LHC Fixed Targets for physics

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Outline

- Introduction: context, physics beyond colliders at CERN, LHCb ...
- Physics case(s): briefly
  - understanding $\bar{p}$ flux in cosmic rays
  - measuring magnetic/electric dipole moments of decaying charged particles
  - studying charm production in hot dense matter
- Solid targets in LHC
- Gas targets in LHC
- Summary and outlook

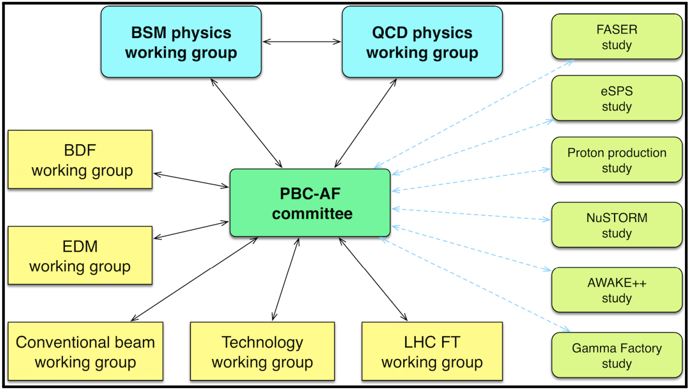
Introduction

Physics Beyond Colliders is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments. The mandate of the study team may be found here.

The kick-off workshop held in September 2016 identified a number of areas of interest. Working groups have been set-up to pursue studies in these areas. See organization for a detailed breakdown of the current structure. The Physics Beyond Colliders study remains open to further ideas for new projects.

Should you wish to receive general announcements and occassional updates, please subscribe to the e-group PBC-info here.

cern.ch/pbc



$\Rightarrow$ input to ESPP update

Introduction

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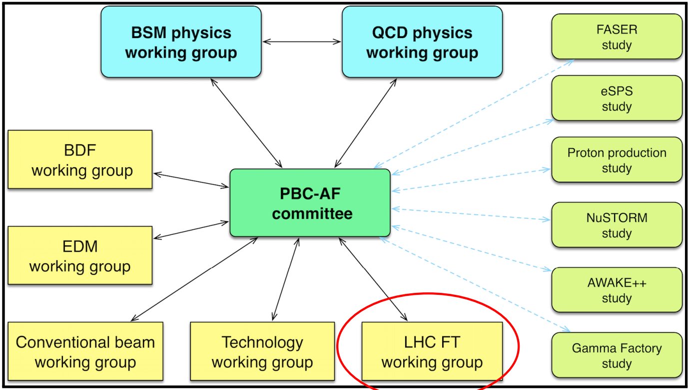

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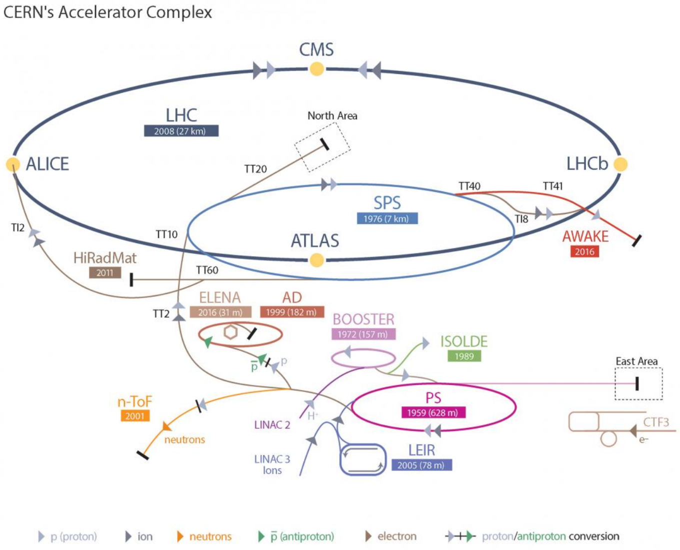
Introduction

Physics Beyond Colliders



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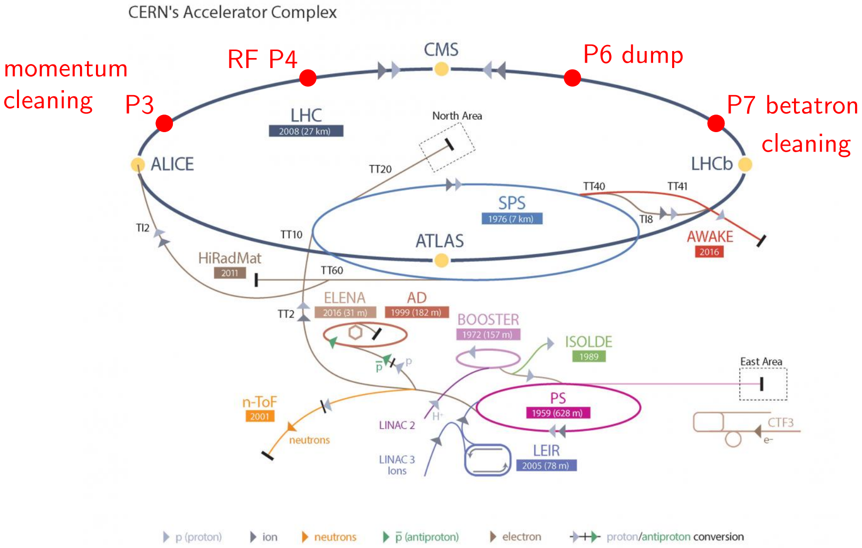
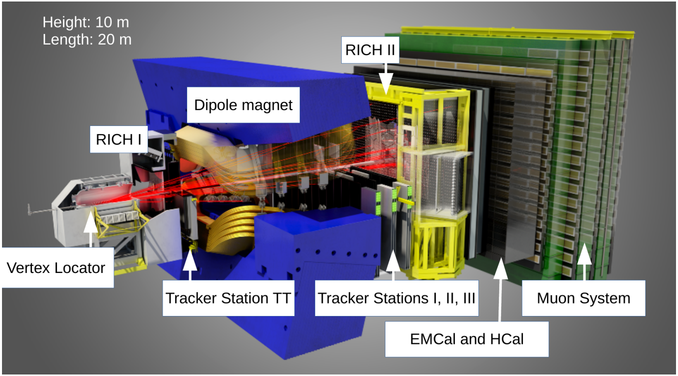


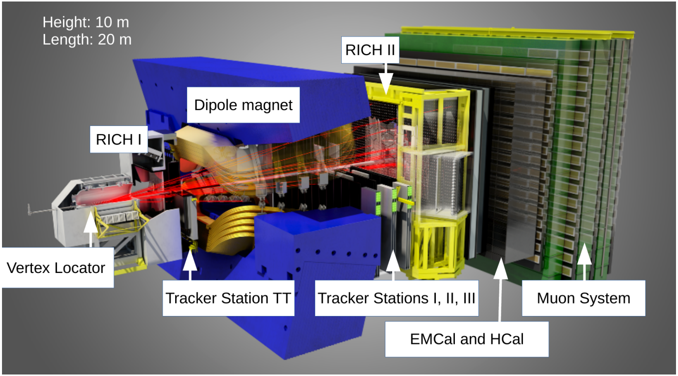
A fixed target experiment ?



Introduction

A fixed target experiment ?

No, it is LHCb



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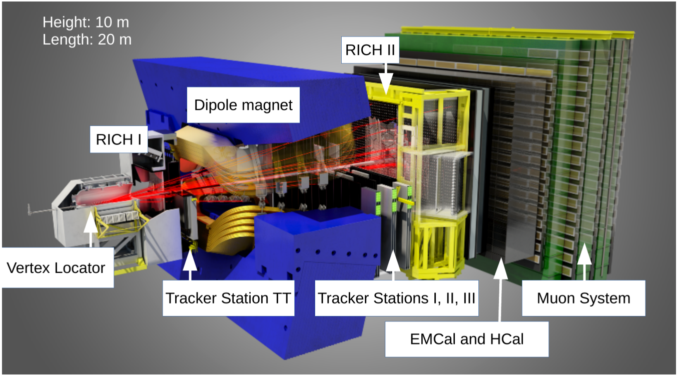

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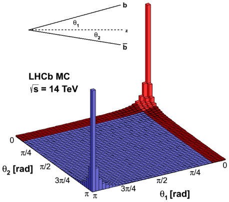

Physics Beyond Colliders

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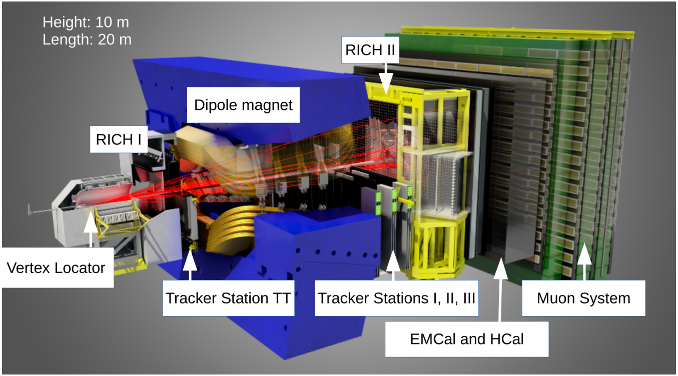

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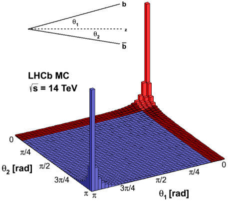

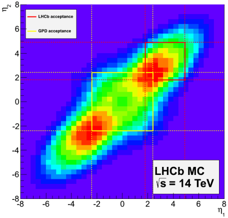

- Acceptance: from about +2 to +5 in pseudorapidity.

Introduction

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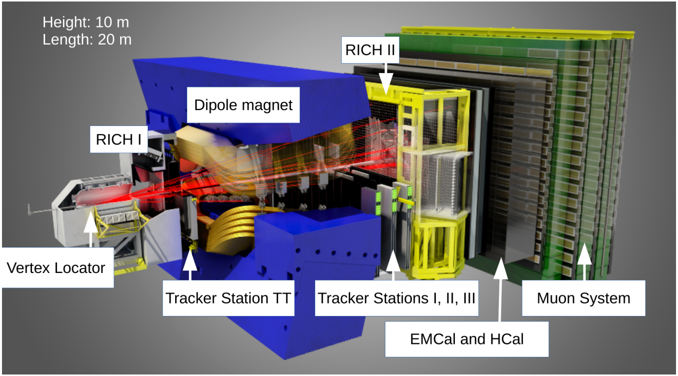

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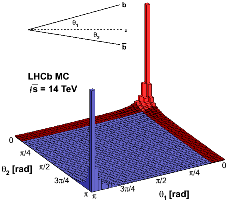

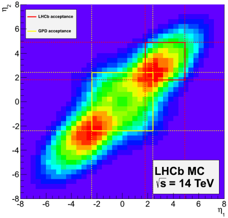

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- And "SMOG": gas target inside the beam-VELO (Vertex Locator) vacuum

Introduction

A fixed target experiment ?

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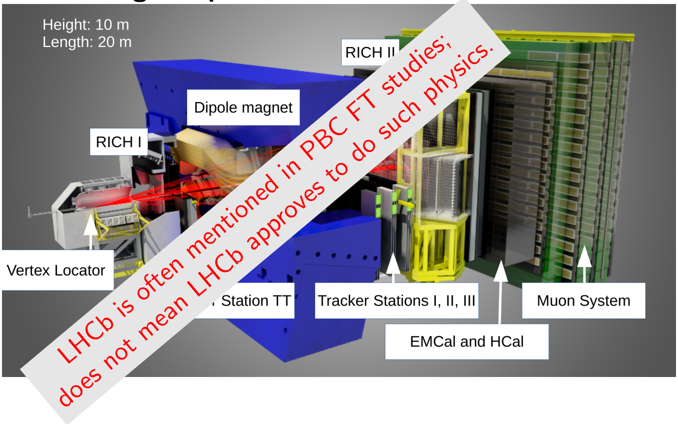
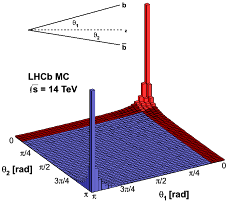
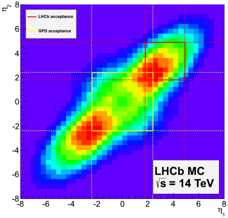


LHCb is often mentioned in PBC FT studies;
does not mean LHCb approves to do such physics.





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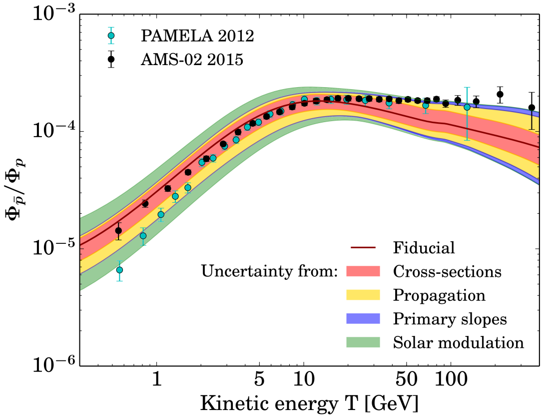
Physics case(s)

Astroparticle physics: in need of cross section measurements

- Antiproton flux measured in space
- Models: uncertainties due to bkg production of $\bar{p}$ from interstellar medium (ISM)
  - a good deal due to He



Physics case(s)

Other interesting measurements for models of cosmic rays through the ISM:

- sparse data for $\bar{p}$ production in pp; predictions mostly based on SPS data, limited to $\sqrt{s_{NN}} < 29$ GeV. Accuracy of extrapolations to higher $\sqrt{s_{NN}}$ are problematic
- little data on production of anti-hyperons, which are thought to constitute 20-30% of total $\bar{p}$ production;
- no direct data on $\bar{n}$ production at relevant energies. Usual assumption of equal $\bar{p}$ and $\bar{n}$ production. (NA49 data: hints for a isospin violation ? [11])
- $\bar{p}$ production in p-H and p-D (constraint on $\bar{n}$ production ?)
- production of π^+, K^+ (positron flux)
- production of high energy γ (bkg to γ astronomy)
- light anti-nuclei ($\bar{d}$, ${}^{3,4}\bar{He}$), etc...

Most of these measurements can be carried out with small integrated luminosities, of order nb^{-1}.

Physics case(s)

... or for modelling cosmic ray showers.

- Interpretation of UHE showers is presently limited by uncertainties on the modelling of hadronic particle production
- LHC FT configuration is complementary to LHC beam-beam collisions and offers wider choice of collision systems, including light nuclei
  - interactions in air can be modeled by interpolating currently available SMOG samples (p-He, p-Ne and p-Ar),
  - N and O targets could perhaps also become possible
- charm production, bkg from UHE showers to the high energy neutrino flux (IceCube)

and QCD per se ...

- Nucleon structure, trans-momentum dependent PDFs
- phase transition between hadronic matter and QGP

Magnetic dipole moments of baryons and other charged particles

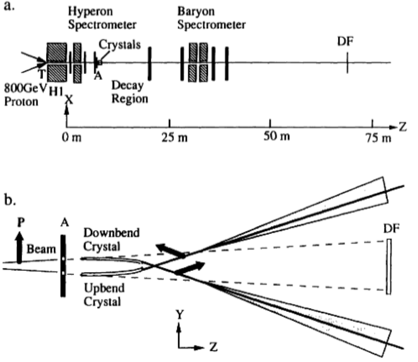


FIG. 1. (a) Plan view of the incident proton beam and spectrometer system. The horizontal scale (z) correctly illustrates the length of the apparatus, the vertical scale (x) is schematic only. (b) Elevation view of the channeling apparatus (not to scale). The arrows illustrate the spin precession in the crystals. Shaded areas depict the Σ^+ decay cone. The scintillation counters A and DF are part of the trigger and are described in the text.

figure from [2]

E761 measured (1992) MDM of Σ^+ (in $\to p\pi^0$) using a bent channeling crystal

Principle of polarization precession described in [1]

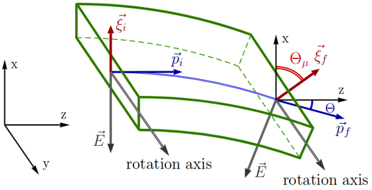
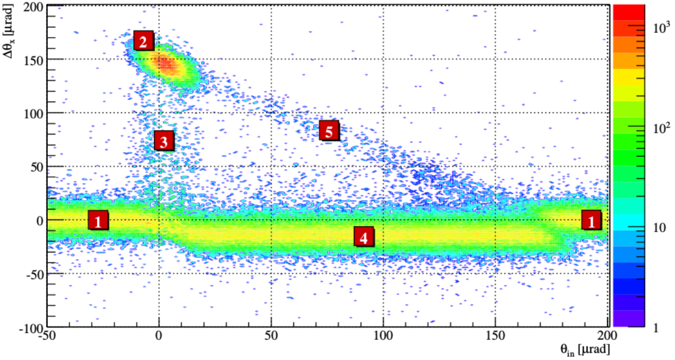


figure from [5]

bent crystal channeling works

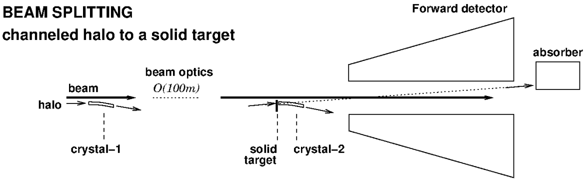


"Textbook" example from D. Mirarchi's thesis [?]

Solid targets

It was proposed to measure MDMs with crystals at the LHC [3], [5]

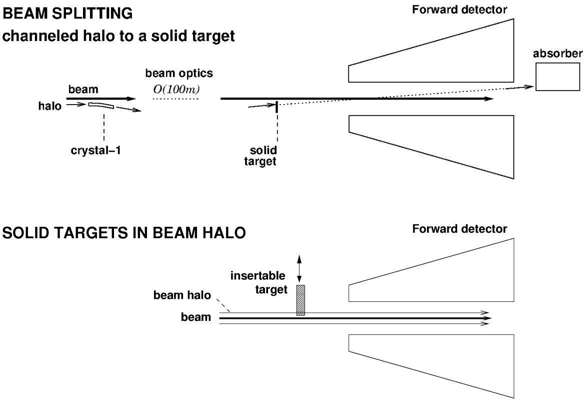
And later also to measure the EDM of baryons [6] and the MDM of τ [8]



Solid targets

Fixed-target physics with different solid targets

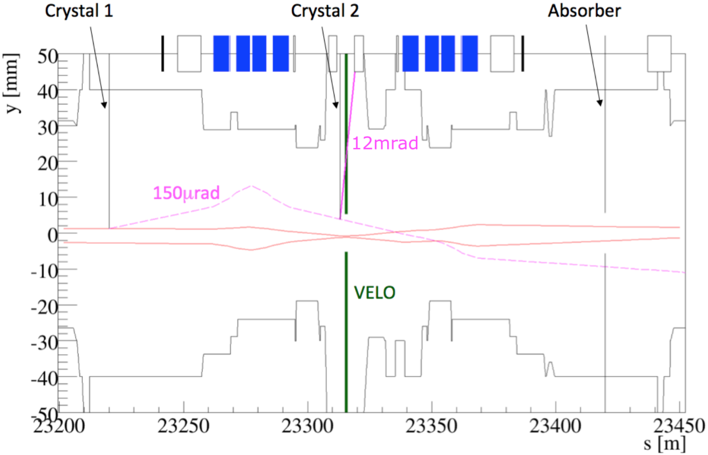
The method of beam splitting of beam halo from the core has also been proposed to perform fixed-target physics (no need of a second crystal).



(Extracting a beam to an external target has also been mentioned, but is prohibitively expensive)

Solid targets

First implementation study of 2-crystal setup for IP8 study and figure by D. Mirarchi



A better (long-term ?) alternative: find a dedicated area for this experiment (a collimation area ?).

Minimal setup: W+crys2, vtx detector, small aperture magnet, trker, absorber.

Solid targets

Challenges of 2-crystal setup at LHC IP8:

- affordable flux of protons on W target (life time, background, heat loads)
- disposal of non-(hard-)interacting protons
- prove that one can make a crystal with at least 12 mrad bending angle and sizable channeling efficiency
- implementation and operation of target and crsytal-2 in front of LHCb
  - must be in beam vacuum, movable, safe, etc
- operational scenarios (run in parallel versus dedicated beam time)

Solid targets

study with $\Lambda_c^+ \to pK^-\pi^+$ produced with 7 TeV p on W

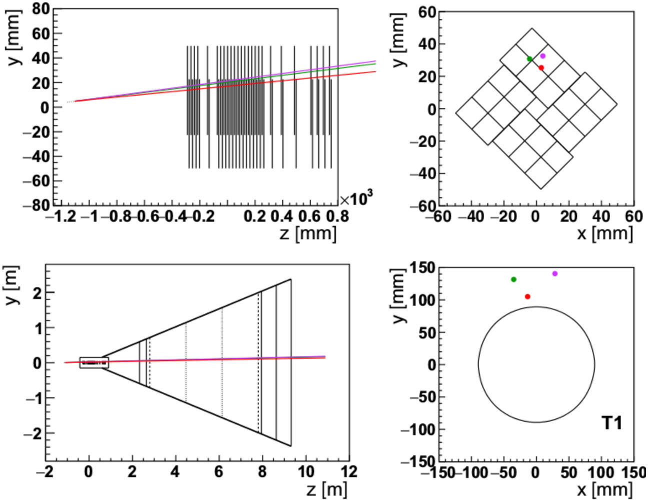
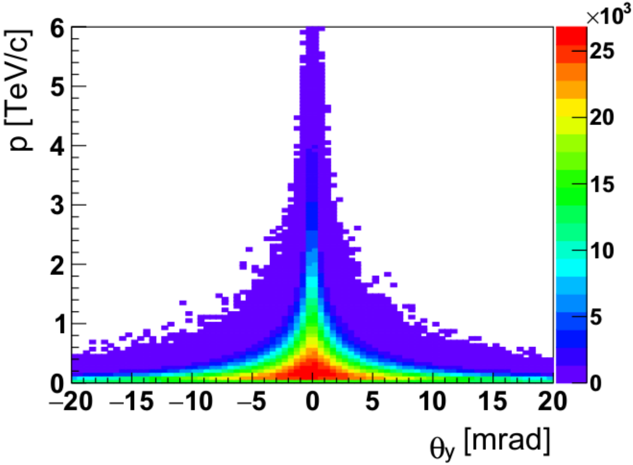


figure from [7]

Note: the decay products have typical energy in range 100-500 GeV

Solid targets

figure from [7]



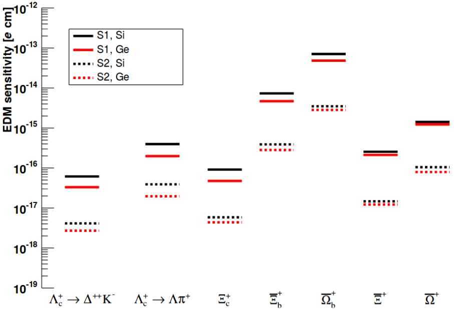
Distribution of angle θ_y (in bending plane, relative to entrance axis) versus momentum for Λ_c^+ baryons produced in 7 TeV proton beam collisions on protons at rest using Pythia

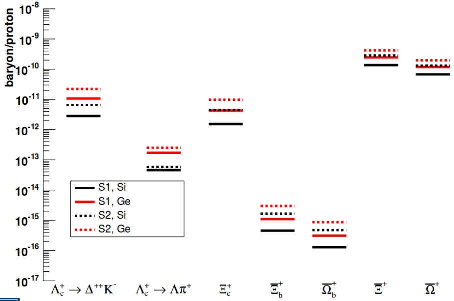
Solid targets

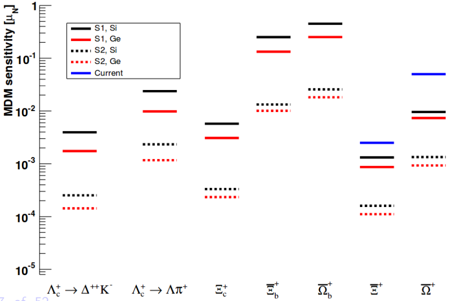
Studies of MDM/EDM reach using a W target and 2nd crystal in front of spectrometer

Si and Ge crystals with different parameters

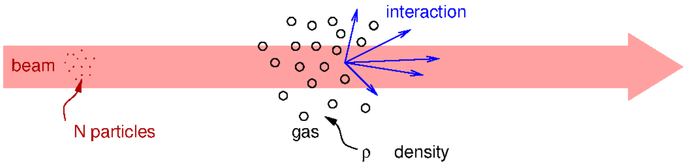
$S1 = 10^{15}$, $S2 = 10^{17}$ pots







Gas targets



$\rho(z)$ = density of gas atoms along the beam path z

At $T = 293\ K$, $p = 10^{-7}$ mbar means $\rho = 2.5 \cdot 10^{9}\ \mathrm{Molec/cm^3}$

N = number of beam particles passing

$\Theta = \int \rho(z)\, dz$ = "target thickness" (areal density)

$\mu = \sigma_{\mathrm{phys}} \cdot N \cdot \Theta$ = probability of an interaction per pass

$R = f_{\mathrm{rev}} \cdot \mu = \sigma_{\mathrm{phys}} \cdot L$ = rate of interactions is

$L = f_{\mathrm{rev}} \cdot N \cdot \Theta$ = luminosity

$\tau^{-1} = \sigma_{\mathrm{phys}}\, f_{\mathrm{rev}}\, \Theta$ = life time

Beam-gas imaging at LHCb: the genesis of SMOG

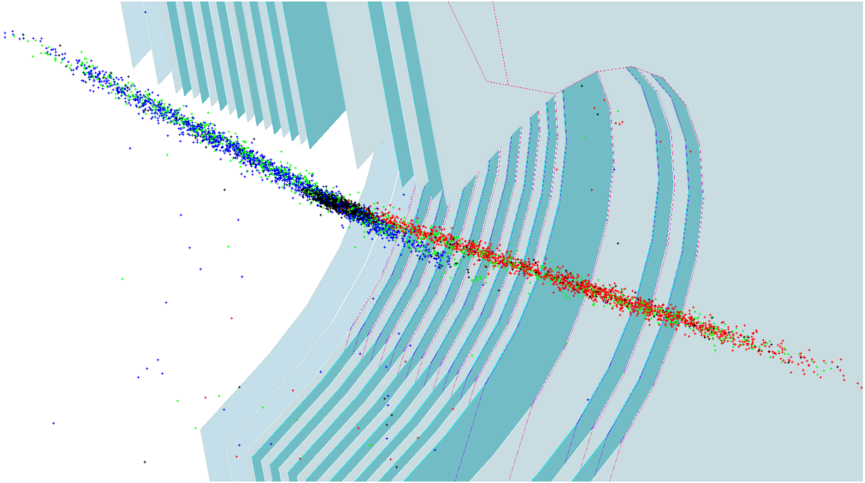
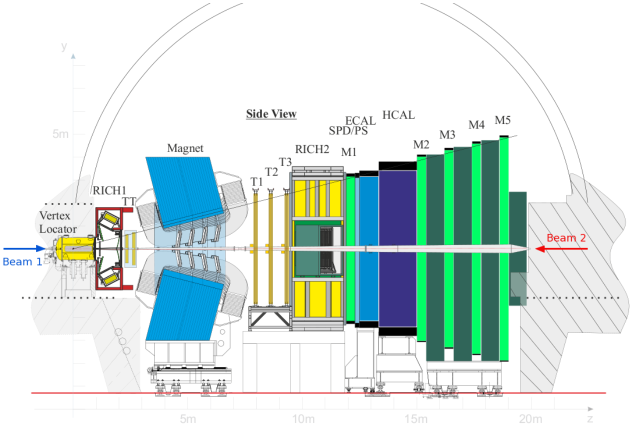
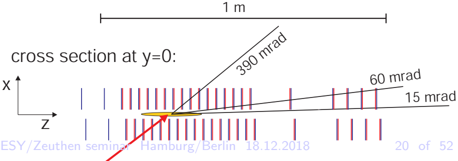


figure from [12]

Physics Beyond Colliders

Beam-gas imaging: LHCb

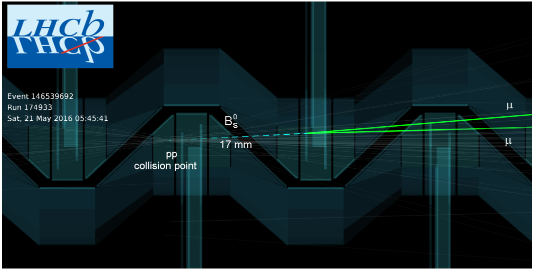




Beam-gas imaging: key detector is the VELO

- silicon strips
- 8 mm from the beams
- vertical planes
- excellent vertex resolution
- good acceptance in θ and z
- also for forward-boosted beam-gas interactions!

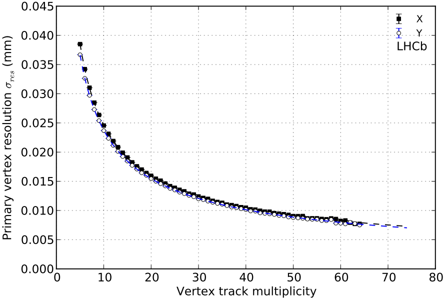
a $p + p$ interaction



Beam-gas imaging: crucial is the vertex resolution

Beam size at LHCb during luminosity calibration runs is typically 0.10 mm.

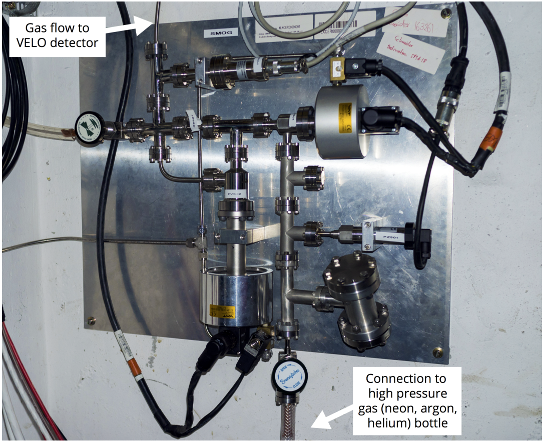
Resolution for $p + p$ interactions:



LHCb actually performed a first beam-gas imaging luminosity calibration with just residual gas ... and then wanted more of it!

figure from [12]

Beam-gas imaging: **S**ystem for **M**easuring the **O**verlap with **G**as



Vacuum too good :-)

Stop the VELO ion pumps (beam vacuum)

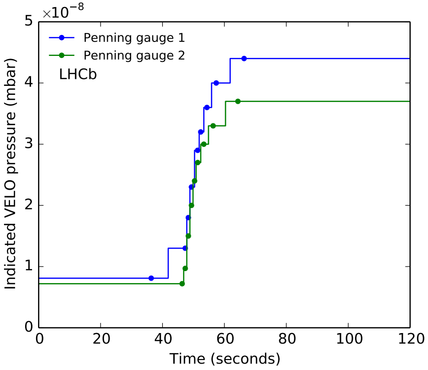
Inject tiny amount of gas (Ne, He, Ar) in VELO beam vacuum

Increase pressure from 10^{-9} to 10^{-7} mbar

Physics Beyond Colliders

Beam-gas imaging: first smogging in the LHC, 2012

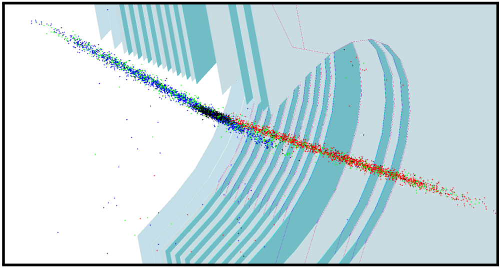
Adding a little bit of gas (here Neon) [12]



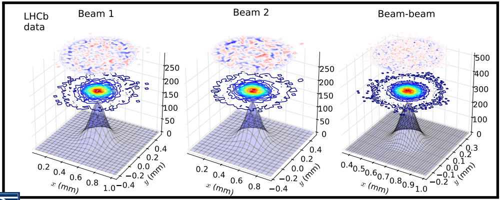
Beam-gas rate increases. As expected.

Gas targets

Beam-gas imaging: [12, 13]



$\Downarrow$



Measure and fit the vertex distributions of each of the two colliding beams and of the collision region, then calculate the overlap integral

$$\Omega = 2c \int \rho_1(\mathbf{r},t)\,\rho_2(\mathbf{r},t) dr^3\, dt$$

which gives the luminosity (bunch populations are measured separately)

$$L = f_{\text{rev}} N_1\, N_2\, \Omega$$

Final L precision $< 2\%$

NB: you don't need to know the gas density!

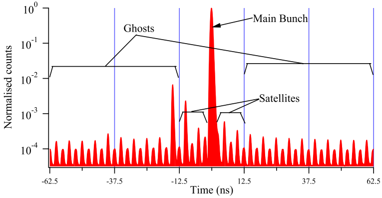
Physics Beyond Colliders

Beam-gas imaging: ghost charge

Bunch population normalisation at LHC:

$$L = f_{\mathrm{rev}} \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

- crucial for direct luminosity determination
- **D**irect **C**urrent **C**urrent **T**ransformer measures precisely the total beam population
- **F**ast **B**unch **C**urrent **T**ransformer measures relative bunch charge, but not if charge is below a certain threshold.



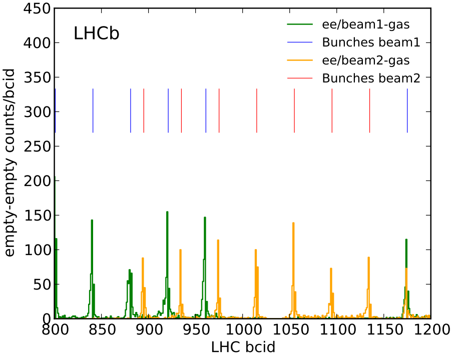
(courtesy of J. Adam)

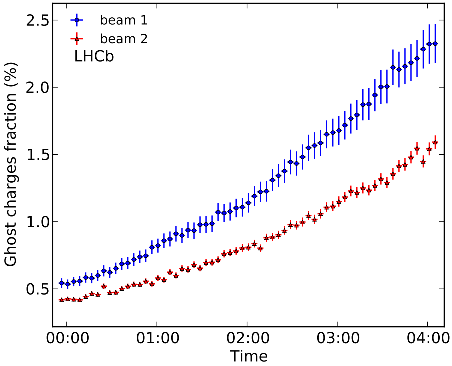
⇒ **How to normalize the N_1 and N_2 ?**

⇒ **How much charge in non-filled bunch slots ?? (ghost charge)**

Gas targets

Beam-gas imaging: ghost charge measured by beam-gas rates [12]





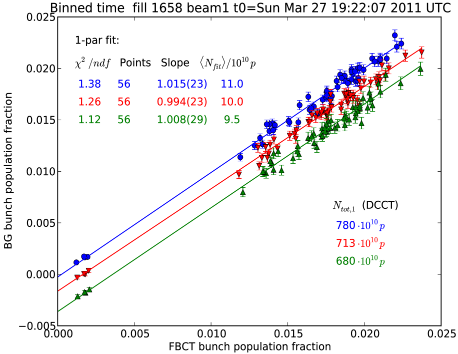
Left: filled-slot rates are suppressed from plot

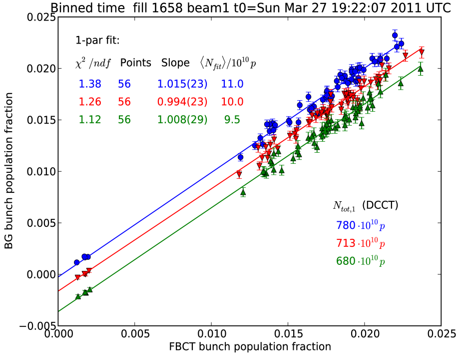
Right: ghost population over total beam population vs time

Gas targets

Physics Beyond Colliders

Beam-gas imaging: relative bunch population measurements by beam-gas rates [14]



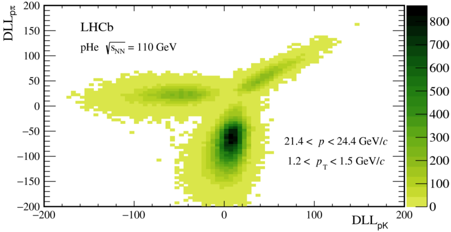


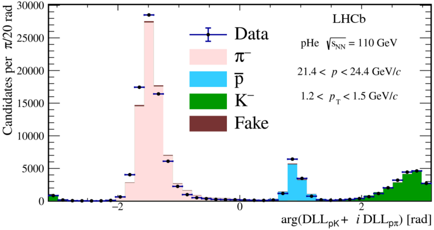
Different colors/markers are just different time periods (with an artificial offset for clarity, except for the blue)

SMOG: switch Neon to Helium...

6.5 TeV beam on gas target

figures from [9]



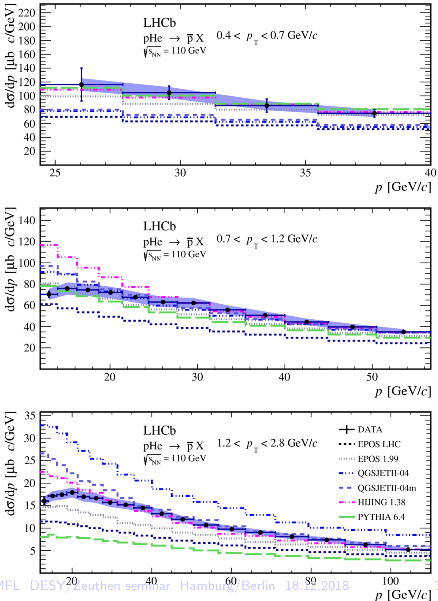


fit the PID distribution of neg charged tracks and get the relative contribution of π^-, K^- and $\bar{p}$

result of the fit projected into the variable arg(DLLpK+iDLLpπ).

Gas targets

figure from [9]



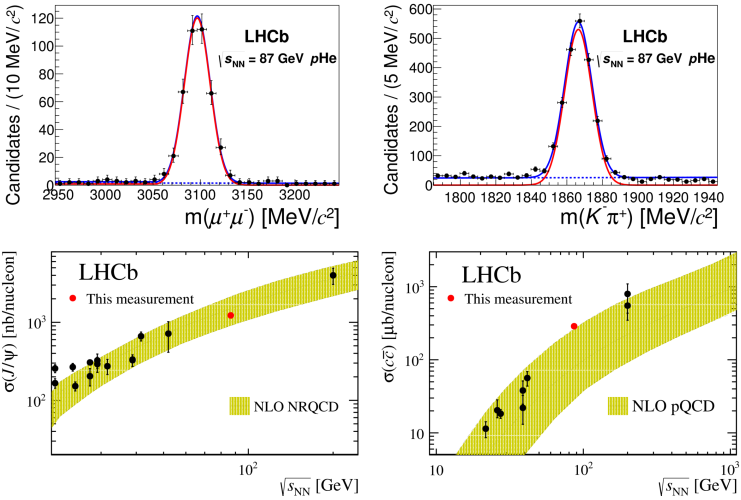
differential cross section for production of $\bar{p}$ from p-He interactions (vs the $\bar{p}$ momentum) in three different transverse momentum bins (p_T)

But ? ... gas density not known
how was the cross section normalized ?

see later

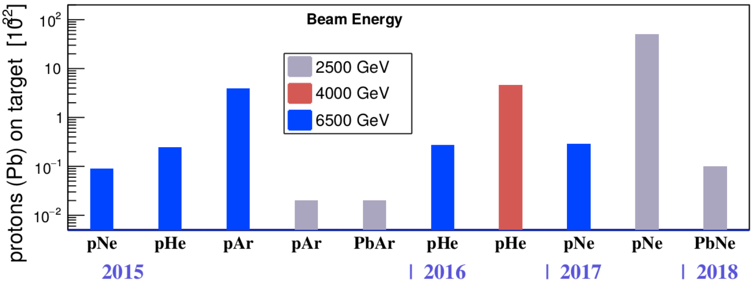
Gas targets

figures from [10]



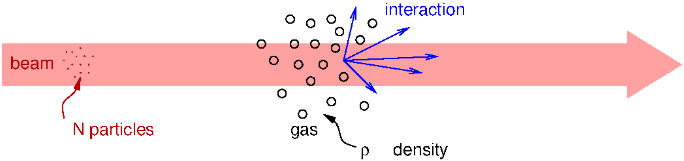
Gas targets

Summary of FT physics samples collected by LHCb



The data size is given in terms of delivered p or Pb on target (pot).
At $2 \cdot 10^{-7}$ mbar, 10^{22} pots $\Leftrightarrow 5\ \mathrm{nb}^{-1}$ per meter of gas
(actual pressure and data taking efficiency vary among samples)
(PbNe VALUE TO BE UPDATED...)

Gas targets



Typical LHCb SMOG performance (Run2)

$\rho(z) \approx 5 \cdot 10^9 \text{cm}^{-3}$ ($\approx 2 \cdot 10^{-7}$ mbar at 293 K)

$N \approx 10^{11}$ one bunch

$\Theta = \int \rho(z)\, dz \approx 5 \cdot 10^{11} \text{cm}^{-2}$ (useful over about 1 m)

$L_{\text{bunch}} = f_{\text{rev}} \cdot N \cdot \Theta \approx 6 \cdot 10^{26} \text{cm}^{-2}\,\text{s}^{-1}$ per bunch

$n_{\text{bunches}} \approx 10...50$

$\tau >$ thousands of hours...

Gas targets

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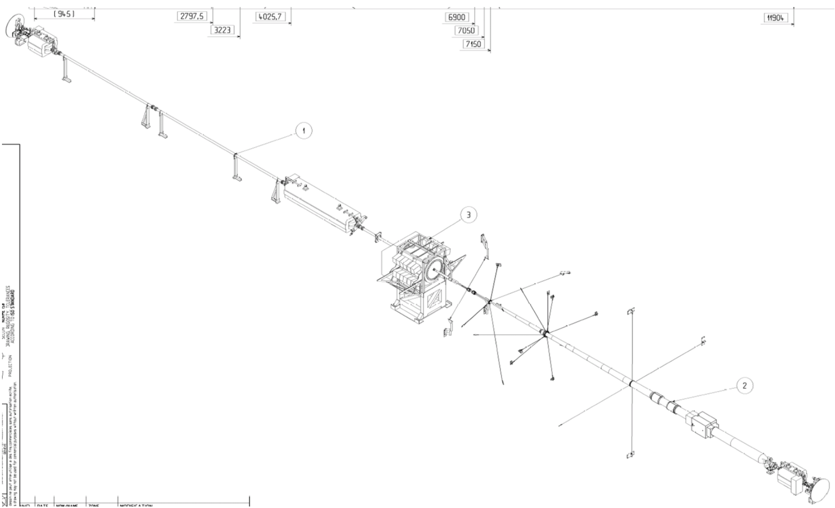
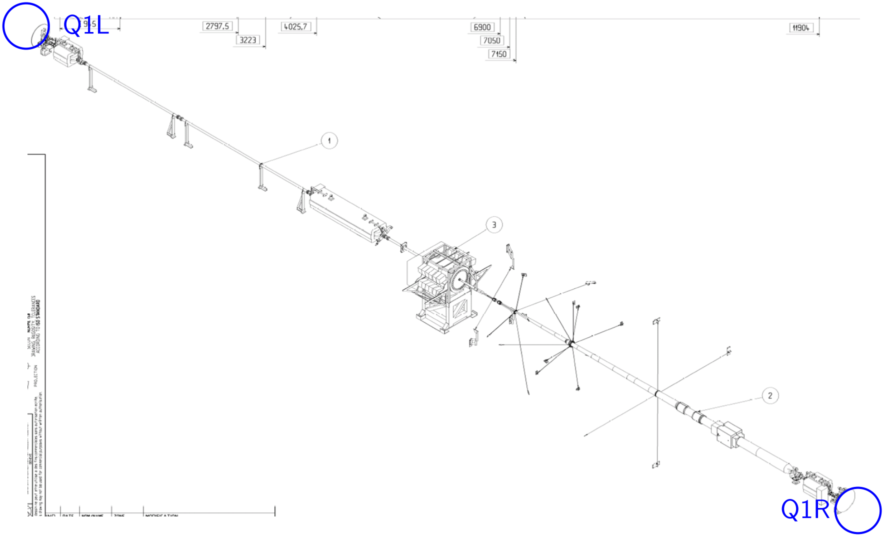
SMOG shortcomings

How to do better than SMOG ?

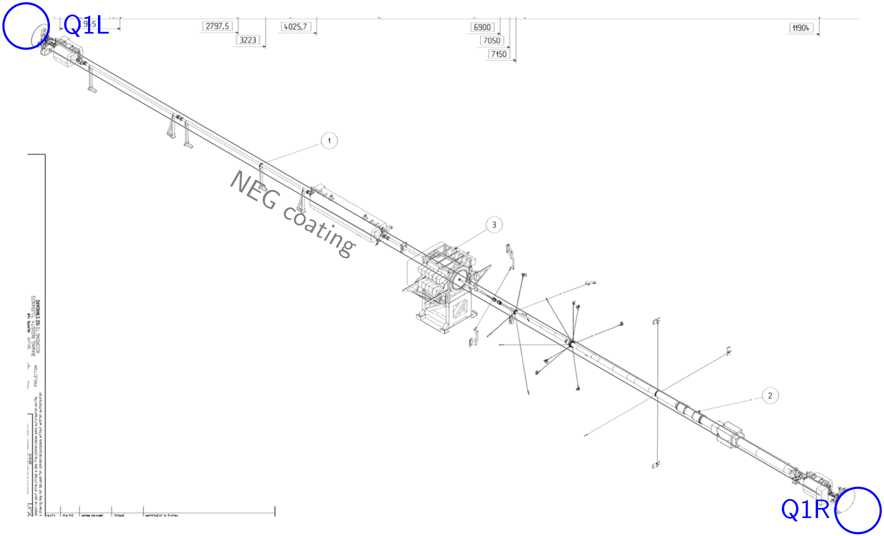
Gas targets



Gas targets



Gas targets


Q1L
2797,5
3223
4025,7
6900
7050
7150
11904
1
NEG coating
3
2
Q1R

Storage cell principle: see e.g. in [15]
flux Q in center of cell (in mbarℓ/s)
gas of molecular mass M.
Tube conductance (in ℓ/s):

$$C = 3.81 \sqrt{\frac{T}{M}} \frac{D^3}{L + 1.33D}$$

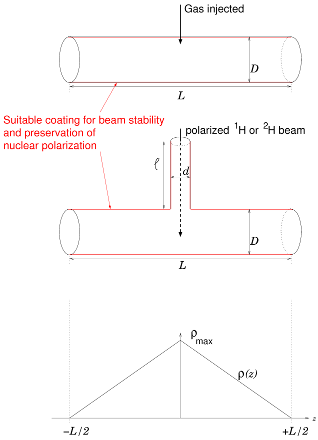
for a tube at temperature T (in K),
length/diameter L/D (in cm).
Total cell conductance:

$$C_{\rm cell} = 2\,C(\tfrac{L}{2}, D) + C(\ell, d)$$

polarized case

Peak density value

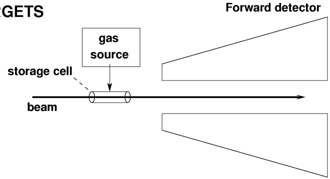
$$\rho_{\rm max} = \frac{Q}{C_{\rm cell}} 2.5 \cdot 10^{16} \frac{\text{molec}}{\text{mbar cm}^3}$$



Gas targets

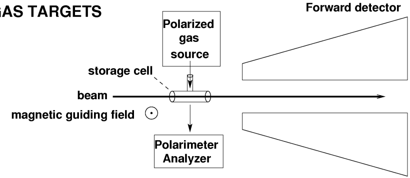
UNPOLARIZED GAS TARGETS

He, Ne, Ar, H_2, D_2, N_2 ...



POLARIZED GAS TARGETS

H, D, ^{3}He



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typical wish list (LHC FT luminosities with unpol. gases) (not approved!)

Assuming: 3 yrs, $\mu < 0.4$,

System	$\sqrt{s_{NN}}$ (GeV)	avg pressure (mbar)	L ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\mathcal{L}$ (pb^{-1})
pH$_2$	115	$4 \cdot 10^{-5}$	$6 \cdot 10^{31}$	4.6	$2.5 \cdot 10^{6}$	150
pD$_2$	115	$2 \cdot 10^{-5}$	$3 \cdot 10^{31}$	4.3	$0.3 \cdot 10^{6}$	9
pAr	115	$1.2 \cdot 10^{-5}$	$1.8 \cdot 10^{31}$	11	$2.5 \cdot 10^{6}$	45
pKr	115	$0.8 \cdot 10^{-5}$	$1.2 \cdot 10^{31}$	12	$2.5 \cdot 10^{6}$	30
pXe	115	$0.6 \cdot 10^{-5}$	$0.9 \cdot 10^{31}$	12	$2.5 \cdot 10^{6}$	22
pHe	115	$2 \cdot 10^{-5}$	$3 \cdot 10^{31}$	3.5	$3.3 \cdot 10^{3}$	0.1
pNe	115	$2 \cdot 10^{-5}$	$3 \cdot 10^{31}$	12	$3.3 \cdot 10^{3}$	0.1
pN$_2$	115	$1 \cdot 10^{-5}$	$1.5 \cdot 10^{31}$	9.0	$3.3 \cdot 10^{3}$	0.1
pO$_2$	115	$1 \cdot 10^{-5}$	$1.5 \cdot 10^{31}$	10	$3.3 \cdot 10^{3}$	0.1
PbAr	72	$8 \cdot 10^{-5}$	$1 \cdot 10^{29}$	0.3	$6 \cdot 10^{5}$	0.060
PbH$_2$	72	$8 \cdot 10^{-5}$	$1 \cdot 10^{29}$	0.2	$1 \cdot 10^{5}$	0.010
pAr	72	$1.2 \cdot 10^{-5}$	$1.8 \cdot 10^{31}$	11	$3 \cdot 10^{5}$	5

See also in [17]

Gas targets

Challenges for storage cell targets in LHC:

- presence of cryogenic (superconducting) magnets near interaction points
  - heat load due to interaction products (quench limit!)
  - gas accumulation by cryosorption (SEY!)
- presence of Non-Evaporable Getter (NEG) coatings in all the warm beam pipe sections
  - coating saturation by gas load (except noble gases)
- wake fields and impedance constraints on the storage cell implementation
- aperture constraints on the storage cell implementation
  - larger aperture required at injection energy
- for the polarized gas: nuclear polarization preservation
  - suitable SC coating ?
  - depolarization mechanisms from beam beam RF fields
- how to measure the density (luminosity)?
- how to measure the polarization ?

Gas targets

Physics Beyond Colliders

Non-getterable gases (He, Ne, Ar, Kr, Xe):

- gas is not pumped by NEG coating, diffuses to warm-to-cold transitions
- cryosorption, impacts on local Secondary Electron Yield
- He, Ne, Ar: deposits can be "cured" by partial warm up of cold areas (migration to cold bore)
- Kr, Xe: same trick does not work, too high temperature is required

Getterable gases (H_2, D_2, O_2, N_2):

- Pumping capacity is eaten up by the injected gas
- SEY remains probably OK (to be checked)
- hydrogen is a special case: diffuses in bulk, NEG coating becomes brittle (peel off!)
  - embrittlement limit for H_2 in commercial NEG: about 40 mbar $\ell/g^{-}1$
  - Safe margin for TiZrV films (LHC): 4 mbar $\ell/g^{-}1$
  - Nominal thickness: $2\ \mu$m
  - Mass density: 5.5 g/cm^3
  - NEG film mass per metre of beam pipe (D=5 cm): 1.7 g/m

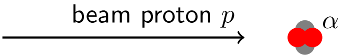
⇒ dedicated pumping schemes / injection scenarios for diff. gas species

Gas targets

Luminosity (gas density) measurement

Use a calibrated pressure gauge and molflow simulations ? (can reach 10%?)

Or look for a known reference cross section ... Example: p-He



p-α interactions
tough
no usable ref reaction

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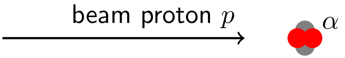

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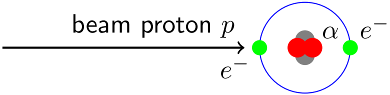
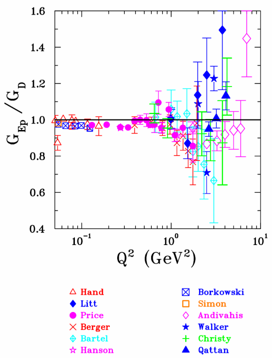


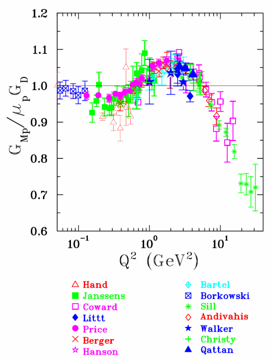
elastic p-e scattering
Measure n_e
Assume $n_\alpha = 2\,n_e$

Gas targets

$e + p \to e + p$ cross section

$$\frac{1}{2\pi}\frac{d\sigma}{d\cos\theta} = \frac{G_{E,p}^2 + \kappa\left(1 + 2\left(1+\kappa\right)\mathrm{tg}^2\frac{\theta}{2}\right)G_{M,p}^2}{1+\kappa} \qquad \kappa = \frac{Q^2}{4M^2} \tag{1}$$





figures from [16]

$$\begin{aligned} G_{E,p} &\approx G_D \\ &= \left(1 + \frac{Q^2}{0.71\ \frac{\mathrm{GeV}}{c^2}}\right)^{-2} \\ G_{M,p} &\approx 2.79\, G_{E,p} \end{aligned} \tag{2}$$

Assuming some acceptance and efficiency for the elastic e^- events, one guestimate that with a $L \sim 2 \cdot 10^{28}\ \mathrm{Hz/cm^2}$ the rate is about 1 Hz.
Such a luminosity can be achieved with a helium pressure of about $2 \cdot 10^{-7}$ mbar and 35 proton bunches of 10^{11} p.

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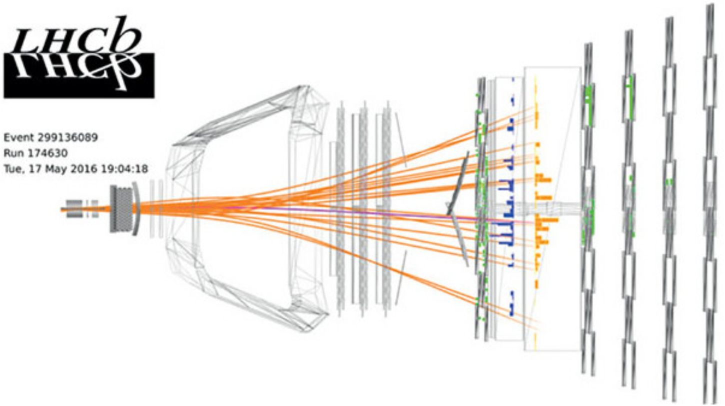
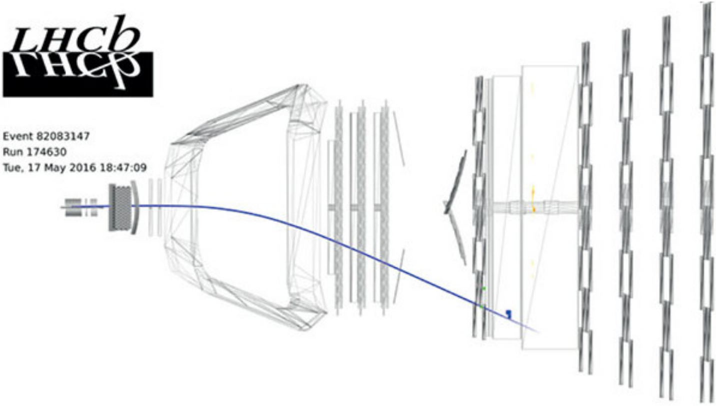
A p-He inelastic (hadronic) event in LHCb



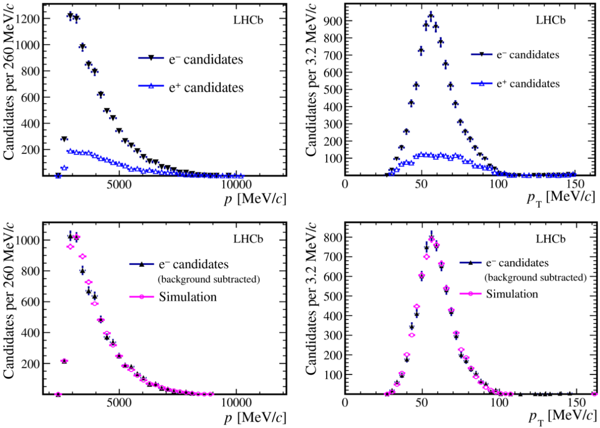
Gas targets

A p-He elastic electron event in LHCb



Gas targets

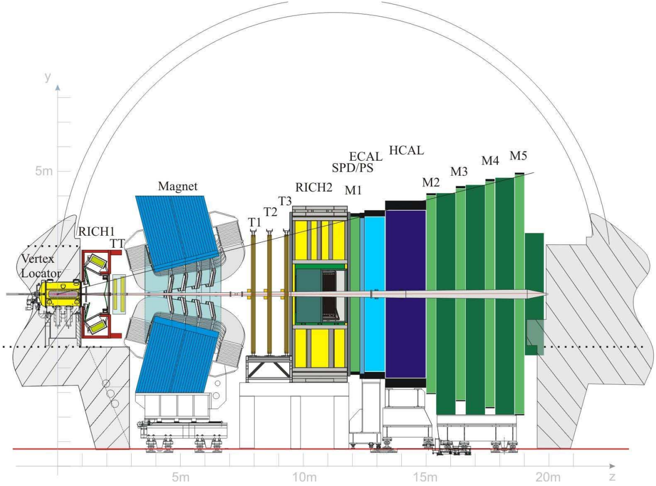
figure from [9]



"LHCb est mort. Vive LHCb!"

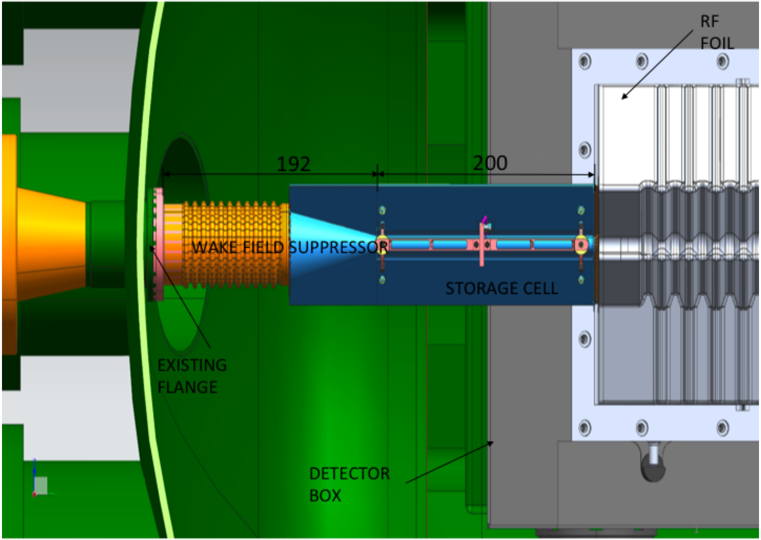
Gas targets

LHCb Upgraded detector (now being installed)



Gas targets

SMOG2 = SMOG upgrade, introducing a storage cell in the VELO



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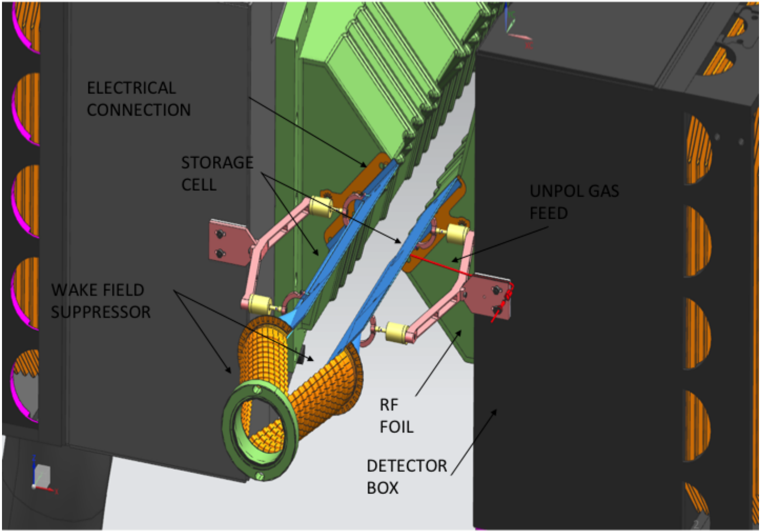

Summary and outlook

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  - Bent channeling crystals, solid targets
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- A first step using a storage cell in LHCb is already being taken
- Future: crystals, solid targets, polarized gas targets in LHCb ?
- ... or elsewhere in the LHC ?

THANK YOU FOR YOUR ATTENTION

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