Future of High Energy Physics

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CERN-Fermilab Hadron Collider Physics Summer School

Predicting the Future

Visit to the World's Fair 2014

By ISAAC ASIMOV

August 16, 1964 (abridged - from the NYTimes) http://www.nytimes.com/books/97/03/23/lifetimes/asi-v-fair.html

- There is every likelihood that highways at least in the more advanced sections of the world*will have passed their peak in 2014; there will be increasing emphasis on transportation that makes the least possible contact with the surface. There will be aircraft, of course, but even ground travel will increasingly take to the air*a foot or two off the ground. !!

- Bridges will also be of less importance, since cars will be capable of crossing water on their jets, though local ordinances will discourage the practice.

- ✔ Communications will become sight-sound and you will see as well as hear the person you telephone. The screen can be used not only to see the people you call but also for studying documents and photographs and reading passages from books.

- .. a school of the future ... closed-circuit TV and programmed tapes aid the teaching process. It is not only the techniques of teaching that will advance, however, but also the subject matter that will change. All the high-school students will be taught the fundamentals of computer technology will become proficient in binary arithmetic and will be trained to perfection in the use of the computer languages that will have developed out of those like the contemporary "Fortran" (from "formula translation"). ??

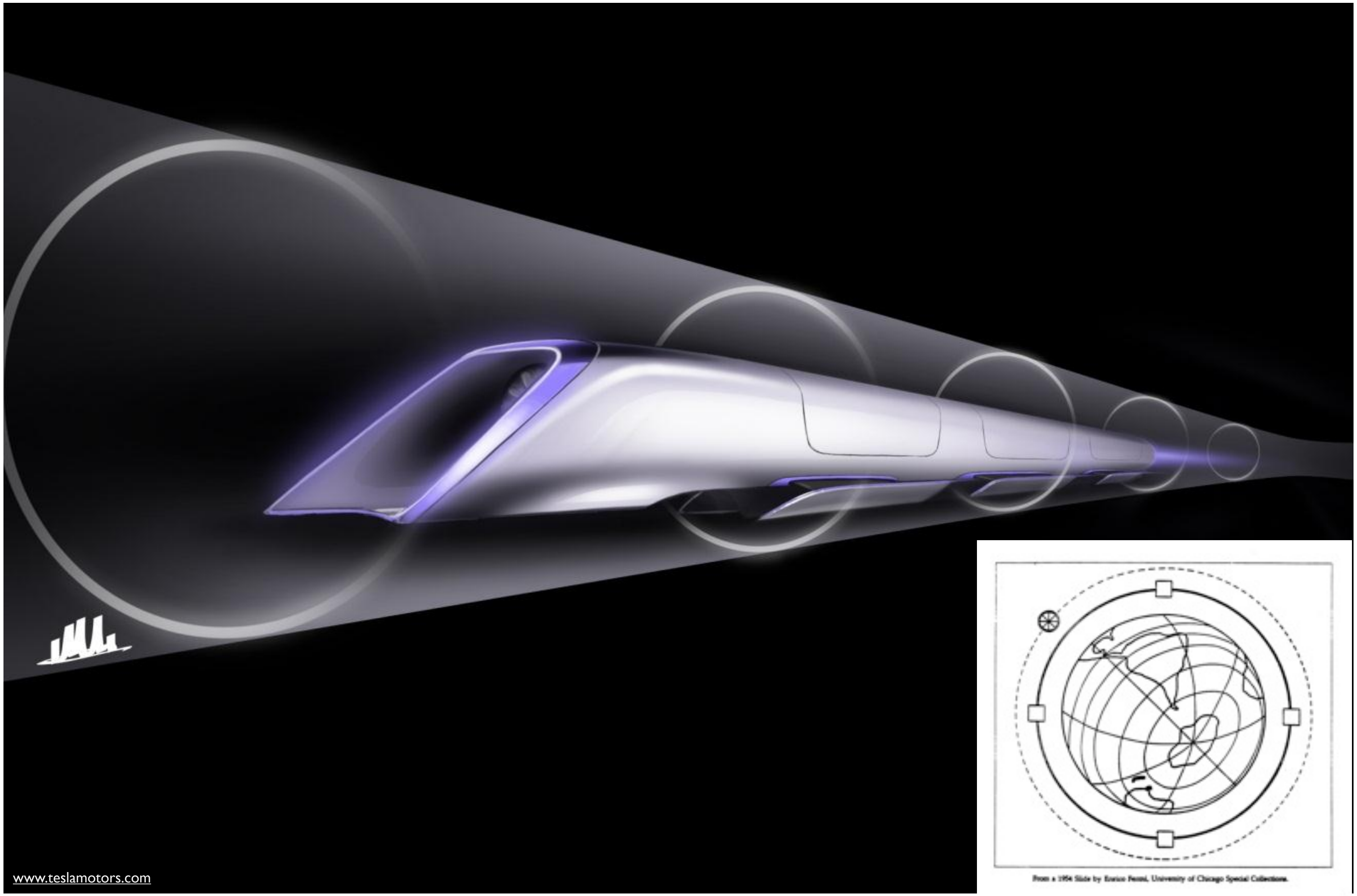
- Indeed, the most somber speculation I can make about A.D. 2014 is that in a society of enforced leisure, the most glorious single word in the vocabulary will have become *work!*

What is High Energy Physics?

How do we define our field?

➡ What are the most elementary constituents of nature and what are the forces that cause them to interact?

We have big dreams



Big dreams require innovation and a lot of planning!

Planning for the future

- Our science often demands large scale facilities.
- Funding does not always match our dreams.
- There is an increased need for global planning.

- The discovery of the Higgs and the observation of a large value for θ_{13} for neutrino mixing in 2012 ==> 2013 is a good time to review the plans.

- HEP planning processes have been recently completed or in progress around the world.
  - Process to be repeated every 5 years or so.
  - Look ahead about 20 years, examine the opportunities and determine R&D required.
  - Look at the science case first - then consider the budget.
    - Large scale projects require global partnerships.

European Strategy for Particle Physics

- Update adopted by CERN Council in May 2013.
- chair: Tatsuya Nakada
- Included Member states, Associate members and Observers states.
  - Strategy statements take into account the global context.
  - Process has been well accepted in the community.
- http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/

US HEP Planning

Snowmass 2013 -

A Community Planning Meeting (Oct 2012) and Community Summer Study (Summer 2013) were organized by the Division of Particles and Fields of the American Physical Society.

Chair: Jon Rosner

http://www.snowmass2013.org

Community planning to be followed with prioritization by a HEPAP subpanel (P5) in the coming months.

Global Planning

- CERN has become more global, but is not responsible for global HEP planning.
  - The LHC experiments are run by global collaborations.

- Who is? Does HEP have an organization to coordinate global plans?

  ICFA, the International Committee for Future Accelerators, was created to *facilitate international collaboration in the construction and use of accelerators* for high energy physics. It was created in 1976 by the International Union of Pure and Applied Physics.

  The Committee has sixteen members, selected primarily from three global regions. ICFA has had an oversight role for the global development of the ILC.

- The construction and operation of large global research infrastructures will require a new model of governance.

  Ideas welcome!

The physics frontier

The physics case for the LHC was clear. And there is still much more to be learned at the LHC.

We know there are reasons to look beyond the standard model:

dark matter, insufficient CP violation for the observed baryon excess, neutrino masses and mixing, gauge unification, hints of new physics in $(g-2)_\mu$, ...

The physics of the future will require a united effort on all frontiers: Energy, Intensity, Cosmic, and Technology

What are the big questions for the future?

Standard Model:

Quarks
Leptons

Forces
+

Snowmass Big Questions for 2013

- How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the universe? Is there one Higgs particle or many? Is the Higgs particle elementary or composite?

- What principle determines the masses and mixings of quarks and leptons? Why is the mixing pattern apparently different for quarks and leptons? Why is the CKM CP phase nonzero? Is there CP violation in the lepton sector?

- Why are neutrinos so light compared to other matter particles? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions invisible except through their role in neutrino physics?

- What mechanism produced the excess of matter over anti-matter that we see in the universe? Why are the interactions of particles and antiparticles not exactly mirror opposites?

Snowmass Big Questions

- Dark matter is the dominant component of mass in the universe. What is the dark matter made of? Is it composed of one type of new particle or several? What principle determined the current density of dark matter in the universe? Are the dark matter particles connected to the particles of the Standard Model, or are they part of an entirely new dark sector of particles?

- What is dark energy? Is it a static energy per unit volume of the vacuum, or is it dynamical and evolving with the universe? What principle determines its value?

- What did the universe look like in its earliest moments, and how did it evolve to contain the structures we observe today? The inflationary universe model requires new fields active in the early universe. Where did these come from, and how can we probe them today?

- Are there additional forces that we have not yet observed? Are there additional quantum numbers associated with new fundamental symmetries? Are the four known forces unified at very short distances? What principles are involved in this unification?

Snowmass Big Questions

* Are there new particles at the TeV energy scale? Such particles are motivated by the problem of the Higgs boson, and by ideas about spacetime symmetry such as supersymmetry and extra dimensions. If they exist, how do they acquire mass, and what is their mass spectrum? Do they carry new sources of quark and lepton mixing and CP violation?

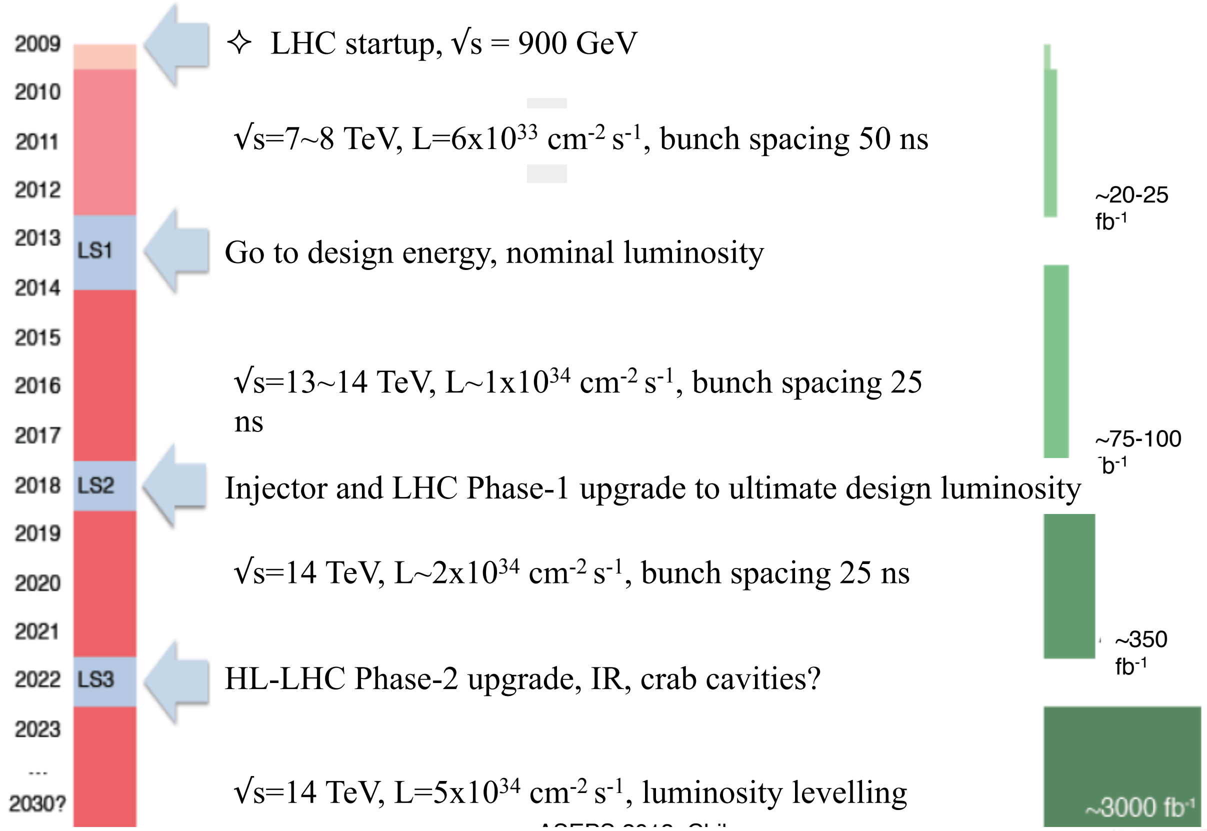
* Are there new particles that are light and extremely weakly interacting? Such particles are motivated by many issues, including the strong CP problem, dark matter, dark energy, inflation, and attempts to unify the microscopic forces with gravity. What experiments can be used to find evidence for these particles?

* Are there extremely massive particles to which we can only couple indirectly at currently accessible energies? Examples of such particles are seesaw heavy neutrinos or GUT scale particles mediating proton decay.

European Strategy Statement on LHC

- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. LHC is in a unique position to pursue this programme. *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 initial design, by around 2030.* *This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

LHC program



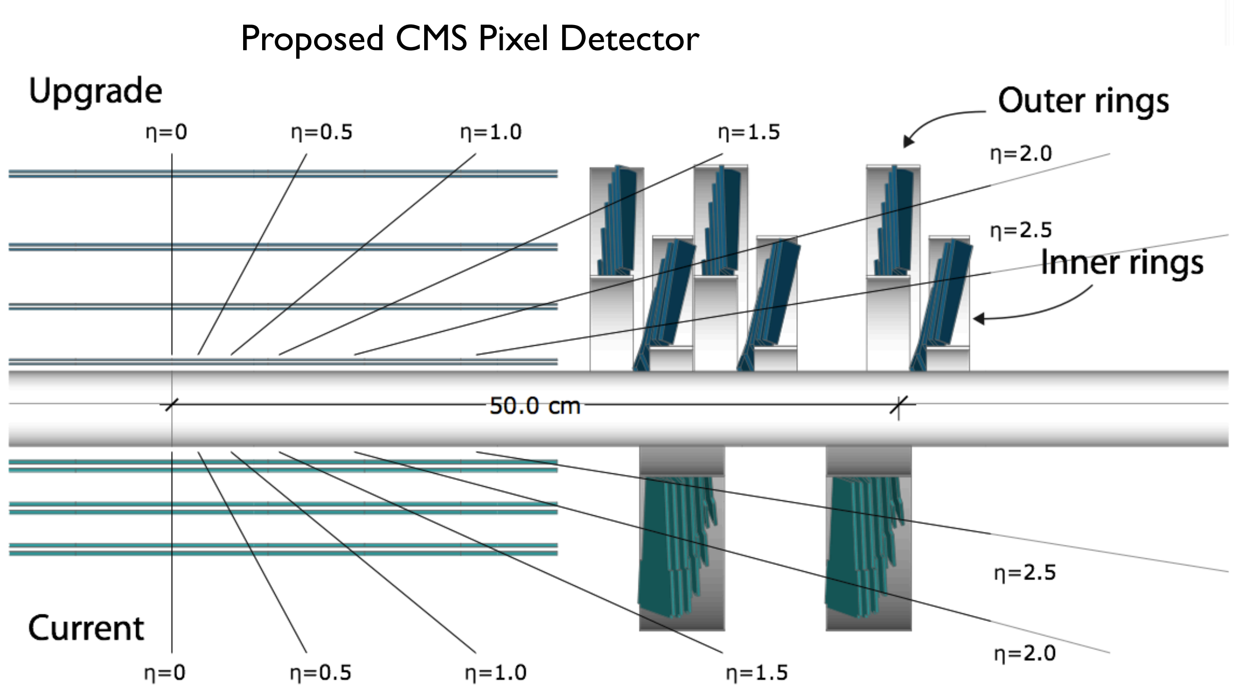
Great anticipation for upcoming run at 13/14 TeV.

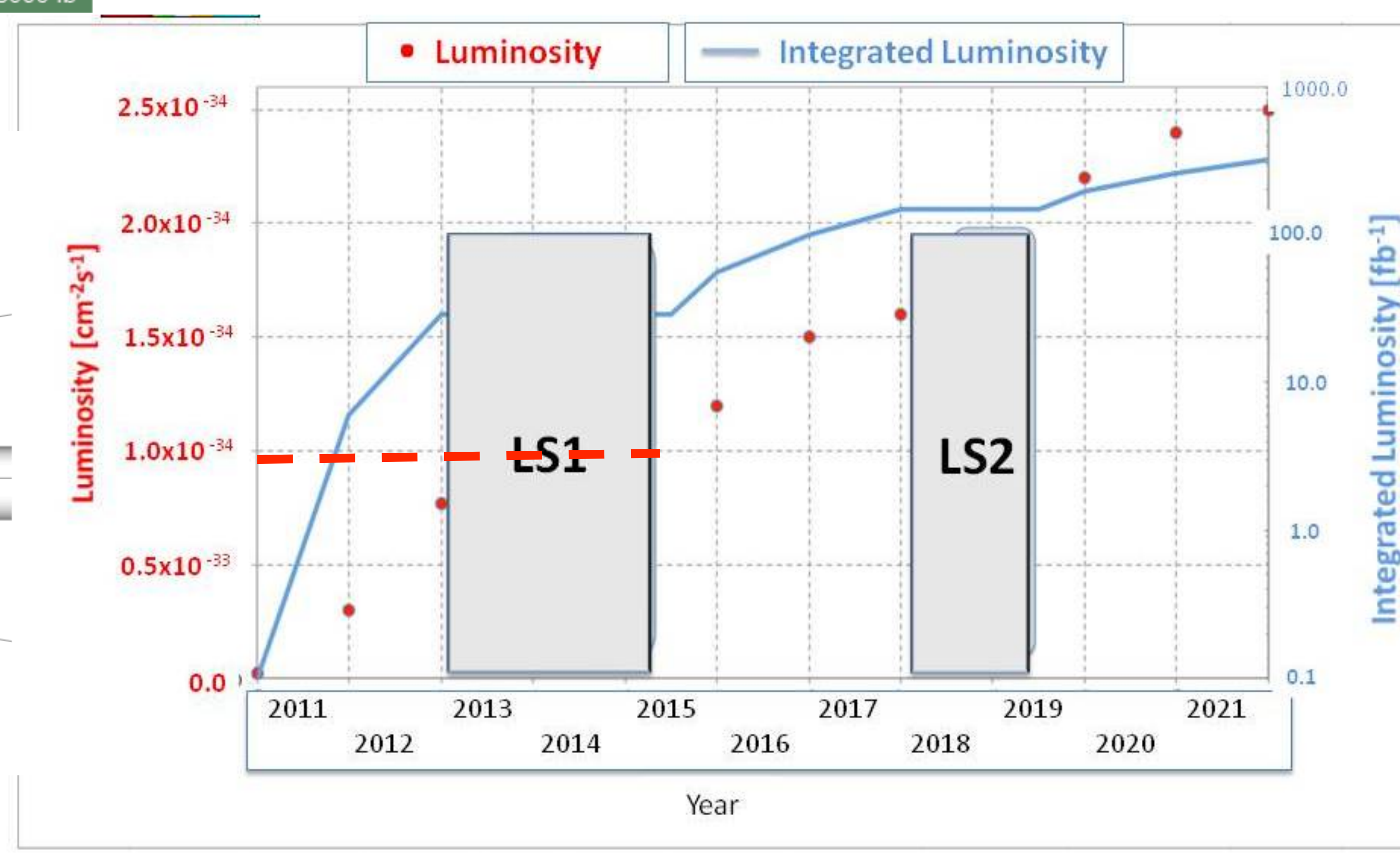
The LHC and the experiments are making improvements are planning for detector upgrades.

LHC Run Plans:

~300 fb^{-1} @ ~14 TeV before LS3.

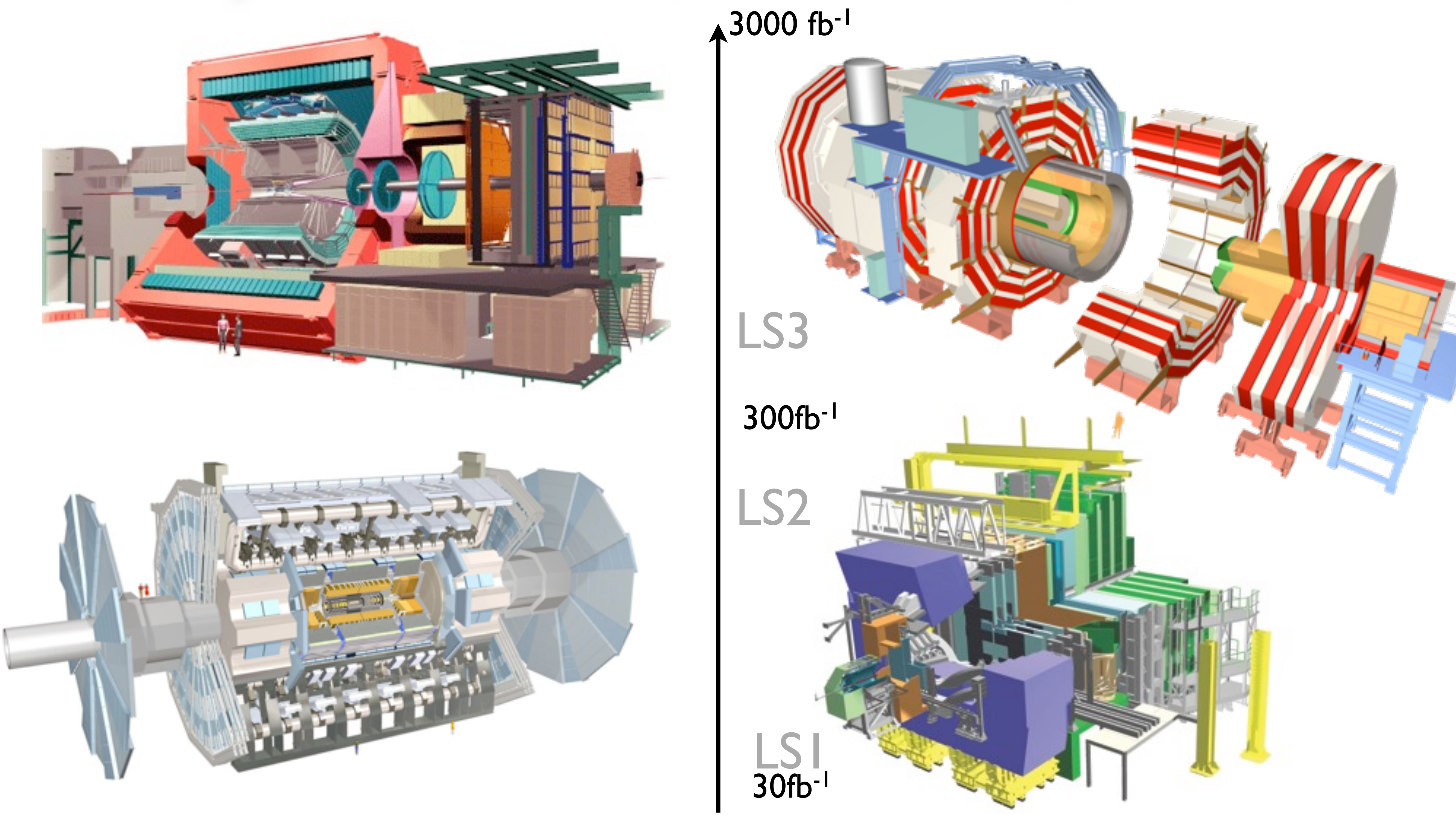
HL-LHC: ~3000 fb^{-1} by around ~2030.





LHC ... HL-LHC ...

- A series of upgrades are planned to maintain the performance of the LHC detectors to 2030.



European Strategy - 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 and electron-positron high-energy frontier machines.* *These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Future Accelerators

Questions discussed at Snowmass:

* How would one build a 100 TeV scale hadron collider?
* How would one build a lepton collider at >1 TeV?
* How would one generate 10 MW of proton beam power?
* Can multi-MW targets survive? If so, for how long?
* Can plasma-based accelerators achieve energies & luminosities relevant to HEP?
* Can accelerators be made 10x cheaper per GeV? Per MW?

The next large accelerator is likely to be a global enterprise.

International Linear Collider

- Mature design, TDR completed and reviewed.
  - The ILC design is technically ready to go.
  - Global participation in the design.
- An ILC proposal is expected from Japan.
  - Coming up: build a global partnership for construction.
- The design has an upgrade path to higher energy and luminosity. (> 500 GeV, > 10^{34} $cm^{-2}s^{-1}$)

Global support for the ILC

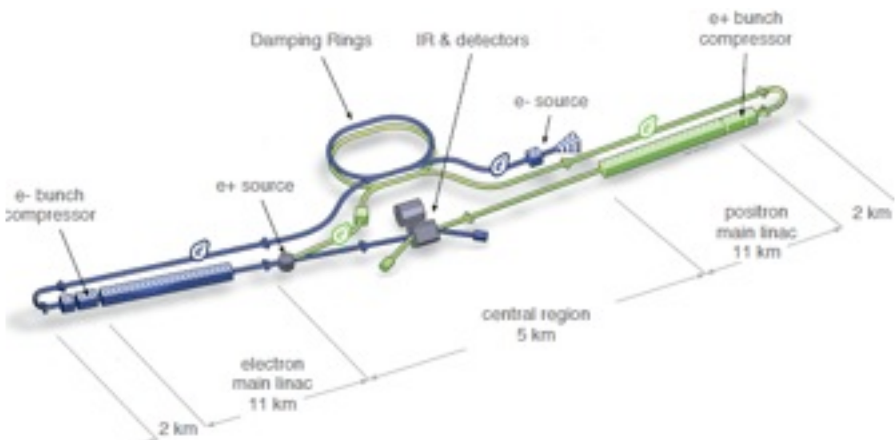
from the European Strategy

- 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 unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European 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.*

- *from the other regions:*
  - Support from Japanese HEP community and KEK management.
  - AsiaHEP/ACFA welcomes the proposal by the Japanese HEP community for the ILC to be hosted in Japan. AsiaHEP/ACFA looks forward to a proposal from the Japanese Government to initiate the ILC project.
  - Members of the US community at Snowmass explored the physics case for the ILC and welcome the Japanese initiative. Next step is P5.

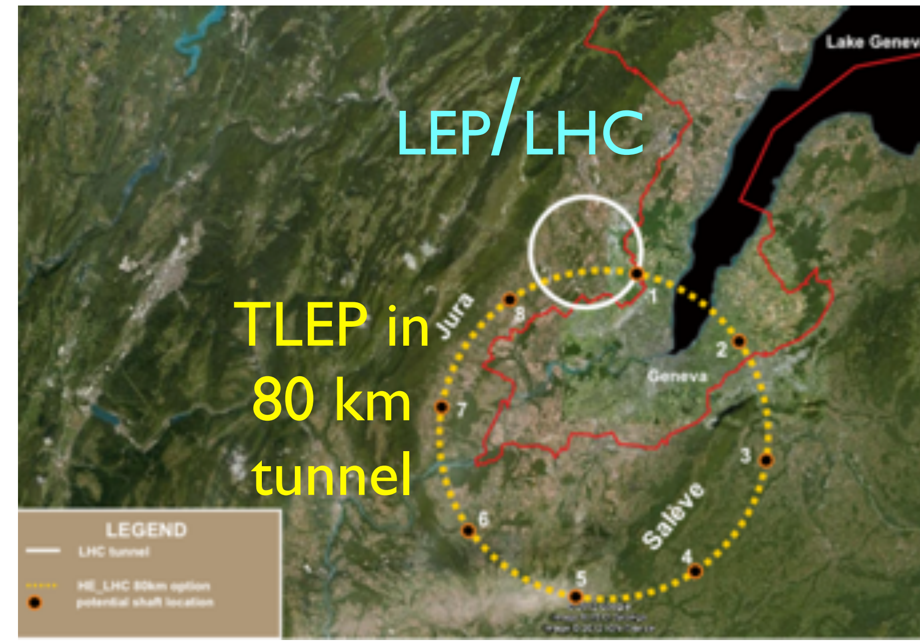
Possible Higgs Factories

Linear Colliders
(ILC, CLIC)



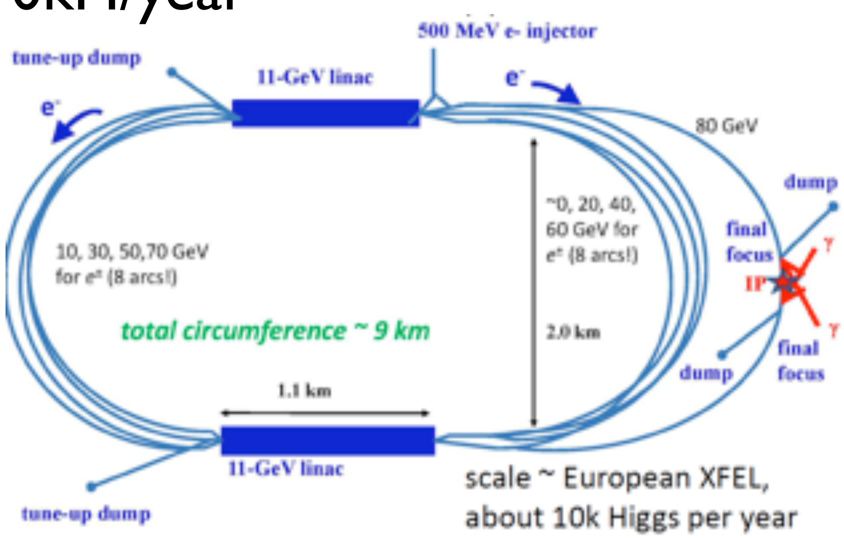
~14kH/year

Circular e+e- Colliders
(TLEP, super TRISTAN, IHEP…)



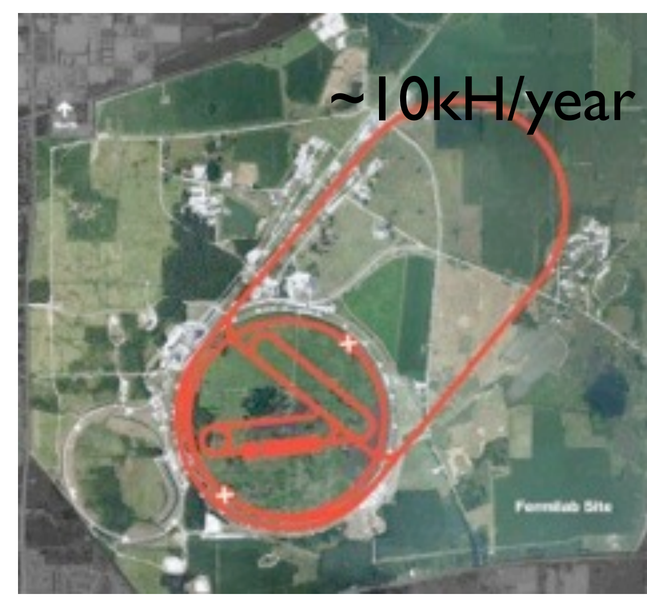
~400kH/year (4 det.)

~10kH/year



γγ Colliders
(SAPPHIRE, SILC, CLICHE, HFiTT)

~10kH/year (2det.)

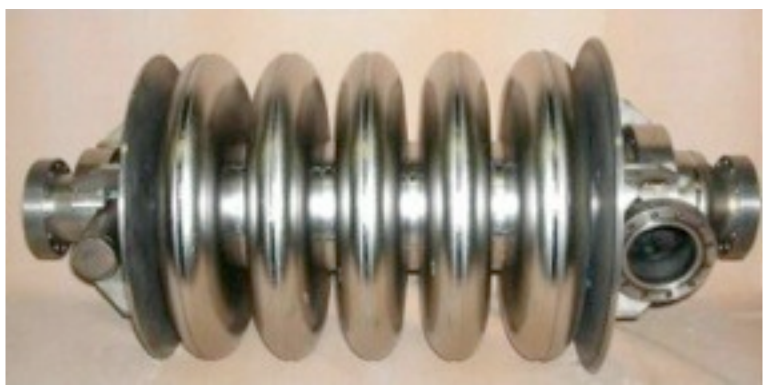


Muon Colliders
(ν-Fact. as possible 1st step

TLEP Ring e+e- collider:

Builds on existing technologies (LEP, KEKB, PEPII…)

with SC cavities



TLEP could cover a wide range of energy -- up to 350 GeV collision energy.

80 km tunnel could be used for a VHE-LHC at 80-100 TeV and possibly ep collisions

Energy CM (GeV)	90	160	240	350
Beam size (σx μm/σy nm)	124/270	78/140	68/140	100/100
Cavity Gradient (MV/m)	20	20	20	20
#5-cell SC cavities	600	600	600	600
Beam lifetime (mn)	67	25	16	27
Total AC power (MW)	250	250	260	284

from R. Alexsan 7/25/2013

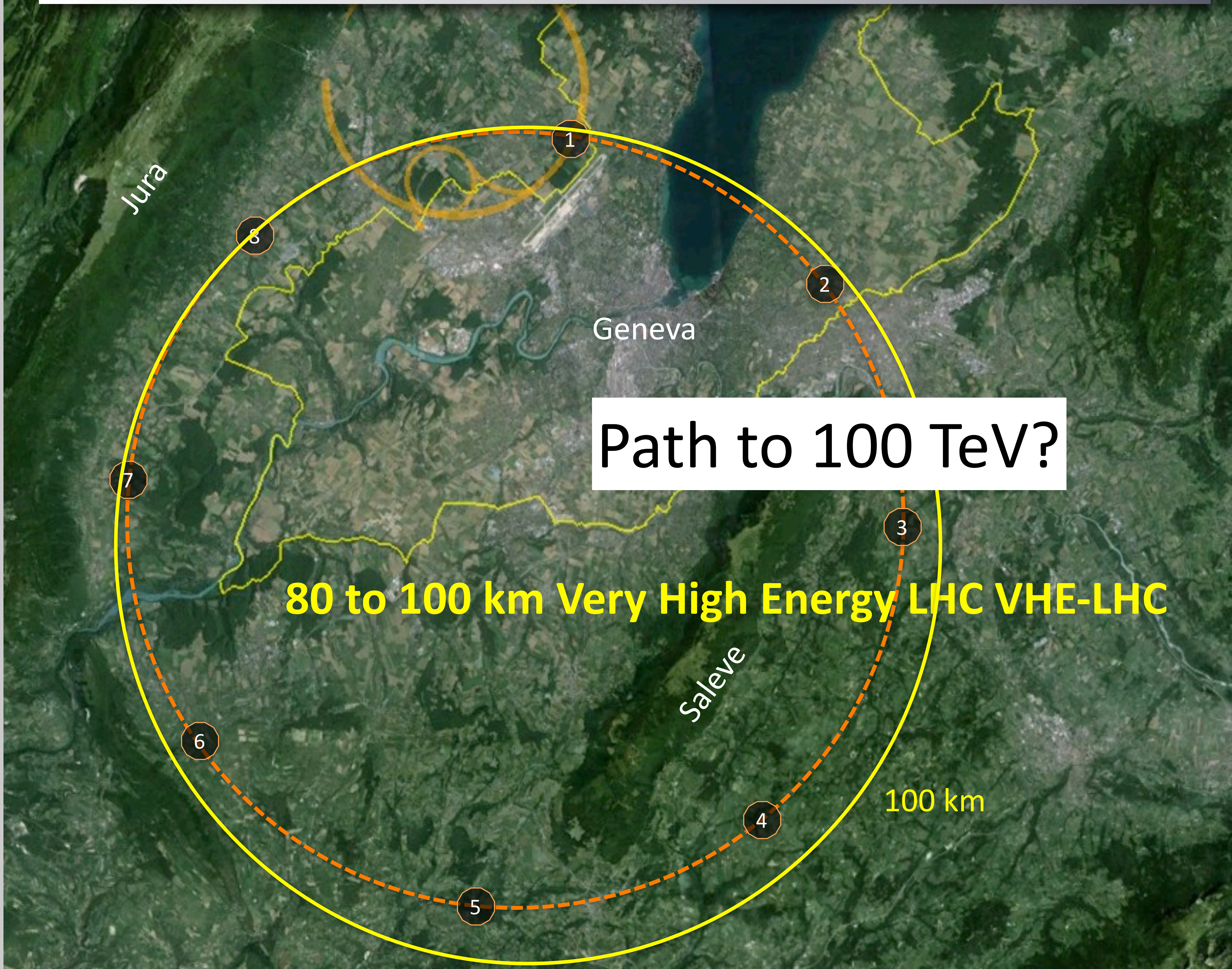
Proton colliders - beyond the LHC

- There is renewed interest in a ~100 TeV proton proton collider.
  - All the usual caveats - 14 TeV LHC physics, magnet R&D needed.

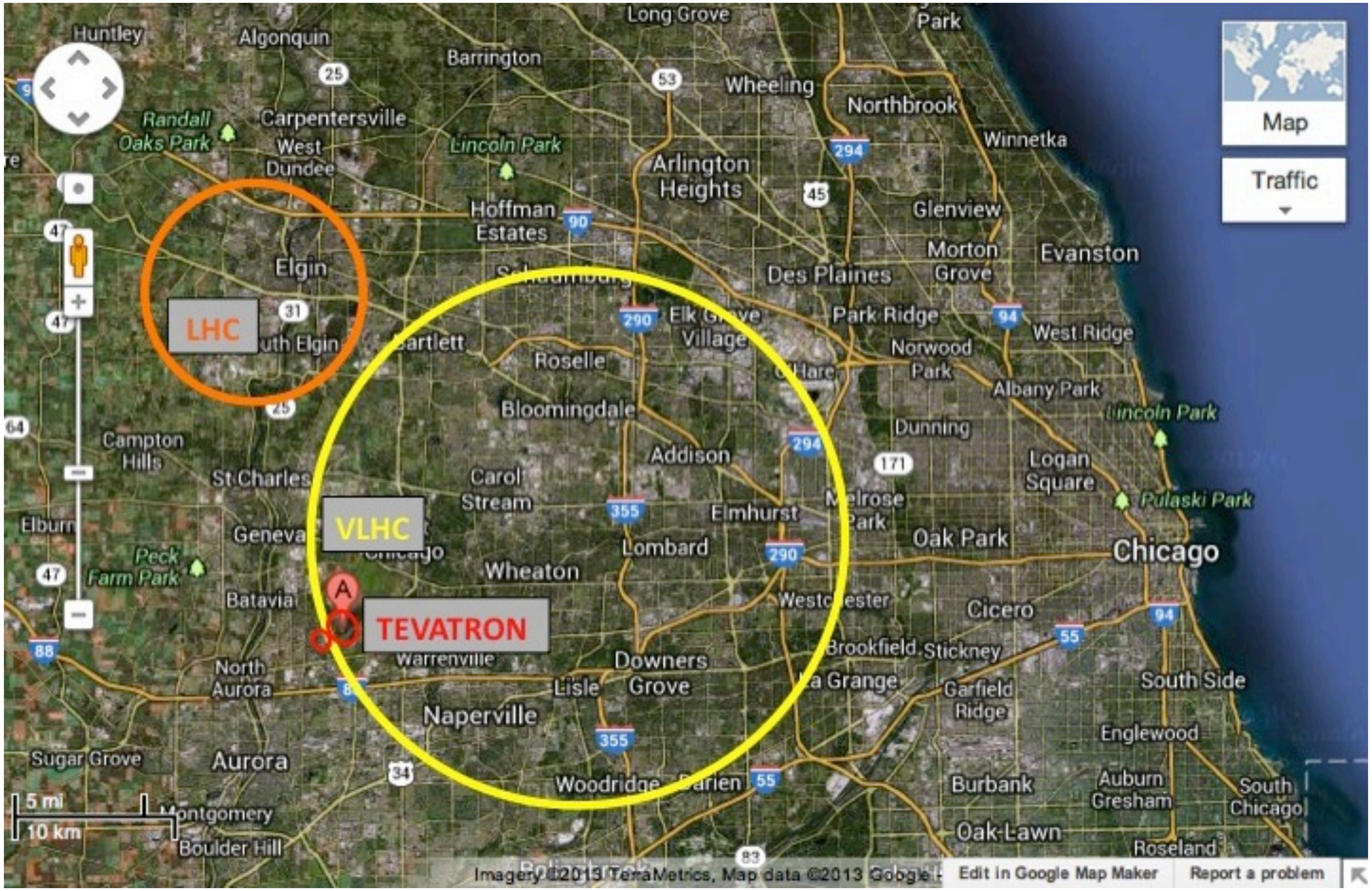
- We need a global effort to explore the possibilities for a high energy collider in a large tunnel.
  - Technical studies needed in many areas: Beam dynamics, magnets, vacuum systems, machine protection.

- R&D requirements
  - New engineering conductors (e.g., small filament HTS)
  - Advanced magnets – greater temperature margin, stress management techniques, magnet protection, novel structural materials

Next pp collider?



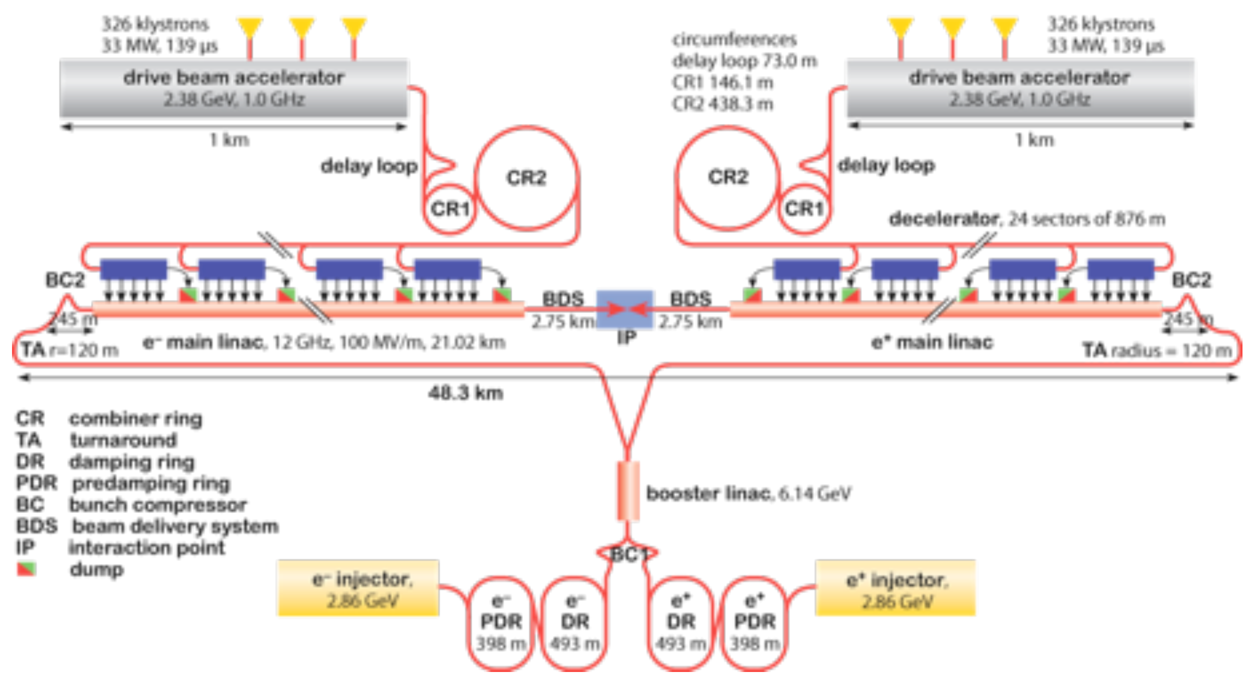
Next pp collider?



or elsewhere - China...?

Multi-TeV Lepton Colliders

- CLIC - High gradient, warm linac with a two beam acceleration concept - connections to global ILC program.



- Muon Collider (MC) - Connection to intensity frontier & intense neutrino sources (neutrino factories)
- Wakefield accelerators (plasmas & dielectrics)
  - Compelling progress; but need integrated proof-of-principal tests
  - Issues: Positron acceleration, multi-stage acceleration, control of beam quality, plasma instabilities at 10's of kHz rep rate

Colliders Overview

pp colliders

Facility	Years	E_{cm} [TeV]	Luminosity [$10^{34}/cm^2 s$]	Int. luminosity [fb^{-1}]	Comments
Design LHC	2014–21	14	1–2	300	
HL-LHC	2024–30	14	5	3000	Luminosity levelling
HE-LHC	>2035	26–33	2	100–300/yr	Dipole fields 16–20 T
VHE-LHC	>2035	42–100			New 80 km tunnel

e^+e^- colliders

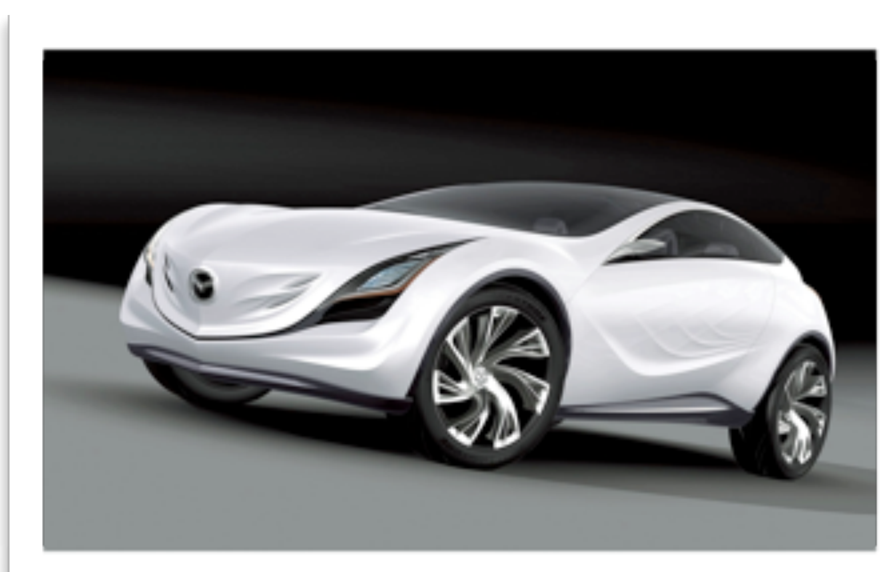
Facility	Year	E_{cm} [GeV]	Luminosity [$10^{34}\,cm^{-2}s^{-1}$]	Tunnel length [km]
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~ 30
ILC 1000		1000		~ 50
CLIC 500	>2030	500	2.3 (1.3)*	~ 13
CLIC 1400		1400 (1500)*	3.2 (3.7)*	~ 27
CLIC 3000		3000	5.9	~ 48
LEP3	>2024	240	1	LEP/LHC
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

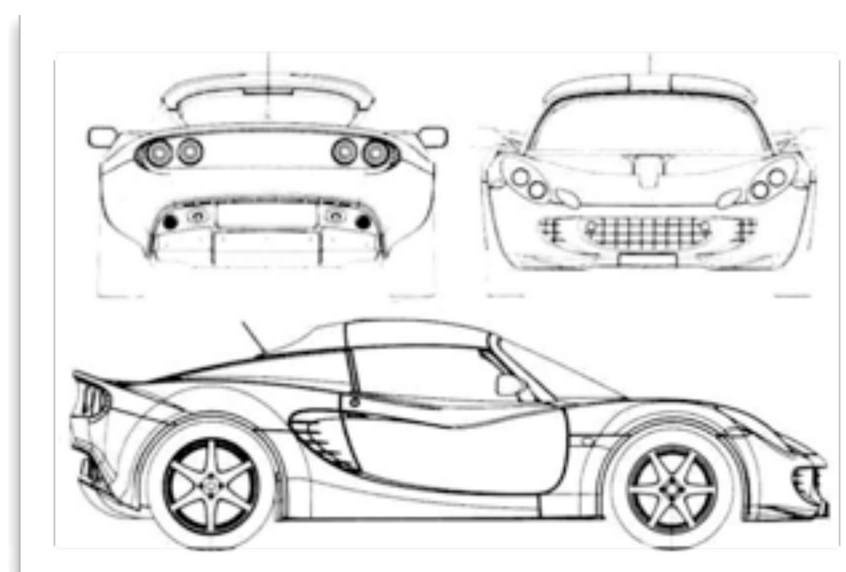
HL-LHC is proposed to operate until ~2030.

In 2030, there could be an ILC in Japan and a new machine starting construction.

The Proposal

LHC 100/fb	LHC 300/fb	LHC 3/ab	ILC 250-500GeV	ILC 1TeV	CLIC >1TeV	MC	TLEP	VLHC
years beyond TDR	TDR	LOI	TDR	TDR	CDR			





The Higgs Boson message

1. **Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.**

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

2. **Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.**

3. **Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.**

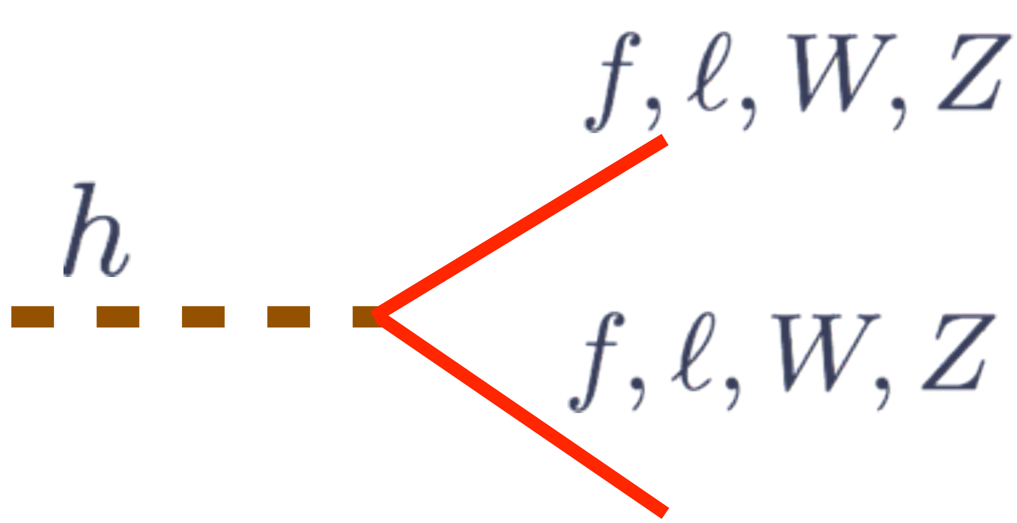
Origin of EWSB | Origin of matter | Naturalness | Unification | New forces | Dark matter | Elementary?

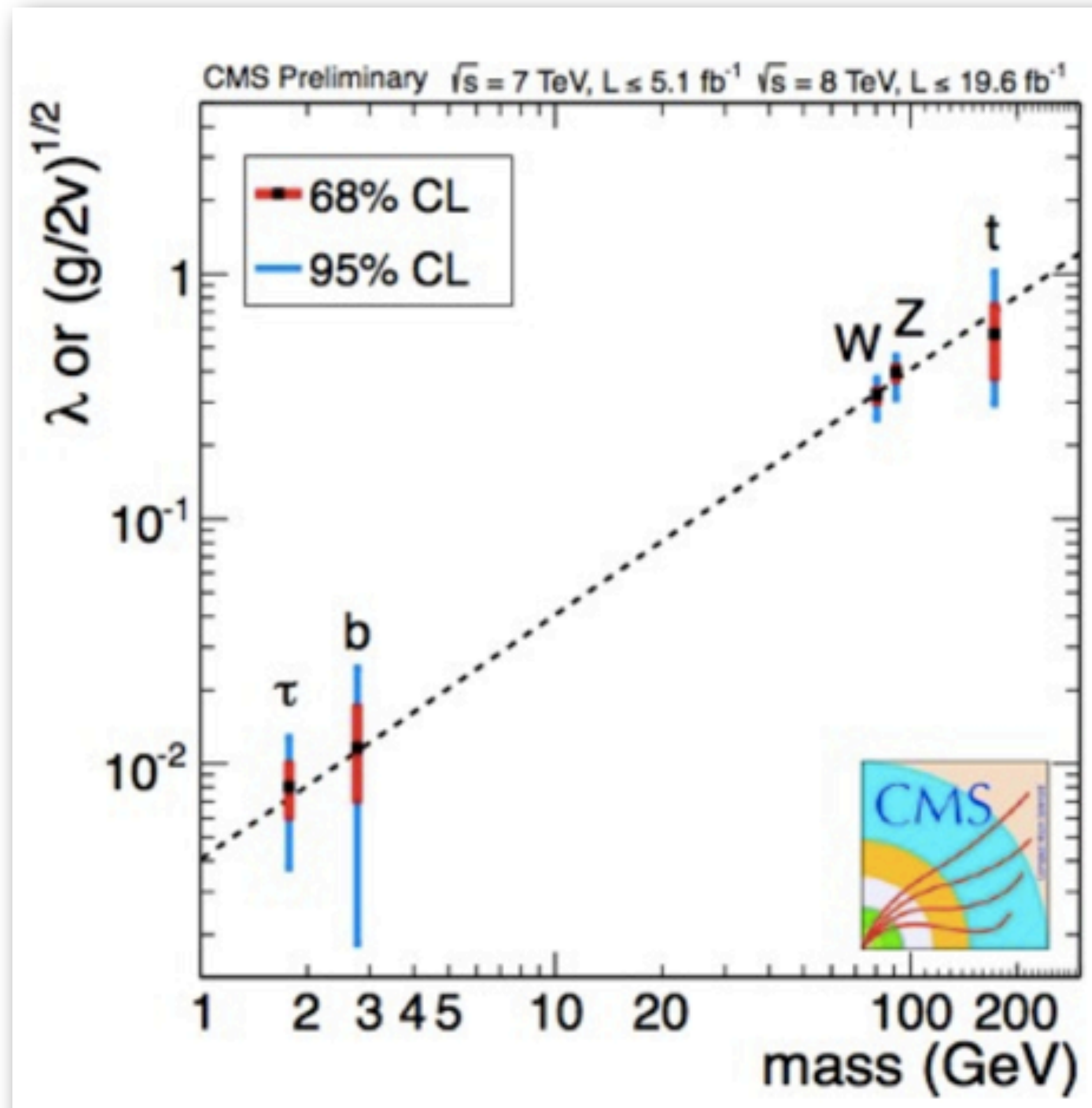
couplings

1. Higgs discovery started a new industry:

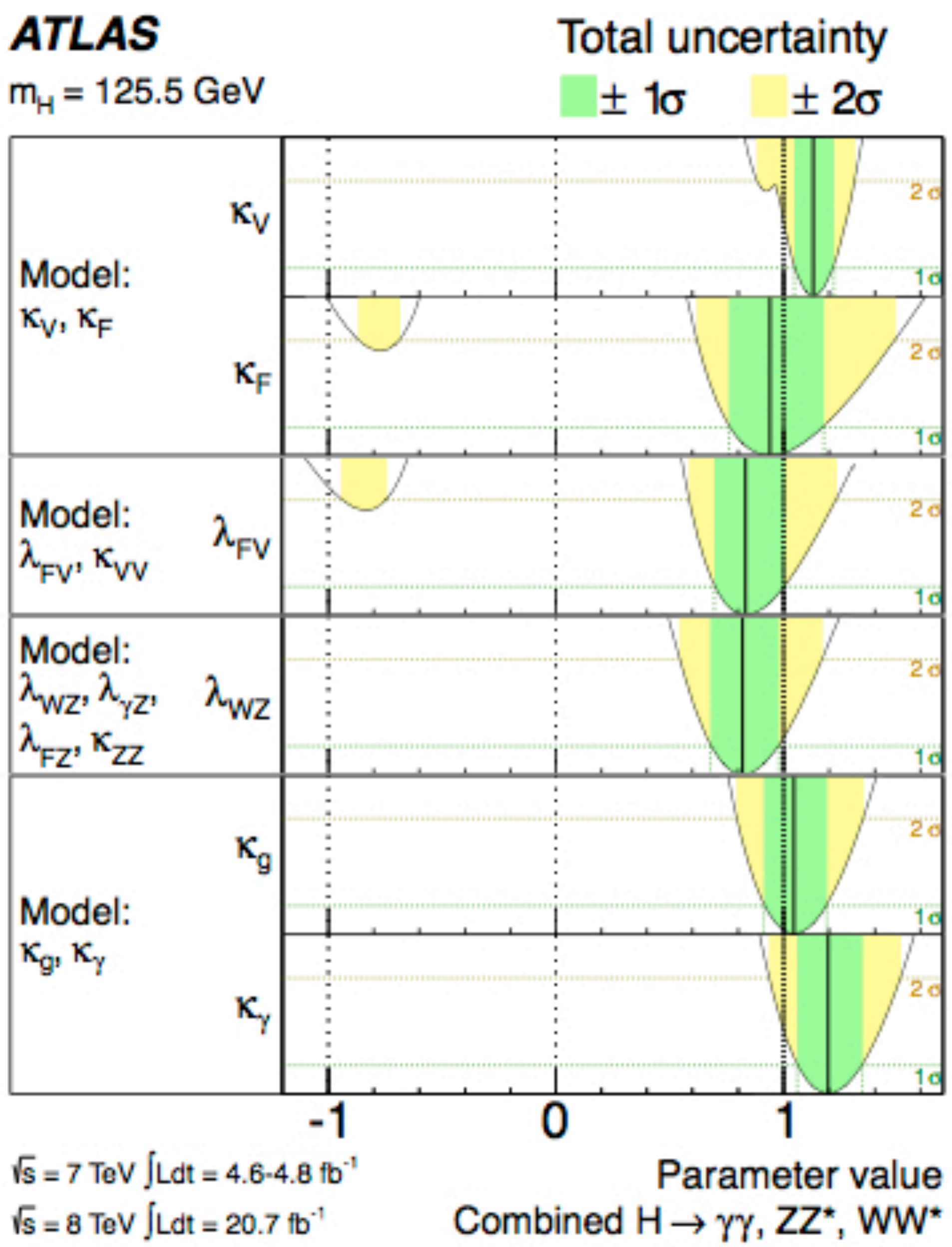
precision fitting of couplings

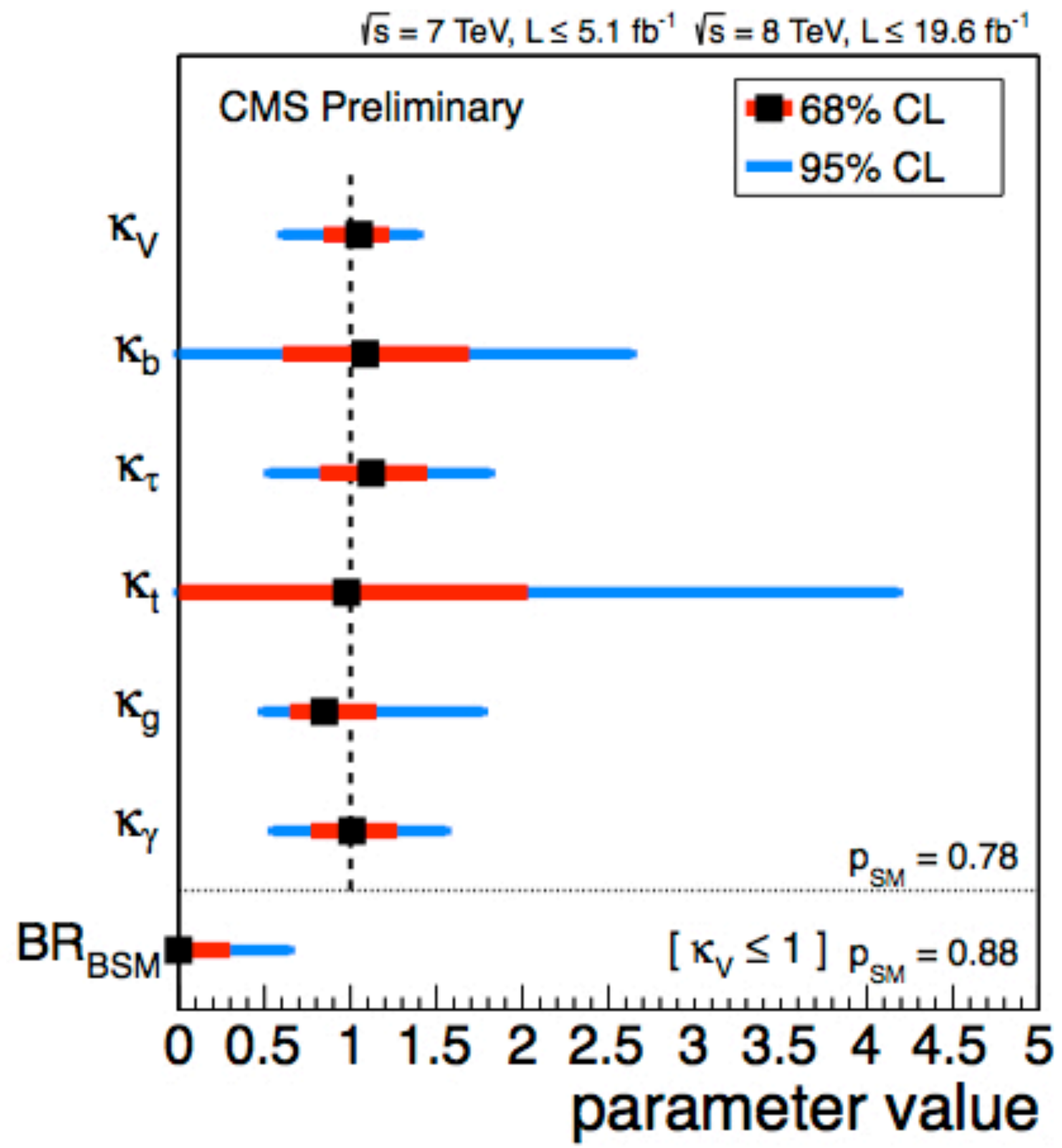
$$\mathcal{L} \propto \sum_i \kappa_i SM\left[h\bar{\psi}_i\psi_i\right]$$





to date:


ATLAS
m_H = 125.5 GeV
Total uncertainty
± 1σ
± 2σ
Model: κ_V, κ_F
κ_V
κ_F
Model: λ_FV, κ_VV
λ_FV
Model: λ_WZ, λ_γZ, λ_FZ, κ_ZZ
λ_WZ
Model: κ_g, κ_γ
κ_g
κ_γ
-1
0
1
Parameter value
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Combined H→γγ, ZZ*, WW*


√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
CMS Preliminary
68% CL
95% CL
κ_V
κ_b
κ_τ
κ_t
κ_g
κ_γ
p_SM = 0.78
BR_BSM
[κ_V ≤ 1] p_SM = 0.88
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
parameter value

couplings by facility

Extrapolating LHC requires a strategy

2 numbers shown:

optimistic* – conservative

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

*$$\delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}} \quad \& \quad \delta(\text{theory}) \downarrow 1/2$$

Brock/Peskin Snowmass 2013

Higgs: Couplings

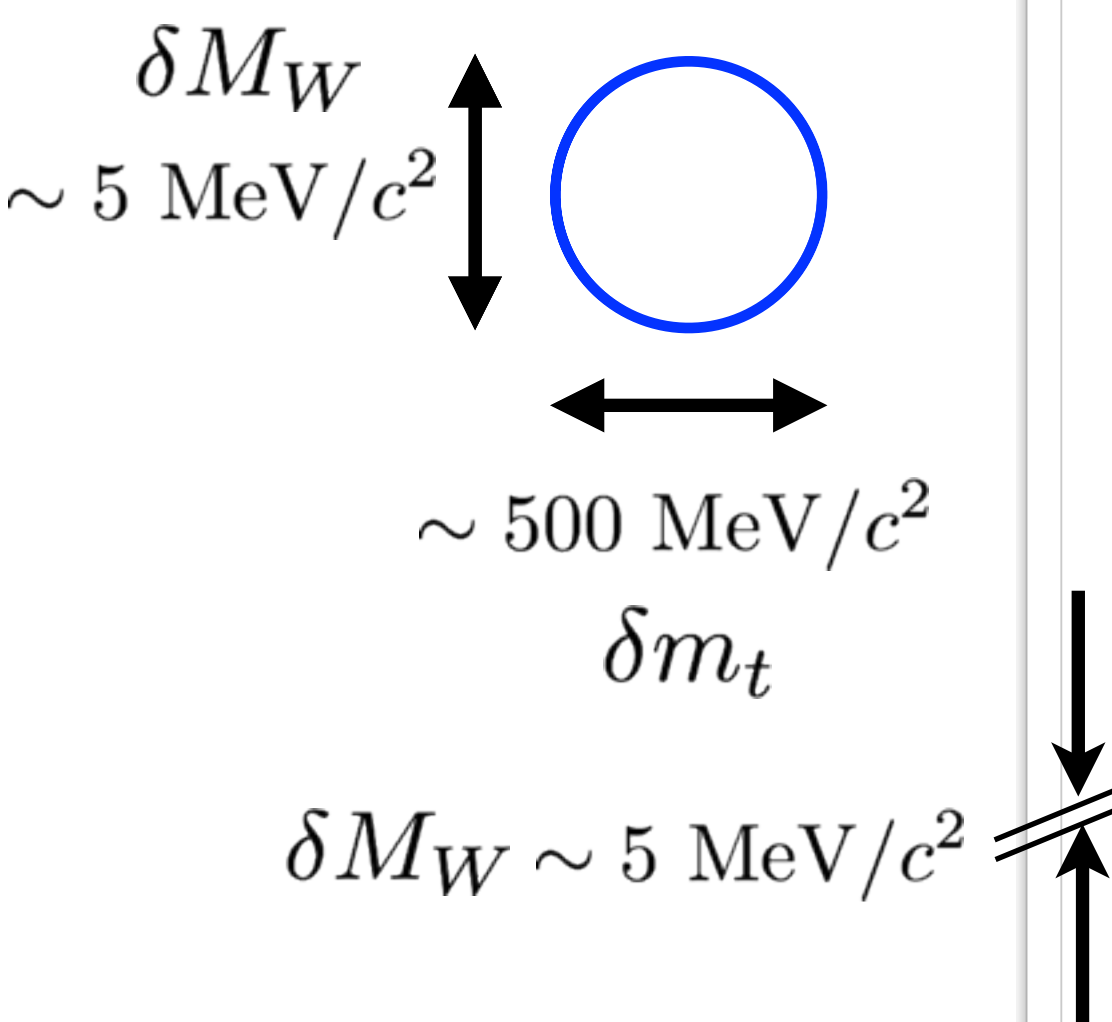
1. **Models with new TeV particles give corrections to Higgs couplings of a few %.**
2. **An experimental program to determine these couplings is achievable.**
   - LHC is the facility to study Higgs in the next decade
   - Interesting precision begins with the 300/fb running
   - Success requires considerable theoretical effort
3. **Lepton colliders are required in order to measure sub-% precision in couplings in a model-independent fashion.**
   - with access to invisible and exotic decay modes

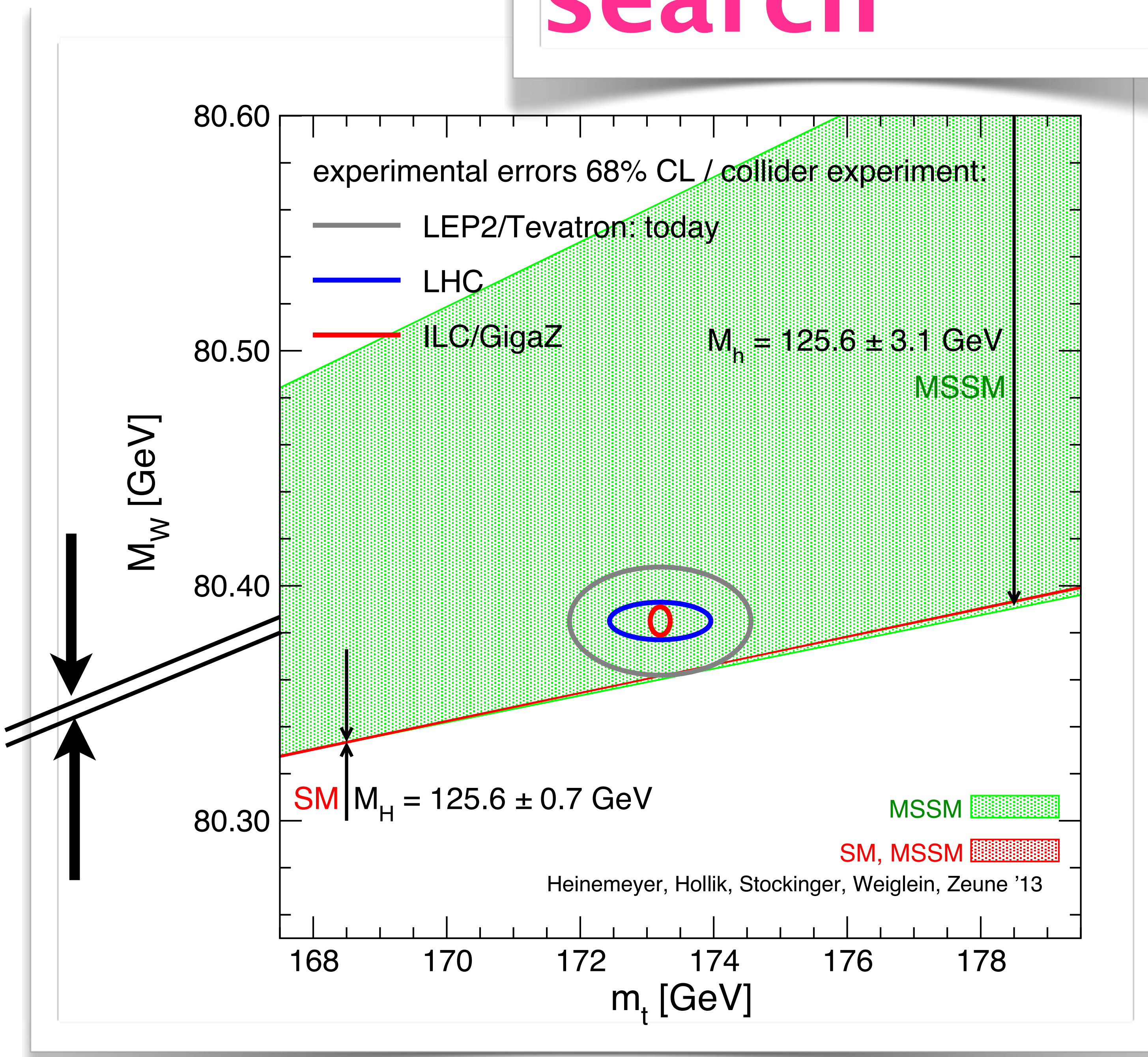
Now...a new target: BSM

This is now a BSM search

Premium on M_W

Now fits include M_h





M_W precision

M_W at the LHC

- δM_W ~ 5 MeV requires x7 improvement in PDF uncertainty

  a critical need

M_W at the lepton colliders

- A *WW* threshold program can achieve 2.5 – 4 MeV at ILC, sub-MeV at TLEP.

Furthermore: $\sin^2\theta_{eff}$

- Running at the Z at ILC (Giga-Z) can improve $\sin^2\theta_{eff}$ by a factor 10 over LEP/SLC;
- TLEP might provide another factor 4.

The EW physics message

1. **The precision physics of W's and Z's has the potential to probe indirectly for particles with TeV masses.**
   This precision program is within the capability of LHC, linear colliders, TLEP.

2. **Measurement of VB interactions probe for new dynamics in the Higgs sector.**
   In such theories, expect correlated signals in triple and quartic gauge couplings.

Origin of EWSB | Naturalness | New forces | Unification | Elementary?

NP: Themes

1. **Necessity for new particles at TeV mass**

the questions of fine tuning and dark matter are still open

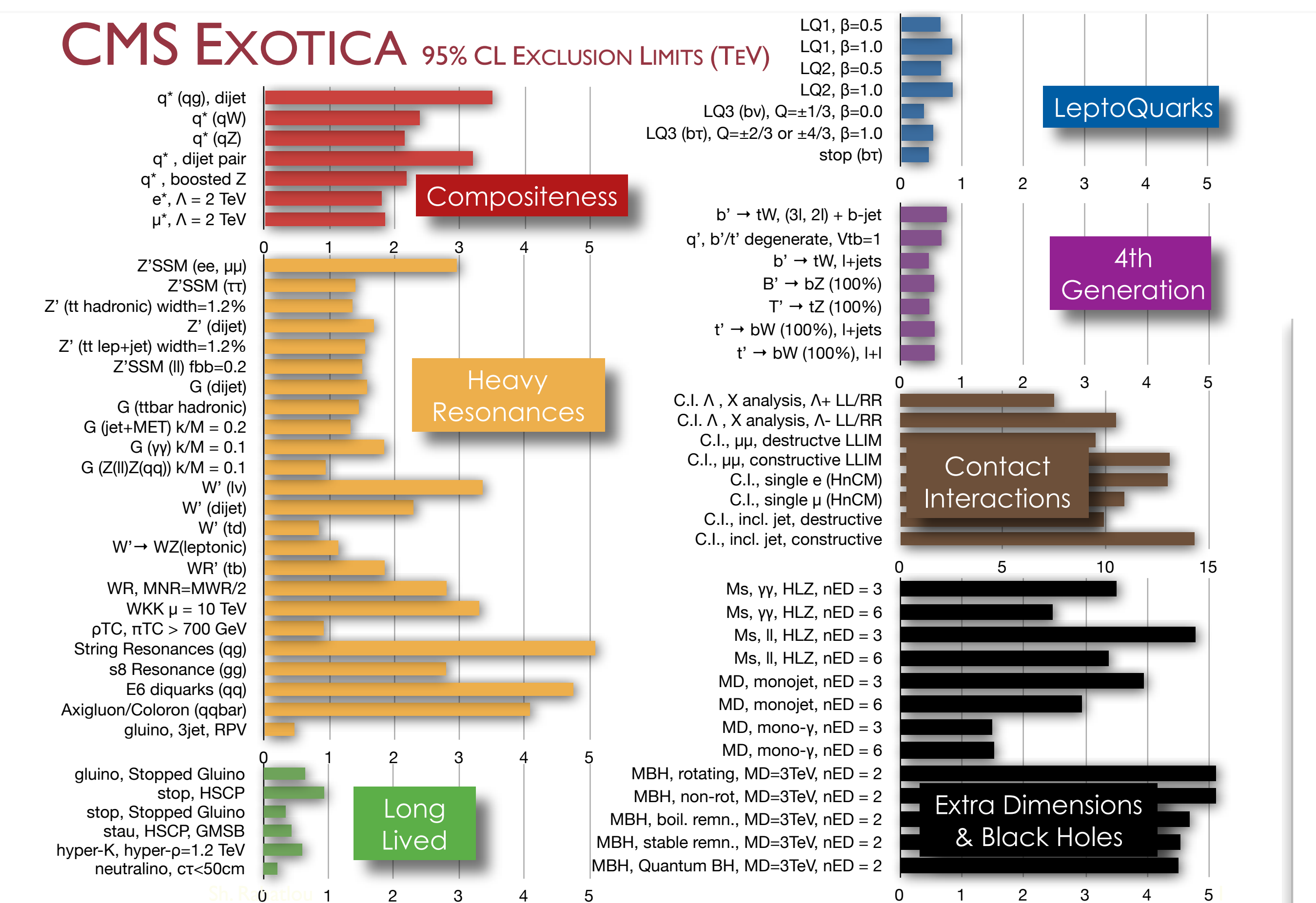
2. **Candidate TeV particles**
    - weakly coupled: SUSY, Dark Matter, Long-lived
    - strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles
    - evolution of robust search strategies

3. **Connection to dark matter problem**

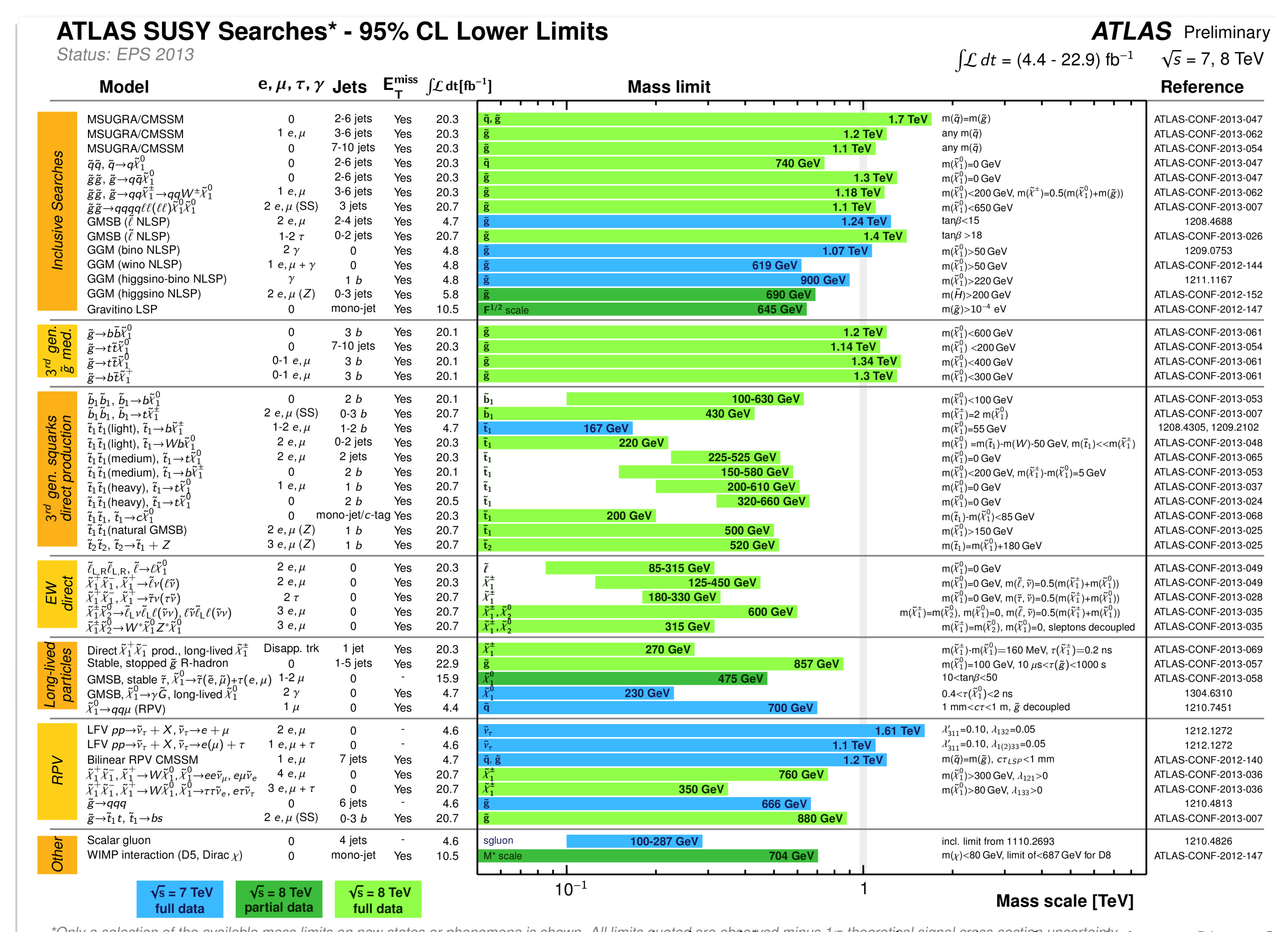
4. **Connection to flavor issues**

current LHC searches

New particle searches at the current LHC.



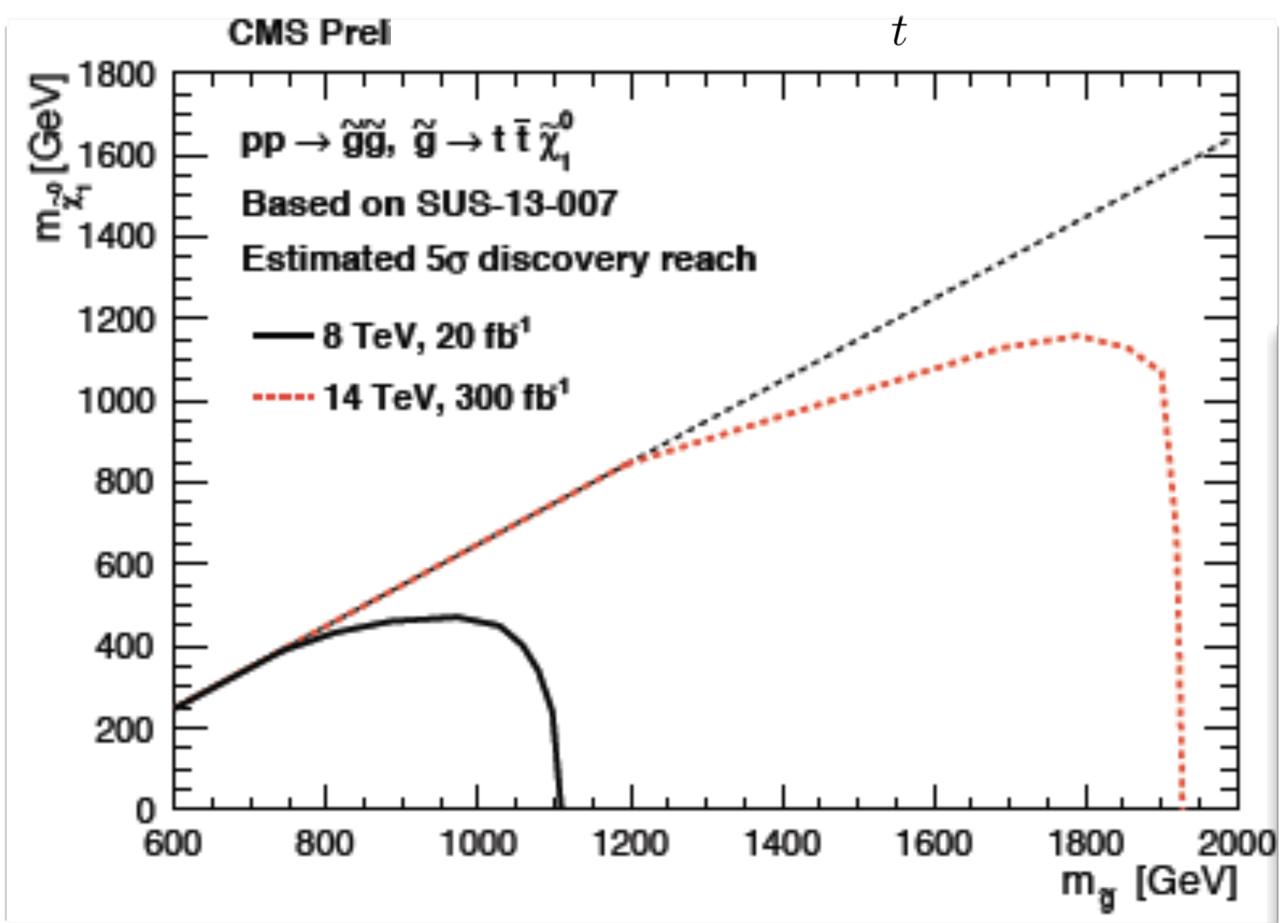
*similar results obtained by ATLAS

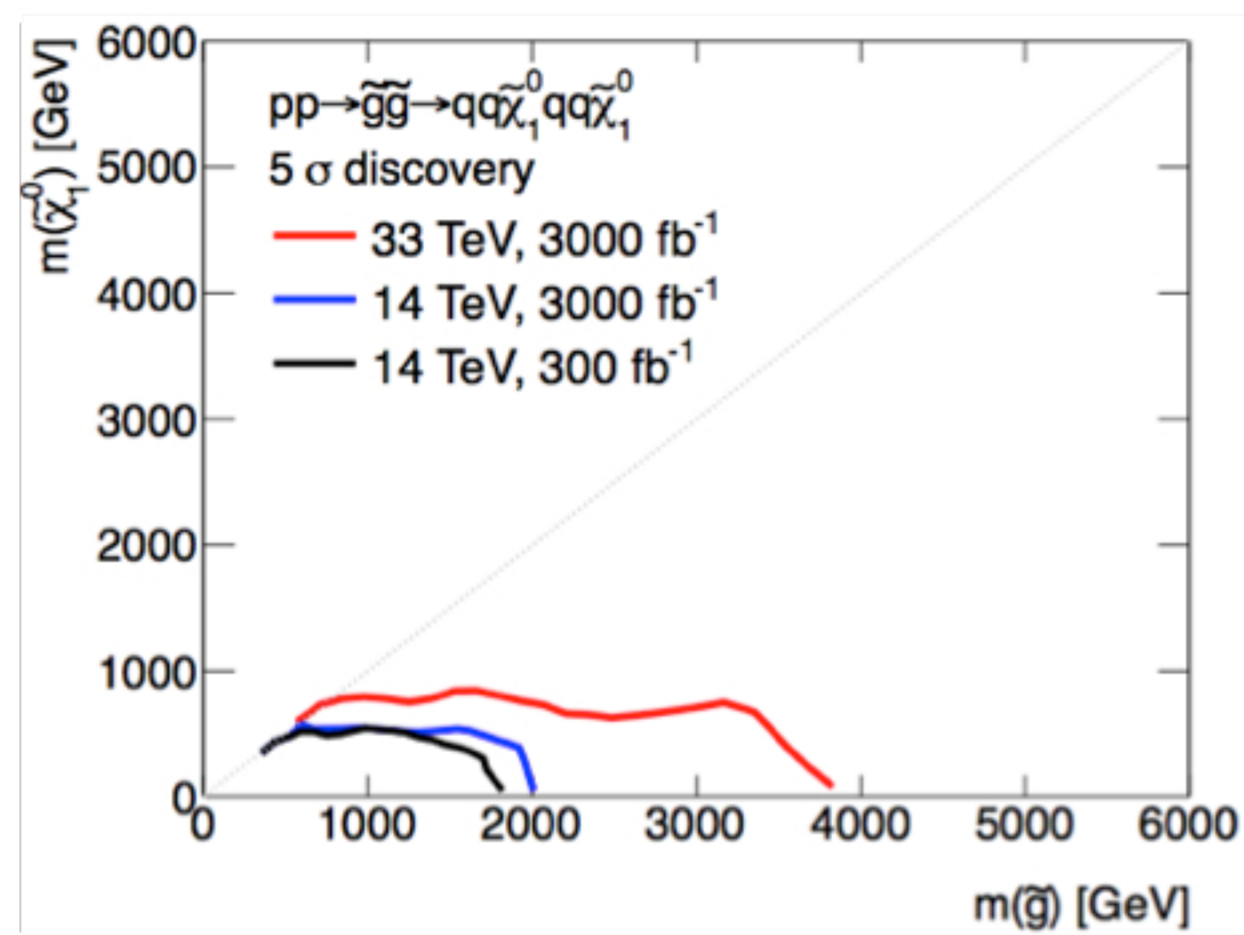


*similar results obtained by CMS

gain from now to 300/fb & beyond

x2 in gluino mass reach 8–14 TeV, & more 14–33 TeV





The NP Physics Message

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.
2. LHC and future colliders will give us impressive capabilities for this study.
3. This search is integrally connected to searches for dark matter and rare processes.
4. A discovery in any realm is the beginning of a story in which high energy colliders play a central role.

Origin of EWSB | Dark matter | Origin of matter | Naturalness | New spacetime | Unification

New forces | Elementary? | Origin of flavor | ν mass

LHC: $300\ fb^{-1}$

Higgs EW Top QCD NP/flavor

1. **Clarification of Higgs couplings, mass, spin, CP to the 10% level.**
2. First direct measurement of top-Higgs couplings
3. Precision W mass below 10 MeV.
4. First measurements of VV scattering.
5. Theoretically and experimentally precise top quark mass to 600 MeV
6. Measurement of top quark couplings to gluons, Zs, Ws, photons with a precision potentially sensitive to new physics, a factor 2-5 better than today
7. **Search for top squarks and top partners and ttbar resonances predicted in models of composite top, Higgs.**
8. New generation of PDFs with improved g and antiquark distributions.
9. Precision study of electroweak cross sections in pp, including gamma PDF.
10. **x2 sensitivity to new particles: supersymmetry, Z’, top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.**
11. Deep ISR-based searches for dark matter particles.

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**
2. Measurement of rare Higgs decays: mu mu, Z gamma with 100 M Higgs.
3. **First measurement of Higgs self-coupling.**
4. Deep searches for extended Higgs bosons
5. Precision W mass to 5 MeV
6. **Precise measurements of VV scattering; access to Higgs sector resonances**
7. Precision top mass to 500 MeV
8. Deep study of rare, flavor-changing, top couplings with 10 G tops.
9. Search for top squarks & partners in models of composite top, Higgs in the expected range of masses.
10. Further improvement of q, g, gamma PDFs to higher x, Q^2
11. A 20-40% increase in mass reach for generic new particle searches - can be 1 TeV step in mass reach
12. **EW particle reach increase by factor 2 for TeV masses.**
13. **Any discovery at LHC–or in dark matter or flavor searches–can be followed up**

ILC, up to 500 GeV

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**
3. Higgs CP studies in fermionic channels (e.g., tau tau)
4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**
5. Improvement of triple VB couplings by a factor 10, to accuracy below expectations for Higgs sector resonances.
6. Theoretically and experimentally precise top quark mass to 100 MeV.
7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**
8. Search for rare top couplings in e+e- -> t cbar, t ubar.
9. Improvement of α_S from Giga-Z
10. **No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter**

Higgs EW Top QCD NP/flavor

CLIC: 350 GeV, 1 TeV, 3 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 10%**
3. Model-independent search for extended Higgs states to 1500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. Precise measurement of VV scattering, sensitive to Higgs sector resonances.
6. **Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.**
7. Search for Z' using e+e- -> f fbar above 10 TeV
8. **Any discovery of new particles dictates a lepton collider program** as with the 1TeV ILC

Higgs EW Top QCD NP/flavor

muon collider: 125 GeV,

1. Similar capabilities to e+e- colliders described above. (Still need to prove by physics simulation that this is robust against machine backgrounds.)
2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances. This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.**

Higgs EW Top QCD NP/flavor

TLEP, circular e+e−

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.** (Note: luminosity is a steeply falling function of energy.)
2. Precision electroweak programs that could improve on ILC by a factor 4 in sstw, factor 4 in mW, factor 10 in mZ.
3. Search for rare top couplings in e+e- -> t cbar, tubar at 250 GeV.
4. Possible improvement in alphas by a factor 5 over Giga-Z, to 0.1% precision.

Higgs EW Top QCD NP/flavor

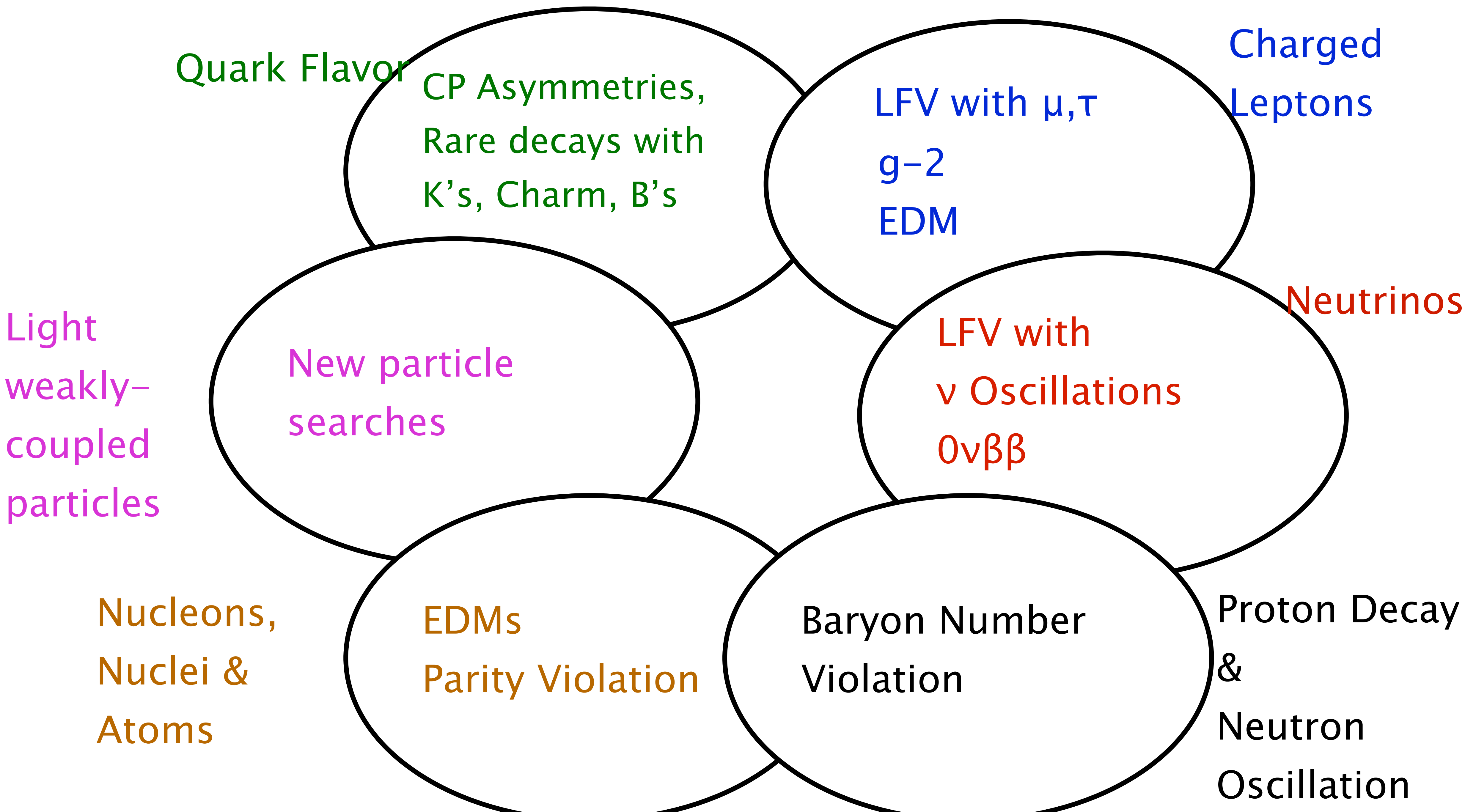
pp Collider: 33/100 TeV

1. High rates for double Higgs production; measurement of triple Higgs couplings to 8%.
2. Deep searches, beyond 1 TeV, for extended Higgs states.
3. Dramatically improved sensitivity to VB scattering and multiple vector boson production.
4. Searches for top squarks and top partners and resonances in the multi-TeV region.
5. **Increased search reach over LHC, proportional to the energy increase, for all varieties of new particles (if increasingly high luminosity is available). Stringent constraints on "naturalness".**
6. **Ability to search for electroweak WIMPs (e.g. Higgsino, wino) over the full allowed mass range.**
7. Any discovery at LHC -- or in dark matter or flavor searches -- can be followed up by measurement of subdominant decay processes, search for higher mass partners. Both luminosity and energy are crucial here.

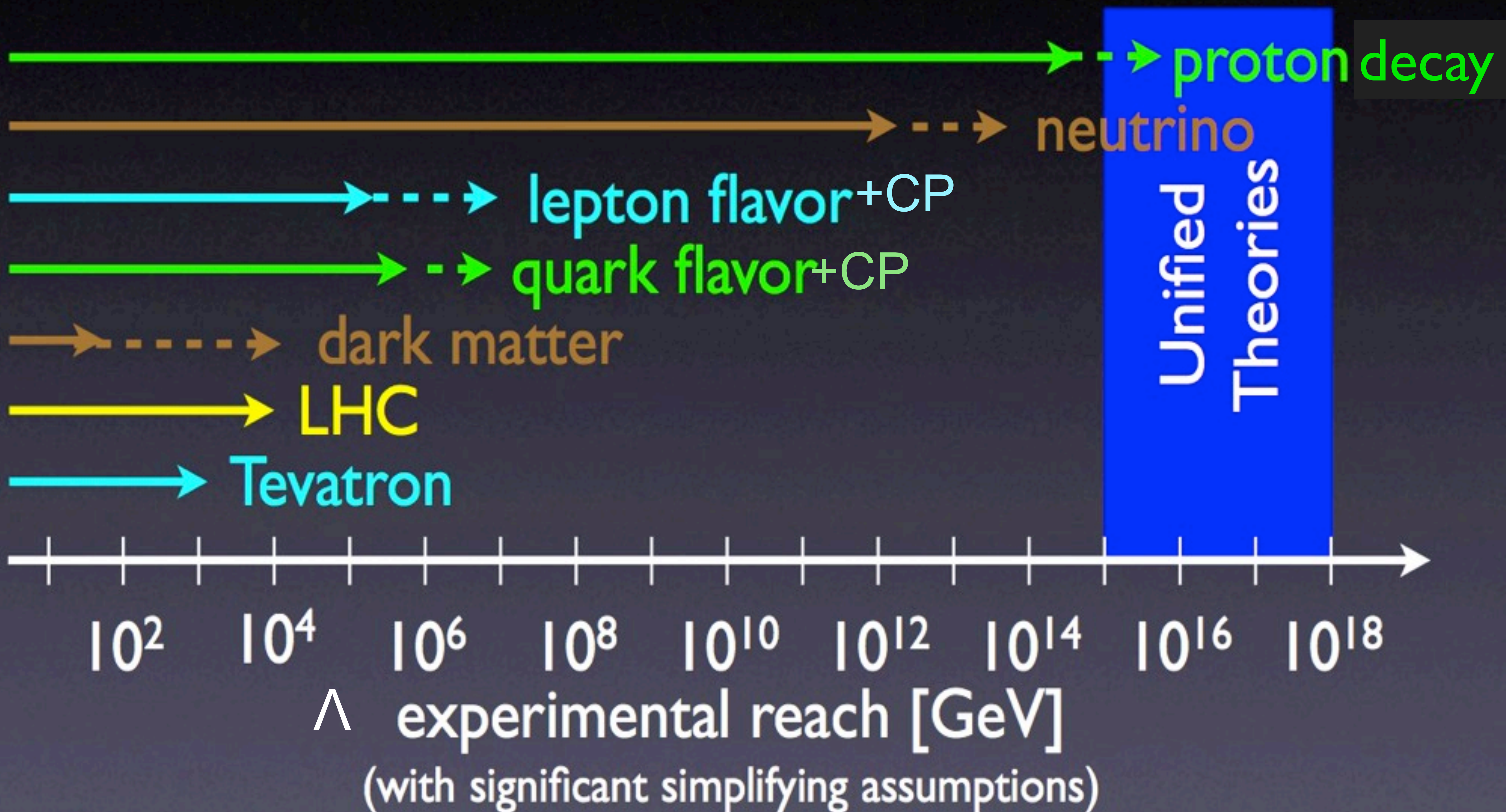
Higgs EW Top QCD NP/flavor

What is the Intensity Frontier

The Intensity Frontier is a <u>broad</u> and <u>diverse</u>, yet connected, set of science opportunities



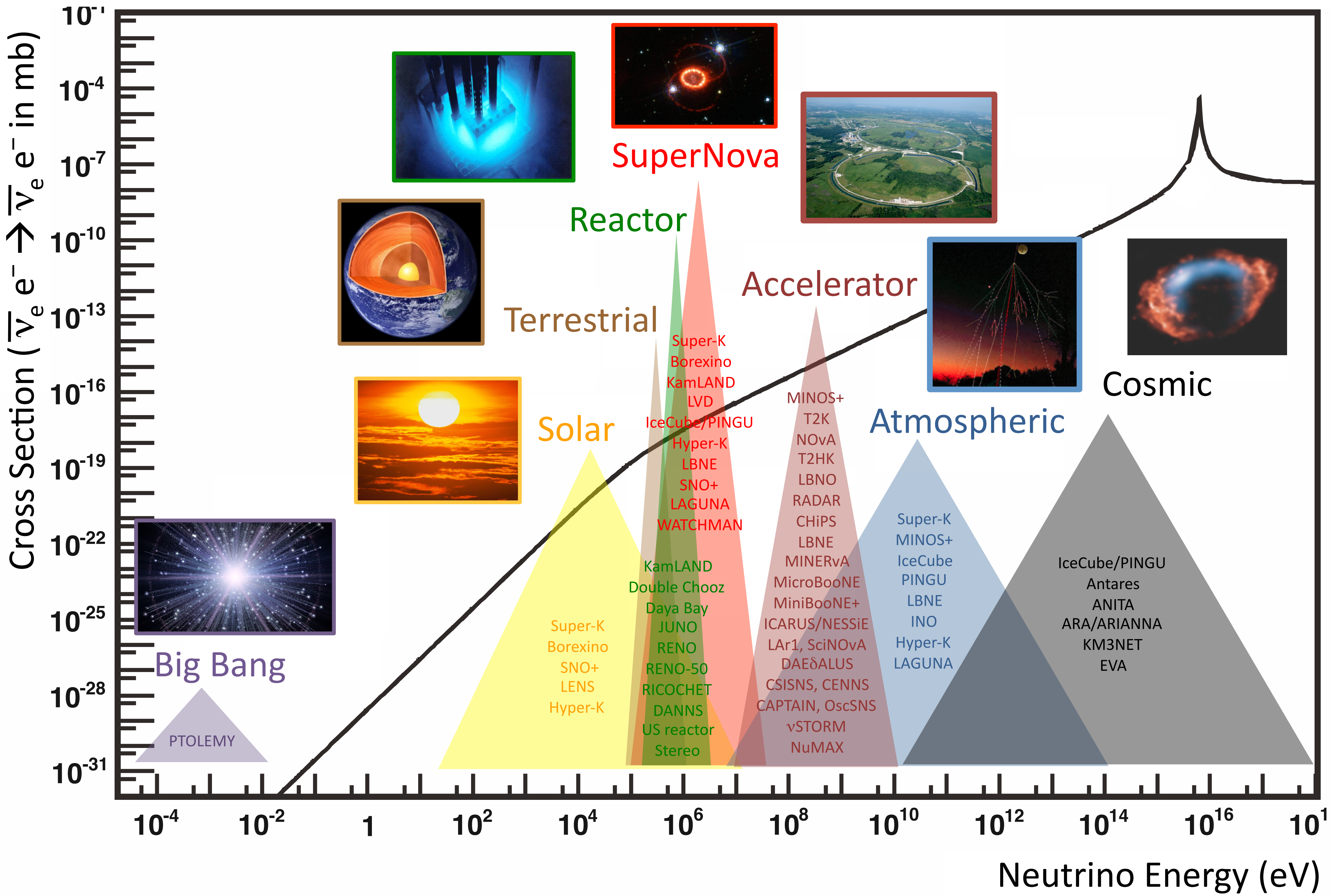
Power of Expedition



courtesy Ligeti/Murayama

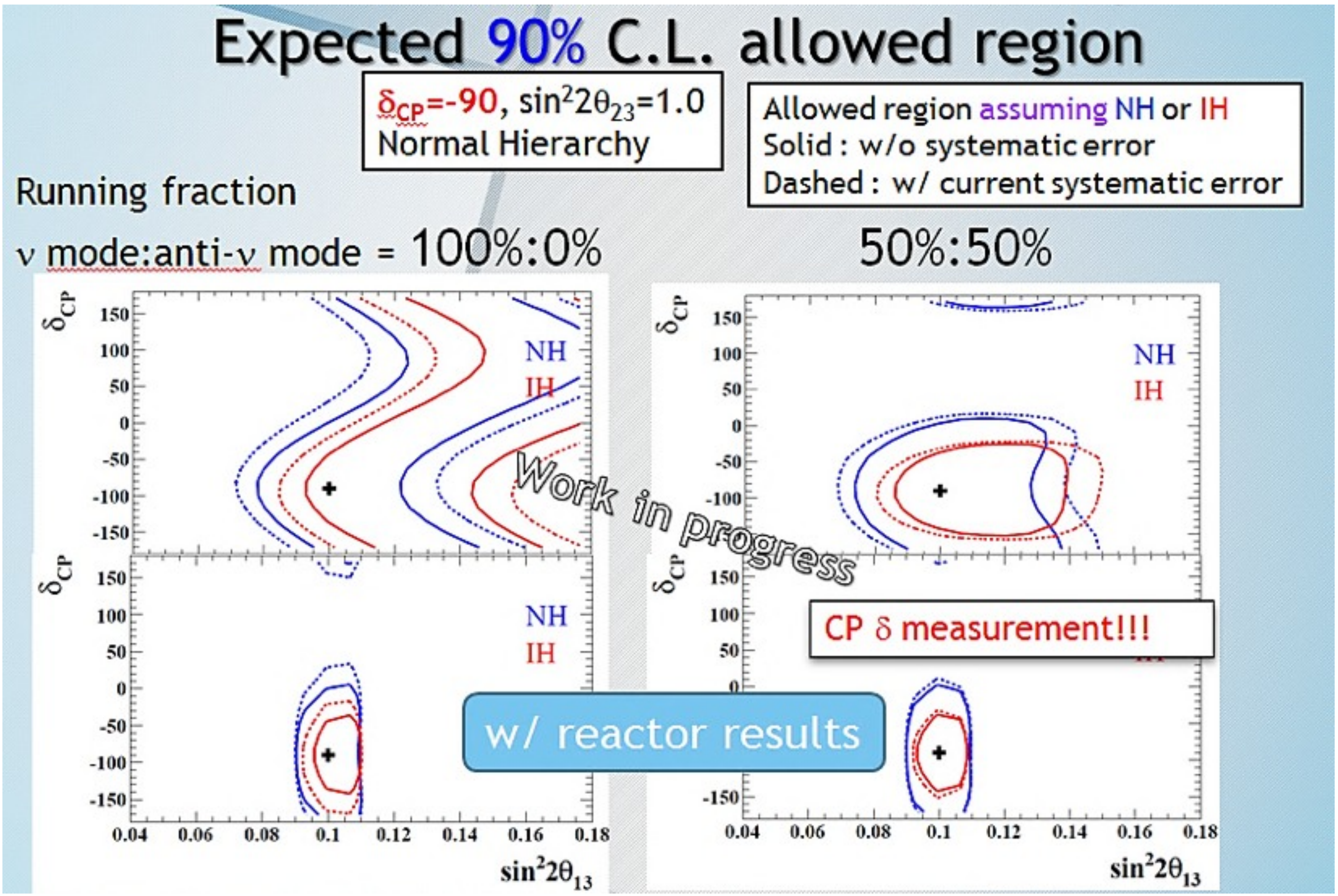
Neutrinos

- Many sources and many options for experiments



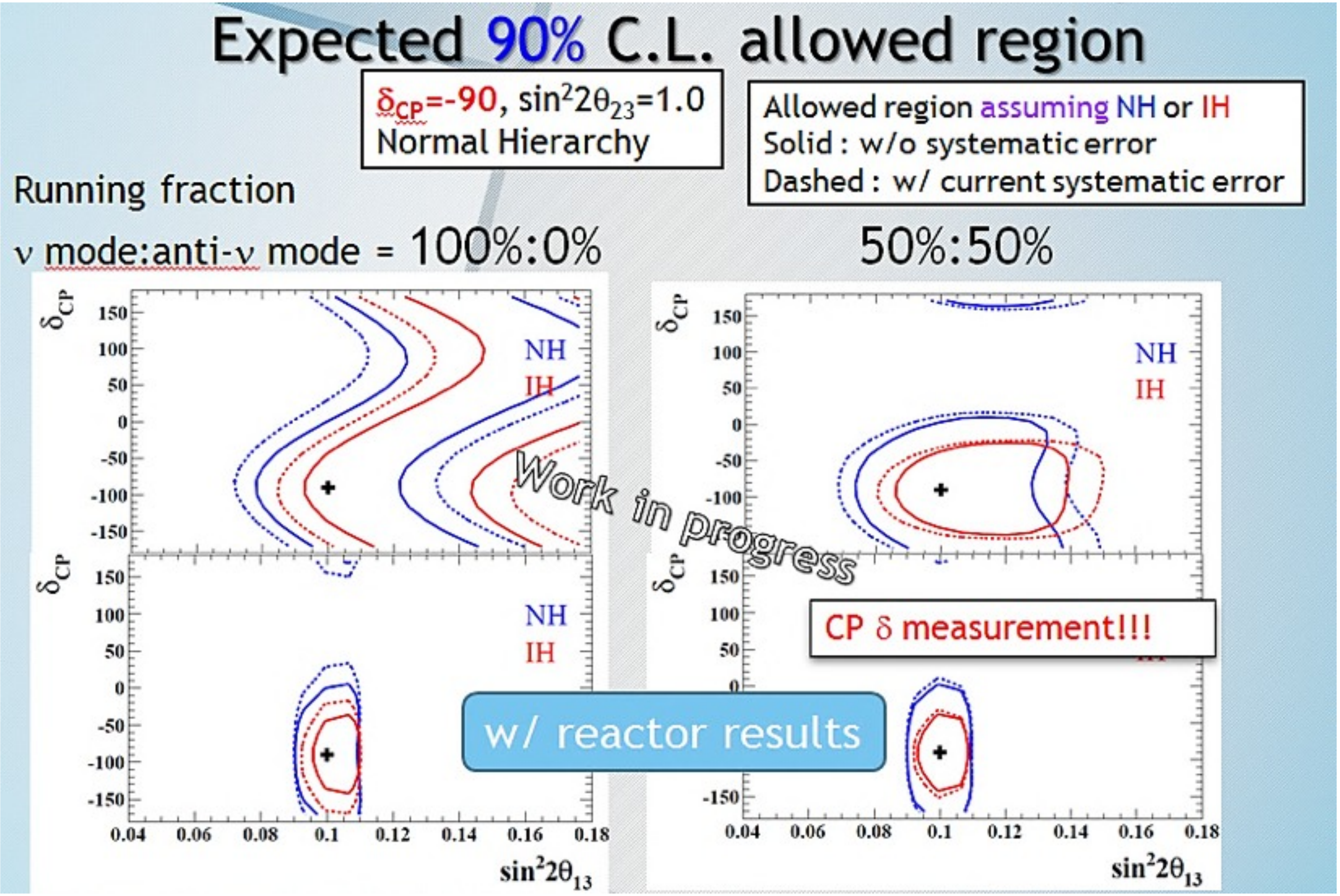
T2K sensitivity

@7.8E21 POT(750kW x 5e7sec @ 30GeV)



T2K sensitivity
@7.8E21 POT(750kW x 5e7sec @ 30GeV)

May 2012	2014	2018
190kW	300kW **500kW**	750kW



U.S. Accelerator-based Neutrino Experiments

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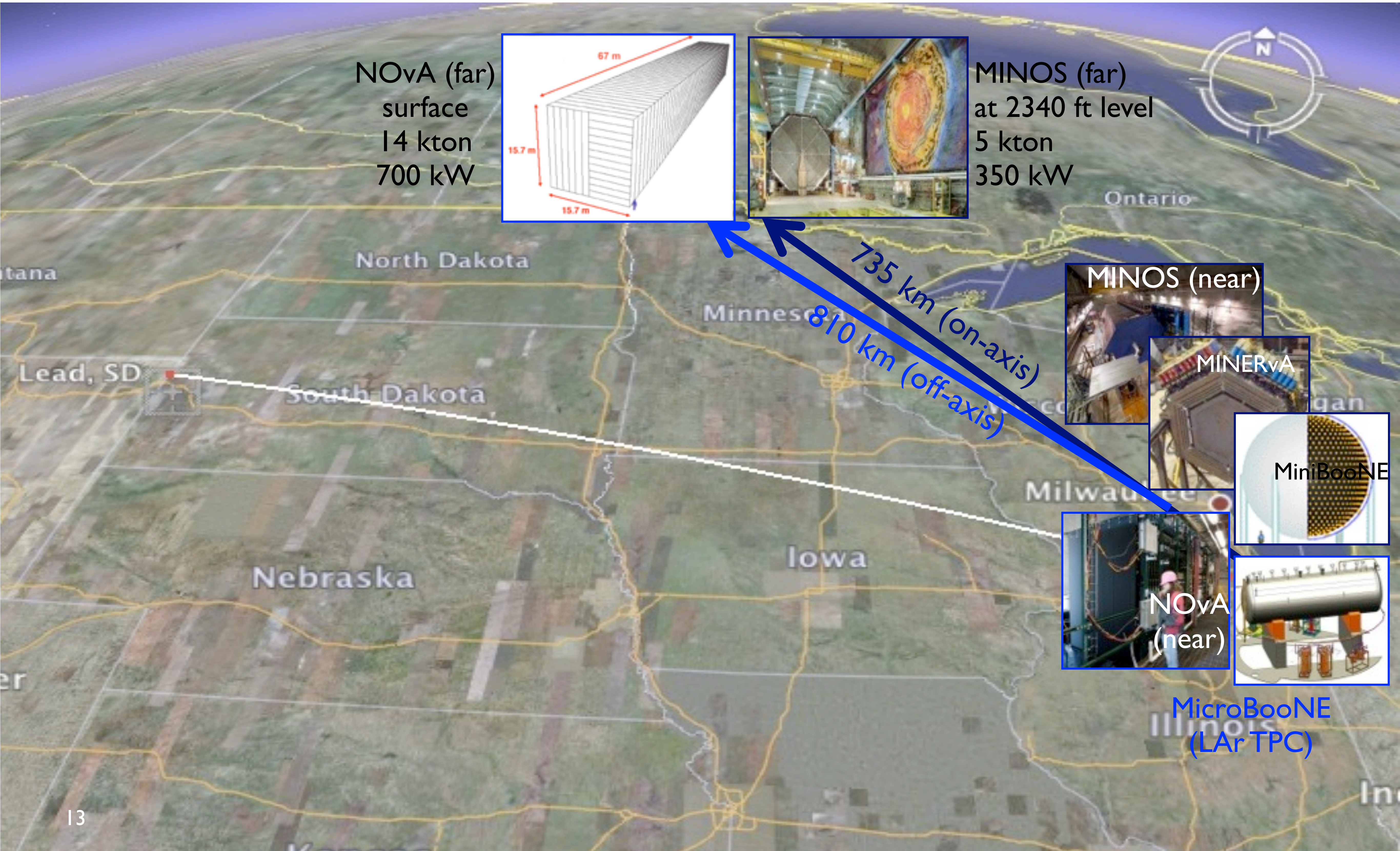
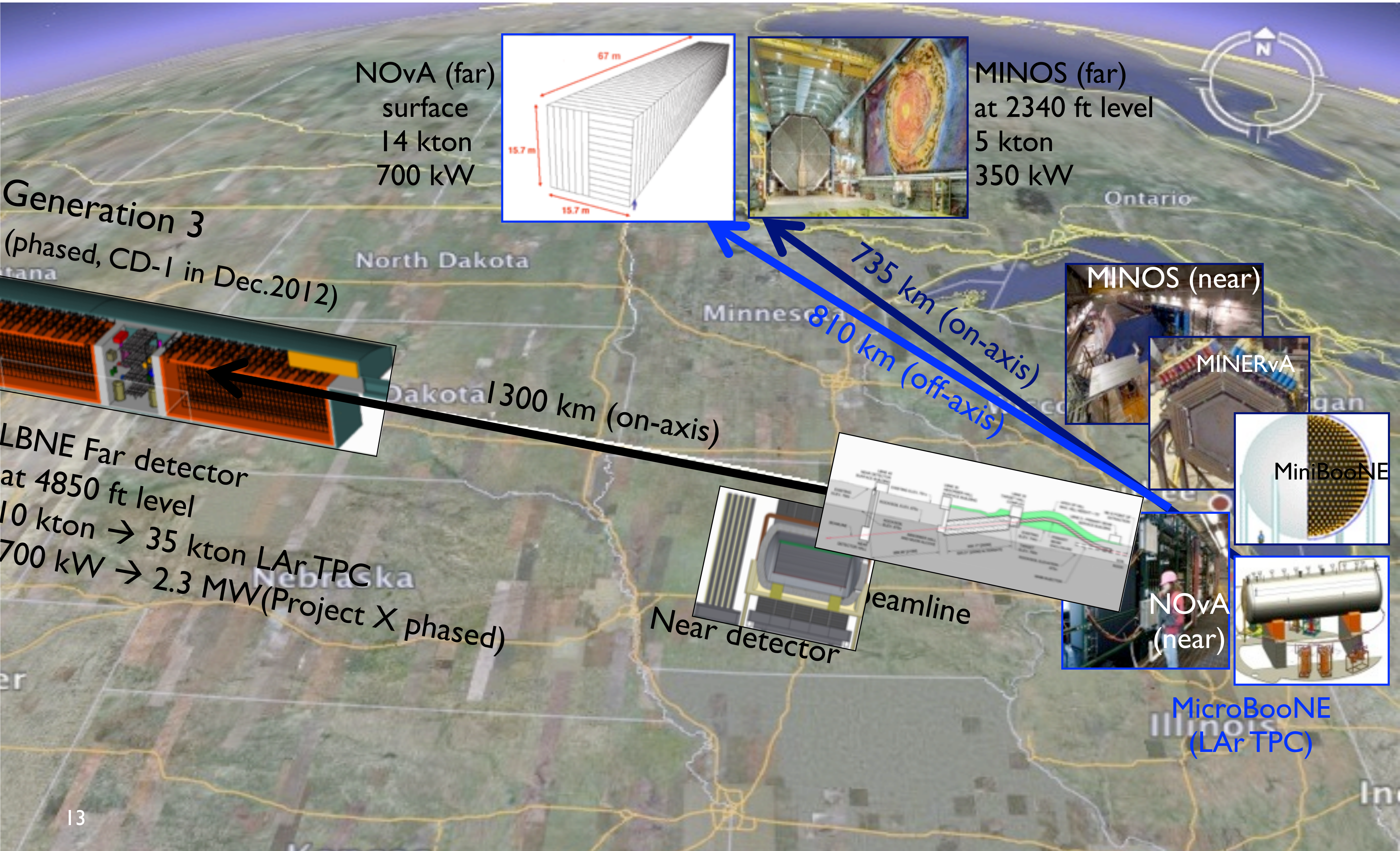


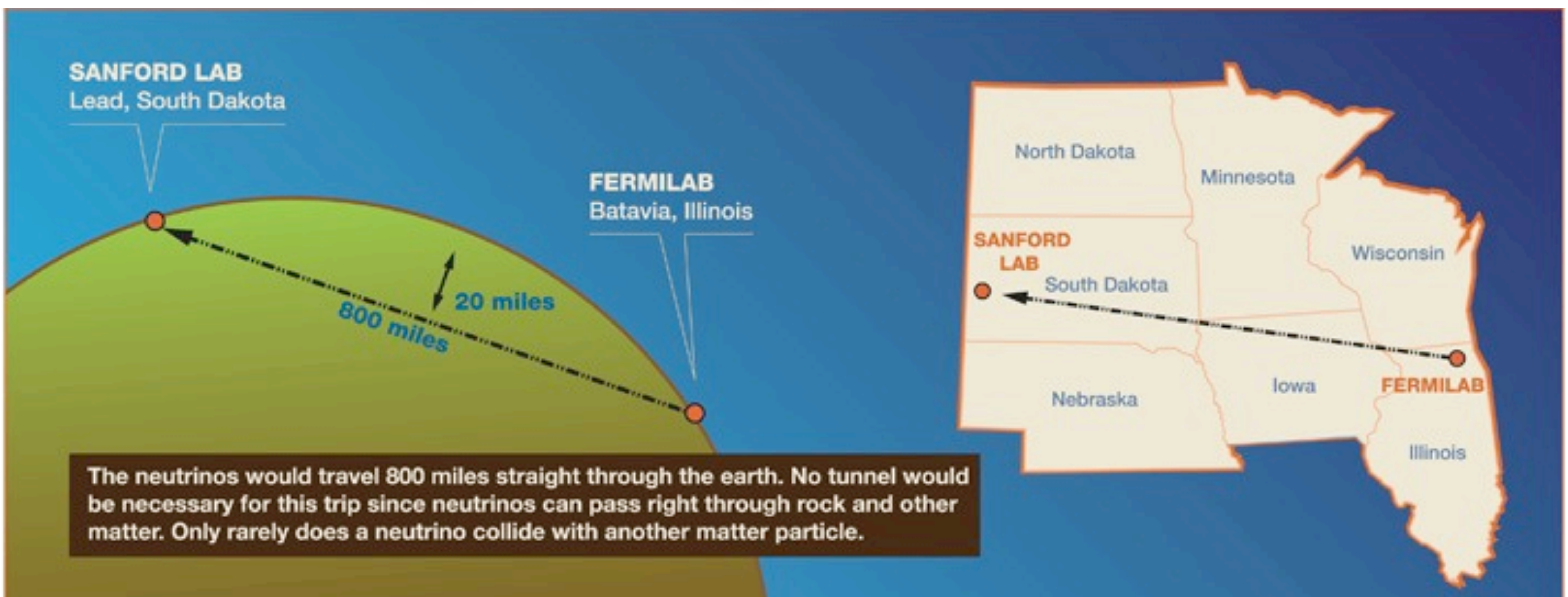
U.S. Accelerator-based Neutrino Experiments



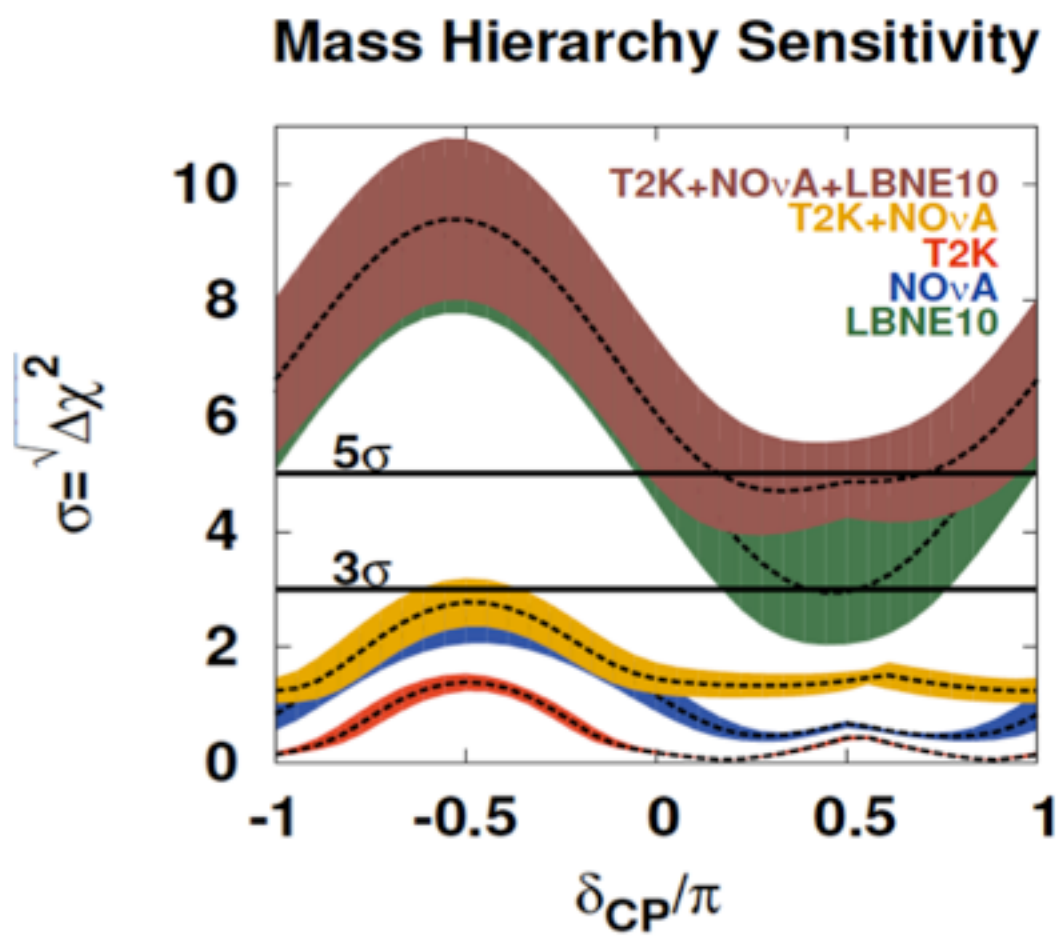
LBNE

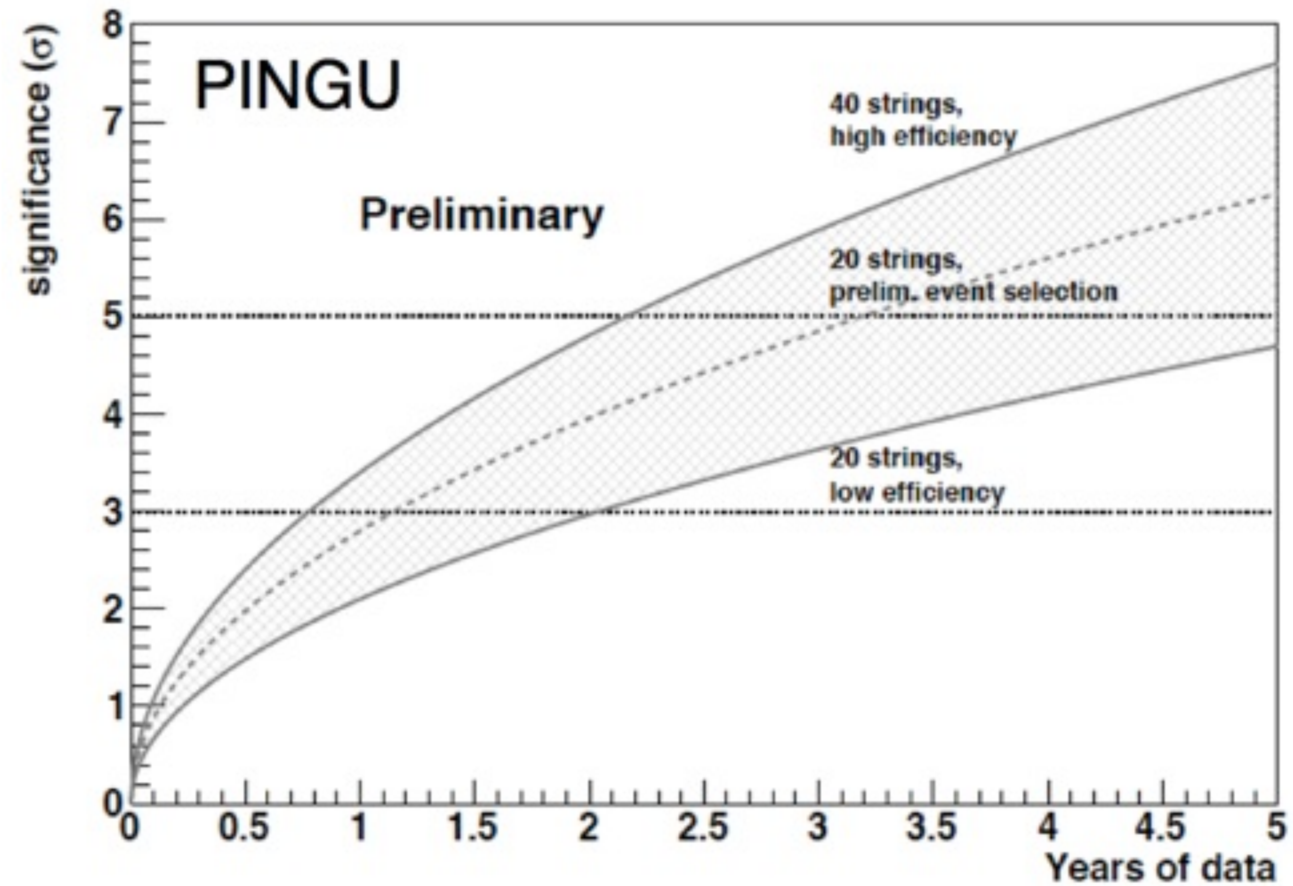
Explore CP violation, mass hierarchy, non-standard interactions in neutrinos (phased implementation)

- New neutrino beam at FNAL
  - 700 kW, 60-120 GeV proton beam
  - 2.3 MW capable
- Near detector for neutrinos
- 34 kton far detector at 1300 km baseline (at Sanford Underground Research Facility, SURF)
  - Ultimately positioned underground with 4850' overburden



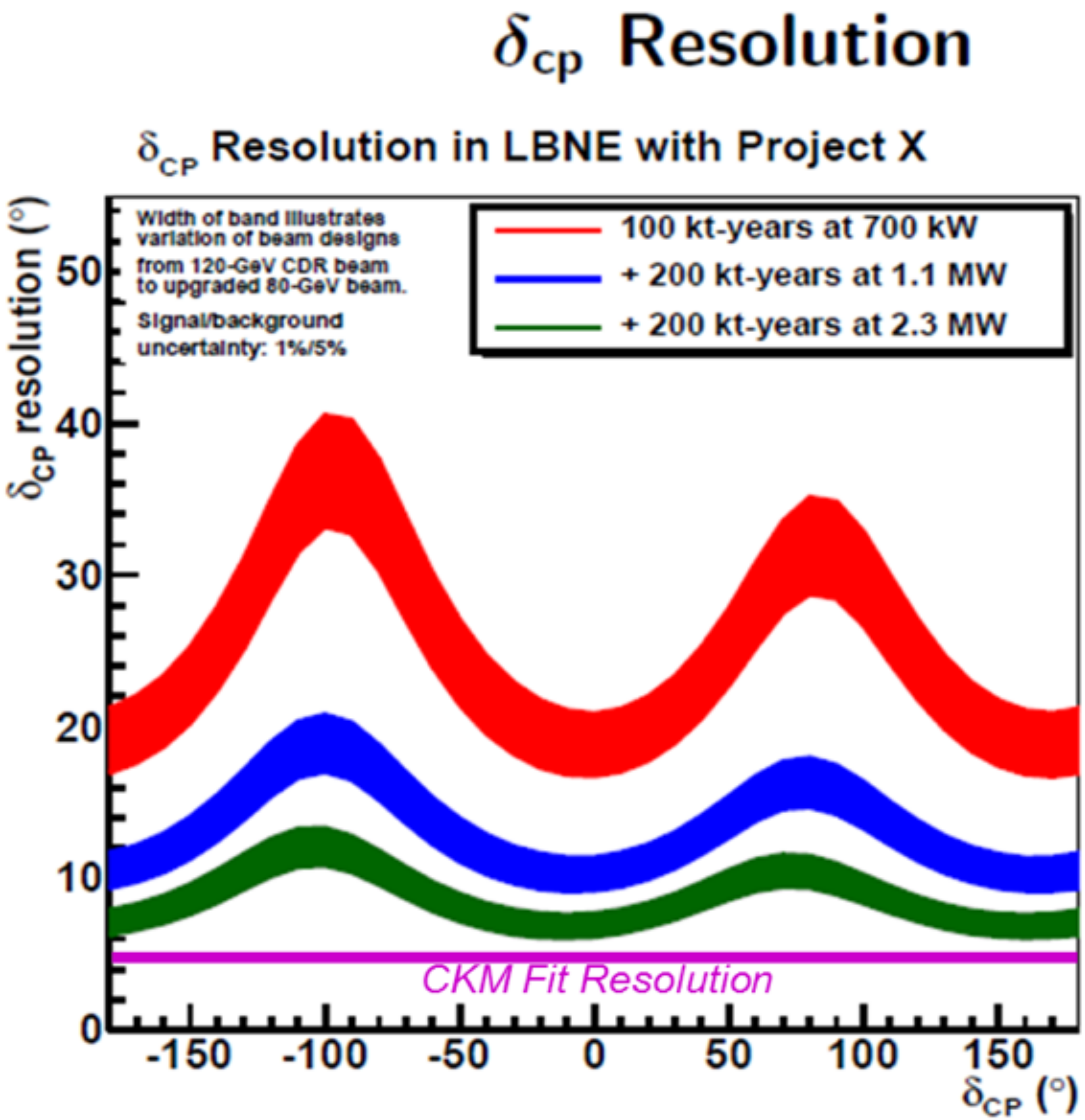
Mass hierarchy





- MH determination by long-baseline experiments “guaranteed” with sufficient exposure
- Other possibilities are promising; systematics challenging
  - PINGU IceCube infill: atmospheric neutrinos
  - JUNO/RENO-50 reactor experiments
- There could also be information from cosmology

CP Violation @ LBNE



LBNE + Project X enable an era of high-precision neutrino oscillation measurements.

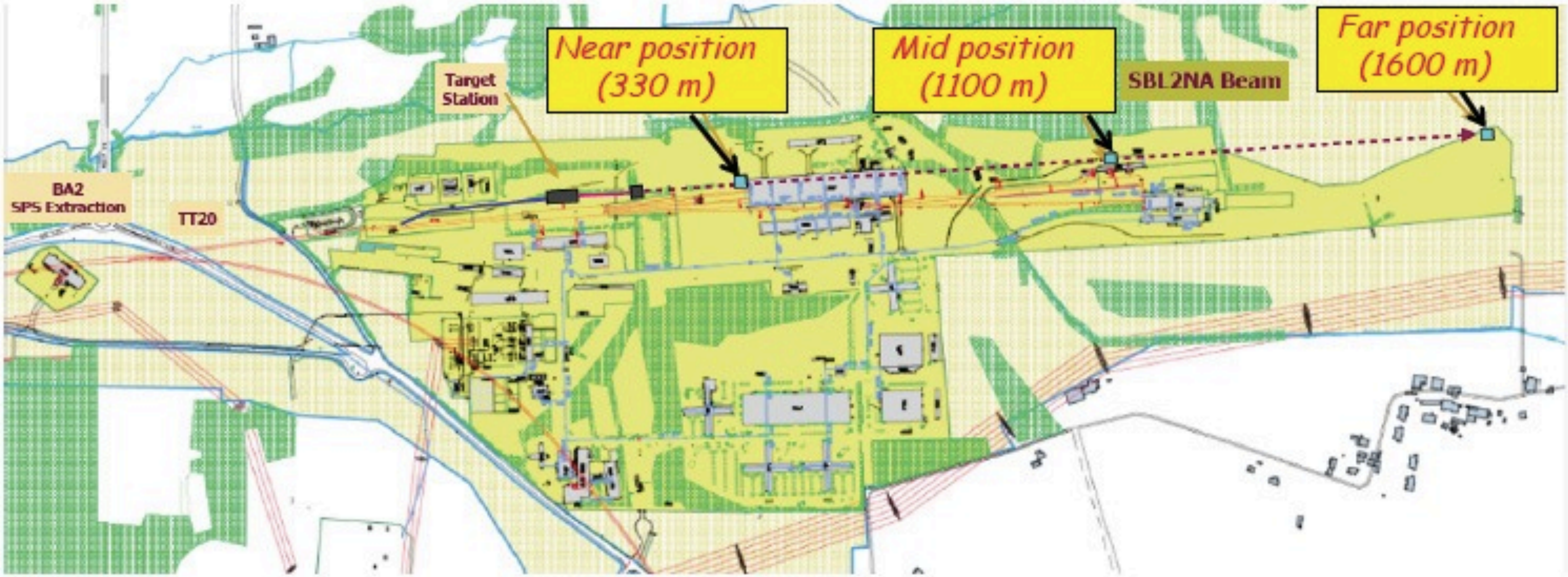
The Neutrino goes global

From the European Strategy

- Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a 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 neutrino projects in the US and Japan.*

- *The US is working to make the LBNE program a global partnership. (Fermilab)*
- *Hyper-Kamiokanda is the proposal for a Long Baseline experiment in Japan. (J-PARC)*
- *Europe's Long Baseline proposal is LBNO (CERN - Laguna)*

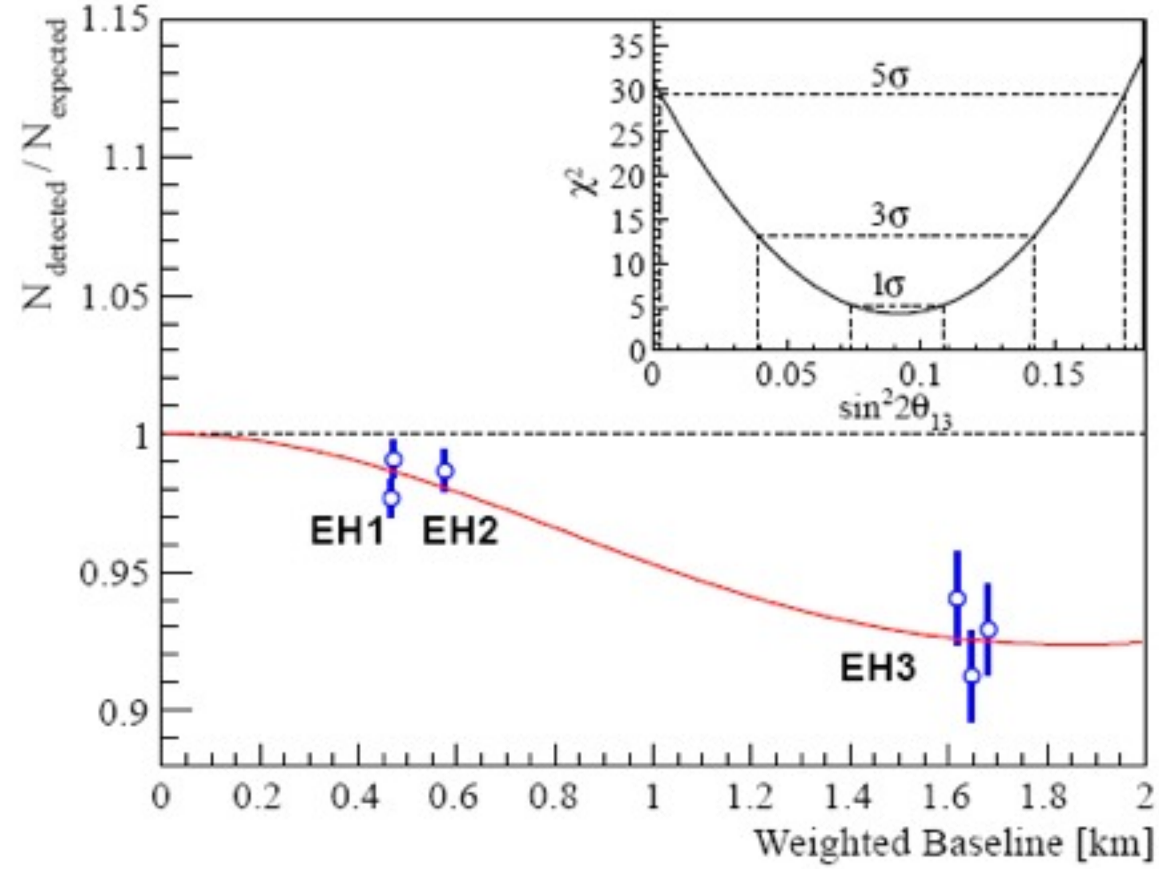
New Neutrino Facility in the CERN North Area



100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.
Neutrino beam angle: pointing upwards; at -3m in the far detector ~5mrad slope.

2. Projects in China

- **Reactor-based**



$\mathrm{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

$\chi^2/\mathrm{NDF} = 4.26/4$, 5.2 σ for non-zero θ_{13}

F.P. An et al., NIM. A 685(2012)78; Phys. Rev. Lett. 108, (2012) 171803

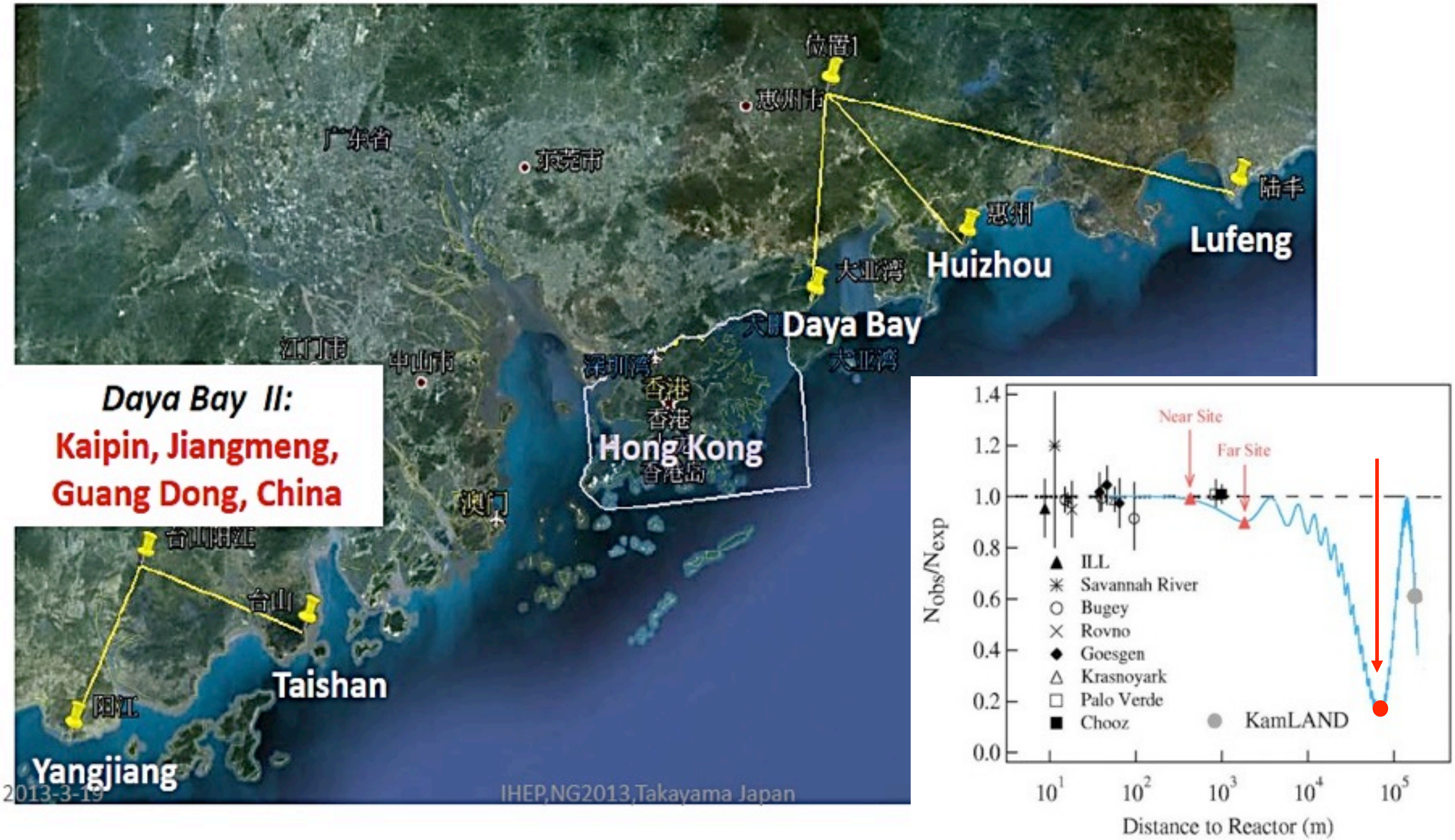
$\mathrm{Sin}^2 2\theta_{13} = 0.089 \pm 0.010\ (\mathrm{stat}) \pm 0.005(\mathrm{syst})$

$\chi^2/\mathrm{NDF} = 3.4/4$, 7.7 σ for non-zero θ_{13}

F.P. An et al., Chin. Phys.C 37(2013) 011001

New site：Kaiping county, Jiangmen city

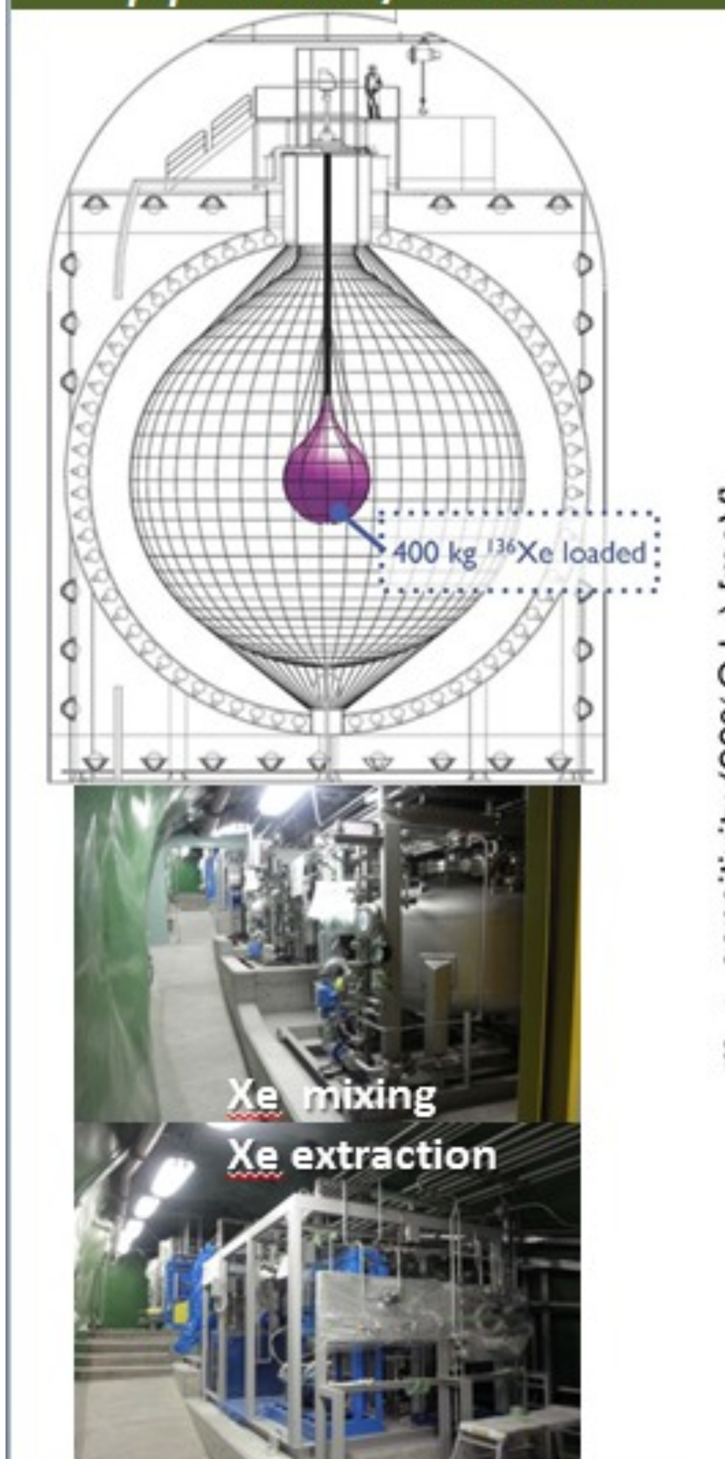
	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW (~2017)	18.4 GW(~2014,?)

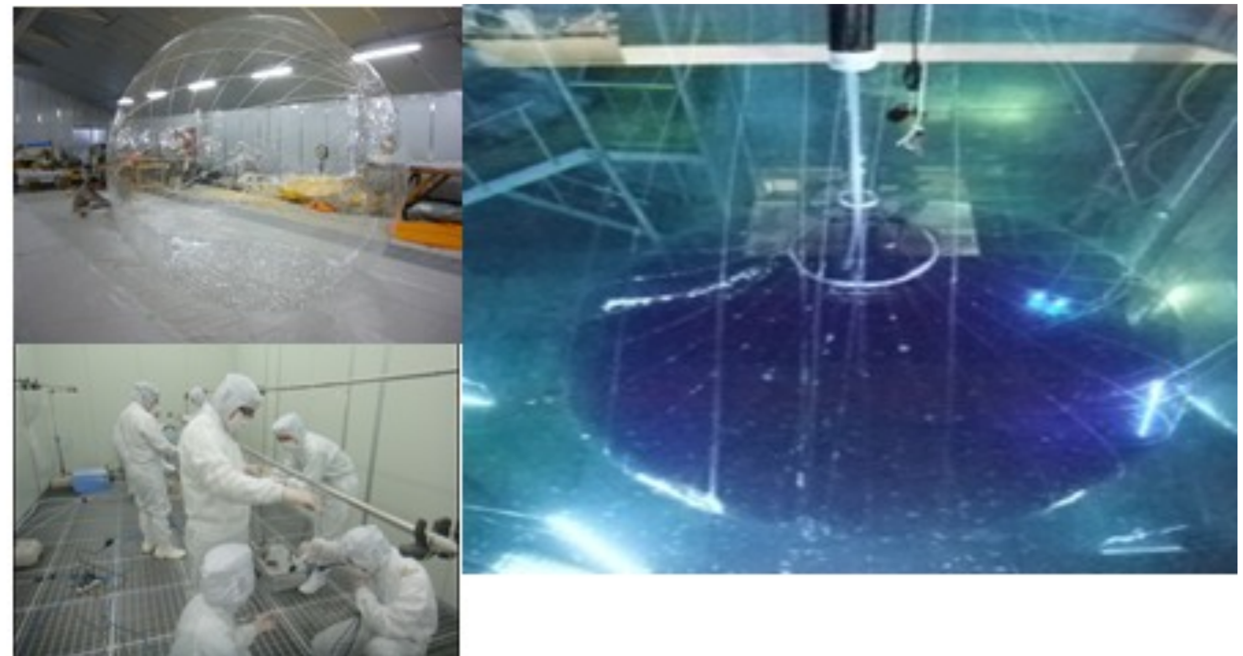


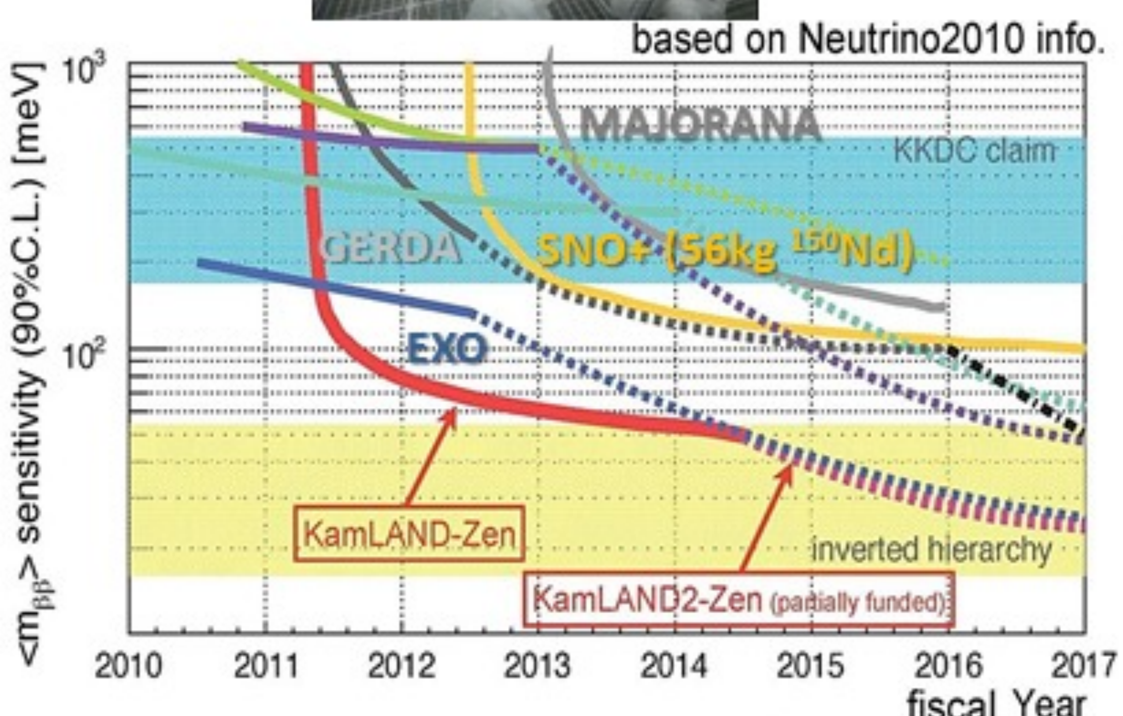
1. Projects in Japan

● Underground Physics at Kamioka

KamLAND-Zen
ββ-Decay Search

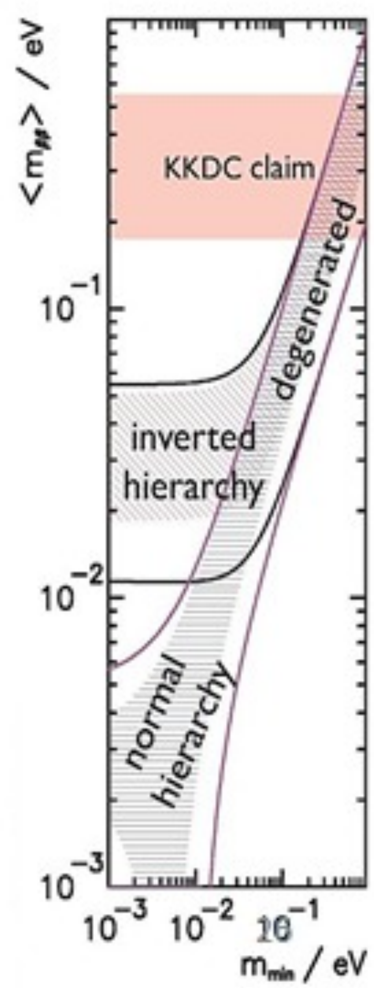






1st step : 400 kg ^{136}Xe

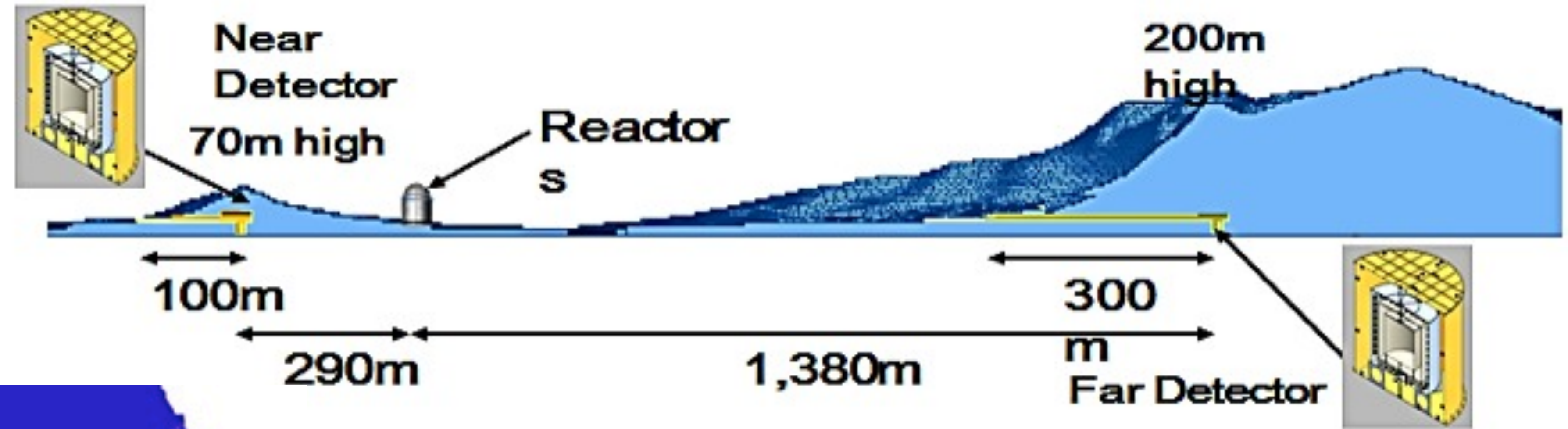
2nd step : 1 ton ^{136}Xe
(possible to 10 ton)

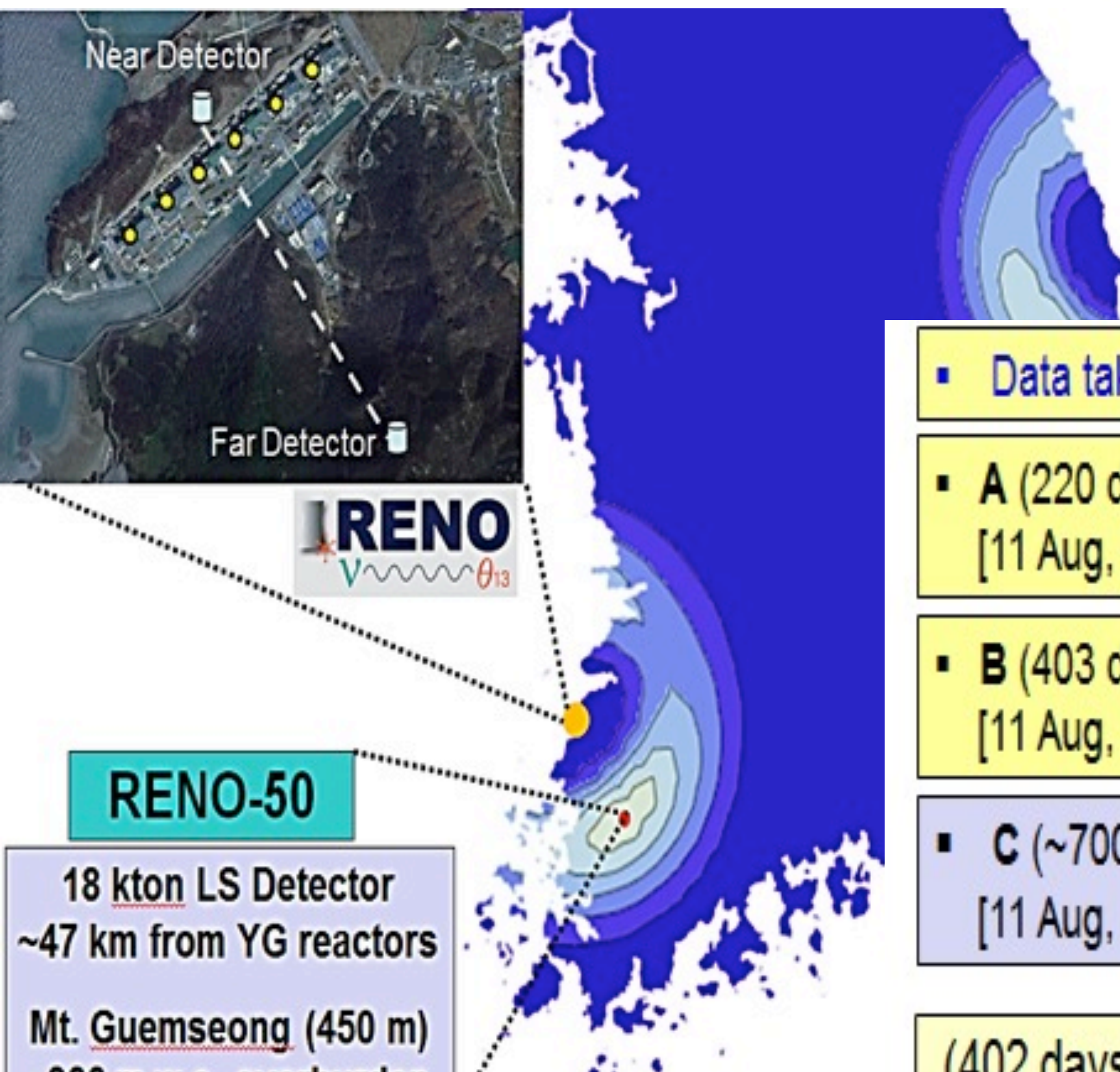


3. Projects in Korea

● Reactor-based

KNRC
Korea Neutrino Research Center





RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

RENO Status

- Data taking began on Aug. 1, 2011 with both near and far detectors.
- **A** (220 days) : First θ_{13} result $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$
  [11 Aug, 2011~26 Mar, 2012] PRL 108, 191802 (2012)
- **B** (403 days) : Improved θ_{13} result $\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.015(syst)$
  [11 Aug, 2011~13 Oct, 2012] NuTel 2013
- **C** (~700 days) : Shape+rate analysis (in progress) (expected total error: ~0.01)
  [11 Aug, 2011~31 Jul, 2013]

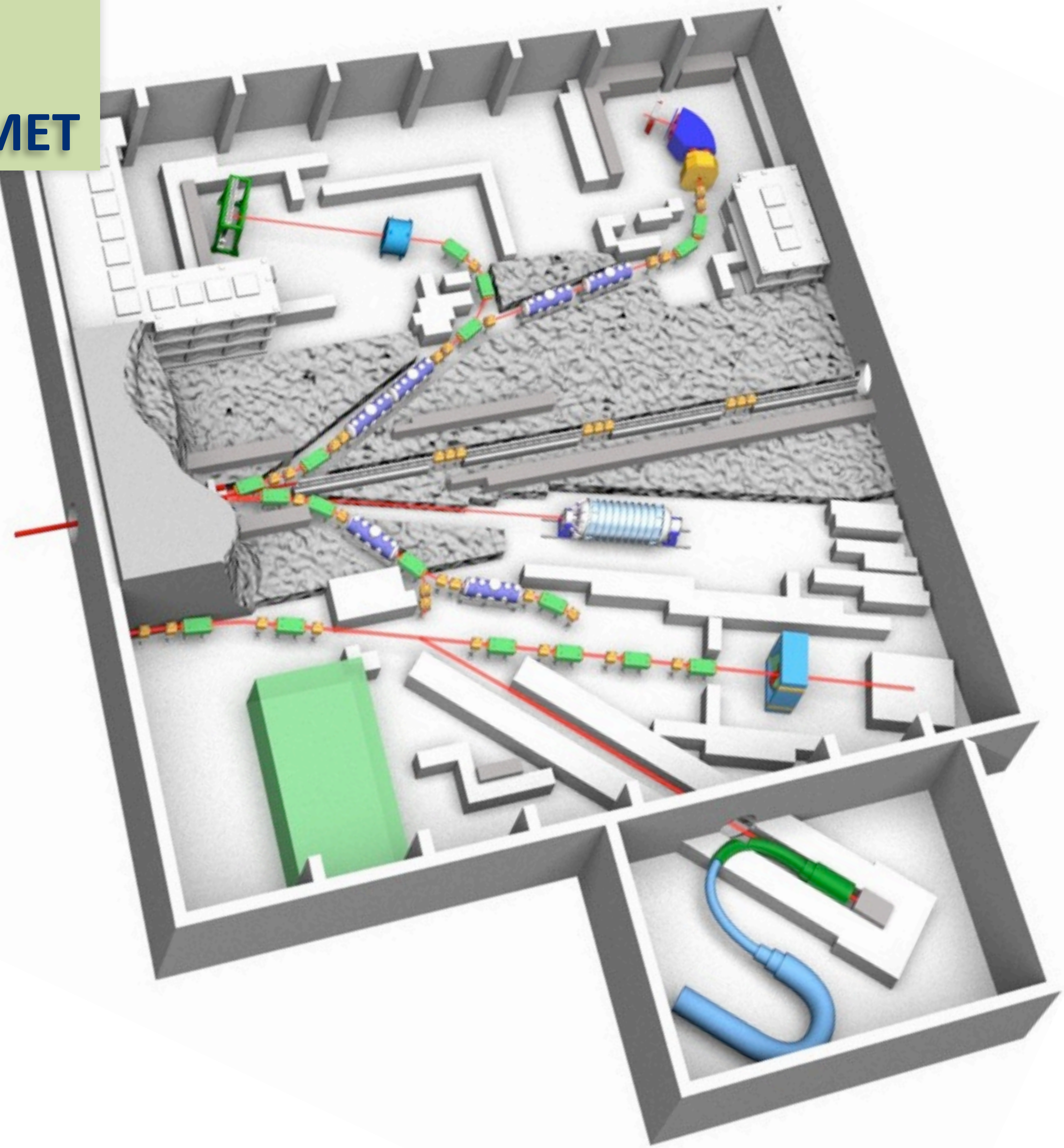
(402 days) 0.100 ± 0.018 (5.6 σ) ⇒ ± 0.007 (~ 14 σ) (5 years)

(7 % precision)

1. Projects in Japan

- Intensity Frontier

  J-PARC/ KOTO, COMET

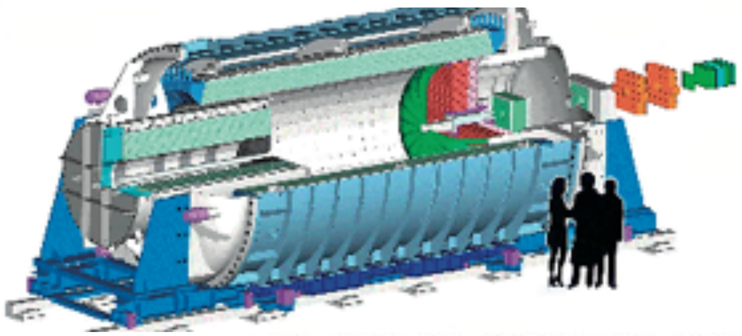


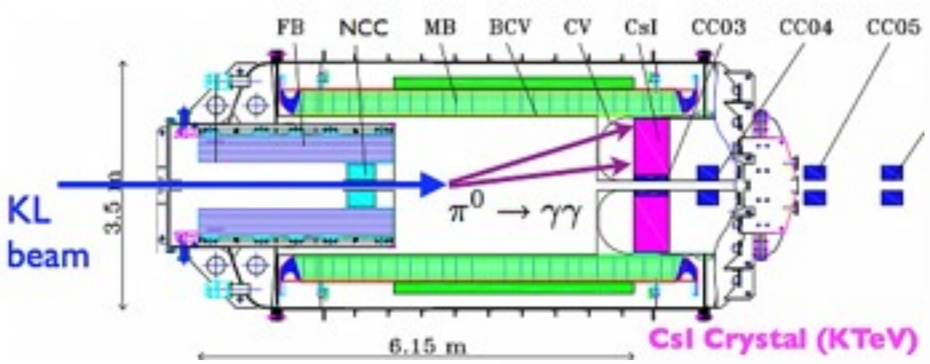
1. Projects in Japan

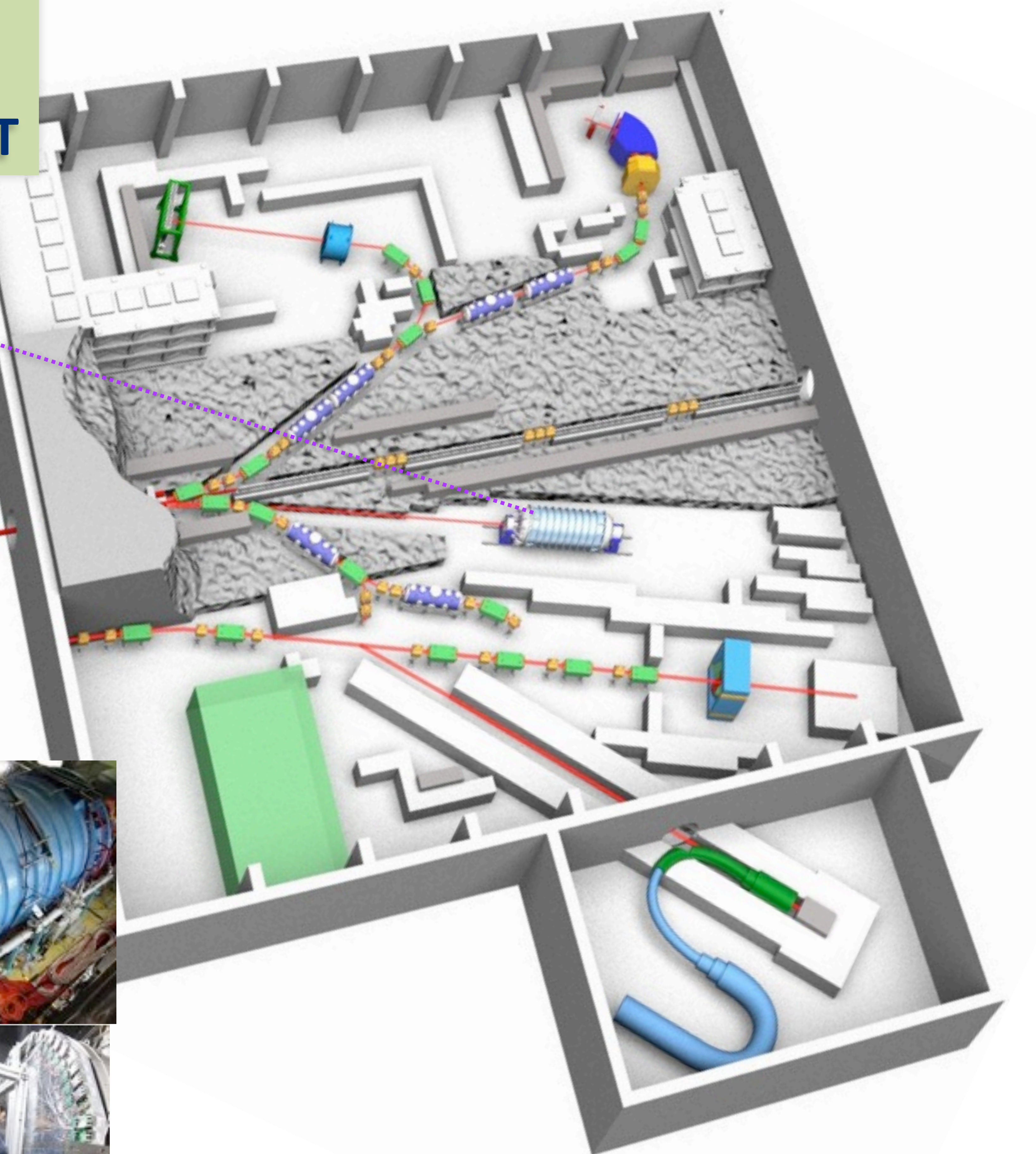
- **Intensity Frontier**

  J-PARC/ KOTO, COMET

Rare Kaon Decay
$K_L^0 \to \pi^0 \nu \bar{\nu}$







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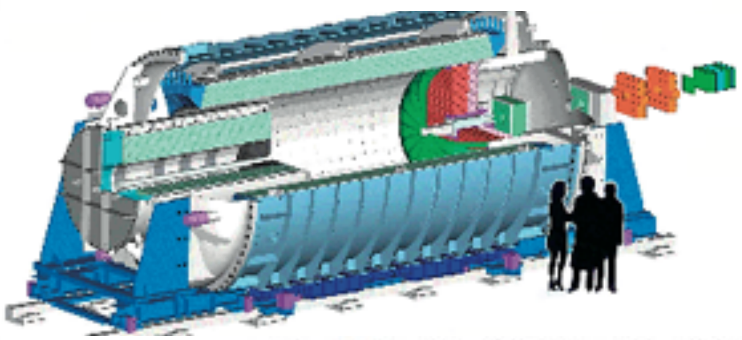

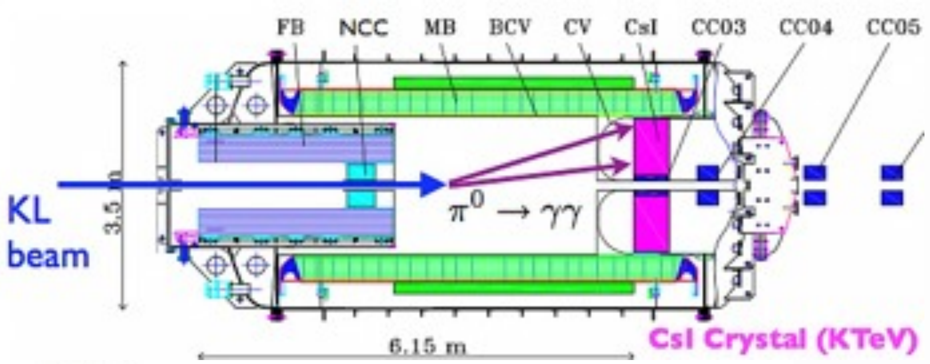

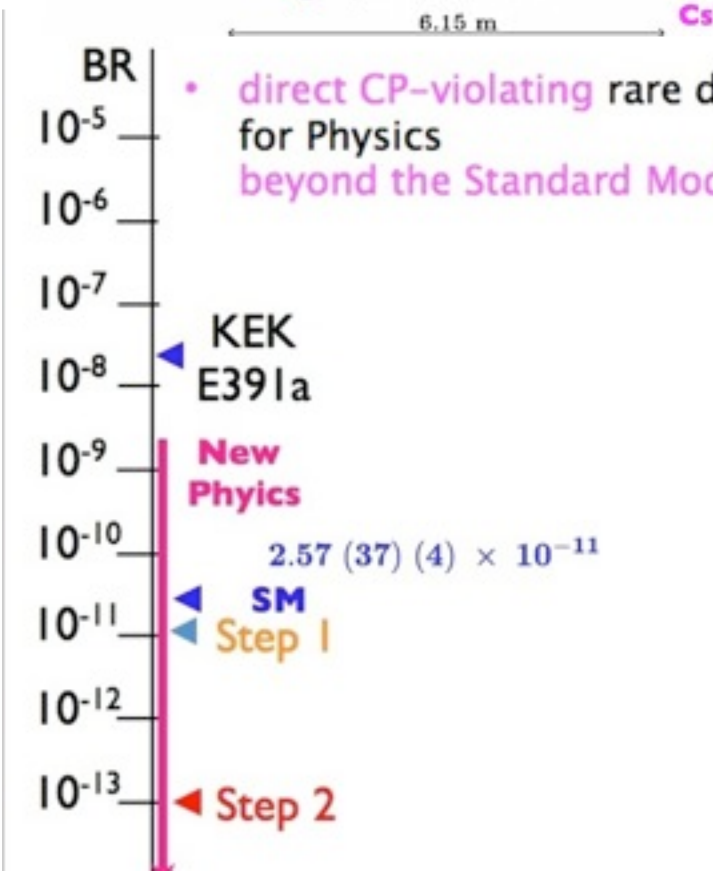

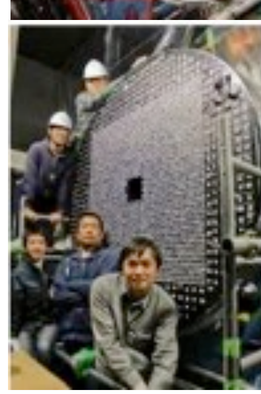

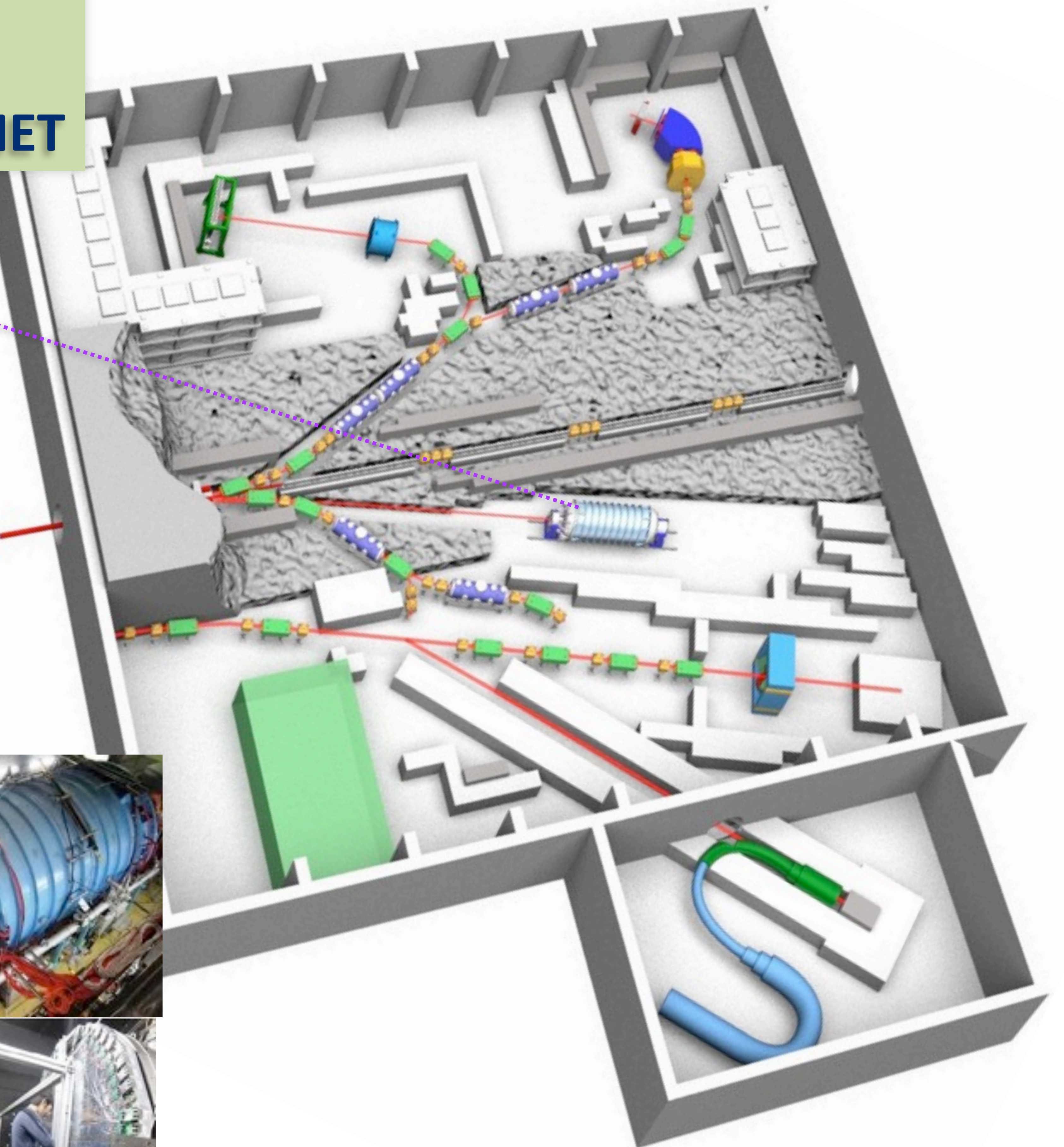

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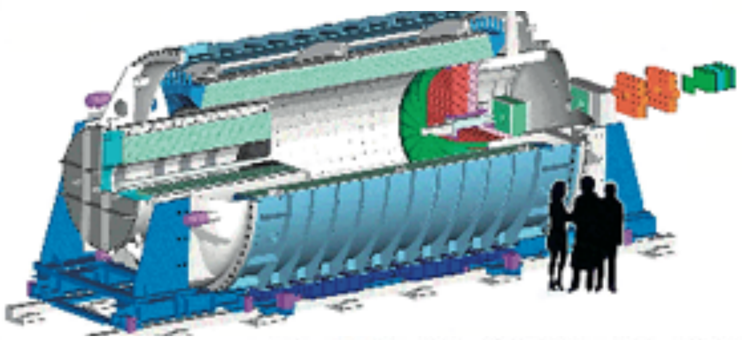

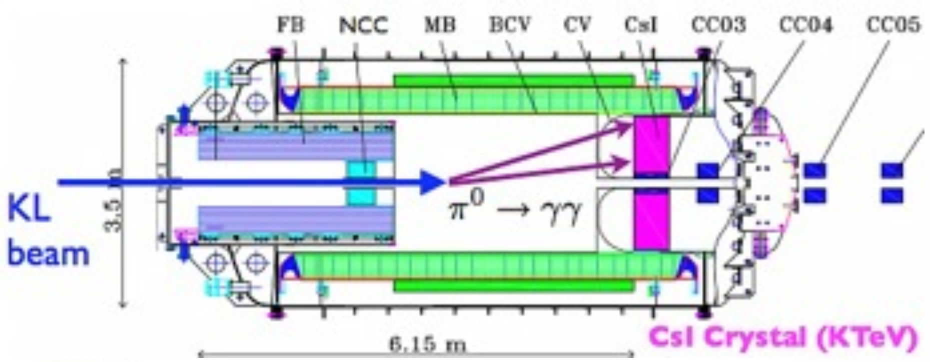

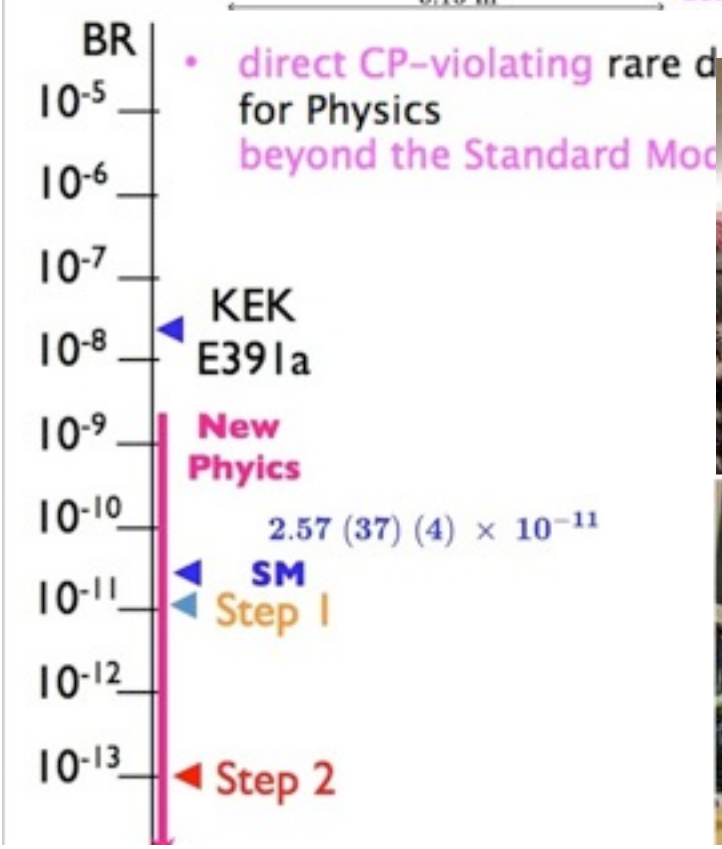

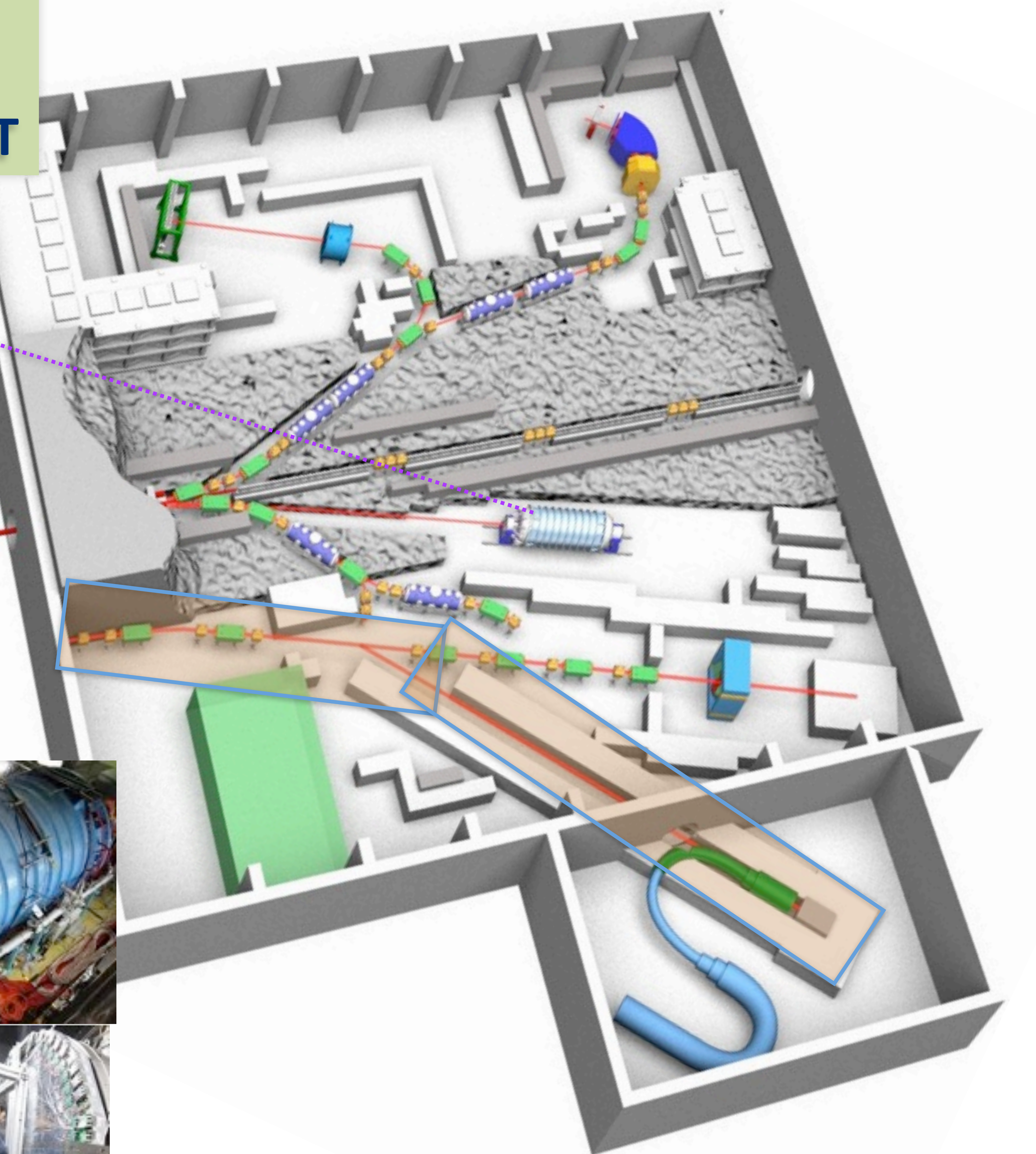

1. Projects in Japan

- **Intensity Frontier**

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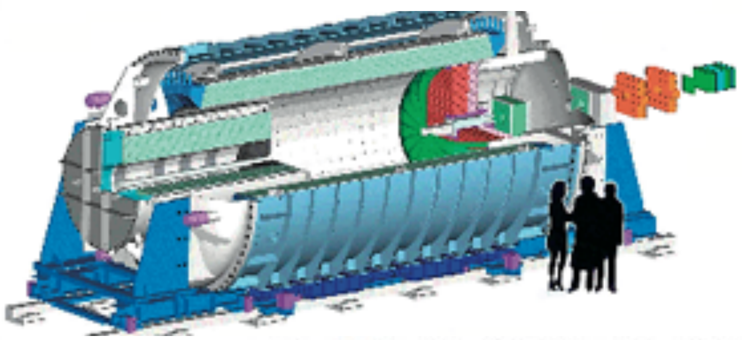
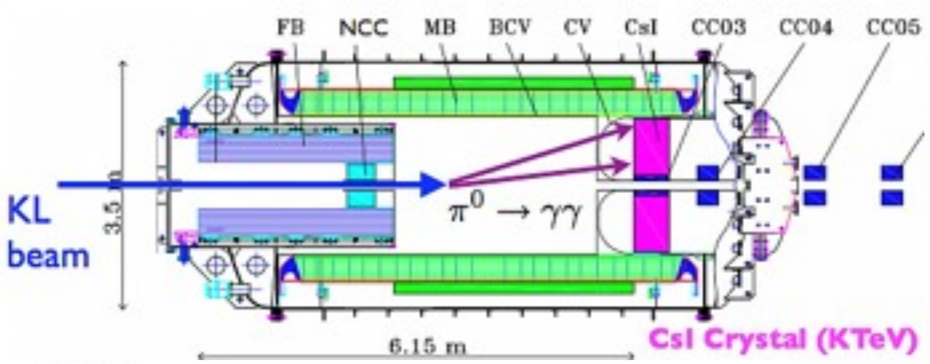
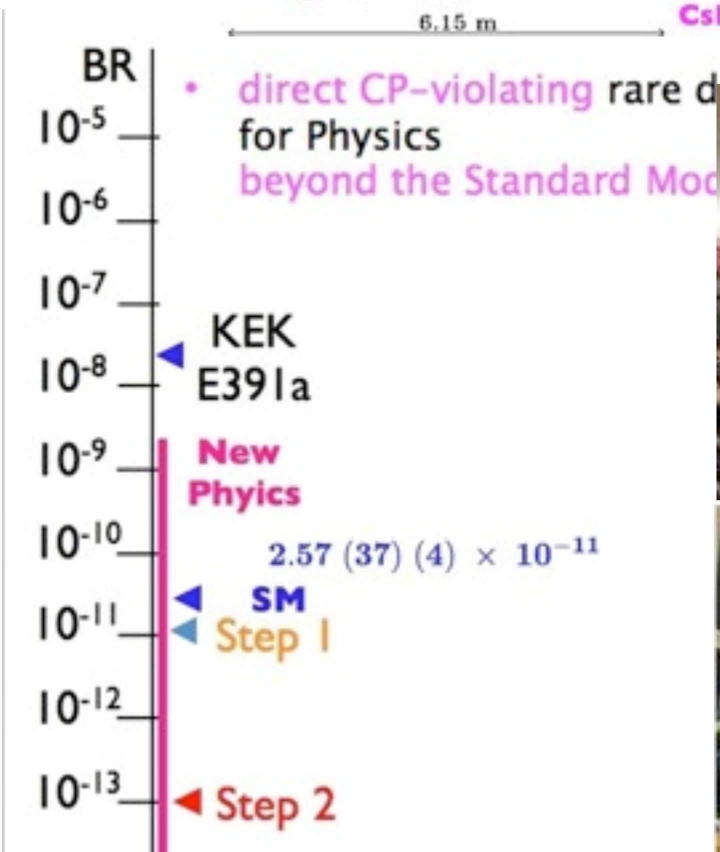
COMET: $\mu \rightarrow$ e Conversion

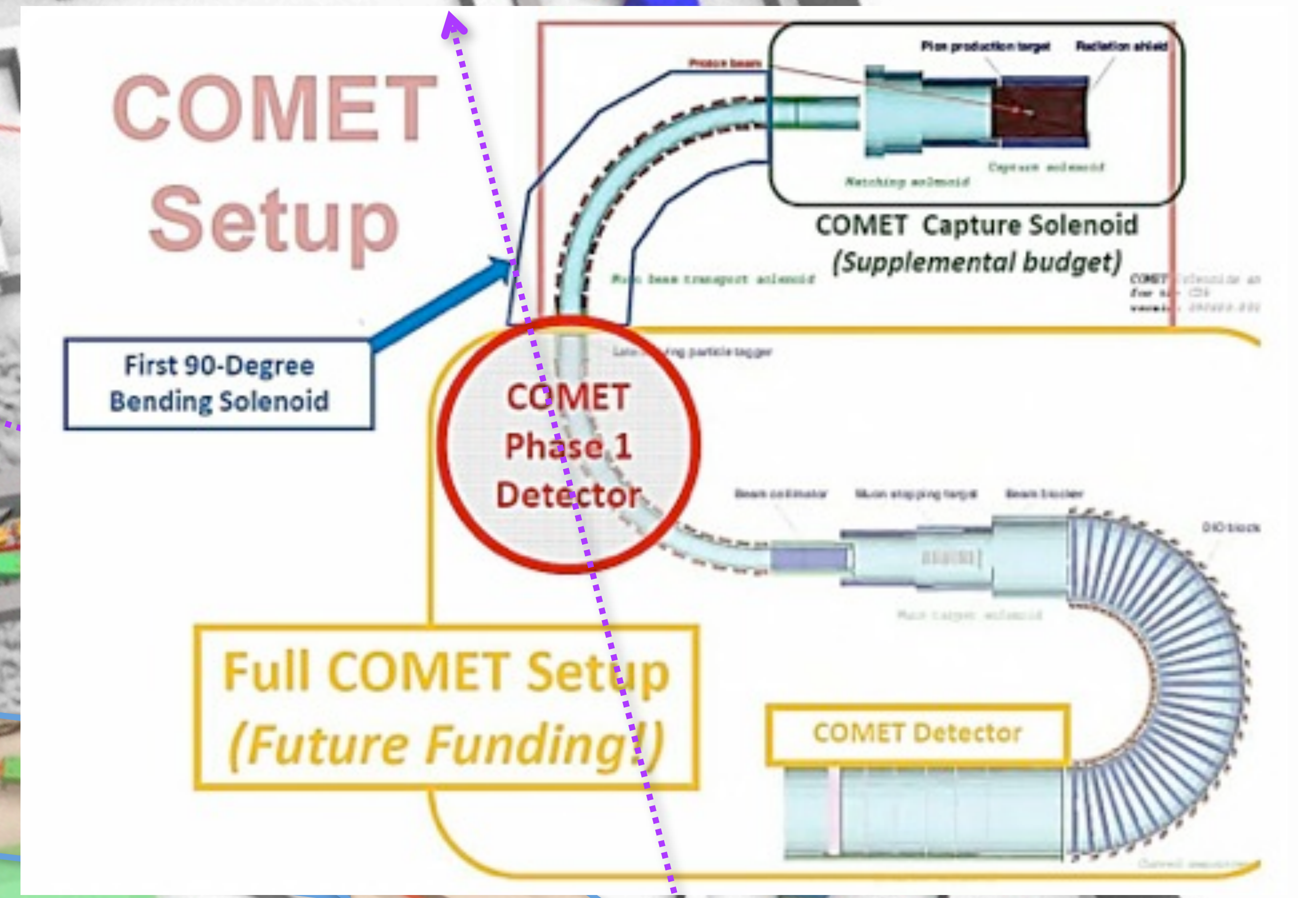
Signal : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

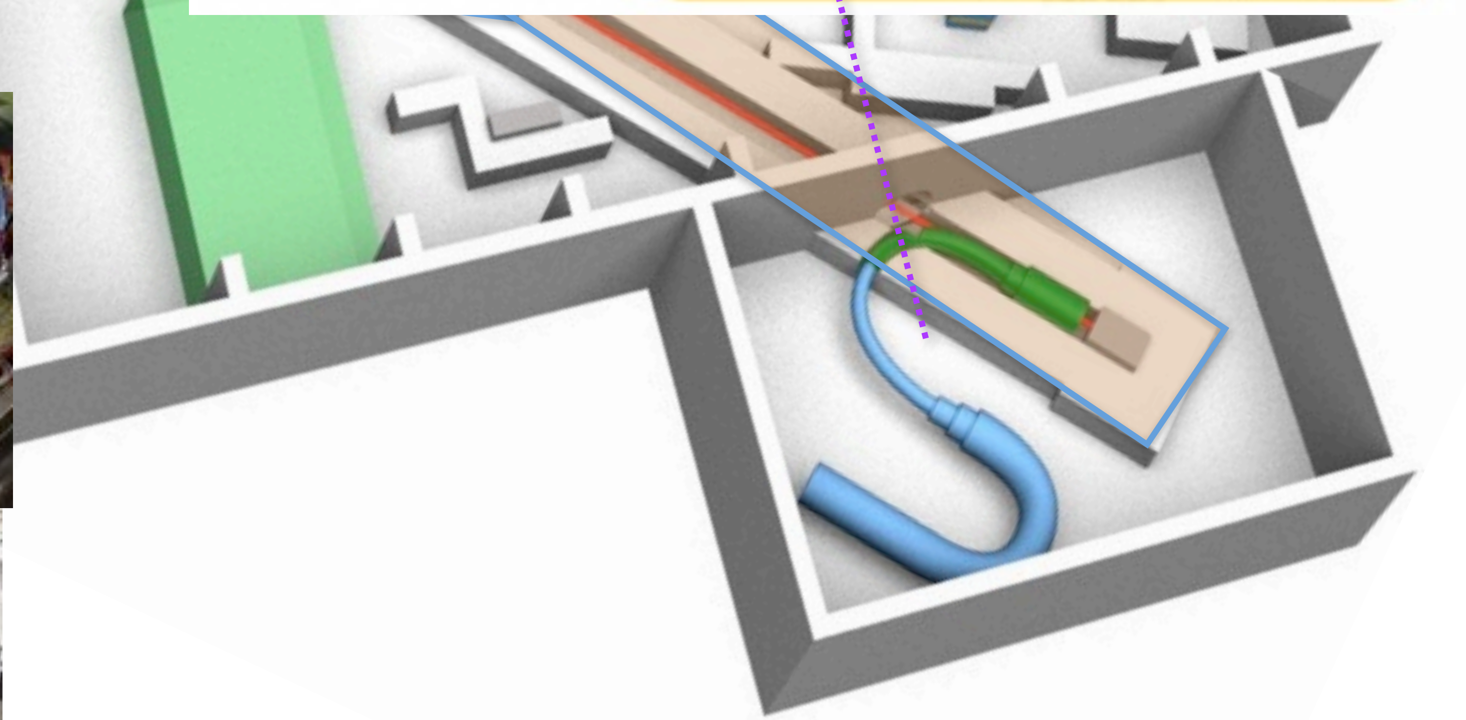
Rare Kaon Decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$











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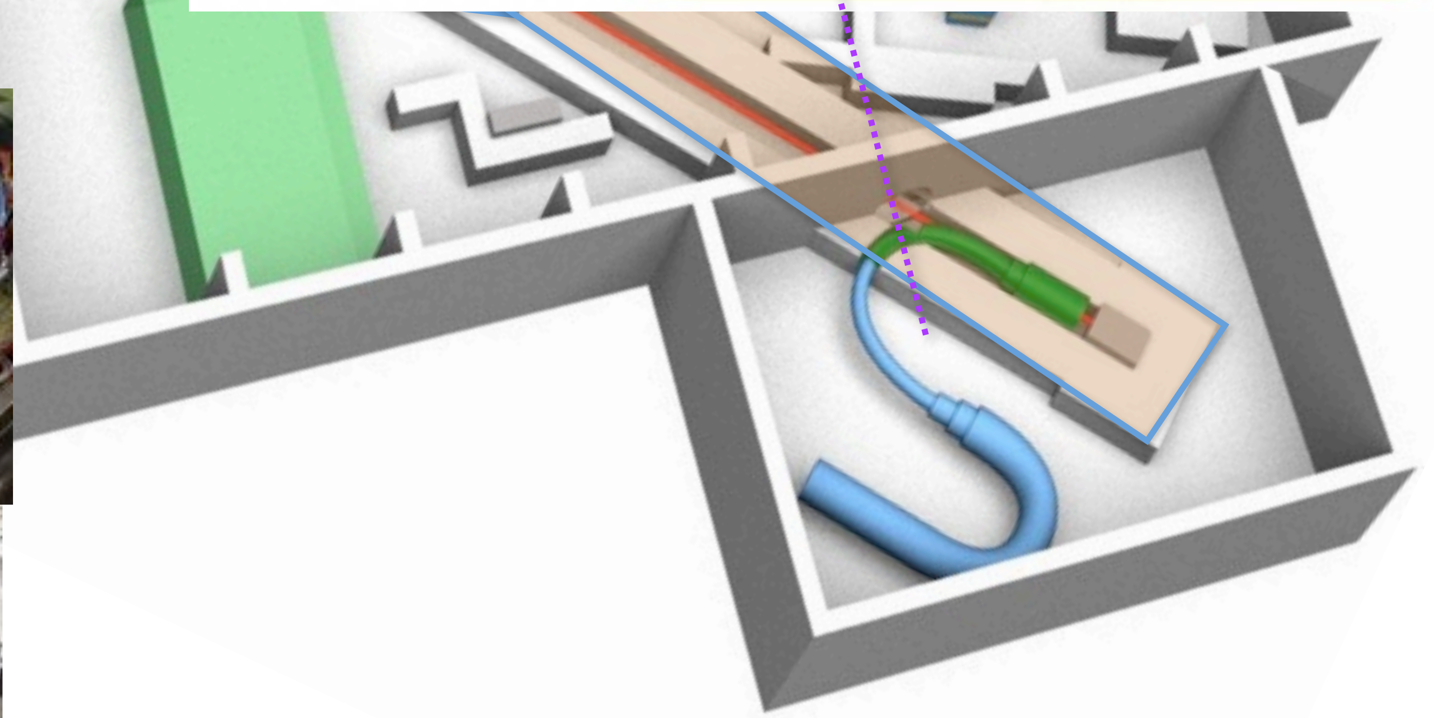

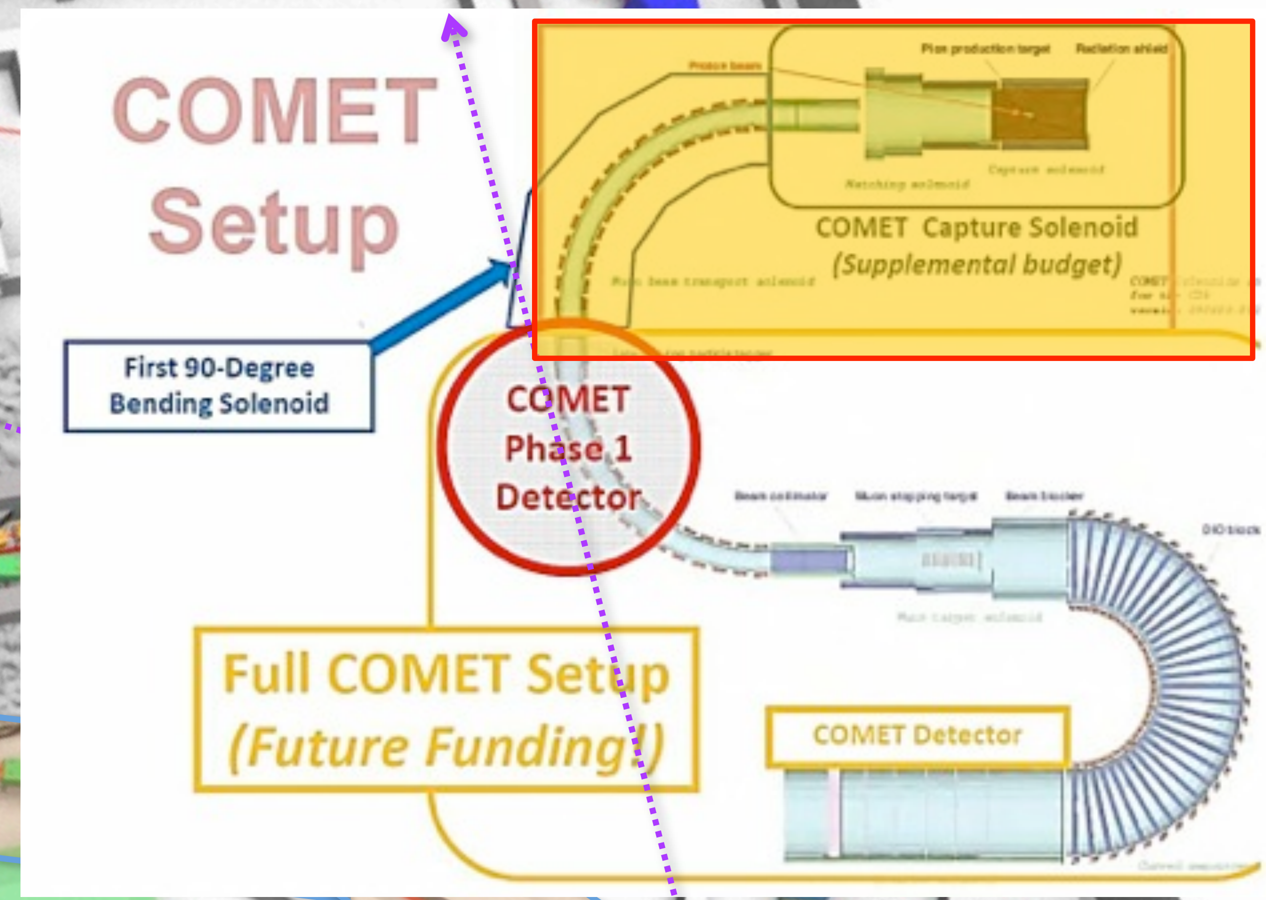

KOTO

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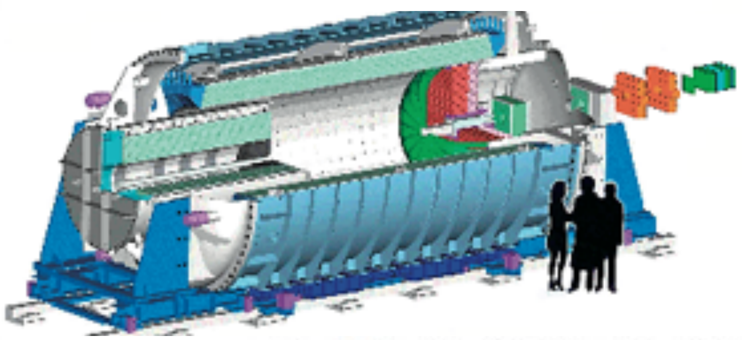

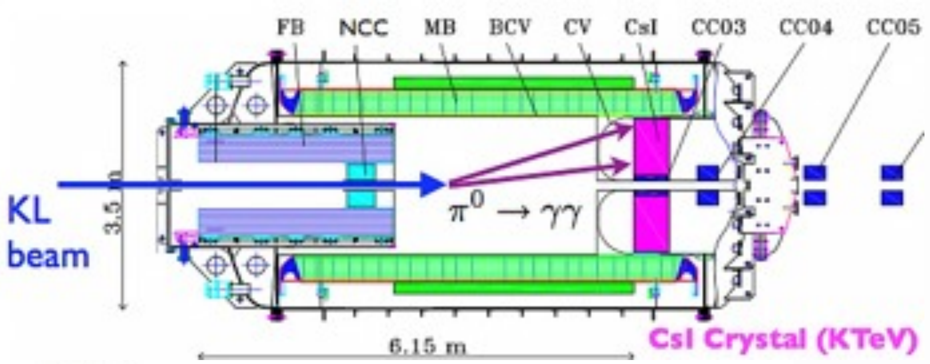

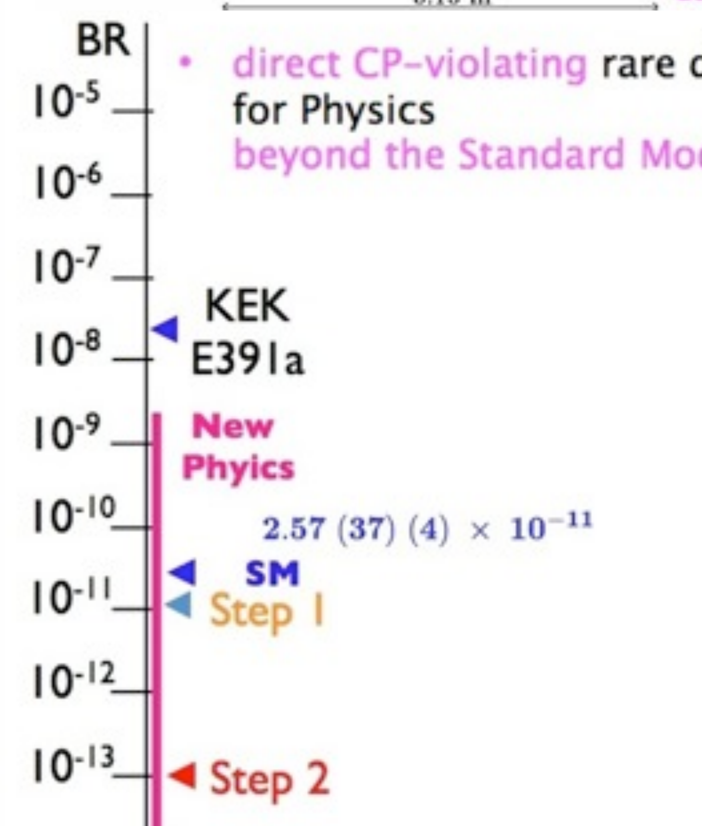

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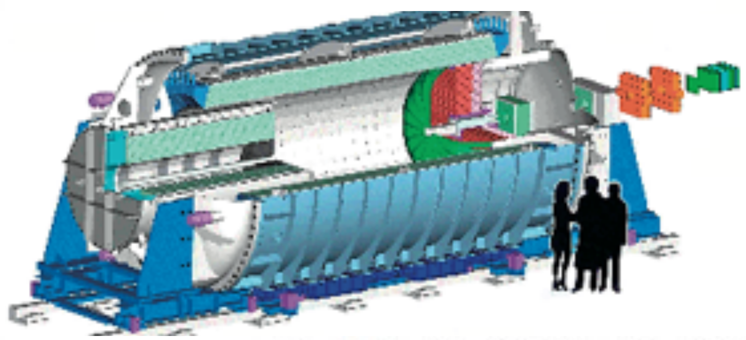
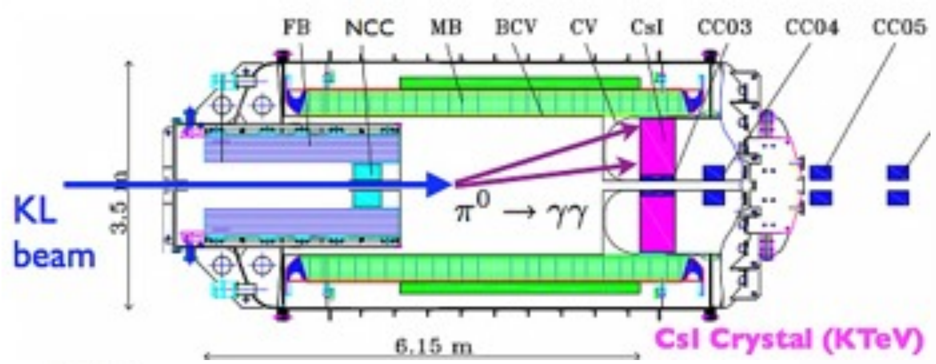
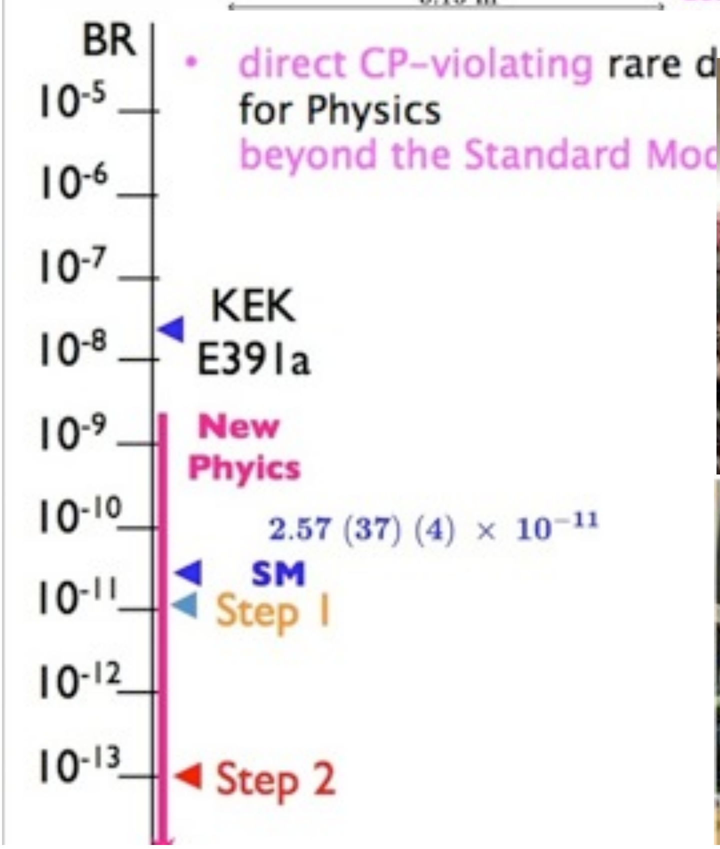
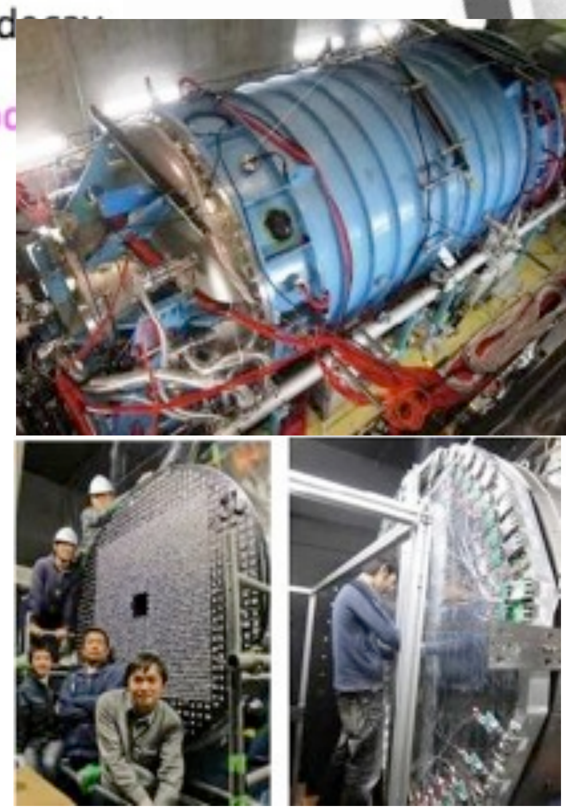
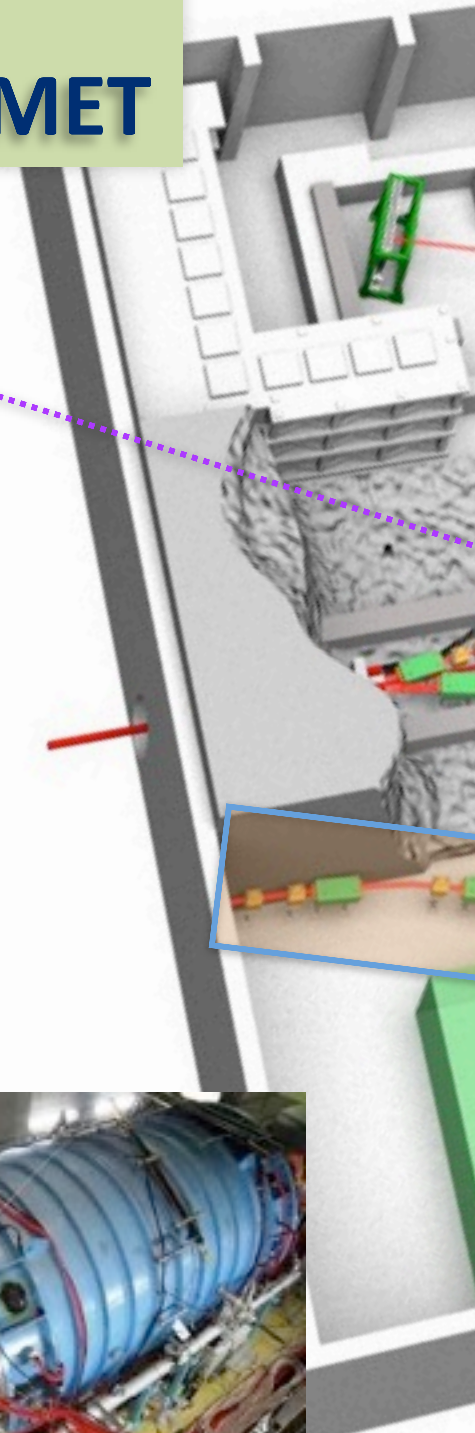
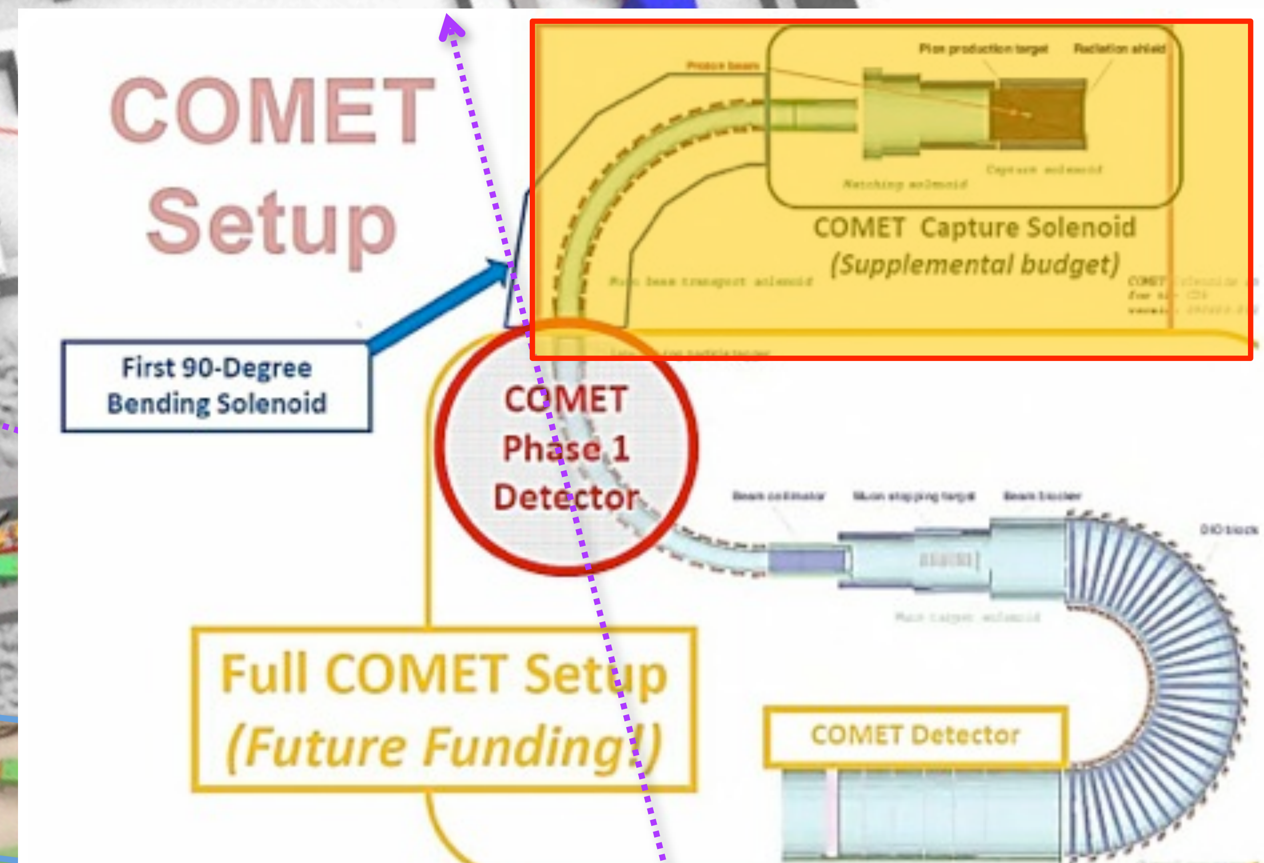


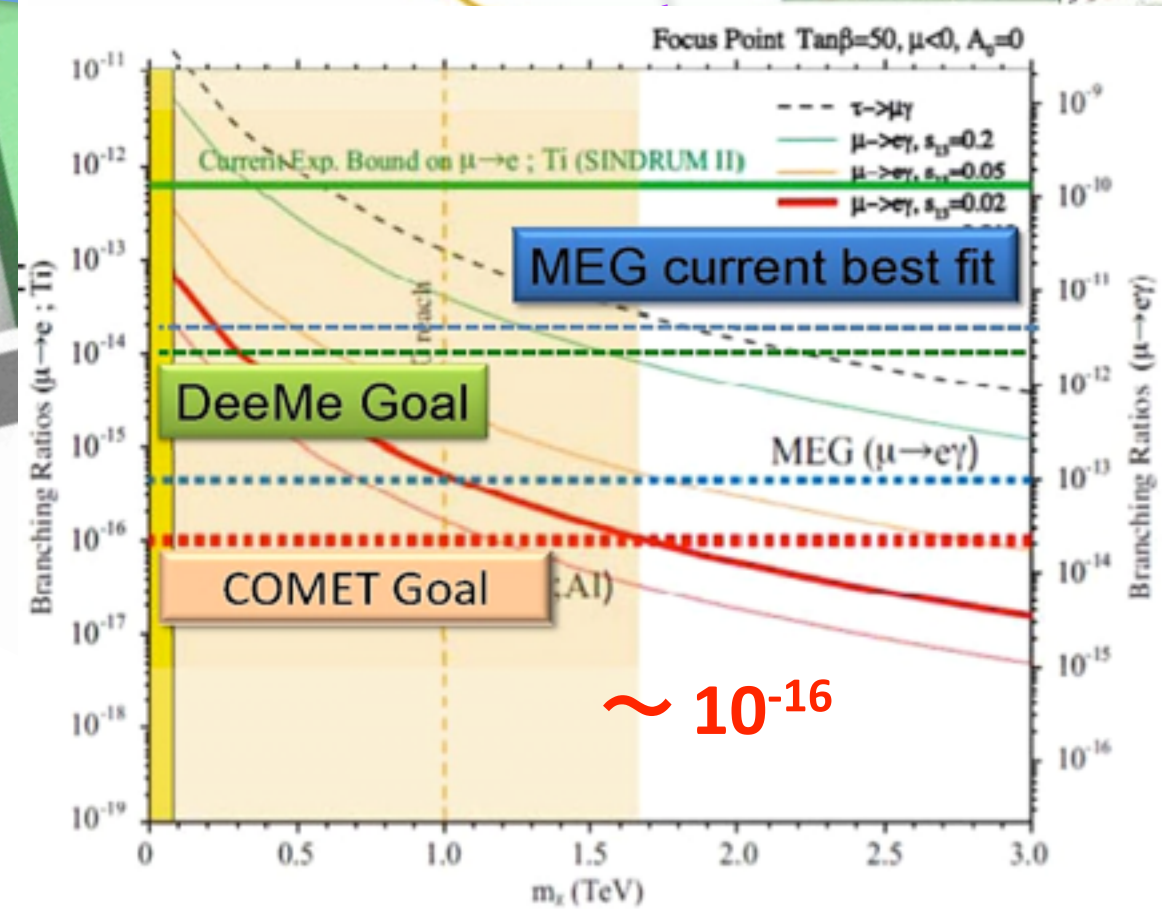




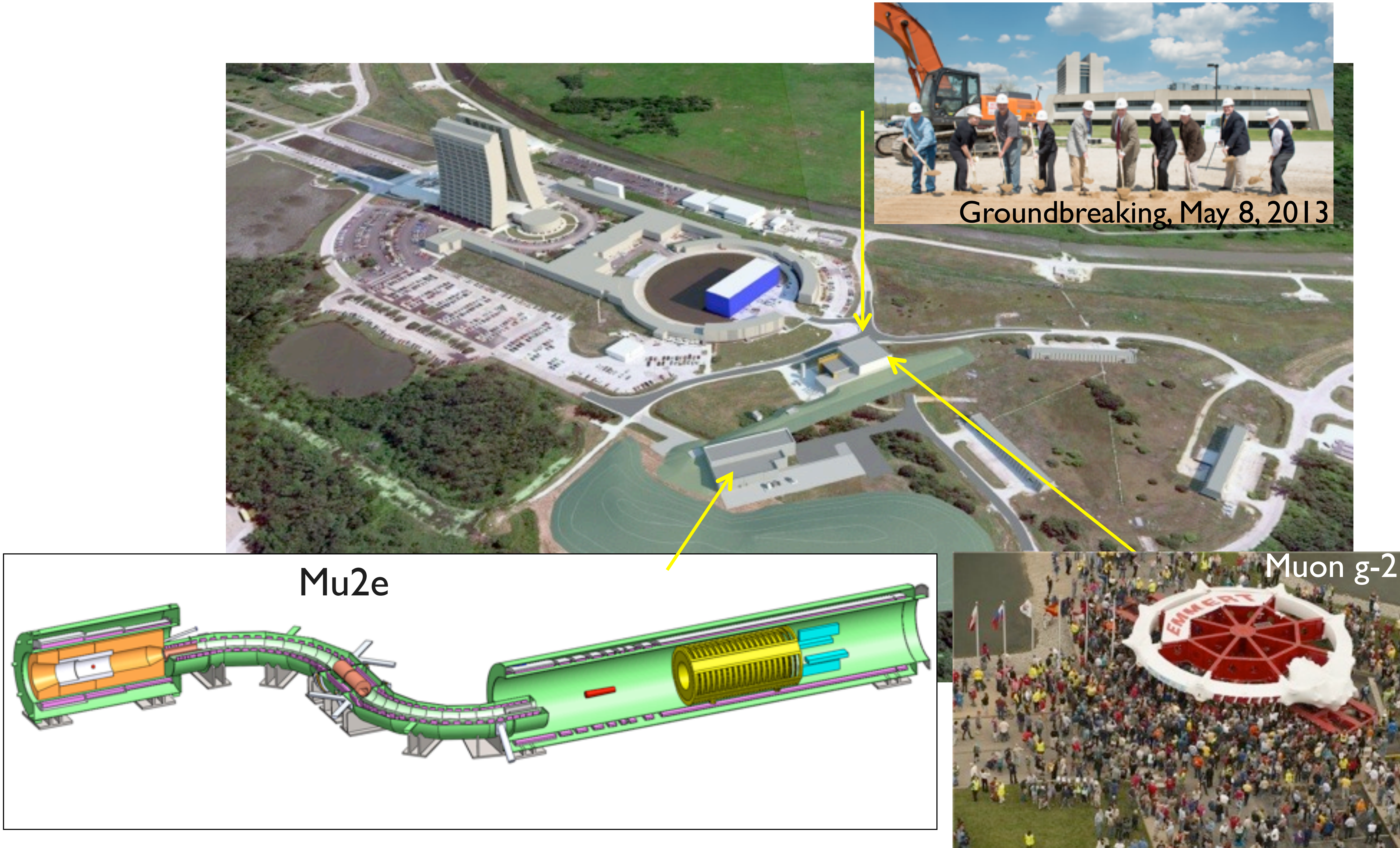




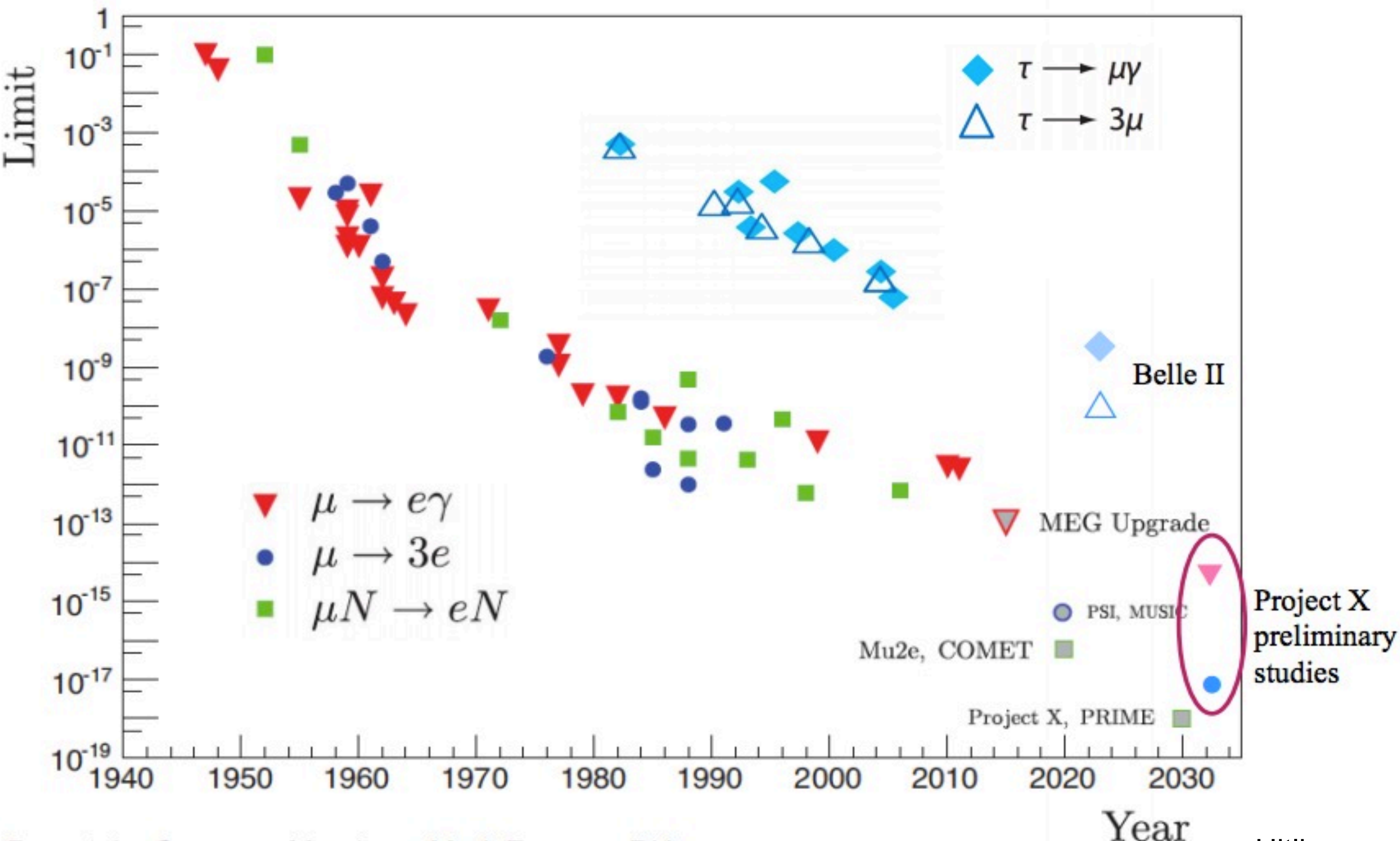




The Fermilab Muon Campus



Charged Lepton Flavor Violation Timeline

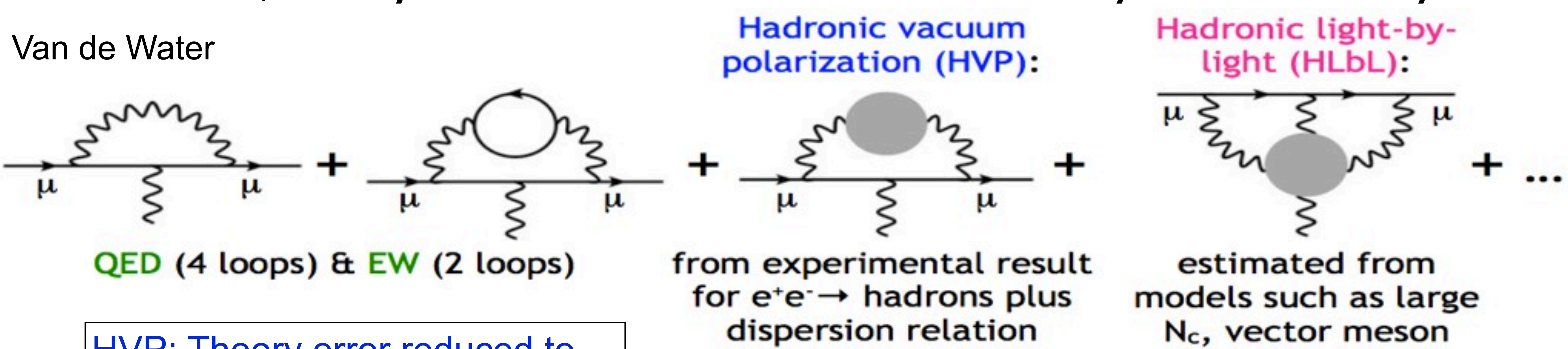


Bernstein, Cooper + Marciano, Mori, Roney + DH

Anomalous Magnetic Moment of the Muon

- Discrepancy between exp't and SM at 3.6σ : $\Delta a_\mu = 287(80) \times 10^{-11}$
- Ring has arrived at Fermilab
  - » Run begins 2016/17
- Lattice/analytic results can reduce theory uncertainty

Van de Water

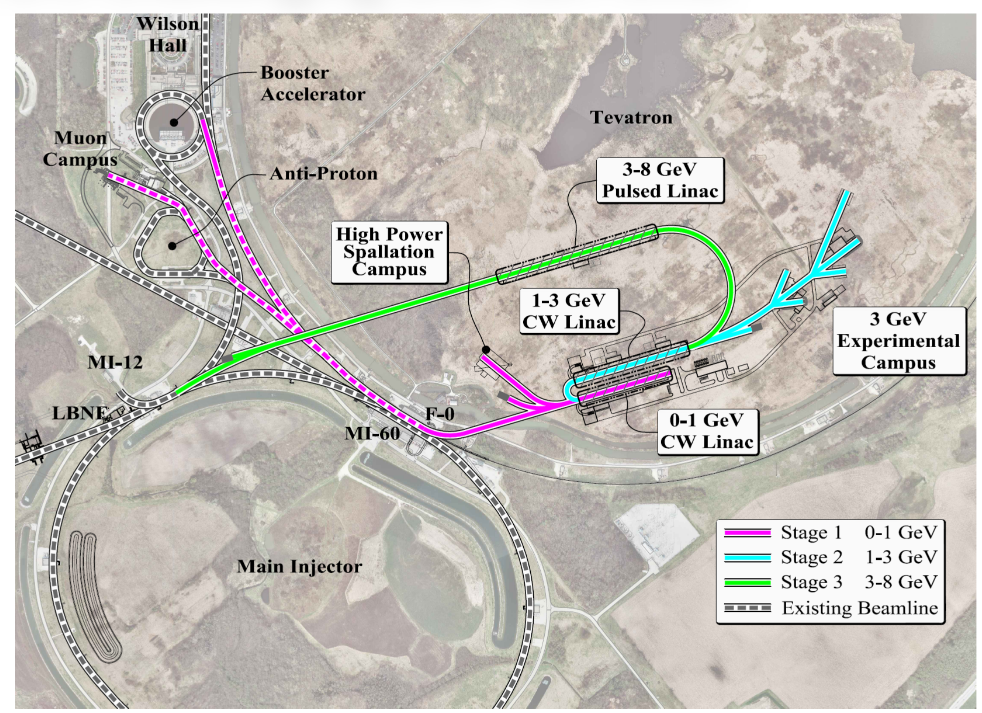


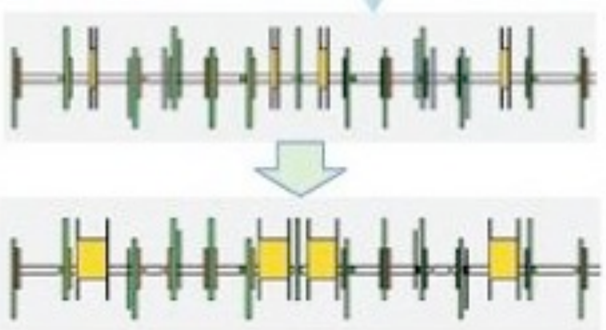
HVP: Theory error reduced to 2% due to theoretical improvements and more CPU on timescale of exp't

HLBL: 15% precision possible, but not guaranteed. Lattice community working hard!

Intensity Frontier - Proton Facilities

- The Intensity Frontier is diverse
    - A survey of anticipated particle physics requirements for secondary beams, i.e. neutrino, kaon, muon, neutron, etc. resulted in large number of different secondary beams.
- <u>Next generation of intensity frontier experiments will require proton beam intensities & timing structures beyond the capabilities of any existing accelerators.</u>
    - Project X is a proposal for a next generation facility based on a modern multi-MW SCRF proton linac that can provide a flexible "on-demand" beam structure.
- High power targets are needed. These targets are challenging and can limit facility performance.

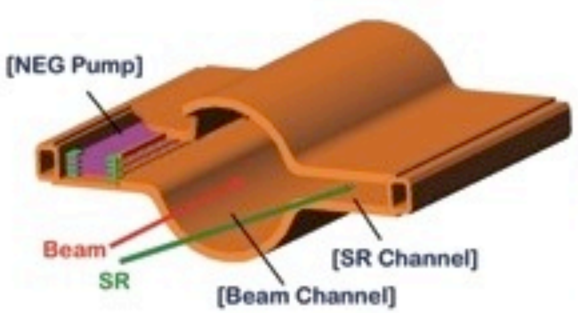


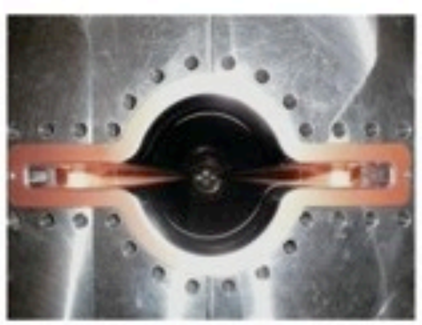


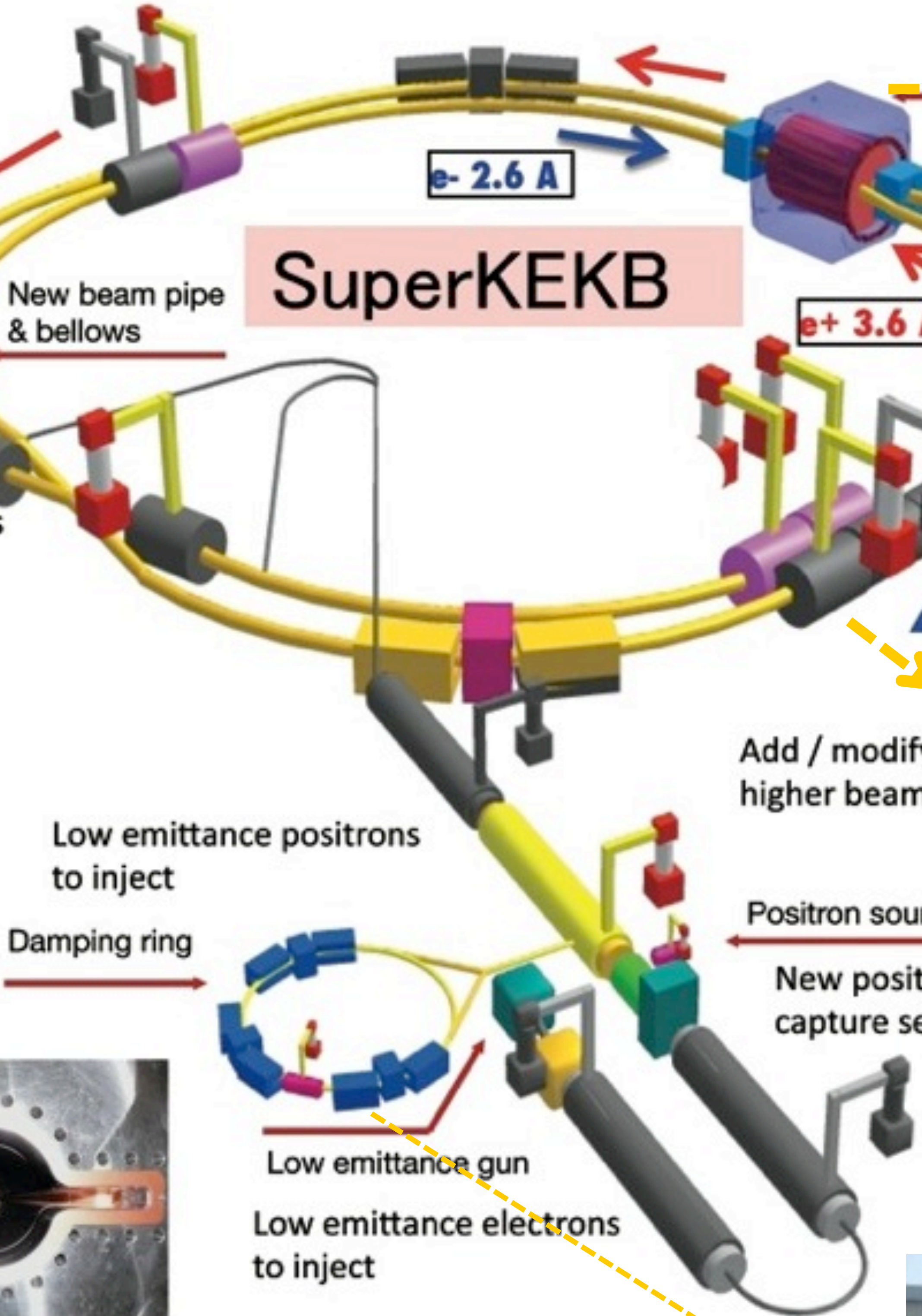
Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

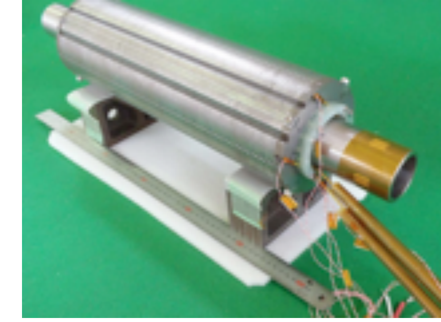
Installation of 100 new LER dipole magnets completed.

TiN coated beam pipe with antechambers









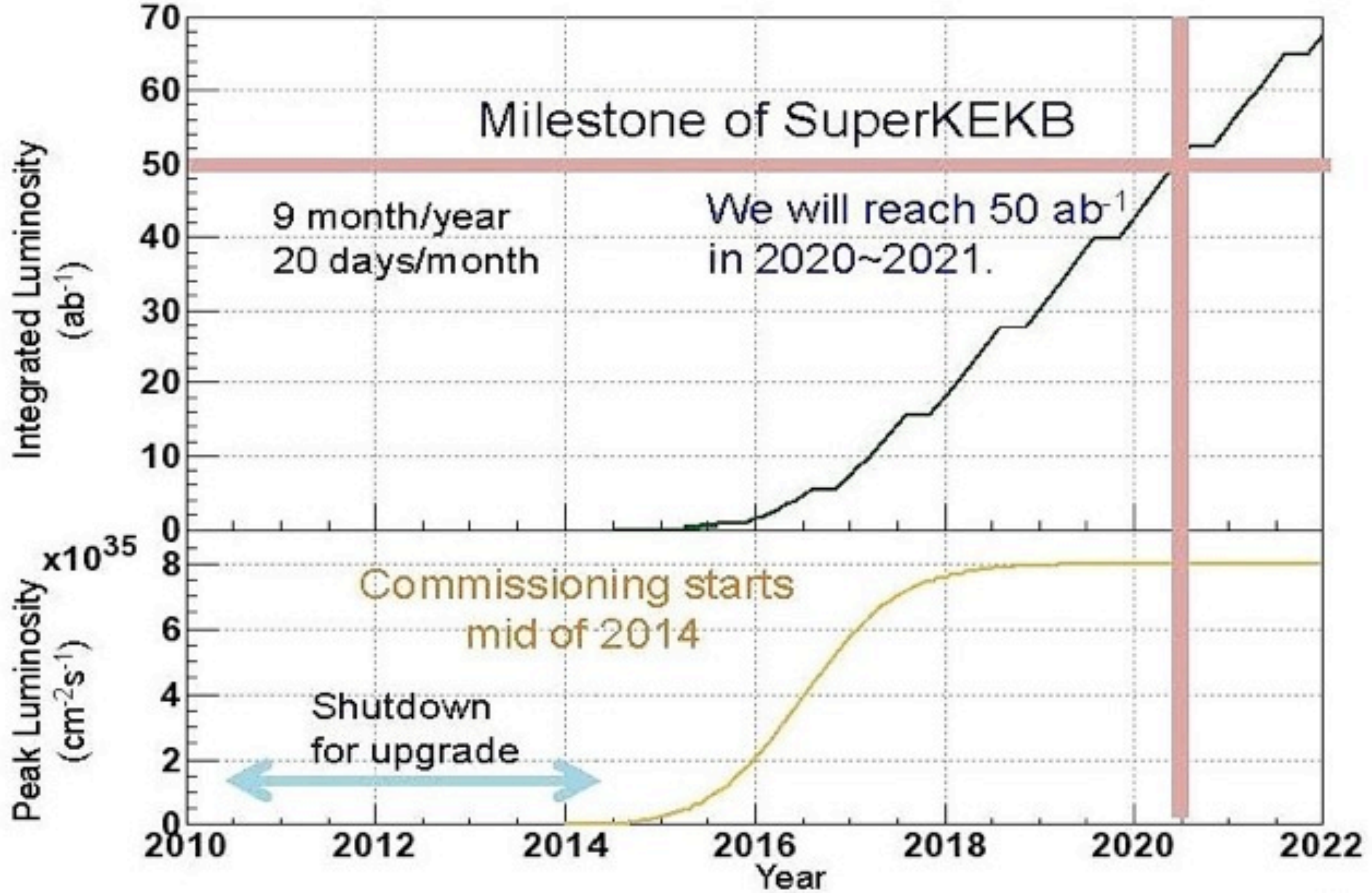
SC final focus: Successfully tested without any quench up to 2157A, well over the design value for nominal operation.

ARES cavities moved from HER to LER, and wiggler magnets for HER installed in D5 Oho straight section.

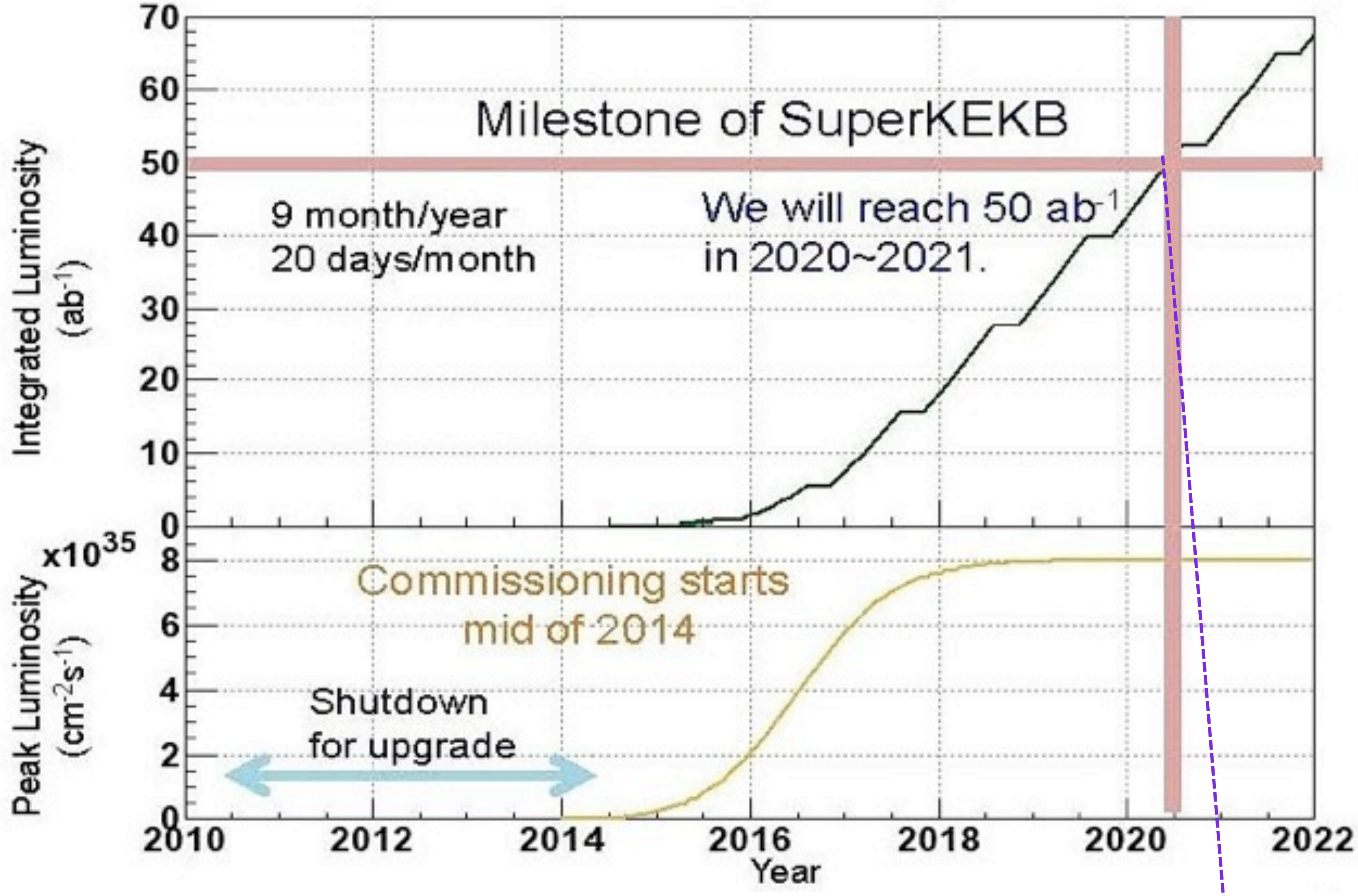
Beam pipe production at BINP

Beam pipes after baking and TiN coating in a stock area.

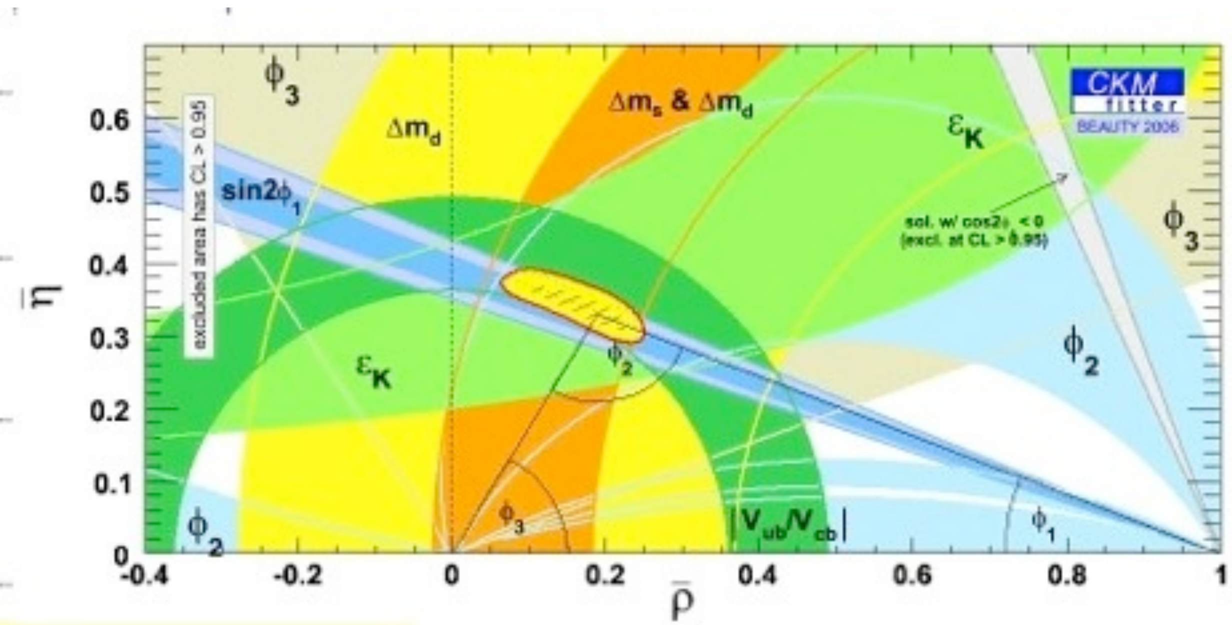
SuperKEKB luminosity projection

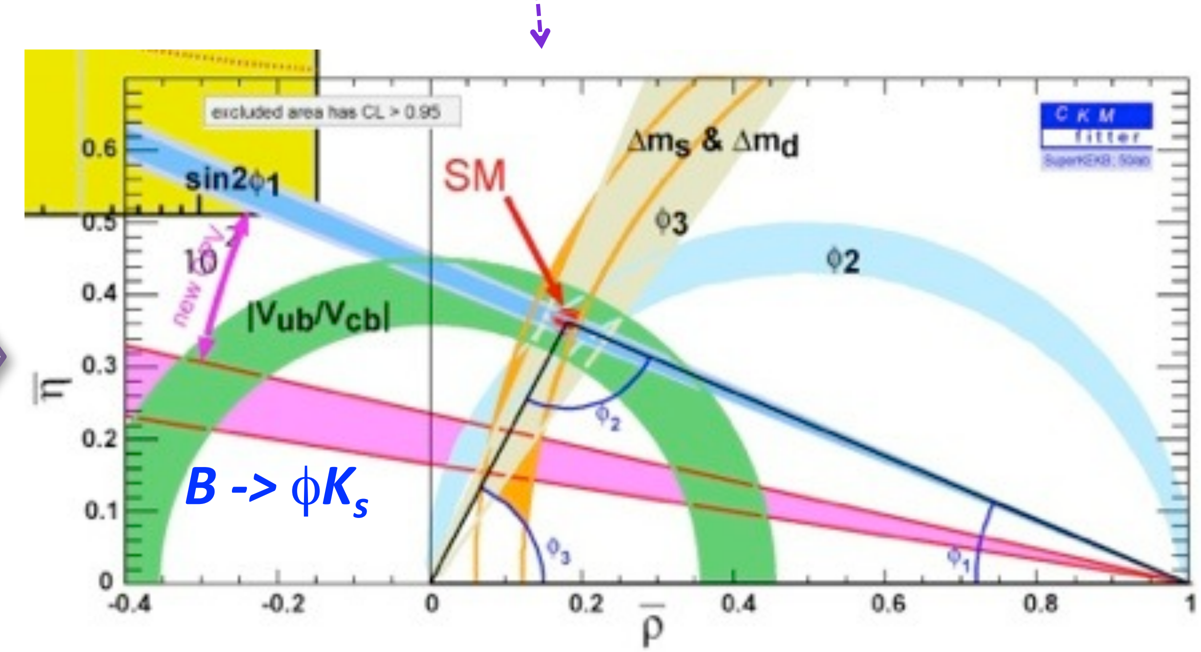


SuperKEKB luminosity projection

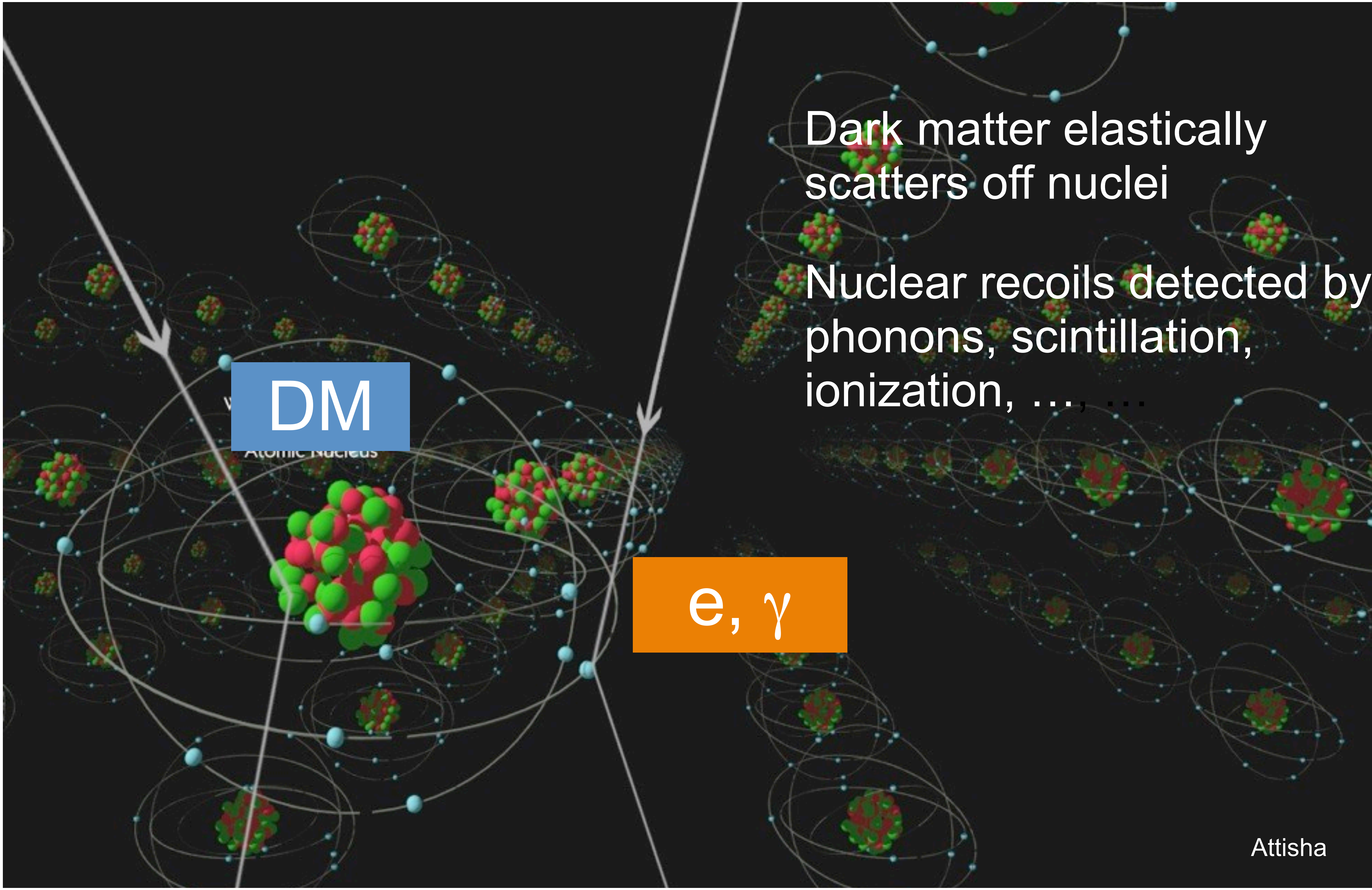


Inconsistency in unitarity triangle?





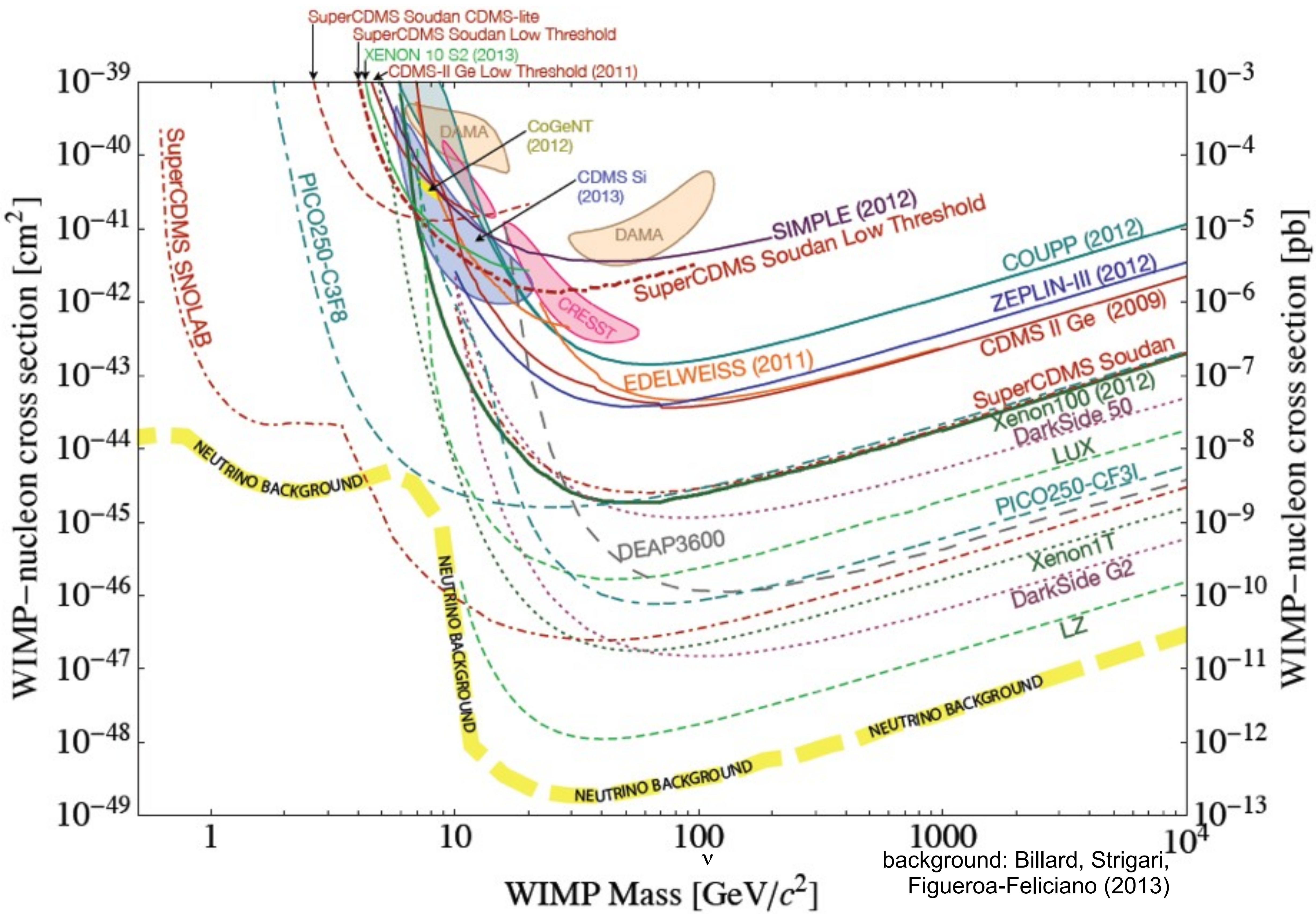
Dark Matter - DIRECT DETECTION



Dark matter elastically scatters off nuclei

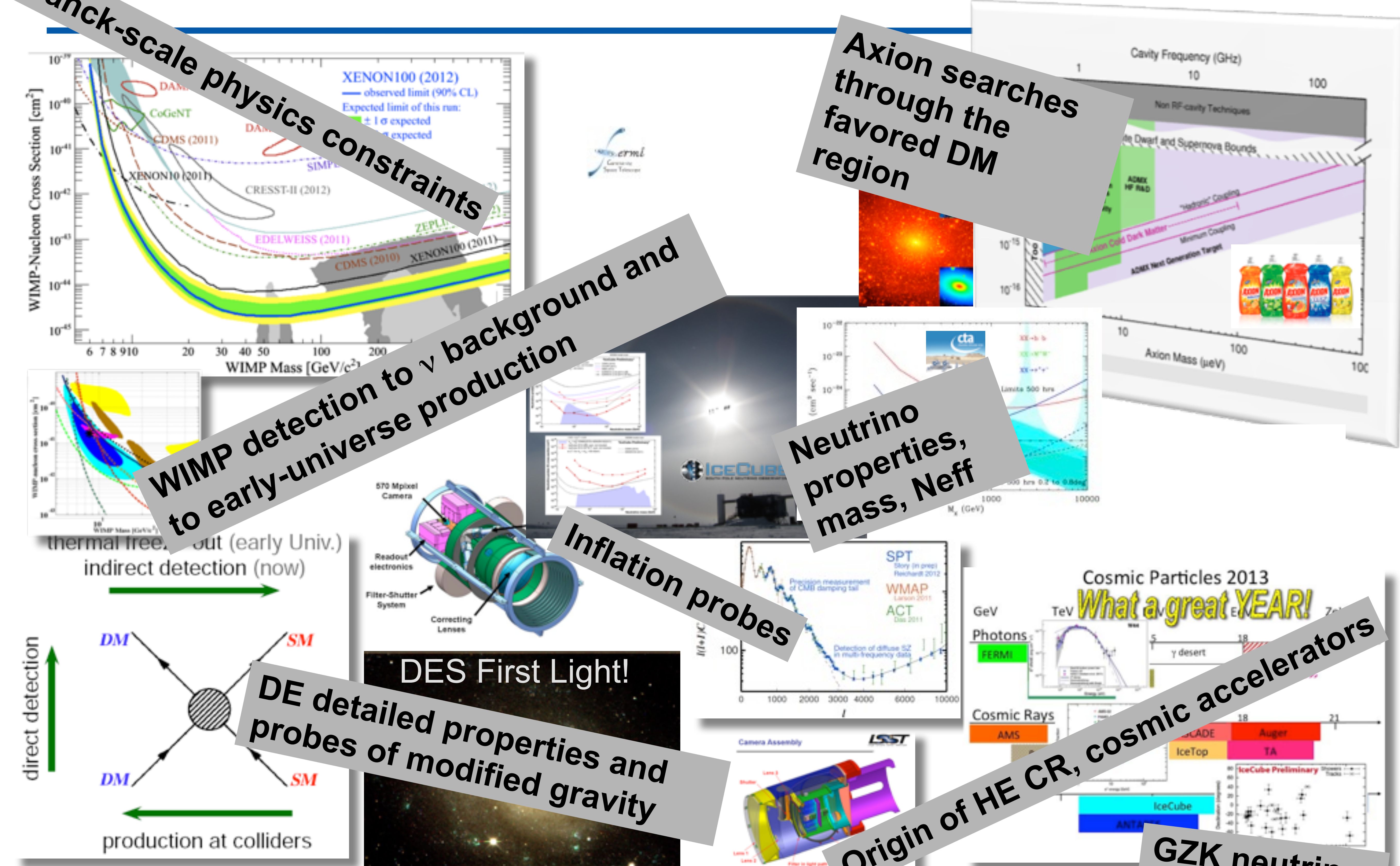
Nuclear recoils detected by phonons, scintillation, ionization, …, …

CURRENT STATUS AND FUTURE PROSPECTS



background: Billard, Strigari, Figueroa-Feliciano (2013)

THE COSMIC FRONTIER MENU



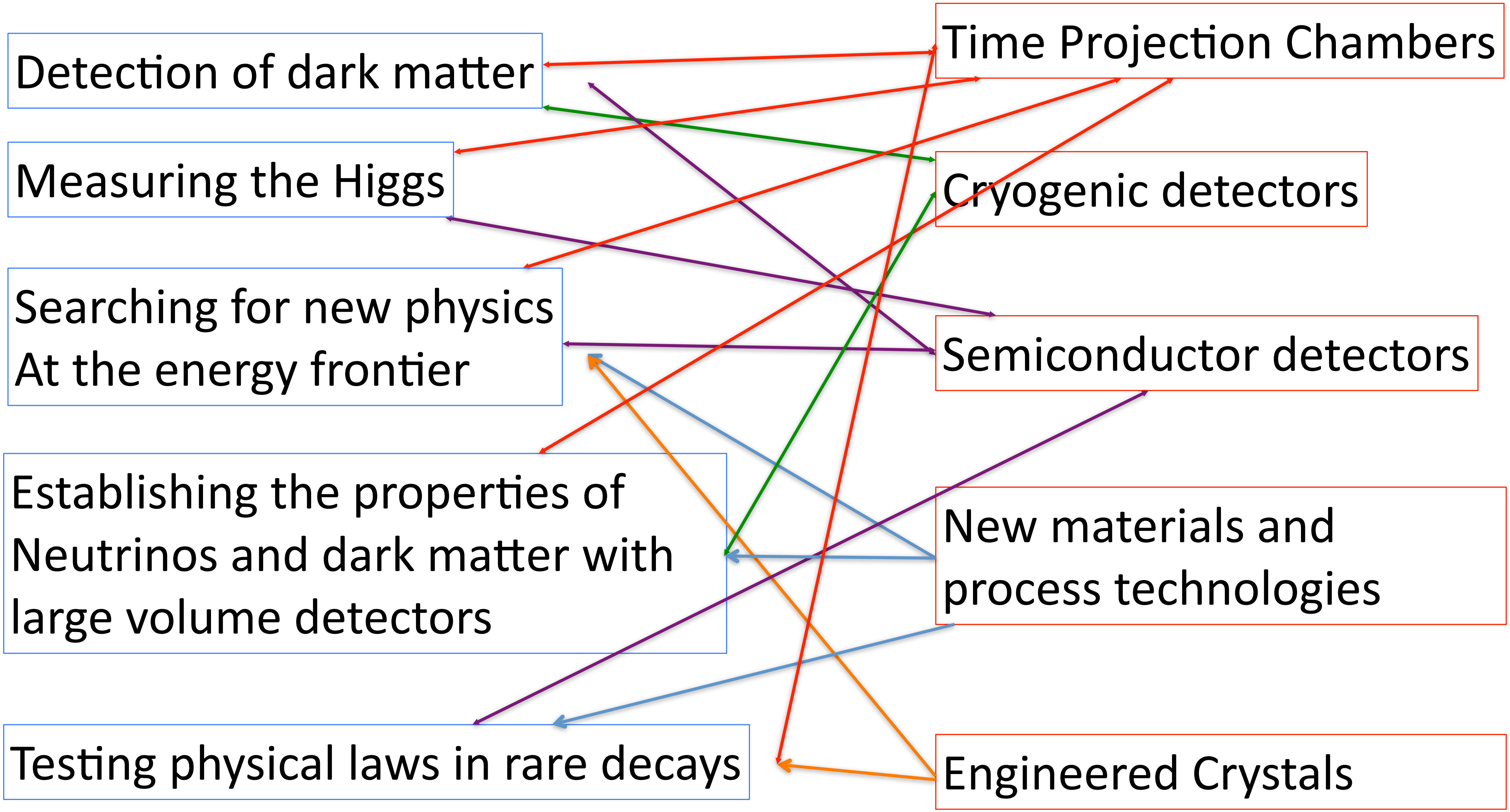
Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments

Cosmic Frontier

- Dark Matter - searches use complementary approaches: direct detection, indirect detection, accelerator-based searches, simulations and astrophysical surveys
- Cosmic imaging and spectroscopic surveys will test the behavior of dark energy and general relativity over a range of distance scales. DES survey just started last week.
- CMB experiments will probe the physics of inflation with sufficient sensitivity to falsify significant classes of models.
- Study of neutrinos could yield information on the mass hierarchy, number of light neutrinos, sum of the masses of neutrino species, and the study of high energy neutrino interactions.

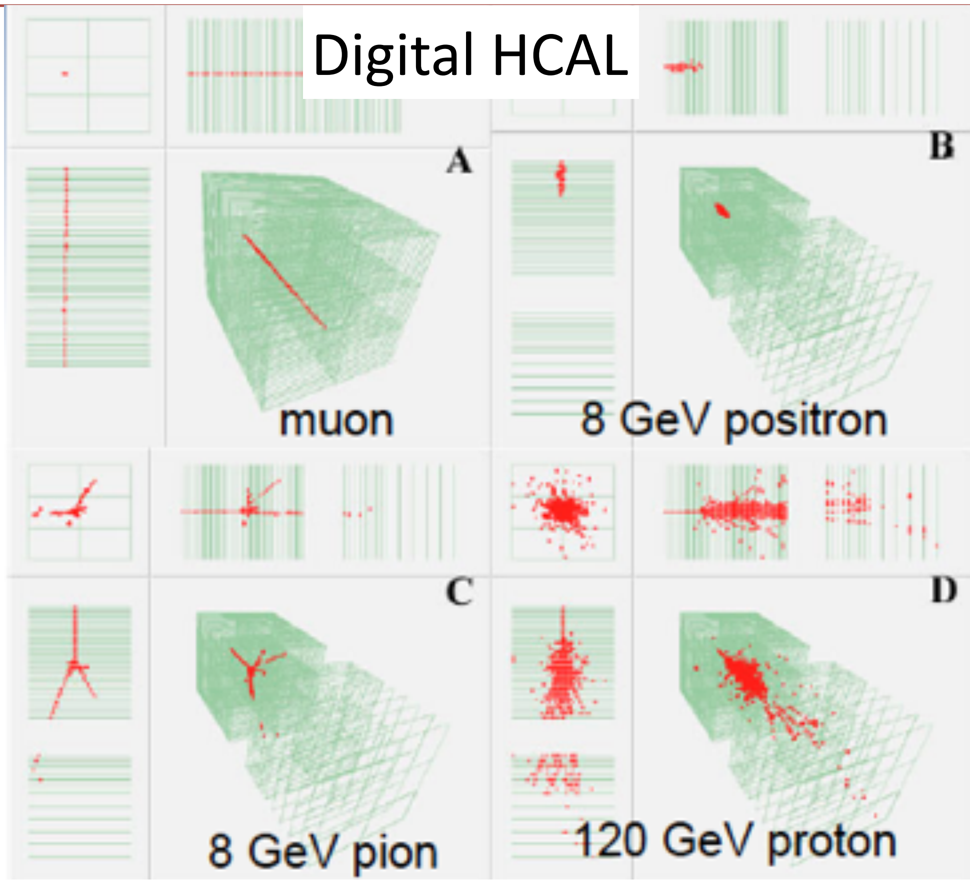
DES image

Instrumentation
Technologies across boundaries

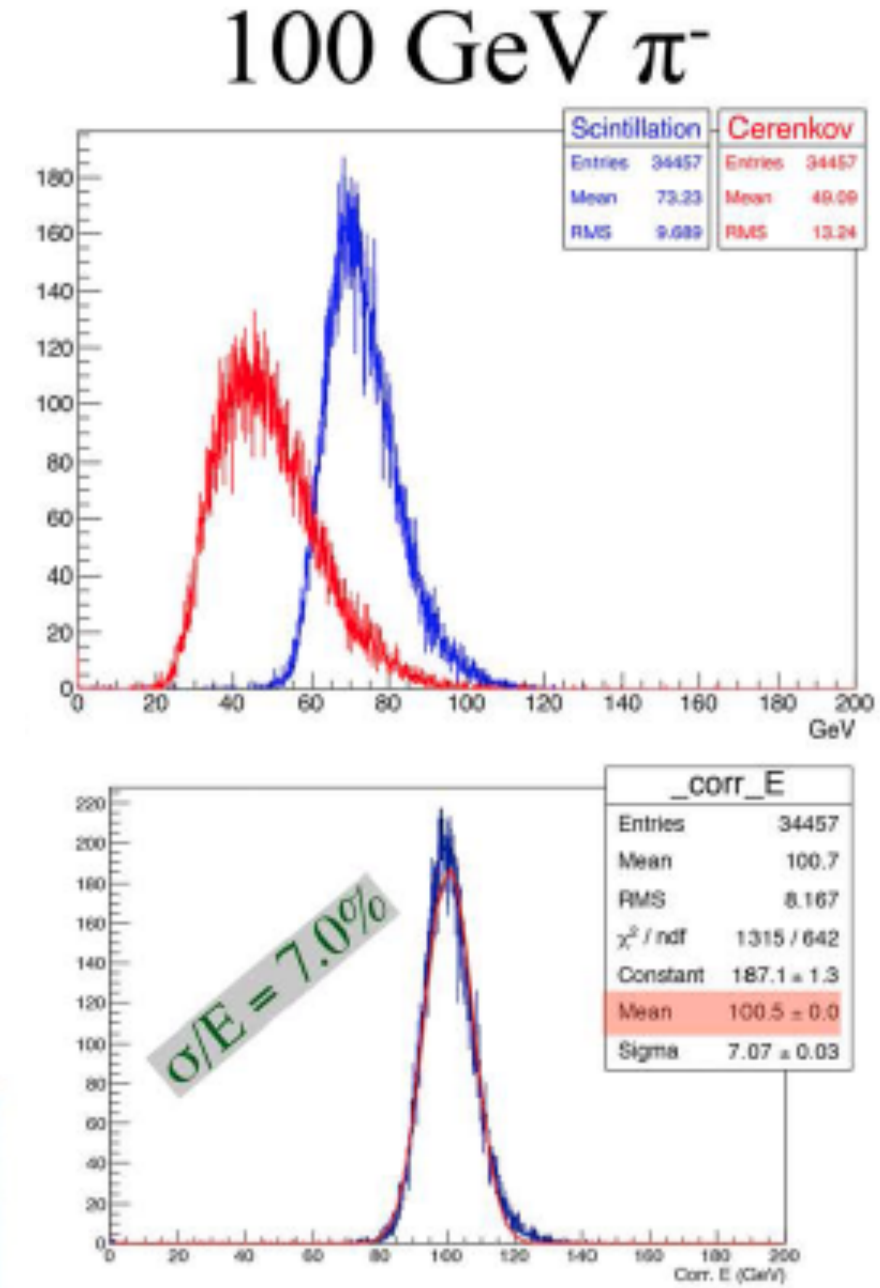


R. Lipton

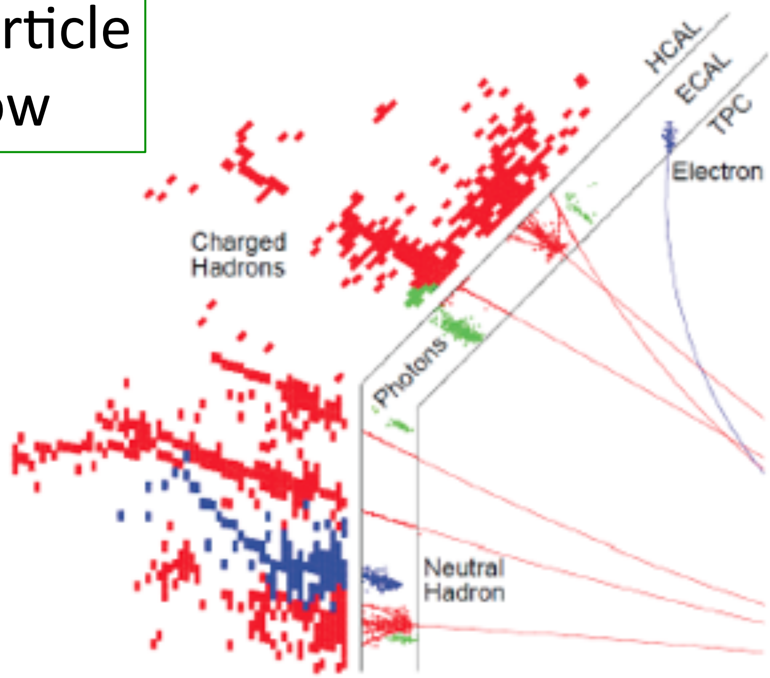
Linear Collider Initiated Technologies



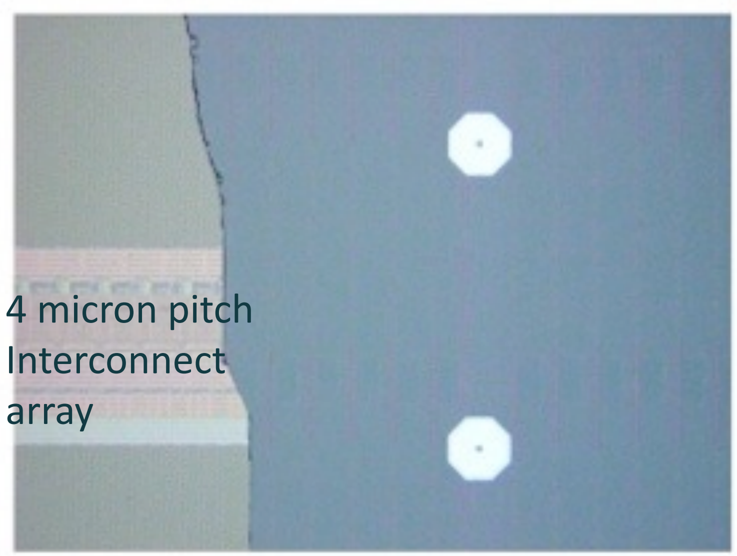
Dual Readout Calorimeter



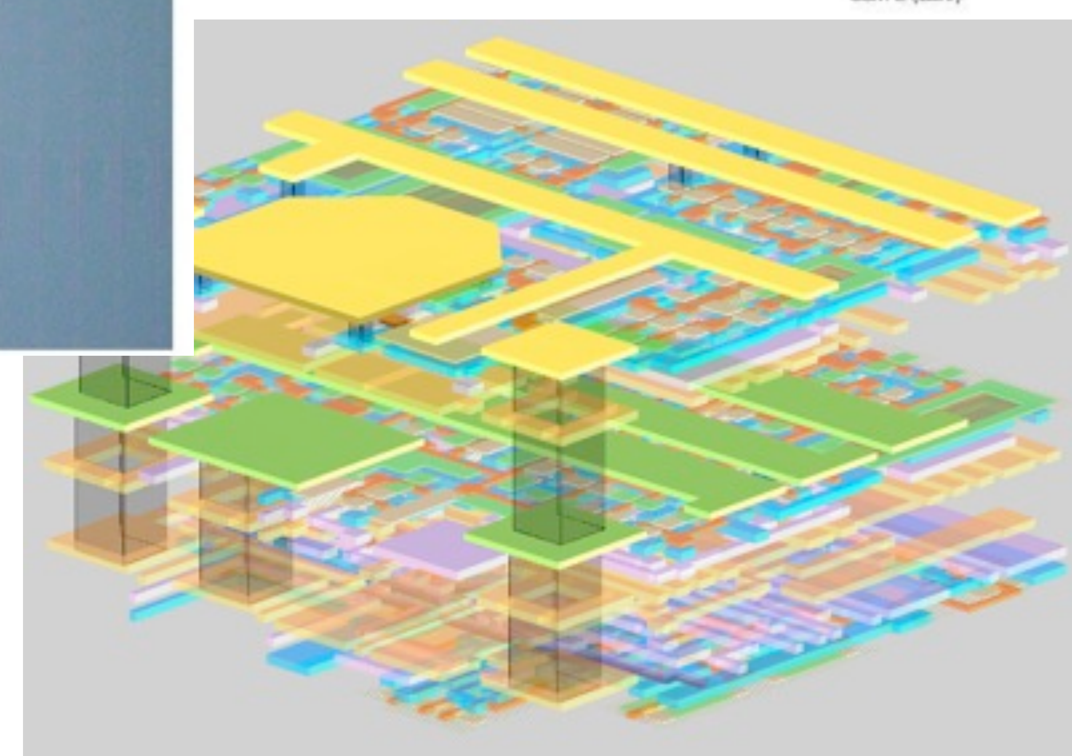
Particle flow



Typical topology of a simulated 250GeV jet in CLIC ILD



3D Vertex Detector electronics

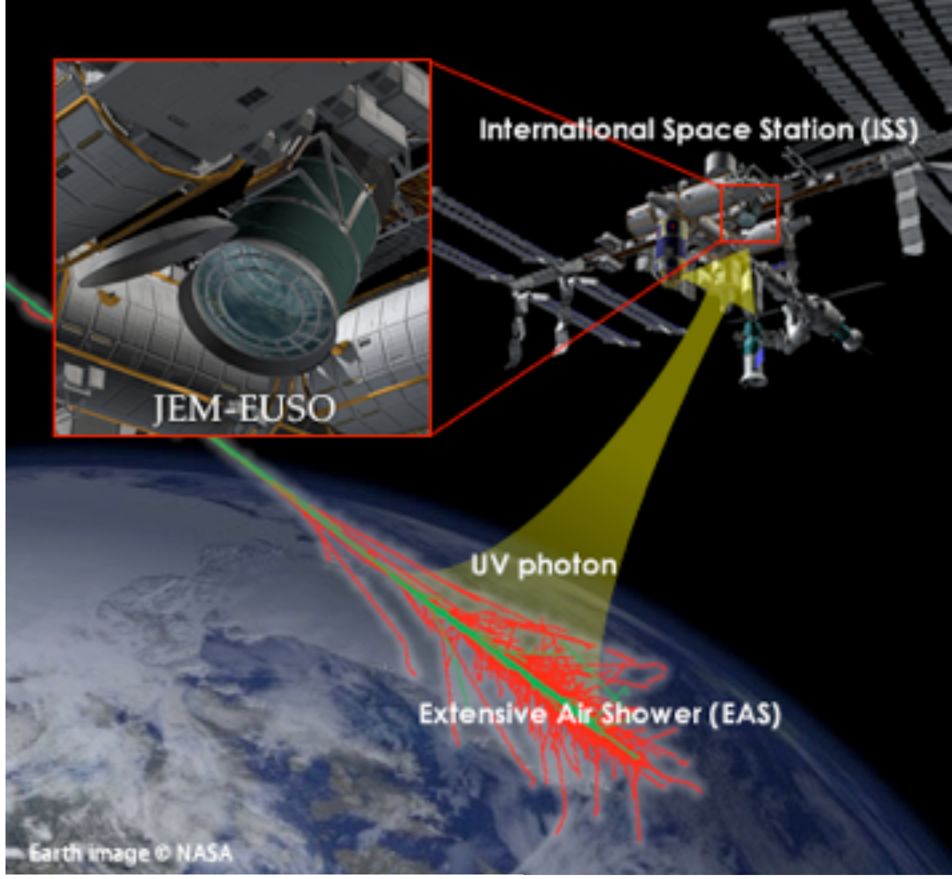


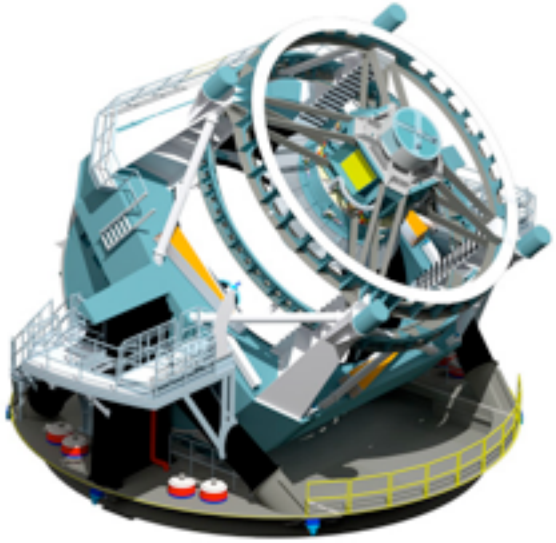
R

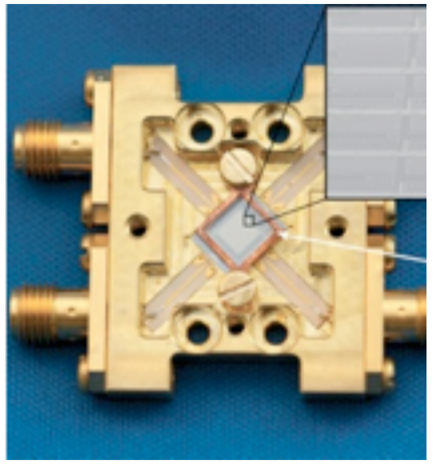
Cosmic Frontier Challenges

Broad, program with significant opportunities for progress

- UHE cosmic rays and neutrinos
  – Low rates at high energy require large exposures/ aperture to make progress
- Gamma rays
  – R&D: Cherenkov and water tank arrays, Low-cost photosensors/low-power digitizers
  – Distributed timing across large arrays
- Dark Energy – next generation
  – Order of magnitude improvement in sensitivity, ~km^2 effective area, and extended energy
- Dark Matter
  – Almost every experiment is a new detector idea. There is a large program looking for larger mass, lower thresholds and directionality
- CMB
  – Large area spectrally sensitive arrays low power readout and high bandwidth DAQ



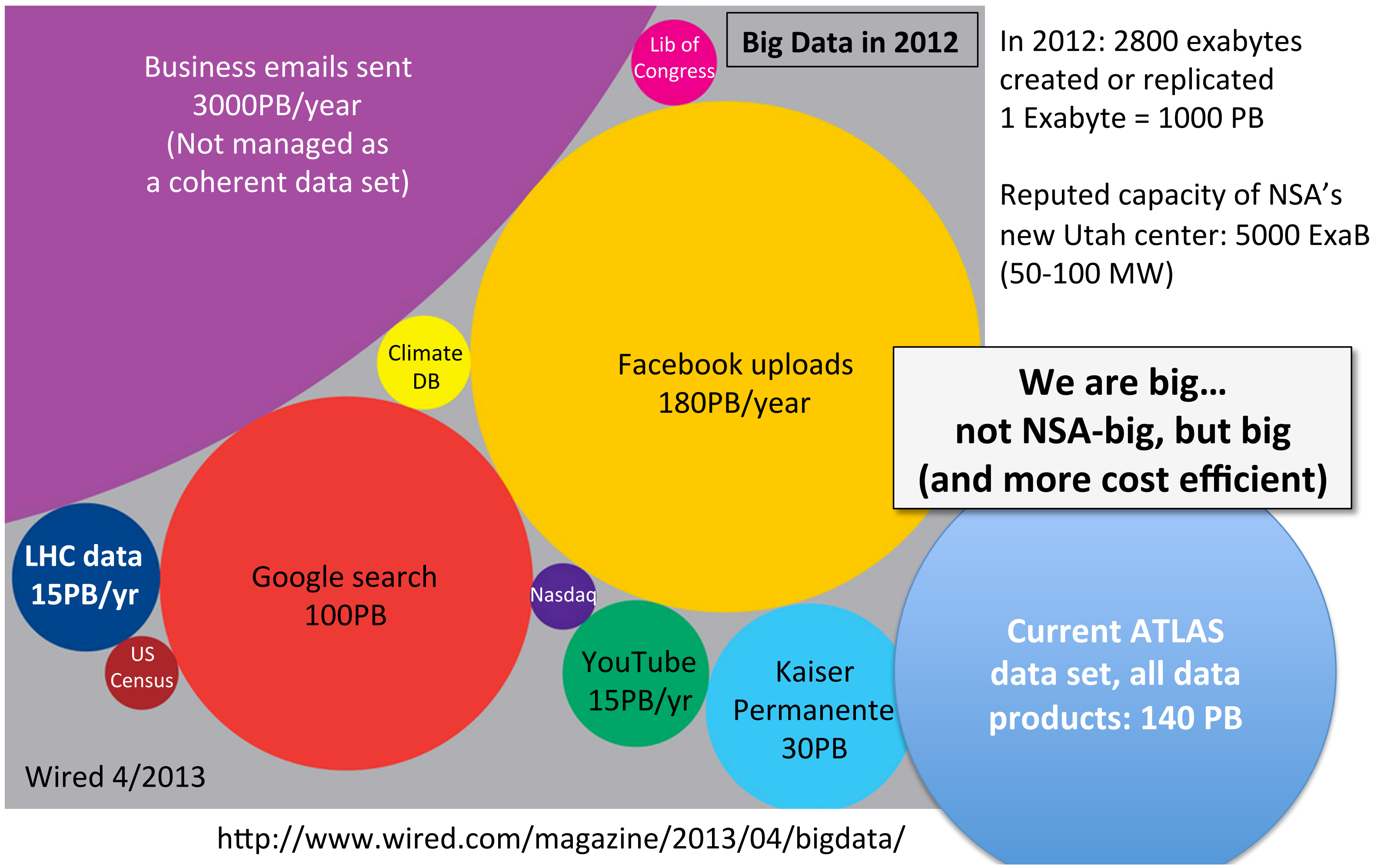




HEP Computing

Data Management

Where is HEP in Big Data Terms?



http://www.wired.com/magazine/2013/04/bigdata/

Snowmass+T.Wenaus/DPF 2013

HEP science demands **substantial growth** in data and computing in coming years

- **Data management and access** must see large gains in efficiency, and prospects of achieving that are good, with continued R&D and development

- **Networks** are a powerful foundation and enabler, a resource requiring investment and paying big dividends

- We are entering an unavoidable, challenging **re-architecting of our serial software**

What about in 2030?

- Precision Higgs couplings measured at the LHC and ILC
- Mass hierarchy and CP violation measurements in neutrino sector
- Direct detection of dark matter??
- An unexpected particle ??   SUSY??
- Charged Lepton Flavor Violation ??
- ...
- Cars without drivers

Summary

- There is a rich future for HEP with many opportunities to explore our physics questions over the next 20 years and beyond.
- The HEP community is anxiously awaiting the results from the LHC at 13/14 TeV.
  - An ECFA High Luminosity LHC Workshop will be held next month to look at the physics of the HL-LHC
- Expecting exciting results in all frontiers.

- There is a need for global planning. Ideas welcome!
  - P5 prioritization panel in the US starting work this month.
  - Update of the European Strategy for Particle Physics adopted in May.
- Future colliders and long-baseline neutrino program require global partnership.
  - The LHC is already a global project.

My apologies because many, many programs could not be included here.

Homework

- Probe the highest possible energies and smallest distance scales with the existing and upgraded Large Hadron Collider
- Study the properties of the Higgs boson in full detail
- Reach for even higher precision with a lepton collider
- Develop technologies for the long-term future to build multi-TeV lepton colliders and 100 TeV hadron colliders
- Perform precision tests of the neutrino sector
- Execute a underground detector program for precision neutrino studies with global participation

Homework Questions

- Search for new physics in quark and lepton decays in conjunction with precision measurements of electric dipole and anomalous magnetic moments
- Identify the particles that make up dark matter through complementary experiments deep underground, on the Earth's surface, and in space, and determine the properties of the dark sector
- Map the evolution of the universe to reveal the origin of cosmic inflation, unravel the mystery of dark energy, and determine the ultimate fate of the cosmos

Backup

Credits and resources

- The Update to the European Strategy for Particle Physics: European Strategy Briefing Book (Jan. 2013) and the European Strategy Group Open Session (Krakow, Sept 2012).
- The American Physical Society Division of Particles and Fields "Snowmass" Community Summer Study 2013. (snowmass2013.org)
- DPF2013 in UCSC (August 2013)
- Asia-Europe Physics Summit (ASEPS) (July 2013)

- Special thanks to the European Strategy Preparatory Group, the Snowmass conveners, The DPF EC, CERN, N.Lockyer, A. Suzuki, and YFWang.

High Energy Physics - a Big Science

"We simply do not know how to obtain information on the most minute structure of matter (high-energy physics), or on the grandest scale of the universe (astronomy and cosmology), or statistically elusive (systematic genetics) results without large effort and large tools."

W.K.H. Panofsky from *Big Science: The Growth of Large-scale Research*; edited by Peter Galison 1992

HEP has Big Questions....

Big Questions (short version)

- The Higgs particle is unlike any other particle we have ever encountered. Why is it different? Are there more?
- Neutrinos are very light, elusive particles that change their identity as they travel. How do they fit into our understanding of nature?
- Known particles constitute 1/6 of all the matter in the universe. The rest we call dark matter. But what is it? Can we detect these particles in our labs? Are there other undiscovered particles in nature?
- There are four known forces in nature. Are these manifestations of a single unified force? Are there unexpected new forces?
- Are there new hidden dimensions of space and time?
- Both matter and anti-matter were produced in the Big Bang, but today our world is composed only of matter. Why?
- Why is the expansion of the universe accelerating?

Alphabet Soup

- There are a variety of organizations involved in strategic planning for particle physics.
  - The large HEP and national laboratories: CERN, Fermilab, KEK...
  - HEP community organizations: ECFA, EPS HEPP, DPF, JPS, AsiaHEP, ...
  - Panels and advisory committee: P5, HEPAP, European Strategy
  - Global committees: ICFA, FALC
  - National funding agencies
  - Large projects and facilities

- As projects become larger and too expensive for a single region to fund alone, the need for global coordination and planning grows.

Future Collider

Collider scenarios examined at Snowmass; (lots of simulation required)

5 pp colliders, $(E_{cms}; \int \mathcal{L}dt)$ =

pp(14; 300, 3000), (33; 3000), (100, 3000) TeV, fb^{-1}

9 lepton colliders, $(E_{cms}; \int \mathcal{L}dt)$ =

Linear ee*: (250; 500), (500;500), (1000;1000)

(1400;1400) GeV, fb^{-1}

Cir ee: (250; 2500), (350,350) GeV, fb^{-1}

$\mu\mu$: (125; 2), (1500; 1000), (3000, 3000) GeV, fb^{-1}

$\gamma\gamma$: (125; 100), (200; 200), (800, 800) GeV, fb^{-1}

1 ep collider, $(E_{cms}; \int \mathcal{L}dt)$= e/p (60/7000; 50)GeV/GeV, fb^{-1}

More complete summaries can be found in the White Papers and in the Energy Frontier write-ups.

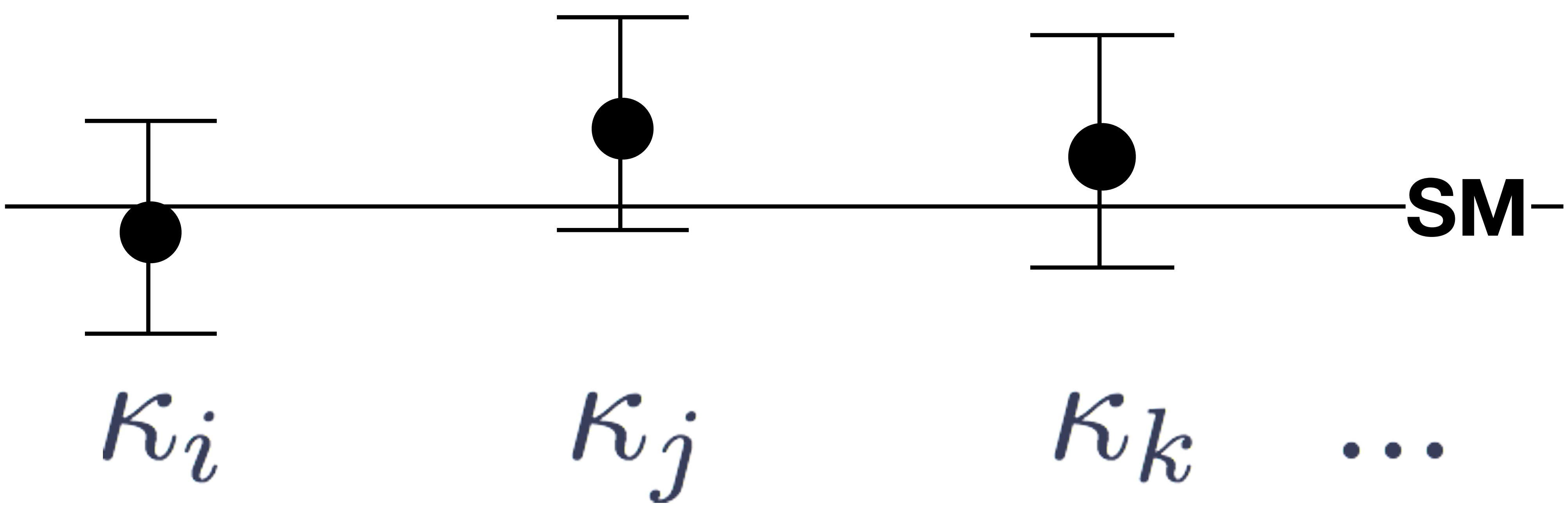
* incl polarization choices

how precise?

Higgs working group evaluated models

- when new particles are ~1TeV:

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



Brock/Peskin Snowmass 2013

The QCD Physics Message

1. **Improvements in PDF uncertainties are required.**
   - There are strategies at LHC for these improvements.
   - QED and electroweak corrections must be included in PDFs and in perturbative calculations.
2. **alphas error ~ 0.1% is achievable**
   - lattice gauge theory + precision experiments
3. **Advances in all collider experiments, especially on the Higgs boson, require continued advances in perturbative QCD.**

Origin of matter | Unification | Elementary?

P1 precision program enabling the energy frontier

The Top Quark physics message

1. Top is intimately tied to the problems of symmetry breaking and flavor

2. Precise and theoretically well-understood measurements of top quark masses are possible both at LHC and at e+e− colliders.

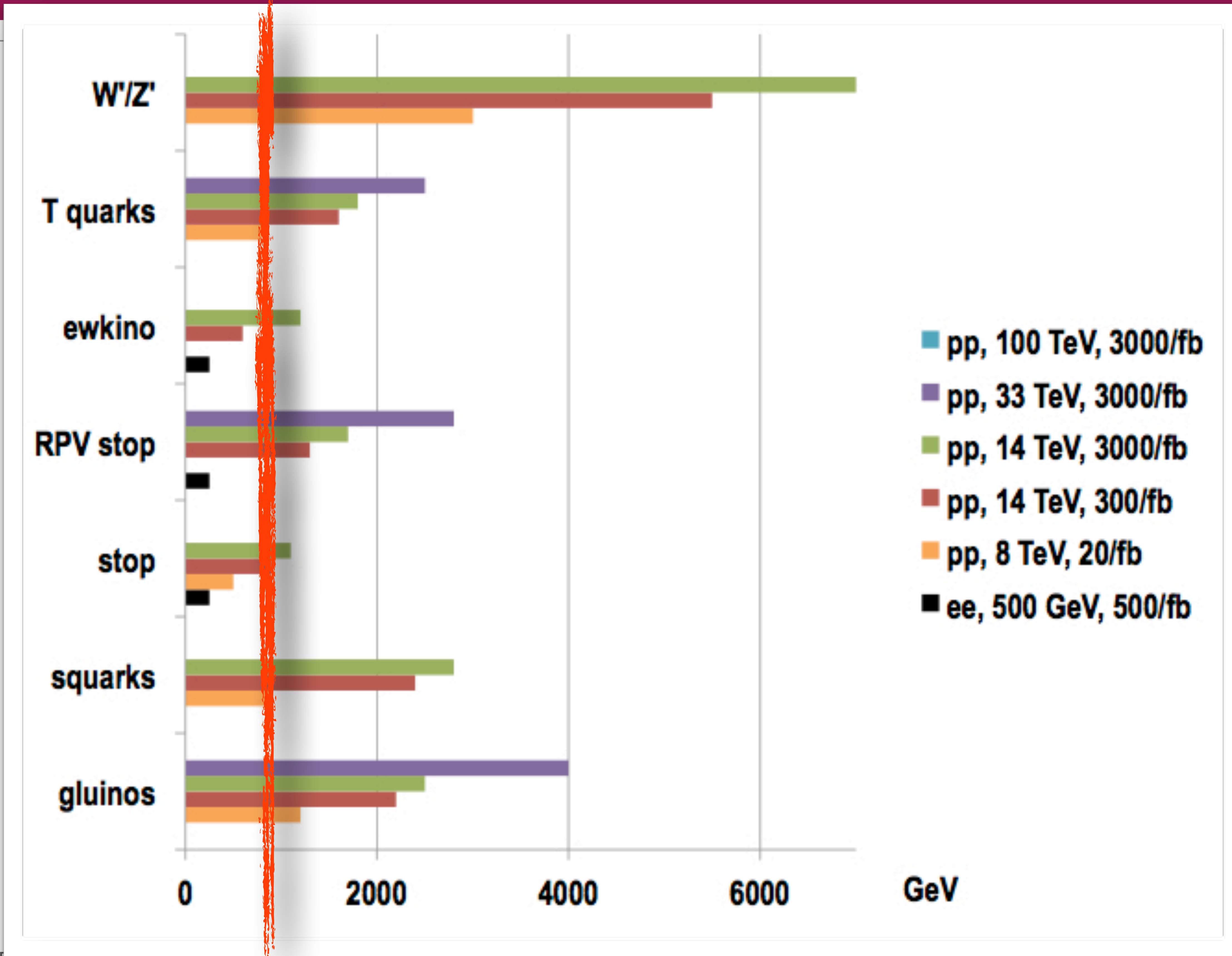
3. New top couplings and new particles decaying to top play a key role in models of Higgs symmetry breaking.

LHC will search for the particles;

Linear Colliders for coupling deviations.

Origin of EWSB | Origin of flavor | Naturalness | New forces | Elementary?

the TeV scale is in sight



Brock/Peskin Snowmass 2013

ILC 1 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 13% accuracy**
3. Model-independent search for extended Higgs states to 500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**
6. Search for Z' using e+e- -> f fbar to ~ 5 TeV, a reach comparable to LHC for similar models. Multiple observables for Z' diagnostics.
7. **Any discovery of new particles dictates a lepton collider program**:
   search for EW partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, BRs and couplings with polarization observables, search for flavor and CP-violating interactions

Higgs EW Top QCD NP/flavor

photon collider

1. An ee collider can be converted to a photon-photon collider at ~ 80% of the CM energy. This allows production of Higgs or extended Higgs bosons as s-channel resonances, offering percent-level accuracy in gamma gamma coupling.
2. **Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.**

Higgs EW Top QCD NP/flavor

On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if

1. Projects in Japan
● Intensity Frontier
J-PARC/T2K

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

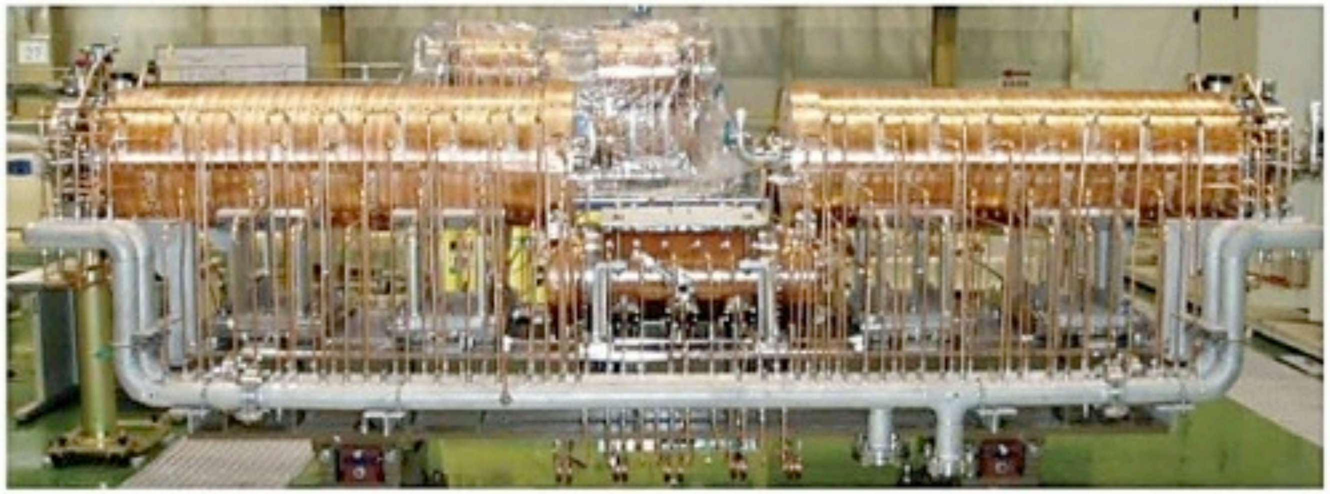
Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

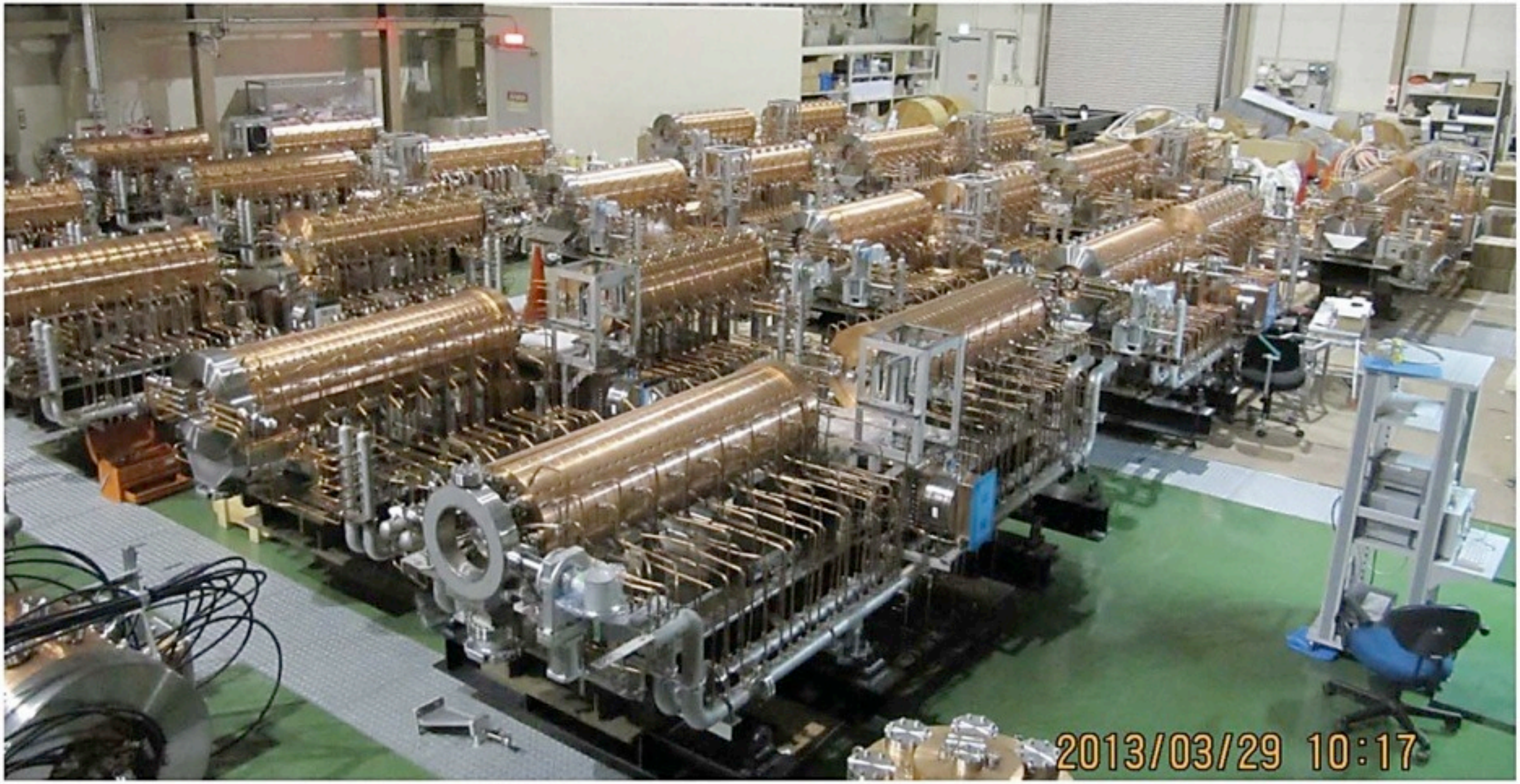
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

ACS modules for the energy upgrade of J-PARC Linac



Annular Couple Accelerator



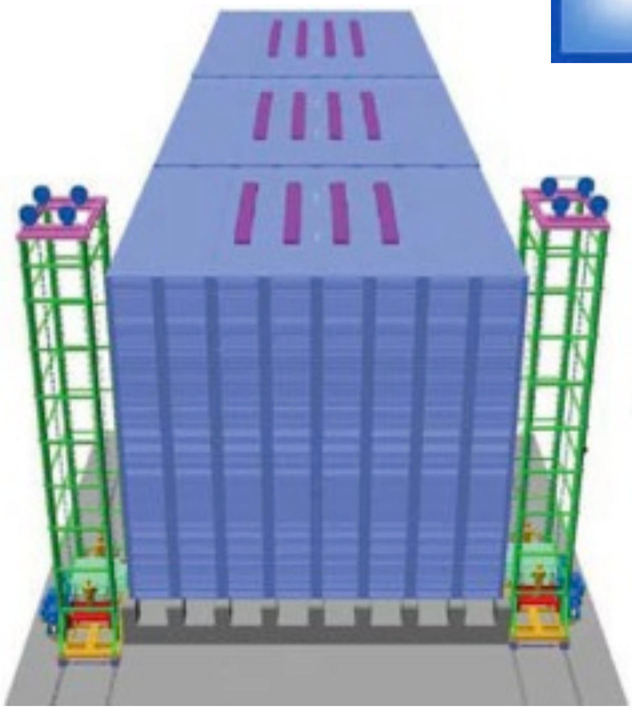
Neutrino Oscillation Experiments

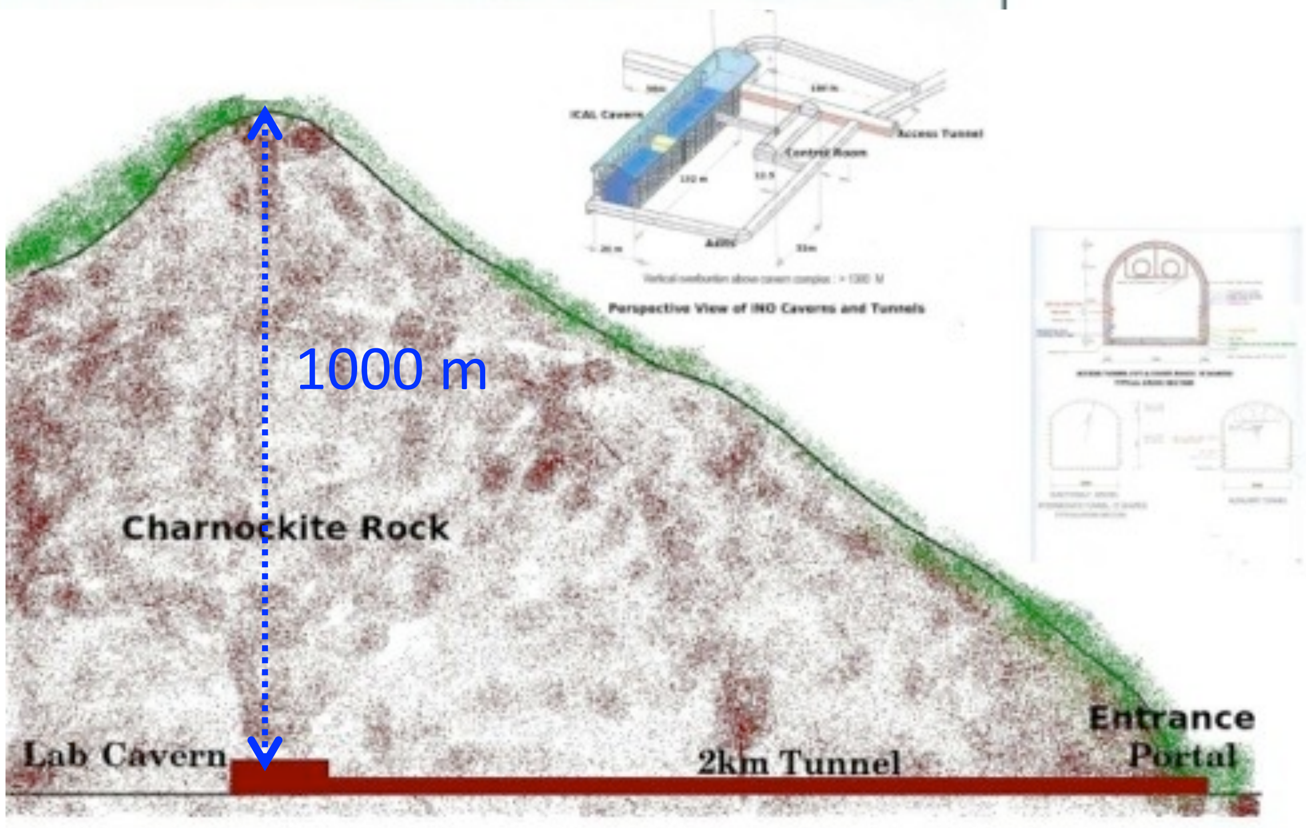
Category	Experiment	Status	Osc params
accelerator	T2K	data-taking	MH/CP/octant
accelerator	NOνA	commissioning	MH/CP/octant
accelerator	RADAR	R&D	MH/CP/octant
accelerator	CHIPS	R&D	MH/CP/octant
accelerator	T2HK	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
supernova	existing	N/A	MH

4. Projects in India

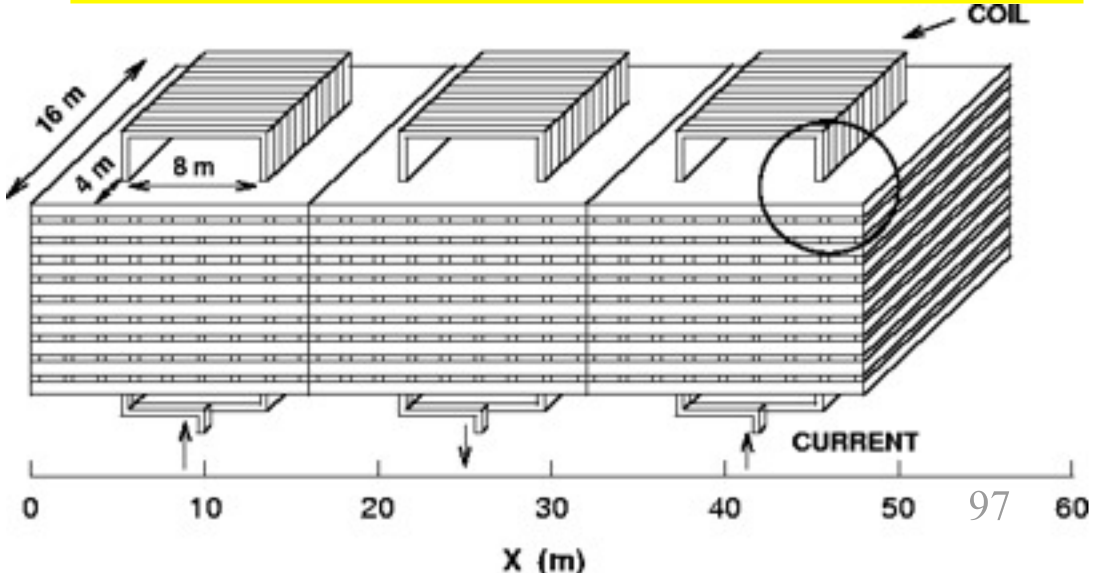
- **Underground Physics**

INO : India-based Neutrino Observatory





50 kton magnetized iron module(s) with 30,000 channel RPC



2. Projects in China

- **Accelerator-based**

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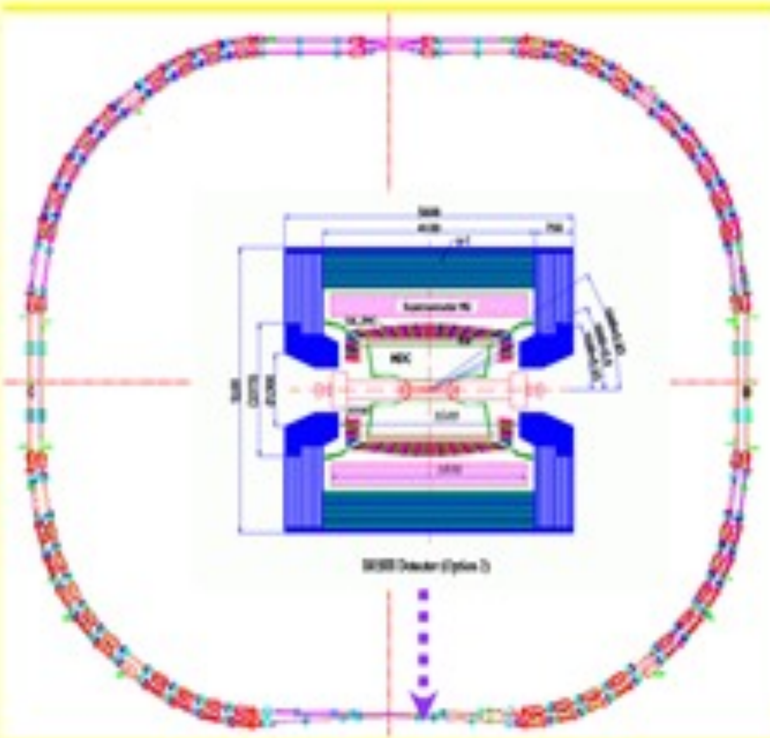
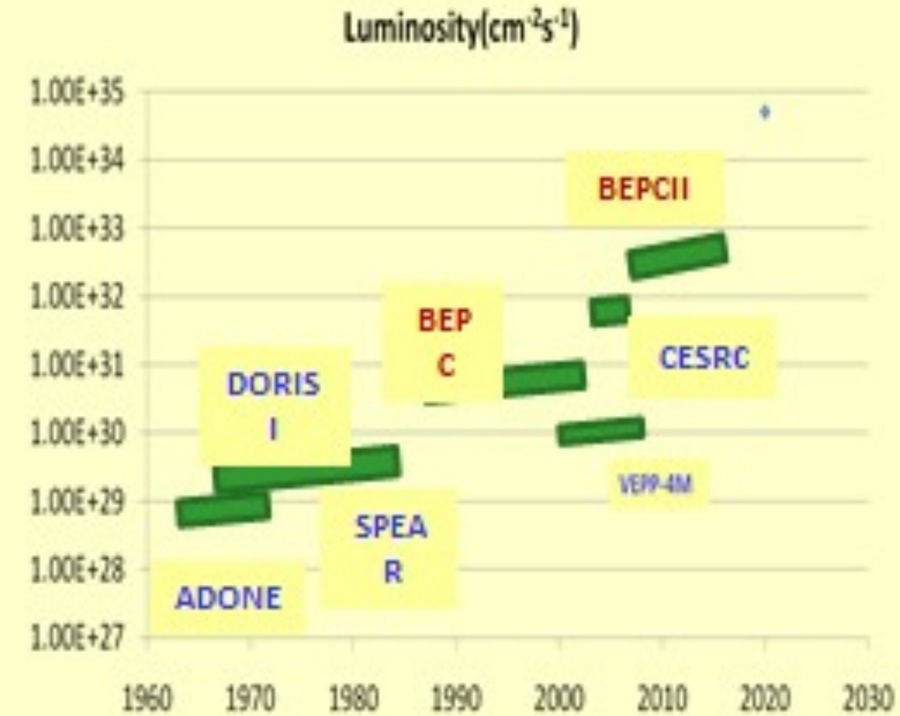
- **Accelerator-based**

BEPCII/BESIII: Operational since

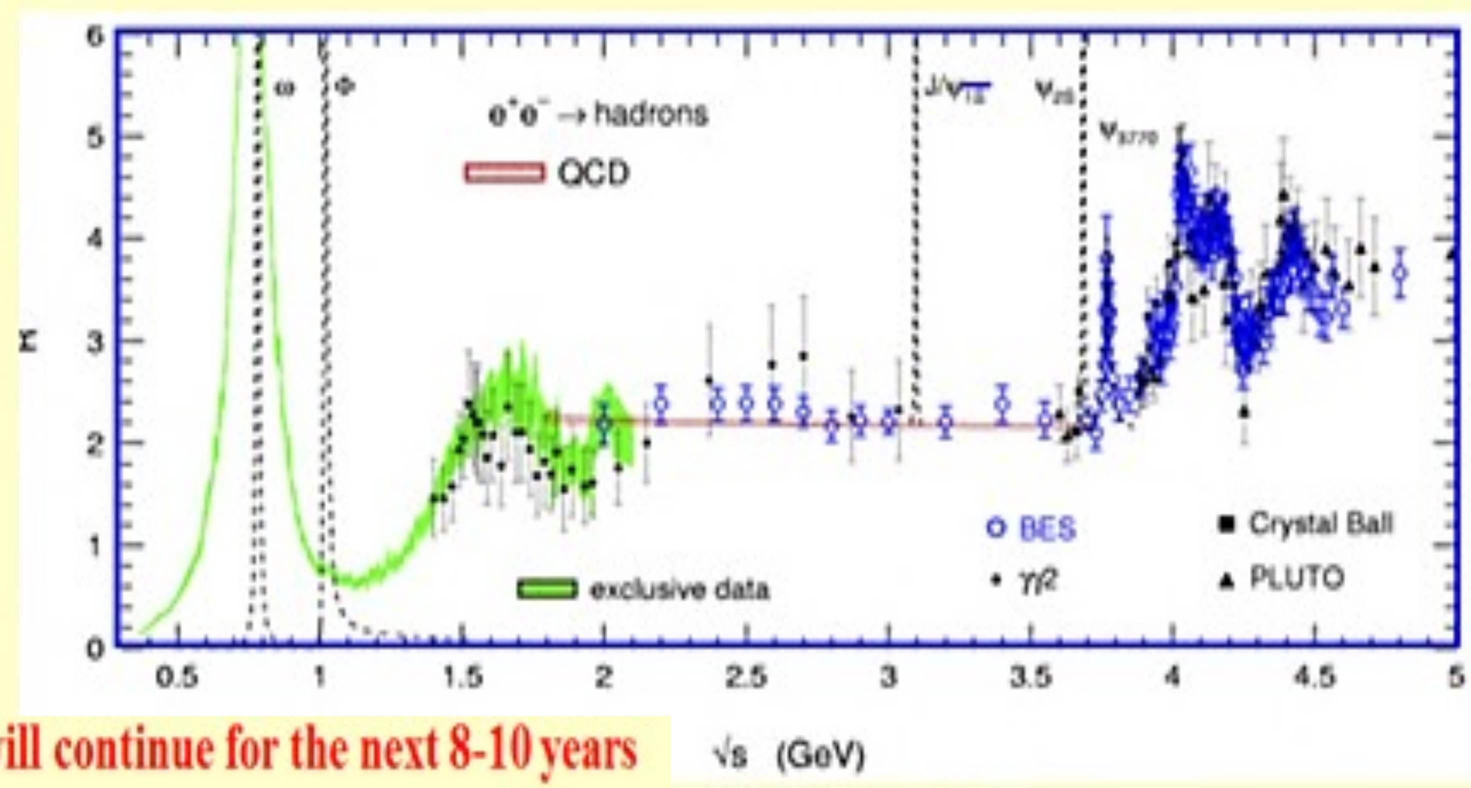
A high lumi. e^+e^- collider at the τ-c energy region





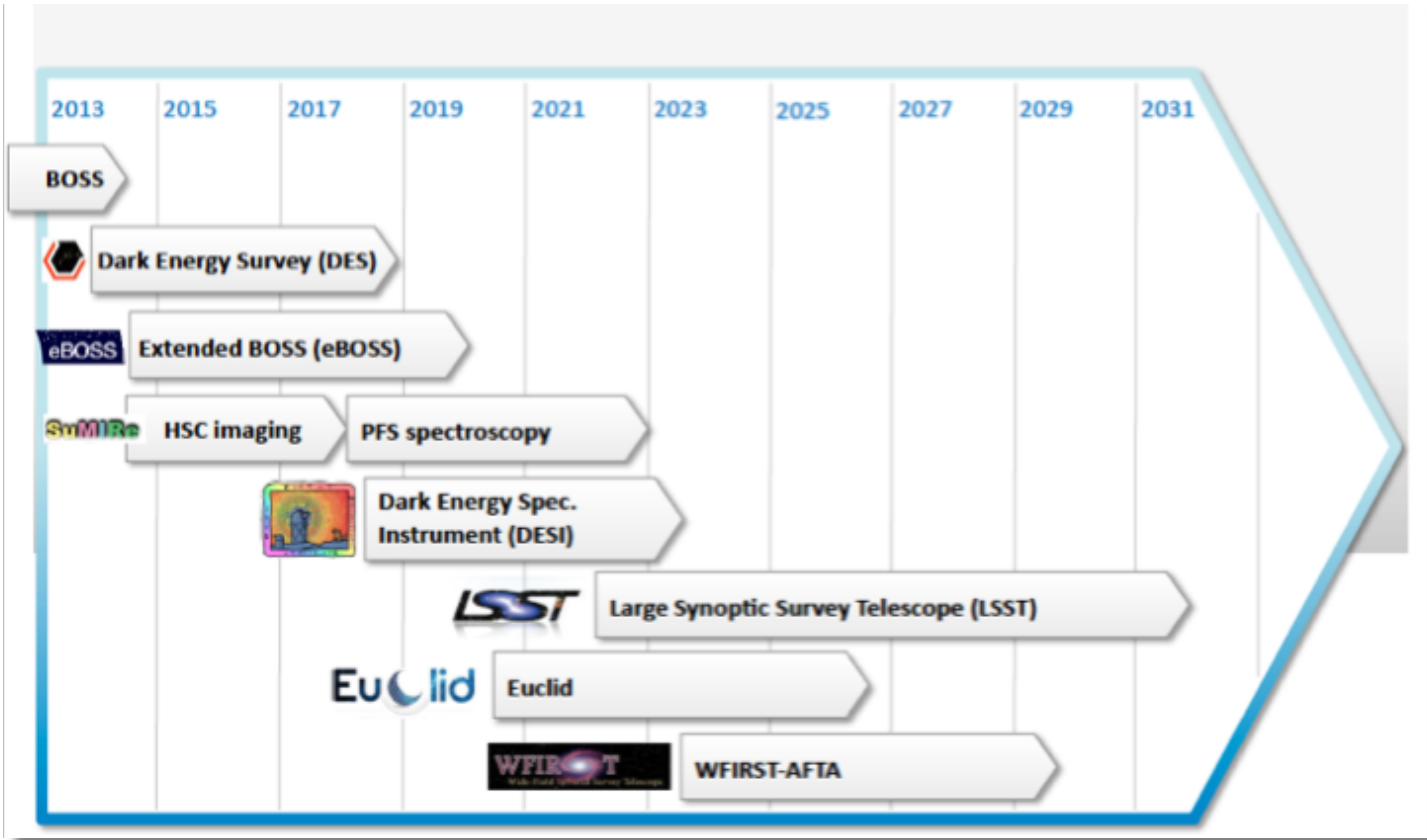
BESIII data taking status & plan

	Previous Data set	BESIII Near future
J/psi	BESII 58M	2009: 200M, 2012: 1 B
Psi'	CLEO: 28 M	2009: 100M, 2012: 0.4 B
Psi"	CLEO: 0.8 /fb	2010: 0.9/fb, 2011: 2.6/fb
ψ(4040)/ψ(4160) & scan	CLEO: 0.6/fb @ ψ(4160)	2011: 0.4/fb @ ψ(4040) 2013: 0.5/fb (4260), 0.5/fb (4360)
R scan & Tau	BESII	2013: 1.5/fb (4260)



BESIII will continue for the next 8-10 years

THE DARK ENERGY PROGRAM



Instrumentation and Infrastructure

European Strategy Statement:

- The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing. *Detector R&D programmes should be supported strongly at national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*

- *A healthy, well-supported R&D program in detector technologies is vital and helps to connect HEP to other fields.*

- *An ICFA instrumentation panel has existed for some time. In the U.S. the DPF CPAD Panel examines long-term issues in Instrumentation and Detector R&D.*

Theory

- Theory is a strong driver of particle physics and provides essential input to experiments, witness the major role played by theory in the recent discovery of the Higgs boson, from the foundations of the Standard Model to detailed calculations guiding the experimental searches. *Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.*

- The DPF Theory Panel was part of the Snowmass process in the U.S. A draft report is available.

Energy Frontier – LHC

Focused Challenges:

- Maintain detector performance in the presence of 140 int/xing
  - Low mass tracking
  - Fast timing
  - DAQ
- Extend forward calorimetry and tracking to $\eta=4$ for WW scattering and HH studies
- Radiation hardness

Technology	Need	Implementation
Pixelization	Lower occupancy Track primitives	Tracker segmentation Track stubs, ROI
ASIC and electronics	Inner pixel IC	65 nm rad hard designs Low power design
Trigger and DAQ	Track triggers High BW optical	Assoc. memory Mach Zender modulators
Mechanics and power	Cable mass Cooling to -25 deg	DC-DC/serial power Co2, carbon foams
Photosensors	Rad hard compact sensors	SiPMs
Speed	isolate primary vertex	10 ps resolution tof
Sensors	Rad hard, pixelated	Thin silicon 3D silicon diamond

Intensity Frontier Instrumentation Needs

Calorimeters

- Fast (Mu2e→LYSO, g-2→PbF2, MEG→ LXe, ORKA→Pb-scint.)
- $\varepsilon_{\pi 0}$ >99.9999% ($K \rightarrow \pi \nu \nu$) with 4π fully hermetic photon detection
- KOPIO+ needs energy, time, position and direction

Trackers:

- Low mass (drift chambers, straws, Si)
- Good space/timing resolution
- Operation in vacuum (e.g. g-2, Mu2e, NA62/CKM straws in vacuum)

Massive Detectors:

- Need cost effective detection of scintillation or Cherenkov light
- Need cost effective detection of ionization electrons

DAQ

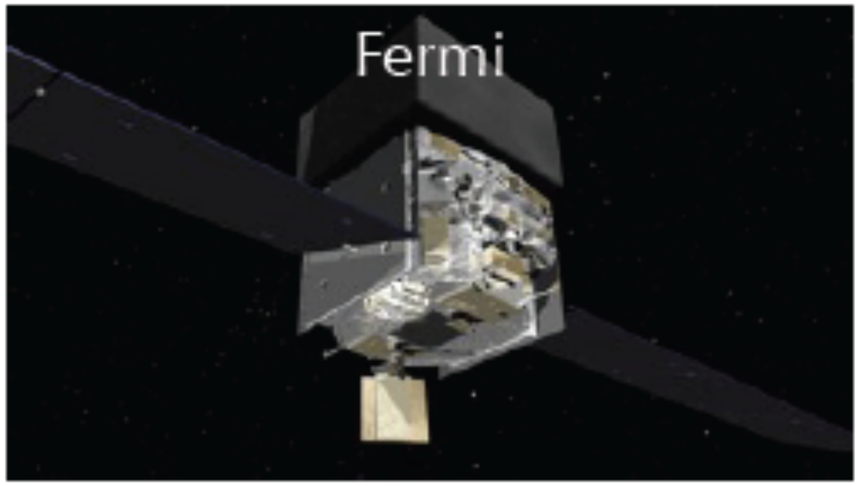
- sensitivity gains afforded by the high-level processing of all events

Simulations and Computing

- reasonably and economically steward 1-10 Peta-Bytes
- Include neutrino-nucleus interactions within GEANT4

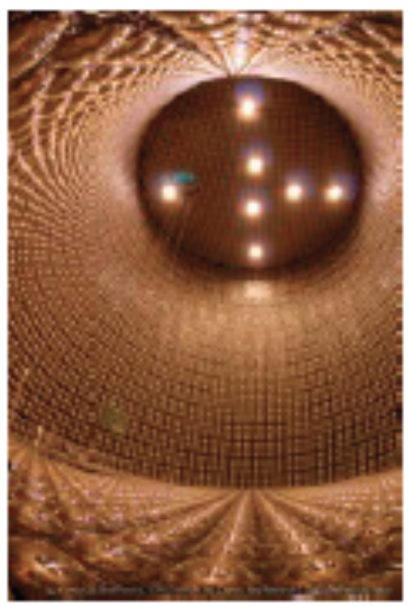
Dark Matter Indirect Detection

(Buckley)

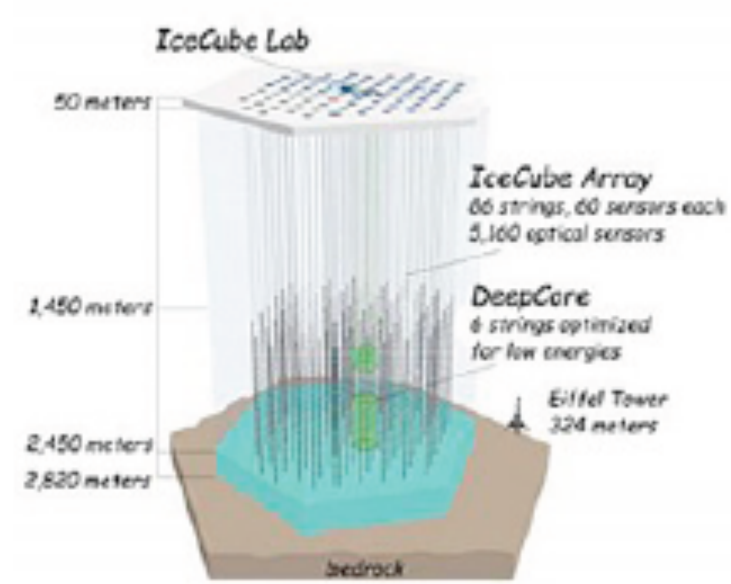


γ

Super-K



ν



ICECUBE

PAMELA

$$e^-, e^+, p, \bar{p}$$

AMS

Tasks for us all

- Invest in the development of new, enabling instrumentation and accelerator technology
- Invest in advanced computing technology and programming expertise essential to both experiment and theory
- Carry on theoretical work in support of these projects and to explore new unifying frameworks
- Invest in the training of physicists to develop the most creative minds to generate new ideas in theory and experiment that advance science and benefit the broader society
- Increase our efforts to convey the excitement of our field to others