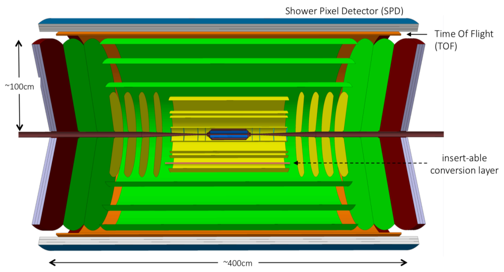
Revue expérimentale au LHC long terme



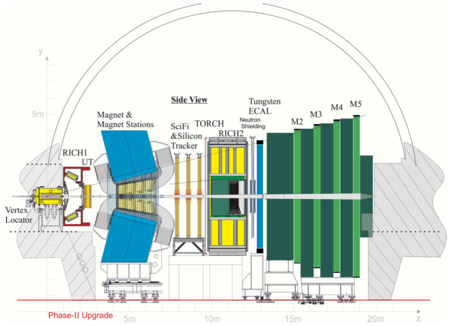
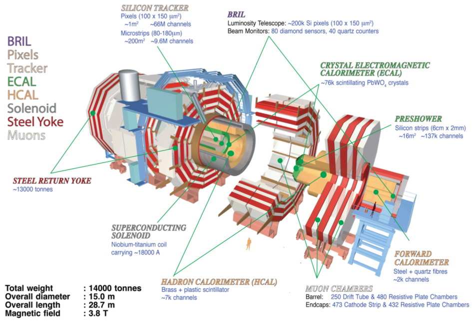


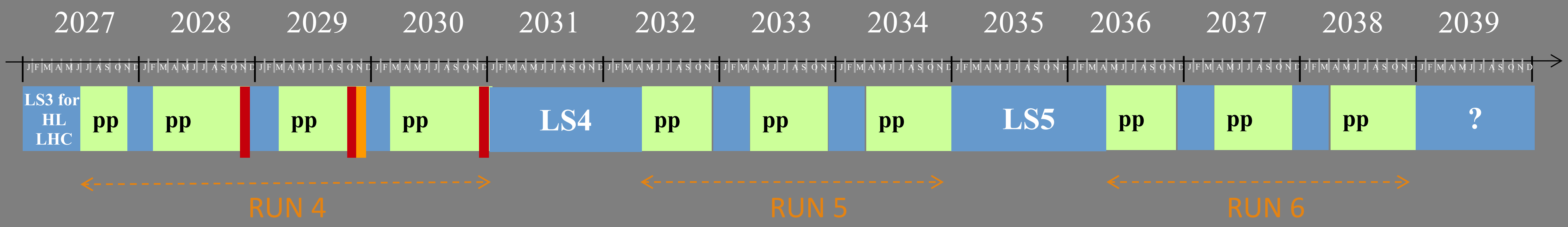
Figure 4.1: Schematic side view of the Phase-II detector.



Sarah Porteboeuf Houssais
et Antonin et Maxime et Michael et Rachid et Émilie et Benjamin et Matt et Alexandre
ainsi que toutes contributions directes et indirectes!

Prospectives IN2P3 GT03 ”Physique Hadronique”
Nantes 2-3 Mars 2020

QGP post LHC-RUN4 : échelle de temps*



- RUN5 : démarrage en 2032 => dans 12 ans
- Demande du WG5 : O-O et p-O dès le RUN3, à priori ok RUN4 avec un potentiel ion lourd plus important (extension en 2029 de 4 à 6 semaines)
- Pas de *runs* dédiés ion-lourds planifiés aujourd'hui au RUN5, espèces plus légères envisagées, ex. Ar-Ar

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

QGP post LHC-RUN4 : 4 contributions, 39 signataires

Unravelling the hadronic collision structure with Large-Scale System and Energy Scan

By alphabetic orders :

Cvetan Cheshkov[1], Zaida Conesa del Valle[2], Bruno Espagnon[2], Marie Germain[3], Maxime Guilbaud[3], Cynthia Hadjidaki[2], Hubert Hansen[1], Boris Hippolyte[4], Jean-Philippe Lansberg[2], Antonin Maire[4], Gines, Martinez[3], Laure Massacrier[2], Sarah Porteboeuf Houssais[5] **(Contact Person)**, *Alexandre Shabetai[3], Christophe Suire[2], Antonio Uras[1], Klaus Werner[3]*

1. Institut de physique des deux infinis - Lyon (IP2I)
2. Institut de Physique Nucléaire d'Orsay (IPNO, Orsay)
3. Laboratoire de Physique Subatomique et Technologies associées (SUBATECH, Nantes)
4. Institut Pluridisciplinaire Hubert Curien (IPHC, Strasbourg)
5. Laboratoire de Physique Corpusculaire de Clermont-Ferrand (LPC)

Abstract

At the LHC, signs of QGP-like features are found in small colliding systems, proton-proton (pp) and proton-nucleus (pA). The question of whether a QGP can form in small collision systems is deeply linked to the description of the collision structure and the emergence of collectivity. To develop a unified paradigm describing hadronic collisions, we propose a large-scale collision system and energy scan. It implies complementary experimental paths to be investigated: LHC, Fixed Target at LHC, EIC and FCC. This program extends the planned physics cases of the above projects which are developed in dedicated contributions.

Heavy ion physics with the Compact Muon Solenoid

M. Nguyen*[1], R. Granier de Cassagnac[1], F. Arleo[1], and É. Chapon[2]

[1]*Laboratoire Leprince Ringuet, Palaiseau, France*
[2]*CERN, Geneva, Switzerland*

Abstract
The capabilities of the CMS experiment for heavy ion physics have been well established over the course of the first two Runs of the LHC (2010 – 2018). Pivotal discoveries in the field emerged from the CMS heavy-ion program, such as the sequential suppression of the Υ states in PbPb collisions, as well as the surprising evidence of collectivity seen in high multiplicity pp collisions. The CMS detector will be dramatically upgraded for the high-luminosity era, which is set to begin around 2025. This document outlines the prospects for future measurements in heavy-ion collisions with the upgraded CMS detector.

Heavy-ion physics at LHCb

Prospectives IN2P3, GT03, Physique hadronique

Contact: Émilie Maurice (LLR), emilie.maurice@llr.in2p3.fr, 01 69 33 55 72
Benjamin Audurier (LLR), Frédéric Fleuret (LLR), Patrick Robbe (LAL)

November 2019

The LHCb Heavy-ion physics program has been endorsed by the LHCb collaboration in 2015. Since then, Heavy-ion data have been recorded at the LHC in collider mode (pPb and PbPb collisions) but also in fixed-target configuration thanks to the LHCb unique internal gaseous target. With the upcoming upgrade of the detector and of the fixed-target setup, both scheduled for 2021, LHCb physics program will be extended towards precise studies of the QGP features with PbPb collisions, but also towards the first observation and characterization of the QGP phase transition with the fixed-target configuration.

Une expérience de nouvelle génération pour la QCD au HL-LHC

Détecteur ITS-3 d'ALICE et proposition d'expérience ANGHIE

Personne de contact :
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Auteurs (ordre alphabétique) :
- Équipe ALICE IPHC : Iouri Belikov, Arthur Gal (doctorant), Boris Hippolyte, Marc Imhoff, Christian Kuhn, Antonin Maire, Fouad Rami, Christelle Roy, Serhiy Senyukov, Yves Schutz
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Prospectives QGP-France
10/11 Décembre 2019

https://indico.cern.ch/event/862727/

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Petits Systèmes avec LHC, EIC, FCC

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Après RUN4 : Ère de Précision

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

! HL-LHC = RUN3/4 for WG5

1. **Characterizing the macroscopic long-wavelength QGP properties with unprecedented precision.**
    1. *Temperature*
    2. *QCD phase transition at* $\mu_B \simeq 0$
    3. *Viscosity and further QCD transport coefficients*
    4. *Heavy-quark transport coefficients*
    5. *Searching for transport phenomena related to the presence of strong electrodynamic fields*

2. **Accessing the microscopic parton dynamics underlying QGP properties.**
    1. *Constraining with jet quenching the colour field strength of the medium*
    2. *Investigating the quasi-particle structure of QCD matter with jet and heavy-quark measurements*
    3. *Testing colour screening with bottomonium production*
    4. *Testing colour screening and regeneration dynamics with charmonium production*
    5. *Formation of hadrons and light nuclei from a dense partonic system*

Après RUN4 : Ère de Précision

3. Developing a unified picture of particle production from small (pp) to larger (p–A and A–A) systems.

   1. *Flow measurements in* pp *and* p–A *systems: Onset and higher-order correlations*
   2. *Flow of heavy flavour and quarkonium in smaller systems*
   3. *Strangeness production as a function of system size*
   4. *Searching for the onset/existence of energy-loss effects in small systems*
   5. *Searching for the onset/existence of thermal radiation in small systems*

4. Probing parton densities in nuclei in a broad (x, Q2) kinematic range and searching for the possible onset of parton saturation.

   1. *Precise determination of nuclear PDFs at high* Q2
   2. *Constraining nuclear PDFs at low* Q2
   3. *Access to non-linear QCD evolution at small-x*

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Une partie de ce programme de physique sera fait aux RUNs 3 et 4
Upgrades en cours, présentés par Antonin

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Dans la suite : **synthèse des questions de physique encore ouvertes après le RUN4**,
et considérées par la communauté Française
input des prospectives + QGP-France https://indico.cern.ch/event/862727/

Après RUN4 : programme proposé par la communauté française

1. Characterizing the macroscopic long-wavelength QGP properties with unprecedented precision.

1. Temperature

2.QCD phase transition at $\mu_B \simeq 0$

ANGHIE

I.2 – HL-LHC QCD+QGP : low mass (e^+e^-) as virtual γ

1. QGP temperature = f(time) via thermal virtual photons ($m_{e+e-} \in [0;2.5]$ GeV/c^2)
   high m_{e+e-} = high T, i.e. early times

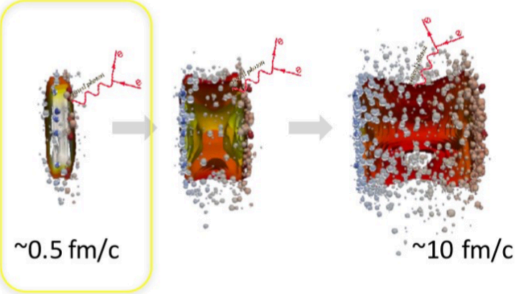
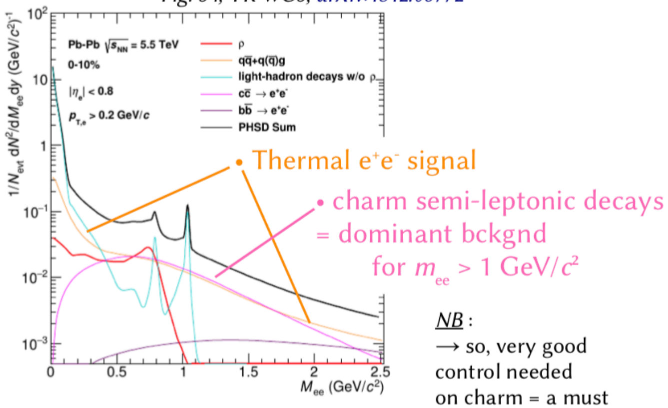
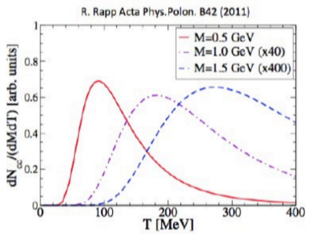


Fig. 54, YR WG5, arXiv:1812.06772





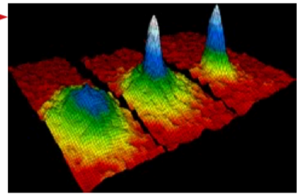
NB :
→ so, very good control needed on charm = a must

Antonin.MAIRE@cern.ch – IPHC Strasbourg / QGP France Prospectives GT03 2019

I.5 – HL-LHC QCD+QGP : why caring about the low-p_T $\pi^\pm$

1. Getting dN/dp_Tdy + $v_n(h^\pm)$ down to non-relativistic p_T (e.g. p_T < 0,05 GeV/c ⟶ $\beta_{\pi^\pm} \approx$ 0,34)
   ⟶ change from non-relativistic (linear) to relativistic hydro. (quadratic behaviour)

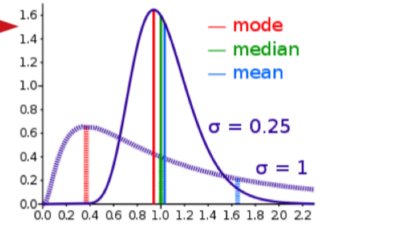
2. Chiral disoriented condensate + π condensate
   if present, p_T < 1/2 m_π



Wikipedia: Bose-Einstein condensate

3. Net quantum numbers fluctuations at (μ_B = 0)
   Q : net charge (h^+ - h^-),
   B : net baryon (p - $\bar{p}$, Λ - $\bar{\Lambda}$, ...)
   S : net strangeness (K^+ - K^-, Λ - $\bar{\Lambda}$, ...)

Measure event-by-event fluctuations into distributions with p_T > 0 GeV/c, over large y :
- 1st moment, m_1 : mean μ
- 2nd moment, m_2 : std deviation
- 3rd moment, m_3 : skewness
- 4th moment, m_4 : kurtosis
- 5th moment, m_5 : *no name*
- 6th moment, m_6 : ...
- 7th moment, m_7 : ...



Wikipedia:Skewness

⟶ *one key (today)* : ratio m_6/m_4 to access direct comparison to LQCD for (deconfinement dof + transition + chiral restoration)

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Après RUN4 : programme proposé par la communauté française

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1. Temperature

2.QCD phase transition at $\mu_B \simeq 0$

3.Viscosity and further QCD transport coefficients

Hydrodynamique aux limites relativistes : à y ≈ 0, v_n(h±), jusqu'à des p_T faiblement relativistes, p_T < 0,05 GeV/c

4.Heavy-quark transport coefficients

I.3 – HL-LHC QCD+QGP : heavy-flavours facing collectivity

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Λ_c^+ (m = 2.286 GeV/c² / cτ = 60 μm)

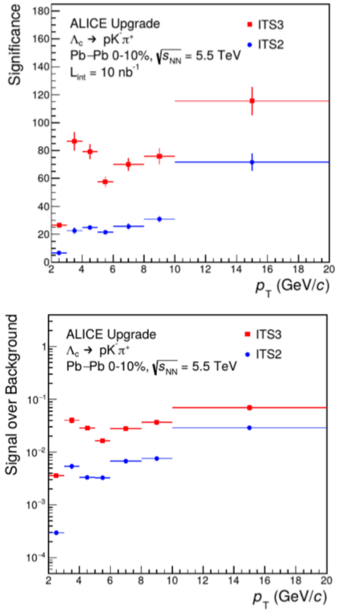

Fig 13, EoI ITS3, ALICE-PUBLIC-2018-013

⟶ diffusion coefficient / hydrodynamization / in-medium energy loss / hadronisation

- total charm cross-section $c\bar{c}$: η_c(1S), J/ψ, ψ(2S), χ_{cj} + D^0, D^+, D_s^+, D(2010)$^\pm$ + Λ_c^+
- beauty :
  - baryons $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
  - mesons $B^0 \to D^-\pi^+$, $B^\pm \to D^0\pi^\pm$, $B_s^0 \to$ non-prompt D_s^+
- recombination :
  - $p/\pi^+ \to \Lambda/K^0_s \to \Lambda_c^+/D^+ \to \Lambda_b^0/B^0$
- charm-strange baryons
  - (cτ ~ 30-130 μm + 2-to-6 final states cascade decays) :
  - = $\Lambda_c^+(udc)$, $\Xi_c^+(usc)$, $\Xi_c^0(dsc)$, $\Omega_c^0(ssc)$, $\Xi_{cc}^{2+}(ucc)$, … , $\Omega_{ccc}^{2+}(ccc)$
- charm hypernuclei, c-deuteron = Λ_cn bound state
- tetraquark X(3872) ⟶ J/ψ π^+ π^-

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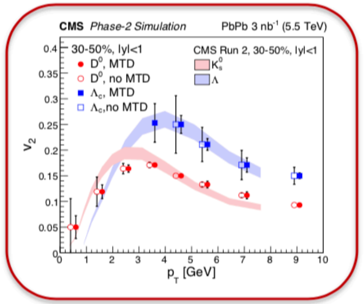
See also QM 2019, G.-M. Innocenti for ITS-1 Pb-Pb or pp physics of Λ_c^+ … Antonin.MAIRE@cern.ch – IPHC Strasbourg / QGP France Prospectives GT03 2019

Open heavy flavor

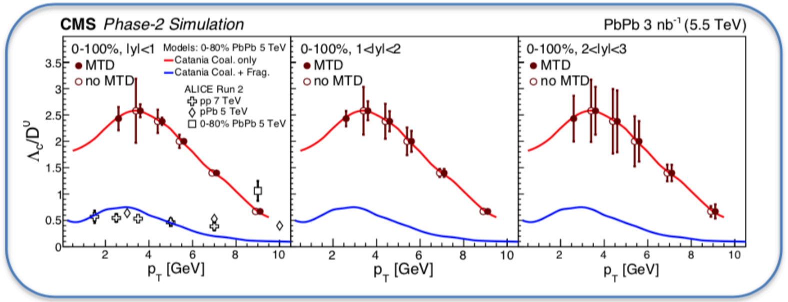
CMS

$\Lambda_c \to \pi + K + p$ is the PID physics case par excellence

Heavy quark dynamics via elliptic flow



Hadronization by recombination from baryon-to-meson ratio



+ Combining w/ other experiments, can measure total charm x-section, e.g., for onia dissociation studies

Light nuclei & hyper-nuclei is another interesting PID application

Après RUN4 : programme proposé par la communauté française

2. Accessing the microscopic parton dynamics underlying QGP properties.

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CMS

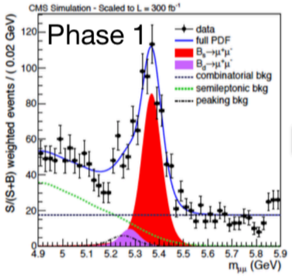
LHCb

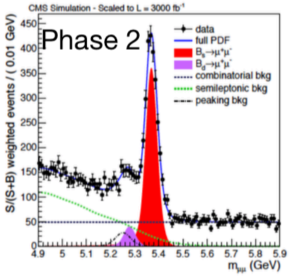
Quarkonia dissociation

Tracker+muon upgrades will improve triggering + reconstruction efficiency

50% gain in mass resolution

B_0/B_s separation



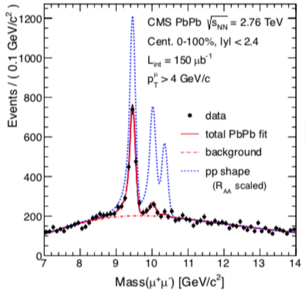


Separation of the ϒ family

→ Observe the ϒ(3s) (or place more stringent limits)

→ Improve significance of other low S/B peaks: ψ(2s), X(3872), etc.

Phase 1



Phase 2

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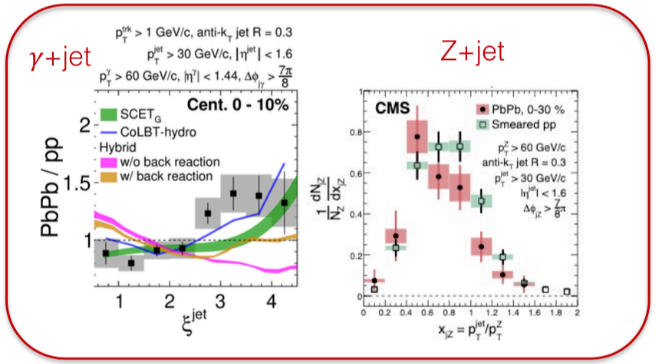
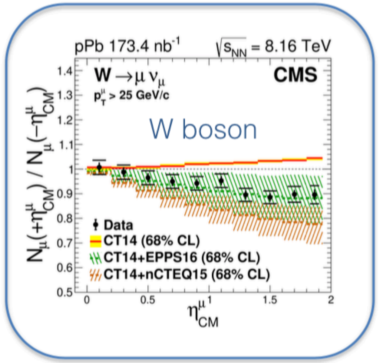
Precision quenching & nPDFs

Large acceptance, hermetic detectors essential for precise measurements of:

- Jet quenching in AA with γ+jet and Z+jet balancing
  → to fully constrain entire energy of the recoiling jet
- nPDFs with dijets and with weak bosons
  → to probe the forward region, which is most sensitive to nuclear effects





Phase II features full particle flow (tracker+HGCal+muon) to $\eta \approx 3$
Current detector goes to $\eta \approx 2.4$, but often limited by poor endcap performance

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https://indico.cern.ch/event/862727/

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Petits Systèmes avec LHC, EIC, FCC

CMS

LHCb

ANGHIE

Enlarge the program

- LHC Run 3-4 will be a great playground for small systems physics
- But will not solve all the open questions
  - Is a multiplicity hadronic event the same independently of the energy of the collisions ?
  - Is a multiplicity hadronic event the same independently of the size of the system ?
- An Ideal physics program would scan a very wide range of energy and systems scanning all multiplicities up to LHC central Pb-Pb => Not possible
- Large-scale collisions system and energy scan, having the goal to reach the highest possible multiplicity classes

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At LHC Run 5/6, horizon 2030

- LHC experiments are planning upgrades
- Particle physics experiments will open phase space for heavy ion studies, examples :
  - Centrality reconstruction for LHCb
  - CMS PID
- ALICE proposal for for a 4π compact silicium detector with very low momentum resolution (p_T > 20 MeV) with PID and TOF
- Need for a system scan and higher multiplicities measurements to be determined for small systems

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Impact for the community

- Not an additional project, a change of paradigm to exploit the foreseen facilities
- Any new insight on a universal description of hadronic collisions would bring significant outcome on the theory side
- This field has a strong impact for the event generator community: modeling of hadronic collisions in PYTHIA, EPOS, HERWIG, DISPY, …
- Could even impact the modelling of minimum bias pp collisions
- Could be of importance the particle physics community:
  - Rare events with high number of charged particles have specific dynamics
  - High Q^2, mass, p_T selected particle bias the selection towards those type of events
  - This physics will impact the underlying event description of the particle physics community

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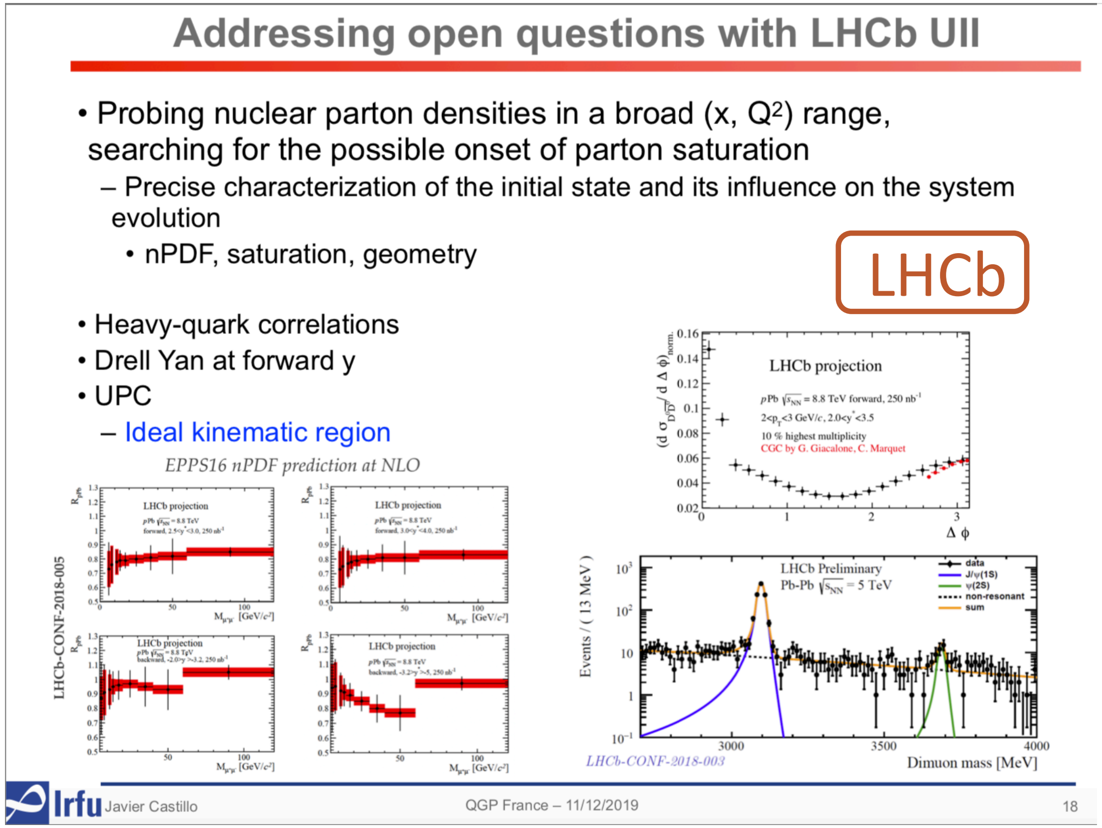
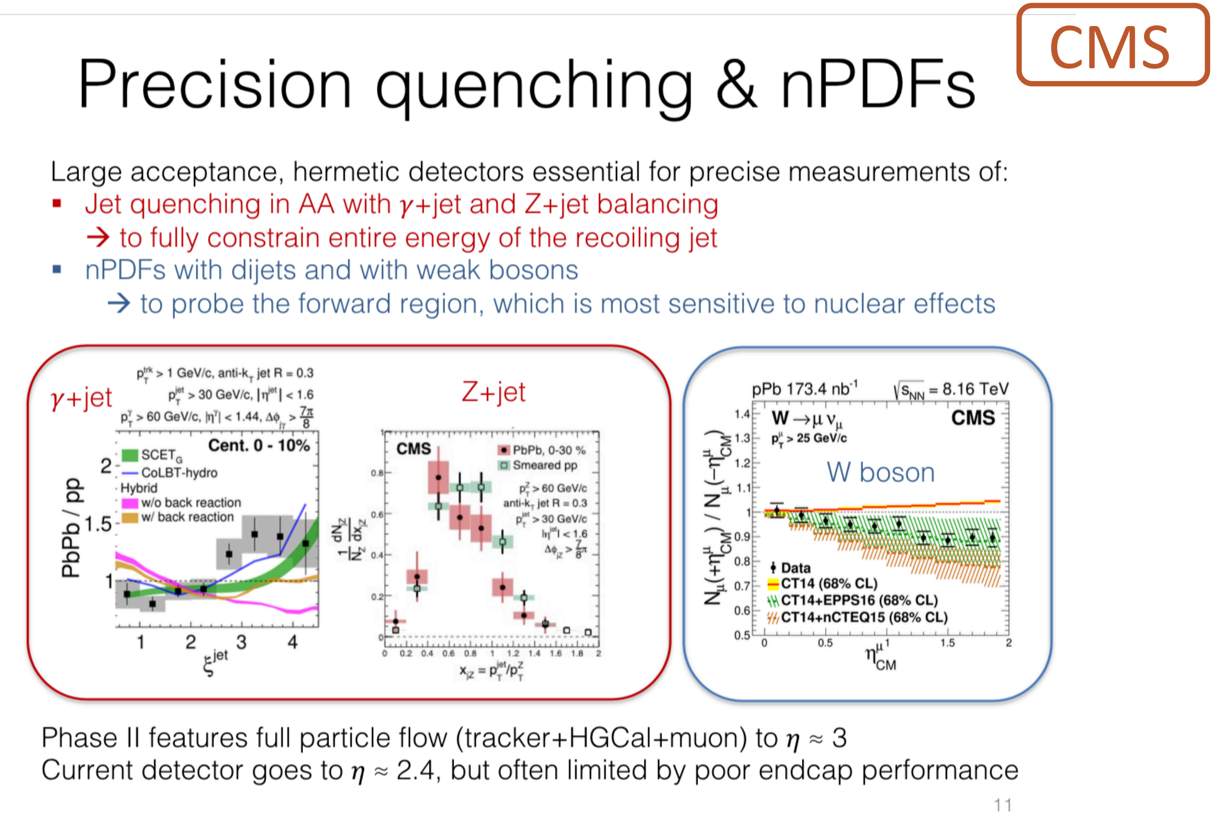
https://indico.cern.ch/event/862727/

Après RUN4 : programme proposé par la communauté française

4. **Probing parton densities in nuclei in a broad (x, Q2) kinematic range and searching for the possible onset of parton saturation.**
   1. Precise determination of nuclear PDFs at high Q2
   2. Constraining nuclear PDFs at low Q2
   3. Access to non-linear QCD evolution at small-x





Après RUN4 : programme proposé par la communauté française

5. Standard Model in Heavy Ion

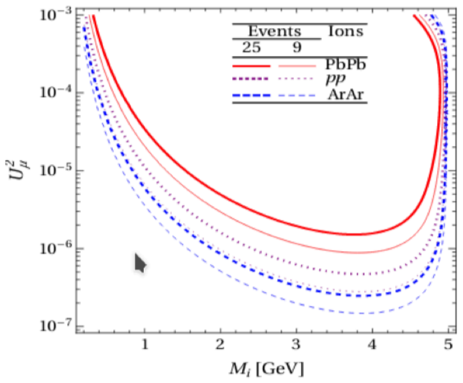
I.7 – HL-LHC QCD+QGP : SM/BSM searches

ANGHIE

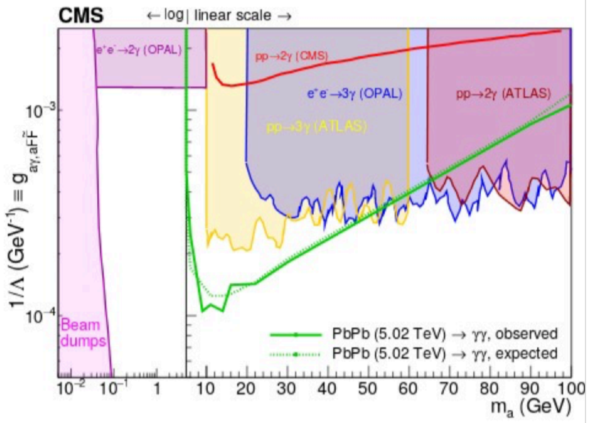
- axion-like particle (ALP) in UPC light by light,
- Long-lived particles,
- sexaquarks
- magnetic monopoles

…

d'Enterria ESPP, arXiv:1812.07688



Heavy neutrino searches in B decays

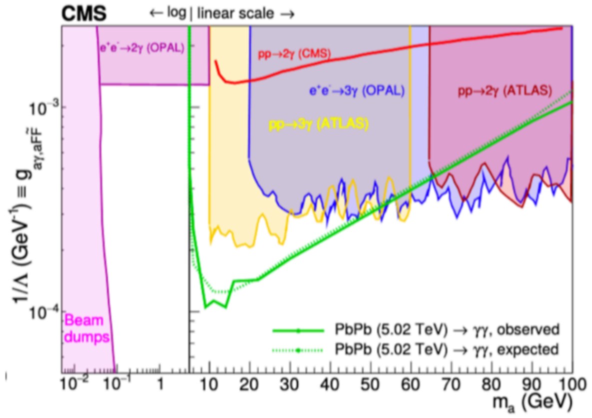


Current 95% CL exclusion limits
ALP coupling to γ Vs ALP mass

BSM in heavy ions

CMS

One example:
γγ from UPCs provides an exclusion limit on axion-like particles (ALPs)



Rate for UPCs of heavy ions ~ Z^4

However, factoring in beam intensity, light-ion collisions become competitive

		$^{16}_{8}$O	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{78}_{36}$Kr	$^{129}_{54}$Xe	$^{208}_{82}$Pb
γ	[10^3]	3.76	3.39	3.76	3.47	3.15	2.96
$\sqrt{s_{NN}}$	[TeV]	7	6.3	7	6.46	5.86	5.52
σ_{had}	[b]	1.41	2.6	2.6	4.06	5.67	7.8
N_b	[10^9]	6.24	1.85	1.58	0.653	0.356	0.19
ϵ_n	[μm]	2	1.8	2	1.85	1.67	1.58
Z^4	[10^6]	$4.1 \cdot 10^{-3}$	0.01	0.16	1.7	8.5	45
$\widehat{\mathcal{L}}_{AA}$	[10^{30} cm^{-2}s^{-1}]	14.6	1.29	0.938	0.161	0.0476	0.0136
$\widehat{\mathcal{L}}_{NN}$	[10^{33} cm^{-2}s^{-1}]	3.75	2.06	1.5	0.979	0.793	0.588
$\langle\mathcal{L}_{AA}\rangle$	[10^{27} cm^{-2}s^{-1}]	8990	834	617	94.6	22.3	3.8
$\langle\mathcal{L}_{NN}\rangle$	[10^{33} cm^{-2}s^{-1}]	2.3	1.33	0.987	0.576	0.371	0.164
$\int_{month}\mathcal{L}_{AA}dt$	[nb^{-1}]	$1.17 \cdot 10^4$	1080	799	123	28.9	4.92
$\int_{month}\mathcal{L}_{NN}dt$	[fb^{-1}]	2.98	1.73	1.28	0.746	0.480	0.210

For searches of long-lived particles (LLP) light ions are even more advantageous

Contribution submitted to the update to the European Particle Physics Strategy
arXiv:1812.07688

And after Run 4?

- LHC Run 2 is not over yet
- LHC Run 3 and Run 4 will finish in more than 10 years from now …
  - An ambitious plan is laid down and expected performances have been estimated and are being revisited …
  - We have predicted where we will be at the end of Run 4
  - We can therefore try to predict what will be missing afterwards …
    - …

- Let's also give it a chance to the unexpected, especially since the unexpected has happened
  - Jet suppression
  - J/ψ regeneration
  - QGP-like effects in small systems
  - …

- We can always look for **smoking guns** in **money plots** of **flagship measurements**, and we should, but let's be honest to ourselves, the one lesson from about 30 years of HI physics is that we need systematic and comprehensive program of all observables and probes of the QGP

Irfu Javier Castillo QGP France – 11/12/2019 22

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Irfu Javier Castillo QGP France – 11/12/2019 22

L'ensemble du programme identifié par le WG5 ne sera pas finalisé au RUN4:
- capacité des détecteurs
- statistiques
- systèmes et énergies

Étude systématique des observables (anciennes et nouvelles) en fonction de l'énergie, du système, de la multiplicité (ou d'autres observables de classification développées aux RUN 3 et 4)

"Comprehensive program" inclut développement théorique parallèle

Quel(s) détecteur(s) pour ce programme de physique ?

What's next ?

Prospectives QGP-France 2018

Dreaming of the ideal detector for small systems: *ALICMSb*

1. Hermeticity = large η coverage
2. Tracking low p_T > 0 GeV/c
   = low B field
   = low material budget
3. PID over a large p_T range
   No TPC (slow), No Cerenkov (material budget)
4. Electromagnetic and hadronic calorimeter
5. Muon chambers 4π
6. Computing ressources

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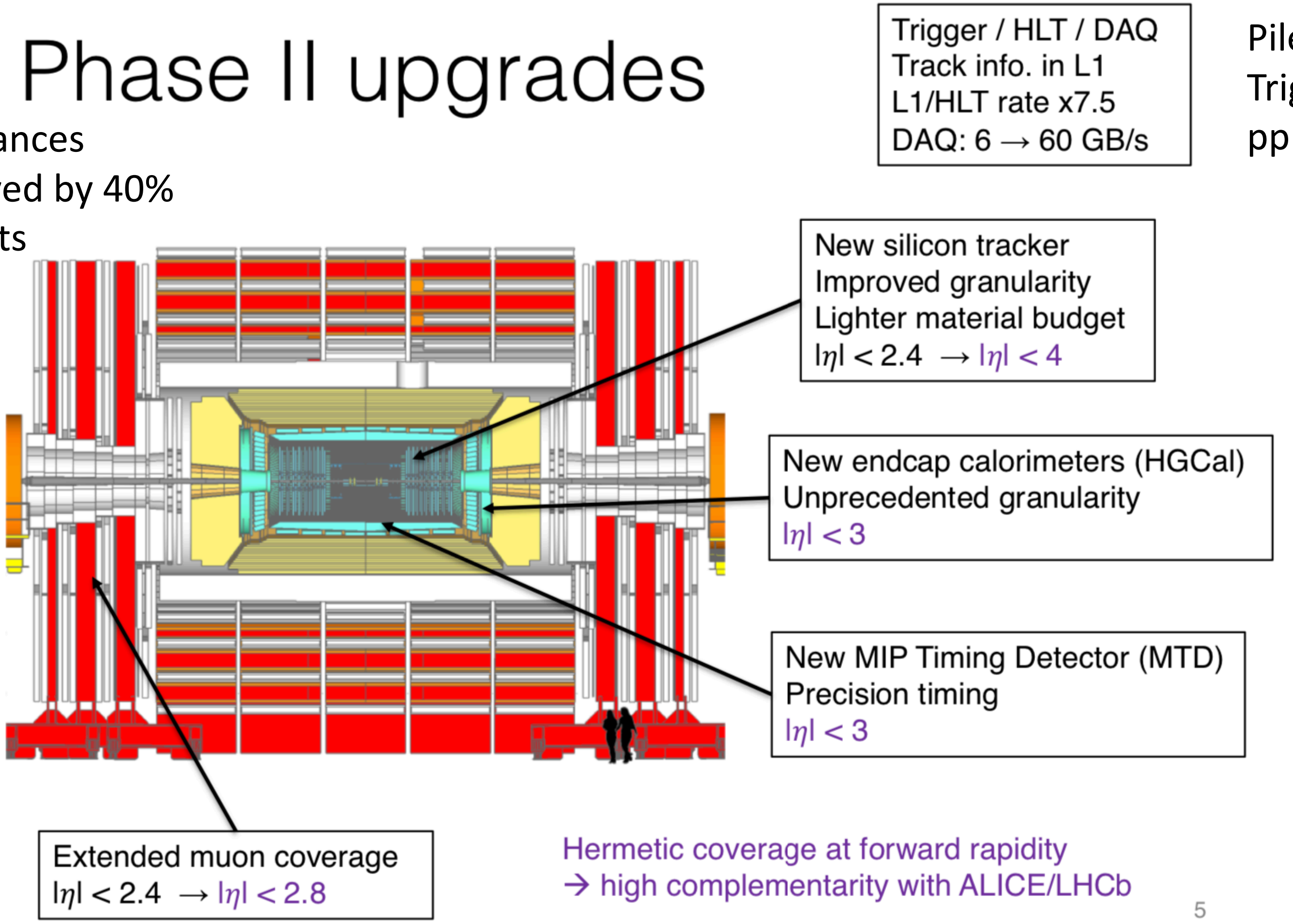
CMS at RUN 5

- Quasiment reconstruit au LS3, capacité similaire à celle du RUN4

Improved mass resolution for resonances
Impact parameter resolution improved by 40%
Improved heavy flavor measurements
(B/D hadrons & b/c-jet tagging)



Pile-up rejection in high lumi pp
Triggering on high multiplicity
pp collisions in low PU

Isolated photons

NEW, PID:
Similar ALICE/STAR PID
capabilities

Improve track matching with
silicon tracker at large occupancy :
Improve charm/beauty separation

LHCb UII

- Upgrade séquentiel (à chaque LS), de plus en plus favorable à la physique QGP
- Pile-up (pp) = 42 avec Sci FI amélioré (fibre scintillante) et Mighty Tracker (CMOS)
  => reconstruction ion lourd central envisageable
- TORCH : PID low-*p*

Mighty Tracker

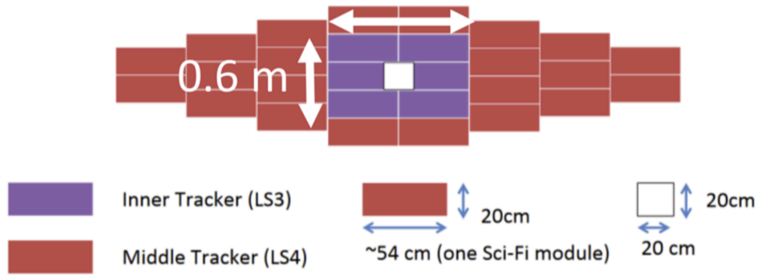


Table 5.1: Summary of the modifications under consideration for LS3, and those for Phase-II (LS4). Priorities will be assigned for the LS3 activities after further studies.

Detector	LS3	Phase-II
VELO	Deployment of prototype modules	New detector with fast timing
Tracking	Insert silicon IT, modify SciFi; install MS	Silicon UT and IT, SciFi OT
RICH	New photodetectors for selected regions; use of timing information	New optics; full replacement of photodetectors
TORCH	Installation for low-p hadron identification	Higher granularity photodetectors
CALO	Tungsten sampling modules installed in inner region	New modules in middle and outer regions
Muon	Replace HCAL with iron shielding; installation of high-rate chambers	Complete chamber installation
Trigger and data processing	Adiabatic software improvements; review of offline processing; installation of downstream track-finding processor	Expansion/replacement of links, readout boards and servers

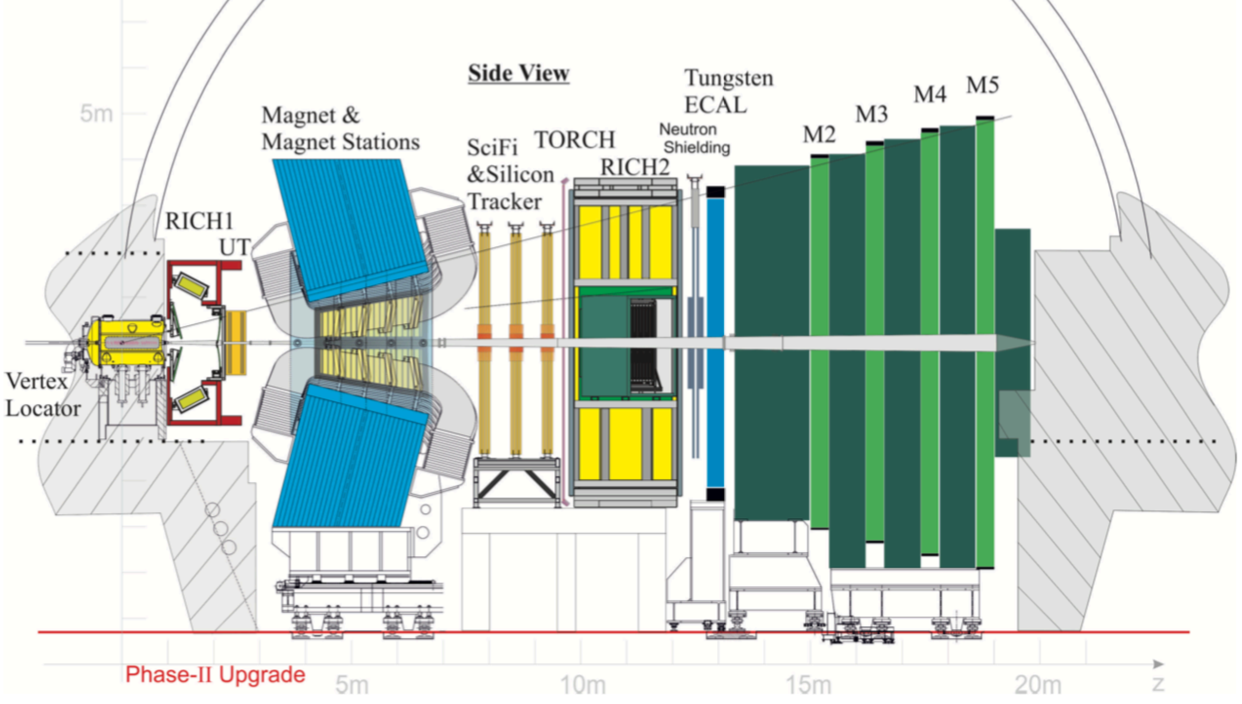


Figure 4.1: Schematic side view of the Phase-II detector.

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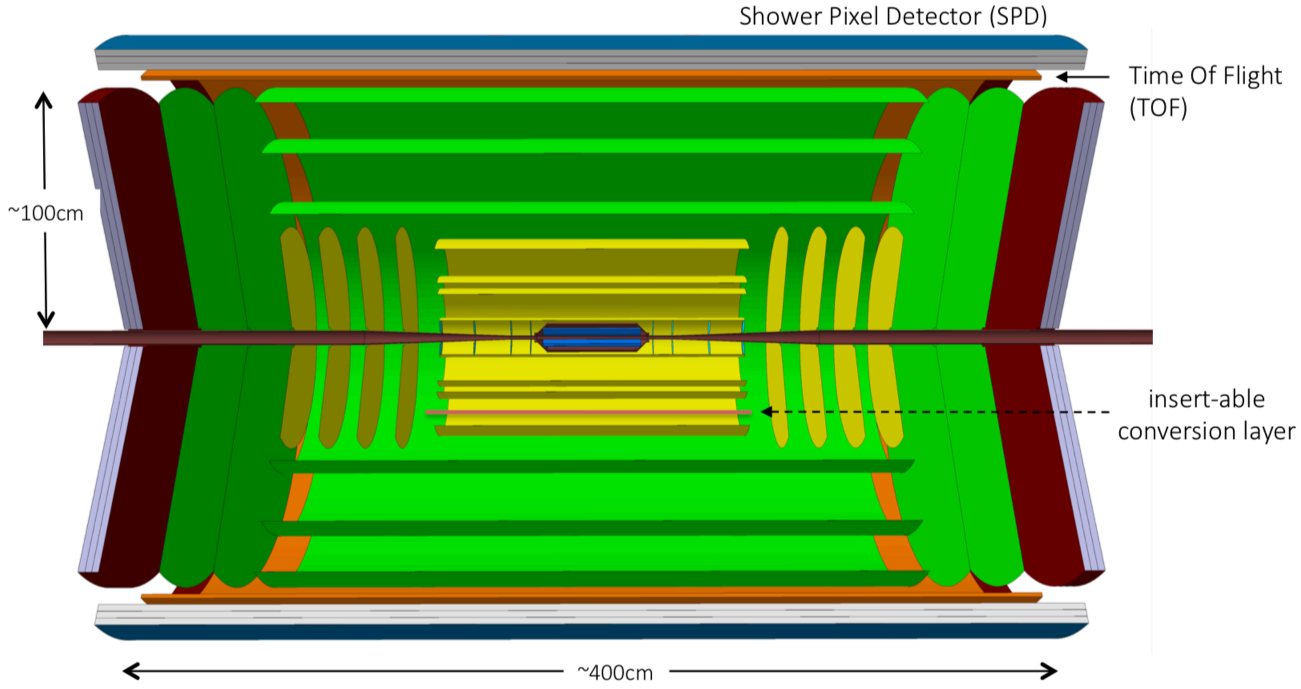
ANGHIE

A new experiment based on an "all-silicon" detector

- Tracking over : $|\eta| < 4$ + ($p_T > 30\text{-}50$ MeV/c at y=0)
- Space resolution ≈ < 5 µm
- Magnetic field B= 0.5T (ALICE magnet) or 1T



Central barrel $|\eta| < 1.4$:

- Inner Tracker (IT) : 3 layers inside the beam pipe
- Outer Tracker (OT) with 7 layers
- Time-Of-Flight (TOF) for the identification of hadrons and electrons at very low transverse momentum ($p_T < 500$ MeV/c)
- Shower Pixel Detector (SPD), identification of electrons and photons ($p_T > 500$ MeV/c)

Two endcaps $1.4 < |\eta| < 4$, contain each :

- 4 disks in the IT
- 6 disks in the OT
- 1 disk in the SPD

Exercice comparatif

Quelques exemples de mesures, Non exhaustif!	ANGHIE p_T>0.05 GeV/c $y \in$ [-4,4]	CMS Chargée $\eta \in$ [-4,4] PID (MTD) in η [-3,3] Muons in η [-2.8,2.8]	LHCb collider Centrality reconstruction PID (*low-p*) - $2<\eta<5$
COMPORTEMENT COLLECTIF			
Température - Dileptons de basse masse	Très favorable (diélectrons, hermiticité, très bas p_T)	À investiguer (hermiticité, bas p_T)	Très favorable à l'avant (dimuons)
Transition de phase (moment d'ordre supérieur)	Très favorable (hermiticité, très bas p_T)	Favorable (hermiticité, bas p_T)	Peu Favorables (∅hermiticité)
Emergence de la collectivité – petits systèmes	Très favorable	Très favorable (trigger avec MTD)	Peu Favorables pour les sondes collectives en mode collider (∅hermiticité) , peu de possibilité de corrélation avant-central
Jets et Jet quenching			
Jets de bas p_T	Très favorable	Favorable	À l'avant à investiguer
γ-jets, Z-jets	À investiguer	Très favorable	Peu Favorables
Jets et jet quenching dans les petits systèmes	Très favorable	Très favorable	À l'avant à investiguer

Disclaimer: table non officielle, comportant des imprécisions, table nécessitant d'être approfondie!

Exercice comparatif

Quelques exemples de mesures, Non exhaustif!	ANGHIE p_T>0.05 GeV/c $y \in$ [-4,4]	CMS Charged $\eta \in$ [-4,4] PID (MTD) in η [-3,3] Muons in η [-2.8,2.8]	LHCb collider Centrality reconstruction PID (*low-p*) - $2<\eta<5$
CHARME et BEAUTÉ			
Section efficace totale du charme	Très favorable		
Upsilon(3S)	Peu Favorable (∅muons, résolution en p_T)	Très favorable	Très favorables à l'avant si reconstruction en centrale
χ_c	À investiguer (4 pions / J/Ψ + γ)	À investiguer (4 pions / 4 μ)	À investiguer à l'avant (4 μ) si reconstruction en centrale
Baryons multi-charmés	Très favorable	Très favorable	Très favorables à l'avant si reconstruction en centrale
Charme et beauté dans les petits systèmes	Très favorable	Très favorable	Très favorables à l'avant
Matière Nucléaire Froide - NPDF			
Bosons faibles	Peu Favorable (∅muons)	Très favorable	Très favorable à l'avant
Di-jets	Très favorable	Très favorable	À l'avant à investiguer
UPC	À investiguer	Très favorable	Très favorable à l'avant
Physique des particules en ions lourds			
BSM signatures	Très favorable	Très favorable	Très favorable à l'avant

Disclaimer: table non officielle, comportant des imprécisions, table nécessitant d'être approfondie!

Conclusions (1)

- Les 4 (+1) grandes questions identifiées par le WG5 ne seront pas entièrement adressées après le RUN 4, e.g. (communauté française) :
  - Dileptons de basses masses, jets quenching, section efficace totale du charm, baryons multi-charmés, χ_c, Υ(3S), physique à très bas p_{T}, Model Standard en ion lourd.
  - Systèmes intermédiaires (Ar-Ar et autres)
  - Toutes les analyses faites de façon systématique dans tous les systèmes, suivant différents classificateurs de collisions (centralité, multiplicité, autres)

- LHC long terme : 3 Manips sur les rails, à des stades plus ou moins avancées de R&D et financement
  - CMS Upgrade, déjà opérationnel dès le RUN 4
  - LHCb II, reconstruction ion-lourds centraux, muons à l'avant
  - ANGHIE, ultra compact, très bas p_T

- Le RUN5 est dans 12 ans, nous avons le temps !

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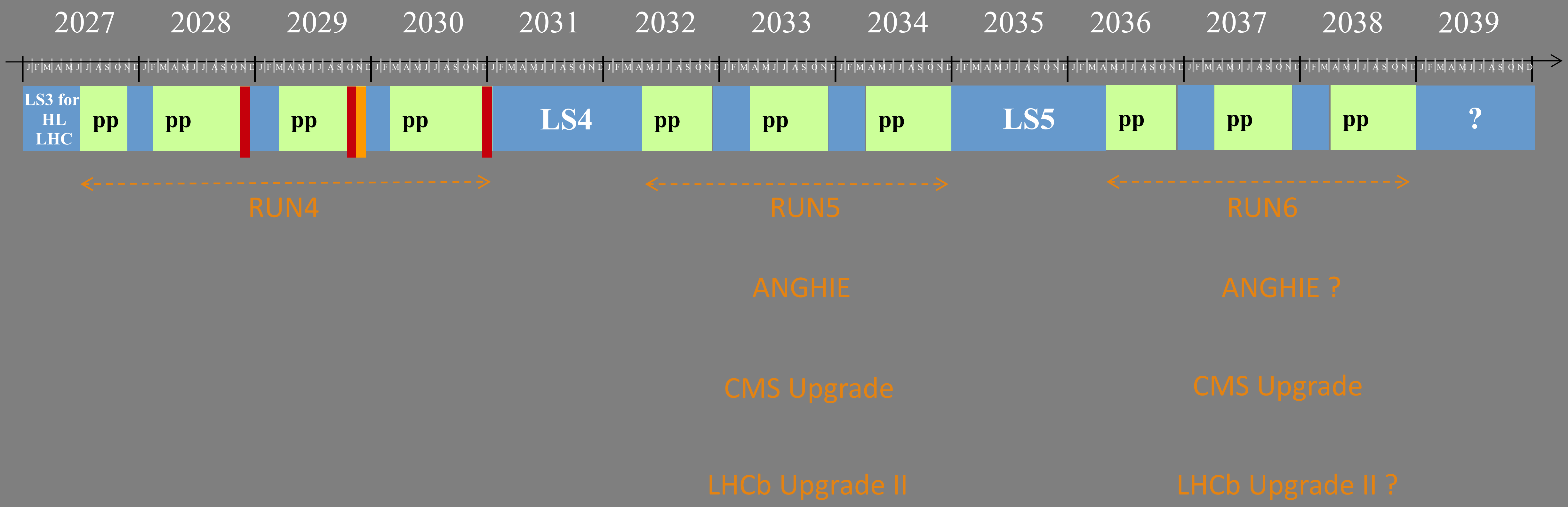
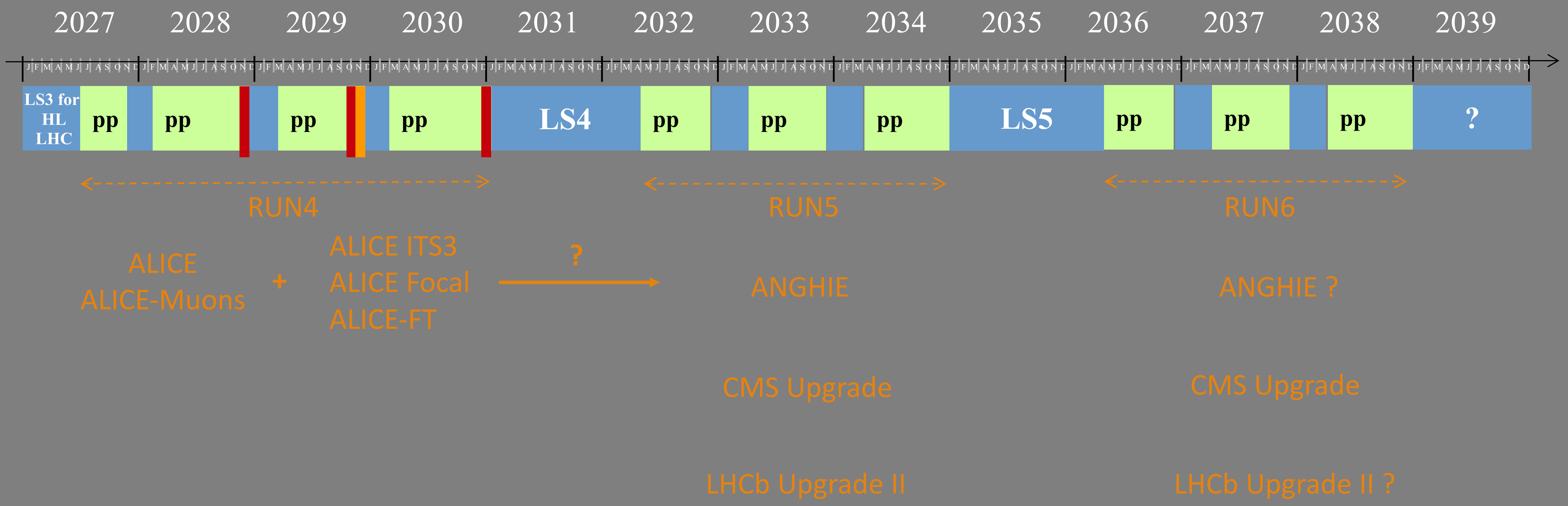
Si seulement …

Retour vers le futur

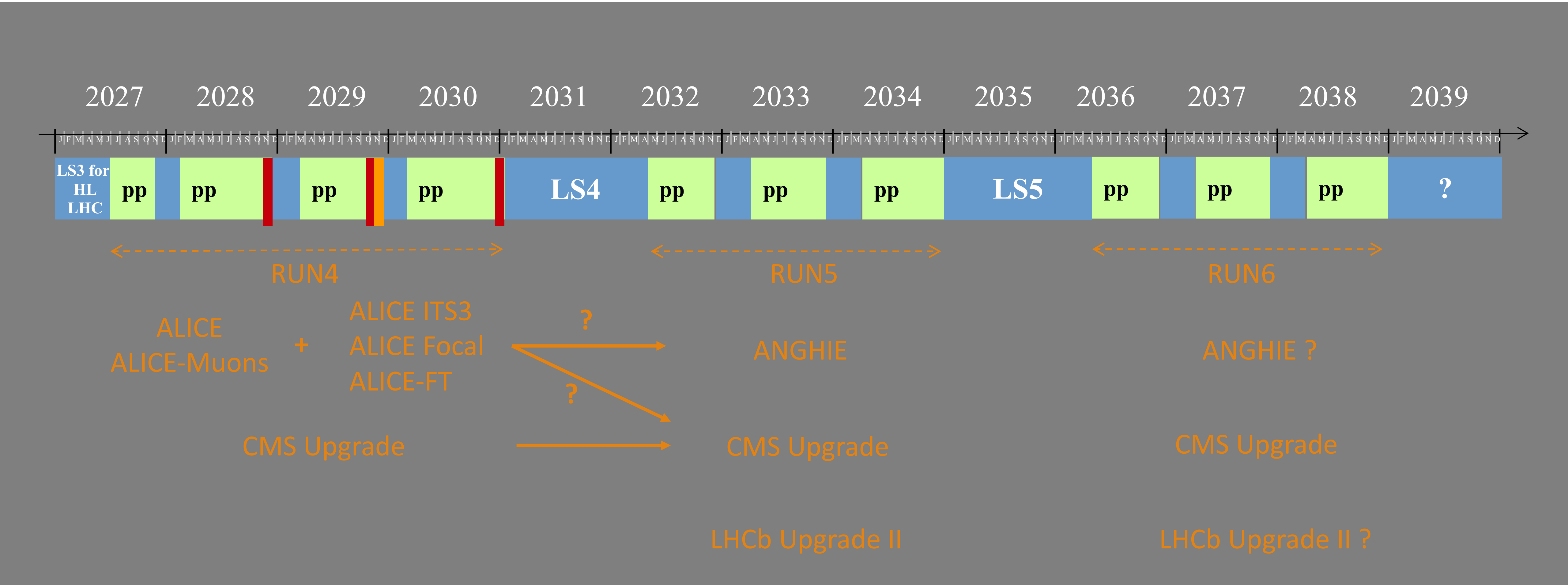


Retour vers le futur



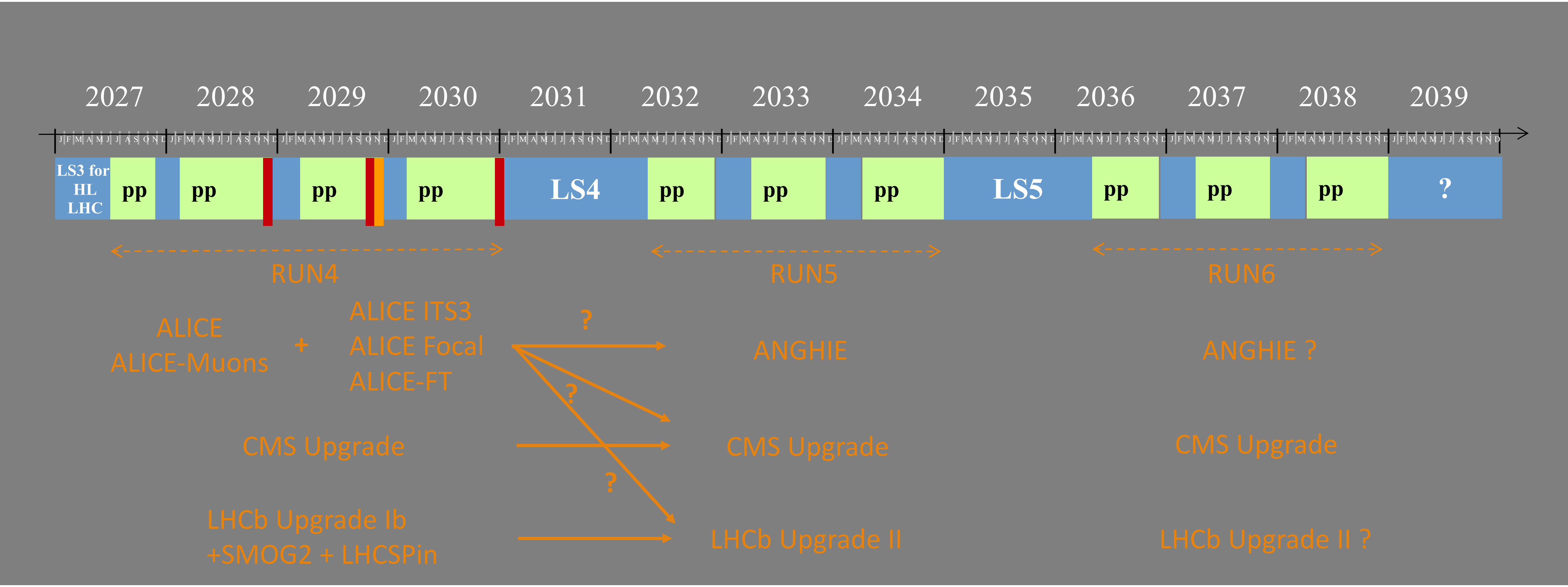
- Au RUN4, ALICE avec éventuellement ITS3, FOCAL et ALICE-FT
- ITS3 et FOCAL, développement technologique pour ANGHIE
- Si ITS3 et FOCAL ne se font pas, quel impact pour ANGHIE et le programme de physique ?

Retour vers le futur



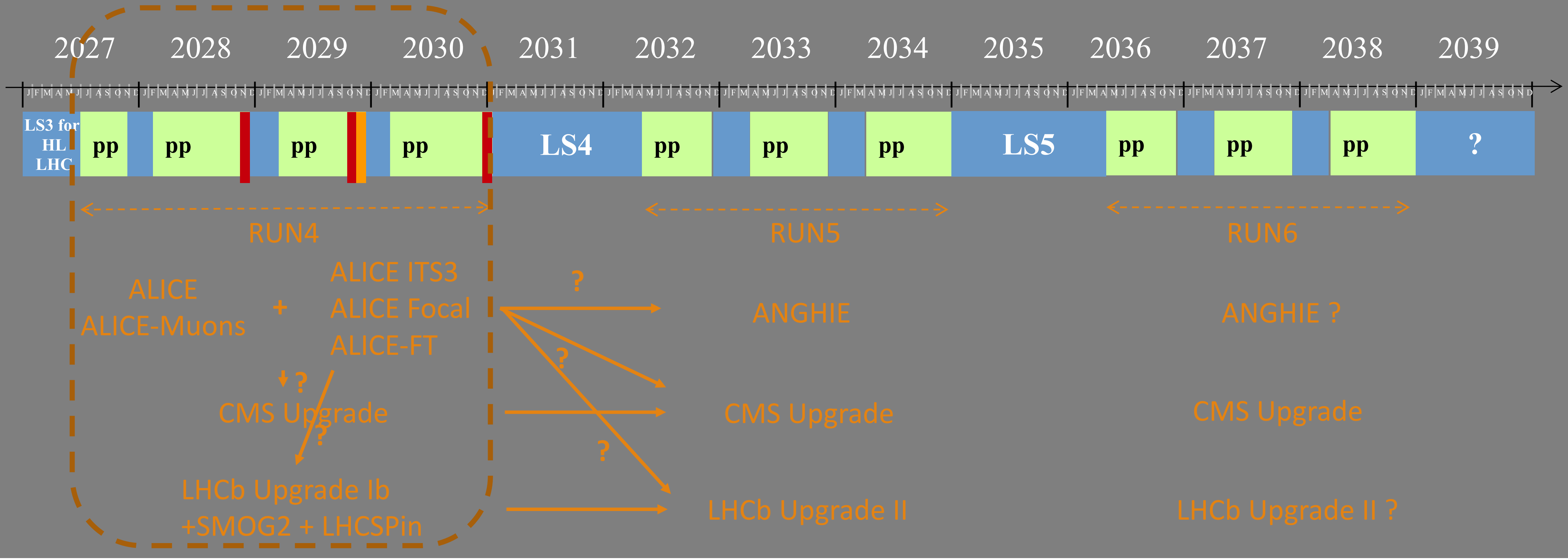
- L'upgrade de CMS, très favorable à la physique du QGP, sera opérationnel dès le RUN4

Retour vers le futur



- LHCb, upgrades au RUN4 et au RUN5 très favorable QGP
- avec programme cible fixe au RUN4, en question au RUN5

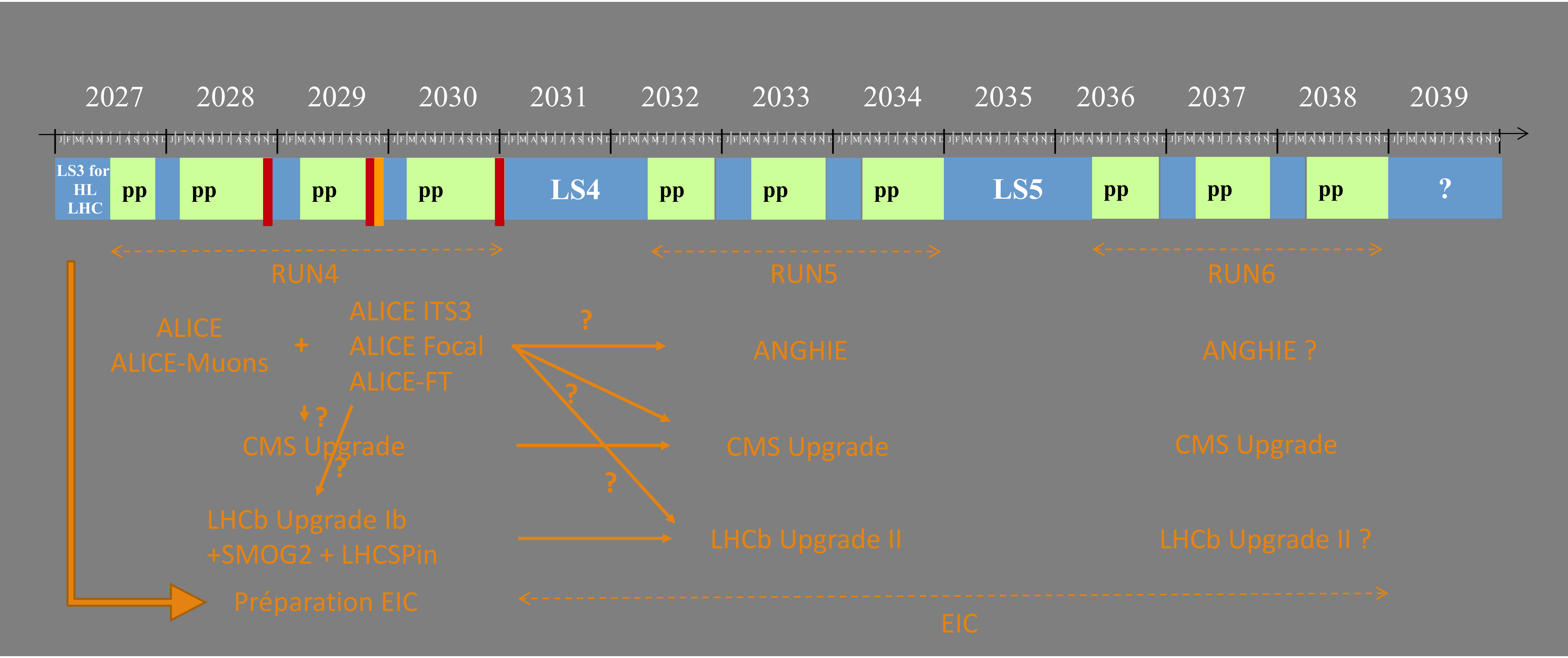
Retour vers le futur



Quelle stratégie au RUN4 en fonction de l'objectif du RUN5 ?

Le RUN4 démarre dans 7 sept ans, le LS3 dans 5 ans …

Retour vers le futur



- Un programme de physique ”QGP” est aussi à développer à EIC, timeline // RUN5, se prépare // RUN4

L'avenir lointain …

CERN-ESU-005
29 September 2019

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

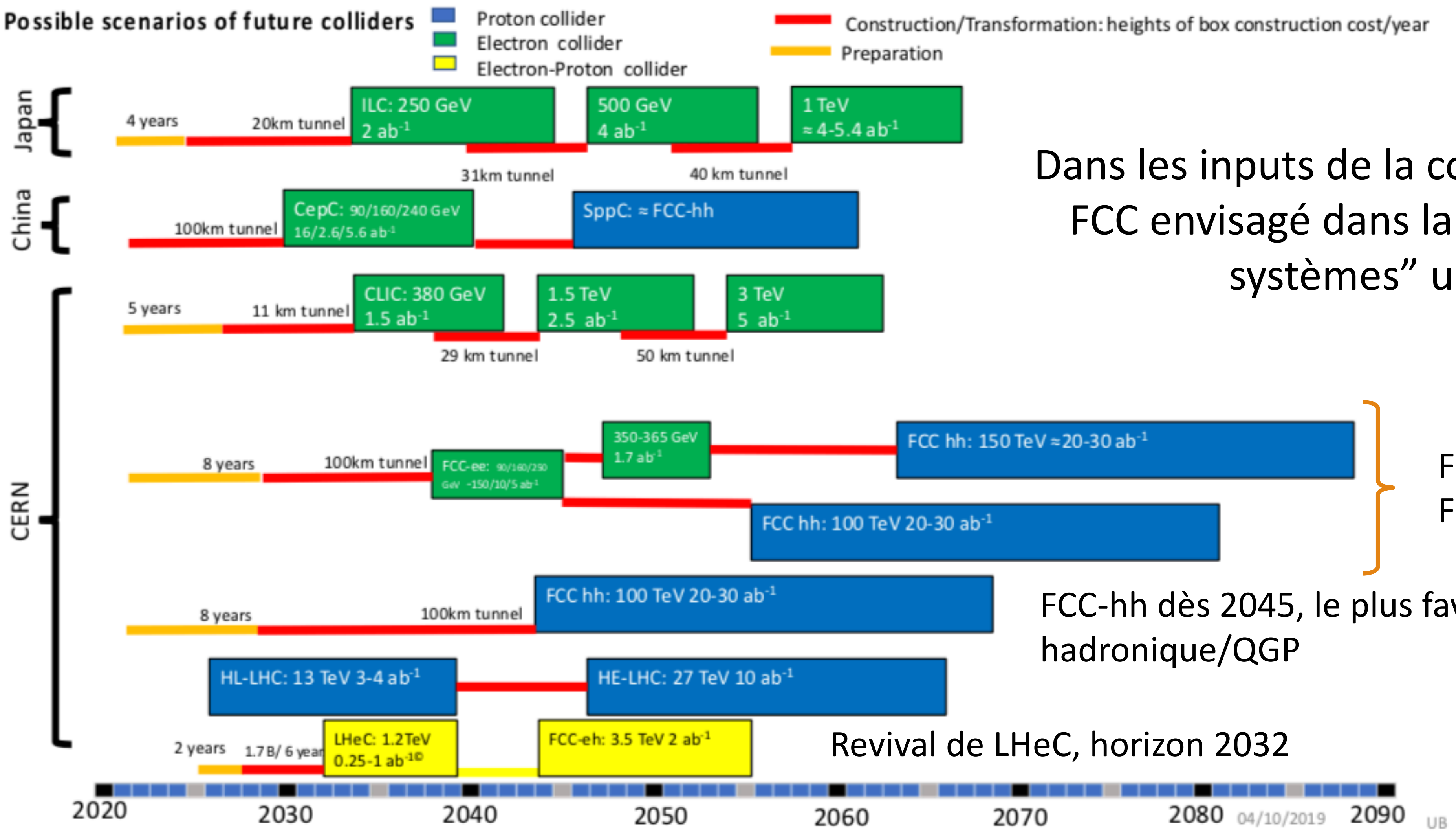
SUPPORTING NOTE FOR BRIEFING BOOK 2020

Towards an update of the European Strategy for Particle Physics

Pour l'après HL-LHC (après RUN6),
réflexion sur 5 scénarios impliquant CLIC,LHC-HE, FCC-ee, FCC-hh et LHeC pour les machines CERN
Horizon 2040 (dans 20 ans …)

	2020-2040	2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC	HL-LHC	CLIC380-1500	CLIC3000
CLIC-FCC-mixed	HL-LHC	CLIC380	FCC-h/e/A (Adv HF magnets)
FCC	HL-LHC	FCC-ee (90-365)	FCC-h/e/A (Adv HF magnets)
LE-to-HE-FCC-h/e/A	HL-LHC	LE-FCC-h/e/A (LF magnets)	FCC-h/e/A (Adv HF magnets)
LHeC+FCC-h/e/A	HL-LHC + LHeC	LHeC	FCC-h/e/A (Adv HF magnets)

FCC ou pas FCC (et quand)?



Dans les inputs de la communauté française, FCC envisagé dans la contribution ”petits systèmes” uniquement.

FCC-ee puis FCC-hh
FCC-hh en 2050 ou 2060

FCC-hh dès 2045, le plus favorable pour la physique hadronique/QGP

Revival de LHeC, horizon 2032

Questions à la communauté

Additionally, we seek to collect pro/con arguments that are to be considered for discussion by the European Strategy Group in answering the following questions and with a view to update the 2013 European Strategy for Particle Physics[1].

1. In the absence of clear indications for new physics, is a broad exploration an adequate approach for our global field? Do we want to move forward in the largest variety of directions?
2. Would it be appropriate/sufficient to move the scientific diversity program to among the highest priorities for Europe? Should the strategy engage in ranking proposals according to priority? Which are the key proposals?
3. Should we consider statements to strengthen the LHC and HL-LHC program? Should we stimulate the creation of coordinated programs at CERN and/or in Europe, e.g. AI@LHC for both data analysis and for control of instruments, etc?
4. Should we also support the fixed-target projects at (HL-)LHC?
5. Because of the competition for the Interaction Region at Point-2@LHC, should we consider for the period beyond LS4 a choice between the next generation heavy-ion experiments at the HL-LHC and the LHeC? ANGHIE vs. LHeC
6. Do we remain open towards strong participation in future collider programs outside Europe? Should such a statement remain among the highest priorities? Should we extend the scope to include a variety of options like ILC@Japan, EIC@US, CEPC@China, … ?
7. Anno 2013: "*CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*" Is the continuation of the CERN Neutrino Platform appropriate? Should we propose to extend the scope of the Neutrino Platform beyond long-baseline neutrino projects?
8. Anno 2013: "*Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.*" Should we strengthen this statement? Should we provide guidance how to achieve this?
9. Anno 2013: "*Detector R&D programmes should be supported strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*" Should we strengthen this statement? Should we provide guidance how to achieve this? For example, related to new R&D cluster programs at CERN and in Europe, and related to the balance between blue sky R&D versus focused R&D.

Link to 2013 strategy document: https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

10. Should we make concrete the technology collaboration with the gravitational wave community?
11. Should the HE-LHC feature in our strategy update?
12. In the context of the LE-to-HE-FCC-h/e/A scenario, would an adiabatic evolution from 6T to 16T/HTS magnets for FCC-h/e/A be an avenue to explore?

Les choix de la communauté particule, à long terme, ont un impact à moyen et/ou court terme sur la physique QGP.

Lien avec la communauté de physique des particules

- Au RUN 5, 2 des expériences (CMS + LHCb) sont initialement issues de physique des particules

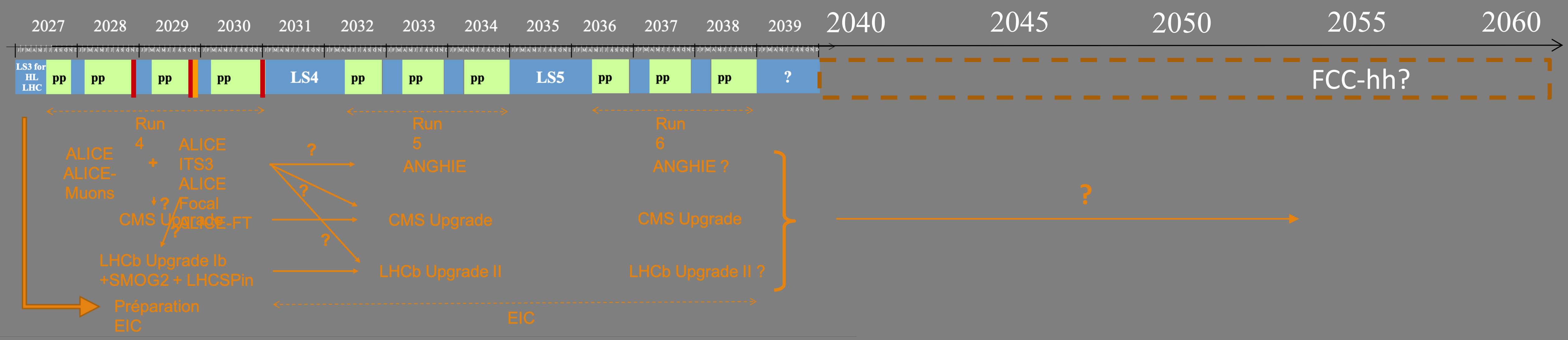
- Développement d'un programme QGP

- Upgrade très favorable pour notre physique
  Physique QGP moteur d'innovation : CMOS MAPS (ALICE ITS MFT), quadrupole GEM (ALICE TPC upgrade)

- Quel impact pour la physique des particules?
  - Petits systèmes : underlying event, MPI, QGP, hadronisation (en milieu dense) = PYTHIA développement
  - Physique des particules en collision d'ion lourds
  - à 100 TeV, la fraction des événements présentant des caractéristiques « QGP » sera beaucoup plus importante

- L'implication dans les RUNs 5 et 6 au LHC doit aussi être vue dans le cadre plus générale de la physique des particules et de son avenir lointain (2040-2060)

Retour vers le futur II



- Certes ces projets sont à des échelles de temps bien supérieures à celle des prospectives GT03
- Malgré tout les choix pour les RUNS 5/6 sont impactés par ceux du RUN 4 et impacterons les projets du futur

Conclusions (2)

- Les 4 (+1) grandes questions identifiées par le WG5 ne seront pas entièrement adressées après le RUN4 au LHC, e.g. (communauté française) :
    - Dileptons de basses masses, jets quenching, section efficace totale du charm, baryons multi-charmés, χ_c, Υ(3S), physique à très bas $p_{T,}$ Model Standard en ion lourd.
    - Systèmes intermédiaires (Ar-Ar et autres)
    - Toutes les analyses faites de façon systématique dans tous les systèmes, suivant différents classificateurs de collisions (centralité, multiplicité, autres)

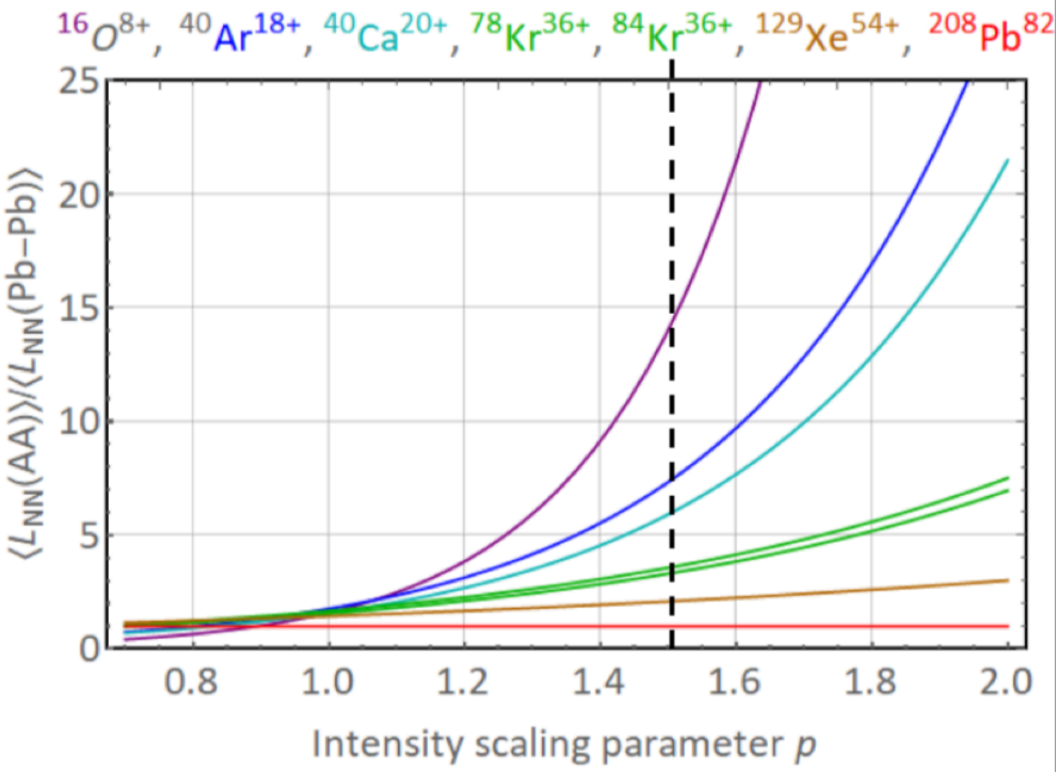
- Le programme de physique du RUN5 doit se préparer dès le RUN4

- En ayant en tête les questions :
    - À partir du RUN5 : ANGHIE vs. CMS Upgrade vs. LHCb II
    - Implication dans EIC (en parallèle)
    - (EIC vs. LHeC, LHeC vs. ANGHIE)
    - Devons-nous intégrer FCC dans les prospectives à très long terme ?
      Quid du rapprochement avec la communauté de physique des particules ?

BACKUP

Time-averaged luminosity ratio

- Showing ratio of time-averaged luminosity to Pb-Pb
- Analytical calculation with burnoff only – not full simulation
- Assuming 2.5 h turnaround time, 3 experiments with full luminosity
- Nucleon-nucleon luminosity in 1-month run: gains ranging up to a factor ~13 for lightest considered ion (O) at p=1.5



- The dramatic improvements in transmitted Pb intensity in 2015-16 were the result of many detailed studies and improvements
- Results have large uncertainties!

https://indico.cern.ch/event/758181/

ANGHIE

D.1 – ANGHIE : In2p3 prospectives, GT03 contribution

	ITS-2 [3]	ITS-3 [6]	ANGHIE [8]
Période LHC	Run III + IV (2021-29)	Run IV (2026-29)	≥ Run V (>2030)
Nombres de couches	3+*4*	3 (*+4 ITS-2*)	*O*(3+*7*)
R_{tube}	1,82 cm	1,6 cm	1,6 ou 2,9[2]
r_{L0} / r_{L1} / r_{L2} … r_{Last} (cm)	2,3 / 3,2 / 3,9 … *39,3*	1,8 / 2,4 / 3,0 … *39,3*	1,8 / … ≈ *100*
Champ magnétique $B_{solénoïde}$	0,2 ou 0,5 T	0,2 ou 0,5 T	0,2 à 1 T
Matière par couche (x/X_0)	0,3 % à *0,8 %*	0,07 % à *0,8 %*	0,05 % à *0,5 %*
Taille d'un pixel (µm²)	≈ 30 x 30	≈15 x 15 (+ *30* x *30*)	≈10 x 10 (+ *30* x *30*)
Résolution temporelle	≥ 2-5 µs	2-5 µs	≤ 1 µs
Résolution spatiale	5 µm	5 µm	≈ 3-*5* µm
Couverture en η	|η| < 2,0 à *1,3*	|η| < 2,0 à *1,3*	|η| < 4,0
$\varepsilon_{tracking}(p_T(h^{\pm}) = X\ GeV/c)$	1 0,1 0,05	1 0,1 0,05	1 0,1 0,05
	98 % 60 % 10 %	98 % 75 % 20 %	98 % 75 % 20 %
Coûts totaux (R&D + Constr.)	≈ 10 MCHF	5,3 MCHF	≈ 80-100 MCHF
Nb d'instituts / Nb de pays	30 / 16	30 / 16	(>399 signataires)

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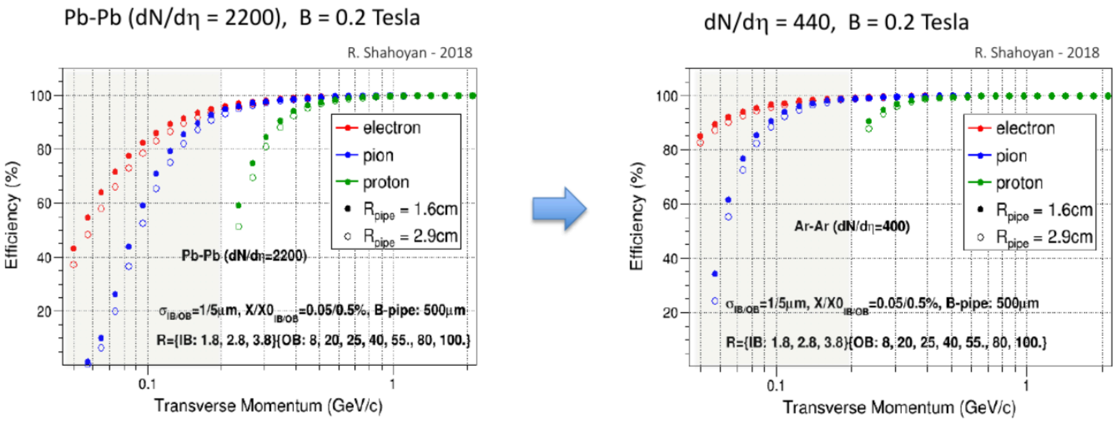
D.2 – ANGHIE : tracking efficiencies

Operation at reduced B field for tracking low p_T particles



Efficiency requiring that all particles reach the outermost layer at 1m (10 layers)

⇨ optimization possible (e.g. using only layers up to 40cm)

⇨ improvement for lower dN/dη

Further layout optimization possible!

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ANGHIE

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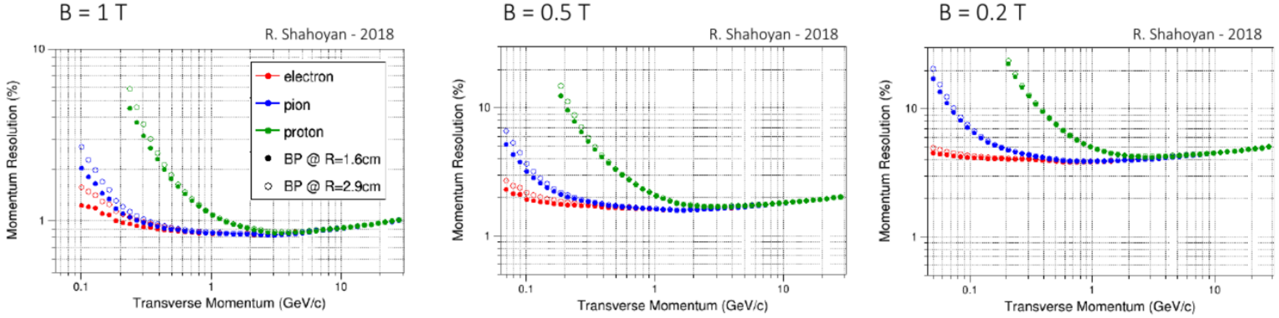
D.3 – ANGHIE : momentum resolution

Compared to ALICE in Run3, same performance at high p_T, some improvement at very low p_T



momentum resolution for 1GeV/c pions: ≈ 0.8% (1 T), ≈1.6% (0.5 T), ≈ 4% (0.2 T)

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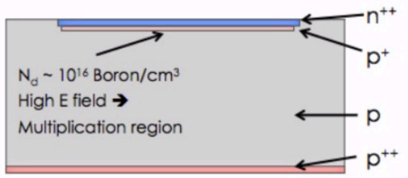
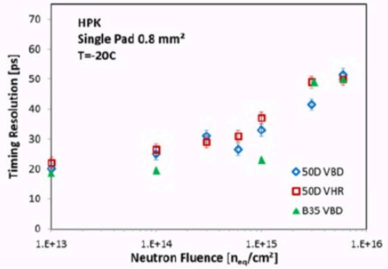
D.4 – ANGHIE : Particle Identification

Electron and hadron ID with TOF

LGAD (Low Gain Avalanche Diode)

- Technology proposed for ATLAS and CMS LS3 upgrades (timing layer)
- Developed for high radiation environment ($10^{14} – 10^{15}$ 1MeV n_{eq}/cm^2)
- Currently low granularity O(1 mm^2)
- Add a thin layer of doping to produce low controlled multiplication
- Several vendors: Hammamatsu, FBK, CNN





Time resolution vs. neutron fluence of LGAD produced by HPK with a thickness of 50µm (50D) and 35µm (35D)

Resolution of 20-30ps demonstrated

Cost (CMS estimate) ~ 50 CHF/cm^2

Can such a gain layer be implemented using CMOS? ⇨ large cost saving

⇨ Single Photon Avalanche Diodes (SPADs)

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ANGHIE

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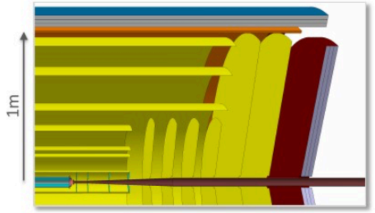
D.5 – ANGHIE : TOF

Electron and hadron ID with TOF

TOF PID – few barrel layers instrumented with LGAD or high-granularity SPAD sensors



SPAD Sensors (Single Photon Avalanche Diode) ≝ arrays of avalanche photodiodes reverse-biased above their breakdown voltage

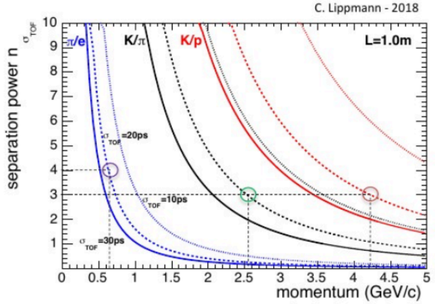
SPAD detectors of recent generation feature a time jitter of tens of picoseconds

Number of layers will depend on time resolution and spatial fill factor achieved in the single layer

Ideal track length and p measurement for 3 scenarios (10ps, 20ps , 30ps) are show in figure

For σ_{TOF} = 20ps

- e/π (4σ) separation ≲ 650 MeV/c
- π /K (3σ) separation ≲ 2.6 GeV/c
- K/p (3σ) separation ≲ 4.2 GeV/c



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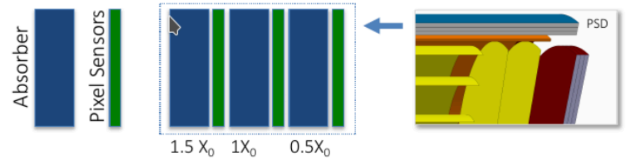
D.6 – ANGHIE : electron pre-shower, PSD…

Electron ID with Pixel Shower Detector

Shower Detector (3 X_0) based on high-granularity digital calorimetry (CMOS pixel sensors)

➪ great potential to identify electrons down to few hundred MeV by detailed imaging of the initial shower (particle counting, geometry)



Work in progress – A first look

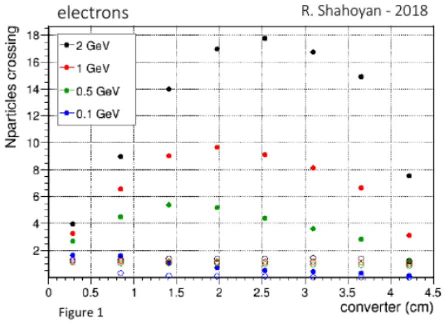


Figure 1

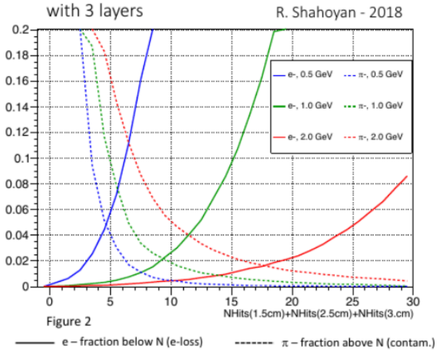


Figure 2

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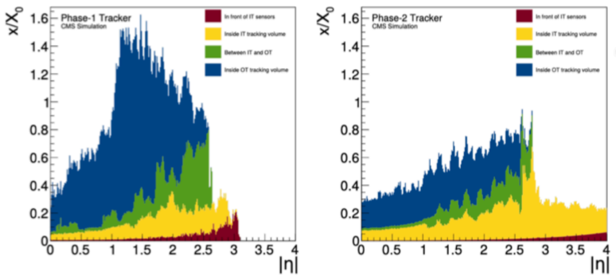
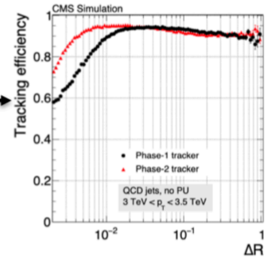
CMS

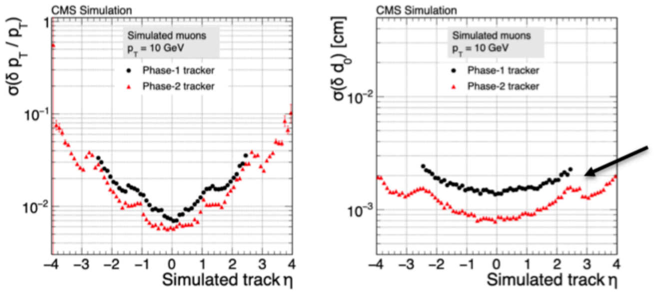
Tracker upgrade



Reduced material budget by up to 2x
→ improved tracking efficiency in AA

… as evidenced by the improved separation of nearby tracks





Improved p_T resolution by about 25%
→ Improved mass resolution for resonances

Impact parameter resolution improved by 40%
→ Improved heavy flavor measurements (B/D hadrons & b/c-jet tagging)

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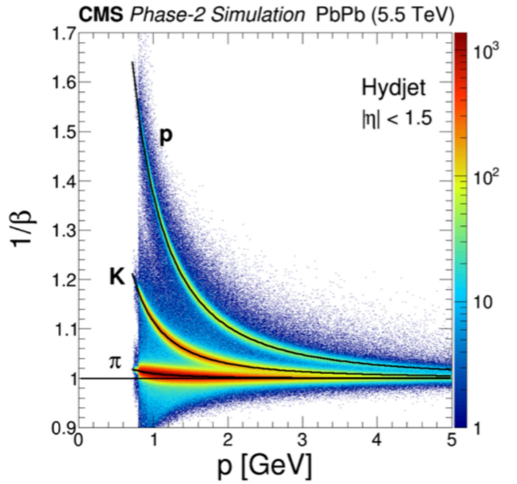
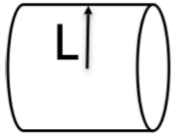
MIP timing detector (MTD)

- Timing resolution of 30 – 40 ps
  → comparable PID to STAR/ALICE
  - Protons identifiable up to p ≈ 5 GeV
  - Pion and kaons up to p ≈ 2.5 GeV
- Pile-up rejection in high lumi pp
- Triggering on high multiplicity pp collisions in low PU data





Experiment	η coverage	L at $\eta = 0$ (m)	σ_T (ps)	L/σ_T ($\times 100$)
CMS	$\|\eta\| < 3.0$	1.16	30	3.9
ALICE	$\|\eta\| < 0.9$	3.7	56	6.6
STAR	$\|\eta\| < 0.9$	2.2	80	2.2

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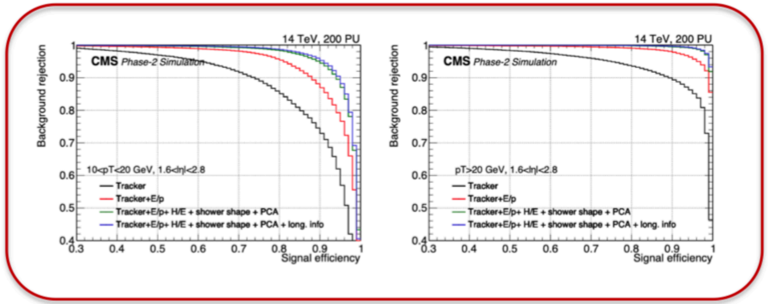
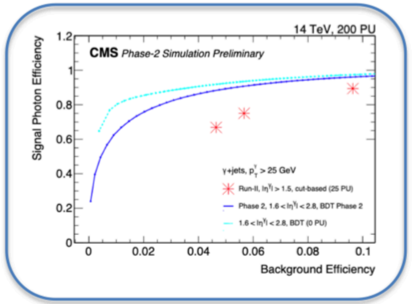
CMS

High granularity calorimeter (HGCal)

- Unprecedented transverse and longitudinal sampling
  → "particle flow calorimetry"
- Isolated electrons: 95% efficiency for background rejection of 100x at p_T > 20 GeV





- Isolated photons: 90% efficiency for background rejection of 20x p_T > 25 GeV
- Comparable jet performance to barrel region:
  e.g., for substructure, soft drop mass resolution of ~ 10%

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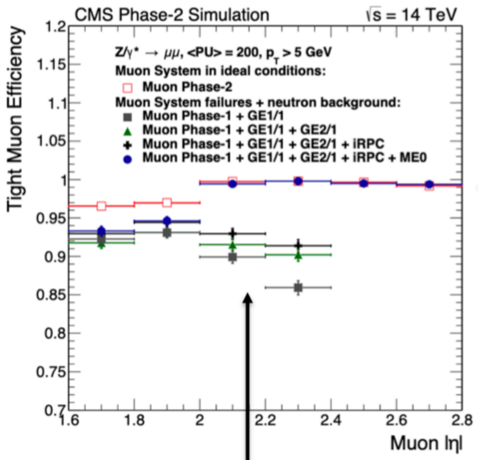
Muon upgrades



Extension to $|\eta| < 2.8$ with GEM detectors

Further redundancy in forward region ($1.2 < |\eta| < 2.8$)
→ improve matching to tracks from silicon tracker, where the occupancy is largest

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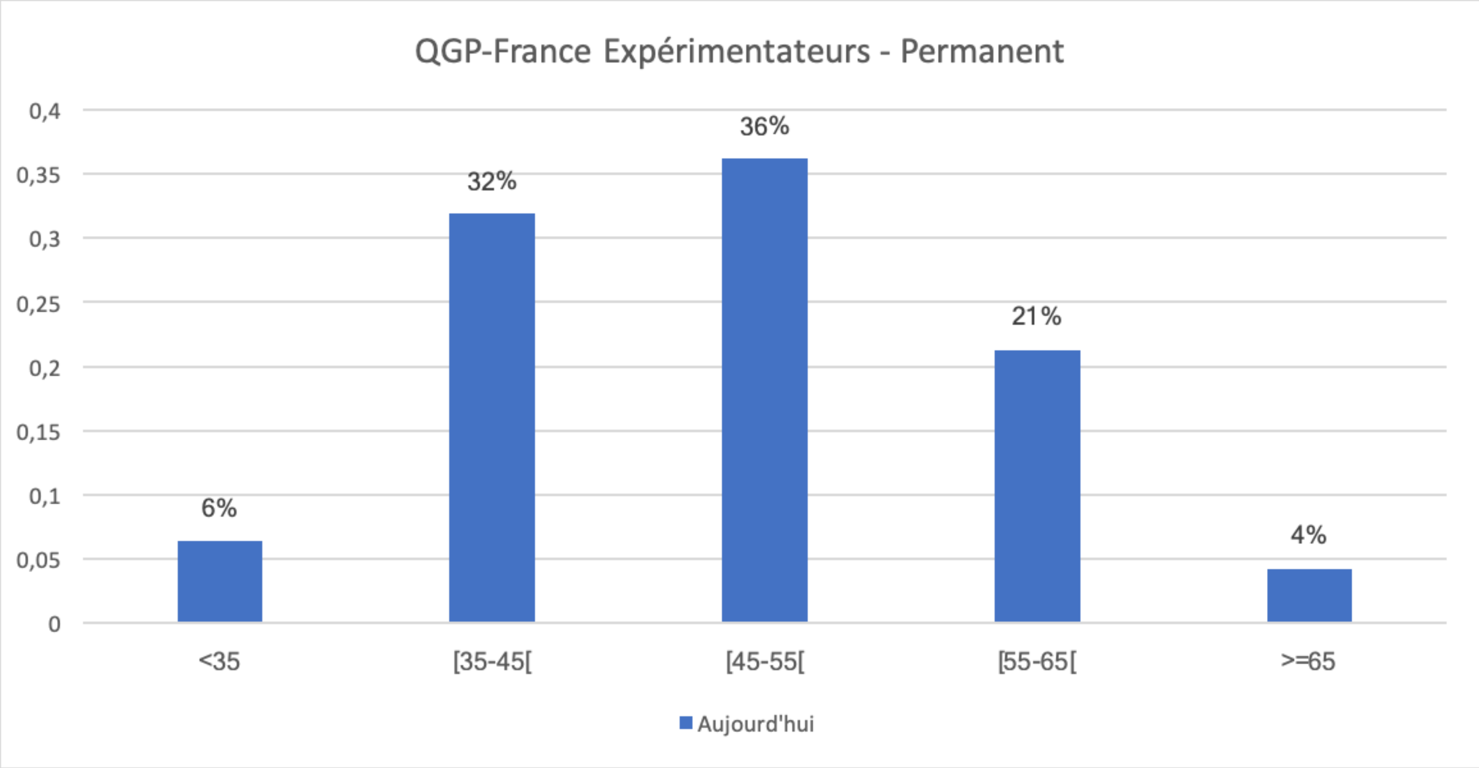
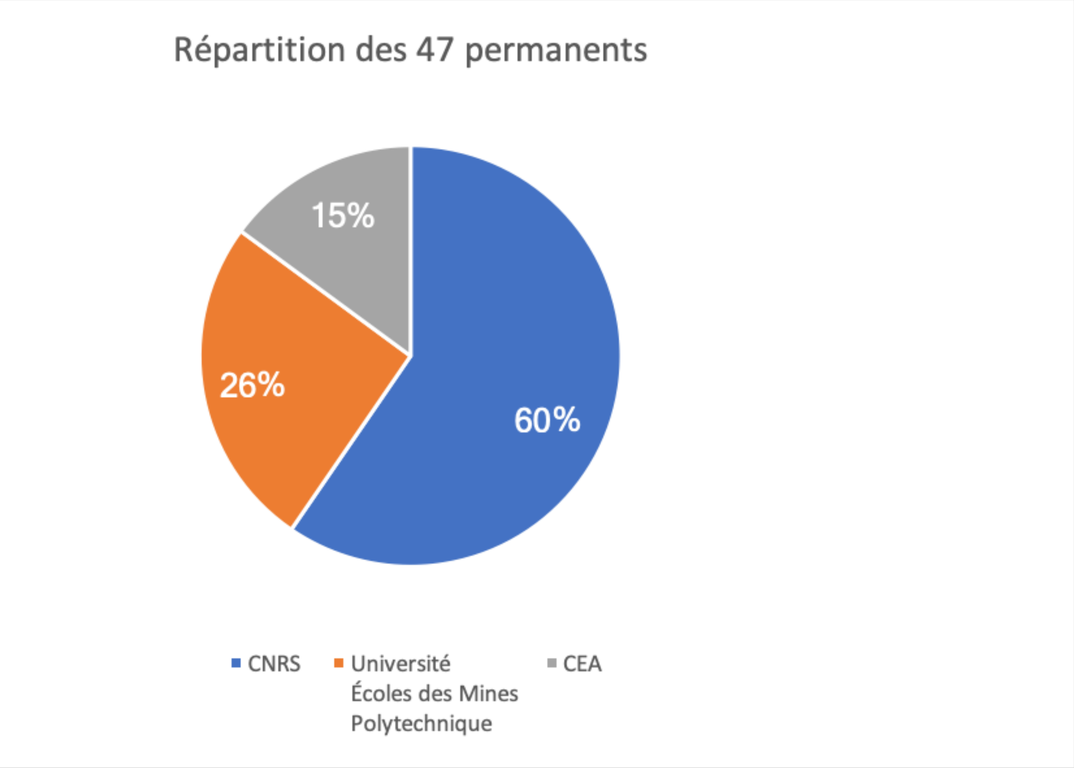
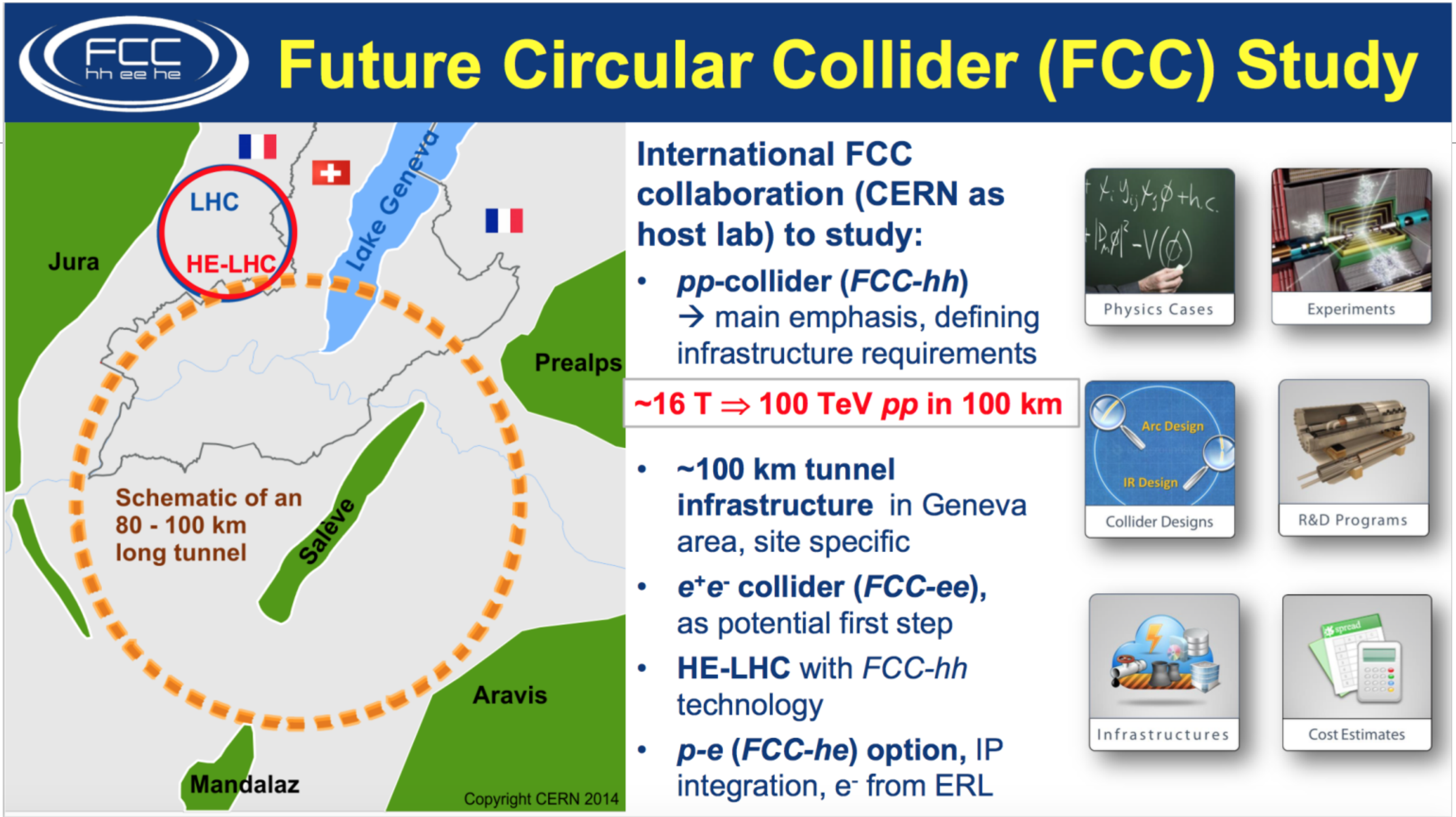
Thermodynamique de la communauté : aujourd’hui







* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

FCC study: physics and performance targets

FCC-ee:

- Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_{Z}, m_W, m_{top}, $\sin^2 \theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$ α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks

➢ Machine design for 100 TeV c.m. energy & integrated luminosity ~ $20ab^{-1}$ within 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

➢ Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	2000	393	48	39
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.1	0.44	2.0	9.5	10.9
long. damping time [turns]	1281	235	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.34	1.45
vert. geom. emittance [pm]	1.0	1.0	1.3	2.7	2.7
bunch length with SR / BS [mm]	3.5 / 12.1	3.3 / 7.6	3.1 / 4.9	2.5 / 3.3	2.5 / 3.2
luminosity [10^{34} $cm^{-2}s^{-1}$]	>200	>30	>7	>1.5	>1.3
beam lifetime rad Bhabha / BS [min]	70 / >200	500 / 20	42 / 20	39 / 24	39 / 25

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

FCC-hh detector – new reference design

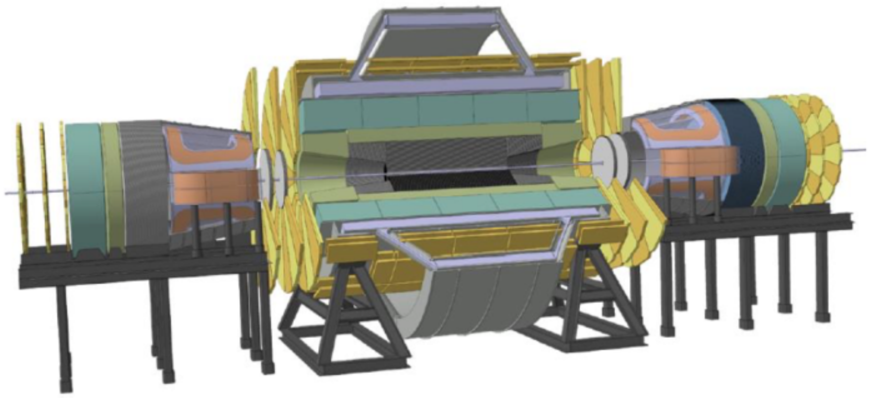
6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

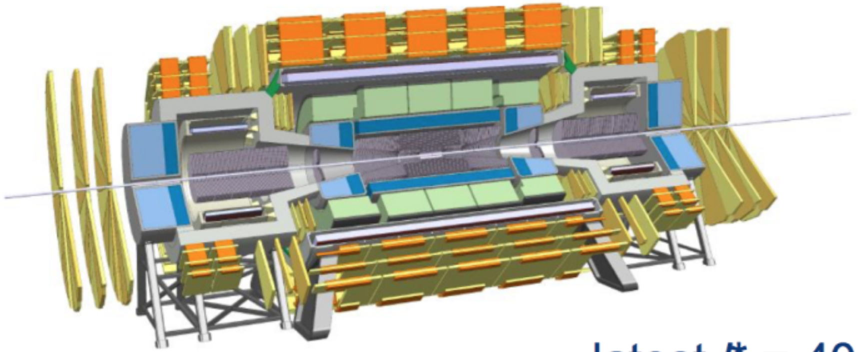
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

→

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

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project





latest l^* = 40 m

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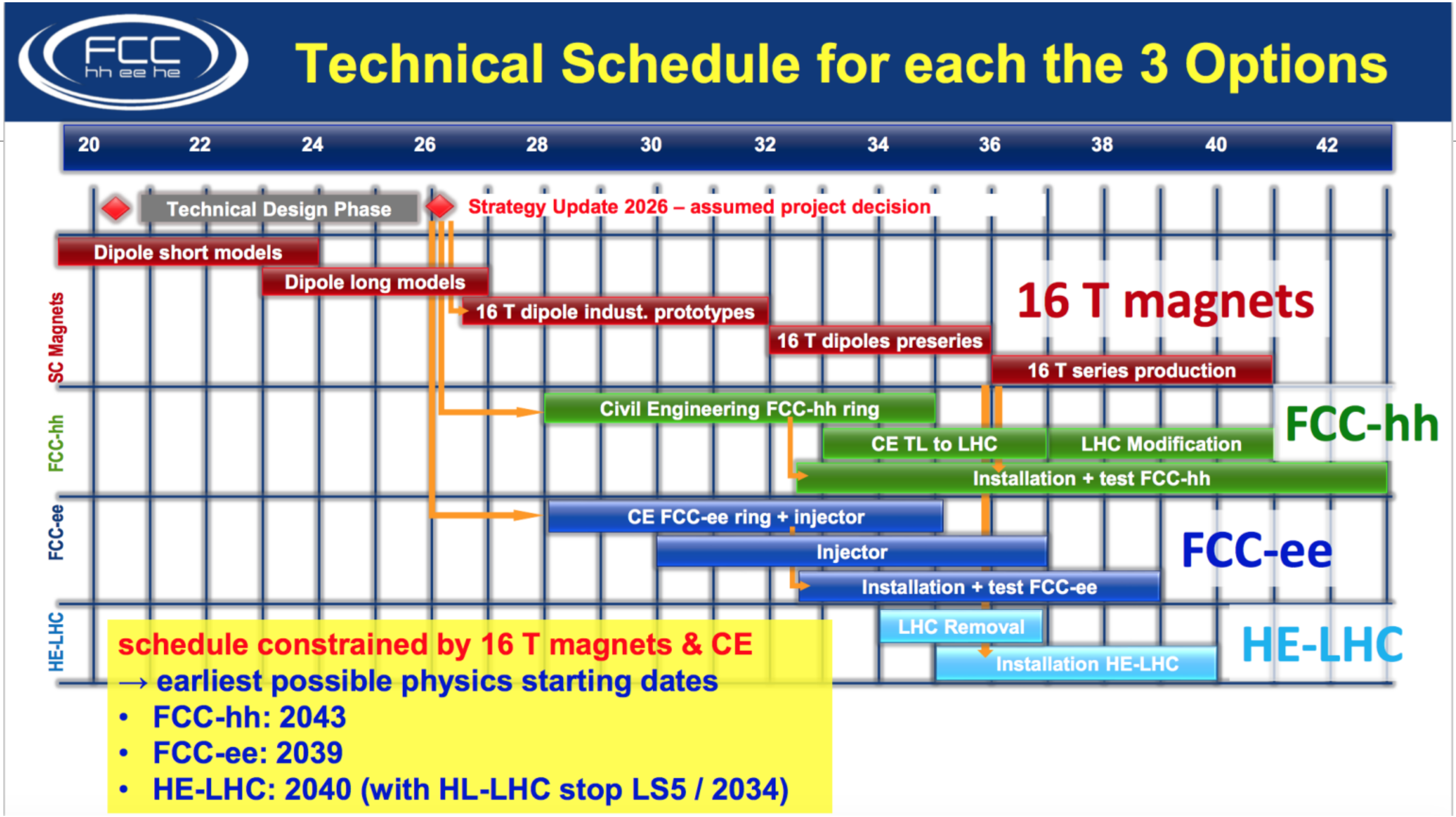

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Exercice comparatif

- ANGHIE

  + Herméticité + très bas p_T

- CMS

  + Herméticité + PID + bas p_T + muons

- LHCb

  + reconstruction ion-lourds centraux
  + Spectromètre à muons, couvre la zone avant, complémentarité avec CMS et ANGHIE