Beam-gas interactions (are not just a nuisance)

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A dual view

Nuisance

Asset
Outline

• Introduction:
  ▶ beam-gas basics
  ▶ beam-gas interaction cross sections
  ▶ beam-gas losses and beam life time

• Detector background:
  ▶ take an example (ALICE)

• Beam-gas imaging: (from LHCb)
  ▶ beam profiles
  ▶ ghost charge, etc

• Gaseous fixed targets:
  ▶ physics with beam-gas (from LHCb)
Introduction

beam

gas

interaction
Introduction: the Beam & the Gas

Beam Residual gas

particles: \( p^\pm, e^\pm, ^{208}\text{Pb}^{82+}, \ldots \)
molecules, mostly containing the following atoms: 
H, C, O, (N, He) ...

velocity: \( \approx c = 3 \cdot 10^8 \text{ m/s} \)
\( \approx 100 \text{ m/s} (\ll c) \)

energy: typically MeV to TeV, and
often \( E \gg mc^2 \)
thermal, \( E_{\text{kin}} = \frac{3}{2} k_B T \approx 1...40 \text{ meV} \)
A typical spectrum (LHCb VE_{rtexLO}cator vacuum, Rest Gas Analyzer)
Introduction: the Gas

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What is a beam-gas interaction?
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Beam particles can interact with residual gas atoms by

- **strong interaction** ("hadronic"): relevant only for **hadron** beams (protons, ions, ...), which interact with the **nuclei** of the residual gas atoms
  - strong, but range is short $\sim 1\text{ fm} \sim \text{size of a nucleon}$

Q1: Generally, are beam-gas interactions more relevant for cyclical accelerators or linacs?
Introduction: beam-gas interactions

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  - medium strong (strong/137), but long range (infinite!)
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NB: the weak interaction is irrelevant in this context.

Q1: Generally, are beam-gas interactions more relevant for cyclical accelerators or linacs?
Introduction: beam-gas interactions

The density of gas atoms along the beam path $z$ is $\rho(z) = \text{density of gas atoms along the beam path } z$.

What is the probability $\mu$ of an interaction per pass?

Define:
- $N = \text{number of beam particles passing}$
- $\Theta = \int \rho(z) \, dz = \text{“target thickness”}$

Clearly, expect $\mu \propto N \cdot \Theta$

The proportionality constant $\sigma_{\text{phys}}$

$$\mu = \sigma_{\text{phys}} \cdot N \cdot \Theta$$

is the cross section of the physical process.
Units of $\sigma_{\text{phys}}$ are those of a surface area, but... tiny, tiny.

Hence, define the **barn**:  $1 \text{ b} = 10^{-24} \text{ cm}^2$

barn (en) = grange (fr) = Scheune (de) = fienile (it) = ladugård (se)

For fun, the origin of this name from wikipedia

**Etymology**  [edit]

The etymology of the unit barn is whimsical: during wartime research on the atomic bomb, American physicists at **Purdue University** needed a secretive unit to describe the approximate cross sectional area presented by the typical nucleus ($10^{-28} \text{ m}^2$) and decided on "barn." This was particularly applicable because they considered this a large target for particle accelerators that needed to have direct strikes on nuclei and the American idiom "couldn't hit the broad side of a barn"[2] refers to someone whose aim is terrible. Initially they hoped the name would obscure any reference to the study of nuclear structure; eventually, the word became a standard unit in nuclear and particle physics.[3][4]
Repeat the passes many times, say, at a frequency $f$. The rate $R$ of interactions is then

$$R = f \cdot \mu = \sigma_{\text{phys}} \cdot L$$

where $L = \text{luminosity}$ (how intense or dense the beam and target are)

$$L = f \cdot N \cdot \Theta$$
For example, hadronic cross section of $p + p$ (total and elastic) from [4]
\( \sqrt{s} \)? what’s that?
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You can change frame of reference, i.e. move yourself relative to the gas and beam. This changes the apparent speed of the gas and beam particles.
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But the total interaction rate **cannot** (and does not) depend on the speed of the observer!
It is the same for all observers!
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We need a bit of relativistic kinematics.
Introduction: beam-gas interactions

\[ \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} \]

\[ m \]

\[ \text{Einstein} \]
Introduction: beam-gas interactions
**Lorentz boost** (along $z$): There should be a $c$ multiplying each momentum component. Here suppressed, set $c = 1.$

Observe particle with energy $E$ and momentum $\mathbf{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$

Move yourself by velocity $v$ along $z$.

Define $\beta = \frac{v}{c}$ and $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$

The new “four-momentum” vector is:

$\begin{pmatrix} \tilde{E} \\ \tilde{p}_x \\ \tilde{p}_y \\ \tilde{p}_z \end{pmatrix} = \begin{pmatrix} \gamma (E - \beta p_z) \\ p_x \\ p_y \\ \gamma (p_z - \beta E) \end{pmatrix}$

These are the particle’s energy and momentum that you observe in your new frame.
The (invariant) rest mass $m$ of a particle $(E, \mathbf{p})$ is given by
\[ m^2 = E^2 - p^2 = E^2 - (p_x^2 + p_y^2 + p_z^2) \]
... $m$ should be $mc^2$

Coming back to our beam particle $(E_1, \mathbf{p}_1)$ and gas particle $(E_2, \mathbf{p}_2)$ ...

The frame invariant $s$ is defined as

\[
s = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 \\
= m_1^2 + m_2^2 + 2 (E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)
\]

Exercise: check $s$ is the same in any observer frame.

$\sqrt{s}$ is the **total available energy** in the system where $\mathbf{p}_1 = -\mathbf{p}_2$. 
Introduction: beam-gas interactions

Two standard cases:

a) like particles collider mode
\[ p_1 = -p_2 \text{ and } m_1 = m_2, \ E_1 = E_2 = E: \]
\[ \sqrt{s} = E_1 + E_2 = 2E \]

b) fixed target mode
\[ p_1 \neq 0, \ p_2 = 0: \]
\[ \sqrt{s} = (m_1^2 + m_2^2 + 2E_1m_2)^{\frac{1}{2}} \approx (2E_1m_2)^{\frac{1}{2}} \text{ (if } E_1 \gg m_1, m_2) \]

For LHC, with 6.5 TeV proton beams:
\[ p + p \text{ collider: } \sqrt{s} = 13 \text{ TeV} \]
\[ p + ^1H \text{ beam-gas: } \sqrt{s} = \text{Exercise} \ (\text{gas is here hydrogen nucleus, i.e. also } p) \]
Introduction: beam-gas interaction cross sections

For example, cross section of $p + p$ (total and elastic) from [4]
Next, we give some approximate formulas for estimating rates of beam-gas interactions.

If looking at beam-gas losses and beam life times, we are mostly interested in total cross sections (assuming, to first order, any interaction will disturb the beam particle).

In what follows, $A$ and $B$ denote nucleon numbers, as well as particle species.
1.a proton beam

- $A$ is a nucleus at rest
- Hadronic interactions. Elastic or inelastic.
  - short range $\sim 1 \text{ fm} \sim$ size of a nucleon
- For a proton beam and proton target ($B = A = 1$): $p^1H$ is known from $p + p$ experiments which gives the cross section $\sigma_{p+p}$ usually in center of mass frame. $\Rightarrow$ find the corresponding $p_{\text{lab}}$.
- For other gases: inelastic cross section $p + A$ is [8]

\[
\sigma_{p+A} \approx \sigma_{p+p} \cdot A^{0.7}
\]

at the equivalent $\sqrt{s_{pp}}$ !

(each nucleon carries a fraction $A^{-1}$ of the nuclear momentum)

Exercise: $p + \text{Ne}$
Introduction: beam-gas interaction cross sections

1.b ion beam

- For ion beam $B$ (like $B = 208$): $B^+ + ^1H$ is same as $p + A$ but boosted to rest frame of $p$.
- For nuclei other than H, the inelastic cross section is often seen as

$$\sigma_{A+B} = \sigma_{p+p} \cdot (A^{\frac{1}{3}} + B^{\frac{1}{3}})^2$$

This is approximate, but good for guesstimates.
There are other formulae depending on energy regime and size of $A$ and $B$... See e.g. [7] which gives

$$\sigma_{A+B} = 54 \text{ mb} \cdot (A^{\frac{1}{3}} + B^{\frac{1}{3}} - 4.45/(A^{\frac{1}{3}} + B^{\frac{1}{3}}))^2$$

at 1.88 GeV/nucleon.
2. electron beams

- only electromagnetic interactions
- elastic $e + p$: see next slide.
- inelastic $e + A$, see [9]
- inelastic $e + (A + Ze^-)$, see [12]

NB: screening of nuclear charge by atomic electrons can be important

- Bremsstrahlung
  $e^- + \text{Coulomb field} \rightarrow e^- + \gamma$
- Pair production
  $e^- + \text{Coulomb field} \rightarrow e^- + e^+ + e^-$
- Møller scattering
  $e^- + e^- \rightarrow e^- + e^-$
- Bhabha scattering
  $e^+ + e^- \rightarrow e^+ + e^-$
- Annihilation
  $e^+ + e^- \rightarrow 2\gamma$

NB: nucleus is not at all to scale!
Example: $e + p \rightarrow e + p$ cross section

Work in the Proton Rest Frame [10] (neglecting the electron mass $m$)

$$\frac{1}{2\pi} \frac{d\sigma}{d\cos\theta} = \left[ \frac{2\alpha \hbar c E \cos\frac{\theta}{2}}{Q^2} \right]^2 \frac{E'}{E} \frac{G_{E,p}^2 + \tau (1 + 2 (1 + \tau) \tan^2\frac{\theta}{2}) G_{M,p}^2}{1 + \tau}$$

$\theta = \text{polar electron angle after scattering}$

$q = p - p' = \text{momentum transfer with } p/p' \text{ and } E/E' \text{ the electron momenta and energies before/after scattering in the PRF.}$

$Q^2 = q^2 - \nu^2 = 4EE' \sin^2\frac{\theta}{2} = 4\text{-momentum transfer squared.}$

$\nu = E - E' = \text{energy transfer.}$

$\tau = Q^2/4M^2, \ M \text{ is the proton mass.}$

$\alpha \approx 1/137 \approx 0.0073 \ (\text{fine structure constant}), \ \hbar c \approx 0.1973 \ \text{GeV fm.}$

$G_{E,p}(Q^2), \ G_{M,p}(Q^2) = \text{electric and magnetic proton form factors ...}$
**Example:** \( e + p \rightarrow e + p \) cross section

\( G_{E,p} \) and \( G_{M,p} \) are the electric and magnetic proton form factors. Describe the charge and magnetic distribution in the proton. Approximately given by dipole formula [10]

\[
G_{E,p} \approx G_D = \left(1 + \frac{Q^2}{0.71 \text{ GeV}/c^2}\right)^{-2} \quad G_{M,p} \approx 2.79 \ G_{E,p}
\]

More accurate fits of exp. data can be found in literature.
Introduction: beam-gas interaction cross sections

Example: $e + p \rightarrow e + p$ cross section continued ...

Figure: figures from scholarpedia [11]
Introduction: beam-gas losses and beam life time

Losses due to beam-gas collisions, via some process $\sigma_{\text{phys}}$, in a cyclical accelerator, with constant static pressure. (assuming this is the only source of bunch population losses!)

Bunch with population $N(t)$. Decay rate is

$$-\frac{dN}{dt} = R = N(t) \cdot \sigma_{\text{phys}} f \cdot \Theta = \frac{N(t)}{\tau}$$

where we defined

$$\tau^{-1} = \sigma_{\text{phys}} f \Theta$$

The solution is simply

$$N(t) = N(0) \cdot e^{-t/\tau}$$

And $\tau$ is the **life time** of the bunch population $N(t)$. 
Example:

Residual pressure $p = 10^{-9}$ mbar, hydrogen ($\text{H}_2$), at $T = 5$ K, over 20 km

$$pV = n k_B T \quad \Rightarrow \quad \rho = \frac{p}{k_B T} \approx 1.5 \cdot 10^9 \, \text{H}_2/\text{cm}^3$$

This is the concentration of molecules.

Atoms: multiply by 2.

Take $\sigma_{\text{phys}} = 55$ mb and $f = 11245$ Hz

$$\tau = (5.5 \cdot 10^{-26} \, \text{cm}^2 \cdot 11 \, \text{kHz} \cdot 3 \cdot 10^9 \, \text{cm}^{-3} \cdot 2 \cdot 10^6 \, \text{cm})^{-1}$$

$$= 2.8 \cdot 10^5 \, \text{s} = 77 \, \text{h}$$
Are there other ways to lose beam particles? Yes, sure! Ideally we want to lose them all at the experiment (the Interaction Point)
Let’s compare to beam-gas losses.
Consuming particle bunches by collisions is called “burn off”:

\[
- \frac{dN_1}{dt} = - \frac{dN_2}{dt} = R = C \ N_1(t) \ N_2(t)
\]

with \( C = \sigma_{\text{phys}} \cdot f/(4\pi\sigma_x\sigma_y) \)
This can be solved by wrestling with hyperbolic functions...
It is more digestable when \( N_1(t = 0) = N_2(t = 0) \equiv N_0 \):

\[
\frac{dN}{dt} = -C \ N^2(t) \quad \Rightarrow \quad N(t) = \frac{N_0}{C \ t \ N_0 + 1}
\]

The value \( \tau = (C \ N_0)^{-1} \) is the half life of \( N(t) \).
Example of burn off:

Take some collider with

- $\sigma_{\text{phys}} = 105 \text{ mb}$
- $f = 11245 \text{ Hz}$
- $N_0 = 1.2 \cdot 10^{11}$ protons
- $\sigma_x = \sigma_y = 11 \mu\text{m}$
- 2 equally eager experiments

\[
\Rightarrow \tau_{\frac{1}{2}} = 15 \text{ h}.
\]

Compare to previous $\tau = 77 \text{ h}$.

Usually, one wants $\tau(\text{beam-gas}) > \tau_{\frac{1}{2}}(\text{burnoff})$
In some cases, it can happen that the beam-gas interactions in the neighborhood of an experiment become a problem.

A notable example: ALICE at LHC.

But why ALICE?

Long story short: ALICE is designed for low luminosity compared to ATLAS, CMS and LHCb :-)\), and the LHC in $p + p$ mode runs primarily for the latter experiments

There is a factor $10^4$ mismatch in luminosity requirement !!
Detector background: meet ALICE
Detector background: meet ALICE

ALICE = huge Time Projection Chamber (TPC) [5]

- inner/outer diameter of 1.2/5 m, length 2 × 2.5 m
- Drift time up to 90 µs (one LHC revolution !)
- Huge high voltage in field cage, 100 kV
- Current trip limit: 7 µA, i.e. about 500 kHz, $7 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$

Two running modes (trigger configurations):
- “Minimum bias” acquisition, $2 \cdot 10^{29} \text{cm}^{-2}\text{s}^{-1}$, rate ≈ 150 kHz
- “Rare events” acquisition, $8 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$, rate ≈ 600 kHz
Detector background: TPC cartoon

Time projection chamber principle

- Field cage
- Electric field
- Gas
- Segmented detectors
- Measure R, Phi, T
- Beam 1
- Beam 2
Detector background: TPC cartoon

Charged particle ionizes, liberates electrons
Electrons drift $\sim 0.7$ mm per bunch crossing of 25 ns
Bad luck! Overlapping track from new interaction...
Confusing result
ALICE had two main problems:

1. Minimum bias trigger accepts beam-gas events
2. Beam-gas rates precluded turning on the high voltage of the TPC

But how does one find out it is due to beam-gas interactions?

What are the signatures?
Detector background: ALICE pinning down beam-gas
Detector background: ALICE pinning down beam-gas
1. Use (two) timing detectors to discriminate from beam-beam collisions
   Time sum versus time difference will discriminate from bb collisions
2. Plot background rate versus beam\_intensity \times pressure
   If proportional, it’s likely to be beam-gas
   Caveat: pressure itself can depend on beam intensity!
3. Use forwardness of tracks
   If tracks flying fwd and bwd, it’s likely not a beam-gas.
4. Use vertexing to distinguish beam-gas from halo
   If all tracks point to a vertex inside beam pipe, it’s a beam-gas
Detector background: ALICE modeling beam-gas
There are powerful simulation tools around

- FLUKA simulation tool [16]
- GEANT simulation tool [17]
- Pythia - The Lund Monte Carlo! [18]
- EPOS generator [19]
- HIJING Monte Carlo Model, [20]
- SixTrack - 6D Tracking Code [21] etc...

Hello Lund ;-)
Fig. 6: Map of the charged particles fluence (in cm$^{-2}$) inside UX25 per beam–gas interaction in LSS2. Schematic of the ALICE geometry in R–Z coordinates is overimposed.

From ref. [15]
Detector background: pressures around IP2

**Exercise:** ALICE pressure requirement

Assume:

- beam-gas interactions originating from up to \( L = 100 \text{ m} \) away leave tracks in TPC and induce a triggered event.
- flat profile of hydrogen residual pressure \( P(\text{H}_2) \) at \( T = 293 \text{ K} \).
- nominal LHC conditions (\( N = 1.1 \cdot 10^{11} \text{ p/bunch}, \ n_b = 2800 \text{ bunches at 7 TeV} \)).

**Question:** How low should the pressure \( P(\text{H}_2) \) be to contribute less than 50 kHz of triggers in ALICE?

**Answer:**
\[
\sigma_{\text{inelastic}, p+p} = 45 \text{ mb (elastics do not contribute!)}
\]

\[
R = \sigma_{\text{inelastic}, p+p} \ n_b \ N \ f \cdot \int \rho_{\text{H}}(z) \ dz
\]

Thus
\[
P(\text{H}_2) = \frac{1}{2} \ k_B \ T \ \rho_{\text{H}} < \frac{\frac{1}{2} \cdot 1.38 \cdot 10^{23}}{100 \text{ m} \cdot 3 \cdot 10^{14} \cdot 11245 \text{ Hz} \cdot 4.5 \cdot 10^{-30} \text{ m}^2} \cdot 293 \text{ K} \cdot 50 \text{ kHz} = 5 \cdot 10^{-10} \text{ mbar}
\]

1 mbar = 100 Pa
Detector background: IR2 mitigations

Implemented:

- Added proper low SEY coatings on warm surfaces of critical vacuum chambers
- Added pumping (ion pumps and getters)
- Added solenoids to reduce electron multipacting
- Conditioned (scrubbed) beam-viewing surfaces
- Optimized bunch patterns to reduce beam-induced vacuum degradation

Result: pressure reduced by more than one order of magnitude
Beam-gas imaging
In LHCb: beam-gas interactions are much appreciated. They are used for many purposes!

1. Beam profile measurements
2. Ghost charge measurements
3. Bunch charge measurements
4. Leads to precision luminosity measurements
5. Fixed-target physics as opposed to collider mode
6. Soon ... dynamic vacuum studies ??
3.3. TRACKING SYSTEM

3.3.2 Vertex Locator

The VELO \[54, 55, 57\] is installed directly around the interaction point. It allows to measure the trajectories of charged particles and to determine the vertices from which they originate. At LHCb, the average distance between the production vertex and the vertex of a decayed $B$-hadron is approximately 12 mm \[58\]. The trigger system uses this relatively long decay length to select $B$-events. The resolution is sufficient to identify and reconstruct $B$-hadron decays as well as to measure their lifetime and the $B_s$ oscillation frequency. An average uncertainty in the primary vertex position of 42 µm along the beam and 10 µm in the perpendicular plane is predicted, which translates into an average $B$-decay proper-time resolution of 40 fs.

The sensitive component of the VELO detector is formed by 21 stations, each consisting of two halves with each two silicon strip sensors, which measure the $R$ and $\phi$ coordinates. These are placed along the beam, enclosing the nominal interaction point. The layout of the stations is such that tracks between 15 and 390 mrad from a vertex located inside 106 mm, which corresponds to 2 of the nominal interaction point, cross at least three stations. This requirement ensures that the track will be properly reconstructed. The resulting arrangement of the stations which respects the requirements, while being close to the beam for precision, and introducing a minimum amount of material to traversing particles, is shown in figure 3.7. An additional two VELO stations, located more upstream, are called the pile-up system. This identifies bunch crossings with multiple interactions and through the first-level hardware trigger vetoes such events, as detailed in subsection 3.5.1.

$\sigma = 390$ mrad

1 m

cross section at $y=0$:

A key detector: VErtex LOcator
**key detector: VELO**

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

**resolution for $p + p$ colliding**
In a $p + p$ interaction

Event 146539692
Run 174933
Sat, 21 May 2016 05:45:41

$B_s^0$

pp collision point

17 mm
In a $p + A$ interaction
Beam-gas imaging: SMOG

System for Measuring the Overlap with Gas

Vacuum too good :-)
Inject tiny amount of gas (Ne, He, Ar) in VELO beam vacuum
Increase pressure from $10^{-9}$ to $10^{-7}$ mbar

Q3: Why Ne, He, Ar? see lecture 6
Beam-gas imaging: smogging

First SMOG in the LHC! 2012.

Adding a little bit of gas (here Neon)

Q4: should it not be $10^{-7}$ mbar ? why $4 \cdot 10^{-8}$ mbar ? see lecture 5

Beam-gas rate increases. As expected ?
**Exercise:** LHCb rate of beam-gas events

Assume:

- the LHCb high level trigger select beam-gas events that have a vertex in $-1m < z < 0$.
- flat profile of neon pressure $P(\text{Ne}) = 1.6 \cdot 10^{-7}$ mbar at $T = 293 \, K$.
- $N = 8 \cdot 10^{10}$ p/bunch at 4 TeV.

**Question:** Calculate beam-gas rate $R$ per bunch.

**Answer:**

\[
\sigma_{\text{inelastic},p+\text{Ne}} = \sigma_{\text{inelastic},p+p} \cdot 20^{0.7} = 45 \, \text{mb} \cdot 8.1 = 366 \, \text{mb}
\]

\[
\rho_{\text{Ne}} = \frac{P(\text{Ne})}{k_B T} = 4 \cdot 10^9 \, \text{cm}^{-3}
\]

\[
R = \sigma_{\text{inelastic},p+\text{Ne}} \cdot N \cdot f \cdot \rho_{\text{Ne}} \cdot \Delta z = 130 \, \text{Hz}
\]

Not exactly what the measurement says... But do not worry about that! The devil is in the details (acceptance, cross section, efficiency)
Beam-gas imaging: actually!

Ref. [1]
Beam-gas imaging: ghost charge

Bunch population normalisation at LHC:

- crucial for direct luminosity determination
- **Direct Current Transformer** measures precisely the total beam population
- **Fast Bunch Current Transformer** measures relative bunch charge, but not if charge is below a certain threshold.

\[ L = f \frac{N_1 \cdot N_2}{4\pi \sigma_x \sigma_y} \]

⇒ How to normalize the \( N_1 \) and \( N_2 \)?
⇒ How much charge in non-filled bunch slots?? (ghost charge)

(courtesy of J. Adam)
Beam-gas imaging: ghost charge

Examples of LHCb **ghost charge measurements** by beam-gas rates [1]

Left: filled-slot rates are suppressed from plot
Right: ghost population over total beam population vs time
Beam-gas imaging: relative bunch populations

Examples of LHCb **relative bunch charge** measurements by beam-gas rates [6]

Different colors/markers are just different time periods (with an artificial offset for clarity, except for the blue)
Gaseous fixed targets
Gaseous fixed targets: physics with beam-gas

Astrophysical flux ratio $\Phi(\bar{p})/\Phi(p)$ [13]

- Dark matter hint?
- Or just a background model inaccuracy?
- How many $\bar{p}$ produced by $p + \text{He}$ collisions?
- Not so well known...

Right. Now we are talking...

*We can even do physics with beam-gas interactions.*
LHCb as a fixed-target experiment: $p + A$, $Pb + A$, $A =$He, Ne, Ar ...

Here, example $p + He \rightarrow \bar{p} + X$ (preliminary)

But how to normalize the cross sections?

Remember: $\sigma_{phys} = \frac{R}{N \cdot f \cdot \Theta} \quad \Theta = \int \rho(z) \, dz = \text{target thickness}$

We need the absolute gas density. Somehow.
**Two ways** to measure the luminosity

1. **Direct**: measure the absolute density of gas

2. **Indirect**: measure $p + e$ elastic events (or $Pb + e$) [14]

   $\sigma_{\text{phys}, e+p}$ has been measured by others

   Use $e^+$ and charge symmetry to check background

   Assume

   $$\rho_A = \frac{\rho_e}{Z}$$

   **Q5**: How to do that?

   **Q6**: Could that be wrong?

   "From JLAB to LHC"… Exercise: calc. boost at LHC, compare to JLAB.
Single electron event!
Gaseous fixed targets: physics with beam-gas

![Graphs showing the number of candidates per 260 MeV/c and 2.4 MeV/c for different p values, with LHCb Preliminary data indicating e⁻ candidates and e⁺ candidates.](image)
Beam-gas interactions: other effects

Sorry, no time to cover:

- radiation from beam-gas interactions (to downstream devices) see lecture 4 and Ref. [15]
  - apart from luminosity, very similar to radiation from collimation
  - exercise: why is this negligible for ATLAS, CMS and LHCb?
- exotic accelerators: muons, pions, ions, ... you dream it
tack för din uppmärksamhet
check these lectures when available...

**Lecture 1:**
“Fundamentals of Vacuum Technology”, Eshraq AL DMOUR

**Lecture 2:**
“Materials & Properties IV: Outgassing”, Paolo CHIGGIATO

**Lecture 3:**
“Beam Induced Desorption”, Oleg MALYSHEV

**Lecture 4:**
“Beam Induced Radioactivity & Radiation Hardness”, Francesco CERUTTI

**Lecture 5:**
“Vacuum Gauges I & II”, Karl JOUSTEN

**Lecture 6:**
“Getter Pumps”, Enrico MACCALLINI
References I


