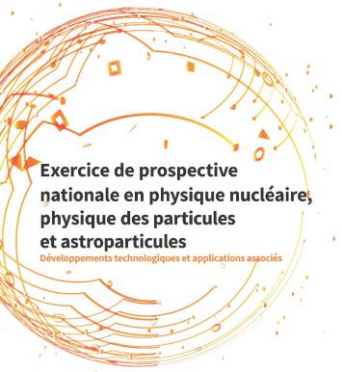


Colloque de restitution de l'exercice de prospective nationale

GT03 – Physique hadronique

Understanding strong interactions

19 octobre, 2021

Comité de pilotage: Klaus Werner (SUBATECH), Carlos Munoz (IJCLab), Béatrice Ramstein (IJCLab), Frédéric Fleuret (LLR), Laurent Vacavant (IN2P3)

GT03 - Hadronic physics

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

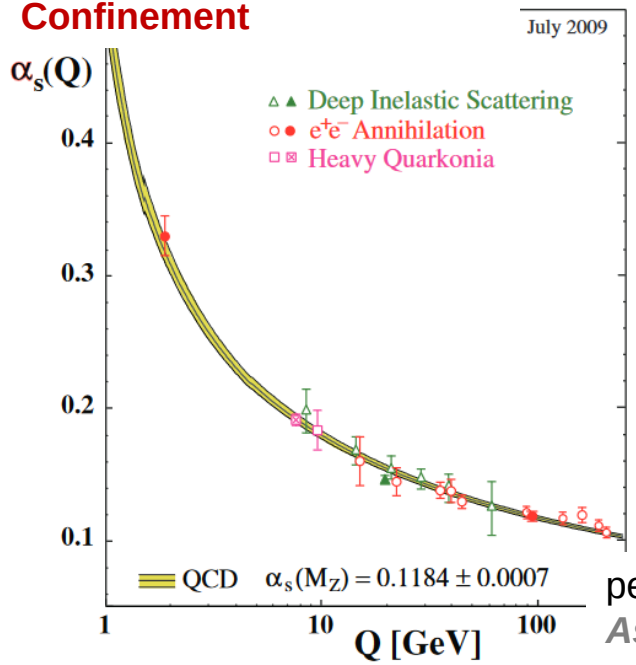
hadron structure and QGP

95% of the visible mass in the universe is due to QCD !

$M_e << m_{u,d\ quarks} \sim 1/200\ m_{proton}$

Non-perturbative (strong) QCD

Confinement



perturbative QCD

Asymptotic freedom

Open questions:

- What is the **dynamical origin of confinement ?**

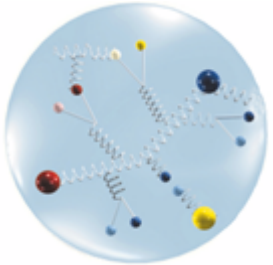
- How does the **hadron spectrum** (baryons, mesons, glueballs,…) **and** hadron **properties** (mass, spin,…) arise from the quarks and gluons ?

- What are the different **hadronic matter phases** ?

GT03 - Hadronic physics

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

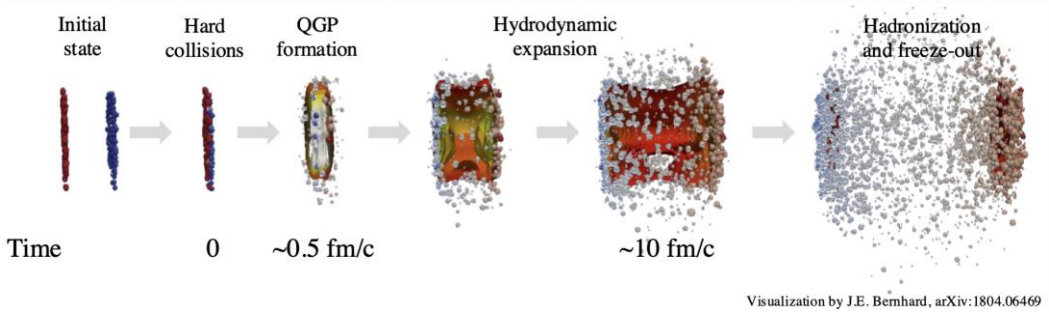
1. Nucleon Structure (NUST)
Study QCD bound states (hadrons, glueballs,hybrids,...)



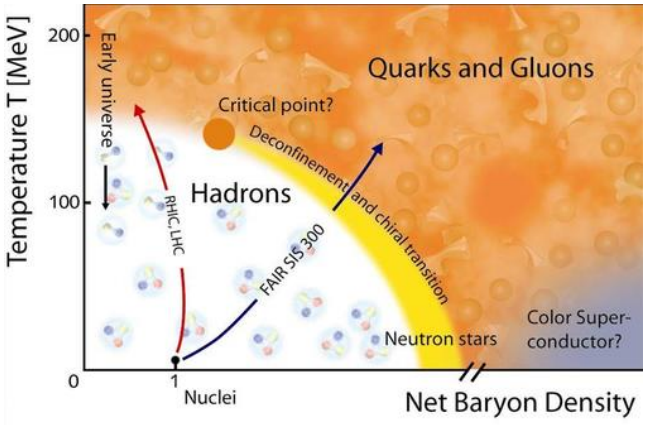
IN2P3 studies (GT03): Jlab, EIC

2. Strongly Interacting Matter (SIMP)
Study the phases of strongly interacting matter

IN2P3 studies (GT03): Alice, CMS, LHCb, HADES



Visualization by J.E. Bernhard, arXiv:1804.06469



GT03 - Science Drivers (SD)

- **SD1: Understanding the origin of proton mass**
  - How quantum fluctuations of quark-antiquark pairs, gluons and the dynamics of their interactions eventually generate most of the ***mass of the nucleon*** ?

- **SD2: Mapping the structure of nucleons and nuclei**
  - ***quark content:*** how do the different flavours of quarks distribute in space and momentum inside hadrons?
  - ***Gluon content:*** how do the nucleon and nuclei look like at high energy, where gluons are dominant ?
  - ***Saturation:*** how could gluon recombination lead to a saturation of the number of gluons inside nucleons and nuclei, creating a regime of high parton density, but small coupling ?

- **SD3: Understanding the deconfined state of quarks and gluons**
  - ***Nature of QGP:*** how dense and viscous is the medium ? how does color screening apply ? How fast and how does the system reaches equilibrium? What is the role of saturation for the initial state.
  - ***Collectivity:*** are collective-like effects observed in small systems of the same nature as in large systems ? what are the conditions of collectivity ?
  - ***Chiral symmetry restoration:*** can signals be observed and is the restoration of this fundamental symmetry of QCD simultaneous to the deconfinement transition at finite baryon densities ?

- **SD4: establishing the equation of state of strong interactions**
  - ***Phase transition:*** what are the thermodynamic parameters and the order of the transition ?
  - ***Critical point:*** where is it located in the phase space diagram ?
  - ***Hadronic matter:*** what is its microscopic structure (baryon resonances, strangeness,...) and how are hadrons modified in dense and hot hadronic matter ?

GT03 - 14 Contributions received

Title of the contribution	Signatory Lab (number of people signing)
Physique hadronique à Jefferson Lab	IJClab (7), CPhT (2)
The electron-ion Collider	IJClab(14), CPhT(4), Subatech(4), LLR(2), LPSC(2), IPhT(1)
Prospects on QGP characterization and heavy-ion collisions	Subatech(12), IJClab(6), IPhT(4), LLR(3), LPC(3), LPSC(3), IP2I(2), IPHC(2), CERN(1), IFJPAN(1)
French community support for a fixed-target program for the LHC	IJClab(13), CPhT(3), Subatech(3), LLR(2), CERN(1), IP2I(1), LPC(1), LPTHE(1)
Une expérience de nouvelle génération pour la QCD au HL-LHC - ITS3/ANGHIE	IPHC(10), LPSC(3), IPhT(1)
The ALICE FoCal proposal and small-x physics at the LHC	LPSC(7)
Heavy-ion physics with the Compact Muon Solenoid	LLR(3), CERN(1)
Heavy-ion physics at LHCb	LLR(3), IJClab(1)
Unravelling the hadronic collisions structure w/ large-scale system & energy scan	IJClab(6), Subatech(5), IP2I(3), IPHC(2), LPC(1)
Dense baryon-rich matter : the NA60+ experimental project at CERN-SPS	Subatech(9), IP2I(5), LPSC(1), IJClab(1)
Dense baryon-rich matter: The HADES and CBM experiments at GSI and FAIR	Subatech(9), IP2I(5), LPSC(1), IJClab(1)
Dense baryon-rich matter: The experimental program at J-PARC	Subatech(9), IP2I(5), LPSC(1), IJClab(1)
Theory of dense baryon-rich matter: heavy-ion collisions and compact stars	Subatech(9), IP2I(5), LPSC(1), IJClab(1)
Neutron stars, gravitational waves and the QCD equation of state	APC(4), LUTH(1)

GT03 - Séminaire thématique

- 2-3 mars 2020, Subatech, Nantes
  - https://indico.in2p3.fr/evet/20116
  - https://webcast.in2p3.fr/container/le-seminaire-thematique-gt03

- Agenda :
  - **Panorama** *théorique :* Samuel Wallon
  - **Panorama** *des installations expérimentales :* Barbara Erazmus
  - **Revue théorique** - *structure des nucléons et noyaux :* Cyrille Marquet
  - **Revue expérimentale** - *structure des nucléons et noyaux :* Raphaël Dupré
  - **Revue théorique** - *matière déconfinée à haute température et de la matière riche en baryons :* Marlène Nahrgang
  - **Revue expérimentale** - *matière riche en baryons :* Antonio Uras
  - **Revue expérimentale** - *LHC moyen terme :* Antonin Maire
  - **Revue expérimentale** - *LHC long terme :* Sarah Porteboeuf-Houssais

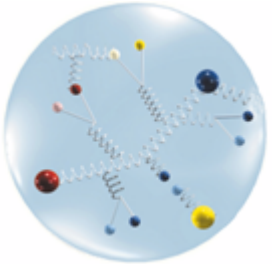
Outline

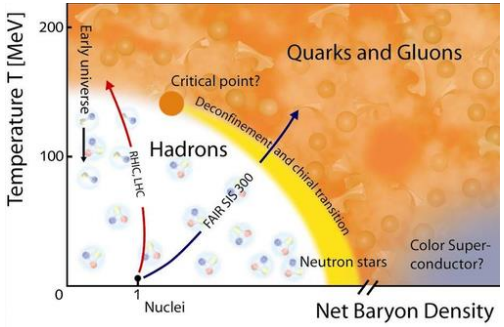
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

Nucleon and nUclei STructure

Jlab

EIC





Strongly Interacting Matter

LHC

FAIR/SPS/JPARC

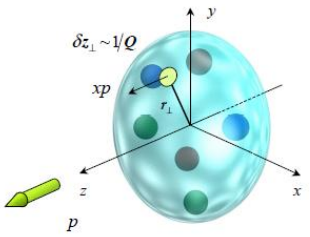
The role of theory

Nucleon structure

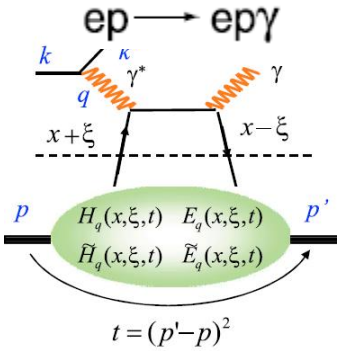
QCD matter

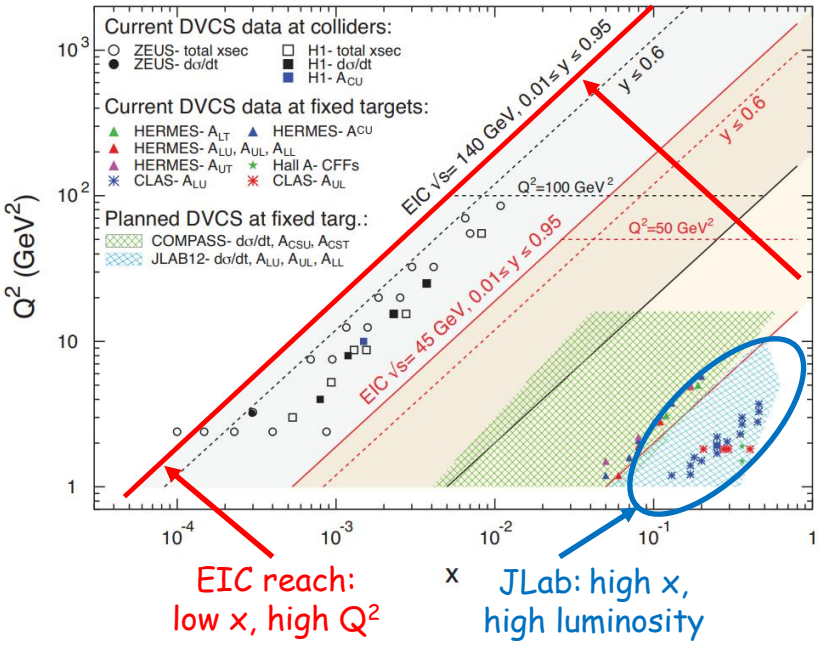
Structure of nucleon and nuclei

Exercice de prospective nationale en physique nucléaire, physique des particules



Deeply Virtual Compton Scattering (DVCS)





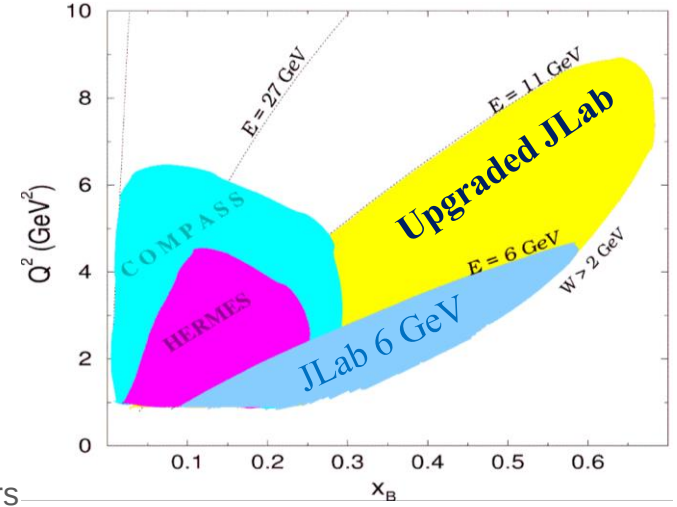
- **e-p/A collisions** : electromagnetic probes → cleanest access
- **High beam energy** (>10 GeV) needed to resolve quarks and gluons
- **High luminosity** required : small cross sections (**exclusive process**)

French groups

- Important **theoretical expertise**
- Current experimental activities at **Jefferson lab** (USA)
- Future activities at the **electron-ion collider** (BNL, USA)

Jefferson lab (Jlab)

- **Strong involvement of French community**, particularly in the field of Generalized Parton Distributions (**GPDs**):
- Measurements of **exclusive reactions** (DVCS, DVMP…)
- Contributions to **phenomenology of GPDs**
- Several important **technical contributions** over the years

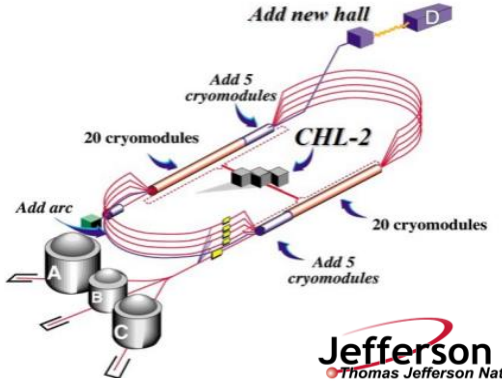


Recent upgrade of the accelerator to a higher beam energy (6 → 11 GeV) & detectors to higher luminosity (x10)

- **IN2P3** and **IRFU** leaders of several **high-impact experiments** in the coming years
- **Detector contribution** ongoing (Hall B, Hall C)
- Physics program well established for the next **10-15+ years**

Physics goals:

- Precision study of 3D nucleon structure (**GPDs**, **TMDs**)
- Hadron spectroscopy
- **Nuclear structure** (nuclear-medium effects, hadronization…)
- BSM searches : Parity violation, **dark matter** …



Jefferson Lab
Thomas Jefferson National Accelerator Facility

Electron-Ion collider (EIC)

Physics goals : high *Energy* / small *x*

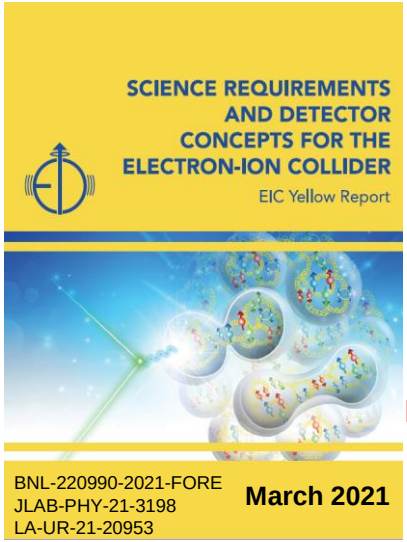
- **Saturation**: non-linear regime of QCD
- **Distributions of** positions, momenta, angular momentum of **gluons**…
- **Role of gluons** in the nuclear medium

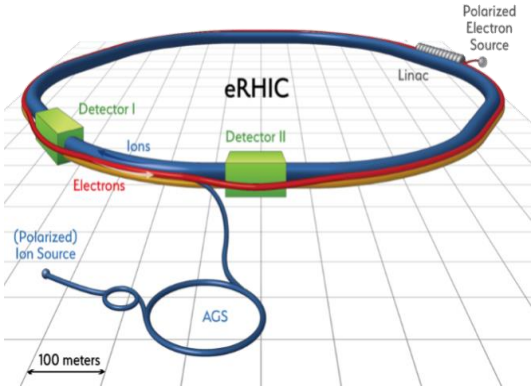
Collisions e-p/A:

- E_{cdm}=29-140 GeV, **Polarized beams** : e, p, d/^{3}He
- Electron beam: 5-18 GeV
- Luminosity L_{ep}~$10^{33\text{-}34}$ $cm^{-2}s^{-1}$ (100-1000 x HERA)
- Wide choice of nuclei

Project timeline

- **CD-0 (December 2019):** Mission Need
- **CD-1 (July 2021):** Start of project execution
- **CD-2 (~Jan'23):** R&D completed
- **CD-3 (~Mar'24):** TDR completed; start of construction
- **CD-4a (~Jul'31):** Start of operations
- **CD-4b (~Jul'33):** Projet completion





French labs signing EIC Yellow Report

IJClab (6), Irfu (9), CPhT (2)

Call for Collaboration proposals for detectors at the Electron-Ion Collider

- **Deadline** for submission: **December 1, 2021**
- Strong French involvement: **IN2P3/IRFU**

Electron-Ion collider (EIC)

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

Main physics interests from French experimental groups

- **3D imaging** of nucleons and nuclei

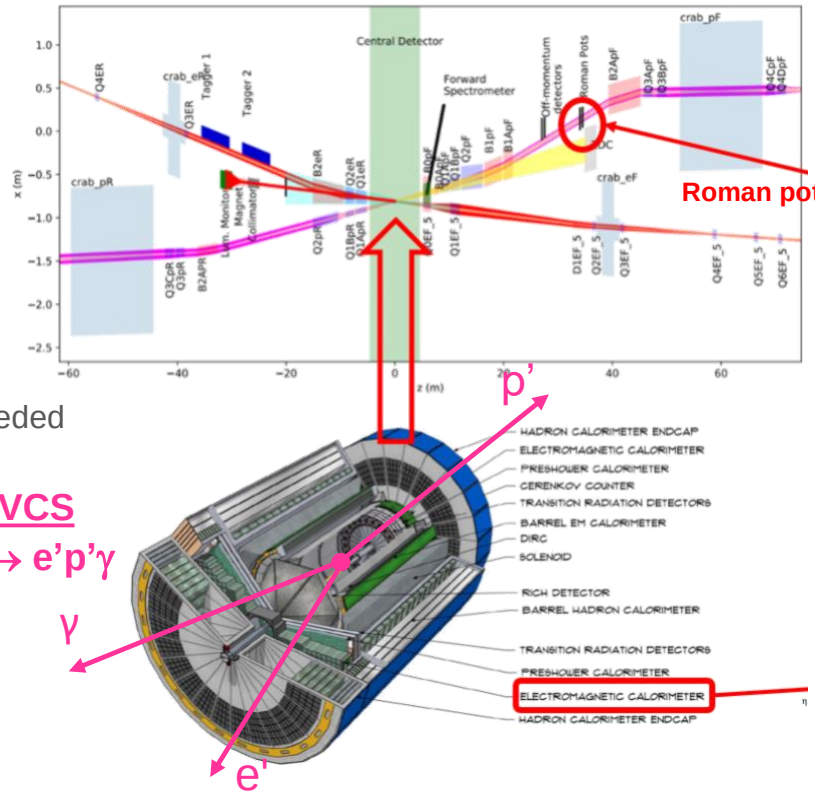
Physics observable

- **Exclusive reactions (DVCS):** very forward and backward detection needed

Possible hardware contributions

- **Electromagnetic calorimeter**
  - Crystals ($PbWO_4$) and scintillating glass (SciGlass)
  - Readout by SiPMs (or APDs)

- **Roman pots (proton/ions) – 30 m from IP**
  - AC-LGAD for fast timing and excellent spatial resolution
  - Readout ASIC under development



SIMP - Heavy-ion physics
understanding QCD in multi-body systems

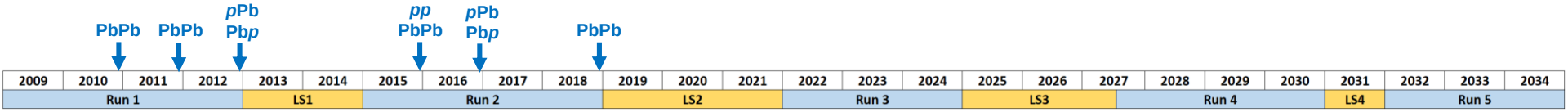
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

QGP = thermalized medium of deconfined partons

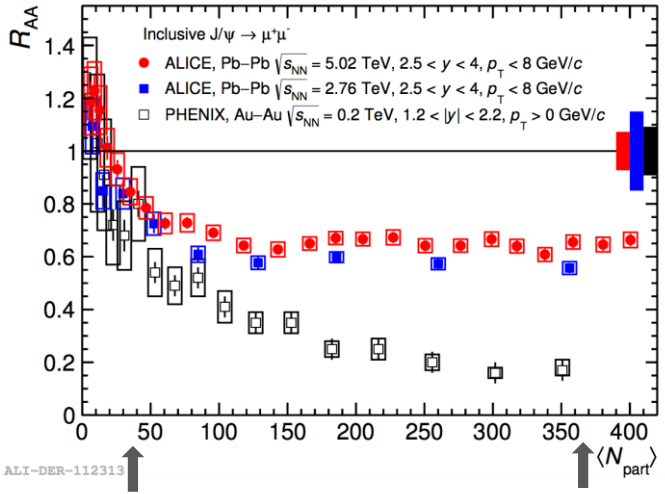
- **QGP as a privileged playground for QCD studies**
  - Transition from confined to deconfined medium : color screening, jet quenching…
  - Collective motion of a medium governed by QCD interactions : flow, …
  - Transition from deconfined to confined medium : hadronization, …

- **QGP and astrophysics/cosmology**
  - Early universe (high T, low baryonic chemical potential)
  - Neutron stars (high baryonic chemical potential)

SIMP – heavy ion physics@LHC



- **LHC Run 1 and 2 results** confirmed and refined the picture of a **nearly-perfect fluid (sQGP) observed in PbPb collisions** (first observed at RHIC/BNL):
  - Very dense medium (**jet quenching**)
  - Azimuthal and long-range correlations (**elliptic, triangular flow, ridge**)
  - **hadron yields** following statistical (thermal) models
  - **Heavy-quark (c,b)** energy loss and thermalization, **recombination**

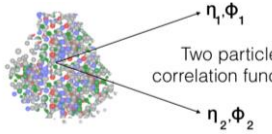


$$R_{AA} = \frac{\sigma_{AA}}{A^2 \sigma_{pp}}$$

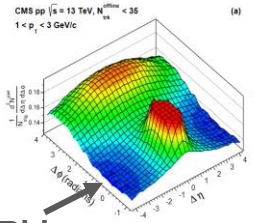
SIMP – heavy ion physics@LHC

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

- **LHC Run 1 and 2** also lead to **Striking new results**:
  - **Collective-like effects** observed **also in** high-multiplicity ***pp*** and ***p*Pb** collisions,

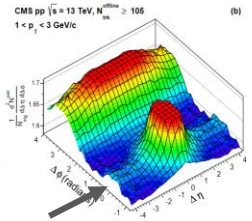


Low multiplicity pp



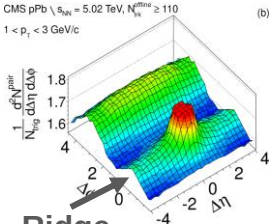
No Ridge

High multiplicity pp



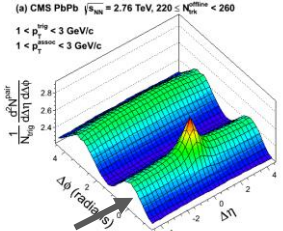
Ridge

High multiplicity pPb



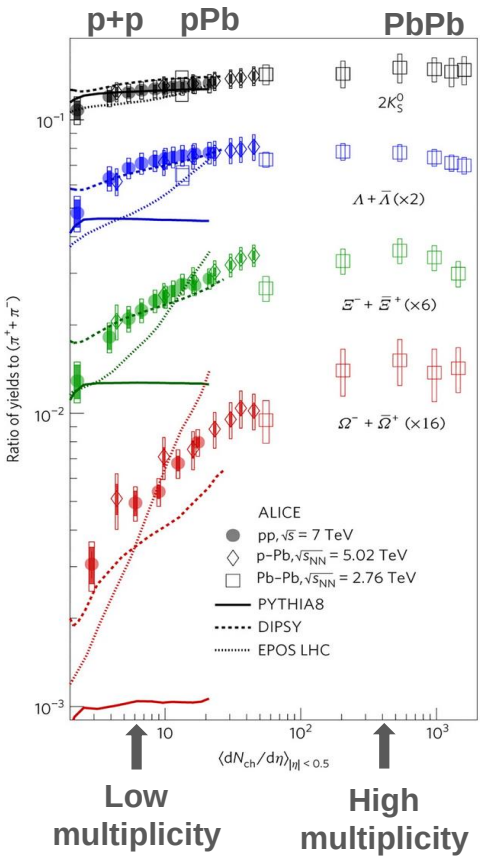
Ridge

High multiplicity PbPb



Ridge

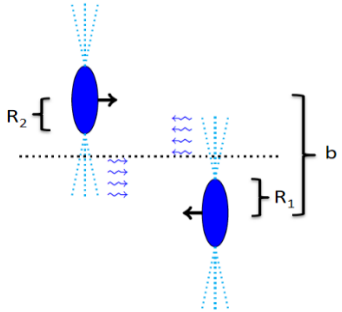
  - **Smooth transition from small (pp) to big (PbPb) systems**
    - The conditions achieved in AA can be approached in *pp*
    - Understanding the cross-over from free-streaming particles in vacuum to a strongly-interacting system is **now a major focus of "heavy-ion" physics**



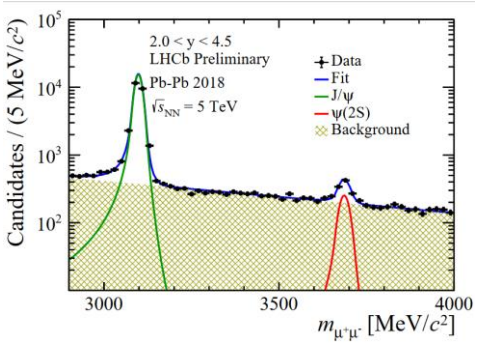
SIMP – heavy ion physics@LHC

Exercice de prospective nationale en physique nucléaire,

- **LHC Run 1 and 2, and also :**
  - **Ultra-Peripheral Collisions (UPC):**
    - photoproduction → γ-γ, γ-p, γ-Pb collisions
    - Intensity of the **photon flux proportional to Z²**
      (1 UPC pPb coll ≡ 82² pp,
      1 UPC PbPb coll ≡ 82²×82² pp ≡ 4.10⁷ *pp*)



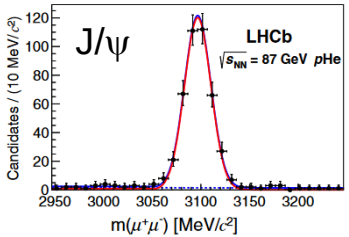
$R_1+R_2<b$ → UPC

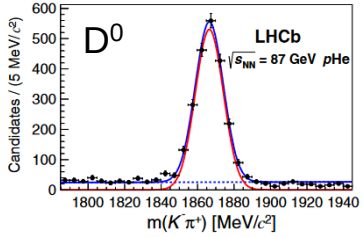


  - **Fixed-Target program at LHC (*AFTER*)**
    - Fixed-target in **LHCb** (since 2015)
      - Gas injected into the Vertex Locator (VELO)
      - Heavy flavor production at $\sqrt{s_{NN}}$ ~ 70 GeV

    - Studies on-going for a Fixed-target with bent-crystal and internal solid target in **ALICE**

Phys. Rev. Lett. 122, 132002 (2019)





SIMP – heavy ion physics@LHC

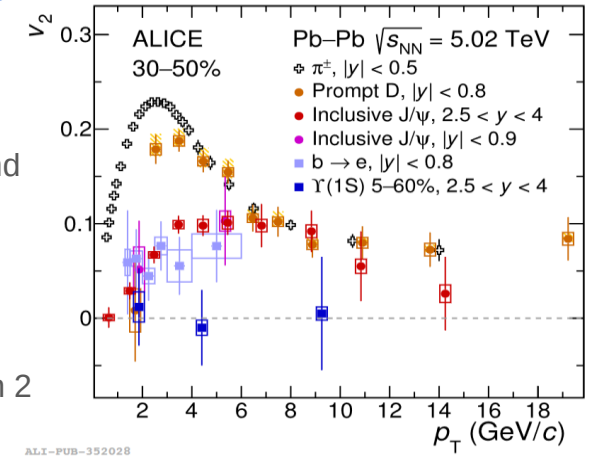
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

LHCb/ALICE Major upgrades — *pp*, *p*Pb/Pbp, Pb*Pb* — CMS/ATLAS Major upgrades — *pp*, *p*Pb/Pbp, Pb*Pb*

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Run 1				LS1		Run 2				LS2			Run 3			LS3			Run 4			LS4	Run 5		

- **Next (2022-2030)**: **towards accurate quantitative description**
  - Build appropriate/**accurate models**
  - Develop **tools for model/data** comparison and **global** interpretation
  - Explore **collective-like effects** (multi-parton to fluid dynamics) in *pp* and *p*Pb
  - Focus on **pQCD-calibrated probes** – heavy-flavor and high p_T jets (boson+jets)

- **LHC Run 3 and Run 4**
  - **More luminosity** and **improved instrumentation**
    - ~10x more luminosity than LHC Run 1 and Run 2 (13 nb^{-1} expected in PbPb)
    - experiment upgrades



p_T<3 GeV/c
V2(J/ψ) < v2(D) < v2(π^{+-}) : consistent w/ hydrodynamics
3 < p_T < 6 GeV/c
V2(J/ψ) < v2(D) ~v2(π^{+-}) : Heavy quark (D) hadronization via coalescence with flowing light quarks
p_T > 6-8 GeV/c
V2(J/ψ) ~v2(D) ~v2(π^{+-}) : Similar path-length energy loss for heavy and light quarks
no flow for ϒ : expected from smaller regeneration contribution

SIMP – heavy ion physics@LHC

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

LHCb/ALICE
Major upgrades
(Under review by LHCC)

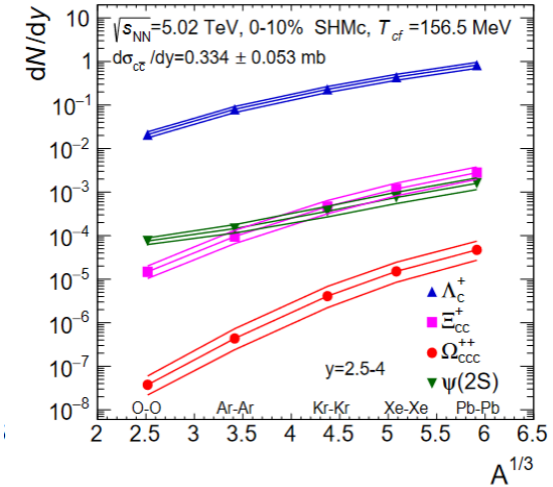
pp, pA, Ap, AA

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Run 1				LS1		Run 2				LS2			Run 3			LS3			Run 4			LS4	Run 5		

- **Next-to-next (2030+): towards thorough quantitative description**
  Consolidate theoretical models/framework
  testing them against other systems than PbPb

- **LHC Run 5 and Run 6**
  - High precision/luminosity with **lighter ion** systems
  - Testing theoretical models/framework against smaller systems
  - Explore collective-like effects and ***physics continuum*** **from *pp* to PbPb**

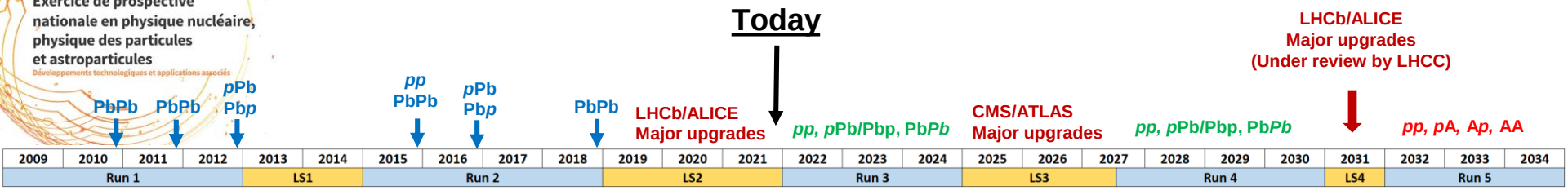
pp → ***p*O** → *p*Pb → **OO** → **ArAr** → **XeXe** → PbPb



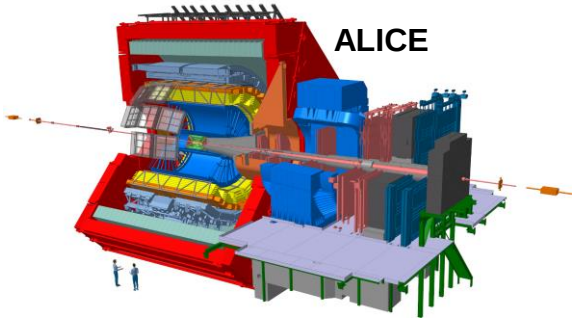
Multi-charm hierarchy,
Andronic et al.: JHEP07(2021)035

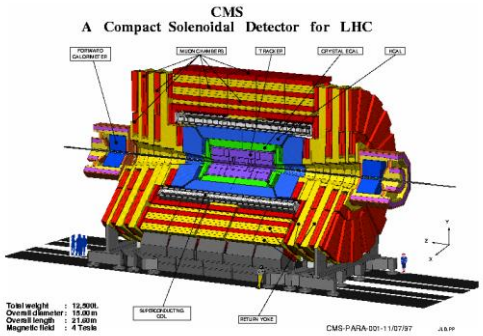
SIMP – heavy ion physics@LHC

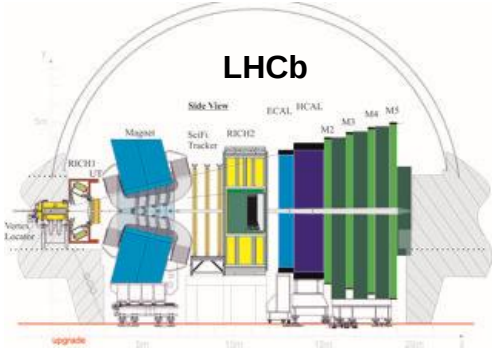
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés



All four experiments (ALICE, ATLAS, CMS, LHCb) are involved in QGP physics







French community participates to :

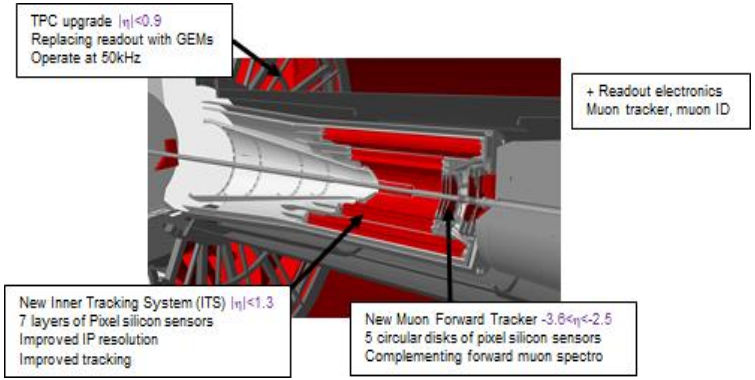
- O(45 people) **ALICE :** IJClab-Orsay, LPC-Clermont, LPSC-Grenoble, IP2I-Lyon, IPhC-Strasbourg, Subatech-Nantes + DPhN/Irfu/CEA (since 2009)
- O(5 people) **CMS :** LLR-Palaiseau (since 2009)
- O(5 people) **LHCb :** IJClab-Orsay, LLR-Palaiseau (since 2015)

SIMP – heavy ion physics@LHC w/ ALICE

- **Run 3 (commisionning ongoing) :** continuous readout at 50 kHz coll. rate

ALICE - upgrades

  - Central region: **ITS2, TPC-GEM**
    - **Low material budget**, **PID**, improved tracking,
    - Lumi x 100
    - IPHC, LPSC
  - Forward region: **Muon Tracking+ID, MFT**
    - Capability to separate **promt/non-prompt muons**
    - IJClab, IP2I, LPC, Subatech + DPhN/Irfu/CEA



- **Upgrades for Run 4**
  - Central region: **ITS3** (LoI:CERN-LHCC-2019-018)
    - Replace ITS2 first 3 layers with ultra-thin Si CMOS, closer to the beam
    - **Tracking** of short-lived particles. Better precision and efficiency at **low p_T**
  - Forward region: **FoCal** 3.2<η<5.8 (LoI:CERN-LHCC-2020-009)
    - *FOCal-E:* fine grain Si-W sampling calorimeter for **3D photon shower reconstruction**
    - Gluon saturation, correlations forward/central rapidities
  - ***Fixed-target program*** with bent-crystal and internal solid target *under investigation*

SIMP – heavy ion physics@LHC w/ ALICE

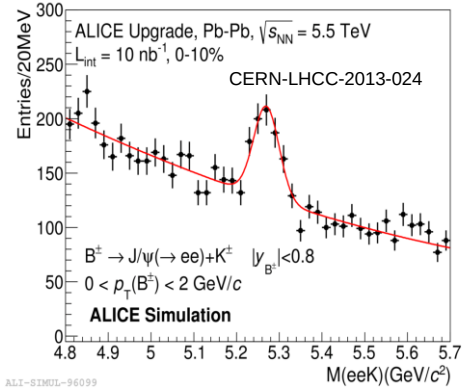
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

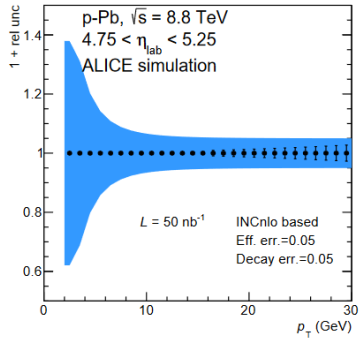
ALICE - physics program foreseen (Run 3/4)

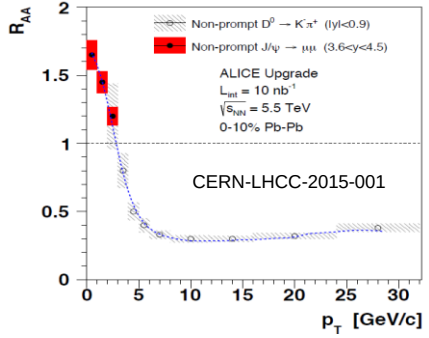
Extension of the inclusive+differential measurements wrt bulk (u,d,s+c,b)

- **Open heavy flavor**
  - charm/beauty meson and baryon production at mid-rapidity
- **Quarkonia**
  - J/Ψ and Ψ‘ production at mid and forward rapidity
  - prompt/non-prompt J/Ψ separation down to lowest p_T
- **Low-mass and low-p_T di-leptons**
  - Vector mesons and thermal photons
- **Jet quenching and fragmentation**
  - PID of jet particle content
  - Heavy flavour tagging

ALICE - upgrades



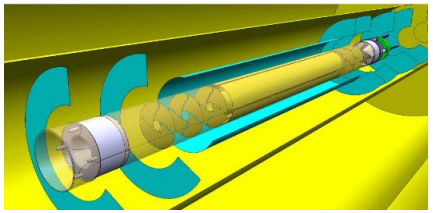


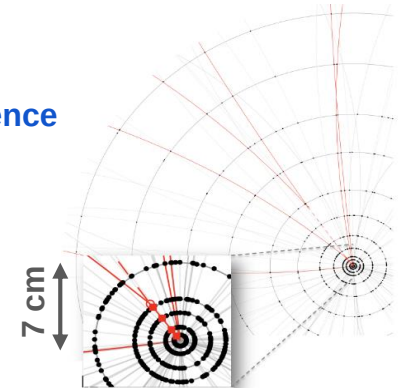


SIMP – heavy ion physics@LHC w/ ALICE

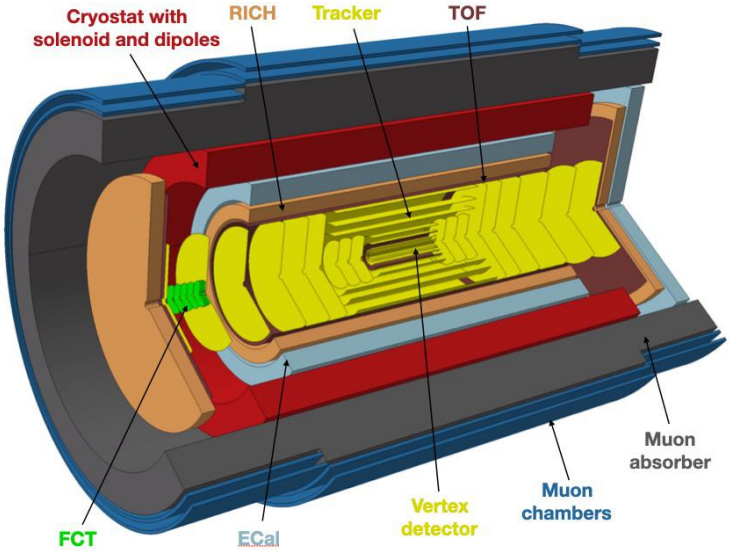
Upgrade for Run 5 (2032+): ALICE 3 (previously ANGHIE)

- Physics goal : Enlarge phase-space exploration towards **exhaustive description/understanding of the medium**
- Excellent tracking and vertex resolution down to low p_T **→ excellent HF resolution**
- Low material budget **→ low background for EM probes**
- Large η acceptance **→ correlations, flow and density dependence**
- **LoI to be submitted to LHCC nov. 2021**





ALICE - upgrades



147th LHCC Meeting – open session – sep. 2021
(ALICE status Report)

Main characteristics wrt Run 4 :
- **more hermetic** (y ∈ [-4;+4] + p_T ∈ [0.05 ; O(10)] GeV/*c*)
- **extended PID** (innerTOF, outerTOF, endcapTOF, RICH, …)
- **faster** (1 MHz continuous readout)

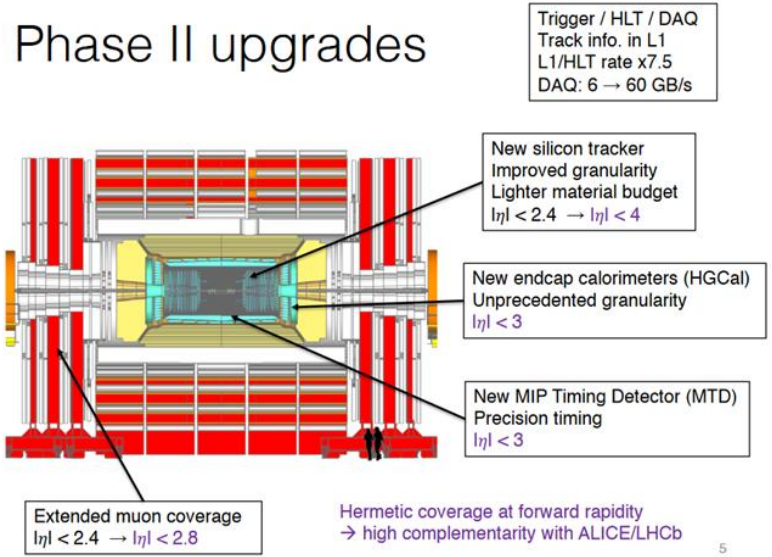
SIMP – heavy ion physics@LHC w/ CMS

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

CMS - upgrades

- **Major CMS upgrade for Run 4 (2026+)**
  - Objective: maintain current performance in pp for an average pileup of ~200 (curr. ~50)

- The phase II upgrades **enhance the physics potential for heavy ions**
  - **Large acceptance**, full particle flow to |η|~3
    - Lighter, more granular tracker
    - Super-granular endcap calorimeter
    - Extended muon coverage
  - **New PID capabilities** with MTD

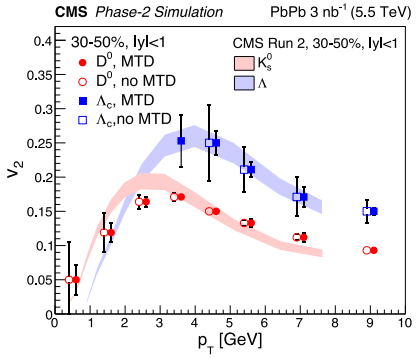


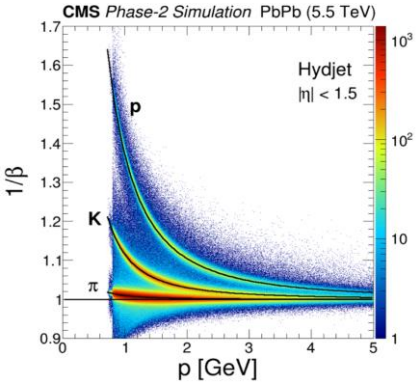
SIMP – heavy ion physics@LHC w/ CMS

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

CMS - physics program foreseen (Run 4)

- **Precision measurement of jet quenching**
  - High statistics boson (Z/γ) + Jet measurements
  - capture full energy of recoiling jets (thanks to large acceptance calorimeters)

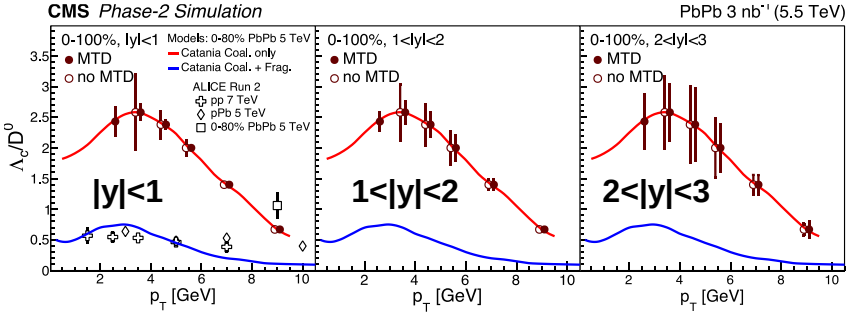




- **Bulk particle production**
  - Long-range correlations (ridge) over 8 units of eta
  - Hadrochemistry (π, K, *p* separation capability thanks to MTD)

- **Heavy Flavor open mesons/baryons** at low p_T (PID thanks to MTD)
  - Down to p_T~0 GeV/c for D^0, p_T~2 GeV/c for Λ_c)

- **Quarkonium states**
  - Precisely measure upsilon family (including (3S))



SIMP – heavy ion physics@LHC w/ LHCb

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

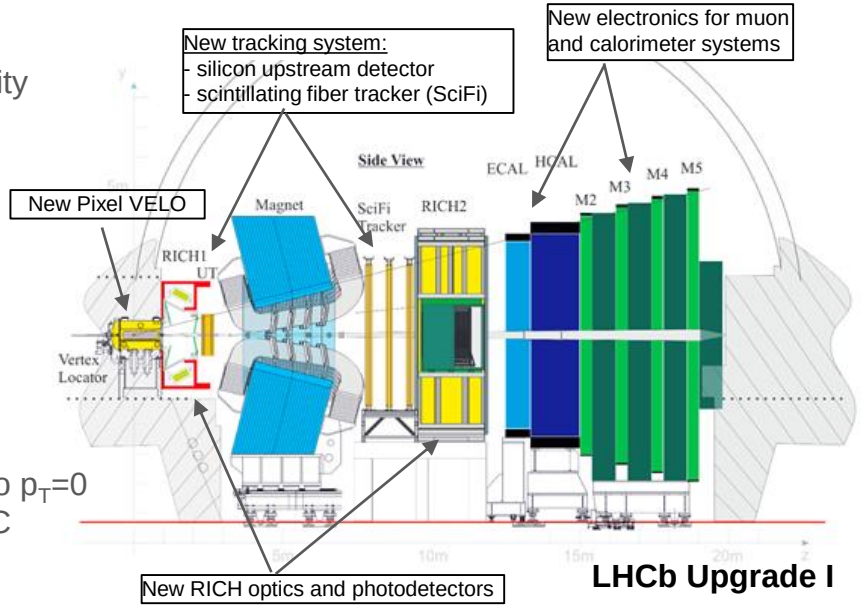
LHCb – upgrades – phase I

- **Upgrade I for Run 3 and Run 4** (resp.)
  - Objective: cope with pileup ~5 – 10 in *pp* (curr. ~1)
  - **+ new gas target system (SMOG2)** → 100x more density
  - **Enhance the physics potential for heavy ions**
    - Improve PbPb Centrality reach
    - High lumi Fixed-target program

- **Physics program foreseen**

Coll. mode : **Heavy Flavor, hadrochemistry:** $2<\eta<5$ down to $p_T=0$
  - Full physics program in *pp*, *p*Pb, Pb*p*
  - Full physics program in PbPb up to 30% centrality

Fixed-target : Heavy Flavor, hadrochemistry: $-2.5<y^*<0.5$ down to $p_T=0$
  - $\sqrt{s_{NN}}$~70 -110 GeV → fill the gap between SPS and RHIC
  - Expect no centrality limitation in PbA (A=He, Ne, Ar)



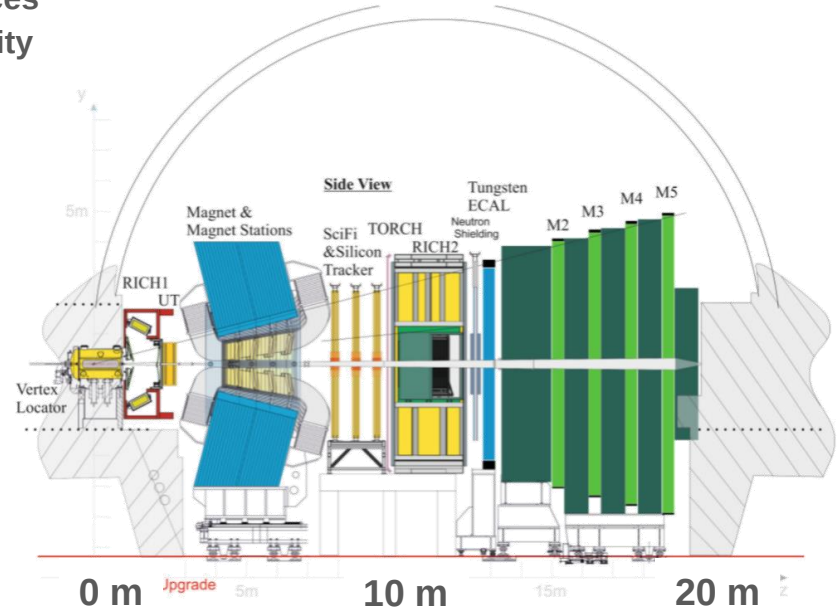
SIMP – heavy ion physics@LHC w/ LHCb

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

LHCb – upgrades – phase II

- **Upgrade II for Run 5 (2032+)**
  - Objective : **Improve tracking and calorimetry performances to cope with pileup ~40 in *pp* and with full PbPb centrality**
  - + new **DAQ**
  - + New vertex detector
  - + New **Upstream Tracker** and Mighty Tracker
  - + New TOF
  - + New **ECAL**
  - Framework TDR draft submitted to LHCC (sep. 2021)

- **Further enhance heavy-ion physics potential**
  - Heavy-Flavor, hadrochemistry
  - Both in collider and Fixed-Target programs
  - No limitation on centrality reach



SIMP – heavy ion physics@LHC

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

LHC run 5+ (phase II) – 2032+

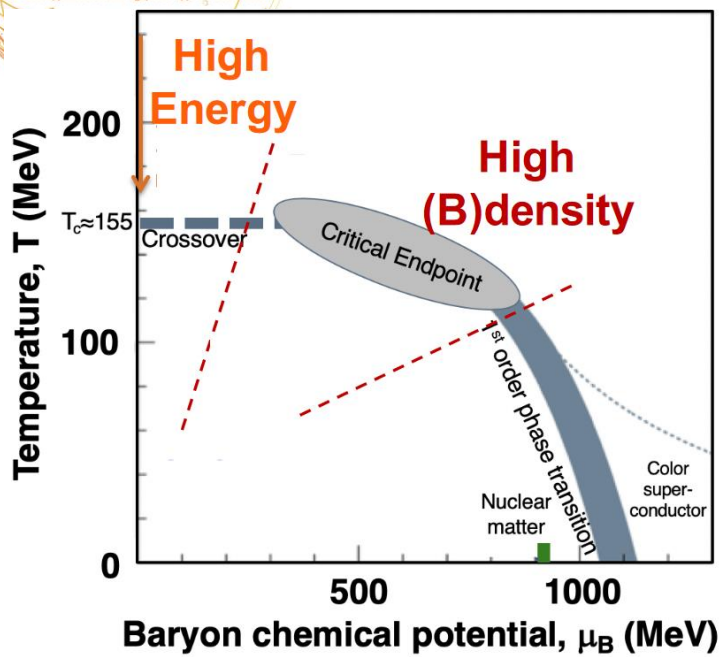
Current status

Exp.	participating/interested perm. Phys.	Status	Main specs
ALICE3	IN2P3 O(10)	LOI to be submitted to LHCC (11/2021)	low p_T, $\|\eta\|<4$, PID, calorimetry, muons
CMS	IN2P3 (2)	TDRs(2017 – 2021) TGIR HL-LHC	Intermediate p_T, $\|\eta\|<4$, PID, calorimetry, muons
LHCb	IN2P3 (9) + Irfu/CEA (7)	Framework TDR draft submitted to LHCC (09/2021)	Low p_T, $2.5<\eta<5$, PID, calorimetry, muons, fixed-target

+ O(10) people undeclared

SIMP – heavy ion physics@FAIR/SPS/JPARC

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés



High Energy : LHC, RHIC

- Quantify properties of QGP fluid
- How is collectivity developed ?
- Collectivity in small systems

High (Baryon) density : FAIR/SPS/JPARC

- **Onset of deconfinement**: where do partonic degrees of freedom start to dominate ?
- Is the **phase transition** of 1st order ?
- Critical **endpoint** ?
- **Microscopic structure** of dense hadronic phase, as existing in the core of compact stars (strangeness, condensates, deconfined states…)

SIMP – heavy ion physics@FAIR/SPS/JPARC

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

	running	project	Starting 2025			project
Facility	SIS18	J-PARC-HI	SIS100	NICA	RHIC	SPS
Experiment	HADES/ miniCBM	DHS, D2S	CBM/ HADES	MPD	STAR	NA60+
$\sqrt{s_{NN}}$ GeV	2.4 – 2.6	2 – 6.2	2.7 – 5	2.7 – 11	3 – 19.6	4.9 – 17.3
μ_B MeV	880 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230
Int. rate (kHz)	20	10 000	10 000	6	0.01 – 2	10 000
Hadrons	+	+	+	+	+	(+)
Dilpetons	+	+	+	+	+	+
Charm		(+)	(+)	+	+	+

Nuclear Physics A 982 (2019) 163–169

FAIR/GSI

- $\sqrt{s_{NN}}$=2.4 - 5 GeV
- HADES and CBM: charged hadrons, ɣ, e^+e^- CBM: $\mu^+\mu^-$
- HADES : bwd acceptance, limited to 200 kHz
  Continuation of IJCLab activities HADES/SIS18
- CBM : fwd acceptance, up to 10 MHz
  IPHC : production of CMOS sensors for MVD of CBM
- possible extension at higher energies in further future
- **SIS100 : First beams in 2025**

J-PARC-HI

- $\sqrt{s_{NN}}$=2.- 6.2 GeV
- Detection of charged hadrons +neutrons, ɣ, e^+e^-, $\mu^+\mu^-$
- Project status: **LOI for J-PARC-HI, july 25, 2016**,
- Start of experiments probably **not before 2029**

NA60+

- $\sqrt{s_{NN}}$=4.9-17.3 GeV
- $\mu^+\mu^-$ + unidentified hadrons (vertex tracker) and real ɣ
- Highlights: thermal dileptons, ρ spectral function,
- Project status: **EOI submitted to SPSC May 3rd 2019** (CERN-SPSC-2019-017), **LOI in preparation**

The role of Theory

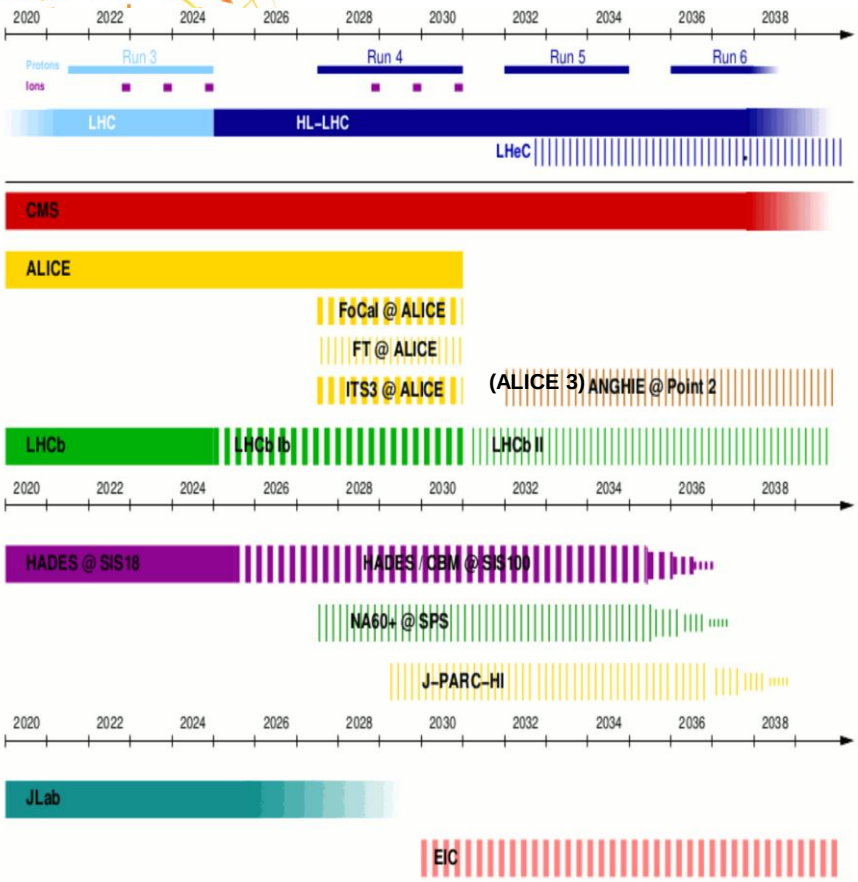
Nucleon structure studies: ~**15 theorists** involved in France

- Factorization frameworks for **TMDs** and **GPDs** *(CPhT, IJClab, Irfu)*
- Modelling 2+3d **Wigner distributions** (*CPhT*)
- **n-pdfs**, role of cold nuclear matter effects (*LLR,LPSC, CPHT, IPhT, Subatech, IJCLab*)

QCD matter studies at zero and finite baryon number: ~**20 theorists** involved in France

- **Equation of State**, properties of QCD matter (*IP2I, Subatech, APC*)
- description of the different collision phases: **Initial state** (*Subatech*), **Thermalization** (*IPHT*), **hadronization** (*Subatech*)
- **Probes of QGP**: jet quenching, open and hidden heavy flavour (*Subatech*, *IJClab*, *IPhT*)
- Understanding the origin of **collectivity in small systems** (*Subatech*)
- **Fluctuations** (related to phase transitions) (*Subatech*)

GT03 – Experimental projects



Project \ Science Driver			SD1	SD2			SD3			SD4		
	project scale	*interest in FR*	a) proton mass	a) quark content	b) gluon content	c) saturation	a) nature of QGP	b) collectivity	c) chiral symmetry	a) phase transition	b) critical point	c) hadronic matter
Structure of the nucleon												
JLAB	€€	★	***	***	*	-	-	-	-	-	-	-
EIC	€€	★★	**	*	***	***	-	*	-	-	-	-
Matter at high temperature												
ALICE	€€	★★★	-	-	**	**	***	***	*	*	-	*
FOCAL@ALICE	€	☆	-	-	**	**	-	-	-	*	-	*
FT@ALICE	<€	☆	-	**	-	-	*	*	**	**	*	*
ITS3@ALICE	€	★	-	-	-	**	***	***	*	*	-	*
(ALICE 3) ANGHIE	€€	★	-	-	**	**	***	***	*	*	-	*
CMS	€€€	☆	-	-	**	**	***	***	*	*	-	*
LHCb Ia+SMOG2	€€	☆	-	**	**	**	*	*	**	**	*	*
LHCb Ib	€	★	-	**	**	**	**	**	**	**	*	*
LHCb II	€€	★	-	**	**	**	***	***	**	**	*	*
Baryon-rich matter												
HADES@SIS18	€	☆	-	-	-	-	-	*	-	**	**	***
HADES/CBM	€	☆	-	-	-	-	*	**	**	***	***	***
NA60+	€	☆	-	-	-	-	**	*	***	***	***	***
J-PARC-HI	€	☆	-	-	-	-	*	**	**	***	***	***

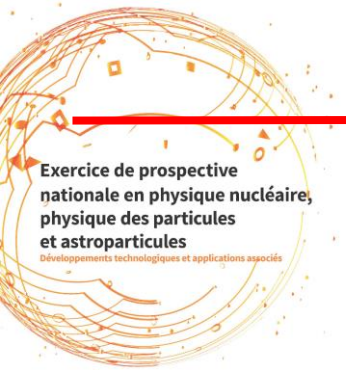
Recommendations - NUST

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules
Développements technologiques et applications associés

1. Support the theory groups to maintain the french leadership over the next decade on the outstanding problems of hadrons and nuclear structure in terms of **TMDs** and **GPDs**, as well as **cold nuclear effects** of interest at the EIC and in p+A collisions at the LHC. Phenomenological studies in close connection with the French experimental program in the field should be encouraged.

2. Capitalize on the investments on the Jefferson Lab experimental program and take full advantage of the recent CEBAF energy upgrade to complete a three-dimensional exploration of the structure of nucleon and nuclei in the **valence quark region**. The program, centered around the determination of the **GPDs**, is well-defined until 2025-2030, with the experiments relying on the CND, NPS and ALERT detectors.

3. Consolidate the french community interested in a participation to the Electron-Ion Collider project which is emerging as a **flagship project** for hadronic physics, **for at least two decades starting around 2030**. A stronger involvement in early studies and design phase, gathering the many and experimental and theoretical expertise, should be supported as the framework for shaping the French scientific project. Contribution to the detector construction should be focussed and commensurate with the size of the interested community.



Recommendations - SIMP

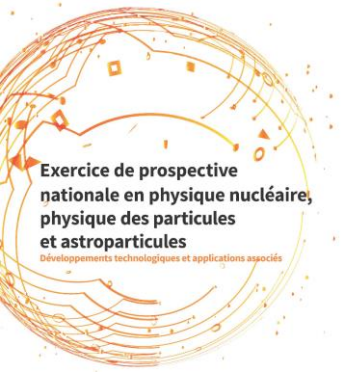
1. Fully exploit the physics potential of LHC Run 3 with the upgraded **ALICE**, **CMS** and **LHCb** (+SMOG2) experiments to pursue the study of matter at high temperature. The three experiments exhibit very **rich** and interesting **complementarities**, which should be promoted by combining their measurements.

2. Strengthen efforts involving theorists and experimentalists towards a global interpretation of data, taking advantage of the forthcoming various and precise data from all experiments at different energies and correlating them. A forum like the **GDR QCD** should be fully exploited to this end. Moreover, the establishment of a **centralized platform**, providing various **model predictions** in a complete manner, as already done in particle and cosmic ray physics, would be highly valuable.

3. Organize the strategic choices to be made for QGP studies after LHC Run 3. Given the size of the French community, and the beginning of the EIC program in the US, strategic orientations should be based on long term perspectives, well-identified French collaborations and **comprehensive studies of the ALICE, CMS and LHCb upgrade-related physics gain**. For instance, a comprehensive comparison between the physics gain of the already upgraded CMS experiment (including low-field configuration) and the ANGHIE project should be performed. Key-decision points for the strategic choices should be planned on timescales compatible with LHC pre-Run 4 and pre-Run 5 installations.

4. Support the scientific production at GSI/FAIR in the baryon-rich sector, and develop prospective activities along new connections to astrophysics, in light of the world-wide development of new projects and the recent detection of gravitational waves. In addition to the participation to the HADES/CBM project at SIS100, interests for NA60+/CERN and J-PARC-HI have been expressed, which demonstrate, together with the developing theoretical activity in France in the field, that a new dynamic is growing in this sector. The objective in the next years should be to **gather a critical mass of physicists** and to elaborate a common project, taking into account investments already made. A research program should be developed in close connection with the astrophysics community interested in the equation of state of the dense hadronic matter.

5. Strongly support theoretical activities on QGP which are closely related to the experimental programs in France, in particular covering open and hidden **heavy flavor**, effective theories of the **QCD phases**, the **hydrodynamic evolution** of quark matter, and their implementation in Monte Carlo **event generators**.



Colloque de restitution de l'exercice de prospective nationale

GT03 – Physique hadronique

Understanding strong interactions

19 octobre, 2021

Comité de pilotage: Klaus Werner (SUBATECH), Carlos Munoz (IJCLab), Béatrice Ramstein (IJCLab), Frédéric Fleuret (LLR), Laurent Vacavant (IN2P3)