Mega-linear vs. Giant-circular.
The next big machine for HEP

F. Bedeschi, INFN

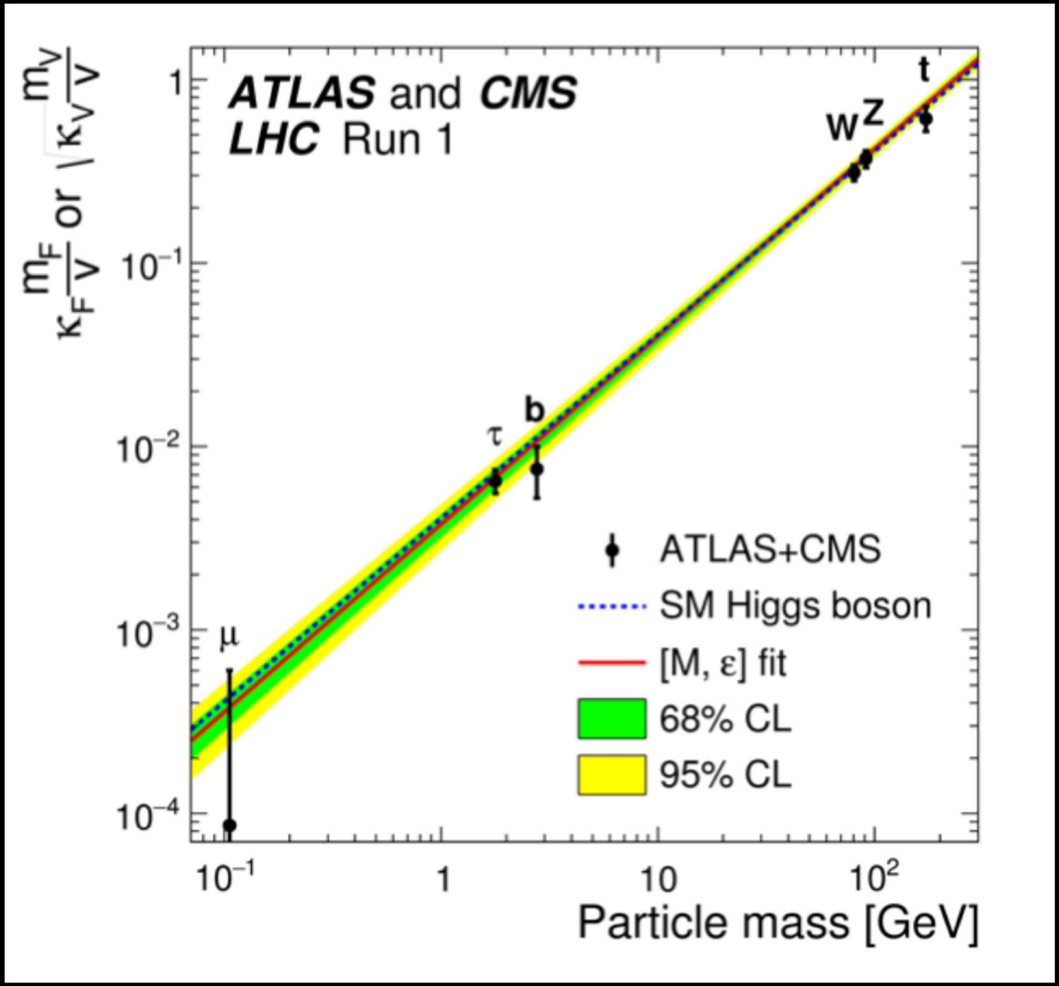
BNL, September 2019

Outline

- Current physics landscape
- Current directions
- Higgs factories e+e-
  - Current status and comments
- Key measurements at FCC-ee and comparisons
- Detector concepts for circular e+e- colliders
  - IDEA and Italian driven detector R&D
- Conclusions

Current physics landscape

- Higgs properties SM-like.



Current physics landscape

- Higgs properties SM-like.
  - After HL-LHC precision level of several %

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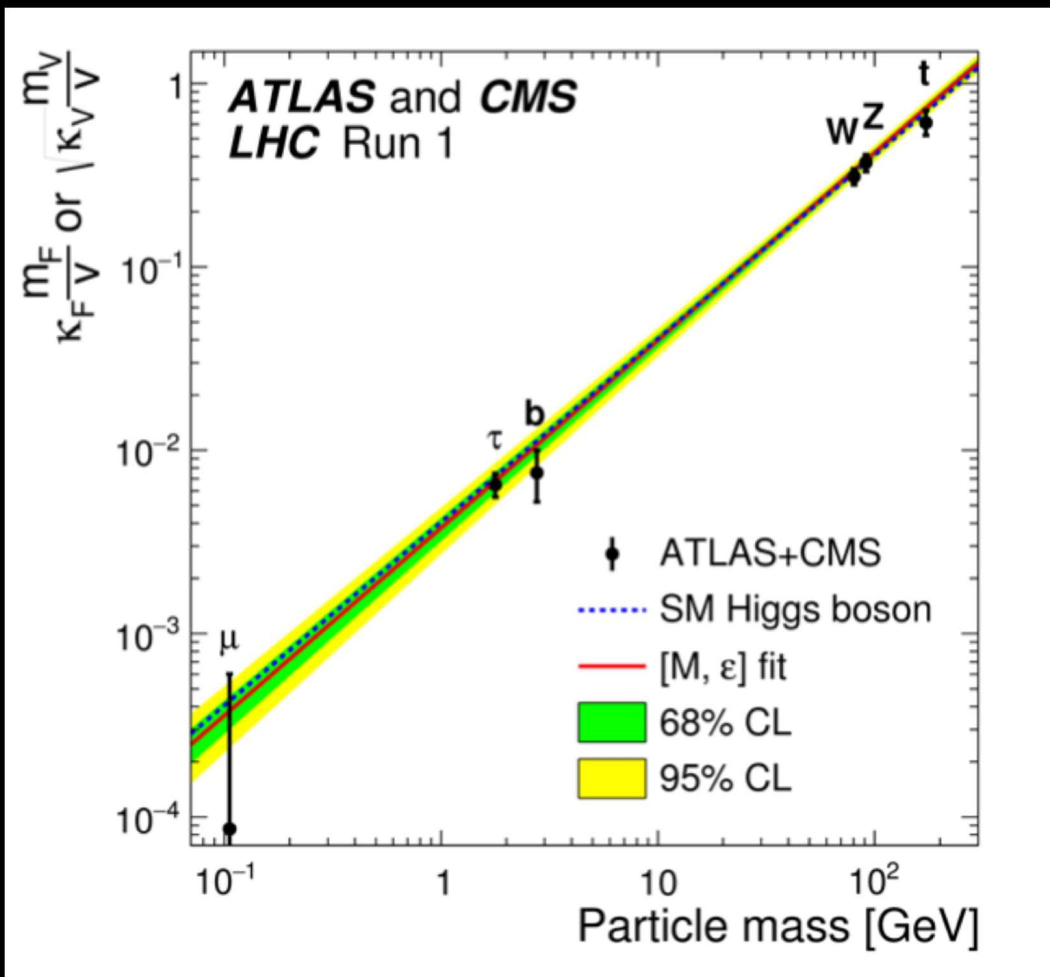

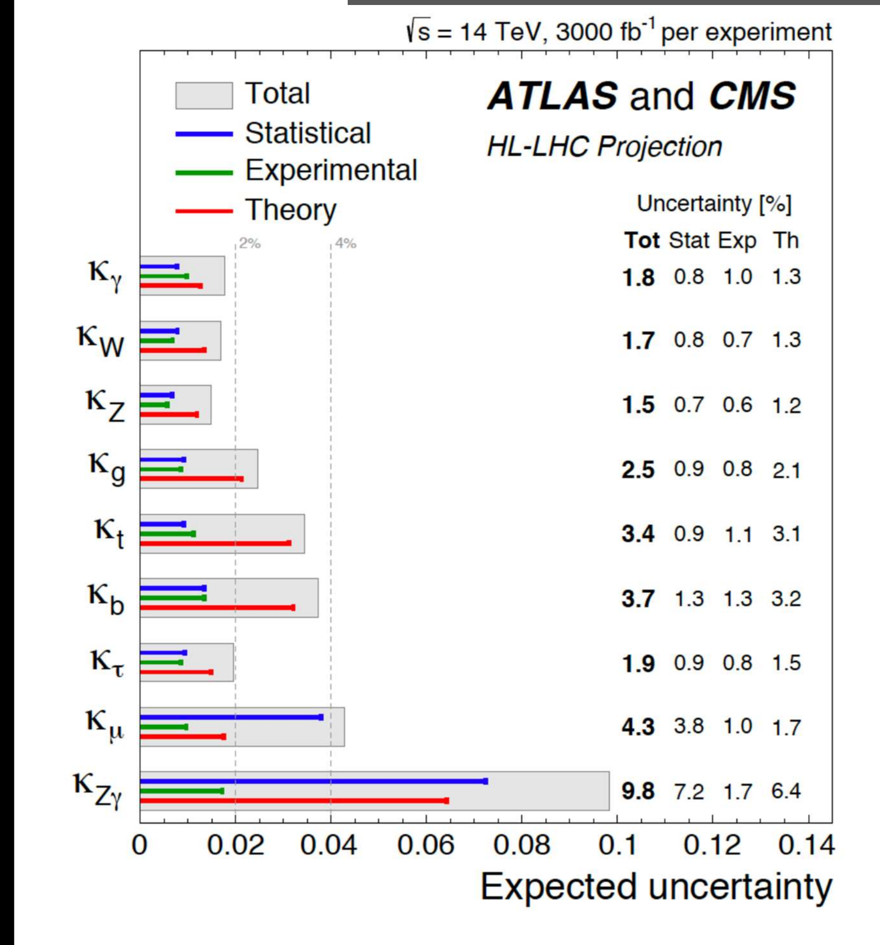

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  - Deviation from SM: $\delta \sim v^2/M^2$
    - M scale of new physics
    - M ~ 1 – 10 TeV → $\delta \sim 6 - 0.06\%$

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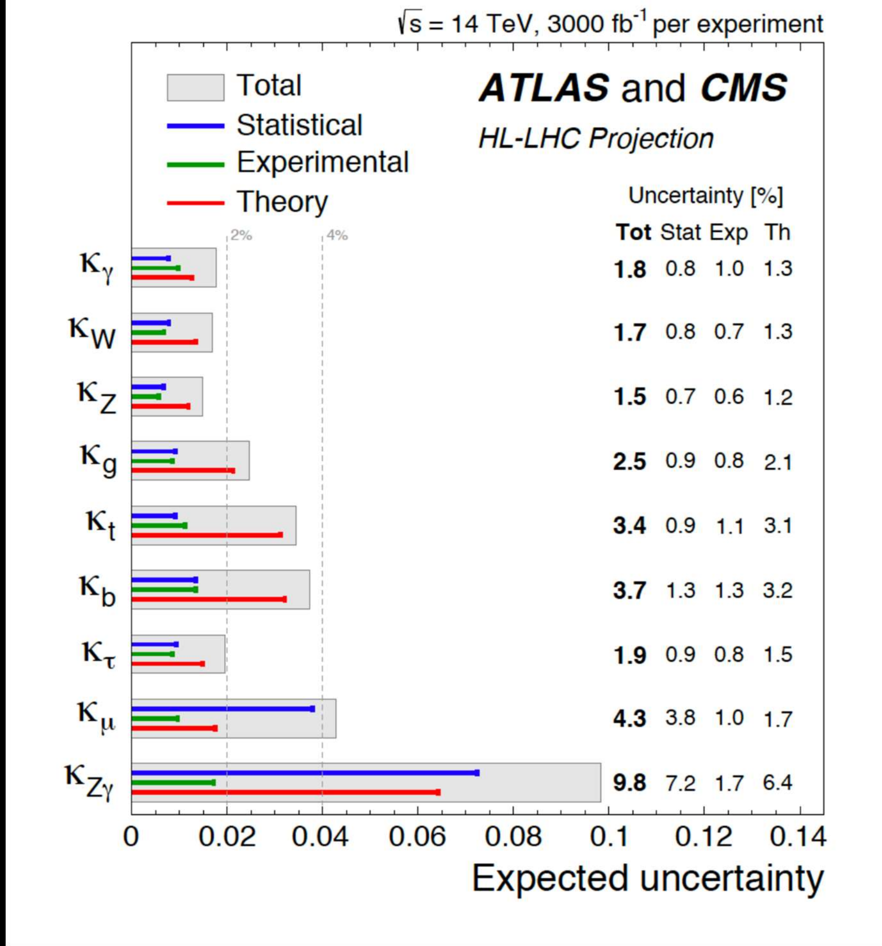

Current physics landscape

- Higgs properties SM-like.
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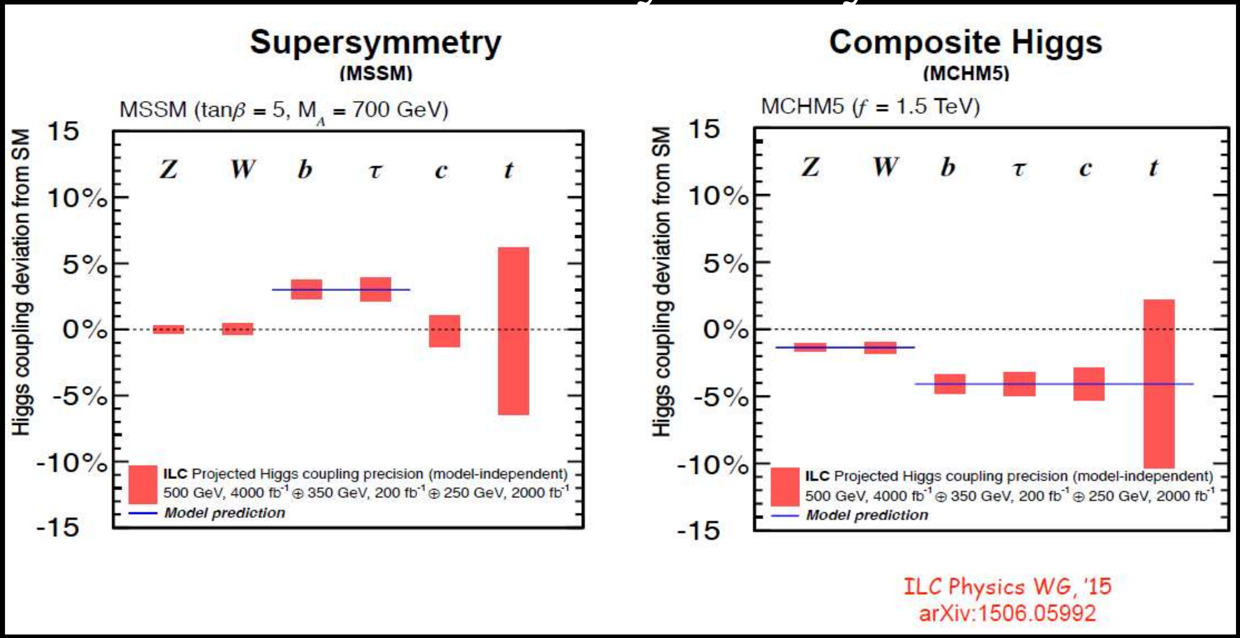
  - Deviation from SM: $\delta \sim v^2/M^2$ $v = 246$ GeV
    - M scale of new physics
    - M ~ 1 – 10 TeV → $\delta \sim 6 - 0.06\%$
  - Need < ~ % sensitivity → beyond HL-LHC



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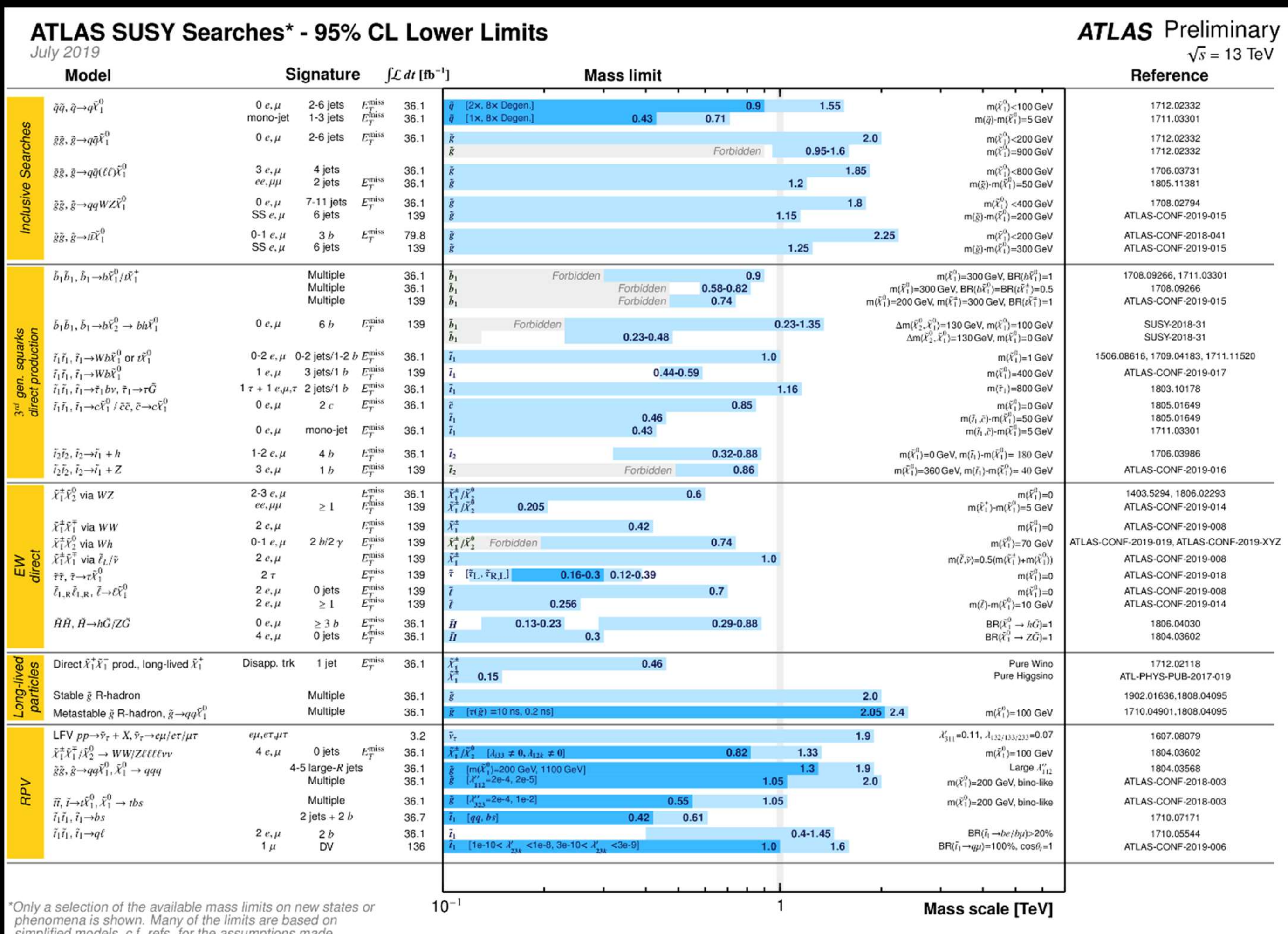

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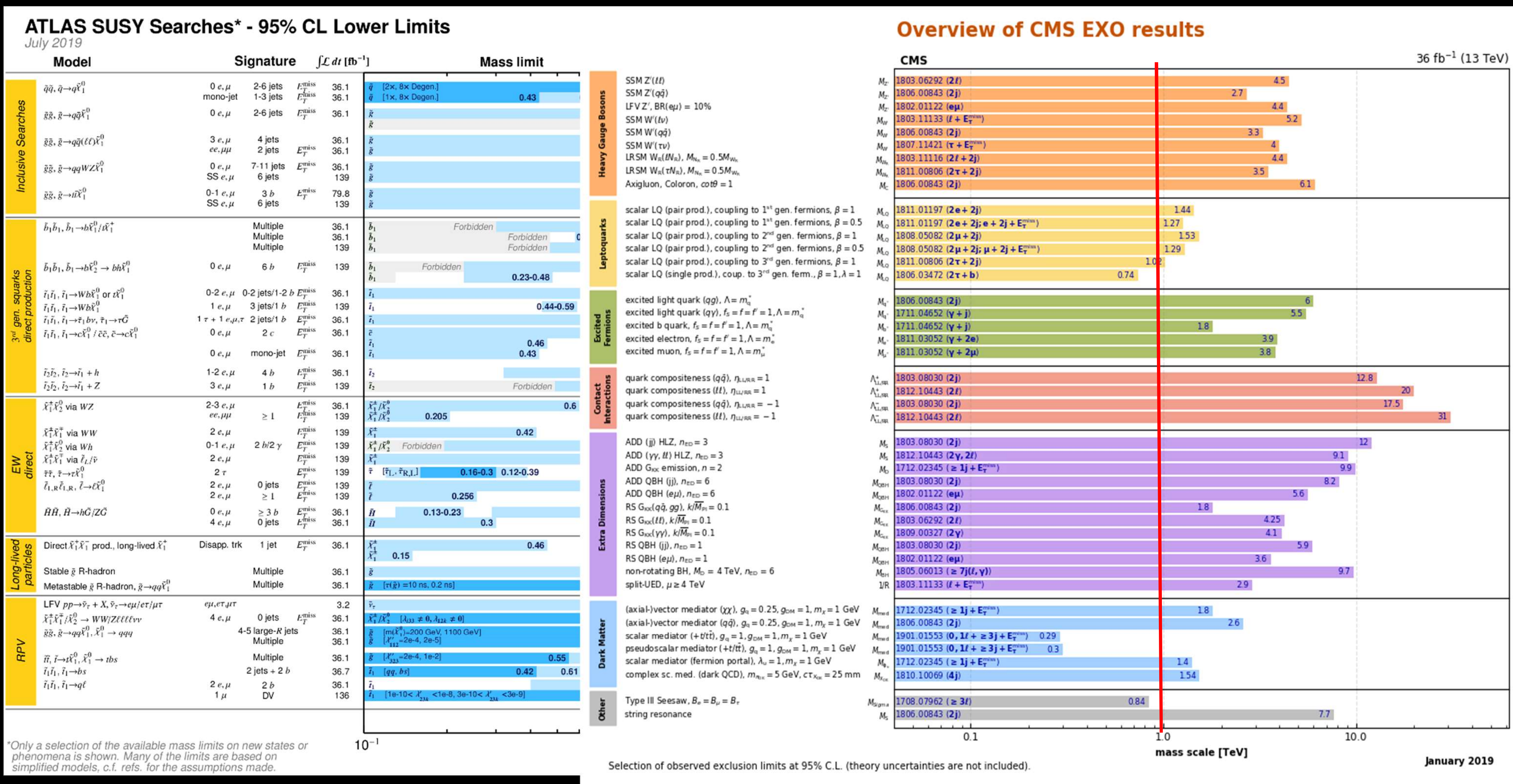

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- What new next accelerator to go beyond SM?

Current directions

- ICFA statement - Tokyo, March 2019:
  - "ICFA confirms the international consensus that the highest priority for the next global machine is a "Higgs Factory" capable of precision studies of the Higgs boson.

    ……………………………………………………………………

    ICFA notes with satisfaction the great progress of the various options for Higgs factories proposed across the world. All options will be considered in the European Strategy for Particle Physics Update and by ICFA.
- ICFA report – LP2019, Toronto, August 2019:
  - Worldwide effort for e+e- Higgs Factory ***must not fail!***
    - Linear or Circular
    - Asia or Europe (or elsewhere?)
- Recent comments on ESPPU preparations (B. Vachon – LP2019)
  - Emerging consensus for the importance of a "**Higgs factory**" to fully explore properties of the Higgs, EW sector, etc.
  - Need to prepare a clear path towards **highest energy**.

The planned machines

Higgs factories

- e+e- linear
  - *ILC*
  - *CLIC*
- e+e- circular
  - *FCC-ee*
  - *CepC*
- *μ+μ-* circular
  - *μ-HF*

Requirement: high luminosity $O(10^{34})$ at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine :

- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" *

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Higgs factories

INFN Istituto Nazionale di Fisica Nucleare

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Difficult

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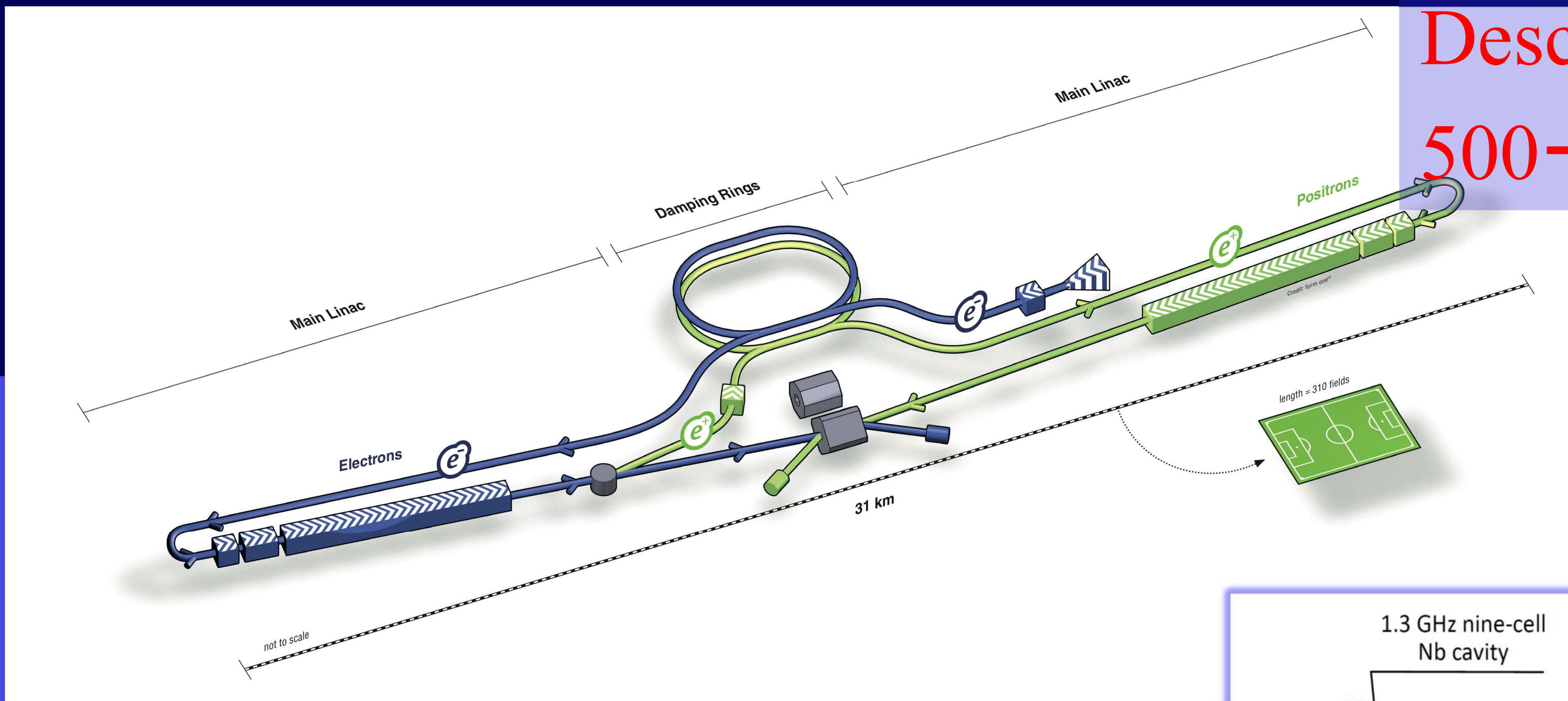
International Linear Collider



Descoped
500→250 GeV

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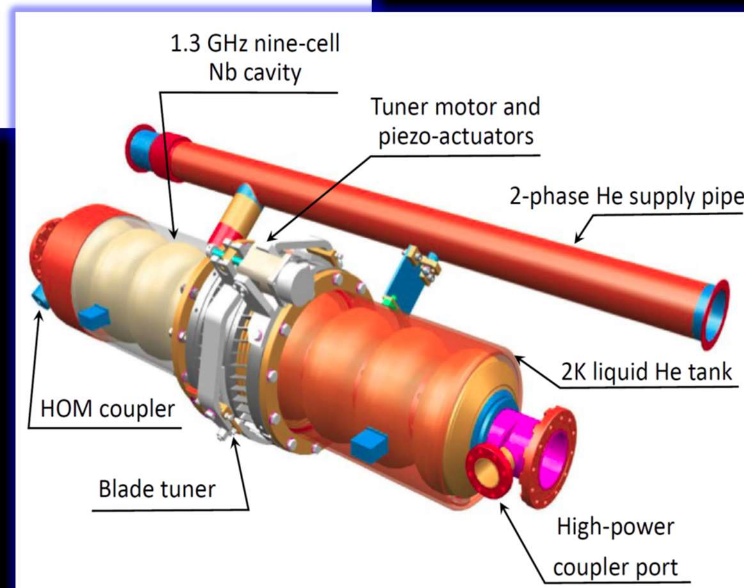
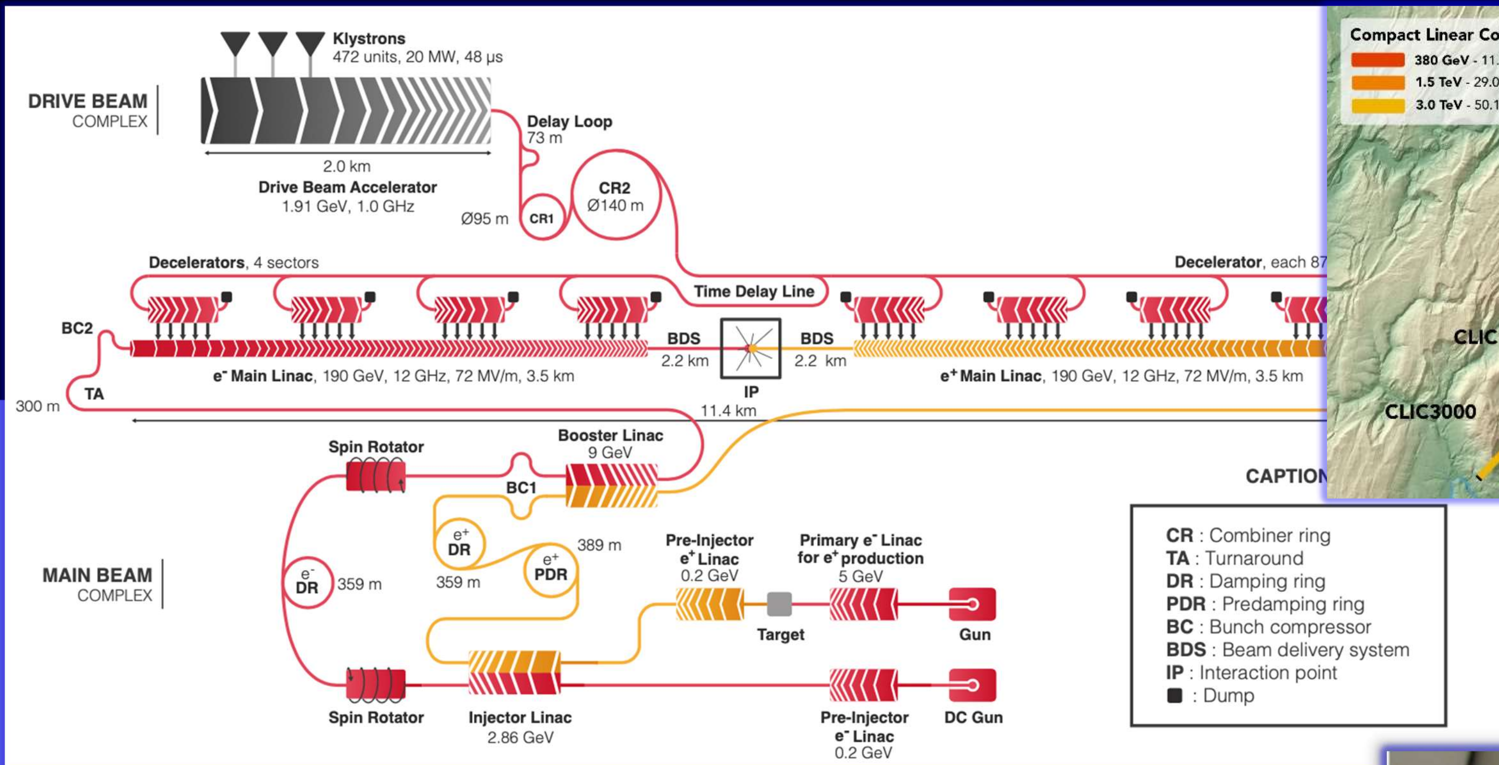
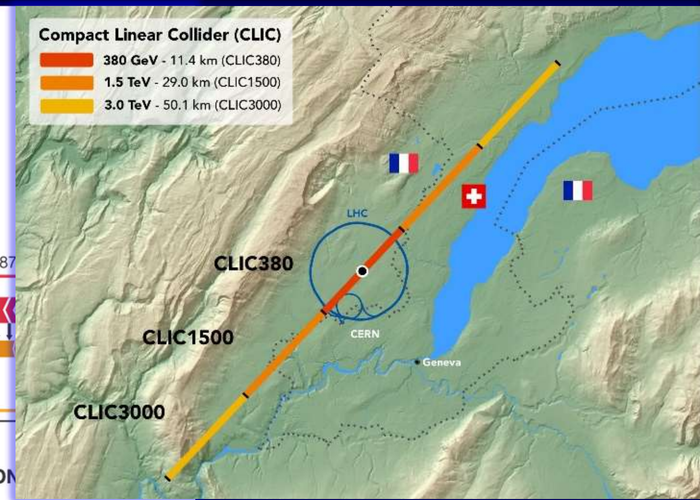
- Key facts:
  - 20 km, including 5 km of Final Focus
  - SRF 1.3 GHz, 31.5 MV/m, 2 K
  - 130 MW site power @ 250 GeV c.m.e.
  - Cost estimate 700 B JPY = 5.8 B€

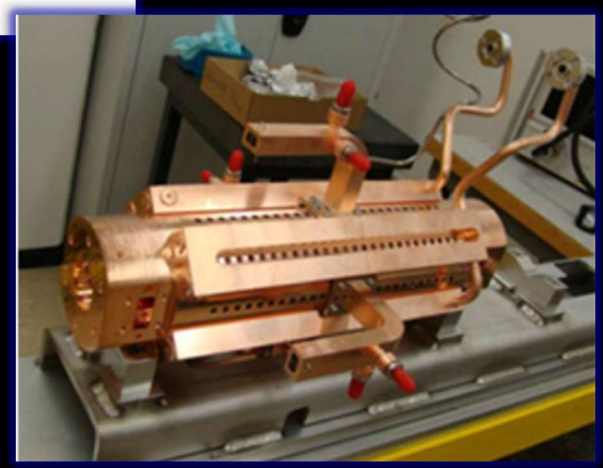


Compact LInear Collider





- ❖ Key facts:
  - 11 km main linac @ 380 GeV c.m.e.
  - NC 12 GHz RF 72 MV/m, two-beam scheme
  - 168 MW site power (~9MW beams)
  - Cost est. 5.9 BCHF (klystrons + 1.4 BCHF)



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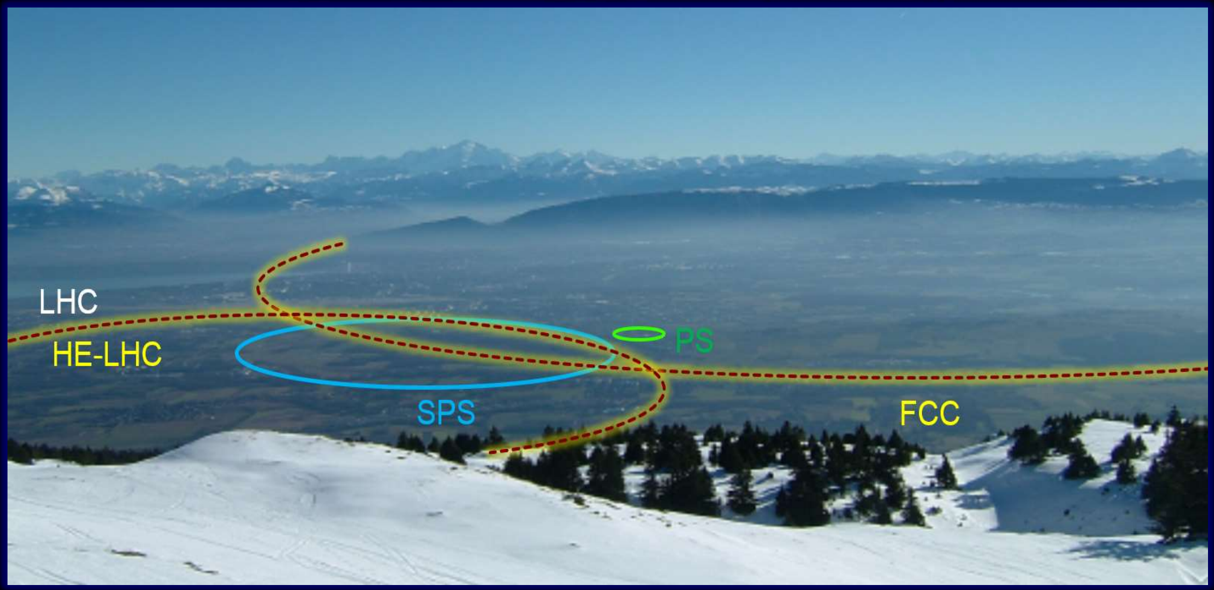
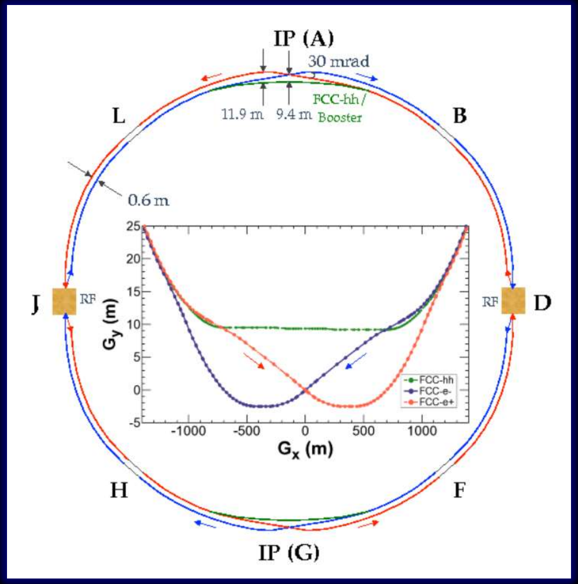
Circular e+e- Higgs Factories





❖ Key facts:

- 100 km tunnel, three rings (e-, e+, booster)
- SRF power to beams 100 MW
- Total site power <300MW (tbd)
- Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)

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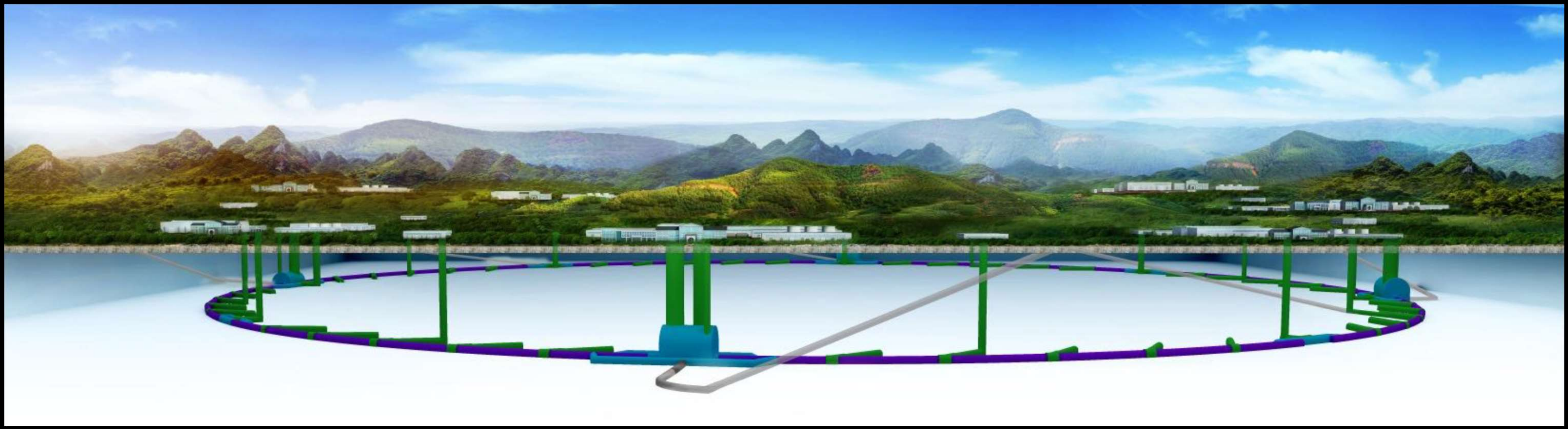

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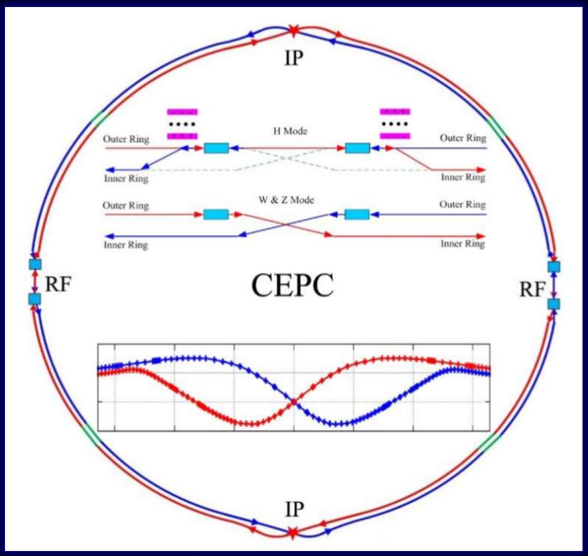
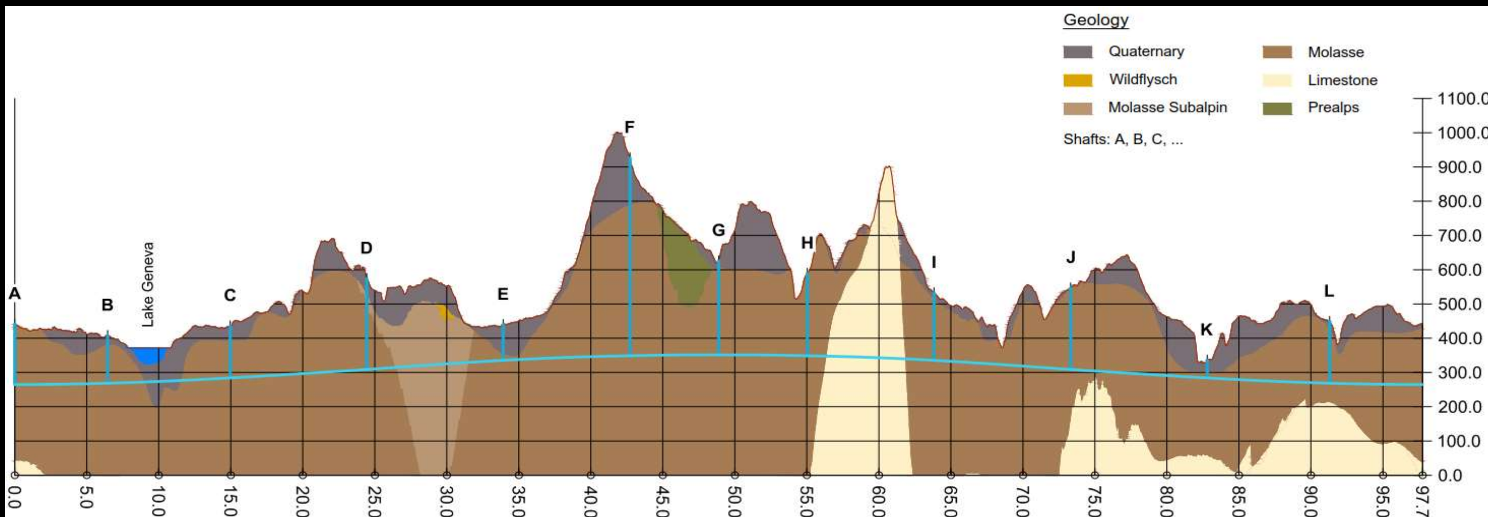
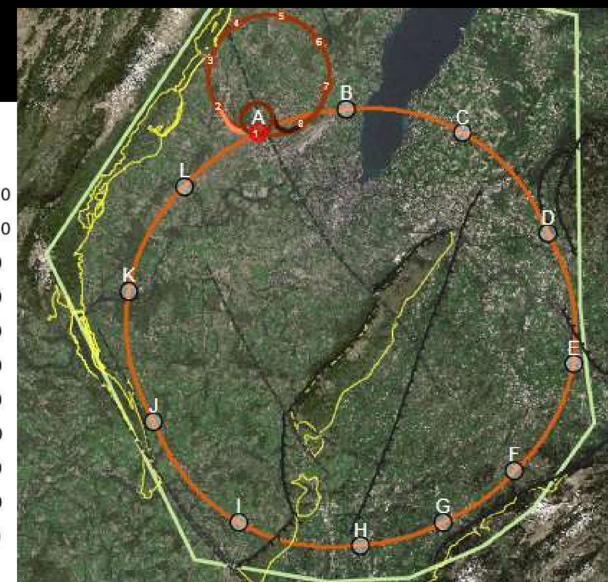
❖ Key facts:
- 100 km tunnel, three rings (e-, e+, booster)
- SRF power to beams 100 MW (60 MW in CepC)
- Total site power <300MW (tbd)
- Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)
  - (“< 6BCHF” cited in the CepC CDR)

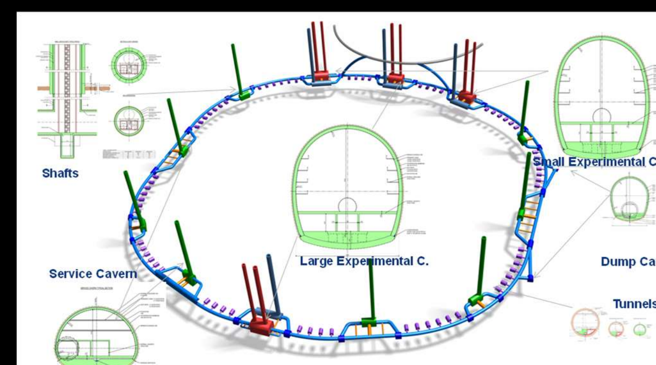


FCC integrated program
inspired by succesful LEP – LHC programs at CERN

Implementation studies in Geneva basin:







baseline position was established considering:

- minimum risk for construction, fastest and cheapest construction
- efficient connection to CERN accelerator complex

- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

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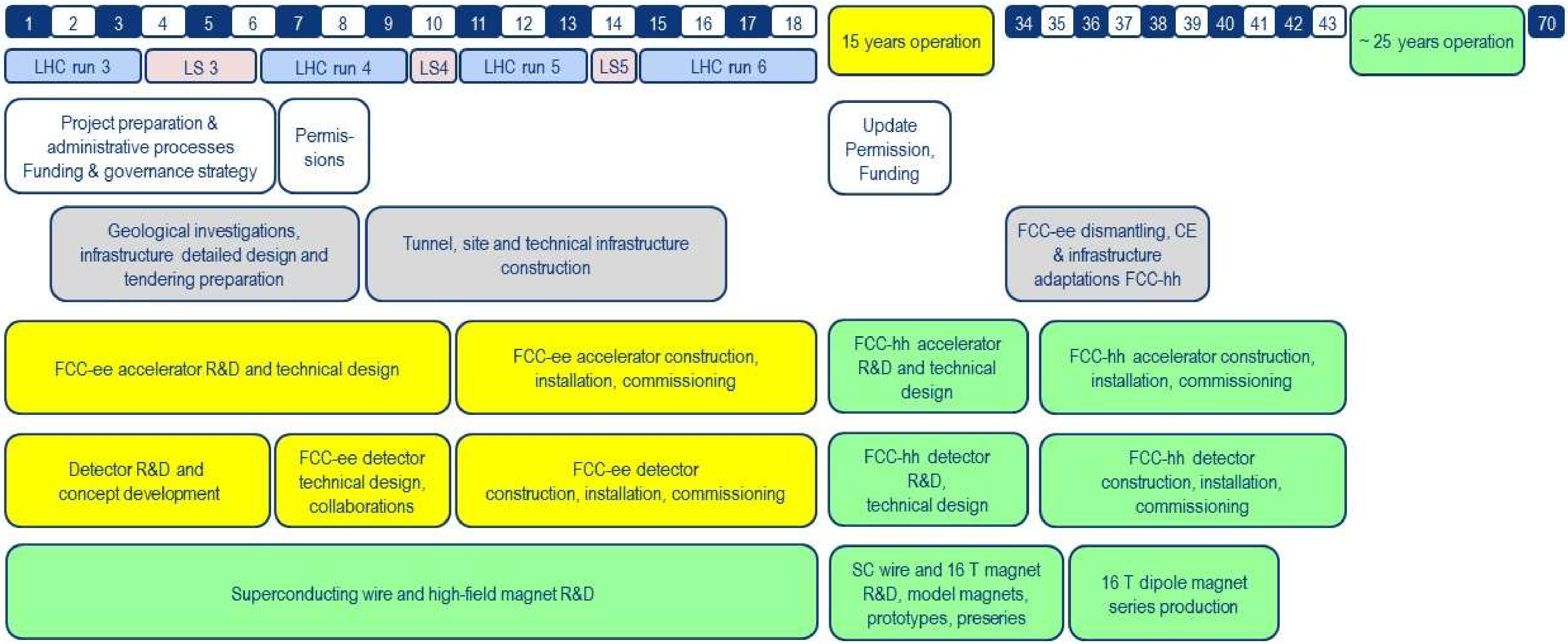
FCC-ee + FCC-hh



FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

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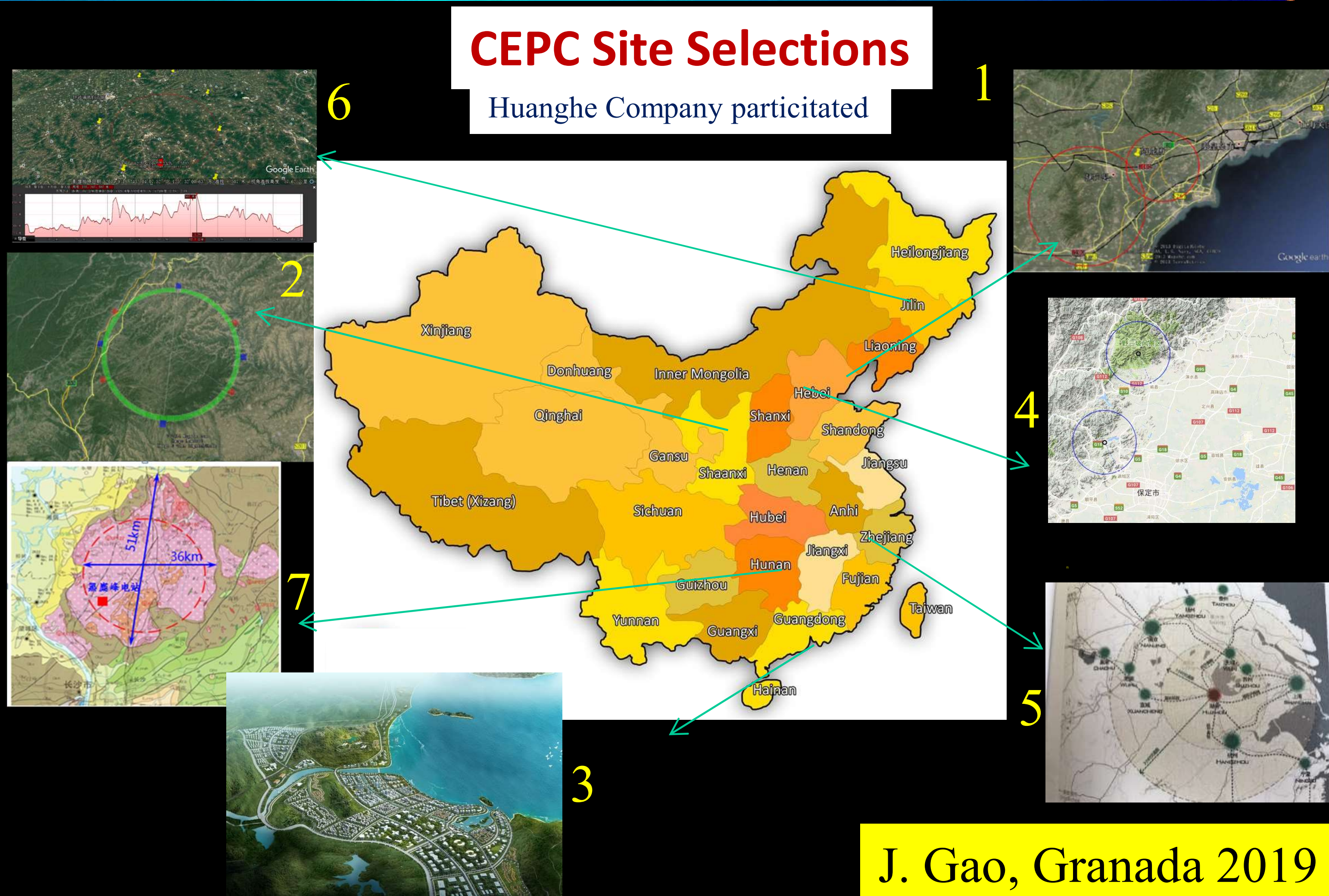
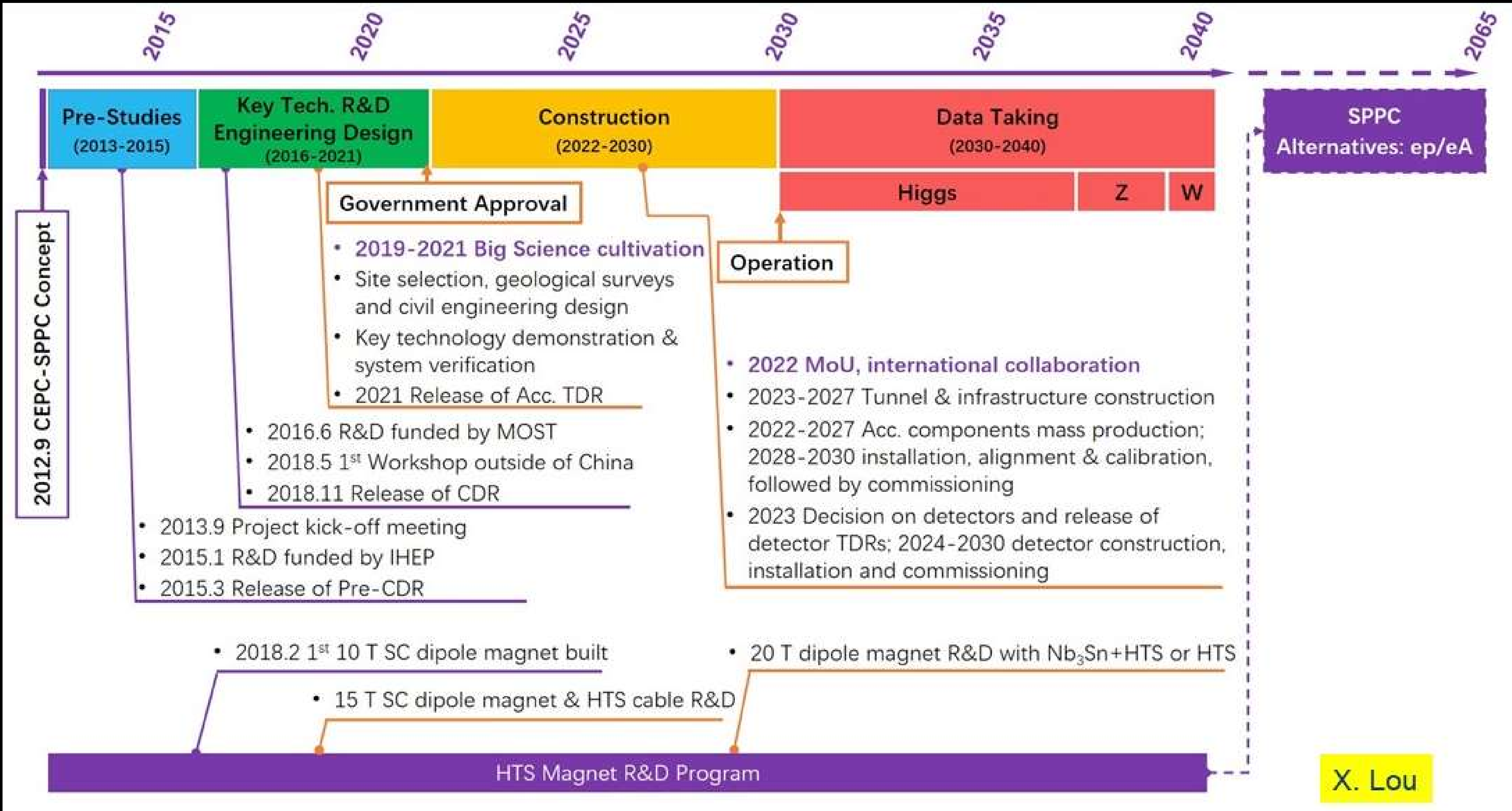
CEPC-SppC: site studies

1) Qinhuangdao, Hebei ProvinceCompleted 2014)
2) Huangling, Shanxi Province （Completed 2017)
3) Shenshan, Guangdong Province(Completed 2016)
4) Baoding (Xiong an), Hebei Province (Started August 2017)
5) Huzhou, Zhejiang Province (Started March 2018)
6) Chuangchun, Jilin Province (Started May 2018)
7) Changsha, Hunan Province (Started Dec. 2018)

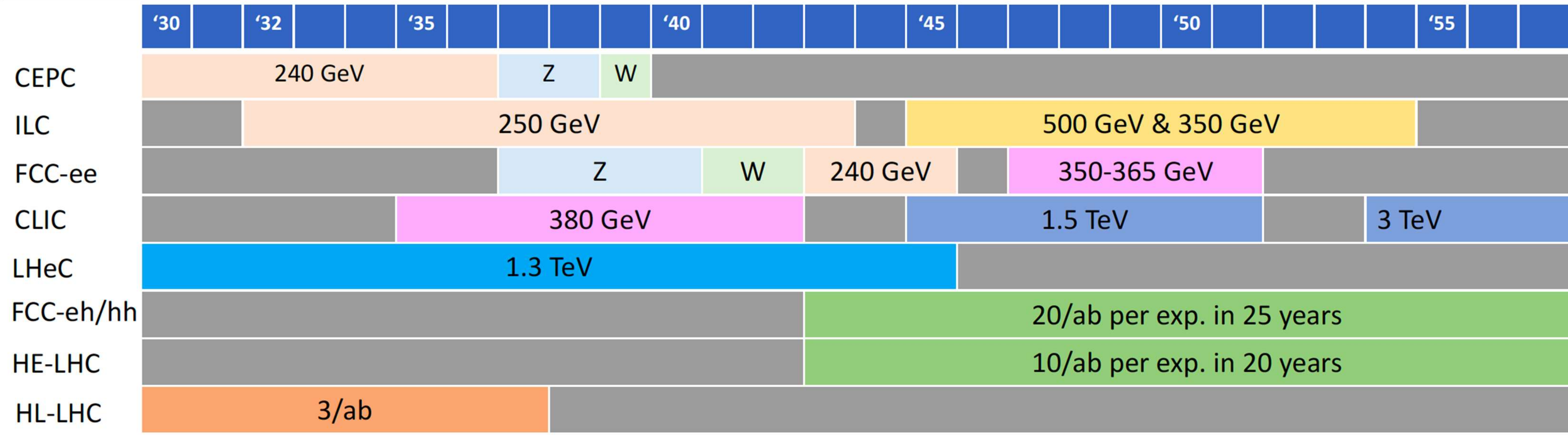


CEPC



2015
2020
2025
2030
2035
2040
2065
Pre-Studies
(2013-2015)
Key Tech. R&D
Engineering Design
(2016-2021)
Construction
(2022-2030)
Data Taking
(2030-2040)
SPPC
Alternatives: ep/eA
Higgs
Z
W
2012.9 CEPC-SPPC Concept
Government Approval
Operation
• 2019-2021 Big Science cultivation
• Site selection, geological surveys and civil engineering design
• Key technology demonstration & system verification
• 2021 Release of Acc. TDR
• 2016.6 R&D funded by MOST
• 2018.5 1st Workshop outside of China
• 2018.11 Release of CDR
• 2013.9 Project kick-off meeting
• 2015.1 R&D funded by IHEP
• 2015.3 Release of Pre-CDR
• 2022 MoU, international collaboration
• 2023-2027 Tunnel & infrastructure construction
• 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
• 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning
• 2018.2 1st 10 T SC dipole magnet built
• 15 T SC dipole magnet & HTS cable R&D
• 20 T dipole magnet R&D with Nb3Sn+HTS or HTS
HTS Magnet R&D Program
X. Lou

Schedules



Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)

- Very optimistic!!!

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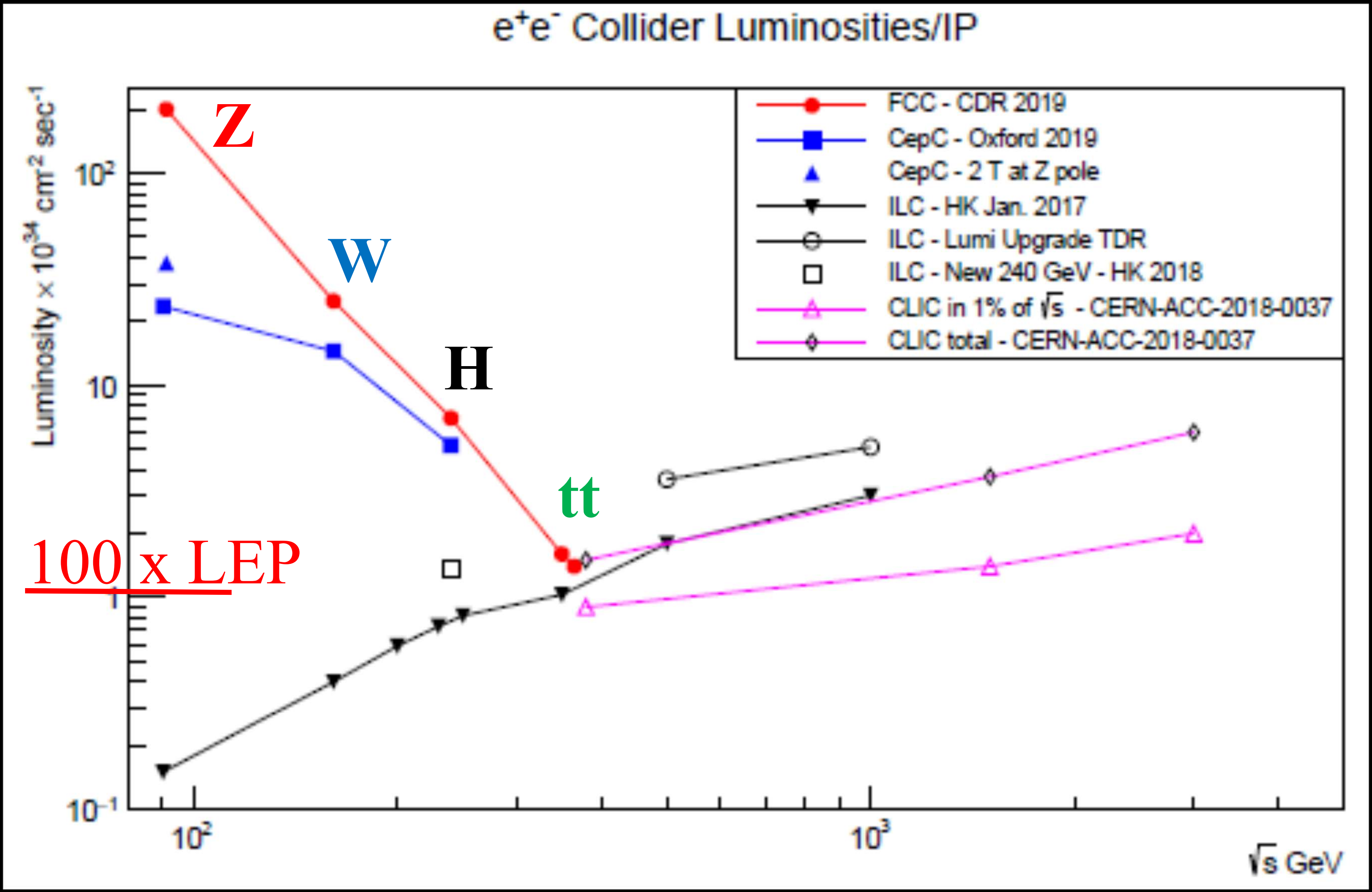
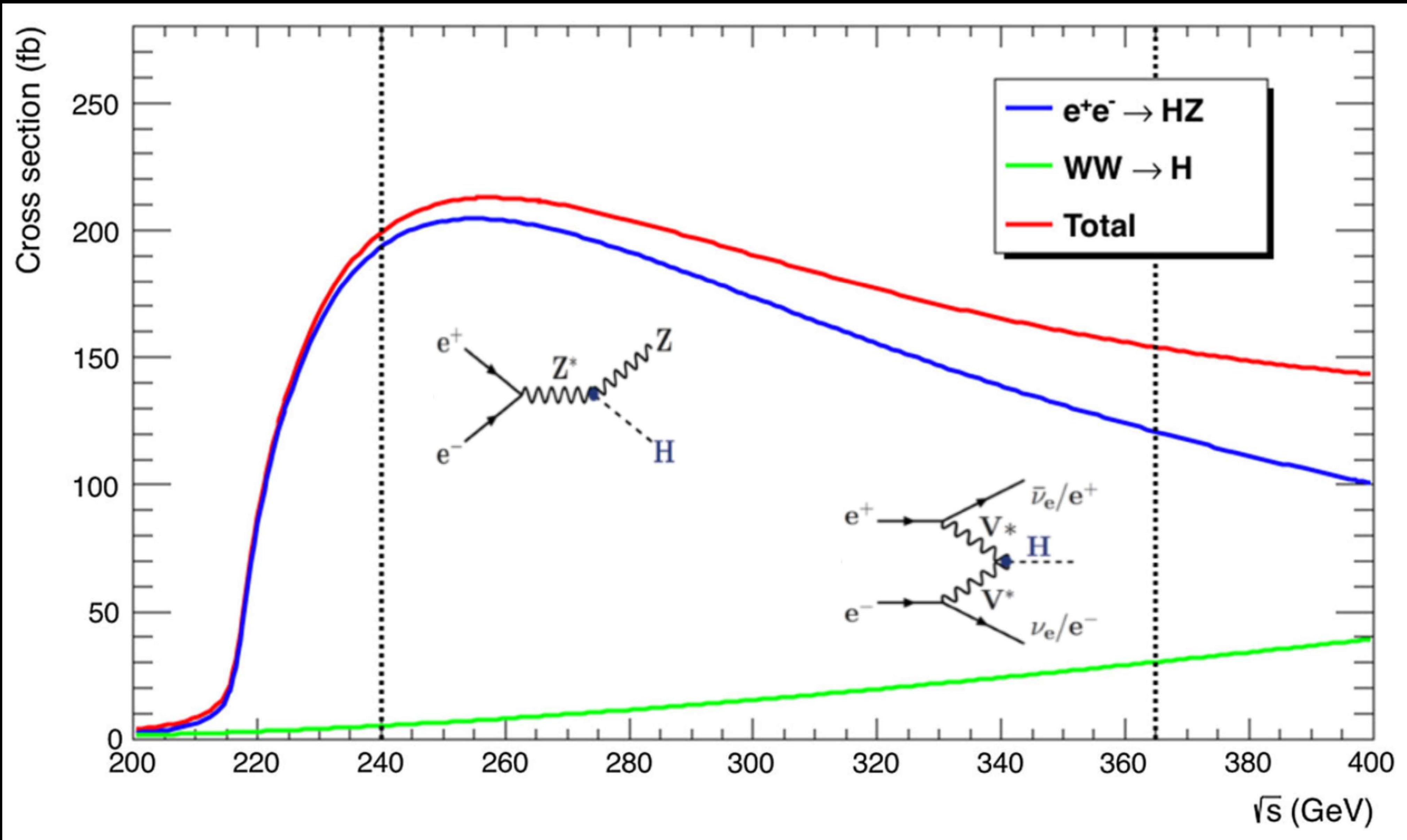
Luminosity comparison



Higgs production



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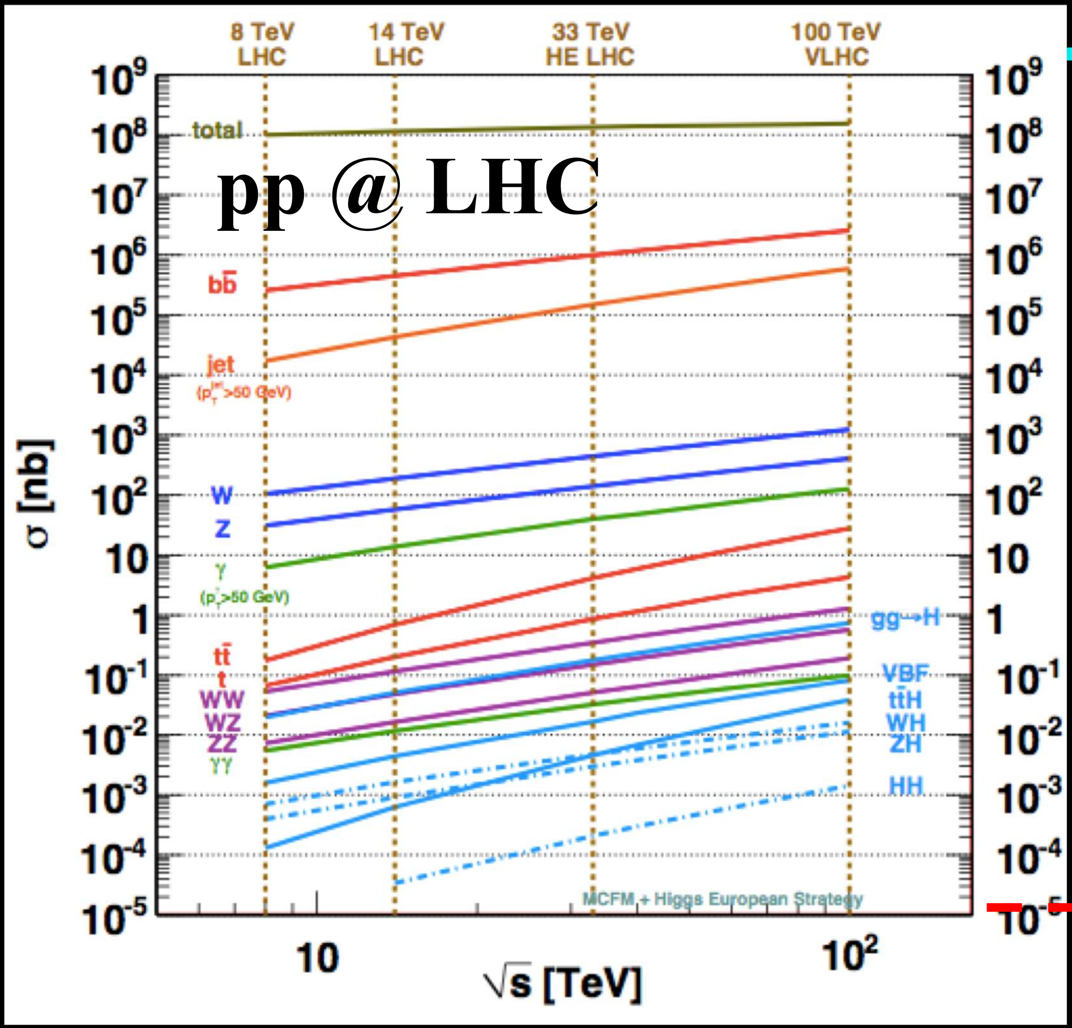
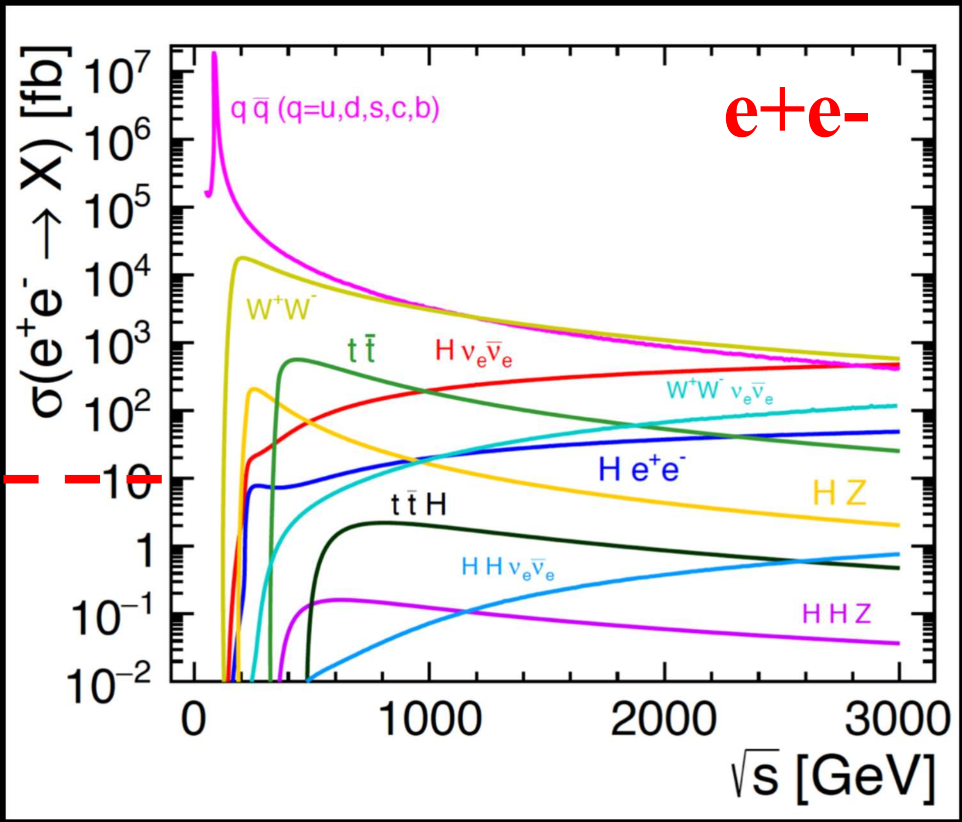
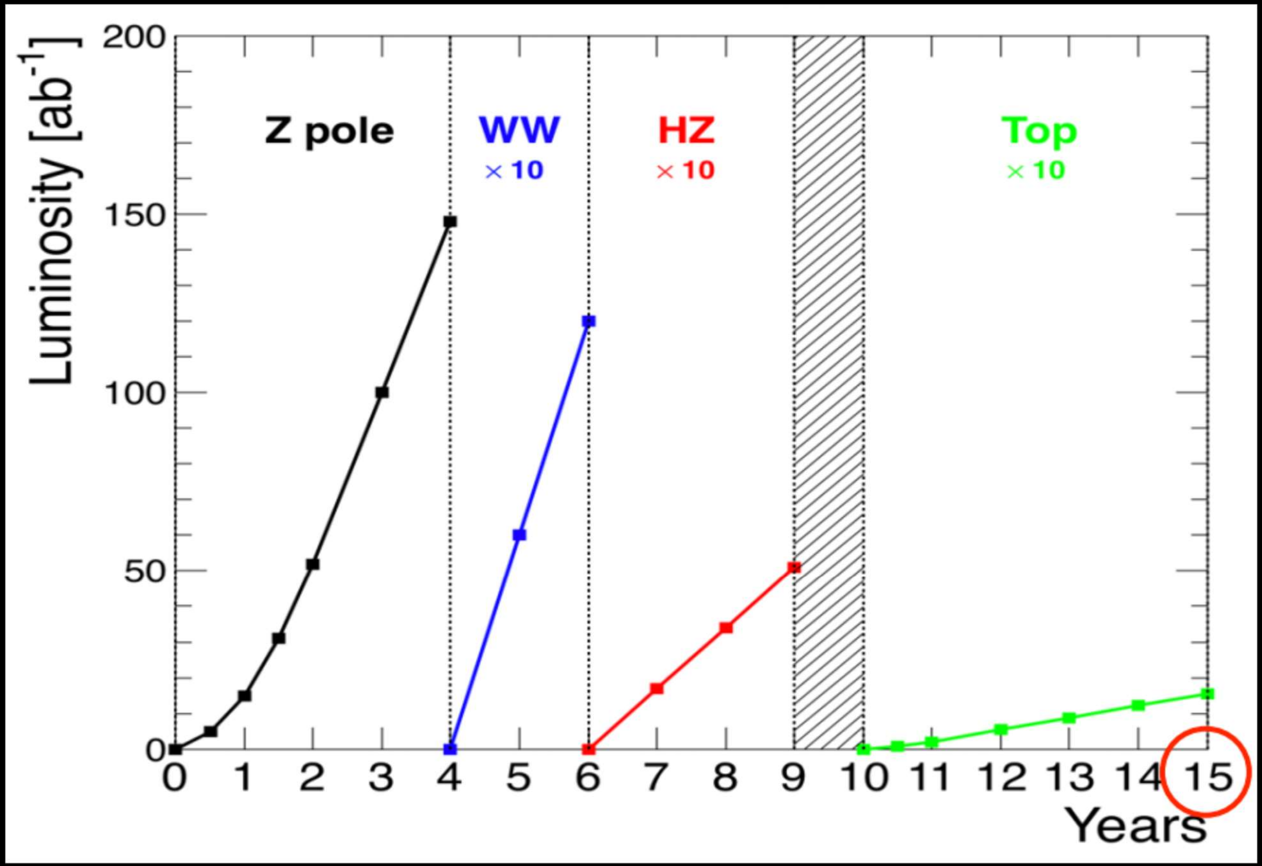


Very clean production in e+e-



Physics at FCC-ee

- Higgs factory
  - 10^6 $e^+e^- \rightarrow HZ$



Physics at FCC-ee

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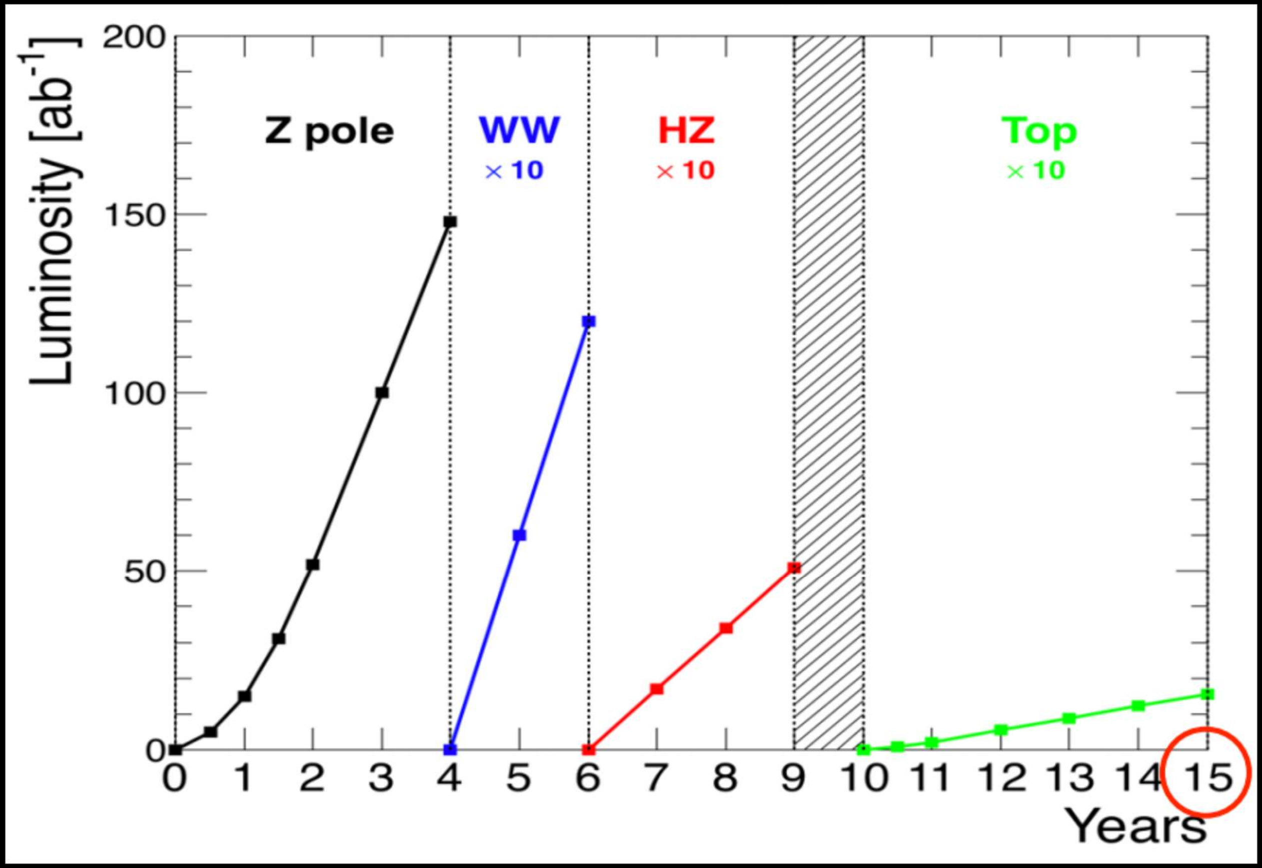
- EW & Top factory
  - $3x10^{12}$ e+e- → Z
  - 10^8 e+e- → W+W- ;
  - 10^6 e+e- → tt



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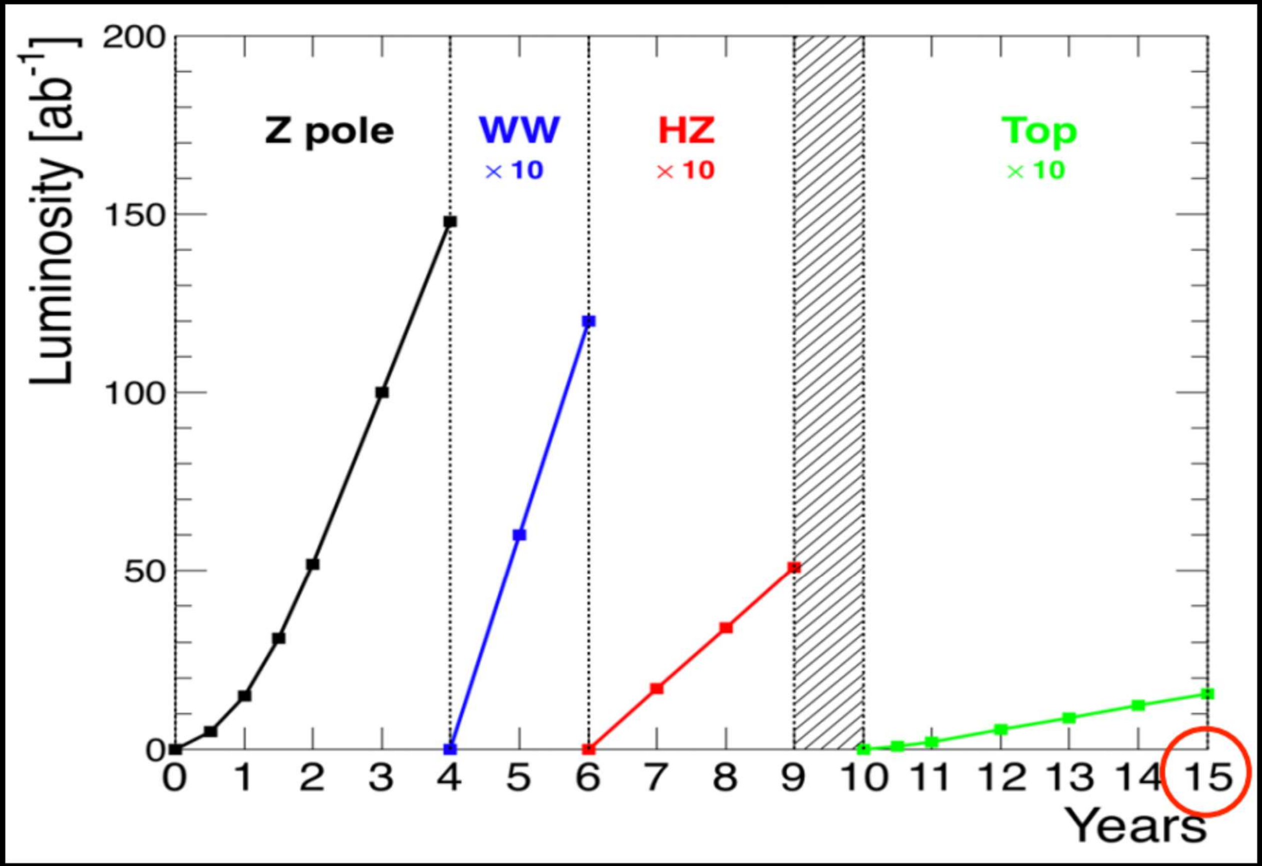
- Flavor factory
  - 5×10^{11} e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**



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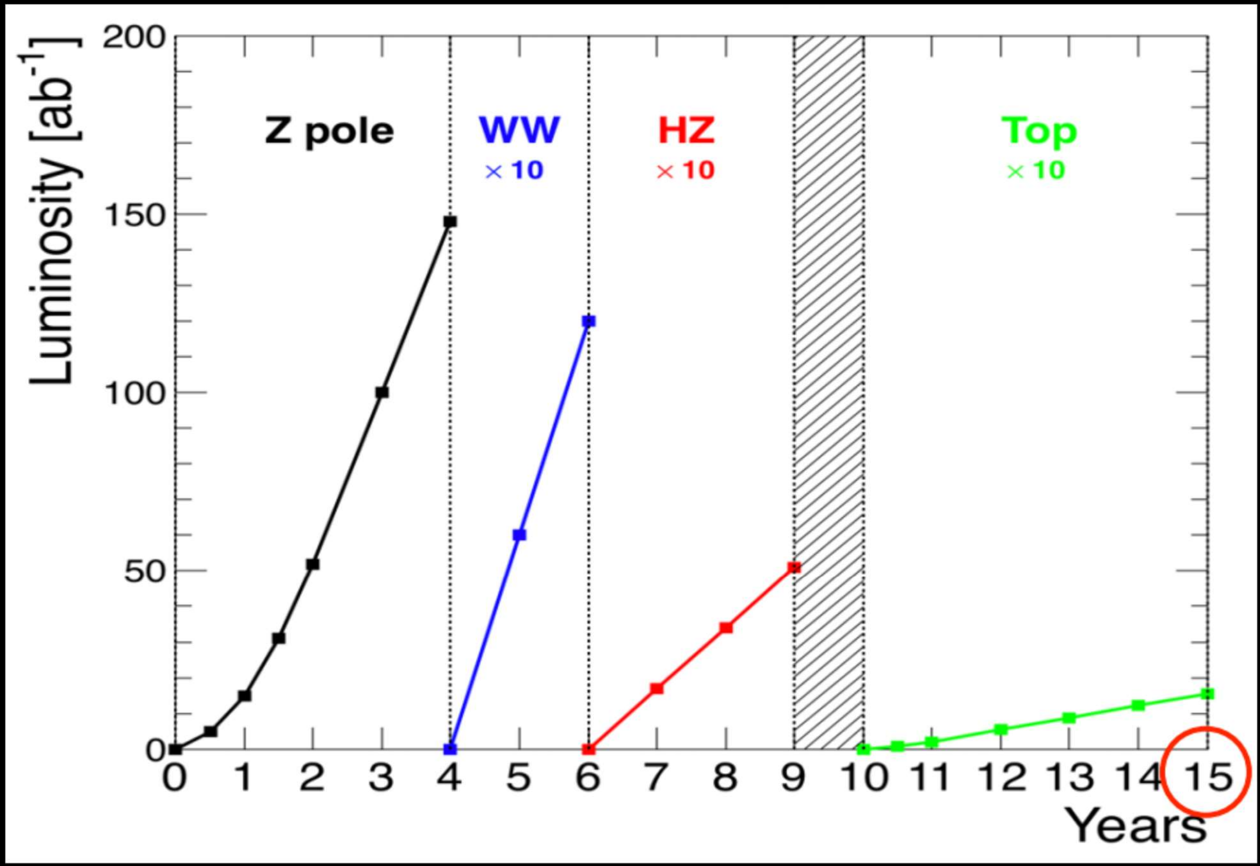
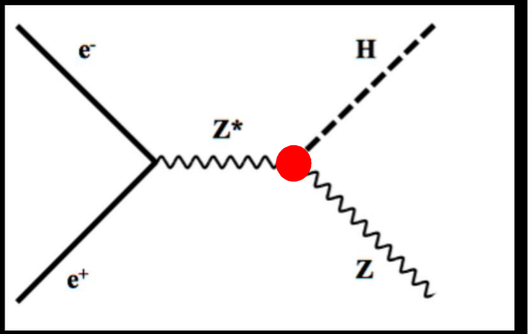
  - 10^{11} e+e- → **τ+τ-**
- Potential discovery of NP
  - ALPs, RH ν's, …

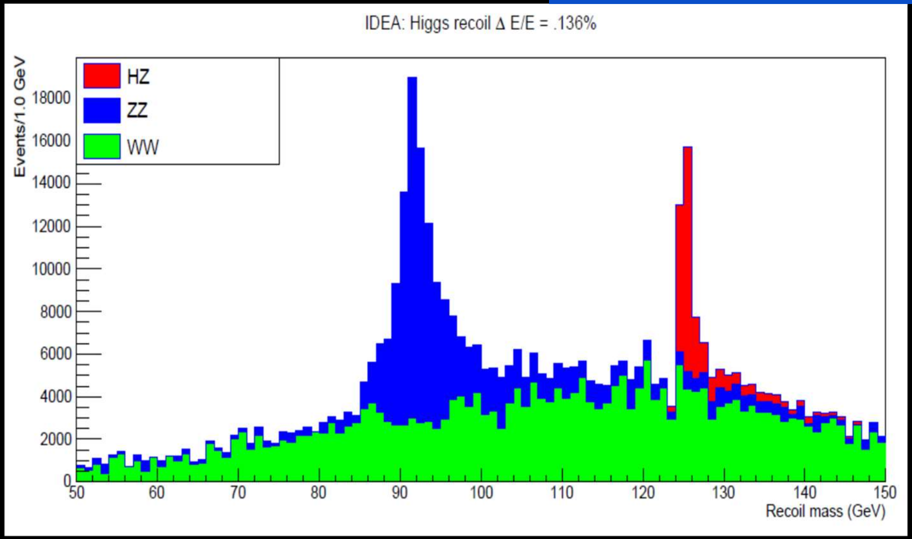


Higgs total width

- Higgs recoil provides model independent measurement of coupling to Z
  - $\sigma(HZ) \propto g^2_{HZ}$

L = 5 ab^{-1}





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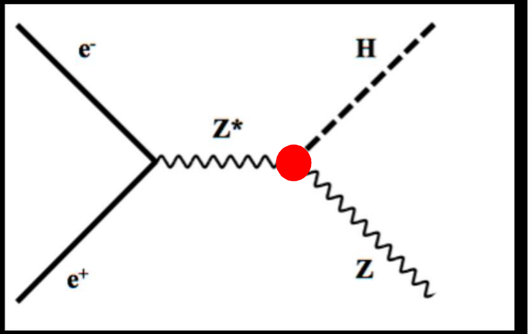

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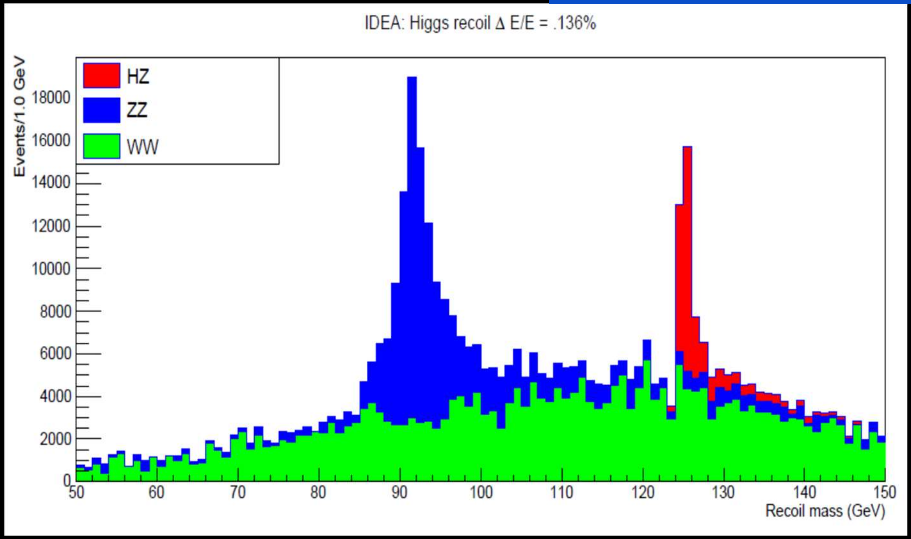
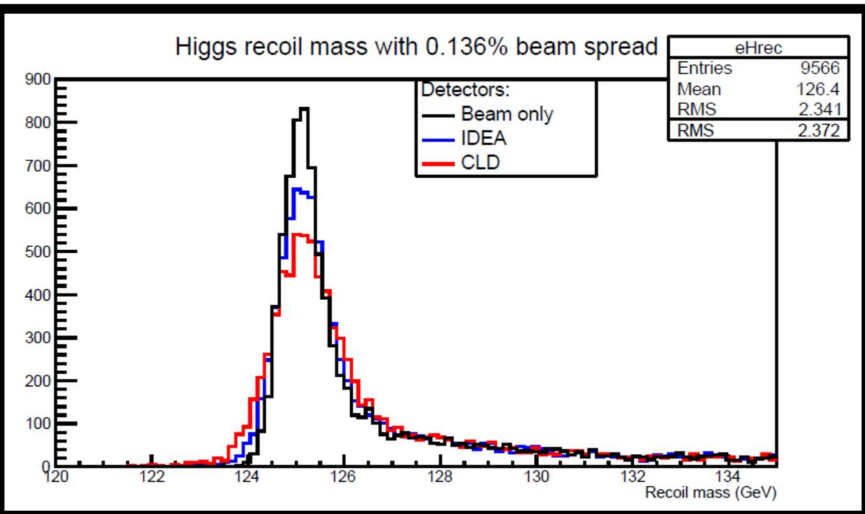


  - Critical:
    - Beam energy spread: SR+BS
    - Detector resolution



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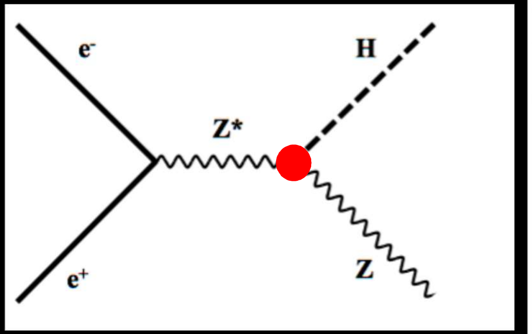
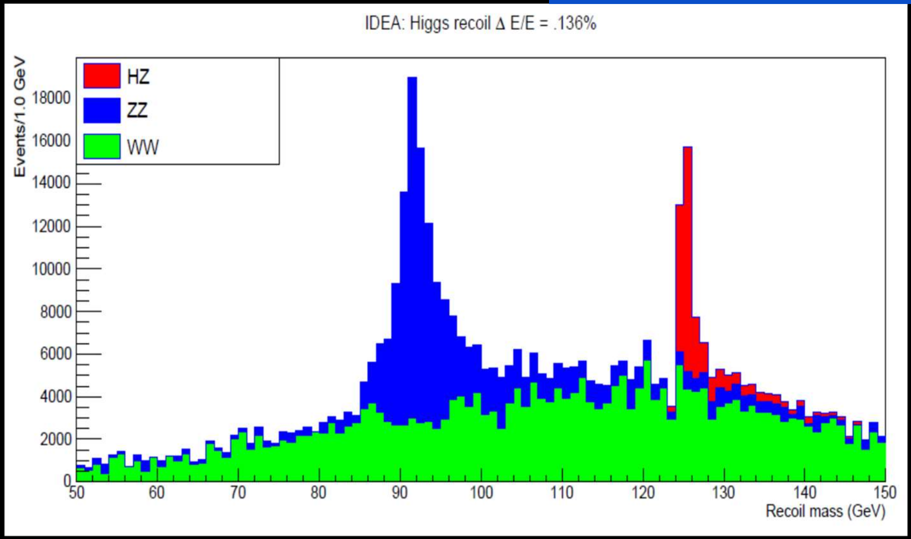
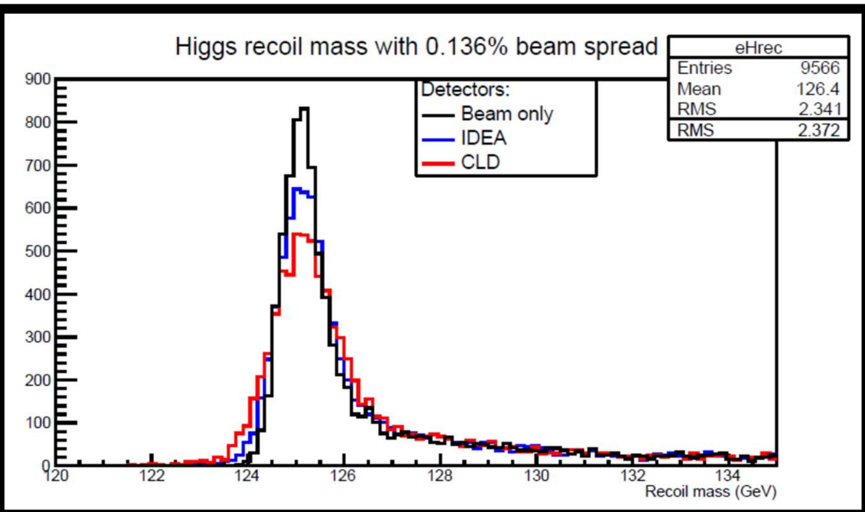




  - Critical:
    - Beam energy spread: SR+BS
    - Detector resolution

- Total width combining with decays in specific channels

$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g^4_{HZ}}{\Gamma}$$



Higgs coupling fits

- Kappa framework

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

$$\kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

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  - Extension

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

BRinv measured at FCC-ee

BRunt 100% correlated with Γ_H

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BRinv measured at FCC-ee

BRunt 100% correlated with Γ_H

- EFT framework
  - Leading order NP effects weighted sum of all dim-6 operators

$$O = O_{\mathrm{SM}} + \delta O_{\mathrm{NP}} \frac{1}{\Lambda^2}$$

□ 59 B&L conserving operators

Higgs coupling fits

- Kappa framework

$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i\cdot\Gamma_f}{\Gamma_H},\qquad \kappa_H^2\equiv\sum_j\frac{\kappa_j^2\Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}\quad\to\quad\mu_i^f\equiv\frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}}=\frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

  - Extension $$\Gamma_H=\frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$
    BRinv measured at FCC-ee
    BRunt 100% correlated with Γ_H

- EFT framework
  - Leading order NP effects weighted sum of all dim-6 operators

    $$O=O_{\mathrm{SM}}+\delta O_{\mathrm{NP}}\frac{1}{\Lambda^2}$$

    □ 59 B&L conserving operators
  - Includes interference with SM operators
  - Simultaneous fit of Higgs, EWPO, aTGC, topEW
  - Fit results projected into effective Higgs couplings $g_{HX}^{\mathrm{eff}\ 2}\equiv\frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}$

Higgs coupling fits

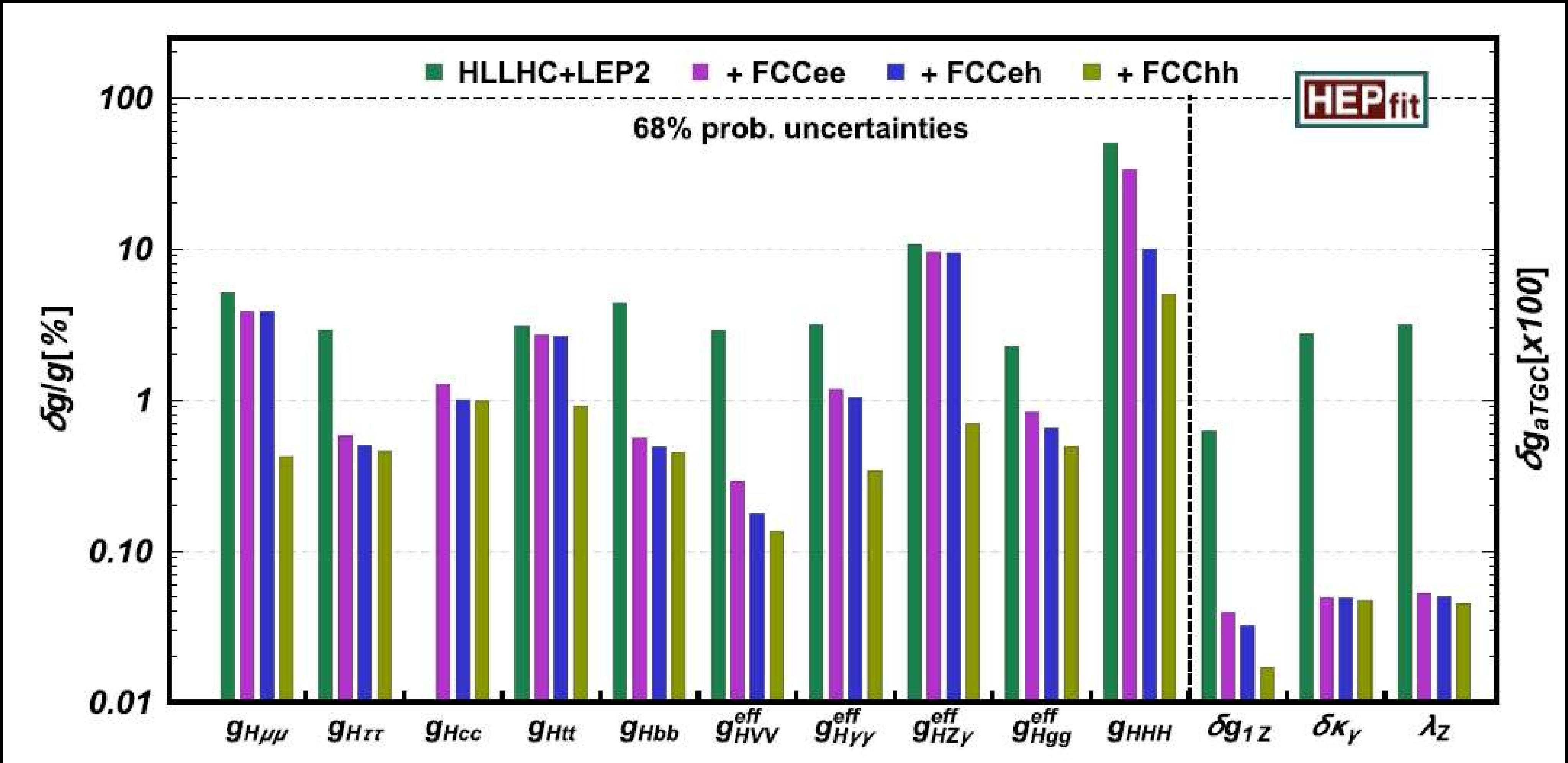
❖ Results limited only by statistics

κ EFT

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\rightarrow 365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

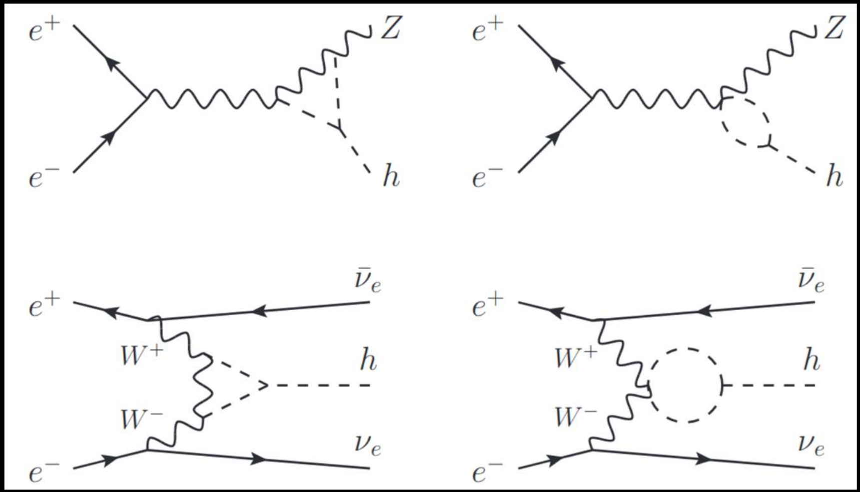
Higgs coupling fits

- Results limited only by statistics



Triple Higgs

- No direct production @ FCC-ee
  - Sensitivity through loop effects



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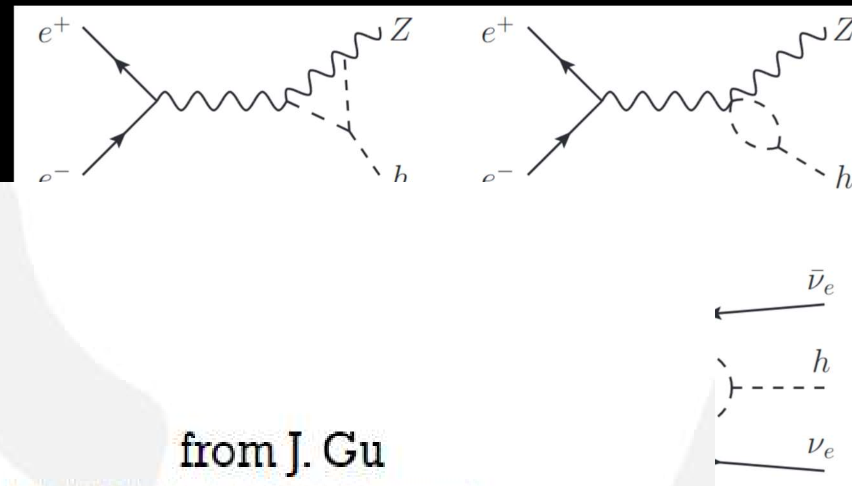

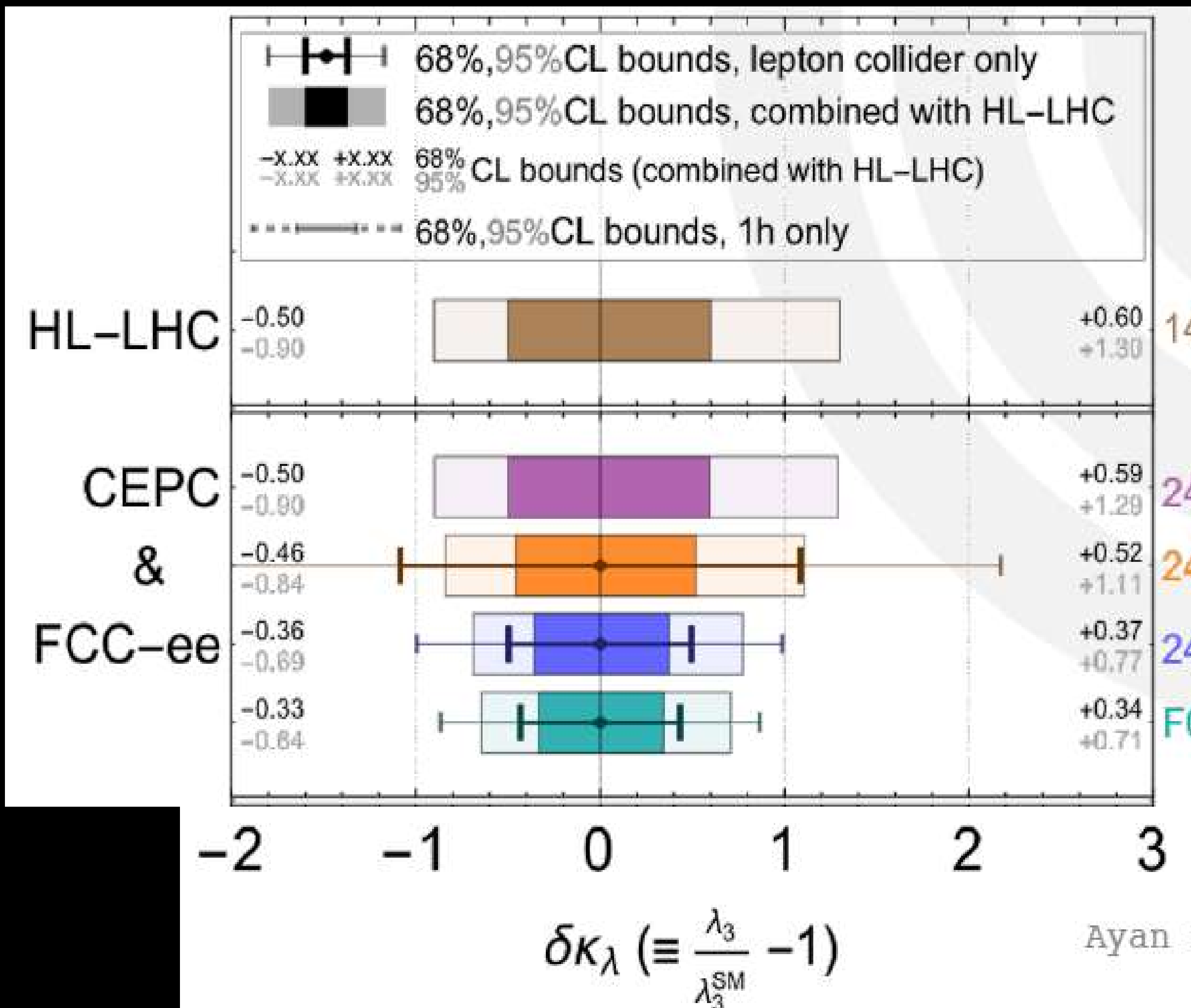

from J. Gu

Ayan Paul — EPS 2019 — Ghent.

Triple Higgs

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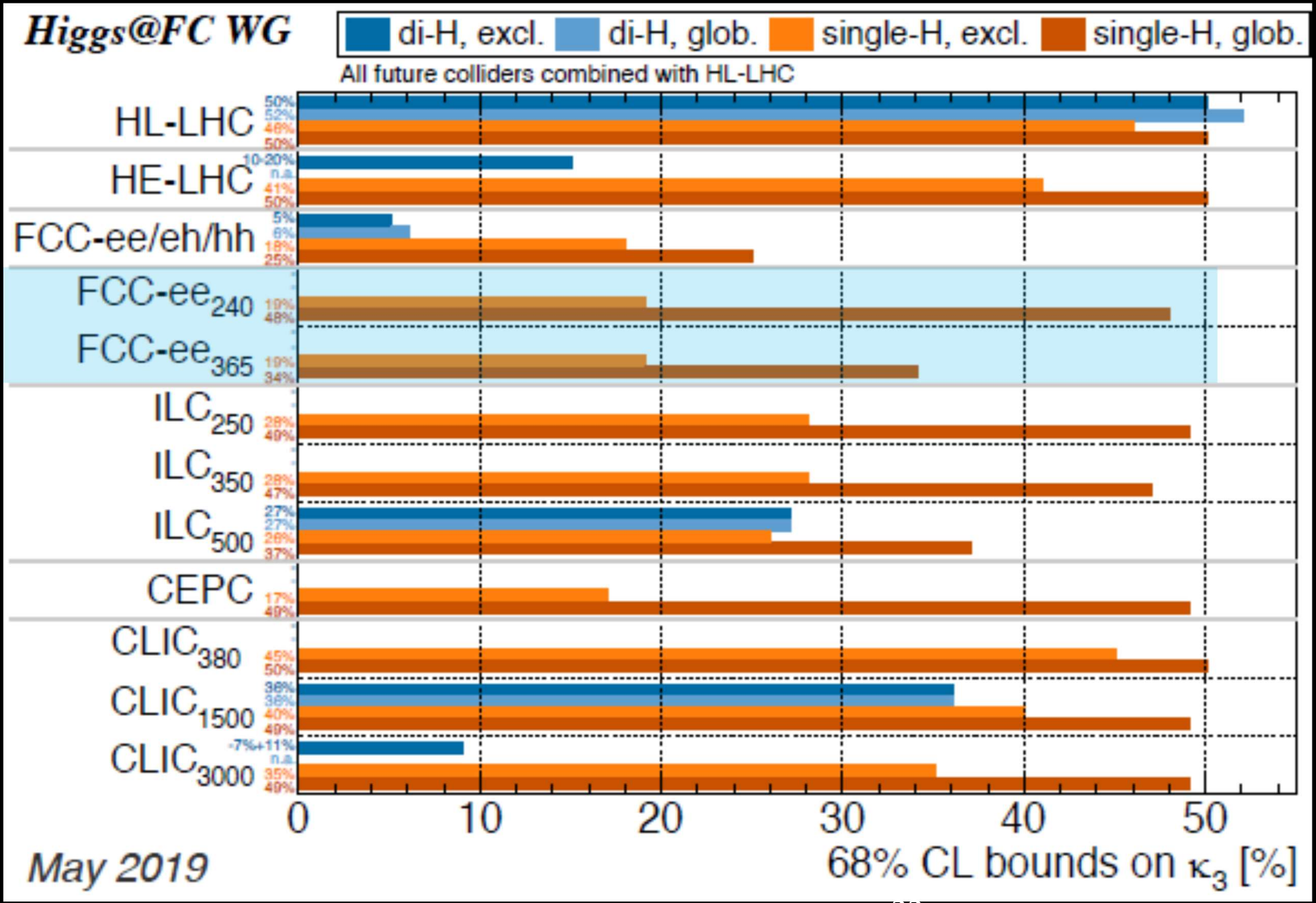


Higgs coupling comparison

- Improvement factors relative to HL-LHC

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

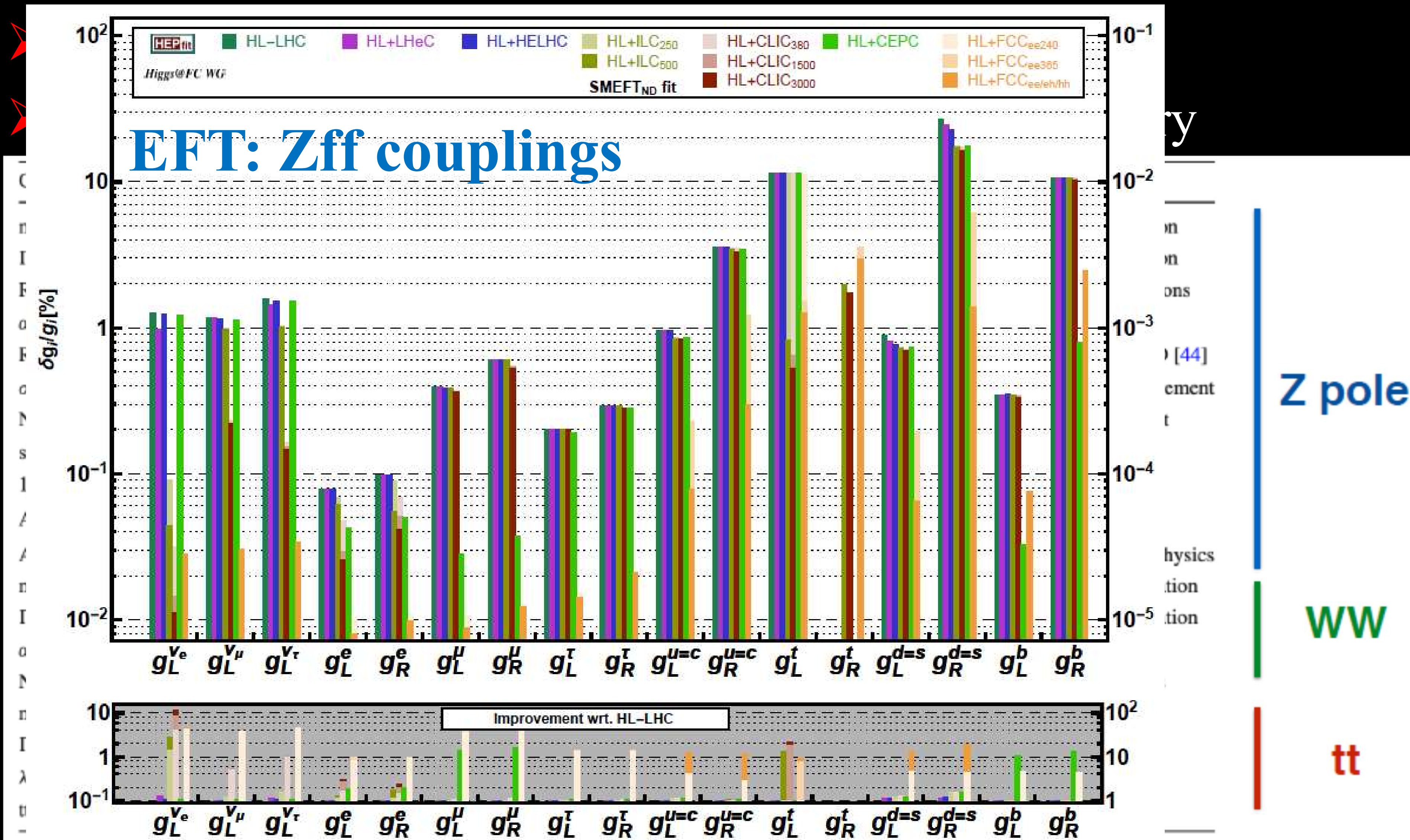
EWK

- Outstanding program of precision EWK measurements
  - O(10-100) better than LEP precision
  - Substantially reduce parametric uncertainties in theory

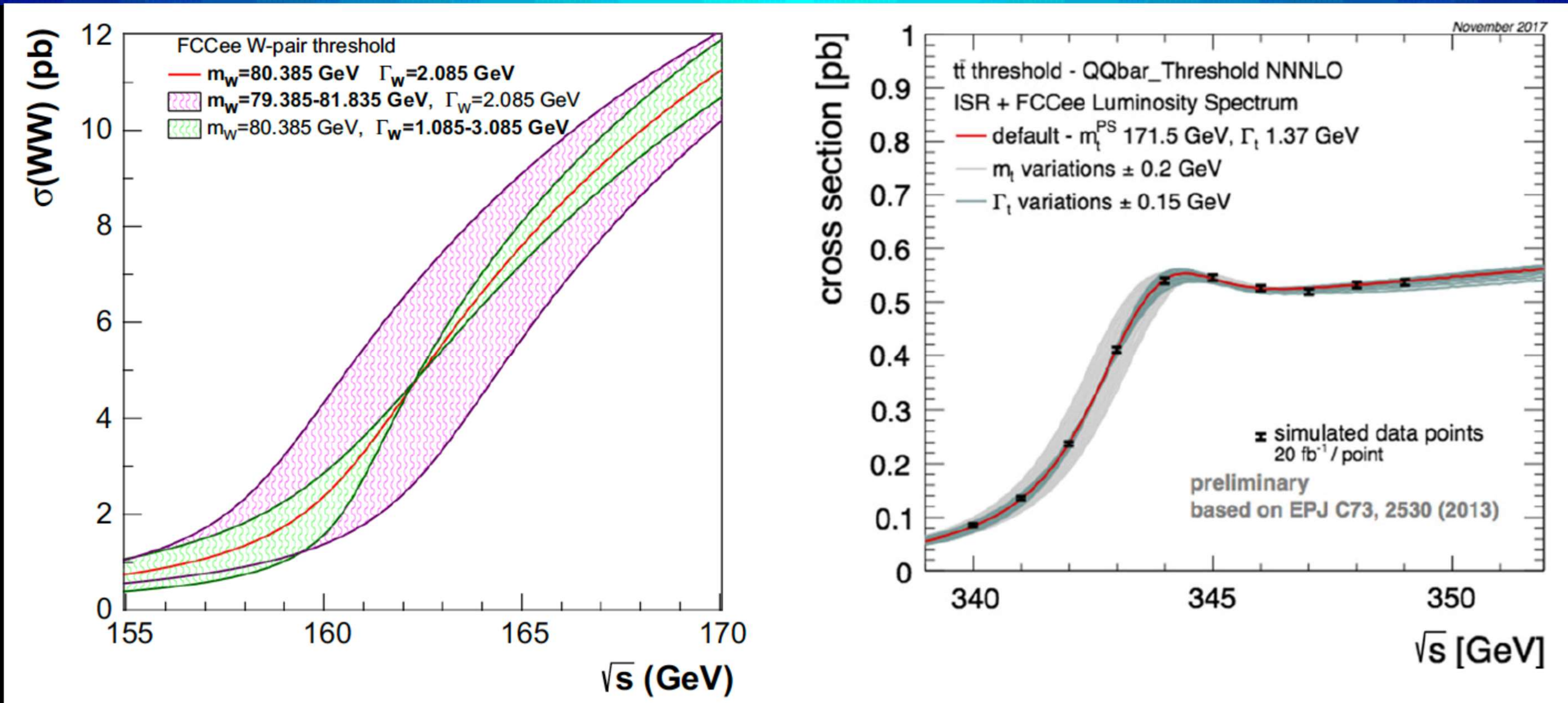
Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	
m_Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration	Z pole
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration	
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons	
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]	
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]	
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement	
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement	
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231,480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128,952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]	
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics	
m_W (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration	WW
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration	
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]	
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate	tt
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run	

EWK

❖ Outstanding program of precision EWK measurements

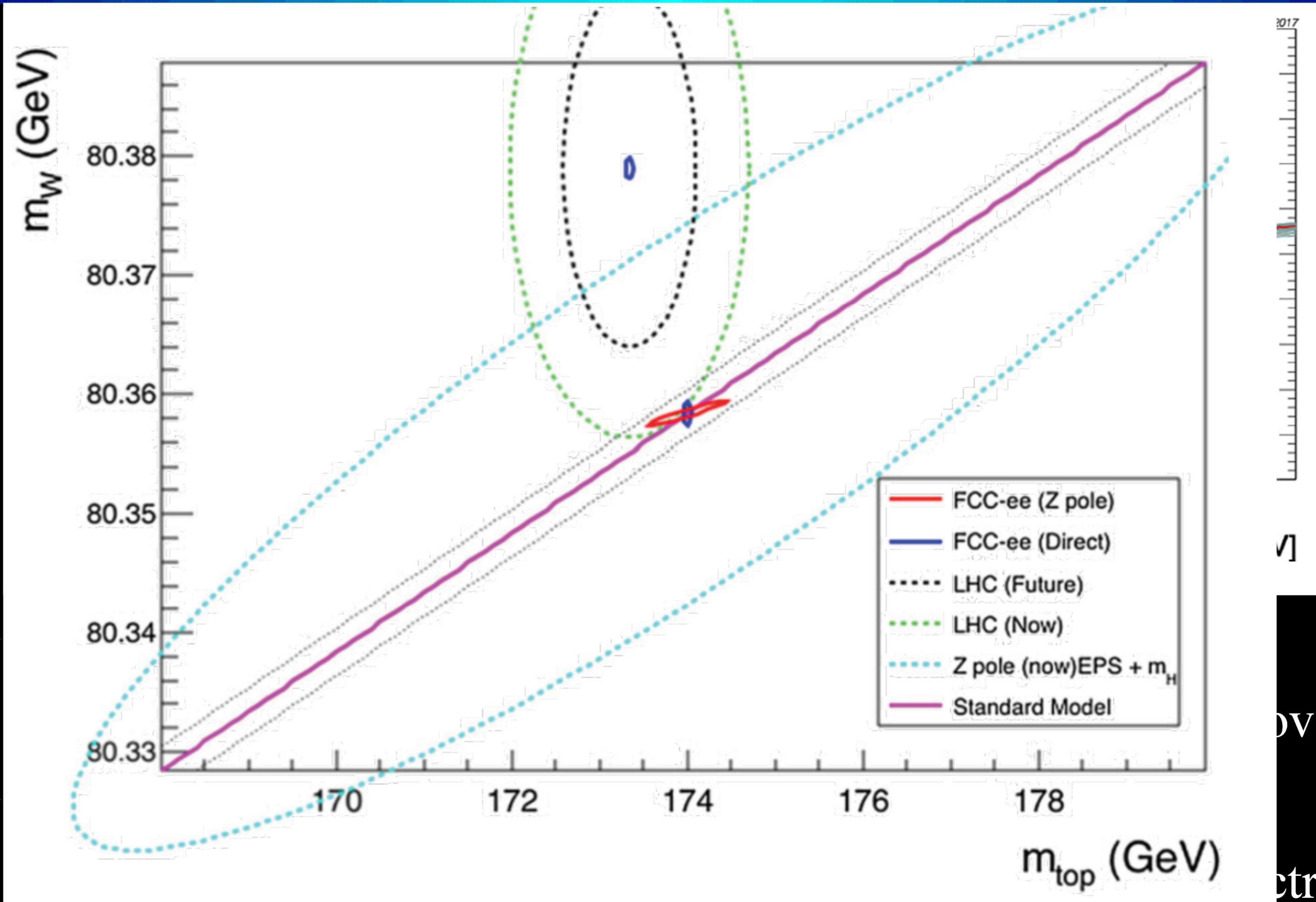


EWK examples



- W mass/width → 0.5/1.2 MeV resolution
  - WW threshold scan/ direct measurements check and improve
- Top quark mass/width → 17/45 MeV resolution
  - tt threshold scan – N^3LO, ISR and FCCee luminosity spectrum

EWK examples



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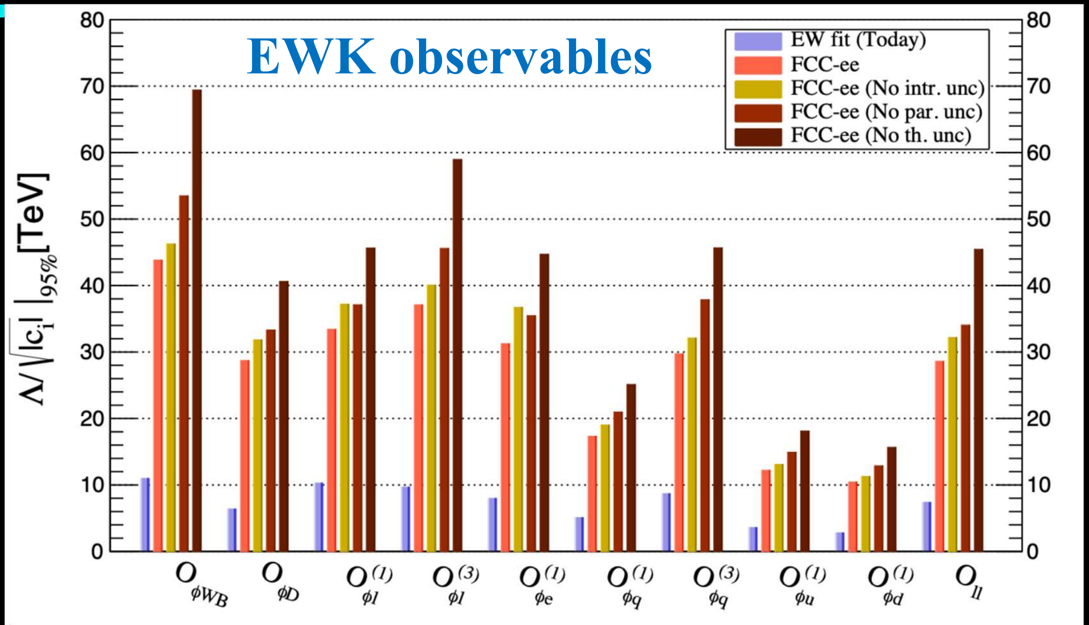
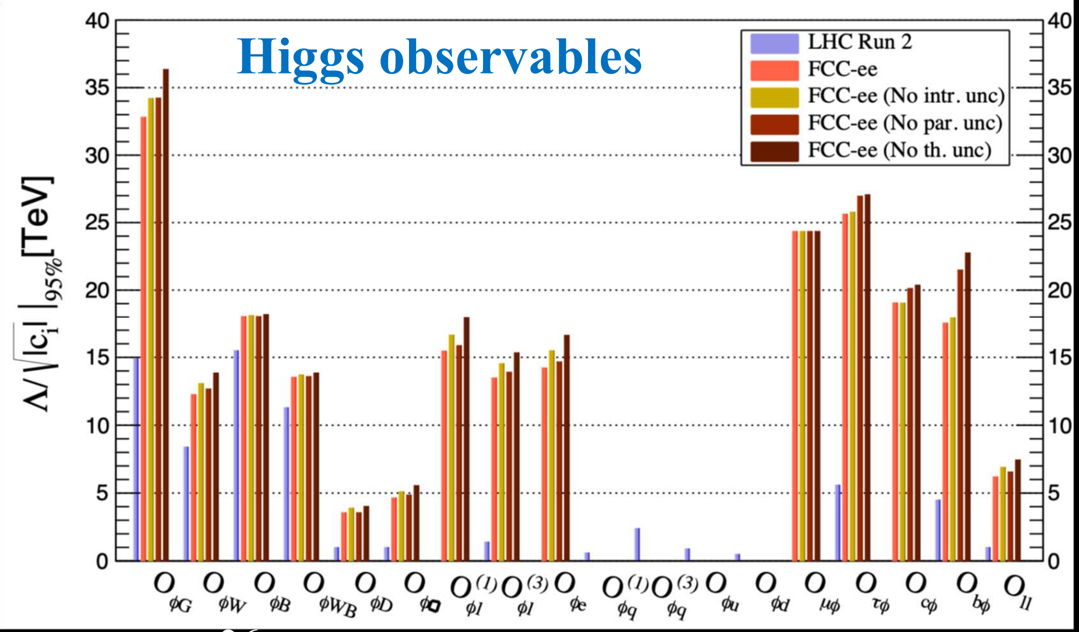
ctrum

NP sensitivity from EFT fits

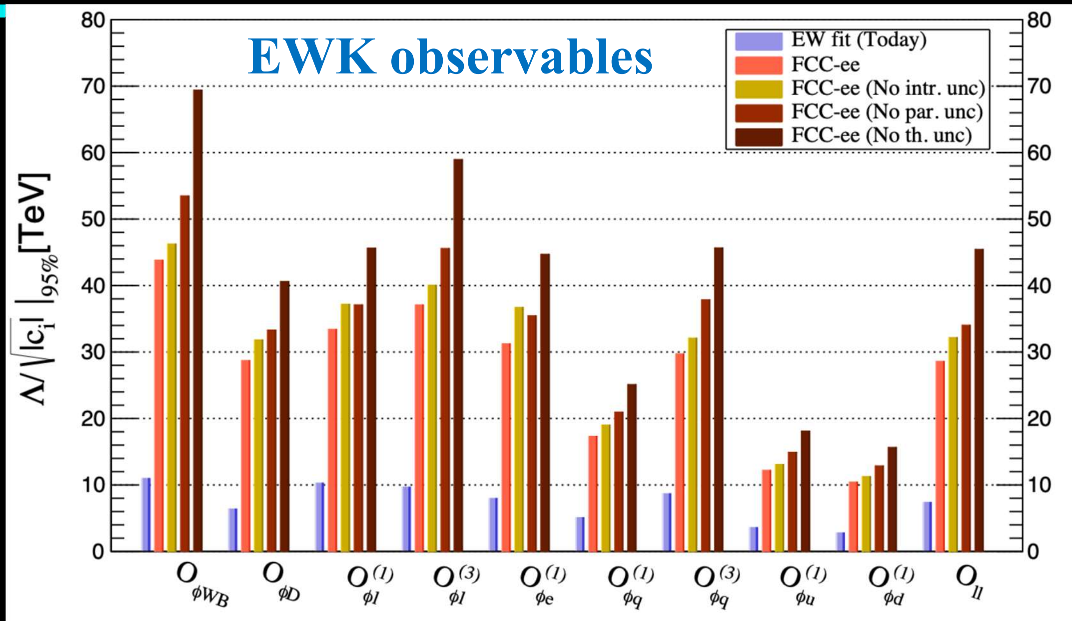
- From exclusive fits
  - Reach to several 10's TeV

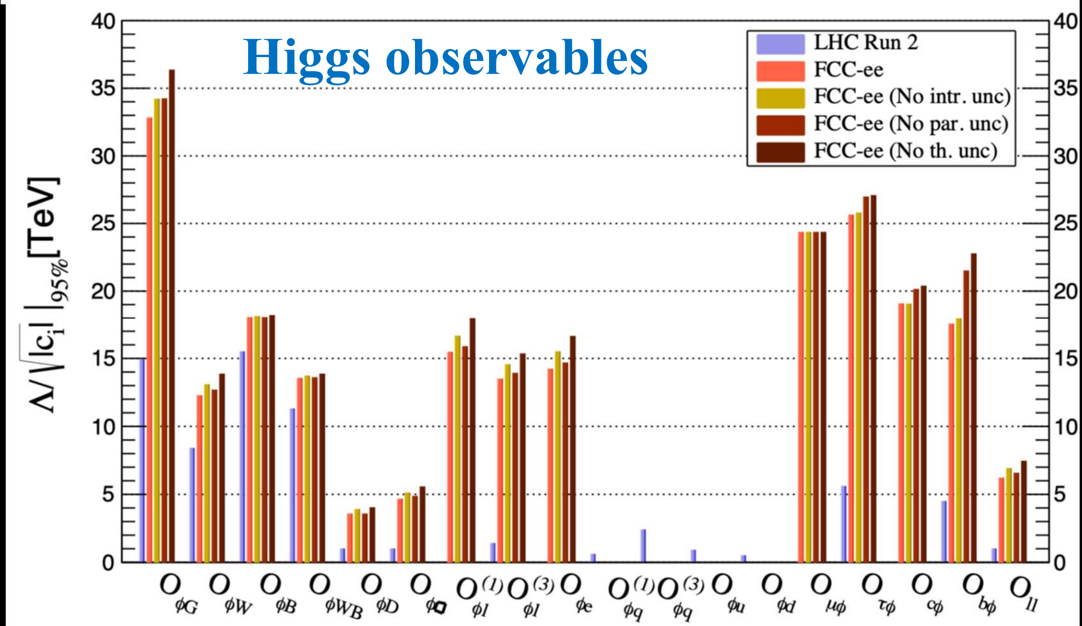




NP sensitivity from EFT fits

- From exclusive fits
  - Reach to several 10's TeV
- Theory uncertainties
  - Parametric~ exp. precision
  - Theory precision need
    - 3 loop Z pole
    - 2 loop WW





Heavy flavors

- Large heavy flavor production at Z pole

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

  - Very clean, well separated, pairs

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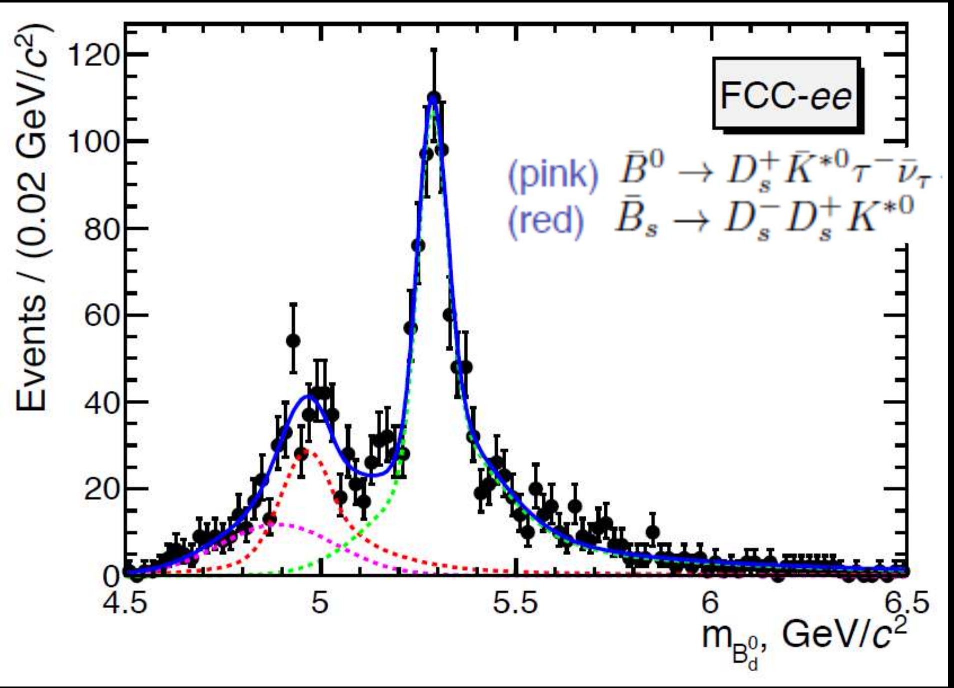
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

  - Very clean, well separated, pairs

- Example:
  - Lepton universality

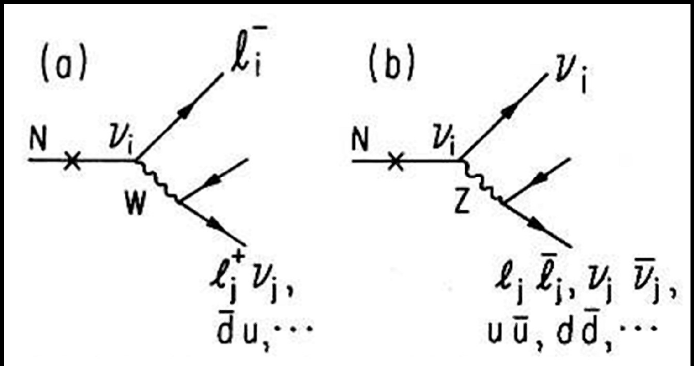
in $B^0 \to K^{*0}\ \tau+\tau-$

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)



Direct NP search example: HNL

- HNL mix with active neutrino's
  - Fully reconstructable decay with W
  - Small mixing → long lifetime



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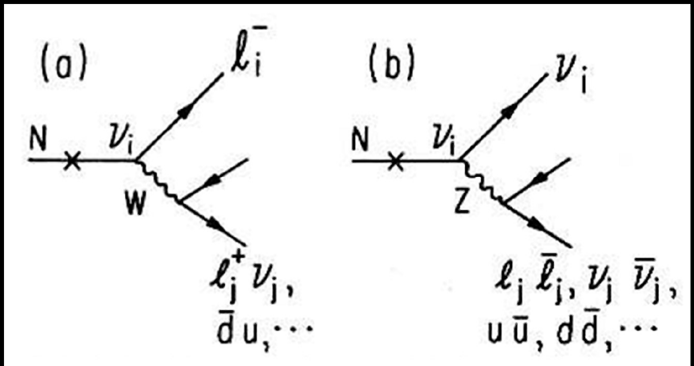

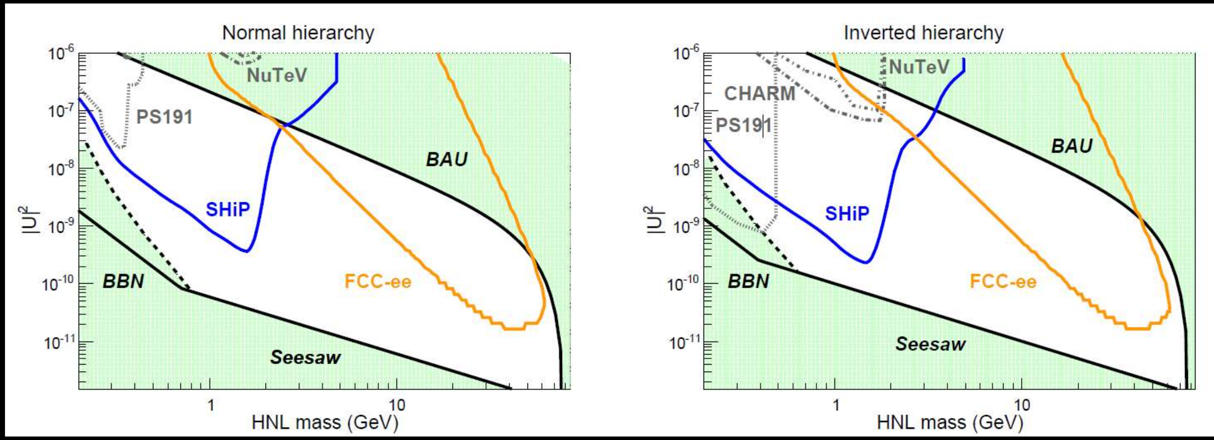

10 cm < cτ < 100 cm

10^{12} Z

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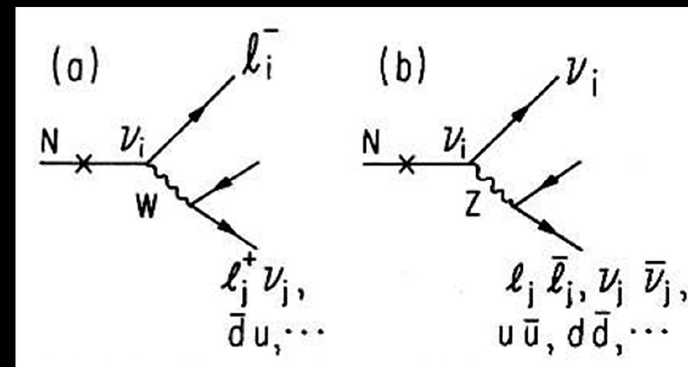
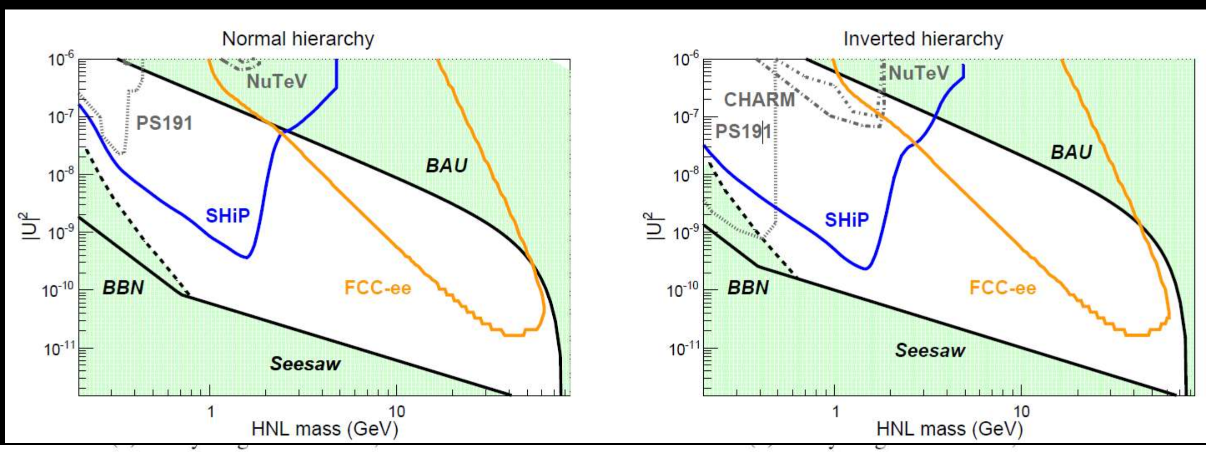
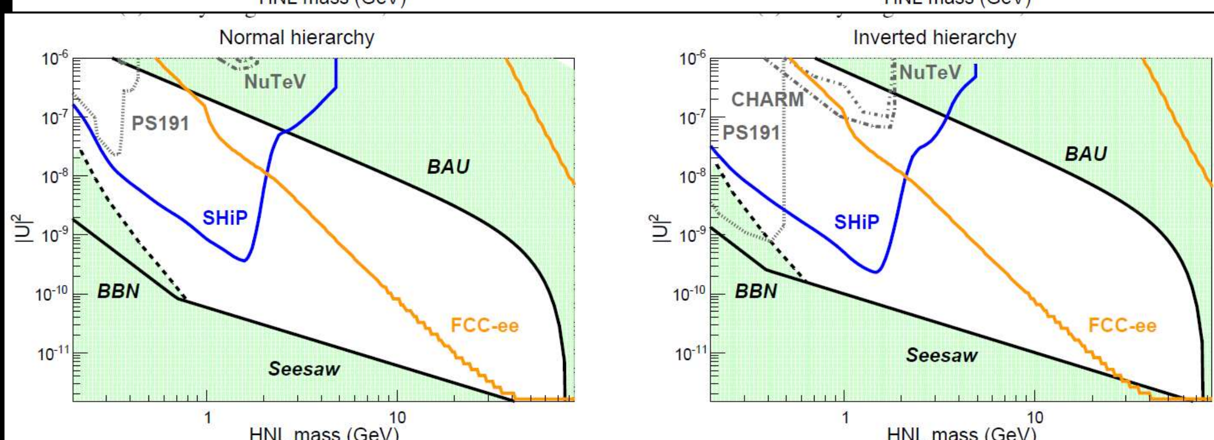




$10 \text{ cm} < c\tau < 100 \text{ cm}$

10^{12} Z



$0.01 \text{ cm} < c\tau < 500 \text{ cm}$

10^{13} Z

The detectors

Detectors for circular e+e-

- Requirements:
  - Constraints from physics (similar to LC …. more or less)

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

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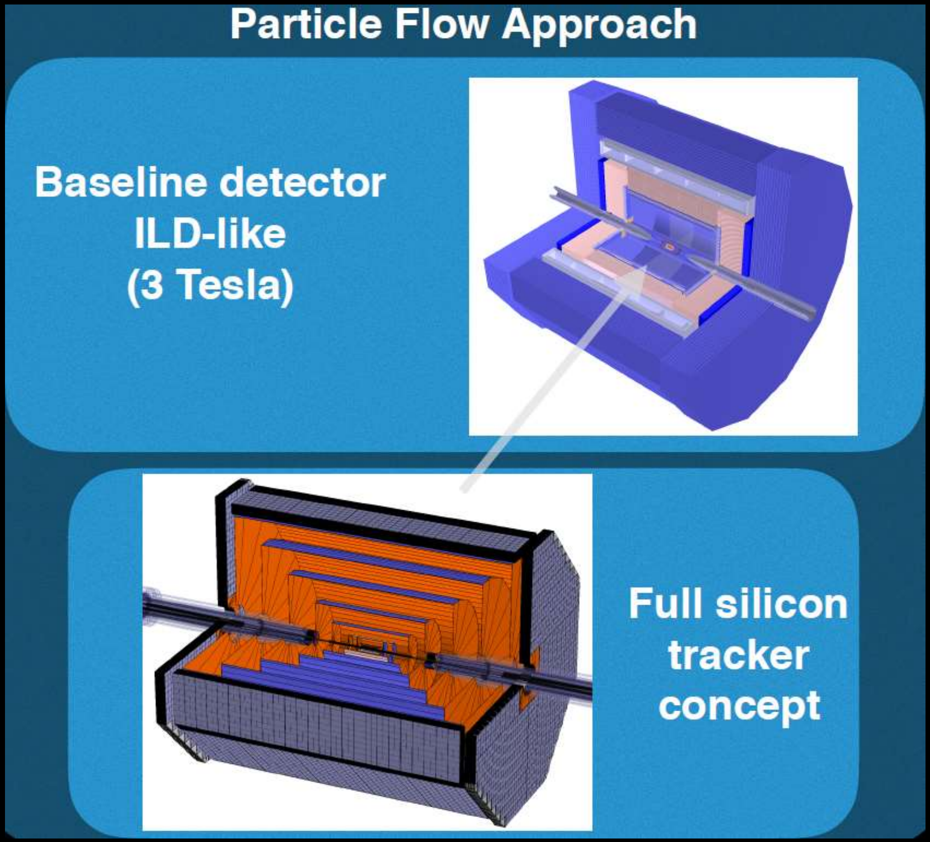
$H \to q\bar{q},\ VV$	$BR(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\text{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$BR(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

- Additional constraints
  - Excellent acceptance and luminosity control
  - PID & π^0 ID for HF/τ physics
  - Low B field to avoid emittance blow up
  - Power pulsing not allowed

} Not present at LC

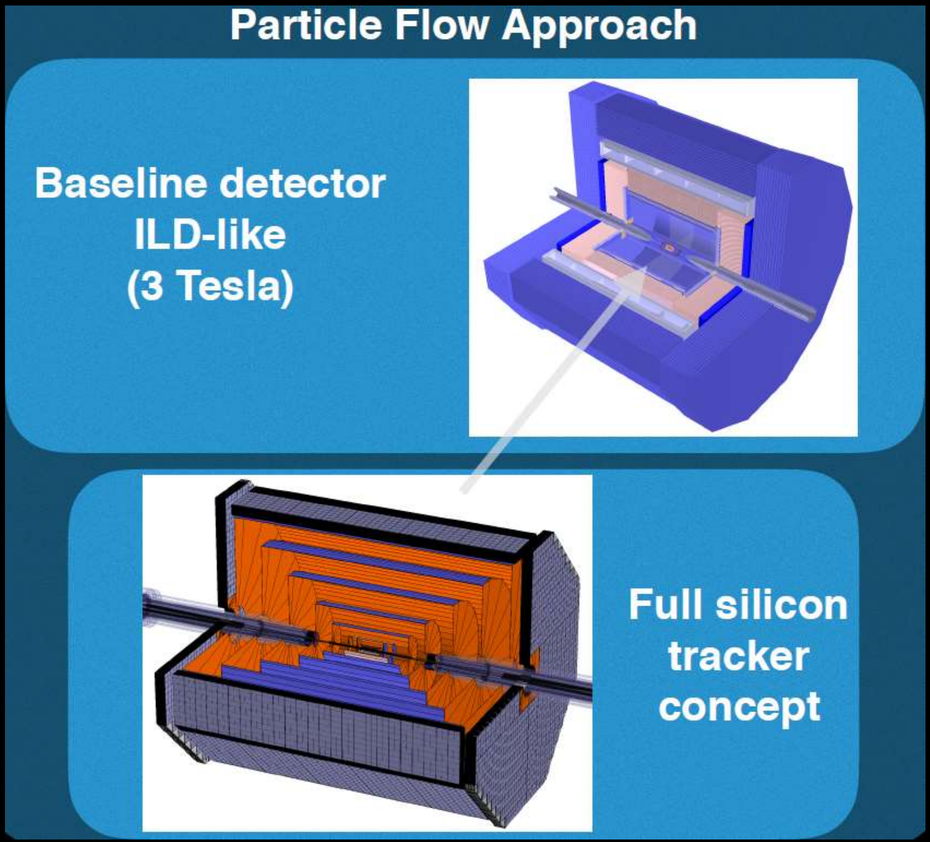
Detector concepts CepC

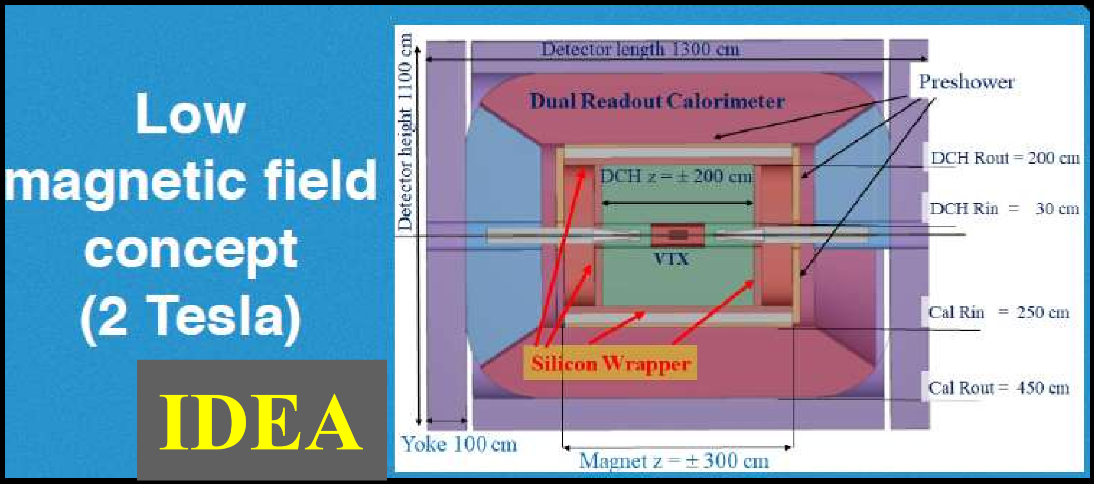
- ILD-like (baseline)/SiD-like w/ PF calorimetry & TPC/Si



Detector concepts CepC

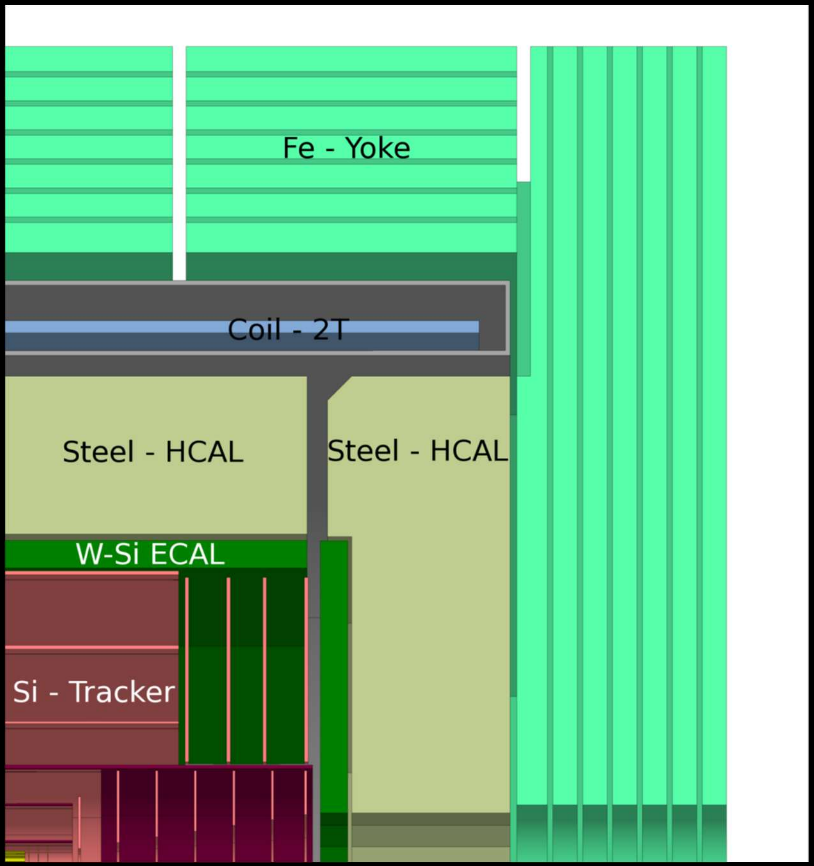
- ILD-like (baseline)/SiD-like w/ PF calorimetry & TPC/Si
- Alternate detector, IDEA w/ DR calorimetry & Drift Ch.





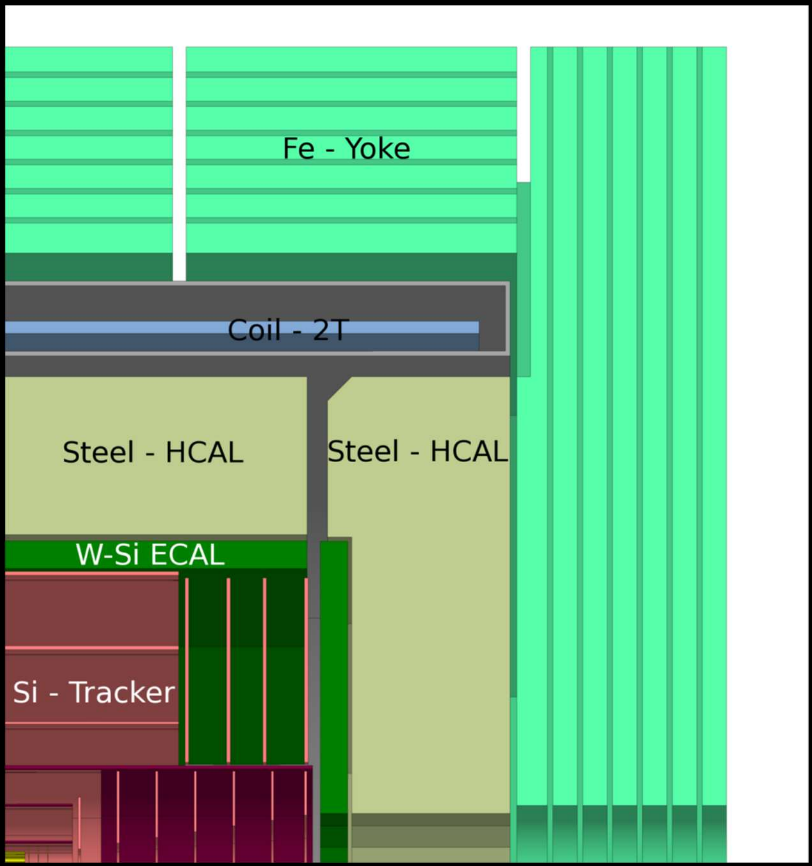
Detector concepts FCCee

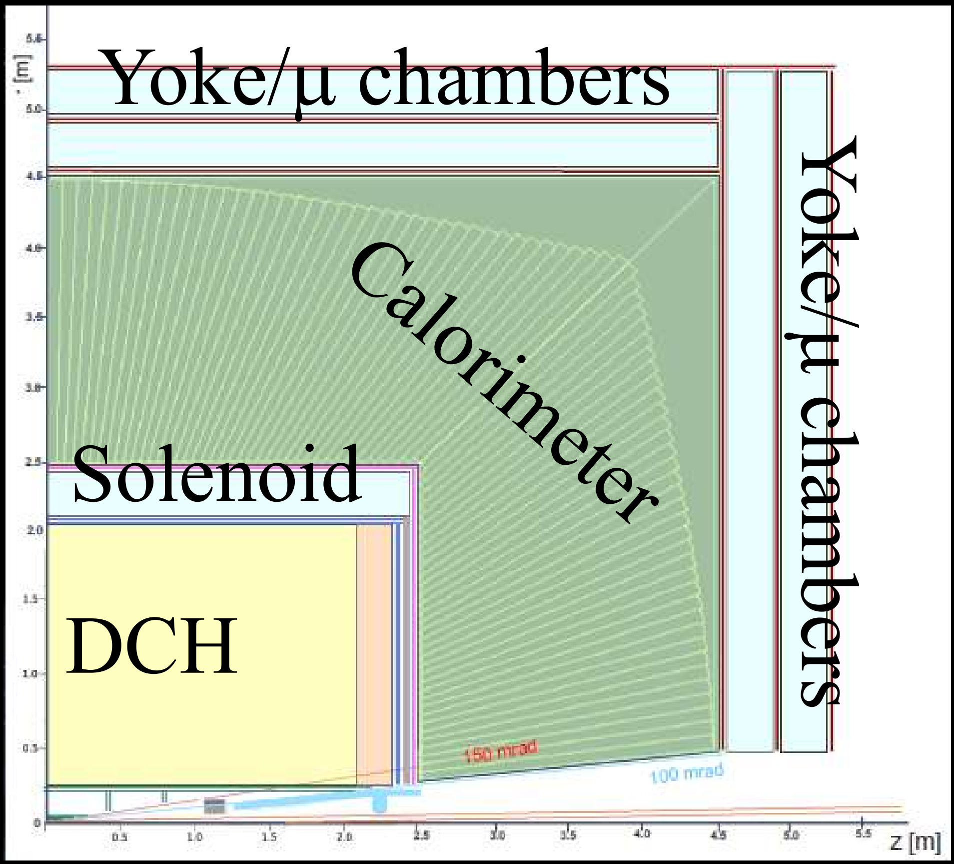
- CLD (CLIC like): PF calorimetry/Si



Detector concepts FCCee

- CLD (CLIC like): PF calorimetry/Si
- IDEA: DR calorimetry/Drift chamber





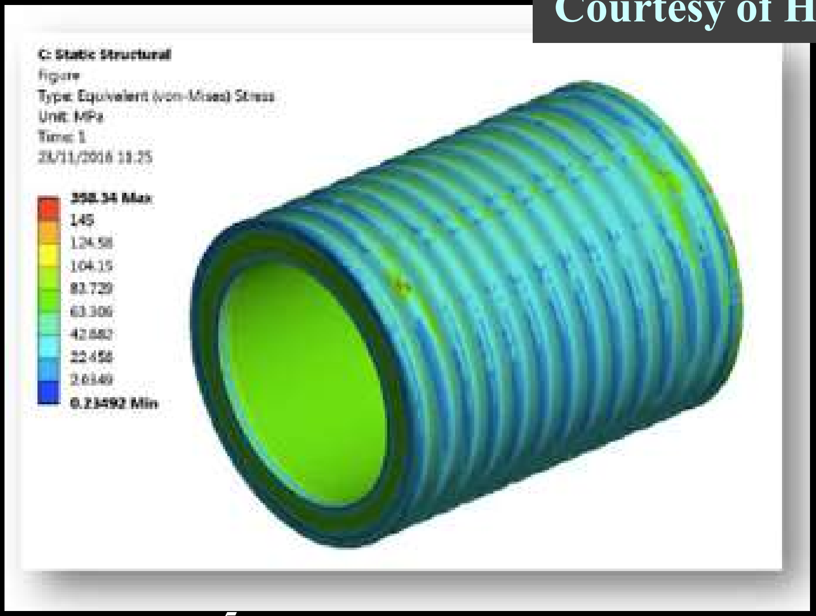
Innovative Detector for Electron-positron Accelerator

- Basic design guidelines for IDEA
  - Low 2T field magnet to maximize luminosity at low energy
    - Maximize tracking volume
      - Calorimeter outside → thin low mass solenoid → small yoke
  - Fast, low mass tracker
    - Air cooled VTX detector with fine pitch
    - DCH with small ~ 1 cm cells (much faster than TPC)
    - DCH provides excellent PID with cluster counting
  - Pre-shower to control γ acceptance and compensate for magnet
  - Dual Readout calorimetry
    - Electronics in back → no cooling issues
    - Longitudinal segmentation with timing

Detector solenoid

- 2T field solenoid – Rin ~ 2 m
  - Can be made very thin ~30 cm total = 0.74 X_0 (0.16 λ) at $\theta = 90^{\circ}$
    - Calorimeter can be located outside coil
  - Small yoke thickness 50-100 cm Fe
    - Scales with B R^2 → cost reduction over large coil

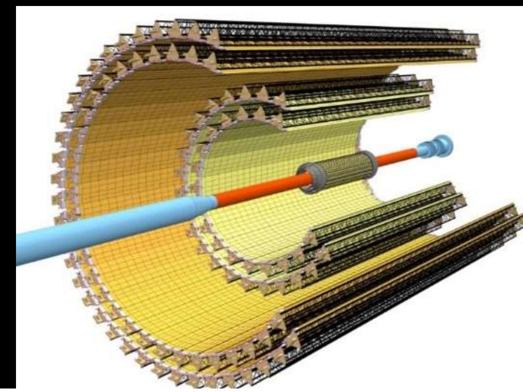
Property	Value
Magnetic field in center [T]	2
Free bore diameter [m]	4
Stored energy [MJ]	170
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

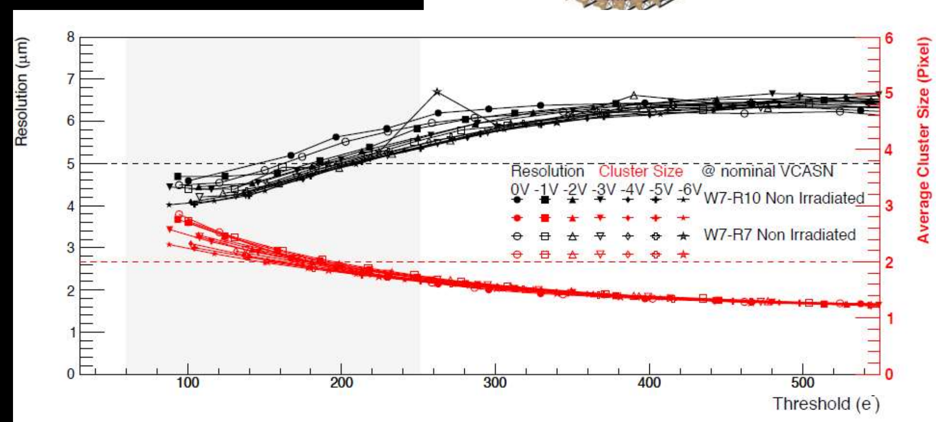


Courtesy of H. ten Kate

Vertex detector

- Build on ALICE ITS technology
  - 30x30 μm MAPS (ALPIDE)
    - 5 μm spatial resolution demonstrated
    - 0.3-1.0% X_0 (in-out)
    - 41-27 mW/cm2 (in-out)





Courtesy of ALICE J.W. van Hoorne

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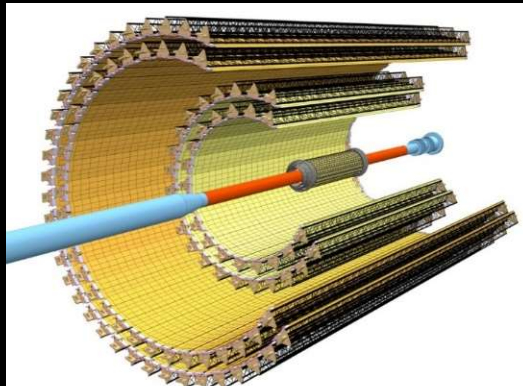
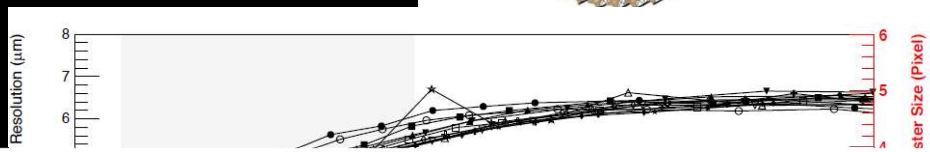
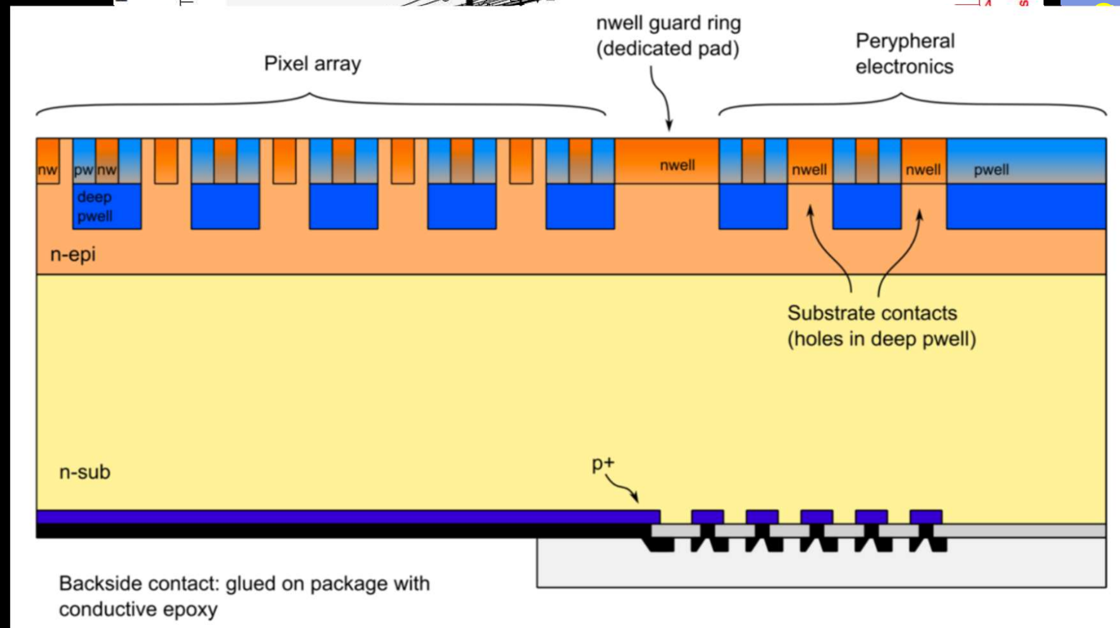


f ALICE J.W. van Hoorne

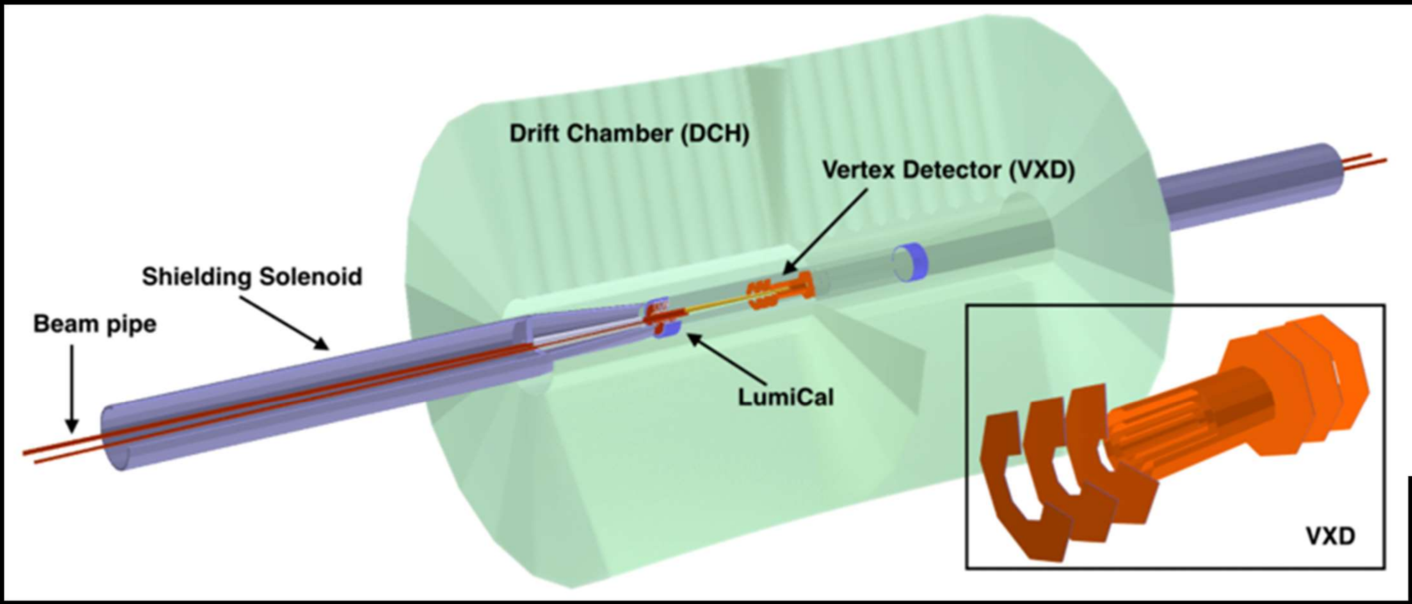


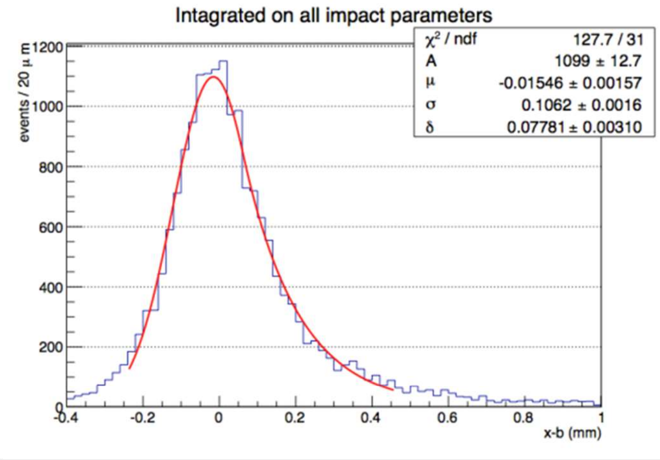
- New R&D: ARCADIA
  - 20x20 µm MAPS
  - Aim to <20mW/ch
  - Stiching
  - Fast readout



Tracker

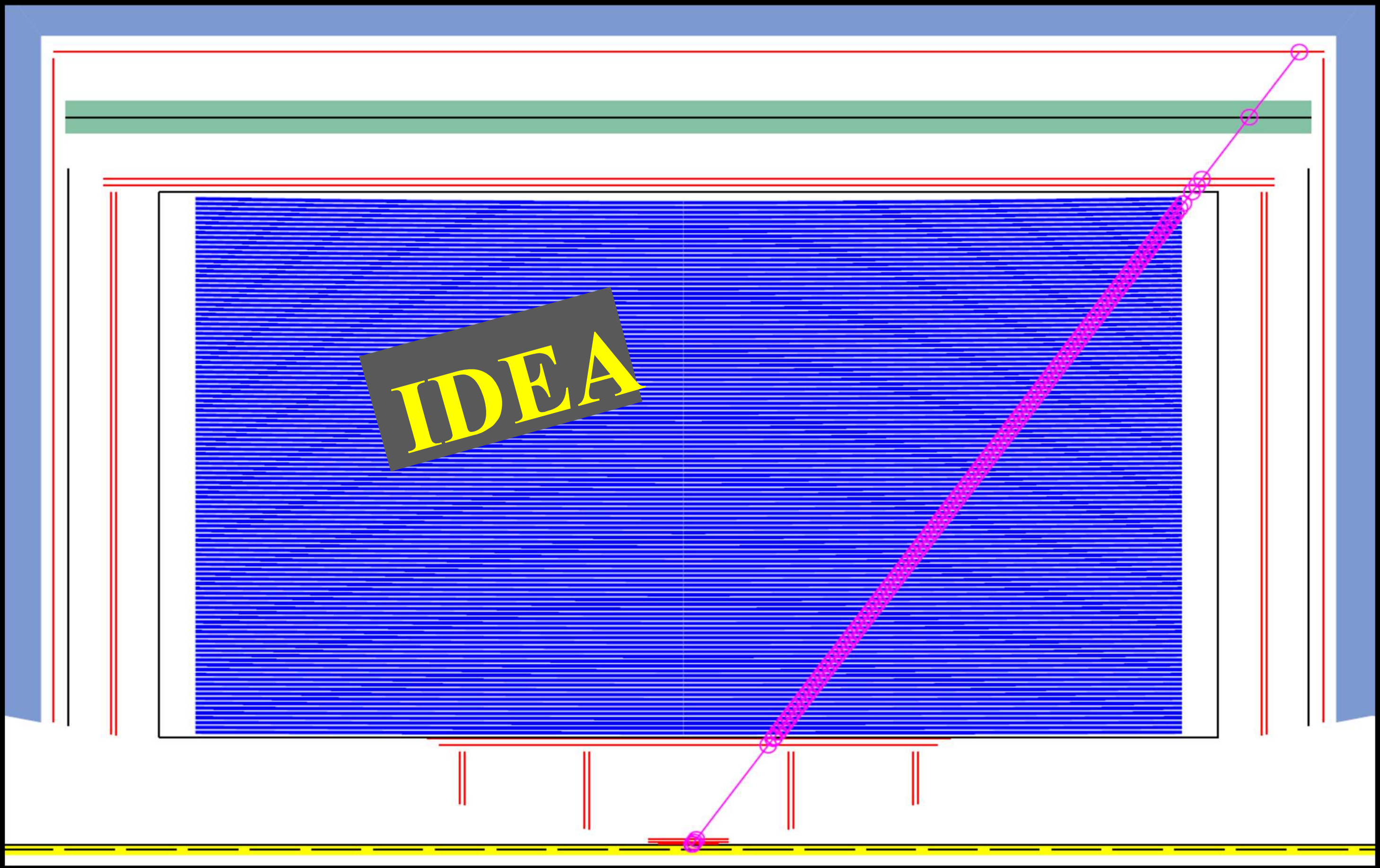
- Drift Chamber: fast, good resolution/dE/dx w/ cluster count
  - Ultralight chamber (<1% X_0) – gas: He 90% - iC_4H_{10} 10%
    - Lighter than air!
  - 4 m long, drift length ~1 cm, drift time ~400ns, σ_{xy} < 100 μm
  - Novel construction with separate gas envelope





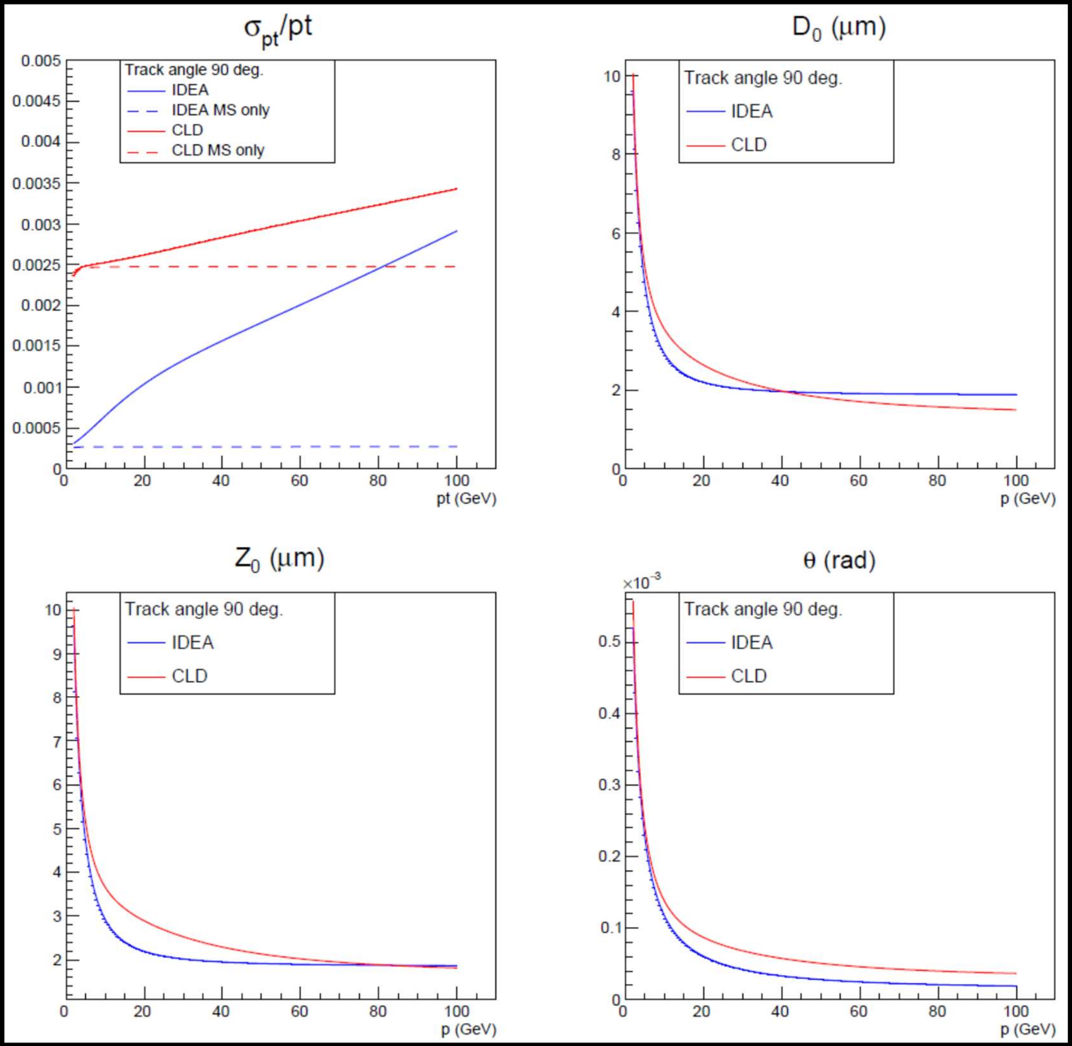
Tracker performance

- Tracking system has excellent resolution



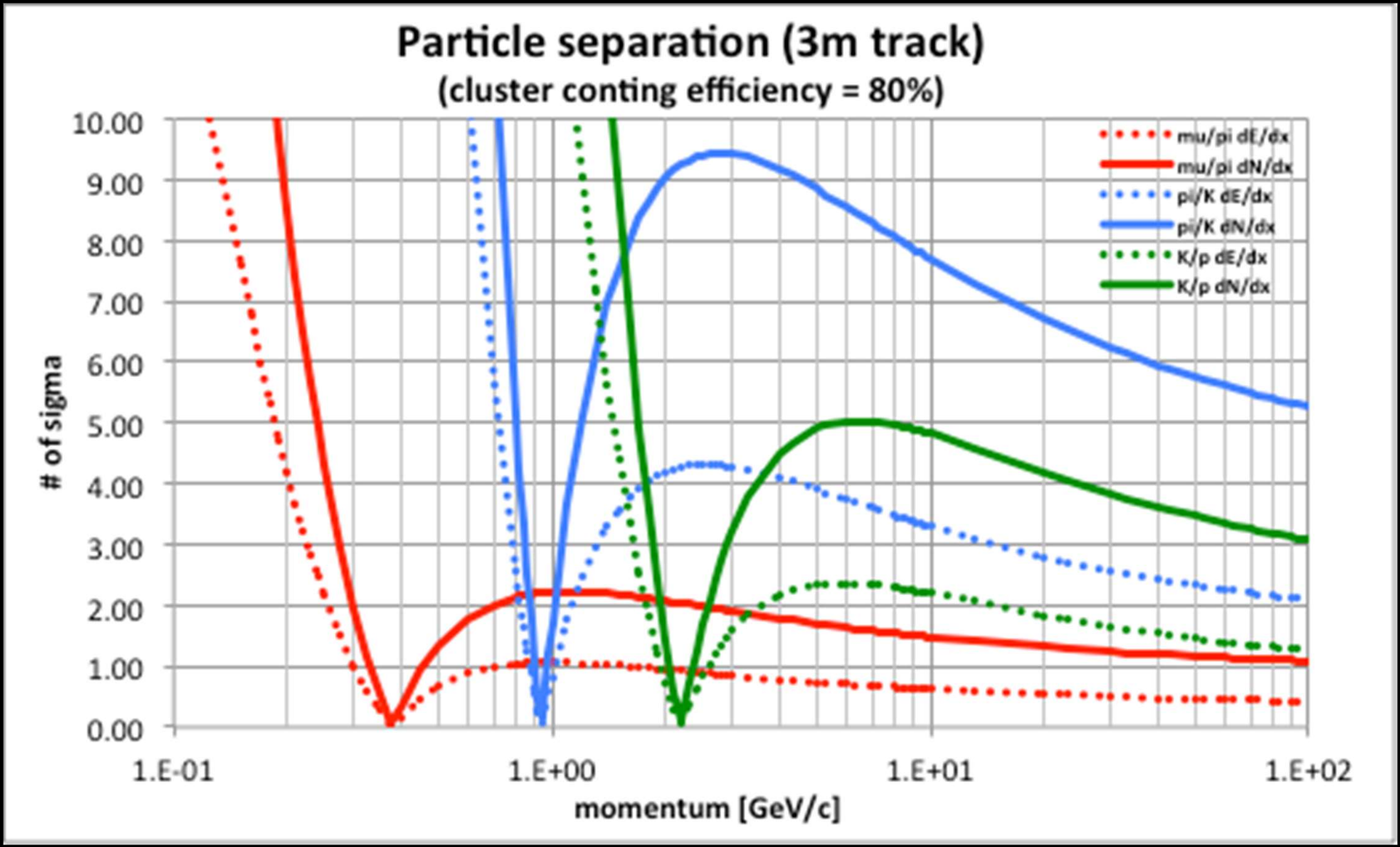
Tracker performance

- Tracking system has excellent resolution
  - Transparency very important



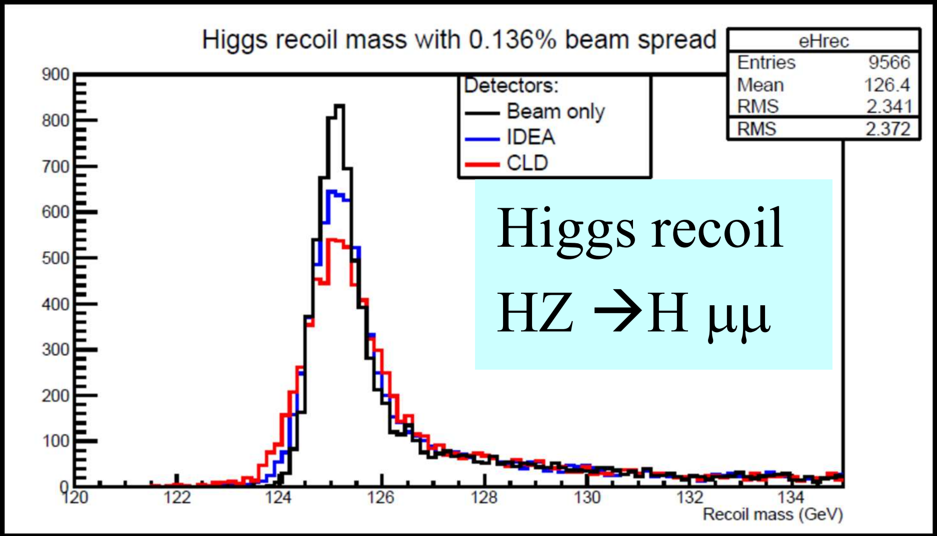
Tracker performance

- Tracking system has excellent resolution
  - Transparency very important
  - Excellent dE/dx with cluster counting



Tracking system performance

- Higgs recoil from ZH with Z→μμ



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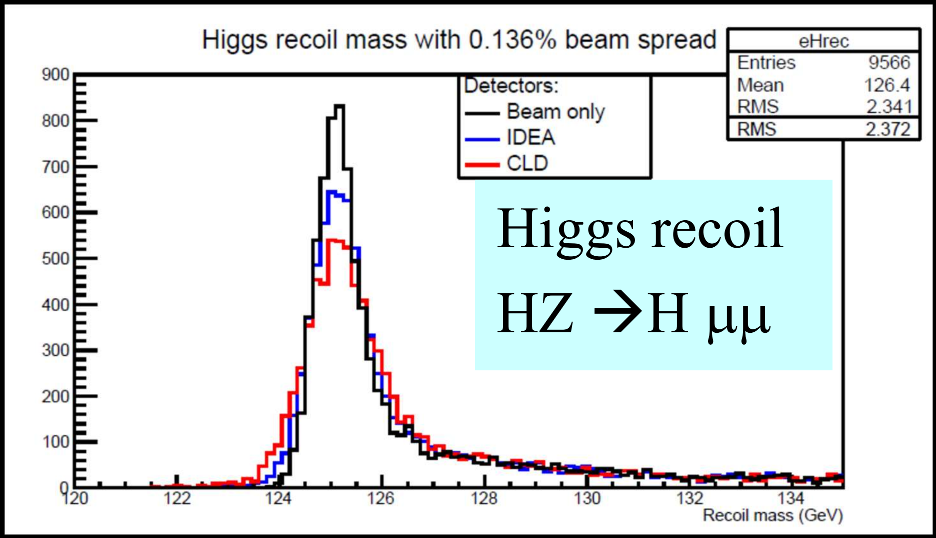
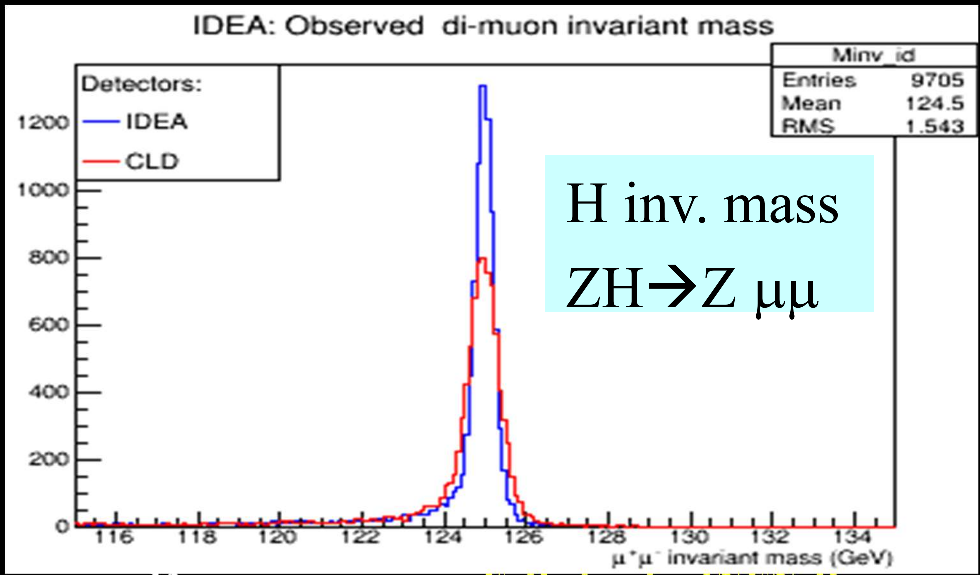


- H→μμ in ZH events



Calorimeter system

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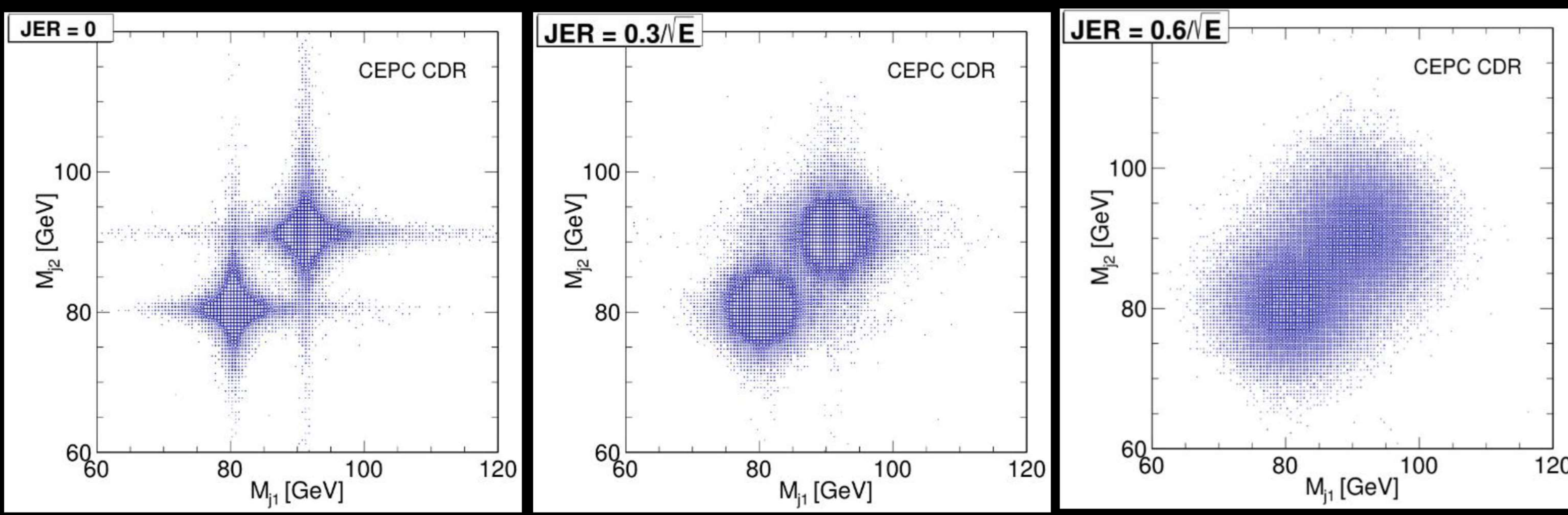
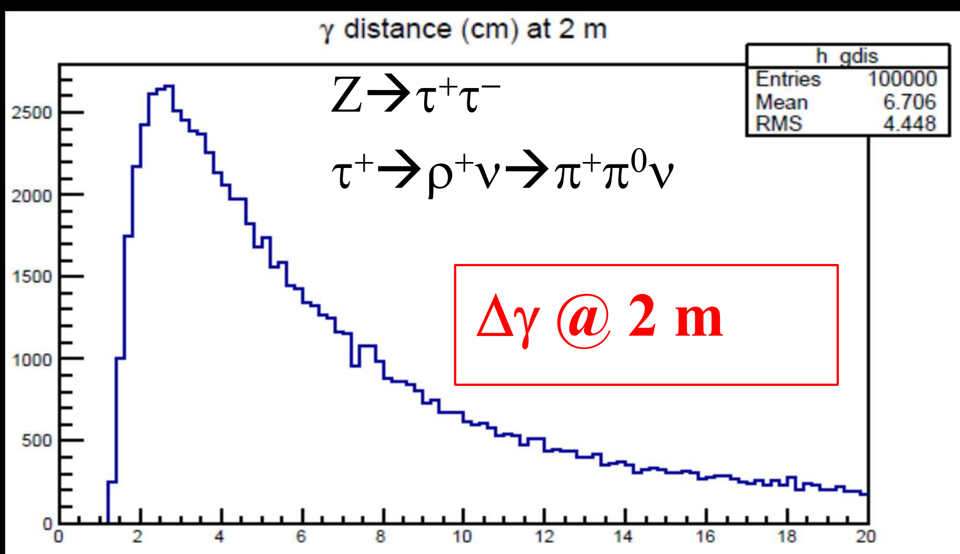
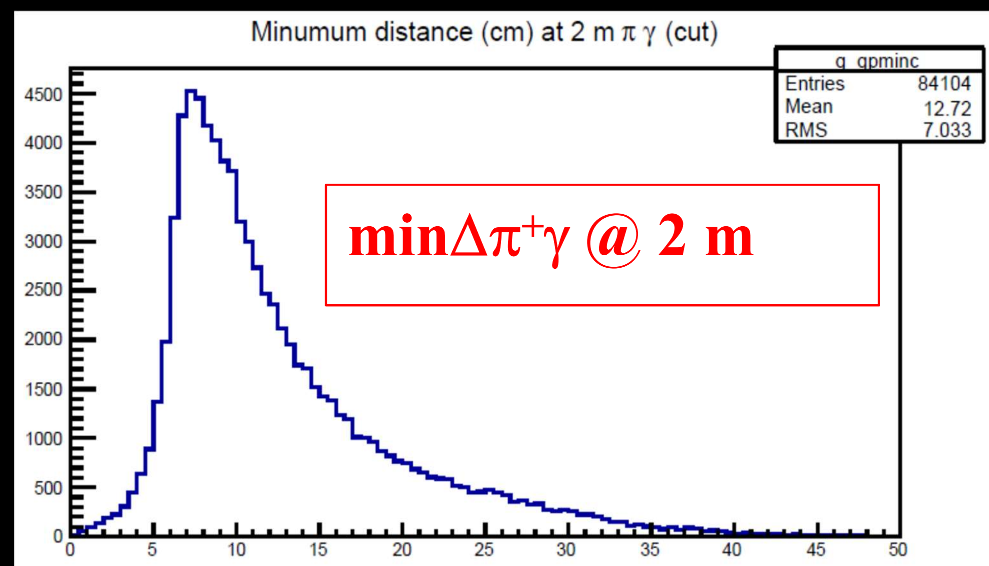


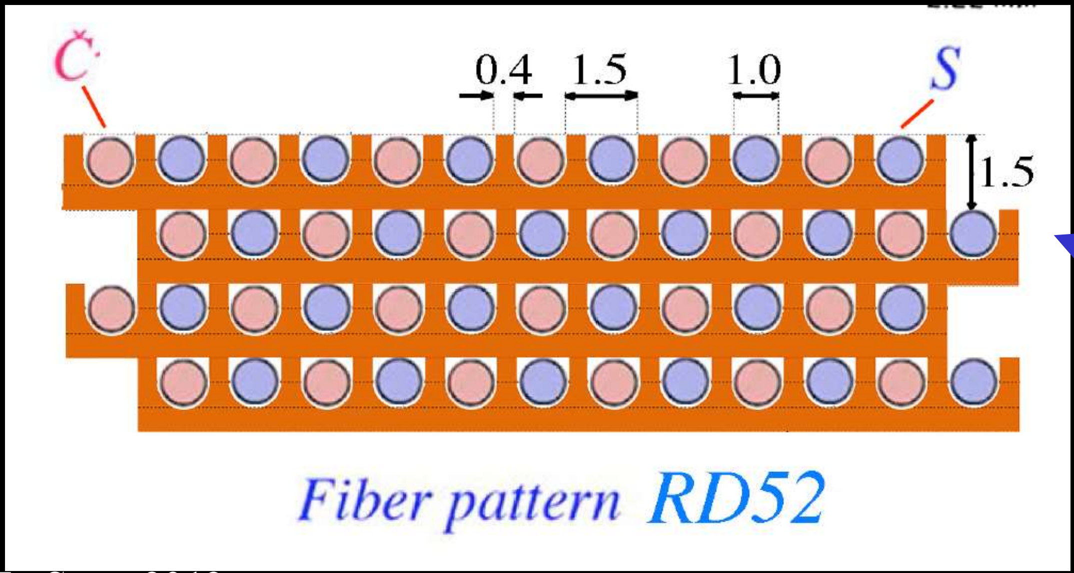
Calorimeter system

- $H \rightarrow \gamma\gamma$ ➔ good ECAL resolution – not extreme
- WW/ZZ → jets separation ➔ very good HCAL resolution
- Good π_0 ID – Example $Z \rightarrow \tau+\tau-$
  - Set transverse separation scale





Dual Readout: Working principle



Alternating scintillating and clear fibers in metal matrix

Dual Readout: Working principle

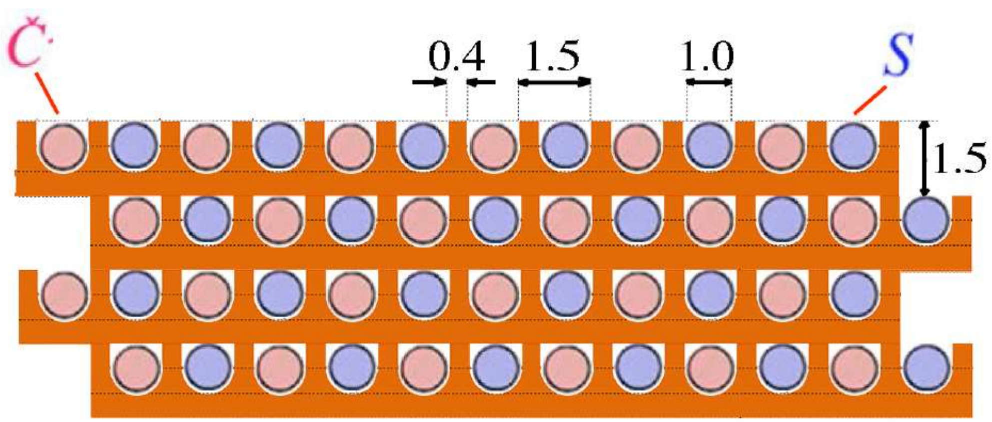
- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with e-
- Unfold event by event f_{em} to obtain corrected energy

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$



Fiber pattern RD52

Alternating scintillating and clear fibers in metal matrix

Dual Readout: Working principle

EM and Hadronic calorimeter in a single package with all active sensors and electronics in the back

- Calibrate both signals with e-
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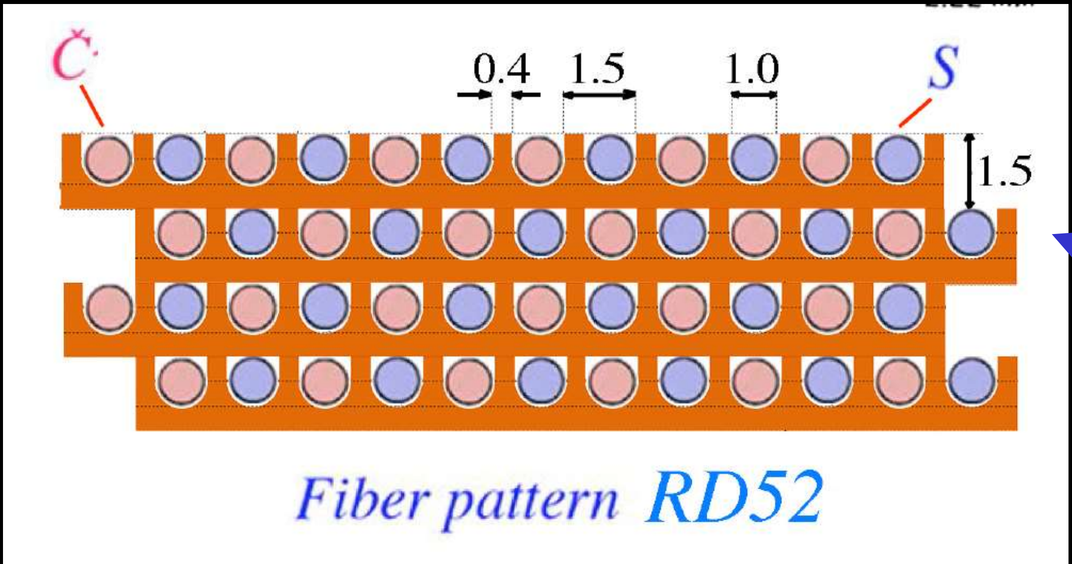
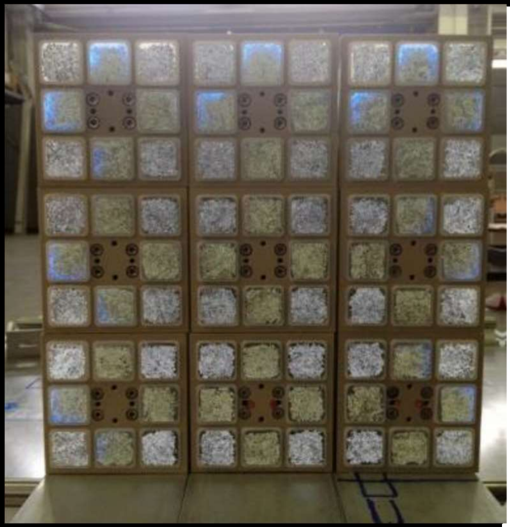


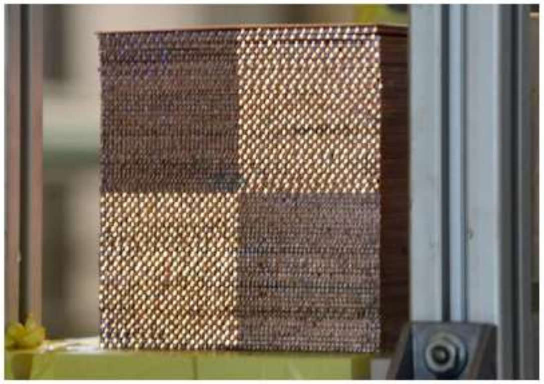
Alternating scintillating and clear fibers in metal matrix

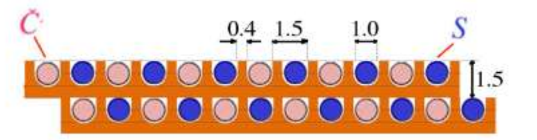
Calorimeter performance

- Dual readout calorimeter
  - Build on DREAM/RD52 experience
    - Transverse granularity ~ 2 mm
    - Upgrade to SiPM readout

Courtesy of DREAM/RD52







Details in next talk by M. Antonello

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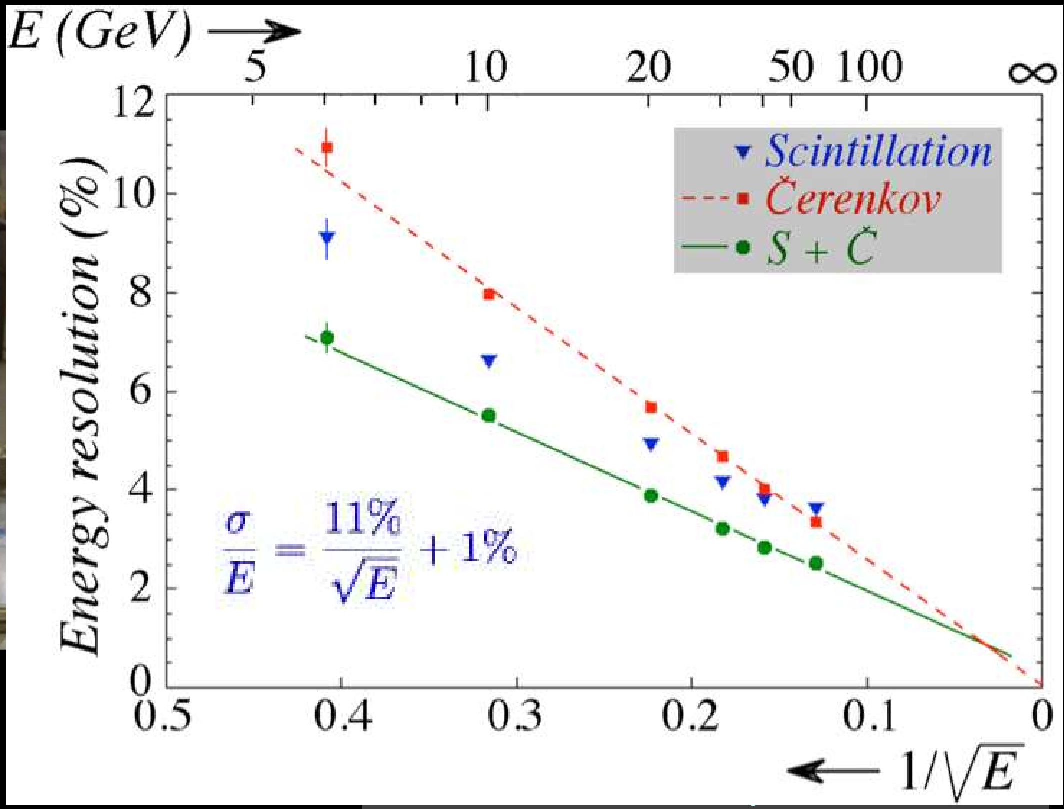

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  - Had. resolution extr. with GEANT4 due to lat. leakage

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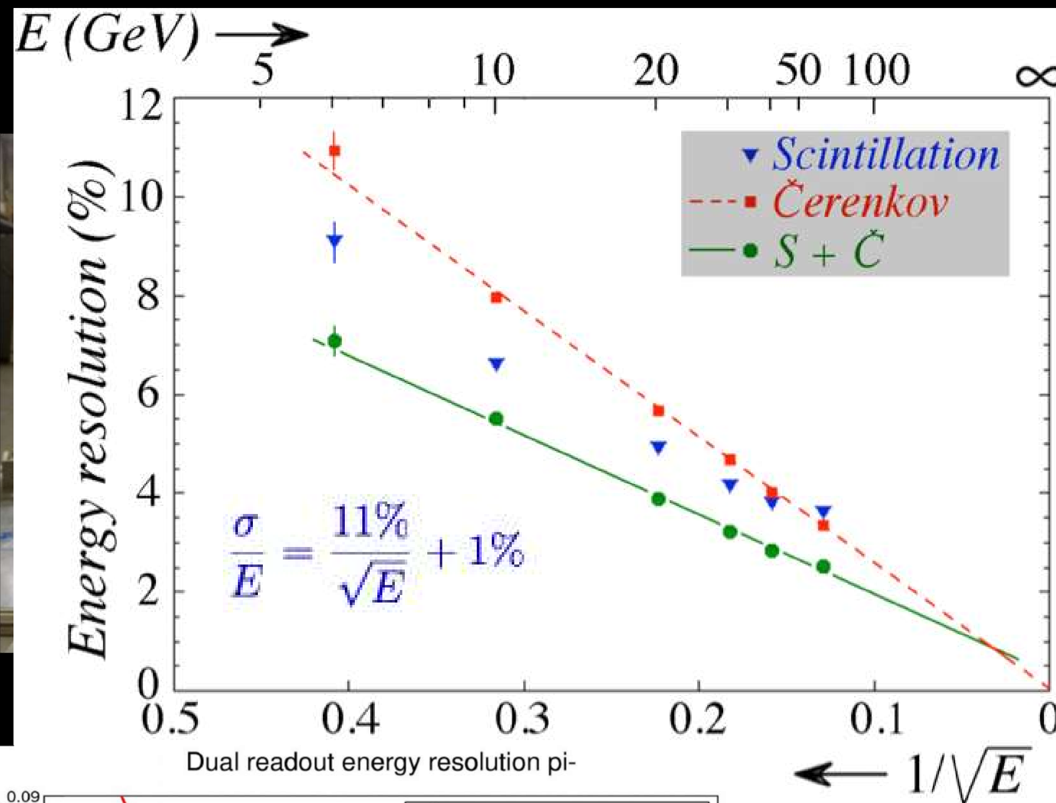
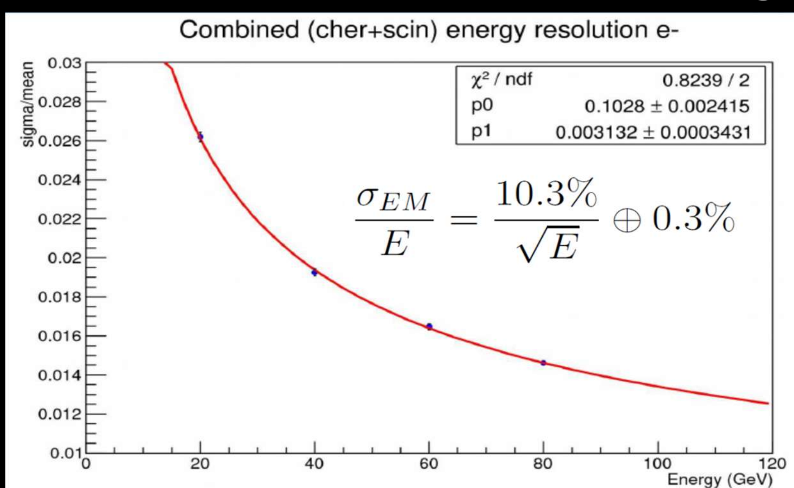
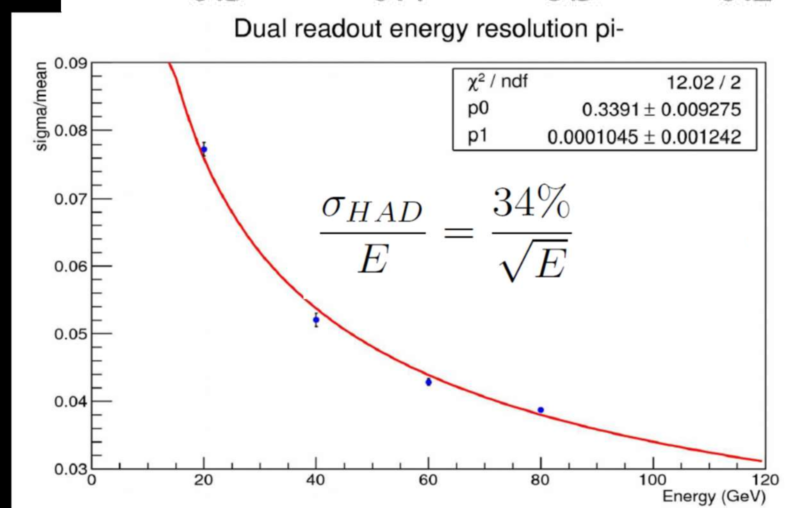
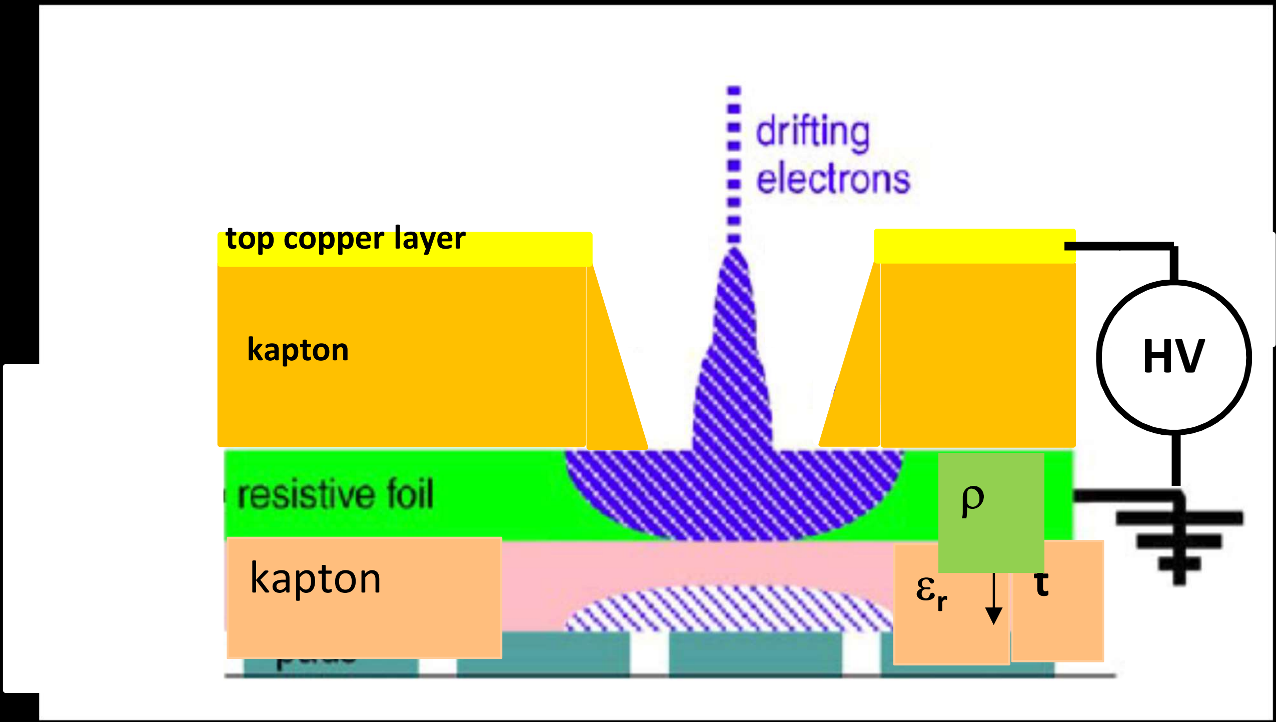


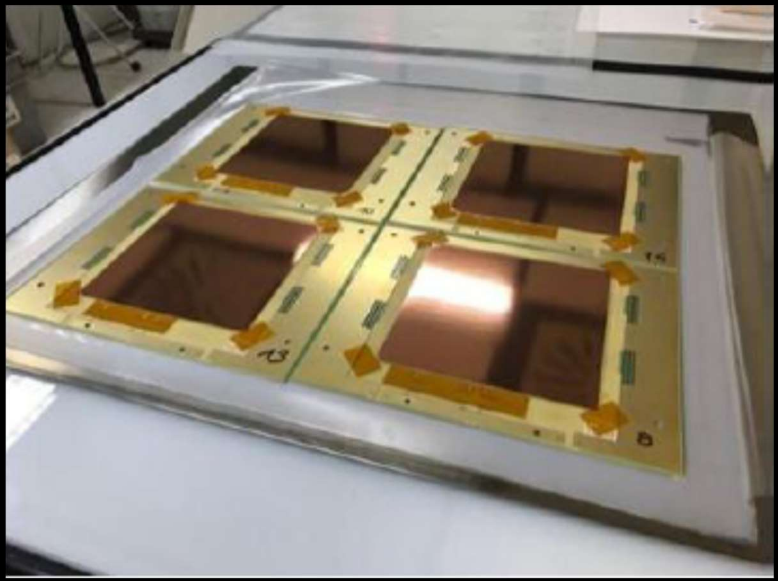




Muon Chambers

- Exploring new mRwell technique
  - Significantly cheaper and simpler than GEM/Micromegas
  - No foils to stretch – Just a large printed circuit
  - Extensive ongoing work to transfer technology to industry





Detector layout

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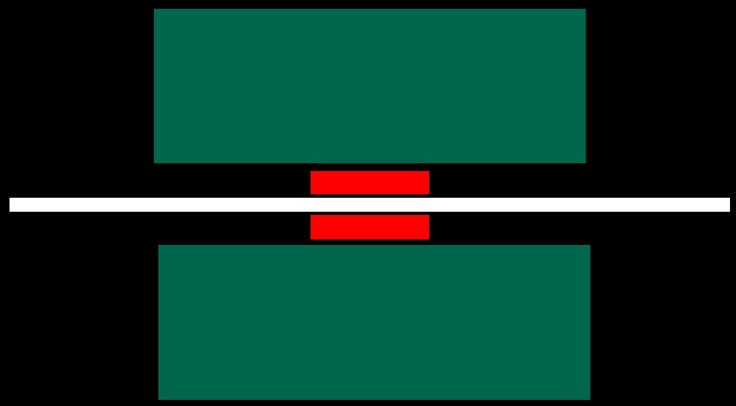

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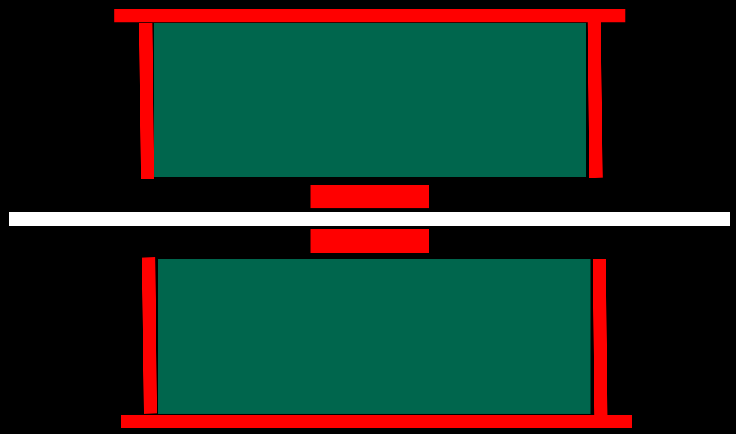

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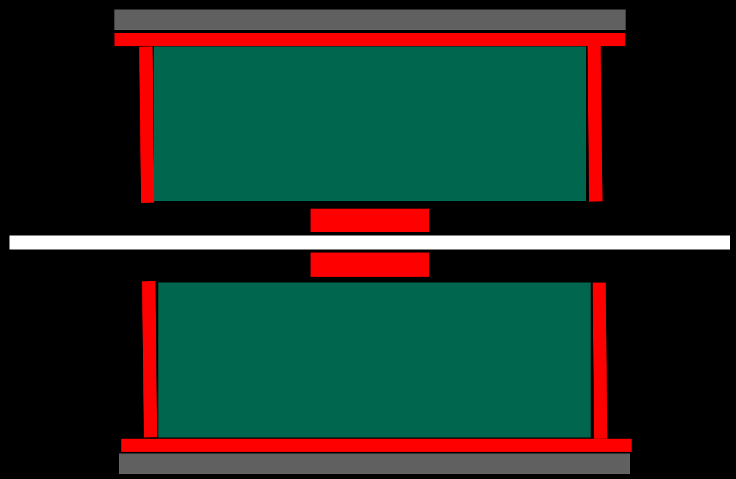

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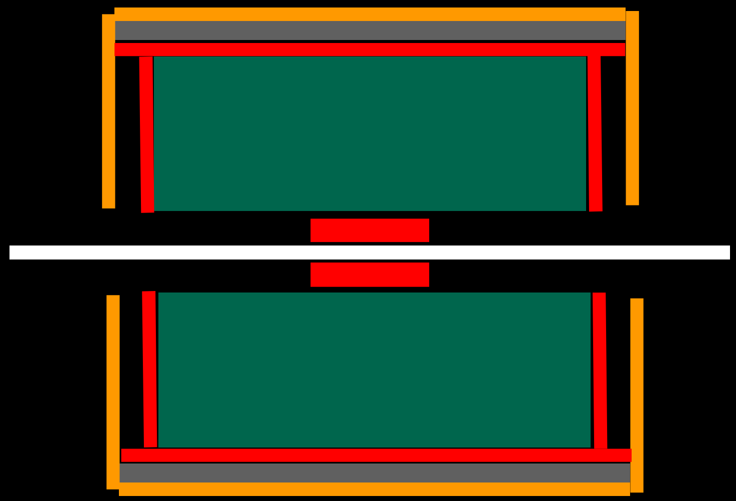

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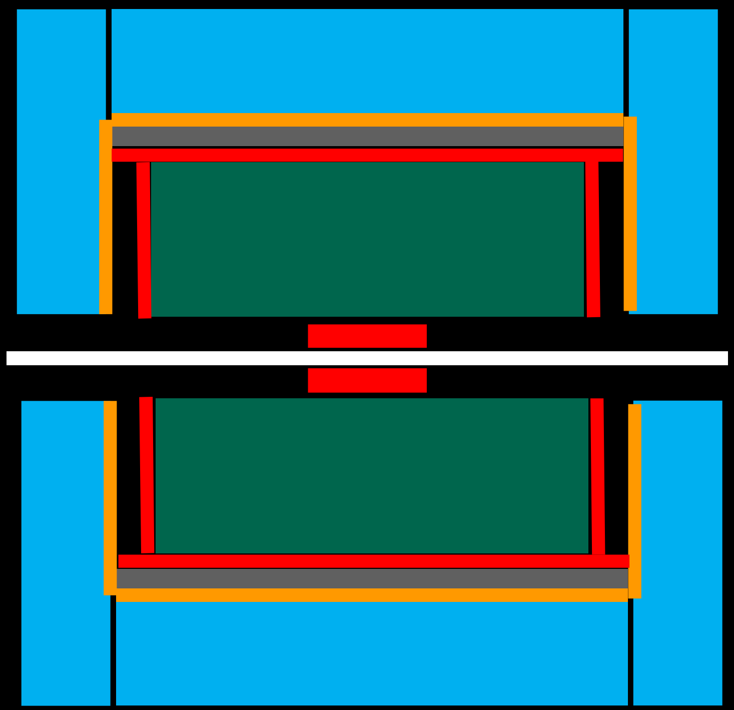

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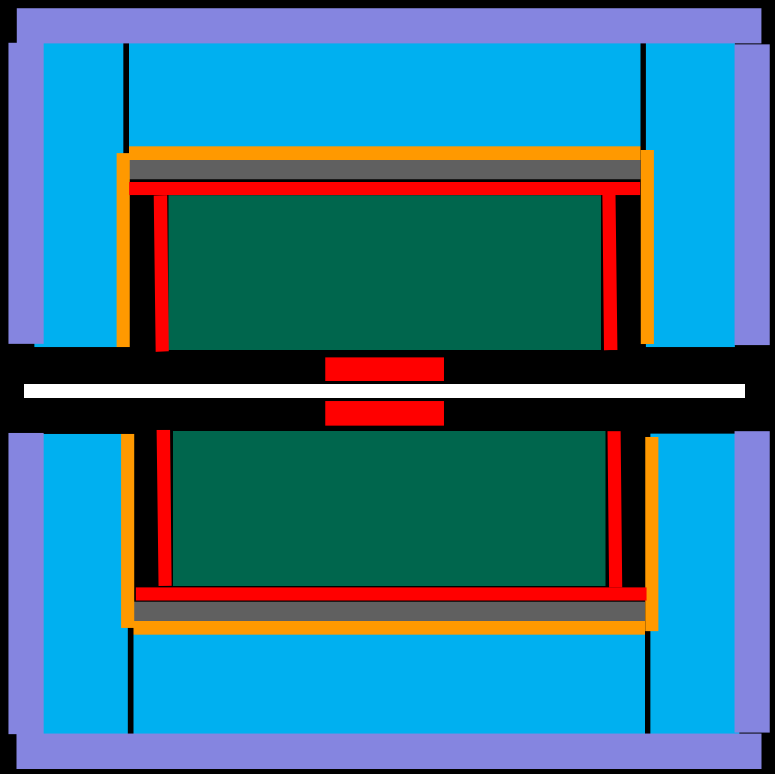
- Yoke + muon chamber



Conclusions

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  - Study Higgs x10 better than HL-LHC
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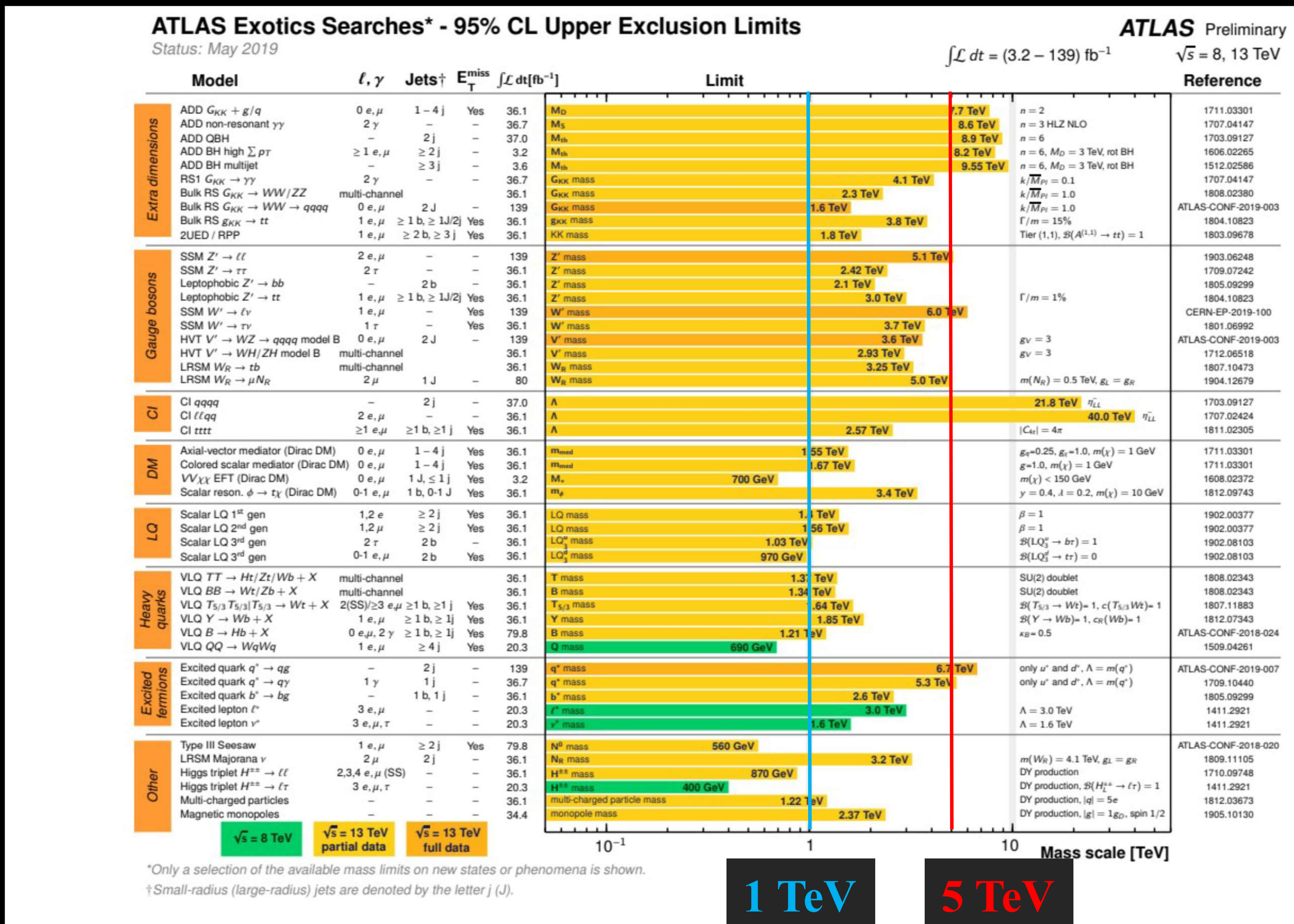
- The cost is significant but not outrageous for a future for our field – It's a 70 year program!

Conclusions

- **Let’s do it!**

ADDITIONAL SLIDES

LHC BSM exclusion



Linear Colliders *e+e-* Higgs Factories

- Advantages:
  - Based on mature technology (Normal Conducting RF, SRF)
  - Mature designs: ILC TDR, CLIC CDR and test facilities
  - Polarization (ILC: 80%-30% ; CLIC 80% - 0%)
  - Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
  - Well-organized international collaboration (LCC) → "we're ready"
  - Wall plug power ~130-170 MW (i.e. <= LHC)
- Pay attention to:
  - Cost more than LHC ~(1-1.5) LHC
  - LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
    - e.g. factor of 4 for ILC: x2 Nbunches and 5 Hz → 10 Hz
  - Limited LC experience (SLC), two-beam scheme (CLIC) is novel,
    - klystron option as backup
  - Wall plug power may grow >LHC for lumi / E upgrades

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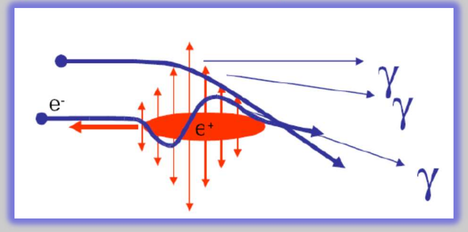
Challenges of Linear Colliders
Higgs Factories

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

- Luminosity spectrum (Physics)



  - $\delta E/E$ ~1.5% in ILC
  - Grows with E: 40% of CLIC lumi 1% off $\sqrt{s}$

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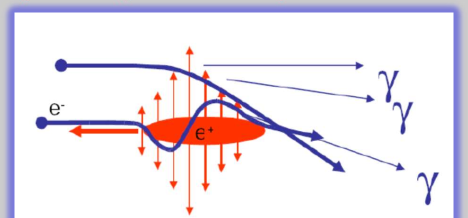

- $\delta E/E \sim 1.5\%$ in ILC
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❖ Beam Current (RF power limited, beam stability)

- Challenging $e+$ production (two schemes)
- CLIC high-current drive beam bunched at 12 GHz

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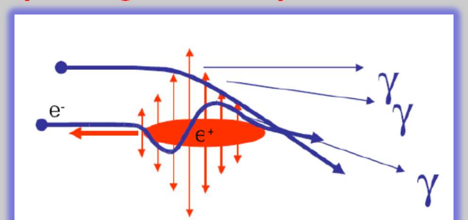

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❖ Beam Quality (Many systems)

- Record small DR emittances
- 0.1 μm BPMs
- IP beam sizes

ILC 8nm/500nm

CLIC 3nm/150nm

Limits of Linear e^+e^- Colliders

- Both ILC and CLIC offer staged approach to ultimate E

- The limits are set by:
  - Cost
    - ILC TDR 1 TeV 17 B$
    - CLIC CDR 3 TeV 18.3BCHF

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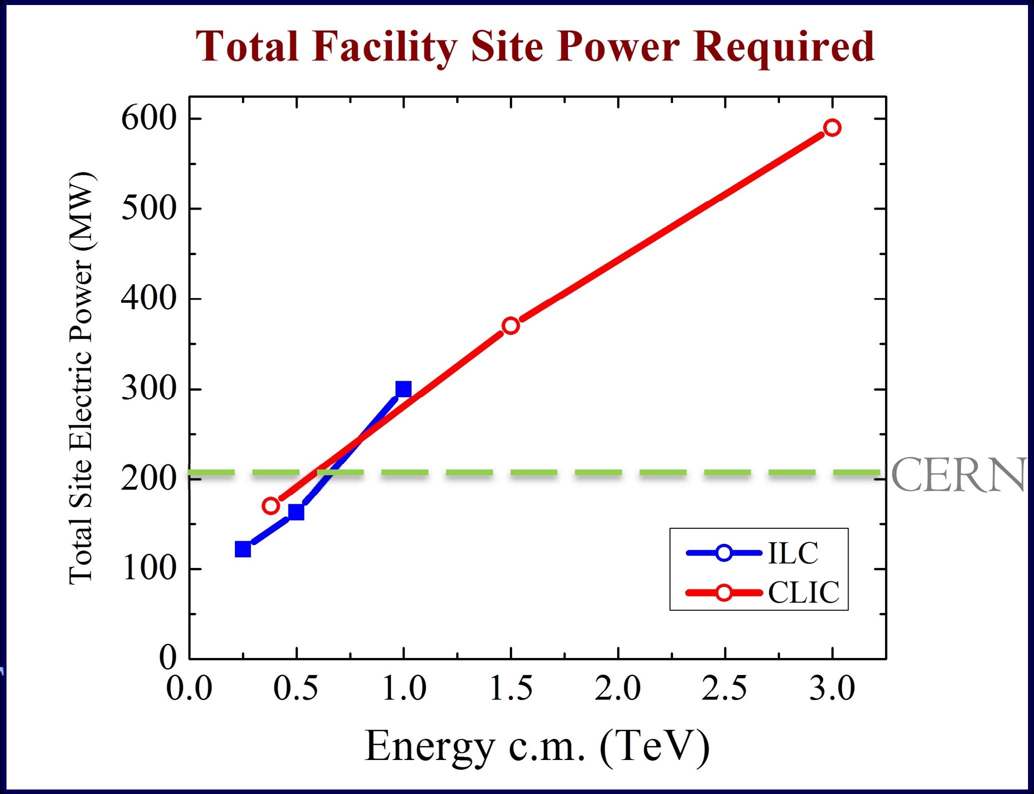

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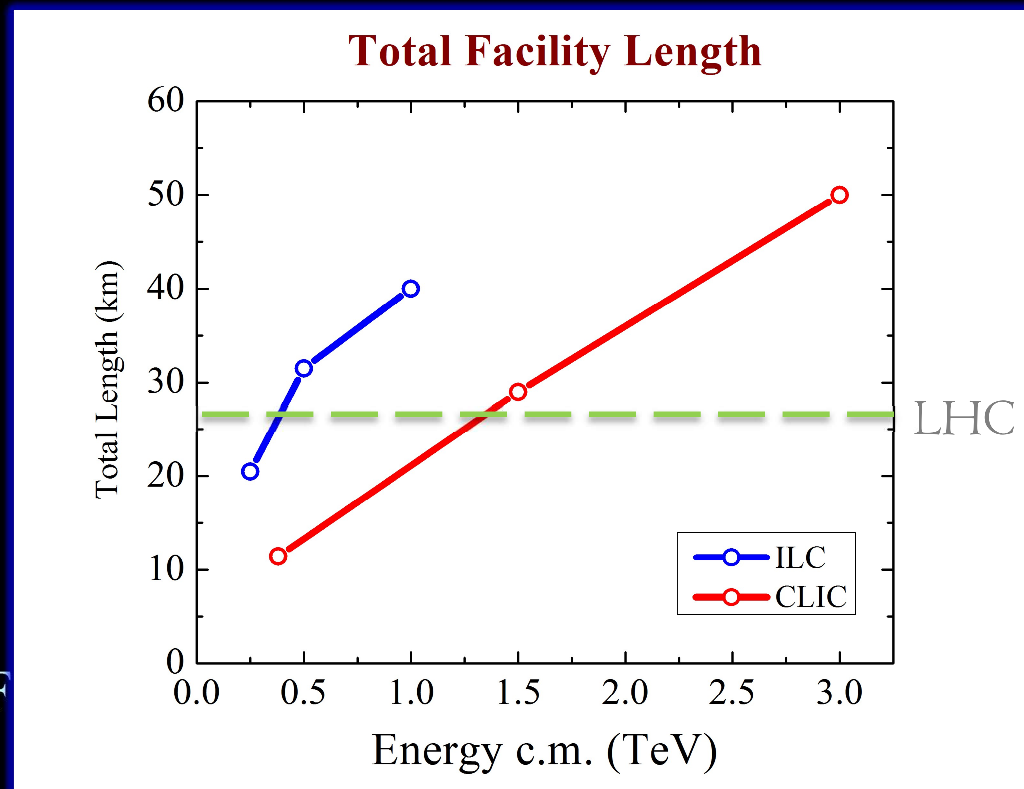

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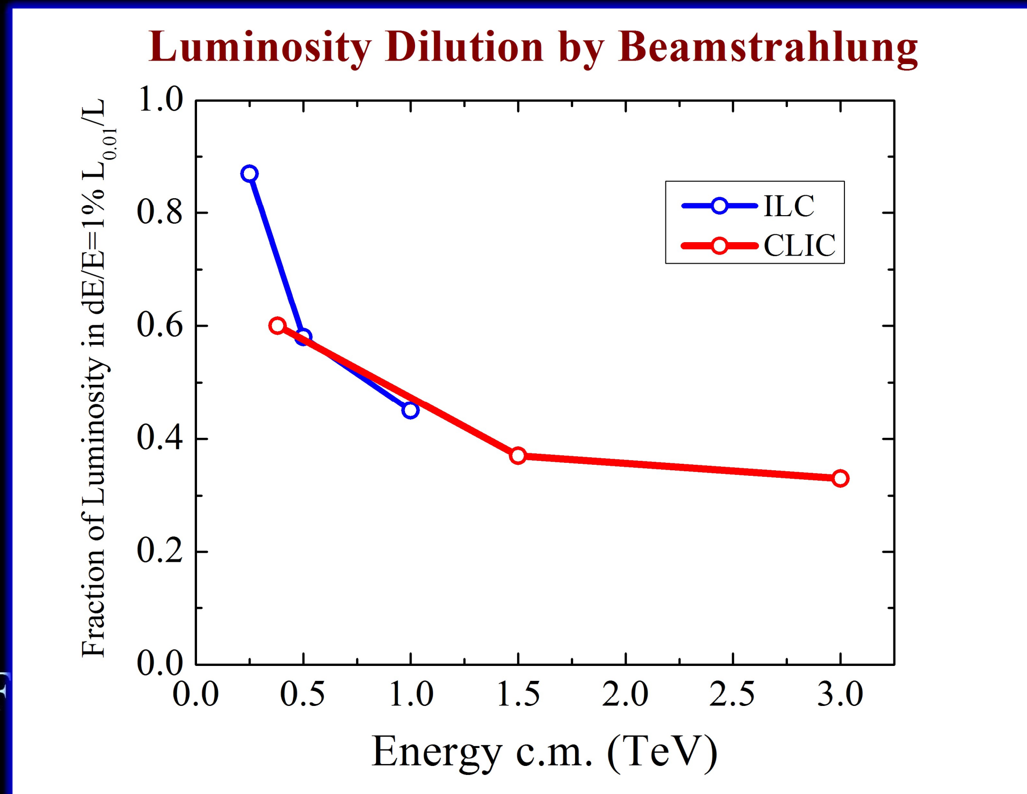

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  - (complication of) Beamstrahlung

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e^+e^- Ring Higgs Factories

INFN Istituto Nazionale di Fisica Nucleare

- Advantages:
  - Based on mature technology (SRF) and rich experience
    - → lower risk
  - High(er) luminosity and ratio luminosity/cost;
    - Up to 4 IPs, EW factories
  - 100 km tunnel can be reused for a pp collider in the future
  - Transverse polarization ($\tau\sim$ 18 min at tt) for E calibration O(100keV)
  - CDRs addressed key design points, mb ready for ca 2039 start
  - Very strong and broad Global FCC Collaboration

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Challenges of e^+e^- Ring HF's

- Power limited regime
  - Synchrotron radiation power from both beams limited to 100 MW (P/η=total site power) → current I is set by power

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

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

- Luminosity
  - Determined by bend radius ρ, beam-beam parameter ξ_y, beta function at the IP β_y^* and power
  - Beam life ~18 min requires full energy booster ring

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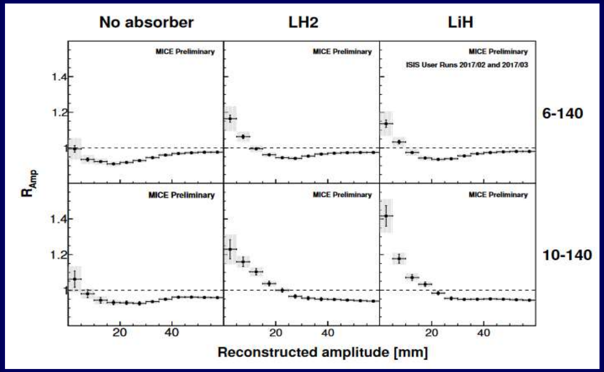
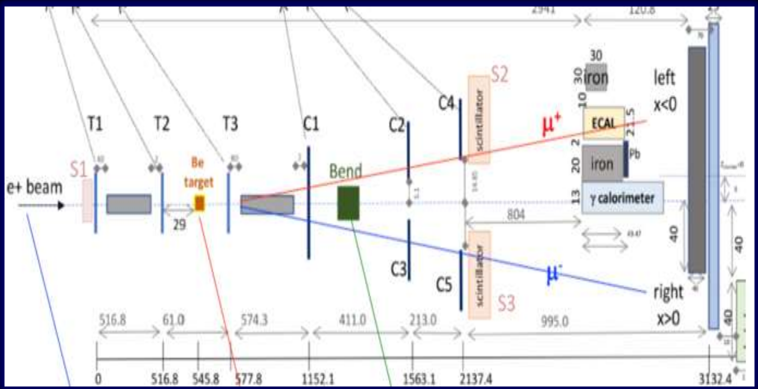
$\mu^+\mu^-$ Collider progress

- Ionization cooling of muons:
  - Demonstrated in MICE @ RAL
  - 4D emittance change O(10%)
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP Collaboration → Int'l
- Low emittance (no cool) concept
  - 45 GeV $e^+ + e^- \rightarrow \mu^+\mu^-$: CERN fixed target

arXiv:1810.13224





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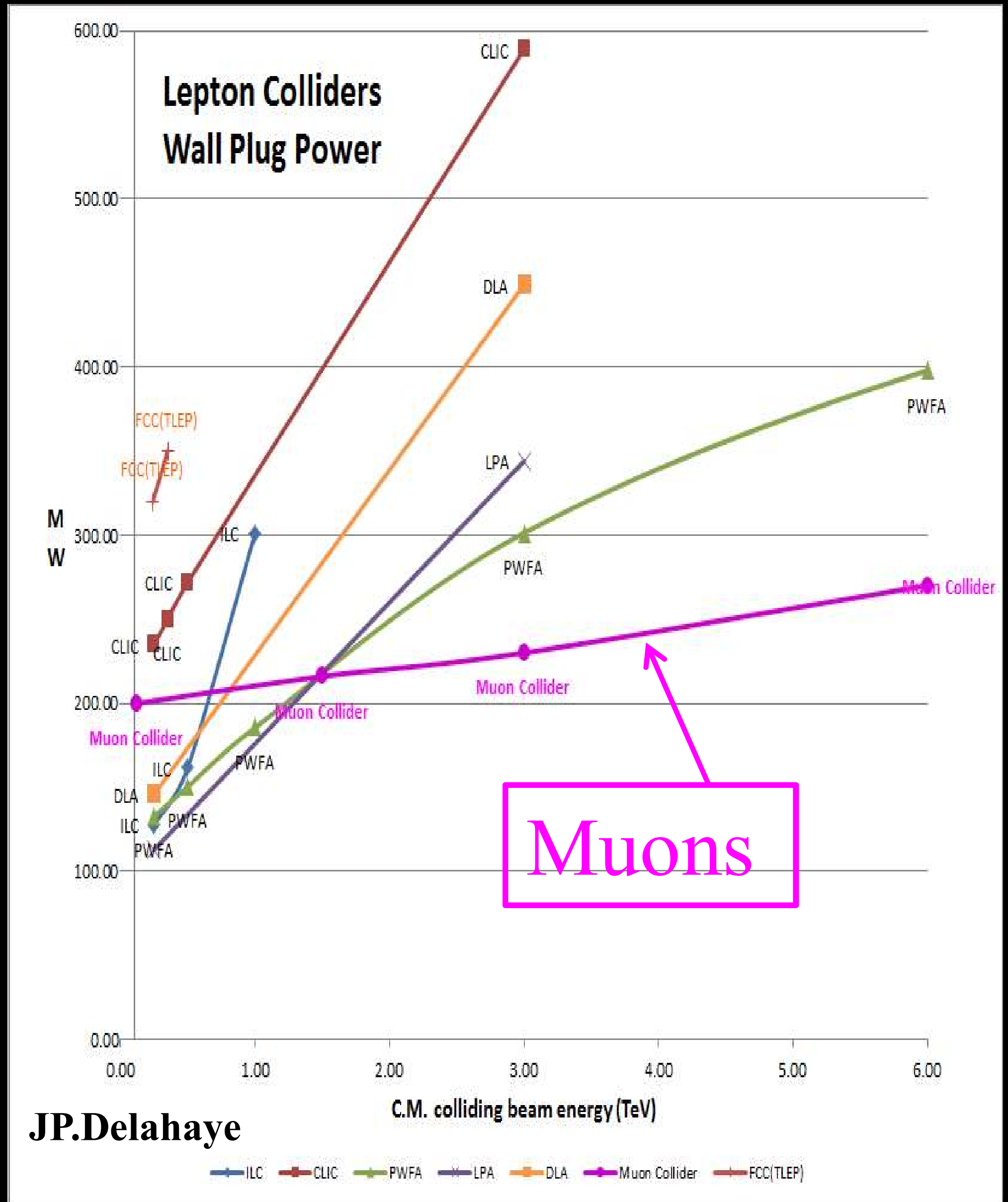
High Energy $\mu^+\mu^-$ Colliders

- Advantages:
  - μ's do not radiate / no beamstrahlung
    - acceleration in rings
    - low cost & great power efficiency



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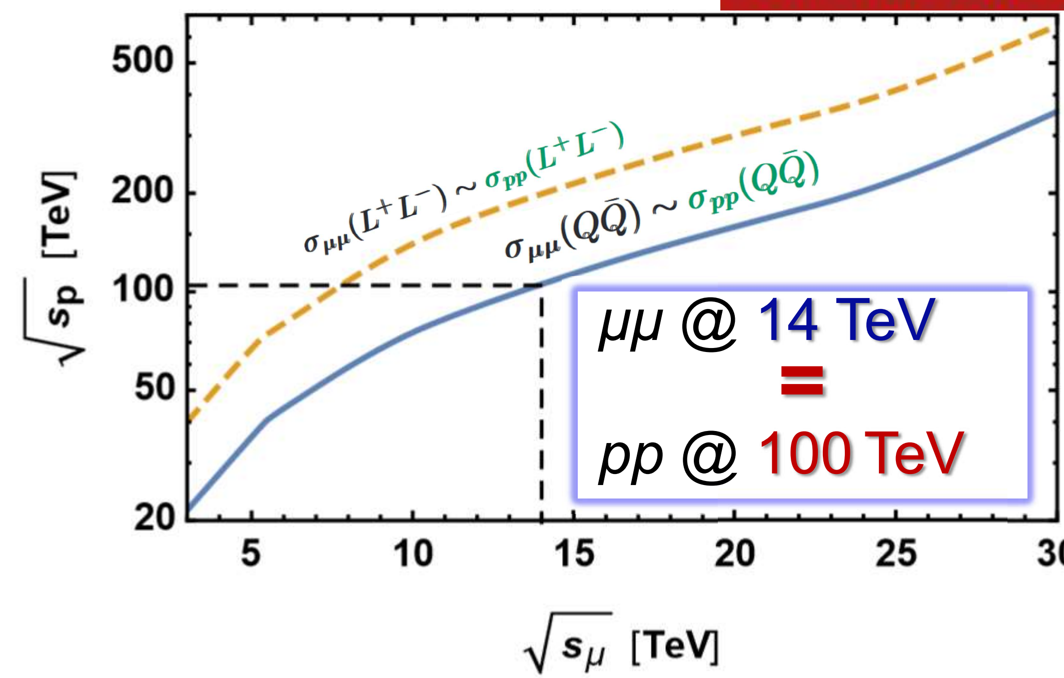
arXiv:1901.06150



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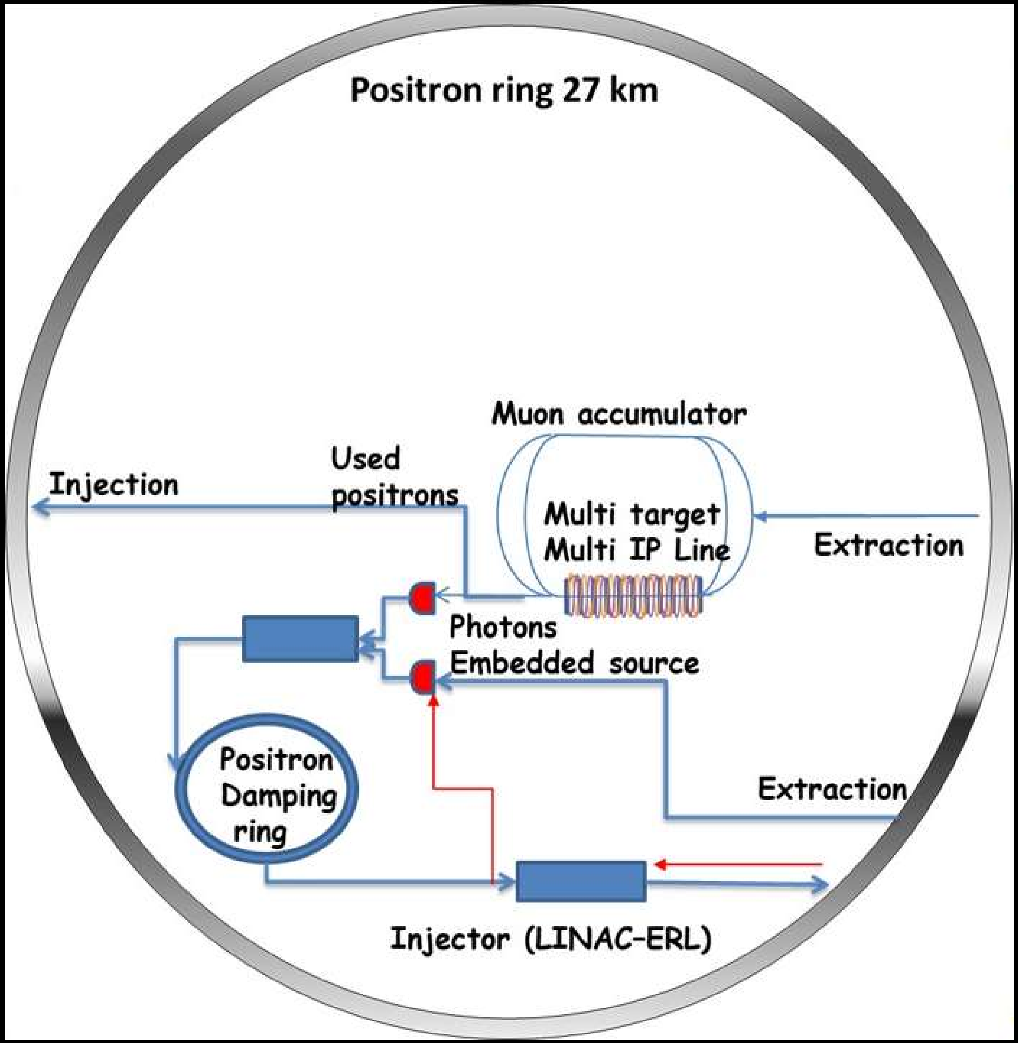
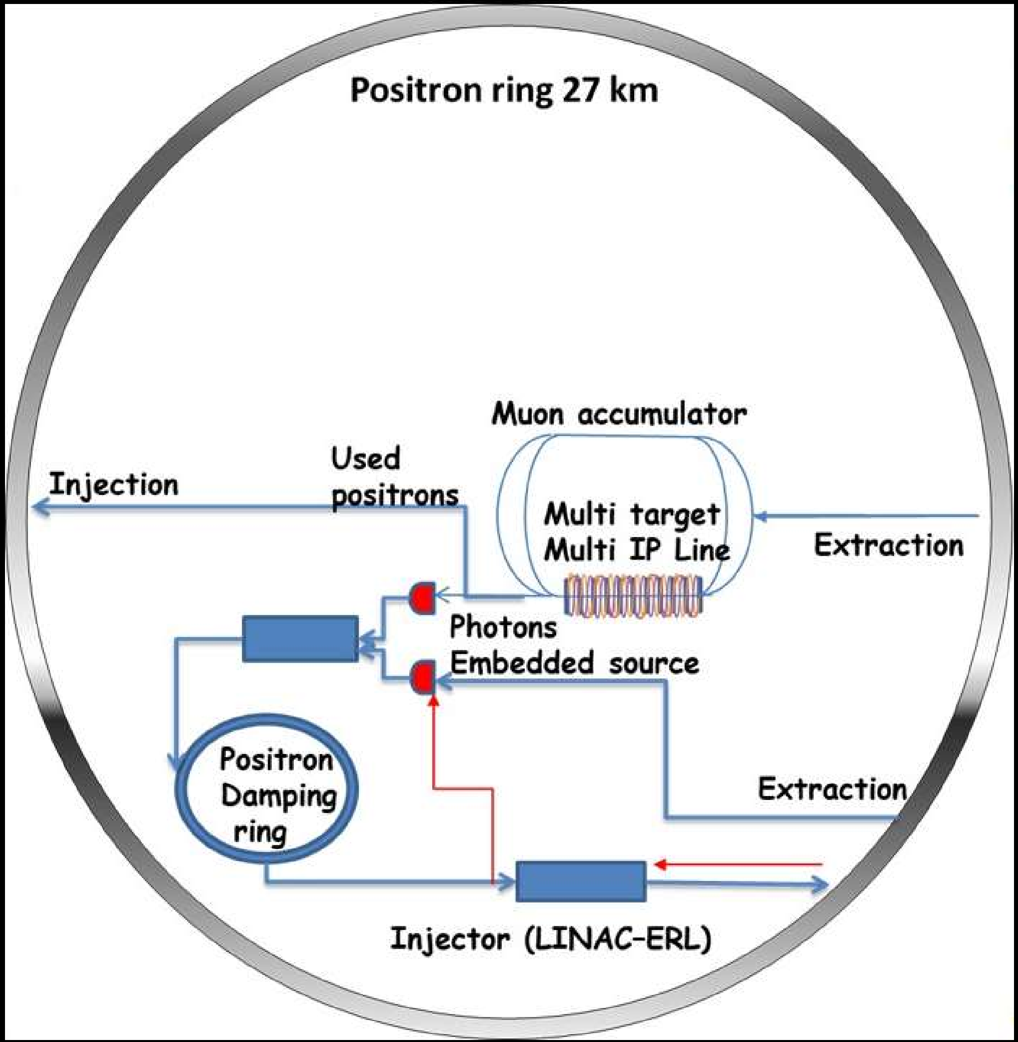
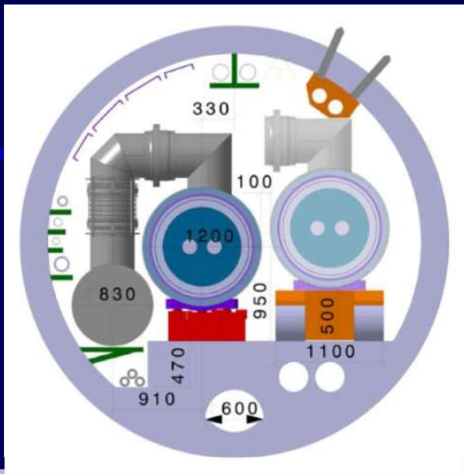


High Energy $\mu^+\mu^-$ Colliders

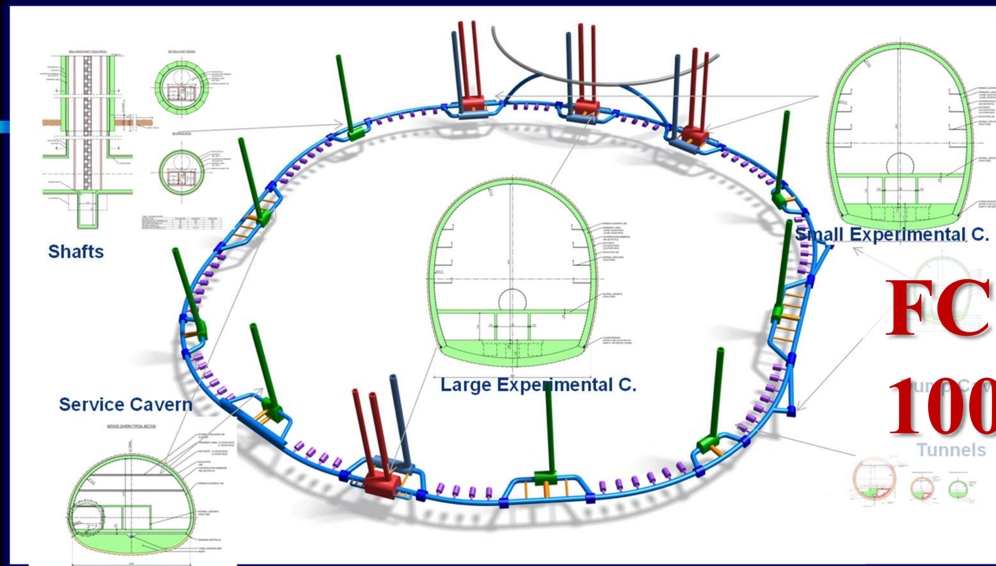
- Advantages:
  - μ's do not radiate / no beamstrahlung
    - acceleration in rings
    - low cost & great power efficiency
- ~ x7 energy reach vs pp
- New positron driven approach
- Key to success:
  - Test facility to demonstrate performance implications
    - muon production and 6D cooling,
    - study LEMMA e+-45 GeV + e- at rest
    - design study of acceleration, detector background and neutrino radiation



Circular *pp* Colliders



HE-LHC 27 TeV



FCC-hh
100 TeV

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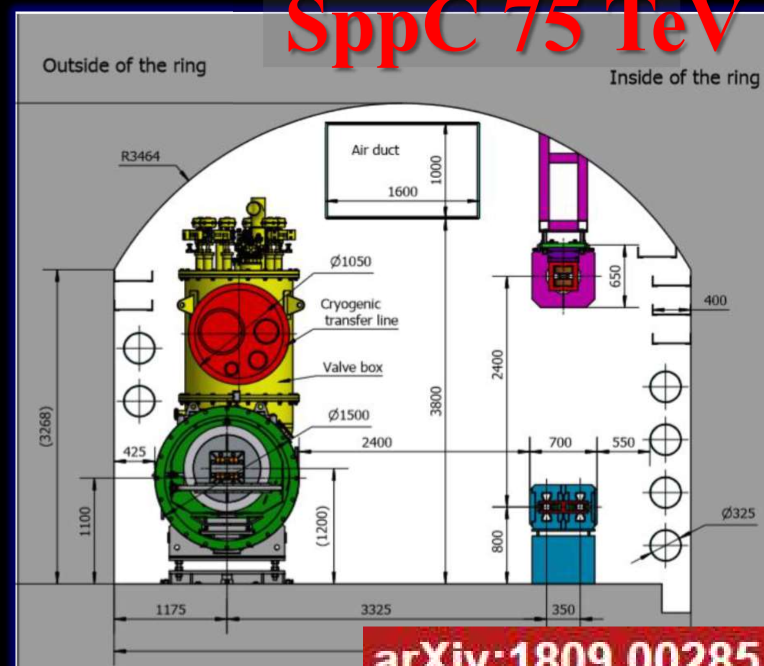
- ❖ Key facts: HE-LHC / FCC-hh* / SppC*
  - * follow up after e+e- Higgs factories
- ➢ Large tunnel – 27 / 100 / 100 km
- ➢ SC magnets – 16 / 16 / 12 T
- ➢ High Lumi / pileup O(1035) / O(500)
- ➢ Site power (MW) – 200 / 500? / ?
- ➢ Cost (BCHF) – 7.2 / 17.1 / ?
- ➢ Unexplored possibility:
  - FCC with conventional magnets

SppC 75 TeV



arXiv:1809.00285

HE-LHC timeline

Timeline dominated by magnet R&D/Production

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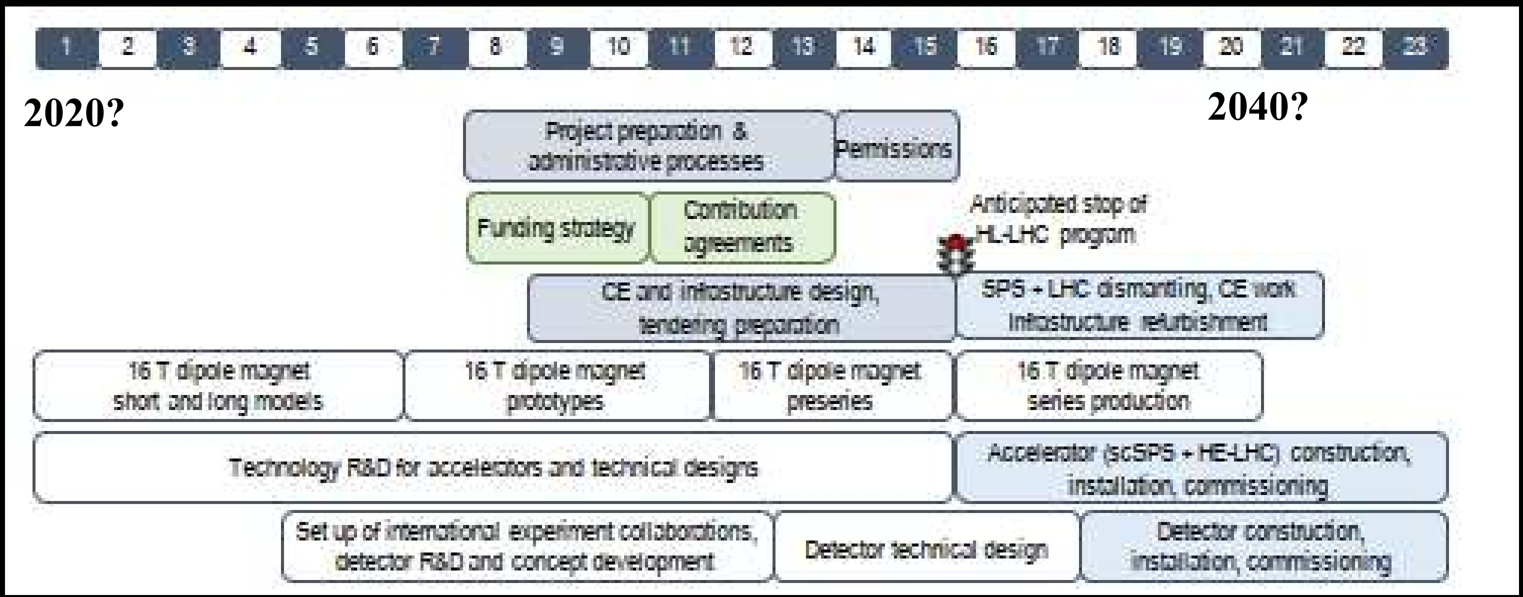

Domain	Cost [MCHF]
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil engineering	300
Total cost	7,200

2900 Magnets; 260 for LHC disposal

1 TeV beam from SPS

What if just 12 T magnets

Somewhat faster - Similar cost – 21 TeV

	2020					2025					2030					2035					2040	
Design & Parameters Opt.																						
Superconductor Nb_3Sn	Develop. & pilots			Prototypes		Conntruction																
Magnet Eng & Proto			Models			Prototypes																
Industrialization					1st generation			2nd gener.cost opt.														
Construction									Pre-series		Series...											
Installation & HW Comm.																						

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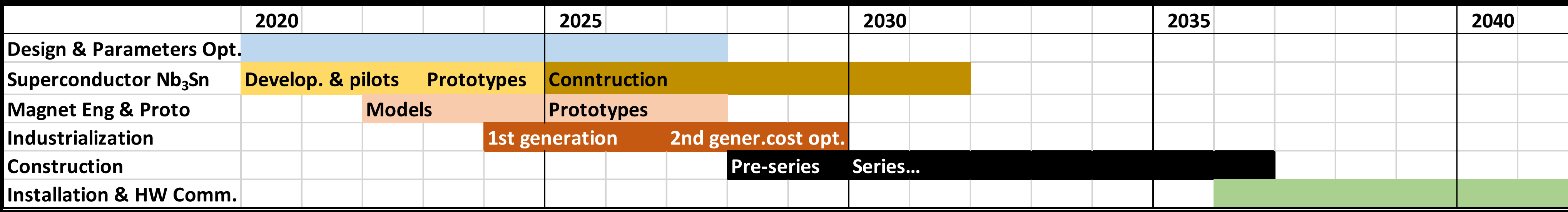
Somewhat faster - Similar cost – 21 TeV



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Cost scaled from 2019 HE-LHC study. If it is of real interest the study could be done

Domain	Cost MCHF	Comments	Wrt HE-LHC
Collider	4500	2400 for Magnets	-500
Injectors	500 ÷ 1100	New optimization TBD	0 ÷ -600
Tech Infr.+C.E.	900 ÷ 1100	Probably is less (< P_{syn})	? (-200?)
TOT	**6100 ÷ 6700**	(LHC2008 was 3400)	Cost should be optimized as upgrade

Other comparisons

- *F1* "Technology Readiness" :

Green	- TDR
Yellow	- CDR
Red	- R&D

- *F2* "Energy Efficiency"

Green	: 100-200 MW
Yellow	: 200-400 MW
Red	: > 400 MW

- *F3* "Cost" :

Green	: < LHC
Yellow	: 1-2 x LHC
Red	: > 2x LHC

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Other comparisons

Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*

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Other comparisons

Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*
Highest Energy			
ee Linear *1-3TeV*			
pp Rings *HE-LHC*			
FCC-hh/SppC			
μμ Coll. *3-14 TeV*			*

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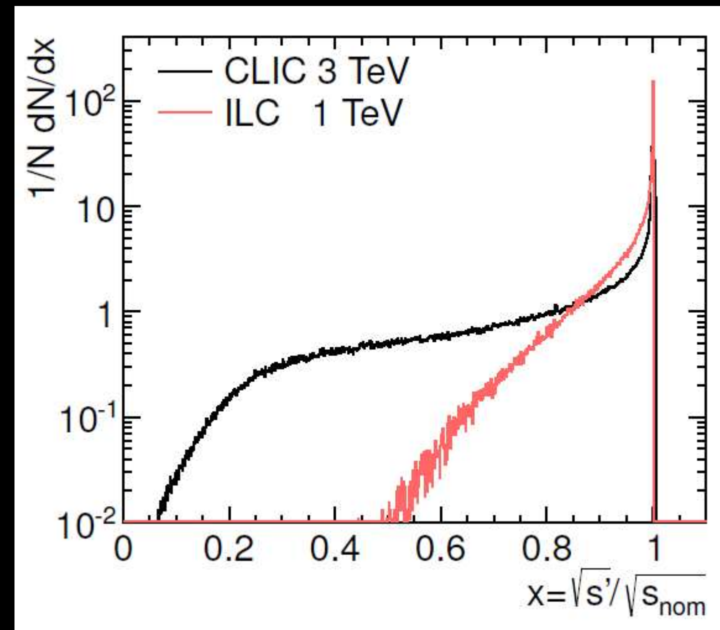
Beamstrahlung

- $\delta_{BS} \quad \left(\frac{E_{CM}}{\sigma_z}\right)\frac{N^2}{\sigma_x{}^2}$

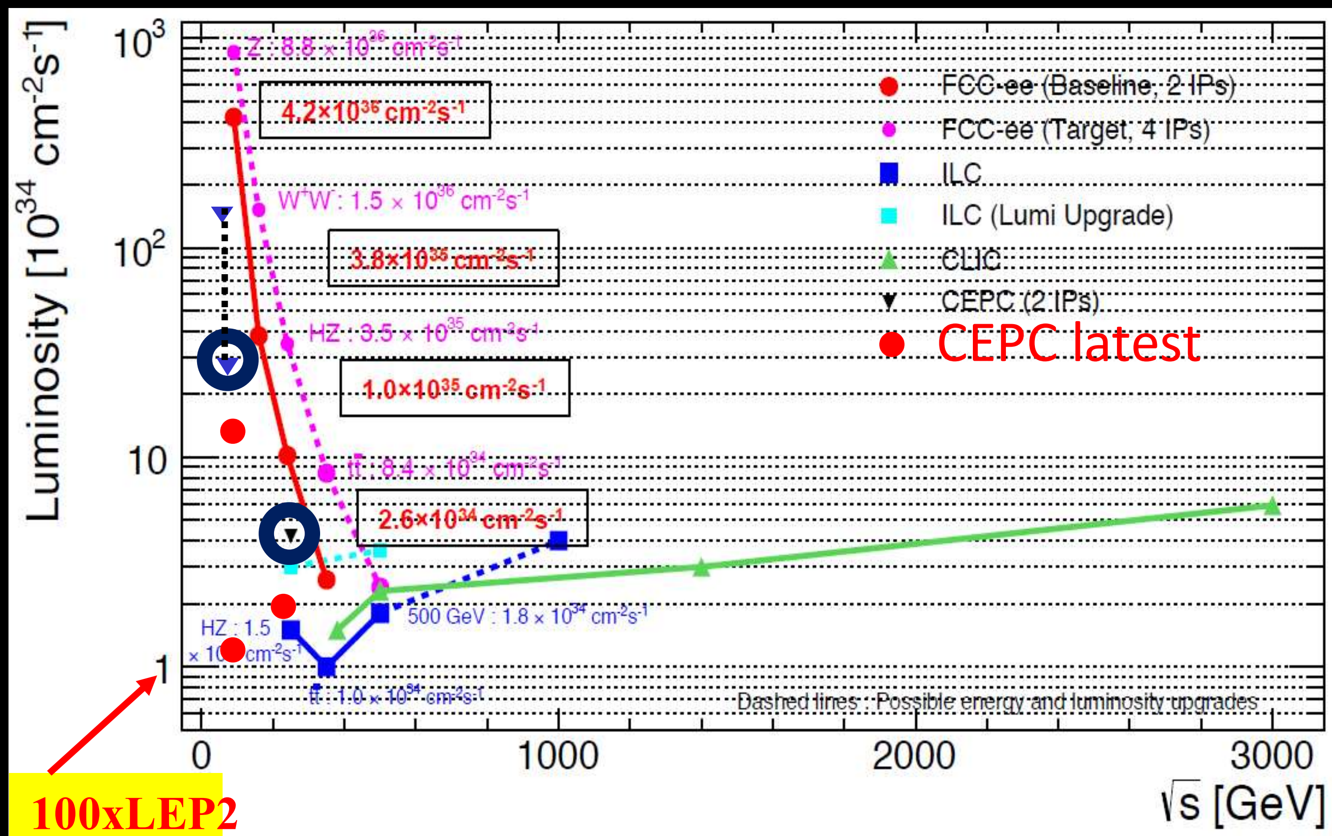
	Unit	ILC		CLIC
$\sqrt{s}$	GeV	500	1000	3000
$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	4.3	5.9
Υ_{av}		0.15	0.20	4.9
δ_B	%	3.7	10	28
n_γ		1.7	2.0	2.1



- ILC 240 ~ 1.6%

Luminosity issues

- Physics reach driven by luminosity
  - Success driven by luminosity!



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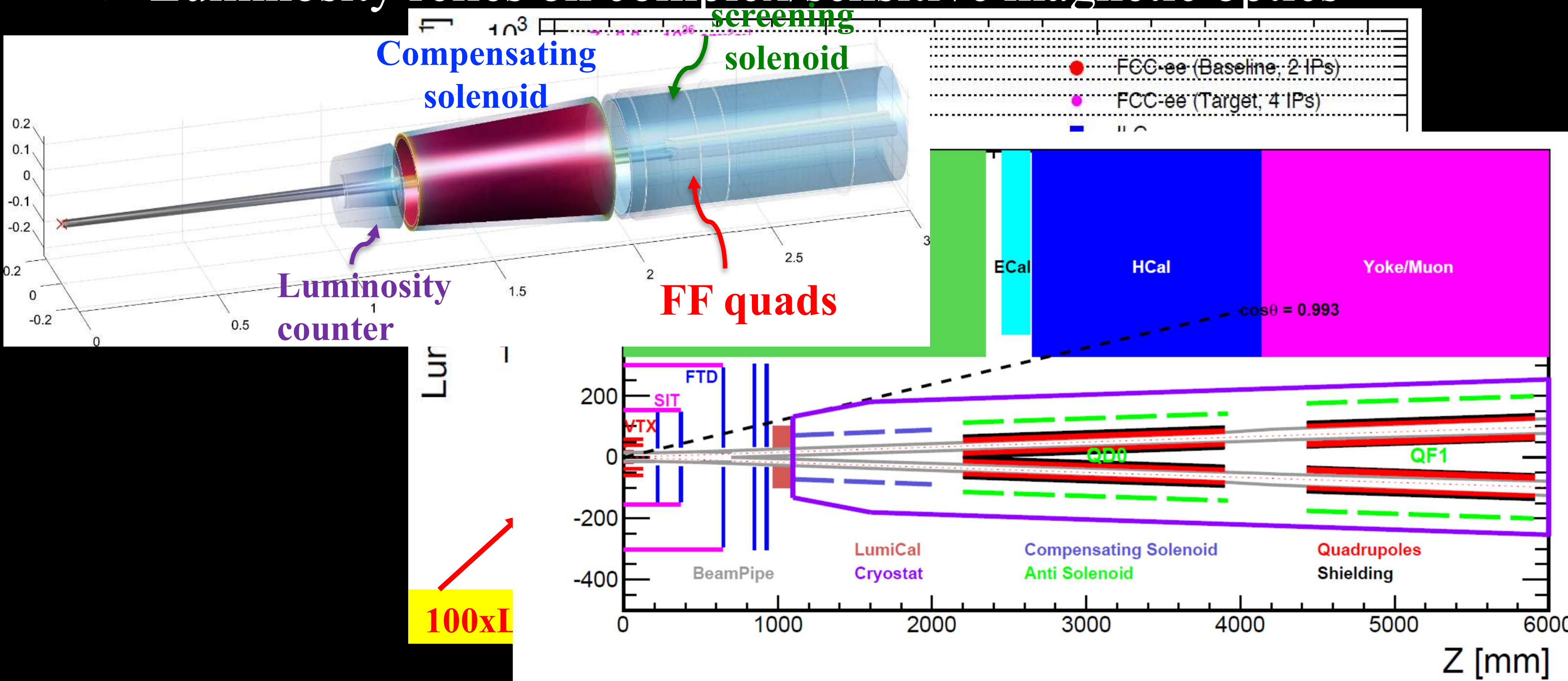

Luminosity issues

- Physics reach driven by luminosity
  - Success driven by luminosity!
  - Luminosity relies on complex/sensitive magnetic optics
  - Large detector solenoid fields affect luminosity