Outlook and Future Prospects for HEP

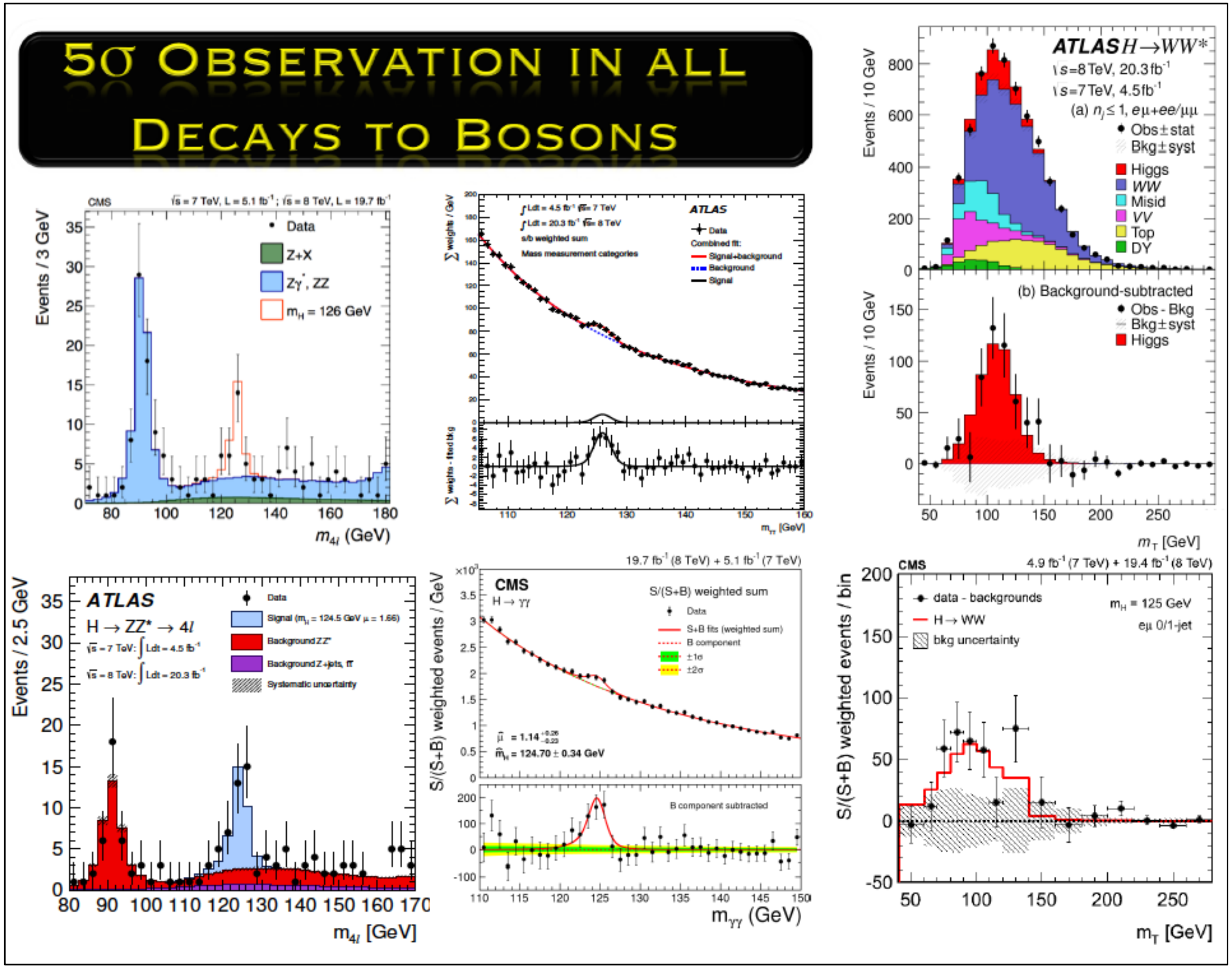
CERN-JINR European School of High Energy Physics
Bansko, Bulgaria
2 - 15 September 2015

Tatsuya Nakada
EPFL-LPHE
Lausanne, Switzerland

Current Situation (I)

- We learned that the Standard Model is now complete
  - All the necessary particles discovered

Including Higgs

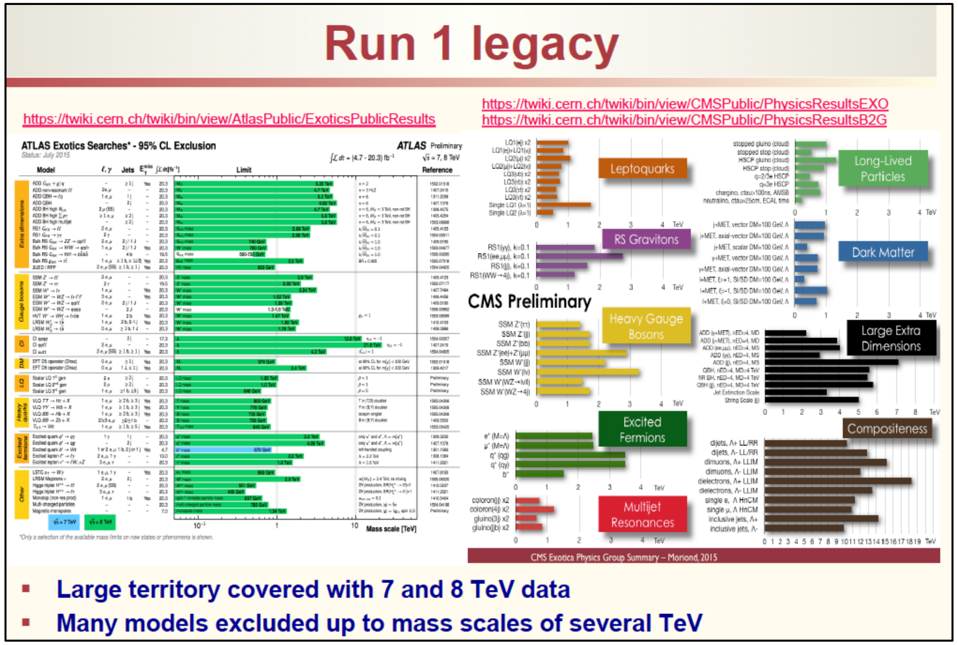


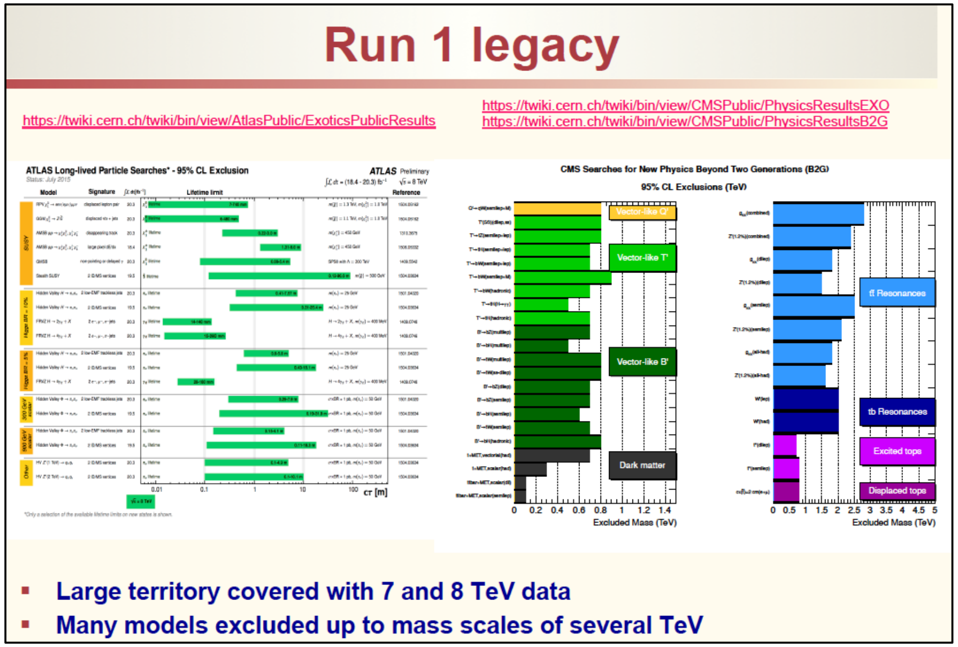
by Pierre Savard, EPS 2015 Vienna

Current Situation (I)

- We learned that the Standard Model is now complete
  - All the necessary particles discovered
  - No additional particle discovered

New particle search by ATLAS and CMS





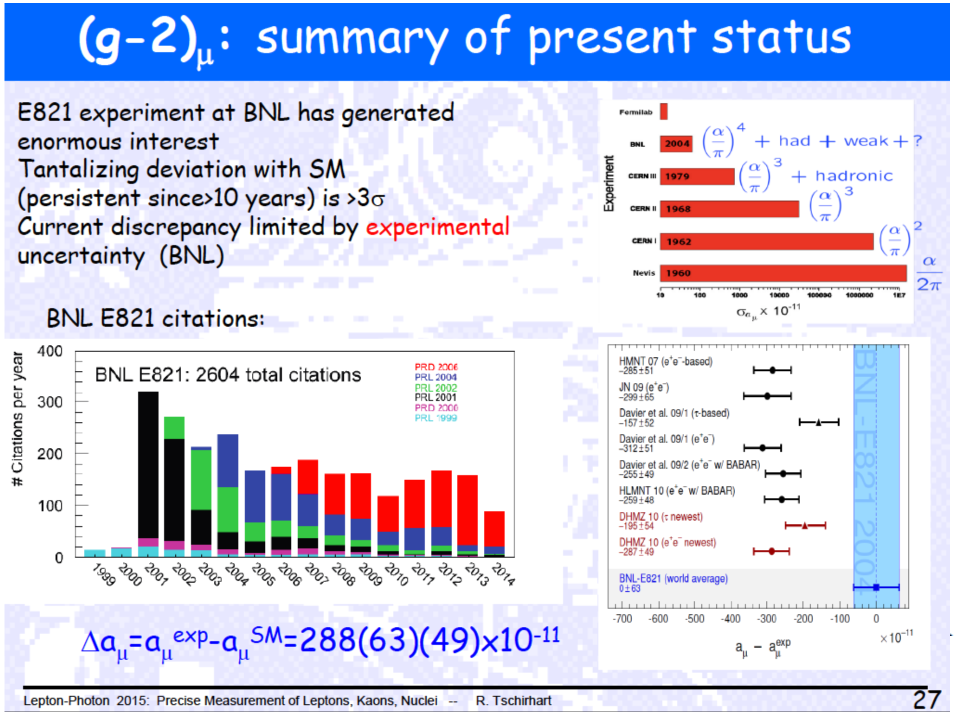
by Ivan Mikulec, EPS 2015 Vienna

Current Situation (I)

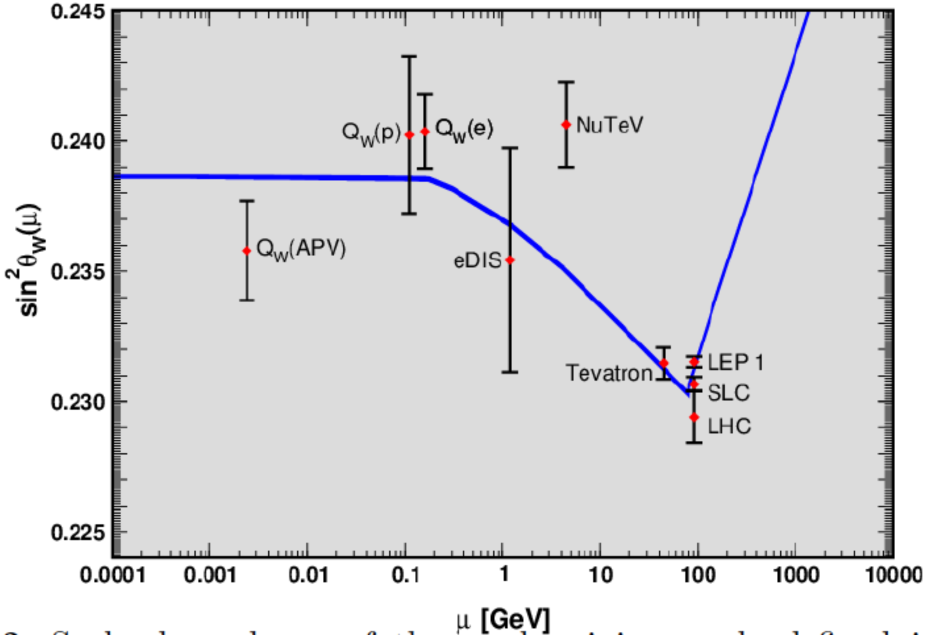
- We learned that the Standard Model is now complete
  - All the necessary particles discovered
  - No additional particle discovered
  - Precision measurements in electroweak and flavour physics are in agreement with the Standard Model predictions:

Current Situation (I)

- We learned that the Standard Model is now complete
  - All the necessary particles discovered
  - No additional particle discovered
  - Precision measurements in electroweak and flavour physics are in agreement with the Standard Model predictions: with some interesting deviations…
    - $\mu(g-2)$ with ~3σ, A^{b}_{FB} with ~2.6σ, θ_W from NuTeV?
    - some interesting features in $b\to s l^+ l^-$ signature?
    - $Br(B\to D^{(*)}\tau\nu)/Br(B\to D^{(*)}\mu\nu)$, $Br(B\to K\mu\mu)/Br(B\to Kee)$
    - $Re(\varepsilon'/\varepsilon)$ too large by (2~3σ)? …



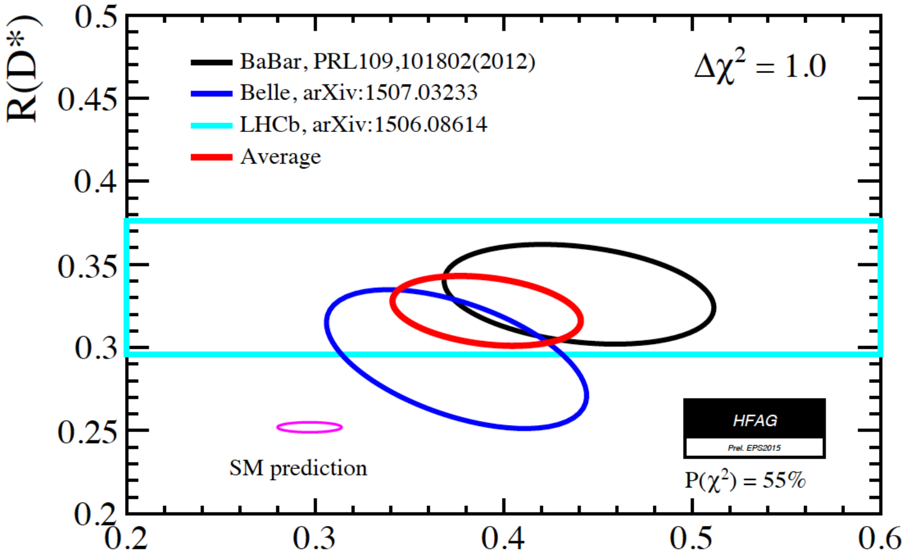
by Bob Tschirhart, Lept-Phot 2015, Ljubljana



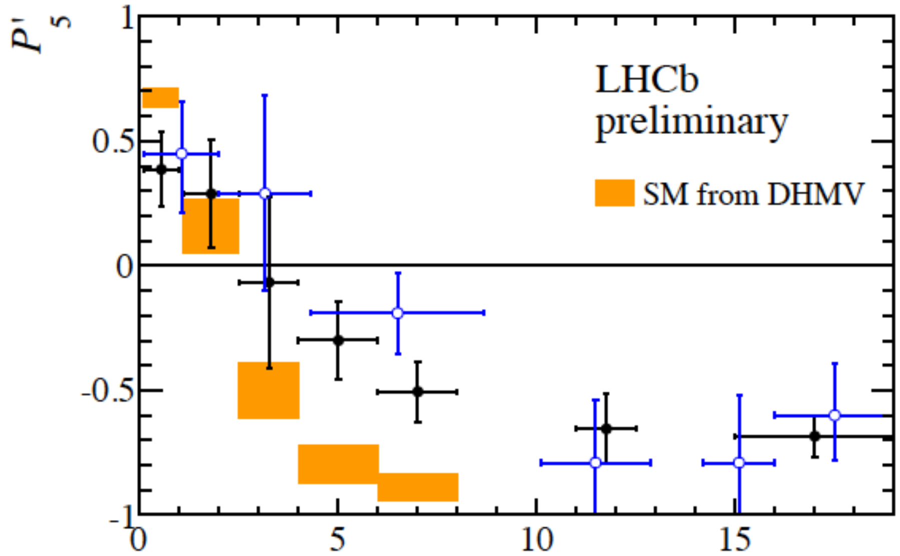
2014 Review of Particle Physics

$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01616 ± 0.00008	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1029 ± 0.0003	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0003	-0.5

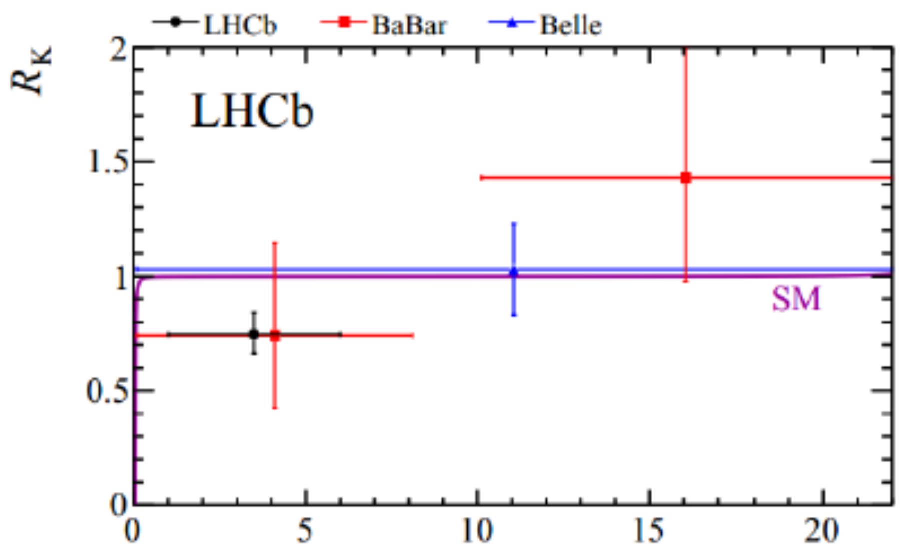
2014 Review of Particle Physics



HFAG EPS-HEP 2015 average



LHCb-CONF-2015-002



LHCb PRL 2014

Anatomy of ε'/ε – A new flavour anomaly?

AJB, Gorbahn, Jäger, Jamin,, 1507.xxxx

(3.2σ) $\varepsilon'/\varepsilon = (2.2 \pm 3.8) \cdot 10^{-4}$ — RBC-QCD values $B_6^{(1/2)} = 0.57 \pm 0.15$, $B_8^{(3/2)} = 0.76 \pm 0.05$

$\varepsilon'/\varepsilon = (6.3 \pm 2.5) \cdot 10^{-4}$ — large N bounds (AJB, Gérard) $B_6^{(1/2)} = B_8^{(3/2)} = 0.76$

$\varepsilon'/\varepsilon = (9.1 \pm 3.3) \cdot 10^{-4}$ — large N bounds (AJB, Gérard) $B_6^{(1/2)} = B_8^{(3/2)} = 1.0$

exp: $\varepsilon'/\varepsilon = (16.6 \pm 3.3) \cdot 10^{-4}$

by Andrzej Buras, EPS 2015 Vienna

Current Situation (I)

- We learned that the Standard Model is now complete
  - All the necessary particles discovered
  - No additional particle discovered
  - Precision measurements in electroweak and flavour physics are in agreement with the Standard Model predictions: with some interesting deviations…
    - μ(g−2) with ~3σ, A^{b}_{FB} with ~2.6σ, θ_W from NuTeV?
    - some interesting features in $b \to s l^{+} l^{-}$ signature?
    - $Br(B \to D^{(*)}\tau\nu)/Br(B \to D^{(*)}\mu\nu)$, $Br(B \to K\mu\mu)/Br(B \to Kee)$
    - $Re(\varepsilon'/\varepsilon)$ too large by (2~3σ)?…
  - No deeper understanding on the structure of the Standard Model: mass matrix (quark&leptons), three generations, three different gauge interactions, small $<\theta_{QCD}>$ i.e. no CPV in strong interactions, m_H, etc. etc. …

Current Situation (I)

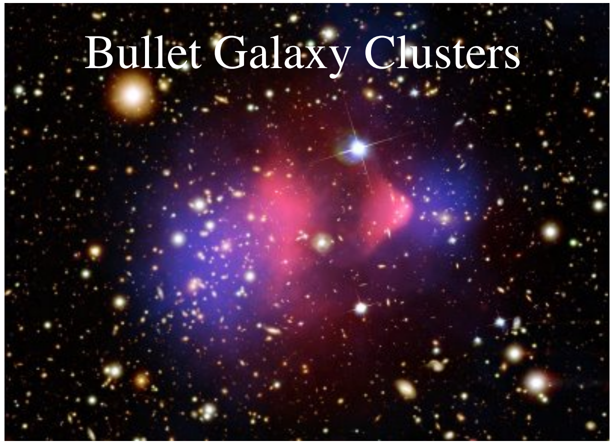
- We learned that the Standard Model is now complete
  - All the necessary particles discovered
  - No additional particle discovered
  - Precision measurements in electroweak and flavour physics are in agreement with the Standard Model predictions: with some interesting deviations…
    - $\mu(g-2)$ with ~3σ, A^{b}_{FB} with ~2.6σ, θ_W from NuTeV?
    - some interesting features in $b \to s l^+ l^-$ signature?
    - $Br(B \to D^{(*)}\tau\nu)/Br(B \to D^{(*)}\mu\nu)$, $Br(B \to K\mu\mu)/Br(B \to Kee)$
    - $Re(\varepsilon'/\varepsilon)$ too large by (2~3σ)?…
  - No deeper understanding on the structure of the Standard Model: mass matrix (quark&leptons), three generations, three different gauge interactions, small $<\theta_{QCD}>$ i.e. no CPV in strong interactions, m_H, etc. etc. …

Current Situation (II)

- Observational evidences for New Physics
  - Neutrino oscillations, i.e. $m_\nu \neq 0$ (0 in SM)

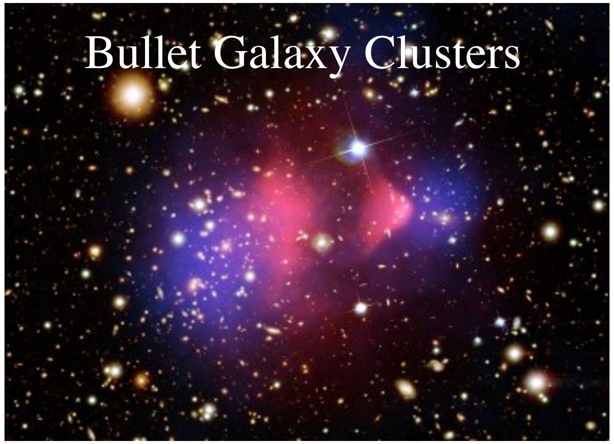
Current Situation (II)

- Observational evidences for New Physics
  - Neutrino oscillations, i.e. $m_\nu \neq 0$ (0 in SM)
  - Dark matter (no SM candidate)

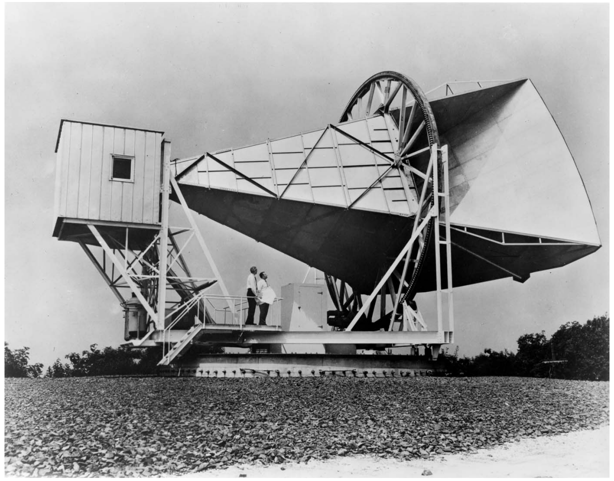


Current Situation (II)

- Observational evidences for New Physics
  - Neutrino oscillations, i.e. $m_\nu \neq 0$ (0 in SM)
  - Dark matter (no SM candidate)
  - $N_B / N_\gamma = 10^{-10}$ (far larger than SM)

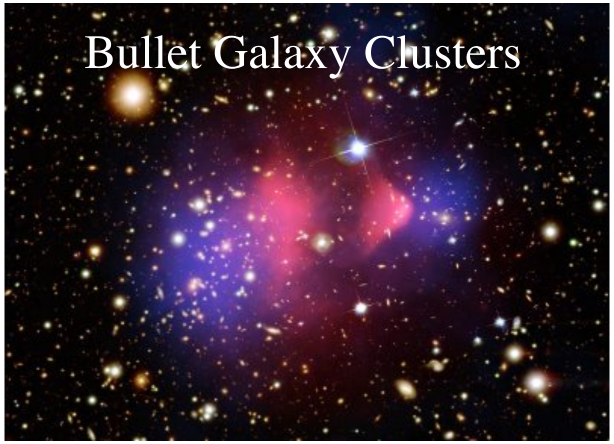


The Horn Antenna
Bell Telephone Laboratory

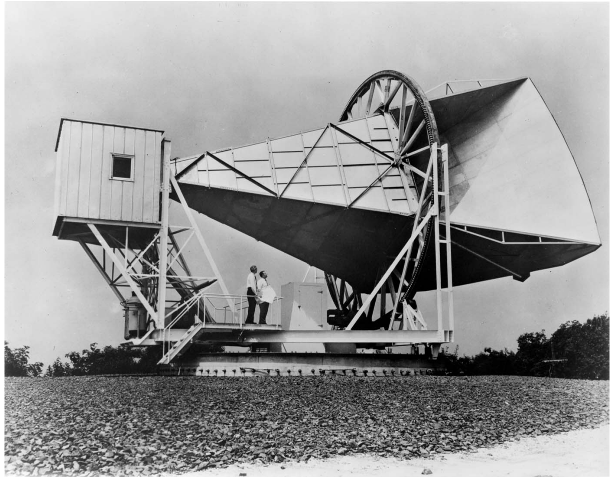


Current Situation (II)

- Observational evidences for New Physics
  - Neutrino oscillations, i.e. $m_\nu \neq 0$ (0 in SM)
  - Dark matter (no SM candidate)
  - $N_B / N_\gamma = 10^{-10}$ (far larger than SM)



The Horn Antenna
Bell Telephone Laboratory



- However, no experimental indication on the energy scale for New Physics, i.e. it can be anywhere!
  ⇒ planning of future options interesting/difficult

Current Situation (III)

- New physics could be:
    1. open at energy scales not very far from the electroweak energy scale, with particles "strongly" couple to the SM particles: resulting in very rich phenomenology at that energy scales (SUSY, composite Higgs, etc. etc.)
    $\Rightarrow$ If new physics were discovered we would be singing and dancing and busy working! 😄

Current Situation (III)

- New physics could be:
  1. open at energy scales not very far from the electroweak energy scale, with particles "strongly" couple to the SM particles: resulting in very rich phenomenology at that energy scales (SUSY, composite Higgs, etc. etc.)
     ⇒ If new physics were discovered we would be singing and dancing and busy working! 😄

or

  2. active at only very high energy scales, GUT or even Plank, possibly with a few low mass new particles couple very weakly to the SM particles (νMSM, …)
     ⇒ If new physics were discovered, it would not be clear how to proceeds from there on. 😨

Current Situation (IV)

- Multi-prong approach is mandatory
  - Search for new particles at the highest energy:
    - Which kind, e^+e^-, $\mu^+\mu^-$, ep, pp, $\gamma\gamma$, …?
    - At which energies?

Current Situation (IV)

- Multi-prong approach is mandatory
  - Search for new particles at the highest energy:
    - Which kind, e^+e^-, $\mu^+\mu^-$, ep, pp, $\gamma\gamma$, …?
    - At which energies?
  - Precision measurements to look for deviation from the Standard Model predictions in electroweak, and quark and lepton flavour physics, including very weakly interacting particles:
    - accelerator beams
    - reactor beams
    - cosmic rays

Current Situation (IV)

- Multi-prong approach is mandatory
  - Search for new particles at the highest energy:
    - Which kind, e^+e^-, $\mu^+\mu^-$, ep, pp, $\gamma\gamma$, …?
    - At which energies?
  - Precision measurements to look for deviation from the Standard Model predictions in electroweak, and quark and lepton flavour physics, including very weakly interacting particles:
    - accelerator beams
    - reactor beams
    - cosmic rays
  - Astronomy/cosmology and astroparticle
    - ground based
    - space based

Let us elaborate

- As an example, let us take a costly facility, i.e. colliders particularly at high energies, for a thought process…

Colliders in 2006

- The first European strategy for particle physics was adopted in June 2006: Colliders at the moment were:

– HERA @ DESY	ep	DE
– DAFNE @ LNF	e^+e^-	I
– LHC @ CERN under construction	pp	CH
– CESR-C @ Cornell	e^+e^-	US
– Tevatron @ FNAL	pp	US
– RICH @ BNL	$(p,d,Cu,Au,U)^2$	US
– PEP II @ SLAC	e^+e^-	US
– KEKB @ KEK	e^+e^-	JP
– BEPC-II @ IHEP under construction	e^+e^-	CN
– VEPP4M @ BINP	e^+e^-	RU
– VEPP2000 @ BINP under construction	e^+e^-	RU

Then…

- The first European strategy for particle physics was adopted in June 2006: Colliders at the moment were:
  - ~~HERA @ DESY ep DE~~
  - DAFNE @ LNF e^+e^- I
  - LHC @ CERN under construction pp CH
  - ~~CESR-C @ Cornell e^+e^- US~~
  - ~~Tevatron @ FNAL pp US~~
  - RICH @ BNL $(p,d,Cu,Au,U)^2$ US
  - ~~PEP II @ SLAC e^+e^- US~~
  - ~~KEKB @ KEK e^+e^- JP~~
  - BEPC-II @ IHEP under construction e^+e^- CN
  - VEPP4M @ BINP e^+e^- RU
  - VEPP2000 @ BINP under construction e^+e^- RU

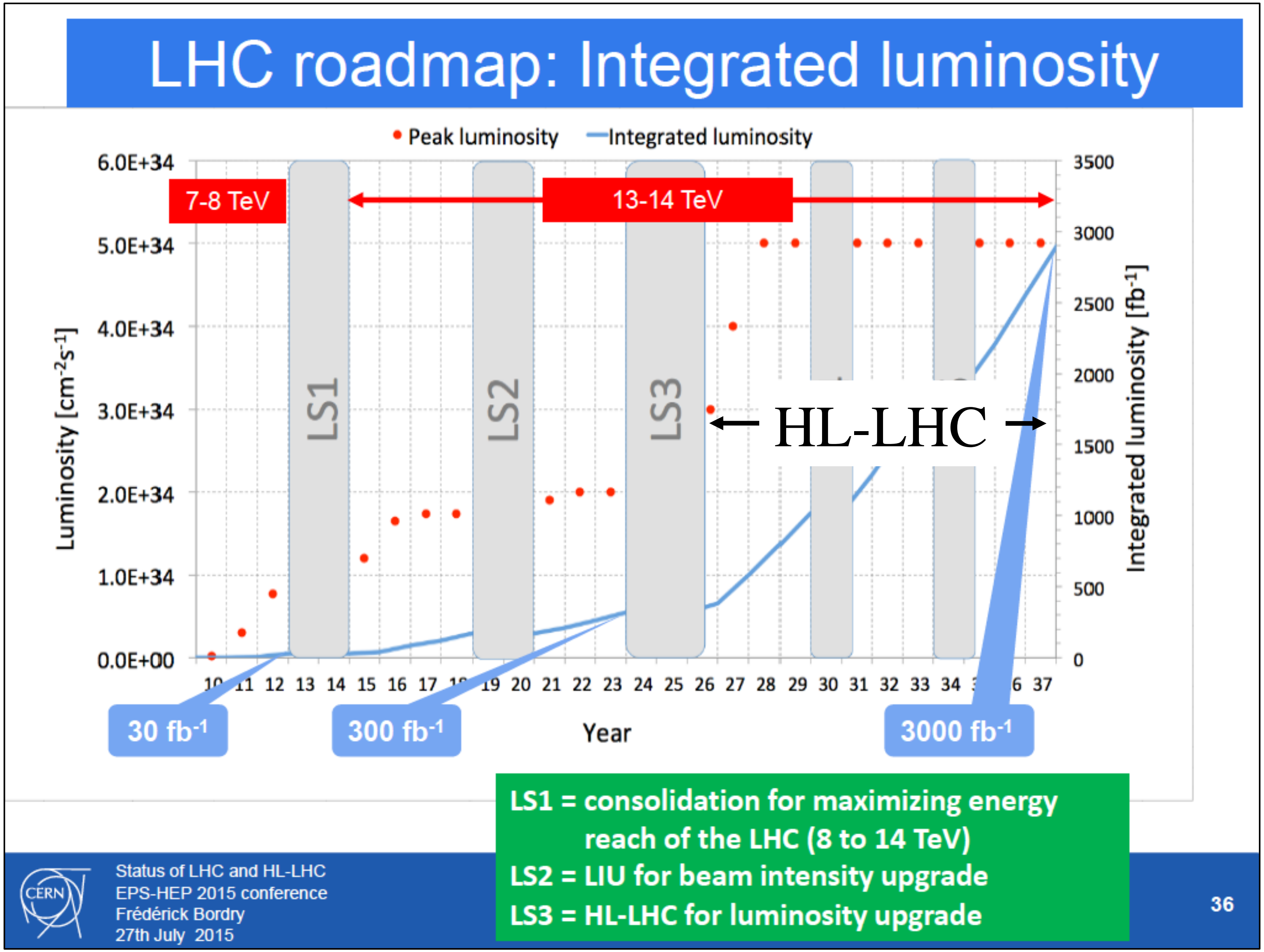
Some have been stopped…

And now

- The last European strategy for particle physics was adopted in May 2013: Existing colliders were:
  - DAFNE @ LNF e^+e^- I
  - LHC @ CERN pp CH
  - RICH @ BNL $(p,d,Cu,Au,U)^2$ US
  - SuperKEKB @ KEK under construction e^+e^- JP
  - BEPC-II @ IHEP e^+e^- CN
  - VEPP4M @ BINP e^+e^- RU
  - VEPP2000 @ BINP e^+e^- RU

Five closed down and **only one has been approved**…

For sure to happen at high energies

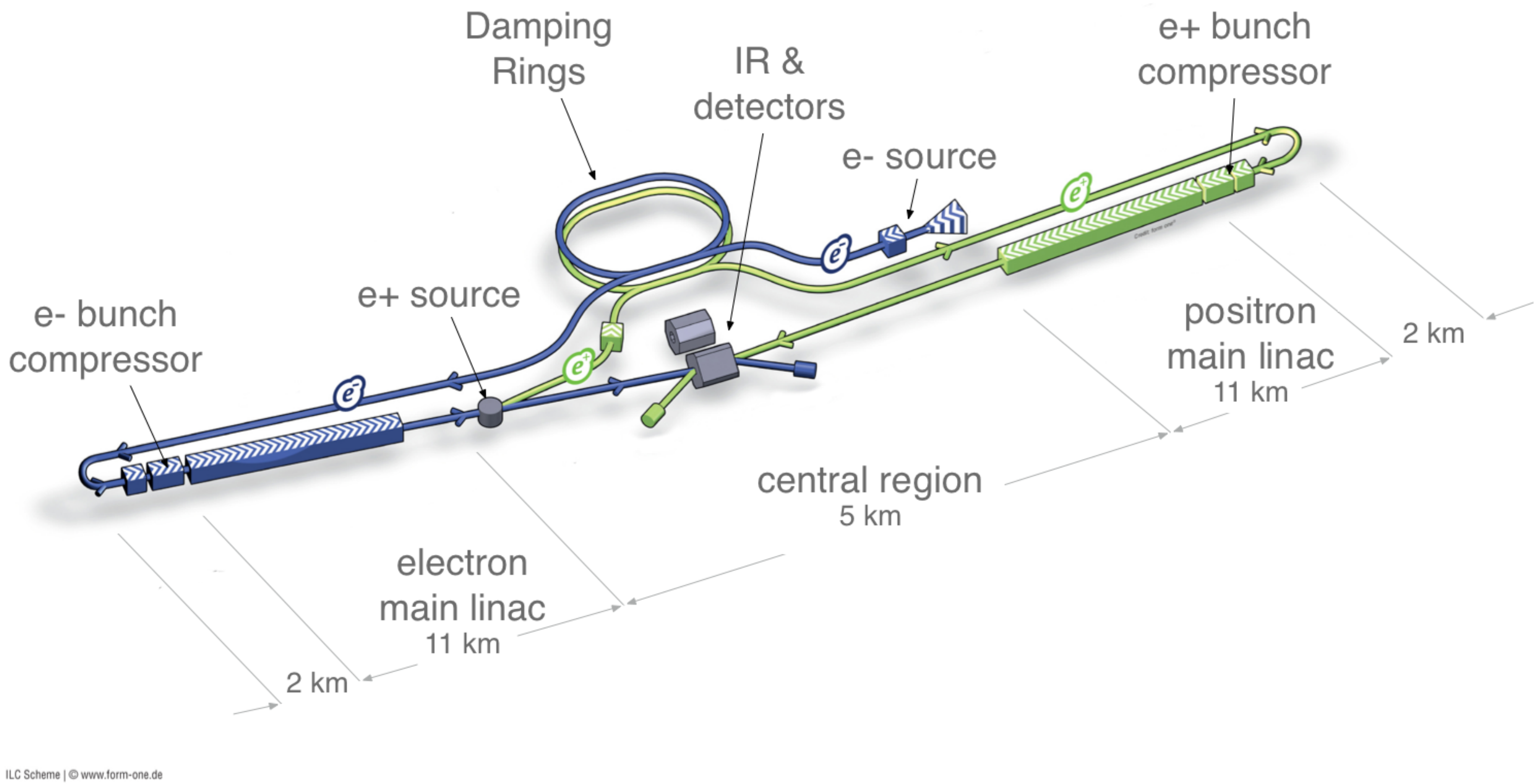


But many ideas are around (I)

- e^+e^- Linear Collider
  - ILC: superconductive cavities, up to 500 GeV-1 TeV, $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$
    technically ready to start as construction project
  - CLIC: double beam acceleration, up to ~3 TeV, $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$
    still R&D required to be ready for construction

ILC

- TDR Generic design for 500 GeV, $\sim 10^{34} cm^{-2} s^{-1}$: ~30km

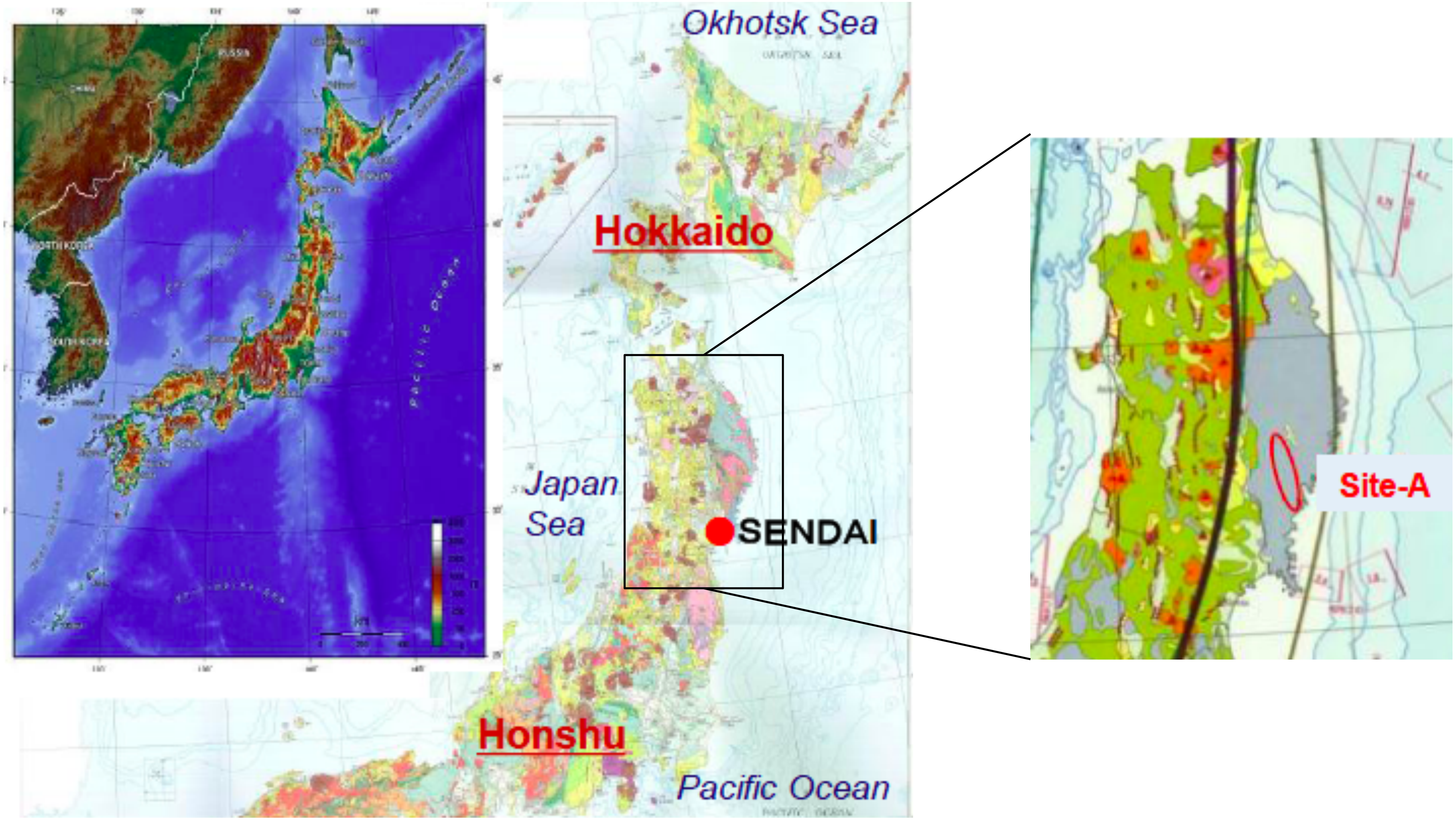


ILC

- Long lasting worldwide effort
  e.g. ECFA study group since early 2000
- Technology is mature, many R&D works have been done including the industrialisation of SCRF, with "module 0", i.e. European XFEL @ Hamburg
- Cover a wide energy range: from 250 GeV, can be boosted to ~1 TeV
- Require a rather long tunnel (30km for 500 GeV)
- A solution to accommodate multiple detectors (push-pull), which may not be very practical

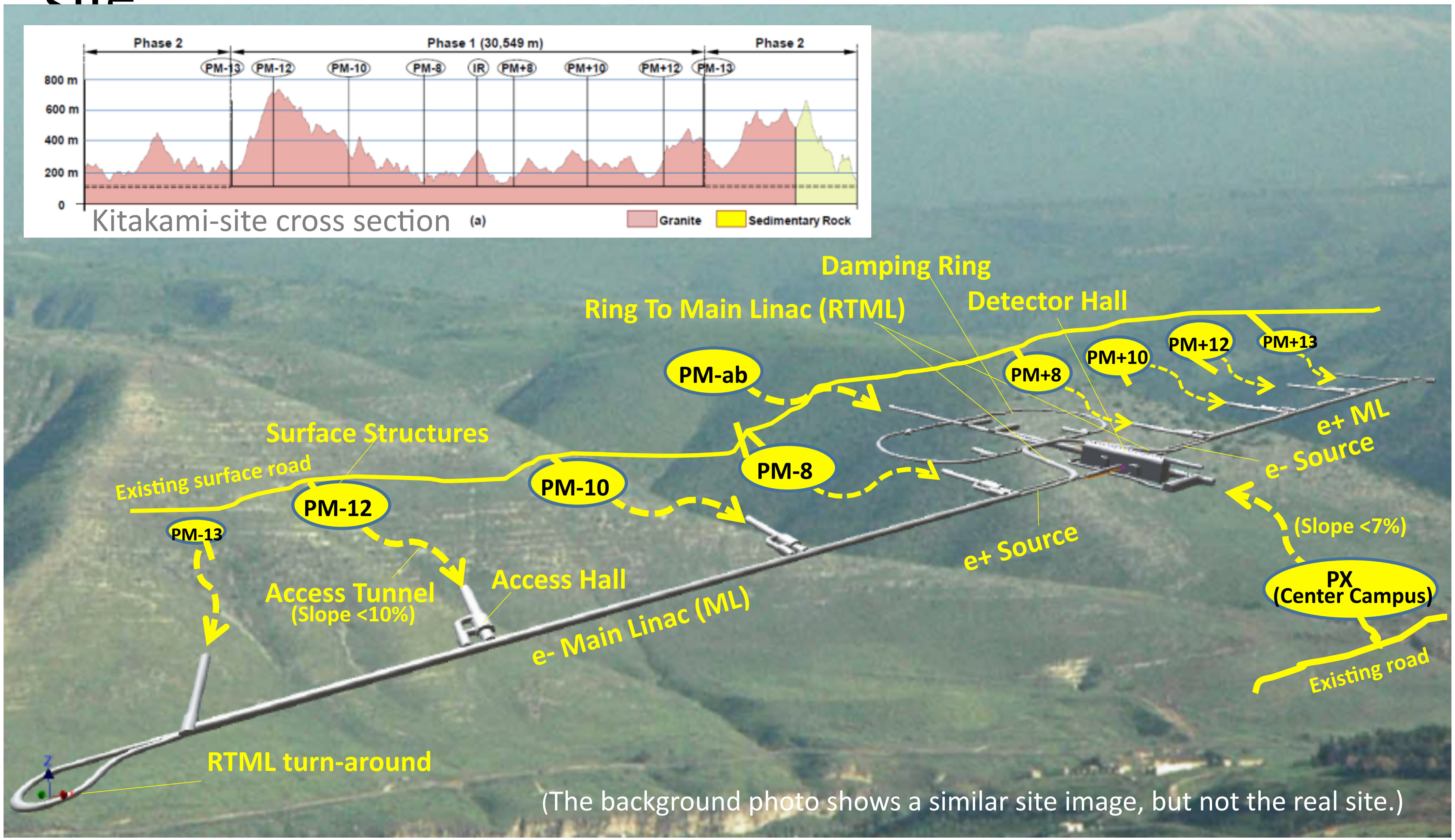
ILC Japanese site candidate

- Kitakami site selected by the Japanese scientists



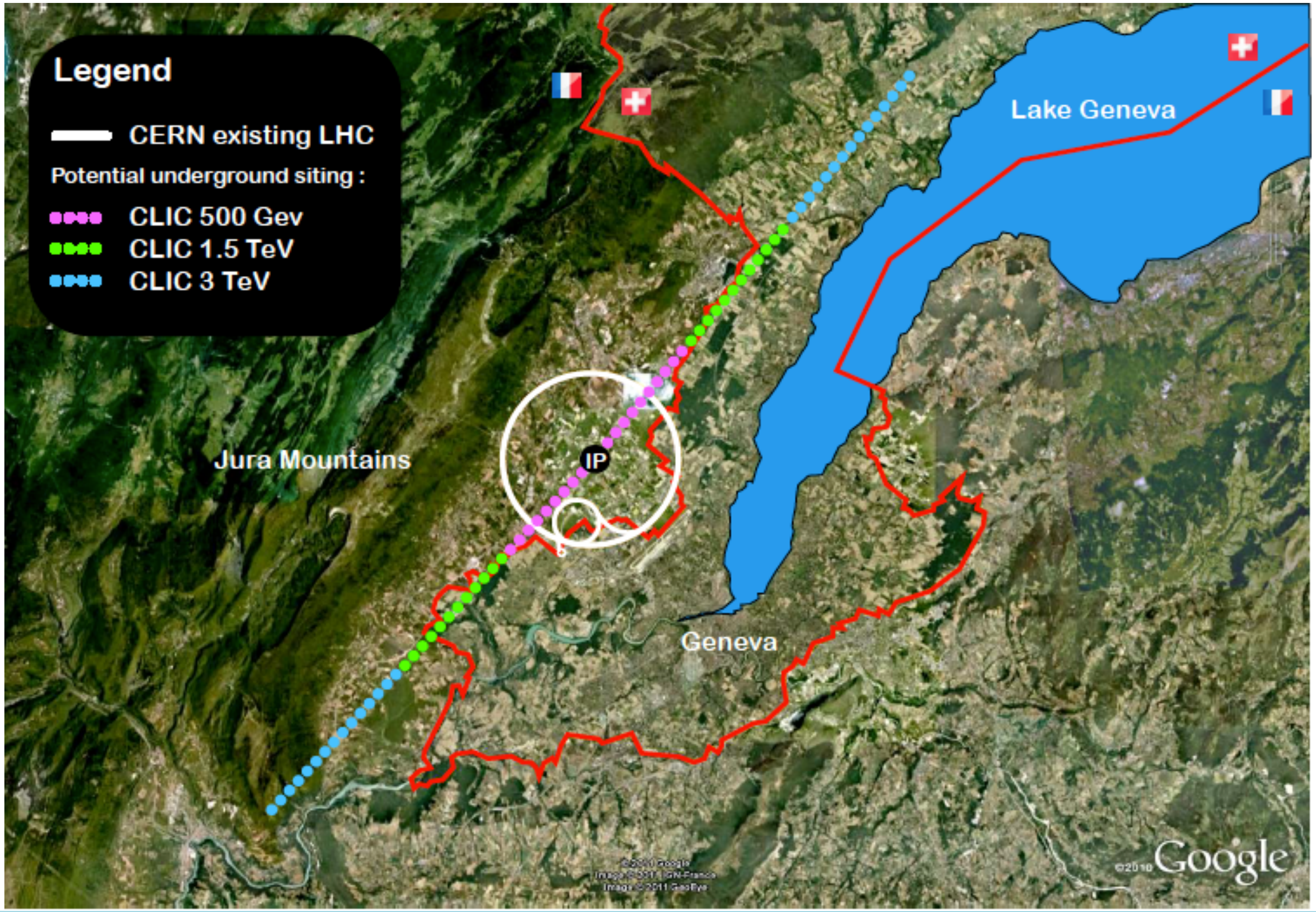
ILC

- The design being adjusted for the Japanese Kitakami site

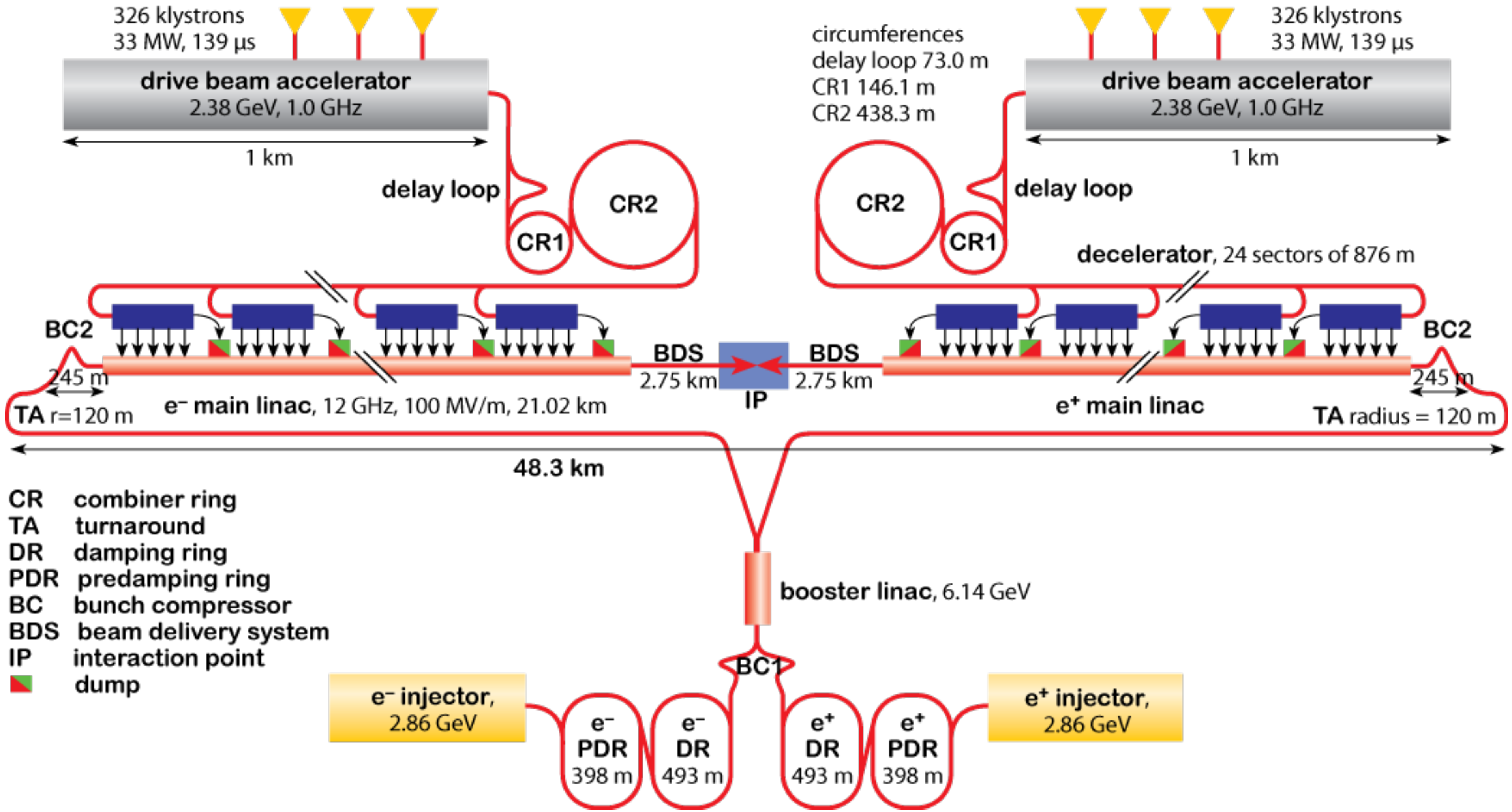


CLIC

- R&D effort started at CERN quite sometime ago, aiming at a higher acceleration gradient with two beam technology, go beyond 1 TeV, up to ~3 TeV



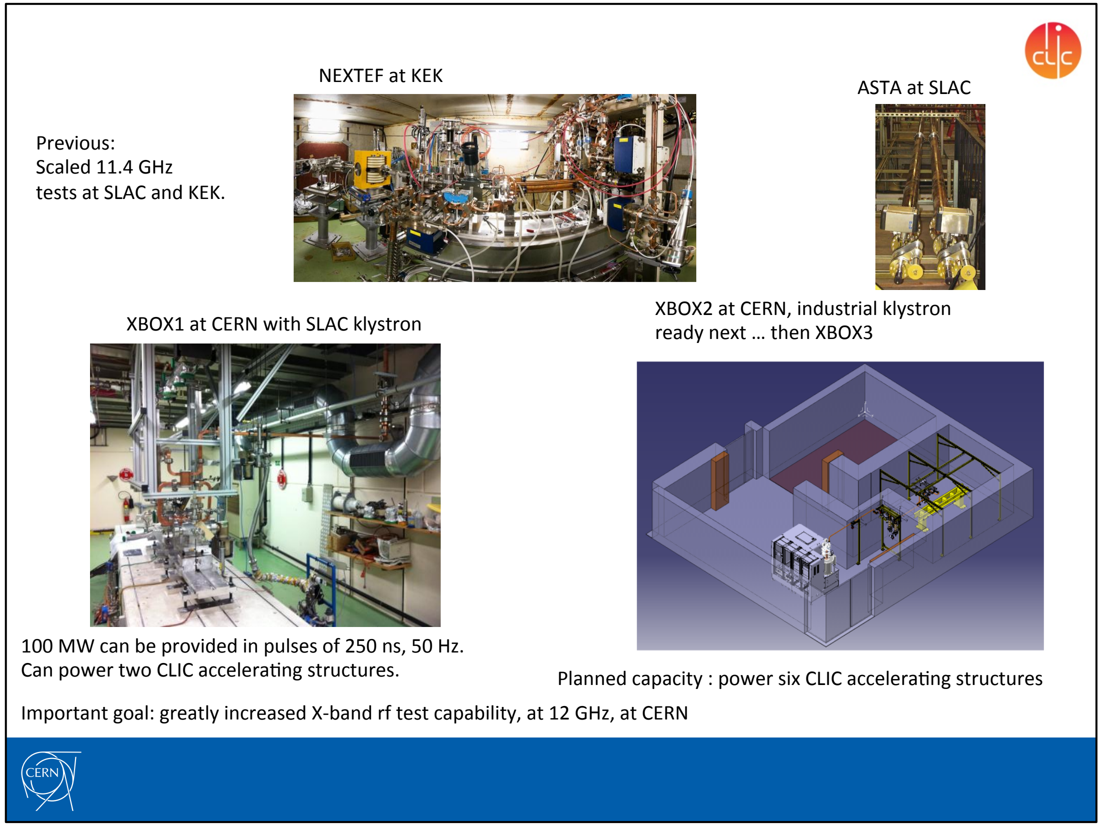
CLIC



326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
decelerator, 24 sectors of 876 m
BC2
245 m
TA r=120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
BDS
2.75 km
IP
BDS
2.75 km
e⁺ main linac
BC2
245 m
TA radius = 120 m
48.3 km
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
booster linac, 6.14 GeV
BC1
e⁻ injector,
2.86 GeV
e⁻
PDR
398 m
e⁻
DR
493 m
e⁺
DR
493 m
e⁺
PDR
398 m
e⁺ injector,
2.86 GeV

CLIC

- Many R&D effort by an international collaboration, a la HEP experiment



- Still more R&D needed to reach the TDR level. Collaboration with ILC.

But many ideas are around (I)

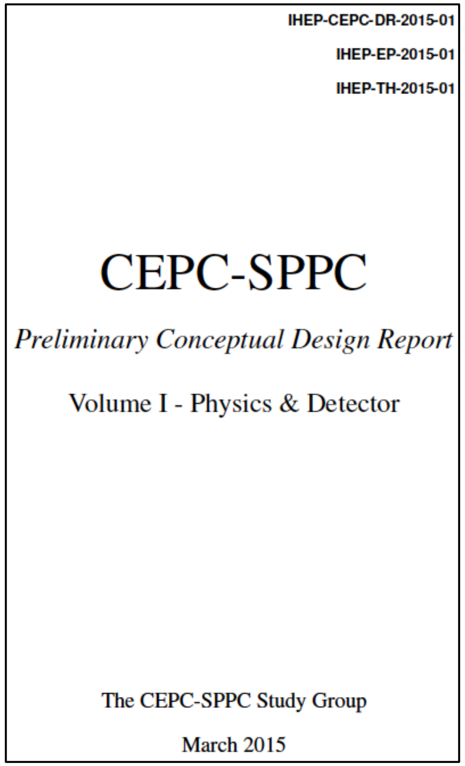
- e^+e^- Linear Collider
  - ILC: superconductive cavities, up to 500 GeV-1 TeV, $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    technically ready to start as construction project
  - CLIC: double beam acceleration, up to ~3 TeV, $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    still R&D required to be ready for construction

But many ideas are around (I)

- e^+e^- Linear Collider
  - ILC: superconductive cavities, up to 500 GeV-1 TeV, ~10^{34}cm^{-2}s^{-1}
    technically ready to start as construction project
  - CLIC: double beam acceleration, up to ~3 TeV, ~10^{34}cm^{-2}s^{-1}
    still R&D required to be ready for construction
- e^+e^- Circular Collider
  - LEP 3: with the existing LEP/LHC tunnel, up to 240 GeV
  - TLEP: new 80 to 100km tunnel, up to 350 GeV → see FCC later
  - Other similar ideas are IHEP (Beijing) Circular Electro Positron Collider, SuperTRISTAN (KEK) with $\gtrsim$ 50km new tunnel

  mature technology, easy to accommodate several experiments

CEPC


IHEP-CEPC-DR-2015-01

IHEP-EP-2015-01

IHEP-TH-2015-01

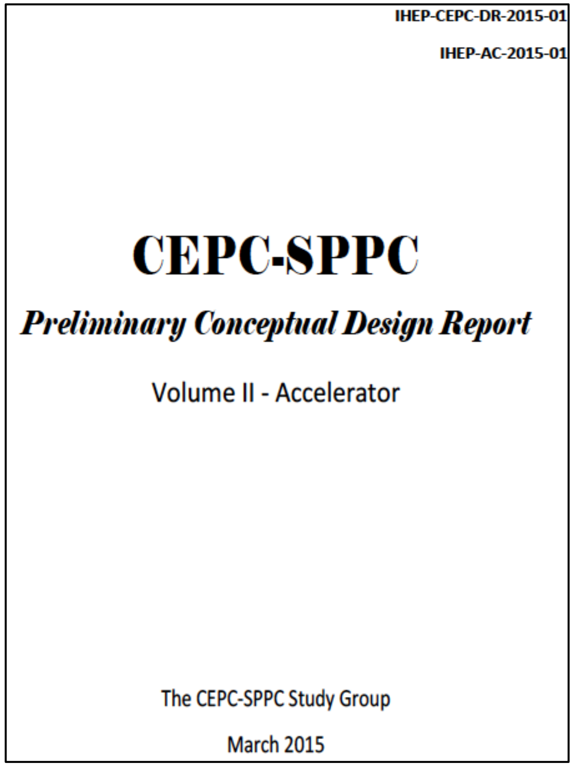
CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015


IHEP-CEPC-DR-2015-01

IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

The CEPC-SPPC Study Group

March 2015

CEPC Pre-CDR

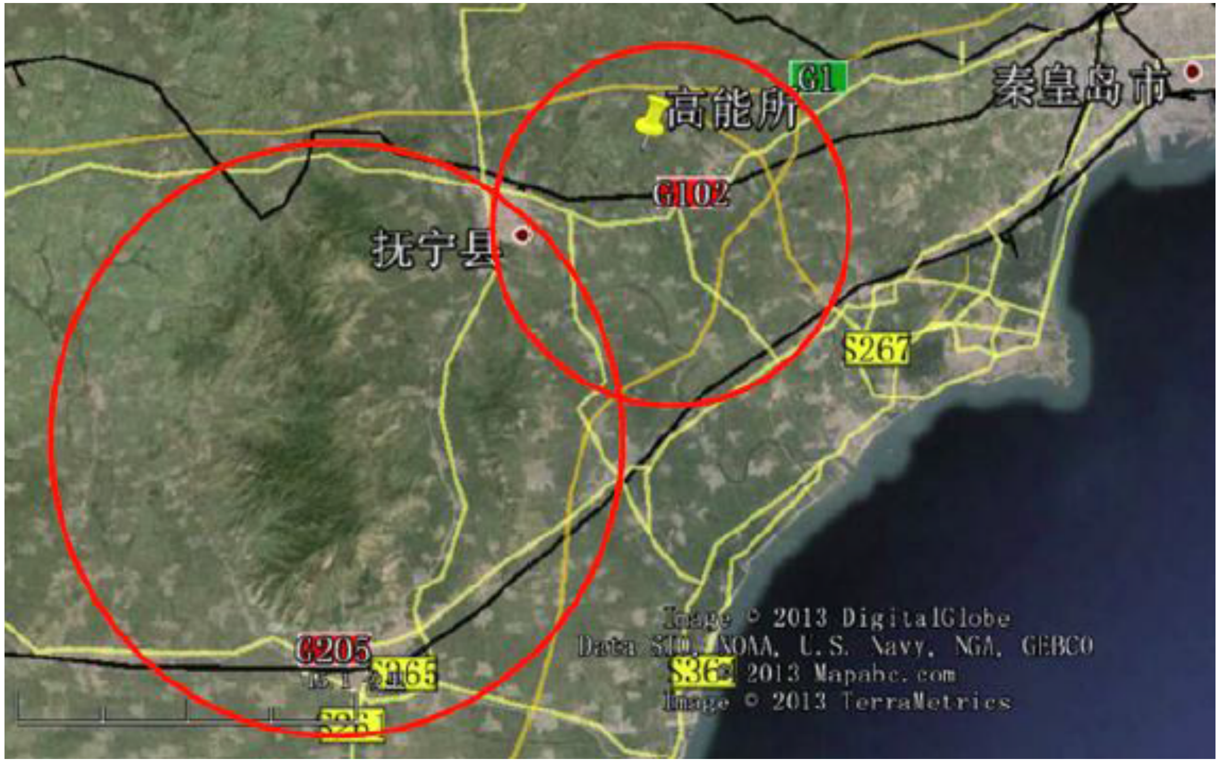
R&D funding requested to Chinese Government for 2016-2020

→Aim to follow this by construction 2021-2027

(and construction for pp option 2035-2042)

e^+e^- @ 240 GeV/c (pp @ 50 ~ 100 TeV)

CEPC



Circumference 50 ~ 100 km single ring

$L \approx 2{\times}10^{34}$ cm^{-2} s^{-1}@ 240 GeV/c, ≈10^6 Higgs/y (y =10^7 s)

But many ideas are around (I)

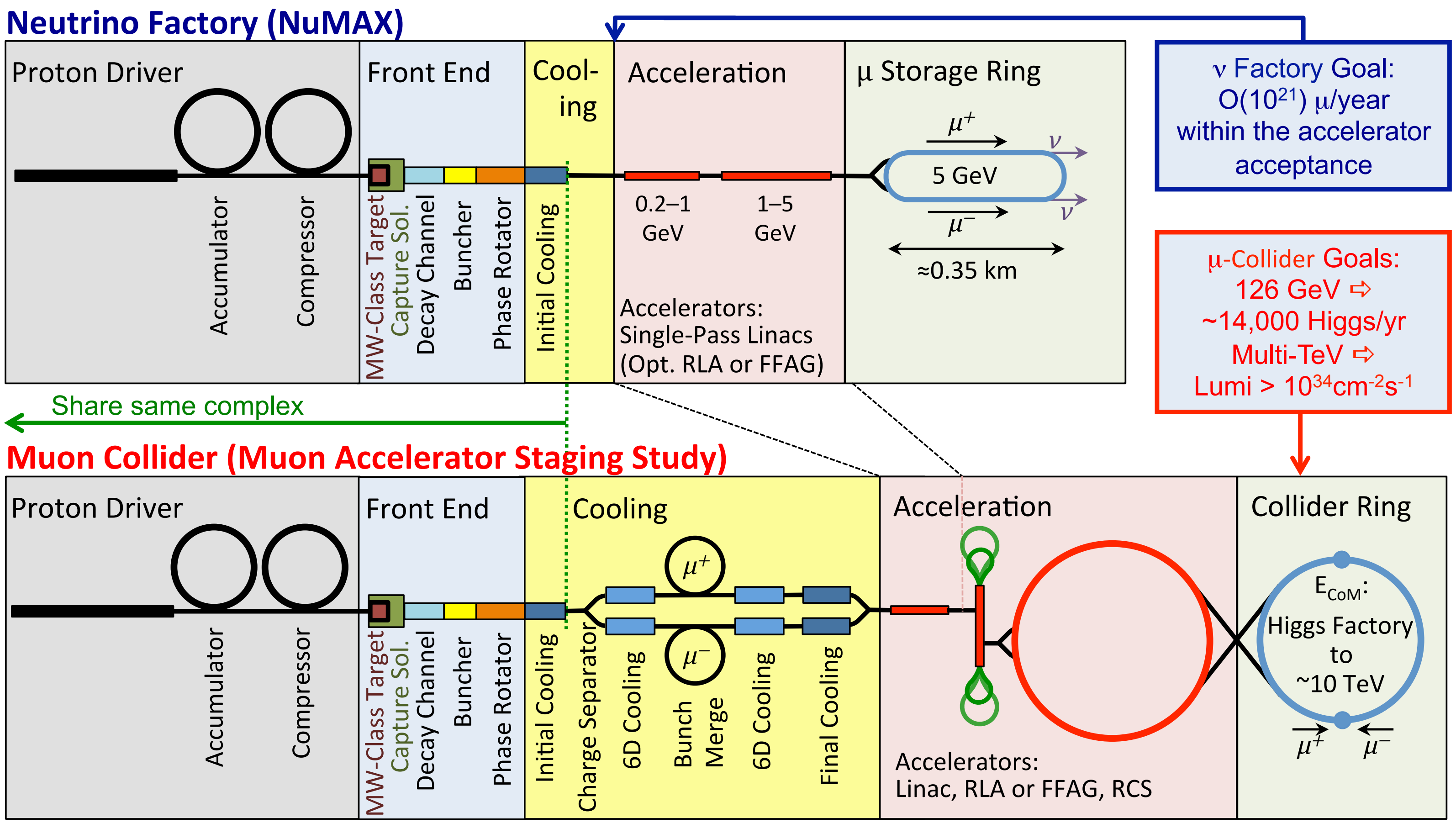
- e^+e^- Linear Collider
  - ILC: superconductive cavities, up to 500 GeV-1 TeV, ~10^{34}cm^{-2}s^{-1}
    technically ready to start as construction project
  - CLIC: double beam acceleration, up to ~3 TeV, ~10^{34}cm^{-2}s^{-1}
    still R&D required to be ready for construction
- e^+e^- Circular Collider
  - LEP 3: with the existing LEP/LHC tunnel, up to 240 GeV
  - TLEP: new 80 to 100km tunnel, up to 350 GeV → see FCC later
  - Other similar ideas are IHEP (Beijing) Circular Electro Positron Collider, SuperTRISTAN (KEK) with $\gtrsim$ 50km new tunnel

  mature technology, easy to accommodate several experiments
- $\mu^+\mu^-$ Circular Collider

  ~10 TeV or above with a similar size as Tevatron/LHC, synergy with neutrino factory, quite some R&D needed for a conceptual design

Muon collider

- Some R&D, such as target and cooling, are in progress by international collaborations in view of a neutrino factory.

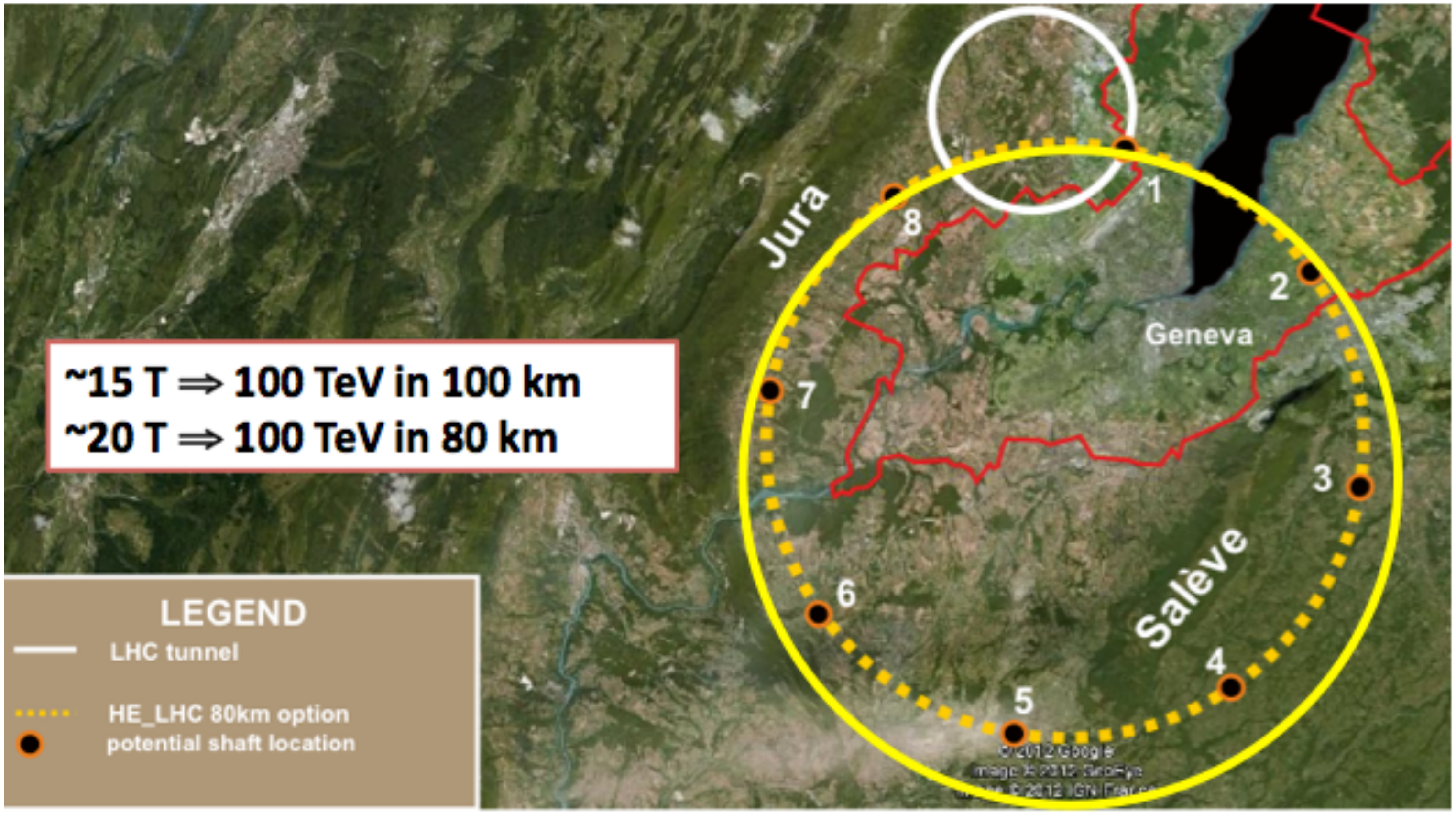


But many ideas are around (II)

- pp Circular Collider
  - HL-LHC: luminosity upgrade of the exiting LHC, $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
    10 times more $\int L\mathrm{d}t$, basically approved upgrade step for LHC
  - HE-LHC: in the LHC tunnel, up to ~33 TeV
    20T dipole required for 33 TeV
  - VHE-LHC: with 80 to 100km tunnel, up to ~100 TeV
    same tunnel with TLEP, 15T dipole for 100 km → FCC
- ep(ion) Collider
  - LHeC: p(ion) of LHC against e from a 60 GeV linac
  - eRICH: p(ion) of RICH against e from a 5-30 GeV linac
  - ep option for FCC

Future Circular Collider

- Study effort initiated by CERN, based on 80~100 km tunnel, with a primary goal for 100 TeV pp collider. The tunnel could accommodate 350 GeV e^+e^- machine, and ep collider.



Future Circular Collider

- Kick-off workshop by in Geneva in February 2014, 2nd workshop in Washington in March 2015:
- worldwide interest and establish global working groups for technical aspects and physics potential -

FCC pp collider	
Circumference	100 km
$\sqrt{s}$	100 TeV
L	$5 \rightarrow 25\ 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
Bunch spacing	25 or 5 nsec

Aiming $\int L dt = 20\ \text{ab}^{-1}$ over ~25 years of data taking

Future Circular Collider

- Kick-off workshop by in Geneva in February 2014, 2nd workshop in Washington in March 2015:
- worldwide interest and establish global working groups for technical aspects and physics potential -

FCC e^+e^- option	
$\sqrt{s}$	90 to 350 GeV (Z^0, W^+W^-, Z^0H and tt)
L	$21\sim280\times10^{34}$ cm^{-2} s^{-1} for Z^0
	$5\sim11\times10^{34}$ cm^{-2} s^{-1} for Z^0H
	$1.5\sim2.6\times10^{34}$ cm^{-2} s^{-1} for tt

Aiming at $O(10)$ more luminosities than LC for H

Future Circular Collider

- Kick-off workshop by in Geneva in February 2014, 2[nd] workshop in Washington in March 2015:

\- worldwide interest and establish global working groups for technical aspects and physics potential -

Technical challenges

Very high field superconductive magnet ≳16 T

Protection against large stored energy

Civil engineering, i.e. tunnel around the Geneva area

But many ideas are around (II)

- pp Circular Collider
  - HL-LHC: luminosity upgrade of the exiting LHC, 5×10^{34}cm^{-2}s^{-1}
    10 times more $\int L\mathrm{d}t$, basically approved upgrade step for LHC
  - HE-LHC: in the LHC tunnel, up to 33 TeV
    20T dipole required for 33 TeV
  - FCC: with 80 to 100km tunnel, up to 100 TeV
    16T dipole for 100 km
- ep(ion) Collider
  - LHeC: p(ion) of LHC against e from a 60 GeV linac
  - eRICH: p(ion) of RICH against e from a 5-30 GeV linac
  - ep option for FCC

But many ideas are around (II)

- pp Circular Collider
  - HL-LHC: luminosity upgrade of the exiting LHC, $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
    10 times more $\int L\text{d}t$, basically approved upgrade step for LHC
  - HE-LHC: in the LHC tunnel, up to 33 TeV
    20T dipole required for 33 TeV
  - FCC: with 80 to 100km tunnel, up to 100 TeV
    16T dipole for 100 km
- ep(ion) Collider
  - LHeC: p(ion) of LHC against e from a 60 GeV linac
  - eRICH: p(ion) of RICH against e from a 5-30 GeV linac
  - ep option for FCC
- γγ Collider as a Higgs factory (inverse of H→γγ)
  - 80 GeV e^- linacs is sufficient, i.e. no e^+ needed
  - laser part requires many R&D

Issues for making-up our mind

- Scientific requirements
- Technological maturity
- Cost
- Sociology/international politics
- Funding availability

Issues for making-up our mind

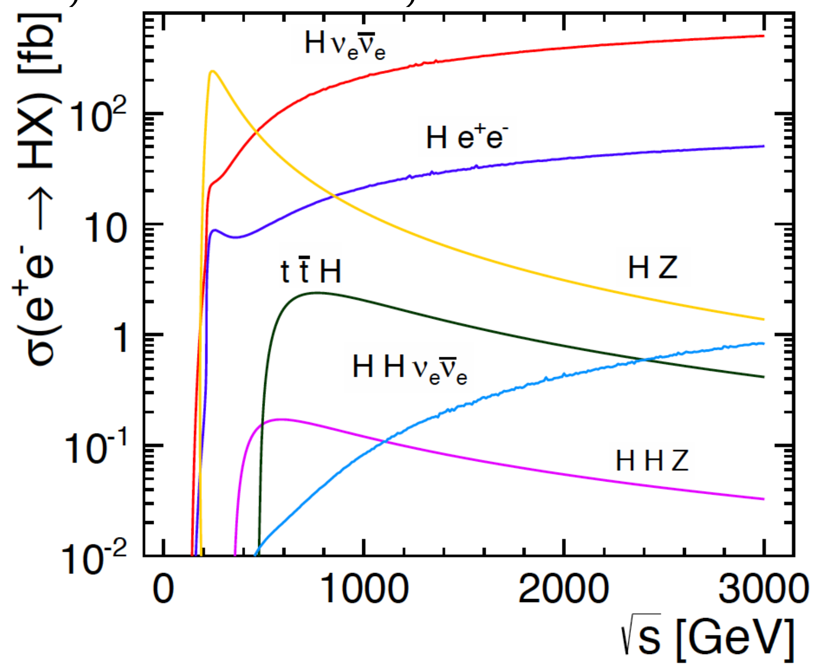
- Scientific requirements
- Technological maturity
- Cost
- Sociology/international politics
- Funding availability

They all change with time

Unfortunately, the last three issues cannot be ignored

e^+e^- collider case

- e^+e^- colliders have unique advantages over a hadron machine: able to measure Higgs absolute branching fractions and couplings to more states:
  at ~250 GeV: with $e^+e^- \to HZ$, clean studies of H decays by tagging Z
  i.e. can access to decays into $\bar{c}c$, invisible, …
  - at ~500 GeV: with $e^+e^- \to Ht\bar{t}$, coupling to tt
  - for H self-coupling, >1 TeV needed
- At lower energies, Z and W factories

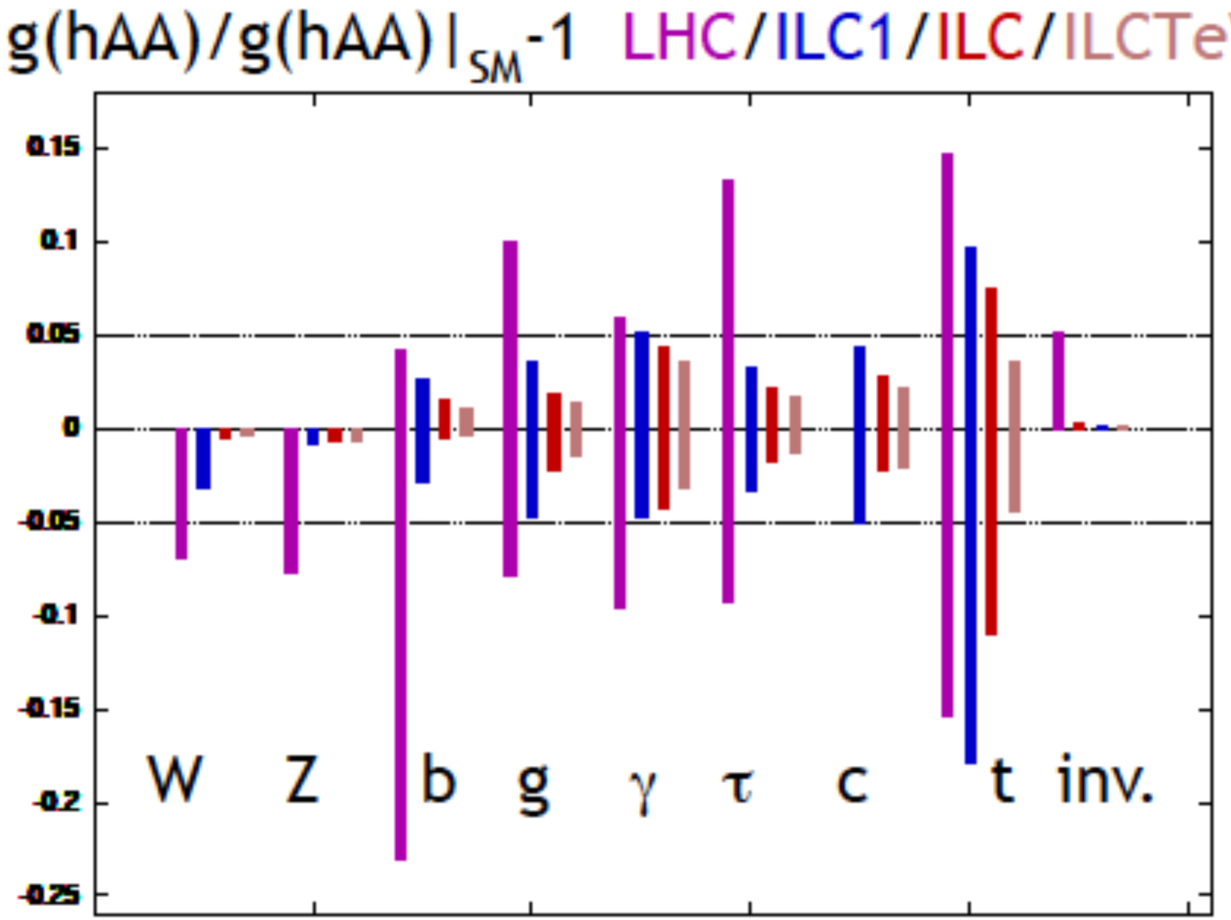


☞ L and $\sqrt{s}$ both important

Case for the e^+e^- colliders

- e^+e^- Higgs factory has already a clear physics goal
  - LC strategy: exploiting the full energy range up to 500 GeV $ee \rightarrow ZH$ @ $L \approx 10^{34}$ $cm^{-2}s^{-2}$ (~10^6 H/year)
  - CC strategy: exploiting the high integrated luminosity at 250 GeV (with an extension to 100 TeV pp machine later a la LEP but an injection system for CC will not be cheap) $ee \rightarrow ZH$ @ $L \approx 10^{35}$ $cm^{-2}s^{-2}$

Higgs coupling comparisons



M. Peskin , arXiv:1207.2516

LHC: 14 TeV 300 fb^{-1}
ILC1: 250 GeV 250 fb^{-1}
ILC: 500 GeV 500 fb^{-1}
ILCTeV: 1 TeV 1 ab^{-1}

CEPC: similar to ILC1
FCCee: aim for ~20 times more data, ~5 times smaller error

Case for the e^+e^- colliders

- e^+e^- Higgs factory has already a clear physics goal
  - LC strategy: exploiting the full energy range up to 500 GeV $ee \to ZH$ @ $L \approx 10^{34}$ cm^{-2}s^{-2}
  - CC strategy: exploiting the high integrated luminosity at 250 GeV (with an extension to 100 TeV pp machine later a la LEP but an injection system for CC will not be cheap) $ee \to ZH$ @ $L \approx 10^{35}$ cm^{-2}s^{-2}
- Input from the 14 TeV LHC:
  - If no new physics < 1 TeV, difficult to motivate CLIC
  - If new particles were found > 250 GeV/c^2, motivation for ILC weakens, unless going up to 1 TeV.

Case for the e^+e^- colliders

- e^+e^- Higgs factory has already a clear physics goal
  - LC strategy: exploiting the full energy range up to 500 GeV $ee \rightarrow ZH$ @ $L \approx 10^{34}$ $cm^{-2}s^{-2}$
  - CC strategy: exploiting the high integrated luminosity at 250 GeV (with an extension to 100 TeV pp machine later a la LEP but an injection system for CC will not be cheap) $ee \rightarrow ZH$ @ $L \approx 10^{35}$ $cm^{-2}s^{-2}$
- Input from the 14 TeV LHC:
  - If no new physics < 1 TeV, difficult to motivate CLIC
  - If new particles were found > 250 GeV/c^2, motivation for ILC weakens, unless going up to 1 TeV.
  - If no new particles at all, what is the required L and $\sqrt{s}$ to still probe $\gtrsim$ 10 TeV scale from precision Higgs studies?

Case for pp colliders

- If new physics were found by 14 TeV LHC data
  - All pp colliders considered will explore the mass spectrum of particle associated to new physics.

Case for pp colliders

- If new physics were found by 14 TeV LHC data
  - All pp colliders considered will explore the mass spectrum of particle associated to new physics.

- If new physics were not found by 14 TeV LHC data:
  - For 100 TeV pp collider, energy scale for new physics could be ~10 TeV
  - For lower energy pp colliders, pushing the SM precision measurements further may result in deviations

  ⇒ really difficult case for a large investment …

Other colliders

- Muon Collider
  - *s*-channel Higgs production, very precise coupling to μ, and Higgs mass and width measurements
  - synergy with ν factory, and can aim for 10 TeV scale
  - real estate requirement is very modest, i.e. Higgs factory in the ISR tunnel, 10 TeV machine in the LHC tunnel…?
  - Intensive R&D needed, but should be focused in the goal and time, i.e. should not become perpetual!
  - Luminosity may not be sufficient (~10^{32}cm^{-2}s^{-1}, ~10^{4} H/year)

Other colliders

- Muon Collider
  - *s*-channel Higgs production, very precise coupling to μ, and Higgs mass and width measurements
  - synergy with ν factory, and can aim for 10 TeV scale
  - real estate requirement is very modest, i.e. Higgs factory in the ISR tunnel, 10 TeV machine in the LHC tunnel…?
  - Intensive R&D needed, but should be focused in the goal and time, i.e. should not become perpetual!
  - Luminosity may not be sufficient (~10^{32}cm^{-2}s^{-1}, ~10^4 H/year)
- γγ Collider ($\sqrt{s}\approx 125$ GeV, ~6×10^{32}cm^{-2}s^{-1}, ~10^4H/y)
  - *s*-channel Higgs production, via loop diagram

Other colliders

- Muon Collider
  - *s*-channel Higgs production, very precise coupling to μ, and Higgs mass and width measurements
  - synergy with ν factory, and can aim for 10 TeV scale
  - real estate requirement is very modest, i.e. Higgs factory in the ISR tunnel, 10 TeV machine in the LHC tunnel…?
  - Intensive R&D needed, but should be focused in the goal and time, i.e. should not become perpetual!
  - Luminosity may not be sufficient ($\sim 10^{32}$cm^{-2}s^{-1}, $\sim 10^{4}$ H/year)
- γγ Collider ($\sqrt{s} \approx 125$ GeV, $\sim 6 \times 10^{32}$cm^{-2}s^{-1}, $\sim 10^{4}$H/y)
  - *s*-channel Higgs production, via loop diagram
- LHeC or FCCeh (LHeC 7TeV$\oplus$60GeV, $\sim 10^{33}$cm^{-2}s^{-1}, $\sim 10^{3}$H/y)
  - primary physics goal is the QCD studies: has its own physics merit Higgs production via electroweak interactions: Can get enough *L*?

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. "guaranteed" physics

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. “guaranteed” physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. "guaranteed" physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.
- For CLIC and Muon Collider, Higgs "factory" is a demonstrator, goal is for higher energies, ~1 TeV.

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. “guaranteed” physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.
- For CLIC and Muon Collider, Higgs “factory” is a demonstrator, goal is for higher energies, ~1 TeV.
- e^+e^- circular colliders are technically safe way to prove $Z \rightarrow W \rightarrow H \rightarrow t$.

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. “guaranteed” physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.
- For CLIC and Muon Collider, Higgs “factory” is a demonstrator, goal is for higher energies, ~1 TeV.
- e^+e^- circular colliders are technically safe way to prove $Z \rightarrow W \rightarrow H \rightarrow t$.
- 100km pp colliders are only the way currently know to access 10 TeV energy scale.

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. "guaranteed" physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.
- For CLIC and Muon Collider, Higgs "factory" is a demonstrator, goal is for higher energies, ~1 TeV.
- e^+e^- circular colliders are technically safe way to prove $Z \rightarrow W \rightarrow H \rightarrow t$.
- 100km pp colliders are only the way currently know to access 10 TeV energy scale.→ Is it high enough?

Reflection

- For high energy lepton colliders, Higgs is a reference point: i.e. “guaranteed” physics
- LC principle demonstrated by the SLC, but long term stable operation at high luminosities not.
- For CLIC and Muon Collider, Higgs “factory” is a demonstrator, goal is for higher energies, ~1 TeV.
- e^+e^- circular colliders are technically safe way to prove Z→W→H→t.
- 100km pp colliders are only the way currently know to access 10 TeV energy scale.→ Is it high enough?
- RF cavity <100 MeV/m (ILC 31 MeV/m, CLIC 72~100 MeV/m), Plasma wakefield ×100, at the moment SF but…

Another topic: Quark Flavour

- Established track record to probe energy scales much higher than directly accessible:

Another topic: Quark Flavour

- Established track record to probe energy scales much higher than directly accessible:
  - Δm_K and $Br(K_L \rightarrow \mu^+\mu^-) \Rightarrow m_c$ Lee&Gaillard (1974) charm discovery Aubert et al., Augustin et al., 1974 (Niu et al. 1971?)

Another topic: Quark Flavour

- Established track record to probe energy scales much higher than directly accessible:
  - Δm_K and $\mathrm{Br}(K_L \to \mu^+\mu^-) \Rightarrow m_c$ Lee&Gaillard (1974) charm discovery Aubert et al., Augustin et al., 1974 (Niu et al. 1971?)
  - CP: 1964, J.H. Christenson et al., $\mathrm{Br}(K^0_L \to \pi^+\pi^-) \neq 0$ $\Rightarrow$ Third family Kobayashi&Maskawa (1973)

Another topic: Quark Flavour

- Established track record to probe energy scales much higher than directly accessible:
  - Δm_K and $Br(K_L \rightarrow \mu^+\mu^-) \Rightarrow m_c$ Lee&Gaillard (1974) charm discovery Aubert et al., Augustin et al., 1974 (Niu et al. 1971?)
  - CP: 1964, J.H. Christenson et al., $Br(K^0_L \rightarrow \pi^+\pi^-) \neq 0$ $\Rightarrow$ Third family Kobayashi&Maskawa (1973)
  - B^0-$\overline{B}^0$ oscillations (Δm_B): ARGUS (1987) $\Rightarrow m_t > 50$ GeV/c^2 (NB: UA1 1984 $20 < m_t < 50$ GeV/c^2) top discovery by CDF and D0 in 1995 ($m_t = 171.2 \pm 2.1$ GeV/c^2)

Top Story

UA1, 1984

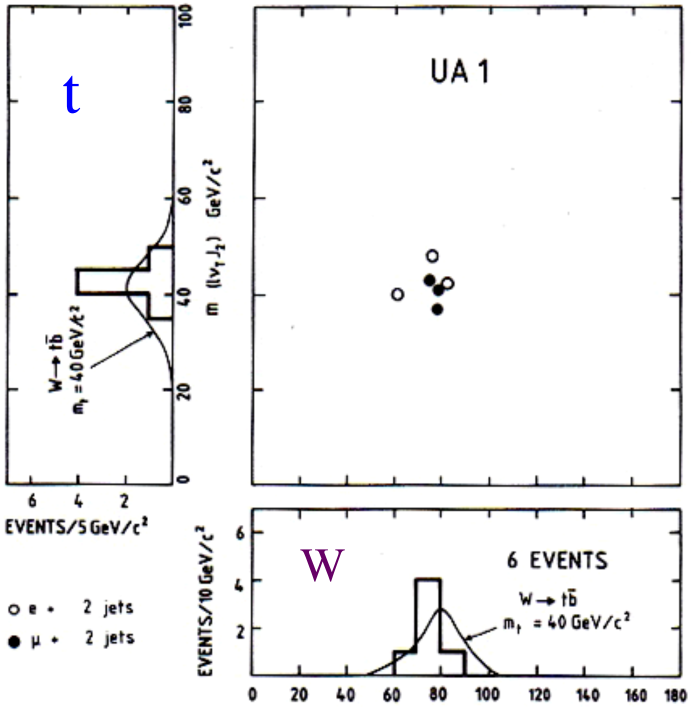
$p\bar{p} \to W^+ + X$

$\quad \hookrightarrow t\,\bar{b} \to$ jet

$\quad\quad \hookrightarrow b l \nu$

$\quad\quad\quad \hookrightarrow$ jet

$m_t = 30 \sim 50$ GeV/c^2



Phys. Lett. 147B (1984) 493

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

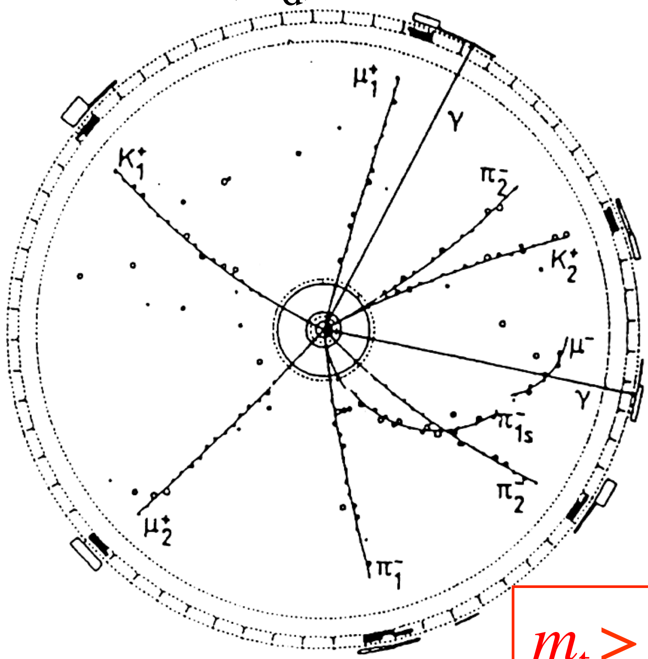
$\Upsilon(4S) \to B_d^0 \overline{B}_d^0$

$\to B_d^0 B_d^0$ or $\overline{B}_d^0 \overline{B}_d^0$

$\to \ell^+ \ell^+$ or $\ell^- \ell^-$

24.8±7.6±3.8

$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$



$m_t > 50$ GeV/c^2

Another topic: Quark Flavour

- Established track record to probe energy scales much higher than directly accessible:
  - Δm_K and $Br(K_L \rightarrow \mu^+\mu^-) \Rightarrow m_c$ Lee&Gaillard (1974) charm discovery Aubert et al., Augustin et al., 1974 (Niu et al. 1971?)
  - CP: 1964, J.H. Christenson et al., $Br(K^0_L \rightarrow \pi^+\pi^-) \neq 0$ $\Rightarrow$ Third family Kobayashi&Maskawa (1973)
  - B^0-$\overline{B}^0$ oscillations (Δm_B): ARGUS (1987) $\Rightarrow m_t > 50$ GeV/c^2 (NB: UA1 1984 $20 < m_t < 50$ GeV/c^2) top discovery by CDF and D0 in 1995 ($m_t = 171.2 \pm 2.1$ GeV/c^2)
- They were done before the direct discovery of c, b and t quarks

Another topic: Quark Flavour

- It is sensitive to coupling ⊗ mass of new particle
  ⇒ Complementary with direct search

Another topic: Quark Flavour

- It is sensitive to coupling $\otimes$ mass of new particle
  $\Rightarrow$ Complementary with direct search
- Sensitive to the new physics amplitude A_{NP} in
  - Absolute value: branching fractions
  - Phase: CP violation
  - Lorentz structure: decay products angular distribution remains sensitive even for MFV case

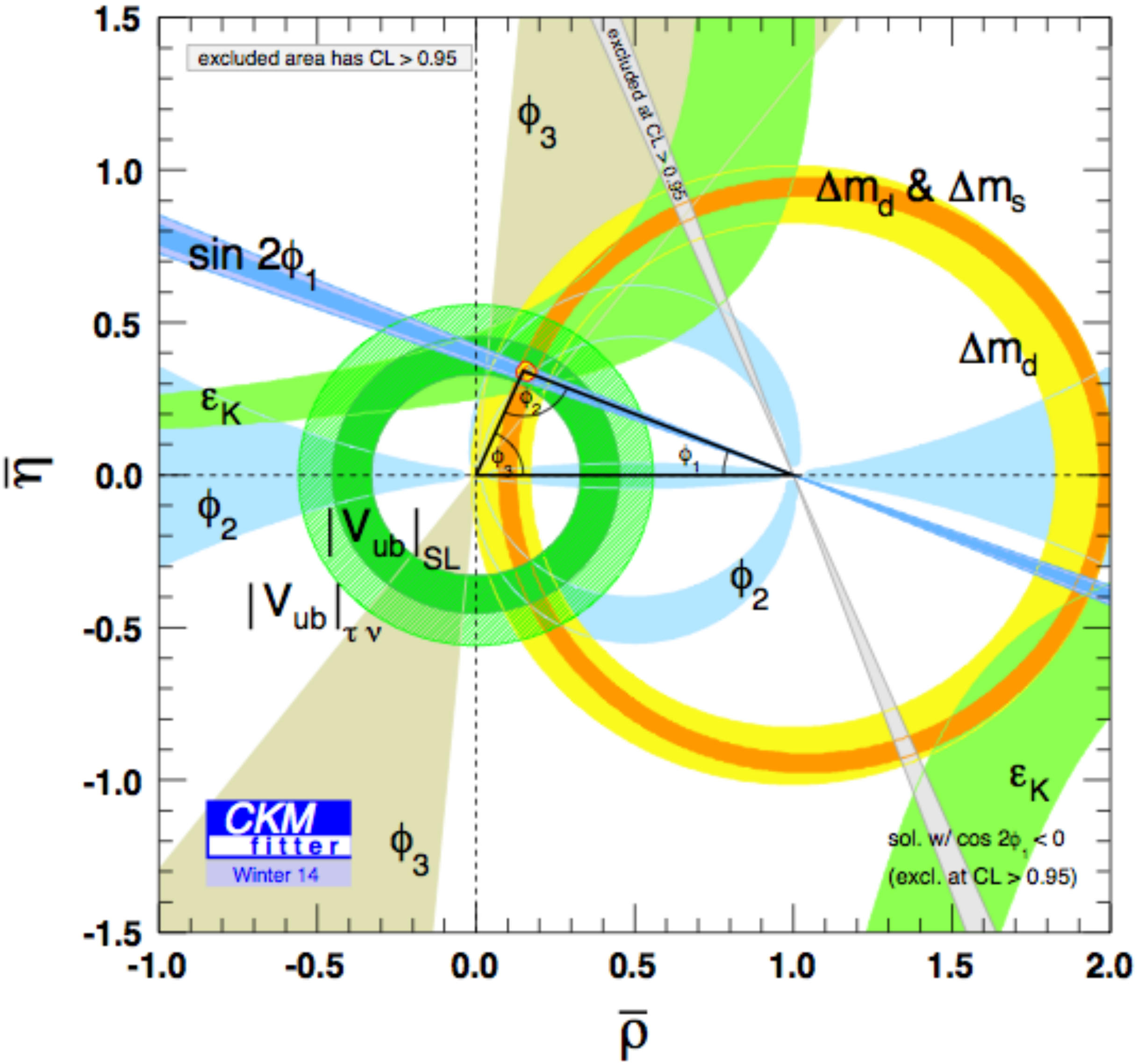
Another topic: Quark Flavour

- It is sensitive to coupling ⊗ mass of new particle
  ⇒ Complementary with direct search
- Sensitive to the new physics amplitude A_{NP} in
  – Absolute value: branching fractions
  – Phase: CP violation
  – Lorentz structure: decay products angular distribution remains sensitive even for MFV case
- Interpretation often limited by the theory predictions, i.e. SM soft QCD matrix element calculations: e.g.
  if Bf_B^2 is better known, Δm_d and CPV in $B_d \to J/\psi K_S$ will give a much more precise (ρ, η) than now

Even now

- Only
  - sin $2\phi_1$,
  - ϕ_2
  - ϕ_3

statistically limited



Another topic: Quark Flavour

- Good prospects for the next 10~15 years:
  - LHCb: Superseded Tevatron in B_s and B factories in $B_{u,d}$. Errors will be reduced by two or more with the coming runs followed by upgrade for another 10 times more statistics
  - SuperKEKB collider will study two orders more $B_{u,d}$ than BABAR and BELLE studied, with a better hermetic detectors including neutrals

Another topic: Quark Flavour

- Good prospects for the next 10~15 years:
  - LHCb: Superseded Tevatron in B_s and B factories in $B_{u, d}$. Errors will be reduced by two or more with the coming runs followed by upgrade for another 10 times more statistics
  - SuperKEKB collider will study two orders more $B_{u, d}$ than BABAR and BELLE studied, with a better hermetic detectors including neutrals
  - $K^+ \to \pi^+ \nu \bar{\nu}$ (NA62) at CERN and $K_L \to \pi^0 \nu \bar{\nu}$ (KOTO) at JPARC, proving flavour universality…

Another topic: Quark Flavour

- Good prospects for the next 10~15 years:
  - LHCb: Superseded Tevatron in B_s and B factories in $B_{u,\,d}$. Errors will be reduced by two or more with the coming runs followed by upgrade for another 10 times more statistics
  - SuperKEKB collider will study two orders more $B_{u,\,d}$ than BABAR and BELLE studied, with a better hermetic detectors including neutrals
  - $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (NA62) at CERN and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ (KOTO) at JPARC, proving flavour universality…
  - No tau-charm factory plan yet, but τ and c are also covered by LHCb and SuperKEKB

Another topic: Quark Flavour

- Good prospects for the next 10~15 years:
  - LHCb: Superseded Tevatron in B_s and B factories in $B_{u,d}$. Errors will be reduced by two or more with the coming runs followed by upgrade for another 10 times more statistics
  - SuperKEKB collider will study two orders more $B_{u,d}$ than BABAR and BELLE studied, with a better hermetic detectors including neutrals
  - $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (NA62) at CERN and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ (KOTO) at JPARC, proving flavour universality…
  - No tau-charm factory plan yet, but τ and c are also covered by LHCb and SuperKEKB
- Can theory catch up?

Another topic: Quark Flavour

- Good prospects for the next 10~15 years:
  - LHCb: Superseded Tevatron in B_s and B factories in $B_{u,d}$. Errors will be reduced by two or more with the coming runs followed by upgrade for another 10 times more statistics
  - SuperKEKB collider will study two orders more $B_{u,d}$ than BABAR and BELLE studied, with a better hermetic detectors including neutrals
  - $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (NA62) at CERN and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ (KOTO) at JPARC, proving flavour universality…
  - No tau-charm factory plan yet, but τ and c are also covered by LHCb and SuperKEKB
- Can theory catch up? And what will be after?

Also Charged Lepton Flavour

- Charged lepton flavour violation due to neutrino oscillations are negligible, e.g. $Br(\mu \to e\gamma) \approx 10^{-54}$
- 😄 Most of the New Physics scenario (1 in page 17) generates charged lepton flavour violation.

Also Charged Lepton Flavour

- Charged lepton flavour violation due to neutrino oscillations are negligible, e.g. Br($\mu \rightarrow e\gamma$) ≈ 10^{-54}
- 😄 Most of the New Physics scenario (1 in page 17) generates charged lepton flavour violation.
  😕 However physics generates ν oscillations are very different and not relate the charged leptons in general, i.e. ν oscillations are not necessarily good reason to expect charged lepton flavour violation (2 in page 17), I think.

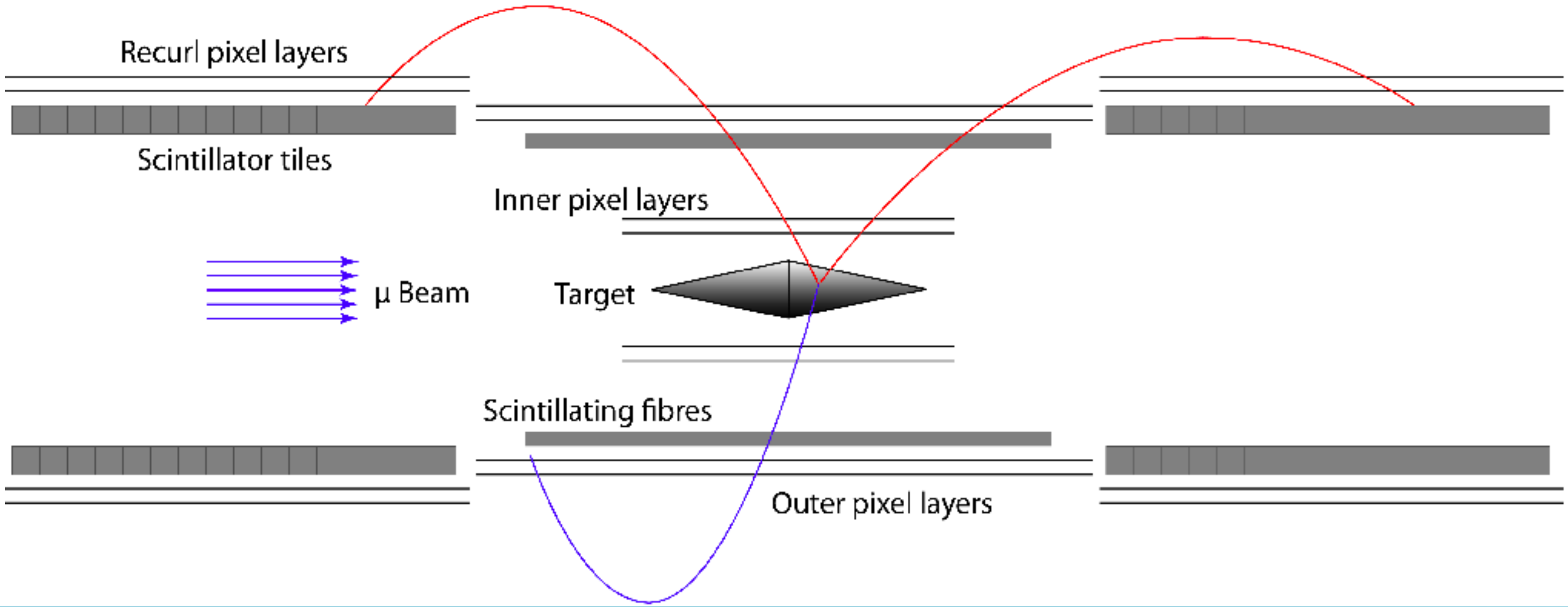
Also Charged Lepton Flavour

- Good prospects for the next 10~15 years, thanks to
  - more powerful μ beam lines with upgrade in view
  - development in new detector technology

- Original SINDRUM experiment with cylindrical MWPC

$\Downarrow$

Scintillating fibre tracker with SiPMT readout
Si Pixel detector



Also Charged Lepton Flavour

- Good prospects for the next 10~15 years, thanks to
  - more powerful μ beam lines with upgrade in view
  - development in new detector technology
- Already in portfolio with >10 improvement
  - $\mu \rightarrow e\gamma$ MEG (PSI) data taking and upgrade
  - $\mu \rightarrow e$ conversion Mu2e (FNAL), COMET (JPARC)
  - $\mu \rightarrow eee$ Mu3e (PSI)
  - τ decays at SuperKEKB and LHCb

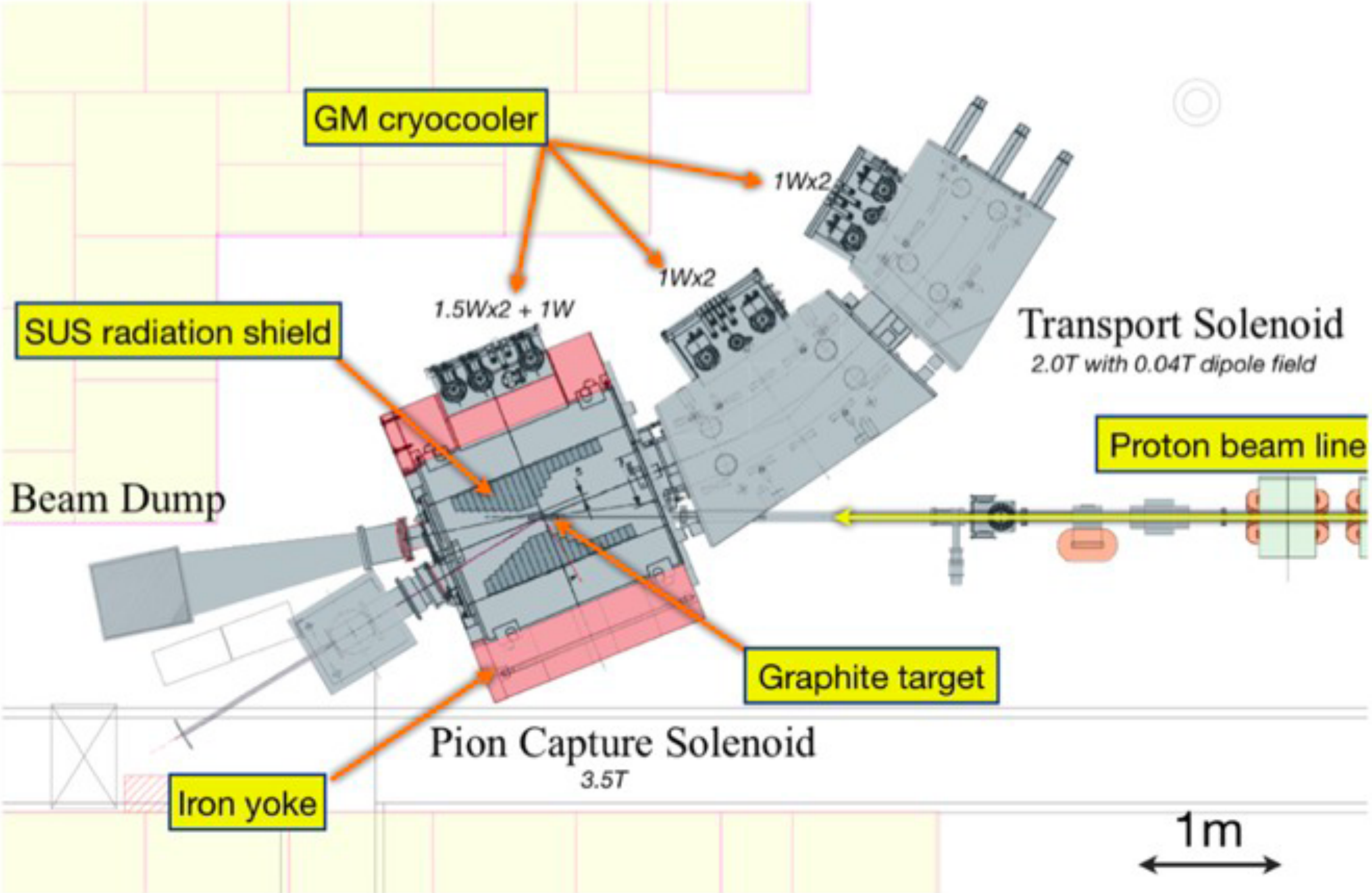
Also Charged Lepton Flavour

- Good prospects for the next 10~15 years, thanks to
  - more powerful μ beam lines with upgrade in view
  - development in new detector technology
- Already in portfolio with >10 improvement
  - $\mu \rightarrow e\gamma$ MEG (PSI) data taking and upgrade
  - $\mu \rightarrow e$ conversion Mu2e (FNAL), COMET (JPARC)
  - $\mu \rightarrow eee$ Mu3e (PSI)
  - τ decays at SuperKEKB and LHCb
- Their results are closely related to quark flavour physics and direct search

Also Charged Lepton Flavour

- Good prospects for the next 10~15 years, thanks to
  - more powerful μ beam lines with upgrade in view
  - development in new detector technology
- Already in portfolio with >10 improvement
  - $\mu \rightarrow e\gamma$ MEG (PSI) data taking and upgrade
  - $\mu \rightarrow e$ conversion Mu2e (FNAL), COMET (JPARC)
  - $\mu \rightarrow eee$ Mu3e (PSI)
  - τ decays at SuperKEKB and LHCb
- Their results are closely related to quark flavour physics and direct search
- A further step (>10 years) with more efficient capture for the muon beam?

more efficient muon beam



Neutrinos

- Progress in Neutrino physics is a little decoupled and can define its own programme relatively independent from the results in the other filed and will occupy for the next 10 to 20 years

Neutrinos

- Progress in Neutrino physics is a little decoupled and can define its own programme relatively independent from the results in the other filed and will occupy for the next 10 to 20 years
  - *** absolute mass scale, mass hierarchy, $0\nu\beta\beta$ decay
  - ** CP violation phase
  - * mixing angle measurements

Neutrinos

- Progress in Neutrino physics is a little decoupled and can define its own programme relatively independent from the results in the other filed and will occupy for the next 10 to 20 years
  - *** absolute mass scale, mass hierarchy, $0\nu\beta\beta$ decay
  - ** CP violation phase
  - * mixing angle measurements
- Whether we need a neutrino factory depends on the ** and * results

Neutrinos

- Progress in Neutrino physics is a little decoupled and can define its own programme relatively independent from the results in the other filed and will occupy for the next 10 to 20 years
  - *** absolute mass scale, mass hierarchy, $0\nu\beta\beta$ decay
  - ** CP violation phase
  - * mixing angle measurements
- Whether we need a neutrino factory depends on the ** and * results
- Existing neutrino anomalies must be sorted out:
  - LNSD/MinuBooNE, Reactor flux, Ga
  - short and very short baseline experiments in preparation

By the way, what would happen,

- if 0νββ were found?
- if neutral leptons, ~1 GeV, were found in a beam dump experiment?
- if LSND sterile neutrino were found?
- if CP violation were found in ν oscillations?
- if axion were found?

By the way, what would happen,

- if $0\nu\beta\beta$ were found?
- if neutral leptons, ~1 GeV, were found in a beam dump experiment?
- if LSND sterile neutrino were found?
- if CP violation were found in ν oscillations?
- if axion were found?

- They are all great breakthrough, but consequence to the other fields of particle physics is not so clear…

Before conclude

- I am sorry for not to mention:
  - direct dark matter search,
  - $\mu(\gamma-2)$,
  - EDM,
  - and all other things I should have mentioned

Before conclude

- And, I am sorry for having not much vision in this talk.

To Conclude

- Particle physics community has well established programme for the next 10 to 15 years, at high energy frontier (LHC), quark and lepton flavour physics, neutrino physics, and others.

To Conclude

- Particle physics community has well established programme for the next 10 to 15 years, at high energy frontier (LHC), quark and lepton flavour physics, neutrino physics, and others.
- However, if no sign of new physics emerges from LHC by ~2018,
  - Purely scientific decision on the next high energy frontier machine will become very difficult
  - One may need to increase effort on non energy frontier physics, e.g. high intensity beam-dump experiment,

To Conclude

- Particle physics community has well established programme for the next 10 to 15 years, at high energy frontier (LHC), quark and lepton flavour physics, neutrino physics, and others.
- However, if no sign of new physics emerges from LHC by ~2018,
  - Purely scientific decision on the next high energy frontier machine will become very difficult
  - One may need to increase effort on non energy frontier physics, e.g. high intensity beam-dump experiment,
  - Importance for R&D increases: high performance target, high field magnet, **new acceleration technology**, …

To Conclude

- Particle physics community has well established programme for the next 10 to 15 years, at high energy frontier (LHC), quark and lepton flavour physics, neutrino physics, and others.
- However, if no sign of new physics emerges from LHC by ~2018,
  - Purely scientific decision on the next high energy frontier machine will become very difficult
  - One may need to increase effort on non energy frontier physics, e.g. high intensity beam-dump experiment,
  - Importance for R&D increases: high performance target, high field magnet, **new acceleration technology**, …

New Physics must be searched at all fronts!

To Conclude

- And many thanks to the audience and organisers!!!