NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Experimental Overview of Future Colliders

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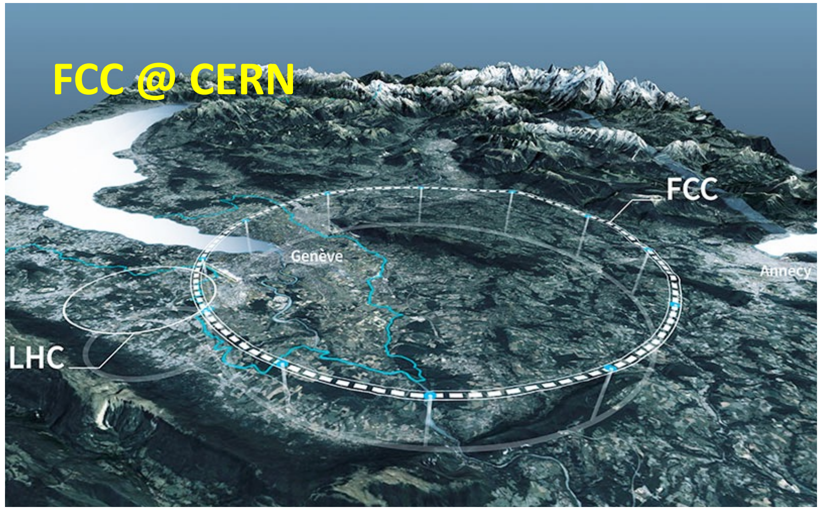
Niels Bohr Institute, Copenhagen

Young Nordic Future-Collider Day
Lund, 14 May, 2024

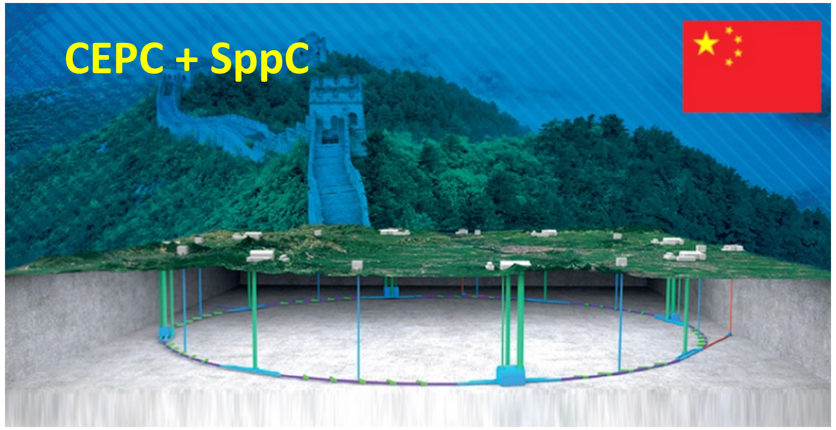
Gratefully acknowleging all colleagues and friends from whom material has been borrowed and not in all cases properly referenced

The Future Collider Market

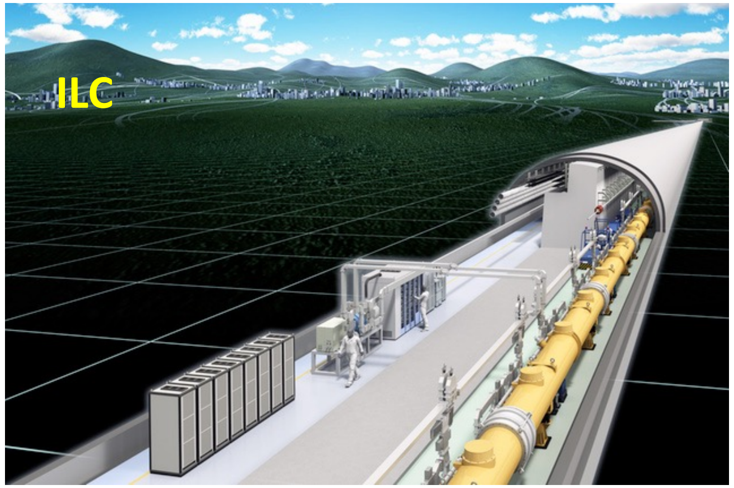
Circular e^+e^- followed by pp



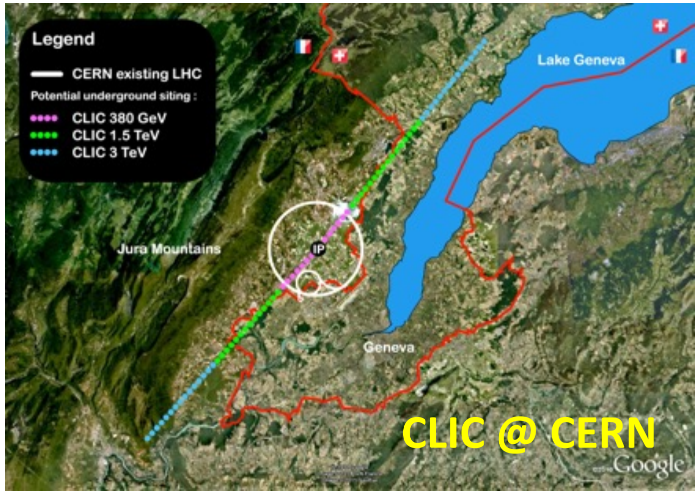
$e+e^-$: $\sqrt{s}$ = 90 - 365 GeV
pp : $\sqrt{s} \geq$ 100 TeV



Linear e^+e^-

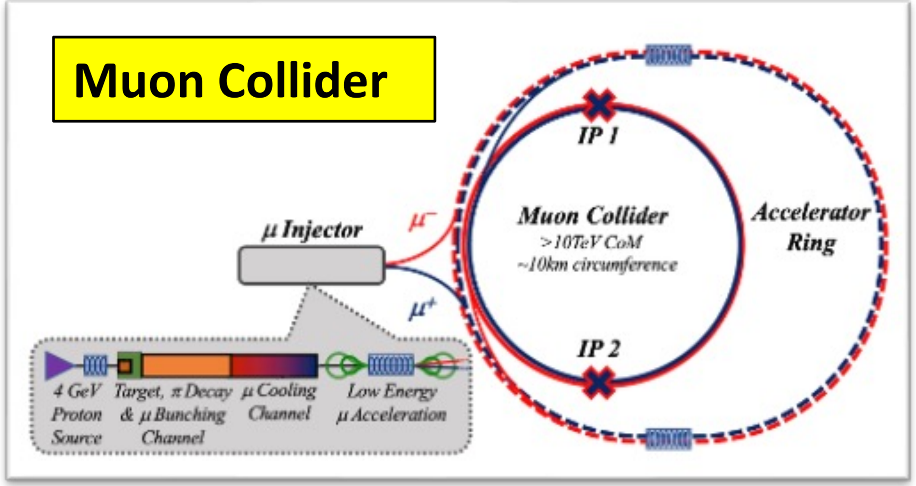


$\sqrt{s}$ = 250 GeV (→ 500/1000 GeV)



$\sqrt{s}$ = 380 GeV (→ 1000/3000 GeV)

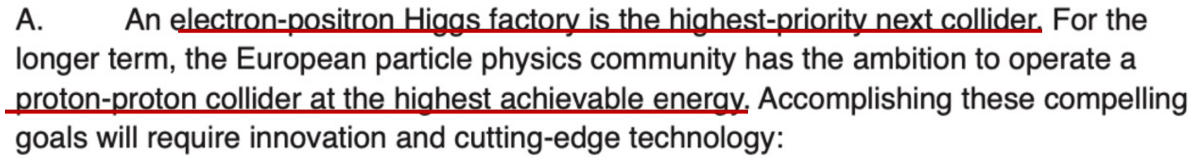
Muon Collider

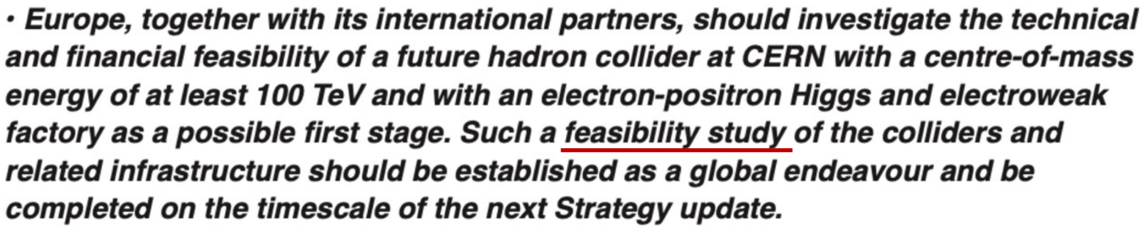


$\sqrt{s}$ = … 3 TeV, 10 TeV, …

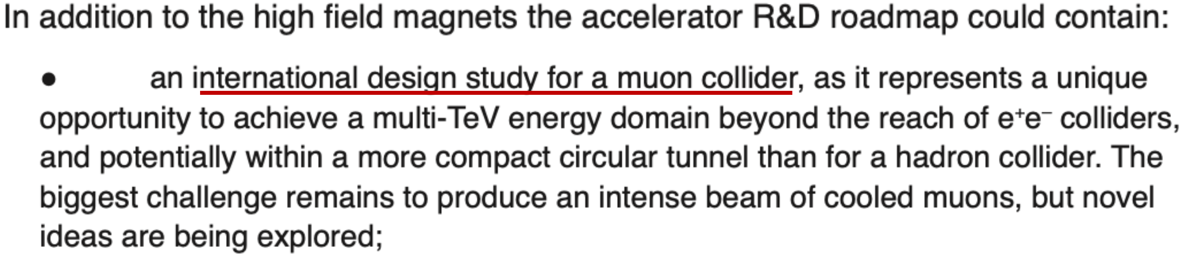
Collider Strategies

European Strategy 2020


A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:


- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

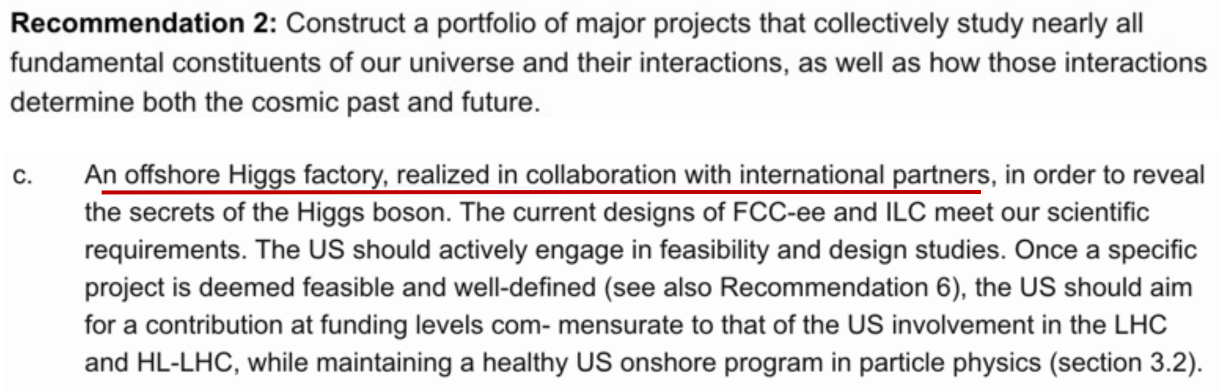
Adopted by CERN Council, June 2021.
FCC Feasibility Study initiated
- ongoing, input to 2025 Strategy update


In addition to the high field magnets the accelerator R&D roadmap could contain:

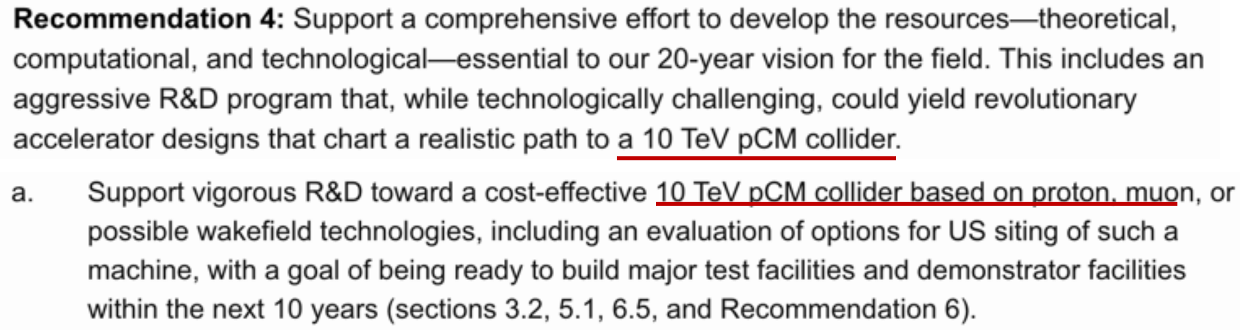
- an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e^+e^- colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

☞ International Muon Collider Collaboration

US P5, 2023


Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

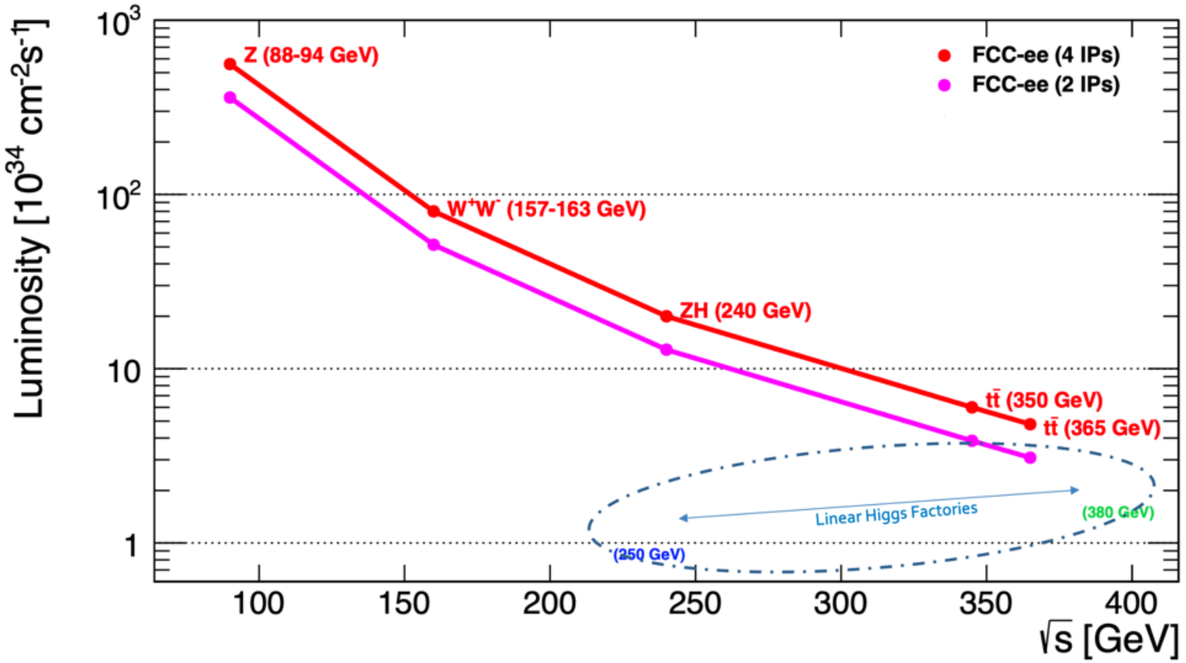
c. An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels com- mensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US onshore program in particle physics (section 3.2).


Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5, and Recommendation 6).

So, the (international) strategy is clear:
- First, an electron-positron collider for precision studies
- Then, a discovery machine, either proton or muon collider

e^+e^- Higgs Factory – Linear or Circular ?



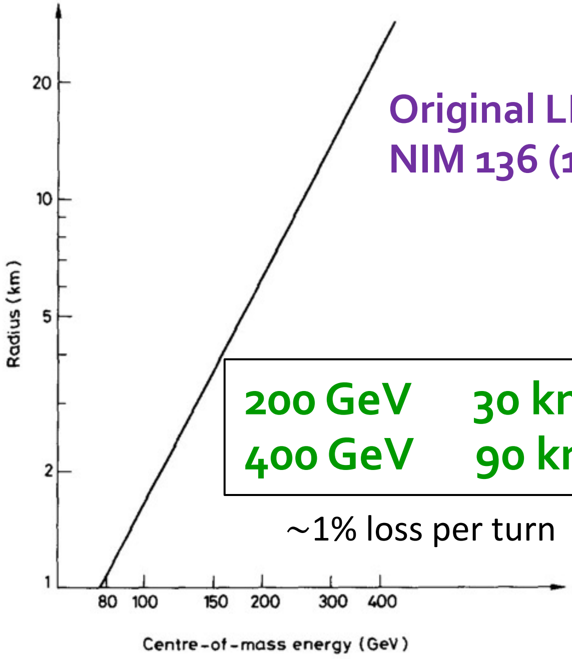
The main advantage of a **circular** e^+e^- Higgs Factory is the **enormous luminosity advantage** for centre-of-mass energies up to ~300 GeV

- Linear collider: Use e^- and e^+ bunches only once
- Circular collider: Reuse of bunches until they are “worn out” by physics (Bhabha scattering)

But due to synchrotron radiation

$$\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$$

a circular collider has to be large



Original LEP proposal, 1976
NIM 136 (1976) 47-60

200 GeV 30 km
400 GeV 90 km

~1% loss per turn

LEP: 27 km

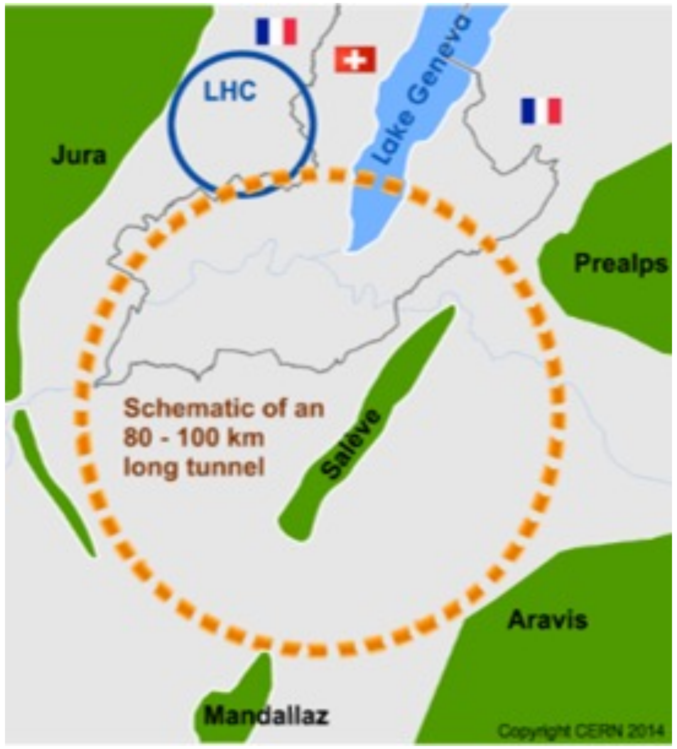
FCC-ee: 91 km

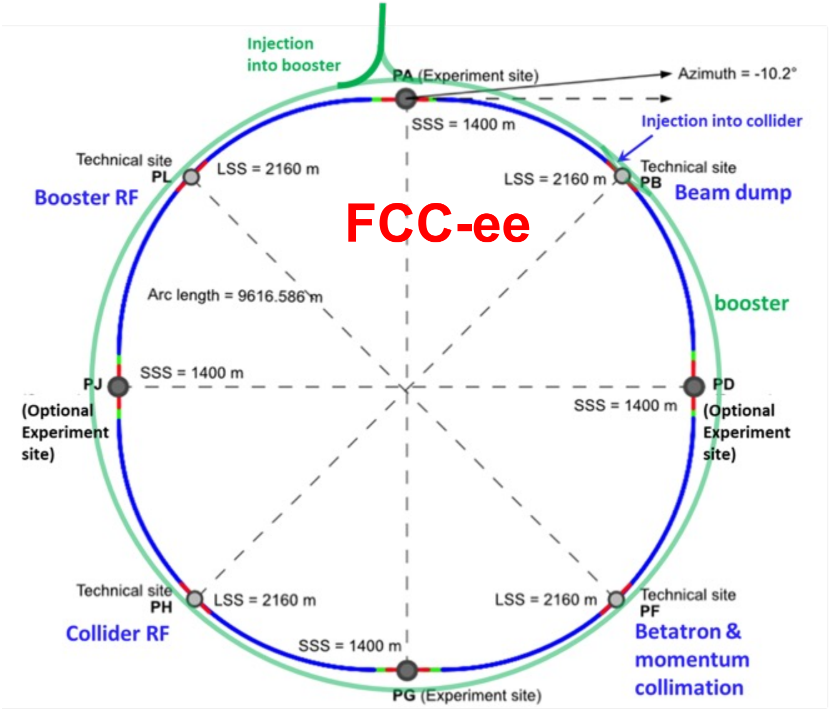
FCC integrated program

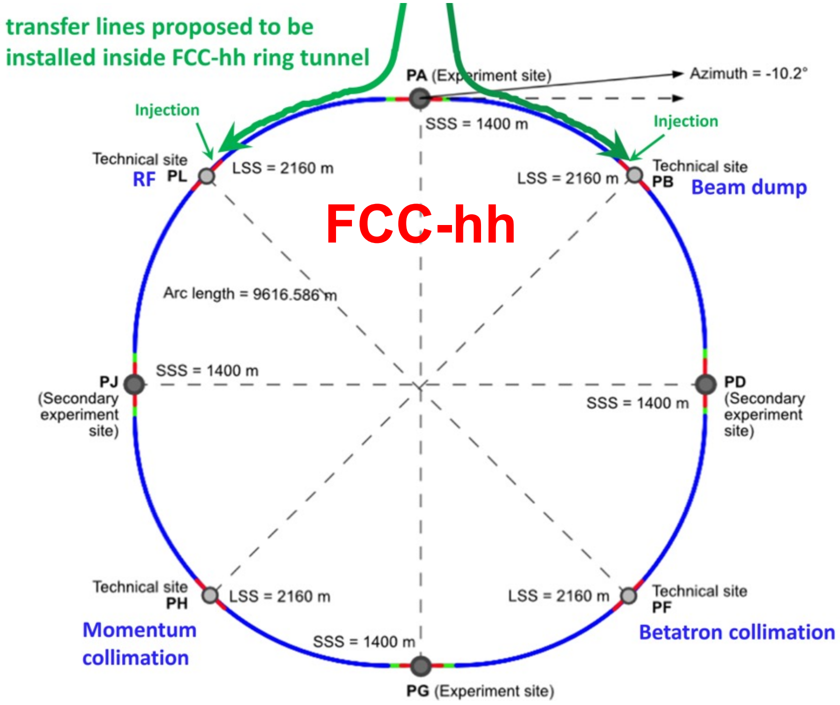
Michael Benedikt
2nd U.S. FCC Workshop
25/03/2024

comprehensive long-term program maximizing physics opportunities

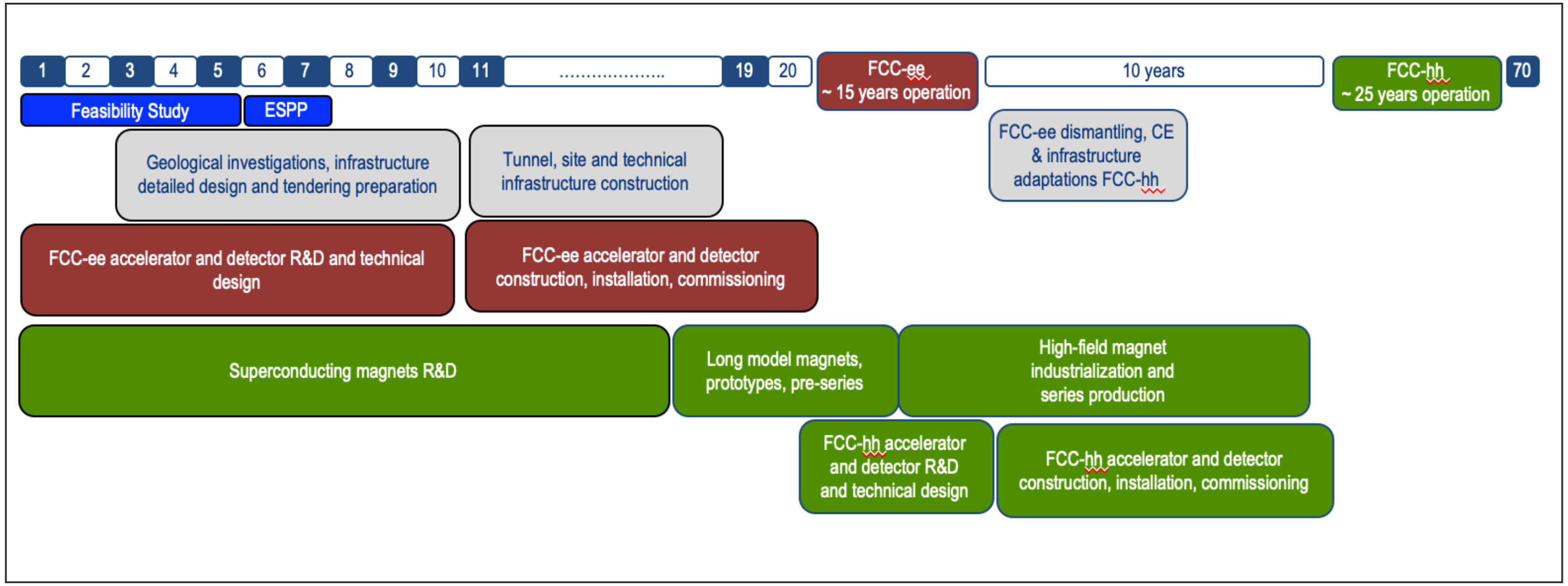
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







FCC integrated program - timeline



1 2 3 4 5 6 7 8 9 10 11 ………………… 19 20

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

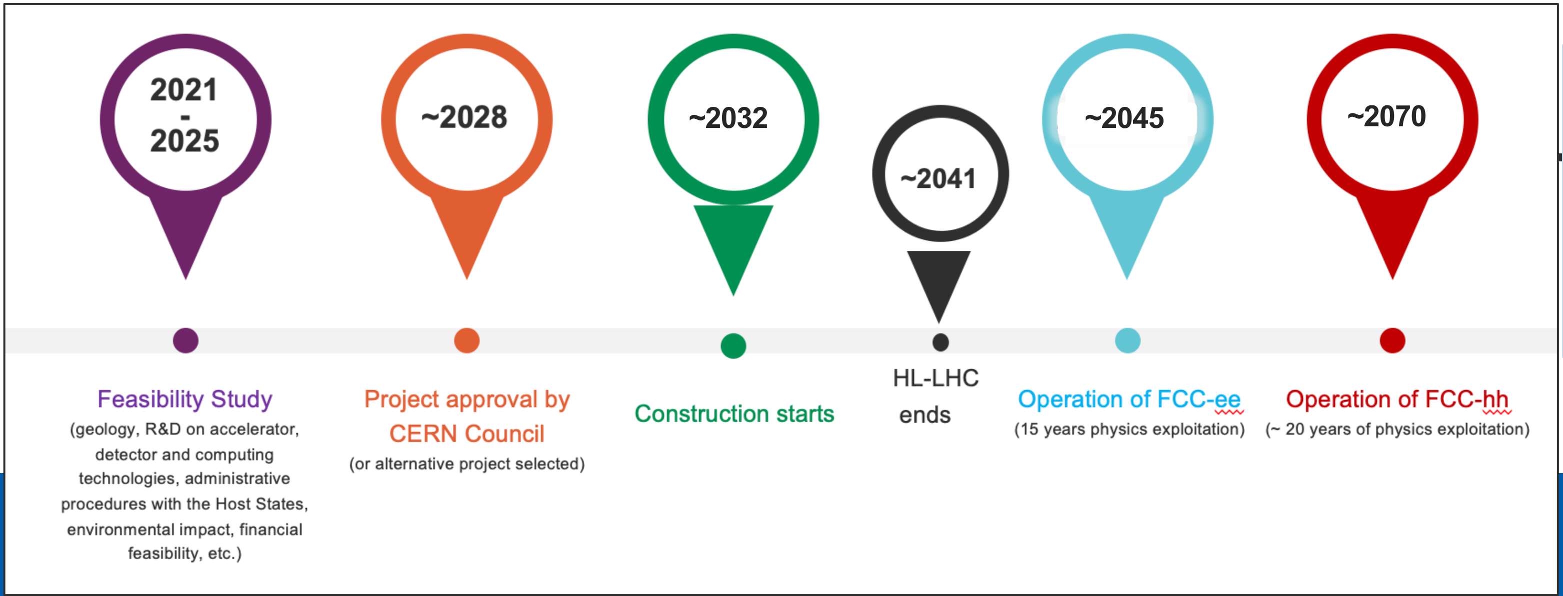
Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



2021 - 2025
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028
Project approval by CERN Council
(or alternative project selected)

~2032
Construction starts

~2041
HL-LHC ends

~2045
Operation of FCC-ee
(15 years physics exploitation)

~2070
Operation of FCC-hh
(~ 20 years of physics exploitation)

Ambitious schedule taking into account:

- ☐ past experience in building colliders at CERN
- ☐ approval timeline: ESPP, Council decision
- ☐ that HL-LHC will run until 2041
- ☐ **project preparatory phase with adequate resources immediately after Feasibility Study**

FCC-ee Basic Design Choices

Double ring e^+e^- collider, 90.7 km

Follows same footprint as FCC-hh,
except around IPs

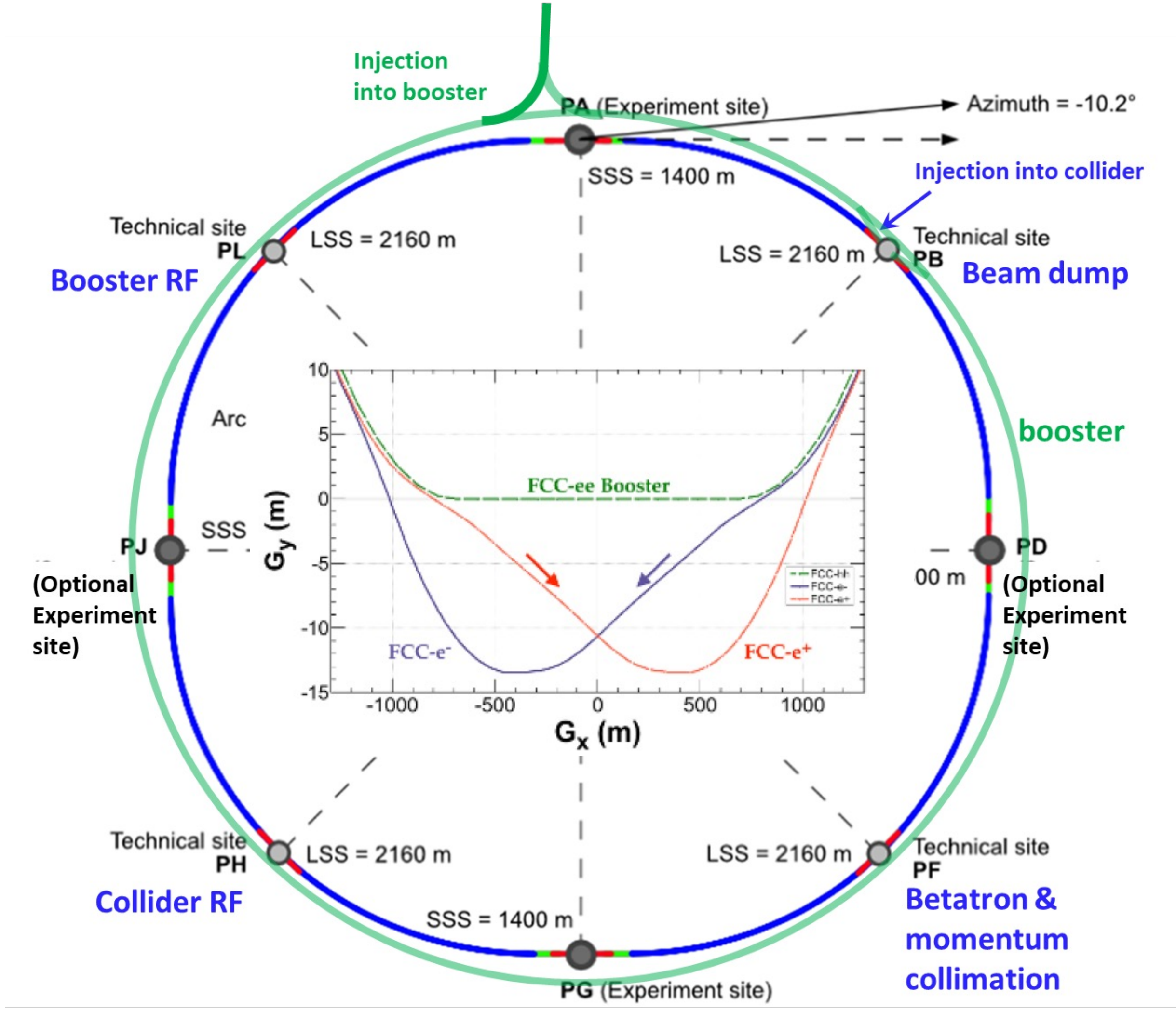
Asymmetric IR layout & optics
to limit synchrotron radiation
towards the detector

Fourfold super-periodicity
allows 4 interaction points (now default)

Large horizontal crossing angle **30 mrad,**
crab-waist optics

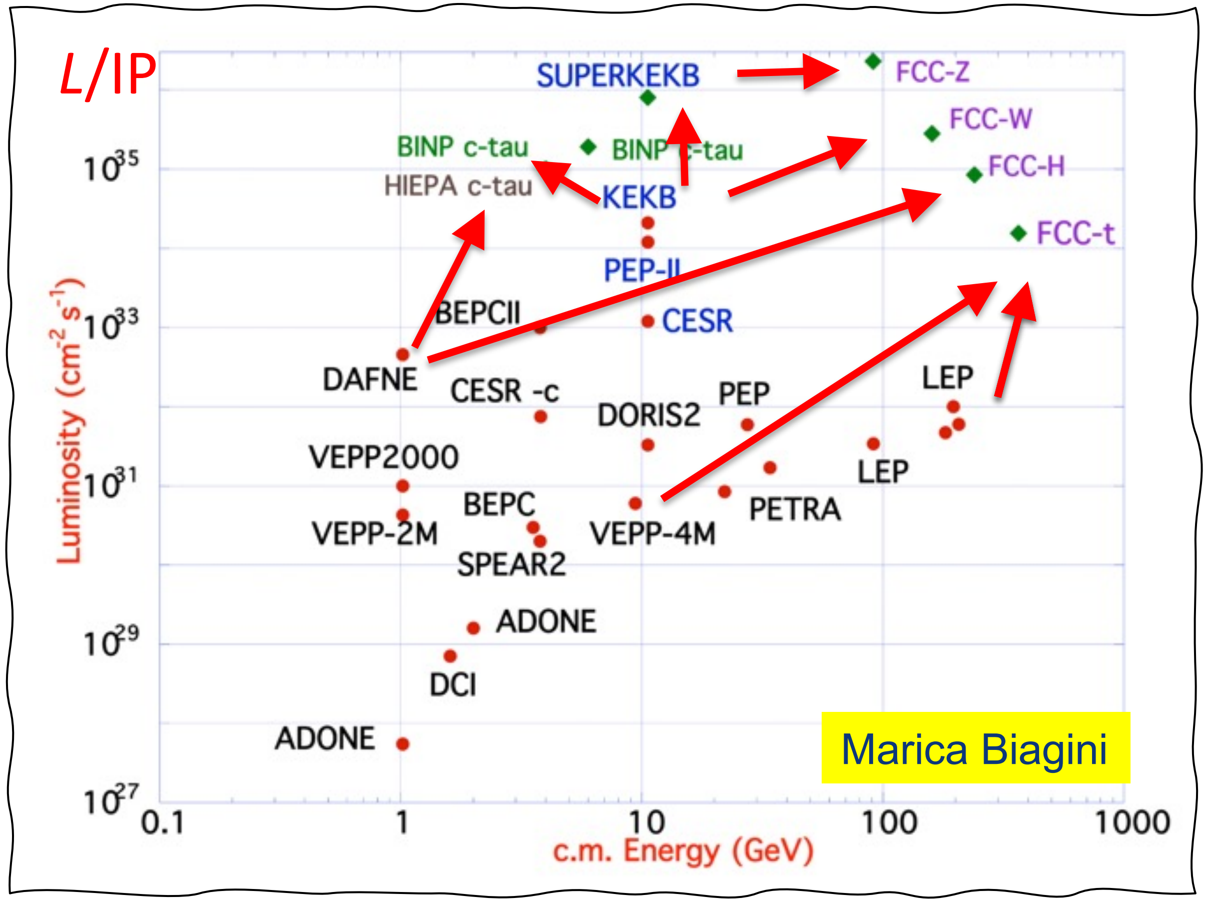
Synchrotron radiation power 50 MW/beam
at all beam energies

Top-up injection scheme;
requires **booster synchrotron in collider tunnel**



FCC-ee Performance

FCC-ee reaches highest luminosities & energies
by combining ingredients and well-proven concepts of several recent colliders:



B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

Super B-fact., **S-KEKB: low β_y***

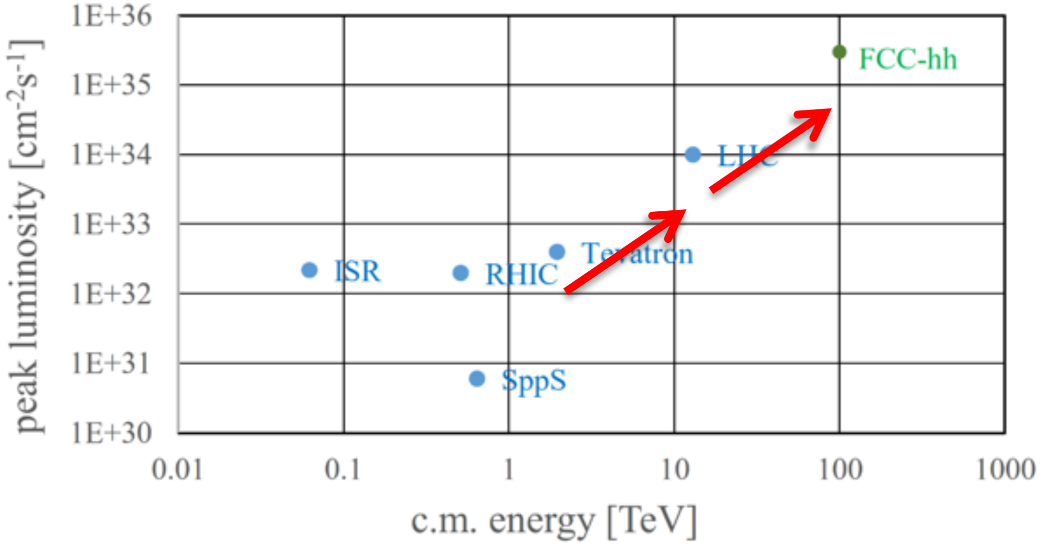
LEP high energy, SR effects

VEPP-4M, LEP:
precision E calibration

KEKB: *e^+* source

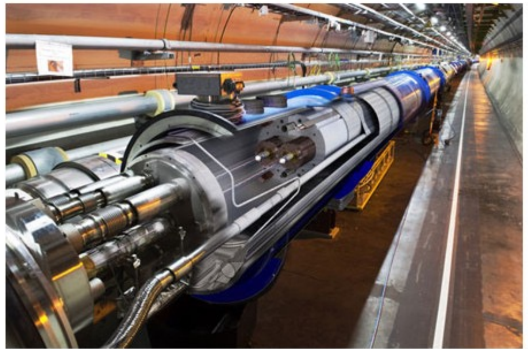
HERA, LEP, RHIC: spin gymnastics

FCC-hh Performance



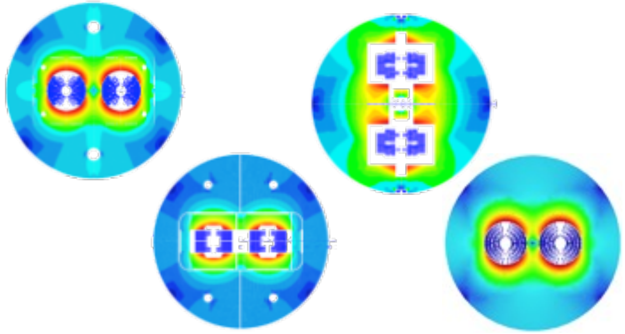
- Aim at **~one order of magnitude performance increase** in both **energy and luminosity w.r.t LHC**
- **100+ TeV CoM collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation time (vs 3 ab^{-1} for LHC).
- Similar performance increase as from Tevatron to LHC.
- **Key technology: High-field magnets**

From LHC technology
8.3 T NbTi



via HL-LHC technology
11 T Nb_3Sn

to 16-20 T Nb_3Sn
possibly combined with HTS.
EuroCirCol, Chart, US MDP



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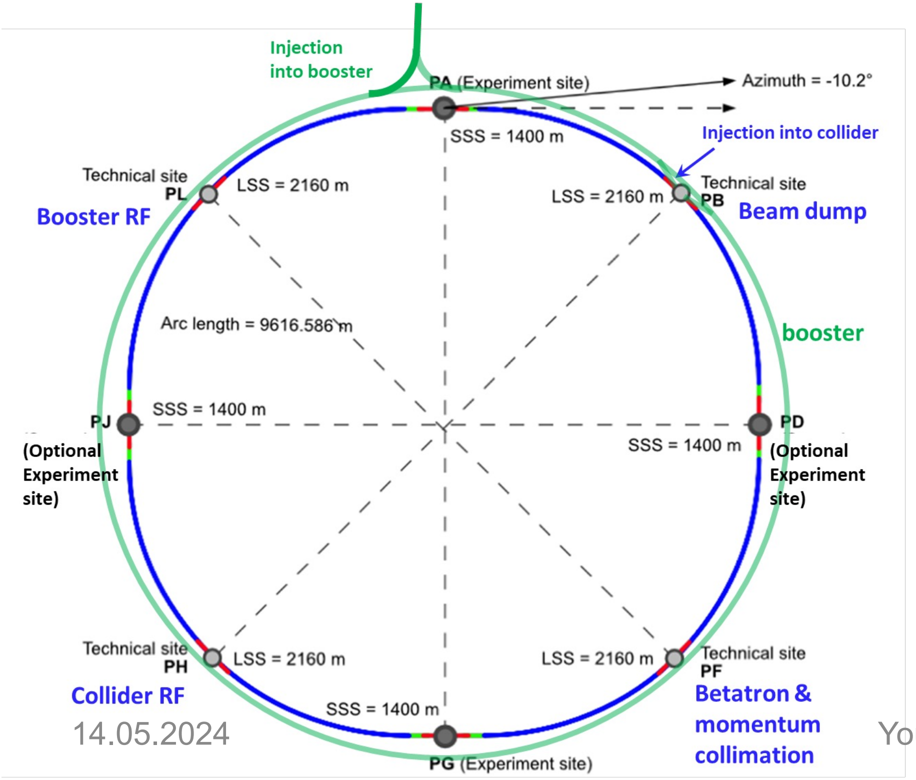
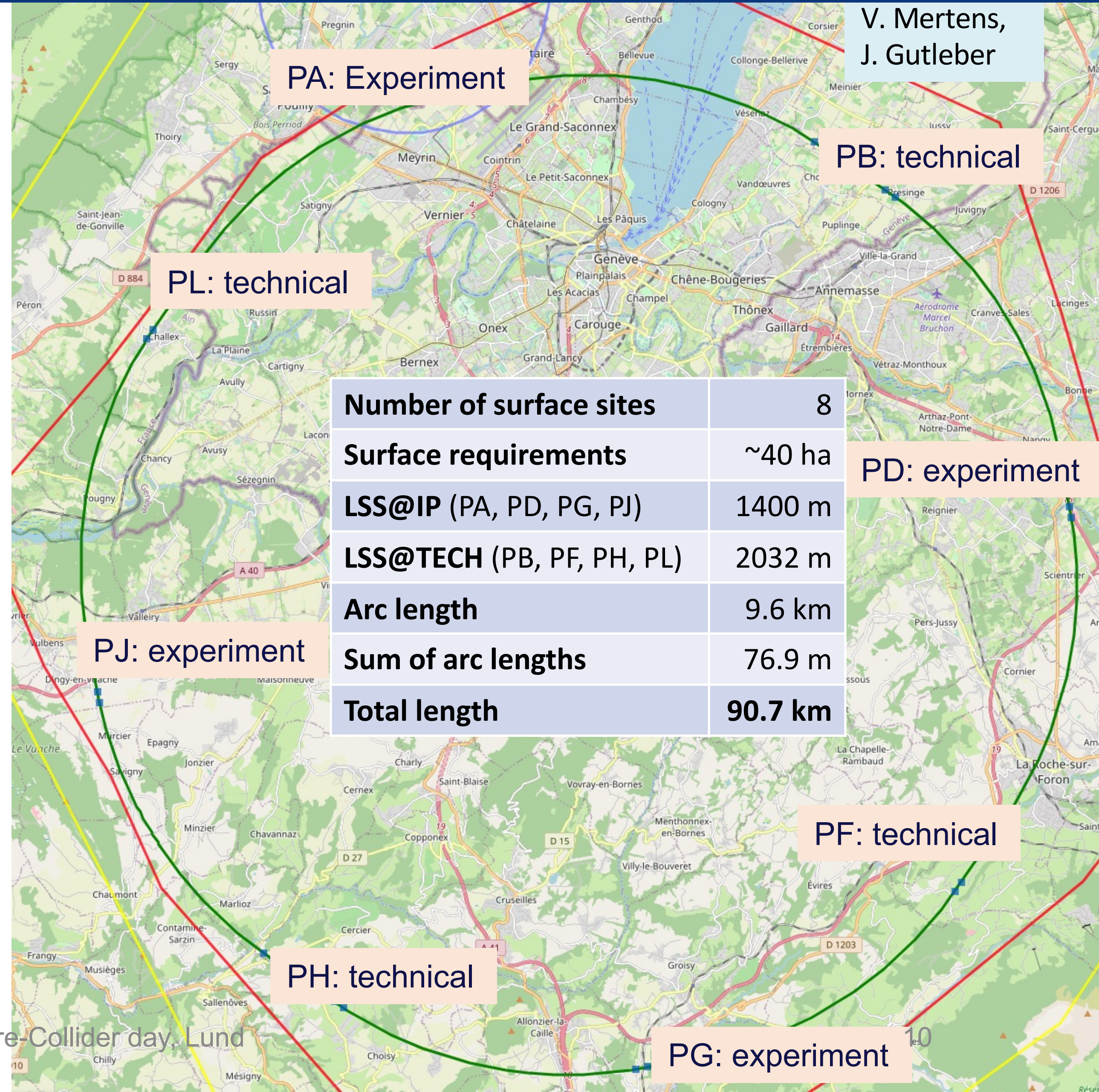
Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce-compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





V. Mertens, J. Gutleber

Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

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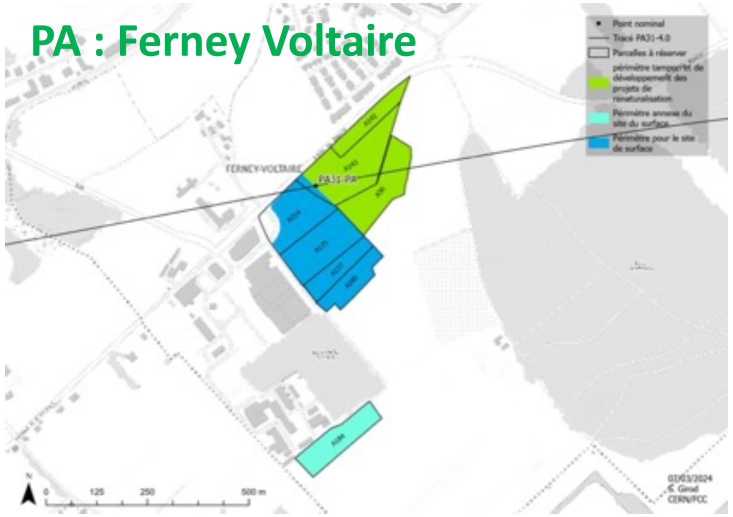
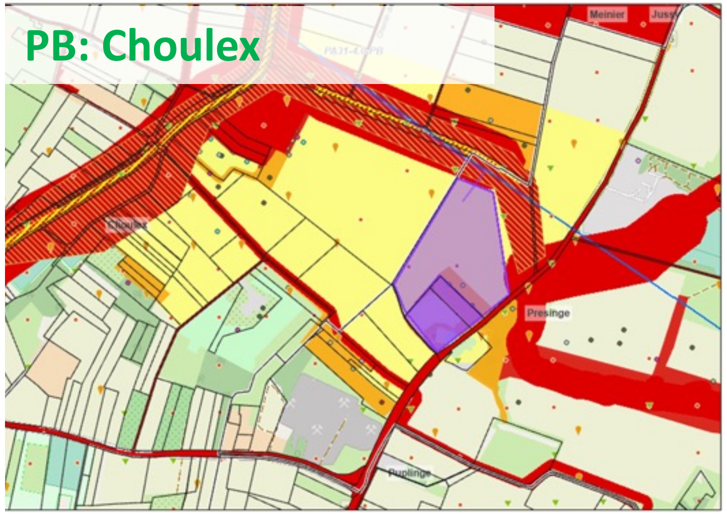
Surface sites development and reservation of land-plots

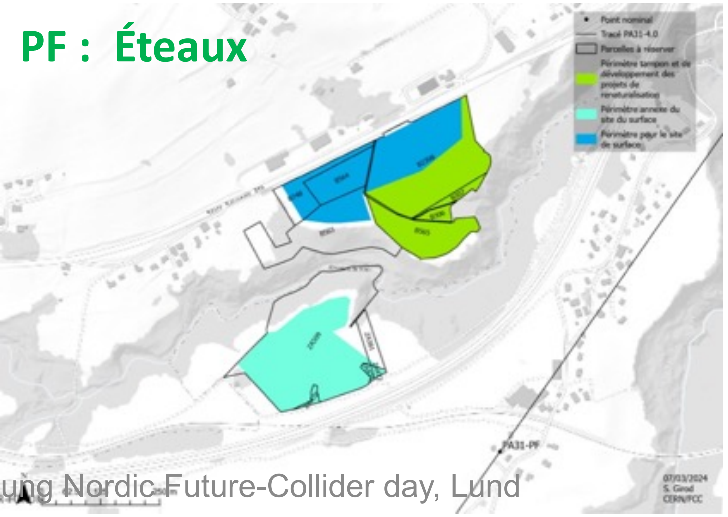
Meetings ongoing with all communes concerned by surface sites to identify individual land-plots for development of surface site layout and land reservation.

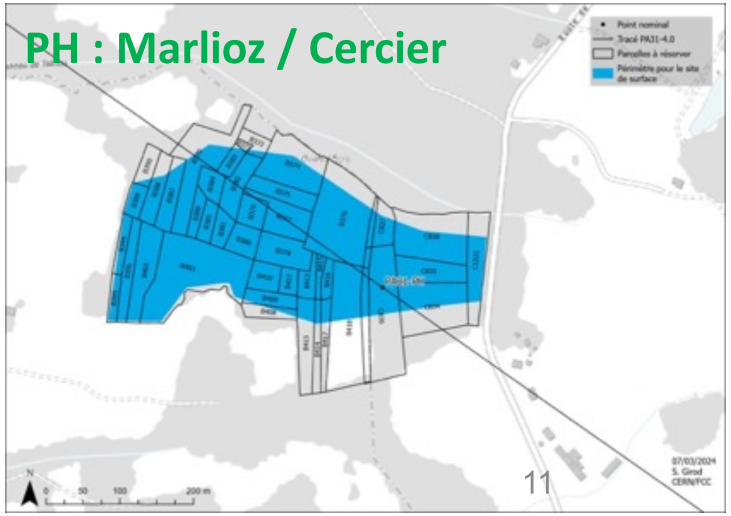
- **PA : Ferney Voltaire: 01/2024**
- **PB: Choulex : 12/2023**
- **PB: Presinge : 01/2024, plenary session with community council 04/2024**
- **PD : Nangy: 05/2024**
- **PF : Éteaux : 03/2024**
- **PG : Groisy / Charvonnex: 04/2024**
- **PH : Marlioz / Cercier : 02/2024**
- **PJ : Vulbens / Dingy en Vuache : 09/2023, 01/2024**
- **PL : Challex: 03/2024, further meetings in Q2/24 to identify best site location**

Green: parcelles identified and agreed
Blue: ongoing


PA : Ferney Voltaire


PB: Choulex


PF : Éteaux


PH : Marlioz / Cercier

FCC tunnel implementation

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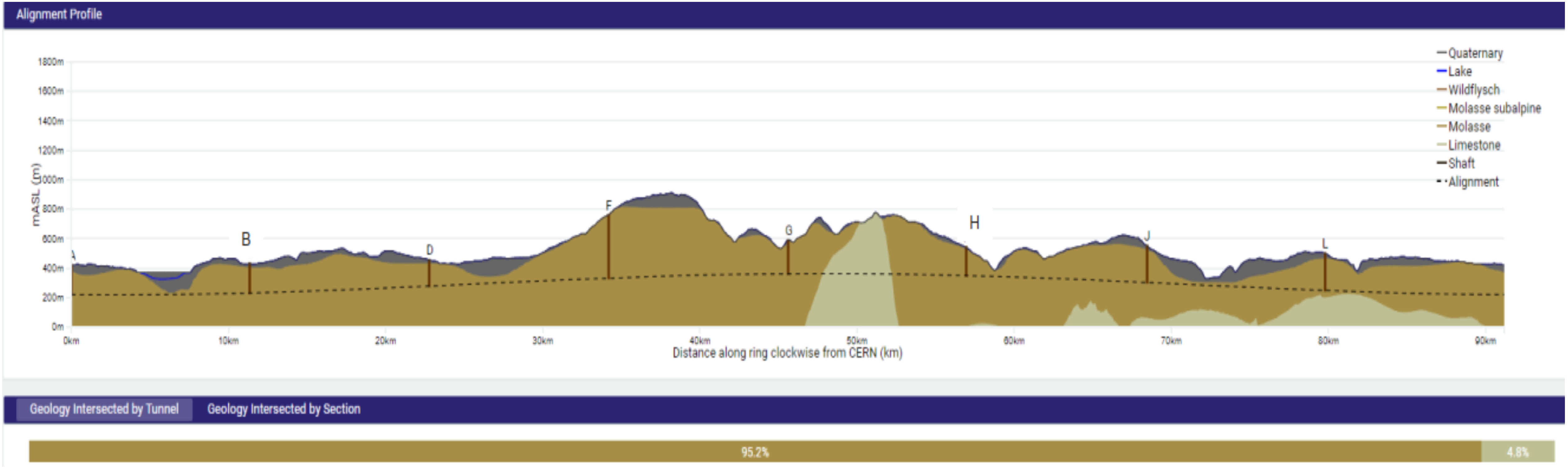
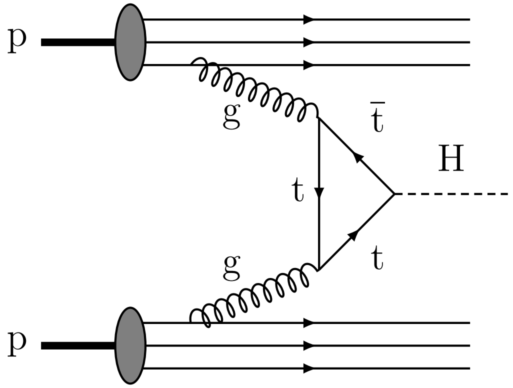
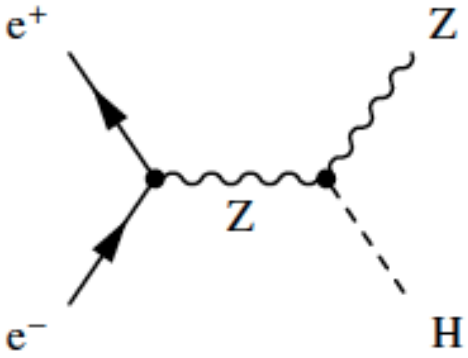


Tunnel implementation summary

- **91 km circumference**
- **95% in molasse geology for minimising tunnel construction risks**
- **Site investigations in zones where tunnel is close to geological interfaces: moraines-molasse-limestone**

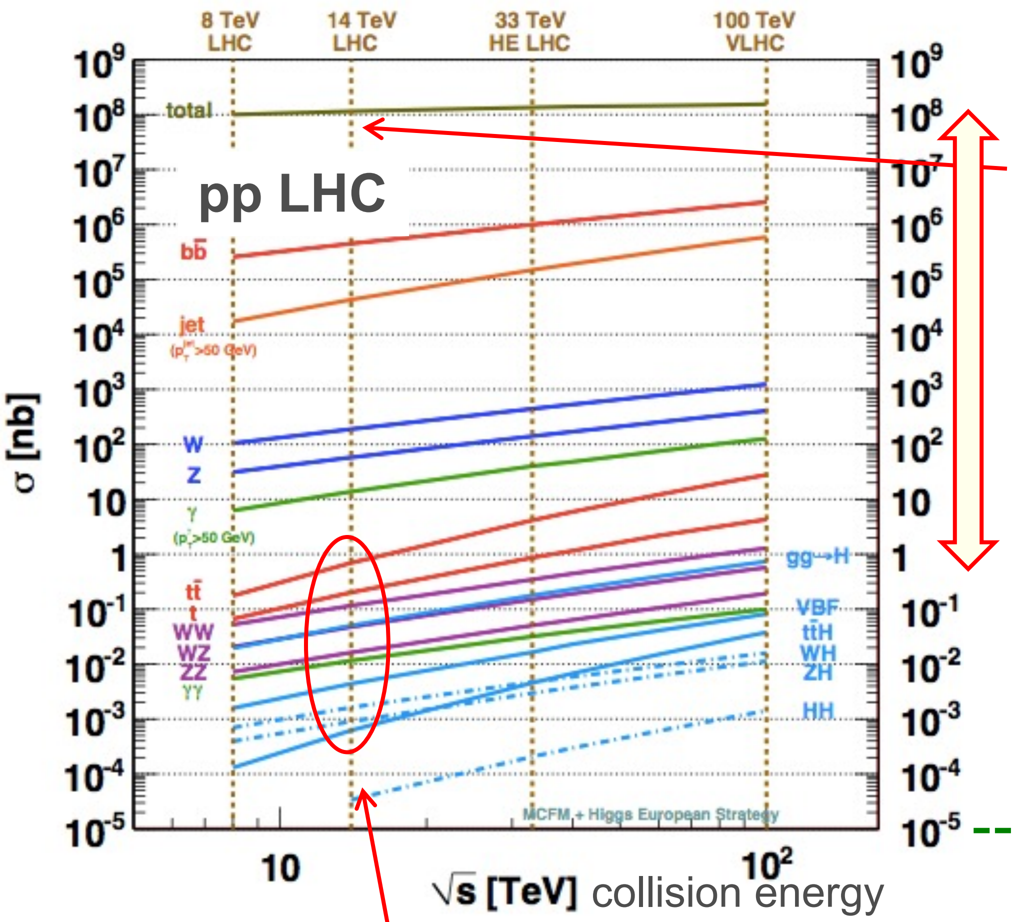
Reminder: pp vs. e^+e^- collisions (i)





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (E, $\boldsymbol{p}$) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**

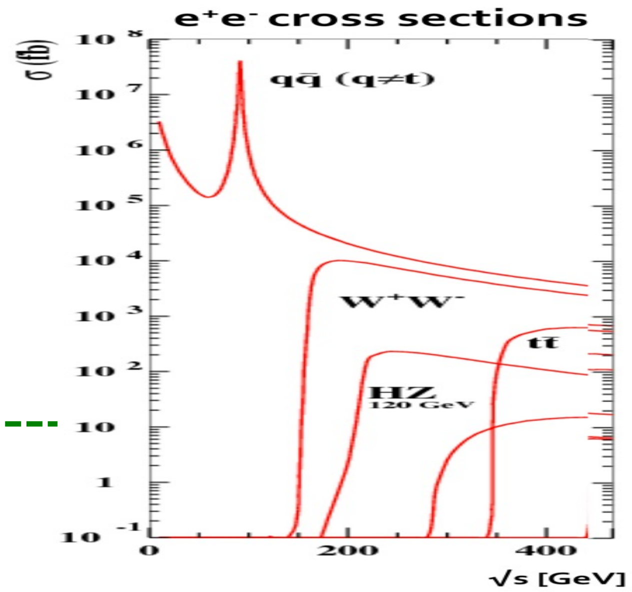
Reminder: pp vs. e^+e^- collisions (ii)



LHC total cross section
factor > 100 million !!

At LHC, much of the interesting physics needs to be found among a huge number of collisions

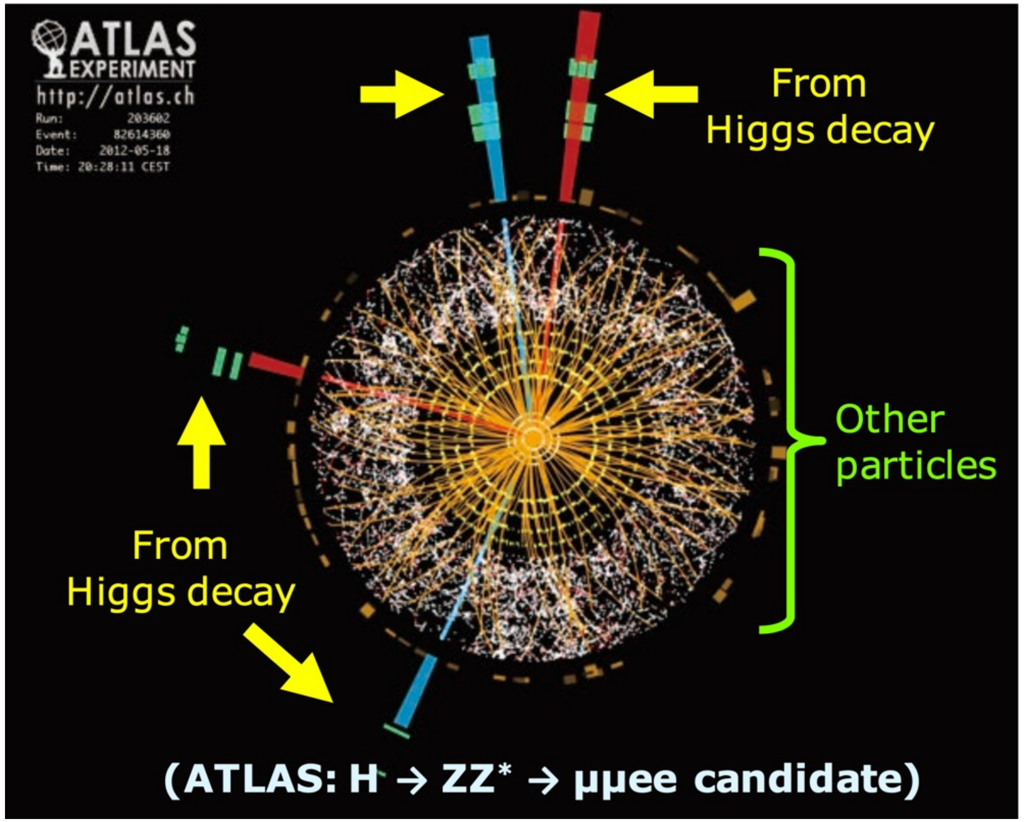
In e^+e^- collisions the total cross section equals the electroweak cross section.



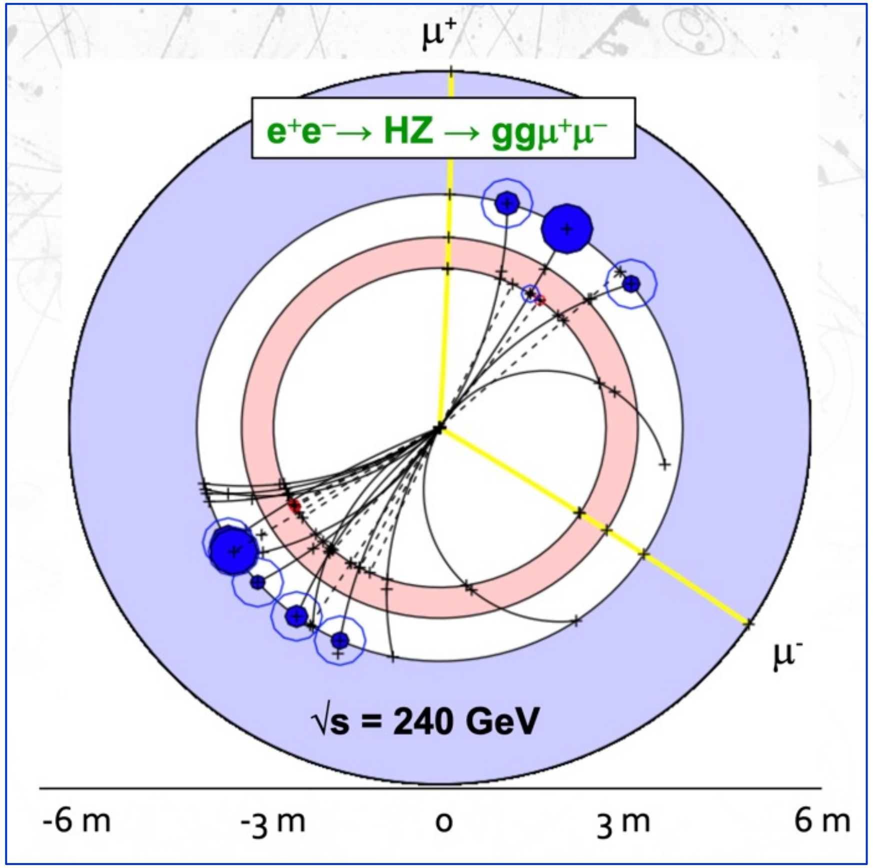
e^+e^- events are "clean"

Reminder: pp vs. e^+e^- collisions (iii)

Higgs event in pp



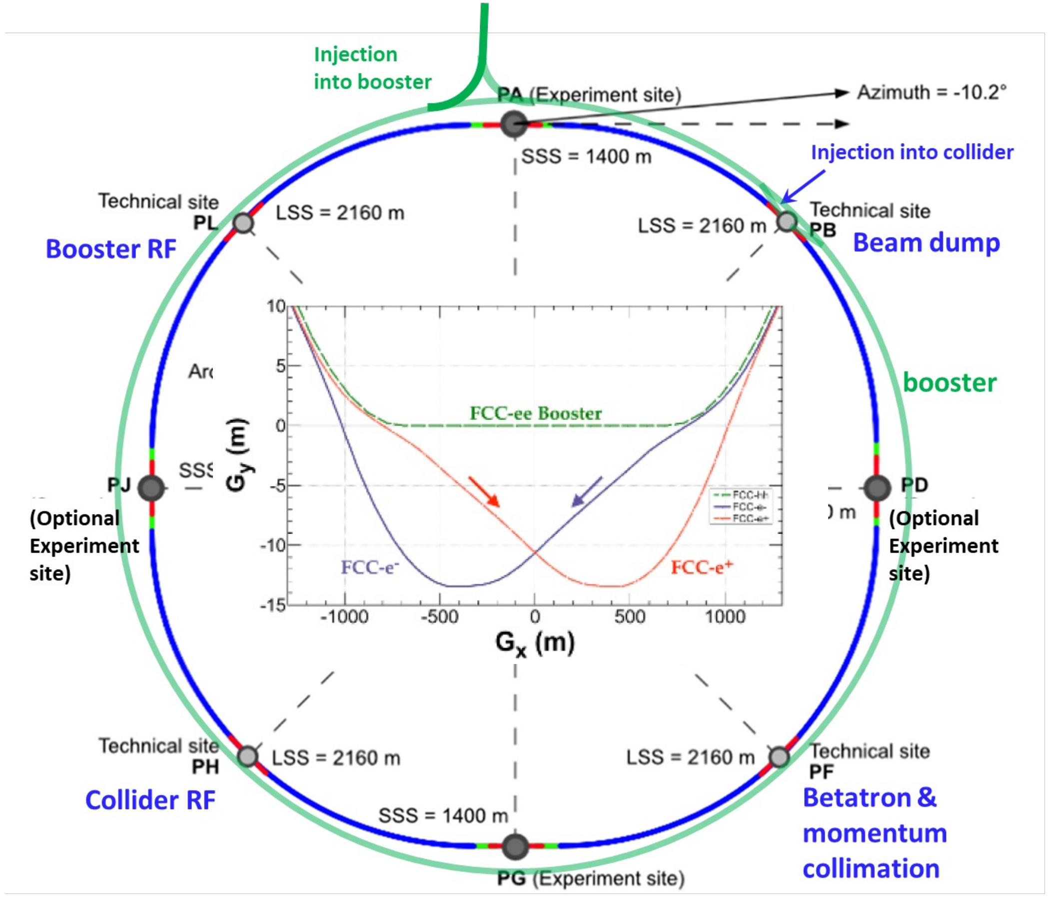
Higgs event in e^+e^-

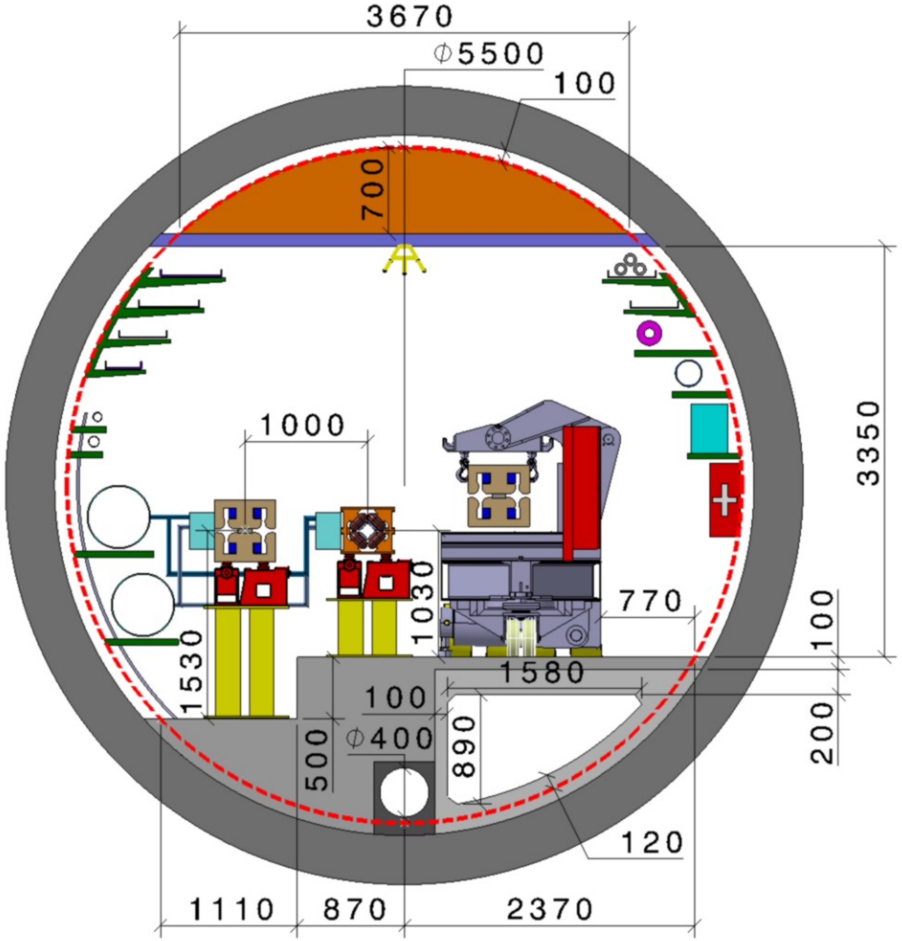


pp: look for striking signal in large background

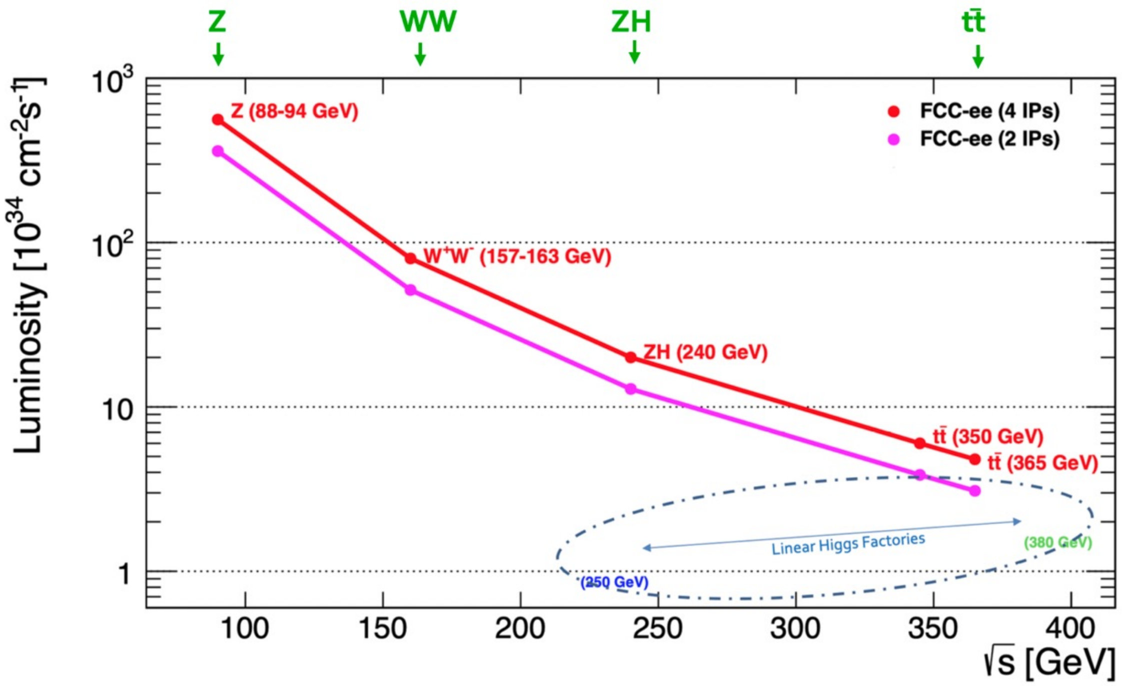
e^+e^-: detect everything; measure precisely

FCC-ee


Injection
into booster
PA (Experiment site)
Azimuth = -10.2°
SSS = 1400 m
Injection into collider
Technical site
PL
Booster RF
LSS = 2160 m
LSS = 2160 m
Technical site
PB
Beam dump
booster
Arc
SSS
PJ
(Optional
Experiment
site)
PD
(Optional
Experiment
site)
FCC-ee Booster
FCC-e⁻
FCC-e⁺
FCC-hh
FCC-e-
FCC-e+
G_y (m)
G_x (m)
10
5
0
-5
-10
-15
-1000
-500
0
500
1000
Technical site
PH
Collider RF
LSS = 2160 m
LSS = 2160 m
Technical site
PF
Betatron &
momentum
collimation
SSS = 1400 m
PG (Experiment site)


3670
Φ5500
100
700
3350
1000
770
1030
1530
1580
100
100
Φ400
500
890
200
120
1110
870
2370

FCC-ee Luminosity and Conditions



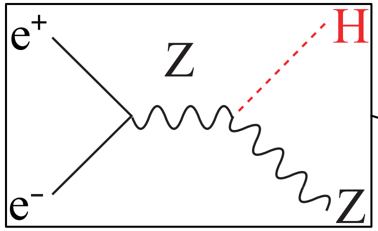
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$
$\bar{t}t$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \to \bar{t}t$
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \to H_{125}$]

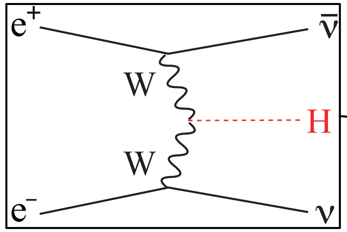
FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**140**	20	5.0	1.25
Bunch spacing	ns	25	160	680	5000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	70,000	30	10	8
Event rate	Hz	**100,000**	6	0.5	0.1
"Pile up" parameter [μ]	**10^{-6}**	2,500	1	1	1

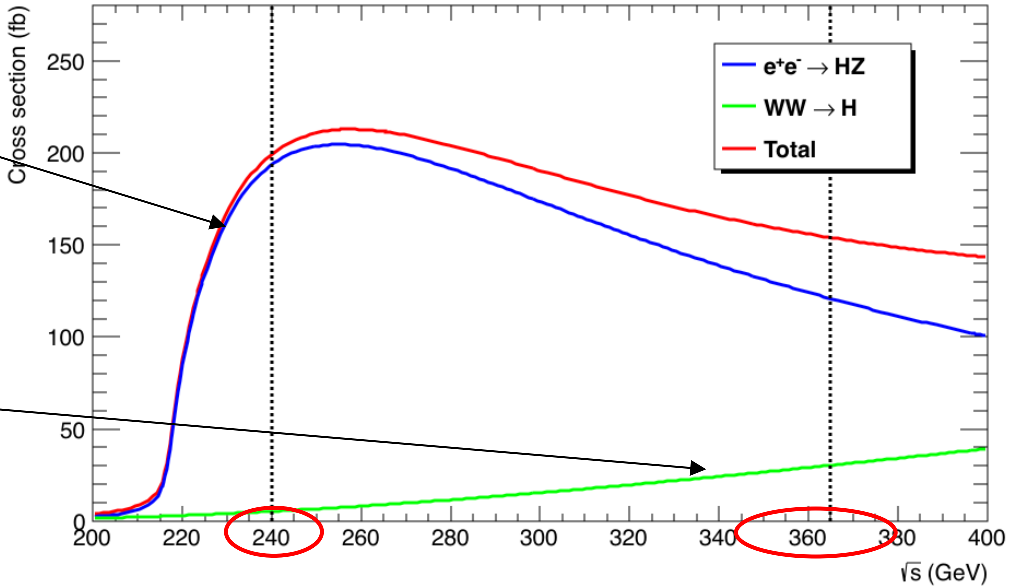
Experimentally, Z pole most challenging

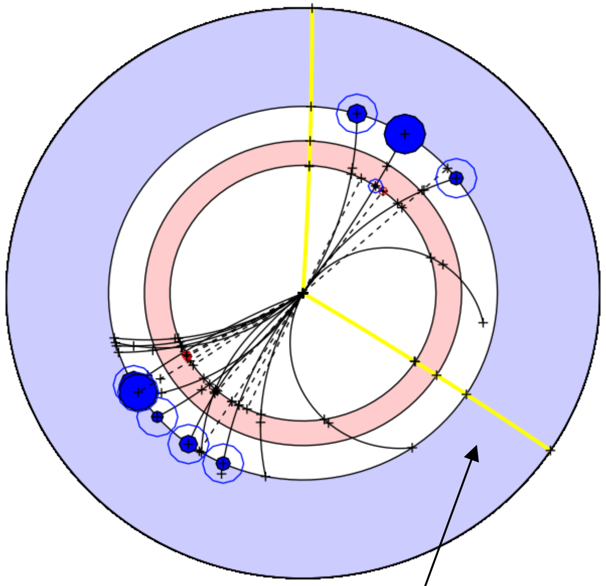
- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 25 ns
  - "Continuous" bunches, no bunch trains, no power pulsing
- No pileup, no underlying event …
  - …well, pileup of 2×10^{-3} at Z pole

FCC-ee as a Higgs factory

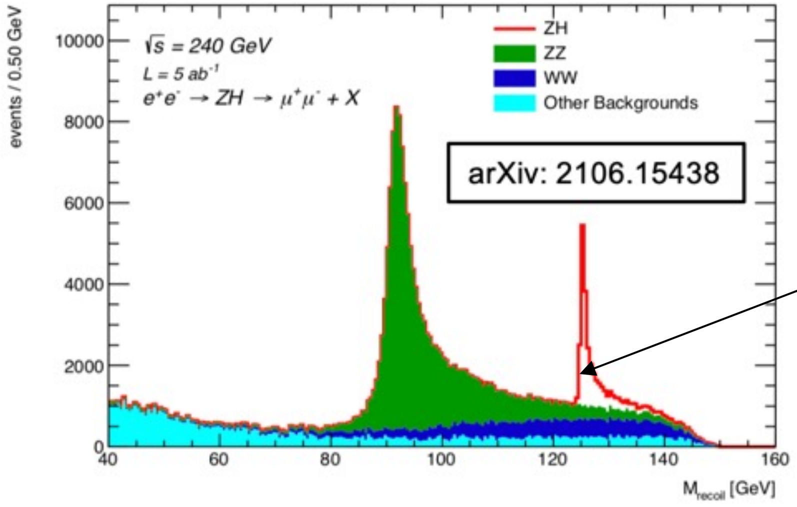








- 10^6 Higgsstrahlung (HZ) event at $\sqrt{s} \simeq 240$ GeV
- Complemented with 200k events at $\sqrt{s} = 350 - 365$ GeV
  - ❑ Of which 30% in the WW fusion channel (important for the Γ_H precision)

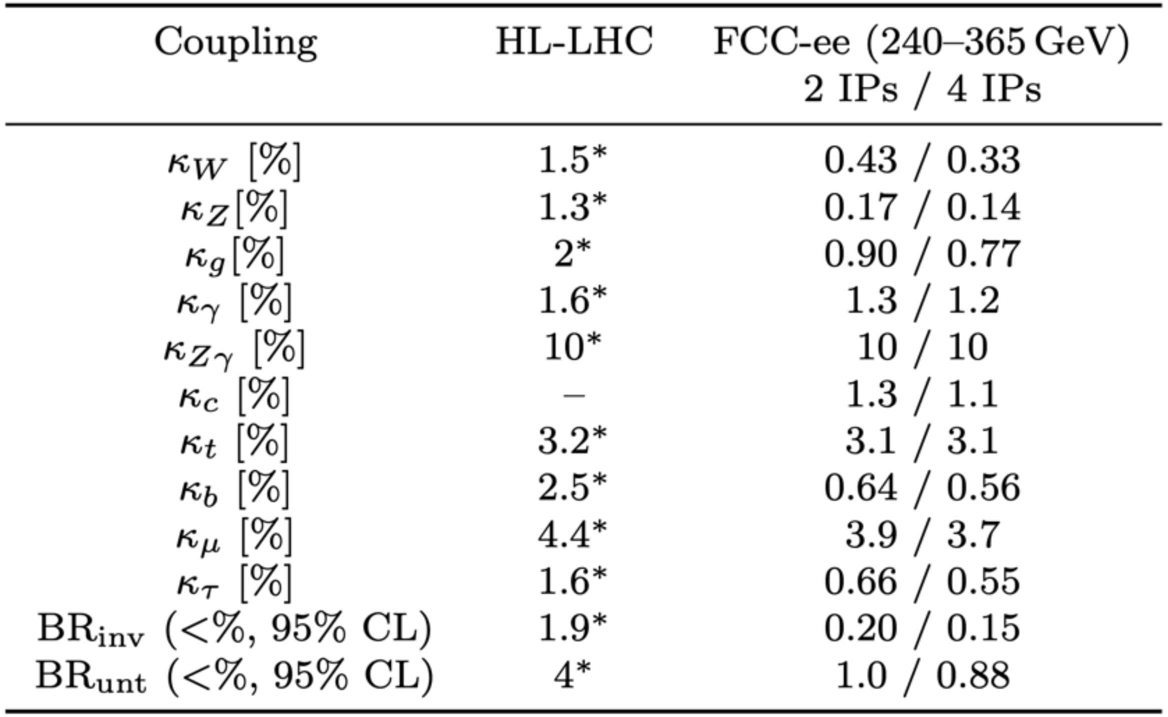


arXiv: 2106.15438

ZH events tagged by presence of identified Z decay recoiling against 125 GeV particle

- ❑ Here cleanest signature, $Z \to \mu^+\mu^-$

Higgs: Results of "kappa" fit



Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

HL-LHC + FCC-ee

* Assumption that $|\kappa_V| \leq 1$

Reminder: Standard Model branching fractions

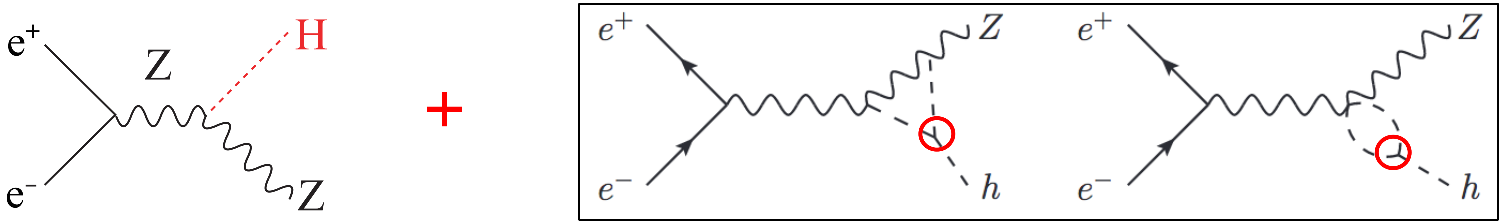
m_H = 125 GeV

Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.07

- FCC-ee precision better than HL-LHC by sizable factors (in copious modes)
  - With no need for additional assumptions
- Important precision gain from from 2IP → 4IP : factor 1.7 higher statistics
- Important to have two energy points (240 and 365 GeV)
- (HL-)LHC measures the σ_{ttH} , but requires assumptions for the g_{Htt}
  - Absolute g_{Htt} measurement in a combination with FCC-ee (precision: 3.1%)

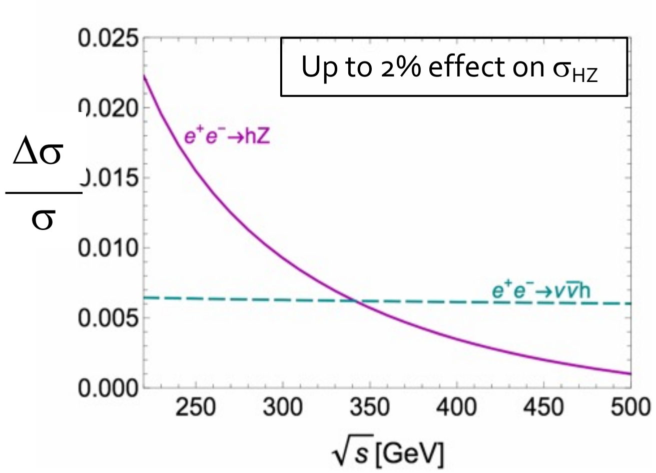
Higgs self-coupling at FCC-ee

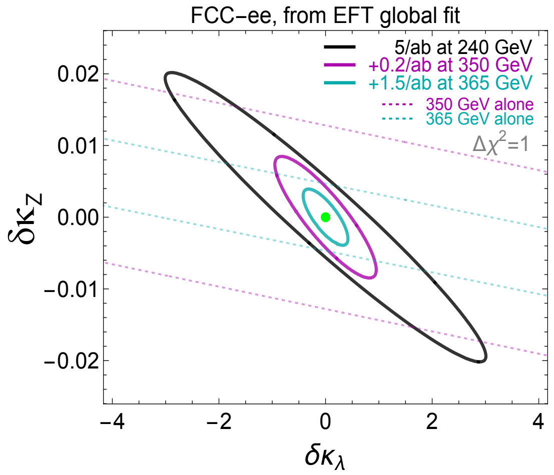
- FCC-ee does not have high enough energy to produce Higgs pairs, from which self coupling can be extracted
- But loops including Higgs self coupling contribute to Higgs production



M. McCullough
arXiv:1312.3322

- Effect of Higgs self coupling (κ_λ) on σ_{ZH} and $\sigma_{\nu\nu H}$ depends on $\sqrt{s}$





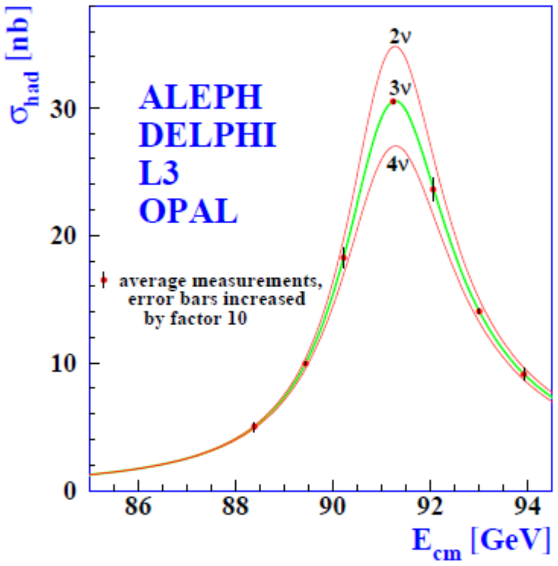
C. Grojean et al.
arXiv:1711.03978

- ❑ Two energy points (240 and 365 GeV) lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$
  - ❖ Precision on κ_λ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : ±34% **(3σ)** ; in the SM : ±12%

A. Blondel, P. Janot
arXiv:1809.10041

Precision Electroweak Measurements

Z reconance: TeraZ



Lineshape

- Exquisite E_{beam} knowledge (unique!)
- m_Z, Γ_Z to < 100 keV (current: 2.2 MeV)

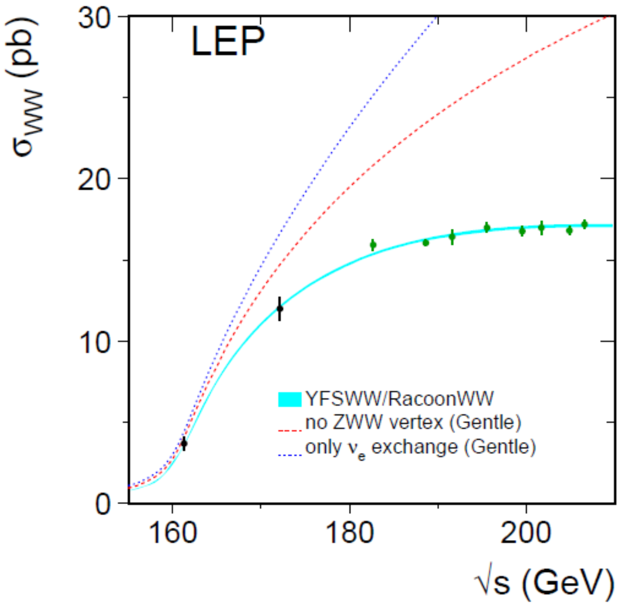
Asymmetries

- $\sin^2\theta_W$ to 2.4×10^{-6} (1.6×10^{-4})
- $1/\alpha_{QED}(m_Z)$ to 3×10^{-3} (15×10^{-3})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.003)

WW threshold scan: OkuW



Threshold scan

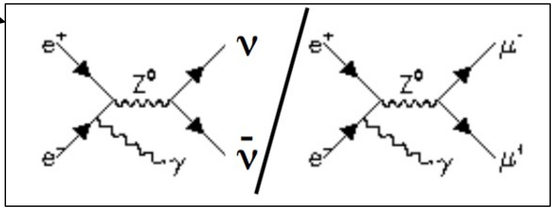
- m_W to 0.3) MeV (15 MeV

Branching ratios R_l, R_b

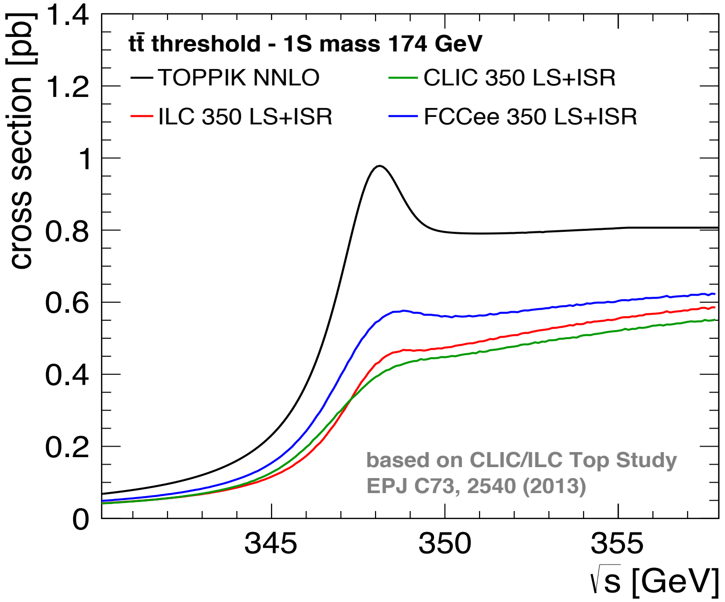
- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.0008 (0.008)



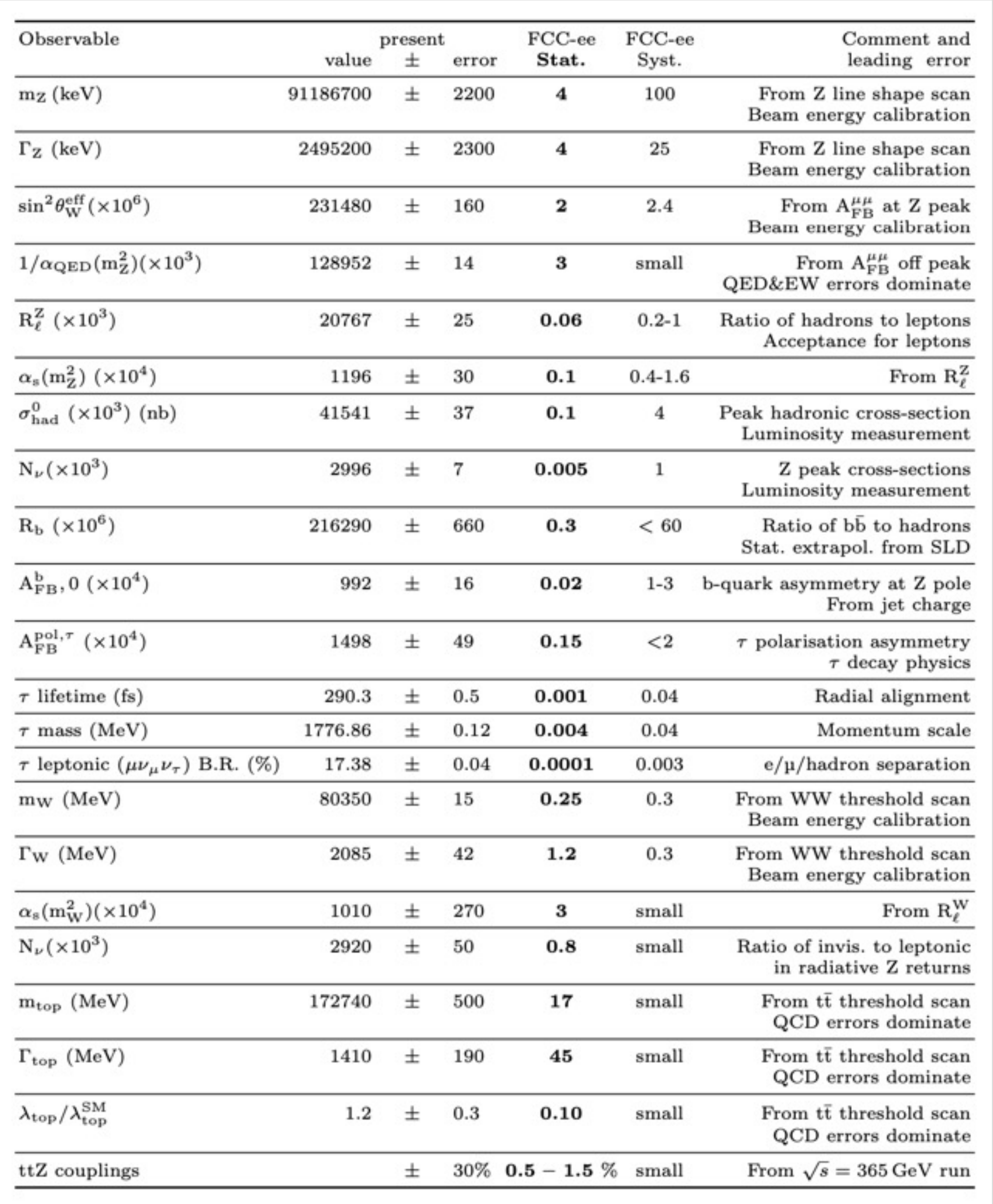
$t\bar{t}$ threshold scan: MegaTop



Threshold scan

- m_{top} to 17 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%

High Precision EW Measurements – Main Experimental Challenge



Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff} (\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu (\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	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 asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu (\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
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	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

- FCC-ee EWPO measurements with unprecedented ***statistical*** precision
  - ❑ 5 x 10^{12} hadronic Z decays at Z-pole
    - ❖ Also flavour factory: 7×10^{11} $Z \rightarrow bb$, 1.5×10^{11} $Z \rightarrow \tau^+\tau^-$
  - ❑ **Statistical precision** for EWPOs is **typically 500 times smaller than the current uncertainties**
  - ❑ Systematic uncertainty will have to be reduced
  - ❑ Can achieve indirect sensitivity to new physics up to a scale $\Lambda_{\text{new physics}}$ of 70 TeV
- Require ***systematic*** precision to match
  - ❑ Comensurate control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
  - ❑ Higher order theoretical computations, e.g. N…NLO
  - ❑ **Minimizing detector systematics**

Challenges at FCC-ee

- At the Z pole, high beam currents with bunch spacing 20 ns
  - ❑ Almost continuous beam has implications on power management/cooling, density, readout,…
- Extremely high luminosities L ~ $1.8 \times 10^{36}/\mathrm{cm}^2\mathrm{s}$ at Z-pole
  - ❑ Require absolute luminosity measurements to 10^{-4} to achieve desired physics sensitivity
  - ❑ Online/Offline handling of high data rates/total volume.
- Physics interaction rate at Z pole ~ 100 kHz
  - ❑ Implications on detector response time, event size, FE electronics and timing
- Beam dynamics
  - ❑ 30 mrad crossing angle sets constraints on the solenoid field to 2 T → larger tracker volume
  - ❑ Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR) to a lesser extent
- High Luminosities
  - ❑ High statistical precision: Requires control of systematics down to 10^{-6} – 10^{-5} level.
  - ❑ Online and Offline data handling O(10^{13}) events
  - ❑ Physics events up to 100 kHz imposes requirements on detector response time, FE electronics and DAQ.

FCC-ee Detector Requirements

Higgs Factor Program

- 1.2M ZH events at vs = 240 GeV
- 75k WW → H events at $\sqrt{s}$ = 365 GeV
- Higgs Couplings to fermions
- Higgs self-couplings (2-4 s) via loop diagrams
- Unique possibility to measure electron self-coupling in s-channel e+e- → H at $\sqrt{s}$ = 125 GeV.

→

- Momentum Resolution $^{\sigma_{pT}}/_{p_T} \simeq 10^{-3}\ at\ p_T \sim 50\ \mathrm{GeV}$.
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for *b, c* tagging

Precision EW and QCD Program

- 5 x 10^{12} Z and 10^8 WW events
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, m_W, Γ_W, …
- 10^6 tt events
  - m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics

→

- Absolute normalization of luminosity to 10^{-4}.
- Relative normalization to 10^{-5} (eg Γ_{had}/Γ_l)
- Jsuperior momentum resolution, limited by multiple scattering → minimize material.
- Track angular resolution < 0.1 mrad
- Stability of B-field to 10^{-6}

More FCC-ee Detector Requirements

Heavy Flavor Program

- 10^{12} bb, cc; 1.7 x 10^{11} $\tau\tau$ produced in a clean environment.
    - CKM matrix, CP measurements, flavor anomaly studies eg b→s$\tau\tau$, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity.

→

- Superior impact parameter resolution
    - Precisely tag and identify secondary vertices and measure lifetimes.
- ECAL resolution at few $\%/\sqrt{E}$
- Excellent π^0/γ separation for tau identification
- Particle ID: K/π separation over a wide momentum range → precision timing.

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z.
- Axion-like particles, dark photons, Heavy neutral leptons,
- Long lifetimes LLPs.

→

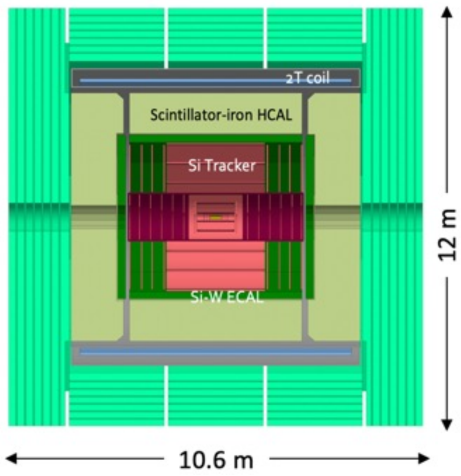
- Benchmark study: Z →νN with N decaying late
- Sensitivity to far detached vertices
    - Tracking: more layer, continuous tracking
    - Calorimeter: granularity, tracking capability
- Large decay length → extended decay volume
- Precise timing
- Heremeticity

Detector Requirements Summary

- In summary, we require:
    - Ultra-lightweight material
    - Precision momentum ($\sigma(1/p_T) < 3 \times 10^{-5}$ GeV^{-1}) and angular res. (< 0.1 mrad)
    - Excellent EM resolution with low constant term
    - Unprecedented low jet energy resolution to distinguish W/Z/H to dijets.
    - Micron-precision b- and c- tagging capability
    - Particle ID in a broad momentum range, incl. pico-second timing capability

Developing FCC-ee Proto Detectors

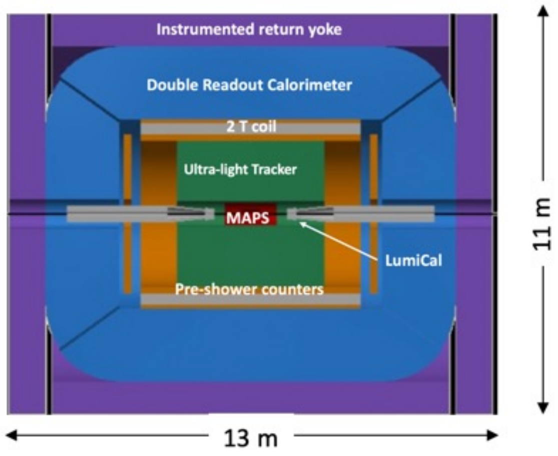
CLD



- Well established design
  - ILC/ILD → CLIC detector → CLD
- Detector components:
  - Full Silicon VTX deector + tracker;
  - CALICE-like calorimetry;
  - Large coil outside calorimerters,
  - Muon system in return yoke
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?
  - …

CDR

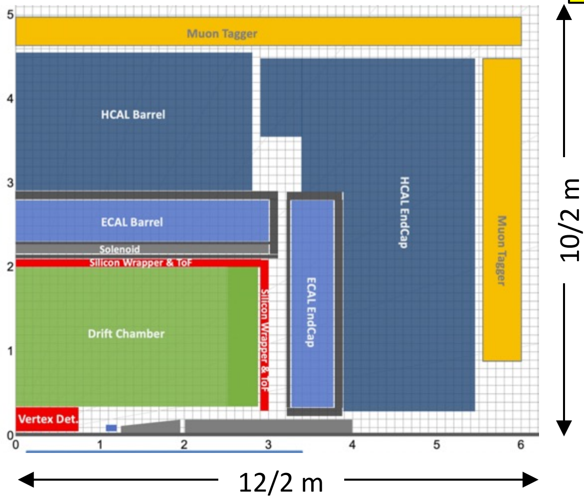
IDEA



- Less established design
  - But still ~15y history
- Detector components:
  - Si VTX detector
  - Ultra light drift chamb. w. powerfull PID;
  - compact, light coil inside calorimeter
  - monolitic dual readout calorimeter;
    - Possibly augmented by crystal ECAL
  - Muon system
- Active community
  - Prototype designs, test beams, …
  - Software

Allegro

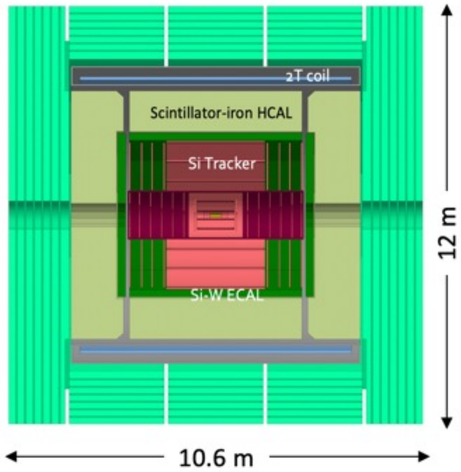
new



- A design in its infancy
- Detector components:
  - VTX + Drift chamber a la IDEA
  - High granularity Noble Liquid ECAL
    - Pb + LAr (or possibly denser W + LKr)
  - TileCal HCAL (a la ATLAS)
  - Coil outside ECAL enclosed in same cryostat as LAr
  - Muon system
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

Developing FCC-ee Proto Detectors

CLD



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  - Full Sili
  - CA
  - Larg orimerters,
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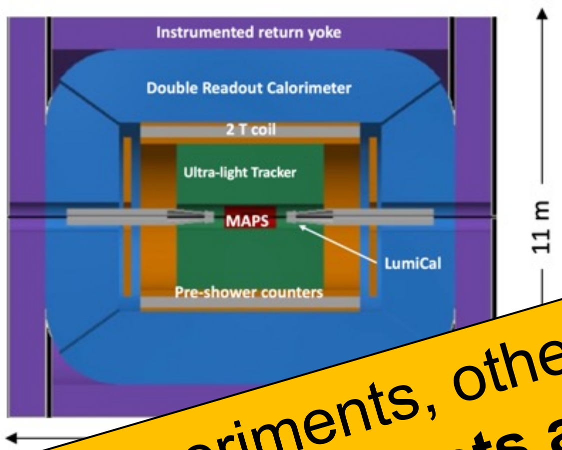
  - …

CDR

IDEA



y history

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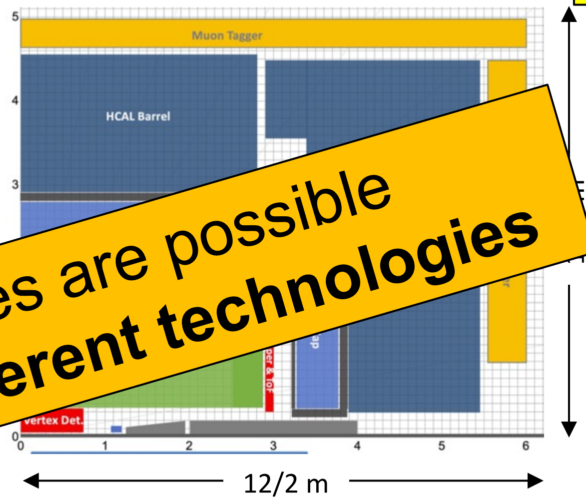
Allegro

new



- A design in its infancy
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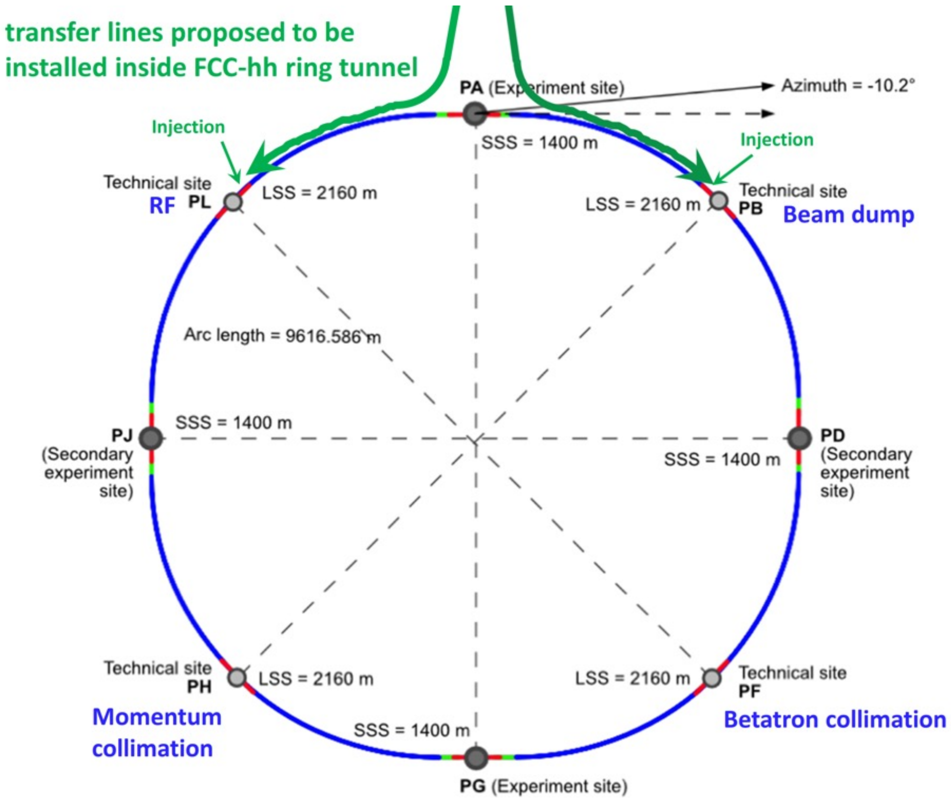
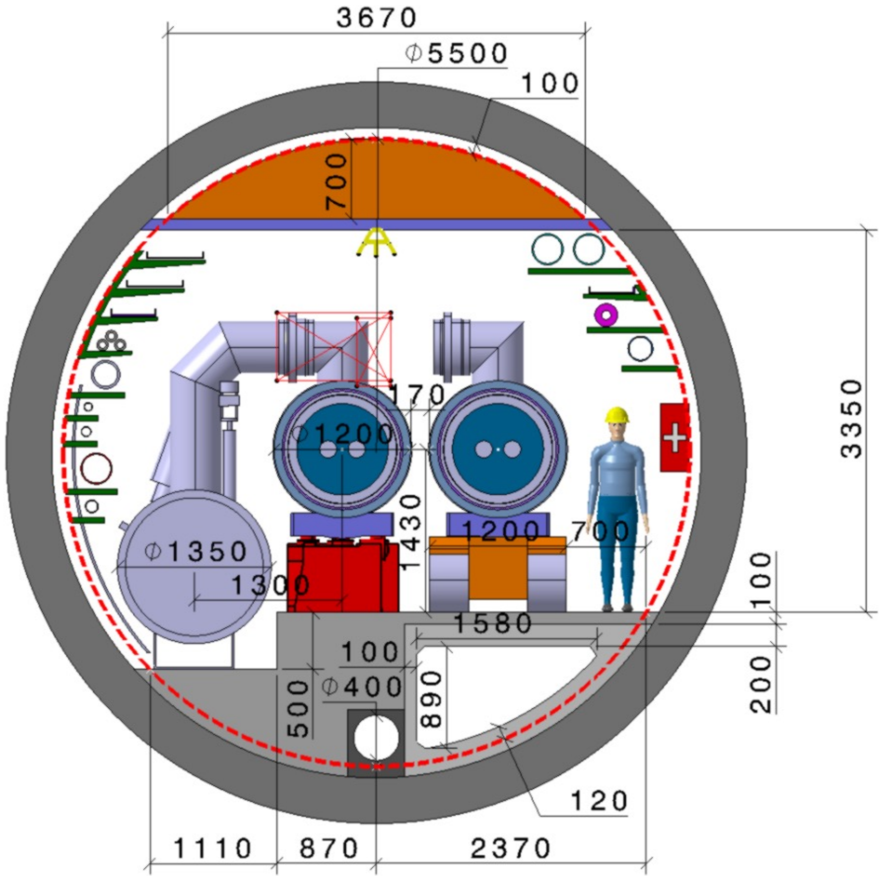
  - TileCal HCAL (a la ATLAS)
  - Coil outside ECAL enclosed in same cryostat as LAr
  - Muon system
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

These are examples of three experiments, other choices are possible

→ A lot of **room for other ideas, other concepts and different technologies**

FCC-hh


transfer lines proposed to be installed inside FCC-hh ring tunnel
PA (Experiment site)
Azimuth = -10.2°
Injection
Injection
SSS = 1400 m
Technical site
RF PL
LSS = 2160 m
LSS = 2160 m
Technical site
PB Beam dump
Arc length = 9616.586 m
SSS = 1400 m
PJ
(Secondary experiment site)
SSS = 1400 m
PD
(Secondary experiment site)
Technical site
PH
LSS = 2160 m
Momentum collimation
LSS = 2160 m
Technical site
PF
Betatron collimation
SSS = 1400 m
PG (Experiment site)


3670
Φ5500
100
700
170
Φ1200
1200
700
Φ1350
1300
1430
3350
1580
100
100
Φ400
200
500
890
120
1110
870
2370

FCC-hh parameters

Michael Benedikt
2nd U.S. FCC Workshop
25/03/2024

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly
more time for high-field magnet R&D
aiming at highest possible energies

Formidable challenges:

- ☐ high-field superconducting magnets: 14 - 20 T
- ☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ☐ stored beam energy: ~ 9 GJ → machine protection
- ☐ pile-up in the detectors: ~1000 events/xing
- ☐ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays $(\gamma\gamma, Z\gamma, \mu\mu)$
- ☐ Final word about WIMP dark matter

F. Gianotti

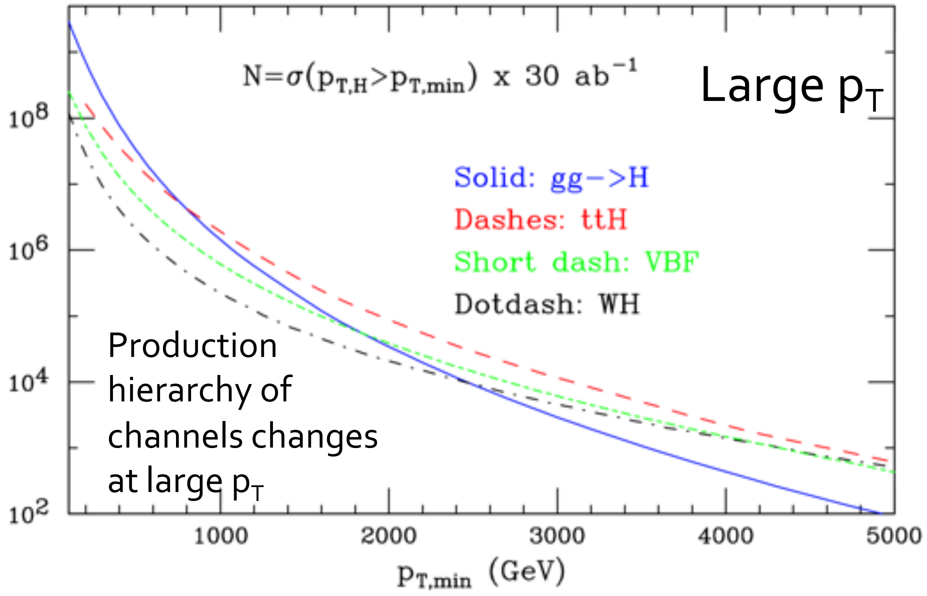
Important example of FCC-hh physics - Higgs

Huge production rates

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

FCC-hh 100 TeV
30 ab^{-1}

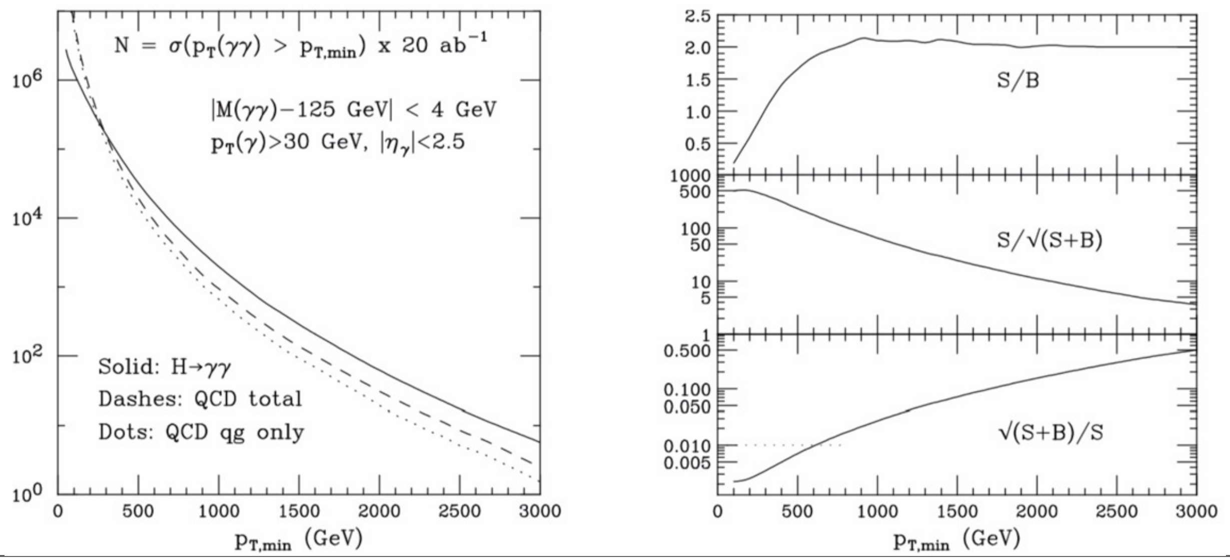
LHC 14 TeV
3 ab^{-1}



Large p_T

Production hierarchy of channels changes at large p_T

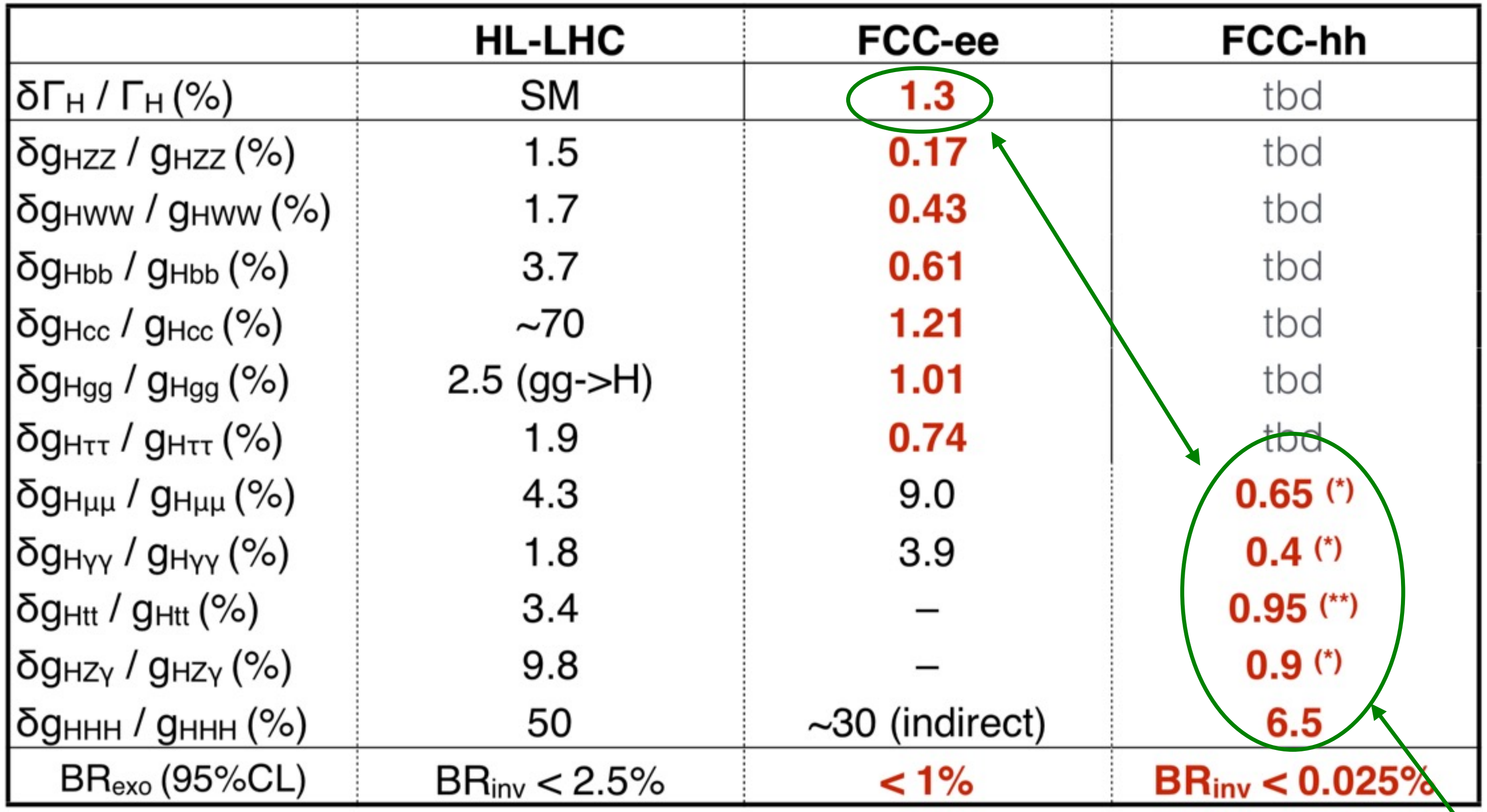
Example of study: gg → H → $\gamma\gamma$ at large p_T



- At LHC, S/B in H → $\gamma\gamma$ channel is $\mathcal{O}$(few %)
- At FCC, for p_T > 300 GeV, S/B ~ 1 → **Clean !!**
- Potentially accurate probe of H p_T spectrum up to large p_T

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

Higgs couplings after FCC-ee / hh



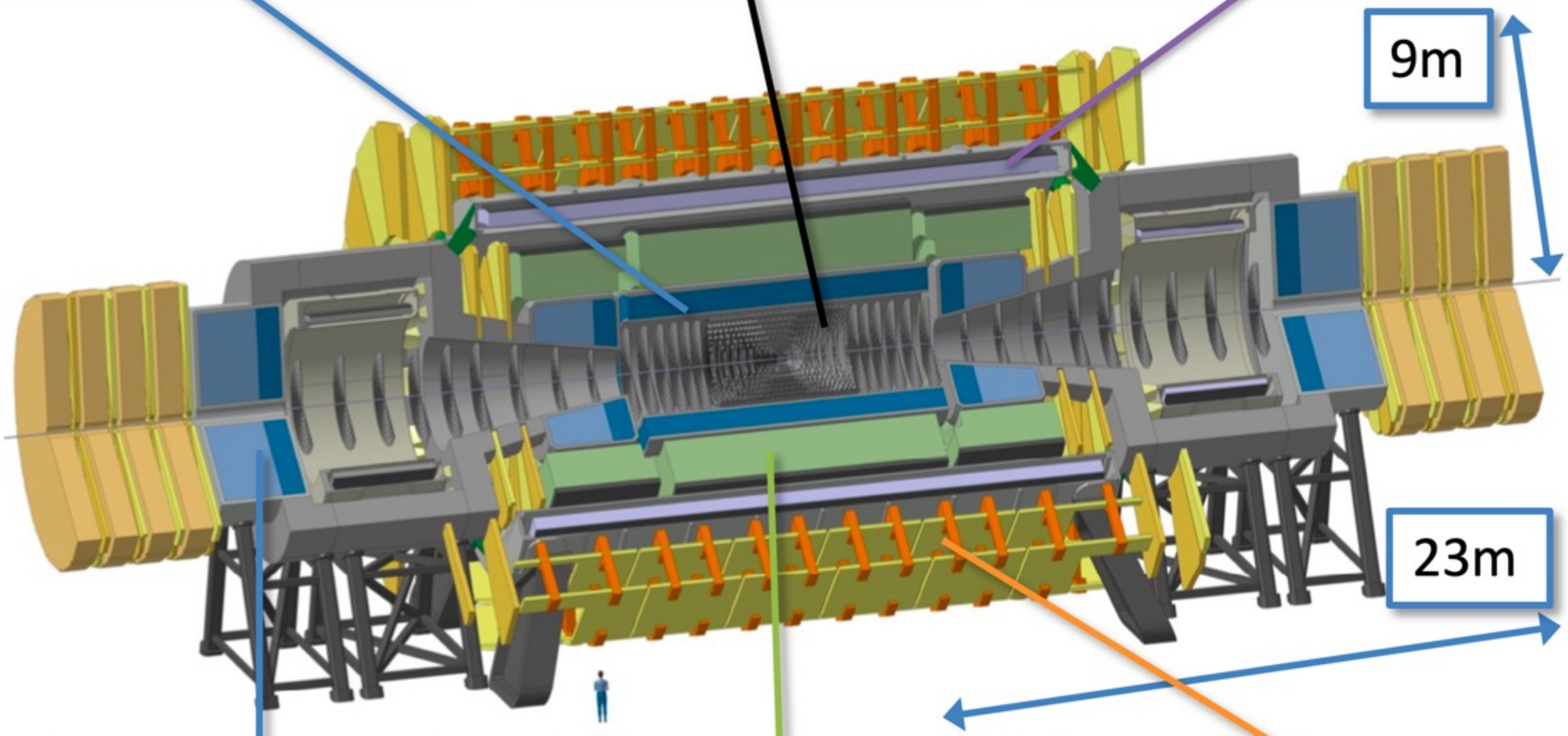
	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 $^{(*)}$**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 $^{(*)}$**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 $^{(**)}$**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 $^{(*)}$**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Absolute coupling measurements facilitated by width measurement from FCC-ee

A Possible FCC-hh Detector – Reference Design for CDR



Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{pT}/p_T \approx 10\text{-}20\%$ at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

Forward detectors
up to $\eta=6$

Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

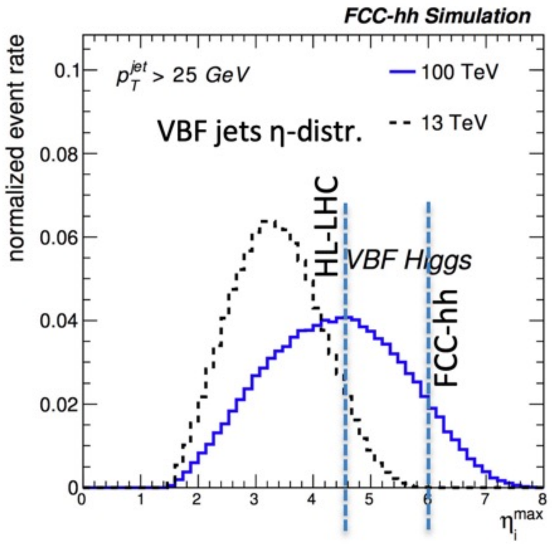
Muon System:
$\sigma_{pT}/p_T \approx 5\%$ at 10TeV

- **Reference design for an FCC-hh experiment for FCC CDR**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**

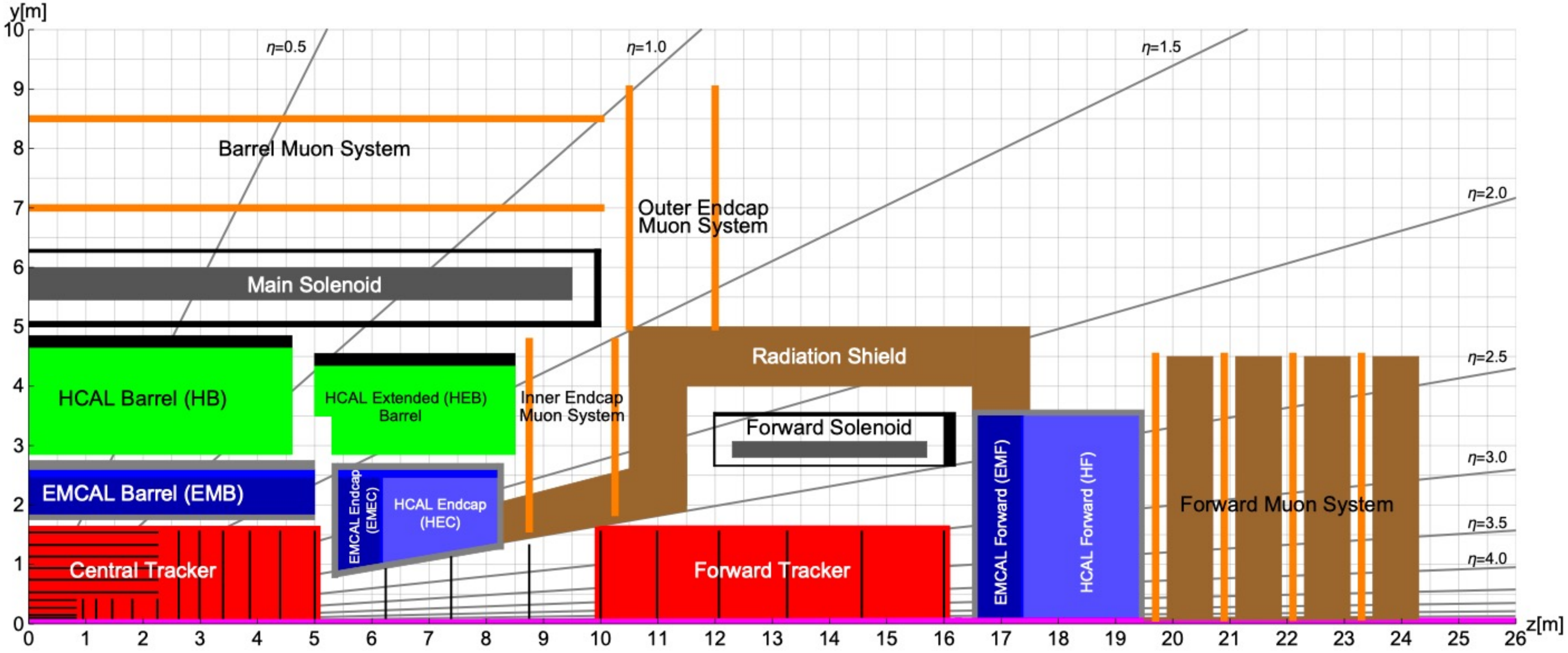
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

Reference Design for CDR

- E_{cm} = 1oo TeV
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $\int \mathcal{L} = 30\ \mathrm{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up <μ> ≈ 1000
- 4 THz of charged tracks

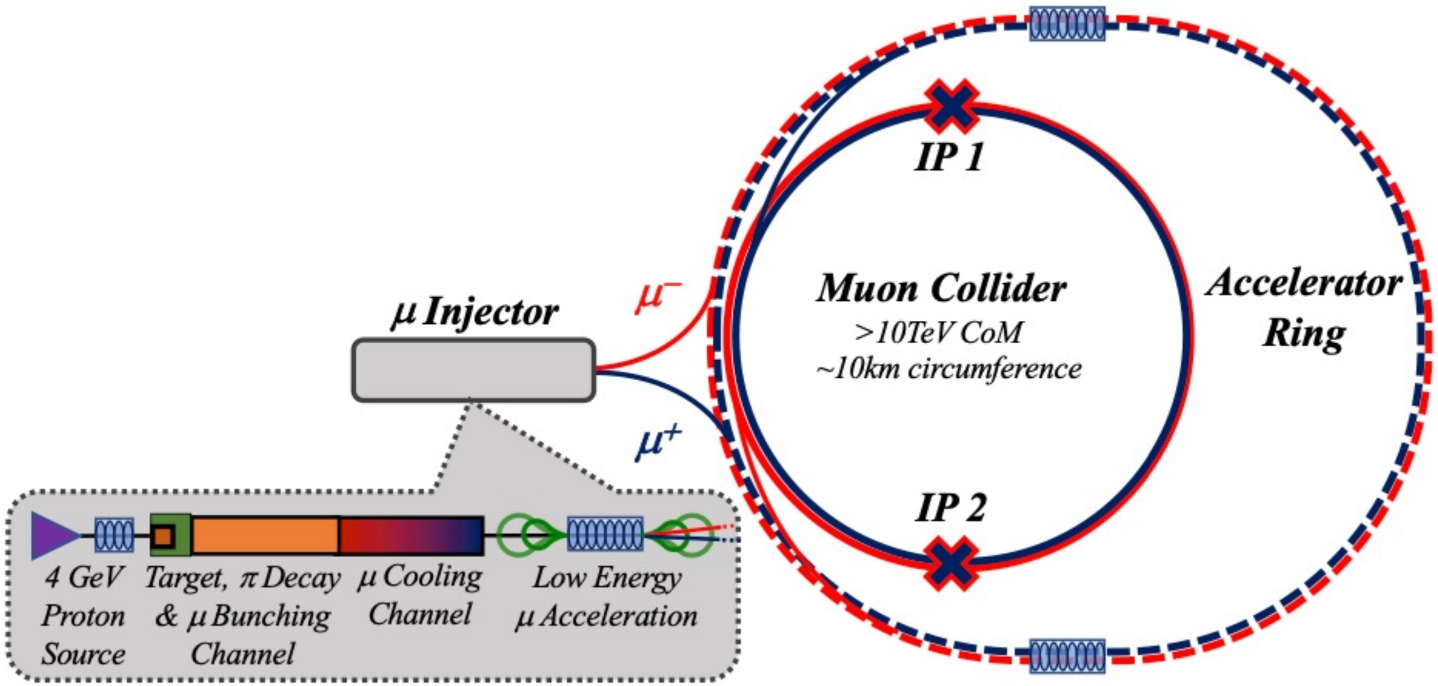


- ”Light” particles produced with increasing forward boost



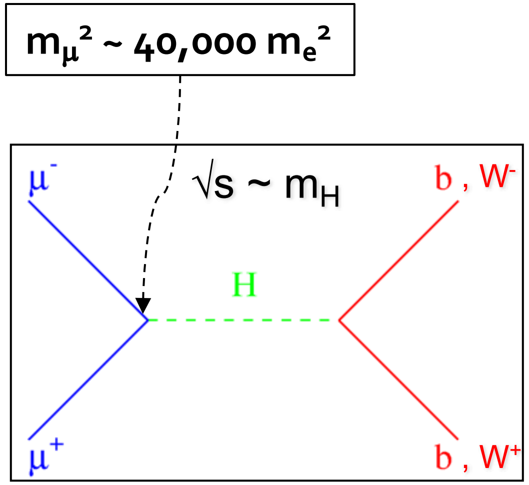
Forward solenoid adds about one unit of η with full lever-arm

Muon Collider

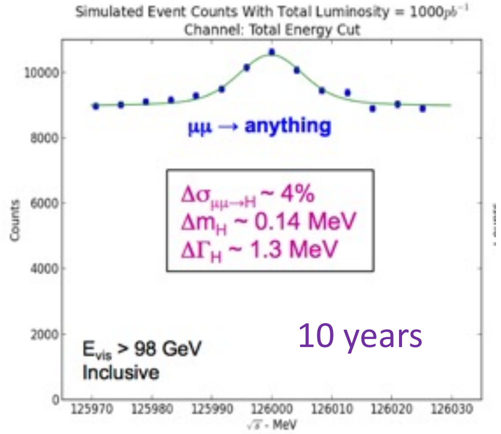


Why muon colliders ?

- Muons are leptons (like electrons)
  - Collisions at the full energy, small physics background, (E,p) conservation
    - Muons can *a priori* do all what electrons can do
- Muons are heavy (like protons)
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up to large √s
    - Excellent energy definition (up to a few 10^{-5})
  - Large direct coupling to the Higgs boson
    - Unique *s*-channel Higgs factory at √s = 125.11x GeV
- Muons are naturally longitudinally polarized (100%)
  - Because arising from $\pi^\pm$ decays to $\mu^\pm\nu_\mu$
    - Ultra-precise beam energy and beam energy spread measurement
- Muons eventually decay (in 2.2 μs) to $e\nu_\mu\bar{\nu}_e$
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories ?

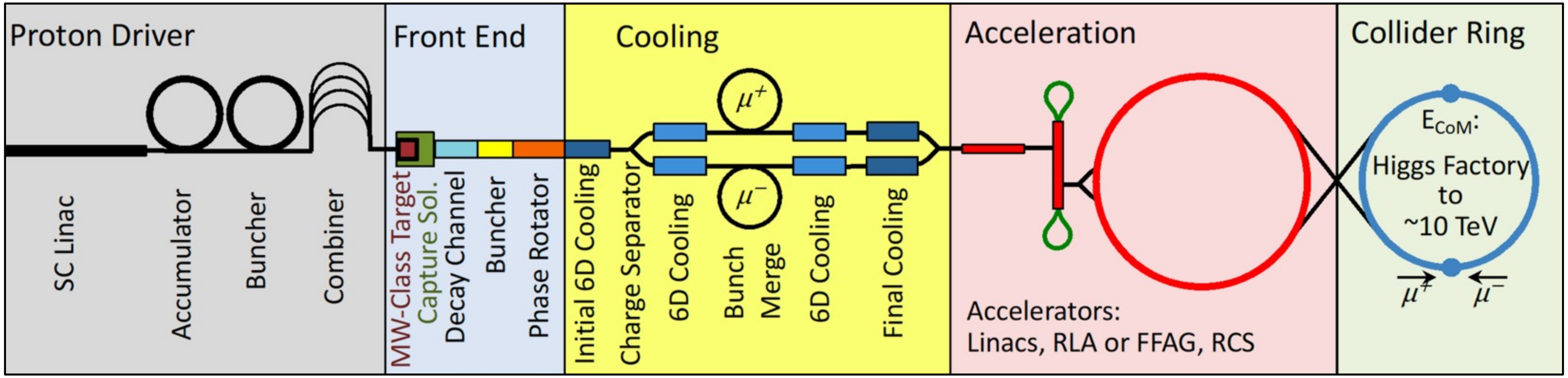


A muon collider s-channel Higgs Factory is a priori a great idea! However, realistic accelerator studies show that luminosity will be limited to about 13k Higgs events per year.



Muon collider Layout and Challenges

- Muons have short lifetime (2.2 µsec) : Produce, Collect, Cool, Accelerate and Collide them *fast* !



- ❑ Intense proton driver to get the adequate number of muons
  - ❖ At least 4 MW for the desired luminosities
- ❑ Robust target to not evaporate at the first proton bunch
  - ❖ Re-circulating liquid metal
- ❑ Efficient muon collector from pion decays
  - ❖ Magnetic fields of 20 T
- ❑ Unique 6D muon cooling
  - ❖ To reduce beam sizes and beam energy spread
- ❑ Fast acceleration and injection into circular ring(s)

All these aspects are at the level of intense R&D. Will require a decade (at least) to demonstrate feasibility

Some Possible Muon Collider

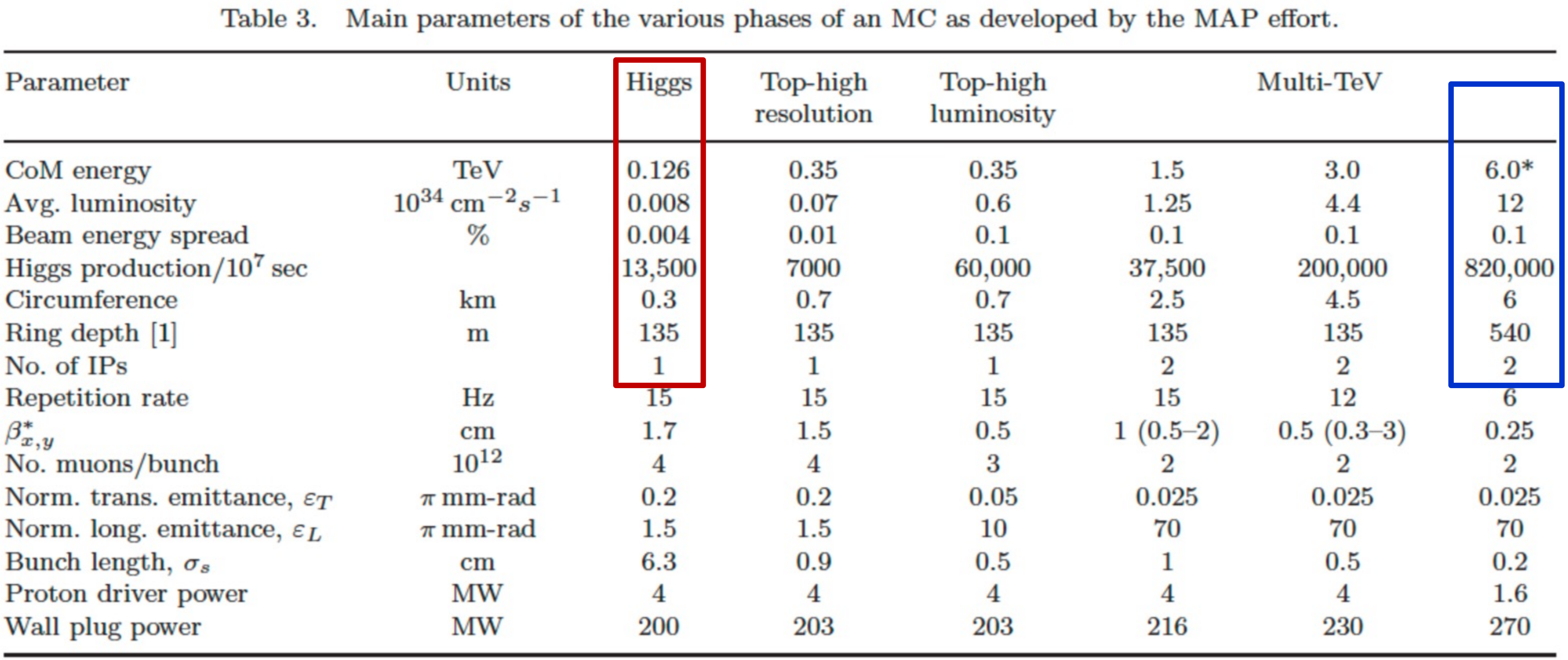


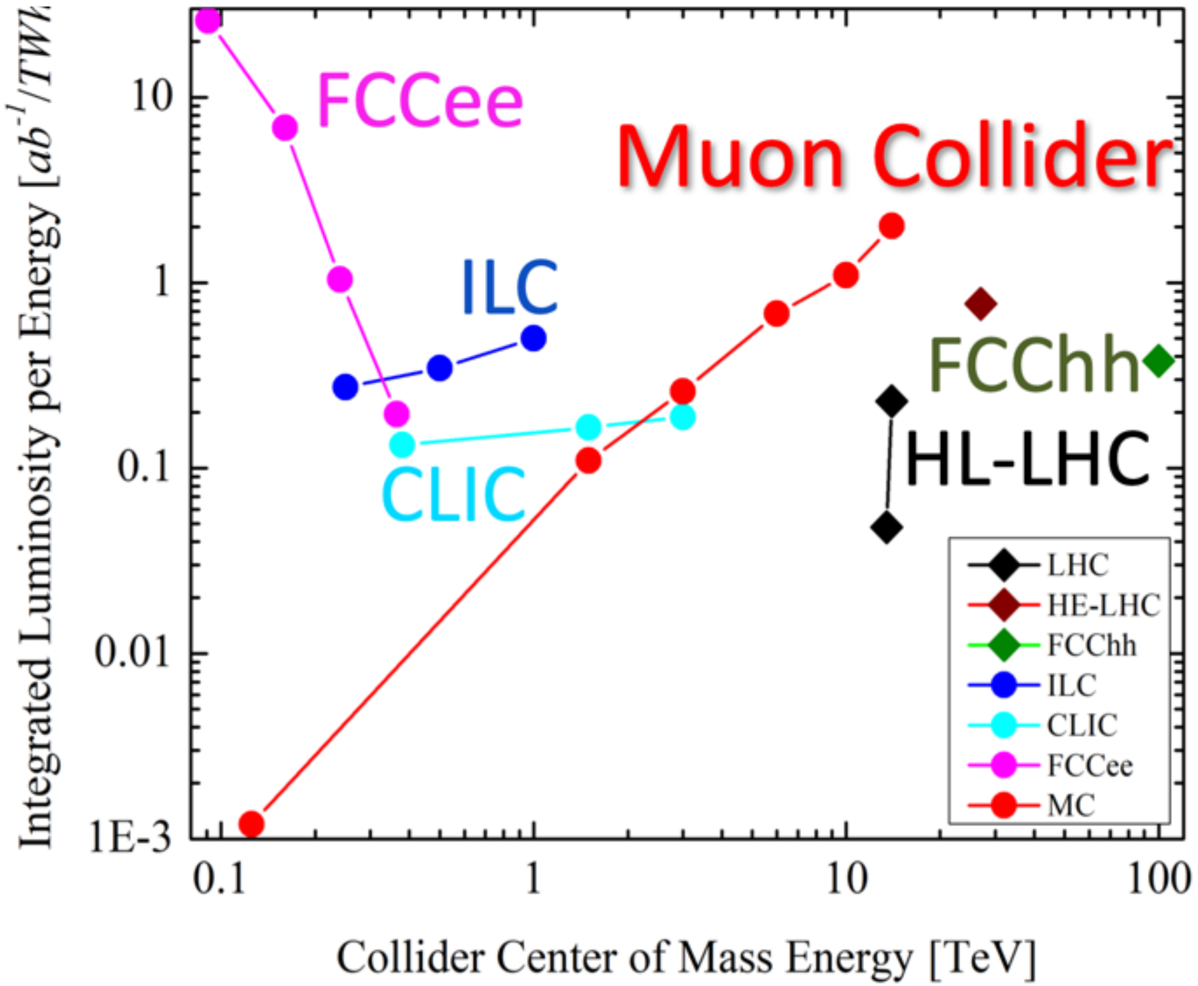
Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm^{-2}s^{-1}	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

RAST, Vol 10, No. 01, pp. 189-214 (2019)

- A *s*-channel Higgs factory would be compact (300 m circumference), but unfortunately has limited luminosity
- A 6 TeV collider would fit in the Tevatron tunnel
  - The LHC tunnel could house a 24 TeV collider

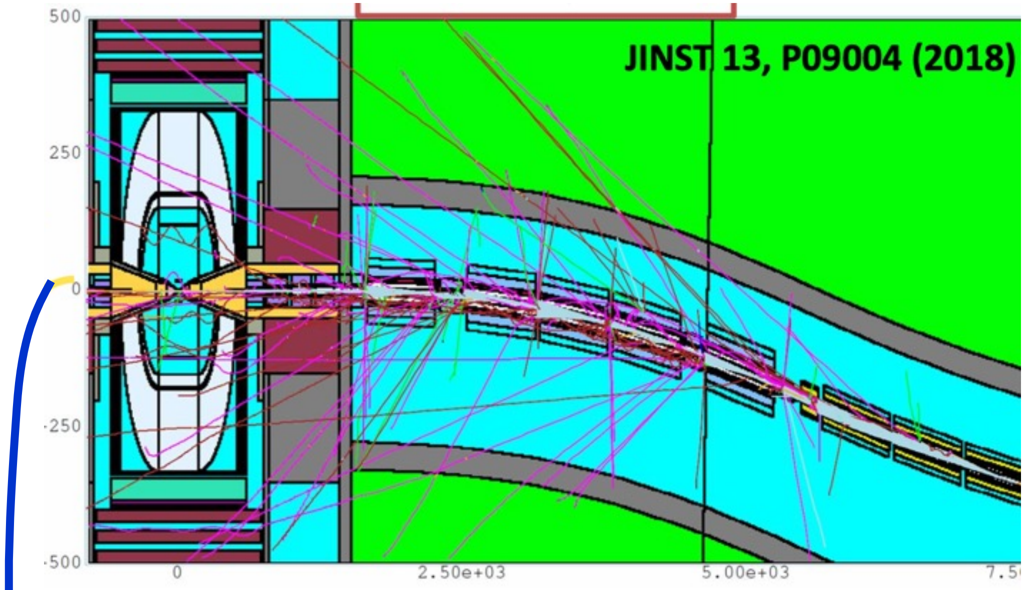
Energy Efficiency of Future Colliders



Nature, Vol 17, 2021, 289-292

☞ **For TeV-scale lepton colliders, muons seems the way to go** ☜

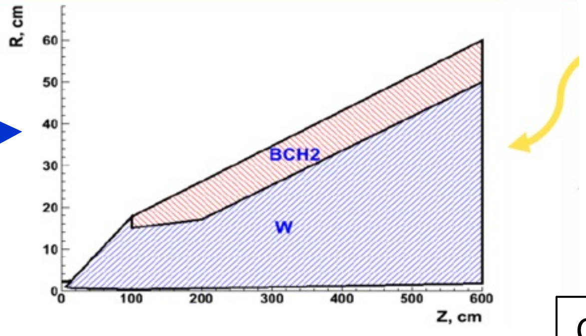
Beam Induced Backgrounds and Detector Design



JINST 13, P09004 (2018)

Beam muons decay ⇒ Beam induced Background
- Partially mitigated by placing W nozzle close to beam line

Two ~10^0 shielding tungsten nozzles, cladded with a 5-cm layer of borated polyethylene, play a crucial role in background mitigation inside the detector.

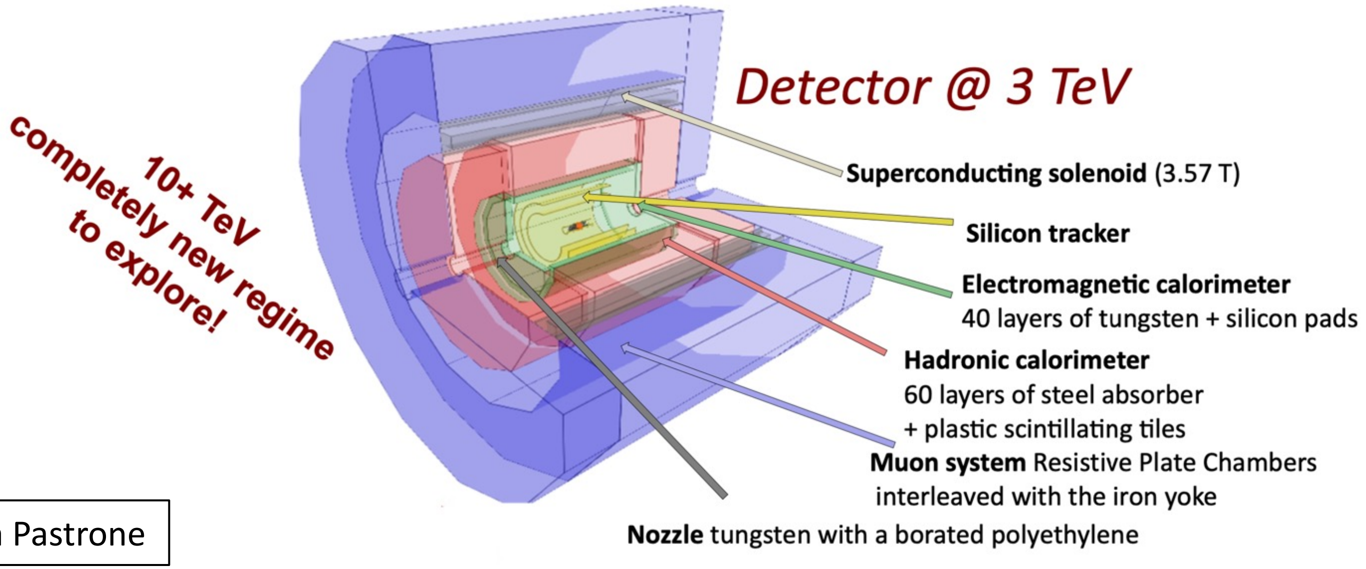


Courtecy Nadia Pastrone

Using CLIC Detector at Starting point

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology



Detector @ 3 TeV

10+ TeV completely new regime to explore!

Superconducting solenoid (3.57 T)

Silicon tracker

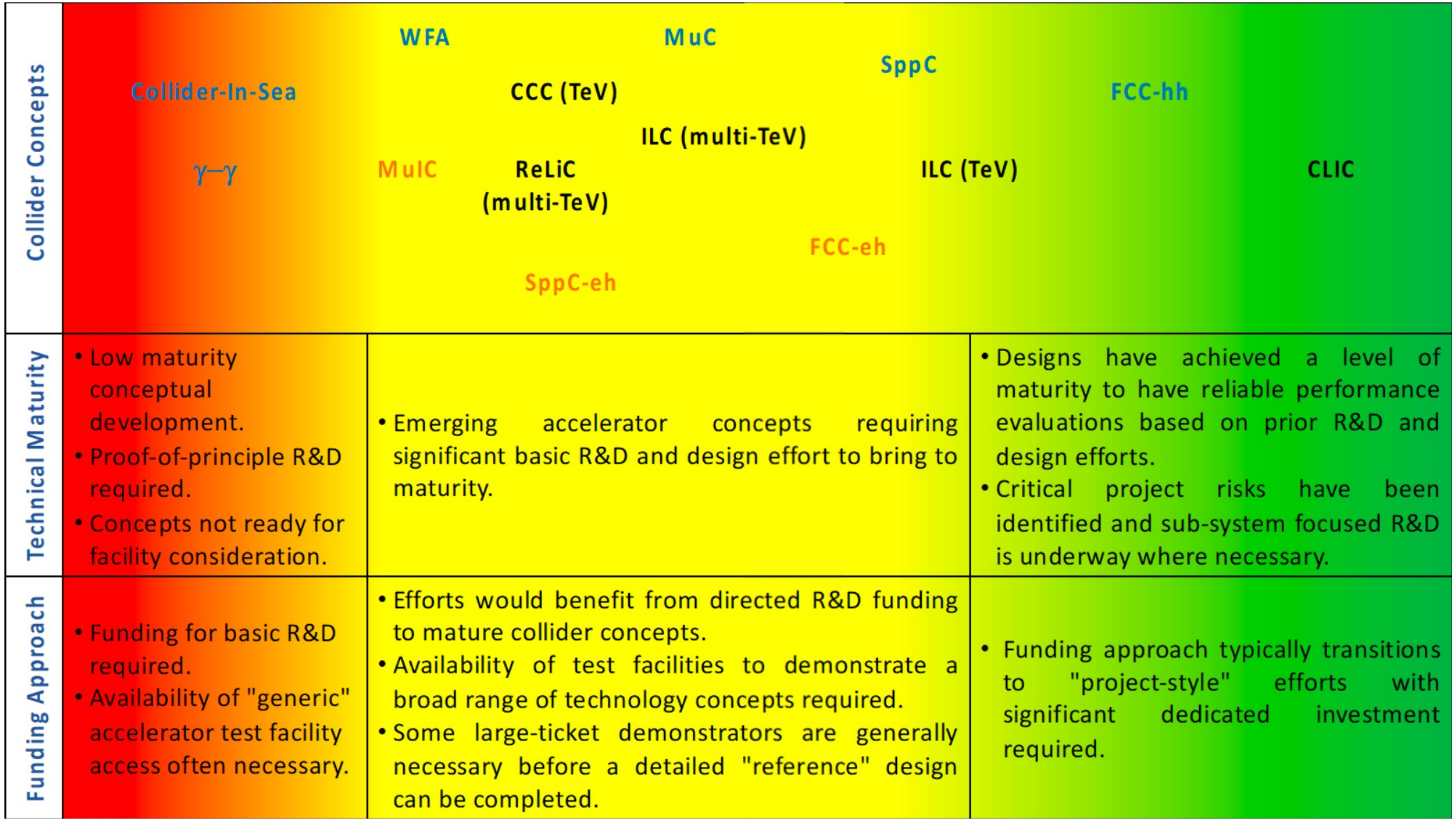
Electromagnetic calorimeter
40 layers of tungsten + silicon pads

Hadronic calorimeter
60 layers of steel absorber
+ plastic scintillating tiles

Muon system Resistive Plate Chambers
interleaved with the iron yoke

Nozzle tungsten with a borated polyethylene

Maturity level of proposed Future Accelerators



Collider Concepts

WFA

MuC

SppC

Collider-In-Sea

CCC (TeV)

FCC-hh

ILC (multi-TeV)

γ–γ

MuIC

ReLiC (multi-TeV)

ILC (TeV)

CLIC

FCC-eh

SppC-eh

Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

From Snowmass Accelerator Frontier
Topical Group on Multi-TeV Colliders (AF4)

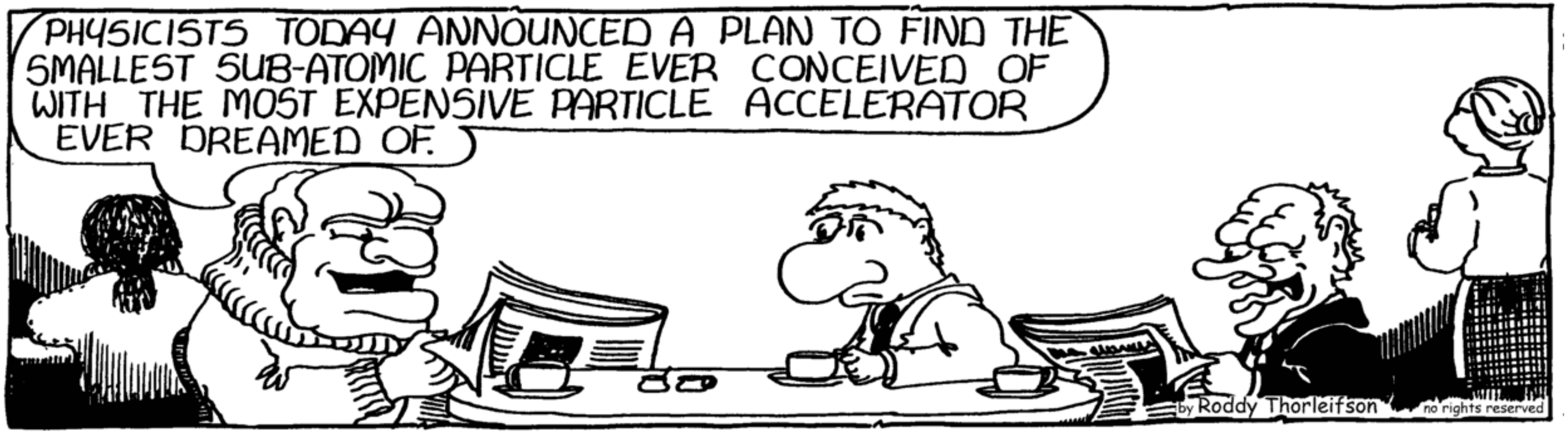
- Quotes:
  - “Significant R&D required to mature concepts in the yellow area”
  - “Green maturity level required for decision making and informed comparisons”

Outlook

- FCC Feasibility Study ongoing at CERN since decision by CERN Council, June 2021
- Mid Term Report positively received by Scientific Advisory Committee and CERN Council, Winter 2023-24
  - ⇒ Accelerated schedule towards next European Strategy Update
- Final Feasibility Study Report due in Spring 2025
  - ❑ Input to 2025 European Strategy Update
- If European Strategy falls out positive, could have FCC-ee approval by 2028 (?)
  - ❑ FCC-ee as high-luminosity factory for Z, W, and Higgs bosons, top quarks, and flavour incl. tau leptons
  - ❑ Followed (possibly) by 100 TeV discovery (and precision) FCC-hh proton-proton collider

- In parallel, exciting studies ongoing for muon collider option

Exciting future for particle physics ahead!



“*No doubt that future high energy colliders are extremely challenging projects.*

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

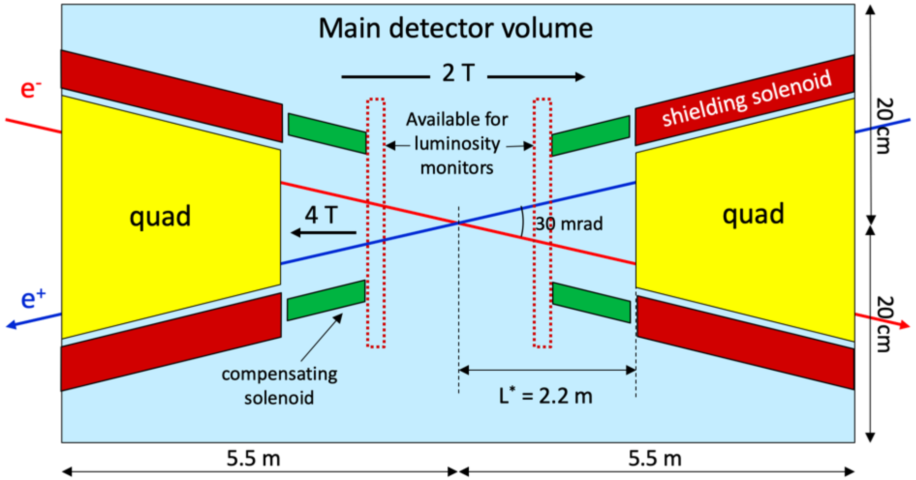
Fabiola Gianotti, DG CERN

Extras

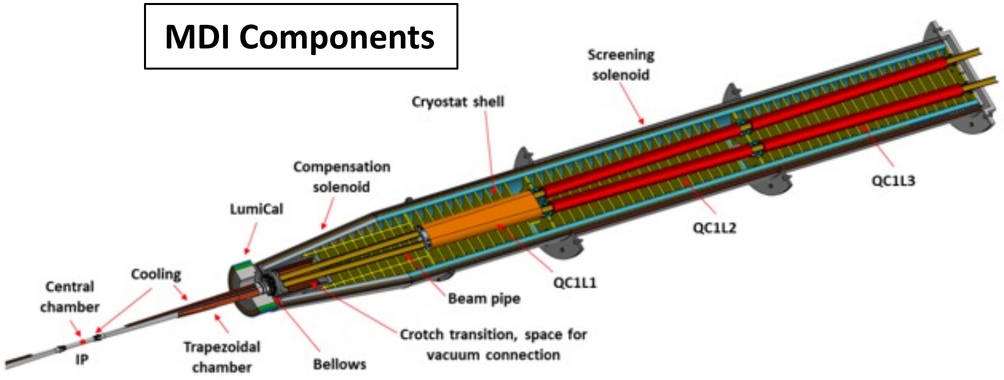
Experimental Challenges

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla (at Z-peak operation)
  - Tightly packed MDI (Machine Detector Interface)
- ”Continuous” bunches (no bunch trains); bunch spacing down to 25 ns
  - Power management and cooling (no power pulsing as planned for linear colliders)
- Extremely high luminosities
  - High statistical precision -- control of systematics down to $\sim 10^{-5}$ level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics
    - ”Big Data”
- Physics events at up to 100 kHz
  - Detector response time $\lesssim 1$ µs to minimise dead-time and event overlaps
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …

Central part of detector volume – top view



MDI Components

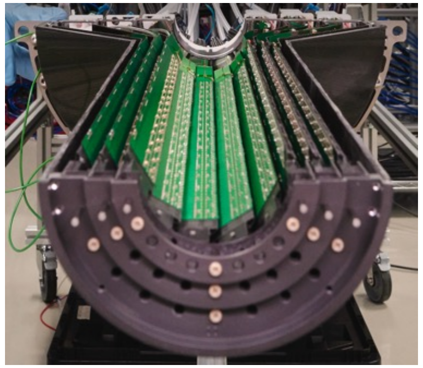


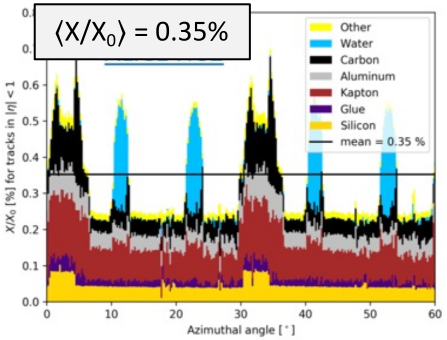
FCC-ee Detector Component: Vertex Detector

- Measurement of impact parameter, reconstruction of secondary vertices, flavour tagging, lifetime measurements
- Very strong development
  - **Lighter, more precise, closer**

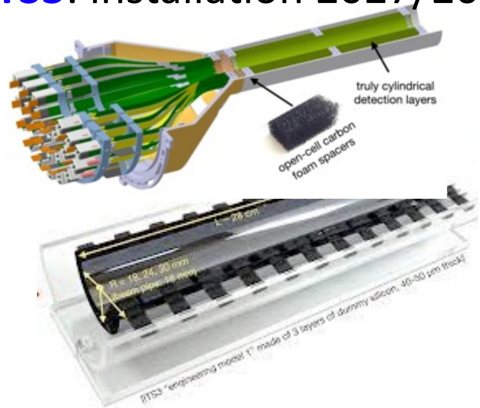
Strong ALICE Vertex detector development

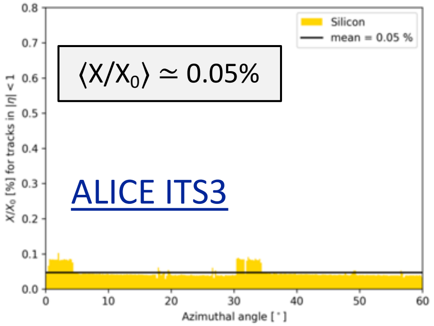
ITS2: installed in 2021





ITS3: installation 2027/2028

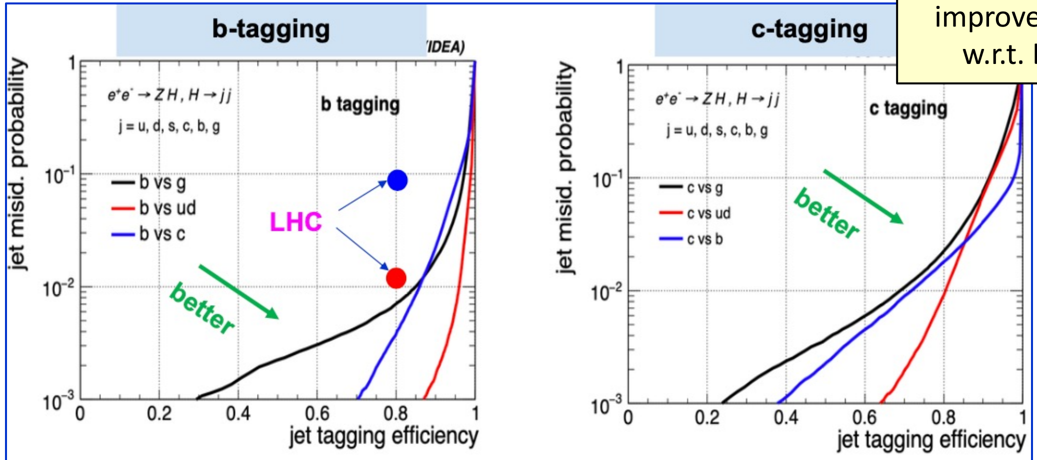




ALICE ITS3

- Many conditions/requirements common between ALICE and FCC-ee
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key
- Heavy flavour tagging results (simulation)
  - ML based: large lifetimes, displaced vertices/tracks, large track multiplicity, non-isolated e/μ

Very substantial improvement w.r.t. LHC



WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%

WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

ML-based - ParticleNet
F.Bedeschi, M.Selvaggi, L.Goukas, EPJ C 82 646 (2022) link

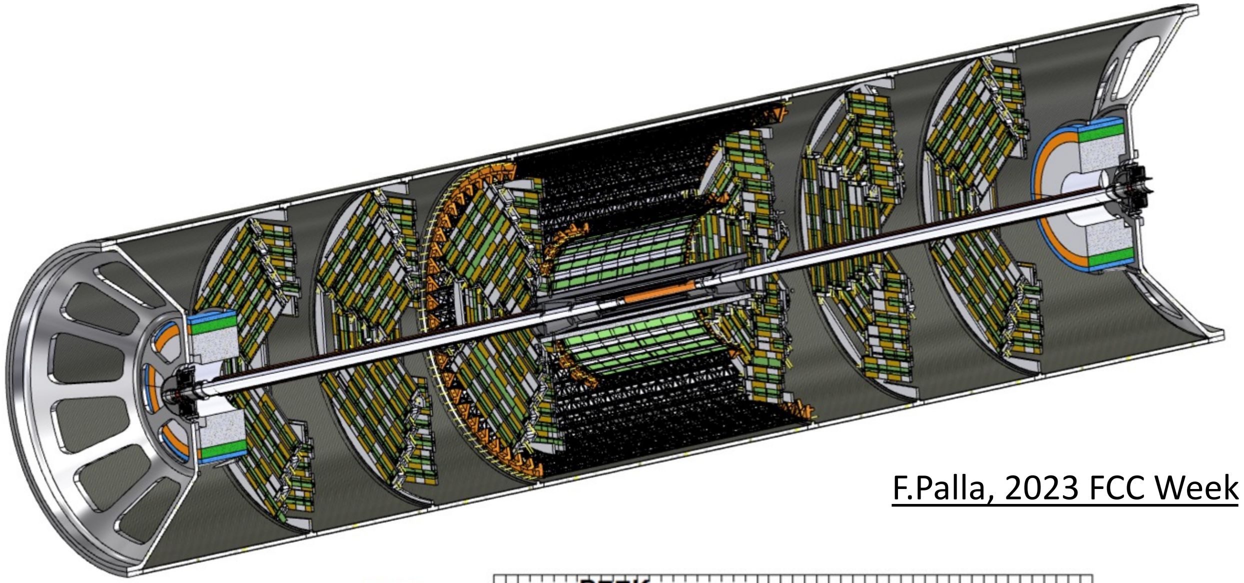
IDEA Detector Concept Vertex Detector

Vertex detector

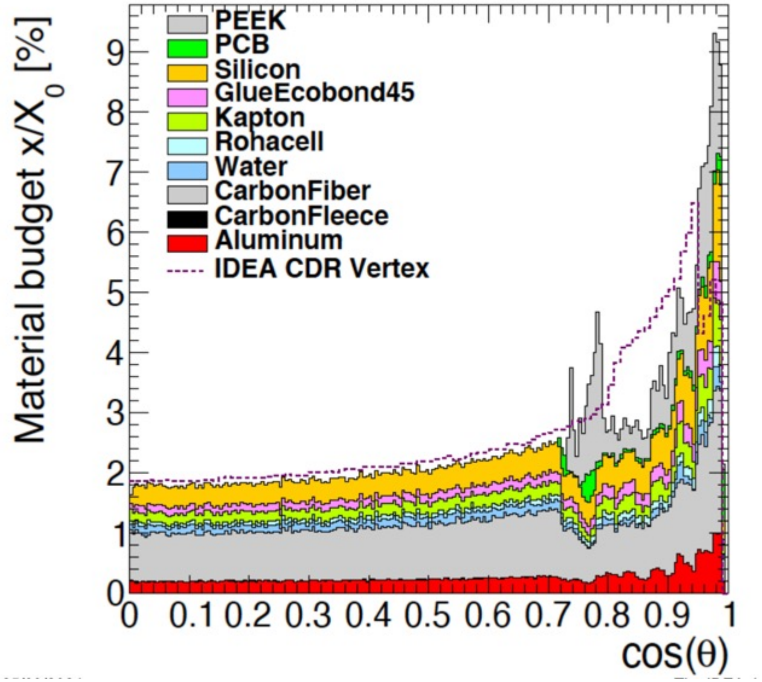
Inspired by Belle II (and ALICE ITS) based on DMAPS (Depleted Monomithic Active Pixels) technology

- Inner Vertex (ARCADIA based)
  - Modules of 25 x 25 µm pixel size, 50 µm thick
  - 3 barrel layers at 13.7, 22.7, 33 mm
    - 0.3% X_0 per layer
  - Point resolution of ~3 mm
- Outer Vertex and disks (ATLASPIX3 based)
  - Modules of 50 x 150 µm pixel size, 50 µm thick
  - 2 barrel layers at 130, 315 mm; 2 x 3 disk layers
    - 1% X_0 per layer

- Performance
  - Efficiency of ~100%
  - Extremely low fake hit rate

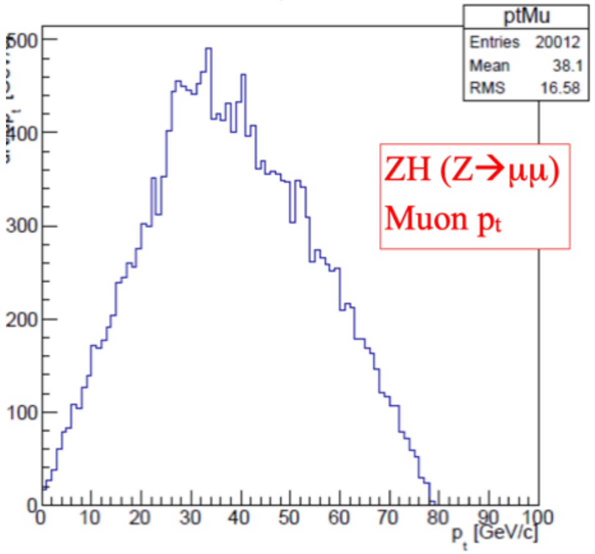


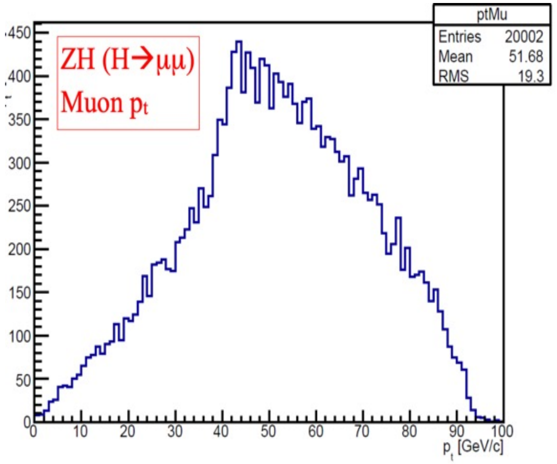
F.Palla, 2023 FCC Week



FCC-ee Detector: Momentum Measurement

Particles from Higgs production process are generally of moderate momentum





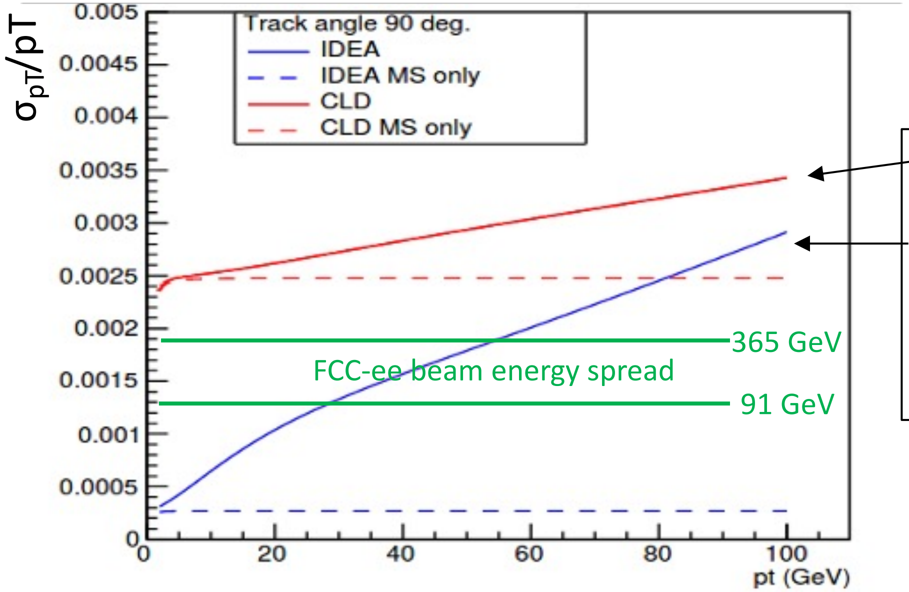
Momentum resolution tends to be multiple scattering dominated

⇒ Asymptotic resolution not reached

$$\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}^2 = a \oplus \frac{b}{p\sin\theta}$$

mult.scat

resolution



CLD: All-Si tracker with total material budget of 11%

IDEA: Drift Chamber as main tracking device with a material budget of 1.6%. Supplemented by VTX and Silicon "wrapper" surrounding drift chamber.

$$\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Thinning of Si sensors helps (only) as √ of thickness

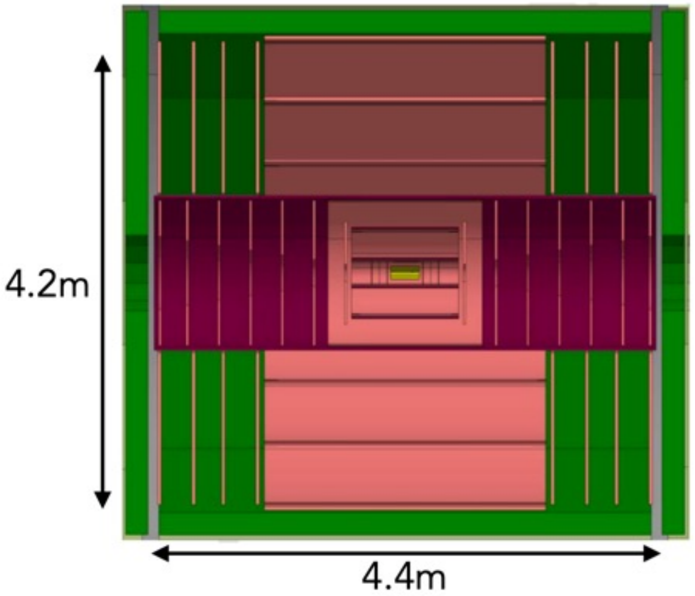
⇒ Detector transparency more important than asymptotic resolution ⇐

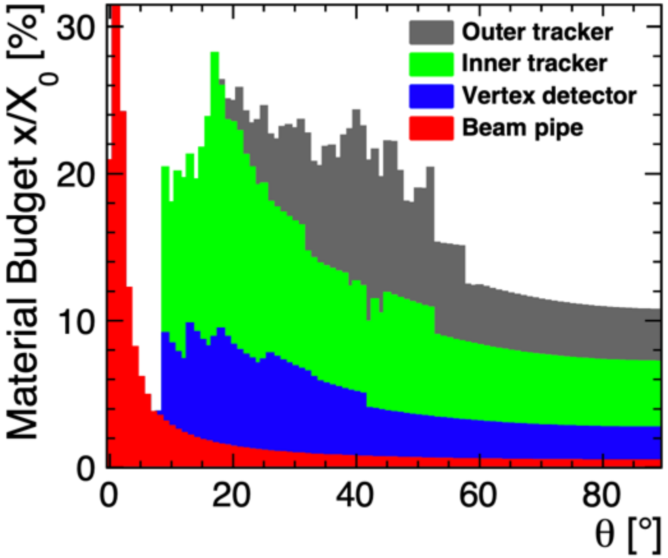
https://doi.org/10.1016/j.nima.2018.08.078

FCC-ee Component: Tracking System

Two solutions under study

- CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube (2.5% X_0)

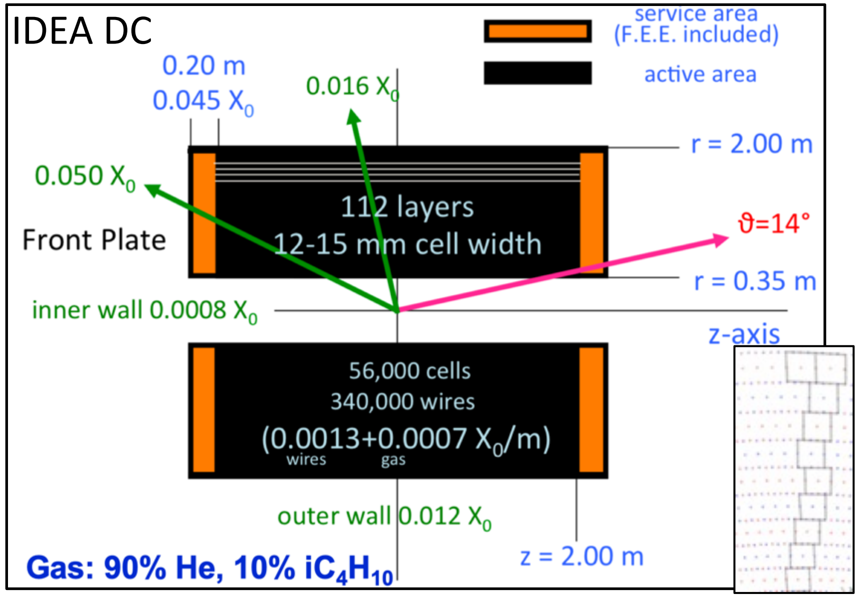


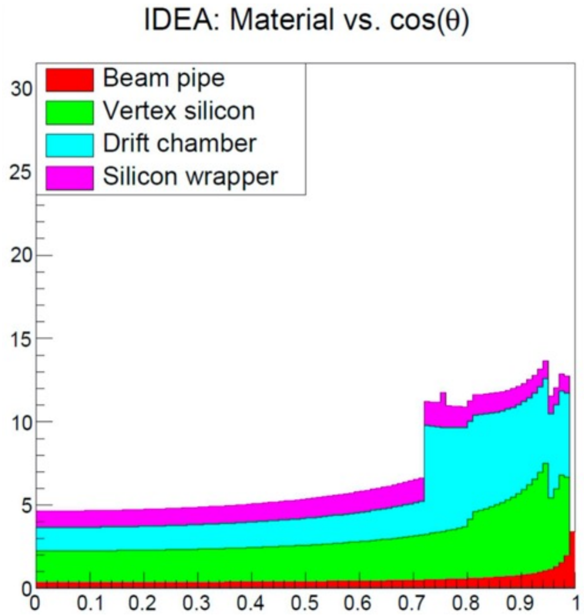


- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"

What about a TPC?

- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties…

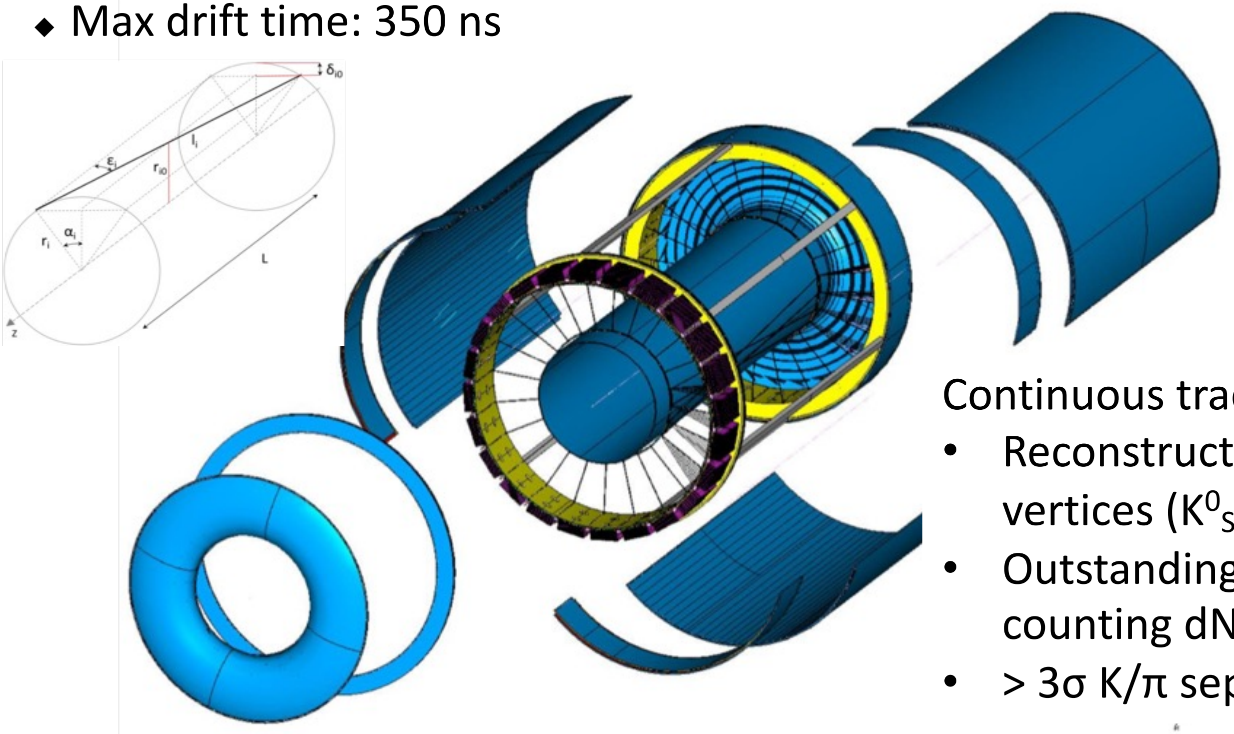




IDEA Drift Chamber

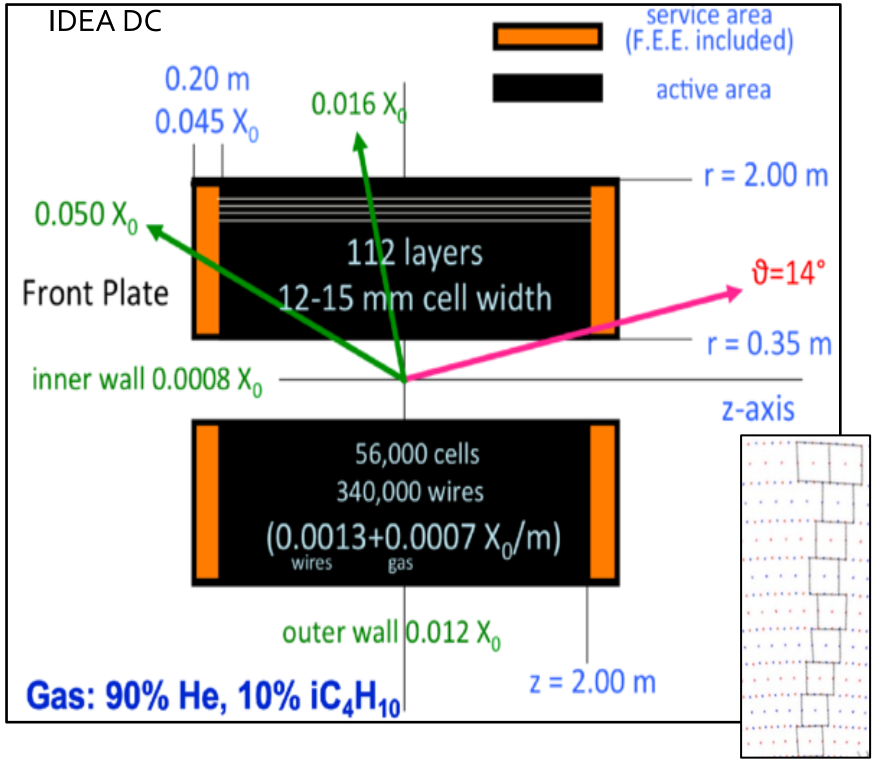
Extremely transparent Drift Chamber

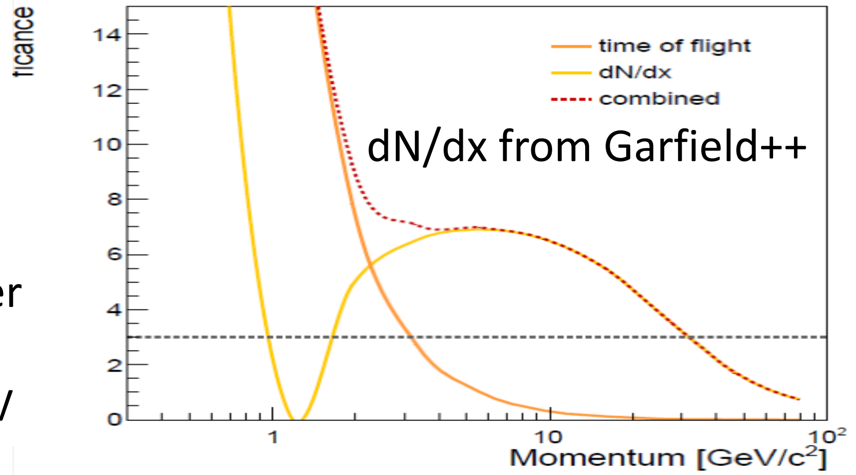
- Gas: 90% He – 10% iC_4H_{10}
- Radius: 0.35 – 200 cm
- Total thickness: 1.6% of X_0 at 90°
  - Tungsten wires dominant contributor
    - Possibility of using (gold-plated) carbon-fibre wires ?
- 112 layers for each 15° azimuthal sector
- Max drift time: 350 ns



Continuous tracking:

- Reconstruction of far-detached vertices (K^0_S, Λ, BSM, LLPs)
- Outstanding particle ID via cluster counting dN/dx or dE/dx
- > 3σ K/π separation up to 35 GeV

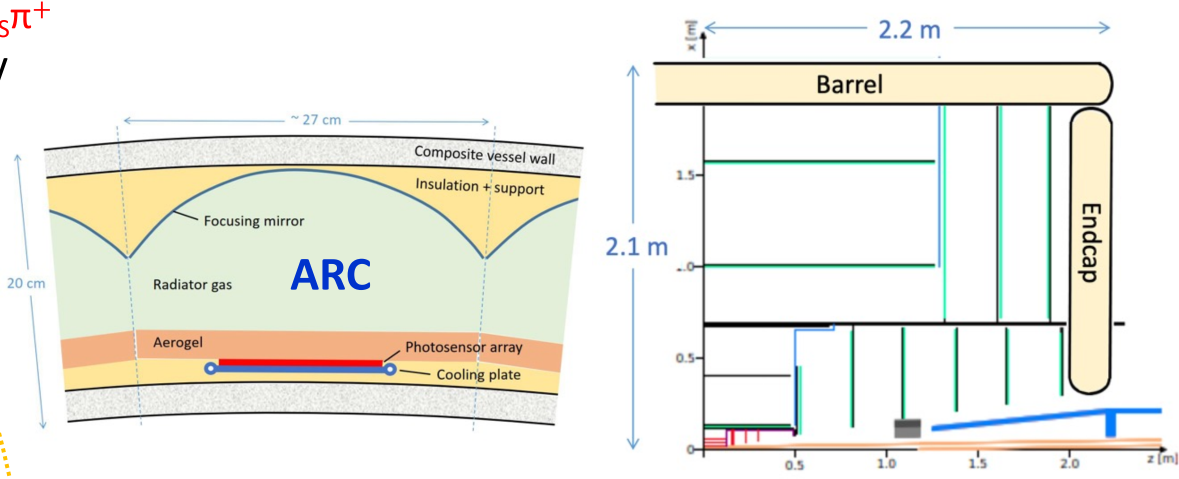


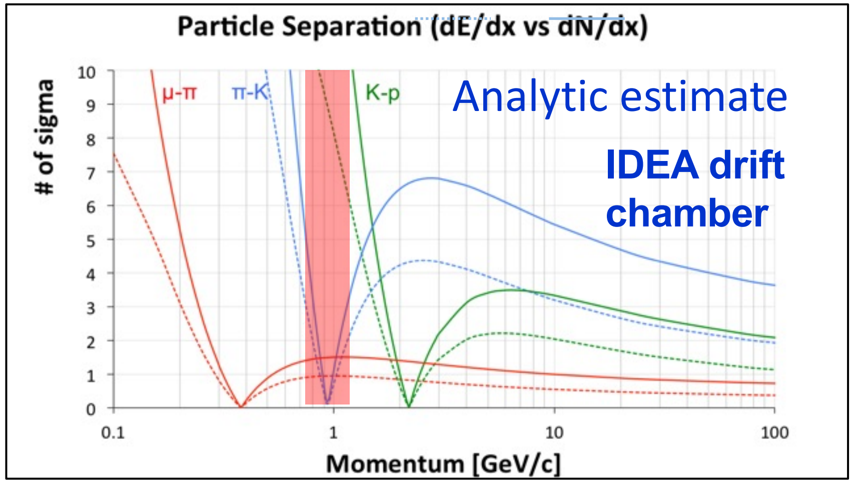


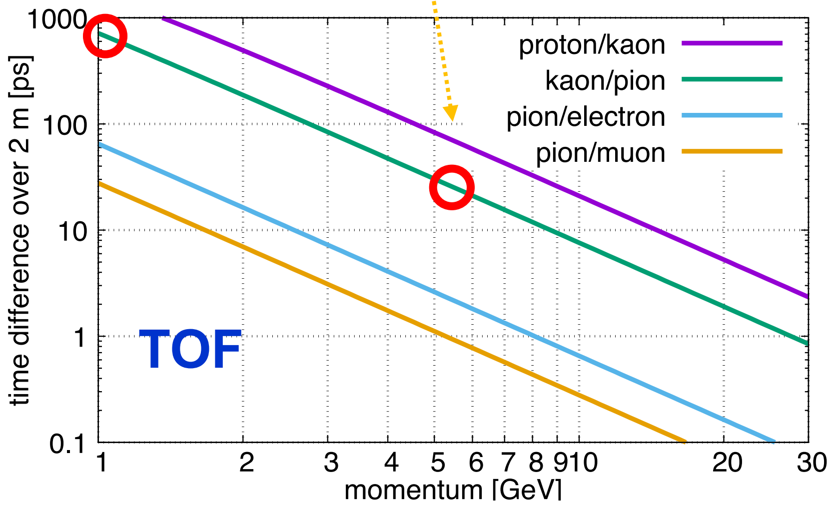
Particle Identification

- **PID capabilities across a wide momentum range** is essential for flavour studies; will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_S \rightarrow D^{\pm}_S K^{\mp}$ → require K/π separation over wide momentum range to suppress same topology $B^0_S \rightarrow D^{\pm}_S \pi^{\mp}$
- **E.g. IDEA drift chamber** promises >3σ π/K separation up to 35-100 GeV
  - Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of $\delta T \lesssim 0.5$ ns
- **Time of flight (TOF) alone** δT of ~10 ps over 2 m (LGAD)
  - could give 3σ π/K separation up to ~5 GeV
- **Alternative approaches**, in particular (gaseous) **RICH** counters are also investigated (e.g. A pressurized RICH Detector – **ARC**)
  - could give 3σ π/K separation from 5 GeV to ~80 GeV

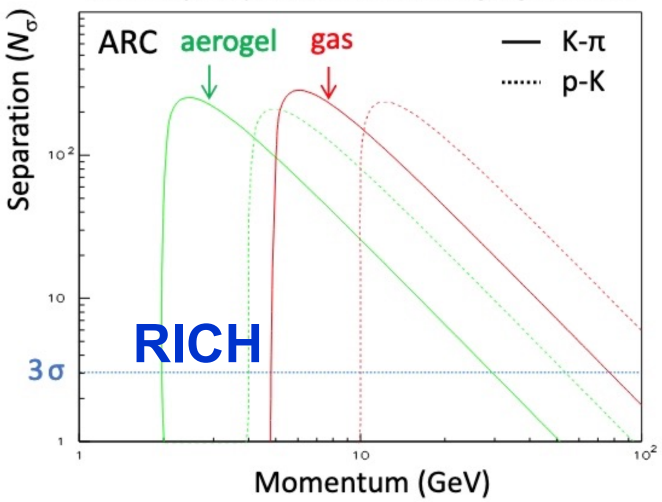
Possible RICH layout in an FCC-ee experiment







Preliminary! analytic calc., assumes focusing target achieved



Calorimetry – Jet Energy Resolution

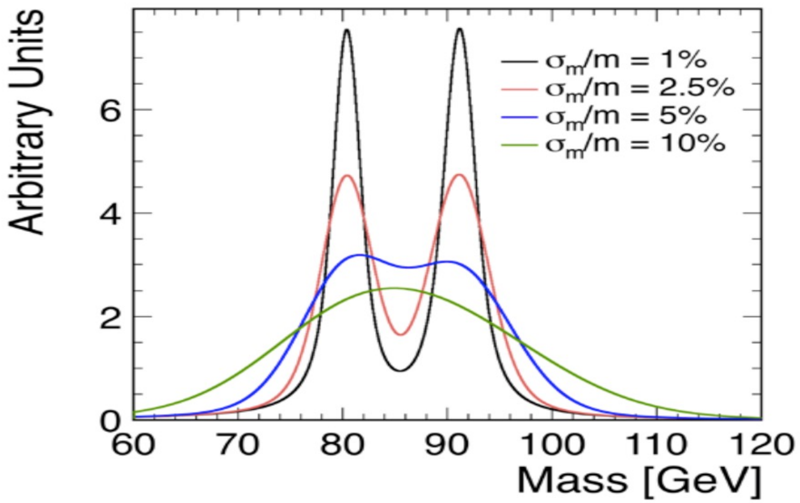
Energy coverage < 300 GeV : $22\ X_0$, 7λ
Precise jet angular resolution

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E\ [\text{GeV}]}$

⇒ Mass reconstruction from jet pairs

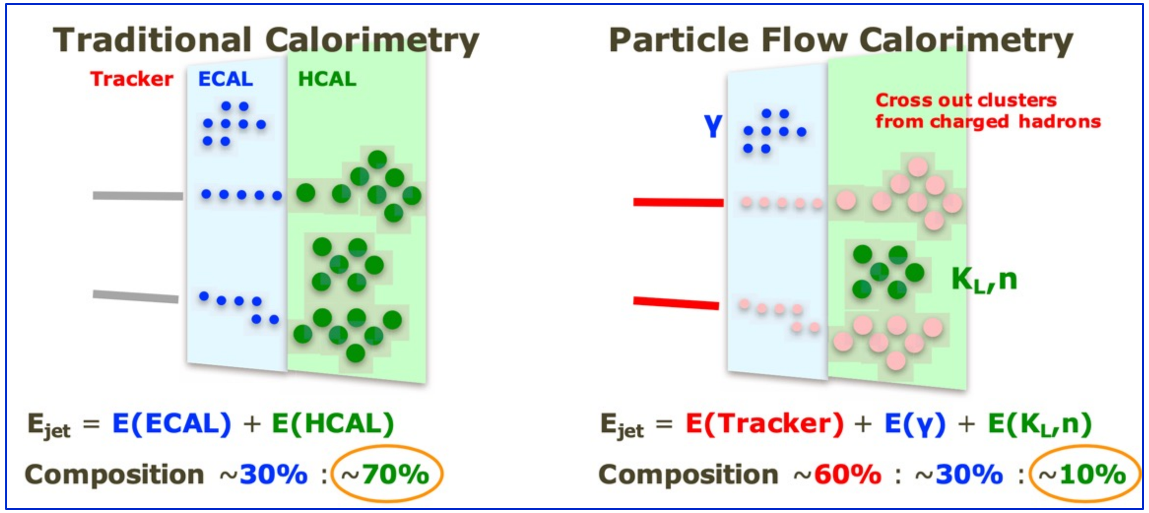
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, tt events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E\ [\text{GeV}]}$, detector resolution is comparable to natural widths of W and Z bosons



How to reach jet energy resolutions of 3-4% at 50 GeV:

- **Highly granular calorimetes**
- **Particle Flow Analysis techniques**
- The above possibly combined with techniques to correct for non-compensation (e/h ≠ 1), e.g. via *dual readout*



E_{jet} = E(ECAL) + E(HCAL)
Composition ~30% : ~70%

E_{jet} = E(Tracker) + E(γ) + E(K_L,n)
Composition ~60% : ~30% : ~10%

High granularity !
Possibly combined with dual readout

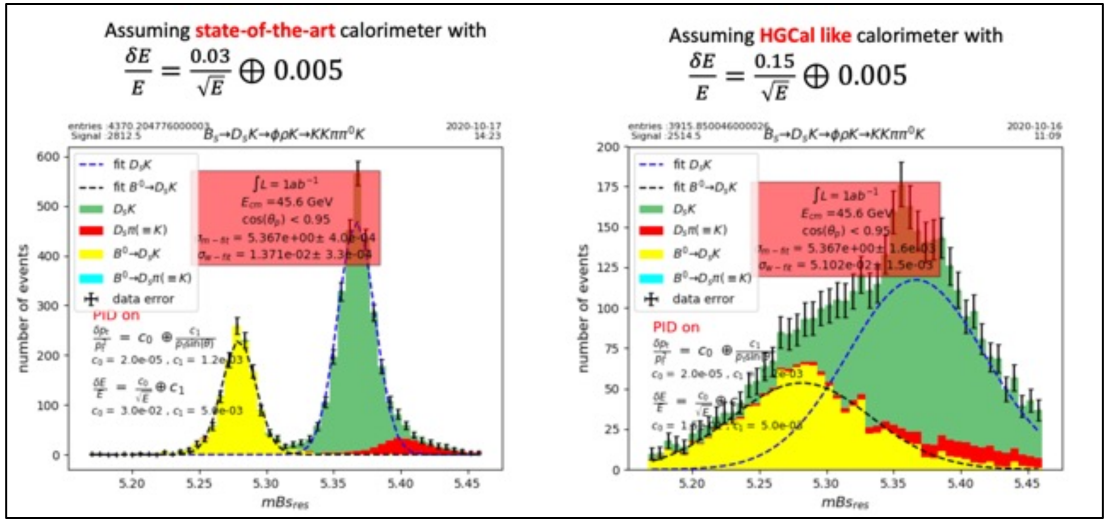
Calorimetry - Requirements

Incomplete list of requirements – all under study

- Energy resolution
  - Photons and neutral hadrons for PFlow
  - Electrons and charged hadrons for PID (E/p measurement)
- Dynamic range: 200 MeV – 180 GeV
  - For π^0 identification in flavour physics, sensitivity to photons down to few 100 MeV (as at LEP)
  - Much lower than at LHC
- Granularity: PID (γ vs. π^0), disentangle showers for Pflow
  - Requirement under study
- Hermeticity, uniformity, calibrability, stability
  - Low systematics for precision measurements
  - Complex engineering questions
- No need to be particularly fast
  - But can precise timing help in reconstricting showers?

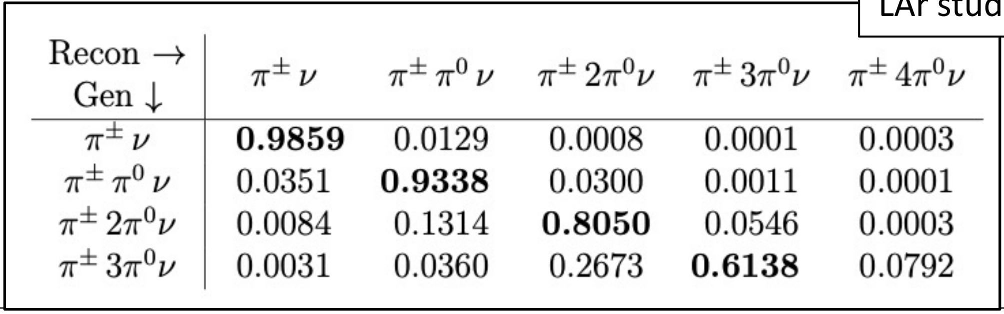
Examples of specific requirements

- Much improved flavour and tau physics reach from improved ECAL energy and spatial resolution
  - For b-physics by making accesible exclusive channels with π^0's


Assuming **state-of-the-art** calorimeter with $\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$

Assuming **HGCal like** calorimeter with $\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$

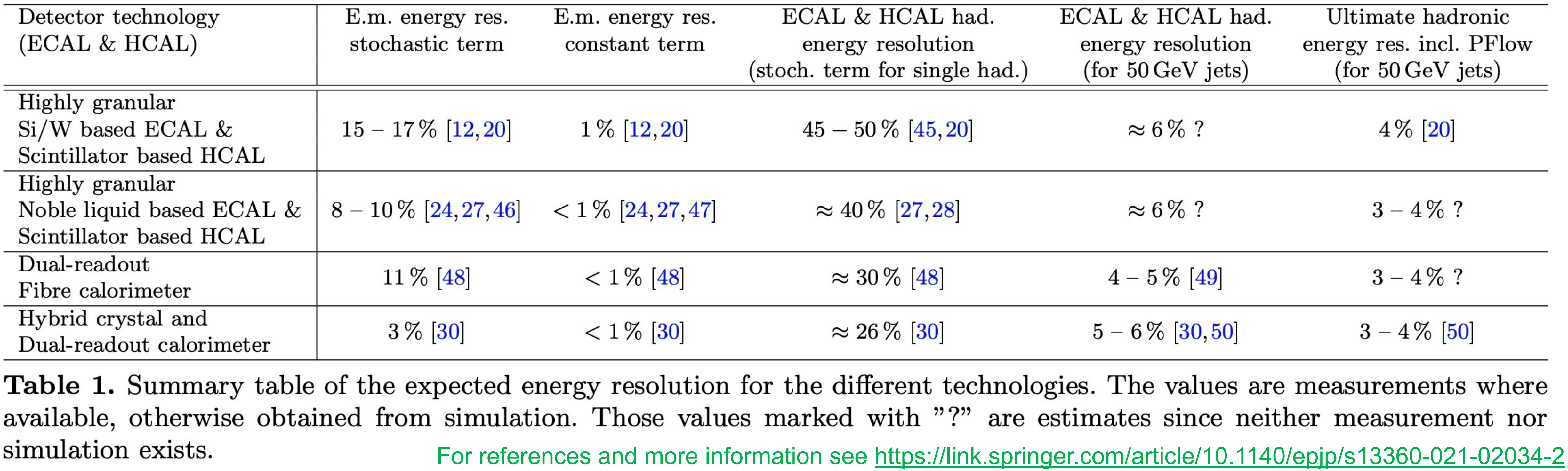
  - For tau-physics, control of decay-mode migration matrix essential



Recon → Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9859**	0.0129	0.0008	0.0001	0.0003
$\pi^\pm \pi^0 \nu$	0.0351	**0.9338**	0.0300	0.0011	0.0001
$\pi^\pm 2\pi^0 \nu$	0.0084	0.1314	**0.8050**	0.0546	0.0003
$\pi^\pm 3\pi^0 \nu$	0.0031	0.0360	0.2673	**0.6138**	0.0792

LAr study

Calorimetry – Overview of Technologies



Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12, 20]	1 % [12, 20]	45 – 50 % [45, 20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24, 27, 46]	< 1 % [24, 27, 47]	≈ 40 % [27, 28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30, 50]	3 – 4 % [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

- **Excellent Jet resolution:** ≈ 30%/√E
- **ECAL resolution:** Higgs physics ≈ 15%/√E; but for heavy flavour programme better resolution beneficial → 8%/√E → 3%/√E
- **Fine segmentation for PF algorithm** and powerful **γ/π⁰ separation** and measurement
- **Other concerns:** Operational stability, cost, …
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, …

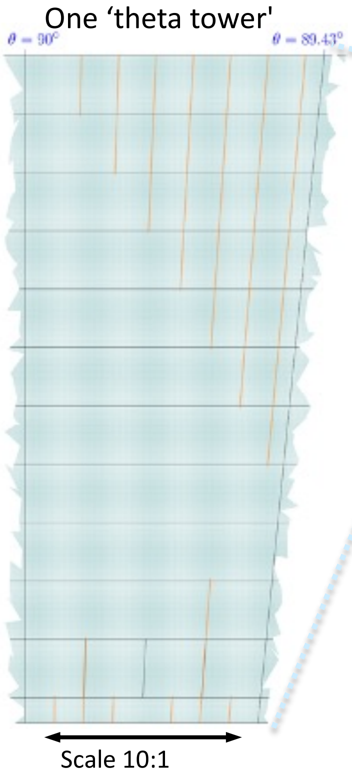
Allegro Detector Concept - High Granularity Noble-Liquid Calorimeter

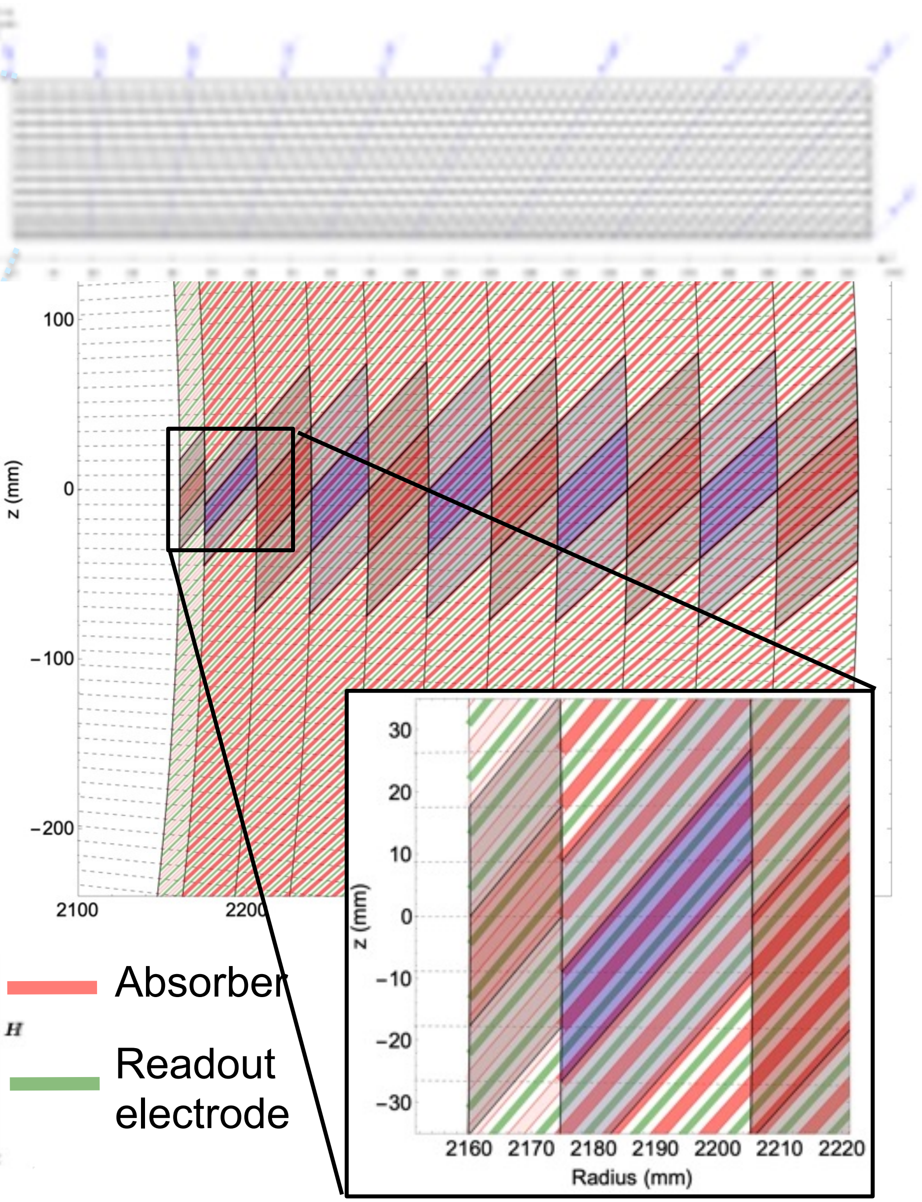
Baseline design

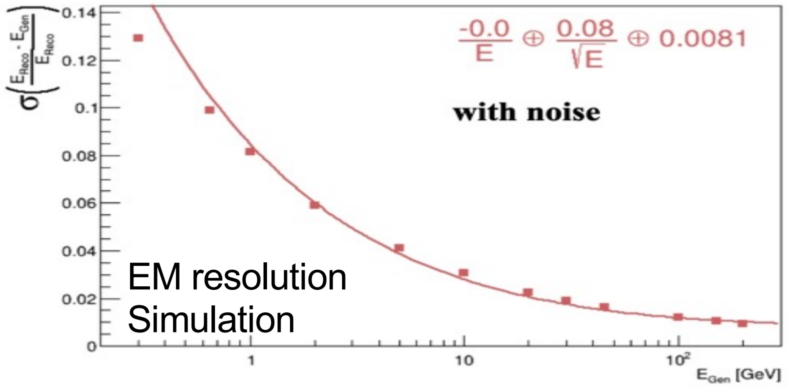
- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40 cm deep (≈ 22 X_0)
- Segmentation:
  - 11 longitudinal compartments
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells
  - $\Delta\phi$ = 8 mrad

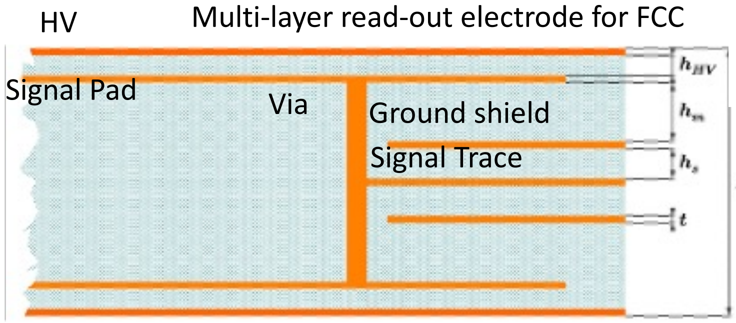
Possible options

- LKr or LAr active, W or Pb absorbers
- Absorbers with growing thickness
- Al or carbon fibre cryostat
- Warm or cold electronics







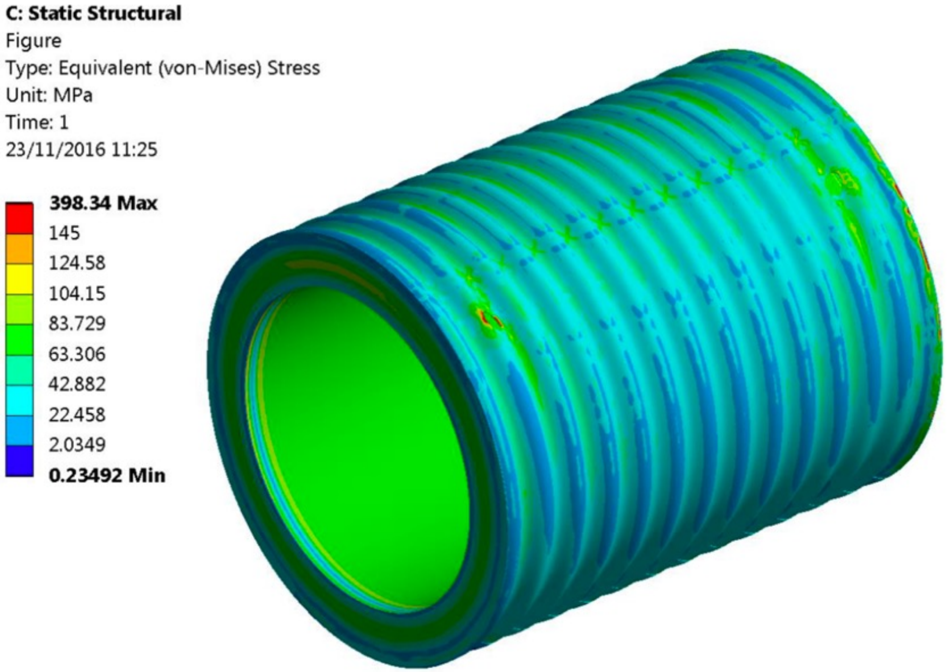


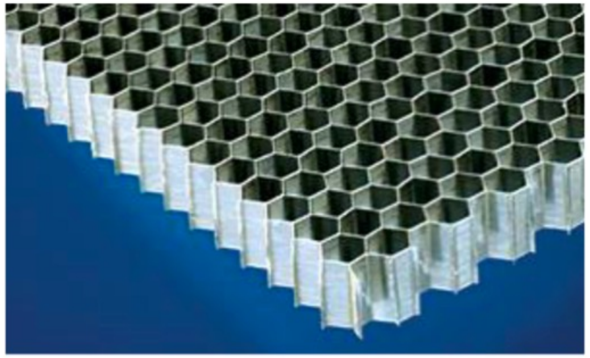
Thin, transparent Superconducting solenoid

Ultra light 2 T solenoid inside calorimetry

- Radial envelope 30 cm
- Single layer self-supporting winding (20 kA)
  - Cold mass: $X_0 = 0.47$, $\lambda = 0.09$
- Vacuum vessel (25 mm Al): $X_0 = 0.28$
  - Can be improved with new technologies
    - Corrugated plate: $X_0 = 0.11$
    - Honeycomb: $X_0 = 0.04$

Courtesy of H. TenKate





A few words on Readout, DAQ, Data Handling

- In particular at Giga-Z operation, challenging conditions
  - ❑ 40 MHz BX rate
  - ❑ Physics rate at 100 kHz plus similar LumiCal rate
  - ❑ Absolute normalisation goal of 10^{-4} or better
- Different detector components tend to prefer different integration times
  - ❑ Silicon VTX/tracker sensors: $\mathcal{O}$(1 µs) [also to save power]
    - ❖ BX identification via time-stamping (at least at track level) will be needed
  - ❑ LumiCal: Preferential at ~BX frequency (25 ns)
    - ❖ Avoid additional event pileup
- How to organize readout?
  - ❑ **Hardware trigger** with latency buffering a la LHC ??
    - ❖ Probably not… or ???
    - ❖ Which detector element would provide the trigger to the required precision?
  - ❑ **Free streaming** of self-triggering sub-detectors; event building based on time stamping
    - ❖ Need careful treatment of relative normalisation of sub-detectors to 10^{-5} level

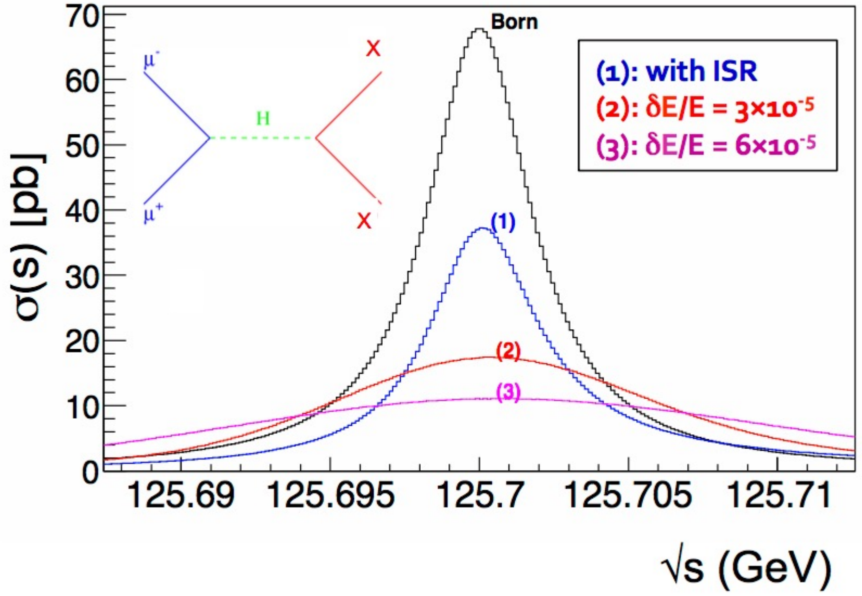
- Need to consider Trigger(?) & DAQ issues as an integral part of detector design
  - ❑ "Thinking about the DAQ later" will very likely lead us into trouble
- Plus, need to plan for off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - ❑ Plus Monte Carlo

Hardware trigger
- trigger buckets as in ATLAS/CMS

Free streaming
-LHCb DAQ upgrade
-Detectors at EIC

Muon collider as a Higgs factory (1)

- Challenges for the Higgs factory
  - Γ_H is small (4.2 MeV in the SM)
    - Similar or smaller beam energy spread is required ($3 \cdot 10^{-5}$)
      - Fast longitudinal cooling to reduce energy spread
    - Beam energy reproducibility must be at the same level or better



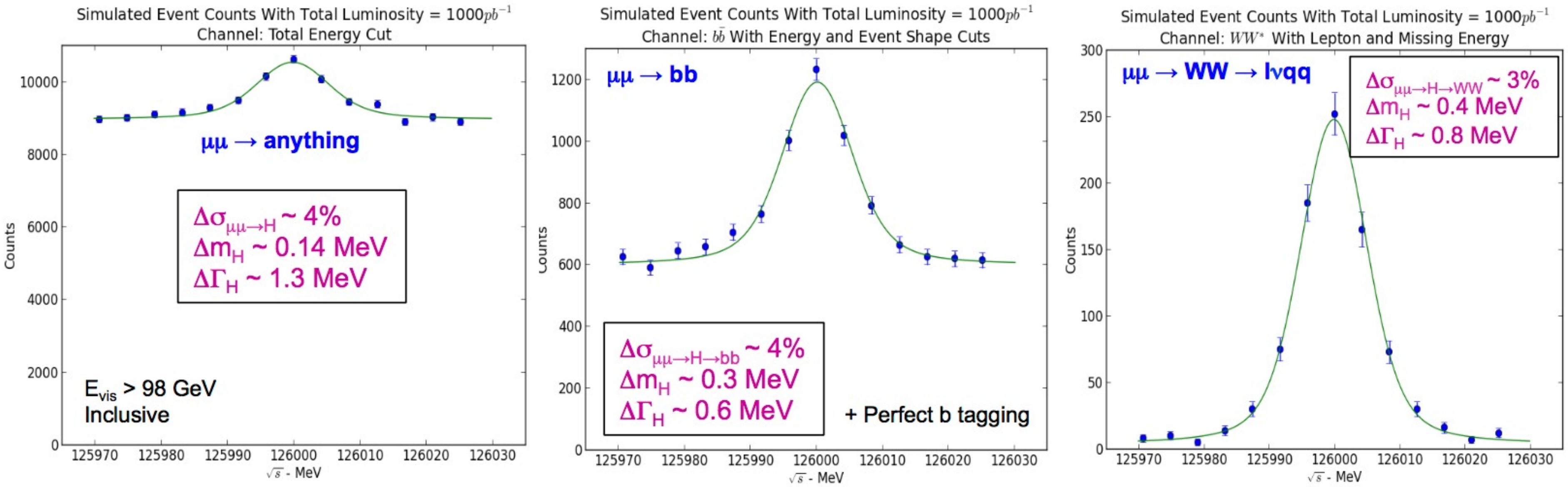
  - $\sigma(\mu^+\mu^- \to H)$ is about 20 pb
    - Luminosity must be at the level of **1.6×10^{32} cm^{-2}s^{-1} for the same number of Higgs bosons as ILC …**
    - **and at the level of 1.6×10^{33} cm^{-2}s^{-1} for the same number of Higgs bosons as FCC-ee**
      - **Fast transverse cooling to reduce beam spot dimensions**

And the Higgs bosons produced are not tagged with a Z anyway …

  - **Problem**
    - **Longitudinal and transverse cooling are antagonistic**
      - **Luminosity is limited (as of today's knowledge) to a few 10^{31} cm^{-2}s^{-1}**

Muon collider as a Higgs factory (2)

- Physics performance of a Higgs factory
  - Scan of Higgs resonance in the inclusive bb and WW final states
    - Ten years of data taking at 10^{31} cm^{-2}s^{-1}, just count events



  - Measure Γ_H to 5% in 10 years (cf. 4% at ILC, <1% at FCC-ee)
    - Only way to see a structure in the resonance (several Higgs bosons?)
  - Measure σ_{peak} ~ $BR_{\mu\mu}$ to 2-3% in 10 years
  - Other expected measurement on the figures

Muon collider as a Higgs factory (3)

- Summary of precision measuremetns (after ~10 years of running)

Error on	μμ collider	ILC$_{250}$	FCC-ee
m_H (MeV)	0.06	14	8
Γ_H (MeV)	0.17	0.11	0.06
g_{Hbb}	2.3%	1.8%	0.61%
g_{HWW}	2.2%	1.7%	0.43%
$g_{H\tau\tau}$	5%	1.9%	0.80%
$g_{H\gamma\gamma}$	10%	6.4%	3.8%
$g_{H\mu\mu}$	2.1%	13%	8.6%
g_{HZZ}	-	0.35%	0.17%
g_{Hcc}	-	2.3%	1.2%
g_{Hgg}	-	2.2%	1.0%
BR_{invis}	-	<0.5%	<0.1%

Not obvious what is the practical use of such high precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

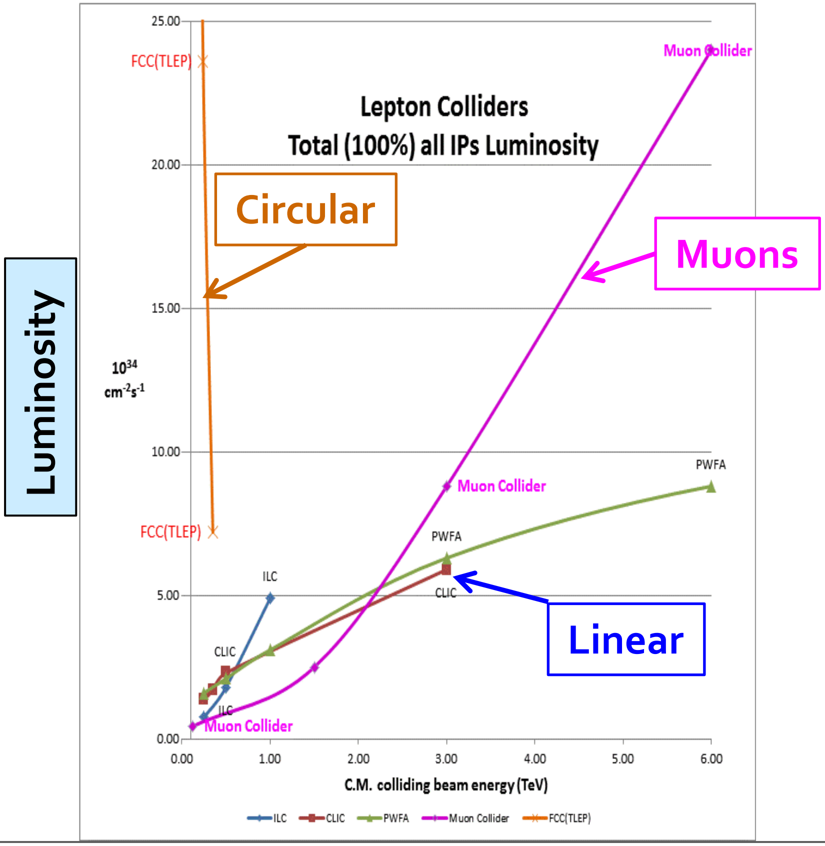
The Higgs coupling to muons is *the* added value of a μμ collider

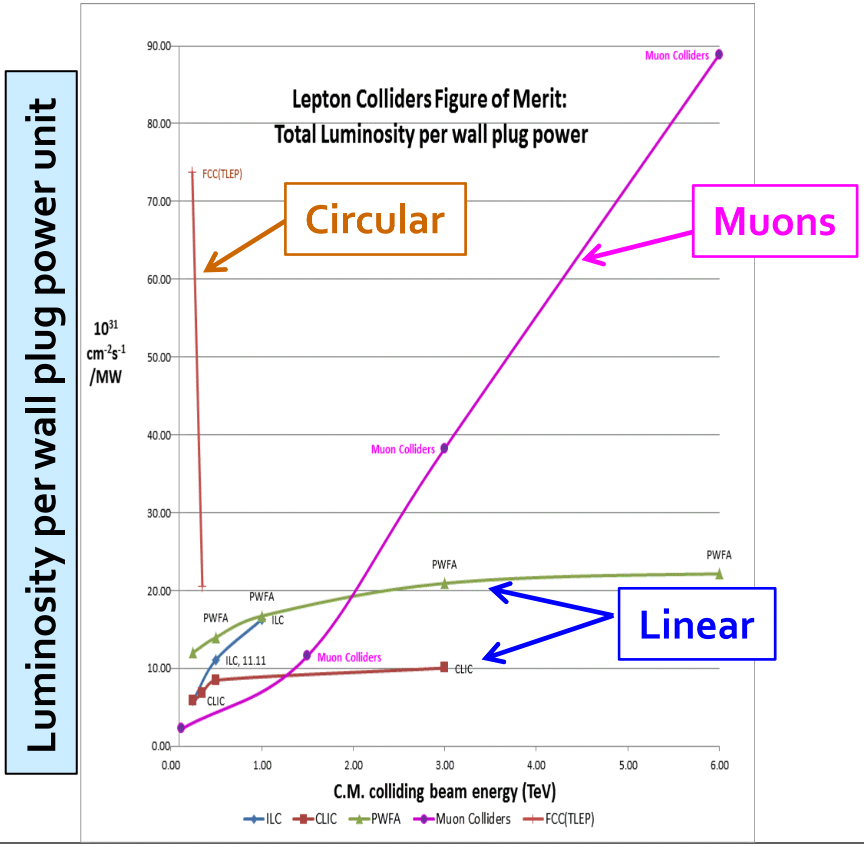
These Higgs couplings are *only* measured at ee colliders *)

- Note: BR(H→μμ) can be also measured with % precision af FCC-hh (Will be already 5% after HL-LHC)

Muon colliders at the energy frontier

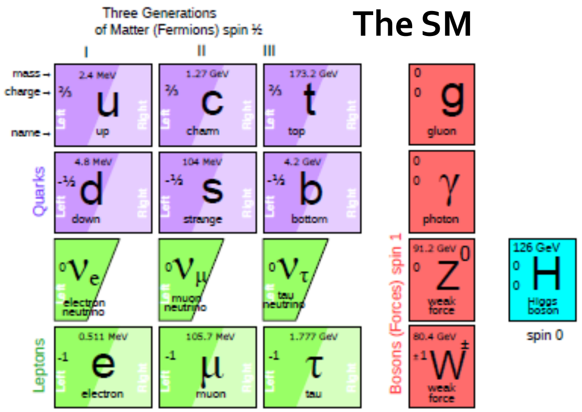
- Muon colliders might be a solution for high energy in the (far?) future
  - Many challenges to solve with sustained R&D and innovative thinking, as to
    - Increase luminosity for precision studies
    - Solve the radiation hazard at high energy (decay neutrino interactions in Earth)
  - Target luminosity competitive with CLIC above 2-3 TeV
    - With the possibility of several IPs

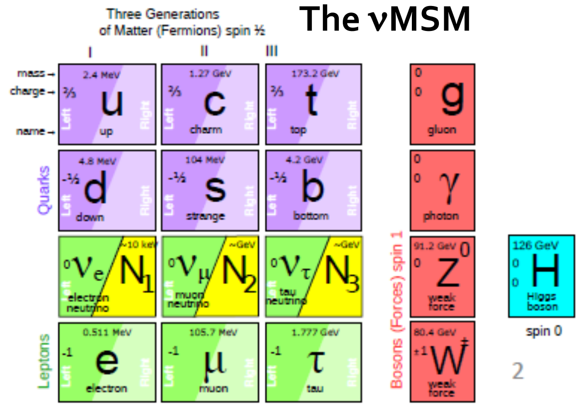




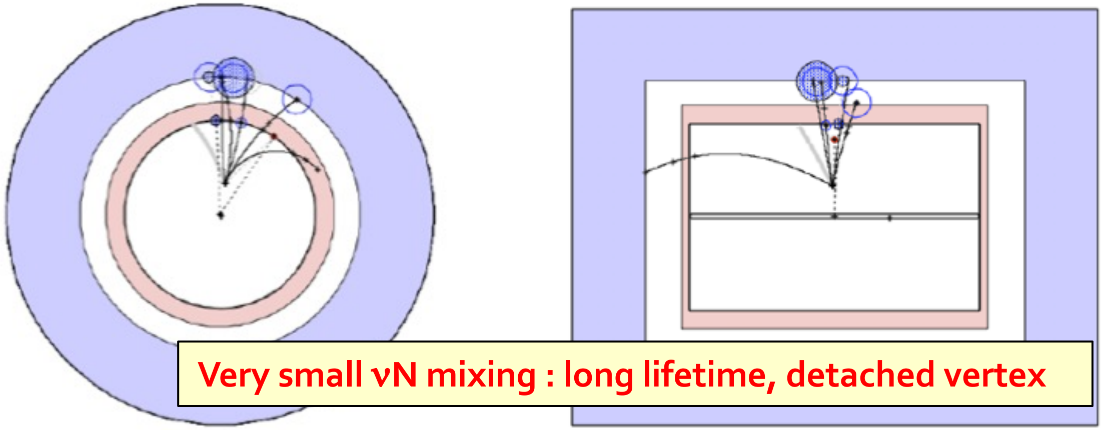
Potential for direct discoveries – Feebly interacting particles

- Example: Right-handed neutrinos
  - ❑ νMSM : Complete particle spectrum with the missing three right-handed neutrinos

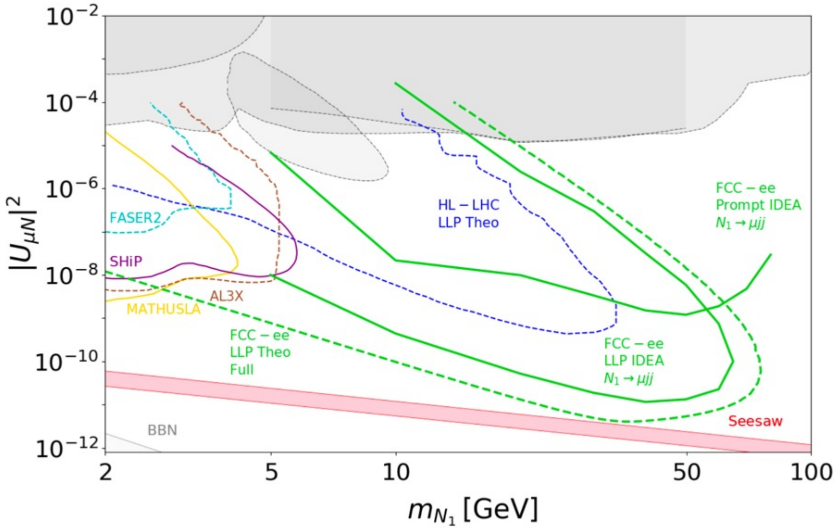




    - ❖ Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
  - ❑ Searched for in very rare $Z \to \nu N_{2,3}$ decays, followed by $N_{2,3} \to W^* \ell$ or $Z^* \nu$
    - ❖ TeraZ sample: perfect!

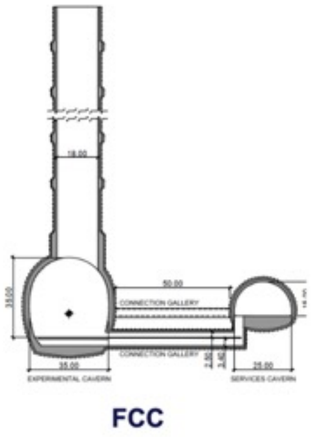


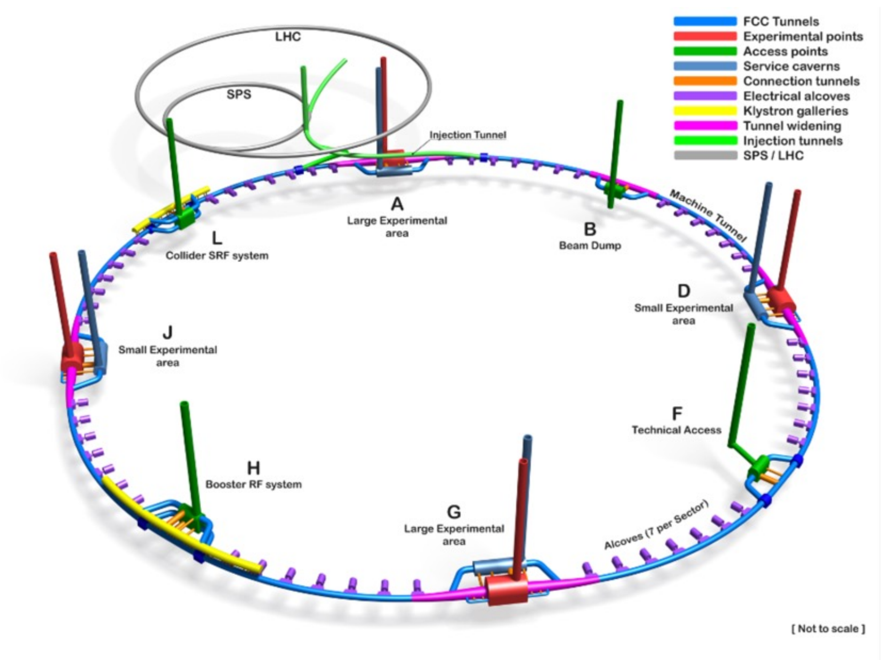
Very small νN mixing : long lifetime, detached vertex



FCC Strengths

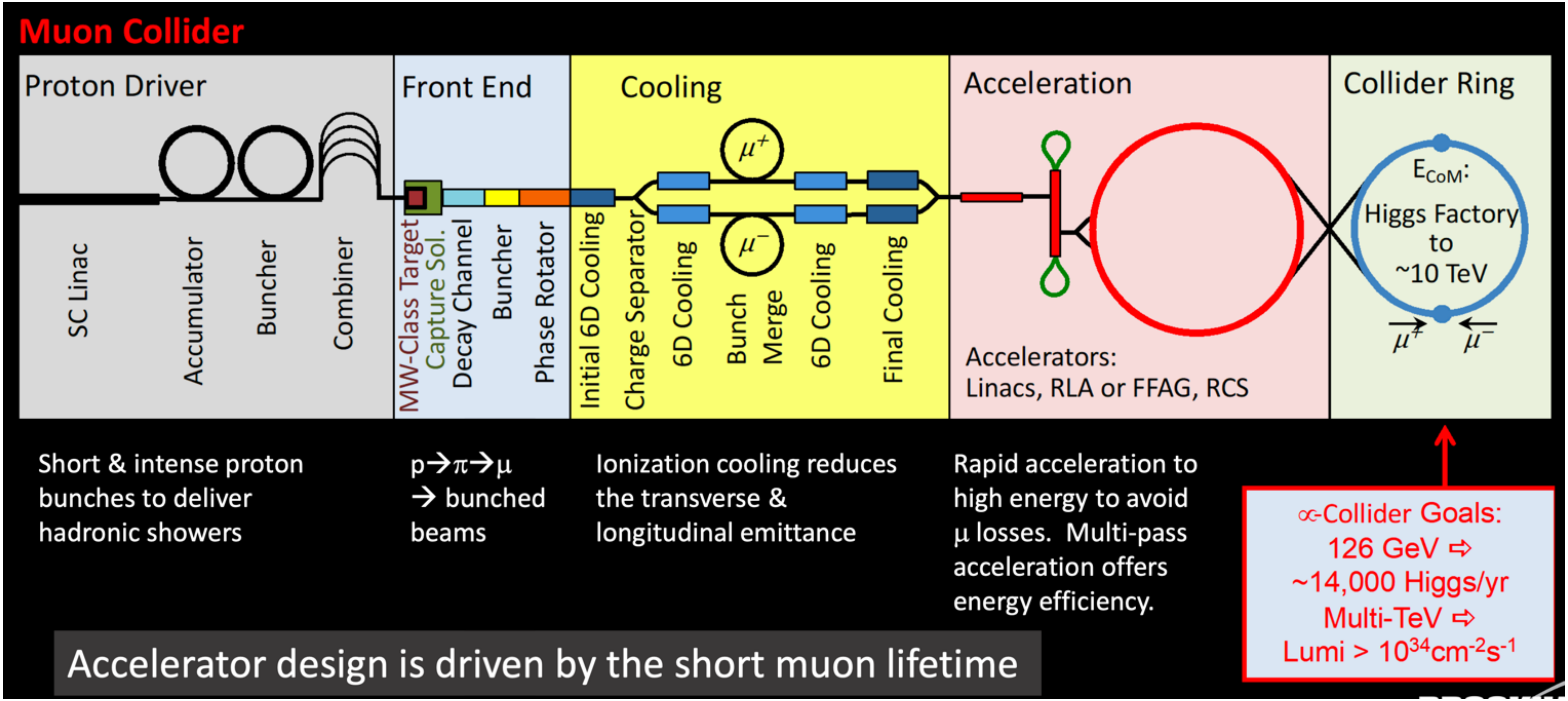
- Shared infrastructure (as for LEP + LHC)
  - Using one tunnel and one set of caverns for both stages
    - 90.7 km ring, 8 surface points
    - 4 experimental areas
      - Accomodating the size of the CERN community





- Time scale
  - FCC-ee technology is mature → construction in parallel with HL-LHC operation
  - Physics operation few years after HL-LHC
  - Allows 20 years of R&D towards optimal and affordable FCC-hh high-field magnets
    - 16-20 Tesla

Muon Collider Layout



Muon Collider

Accelerators:
Linacs, RLA or FFAG, RCS

Short & intense proton bunches to deliver hadronic showers

p→π→μ
→ bunched beams

Ionization cooling reduces the transverse & longitudinal emittance

Rapid acceleration to high energy to avoid μ losses. Multi-pass acceleration offers energy efficiency.

∝-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > $10^{34}cm^{-2}s^{-1}$

Accelerator design is driven by the short muon lifetime

FCC-ee – A plethora of Detector Requirements

”Higgs Factory” Programme	• At two energies, 240 and 365 GeV, collect in total • 1.2M HZ events and 75k WW → H events • Higgs couplings to fermions and bosons • Higgs self-coupling (2-4 σ) via loop diagrams • Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ √s = 125 GeV	• Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread • Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation • Superior impact parameter resolution for c-, b- tagging, PID for s-tagging
Ultra Precise EW Programme & QCD	Measurement of EW parameters with factor ~300 improvement in *statistical* precision w.r.t. current WA • 5×10^{12} Z and 10^8 WW: **m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…** • 10^6 tt: **m_{top} , Γ_{top} , EW couplings** Indirect sensitivity to new physics up to Λ=70 TeV scale	• Absolute normalisation (luminosity) to 10^{-4} • Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5} • Momentum resolution ”as good as we can get it” • Multiple scattering limited • Track angular resolution < 0.1 mrad (BES from μμ) • Stability of B-field to 10^{-6} : stability of √s meast
Heavy Flavour Programme	• Enormous statistics from Z decays: 10^{12} bb, cc; 1.7×10^{11} ττ • Extremely clean environment, favourable kinematic conditions (boost) from Z decays • CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality	• Impact parameter resolution: secondary vertices, tagging, identification, life-times • ECAL resol. at few %/√E for mass of final states with π^0s / γs • Excellent π^0/γ separation and measurement (granularity) • PID: K/π separation over wide momentum range

Feebly Coupled Particles - LLPs	Intensity frontier (Z decays): Opportunity to directly observe new feebly interacting particles with masses below m_Z :
	• Axion-like particles, dark photons, Heavy Neutral Leptons
	• Signatures: long lifetimes – LLPs or ”mono-jets”
		• Benchmark signature: Z → νN, with N decaying late
		• Sensitivity to far detached vertices (mm → m)
		  • Tracking: more layers, continous tracking
		  • Calorimetry: granularity, tracking capability
		• Precise timing for velocity (mass) estimate
		• Hermeticity