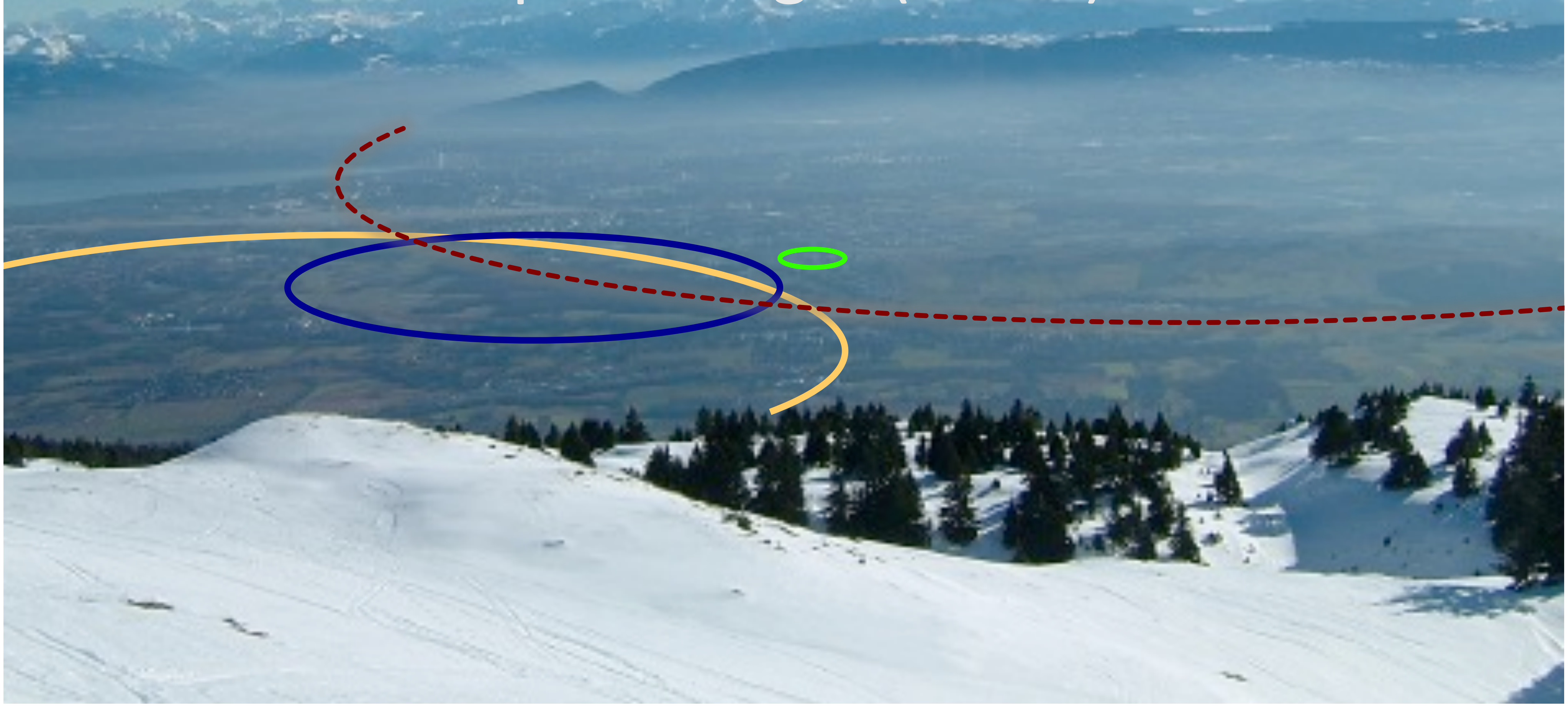
Future *pp* colliders and experiments

Filip Moortgat (CERN)



Outline

- Parameters & design challenges for future pp colliders
- A possible layout for an experiment
- Some LLP physics examples

This presentation contains material from:

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Michele Selvaggi, Heather Gray, Phil Harris, Tristan du Pree, Ryu Sawada, Shoji Asai, Masahiko Saito, Koji Terashi, Loukas Gouskos,
Benedikt Hegner, Andreas Salzburger, Julia Hrdinka, Valentin Volkl, Joschka Lingemann

and others …

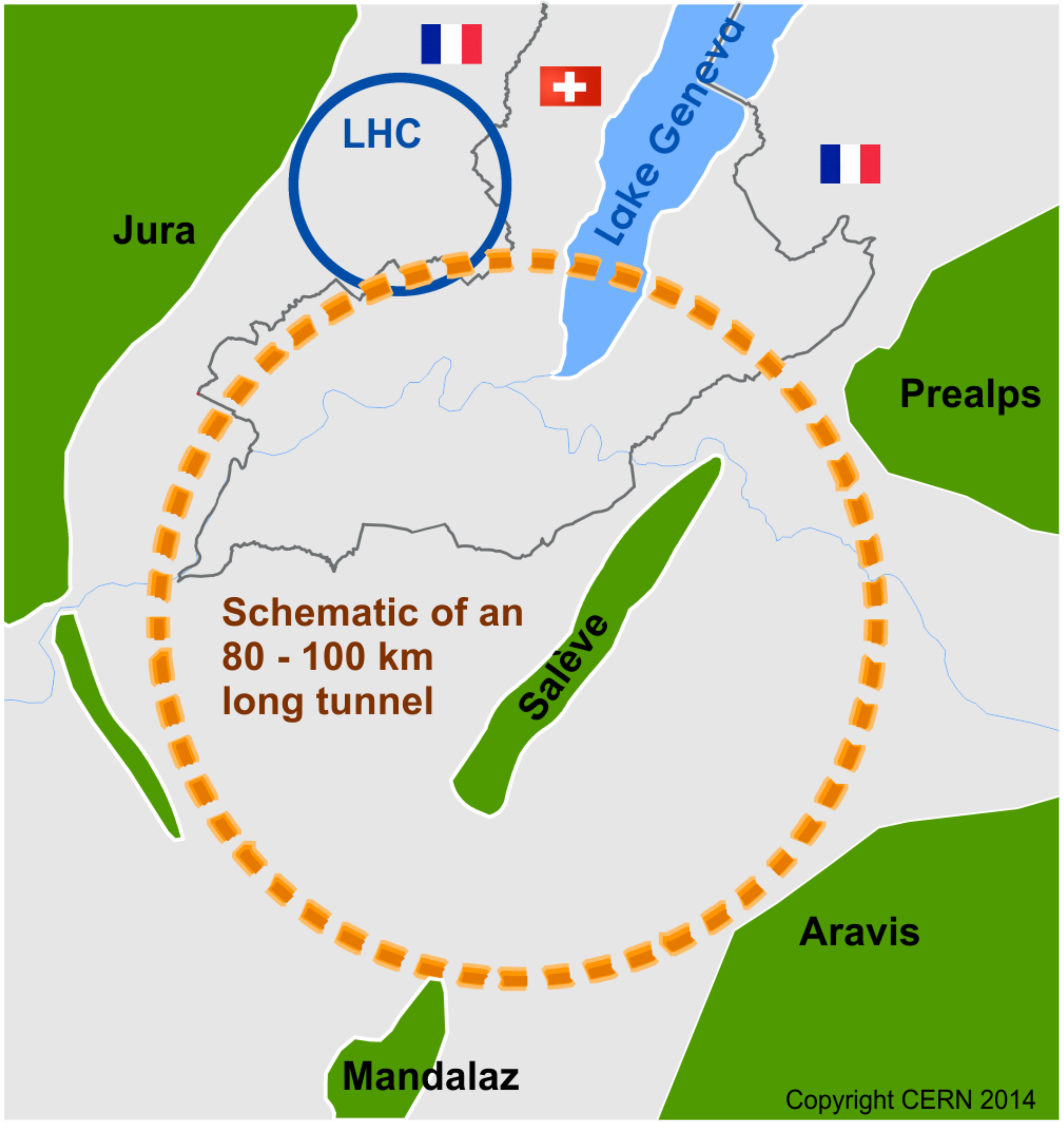
Future Circular Collider Study – SCOPE

Since 2014: international collaboration to study

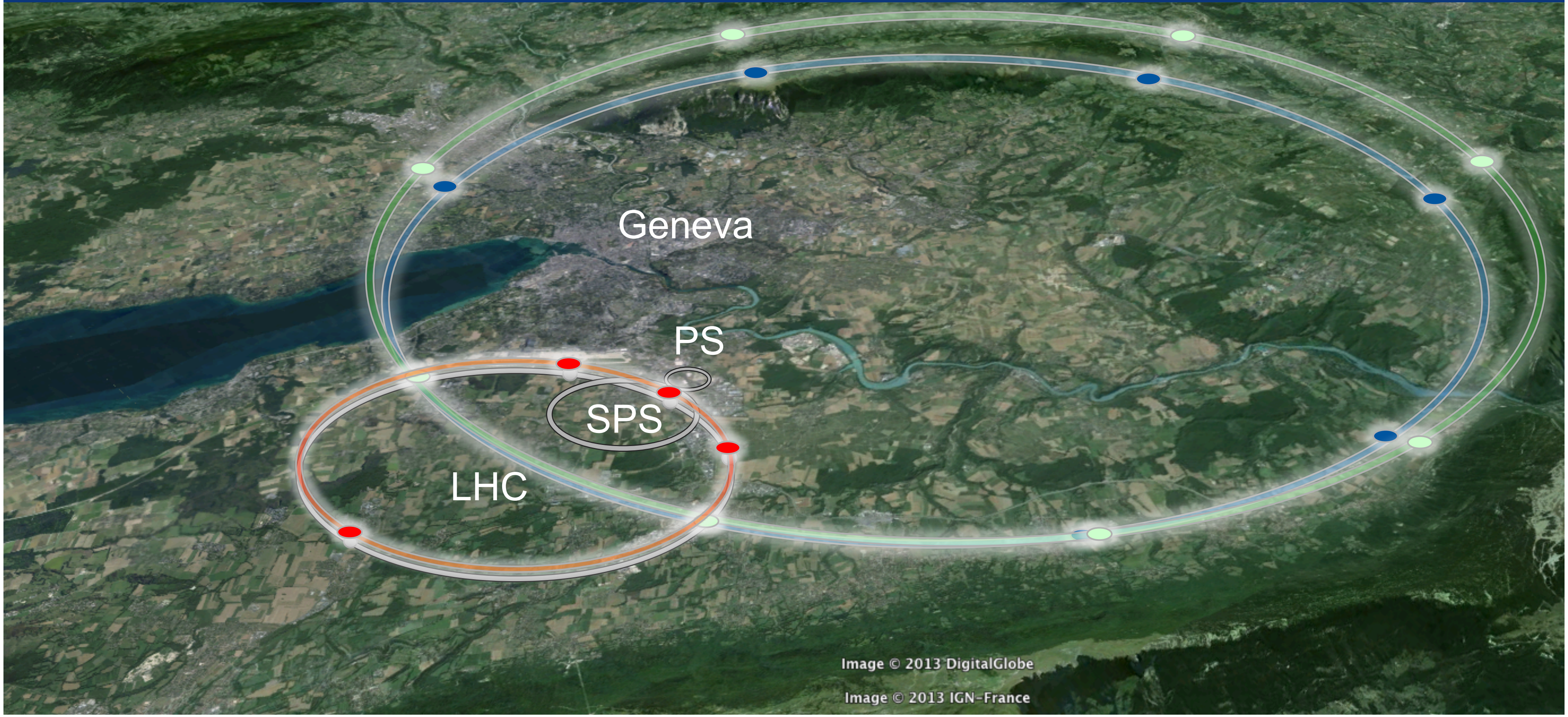
- ***pp*-collider (*FCC-hh*)**
  → main emphasis,
  defining infrastructure

~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, **16 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	27 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

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

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 for FCC-hh is:

- peak luminosity baseline: $5x10^{34}$
- peak luminosity ultimate: ≤ $30x10^{34}$

- integrated luminosity baseline ~250 fb^{-1} (average per year)
- integrated luminosity ultimate ~1000 fb^{-1} (average per year)

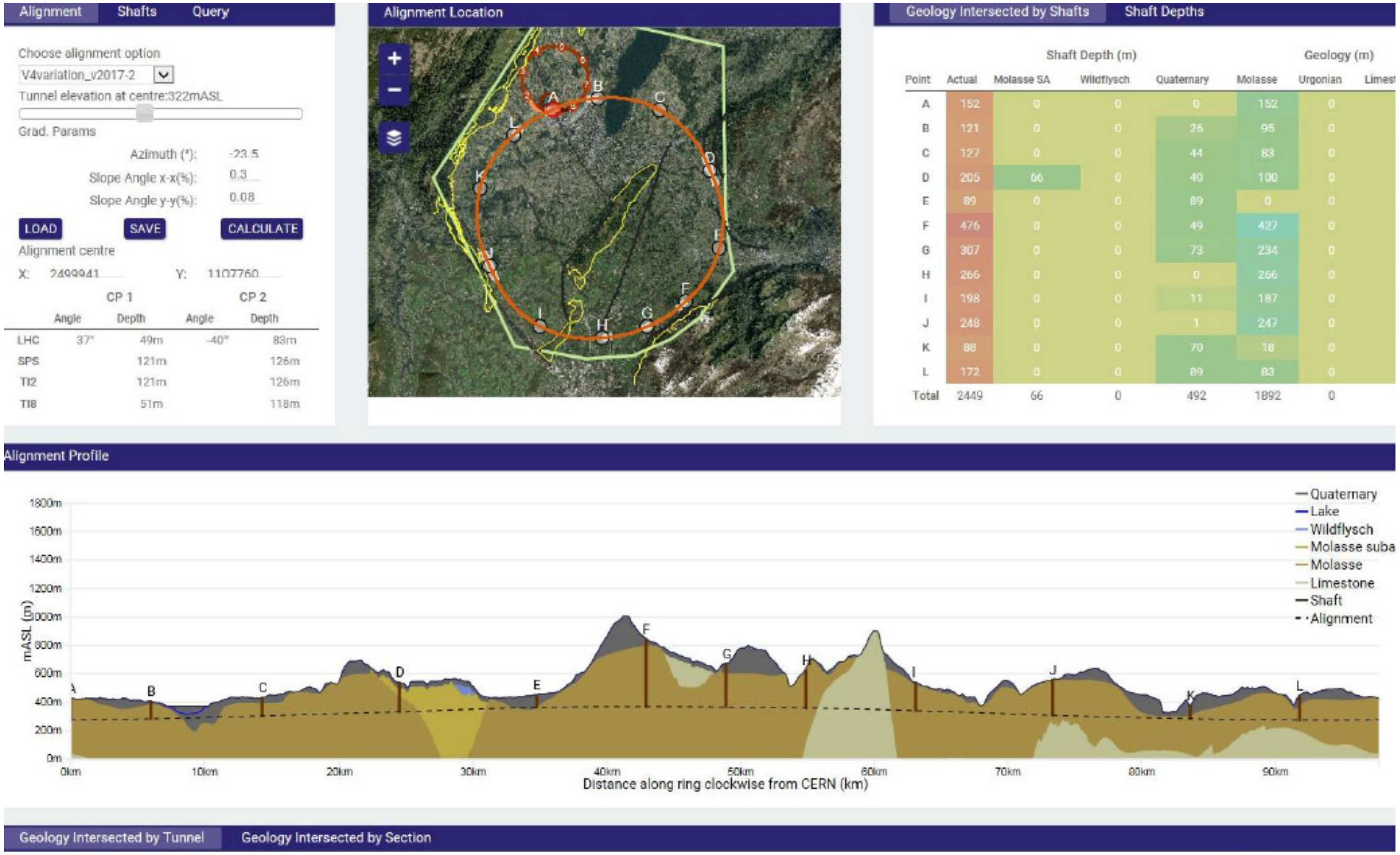
Total integrated luminosity: 20 ab^{-1}

For HE-LHC:

- peak luminosity: $25x10^{34}$

Total integrated luminosity: 15 ab^{-1}

Site study 97.5 km baseline



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

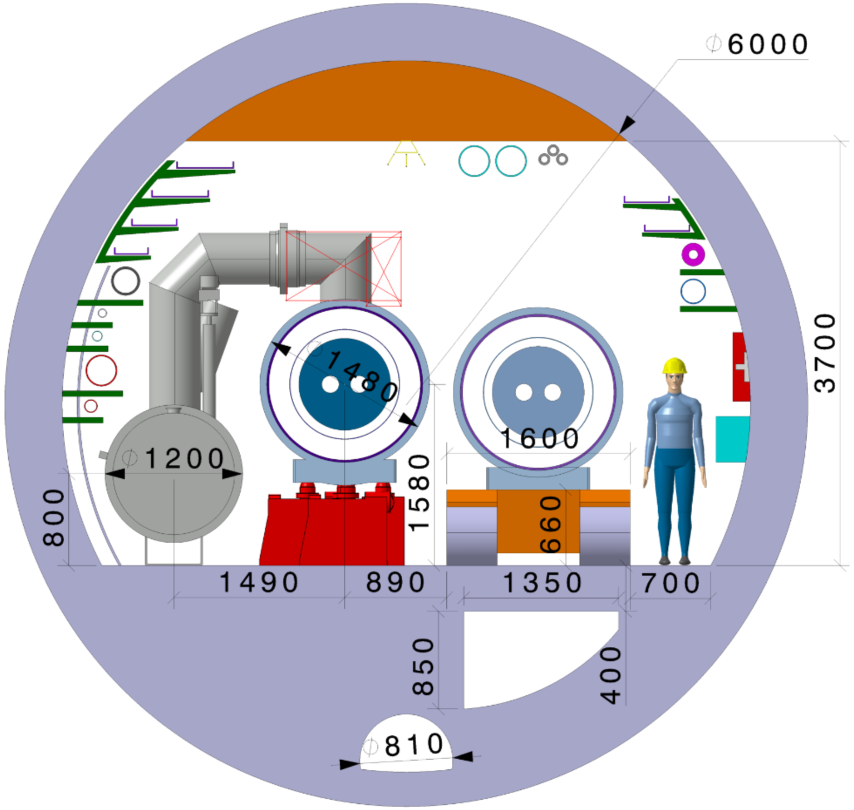
CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042

Yifang Wang

Hadron collider parameters

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

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.

HE-LHC Integration

working hypothesis for HE LHC design:

no major CE modifications on tunnel and caverns

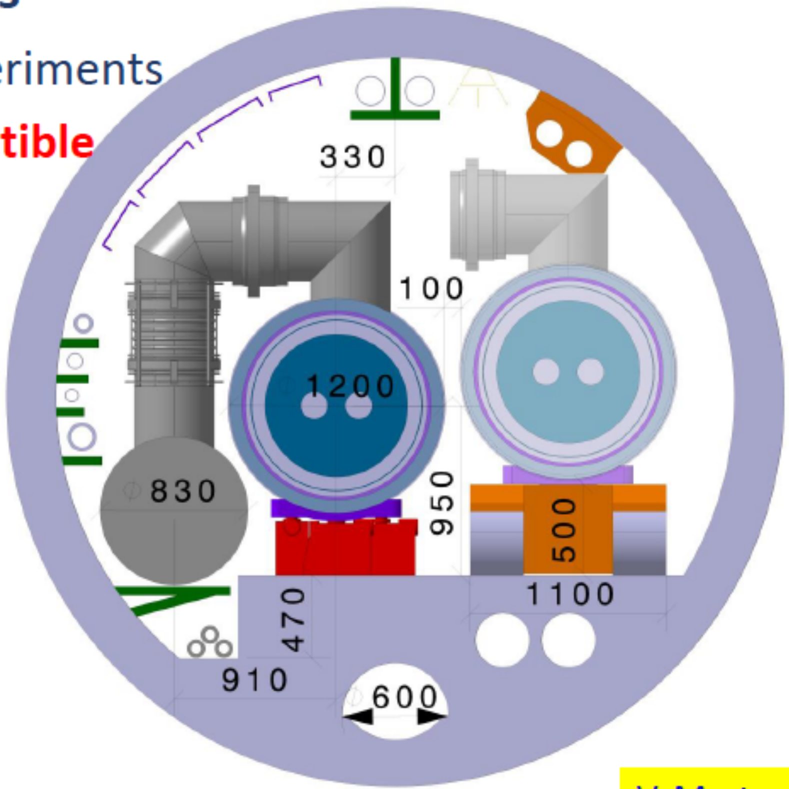
- similar geometry and layout as LHC machine and experiments
- **maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **lassical cryostat design gives ~1500 mm diameter!**

strategy: develop optimized 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **allow stray-field and/or cryostat as return-yoke**
- **optimization of inter-beam distance (compact)**

→ smaller diameter also relevant for FCC-hh cost

LHC tunnel diameter 3.8 m



V. Mertens

FCC-hh: high-field magnet R&D

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

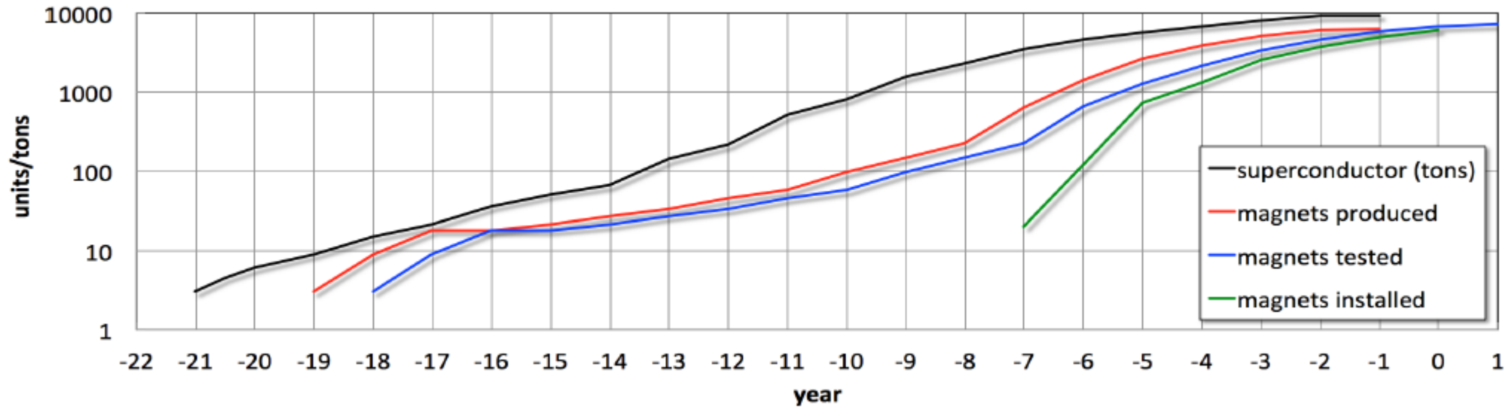
Develop Nb_3Sn-based 16 T dipole technology (at 4.2 K?),
- conductor developments
- short models with sufficient aperture (40 – 50 mm) and
- accelerator features (margin, field quality, protect-ability, cycled operation).

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

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

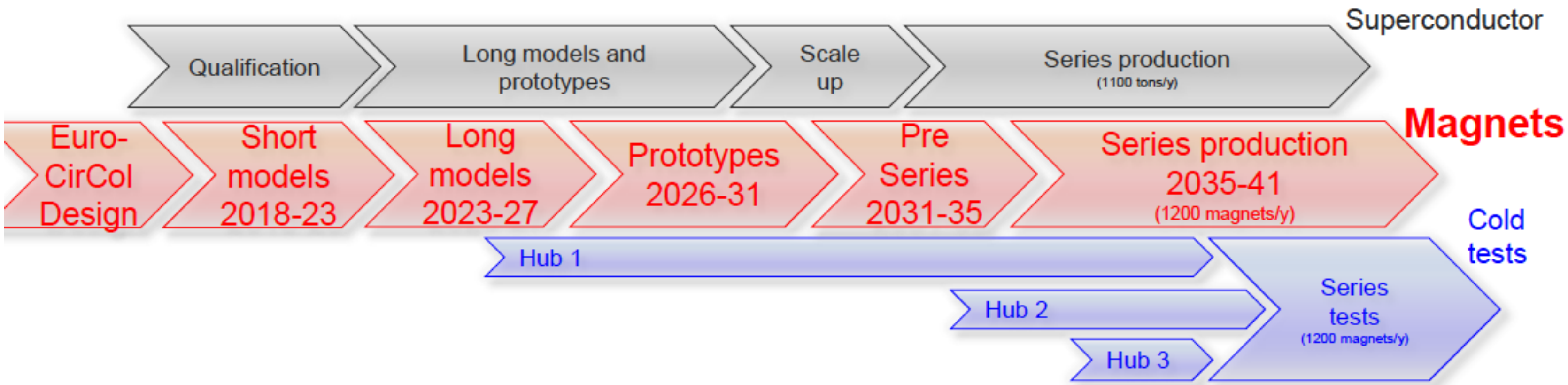
Goal: Demonstrate HTS/LTS 20 T dipole technology:
- 5 T insert (EuCARD2), ~40 mm aperture and accelerator features
- Outsert of large aperture ~100 mm, (FRESCA2 or other)

16T magnet development timeline



Total duration of magnet program:

~20 years



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

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.

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

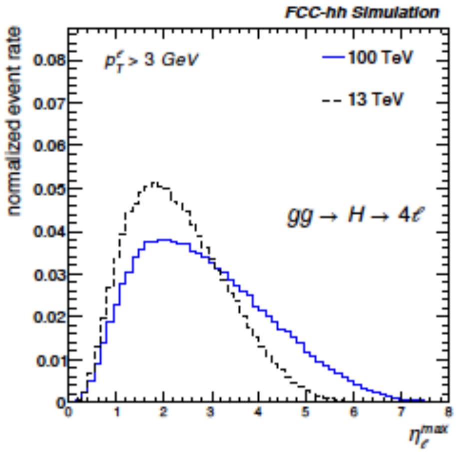
Refs to FCC-hh, HL-LHC, LHeC

- **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**

Physics constraints for detector

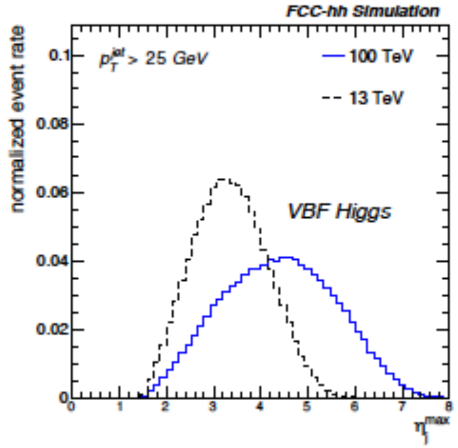
- Known Physics will be more boosted and more forward
- Heavy new physics will lead to higher P_T

E.g.: use H→ZZ to define muon acceptance



Pseudorapidity of the most forward muon in H→ZZ*→4mu, at 13 TeV and 100 TeV

E.g.: use VBF Higgs to define calorimeter acceptance



Pseudorapidity of the most forward VBF jet in VBF Higgs production, at 13 TeV and 100 TeV

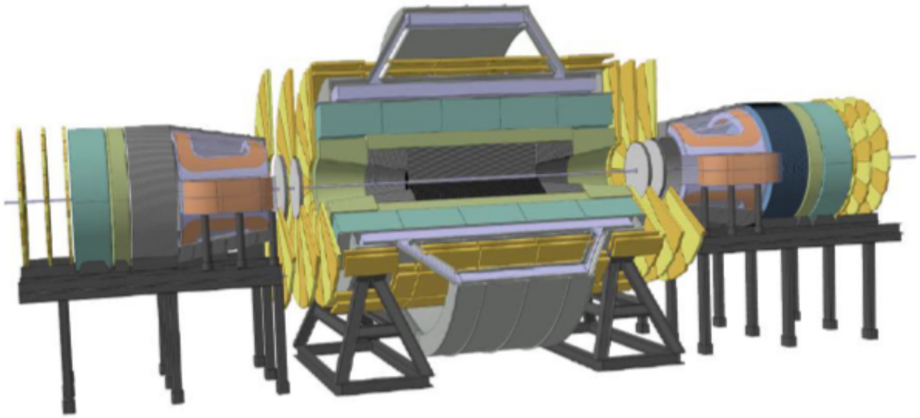
A detector design?

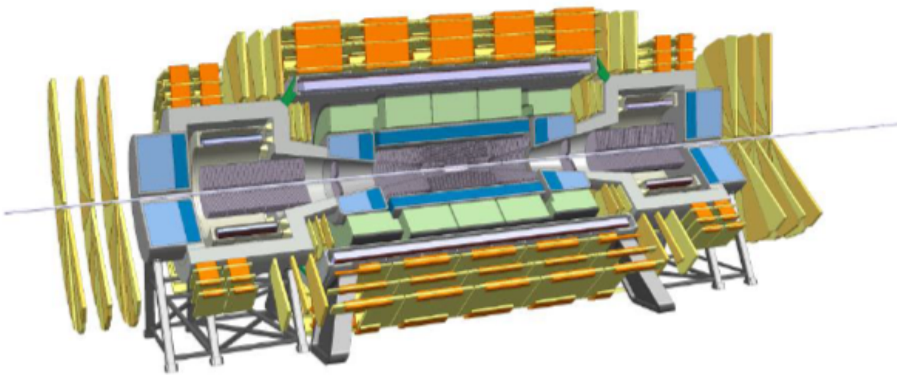
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

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

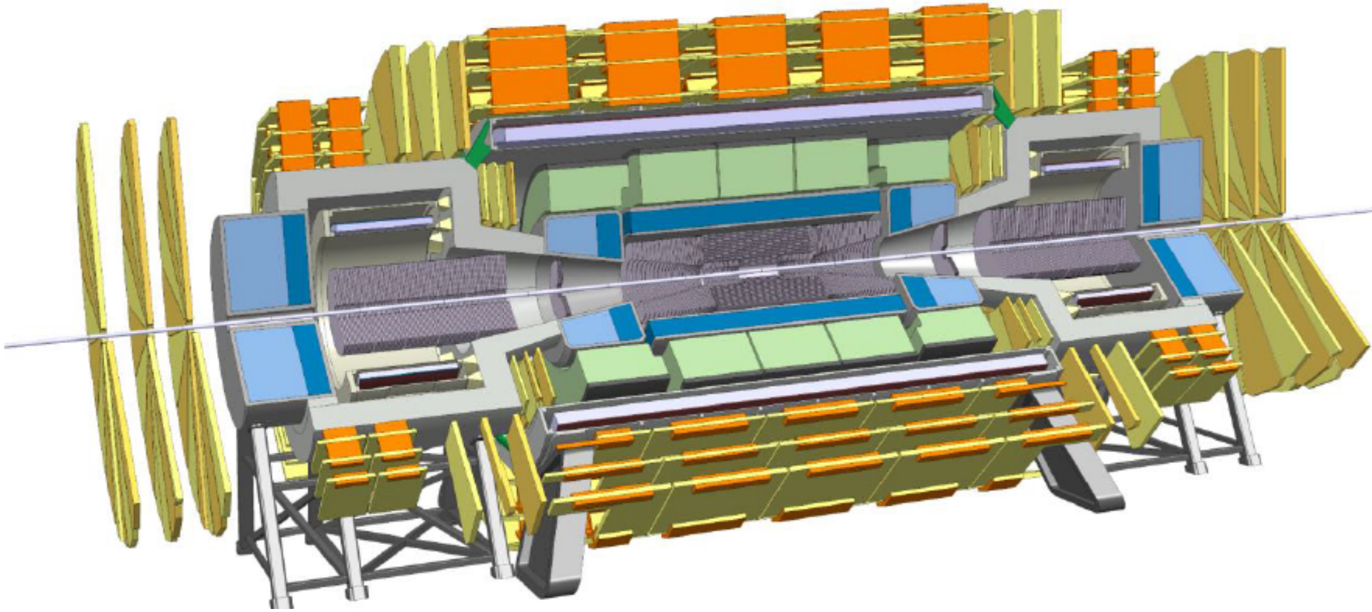
4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

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

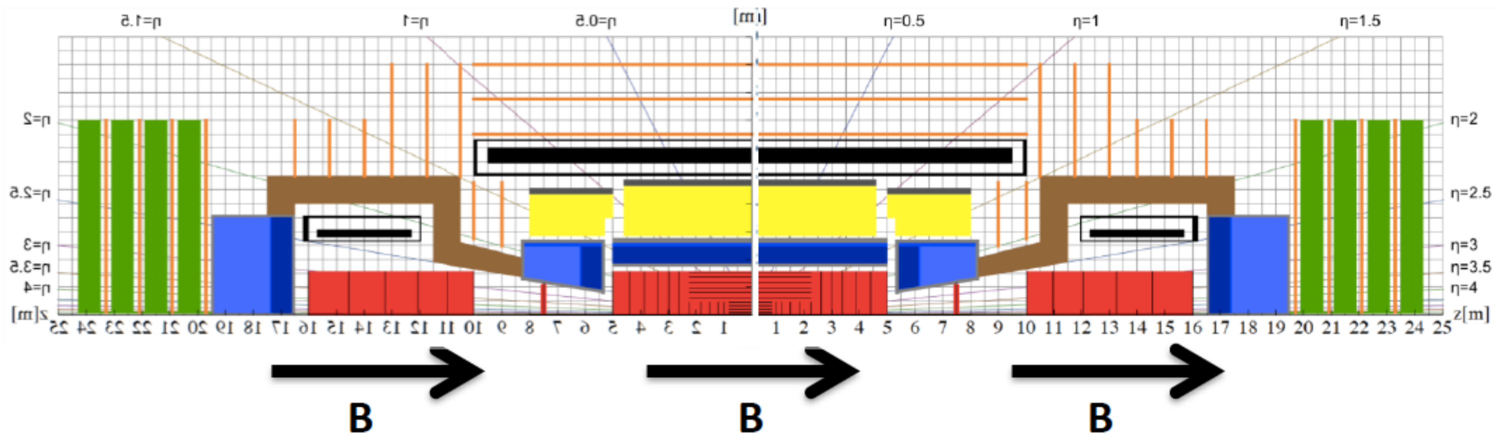




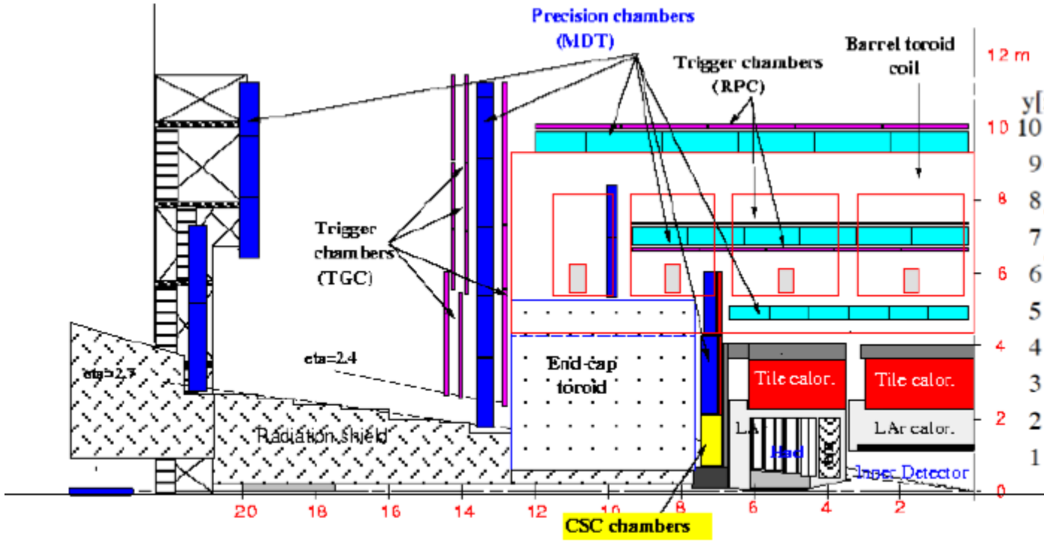
A reference detector design

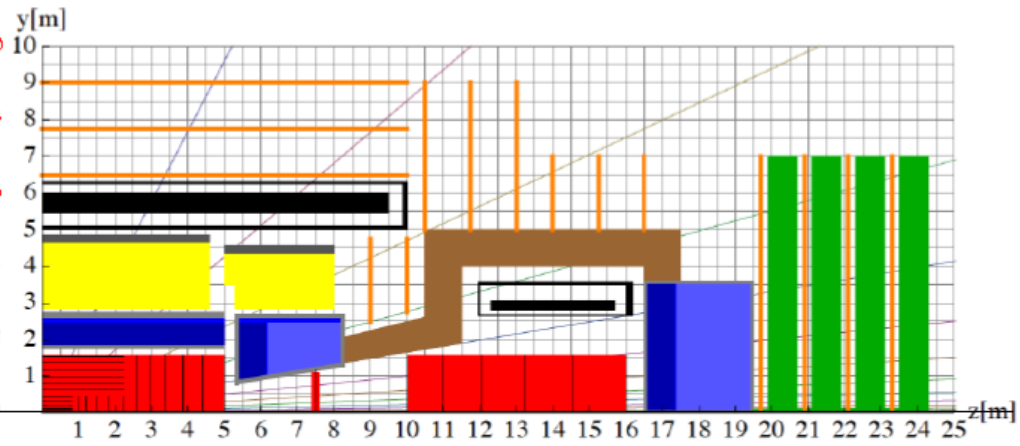


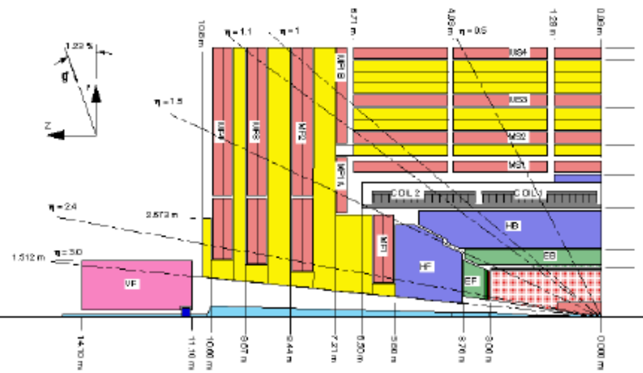
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

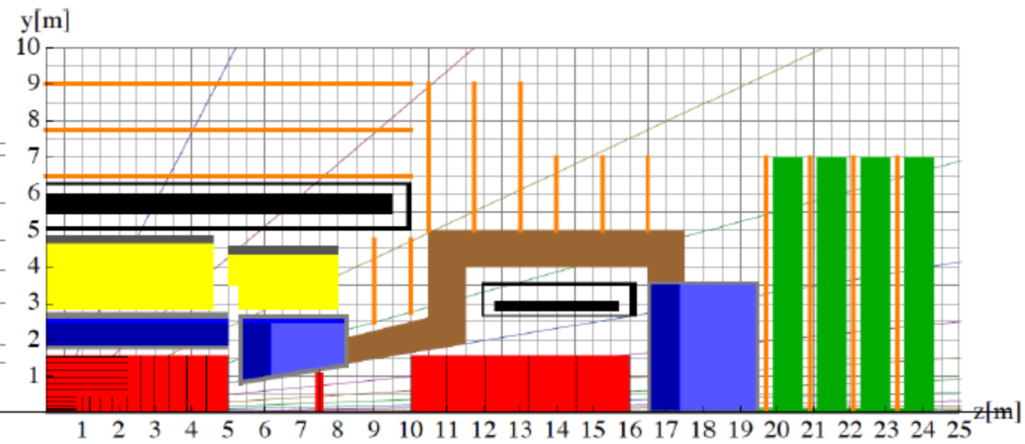


Comparison to ATLAS & CMS



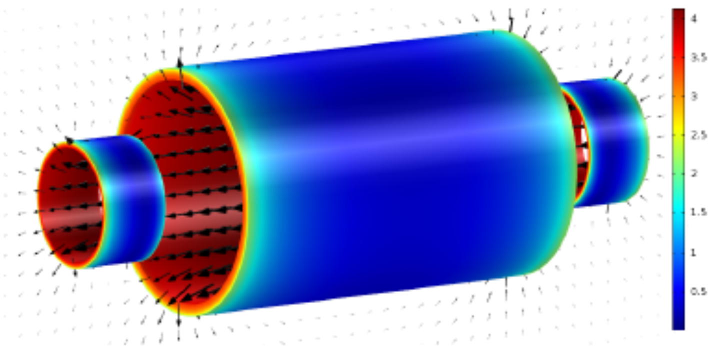






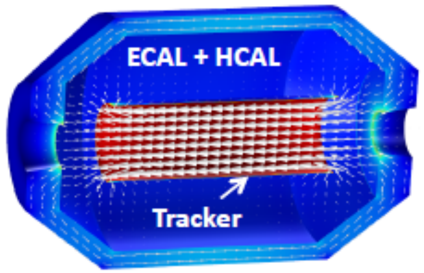
Current detector baseline

- 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

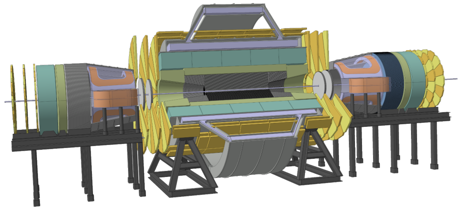


Alternative challenging design:

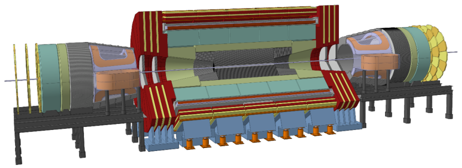
4T/4m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!

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

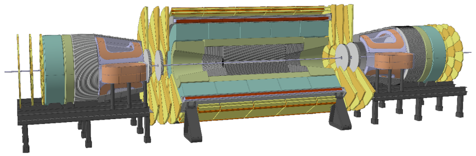
Magnet systems under consideration



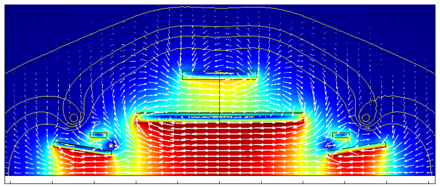
**Twin solenoid with dipoles
(min. shaft diameter 27.5m)**



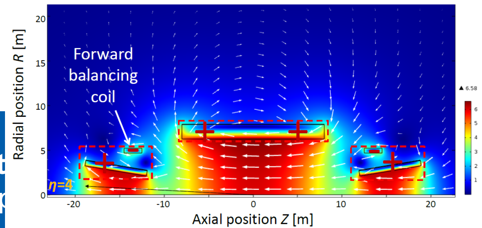
Partially shielded solenoid with dipoles



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

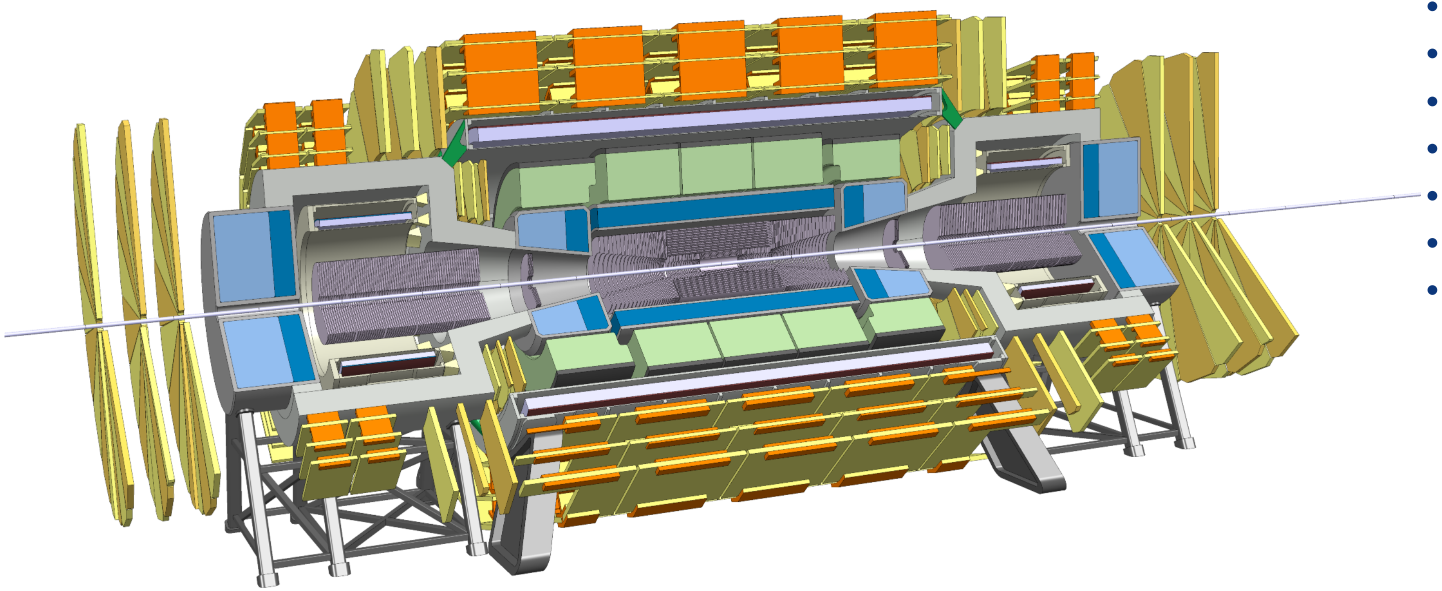


Twin solenoid with balanced conical solenoid



Unshielded solenoid with balanced conical solenoid

Reference detector

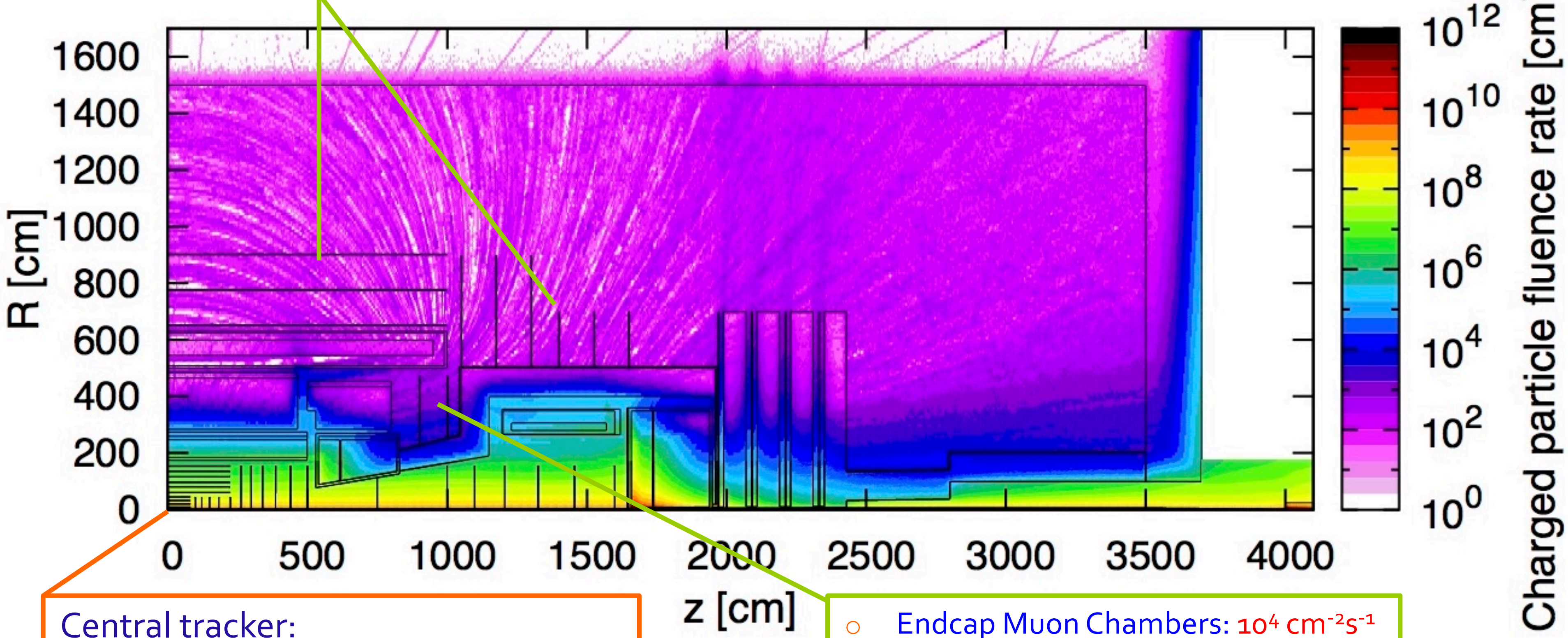


- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

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?

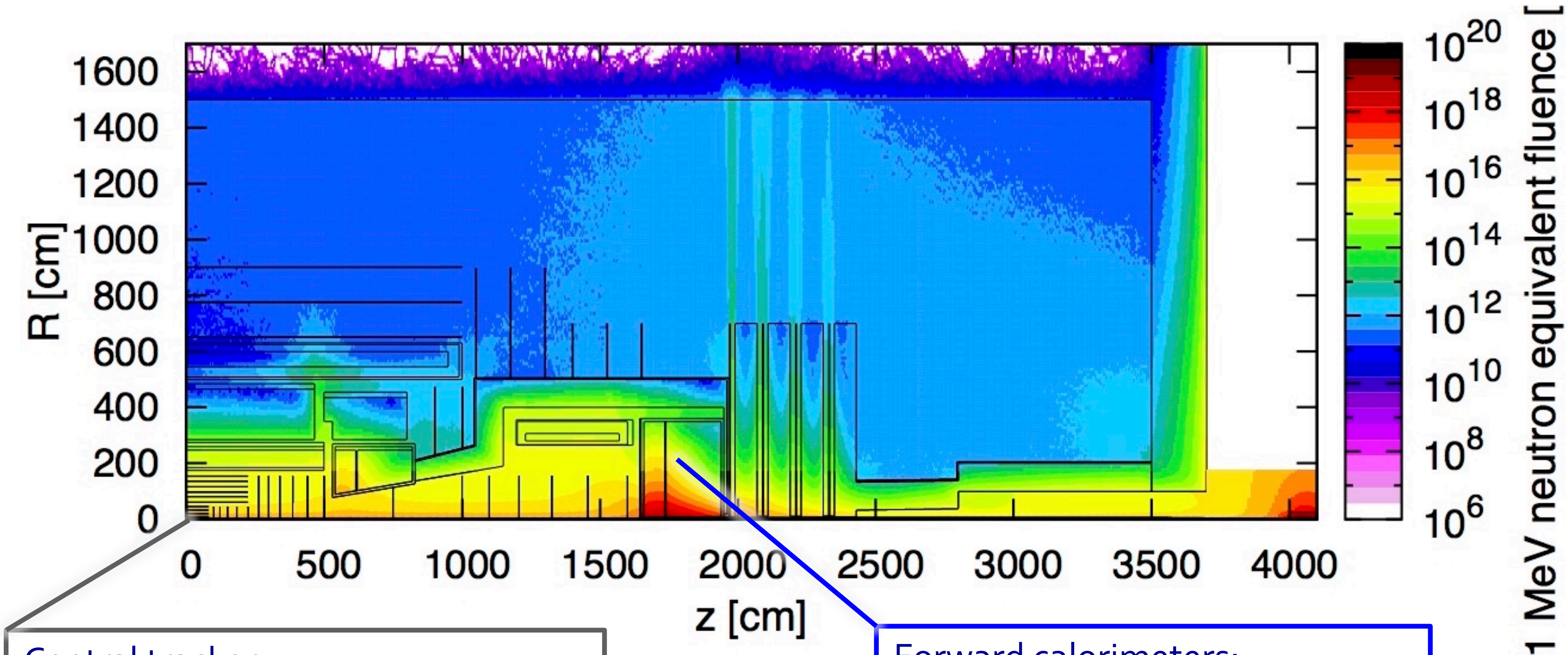
- Barrel muon chambers: ~300 $cm^{-2}s^{-1}$ to ~500 $cm^{-2}s^{-1}$



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} $cm^{-2}s^{-1}$

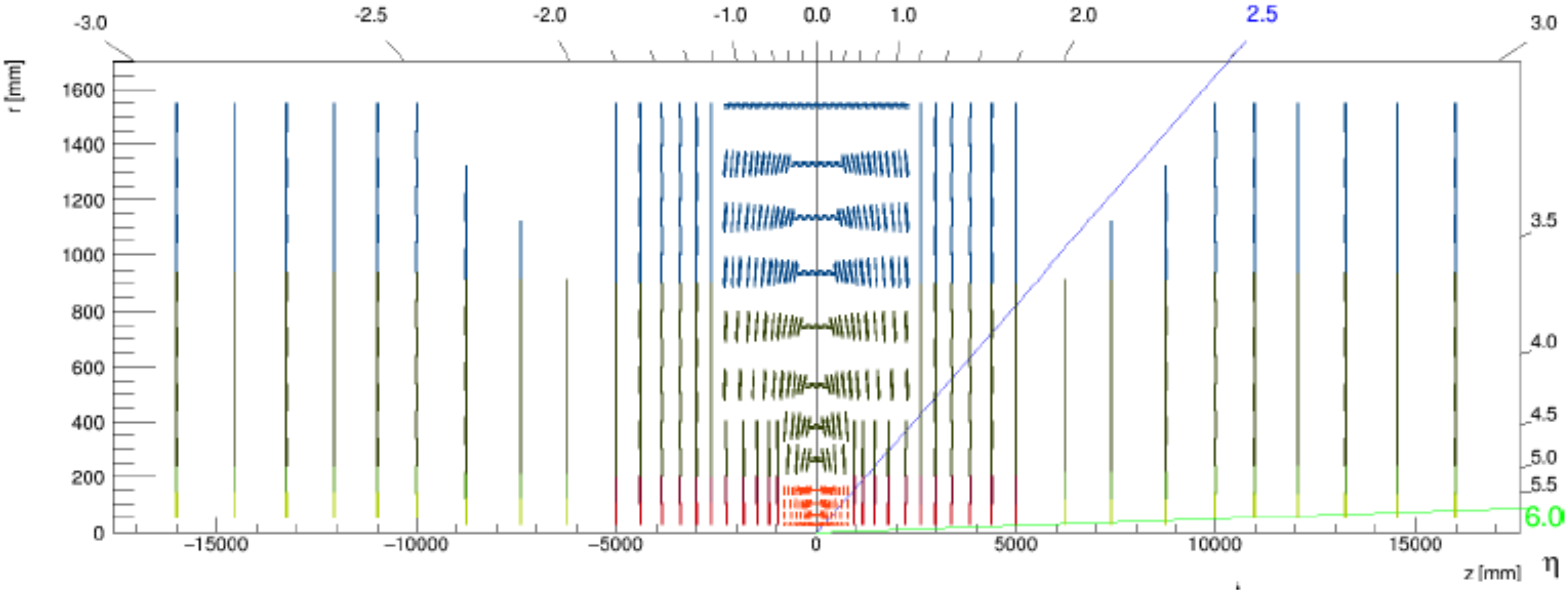
Neutron background?



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

Tracking



-3.0
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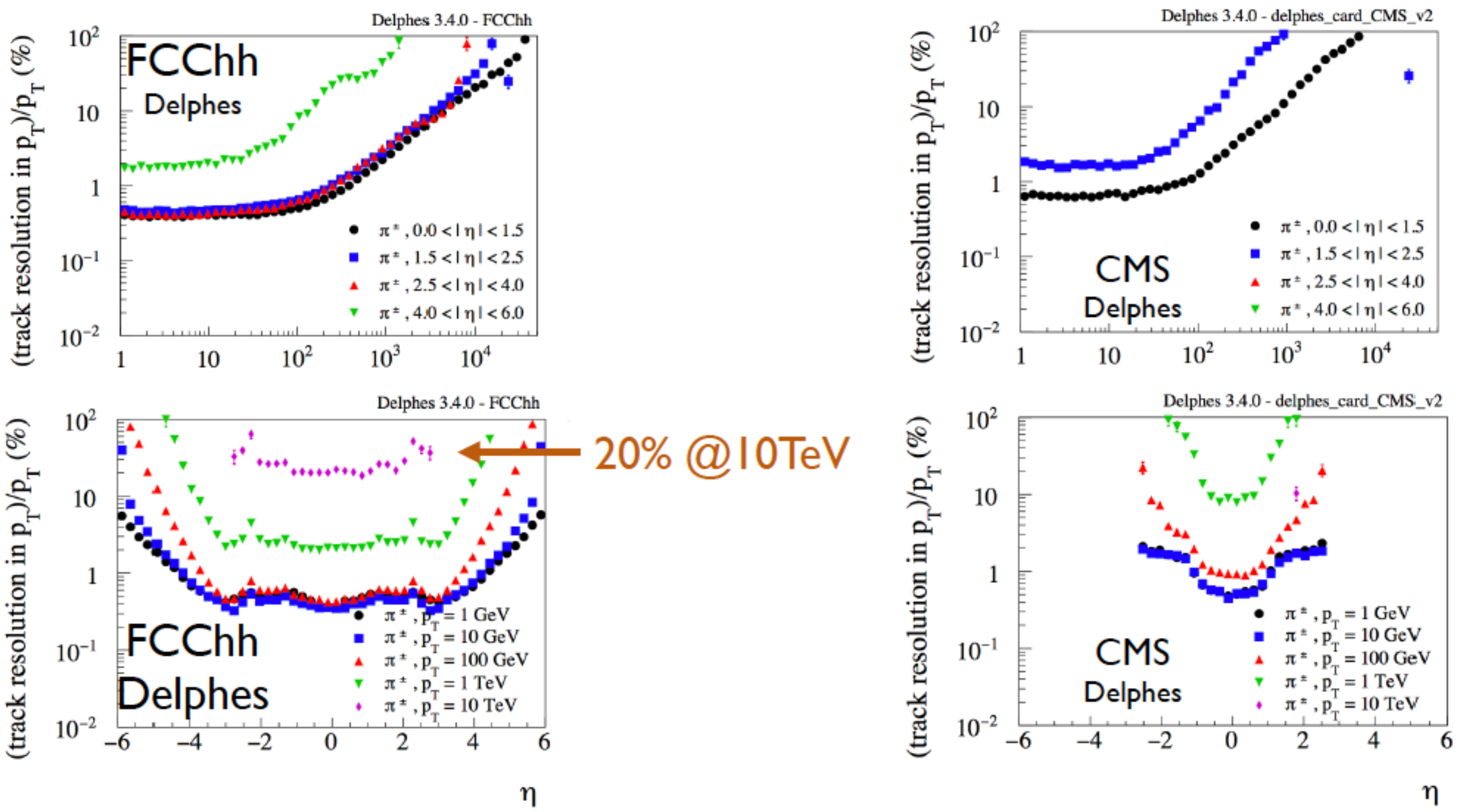
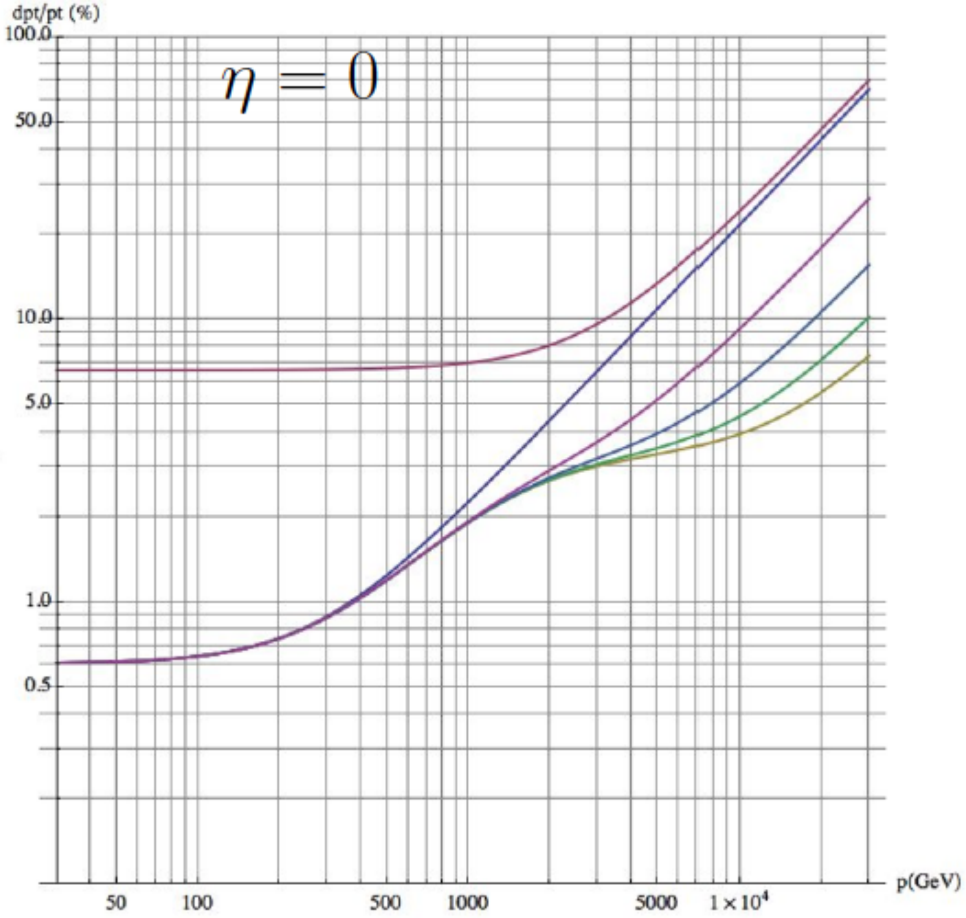
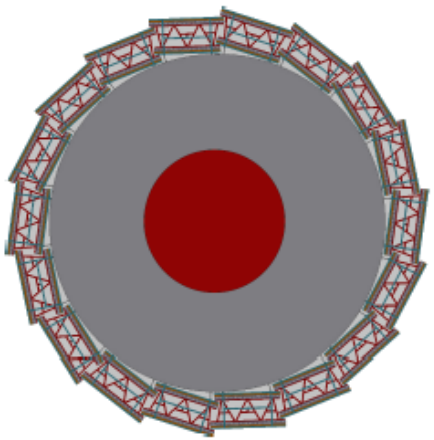
FCC-hh baseling tracking



Muon performance

Muon chambers

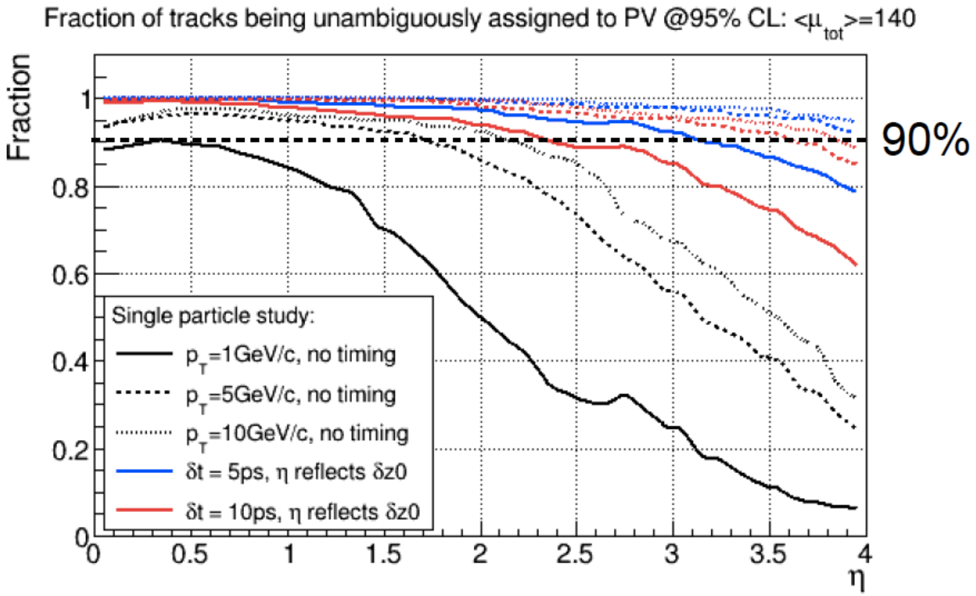




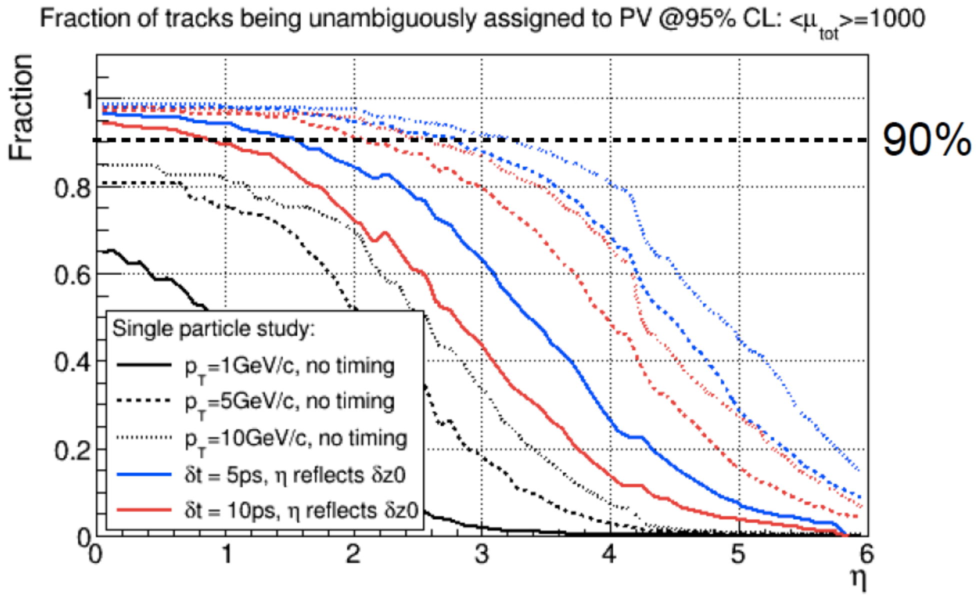
Timing detector(s)?

→ 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



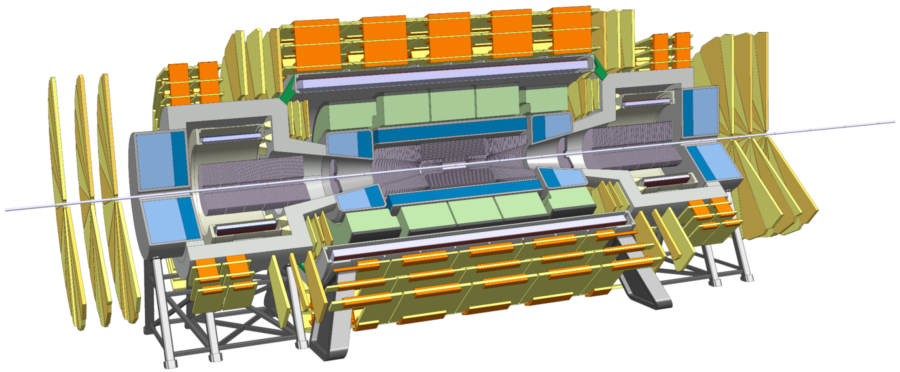
Trigger/DAQ?

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.

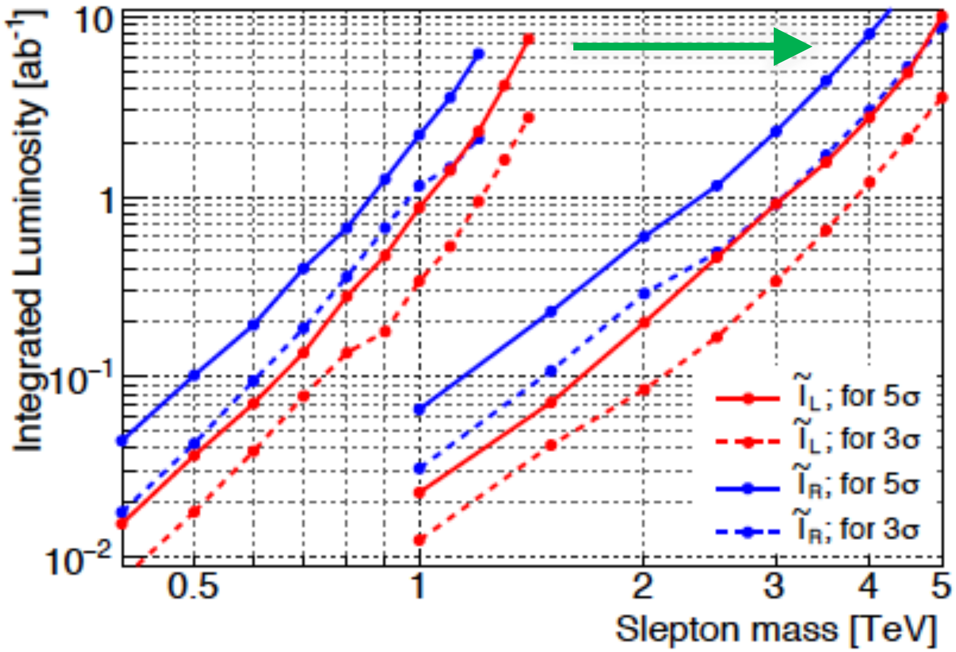
Benchmark: long-lived sleptons

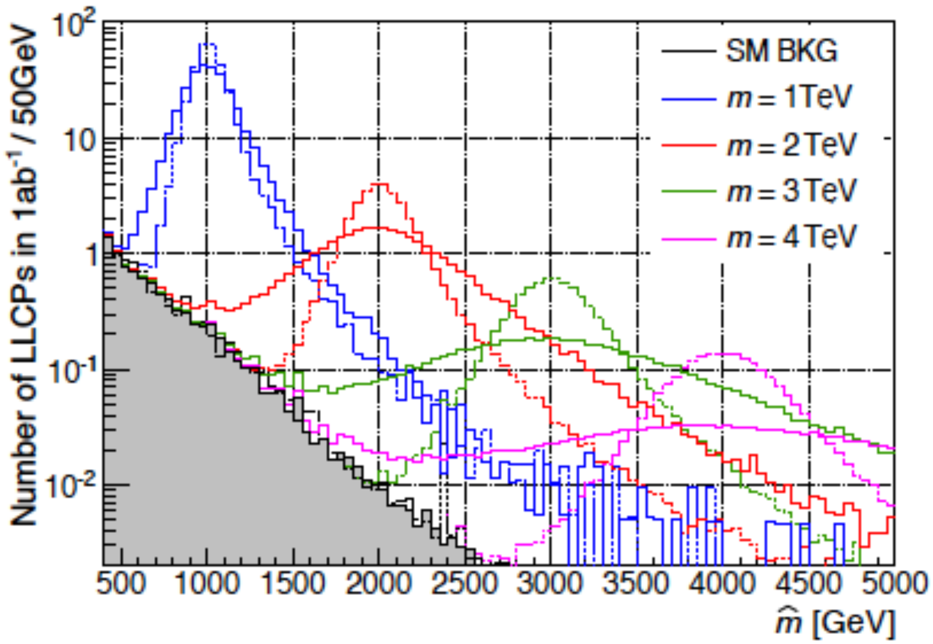
arxiv:1606.00947

$\tilde{\ell}_R$ LLCP

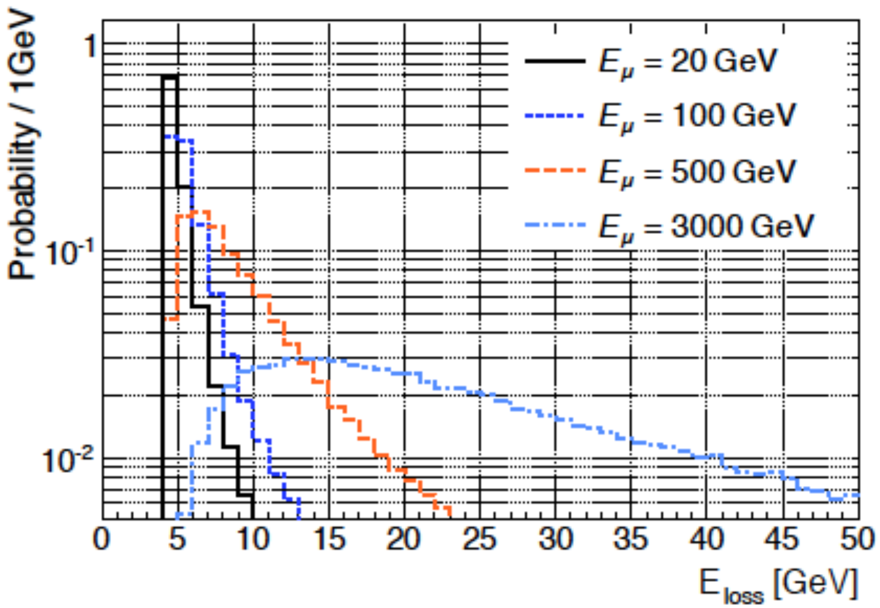
Assume only DY production: $pp \to (\gamma, Z) \to \tilde{\ell}_R \tilde{\ell}_R^*$

LHC FCC-hh



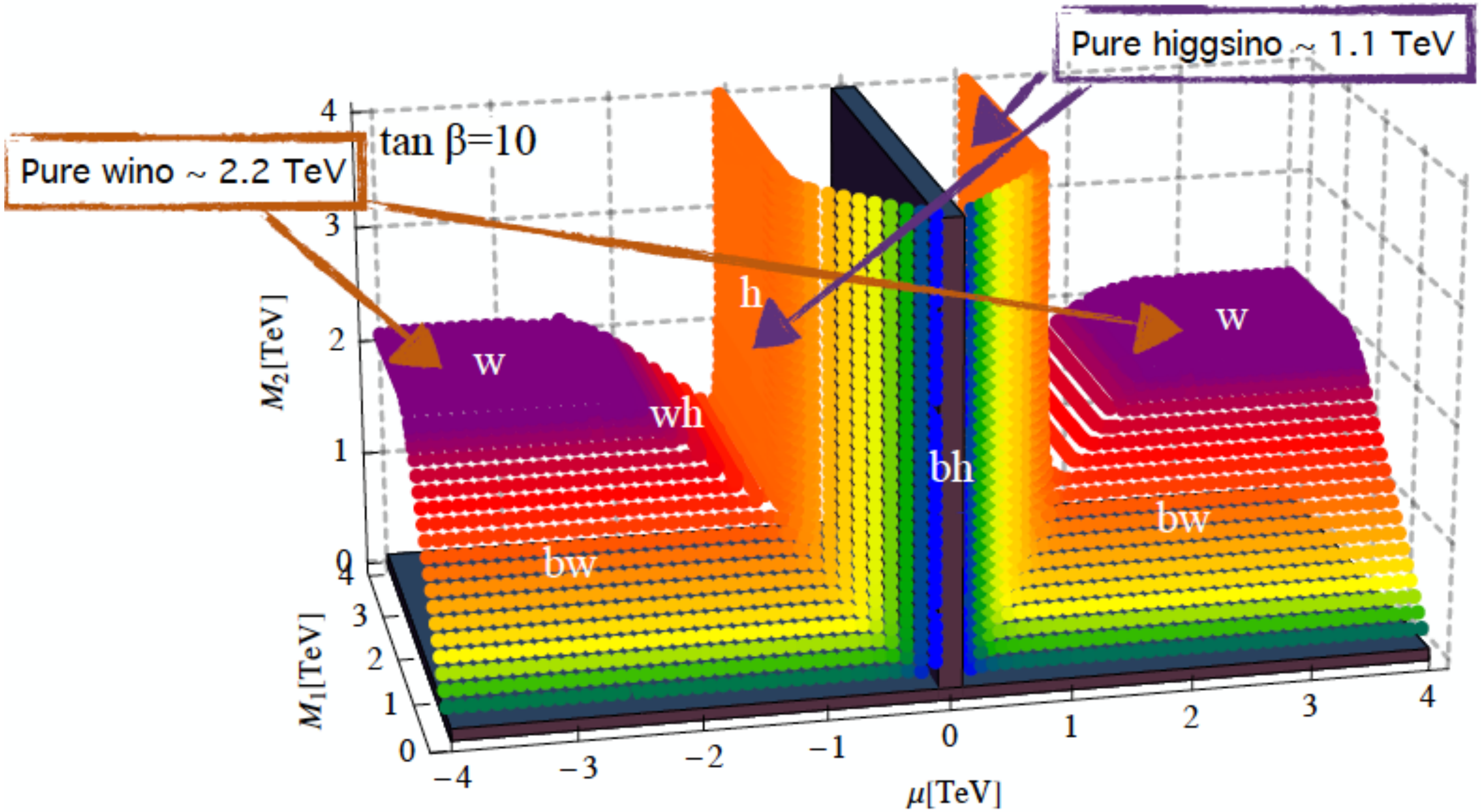


Extra handle at 100 TeV: TeV muon energy loss



e.g. requiring E_{loss} < 30 GeV reduces muon background by 18% per muon

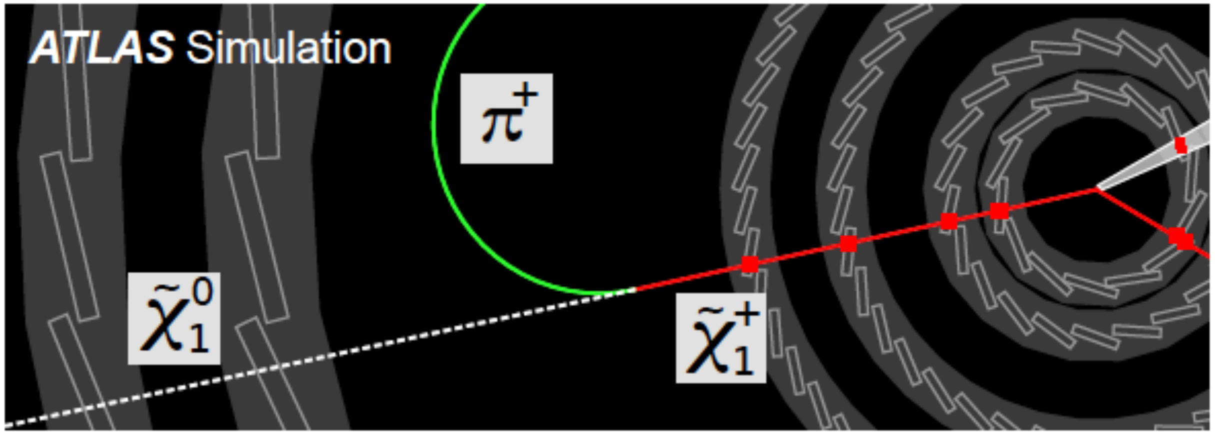
Relic neutralino parameter space for tan β = 10



$m_{\chi_1^0}$ = ●0.1 || ●0.25 || ●0.5 || ●1 || ●1.5 || ●2 TeV

Relic dark matter for all params decoupled except Higgs doublet vevs (μ,tan β) and the bino and wino majorana masses (M_1,M_2)

- Wino or higgsino LSP leads meta-stable chargino
- $c\tau$ ~ 6 cm (wino), 7 mm (higgsino) → directly detectable
  - chargino tracks disappear in the tracker.



Ryu Sawada

arXiv:1712.02118 ATL-PHYS-PUB-2017-019

- ATLAS limit for wino (higgsino) LSP : 460 GeV (152 GeV)
- CMS limit : 715 GeV @ τ = 3 ns, ~ 310 GeV @ τ = 0.2 ns (wino LSP)

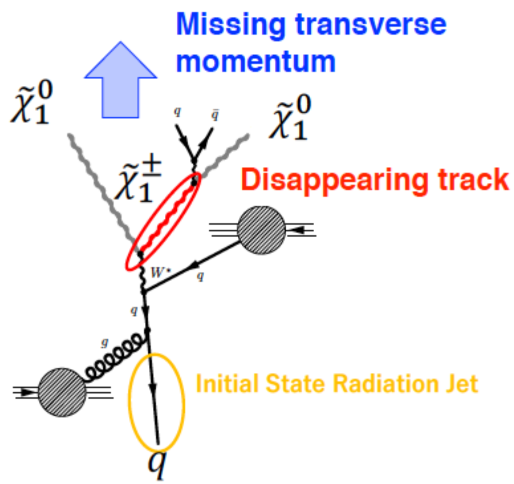
CMS-PAS-EXO-16-044

Does FCC have a potential to definitively confirm/exclude that a thermally produced WIMP exists ?

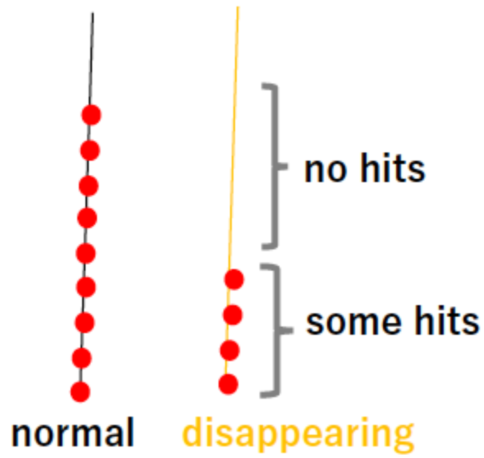
Analysis Overview

- Require a high p_T ISR jet and large E_T^{miss}
  - In ATLAS, jet pT>140, E_T^{miss} > 140 GeV

Layout	Default (#1)	Alternative (#2)	Alternative (#3)
	wino ($m_{\tilde{\chi}_1^\pm}$ = 3 TeV)		
Leading jet p_T threshold [TeV]	1	1	1
E_T^{miss} threshold [TeV]	4	3	2
Signal yield	28.5	86.5	287
Background yield	1.9	7.2	42.6
Significance	10.4	17.8	26.8
	higgsino ($m_{\tilde{\chi}_1^\pm}$ = 1 TeV)		
Leading jet p_T threshold [TeV]	1	1	1
E_T^{miss} threshold [TeV]	1	4	4
Signal yield	2.7	6.6	19.0
Background yield	673	1.8	1.6
Significance	0.0	3.4	8.0



- Require "disappearing track"
  - Defined as having no associated hits after a layer
  - Required at least 4 or 5 hits in a track.
  - Only the central ($|\eta|$ < 1.9 by default) to suppress BG.



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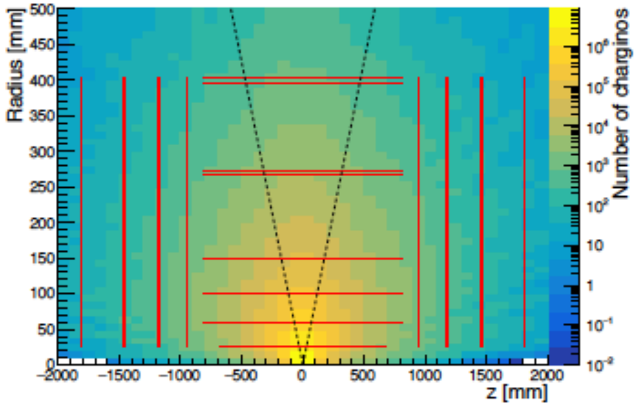
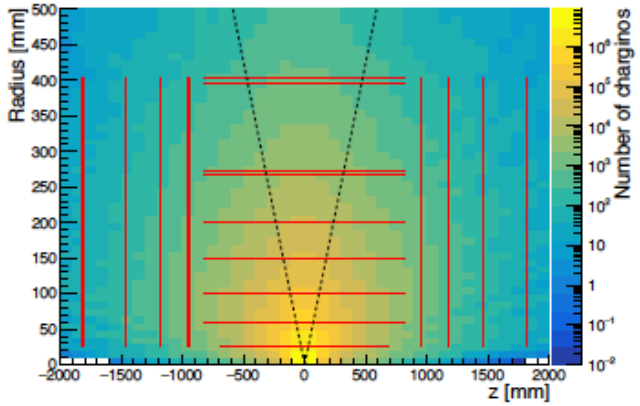
3 detector layouts considered

#1: Default



#2: Extra layer at 200 mm



#3: Extra layer < 150 mm

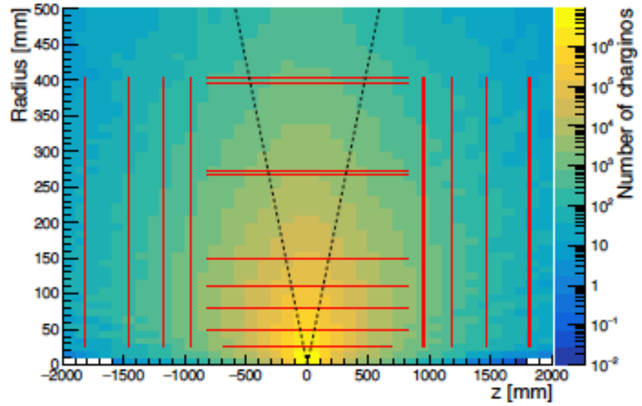


Table 1.1: Signal acceptance for wino and higgsino with $|\eta| < 1$ and 4 or 5 layer hits. The acceptance at alternative layout (#3) is larger than others because the layer radius is closer to the beam pipe.

Layout	Default (#1)	Alternative (#2)	Alternative (#3)
	wino ($m_{\tilde{\chi}_1^\pm}$ = 3 TeV)		
$N_{\text{layer}}^{\text{hit}} \geq 4$	2.5 %	2.5 %	4.4 %
$N_{\text{layer}}^{\text{hit}} \geq 5$	0.57 %	1.3 %	2.5 %
	higgsino ($m_{\tilde{\chi}_1^\pm}$ = 1 TeV)		
$N_{\text{layer}}^{\text{hit}} \geq 4$	0.0043 %	0.0043 %	0.016 %
$N_{\text{layer}}^{\text{hit}} \geq 5$	0.00022 %	0.0011 %	0.0043 %

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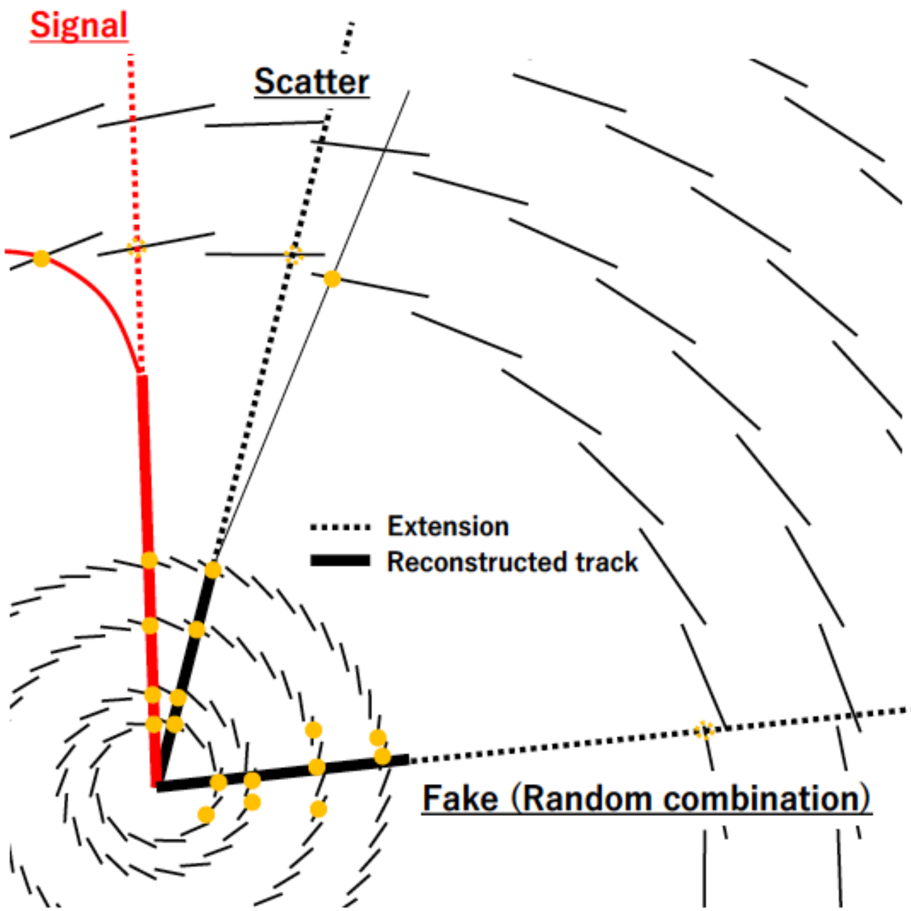
Background



- **Physical background**
  - Missing hits due to material interaction
  - Dominant source is $W \to \ell\nu$, where ℓ is an electron or a τ.
    - E_T^{miss} from ν and an isolated electron or a pion from 1-prong τ decay.

Dominant at μ=500 pileup

- **Unphysical background**
  - Random combination of hits
  - The rate depends on the detector layout, pileup etc.

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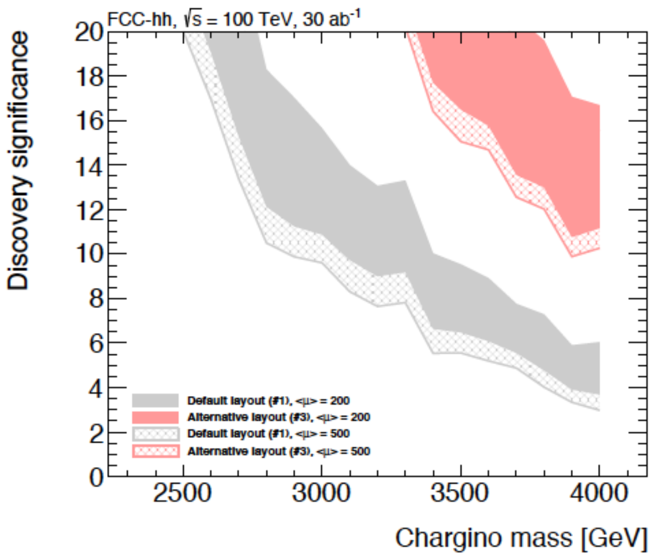
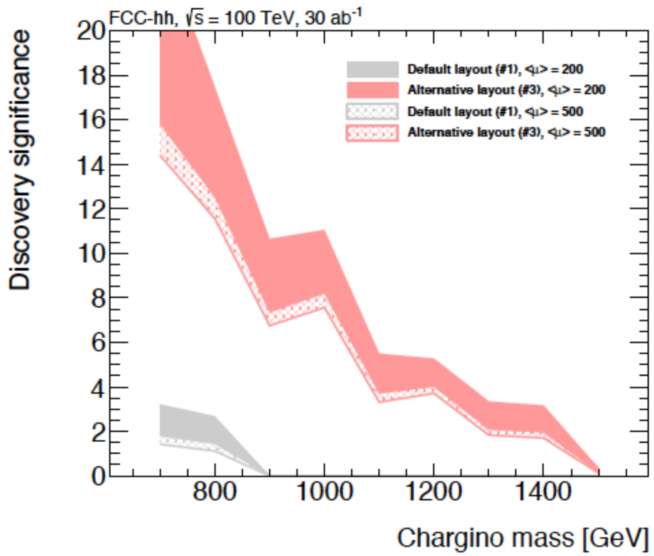
Results:



(a) wino



(b) higgsino

Figure 1.33: Expected discovery significance at 30 ab^{-1} with requirements of good time-fit quality, 200 or 500 pileup collisions. The reduction rate by time information with 200 pileup collisions are assumed to be same for the one with 500 pileup collisions. The grey band shows the significance using the default layout (#1). The red band shows the significance using the alternative layout (#3). Results assuming the average $\mu = 200$ and 500 are shown. The band width corresponds to the difference of the two configurations of the soft QCD processes.

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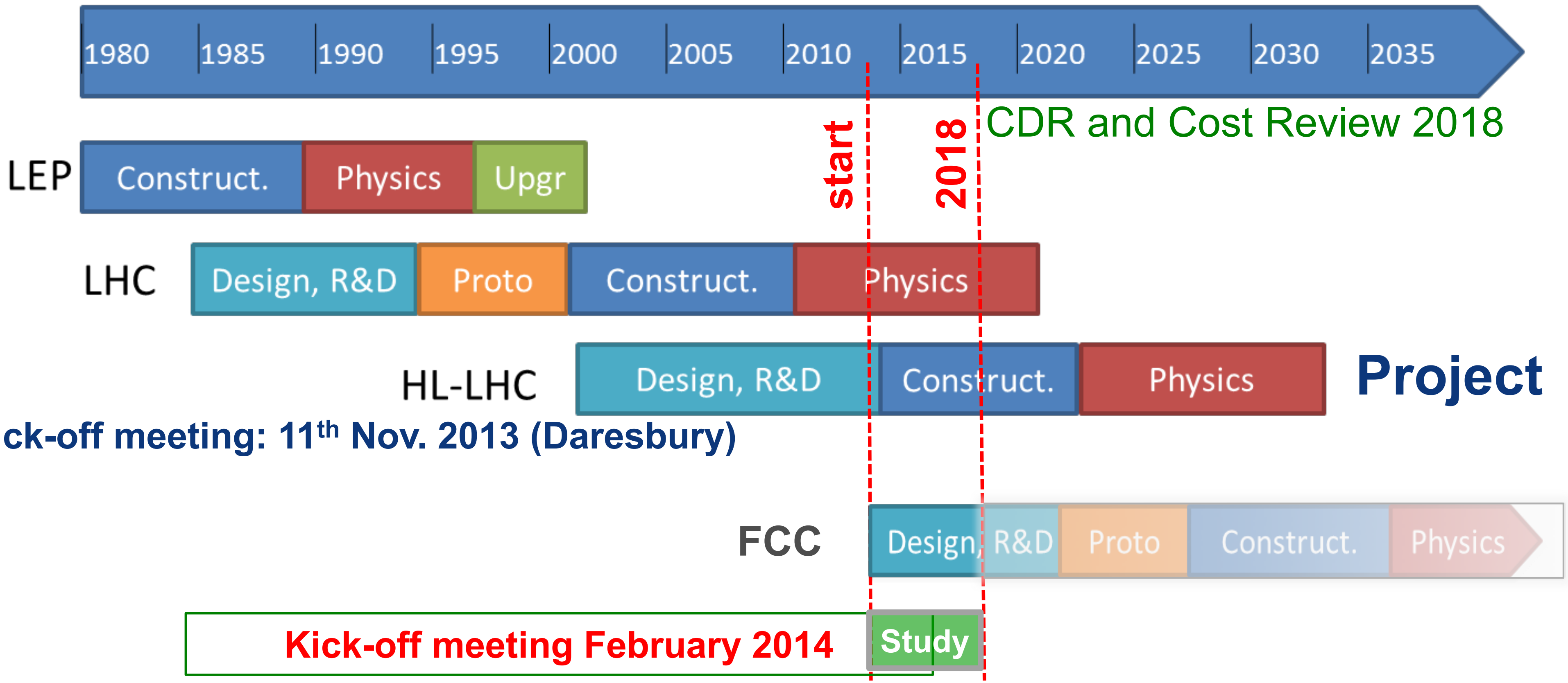
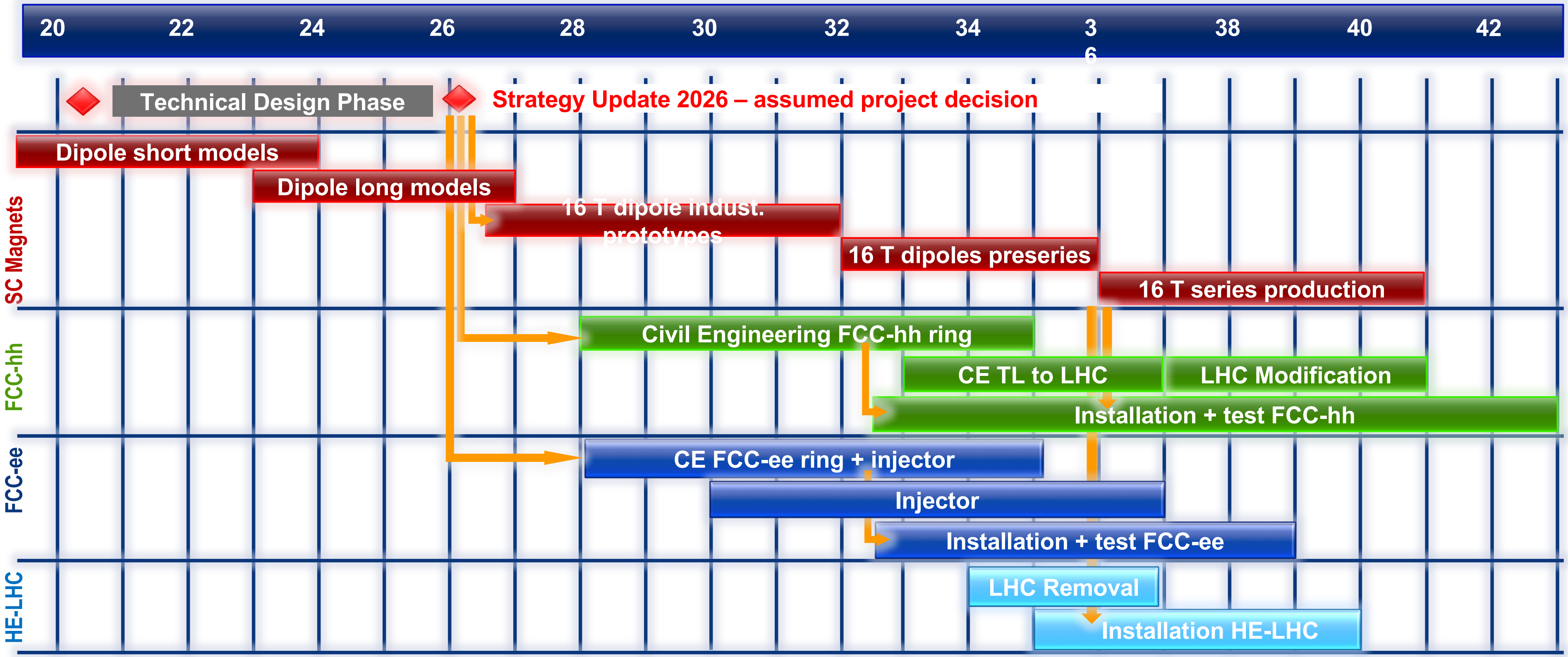
CERN roadmap and FCC planning



CDR and Cost Review for 2018

Draft schedule



In Conclusion

- The HEP community in Europe is entering a phase of strategic discussions about the future

- A Conceptual Design Report (CDR) for FCC (ee, eh and hh) is being finalized. Also, a Yellow Report for HL/HE-LHC is in preparation.

- While some LLP benchmarks are being considered in these documents, I encourage the LLP community to focus some of their creative energy on these future pp colliders & detectors

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

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

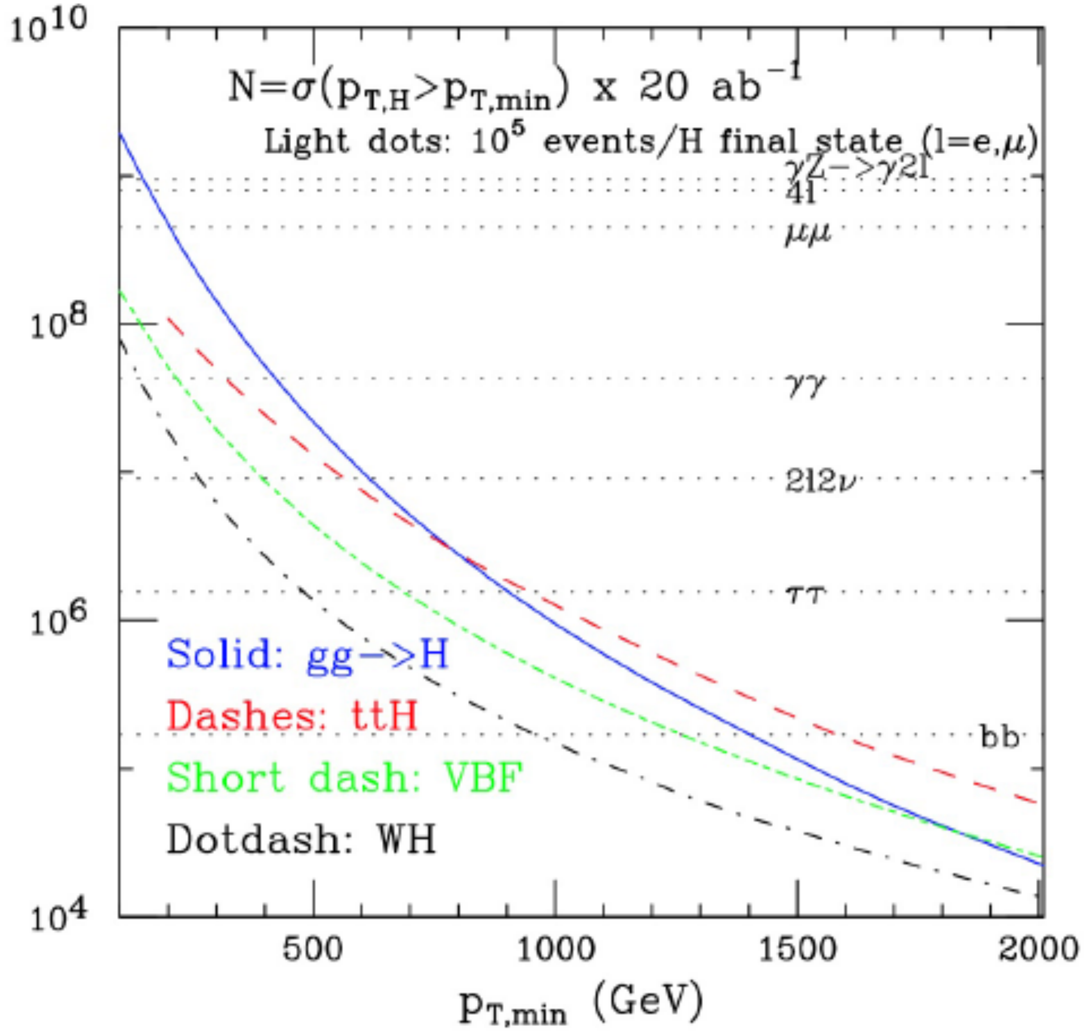
	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

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

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

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

H at large p_T



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

- $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
- $\sigma(VBF) > \sigma(gg \to H)$ 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%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<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→γγ)/BR(H→ZZ*)
loop-level — tree-level

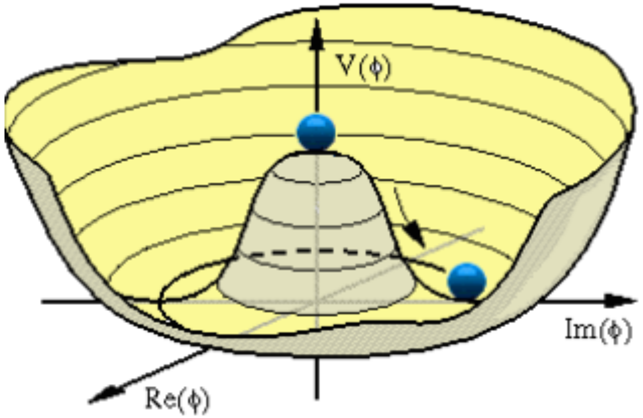
BR(H→μμ)/BR(H→ZZ*)
2nd gen'n Yukawa — gauge coupling

BR(H→γγ)/BR(H→Zγ)
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 σ(gg→H) (if colored) ⇒ detectable from various production and/or decays ratios

The Higgs potential

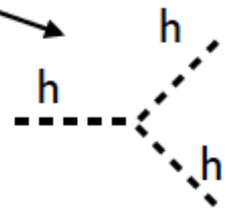
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



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?

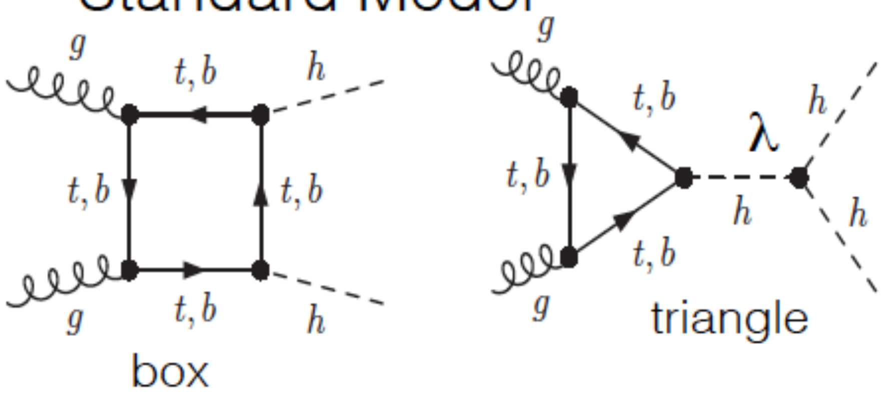
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

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

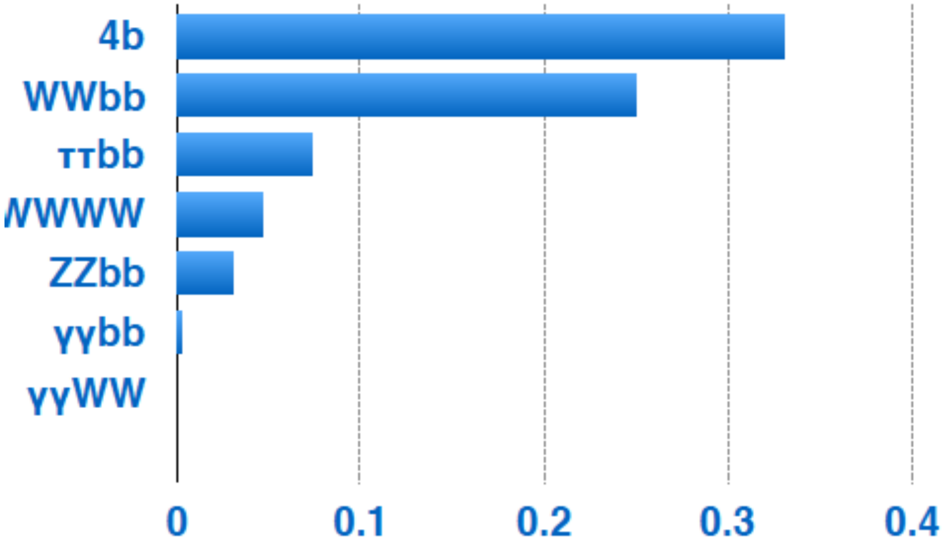
Standard Model

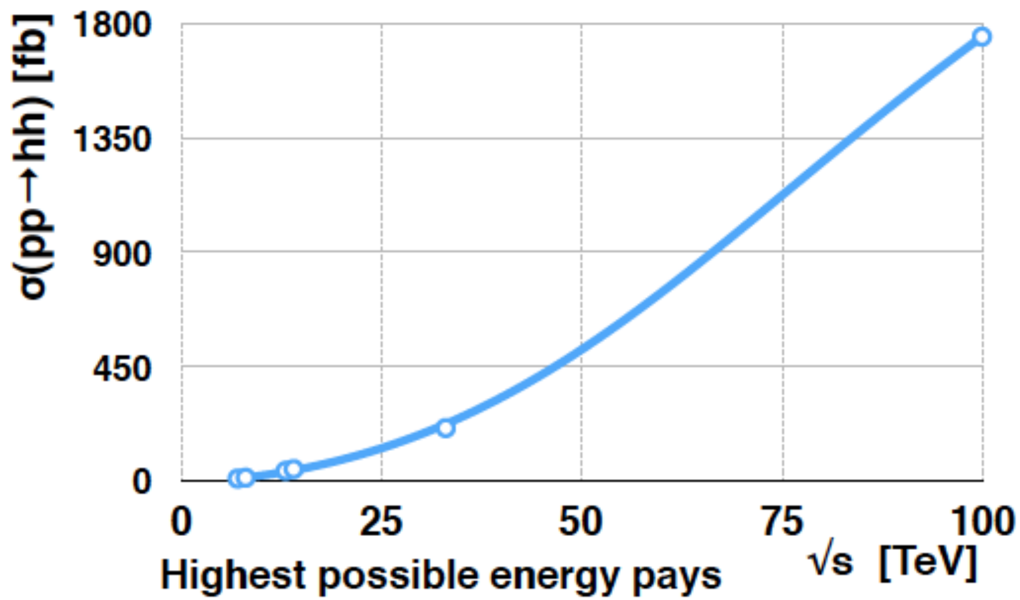


NNLO with full top mass *NLO $m_t \to \infty$

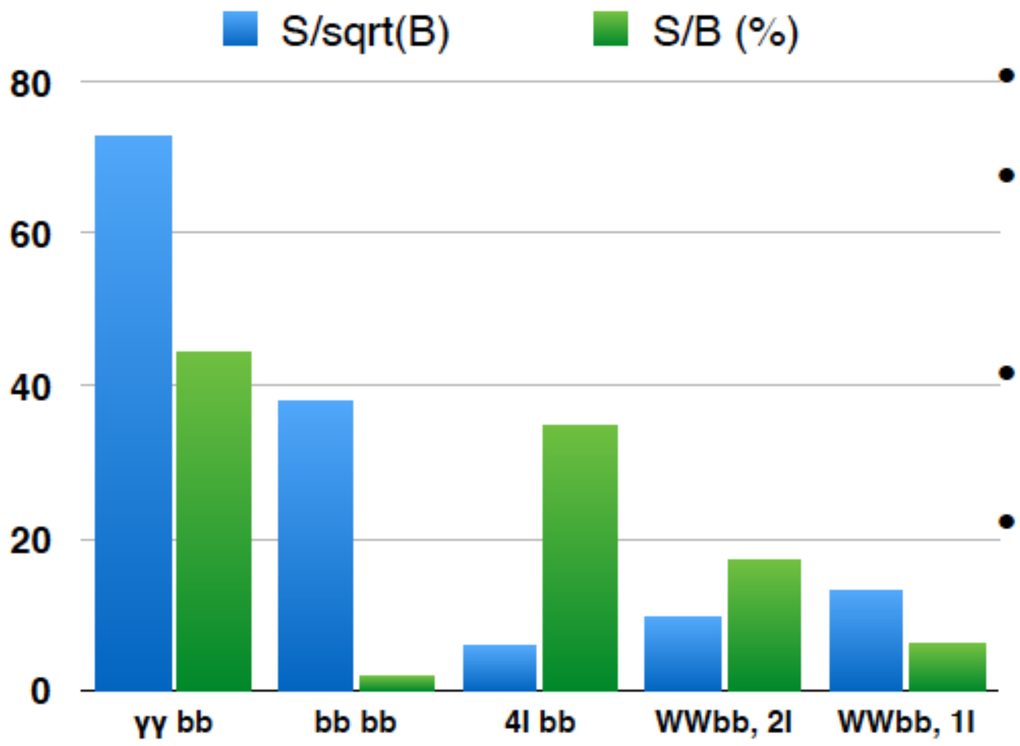
m_h = 125.09 GeV	σ(fb)	scale unc. (%)	PDF unc. (%)	α_s unc.
√s = 7 TeV	7.71	+4.0/-5.7	± 3.4	± 2.8
√s = 8 TeV	11.17	+4.1/- 5.7	± 3.1	± 2.6
√s = 13 TeV	37.91	+4.3/-6.0	± 2.1	± 2.3
√s = 14 TeV	45.00	+4.4-6.0	± 2.1	± 2.2
√s = 33 TeV*	206.6	+15.1 - 12.5	+5.8/-5.0	
√s = 100 TeV	1748	+5.1/-6.5	± 1.7	± 2.0

Higgs decay branching fraction





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 $n_B \to r_B \times n_B$
- uncertainty on signal rate $\Delta_S = \frac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$

using "medium" calorimeter resolution

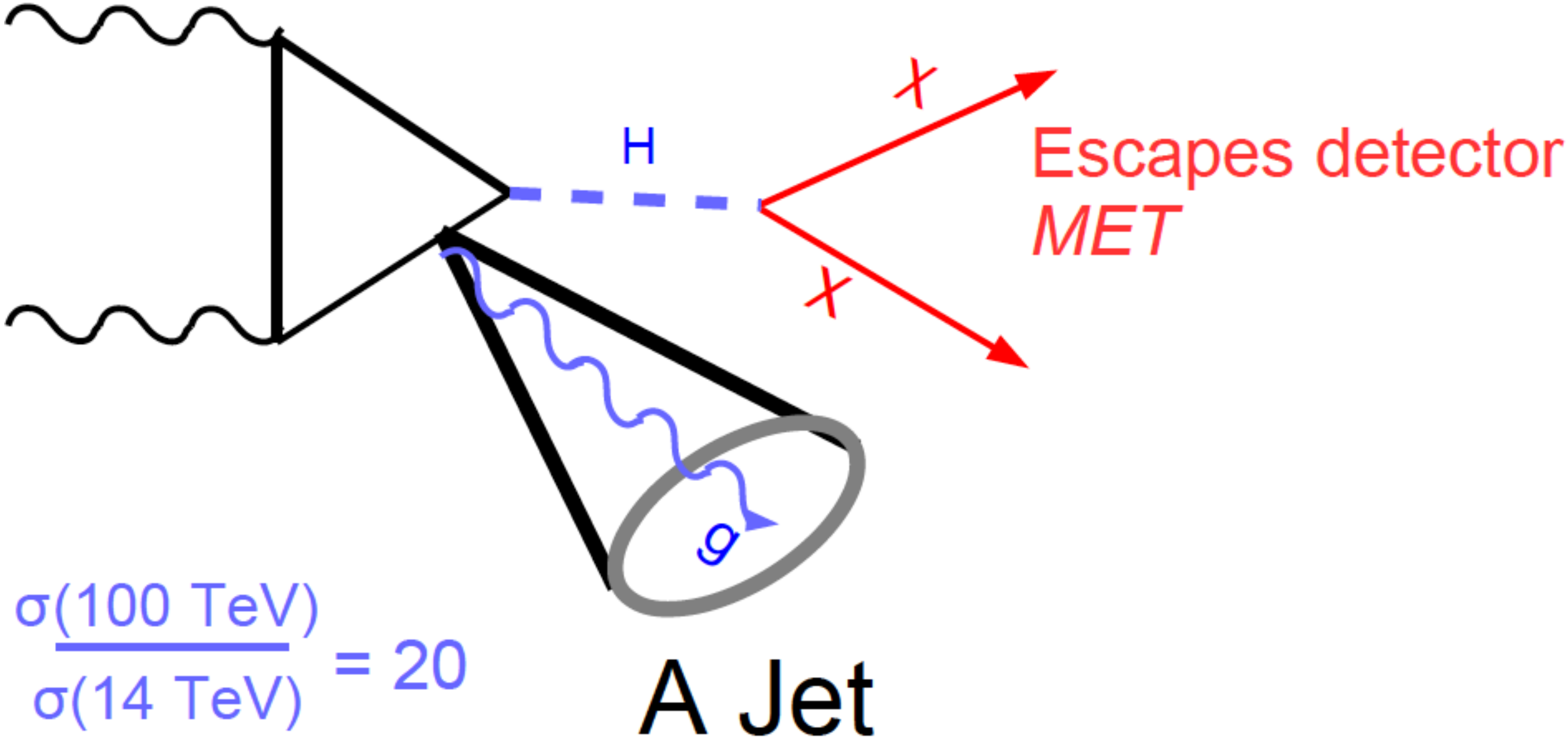
For $\Delta_S \gtrsim 2.5\%$ the precision on λ_3 is dominated by the theory error on the signal: $\Delta\lambda_3 \simeq 2\Delta_S$

$\Delta\lambda_3$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	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/

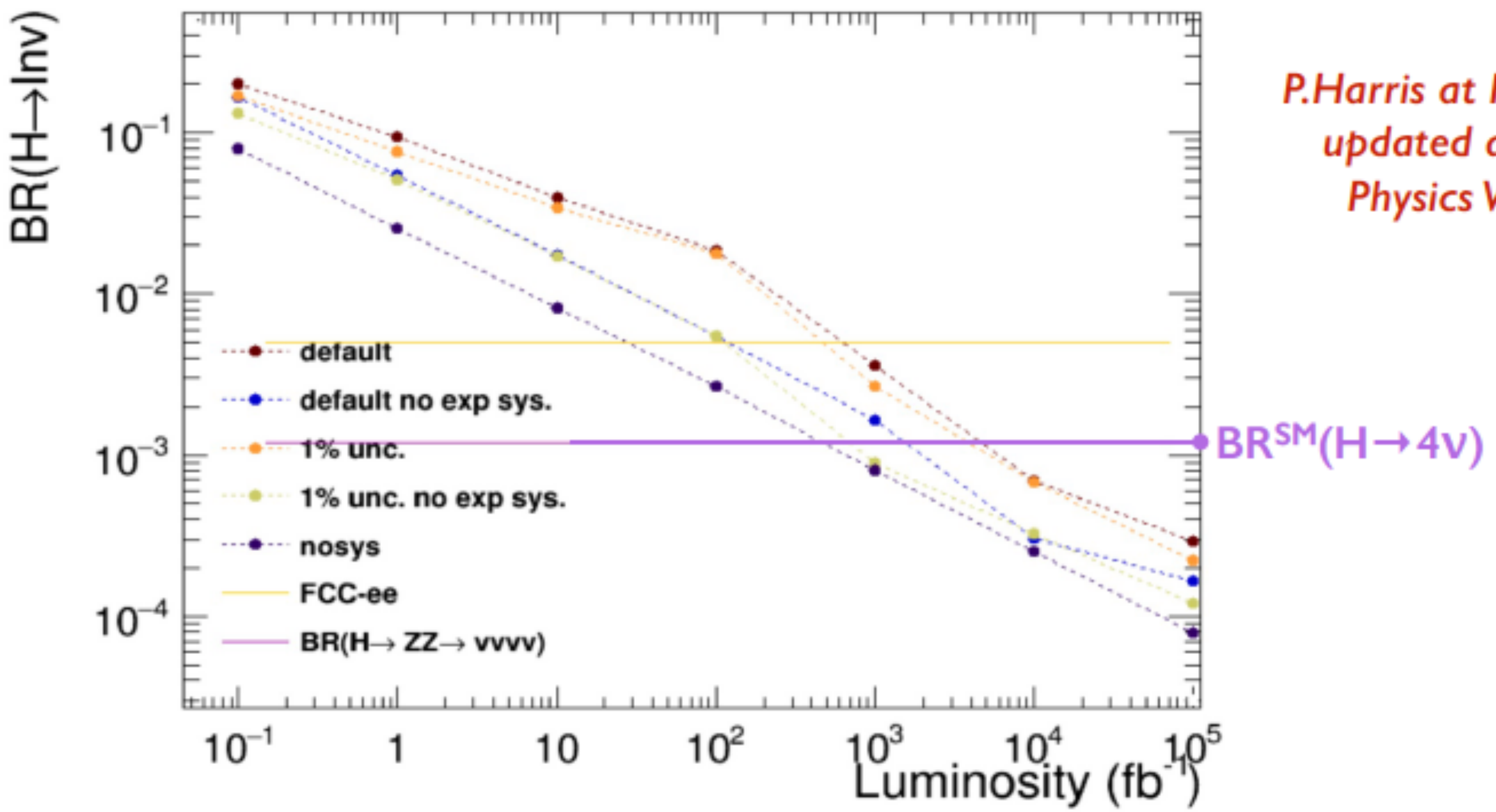
Invisible Higgs decays



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

Invisible Higgs decays

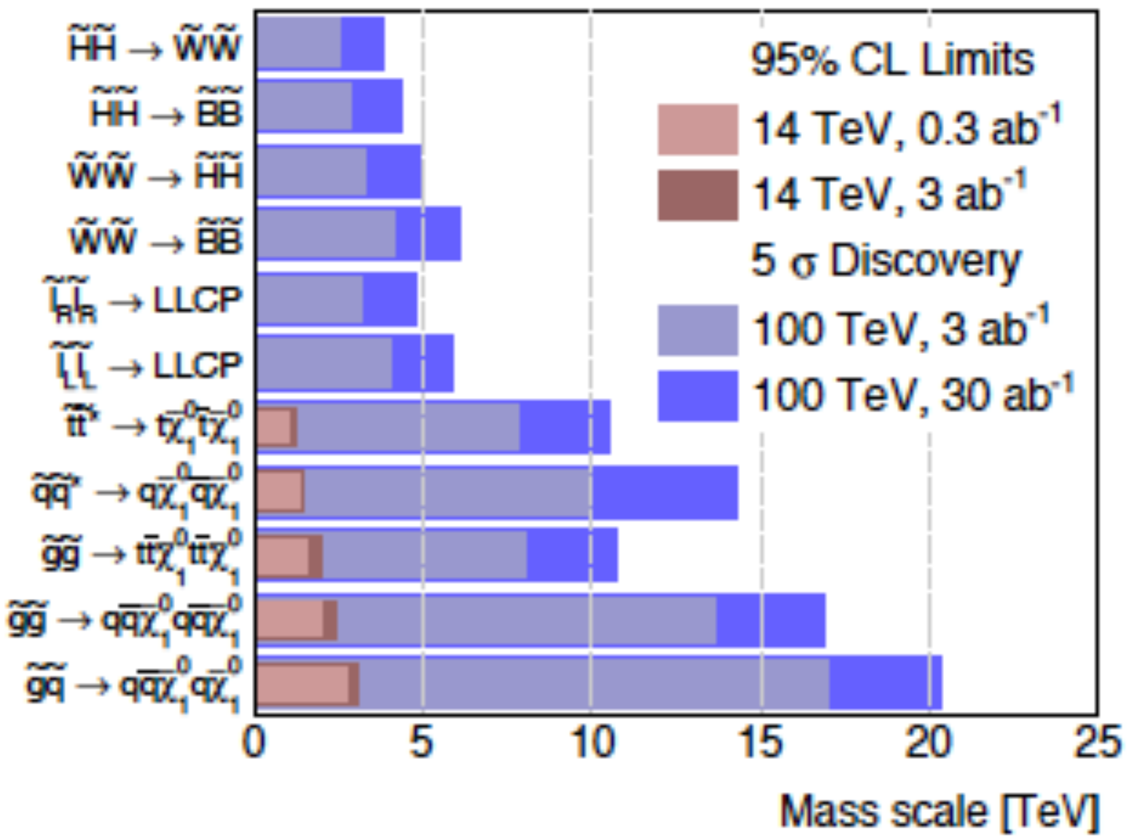
Constrain bg pt spectrum from $Z \rightarrow \nu\nu$ to the % level using NNLO QCD/EW* to relate to measured $Z \rightarrow ee$, W and γ spectra



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

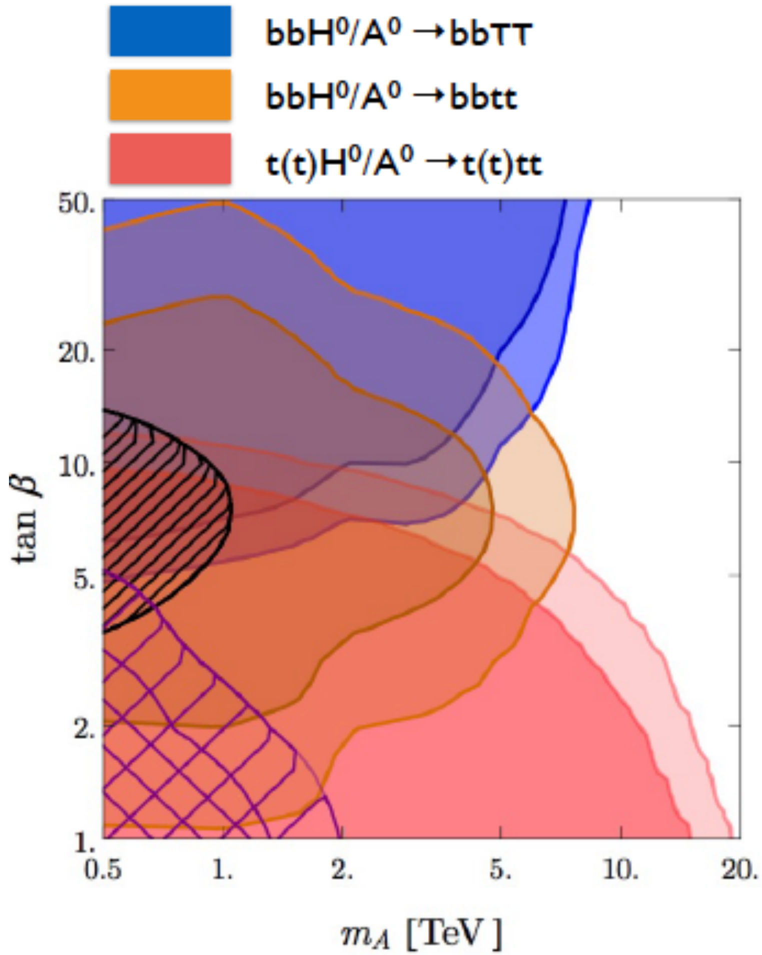
SM sensitivity with 1ab⁻¹, can reach few x 10⁻⁴ with 30ab⁻¹

SUSY reach

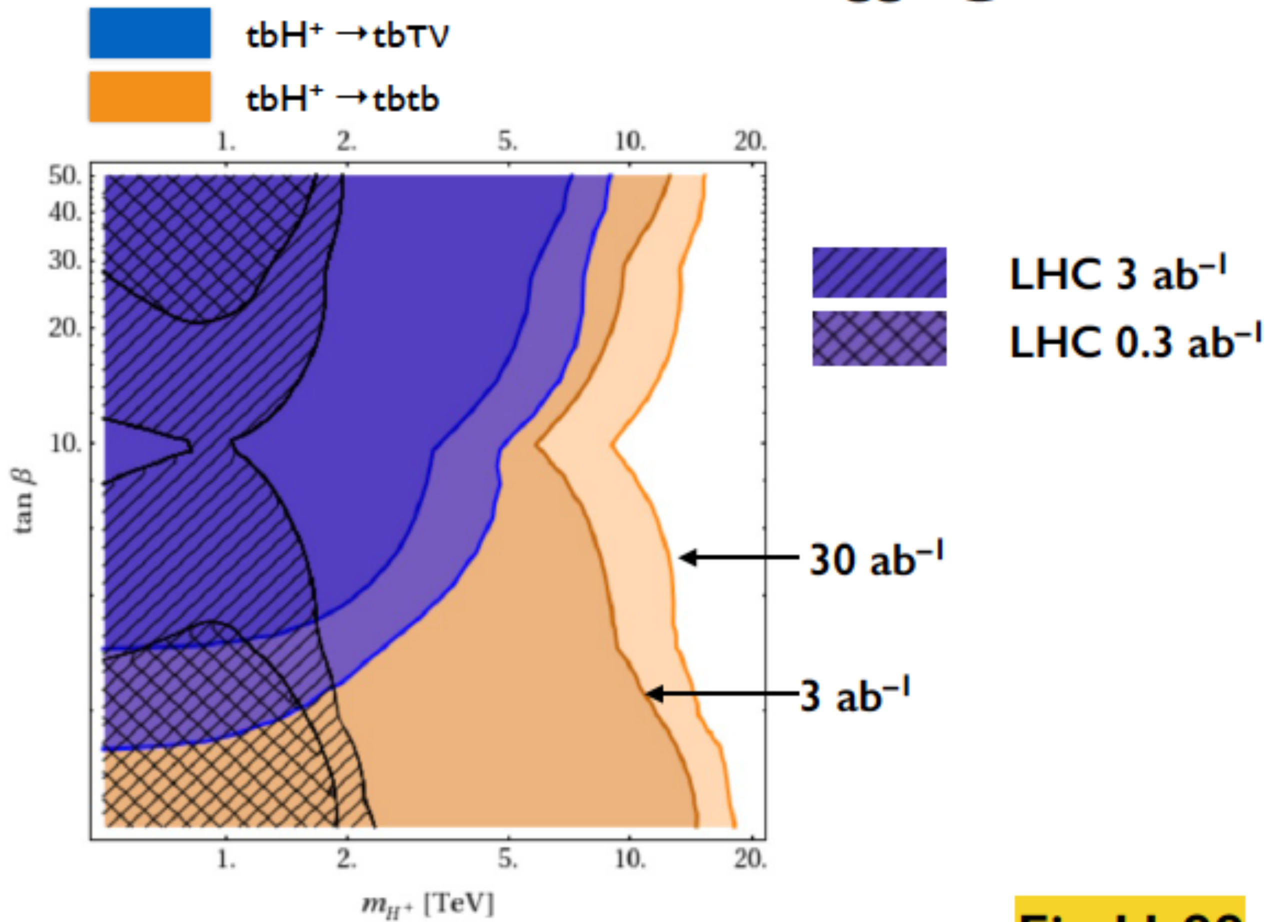


95% CL Limits
14 TeV, 0.3 ab⁻¹
14 TeV, 3 ab⁻¹
5 σ Discovery
100 TeV, 3 ab⁻¹
100 TeV, 30 ab⁻¹
→ LLCP
→ LLCP
0
5
10
15
20
25
Mass scale [TeV]

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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