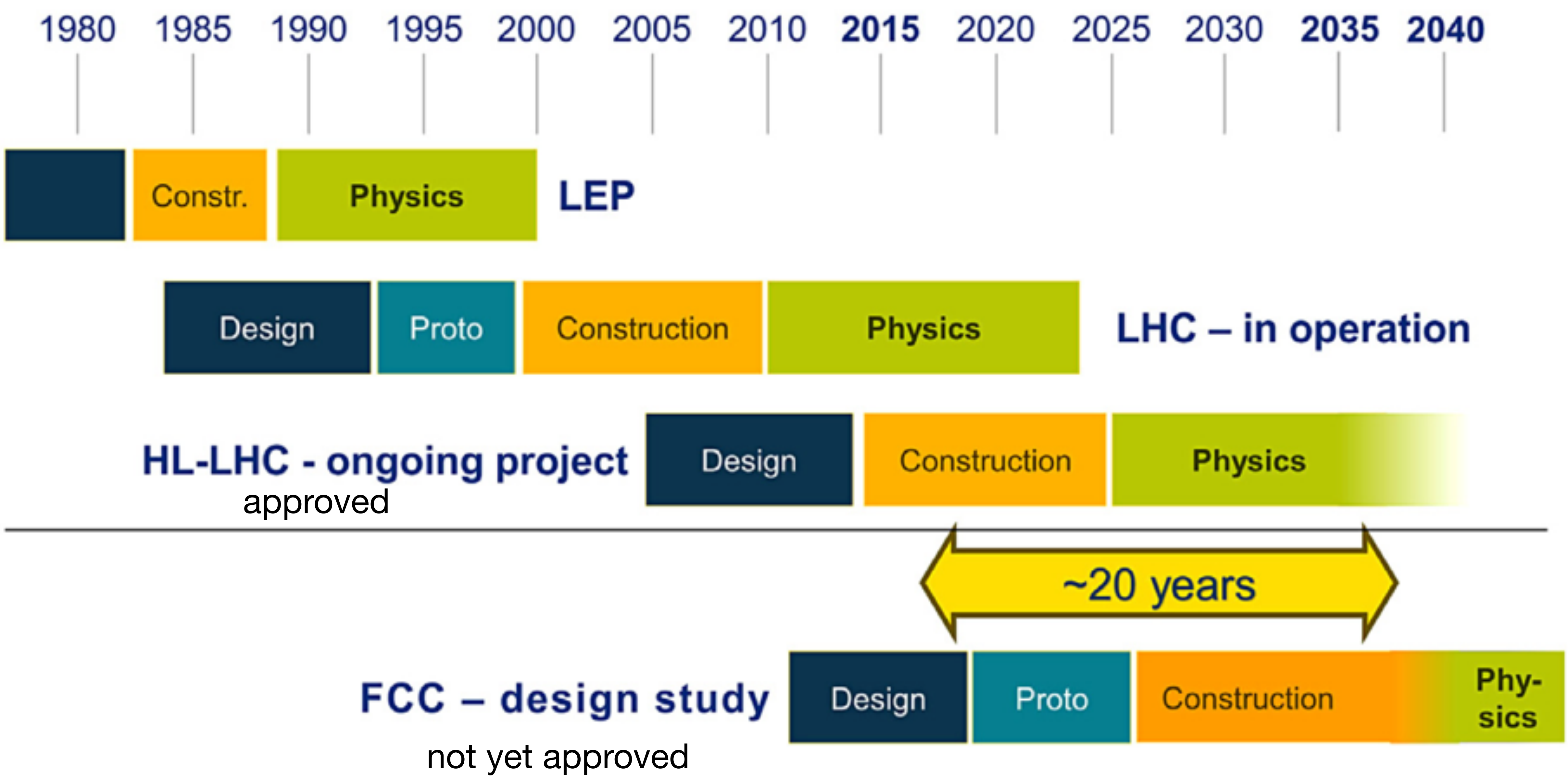
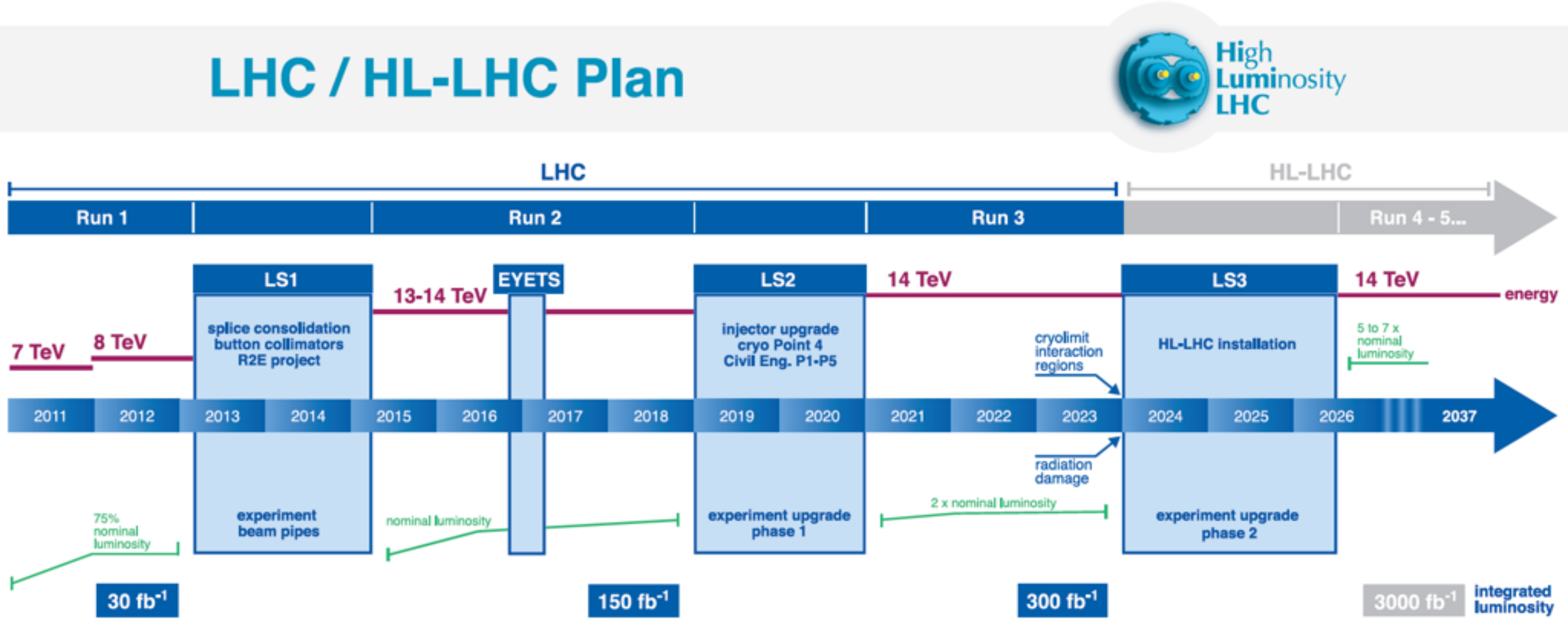
Lecture 4: future facilities at CERN

S.Xella

Future @ CERN


1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
Constr.
Physics
LEP
Design
Proto
Construction
Physics
LHC – in operation
HL-LHC - ongoing project
approved
Design
Construction
Physics
~20 years
FCC – design study
not yet approved
Design
Proto
Construction
Phy-
sics

HL-LHC


LHC / HL-LHC Plan
High Luminosity LHC
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
injector upgrade
cryo Point 4
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
radiation
damage
75%
nominal
luminosity
experiment
beam pipes
nominal luminosity
experiment upgrade
phase 1
2 x nominal luminosity
experiment upgrade
phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

HL-LHC

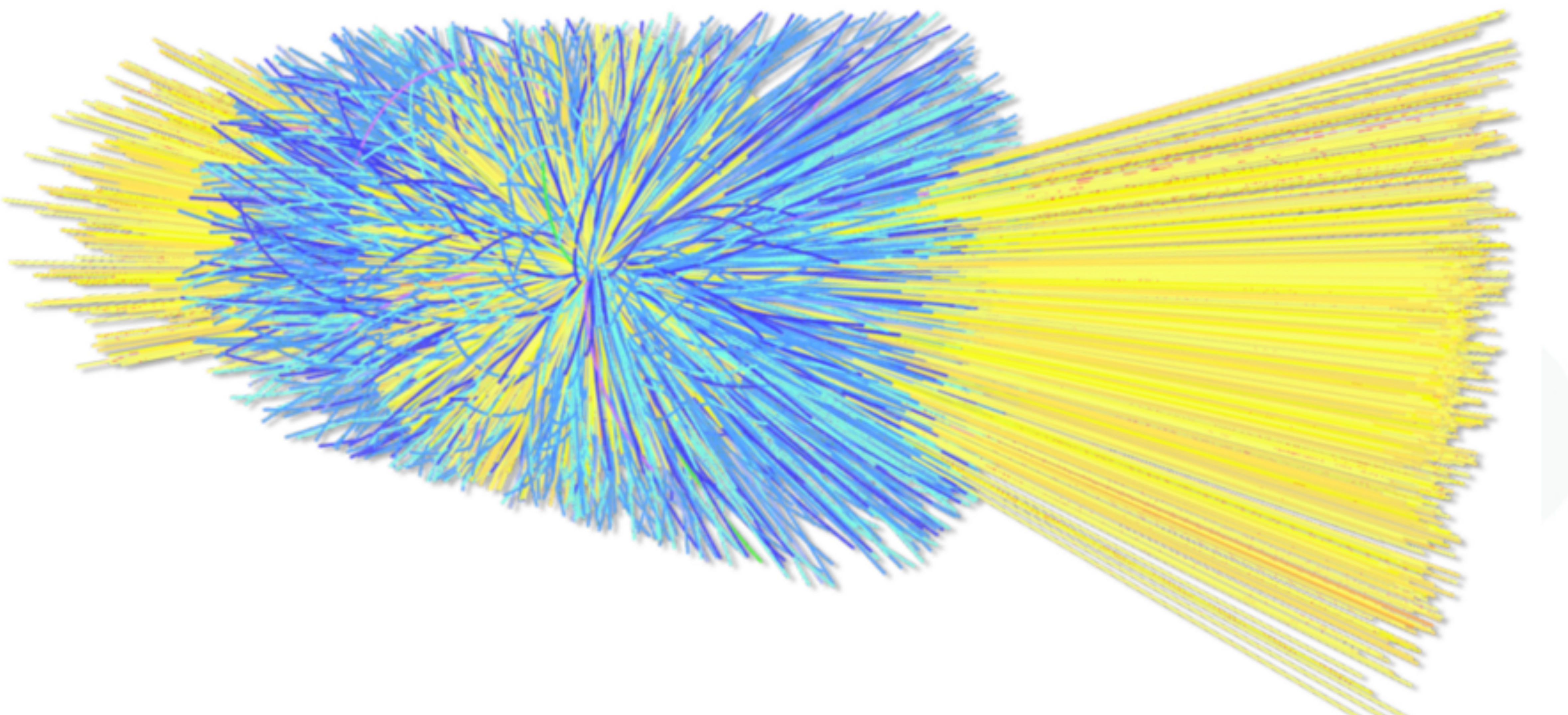
2012 ATLAS event, with 25 reconstructed vertices (μ=25)

Beam spot length: σ_z = ~5cm

At the HL-LHC (upgrade phase 2) we expect μ=200 within a similar space
=> 10 more dots between each dot in figure above

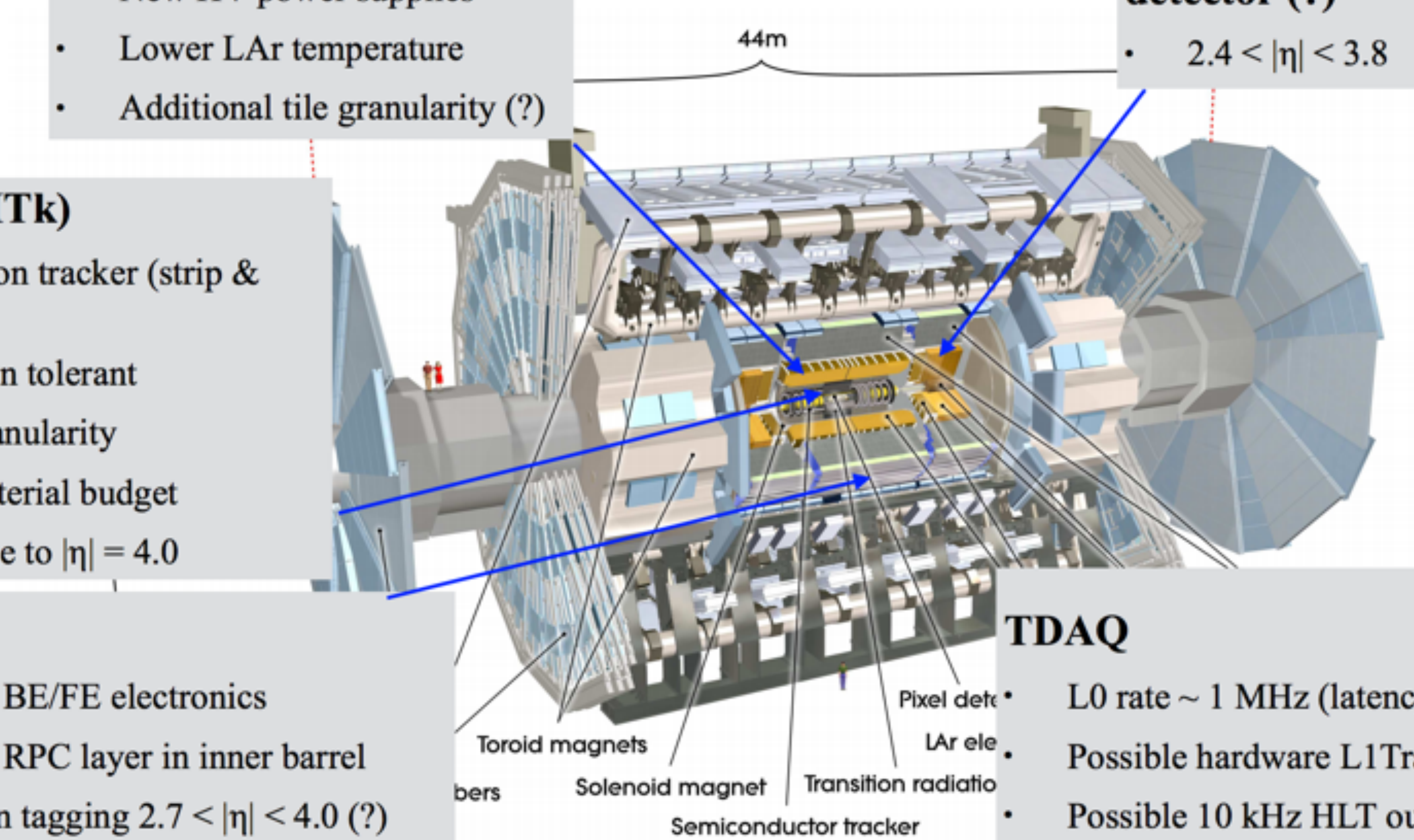
HL-LHC

Simulated HL-LHC event, with 200 reconstructed vertices (μ=200)



At the HL-LHC (upgrade phase 2) we expect μ=200 within a similar space
=> 10 more dots between each dot in figure above

ATLAS upgrades HL-LHC



Calorimeters

- New BE/FE electronics
- New HV power supplies
- Lower LAr temperature
- Additional tile granularity (?)

High granularity timing detector (?)

- $2.4 < |\eta| < 3.8$

Tracker (ITk)

- All silicon tracker (strip & pixel)
- Radiation tolerant
- High granularity
- Low material budget
- Coverage to $|\eta| = 4.0$

Muon

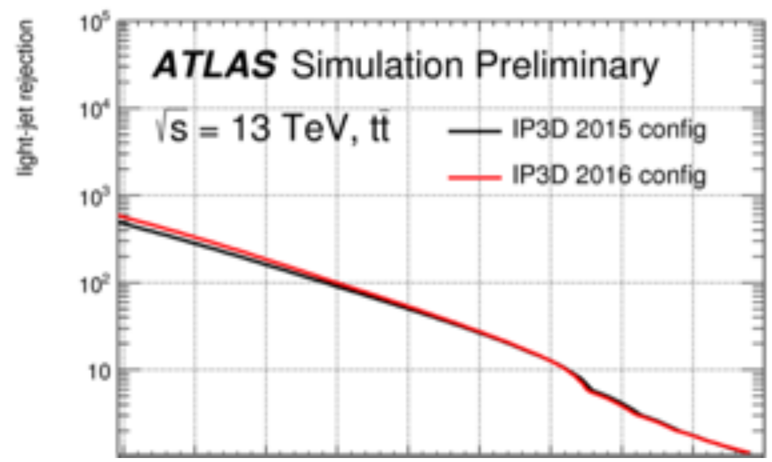
- New BE/FE electronics
- New RPC layer in inner barrel
- Muon tagging $2.7 < |\eta| < 4.0$ (?)

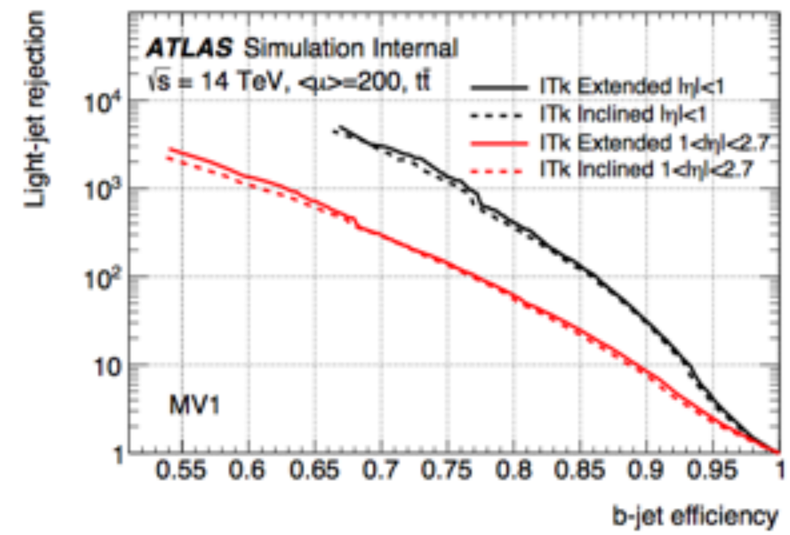
TDAQ

- L0 rate ~ 1 MHz (latency up to 10 μs)
- Possible hardware L1Track
- Possible 10 kHz HLT output

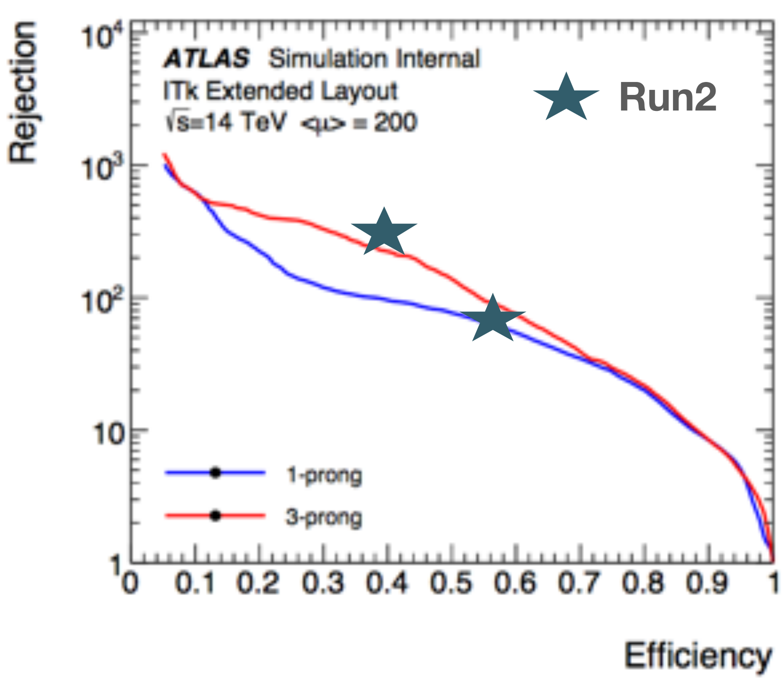
Performance remains similar to Run-2

b-tagging

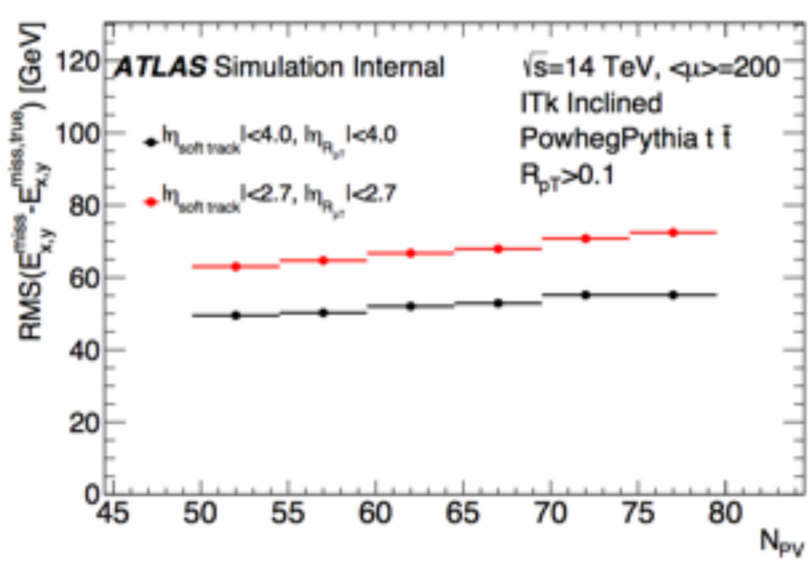




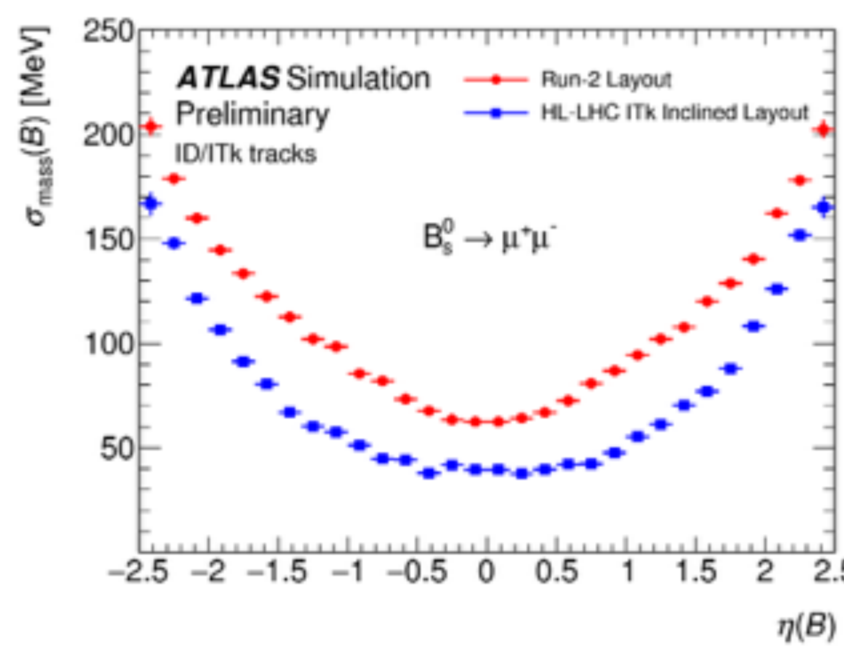
tau identification + reconstruction



ETmiss

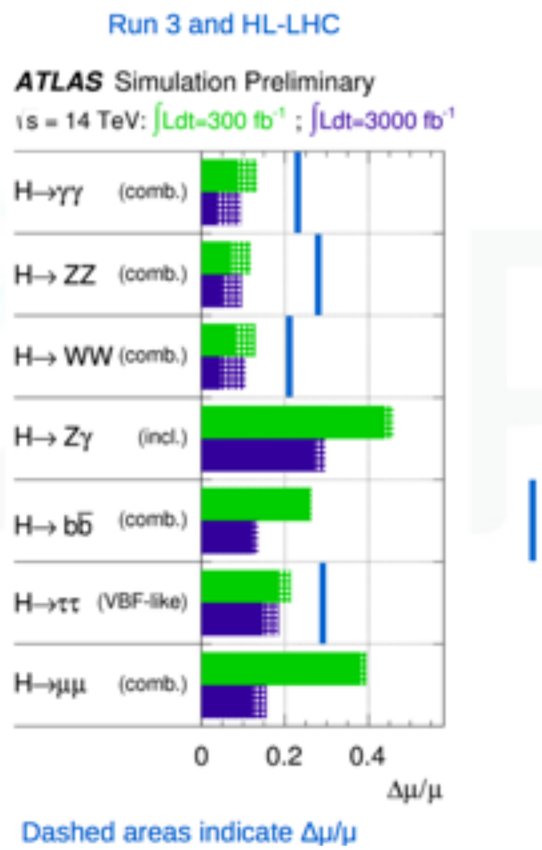


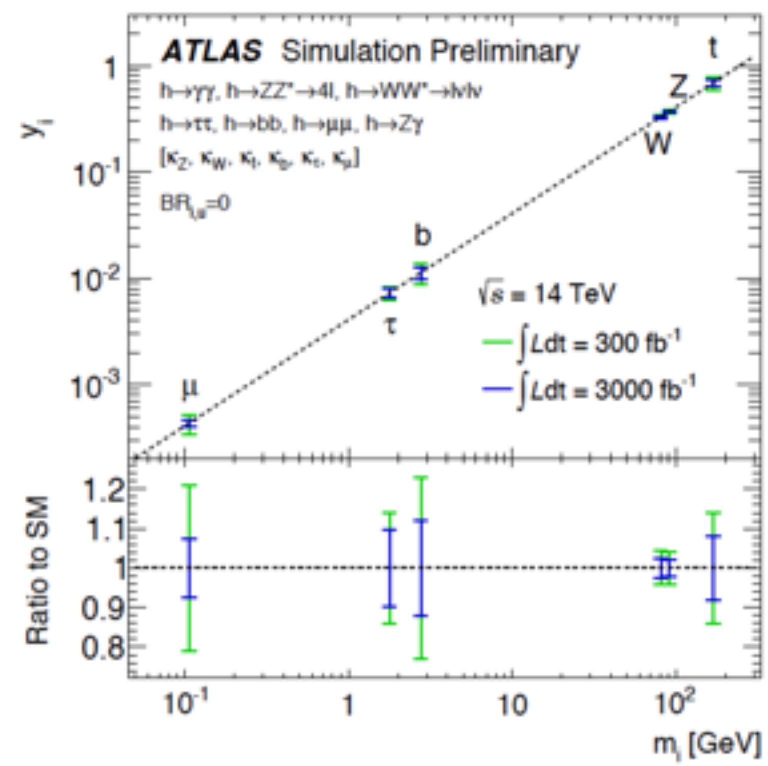
b-physics



Higgs physics

ATL-PHYS-PUB-2014-016





Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b}+b\bar{b}$	33%	40,000
$b\bar{b}+W^+W^-$	25%	31,000
$b\bar{b}+\tau^+\tau^-$	7.3%	8,900
$ZZ+b\bar{b}$	3.1%	3,800
$W^+W^-+\tau^+\tau^-$	2.7%	3,300
$ZZ+W^+W^-$	1.1%	1,300
$\gamma\gamma+b\bar{b}$	0.26%	320
$\gamma\gamma+\gamma\gamma$	0.0010%	1.2

<μ> = 140 and old performance functions 14

limit λ/λ_{SM}

-3.5 to 11 ATL-PHYS-PUB-2016-024

-4 to 12 ATL-PHYS-PUB-2015-046

-1 to 7 ATL-PHYS-PUB-2017-001

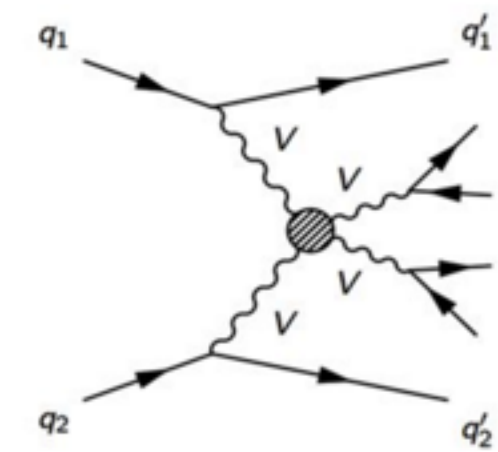
hopefully combining all channels we can measure lambda

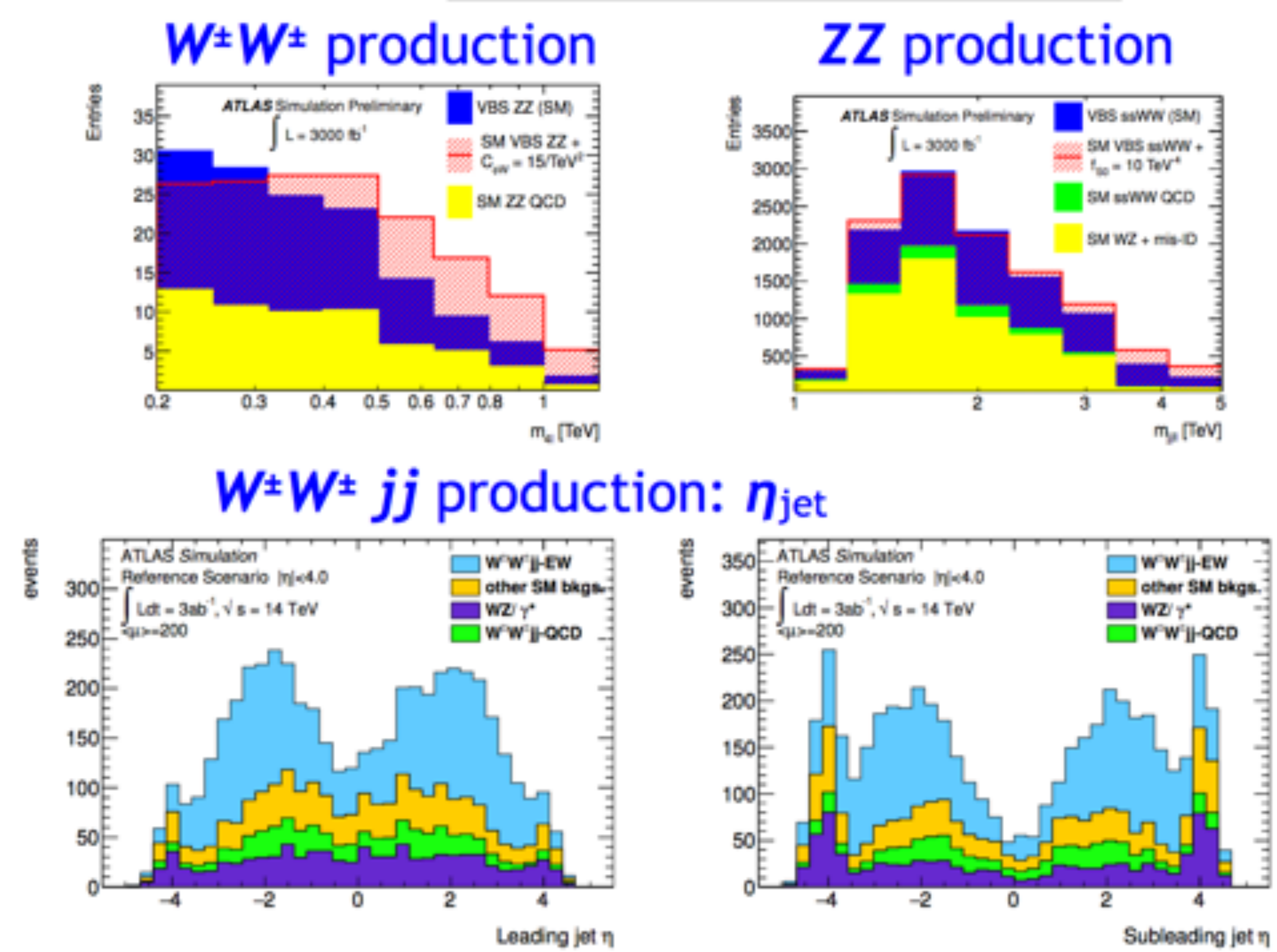
Vector-boson scattering

Sensitive test of the vector boson vertices in Standard Model

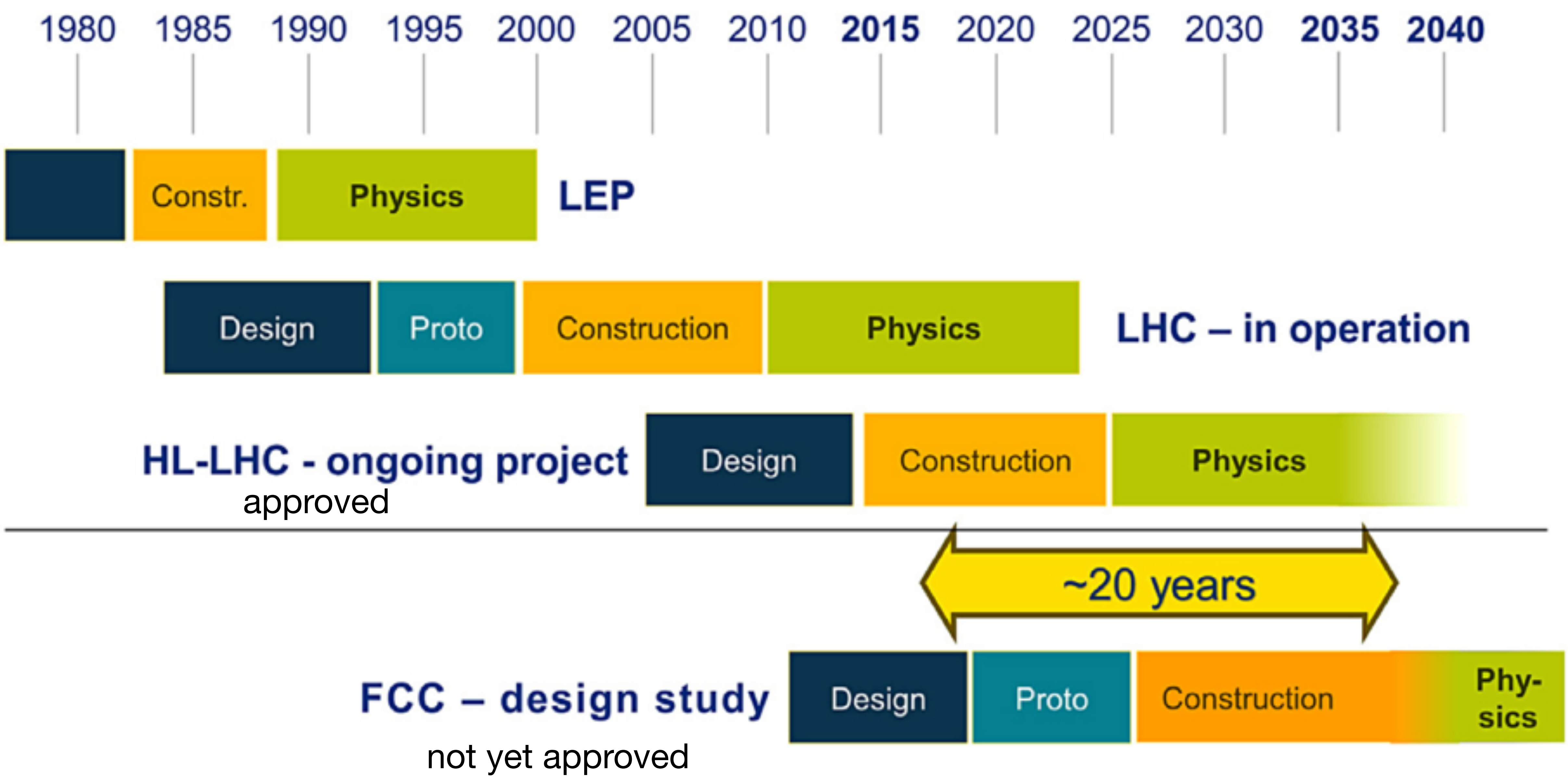
- clean observation of W±W±, ZZ and WZ scattering above backgrounds
- Sensitive to dimension-8 operators at scales of ~1 TeV (eg arXiv:1802.02366)

significance of EWK W±W±jj production ~11σ
➡cross section precision $\Delta\sigma/\sigma$ = 5.9%





Future @ CERN



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approved
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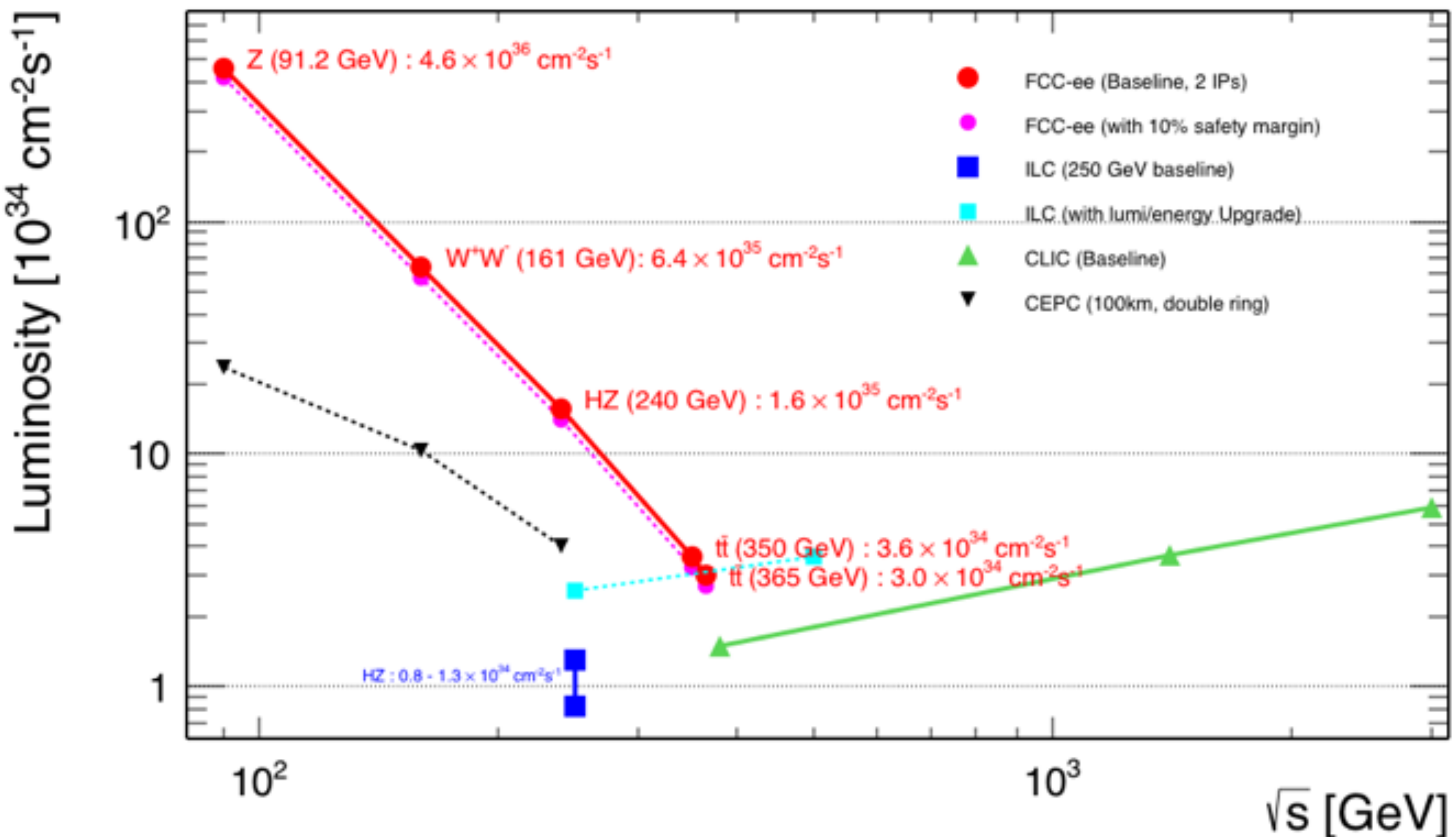
Construction
Physics
~20 years
FCC – design study
not yet approved
Design
Proto
Construction
Phy-
sics

FCC

https://fcc.web.cern.ch/

FCC-ee will happen first



$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (VV → H)
$\mathscr{L}$/IP (cm^{-2} s^{-1})	$2.2{\cdot}10^{36}$	$1.1{\cdot}10^{36}$	$3.8{\cdot}10^{35}$	$8.7{\cdot}10^{34}$	$2.1{\cdot}10^{34}$	$2.1{\cdot}10^{34}$
$\mathscr{L}_{\rm int}$ (ab^{-1}/yr/IP)	22	11	3.8	0.87	0.21	0.21
Events/year (4 IPs)	$3.7{\cdot}10^{12}$	$1.3{\cdot}10^{4}$	$6.1{\cdot}10^{7}$	$7.0{\cdot}10^{5}$	$4.2{\cdot}10^{5}$	$2.5{\cdot}10^{4}$
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

Table 1: *Target luminosities, events/year, and years needed to complete the W, Z, H and top programs at FCC-ee.* [$\mathscr{L} = 10^{35}$ cm^{-2} s^{-1} *corresponds to* $\mathscr{L}_{\rm int}$ = 1 ab^{-1}/yr *for* 1 yr = 10^7 s].

FCC-ee

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} cm^{-2}s^{-1}]	230	32	8	1.5
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS ("weak") [min]	> 200	20	20	25

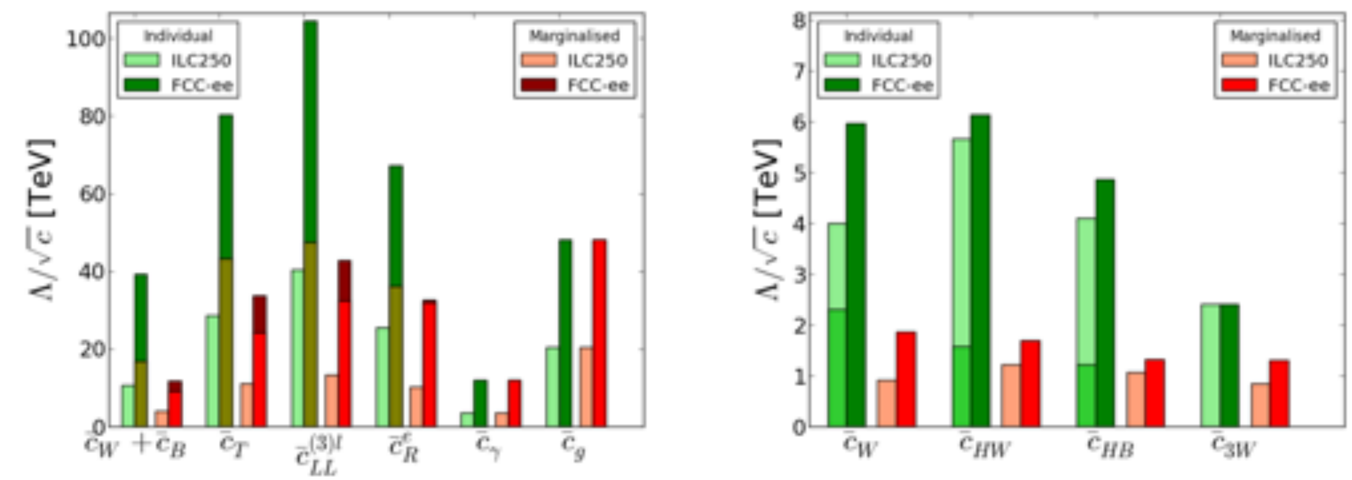
FCC-ee physics

arXiv:1601.06640

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corrs.
Γ_Z (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corrs.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corrs.
R_b	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to b\bar{b}$
$A_{FB}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$e^+e^- \to \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	–
$\alpha_s(m_Z)$	$R_\ell, \sigma_{had}, \Gamma_Z$	0.1196 ± 0.0030	0.00001	0.00015	New physics
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ around Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_W (MeV)	WW threshold scan	80385 ± 15	0.3	< 1	QED corr.
$\alpha_s(m_W)$	B_{had}^W	$B_{had}^W = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_t (MeV)	threshold scan	173200 ± 900	10	10	QCD
$F_{1V,2V,1A}^{\gamma t, Zt}$	$d\sigma^{t\bar{t}}/dx\,d\cos(\theta)$	4%–20% (LHC-14 TeV)	(0.1–2.2)%	(0.01–100)%	–

Table 2: *Examples of achievable precisions in representative Z, W and top measurements.*

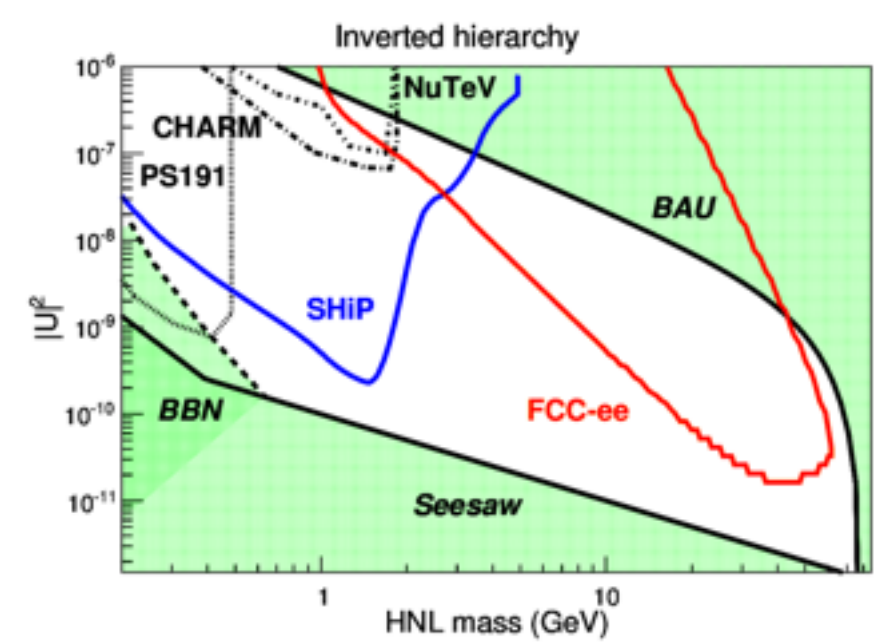
arXiv:1510.04561



Standard Model effective field theory (SM EFT)
dim-6 operators

Observable	240 GeV	240+350 GeV
g_{HZZ}	0.16%	0.15%
g_{HWW}	0.85%	0.19%
g_{Hbb}	0.88%	0.42%
g_{Hcc}	1.0%	0.71%
g_{Hgg}	1.1%	0.80%
$g_{H\tau\tau}$	0.94%	0.54%
$g_{H\mu\mu}$	6.4%	6.2%
$g_{H\gamma\gamma}$	1.7%	1.5%
Γ_{tot}	2.4%	1.2%
BR_{inv}	0.25%	0.2%
BR_{exo}	0.48%	0.45%

\+ measure g_{Hee} in the ee->H operation mode
\+ measure $g_{Hu,d,s}$ via H-> ρ,ω,ϕ + γ



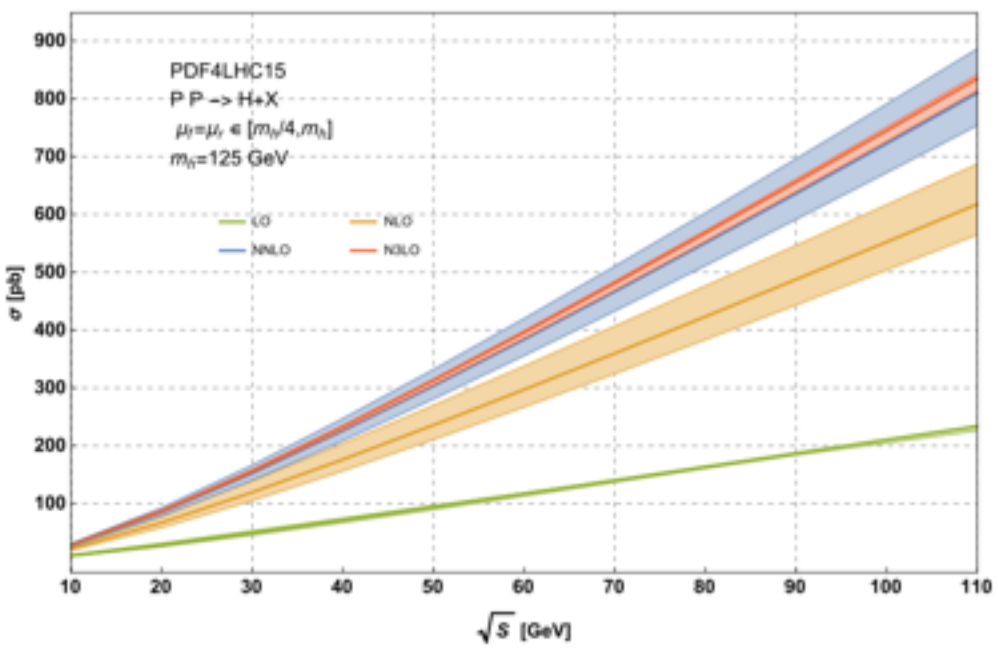
right-handed N in neutrino MSM

FCC-hh

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference C [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3
Physics performance and beam parameters				
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Total / inelastic cross section σ_{proton} [mbarn]	111 / 85		129 / 93	153 / 108
Luminous region RMS length [cm]				5.7 (5.3)
Beam lifetime due to burn off [h]	45	15.4	5.7	19.1 (15.9)
Beam parameters				
Number of bunches n at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population N[10^{11}] - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2
Nominal transverse normalized emittance [μm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44

Physics at the FCC-hh, a 100 TeV pp collider, CERN-2017-003-M

FCC-physics

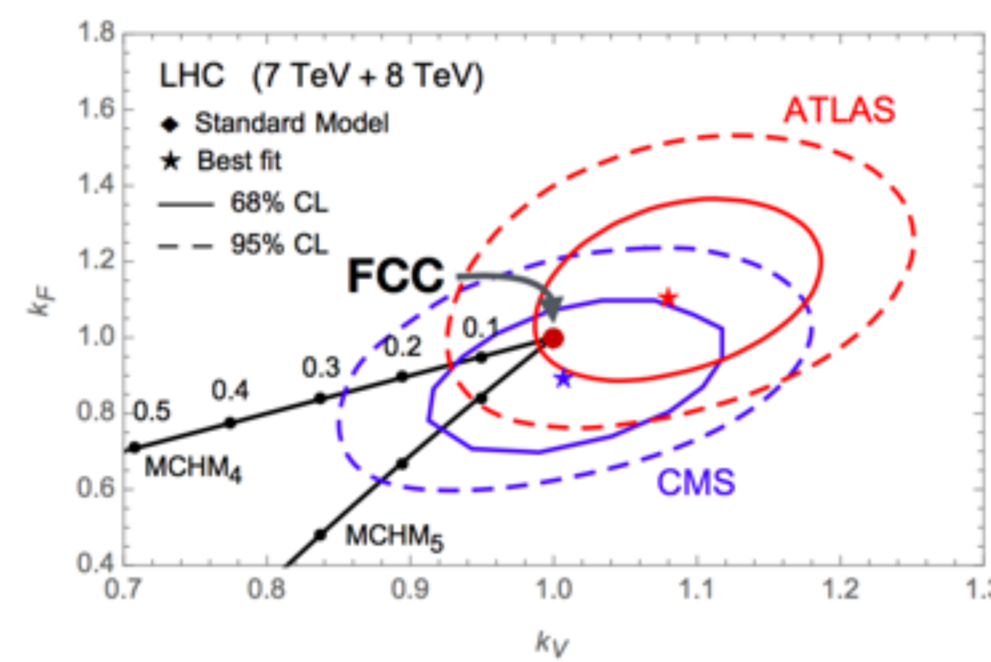


	N_{100}	N_{100}/N_8	N_{100}/N_{14} (HL-LHC)
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

30 ab-1

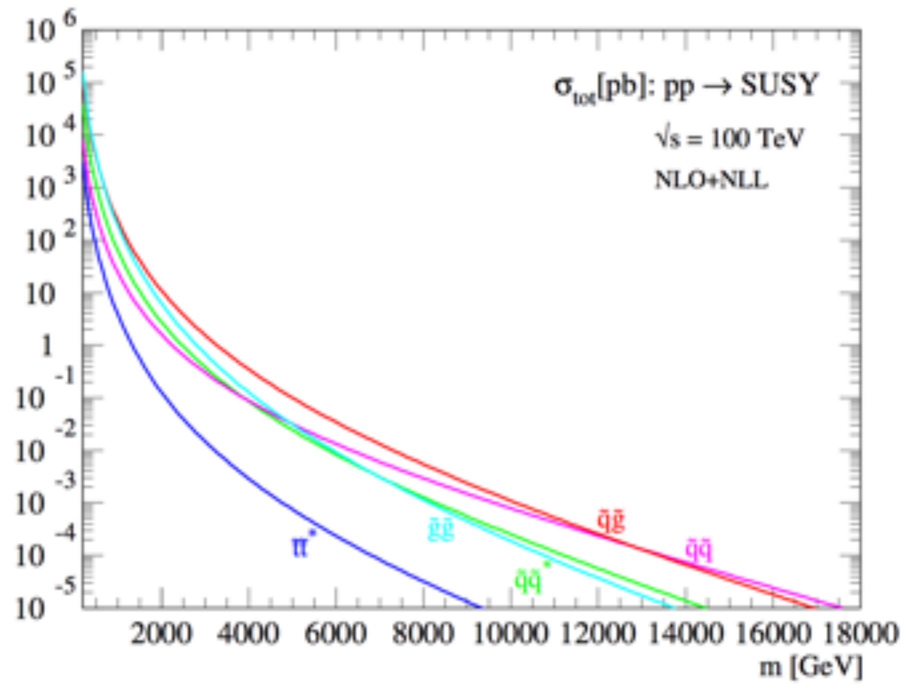
can access also H^4 vertex

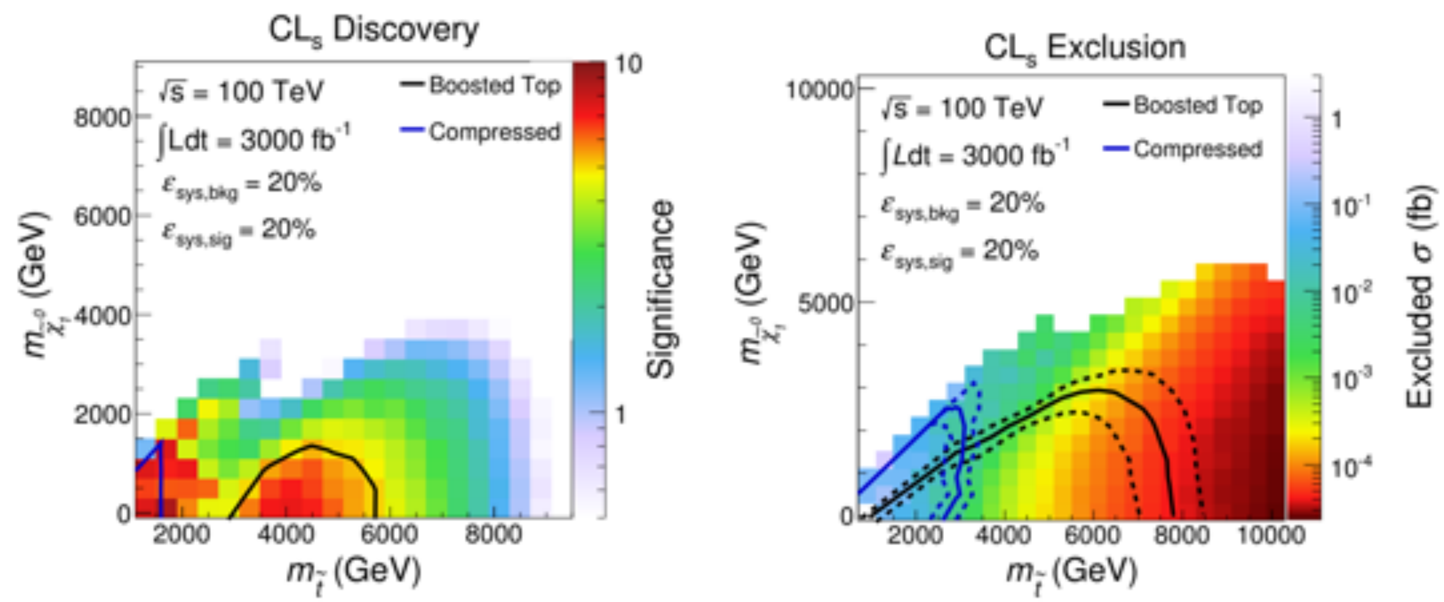


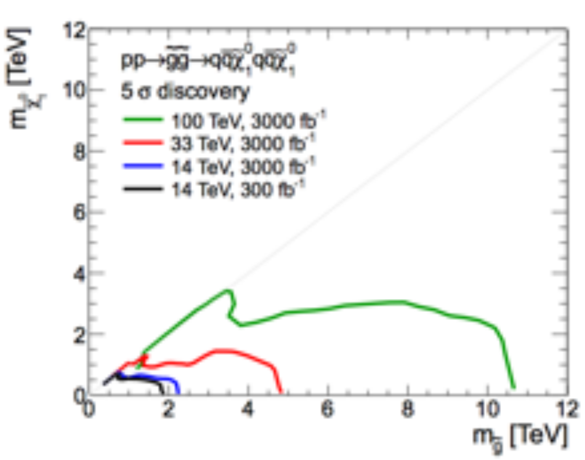
Physics at the FCC-hh, a 100 TeV pp collider, CERN-2017-003-M

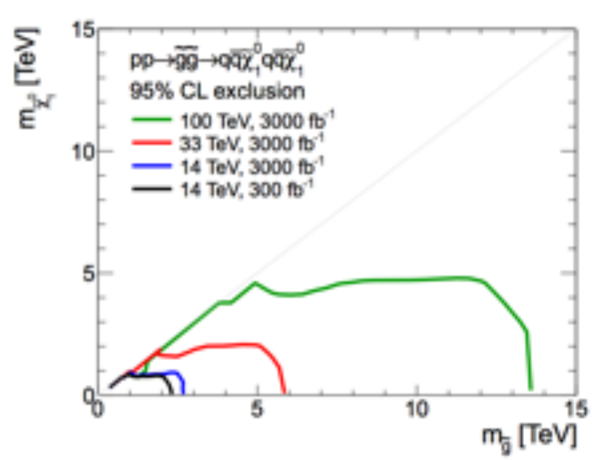
arXiv: 1810.11263

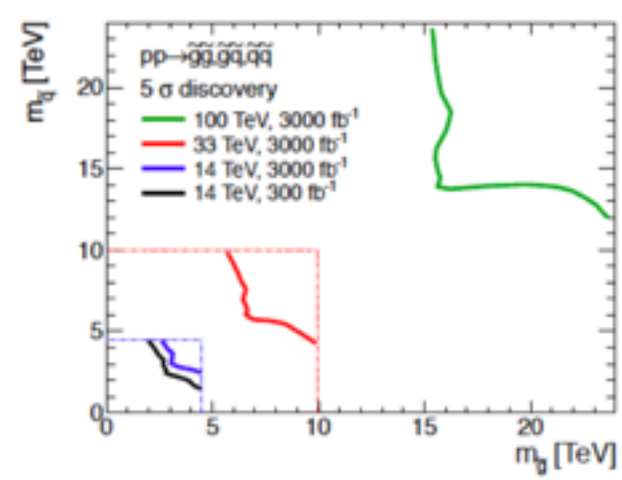
FCC-physics

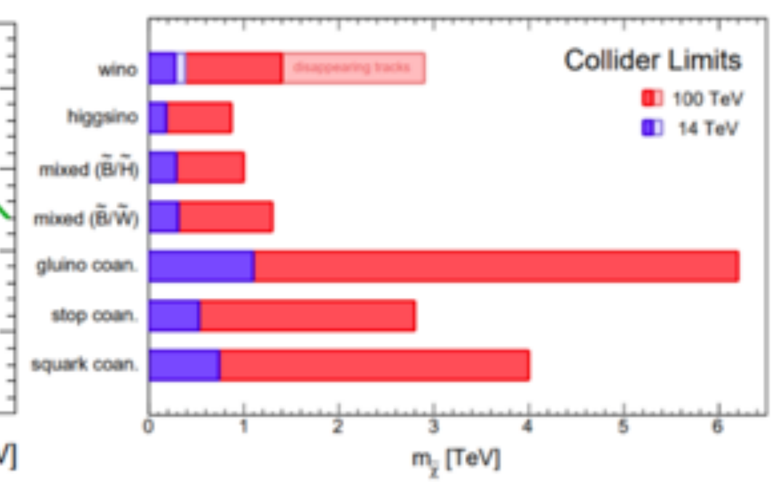








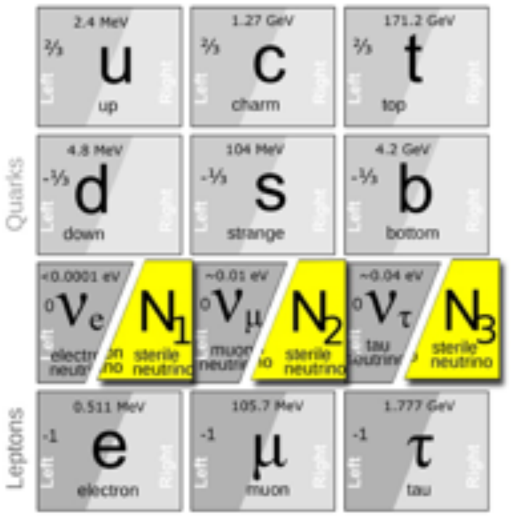


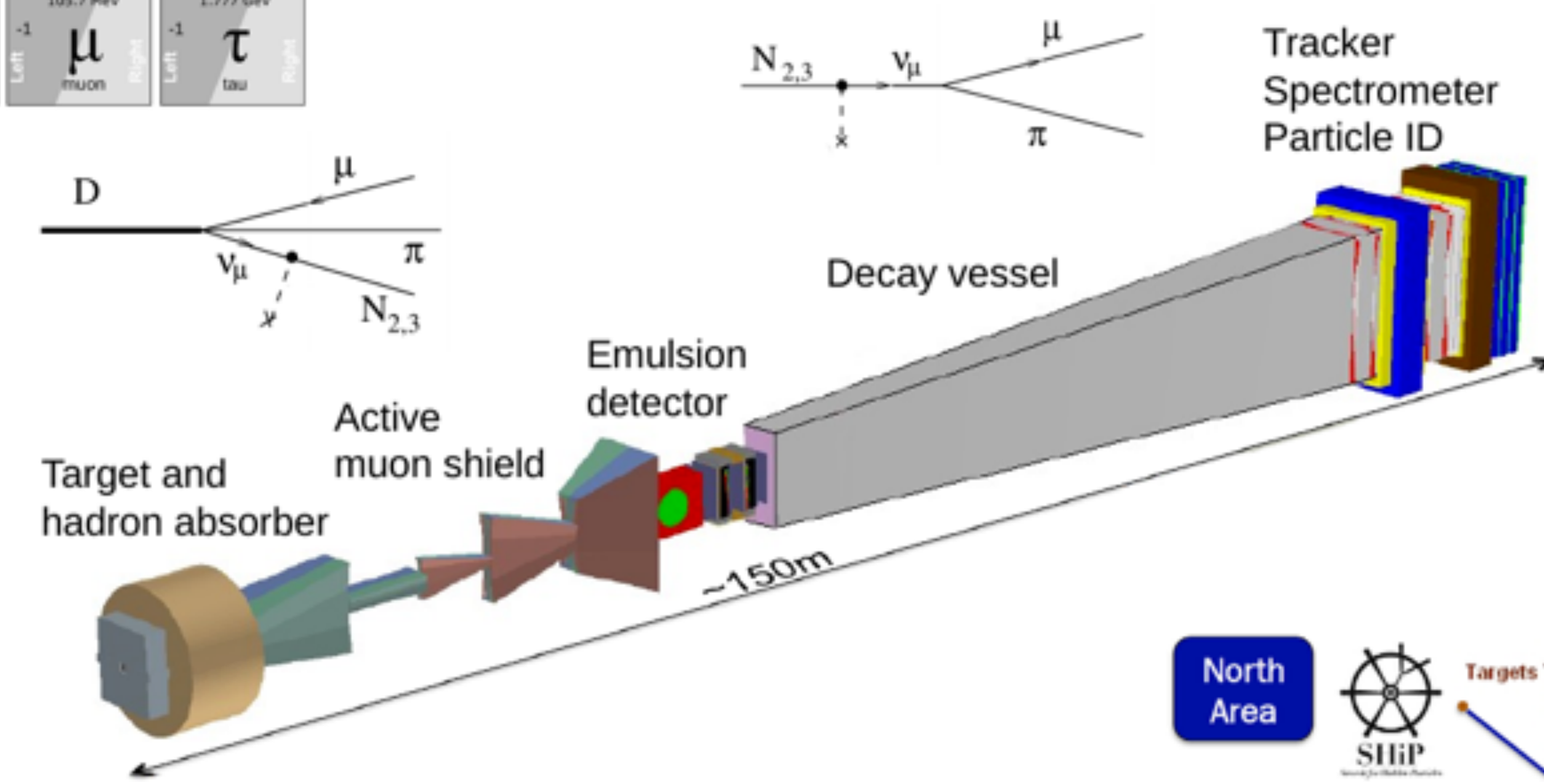


Other possible projects @CERN

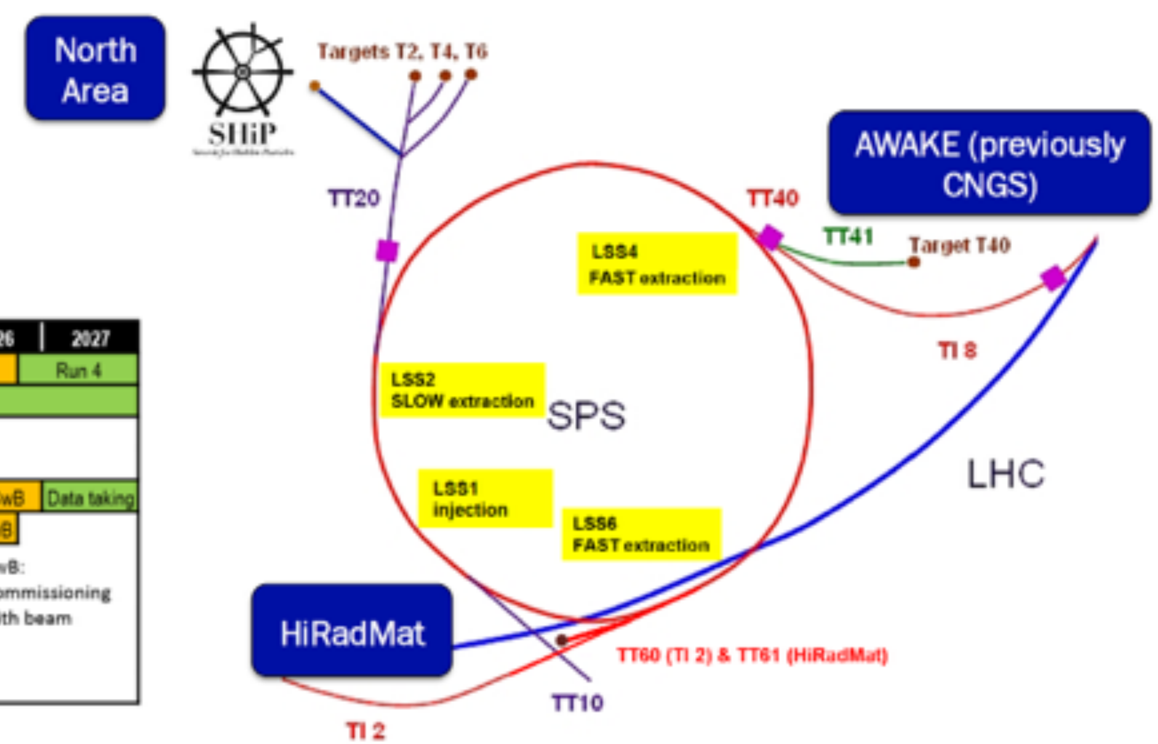
- SHiP
- Mathusla

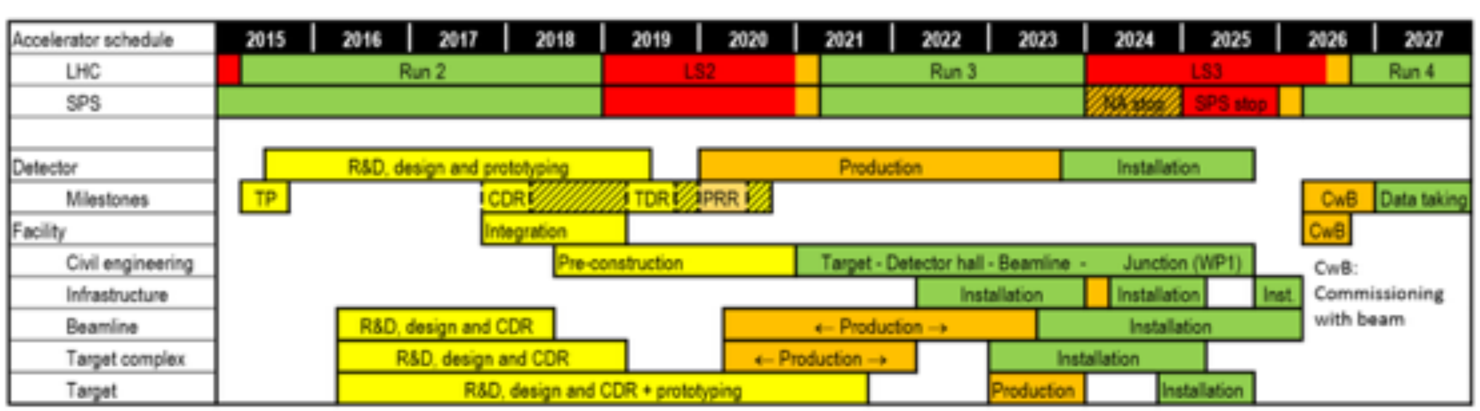
SHiP





not approved yet
cost ~ 100 MCHF





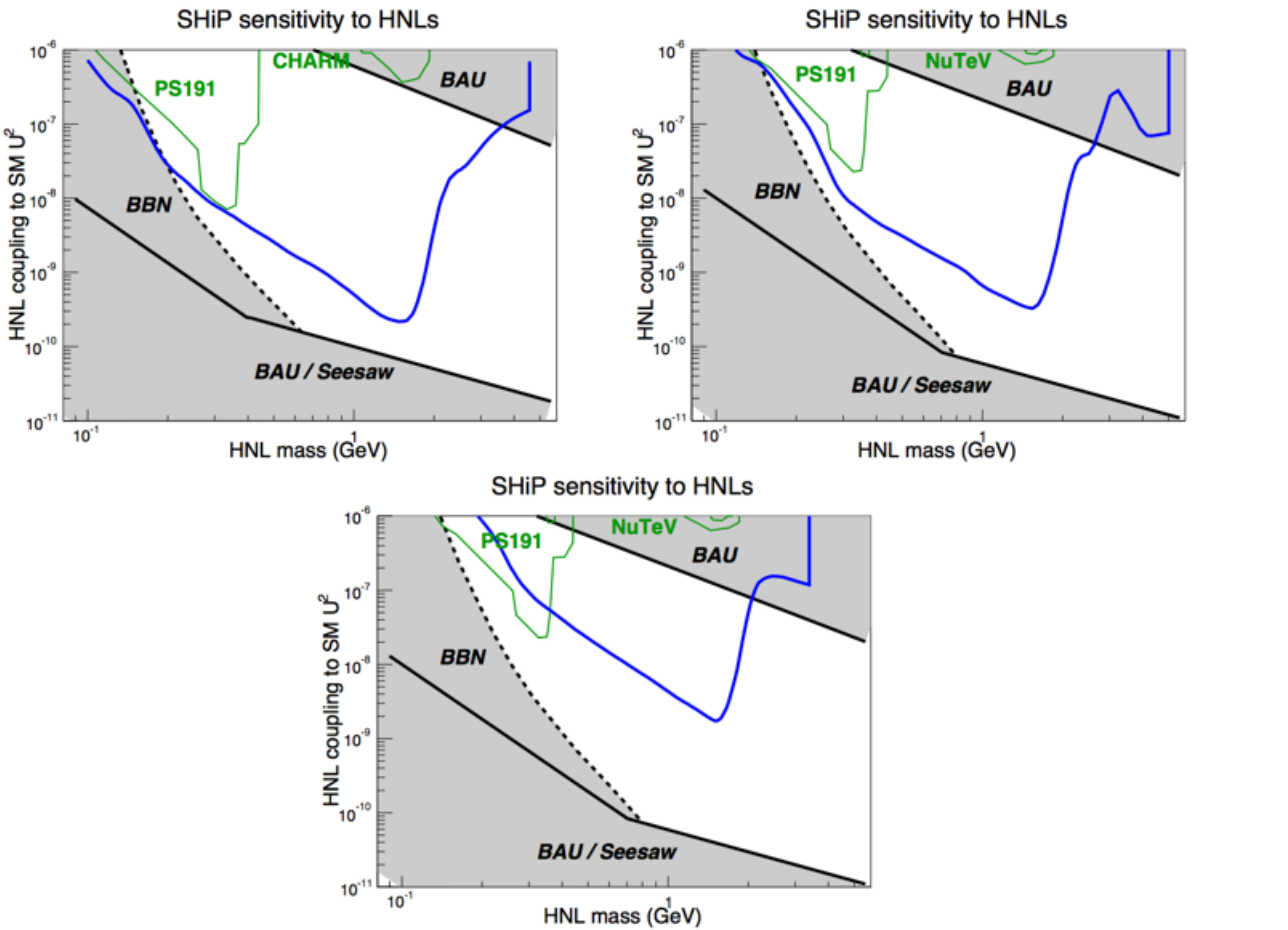


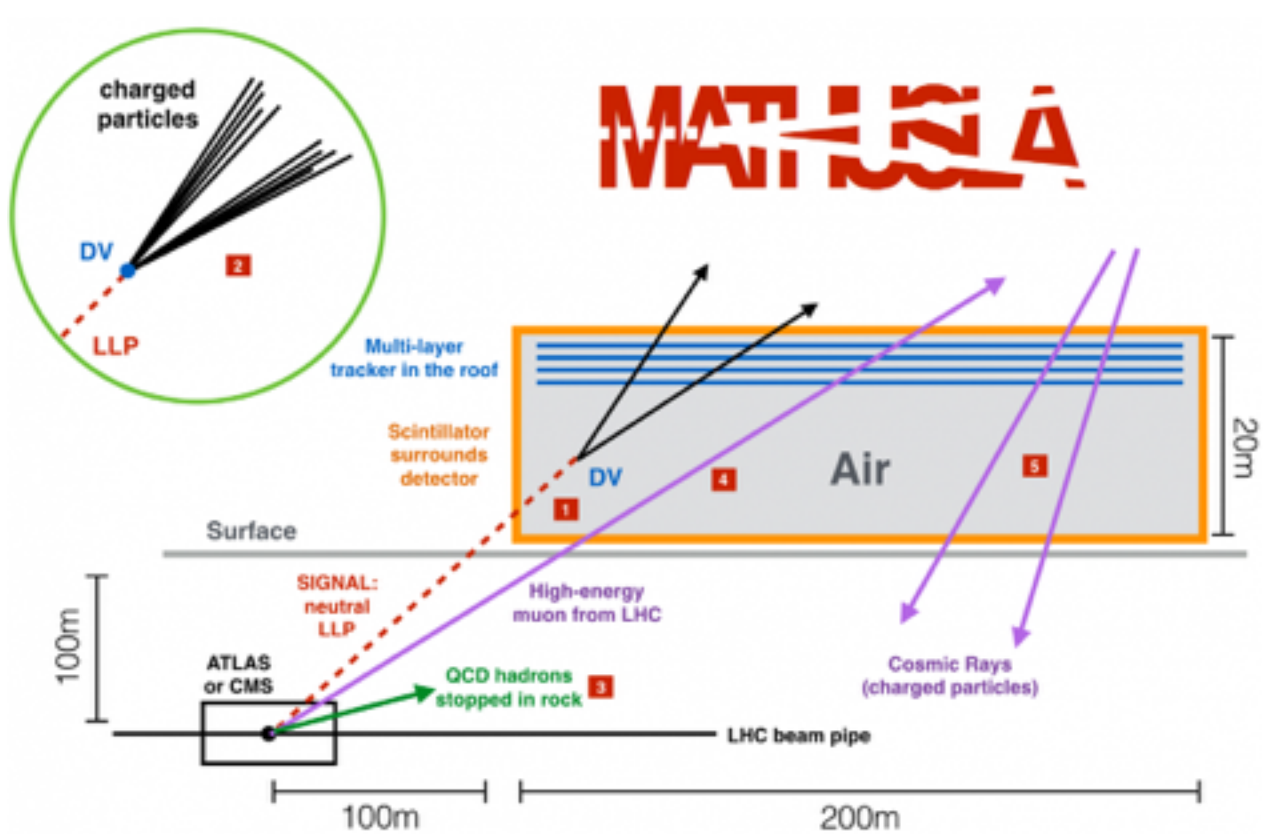
Figure 5.19: Sensitivity regions in the parameter space of the νMSM, for three scenarios where U_e^2, U_μ^2 and U_τ^2 dominate respectively (models I, II and III of Ref. [187]).

arXiv: 1811.00927

Mathusla

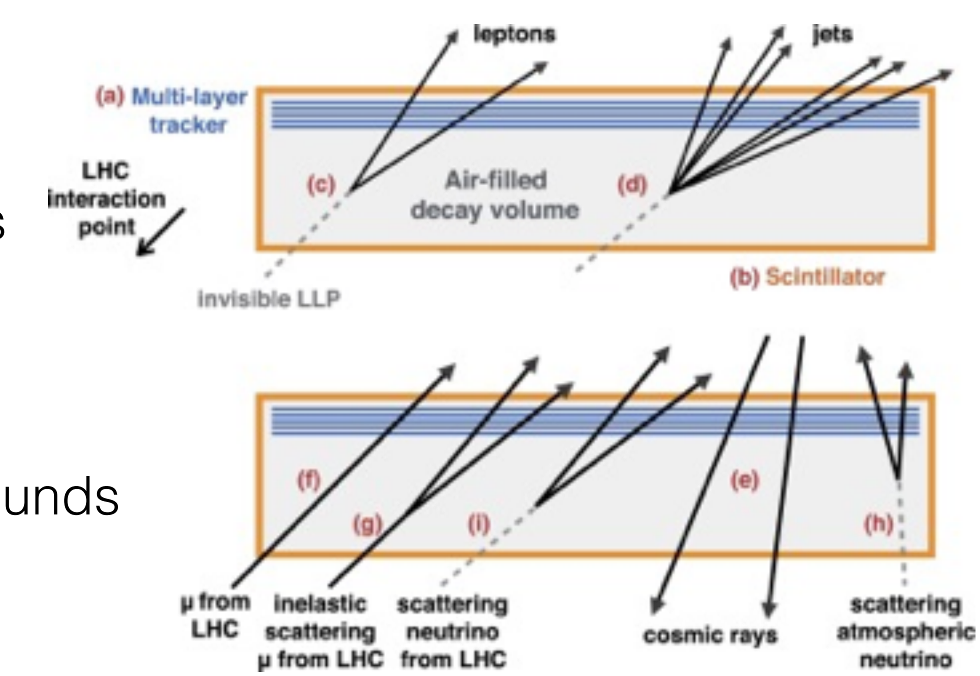
not approved yet

- MATHUSLA (Massive Timing Hodoscope for Ultra Stable Neutral Particles)
- planned to be a surface detector placed 100 metres above either ATLAS or CMS.
- It would be an enormous (200 × 200 × 20 m) box, mostly empty except for the very sensitive equipment used to detect LLPs produced in LHC collisions.



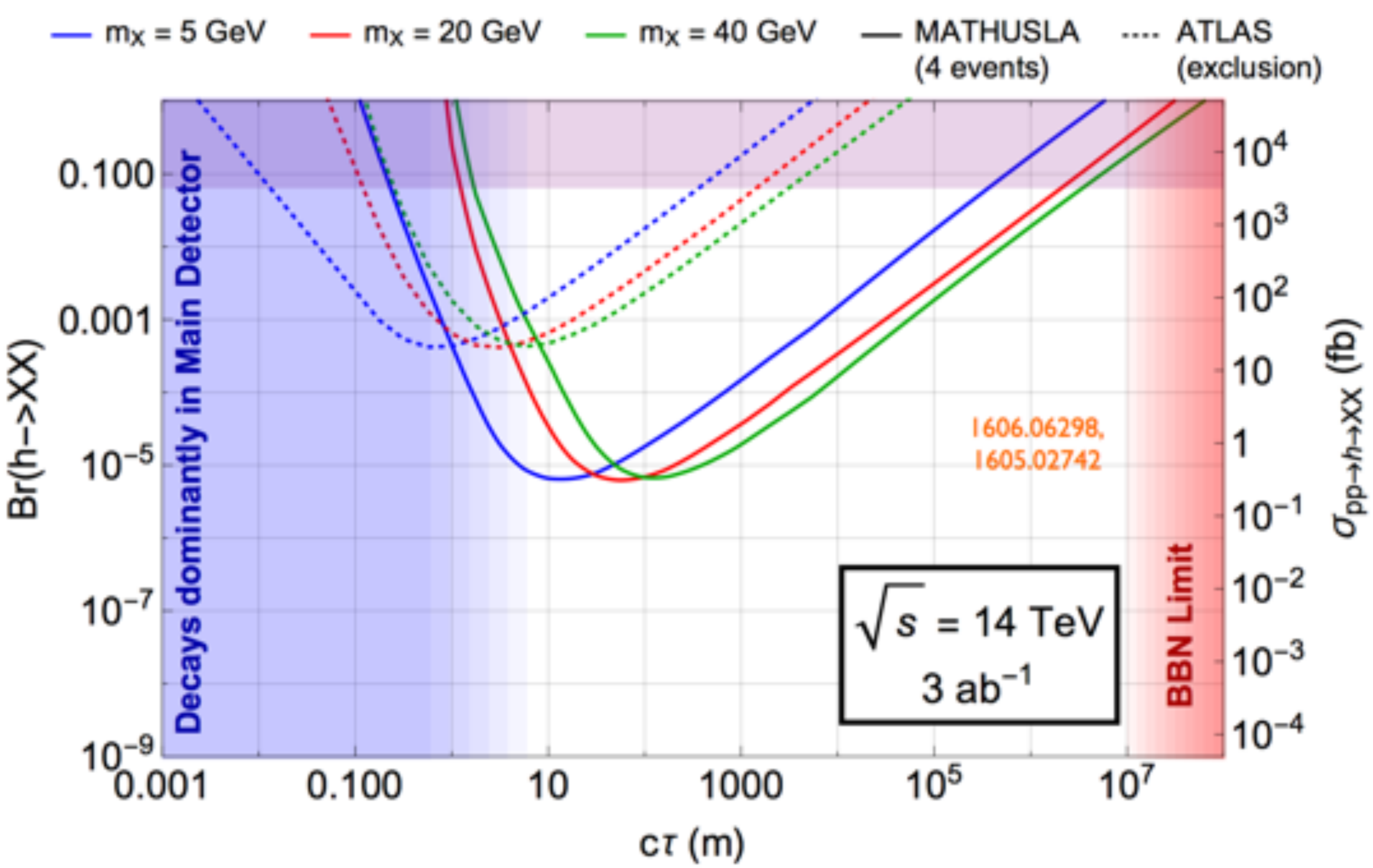
signals

backgrounds

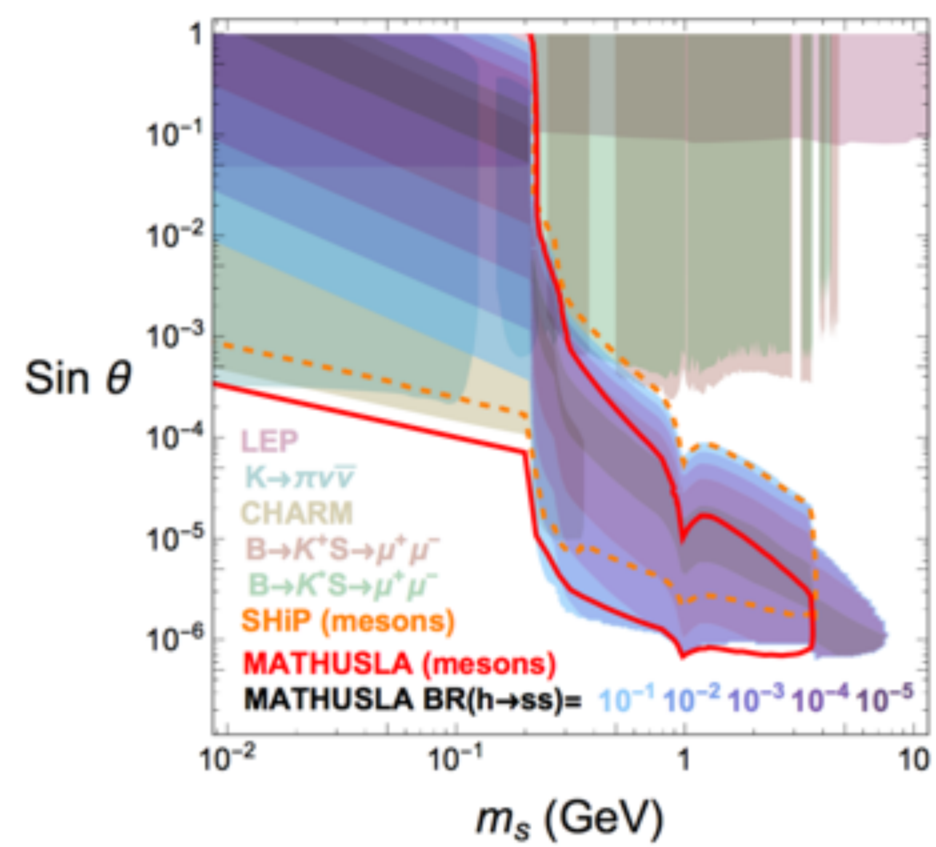


Potential

exotic Higgs decays



scalar portal



.. and more (extend SUSY coverage, etc…)