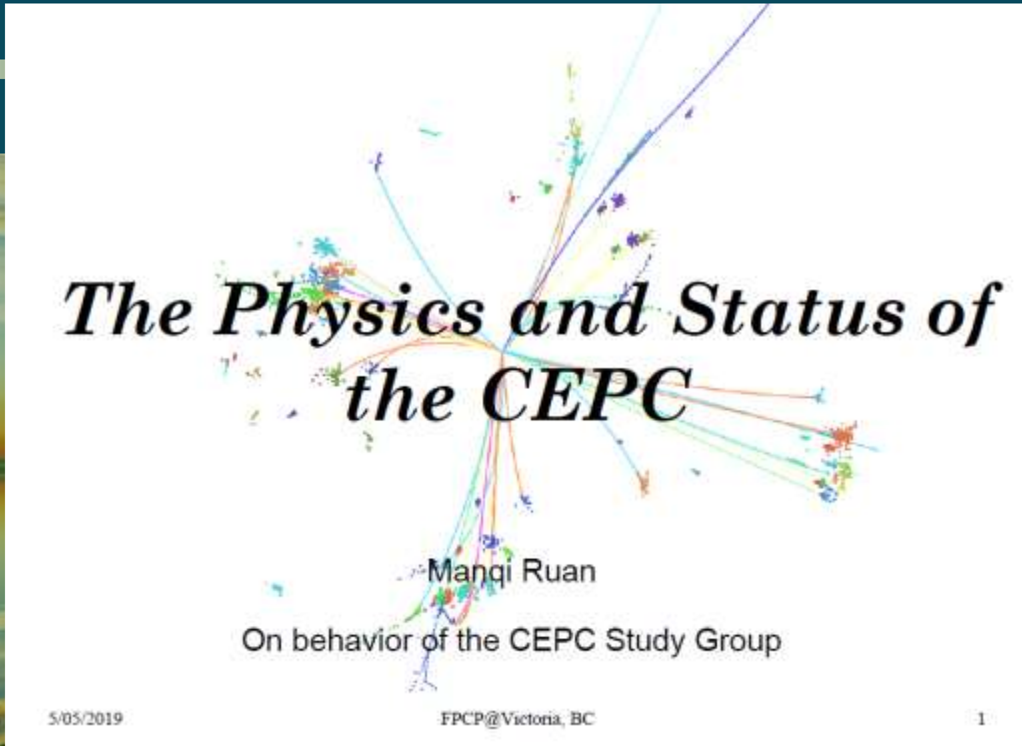


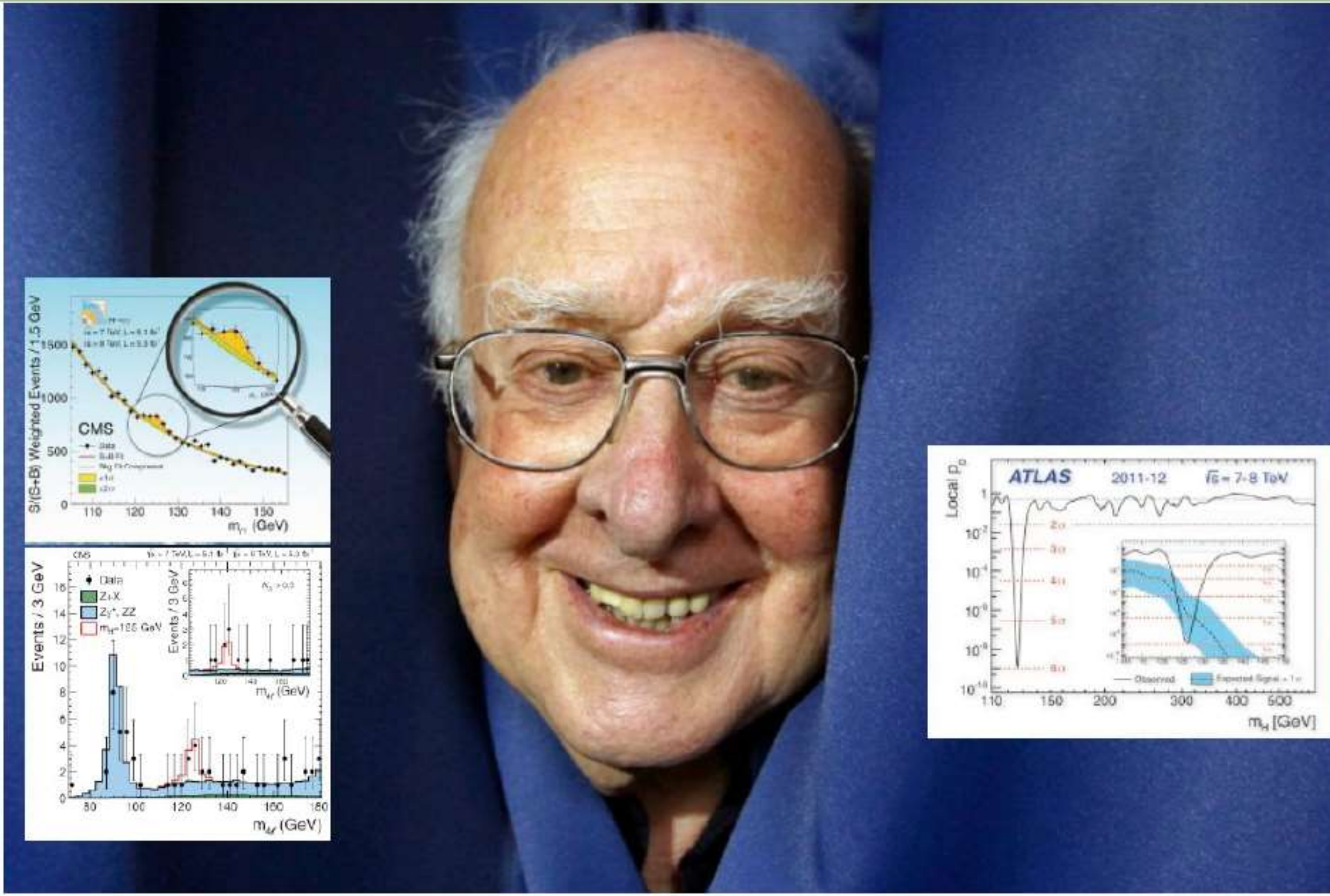

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

# Future High Energy Frontier Facilities

**Manqi RUAN (CepC/IHEP) and Vladimir SHILTSEV (Fermilab)**

*Conference on Flavor Physics and CP Violation (FPCP 2019)*

06-10 May 2019 – University of Victoria

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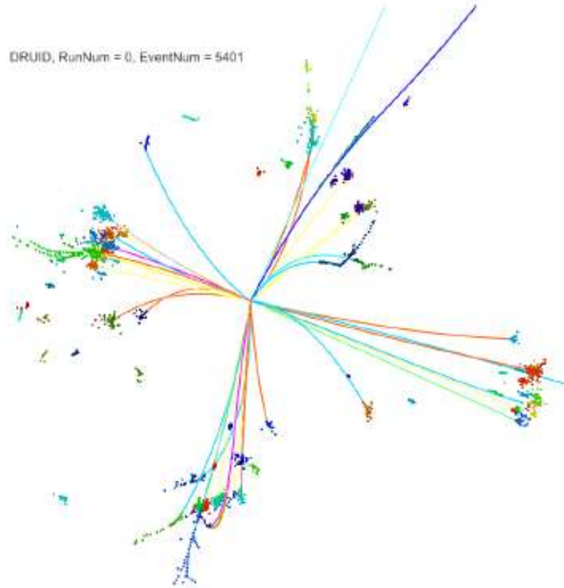
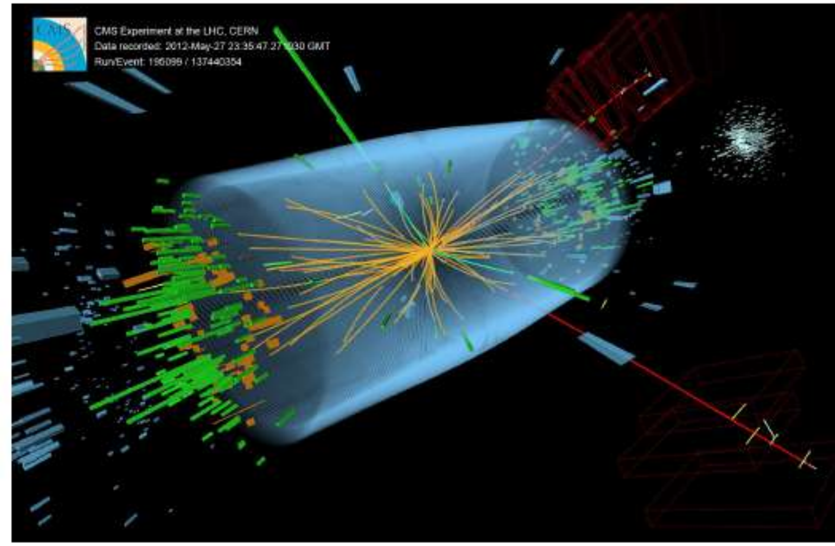
# Higgs measurement at e+e- & pp




| | Yield | efficiency | Comments |
|---|---|---|---|
| LHC | Run 1: $10^6$<br>Run 2/HL: $10^{7\text{-}8}$ | ~o($10^{-3}$) | High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to g(ttH), and even g(HHH) |
| CEPC | $10^6$ | ~o(1) | Clean environment & Absolute measurement, Percentage level accuracy of Higgs width & Couplings |

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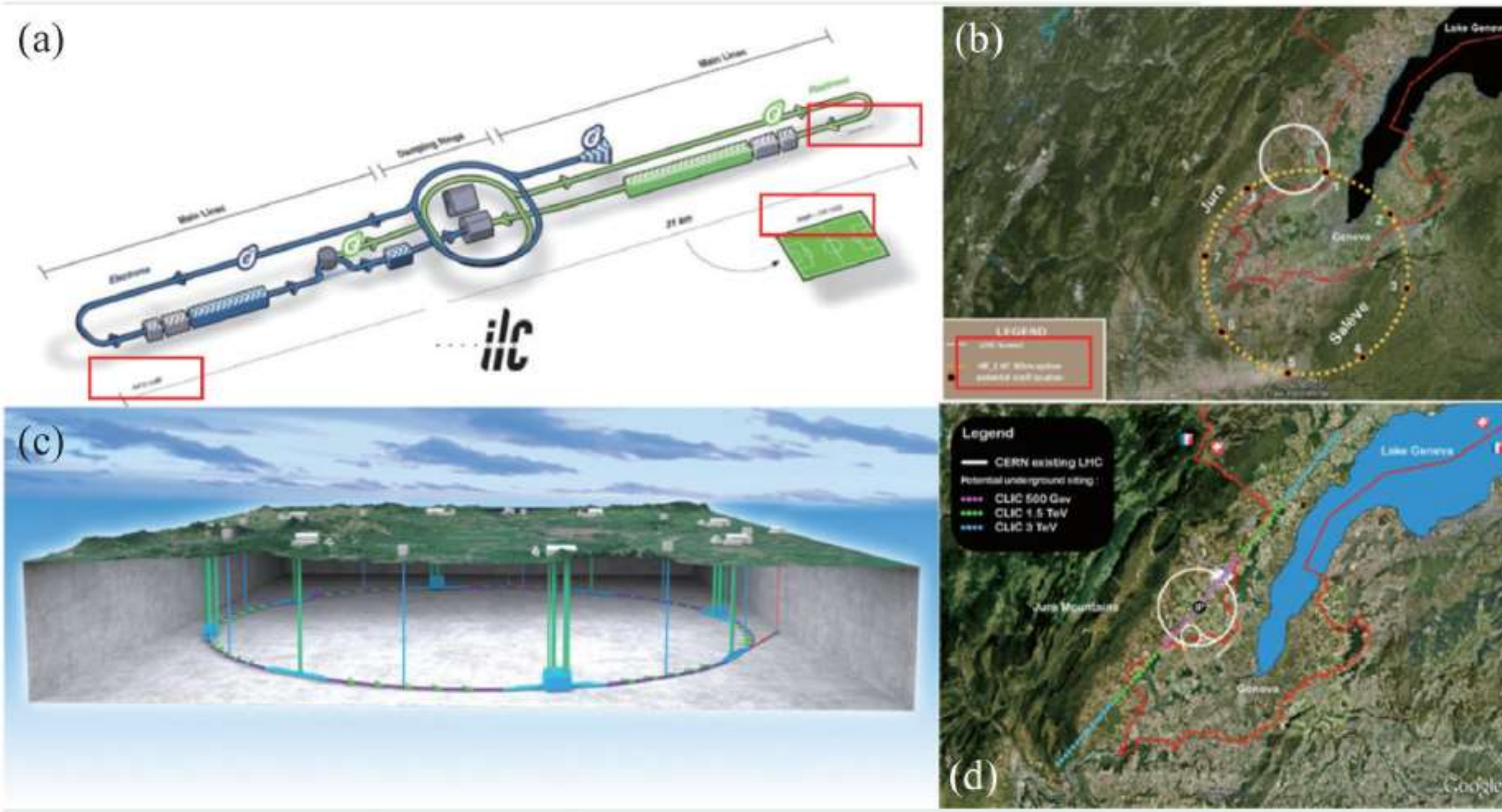
# Multiple e+e- Higgs factories are proposed



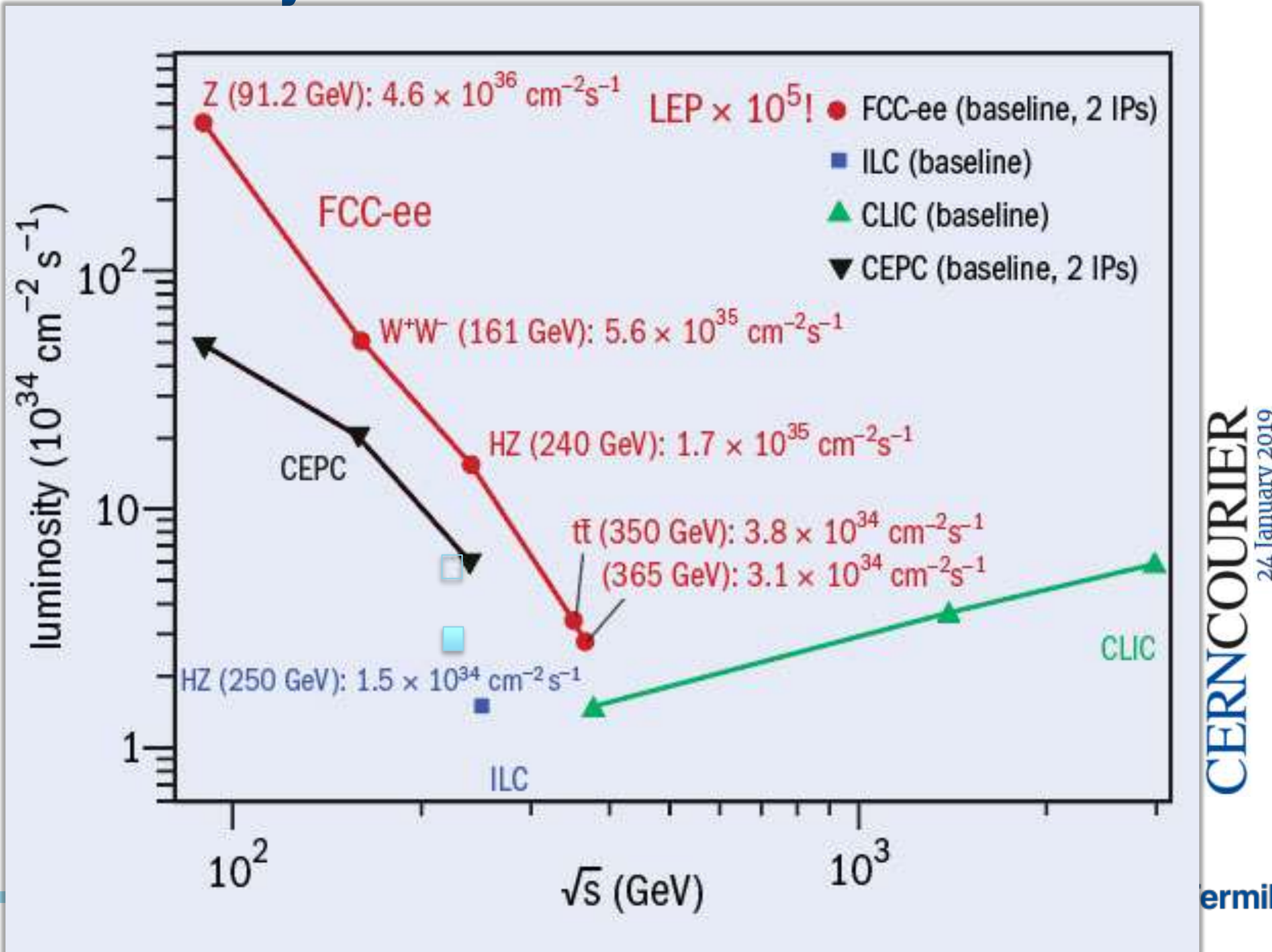

ILC (a): TDR released in 2013
FCC (b): CDR released in 2019
CEPC (c): CDR released in 2018
CLIC (d): CDR released in 2013

20 km, SRF, 130 MW power, 250 GeV c.m.e. Cost estimate 7 B$
100 km, three rings, power ~300MW (tbd) Cost est. 10.5 BCHF
100 km, three rings, ~200-300 MW, Cost est. “<6 B$”
11 km for 380 GeV c.m.e.NC RF, 168 MW Cost est. 5.9 BCHF



LHC is 27 km long, SC magnets, 150 MW, 3.8-4.8 BCHF *

# Luminosity *e+e-* : Circular vs Linear



# Challenges of e+e- Ring HF's

- Power limited regime. Synchrotron radiation power from both beams limited to 100 MW ($P/\eta$=total cite power). Beam current $I$ is determined by power.

$$I = \frac{e\rho}{2C_\gamma E^4} P_T,$$

- Luminosity determined by bend radius $\rho$, beam-beam parameter $\xi_y$, beta function at the IP $\beta_y$* and power

$$\mathcal{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)} \left[ \rho \frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z) \right]$$

- $\xi_y$ =0.13 new beam-beam instability; while synchrotron radiation $\Delta E_{turn}/E \sim$ 0.1-5% per turn *Z* to 360 GeV, the beam-strahlung is at IPs only and spreads $\delta E/E$ ~0.1-0.2% , but tails upto 10x that ±2.5% determine 18 min beam lifetime ~18 min → need large acceptance optics $\beta_y$* = 0.8-1.6 mm and full energy booster

# Comparison: Linear & Circular

- Linear:
  - Center of mass energy can be efficiently increased from the minimal energy of a e+e- Higgs factory (240/250 GeV),
  - Access to tt threshold (350 GeV), ttH and Higgs self couplings (500 GeV or higher)
  - Significantly increase the accuracy on the Higgs width measurement (as the W fusion process's Xsec and signal-background separation increases and improves at high energy)
  - Longitudinal Polarized beam could significantly increase the physics reach
- Circular:
  - Very efficient in delivering luminosities at low energy!
  - 100 Million/1 Giga of W boson, 1 Tera Z boson or higher at CEPC/FCC
  - Precise determination of the beam energy using resonant depolarization method
  - Huge potential to Higgs physics, EW, Flavor, QCD, top physics...
  - Can be upgraded to pp collider with c.m.s energy ~ 100 TeV.

***linear – circular Complementarity***

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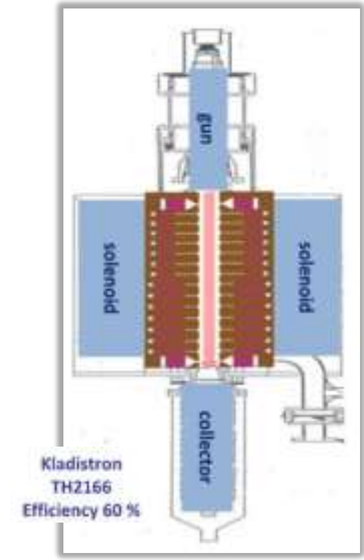
*NB: Real complimentarity is hardly possible because of the cost of these facilities (> LHC)*

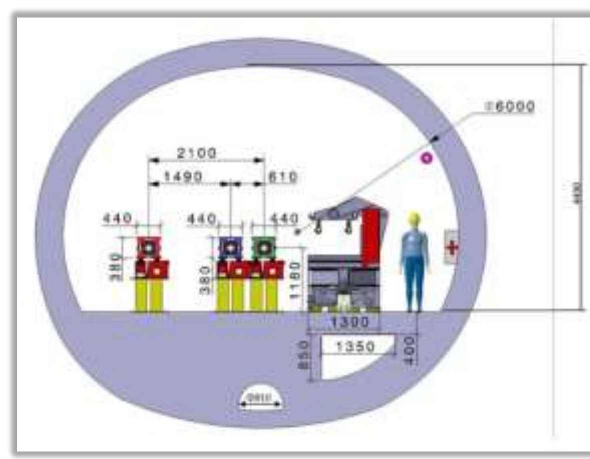
# Linear Higgs Factories

- All key items addressed by R&D and test facilities:
  - 31.5 MV/m at FNAL, KEK, etc … "ready now"
- Radiation at IP (beam strahlung) is growing issue :
  - $\delta E/E$ ~1.5% in ILC, 40% of CLIC lumi 1% off $\sqrt{s}$




# Ring Higgs Factories's - R&D ahead :

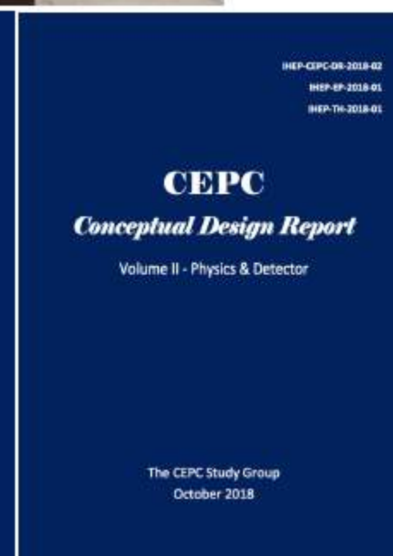
- High efficient RF sources:
  - Klystron 400/800 MHz $\eta$ from 65% to >85%
- High efficiency SRF cavities:
  - 10-15 MV/m and high $Q_0$; Nb-on-Cu, $Nb_3Sn$
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10 million cu.m. out of 100 km tunnel



# Chinese Electron Positron Collider CepC

## CDR released in Nov. 2018





# CEPC CDR Parameters

D. Wang

| | *Higgs* | *W* | *Z (3T)* | *Z (2T)* |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Beam energy (GeV) | **120** | **80** | **45.5** | |
| Circumference (km) | 100 | | | |
| Synchrotron radiation loss/turn (GeV) | 1.73 | 0.34 | 0.036 | |
| Crossing angle at IP (mrad) | 16.5×2 | | | |
| Piwinski angle | 2.58 | 7.0 | 23.8 | |
| Number of particles/bunch $N_e$ ($10^{10}$) | 15.0 | 12.0 | 8.0 | |
| **Bunch number (bunch spacing)** | **242 (0.68μs)** | **1524 (0.21μs)** | **12000 (25ns+10%gap)** | |
| Beam current (mA) | 17.4 | 87.9 | 461.0 | |
| **Synchrotron radiation power /beam (MW)** | **30** | **30** | **16.5** | |
| Bending radius (km) | 10.7 | | | |
| Momentum compact ($10^{-5}$) | 1.11 | | | |
| **β function at IP $\beta_x^*$ / $\beta_y^*$ (m)** | **0.36/0.0015** | **0.36/0.0015** | **0.2/0.0015** | **0.2/0.001** |
| Emittance $\varepsilon_x/\varepsilon_y$ (nm) | 1.21/0.0031 | 0.54/0.0016 | 0.18/0.004 | 0.18/0.0016 |
| Beam size at IP $\sigma_x/\sigma_y$ (μm) | 20.9/0.068 | 13.9/0.049 | 6.0/0.078 | 6.0/0.04 |
| Beam-beam parameters $\xi_x/\xi_y$ | 0.031/0.109 | 0.013/0.106 | 0.0041/0.056 | 0.0041/0.072 |
| RF voltage $V_{RF}$ (GV) | 2.17 | 0.47 | 0.10 | |
| RF frequency $f_{RF}$ (MHz) (harmonic) | 650 (216816) | | | |
| Natural bunch length $\sigma_z$ (mm) | 2.72 | 2.98 | 2.42 | |
| Bunch length $\sigma_z$ (mm) | 3.26 | 5.9 | 8.5 | |
| HOM power/cavity (2 cell) (kw) | 0.54 | 0.75 | **1.94** | |
| Natural energy spread (%) | 0.1 | 0.066 | 0.038 | |
| Energy acceptance requirement (%) | **1.35** | **0.4** | **0.23** | |
| Energy acceptance by RF (%) | 2.06 | 1.47 | 1.7 | |
| Photon number due to beamstrahlung | 0.1 | 0.05 | 0.023 | |
| Lifetime _simulation (min) | 100 | | | |
| Lifetime (hour) | **0.67** | **1.4** | **4.0** | **2.1** |
| $F$ (hour glass) | 0.89 | 0.94 | 0.99 | |
| **Luminosity/IP $L$ ($10^{34}$cm$^{-2}$s$^{-1}$)** | **2.93** | **10.1** | **16.6** | **32.1** |

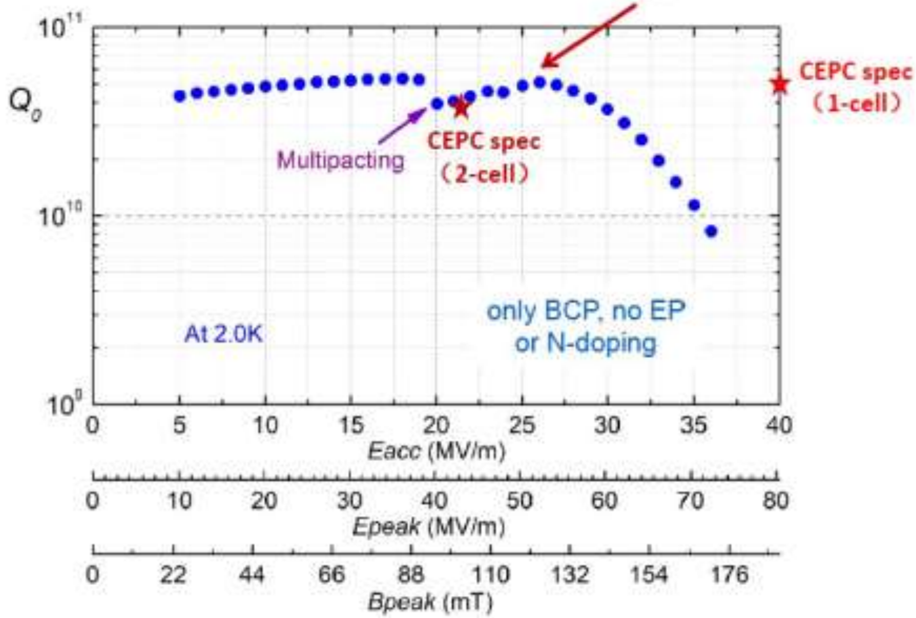
# CEPC SCRF Cavities

## 650 MHz 1-cell cavity

Accelerating gradient (Eacc) reach 36.0 MV/m， **Q = 5.1E10 @ Eacc = 26 MV/m。**

Next, increase the Q and Eacc through N-doping, EP, etc. Target: **5E10@42MV/m** for vertical test.

**Record highest Q-factor in China**




650 MHz 1-cell cavity

# 1st 650MHz Klystron Manufacturer and Infrastructure Preparation Progress

Z.S. Zhou

Modulator anode components

Cavities components

Klystron output window

Assembly plant construction

Large size baking furnace commissioning

# Civil Engineering & Site Selection


Factors affecting site selection:

1、Social factors:

National planning, Regional economic conditions, Cultural environment, Immigration, Environmental protection.

2、Natural conditions and engineering factors:

Climate, Traffic, Topographical geology, Engineering layout, Construction Conditions, Engineering investment.

3、Operating factor:

Water supply, power supply, operating costs

In China, there are many sites that meet the construction conditions.

# International Science City

**Overall Scale** : 3.3km² of construction area for short-term use & 6.7km² for future use.

# Future Energy Frontier Colliders

- All proposals are focused on :
  - *(Affordable) Cost and Luminosity*
- Usually :
  - *Scale of civil construction grows with Energy*
  - *Cost of accelerator components grows with Energy*
  - *Requirement site power grows with Energy*
- So, the total cost grows with ENERGY
  - Thankfully, not linearly , more like $cost \sim \beta E^{\kappa}$, $\kappa \approx \frac{1}{2} \pm 1/6$
    - *Take ILC as an example: 0.25 → 0.5 → 1 TeV* **0.69 : 1 : 1.67**
  - Still, huge challenge for energies $E$ some x10 of LHC
  - Choice of technology ( $\beta$ ) and *prior investments* are critical

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# Let's Consider
# Limits of Linear $e+e-$ Colliders

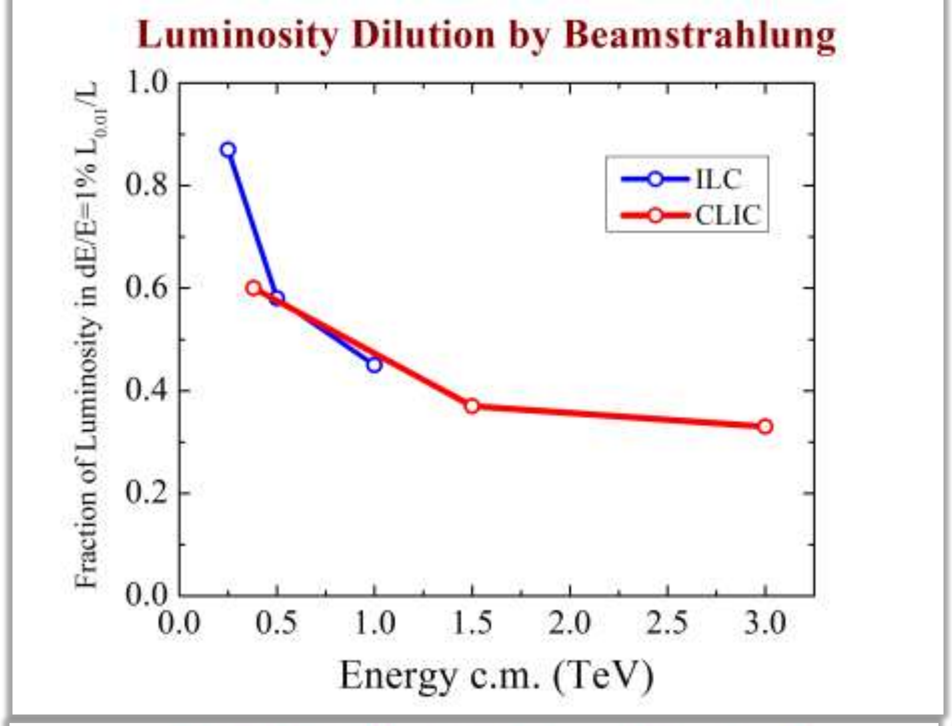
- Both ILC and CLIC offer staged approach to ultimate $E$
- The limits are set by:

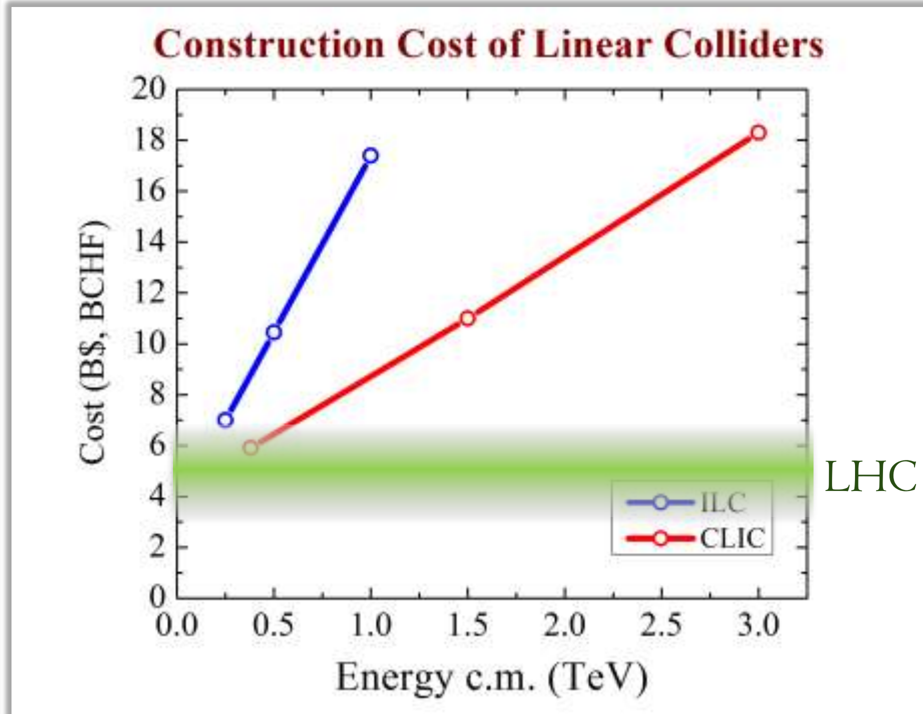
  Cost

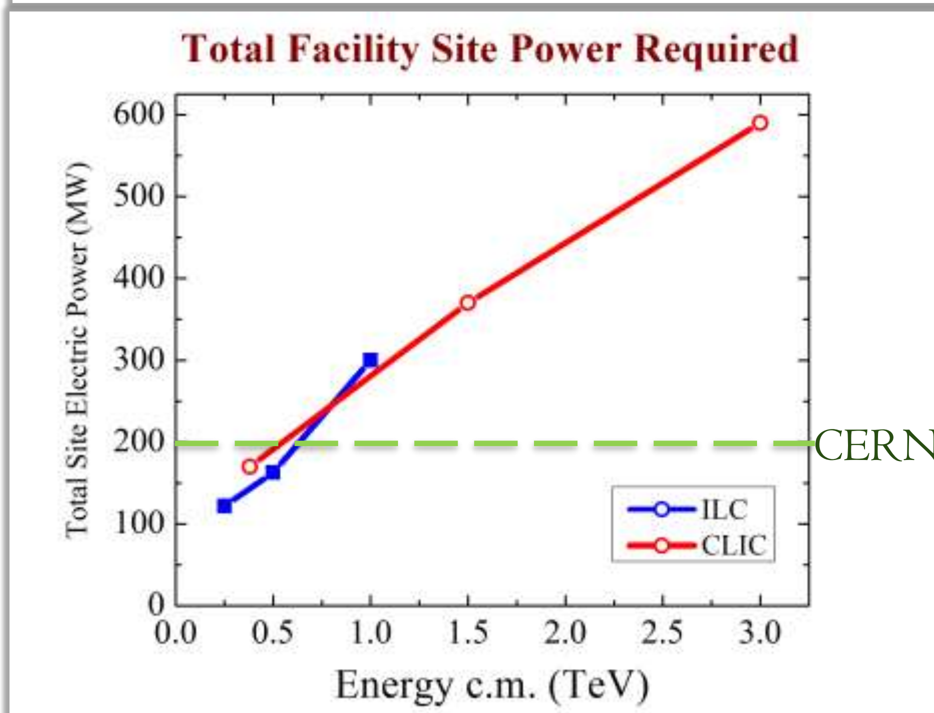
  Site power requirements

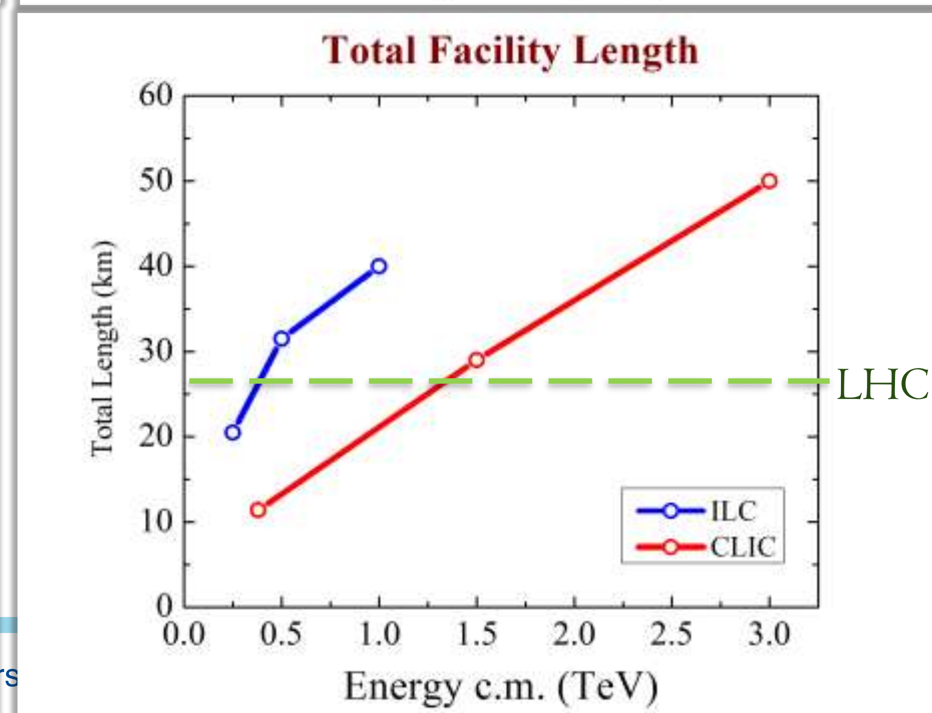
  Total length

  Beamstrahlung


Luminosity Dilution by Beamstrahlung
Fraction of Luminosity in dE/E=1% L0.01/L
Energy c.m. (TeV)
ILC
CLIC

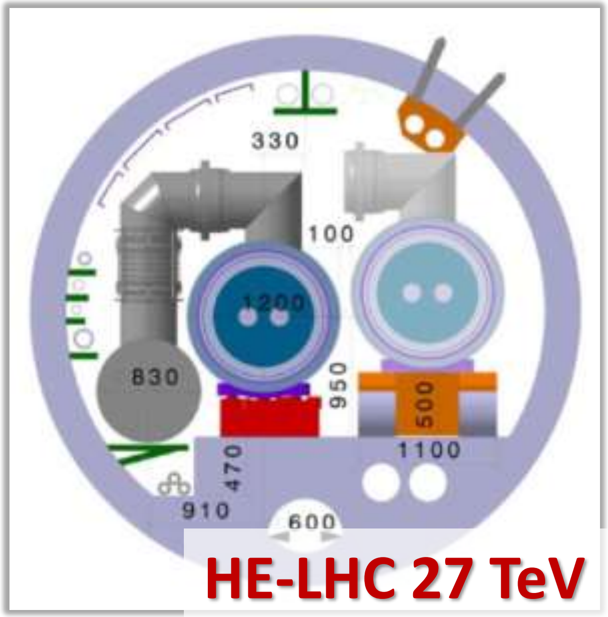

Construction Cost of Linear Colliders
Cost (B$, BCHF)
Energy c.m. (TeV)
LHC
ILC
CLIC

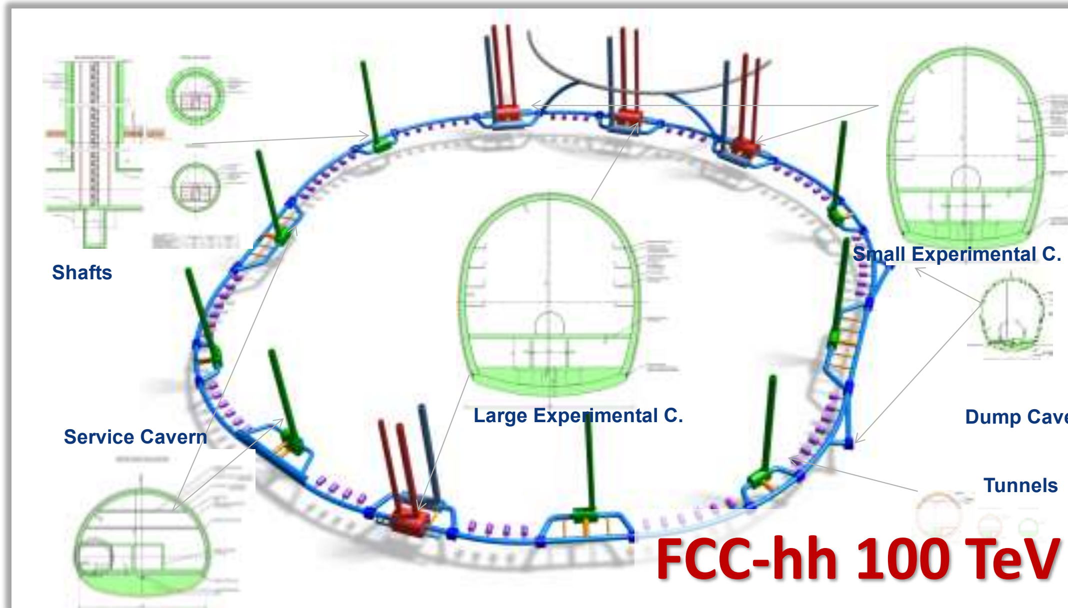

Total Facility Site Power Required
Total Site Electric Power (MW)
Energy c.m. (TeV)
CERN
ILC
CLIC

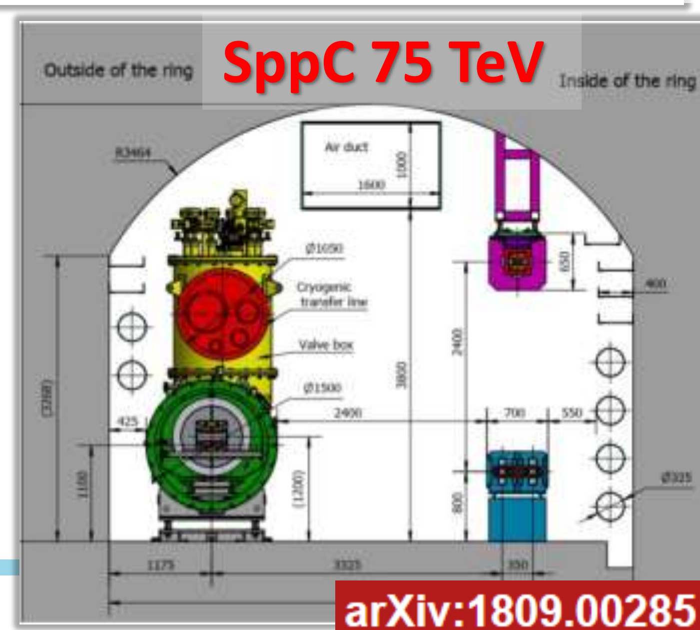

Total Facility Length
Total Length (km)
Energy c.m. (TeV)
LHC
ILC
CLIC

# Circular *pp* Colliders

HE-LHC CDR (2018) FCC-hh CDR (2018)




**Key facts:** *HE-LHC / FCC-hh* / SppC**

Large tunnel – 27 / 100 / 100 km

SC magnets – 16 / 16 / 12 T

High Lumi & pileup *O*($10^{35}$) , *O*(500)

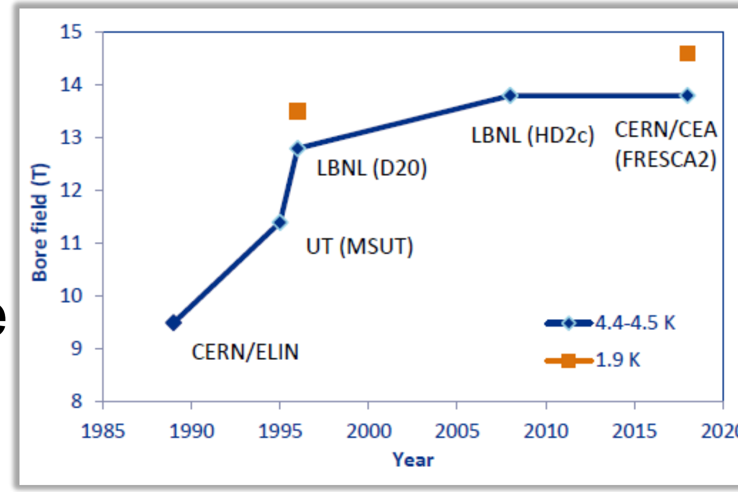
Site power (MW) – 200 / 500? / ?

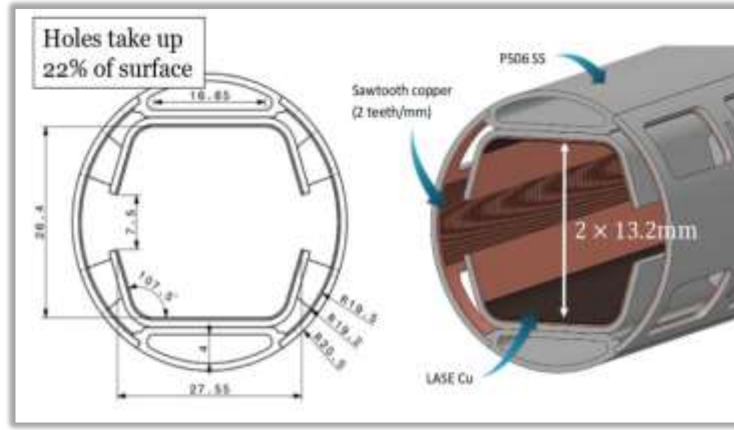
Cost (BCHF) – 7.2 / 17.1 / ?

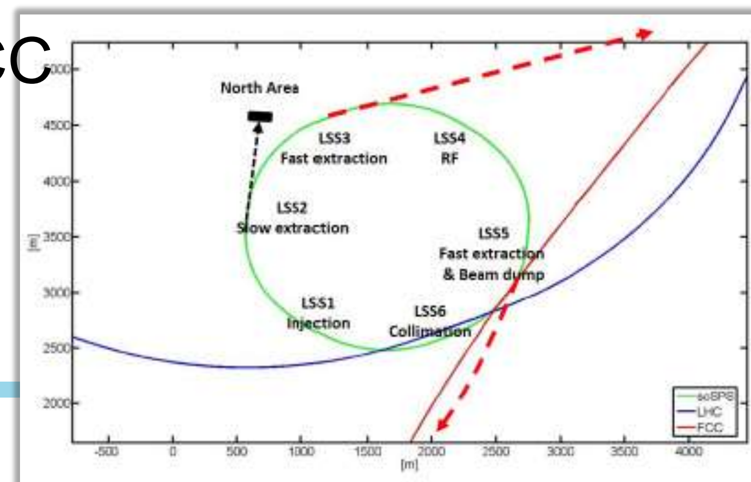
** follow up after e+e- Higgs factories*

# Strategic R&D Ahead :

- High field dipoles:
  - Nb3Sn 16 T / iron-based 12 T, wire
  - (see also Akira's talk)
- Intercept of synchr radiation :
  - 5 MW FCC-hh / 1 MW CepC
- Collimation :
  - x7 LHC circulating beam power
- Optimal injector:
  - 1.3TeV scSPS, 3.3 TeV in LHC/FCC
- Overall machine design :
  - IRs, pileup, vacuum, etc
  - Power and cost reduction




*All that might take 12-18 years*

# HTC Superconducting Cables

- Huge impact If magnet can be used at ~ 4.5K - 20 K
- Fe-based HTC cable
  - Metal, easy to process; Isotropic; Cheap in principle
- Background in CAS
  - World highest Tc Fe-based materials
  - World first ~ 115 m Fe-based SC cables: 12000 A/cm$^2$ @ 10 T
- A collaboration on “HTC SC materials” : Institute of Physics, USTC, Institute of electric engineering, IHEP, 3 SC cable companies in China
  - Iron based HTC cables
  - ReBCO & Bi-2212
  - Goal: ~ 3-5 $ /kA·m
    - Current density: × 10
    - Cost/m: ÷10

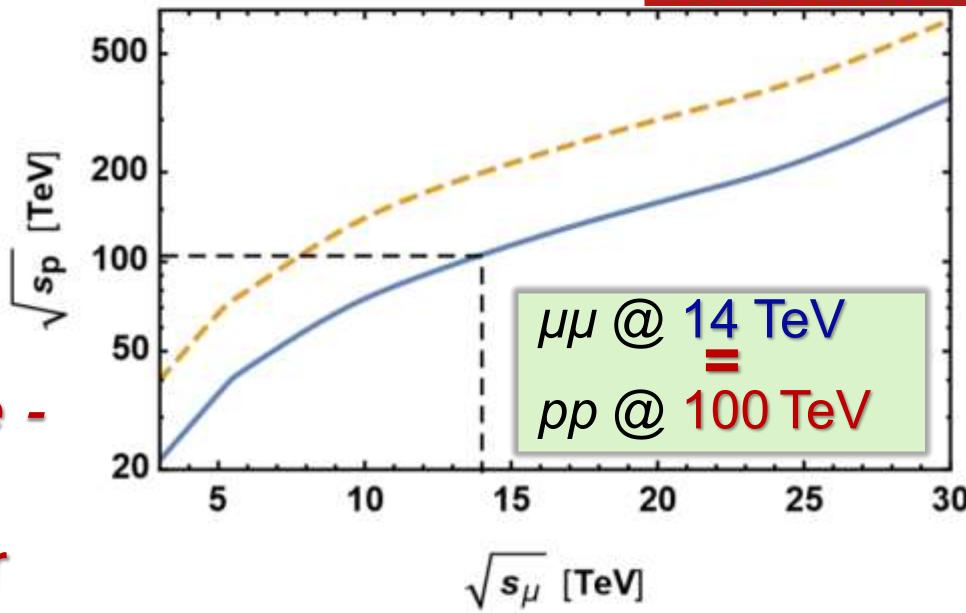
# High Energy $\mu$+$\mu$- Colliders

JINST Special Issue (*MUON*)

arXiv:1901.06150

## *Advantages*:

- ***μ***’s do not radiate / no beamstrahlung→ acceleration in rings → *low cost & great power efficiency*
- ~ *x7* energy reach vs *pp*




**Offer** *“moderately conservative - moderately innovative”* path **to cost affordable** energy frontier colliders:

- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like “strawman” parameter table*

## Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA $e^+$-45 GeV + $e^-$ at rest $\rightarrow \mu^+$-$\mu^-$ , design study of acceleration, detector background and neutrino radiation

# 7-10 YEARS FROM NOW

## WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

- ***ILC:***
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)
- ***CLIC:***
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning
- ***CepC:***
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)
- ***FCC-ee:***
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039
- ***HE-LHC:***
  - **R&D and prepar'ns** 2020-2035
  - Construction 2036-2042
- ***FCC-hh*** (w/o FCC-ee stage)***:***
  - **16T magnet prototype** 2027
  - Construction 2029-2043
- ***$\mu^+$-$\mu^-$ Collider :***
  - **CDR completed** 2027, cost known
  - Test facility constructed 2027
  - Tests and TDR 2028-2035

# Summary

- The world needs electron/positron Higgs factories, to profoundly understood the nature of the Higgs boson and the SM.
- Four electron positron Higgs factories, 2 linear and 2 circular are proposed, and significant progress have been made in the R&D: ready to be build.
- The Chinese High Energy Physics Community takes initiative on the CEPC project and other electron positron Higgs factories
  - The CEPC is the first Chinese efforts for a HEP Science project of this scale -> challenges everywhere
  - Tremendous progress made, and still long way to go
    - CEPC CDR released in Nov 2018: entering TDR phase
    - Lots of Critical progress delivered & aiming at the first collision ~ 2030
  - Giving the importance of electron positron Higgs factory, we hope at least one of them (FCC, ILC, CLIC, and CEPC) can be realized
  - We fully support these global efforts, even it is not build in China.

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# Summary – cont'd (VS):

- Remarkable progress of the projects/proposals/technologies:
  - esp. ILC, CLIC, FCC-*ee*, -*hh*, CepC, *μ*-Colliders, plasma, …
  - allow in-depth evaluation of readiness, power and costs
- Higgs Factories Implementation :
  - several  feasible options on the table
  - the choice might define high-energy future collider choice
- Highest Energy Future Colliders:
  - demand very high AC power & cost; some options to save
  - each machine has a set of key R&D items for next 7-10 yrs
  - core acceleration technology R&D – SC magnets, SRF and plasma – are of general importance and help all - *pp/ee/μμ*
- We also expect to gain valuable experience from the machines to be built and operated over the next decade
  - *SuperKEKB, HL-LHC, NICA, PIP-II, ESS, EIC, Super C-Tau, etc*