LECTURE 21

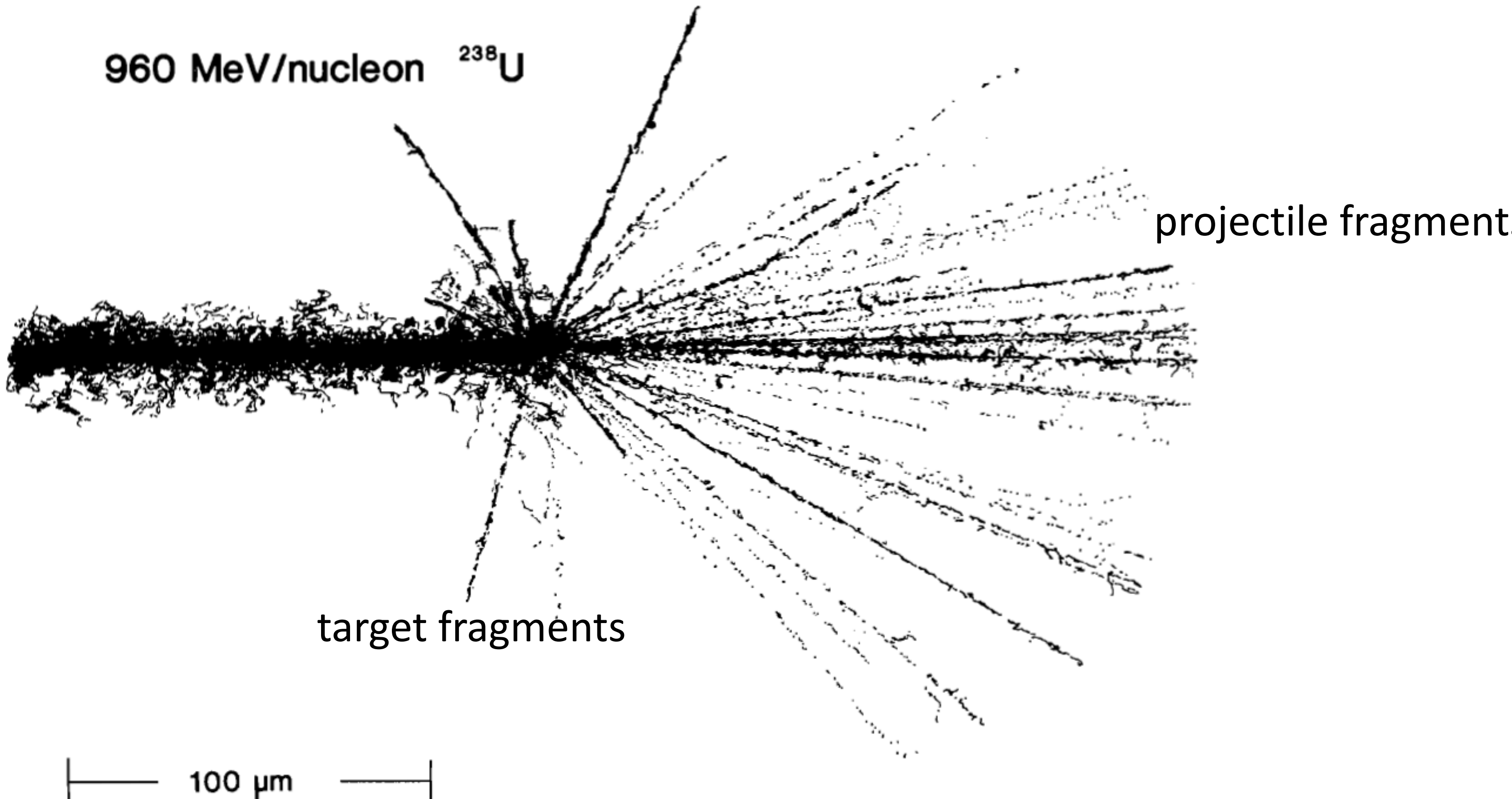
PART 3: COLLISIONS OF RELATIVISTIC NUCLEI

Kai Schweda

OUTLINE

- brief history
- some kinematics / collision geometry
- the large hadron collider
- the ALICE apparatus
- the next decade

A RELATIVISTIC NUCLEAR COLLISION @BEVALAC

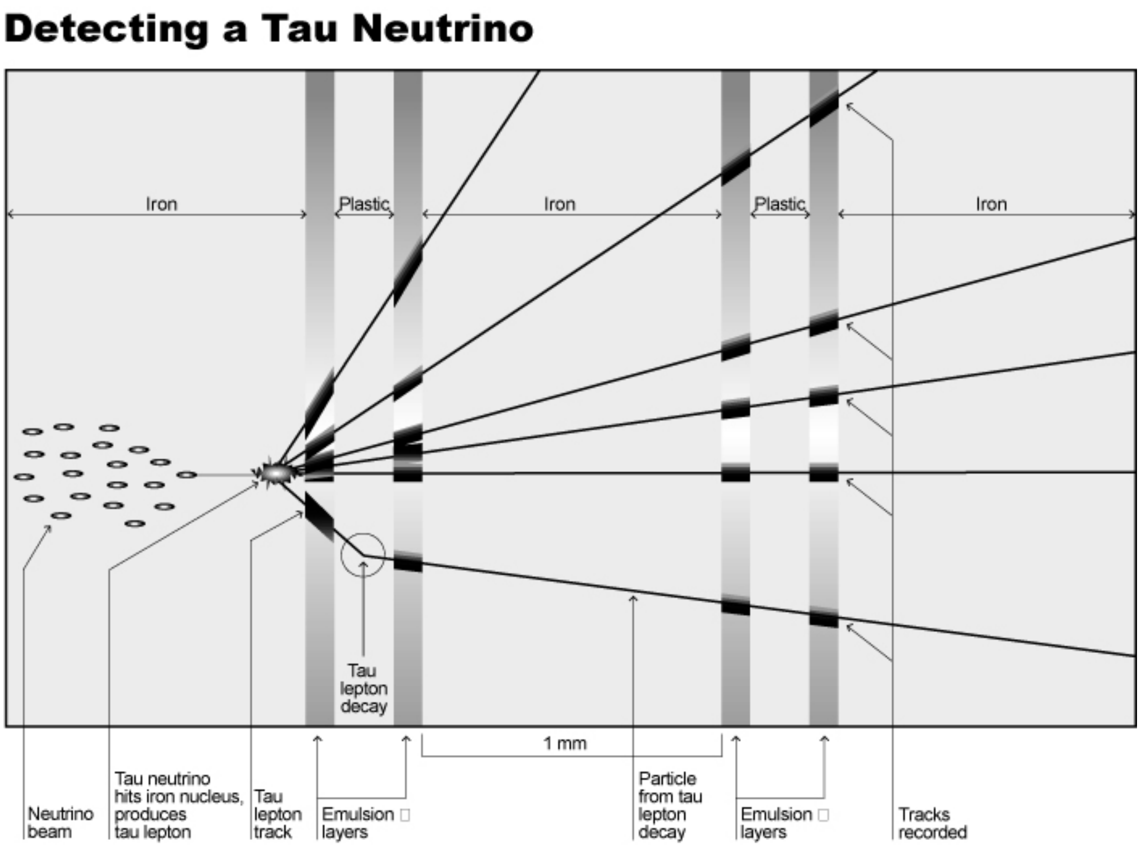


Phys.Rev.C 27 (1983) 2436

Fig. II.8-C. The pattern of tracks left by a 960-MeV-per-nucleon ^{238}U nucleus colliding with another nucleus in a photographic emulsion.

- $^{238}U^{92+}$ in nuclear emulsion (Ag-Br), photo emulsion, developed, using microscope
- forward: projectile fragments
- star-like: target fragment

DISCOVERY OF THE TAU NEUTRINO



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

- Direct Observation of ν_τ (DONUT)
- ν_τ beam from Fermilab
- $\nu_\tau + N \rightarrow \tau^- + X$
  $\tau \rightarrow \nu_\tau + h$ (or $\mu + \bar{\nu}_\mu$)
- lifetime: 81.7µm
- **emulsion** used for **micrometer precision**
- also, e.g. T2K, OPERA

DONUT Collaboration, Phys.Lett.B504 (2001) 218, arXiv: 0012035.

THE BEGINNING

“It would be **intriguing** to explore **new phenomena** by **distributing** **high energy** or **high nuclear matter** over a relatively **large volume**.”
“In this way one could temporarily **restore** broken **symmetries** of the physical vacuum and possibly **create** abnormal **states** of **nuclear matter**.”
T.D. Lee, Bear Mountain, NY, 1974.

“Nevertheless, such speculations reminds us that the **possibility** of totally **unexpected phenomena** may be the **most compelling** reason to consider **relativistic nucleus-nucleus collisions**. It is regrettable that It is so **hard** to **estimate** the **odds** for this to happen.”

J.D. Bjorken, FNAL, PRD 27 (1983) 140.

THE HAGEDORN LIMITING TEMPERATURE

hadron mass spectrum (number of states with increasing mass) rises exponentially

Hagedorn concluded that $T_H = 0.15$ GeV would be the ultimate temperature of all matter, R Hagedorn 1965 Nuovo Cim. Suppl. **3** 147.

1967: 1411 states known

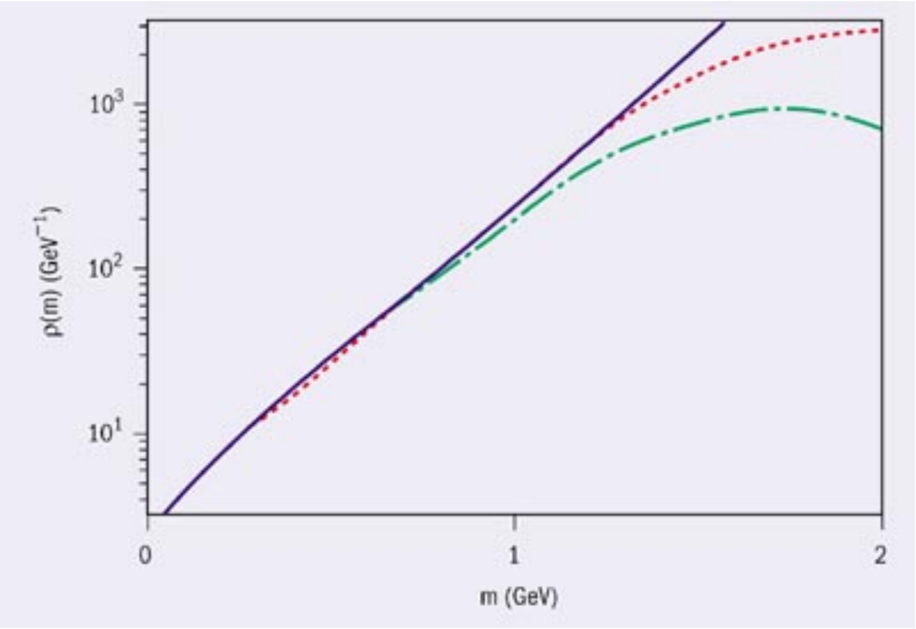
1996: 4627 states known

exponential fit, $T_H = 0.158$ GeV

$T_H = 1.7 \times 10^{12}$ K

Physical reason:

Energy put into the system excites high-mass resonances



source: CERN Courier, Sep. 3, 2003

This prevents a further increase of the temperature:

resonance gas: density of resonances ~ energy density

average energy per resonance ~ $k_B T$~ const

QGP — THE IDEA

1973 — Birth of QCD

All ideas in place:
Yang-Mills theory; SU(3) color symmetry; asymptotic freedom; confinement in color-neutral objects

1975 — Idea of quark deconfinement at high temperature and/or density

Collins, Perry, PRL 34 (1975) 1353

"Our basic picture then is that matter at densities higher than nuclear matter consists of a quark soup."

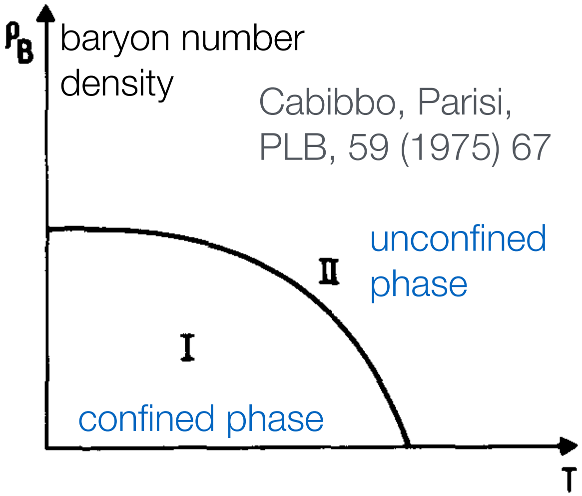
Idea based on weak coupling (asymptotic freedom)

Cabibbo, Parisi, PLB, 59 (1975) 67

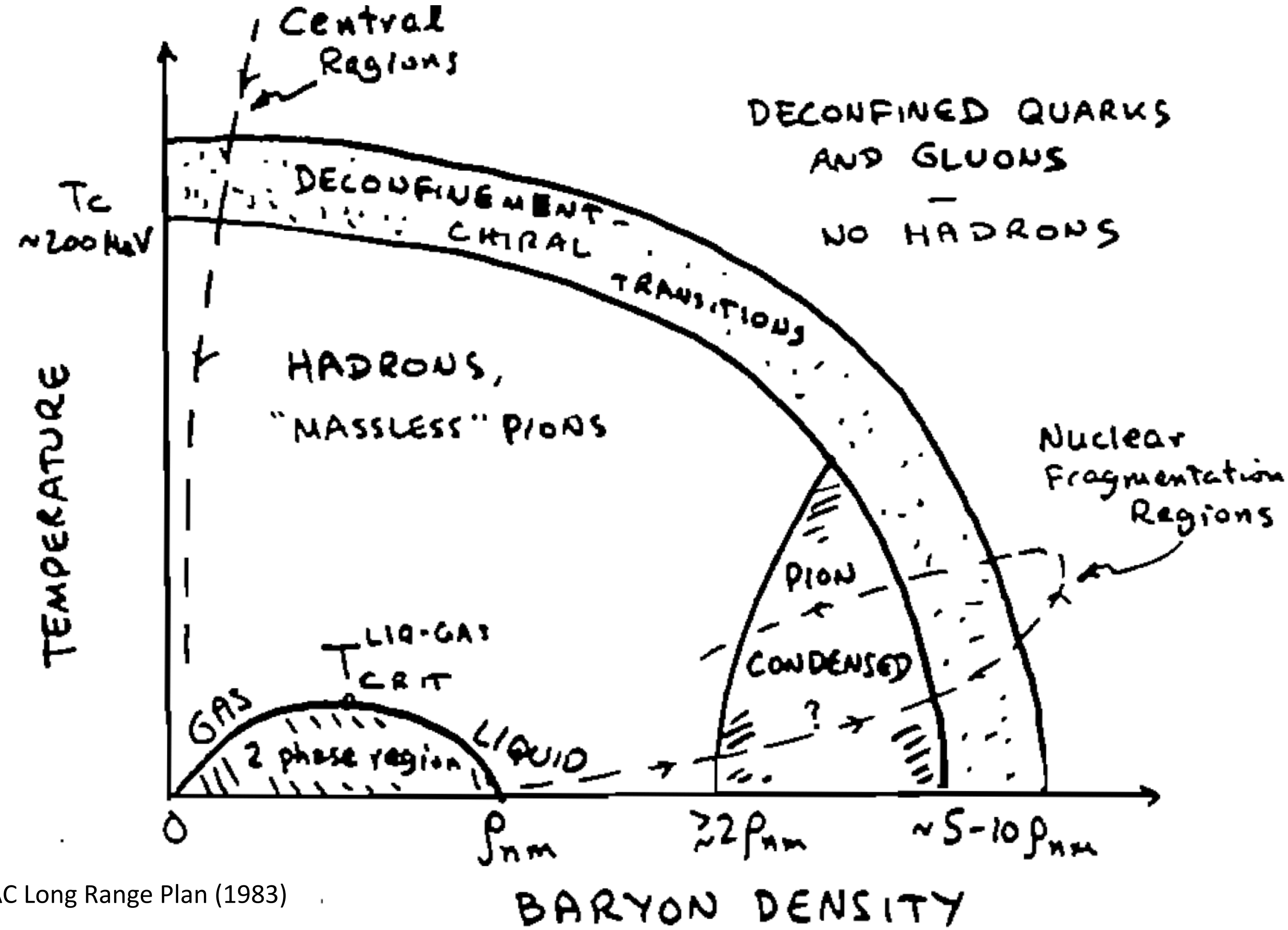
Exponential hadron spectrum not necessarily connected with a limiting temperature

Rather: Different phase in which quarks are not confined

It was soon realized that this new state could be created and studied in heavy-ion collisions

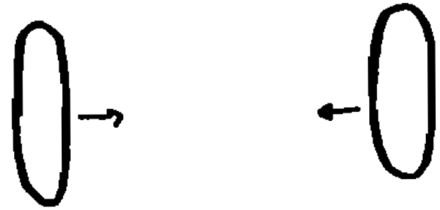


PHASE DIAGRAM OF STRONGLY INTERACTING MATTER



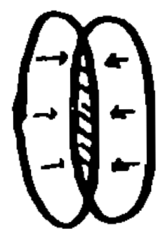
source: NSAC Long Range Plan (1983)

CENTRAL HEAVY ION COLLISIONS



BEFORE COLLISION, IN CENTER-OF-MASS

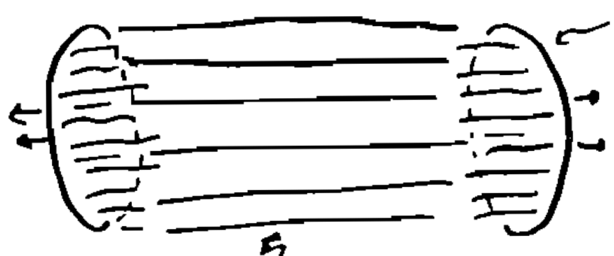
1) AT LAB ENERGIES $\lesssim$ 10 GEV PER NUCLEON



: SUBSTANTIAL STOPPING

: LARGE COMPRESSION OF NUCLEI

2) AT HIGHER ENERGIES : TRANSPARENCY



HIGHLY EXCITED BARYON-RICH NUCLEAR FRAGMENTATION REGIONS

CENTRAL REGION, HIGH ENERGY DENSITY, LOW BARYON DENSITY

source: NSAC Long Range Plan (1983)

BRIEF HISTORY

1974 Bear mountain workshop 'BeV/nucleon collisions of heavy ions' [link]

Focus on exotic matter states and astrophysical implications

1983 long range plan for nuclear physics in US:
Realization that the just abandoned pp collider (CBA/Isabelle) project at Brookhaven could be turned into a nuclear collider inexpensively

1984: 1-2 GeV/*c* per nucleon beam from SuperHILAC into Bevalac at Berkeley

1986

beams of silicon at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)

beams of oxygen/sulfur at CERN SPS ($\sqrt{s_{NN}} \approx 20$ GeV)

1992/1994

beams of gold at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)

beams of lead at CERN SPS ($\sqrt{s_{NN}} \approx 17$ GeV)

2000: gold-gold collisions at RHIC ($\sqrt{s_{NN}} \approx 200$ GeV)

2010: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 2760$ GeV)

2015: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 5020$ GeV)

G. Baym, arXiv:1701.03972
and arXiv:hep-ph/0104138v2

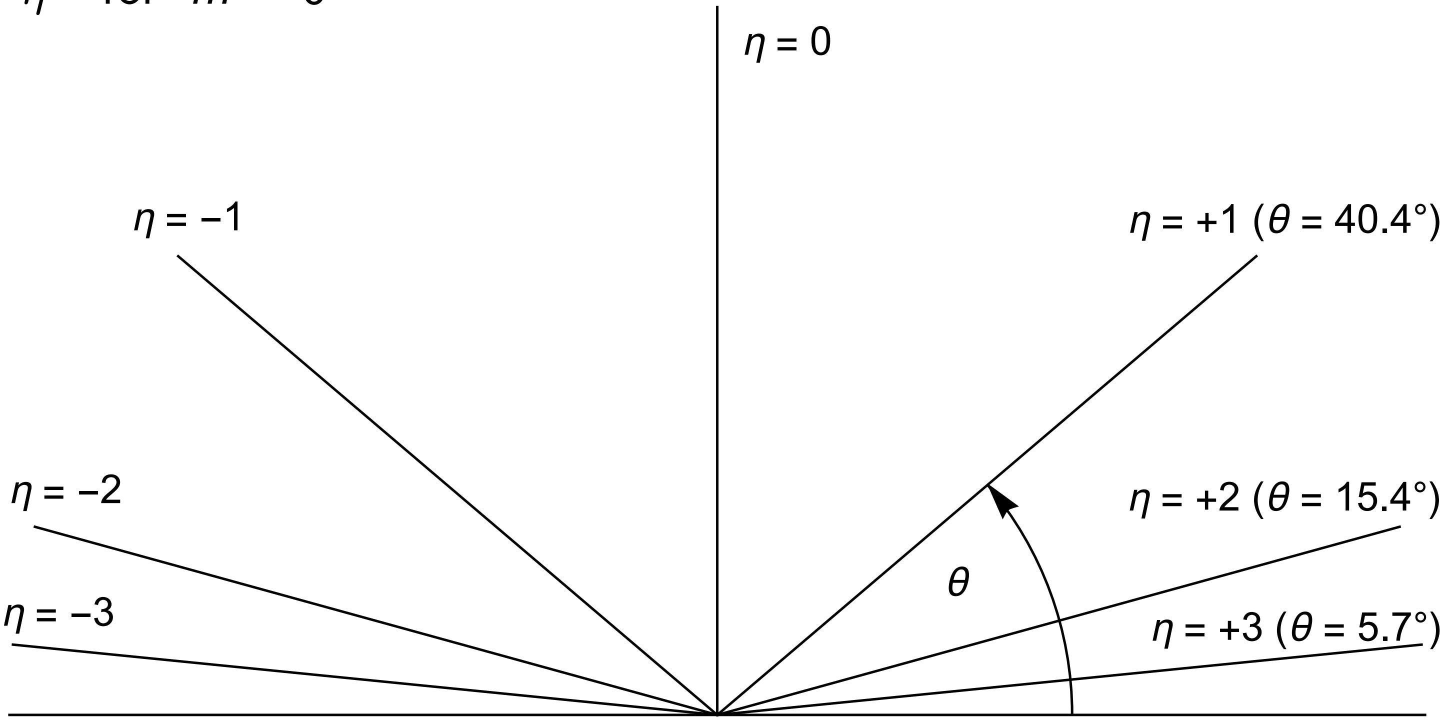
Pseudorapidity η

courtesy of Klaus Reygers, QGP Physics, SS2017

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

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

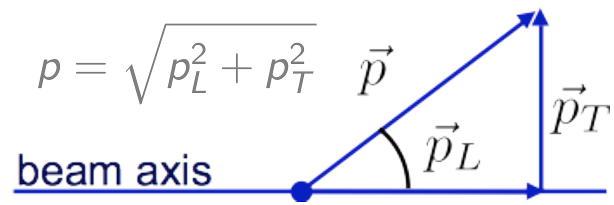
$y = \eta \quad \text{for} \quad m = 0$



Analogous to the relations for the rapidity we find:

$$p = p_T \cdot \cosh\eta, \qquad p_L = p_T \cdot \sinh\eta$$

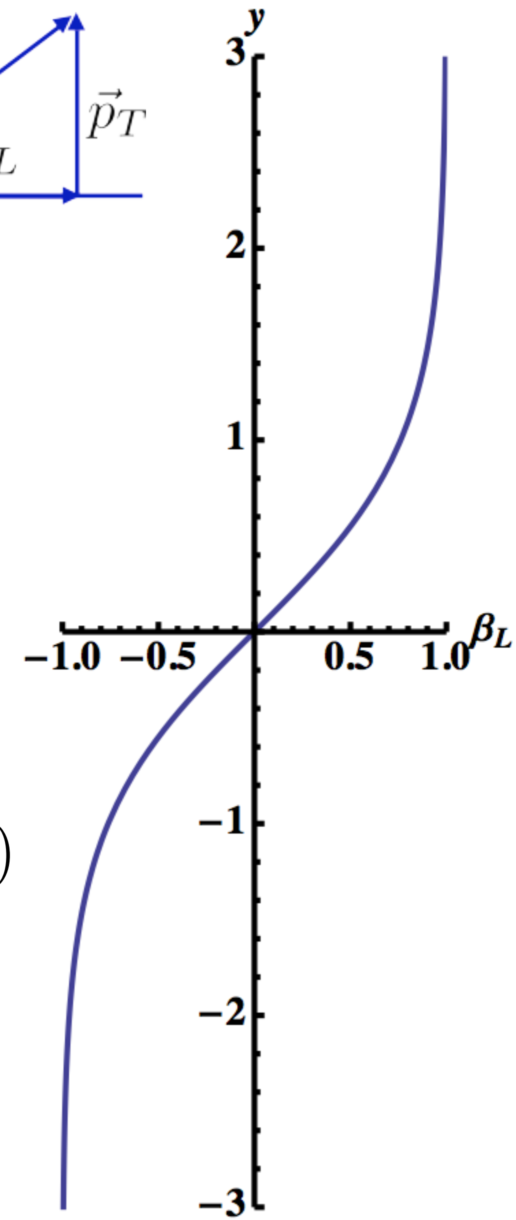
Rapidity



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

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

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

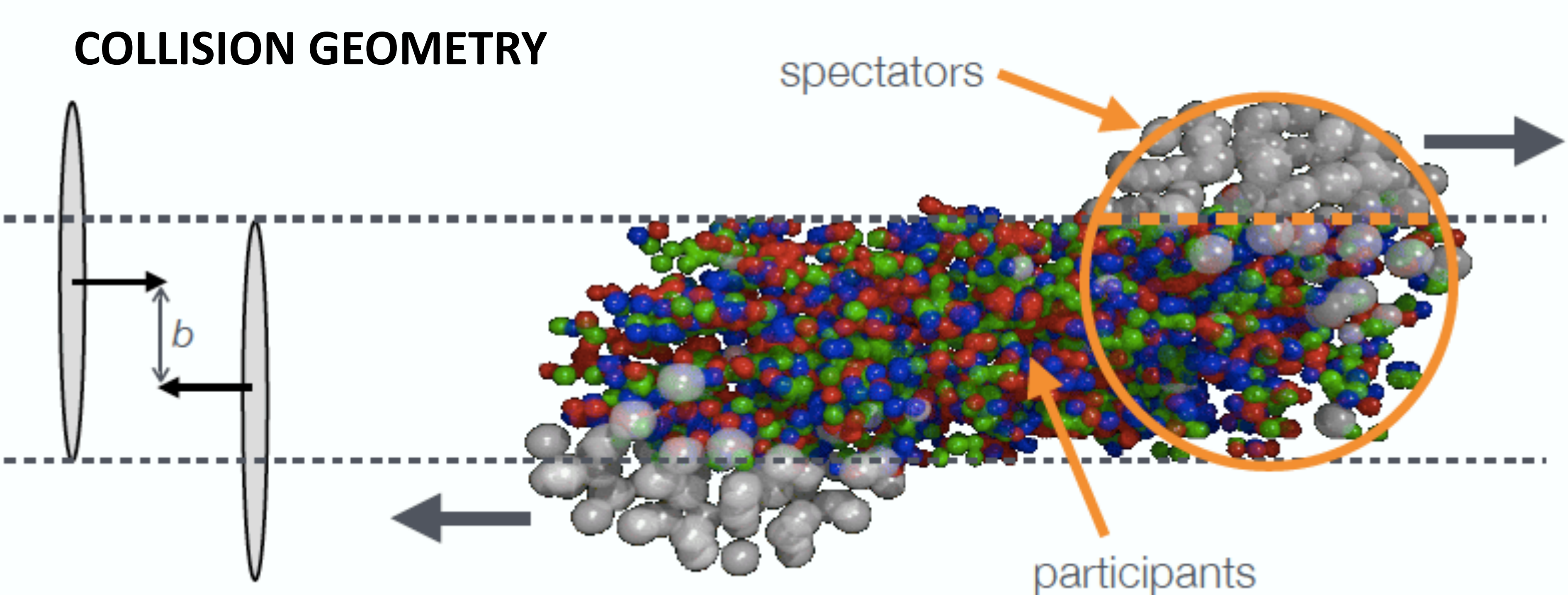
where $\quad m_T := \sqrt{m^2 + p_T^2}\quad$ is called *transverse mass* courtesy of Klaus Reygers, QGP Physics, SS2017

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

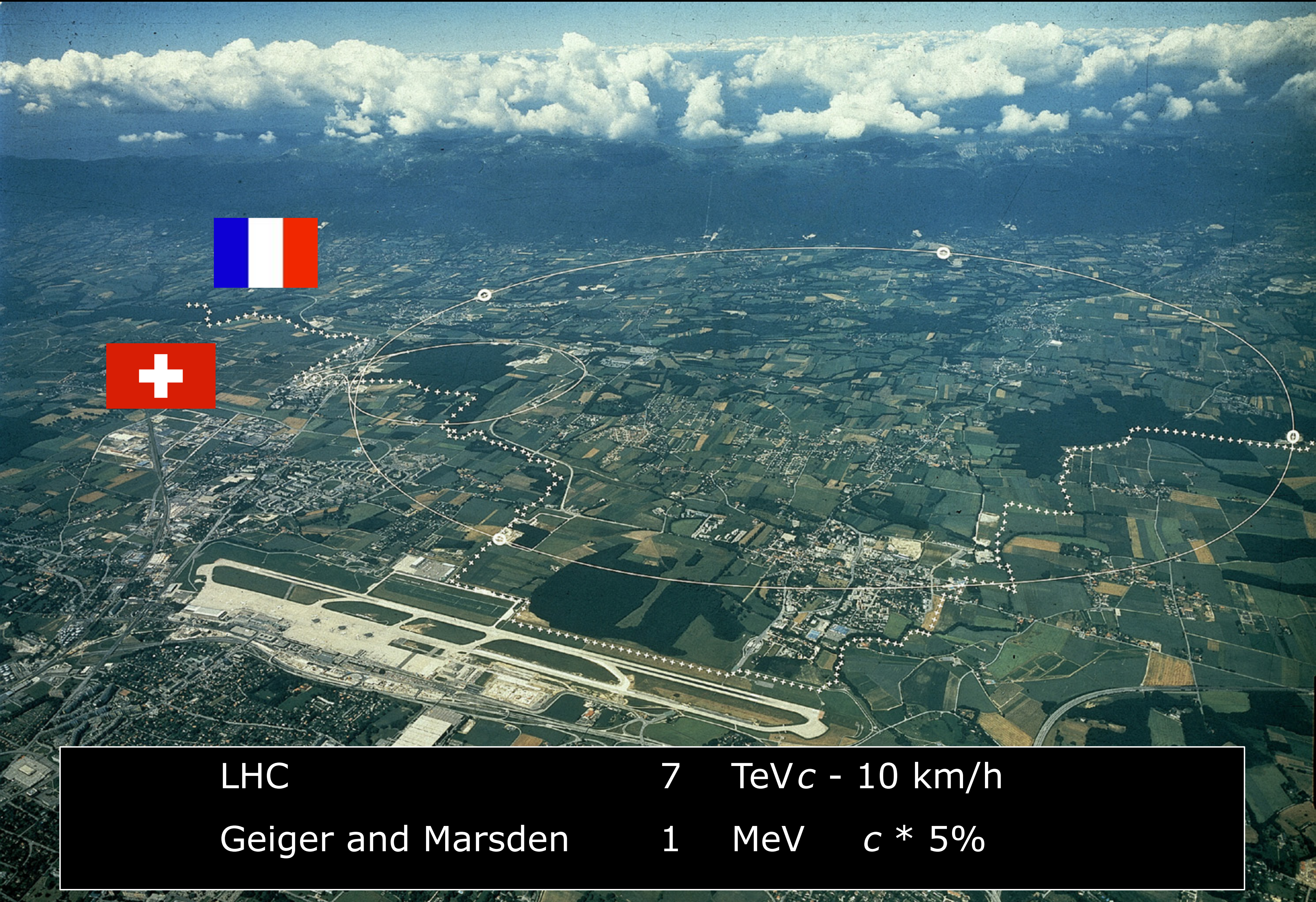
COLLISION GEOMETRY



Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{part} \rangle$	RMS	(*sys.*)	$\langle N_{coll} \rangle$	RMS	(*sys.*)	$\langle T_{AA} \rangle$ 1/mbarn	RMS 1/mbarn	(*sys.*) 1/mbarn
0–5%	0.00	3.50	382.7	17	3.0	1685	140	190	26.32	2.2	0.85
5–10%	3.50	4.94	329.4	18	4.3	1316	110	140	20.56	1.7	0.67
10–20%	4.94	6.98	260.1	27	3.8	921.2	140	96	14.39	2.2	0.45
20–40%	6.98	9.88	157.2	35	3.1	438.4	150	42	6.850	2.3	0.23
40–60%	9.88	12.09	68.56	22	2.0	127.7	59	11	1.996	0.92	0.097
60–80%	12.09	13.97	22.52	12	0.77	26.71	18	2.0	0.4174	0.29	0.026
80–100%	13.97	20.00	5.604	4.2	0.14	4.441	4.4	0.21	0.06939	0.068	0.0055

Der Large Hadron Collider am CERN

Der Large Hadron Collider am CERN



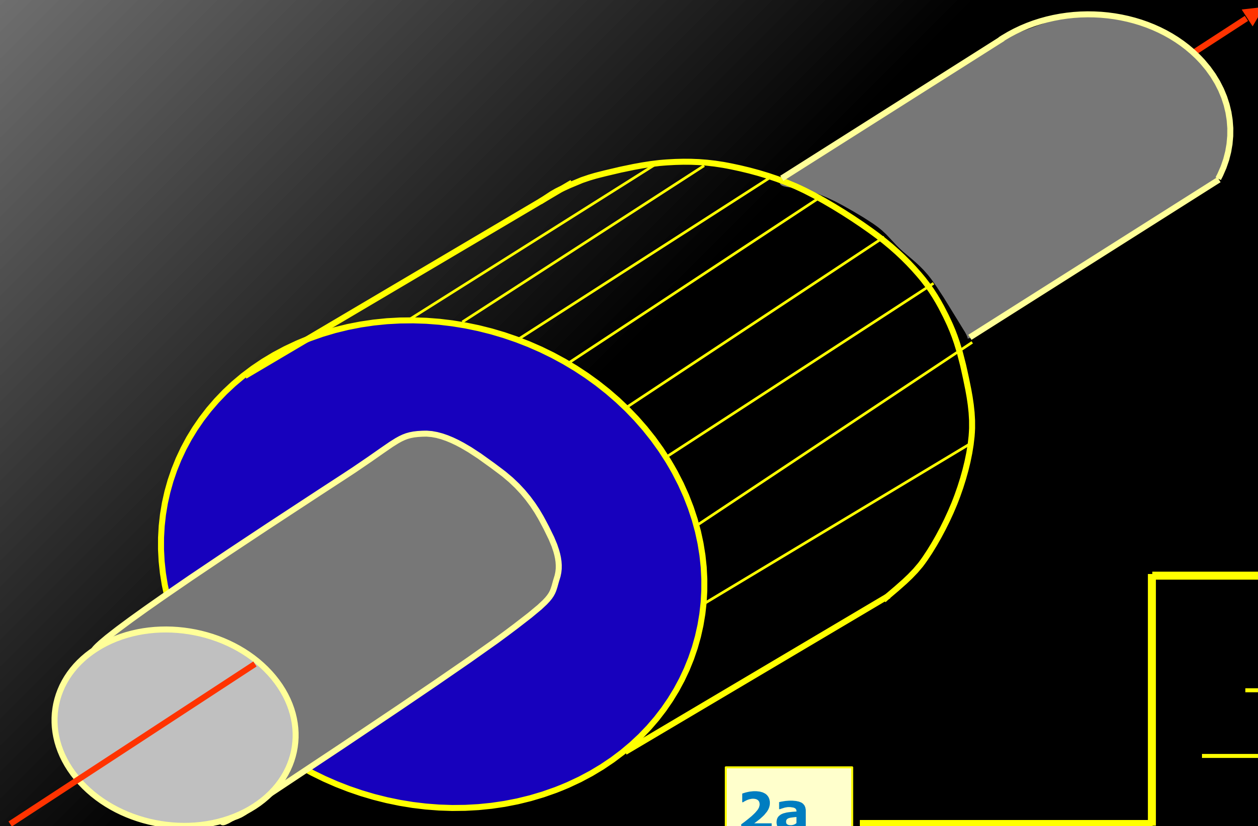
LHC	7	TeV	*c* - 10 km/h
Geiger and Marsden	1	MeV	*c* * 5%

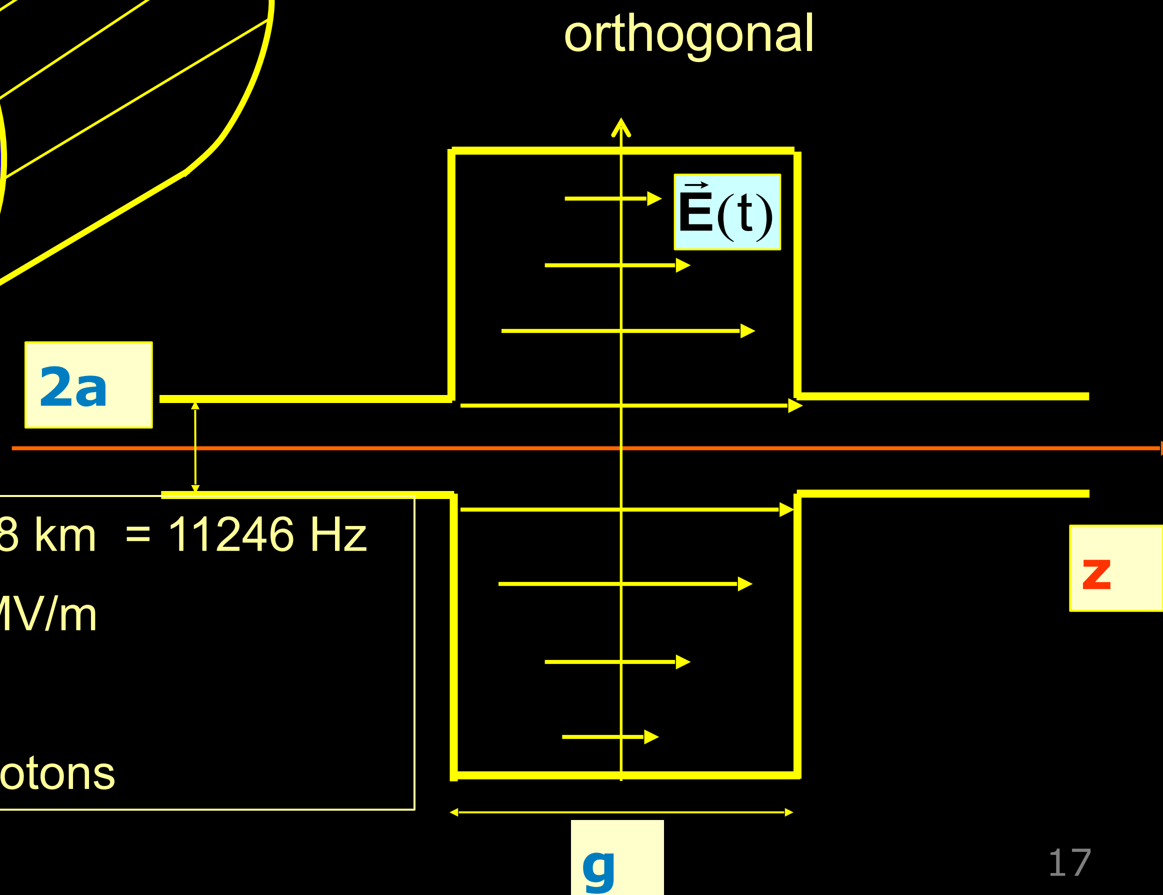
Der Large Hadron Collider am CERN

LHC	7	TeV*c* - 10 km/h	
Geiger and Marsden	1	MeV	*c* * 5%

The Large Hadron Collider at CERN

LHC	7	TeV	*c* - 10 km/h
Geiger and Marsden	1	MeV	*c* * 5%





Revolution frequency: c / 26.8 km = 11246 Hz

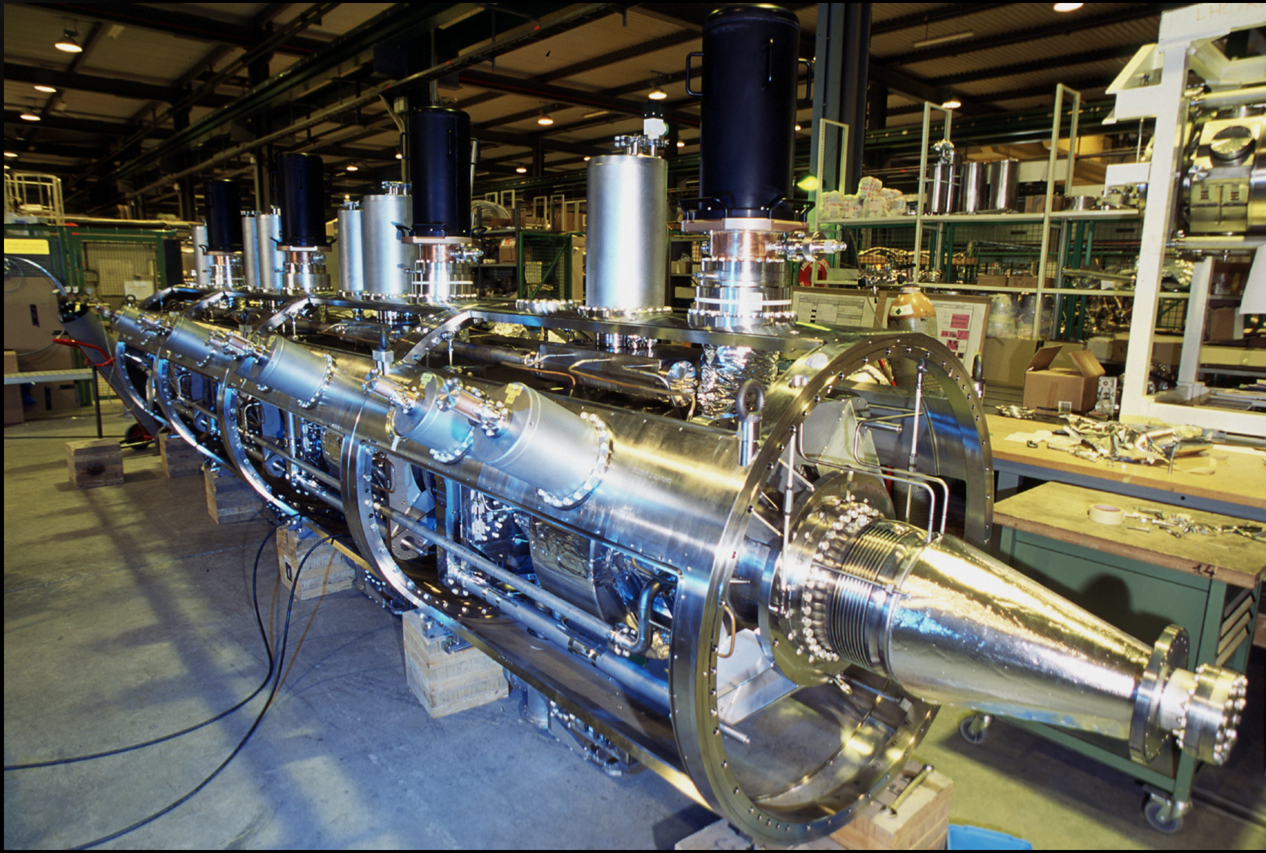
Time varying field, up to 20 MV/m

LHC RF frequency 400 MHz

Consequence: bunches of protons

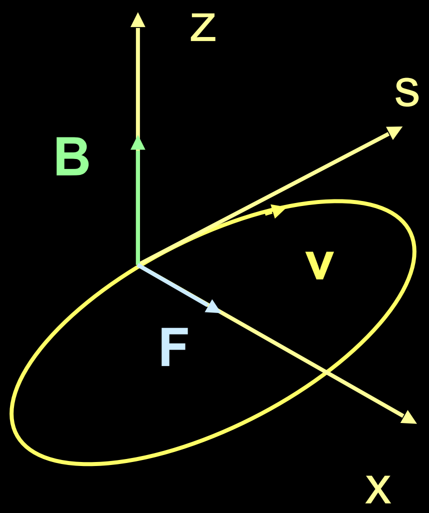
400 MHz system:

16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules



$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$



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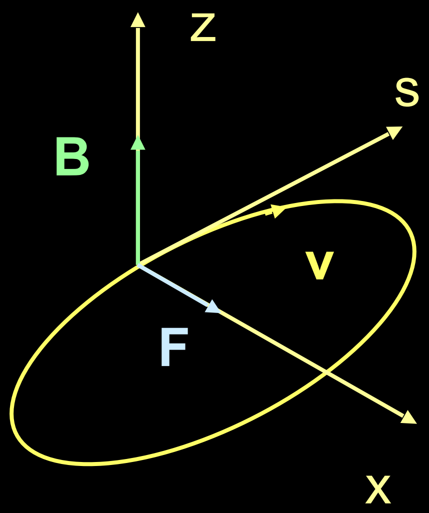
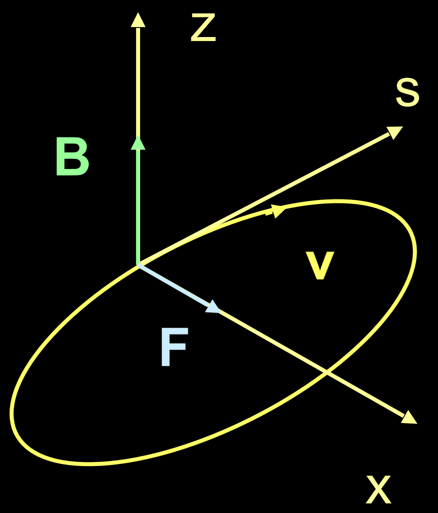


- Maximum momentum 7000 GeV/c

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$

- Maximum momentum 7000 GeV/c
- Bending radius 2805 m fixed by LEP tunnel



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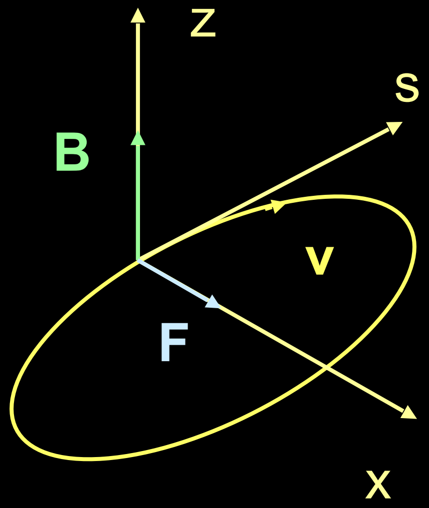
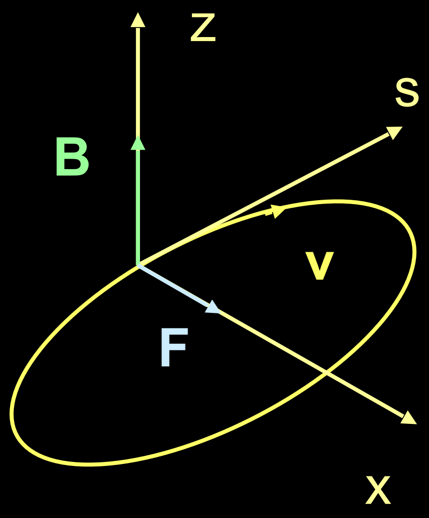


- Maximum momentum 7000 GeV/c
- Bending radius 2805 m fixed by LEP tunnel
- Magnetic field B = 8.33 Tesla

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$

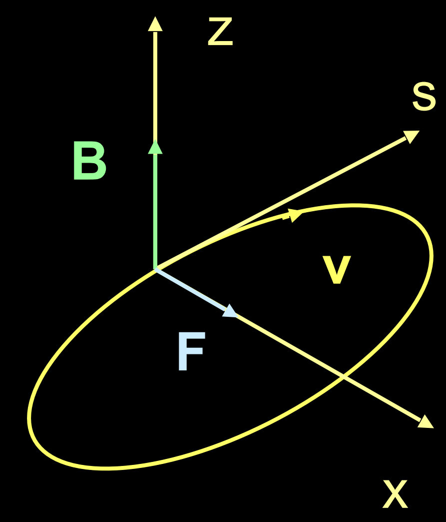


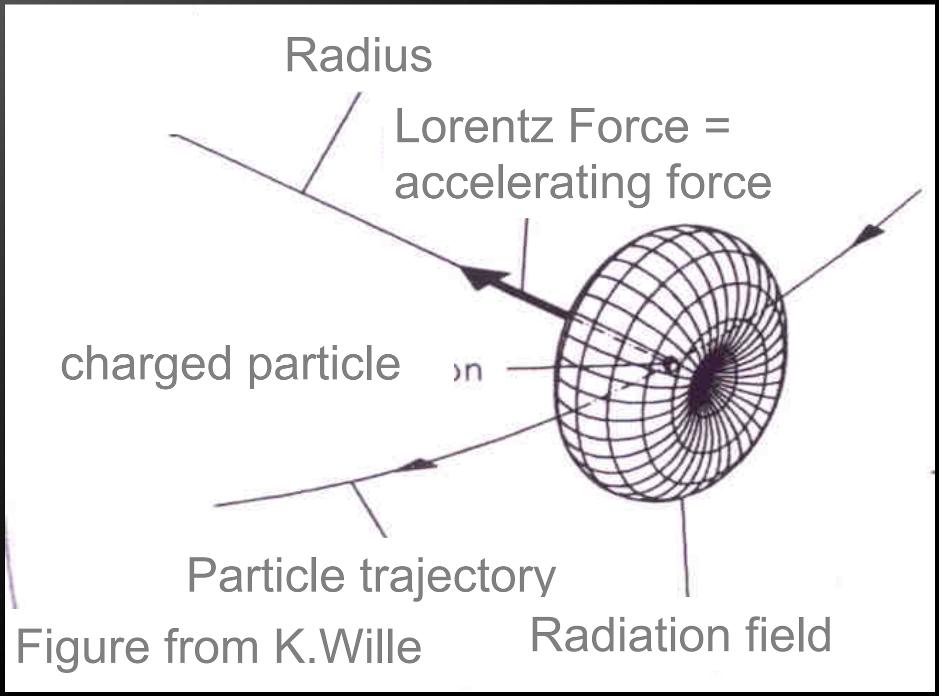
- Maximum momentum 7000 GeV/c
- Bending radius 2805 m fixed by LEP tunnel
- Magnetic field B = 8.33 Tesla
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$

- Maximum momentum 7000 GeV/c
- Bending radius 2805 m fixed by LEP tunnel
- Magnetic field B = 8.33 Tesla
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions





Power emitted for one particle: $P_s = \dfrac{e_0^2 \cdot c}{6 \cdot \pi \cdot \varepsilon_0 \cdot \left(m_0 \cdot c^2\right)^4} \cdot \dfrac{E^4}{\rho^2}$

with E = energy, m_0 = rest mass, e_0 = charge, and ρ = radius

$E_{lep} := 100GeV$ $E_{lhc} := 7000GeV$

Energy loss for one particle per turn:

$U_{lep} = 3.844 \times 10^{9}\,eV$ $U_{lhc} = 8.121 \times 10^{3}\,eV$

Total power of synchrotronradiation:

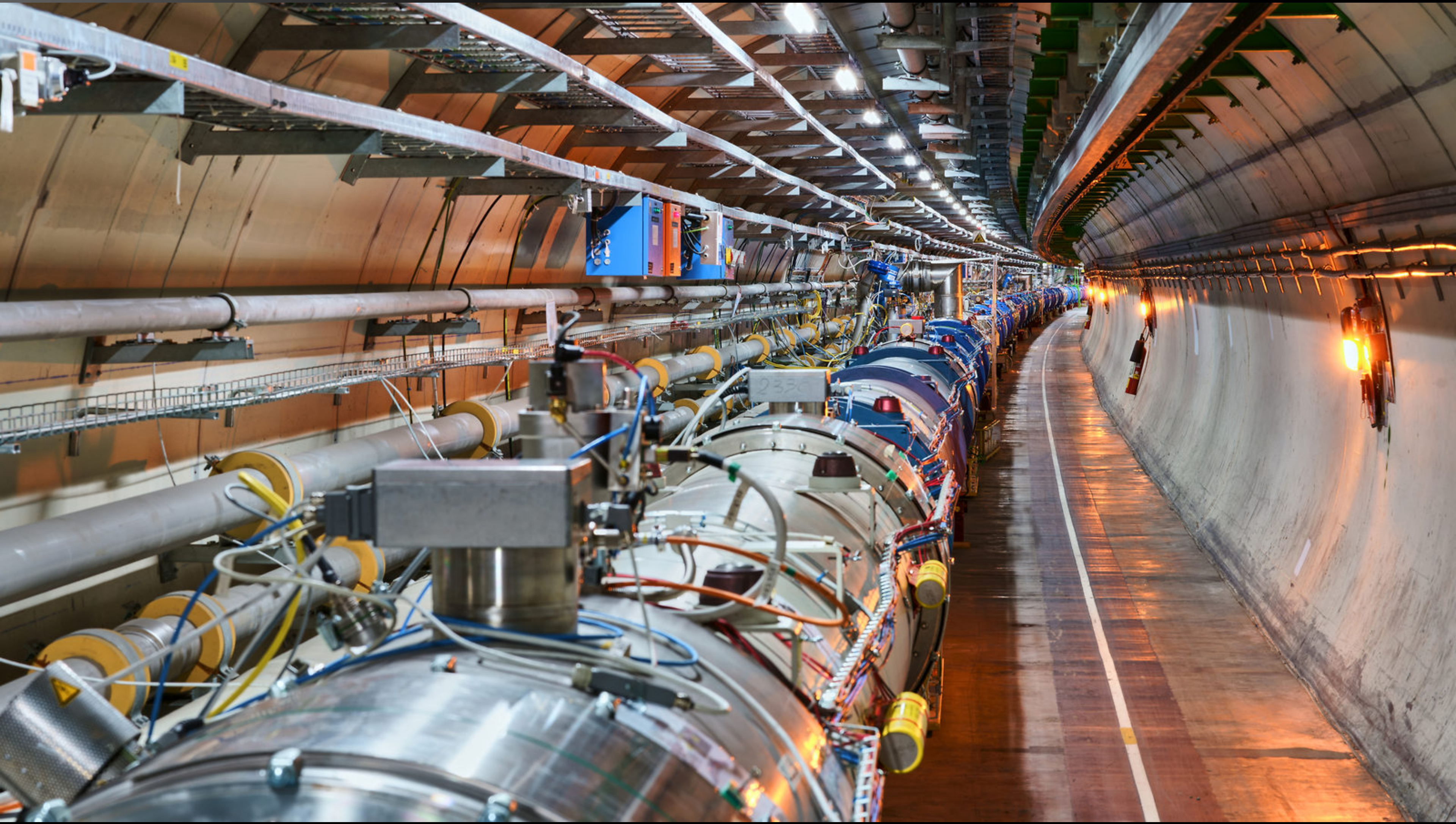
Number of electrons in LEP: $N_{lep} := 10^{12}$ Number of protons in LHC $N_{lhc} := 10^{14}$

$P_{total\_lep} := N_{lep} \cdot P_{lep}$ $P_{total\_lhc} := N_{lhc} \cdot P_{lhc}$

$P_{total\_lep} = 1.278 \times 10^{7}\,W$ $P_{total\_lhc} = 2.699 \times 10^{3}\,W$

The power of the synchrotronradiation emitted at the LHC is very small, but the radiation goes into the supraconducting magnets at 1.9 K ... 20 K

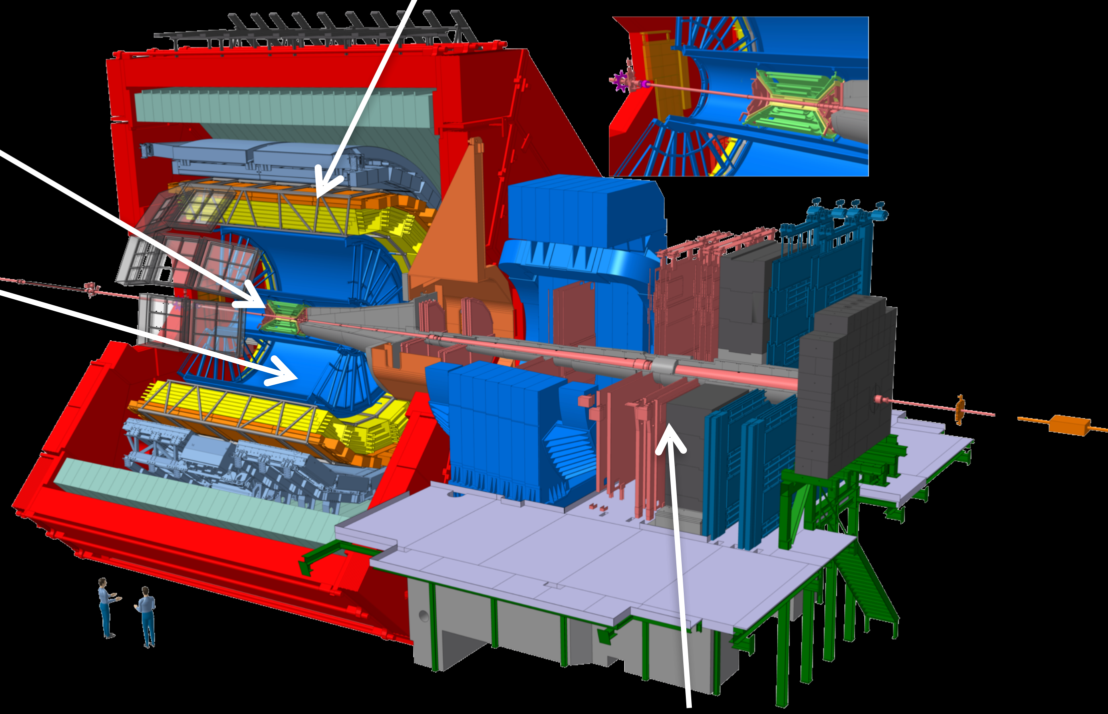
INSIDE THE LHC TUNNEL



ALICE

- Inner Tracker, silicon tracking & PID
- Time Projection Chamber tracking & PID
- Particle ID: 0.1-20 GeV/*c*
- Material budget: 0.08 X_0
- Momentum resolution ~1-7% for p_T = 0.1-100 GeV/*c*

Time of flight – PID



Muon spectrometer

DATA SET – RUN 1 AND RUN 2

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} , ~59 pb^{-1}

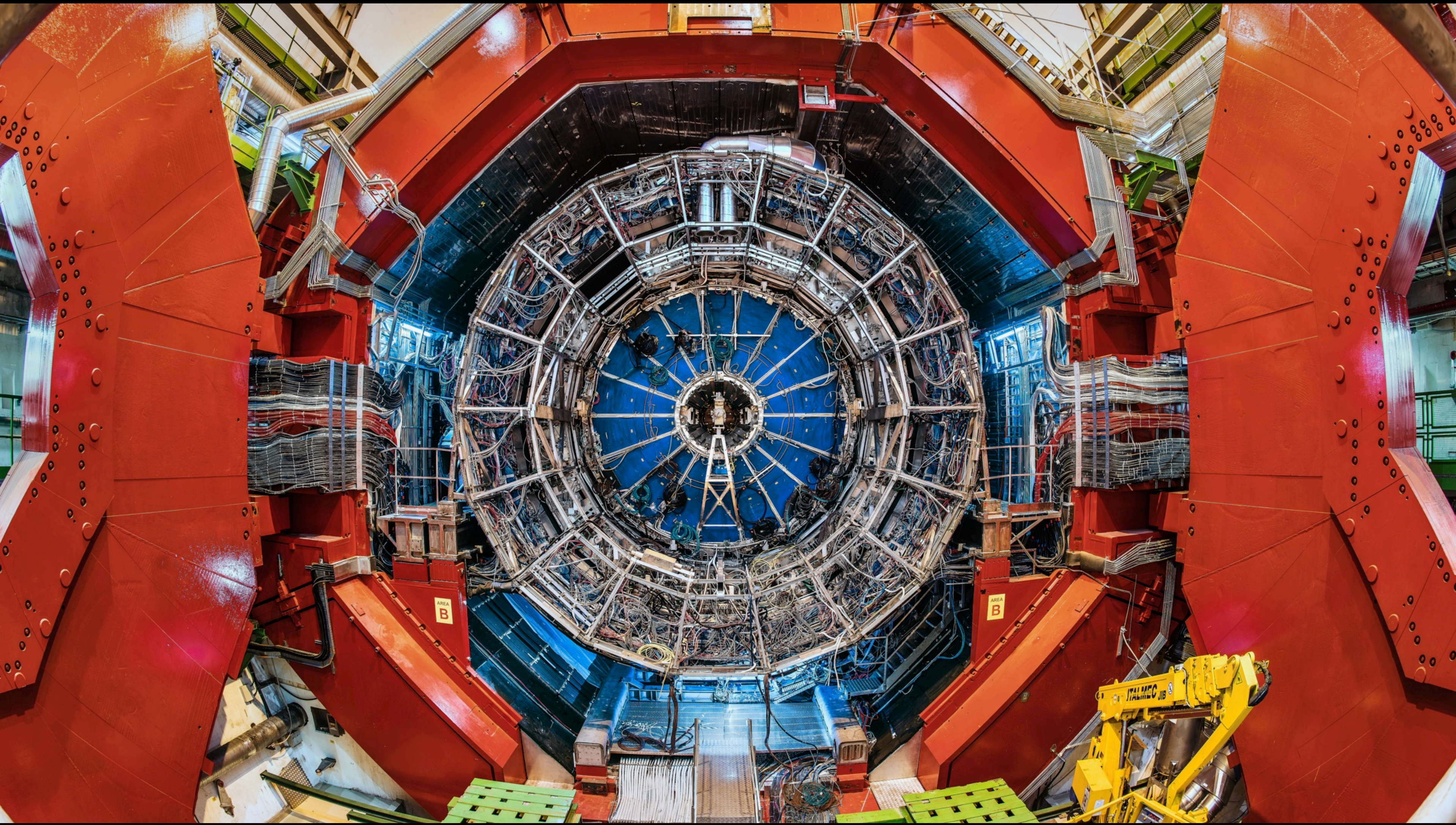
System size

9x central collisions

8h LHC pilot run

Reference data, initial state

New pp reference, high-multiplicity triggers


AREA B
AREA B
ITALMEC JIB

ALICE

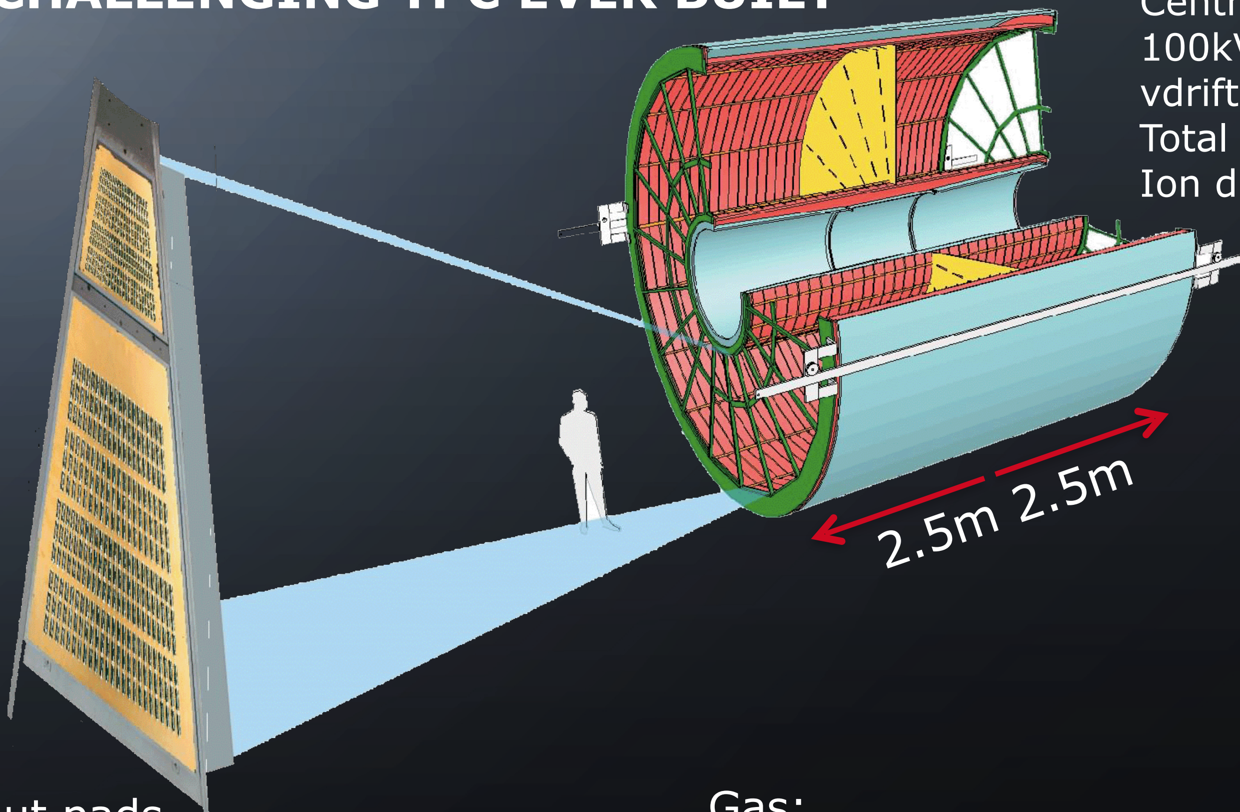
THE ALICE TPC IN NUMBERS

MOST CHALLENGING TPC EVER BUILT

Central HV electrode
100kV → 400 V/cm
vdrift = 2.73 cm/μs
Total drift time 92 μs
Ion drift time ~ 0.5 s

2x18 inner readout chambers

2x18 outer readout chambers

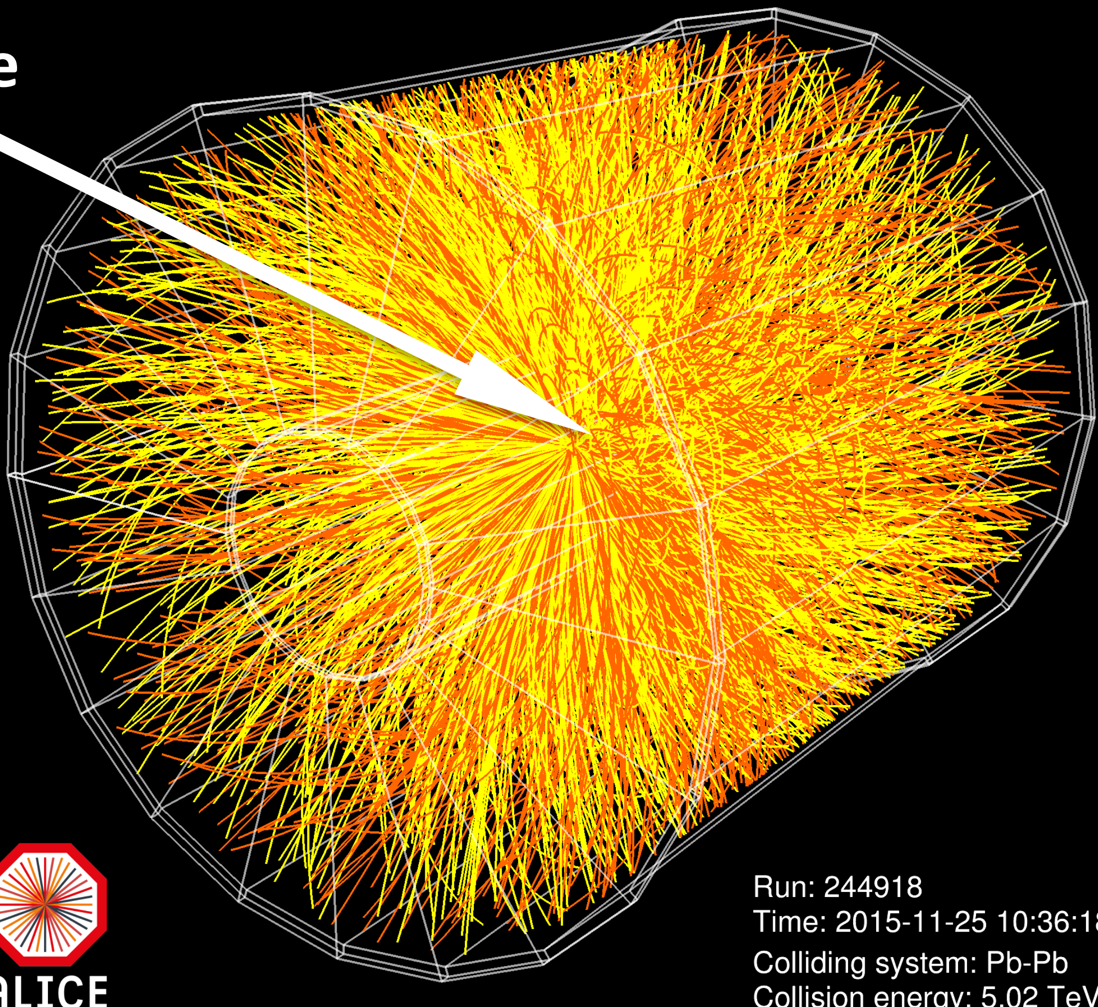


557568 readout pads
1000 samples in time direction
Designed for charged-particle tracking and dE/dx measurement
in Pb-Pb collisions with dNch/dη=8000, σ(dE/dx)/(dE/dx)<10%

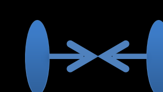
Gas:
~90 m3
Ar-CO2[-N2] (90-10[-5])
temp. homogeneity and stability < 100mK

A SINGLE LEAD-LEAD COLLISION

- **collision happens here**
- **4k charged particles** over two units of rapidity
- ALICE **tracks** and **identifies** almost all particles

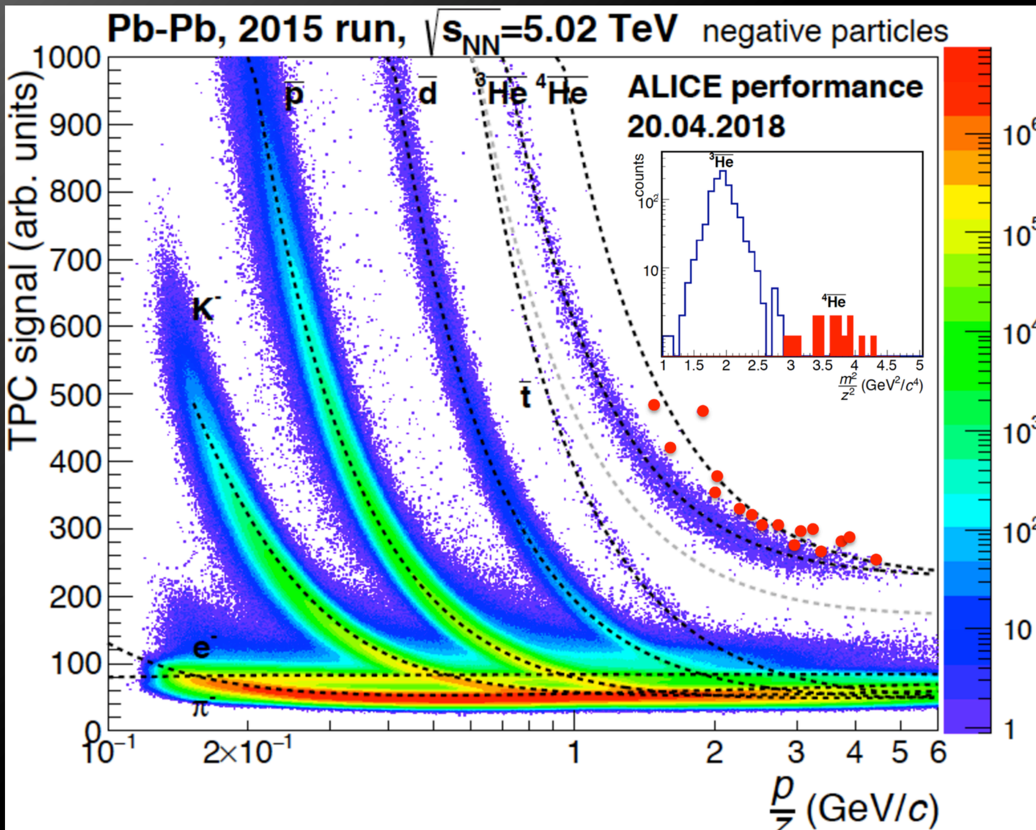


- **Multiplicity** is a measure of the **medium s size**



Central collision

PARTICLE IDENTIFICATION IN TPC AND TOF



- Specific energy loss in TPC-gas
- Large dynamic range (20 x MIP)
- Low material budget: 0.08 X_0
- QGP studies: PID is the only game in town

Anti-α particle, discovered by STAR@RHIC, BNL, Upton, NY. Nature 473, 353 (2011).

Mass difference ^{3}He – anti-^{3}He

→ Test of **CPT invariance**

ALICE: Nature Physics 11 (2015) 811-814.

$$\beta\gamma = p/m$$

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

PHOTON CONVERSIONS

TPC as photon spectrometer:

$$\gamma + Z \rightarrow e^+ + e^- + Z$$

full kinematic reconstruction:

$$P_\gamma = P_{e^+} + P_{e^-} \quad |(^2)$$

$$m_{\text{inv}}^2 = m_{e^+}^2 + m_{e^-}^2 + 2P_{e^+} \cdot P_{e^-}$$

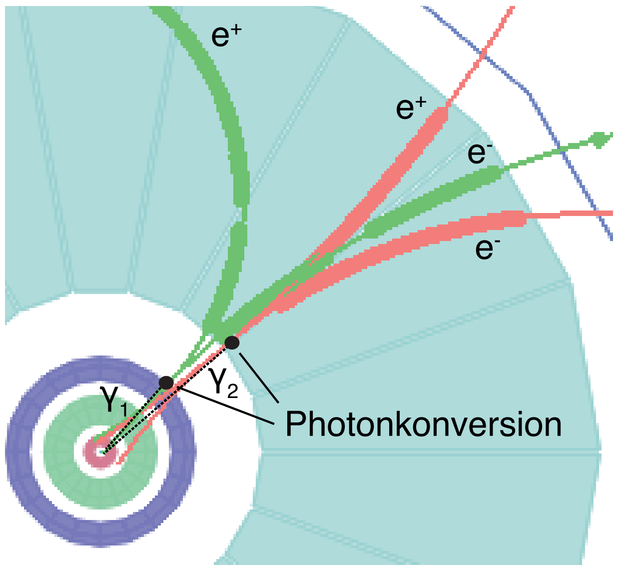
$$m_{\text{inv}}^2 = 2E_{e^+}E_{e^-} - 2E_{e^+}E_{e^-} \cdot \cos\alpha$$

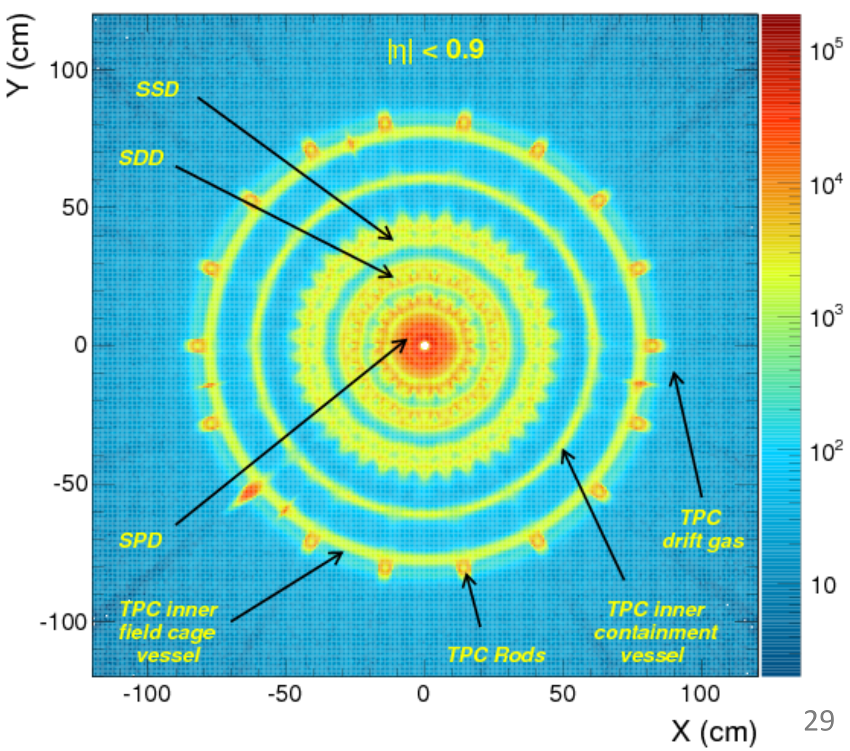
$$m_{\text{inv}}^2 = 2E_{e^+}E_{e^-}(1 - \cos\alpha)$$

X-ray tomography:

access ALICE material budget

access QGP thermal photon emission

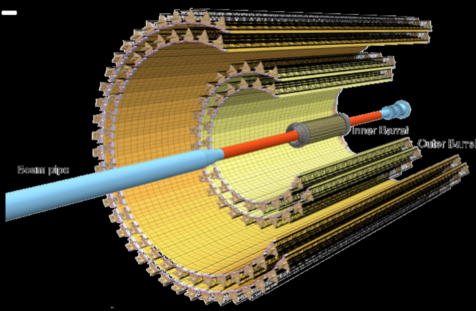




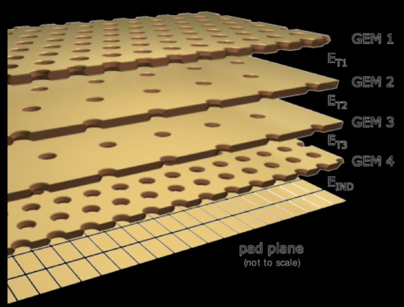
Int. J. Mod. Phys. A 29 (2014) 1430044,
Phys. Lett., vol. B754, pp. 235–248, 2016.

LS2 – GET READY FOR 50 KHZ PB-PB - CONTINUOUS READOUT

Inner Tracking System
10 m² active silicon area (12.5 G-pixels)
Spatial resolution ~5µm
Material budget: 0.0035 X_0 per layer

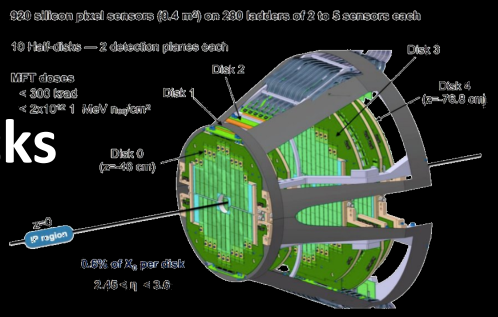


ITS

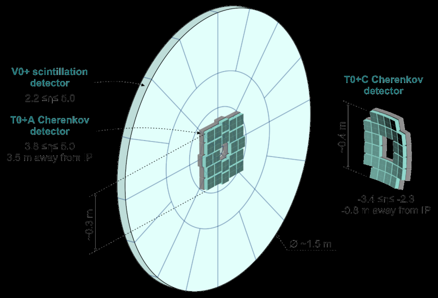


TPC

Time Projection Chamber
Replace MWPC with **GEM-4 stacks**
570k pads, **3.4 TBytes/sec**



MFT



FIT

Muon Forward Tracker
Forward Interaction Trigger

next 10 years: 100x more data @ unprecedented precision

RESTART OF THE LHC - RUN 3

- Live event July 5, 16h00
- https://home.cern/news/news/cern/watch-launch-run-3-live-cerns-internal-screens-or-social-media

- DON'T MISS IT!