ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 4

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Preliminaries

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Bibliography

♠ Bibliography

- K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
- F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

♠ Other basic bibliography:

- A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2nd Edition(2009)(DF).
- D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
- B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2nd Edition(2004).(BP)
- D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2nd Edition(2000).
- Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

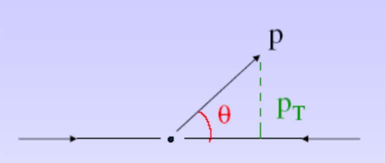
♠ Bibliography of this Lecture

- T.Han, *Collider Phenomenology: Basic Knowledge and Techniques*, arXiv:hep-ph/0508097 (TAO)

Contents

Kinematical Variables: p_T

- The **geometry**of collisions is **cylindrical**,it can be used cylindrical coordinates:
  - azimuthal angle ϕ
  - polar angle θ
  - momentum p
- energy E
- transverse momentum p_T
- longitudinal momentum p_L



$$p_T = p\sin\theta$$
$$p_L = p\cos\theta$$

- Physics is symmetric in ϕ.
- As consequence of the collision kinematics, the longitudinal momentum p_z is not known, therefore it is convenient to use the **conservation of the transverse momentum p_T in plane perpendicular to the beam**.

Rapidity and Pseudorapidity

- rapidity:

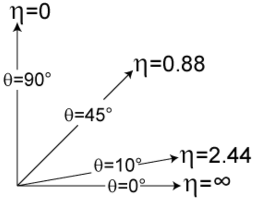
  $y \;=\; \frac{1}{2}\ln\frac{E\,+\,p_L}{E\,-\,p_L}$

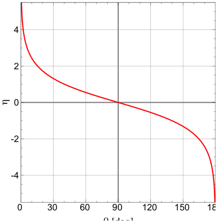
  $\Downarrow \quad m \;<<\; E, p_L$

  %

Rapidity and Pseudorapidity

- rapidity:
  $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$
  $\Downarrow \quad m << E, p_L$
  $\%$
- **Pseudorapidity**:
  $\boldsymbol{\eta = -\ln \tan \frac{\theta}{2}}$
  , Derivation in Appendix A.
- The **difference** between the (Pseudo)**rapidities** of two particles is **invariant** with respect to **Lorentz boosts** along the **z-axis**.This is the key reason why rapidities are so crucial in accelerator physics.





For highly relativistic particles, $y \simeq \eta$ (η is easier to estimate)

Kinematic Variables

- Rapidity differences are invariant with respect to Lorentz boosts along the beam axis.

$$\text{rapidity} \quad y = \frac{\sqrt{E + p_L}}{\sqrt{E + p_L}} \qquad y' = \frac{\sqrt{E' + p'_L}}{\sqrt{E + p_L}}$$

$$\Downarrow \qquad \text{Derivation Appendix B}$$

$$y' = y - \tanh\beta$$

Suppose we have two particles ejected after a collision, and they have rapidities y_1 and y_2 when measured by some observer.Now, let some other observer measure these same rapidities, and obtain y'_1 and y'_2 . the difference between the rapidities in the unprimed frame is $y_1 - y_2$, and in the primed frame it becomes:

$$\boldsymbol{y'_1 - y'_2} = (y_1 - \tanh\beta) - (y_2 - \tanh\beta) = \boldsymbol{y_1 - y_2}$$

Therefore the **difference between the rapidities of two particles is invariant with respect to Lorentz boosts along the z-axis**.

Kinematic Variables

Kinematic Variables

- rapidity:
  $$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L}$$
  $$\Downarrow \quad m << E, p_L$$

- Pseudorapidity:
  $$\eta = -\ln\tan\frac{\theta}{2}$$

Contents

Reaction rate and Luminosity

Reaction rate and Luminosity

The reaction rate can be written as function of luminosity [a] :

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \Phi_a \cdot \; N_b \cdot \sigma_b = \mathcal{L} \cdot \sigma_b$$

Φ_a = number of projectiles hitting the target per unit area and per unit time
N_b = number of scattering centers in the target
σ_b = cross section

[a] $\sigma_b = \frac{\mathrm{d}N}{\mathrm{d}t \cdot \Phi_a \cdot \; N_b}$

Luminosity in colliding beams

♠ For *colliding beam* experiments. Analogous for two particle beams colliding in a storage ring.Assume N_a and N_b particles are the number of particles inside particle packets.The two particle types circulate with velocity v in opposite directions.

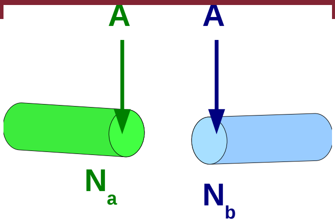


Figure : Colliding beams.

Luminosity

$$\mathcal{L} = \frac{N_a \cdot \ N_b}{\text{A}} \cdot f$$

N_a, N_b are the number of particles inside particle packets of each beam
f number of particle packets collisions per unit time (collision frequency).
A = beam cross section at the collision point.

For a Gaussian distribution of the beam particles around the beam center (with horizontal and vertical standard deviations σ_x and σ_y respectively), A is given by:

$$A = 4\,\pi\sigma_x \cdot \sigma_y$$

To achieve a high luminosity, the beams must be focused at the interaction point into the smallest possible cross sectional area possible.Typical beam diameters are of the order of tenths of millimeters or less.

The interpretation is straightforward. The hypothesis is that the particles of colliding beams are uniformly distributed inside a packet with a cylinder shape and section A.The second packet can be considered as target.The flux of first packet $\Phi_a = f\frac{N_A}{A}$ then:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \Phi_a \cdot N_b \cdot \sigma_b = f \cdot \frac{N_a}{A} \cdot N_b \cdot \sigma_b = \mathcal{L} \cdot \sigma_b$$
$$\Longrightarrow \mathcal{L} = \frac{N_a \cdot N_b}{A} \cdot f$$

The cross section can be easily derived:

$$\sigma_b = \frac{\frac{\mathrm{d}N}{\mathrm{d}t}}{\mathcal{L}} = \frac{\frac{\mathrm{d}N}{\mathrm{d}t}}{N_A \cdot N_b \cdot f} \cdot A$$

Integrated luminosity

In an experiment the number of event produced is during data taking is:

$$N = \sigma_b \cdot \int \mathcal{L}\, \mathrm{d}t$$

the integral is extended to the duration of data taking.

Integrated luminosity

The integrated luminosity (i.e., sum over a period of time)of an instantaneous luminosity, is defined as:

$$\int \mathcal{L} \mathrm{d}t$$

dimension $[\mathrm{m}^{-2}]$.

A glance at nowadays:luminosity at Large Hadron Collider (LHC)

The $\mathcal{L}$ is one of the most important parameter of an accelerators, as LHC.It is a measurement of the number of collisions that can be produced in a detector per cm and per second. The bigger is the value of $\mathcal{L}$, the bigger is the number of collisions.To calculate the number of collisions we need also to consider the cross section.

$\mathcal{L}$ can be obtained as:

- N^2 : number of protons,because each particle in a bunch might collide with anyone from the bunch approaching head on.

Figure : Schematic of LHC beam crossing

- t time between bunches.
- $\mathrm{S_{eff}}$: section effective of collision that depends on the cross section of the bunch (*effective* because the beam profile doesn't have a sharp edge); the formula for this is given by : $\mathrm{S_{eff}} = 4\pi\sigma^2$ with $\sigma = 16$ microns or $16 \cdot 10^{-4}$ cm (transverse size of the bunch at Interaction Point,IP).
- Other parameter to be considered is F, the geometric luminosity reduction factor, due to the crossing angle at the interaction point. But in 2011 $F \approx 0.95$, so it can be taken as 1.

$$\mathcal{L} = \frac{N^2}{t \cdot \mathrm{S_{eff}}}$$

$$\text{Now, with: } N^2 = (1.15 \cdot 10^{11})^2$$

$$t = 25 \cdot 10^{-9}\mathrm{s},\ \mathrm{S_{eff}} = 4 \cdot \pi(16 \cdot 10^{-4})^2\mathrm{cm}^2$$

$$\mathcal{L} \sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- If we use the bunches crossing frequency (f, in this case $40 \cdot 10^6$), we can express the Luminosity in a more well-known way:

$$\mathcal{L} \sim f \cdot \frac{N^2}{S_{\text{eff}}} \quad = \quad f \cdot \frac{N^2}{4\pi\sigma^2}$$

- And considering different number of protons per crossing bunches, and x and y components for σ separately:

$$\mathcal{L} \sim f \cdot \frac{N_1 \cdot \ N_2}{4\pi\sigma_x \cdot \sigma_y}$$

This value, $\mathcal{L} \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$, means that in the LHC detectors might produce 10^{34} collisions per second and per cm^2 The integral of delivered luminosity Integrated Luminosity, $\int \mathcal{L}dt$, is:

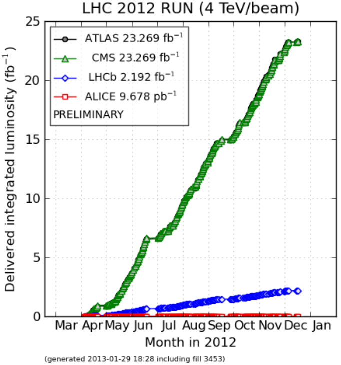


Figure : Integrated Luminosity $\int \mathcal{L}dt$ at LHC (January 2013)

LHC luminosity 2017

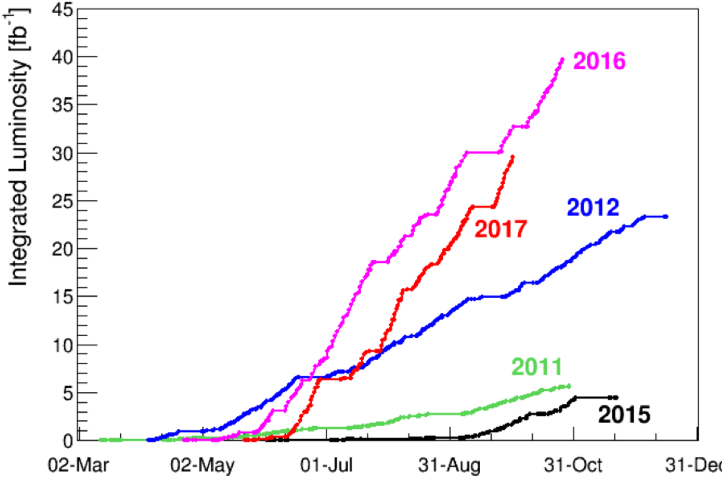


Figure : Integrated Luminosity $\int \mathcal{L} dt$ at LHC (September 2017)

LHC luminosity 2017

September 2017:

- 10 000 000 000 000 000, or ten million billion.This is the cumulative number of potential collisions brought at the centre of ATLAS and CMS since the LHC started its operation in 2010.
- LHC has delivered over $100 fb^{-1}$ (inverse femtobarn) of integrated luminosity to each of ATLAS and CMS, where one inverse femtobarn corresponds to around 100 million million (potential) collisions.
- The target for 2017 and 2018 was raised to $90 fb^{-1}$ for the two years combined.
- This milestone was reached on 28 September and only takes into account the data taking with proton bunches spaced by 25 nanoseconds.
- Now $150 fb^{-1}$

LHC luminosity 2018

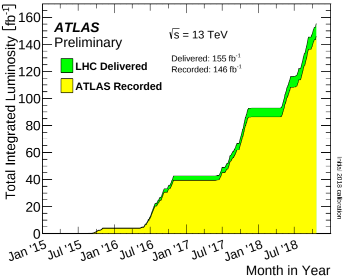


Figure : Integrated Luminosity $\int \mathcal{L} dt$ at LHC (October 2018)

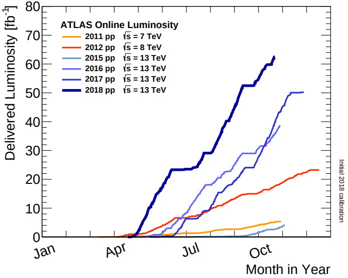


Figure : Delivered Luminosity $\int \mathcal{L} dt$ at LHC (October 2018)

Contents

Motivation

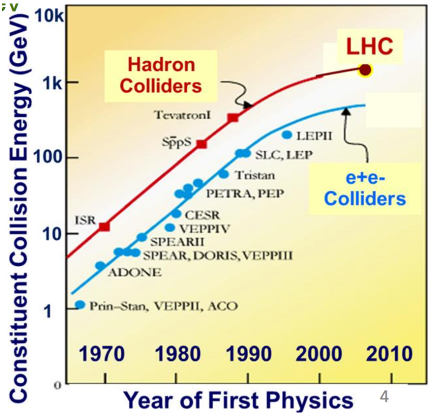
Advantage of hadron collider

• Can reach higher energies in ring (less syncrotron radiation)

Disadvantage of hadron collider

• Hadron are composites → **parassitic collisions** beyond hard parton scattering.

• Energy and type of colliding parton unknown → **kinematics partially unconstrained**.



Synchrotron Radiation Loss

Energy loss per turn for electron at sufficient high energy v ≈ c. In familiar units can be written:

$$\Delta E \ = \ 8.85 \cdot 10^{-5} \frac{E^4}{r} \ \ \text{MeV} \ \ \text{per} \ \ \text{turn}$$

The energy E is in GeV and r in kilometers.For **proton** the energy loss per turn is of course down of the fourth power of mass ratio:

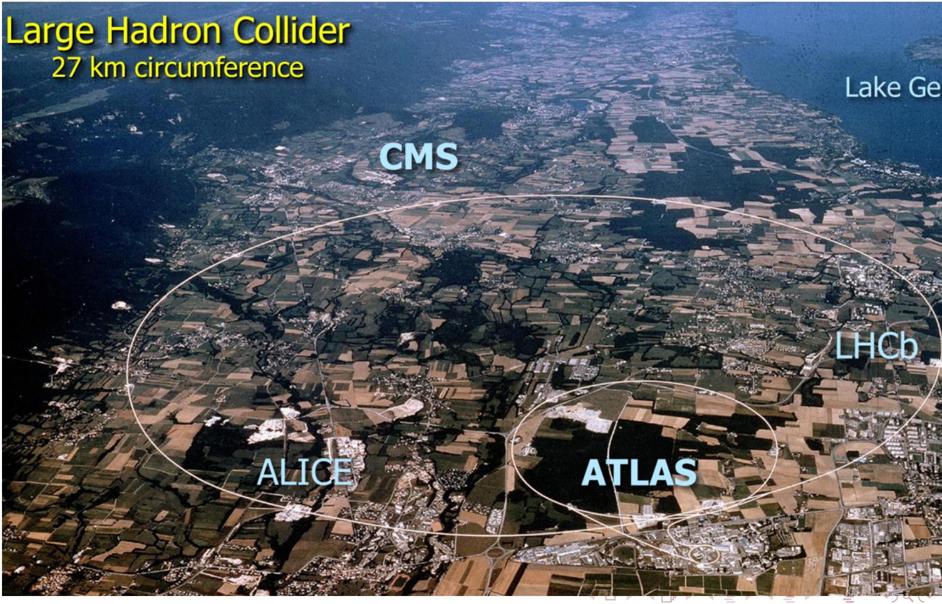
$$\Delta E \ = \ 7.8 \cdot 10^{-3} \frac{E^4}{r} \ \ \text{keV} \ \ \text{per} \ \ \text{turn}$$

The energy E is in TeV and r in kilometers.

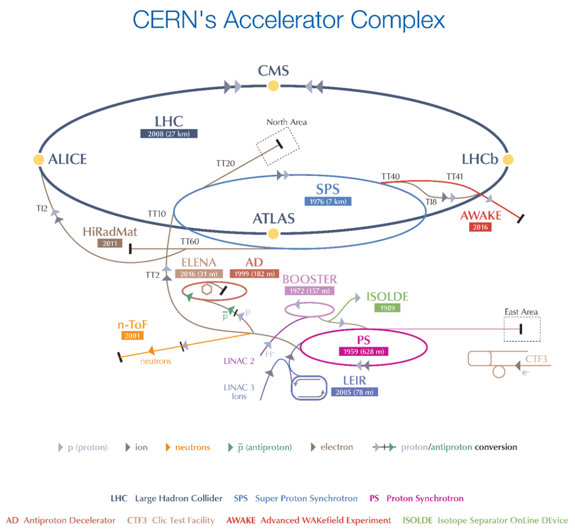
- LEP1 electrons E = 45 GeV L = 27 Km, r = bending radius 3026m, Δ E ∼ 120 MeV
- LEP2 electrons E = 100 GeV L = 27 Km, r = bending radius 3026m Δ E ∼ 2.9 GeV
- LHC proton E = 8 TeV L = 27 Km, r = bending radius 3026m, Δ E ∼ 7 KeV

The electron synchrotrons are limited by radiation losses.

Large Hadron Collider



CERN accelerator complex



CERN accelerator complex

Table : Summary accelerator parameters

accelerator	Top energy/GeV	Circumference/m
Linac	0.12	30
Booster	1.4	157
PS	26	628
SPS	450	6.911
LHC	7000	26.657

Underground

The LHC design parameters

- Superconducting dipoles 1232, at 1.9K 15m long, B = 8.33 T, inner diamater 56mm
- Energy protons 7 TeV
- Energy protons at iniejction 450 GeV

For all parameters see: Link

- Design Luminosity $10^{34} cm^{-2} s^{-1}$ achievement: higher more than design!
- Number of protons per bunch 1.15.10^{11}
- Bunch spacinq 25ns
- Stored beam energy 360 MJ
- Stored energy in magnets 11 GJ
- Beam lifetime 10h
- Emittance $\epsilon_n = 3.75$ mm μrad
- Beta function, $\beta^* =$0.55m

VIDEO

$$\mathcal{L} = \frac{N_a \cdot \ N_b}{\text{A}} \cdot f \qquad \mathcal{L} = f \cdot \frac{N_a \cdot \ N_b}{4\pi\sigma_x \cdot \sigma_y}$$

σ_x, σ_y = Gaussian transverse beam profiles in the horizontal (bend) and vertical directions (assumed bunch identical in beam profile, for semplification).

• The beam size can be expressed in terms of two quantities, one termed the transverse emittance, ϵ , and the other, the amplitude function, β.[1]

- The transverse emittance is a beam quality concept reflecting the process of bunch preparationextending all the way back to the source for hadrons .
- A low emittance particle beam is a beam where the particles are confined to a small distance and have nearly the same momentum.
- A beam transport system will only allow particles that are close to its design momentum, and of course they have to fit through the beam pipe and magnets that make up the system. In a colliding beam accelerator, keeping the emittance small means that the likelihood of particle interactions will be greater resulting in higher

- Emittance can be defined as the smallest opening you can squeeze the beam through, and can also be considered as a measurement of the parallelism of a beam.
- The dimension parallel to the motion of the particle is called the longitudinal emittance. The other two dimensions are referred to as the transverse emittances.

The amplitude function is a beam optics quantity and is determined by the accelerator magnet configuration.When expressed in terms of σ and β the transverse emittance becomes

$$\epsilon = \sigma^2/\beta$$

Beta,β is roughly the width of the beam squared divided by the emittance. If Beta $\beta$is low, the beam is narrower, **squeezed**. If Beta is high, the beam is wide and straight.Beta has units of length.

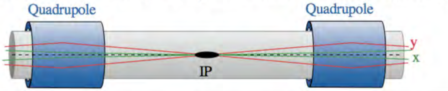
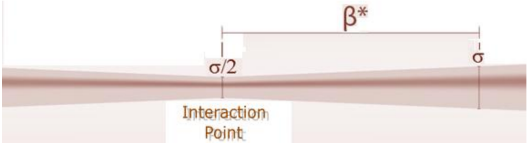


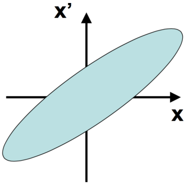
Figure : IP Interaction point

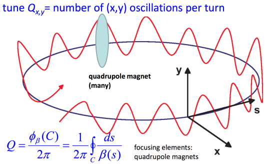
Sometimes β is referred as the distance from the focus point that the beam width is twice as wide as the focus point, ***beta****



In the experiments (detectors), the beam will be *squeezed* as much as possible, to increase the number of collisions, so at a distance of beta before the focus point, the beam is also twice as wide. Of particular significance is the value of the amplitude function at the interaction point, β^*.

Few concept





- transverse emittance"area in phase space" occupied by beam $= \pi \times \epsilon$

$$\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle}$$

For gaussian distribution ϵ_{rms} contain 39% beam

- The amplitude function is a beam optics quantity and is determined by the accelerator magnet configuration.beam size at collision point:

$$\sigma^* = \sqrt{\frac{\beta^*\epsilon_N}{\gamma}}$$

Clearly one wants β^* to be as small as possible; how small depends on the capability of the hardware to make a near-focus at the interaction point.$\mathcal{L}$ in terms of emittances and amplitude functions as:

$$\mathcal{L} \; = \; f \cdot \frac{N_a \cdot \; N_b}{4\pi\sqrt{\epsilon_x^* \beta_x^* \epsilon_y^* \beta_y^*}}$$

Simplified:

$$\mathcal{L} \; = \; f \cdot \frac{N^2}{4\pi\epsilon^*\beta^*}$$

LHC: The nominal LHC peak luminosity $\mathcal{L} \; = \; 10^{34} cm^{-2} s^{-1}$ corresponds to: $\beta^* = 0.55m, \;\; \beta^* = \; 3.75\mu m$

Basic Relation 1

Instantaneous luminosity is a measurement of the number of collisions that can produced in an interaction point peer cm^2 and per second. To calculate the number of events per second for a particular process it is necessary consider cross section and branching ratio.[2]

$$\text{event rate} \quad \frac{dN}{dt} = \sigma \cdot Br \cdot \mathcal{L}$$

Luminosity:

$$\mathcal{L} = \frac{N_b^2 n_b \, f\gamma}{4\pi\epsilon\beta^*} F$$

N_b = number of proton per bunch
n_b = number of bunches
f = rotation frequency ($\sim$ 11 Hz)
F = crossing angle factor
ϵ = transverse emittance(sametimes renorm.)
β^* = optics at meam crossing(m)
γ = relativistic factor

[2] For your fun : Luminosity calculator https://lpc.web.cern.ch/lumi2.html

Basic Relation 2

$$N = \sigma_b \cdot \int \mathcal{L}\, \mathrm{d}t$$

the integral is extended to the duration of data taking.The Integrated luminosity is the integral of $\mathcal{L}$ over time, depends on efficiency of the machine/dutycycle/ luminosity lifetime ...

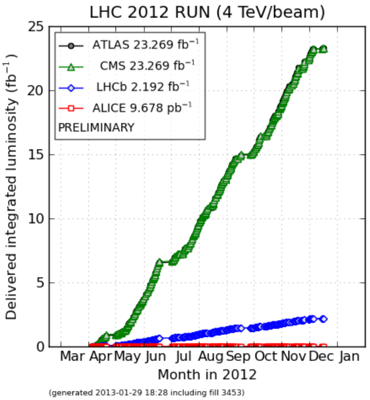
In one year 10^7 s the Hubner factor $\approx 20\%$ is the ratio of actual delivered luminosity to the amount you could collect by running continuously at the peak luminosity.The number of events collected in one year:

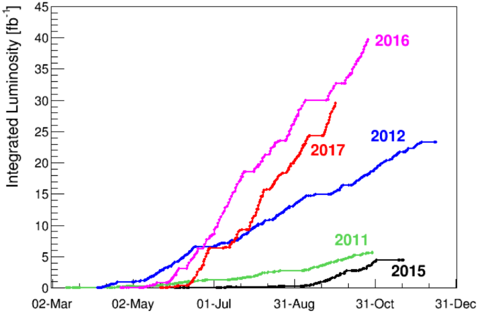
$$\frac{N}{\text{year}} = \sigma \cdot \mathcal{L} \cdot 10^7 \cdot \mathrm{Br} \cdot 0.2$$

At 13 TeV $\sigma_{\mathrm{H}iggs} = 55.7$ pb , $\mathrm{Br(ZZ)} \rightarrow 4\ell \sim 1.25 \cdot 10^{-4}$

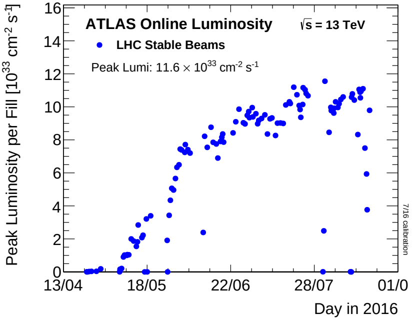
$$\frac{\mathrm{N}}{\text{year}} = 56 \cdot 10^{-36}\mathrm{cm}^{-2} \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \cdot 10^7 \cdot 10^{-4} \cdot 0.2 \approx 560$$

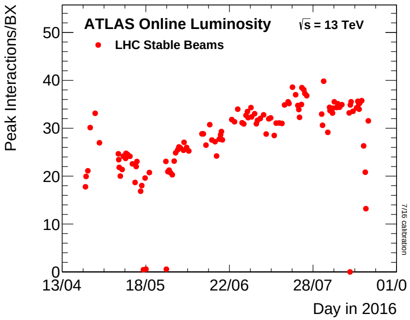
Integrated Luminosity delivered





Peak Luminosity





Excellent performance More than expected!

Run 2 running conditions

After 2 years of shut down for machine upgrade.

Parameter	Run 1	Overall Run 2 (expected)	Design
Center of Mass Energy	7 (8) TeV	13 (14) TeV	14 Tev
Bunch spacing	50 ns	25 ns	25 ns
Integrated Luminosity	~ 30 fb^{-1}	~100 – 150 fb^{-1}	500 fb^{-1} (*)
Peak Instantaneous luminosity	7.5 10^{33} cm^{-2} s^{-1}	**1.3-1.5 10^{34} cm^{-2} s^{-1}**	10^{34} cm^{-2} s^{-1}
# bunches	1400	2550-2808	2808
Max pile-up	~30	**~40**	~25 

The project

- 1982 first studies for LHC project
- 1983 Z discovery at SPS $p\bar{p}$collider
- 1989 Lep start ($\sim \sqrt{s} \sim$ 92 GeV) Z factory
- 1994 Approval LHC from CERN Council
- 1996 Final decision to start LHC construction
- 1996 LEP2 at $\sim \sqrt{s} \sim$ 200 GeV production of W^+W^-
-
- 2000 end of LEP operation
- 2003 Start of LHC installation - infrastructure
- 2006 Start of LHC magnet installation in the tunnel
- 2007 installation completed,starting cooling down
- 2008 commission with beam and first collisions

26 years from first studies, 14 years from approval, 7 years from LEP end

LHC runnig

- 10 September 2008 first beams
- 19 September 2008 incident, due to a failure in a resistive zone, helium released under high pressure, a relief discs was unable to maintain the pressure.
- 2009 lot work of repair (14 quadrupole and 39 dipole replaced)
- Nov 2009 restart successfully
- Since March 2010 run successfully at $\sqrt{s} = 7$ TeV
- 2011-2012 data taking at $\sqrt{s} = 7 - 8$ TeV
- Since May 2015 - **at present data taking at $\sqrt{s} = 13$ TeV**
- 26 June 2016 The LHC achieves a luminosity of $1.0 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, its design value

From Paradise to Hell

Figure : LHC Control room 10 September 2008

Figure : relief discs 19 September 2008

23 Nov 2009: First collisions at 900 GeV

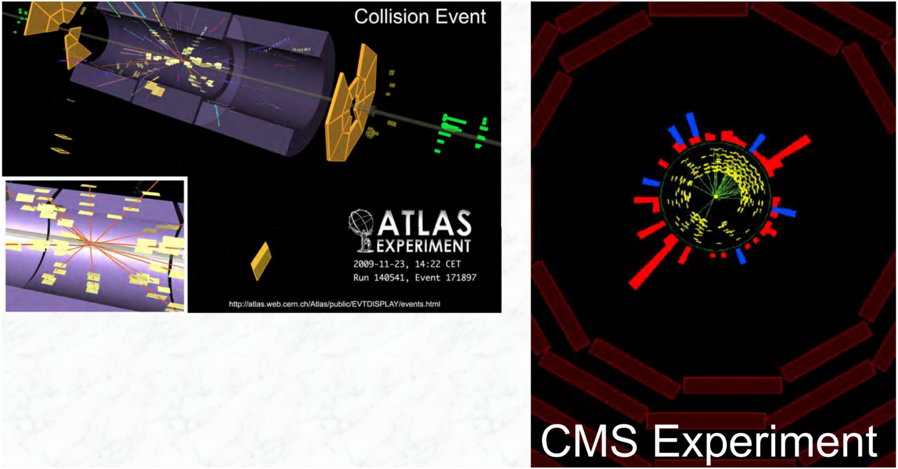
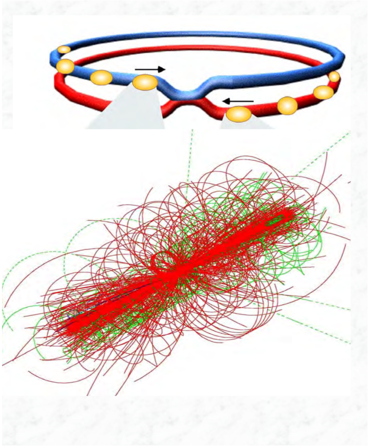


Figure : First collisions at 900 GeV

Main characteristics of proton-proton collisions at LHC



proton-proton

- 2808 × 2808 bunches, separation: 7.5 m (**25 ns**)
- 10^{11} protons/bunch 40 MHz
- Luminosity $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\sim 10^9$ pp collisions/s (superposition of >20 pp interaction per crossing *pile up*)
- $\sim$ 1660 charged particles in the detector
- **high particles densities high requirements on detectors**

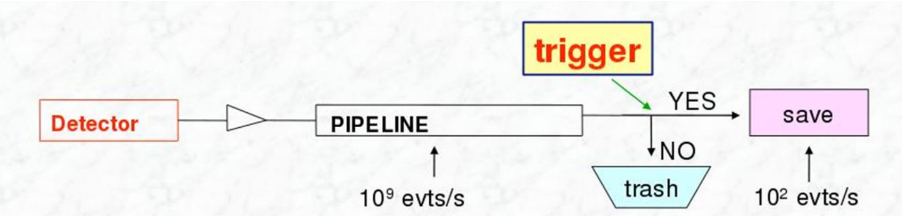
Main characteristics of proton-proton collisions at LHC

40 MHz bunch crossing rate (25ns = 7.5m bunch spacing)	**Fast trigger, precise timing and "pipeline" electronics: Level-1 latency < 2.5μs**
~1 GHz interaction rate at $L = 10^{34}$ cm^{-2}s^{-1} (~25 ias. per bunch crossing)	**Efficient pattern recognition to reduce:** GHz @ **L1** → 75 kHz @ **HLT** → 200 Hz to disk
~300 Mbytes/seconds data rate (200 Hz ⇒ O(1.5 MB/event))	**Powerful data processing farms**: distribute data analysis to computing centres worldwide
Irradiation rate / 10 LHC years: 5×10^{14} n_{eq}/cm^2 (300 kGray [= J/kg])	**Radiation hard inner tracker** (pixel with large S/B) **and forward calorimeter technology**
High charged multiplicity (O(1000) tracks per event, 10^{12} / sec)	**High-granular pixel/silicon** or **fine-grained straw tracker** technologies
High background rates (beam halo muons, neutrons, beam-gas collisions)	**Precise muon timing,** redundant pattern recognition, radiation hardness

LHC data handling, GRID computing

Selection of events

- Bunch crossing rate: 40MHz, ≈ **20 interactions per beam crossing**(10^9 evts/s)→ can record ≈ 200 event/s (1.5MB each) at 300 MB/s data rate
- Need highly efficient and high selective TRIGGER→ raw data (70TB/s) are stored in pipeline



- ATLAS trigger has 3 levels (CMS 2 levels)
  - **Level-1**: hardware $\approx 3\ \mu$s decision time, **40 MHz $\rightarrow$ 100kHz**
  - **Level-2**: software $\approx 40\ \mu$s decision time, **100kHz $\rightarrow$ 2kHz**
  - **Level-3**: software 4s decision time, **2kHz $\rightarrow$ 200Hz**

Trigger efficiency enters in the calculation of cross sections, together other efficiencies,(ϵ) and acceptance (A).

$$\sigma = \frac{\mathrm{N}}{A \cdot \epsilon \cdot \int \mathcal{L}\,\mathrm{d}t}$$

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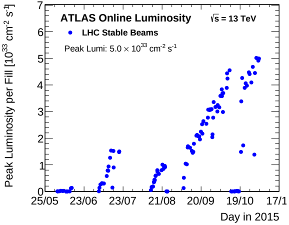
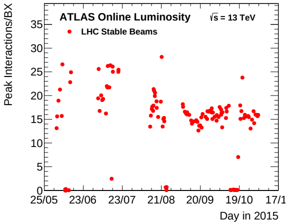
Pile up

The price to pay to get high $\mathcal{L}$ is the pile up.

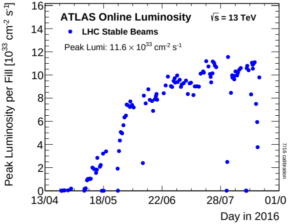
2015



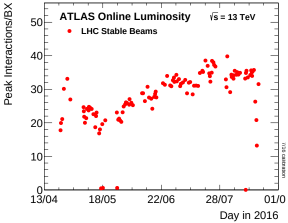
2015



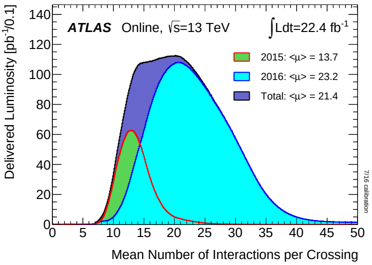
2016

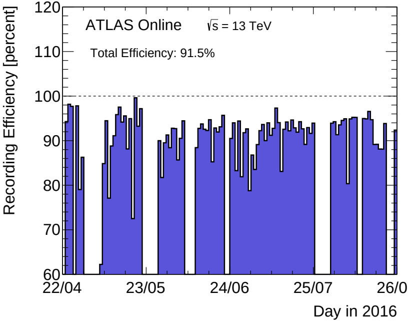


2016

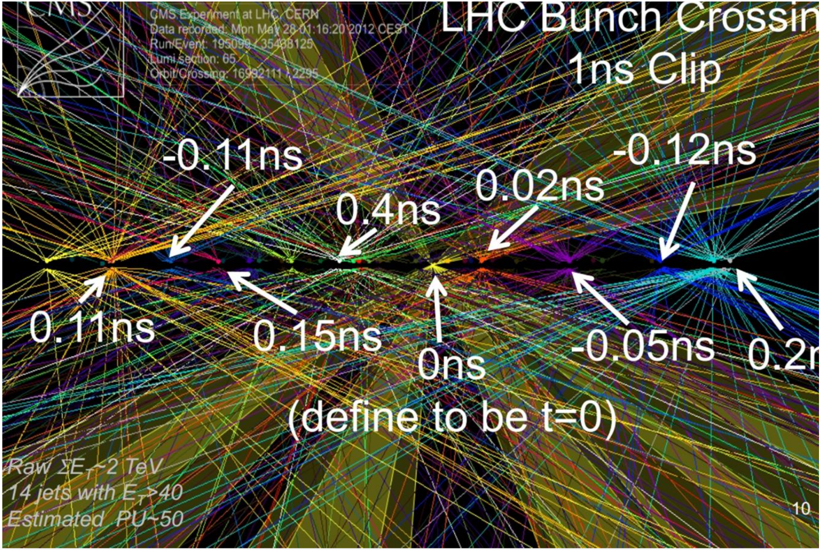


Pile up and recording efficiency

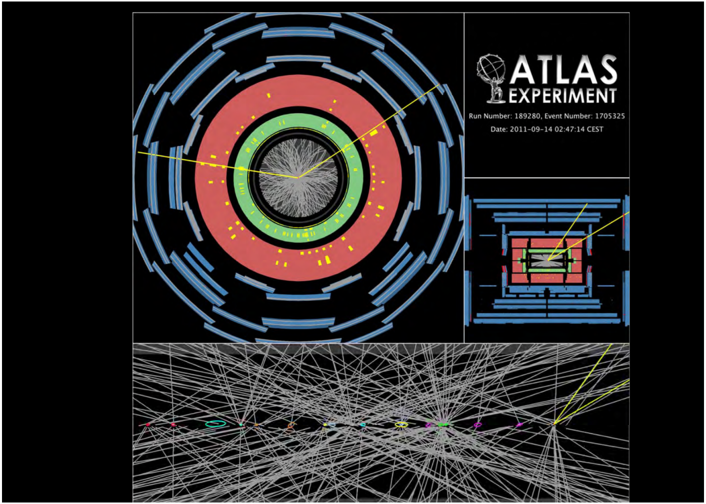




An example of pile up



An example of pile up



a needle in a haystack

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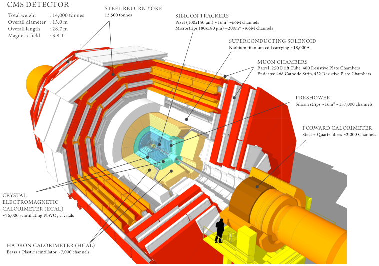
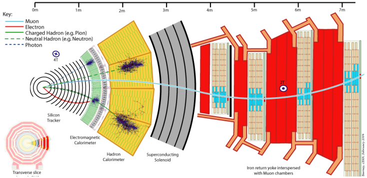
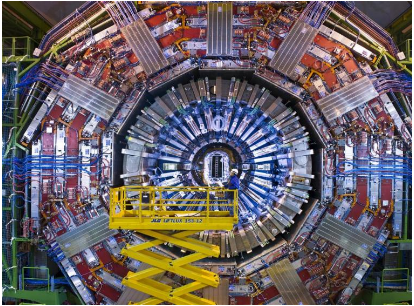
CompactMuonSolenoid

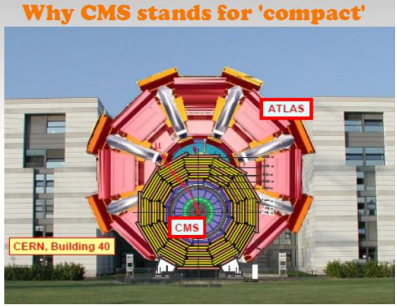




Slice.pdf

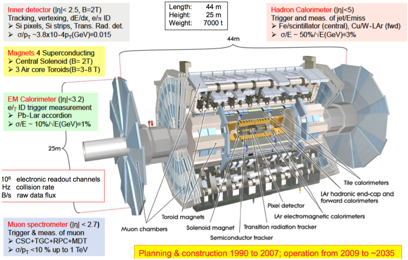
CompactMuonSolenoid

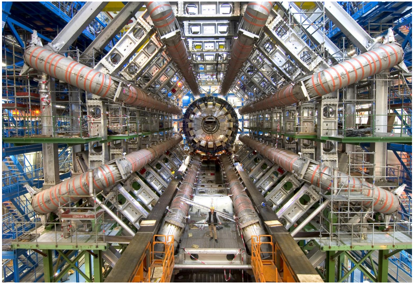




A Toroidal LHC ApparatuS

•





This huge volume **aligned at 35 μm.**

ATLAS & CMS: Design & Performance Overview

	ATLAS (7 ktons)	CMS (12.5 ktons)
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2$ T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 3.8$ T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field	• 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	• Pb / Liquid Ar sampling accordion • $\sigma(E) \sim 10$–$12\% / \sqrt{E} \oplus 0.2$–$0.35\%$ • Longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim 3$–$5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\% / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes & CSC (EC) + RPC • $\sigma(p_T) \sim 13\% / 4.5\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Key Component : the People

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Appendix A From rapidity to pseudorapidity

Knowing that for a highly relativistic particle, pc is far bigger than mc^2, we factor pc out of each square root and use a binomial expansion to approximate what is left inside.

$$\begin{aligned} y &= \tfrac{1}{2}\ln\left(\frac{pc\left(1+\frac{m^2c^4}{p^2c^2}\right)^{\frac{1}{2}}+p_zc}{pc\left(1+\frac{m^2c^4}{p^2c^2}\right)^{\frac{1}{2}}-p_zc}\right) \\ &\simeq \tfrac{1}{2}\ln\left(\frac{pc+p_zc+\frac{m^2c^4}{2pc}+\cdots}{pc-p_zc+\frac{m^2c^4}{2pc}+\cdots}\right) \\ &\simeq \tfrac{1}{2}\ln\left(\frac{1+\frac{p_z}{p}+\frac{m^2c^4}{2p^2c^2}+\cdots}{1-\frac{p_z}{p}+\frac{m^2c^4}{2p^2c^2}+\cdots}\right). \end{aligned} \tag{15}$$

Now $p_z/p = \cos\theta$, where θ is the angle made by the particle trajectory with the beam pipe, and hence we have

$$1+\frac{p_z}{p} = 1+\cos\theta = 1+\left(\cos^2\frac{\theta}{2}-\sin^2\frac{\theta}{2}\right) = 2\cos^2\frac{\theta}{2}. \tag{16}$$

Similarly

$$1-\frac{p_z}{p} = 1-\cos\theta = 1-\left(\cos^2\frac{\theta}{2}-\sin^2\frac{\theta}{2}\right) = 2\sin^2\frac{\theta}{2}. \tag{17}$$

Substituting these back into Equation 15 we obtain

$$y \simeq \frac{1}{2}\ln\frac{\cos^2\frac{\theta}{2}}{\sin^2\frac{\theta}{2}}, \tag{18}$$

or

$$y \simeq -\ln\tan\frac{\theta}{2}. \tag{19}$$

We define the pseudorapidity η as

$$\eta = -\ln\tan\frac{\theta}{2}, \tag{20}$$

so that for highly relativistic particles, $y \simeq \eta$. Pseudorapidity is particularly

Appendix B Difference of rapidity

$$y = \ln\sqrt{\frac{E+p_zc}{E-p_zc}} = \ln\left(\frac{E+p_zc}{\sqrt{E-p_zc}\sqrt{E+p_zc}}\right).$$

Using the energy–momentum–mass relation this becomes

$$y = \ln\left(\frac{E+p_zc}{\sqrt{E^2-p_z^2c^2}}\right) = \ln\left(\frac{E+p_zc}{M_Tc^2}\right). \tag{8}$$

The next neat expression for rapidity is found by using hyperbolic tangents. Recall that $\tanh\theta = (e^\theta - e^{-\theta})/(e^\theta + e^{-\theta})$. We write

$$\begin{aligned}
y &= \tanh^{-1}\left(\tanh\left(\ln\left(\tfrac{E+p_zc}{M_Tc^2}\right)\right)\right).\\
&= \tanh^{-1}\left(\frac{\exp\left(\ln\frac{E+p_zc}{M_Tc^2}\right)-\exp\left(-\ln\frac{E+p_zc}{M_Tc^2}\right)}{\exp\left(\ln\frac{E+p_zc}{M_Tc^2}\right)+\exp\left(-\ln\frac{E+p_zc}{M_Tc^2}\right)}\right)\\
&= \tanh^{-1}\left(\frac{\frac{E+p_zc}{M_Tc^2}-\frac{M_Tc^2}{E+p_zc}}{\frac{E+p_zc}{M_Tc^2}+\frac{M_Tc^2}{E+p_zc}}\right)\\
&= \tanh^{-1}\left(\frac{\frac{(E+p_zc)^2-M_T^2c^4}{M_Tc^2(E+p_zc)}}{\frac{(E+p_zc)^2+M_T^2c^4}{M_Tc^2(E+p_zc)}}\right)\\
&= \tanh^{-1}\left(\frac{(E+p_zc)^2-M_T^2c^4}{(E+p_zc)^2+M_T^2c^4}\right)\\
&= \tanh^{-1}\left(\frac{E^2+2Ep_zc+p_z^2c^2-M_T^2c^4}{E^2+2Ep_zc+p_z^2c^2+M_T^2c^4}\right)\\
&= \tanh^{-1}\left(\frac{2Ep_zc+2p_z^2c^2}{2E^2+2Ep_zc}\right)\\
&= \tanh^{-1}\left(\frac{p_zc(E+p_zc)}{E(E+p_zc)}\right)\\
y &= \tanh^{-1}\left(\frac{p_zc}{E}\right).
\end{aligned} \tag{9}$$

Now let us show how rapidity transforms under Lorentz boosts parallel to the z axis. Start with Equation 6 and perform a Lorentz boost on E/c and p_z

$$
\begin{aligned}
y' &= \tfrac{1}{2}\ln\left(\tfrac{\gamma E/c-\beta\gamma p_z+\gamma p_z-\beta\gamma E/c}{\gamma E/c-\beta\gamma p_z-\gamma p_z+\beta\gamma E/c}\right) \\
&= \tfrac{1}{2}\ln\left(\tfrac{\gamma(E/c+p_z)-\beta\gamma(E/c+p_z)}{\gamma(E/c-p_z)+\beta\gamma(E/c-p_z}\right) \\
&= \tfrac{1}{2}\ln\left(\tfrac{E/c+p_z}{E/c-p_z}\tfrac{\gamma-\beta\gamma}{\gamma+\beta\gamma}\right) \\
&= \tfrac{1}{2}\ln\left(\tfrac{E+p_z c}{E-p_z c}\right)+\ln\sqrt{\tfrac{1-\beta}{1+\beta}} \\
.y' &= y+\ln\sqrt{\tfrac{1-\beta}{1+\beta}} \\
.
\end{aligned} \tag{10}
$$

This can be simplified further by noting that

$$
\begin{aligned}
\ln\sqrt{\tfrac{1-\beta}{1+\beta}} &= \tanh^{-1}\left(\tanh\,\ln\sqrt{\tfrac{1-\beta}{1+\beta}}\right) \\
&= \tanh^{-1}\left(\tfrac{\sqrt{\frac{1-\beta}{1+\beta}}-\sqrt{\frac{1+\beta}{1-\beta}}}{\sqrt{\frac{1-\beta}{1+\beta}}+\sqrt{\frac{1+\beta}{1-\beta}}}\right) \\
&= \tanh^{-1}\left(\tfrac{(1-\beta)-(1+\beta)}{(1-\beta)+(1+\beta)}\right) \\
&= -\tanh^{-1}\beta.
\end{aligned} \tag{11}
$$