Beam-gas interactions (are not just a nuisance)

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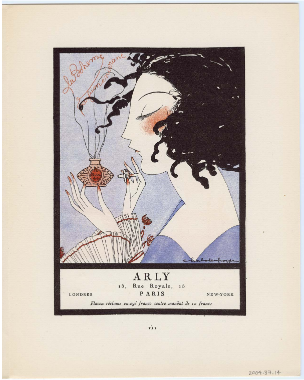
A dual view

Nuisance



Asset

Outline

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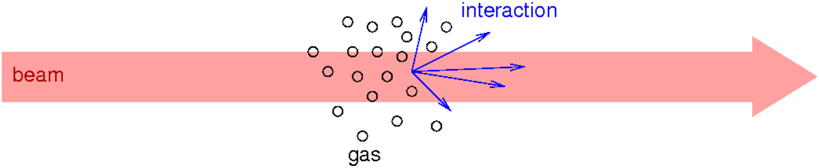
- Introduction:
  - beam-gas basics
  - beam-gas interaction cross sections
  - beam-gas losses and beam life time
- Detector background:
  - take an example (ALICE)
- Beam-gas imaging: (from LHCb)
  - beam profiles
  - ghost charge, etc
- Gaseous fixed targets:
  - physics with beam-gas (from LHCb)

Introduction



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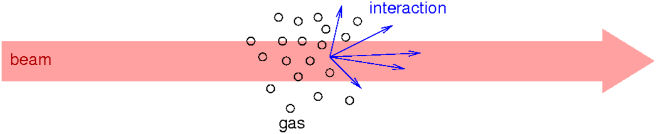
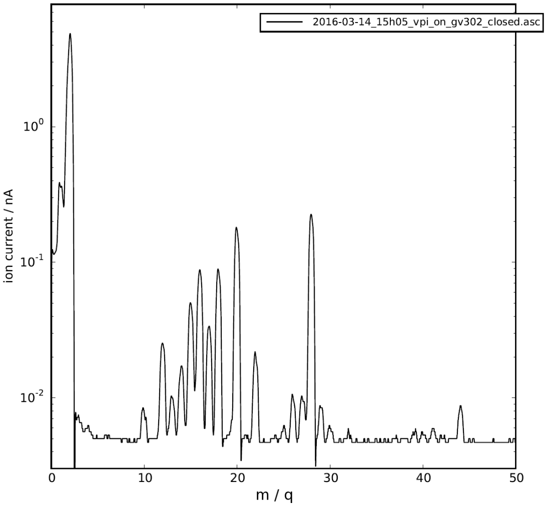


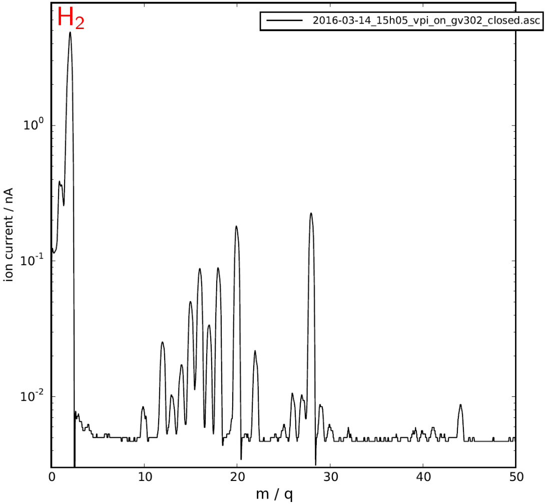
	Beam	**Residual gas**
particles:	$p^{\pm}$, $e^{\pm}$, $^{208}\mathrm{Pb}^{82+}$, ...	molecules, mostly containing the following atoms: H, C, O, (N, He) ...
velocity:	$\approx c = 3 \cdot 10^8$ m/s	≈ 100 m/s ($\ll c$)
energy:	typically MeV to TeV, and often $E \gg mc^2$	thermal, $E_{\mathrm{kin}} = \frac{3}{2} k_B T \approx$ 1...40 meV

Introduction: the Gas



A typical spectrum (LHCb VE$_{\text{rtex}}$LO$_{\text{cator}}$ vacuum, Rest Gas Analyzer)

Introduction: the Gas



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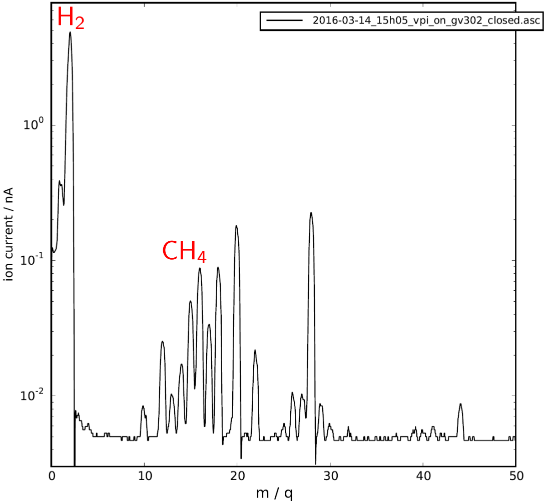

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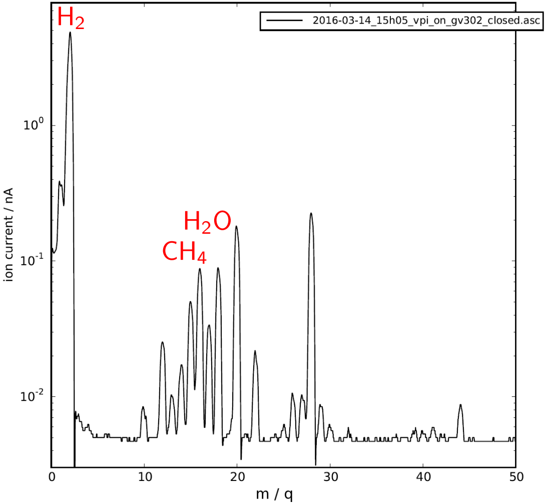

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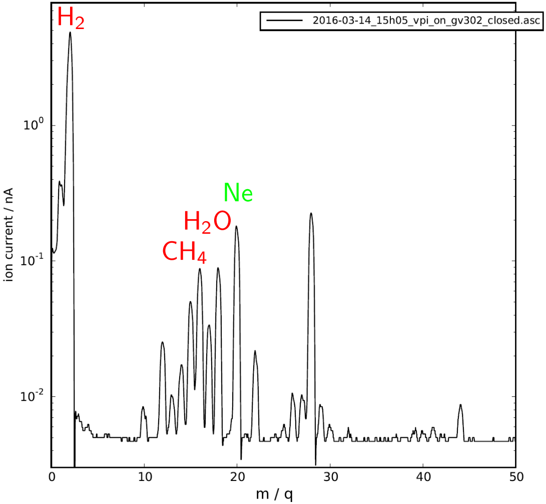

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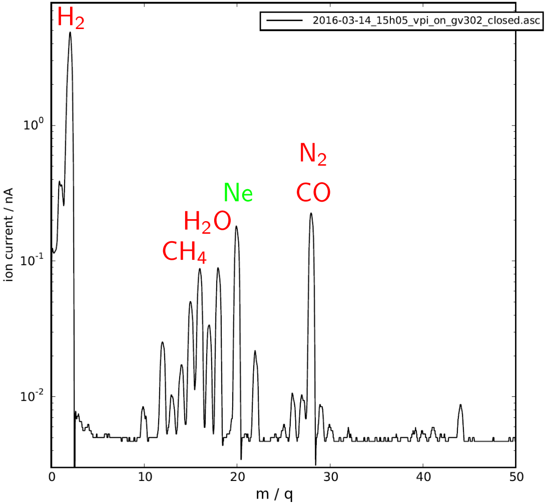

A typical spectrum (LHCb VE$_{rtex}$LO$_{cator}$ vacuum, Rest Gas Analyzer)

What is a beam-gas interaction ?

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What is a beam-gas interaction ?

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 $\sim 1\ \mathrm{fm} \sim$ size of a nucleon $\quad f = 10^{-15}$

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- electromagnetic interaction: relevant for all beams, interaction with **nuclei** and **atomic electrons**
  - medium strong (strong/137), but long range (infinite!)

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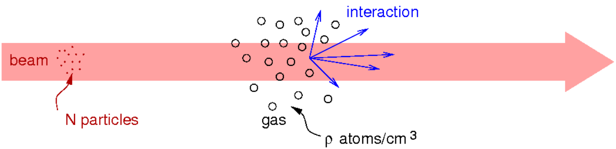
NB: the weak interaction is irrelevant in this context.

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



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

What is the probability μ of an interaction per pass ?

Define:

- N = number of beam particles passing
- $\Theta = \int \rho(z)\, dz$ = "target thickness"

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

Q2: Clearly... Really ?

The proportionality constant σ_{phys}

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

is the **cross section** of the physical process.

Introduction: beam-gas interactions

Units of $\sigma_{\rm phys}$ are those of a **surface area**, but... **tiny, tiny**.

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

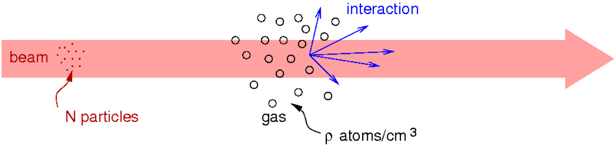
barn (en) = grange (fr) = Scheune (de) = fienile (it) = ladugård (se)

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} 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]

Introduction: beam-gas interactions



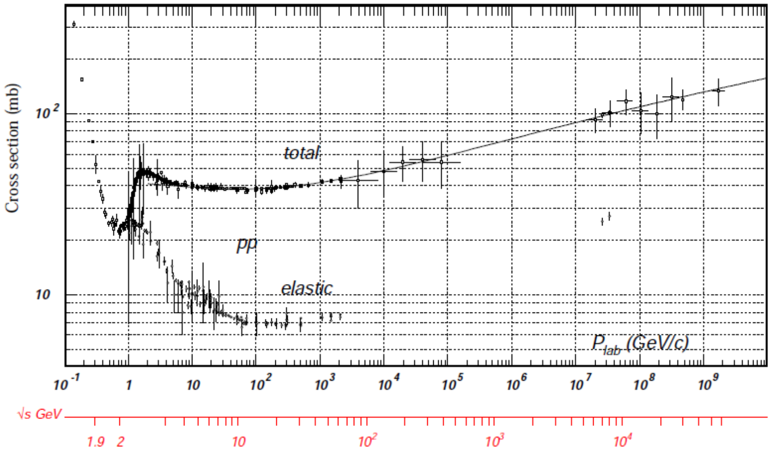
Repeat the passes many times, say, at a frequency f.
The rate R of interactions is then

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

where L = 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 ?

Introduction: beam-gas interactions

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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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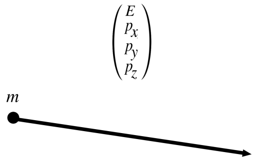
We need a bit of relativistic kinematics.

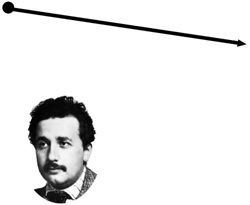
Introduction: beam-gas interactions



Introduction: beam-gas interactions

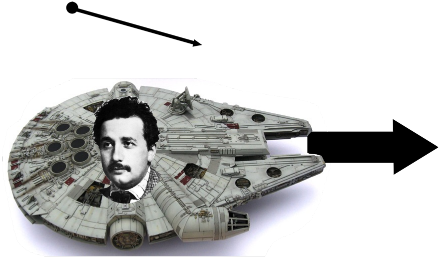
$$\begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

m



$$\begin{pmatrix} \tilde{E} \\ \tilde{p}_x \\ \tilde{p}_y \\ \tilde{p}_z \end{pmatrix}$$

m



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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.

Introduction: beam-gas interactions

The (invariant) rest mass m of a particle $(E, \mathbf{p})$ is given by
$m^2 = E^2 - \mathbf{p}^2 = E^2 - (p_x^2 + p_y^2 + p_z^2)$ ...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

$$
\begin{aligned}
s &= (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 \\
&= m_1^2 + m_2^2 + 2\,(E_1\, E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)
\end{aligned}
$$

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
$\mathbf{p}_1 = -\mathbf{p}_2$ and $m_1 = m_2$, $E_1 = E_2 = E$:

$$\sqrt{s} = E_1 + E_2 = 2\,E$$

b) fixed target mode
$\mathbf{p}_1 \neq 0$, $\mathbf{p}_2 = 0$:

$$\begin{aligned}\sqrt{s} &= (m_1^2 + m_2^2 + 2\,E_1\,m_2)^{\frac{1}{2}} \\ &\approx (2\,E_1\,m_2)^{\frac{1}{2}} \quad (\text{if} \quad E_1 \gg m_1,\, m_2)\end{aligned}$$

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

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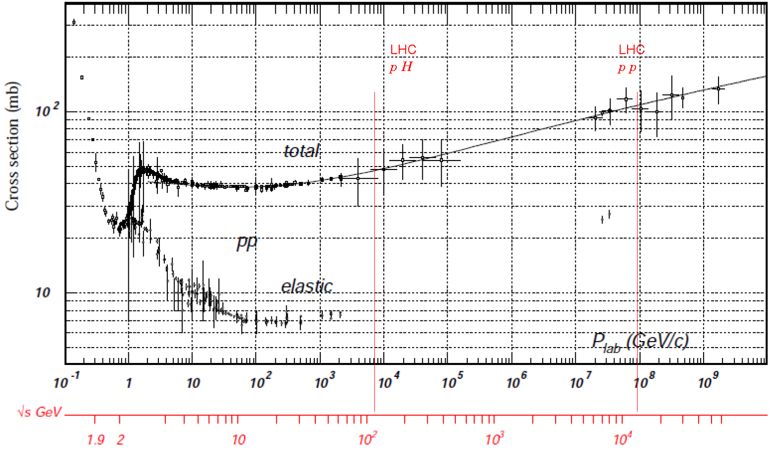
For example, cross section of $p + p$ (total and elastic) from [4]



Introduction: beam-gas interaction cross sections

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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.

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1.a proton beam

- A is a nucleus at rest — forget the atomic electrons for a moment
- Hadronic interactions. Elastic or inelastic.
  - short range ~ 1 fm $\sim$ size of a nucleon
- For a proton beam and proton target ($B = A = 1$): $p+{}^1\mathrm{H}$ is known from $p+p$ experiments which gives the cross section σ_{p+p} usually in center of mass frame. $\Rightarrow$ find the corresponding p_{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: $p + \mathrm{Ne}$

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1.b ion beam

fully stripped

- For ion beam B (like $B = 208$): $B + {}^1\mathrm{H}$ 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

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

at 1.88 GeV/nucleon.

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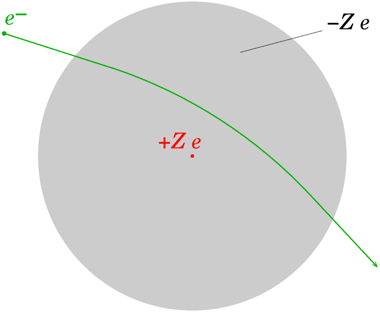
2. electron beams

- 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
    $e^- + \mathrm{Coulombfield} \rightarrow e^- + \gamma$
  - Pair production
    $e^- + \mathrm{Coulombfield} \rightarrow e^- + e^+ + e^-$
  - 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)

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

θ = polar electron angle after scattering

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

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

$\nu = E - E'$ = energy transfer.

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

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

$G_{E,p}(Q^2)$, $G_{M,p}(Q^2)$ = electric and magnetic proton form factors ...

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

$G_{E,p}$ and $G_{M,p}$ are the electric and magnetic proton form factors.

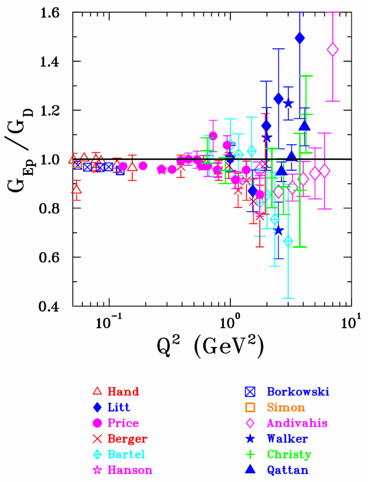
Describe the charge and magnetic distribution in the proton.

Approximately given by dipole formula [10]

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

More accurate fits of exp. data can be found in literature.

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



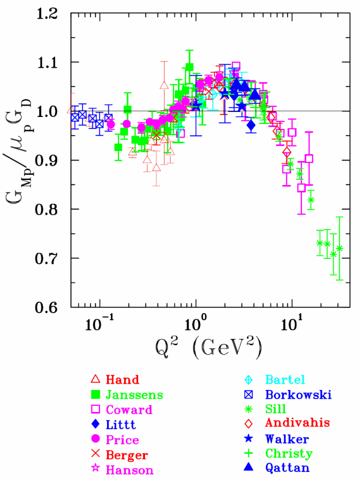


Figure: figures from scholarpedia [11]

Introduction: beam-gas losses and beam life time

Losses due to beam-gas collisions, via some process $\sigma_{\rm phys}$, 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

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

where we defined

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

The solution is simply

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

And τ is the **life time** of the bunch population $N(t)$.

Example:

1 mbar = 100 Pa

Residual pressure $p = 10^{-9}$ mbar, hydrogen (H_2), at $T = 5$ K, over 20 km

$$pV = n\,k_B\,T \quad \Rightarrow \quad \rho = \frac{p}{k_B\,T} \approx 1.5 \cdot 10^9 \ \mathrm{H_2/cm^3}$$

This is the concentration of **molecules**.
Atoms: multiply by 2.

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

$$\begin{aligned}\tau &= (5.5 \cdot 10^{-26}\ \mathrm{cm}^2 \cdot 11\ \mathrm{kHz} \cdot 3 \cdot 10^9\ \mathrm{cm}^{-3} \cdot 2 \cdot 10^6\ \mathrm{cm})^{-1} \\ &= 2.8 \cdot 10^5\ \mathrm{s} = 77\ \mathrm{h}\end{aligned}$$

Introduction: beam-gas losses and beam life time

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

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

The value $\tau_{\frac{1}{2}} = (C\, N_0)^{-1}$ is the **half life** of $N(t)$.

Example of burn off:

Take some collider with

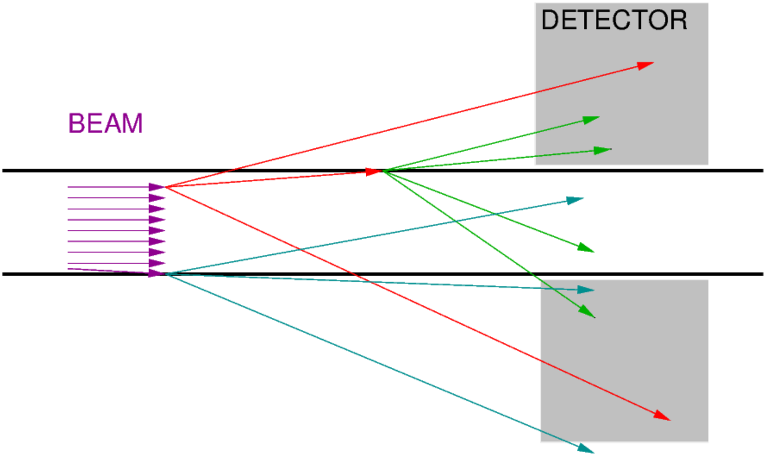
- $\sigma_{\mathrm{phys}} = 105$ mb
- $f = 11245\ \mathrm{Hz}$
- $N_0 = 1.2 \cdot 10^{11}$ protons
- $\sigma_x = \sigma_y = 11\ \mu$m
- 2 equally eager experiments — doubles the rate R

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

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

Usually, one wants τ(beam-gas) $> \tau_{\frac{1}{2}}(\mathrm{burnoff})$

Detector background



Detector background: what's the problem ?

In some cases, it can happen that the beam-gas interactions in the neighborhood of an experiment become a problem.

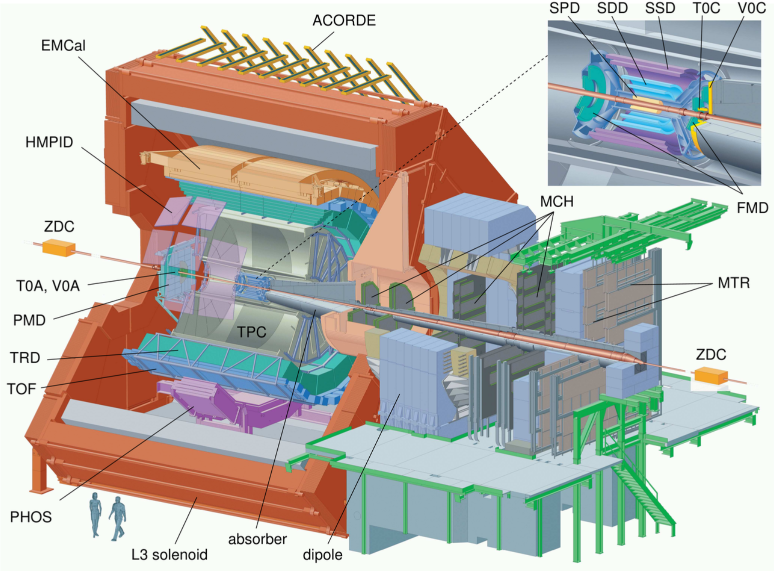
A notable example: ALICE at LHC.

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]

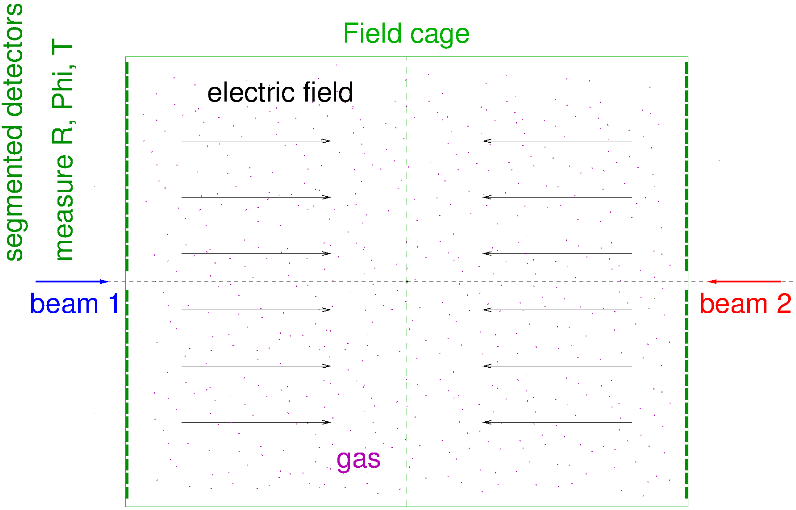
- inner/outer diameter of 1.2/5 m, length 2×2.5 m
- Drift time up to 90 μs (one LHC revolution !)
- Huge high voltage in field cage, 100 kV
- Current trip limit: 7 μA, i.e. about 500 kHz, $7 \cdot 10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Two running modes (trigger configurations):

- "Minimum bias" acquisition, $2 \cdot 10^{29} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, rate $\approx$ 150 kHz
- "Rare events" acquisition, $8 \cdot 10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, rate $\approx$ 600 kHz

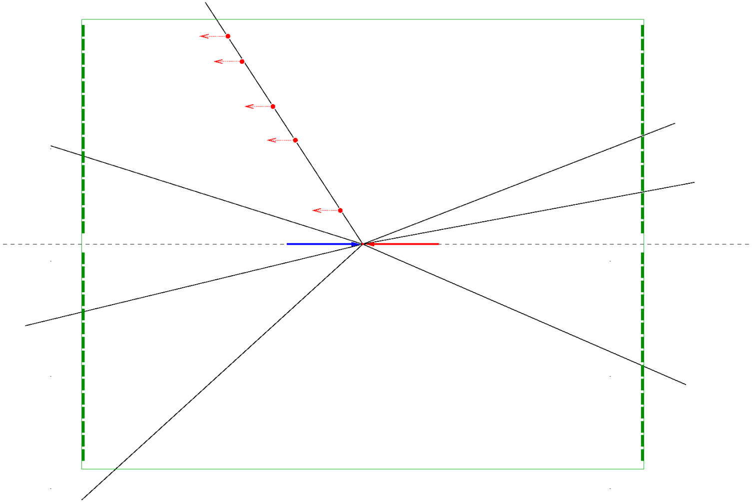
Detector background: TPC cartoon

Time projection chamber principle



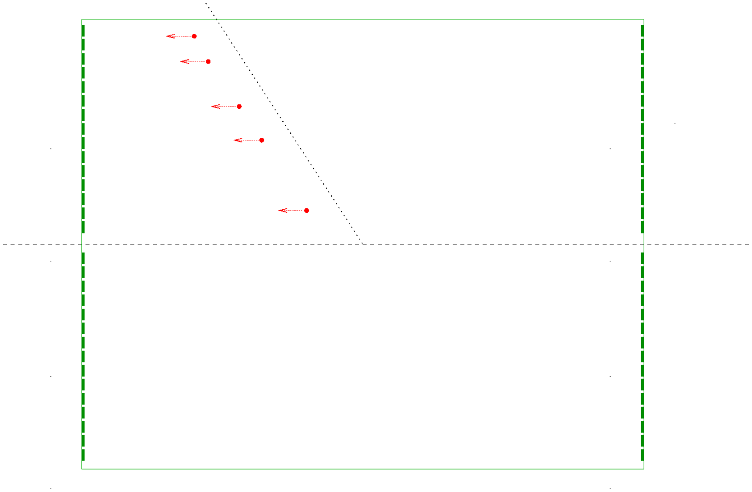
Detector background: TPC cartoon

Charged particle ionizes, liberates electrons



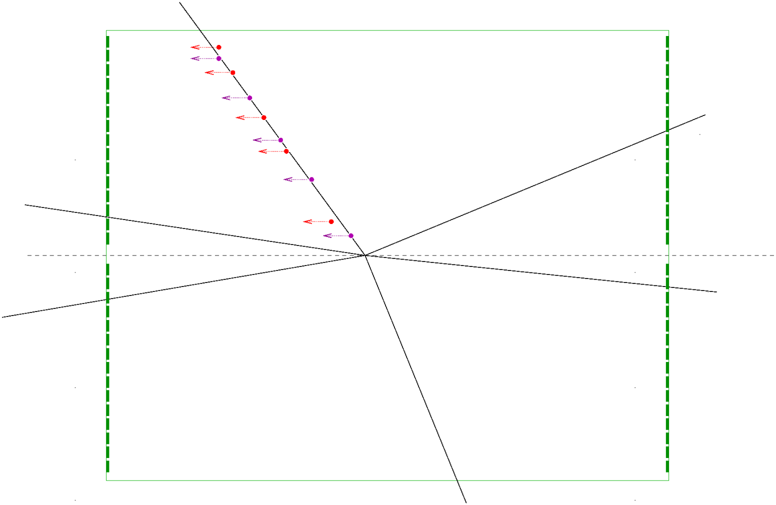
Detector background: TPC cartoon

Electrons drift ~ 0.7 mm per bunch crossing of 25 ns



Detector background: TPC cartoon

Bad luck! Overlapping track from new interaction...



Detector background: TPC cartoon

Confusing result

Detector background: ALICE in 2011

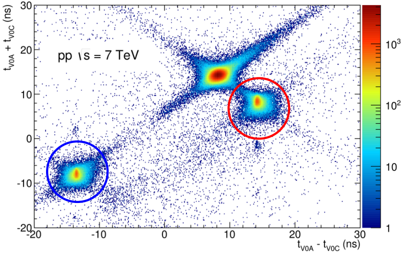
ALICE had two main problems:

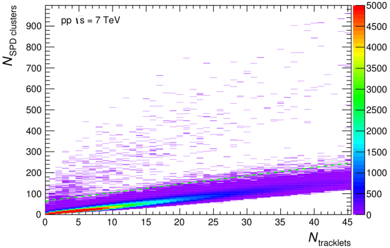
1. Minium bias trigger accepts beam-gas events
2. Beam-gas rates precluded turning on the high voltage of the TPC

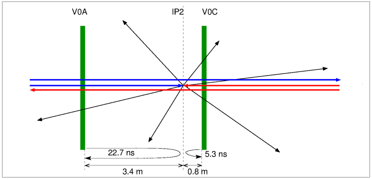
But how does one find out it is due to beam-gas interactions ?

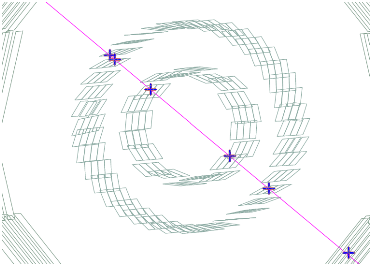
What are the signatures ?

Detector background: ALICE pinning down beam-gas

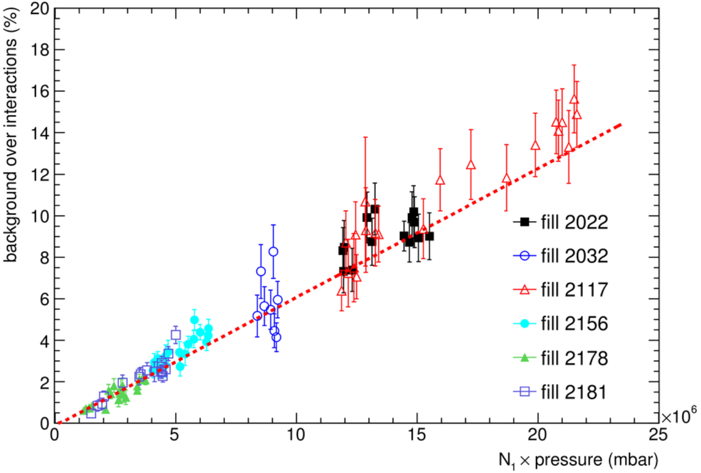








Detector background: ALICE pinning down beam-gas



Detector background: pinning 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 × pressure

   If proportional, it's likely to be beam-gas
   Caveat: pressure itself can depend on beam intensity!

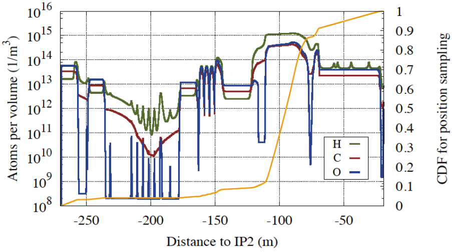
3. Use forwardness of tracks

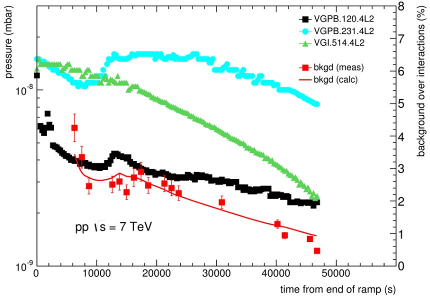
   If tracks flying fwd and bwd, it's likely not a beam-gas.

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] Hello Lund ;-)
- EPOS generator [19]
- HIJING Monte Carlo Model, [20]
- SixTrack - 6D Tracking Code [21]

etc...

Detector background: ALICE modeling beam-gas

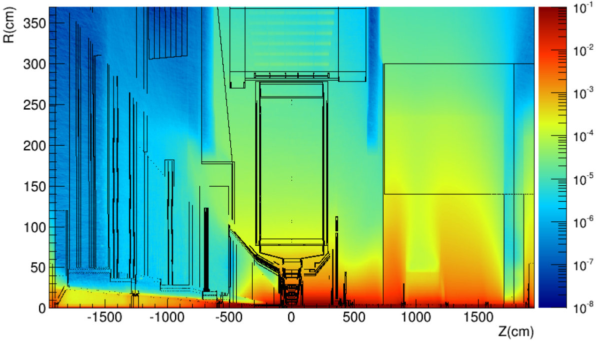


Fig. 6: Map of the charged particles fluence (in cm^{-2}) inside UX25 per beam–gas interaction in LSS2. Schematic of the ALICE geometry in R–Z coordinates is overimposed.

From ref. [15]

Exercise: ALICE pressure requirement

Assume:

- beam-gas interactions originating from up to $L = 100$ m away leave tracks in TPC and induce a triggered event.
- flat profile of hydrogen residual pressure $P(\mathrm{H_2})$ at $T = 293\ K$.
- nominal LHC conditions ($N = 1.1 \cdot 10^{11}\ p/\text{bunch}$, $n_b = 2800$ bunches at 7 TeV).

Question: How low should the pressure $P(\mathrm{H_2})$ be to contribute less than 50 kHz of triggers in ALICE ?

Answer:

$\sigma_{\mathrm{inelastic},p+p} = 45\ mb$ (elastics do not contribute!)

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

Thus

$$P(\mathrm{H_2}) = \frac{1}{2}\, k_B\ T\, \rho_{\mathrm{H}} < \frac{\frac{1}{2}\cdot 1.38\cdot 10^{23}\ \ \frac{\mathrm{J}}{\mathrm{K}}\cdot 293\ \ \mathrm{K}\cdot 50\ \ kHz}{100\ \ \mathrm{m}\cdot 3\cdot 10^{14}\cdot 11245\ \ \mathrm{Hz}\cdot 4.5\cdot 10^{-30}\ \ \mathrm{m^2}} = 5\cdot 10^{-10}\ \mathrm{mbar}$$

1 mbar = 100 Pa

Detector background: IR2 mitigations

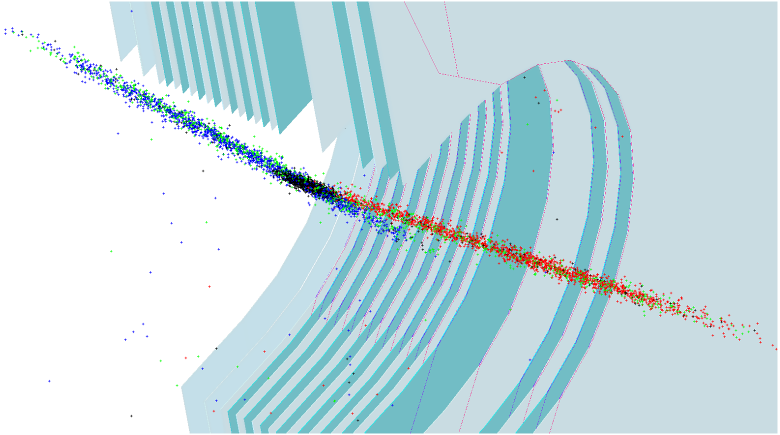
Implemented:

- 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

see lecture 3

Result: pressure reduced by more than one order of magnitude

Beam-gas imaging

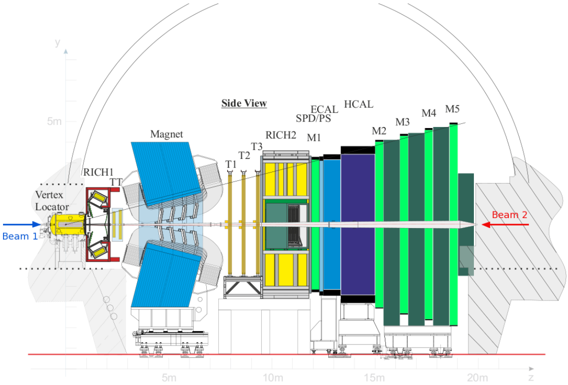


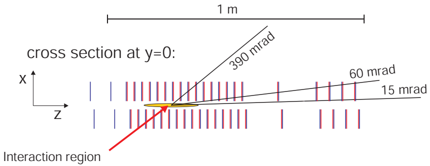
Beam-gas imaging: the asset

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 ??

Beam-gas imaging: meet LHCb





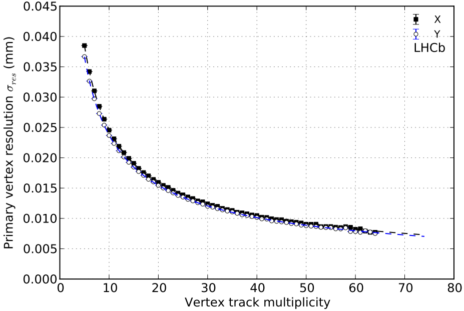
A key detector: **VE**rtex **LO**cator

Beam-gas imaging: meet LHCb

key detector: VELO

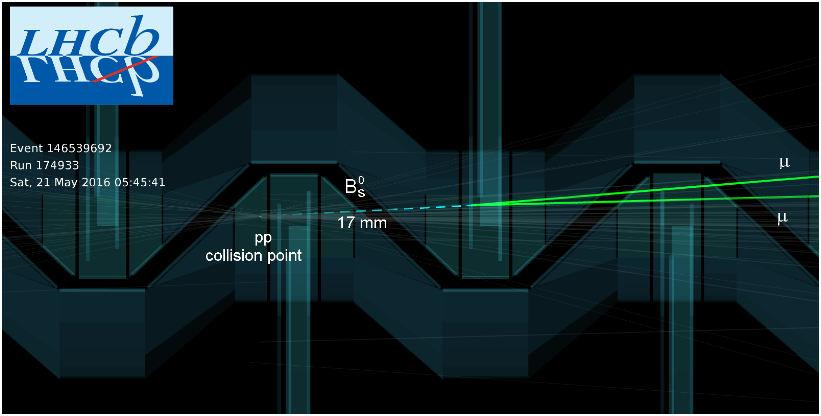
- silicon strips
- 8 mm from the beams
- vertical planes
- excellent vertex resolution
- good acceptance in θ and z
- also for forward-boosted beam-gas interactions!

resolution for $p + p$ colliding



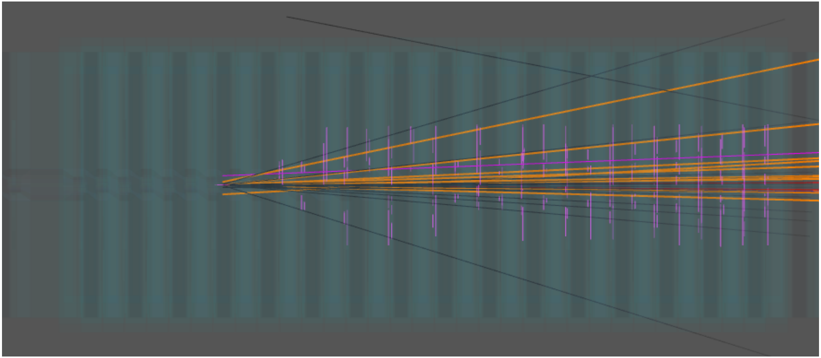
Beam-gas imaging: vertexing

In a $p + p$ interaction



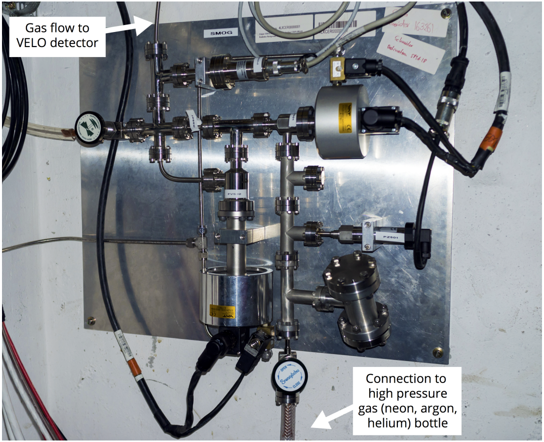
Beam-gas imaging: vertexing

In a $p + A$ interaction



Beam-gas imaging: SMOG

System for **M**easuring the **O**verlap with **G**as



Vacuum too good :-)

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

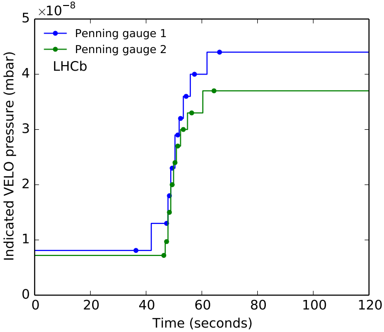
Increase pressure from 10^{-9} to 10^{-7} mbar

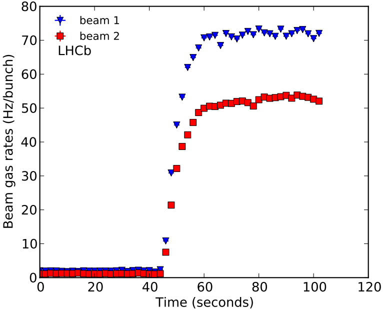
Q3: Why Ne, He, Ar ?
see lecture 6

First SMOG in the LHC! 2012.

Adding a little bit of gas (here Neon) [1]

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 $P(\mathrm{Ne}) = 1.6 \cdot 10^{-7}$ mbar at $T = 293\ K$.
- $N = 8 \cdot 10^{10}\ p/$bunch at 4 TeV.

Question: Calculate beam-gas rate R per bunch.

Answer:

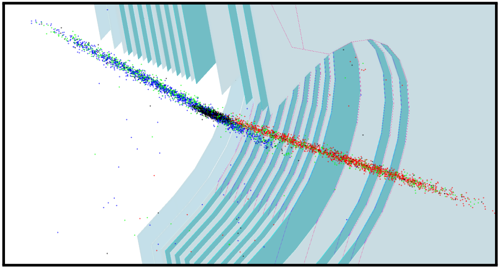
$$\sigma_{\mathrm{inelastic},p+\mathrm{Ne}} = \sigma_{\mathrm{inelastic},p+p} \cdot 20^{0.7} = 45\ \mathrm{mb} \cdot 8.1 = 366\ \mathrm{mb}$$

$$\rho_{\mathrm{Ne}} = \frac{P(\mathrm{Ne})}{k_B\ T} = 4 \cdot 10^{9}\ \mathrm{cm}^{-3}$$

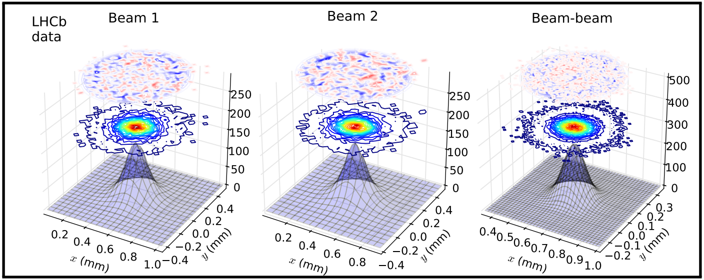
$$R = \sigma_{\mathrm{inelastic},p+\mathrm{Ne}} \cdot N \cdot f \cdot \rho_{\mathrm{Ne}} \cdot \Delta z = 130\ \mathrm{Hz}$$

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]



⇓

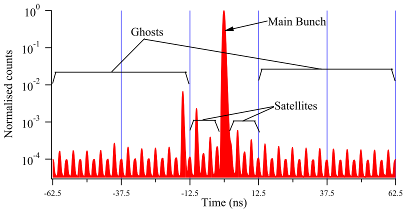


Beam-gas imaging: ghost charge

Bunch population normalisation at LHC:

- crucial for direct luminosity determination
- **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.

$$L = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

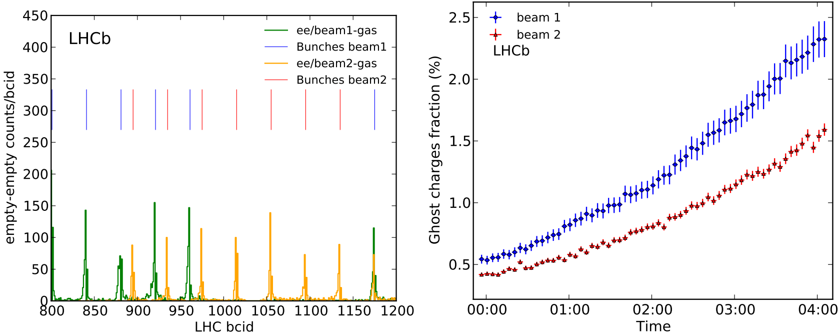


(courtesy of J. Adam)

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

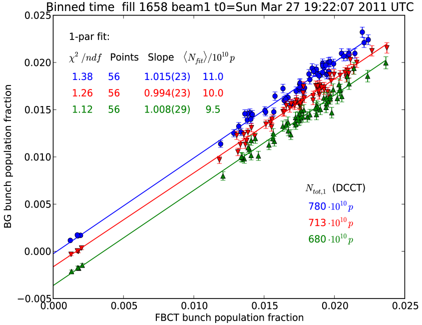
Beam-gas imaging: ghost charge

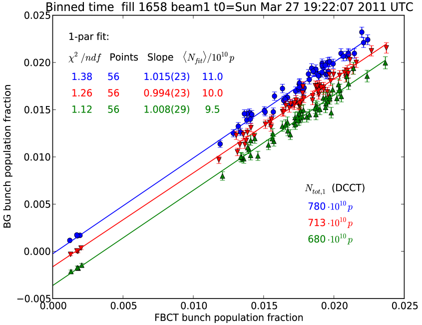
Examples of LHCb **ghost charge measurements** by beam-gas rates [1]



Left: filled-slot rates are suppressed from plot
Right: ghost population over total beam population vs time

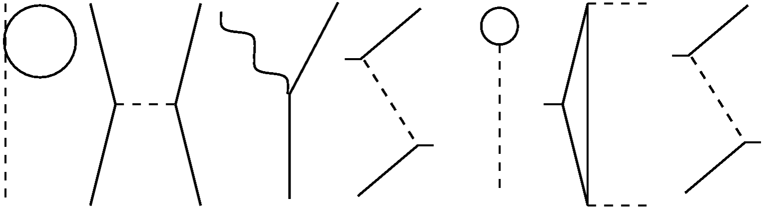
Examples of LHCb **relative bunch charge** measurements by beam-gas rates [6]



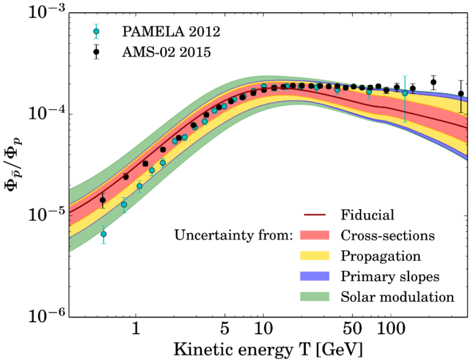


Different colors/markers are just different time periods (with an artificial offset for clarity, except for the blue)

Gaseous fixed targets



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

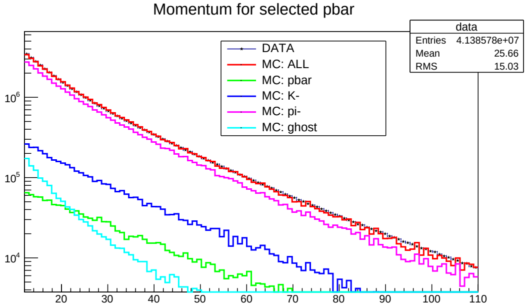


- Dark matter hint ?
- Or just a background model inaccuracy ?
- How many $\bar{p}$ produced by $p + \mathrm{He}$ collisions ?
- Not so well known...

Right. Now we are talking...
We can even do physics with beam-gas interactions.

LHCb as a fixed-target experiment: $p + A$, $\mathrm{Pb} + A$, $A =$He, Ne, Ar ...

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



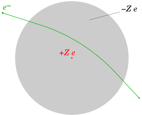
Momentum spectrum in GeV$/c$

But how to normalize the cross sections ?

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

We need the **absolute gas density**. Somehow.

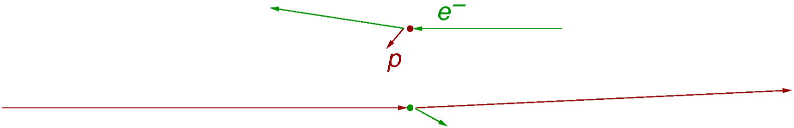
The CERN Accelerator School



Two ways to measure the luminosity

1. Direct: measure the absolute density of gas Q5: How to do that ?
2. Indirect: measure $p + e$ elastic events (or Pb+e) [14]
   $\sigma_{\mathrm{phys},e+p}$ has been measured by others
   Use e^+ and charge symmetry to check background

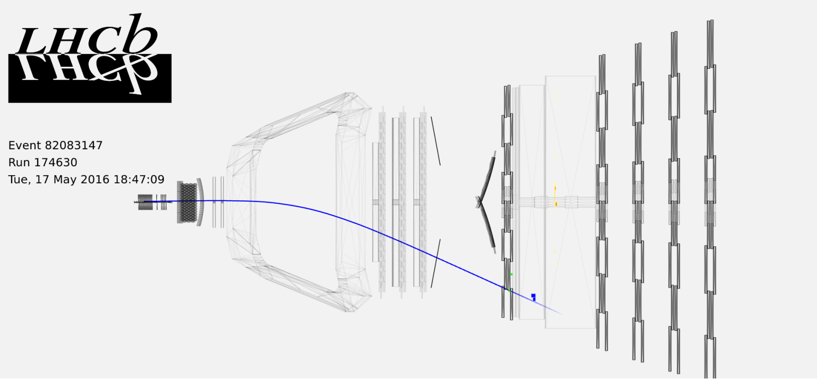
Assume $$\rho_A = \rho_e / Z$$ Q6: Could that be wrong ?

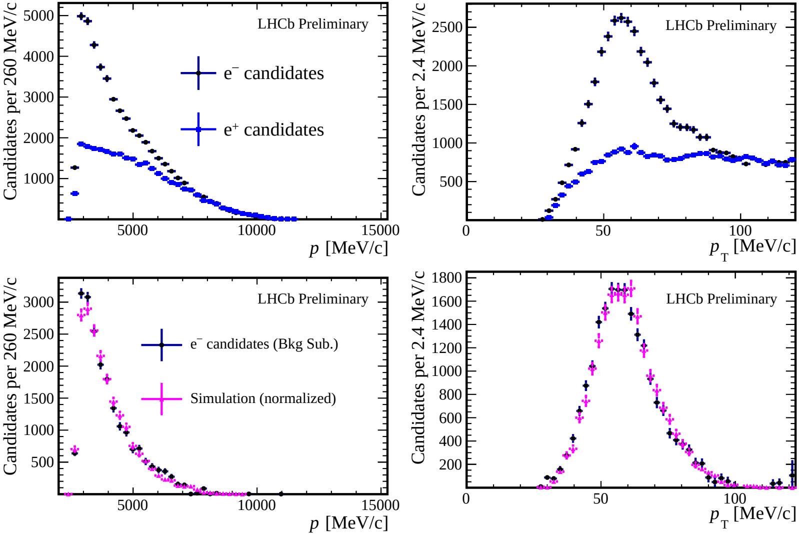


"From JLAB to LHC"... Exercise: calc. boost at LHC, compare to JLAB.

Gaseous fixed targets: physics with beam-gas

Single electron event !




LHCb Preliminary
Candidates per 260 MeV/c
e^- candidates
e^+ candidates
p [MeV/c]
Candidates per 2.4 MeV/c
p_T [MeV/c]
e^- candidates (Bkg Sub.)
Simulation (normalized)

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

CAS-2017 lectures referred to in this talk

The CERN Accelerator School

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

[1] "Precision luminosity measurements at LHCb with beam-gas imaging", C. Barschel, CERN-THESIS-2013-301, https://cds.cern.ch/record/1693671.

[2] "Precision luminosity measurements at LHCb" The LHCb collaboration, JINST 9, (2014) P12005, http://stacks.iop.org/1748-0221/9/i=12/a=P12005.

[3] "ALICE vacuum requirements and TDI-related background issues in Run 1+2", A. di Mauro, in TDIS Internal Review, 1 Dec. 2016, CERN, https://indico.cern.ch/event/579995/timetable.

[4] "The Review of Particle Physics (2016)", C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

[5] "Performance of the ALICE Experiment at the CERN LHC", ALICE Collaboration, Int. J. Mod. Phys. A 29 (2014) 1430044, http://www.worldscientific.com/doi/abs/10.1142/S0217751X14300440.

[6] "Study of the relative LHC bunch populations for luminosity calibration", G. Anders *et al.*, CERN-ATS-Note-2012-028 PERF, BCNWG Note 3, https://cds.cern.ch/record/1427726.

[7] "Cross-sections of high energy nuclear reactions", T.F.Hoang et al, Z. Physik C, Particles and Fields 29 (1985) 611, http://link.springer.com/article/10.1007/BF01560296.

[8] "Compilation of cross sections for proton-nucleus interactions at the HERA energy, J. Carvalho, Nuclear Physics A 725 (2003) 269-275. https://doi.org/10.1016/S0375-9474(03)01597-5.

[9] "Electron Scattering and Nuclear Structure", T.W. Donnelly and J.D. Walecka,

[10] See for example in D.H. Perkins, "Introduction to High Energy Physics", 3rd edition, Addison-Wesley Publishing Company, Inc., ISBN 0-201-12105-0.

[11] See for example in http://www.scholarpedia.org/article/Nucleon_Form_factors.

[12] "Pair production and bremsstrahlung of charged leptons", Yung-Su Tsai, Review of Modern Physics, Vol. 46, No. 4, October 1974.

[13] "MS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for Dark Matter" G. Giesen *et al.*, arXiv:1504.04276v3 [astro-ph.HE] 9 Sep 2015.

[14] "Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV", CERN-LHCb-CONF-2017-002, The LHCb Collaboration, 52nd Rencontres de Moriond on Electroweak Interactions and Unified Theories, La Thuile, Italy, 18 - 25 Mar 2017, https://cds.cern.ch/record/2260835.

[15] "Radiation Dose and Fluence in ALICE after LS2", A. Alici, A. Di Mauro, W. Riegler and A.Tauro, public ALICE note, to be published (CERN, Geneva).

References II

[16] FLUKA simulation tool, http://www.fluka.org/fluka.php.

[17] GEANT4 simulation tool, http://geant4.cern.ch/.

[18] Pythia - The Lund Monte Carlo!, http://home.thep.lu.se/ torbjorn/pythia81html/Welcome.html

[19] EPOS generator, see B. Guiot and K. Werner, Journal of Physics: Conference Series 589-1 (2015) 012008 and references therein. http://stacks.iop.org/1742-6596/589/i=1/a=012008,

[20] HIJING Monte Carlo Model, http://ntc0.lbl.gov/ xnwang/hijing/.

[21] SixTrack - 6D Tracking Code, http://sixtrack.web.cern.ch/SixTrack/.