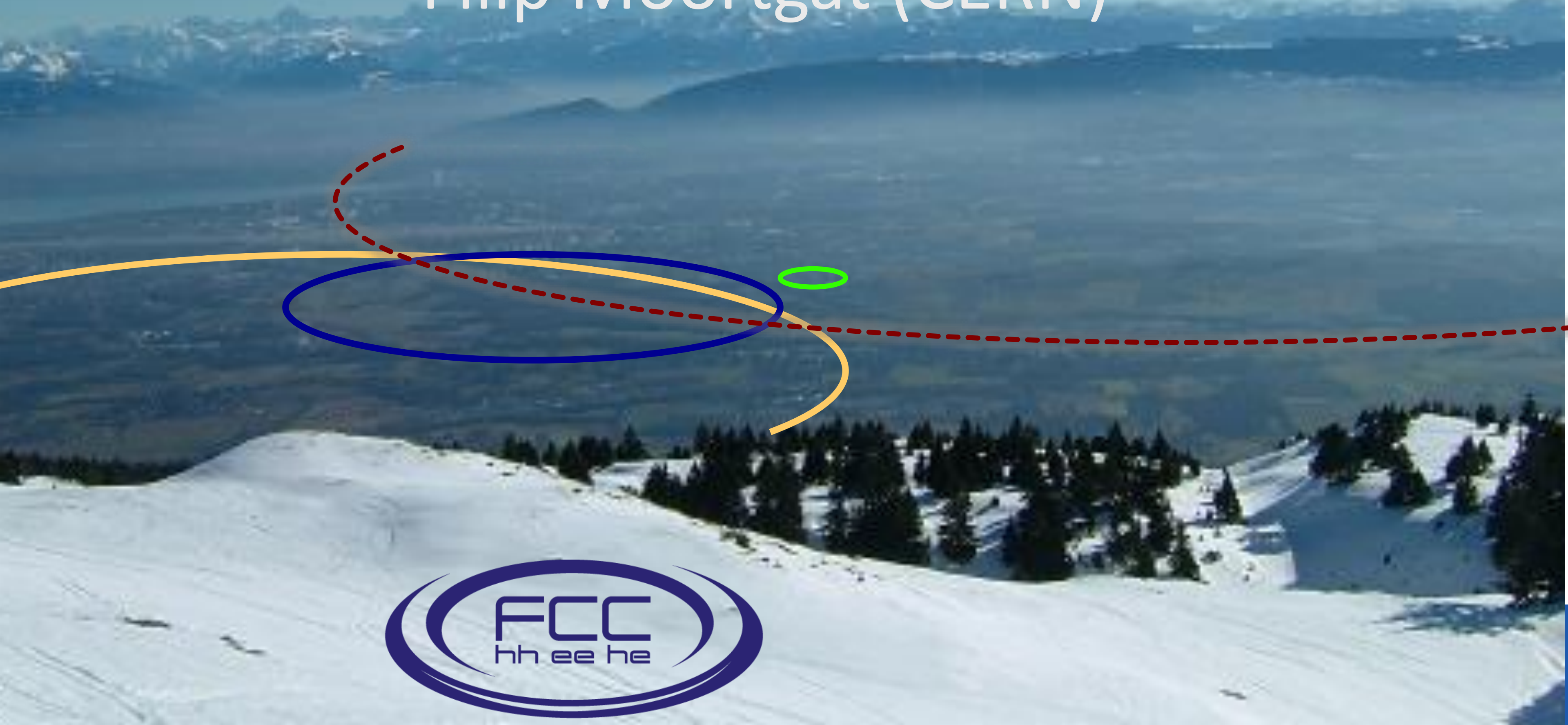
Physics
at a 100 TeV *pp* collider

Filip Moortgat (CERN)



Outline

- Introduction
- Parameters & design challenges
- Physics case
- A possible layout for an experiment

This presentation contains material from:

Michael Benedikt, Daniel Schulte, Werner Riegler, Michelangelo Mangano
Martin Aleksa, Ana Henriques, Clement Helsens, Jana Faltova, Coralie Neubüser, Anna Zaborowsk, Tony Price, Phil Allport, Sergei Chekanov
Jim Brooke , Simone Bologna, Paris Sphicas
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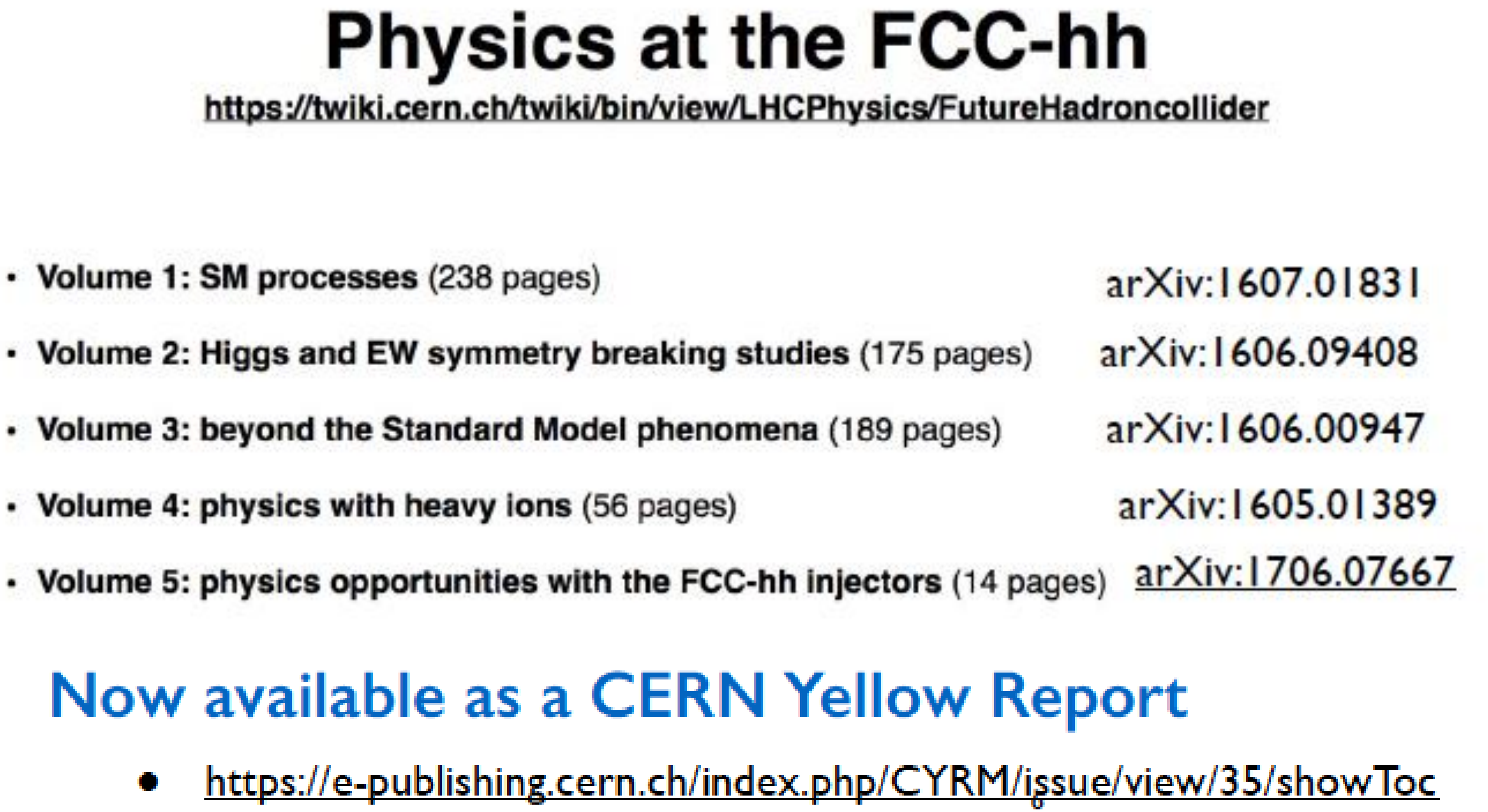
Michele Selvaggi, Heather Gray,
Phil Harris, Tristan du Pree
Benedikt Hegner, Andreas Salzburger, Julia Hrdinka, Valentin Volkl, Joschka Lingemann

and others …

Reading material



Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Volume 1: SM processes (238 pages)	arXiv:1607.01831
Volume 2: Higgs and EW symmetry breaking studies (175 pages)	arXiv:1606.09408
Volume 3: beyond the Standard Model phenomena (189 pages)	arXiv:1606.00947
Volume 4: physics with heavy ions (56 pages)	arXiv:1605.01389
Volume 5: physics opportunities with the FCC-hh injectors (14 pages)	arXiv:1706.07667

Now available as a CERN Yellow Report

- https://e-publishing.cern.ch/index.php/CYRM/issue/view/35/showToc

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

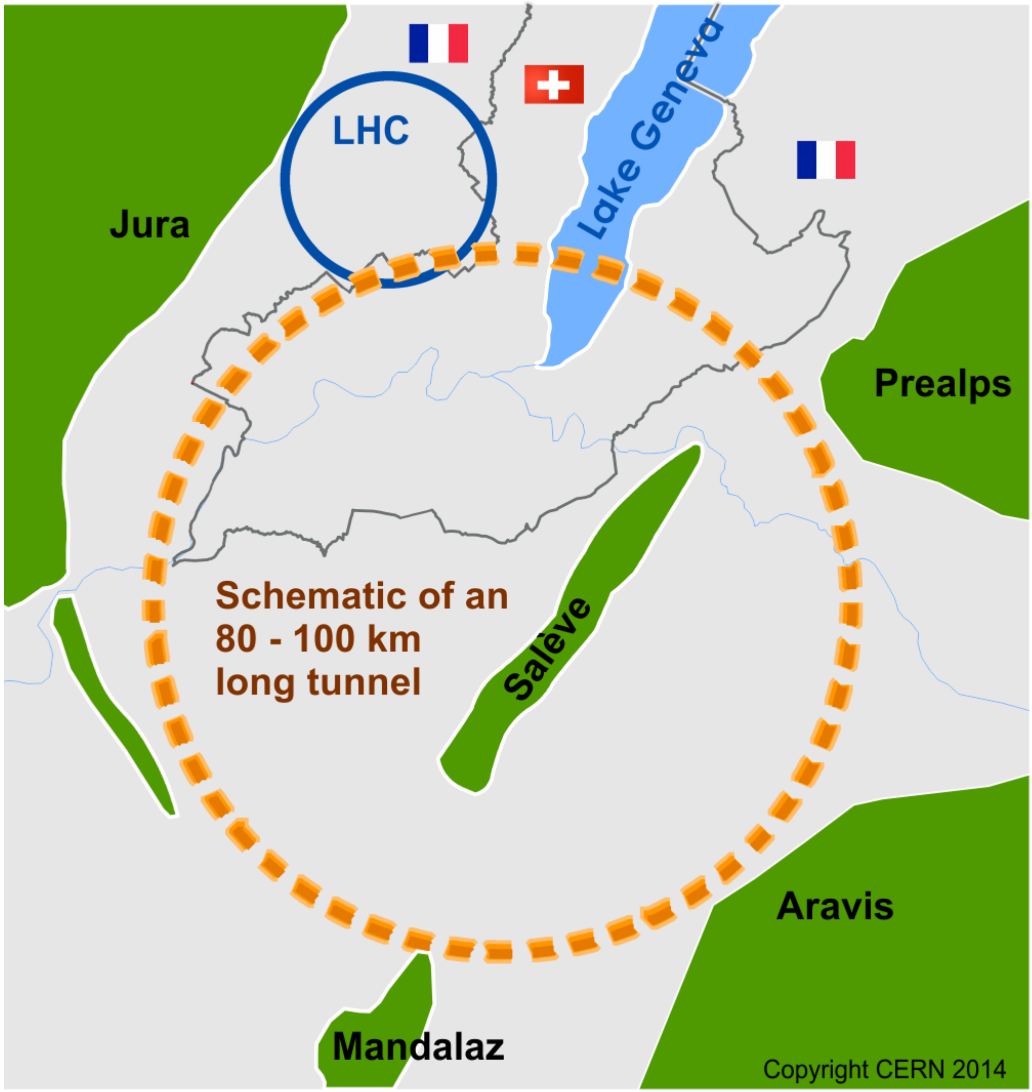
Future Circular Collider Study – SCOPE

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**



Schematic of an 80 - 100 km long tunnel

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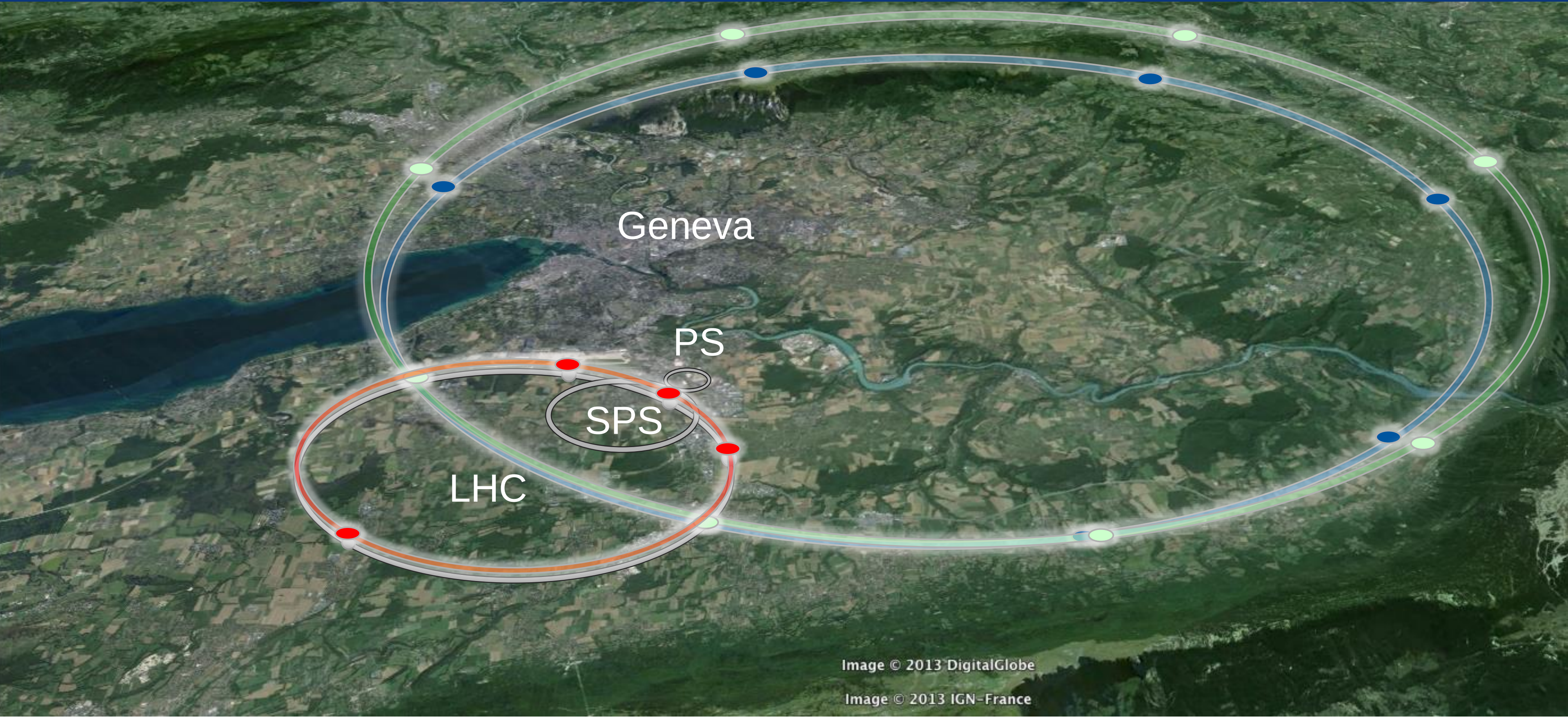
FCC-hh integration and options



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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.)

FCC hh: pushing the energy frontier

The name of the game of a hadron collider is energy reach

$$E \propto B_{\text{dipole}} \times \rho_{\text{bending}}$$

Cf. LHC: factor 3-4 in radius, factor 2 in field → factor 7-8 E

→ 100 TeV

- Access to new particles (direct production) in the few TeV to 30 TeV mass range, far beyond LHC reach.
- Much-increased rates for phenomena in the sub-TeV mass range →increased precision w.r.t. LHC and possibly ILC

Hadron collider comparison

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

Luminosity assumptions

The present working hypothesis is:

- **peak luminosity baseline: 5×10^{34}**
- **peak luminosity ultimate: ≤ 30×10^{34}**

- **integrated luminosity baseline ~250 fb-1 (average per year)**
- **integrated luminosity ultimate ~1000 fb-1 (average per year)**

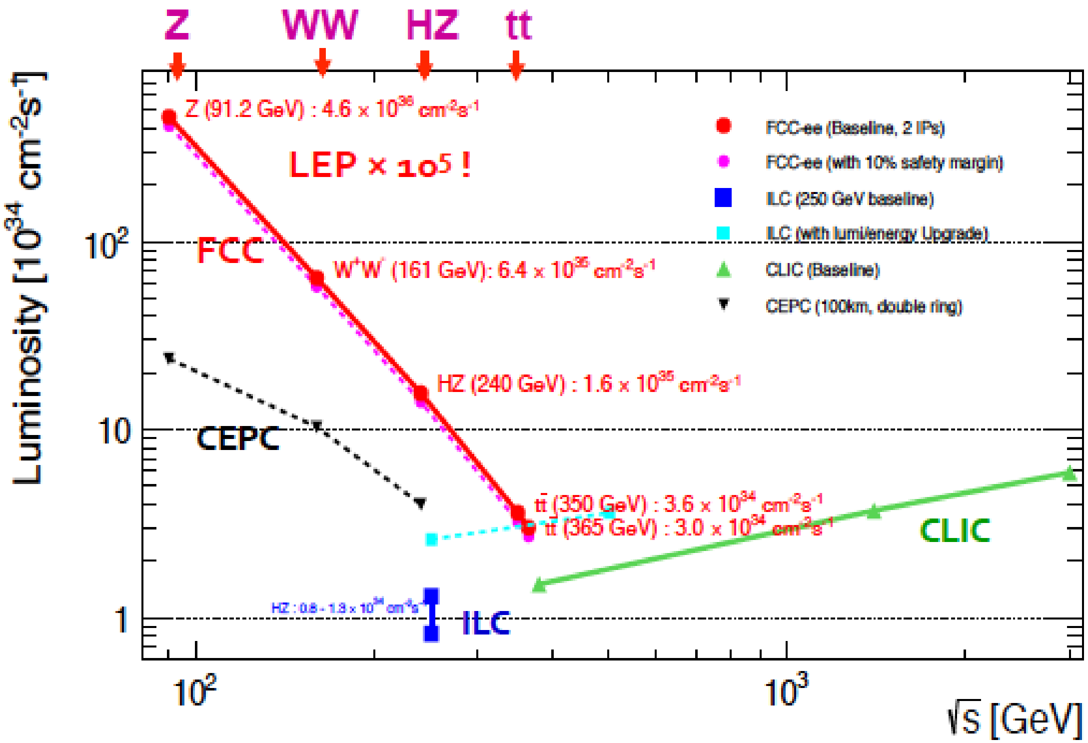
An operation scenario with:

- **10 years baseline, leading to 2.5 ab-1**
- **15 years ultimate, leading to 15 ab-1**

would result in a total of O(20) ab-1 over 25 years of operation.

Just as a reminder : FCC-ee

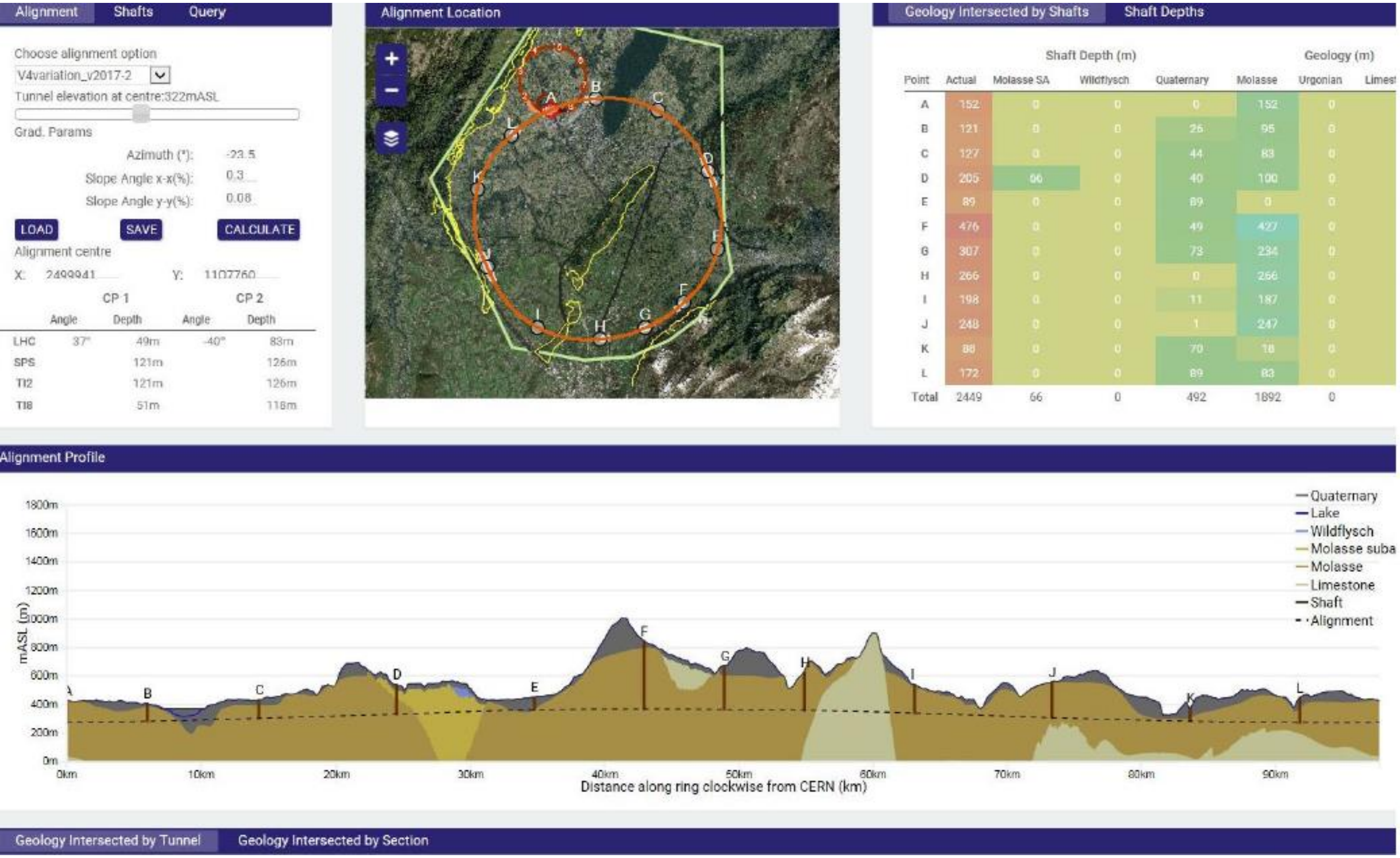
The money plot:



- Ultimate precision with
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W in 5 years at LEP
  - 1 500 Higgs bosons / day
    - 10-20 times more than ILC
  - 1 500 top quarks / day

… in each detector

Site study 97.5 km baseline



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
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

	Shaft Depth (m)	Geology (m)					
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limest
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	

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

Tunneling

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

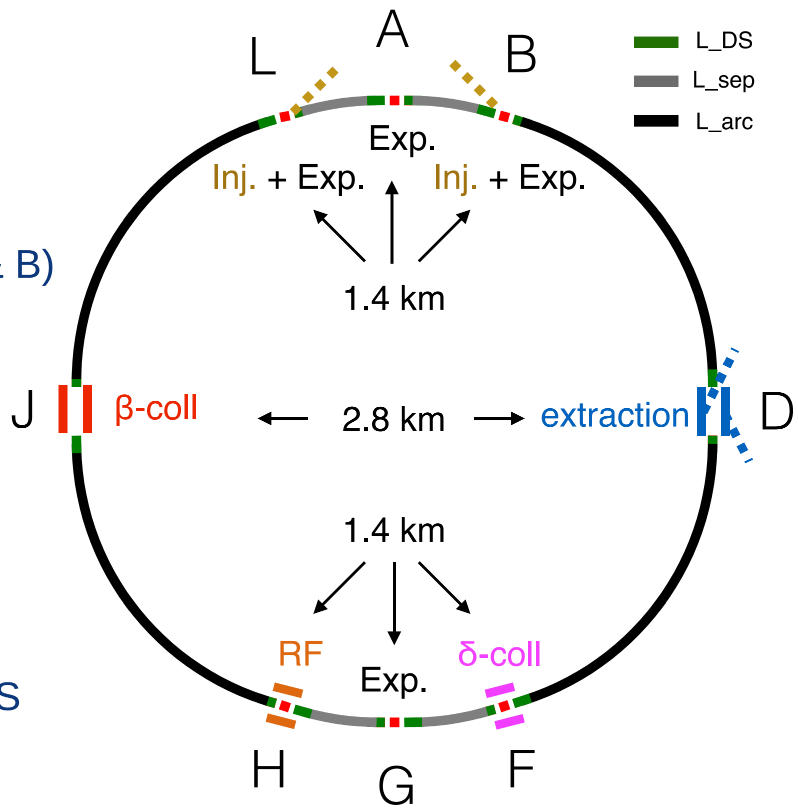
Shallow implementation

- ~ 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

Current layout

- Two high-luminosity experiments (A & G)
- Two other experiments combined with injection (L & B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Compatible with LHC or SPS as injector

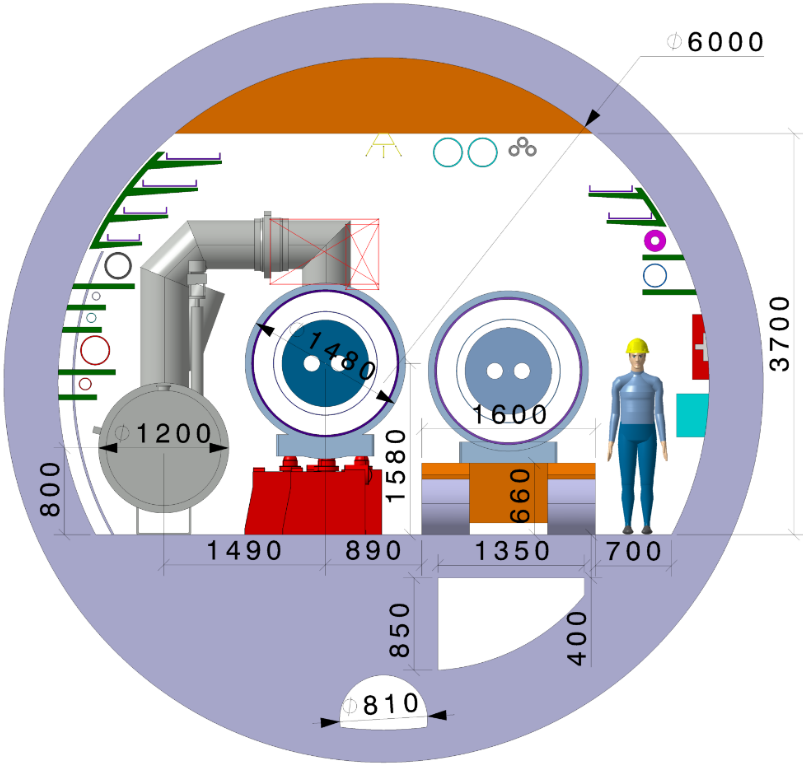


New features:

- **Overall length 97.75 km**
- **Economy length 2.25 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**

Fixing this layout for CDR

FCC-hh tunnel



Basic layout following LHC concept

- **6 m inner tunnel diameter**
- Main space allocation:
  - 1200 mm cryo distribution line (QRL)
  - 1480 mm installed cryomagnet
  - 1600 cryomagnet magnet transport
  - >700 mm free passage.

FCC-hh: high-field magnet R&D

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

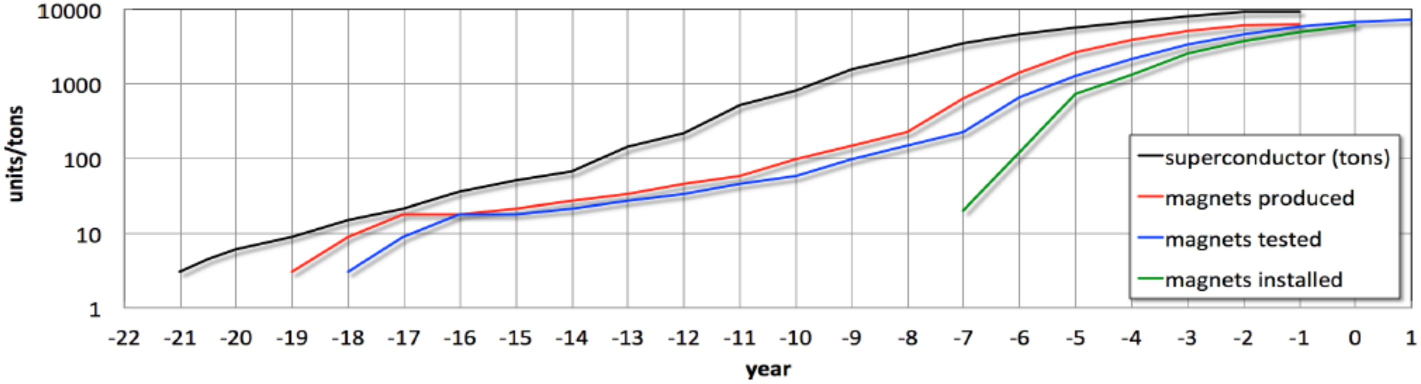
Develop Nb_3Sn-based 16 T dipole technology (at 4.2 K?),
- conductor developments
- short models with sufficient aperture (40 – 50 mm) and
- accelerator features (margin, field quality, protect-ability, cycled operation).

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

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

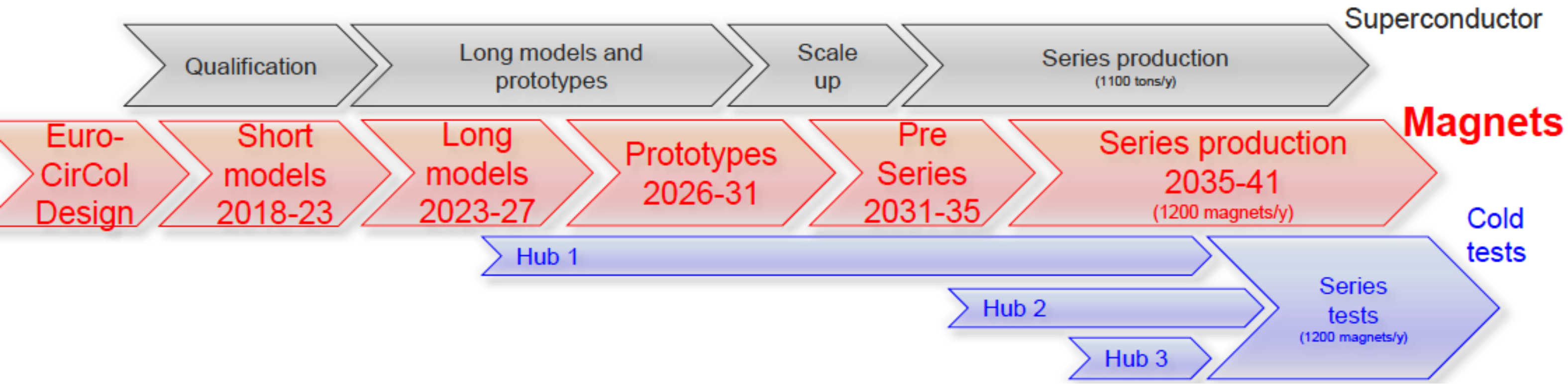
Goal: Demonstrate HTS/LTS 20 T dipole technology:
- 5 T insert (EuCARD2), ~40 mm aperture and accelerator features
- Outsert of large aperture ~100 mm, (FRESCA2 or other)

16T magnet development timeline



Total duration of magnet program:

~20 years



Superconductor

Qualification

Long models and prototypes

Scale up

Series production
(1100 tons/y)

Magnets

Euro-CirCol Design

Short models 2018-23

Long models 2023-27

Prototypes 2026-31

Pre Series 2031-35

Series production 2035-41
(1200 magnets/y)

Cold tests

Hub 1

Hub 2

Hub 3

Series tests
(1200 magnets/y)

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

FCC-hh: some design challenges

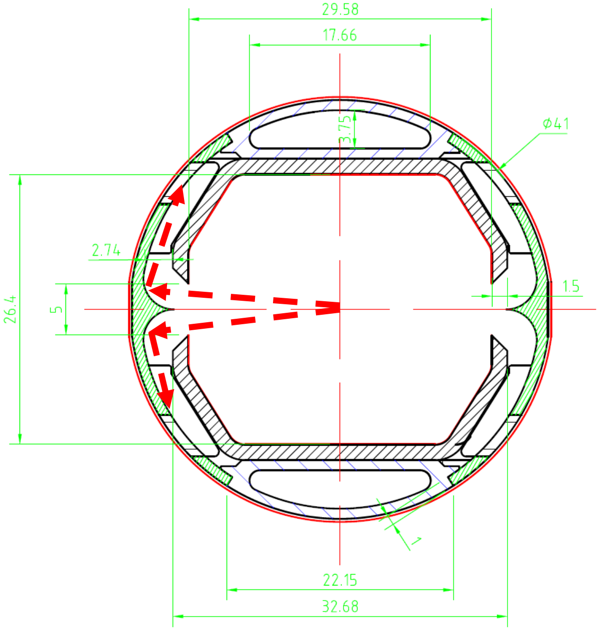
- **Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total**
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h)

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

Cryogenic beam vacuum system

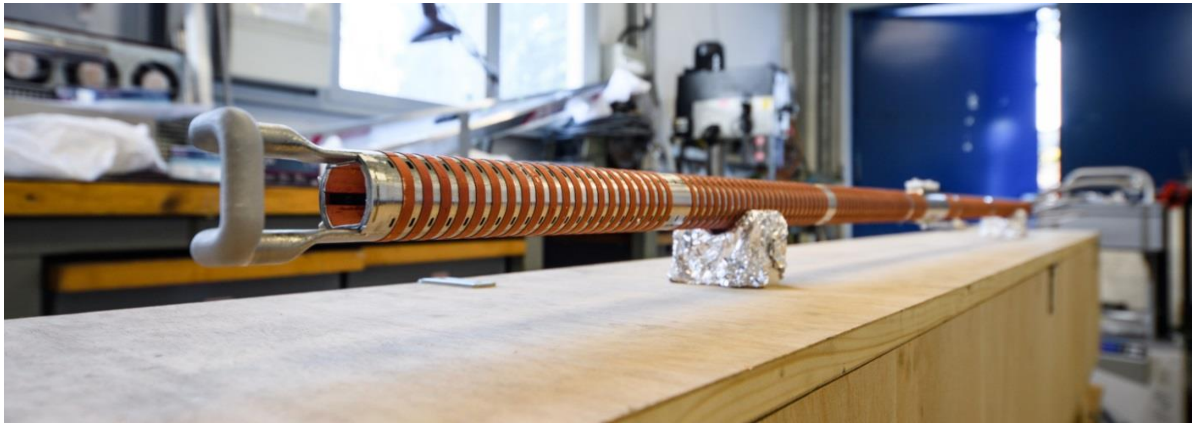
One of the most critical elements for FCC-hh

- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.



FCC Beamscreen prototype for test at ANKA:

External copper rings for heat transfer to cooling tubes



Remember: synchrotron radiation $-\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$

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

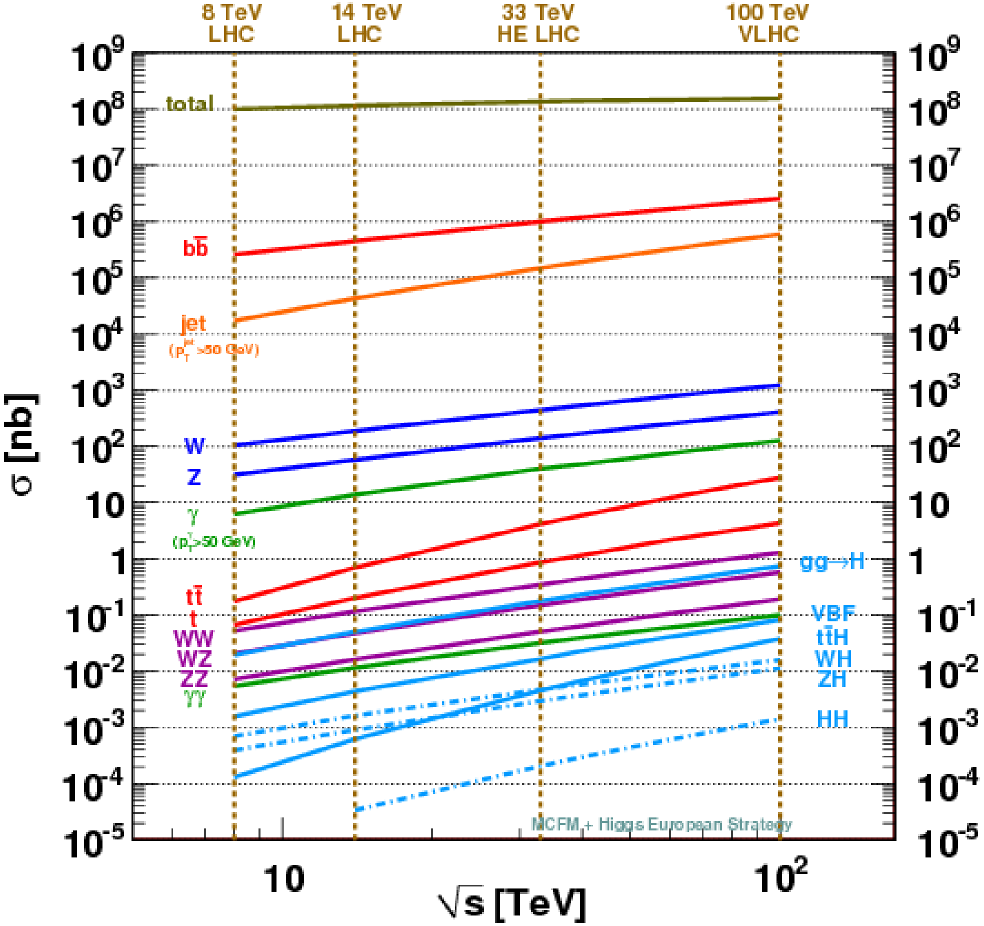
➥ Immense rates for phenomena in the sub-TeV mass range ⇒

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

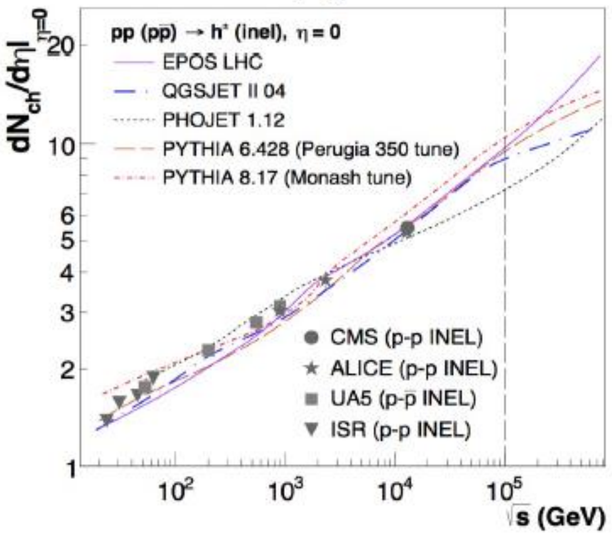
Cross section evolution



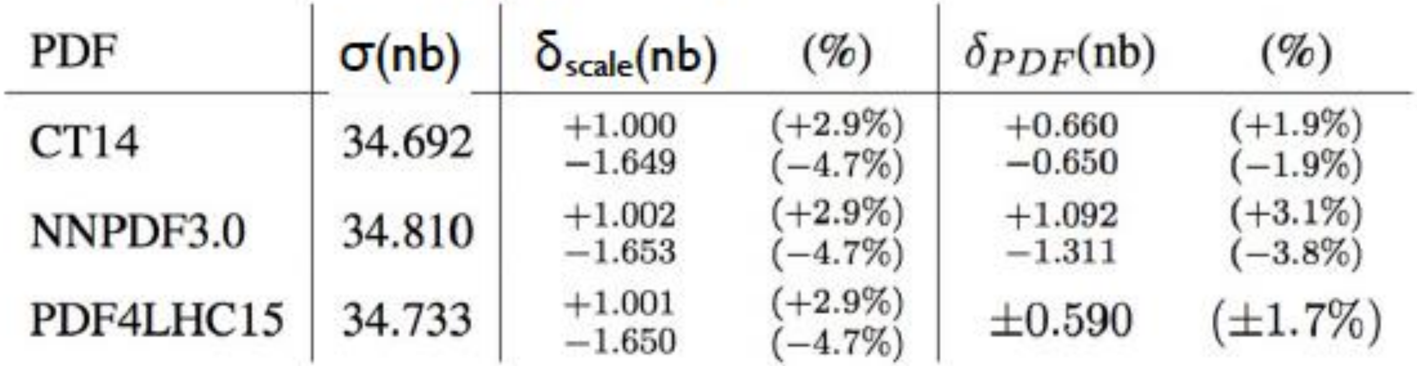
Total cross section and Minimum Bias Multiplicity show only a modest increase from LHC to FCC-hh.

The cross-section for interesting processes shows however significant increase !

track density @ 90° ~ 1.6 x LHC



Top quark production

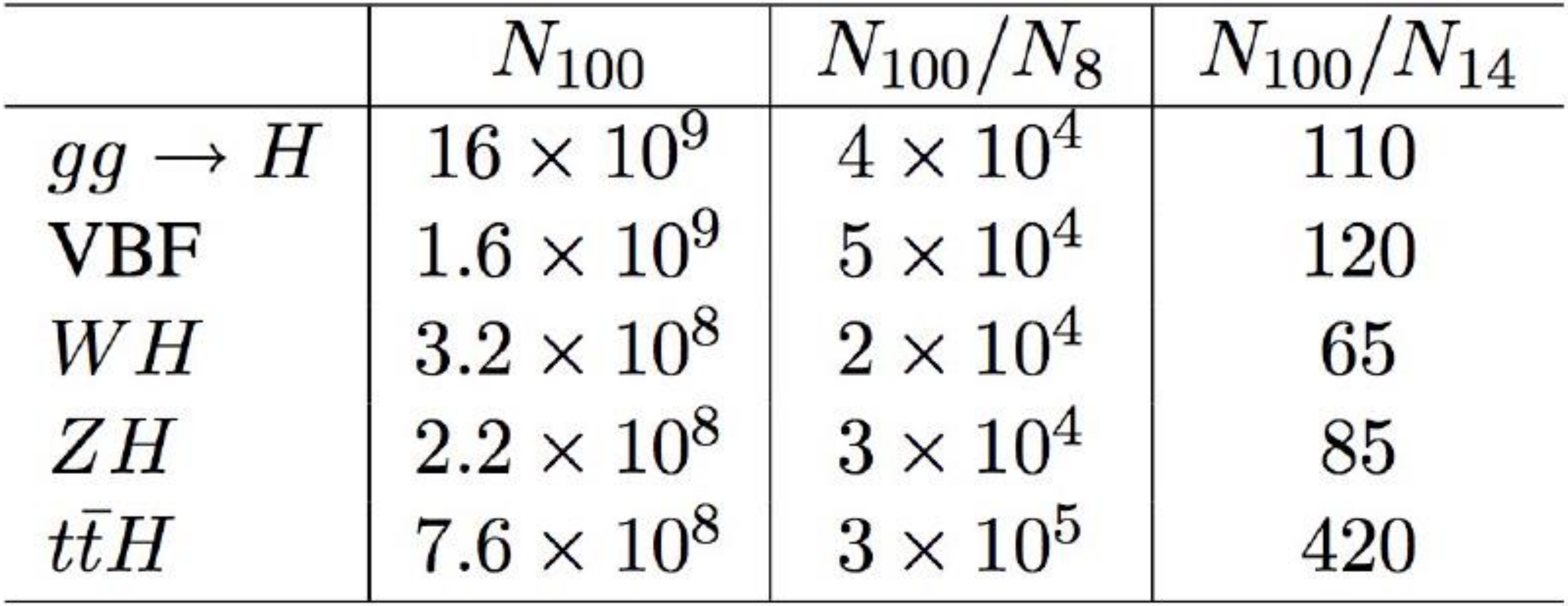


PDF	σ(nb)	δ_{scale}(nb)	(%)	δ_{PDF}(nb)	(%)
CT14	34.692	$+1.000$ -1.649	$(+2.9\%)$ (-4.7%)	$+0.660$ -0.650	$(+1.9\%)$ (-1.9%)
NNPDF3.0	34.810	$+1.002$ -1.653	$(+2.9\%)$ (-4.7%)	$+1.092$ -1.311	$(+3.1\%)$ (-3.8%)
PDF4LHC15	34.733	$+1.001$ -1.650	$(+2.9\%)$ (-4.7%)	± 0.590	$(\pm 1.7\%)$

σ_{tot}(100 TeV) ~ 35 x σ_{tot}(14 TeV)

- ⇒ about 10^{12} top quarks produced in 20 ab^{-1}
  - rare and forbidden top decays
  - 10^{12} fully inclusive W decays, triggerable by "the other W"
    - rare and forbidden W decays
    - 3 10^{11} W → charm decays
    - 10^{11} W → tau decays
  - 10^{12} fully charge-tagged b hadrons

Higgs production rates



	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \rightarrow H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

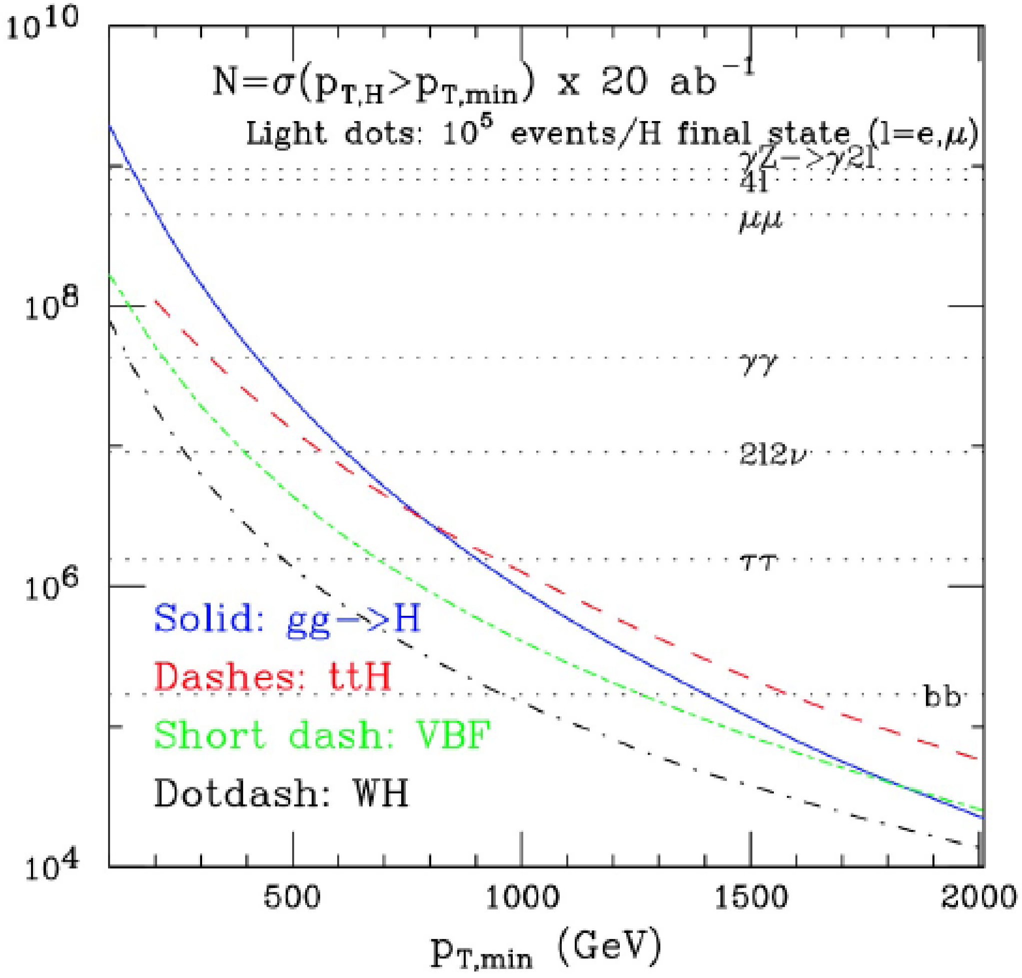
$N_8 = \sigma_{8\,\text{TeV}} \times 20\ \text{fb}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

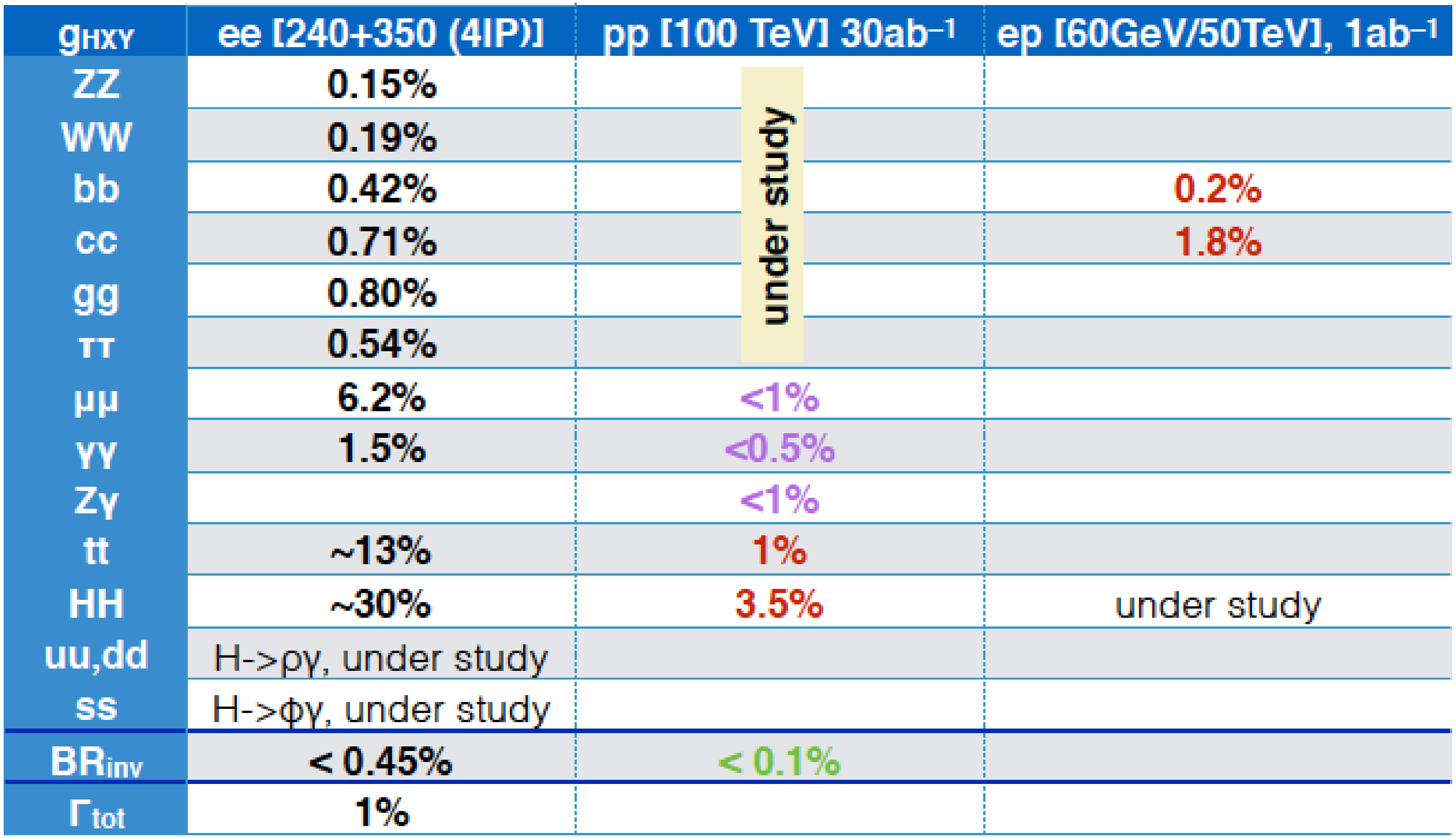
H at large p_T

Lesson: Hierarchy of production channels changes at large p_T(H):

- σ(ttH) > σ(gg→H) above 800 GeV
- σ(VBF) > σ(gg→H) above 1800 GeV



Higgs couplings @ FCC



g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%	under study	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
$\tau\tau$	0.54%		
$\mu\mu$	6.2%	<1%	
$\gamma\gamma$	1.5%	<0.5%	
$Z\gamma$		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR_{inv}	< 0.45%	< 0.1%	
Γ_{tot}	1%		

- detailed study, stat+syst
- rather detailed, stat only (understood/limited/negligible theory syst)
- parton level S and B (from ratios, negligibleTH syst, small exp syst)
- very preliminary estimates of exp/th syst (not stat-limited)

FCC-hh as a precision machine

One should not underestimate the value of FCC-hh standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

$BR(H\to\gamma\gamma)/BR(H\to ZZ^*)$

loop-level — tree-level

$BR(H\to\mu\mu)/BR(H\to ZZ^*)$

2nd gen'n Yukawa — gauge coupling

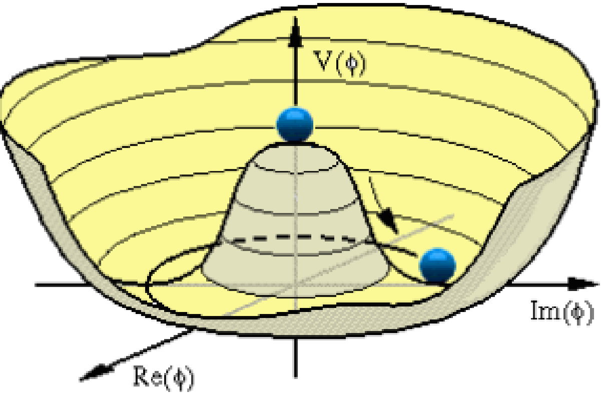
$BR(H\to\gamma\gamma)/BR(H\to Z\gamma)$

different EW charges in the loops of the two procs

Higgs decays to BSM, affecting Γ_{tot}, would impact Γ_{inv},(if weakly interacting), or $BR_{\gamma\gamma}$ (if charged), or $\sigma(gg\to H)$ (if colored) ⇒ detectable from various production and/or decay ratios

The Higgs potential

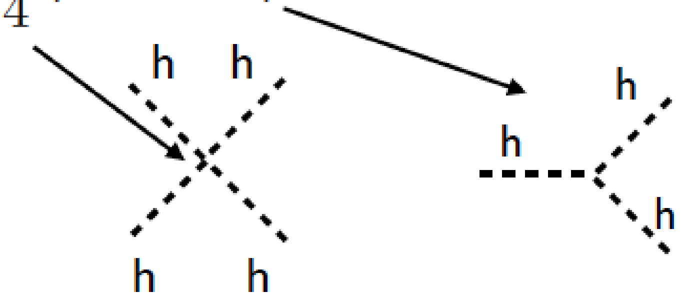
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



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?

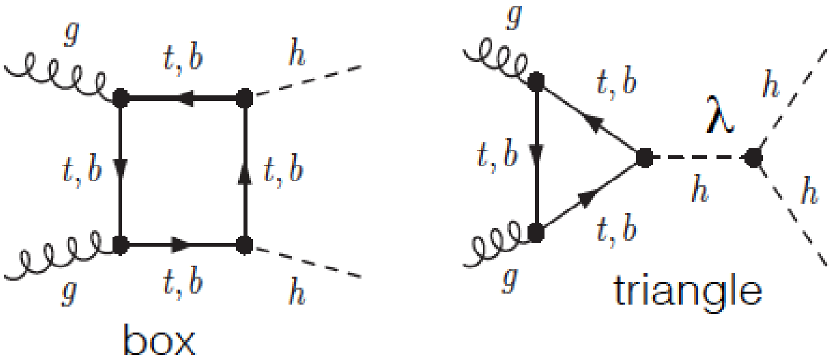
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

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

Standard Model



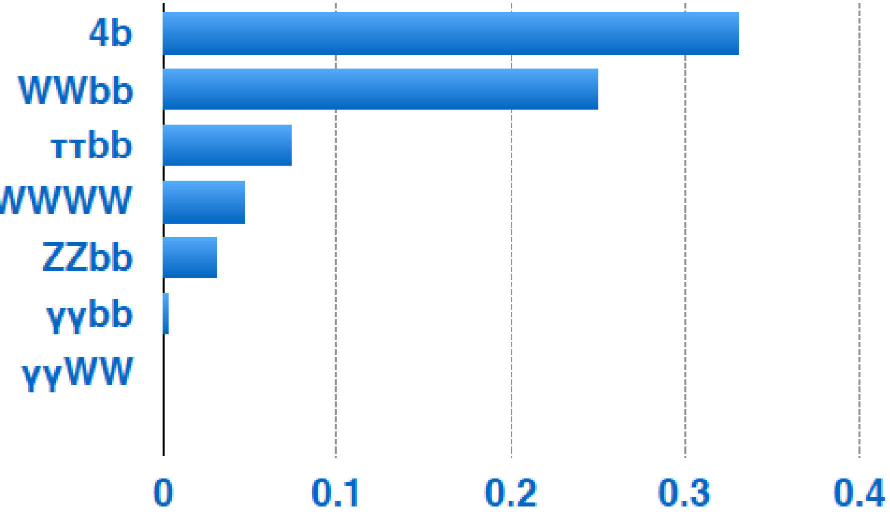
box

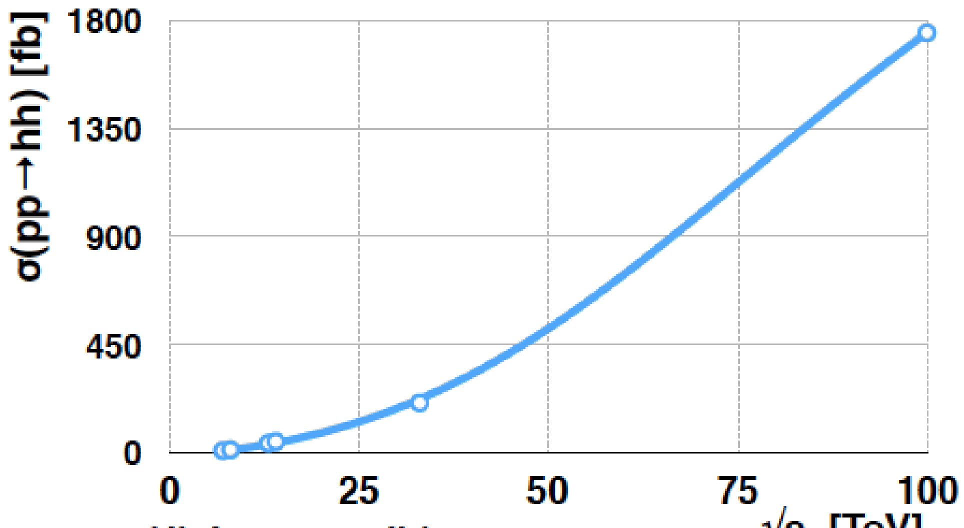
triangle

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

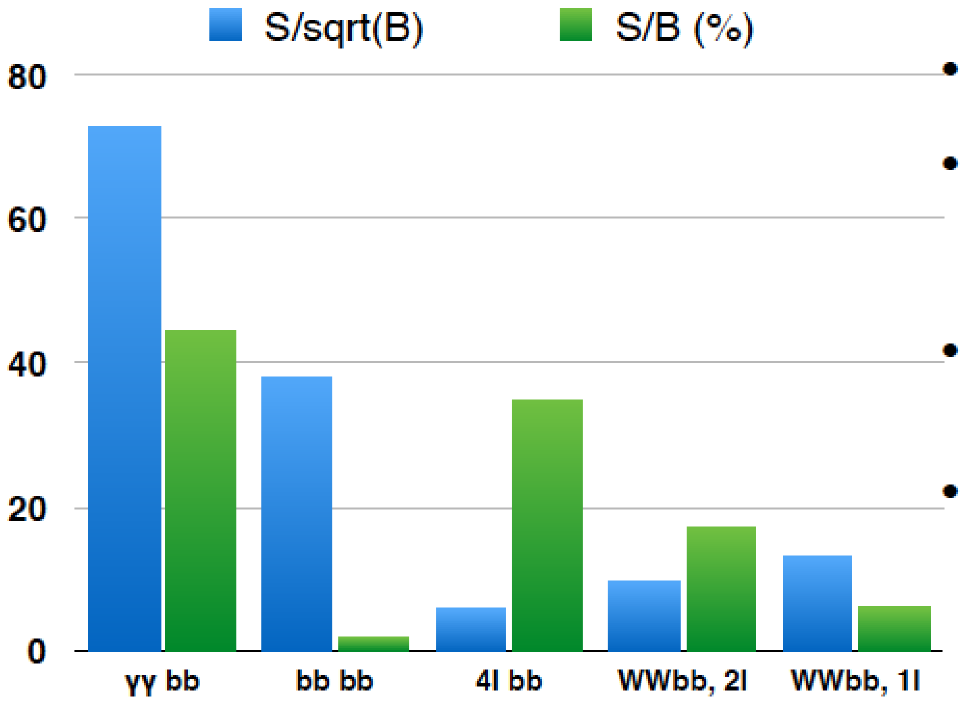
Higgs decay branching fraction





Highest possible energy pays

HH discovery channels at 100 TeV



- 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;

H selfcoupling determination

Contino, Englert, Panico, Papaefstathiou, Ren, Selvaggi, Son, Spannowsky, Yao

- overall rescaling of background rate $n_B \to r_B \times n_B$

using "medium" calorimeter resolution

- uncertainty on signal rate $\Delta_S = \dfrac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$

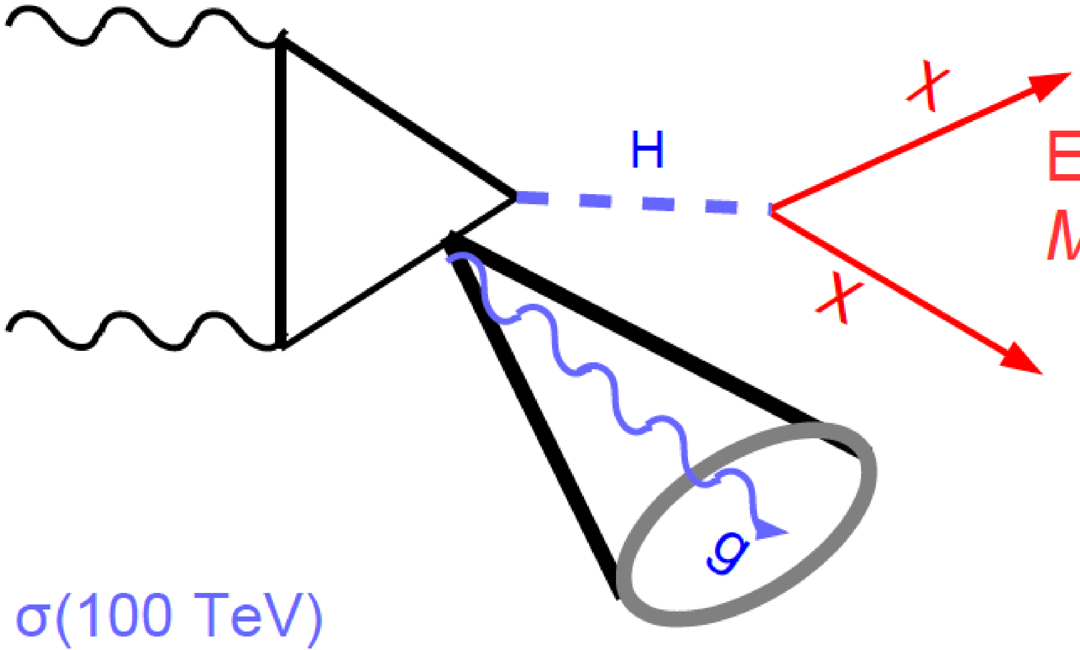
For $\Delta_S \gtrsim 2.5\%$ the precision on λ_3 is dominated by the theory error on the signal: $\Delta\lambda_3 \simeq 2\Delta_S$

$\Delta\lambda_3$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

Tab H-30

Results updated/confirmed with improved analysis by M.Selvaggi, https://indico.cern.ch/event/613195/

Invisible Higgs decays



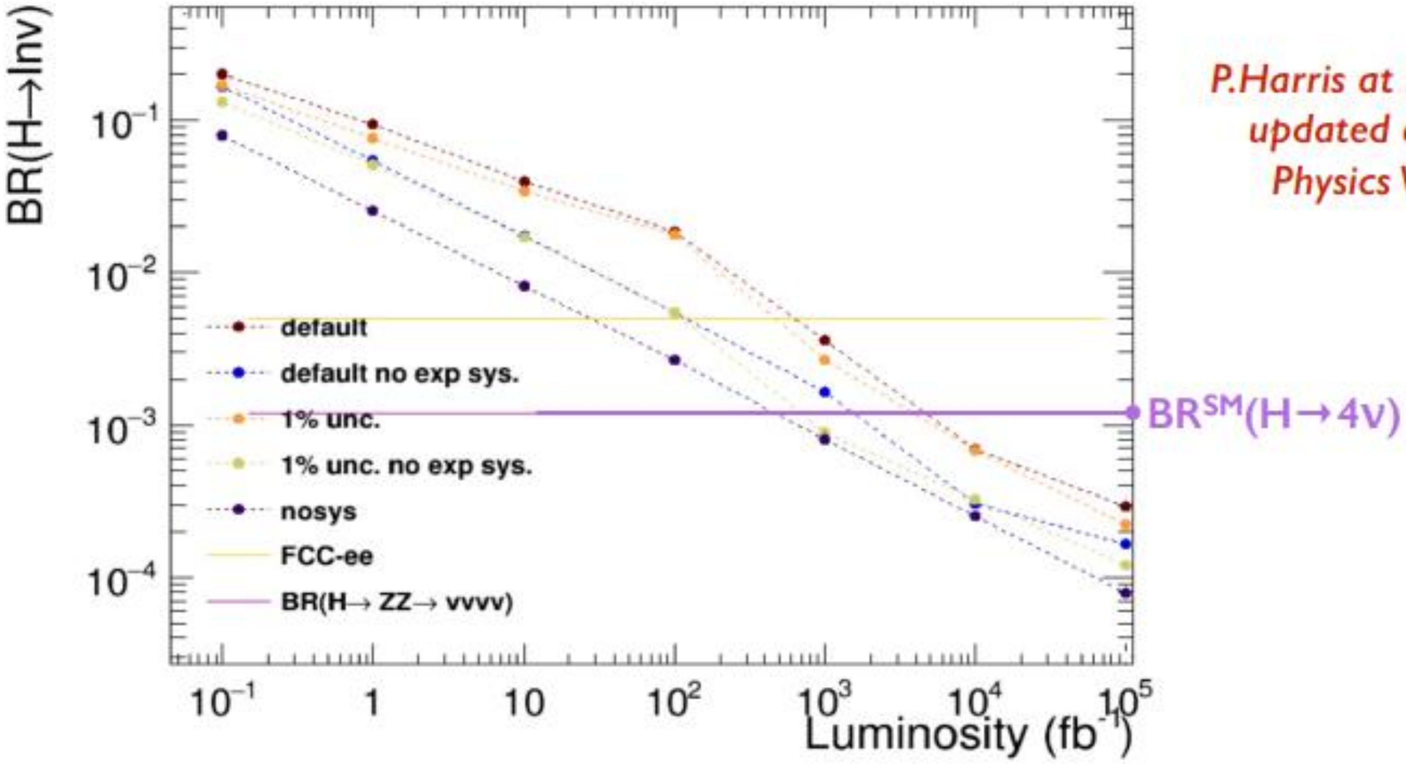
Escapes detector
MET

A Jet

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

Invisible Higgs decays

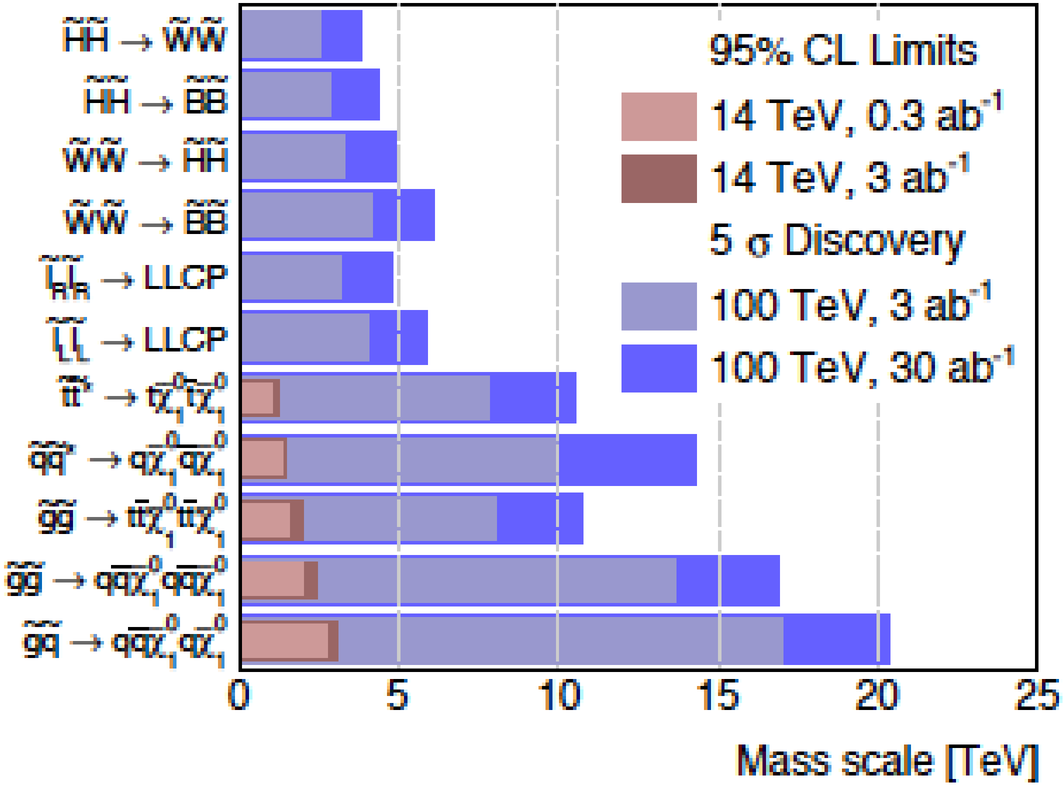
Constrain bg pt spectrum from Z→νν to the % level using NNLO QCD/EW* to relate to measured Z→ee, W and γ spectra



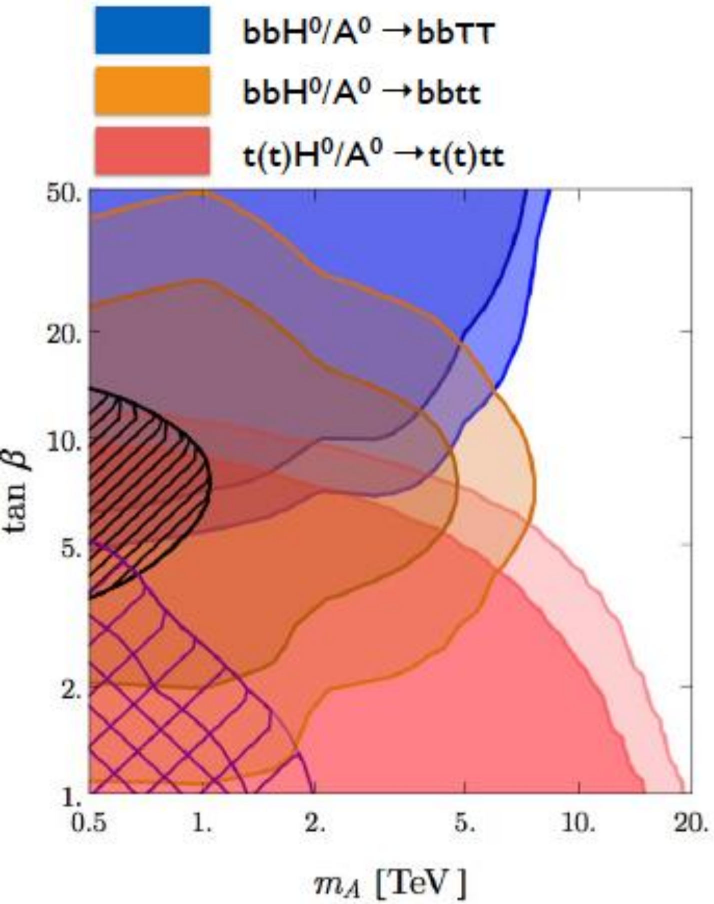
P.Harris at FCC wshop, updated at Feb 21 Physics WG mtg

SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

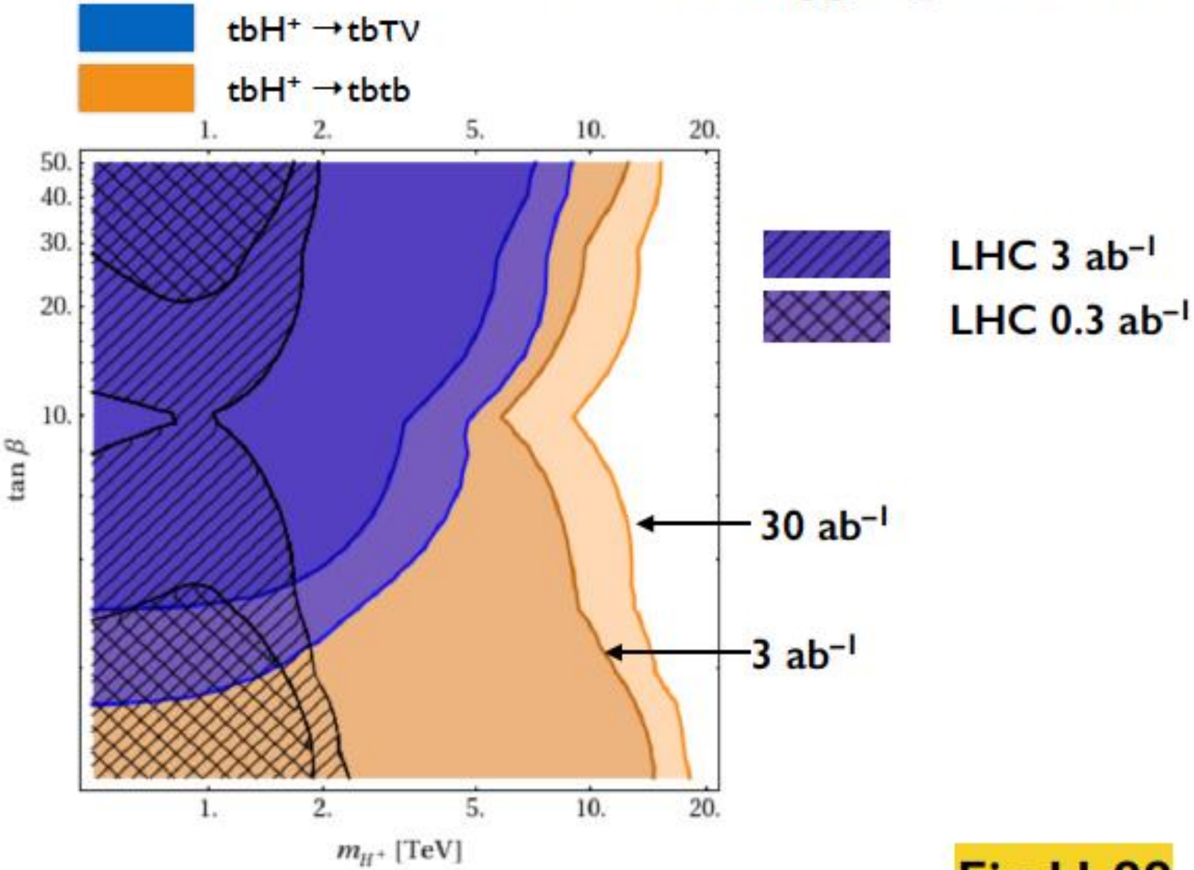
SUSY reach


$\tilde{H}\tilde{H} \to \tilde{W}\tilde{W}$
$\tilde{H}\tilde{H} \to \tilde{B}\tilde{B}$
$\tilde{W}\tilde{W} \to \tilde{H}\tilde{H}$
$\tilde{W}\tilde{W} \to \tilde{B}\tilde{B}$
$\tilde{l}_R\tilde{l}_R \to$ LLCP
$\tilde{l}_L\tilde{l}_L \to$ LLCP
$\tilde{t}\tilde{t}^* \to t\chi_1^0\bar{t}\chi_1^0$
$\tilde{q}\tilde{q}^* \to q\chi_1^0\bar{q}\chi_1^0$
$\tilde{g}\tilde{g} \to t\bar{t}\chi_1^0 t\bar{t}\chi_1^0$
$\tilde{g}\tilde{g} \to q\bar{q}\chi_1^0 q\bar{q}\chi_1^0$
$\tilde{g}\tilde{q} \to q\bar{q}\chi_1^0 q\chi_1^0$
95% CL Limits
14 TeV, 0.3 ab^{-1}
14 TeV, 3 ab^{-1}
5 σ Discovery
100 TeV, 3 ab^{-1}
100 TeV, 30 ab^{-1}
0
5
10
15
20
25
Mass scale [TeV]

MSSM Higgs @ 100 TeV



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, and H. Zhang, arXiv:1605.08744



J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Fig H-88

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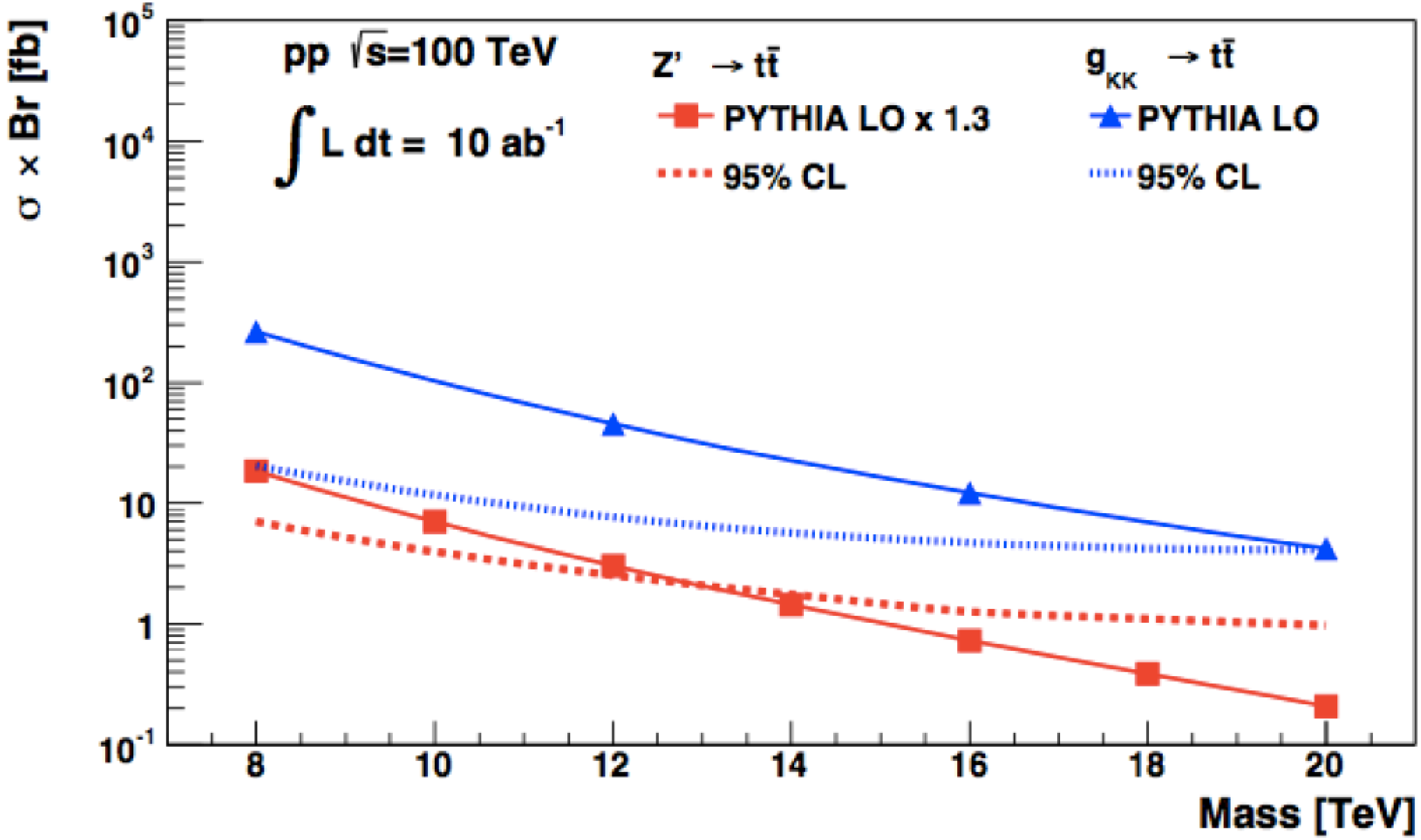
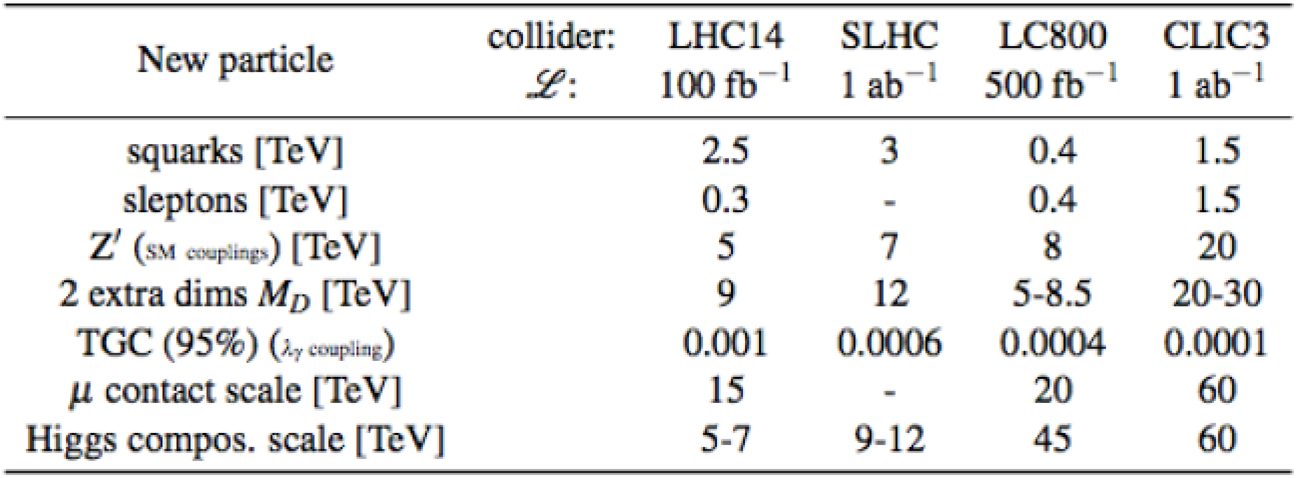
Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



Direct exploration of the high-mass scale



New particle	collider: $\mathscr{L}$:	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/

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

No-lose theorems?

25 years ago, there was a strong selling point for the LHC : the no-lose theorem for the Higgs (mH < 1000 GeV).

Now we don’t seem to have such a clear no-lose theorem for new physics … or do we?

It’s worth to to think of ways to put upper limits on the mass of new particles … even if it’s with some caveats.

Examples:

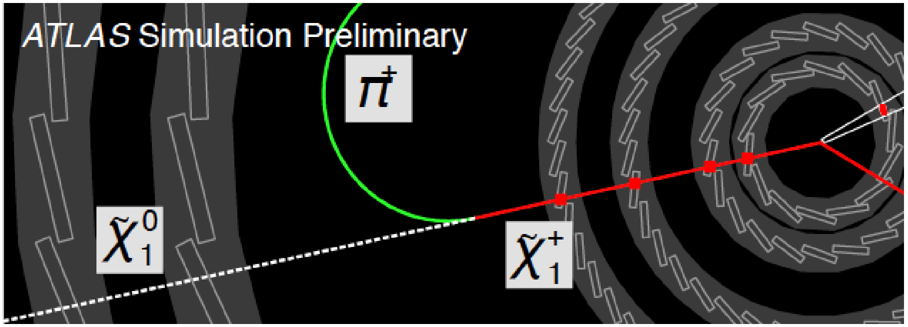
upper limit on stop (from requiring that mH=125 GeV)
wino/higgsino (from relic density in the universe)
gluino (from proton lifetime bounds)

and we have a possible no-lose theorem for models of Electoweak Baryogenesis

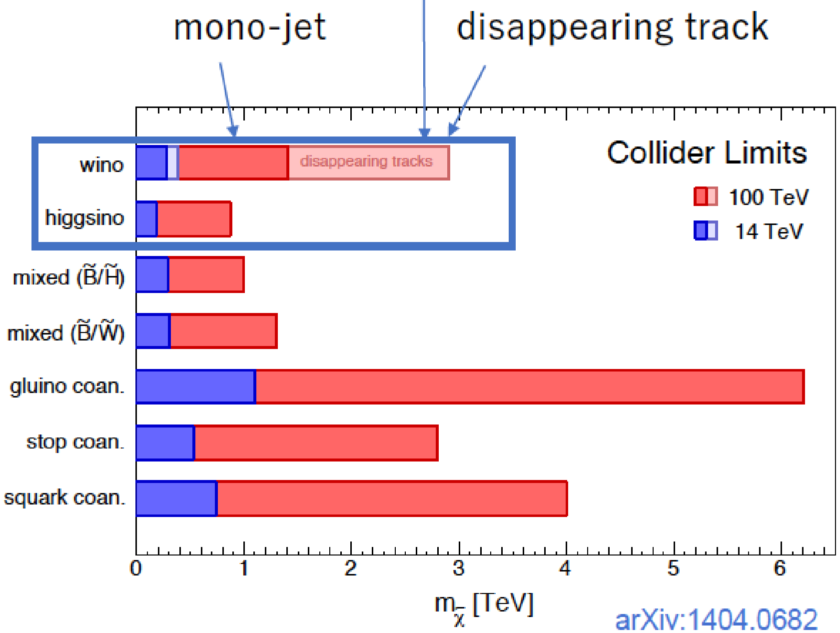
Dark Matter at 100 TeV

<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



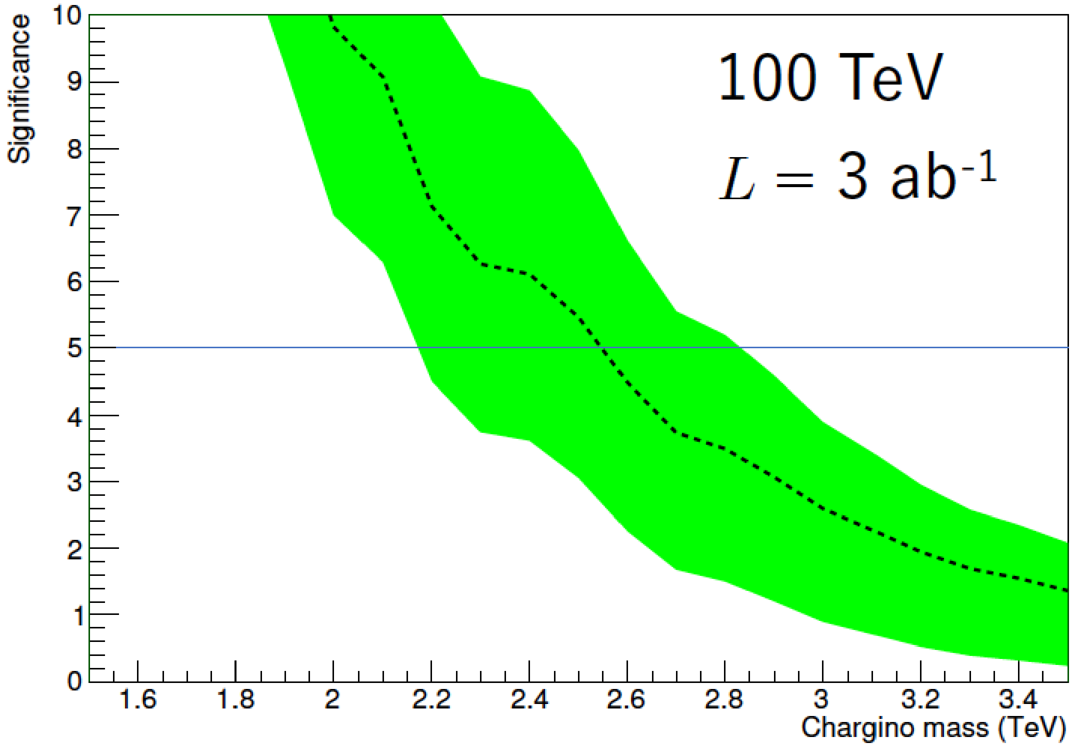
arXiv:1404.0682

- Latest preliminary LHC limit : 430 GeV

Ryu Sawada

Dissapearing track reach

Discovery sensitivity reach ~ 3 TeV



Ryu Sawada

Pure Wino LSP

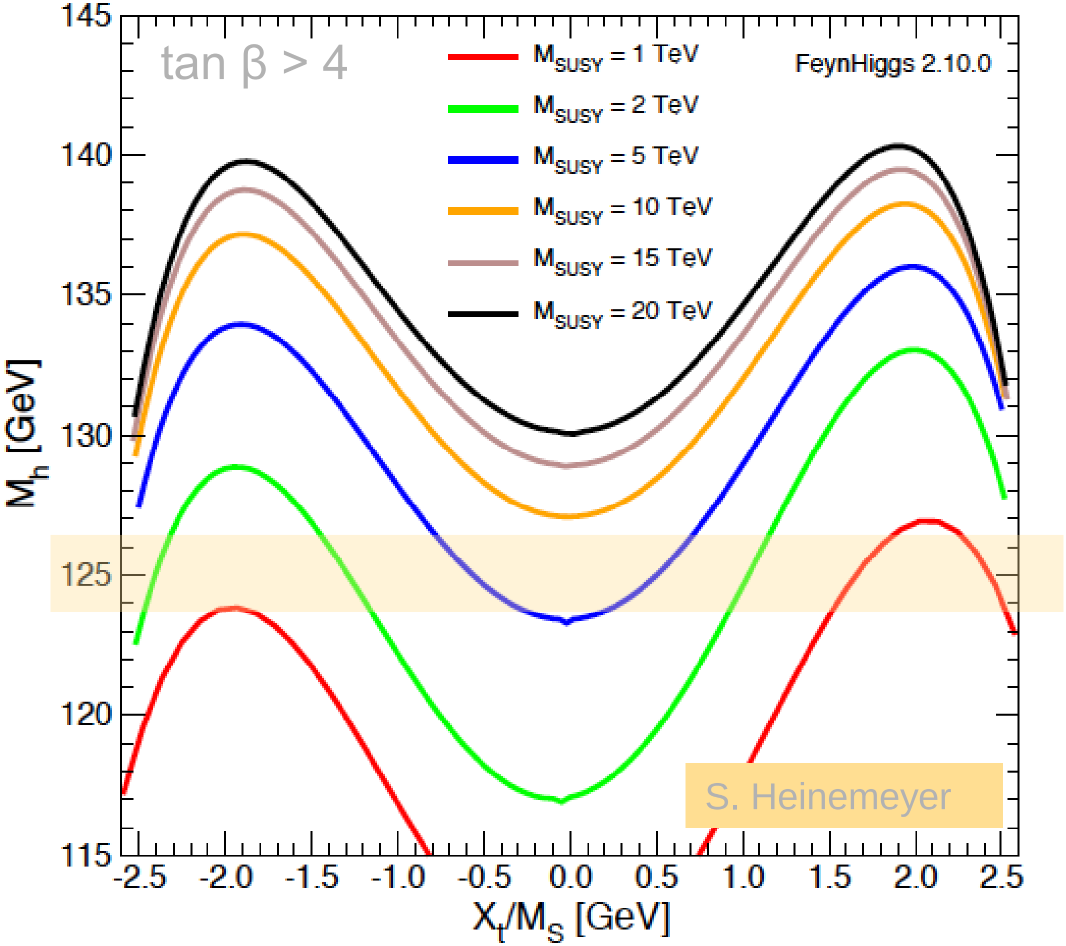
Green band : number of BG scaled by 0.2—5.
The center corresponds to the factor 1

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

A hint from the Higgs?

Higgs mass in the MSSM:
(dominant one-loop)

$$m_h^2 \leq M_Z^2|cos2\beta|^2 + \frac{3m_t^4}{4\pi^2v^2}\left[ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$



Can one derive an upper bound on the stop mass from the measured m_h value?

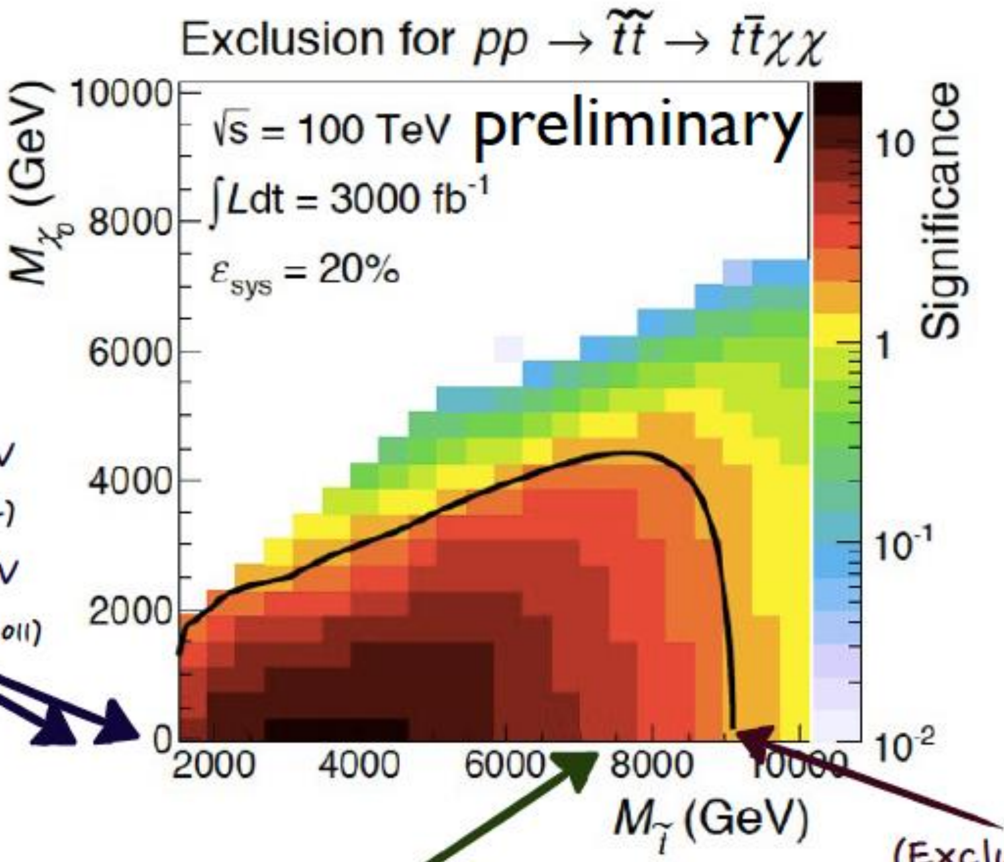
m_h = 125 +/- 1.5 GeV ?
(th. uncert.)

→ M_S = 0.5 – 9 TeV ??

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

Also: Badziak et al., arxiv:1411.1450

Stop @ 100 TeV



LHC8: 650 GeV

(ATL CONF-2013-024)

LHC14: 1.4 TeV

(ATL-PHYS-PUB-2013-011)

(Exclude ~9 TeV Stop)

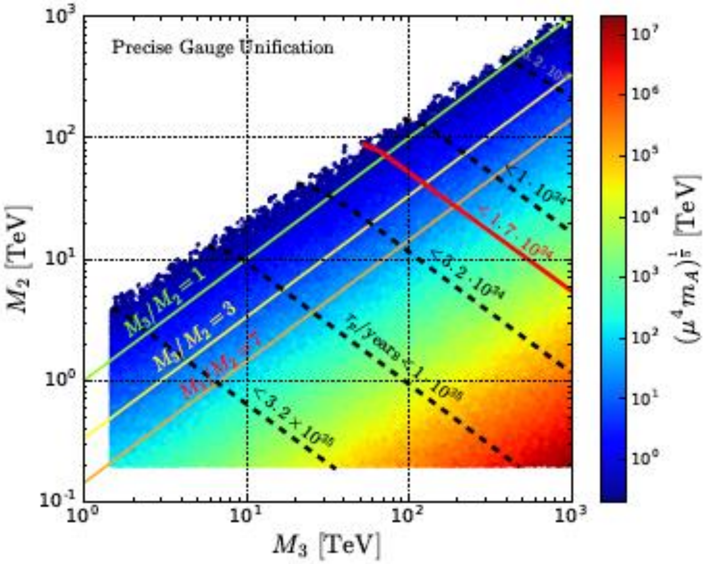
(~ 100 events)

Discover ~7 TeV Stop!

Upper limits on SUSY from proton decay

One can derive upper limits on the gluino and wino mass from lower bounds on the proton lifetime, under the assumption that unification of gauge couplings is *precise* in the MSSM (i.e. with no or highly suppressed threshold corrections).

With the current lower bounds on the proton lifetime, one gets an upper limit of 120 TeV on the gluino mass and 40 TeV on the wino mass.



The next generation of nucleon decay experiments will improve this limit with a factor 10. That would set upper limits of ~10 TeV on the gluino mass and ~3 TeV on the wino mass. That's within the reach of the FCC-hh!

Pokorski, Rolbiecki, Sakurai, arxiv:1707.06720

Minimal stealthy model for a strong EW phase transition: *the "nightmare scenario"*

Curtin, Meade, Yu, arXiv:1409.0005

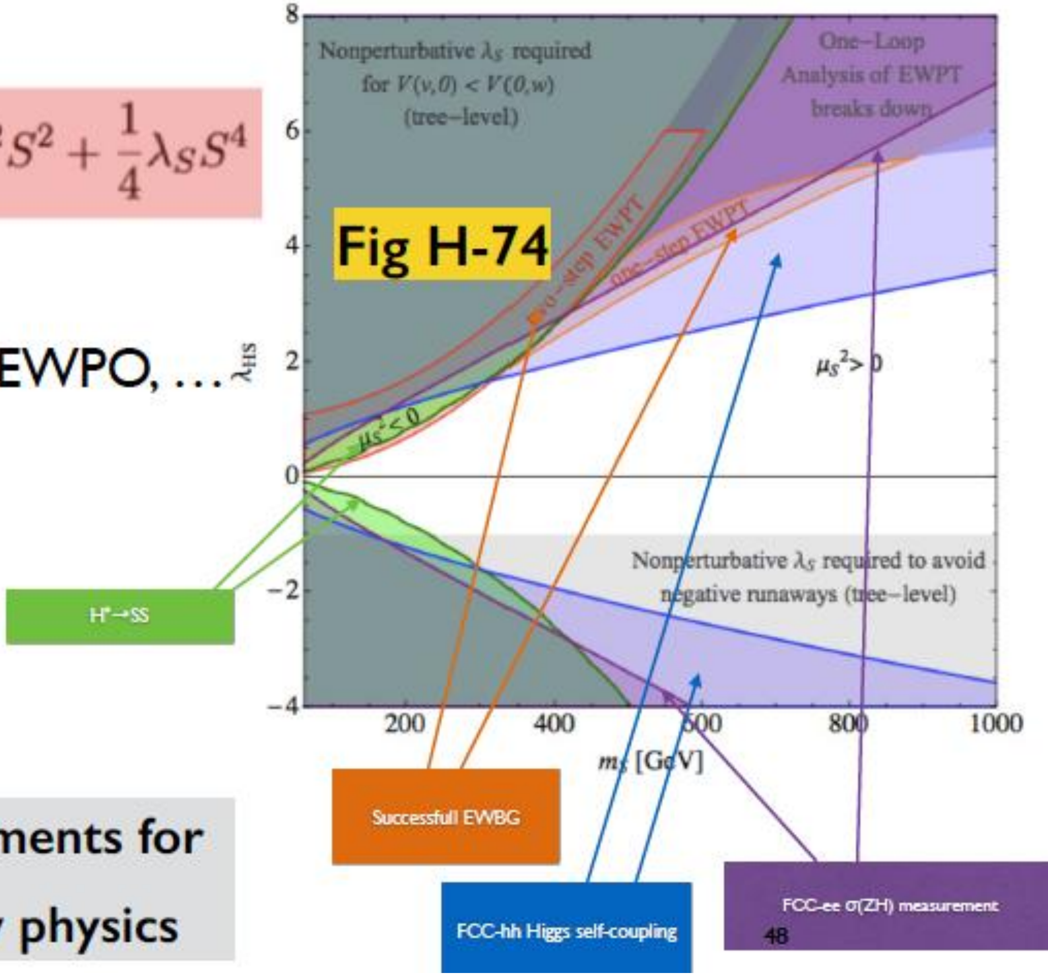
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Unmixed SM+Singlet.
No exotic H decay, no H-S mixing, no EWPO, …

Two regions with strong EWPT

Only Higgs Portal signatures:
- h*→SS direct production
- Higgs cubic coupling
- σ(Zh) deviation (> 0.6% @ TLEP)

⇒ Appearance of first "no-lose" arguments for classes of compelling scenarios of new physics



B anomalies

LHCb (and also Belle) have reported anomalies in their measurement of B → $K^{(*)}$ decays (P5’ and the ratios of BRs into muons vs electrons).

If these deviations turn out not to be statistical fluctuations, or caused by insufficient understanding of the SM predictions, they could point to new physics such as Z’ or leptoquarks (LQ).

Such new particles could be heavy and be beyond the reach of the LHC. Allanach/Gripaios/You studied the sensitivity of future colliders, making rather conservative assumptions. They find:

- All Z’ models can be covered with FCC-hh (most also with HE-LHC)
- Leptoquarks up to 12 TeV can be covered with FCC-hh (extendable to 21 TeV if strong coupling for single LQ prod.) while masses up to 41 TeV could explain the anomalies

Allanach, Gripaios, You, arxiv:1710:06363

Bottom line

The previous examples indicate that a strong physics case can be made for a 100 TeV collider.

Two of the previous examples are less than 3 months old … still a lot of room for new ideas.

A detector design?

For the Conceptual Design Report, we were asked to come up with a detector design which that could enable us to fully exploit the physics of 100 TeV pp collisions

The design that follows is rather conservative and is meant only to demonstrate that such a detector can be built.

Towards defining the FCChh detector

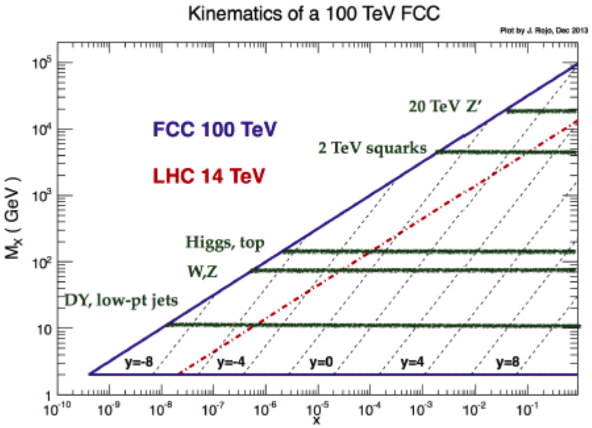
Physics constraints

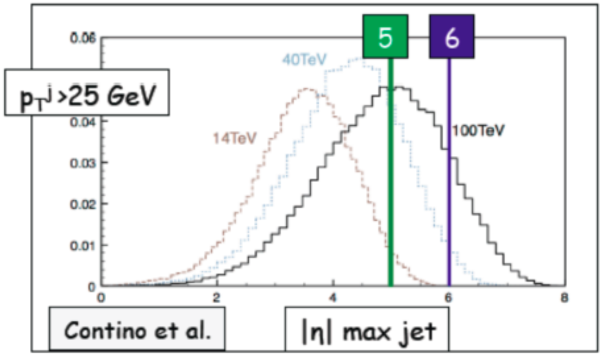
- Physics will be more forward
    - less for “high pT” physics
    - more for “low pT” physics (W/Z/Higgs, top)
    - in order to maintain sensitivity in need **large rapidity** (with tracking) and **low pT** coverage

→ precision muon up to $|\eta| < 4$

→ calorimetry up to $|\eta| < 6$

→ Can we deal with 1k pile-up will at large rapidities?





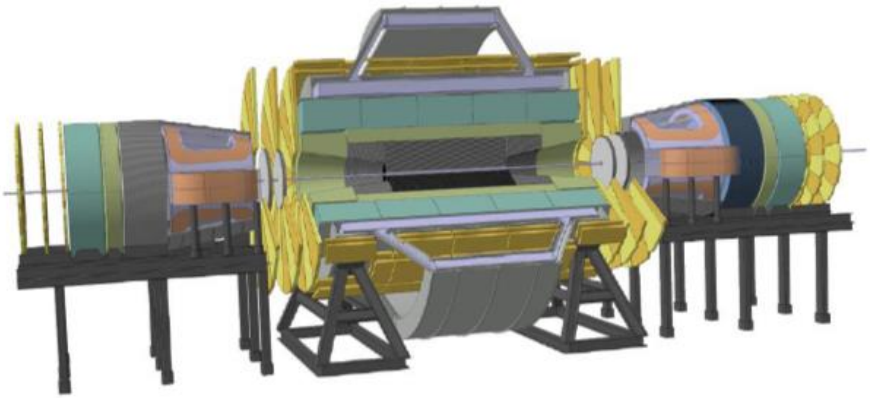
A detector design?

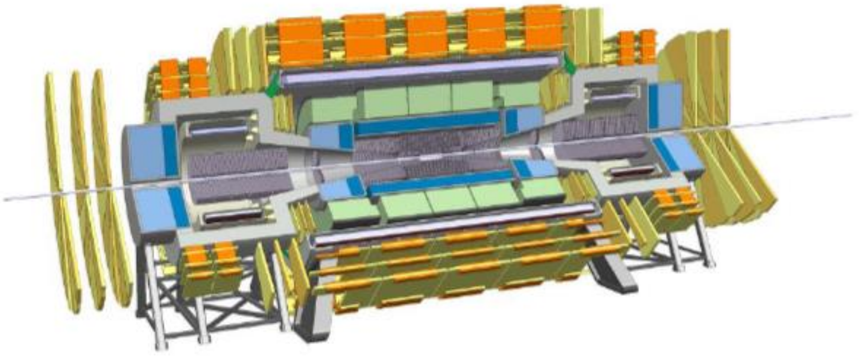
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

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

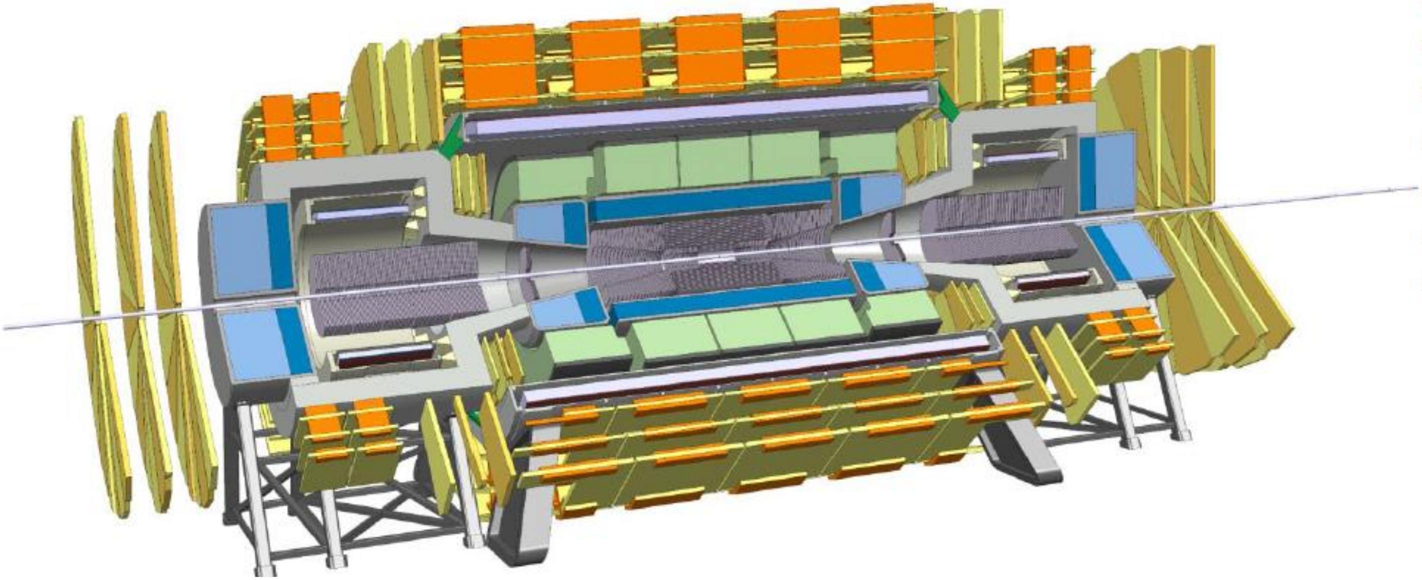
4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

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

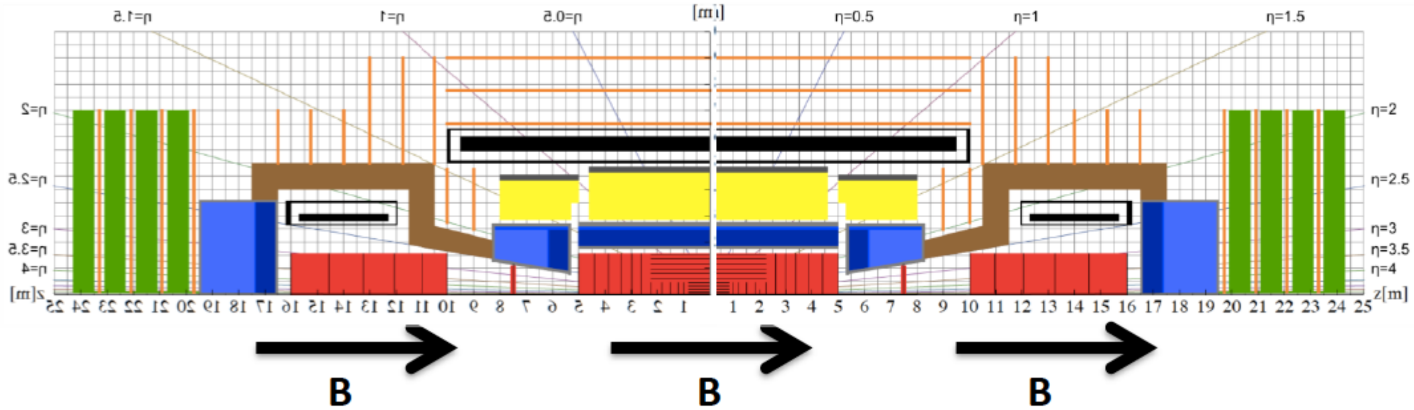




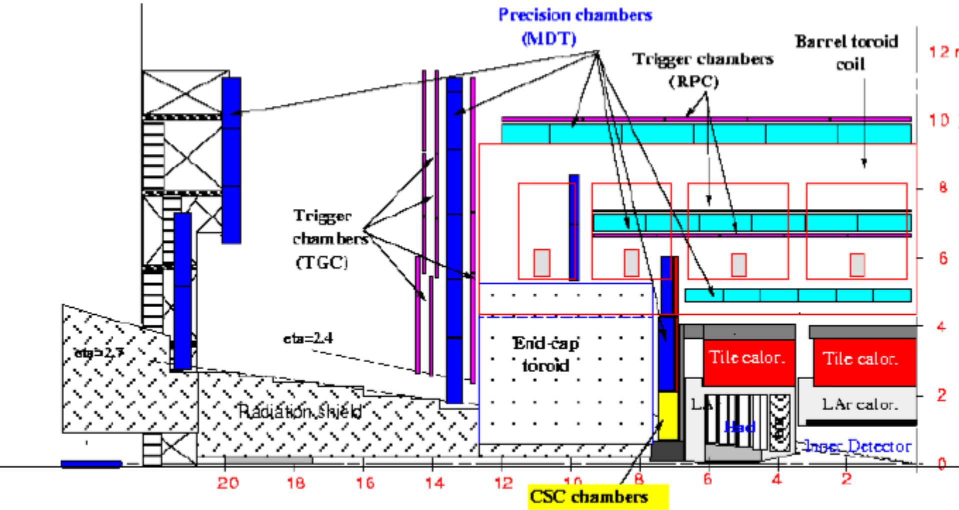
A reference detector design

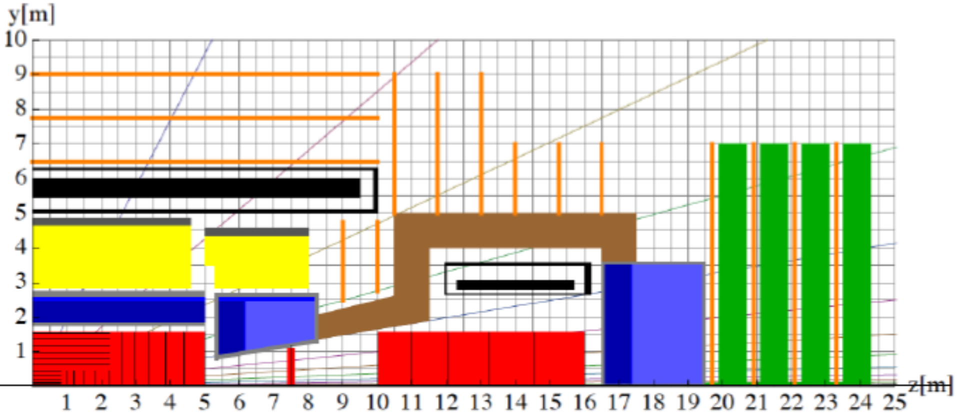


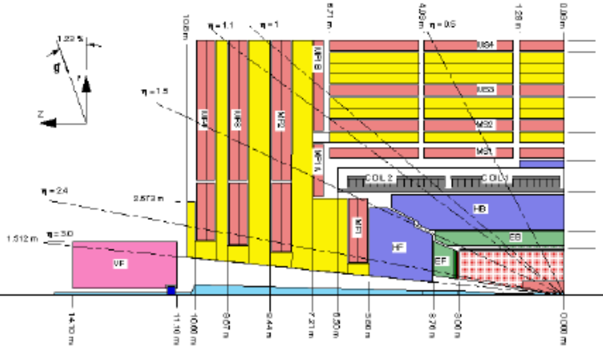
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

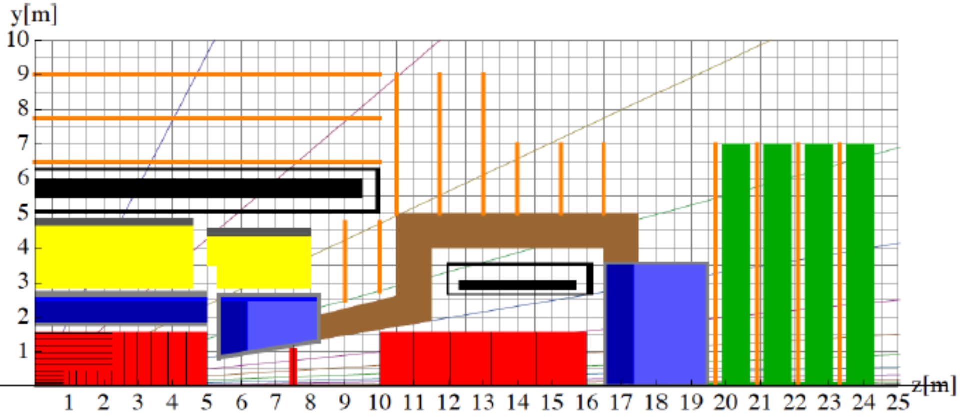


Comparison to ATLAS & CMS



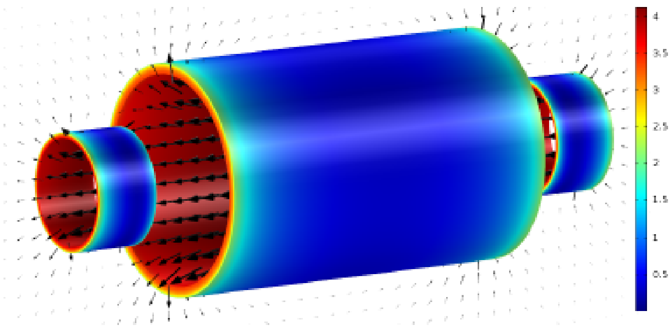






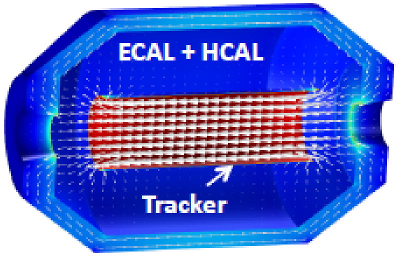
Current detector baseline

- 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

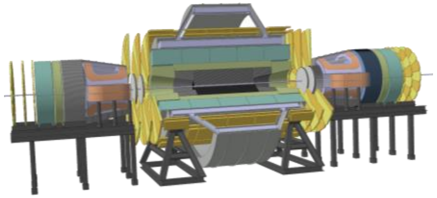


Alternative challenging design:

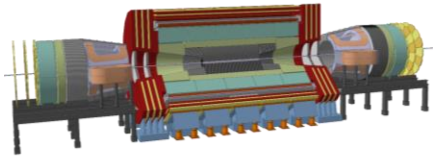
4T/4m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!

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

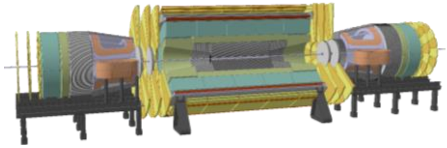
Magnet systems under consideration



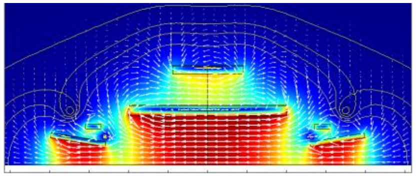
Twin solenoid with dipoles
(min. shaft diameter 27.5m)



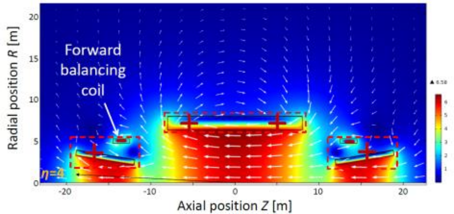
Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles
(min. shaft diameter 16.3m, if rotated under ground)

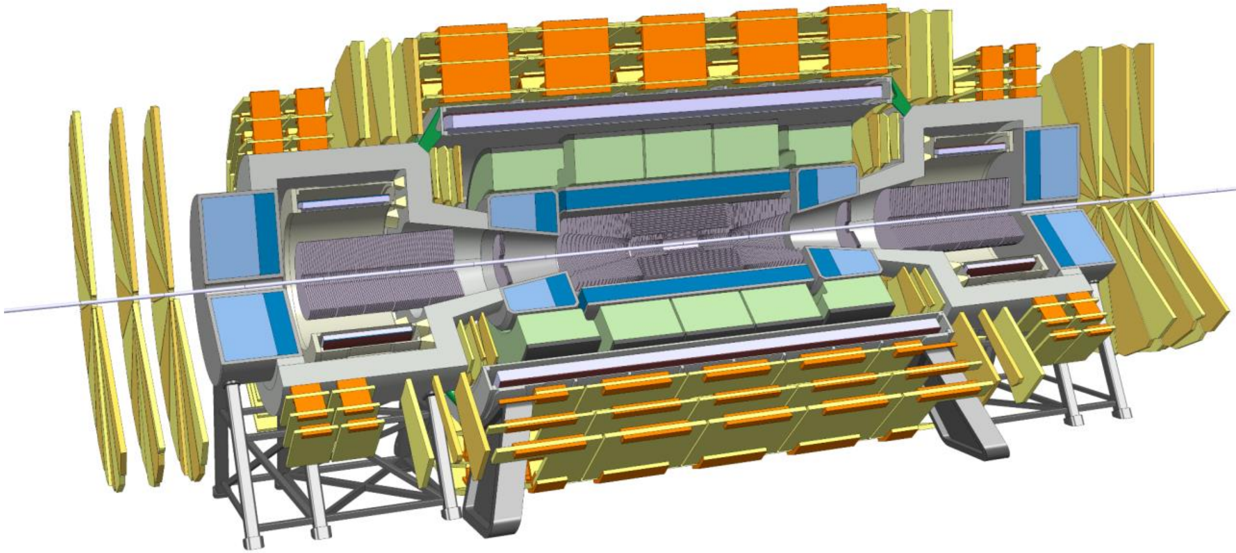


Twin solenoid with balanced conical solenoid



Unshielded solenoid with balanced conical solenoid

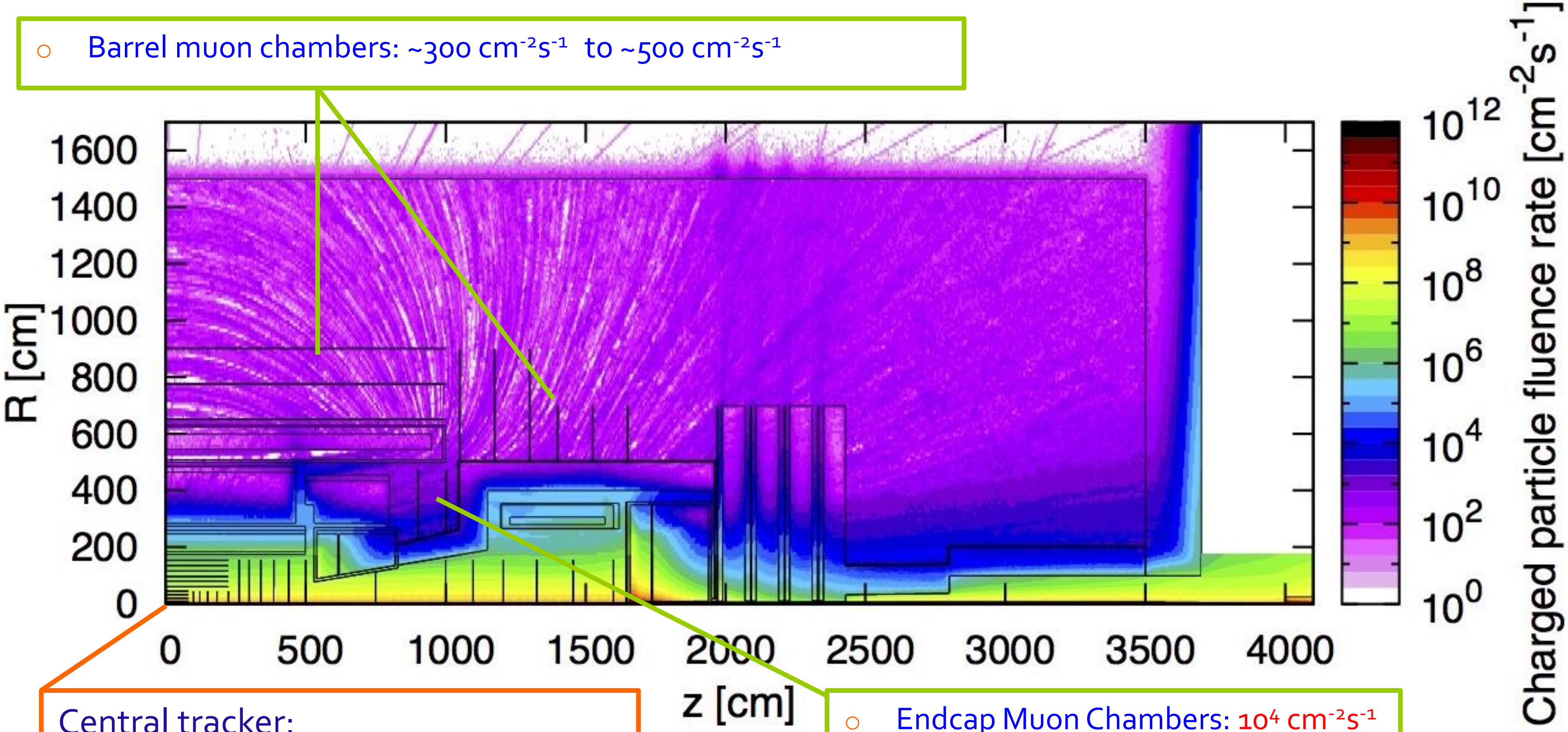
Reference detector



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

This is a reference detector that ‘can do the job’ and that is used to define the challenges. The question about the specific strategy for detectors at the two IPs is a different one.

Charged particle dose?



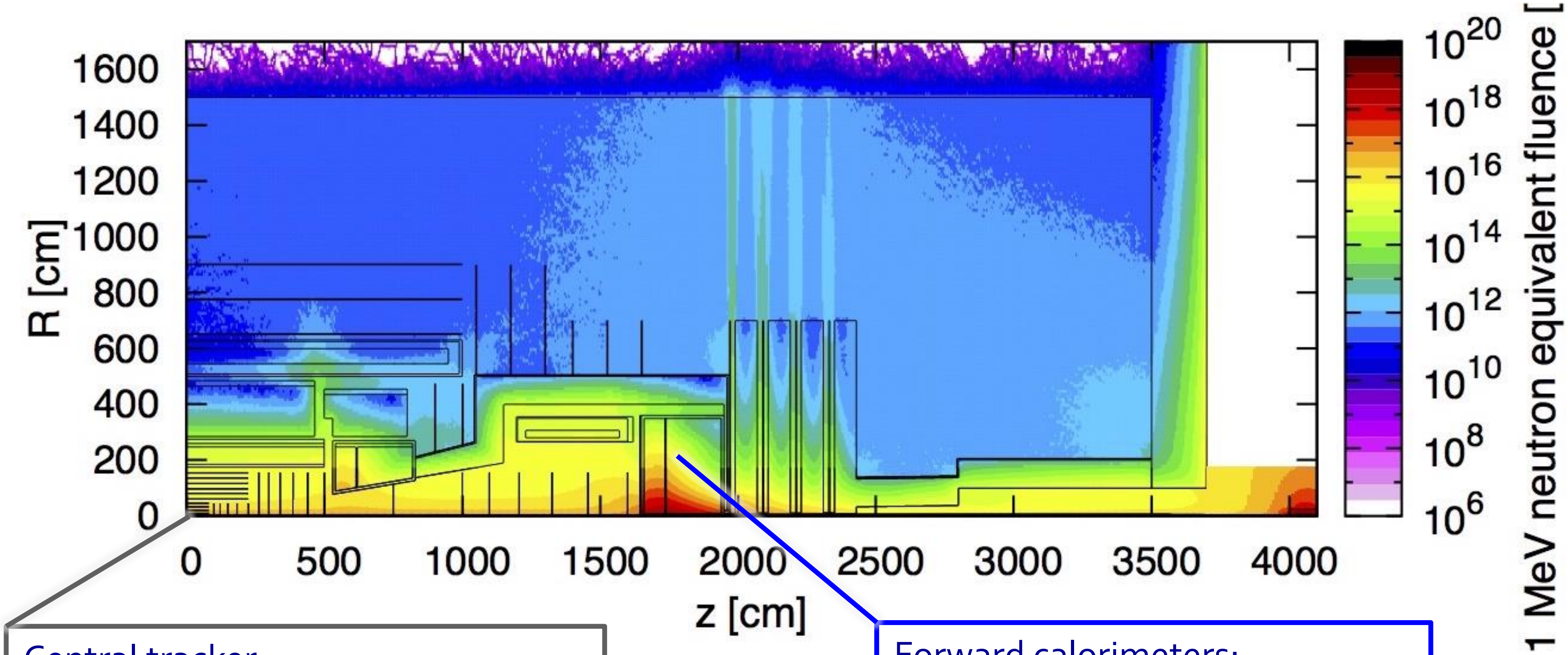
- Barrel muon chambers: ~300 $cm^{-2}s^{-1}$ to ~500 $cm^{-2}s^{-1}$

Central tracker:

- first IB layer (2.5 cm): ~1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^{6} $cm^{-2}s^{-1}$

- Endcap Muon Chambers: 10^{4} $cm^{-2}s^{-1}$

Neutron background?



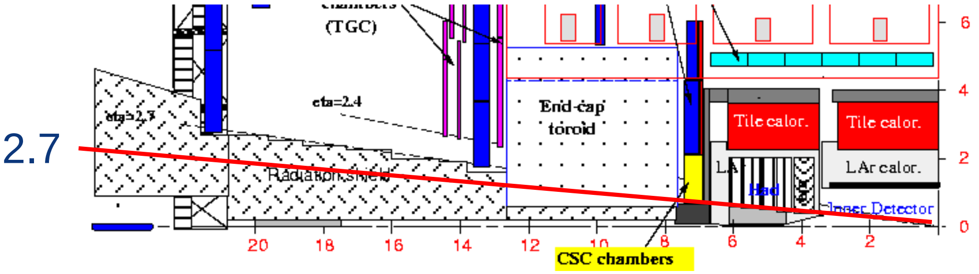
Central tracker:

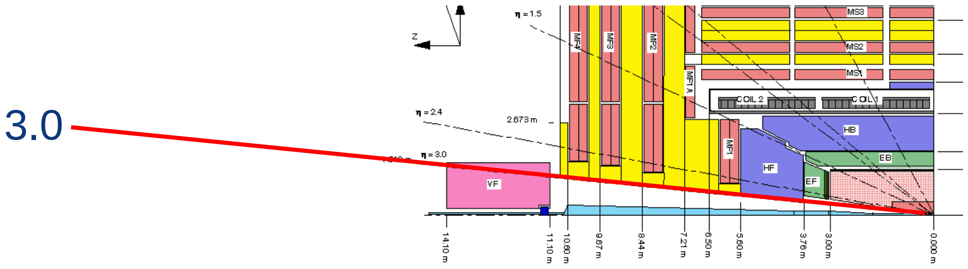
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

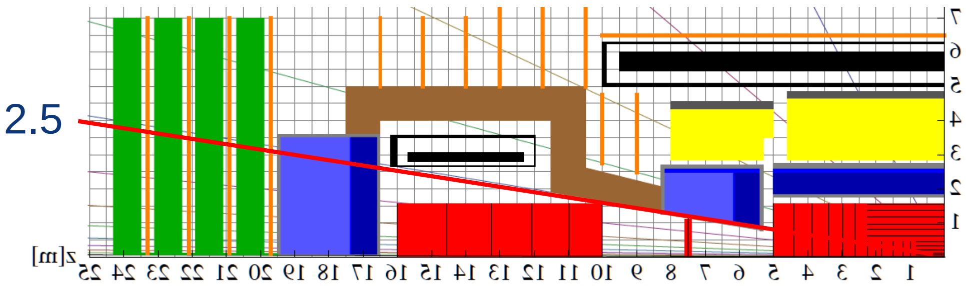
Forward calorimeters:

- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

Comparison to ATLAS/CMS?







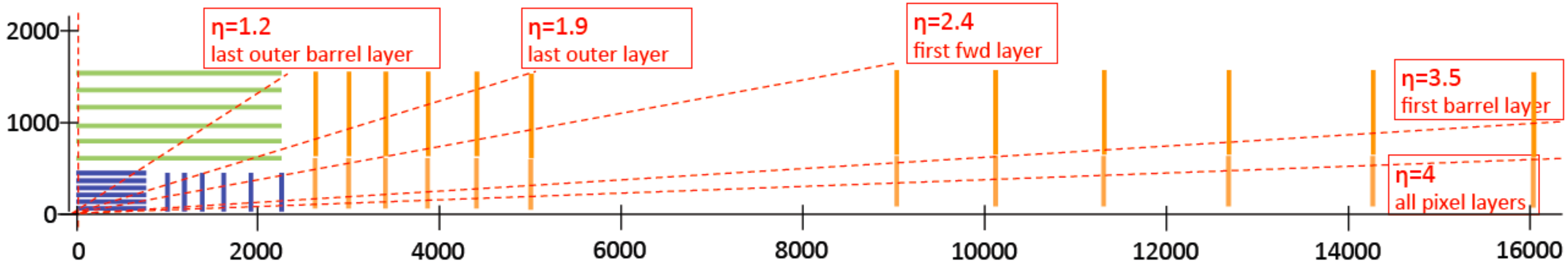
The forward calorimeters are a very large source of radiation (diffuse neutron source).

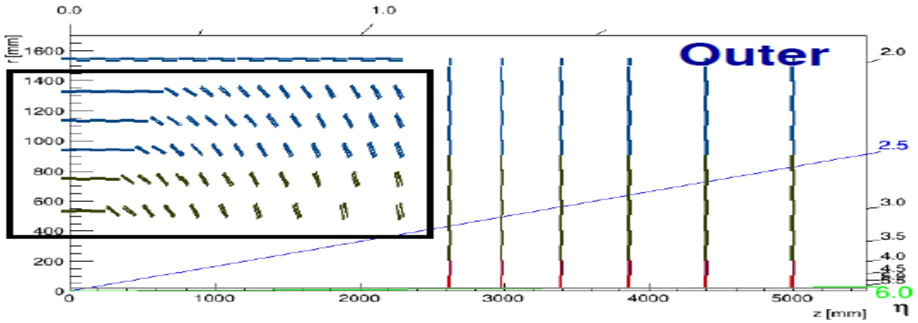
In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is inside enclosed by the return Yoke.

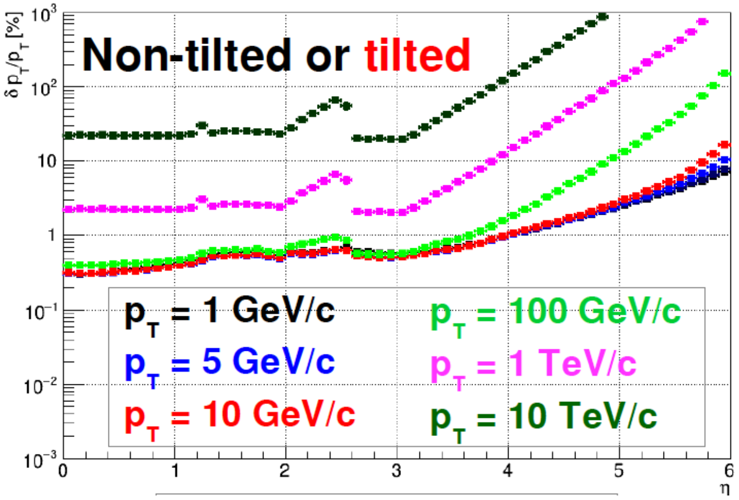
For the FCC, the forward calorimeter is moved far out in order to reduced radiation load and increase granularity.

→ A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

Tracking performance



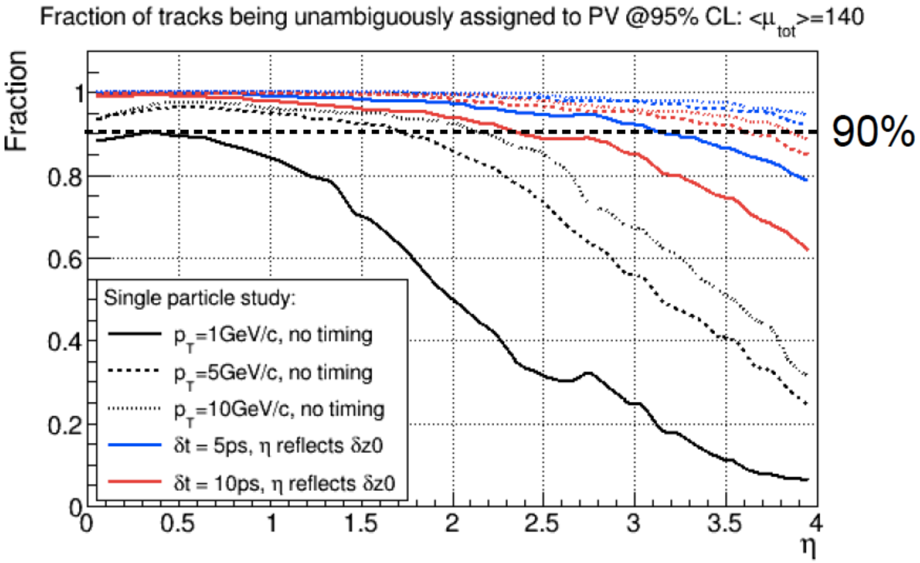




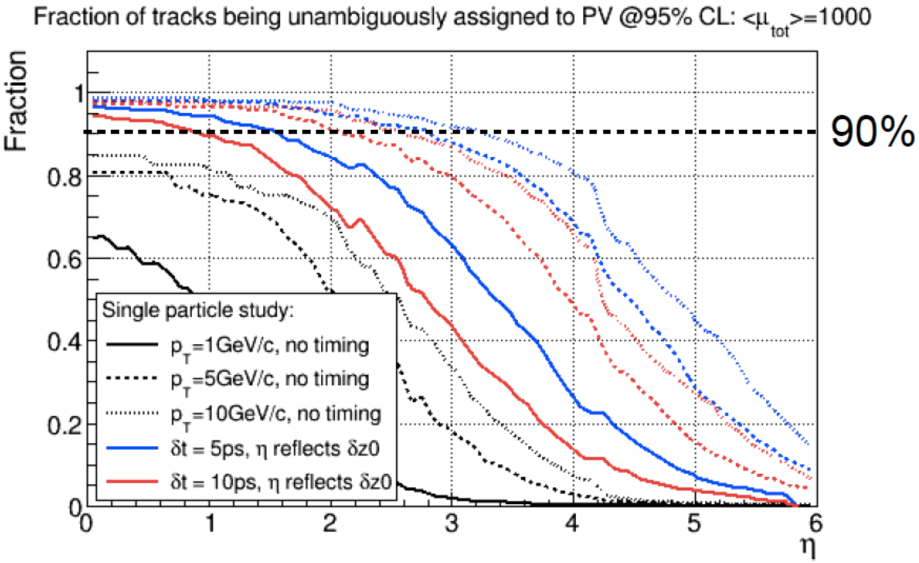
Timing detector(s)?

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

HL-LHC scenario @ PU=140
CMS Ph2 Upgr. tracker

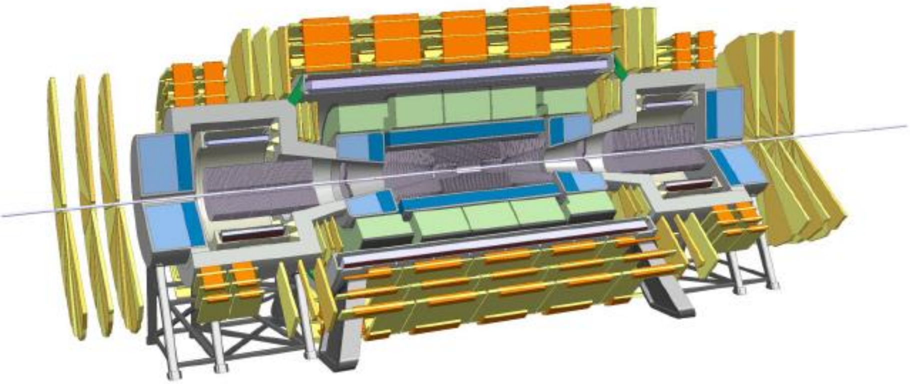


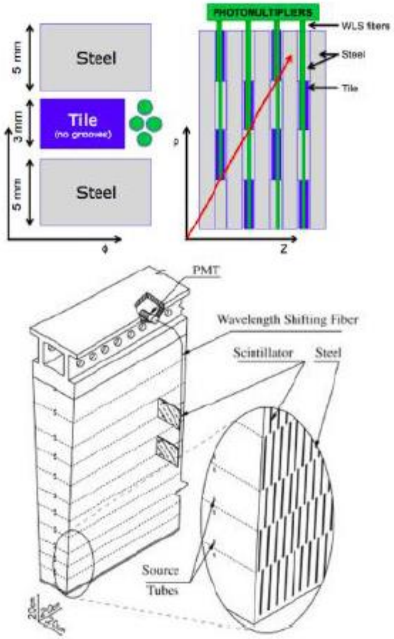
FCC-hh scenario @ PU=1000
Tilted layout

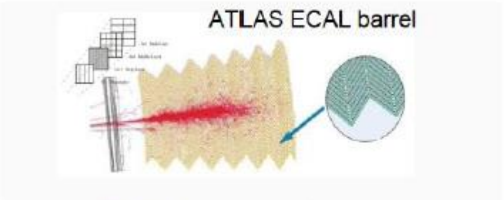


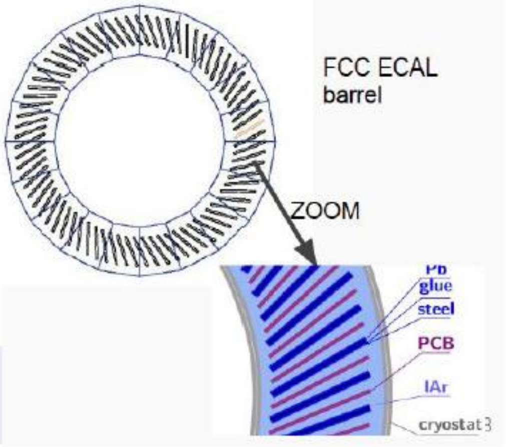
Calorimetry

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.

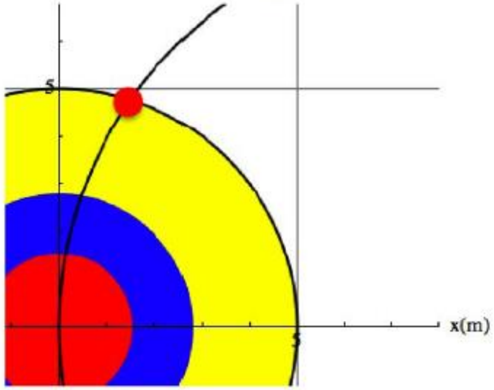
Silicon ECAL and ideas for digital ECAL with MAPS are being discussed.

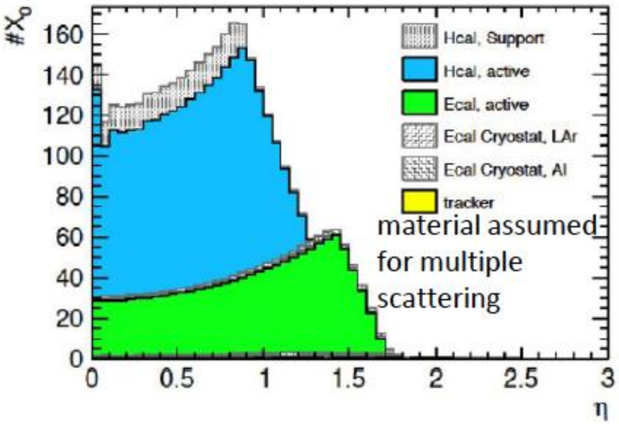
$\sim 11\,\lambda$ FCC-hh HCAL, pion resolution:
$\sigma E/E = 43\,\%/\sqrt{E} \oplus 2.7\%$

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

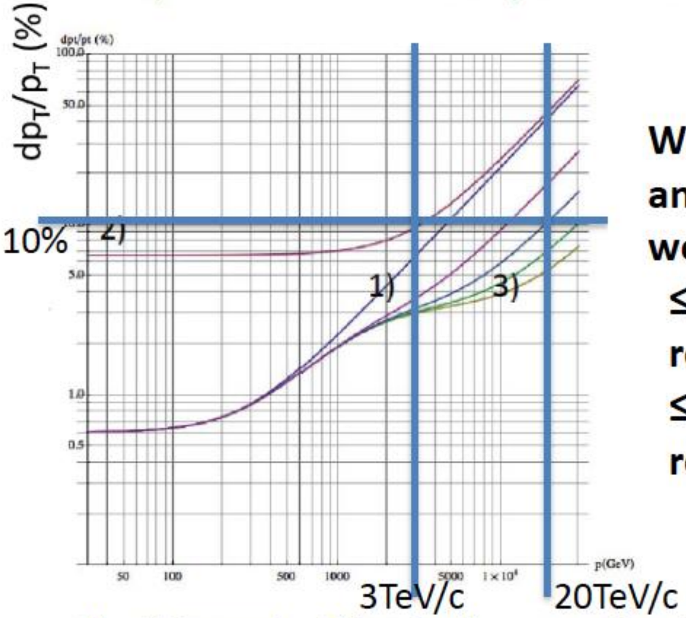




material assumed for multiple scattering

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



All within reach of 'standard' muon system technology

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

W. Riegler

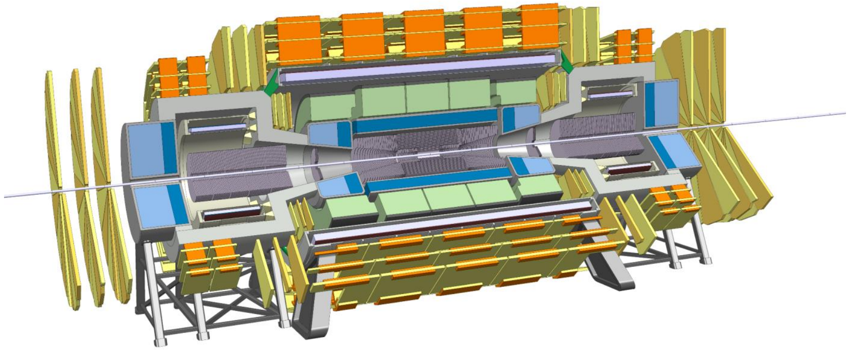
Trigger/DAQ?

Example: ATLAS Phase2 calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.

Muon system will also be read out at 40MHz to produce a L1 Trigger.

Reading out the FCC detector calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.

40MHz readout of the tracker would produce about 800TByte/s.

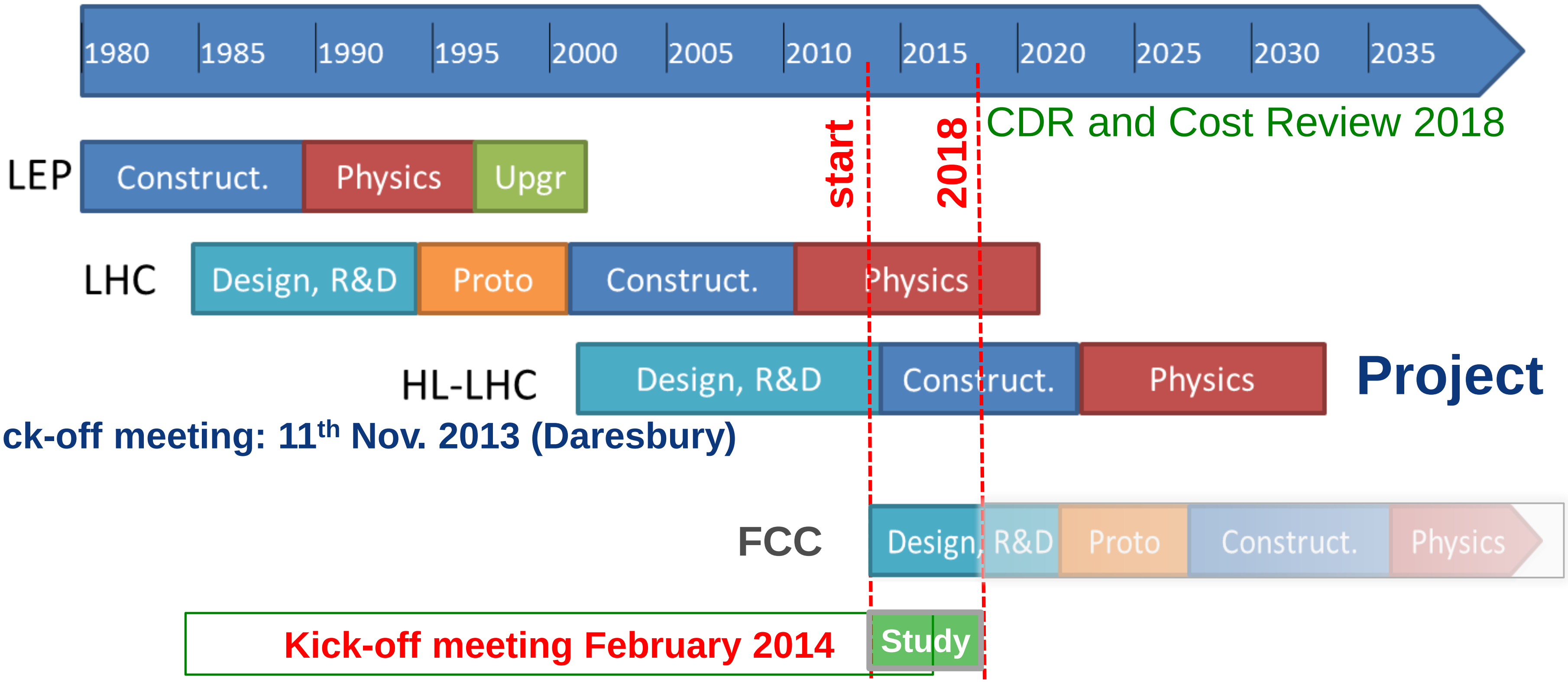


Question:

Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz ?

Un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

CERN roadmap and FCC planning



CDR and Cost Review 2018

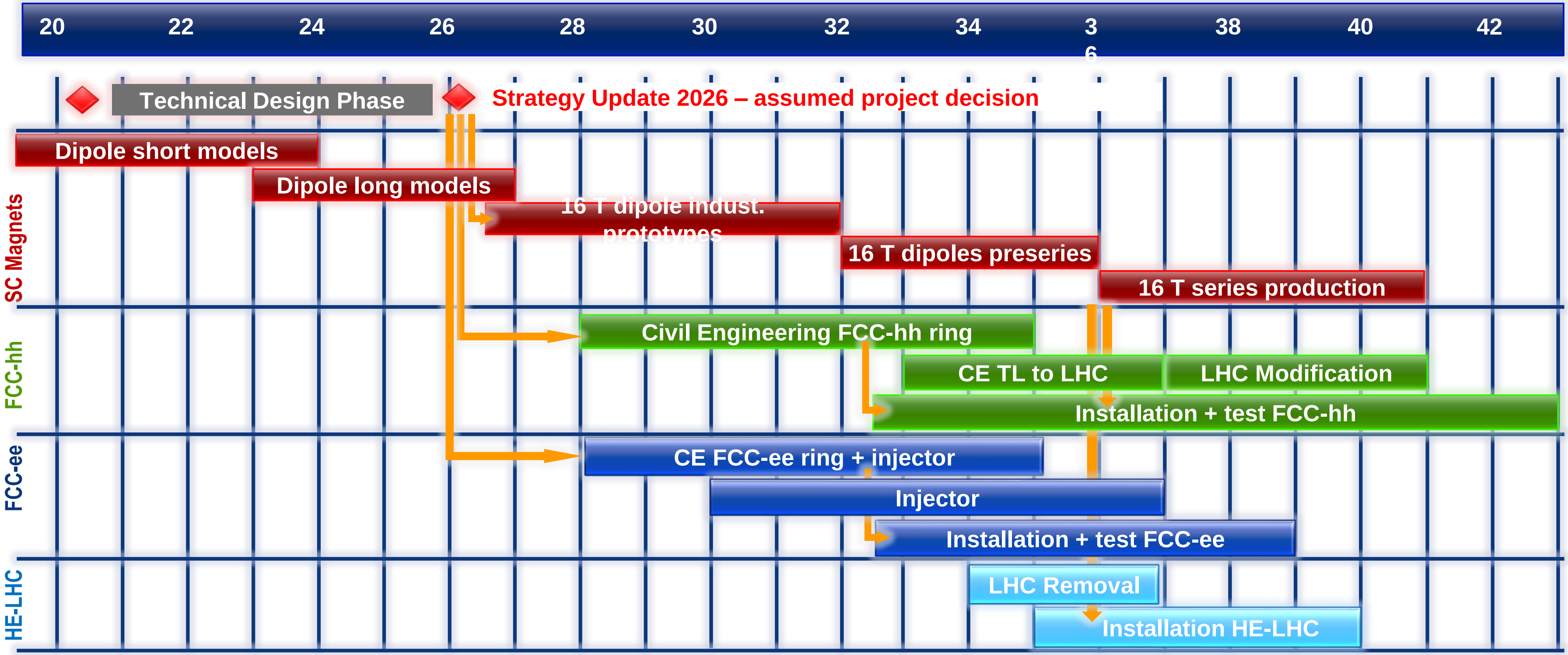
Project

Kick-off meeting: 11th Nov. 2013 (Daresbury)

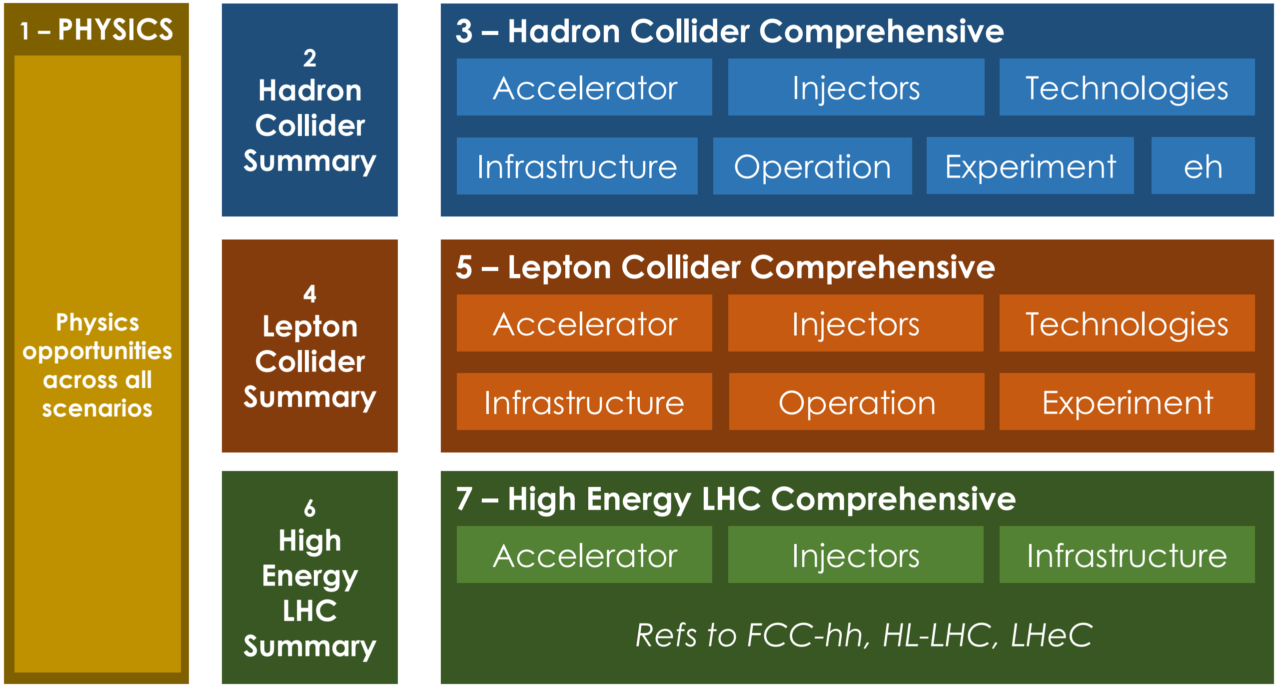
Kick-off meeting February 2014

CDR and Cost Review for 2018

Draft schedule



Conceptual Design Report



1 – PHYSICS

Physics opportunities across all scenarios

2
Hadron Collider Summary

3 – Hadron Collider Comprehensive

Accelerator | Injectors | Technologies

Infrastructure | Operation | Experiment | eh

4
Lepton Collider Summary

5 – Lepton Collider Comprehensive

Accelerator | Injectors | Technologies

Infrastructure | Operation | Experiment

6
High Energy LHC Summary

7 – High Energy LHC Comprehensive

Accelerator | Injectors | Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

Conclusions

- The HEP community needs to think carefully about the next large project it wants to undertake

- The FCC project, with its ee and hh components, offers an excellent physics potential.

- Next goal is to write a Conceptual Design Report by 2018, which can be used as an input to the 2019 European Strategy discussions

- Many possibilities to contribute, both for theorists and experimentalists

The challenge:
answering the big questions

- What's the origin of Dark matter / energy ?
- What's the origin of matter/antimatter asymmetry in the universe?
- What's the origin of neutrino masses?
- What's the origin of EW symmetry breaking?
- What's the solution to the hierarchy problem?
- …