Beam Profile, Primary and Secondary Vertices.

Event rate, $R = \mathcal{L}\sigma$

Accumulated statistics, $N = \int \mathcal{L}\sigma\, dt = \sigma \int \mathcal{L}\, dt$

Integrated luminosity has dimensions of $(cm^2)^{-1}$.

Example: In 2017, the LHC delivered approximately $50\ fb^{-1}$ of luminosity.

The $t\bar{t}$ cross section is about 800 pb at $\sqrt{s} = 13$ TeV.

Number of $t\bar{t}$ events collected: $800 \times 50 \times 1000 = 40 \times 10^6$.

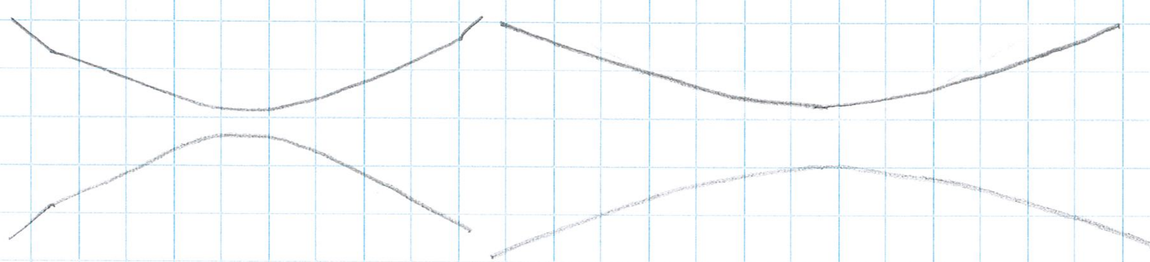
What influences the luminosity of the LHC (or any collider)?

$$\mathcal{L} \sim \frac{f N^2}{4\pi\sigma^2}$$

$f$ is the bunch circulation frequency.
$N$ is the number of colliding bunches.
$\sigma$ is the Gaussian cross sectional area of the beams.

If you can't change $f$ and can't increase $N$, you can really only reduce $\sigma$ to make $\mathcal{L}$ larger.

You can make $\sigma$ smaller by focusing the beams. But an invariant quantity is the beam emittance. You can make $\sigma$ smaller at the expense of increasing the angle at which the beams collide.

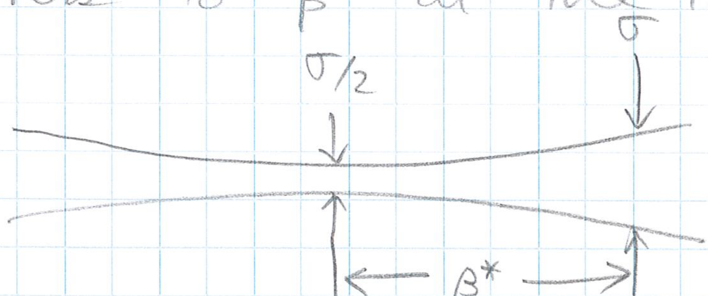


These are related by

$$\beta = \frac{\pi\sigma^2}{\varepsilon}$$

where $\varepsilon$ is a constant. $\beta$ is roughly the length over which the width of the beam is reduced by a factor of 2.

$\beta$ can vary around the accelerator. $\beta^*$ refers to $\beta$ at the interaction point.




So $\mathcal{L} \sim \dfrac{f N^2}{4\varepsilon\beta^*}$

Can't change $f$, $N$, $\varepsilon$, so try to make $\beta^*$ as small as possible.

At nominal LHC luminosity $\mathcal{L} \sim 10^{34}\ cm^{-2}s^{-1}$

$$\beta^* = 55\ cm$$

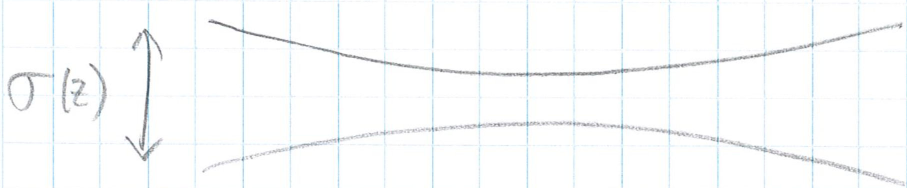
$$\varepsilon_n = 3.75\ \mu m$$

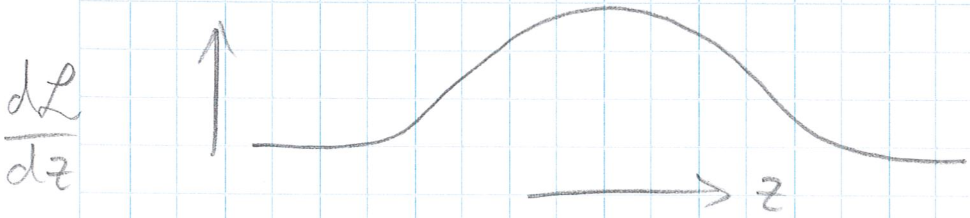
This means that the beams are not of uniform width as a function of $z$.

$$\beta(z) = \beta^* + \frac{z^2}{\beta^{*2}}$$

For long bunches,

$$\mathcal{L} = \mathcal{L}_0 H = \mathcal{L}_0 \frac{1}{\sqrt{\pi}\ \sigma_z} \int_{-\infty}^{\infty} \frac{e^{-z^2/\sigma_z^2}}{1 + (z/\beta^*)^2}\ dz$$




Collisions are spread out over the luminous region in $z$ and in the $x$-$y$ plane.

LHC parameters.

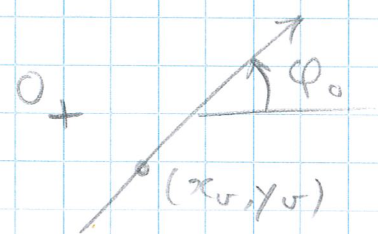
$E(\text{nominal}) = 7\ \text{TeV}$
$\beta^* = 55\ \text{cm}$
$\varepsilon_n = 3.75\ \mu m$
$\sigma^*_{x,y} = 16.6\ \mu m$
$\sigma_z = 7.55\ \text{cm}$
$n_b = 2808$
$N_b = 1.15 \times 10^{11}$
$f = 11245\ \text{Hz}$.

The HL-LHC will achieve higher luminosity by reducing $\varepsilon_n$ to $2.5\ \mu m$, reducing $\sigma^*_{xy}$ to $7.09\ \mu m$ and doubling $N_b$.

Typical $\sigma_z \sim 50$ mm so collisions are spread out over about 10 cm in z.

This is good because it is important to identify which tracks originate from common vertices.

Primary Vertex Reconstruction.




Expected:

$$d_0 = -x_v \sin\phi_0 + y_v \cos\phi_0 .$$

$$z_0 = z_v + s_0 \cot\theta$$

$$s_0 = x_v \cos\phi_0 + y_v \sin\phi_0$$

Measurements:

Original estimate $x_v, y_v, z_v$ + covariance matrix

Track parameters $d_0, \phi_0, z_0, \cot\theta$.
+ covariance matrix

Constraints:

$$g_1 = d_0 + x_v \sin\phi_0 - y_v \cos\phi_0 = 0$$
$$g_2 = z_0 - z_v - s_0 \cot\theta = 0$$

Results of the fit:

$x_v', y_v', z_v'$ + new covariance matrix

$\chi^2$ and $\Delta\chi^2$.

Typical vertex fitting algorithm:

1. Find a collection of tracks that appear to cluster in $z$.

2. Fit to a common vertex

3. Reject track with largest $\Delta\chi^2$.

4. Repeat until $\max \Delta\chi^2$ is small.

The average $x_v, y_v, z_v$ over some period of time can be used to estimate the size, position and shape of the luminous region. This can provide an initial estimate for subsequent vertex fits.

Minimum bias events: primarily light flavor events.

Heavy flavor jets will have secondary vertices.

Properties of heavy quarks (and $\tau$)

| | b | c | $\tau$ |
|---|---|---|---|
| Mass | 4.2 GeV | 1.3 GeV | 1.77 GeV |
| Typical $\tau$ | 1.6 ps | 1 ps | 290 fs |
| $\langle n_{ch} \rangle$ | 5.4 | few | 85% 1-prong |
| semileptonic Br | 10% | 6.5% | 18% |

# Heavy Flavor Fragmentation Functions.

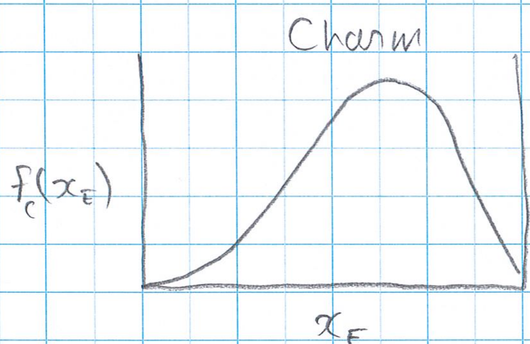
A heavy quark with energy $E$ will fragment into a heavy flavored hadron with energy $x_E E$ where $x_E$ has a probability density

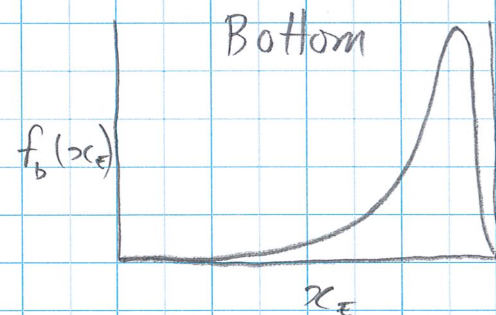
$$f(z) \sim \frac{1}{z}\left(1 - \frac{1}{z} - \frac{\varepsilon}{1-z}\right)^{-2} \qquad (\text{Peterson})$$

$$\sim z^{\alpha}(1-z) \qquad (\text{Kartvelishvili})$$

$$\vdots$$

etc.

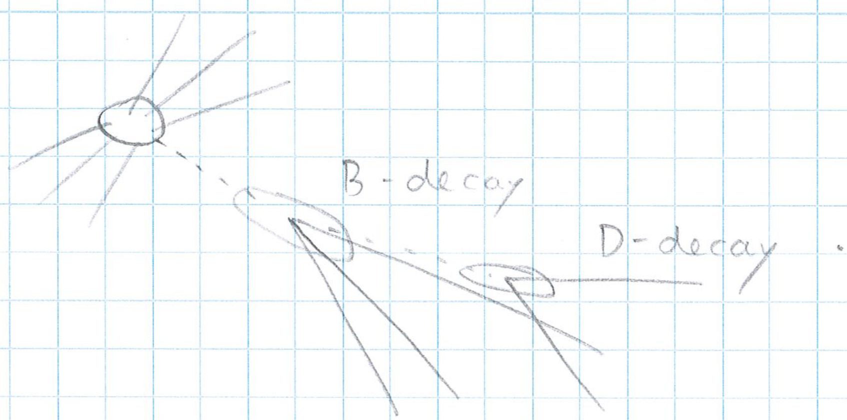



Heavy quarks have more "inertia" and carry it with them when they fragment into hadrons.

So, heavy mesons produced in hard b-jets, eg, from $t \to Wb$ or $H \to b\bar{b}$ will tend to have large energies.

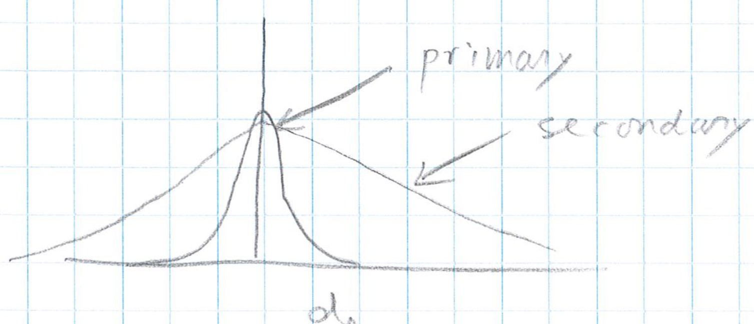
Secondary Vertices




Typical decay lengths: Suppose $P_T \sim 10$ GeV then $\beta\gamma = \dfrac{10 \text{ GeV}}{5 \text{ GeV}} \sim 2$

$$\ell_{xy} = \gamma\beta c\tau = 2 \times 30 \text{ cm/ns} \times 1.6 \text{ ps}$$
$$= 2 \times .3 \text{ mm/ps} \times 1.6 \text{ ps}$$
$$= 1 \text{ mm}.$$

The combination of long $\ell_{xy}$ and large mass gives decay products large impact parameters.



# B-jet tagging.

Exploit the unique properties of b-flavored hadrons.

- long lifetime
- large mass
  - → high decay multiplicity
  - large $p_T^{jet}$

} wide $d_0$ distribution.

- large semileptonic branching fraction.


- Leptons can have large $p_T^{rel}$.

Various ways to exploit all this information.

Example: Jet probability.

Cluster tracks into a jet.
If all tracks were prompt then all $d_0$ would be gaussian distributed about 0 with $\sigma_{d_0}$ calculated from the track fit.