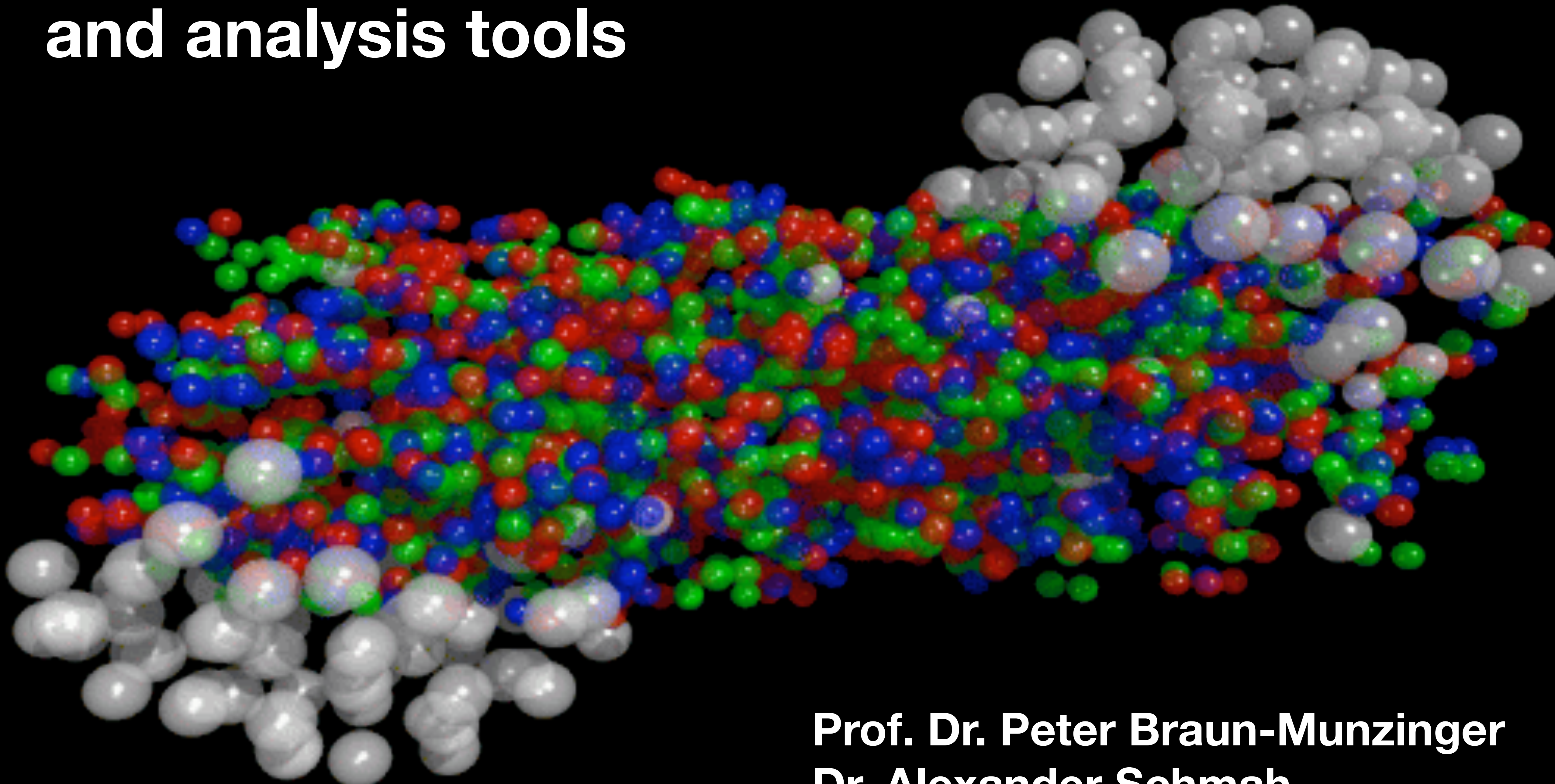
Quark-Gluon Plasma Physics

2. Kinematic variables, detector overview and analysis tools



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SS 2021

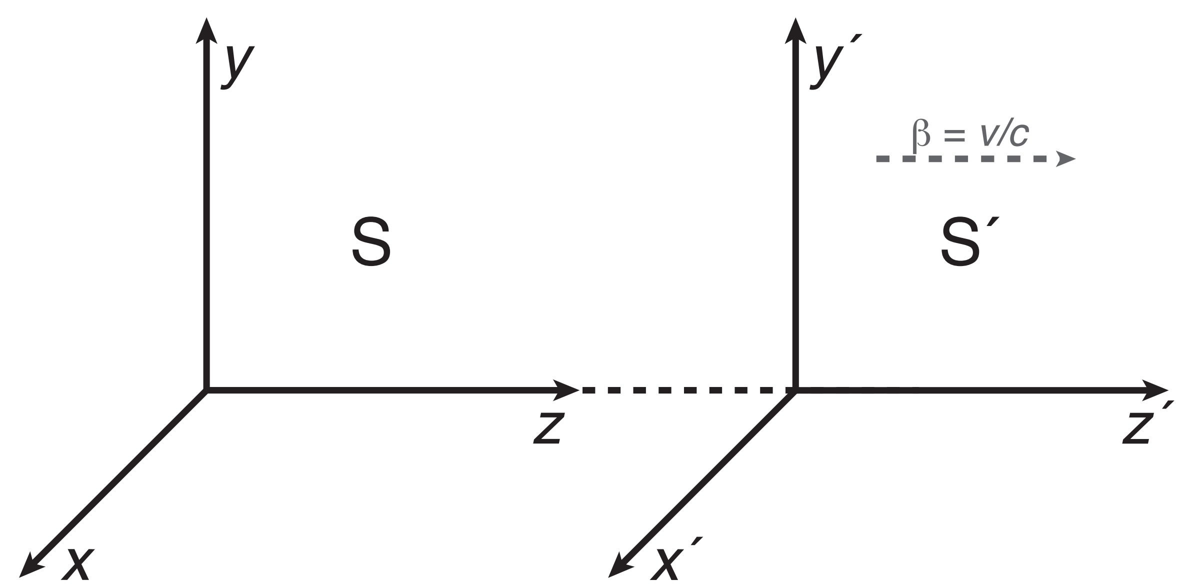
Lorentz transformation

Postulates
1. There is no preferred inertial frame
2. The speed of light in vacuum has the same value *c* in all inertial frames of reference

(Contravariant) space-time four-vector in system S:

$$x^\mu := (x^0, x^1, x^2, x^3) = (t, \vec{x}) = (t, x, y, z)$$

In system S'
(follows from the two postulates)



$$x^{0\prime} = \gamma(x^0 - \beta x^3)$$
$$x^{1\prime} = x^1$$
$$x^{2\prime} = x^2$$
$$x^{3\prime} = \gamma(x^3 - \beta x^0)$$

$$\beta = v/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Energy-momentum four-vector

General four-vector:
transforms under Lorentz transformation like the space-time four-vector

Relativistic energy and momentum:

$$E = \gamma m, \quad p = \gamma \beta m, \qquad m = \text{rest mass} \qquad (\hbar = c = 1)$$

Contravariant four-momentum vector:

$$p^\mu = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, \vec{p}_T, p_z) = (E, p_x, p_y, p_z)$$

Covariant four-vector:

$$x^\mu := (x^0, x^1, x^2, x^3) \quad \rightarrow \quad x_\mu := (x^0, -x^1, -x^2, -x^3)$$

See appendix E

Scalar product of two four-vectors *a* and *b*:

$$a \cdot b = a^\mu b_\mu = a_\mu b^\mu = a^0 b^0 - \vec{a} \cdot \vec{b}$$

Relation between energy and momentum:

$$E^2 = p^2 + m^2 \qquad a \cdot a = E^2 - p^2 = m^2$$

Center-of-Mass System (CMS) [actually: center-of-momentum system]

Consider a collision of two particles. The CMS is defined by

$$\vec{p}_a = -\vec{p}_b$$

$p_a = (E_a, \vec{p}_a)$ $\qquad$ $p_b = (E_b, \vec{p}_b)$

The Mandelstam variable s is defined as

$$s := (p_a + p_b)^2 \overset{CMS}{=} (E_a + E_b)^2$$

Homework A

4-vector

$\sqrt{s}$ is the total energy in the center-of-mass frame ("center-of-mass energy")

Example: LHC. beam energy 6.5 TeV: $\sqrt{s} = 2\,E = 13$ TeV (lab frame = CMS)

More on LHC energies

From 'centripetal force = Lorentz force: $\vec{F}_L = q\vec{v} \times \vec{B} = \frac{mv^2}{r}$

$$R \equiv \frac{p}{q} = r_{\mathrm{LHC,bend}} \cdot B_{\mathrm{LHC}}, \qquad B_{\mathrm{LHC,max}} \approx 8.3\,\mathrm{T} \quad (\rightarrow \text{this limits } \sqrt{s})$$

"rigidity" 1232 dipoles x 14.3 m / (2 π) = 2804 m

Homework B: Calculate p_{max}

protons: $R = p_{\mathrm{proton}}$ ions: $R = \frac{A \cdot p_{\mathrm{nucleon}}}{Z}$

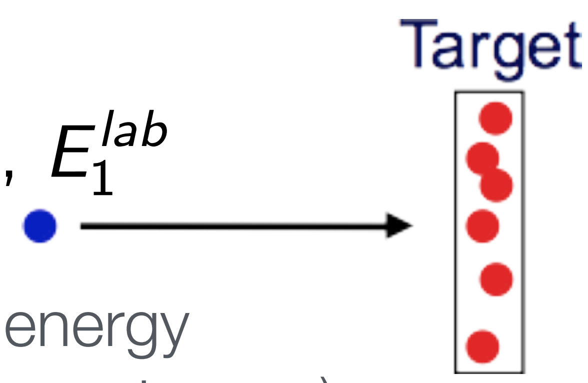
2011/12: $p_{\mathrm{proton}} = 3.5\,\mathrm{TeV} \rightarrow p_{\mathrm{nucleon}} \equiv p_{\mathrm{Pb}}/A = \frac{Z}{A} \cdot p_{\mathrm{proton}} = 1.38\,\mathrm{TeV}$

corresponding energy of nucleons in Pb ion for same *B* field (same rigidity)

Center-of-momentum energy per nucleon-nucleon pair:

Pb-Pb (2011/12): $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ Pb-Pb (2015/18): $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$

$\sqrt{s}$ for Fixed-Target Experiments



$$s = \left[\begin{pmatrix} E_1^{\text{lab}} \\ \vec{p_1} \end{pmatrix} + \begin{pmatrix} m_2 \\ \vec{0} \end{pmatrix} \right]^2$$
$$= m_1^2 + m_2^2 + 2 E_1^{\text{lab}} m_2$$

$$\Rightarrow \sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2 E_1^{\text{lab}} m_2}$$
$$\overset{E_1^{\text{lab}} \gg m_1,\, m_2}{\approx} \sqrt{2 E_1^{\text{lab}} m_2}$$

Example: antiproton production (fixed-target experiment):

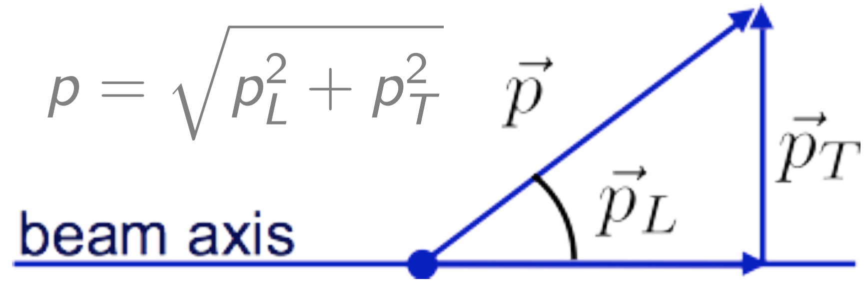
$$p + p \rightarrow p + p + p + \bar{p}$$

Minimum energy required to produce an antiproton: In CMS. all particles at rest after the reaction. i.e.. $\sqrt{s} = 4\, m_{\mathrm{p}}$. hence:

$$4 m_p \overset{!}{=} \sqrt{2 m_p^2 + 2 E_1^{\text{lab,min}} m_p} \quad \Rightarrow \quad E_1^{\text{lab,min}} = \frac{(4 m_p)^2 - 2 m_p^2}{2 m_p} = 7 m_p$$

Rapidity

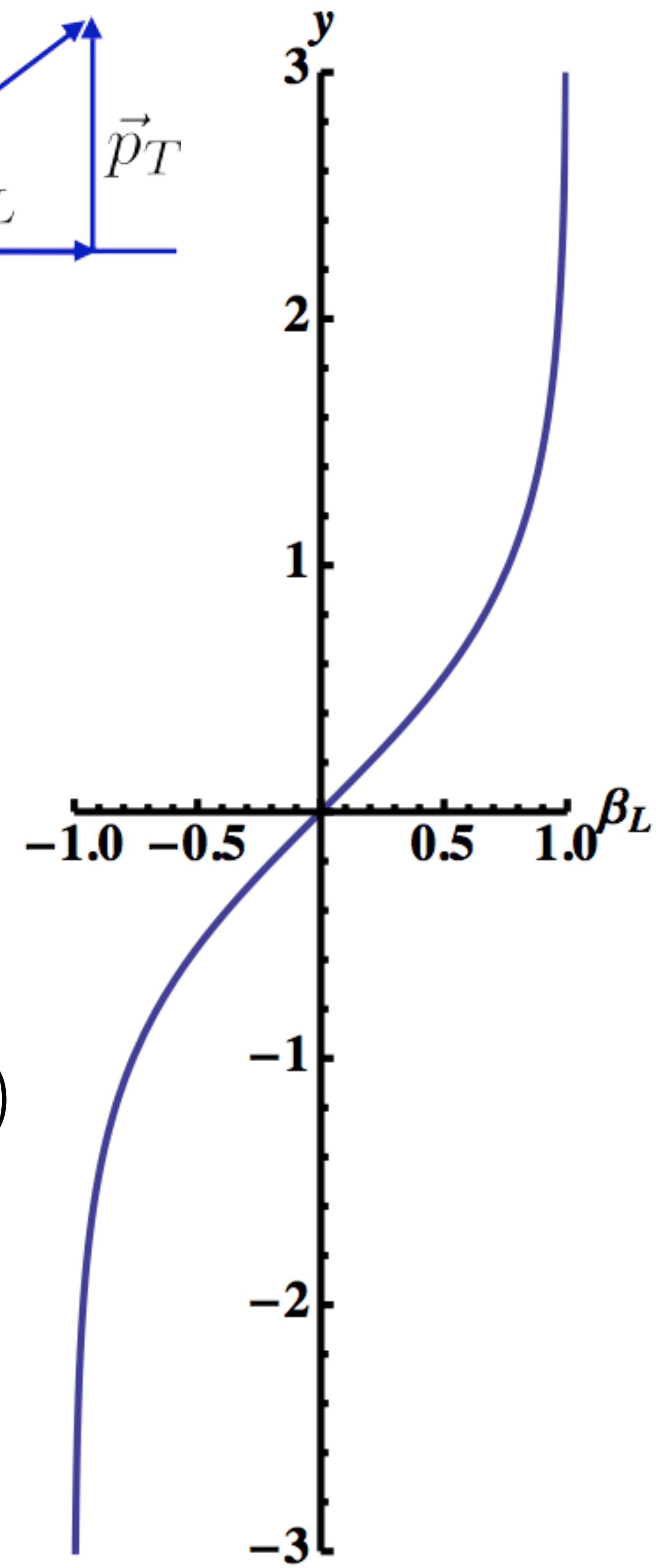
$$\vec{p} = E\vec{\beta}$$



The rapidity y is a generalization of the (longitudinal) velocity $\beta_L = p_L / E$:

$$y := \operatorname{arctanh} \beta_L = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L} = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

$$y \approx \beta_L \quad \text{for} \quad \beta_L \ll 1$$



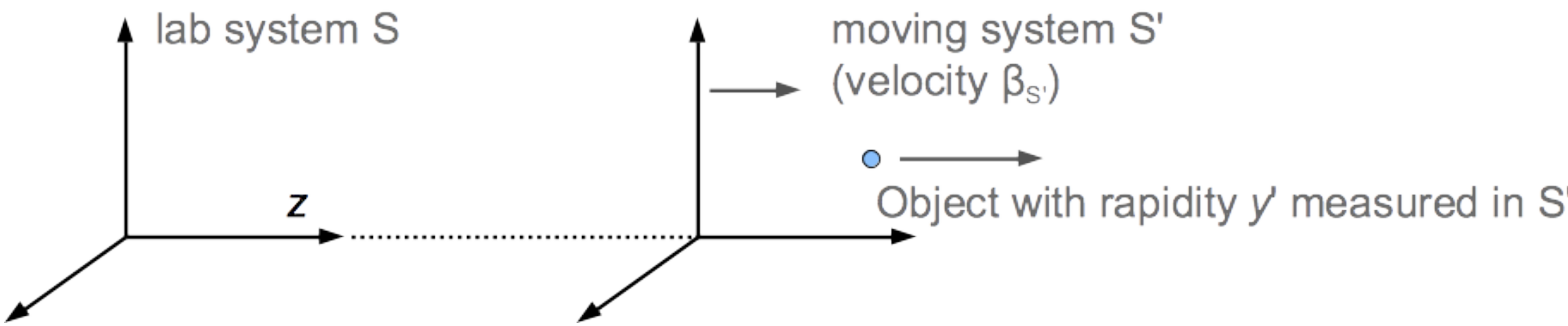
With $$e^y = \sqrt{\frac{E + p_L}{E - p_L}}, \qquad e^{-y} = \sqrt{\frac{E - p_L}{E + p_L}}$$

and $$\sinh x = \frac{1}{2}\left(e^x - e^{-x}\right), \quad \cosh x = \frac{1}{2}\left(e^x + e^{-x}\right)$$

one obtains $$E = m_T \cdot \cosh y, \qquad p_L = m_T \cdot \sinh y$$

where $m_T := \sqrt{m^2 + p_T^2}$ is called *transverse mass*

Additivity of Rapidity under Lorentz Transformation



Lorentz transformation: $E = \gamma(E' + \beta p'_z), \qquad p_z = \gamma(p'_z + \beta E') \qquad (\beta \equiv \beta_{S'})$

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$$= \frac{1}{2} \ln \frac{\gamma(E' + \beta p'_z) + \gamma(p'_z + \beta E')}{\gamma(E' + \beta p'_z) - \gamma(p'_z + \beta E')}$$

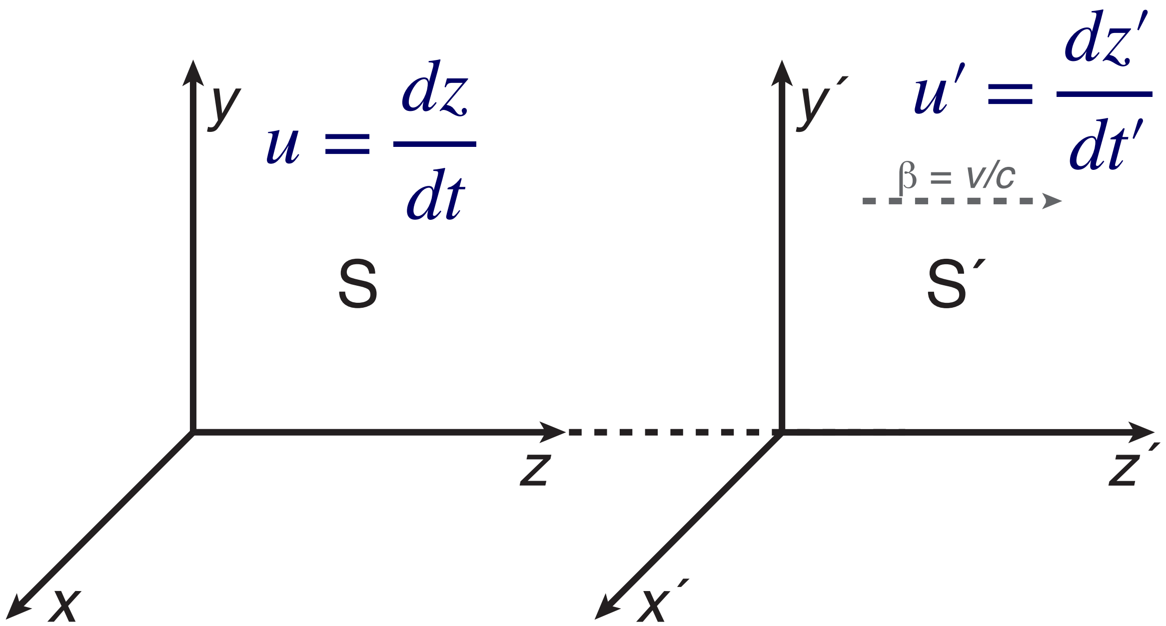
$$= \frac{1}{2} \ln \frac{(1+\beta)(E' + p'_z)}{(1-\beta)(E' - p'_z)}$$

$$= \underbrace{\frac{1}{2} \ln \frac{1+\beta}{1-\beta}}_{\text{rapidity of S' as measured in S}} + \underbrace{\frac{1}{2} \ln \frac{E' + p'_z}{E' - p'_z}}_{y'}$$

y is not Lorentz invariant. however. it has a simple transformation property:

$$y = y' + y_{S'}$$

Velocity Lorentz transformation



$\beta = v/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$

$$z' = \gamma(z - \beta t)$$

$$t' = \gamma(t - z\beta)$$

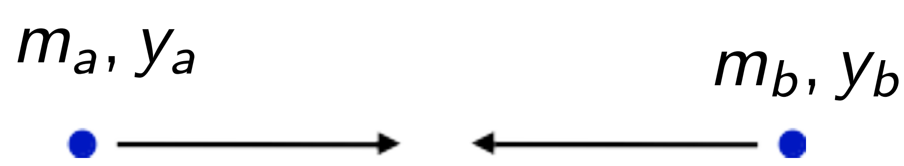
$$u' = \frac{dz'}{dt'}$$

$$\frac{dz'}{dt'} = \frac{\gamma(dz - \frac{v}{c}dt)}{\gamma(dt - \frac{v}{c}dz)} = \frac{\frac{dz}{dt} - \frac{v}{c}}{1 - \frac{v}{c}\frac{dz}{dt}}$$

$$u' = \frac{u - v}{1 - \frac{uv}{c^2}}$$

Much more complicated than rapidity!

Rapidity of the CMS (I)



$$a = (E_a, 0, 0, p_a)$$
$$b = (E_b, 0, 0, -p_b)$$

Velocity of the CMS:

$$a_z^* = \gamma_{\mathrm{cm}}(a_z - \beta_{\mathrm{CM}} a_0) \overset{!}{=} -b_z^* = -\gamma_{\mathrm{cm}}(b_z - \beta_{\mathrm{CM}} b_0) \qquad \Rightarrow \beta_{\mathrm{cm}} = \frac{a_z + b_z}{a_0 + b_0}$$

Using the formula for the rapidity we obtain

$$y = \frac{1}{2} ln \left[\frac{1+\beta_z}{1-\beta_z} \right] \qquad y_{\mathrm{cm}} = \frac{1}{2} \ln \left[\frac{a_0 + a_z + b_0 + b_z}{a_0 - a_z + b_0 - b_z} \right]$$

Writing energies and momenta in terms of rapidity:

$$m_T = m$$
$$E = m_T cosh(y)$$
$$p_z = m_T sinh(y)$$
$$cosh(y) + sinh(y) = e^x$$

$$y_{\mathrm{cm}} = \frac{1}{2} \ln \left[\frac{m_a e^{y_a} + m_b e^{y_b}}{m_a e^{-y_a} + m_b e^{-y_b}} \right] = \frac{1}{2}(y_a + y_b) + \frac{1}{2} \ln \left[\frac{m_a e^{y_a} + m_b e^{y_b}}{m_a e^{y_b} + m_b e^{y_a}} \right]$$

See appendix C

Rapidity of the CMS (II)

For a collision of two particles with **equal mass *m* and rapidities y_a and y_b**. the rapidity of the CMS y_{cm} is then given by:

$$y_{\rm cm} = (y_a + y_b)/2$$

In the center-of-mass frame. the rapidities of particles a and b are:

$$y_a^* = y_a - y_{\rm cm} = -\frac{1}{2}(y_b - y_a) \qquad y_b^* = y_b - y_{\rm cm} = \frac{1}{2}(y_b - y_a)$$

Examples (CMS rapidity of the nucleon-nucleon system)

a) fixed target experiment: $y_{CM} = (y_{\rm target} + y_{\rm beam})/2 = y_{\rm beam}/2$

b) collider (same species and beam momentum): $y_{CM} = (y_{\rm target} + y_{\rm beam})/2 = 0$

c) collider (two different ions species. same *B* field, approximation: p >> m):

$$y_{cm} = \frac{1}{2}\ln\frac{Z_1 A_2}{A_1 Z_2}$$

Homework C

p-Pb beam at LHC: $y_{CM} \approx 0.465$

Example: Beam Rapidities

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \ln \frac{E + p_z}{\sqrt{E^2 - p_z^2}} = \ln \frac{E + p_z}{m} \approx \ln \frac{2E}{m}$$

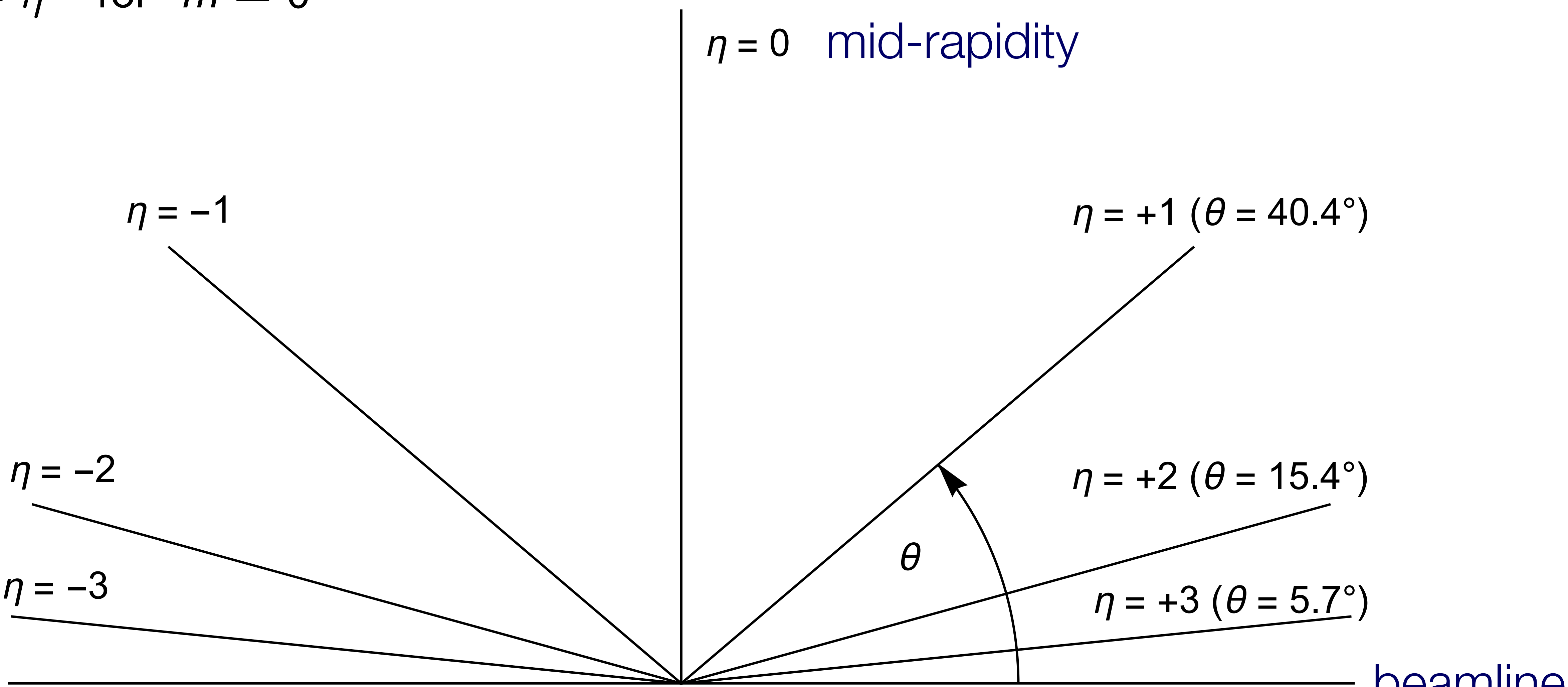
Beam momentum (GeV/*c*)	Beam rapidity
100	5.36
158	5.81
1380 (= 3500·82/208)	7.99
2760 (= 7000·82/208)	8.86
3500	8.92
6500	9.54
7000	9.61

Pseudorapidity η

$\cos(2\alpha) = 2\cos^2\alpha - 1 = 1 - 2\sin^2\alpha$

$$y = \frac{1}{2}\ln\frac{E + p\cos\vartheta}{E - p\cos\vartheta} \overset{p \gg m}{\approx} \frac{1}{2}\ln\frac{1+\cos\vartheta}{1-\cos\vartheta} = \frac{1}{2}\ln\frac{2\cos^2\frac{\vartheta}{2}}{2\sin^2\frac{\vartheta}{2}} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

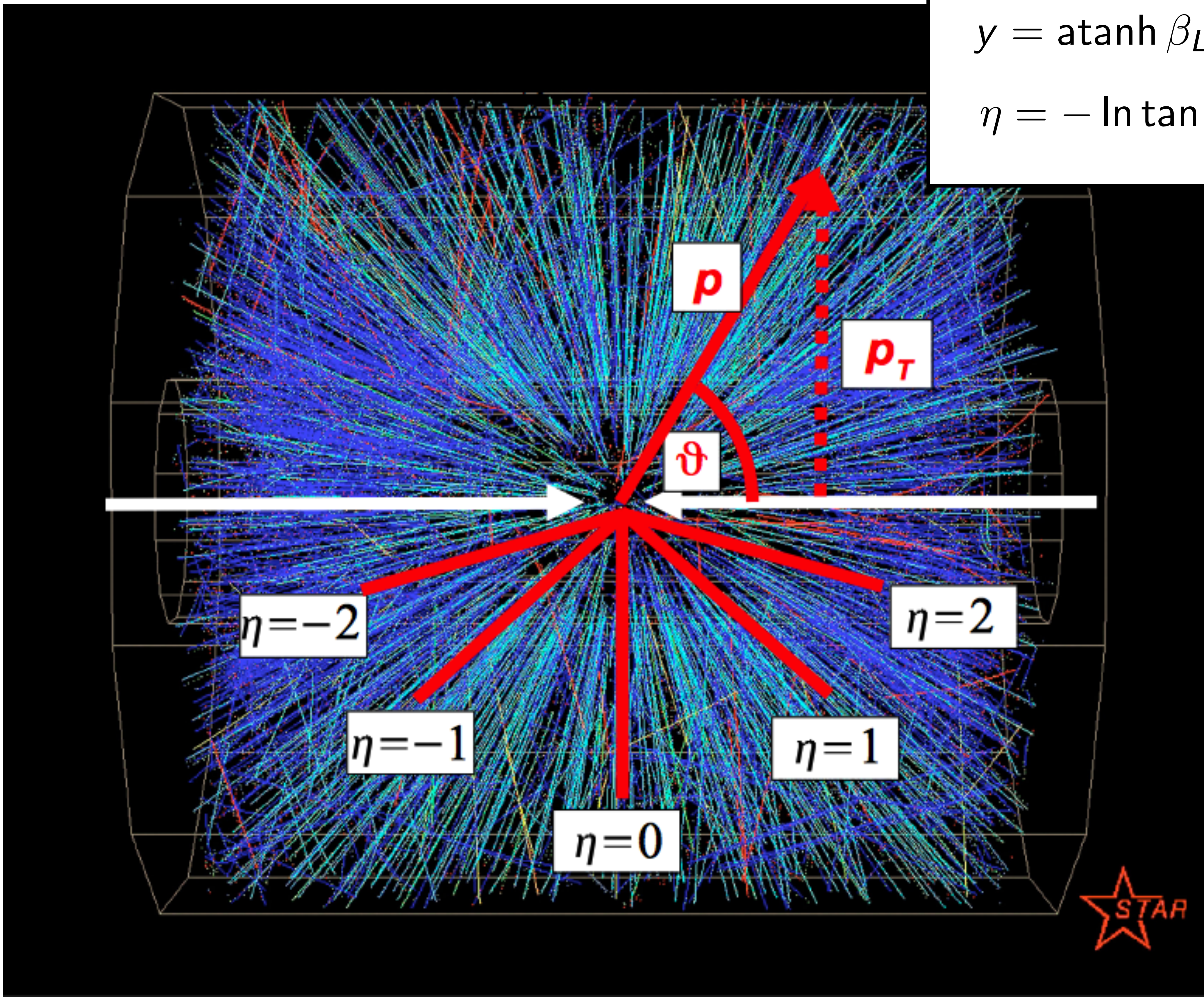
$y = \eta \quad \text{for} \quad m = 0$



Analogous to the relations for the rapidity we find:

$p = p_T \cdot \cosh\eta, \qquad p_L = p_T \cdot \sinh\eta$ **See appendix A**

Brief summary



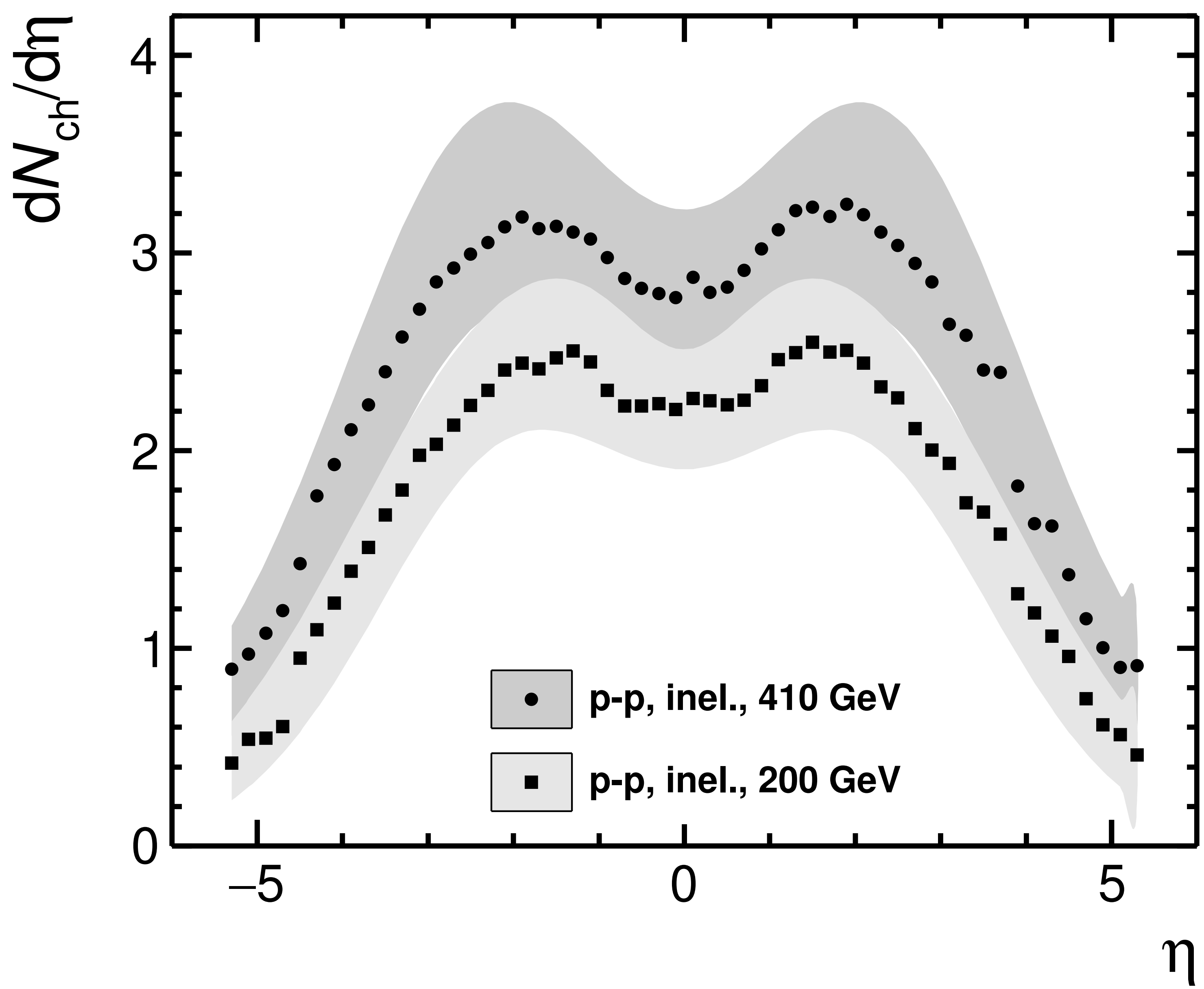
$$p_T = p \sin\vartheta$$

$$y = \operatorname{atanh}\beta_L$$

$$\eta = -\ln\tan\frac{\vartheta}{2}$$

Example of a Pseudorapidity Distribution of Charged Particles

PHOBOS. Phys.Rev. C83 (2011) 024913



Beam rapidity (E = 100 GeV):

$$y_{\text{beam}} = \ln \frac{E+p}{m} = 5.36$$

Average number of charged particles per collision (pp at $\sqrt{s}$ = 200 GeV):

$$\langle N_{ch} \rangle = \int \frac{dN_{ch}}{d\eta} d\eta \approx 20$$

Difference between dN/dy and dN/dη in the CMS

$$\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}} \frac{dN}{dy} \qquad y(\eta) = \frac{1}{2} \log \left(\frac{\sqrt{p_T^2 \cosh^2 \eta + m^2} + p_T \sinh \eta}{\sqrt{p_T^2 \cosh^2 \eta + m^2} - p_T \sinh \eta} \right)$$

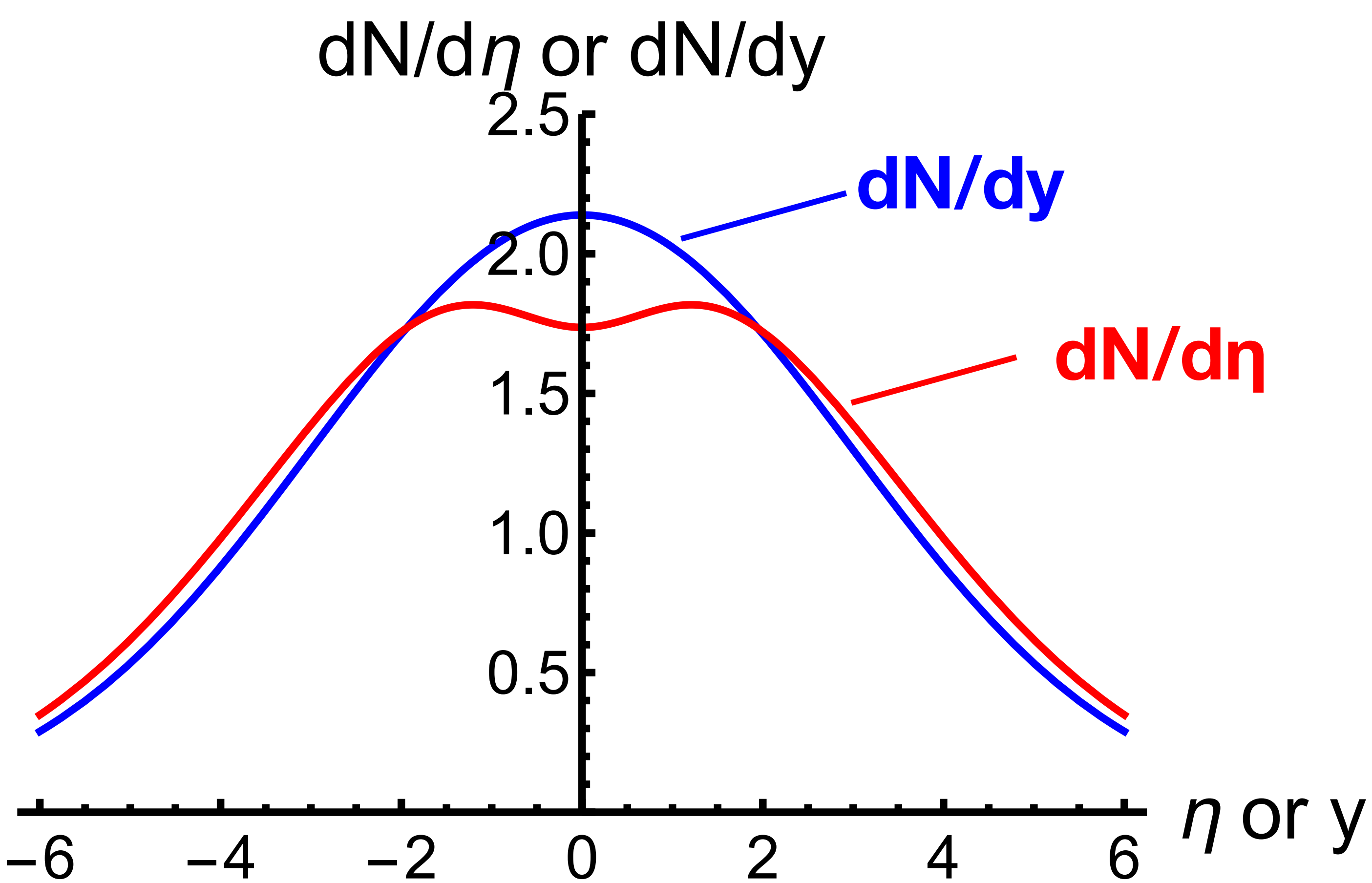
See appendix B

Difference between dN/dy and dN/dη in the CMS at $y = 0$:

Simple example:
Pions distributed according to

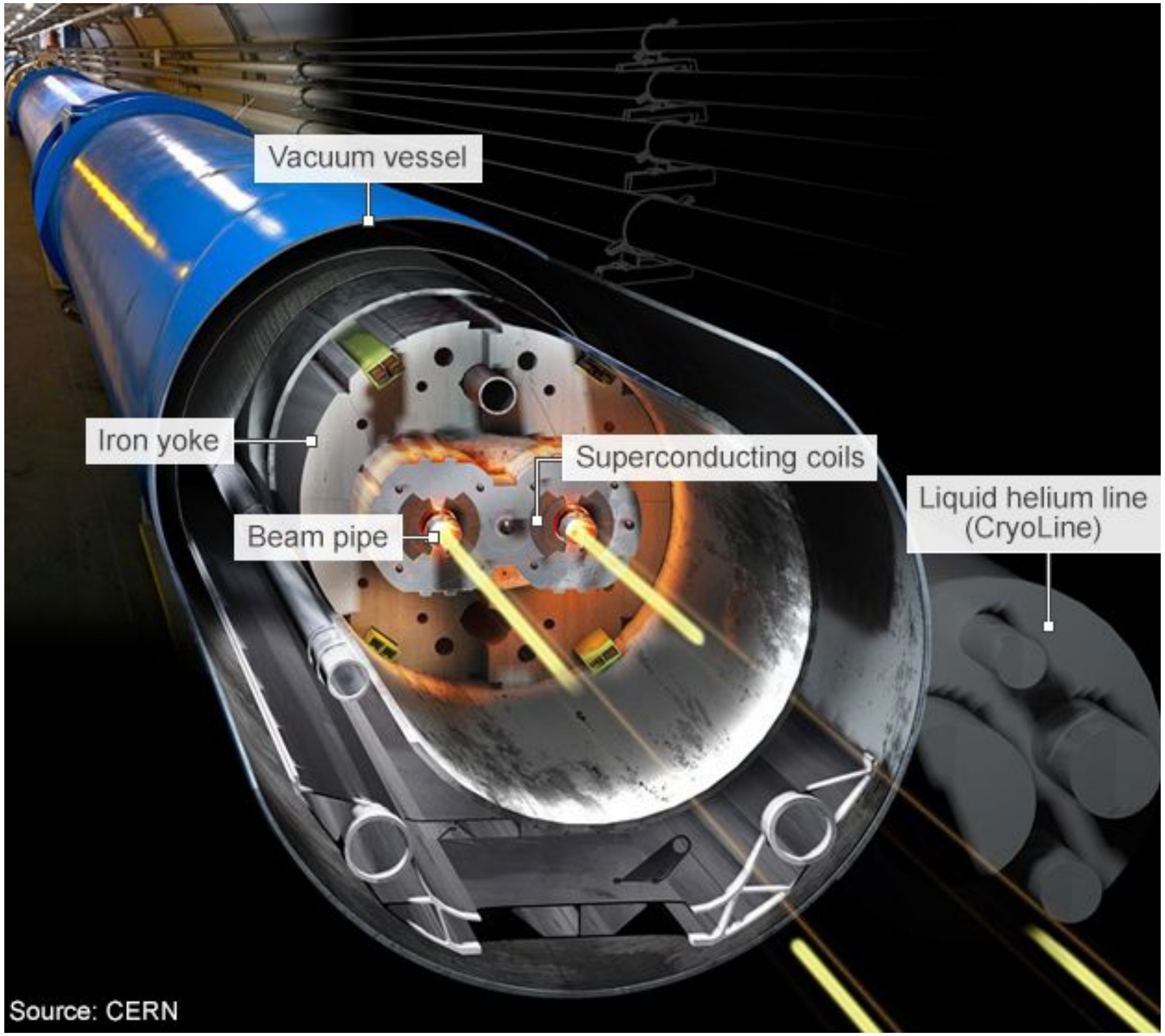
$$\frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} = G(y) \cdot \exp(-p_T/0.16)$$

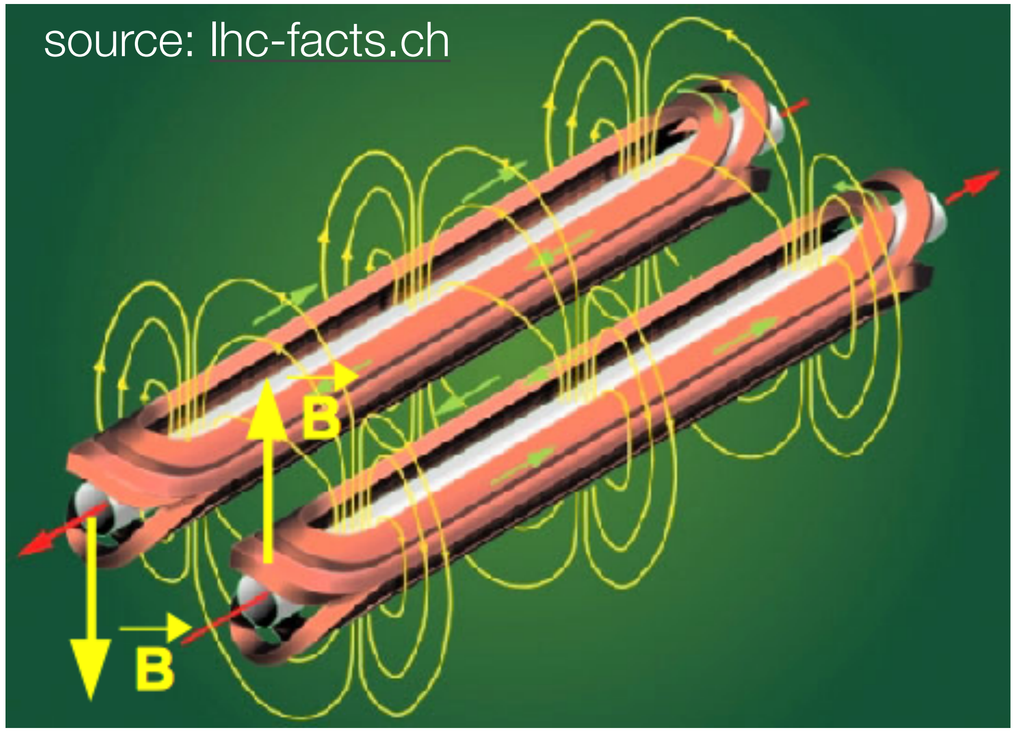
Gaussian with σ = 3 $\quad$ p_T in GeV

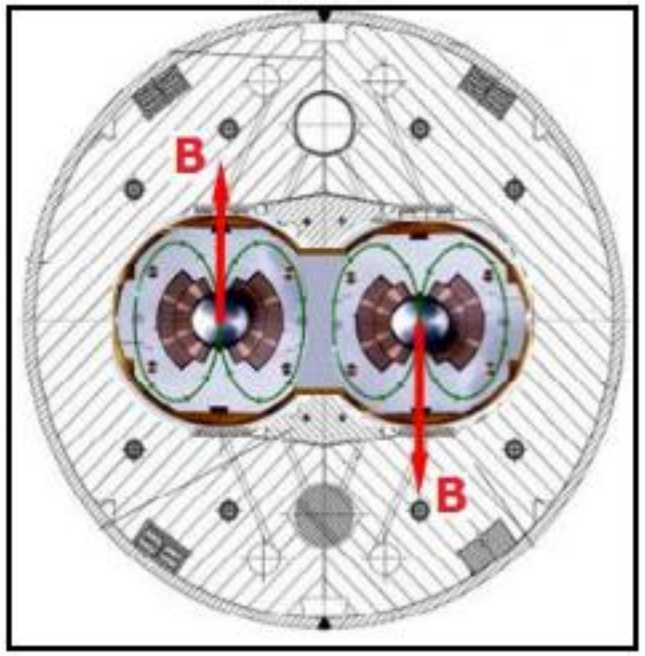


LHC dipole

- Cosine-theta magnet
- Almost constant (opposite) magnetic fields in one yoke







- 14.3 m, up to 8.3 T

LHC parameters

transverse beam radius: about 20 μm
Frequency: ~10kHz (c/27km)

	pp 2011	Pb-Pb 2011
Beam energy (per nucleon)	3.5 TeV	3.5 TeV·82/208
Particles/bunch	$1.35 \cdot 10^{11}$	$1.2 \cdot 10^{8}$
#bunches per beam	1380	358
Bunch spacing	50 ns (= 15 m)	200 ns
RMS bunch length	7.6 cm	9.8 cm
peak luminosity	$3.65 \cdot 10^{33}$ cm^{-2} s^{-1}	$0.5 \cdot 10^{27}$ cm^{-2} s^{-1}

https://home.cern/resources/brochure/accelerators/lhc-facts-and-figures
https://www.lhc-closer.es/taking_a_closer_look_at_lhc/1.lhc_parameters

Luminosity and cross section

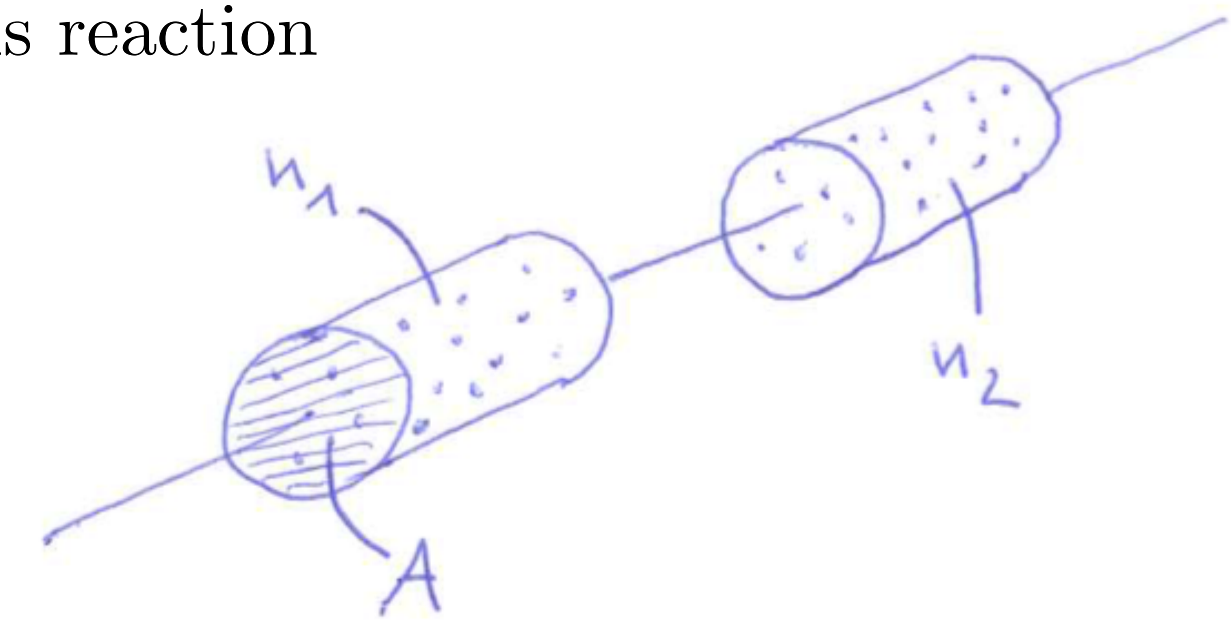
$$\frac{dN_{\text{int}}}{dt} = \sigma \cdot L$$

L = luminosity (in $s^{-1}cm^{-2}$) (Number of particles passing each other per area and time)

dN_{int}/dt = Number of interactions of a certain type per second

σ = cross section for this reaction

$$L = \frac{n_1 n_2 f_{\text{coll}}}{A}$$



$n_1, \; n_2$ = numbers of particles per bunch in the two beams

f_{coll} = bunch collision frequency at a given crossing point

A = beam crossing area ($A \approx 4\pi\sigma_x\sigma_y$)

Lorentz invariant Phase Space Element

Observable: Average density of produced particles in momentum space

$$\frac{1}{L_{\text{int}}}\frac{d^3N_A}{d^3\vec{p}} = \frac{1}{L_{\text{int}}}\frac{d^3N_A}{dp_x dp_y dp_z}$$

However. the phase space density would then not be Lorentz invariant (see next slides for details):

$$\frac{d^3N}{dp'_x dp'_y dp'_z} = \frac{\partial(p_x, p_y, p_z)}{\partial(p'_x, p'_y, p'_z)} \cdot \frac{d^3N}{dp_x dp_y dp_z} = \frac{E}{E'} \cdot \frac{d^3N}{dp_x dp_y dp_z}$$

Lorentz invariant phase space element: $\dfrac{d^3\vec{p}}{E} = \dfrac{dp_x dp_y dp_z}{E}$

The corresponding observable is called Lorentz invariant cross section:

$$E\frac{d^3\sigma}{d^3\vec{p}} = \frac{1}{L_{\text{int}}}E\frac{d^3N}{d^3\vec{p}} = \underbrace{\frac{1}{N_{\text{evt,tot}}}E\frac{d^3N}{d^3\vec{p}}}_{\text{this is called the invariant yield}}\sigma_{\text{tot}}$$

Lorentz invariant Phase Space Element: Proof of invariance

Lorentz boost along the z axis:

$$
\begin{aligned}
p'_x &= p_x \\
p'_y &= p_y \\
p'_z &= \gamma(p_z - \beta E), \qquad & p_z &= \gamma(p'_z + \beta E') \\
E' &= \gamma(E - \beta p_z), \qquad & E &= \gamma(E' + \beta p'_z)
\end{aligned}
$$

Jacobian: $$\frac{\partial(p_x, p_y, p_z)}{\partial(p'_x, p'_y, p'_z)} = \begin{vmatrix} \frac{\partial p_x}{\partial p'_x} & 0 & 0 \\ 0 & \frac{\partial p_y}{\partial p'_y} & 0 \\ 0 & 0 & \frac{\partial p_z}{\partial p'_z} \end{vmatrix}$$

$$\frac{\partial p_x}{\partial p'_x} = 1, \quad \frac{\partial p_y}{\partial p'_y} = 1, \quad \frac{\partial p_z}{\partial p'_z} = \frac{\partial}{\partial p'_z}\left[\gamma\left(p'_z + \beta E'\right)\right] = \gamma\left(1 + \beta\frac{\partial E'}{\partial p'_z}\right)$$

$$\frac{\partial E'}{\partial p'_z} = \frac{\partial}{\partial p'_z}\left[\left(m^2 + p'^2_x + p'^2_y + p'^2_z\right)^{1/2}\right] = \frac{p'_z}{E'} \quad \rightsquigarrow \quad \frac{\partial p_z}{\partial p'_z} = \gamma\left(1 + \beta\frac{p'_z}{E'}\right) = \frac{E}{E'}$$

And so we finally obtain: $$\frac{\partial(p_x, p_y, p_z)}{\partial(p'_x, p'_y, p'_z)} = \frac{E}{E'}$$

Invariant Cross Section

Calculation of the invariant cross section:

$E = m_T \cdot \cosh y, \qquad p_L = m_T \cdot \sinh y$

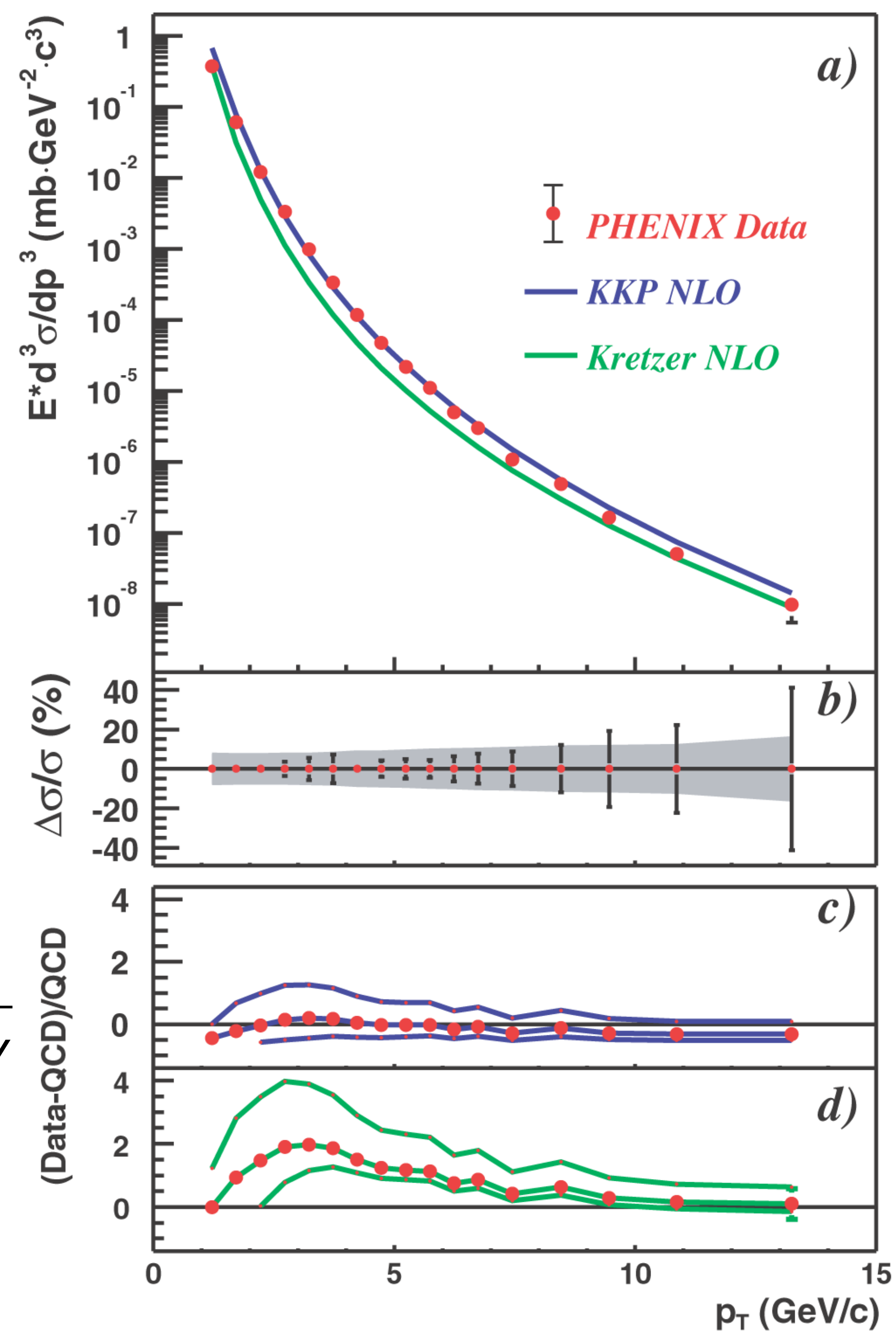
$$E\frac{d^3\sigma}{d^3p} = E\,\frac{1}{p_T}\,\frac{d^3\sigma}{dp_T\,dp_z\,d\varphi}$$

See appendix D

$$\overset{dp_z/dy = m_T \cosh y = E}{=} \frac{1}{p_T}\,\frac{d^3\sigma}{dp_T\,dy\,d\varphi}$$

$$\overset{\text{symmetry in } \varphi}{=} \frac{1}{2\pi p_T}\,\frac{d^2\sigma}{dp_T\,dy}$$

Example: Invariant cross section for neutral pion production in p+p at $\sqrt{s}$ = 200 GeV



Sometimes also measured as a function of m_T:

$$\frac{1}{2\pi m_T}\,\frac{d^2\sigma}{dm_T\,dy} = \frac{1}{2\pi m_T}\,\frac{d^2\sigma}{dp_T\,dy}\,\frac{dp_T}{dm_T} = \frac{1}{2\pi p_T}\,\frac{d^2\sigma}{dp_T\,dy}$$

Integral of the inv. cross section

Average yield of particle X per event

$$\int E\frac{d^3\sigma}{d^3p}\,d^3p/E = \langle N_x\rangle \cdot \sigma_{\text{tot}}$$

Average path length of produced particles before decay

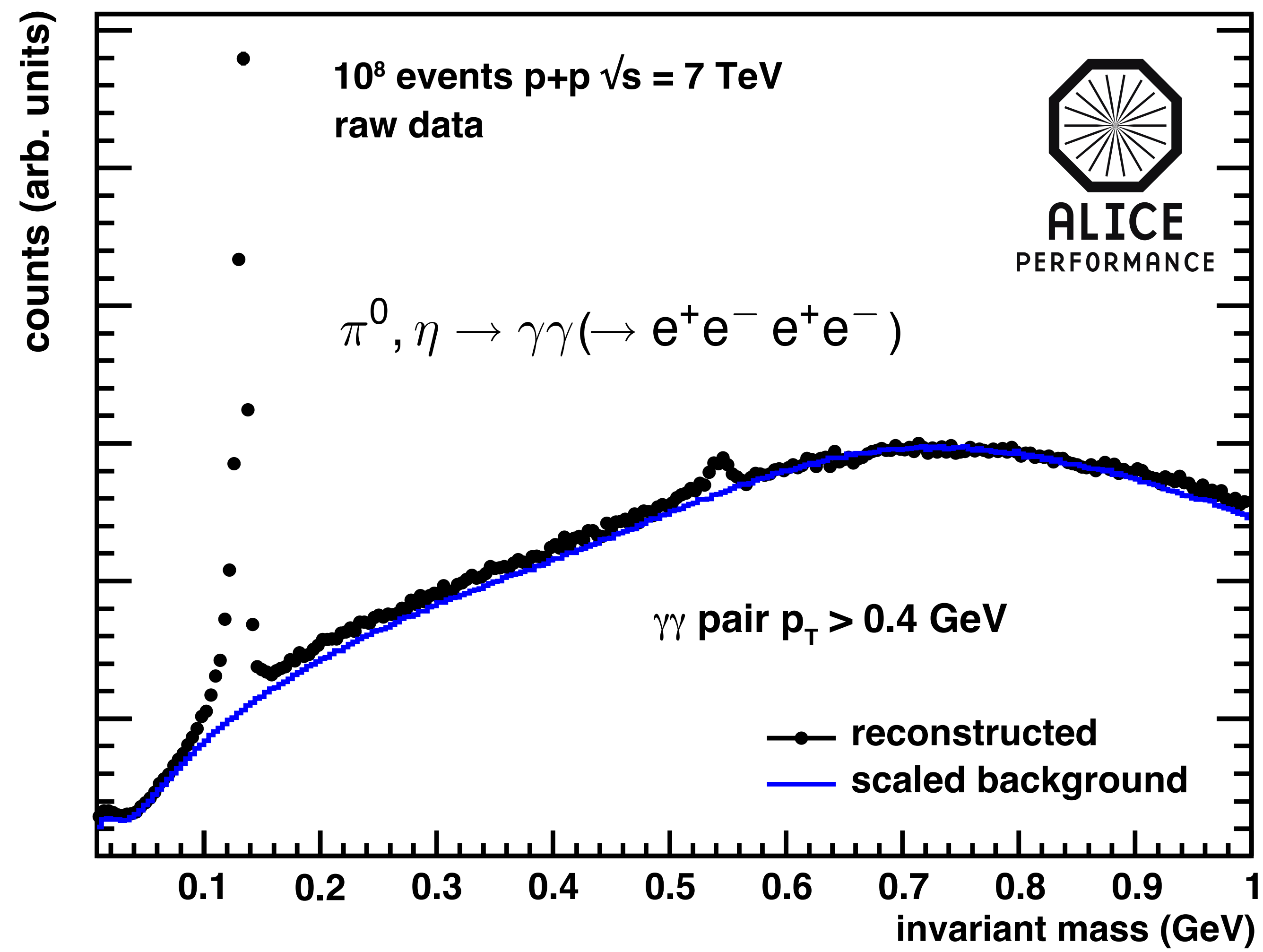
$$L_{\mathrm{lab}} = v \cdot \gamma \cdot \tau = \beta \cdot \gamma \cdot \tau \cdot c = \frac{p}{mc} \cdot \tau \cdot c$$

	mass (MeV)	mean life τ	*c* τ	L_{lab} (p = 1 GeV/c)
π^+, π^-	139.6	$2.6 \cdot 10^{-8}$ s	7.80 m	56 m
π^0	135	$8.4 \cdot 10^{-17}$ s	25 nm	185 nm
K^+, K^-	494	$1.23 \cdot 10^{-8}$ s	3.70 m	7.49 m
K_s^0	497	$0.89 \cdot 10^{-10}$ s	2.67 cm	5.37 cm
K_L^0	497	$5.2 \cdot 10^{-8}$ s	15.50 m	31.19 m
D^+, D^-	1870	$1.04 \cdot 10^{-12}$ s	312 μm	167 μm
B^+, B^-	5279	$1.64 \cdot 10^{-12}$ s	491 μm	93 μm

Reconstruction of unstable particle via the invariant mass calculated from daughter particles

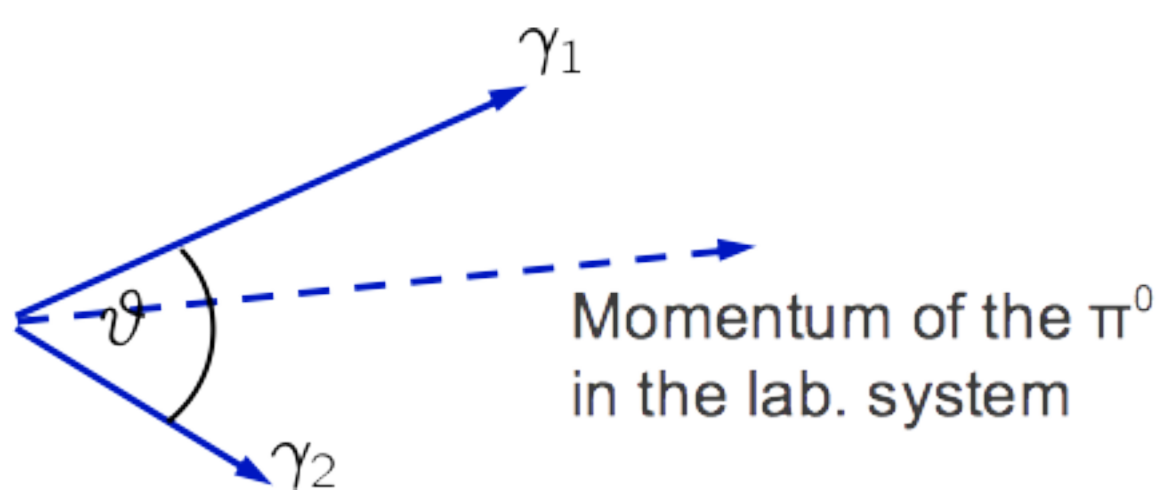
Consider the decay of a particle in two daughter particles. The mass of the mother particle is given by (“invariant mass”):

$$M^2 = \left[\begin{pmatrix} E_1 \\ \vec{p}_1 \end{pmatrix} + \begin{pmatrix} E_2 \\ \vec{p}_2 \end{pmatrix}\right]^2$$
$$= m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2$$
$$= m_1^1 + m_2^2 + 2E_1E_2 - 2p_1p_2 \cos\vartheta$$



Example: π^0 decay:

$$\pi^0 \rightarrow \gamma + \gamma, \; m_1 = m_2 = 0, \; E_i = p_i$$
$$\Rightarrow M = \sqrt{2E_1E_2(1 - \cos\vartheta)}$$



Summary of kinematics part

- Center-of-mass energy $\sqrt{s}$:
  Total energy in the center-of-mass system (rest mass + kinetic energy)

- Observables: Transverse momentum p_T and rapidity y

- Pseudorapidity $\eta \approx y$ for $E \gg m$ ($\eta = y$ for $m = 0$. e.g.. for photons)

- Production rates of particles described by the Lorentz invariant cross section:

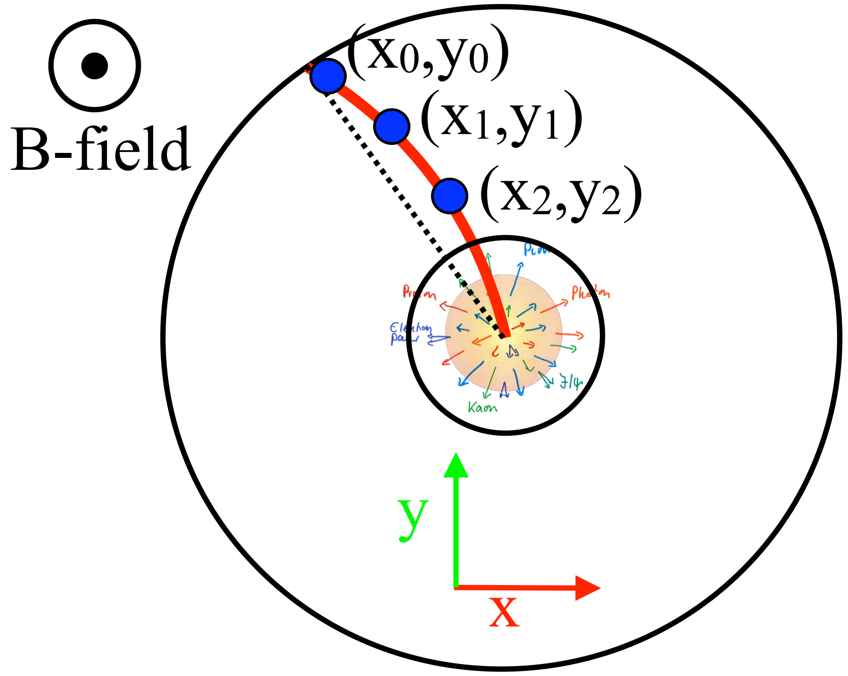
$$E \frac{d^3\sigma}{d^3 p} = \frac{1}{2\pi p_T} \frac{d^2\sigma}{dp_T dy}$$

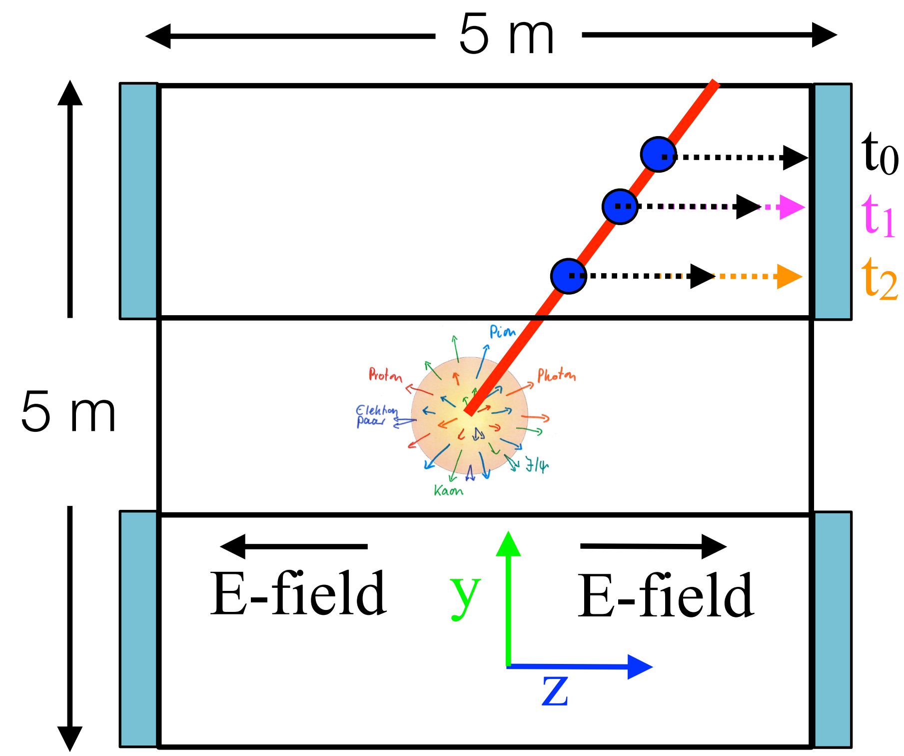
Overview of particle detectors

Why do we need different detectors?

Usage	Characteristics	What is measured?	Detector types
Tracking	Good spacial resolution (µm to mm), large coverage (full azimuth, large eta)	Space points, particle tracks or tracklets → momentum, vertices	Time-projection chamber, silicon strip, MAPS, drift chambers, etc.
Event characterization/ triggering	Fast, large coverage	Event multiplicity, high energetic signal etc.	Scintillators, RPC, gas detectors
Particle identification	Large gain, good time-of-flight resolution (~20 ps)	Energy loss, momentum, total energy, time-of-flight, TR	Gas detectors, calorimeters, RPCs, Cherenkov

Time-Projection Chamber (TPC)





Magnetic field, Lorentz force
→ Momentum

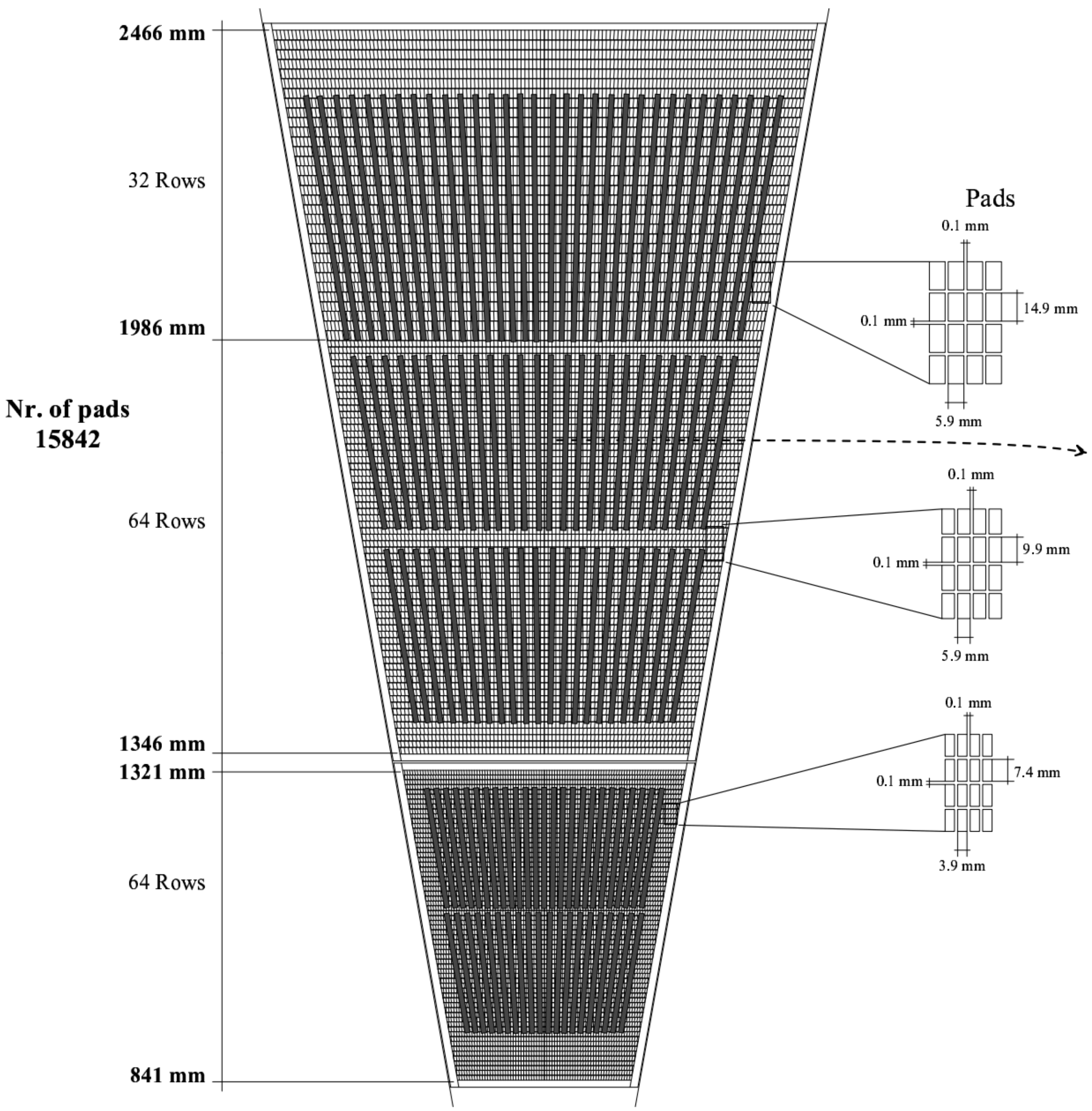
$$z_0 = v_D * t_0$$

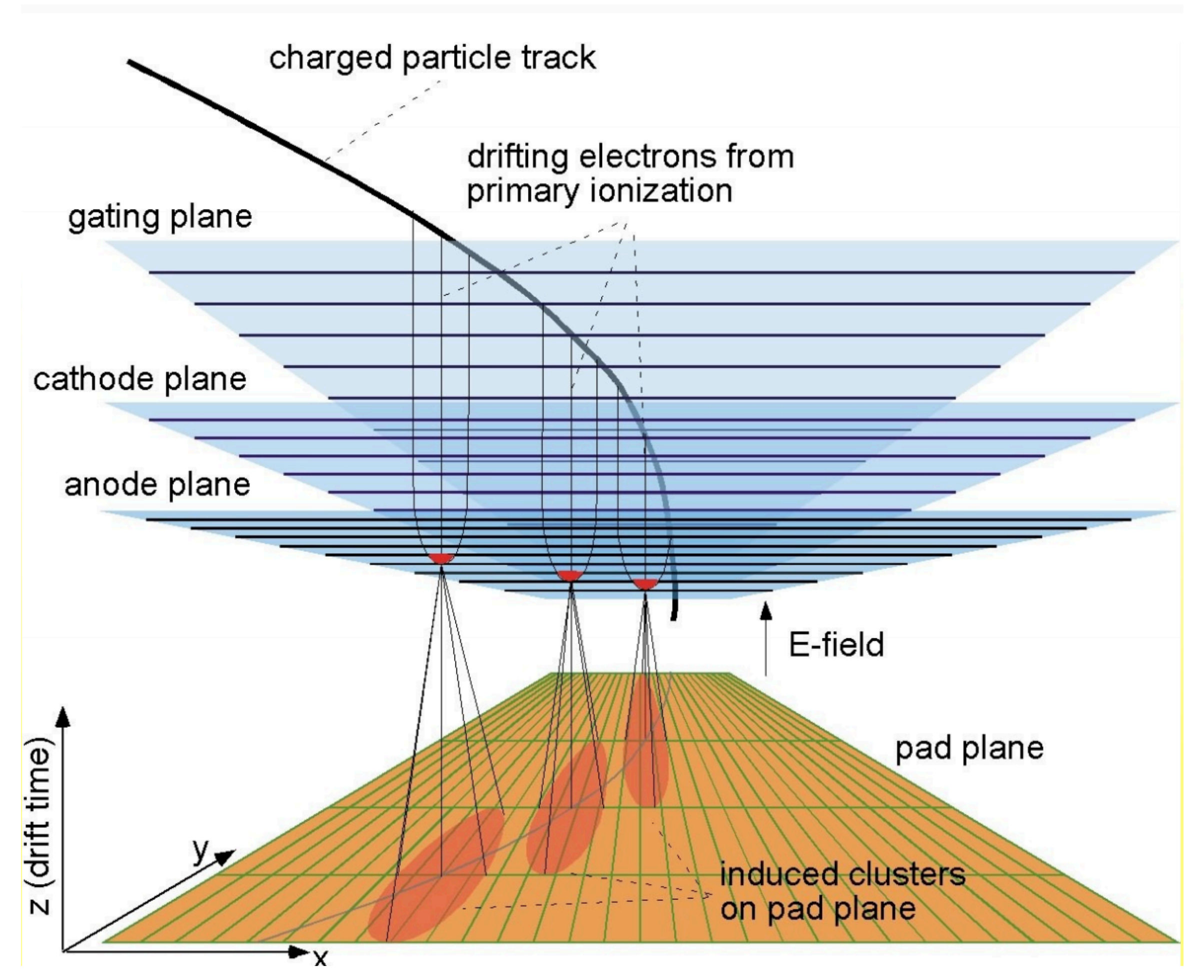
(time) Projected z-coordinate — Drift velocity — Time

- Charged particles ionize the gas in the chamber, electrons are drifting to the end caps
- Typical values: E-field ~400 V/cm, B-field ~0.5 T, v_D ~ 3 cm/μs
- Gas: Ar-CO_2, Ne-CO_2

$$p_T = 0.3\frac{B}{\rho} \qquad \rho = \text{curvature}$$

ALICE TPC Readout

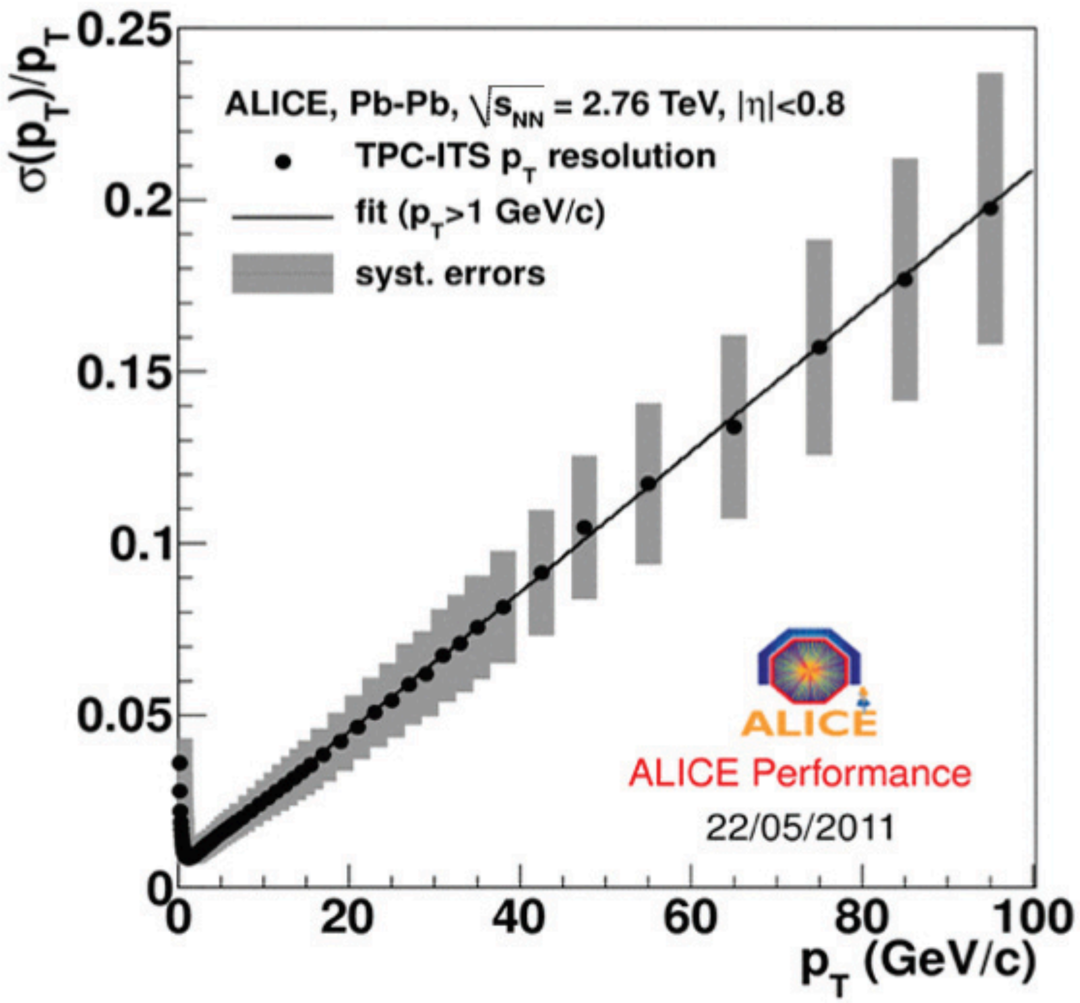


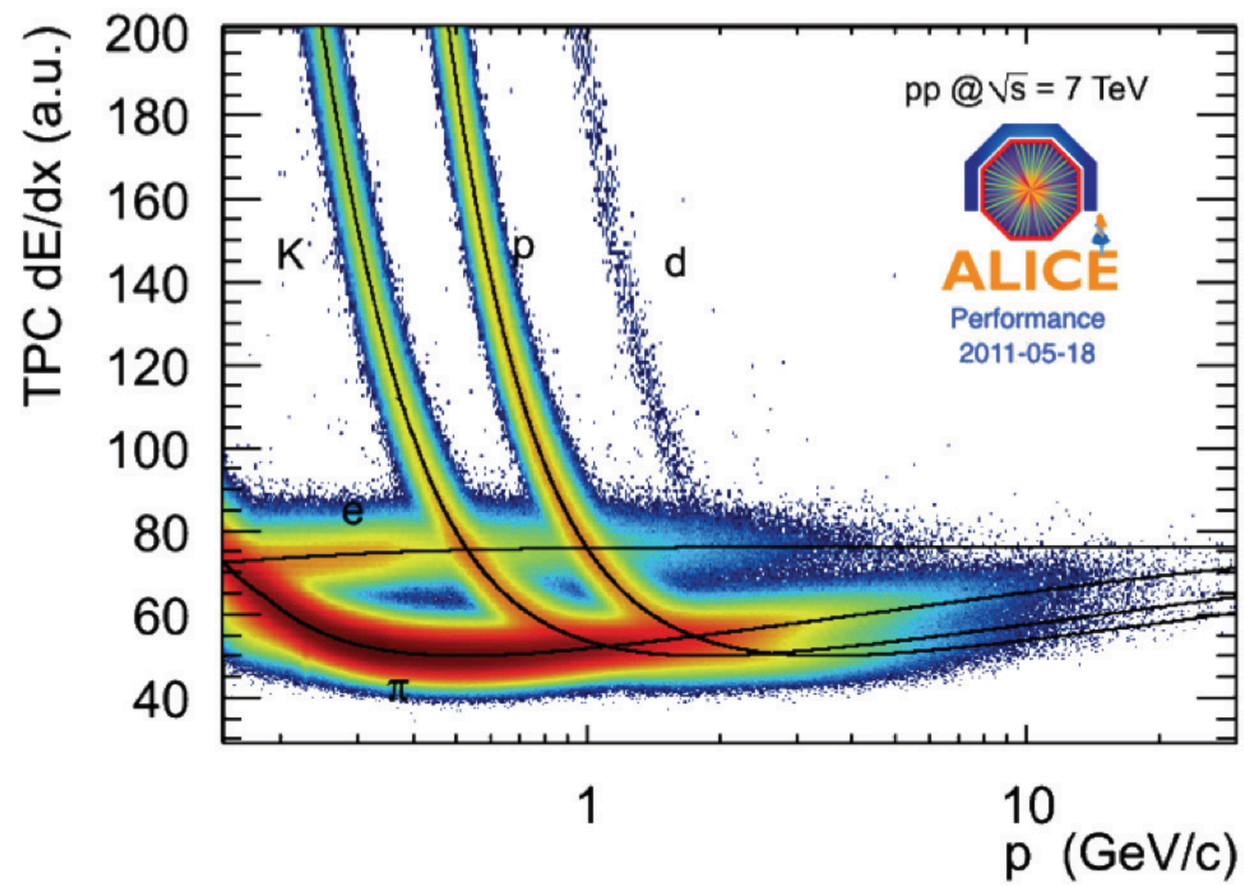


- 560k readout pads
- Space point resolution ~ 1 mm
- (old) TPC gated readout system → avoids ion backdraft
- (new) TPC GEM based pad plane → continuous readout!

ALICE TPC Performance

https://cds.cern.ch/record/451098/files/open-2000-183.pdf
Physics Procedia 37 (2012) 434 – 441

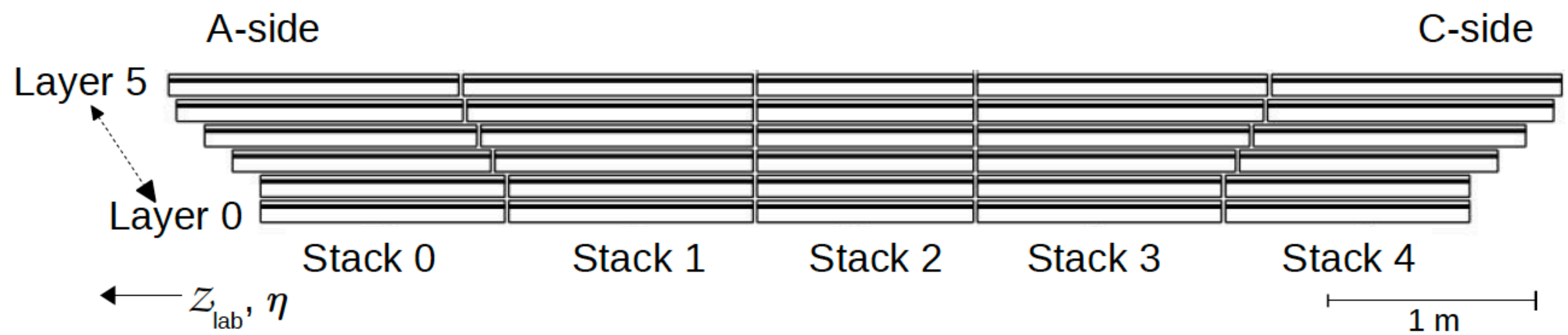


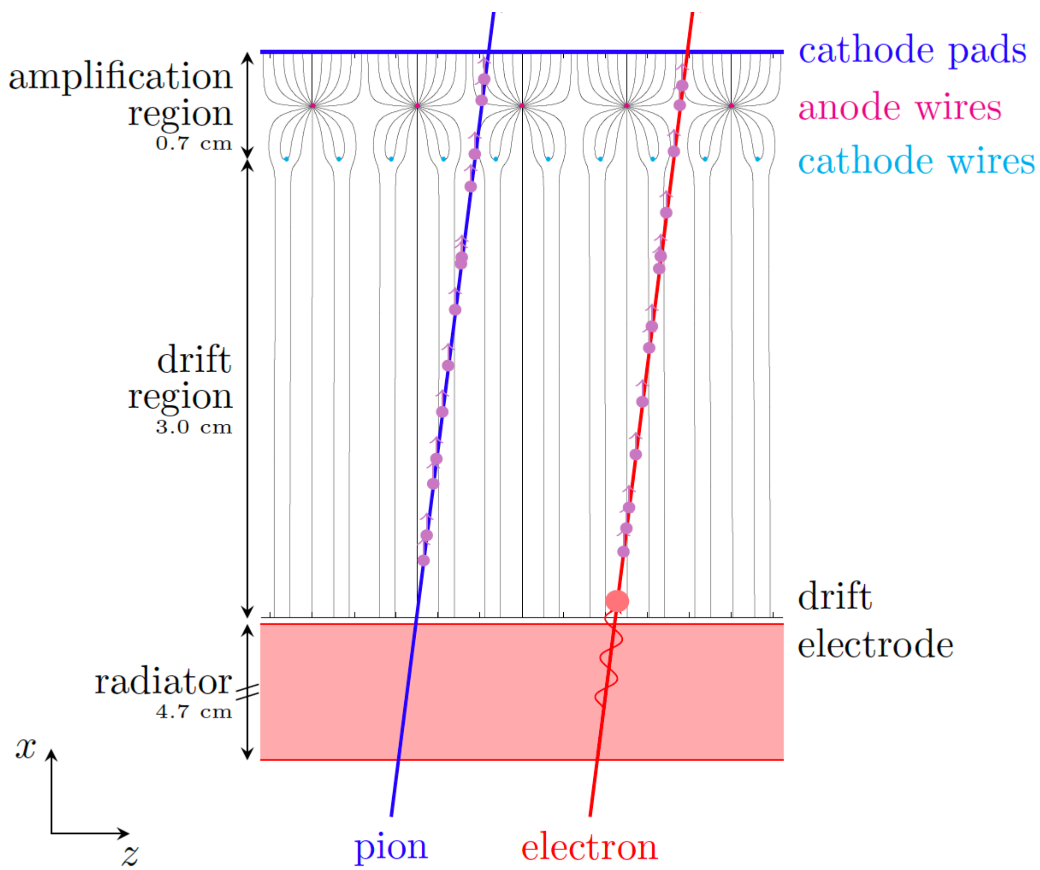


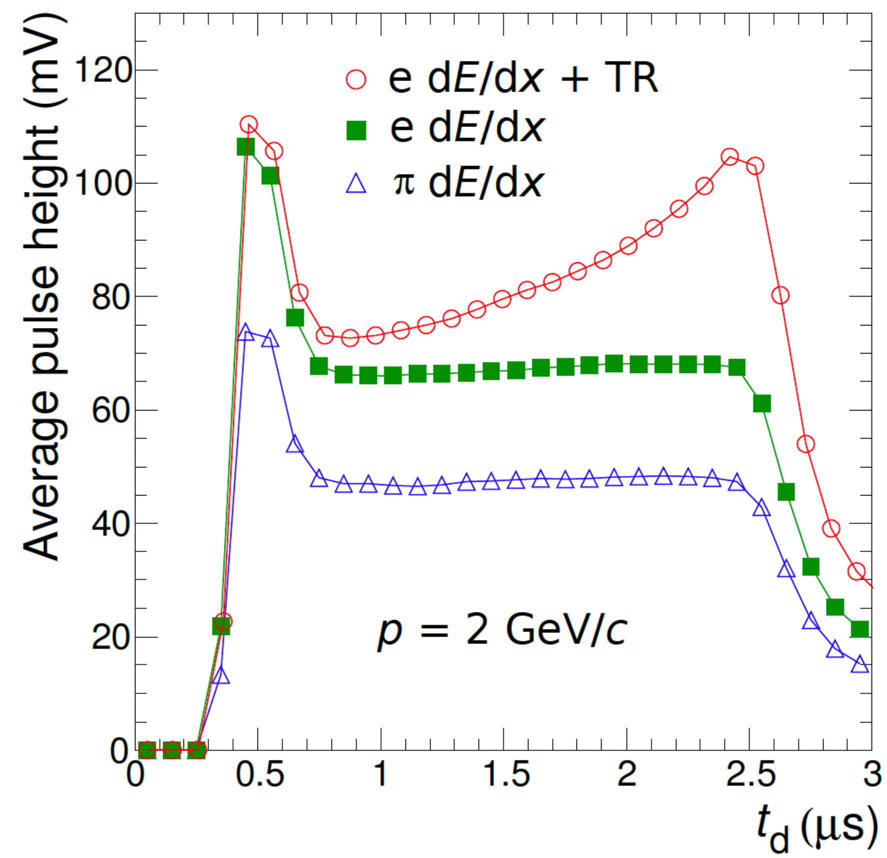
- Used for tracking, momentum resolution ~ few % for $p_T < 20$ GeV/c
- Used for particle identification (PID), specific energy loss (dE/dx)
- Capable of tracking down to low p_T in a high multiplicity environment
  →perfect for central heavy-ion collisions

Transition Radiation Detector (TRD)

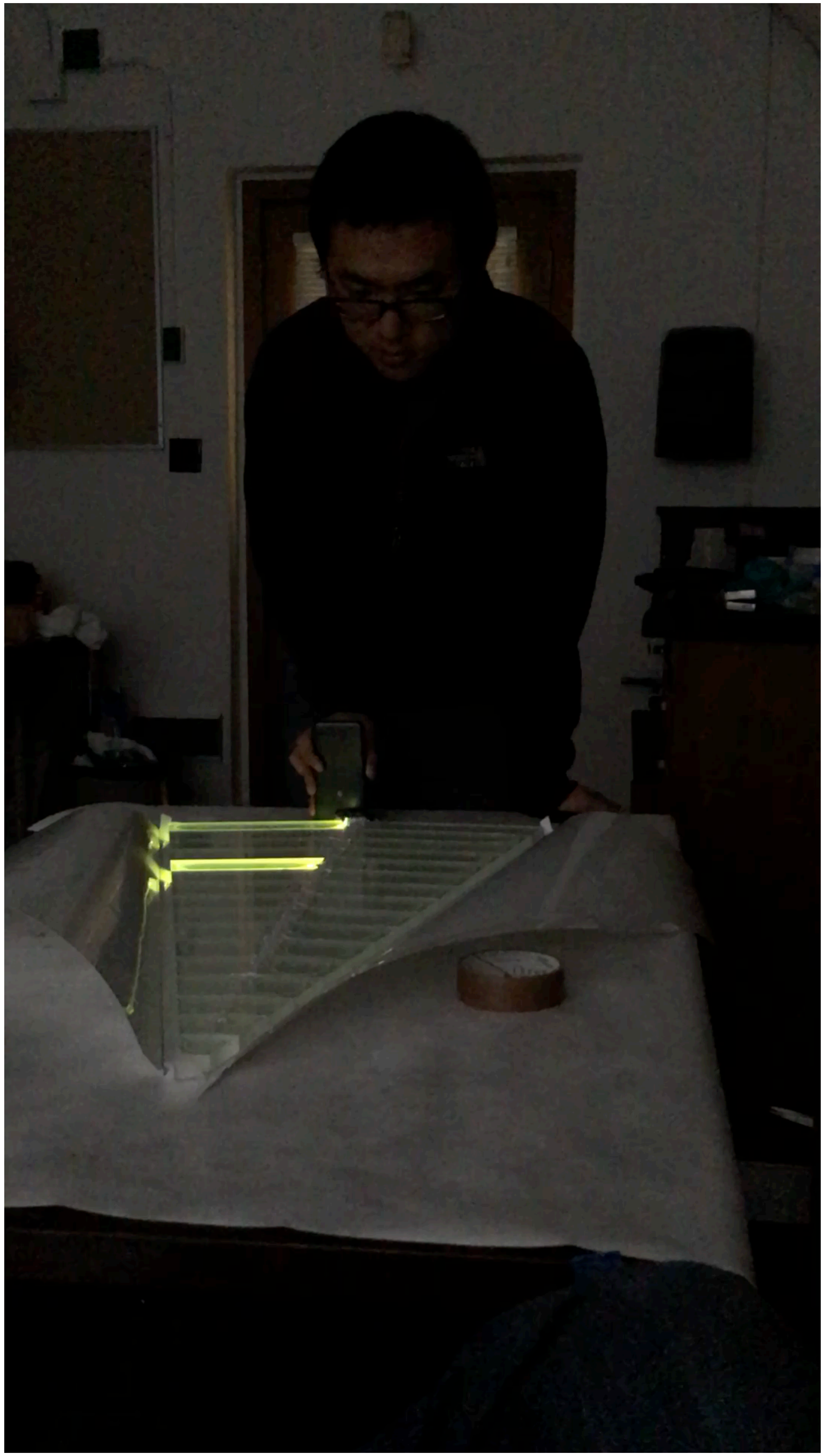
The ALICE Transition Radiation Detector: construction, operation, and performance

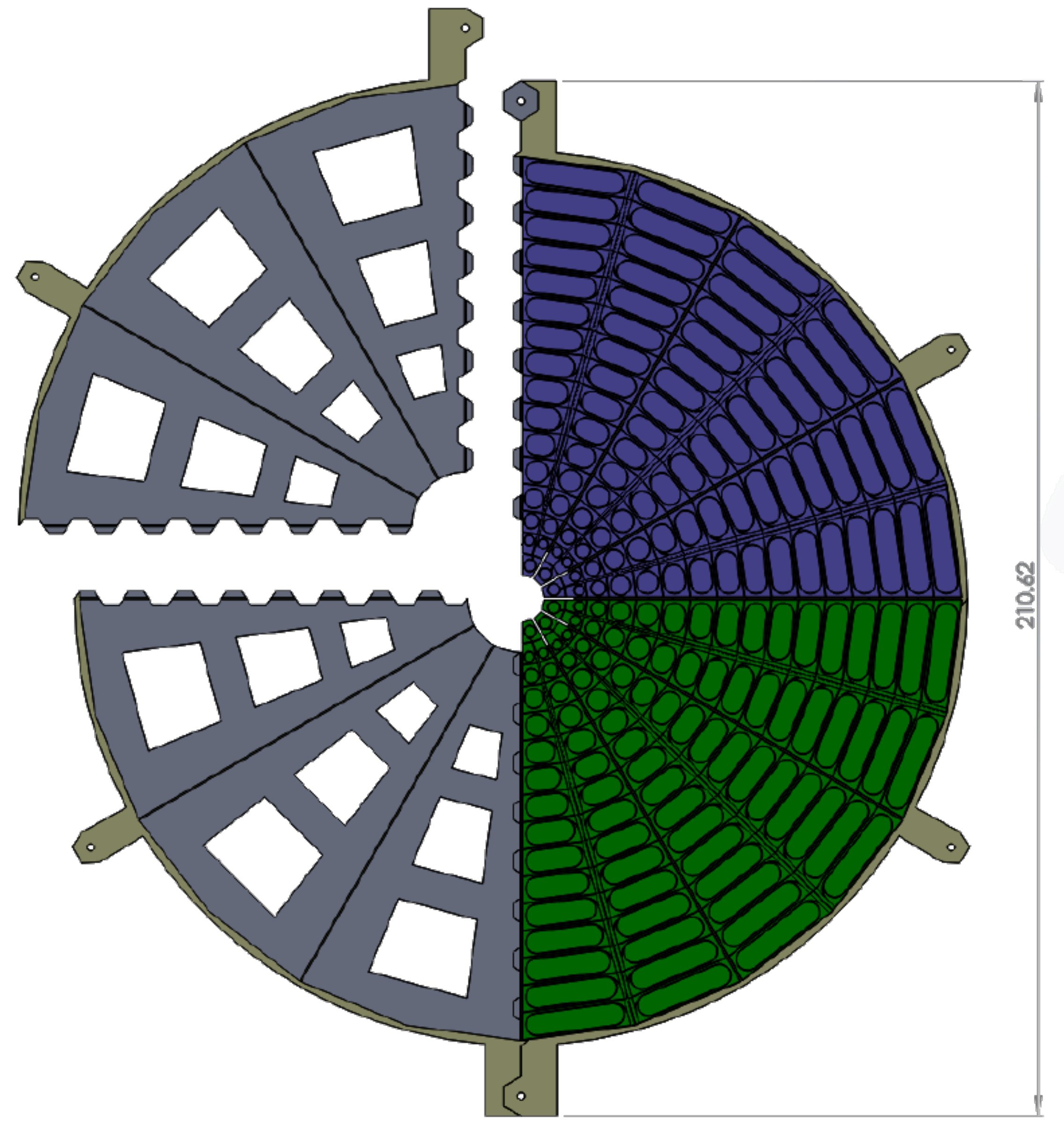






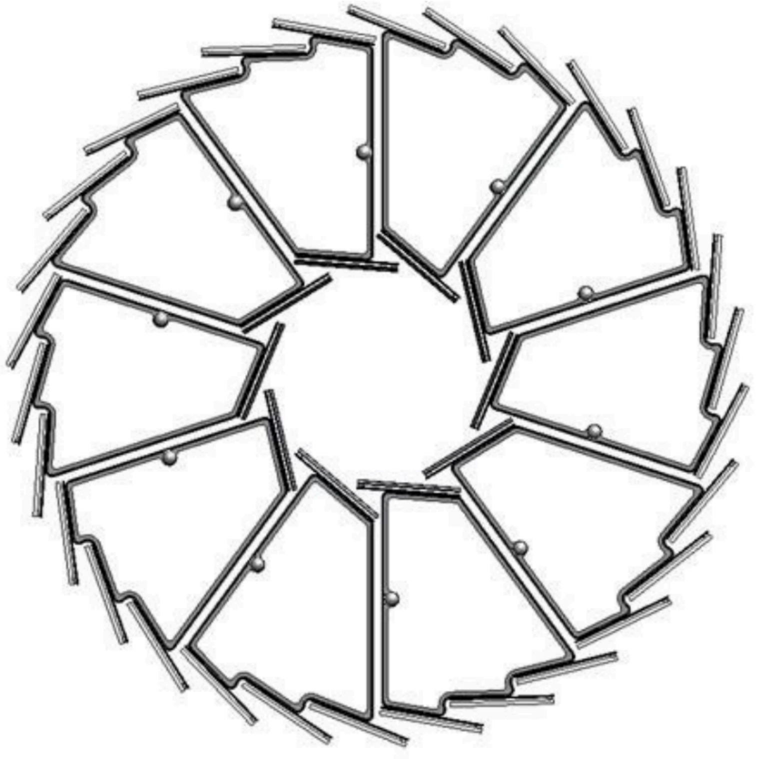
- Similar principle as TPC (gas, drift, dE/dx) but ~500 individual detectors
- High speed electron (large gamma factor) create transition radiation photons in the radiator → additional energy loss
- Used for PID, tracking, triggering





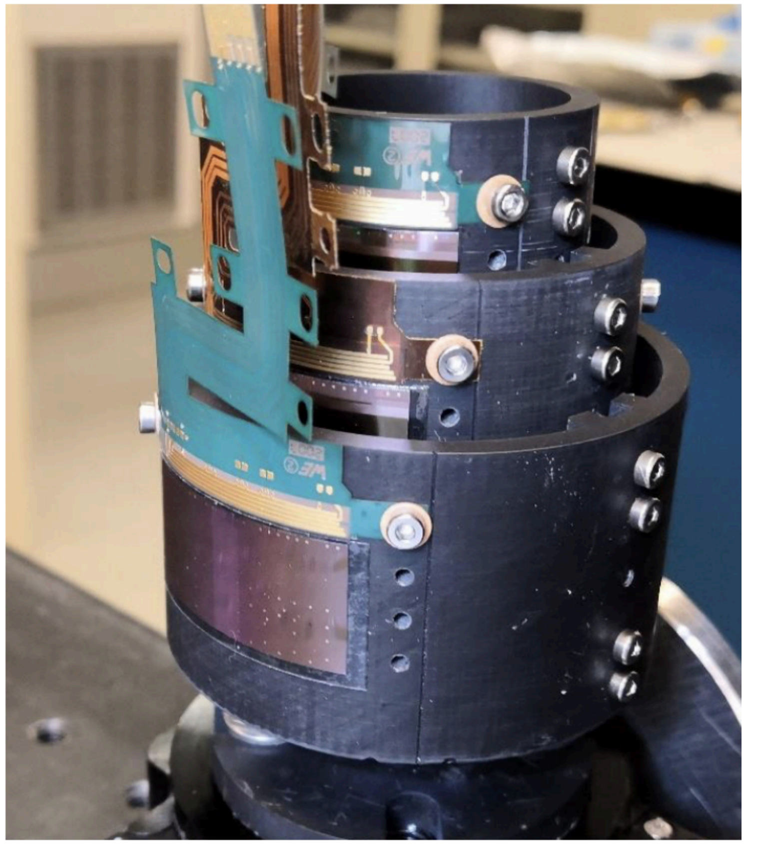
- Used event characterization (event plane, centrality, triggering)
- 744 channels in total, symmetric in eta
- Scintillators + WLS fibers + SiPMs
- Cheap and fast to build

Silicon Pixel Detectors

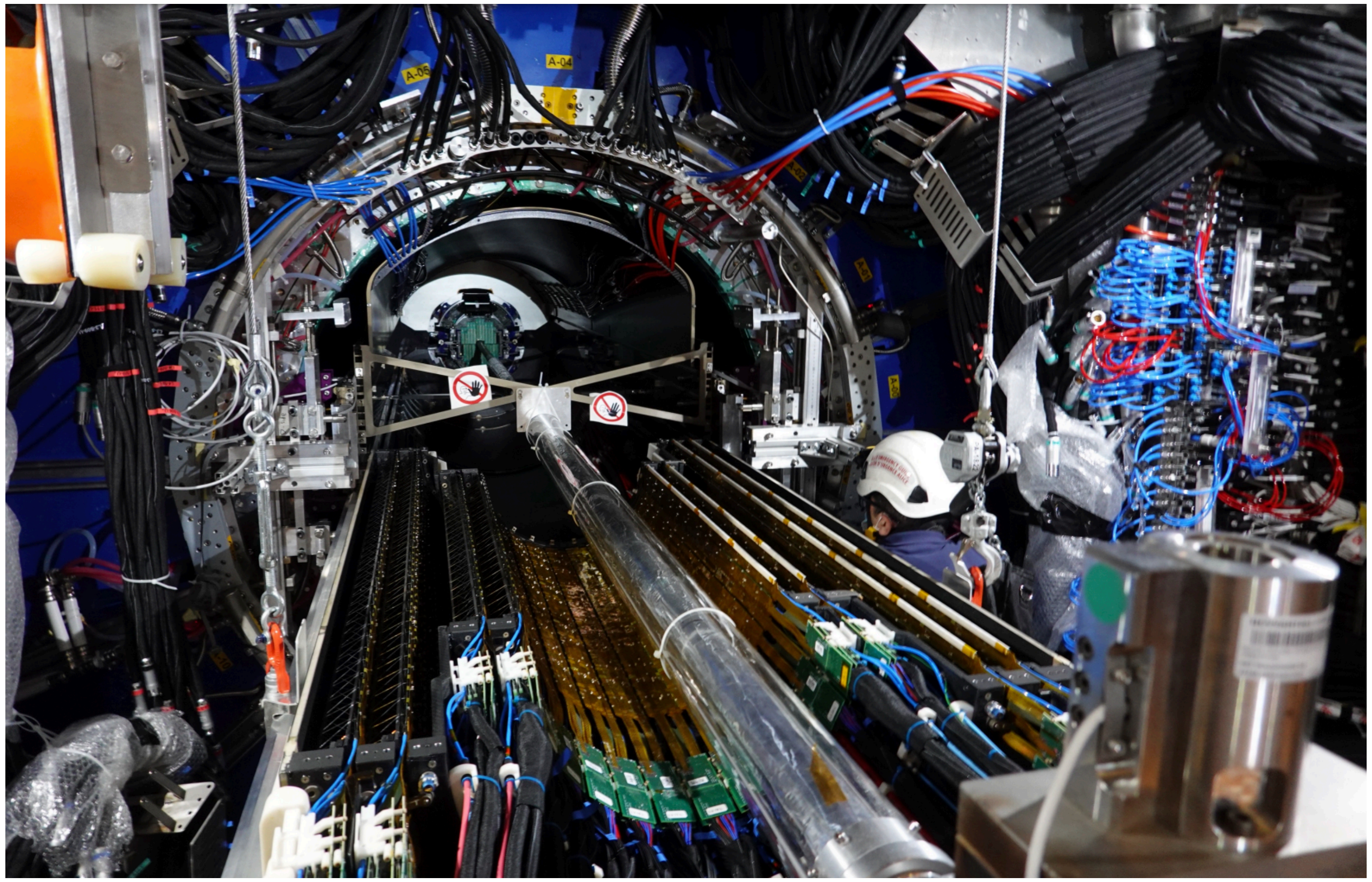


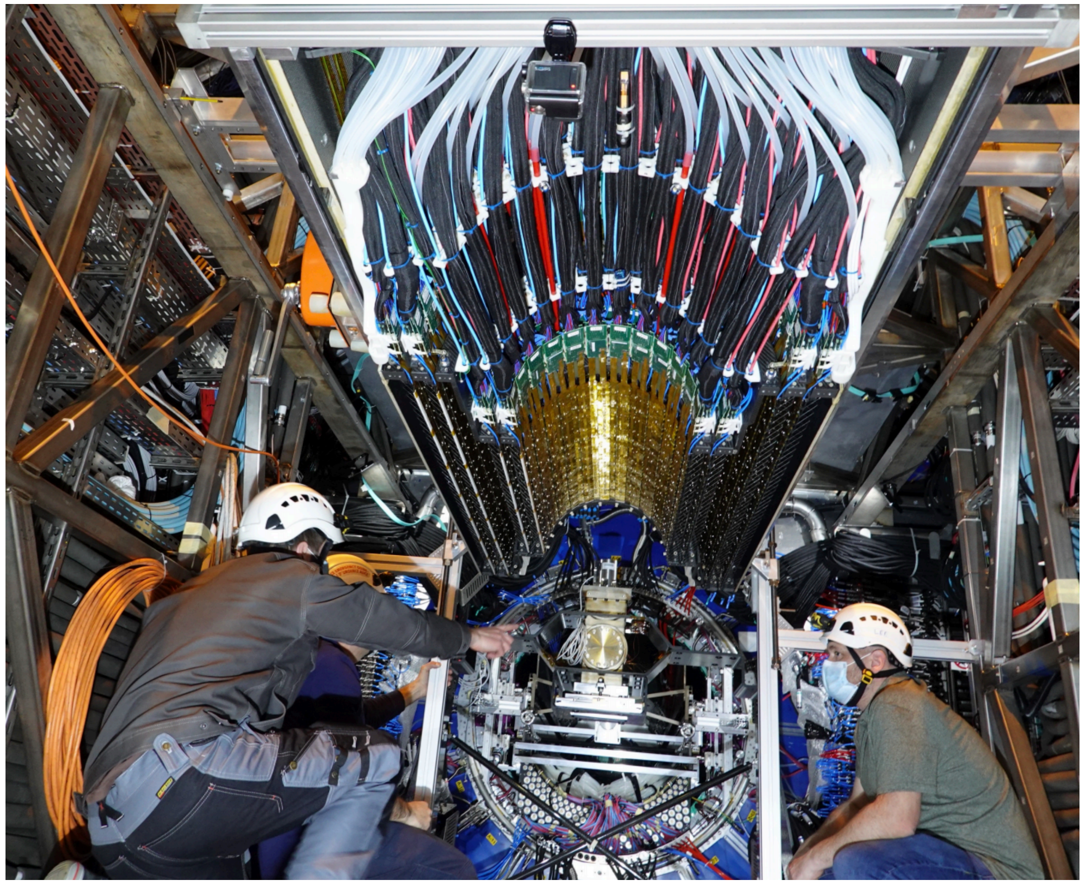
- Monolithic Active Pixel Sensor (MAPS)
  → integrated readout, very thin
- Pixel size (STAR) ~ 20*20 μm

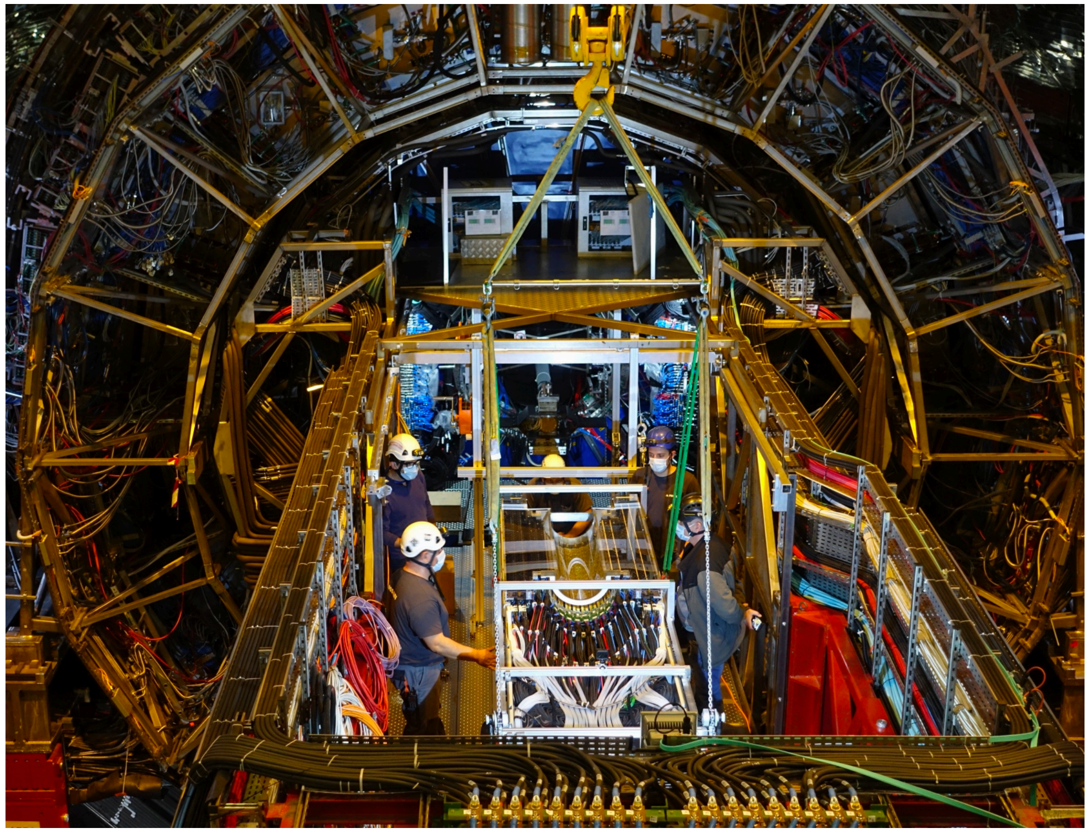
  → high precision vertexing, important for charm reconstruction (e.g. D^0)
- Next generation: bent ALPIDEs for ALICE ITS3 (Inner Tracking System 3rd generation)



ALICE ITS2 Installation

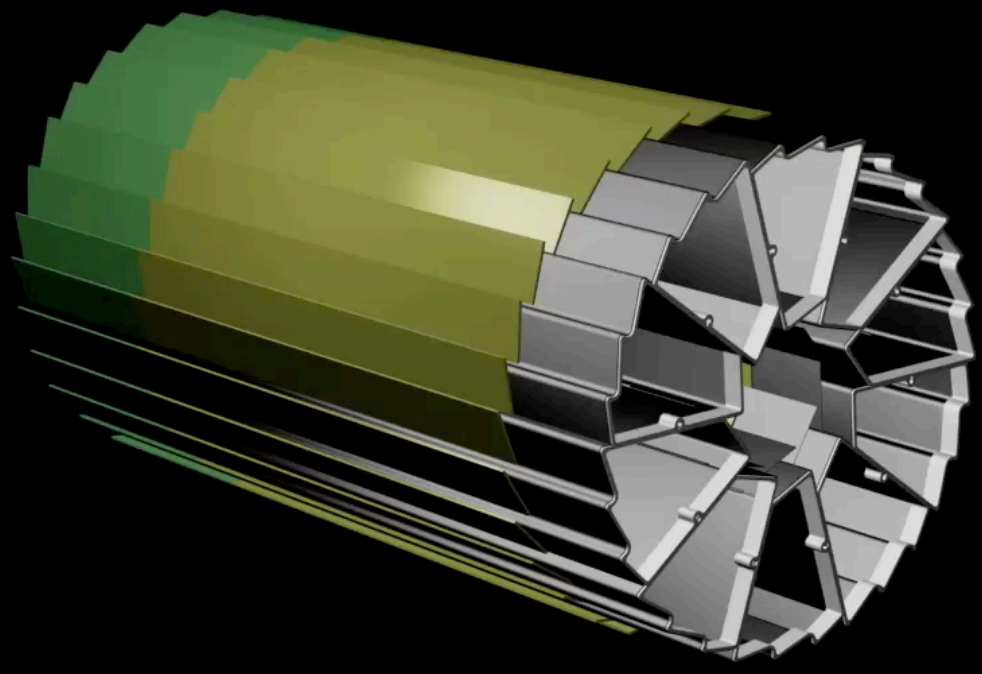






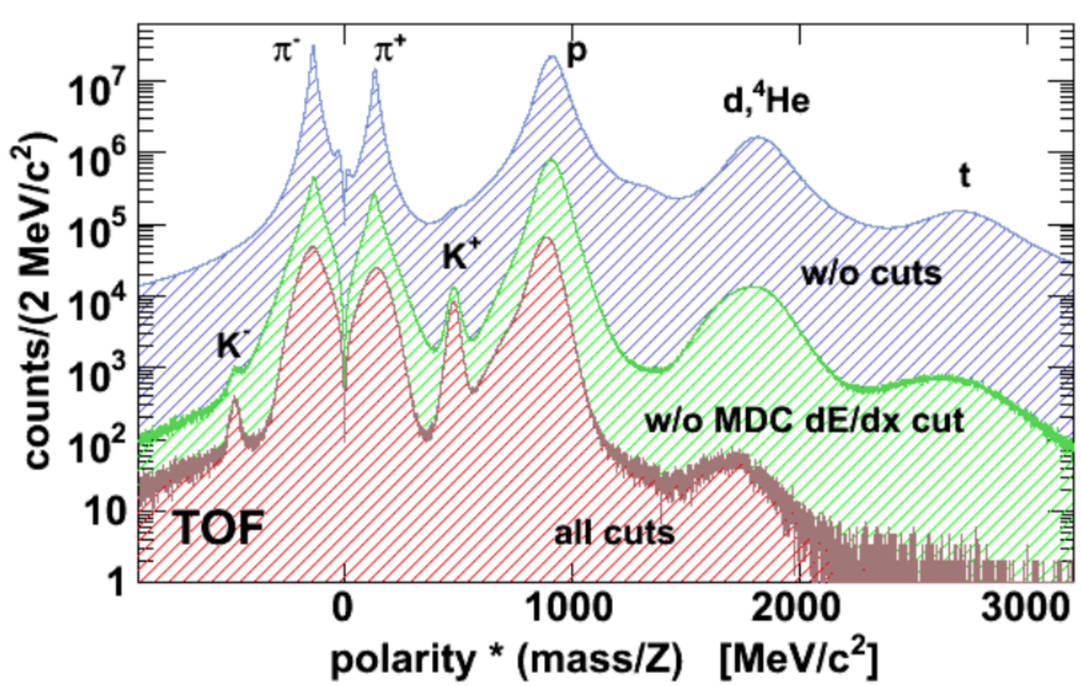
- Monolithic Active Pixel Sensors (MAPS).
- Installed in the past weeks.

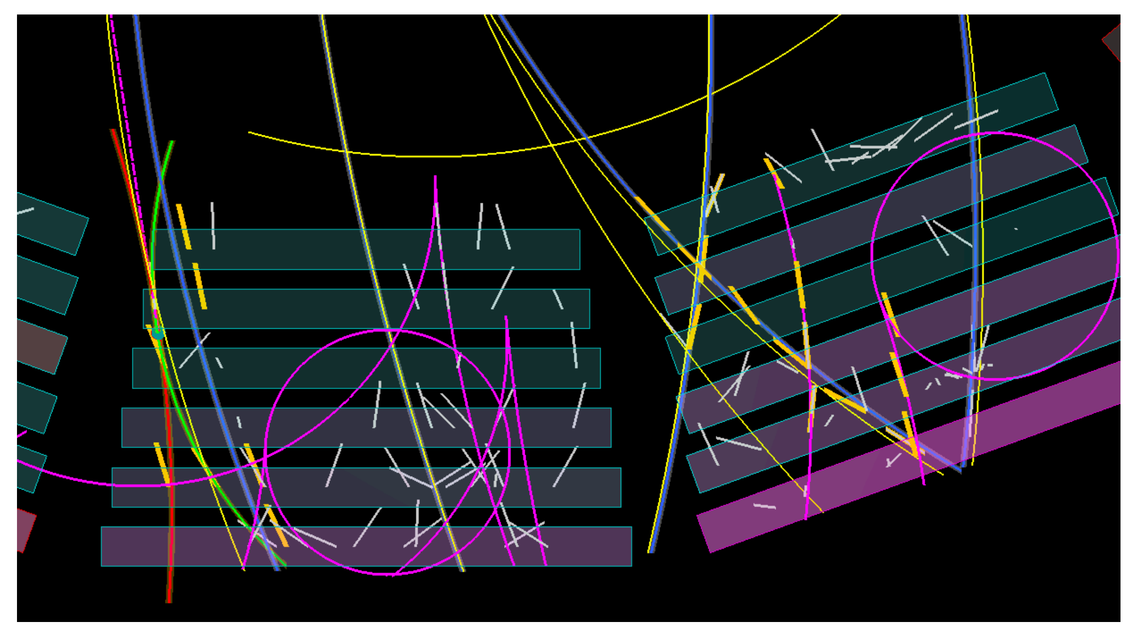
Solenoidal Tracker at RHIC (STAR)



Overview of the ROOT analysis package

- https://root.cern/ can be installed on all platforms
- 6.22/08 is the most recent version
- Used for large scale data analysis
- From simple histograms up to neural networks and 3D graphics, all included in one C++ based framework
- Input/output via ROOT (.root) files → can contain any kind of objects, e.g. histograms (2D, 3D, ND), Ntuples, Trees, etc.
- Interactive sessions and “on-the-fly” compilation of macros or libraries in a complex code





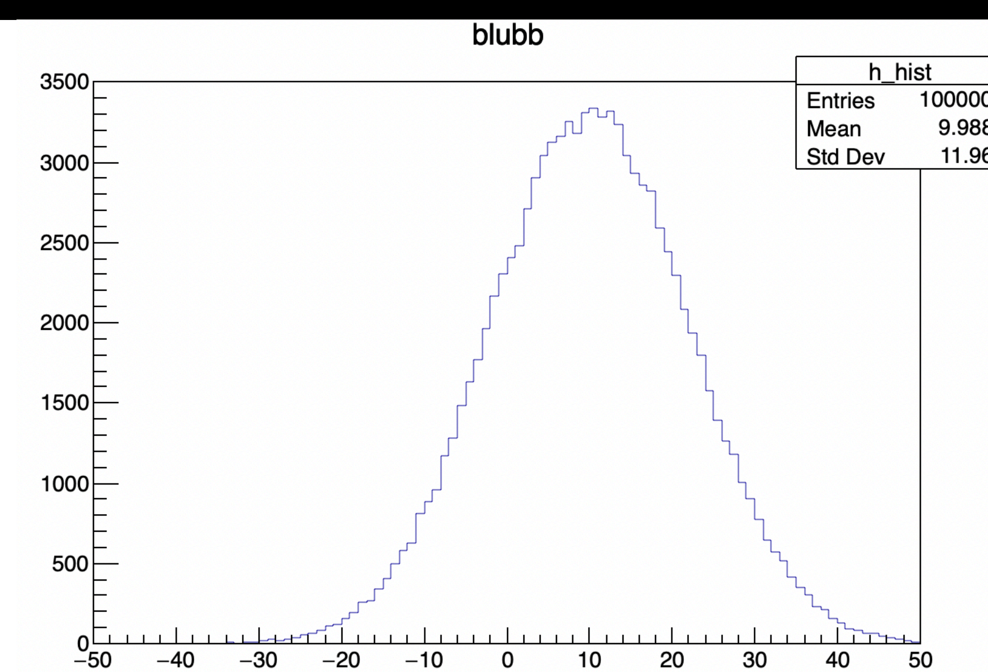
Get started

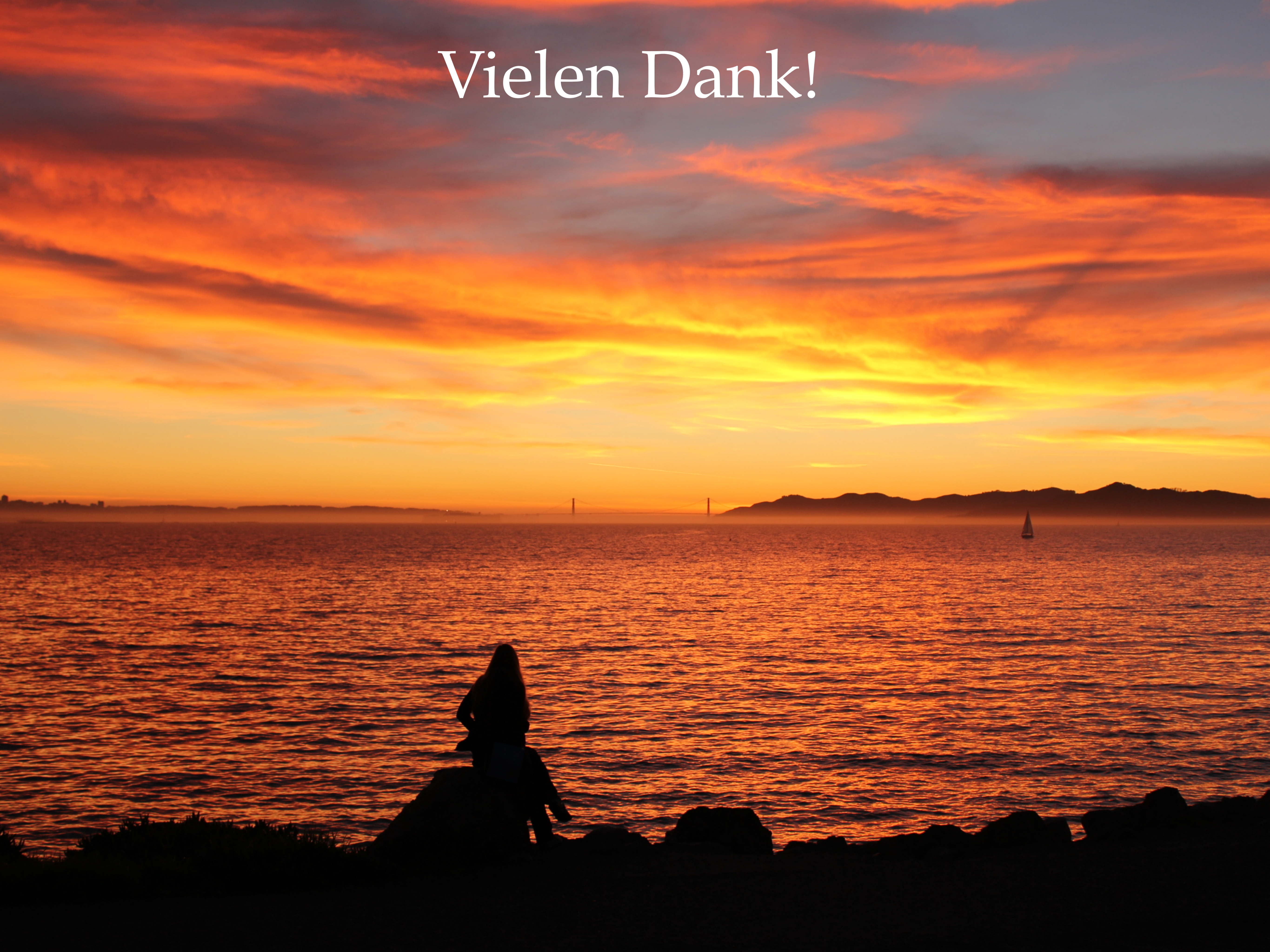
1. Install root (~150 MB, 5 minutes installation)
2. Write the following program with an editor of your choice (vim, efte, emacs, notepad, etc.), save it under the name “Fill_histogram.cc”

```
void Fill_histogram()
{
    // Define the histogram
    TH1D* h_hist = new TH1D("h_hist","blubb",100,-50,50); // name, title, number of bins, lower range, upper range

    Int_t N_itter  = 100000; // number of itterations
    Double_t mean  = 10.0; // mean of Gaussian
    Double_t sigma = 12.0; // sigma of Gaussian

    Double_t ran_value;
    TRandom ran_gen; // random number generator
    for(Int_t i_itter = 0; i_itter < N_itter; i_itter++) // loop
    {
        ran_value = ran_gen.Gaus(mean,sigma); // generate a random number, samples from a Gaussian
        h_hist ->Fill(ran_value);  // Fill the histogram
    }

    h_hist ->Draw(); // Draw the histogram
}
```

3. Type “root” and then “.x fill_histogram.cc”

```
Alexs-MBP-161:Software marialex$ root
   ------------------------------------------------------------------
  | Welcome to ROOT 6.22/03                        https://root.cern |
  | (c) 1995-2020, The ROOT Team; conception: R. Brun, F. Rademakers |
  | Built for macosx64 on Nov 10 2020, 17:25:50                      |
  | From heads/v6-22-00-patches@v6-22-02-2-g3b7967a70f               |
  | Try '.help', '.demo', '.license', '.credits', '.quit'/'.q'       |
   ------------------------------------------------------------------

root [0] .x Fill_histogram.cc
```




Vielen Dank!

Satz (2018):
https://link.springer.com/content/pdf/10.1007%2F978-3-319-71894-1.pdf

Appendix A

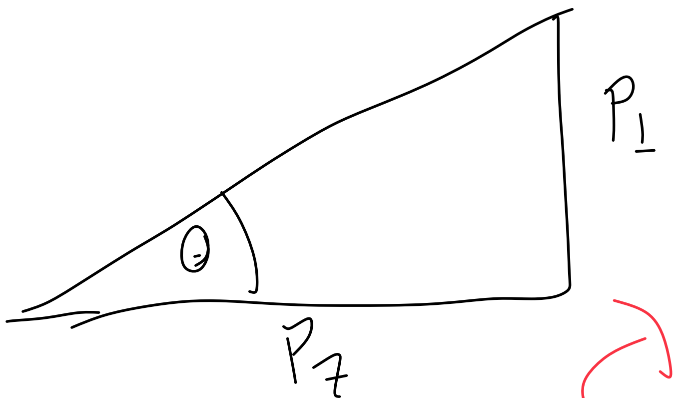
$$y = \frac{1}{2} \ln\left[\frac{E + p_z}{E - p_z}\right]$$

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$p_z = p_\perp \sinh(\eta)$$

$$|p| = p_\perp \cosh(\eta)$$

$$\tan(2\alpha) = \frac{2\tan\alpha}{1-\tan^2\alpha}$$



$$p_z = p_\perp \Big/ \left\{\frac{2e^{-\eta}}{1-(e^{-\eta})^2}\right\} = \frac{1}{2} p_\perp \frac{1-(e^{-\eta})^2}{e^{-\eta}} = p_\perp \underbrace{\frac{1}{2}(e^{\eta} - e^{-\eta})}_{\sinh(\eta)}$$

$$= p_\perp \sinh(\eta)$$

$$\tan\theta = \frac{p_\perp}{p_z}$$

$$\Rightarrow p_z = \frac{p_\perp}{\tan\theta}$$

$$\theta = 2\arctan(e^{-\eta})$$

$$p_z = p_\perp / \tan\left[2\arctan(e^{-\eta})\right]$$

$$p_z = p_\perp \Big/ \left\{\frac{2\tan[\arctan(e^{-\eta})]}{1-\tan^2[\arctan(e^{-\eta})]}\right\}$$

Appendix B

$$y = \frac{1}{2} \ln \left[\frac{\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} + p_\perp \sinh(\eta)}{\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} - p_\perp \sinh(\eta)} \right]$$

$\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} \to E$, $p_\perp^2 \cosh^2(\eta) \to p^2$, $p_\perp \sinh(\eta) \to p_z$

multiply nom. + denom.

$$\left(\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} - p_\perp \sinh(\eta)\right) \cdot \left(\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} + p_\perp \sinh(\eta)\right)$$

$$= p_\perp^2 \cosh^2(\eta) + m^2 - p_\perp^2 \sinh^2(\eta)$$

$$= p_\perp^2 \underbrace{\left(\cosh^2(\eta) - \sinh^2(\eta)\right)}_{1} + m^2$$

$$= p_\perp^2 + m^2$$

$$\Rightarrow y = \ln \left[\frac{\sqrt{p_\perp^2 \cosh^2(\eta) + m^2} + p_\perp \sinh(\eta)}{\sqrt{p_\perp^2 + m^2}} \right]$$

Appendix B

$$y = \ln\left[\frac{\sqrt{p_\perp^2\cosh^2(\eta)+m^2} + p_\perp \sinh(\eta)}{\sqrt{p^2+m^2}}\right]$$

$$E^2 = p^2+m^2 \Rightarrow p = \sqrt{E^2-m^2}$$

$$\frac{dN}{d\eta} = \frac{\partial y}{\partial \eta}\frac{dN}{dy} = \frac{p}{E}\frac{dN}{dy} = \sqrt{1-\frac{m^2}{m_\perp^2\cosh^2(y)}}\;\frac{dN}{dy}$$

mathematica

$$\frac{\overbrace{p_\perp\cosh(\eta)}^{p}}{\underbrace{\sqrt{m^2+\underbrace{p_\perp^2\cosh^2(\eta)}_{p^2}}}_{E}}$$

$$= \frac{p}{E} = \frac{p}{m_\perp\cosh(y)} = \frac{\sqrt{E^2-m^2}}{m_\perp\cosh(y)}$$

$$= \frac{\sqrt{(m_\perp\cosh(y))^2-m^2}}{m_\perp\cosh(y)} = \sqrt{1-\frac{m^2}{m_\perp^2\cosh^2(y)}}$$

$$E = m_\perp\cdot\cosh y$$

$$p_L = m_\perp\cdot\sinh y$$

Appendix C

$$e^{2y} = \frac{E + p_L}{E - p_L}$$

$$E = m_\perp \cosh(y)$$

$$p_L = m_\perp \sinh(y)$$

$m_\perp = m$

for cm since

$p_\perp = 0$

$$\cosh(x) + \sinh(x) = \frac{1}{2} 2 e^x = e^x$$

$$y_{cm} = \frac{1}{2} \ln \left[\frac{E_a + p_a^z + E_b + p_b^z}{E_a - p_a^z + E_b - p_b^z} \right]$$

$$y_{cm} = \frac{1}{2} \ln \left[\frac{m_a \cosh(y_a) + m_a \sinh(y_a) + m_b \cosh(y_b) + m_b \sinh(y_b)}{m_a \cosh(y_a) - m_a \sinh(y_a) + m_b \cosh(y_b) - m_b \sinh(y_b)} \right]$$

$$y_{cm} = \frac{1}{2} \ln \left[\frac{m_a e^{y_a} + m_b e^{y_b}}{m_a e^{-y_a} + m_b e^{-y_b}} \right]$$

$$y_{cm} = \frac{1}{2} \ln \left[\frac{m_a e^{y_a} + m_b e^{y_b}}{m_a \frac{1}{e^{y_a}} + m_b e^{-y_b}} \right]$$

$$y_{cm} = \frac{1}{2} \ln \left[\frac{e^{y_a} \cdot e^{y_b} (m_a e^{y_a} + m_b \cdot e^{y_b})}{m_a e^{y_b} + m_b \cdot e^{y_a}} \right]$$

$$y_{cm} = \frac{1}{2} (y_a + y_b) + \frac{1}{2} \ln \left[\frac{m_a e^{y_a} + m_b e^{y_b}}{m_a e^{y_b} + m_b e^{y_a}} \right]$$

Appendix D

$$d^3p = dp_x\, dp_y\, dp_z = \frac{1}{p_x} p_\perp\, dp_\perp \cdot \cancel{p_x}\, d\varphi \cdot dp_z = p_\perp\, dp_\perp\, d\varphi\, dp_z$$

$$p_y = p_\perp \sin(\varphi) \Rightarrow dp_y = p_x\, d\varphi$$

$$p_\perp = \sqrt{p_x^2 + p_y^2}$$

$$\Rightarrow \sqrt{p_\perp^2 - p_y^2} = p_x$$

$$\frac{dp_x}{dp_\perp} = \cancel{\tfrac{1}{2}\,2}\, p_\perp \frac{1}{\sqrt{p_\perp^2 - p_y^2}} = \frac{p_\perp}{p_x}$$

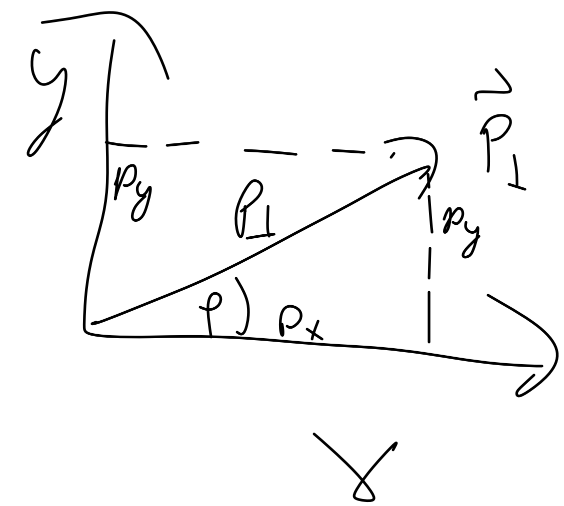
$$\Rightarrow dp_x = \frac{1}{p_x} p_\perp\, dp_\perp$$

$$\cos\varphi = \frac{p_x}{p_\perp}$$

$$\sin\varphi = \frac{p_y}{p_\perp}$$

$$p_y = p_\perp \sin\varphi$$

$$p_x = p_\perp \cos\varphi$$



$$\tan\varphi = \frac{p_y}{p_x}$$

$$\Rightarrow p_y = \tan\varphi \cdot p_x$$

$$\frac{dp_y}{d\varphi} = p_\perp \cos(\varphi) = p_x$$

$$dp_y = p_x\, d\varphi$$

$$\frac{dp_x}{dp_\perp} = -p_\perp \sin(\varphi)$$

Covariant and Contravariant vectors

$\vec{v} = v^i \vec{e}_i$ Contravariant, transforms opposite to basis

$\vec{e}_i \vec{v} = v_i$ Covariant, transforms same way as basis