QGP Physics (collider and fixed-target) with LHCb

1. The LHCb detector for heavy ions
2. Current performances and results: PbPb, *p*Pb/Pb*p*, fixed-target
3. Perspectives for future LHC runs

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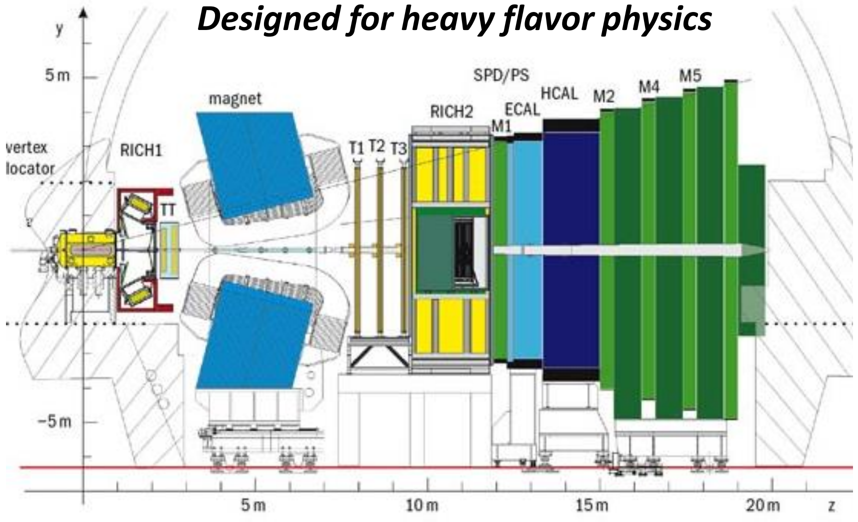
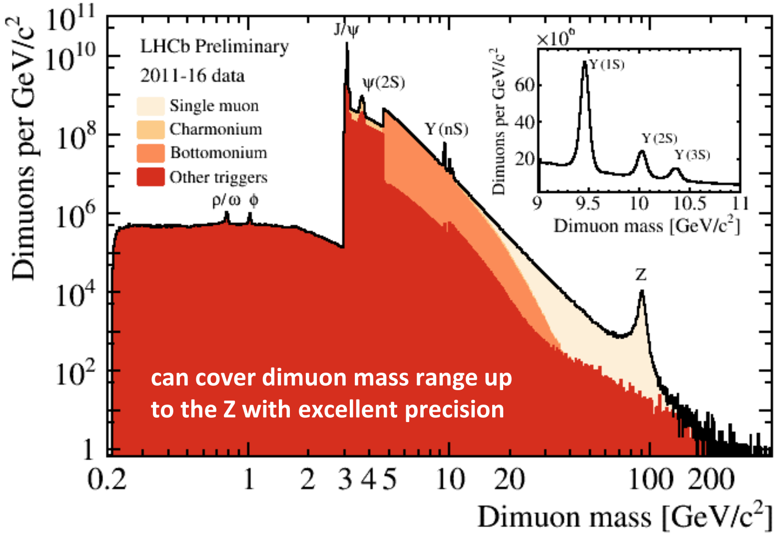
1. The LHCb detector – setup

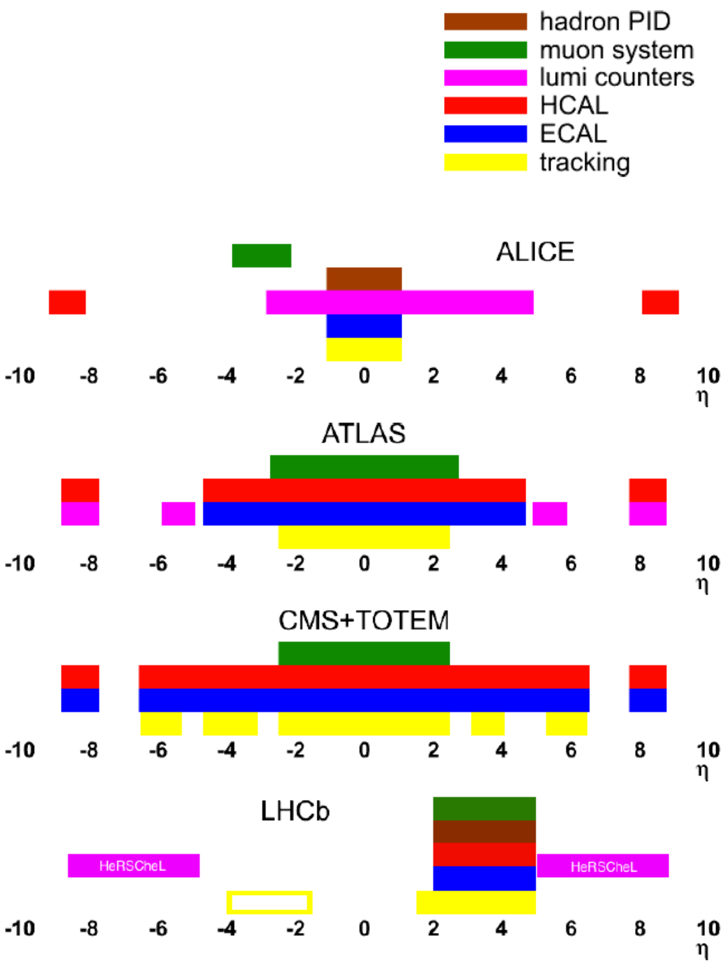
Single arm spectrometer, the only LHC experiment fully instrumented in 2 < η < 5

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Designed for heavy flavor physics



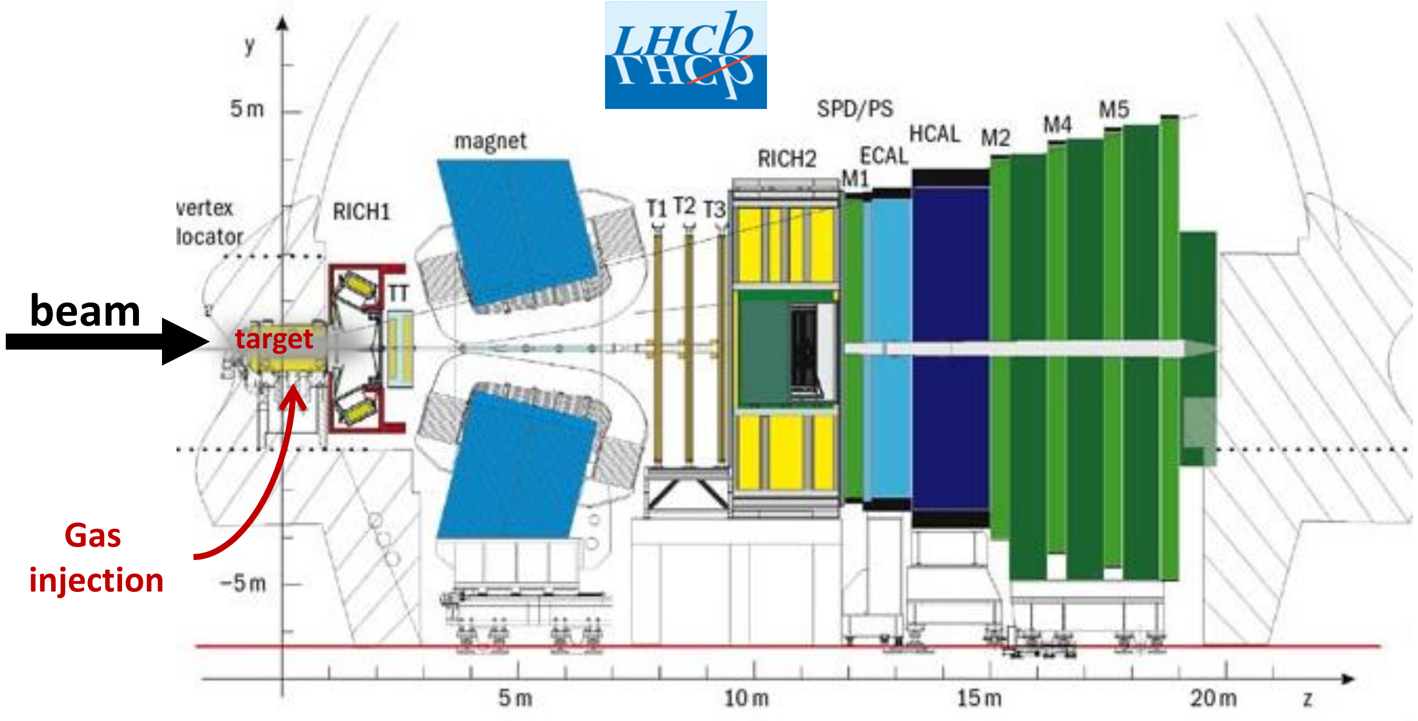


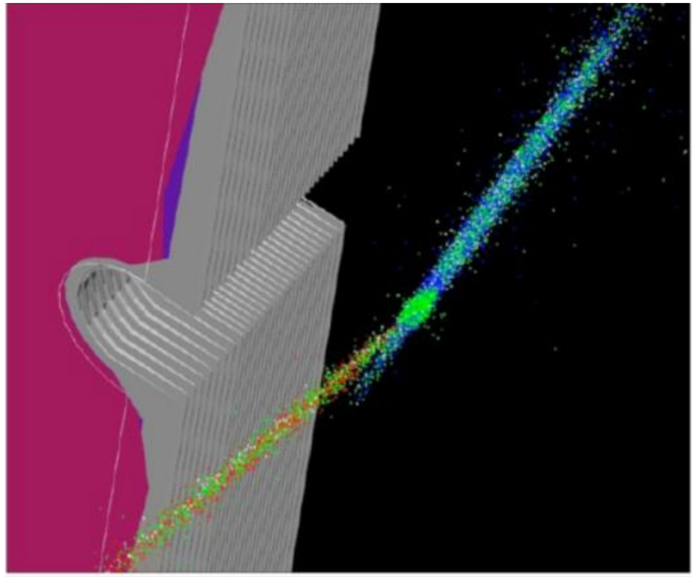


- **LHCb is specialised in heavy flavour precision physics, beauty and charm:**
  - Optimised for low pile-up collisions (*ie* low multiplicity):
    - Precise reconstruction of production and decay vertices
    - Correlations between particles: flavour tagging

- **Some characteristics of the experiment make it attractive for Heavy ion physics :**
  - Instruments fully the forward region: 2<η<5
  - Precise vertexing: separation of prompt production from *B* decay products
  - Precise tracking: reconstruction down to p_T=0
  - Particle identification: full reconstruction of hadronic decays of charm or beauty, such as $D^0 \rightarrow K\pi$

- **Can also operate in fixed-target mode: unique at LHC**
  - Injecting gas in the LHCb VErtex LOcator (VELO) tank, primarily done to perform luminosity measurement.
  - Can be used as an **internal gas target**
  - Allows measurement of *p*-gas and ion-gas interactions



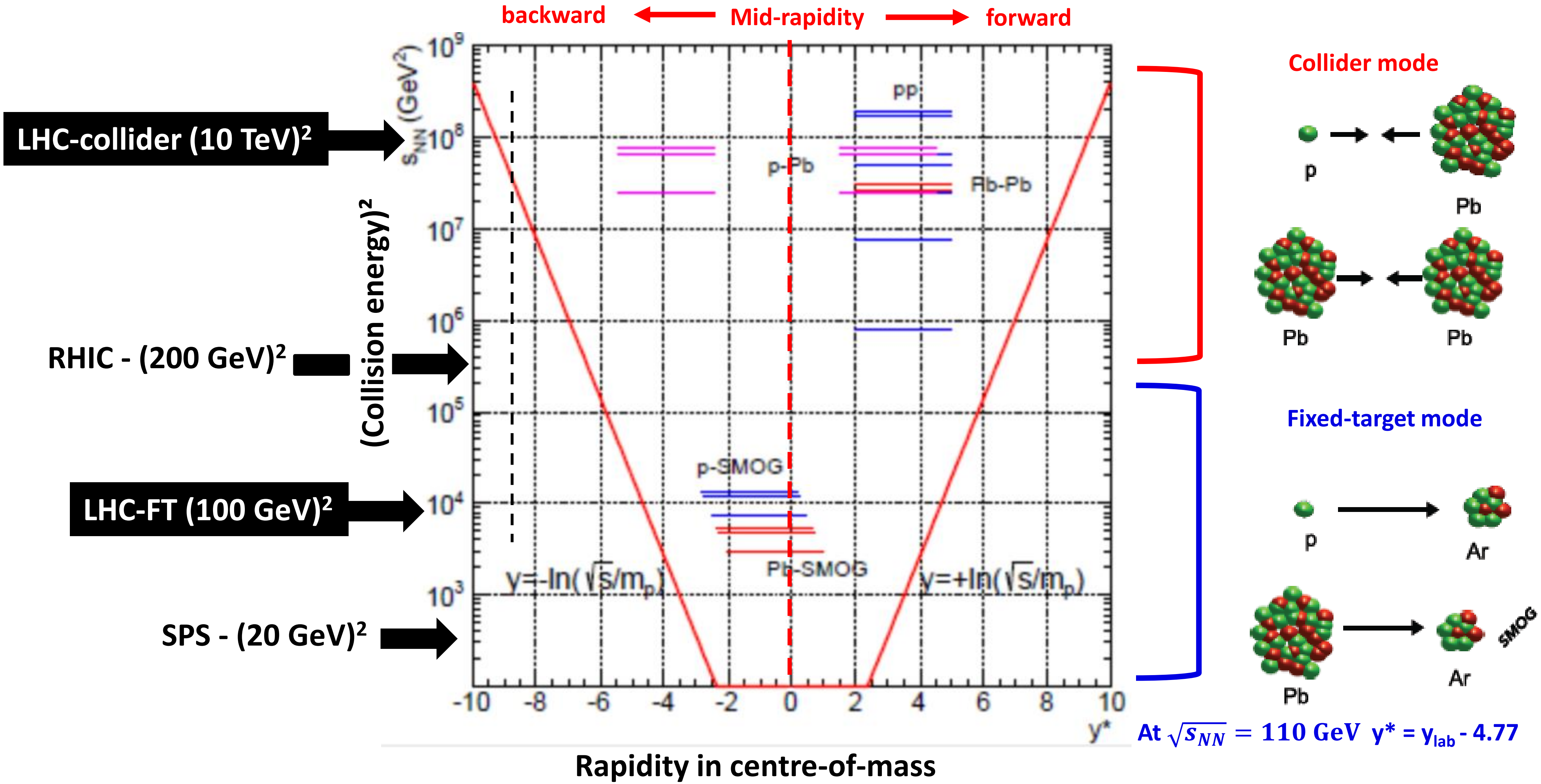


Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

Noble gas only :
(very low chemical reactivity)

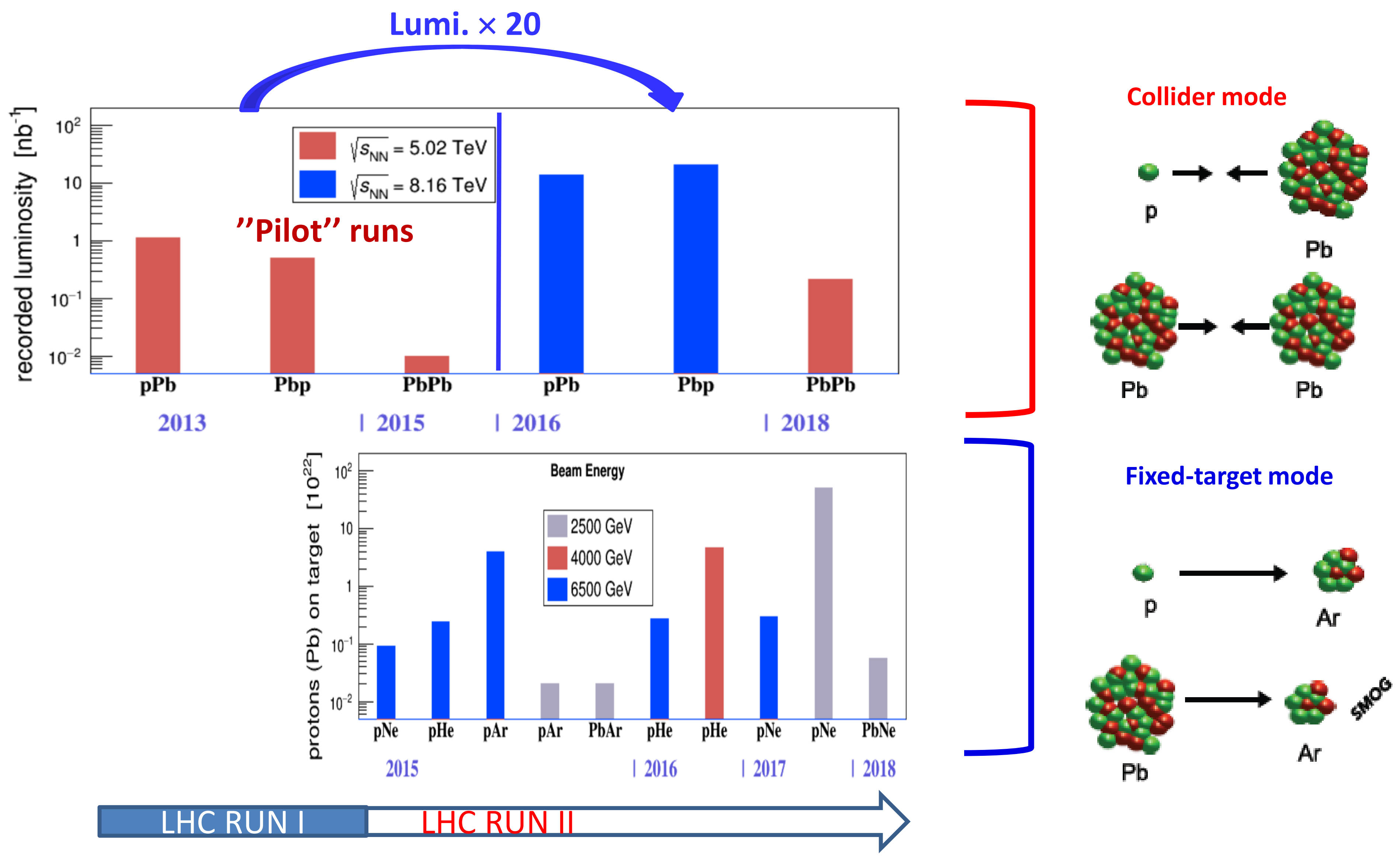
He, Ne, Ar, Kr, Xe
A = 4, 20, 40, 84, 131

Gas pressure:
10^{-7} to 10^{-6} mbar

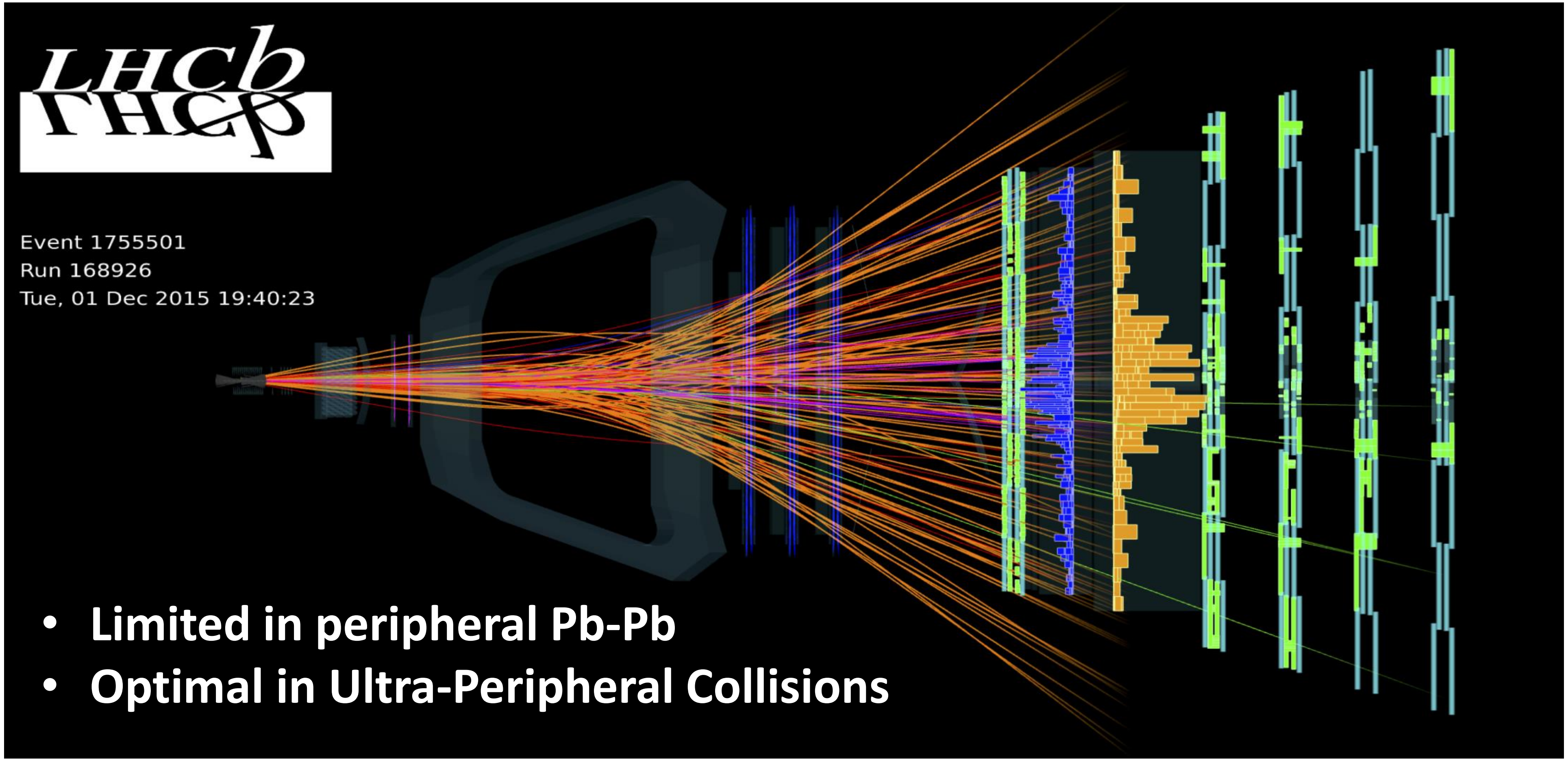


At $\sqrt{s_{NN}} = 110$ GeV $y^* = y_{lab} - 4.77$

1. The LHCb detector – data taking for Heavy Ion physics



2. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV

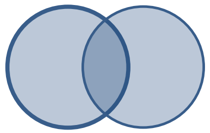


Two data sets:

- $\sqrt{s_{NN}}$ = 5 TeV Pb-Pb interactions recorded in 2015: ~ 10 μb^{-1}
- $\sqrt{s_{NN}}$ = 5 TeV Pb-Pb interactions recorded in 2018: ~ 210 μb^{-1}

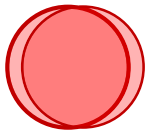
2. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV – 2015 data

Low Ecal Energy



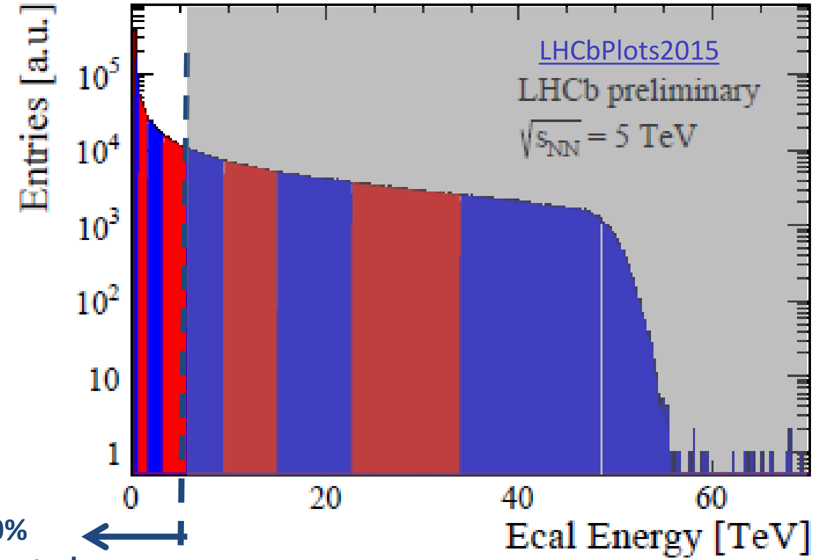
peripheral

High Ecal Energy

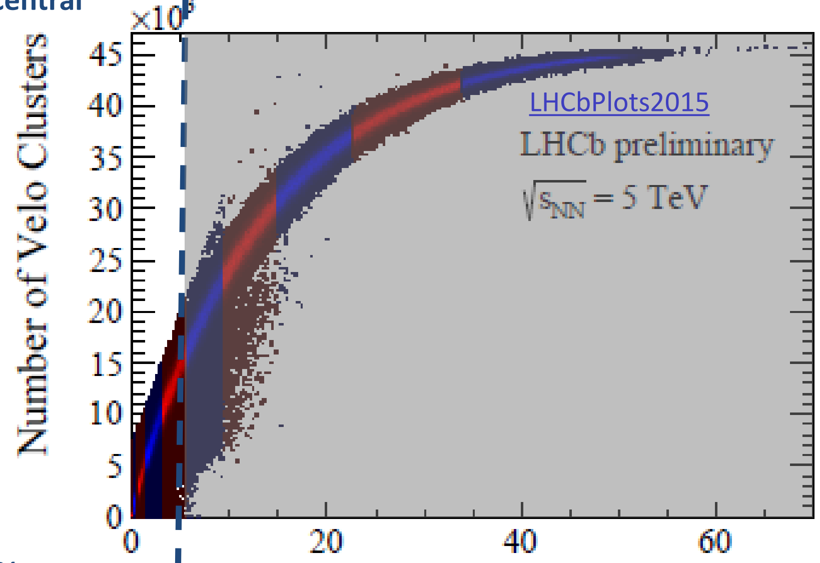


central

- **LHCb centrality reach**
  - Detector limitation due to high occupancy in Pb-Pb collisions
  - No saturation of the calorimeter
  - But, saturation in the Vertex Locator (VELO)
- **LHCb current limitations**
  - Current tracking algorithm efficient up to 50% most central
  - **Physics studies limited to 50% less central events**



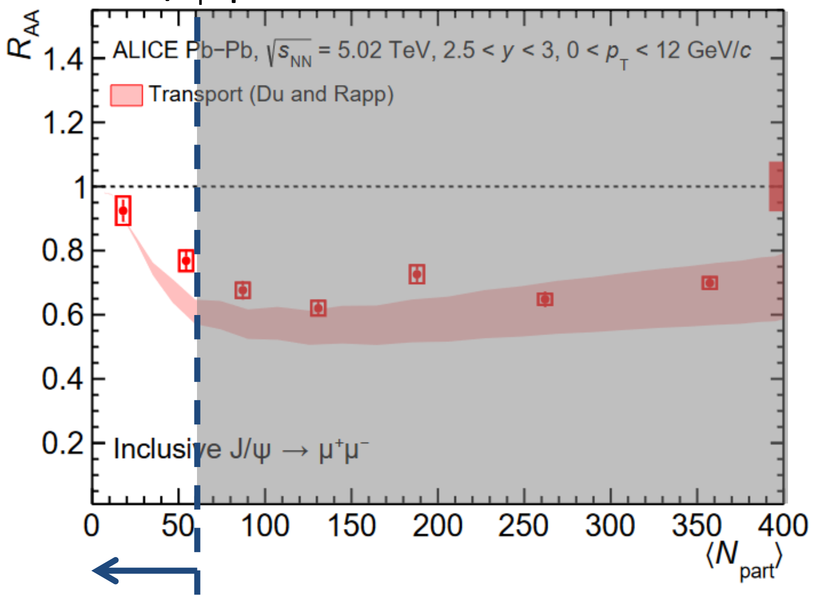
50%
less central



50%
less central

50% most central

J/ψ production – PbPb – ALICE

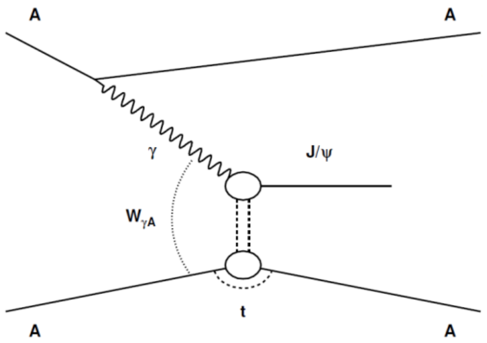


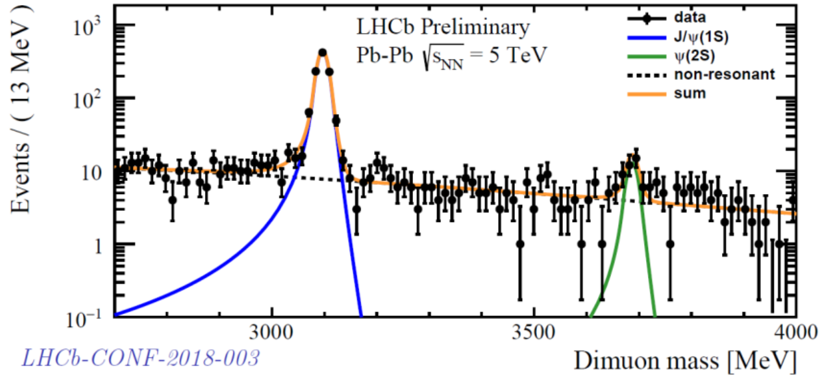
50%
less central

50% most central

2. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV – 2015 data

- $J/\psi \to \mu^+\mu^-$ in Ultra-Peripheral Collisions (UPC)



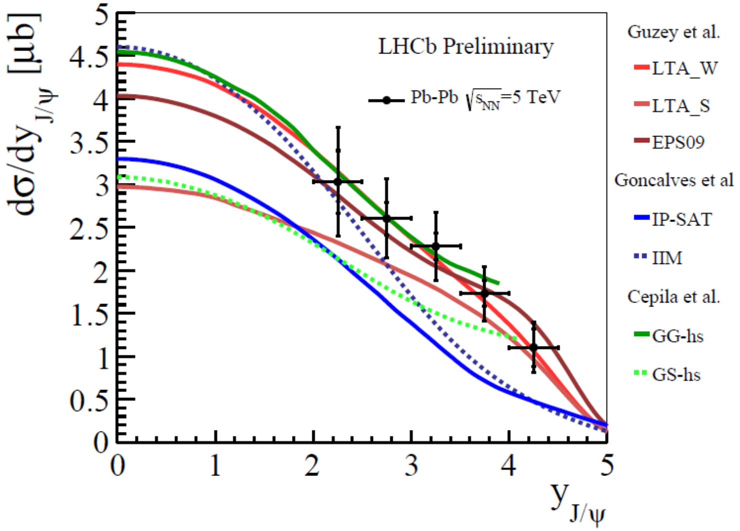


One ion interacts with the electromagnetic field of the other : coherent J/ψ photo-production
Sensitive to nPDF, saturation, …

Nothing in the detector but two tracks

$$\sigma^{\text{coherent}}_{J/\psi} = 5.27 \pm 0.21 \pm 0.49 \pm 0.68\ \text{mb}$$

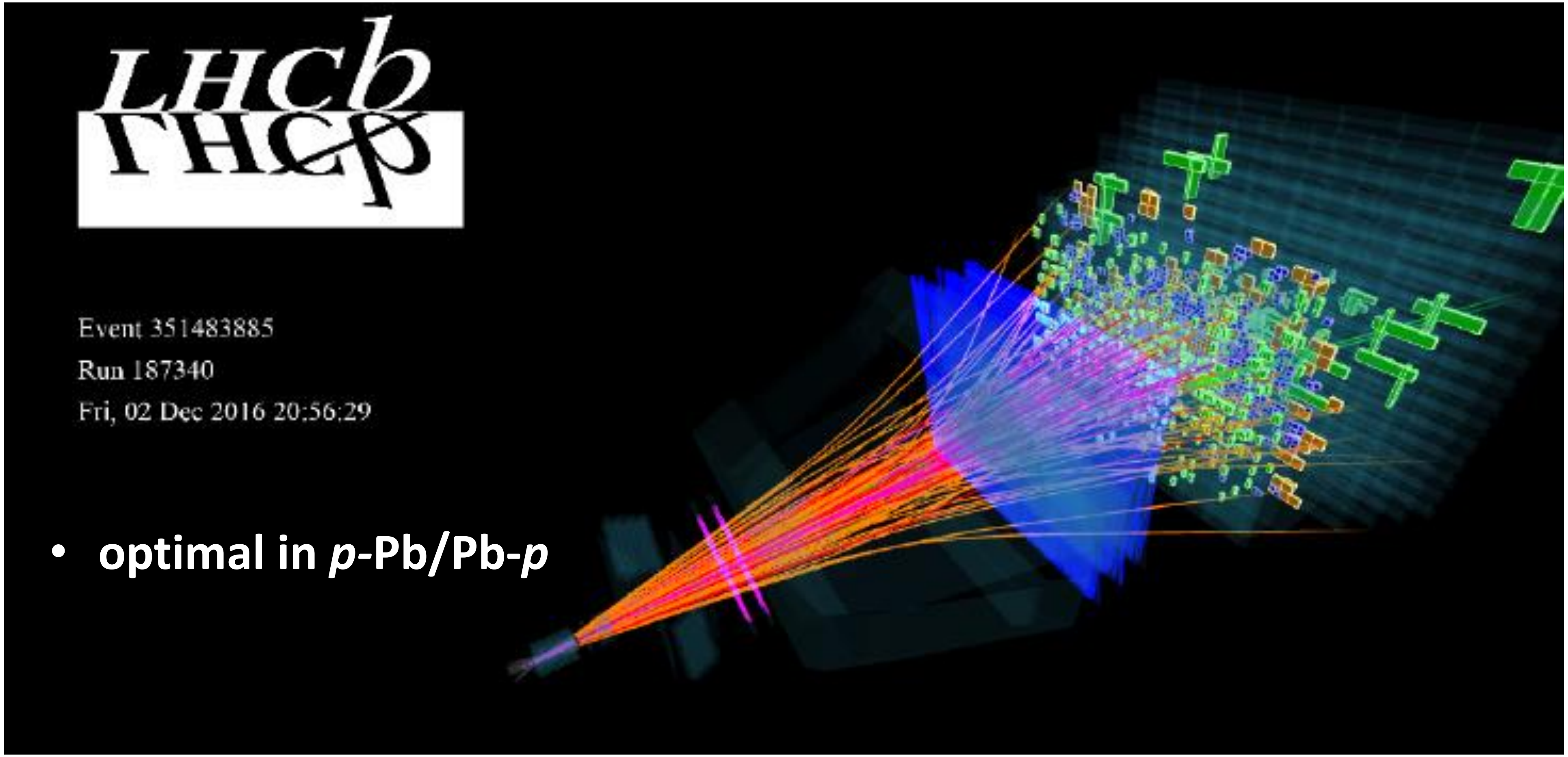
(stat.) (syst.) (lumi.)



LHCb-CONF-2018-003, paper in preparation

Analysis of J/ψ and ψ(2S) production in PbPb 2018 UPC data ongoing (stat. ×20)
Analysis of J/ψ and D^0 production in peripheral PbPb 2018 ongoing (can also do χ_c)

2. Proton-Pb/Pb-proton collisions



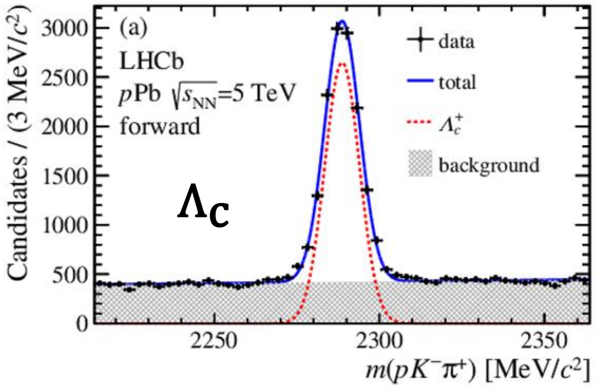
- optimal in *p*-Pb/Pb-*p*

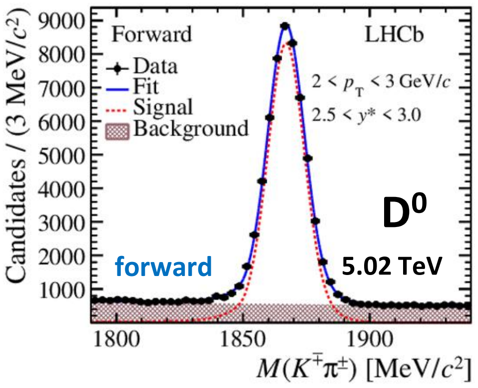
Two data sets :

- $\sqrt{s_{NN}}$ = 5 TeV proton-Pb/Pb-proton interactions recorded in 2013: ~ 1.6 nb^{-1}
- $\sqrt{s_{NN}}$ = 8.16 TeV proton-Pb/Pb-proton interactions recorded in 2016: ~ 30 nb^{-1}

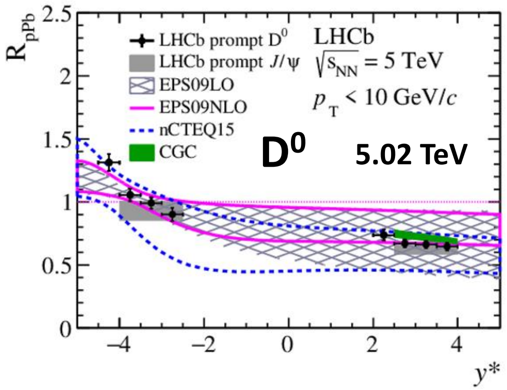
- **Charmonia and Open Charm in pPb@ 5 TeV/8 TeV – 2016/2018 data**

JHEP 02 (2019) 102

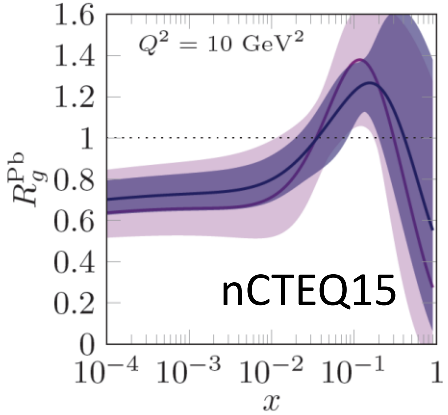




JHEP 10 (2017) 090



arXiv:1906.02512



$$R_{pPb} = \frac{\sigma_{pPb}}{A_{Pb}\sigma_{pp}} = \frac{\sigma_{pPb}}{208\ \sigma_{pp}}$$

Λ_c @$\sqrt{s_{NN}}$ = 8.16 TeV analysis ongoing

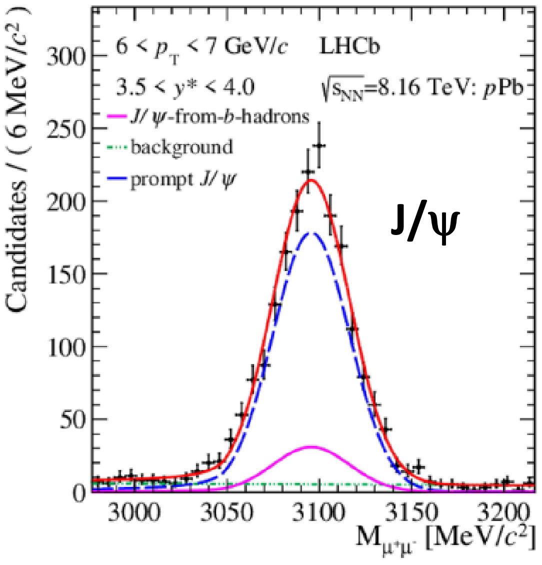
D^0 @$\sqrt{s_{NN}}$ = 8.16 TeV analysis ongoing

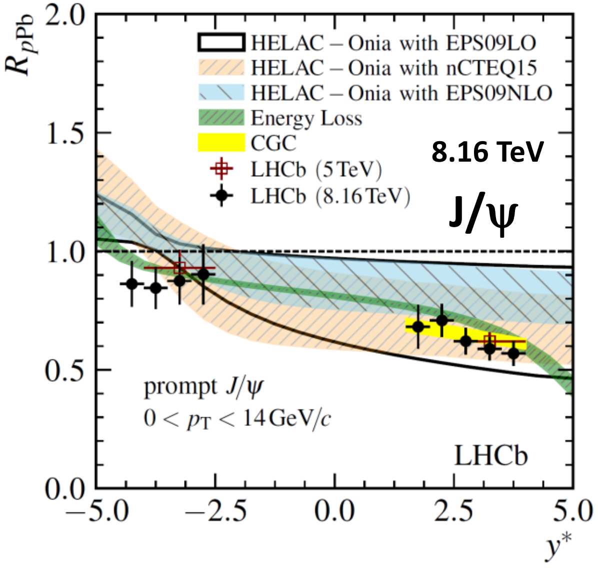
ψ(2S) @$\sqrt{s_{NN}}$ = 8.16 TeV analysis ongoing

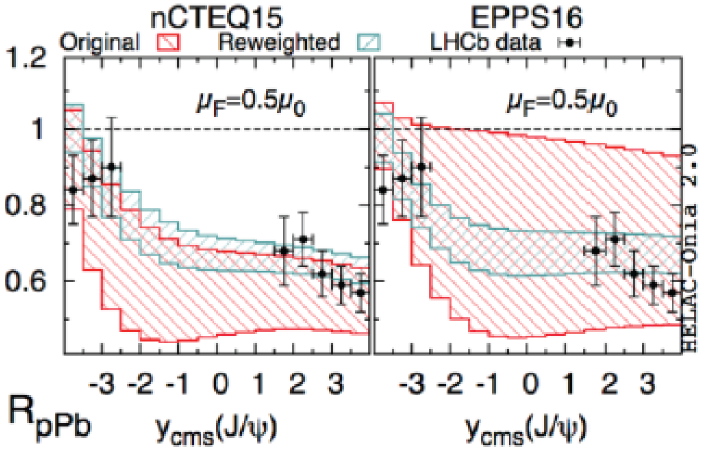
χ_c @ $\sqrt{s_{NN}}$ = 8.16 TeV analysis ongoing

Add new constraints on nPDF

PLB774 (2017) 159





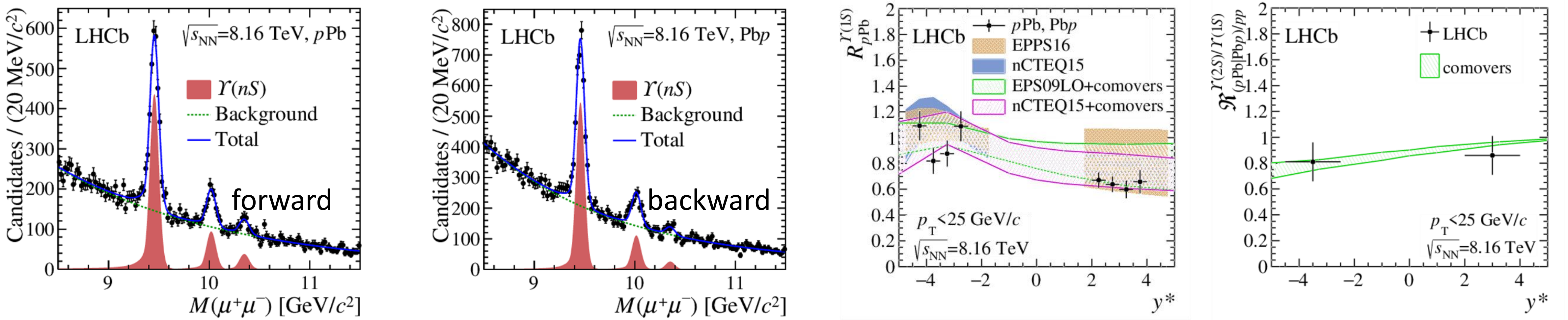


PRL121 (2018) 052004

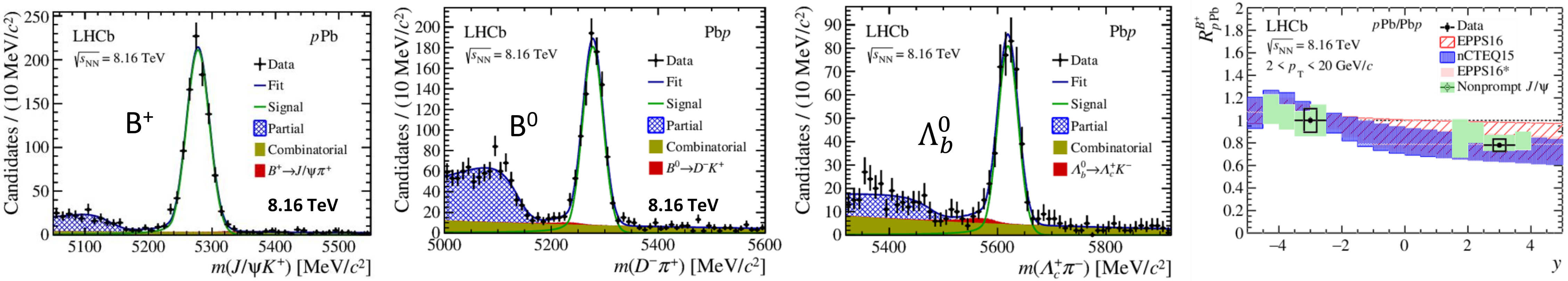
- **Bottomonia and open beauty – pPb@ 8 TeV – 2018 data**

$$R_{pPb} = \frac{\sigma_{pPb}}{A_{Pb}\sigma_{pp}} = \frac{\sigma_{pPb}}{208\ \sigma_{pp}}$$

JHEP11 (2018) 194

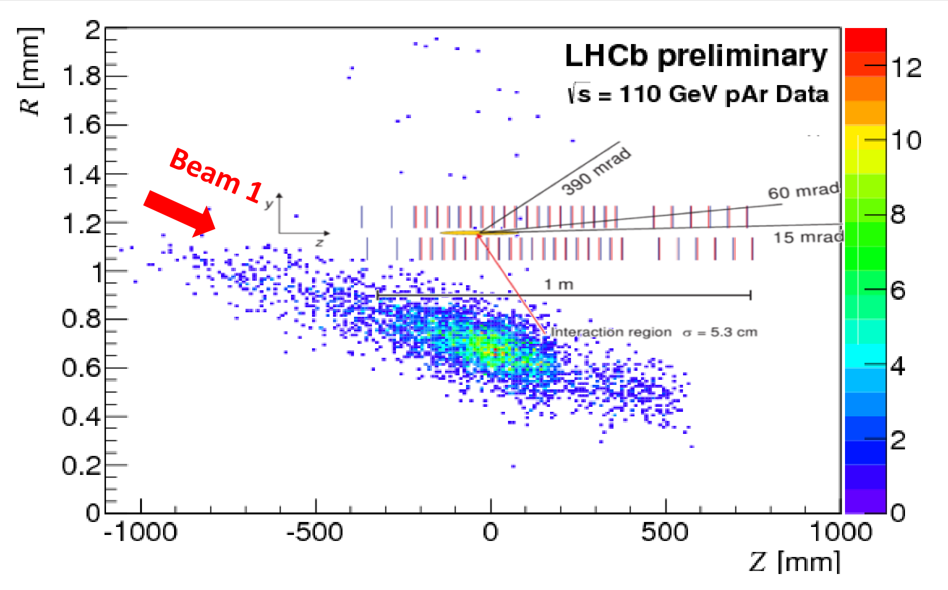


PRD99 (2019) 052011

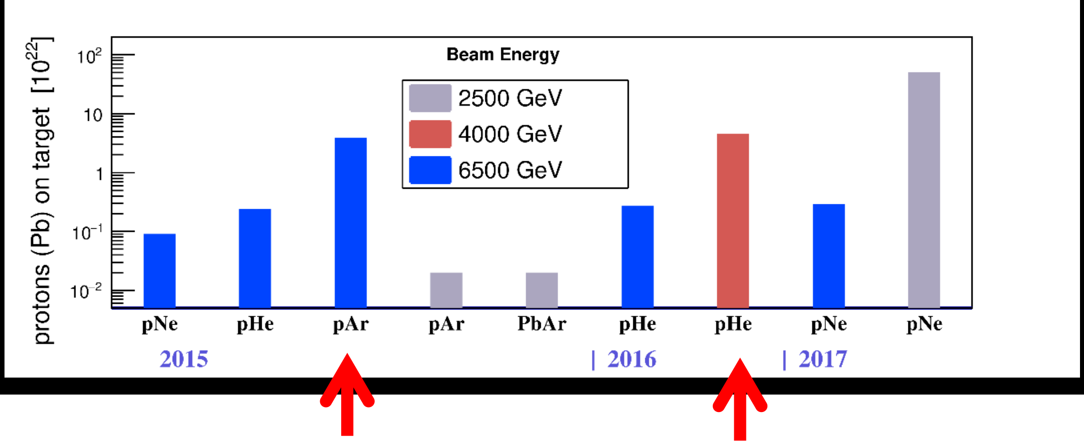


Statistics still limited → HL-LHC

2. Fixed-target collisions



- Unique in fixed-target mode



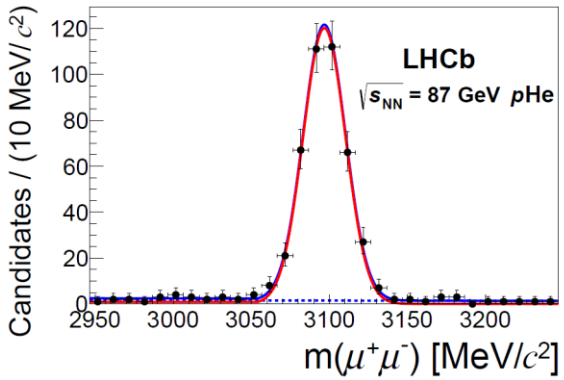
Two data sets presented here:

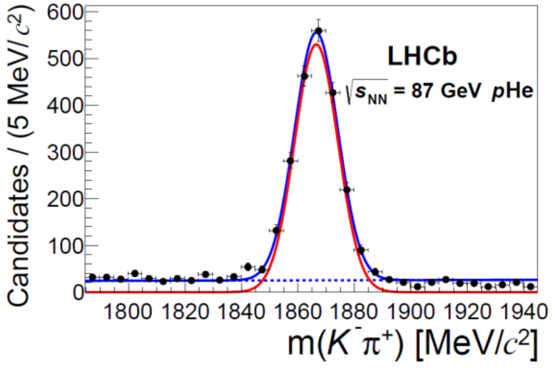
- $\sqrt{s_{NN}}$ = 110 GeV proton-Ar interactions 2015: ~ 4×10^{22} Protons On Target (17h)
- $\sqrt{s_{NN}}$ = 86.6 GeV proton-He interactions 2016: ~ 4×10^{22} POTs (87h) $\mathcal{L}_{pHe} = 7.6 \pm 0.5\ \mathrm{nb}^{-1}$

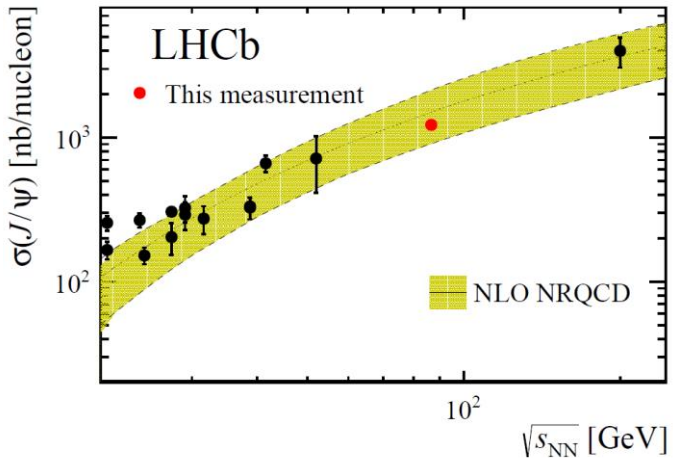
2. Fixed-target collisions

- **J/ψ → $\mu^+\mu^-$ and $D^0 \to K^{\mp}\pi^{\pm}$ in *p*-He @86.6 GeV**

Phys. Rev. Lett. 122 (2019) 132002

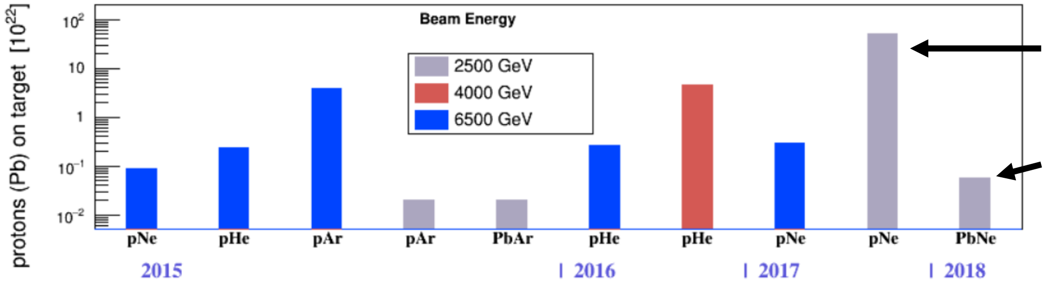


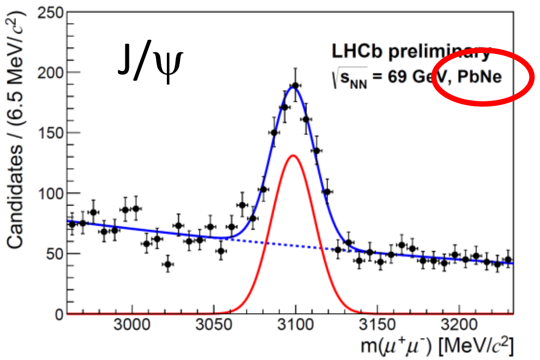


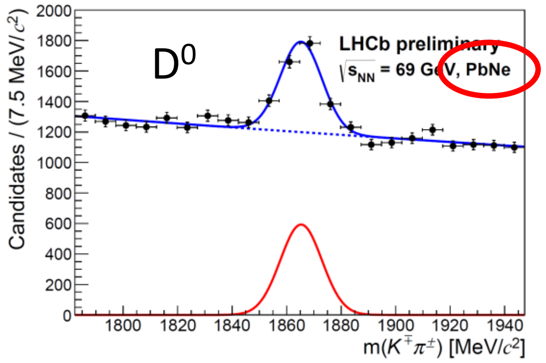


LHCb result in good agreement with other measurements

- **Ongoing analysis**







Analysis of J/ψ and D^0 production in pNe and PbNe ongoing
Analysis of ψ(2S) and χ_c production in pNe ongoing
Analysis of Λ_c production in pNe ongoing

2. Summary of LHCb Run 1 and Run 2 analysis

- **Published results**

Title	Details	Reference
open beauty in p-Pb 8 TeV	PAPER-2018-048	Phys. Rev. D 99, 052011
Status and Prospects for Fixed Target Physics (PBC)	LHCB-PUB-2018-015	
SMOG2 Technical Design Report	LHCB-TDR-020	
Projections for pPb analyses in Run 3 and Run 4	LHCB-CONF-2018-005	
First measurements of charm production fixed-target configuration at the LHC	PAPER-2018-023	PRL 122 (2019) 132002
Study of Upsilon production in pPb collisions at √sNN=8 TeV	PAPER-2018-035	JHEP11(2018)194
Prompt Lc production in pPb collisions at √sNN=5.02 TeV	PAPER-2018-021	JHEP 02 (2019) 102
Measurement of antiproton production in pHe collisions at √sNN=110 GeV	PAPER-2018-031	PRL 121 (2018) 222001
Study of prompt D0 meson production in pPb collisions at √sNN=5 TeV	PAPER-2017-015	JHEP 10 (2017) 090
Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at √sNN=8.16 TeV	PAPER-2017-014	PLB 774 (2017) 159
Study of ψ(2S) production and cold nuclear matter effects in pPb collisions at 5 TeV	PAPER-2015-058	JHEP 03 (2016) 133
Measurements of long-range near-side angular correlations in sNN=5 TeV proton-lead collisions in the forward region	PAPER-2015-040	PLB 762 (2016) 473
Observation of Z production in proton-lead collisions at LHCb	PAPER-2014-022	JHEP 09 (2014) 030
Study of Y production and cold nuclear matter effects in pPb collisions at 5 TeV	PAPER-2014-015	JHEP 07 (2014) 094
Study of J/ψ production and cold nuclear matter effects in pPb collisions at 5 TeV	PAPER-2013-052	JHEP 02 (2014) 72

- **Not yet addressed**
  - No flow analysis
  - No low/intermediate mass dileptons (thermal radiations) analysis
  - Correlations: Double J/ψ, double-D, …
  - Drell-Yan

3. Large statistical increase of LHC run 3 and run 4 – precision era

- **Detailed (proposed) schedule for Heavy ion physics**

Physics of HL-LHC WG5: Future physics opportunities for high-density QCD at the LHC
arXiv1812.06772 - CERN-LPCC-2018-07

LHC | HL – LHC

LS2 → LHCb upgrade 1a
LHC Run 3
LS3 → LHCb upgrade 1b
LHC Run 4
LS4 → LHCb upgrade 2

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	

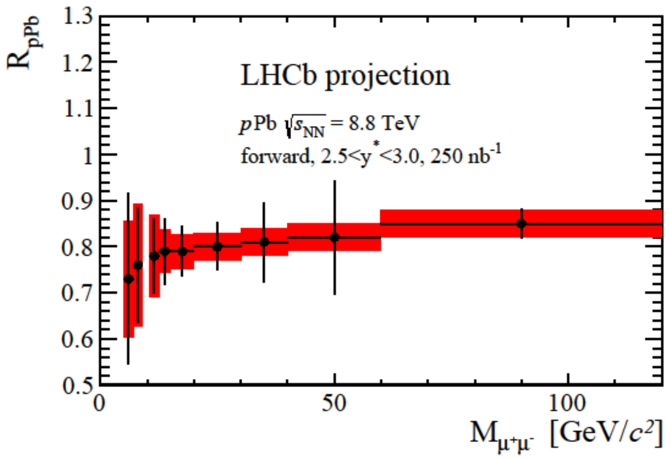
LHCb is very well placed to have a **decisive contribution** to Heavy Ion Physics **in LHC run 3 and HL-LHC**

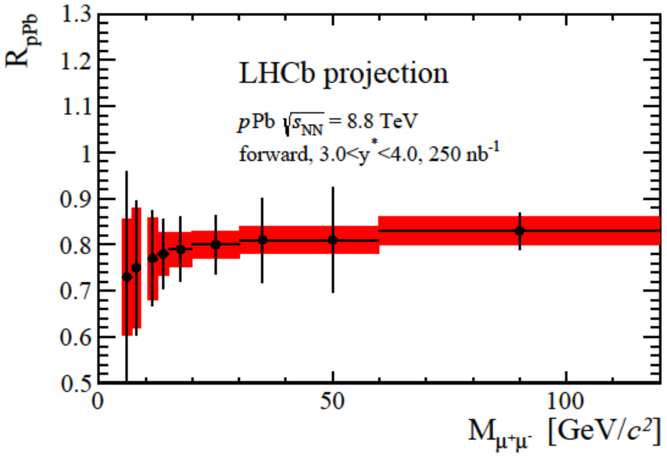
- **Best placed in pp and pPb** at forward rapidity
  - In pPb/Pbp: $\mathcal{L}$ ~ 30 nb^{-1} in run 2 (~1M J/ψ, ~8M D^0) ➔ $\mathcal{L}$ ~ 300 nb^{-1} in run 3 + 300 nb^{-1} in run 4
- **Well placed** (less limited) **in PbPb** at forward rapidity
  - Will benefit from **detector upgrade**
- Start **full physics** program in **fixed-target** mode
  - Will benefit from target and detector upgrade

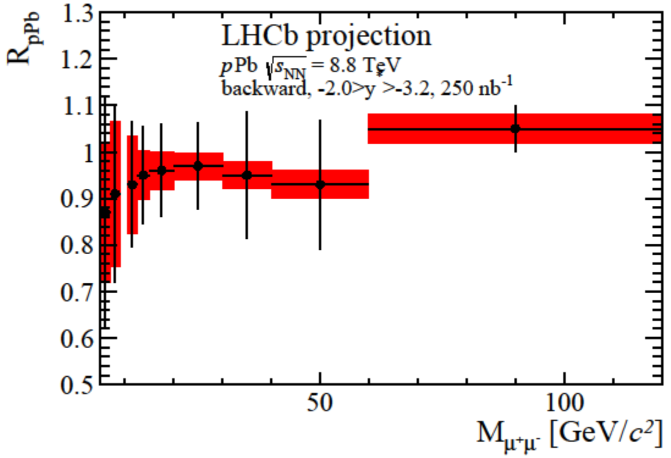
3. proton-Pb/Pb-proton in Run 3 + Run 4

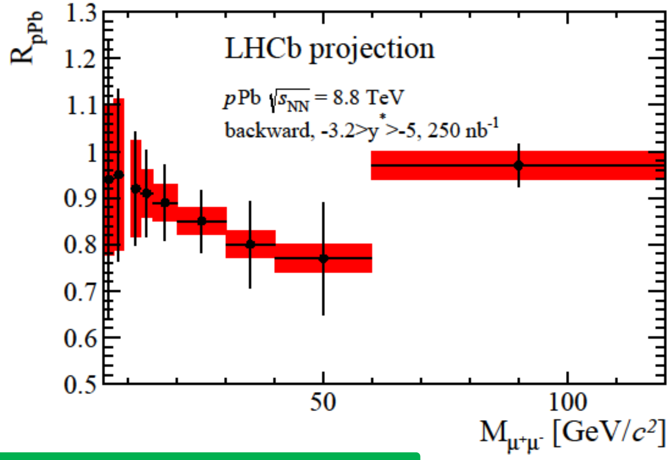
Physics of HL-LHC WG5: Future physics opportunities for high-density QCD at the LHC
arXiv1812.06772 - CERN-LPCC-2018-07

- **Example: Drell-Yan measurement**
  - Expected performances with p-Pb $\mathcal{L}$=0.25 pb^{-1} data samples

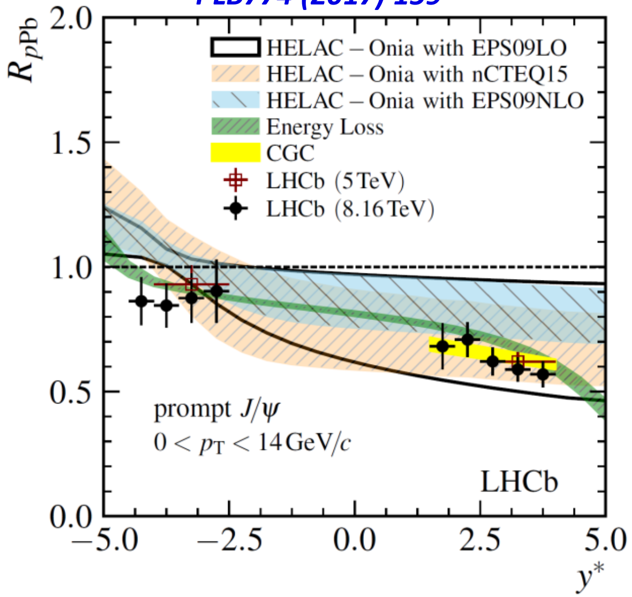


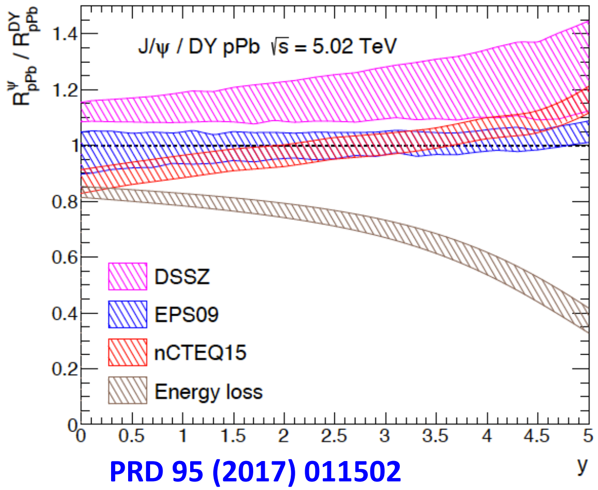






PLB774 (2017) 159





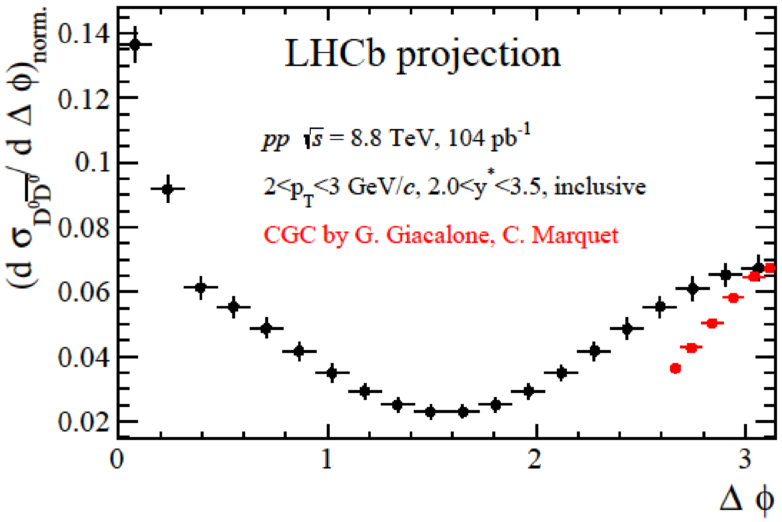
PRD 95 (2017) 011502

Will benefit from HL-LHC increased luminosities

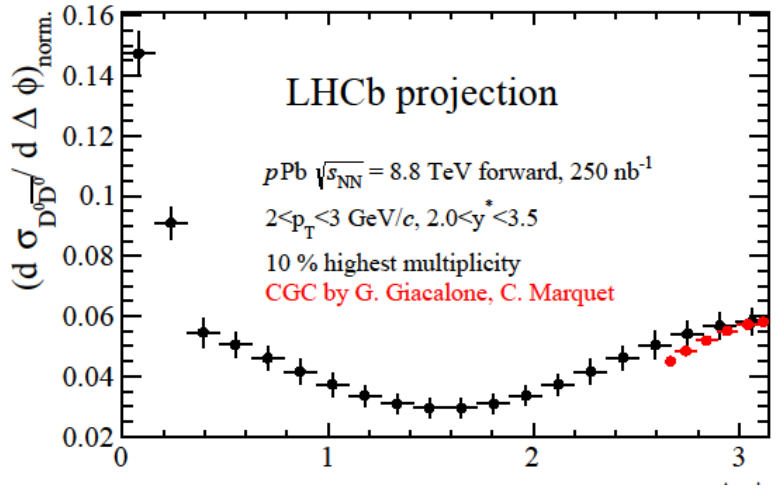
Physics of HL-LHC WG5: Future physics opportunities for high-density QCD at the LHC
arXiv1812.06772 - CERN-LPCC-2018-07

- **Example: Open charm measurement**

$D^0\overline{D^0}$ correlations with 8.8 TeV p-p $\mathcal{L}$=104 pb^{-1}

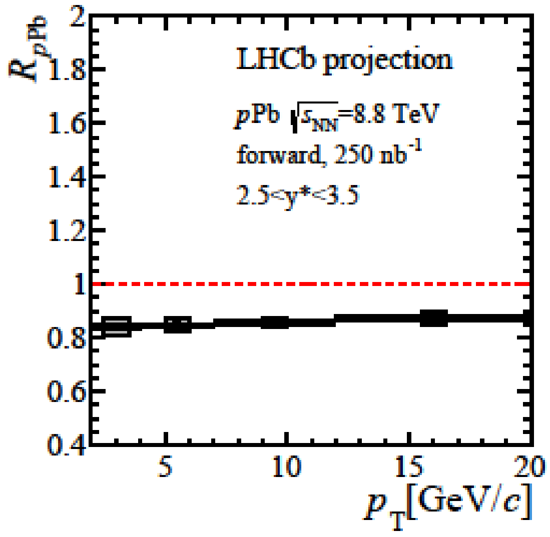


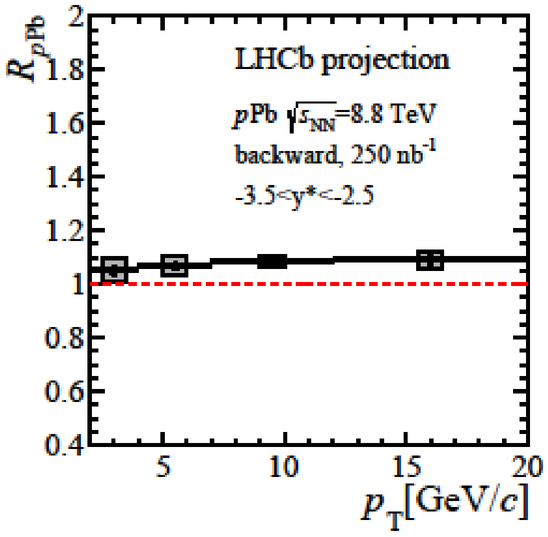
$D^0\overline{D^0}$ correlations with 8.8 TeV *p*-Pb $\mathcal{L}$=0.25 pb^{-1} data samples



- **Example: Open beauty measurement**

B^+ measurement with 8.8 TeV *p*-Pb $\mathcal{L}$=0.25 pb^{-1} and 8.8 TeV Pb-*p* $\mathcal{L}$=0.25 pb^{-1} data samples





3. Detector upgrade – LHCb Upgrade I

9 fb^{-1} (Run 1 – Run 2) | Goal: 50 fb^{-1} (Run 3 – Run 4) | Goal: 300 fb^{-1} (Run 5 – Run 6)

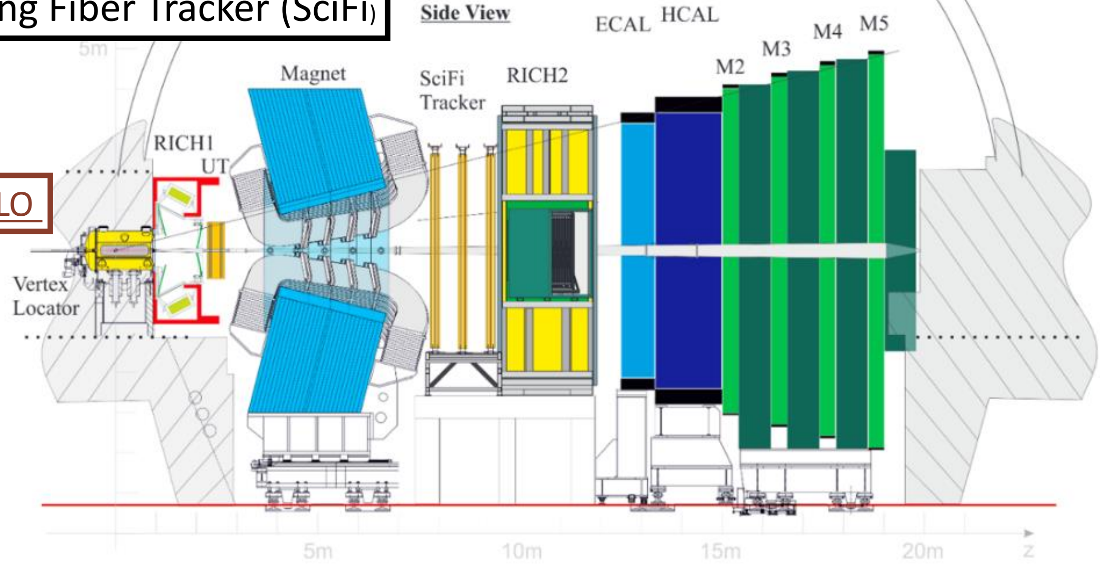
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025	2026 2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037
			Upgrade I		Upgrade Ib		Upgrade II			

- **Upgrade based on pp collision requirements :**
  - Collision rate at 40 MHz.
  - Pile-up factor $\mu \approx 5$
  - Remove L0 triggers (software trigger)
  - Read out the full detector at 40 MHz.
  - Replace the entire tracking system.

New Tracking system :
- Silicon upstream detector (UT)
- Scintillating Fiber Tracker (SciFi)

New electronics for muon and calorimeter systems

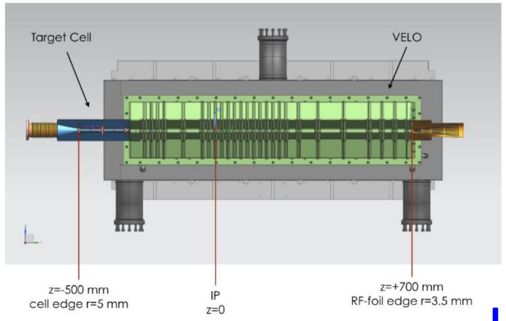
New pixel VELO

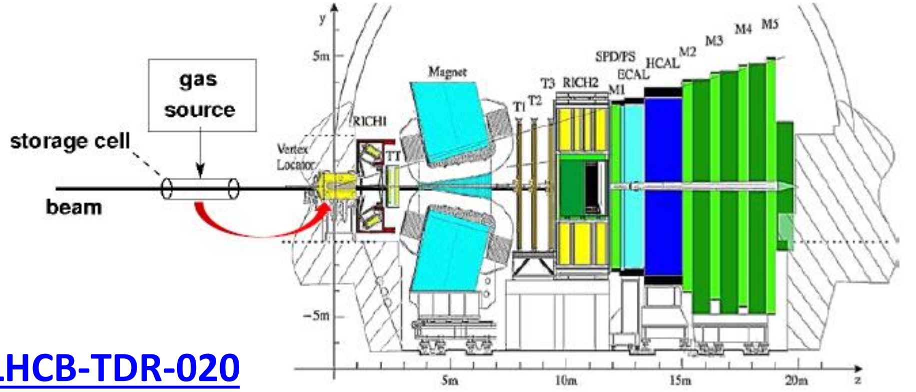


New RICH optics and photodetectors

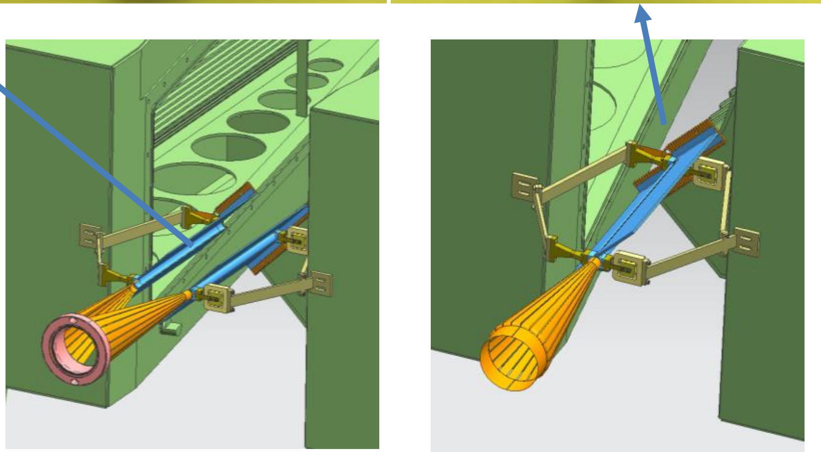
- **Benefit for heavy ion physics**
  - Can reach more central PbPb collisions

- **SMOG2 upgrade**
  - Installation of a **storage cell this winter**
    - Diameter = 1cm, length = 20 cm
    - Uptream of the VELO (-50 à -30 cm w.r.t. IP)
    - Increase of the gas density up to ×100
  - Full physics program starting 2021
    - *Very large statistics*
    - *Various target, including H_2 (pp coll.)*





LHCB-TDR-020



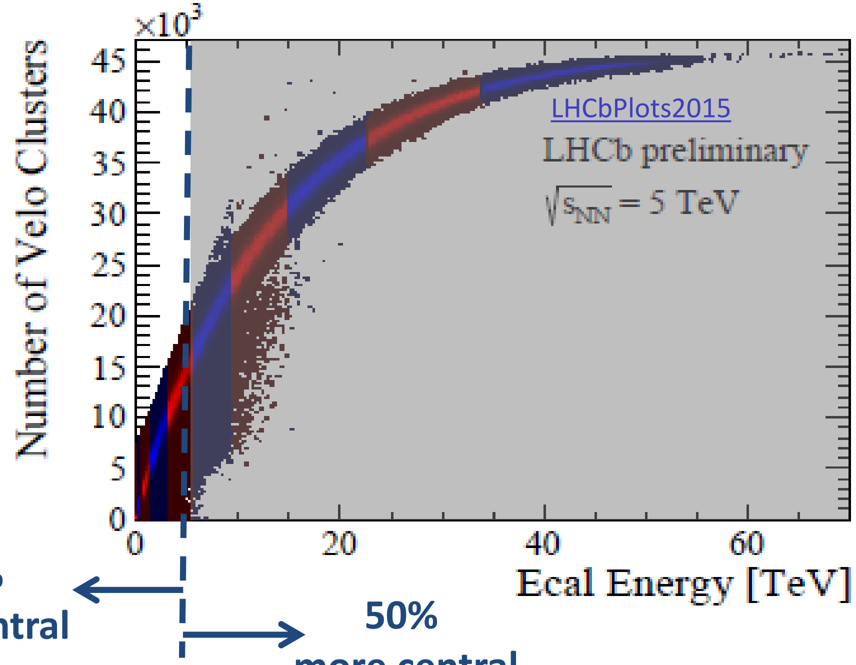
System	$\sqrt{s_{NN}}$ (GeV)
pH_2	115
pD_2	115
pAr	115
pKr	115
pXe	115
pHe	115
pNe	115
pN_2	115
pO_2	115
PbAr	72
PbH_2	72
pAr	72

	Current SMOG result pHe@86 GeV	SMOG largest sample pNe@68 GeV	SMOG2 example pAr@115 GeV
Int. Lumi.	7.6/nb	~ 100/nb	~ 10/pb
syst. error on J/ψ x-sec.	7%	6 - 7%	3 - 4 %
J/ψ yield	400	15k	3.5M
D^0 yield	2000	100k	35M
Λ_c yield	20	1k	350k
ψ' yield	negl.	150	35k
$\Upsilon(1S)$ yield	negl.	10	3k
DY $\mu^+\mu^-$ yield ($5 < M < 9$ GeV)	negl.	10	3k

3. Pb-Pb in Run 3

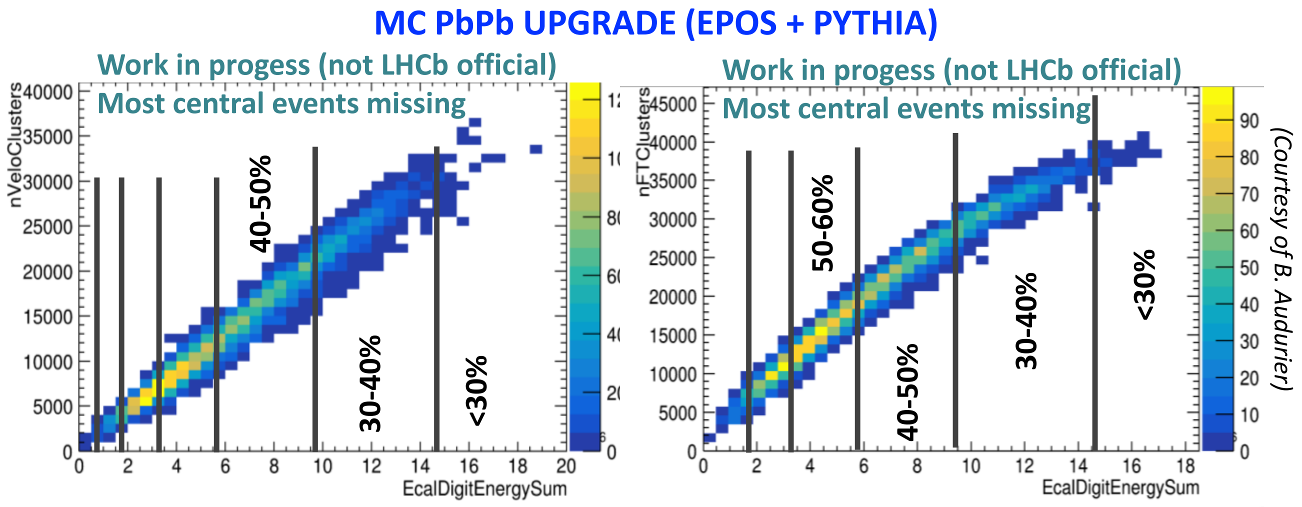
- **Detector performances in Pb-Pb collisions**

Run2 : Vertex Locator saturates



Reconstruction limited to 50% less central

Run 3: **New Vertex Locator does not saturate**
Expect SciFi to saturate in most central collisions

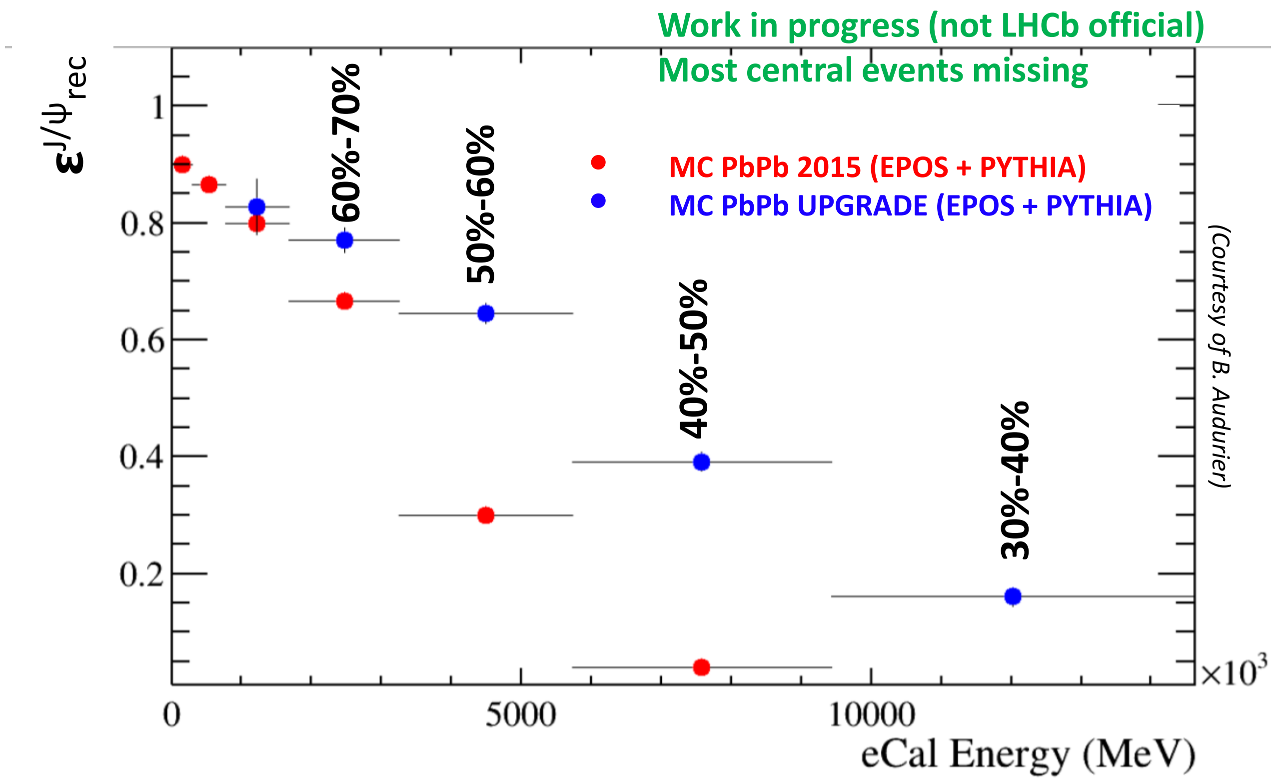


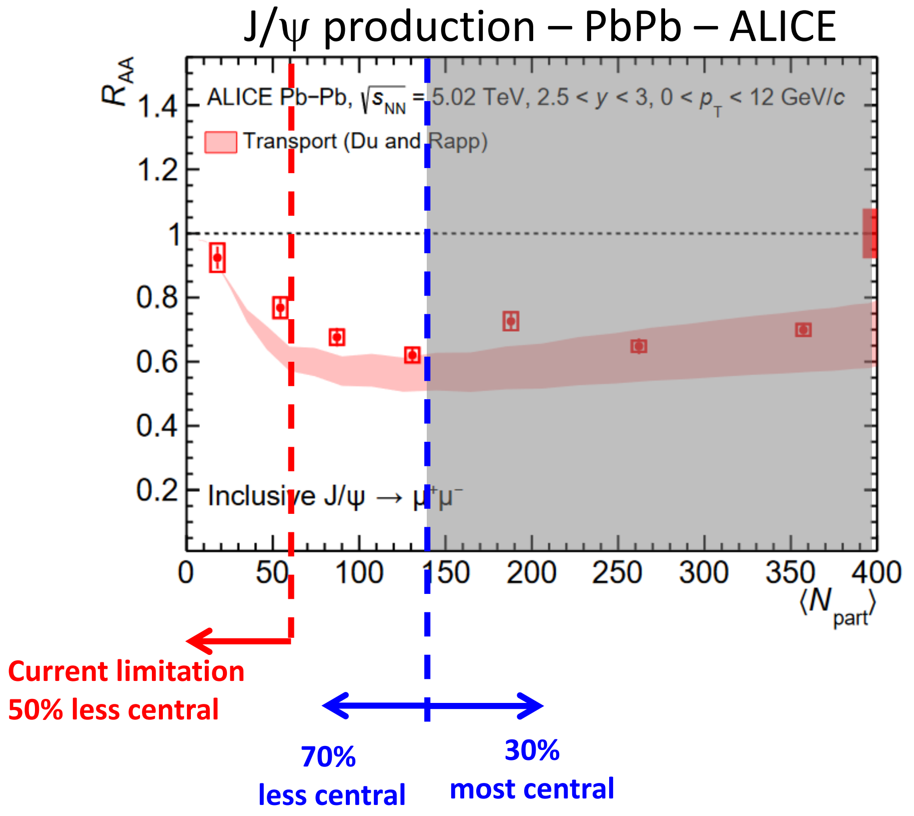
Velo .vs. Ecal SciFi .vs. Ecal

(Most central events missing because of LHCb software issues, currently under investigation, ***work in progress****)*

Expect tracking limitation due to SciFi

- **J/ψ reconstructible up to (at least) 30% centrality**





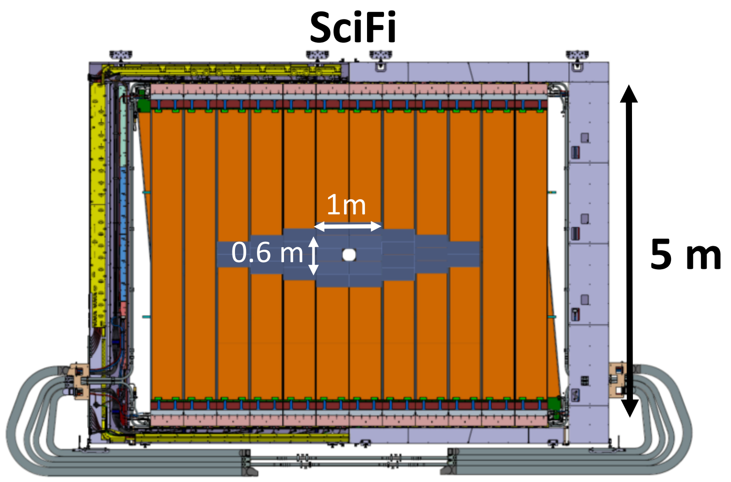
- **LHCb can play a significant role already in Run 3 Pb-Pb collisions**
  - Can precisely study J/ψ, ψ(2S), χ_c, bottomonia, open charm, open beauty

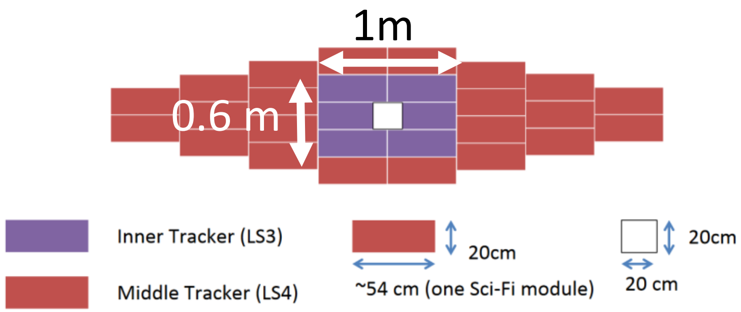
3. High-Luminosity LHC : Run 4 & run 5

- Run 4: increase luminosities up to $\int_{\mathrm{Run3}}^{\mathrm{Run4}} \mathcal{L}$ =10nb^{-1} for PbPb, 0.6 pb^{-1} for pPb/Pbp

- **Run 5: high luminosity runs with intermediate-A nuclei**
  - Typically : ^{16}O-O, ^{40}Ar-Ar, ^{84}Kr-Kr, …
  - **Much higher lumi** than PbPb while still producing a QGP
    - With L~5 pb^{-1} ArAr, will record ~10× (Run3+Run4) pPb stat.
    - Heavy quarks, low mass dileptons, photons, Drell-Yan, …
  - Much lower underlying event multiplicity -> much smaller combinatorics
  - **Bridge between pPb and PbPb,** without requiring centrality selection

- **LHCb Detector upgrades will benefit to heavy ion physics**
  - **LS2 (2019 – 2020)** Upgrade I → Run 3
    - New tracking systems
    - Expect to cover up to 30% most central PbPb collisions (***quantified*** with full MC)
  - **LS3 (2024 – 2025) Upgrade Ib → Run 4**
    - **Mighty tracker stage 1: Inner tracker** – 100 μm × 500 μm pixels or 0.1 mm × 100 mm strips
    - Will **further extend the (PbPb) centrality coverage** → (***to be checked***)
  - **LS4 (2030) Upgrade II → Run 5,…**
    - **Mighty tracker stage 2: Inner tracker + Middle tracker**
  - With appropriate design, **opportunity to cover the full centrality range in Pb-Pb**





Guess-estimate based on ALICE Phys. Rev. Lett. 116, 222302 (2016)

	Centrality	$\langle dN_{ch}/d\eta \rangle$	Ratio wrt 30-40%
	0-5%	1940	3.8
	0-10%	1777	3.5
LHCb Run 4	10-20%	1180	2.3
	20-30%	786	1.5
LHCb Run 3	30-40%	512	1

×2.3

LHCb-INT-2019-007

	Maximum integrated occupancy in %	
	Upgrade Ib	Upgrade II
SciFi only	3.2 ± 0.2	18.4 ± 0.4
With IT	1.4 ± 0.1	6.8 ± 0.3
With IT + MT	-	1.7 ± 0.1

×10.8

The Ion and Fixed Target (IFT) physics group

- **people**
  - The LHCb IFT (Ion and Fixed Target) group is born in 2015 with ~10 people

> LHCb-INT-2015-019 ; CERN-LHCb-INT-2015-019
>
> **Proposal for LHCb Participation to the Heavy Ion Runs**
>
> Blouw, J (MPIK, Heidelberg, Germany) ; Ferro-Luzzi, Massimiliano (CERN) ; Fleuret, F (LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France) ; Manca, Giulia (LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France) ; Massacrier, L (LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France) ; Mueller, K (Physik-Institut der Universitat Zurich,Zurich,Switzerland) ; Robbe, Patrick (CERN) ; Schmelling, Michael (MPIK, Heidelberg, Germany) ; Schmidt, Burkhard (CERN) ; Yang, Zhenwei (Center for High Energy Physics, Tsinghua University, Beijing, China)

  - Since then the group increased from < 10 to nowadays ~25 permanent physicists

- **Institutes**

In 2015:
- CERN,
- Tsinghua (China),
- LAL/LLR (France),
- MPIK-Heidelberg (Germany),
- Zürich (Switzerland)

→

Nowadays:
- CERN,
- Rio de Janeiro (Brazil),
- Tsinghua, SCNU-Guangzhou (China),
- LAL/LLR (France),
- MPIK-Heidelberg (Germany),
- Cagliari, Firenze, Frascati, Milano (Italy),
- IGFAE-Santiago (Spain),
- Zürich (Switzerland),
- LANL-Los Alamos (USA)

  - IFT group still small (with respect to physics potential)
  - **New contributors more than welcome**