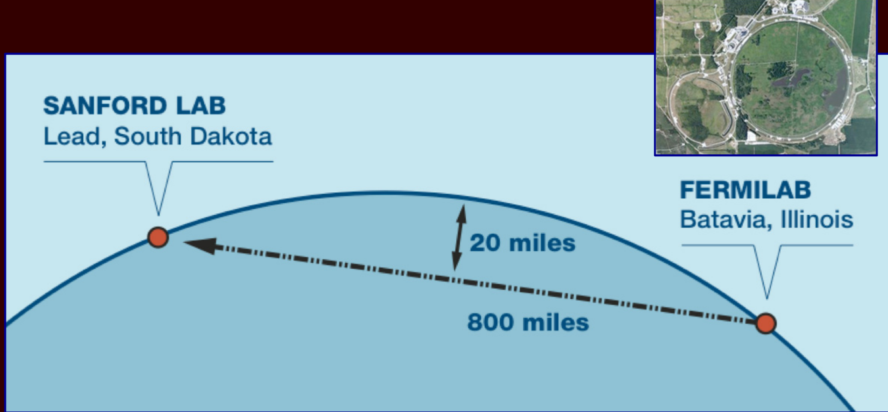
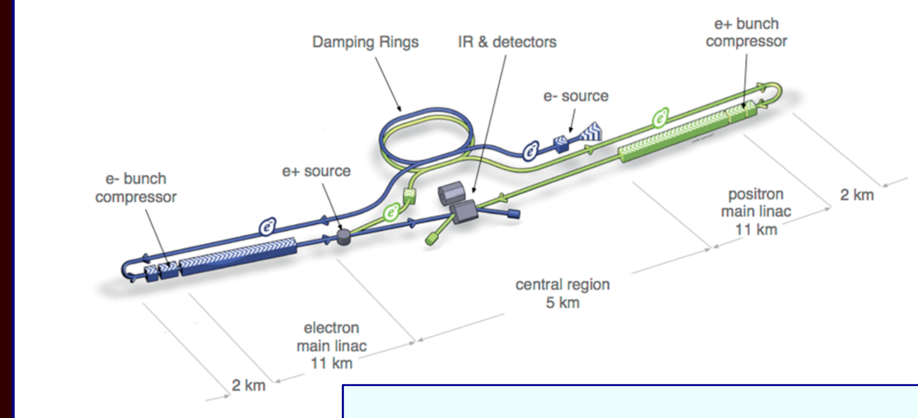
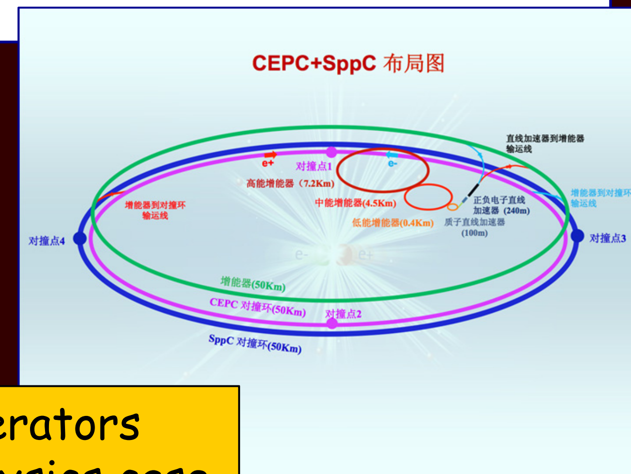
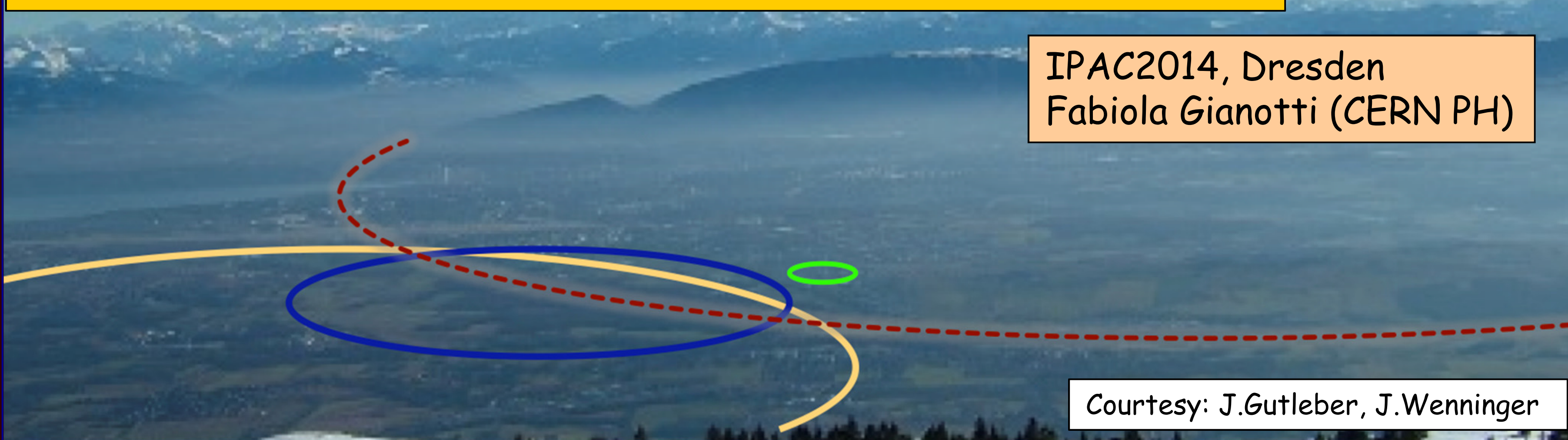






Opportunities and prospects for accelerator-based high-energy physics

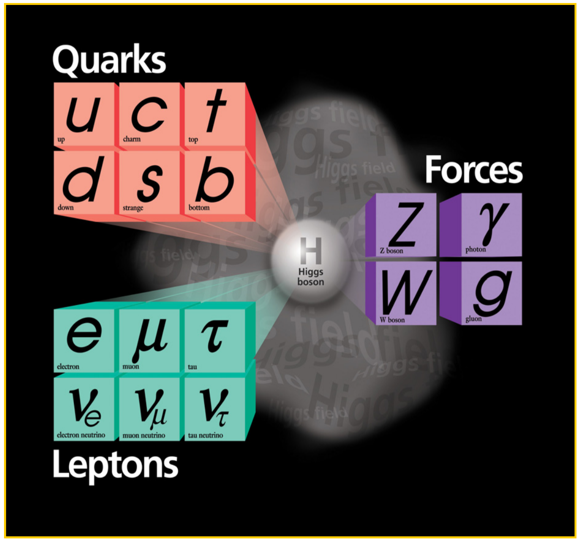
- ❑ Present questions in particle physics and role of accelerators
- ❑ Main options for future HEP accelerators and their physics case
- ❑ Some final remarks



IPAC2014, Dresden
Fabiola Gianotti (CERN PH)

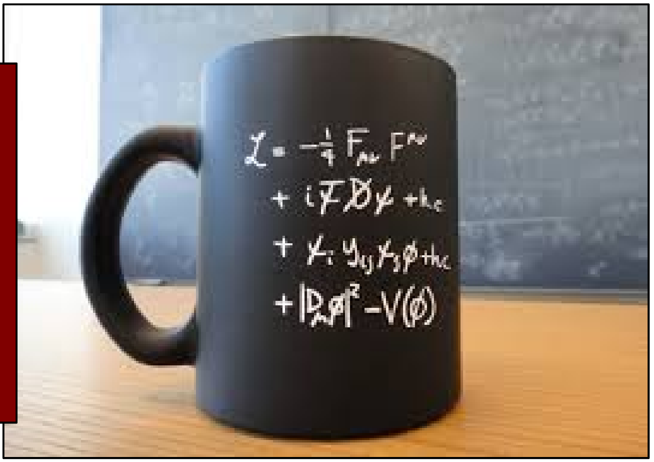
Courtesy: J.Gutleber, J.Wenninger

What did we accomplish so far in particle physics ?



With the discovery of a Higgs boson,
we have completed the Standard Model
(almost 80 years of theoretical and experimental efforts !)

Note: fermions (c, b, t, τ) discovered at accelerators in the US, bosons (g, W, Z, H) in Europe …



We have tested the Standard Model with very high precision (wealth of measurements at accelerators since early '60s)

→ it works BEAUTIFULLY (puzzling …)

→ no significant deviations observed (but difficult to accommodate neutrino masses)

However: SM is not a complete theory of particle physics, as several outstanding questions remain, raised also by experimental observations (e.g. dark matter, Universe's accelerated expansion) that cannot be explained within the SM.

These questions require NEW PHYSICS

Main questions in today's particle physics (a non-exhaustive list ..)

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Do neutral leptons, charged leptons and quarks behave similarly?

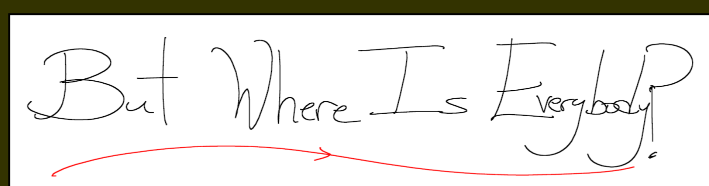
What is the origin of neutrino masses and oscillations ?

What is the composition of dark matter (23% of the Universe) ?

What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)

Why is Gravity so weak ?

Puzzling: NO direct evidence of new physics from LHC (yet ...)



N.Arkani-Hamed

In other words: at what E scale(s) are the answers to these questions ?

These questions are compelling, difficult and intertwined → require all approaches we have in hand (made possible also by strong advancements in accelerator and detector technologies): high-E colliders, neutrino experiments (solar, short/long baseline, reactors, $0\nu\beta\beta$ decays), cosmic surveys, dark matter direct and indirect detection, precision measurements of rare decays and phenomena, dedicated searches (WIMPS, axions, dark-sector particles), …

Main questions and main approaches to address them

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

Combination of ALL these complementary approaches crucial to explore the largest range of E scales, properly interpret signs of new physics → build coherent picture of underlying theory

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New particles and forces	x	x	x	x	
Universe acceleration					x

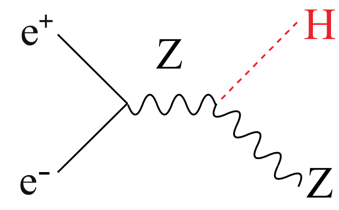
Require high-energy and/or high-intensity accelerators

Combination of ALL these complementary approaches crucial to explore the largest range of E scales, properly interpret signs of new physics → build coherent picture of underlying theory

3 main <u>complementary</u> ways to search for (and study) new physics at accelerators

Direct
production of a given (new or known) particle

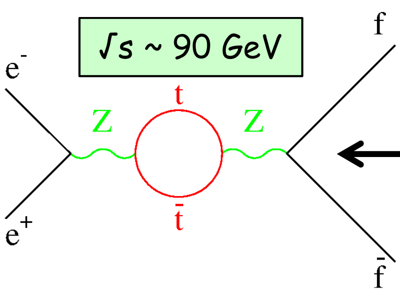
e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ need high E and high L



Indirect
precise measurements of known processes

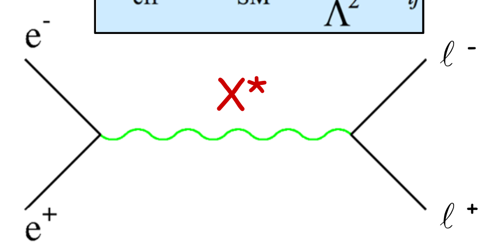
→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales $\Lambda \gg \sqrt{s}$ → need high E and high L

$\sqrt{s}$ ~ 90 GeV



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

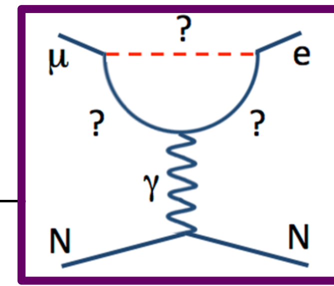
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mathrm{NP}}}{\Lambda^2} O_{ij}$$



Rare processes
suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → need intense beams, ultra-sensitive (massive) detectors ("intensity frontier")

E.g. transitions between charged leptons of different families with Lepton-Flavour-Violation: μ→eγ (MEG@PSI), μ→e (COMET@JPARC, Mu2e@FNAL). Suppressed in SM, can occur if new physics
Note: flavour violation observed for ν (e.g. $\nu_\mu \to \nu_e$) and quarks (e.g. t→ Wb)



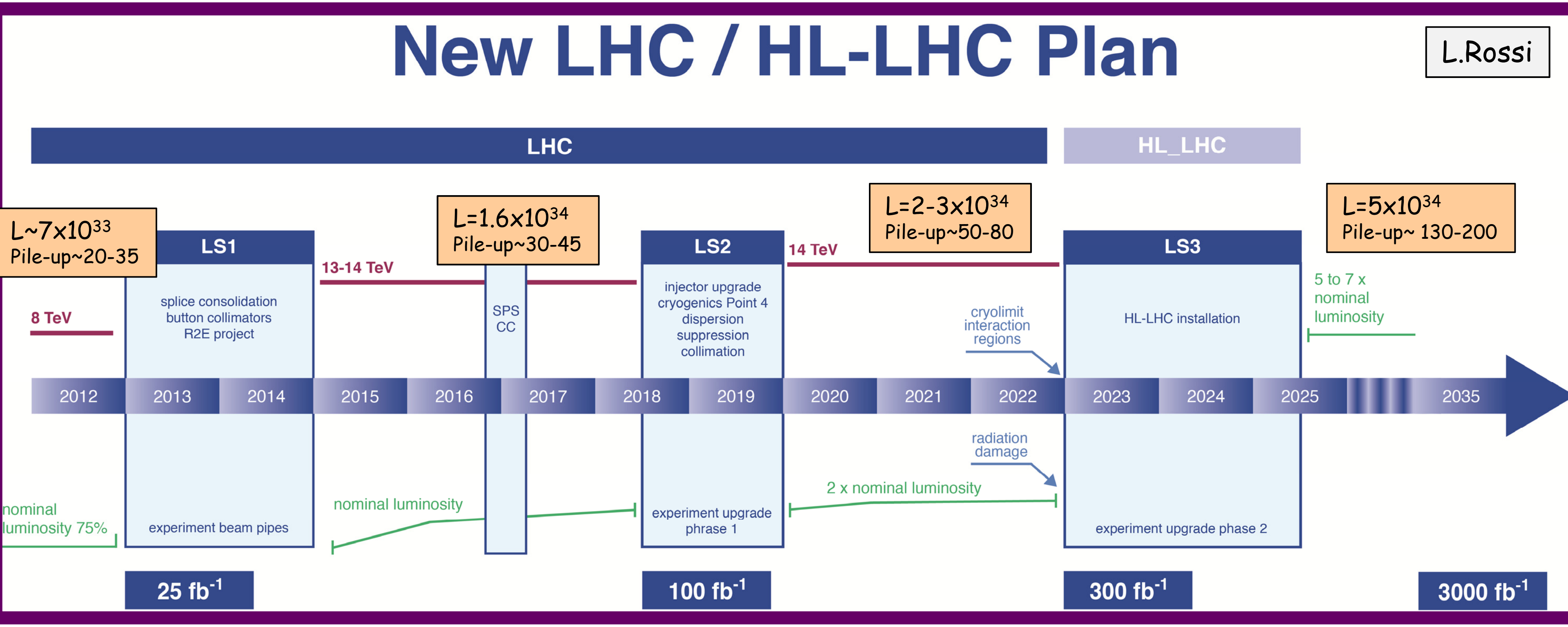
Physics motivations and potential of future HEP accelerators

- ❑ Linear and circular e^+e^- colliders
- ❑ Very high-E proton-proton colliders
- ❑ High-intensity beam facilities for neutrino experiments

Note: above projects are among those which received strongest support from Japan, Europe and US strategy committees

Disclaimer: due to time limitation, I will not discuss other opportunities for E-frontier ($\mu\mu$, ep, $\gamma\gamma$ colliders), and I-frontier (B-factories, kaon and muon beam experiments, …)

The present and near/medium-term future: LHC and HL-LHC



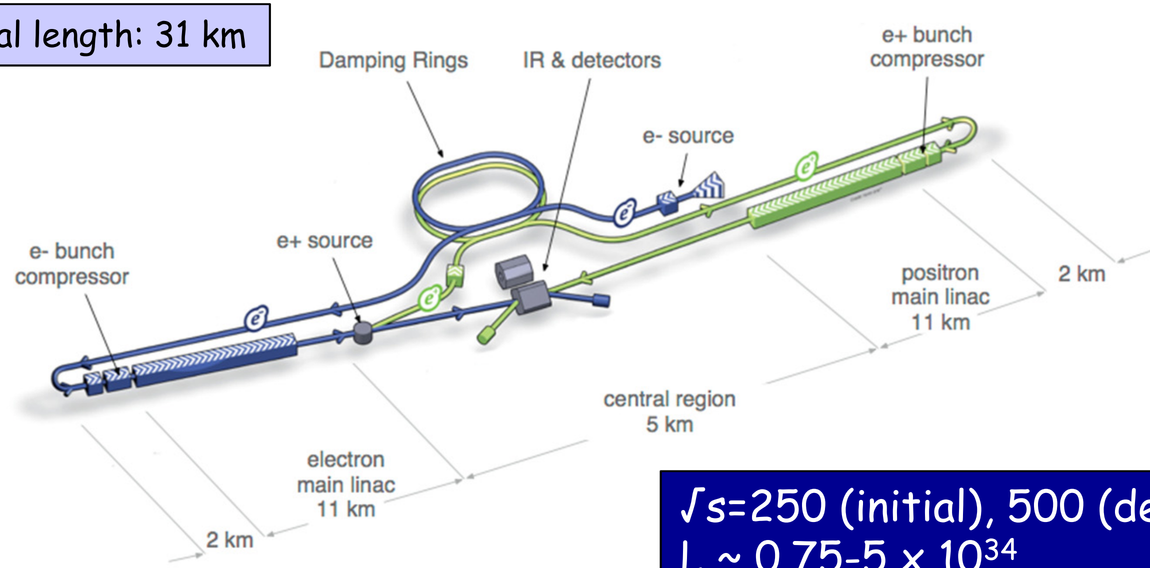
Full exploitation of LHC project with HL-LHC ($\sqrt{s}$ ~ 14 TeV, 3000 fb^{-1}) is MANDATORY
(Europe's top priority per European Strategy, strong support also from Japan and US strategies)

- ❑ Present highest-E accelerator, allowing:
- → detailed direct exploration of the TeV scale up to ~ 10 TeV
- → measurements of Higgs couplings to few percent
- ❑ Results will inform the future

International Linear Collider (ILC)

Technical Design Report released in June 2013

Total length: 31 km



$\sqrt{s}$=250 (initial), 500 (design), 1000 (upgrade) GeV
L ~ 0.75-5 x 10^{34}
(running at $\sqrt{s}$=90, 160, 350 GeV also envisaged)

Main challenges:

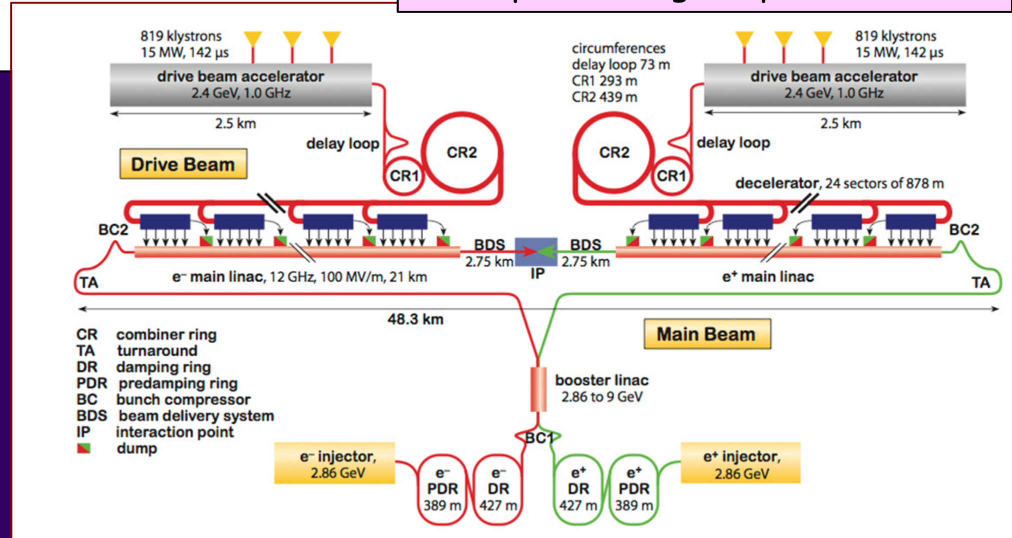
- ❑ ~ 15000 SCRF cavities (1700 cryomodules), 31.5 MV/m gradient
- ❑ 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- ❑ Positron source; suppression of electron-cloud in positron damping ring
- ❑ Final focus: squeeze and collide nm-size beams

❑ Japan interested to host → decision ~2018 based also on ongoing international discussions
Mature technology: 20 years of R&D experience worldwide
(e.g. European xFEL at DESY is 5% of ILC, gradient 24 MV/m, some cavities achieved 29.6 MV/m)
→ Construction could technically start ~2019, duration ~10 years → physics could start ~2030

Compact Linear Collider (CLIC)

Conceptual Design Report end 2012

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



Parameter	Unit	500 GeV	3 TeV
Centre-of-mass energy (*)	TeV	0.5	3.0
Repetition frequency	Hz	50	50
Number of bunches per train		354	312
Bunch separation	ns	0.5	0.5
Accelerating gradient	MV/m	80	100
Total luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.3	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.4	2.0

(*) Currently optimizing for initial stage at √s=350 GeV

If decision to proceed in ~2018 → construction could technically start ~2024, duration ~6 years for √s ≤500 GeV, (26 km Linac) → physics could start 2030++

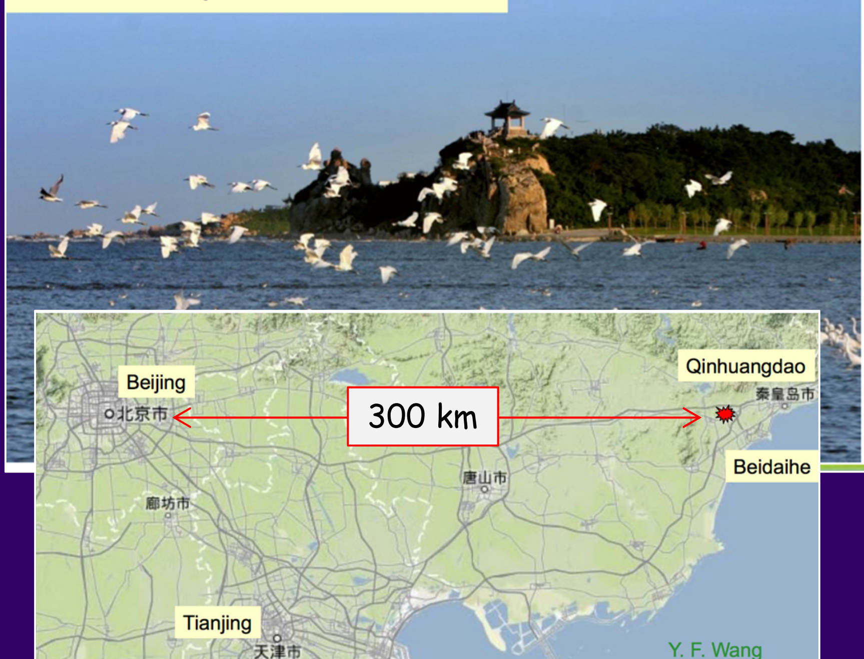
Future high-energy circular colliders

Parameters are indicative and fast evolving, as no CDR yet

China: 50-70 km e^+e^- $\sqrt{s}$=240 GeV (CepC) followed by 50-90 TeV pp collider (SppC) in same tunnel
50 km e^+e^- machine + 2 experiments:
- pre-CDR: end 2014
- construction: 2021-2027
- data-taking: 2028-2035

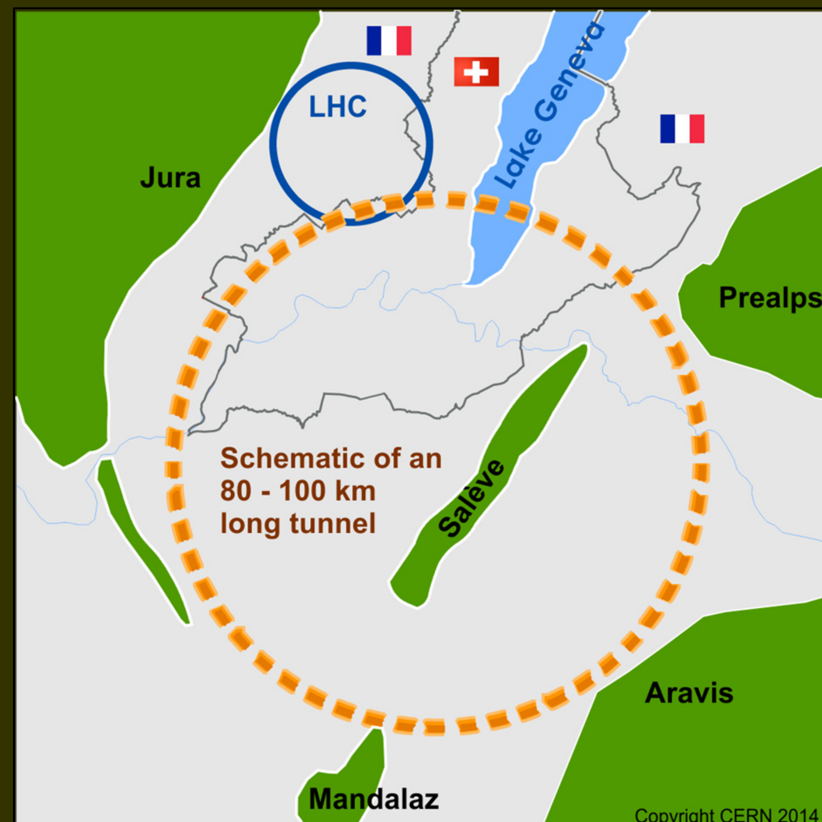
Best beach & cleanest air
Summer capital of China

Possible site: Qinghungdao

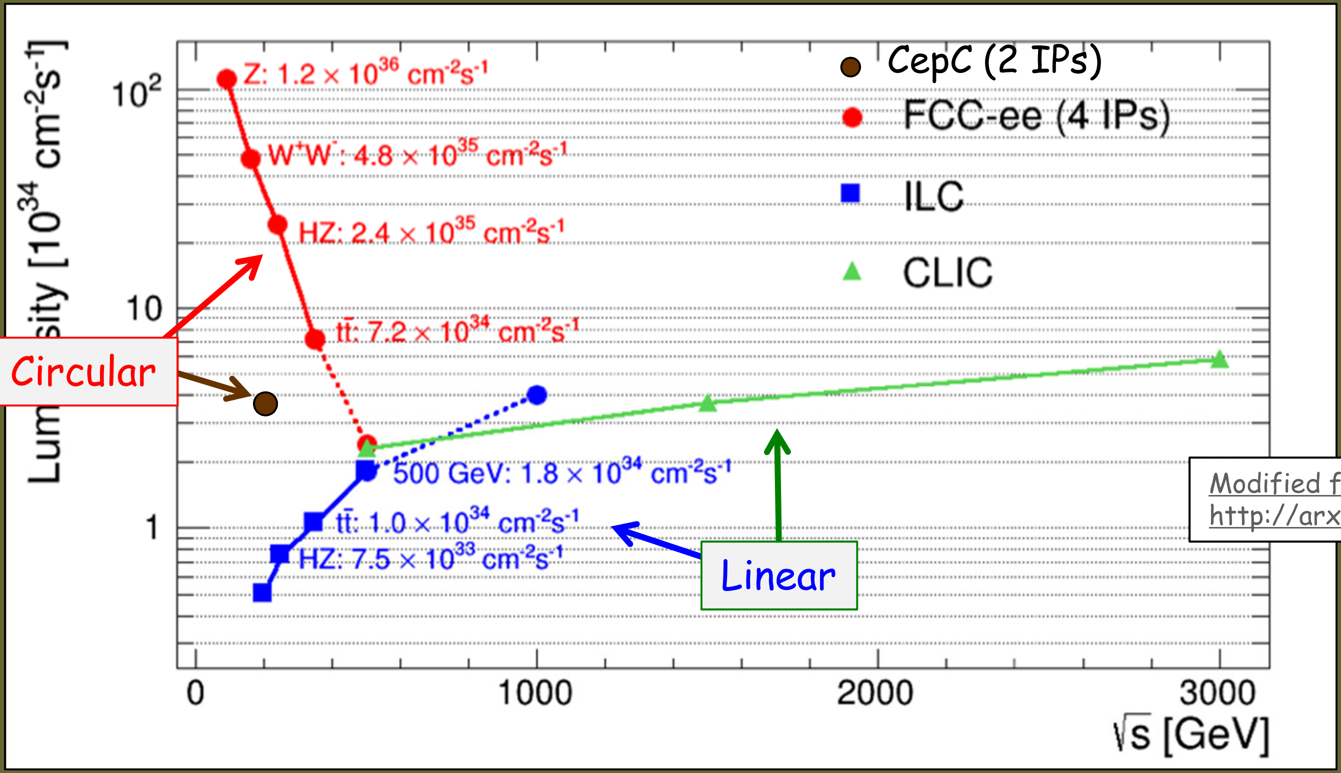


CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:
- 100 TeV pp: ultimate goal (FCC-hh)
- 90-350 GeV e^+e^-: possible intermediate step (FCC-ee)
- $\sqrt{s}$= 3.5-6 TeV ep: option (FCC-eh)

Goal of the study: CDR in ~2018.



Summary of e^+e^- colliders main parameters



Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf

Some typical energy points only

	Size km	$\sqrt{s}$ GeV	RF MV/m	L per IP 10^{34}	Bunch/train x-ing rate(Hz)	σ_x µm	σ_y nm	Lumi within 1% of $\sqrt{s}$	Long. polarisation e^-/e^+
CEPC	54	240	20	1.8	4×10^5	74	160	>99%	considered
FCC-ee	100	240	20	6	2×10^7	22	45	>99%	considered
ILC	31	250	14.7	0.75	5	0.7	7.7	87%	80%/30%
ILC	31	500	31.5	1.8	5	0.5	5.9	58%	80%/30%
CLIC	48	3000	100	6	50	0.04	1	33%	80%/considered

Future pp colliders

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

	Ring (km)	Magnets (T)	$\sqrt{s}$ (TeV)	L (10^{34})
LHC	27	8.3	14	up to 5
HE-LHC	27	16-20	26-33	5
SppC-1	50	12	50	2
SppC-2	70	19	90	2.8
FCC-hh	100	16	100	≥ 5

Nb_3Sn ok up to 16 T; HTS needed for 20 T

May reach ~10^{35}

More parameters of 100 TeV FCC-hh

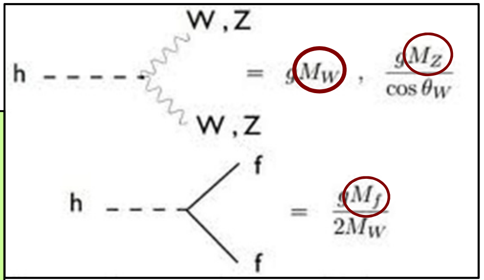
	HL-LHC	FCC-hh
Bunch spacing	25	25
N. of bunches	2808	10600
Pile-up	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

5 ns also considered to mitigate e-cloud

Challenges (many, daunting, …): magnet technology, tunnel excavation, stored beam energy, …

As an Airbus 380 at full speed

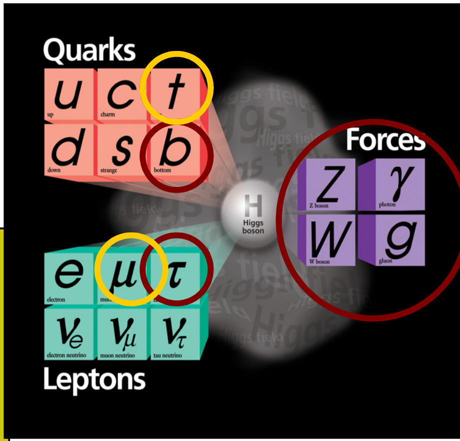
The Higgs boson as a door into new physics ?



Impact of New Physics on Higgs couplings to fermions and bosons

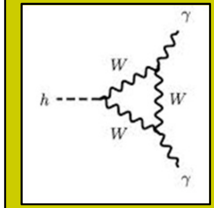
$\Delta\kappa/\kappa \sim 5\%/\Lambda^2_{NP}$ (Λ_{NP} in TeV)

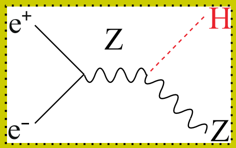
Scenarios exist with no new particles observable at LHC
→ New Physics would appear only through deviations to H couplings
→ 0.1-1% experimental precision needed for discovery

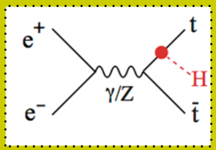


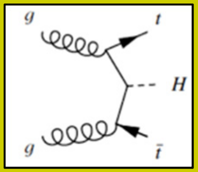
Higgs couplings from studies of:
- ❑ decays (direct or via loops): H→ZZ, WW, γγ(loop), gg(loop), bb, ττ, cc, μμ
- ❑ production: WH, ZH, ttH, gg → H (loop)

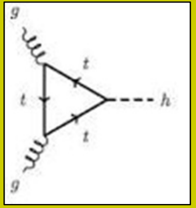
In addition: self couplings H→ HH

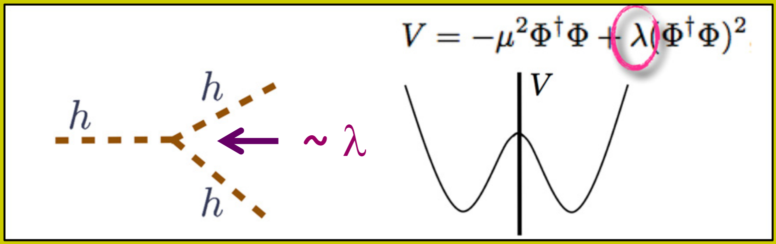












LHC Run-1: ~20% precision on couplings to bosons and 1st generation fermion (ttH indirect)
LHC 14 TeV, 300 fb^{-1} (~2020): 5-10% precision

HL-LHC:
- ❑ 2-5% for most couplings
- ❑ first direct observation of couplings to top (ttH → ttγγ) and 2nd family fermions (H→ μμ)
- ❑ Higgs self-coupling ?

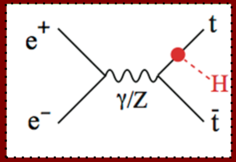
Integrated luminosities correspond to 3-5 years of running at each $\sqrt{s}$ for e^+e^- and 5 years with 2 experiments for pp

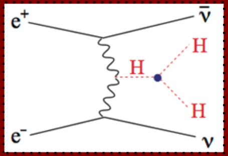
	$\sqrt{s}$ (TeV)	L (ab^{-1})	N_H (10^6)	N_{ttH}	N_{HH}
FCC-ee*	0.24+0.35	10	2	--	--
ILC	0.25+0.5	0.75	0.2	1000	100
ILC-1TeV	0.25+0.5+1	1.75	0.5	3000	400
CLIC	0.35+1.4+3	3.5	1.5	3000	3000
HL-LHC	14	3	180	3600 $tt\gamma\gamma$	250 $bb\gamma\gamma$
FCC-hh	100	6	5400	12000 $tt4l$	20000 $bb\gamma\gamma$

* 4 IP

<10% of events usable

ttH, HH: heavy final states → require energy (≥0.5 TeV) !





K_W , K_Z , K_g , K_c , K_τ , K_b
Best measurements: few 0.1% at FCC-ee (luminosity)

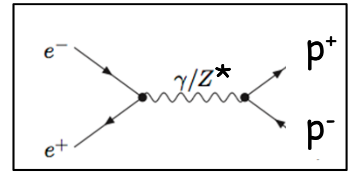
K_μ , K_γ
Best measurements: few 1% (rare decays) at HL-LHC, FCC-ee, FCC-hh, ILC (1000), CLIC (luminosity and/or energy)

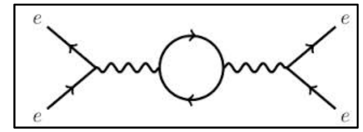
K_t
Best measurements: ≲5% at HL-LHC, ILC(1000), CLIC, FCC-hh (heavy final state → energy)

K_{HH} (self-couplings)
Best measurements: ~ 10% ILC(1000), CLIC, FCC-hh (heavy final state → energy)

Direct and indirect sensitivity to high-E new physics

e^+e^- colliders
- ❑ Direct: discovery potential for new particles coupling to Z/γ^* up to $m \sim \sqrt{s}/2$
- ❑ Indirect: via precise measurements
  → ILC/CLIC/FCC-ee can probe up to $\Lambda_{NP} \sim O(100)$ TeV





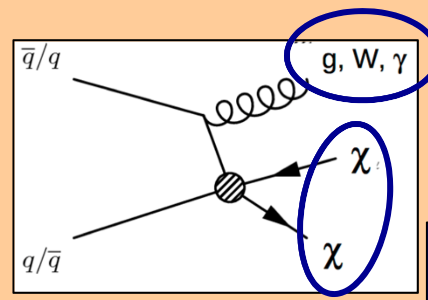
HL-LHC (3000 fb^{-1}) :
- ❑ Direct: discovery potential up to m~10 TeV for single particles (~30% larger than 300 fb^{-1})
- ❑ Indirect sensitivity up to ~50 TeV (e.g. quark compositeness scale)

A 100 TeV pp collider is the instrument to explore the 10-50 TeV E-scale directly

Examples:

Discovery potential for excited quarks q* (expected if quarks are composite): m ~ 50 TeV
Discovery potential for Z' (expected if additional forces exist): m ~ 30 TeV
Discovery potential for SUSY squarks and gluinos (pair produced): m ~ 15 TeV

SUSY has excellent candidate for dark matter (lightest neutralino χ^0): discovery reach up to ~ 4 TeV → cover most of region allowed by cosmology



Mono-jet/γ/W from initial-state radiation provides trigger

χ^0 are invisible → missing E

SUSY would also explain why Higgs mass is so light ("naturalness" problem)

Neutrino physics at high-intensity accelerators

Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos → imply neutrinos have masses and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

$\nu_{e,\mu,\tau}$ = physical states
$\nu_{1,2,3}$ = mass eigenstates
U = mixing angles θ

Oscillation probability (simplified for 2 ν):

$$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \sin^2 (1.267 \Delta m(\mathrm{eV})^2_{ij} \frac{\mathrm{L(km)}}{\mathrm{E(GeV)}})$$

Present experimental measurements

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2\,,(3.2\%) \qquad \Delta m^2_{32} = 2.43^{-0.06}_{+0.1} \times 10^{-3}\,\mathrm{eV}^2\,,(3.3\%)$$

$$\sin^2\theta_{12} = 3.07^{+0.18}_{-0.16} \times 10^{-1}\,,(16\%) \qquad \sin^2\theta_{23} = 3.86^{+0.24}_{-0.21} \times 10^{-1}\,,(21\%)$$

$$\sin^2\theta_{13} = 2.41 \pm 0.25 \times 10^{-2}\,,\ (10\%)$$

Open questions (→ need combination of approaches: accelerators, reactors, cosmic, double-β decays, ...)

- ❑ Origin of ν masses (e.g. why so light compared to other fermions ?)
- ❑ Mass hierarchy: direct (ν_3 is heaviest) or inverted (ν_3 is lightest) ?
- ❑ Why mixing much larger than for quarks ?
- ❑ CP violation (observed in quark sector): do ν and anti-ν behave in the same way?
- ❑ Are there additional (sterile) ν (as hinted by observed anomalies not compatible with 3-ν paradigm)?

Primary task of accelerator experiments: test 3-ν model, determine mass hierarchy, look for CP-violation, ...

using $\nu_\mu \rightarrow \nu_e$ oscillations

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U = mixing angles θ

Oscillation probability (simplified for 2 ν):

$$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \sin^2(1.267 \Delta m(_{\text{eV}})^2_{ij} \frac{L_{(\text{km})}}{E_{(\text{GeV})}})$$

%)

→ Need high-intensity p sources (achieved: < 0.5 MW → desired: > 1 MW), high-power targets, and massive detectors, as ν are very elusive particles (weak interactions only) and searched effects tiny

Open questions (→ need combination of approaches: accelerators, reactors, cosmic, double-β decays, …)

- ❑ Origin of ν masses (e.g. why so light compared to other fermions ?)
- ❑ Mass hierarchy: direct (ν_3 is heaviest) or inverted (ν_3 is lightest) ?
- ❑ Why mixing much larger than for quarks ?
- ❑ CP violation (observed in quark sector): do ν and anti-ν behave in the same way?
- ❑ Are there additional (sterile) ν (as hinted by observed anomalies not compatible with 3-ν paradigm)?

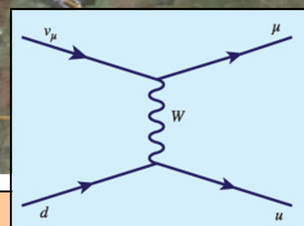
Primary task of accelerator experiments: test 3-ν model, determine mass hierarchy, look for CP-violation, …

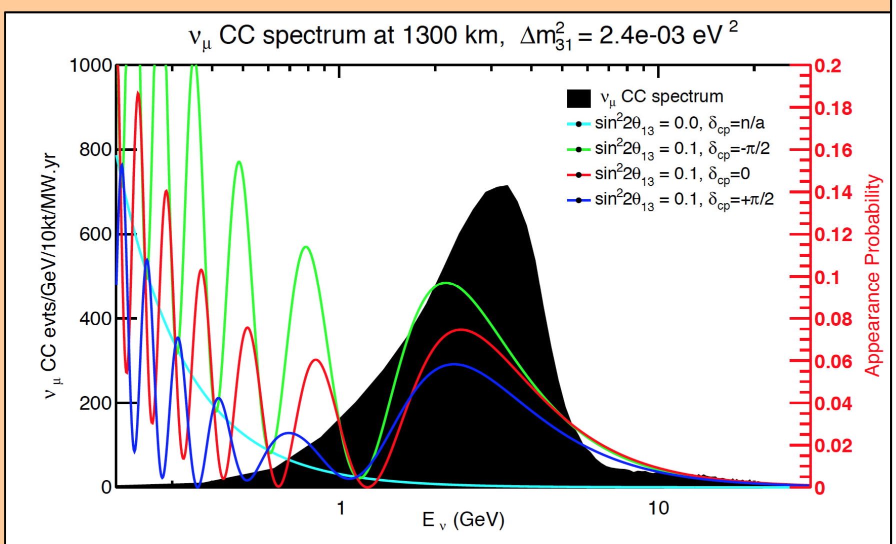
using $\nu_\mu \rightarrow \nu_e$ oscillations

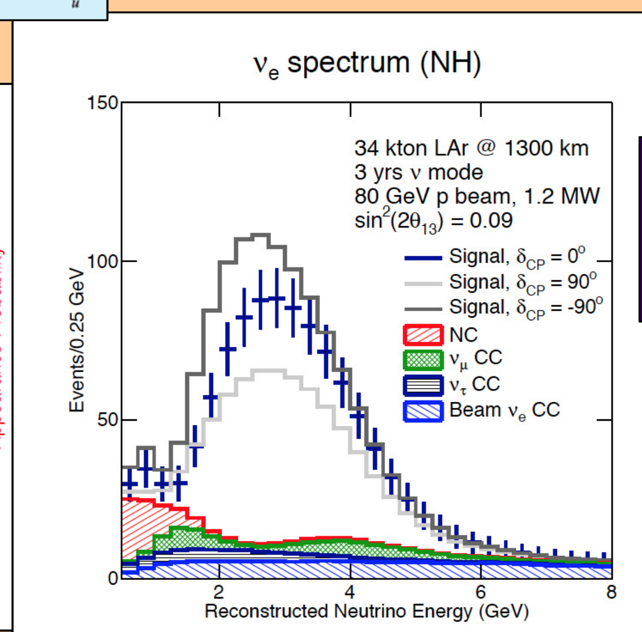
LBNE (=Long Baseline Neutrino Experiment) at FNAL: data-taking ~2030

$0.35 \rightarrow \sim 1.2$ MW p source
(upgrade: 7.5 Hz Booster cycle + SC Linac)
E_p =60-120 GeV $\rightarrow$ E_ν~ 3 GeV
Wide-band ν beam $\rightarrow$ measure oscillation shape

~34 kton LAr detector
1.5 km underground
(Homestake mine South Dakota)

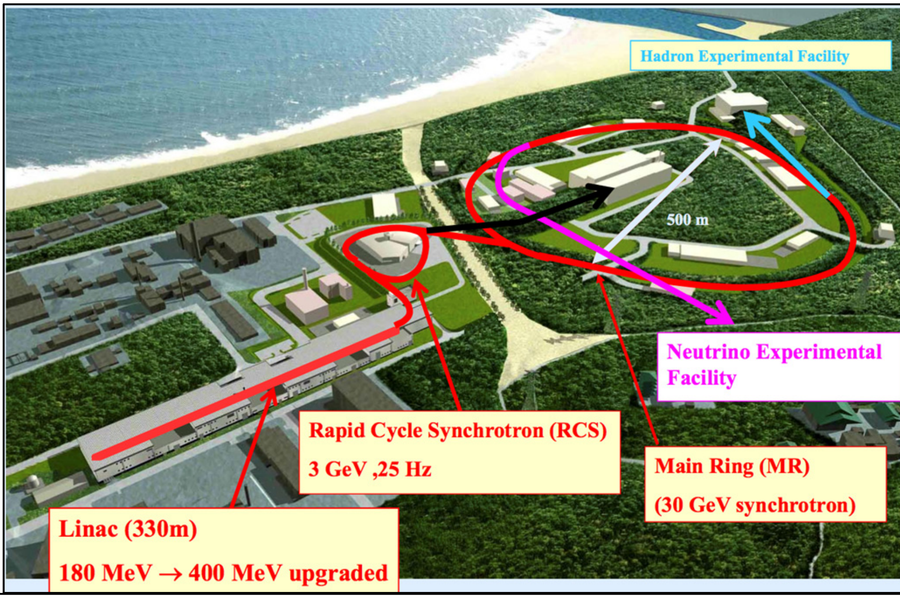




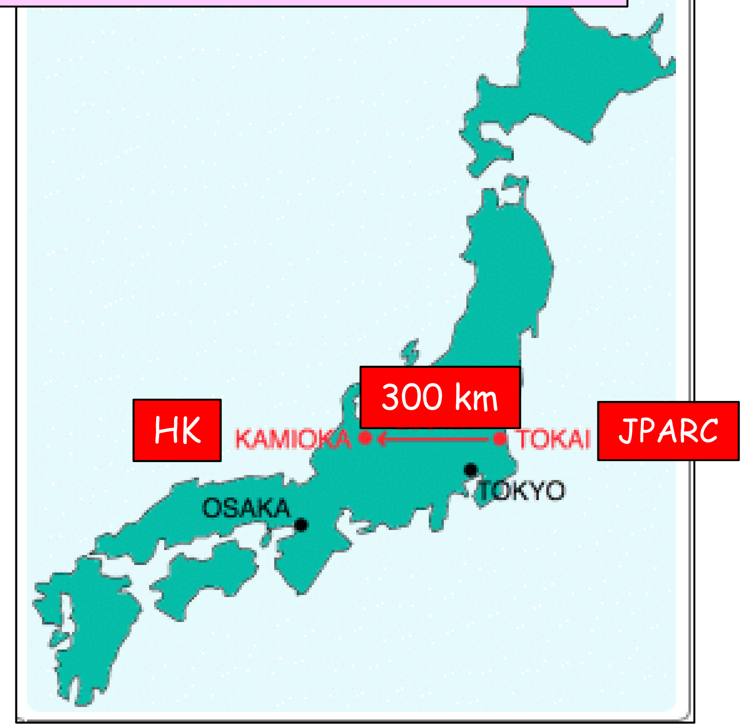


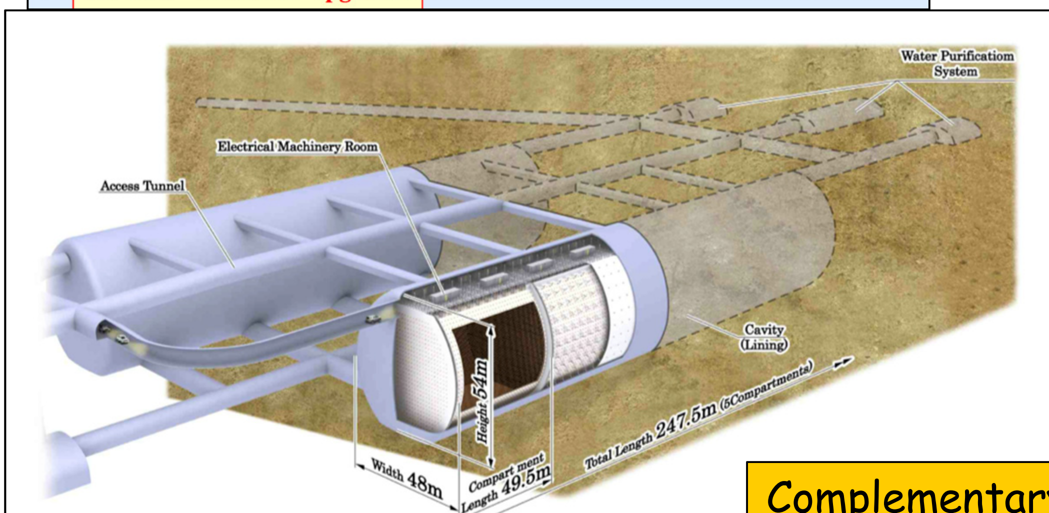
Goal exposure:
~ 600
MW*kton*years

Hyper-Kamiokande, JPARC: construction could start ~2018



→ 0.75→ > 1 MW p source
(upgrade: MR rep. rate and RF, new Booster ?)
E_p = 30 GeV → E_ν~ 0.6 GeV
Narrow-band ν beam
→ high intensity at oscillation peak





~560 kton (fiducial) Water Cerenkov detector (25 x Super-K)
~ 1 km underground
~ 2.5^0 off-axis → narrow-band beam

Complementary to LBNE: different detector technology, shorter baseline (→ less sensitive to mass hierarchy), narrow-band beam (→ high statistics of ν/anti-ν at oscillation peak but limited measurement of oscillation spectrum)

Conclusions

The extraordinary success of accelerator-based particle physics is the result of the ingenuity, vision and perseverance of the worldwide HEP community, and of decades of talented, dedicated work → the demonstrated strength of the community is an asset also for future, even more ambitious, projects.

With the discovery of a Higgs boson, after 80 years of superb theoretical and experimental work, the SM is now complete. However major questions remain.

The full exploitation of present accelerators, and more powerful future facilities, will be needed to address them and to advance our knowledge of fundamental physics.

No doubt that future high-E and high-intensity accelerators are extremely challenging (didn't the LHC also look close-to-impossible in the '80s ??).

However: the correct approach, as scientists, is not to abandon our exploratory spirit, nor give up to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable.

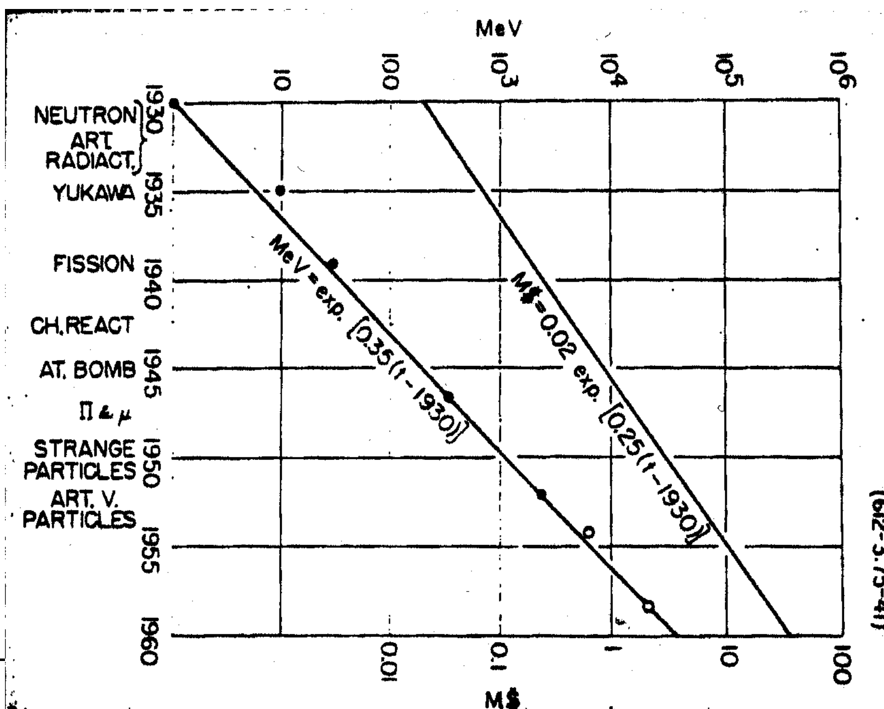
We already did so in the past … →

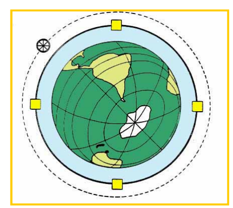
From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954

```
For these reasons....clamoring for higher and higher....
                         Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary
design....8000 km, 20000 gauss
                         Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some
things look for but see others.....Experiems on pions....sharpening
knowledge....spin mass and odd symmetry.....certainly look for multiple
production...
```

Fermi's extrapolation to year 1994:
2T magnets, R=8000 km (fixed target !),
$E_{beam} \sim 5\text{x}10^3$ TeV → $\sqrt{s} \sim 3$ TeV
Cost : 170 B$





Was that hopeless ??

We have found the solution:
we have invented colliders
and superconducting magnets …
and built the Tevatron and the LHC

Only if we are

AMBITIOUS
BRAVE
CREATIVE
DETERMINED

can we also hope to be lucky, and continue to play a leading role in the advancement of knowledge

MANY THANKS TO …

THE ORGANISERS

and

G.Arduini, L.Evans, D.Fournier, M.Harrison, P.Janot, A.Lankford, L.Linssen, Q.Qin, L.Rossi, S.Stapnes, Y.Wang, F.Zimmermann

SPARES

Main questions in today's particle physics

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 (is it responsible for baryogenesis ?)

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

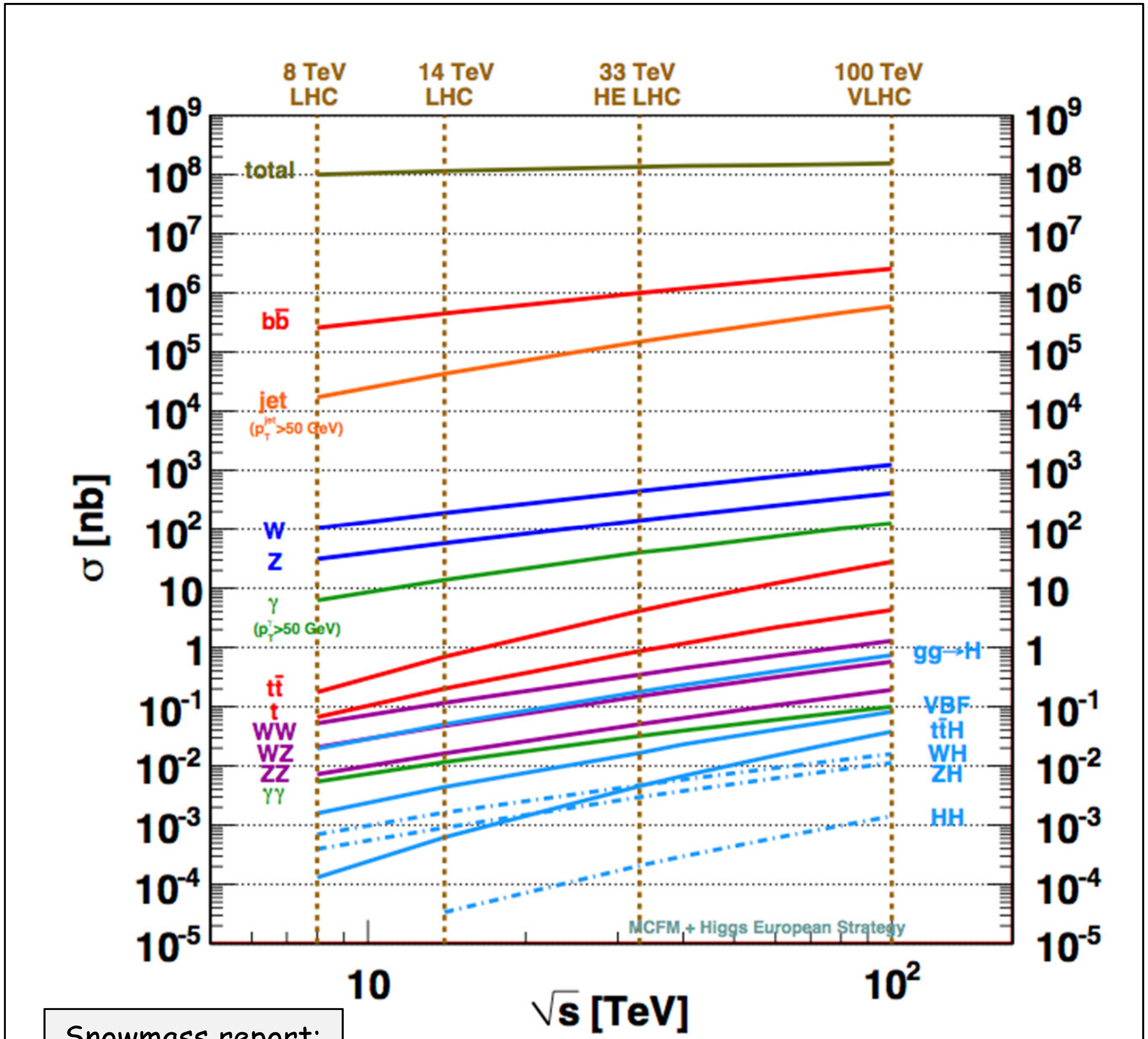
Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

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 ?

Cross sections vs √s



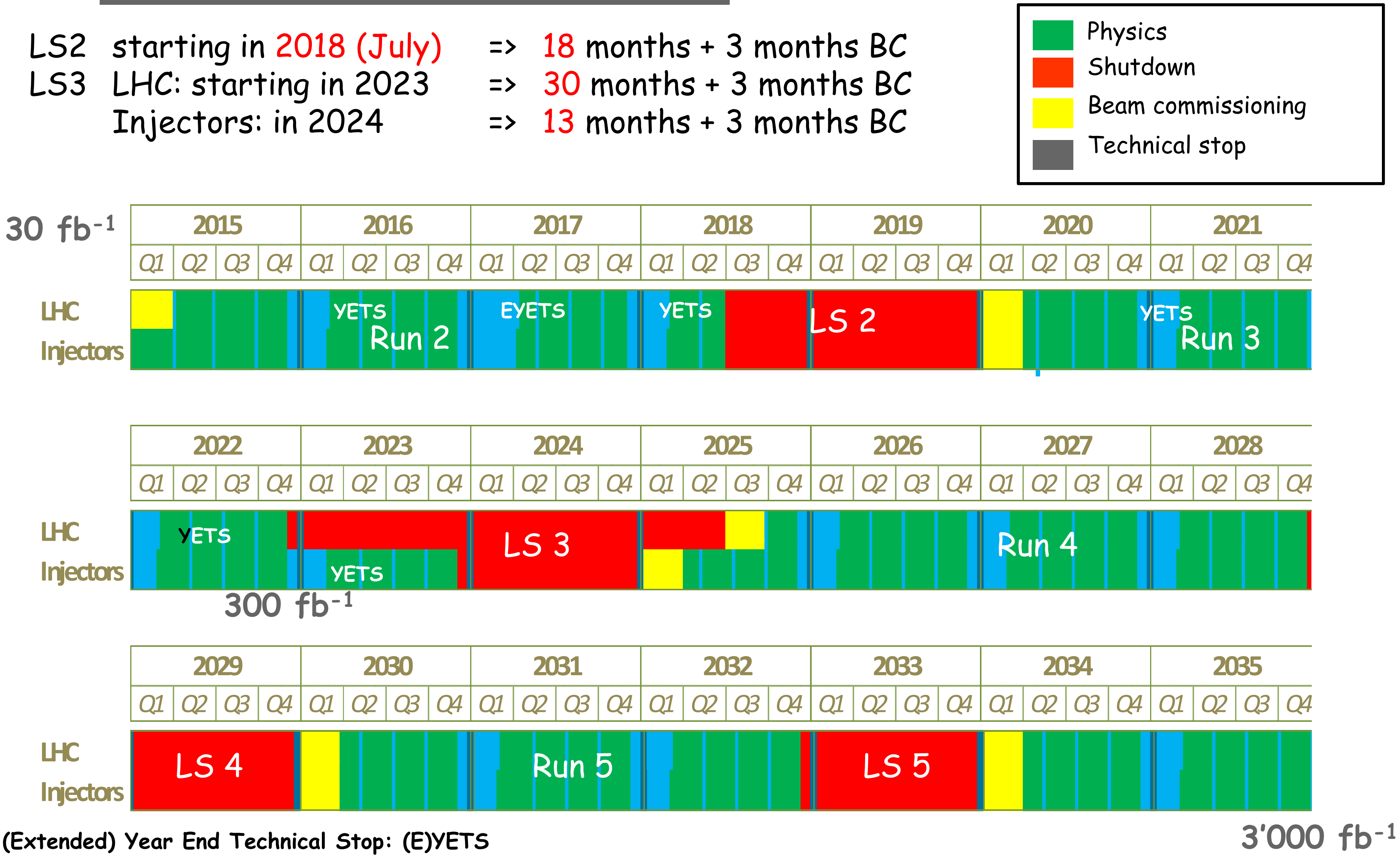
Snowmass report:
arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

→ With 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC



(Extended) Year End Technical Stop: (E)YETS

Table 3.1. Summary table of the 250–500 GeV baseline and luminosity and energy upgrade parameters. Also included is a possible 1st stage 250 GeV parameter set (half the original r linac length)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

CEPC 参数表

Number of IPs	2
Energy (GeV)	120
Circumference (km)	53.6
SR loss/turn (GeV)	3.01
N_e/bunch (10^{11})	3.71
Bunch number	50
Beam current (mA)	16.6
SR power /beam (MW)	50
B_0 (T)	0.065
Bending radius (km)	6.1
Momentum compaction (10^{-4})	0.415
β_{IP} x/y (m)	0.8/0.0012 (ratio:667)
Emittance x/y (nm)	6.8/0.02 (ratio:333)
Transverse σ_{IP} (um)	73.7/0.16 (ratio:470)
ξ_x/IP	0.104
ξ_y/IP	0.074
V_{RF} (GV)	6.87
f_{RF} (MHz)	700
Nature bunch length σ_z (mm)	2.26
Bunch length include BS (mm)	2.6
Nature Energy spread (%)	0.13
Energy acceptance RF(%)	5.4
Energy acceptance(%)	2
n_γ	0.22
δ_{BS} (%)	0.07
Life time due to beamstrahlung-Telnov (minute)	2028
Life time due to simulation (minute)	150
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	1.82

F. Gianotti, LHCP 2014, 6/6/2014

SppC参数表

Physics performance and beam parameters						
Peak luminosity per IP	1.0E34	5.0E34	5.0E34	5.0E34	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.55	0.15	0.35	1.1	0.75	m
Circulating beam current	0.584	1.12	0.478	0.5	1.0	A
Max beam-beam tune shift perIP	0.01	0.015	0.01	0.01	0.0075	
Bunch separation	25	25	25	25 5	25	ns
Number of bunches	2808	2808	2808	10600（8900） 53000（44500）	5333	
Bunch population	1.15E11	2.2E11	1.0E11	1.0E11	2.0E+11	
Normalized rms transverse emittance	3.75	2.5	1.38	2.2	3.3	mm
Beam life time due to burn-off	45	15.4	5.7	19.1/15.9	8.7	hour
Total / inelastic cross section	111/85	111/85	129/93	153/108	140	mbarn
Reduction factor in luminosity（F）					0.85	
Full crossing angle	285	590	185	74	139	mrad
rms bunch length	75.5	75.5	75.5	80/75.5	75.5	mm
rms IP spot size	16.7	7.1	5.2	6.8	8.5	mm
Beta at the 1st parasitic encounter					19.5	m
rms spot size at the 1st parasitic encounter					43.3	mm
Stored energy per beam	0.392	0.694	0.701	8.4/7.0	5.4	GJ
SR power per ring	0.0036	0.0073	0.0962	2.4/2.9	1.5	MW
Arc SR heat load	0.17	0.33	4.35	28.4/44.3	45.8	W/m
Energy loss per turn	0.0067	0.0067	0.201	4.6/5.86	1.49	MeV

F. Gianotti, LHCP 2014, 6/6/2014

Circular e^+e^- colliders

Lepton collider FCC-ee parameters

- **Design choice: max. synchrotron radiation power set to 50 MW/beam**
  - Defines the max. beam current at each energy.
  - 4 Physics working points
  - Optimization at each energy (bunch number & current, emittance, etc).

Parameter	Z	WW	H	tt_{bar}	LEP2
E/beam (GeV)	45	80	120	175	104
I (mA)	1450	152	30	6.6	3
Bunches/beam	16700	4490	170	160	4
Bunch popul. [10^{11}]	1.8	0.7	3.7	0.86	4.2
L (10^{34} $cm^{-2}s^{-1}$)	28.0	12.0	4.5	1.2	0.012

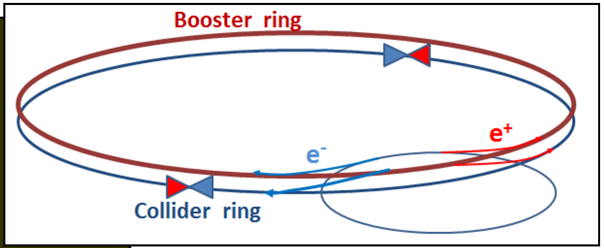
- For H and ttbar working points the beam lifetime of ~few minutes is dominated by Beamstrahlung (momentum acceptance of 2%).

Future Circular Collider Study
Michael Benedikt
CERN, 26th May 2014

6

	CepC	FCC-ee		
Ring (km)	53.6	100		
$\sqrt{s}$ (GeV)	240	240	350	90
E loss per turn (GeV)	3	1.7	7.5	0.03
Total RF voltage (GV)	6.9	5.5	11	2.5
Beam current (mA)	16.6	30	6.6	1450
N. of bunches	50 (one ring!)	1360	98	16700
L (10^{34} cm^{-2} s^{-1})/IP	1.8	6	1.8	28
$e^{\pm}$/bunch (10^{11})	3.7	0.46	1.4	1.8
σ_y/σ_x at IP (μm)	0.16/74	0.045/22	0.045/45	0.25/121
Interaction Points	2	4	4	4
Lumi lifetime (min)	60	21	15	213
SR power/beam	50 MW	50 MW		

Main challenges:
- FCC ring size
- Synchrotron radiation → 100 MW RF system with high efficiency
- Beam polarization for beam energy calibration at Z-pole and WW threshold to <100 keV to measure m_Z, m_W to < MeV at FCC-ee
- Machine design with large energy acceptance over full $\sqrt{s}$ span



Note: Super-KEKB is an excellent "prototype", with more stringent requirements on positron rate, momentum acceptance, lifetime, β_y^*

Among the main targets for the coming months: identify experimental challenges, in particular those requiring new concepts and detector R&D

The two main goals

- ❑ Higgs boson measurements beyond HL-LHC (and any e^+e^- collider)
- ❑ exploration of energy frontier

are quite different in terms of machine and detector requirements

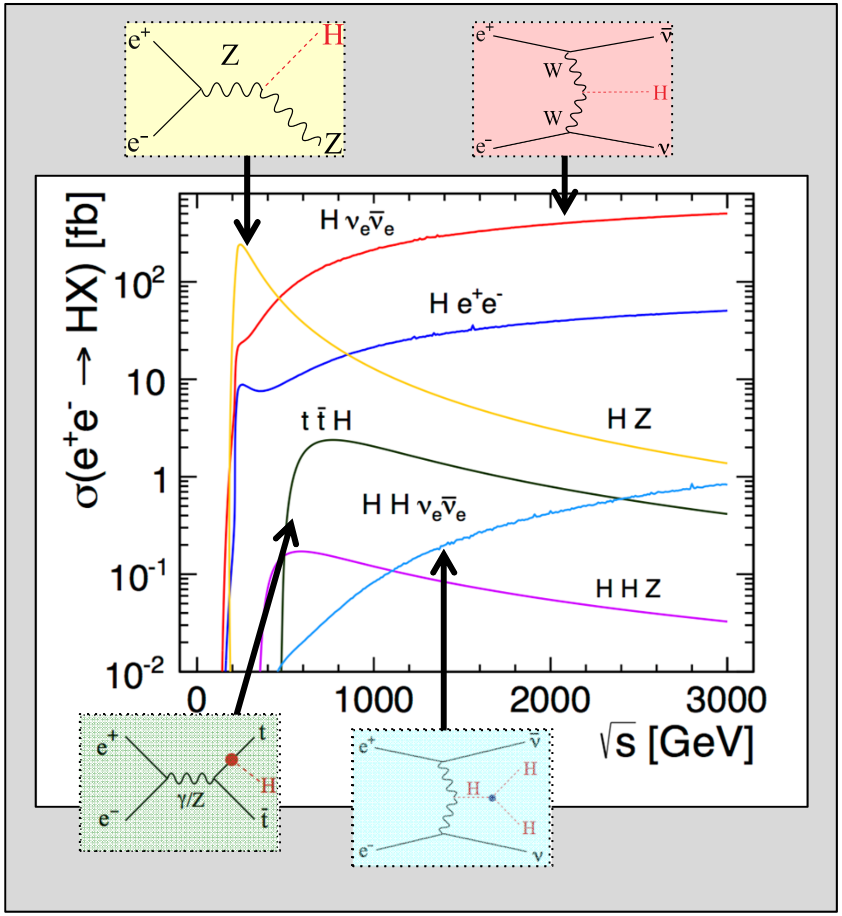
Exploration of E-frontier → look for heavy objects up to m ~30-50 TeV, including high-mass $V_L V_L$ scattering:

- ❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)
- → may require operating at higher pile-up than HL-LHC (~140 events/x-ing)
- ❑ events are mainly central → "ATLAS/CMS-like" geometry is ok
- ❑ main experimental challenges: good muon momentum resolution up to ~ 50 TeV; size of detector to contain up to ~ 50 TeV showers; forward jet tagging; pile-up

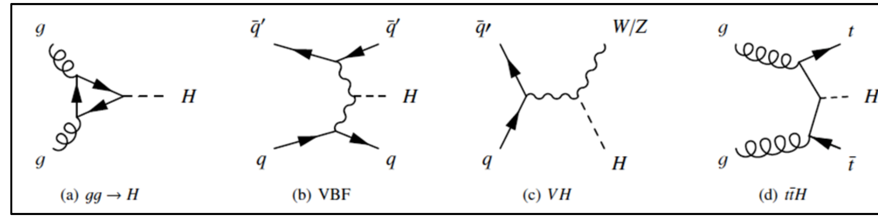
Precise measurements of Higgs boson:

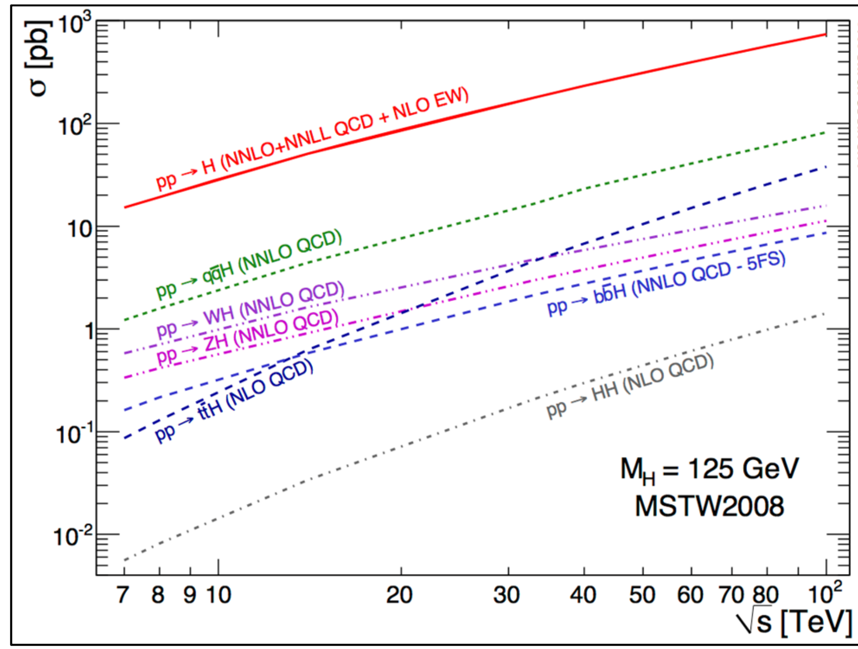
- ❑ would benefit from moderate pile-up
- ❑ light object → production becomes flatter in rapidity with increasing $\sqrt{s}$
- ❑ main experimental challenges: larger acceptance for precision physics than ATLAS/CMS → tracking/B-field and good EM granularity down to $|\eta|$~4-5; forward jet tagging; pile-up

Higgs production at e⁺e⁻ colliders



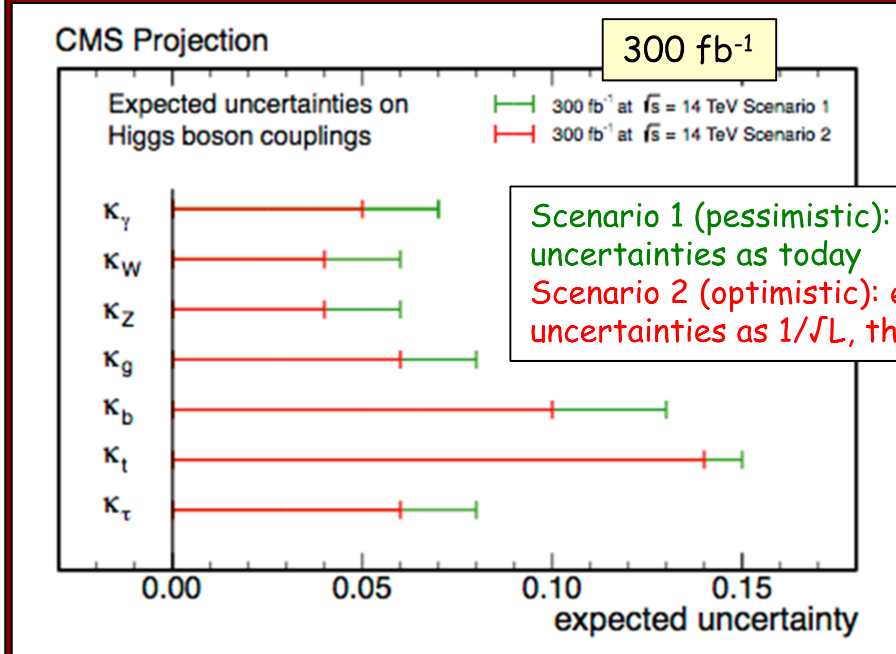
Higgs production at hadron colliders



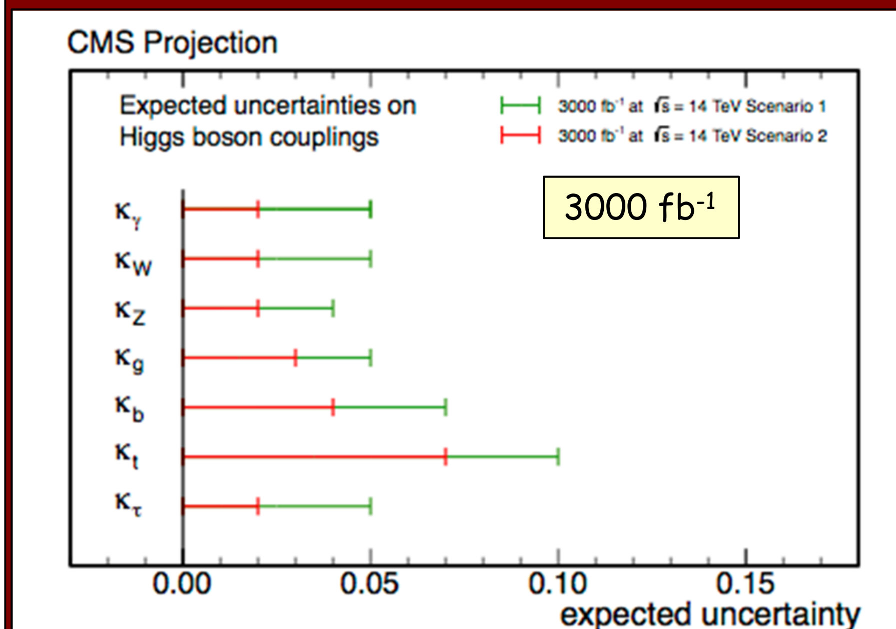


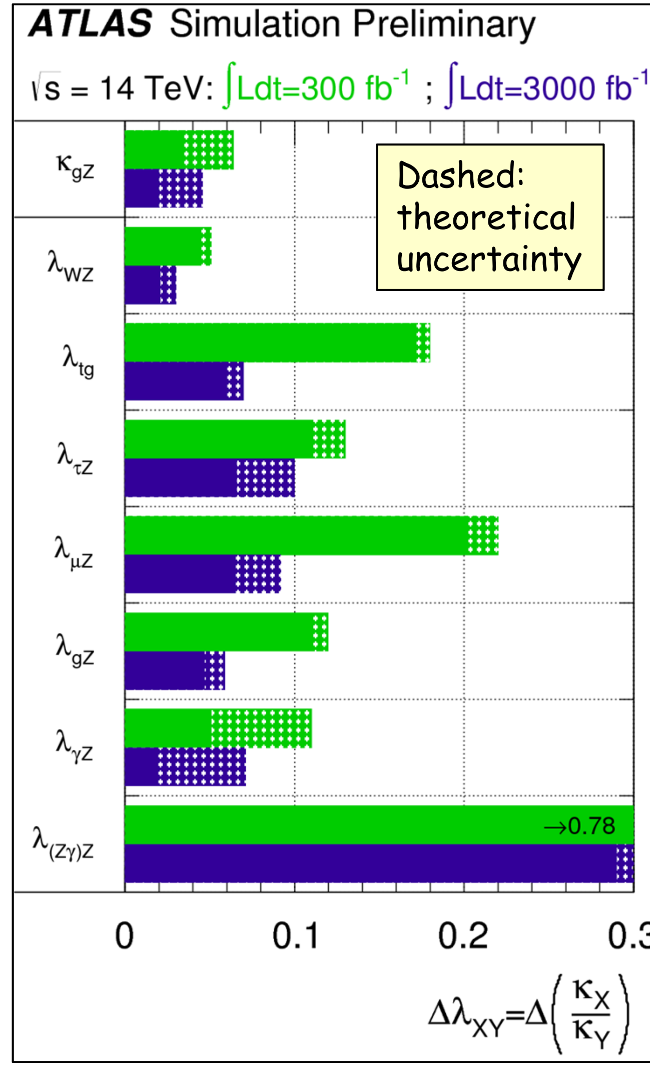
F. Gianotti, IPAC2014, 20/6/2014

Measurements of Higgs couplings



Scenario 1 (pessimistic): systematic uncertainties as today
Scenario 2 (optimistic): experimental uncertainties as $1/\sqrt{L}$, theory halved

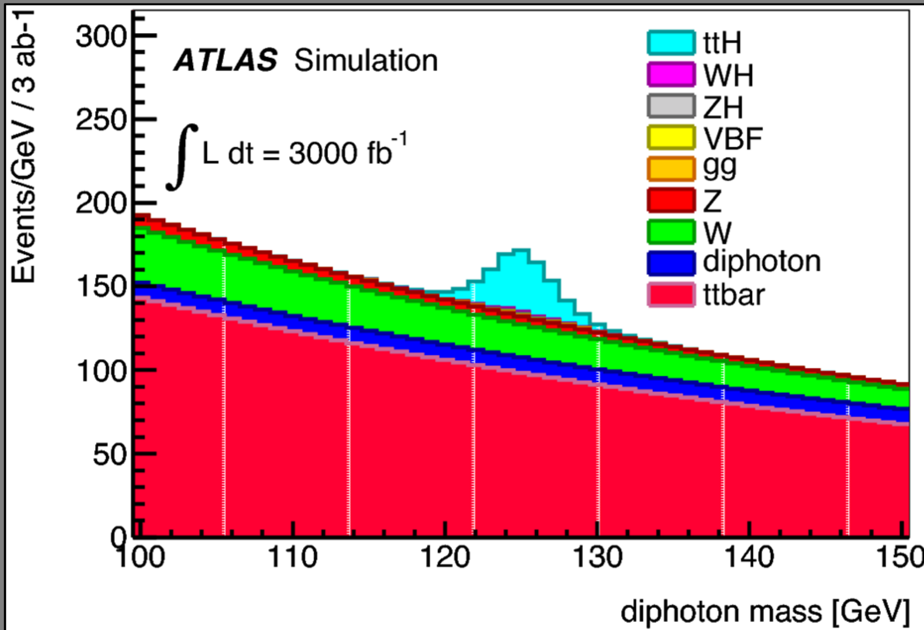




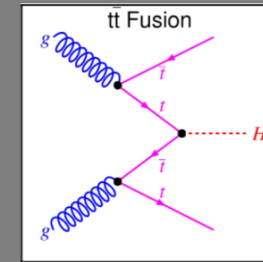
k_i= measured coupling normalized to SM prediction
$\lambda_{ij}=k_i/k_j$

Main conclusions:

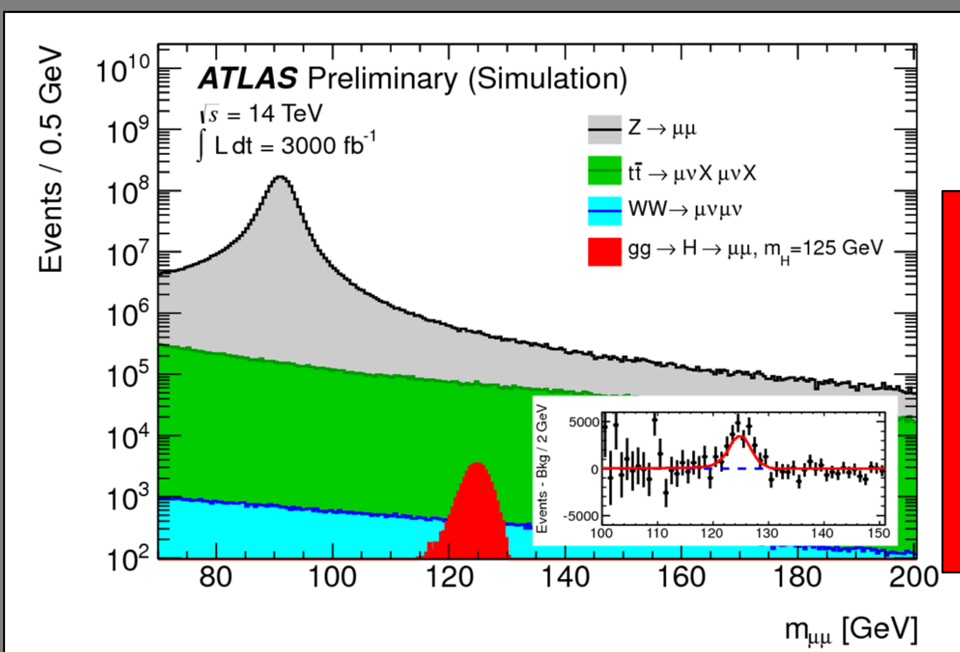
- 3000 fb^{-1}: typical precision 2-10% <u>per experiment</u> (except rare modes)
  → 1.5-2x better than with 300 fb^{-1}
- Crucial to also reduce theory uncertainties



ttH production with H → γγ



- ❑ Gives direct access to Higgs-top coupling (intriguing as top is heavy)
- ❑ Today's sensitivity: 6xSM cross-section
- ❑ With 3000 fb^{-1} expect 200 signal events (S/B ~ 0.2) and > 5σ
- ❑ Higgs-top coupling can be measured to about 10%

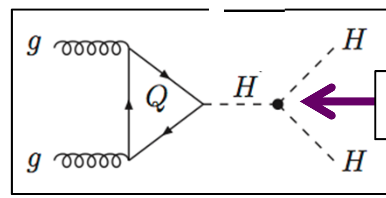


H → μμ

- ❑ Gives direct access to Higgs couplings to fermions of the second generation.
- ❑ Today's sensitivity: 8xSM cross-section
- ❑ With 3000 fb^{-1} expect 17000 signal events (but: S/B ~ 0.3%) and ~ 7σ significance
- ❑ Higgs-muon coupling can be measured to about 10%

Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
gg → HH[e]*(λ=1)*	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

Higgs cross sections (LHC HXS WG)



$g_{HHH} \sim \lambda v$

Higgs self-couplings difficult to measure at any facility (energy is mainly needed ..)

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

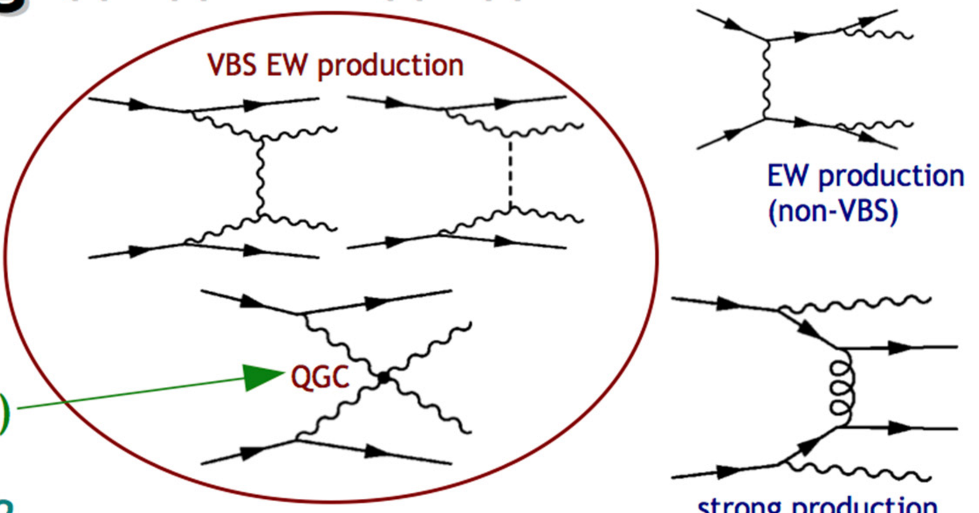
HL-LHC studies not completed yet … ~30% precision expected, but need 3000 fb^{-1}

Vector boson scattering $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$

At high energies, $WW \rightarrow WW$ and $ZZ \rightarrow ZZ$ processes test if the Higgs fully explains electroweak symmetry-breaking: vector boson scattering (VBS) processes

Sensitive to anomalous four-gauge boson interactions (quartic gauge coupling, QGC)

Search for $W^{\pm}W^{\pm}jj$ production in dilepton+2 jet final states, m(jj)>500 GeV



VBS

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} \cdots \right]$$

Observation of **anomalous quartic gauge coupling** would indicate **new physics in the electroweak symmetry breaking sector!**

- HL-LHC enhances discovery range for new higher-dimension electroweak operators by more than a factor of two

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

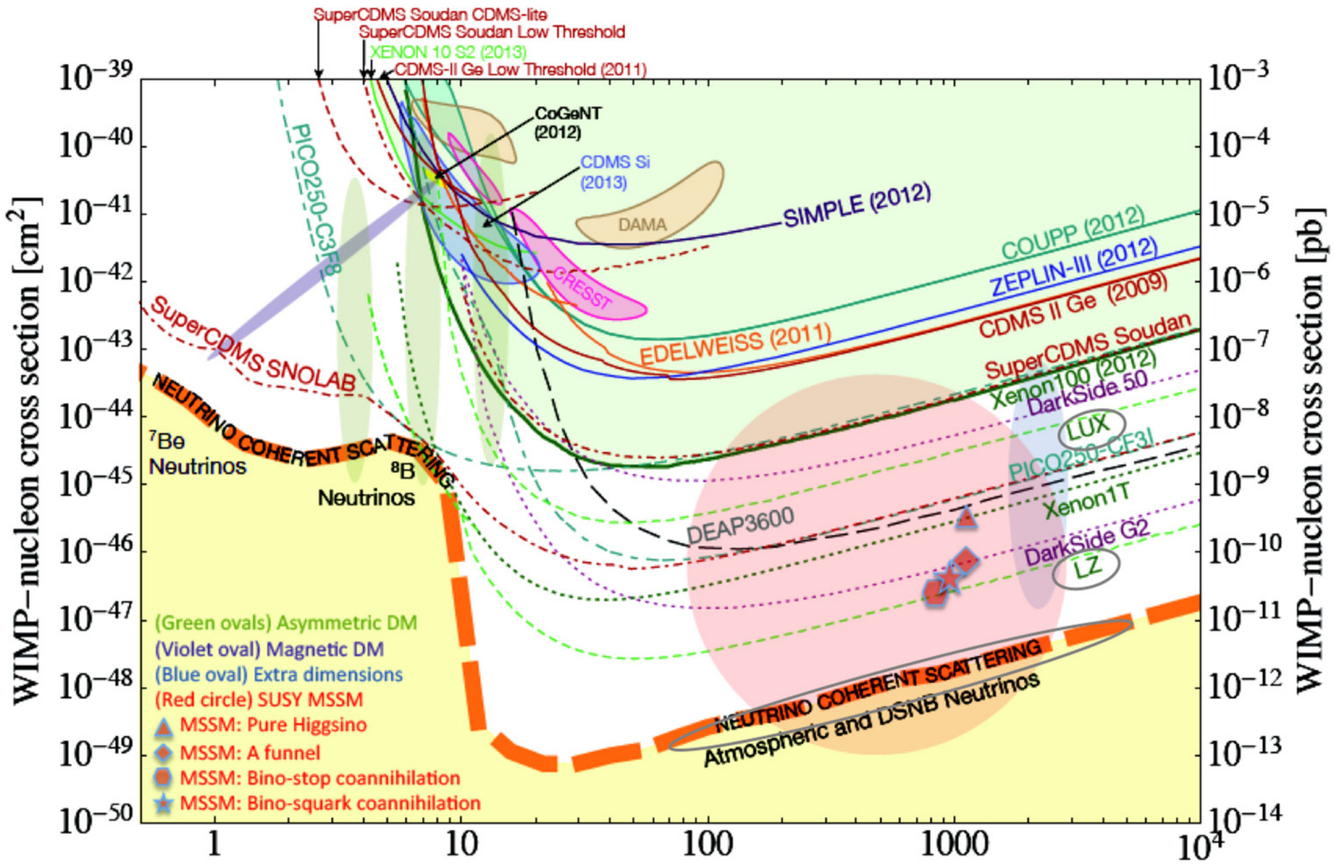
Λ_{UV}: unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1}

SM discovery expected with 185 fb^{-1}

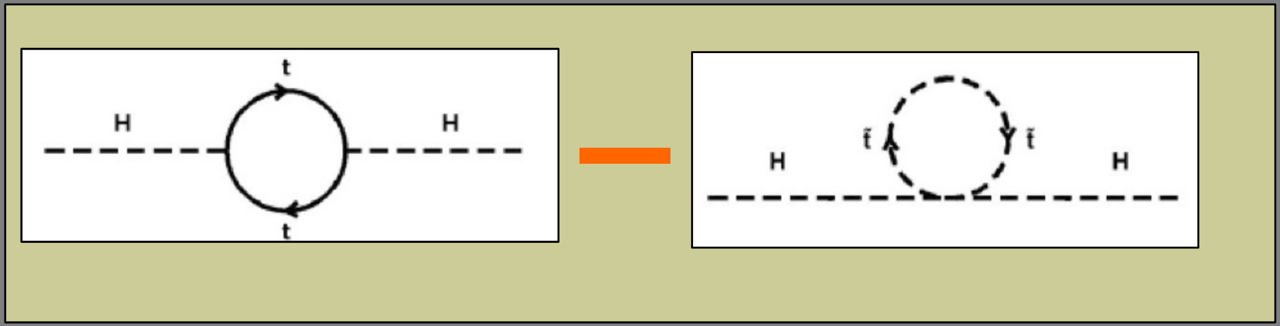
BSM contribution at TeV Scale might be observed at 300 fb^{-1}!

If BSM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

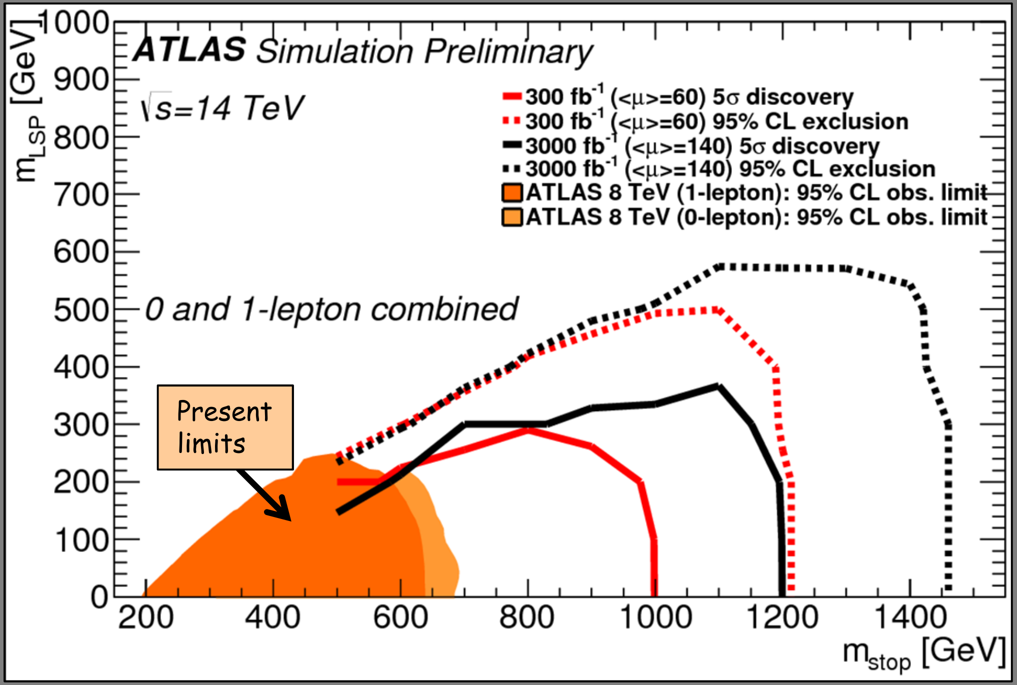
Dark Matter Direct Detection Experiments:
Limits and Future Sensitivity

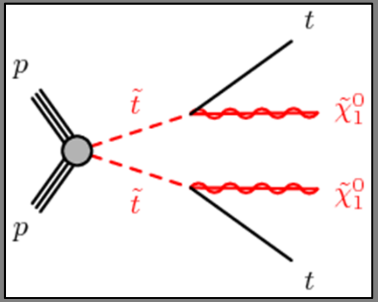


Snowmass CF1 Summary
arXiv:1310.8327



To stabilize the Higgs mass (without too much fine-tuning), the stop should not be much heavier than ~ 1-1.5 TeV (note: the rest of the SUSY spectrum can be heavier)





Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}
→ most of best motivated mass range will be covered at HL-LHC

Parameters of a ~ 100 TeV pp collider

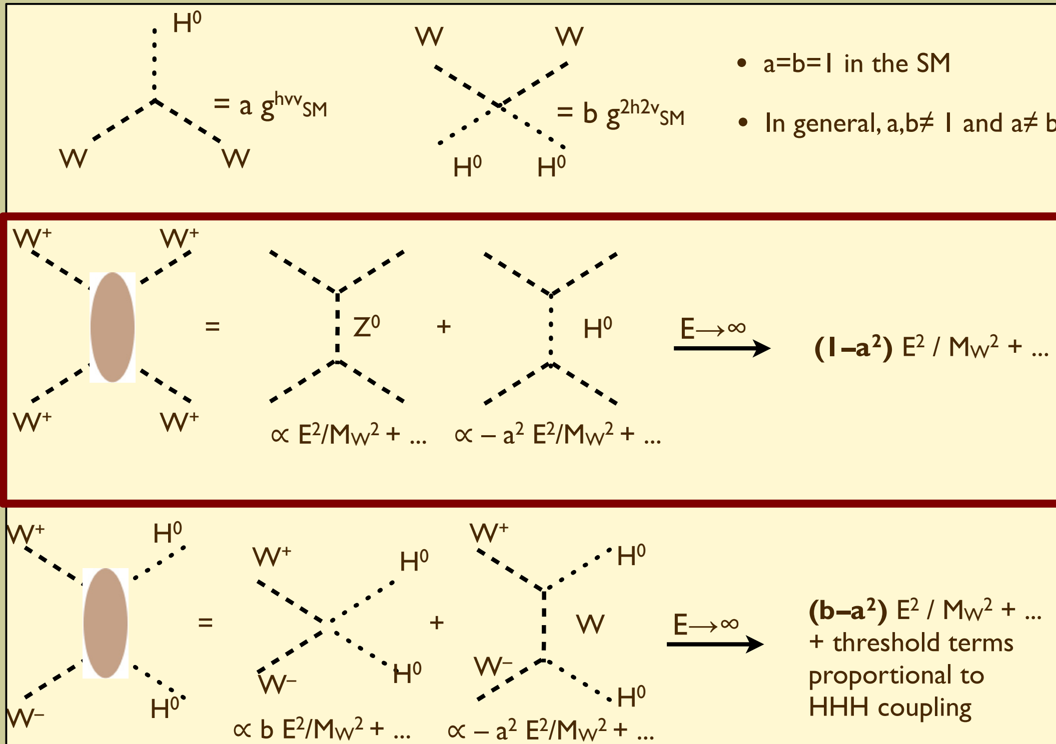
Version 1.0 (2014-02-11) Preliminary, in progress !	LHC	HL-LHC	FHC-hh
c.m. Energy [TeV]	14		100
Circumference C [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	171 34
Number of bunches at - 25 ns - 5 ns	2808		10600 (8900) 53000 (44500)
Bunch population N_b [10^{11}] - 25 ns - 5 ns	1.15	2.2	1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	3.75	2.5	2.2 0.44
IP beta function [m]	0.55	0.15 (min)	1.1
RMS IP spot size [mm] - 25 ns - 5 ns	16.7	7.1 (min)	6.8 3
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)

Nb_3Sn ok up to 16 T; 20 T needs HTS

Largest integrated luminosity needed for heavy physics
→ L=10^{35} may be reached
→ bunch-spacing 5 ns to mitigate pile-up and e-cloud

25 x LHC ! 1 Airbus 380 at full speed

A 100 TeV pp collider would allow a definitive exploration of EWSB



By providing direct access to EW theory in the unbroken regime ($\sqrt{\hat{s}} \gg v=246$ GeV)

$V_L V_L$ scattering violates unitarity at m_{VV} ~TeV without Higgs exchange diagrams

KEYWORD: ENERGY !

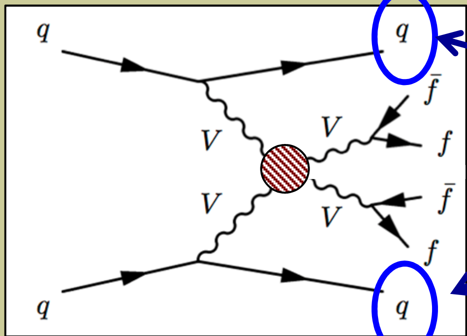
Important to verify that:

- ❑ H (125) regularizes the theory → a crucial "closure test" of the SM
- ❑ Or, else: observe deviations in VV production compared to SM expectation → anomalous quartic (VVVV) gauge couplings and/or new heavy resonances → new physics (Note: several models predict SM-like Higgs but different physics at high E)

- ❑ ILC 1 TeV, 1 ab^{-1} : indirect sensitivity to new resonances up to m~6 TeV (exploit $e^{\pm}$ polarization)
- ❑ CLIC 3 TeV, 1 ab^{-1} : indirect sensitivity to composite Higgs scale Λ~30 TeV from VV→ hh
- ❑ 100 TeV pp: huge cross-sections at high-mass: σ ~ 100 fb m_{WW}> 3 TeV; σ ~ 1 fb m_{HH} > 2 TeV

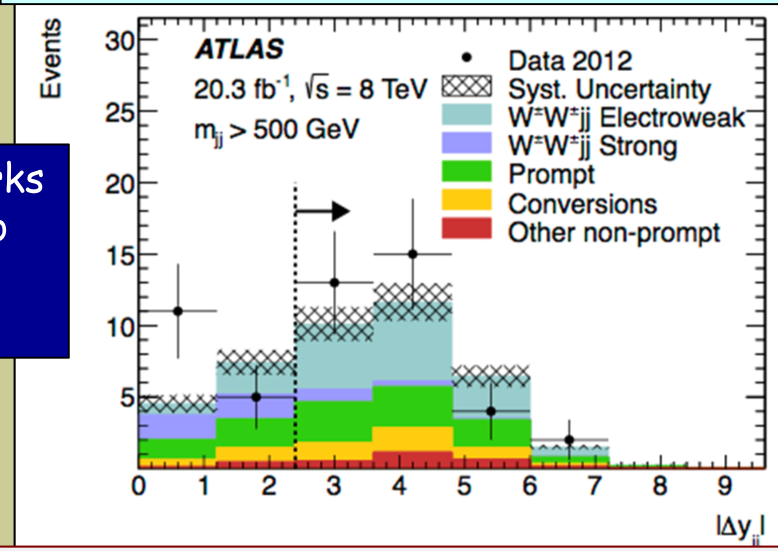
→ detailed <u>direct</u> studies

Evidence for EW VBS reported recently by ATLAS in $pp \rightarrow W^{\pm}W^{\pm}jj$ channel giving 2 same-sign leptons and 2 high-mass jets (m_{jj} > 500 GeV)



Tagging these forward quarks (jets) is crucial signature to distinguish EW VBS from the background

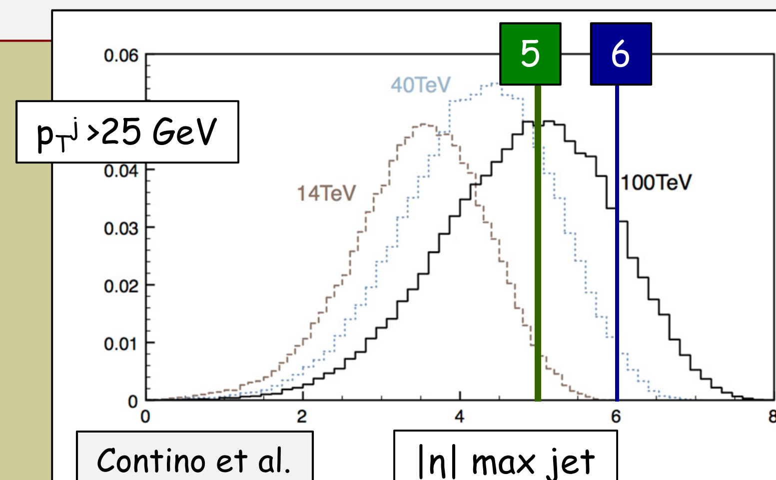
Significance of EW VBS signal: ~3.6σ for large rapidity gap between 2 jets



- HL-LHC: measure SM EW cross-section to 10%; x2 higher sensitivity to anomalous couplings than LHC@300 fb^{-1}, ~5% precision on parameters if new physics observed at LHC@300 fb^{-1}
- ILC 1 TeV, 1 ab^{-1} : indirect sensitivity to new resonances up to m~6 TeV (exploit $e^{\pm}$ polarization)
- CLIC 3 TeV, 1 ab^{-1} : indirect sensitivity to composite Higgs scale Λ~30 TeV from VV→ hh
- 100 TeV pp: huge cross-sections at high-mass: σ ~ 100 fb m_{WW}> 3 TeV; σ ~ 1 fb m_{HH} > 2 TeV

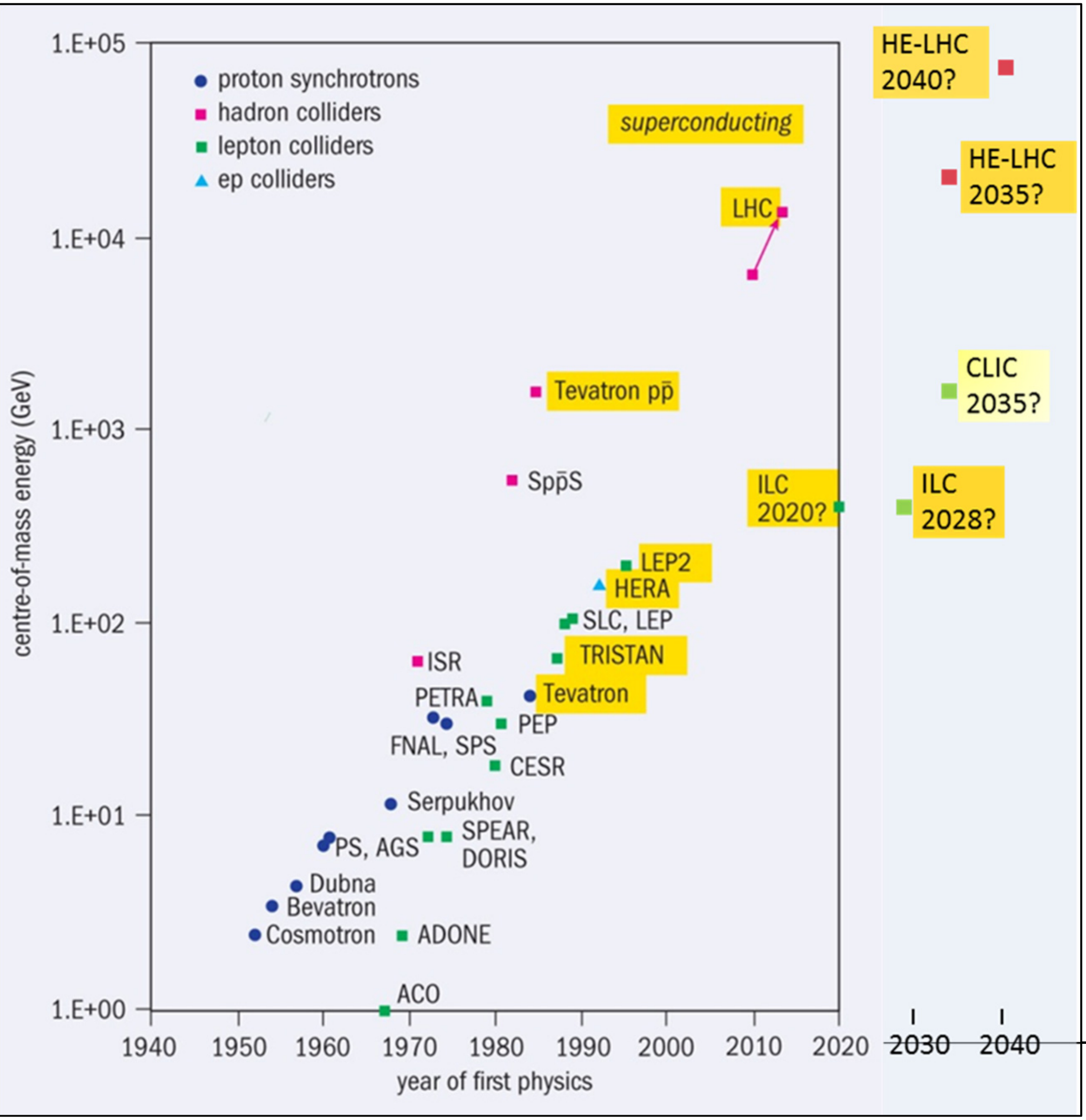
→ detailed direct studies

Maximum jet rapidity vs √s
→ calorimeter coverage over |η| ≥ 6 needed at 100 TeV pp collider (ATLAS, CMS: |η|< 5)
→ challenging: pile-up, radiation, … !!



'30s-'50s: particle physics based mainly cosmic ray observations → discovery of e^+, μ, ..

Accelerator-based particle physics starts in the '50s: here only very few examples



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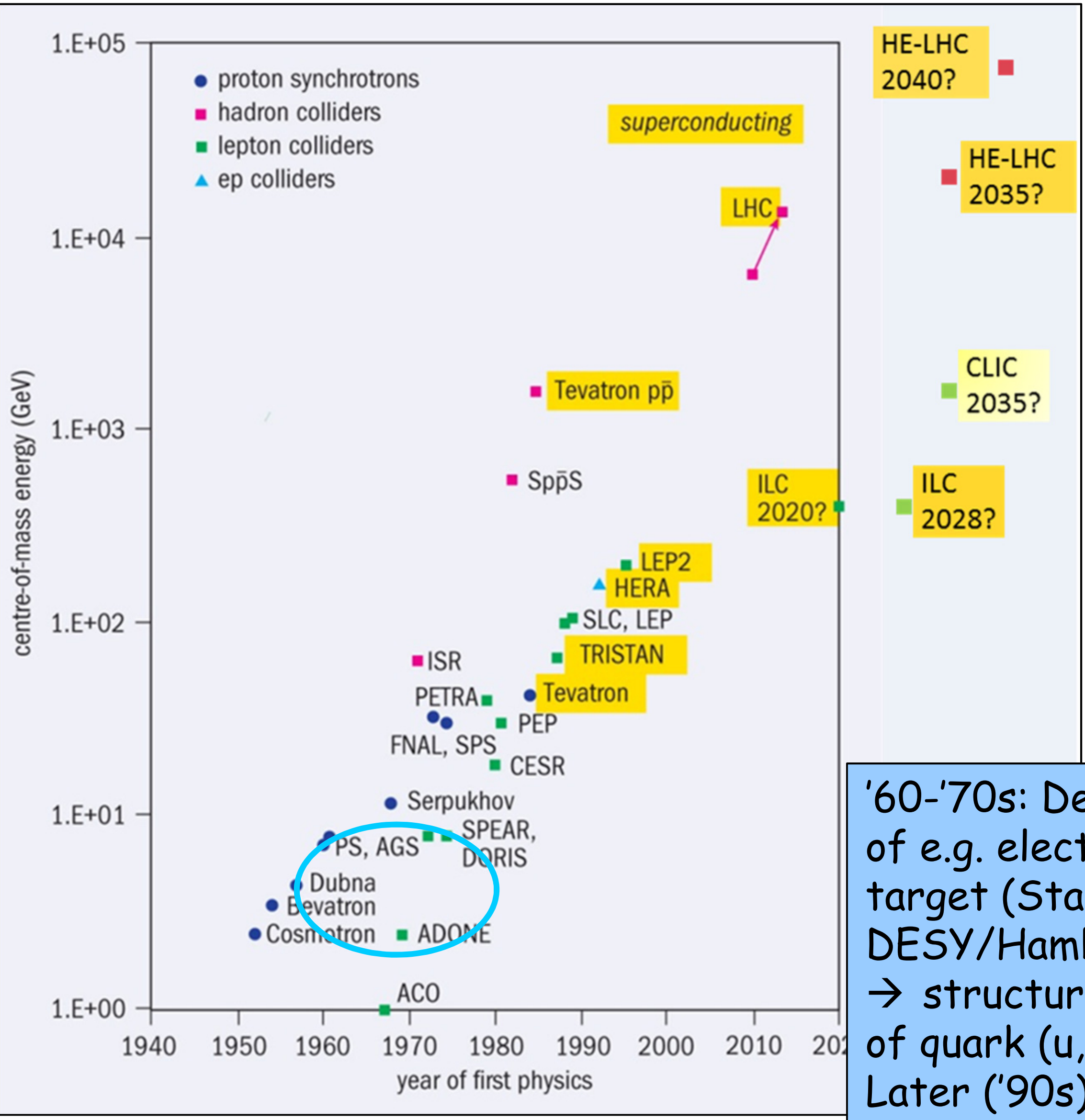
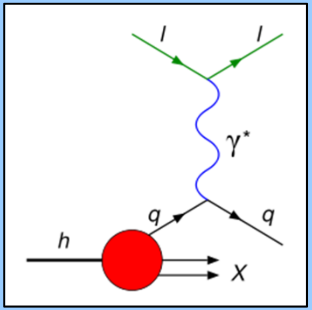


'60-'70s: Deep inelastic scattering of e.g. electron beams on fixed target (Stanford, DESY/Hamburg, etc.):
→ structure of n and p in terms of quark (u, d) constituents
Later ('90s): HERA ep collider



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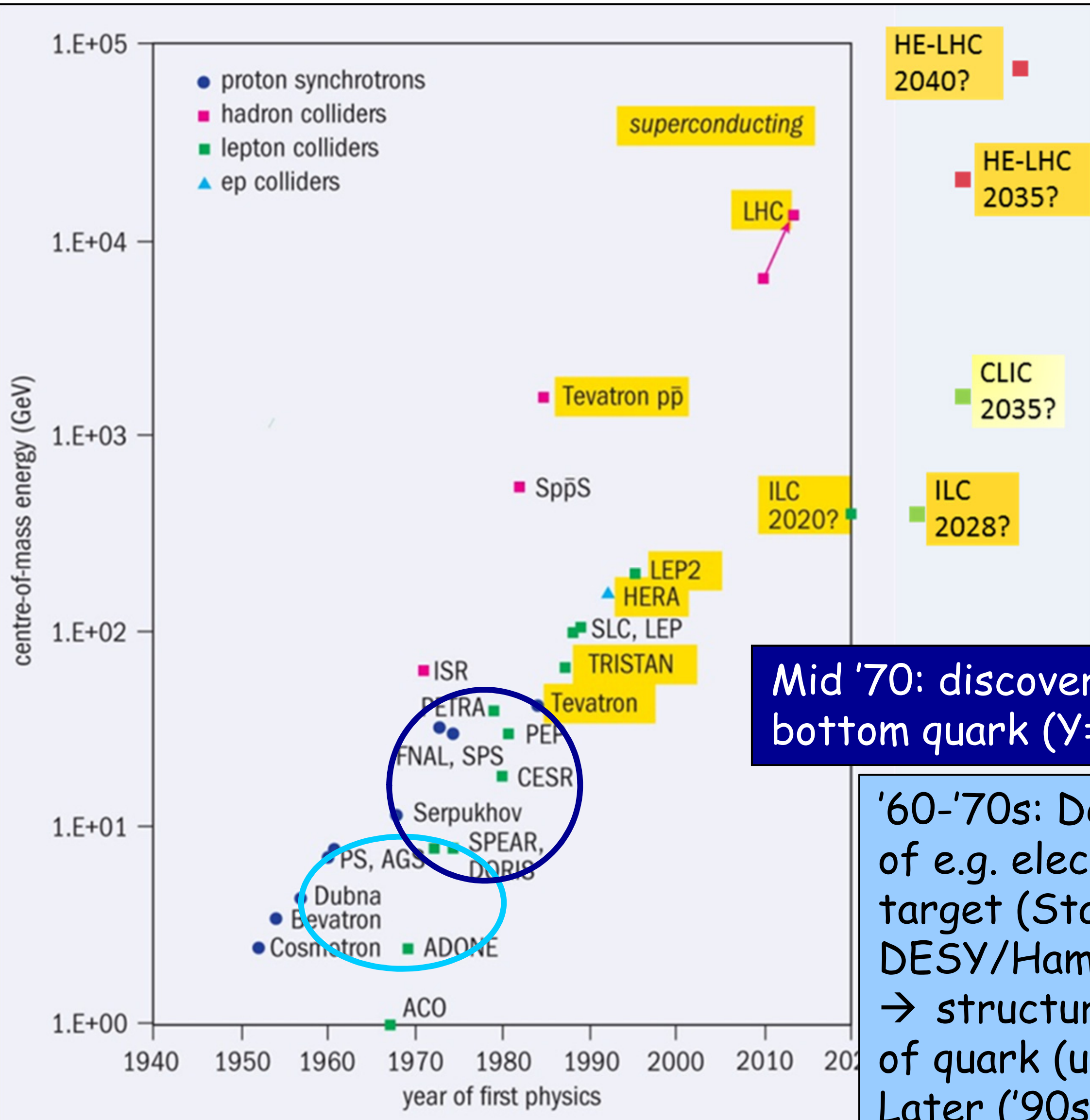

Mid '70: discovery of charm quark (J/ψ=cc BNL, SLAC), bottom quark (Υ=bb, FNAL), τ-lepton (SLAC)

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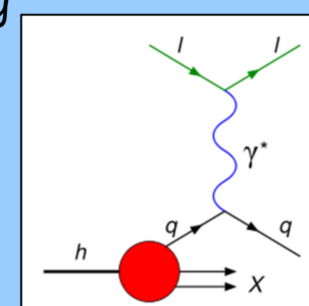

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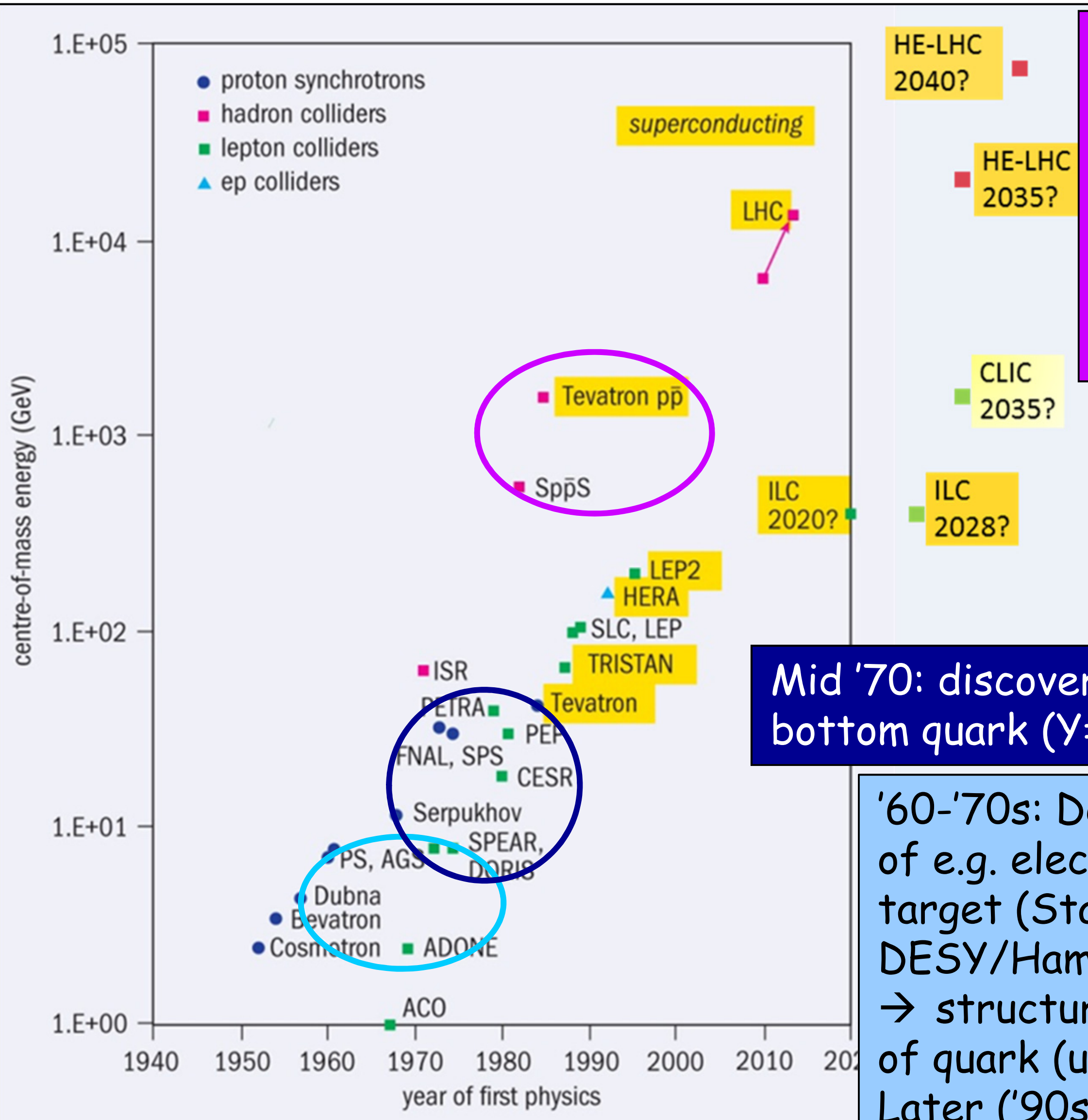

1983: Discovery of W, Z bosons (m ~ 100 GeV) at CERN p-antip collider ($\sqrt{s} \leq 630$ GeV)
1995: Discovery of the top quark (the heaviest elementary particle ever) at the Tevatron p-antip collider ($\sqrt{s} \leq 2$ TeV) at Fermilab/Chicago

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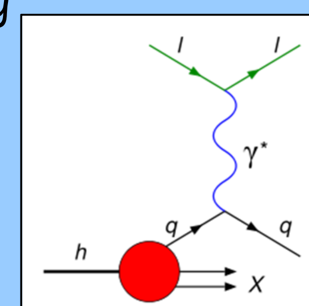

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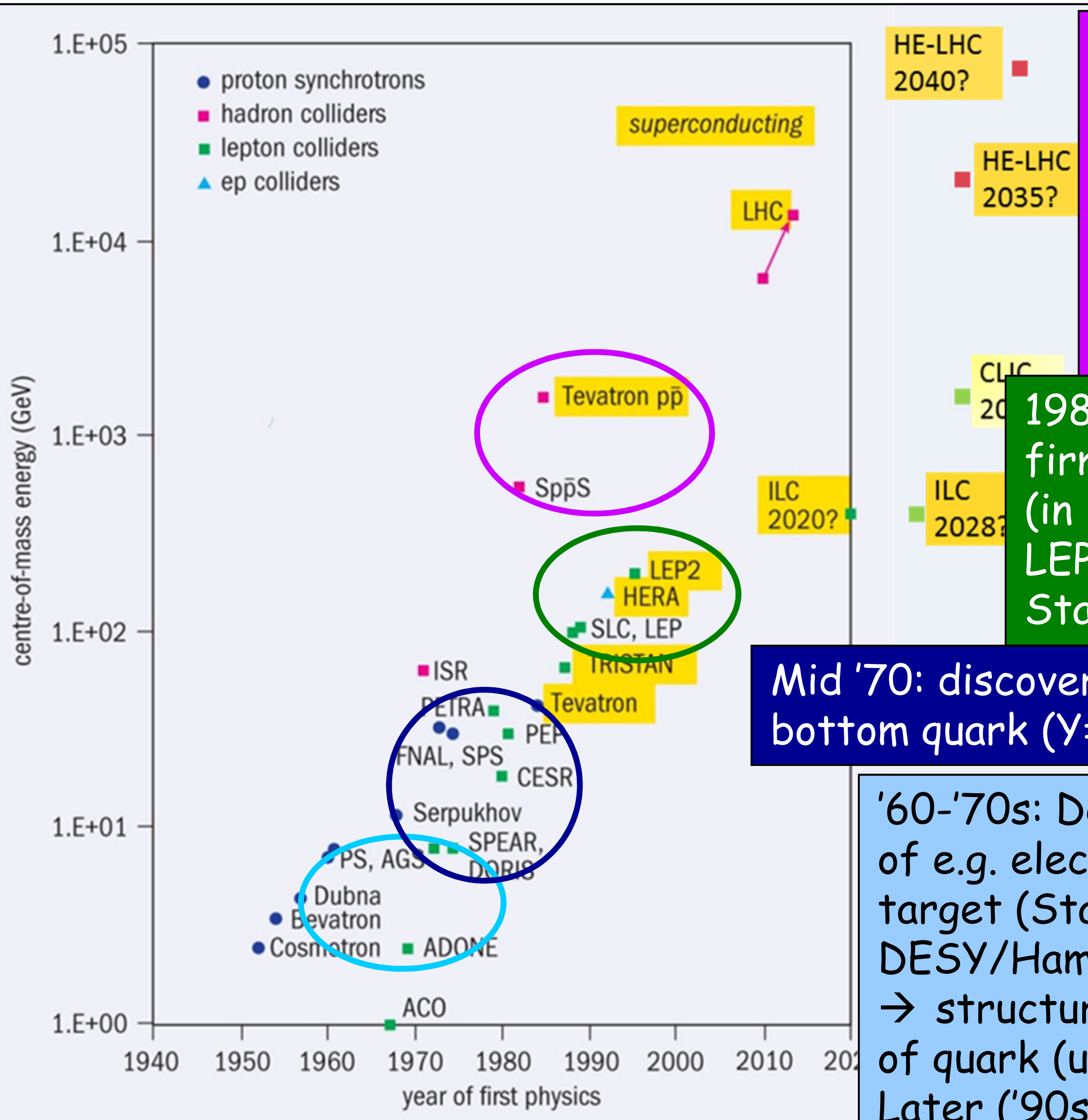

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1989-2000: Standard Model put on very firm grounds by precision measurements (in particular of Z boson) at e^+e^- colliders: LEP at CERN ($\sqrt{s} \to 209$ GeV) and Stanford Linear Collider ($\sqrt{s} \sim 90$ GeV)

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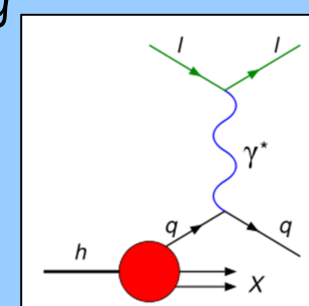


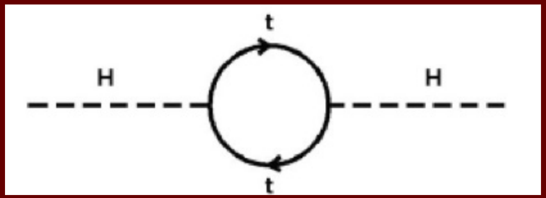
Future e^+e^- colliders

$L \sim 10^{34}$-10^{35} cm^{-2} s^{-1}

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

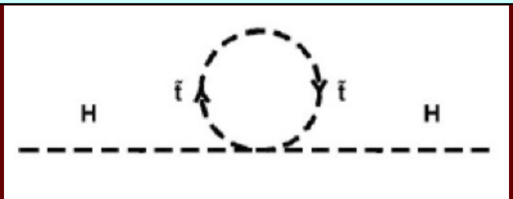
Complementary	Linear colliders	Circular colliders
$\sqrt{s}$ reach	multi-TeV	limited to < 500 GeV by synchrotron radiation SR ~ E^4_{beam}/R
Luminosity	low repetition rate → L from squeezing beams to ~ nm size → large beamstrahlung	large number of continuously circulating bunches → larger beam size → smaller beamstrahlung → cleaner environment, smaller E spread
Injection	fresh bunches need to be injected at each cycle	short L lifetime (~ 30′) due to burn-off → continuous top-up $e^\pm$ injection
L vs $\sqrt{s}$	increases at high E (beam emittance decreases)	increases at low E (less SR → RF power accelerates more bunches)
Number of interaction regions	1 (shared by 2 detectors push/pull?)	several

Why is the Higgs so light ?



In the SM, corrections to m_H diverge as $\Delta M_H^2 \sim \Lambda^2$ (Λ = E scale up to which SM is valid)
"Naturalness" problem

→ Need new physics (close-by, ~TeV scale) to "stabilize" the divergent Higgs mass



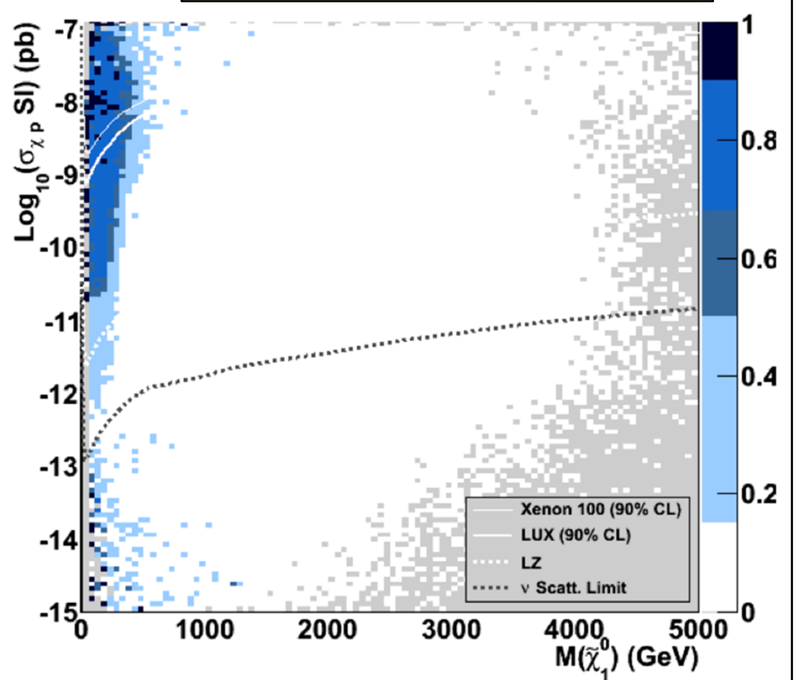
E.g. the SUSY partner of the top (stop) gives rise to same diagram with opposite sign → cancellation
Searches for stop quarks so far unsuccessful
HL-LHC can probe up to 1.5 TeV

Dark Matter searches

Fraction of minimal SUSY parameter space that can be excluded at 95% CL by present experimental constraints and direct DM searches at pp colliders

Arbey, Battaglia, Mahmoudi

HL-LHC, 14 TeV 3000 fb^{-1}



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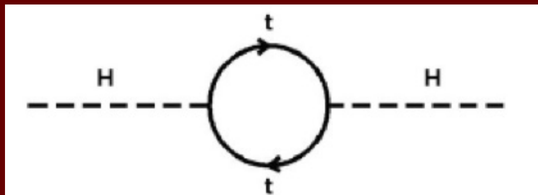

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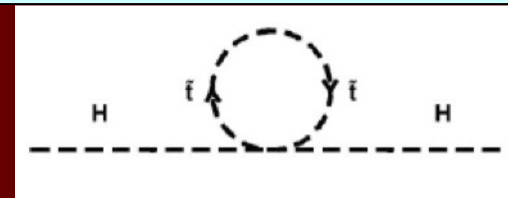

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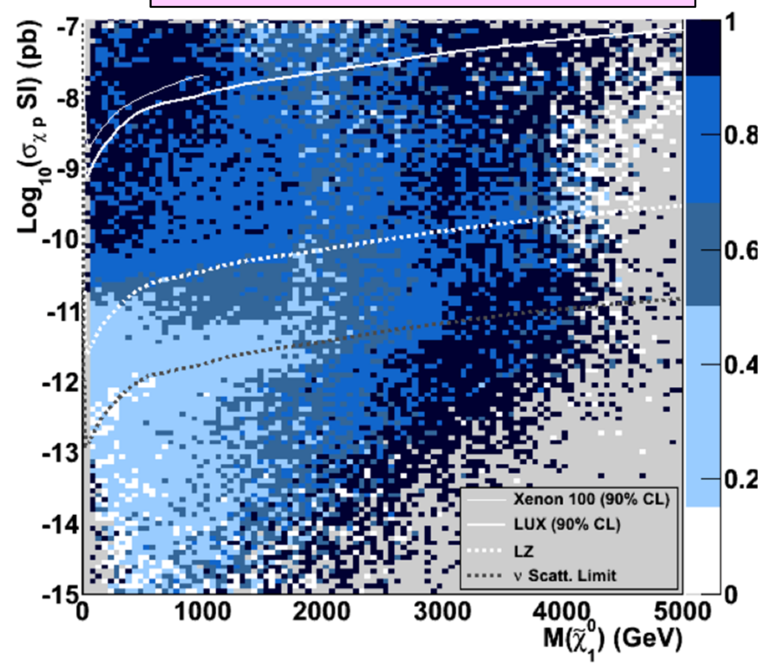
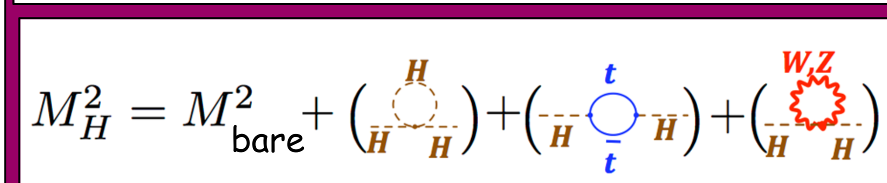
FCC-hh, 100 TeV 5000 fb^{-1}



Arbey, Battaglia, Mahmoudi

The problem of the stability of the Higgs mass a.k.a "naturalness" problem

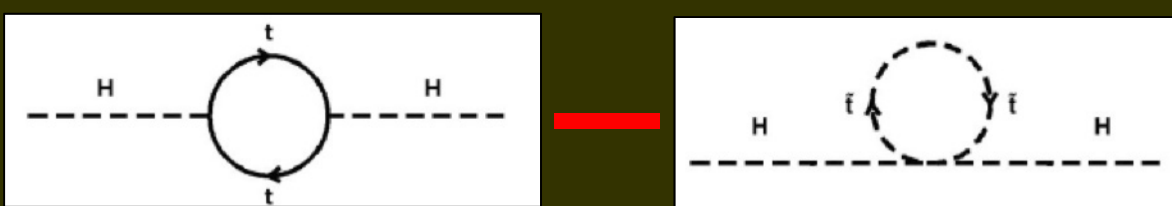
As any other particle ($e^{\pm}$, …) in quantum mechanics Higgs mass receives radiative corrections



Mostly small, except top contribution: ~ $m_t^2\Lambda^2$
Λ^2 = energy scale up to which the SM is valid (or, equivalently, new physics sets in)

2 solutions

1) "Naturalness": Higgs mass stabilized by new physics that cancel the divergences.
E.g. SUSY: the contribution of the supersymmetric partner of the top (stop) gives rise to the same contribution with opposite sign → cancellation

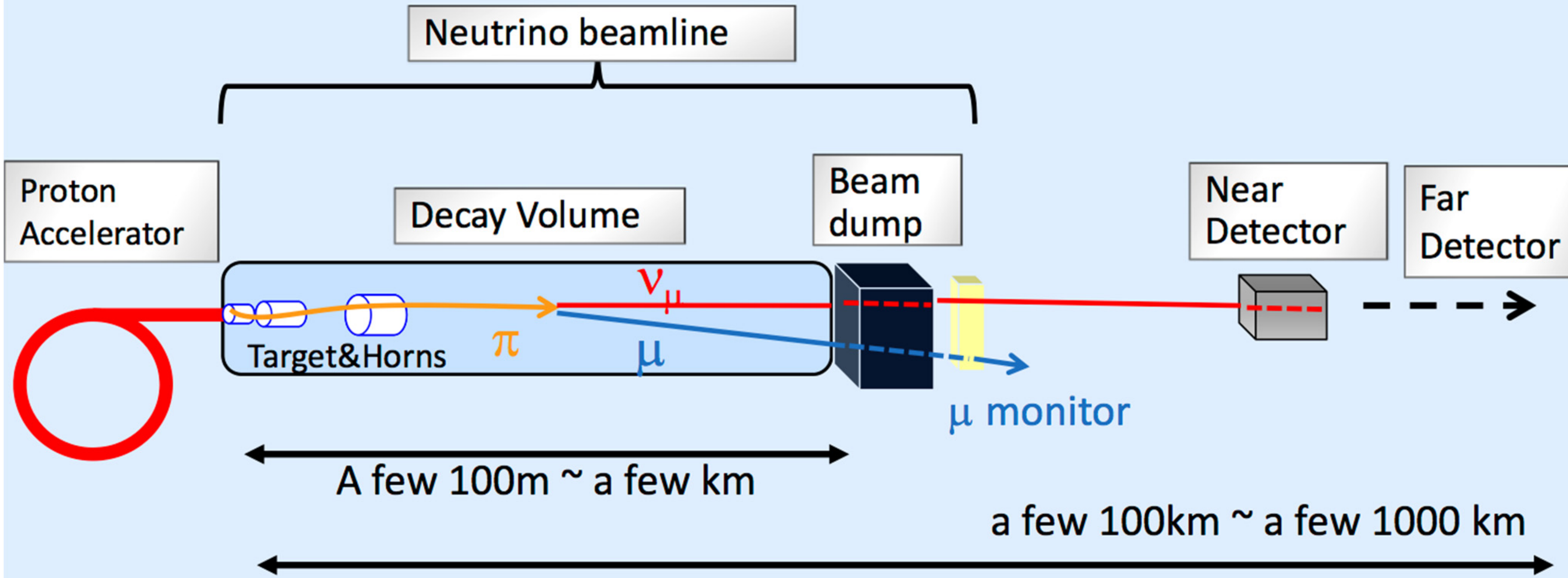


BUT: cancellation only works if stop mass not much larger than top mass → this is one of most compelling motivations for SUSY (or new physics) at TeV scale

2) "Fine tuning": the bare mass cancels the radiative corrections → this becomes more and more "acrobatic" the higher the scale Λ up to which SM is valid (w/o new physics)

E.g. Λ = 10 TeV → M^2 (rad. corr) = 8265625 GeV^2 → need fine-tuned M_{bare}^2 = 8281250 GeV^2 to get M_H^2= (125 GeV)^2 = 15262 GeV^2
Λ= 10^{19} GeV → need fine tuning of M_{bare} to the 33rd digit !! → UNNATURAL

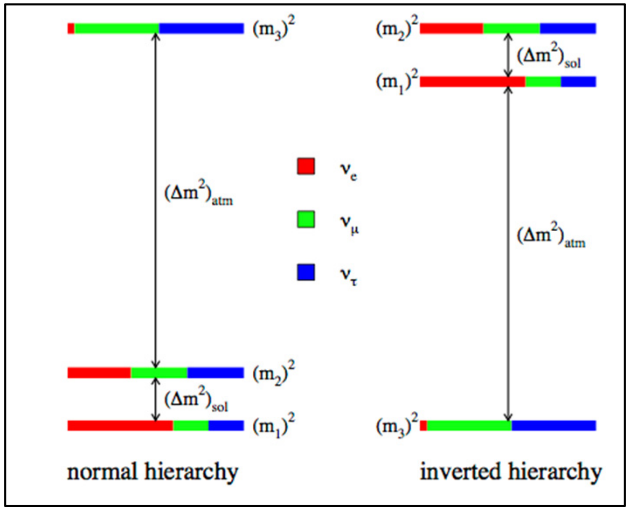
Components of the Long Baseline Neutrino Experiment



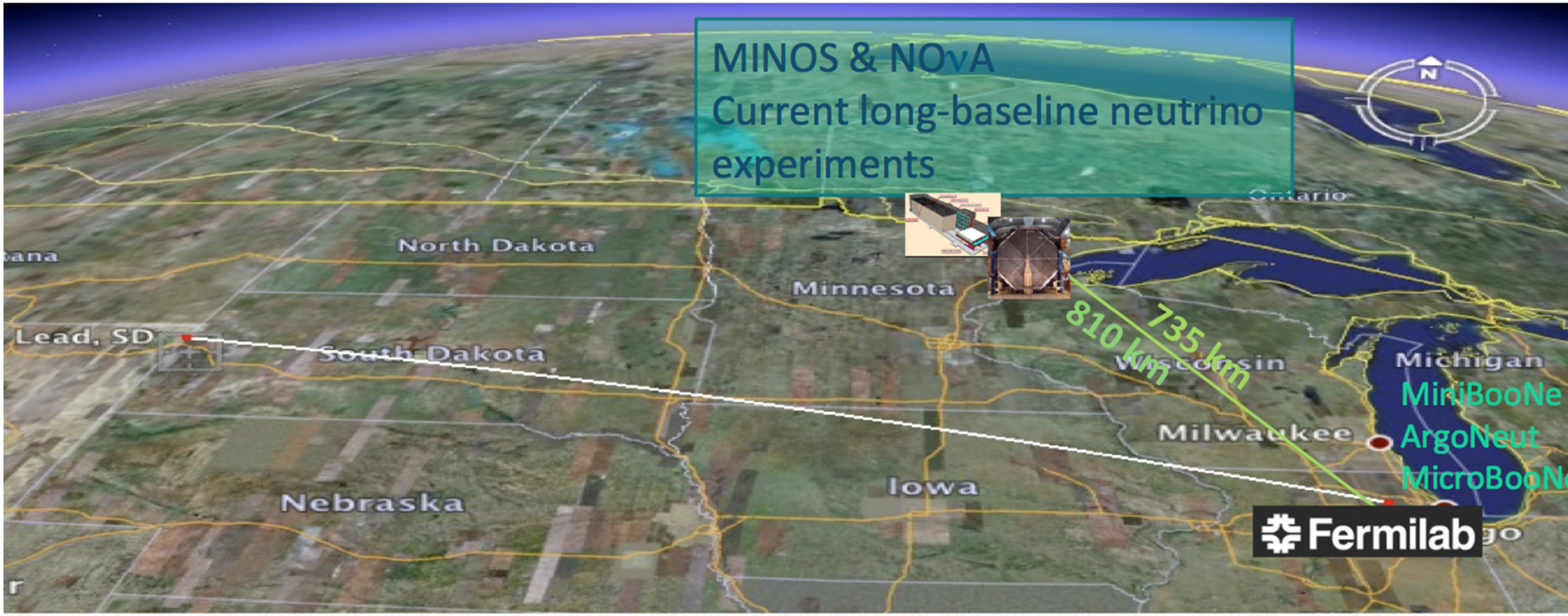
Example:

~1ν/cm^2/s at T2K Far detector(295km away)
(@750kW proton beam power)
among which 10^{-10} interact.

A.K. Ichiawa



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$


MINOS & NOνA
Current long-baseline neutrino
experiments
North Dakota
Minnesota
Lead, SD
South Dakota
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
810 km
735 km
MiniBooNe
ArgoNeut
MicroBooNe
Fermilab