Les expériences du future: détecteurs

École de GIF 2019, 2-6 Septembre 2019

École polytechnique - Palaiseau

D. Contardo - IP2I CNRS/IN2P3

Programme scientifique de l’école

“ Question ouvertes en physique des particules “

- 50 ans de l’école de Gif, J. Iliopoulos
- État de l'art expérimental et théorique, J. Zinn-Justin
- Questions ouvertes en physique des particlues, G. Servant
- Les expériences du futur:
  - Accélérateurs, Frank Zimmermann
  - Détecteurs, D. Contardo
  - Potentiel de physique, G. Hamel de Monchenault
- Évolution des outils:
  - Analyse par apprentissage automatique, D. Rousseau
  - Calcul parallèle et données massives, D. Chamont
- Les réponses venues d’ailleurs, C. Yèche

Future experiments: detectors

- Introduction
  - International context
  - General considerations to design a collider experiment
  - Upgrades of operating experiments and next generation at future colliders
- Detectors: designs and technologies, state of the art and trends for future
  - Tracking systems
  - Calorimeters
  - Gas detectors
  - Radiation detectors (RICH, TRT)
  - Minimum Ionizing Particle Time of Flight detectors
- Outlook
  - Some topics not covered
  - R&D programs

International context

International context: ESPP process

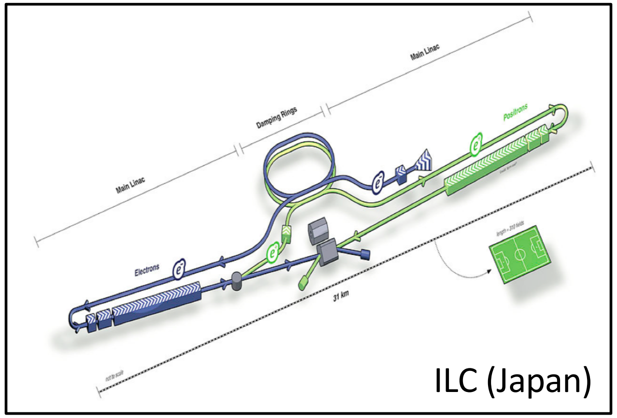
Process engaged by CERN to update the European Strategy for Particle Physics and make recommendations for the next generation of colliders

- Information available at: *https://cafpe.ugr.es/eppsu2019*
    - Inputs from all communities, Dec. 2018
    - Granada symposium, May 2019
    - Briefing book summary from Granada Symposium, Sept. 2019
- Strategy update submission to CERN Council, Mar. 2020
- Approval by CERN Council, May 2020

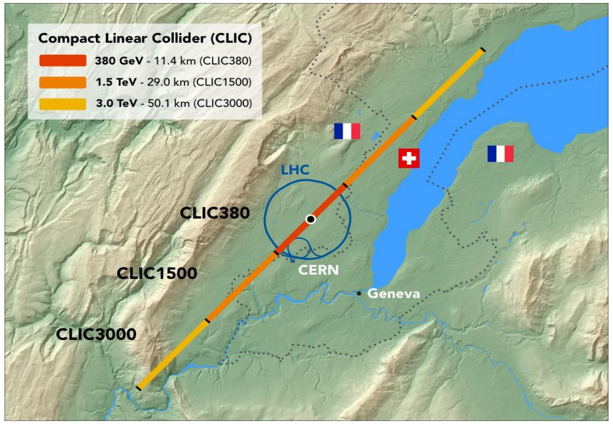
International context: future e-e collider proposals

e^+-e^- collider projects, technologies and overall designs considered mature (R&D $\simeq$ 5 years)

Linear Colliders: 1 Interaction Point

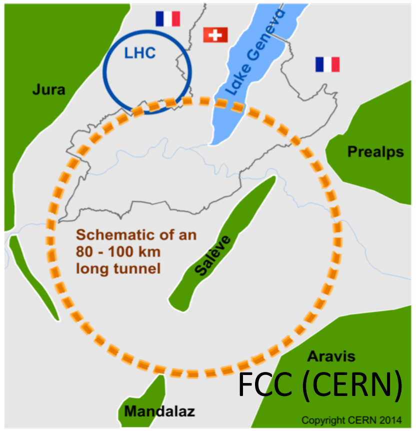


20(30) km 250(500) GeV, 1.3 GHz
SCRF cavities 30 MV/m

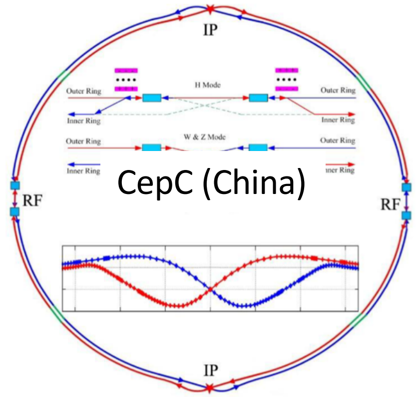


11/29/50 km (0.38/1.5/3 TeV), 12 GHz,
NCRF X-band 72/100 MV/m, e-drive beams

Circular Colliders: 2 Interaction Points



100 km, FCC-ee 360 GeV,
SCRF



100 km, CEPC(ee) 240 GeV,
SCRF

Technical dates, real start depends on approval time
CepC planning seems optimistic

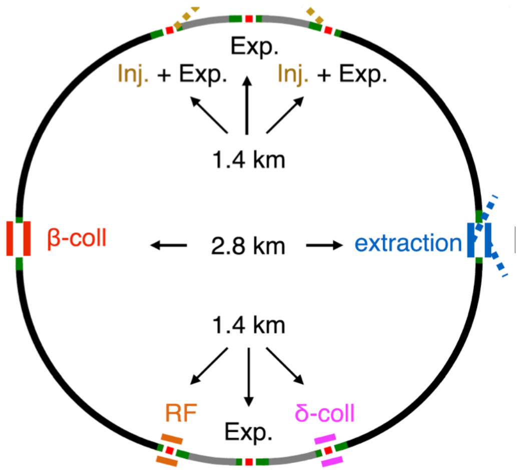
Planning (from projects)	CepC	ILC	CLIC	FCC-ee
Start construction	**2022**	**2024**	**2026**	**2029**
Start physics	**2030**	**2033**	**2035**	**2039**

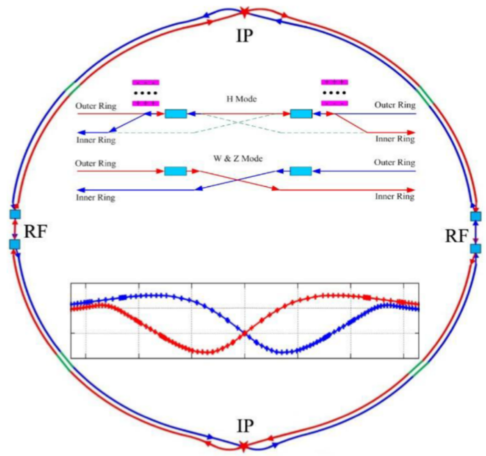
https://indico.cern.ch/event/808335/contributions/3380835/attachments/1845110/3026925/Summary-Accelerators-Granada.pdf

International context: future h-h collider proposals

h-h collider projects, timeline/energy can be adjusted to SC magnet R&D progress

FCC-hh - 100 km
100 TeV, 16 T magnets
2+2 high/low luminosity IPs





SppC (CepC) 100 km
75/120 TeV, 12/24 T magnets
2 high luminosity IPs

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

https://indico.cern.ch/event/808335/contributions/3365195/attachments/1842846/3038724/ESPP-Symp-2019-ay-190513bb.pdf

Future colliders: possible energy and luminosity scenarios

	T_0	+5	+10	+15	+20	...	+26	Cost estimates
ILC	2033; 0.5/ab 250 GeV	1.5/ab 250 GeV	2044; 1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV	2055		4.8/5.3+8 B$ (2012)
CEPC*	2030; 5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$	2040			SppC =>	5B$ (ee)
CLIC	2035; 1.0/ab 380 GeV	2043	2.5/ab 1.5 TeV		5.0/ab => until +28 3.0 TeV			5.9+5.1+7.3 BCHF
FCC*	2039; 150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV	2048; 1.7/ab ee, $2m_{top}$	2054	2063	hh,eh	11.6+17 BCHF (ee+hh) 24 BCHF (hh only)

** Integrated luminosity for 2 Experiments*

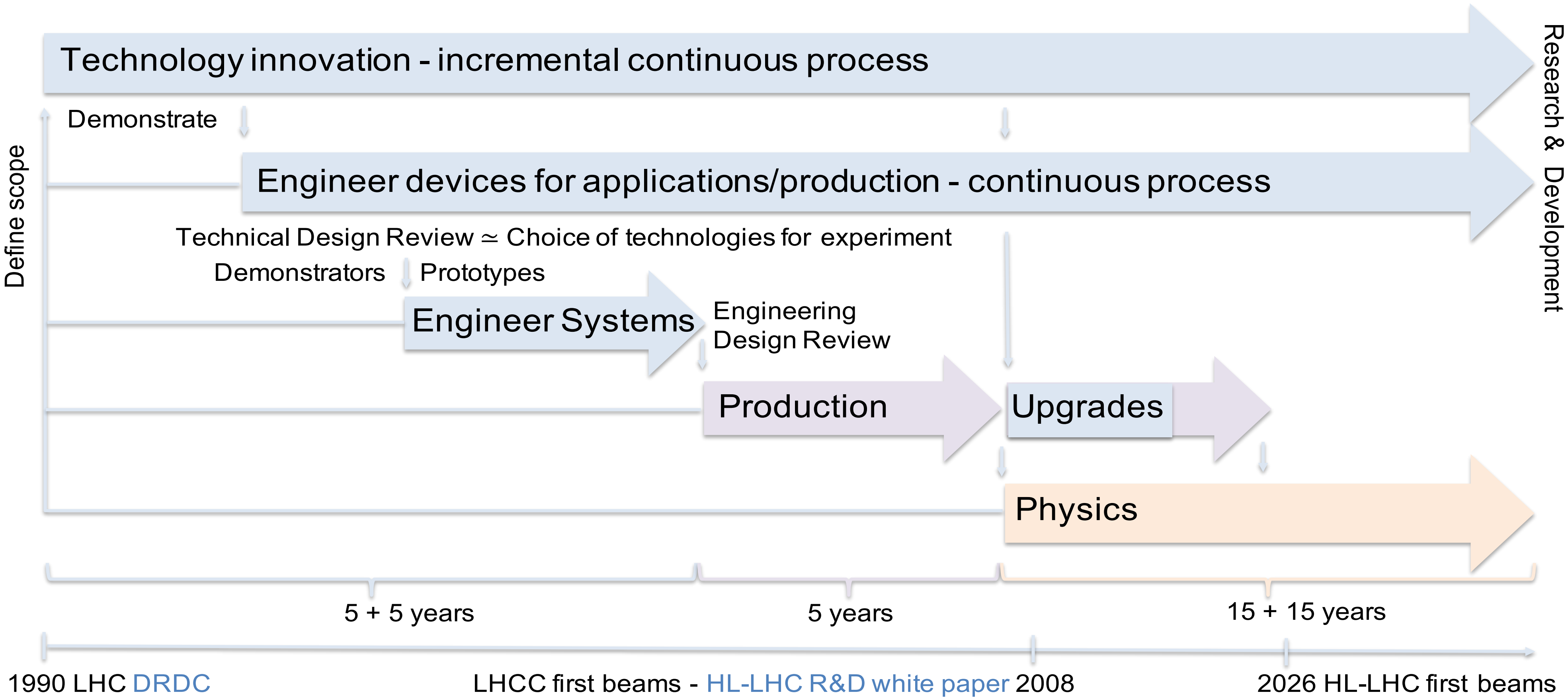
In above scenarios FCC-hh and SppC follow e-e colliders, they could technically start physics earlier

- FCC-hh luminosity scenario includes plan for concurrent operation with e-p, Pb-Pb, e-Pb beams

	√s	L /IP (cm⁻² s⁻¹)	Int. L /IP(ab⁻¹)	Comments
pp FCC-hh	100 TeV	5 x 10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39 TeV	3 x 10^{29}	65 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

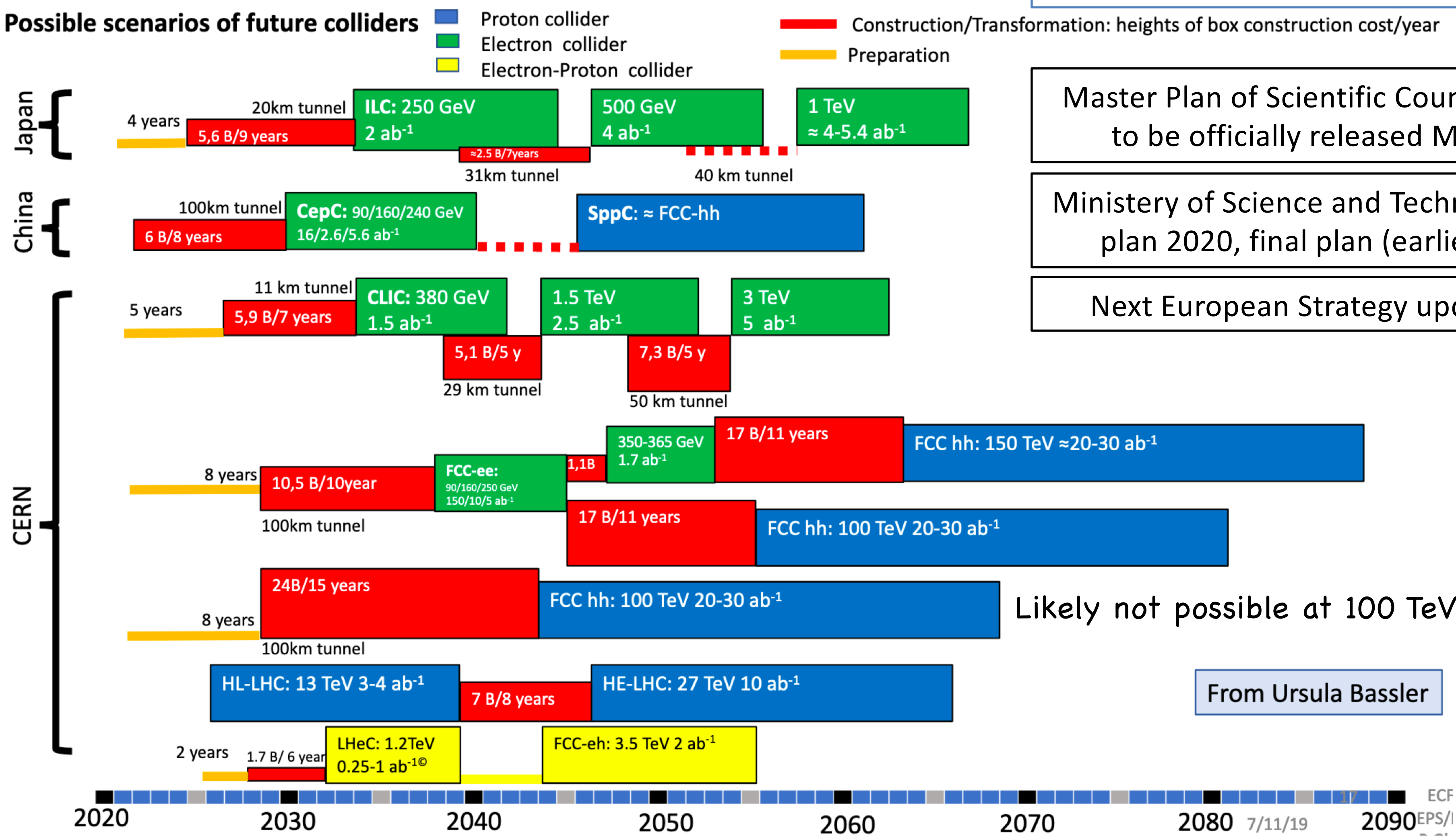
https://indico.cern.ch/event/808335/contributions/3365200/attachments/1843527/3026009/ESPP-Fabiola.pdf
https://indico.cern.ch/event/808335/contributions/3380835/attachments/1845110/3026925/Summary-Accelerators-Granada.pdf

Future colliders: timeline considerations based on LHC experience



Future colliders: project timescales (few more scenarios)

Possible timelines for decisions



Master Plan of Scientific Council of Japan to be officially released May 2020

Ministery of Science and Technology initial plan 2020, final plan (earliest) 2022

Next European Strategy update 2026

Likely not possible at 100 TeV before ≃ 2055

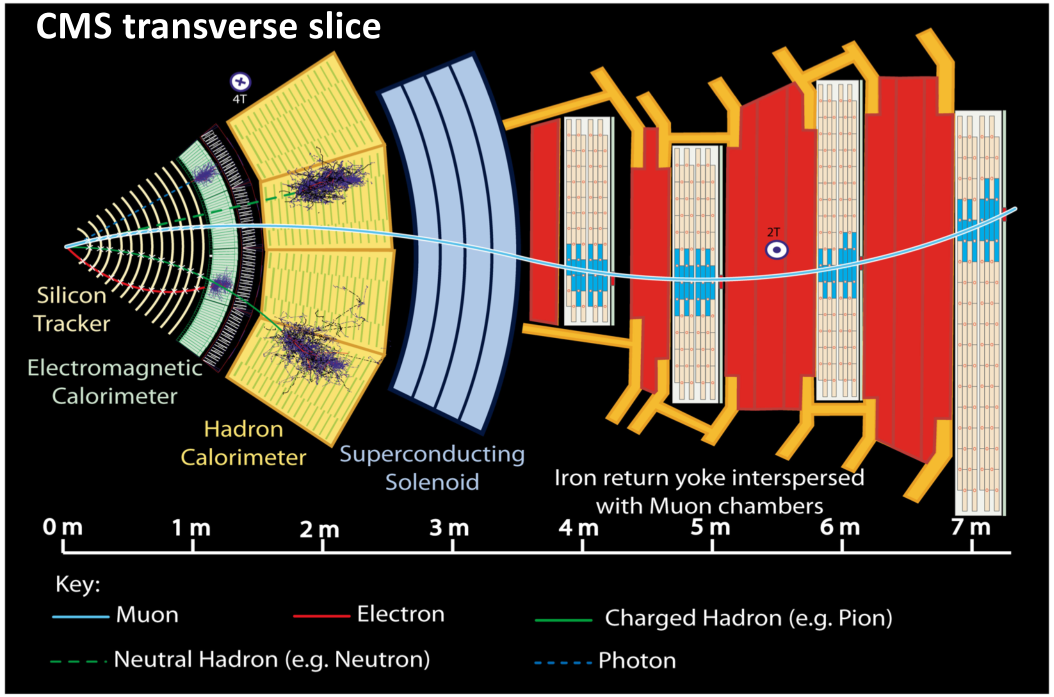
From Ursula Bassler

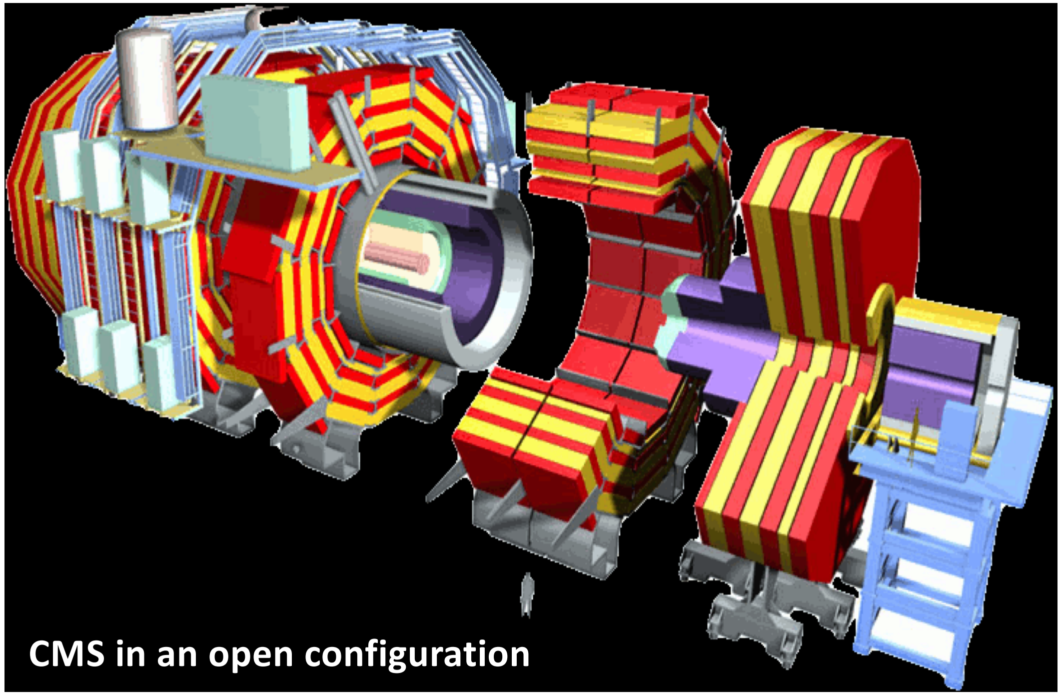
General considerations to design a collider experiment

Collider experiment design considerations: overall drivers

- Technical options and configurations that can achieve performance considering
  - Physics reach
  - Specific operating conditions
- Reliability, and margins of these technical options
  - For large scale production, long term operation
  - With respect to operation uncertainties, progress of data reconstruction & new physics ideas
- Redundancy in configuration
  - To mitigate possible unexpected failures or operation accidents
- Affordability and availability of the technical options and configurations
  - Within expected budget and schedule
- Maintainability and upgradability
  - During regular (Year End) accelerator Technical stops and Long shutdowns (need to consider activation in choice of detector materials, accessibility and appropriate tools…)

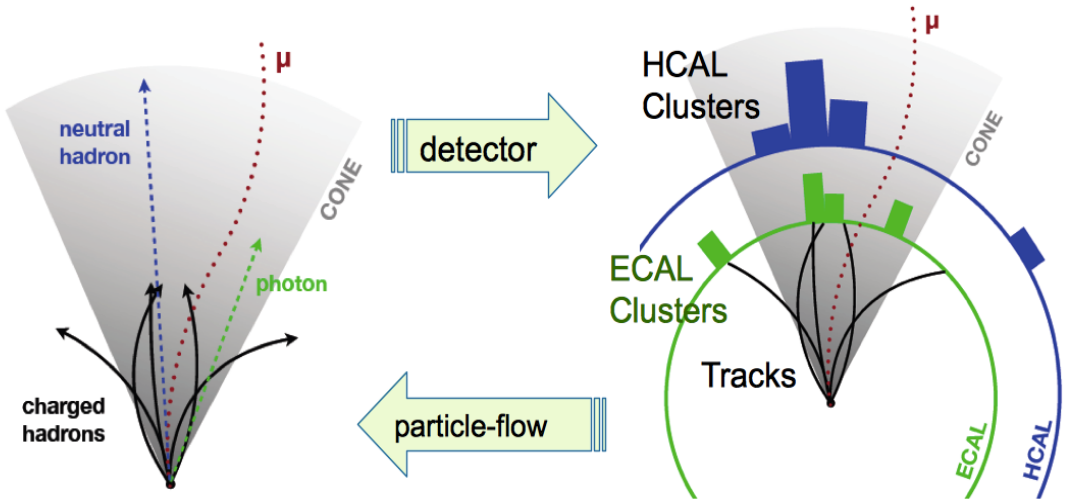
Collider experiment: generic design and specificities





- Magnet(s) choice drives the overall configuration of the detectors
- Choice of technologies is driven by performance optimization and experiment physics priorities
- An ideal detector is as hermetic as possible (crack-less), with largest possible η coverage and allowing maintenance where possible (inner/forward most radiation exposed areas particularly)

Collider experiments: from measurement to physics results

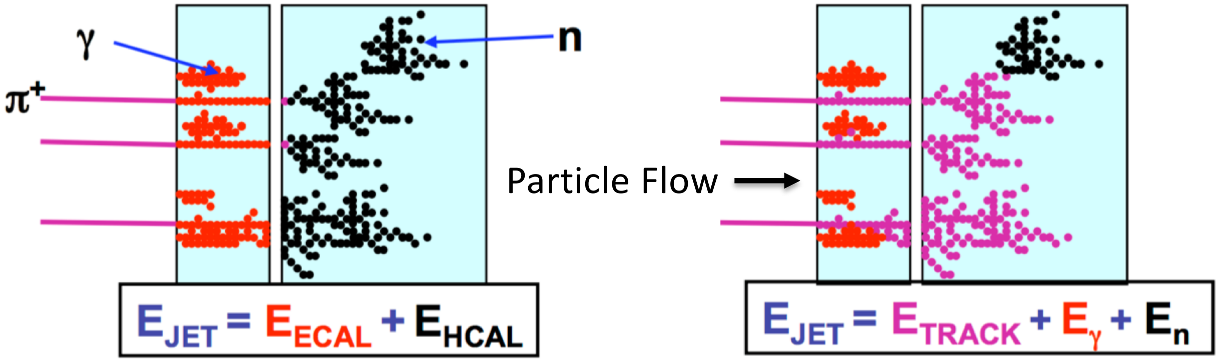


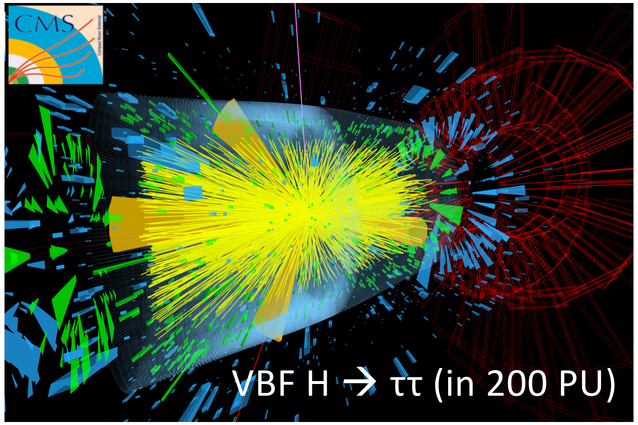
1) Tuning and calibration establish the detector response continuously according to beam, environmental conditions, and detector aging - it requires instrumentation and monitoring tools
   - Operating parameters are tuned to maximize Signal to Noise ratio (S/N) (often at channel level)
   - Signal is calibrated across channels, they are aligned in space and time
2) Local reconstruction establish particle hits, it relates to intrinsic detector granularity and precision
   - Build cluster of channel's response considered to belong to one particle hit

Collider experiments: from measurements to physics results

3) Global reconstruction build particles (physics objects) it relates to technology performance, and detector configurations, individual and combined

- Combine layers and all systems information to
  - Identify and isolate e/μ/τ/γ
  - Build hadron/gluon jets and total and missing energy (ν, dark matter)





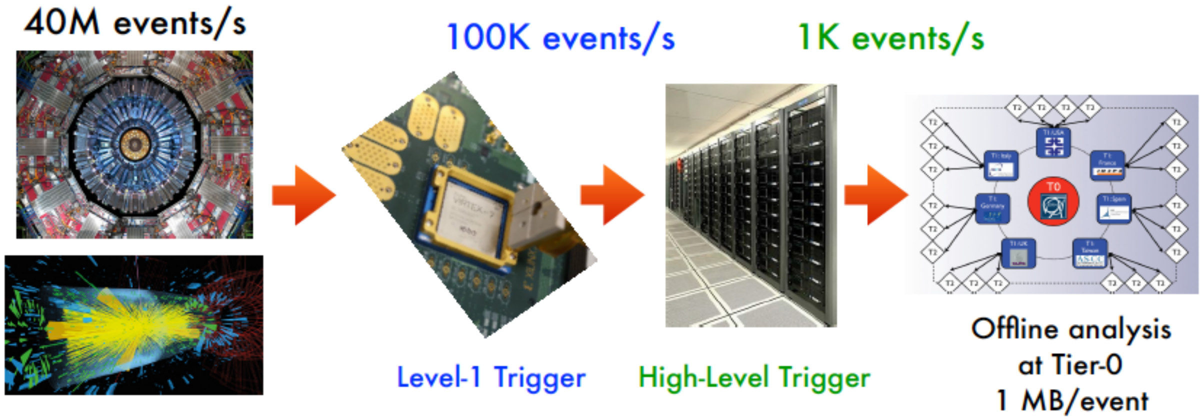
4) Physics analyses establish the ultimate impact of detector performance on specific signals

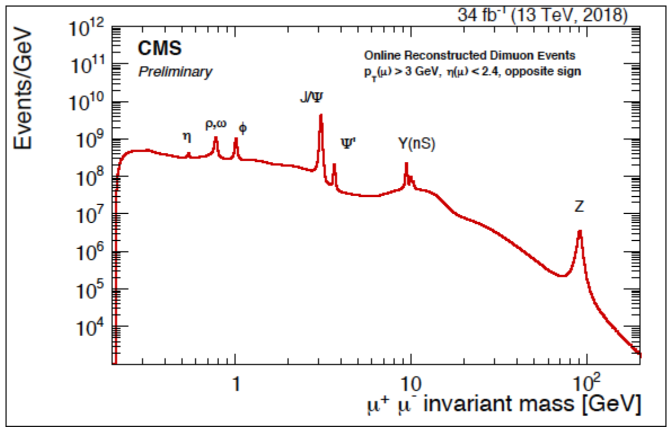
- Reconstruct candidate decay of fundamental particles
  - W, Z, H, t, new particles…
- Extract signal from background, compare to theory and estimate uncertainties

Collider experiments: event selection and data reduction

To fit in computing capacity (storage and processing power), combinatorial background should be eliminated and physics events can be pre-scaled according to cross sections and interest, data from detectors can also be compressed in a two step process

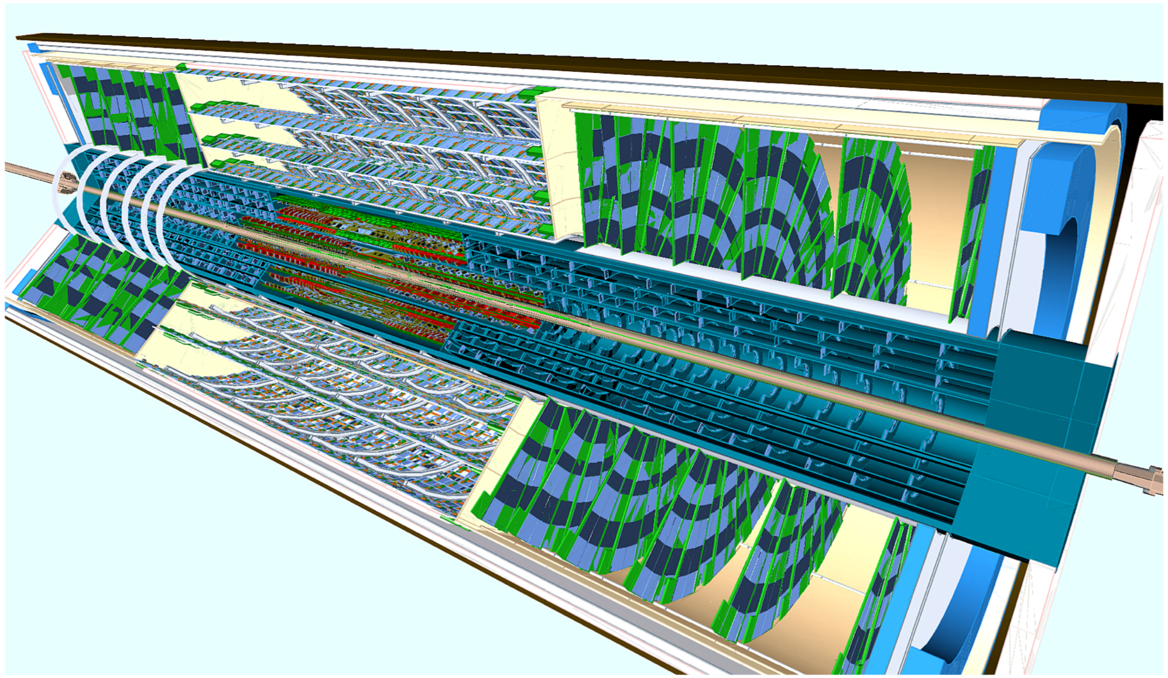
1) Hardware trigger is needed if detectors can't be fully readout due to data transfer bandwidth limits (typically trackers)
   - It is performed in electronics boards with FPGA to be fast O(10) μs, typical example based on CMS:
     - 40 MHz readout of selected calorimeters and muon information (all beam crossings but reduced granularity)
     - Simplified clusters and physics objects formation to select ≃ 100 kHz events for full readout applying energy threshold according to a pre-defined physics menu…
2) High level trigger select final events for registration and to reduce data size, typical example of CMS:
   - Online computing reconstruction in ≃ 30000 commercial CPU cores to select few kHz of events
     - Use all detectors (eg tracker) and full granularity data
     - Use still simplified reconstruction software to process events in O(100) ms





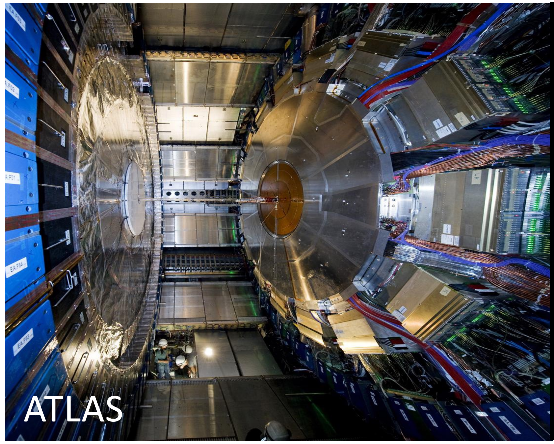
Collider experiments design considerations: simulation

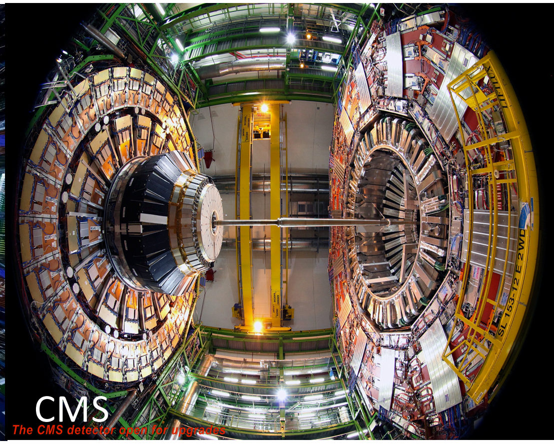
- Design optimizations need careful simulation of their impact on performance up to physics result
  - Accurate description of detectors is needed in Monte Carlo GEANT simulation for design
  - and for corrections of apparatus effects in data (some default in description can be corrected with data)
- Accurate FLUKA simulation of beam backgrounds and irradiation (including beam pipe regions description) are mandatory to establish particle fluence and radiation dose maps

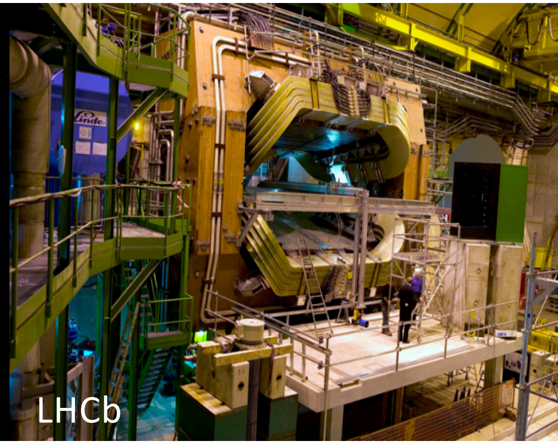


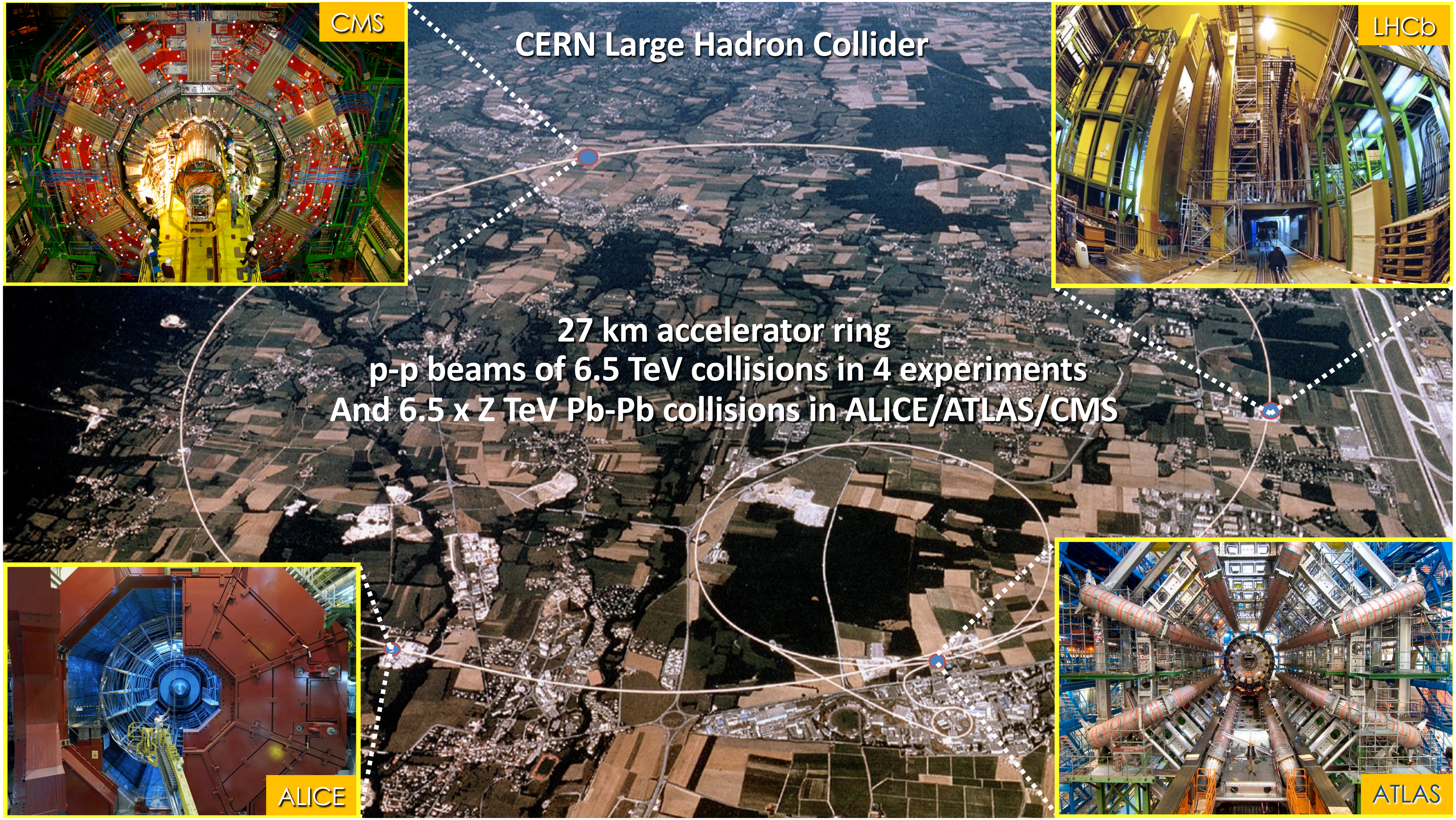
Description of the ATLAS Phase-2 tracker in simulation

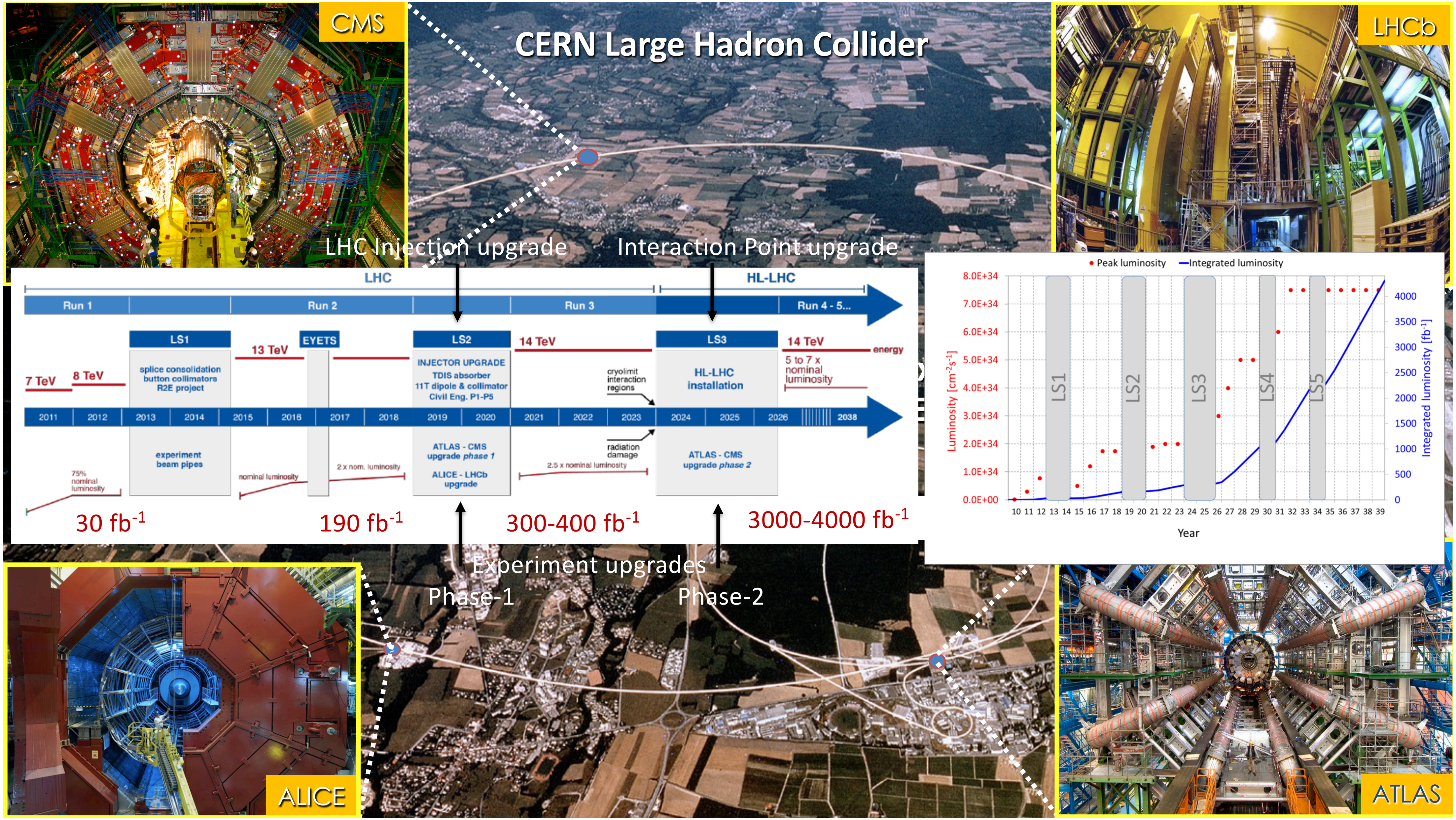
Upgrades of operating collider experiments







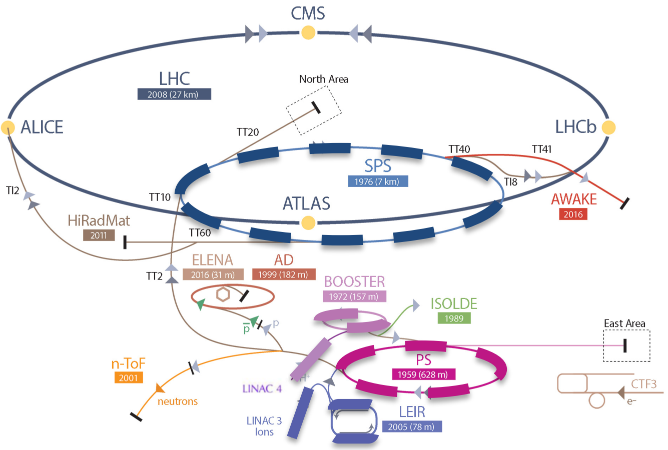

CERN Large Hadron Collider
27 km accelerator ring
p-p beams of 6.5 TeV collisions in 4 experiments
And 6.5 x Z TeV Pb-Pb collisions in ALICE/ATLAS/CMS
CMS
LHCb
ALICE
ATLAS



CMS
CERN Large Hadron Collider
LHCb
LHC Injection upgrade
Interaction Point upgrade
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
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 2038
experiment beam pipes
ATLAS - CMS upgrade phase 1
ALICE - LHCb upgrade
radiation damage
ATLAS - CMS upgrade phase 2
75% nominal luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb^{-1}
190 fb^{-1}
300-400 fb^{-1}
3000-4000 fb^{-1}
Peak luminosity
Integrated luminosity
Luminosity [cm^{-2}s^{-1}]
Integrated luminosity [fb^{-1}]
8.0E+34 7.0E+34 6.0E+34 5.0E+34 4.0E+34 3.0E+34 2.0E+34 1.0E+34 0.0E+00
4000 3500 3000 2500 2000 1500 1000 500 0
LS1 LS2 LS3 LS4 LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
Year
Experiment upgrades
Phase-1
Phase-2
ALICE
ATLAS

LHC accelerator complex and beam conditions: past experience

Proton beams bunch trains are prepared in injection chain, accelerated to 6.5 TeV & collided every 25 ns in LHC



$$N_{events} = L \times \sigma \times \Delta t$$

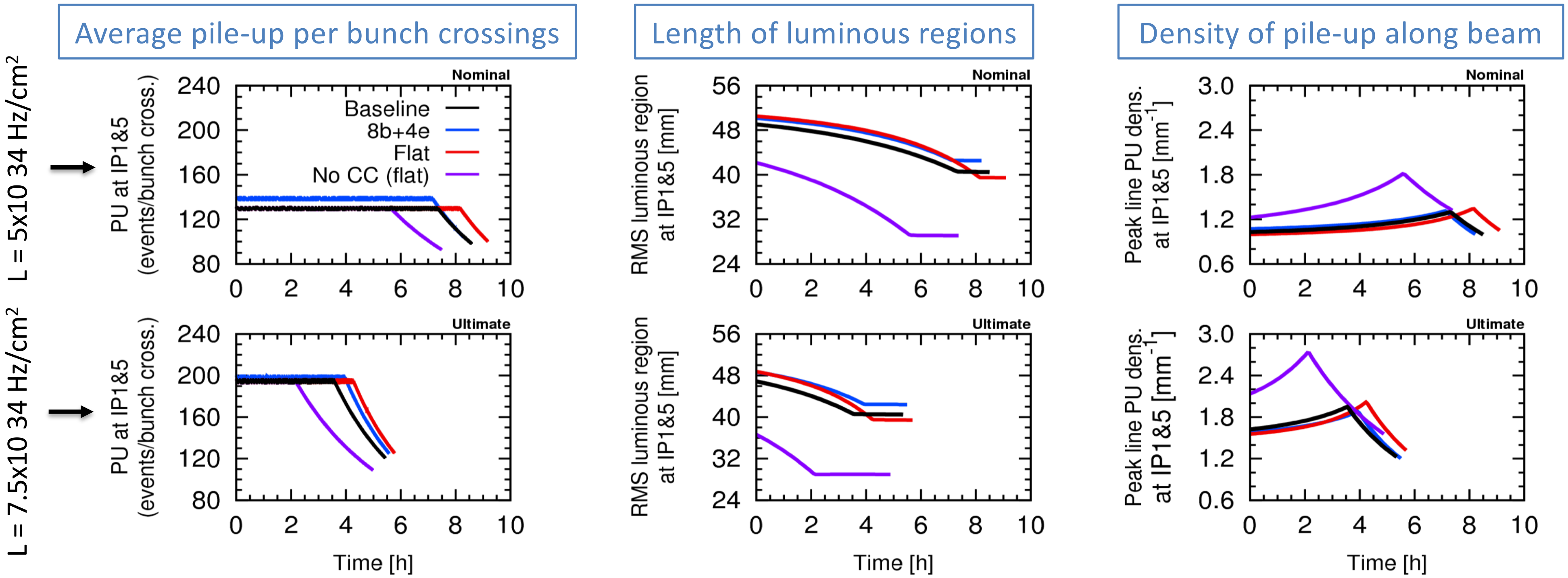
- L (luminosity) = $n_b N_b^2 f_{rev}/4\pi\beta^*\varepsilon_n \times R$ ($cm^2\ s^{-1}$)
  - N_b/ε_n brightness is provided by injection chain
  - Beam focus β^* and overlap $R(\Phi, \beta, \varepsilon_n, \sigma_n)$ at Interaction Point are provided by LHC)
- σ = cross section in cm^{-2}
- Δt = time available for physics data taking (s)

In 2018 LHC reached twice the original design luminosity at $2 \times 10^{34}\ cm^2\ s^{-1}$, with a record of 50% time available for physics data taking

Ideally x 2 design margins are needed for data rates and radiation tolerance
It is not always possible w/o some performance degradation

Parameter	Design	2018
Bunch population N_b [10^{11} p]	1.15	~1.2 (→ 1.4)
No. bunches per train	288	144
No. bunches	2808	2556
Emittance ε [mm mrad]	3.75	~2.2
Full crossing angle [μrad]	285	300 → 260
β^* [cm]	55	30 → 27.5 → 25
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	~2

HL-LHC beam condition scenarios: critical parameters

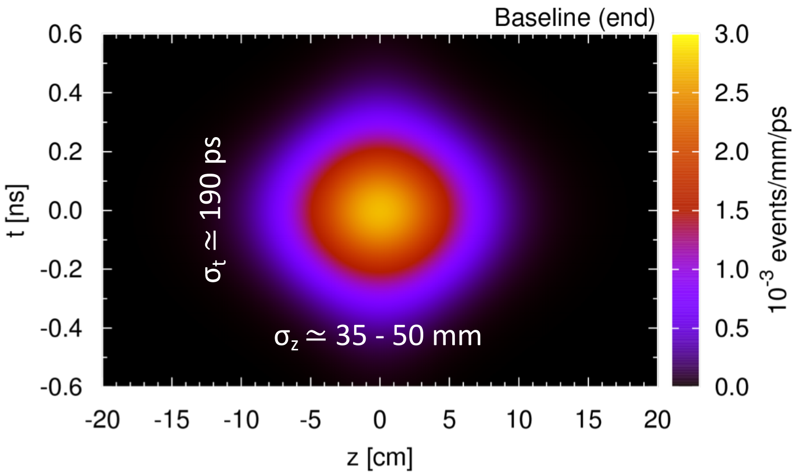


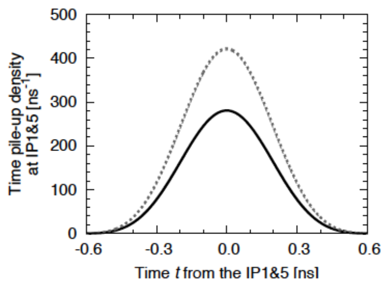
Scenario	Nominal (~140 PU)		Ultimate (~200 PU)	
	$L_{\rm int}$ [fb^{-1}]	$\bar{\rho}$ [mm^{-1}]	$L_{\rm int}$ [fb^{-1}]	$\bar{\rho}$ [mm^{-1}]
Baseline	262	0.80	326	1.20
8b+4e	199	0.82	243	1.17
Flat	267	0.78	340	1.20
No CC (flat)	249	1.03	293	1.58

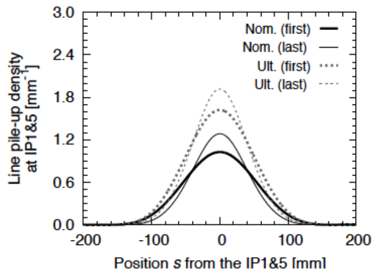
$\bar{\rho}$ is an effective pile-up density integrated over luminous region and fill profiles. $L_{\rm int}$ [fb^{-1}] is estimated for 160 days operation, with a 50%-efficiency and a fill turn-around time ~ 1.5h.

HL-LHC beam condition scenarios: critical parameters

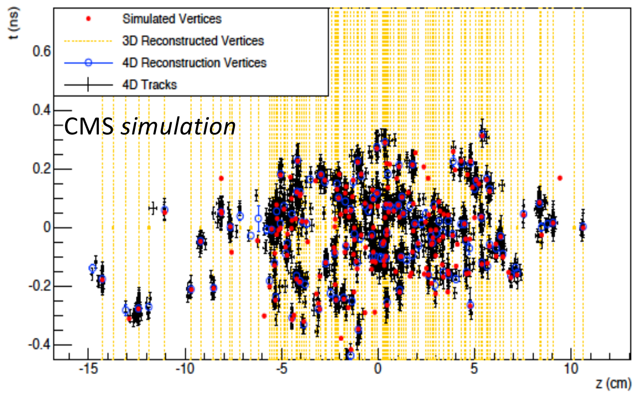
z-t view of luminous region



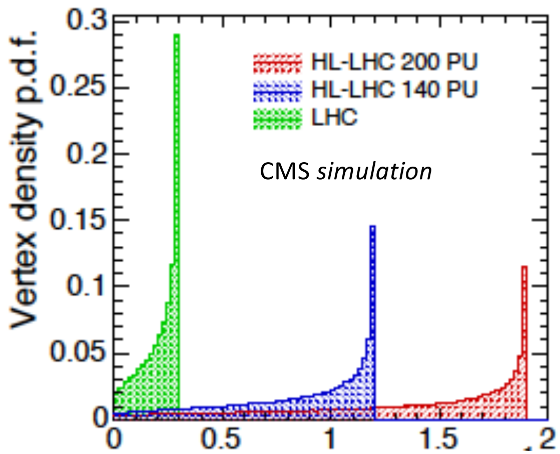




200 p-p collisions (pile-up) in a BC



Vertex density (mm^{-1})



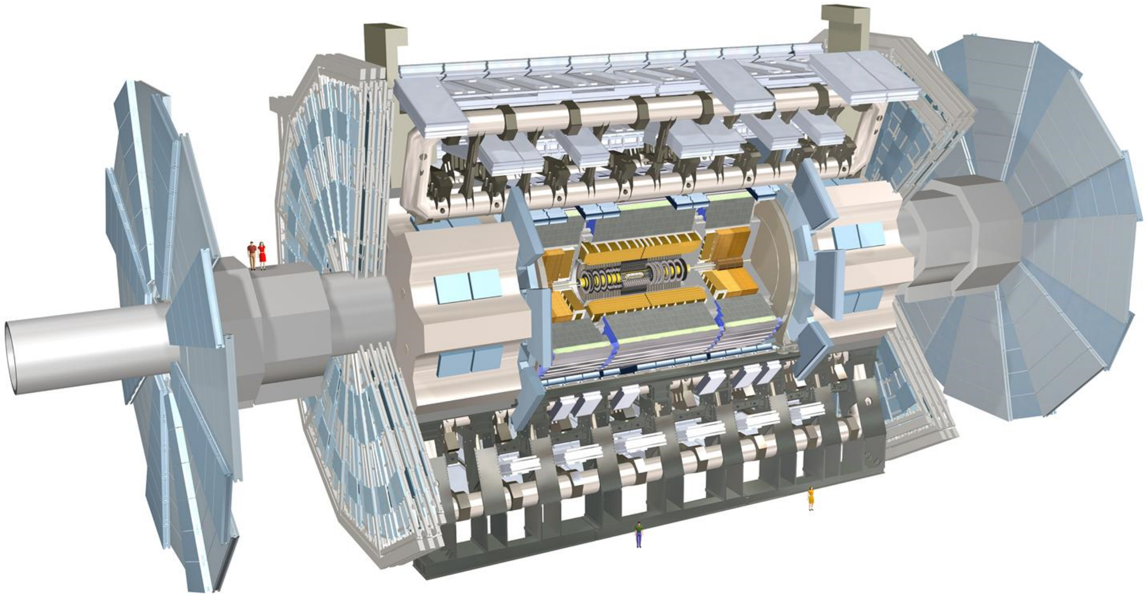
Luminosity is not limited by accelerator capability but by experiments ability to cope with collision pile-up
It can be tuned to performance through the beam leveling process (all physics signals are not equally affected by PU)

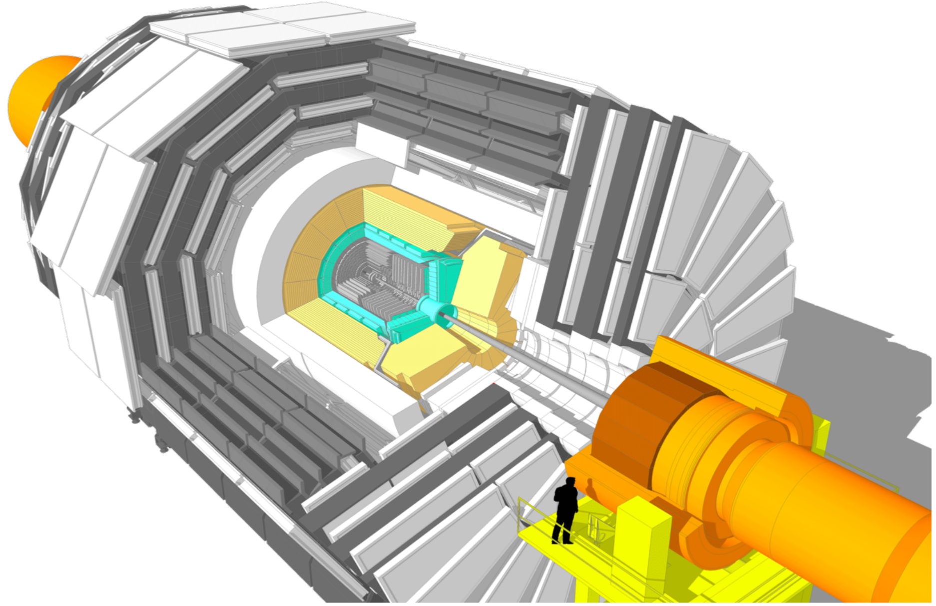
Elimination of collision pile-up needs detectors with high granularity and precision (including timing), and powerful tools for hardware trigger and online/off-line event reconstruction

ATLAS and CMS experiments: different optimizations

ATLAS: 7000 t, Φ = 25 m, L = 45 m
0.5/1 T toroid barrel/endcap, 2T solenoid in ECAL cryostat

CMS: 14000 t, Φ = 15 m, L = 30 m
3.8 T solenoid, Φ = 6 m, L = 13 m





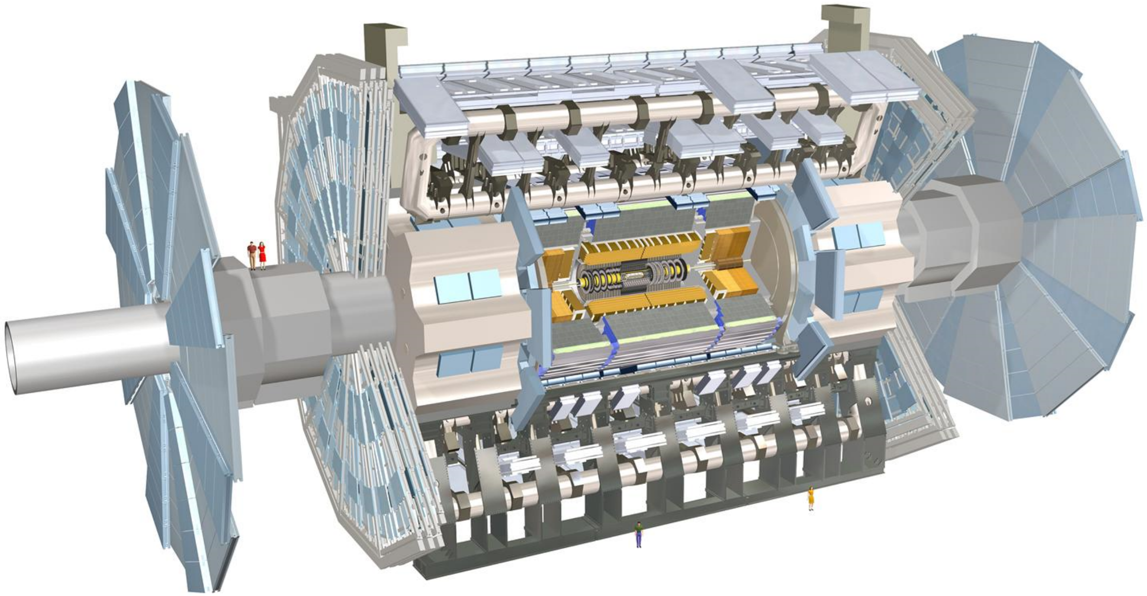
- Si-pixel, Si-strip, TRT tracker
- Liquid Argon sampling ECAL barrel & ECAL/HCAL endcaps
- Scintillating tiles + WLS + PM barrel HCAL
- Muons: DT-RPC / MDT-CSC-TGC in barrel/endcaps

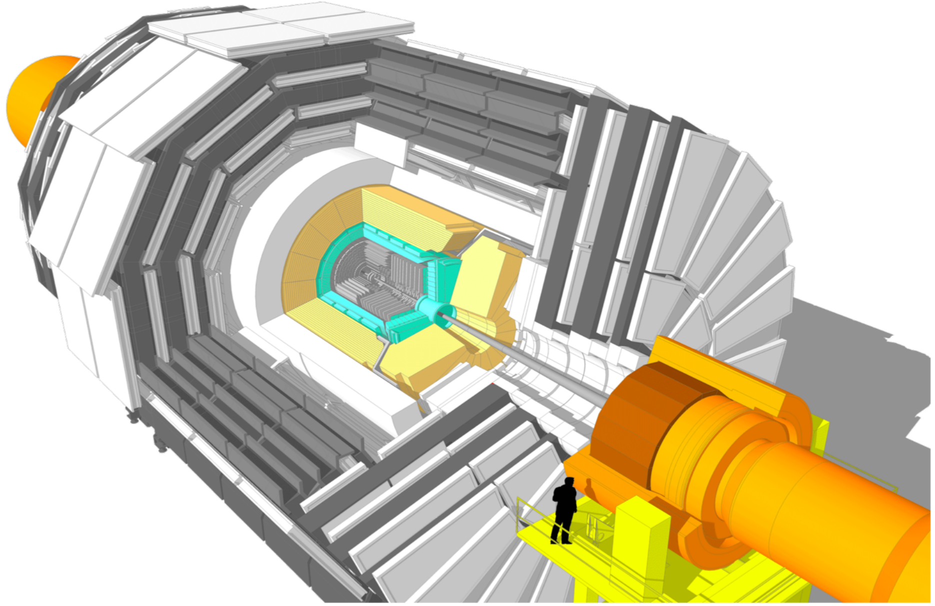
- Si-pixel, Si-strip tracker
- Crystal homogenous ECAL endcap and barrel
- Scintillating tiles + WLS + HPD/PMT barrel/endcaps HCAL
- Si-strip pre-shower in front of ECAL endcap
- Muon: DT-RPC Barrel, CSC-RPC Endcap
- Cerenkov quartz fibers HCAL in forward region

ATLAS and CMS experiments: LS1 to LS2 upgrades

ATLAS: 7000 t, Φ = 25 m, L = 45 m
0.5/1 T toroid barrel/endcap, 2T solenoid in ECAL cryostat

CMS: 14000 t, Φ = 15 m, L = 30 m
3.8 T solenoid, Φ = 6 m, L = 13 m



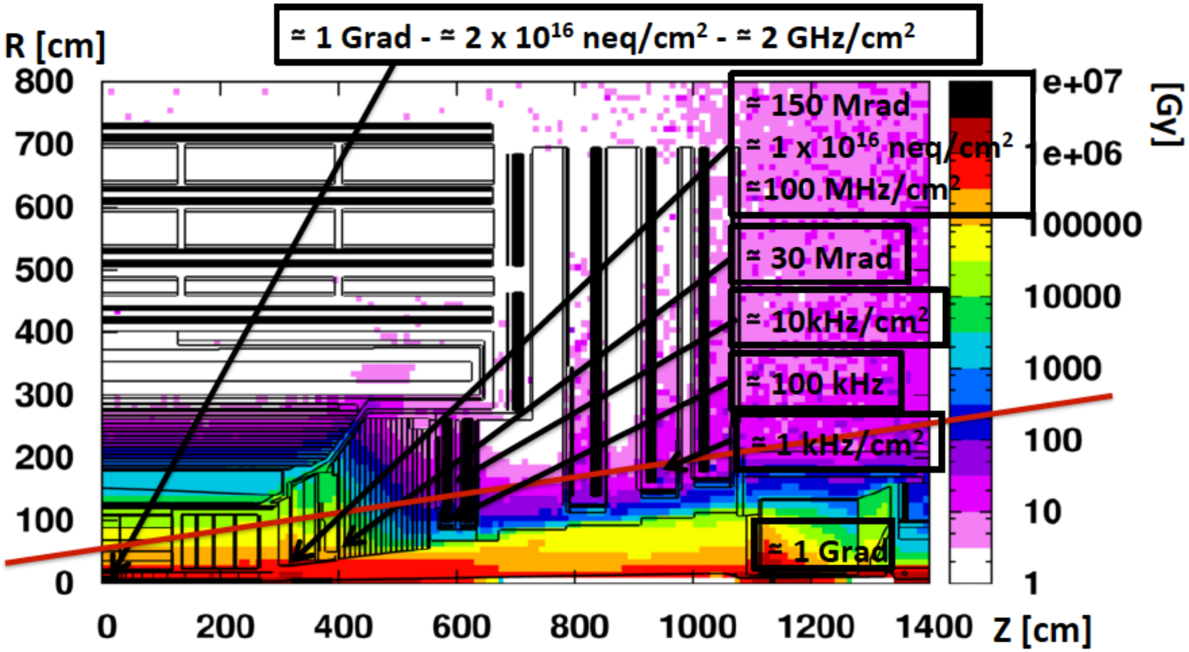


- Si-pixel: one more barrel layer
- Liquid Argon new FE to provide full granularity in triggger
  Scintillating tiles + WLS + PM barrel HCAL
- Muons: new chambers at high η
- Trigger: new BE boards, hardware track trigger input in HLT

- Si-pixel replaced, one more layer/disk and new readout
- New SiPM photoconversion in HCAL
- Muon: new chambers at high η
- Trigger: new BE boards and architecture (multiplexed)

ATLAS & CMS upgrades for HL-LHC: irradiation & particle rates

CMS fluence, rate, dose map for 5 x 10^{34} cm^2 s^{-1} and 3000 fb^{-1} instantaneous/integrated luminosities



Upgrades

On-detector readout binary or with digitization and data compression increased bandwidth data transfer for full granularity readout in hardware trigger

New detectors probing current technology limits both for irradiation and data rates

CMS upgrades for HL-LHC: new systems

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

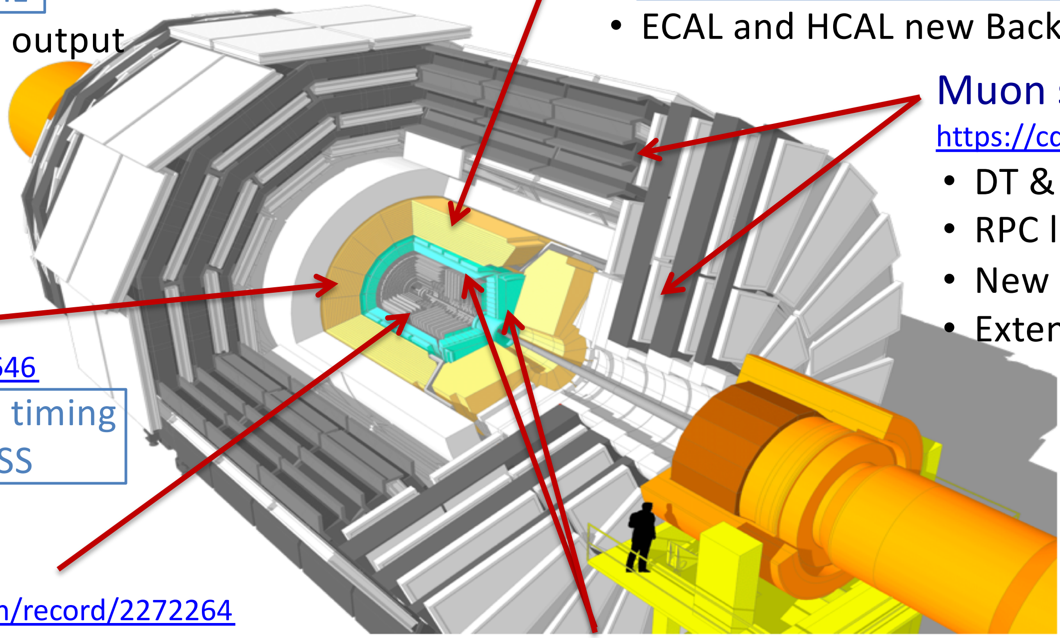
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC link -board
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector https://cds.cern.ch/record/2296612

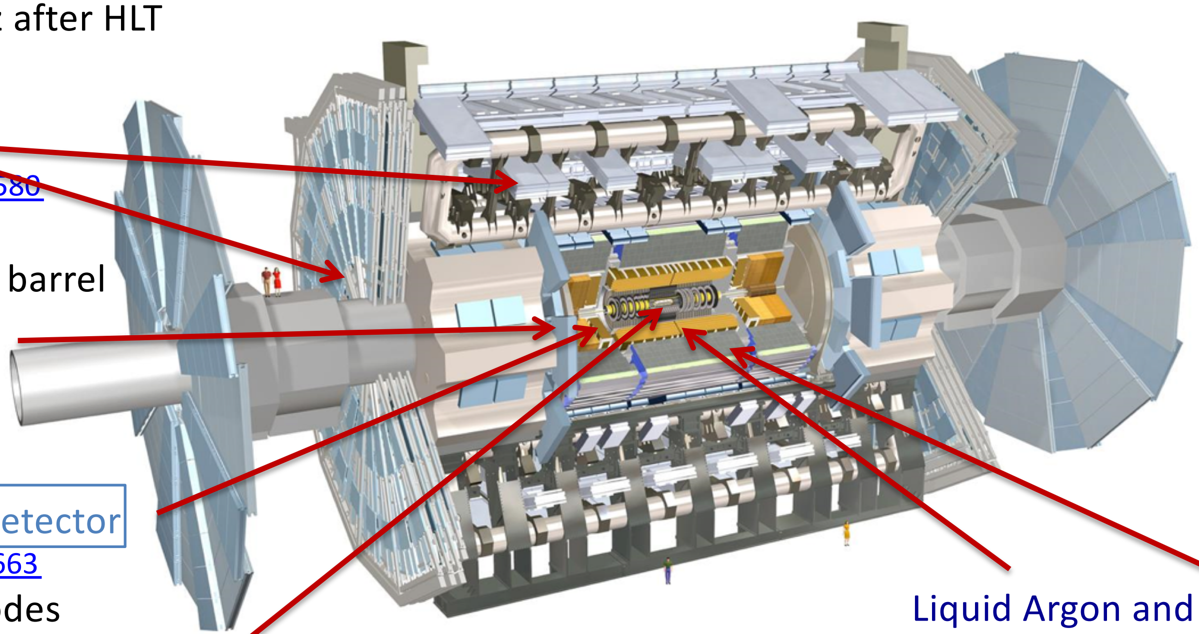
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

ATLAS upgrades for HL-LHC: new systems

Trigger/DAQ https://cds.cern.ch/record/2285584
- Tracker readout at 1 MHz after 10 μs latency
- High Level Trigger input reduced to ≃ 400 kHz with track-trigger after ≃ 30 μs
- Register up to ≃ 10 kHz after HLT

Muon systems
https://cds.cern.ch/record/2285580
- New electronics
- New chambers in inner barrel
- Possible extension of coverage to η ≃ 4



High Granularity Timing Detector
https://cds.cern.ch/record/2623663
- Low Gain Avalanche Diodes $2.4 \lesssim \eta \lesssim 4$

New Tracker: https://cds.cern.ch/record/2257755
https://cds.cern.ch/record/2285585/
- Rad. tolerant, high granularity and light
- Extended coverage to η ≃ 4

Liquid Argon and Tile calorimeter
https://cds.cern.ch/record/2285583
https://cds.cern.ch/record/2285582
- New electronics for full granularity readout at 40 MHz

LHCb upgrades: new systems for installation during LS2

Collect 50 fb^{-1} at 2 x 10^{33} cm^{-2} s^{-1} in runs 3 and 4 (x 10 initial design luminosity)

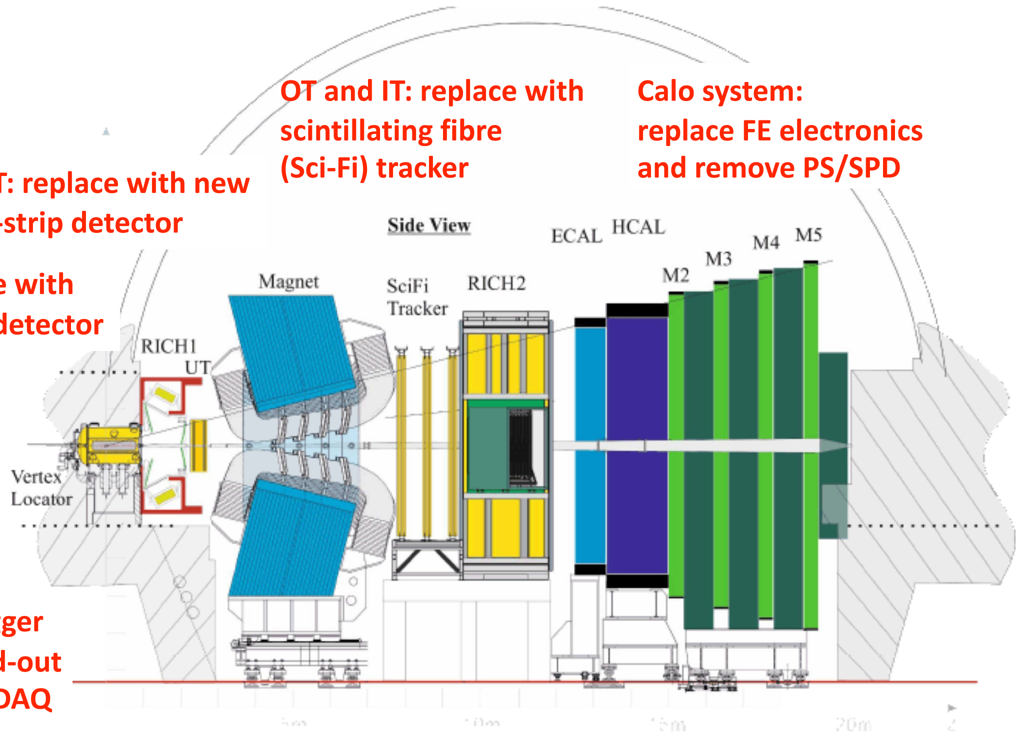
- Software trigger operating at 40 MHz for 20 kHz of p-p events registered
- 4 TB/s (≃ ATLAS/CMS at HL-LHC) to trigger computing farm

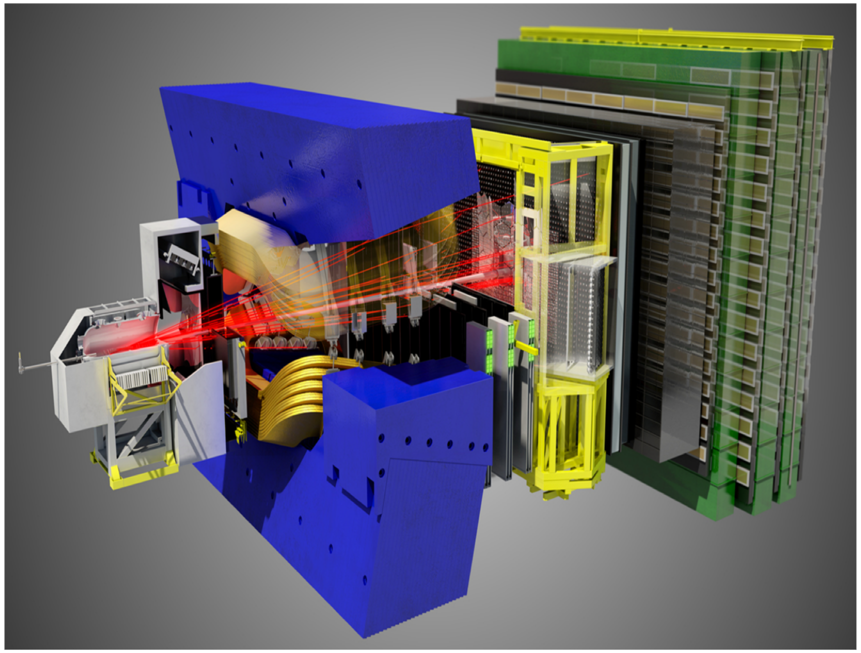
UT: replace with new Si-strip detector

OT and IT: replace with scintillating fibre (Sci-Fi) tracker

Calo system: replace FE electronics and remove PS/SPD

VELO: replace with new Si-pixel detector





Full s/w trigger
Replace read-out boards and DAQ

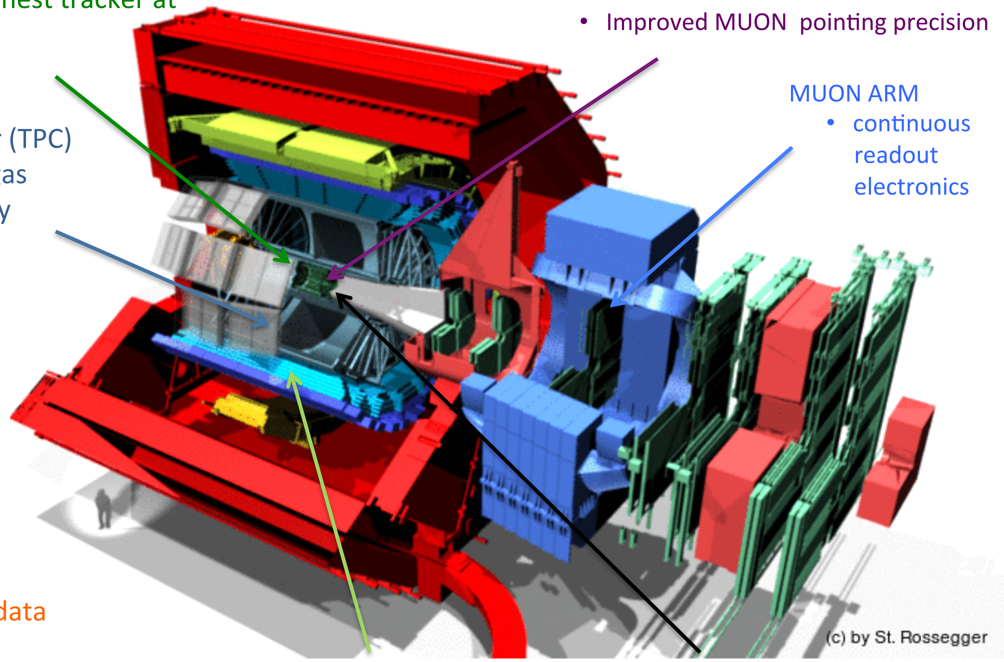
RICH: new photodetectors and FE electronics, and modify RICH1 optics and mechanics

Muon system: replace FE electronics and remove M1

ALICE upgrades during LS2

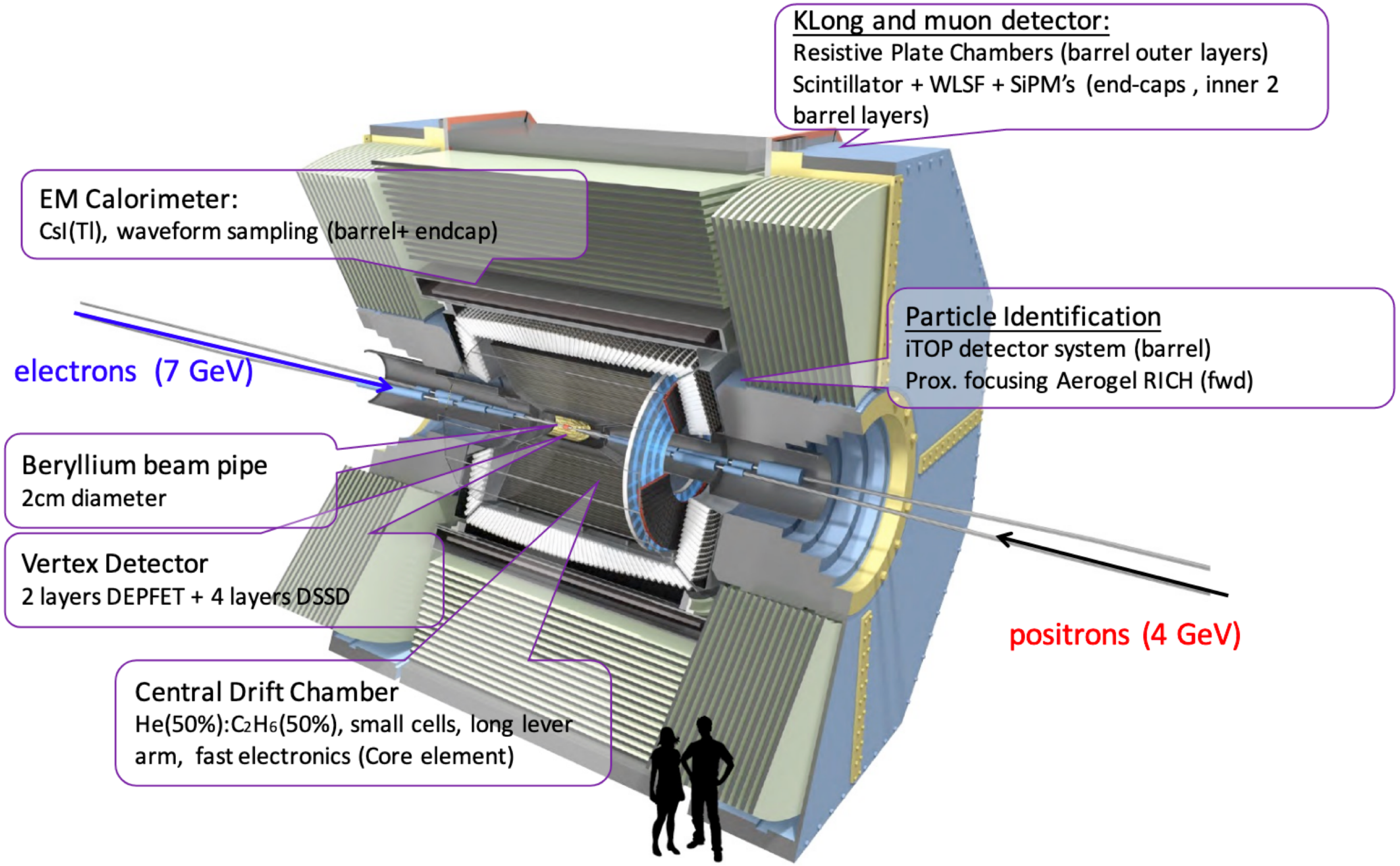
Collect ≃ 10 nb^{-1} at 6 x 10^{27} $cm^{-2}s^{-1}$ (x 2 increase) in runs 3 and 4

- Register all Pb-Pb collisions ≃ 50 kHz with fast online calibration and reconstruction in FPGAs and GPUs for data compression, from 1 TBps to 50 GBps storage (≃ ATLAS/CMS at HL-LHC)



Belle-II upgrade at SuperKEKB

Collect $\simeq$ 50 ab^{-1} (by 2027) at 8 x 10^{35} cm^{-2}s^{-1} (x 40 KEKB)



Experiment concepts for future colliders

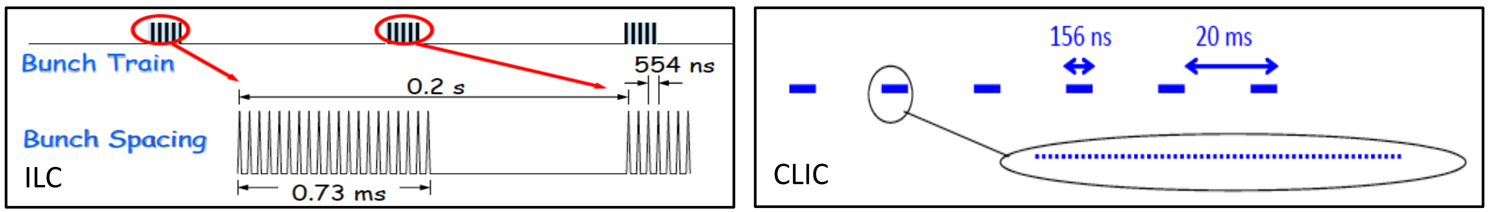
ILC, CLIC, FCC-ee, CepC: operation condition features

Data rates and irradiation are not an issue (orders of magnitude smaller than at LHC)

- Detectors can operate without trigger and relatively slow readout O(μs)
- CLIC is an exception needing ≃ 1(5) ns precision in Calorimeter(Tracker) due to higher background
- 100 kHz Z at Z-peak at FCC-ee could require on-line data compression
- At ILC and CLIC low frequency of bunch trains will allow power pulsing of electronics and airflow cooling
- Challenges are in tracking and calorimetry precision

Beam parameters summary	ILC		CLIC			FCC-ee			CepC	
Energy (TeV)	0.25	0.5	0.38	1.5	3	0.091	0. 24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1}) per IP	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	1.5
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		352	312		16640	393	48	12000	242

Beam structure

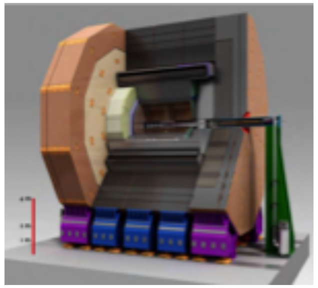


ILC, CLIC, FCC-ee, CepC: detector concepts

Concepts are similar, optimized versus beam properties/background/maximum energy
Supra-conducting solenoids 2 to 4 tesla, with sizes adapted to reach similar momentum precision
Silicon and TPC/DC options for outer tracking and Dual and High Granularity options for calorimetry

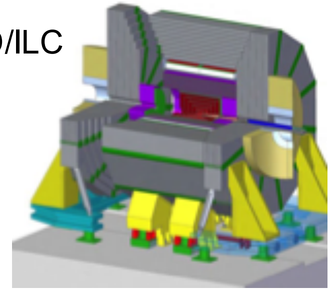
3.5(4) T Solenoid, 8.8 x 8 m
Si Pixel + TPC Tracker R = 1.8(1.5) m

ILD/ILC



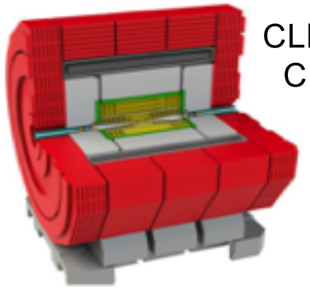
5 T Solenoid, 6 .8 x 6 m
Full Si-Tracker R = 1.2 m

SiD/ILC



4 T Solenoid, 7 x 8.3 m
Full Si-Tracker R = 1.5 m

CLICdet
CLIC

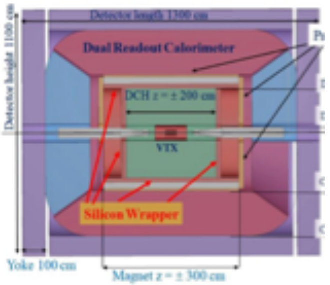


High Granularity Calorimetry

Pre-shower/MPGD
+ Dual Calorimetry

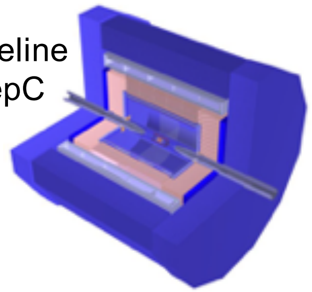
2 T Solenoid 4.2 x 6 m
Si Pixel + Drift Chamber R= 2 m

IDEA
FCC-ee
CepC



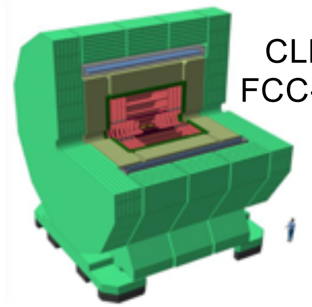
3 T Solenoid 6.4 x 7.8 m
Si Pixel + TPC tracker R = 1.8 m

Baseline
CepC



2T Solenoid 7.4 x 7.4 m
Full Si-Tracker R = 2 m

CLD
FCC-ee



https://cds.cern.ch/record/2254048/files/CLICdp-Note-2017-001.pdf
https://cds.cern.ch/record/2651299/files/CERN-ACC-2018-0057.pdf
http://cepc.ihep.ac.cn/CEPC_CDR_Vol2_Physics-Detector.pdf
https://arxiv.org/ftp/arxiv/papers/1306/1306.6329.pdf

FCC-hh - SPPC: operation condition features

- 30 GHz collisions, <1000> per bunch crossing ≃ 10 x data rates and 30 to 100[1)] x irradiation at HL-LHC
- 100 MHz jets p_T > 50 GeV - 400/120/11 kHz W/Z /t
- 200-300 TBps for Calo. & Muons, 800 TBps for Tracker (at BC rate) (≃ x 50 LHC OL bandwidth for outer tracker)

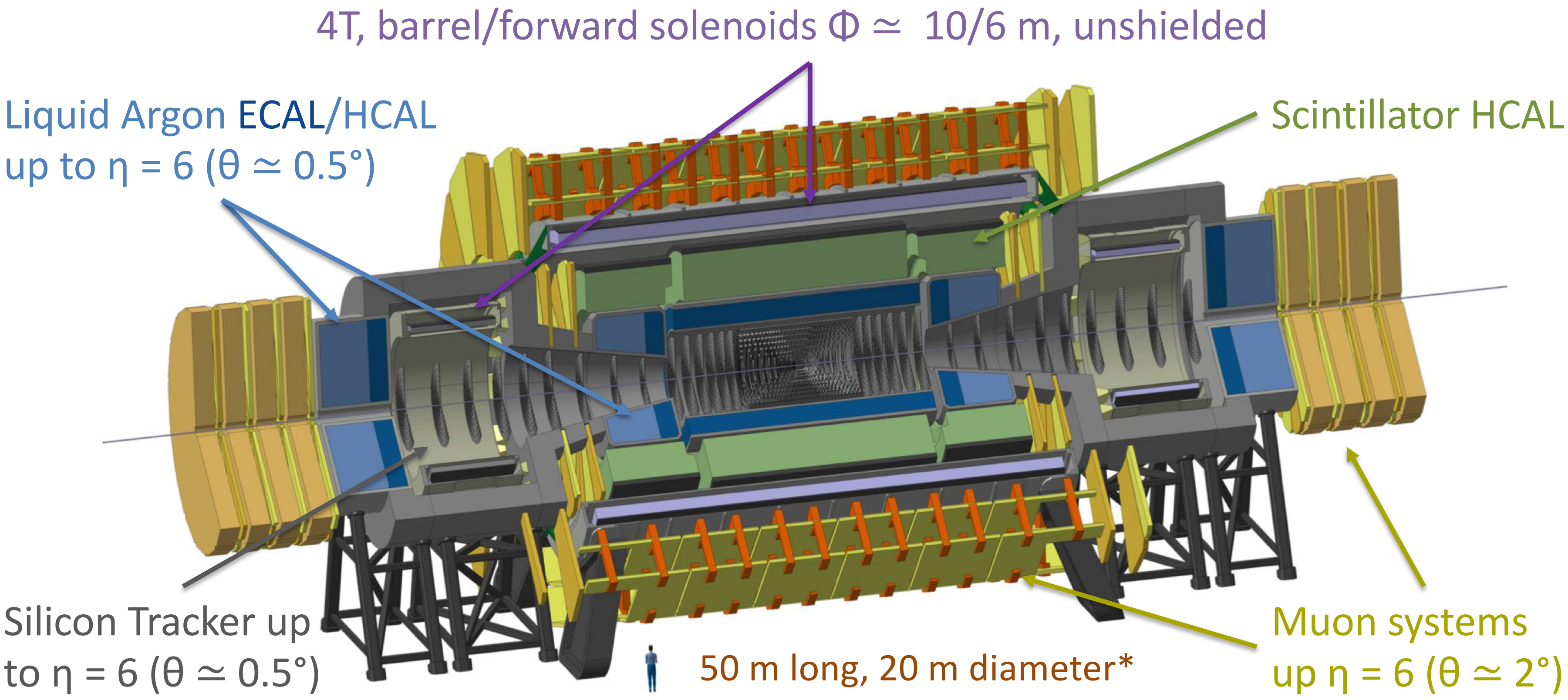
Challenges are in tracking, calorimetry and timing precision to mitigate collision pile-up in data transfer and event selection and reconstruction

Beam/collision parameters summary	HL-LHC	HE-LHC	FCC-hh	SppC
Dipole field (T)	8	16	16	12
Energy CM (TeV)	14	27	100	75
Bunch spacing/rate (ns)/(MHz)	25/31.6	25/31.6	25/32.5	25
Luminosity/IP (10^{34} cm^{-2}s^{-1})	5 (7.5)	16	30	10
σ_{inel} (mb)	80	86	103	-
Mean collisions/crossing (PU)	130 (200)	450	1000	300
Line <Pile-Up> density (mm^{-1})	1.2/1.8	3	8	-
Time <Pile-Up> density (ps^{-1})	0.3/0.3	1	2.4	-
$dN_{ch}/d\eta$ (η=0)	6	7.2	10.2	-

1) From innermost barrel to forward calorimetry regions

FCC-hh, SppC: detector concept

Mix of ATLAS and CMS with size ≃ ATLAS
η coverage extended by 1-1.5 compared to LHC due energy boost → up to O(x100) in irradiation

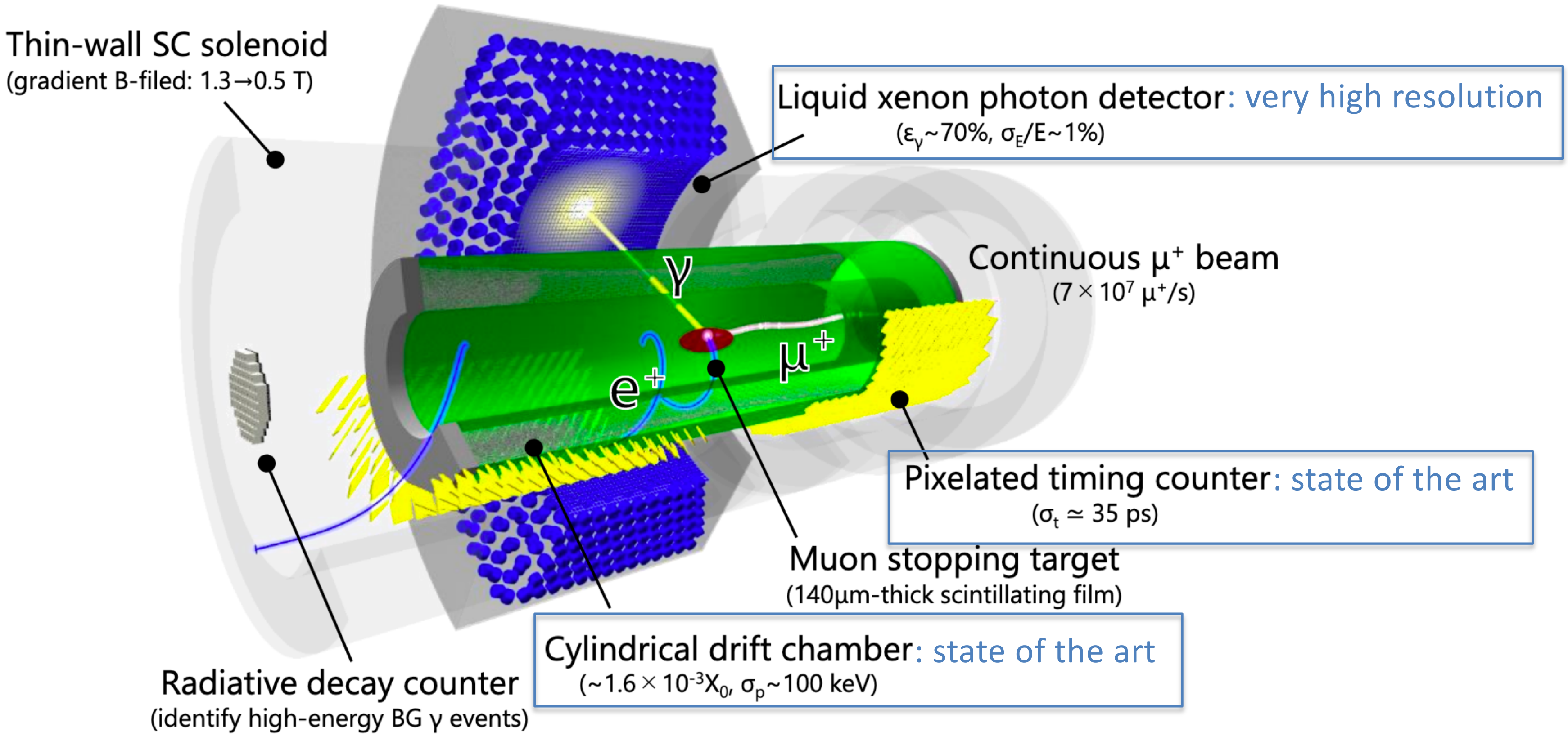


https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

Some non-collider future experiments with challenging detectors

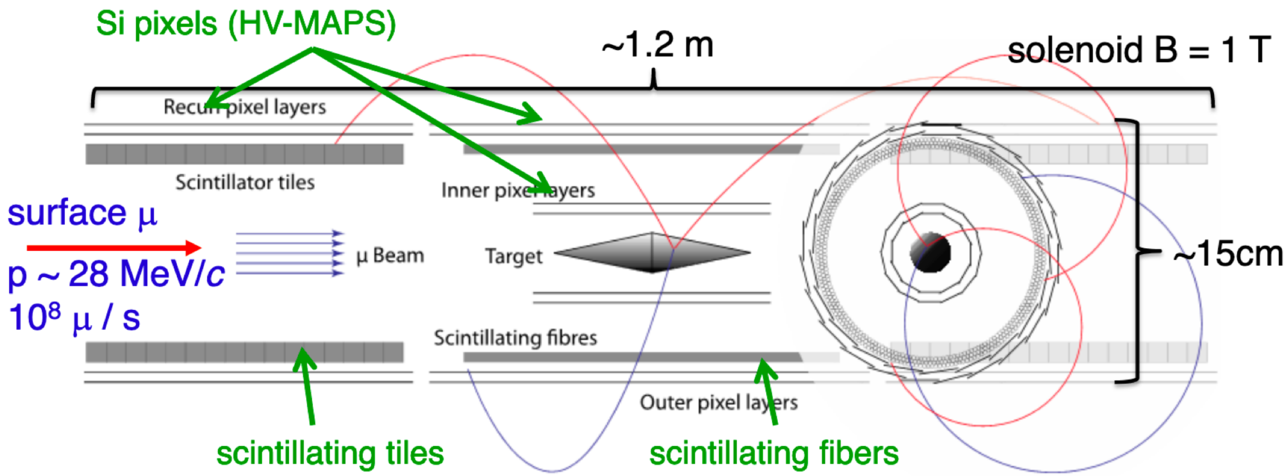
Lepton Flavor violation: MEG-II upgrade

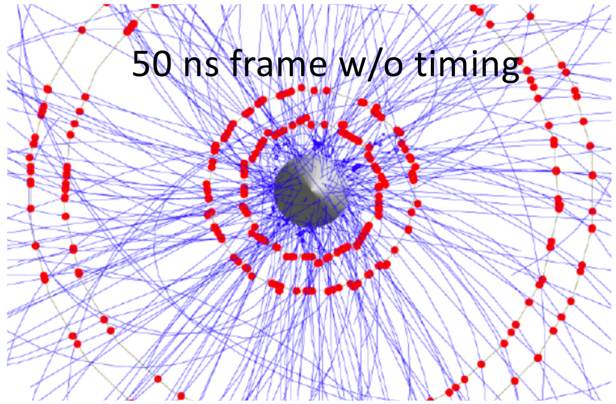
- MEG-II is a detector at PSI for $\mu^+ \rightarrow e^+ \gamma$ decay measurement down to a 6×10^{-14} branching ratio
  - Start physics end 2019

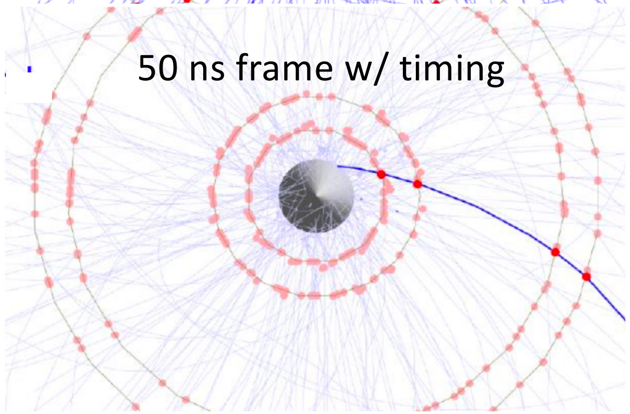


Lepton Flavor violation: Mu3e upgrade

- Mu3e is a detector at PSI for $\mu^+ \rightarrow e^+ e^- e^+$ decay measurement with acceptance down to 10 - 15 MeV
  - Start construction in 2020 and physics in 2022
  - First use of Monolithic Active pixels in HV-CMOS process[1)], 4 layers, 80 x 80 μm^2 pixels, 0.1% X_0 per layer
  - Timing precision of 100(250) ps with scintillating fibers(tiles) + SiPM redout

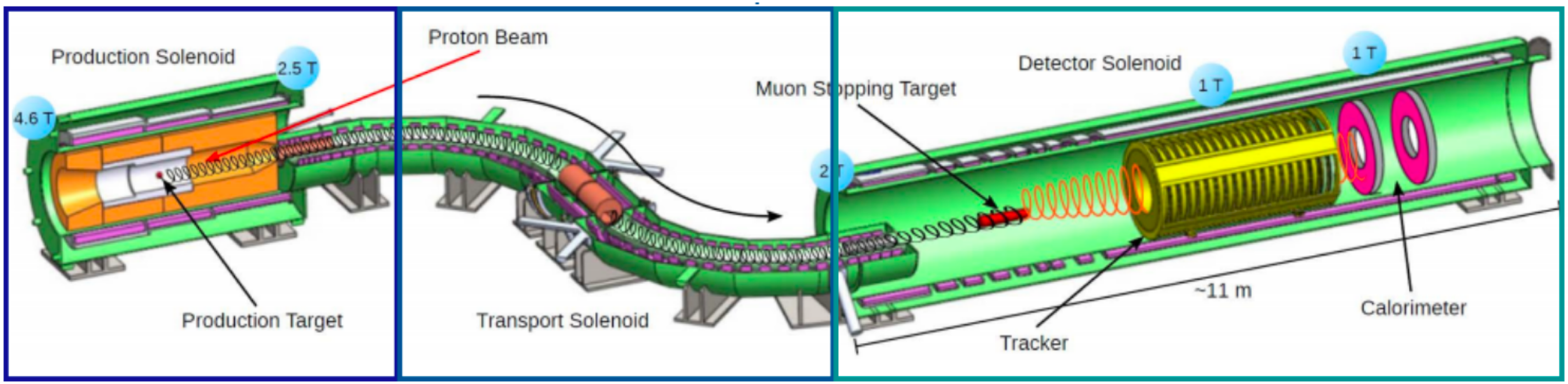






Lepton Flavor violation: Mu2e and COMET experiment

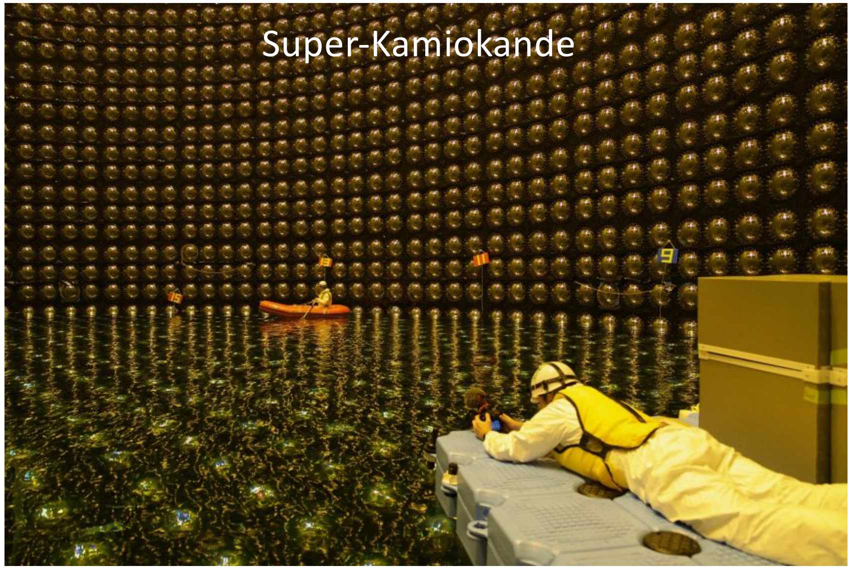
- Mu2e is an experiment at FNAL for $\mu^- + Al \rightarrow e^- + Al$ measurement
  - Construction started, commissioning in 2022
  - Tracking with straw tubes Φ 5 mm, 100 μm and 1ns resolutions
  - Homogenous calorimeter with CsI crystals in two disks, 10% energy resolution and 500 ps precision

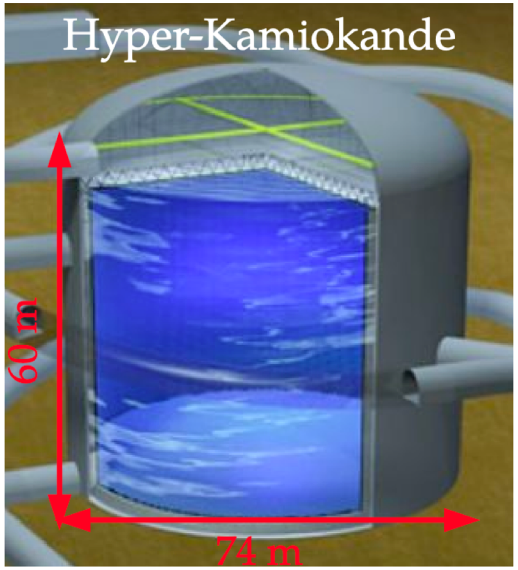


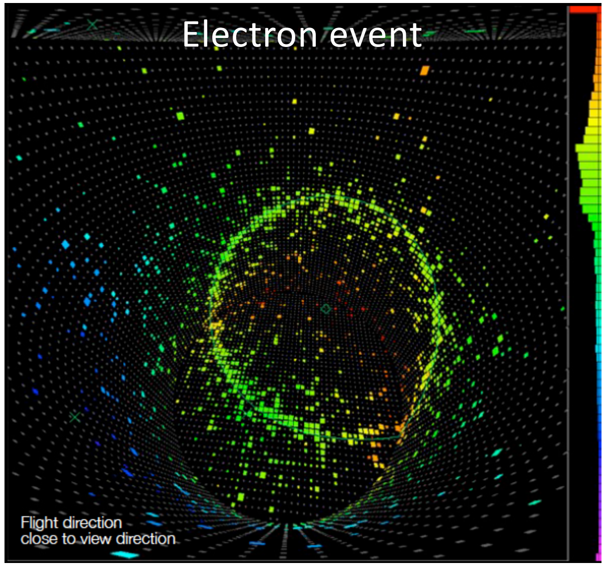
- COMET is an experiment at JPARC with a similar concept as Mu2E
  - Construction started, 1st phase of data taking end 2020
  - Homogenous calorimeter with LYSO crystals

Neutrino experiments: Hyper-Kamiokande

- Hyper-Kamiokande, construction start in 2020 physics in 2027-28
  - 300 km from JPARC (Tokai, Japan) 650 m below surface
  - 60 m x 70 m, 260 ktons of water Cherenkov detector (x 10 Super-Kamiokande)
  - Inner detector with 40 000 PMT Φ = 50 cm, with improved PDE $\simeq$ 30% and 2.6 ns time resolution, outer detector with 67000 PMT Φ = 20 cm



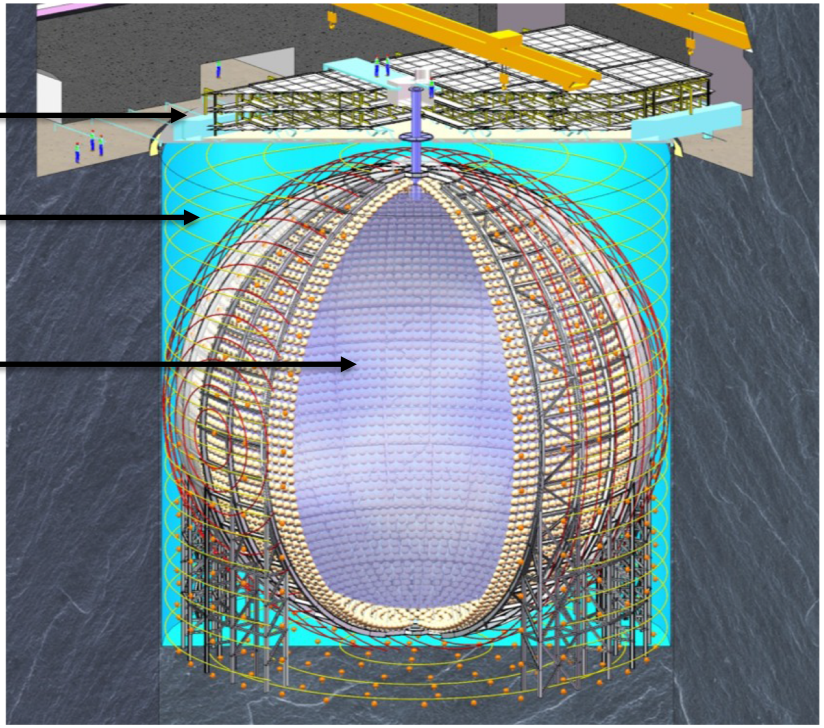




Neutrino experiments: Juno

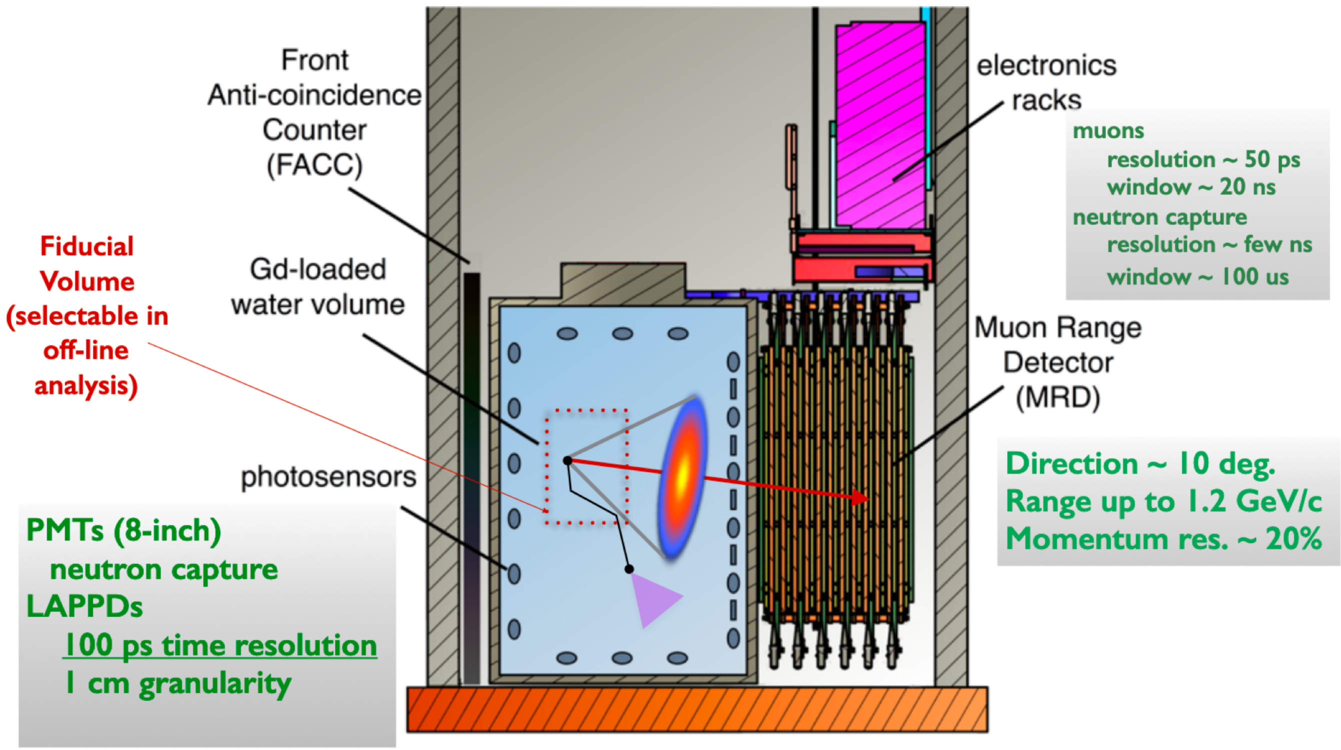
- Jiangmen Underground Neutrino Observatory in China, start physics in 2021
  - 53 km from two nuclear power plant (under construction), 700 underground
  - 20 kt of liquid scintillator in a 35 m sphere
    - High energy resolution $\simeq$ 3%

- Tracking veto , 3 layers of plastic scintillators
- 35 ktv Water Cherenkov veto
  - 2000 PMT Φ 50 cm
- Liquid scintillator readout with 75% coverage
  - 18000 PMT Φ 50 cm
    - MCP and Dynode
  - 25000 PMT Φ 7.5 cm



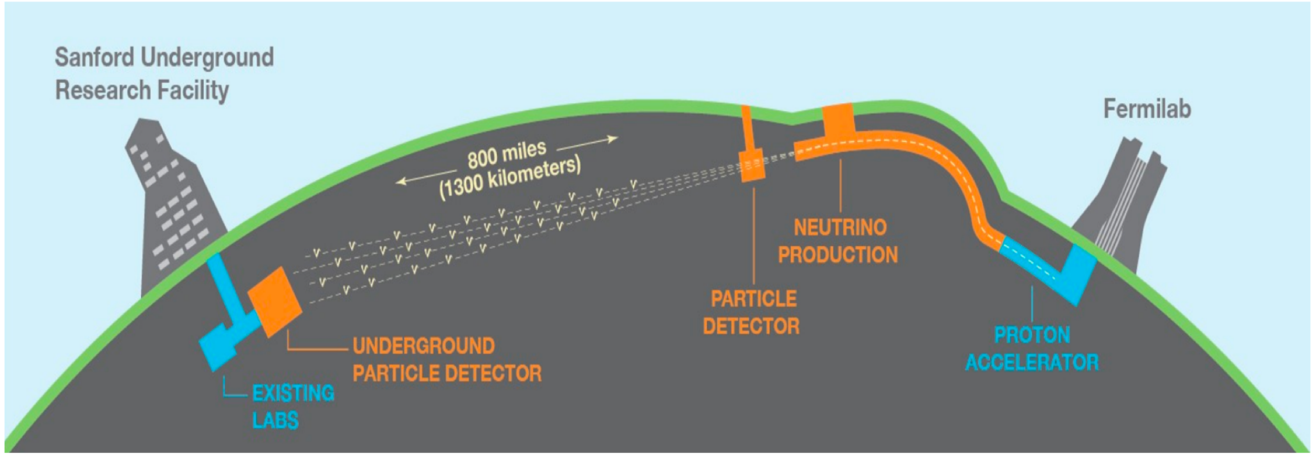
Neutrino experiments: ANNIE upgrade

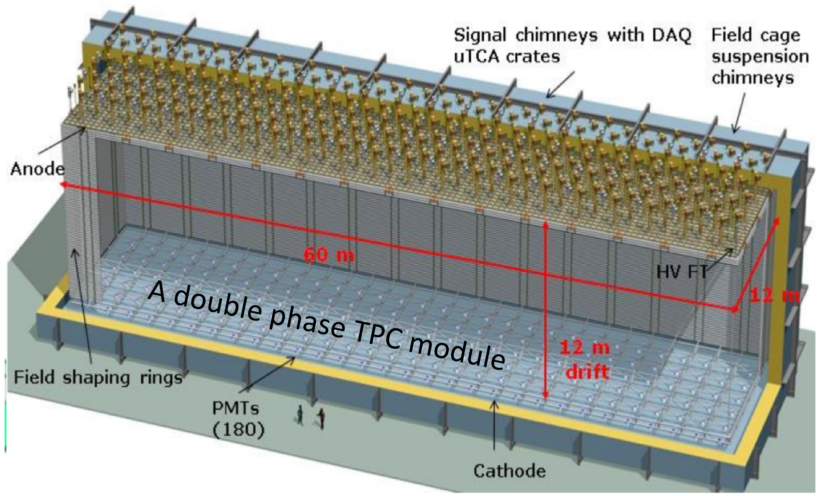
- Accelerator Neutrino Neutron Interaction Experiment at FNAL Booster Neutrino Beam
  - 26 ton Gadolinium[1)] water loaded Cerenkov detector
  - Will be equipped with Large Area Picosecond Photodetectors
    - 20 x 20 cm^2 with Single Photon Time Resolution $\simeq$ 60 ps, 1 cm position resolution

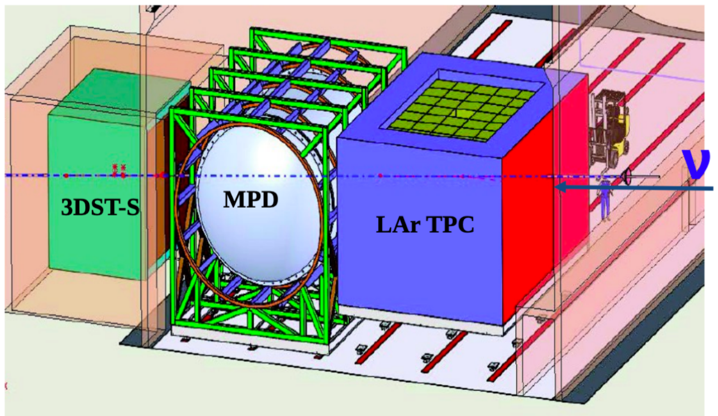


1) for neutron capture

Neutrino experiments: Deep Underground Neutrino Experiment (DUNE)







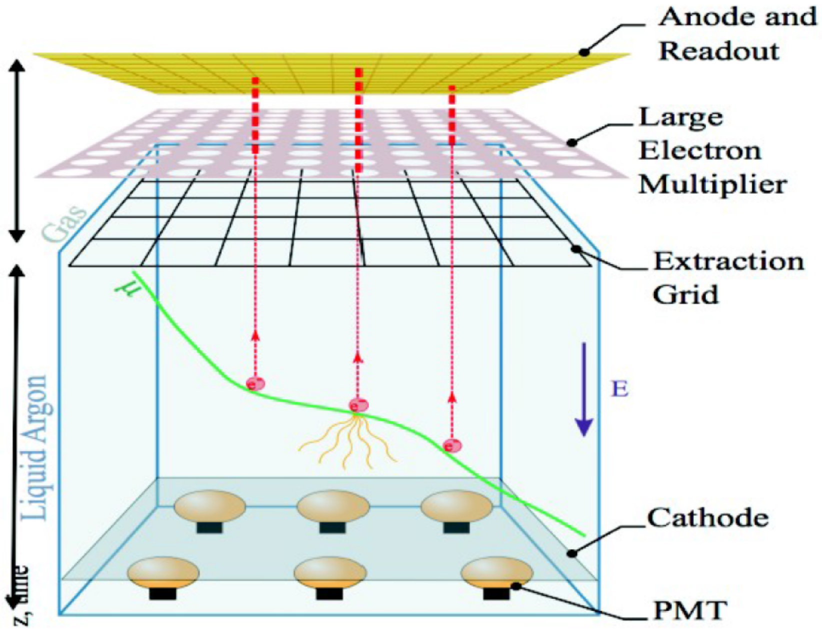
- 4 x 12 kt LAr TPC 1.5 km underground, first module in 2024
  - 1 single and 3 double phase modules

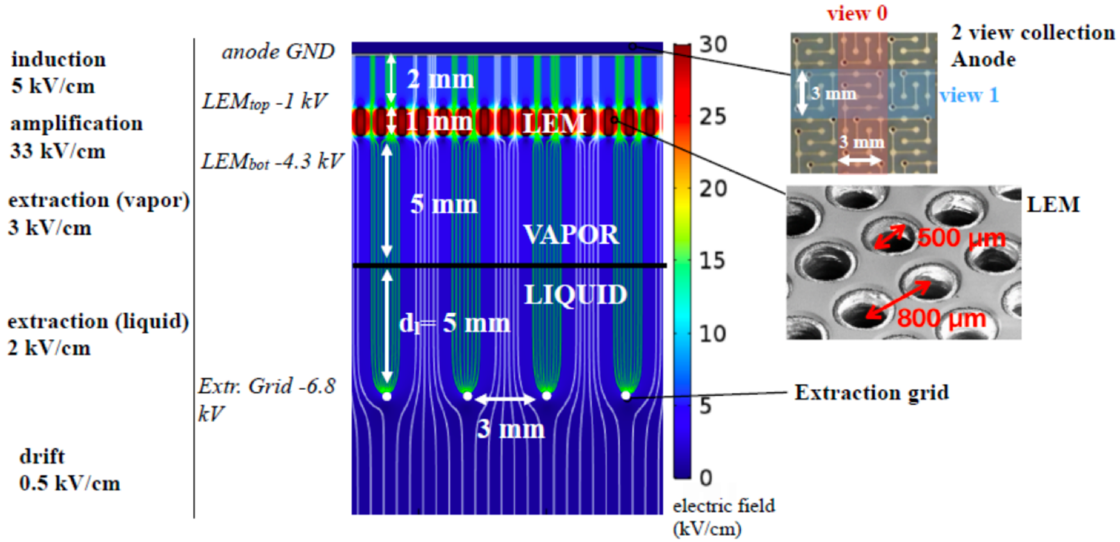
- Multi Purpose Detector: HP gas Ar TPC + ECAL+ magnet
- 3D scintillating tracking

Neutrino experiments: Deep Underground Neutrino Experiment (DUNE)

Double phase TPC, vertical drift 12 m

- TPC provide tracking and calorimetry
  - High field from grid at the liquid-vapor interface extract electron toward LEM amplification
- Scintillation light in the UV range is wave length shifted to visible at the surface of PMT to provide trigger t_0



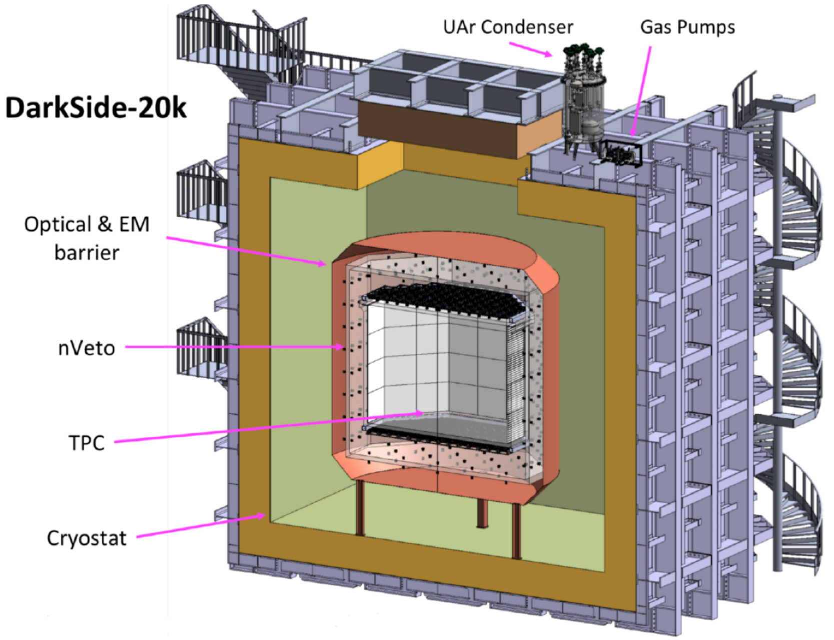


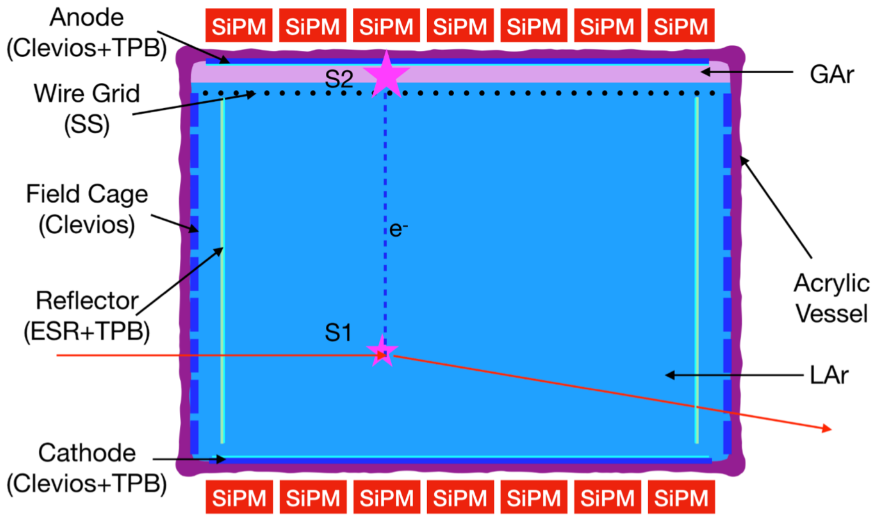
6 x 6 x 6 m^3 Dual Phase prototype ProtoDUNE is being commissioned at CERN

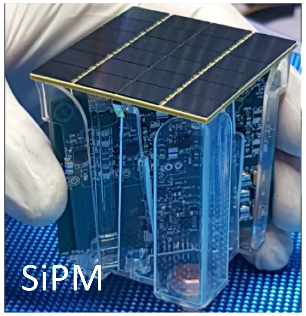
Dark Matter experiments: DarkSide-20k, DARWIN

Dark Matter search at Gran Sasso National Laboratory (Italy) - physics in 2022

- Double phase LAr TPC of 50 t
- 30 m^2 of cryogenic SiPMs readout







DARk matter WImp search with liquid xenoN (DARWIN) project

- Double phase LXe TPC of 40 t readout with PMTs

Summary before detector discussion

Overview of technologies and their application in detectors

A detector is particle physics interaction in matter, material science for production of signal and conversion in sensitive elements, electronics for amplification of signal and for transfer and processing, mechanics for structures, operation services and control

Technology/Detector	Tracker	Calorimeter	Muon	Neutrino/Dark Matter	PID Energy loss	Time of Flight
Silicon sensors: Planar, 3D, MAPs, LGADS	Si-Strips/Pixel	Si-pads in HGC sampling			Low resolution	LGADs, Si-multilayers in HGC for shower deposit
Gas detectors: CSC, DT, RPC, TPC, DC, MPGD (GEM/MicroMegas/THGEM)	TPC with MPGD readout, Drift Chambers	RPC/MM in Hadron HGC sampling	CSC, DT, RPC, GEM, MicroMegas	Surrounding detctors, Noble Gas liquide TPC	TPCs with MPGD readout	Multilayer RPCs, MM
Scintillators: plastic/liquid/crystals	Fibres	Tiles/fibers in homogenous, sampling, dual readout		Liquid scintillator, tiles in some systems	Possible	Single or multilayers in Hadron HGC
Liquid noble gas: Ar Kr, Xe		Liquid Ar sampling		Noble Gas liquid TPCs		
Cerenkov: Quartz, silica aerogel, pure water		Quartz fibers in dual readout calorimeters		Pure water detector	RICH, TOP	Quartz fibers
Photosensors: APDs, HPDs, SiPMs, PMTs		Depending on sensitive elements, B-Field...		SiPMs, PMTs		Depending on sensitive elements, B-Field...
Front-End ASICS	High density, low power					
Data Transfer	High bandwidth, clock timing precision					
Back-End electronic	High bandwidth and processing power					
Power distribution	in situ DCDC conversion, serial distribution for Pixels, switchable for low frequency beams (ILC/CLIC))					
Mechanics	Ultralight and stable	Massive		Very massive and large		
Cooling	$\simeq$ -30/40$\circ$ operation	$\simeq$ -30/40$\circ$ operation		Cryogeny		$\simeq$ -30/40$\circ$ operation