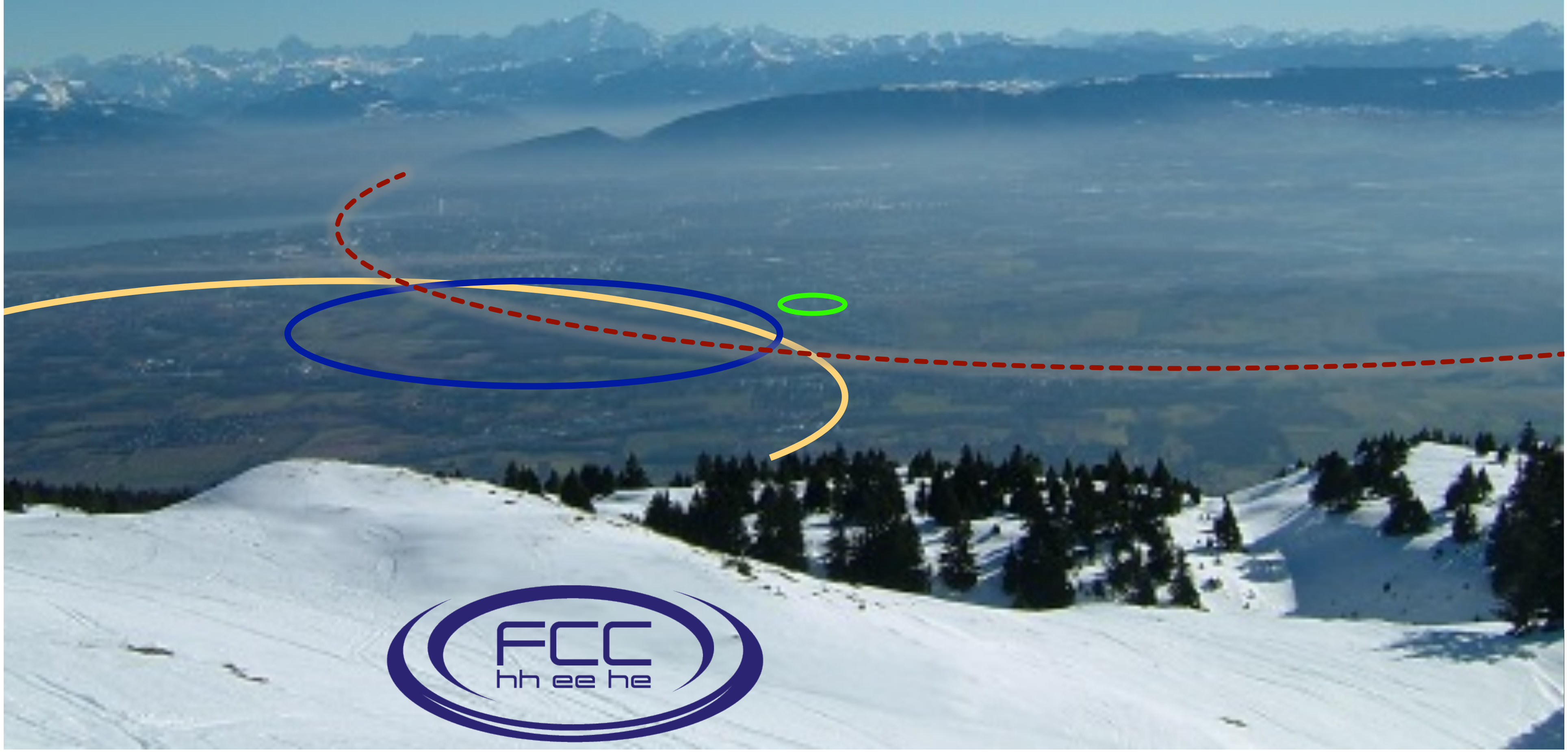
Future Circular Colliders

Filip Moortgat (CERN)



Outline

- Introduction, motivation, scope
- Parameters & design challenges
- Physics case
- Summary

Summary: European Strategy Update 2013

Design studies and R&D at the energy frontier

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

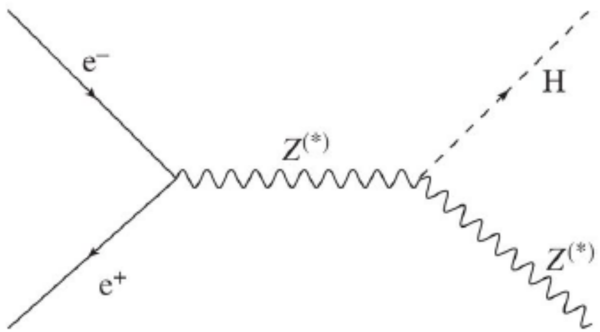
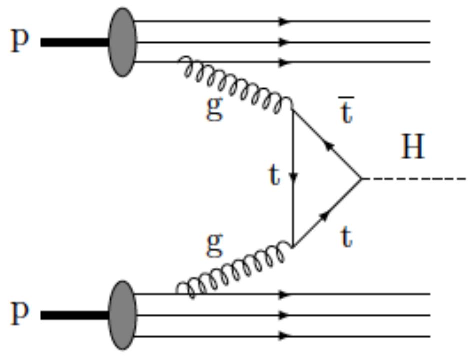
d) CERN should undertake design studies for accelerator projects in a global context,

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

strategy adopted at Brussels in May 2013, during exceptional session of the CERN Council in presence of the European Commission

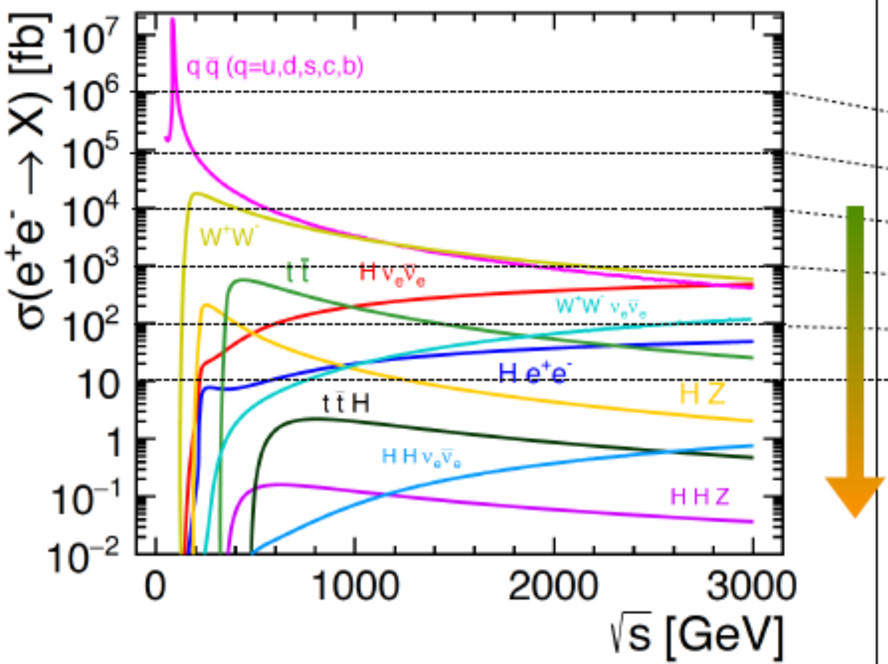
Which type of collider?

e+e- collider	pp collider
	
e^+/e^- are point-like → Initial state well defined (√s / polarisation) → Best for high-precision measurements	proton is compound object → Initial state not known event-by-event → Limits achievable precision
Cleaner experimental environment → Trigger-less readout → Low radiation levels	High rates of QCD backgrounds (next slide) → Complex triggering schemes → High levels of radiation
Superior sensitivity for electro-weak states	High cross-sections for colored states
High energy limited: Limits discovery of heavy particle → <≈350 GeV e^+e^- for circular colliders → <≈3 TeV e^+e^- for linear colliders	High-energy circular pp colliders feasible → Best for discoveries at high energy frontier

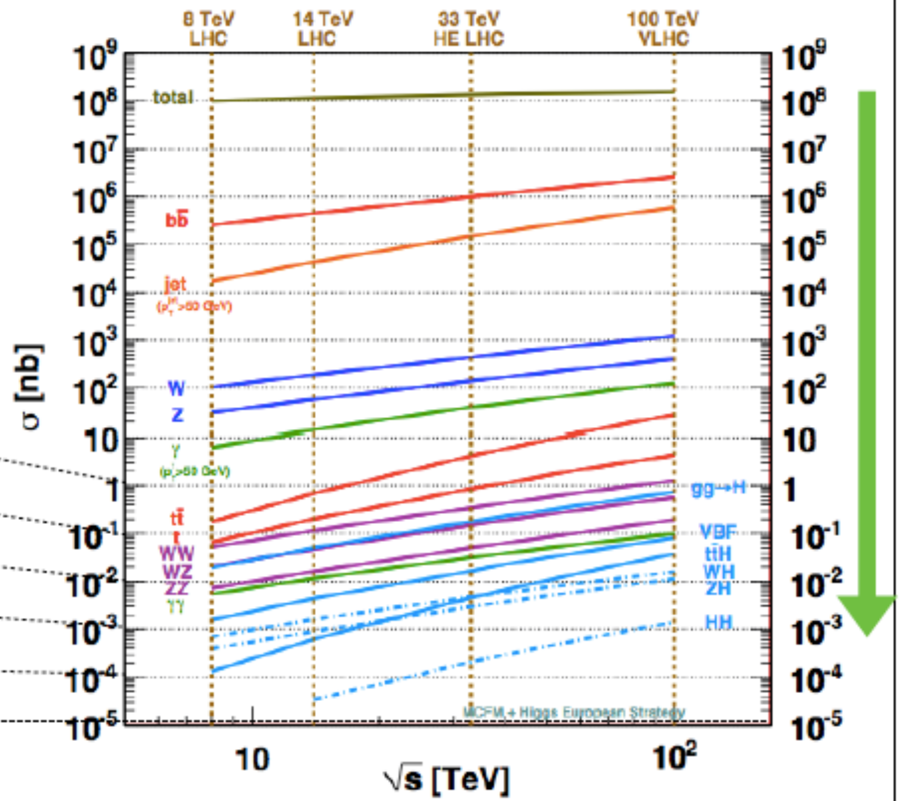
e+e- collider

Lower cross-section

Cleaner experimental environment
→ Trigger-less readout
→ Low radiation levels



pp collider



Higher energy reach

High rates of QCD backgrounds
→ Complex triggering schemes
→ High levels of radiation

e+e- collider	pp collider
Detectors: → No pile up, max. event rate 20kHz@ Z peak → Material budget of inner detector	Detectors: → Huge pile up (200, 1000) → Radiation hardness required → Complex triggering system (computing) → Huge detectors (containment, bending)
Accelerator: → High accelerating gradient → Power consumption	Accelerator: → High field magnets → Stored energy
Machine Detector Interface: → Booster bypass at IP → Detector L<≈ 2.2 m at each side → Large beam crossing angle 30 mrad	Machine Detector Interface: → IP configuration (see later) → shielding

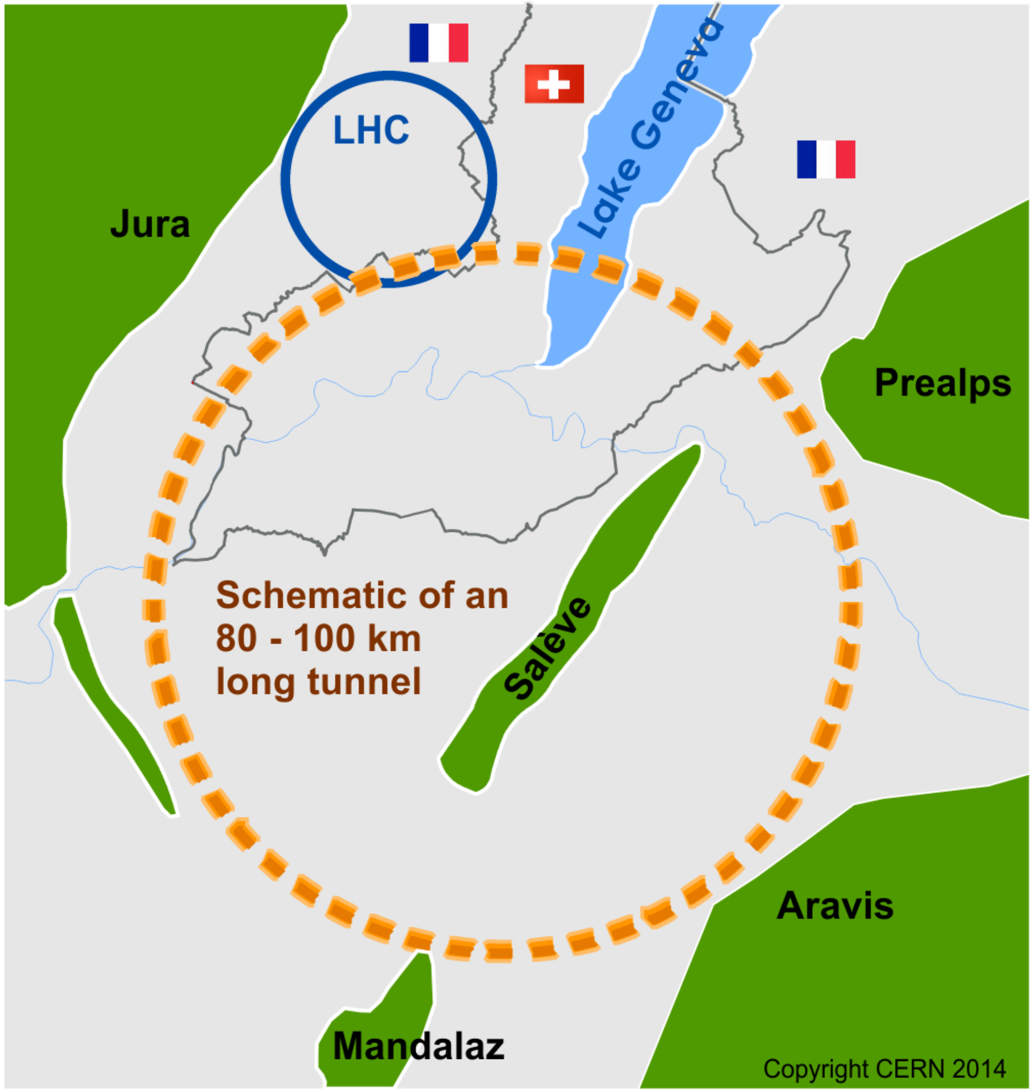
Future Circular Collider Study – SCOPE

Forming an international collaboration to study:

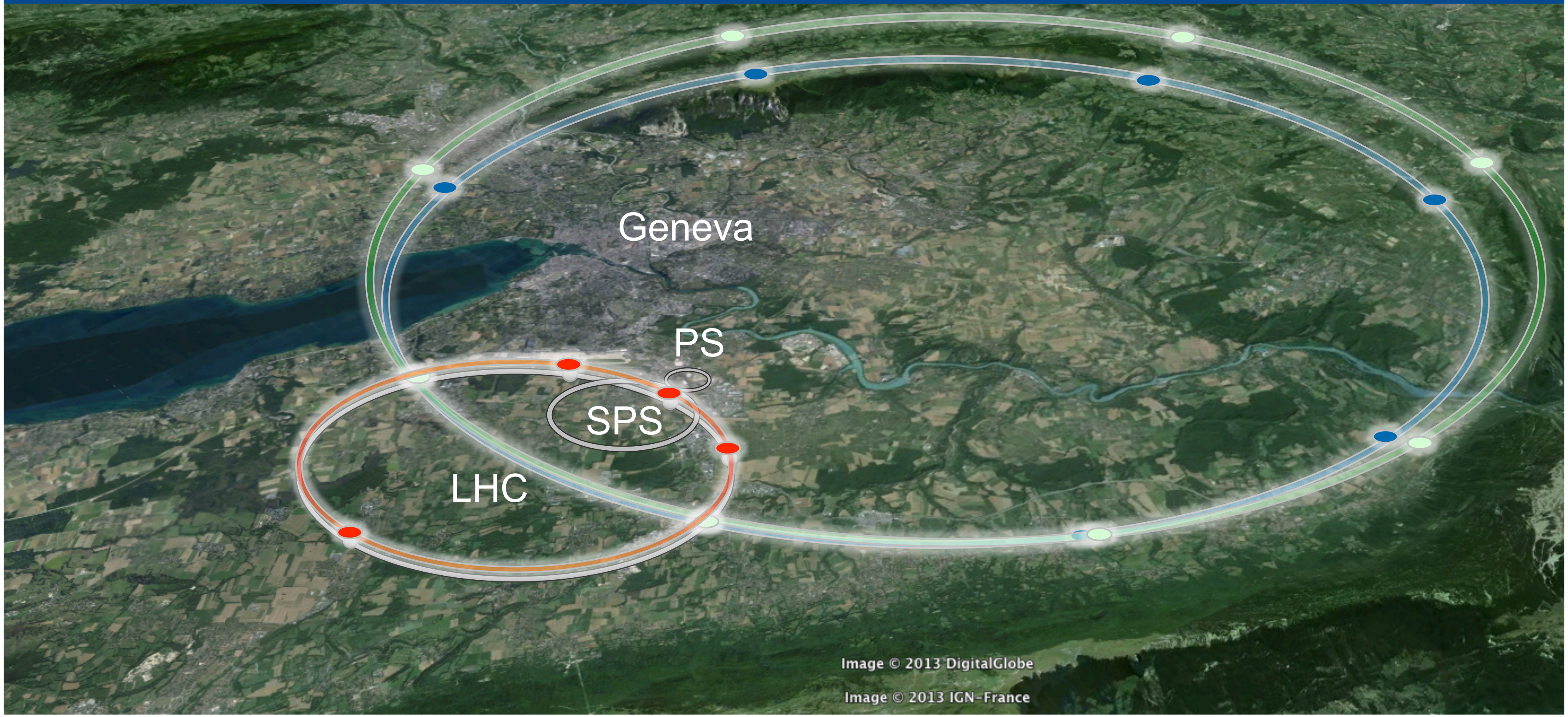
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**

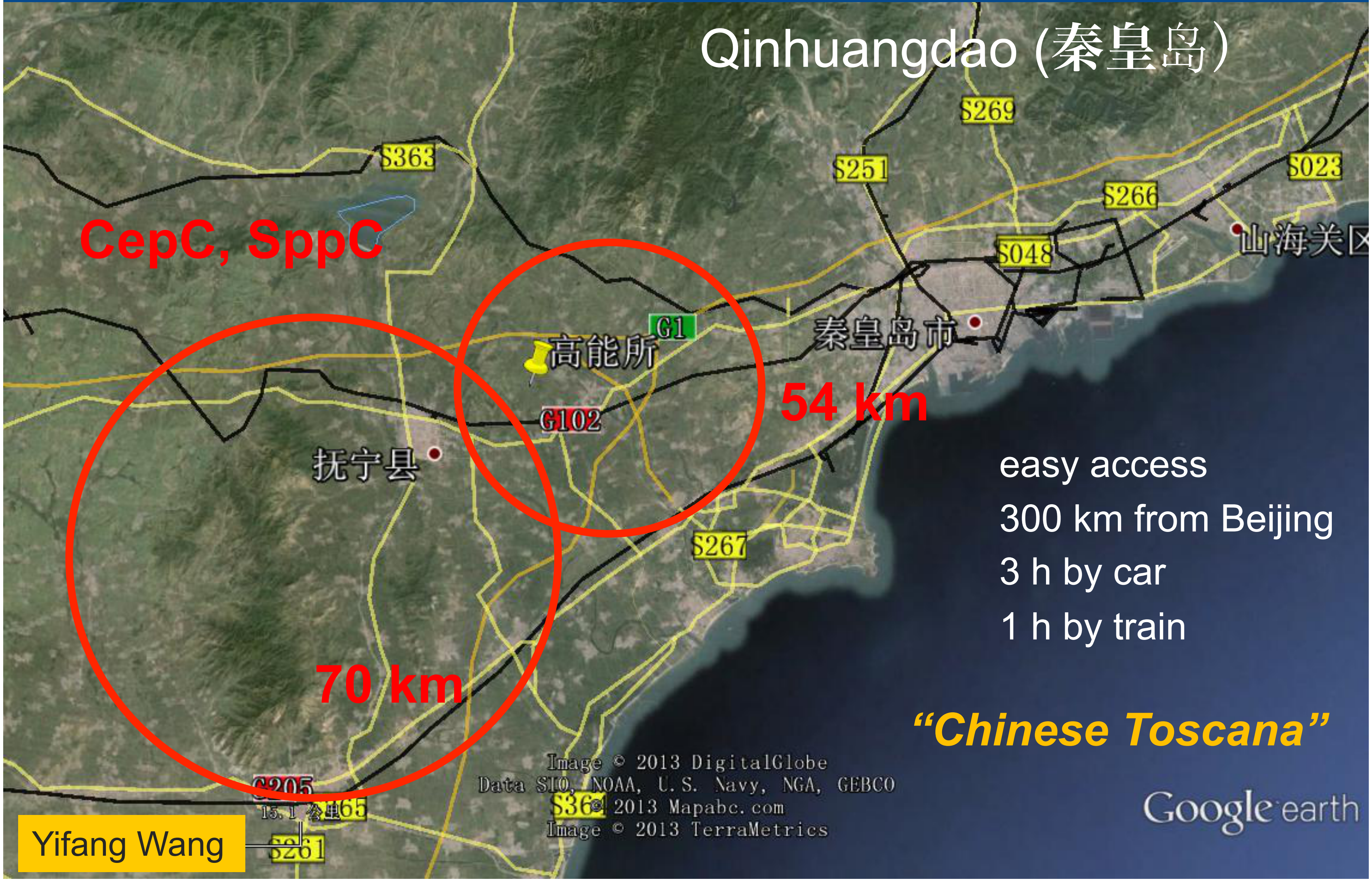


FCC-hh integration and options



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042



Hadron collider FCC-hh parameters

• **Energy**	**100 TeV c.m.**
• **Circumference**	**~ 100 km (baseline) [80 km option]**
• **Dipole field (50 TeV)**	**~ 16 T (baseline) [20 T option]**
• **Dipole field (3 TeV inject.)**	**~ 1 T (baseline) [1.2 T option]**
• **Bunch spacing**	**25 ns [5 ns option]**
• Bunch population (25 ns)	1×10^{11} p
• Emittance normalised	2.15×10^{-6}m, normal.
• #bunches	10500
• **Stored beam energy**	**8.2 GJ/beam**
• # Interaction Points	2 main experiments
• β*	1.1 m [baseline]
• **Luminosity**	$\mathbf{5 \times 10^{34}}$ $\mathbf{cm^{-2}s^{-1}}$ [baseline]
• **Synchroton radiation arc**	**~30 W/m/aperture (fill. fact. ~78% in arc)**

Available from SPS/ LHC today
→3 TeV injector baseline for FCC-hh

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter ?
- **Baryogenesis**
  - did it arise at the cosmological EW phase transition ?
- **EW Symmetry Breaking**
  - what's the underlying dynamics? weakly interacting? strongly interacting ? other interactions, players at the weak scale besides the SM Higgs ?
- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

pp at 100 TeV opens three windows:

- Access to new particles in the few→30 TeV mass range, beyond LHC reach

- Immense rates for phenomena in the sub-TeV mass range ⇒

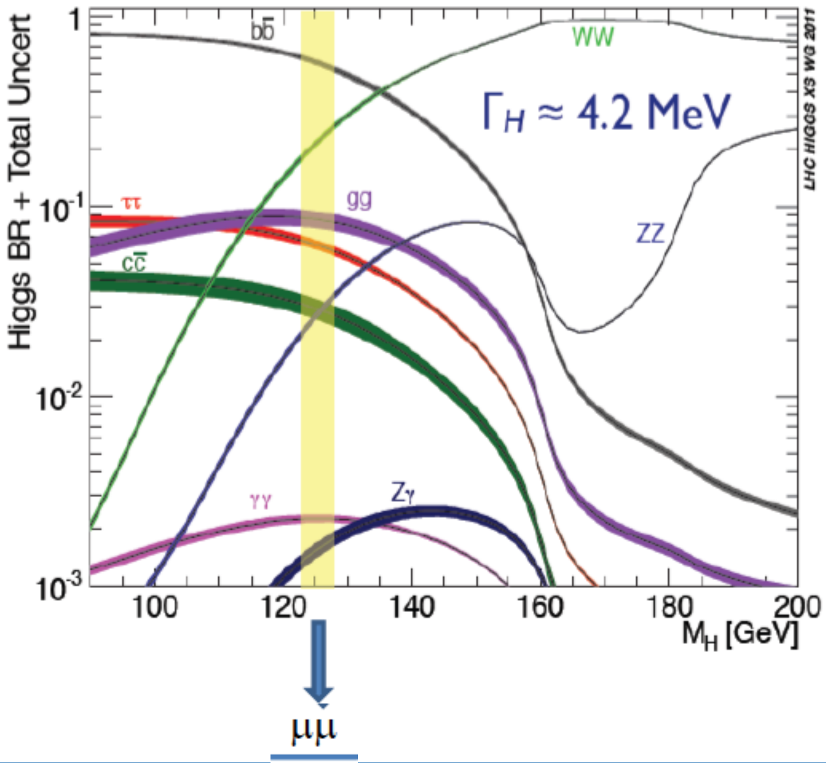
  increased precision w.r.t. LHC

- Access to very rare processes in the sub-TeV mass range ⇒

  search for stealth phenomena, invisible at the LHC

Higgs physics

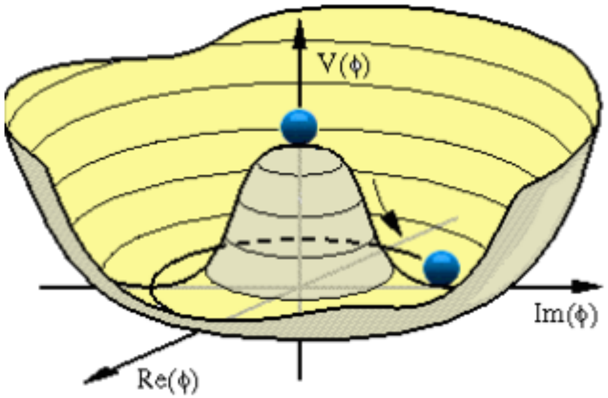
The only know spin=0 elementary particle.
We must study it as thoroughly as we can!



g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	$H\rightarrow \rho\gamma$?	$H\rightarrow \rho\gamma$?	
ss	$H\rightarrow \phi\gamma$?	$H\rightarrow \phi\gamma$?	
ee	**ee → H**		
HH	30%	**<5%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

The Higgs potential

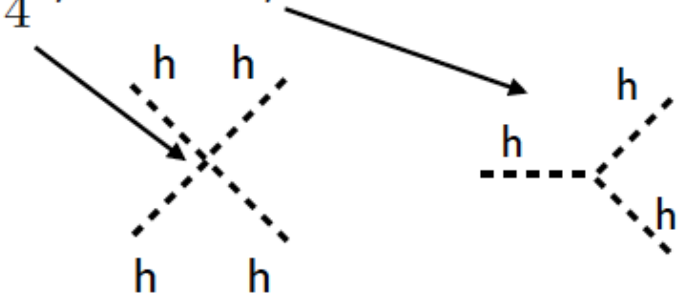
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



After spontaneous symmetry breaking:

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4} \eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$



The strength of the triple and quartic couplings is fully fixed by the potential shape.

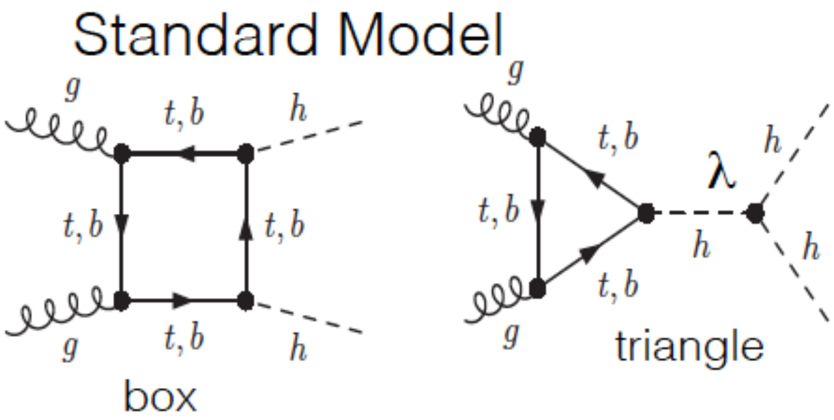
Why is it relevant?

1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

2) It has implications on the stability of the Vacuum;

3) It could make the Higgs boson a good inflation field

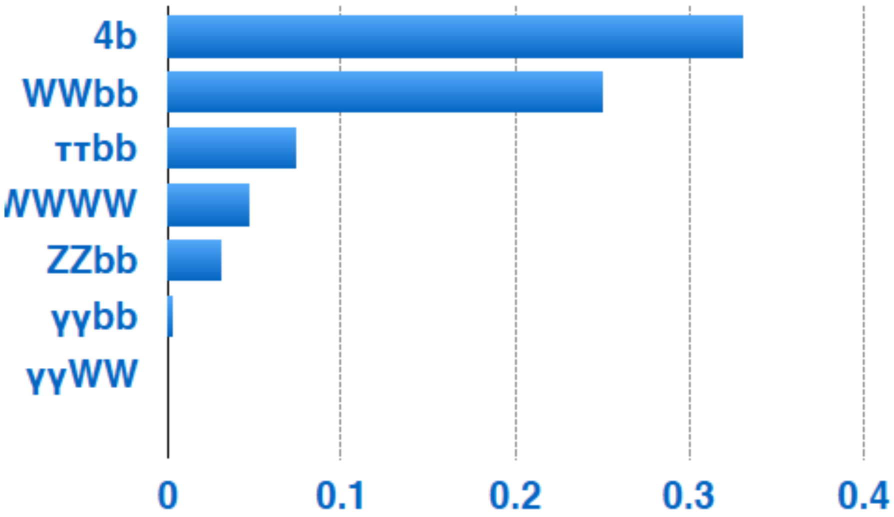
Di-higgs production at pp colliders

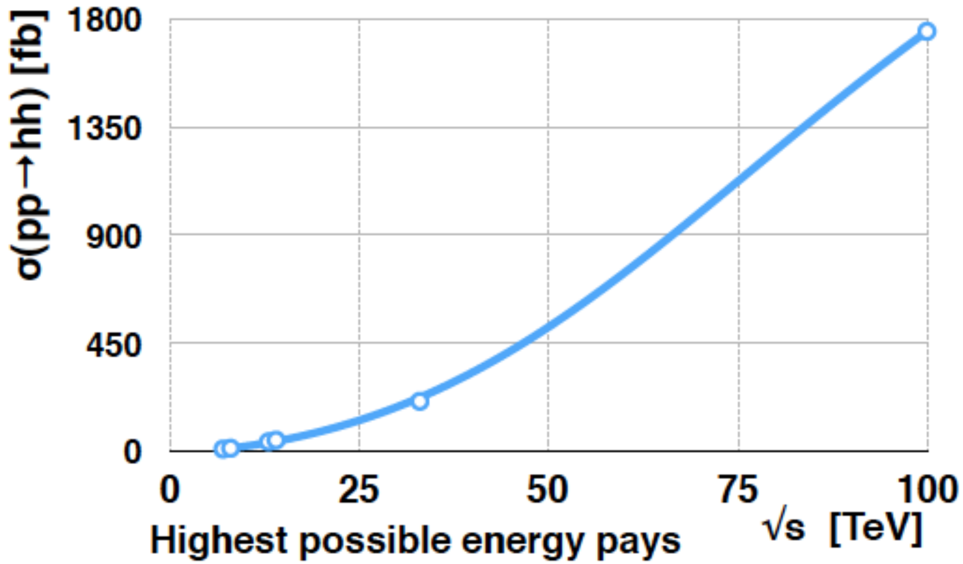


NNLO with full top mass *NLO $m_t \to \infty$

m_h = 125.09 GeV	σ(fb)	scale unc. (%)	PDF unc. (%)	α_s unc.
√s = 7 TeV	7.71	+4.0/-5.7	± 3.4	± 2.8
√s = 8 TeV	11.17	+4.1/- 5.7	± 3.1	± 2.6
√s = 13 TeV	37.91	+4.3/-6.0	± 2.1	± 2.3
√s = 14 TeV	45.00	+4.4-6.0	± 2.1	± 2.2
√s = 33 TeV*	206.6	+15.1 - 12.5	+5.8/-5.0	
√s = 100 TeV	1748	+5.1/-6.5	± 1.7	± 2.0

Higgs decay branching fraction

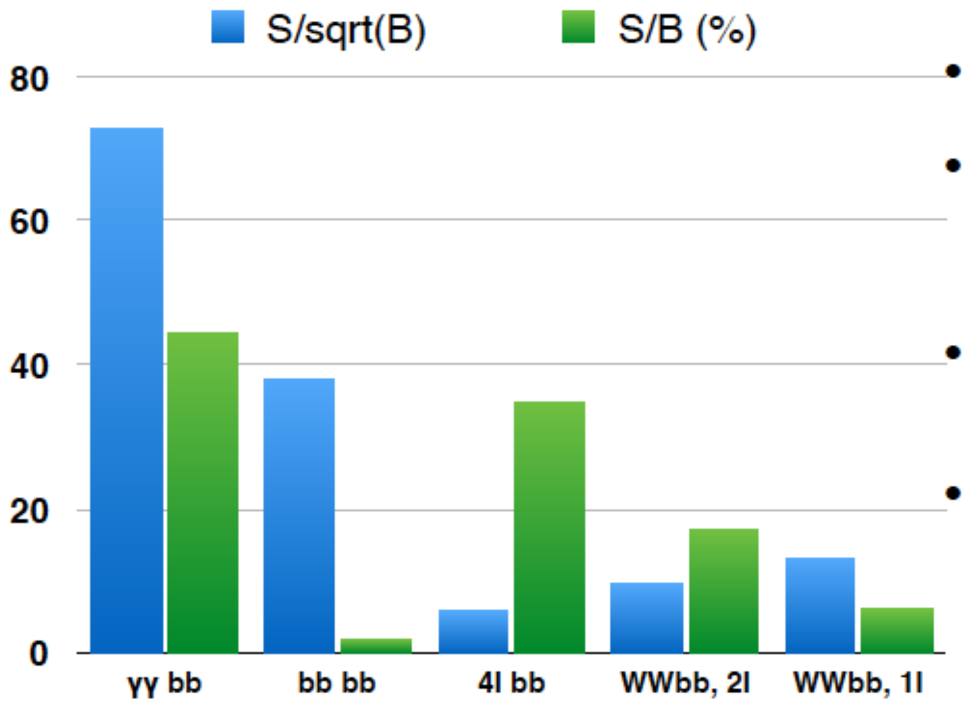




Highest possible energy pays

HH discovery channels at 100 TeV

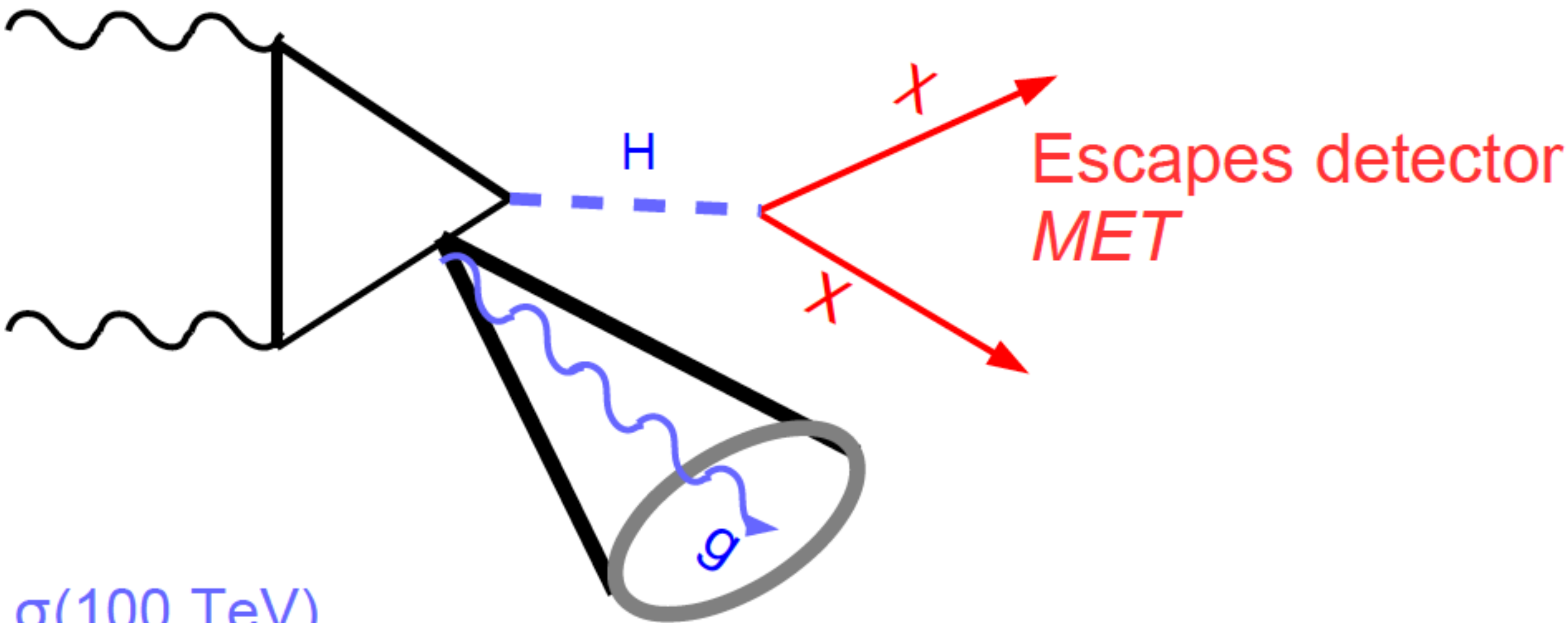
Biaggio Di Micco



- γγbb looks to be the golden channel;
- need to reach maximal accuracy in this channel simulation, implementing pile-up simulation and stronger fake estimate;
- detector design should be driven by minimisation of systematics on it;
- More work needed on WWbb to fully exploit its potentiality;

From Higgs to Dark Matter

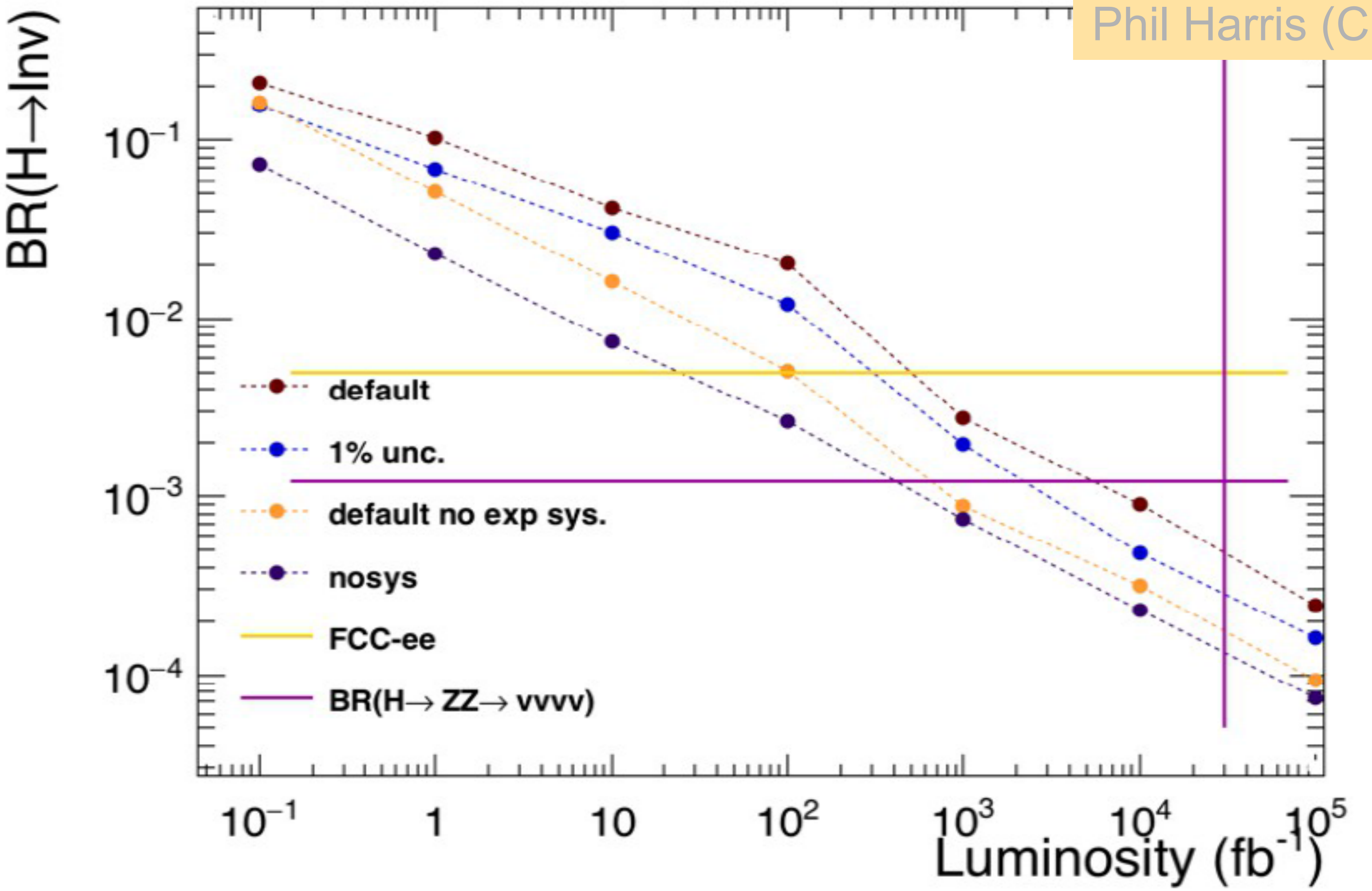
Phil Harris (CERN)



$$\frac{\sigma(100\text{ TeV})}{\sigma(14\text{ TeV})} = 20$$

Invisible Higgs decays

Phil Harris (CERN)

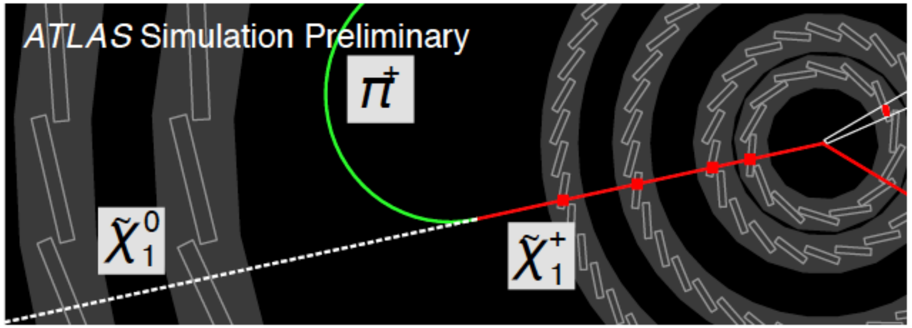


Cross the SM neutrino wall at FCC with < 1 ab^{-1}

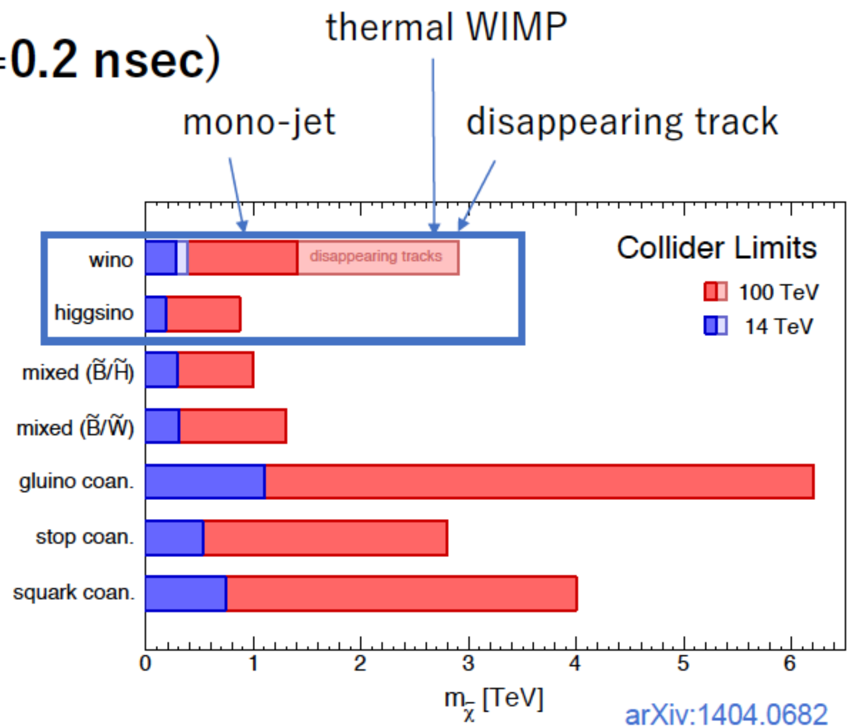
Dark Matter at 100 TeV

<u>DM overclosure upper limits:</u>
$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ ⇒
wino: m≲3 TeV
higgsino: m≲1.1 TeV

- Wino LSP leads **meta-stable chargino** (τ =**0.2 nsec**)
- c τ ~ 6 cm → directly detectable
  - chargino tracks disappear in the tracker.



ATLAS-CONF-2017-0



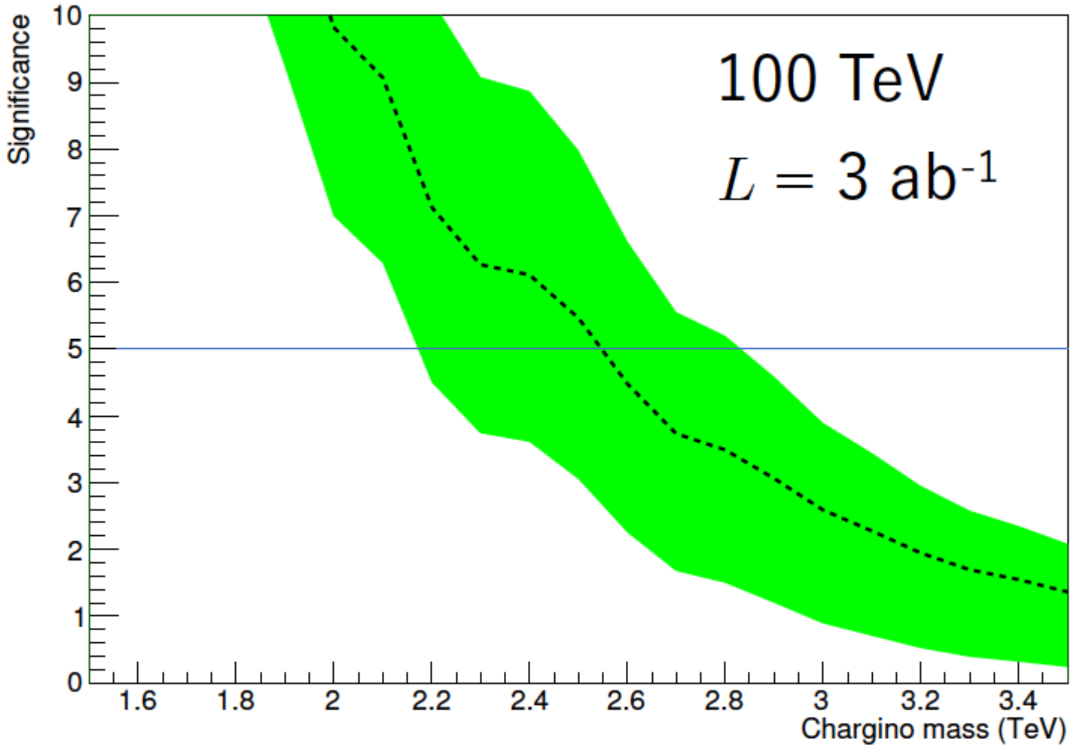
arXiv:1404.0682

- Latest preliminary LHC limit : 430 GeV

Ryu Sawada

Dissapearing track reach

Discovery sensitivity reach ~ 3 TeV



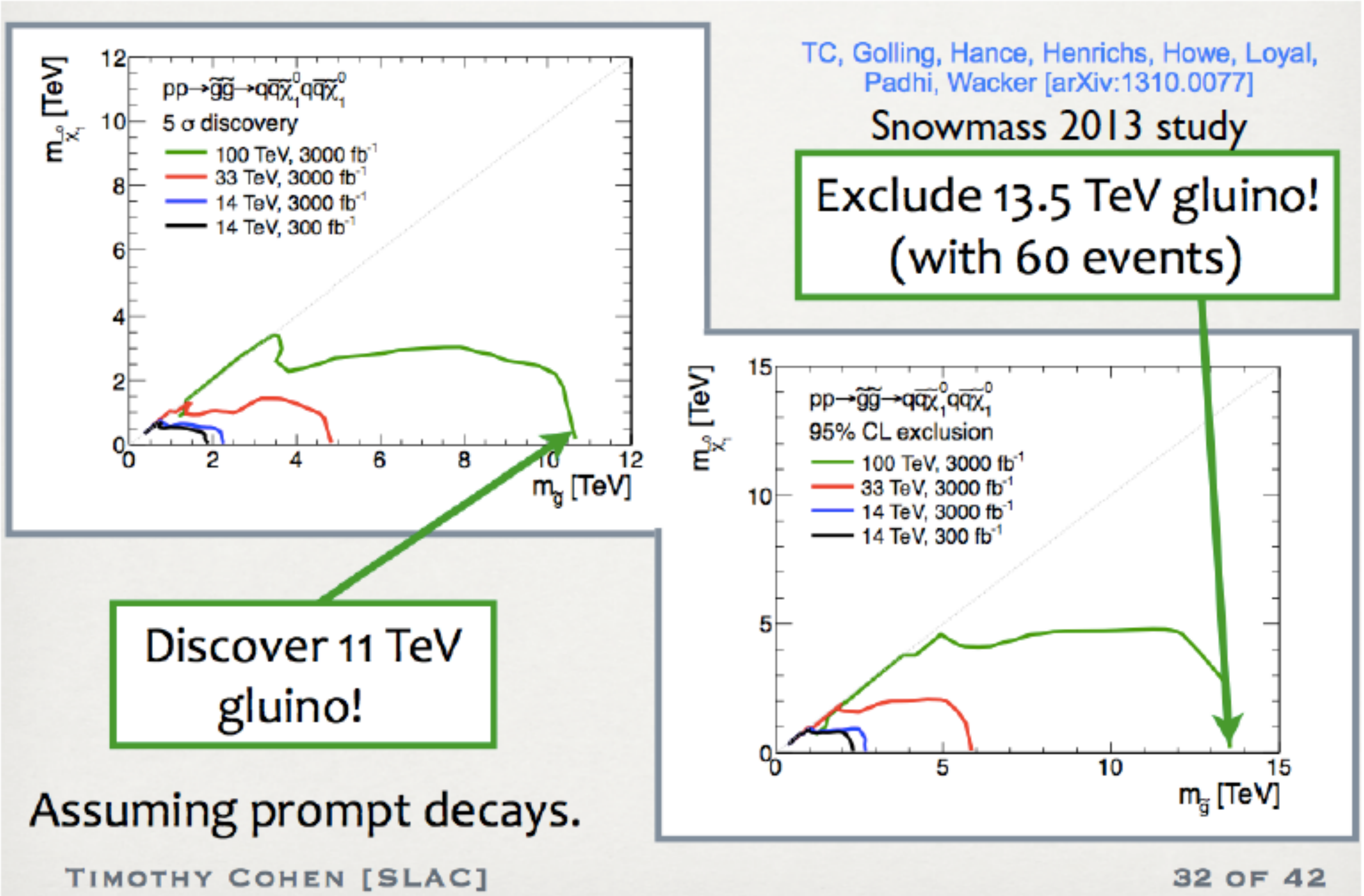
Ryu Sawada

Pure Wino LSP

Green band : number of BG scaled by 0.2—5.
The center corresponds to the factor 1

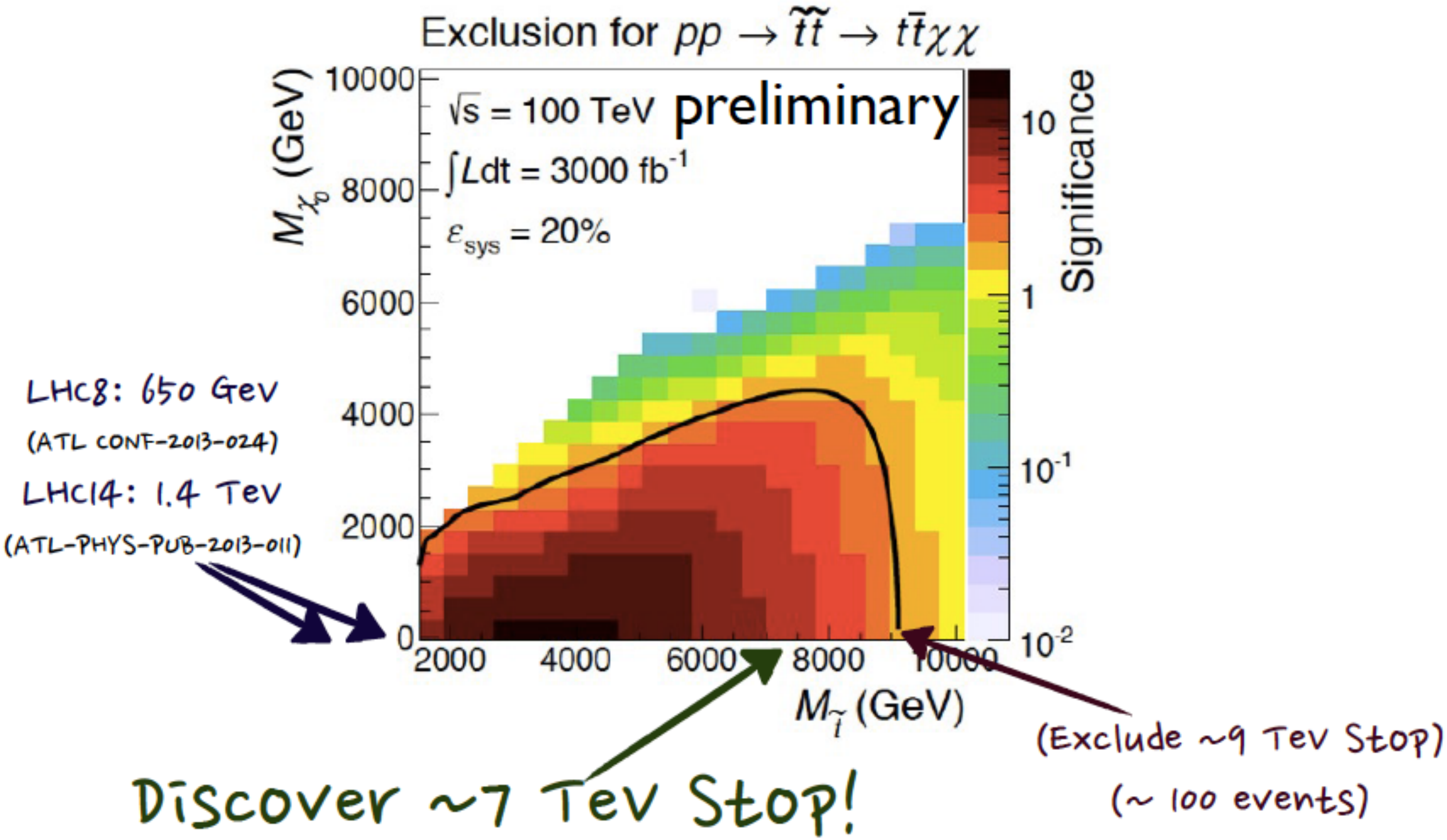
~0.5 TeV higher sensitivity with 30 ab^{-1}

SUSY @ 100 TeV



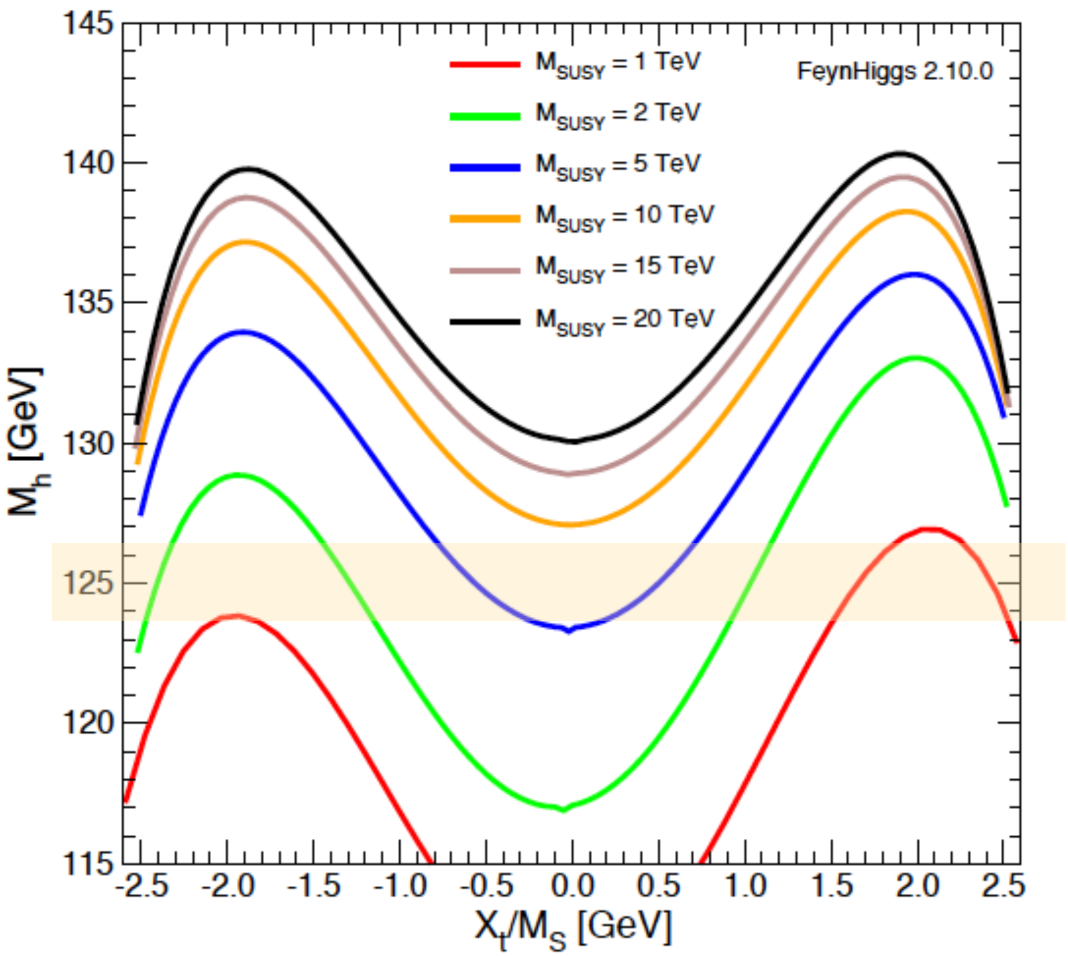
TC, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker [arXiv:1310.0077]
Snowmass 2013 study
Exclude 13.5 TeV gluino!
(with 60 events)
Discover 11 TeV gluino!
Assuming prompt decays.
5 σ discovery
95% CL exclusion
100 TeV, 3000 fb⁻¹
33 TeV, 3000 fb⁻¹
14 TeV, 3000 fb⁻¹
14 TeV, 300 fb⁻¹
[TeV]
Timothy Cohen [SLAC]
32 of 42

Stop @ 100 TeV



Exclusion for $pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t}\chi\chi$
$\sqrt{s}$ = 100 TeV
preliminary
$\int L dt = 3000\ fb^{-1}$
ε_{sys} = 20%
M_{χ_0} (GeV)
$M_{\tilde{t}}$ (GeV)
Significance
10000
8000
6000
4000
2000
0
2000
4000
6000
8000
10000
10
1
10^{-1}
10^{-2}
LHC8: 650 Gev
(ATL CONF-2013-024)
LHC14: 1.4 Tev
(ATL-PHYS-PUB-2013-011)
Discover ~7 Tev Stop!
(Exclude ~9 Tev Stop)
(~ 100 events)

A hint from the Higgs?



Is there an upper limit on the stop mass in the MSSM?

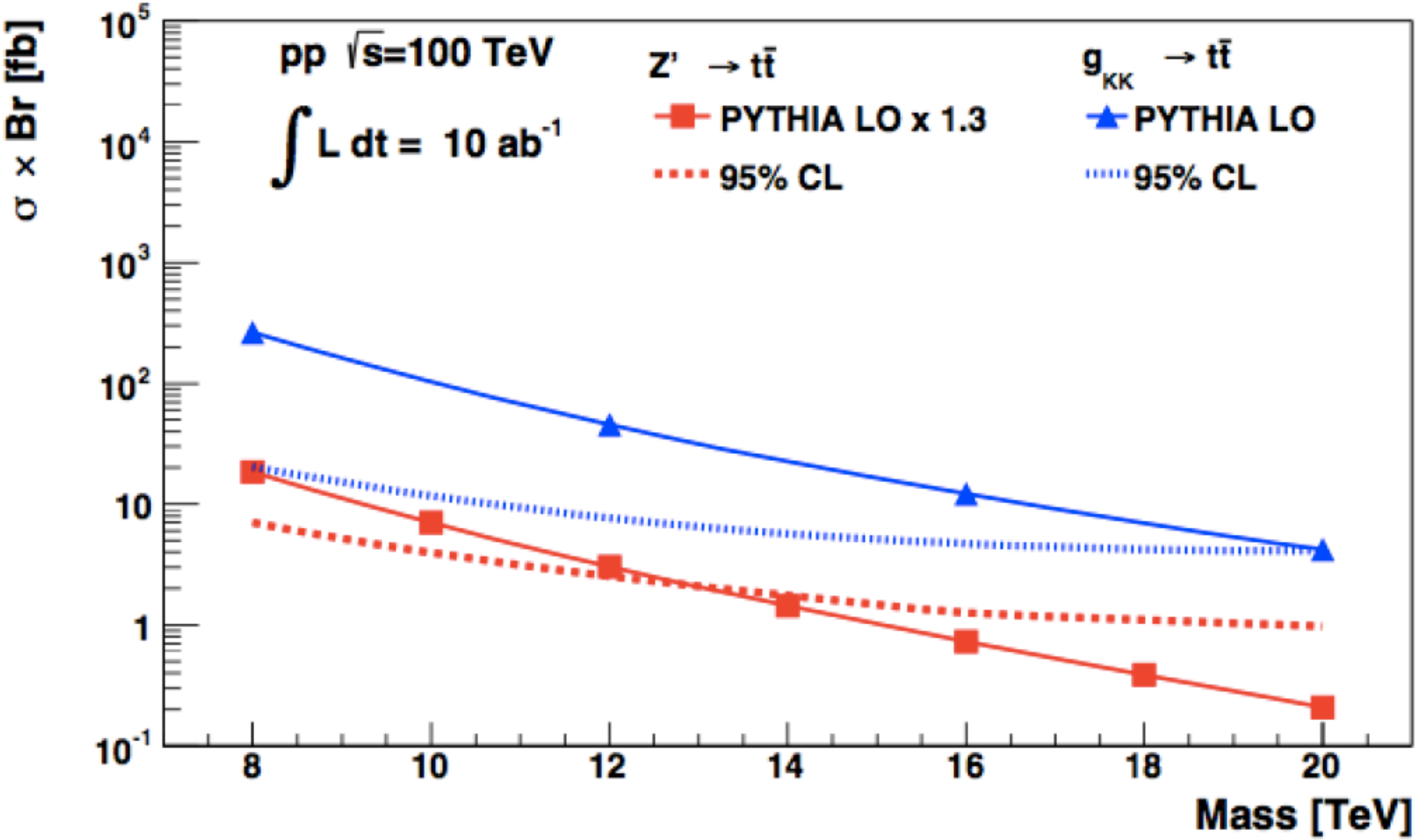
Yes, because m_H = 125 GeV!

→ M_{SUSY} = 1 – 9 TeV ??

→ that's possibly outside of the LHC reach but within the FCC-hh reach!!

Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



Direct exploration of the high-mass scale

New particle	collider: $\mathcal{L}$:	LHC14 100 fb^{-1}	SLHC 1 ab^{-1}	LC800 500 fb^{-1}	CLIC3 1 ab^{-1}	FCC-hh
squarks [TeV]		2.5	3	0.4	1.5	**15**
sleptons [TeV]		0.3	-	0.4	1.5	**1.5 ? ***
Z' (SM couplings) [TeV]		5	7	8	20	**30**
2 extra dims M_D [TeV]		9	12	5-8.5	20-30	**?**
TGC (95%) (λ_γ coupling)		0.001	0.0006	0.0004	0.0001	**?**
μ contact scale [TeV]		15	-	20	60	**100 ?**
Higgs compos. scale [TeV]		5-7	9-12	45	60	**?**

CLIC Physics TDR

First estimates, tbc

** ?'s ⇒ Lots of work to be done to examine the physics opportunities of FCC-hh*

Rule of thumb for mass reach in direct searches at hadron colliders, at equal integrated luminosity:

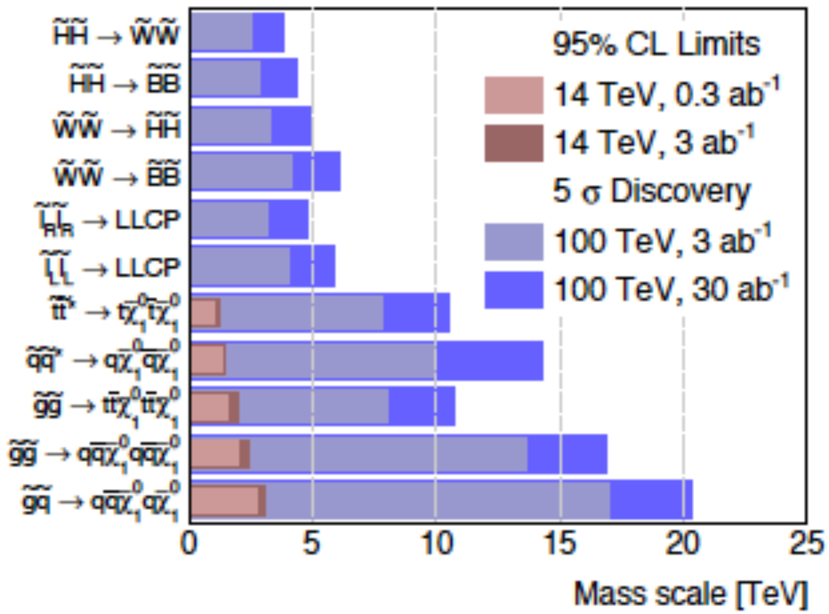
See e.g. Salam and Weiler, http://cern.ch/collider-reach/

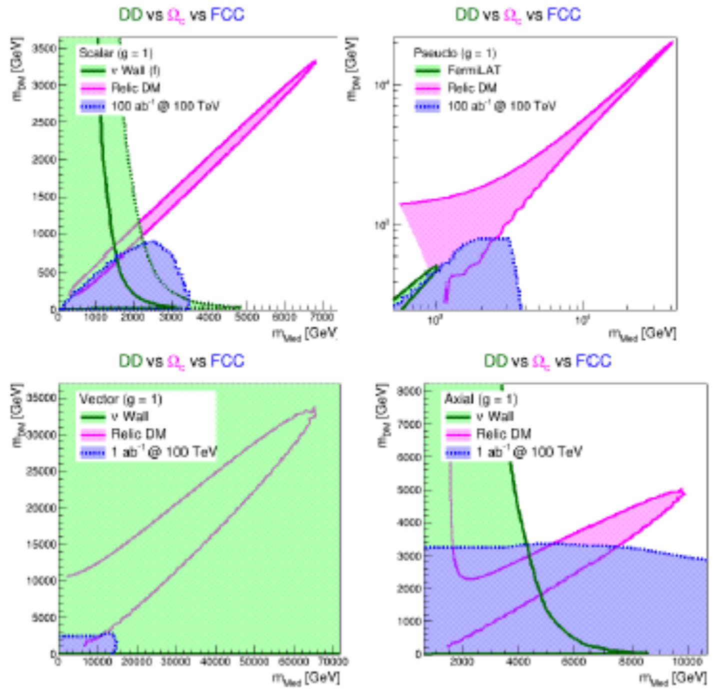
$$M_{reach}\ (100\ TeV) \sim M_{reach}\ (14\ TeV) \times 0.7 \times (100 / 14)$$

100 TeV Physics report

FCC-hh Physics Report (~ 650 pages) released last year

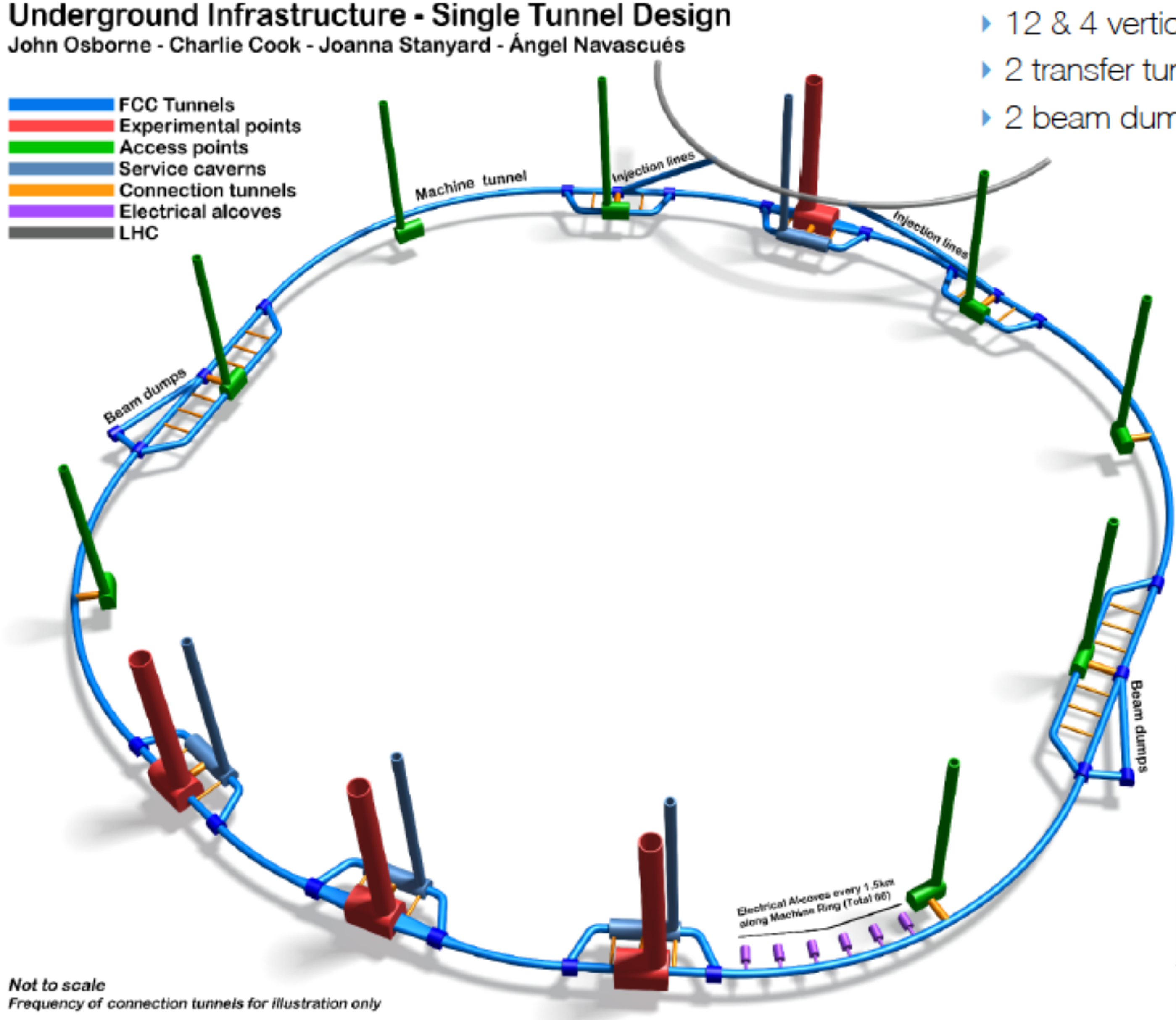
arxiv:1606.00947 and 1606.09408

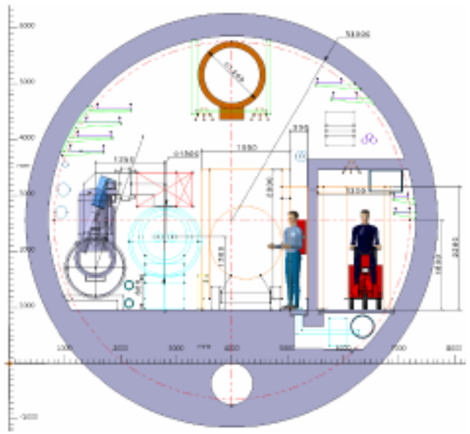




FCC baseline layout

- 100 km tunnel 6 m inner diameter
- 4 large experimental caverns
- 8 service caverns for infrastructure
- 12 & 4 vertical shafts (3 km integral)
- 2 transfer tunnels (10 km)
- 2 beam dump tunnels (4 km)





Site study 97.5 km baseline

Alignment | Shafts | Query

Choose alignment option

V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

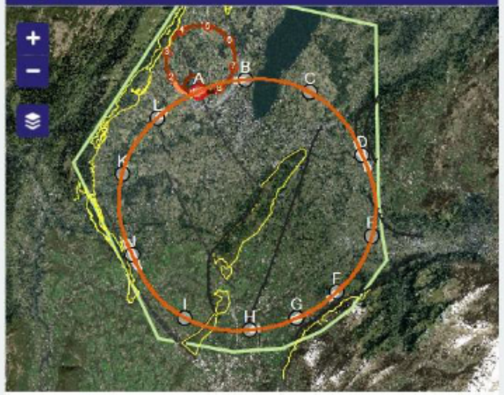
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	37°	49m	-40°	83m
SPS		121m		126m
TI2		121m		126m
TI8		51m		118m

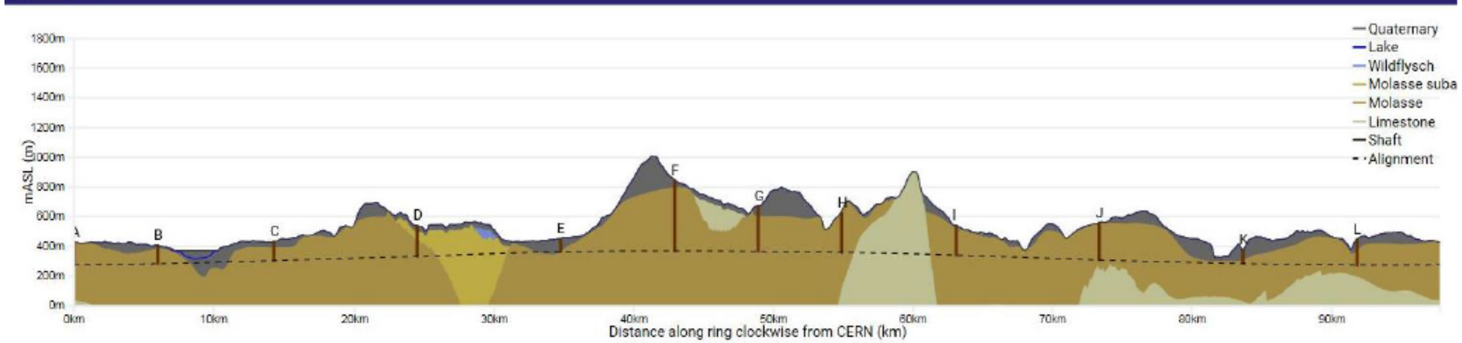
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)			Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian
A	152	0	0	0	152	0
B	121	0	0	26	95	0
C	127	0	0	44	83	0
D	205	66	0	40	100	0
E	89	0	0	89	0	0
F	476	0	0	49	427	0
G	307	0	0	73	234	0
H	266	0	0	0	266	0
I	198	0	0	11	187	0
J	248	0	0	1	247	0
K	88	0	0	70	18	0
L	172	0	0	89	83	0
Total	2449	66	0	492	1892	0

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

Tunneling

- Molasse 90%, Limestone 5%, Moraines 5%

Shallow implementation

- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft **F** (RF or collimation), alternatives being studied, e.g. inclined access

J. Osborne & C. Cook

FCC-hh: high-field magnet R&D

- FHC baseline is 16T Nb_3Sn technology for ~100 TeV c.m. in ~100 km

Develop Nb_3Sn-based 16 T dipole technology (at 4.2 K?),
- conductor developments
- short models with sufficient aperture (40 – 50 mm) and
- accelerator features (margin, field quality, protect-ability, cycled operation).

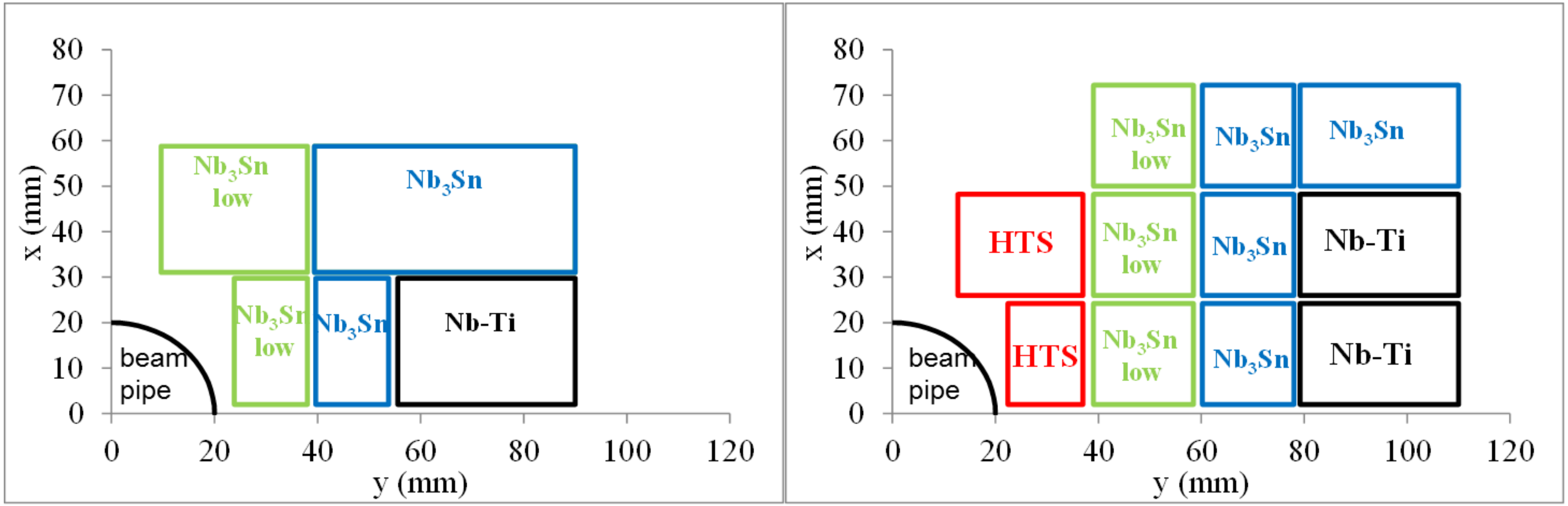
Goal: 16T short dipole models by 2018/19 (America, Asia, Europe)

- In parallel HTS development targeting 20 T (option and longer term)

Goal: Demonstrate HTS/LTS 20 T dipole technology:
- 5 T insert (EuCARD2), ~40 mm aperture and accelerator features
- Outsert of large aperture ~100 mm, (FRESCA2 or other)

Key design issue: cost-optimized high-field dipole magnets

Arc magnet system will be the major cost factor for FCC-hh

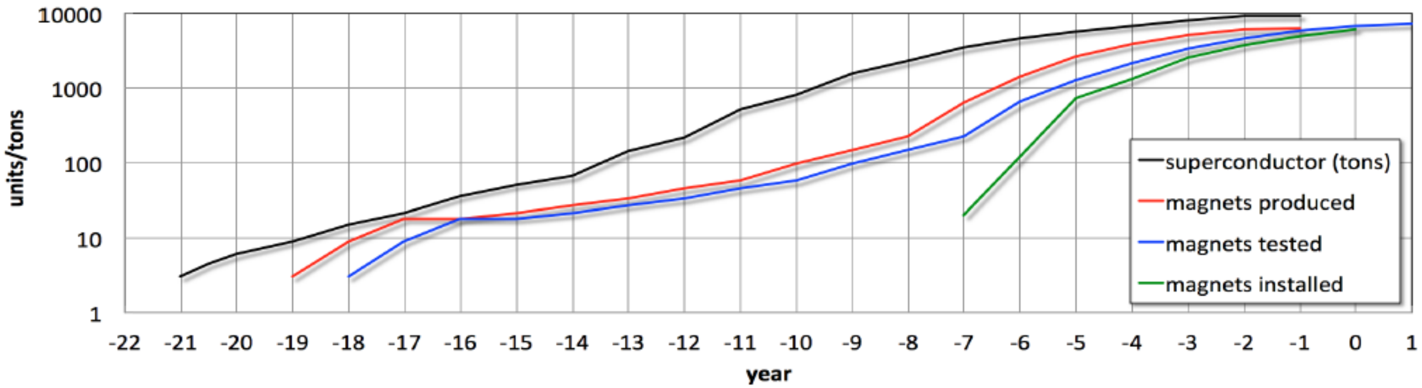


only a quarter is shown

“hybrid magnets”

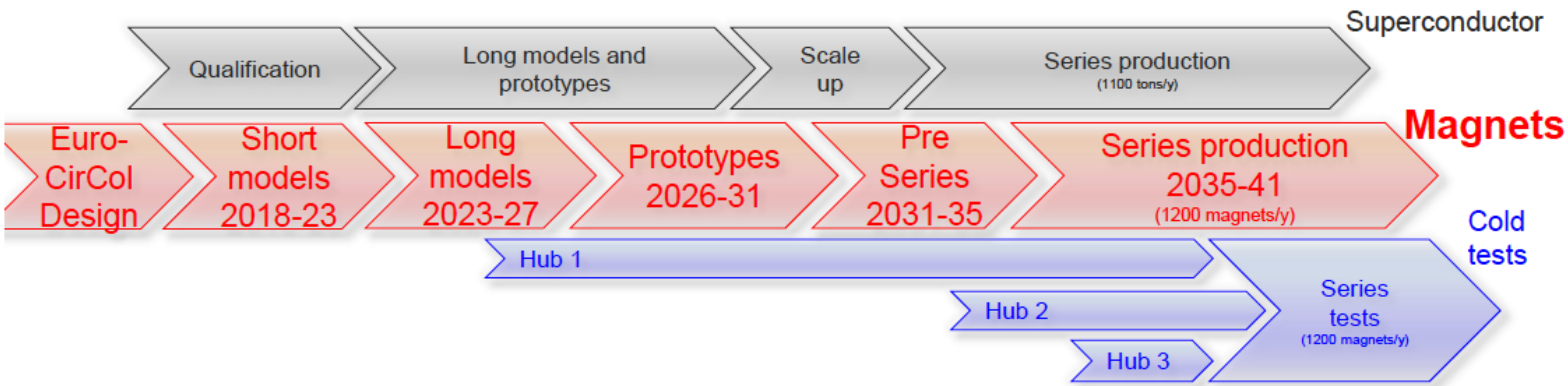
example block-coil layout

16T magnet development timeline



Total duration of magnet program:

~20 years



Would follow on HL-LHC Nb3Sn program with long models with industry from 2023/24

FCC-hh: some design challenges

- **Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total**
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h)

- **Collimation, beam loss control, radiation effects: very important**
- **Injection/dumping/beam transfer: very critical operations**
- **Magnet/machine protection: to be considered from early phase**

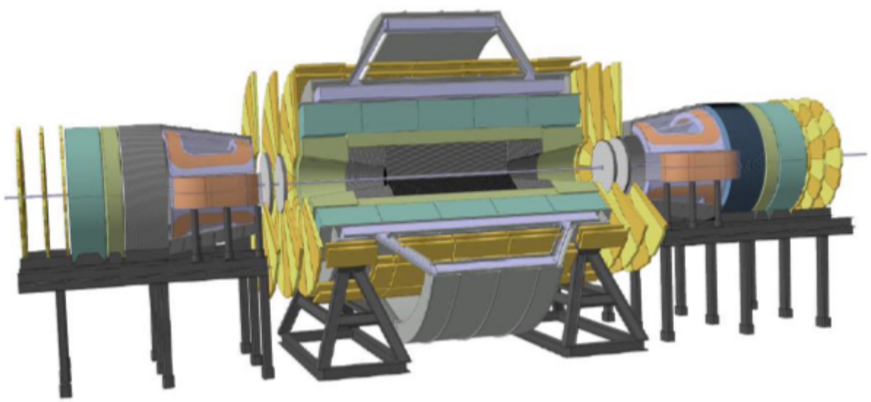
A detector design?

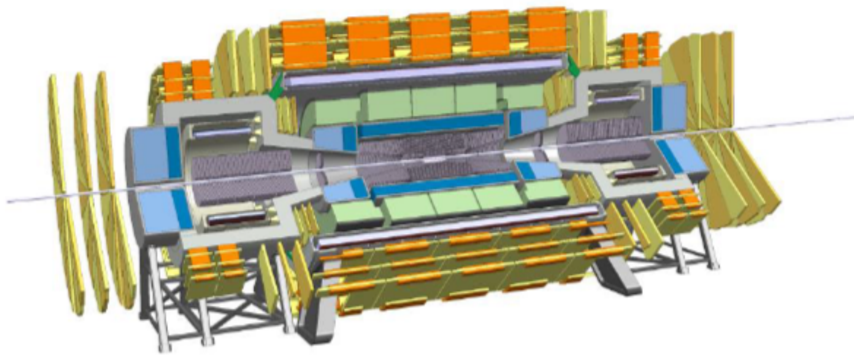
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

→ 65 GJ Stored Energy
→ 28m Diameter
→ >30m shaft
→ Multi Billion project

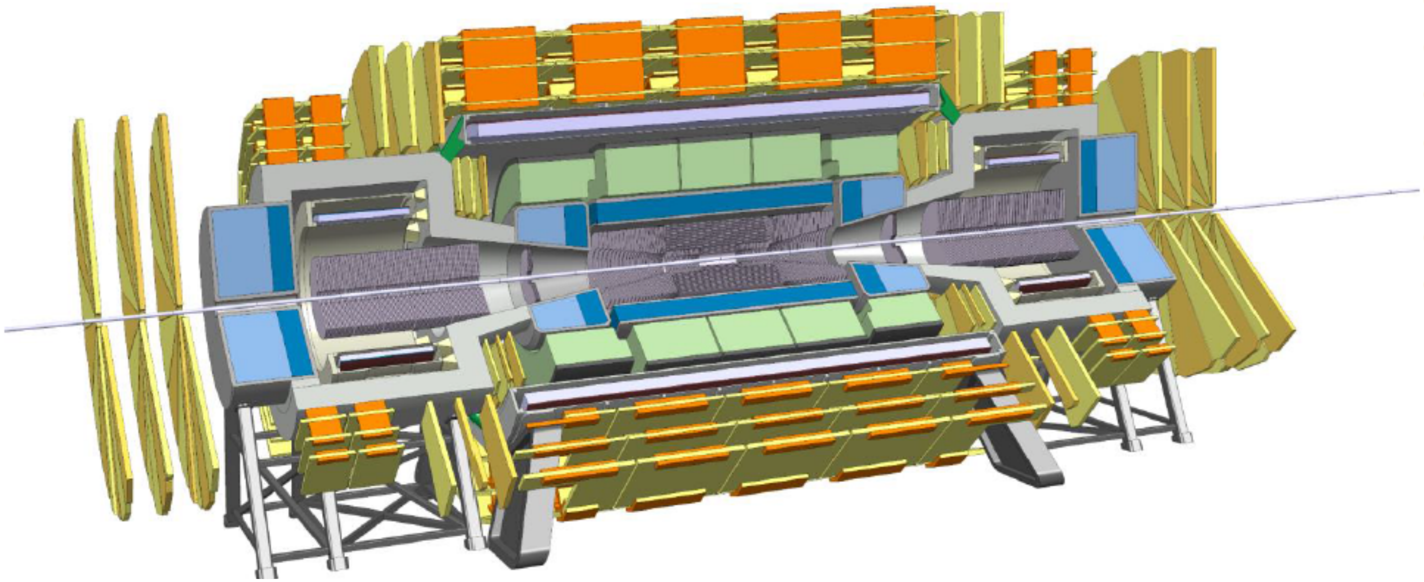
4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

→ 14 GJ Stored Energy
→ Rotational symmetry for tracking !
→ 20m Diameter (≈ ATLAS)
→ 15m shaft
→ ≈ 1 Billion project

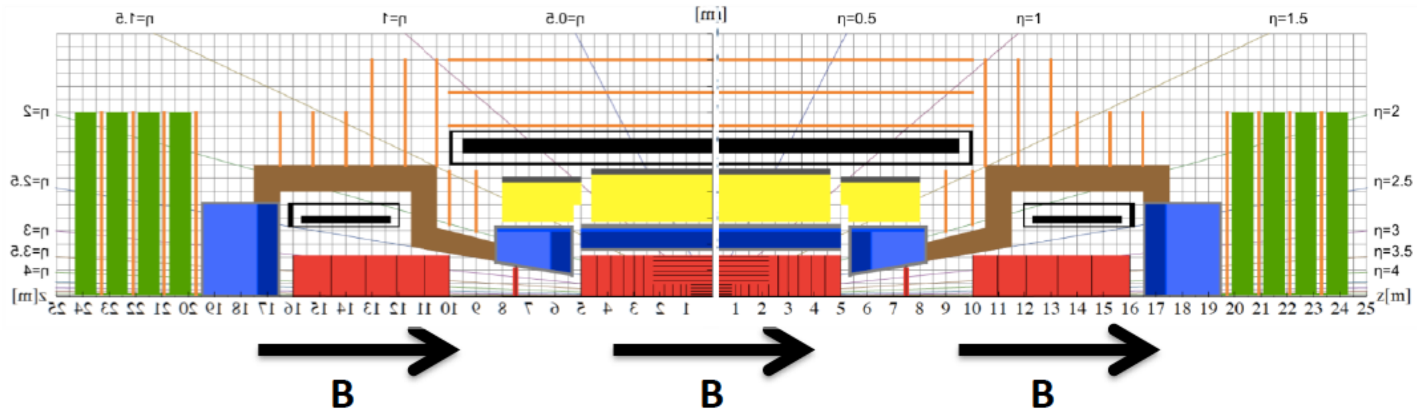




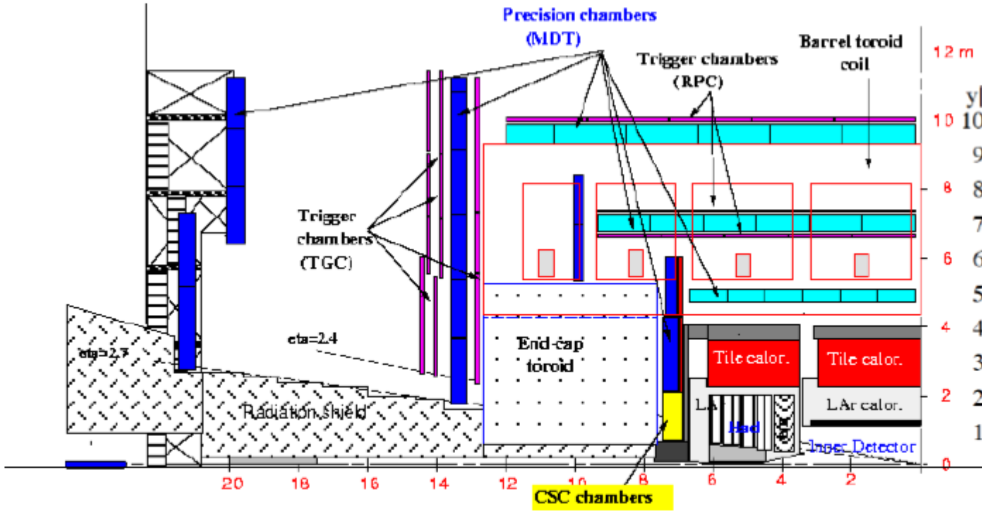
Reference detector for the CDR

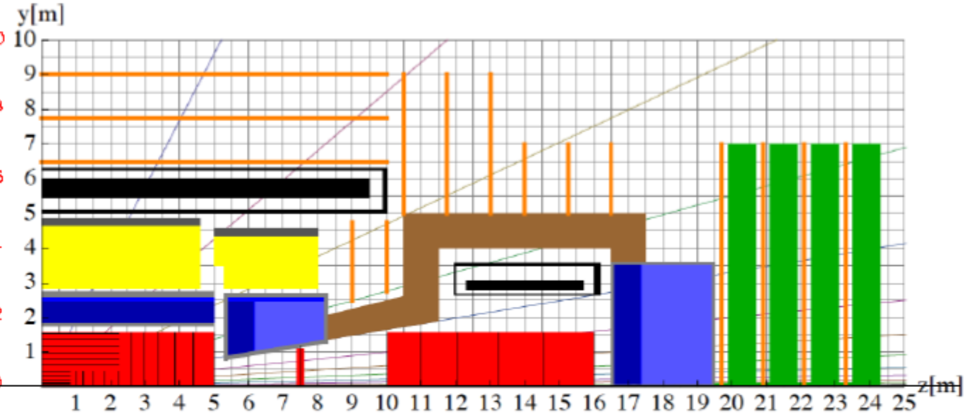


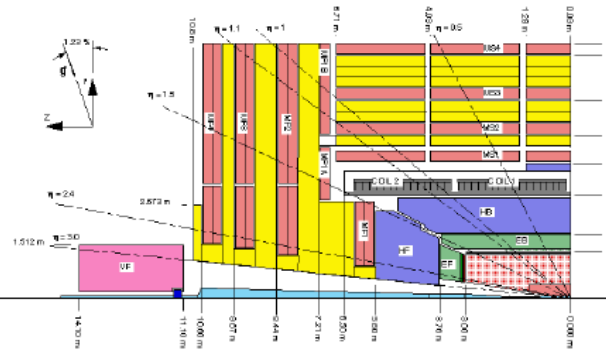
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

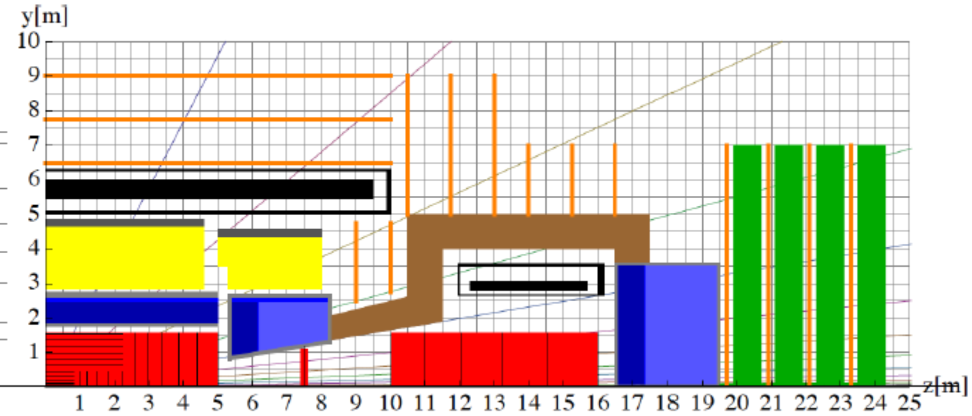


Comparison to ATLAS & CMS



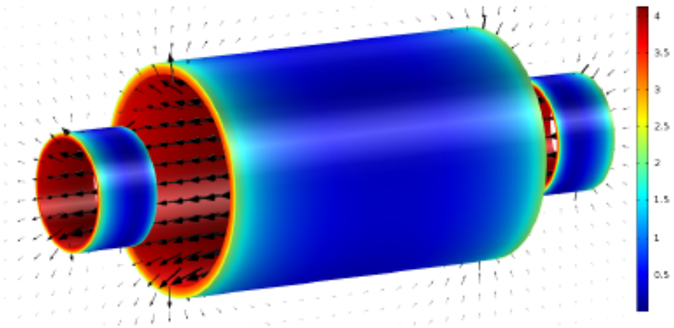






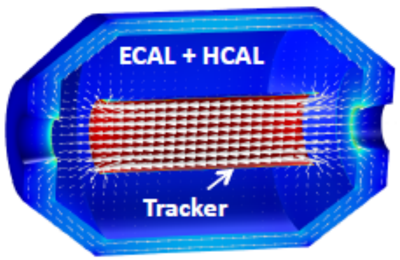
Current detector baseline

- Detector magnet system



Today's baseline:

4T/10m bore 20m long Main Solenoid 4T Side Solenoids – all unshielded
14 GJ stored energy, 30 kA and 2200 tons system weight

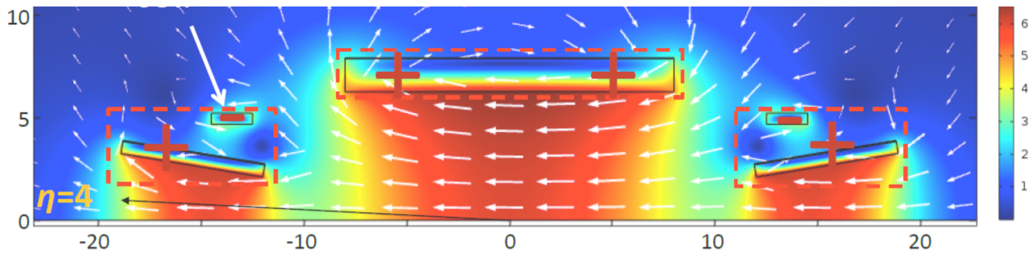


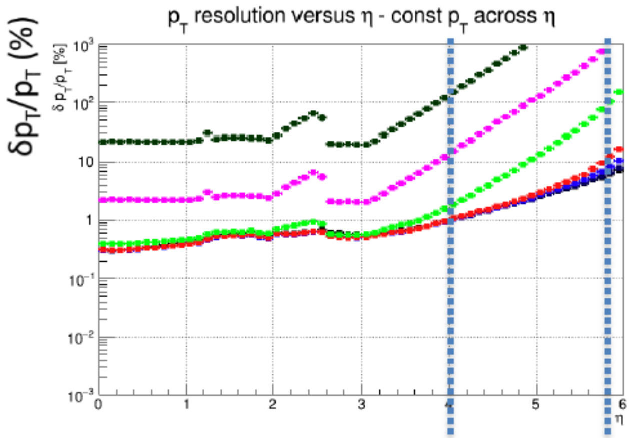
Alternative challenging design:

4T/4m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!

- Detector performance evaluated in first simulation studies
  - fed back into parameterised physics smearing simulation
  - full simulation/reconstruction chain being developed

Tracking performance

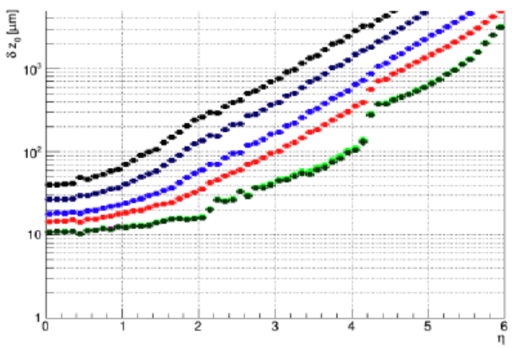


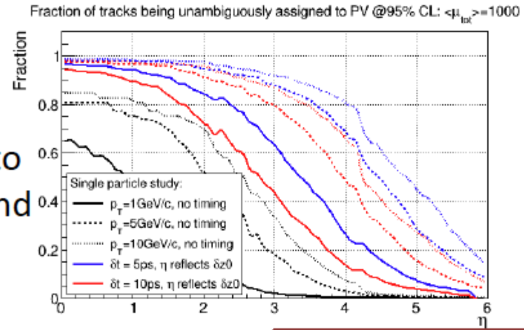


η=4.0 η=5.8

p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

σ_z resolution of single track





$\delta p_T/p_T \leq 10\%$ for

- **$\leq$ 10 GeV/c and $\eta \leq 5.8$**
- **$\leq$ 1 TeV/c and $\eta \leq 4.0$**

$\delta p_T/p_T$ = 20% for 10 TeV/c and η = 0.0

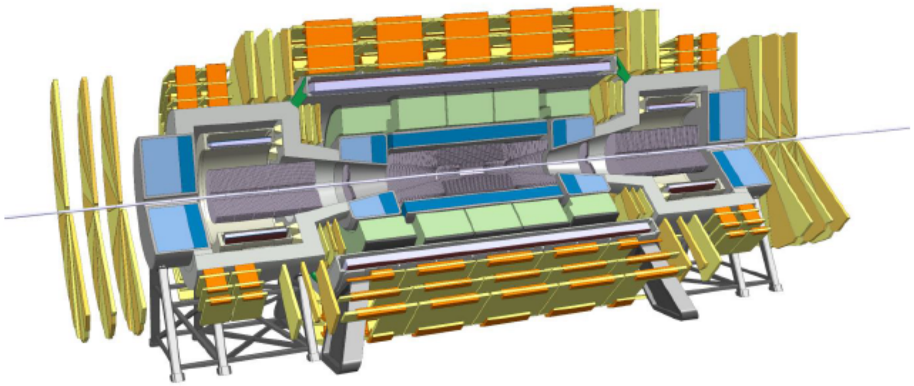
Fraction of tracks correctly assigned to primary vertex w and w/o timing

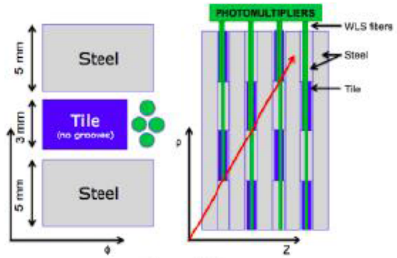
Primary vertexing @ PU~1000 seems very difficult for η>4.0, even with timing res. ~5ps!

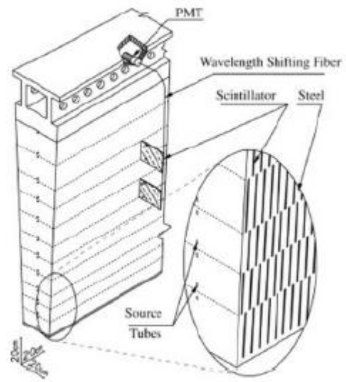
Z. Drasal

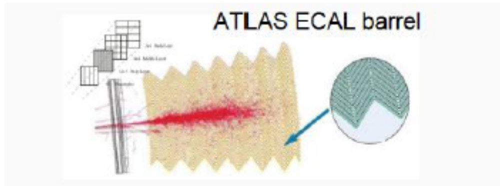
Calorimetry

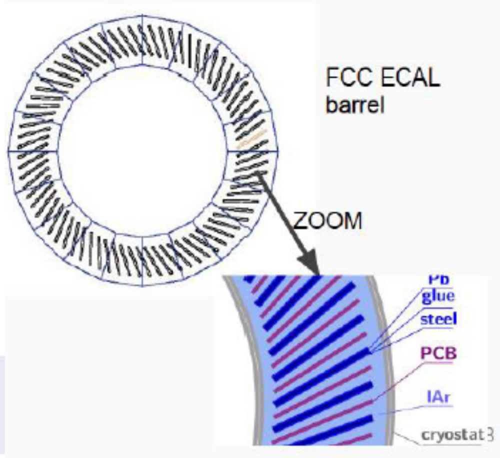
Talks J. Faltova, C. Neubüser











Barrel HCAL in Fe/Sci similar to ATLAS Tilecal

Barrel ECAL, Endcap ECAL/HCAL, Forward ECAL/HCAL are in LAr technology, which is intrinsically radiation hard.

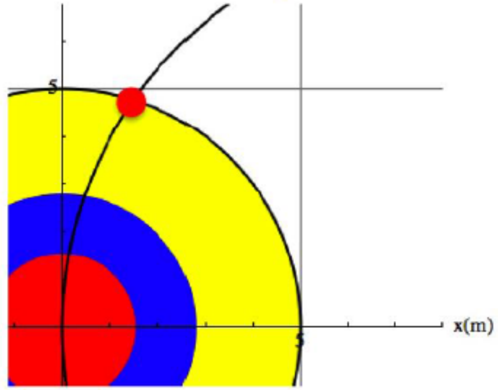
Silicon ECAL and ideas for digital ECAL with MAPS are being discussed.

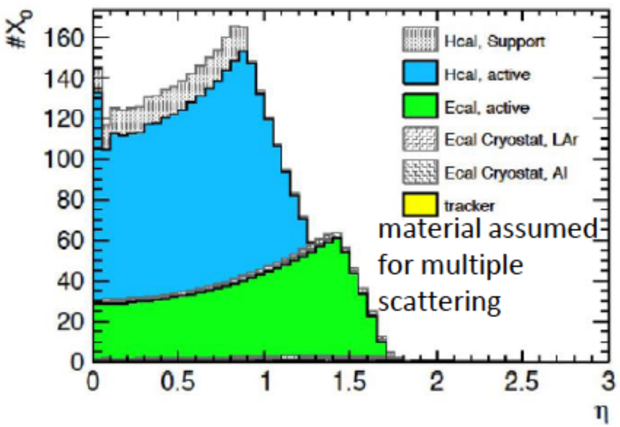
$\sim 11\,\lambda$ FCC-hh HCAL, pion resolution:
$\sigma E/E = 43\,\%/\sqrt{E} \oplus 2.7\%$

Goal energy resolution of 10% / sqrt(*E*) ⊕ 1%

Muon performance

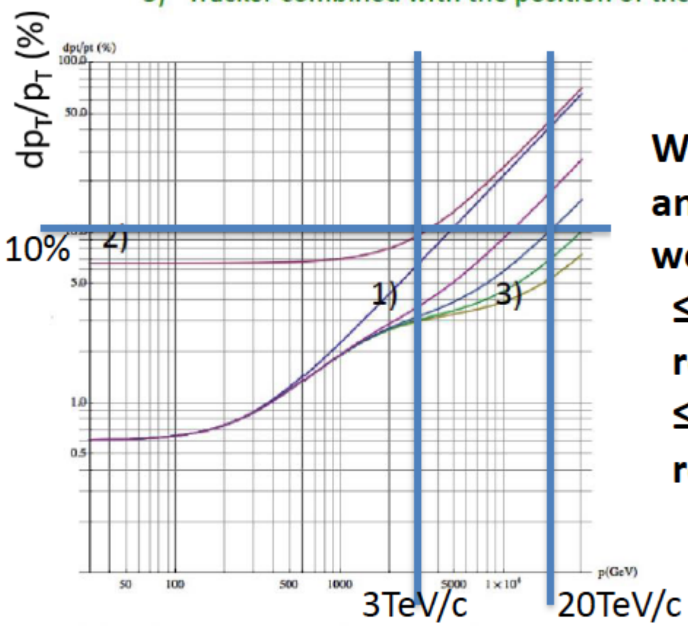
p_t=3.9GeV enters muon system
p_t=5.5GeV leaves coil at 45 degrees





Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil



With 50µm position resolution and 70µrad angular resolution we find (η=0):
- **≤10% standalone momentum resolution up to 3TeV/c**
- **≤10% combined momentum resolution up to 20TeV/c**

All within reach of 'standard' muon system technology

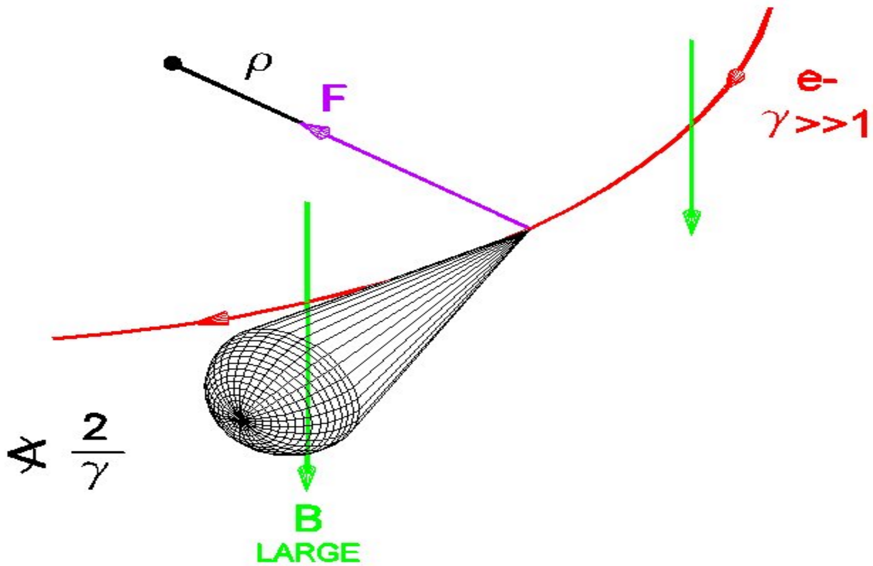
W. Riegler

Lepton collider FCC-ee

- Here the name of the game is **luminosity: as many collisions as possible → high beam current, small beam size.**
- The energy reach of circular e+e- colliders is limited due to synchrotron radiation of charged particles on curved trajectory:

$$\Delta E \propto (E_{kin}/m_0)^4/\rho$$

$$m_{prot} = 2000\ m_{electr}$$

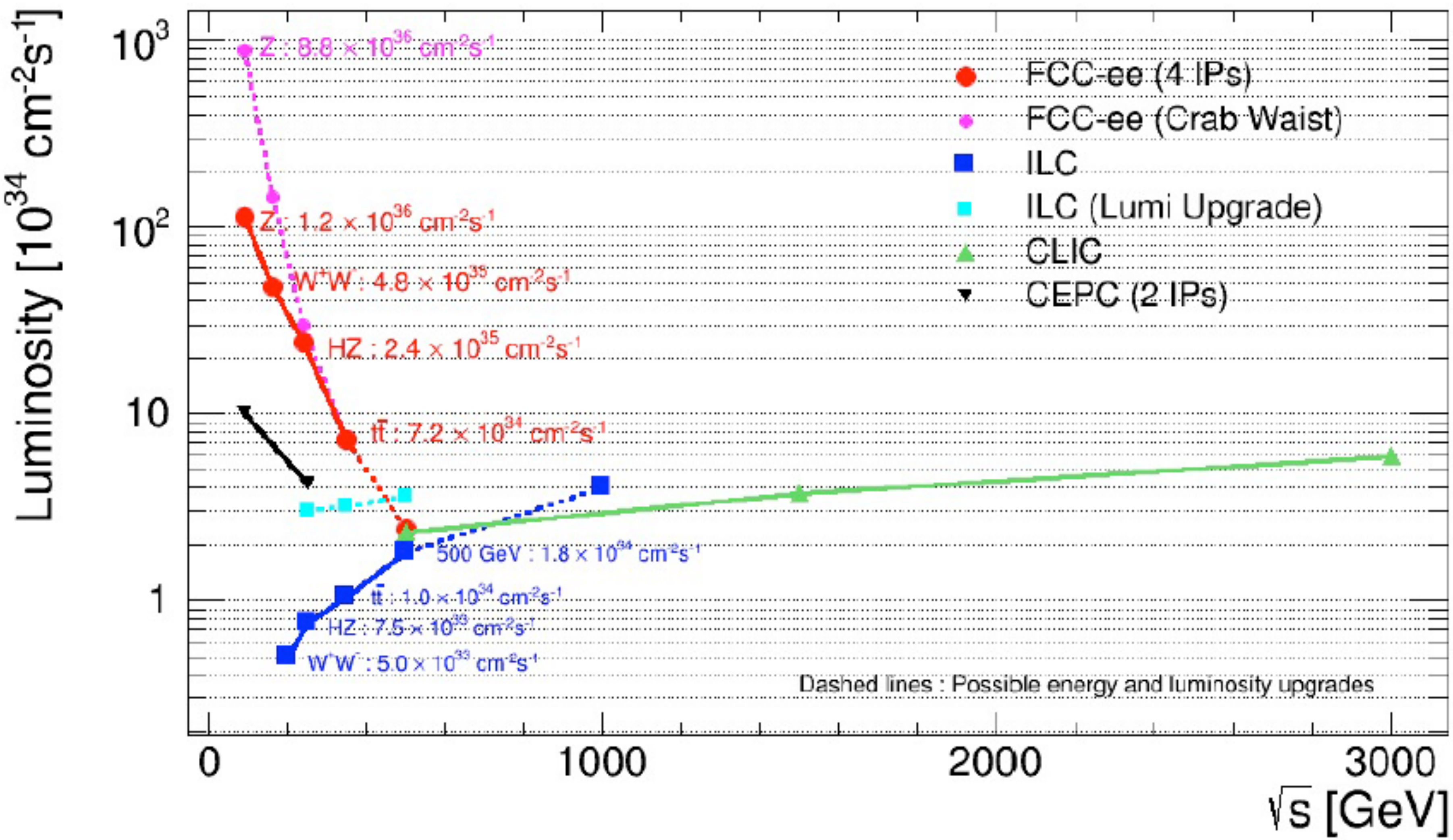


Lepton collider FCC-ee parameters

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

Parameter	Z	WW	H	tt_{bar}	LEP2
E/beam (GeV)	**45**	**80**	**120**	**175**	**104**
I (mA)	**1450**	**152**	**30**	**6.6**	**3**
Bunches/beam	16700	4490	1360	98	4
Bunch popul. [10^{11}]	1.8	0.7	0.46	1.4	4.2
L/IP ($10^{34}cm^{-2}s^{-1}$)	28.0	12.0	6.0	1.7	0.012

- Large number of bunches at Z and WW and H requires 2 rings.
- High luminosity means short beam lifetime (few mins) and requires continues injection.


Luminosity [10^{34} cm^{-2}s^{-1}]
10^3
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
Z : 8.8 × 10^{36} cm^{-2}s^{-1}
Z : 1.2 × 10^{36} cm^{-2}s^{-1}
W^+W^- : 4.8 × 10^{35} cm^{-2}s^{-1}
HZ : 2.4 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 7.2 × 10^{34} cm^{-2}s^{-1}
500 GeV : 1.8 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$: 1.0 × 10^{34} cm^{-2}s^{-1}
HZ : 7.5 × 10^{33} cm^{-2}s^{-1}
W^+W^- : 5.0 × 10^{33} cm^{-2}s^{-1}
FCC-ee (4 IPs)
FCC-ee (Crab Waist)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades

Possible physics plan:

- **physics programs / energies:**
  - ***Z (45.5 GeV) Z pole,*** *'TeraZ' and high precision M_Z & Γ_Z*
  - ***W (80 GeV) W pair production*** *threshold, high precision M_W*
  - ***H (120 GeV) ZH production*** *(maximum rate of H's)*
  - ***t (175 GeV): $t\bar{t}$ threshold****, H studies*
- **beam energy range from 40 GeV to ≈ 190 GeV**
- **highest possible luminosities** *at all working points*
- *possibly* ***H* (126 GeV) direct *s*-channel** production with **monochromatization**
  (**c.m. energy spread <6 MeV**, presentation at IPAC'16)
- **beam polarization up to ≥80 GeV - 100keV E_{beam} calibration**

Precision prospects of FCC-ee runs at the Z pole, WW and tt thresholds

A.Blondel, FCC kickoff

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_Z (keV)	Input	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_Z (keV)	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	PMNS Unitarity sterile ν's	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	PMNS Unitarity sterile ν's	2.92 ±0.05	(γ+Z_inv) (γ+Z→ ℓℓ)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	$\Delta\rho, \varepsilon_3, \varepsilon_2, \Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

H: 5yrs@240 GeV	WW:1-2yrs thrs scan	tt: 5yrs@350 GeV	Z@91GeV: 2yrs + 1 yr(pol)
2×10^6	10^8	10^6	10^{12}

FCC-ee: RF parameters and R&D

- **Synchrotron radiation power: 50 MW per beam**
- **Energy loss per turn: up to 7.5 GeV (at 175 GeV, t)**
- System dimension compared to LHC:
  - **LHC 400 MHz → 2 MV and ~250 kW per cavity, (8 cavities per beam)**
  - **FCC-ee: ~600 cavities 20 MV / 180 kW RF → 12 GV / 100 MW**

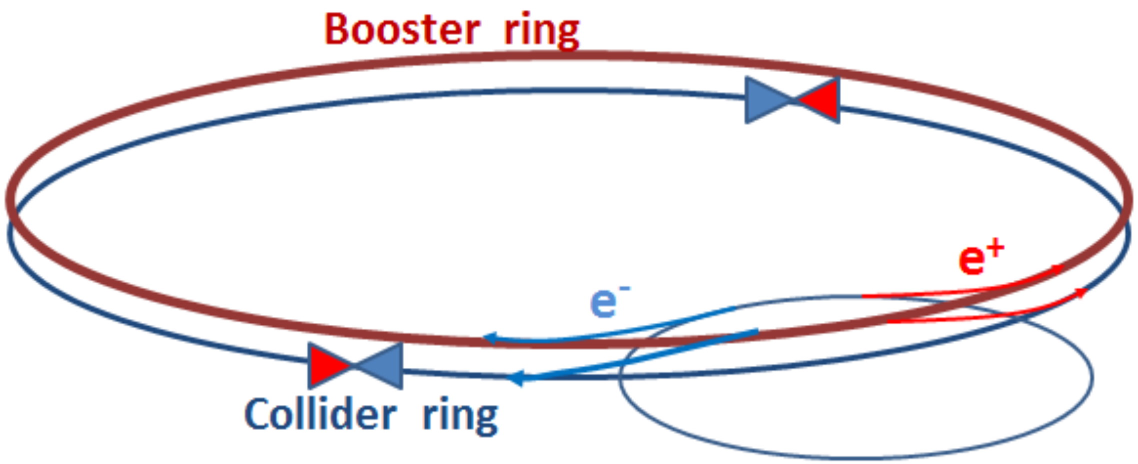
- **R&D Goal is optimization of overall system efficiency and cost!**

1. **SC cavity R&D → large Q_0 , high gradient, acceptable cryo power!**
   - Recent promising results at 4 K with Nb3Sn coating on Nb at Cornell,
   - $800\ ^{\circ}\mathrm{C} \div 1400\ ^{\circ}\mathrm{C}$ heat treatment JLAB, beneficial effect of impurities FNAL.
2. **High efficiency RF power generation from electrical grid to beam**
   - Amplifier technologies
   - Klystron efficiencies >65%, alternative RF sources as solid state amplifier, etc.
3. **High reliability**

FCC-ee top-up injector

Beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection

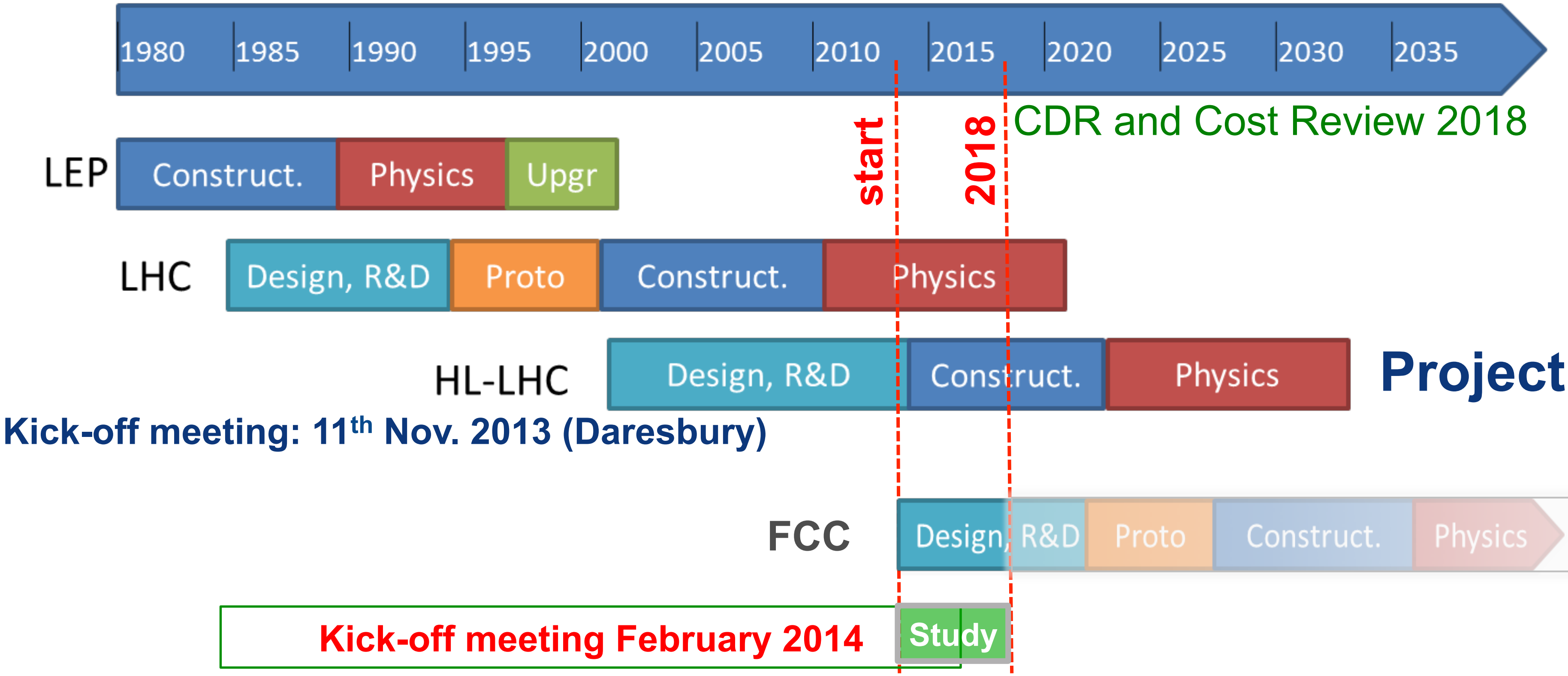
- same RF voltage, but low power (~ MW)
- top up frequency ~0.1 Hz
- booster injection energy ~5-20 GeV
- bypass around the experiments



injector complex for e^+ and e^- beams of 10-20 GeV

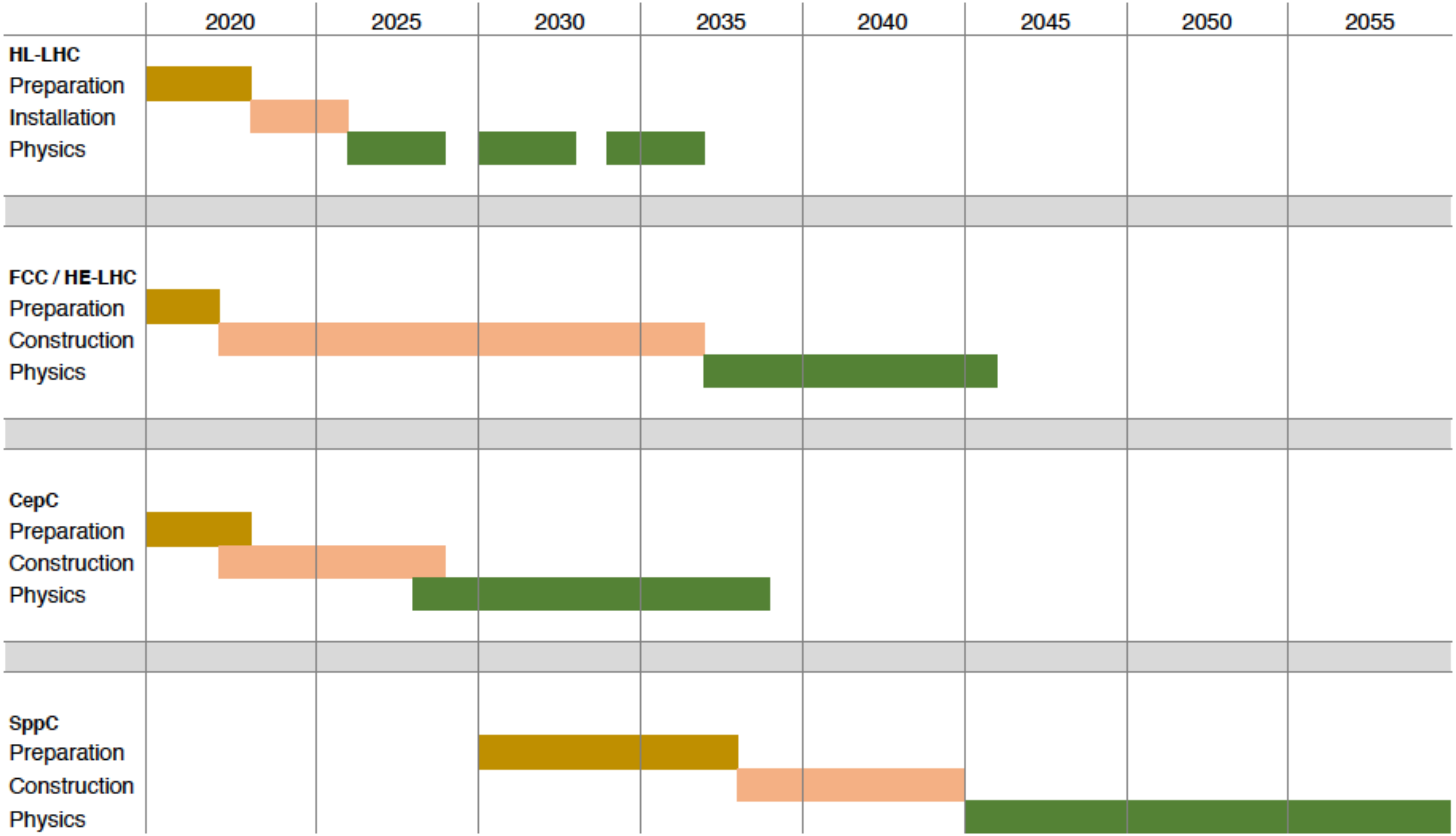
- Super-KEKB injector ~ almost suitable

CERN roadmap and FCC planning



CDR and Cost Review for 2018

For comparison:



Conclusions

- There are strongly rising activities in energy-frontier circular colliders worldwide.
- The FCC collaboration is being formed with CERN as host laboratory, to conduct an international study for the design of Future Circular Colliders (FCC).
- Worldwide collaboration in physics, experiments and accelerators will be essential to advance and reach the goal of a CDR by 2018.
- FCC presents challenging R&D requirements in SC magnets, SRF and many other technical areas.
- **Need to establish global collaboration and use all synergies to move forward!**