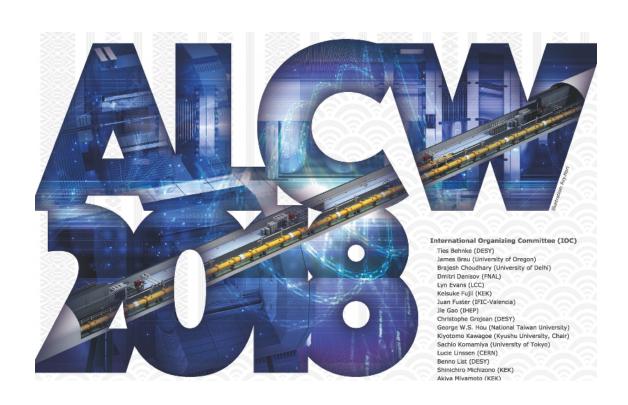
Particle Physics Programme in Europe

Eckhard Elsen

Director Research and Computing





There must be more than the Standard Model...

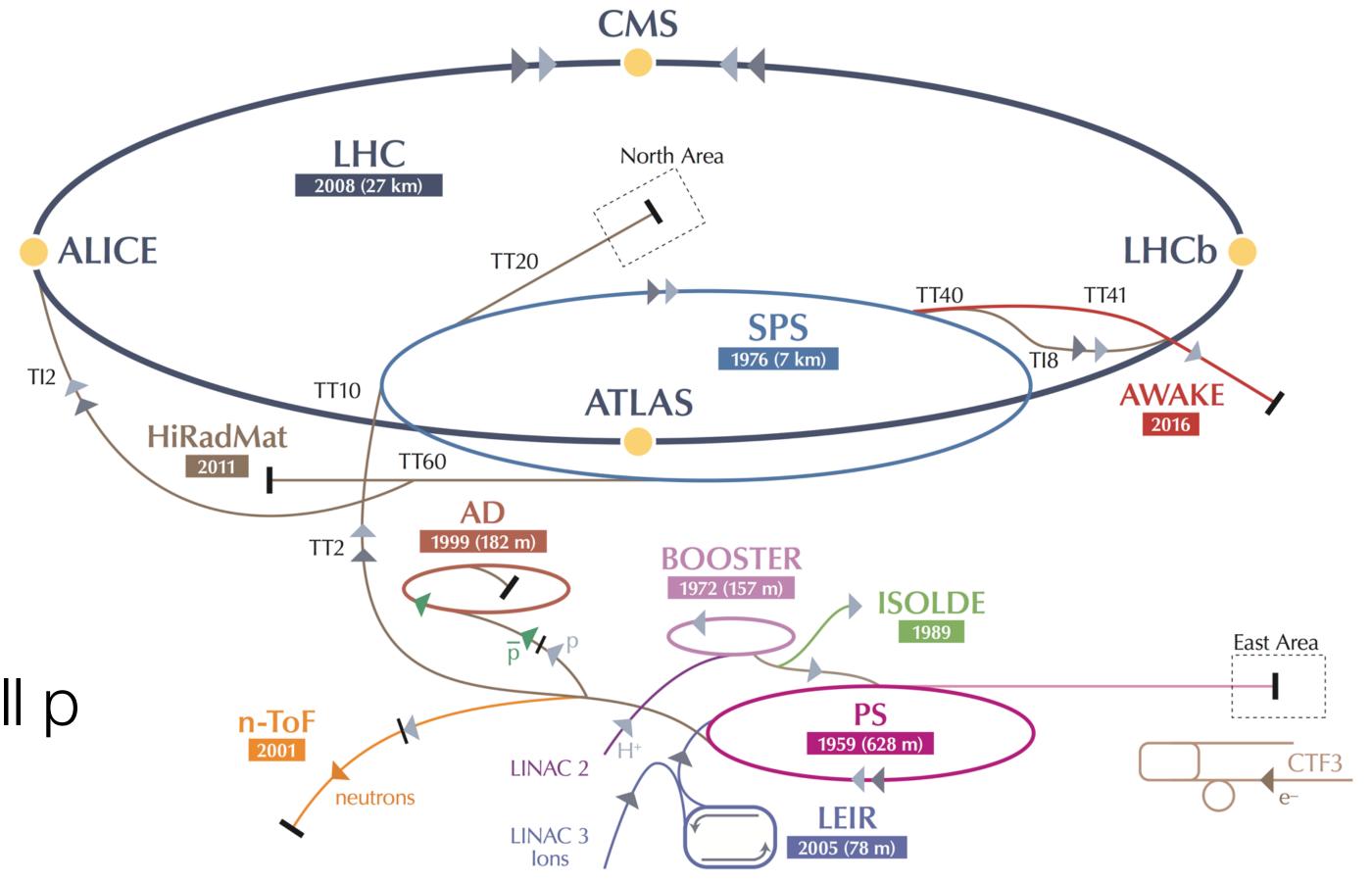


LHC Physics Programme in a broader context

LHC and its injector chain

- · LHC
 - ongoing Run 2 @ 13 TeV
- Injectors supporting
 - Fixed target programme
 - ISOLDE (isotopes)
 - n-ToF

75% of all p



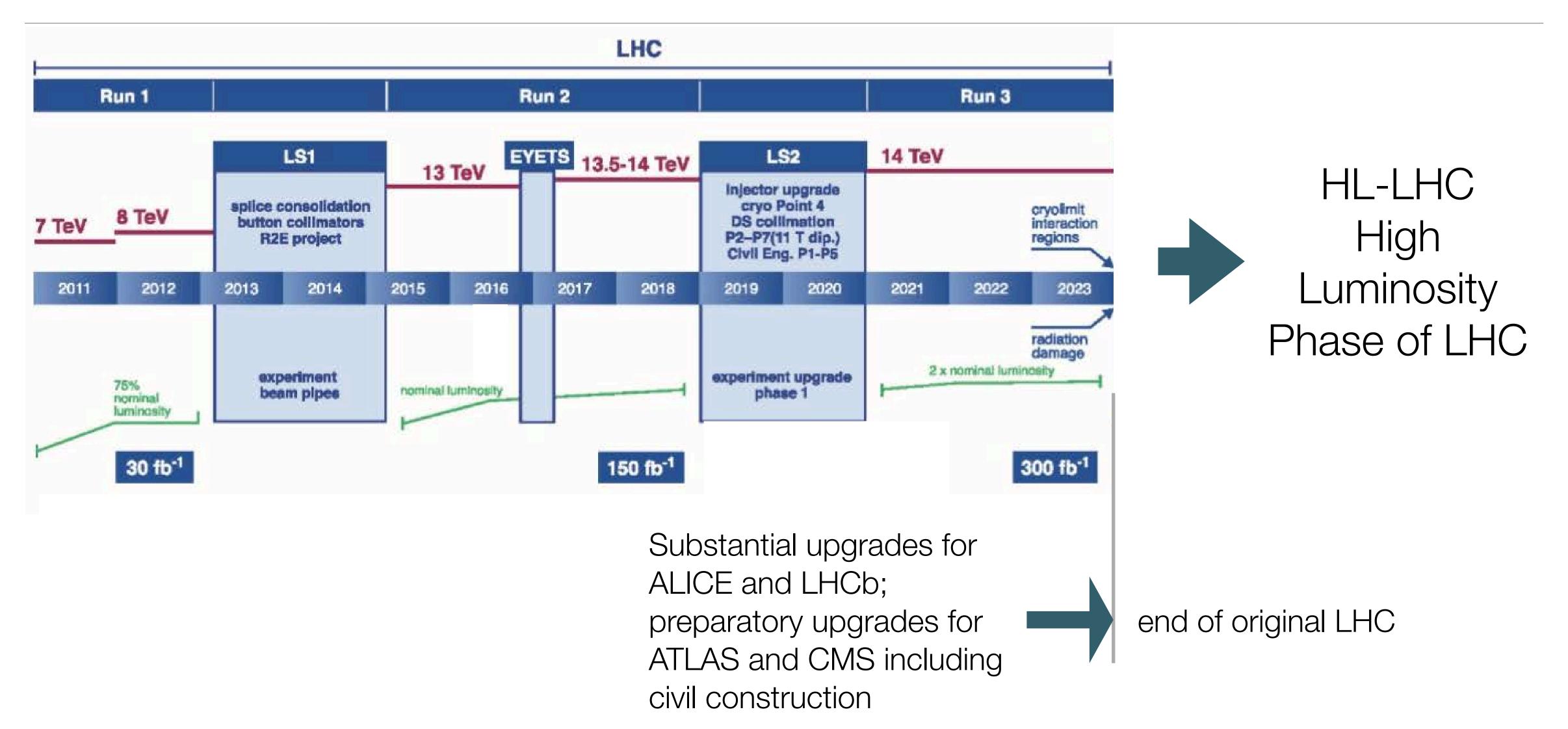
AD-programme

Goals of LHC

Identify the Physics beyond the Standard Model

- Explore an energy regime that has not been chartered before
 - have entered 13 TeV regime in production mode
 - 14 TeV after LS2 and possibly 15 TeV (study group)
- · Look for small deviations (small couplings) from the Standard Model
 - Precision measurements of (rare) processes

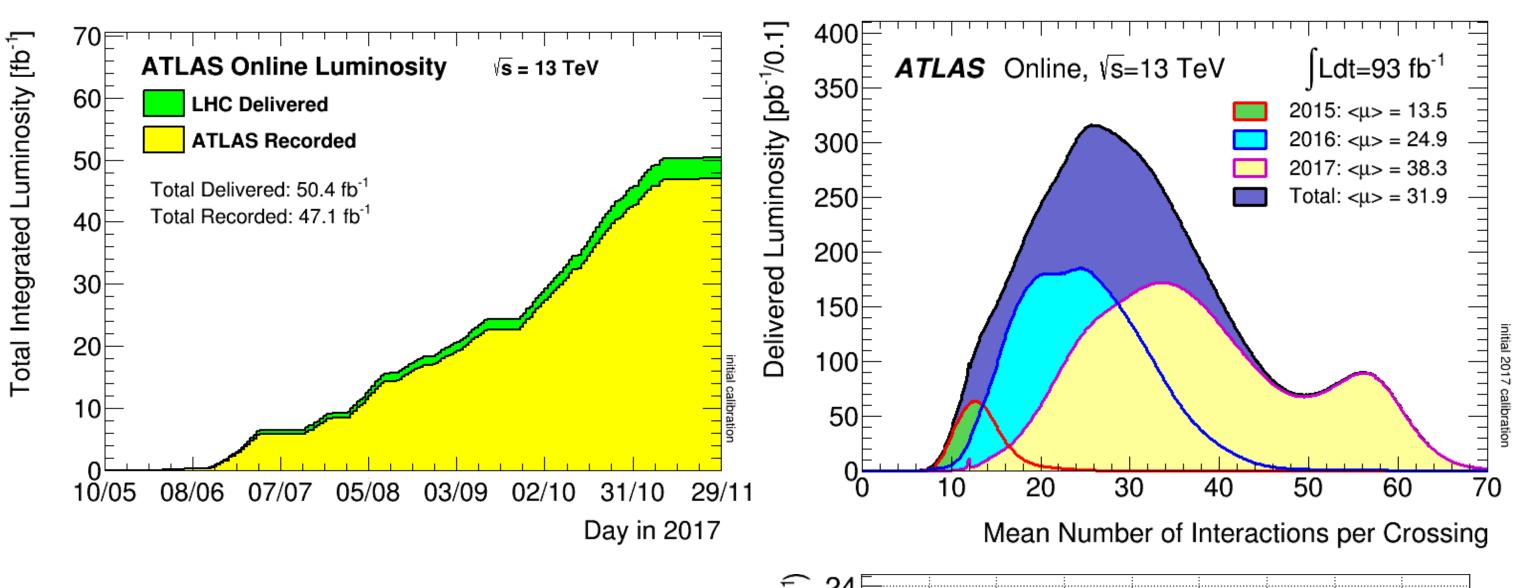
LHC schedule

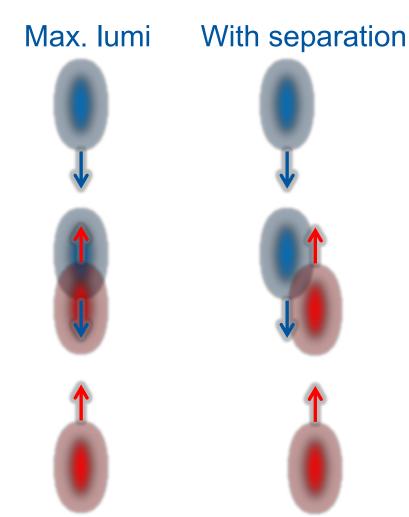


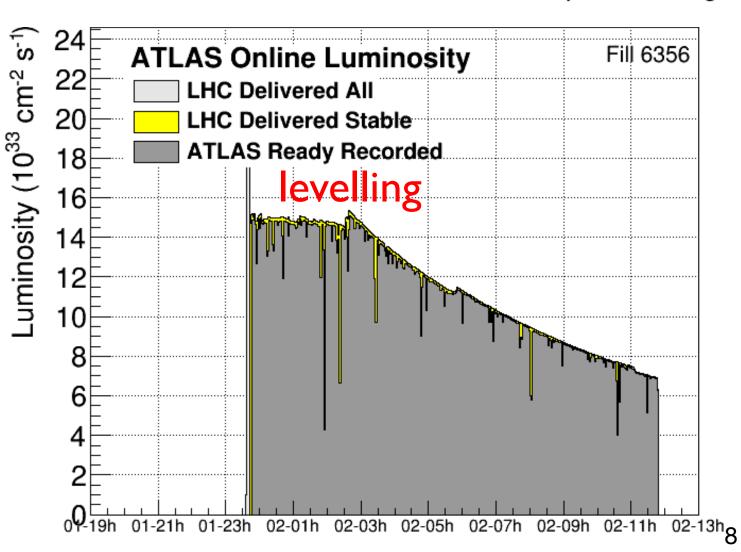
Event Pile-Up and Luminosity Levelling at LHC (2017)

- Peak L $\sim 2 \times 10^{34}$ cm⁻²s⁻¹
- ATLAS and CMS prefer
 L ≤ 1.5×10³⁴ cm⁻²s⁻¹ and
 longer fills (slow beam
 burn-off)
- Initially separate the beams transversely and slowly increase overlap

Levelling leads to cleaner events and only small degradation of integrated luminosity.







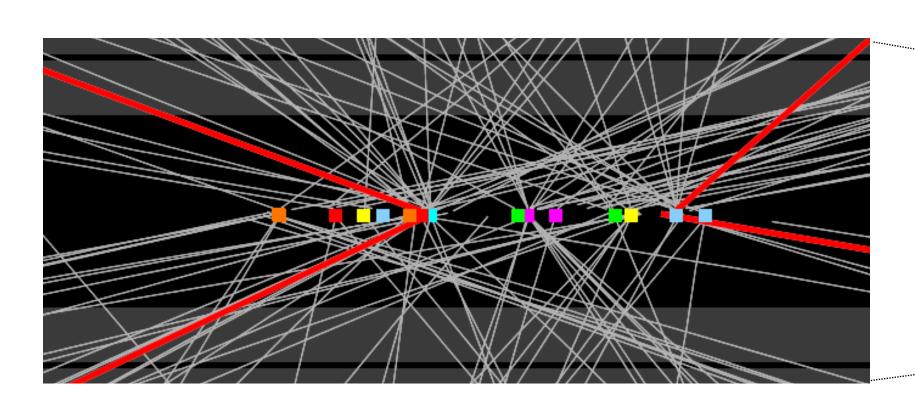
Pile-up affects physics

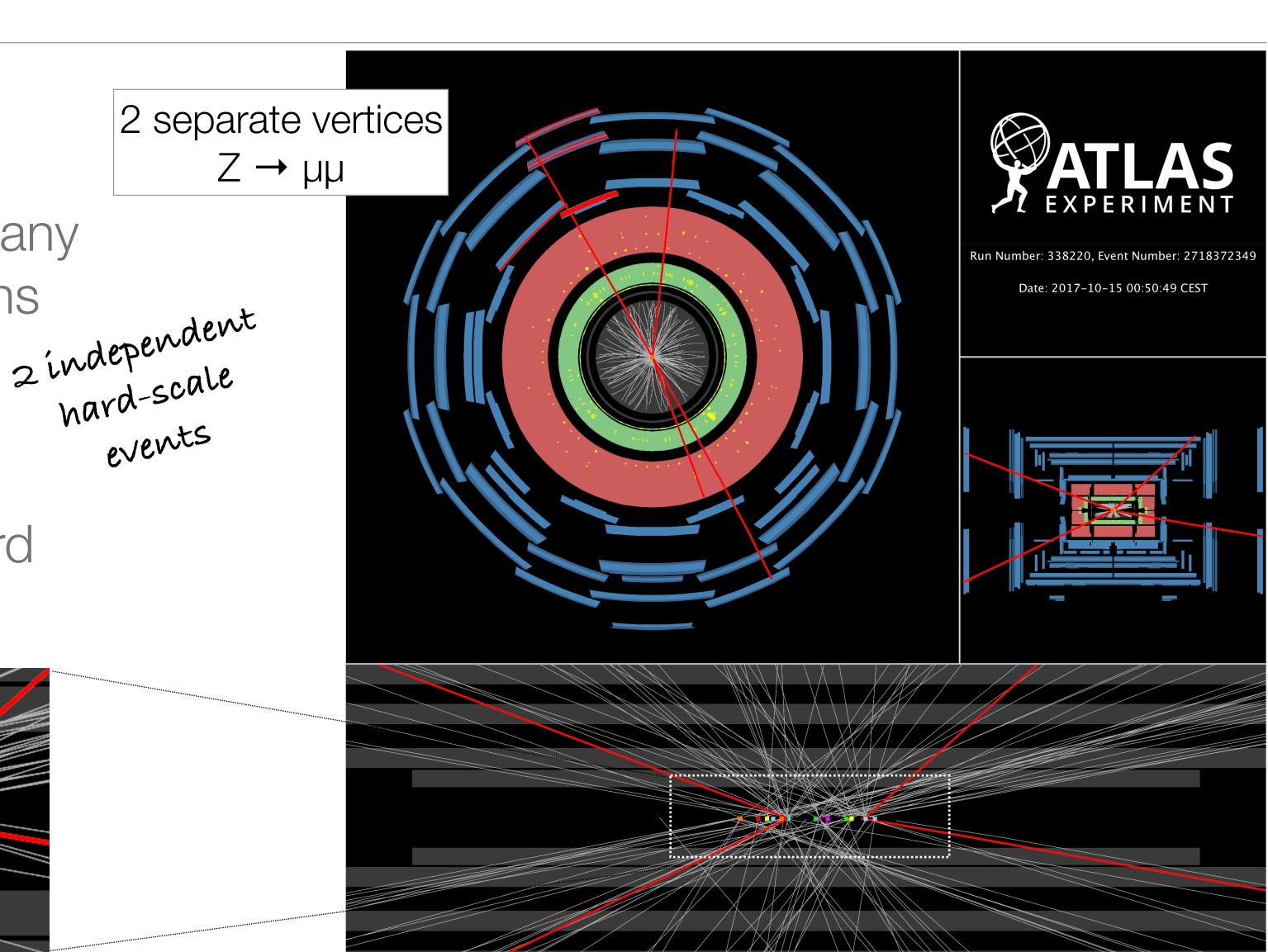
For low pile-up:

 1 hard interaction and many minimum-bias interactions

for high pile-up

 possibly more than 1 hard interaction + min-bias





LHC Configuration 2018

- More bunches
 - also good for LHCb
- Levelled pile-up ~60; bunch luminosity similar to 2018
- Introduction of β*-antilevelling down to 25 cm

dynamically increase particle density in region of beam overlap

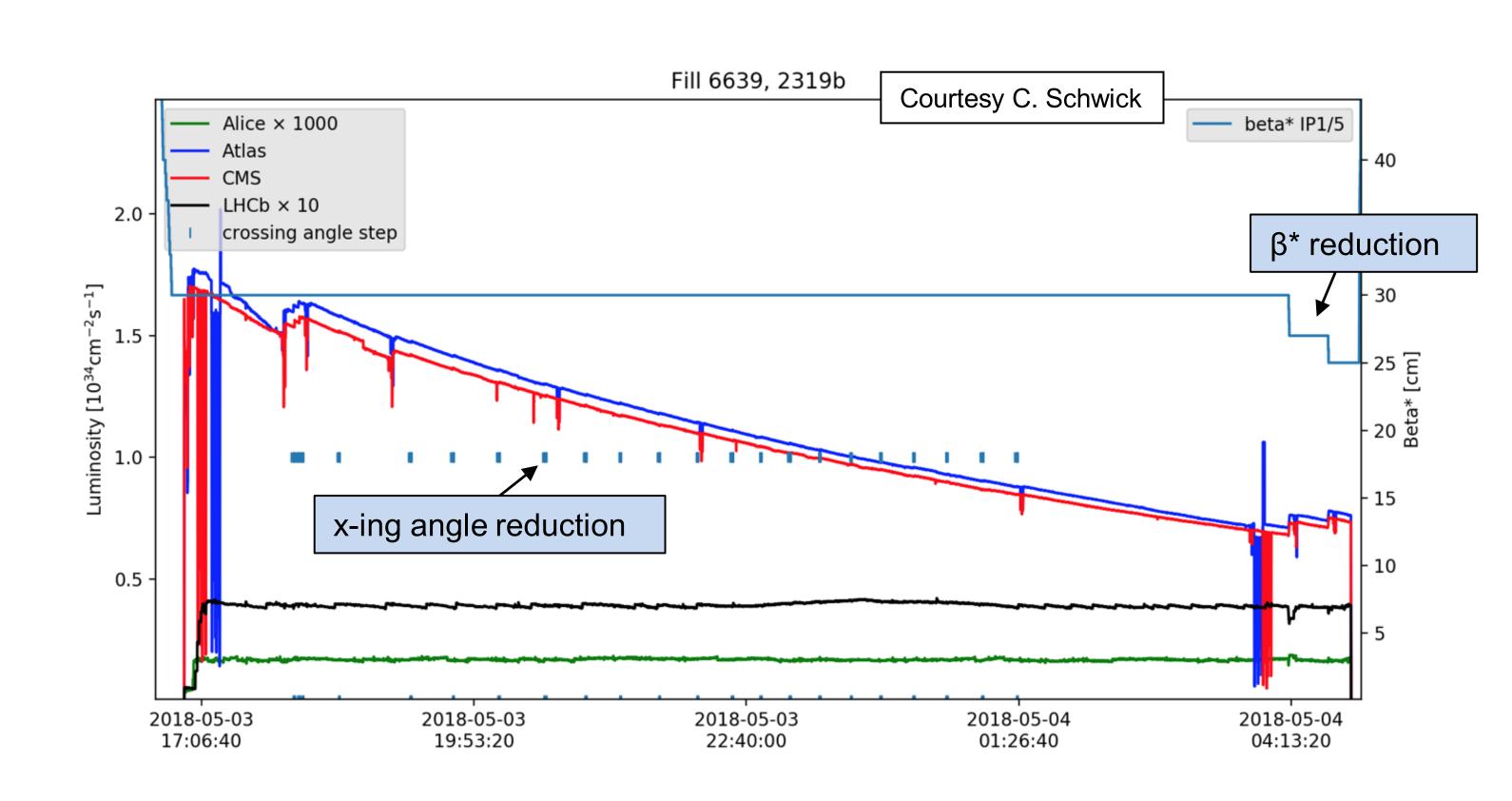
Optics	2017 ATS
Beam type	BCMS (25ns)
Bunch intensity	1.15 - 1.3 x 10 ¹¹ p/bunch
#bunches per train	144
Total number of bunches	2556
Initial/baseline β*	30 cm
Final β* (by leveling) (*)	27/25 cm
½ xing angles(**)	160 /200/ 160 /-250
CMS bump	-1.8 mm

^{*} Use of β^* levelling *initially at end of fills* to make it operational, requiring closing of TCTs in IR1 and IR5 by an additional σ wrt to 2017

^{**} same ATLAS Xing angle polarity as in 2017, continuous crossing angle anti-leveling

Exploiting the fills – maintain high luminosity for extended periods

- Continuous crossing angle reduction (anti-levelling)
 - 160 µrad → 130 µrad during fill (as the bunch charge decreases the inand outgoing bunches interfere less)
- β*-anti-levelling
 - 30 cm → 27 cm → 25 cm
 (nominal LHC value: 55 cm)

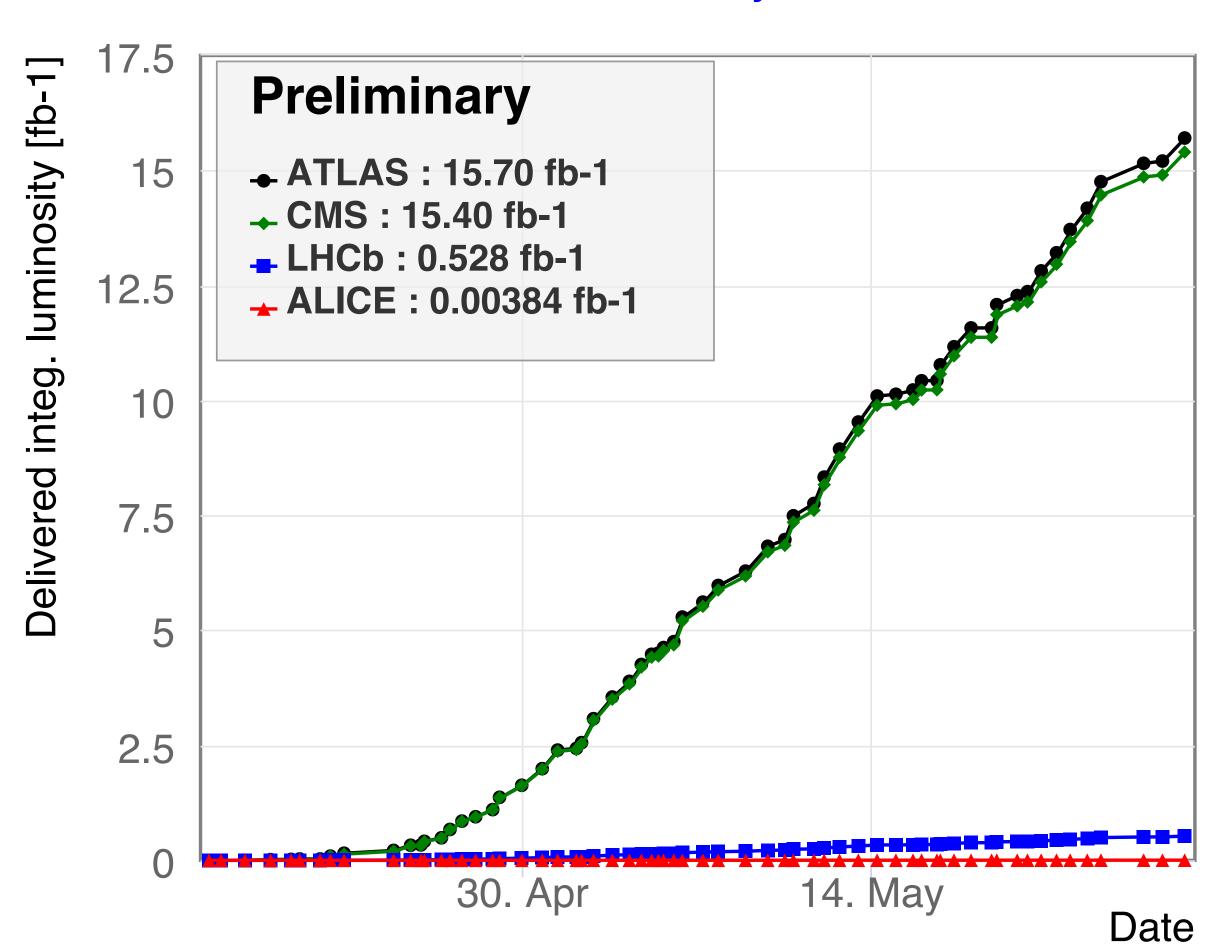


both schemes are seen to work

Great start in 2018

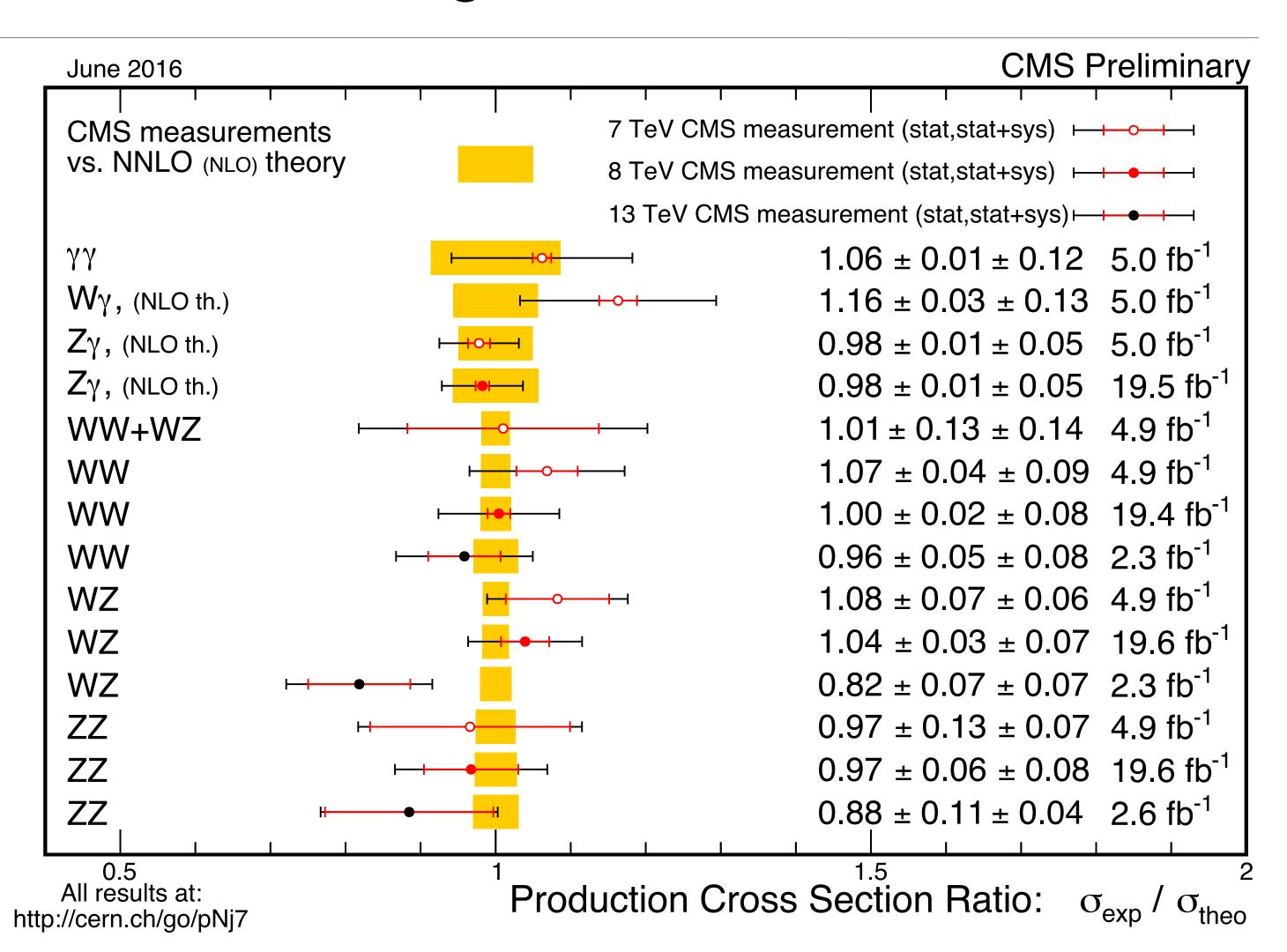
- Luminosity goal for 2018
 60 fb⁻¹
- a month of PbPb running towards the end of the year
- special runs
 - Total cross section at lower energy etc.

Delivered Luminosity 2018



Vector boson and theoretical understanding

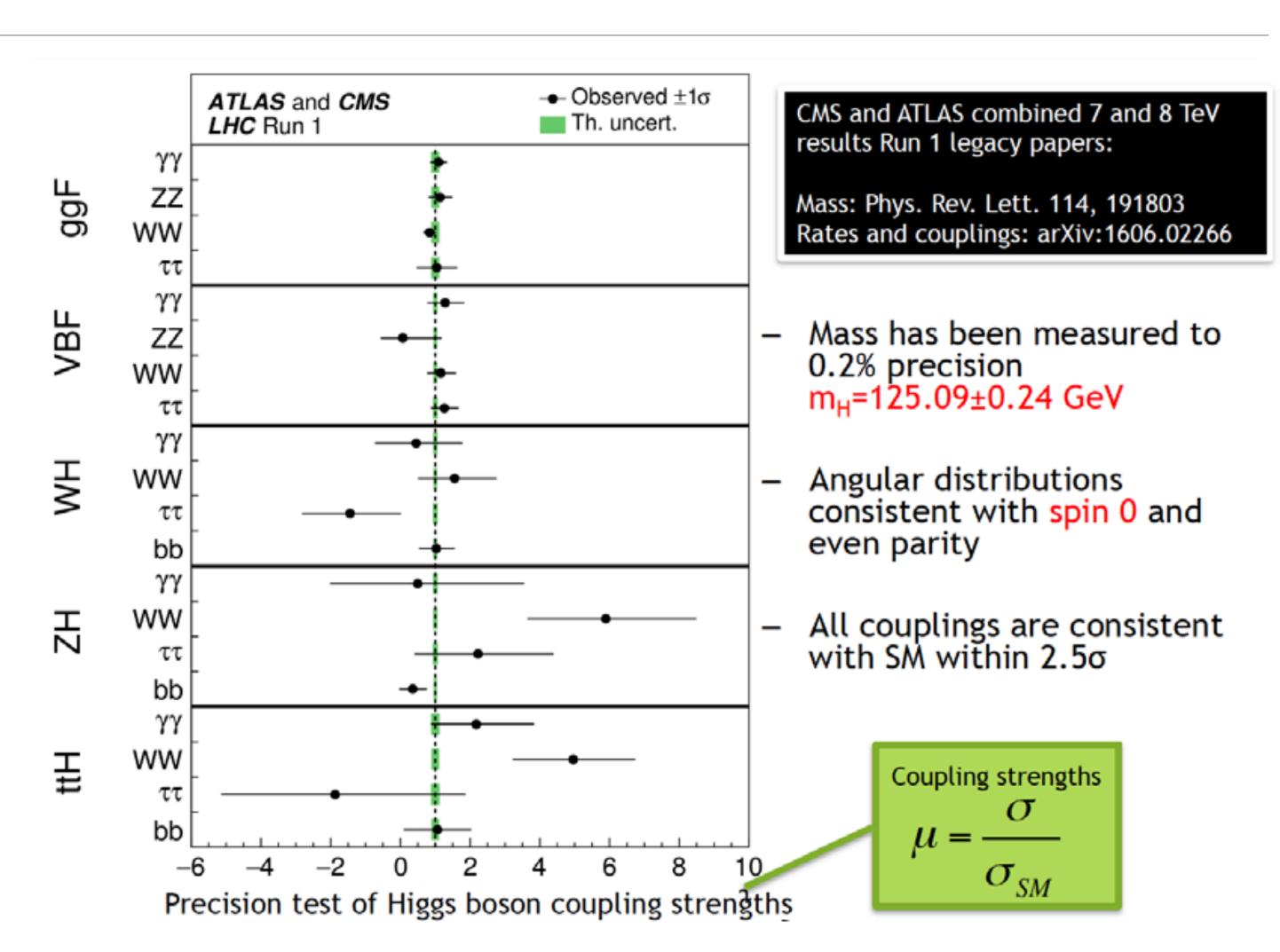
- Rate of interaction, i.e. the cross section for ppcollisions varies dramatically
 - high mass cross sections are of very low rate
 - requires very high selectivity (trigger, event selection)



Higgs Boson at 7 and 8 TeV (Run 1)

ATLAS and CMS have combined their Run 1 data to extract precise measurement of Higgs coupling

Higgs (125 GeV) compatible with SM

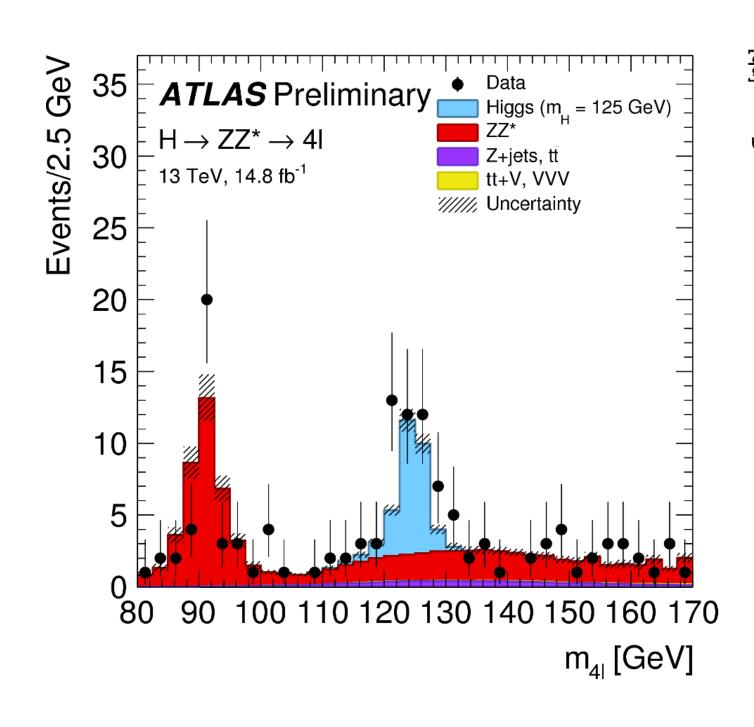


Higgs Production at 13 TeV (Run 2)

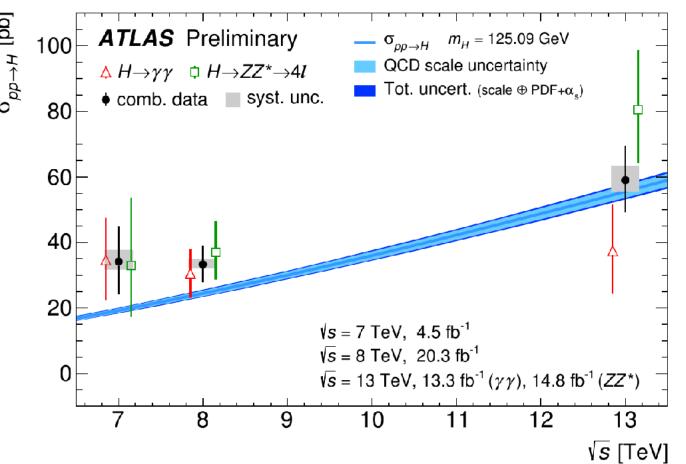
 Overall significance of Higgs production:
 ~10 σ

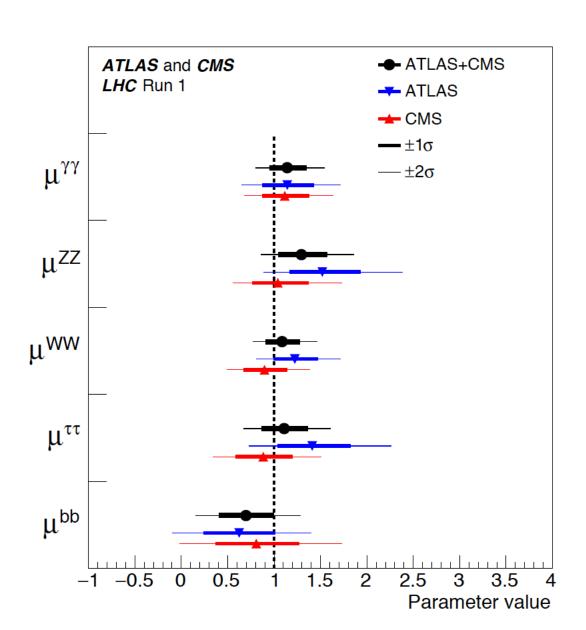
•
$$\sigma(pp \rightarrow H + X) =$$

$$59.0^{+9.7}_{-9.2}$$
 (stat.) $^{+4.4}_{-3.5}$ (syst.) pb



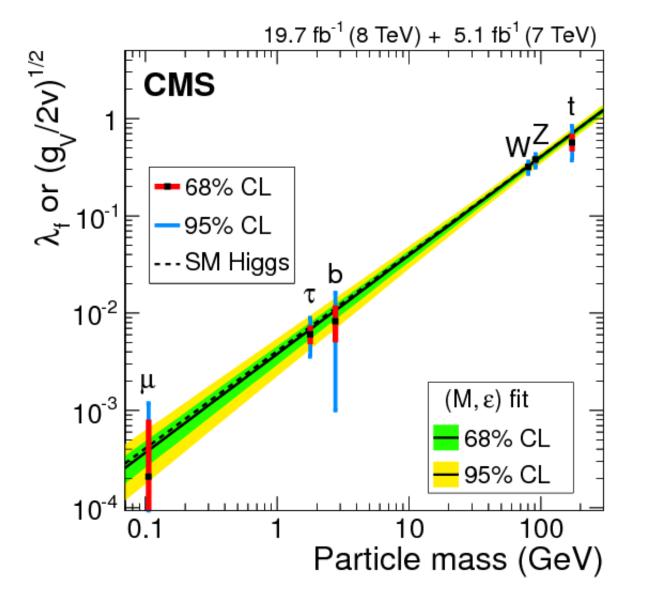


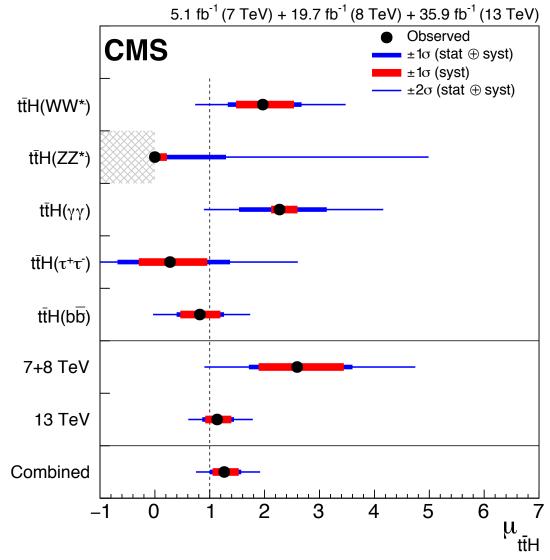




Observation of ttH coupling

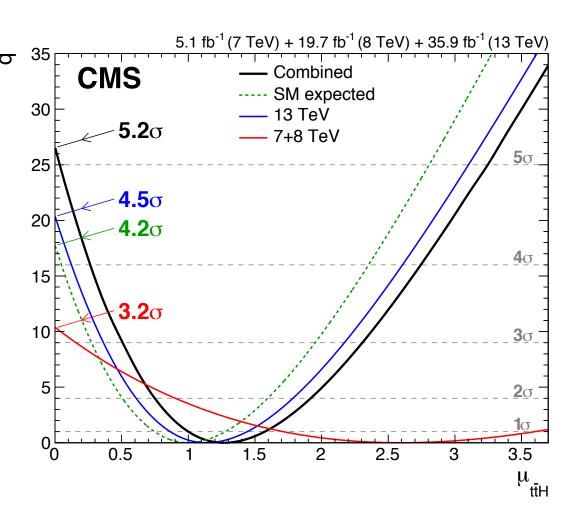
- Higgs boson couples to mass
 - decay to virtual top-quarks is prevalent (explains the γγrate)
- Direct observation is challenging and requires combination of various top decay channels
- CMS combined 7 TeV, 8 TeV and 2016-part of 13 TeV





5.2 σ

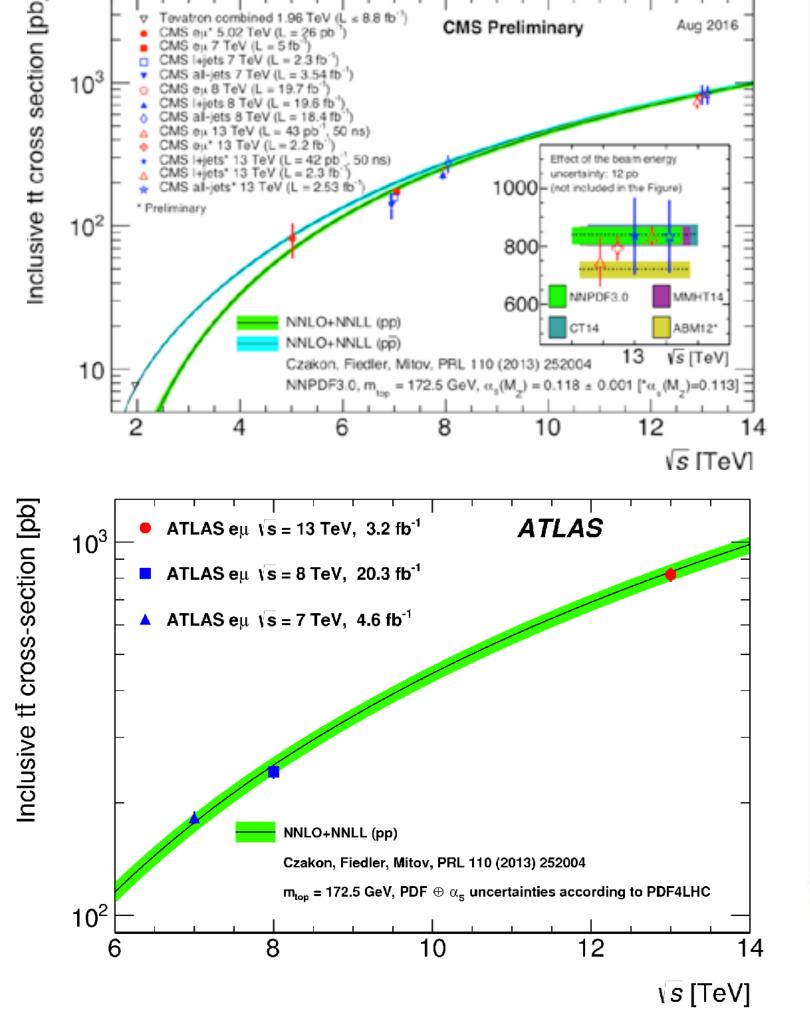
more at LHCP conference

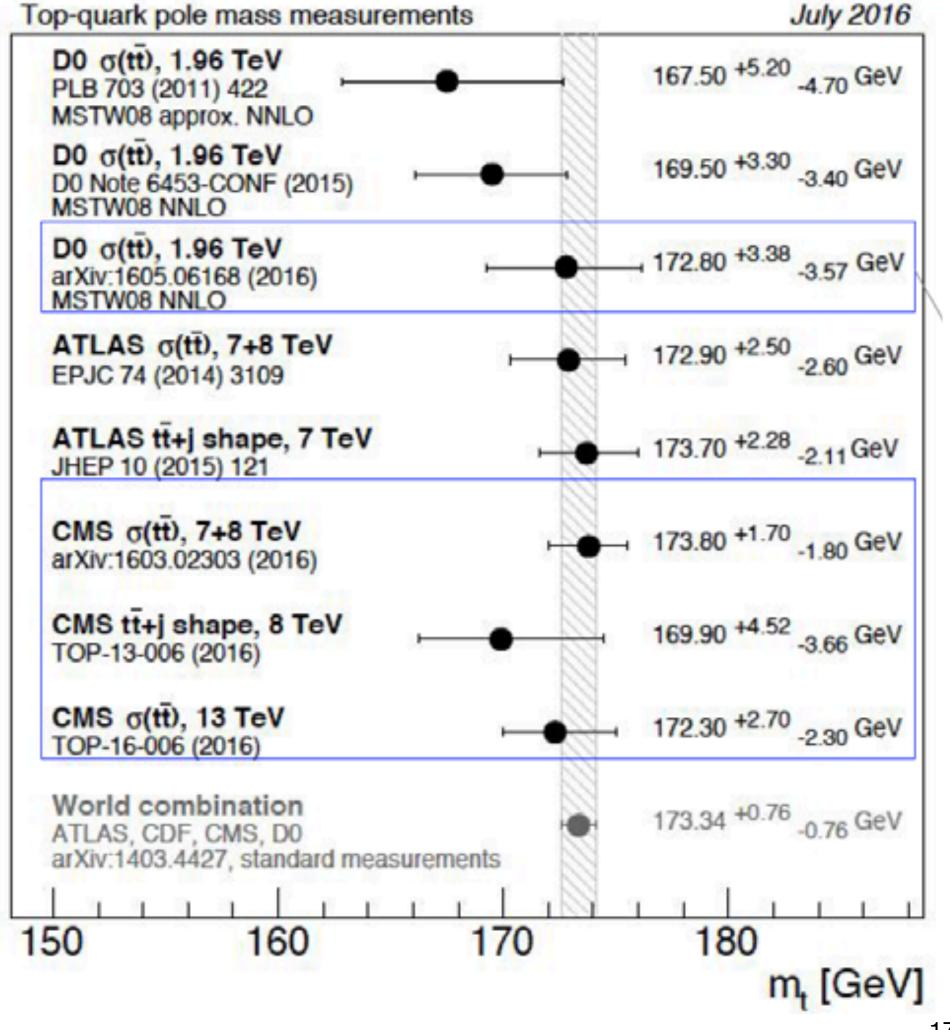


Top Production

Top cross section and mass measurement are key ingredients in predictions for Physics beyond SM

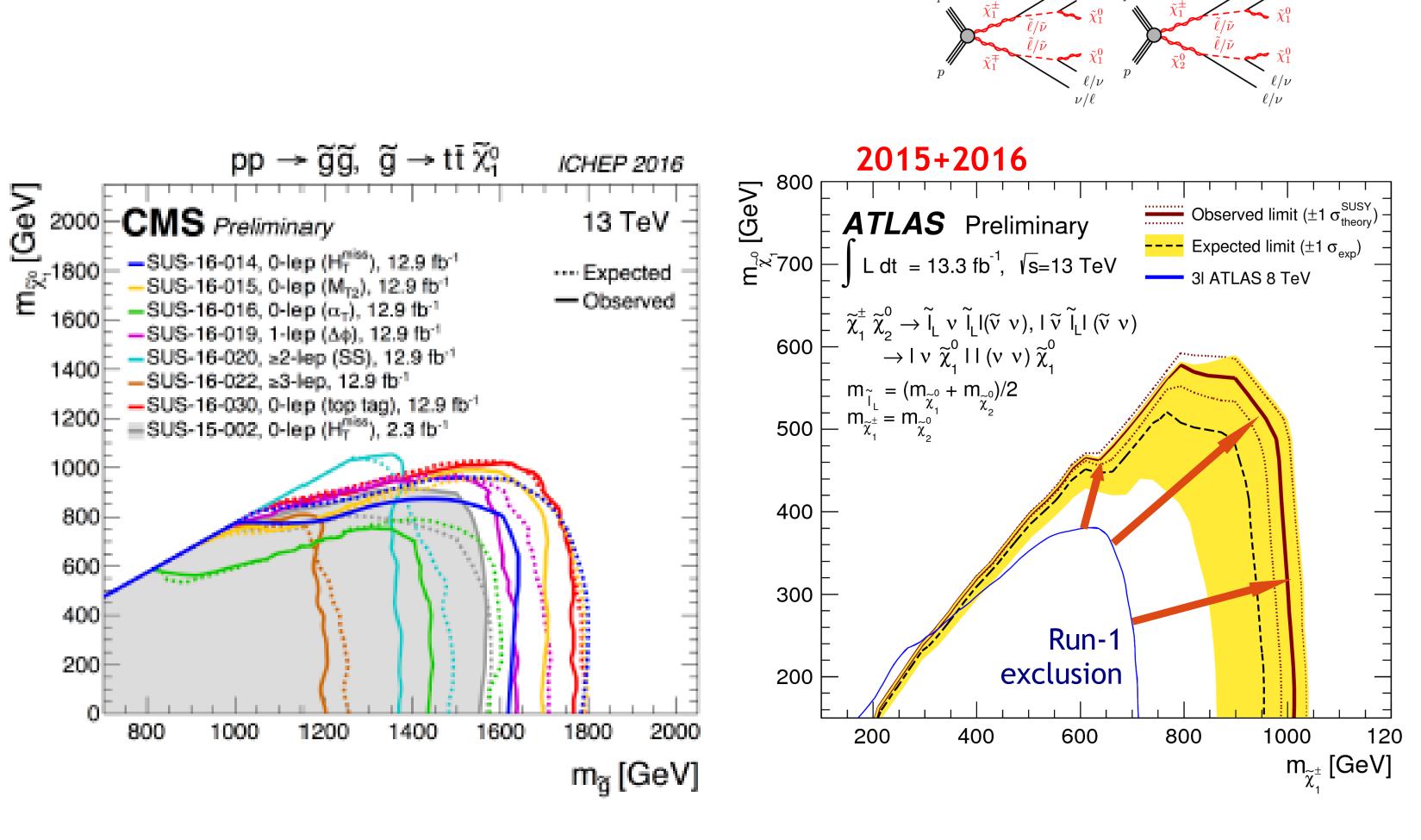
NNLO + NNLL calculations give excellent description of σ





Search for Supersymmetry

- Limits extended into the TeV mass range for specific channels
 - huge step from Run 1 analyses

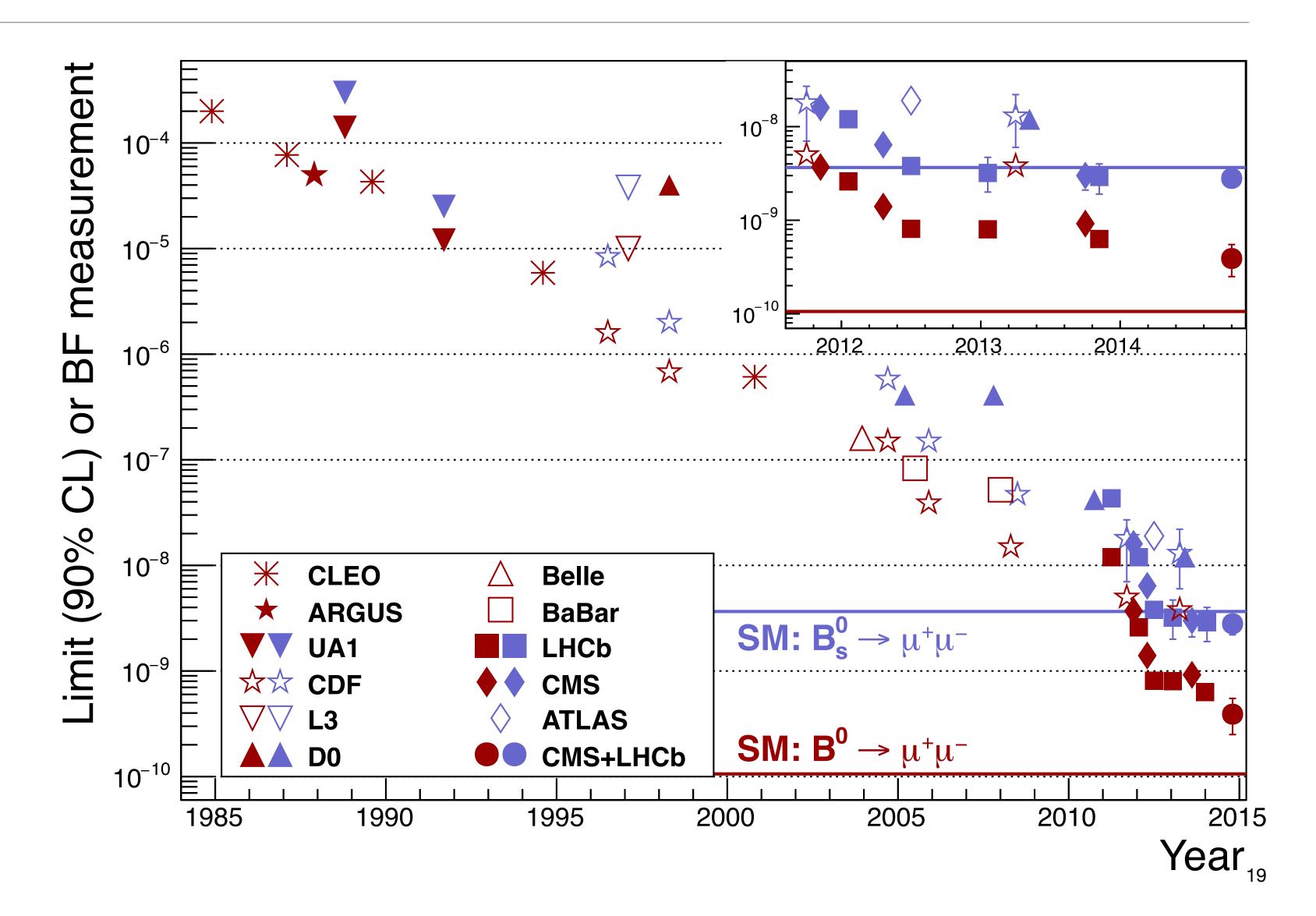


From limit to measurement for $B^0 \rightarrow \mu\mu$

The rare decay was known to be particularly sensitive for new physics.

25 years of experimental research to reach SM sensitivity.

Compatible with SM – new physics not hiding here?

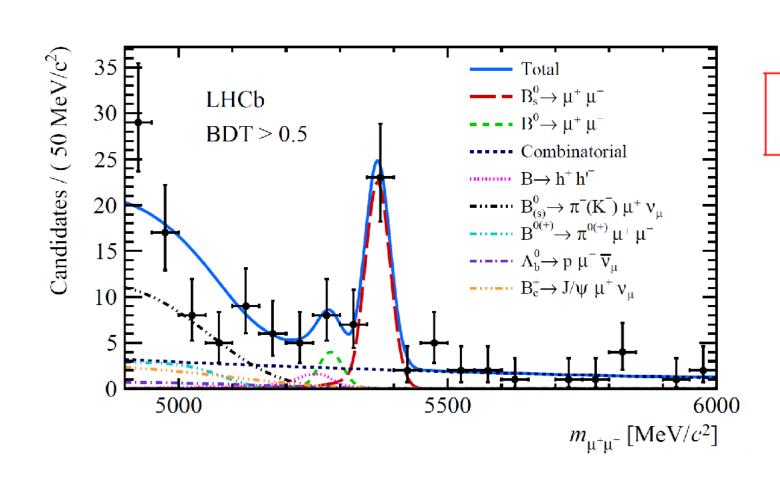


from Lycb alone

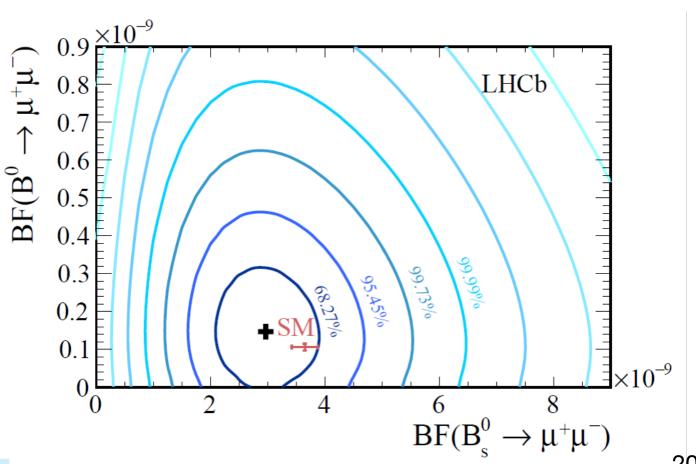
Measurement of BR(B_s $\rightarrow \mu\mu$) and search for B_d $\rightarrow \mu\mu$

- Re-analyse Run 1 data with improved selection (background halved) and add 1.4 fb⁻¹ of Run 2 data
- First single-experiment observation of B_s→µµ mode; measurement of BR has same precision as previous Run 1 LHCb-CMS combined analysis [NATURE 522 (2015) 68].

$$\mathcal{B}(B_s^0 \to \mu^+ \mu^-) = (3.0 \pm 0.6 \text{ (stat)})^{+0.3}_{-0.2} \text{ (syst)} \times 10^{-9}$$
 (7.8 σ)

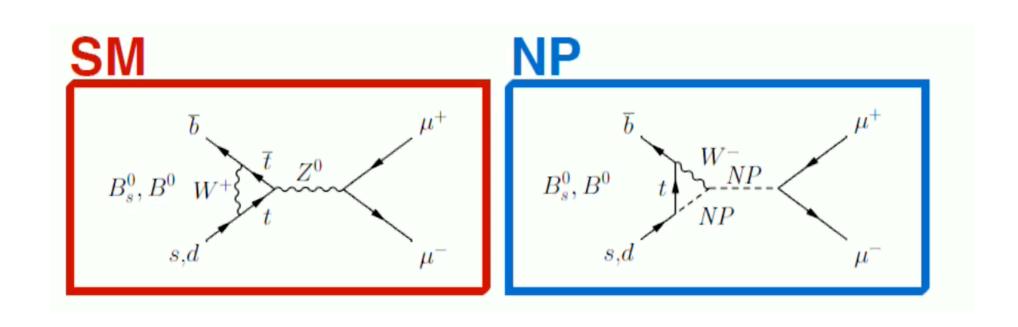


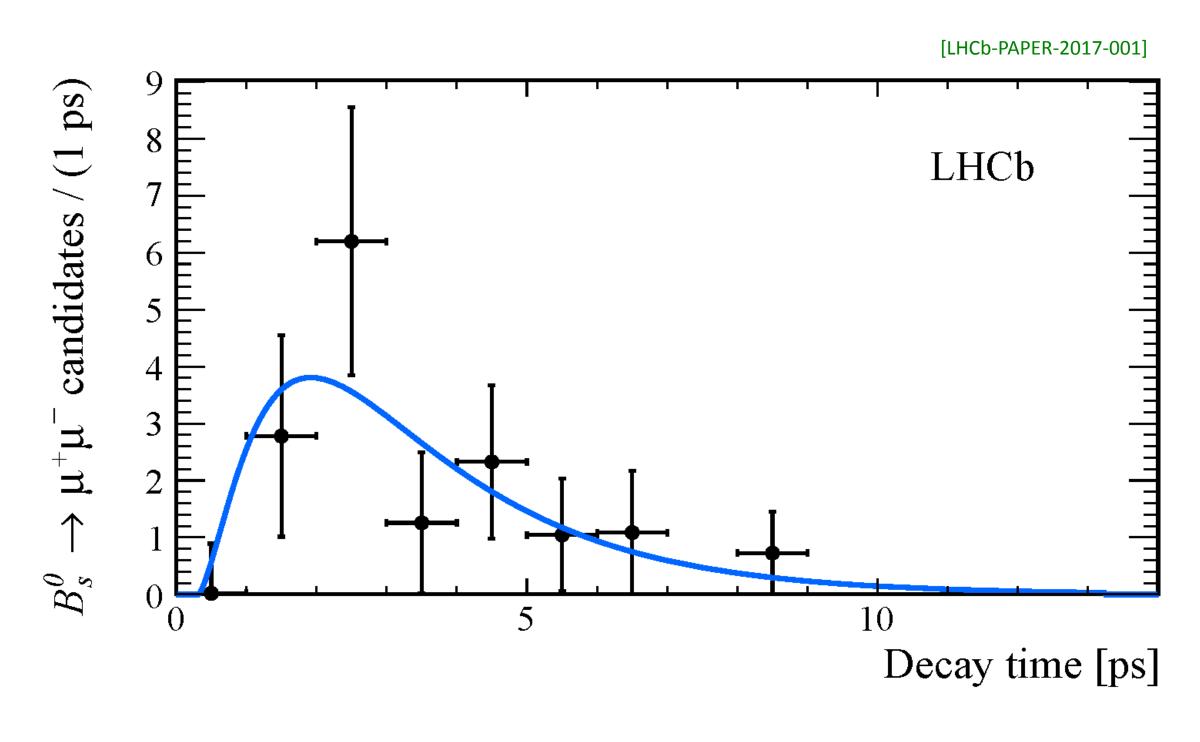
$$\mathcal{B}(B^0 \to \mu^+ \mu^-) < 3.4 \times 10^{-10}$$
 @ 95 % C.L.



First measurement of effective lifetime of $B_s \rightarrow \mu\mu$

- Start to measure new observables for ultra-rare decay: effective lifetime
- e.g. first measurement of the effective lifetime, which with more data will become a powerful probe of New Physics models





$$au(B_s^0 o \mu^+ \mu^-) = 2.04 \pm 0.44 \, ext{(stat)} \pm 0.05 \, ext{(syst)} \, ext{ps}$$

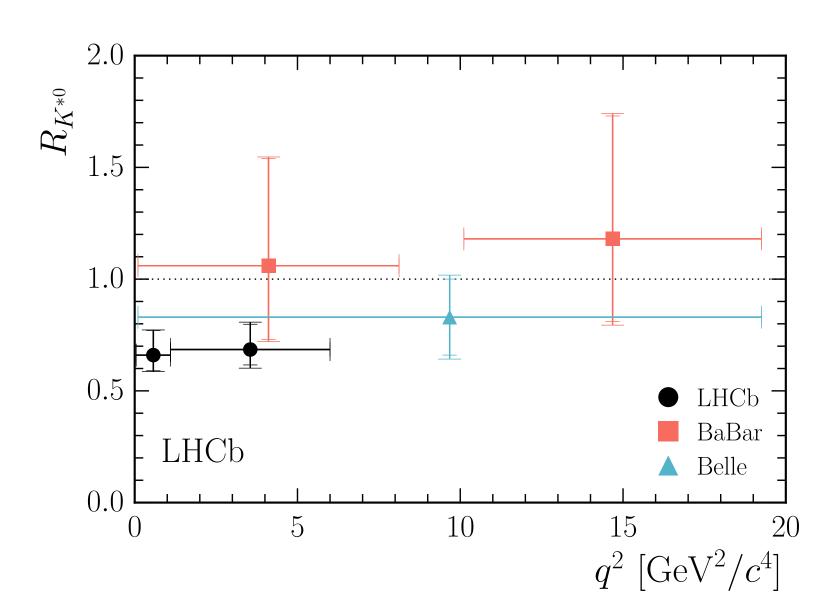
Measurement of Rk*

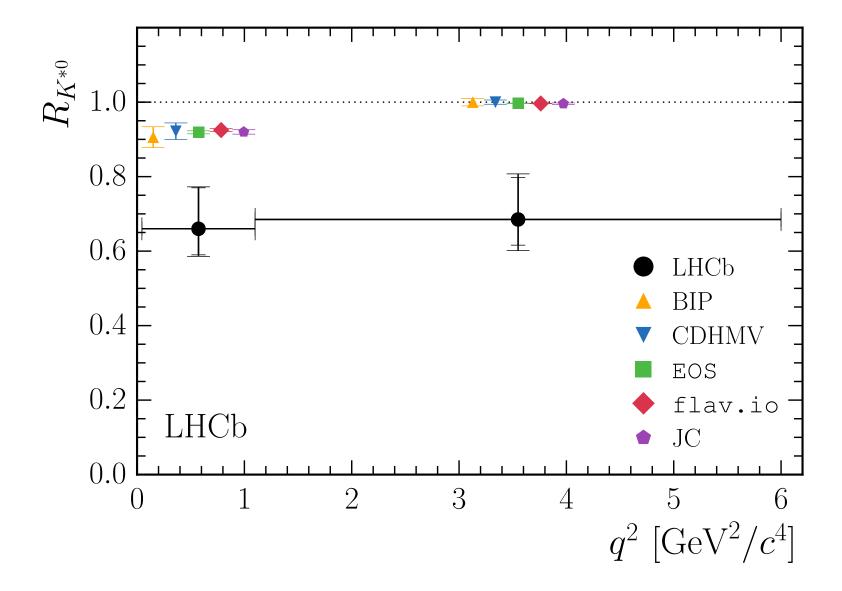
Expect µµ and ee-branchings to be the same – apart from well understood mass contributions

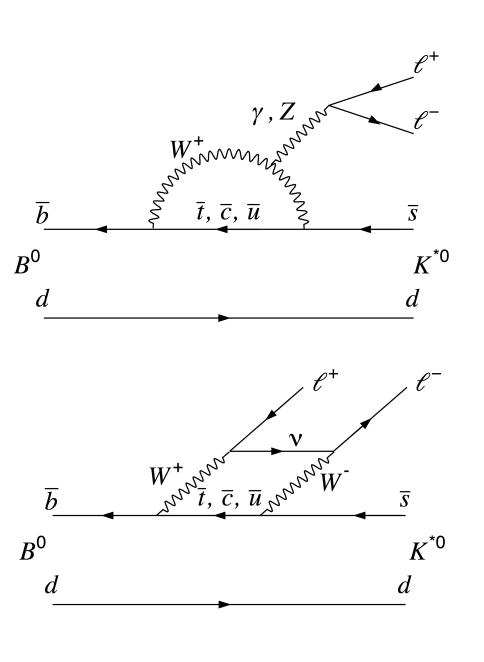
LHCb-Paper-2017-013

So far a ~2.5 o effect

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} / \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$





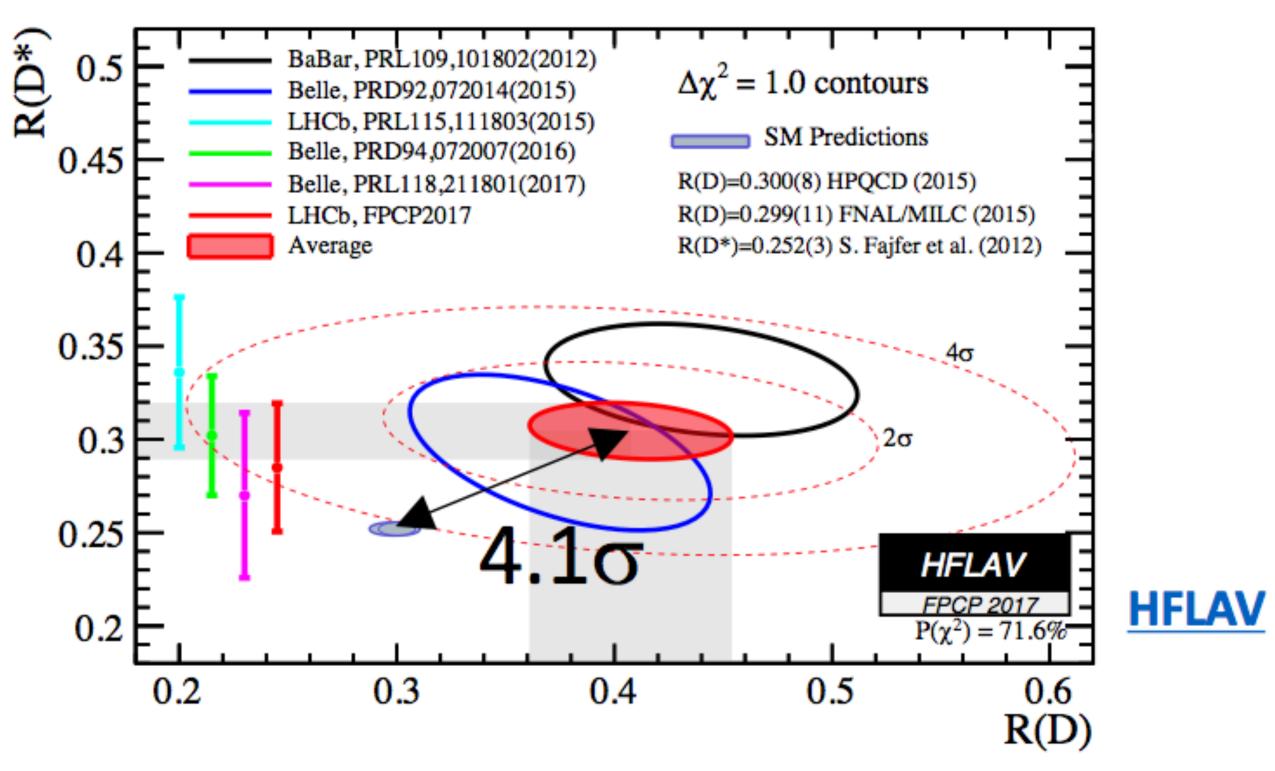


Other B-Anomalies

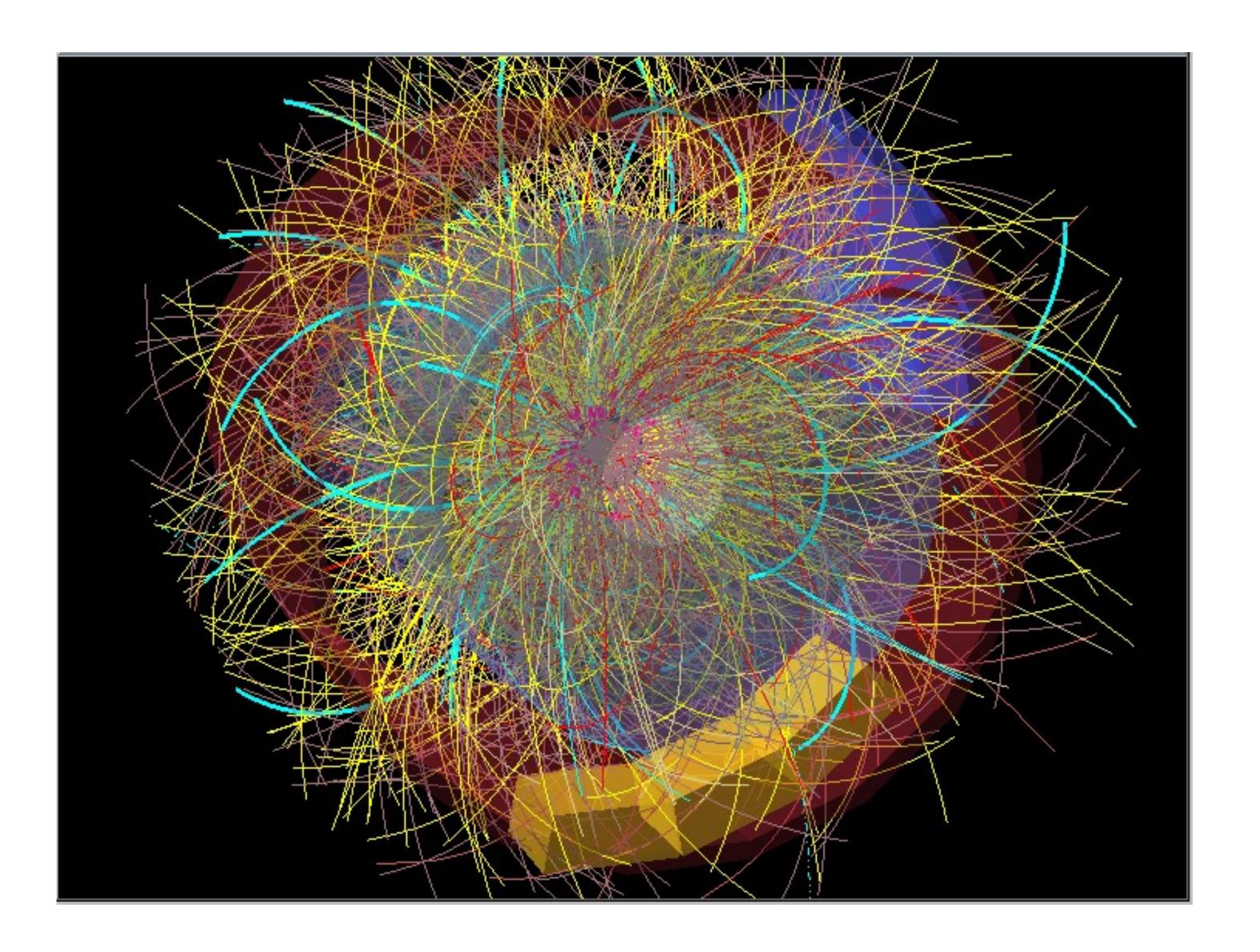
 Eagerly awaiting significant result of single experiment to shed light on the question of lepton flavour universality

Experimental updates on some anomalies still this year

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})}$$



Heavy Ion Physics



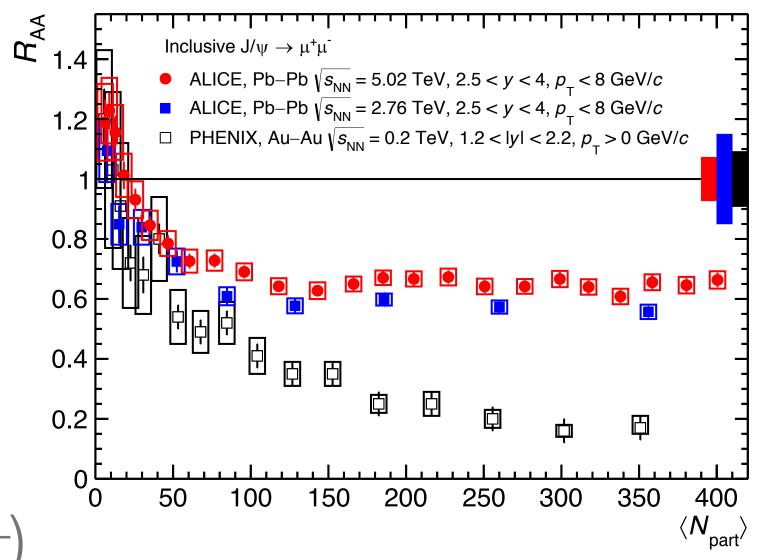
Pb-Pb: J/ψ suppression at 5 TeV

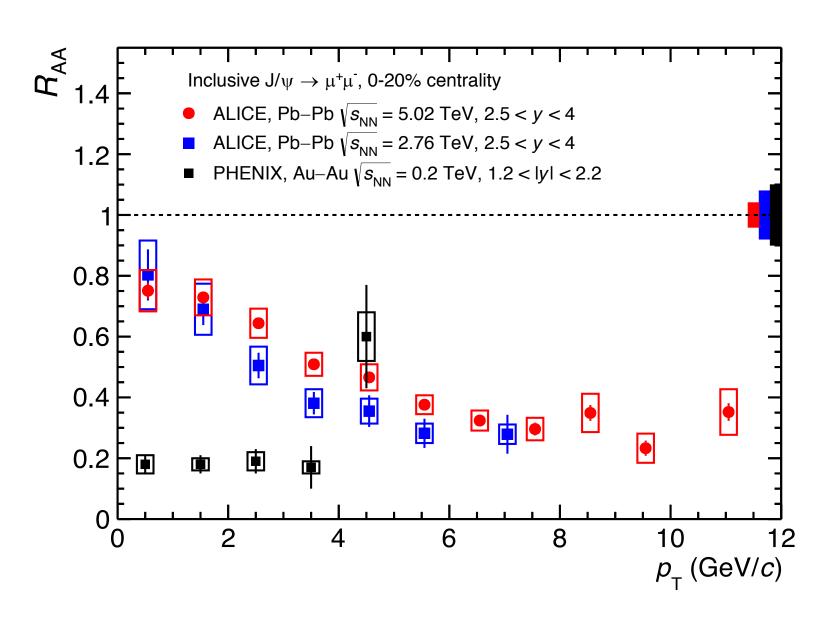
 nuclear modification factor R_{AA}:

$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin} \rangle N(J/\psi)_{pp}}$$

 very different behaviour between LHC and RHIC (vs both centrality and p_T)



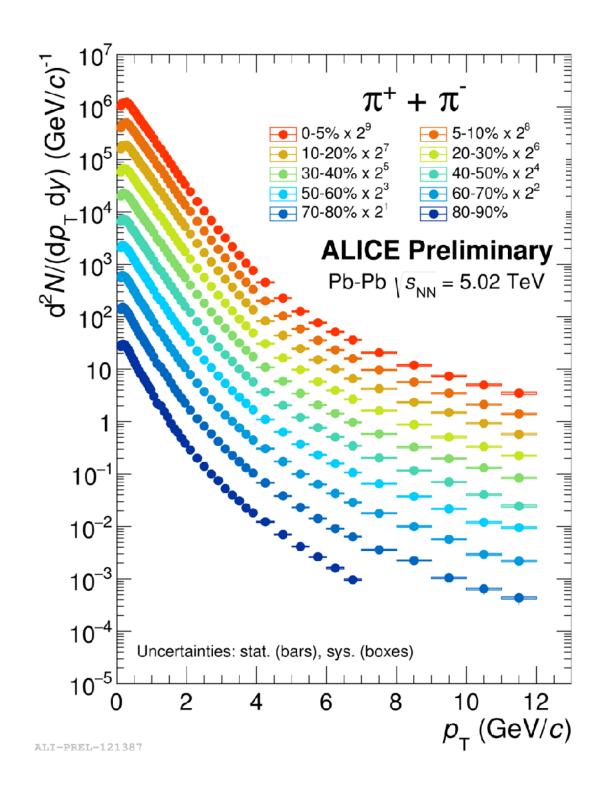


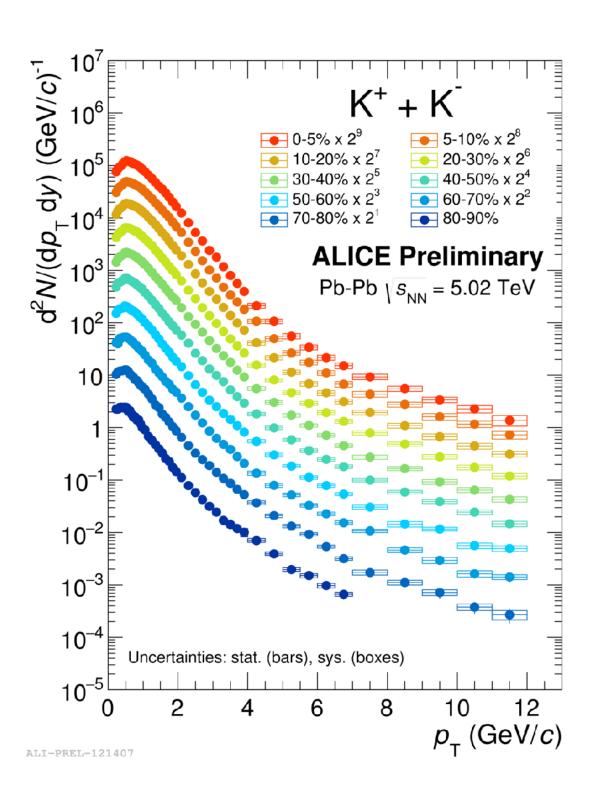


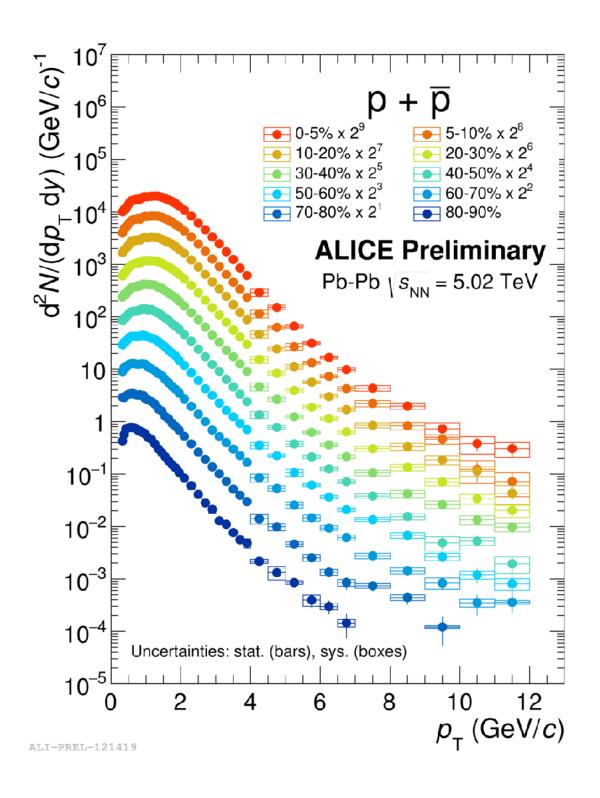
New and precise 5 TeV data support even further increase

Identified particle production in Pb-Pb collisions at √s_{NN}=5.02 TeV

Precision tracking and particle identification over a wide range in pt



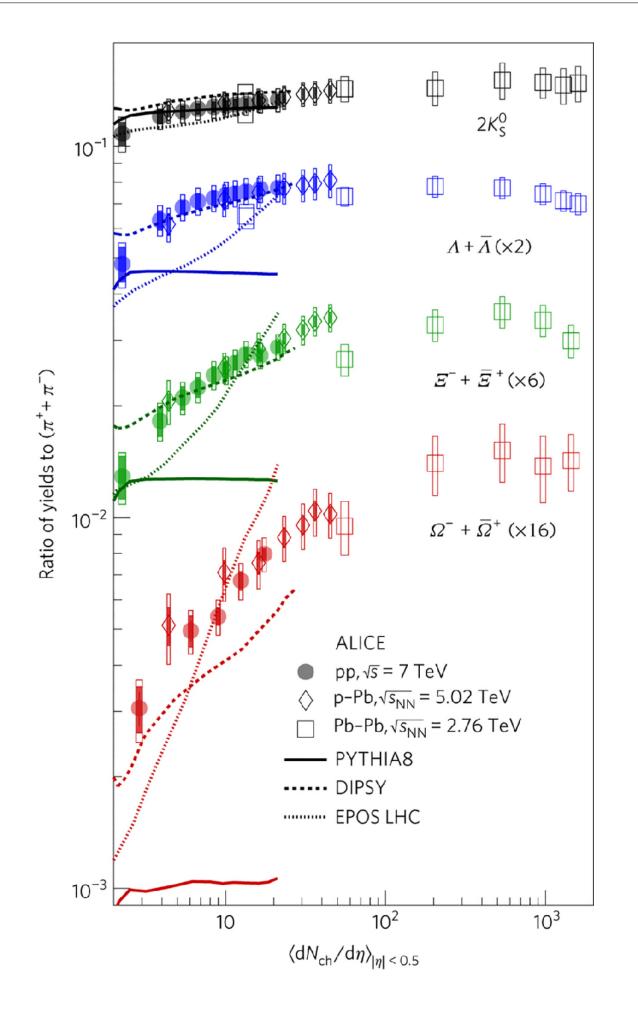


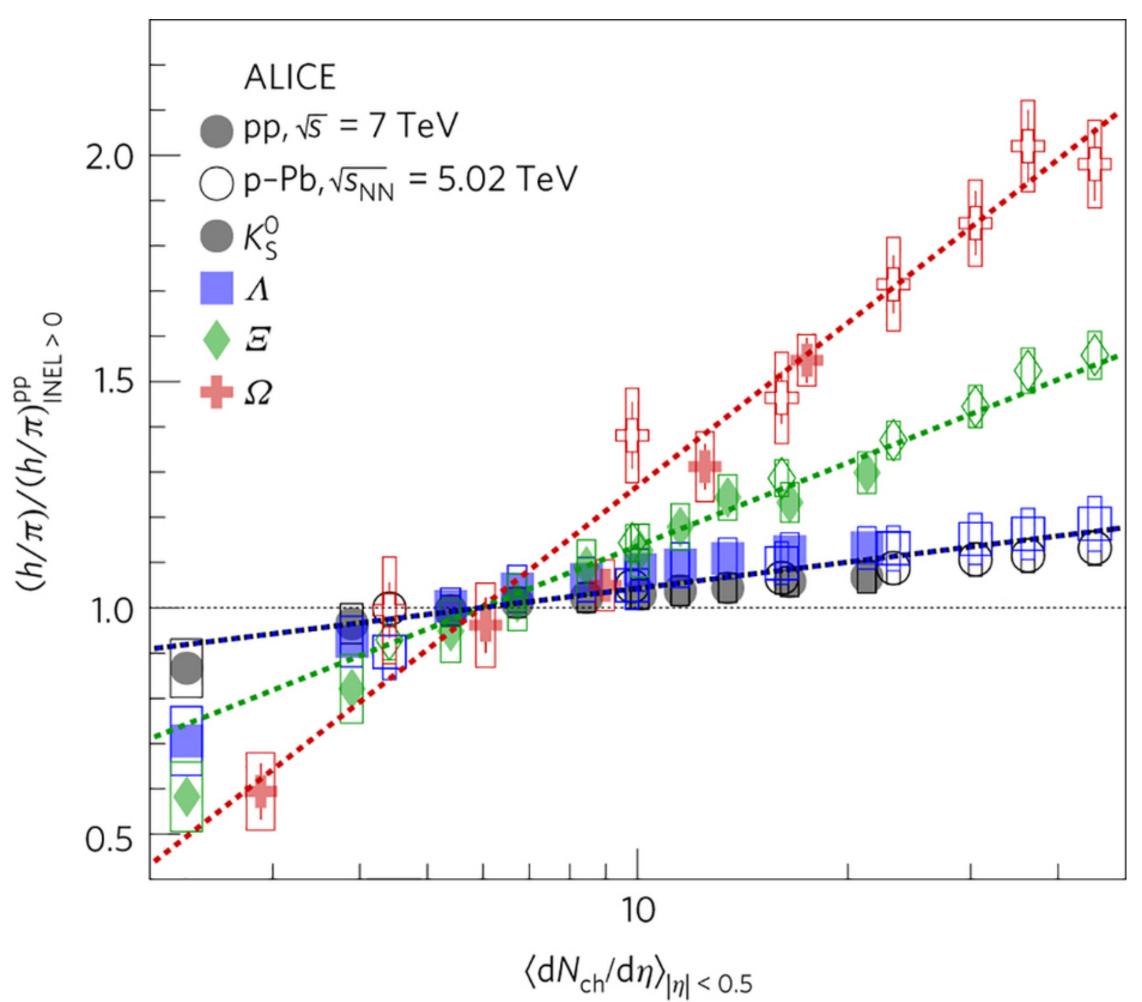


Strangeness production in high-energy pp

Strangeness in high-multiplicity pp-collisions

Evidence for Quark-Gluon plasma in pp collisions

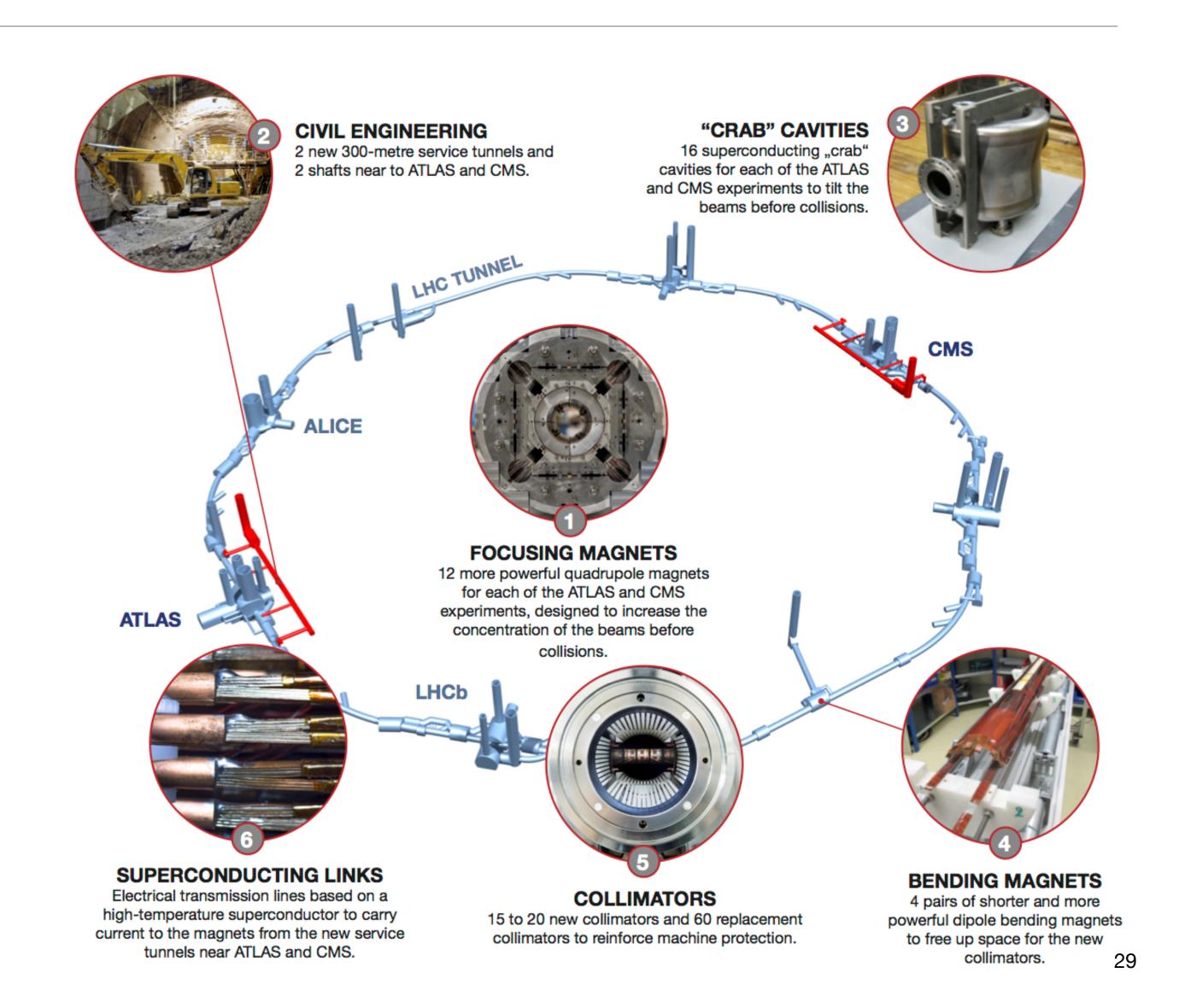




High Luminosity LHC

High-Luminosity LHC (HL-LHC)

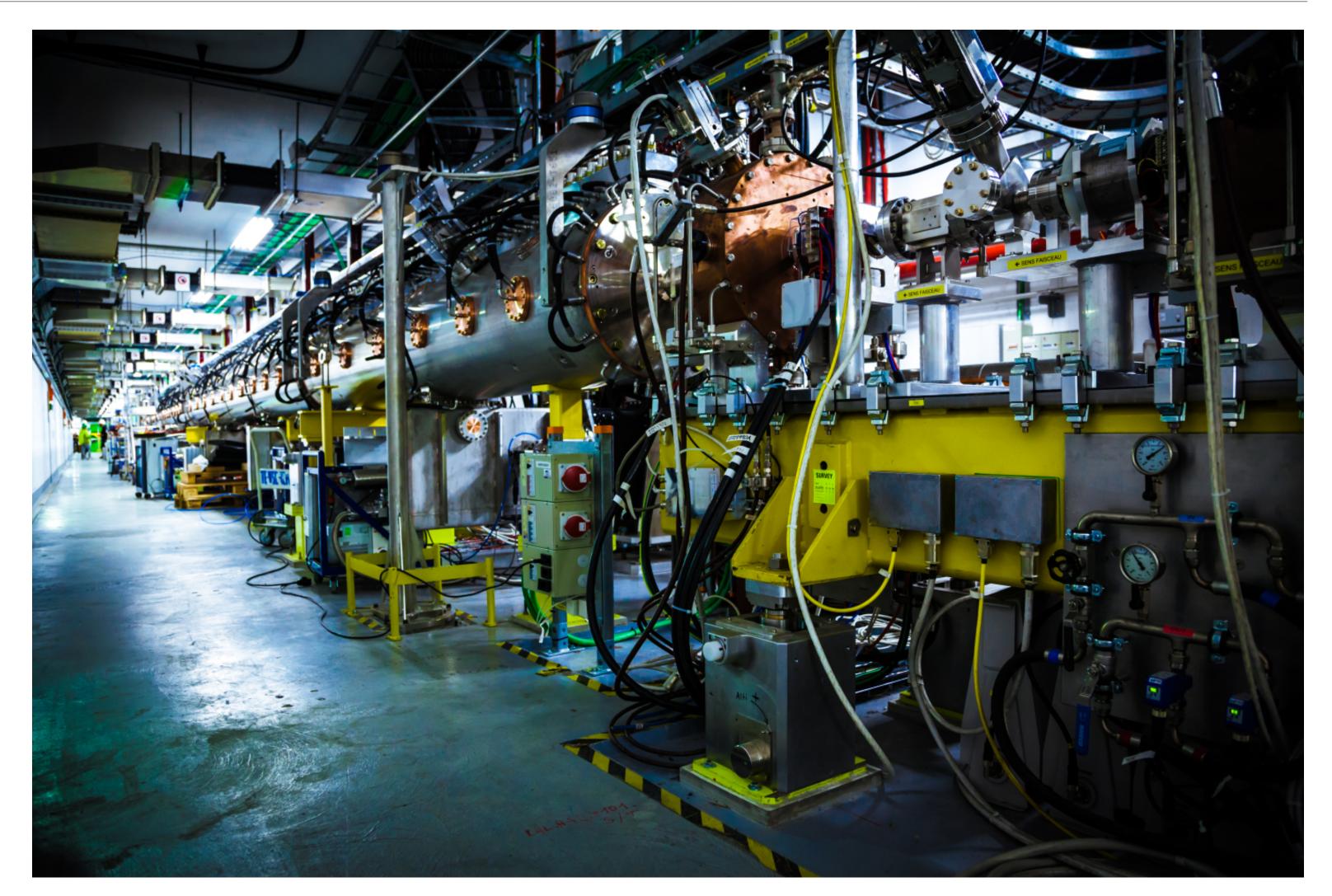
- 5x10³⁴ cm⁻²s⁻¹ levelled; i.e. factor 5 over design
 - to yield 3 ab⁻¹ by ~2035
- requires
 - focussing $\beta^*=15$ cm
 - crab crossing



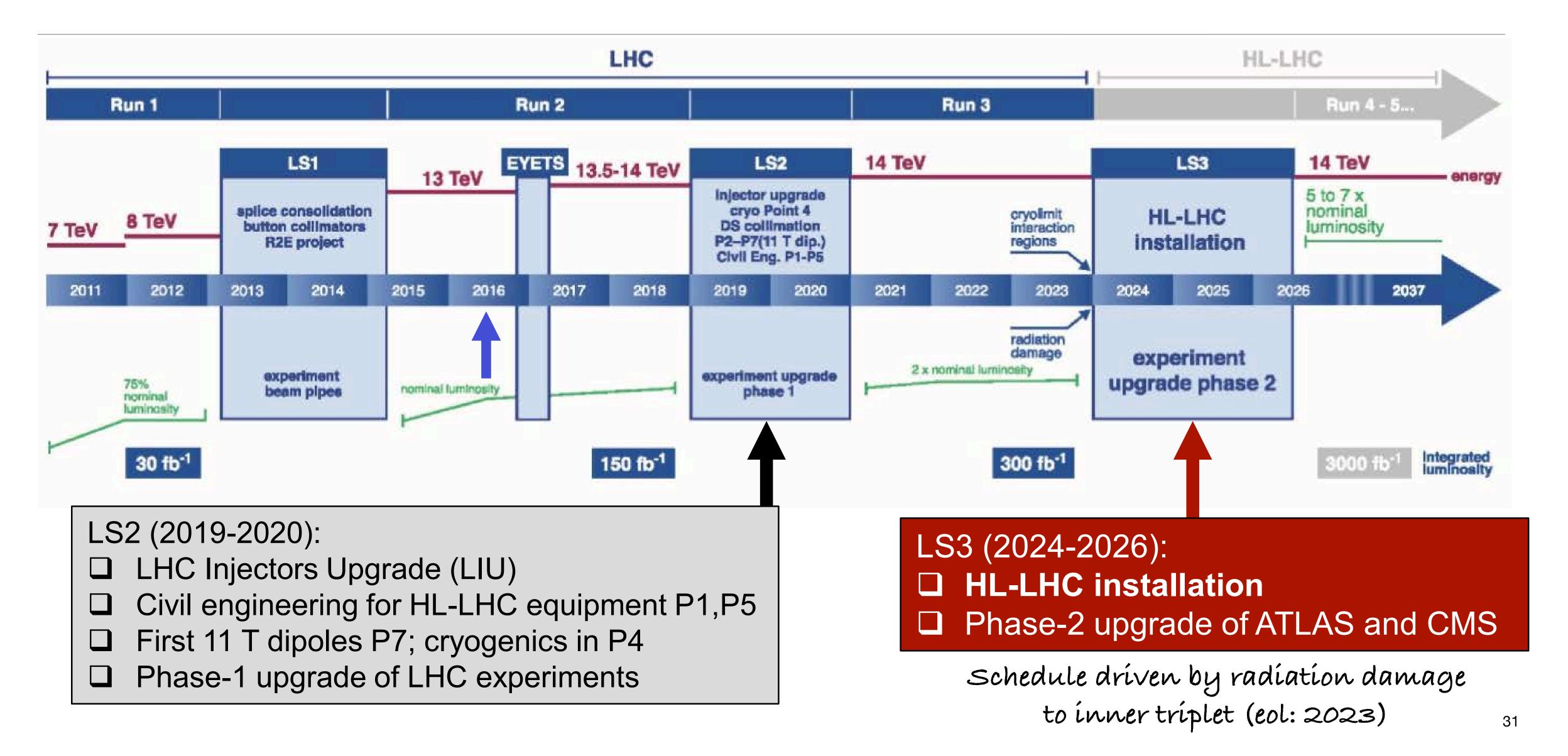
Linac 4 taken into operation

- Commissioning started
 2014
- protons have been accelerated to 160 MeV
- using π-mode structures PIMS for high energy acceleration

Inauguration 9.5.2017

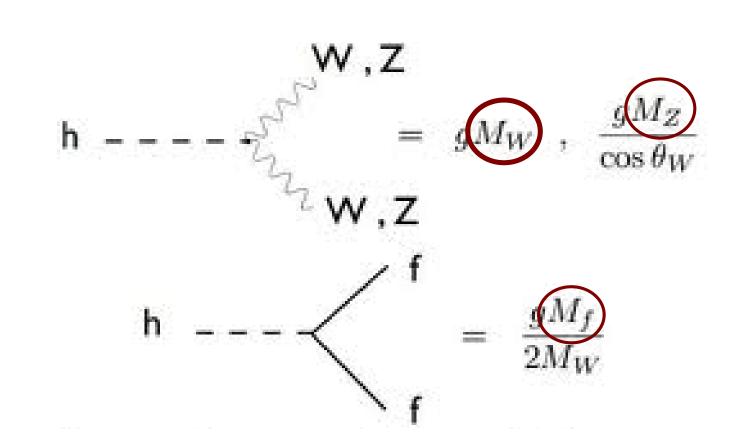


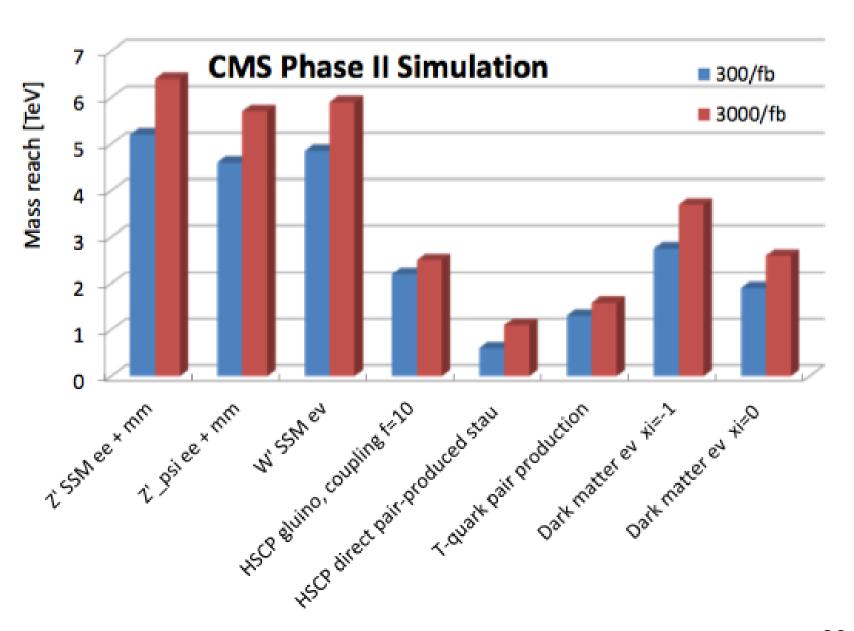
HL-LHC schedule



Just a few physics example for HL-LHC

- measurement of Higgs couplings
 - deviations may be at the few %-level
 - access to second generation couplings H→μμ
- 20-30% larger discovery potential (8 TeV)
 - precision measurements



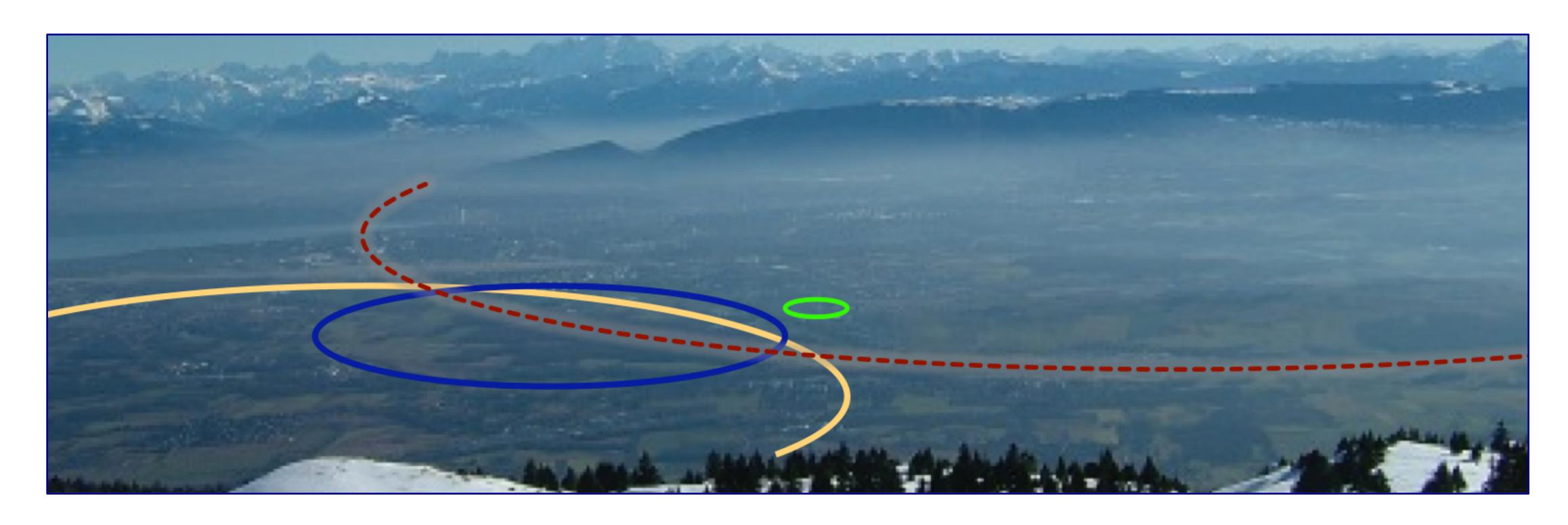


Highest energy

From European Strategy of Particle Physics

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.

Future Circular Collider FCC



- Study for a 100 km ring providing collisions at 100 TeV cms
 - employs injector chain of CERN

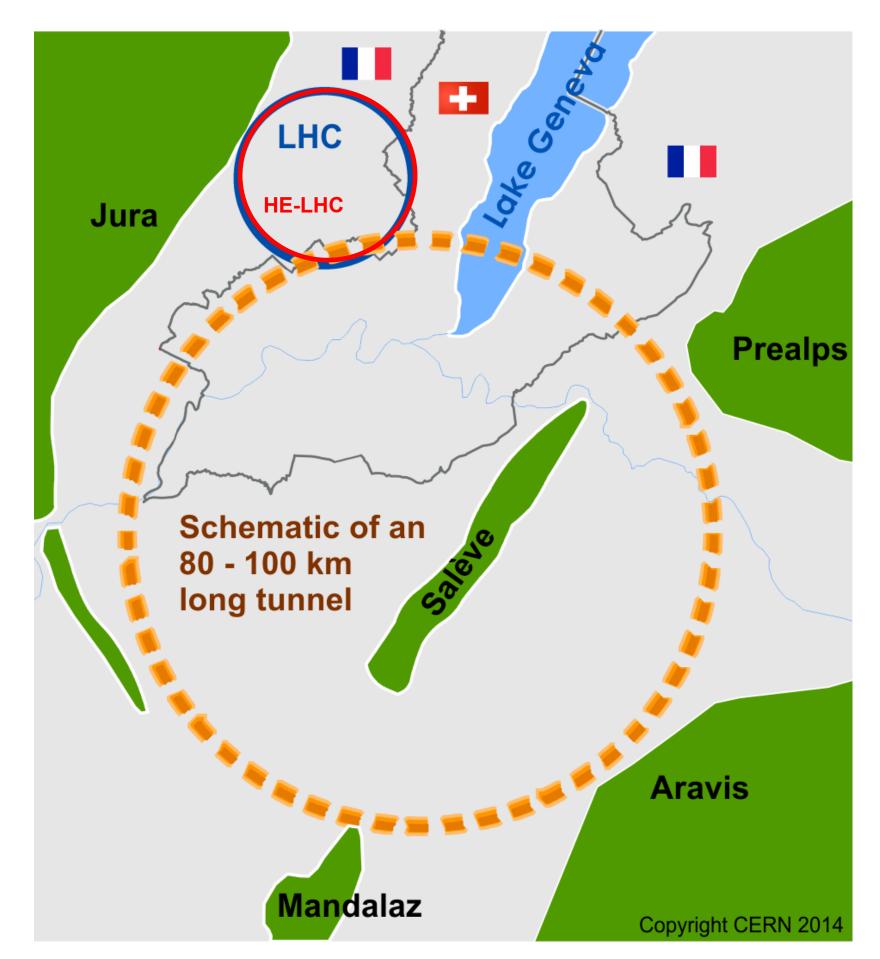
Highest energy with hadron colliders

High-field magnets

- Key to high energies
 - FCC and
 - HE-LHC = use of high field magnets in existing LHC ring
- Technology
 - Nb₃Sn allows ~16 T magnets that need to be developed (size, cost, industry...)
 - HL-LHC magnets provide a ~1.2 km test of the technology (11 T magnets)
 - an insert of HTS may increase field to 20 T (requires much research)

FCC Conceptual Design Report by end 2018

- · pp-Collider (FCC-hh) sets the boundary conditions
 - 100 km ring, √s=100 TeV, L~2x10³⁵
 - HE-LHC is included (~28 TeV)
- e+e--Collider as a possible first step
 - \sqrt{s} = 90 350 GeV, L~1.3x10³⁴ at high E
- eh-Collider as an option
 - $\sqrt{s}=3.5$ TeV, L~10³⁴



FCC-hh Parameters

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		1.1	1.1	0.58
bunch intensity [10 ¹¹]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	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	0.15 (min.)	0.55
normalized emittance [μm]	2.	2.2		2.5	3.75
peak luminosity [10 ³⁴ cm ⁻² s ⁻¹]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

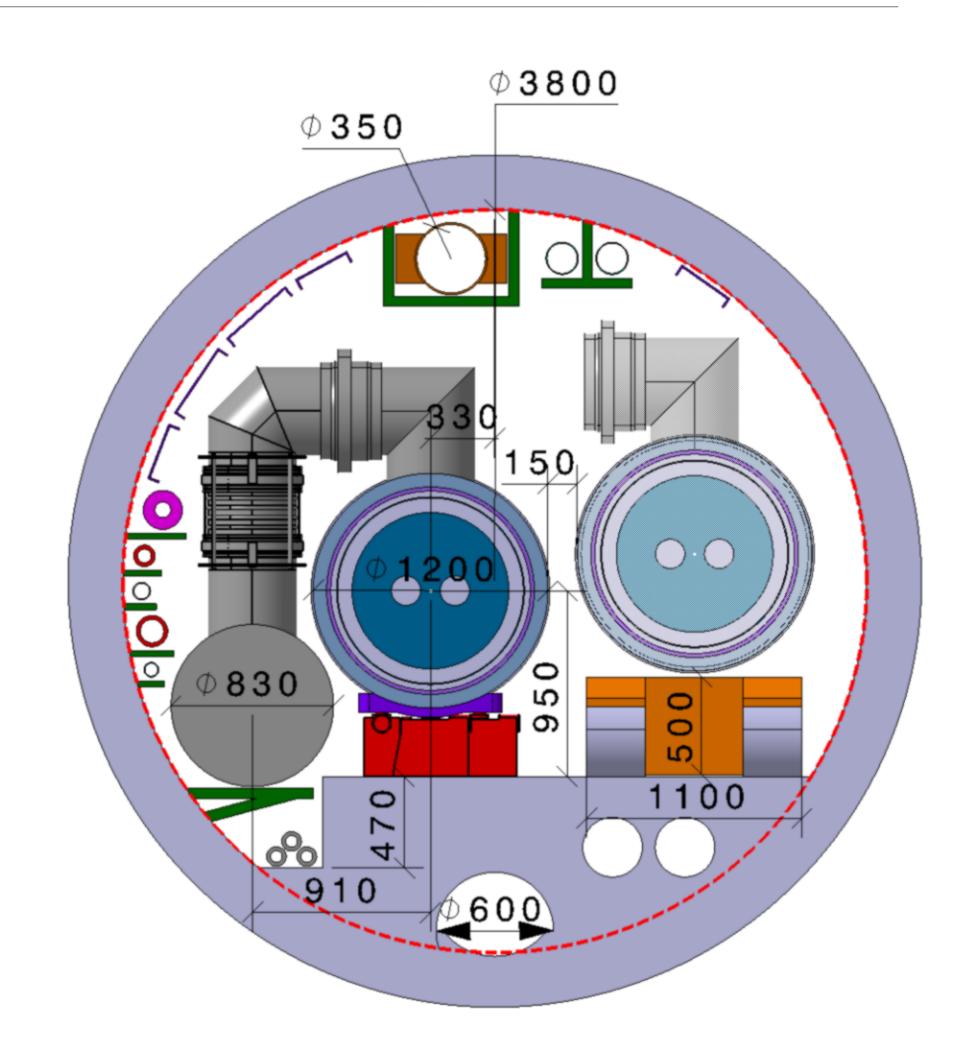
HE-LHC Integration aspects

Minimum civil engineering around the LHC

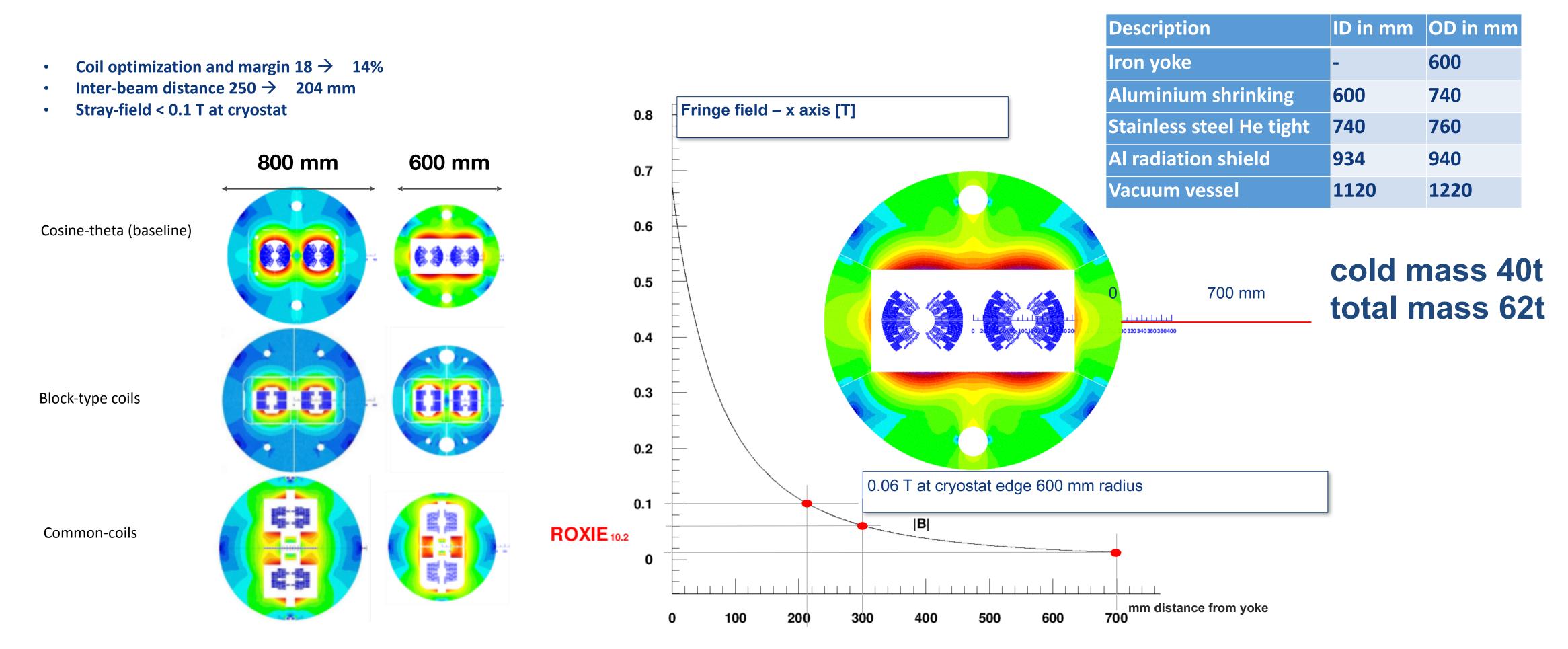
- Similar geometry and layout as LHC machine & experiments
- Maximum magnet cryostat diameter ~1200 mm
- Maximum QRL diameter ~830 mm

Integration Strategy

- Development of optimized 16 T magnet, compatible with both HE-LHC and FCC-hh
- New cryogenic layout to limit QRL dimension

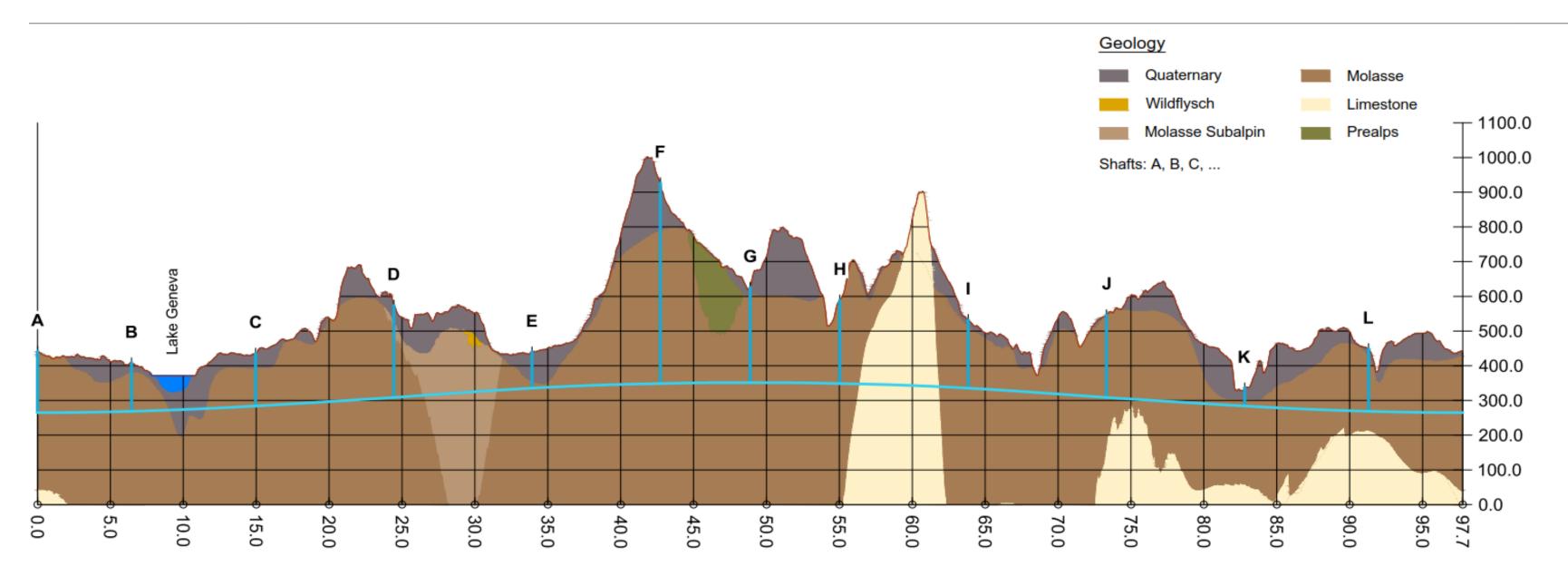


16 T Dipole Design Evolution

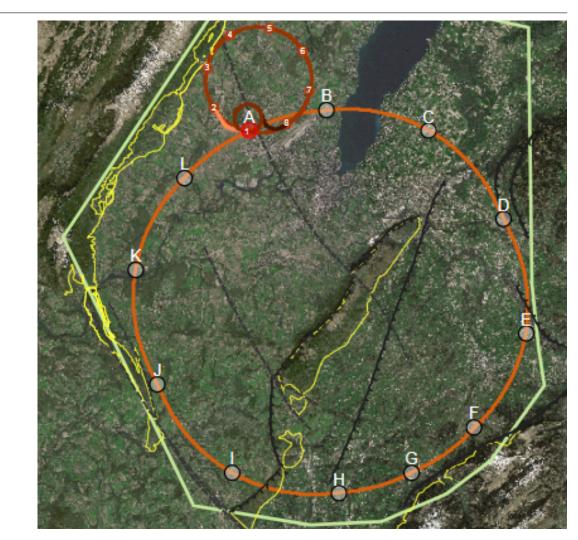


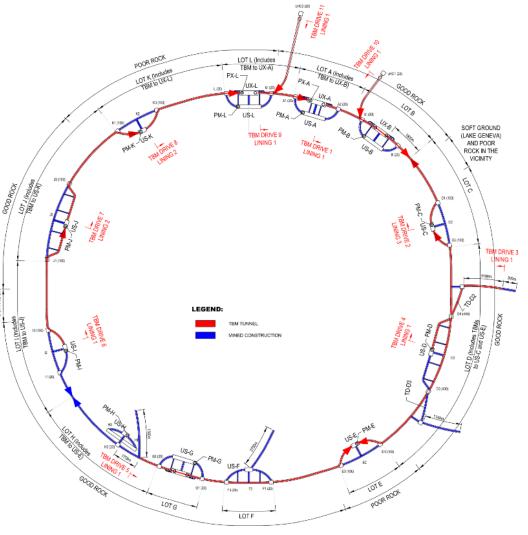
2015 2017

FCC Footprint



- Following geological review of the most challenging areas a new baseline position was established considering:
 - Lowest risk for construction
 - Fastest and cheapest construction
 - Feasible positions for large span caverns (the most challenging structures)



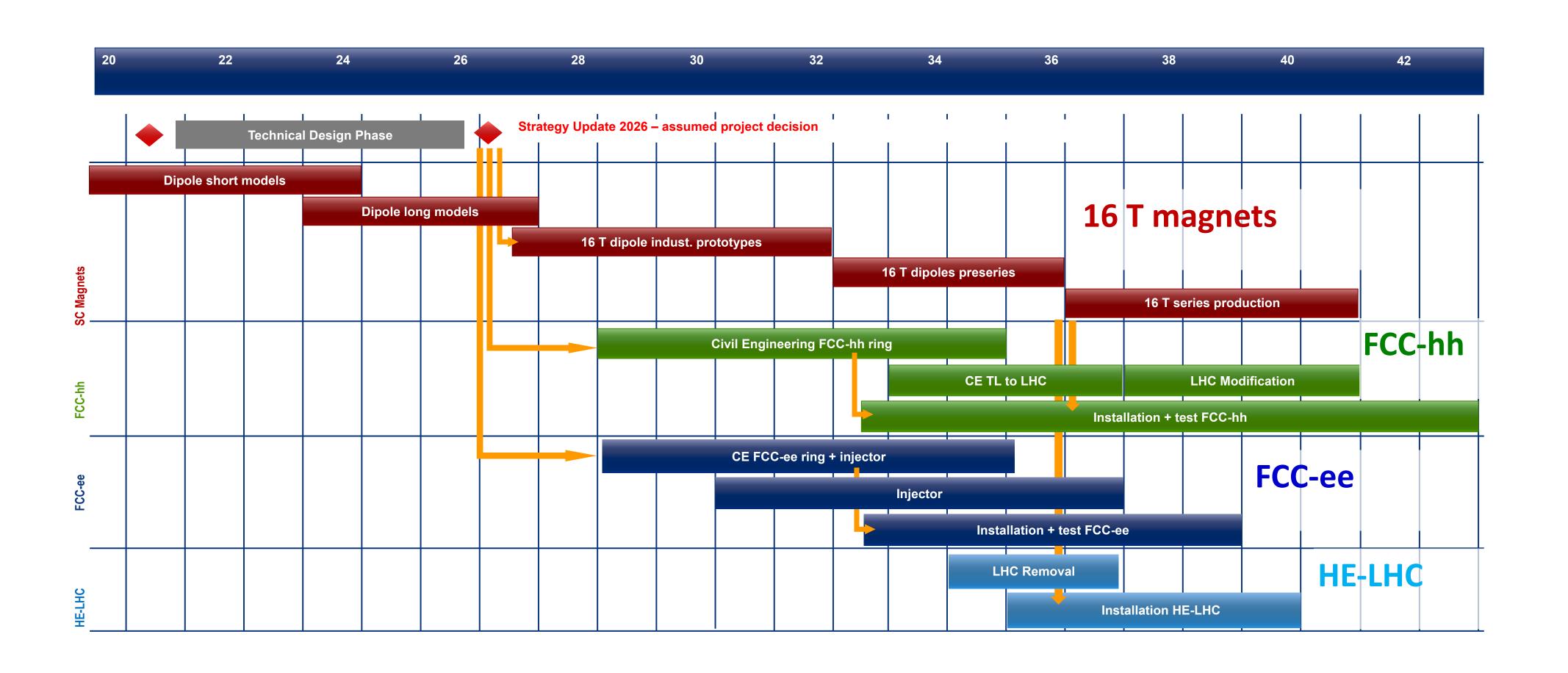


FCC-ee

FCC-ee Operations Model – a 14 years plan

working point	luminosity/IP [10 ³⁴ cm ⁻² s ⁻¹]	total luminosity (2 IPs)/ yr	physics goal	run time [years]			
Z first 2 years	100	26 ab ⁻¹ /year	150 ab ⁻¹	4			
Z later	200	52 ab ⁻¹ /year					
W	25	7 ab ⁻¹ /year	10 ab-1	1			
H	7.0	1.8 ab ⁻¹ /year	5 ab ⁻¹	3			
machine modification for RF installation & rearrangement: 1 year							
top 1st year (350 GeV)	0.8	0.2 ab ⁻¹ /year	0.2 ab ⁻¹	1			
top later (365 GeV)	1.4	0.36 ab ⁻¹ /year	1.5 ab ⁻¹	4			

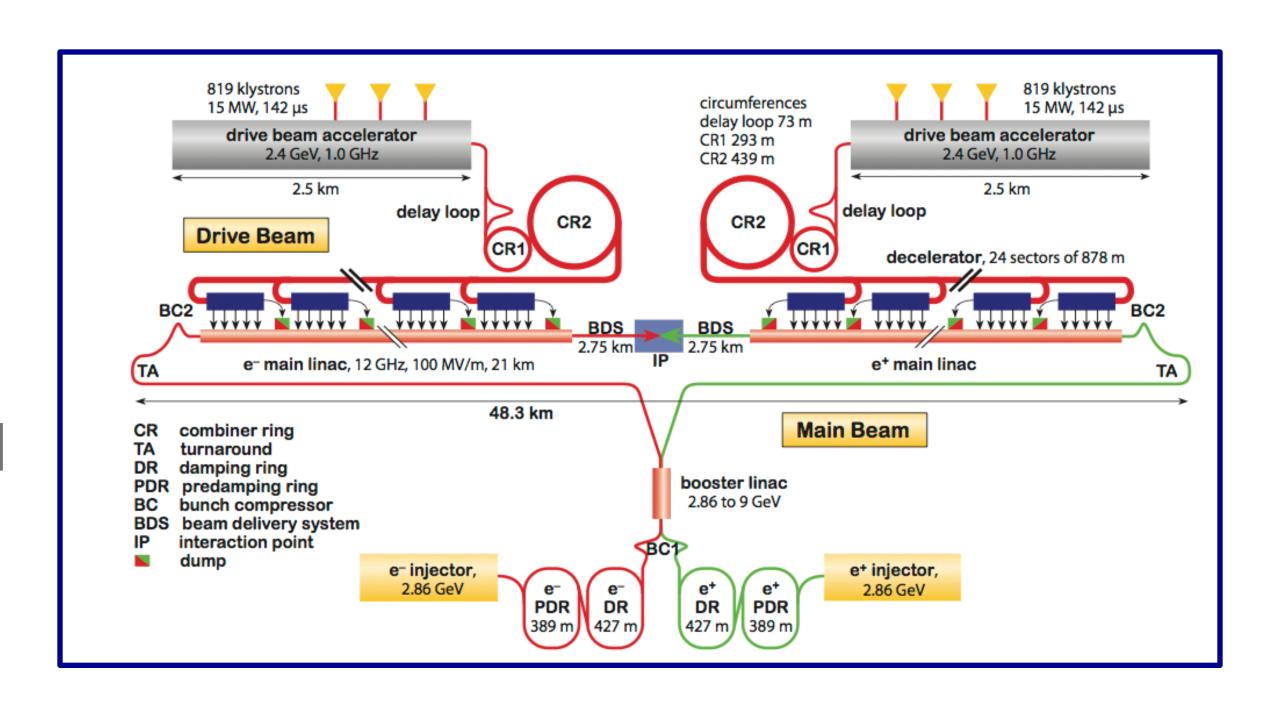
Technically driven schedule for the FCC-hh/ee and HE-LHC options



Highest energy with lepton colliders

Compact Linear Collider CLIC

- e+e- collider 1-3 TeV
- currently only option for the TeV region
- 380 GeV study has been completed both for 2-beam and klystrons approach; 250 GeV for ESPP
- decisive input to next update of European Strategy for Particle Physics



- CDR 2013
- CTF3 has provided key results
 - experimental programme ended 2016
- ready for a demonstrator; interest for FELs

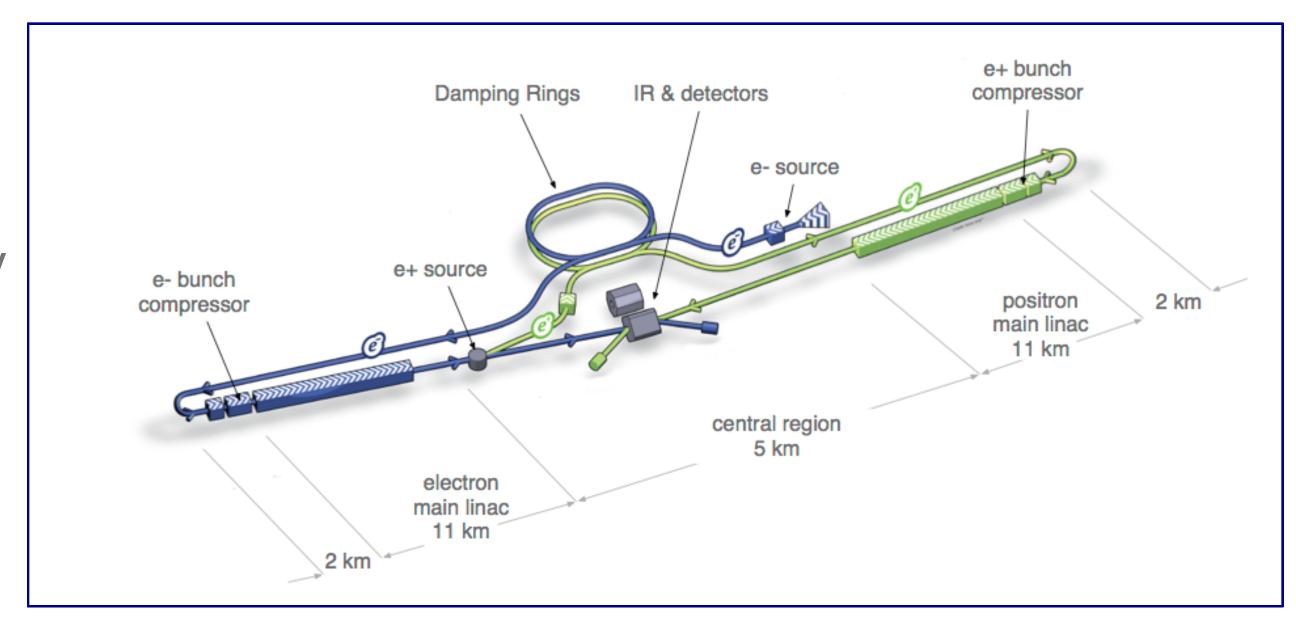
e+e- collider

 There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

Europe looks forward to a proposal from Japan to discuss a possible participation.

International Linear Collider ILC

- e+e- collider √s = 0.5 TeV
 (upgradeable to 1 TeV)
 - staged version for √s = 0.25 TeV
 now considered baseline
- precision Higgs programme; later
 Top and beyond
- Ministry MEXT continues to evaluate the implications of hosting ILC in Japan w.r.t. cost, manpower (skills)



- Project is mature (TDR 2012)
- hosting evaluated by Japanese government
 - international project (without host laboratory)

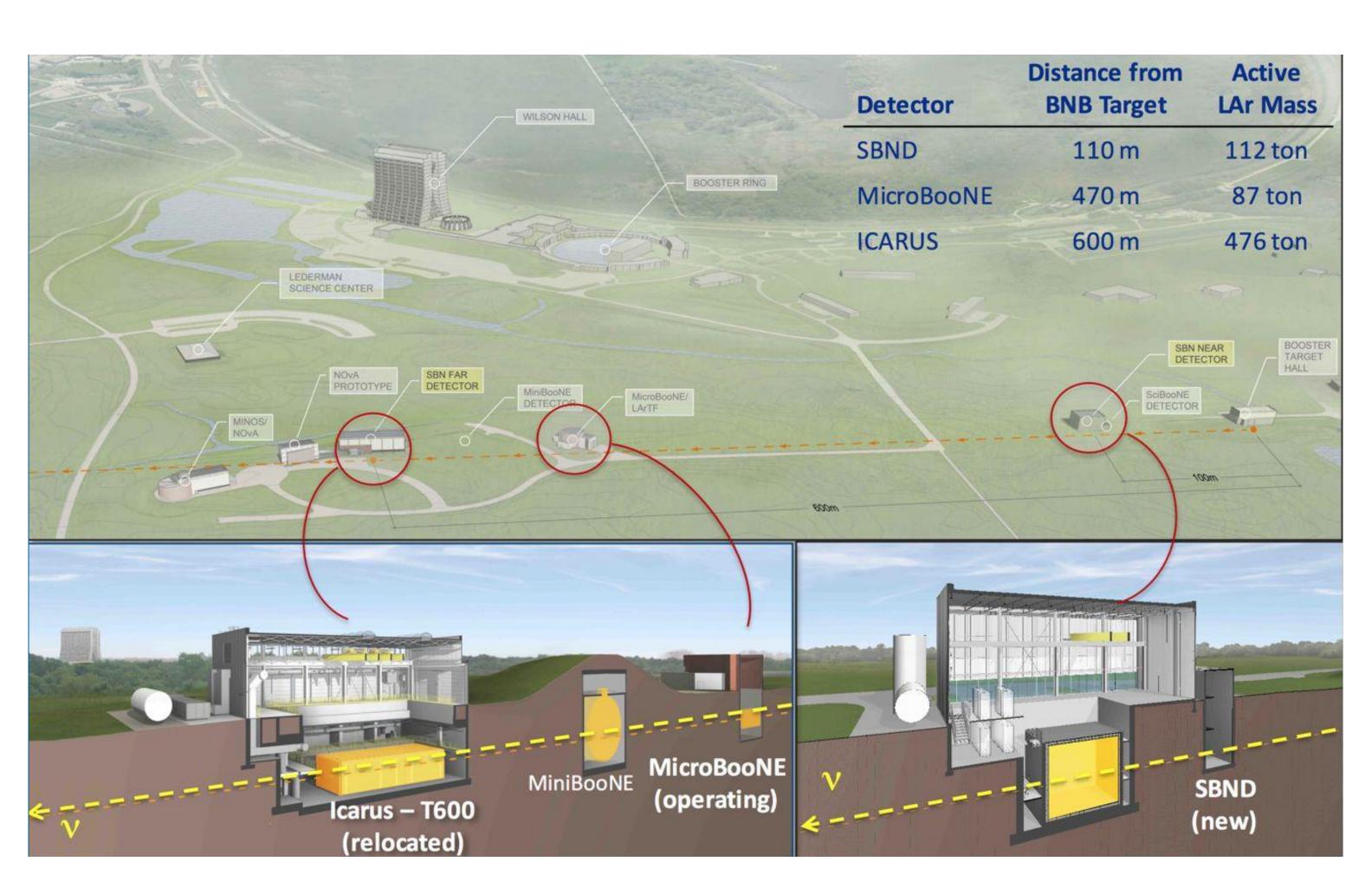
v-physics

From European Strategy of Particle Physics

Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

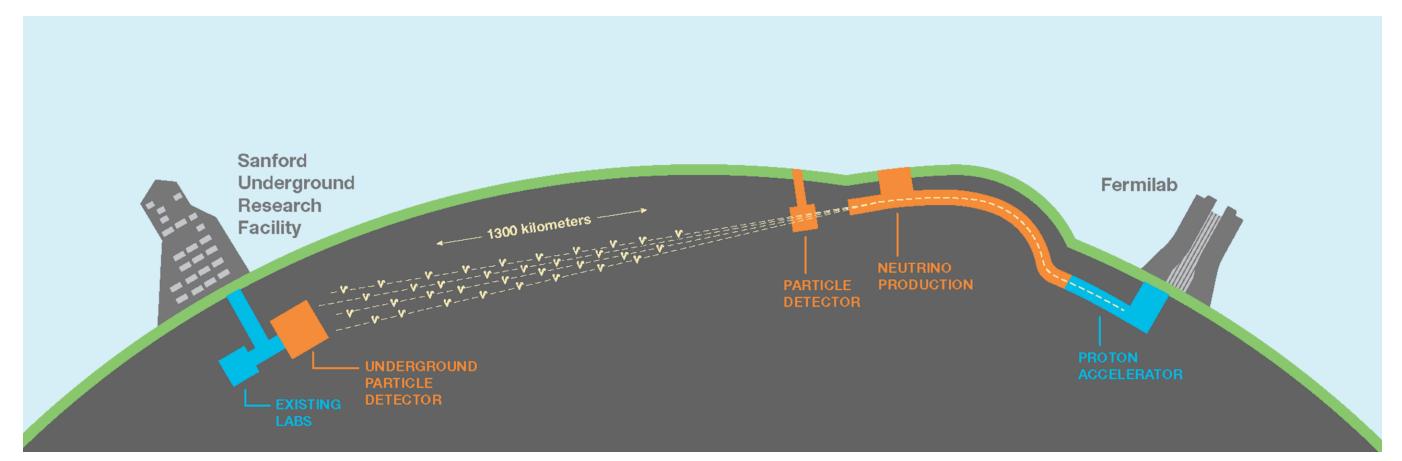
Short baseline programme at Fermilab

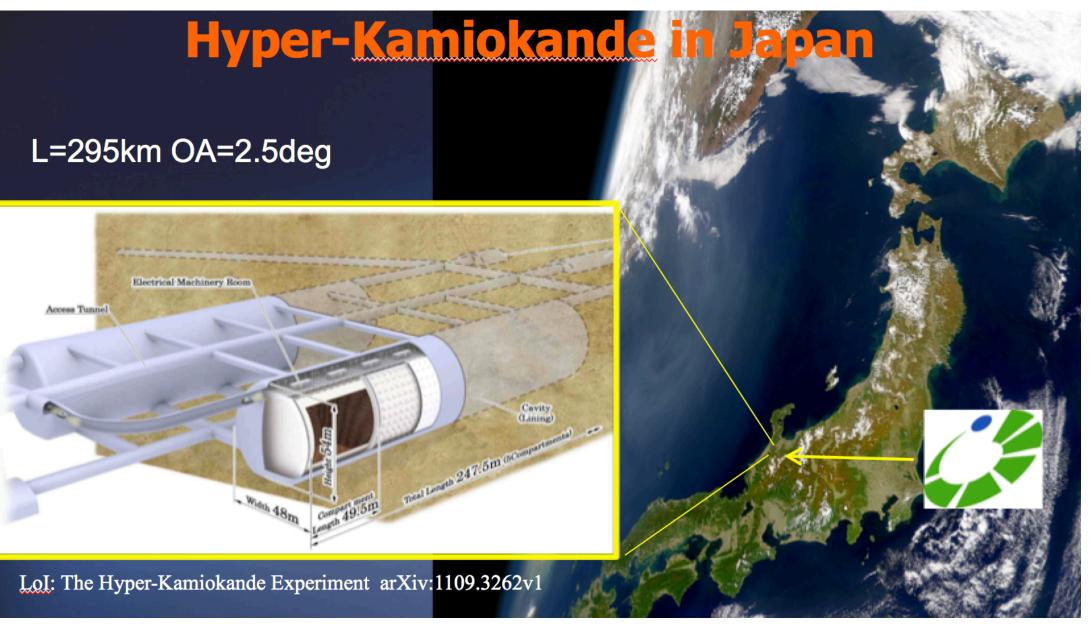
- To resolve experimental inconsistencies in the measured v-spectrum
 - SBND (near detector)
 - MicroBooNE (operating)
 - MiniBooNE
 - refurbished ICARUS at FNAL since 2017



Long baseline neutrino programmes

- Fermilab is planning a long baseline neutrino facility (LBNF), a wide band neutrino beam to the DUNE experiment (LArTPC) in South Dakota
- Tokyo is considering Hyper-K (water Cherenkov detector) at Kamioka
- Goals: neutrino-oscillation parameters, mass hierarchy and CP-violation





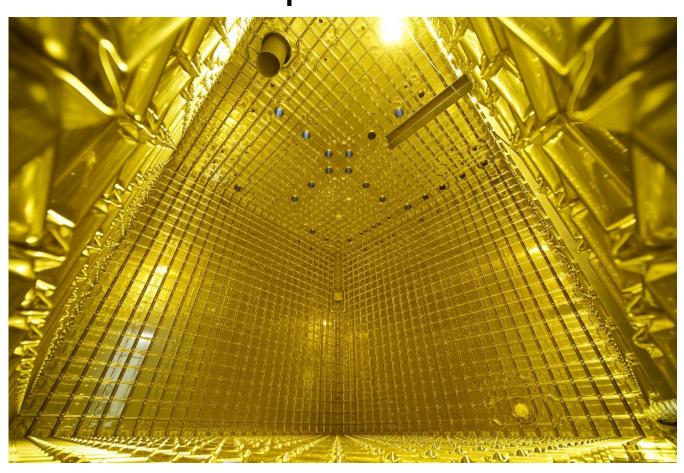
Neutrino Platform at CERN

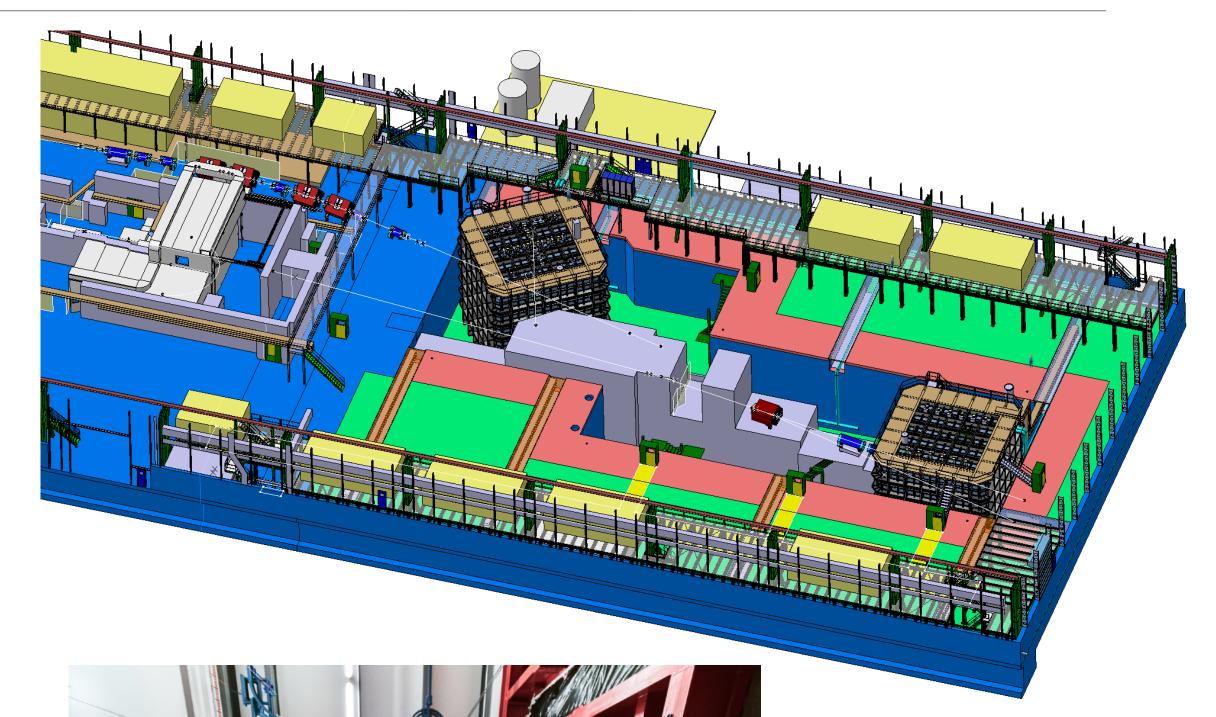
To develop experimental techniques, e.g. protoDUNE

- single phase LArTPC
- double phase LArTPC



inside protoDune







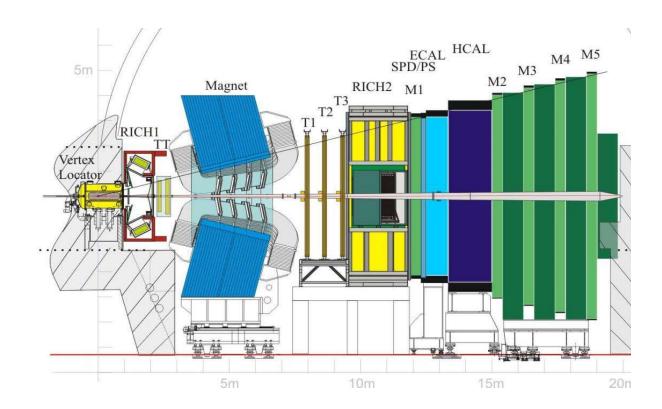
Physics Beyond Collider Study

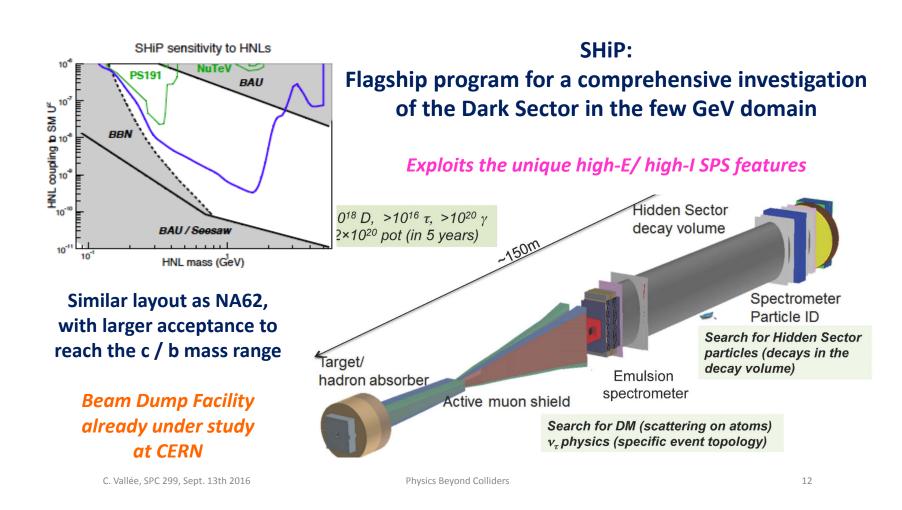


- Kickoff meeting held in September 2016
 - Study of fixed target programme

even with LHC beams

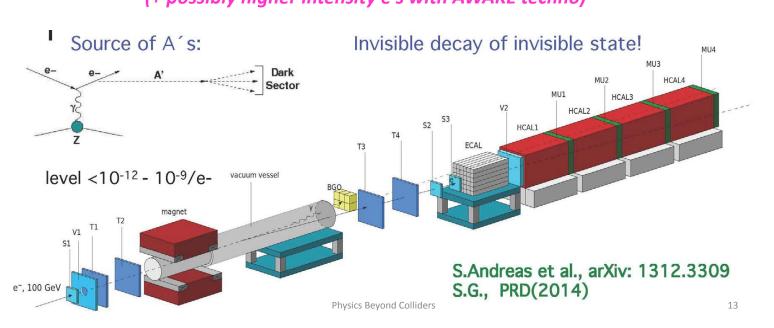
SMOG





Dark sector search complementary to SHiP: invisible decays from missing energy

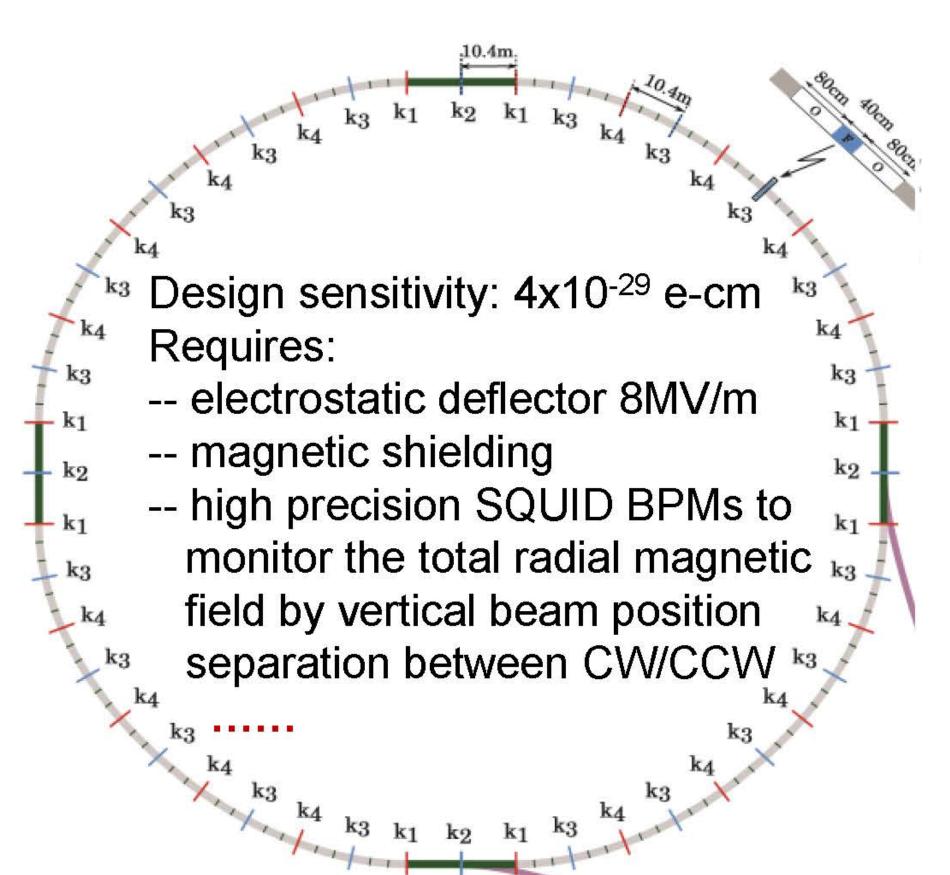
First implementation in 2016 by NA64 on an electron test beam Wish to extend the method to $\mu/\pi/K/p$ beams (+ possibly higher intensity e's with AWAKE techno)

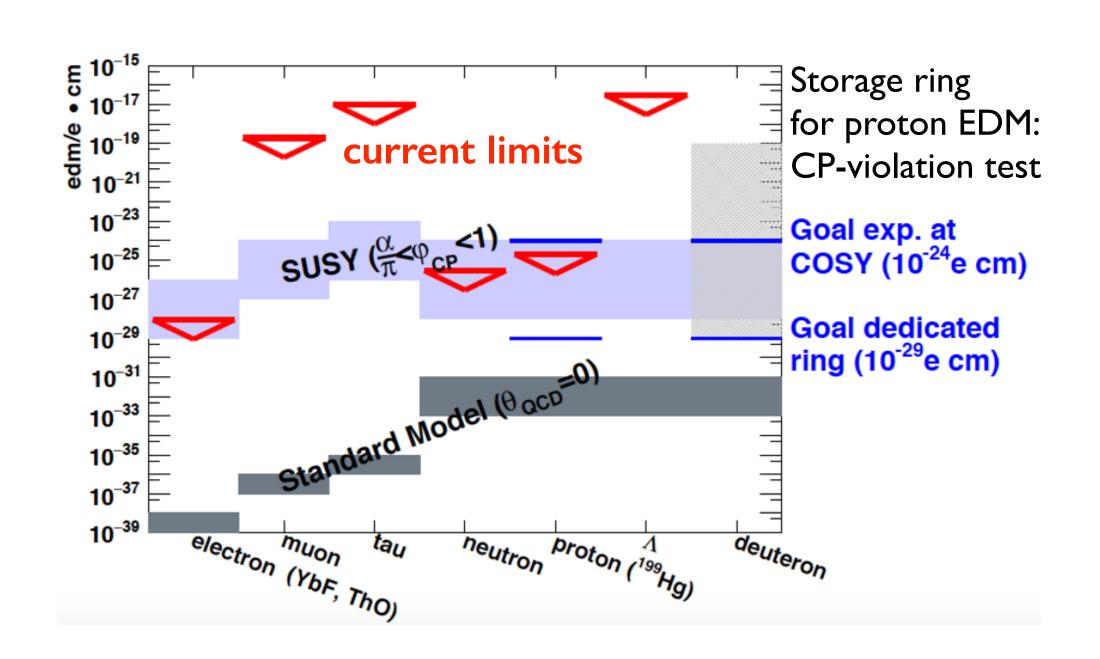






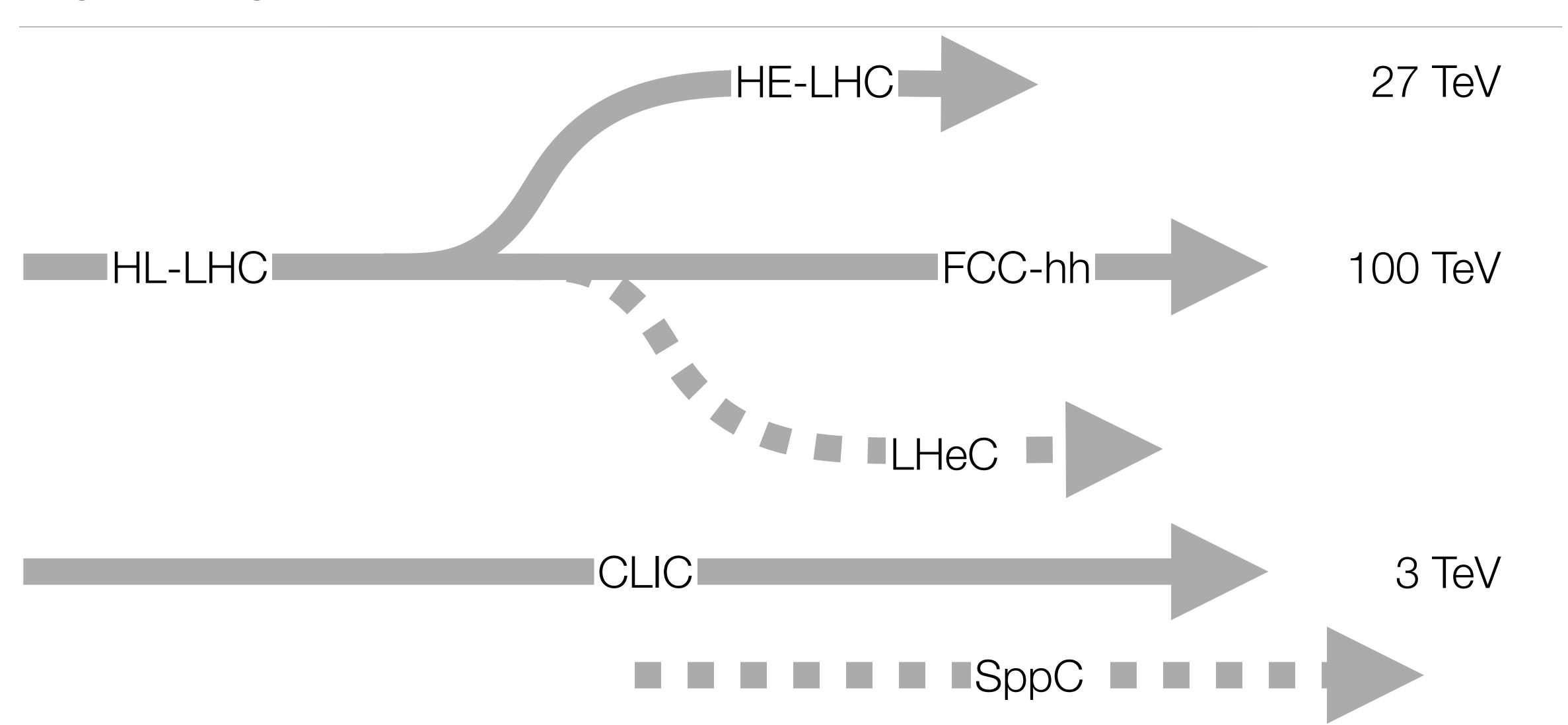
Study of an all-electric storage ring



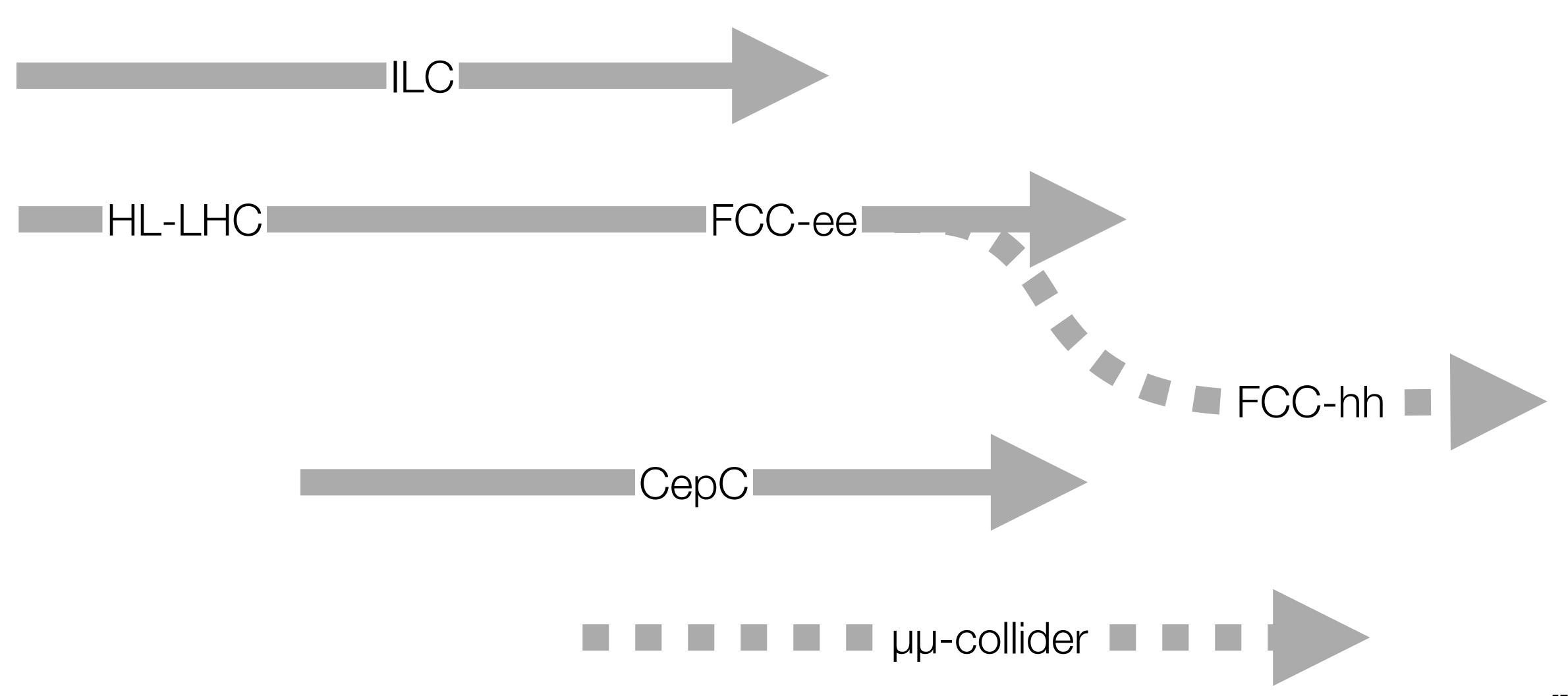


Sensitivity of 10-29 e-cm corresponds to 100 TeV for new physics scale

High-Energy Options



Lepton Collider Options for Higgs and beyond...



Clarification on ILC essential for ESPP update

Is Japan prepared to host ILC as an international project with the typical host contribution for such projects?

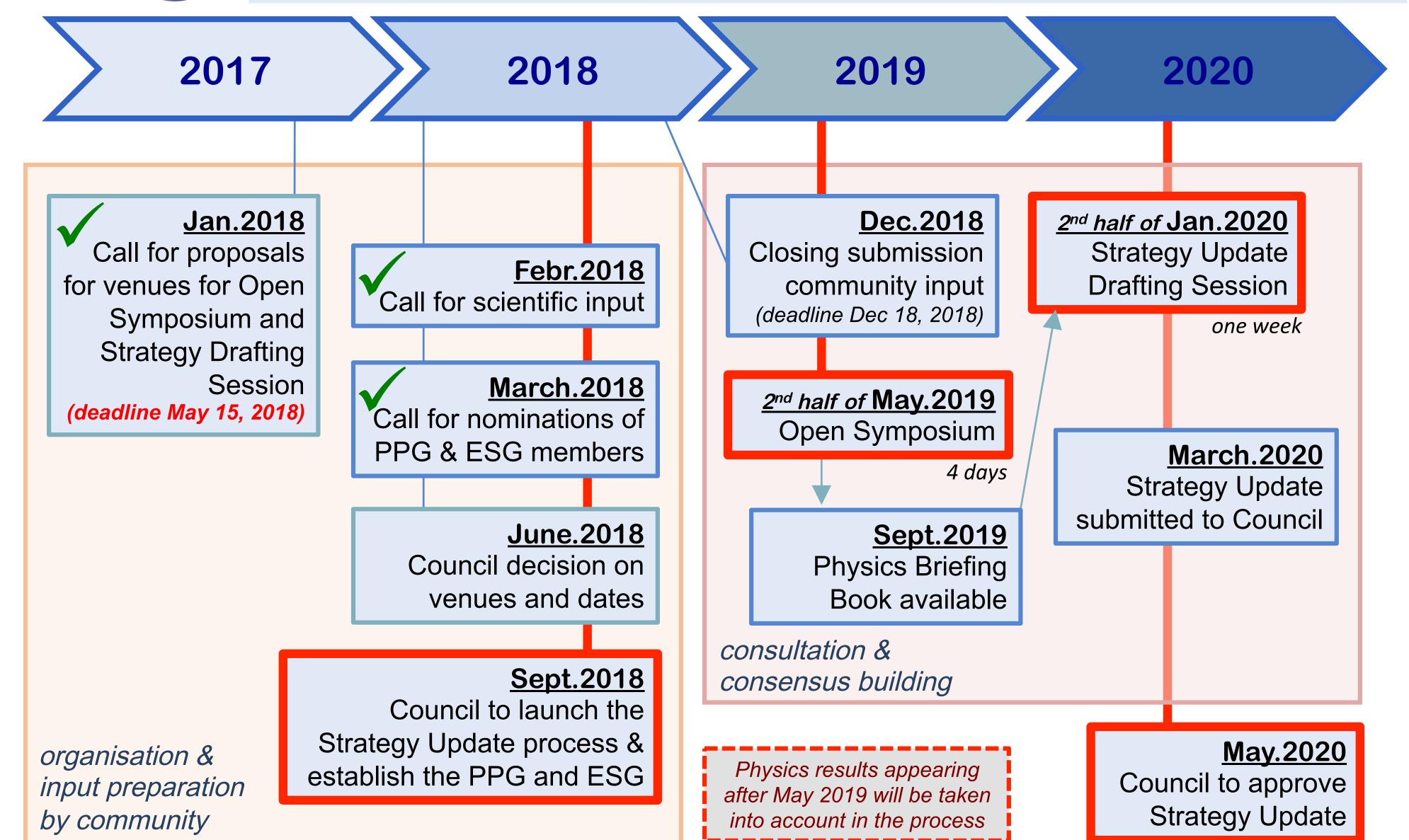
YES

Invigorating for the field

- CERN focus on LHC and its upgrades
- European involvement in ILC to enter a constructive phase after consideration with Funding agencies
 - · Example from ongoing strategy albeit at a smaller scale: Neutrino Programme
- NO
 - · broad discussion on role of lepton colliders as precision tools vis à vis energy frontier machines



European Particle Physics Strategy Update



Summary

- Experimental Programme of LHC extremely rich; long range experimental programme guarantees physics return
 - by exploring the highest energies
 - by searching for violations of the SM in (highly sensitive) rare decays
- Preparing Update of the European Strategy for Particle Physics
 - LHC and HL-LHC
 - Energy Frontier

Vibrant physics programme beyond colliders

2018 (end): reports on Physics

2019: community discussion

2020: update publicly released