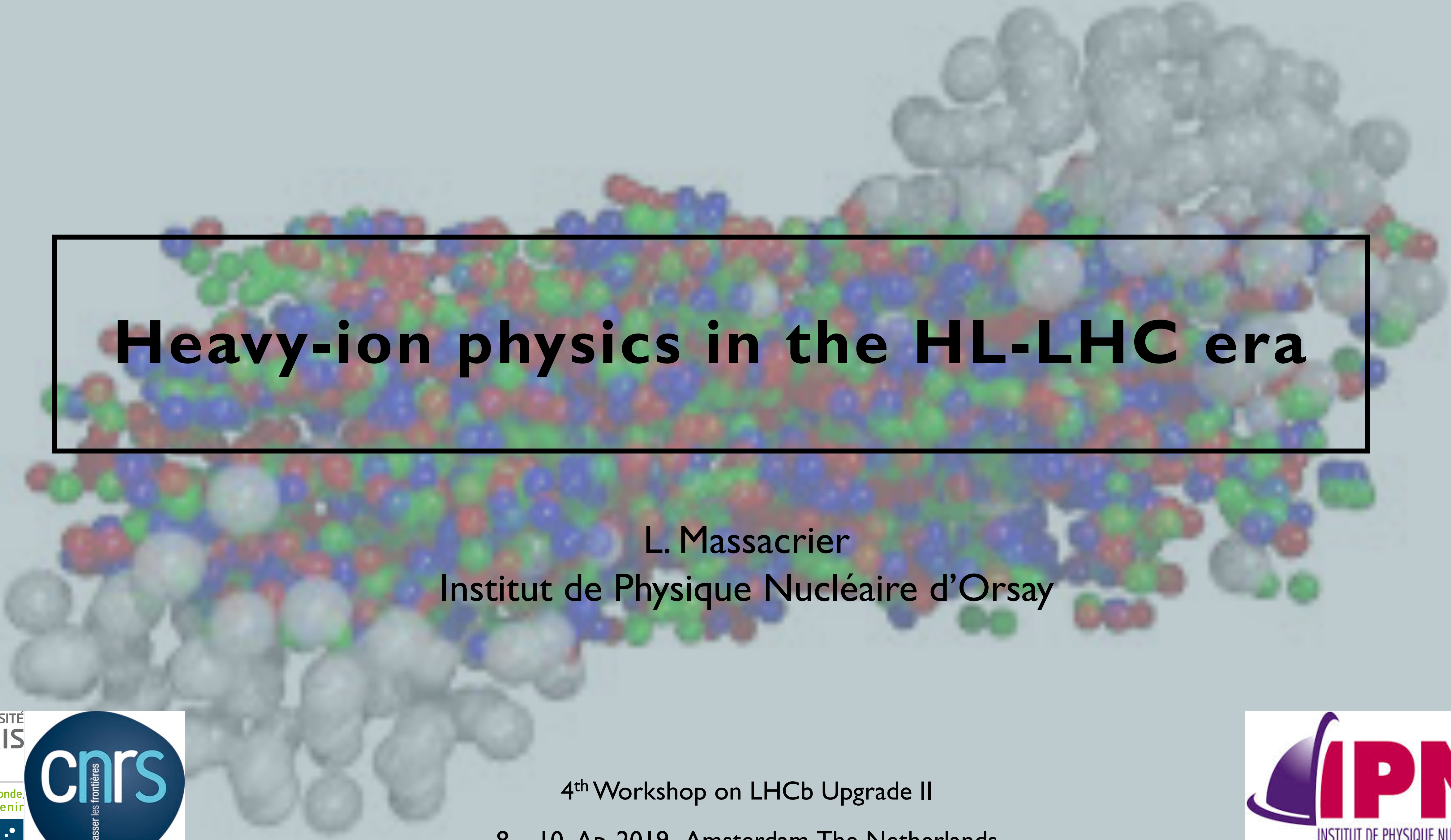


Heavy-ion physics in the HL-LHC era

L. Massacrier
Institut de Physique Nucléaire d’Orsay

4th Workshop on LHCb Upgrade II

8 – 10 Ap. 2019, Amsterdam, The Netherlands

Outline

- ☐ Physics goals identified for the HL-LHC era
- ☐ With which observables?
- ☐ Besides Pb-Pb : pp reference, pA and lighter nuclei
- ☐ Plans for heavy-on data taking at the LHC in the next decade
- ☐ LHC experiment upgrades relevant for heavy-ion physics
- ☐ Prospects for pA and AA collisions in collider mode for HL-LHC and beyond (with main focus on the forward region)
- ☐ Prospects for physics opportunities in fixed target mode for HL-LHC and beyond
- ☐ Conclusions

Physics goals identified for the HL-LHC era

see Z. Citron et al., « Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams», arXiv:1902.10229

1 ***Characterize the macroscopic long-wavelength QGP properties (fluid dynamics) with unprecedented precision***

→ temperature, QCD phase transition at μ_B ~0, viscosity, heavy quark transport coefficients …

2 ***Access the microscopic parton dynamics underlying QGP properties***

→ color field strength of the medium, colour screening/regeneration, evolution of collective partonic system to hadronic phase

3 ***Developing a unified picture of particle production from small (pp) to larger (pA and AA) systems***

→ flow of heavy flavour and quarkonia, energy-loss, thermal radiation in small systems, strangeness production versus system size

4 ***Probing parton density in nuclei in a broad (x,Q^2) kinematic range and search for parton saturation***

→ constraining nuclear PDFs at high and low Q^2, test saturation effects at small x

With which observables ?

At HL-LHC (already starts at Run3 for ions) : focus on rare probes, their coupling with the medium and their (medium-modified) hadronization process in AA collisions.

→ Requires very large statistics, diverse trigger approaches, upgraded detectors

Jets

Characterization of eloss mechanism both as testing ground for multi-particle aspects of QCD and as a probe of medium density

Heavy Flavour

Characterization of mass dependence of eloss, HQ in medium thermalization and hadronization as a probe of medium properties

- Low-p_T production and elliptic flow of several HF hadron species (mainly ALICE, LHCb up to semi-central AA)
- b-jets (mainly ATLAS, CMS)

Quarkonia

Precision study of quarkonium dissociation pattern and regeneration as probes of deconfinement

- Low-p_T charmonia and elliptic flow (mainly ALICE, LHCb up to semi-central AA)
- Multi-differential studies of Υ states (mainly ATLAS and CMS)

Low-mass dileptons

Thermal radiation to map the temperature during system evolution, ρ spectral function modification to probe chiral symmetry restoration

- Low-p_T low mass dilepton production (mainly ALICE, LHCb up to semi-central AA)

Besides Pb-Pb : pp reference, pA, lighter nuclei

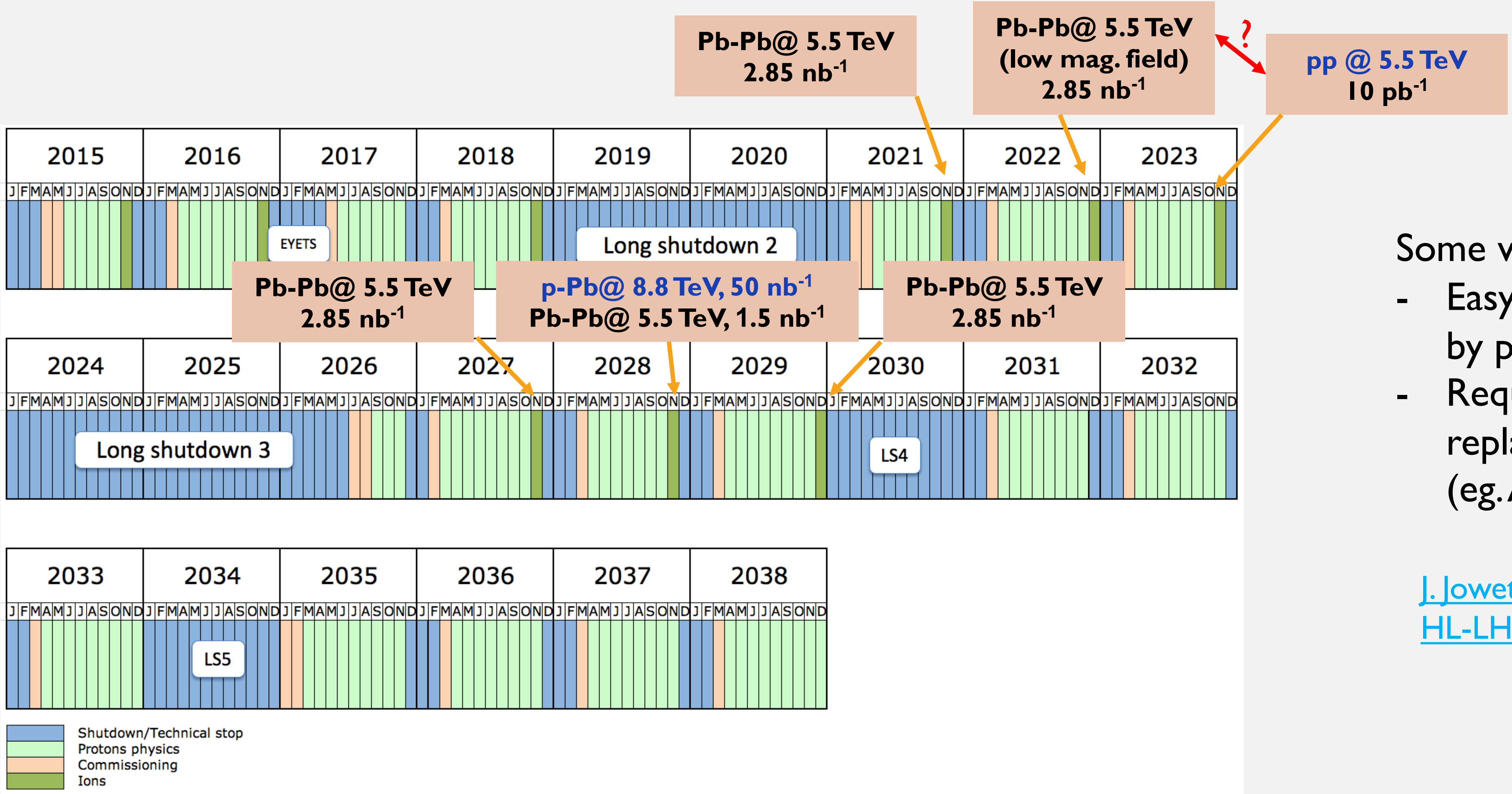
- ☐ ***Need for pp reference at $\sqrt{s}$ = 5.5 TeV:***
  - → ALICE (for HF and quarkonia needs) : ~10 pb^{-1} (see CERN-LHCC-2012-012)
  - → ATLAS/CMS (for high-p_T processes) : ~300 pb^{-1}

- ☐ ***pPb collisions for three main goals:***
  - → Explore the partonic structure of nuclei
  - → Also a reference for Pb-Pb studies (Cold Nuclear Matter effects)
  - → Study the development of collective effects in high-particle density collisions

- ☐ ***Lighter nuclei to study system size dependence and onset of QGP effects***
  - → Larger instantaneous luminosity compensates the reduces yield for hard processes (which scales with A^2)

Plans for heavy-ion data taking at the LHC in the next decade

- ☐ Running scenario and approved species choices according to ALICE LOI (2012) *ALICE Collaboration, J. Phys. G 41 (2014) 087001*
- ☐ Maximum int. rate : 50 kHz in Pb-Pb; peak luminosity : 6 x 10^{27}cm^{-2}s^{-1}; integrated lumi : 10nb^{-1}



Pb-Pb@ 5.5 TeV
2.85 nb^{-1}

Pb-Pb@ 5.5 TeV
(low mag. field)
2.85 nb^{-1}

pp @ 5.5 TeV
10 pb^{-1}

Pb-Pb@ 5.5 TeV
2.85 nb^{-1}

p-Pb@ 8.8 TeV, 50 nb^{-1}
Pb-Pb@ 5.5 TeV, 1.5 nb^{-1}

Pb-Pb@ 5.5 TeV
2.85 nb^{-1}

🟦 Shutdown/Technical stop
🟩 Protons physics
🟧 Commissioning
▨ Ions

Some variations possible:
- Easy modification: replace Pb-Pb by p-Pb or pp ref
- Requiring more preparation: replace Pb-Pb by other specie (eg. Ar-Ar)

J. Jowett, Workshop on the physics of HL-LHC, oct. 2017

Plans for heavy-ion data taking at the LHC in the next decade

☐ New proposal from WG5 on the Physics of HL-LHC:

Z. Citron et al., « Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams», arXiv:1902.10229

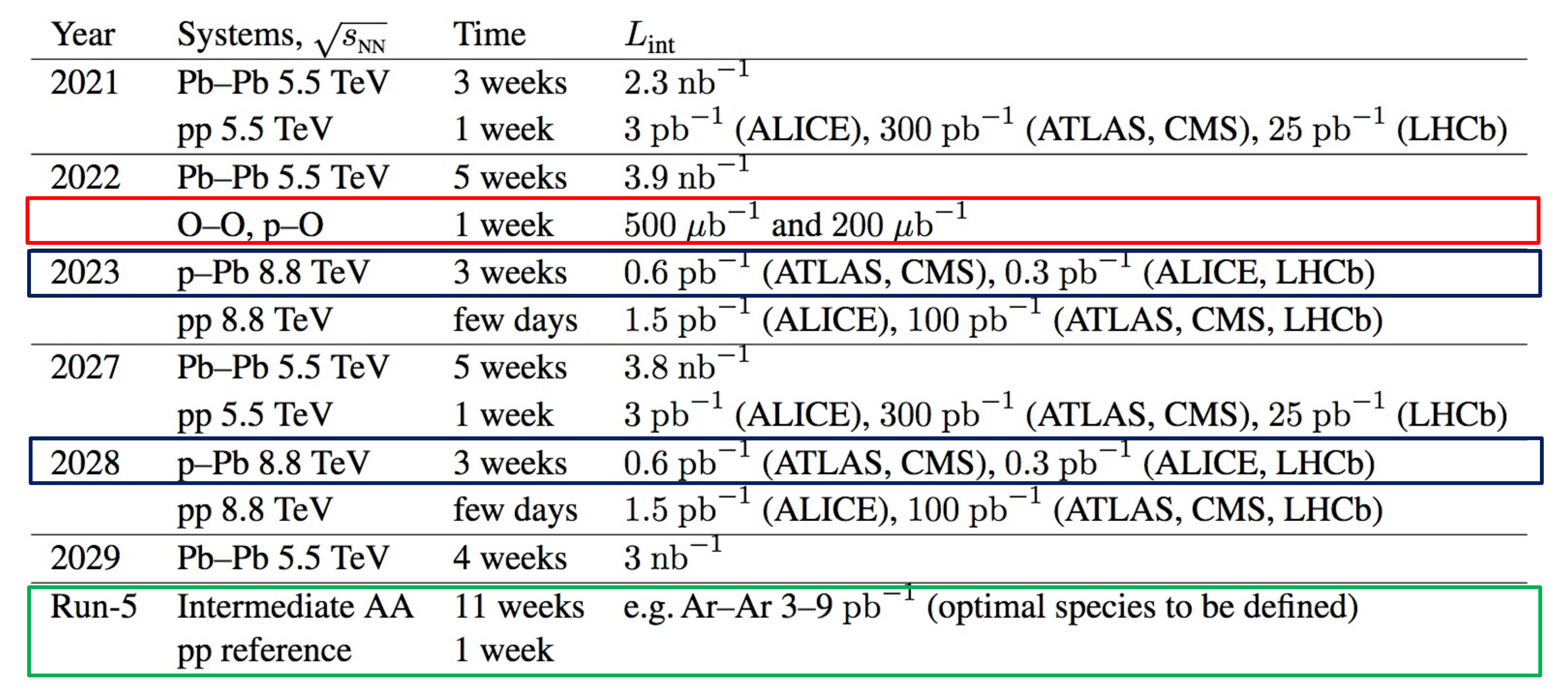
☐ High lumi Pb-Pb and p-Pb programmes remains a priority for Run3&4

☐ Request to increase heavy ion running time from 12 to 14 weeks per run

Larger L_{int} in p-Pb for high precision studies of initial and final state effects, in high multiplicity events

O-O/p-O to study onset of hot-medium effects and to tune cosmic-ray particle production models

Intermediate AA at high lumi to access probes still rare in PbPb



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	

+ a large sample (~ 200 pb^{-1}) of pp collisions at $\sqrt{s}$ = 14 TeV to rich highest possible multiplicities in small system

LHC experiment upgrades relevant for heavy-ion physics

CMS (LS2/LS3)

- ❑ Lighter silicon tracker with extended coverage up to $\eta = 4$ (LS3)
- ❑ GEM muon stations matching the eta coverage of the tracker (LS2)
- ❑ High granularity calorimeter endcaps → particle flow reconstruction at large rapidity (LS3)

ATLAS (LS2/LS3)

- ❑ New tracking detector : tracking and b-tag up to $\eta = 4$ (LS3)
- ❑ Level-1 track trigger : high multiplicity tracking (LS2)
- ❑ Calorimeter electronics upgrade and muon trigger system (LS2)

ATLAS/CMS → focus on « triggerable » signal : muon, jets, displaced tracks
Strong data reduction (50kHz → 100 Hz), HL-LHC : increase of sample x 10 wrt Run2

ALICE (LS2)

- ❑ New ITS : improved resolution, reduced material budget
- ❑ Muon Forward Tracker : heavy flavour verteces and prompt/displaced muon at forward y
- ❑ TPC upgrade + readout upgrade + online data reduction → continous readout at 50 kHz in Pb-Pb

LHCb (LS2)

- ❑ New trackers (pixels, strips, scintillating fibers) → impact on centrality reach in Pb-Pb
- ❑ Readout upgrade : up to 40 MHz in pp → exploit also full delivered pPb luminosity
- ❑ SMOG2

ALICE/LHCb → focus on « untriggerable » signal
ALICE : continous readout at 50 kHz; HL-LHC: minimum bias sample x 100 wrt Run2

LHCb strenght w.r.t ALICE in the forward region after the upgrades

Physics reach of ALICE for several observables after the LS2 upgrade (MUON + new MFT tracker)

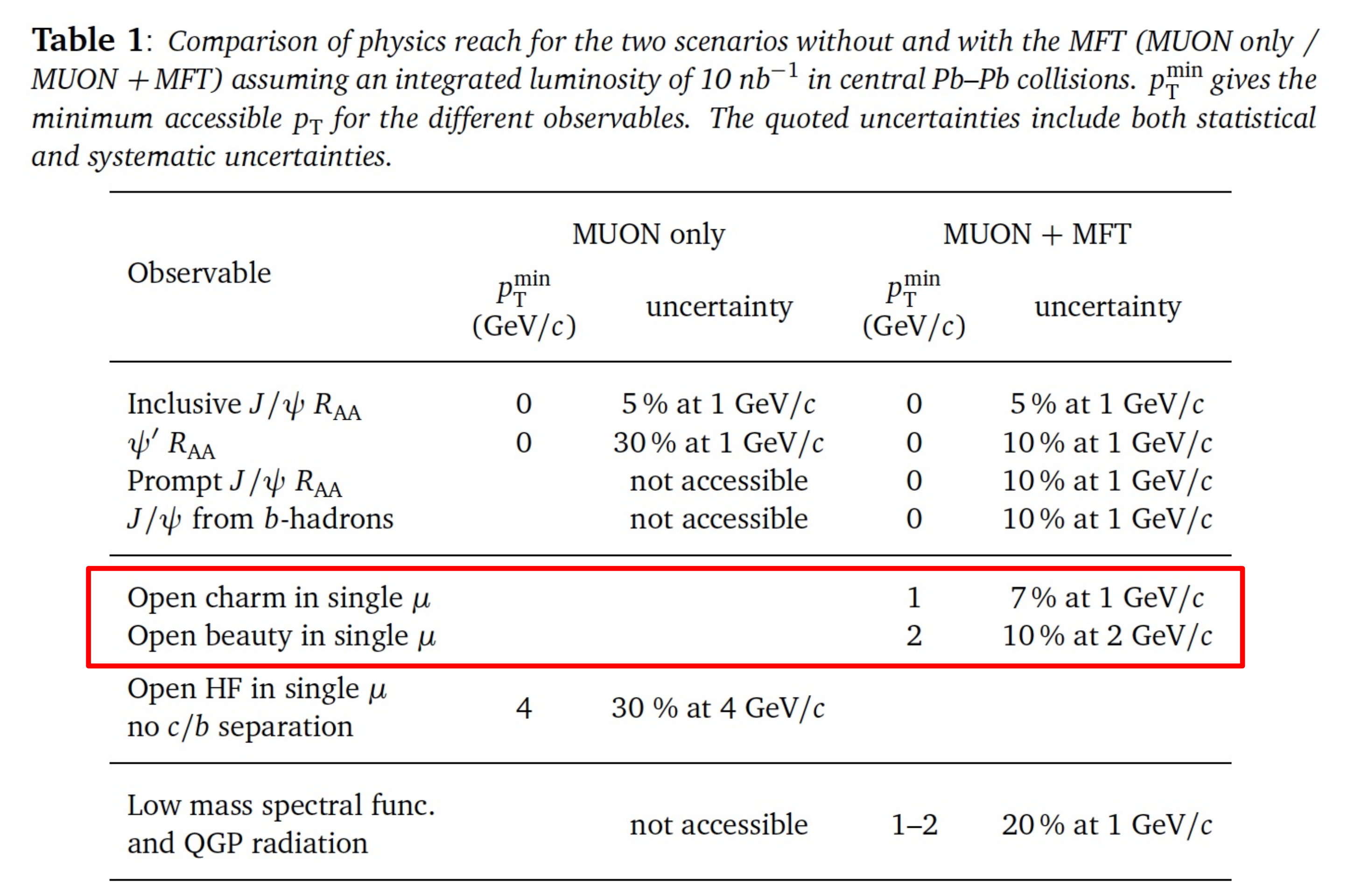


Table 1: *Comparison of physics reach for the two scenarios without and with the MFT (MUON only / MUON + MFT) assuming an integrated luminosity of 10 nb^{-1} in central Pb–Pb collisions. p_T^{min} gives the minimum accessible p_T for the different observables. The quoted uncertainties include both statistical and systematic uncertainties.*

Observable	MUON only		MUON + MFT	
	p_T^{min} (GeV/c)	uncertainty	p_T^{min} (GeV/c)	uncertainty
Inclusive J/ψ R_{AA}	0	5 % at 1 GeV/c	0	5 % at 1 GeV/c
ψ' R_{AA}	0	30 % at 1 GeV/c	0	10 % at 1 GeV/c
Prompt J/ψ R_{AA}		not accessible	0	10 % at 1 GeV/c
J/ψ from b-hadrons		not accessible	0	10 % at 1 GeV/c
Open charm in single μ			1	7 % at 1 GeV/c
Open beauty in single μ			2	10 % at 2 GeV/c
Open HF in single μ no c/b separation	4	30 % at 4 GeV/c		
Low mass spectral func. and QGP radiation		not accessible	1–2	20 % at 1 GeV/c

- ☐ Study of open charm and open beauty still limited
  - Measurement through single muon decay (no PID)
  - Still ~ 20% uncertainty on open charm at p_T = 0
  - Open beauty extraction limited to p_T > 2 GeV/c
- ☐ No calorimeter at forward y (no $X_c \rightarrow \gamma + J/\Psi$)
- ☐ LHCb will remain the only experiment fully equipped in the forward region (with already excellent M, p_T resolution in pA, and accessing most central AA collisions after the Upgrade Phase II)

LHCb Upgrade PHASE II to access the most central AA collisions

- Unique opportunity for a general purpose heavy-ion detector suited for pA up to most central AA collisions at forward y

- Number of tracks in pp collisions at Upgrage Phase II luminosity ~ number of tracks in central Pb-Pb collisions
  → sufficient tracking and calorimeter performances for HI studies

- Lower pile-up in pPb/Pbp with respect to pp running → lower occupancies in pPb/Pbp
  → Precise measurement of low-x regime of QCD

LHCb Collaboration, CERN/LHCC 2018-027, PUB-2018-019

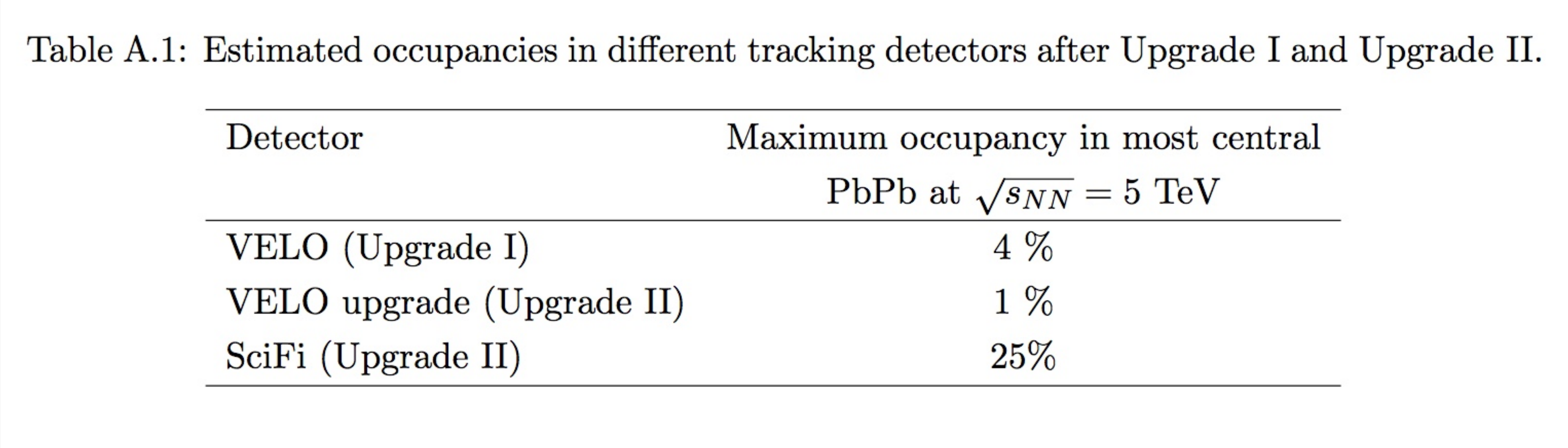


Table A.1: Estimated occupancies in different tracking detectors after Upgrade I and Upgrade II.

Detector	Maximum occupancy in most central PbPb at $\sqrt{s_{NN}} = 5$ TeV
VELO (Upgrade I)	4 %
VELO upgrade (Upgrade II)	1 %
SciFi (Upgrade II)	25%

Prospects for pA and AA collisions in collider mode for HL-LHC and beyond (with main focus on forward region)

Quarkonium and Open HF production in AA collisions

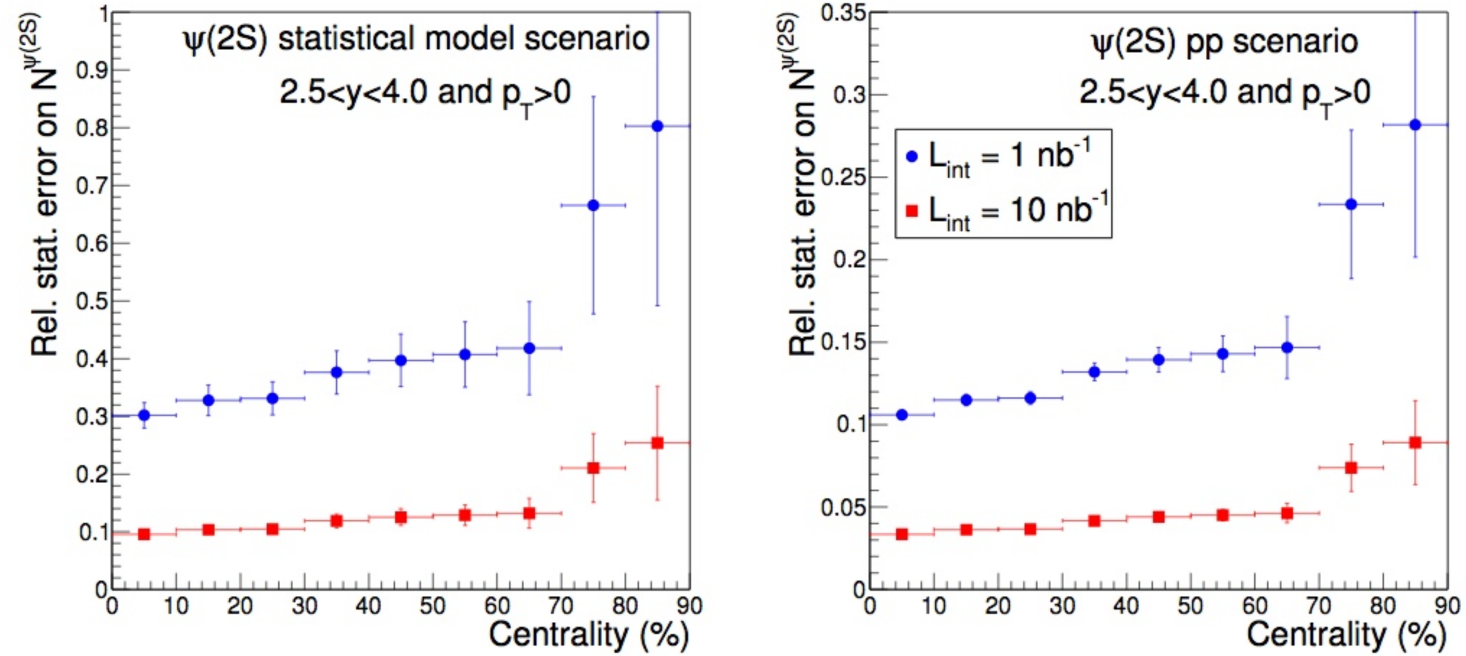
- ☐ Heavy quarks produced at early stages of AA collision → experience full evolution of system
- ☐ Sequential suppression of quarkonia by color screening in the deconfined medium
- ☐ Regeneration of charmonia at low p_T and LHC energy
- ☐ Run 3&4 : precise determination of prompt J/Ψ R_{AA} and v_2 at low-p_T (ALICE) and high-p_T (CMS, ATLAS)

- ☐ Ψ(2S) yield will remain statistically limited (3-10% in most central forward events depending on assumptions)

- ☐ Differential measurements interesting to study the interplay between suppression/regeneration

- ☐ Fully reconstructed open HF hadrons only possible in LHCb in the forward region → interesting in themselves (eloss studies), also normalisation channel for charmonia (total $c\bar{c}$ cross section)

ALICE Collaboration, J. Phys. G 41 (2014) 087001

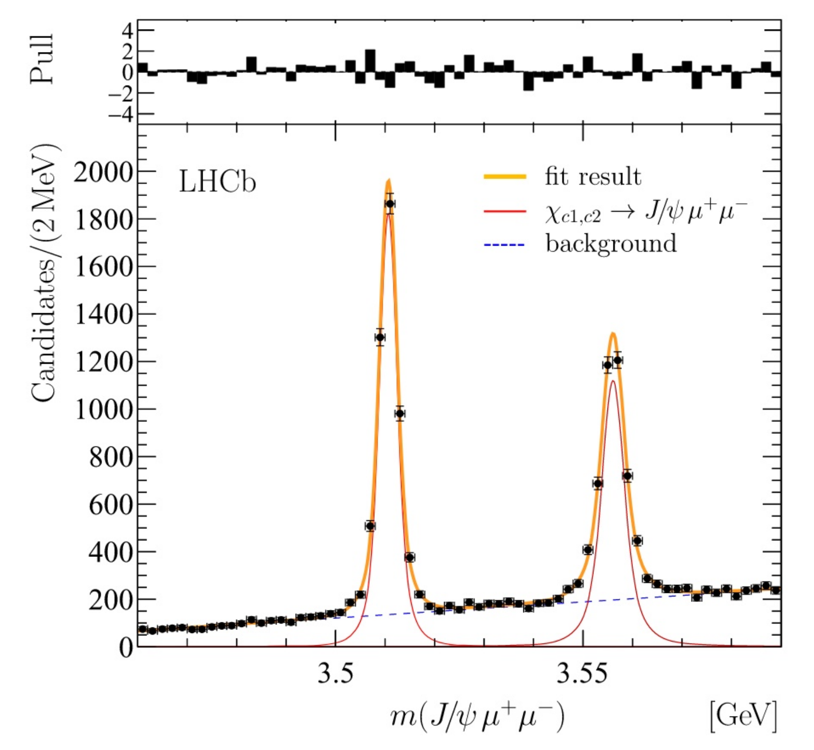


Quarkonium and Open HF production in AA collisions

- X_c measurement challenging in AA
- Complementary to J/Ψ, Ψ(2S) to understand the charmonia suppression/regeneration pattern
- Only LHCb can measure $X_c \rightarrow J/\Psi+\gamma$ at forward y (down to low p_T)
- Interesting new channel $X_c \rightarrow J/\Psi+\mu^+\mu^-$ requires large stat (LHCb, ALICE)
  - → 5 fb^{-1} in pp ~ 100 nb^{-1} Pb-Pb

- Measurement of Y-states with good resolution at forward y
- Together with open beauty hadrons down to low p_T (total $b\bar{b}$ cross section)
- Measurement of baryonic heavy-quark states benefit from the improved vertex reco performances and boost at forward y

LHCb Collaboration, PRL 119, 221801

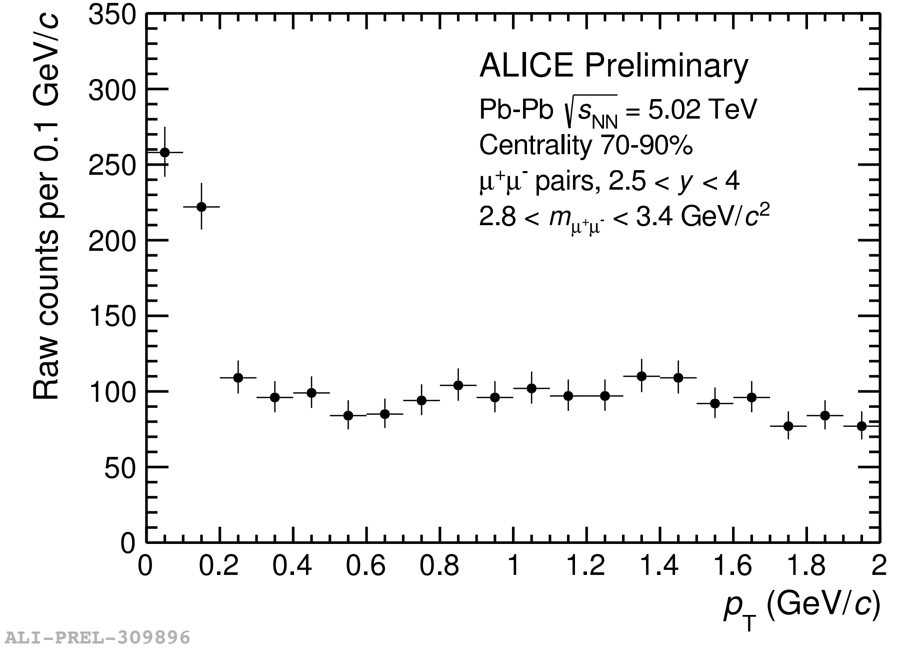


Precise differentiel ψ(2S), X_c, Y production measurements could be studied at forward rapidity down to $p_T = 0$ with suitable open-charm and beauty normalization channels

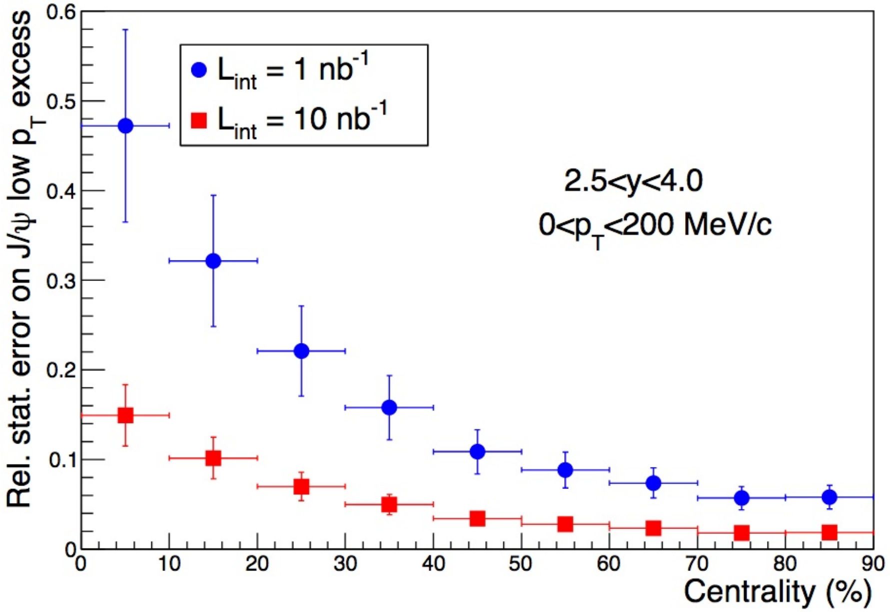
Quarkonium photoproduction in AA collisions with nuclear overlap

- ❑ First observation by ALICE of an excess in the yield of J/ψ at very low-p_T in peripheral AA collisions
  - → attributed to coherent photoproduction of J/ψ in collisions with nuclear overlap
  - → could potentially become a new golden probe of the QGP
- ❑ Run 3&4, measurement in most central AA collisions still challenging (~ 15% uncertainty on the yield)
- ❑ Excellent p_T resolution (LHCb) to study the p_T shape (and confirm the mechanism)
- ❑ Also needs large statistics : polarization measurement, Ψ(2S) and Υ vector mesons to study medium interactions

L. Massacrier, HP2018



ALICE Collaboration, J. Phys. G 41 (2014) 087001



Low mass dileptons and thermal radiation in AA collisions

- Low mass dileptons sensitive to chiral symmetry restoration in the QGP and thermal radiation of the QGP
- Need excellent mass resolution to study the resonance line-shape (down to low p_T)
- Thermal radiation measurement limited by the background subtraction of leptons from HF decays

LHCb Collaboration, Phys. Rev. Lett. 120, 061801

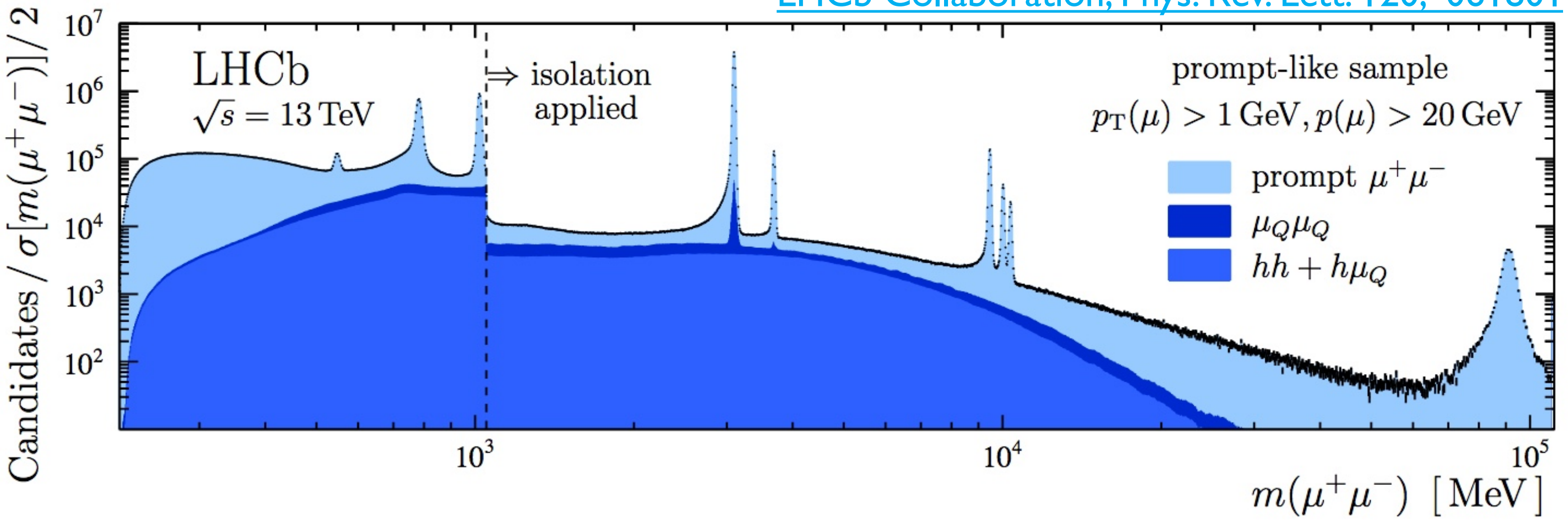


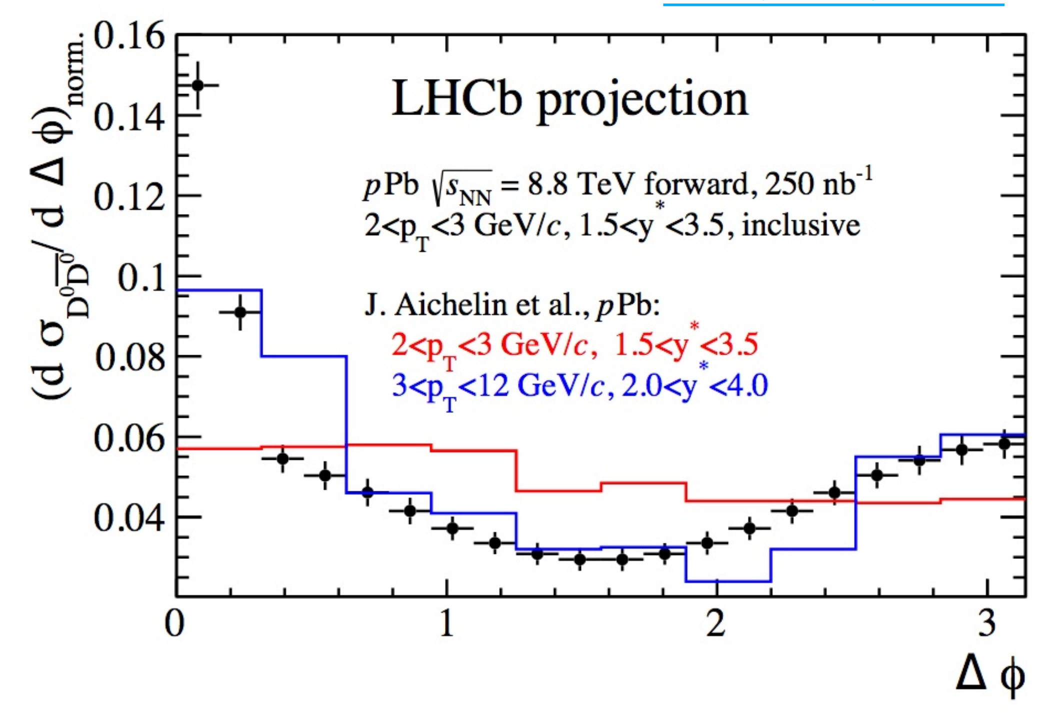
Figure 1: Prompt-like mass spectrum, where the categorization of the data as prompt $\mu^+\mu^-$, $\mu_Q\mu_Q$, and $hh + h\mu_Q$ is determined using the fits described in the text.

LHCb Upgrade II : unique potential to measure precisely dileptons in the dimuon channel and ρ line-shape to probe chiral symmetry restoration

Open Heavy Flavour correlations in pA collisions

- ☐ $D\bar{D}$ correlations in pA collisions provides information to test modification of nPDF
- ☐ Measurements in p_T intervals provide differential information to test theoretical models with precision
- ☐ $D\bar{D}$ correlations in AA sensitive to in-medium eloss of heavy quarks (radiative versus collisional)

arXiv:1902.10229



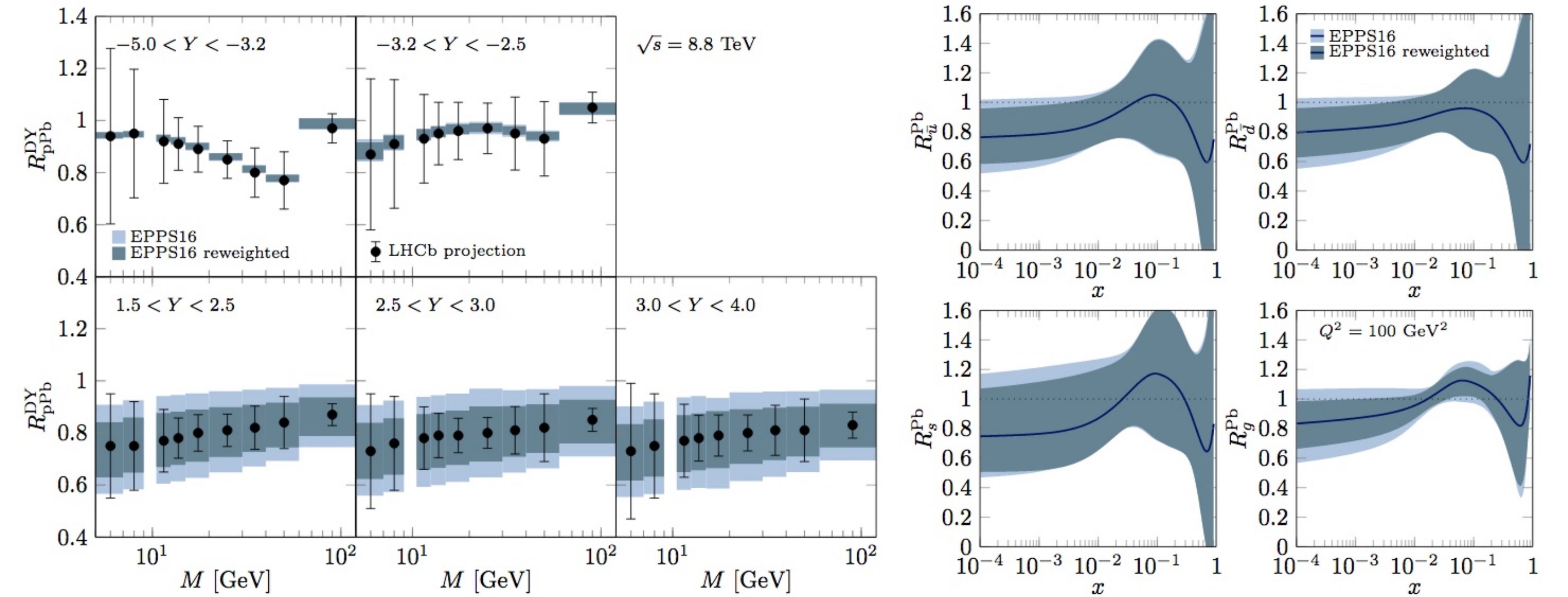
Correlation of fully reconstructed HF hadrons only possible in LHCb in the forward region

- ☐ Run5: Correlation in the $b\bar{b}$ sector needs luminosity ~ 10 pb^{-1} in pPb

Drell-Yan and photon production in pA collisions

- LHCb can access in pA collisions the low-x regime (10^{-3} – 10^{-6}) of the nucleus to look for parton saturation
- Unique low mass Drell-Yan measurement down to charmonium mass range demonstrated by LHCb in pp

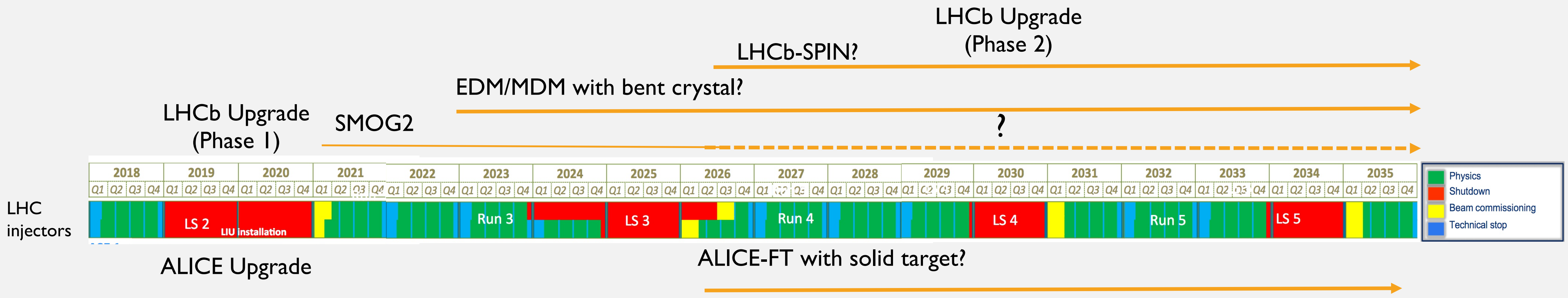
  → similar performances can be expected in pPb with LHCB upgrade II
- Need large luminosities and background rejection of HF decays from VELO
- Also low-p_T photon measurements unique opportunities thanks to improved calorimeter performances at high mult.



arXiv:1902.10229

Prospects for physics opportunities in fixed target mode for HL-LHC and beyond

- ☐ Several proposals in LHCb in the coming years for different physics motivations in the fixed target mode
- ☐ Proposal in ALICE to install a fixed-target setup (solid target or gas-jet) during LS3

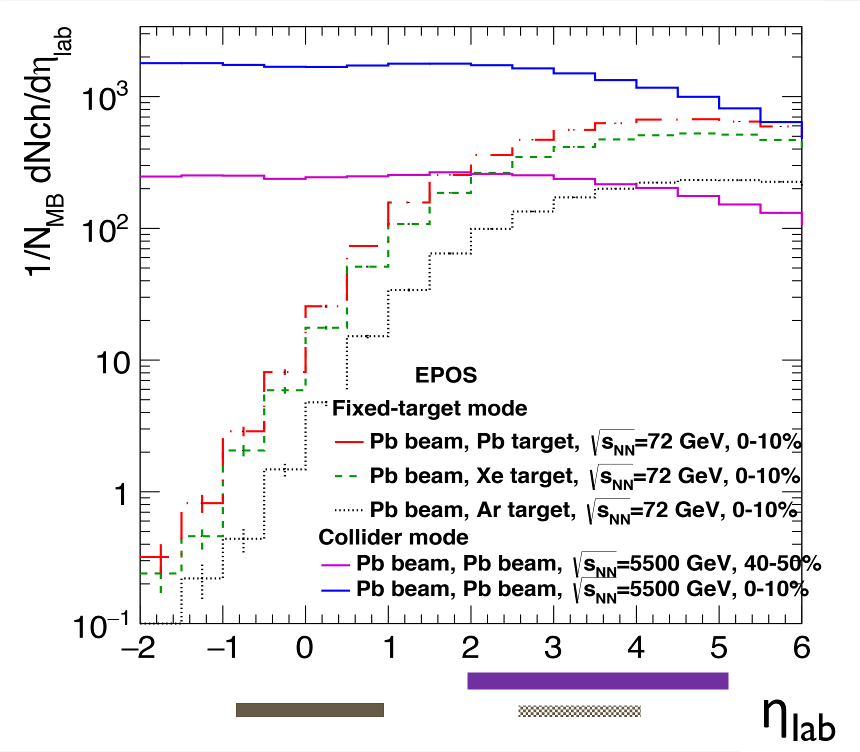


- ☐ Physics opportunities and projections by the AFTER@LHC study group for a LHCb-like detector assuming:
  - $L_{\text{int}} \sim 10$ fb^{-1} for pH collisions
  - $L_{\text{int}} \sim 100$ pb^{-1} for pXe collisions
  - $L_{\text{int}} \sim 30$ nb^{-1} for PbXe collisions

  → Well beyond current expectations for Run3

arXiv: 807.00603

Multiplicities in fixed target mode



L. Massacrier et al., Adv.High Energy Phys. 2015 (2015) 986348

■ ALICE TPC (Z_{target} = 0)

▨ ALICE muon arm (Z_{target} = 0)

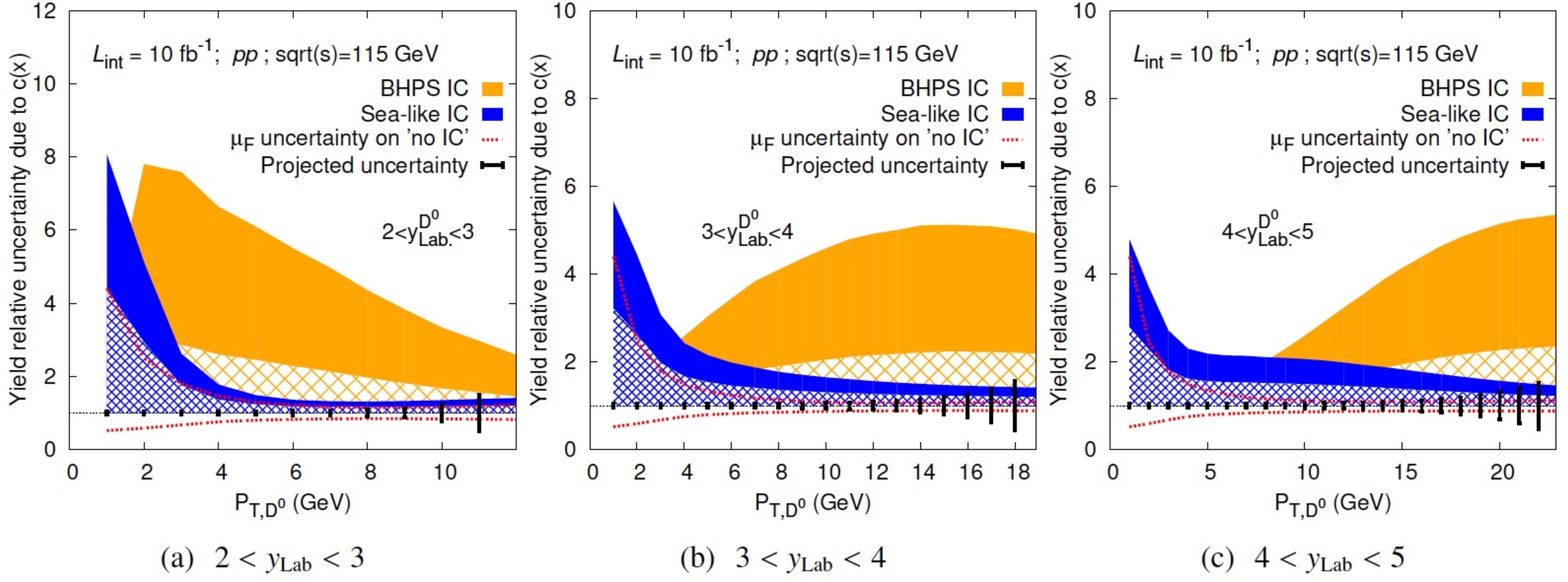
■ LHCb (Z_{target} = 0)

- ❑ Multiplicities in most central fixed target Pb-Xe / Pb-Pb collisions above multiplicity in semi-central Pb-Pb collider events (40-50%) at forward rapidity in the lab
  → need higher granularity from Upgrade Phase II

Explore the high-momentum fraction x frontier in nucleons and nuclei

- **With an emphasis on the high-x gluon and heavy-quark content of the nucleon and nuclei**
  - Study a possible non-perturbative source of c/b quarks in the proton which would carry a relevant fraction of its momentum
    - → Connexion with CR physics : important input to reduce the uncertainties on the prompt atmospheric neutrino flux

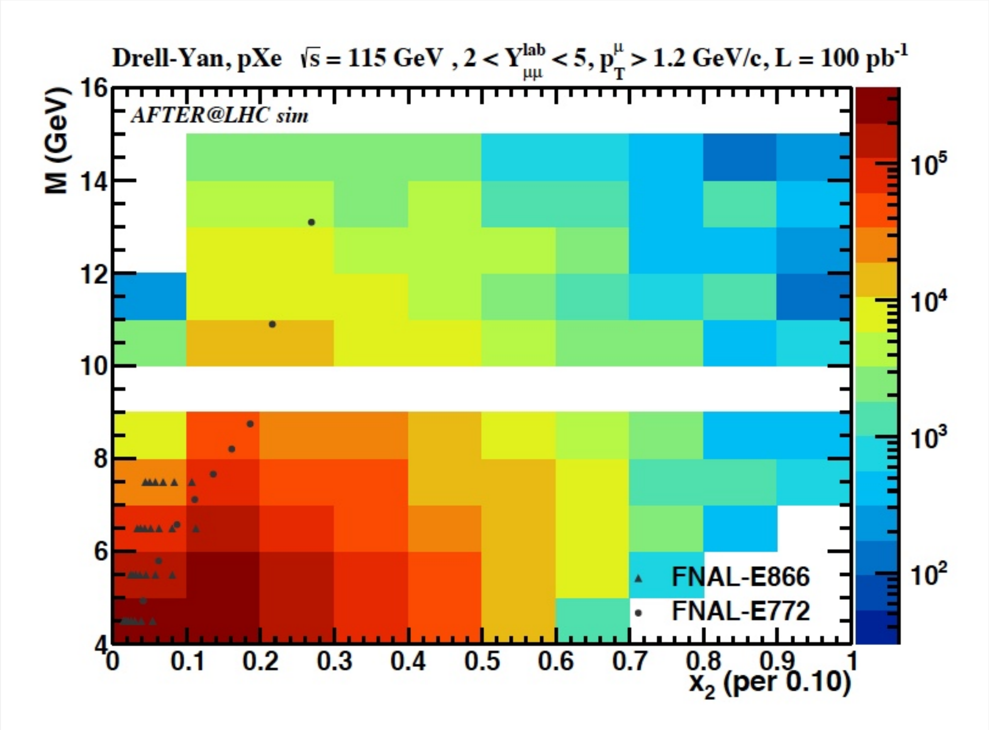
arXiv: 807.00603

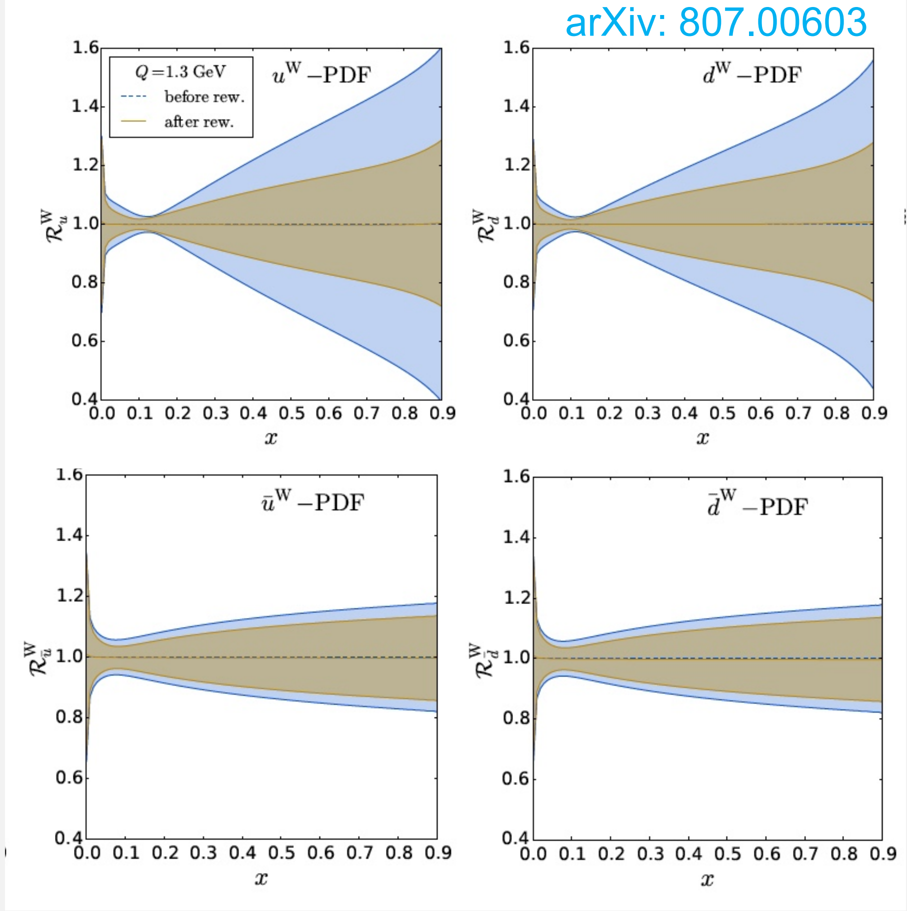


(a) $2 < y_{Lab} < 3$ (b) $3 < y_{Lab} < 4$ (c) $4 < y_{Lab} < 5$

Explore the high-momentum fraction x frontier in nucleons and nuclei

- Improve the knowledge of PDF for the gluon at large-x [also for strange, charm and bottom quark PDFs]
  - → Precise high-x PDFs crucial theoretical inputs for predictions of processes involving heavy new states in BSM theories
- Study the origin of the nuclear EMC effect in nuclei (with gluon and sea quarks)




arXiv: 807.00603

Spin and 3D nucleon structure

❑ **Advance our understanding of the dynamics and spin of quarks and gluons inside (un)polarised nucleons**

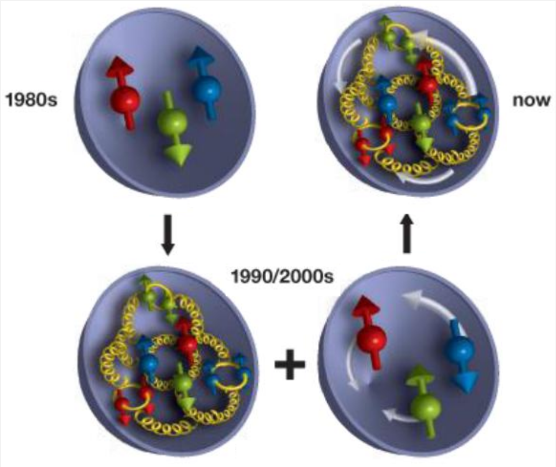
- From the spin crisis to the spin puzzle
- For longitudinally polarised nucleon, with helicity +1/2:

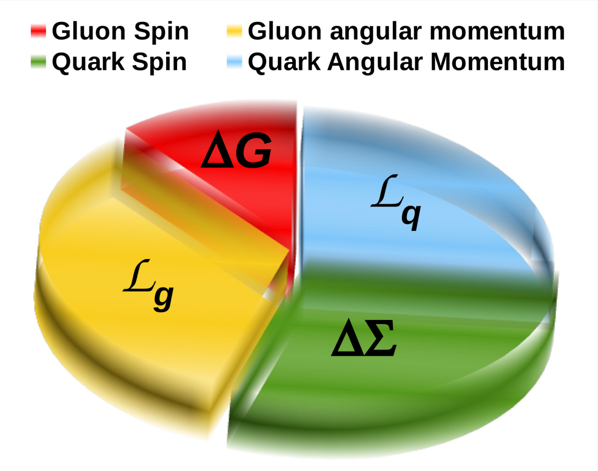
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \underbrace{\ell_g + \ell_q}$$

Spin of quarks and antiquarks

Spin of gluons

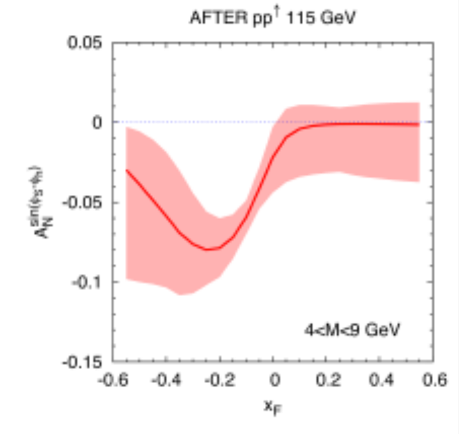
Orbital angular momentum of quarks and gluons





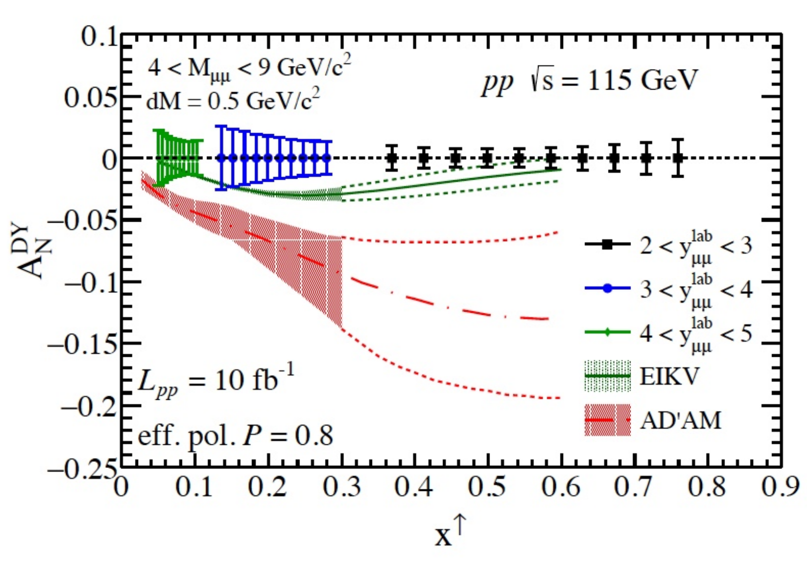
M. Anselmo, Feb. 2013(Courtesy U. d'Alessio)

- First hint by COMPASS that $\ell_g \neq 0$
- Access information on the orbital motion of the partons inside bound hadrons via Single Spin Asymmetries (Sivers effect)
  - Sivers effects : correlation between the parton transverse momentum k_T and the proton spin
    - Gluon Sivers effect at large x_F with gluon sensitive probes
    - Quark Sivers effect at large x_F with Drell-Yan
- Test TMD factorization formalism → sign change of A_N between SIDIS and DY

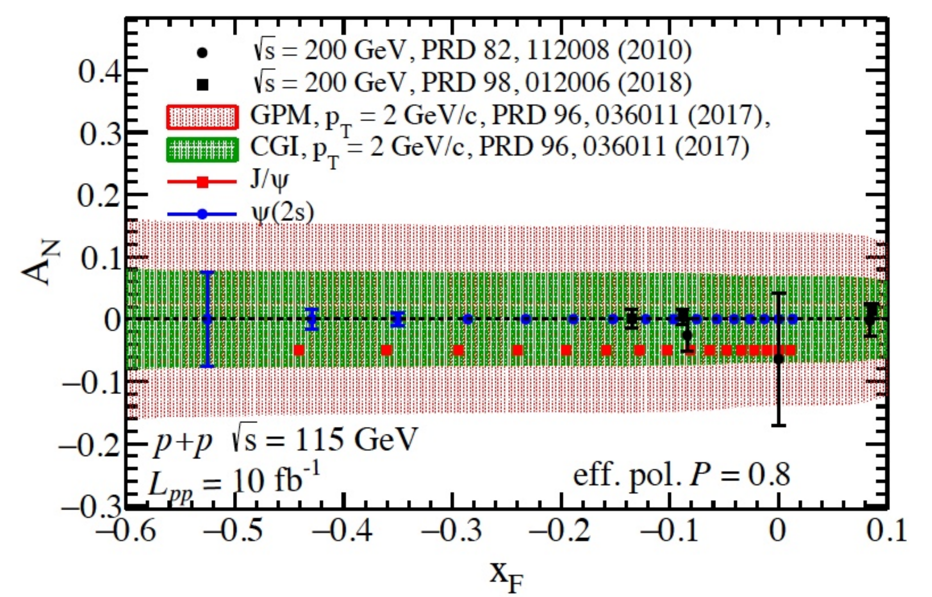


Spin and 3D nucleon structure

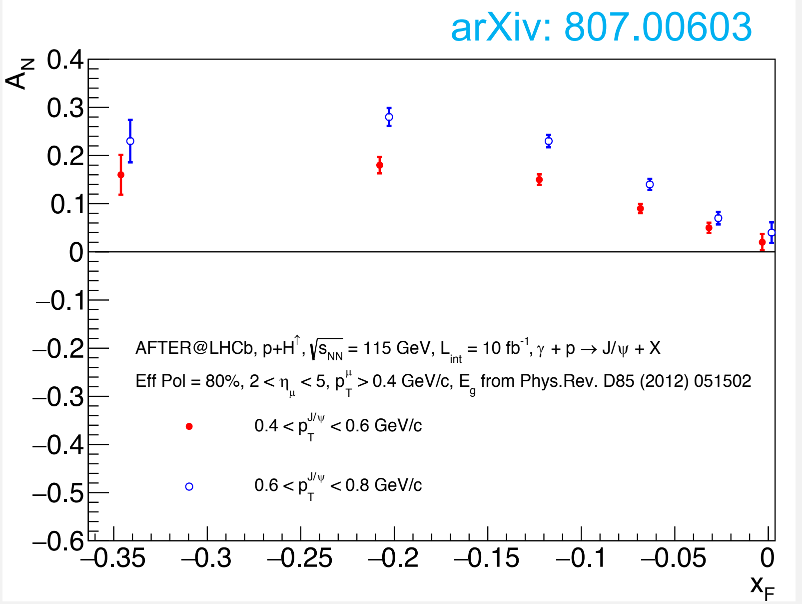
Drell-Yan STSA to probe the quark Sievers effect



J/ψ STSA to probe the gluon Sievers effect



Photoproduced J/ψ to probe the gluon GPD Eg

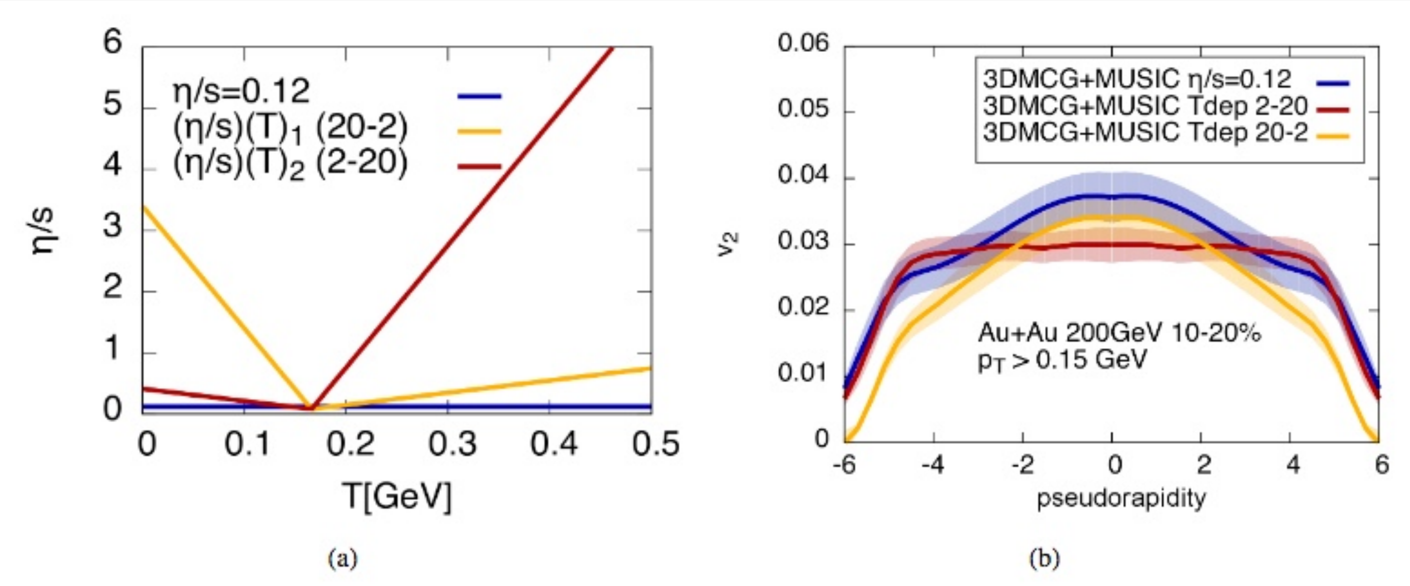

arXiv: 807.00603

$$A_N = \frac{1}{\mathcal{P}_{\mathrm{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

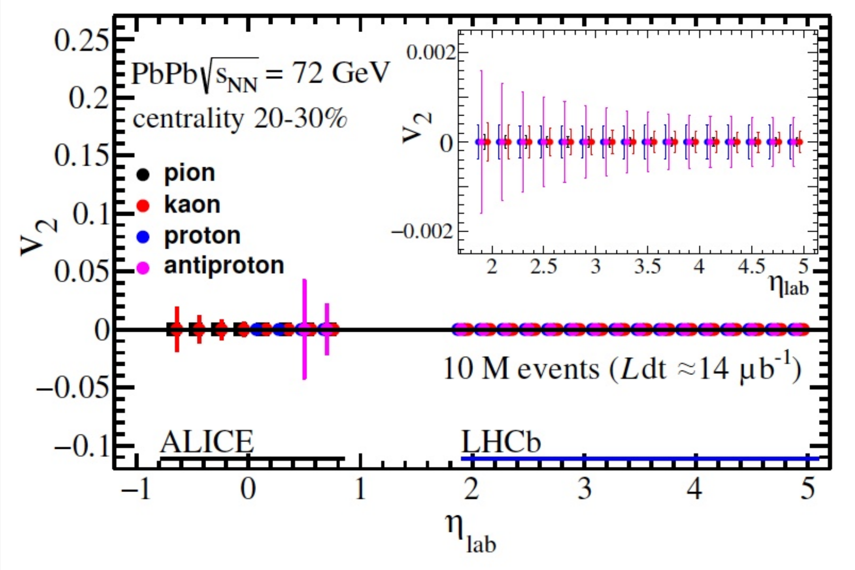
Heavy-ion physics at large rapidity

- ☐ **Advance the understanding of hadronic matter properties under extreme conditions (QGP) and explore the phase diagramme of nuclear matter thanks to a rapidity scan down to the target rapidity**
  - ➢ Rapidity scan at 72 GeV with FT@LHC can complement the RHIC beam energy scan from 62.4 GeV down to 7.7 GeV (at $y_{cms} \sim 0$)

- ☐ **Advance our understanding of QGP macroscopic properties by probing the temperature dependence of the shear viscosity to entropy density ratio (η/s) of the created matter**



arXiv: 807.00603

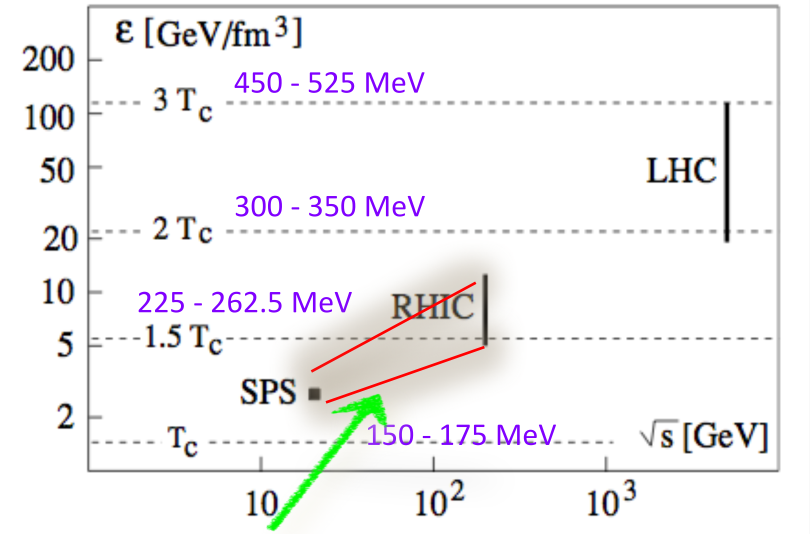


- ☐ **Test the factorization of Cold Nuclear Matter effects with the Drell-Yan process**

Heavy-ion physics at large rapidity

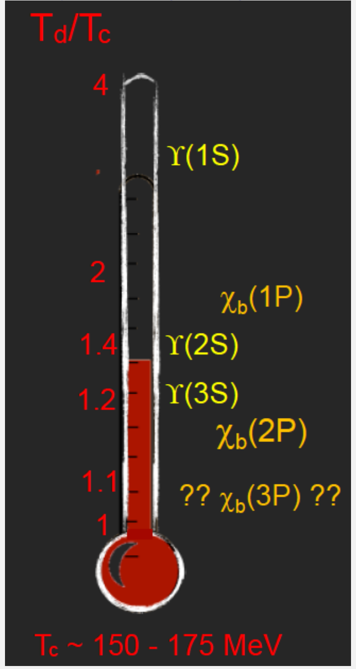
- ☐ **Search for the phase transition by looking at Υ(nS) suppression as a function of rapidity and system size (centrality and several targets)**
  - ➢ In PbA collisions at $\sqrt{s_{NN}}$ ~ 72 GeV, Υ(3S) and Υ(2S) are expected to be suppressed : calibration of the QGP thermometer in AA
  - ➢ Clarify the charmonium suppression pattern between top SPS and RHIC energies (no recombination, high statistics for hard probes)
  - ➢ Probe large gluon x_2 in the target, in particular with Υ(1S) → constrain gluon anti-shadowing and EMC effects in pA

Satz, J. Phys. G32 (2006) R25



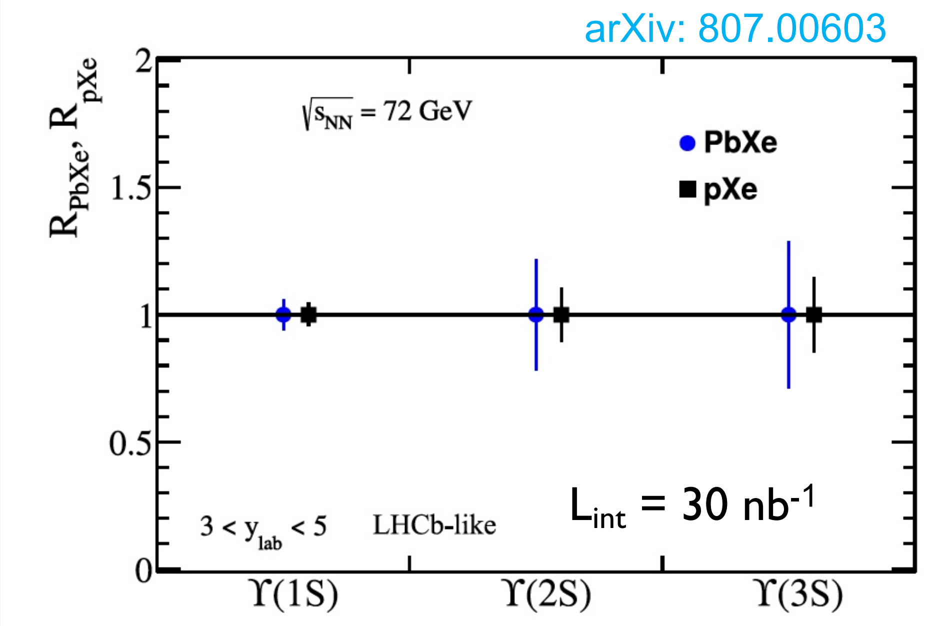
AFTER in PbA
$\sqrt{s_{NN}}$ ~ 72 GeV

Mocsy et al, Int. J. Mod. Phys. A28 (2013) 1340012



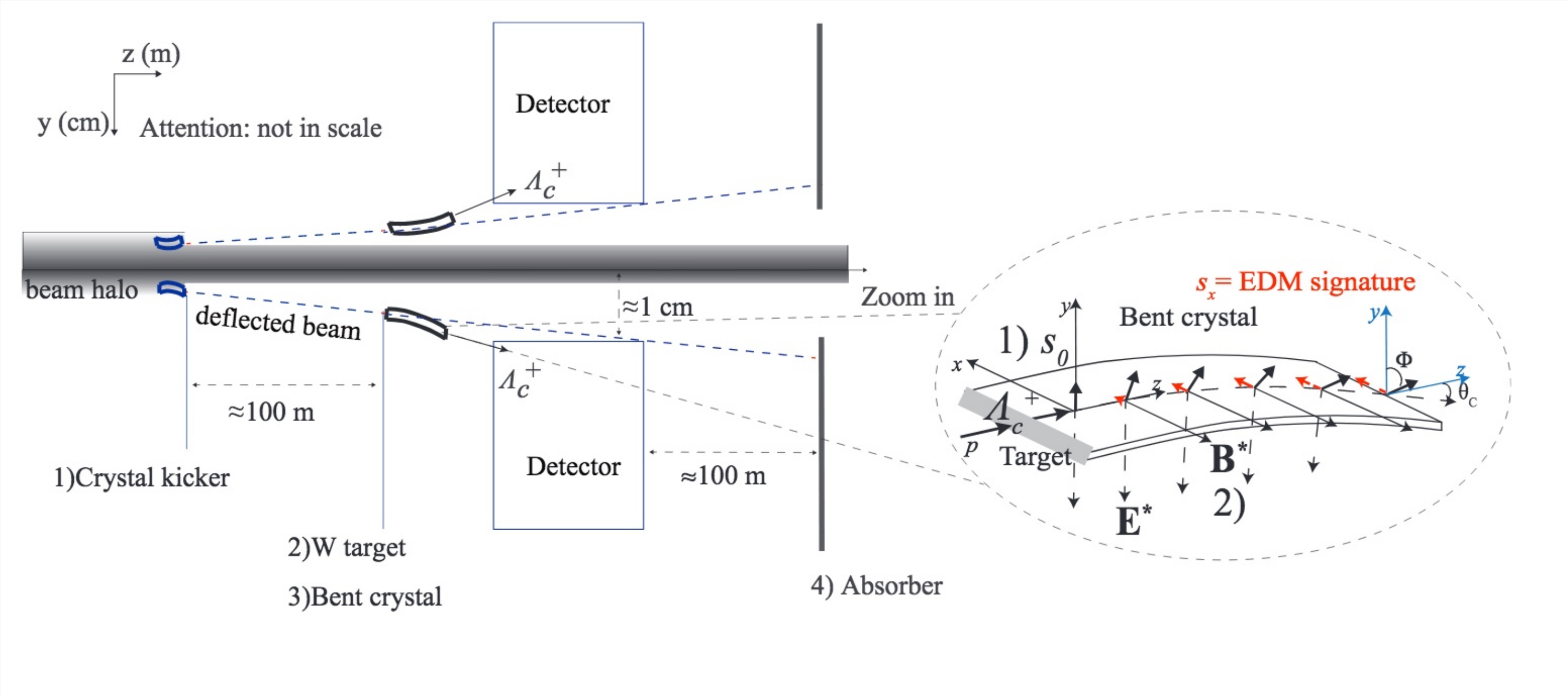
Dissociation temperature from lattice QCD (+hydro)

arXiv: 807.00603



EDM/MDM of heavy and strange baryons

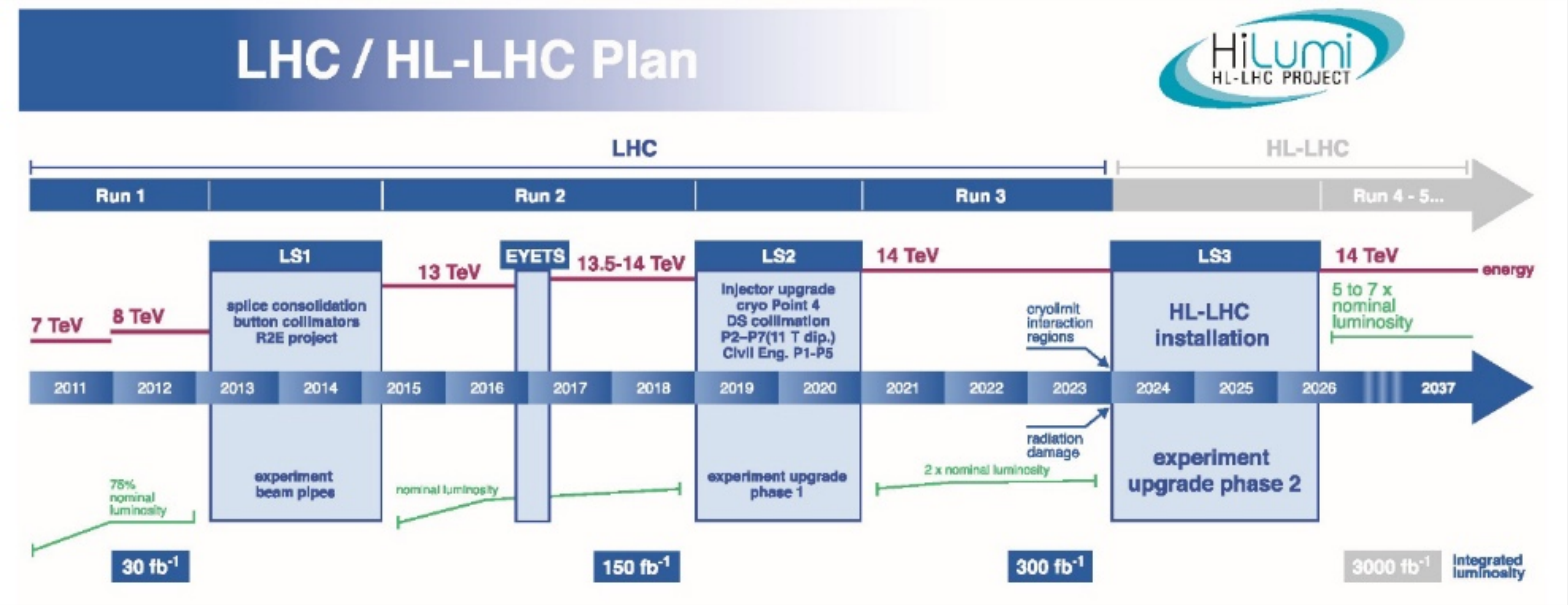
- Measurement of MDM of heavy baryons never performed due to their short lifetime
  - → test of QCD calculations, improve current understanding of internal structure of hadrons
- Measurement of EDM of heavy and strange baryons powerful to probe physics beyond the standard model
- Setup unique to LHCb



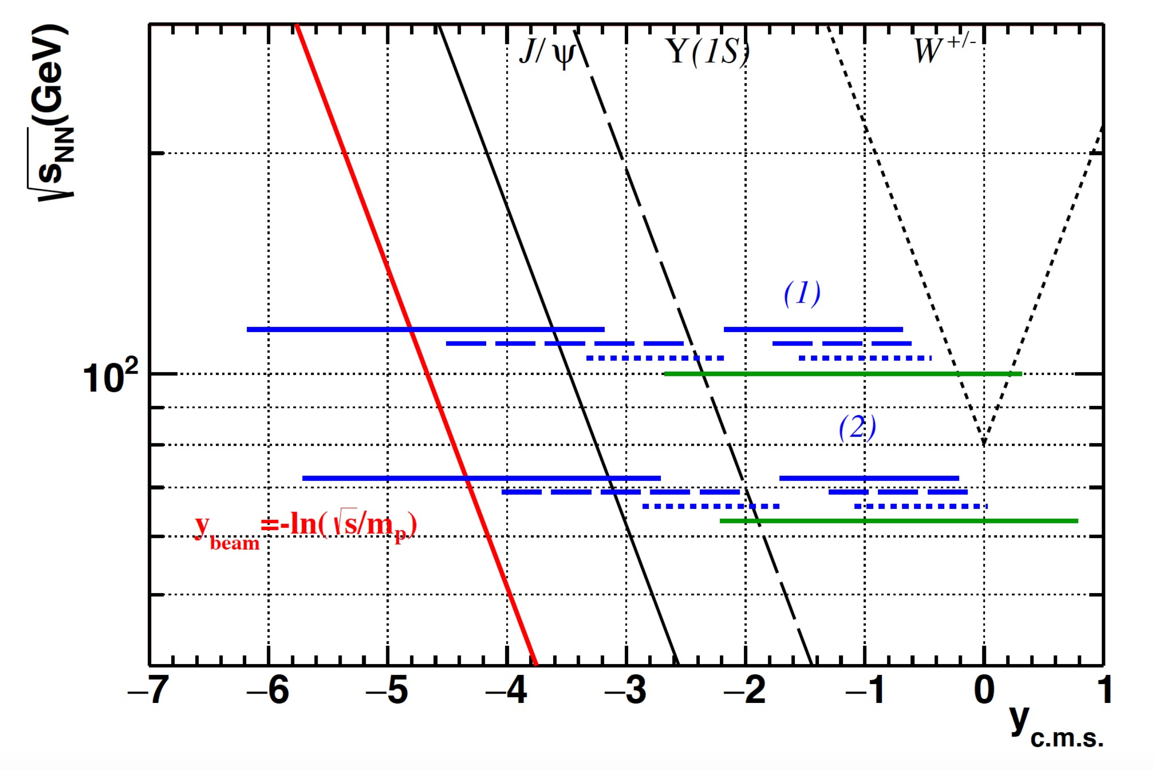
Conclusions

- ❑ HL-LHC already starts with Run3 for Heavy-ions
- ❑ Four main physics goals identified with heavy-ions for Run3&4:
  - Characterize the macroscopic long-wavelength QGP properties (fluid dynamics) with unprecedented precision
  - Access the microscopic parton dynamics underlying QGP properties
  - Developing a unified picture of particle production from small (pp) to larger (pA and AA) systems
  - Probing parton density in nuclei in a broad (x,Q^2) kinematic range and search for parton saturation
- ❑ Altough no current approved plans for ion running beyond LS4, proposal exists (WG5 HL-LHC study group) to extend the heavy ion physics programme
- ❑ **LHCb upgrade phase II represents a great opportunity for LHCb to perform unique measurements in the forward region up to most central AA collisions and down to low p_T (quarkonia, Open HF, low mass dileptons, Drell-Yan…)**
- ❑ **LHCb is currently the only detector working with a fixed target mode and is well placed to conduct a full high-luminosity fixed target programme during HL-LHC and beyond**

BACKUP


LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13.5-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
Injector upgrade
cryo Point 4
DS collimation
P2–P7(11 T dip.)
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
radiation
damage
75%
nominal
luminosity
experiment
beam pipes
nominal luminosity
experiment upgrade
phase 1
2 x nominal luminosity
experiment
upgrade phase 2
30 fb^{-1}
150 fb^{-1}
300 fb^{-1}
3000 fb^{-1}
integrated
luminosity

ALICE versus LHCb rapidity coverage in fixed-target mode



━ LHCb coverage (Z_{target} = 0)

━ ALICE coverage (Z_{target} = 0)

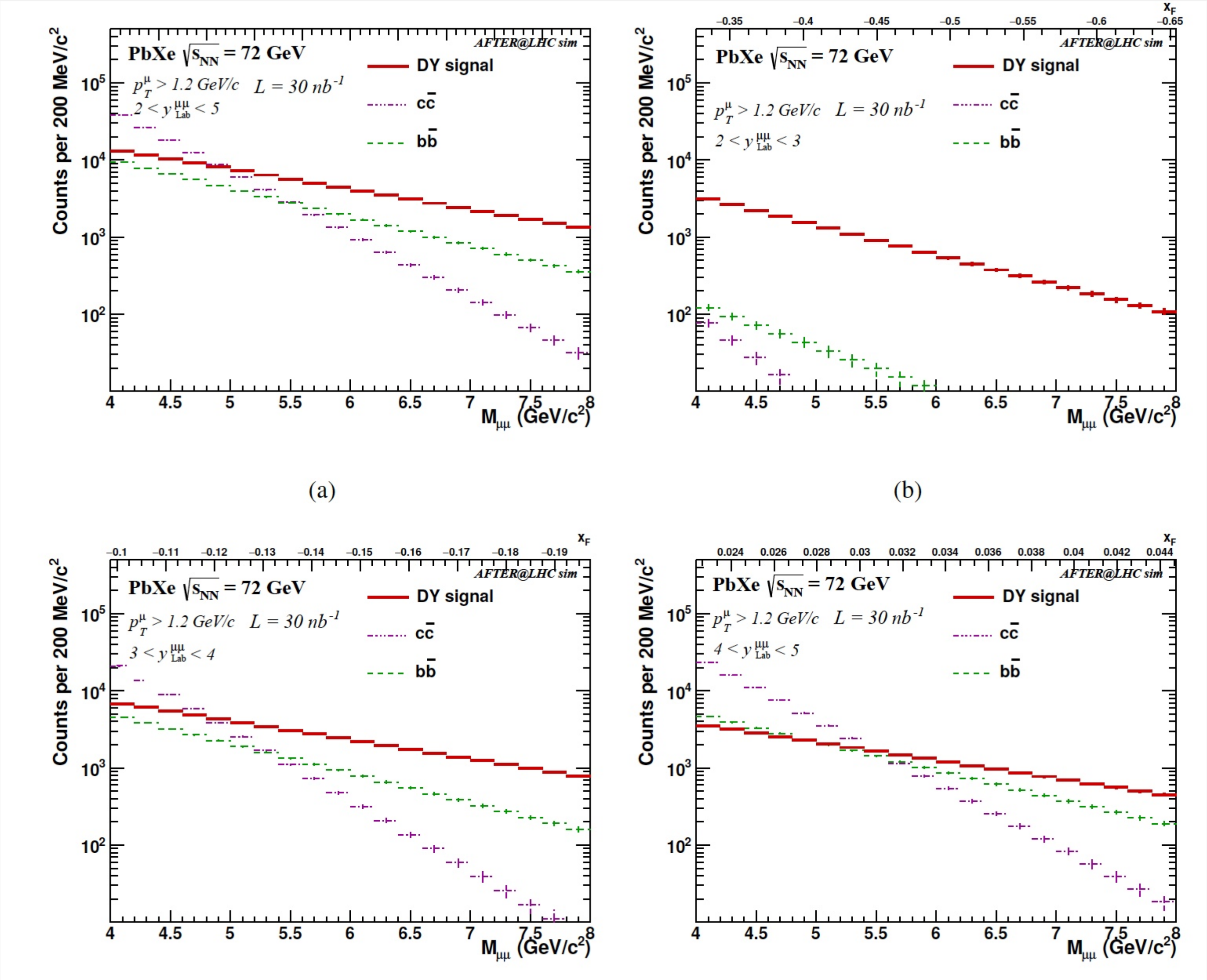
╍ ALICE coverage (Z_{target} = - 2.75m)

┅ ALICE coverage (Z_{target} = - 4.7 m)

(1) pp/pA fixed target collisions

(2) PbA fixed target collisions

Drell-Yan in fixed target AA collisions



(a)

(b)