High luminosity Fixed Target ExpeRiment at the LHC (AFTER@LHC)

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Outline

- A fixed-target experiment with LHC proton and lead beams: main kinematic features and advantages
- Possible technical implementations
- Achievable luminosities in ALICE and LHCb and ongoing investigations/projects

AFTER@LHC review paper arXiv:1807.00603
To be submitted to Physics Report

A Fixed-Target Programme at the LHC:
Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

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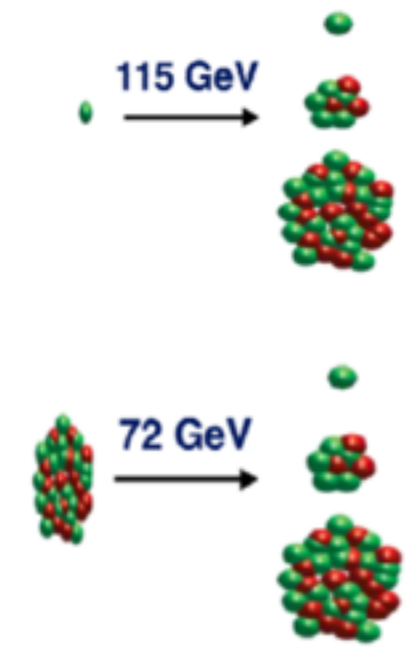
Physics cases and projected performances presented by:
Aleksander Kusina *Probing the high-x content of the nuclei in the fixed-target mode at the LHC*
Jean-Philippe Lansberg *Future heavy-ion facilities: fixed-target at LHC (AFTER)*
Antonio Uras *Heavy-flavour-production studies in a new energy and rapidity domain with the nuclear LHC beams in the fixed-target mode*
Nodoka Yamanaka *Ultra-peripheral collision studies in the fixed-target mode with the proton and lead LHC beams*

A fixed-target experiment at the LHC

Main kinematic features:

Energy range

- 7 TeV proton / 2.76 TeV Pb beam on a fixed target

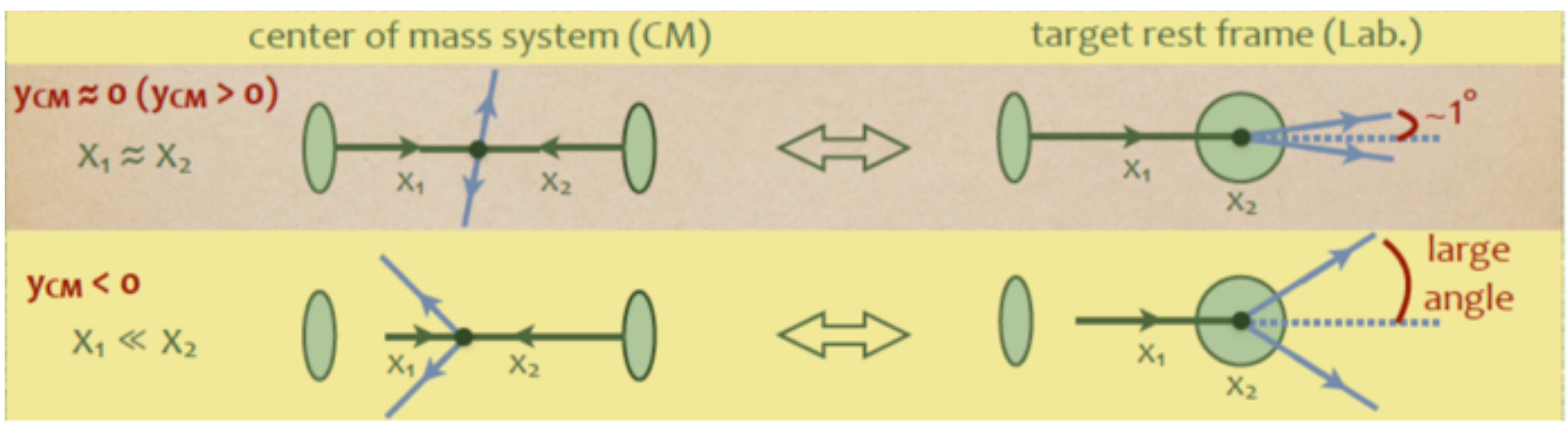


beam type	CM energy $\sqrt{s}_{(NN)}$	boost $\gamma=\sqrt{s}/2m$	rapidity shift
proton (E = 7 TeV)	115 GeV	61	4.8
lead (E = 2.76 TeV)	72 GeV	38	4.2

→ center-of-mass energy in-between SPS at CERN and nominal RHIC

Rapidity range

- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{CM} < 0$) and large parton momentum fraction in the target (x_2)

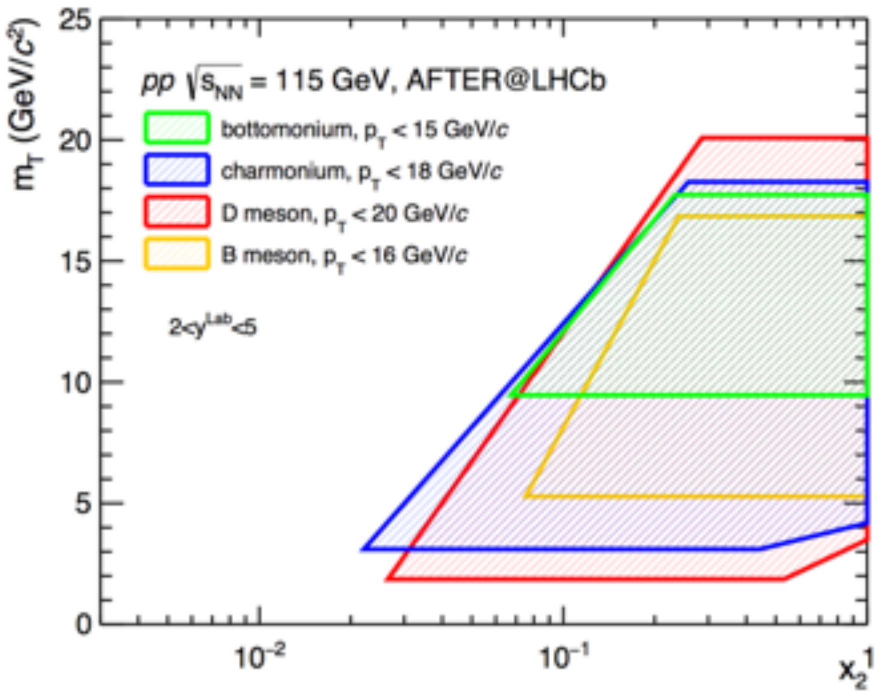


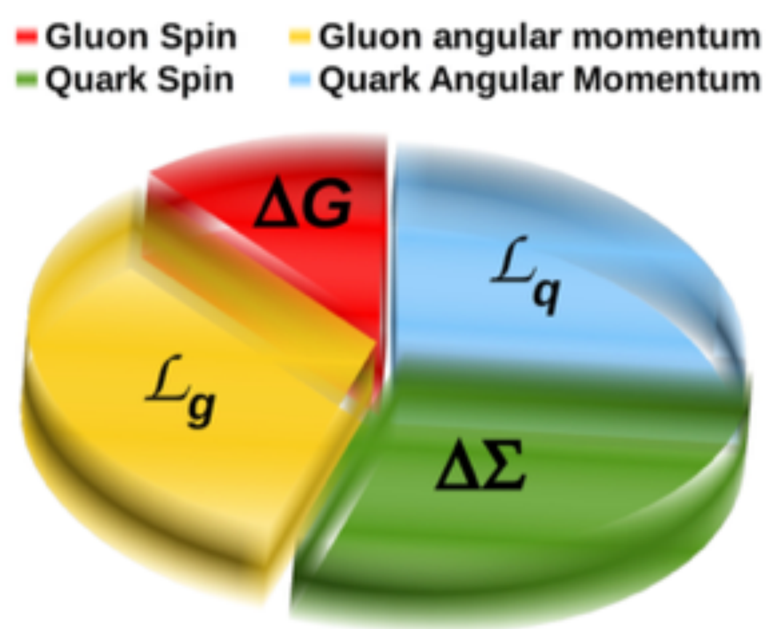
A fixed-target experiment at the LHC

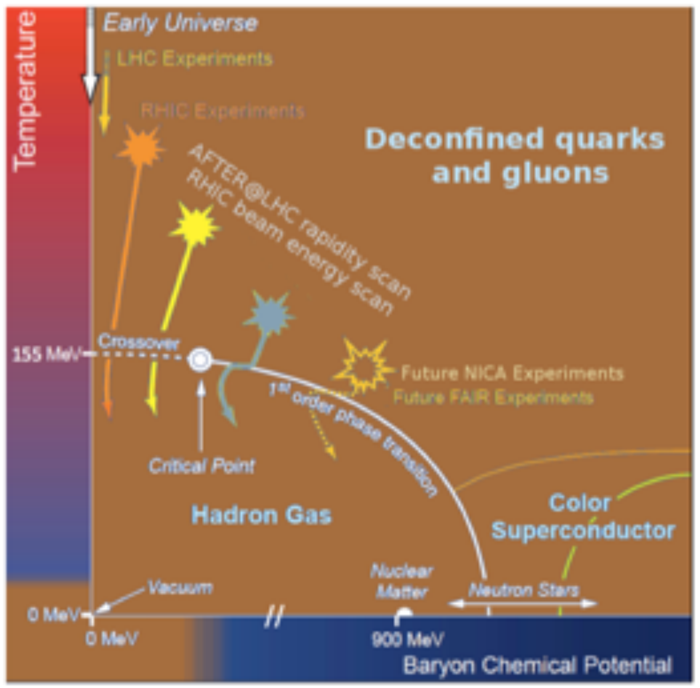
- Several advantages of fixed-target mode:
  - Accessing **high-*x* frontier** ($y_{CM} < 0$ and parton momentum fraction $x > 0.5$)
  - Achieving **high luminosity**
  - Varying **atomic mass number** of the target
  - **Polarising** the target
- This can be realized at LHC in a parasitic mode!
- Fixed-target mode started at LHCb with a low density gas-target (by using SMOG)

Physics motivations

- Advance our understanding of the **high-*x* gluon, antiquark and heavy-quark content in the nucleon and nucleus and its connection to astroparticles**
- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- Study the **quark-gluon plasma** between SPS and RHIC energies over a broad rapidity domain







Possible fixed-target implementations

– Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA, RHIC polarimeter

- Full LHC proton flux: 3.4 x 10^{18} p/s and Pb flux: 3.6 x 10^{14} Pb/s on internal gas target

→ high intensity beam on gas target

– Internal wire/foil target as in HERA-B, STAR

- Beam halo is recycled directly on internal solid targets

– Beam line extracted with a bent crystal

- Beam halo is deflected by a bent crystal
- Expected proton flux ~5 x 10^8 p/s, Pb flux ~2 x 10^5 Pb/s
- Provides a new facility with 7 TeV proton and 2.76 lead beams
- Civil engineering required

– Beam "split" by a bent crystal

- Beam halo is deflected on a solid target internal to the LHC beam pipe
- Similar fluxes as for beam extraction

→ beam halo on dense target

Internal gas and solid target can be coupled with an existing LHC detector

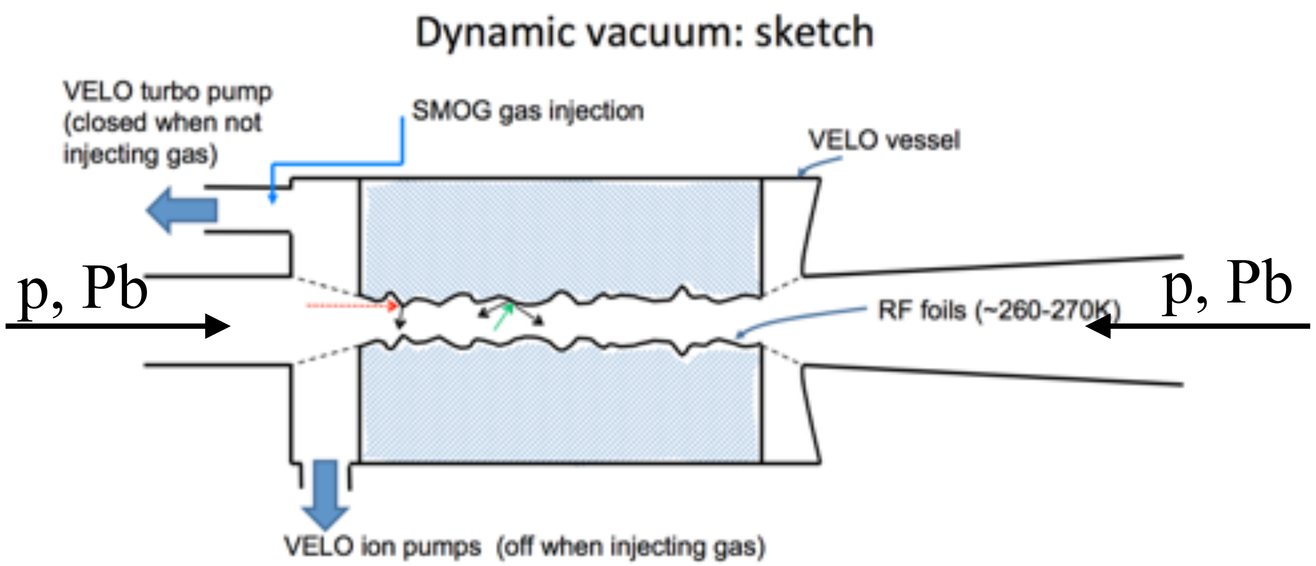
Technical implementations currently discussed within the Physics Beyond Collider working group (http://pbc.web.cern.ch/) with a fixed-target working group evaluating the effect on the LHC beams

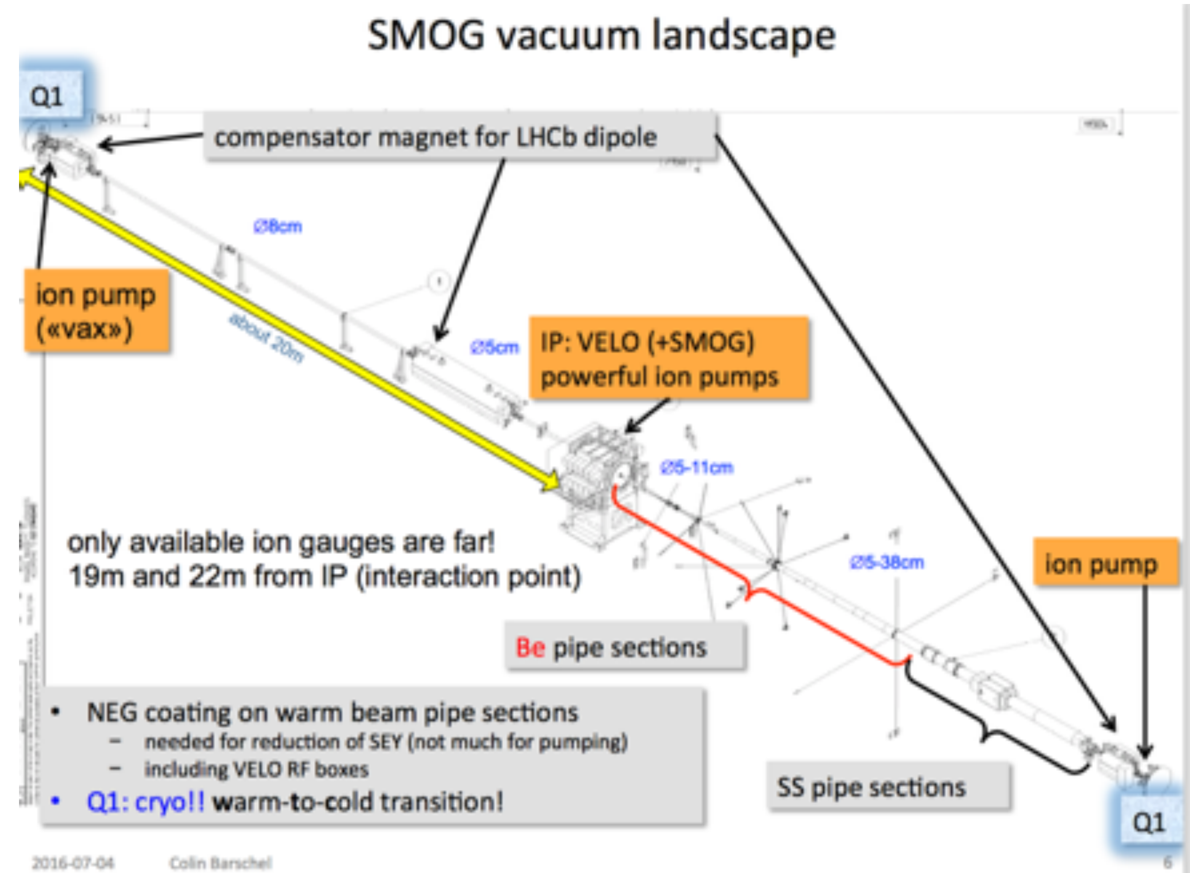
S.Redaelli et al. Proceedings of IPAC2018

Physics Beyond Collider Working Group meeting June 2018: https://indico.cern.ch/event/706741/

SMOG in LHCb: a gas-target demonstrator

VELO (+SMOG)





SMOG/LHCb (System for Measuring the Overlap with Gas)

– Gas injecting into Vertex Locator (VELO) vacuum chamber: P ~1.5 10^{-7} mbar
– LHC vacuum ion pump stations located ±20m on both sides
– Use full intensity of the LHC proton and lead beam without decrease of the beam lifetime
– Limited to noble gases. Already injected: He, Ne, Ar
– Limited luminosities (density, running time, …), no p-H baseline, no heavy nuclei

Luminosity

- Maximum obtained luminosity so far: $\mathscr{L}_{\text{p-Ne@68GeV}} = 100/\text{nb}$

Internal gas target: gas-jet

Polarised H-jet polarimeter at RHIC-BNL ***Zelenski et al. NIM A 536 (2005) 248***

- Used to measure the proton beam polarisation at RHIC
- Polarised gas: free atomic beam source (ABS) crossing the RHIC beam: H, D and $_3$He possible
- 9 vacuum chambers: 9 stages of differential pumping
- Holding field in the target vacuum chamber
- Diagnostic system: Breit-Rabi polarimeter

Density

- Polarised inlet $H_\uparrow$ flux: 1.3 10^{17} H/s
- Areal density $\vartheta_{H\uparrow} = 1.2\ 10^{12}$ atoms/cm^2 (10 × SMOG)
- Much higher density can be obtained for H_2
- Gas target profile at interaction point: gaussian with a full width of ~6 mm

Typical luminosity

- Using nominal LHC bunch number [2808 bunches for proton and 592 for lead] and for 1 LHC year [10^7s proton beam and 10^6s lead beam]
- $\mathscr{L}_{p\text{-}H\uparrow} = 4.5\ 10^{30}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H\uparrow} = 45$/pb]
- $\mathscr{L}_{p\text{-}H2} = 10^{33}$-$10^{34}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H2} = 10$-$100$/fb]
- Other possible gases: $D_\uparrow$, $^3He_\uparrow$

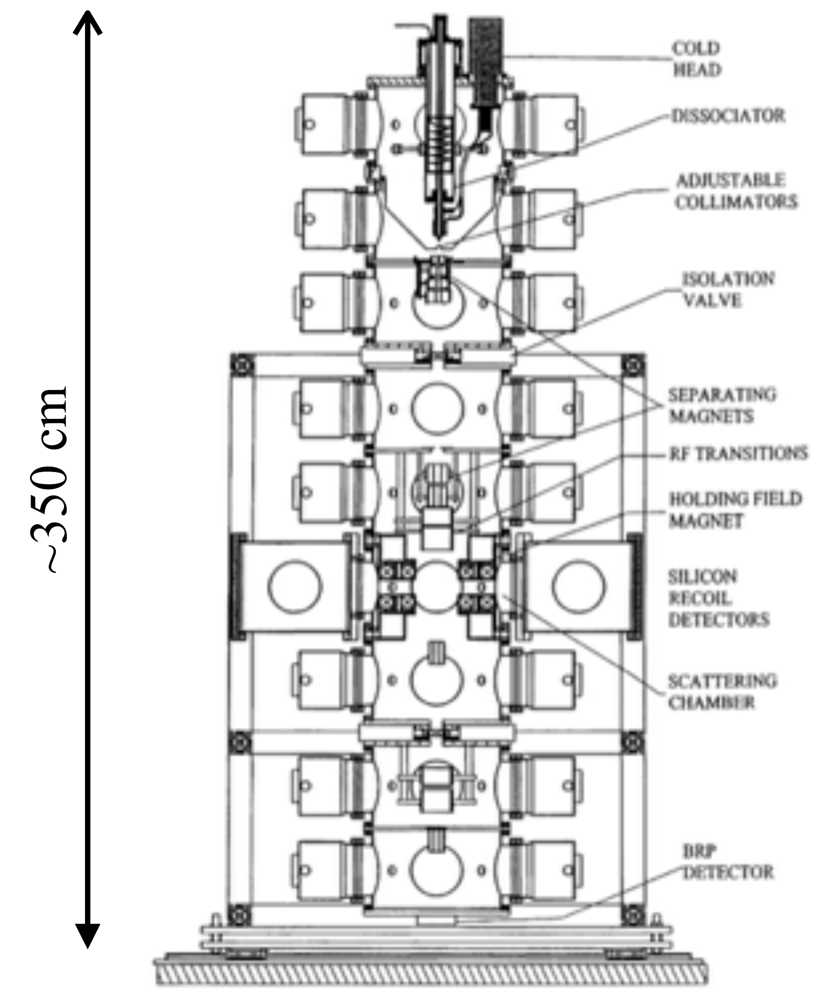
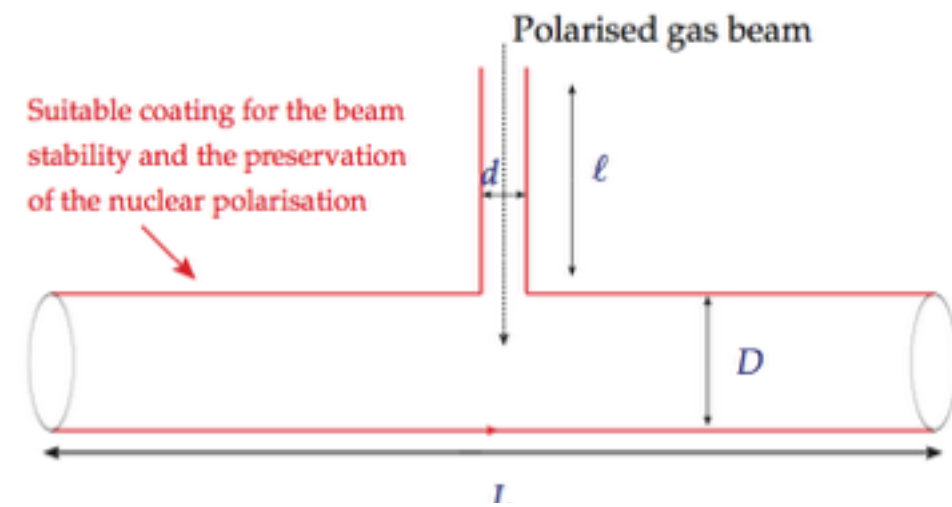


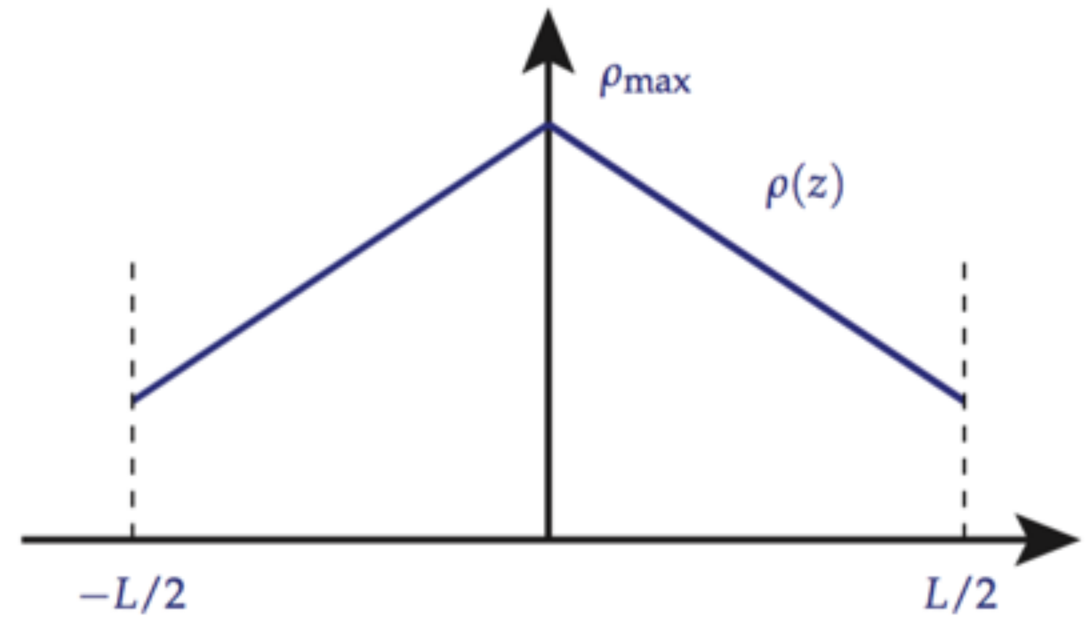
Fig. 1. H-jet polarimeter general layout.

Internal gas target: storage cell

HERMES/DESY T-shape internal storage cell target:
- Vacuum chamber target ~ 72 cm x 50 cm and pumping system
- Polarised gas: atomic beam source
- Holding field in the target chamber
- Diagnostic systems: target gas analyzer and polarimeter
- Unpolarized gas via capillary
- Proposal for LHC using an openable storage cell of 1m long and 2.8 cm wide: ***C. Barschel et al. Adv.High Energy Phys. 2015 (2015) 463141***



Density
- Polarised inlet $H_{\uparrow}$ flux: 6.5 10^{16} $H_{\uparrow}$/s
- Areal density $\vartheta_{H\uparrow} = 2.5\ 10^{14}$ atoms/cm^2 (~100 × gas jet)
- Unpolarised gas pressure limited by beam lifetime



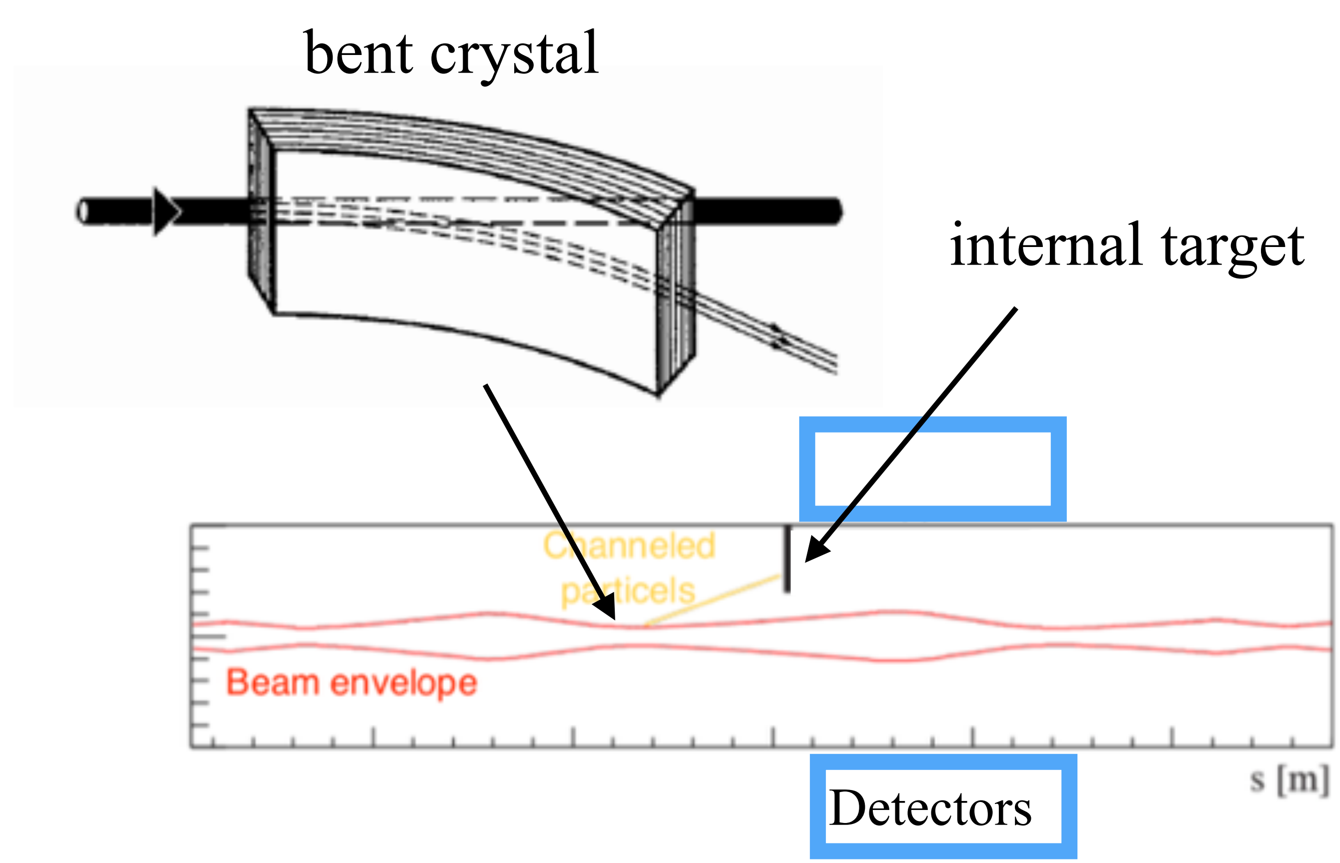
Typical luminosity
- $\mathscr{L}_{p\text{-}H\uparrow} = 0.9\ 10^{33}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H\uparrow} = 9$/fb]
- $\mathscr{L}_{p\text{-}H2} = 5.8\ 10^{33}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H2} = 58$/fb]
- $\mathscr{L}_{Pb\text{-}H\uparrow} = 1.2\ 10^{29}$ cm^{-2}s^{-1} [t = 10^6s: $\mathscr{L}_{Pb\text{-}H\uparrow} = 100$/nb]
- $\mathscr{L}_{Pb\text{-}Xe} = 3\ 10^{28}$ cm^{-2}s^{-1} [t = 10^6s: $\mathscr{L}_{Pb\text{-}Xe} = 30$/nb]
- Other possible gases: $D_{\uparrow}$, $^3He_{\uparrow}$, all noble gases

Beam split by using a bent crystal

Bent crystals

- Studied by UA9 for collimation purpose at the LHC
- Channelled particles of the beam halo are deflected
- Beam split by a bent crystal:
    - Crystal located ~100 m upstream the target
    - Solid target internal to the beam pipe close to an existing experimental apparatus
    - Absorber ~100 m downstream the target

S.Redaelli, Physics Beyond Collider Kickoff workshop, CERN, 2016



Extracted proton and lead flux

- Proton flux ~5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
- Lead flux ~2 x 10^5 Pb/s

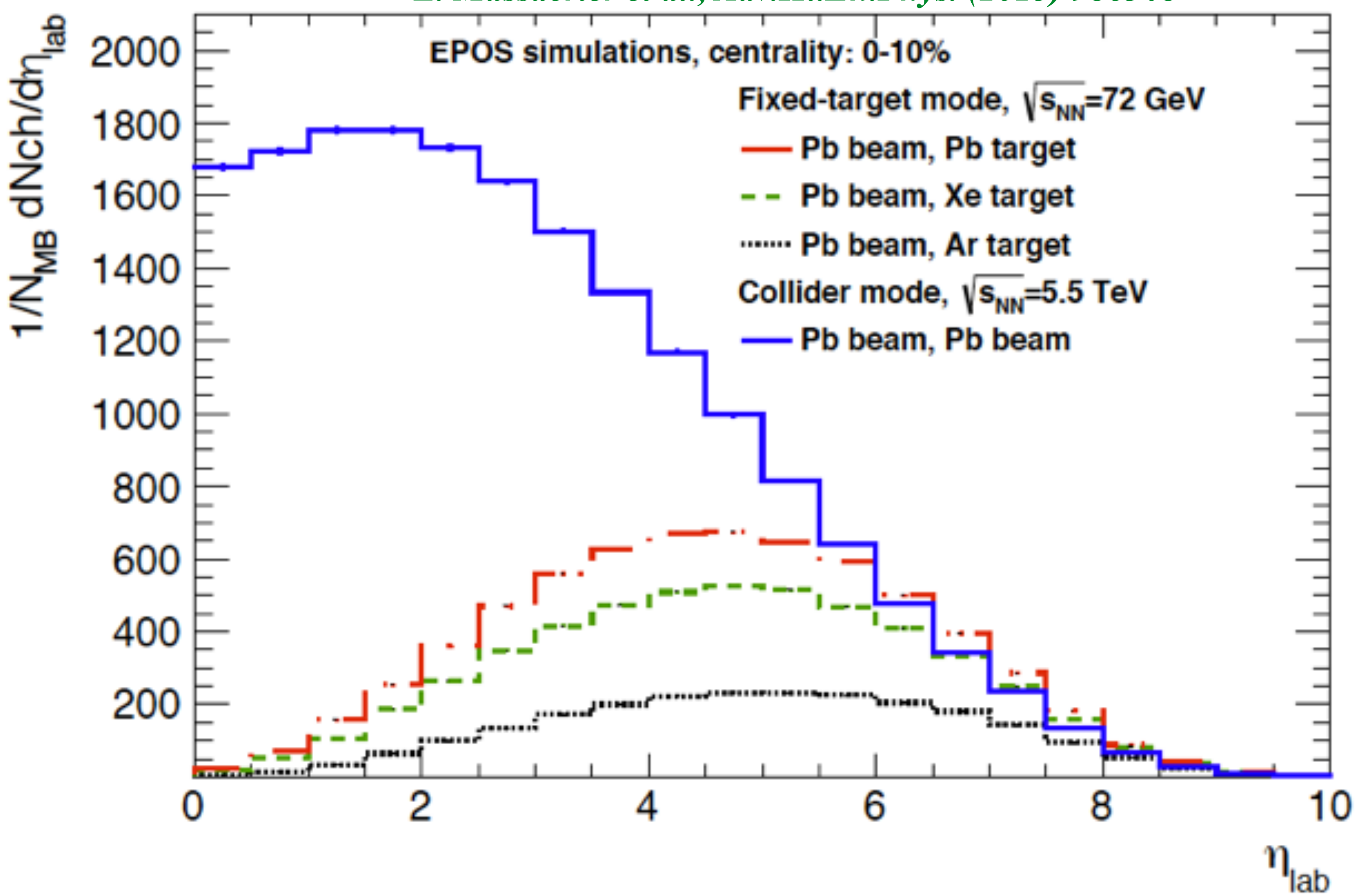
Typical luminosity

- Assuming 5 mm target length
- $\mathscr{L}_{p\text{-}W} = 1.6\ 10^{31}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}W} = 160/pb$]
- $\mathscr{L}_{Pb\text{-}W} = 3\ 10^{27}\ cm^{-2}s^{-1}$ [$t = 10^6 s$: $\mathscr{L}_{Pb\text{-}W} = 3/nb$]
- Target type: Be, C, W, …

Detector requirements for a LHC fixed-target programme

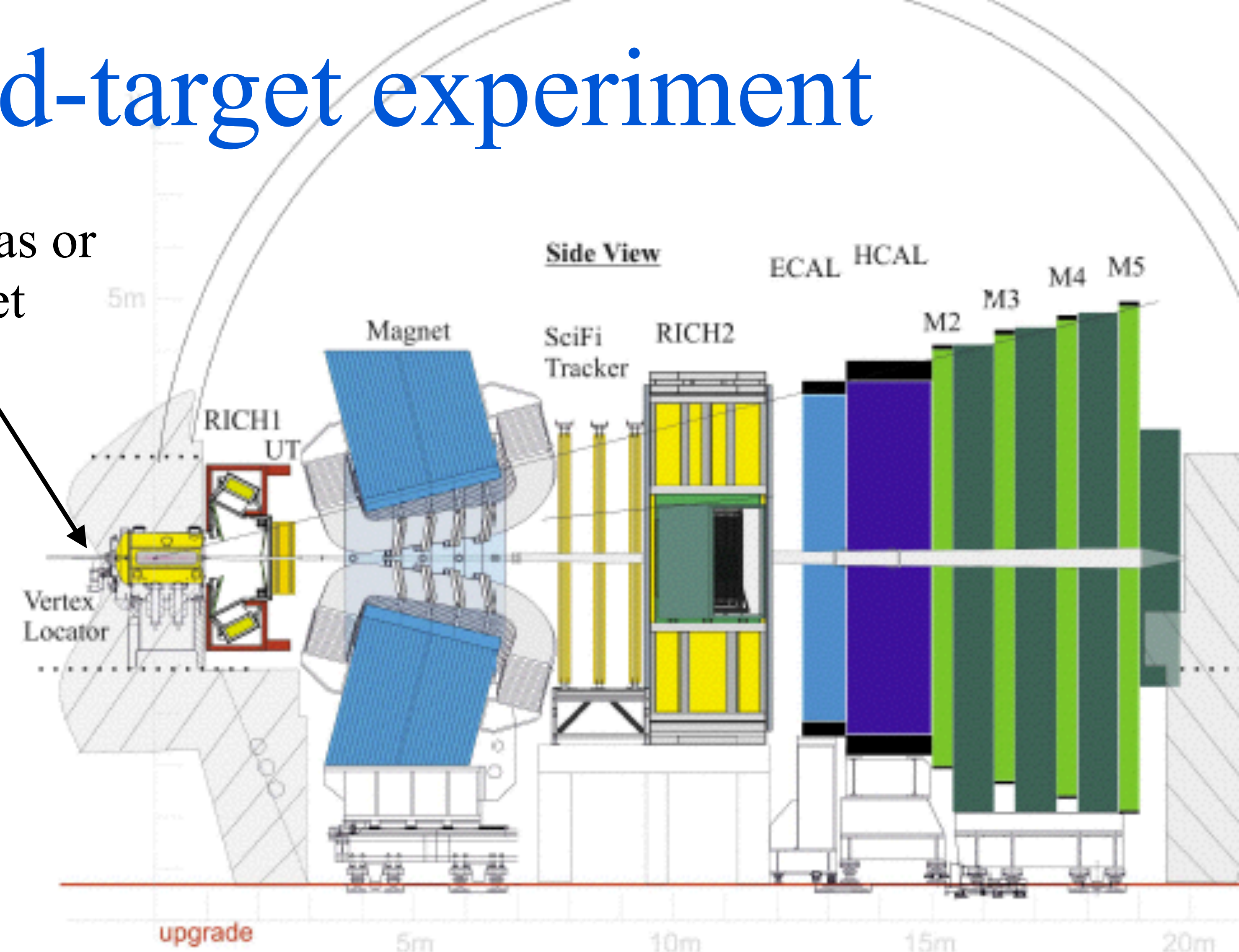
- **Wide rapidity coverage** (rapidity shift: $\Delta y = 4.8$ with proton beam and 4.2 with lead beam) with PID and vertexing capabilities
- Readout **rate similar as LHC** collider: up to 40 MHz in pp, 300 MHz in pA and 200 kHz in PbA
- Heavy-ion: good detector performance in **high-multiplicity events**, up to 600 charged tracks per unit of rapidity at $\eta_{lab} \sim 4$

L. Massacrier et al., Adv.Hi.En.Phys. (2015) 986348



LHCb as a fixed-target experiment

Internal gas or solid target



- Forward detector ($2 < \eta < 5$) with full PID
- Limitation in high-multiplicity event reconstruction (up to ~50% less central events in Pb-Pb collider mode)
- Upgrade LS2:
  - New Vertex Locator
  - New Tracker
  - Readout rate: 40 MHz

Achievable luminosities with gas target (storage cell):

– $\mathscr{L}_{\text{p-H}\uparrow\text{@115GeV}} = 10/\text{fb}$, $\mathscr{L}_{\text{p-Xe@115GeV}} = 300/\text{pb}$ [$t = 10^7$s]

– $\mathscr{L}_{\text{Pb-Xe@72GeV}} = 30/\text{nb}$, $\mathscr{L}_{\text{Pb-H}\uparrow\text{@72GeV}} = 100/\text{nb}$ [$t = 10^6$s]

With beam splitting and 5 mm solid target:

– $\mathscr{L}_{\text{p-W@115GeV}} = 160/\text{pb}$ [$t = 10^7$s]

– $\mathscr{L}_{\text{Pb-W@72GeV}} = 3/\text{nb}$ [$t = 10^6$s]

Projects under investigation in LHCb

Several investigations/projects:

- Beam splitting and internal W solid target (with a second crystal) for Electromagnetic Dipole Moment of charmed baryons
- Polarized storage cell gas target for spin physics
- Unpolarized storage cell gas target (SMOG2)

SMOG2 internal storage cell target:

- Openable storage cell of 20 cm long attached to the VELO
- Unpolarized gas via capillary: gas feed tube in the cell center

P. DiNezza Annual Workshop PBC, November 2017

Density

- Gas pressure up to 100 × SMOG: P ~ 10^{-5} mbar

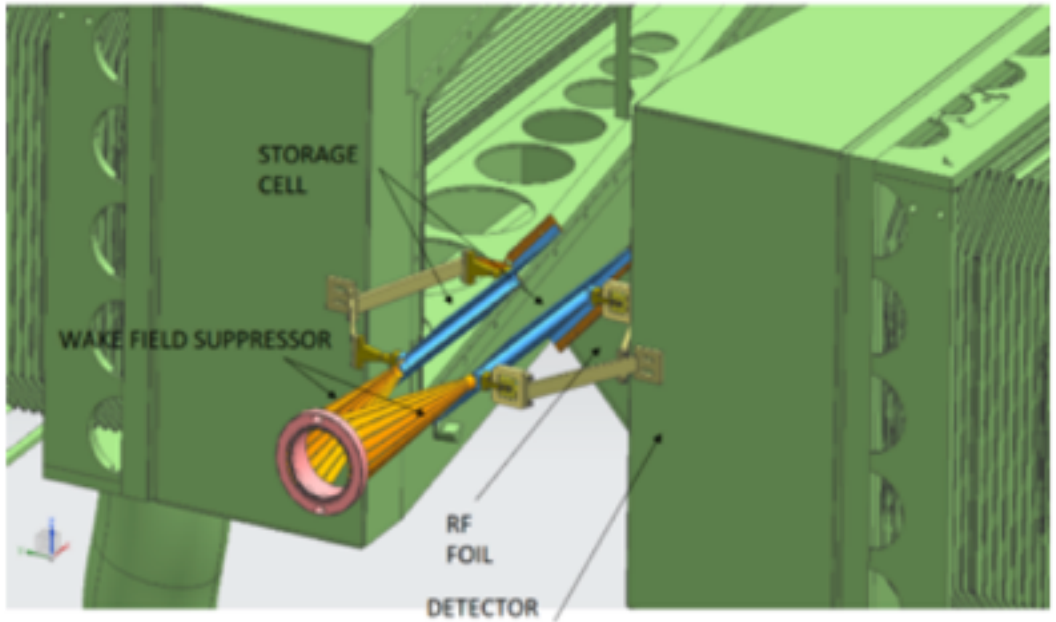
Possible systems and luminosities (not approved by LHCb)

- p-H, p-D, p-Ar, Pb-Ar, …
- $\mathscr{L}_{\text{p-H@115GeV}} = 10/\text{pb}$
- $\mathscr{L}_{\text{p-D@115GeV}} = 10/\text{pb}$
- $\mathscr{L}_{\text{Pb-Ar@72GeV}} = 5/\text{nb}$ (+ $\mathscr{L}_{\text{p-Ar@72GeV}} = 1/\text{pb}$)
- Luminosity increase by up to an order of magnitude could be feasible
- Discussion ongoing on target types, parallel / dedicated running, possible vacuum issue, …

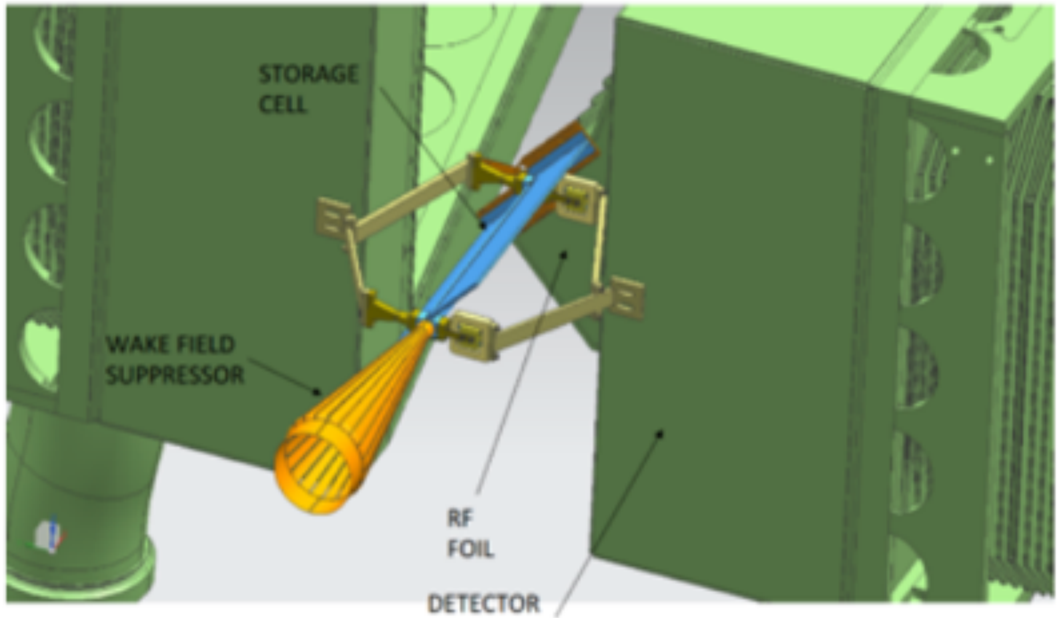
G.Graziani Annual Workshop PBC, June 2018

Formal approval of SMOG2 this Fall and installation foreseen in LS2

Unpolarised storage cell: open position view

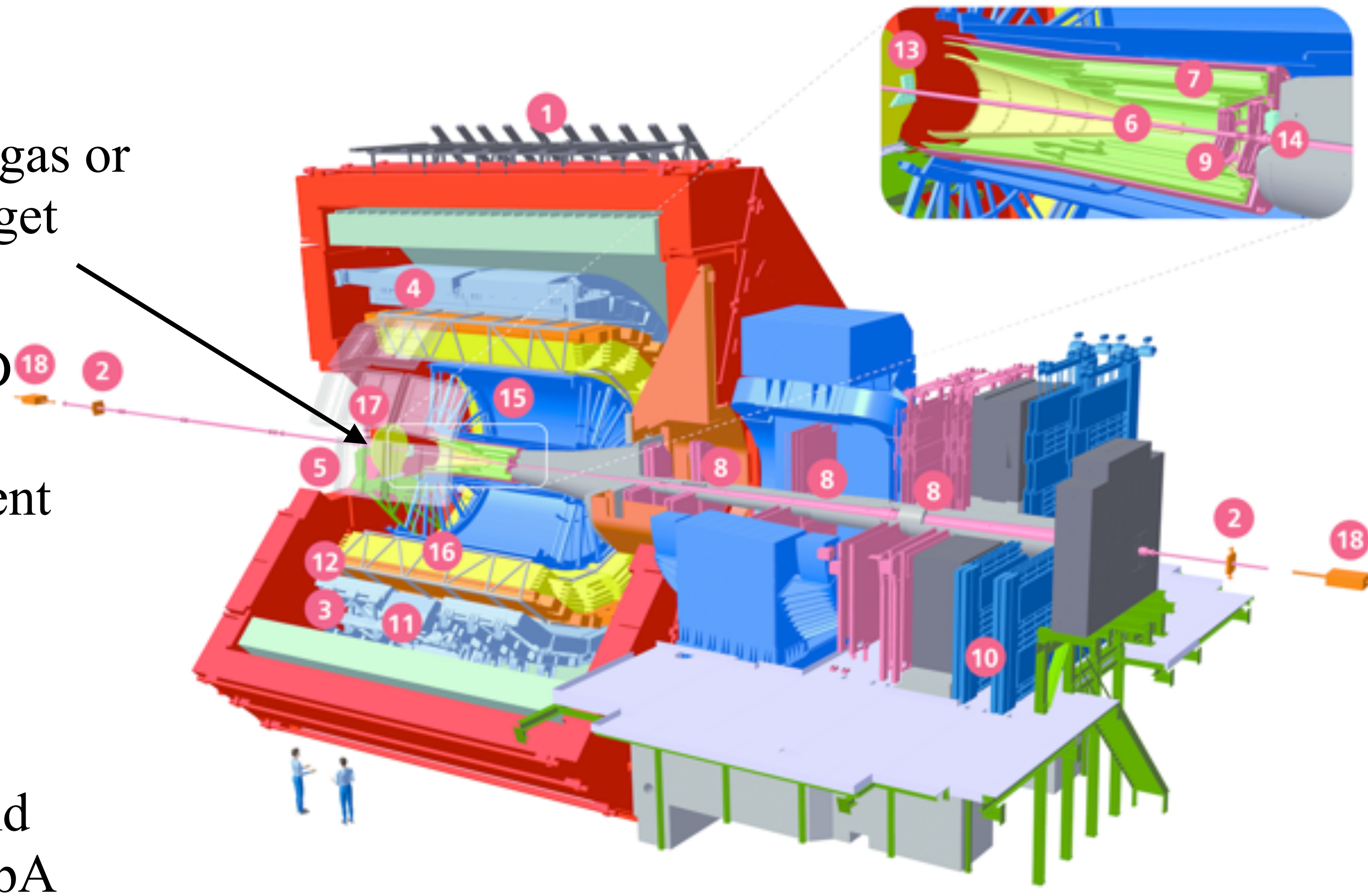


Unpolarised storage cell: closed position view



ALICE in a fixed-target mode

Internal gas or solid target



- Central Barrel ($|\eta| < 0.9$) with full PID
- Muon Spectrometer ($2.5 < \eta < 4$)
- No limitation in high-multiplicity event reconstruction
- Upgrade LS2:
  - New Silicon Tracker
  - A Muon Forward Tracker
  - Readout rate: 50 kHz in PbPb and possibly up to 1 MHz in pp and pA

Achievable luminosities with gas target:

– $\mathscr{L}_{\text{p-H2/H}\uparrow\text{@115GeV}} = 260/\text{pb}$, $\mathscr{L}_{\text{p-Xe@115GeV}} = 8/\text{pb}$

– $\mathscr{L}_{\text{Pb-Xe@72GeV}} = 8/\text{nb}$

With beam splitting and at most 5 mm solid target:

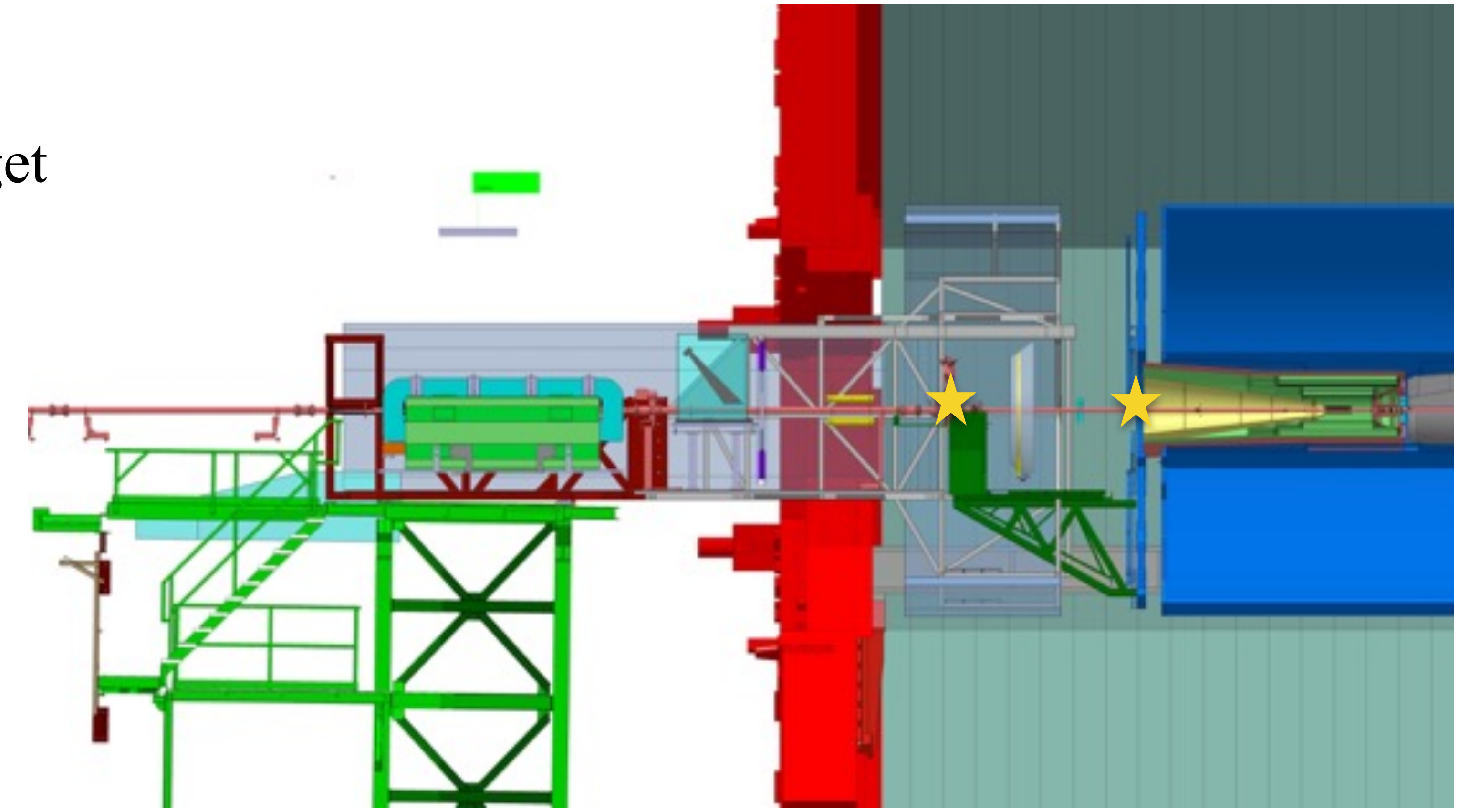
– $\mathscr{L}_{\text{p-W@115GeV}} = 6/\text{pb}$

– $\mathscr{L}_{\text{Pb-W@72GeV}} = 3/\text{nb}$

Fixed-target investigation in ALICE

Current investigation:

- Beam splitting and internal solid target



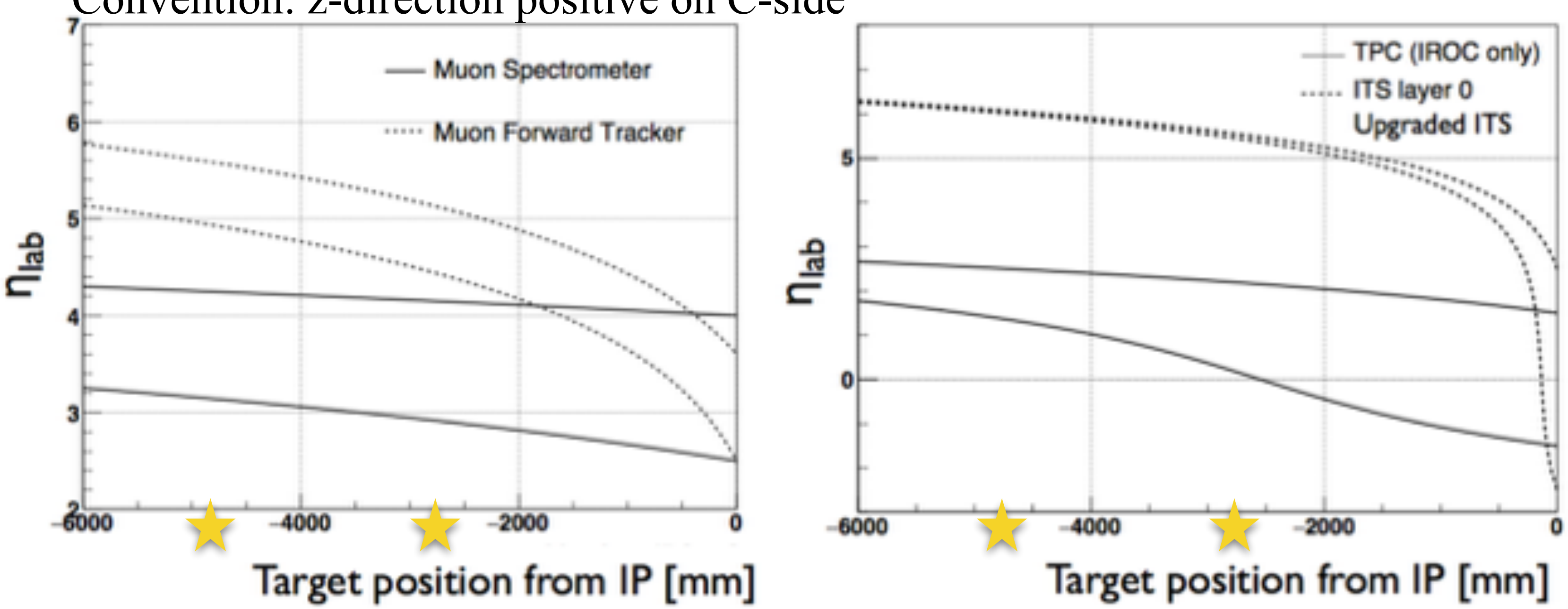
Internal solid target:

- Inside the L3 solenoid
- Pneumatic motion system with two positions IN and OUT of the beam pipe

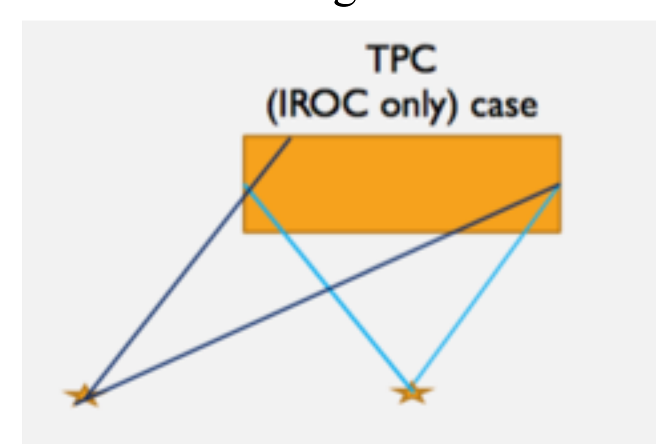
C.H. Annual Workshop PBC, June 2018

Detector acceptance vs z_{target}

Convention: z-direction positive on C-side

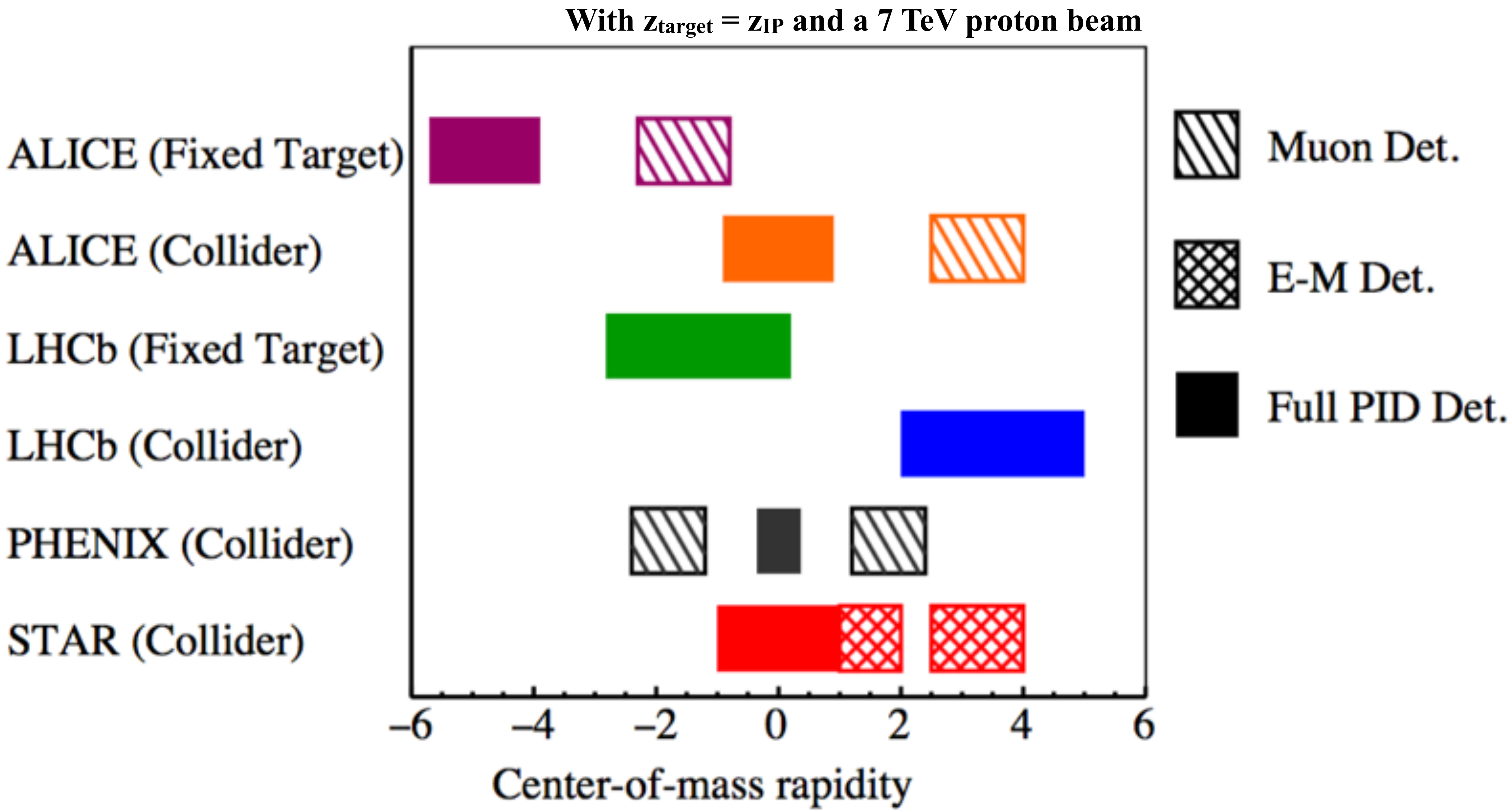


Caveat: simple geometry considerations using reduced track length in TPC



The rapidity coverage is shifted towards larger rapidities (mid-rapidity in the c.m.s) if the vertex is located few meters upstream the I.P.

Acceptance in center-of-mass rapidity



In a fixed-target mode:
– ALICE Central Barrel covers very backward rapidity and Muon Spectrometer covers rapidity interval towards mid-rapidity
– LHCb: wide rapidity range starting from $y_{cms} \sim 0$

Summary

- Three main physics motivations for a high-luminosity fixed-target program at the LHC:
  - –**High-*x* frontier**: nucleon and nuclear structure and connections with astroparticles
  - –**Nucleon spin** and the transverse dynamics of partons
  - –**Quark Gluon Plasma** over a broad rapidity domain
- Two promising technical implementations with large luminosities:
  - **–an internal gas-target (gas-jet or storage cell)**
  - –a slow beam extraction with **a bent crystal on an internal solid target**
- Investigations/projects in **ALICE** and **LHCb** ongoing for the implementation of fixed-target setup

back-up slides

Achievable luminosities in ALICE

Target			ALICE							
			proton beam ($\sqrt{s_{NN}}$ = 115 GeV)				Pb beam ($\sqrt{s_{NN}}$ = 72 GeV)			
			$\mathcal{L}$ [cm^{-2}s^{-1}]	σ_{inel}	Inel rate kHz	$\int \mathcal{L}$	$\mathcal{L}$ [cm^{-2}s^{-1}]	σ_{inel}	Inel rate kHz	$\int \mathcal{L}$
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3 x 10^{30}	39 mb	168	43 pb^{-1}	5.6 x 10^{26}	1.8 b	1	0.56 nb^{-1}
		H_2	2.6 x 10^{31}	39 mb	1000	0.26 fb^{-1}	2.8 x 10^{28}	1.8 b	50	28 nb^{-1}
		$D^{\uparrow}$	4.3 x 10^{30}	72 mb	309	43 pb^{-1}	5.6 x 10^{26}	2.2 b	1.2	0.56 nb^{-1}
		$^3He^{\uparrow}$	8.5 x 10^{30}	117 mb	1000	85 pb^{-1}	2.0 x 10^{28}	2.5 b	50	20 nb^{-1}
	Storage Cell	$H^{\uparrow}$	2.6 x 10^{31}	39 mb	1000	0.26 fb^{-1}	2.8 x 10^{28}	1.8 b	50	28 nb^{-1}
		H_2	2.6 x 10^{31}	39 mb	1000	0.26 fb^{-1}	2.8 x 10^{28}	1.8 b	50	28 nb^{-1}
		$D^{\uparrow}$	1.4 x 10^{31}	72 mb	1000	140 pb^{-1}	2.2 x 10^{28}	2.2 b	50	22 nb^{-1}
		$^3He^{\uparrow}$	8.5 x 10^{30}	117 mb	1000	85 pb^{-1}	2.0 x 10^{28}	2.5 b	50	20 nb^{-1}
		Xe	7.8 x 10^{29}	1.3 b	1000	7.8 pb^{-1}	8.1 x 10^{27}	6.2 b	50	8.1 nb^{-1}
Internal solid target with beam halo	Wire Target	C (500 μm)	2.8 x 10^{30}	271 mb	760	28 pb^{-1}	5.6 x 10^{26}	3.3 b	1.8	0.56 nb^{-1}
		Ti (500 μm)	1.4 x 10^{30}	694 mb	971	14 pb^{-1}	2.8 x 10^{26}	4.7 b	1.3	0.28 nb^{-1}
		W (184 μm[29] / 500 μm[30])	5.9 x 10^{29}	1.7b	1000	5.9 pb^{-1}	3.1 x 10^{26}	6.9 b	2.1	0.31 nb^{-1}
Beam splitting	E1039	$NH_3^{\uparrow}$	2.6 x 10^{31}	39 mb	1000	0.26 fb^{-1}	1.4 x 10^{28}	1.8 b	25	14 nb^{-1}
		$ND_3^{\uparrow}$	1.4 x 10^{31}	72 mb	1000	140 pb^{-1}	1.4 x 10^{28}	2.2 b	30	14 nb^{-1}
	Unpolarised solid target	C (658 μm / 5000 μm)	3.7 x 10^{30}	271 mb	1000	37 pb^{-1}	5.6 x 10^{27}	3.3 b	18	5.6 nb^{-1}
		Ti (515 μm / 5000 μm)	1.4 x 10^{30}	694 mb	1000	14 pb^{-1}	2.8 x 10^{27}	4.7 b	13	2.8 nb^{-1}
		W (184 μm / 5000 μm)	5.9 x 10^{29}	1.7b	1000	5.9 pb^{-1}	3.1 x 10^{27}	6.9 b	21	3.1 nb^{-1}

Table 11: Summary table of the achievable integrated luminosities with the ALICE detector accounting for the data-taking-rate capabilities in the collider mode and by considering the luminosities of Table 9. As detailed in the text, a higher rate depending on the collision system could be envisioned. The inelastic cross sections are taken from EPOS [97, 132].

Achievable luminosities in LHCb

Target			LHCb							
			proton beam ($\sqrt{s_{NN}}$ = 115 GeV)				Pb beam ($\sqrt{s_{NN}}$ = 72 GeV)			
			$\mathcal{L}$ [$cm^{-2}s^{-1}$]	σ_{inel}	Inel rate kHz	$\int \mathcal{L}$	$\mathcal{L}$ [$cm^{-2}s^{-1}$]	σ_{inel}	Inel rate kHz	$\int \mathcal{L}$
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3 x 10^{30}	39 mb	168	43 pb^{-1}	5.6 x 10^{26}	1.8 b	1	0.56 nb^{-1}
		H_2	1.0 x 10^{33}	39 mb	40000	10 fb^{-1}	2.8 x 10^{30}	1.8 b	5000	2.8 pb^{-1}
		$D^{\uparrow}$	4.3 x 10^{30}	72 mb	309	43 pb^{-1}	5.6 x 10^{26}	2.2 b	1.2	0.56 nb^{-1}
		$^3He^{\uparrow}$	3.4 x 10^{32}	117 mb	40000	3.4 fb^{-1}	4.7 x 10^{28}	2.5 b	118	47 nb^{-1}
	Storage Cell	$H^{\uparrow}$	0.92 x 10^{33}	39 mb	35880	9.2 fb^{-1}	1.2 x 10^{29}	1.8 b	216	120 nb^{-1}
		H_2	1.0 x 10^{33}	39 mb	40000	10 fb^{-1}	7.5 x 10^{29}	1.8 b	1400	750 nb^{-1}
		$D^{\uparrow}$	5.6 x 10^{32}	72 mb	40000	5.6 fb^{-1}	1.4 x 10^{29}	2.2 b	308	140 nb^{-1}
		$^3He^{\uparrow}$	1.3 x 10^{33}	117 mb	40000	13 fb^{-1}	4.7 x 10^{29}	2.5 b	1175	470 nb^{-1}
		Xe	3.1 x 10^{31}	1.3 b	40000	0.31 fb^{-1}	3.0 x 10^{28}	6.2 b	186	30 nb^{-1}
Internal solid target with the beam halo	Wire Target	C (500 μm)	2.8 x 10^{30}	271 mb	760	28 pb^{-1}	5.6 x 10^{26}	3.3 b	1.8	0.56 nb^{-1}
		Ti (500 μm)	1.4 x 10^{30}	694 mb	972	14 pb^{-1}	2.8 x 10^{26}	4.7 b	1.3	0.28 nb^{-1}
		W (500 μm)	1.6 x 10^{30}	1.7 b	2720	16 pb^{-1}	3.1 x 10^{26}	6.9 b	2.1	0.31 nb^{-1}
Beam splitting	E1039	$NH_3^{\uparrow}$	7.2 x 10^{31}	39 mb	2808	0.72 fb^{-1}	1.4 x 10^{28}	1.8 b	25	14 nb^{-1}
		$ND_3^{\uparrow}$	7.2 x 10^{31}	72 mb	5100	0.72 fb^{-1}	1.4 x 10^{28}	2.2 b	30	14 nb^{-1}
	Unpolarised solid target	C (5000 μm)	2.8 x 10^{31}	271 mb	7600	280 pb^{-1}	5.6 x 10^{27}	3.3 b	18	5.6 nb^{-1}
		Ti (5000 μm)	1.4 x 10^{31}	694 mb	9720	140 pb^{-1}	2.8 x 10^{27}	4.7 b	13	2.8 nb^{-1}
		W (5000 μm)	1.6 x 10^{31}	1.7 b	27200	160 pb^{-1}	3.1 x 10^{27}	6.9 b	21	3.1 nb^{-1}

Internal solid target (beam splitting)

- First sketch of the target system: pneumatic motion system with three target types
- Size of the target: diameter approximately 5mm, thickness 0.1-5mm
- Target holder: titanium alloy
- Parking position out of the pipe and 2 positions: In/Out
- One valve on each side

- Compatibility of proposed target types (Be, C, Ti, W, …) with LHC conditions to be studied
- Compatibility of the target system with the operation of ALICE forward detectors to be verified