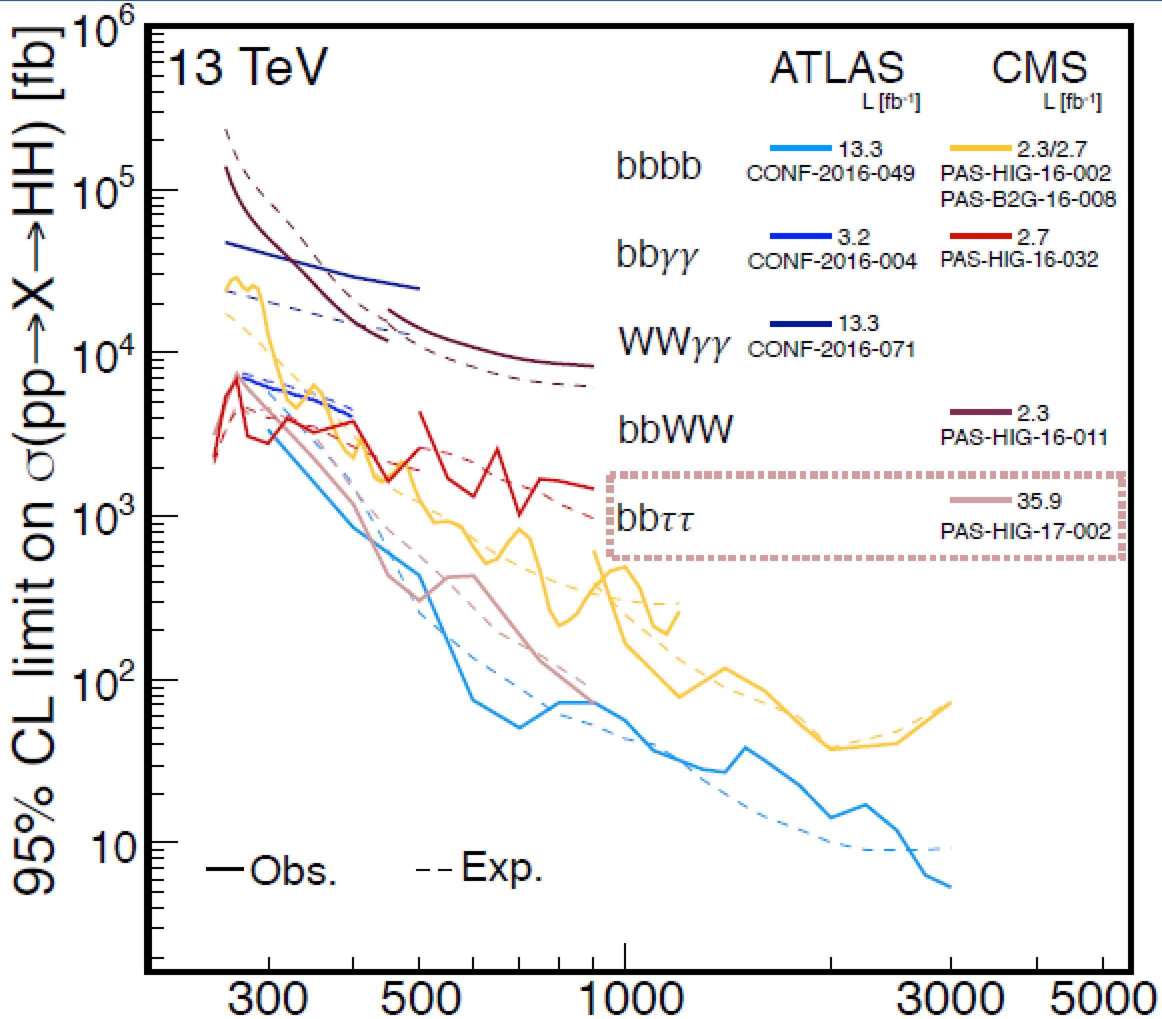
Dynamical Property of Higgs



What is the shape of the symmetry breaking potential and how it is restored at high scale?
Observable is the Higgs self coupling cross section – not measurable at LHC

Higgs self coupling

Crucial to test the shape of V_H and hence origin of E.W. Symmetry breaking



NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227) ▣
bbττ	-	28 (25) ▣
bbγγ	117 (161)	91 (90)
WWγγ	747 (386)	-

2.3-3.2 fb^{-1} | 13.3 fb^{-1} | 35.9 fb^{-1}

▣ : Test of anomalous HH couplings

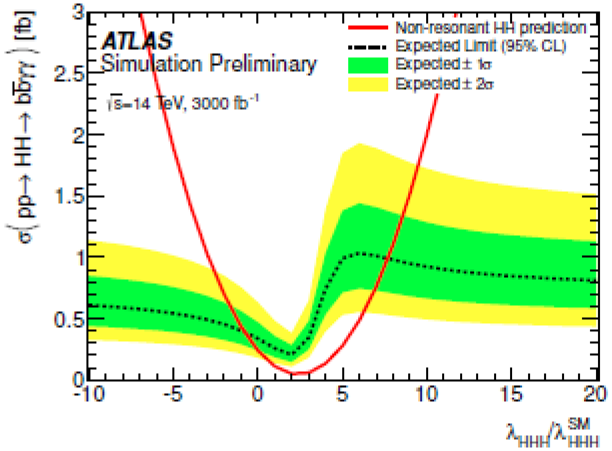
- Complementarity in different mass ranges
  - much to gain from a combination!

Prospects at HL-LHC

- Measurement of σ_{HH} and determination of λ_{HHH} are one of the main points of the physics programme at the HL-LHC (3 ab^{-1} of data)
- Two alternative approaches to estimate the sensitivity to HH production

ATLAS EXPERIMENT

- parametric simulation of upgraded detector response

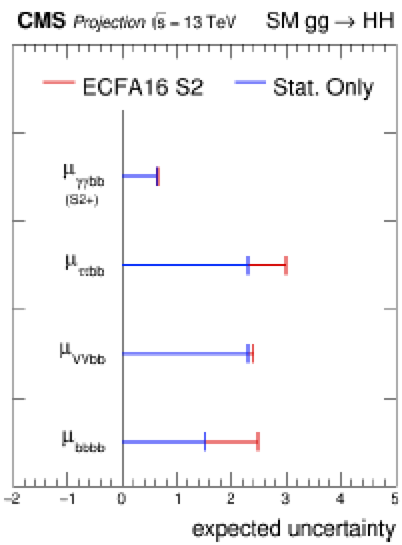


$bb\gamma\gamma$, $bb\tau\tau$ and bbbb studied

- Best significance is 1.05σ from $bb\gamma\gamma$

CMS

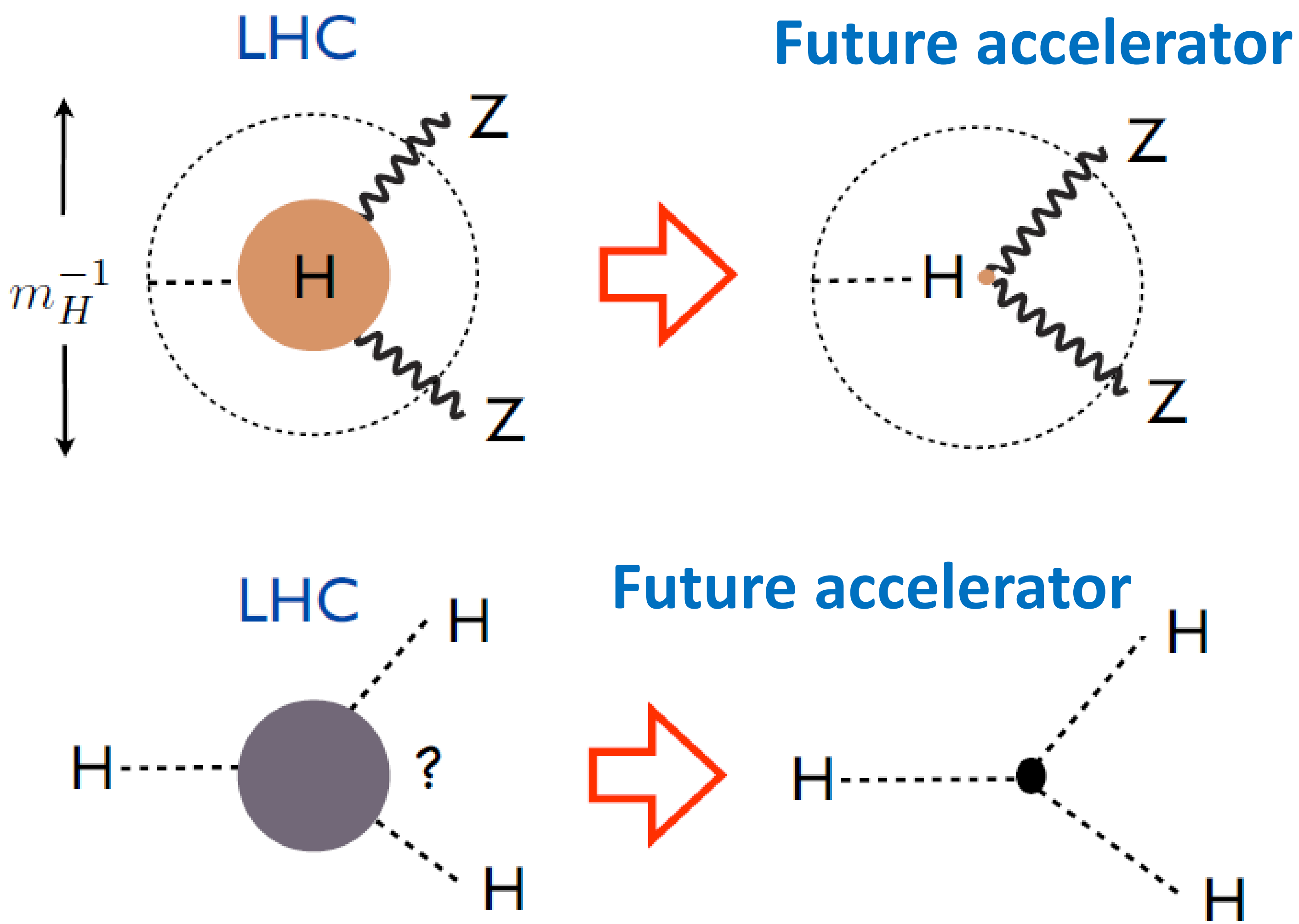
- extrapolation of results from 13 TeV, 2.3/2.7 fb^{-1} to HL-LHC (conservative: current results not optimal for high luminosity)



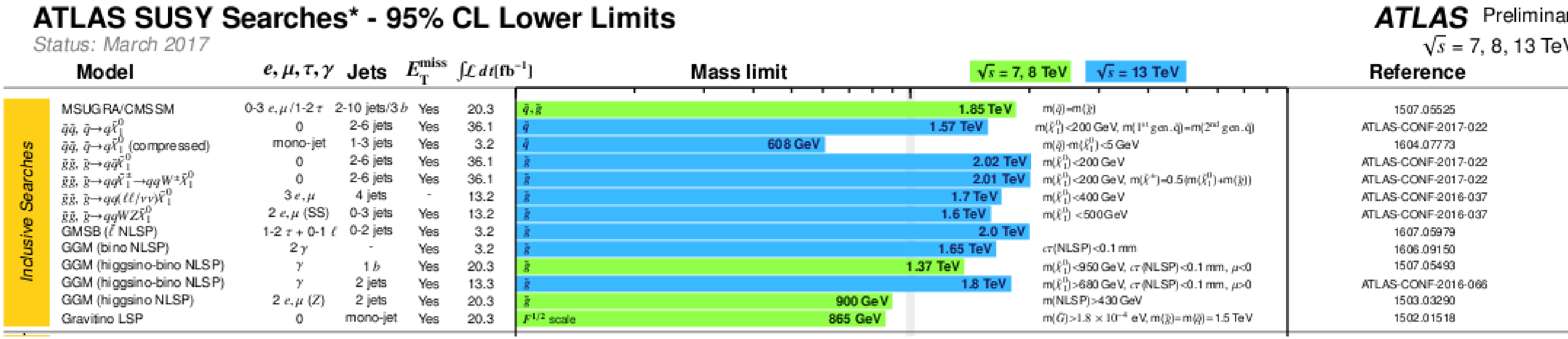
Significance	
$bb\gamma\gamma$	1.6σ
$bb\tau\tau$	0.39σ
bbVV	0.45σ
bbbb	0.39σ

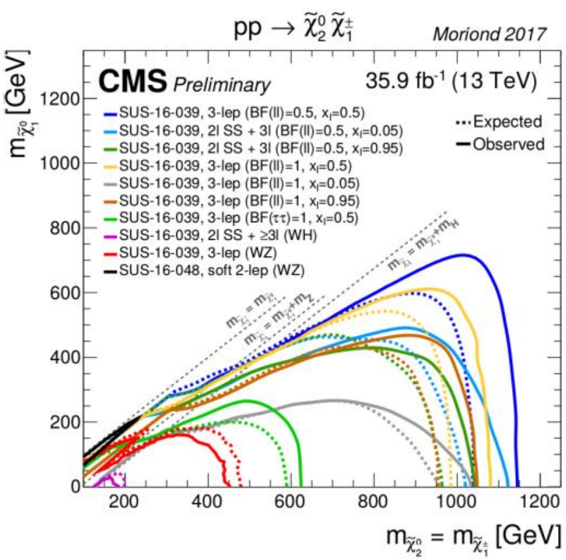
Need new accelerator in the intensity frontier

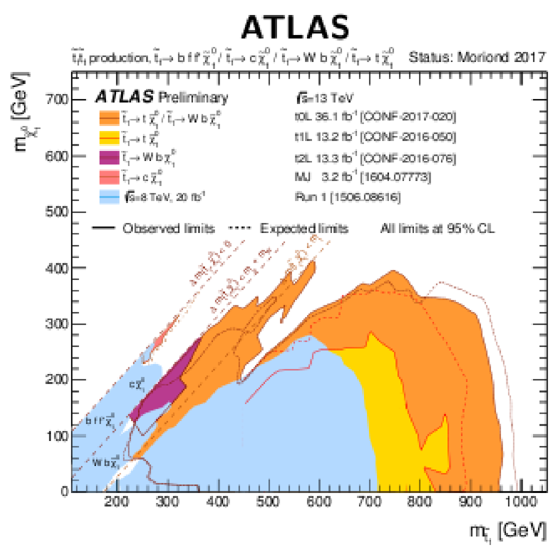
Where we want to go ?

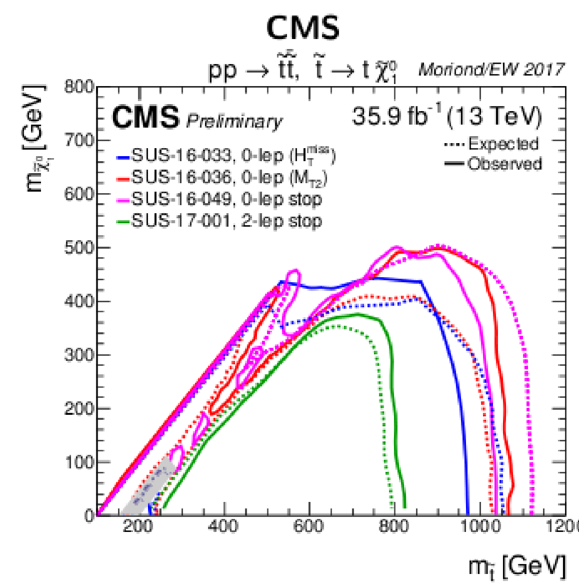


No Evidence for SUSY @LHC





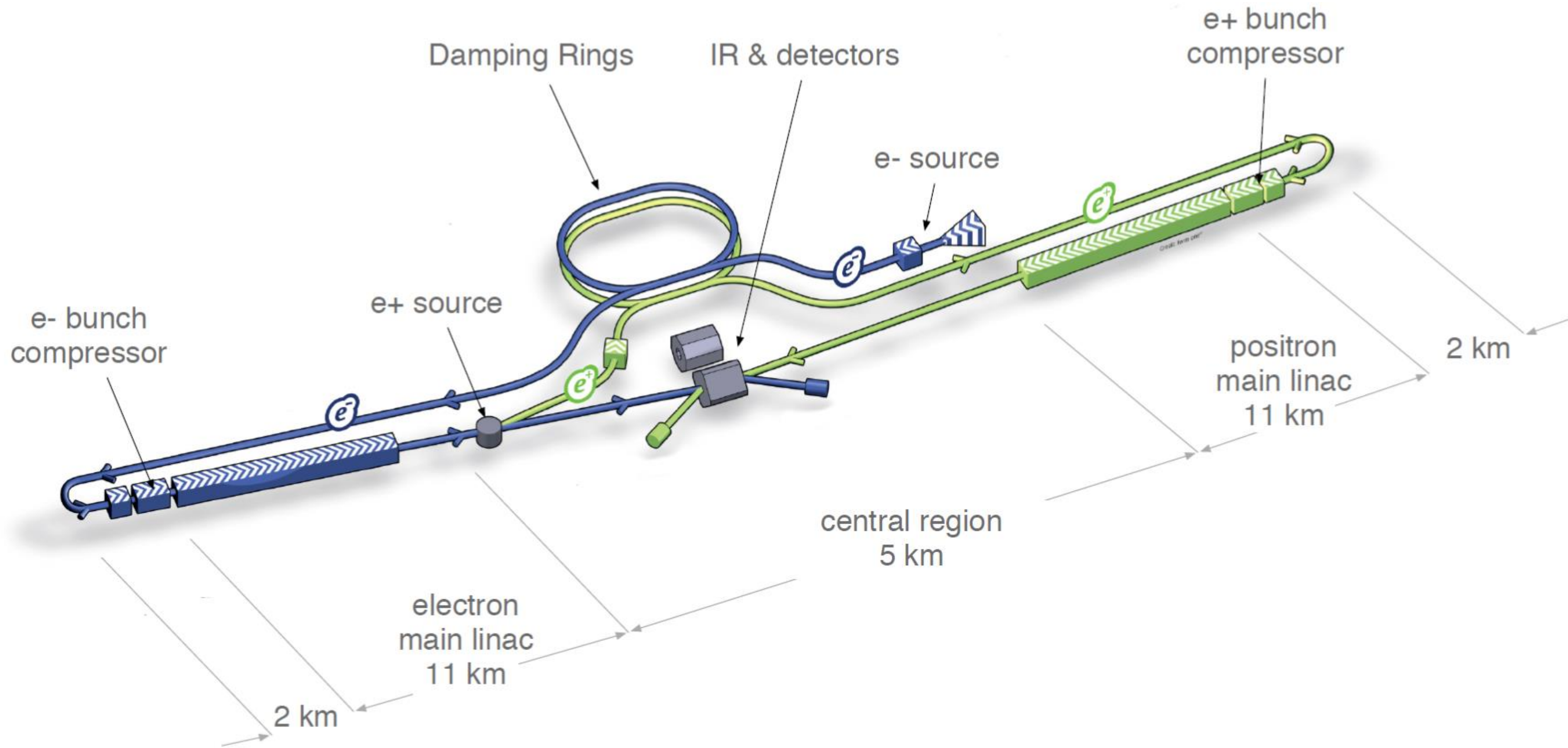




Particle Physics before LHC

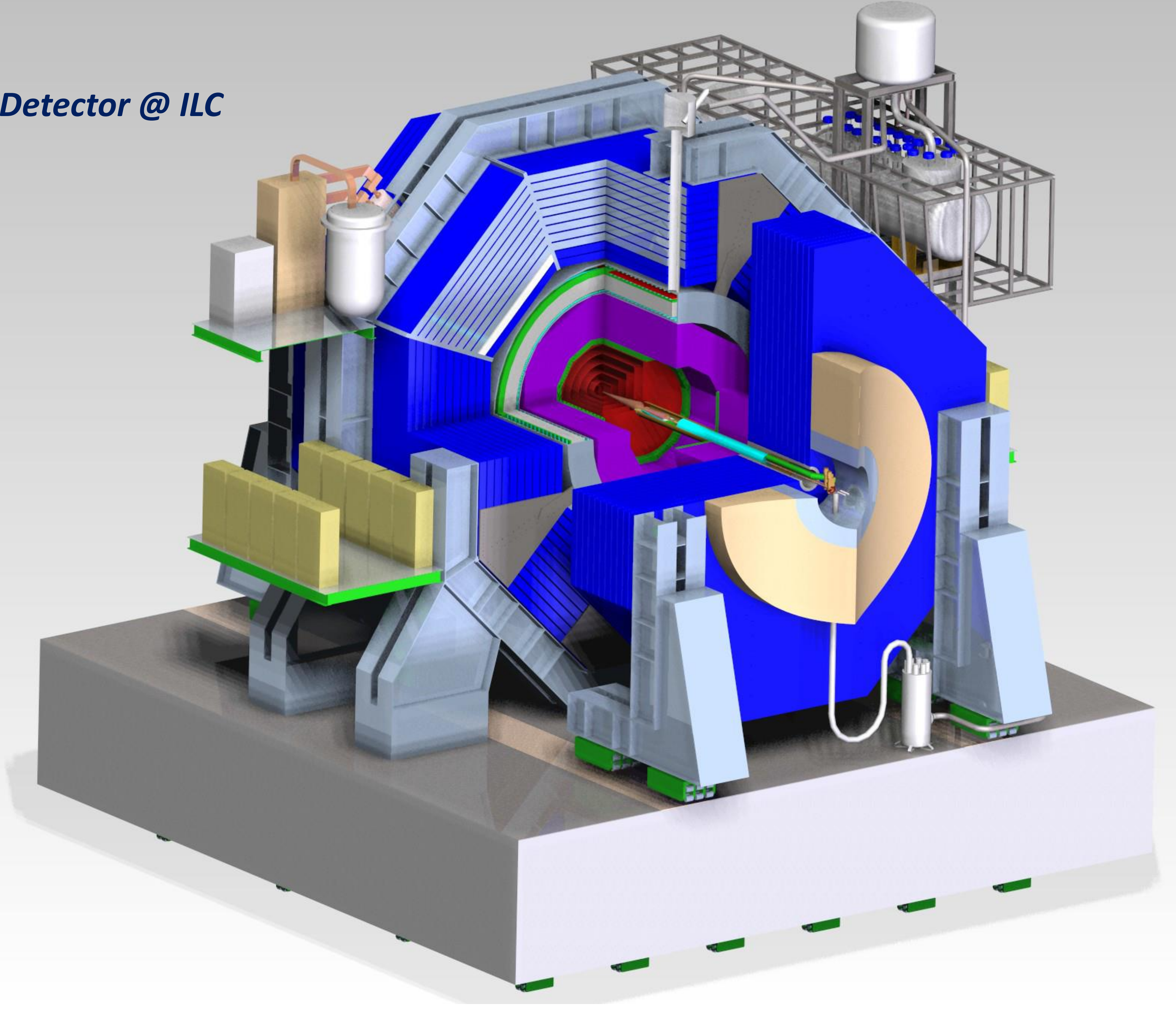
Entering data driven physics era

International Linear Collider

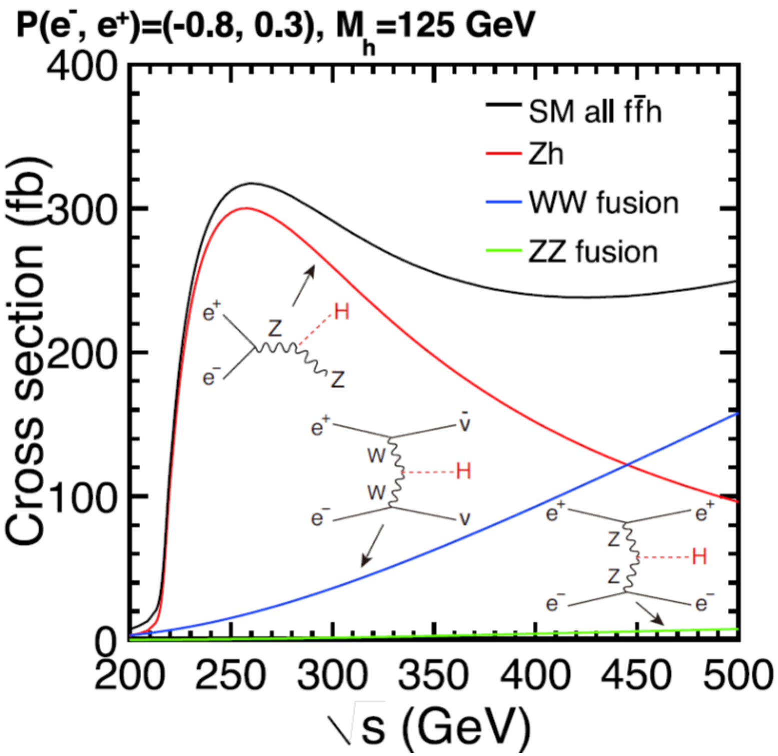


1.3 GHz SCRF cavities @ 31.5 MV/m
1.6 msec Pulse length
14 mrad crossing angle

SiD Detector @ ILC



ILC Physics

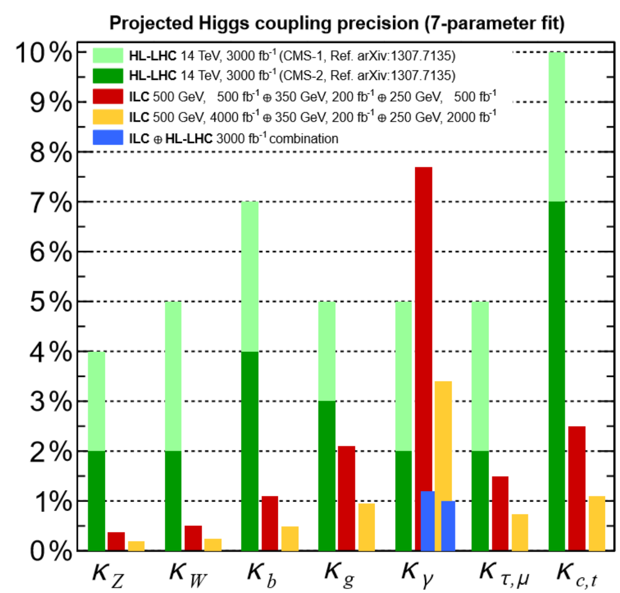


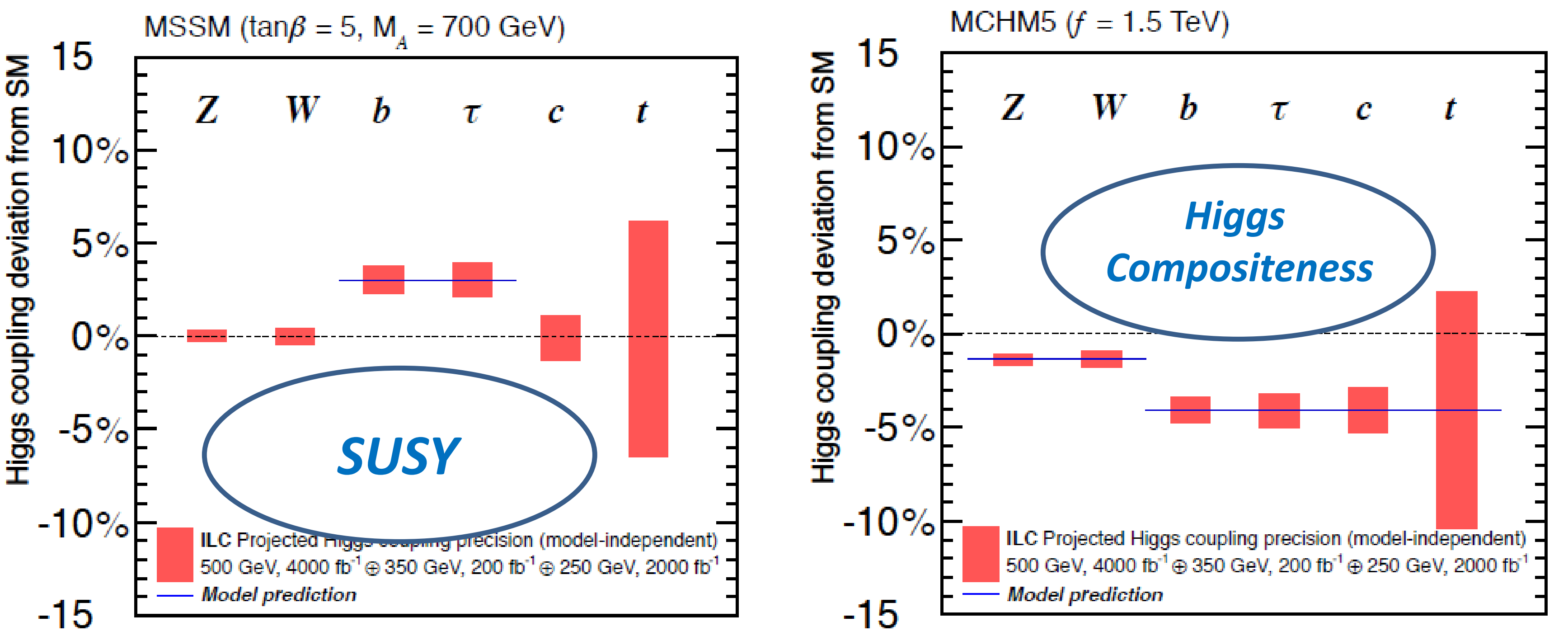
Higgstrahlung $e^+e^- \rightarrow Zh$

(i) Determine the total width Γ_h & absolute normalisation of Higgs coupling.

(ii) Allow us to observe Higgs decay to invisible or exotic mode.

(ii) Coupling to e^+e^- or $\mu^+\mu^-$ gives precise mass of Higgs boson (ΔM ~ 30 MeV).





MSSM (tanβ = 5, M_A = 700 GeV)
Higgs coupling deviation from SM
15
10%
5%
0%
-5%
-10%
-15
Z W b τ c t
SUSY
ILC Projected Higgs coupling precision (model-independent)
500 GeV, 4000 fb⁻¹ ⊕ 350 GeV, 200 fb⁻¹ ⊕ 250 GeV, 2000 fb⁻¹
Model prediction
MCHM5 (f = 1.5 TeV)
Higgs Compositeness

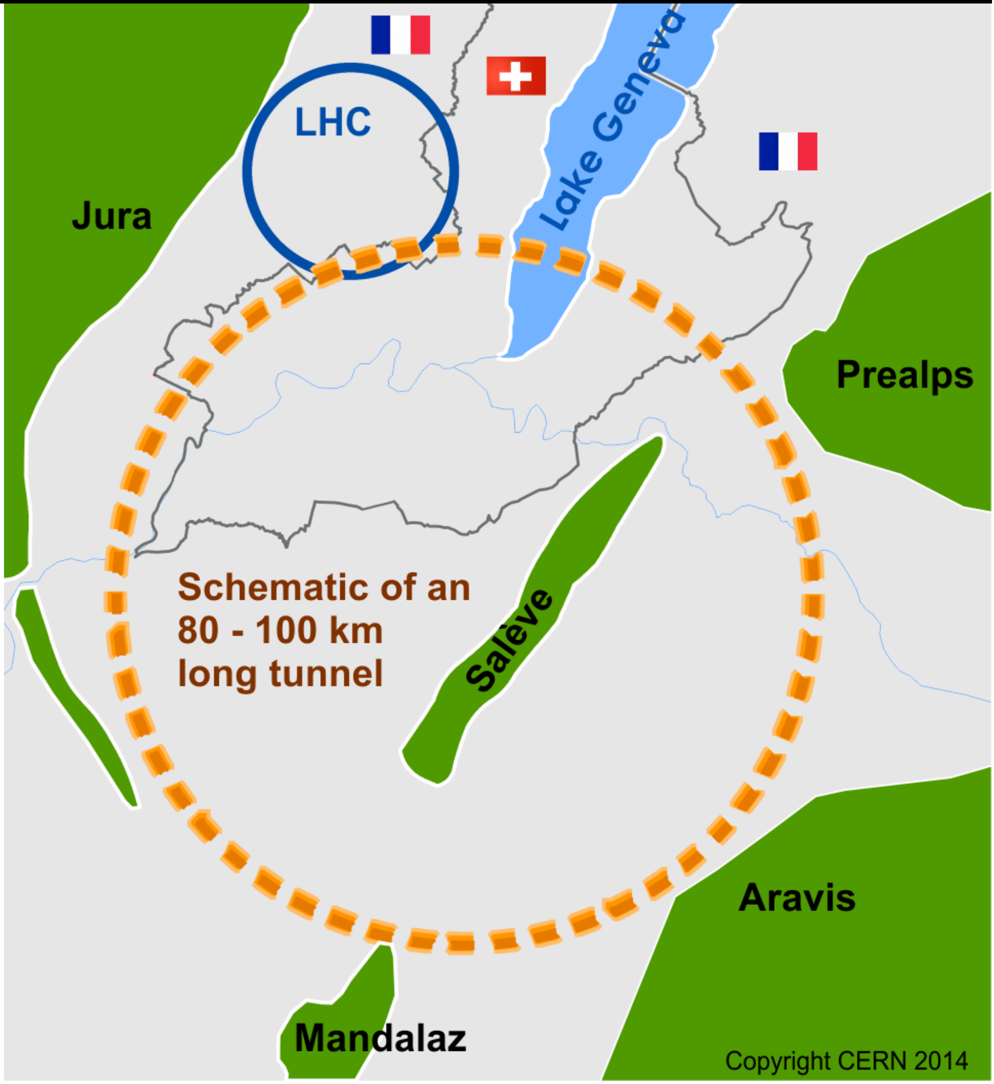
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



Motivations for FCC-hh

- Ultimate discovery machine
  - **directly** probe new physics up to **unprecendented** scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV, [1606.00947]
      "weak" m(Z') ≈ 30TeV,
    - SUSY m(gluino) ≈ 10 TeV,
      m(stop). ≈ 5 TeV

- Precision machine
  - probe Higgs **self-coupling** to few % level, and %-level precision for top yukawa and rare decays
  - measure **SM parameters** with high precision
  - exploit **complementarity with e^+e^-** by probing **high dim.operators** in **extreme kinematic** regimes [1606.09408]

lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Towards defining the FCC-hh detector

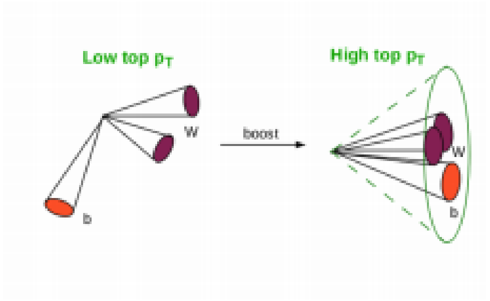
- Physics objects will be more boosted

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

- Tracking target : achieve **σ / p = 10-20% @10 TeV**
- Keep calorimeter **constant term** as small as possible.
- Long-lived particles live **longer**:

ex: 1 TeV **b-Hadron** travels **10 cm** before decaying
1 TeV **tau lepton** travels **2 cm** before decaying

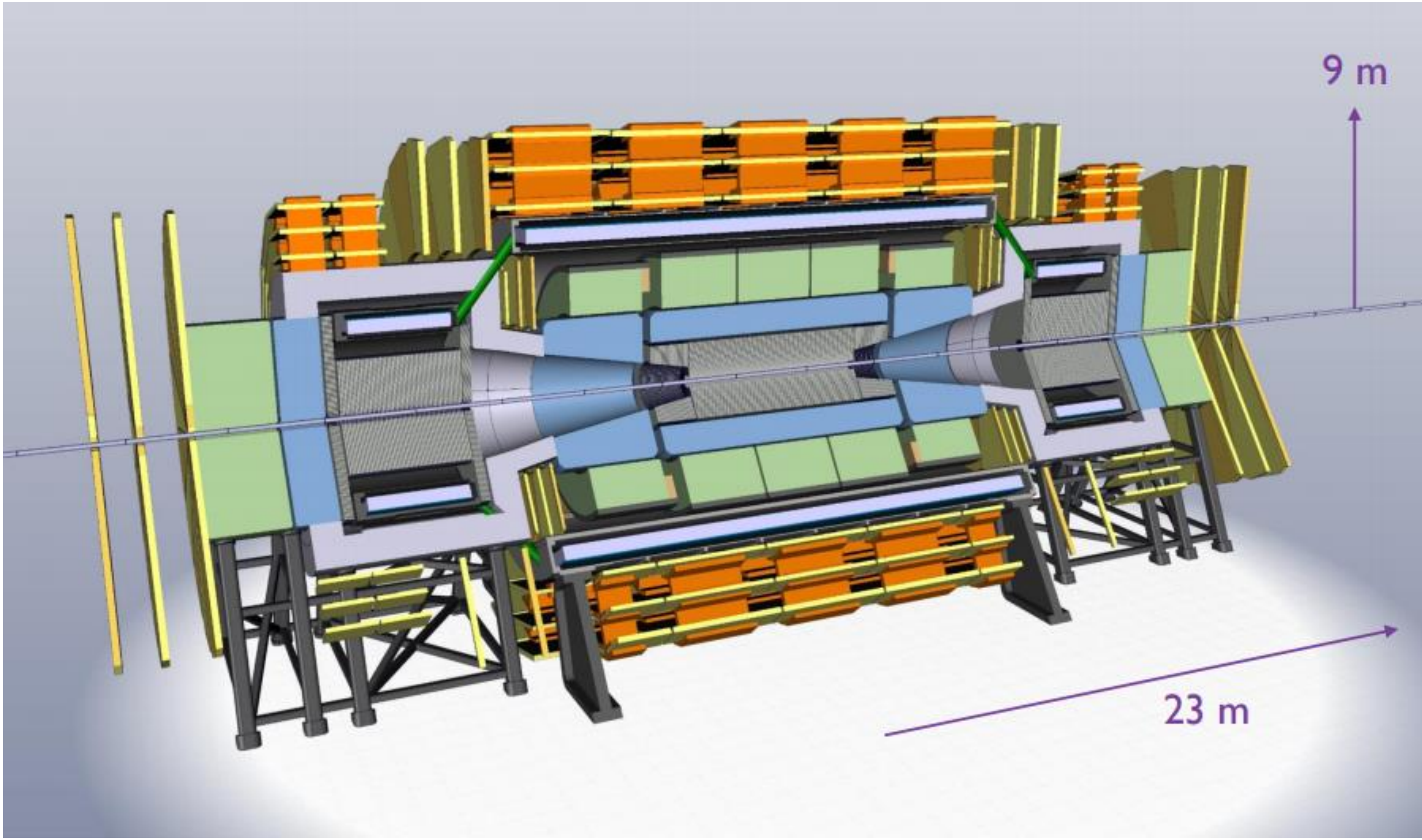
→ re-think reconstruction, include **dE/dx ?**



Require **high granularity** (both in tracker and calos):

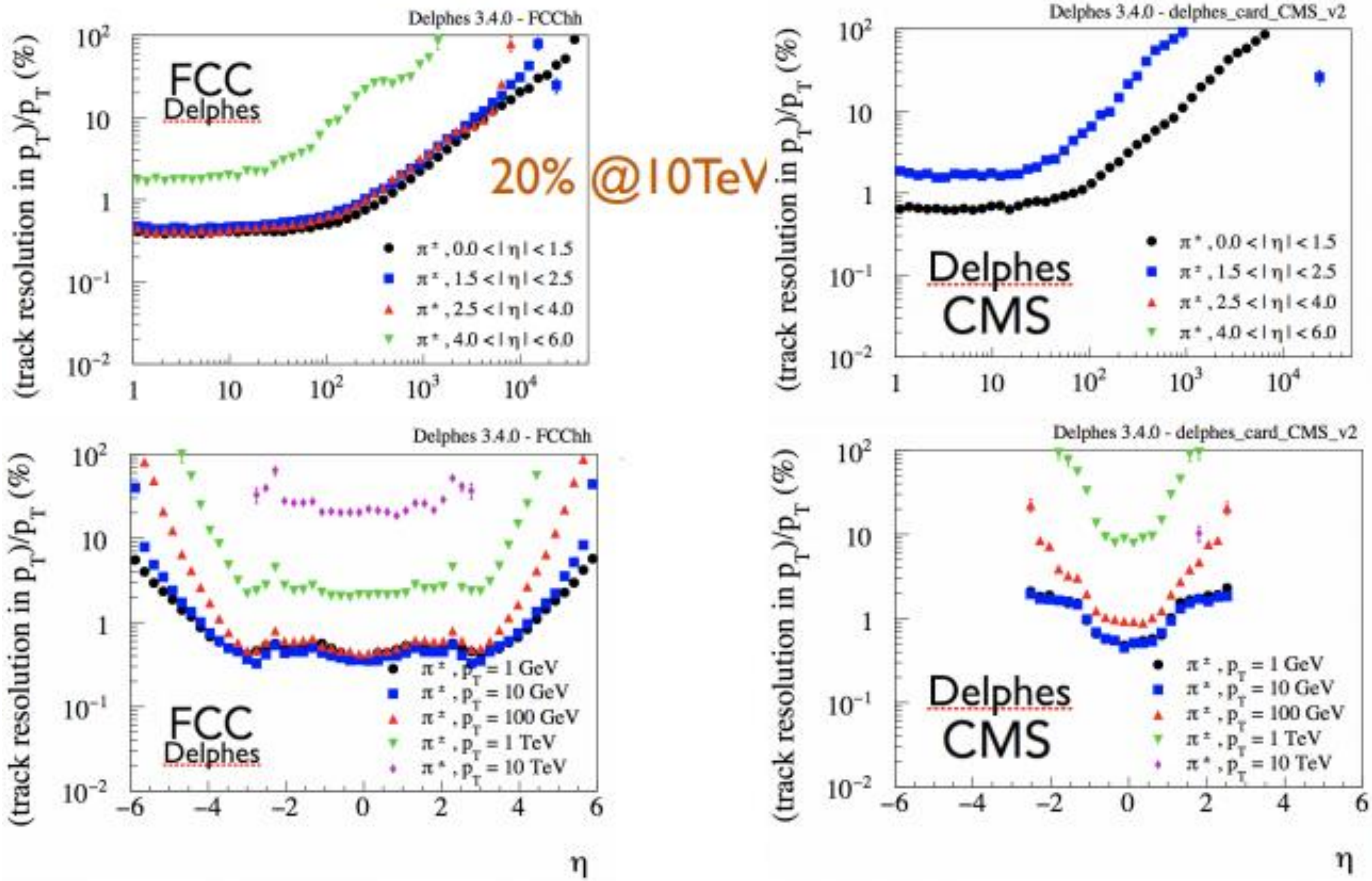
ex: W(10 TeV) will have decay products separated by DR = 0.01

FCC-hh Reference detector



FCC-hh detector performance studies

Tracking

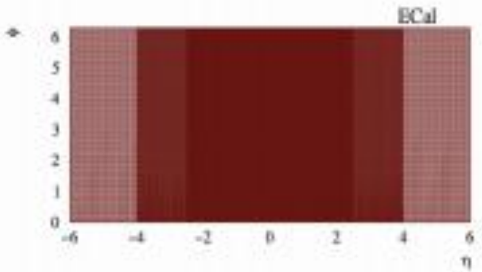


FCC-hh detector performance studies

Calos

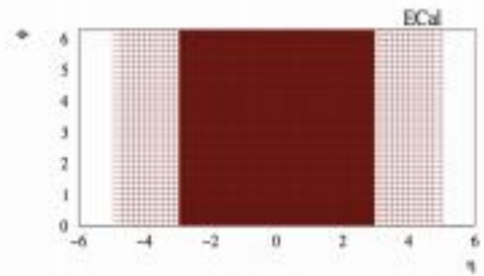
FCC

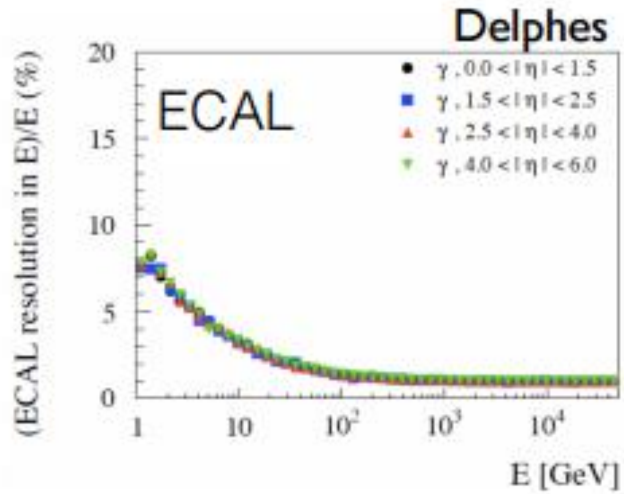
	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 2.5$	0.0125×0.0125	$\frac{10\%}{\sqrt{E}} + 1\%$
$2.5 < \lvert\eta\rvert < 4.0$	0.025×0.025	$\frac{10\%}{\sqrt{E}} + 1\%$
$4.0 < \lvert\eta\rvert < 6.0$	0.05×0.05	$\frac{10\%}{\sqrt{E}} + 1\%$



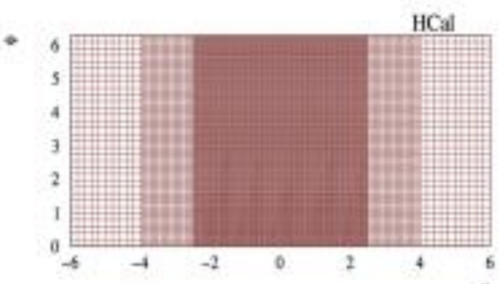
CMS

	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 1.5$	0.02×0.02	$\frac{5\%}{\sqrt{E}} + 1\%$
$1.5 < \lvert\eta\rvert < 2.5$	0.02×0.02	$\frac{5\%}{\sqrt{E}} + 1\%$
$2.5 < \lvert\eta\rvert < 5.0$	$0.175 \times (0.175 - 0.35)$	$\frac{270\%}{\sqrt{E}} + 13\%$

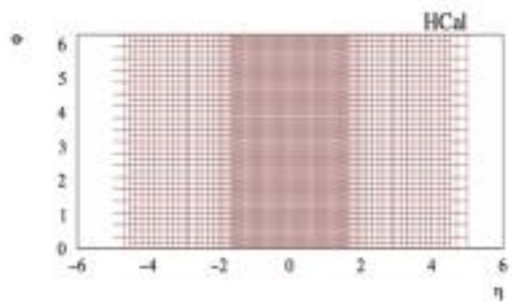


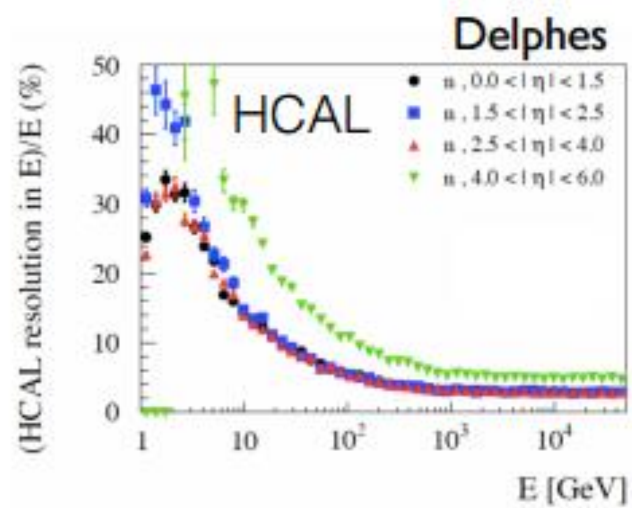


	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 2.5$	0.05×0.05	$\frac{50\%}{\sqrt{E}} + 3\%$
$2.5 < \lvert\eta\rvert < 4.0$	0.1×0.1	$\frac{50\%}{\sqrt{E}} + 3\%$
$4.0 < \lvert\eta\rvert < 6.0$	0.2×0.2	$\frac{100\%}{\sqrt{E}} + 5\%$



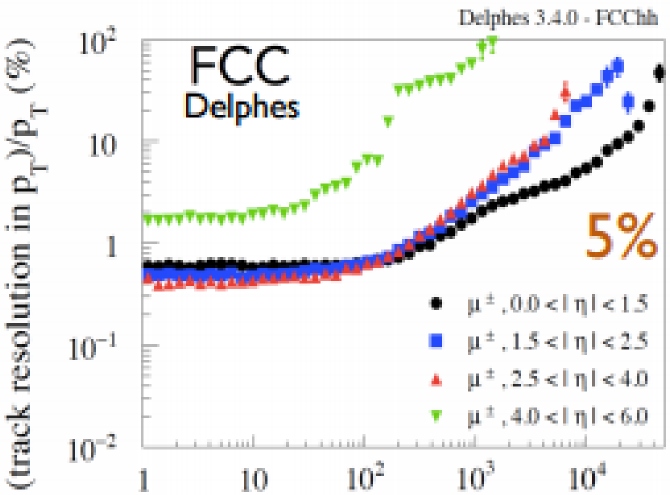
	$\sigma_{(\eta,\phi)}$	$\sigma(E)/E$
$0.0 < \lvert\eta\rvert < 1.5$	0.1×0.1	$\frac{150\%}{\sqrt{E}} + 5\%$
$1.5 < \lvert\eta\rvert < 3.0$	0.2×0.2	$\frac{150\%}{\sqrt{E}} + 5\%$
$3.0 < \lvert\eta\rvert < 5.0$	$0.175 \times (0.175 - 0.35)$	$\frac{270\%}{\sqrt{E}} + 13\%$



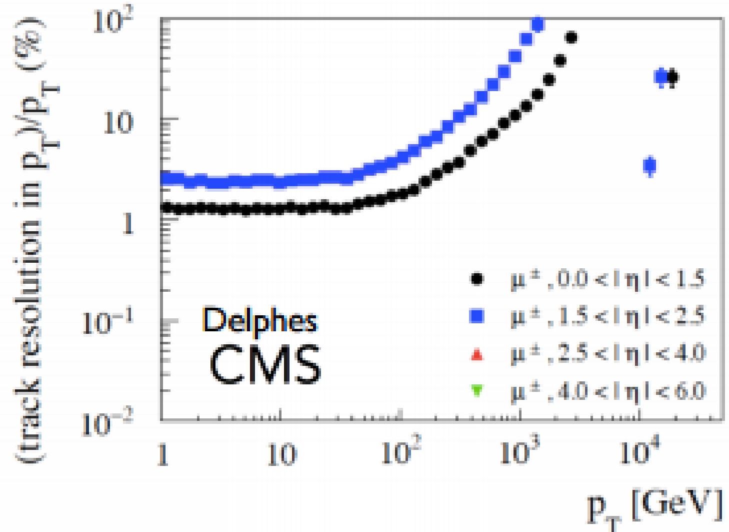


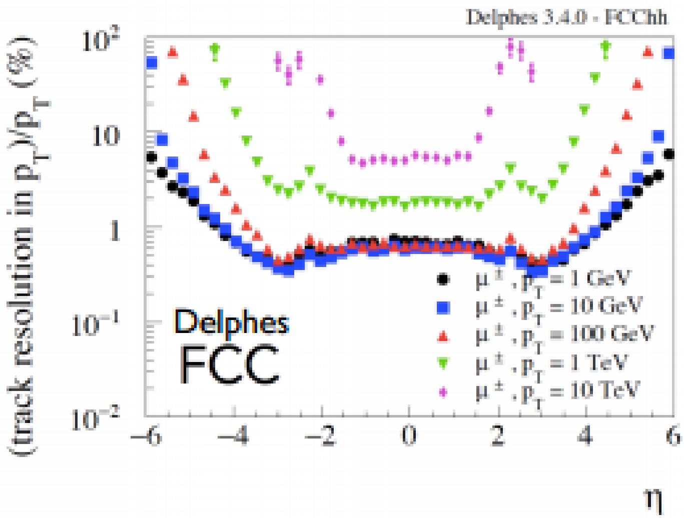
FCC-hh detector performance studies

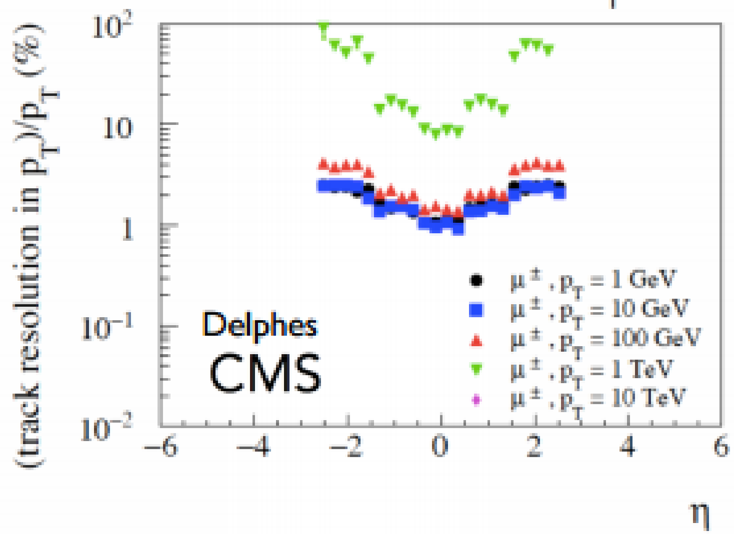
muons



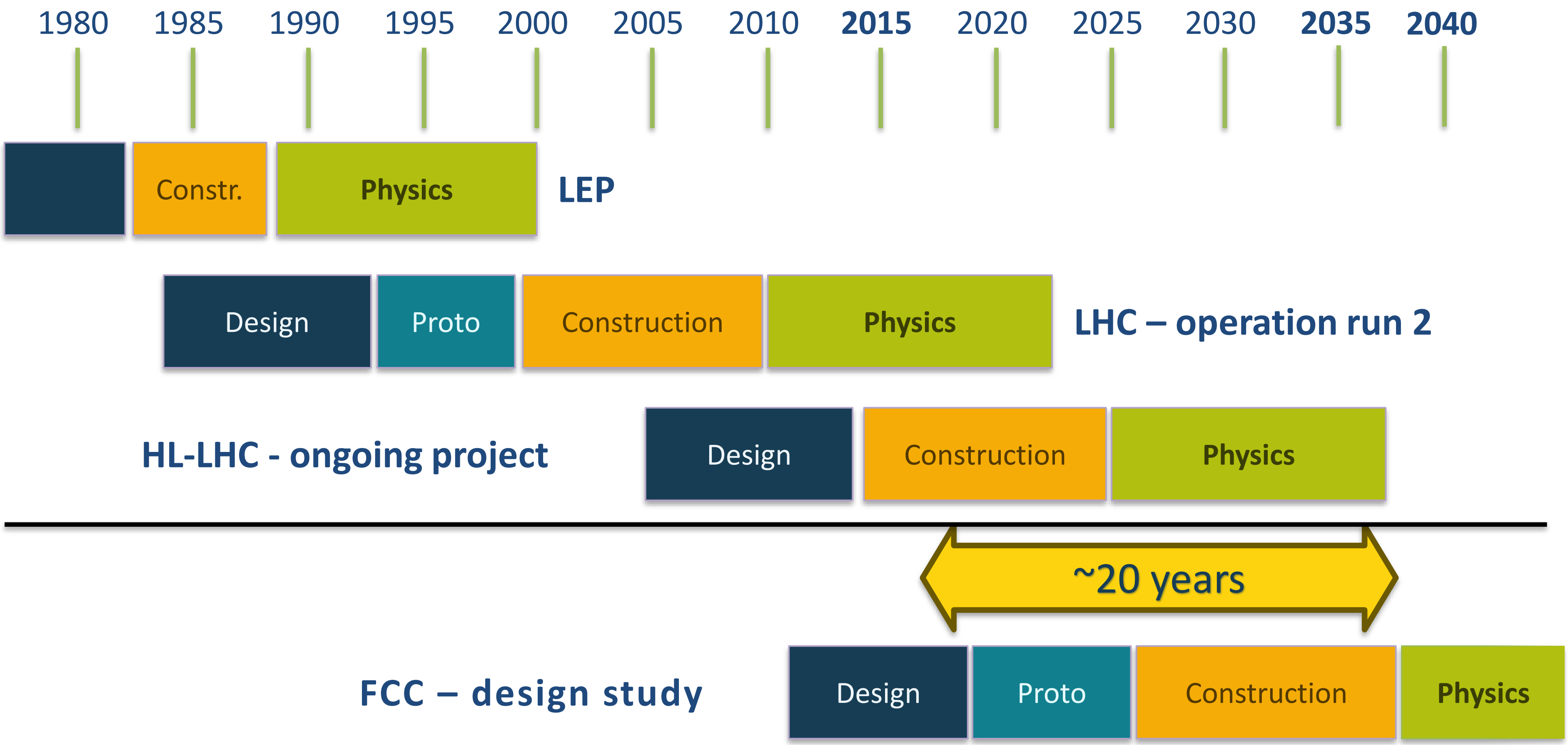
5% @10TeV







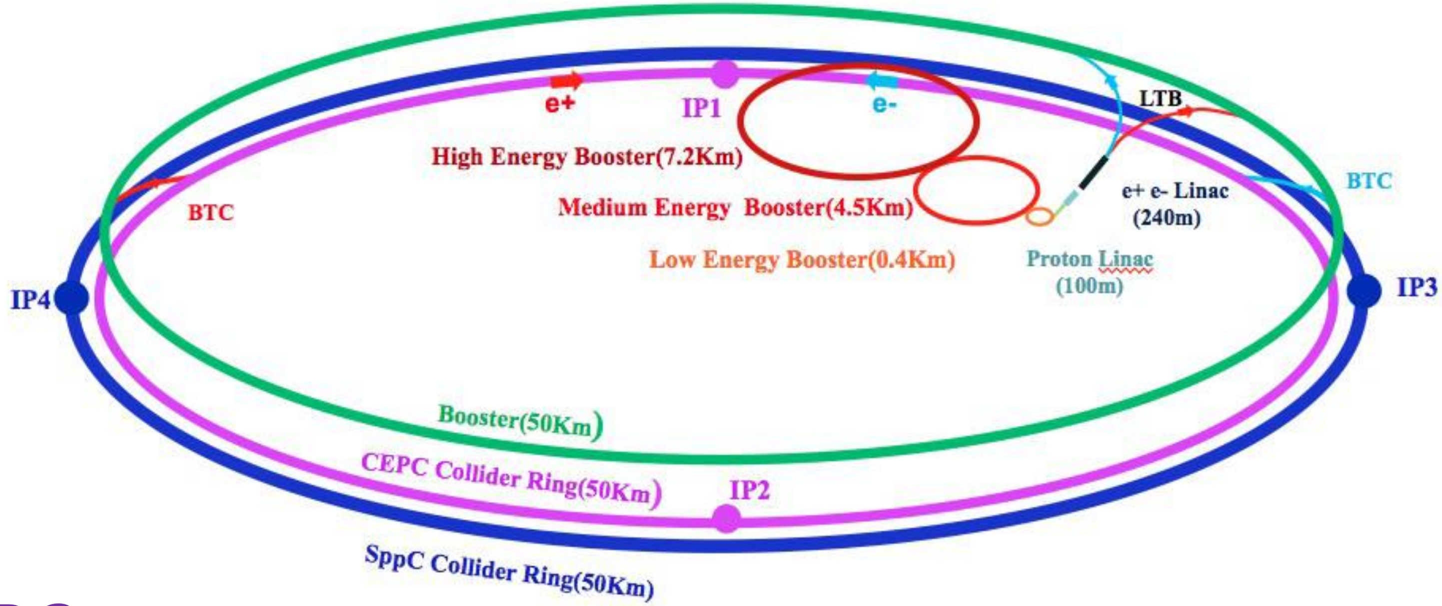
CERN Circular Colliders & FCC



Must advance fast now to be ready for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy

Mean while in China

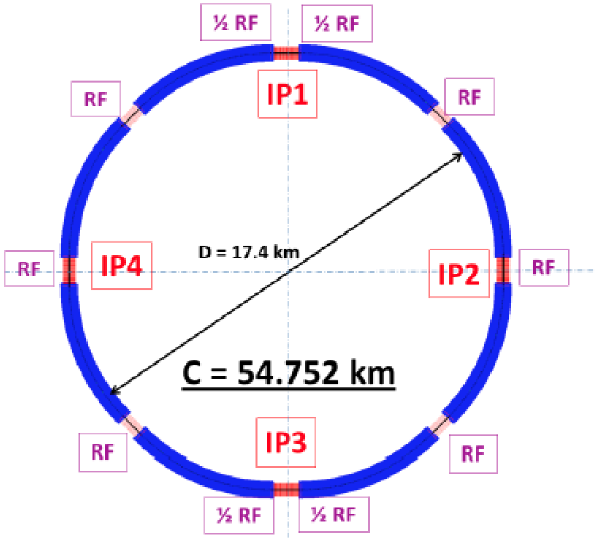


CEPC

SPPC

CEPC Design

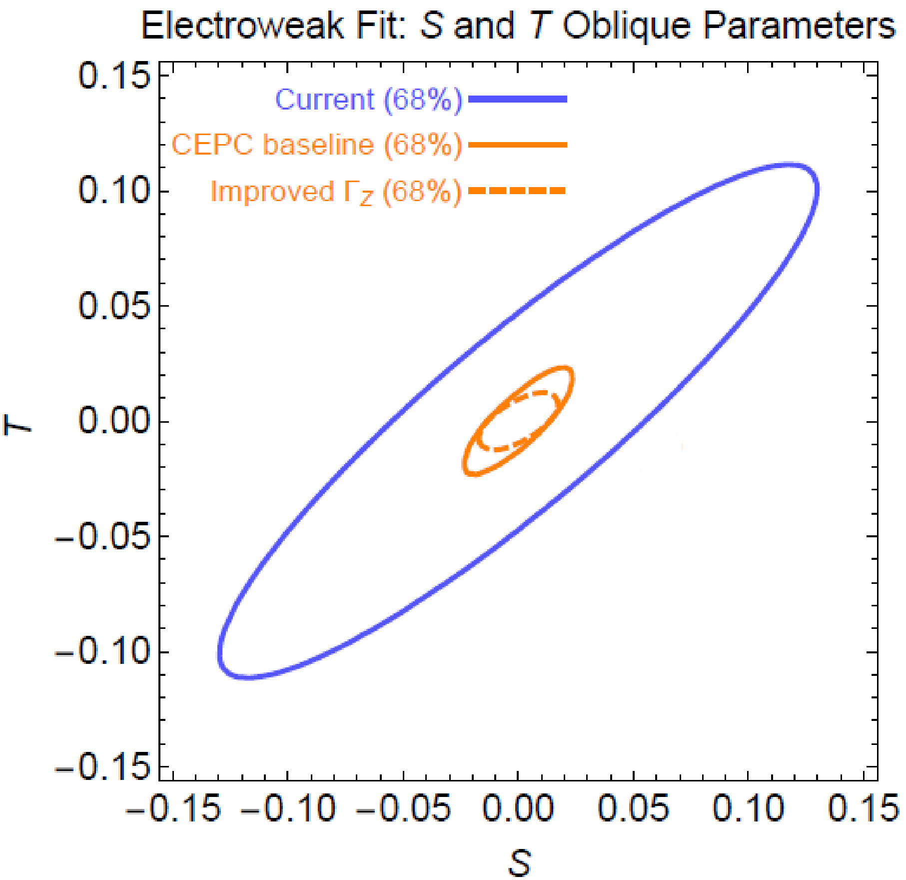
➢ Critical parameters:
- SR power: 51.7 MW/beam
- 8*arcs, 2*IPs
- 8 RF cavity sections (distributed)
- RF Frequency: 650 MHz
- Filling factor of the ring: ~70%



Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	**Circumference [C]**	m	54752
Number of IP[N_{IP}]		2	**SR loss/turn [U_0]**	GeV	3.11
Bunch number/beam[n_B]		50	**Energy acceptance RF [h]**	%	5.99
SR power/beam [P]	MW	51.7	**Beam current [I]**	mA	16.6
emittance (x/y)	nm	6.12/0.018	**β_{IP}(x/y)**	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	**Luminosity /IP[L]**	$cm^{-2}s^{-1}$	2.04E+34

Electroweak Observables

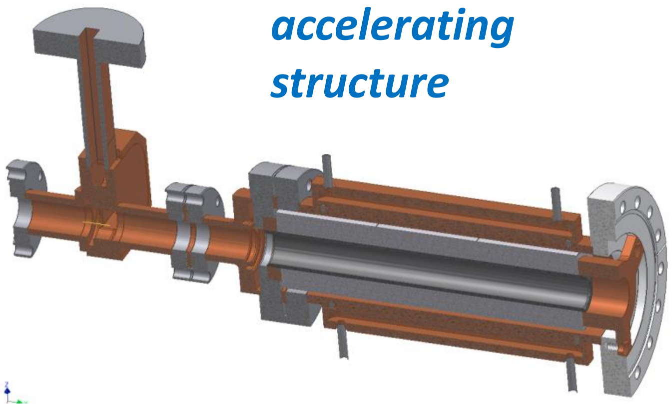
At the Z-pole, the CEPC can produce up to 10^{11} Z bosons,measuring the couplings of the Z to the 10^{-4} level, and improving the limits on precision electroweak observables by an order of magnitude or more.



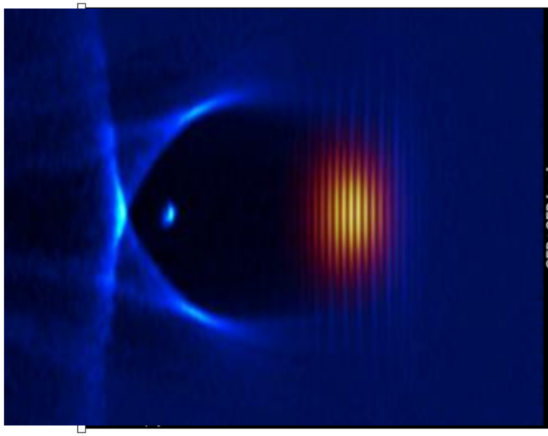
New accelerator techniques

- *Wakefield Acceleration using plasmas or dielectrics*
- *Direct Laser Acceleration*
- *Both particle beam (PWFA) and laser (LWFA) driven wakefield approaches may offer effective gradients of O(1 GeV/m). But luminosity is to be insured.*

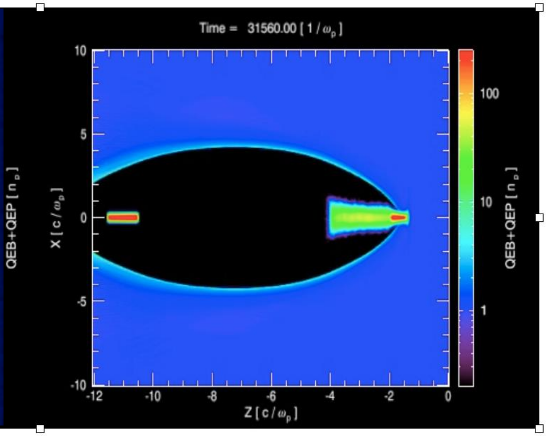
Dielectric accelerating structure



LWFA

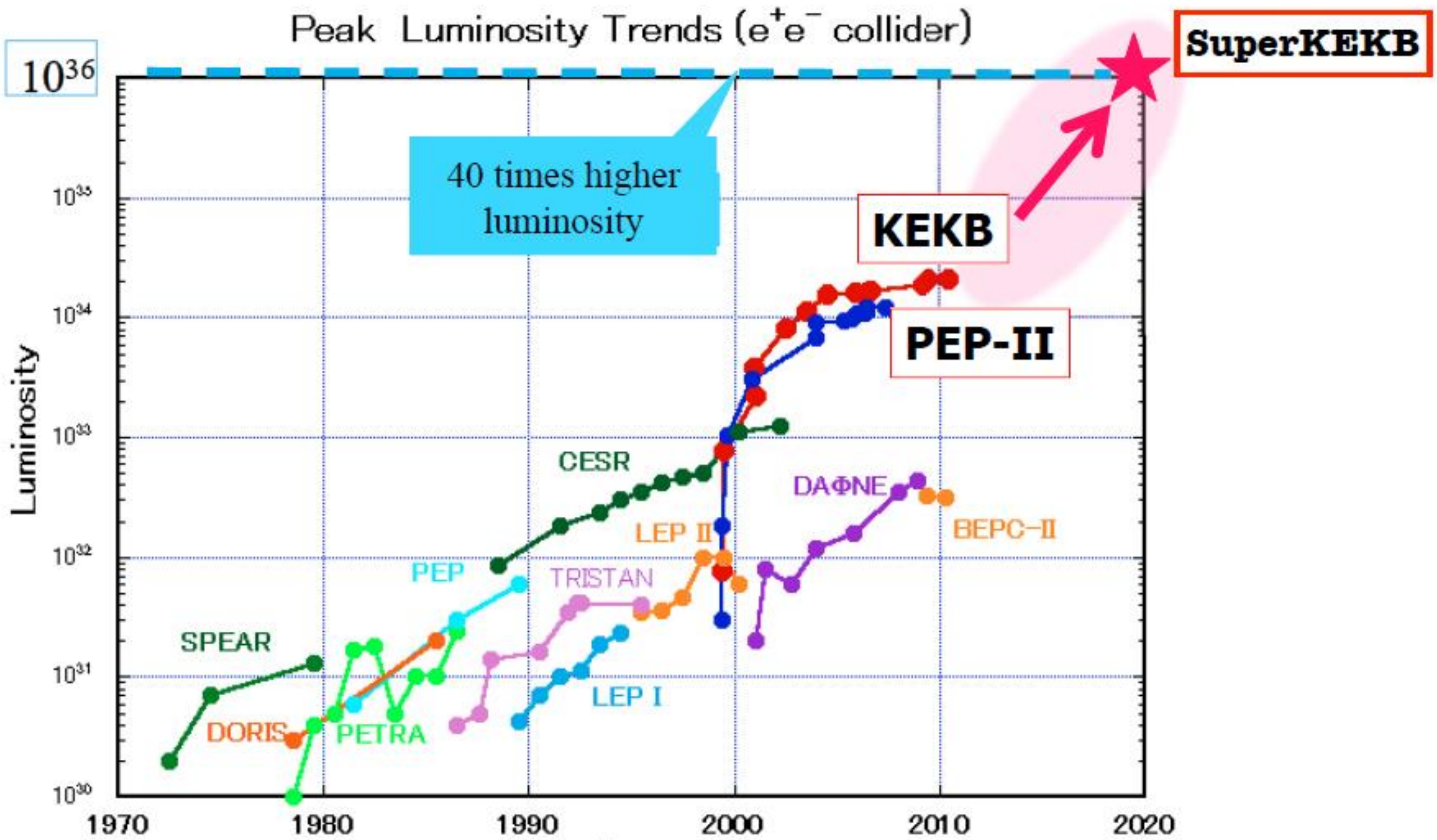


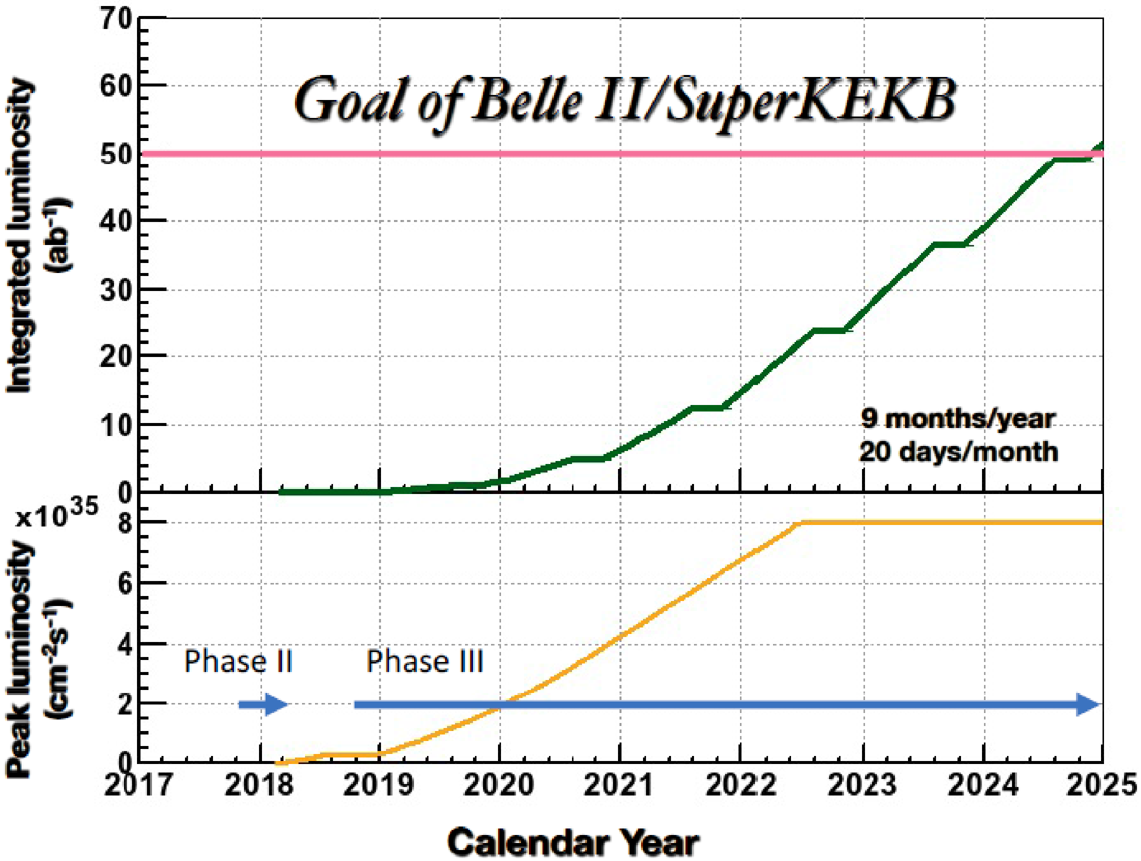
PWFA



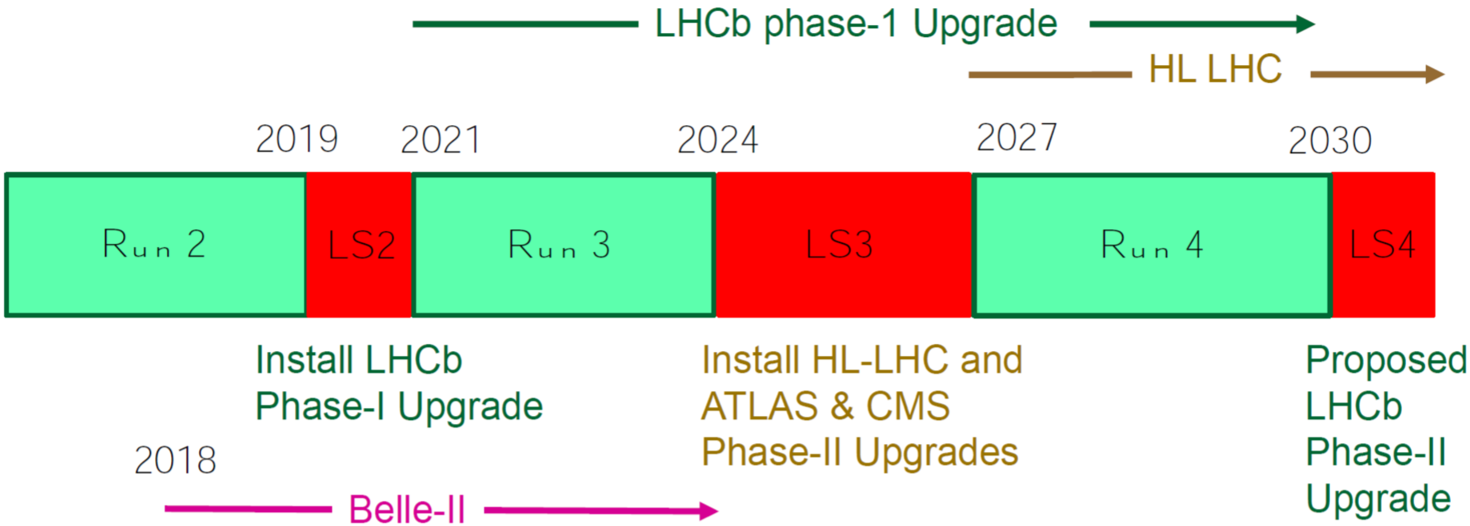
Power of Loops

The intensity frontier/Precision frontier





- Phase I (2016)
  - Circulated both beams but no collisions;
  - Tune accelerator optics, etc.; vacuum scrubbing
  - Beam Background studies with dedicated BEAST II/1 detector
- Phase II
  - First collisions
  - Beam Commissioning
  - Background measurements with BEAST II/2
  - Physics run with Belle II w/o VTX
    - on Υ(4S) and Υ(6S)
- Phase III
  - Physics run

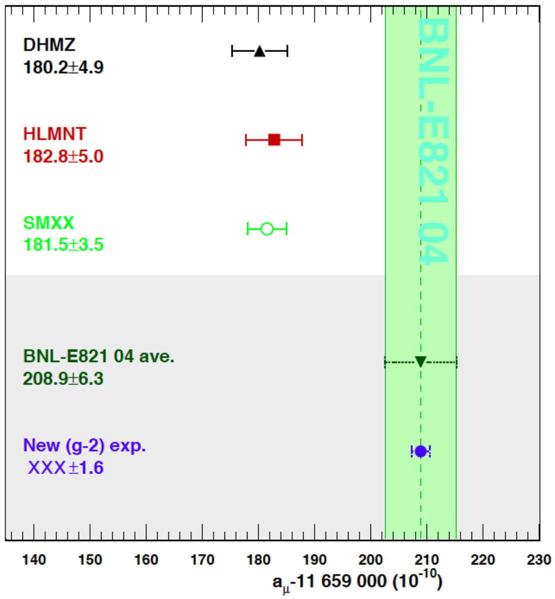


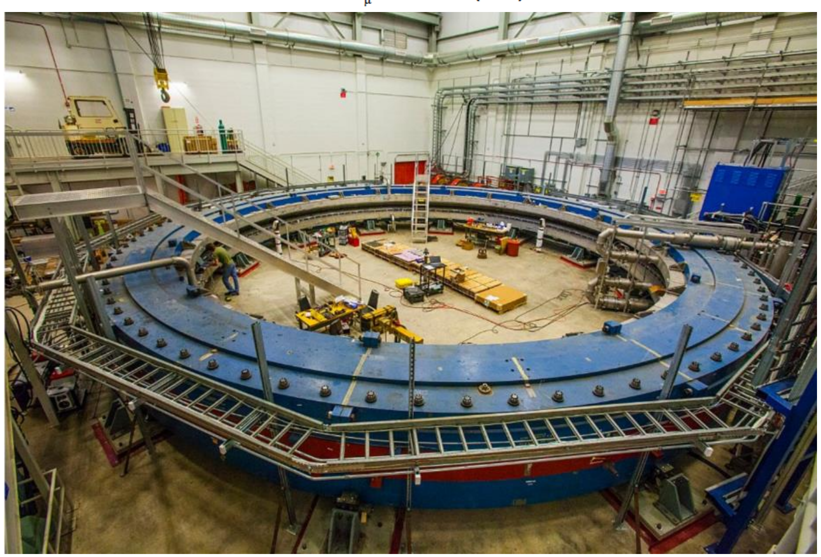
Physics Reach Belle II & LHCb upgrade

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 $\mathrm{A_{FB}}(\mathrm{B} \to \mathrm{K}^*\mu\mu)$	**	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

Muon g-2 program

g-2 @ FNAL

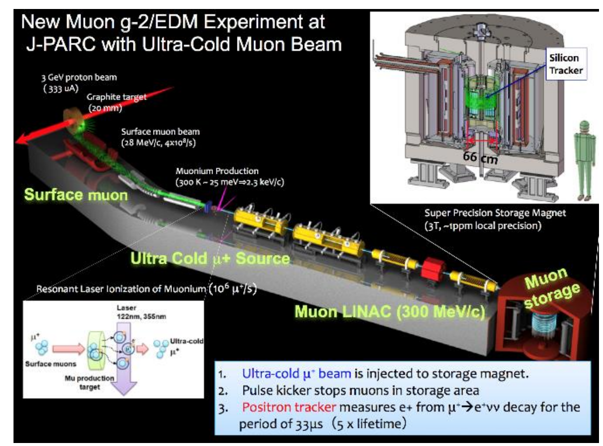




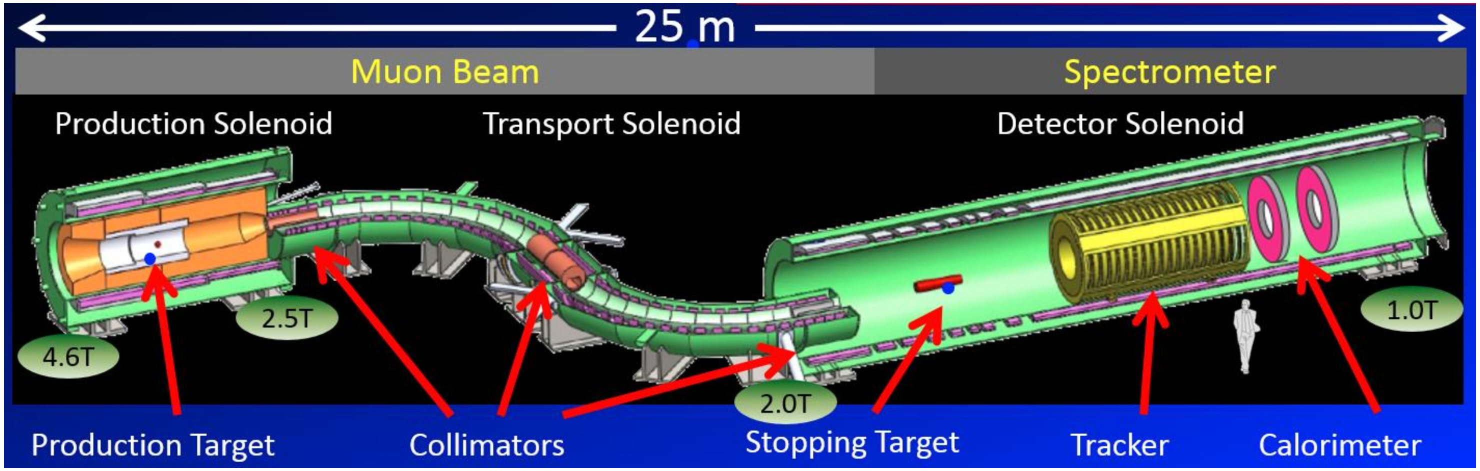
Final result by 2020

g-2/EDM in MLF @ JPARC

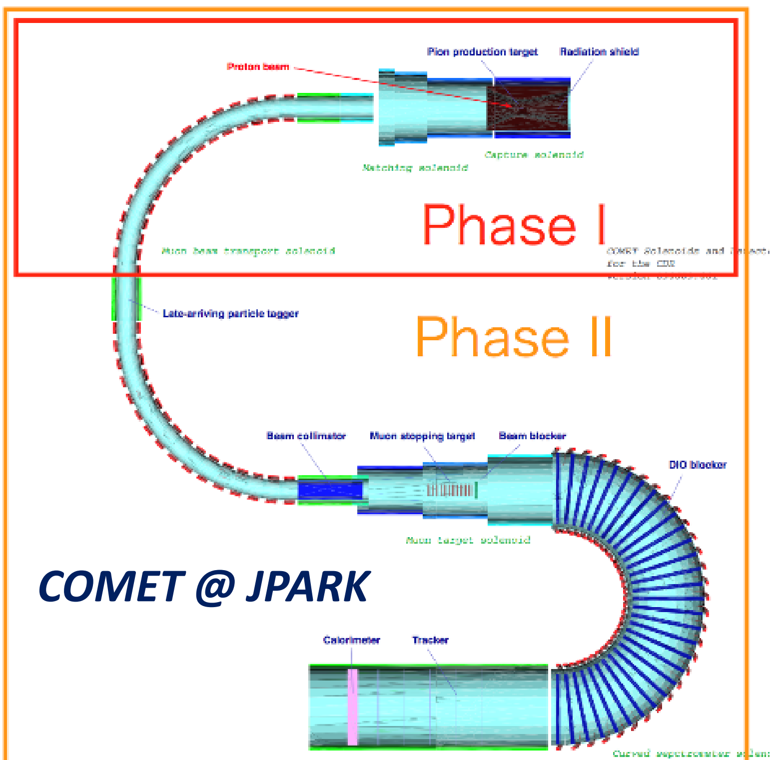
- Ultra cold μ^+ accelerated to 300MeV/c
- Goals
  - g-2 : 3 σ deviation from the SM
    - 0.5 ppm → 0.1 ppm
  - EDM: CP violation in the lepton sector?
    - < 1.8 x 10^{-19} e cm → 2 x 10^{-21} e cm
- Extensive R&D on-going
  - Beam intensity to test BNL g-2 results can be realized soon

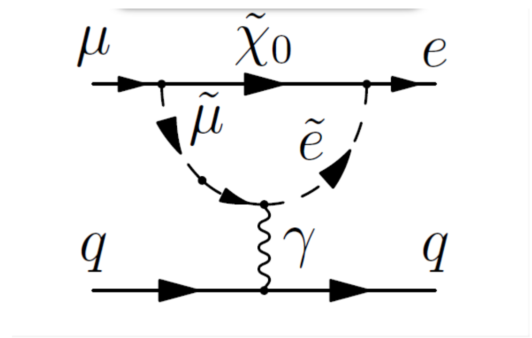


cLFV (μ –> e)



Mu2e @ FNAL

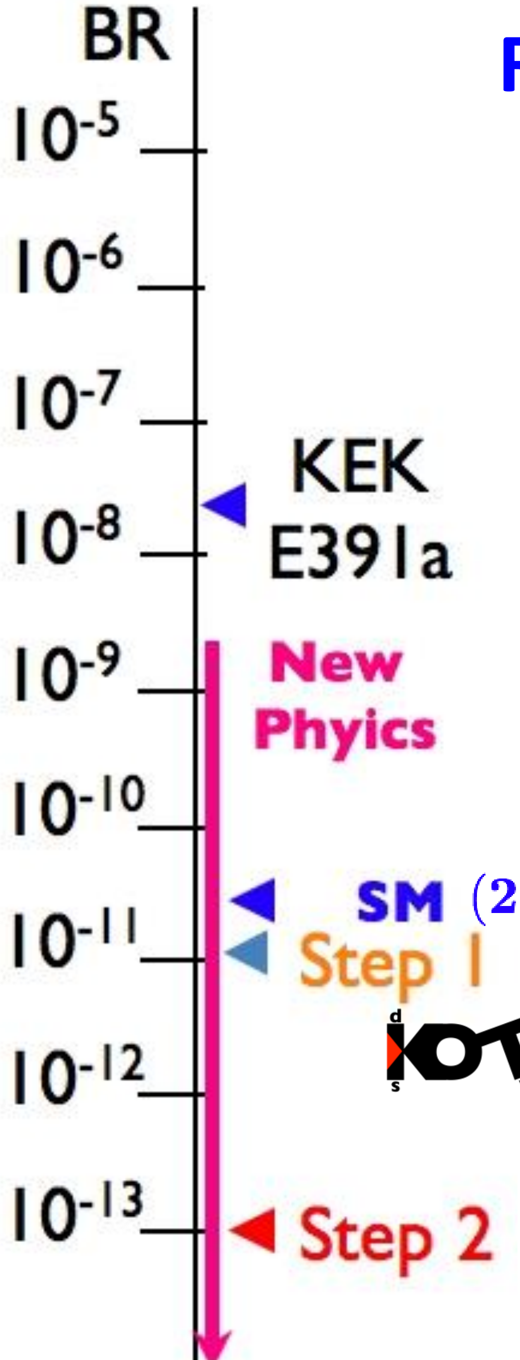




- ***μ→e conversion search***
  - ***$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$***
  - ***Delayed 105MeV e^-***
  - ***Present upper limit ~10^{-12}***
- ***Phased approach***
  - ***Phase-I: Beam study & Search < 10^{-14}***
  - ***Phase-II: Search <10^{-16}***
- ***Construction started!!***

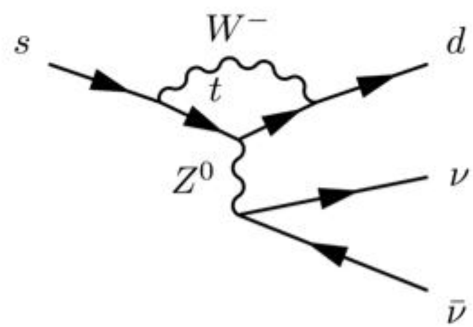
Rare Kaon Decay

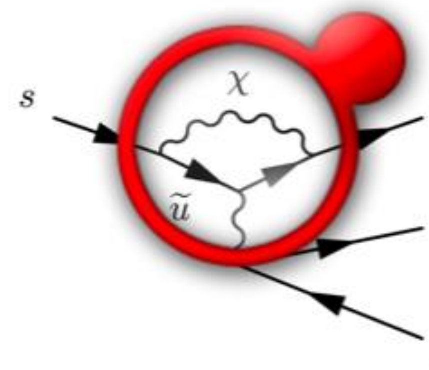
$$K_L^0 \to \pi^0 \nu \bar{\nu}$$



$(2.76 \pm 0.40) \times 10^{-11}$

KOTO @JPARC





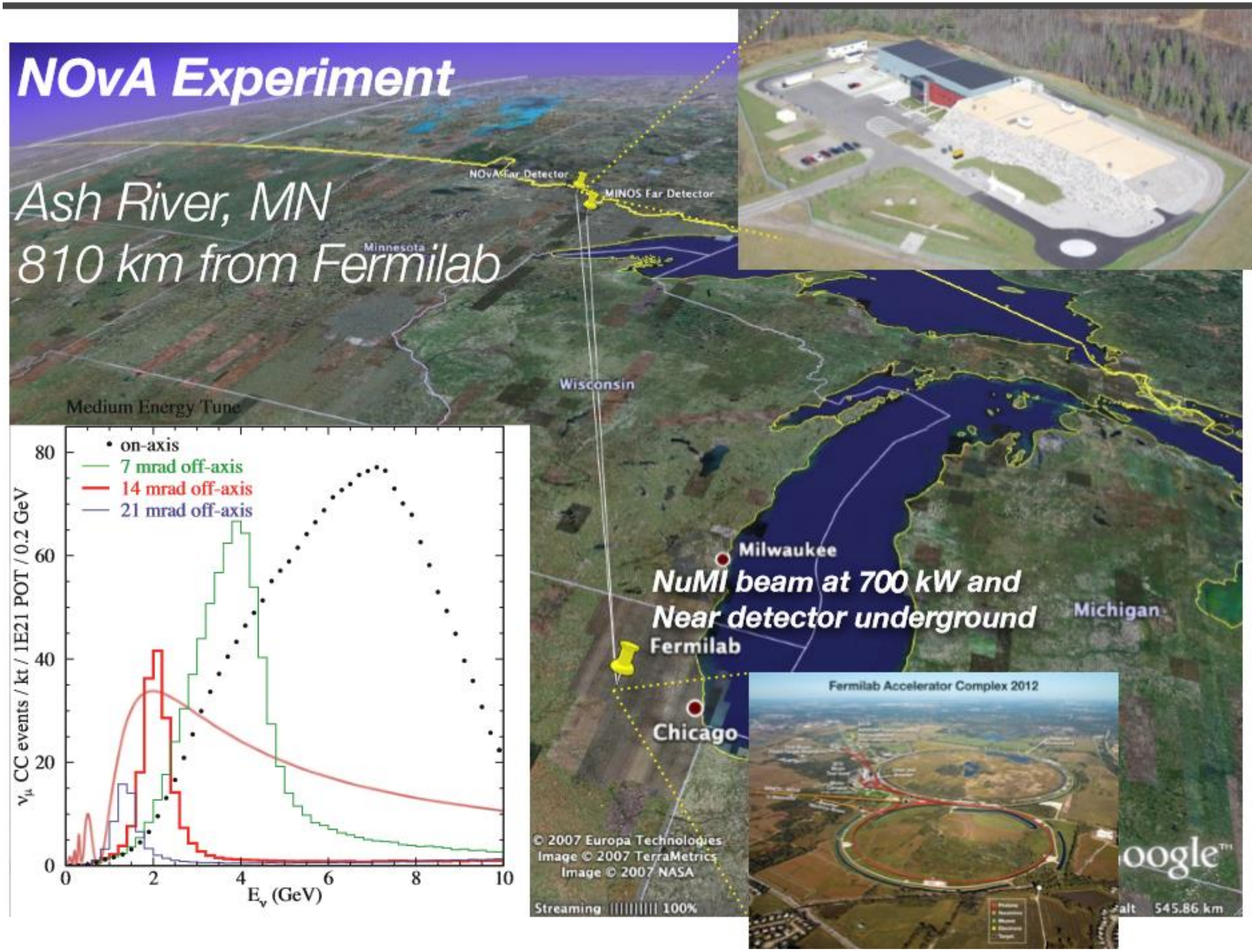
- *Not yet discovered*
- *SM prediction is very small ~2.4e-11 but precise*
- *Discovery beyond SM prediction = Discovery of New Physics*

$$K^+ \to \pi^+ \nu \nu$$

NA 62@CERN, 1st result announced

Important remaining questions in neutrino physics

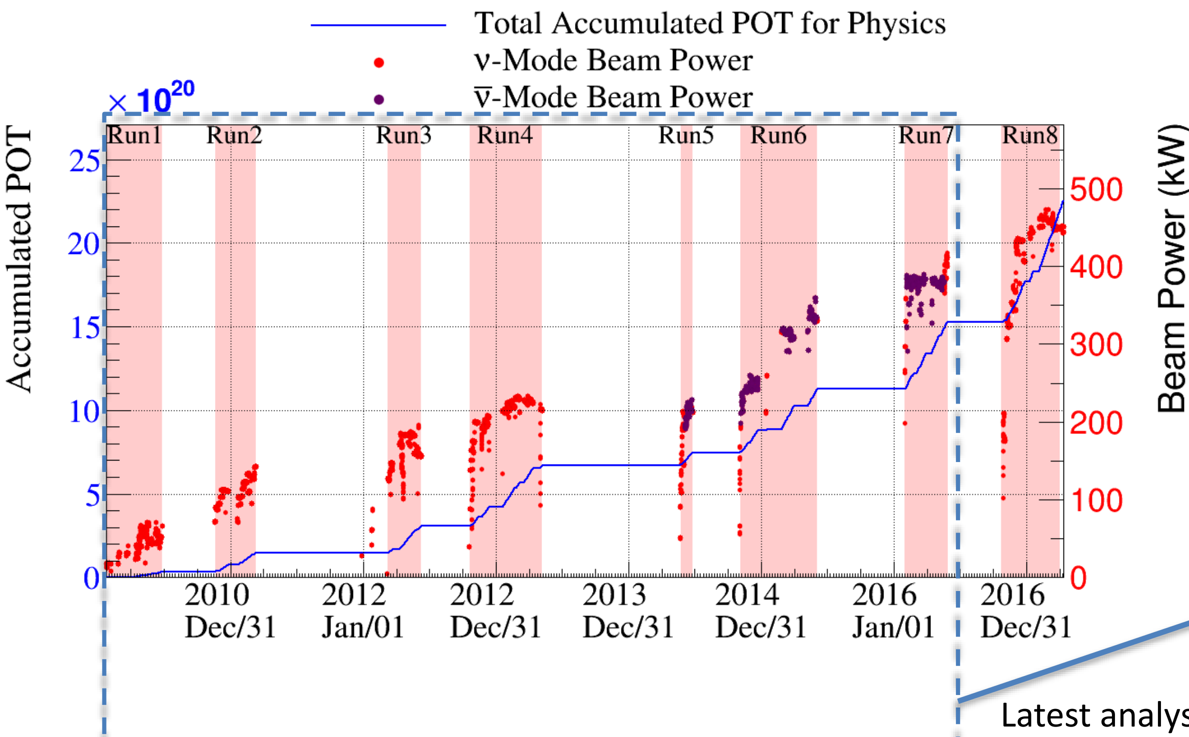
- ***What is the dominant flavour content of ν_3 ?***
  - *—— θ_{23} Octant*
- ***Neutrino mass.***
- ***Neutrino mass ordering.***
- ***Is δ_{cp} non-zero ? (CP violation in neutrino sector)***
- ***Direc or Majorana ?***


NOvA Experiment
Ash River, MN
810 km from Fermilab
NOvA Far Detector
MINOS Far Detector
Minnesota
Wisconsin
Milwaukee
NuMI beam at 700 kW and
Near detector underground
Michigan
Fermilab
Chicago
Fermilab Accelerator Complex 2012
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA
Streaming 100%
545.86 km
Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
νμ CC events / kt / 1E21 POT / 0.2 GeV
Eν (GeV)
0
2
4
6
8
10
20
40
60
80

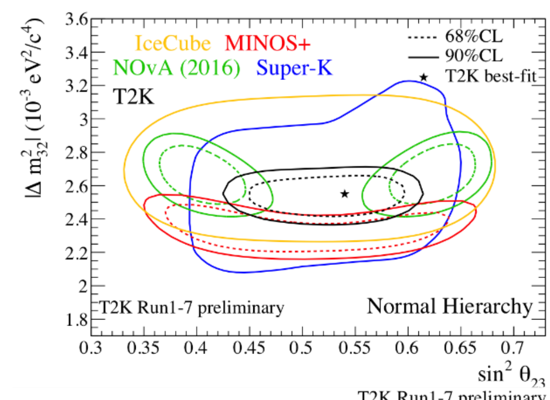
T2K Experiment

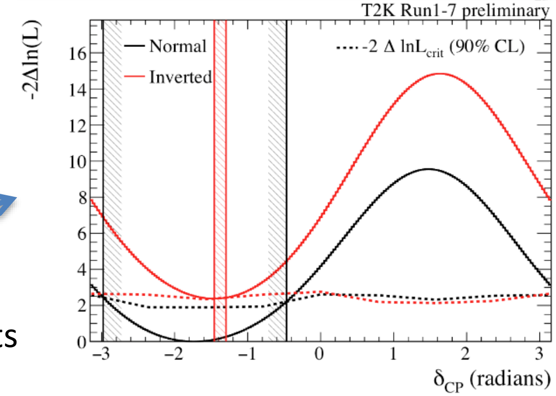
T2K: Current status

- Accumulated POT: *15.3 × 10^{20} (2016 Oct.)*→ **22.5 × 10^{20} (2017 Apr.)**
  - *ν*-beam: *7.7 × 10^{20} (2016 Oct.)*→ **14.9 × 10^{20} (2017 Apr.)**
  - $\bar{\nu}$-beam: 7.6 × 10^{20}
- J-PARC MR achieved continuous 470kW beam delivery to NU beam-line.
  - Trial of 510kW beam extraction to NU beam in Apr. 2017
- The results of *ν* oscillation analysis using the data until 2016 may had been published.
  - Phys. Rev. Lett. 118, 151801
- Preliminary results of improved analysis with new event selection was relased 2017 Feb.
  - Best measurement of the neutrino oscillation between 2nd-3rd generation.
  - The CP conservation hypothesis (δ_{CP}=0, π) is excluded at >90% C.L.
- New results with doubled *ν*-beam data will be released in 2017 Summer.



Latest analysis results





T2K proposes to collect 20×10²¹ POT data to search for evidence of CP violation in the lepton sector with 3σ sensitivity. (arXiv:1609.04111 [hep-ex])
– J-PARC PAC recognizes the scientific merit and gave stage-1 status in 2016.

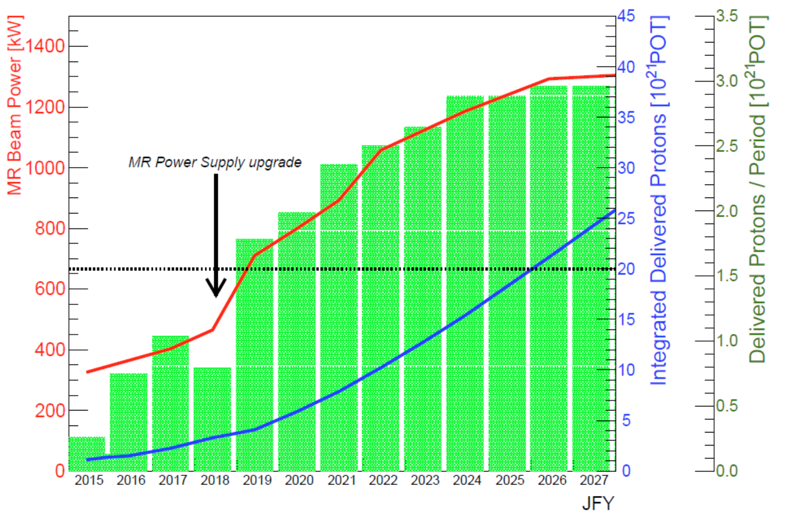
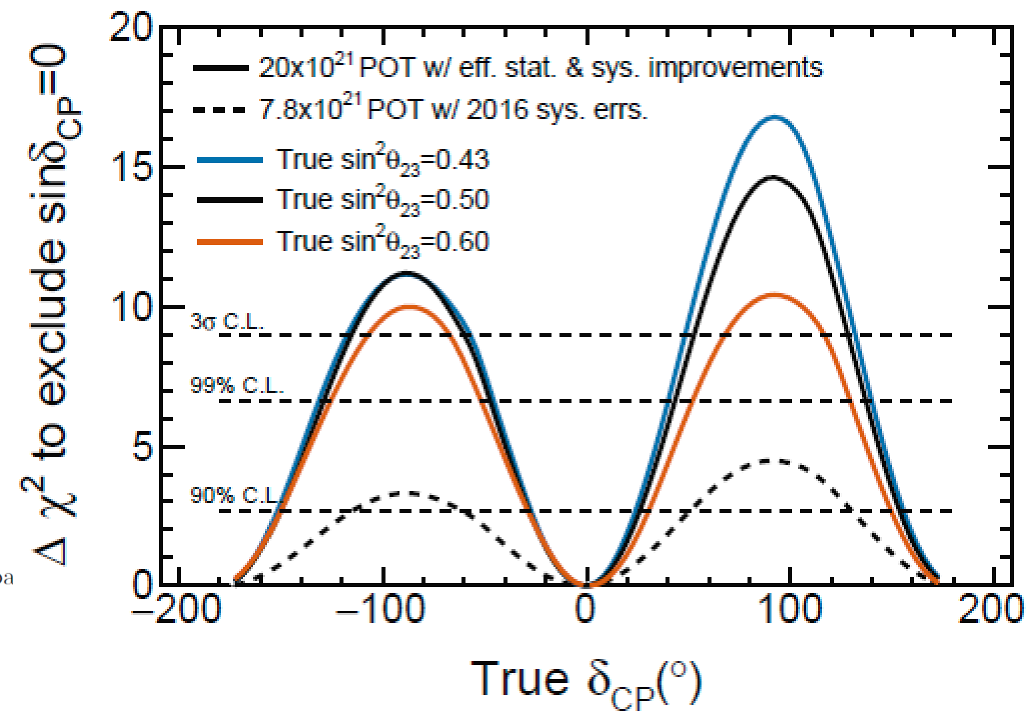


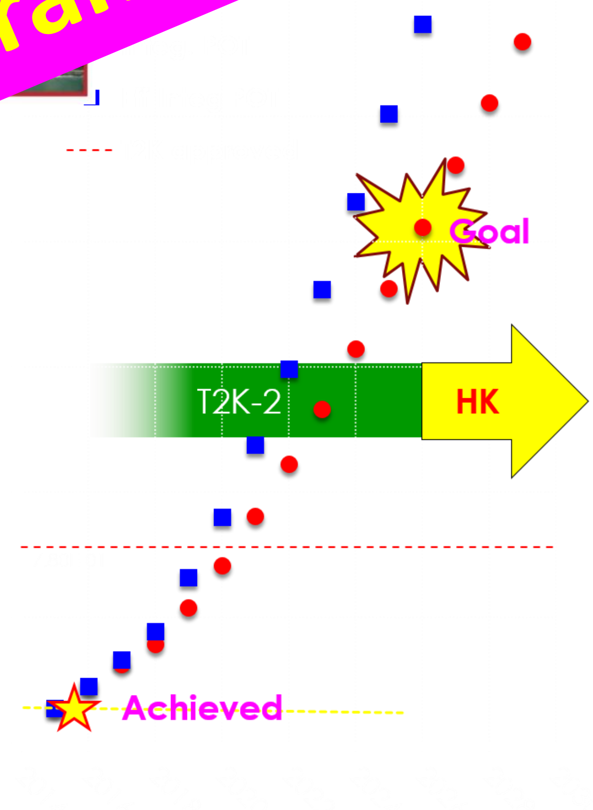
FIG. 1: Anticipated MR beam power and POT accumulation as function of Japa
Fiscal Year (JFY) which starts 1 April of the corresponding calendar year.



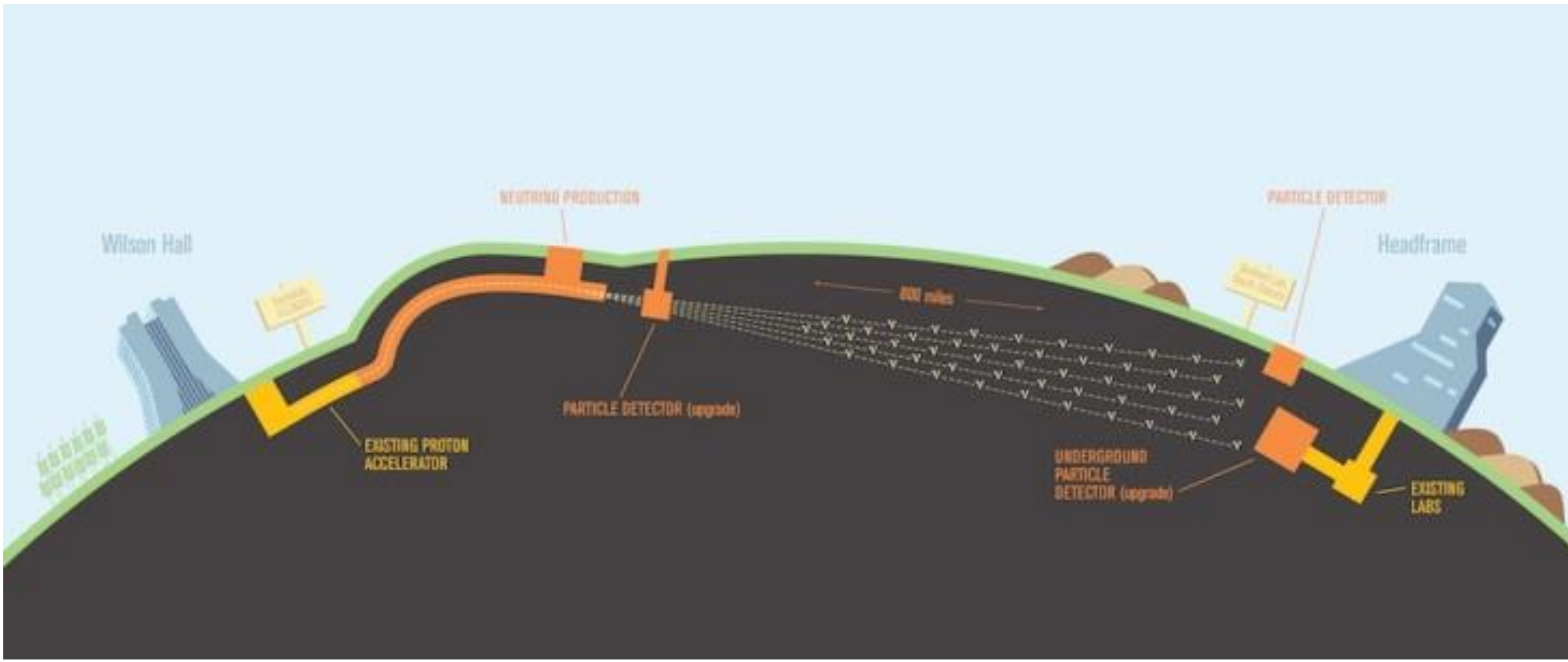
Hyper-Kamiokande (HK) (2026~)

Seamless productive program!

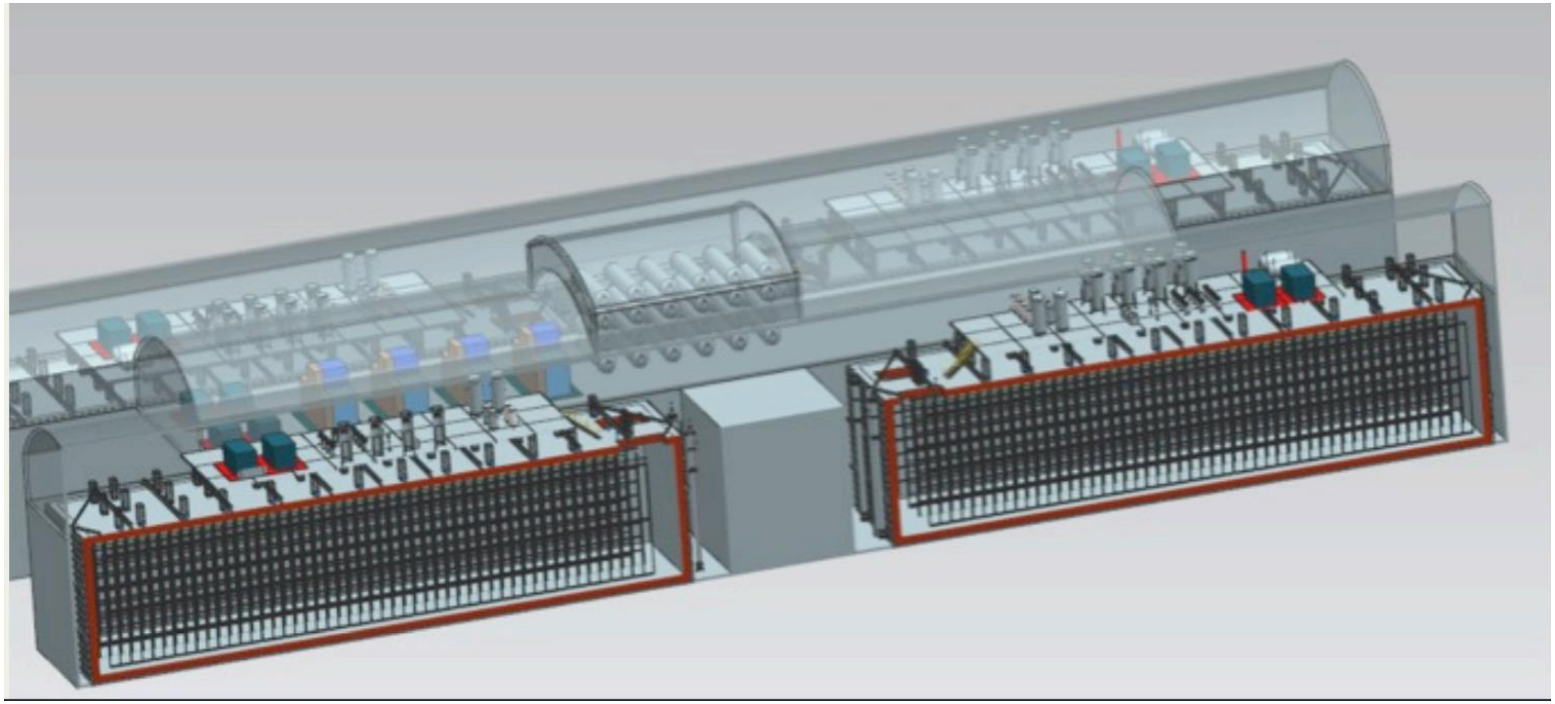
- Beam power : **1300 kW**
- POT goal … **x10⁷sec**
- Distanc… 295km
- D… **(190kt x2)**
  …rea(~1000km) under discussion
-
  – **Observation of CP violation at 8σ($\delta = -\frac{\pi}{2}$)**
  – **Precise measurement of CP phase**
  – **Discovery of proton decay w x10 sens.**
  – **Determination of mass hierarchy**

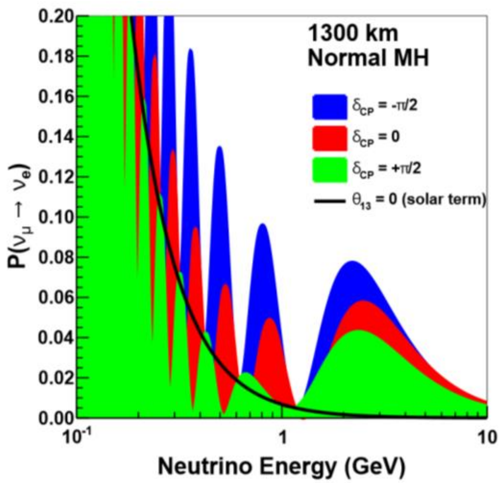


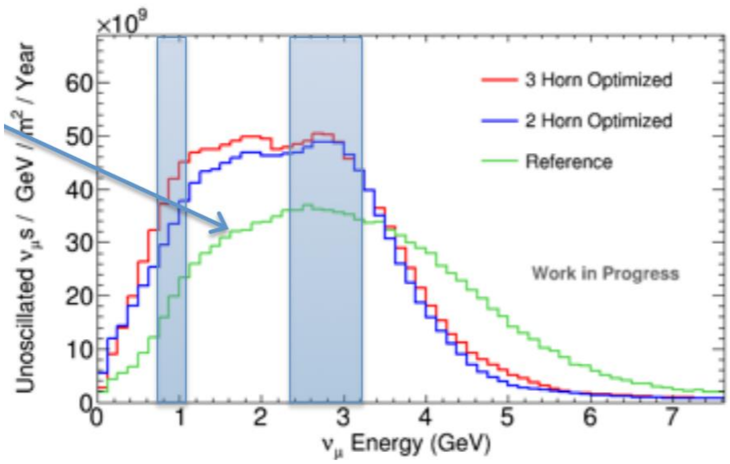
Long Base-Line Neutrino Facility, Fermilab to Homestake



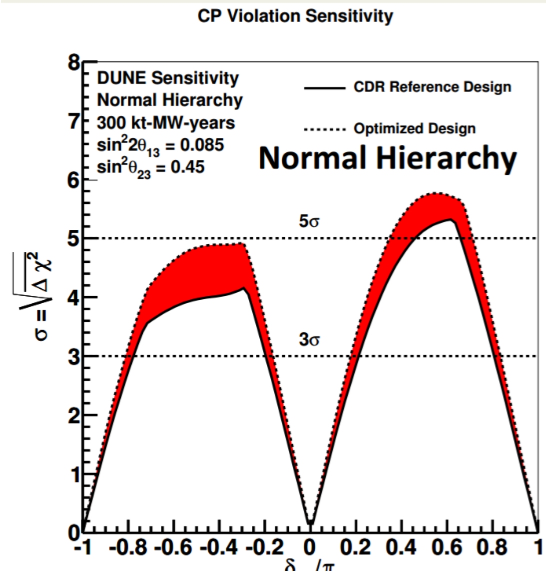
DUNE Experiment at South Dakota

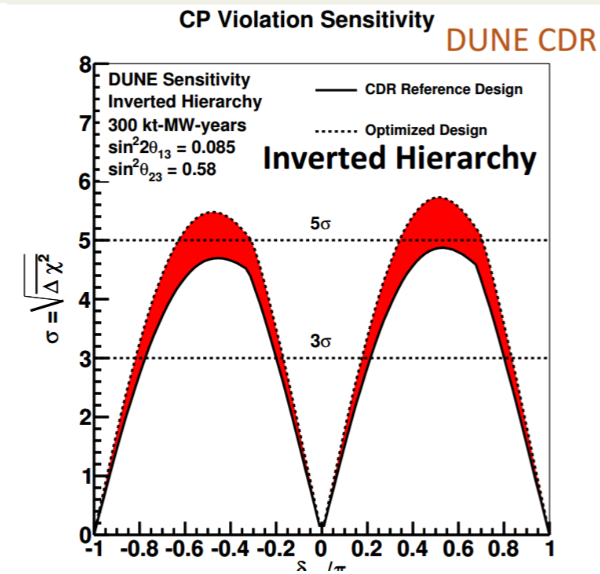


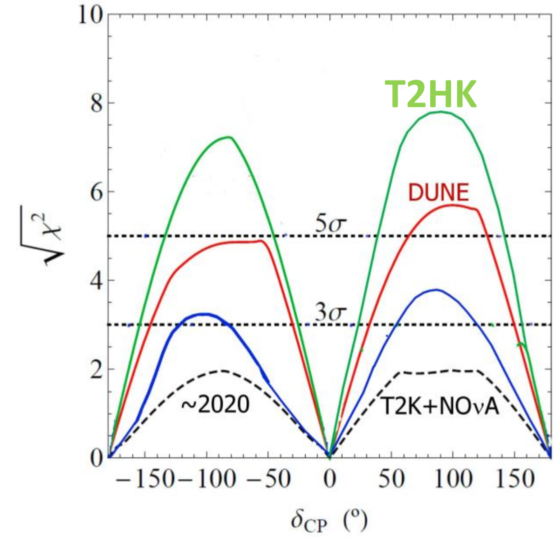


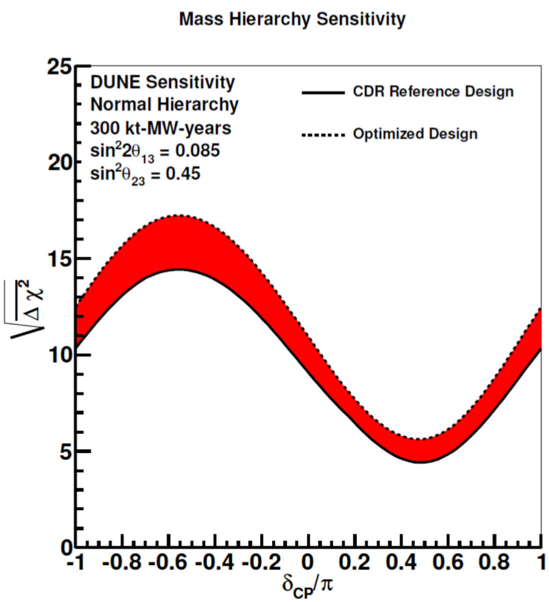


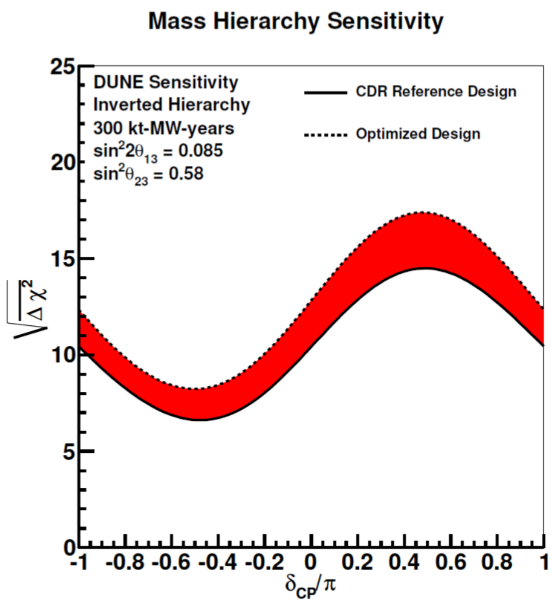
DUNE sensitivities





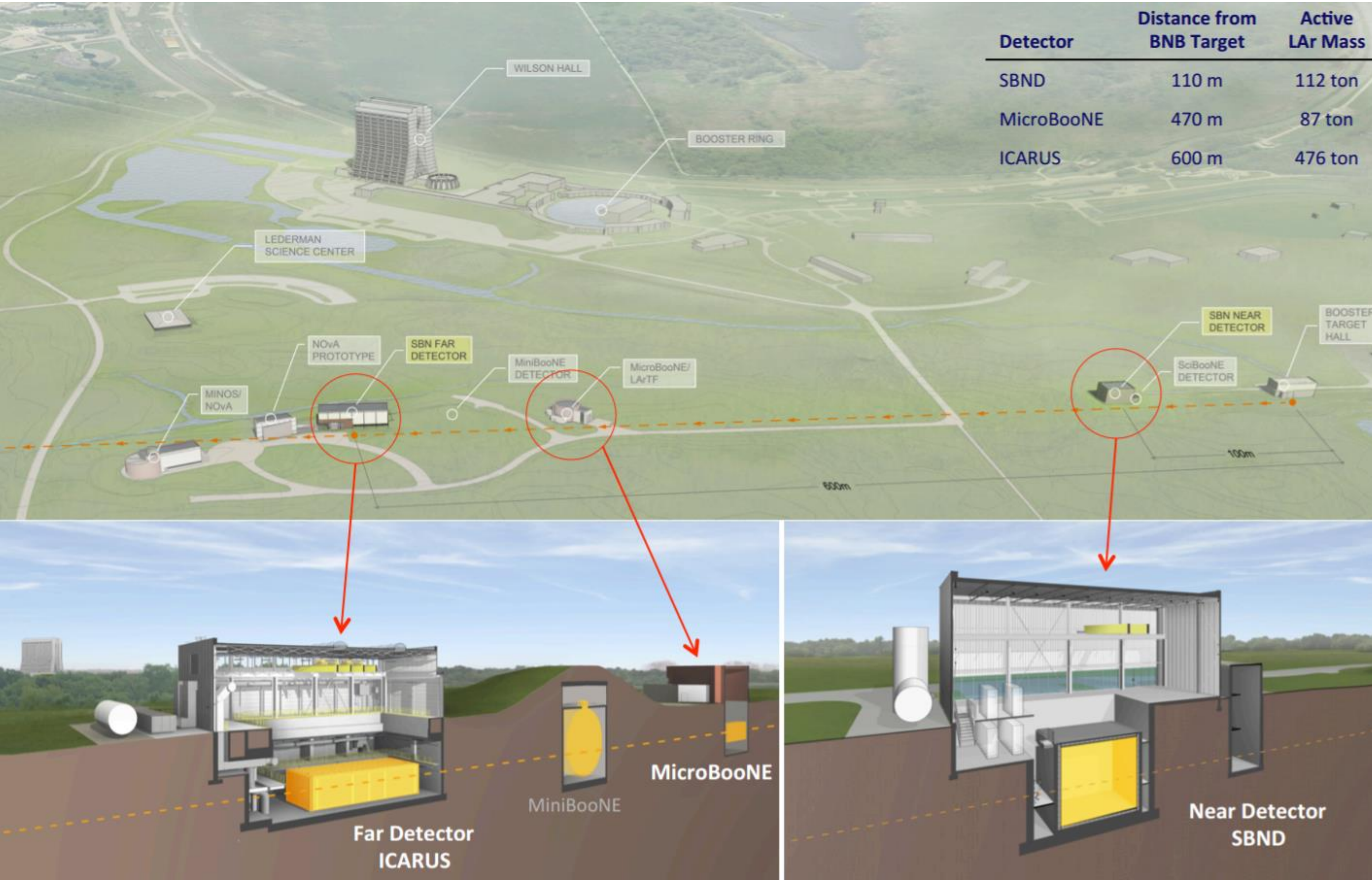


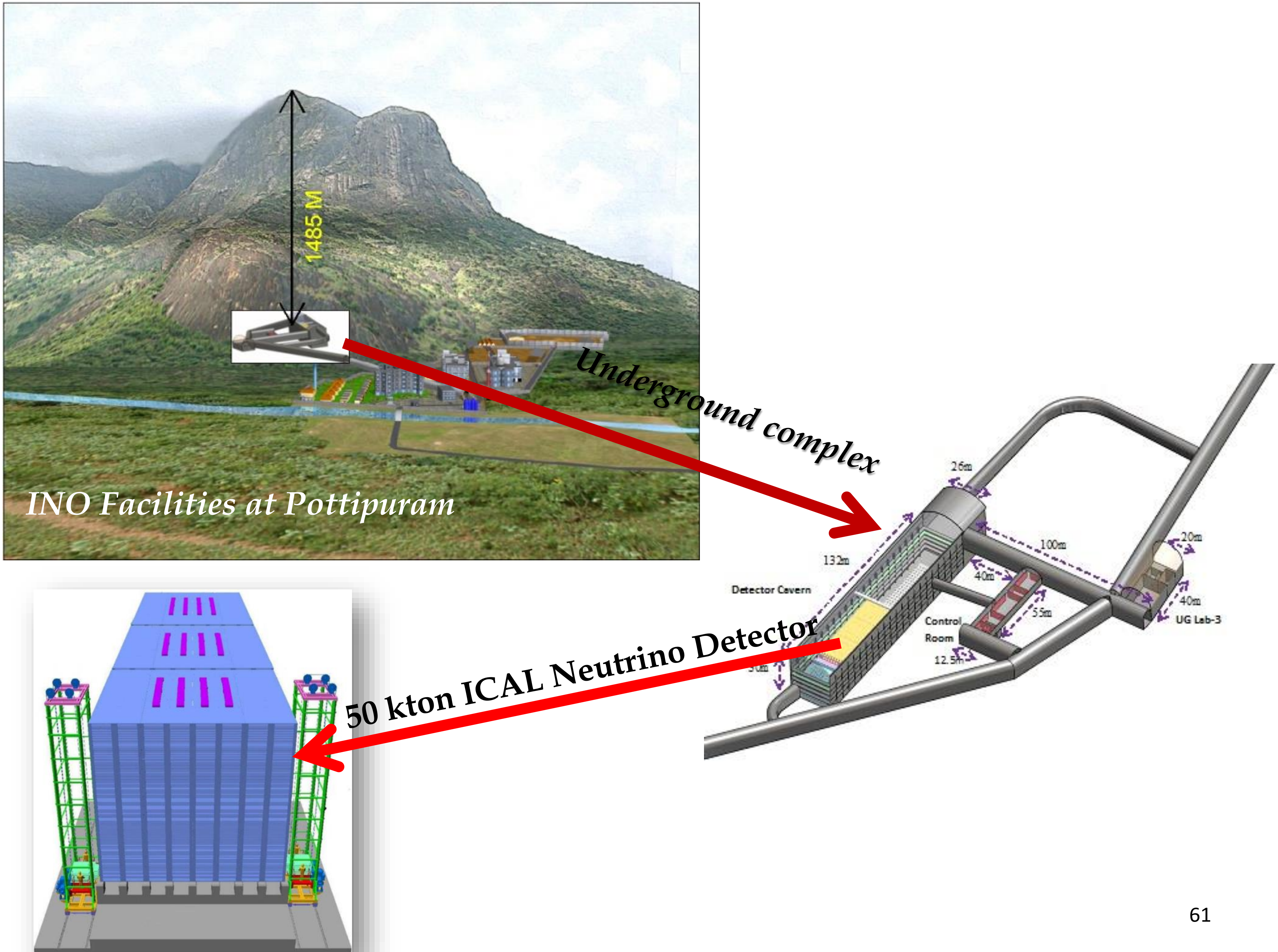




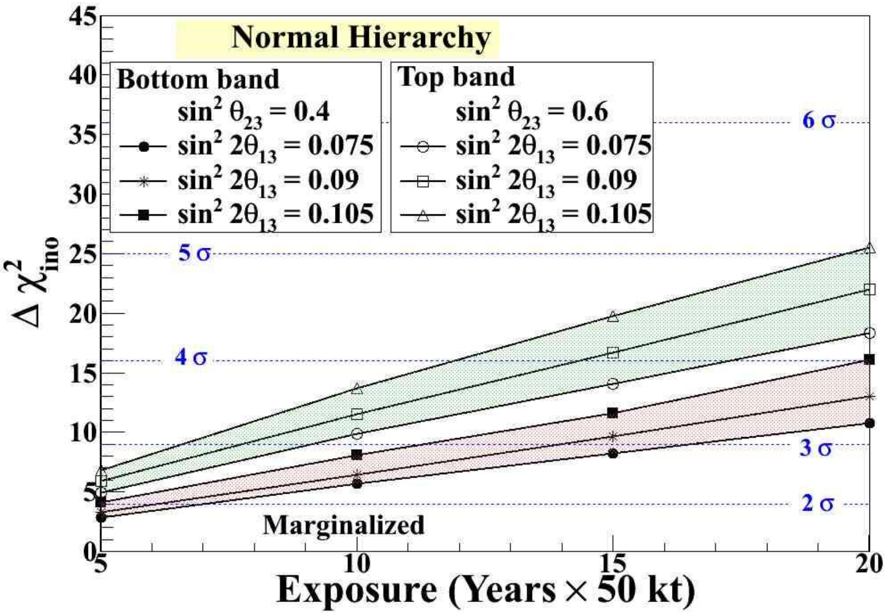
Three detector SBN program at Fermilab

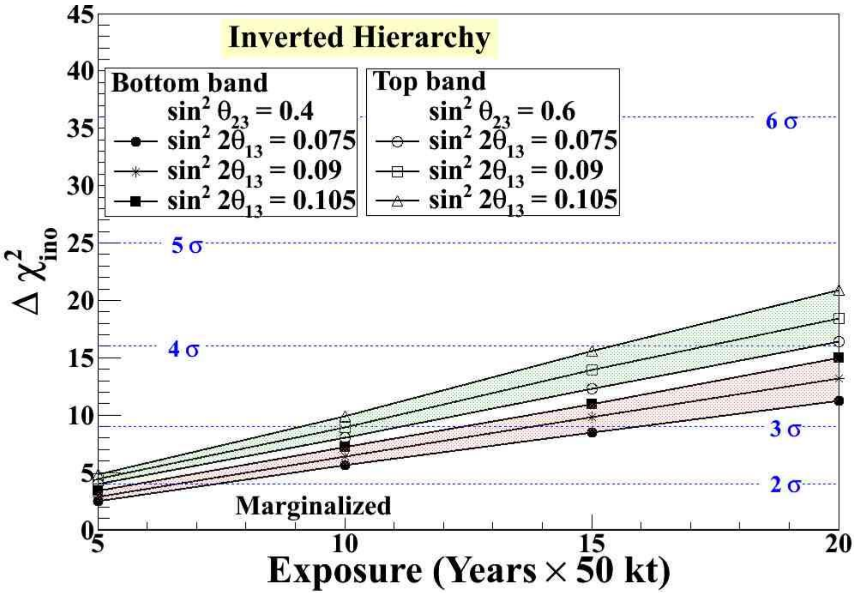
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

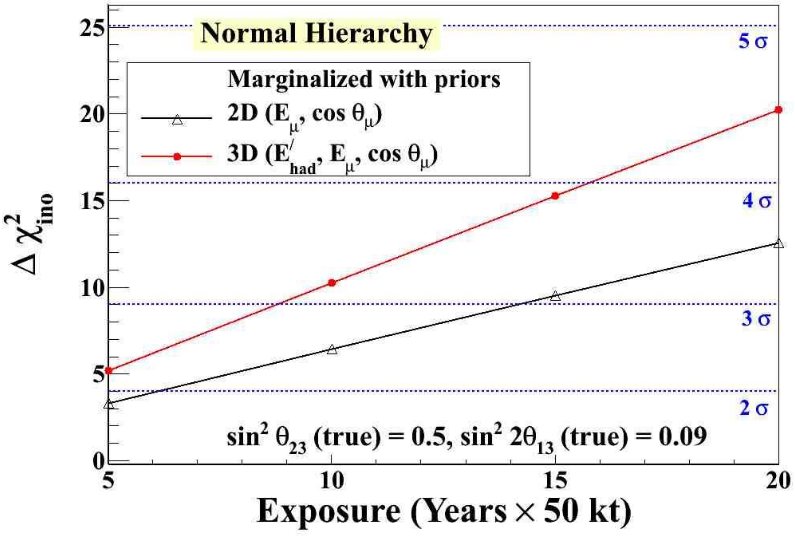



1485 M
INO Facilities at Pottipuram
Underground complex
26m
132m
Detector Cavern
100m
40m
20m
40m
UG Lab-3
55m
Control Room
12.5m
50 kton ICAL Neutrino Detector

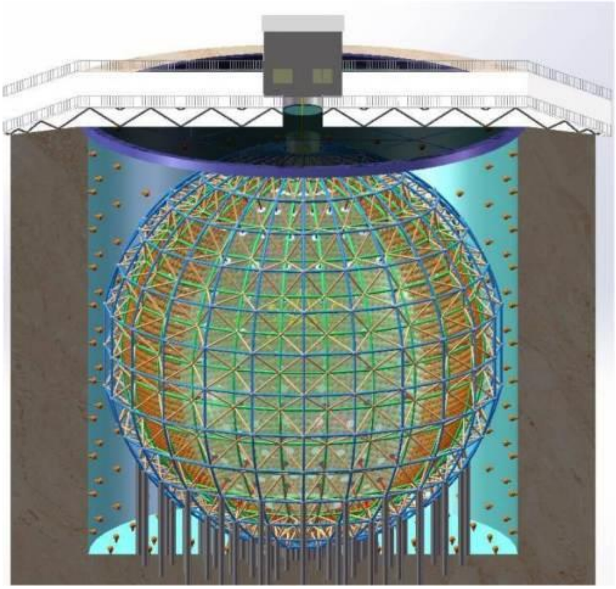
Mass hierarchy including hadron information



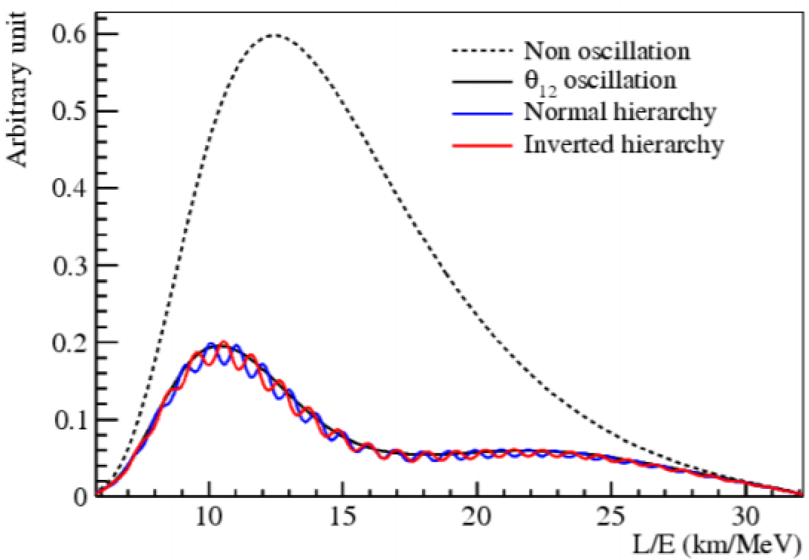


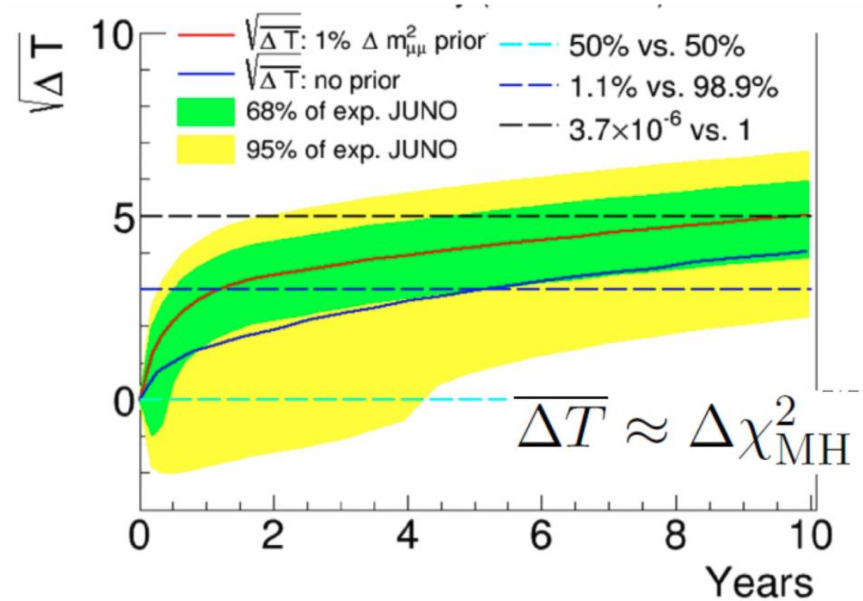


Proposed JUNO Experiment in China



$$\frac{\Delta E}{E} \approx \frac{3\%}{\sqrt{E}}$$

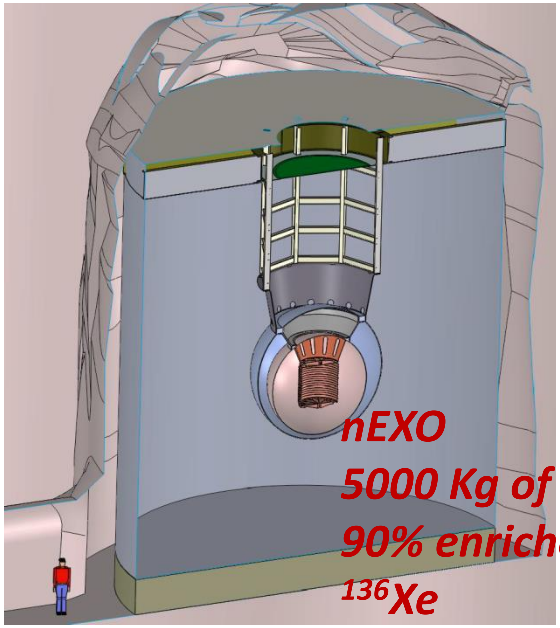




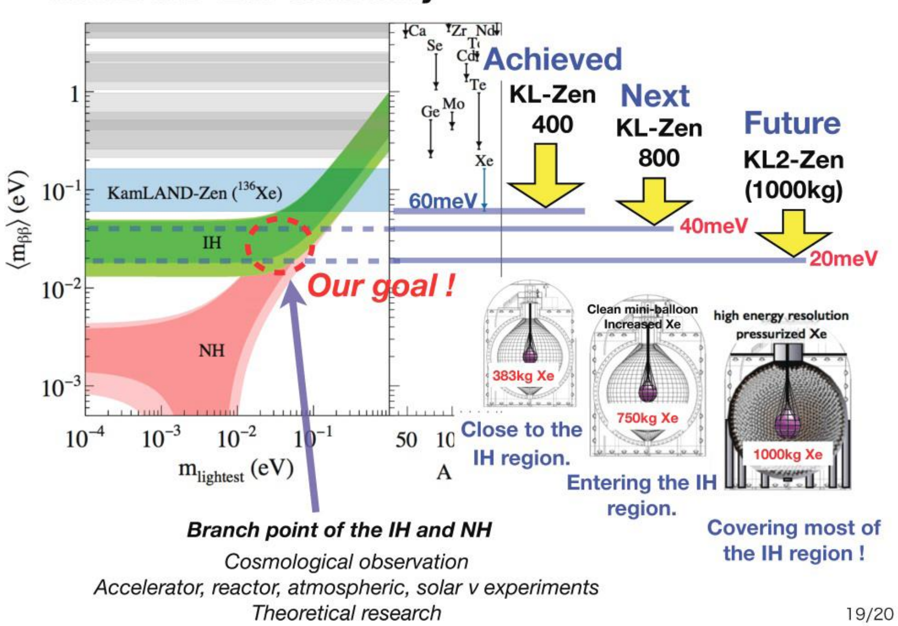
$$\overline{\Delta T} \approx \Delta\chi^2_{\rm MH}$$

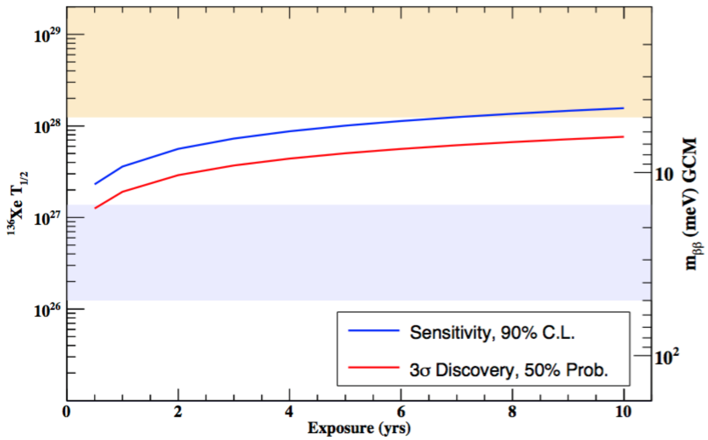
$0\beta\beta\nu$ in near future

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$



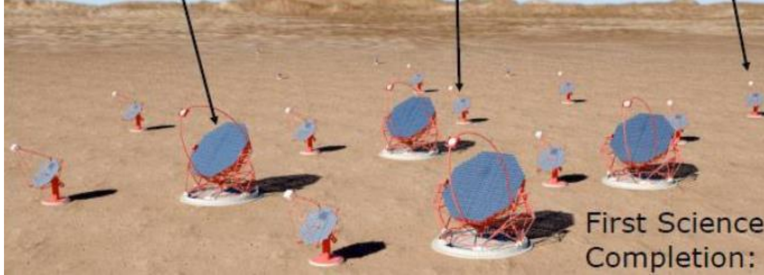
KamLAND-Zen sensitivity

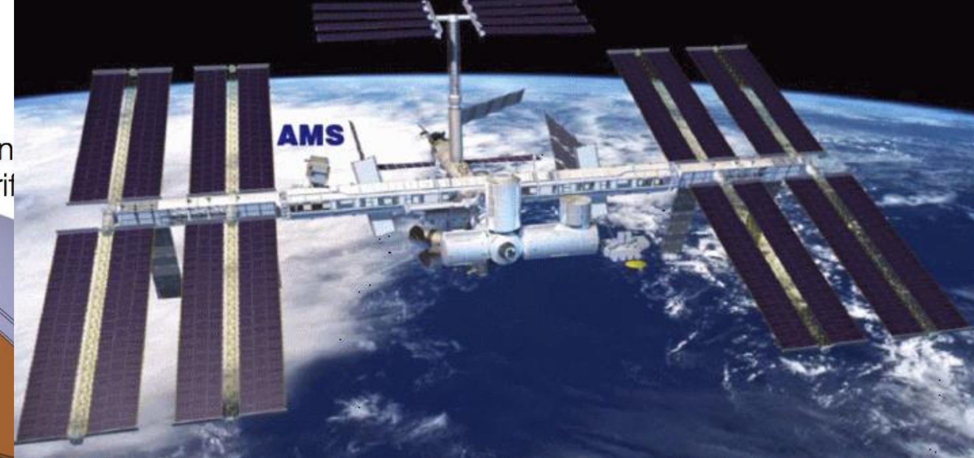


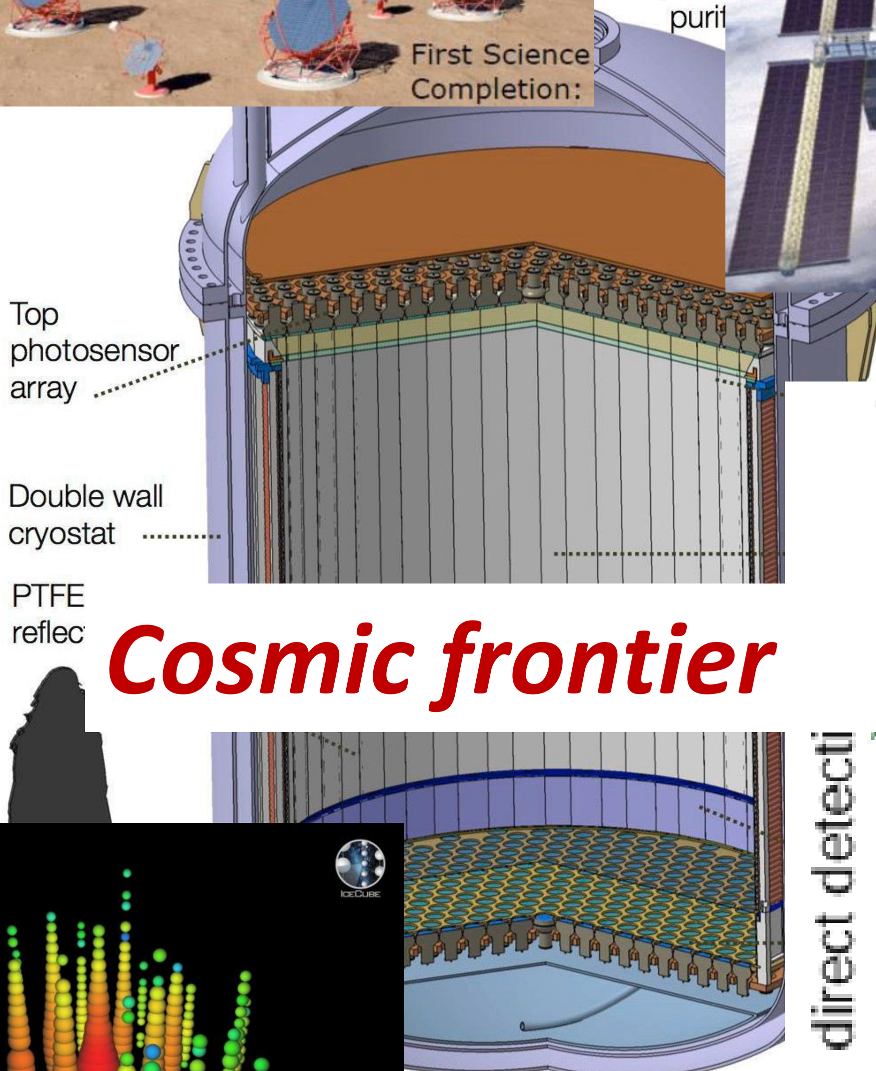


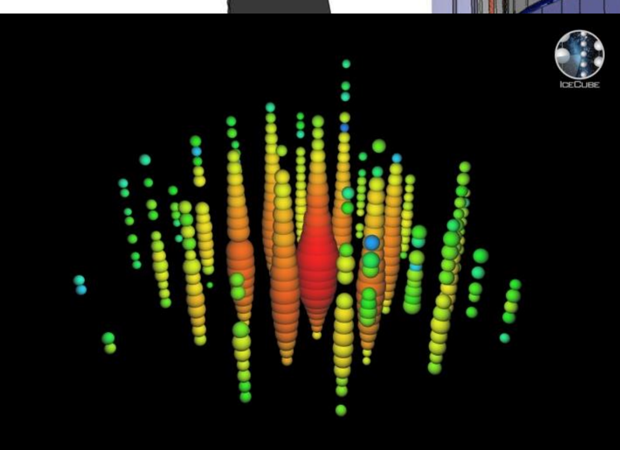
$\langle m_{\beta\beta} \rangle$ < 3 – 8 meV with Ba-136 seperation capability

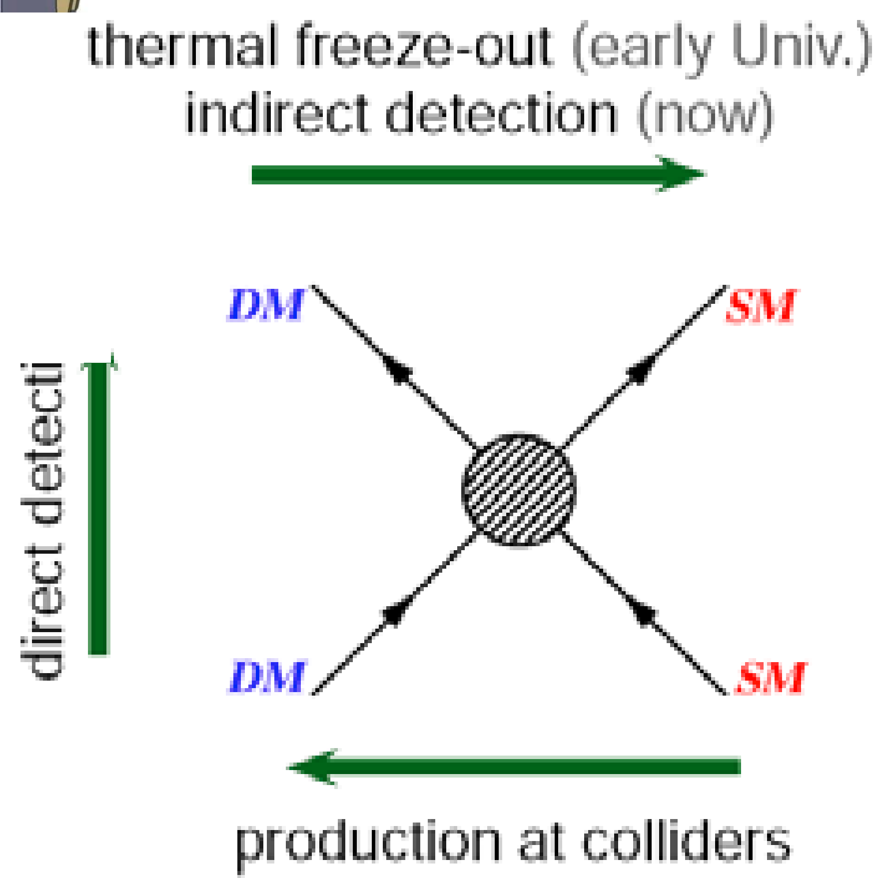
Cosmic frontier



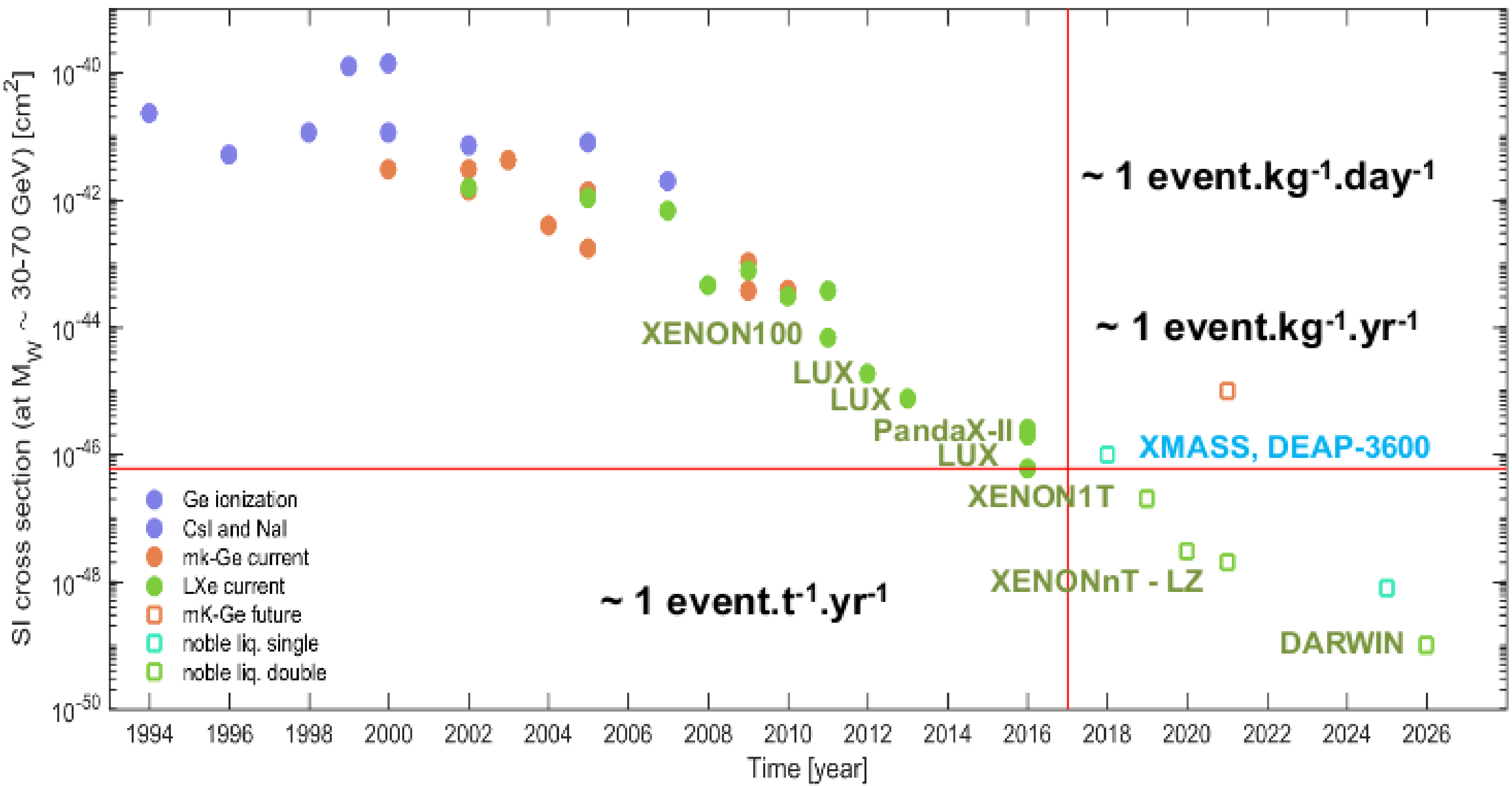




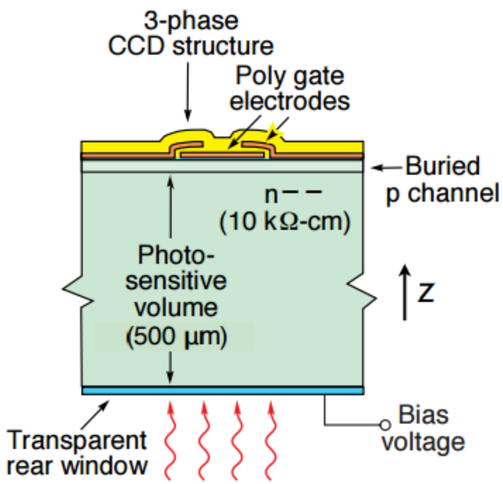




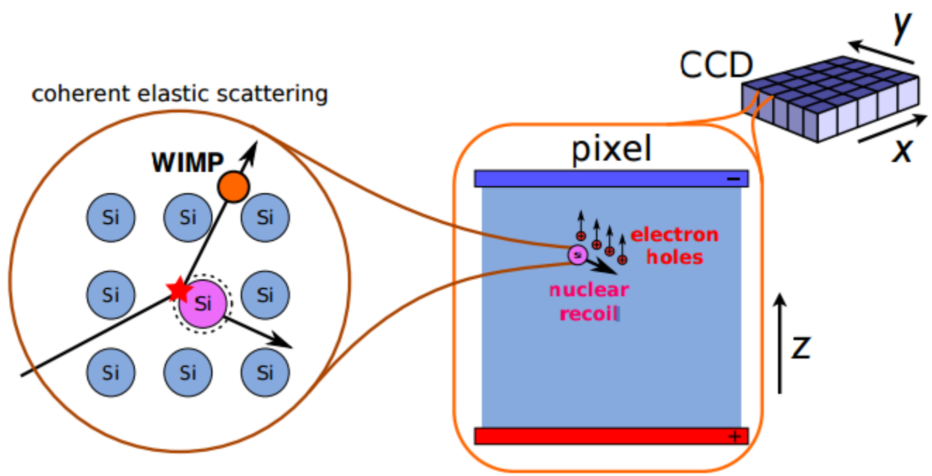
Direct detection of Dark Matter Search : Now and in future



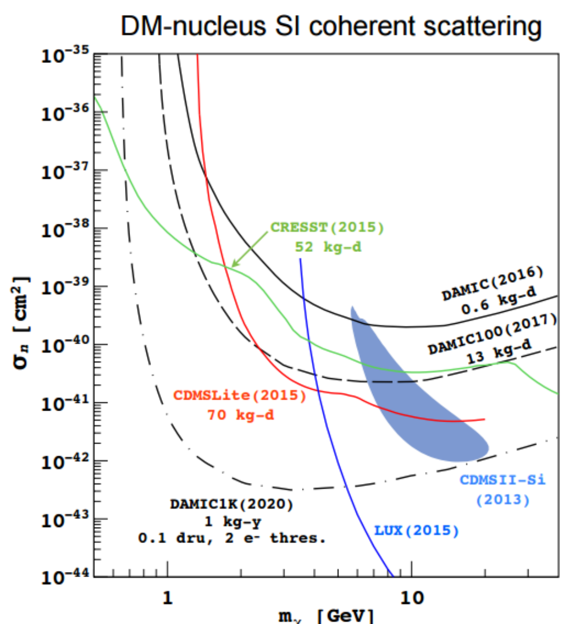
DAMIC Search for low mass WIMPs



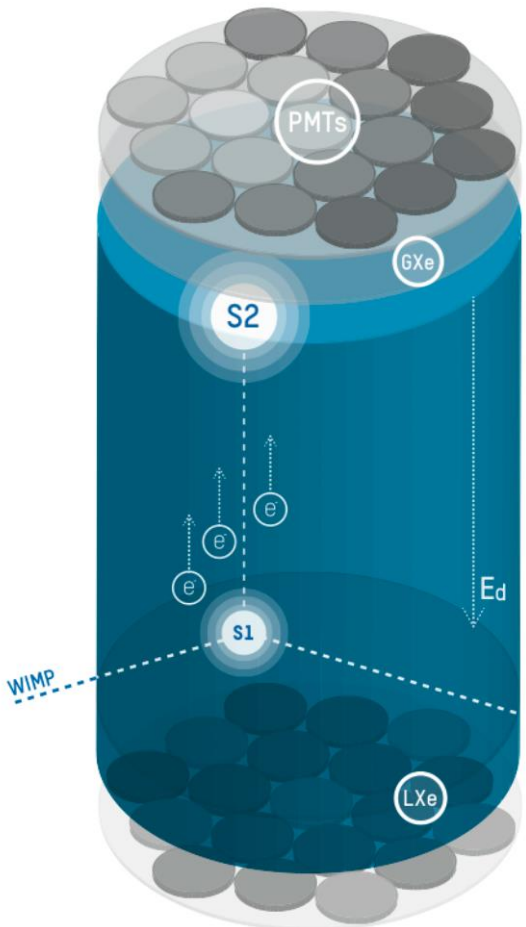
(a) A CCD pixel



(b) WIMP detection in a CCD



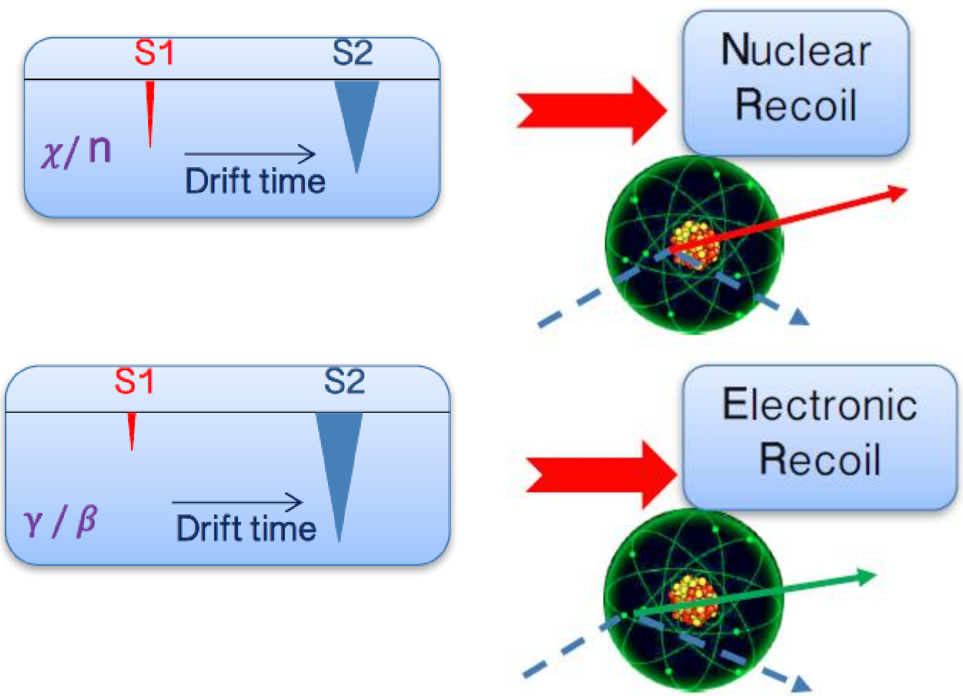
Dual Phase TPC- Principle



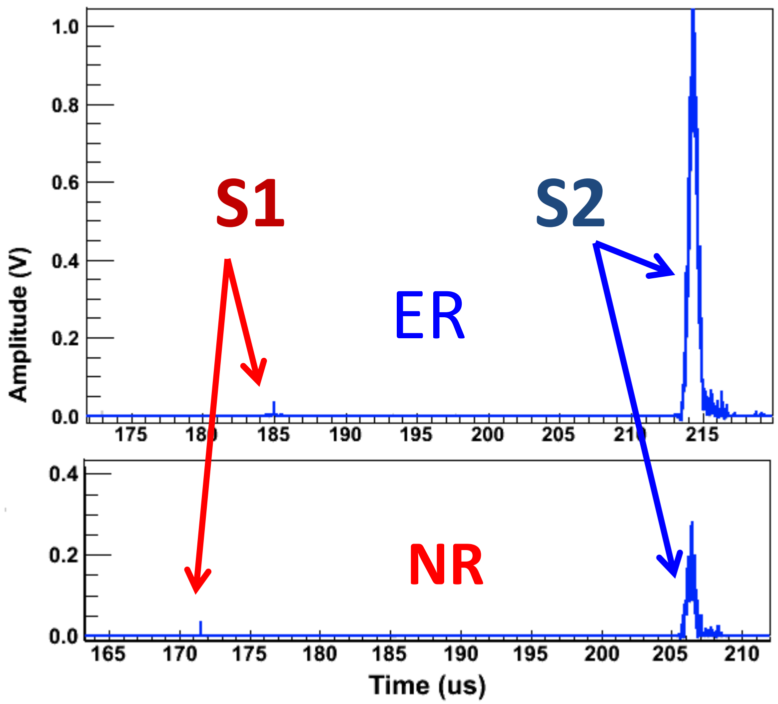
S1: → *Photon (λ = 178 nm)* → *Detected by PMTs*
from Scintillation process

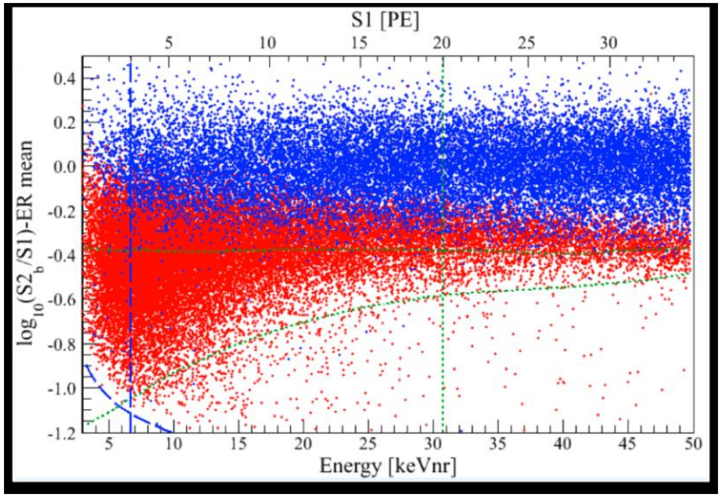
S2: → *Electrons drift*
Extraction in gaseous phase
Proportional scintillation light

3D reconstruction : → X,Y from top array
Z from Drift time



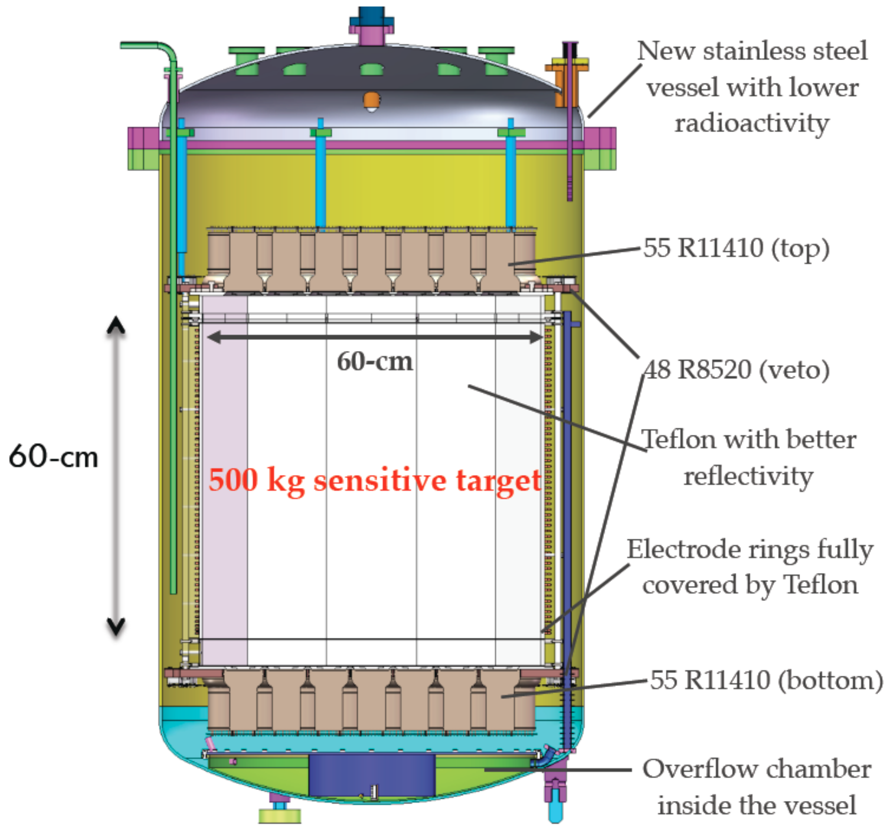
Dual Phase TPC - background vs. signal discrimination



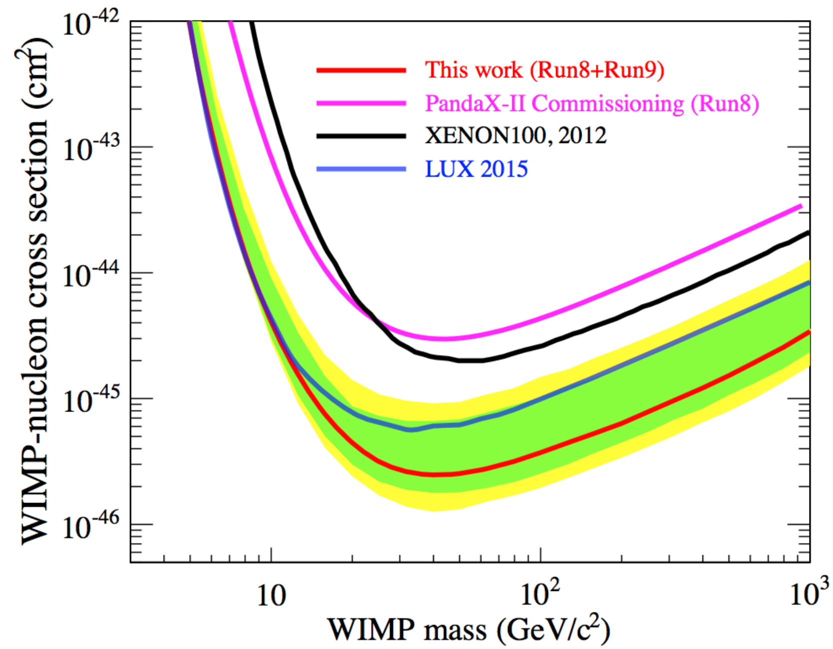


PandaX-II

PandaX-II @ CJPL (China)



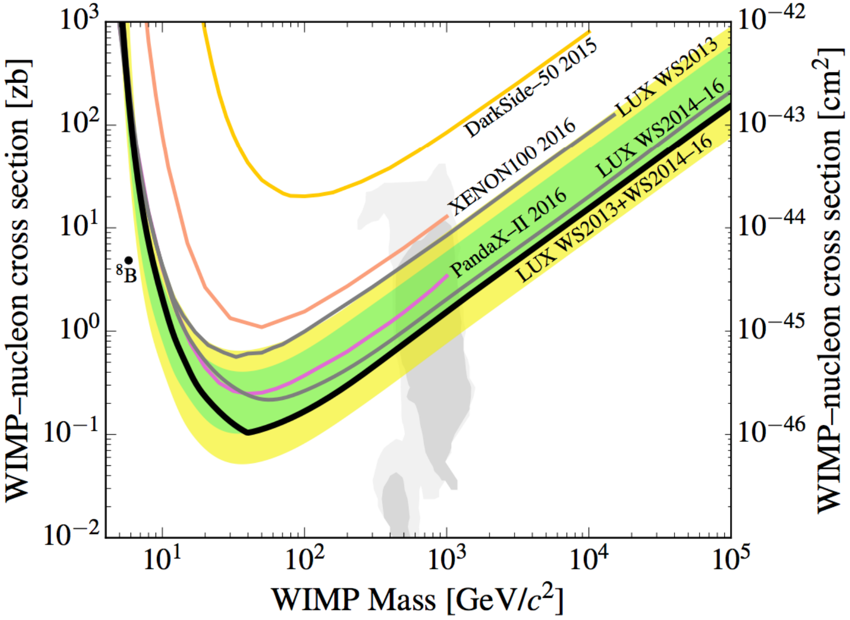
60 cm x 60 cm, ~ 400 kg fiducial
- *2nd largest operating LXe TPC*
- *3.3 x 104 kg.day = 0.1 t.year*
- *No excess*
- *Data tacking for the 2 next years*



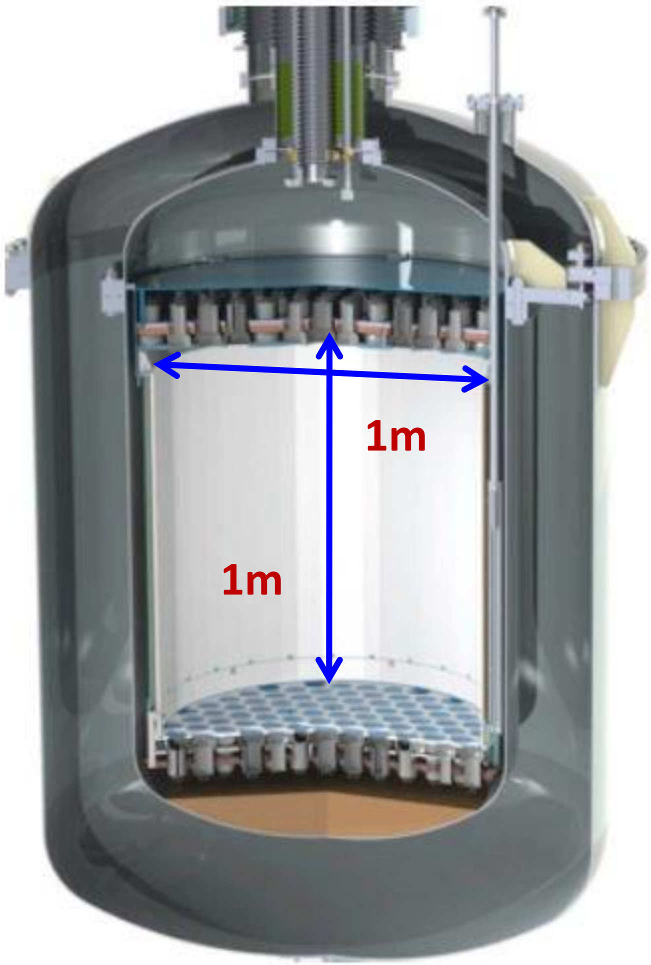
LUX new results SI limits

LUX @ SURF (USA)

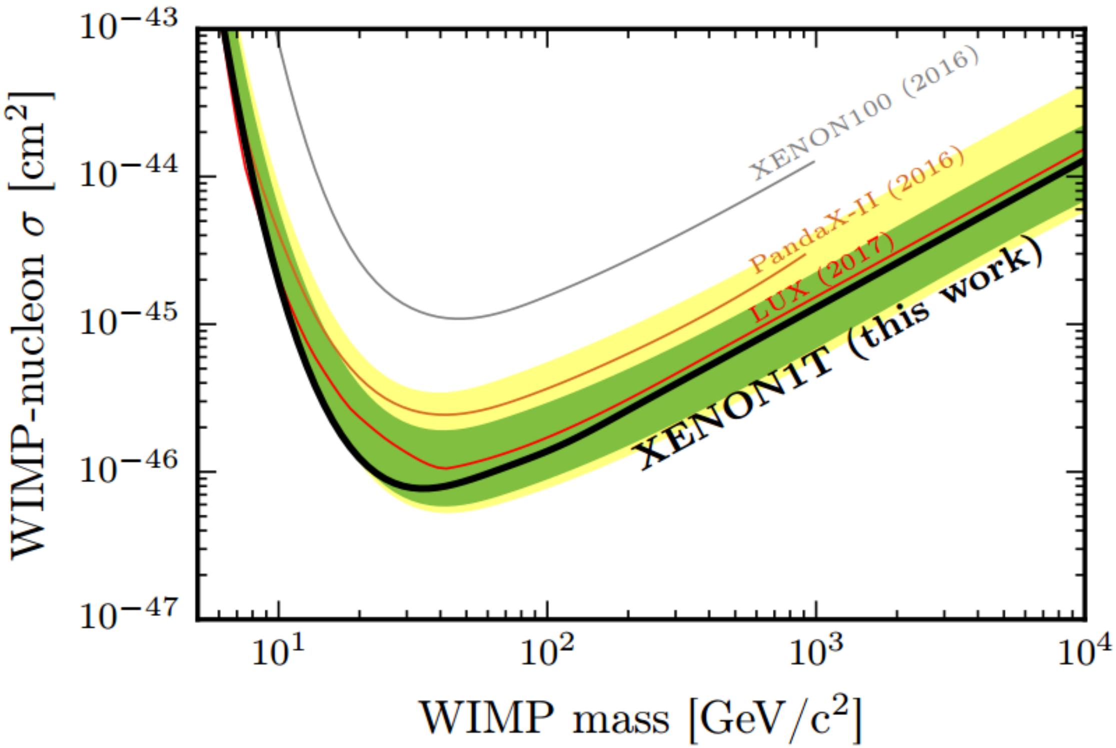
- *49 cm x 49 cm, ~100kg fiducial*
- *332 live-days*
- *3.4 x 104 kg.day = 0.1 t.year*
- *No excess*
- *Stopped*



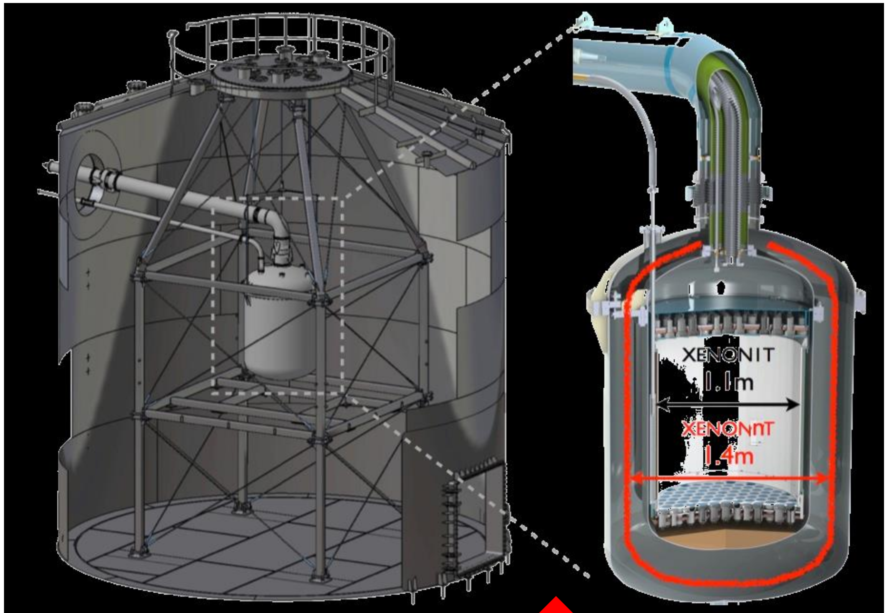
XENON1T : First ton scale detector



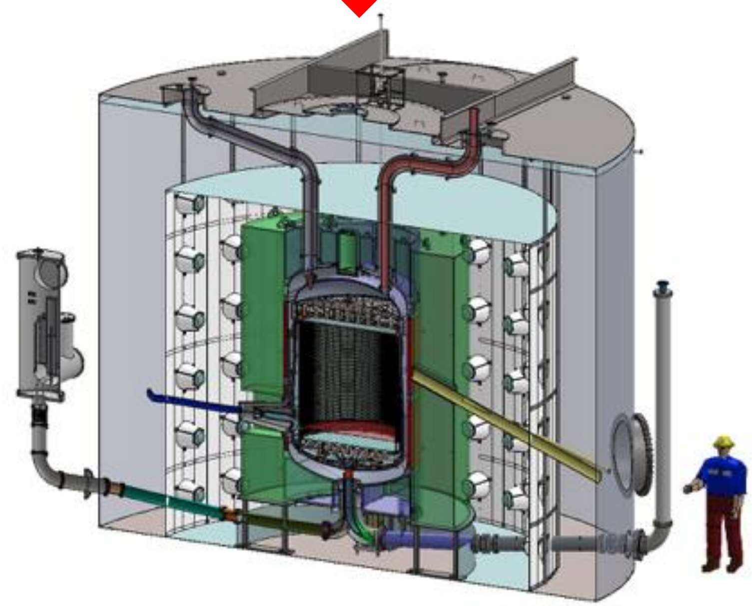
arXiv:1705.06655



Future: LZ & XENONnT

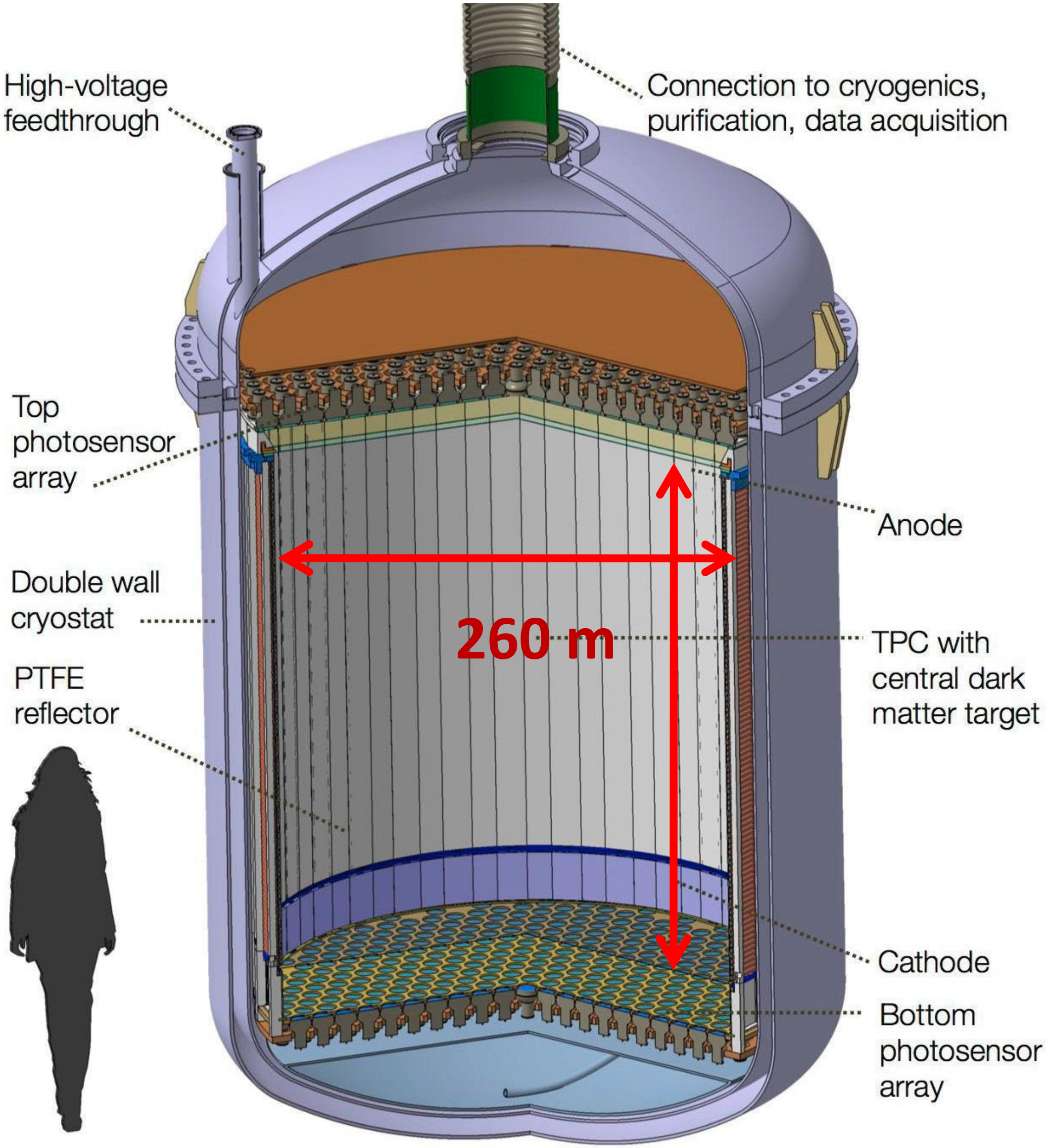


LZ = LUX + ZEPLIN
- *Same location than LUX*
- *Turning on by 2020 with 1 000 initial live-days*
- *10 tons total, 7 tons active,*



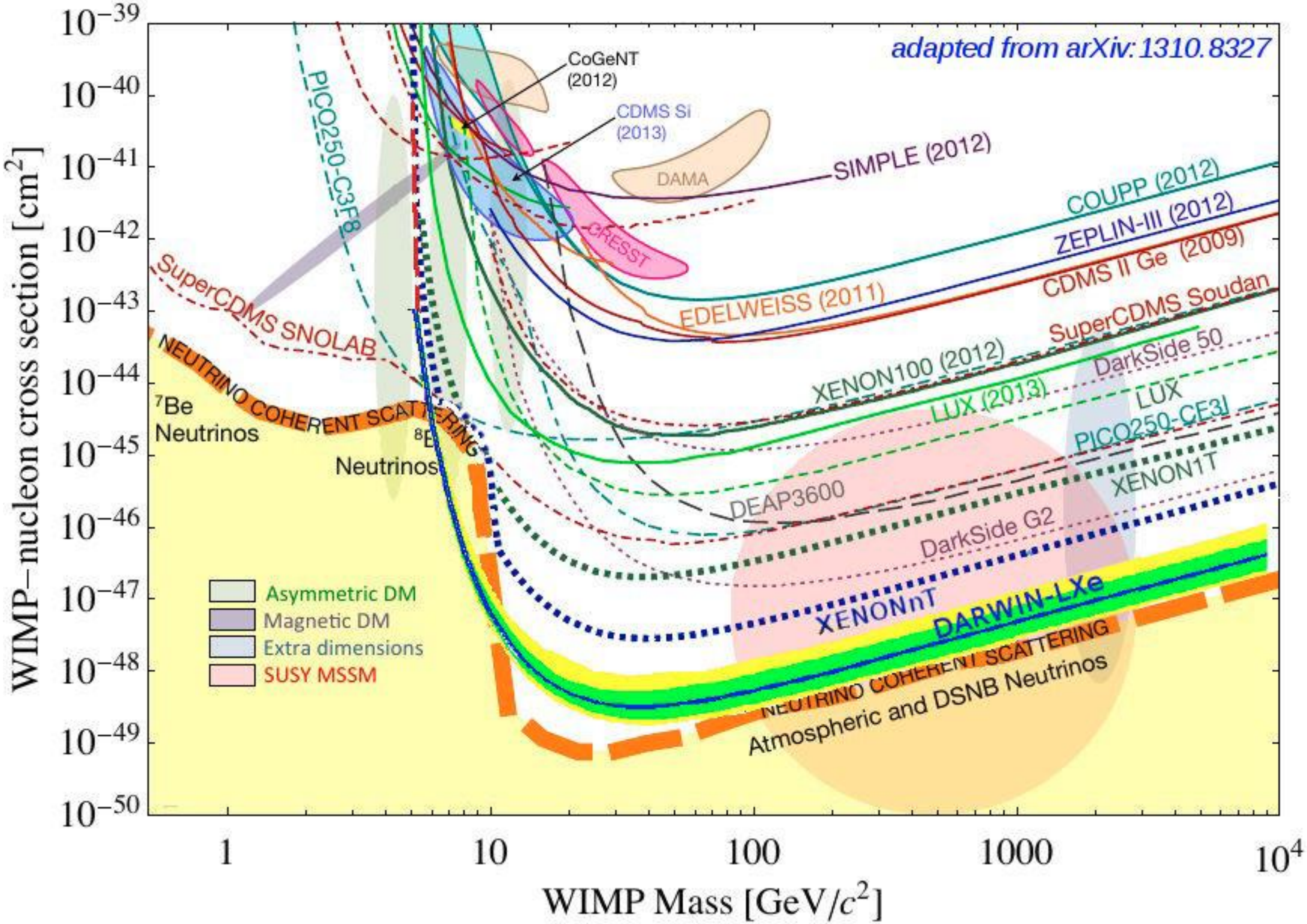
XENONnT:
- *Quick upgrade of TPC and inner cryostat*
- *All major systems remain unchanged*
- *Construct TPC in parallel to XENON1T operation*
- *Upgrade starting 2018*
- *8 tons total, 6 tons active*

DARWIN the ultimate DM detector



- ***Aim at sensitivity of a few 10^{-49} cm^2, limited by irreducible ν-backgrounds***
- ***R&D started***
- ***50 tons total LXe***
  40 tons TPC, 30 tons fiducial

Perspectives



Our journey continues

- *we are about to start our exploration of the dark side of our universe.*
- *“and miles to go before I (and you) sleep”.*
- *no roadmap to guide us.*
- *but will have many candles to guide us in the darkness.*