ALICE DETECTORS

Sidharth Kumar Prasad
(Bose Institute, Kolkata, INDIA)

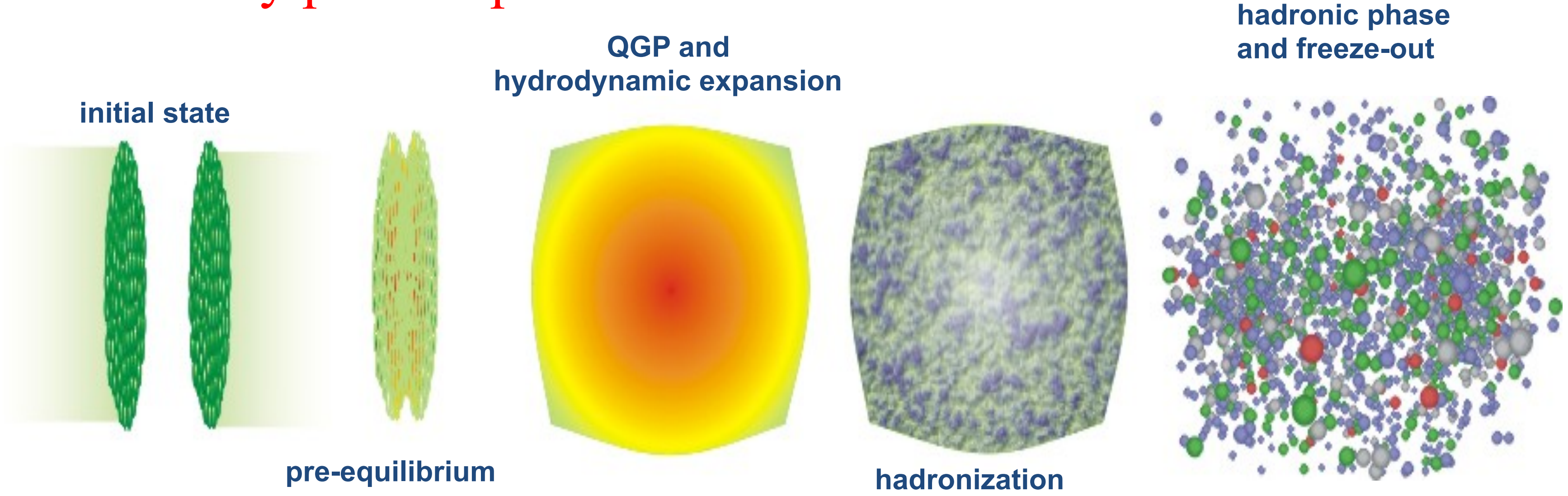
ALICE India School, November 15, 2020

Why heavy ion collisions ?

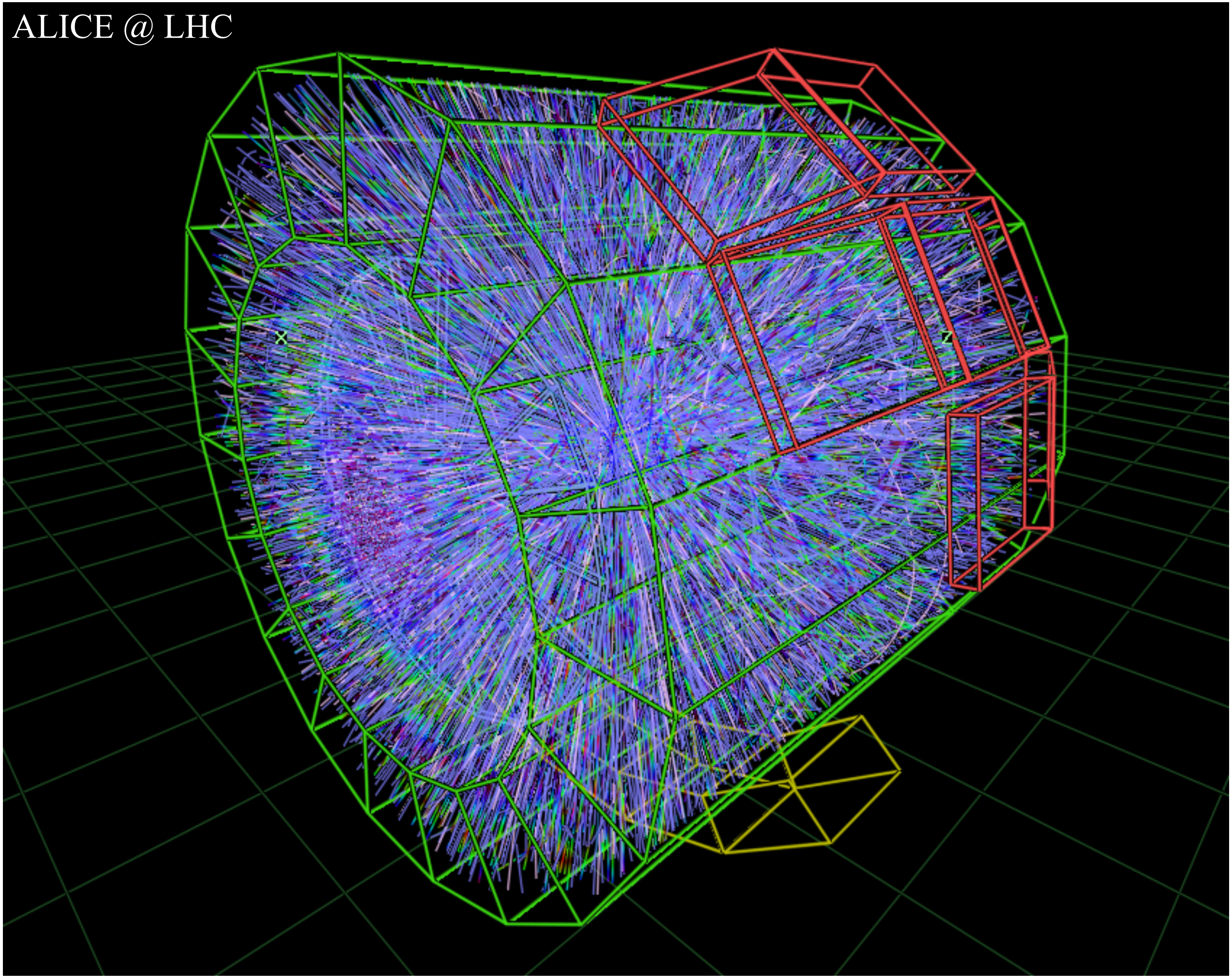
To create and study QGP in the laboratory

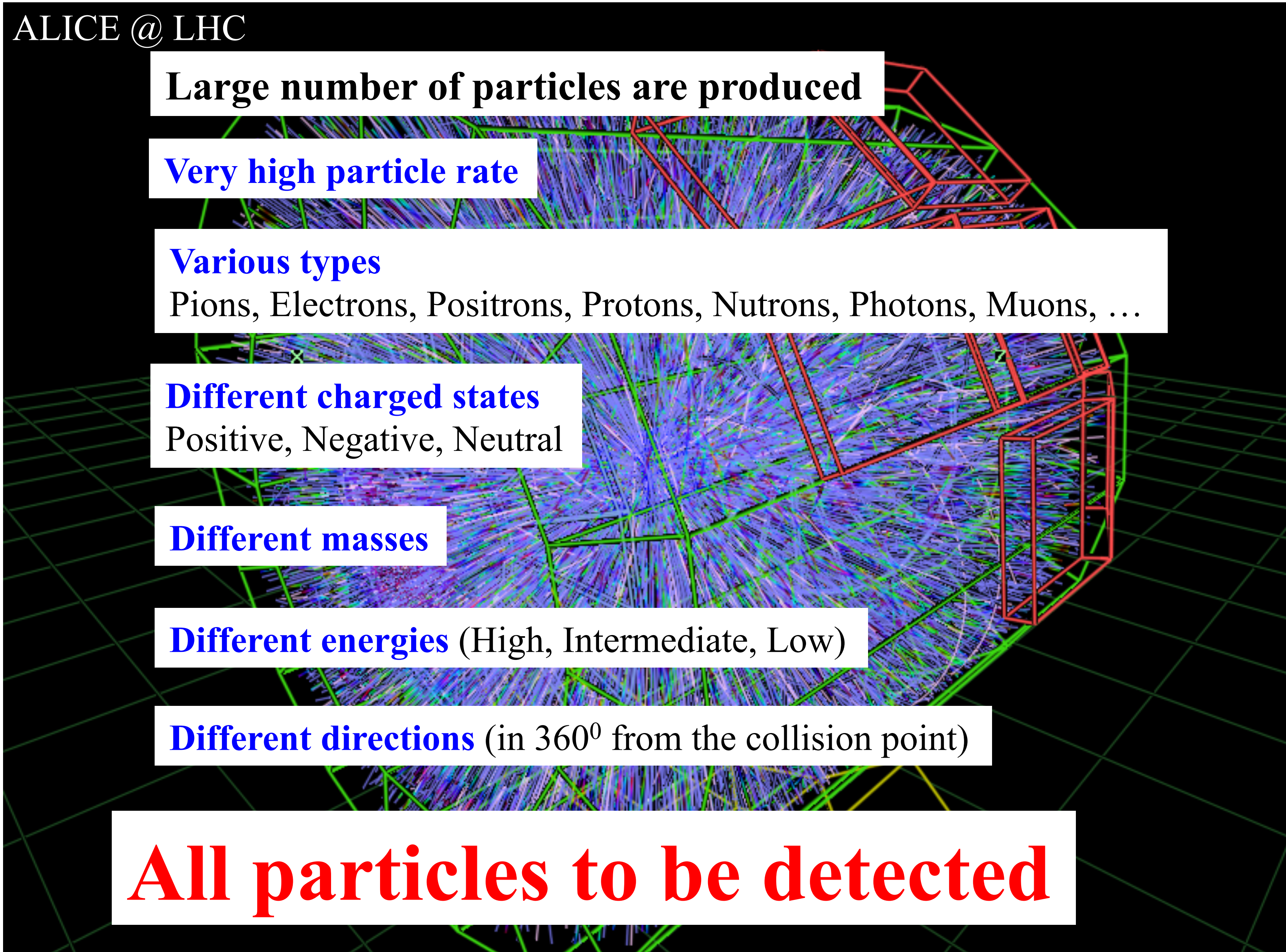
How ?

- Colliding two heavy ions at relativistic speeds
- Formation of QGP for a very short time in very short phase space followed by particle production



- Detect/measure the produced particles
- Study the particle behavior to extract information about the QGP


ALICE @ LHC



ALICE @ LHC

Large number of particles are produced

Very high particle rate

Various types

Pions, Electrons, Positrons, Protons, Nutrons, Photons, Muons, …

Different charged states

Positive, Negative, Neutral

Different masses

Different energies (High, Intermediate, Low)

Different directions (in 360^0 from the collision point)

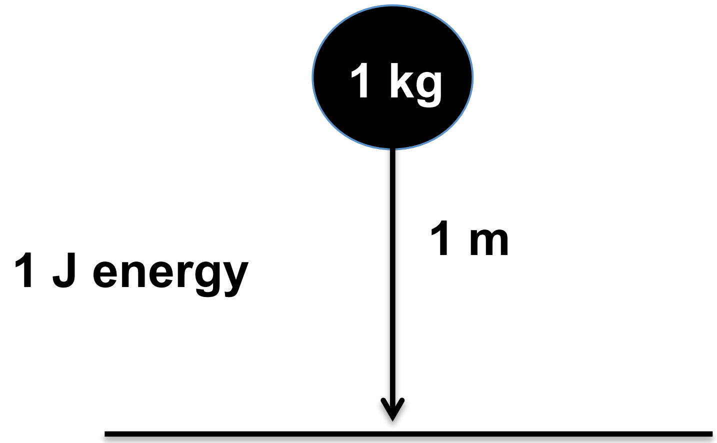
All particles to be detected

A well designed intelligent detection system required

Collisions energy: 13 TeV ??

1 eV = 1.602 x 10^{-19} J

keV = 10^{3} eV
MeV = 10^{6} eV
GeV = 10^{9} eV
TeV = 10^{12} eV



Total collisions energy of the world's most powerful accelerator = 13 TeV
= 13 x 10^{12} x 1.602 x 10^{-19} = **20.826 x 10^{-7} J**

Total Beam Energy

Each proton beam has **2808 bunches**
Each bunch contains **10^{11} protons**
Each proton has energy **7 TeV**

Total beam energy = 350 MJ

As energetic as **400 t train moving at 150 km/h**
This energy can **melt about 500 kg of Copper**

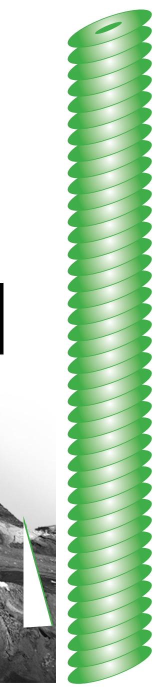
Collisions rate

600 million collisions per second

You can blink your eyes 2-3 times in a second

By the time you blink your eye
200 – 300 million collisions happen at LHC

CD stack with
1 year LHC data!
(~ 20 Km)



Data rate and data volume

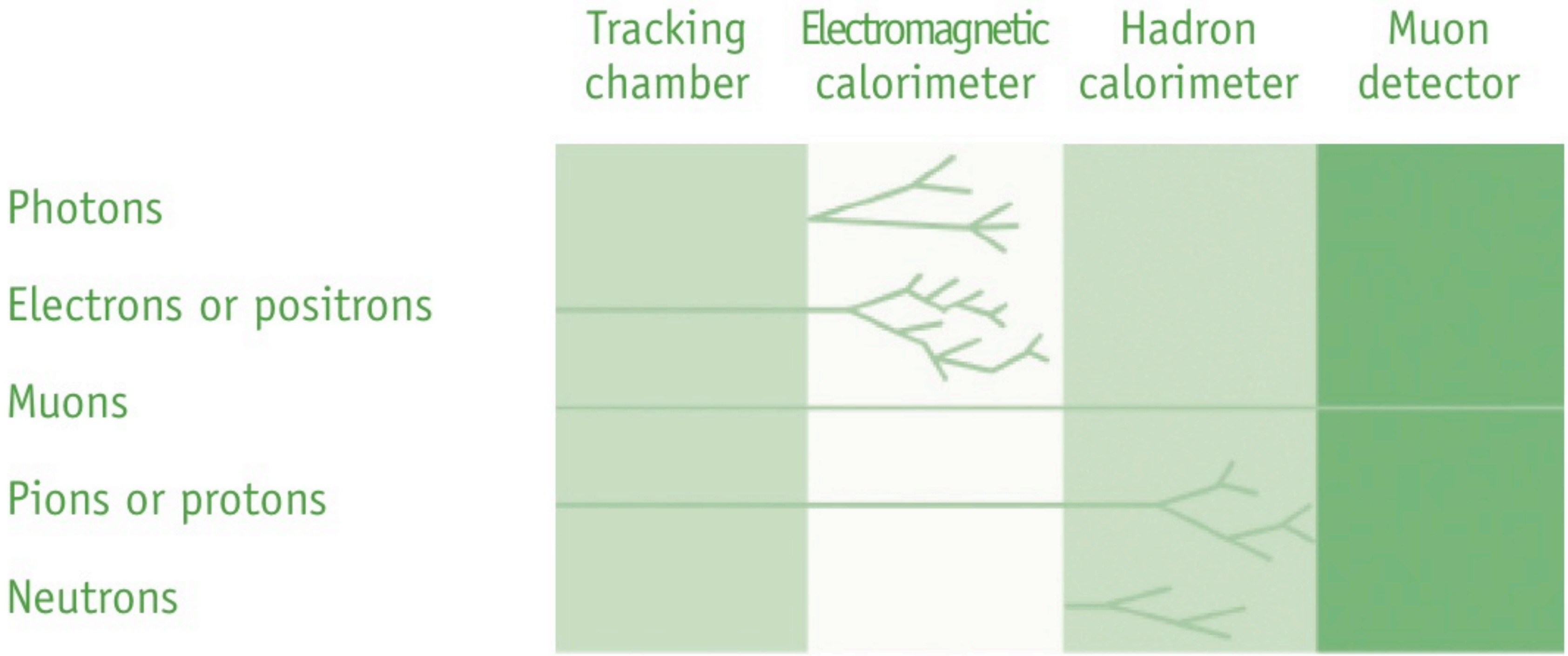
Data flow from four experiments = **700 MB / s**

Data volume in 1 year = 15 000 000 GB (**15 PB**)

Mount Everest 8.8 km

Detection of particles

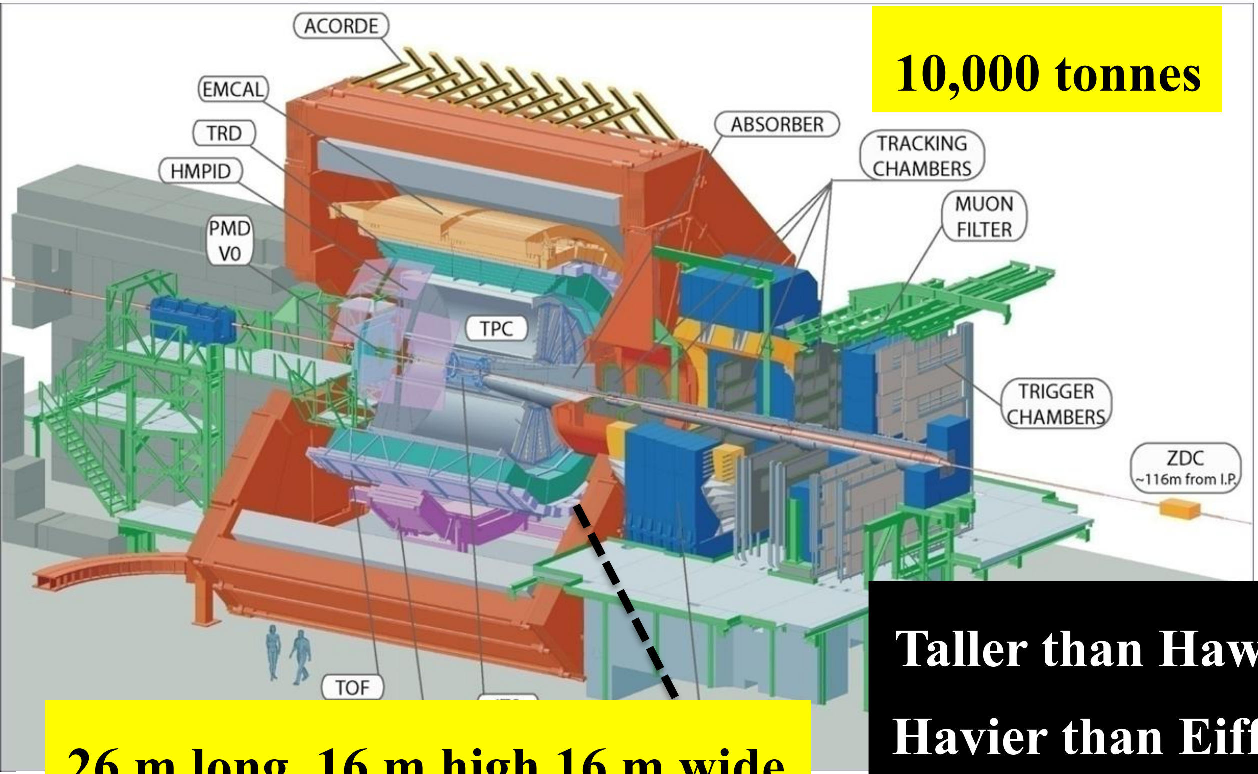
Experiments are designed including a group of sub-detectors



Detection techniques exploit the properties of particle interactions with the matter

Magnetic field is used for momentum determination

A Large Ion Collider Experiment (ALICE)



10,000 tonnes

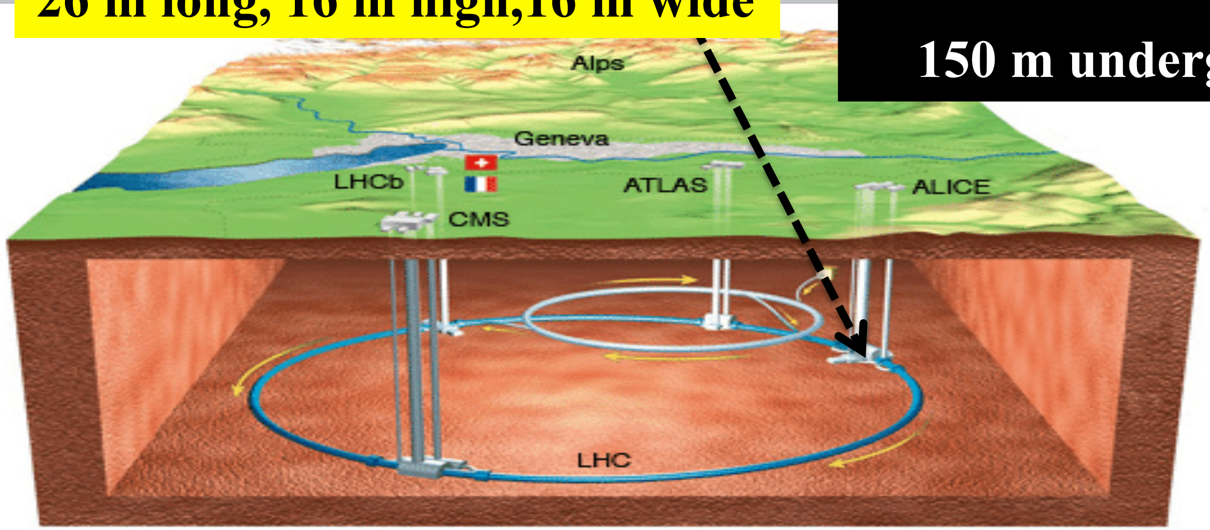
26 m long, 16 m high,16 m wide

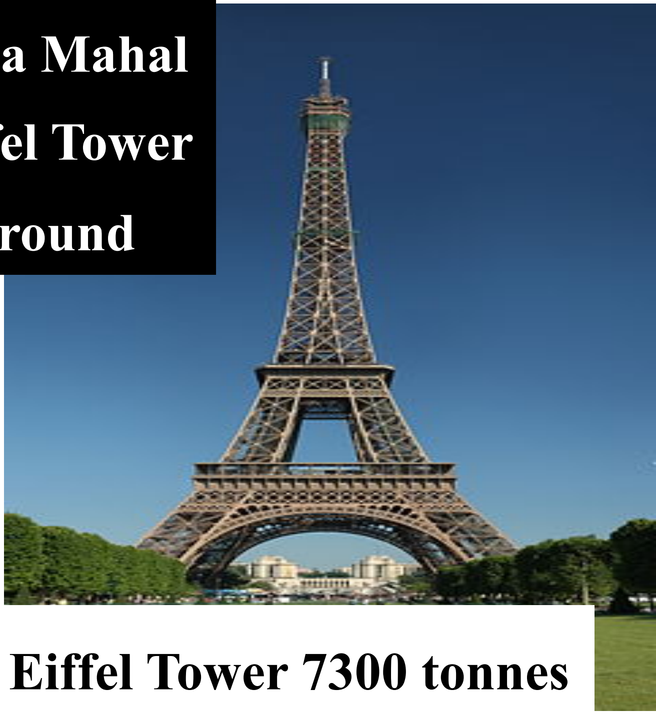
Hawa Mahal 15 m high

Taller than Hawa Mahal

Havier than Eiffel Tower

150 m underground





Eiffel Tower 7300 tonnes

ALICE: Dedicated heavy-ion experiment

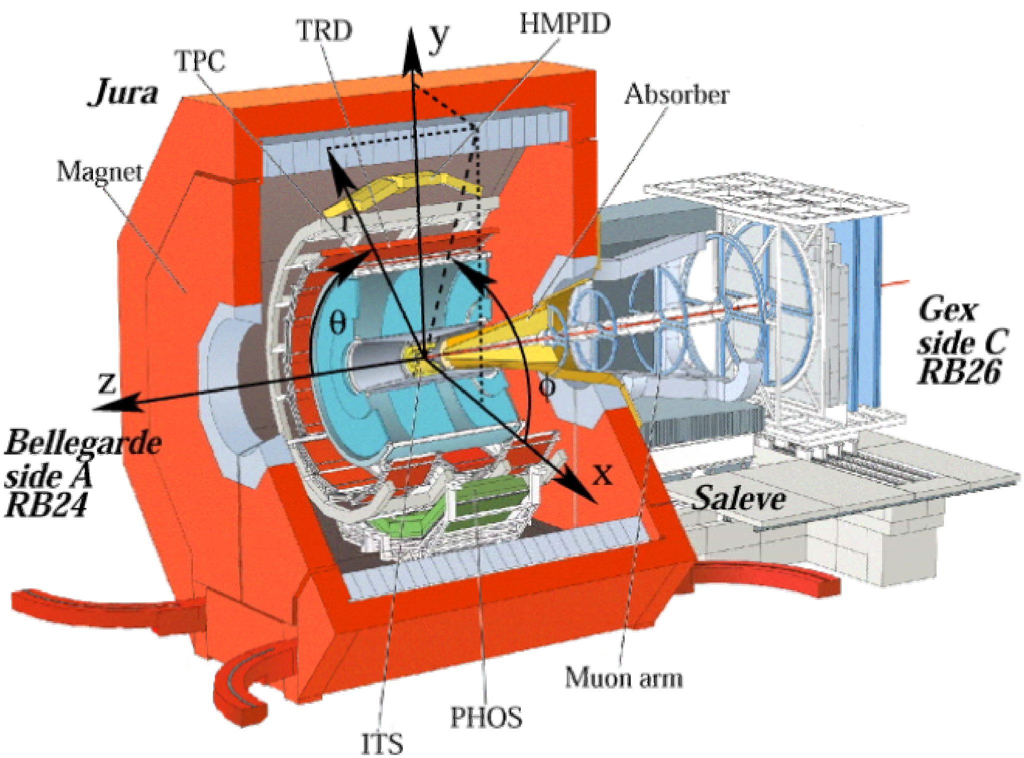
Main Physics goals

- Particle Multiplicity
- Particle spectra
- Particle correlations
- Flow and Fluctuations
- Jets
- Direct photons
- Dileptons
- Heavy quarks and quarkonia
- Ultra peripheral collisions
- Cosmic-ray physics

Jobs in hand

- Luminosity measurements
- Trigger selection
- Event selection
- Event characterization
- Tracking
- Hadron identification
- Electron identification
- Photon measurements
- Muon measurements
- Analysis

ALICE Coordinates: Right Handed Orthogonal Cartesian System



Point of origin: x = y = z = 0 (IP/IP2)

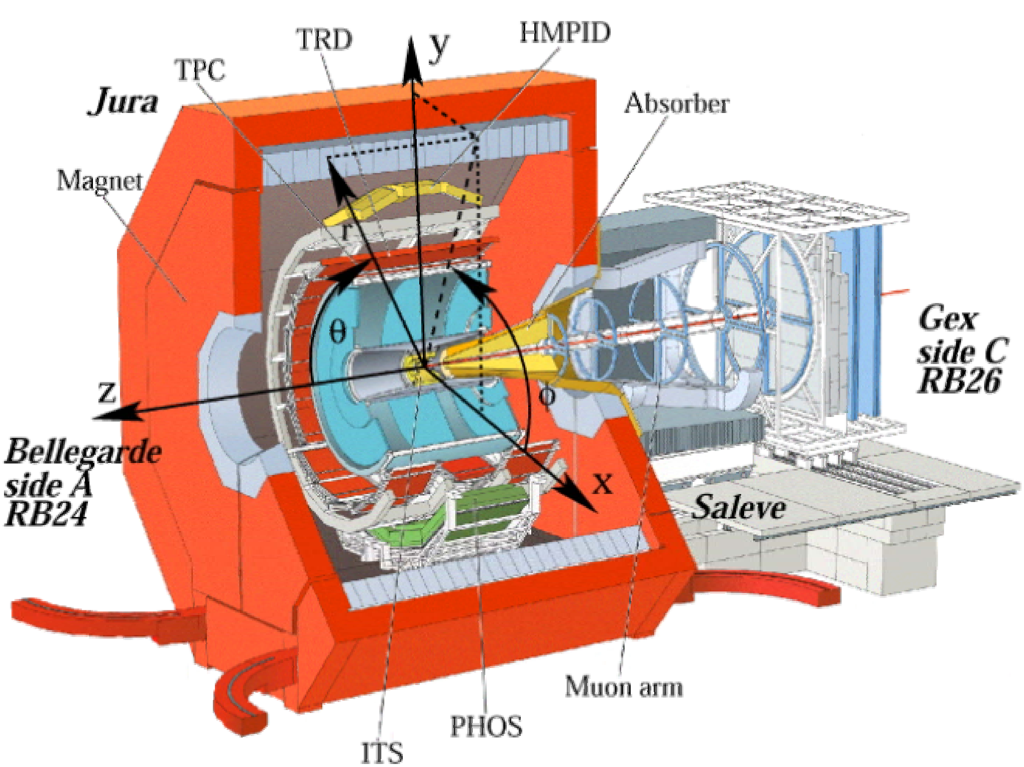
Z-axis: parallel to mean beam direction
+ve: From origin towards RB24 (town of Bellegrade, PMD-side)
-ve: From origin towards RB26 (town of Gex, Muon side)

Y-axis: perpendicular to beam direction pointing upward
+ve: upward from origin
-ve: downward from origin

X-axis: perpendicular to beam direction, aligned with local horizontal and pointing towards accelerator centre
+ve: towards accelerator centre from origin (Saleve side)
-ve: outward from origin (Jura side)

Detector sides:
A-side: towards +z,
C-side: towards –z,
B-side: around z = 0
I-side (Inner side): towards +x,
O-side (Outer side): towards -x
U-side (Up side): towards +y,
D-side (Down side): towards -y

ALICE Coordinates: Right Handed Orthogonal Cartesian System

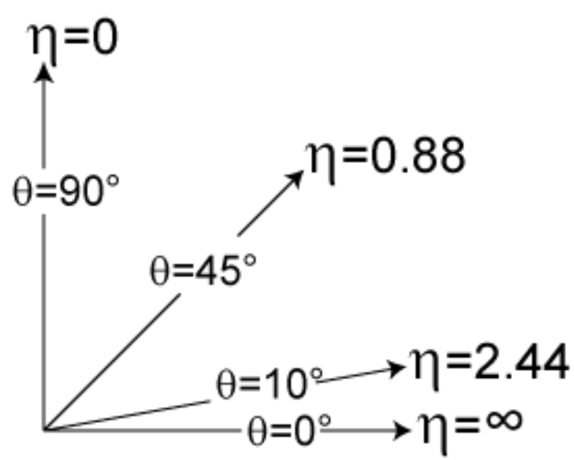


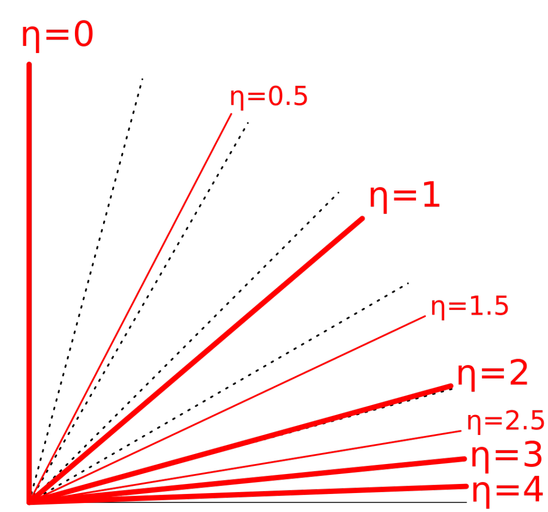
Point of origin: x = y = z = 0 (IP/IP2)

Polar angle (θ): Angle w.r.t. beam direction, increases from +z (θ=0) to x,y plane (θ=π/2) to –z(θ=π)

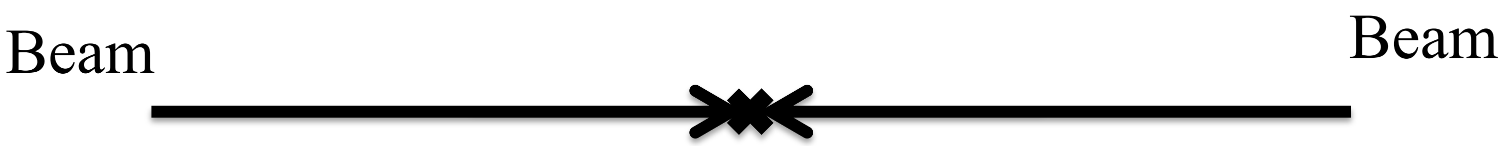
Azimuthal angle (ϕ): increases counter clock wise from x (ϕ=0) to y(ϕ=π/2) direction with observer at +z and looking towards RB26 (Muon side)

$$\eta = \frac{1}{2}\ln\left(\frac{|p| + p_L}{|p| - p_L}\right) = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$





Pseudorapidity (η) and Angle of azimuth (Φ)



$$\eta = \frac{1}{2}\ln\left(\frac{|p| + p_L}{|p| - p_L}\right) = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

where θ is the angle of emission
of particles w.r.t. beam axis

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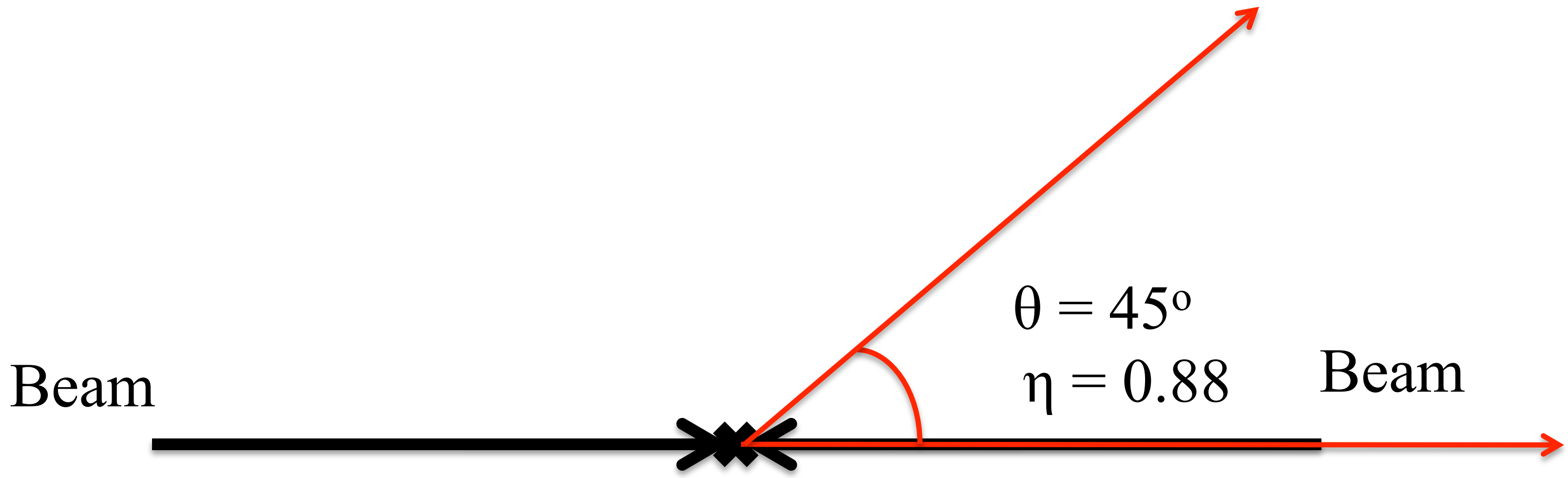

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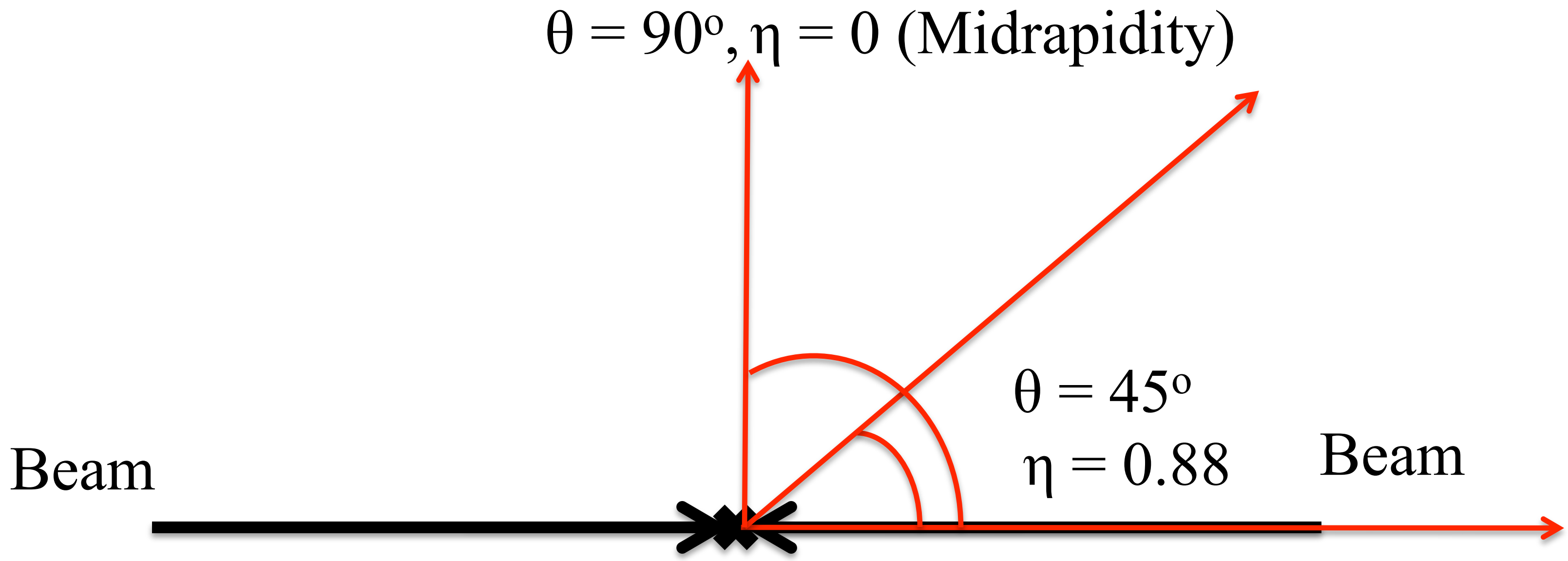

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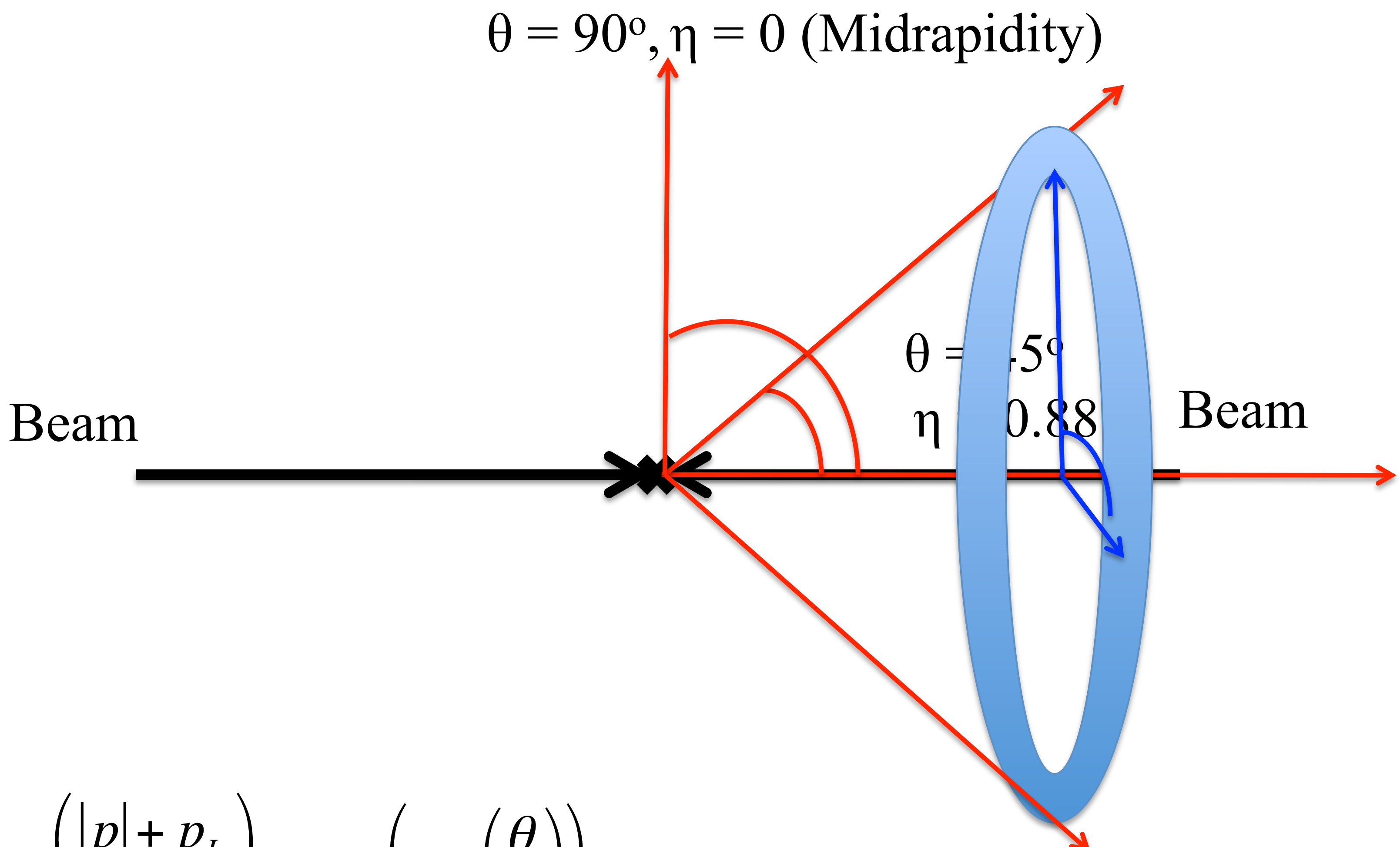
Pseudorapidity (η) and Angle of azimuth (Φ)

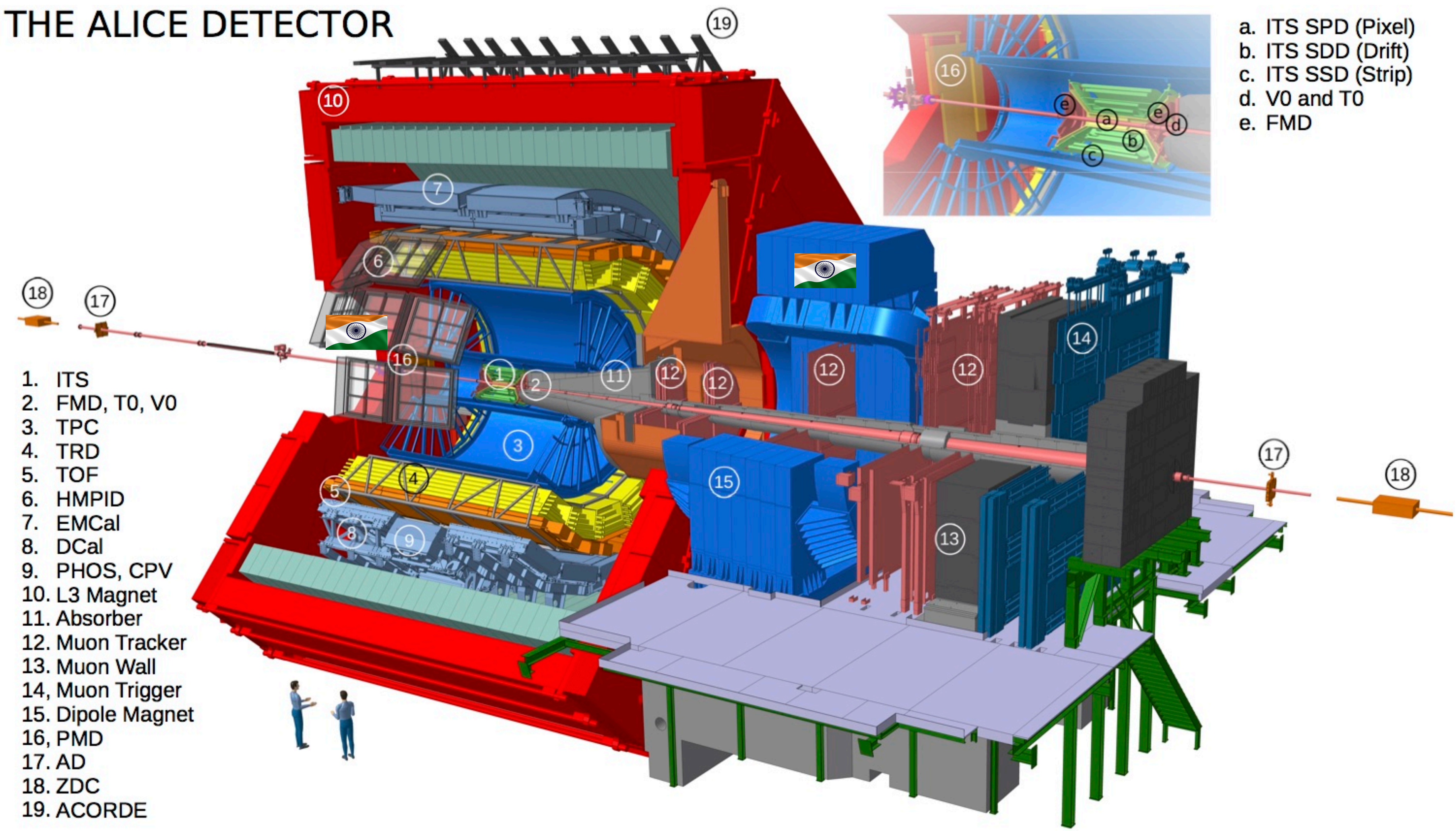


Angle of azimuth, $\Phi = 0$ to 2π

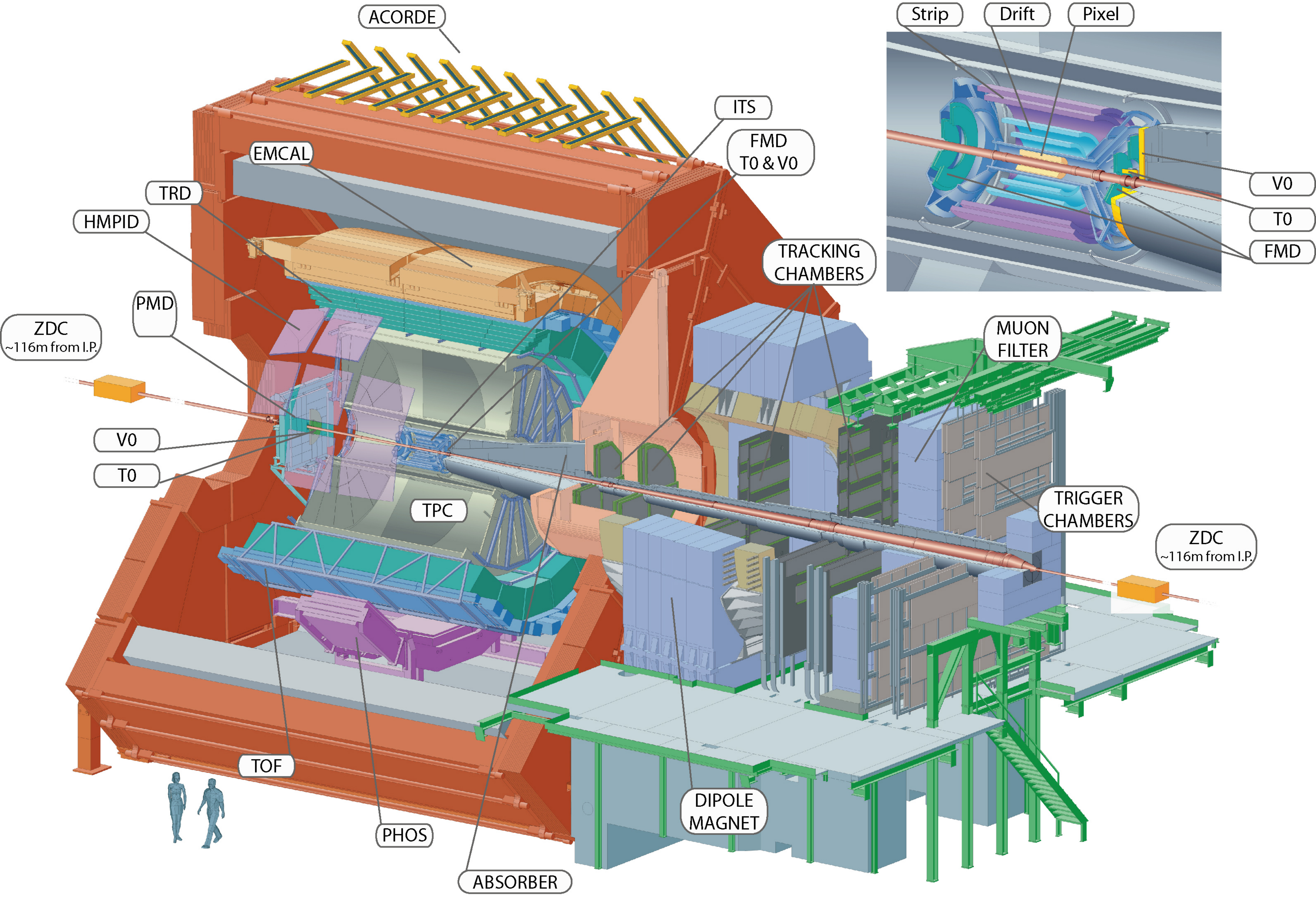
$$\eta = \frac{1}{2}\ln\left(\frac{|p| + p_L}{|p| - p_L}\right) = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

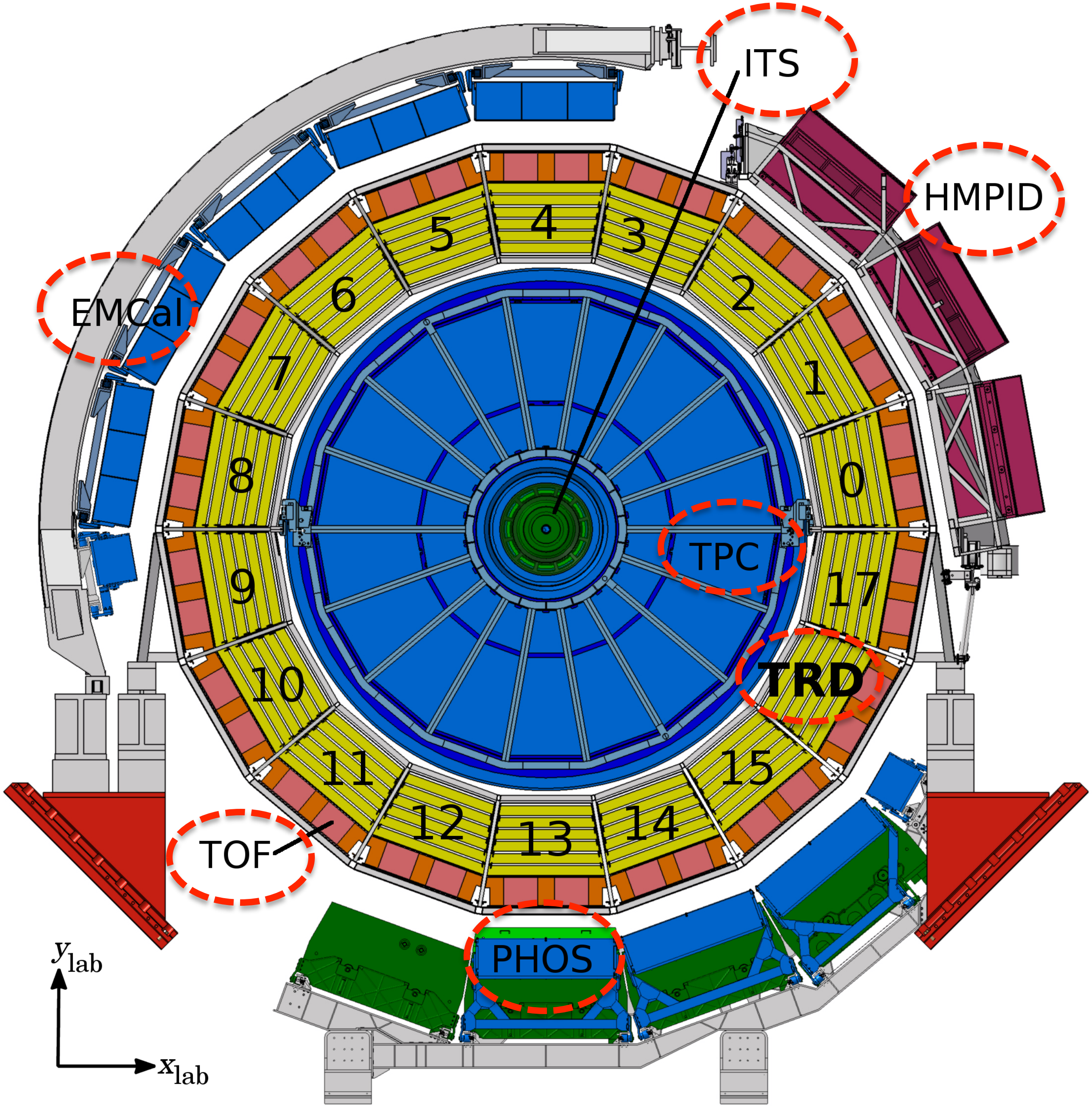
where θ is the angle of emission of particles w.r.t. beam axis

A Large Ion Collider Experiment (ALICE)



ALICE Detectors





ITS

TPC

TRD

TOF

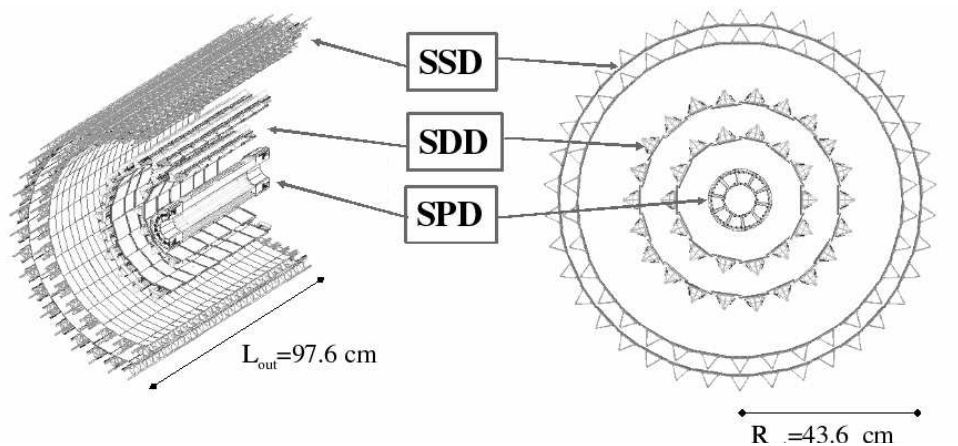
HMPID

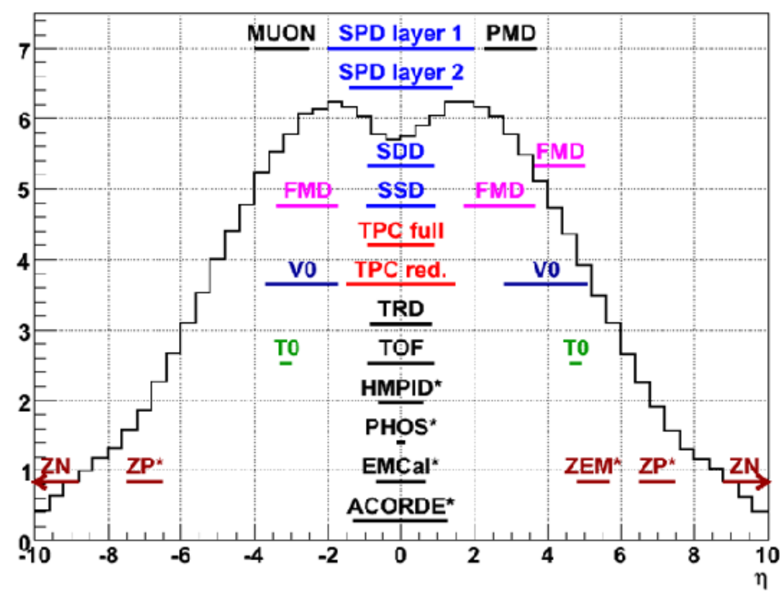
EMCal

PHOS

ALICE Detectors Summary: ITS

Detector	Technology	Purpose	Coverage		Position
			eta	phi	
ITS-SPD (2 layers)	Si-Pixel	Tracking, Vertex	|η| < 2.0 |η| < 1.4	Full Full	r = 3.9 cm r = 7.6 cm
ITS-SDD (2 layers)	Si-Drift	Tracking, PID	|η| < 0.9	Full Full	r = 15 cm r = 23.9 cm
ITS-SSD (2 layers)	Si-Strip	Tracking, PID	|η| < 1.0	Full Full	r = 38 cm r = 43 cm





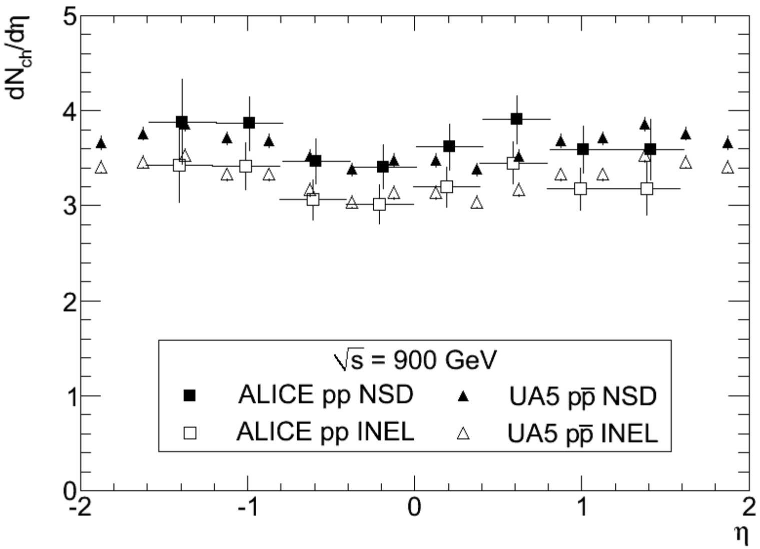
ALICE Detectors Summary: ITS

ITS Goals:

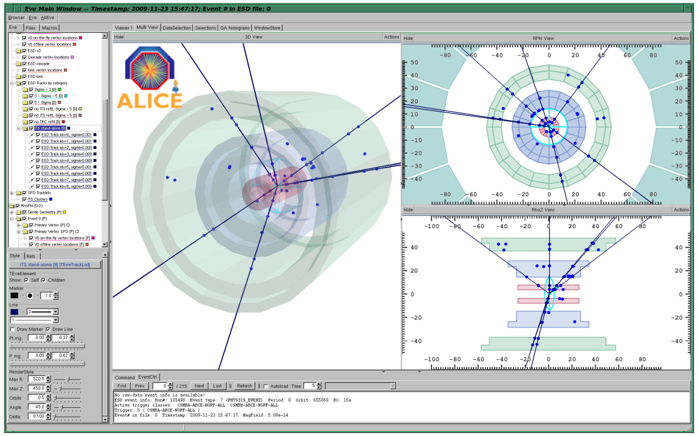
- To localize primary vertex with a resolution better than 100 μm
- To reconstruct the secondary vertex from the decay of hyperons, D-mesons, B-mesons
- Tracking and particle identification below 200 MeV/c
- To improve momentum and angle resolution of particles reconstructed by TPC
- To reconstruct particles traversing in dead regions of TPC

Momentum resolution: ~2% (for pions with momentum 100 MeV/c to 3GeV/c)

Spatial resolution: few ten of micro-meter



1[st] LHC paper by ALICE Nov 23[rd] 2009 (Measurement of the charged-particle pseudorapidity density at √s= 900 GeV)
284 events analyzed using SPD
https://arxiv.org/pdf/0911.5430.pdf



ALICE Detectors Summary

Detector	Technology	Purpose	Coverage		Position (cm)
			eta	phi	
TPC	Ne drift MWPC	Tracking, PID	$\|\eta\| < 0.9$	Full	r = 85 to 247
TRD	TR+Xe drift MWPC	Tracking, $e^{\pm}$ ID	$\|\eta\| < 0.8$	Full	r = 290 to 368
TOF	Quartz	PID	$\|\eta\| < 0.9$	Full	r = 370 to 399

TPC Goals:

- Main tracking detector
- Charged particle momentum measurement
- Particle identification
- Vertex measurement

0.1 GeV/c < p_T < 100 GeV/c

TRD Goals:

- Electron identification (>1 GeV/c where the pion rejection using dE/dx in TPC is insufficient
- Di-electron channel measurements
- Single-electron channel measurements
- Trigger:
  - Electron trigger
  - Hight-pT trigger
  - Charged jet trigger

TOF Goals:

Large area array for particle identification in the intermediate p_T range

Below 2.5 GeV/c for Pions and kaons and upto 4 GeV/c for protons

pi/K and p/K separation better than 3 Sigma

ALICE Detectors Summary

Detector	Technology	Purpose	Coverage		Position
			eta	phi	
HMPID	C_6F_{14} RICH +MWPC	PID	$\|\eta\|<0.6$	$1^0<\varphi<59^0$	r = 490 cm
ACORDE	Scintillator	Cosmics	$\|\eta\|<1.3$	$30^0<\varphi<150^0$	r = 850 cm

HMPID (High Momentum PID) goals:

- Inclusive measurements of identified hadrons at p_T >1 GeV/*c*.
- Enhance the PID capability of ALICE by enabling identification of charged hadrons beyond the momentum attainable in ITS, TPC and TOF.
- Enable π/K and K/p discrimination, on a track-by-track basis, up to 3 GeV/*c* and 5 GeV/*c*, respectively
- Identification of light nuclei and anti-nuclei (d, t, 3He, α) at high p_T.

ACORDE (Alice Cosmic Ray Detector) goals:

- Provides a fast (Level-0) trigger signal, for the commissioning, calibration and alignment procedures of some of the ALICE tracking detectors.
- In combination with the TPC, TRD and TOF, detection of single atmospheric muons and multi-muon events (so-called muon bundles) thus allowing us to study high-energy cosmic rays.

ALICE Detectors Summary

Detector	Technology	Purpose	Coverage		Position (cm)
			eta	phi	
PHOS	$PbWO_4$ (Pb-tungstate)	Photons	$\lvert\eta\rvert < 0.12$	$220^0<\phi<320^0$	r = 460 to 478
CPV	MWPC	Veto	$\lvert\eta\rvert < 0.12$	$220^0<\phi<320^0$	r = 460 to 478
EMCal	Pb+Scintillator	Photons/jets	$\lvert\eta\rvert<0.7$	$80^0<\phi<187^0$	r = 430 to 455

PHOS (Photon Spectrometer) Goals:

The main physics objectives are:

- test of thermal and dynamical properties of the initial phase of the collision extracted from low p_T direct photon measurements
- study of jet quenching through the measurement of high-p_T π^0 and γ-jet correlations.
- EMCal increases ALICE calorimeter coverage. It provides a fast and efficient trigger (L0, L1) for hard jets, photons and electrons. Enhance ALICE jet capability.

CPV (Charged Particle Veto) Goals:

- The CPV is placed on top of the PHOS modules at a distance of about 5 mm.
- The material budget is less than 5% of X_0. The active volume of 14 mm thickness is filled with a gas mixture 80% Ar/20% CO2 at a pressure slightly (1 mbar) above atmospheric pressure.
- Vetoing charged particles.

ALICE Detectors Summary

Detector	Technology	Purpose	Coverage		Position
			eta	phi	
ITS-SPD	Si-Pixel	Tracking, Vertex	$\|\eta\|<2.0$ $\|\eta\|<2.0$	Full Full	r = 3.9 cm r = 7.6 cm
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TPC	Ne drift MWPC	Tracking, PID	$\|\eta\|<0.9$	Full	r = 85 to 247 cm
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ACORDE	Scintillator	Cosmics	$\|\eta\|<1.3$	$30^0<\varphi<150^0$	r = 850 cm

ALICE Detectors Summary

Detector	Technology	Purpose	Coverage		Position
			eta	phi	
PMD	Pb + Proportional Counter	Photons	$2.3 < \lvert\eta\rvert < 3.9$	Full	z = 367 cm
FMD	Si-Strip	Charged particles	$3.6 < \lvert\eta\rvert < 5.0$ $1.7 < \lvert\eta\rvert < 3.7$ $-3.4 < \lvert\eta\rvert < -1.7$	Full Full Full	z = 320 cm z = 80 cm z = -70 cm
VZERO	Scintillator	Charged particles	$2.8 < \lvert\eta\rvert < 5.1$ $-3.7 < \lvert\eta\rvert < -1.7$	Full	z = 329 cm z = -88 cm
T0	Quartz	Time, vertex	$4.6 < \lvert\eta\rvert < 4.9$ $-3.3 < \lvert\eta\rvert < -3.0$	Full	z = 370 cm z = -70 cm
ZDC	W + Quartz Brass + Quartz Pb + Quartz	Forward neutrons Forward protons Photons	$\lvert\eta\rvert > 8.8$ $6.5 < \lvert\eta\rvert < 7.5$ $4.8 < \lvert\eta\rvert < 5.7$	Full $\lvert\phi\rvert < 10^0$ $\lvert 2\phi\rvert < 32^0$	z = ±113 m z = ±113 m z = ±7.3 m
MCH	MWPC	Muon tracking	$-4.0 < \eta < -2.5$	Full	-14.2 m < z < -5.4 m
MTR	RPC	Muon trigger	$-4.0 < \eta < -2.5$	Full	-17.1 m < z < -16.1 m

ALICE DETECTORS

Central Barrel Detectors:

Inner Tracker System (ITS):

01. Silicon Pixel Detector (SPD),
02. Silicon Drift Detector (SDD),
03. Silicon Strip Detector (SSD)
04. Time Projection Chamber (TPC)
05. Transition Radiation Detector (TRD)
06. Time Of Flight (TOF)
07. Photon Spectrometer (PHOS)
08. Charge Particle Veto Detector (CPV)
09. Electromagnetic Calorimeter (EMCAL)
10. High Momentum Particle Identification Detector (HMPID)
11. A Cosmic Ray Detector for ALCE (ACORDE)

Forward detectors:

12. Photon Multiplicity Detector (PMD)
13. Forward Multiplicity Detector (FMD)
14. VZERO (V0)
15. T0
16. Zero Degree Calorimeter (ZDC)
17. Muon Chamber (MCH)
18. Muon Trigger (MTR)
19. The ALICE Diffractive Detector (AD0)

Trigger detectors:

01. TRD
02. TOF
03. PHOS
04. EMCAL
05. ACORDE
06. VZERO
07. T0
08. ZDC
09. MTR

Trigger

What is trigger ?

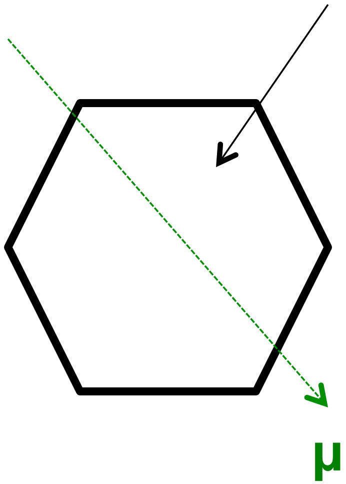
- Signal to enable start and end of data recording by the detectors.
- Detectors in ALICE do not record data on its own, they require a signal (trigger) to start and stop data recording.
- Detectors in proposed CBM experiment are self triggered, they do not any external trigger to start data recording.
- Trigger conditions dictate the detector which events to be recorded.

Why trigger is required:

- Trigger provides information about the collision to the detectors.
- Trigger helps detectors in selecting a fraction of interested events for analysis (jets, direct photons, high-multiplcity, etc.).
- Trigger helps in synchronizing the events to all detectors.

Trigger and data flow

Detector volume (in Active state)



Front End Electronic (FEE): collect generated signal, process it, digitize it, receive trigger and send digitized signal to readout unit

Readout unit: gather information from FEE, pass the data to DAQ, receive/distribute trigger signal, allow detector calibration

Data Acquisition: Collect data from Readout unit, and storage

ALICE Trigger System

Central Trigger Processor (CTP): Generate decision for ALICE based on detector signals and information about LHC filling scheme.

Hardware Level Trigger (Low Level Trigger):

- **Level-0 (L0):** made 0.9 us after the collision using V0, T0, EMCal, PHOS
- **Level-1 (L1):** made 6.5 us after L0 evaluating L0 accepted events

L0 and L1 trigger are sent to all detectors with a latency of 300 ns enable buffering of data by detector FEE

- **Level-2 (L2):** L2 decision is made after 100 us and triggers sending of event data to DAQ and HLT(High Level Trigger).

Input Information:

- Signal from detectors: Inform the CTP that event has happened
- LHC filling scheme: Used by CTP to suppress the background (MCMask tells if bunches are coming from both sides, or one of them or neither of them at a resolution of 25 ns. Beam-gas background are studied by triggering bunches without a collision partner).

ALICE Trigger System

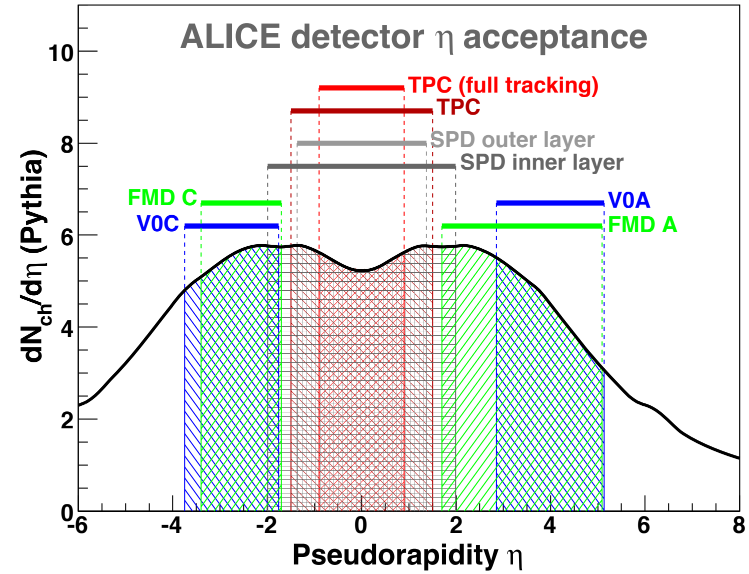
Detector	Function	Level
SPD	hit-multiplicity based trigger and hit-topology based trigger	L0
TRD	electron trigger, high-p_T particle trigger, charged-jet trigger	L1
TOF	multiplicity trigger, topological (back-to-back) trigger, cosmic-ray trigger	L0
PHOS	photon trigger	L0
EMCal	photon trigger, neutral-jet trigger	L0/L1
ACORDE	cosmic-ray trigger (single and multiple hits)	L0
V0	coincidence based minimum-bias interaction trigger, centrality trigger	L0
T0	event-vertex selection trigger, interaction trigger	L0
ZDC	minimum-bias interaction and electromagnetic-dissociation triggers in Pb–Pb	L1
MTR	single-muon trigger, dimuon trigger	L0

Minimum Bias Trigger: (V0 and SPD)

Trigger for collecting un-biased or minimal-biased events sample

MB_{OR}: Requiring a hit in the SPD or in either of the V0 detectors (high-efficiency suitable for low luminosity runs)

MB_{AND}: Requiring a hit in both V0A and V0C (high-purity)



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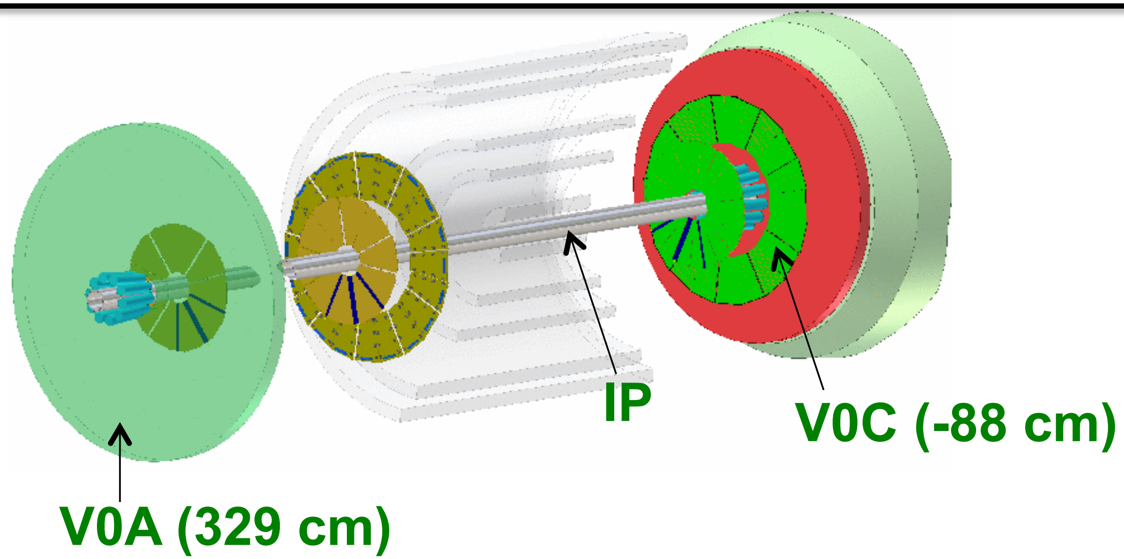
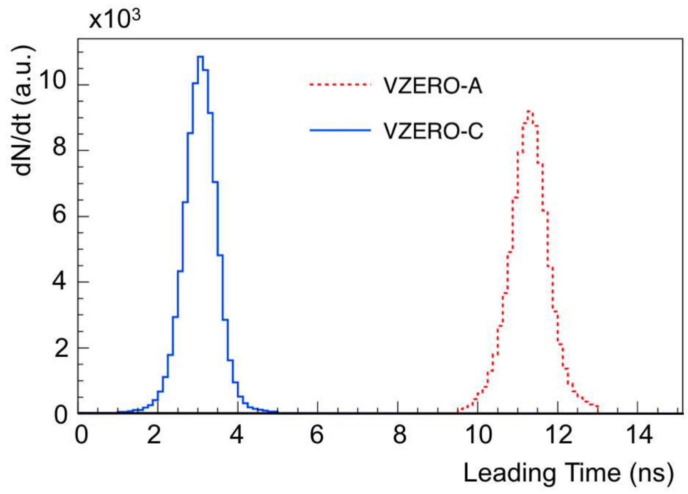
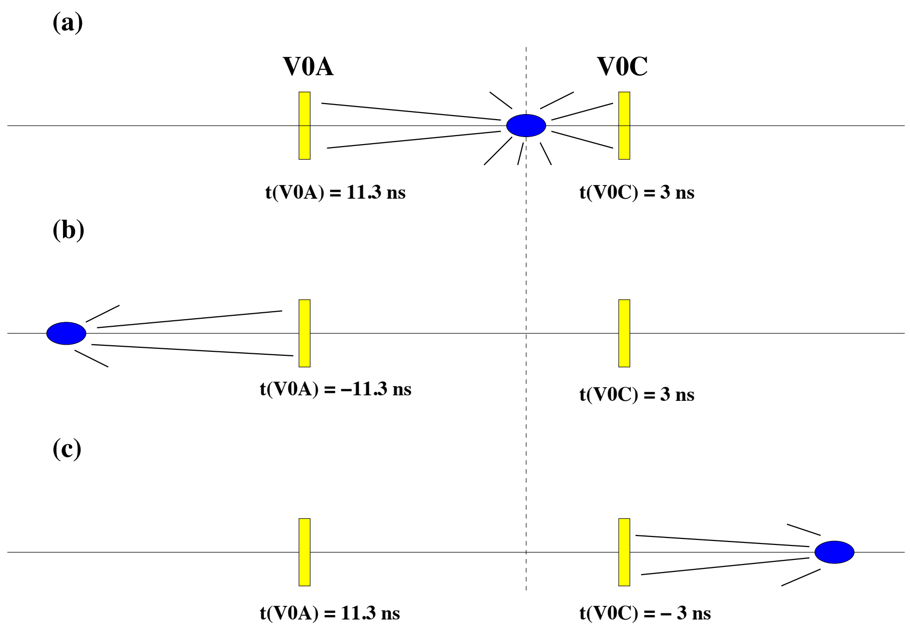
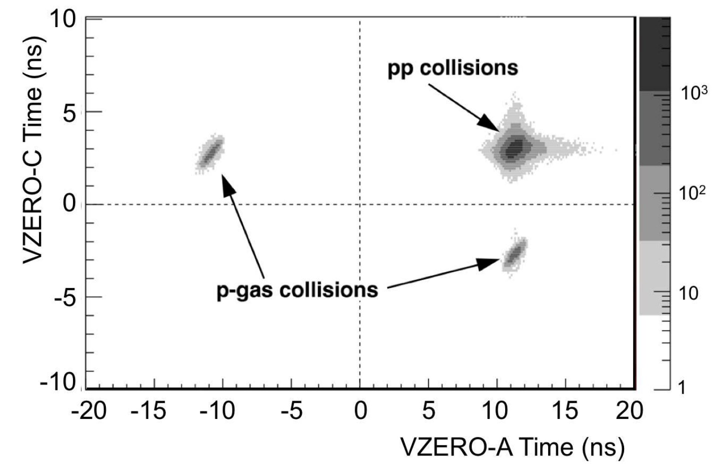








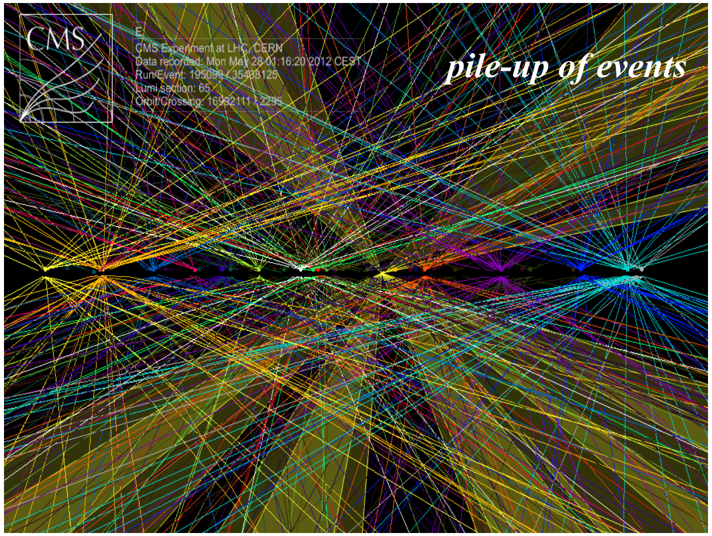
t_0 is the time when bunches cross the nominal IP

ALICE Trigger System

Trigger	Description	Condition
MB-type triggers		
MBor	minimum bias	signals in V0 and SPD
MBand	minimum bias	signals in V0A and V0C
MBZ	minimum bias	MB and signals in both ZDC's
SPI	multiplicity trigger	n hits in SPD
Centrality triggers		
CENT	central	V0 based centrality trigger for Pb–Pb (0–10%)
SEMI	semicentral	V0 based semicentral trigger for Pb–Pb (0–50%)
EMCal rare triggers		
E0	EMCal L0	EMCal L0 shower trigger in coincidence with MB
EJE	neutral jet	EMCal L1 jet algorithm following EMCal L0
EJE2	neutral jet	like EJE but with a lower threshold than EJE
EGA	photon/electron	EMCal L1 photon algorithm following EMCal L0
EGA2	photon/electron	like EGA but with a lower threshold than EGA
TRD rare triggers		
TJE	charged jet	n charged particles in TRD chamber in coincidence with MB
TQU	electron for quarkonia	electron with $p_T > 2$ GeV/c in TRD in coincidence with MB
TSE	electron for open beauty	electron with $p_T > 3$ GeV/c in TRD in coincidence with MB
MUON rare triggers		
MSL	single muon low	single muon in MTR in coincidence with MB
MSH	single muon high	like MSL but with a higher threshold
MUL	dimuon unlike sign	two muons above low threshold, unlike sign, in coincidence with MB
MLL	dimuon like sign	two muons above low threshold, same sign, in coincidence with MB
Miscellaneous triggers		
HM	high multiplicity	high multiplicity in SPD in coincidence with MB
PH	photon by PHOS	PHOS energy deposit in coincidence with MB
EE	single electron	electron signal in TRD (sector 6–8) and EMCal
DG	diffractive	charged particle in SPD and no signal in V0
CUP	barrel ultraperipheral	charged particle in SPD and no signal in V0, for Pb–Pb and p–Pb
MUP	muon ultraperipheral	(di-)muon in MTR and no signal in V0A, for Pb–Pb and p–Pb
ZED	electromagnetic dissociation	signal in any of the neutron ZDCs
COS	cosmic trigger	signal in ACORDE

Event pileup (Event overlap)

No pileup: One interaction per event
Pileup: More than one interaction per event



In bunch pileup: multiple interactions in one event from same bunch crossing

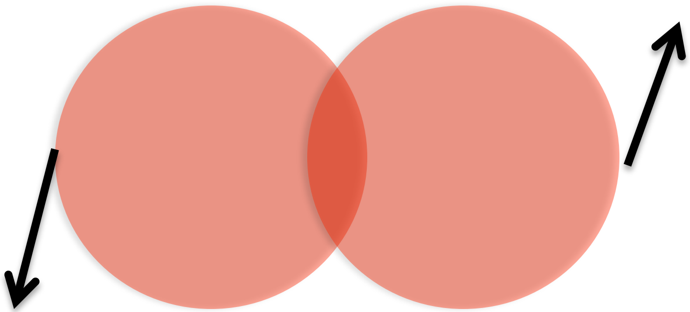
Out-of-bunch pileup: multiple interactions in one event from different bunch crossings

Pileup depends on Beam parameters such as bunch spacing, μ (number of interactions per bunch crossing), and detector integration time.

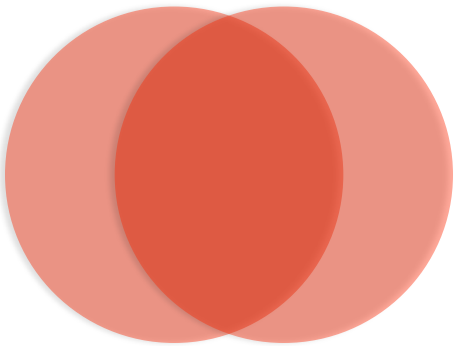
Pileup is minimized by adjusting beam parameters.

During the analysis one way of rejecting pileup events is by looking for multiple vertices.

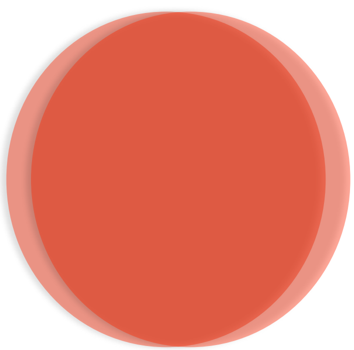
Collision Geometry



Peripheral collision ($b = \sim b_{max}$)

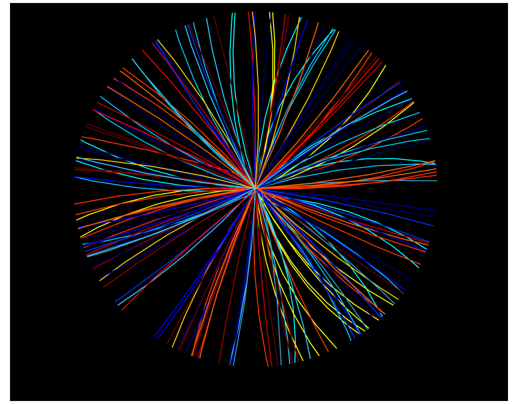


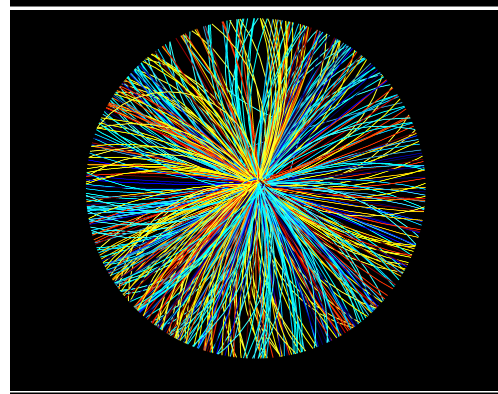
Mid central collision

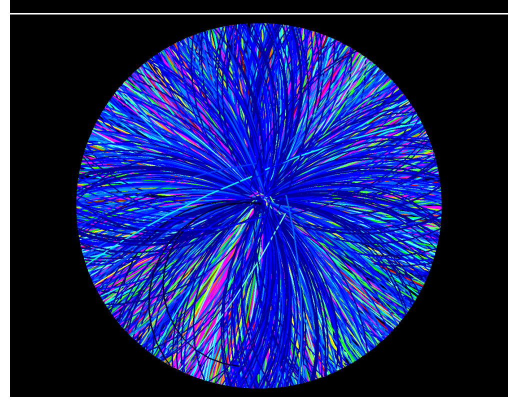


Central collision ($b = \sim 0$)

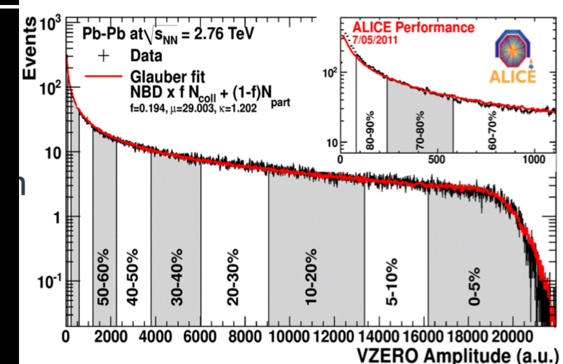
PbPb collisions at 2.76 TeV per nucleon pair







Collision centrality is determined based on multiplicity



Event Characterization

Centrality:

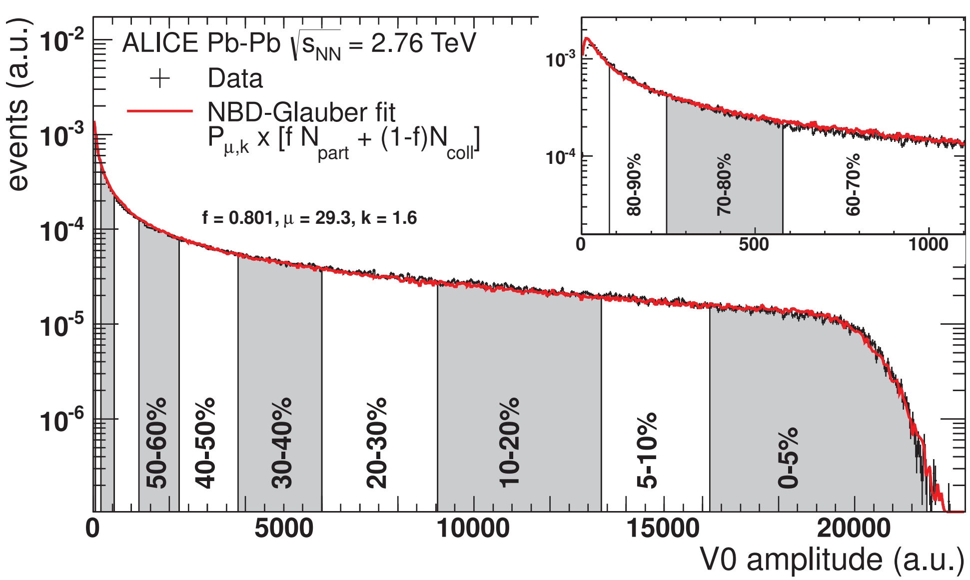
Centrality is expressed in terms of percentage of total hadronic cross section.

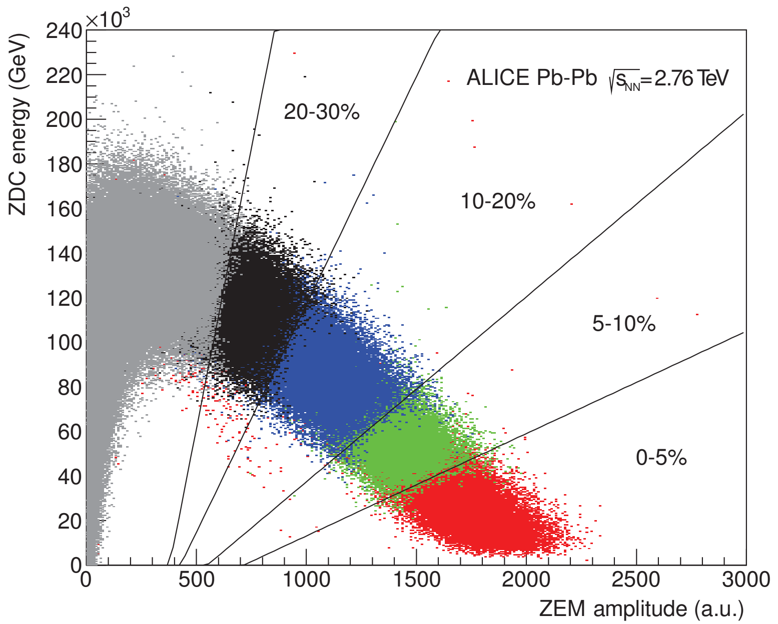
$$c(b) = \frac{\int_0^b \frac{d\sigma}{db'} db'}{\int_0^\infty \frac{d\sigma}{db'} db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} \, db' \, .$$

Central collisions: Impact parameter b = 0

Peripheral collisions: Large impact parameter

Experimentally it is measured as a fraction of total number of events.

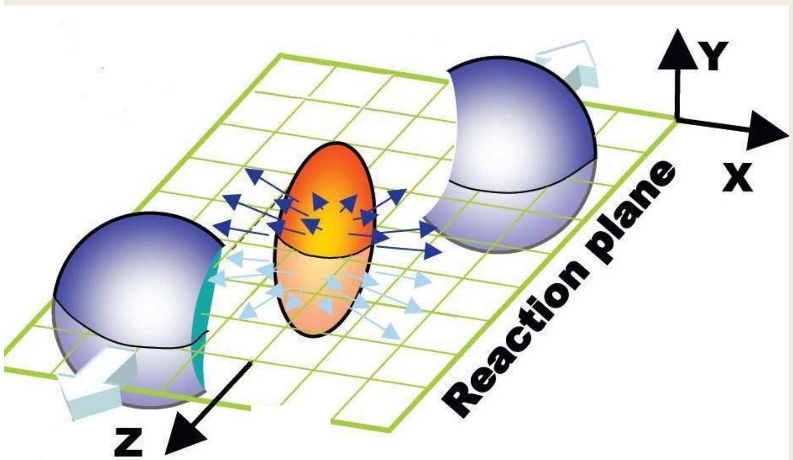


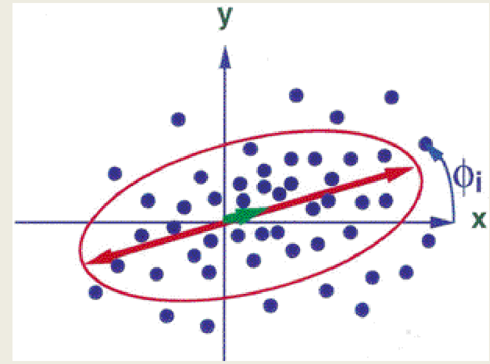


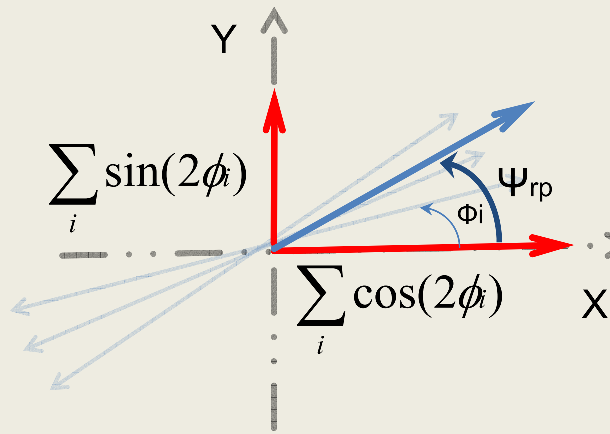
Event Characterization: Event Plane

Reaction plane estimation (Ψ_{rp})

Reaction plane is spanned by the impact parameter vector and the beam direction.
Ψ_{rp}, angle of azimuth of the reaction plane







Reaction plane – Experimentally unknown.
It is estimated from the azimuthal distribution of particles itself also known as "Event Plane"

$$\Psi_{rp} = \frac{1}{2}\tan^{-1}\left(\frac{\sum_i \sin(2\phi_i)}{\sum_i \cos(2\phi_i)}\right)$$

17

Detectors used:

TPC

V0

FMD

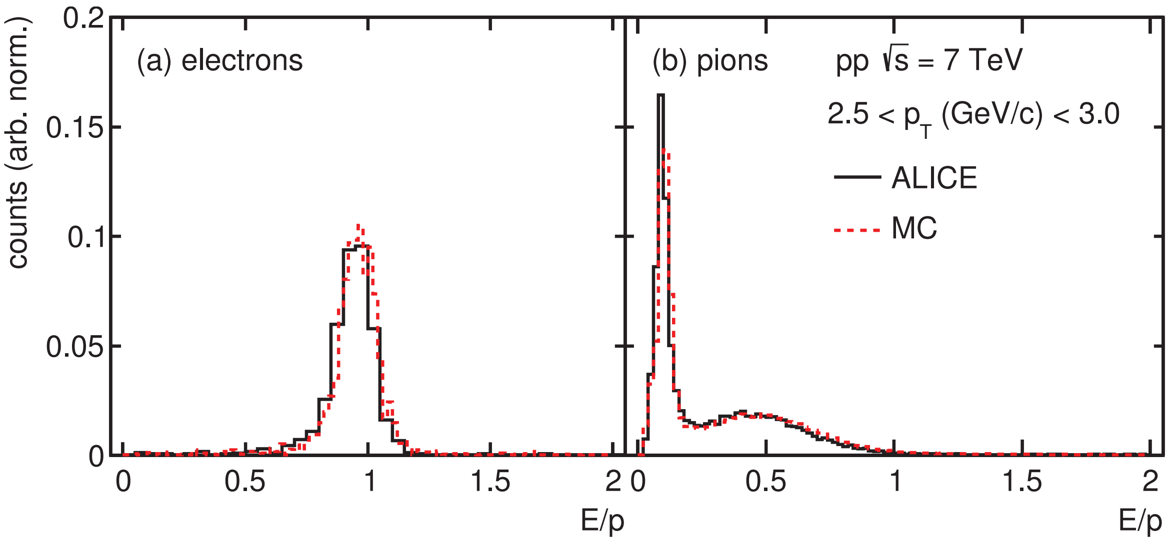
PMD

Electron Identification

In addition to ITS TPC TOF electron identification capability of ALICE is enhanced by TRD, EMCAL and PHOS.

TRD: Measures electrons based on TR and dE/dx

EMCal and PHOS: Measures electrons based on energy deposition and comparing it to measured track momentum



Electron: Peak at E/p ~ 1
Pions: Peak at E/p ~ 0.1

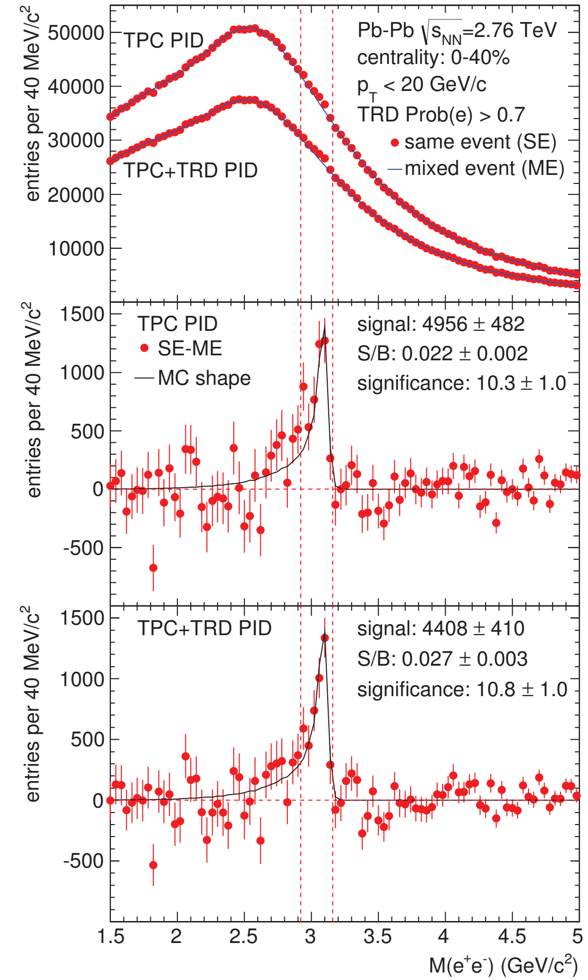
Electron selection is achieved by imposing a cut on E/p value.

Electron Identification

Electron trigger:

TRD: Provides electron trigger at intermediate p_T (2-5 GeV) suited for dilepton measurements including quarkonia.

EMCal and PHOS: Provides trigger for high pT electrons measurements (decay from heavy flavors).



Invariant mass distribution of J/ψ with and without TRD

Improvement of **20%** in signal-to-background ratio by using TRD information.

What do you understand by Signal-to-background ?

Photon Identification

Photon Identification

Neutral particle, tracking system can't detect it.

Detected primarily by reconstructing electromagnetic showers in EMCal and PHOS

Material budget along the particle path: $20X_0$

Sufficient to deposit full energy of photons, electrons and positrons.

Calorimeters are transparent to hadrons and muons. Why ?

Radiation length (X_0) and Nuclear Interaction length (λ_0) ?

Photon Identification:

- Identify clusters in EMCal/PHOS and check that there is no reconstructed tracks near it.
- Contamination from hadronic showers can be rejected based on shower shape parameters
- Neutral meson decay contributions can also be minimized used shower shape and invariant mass distribution.
- Showers produced by single photons, and hadrons, and photons from decay of high p_T π^0 are different.

Photon Identification

Imposing a suitable condition on invariant mass distribution of photons one can discriminate/select π^0 candidates for photon/π^0 measurements.

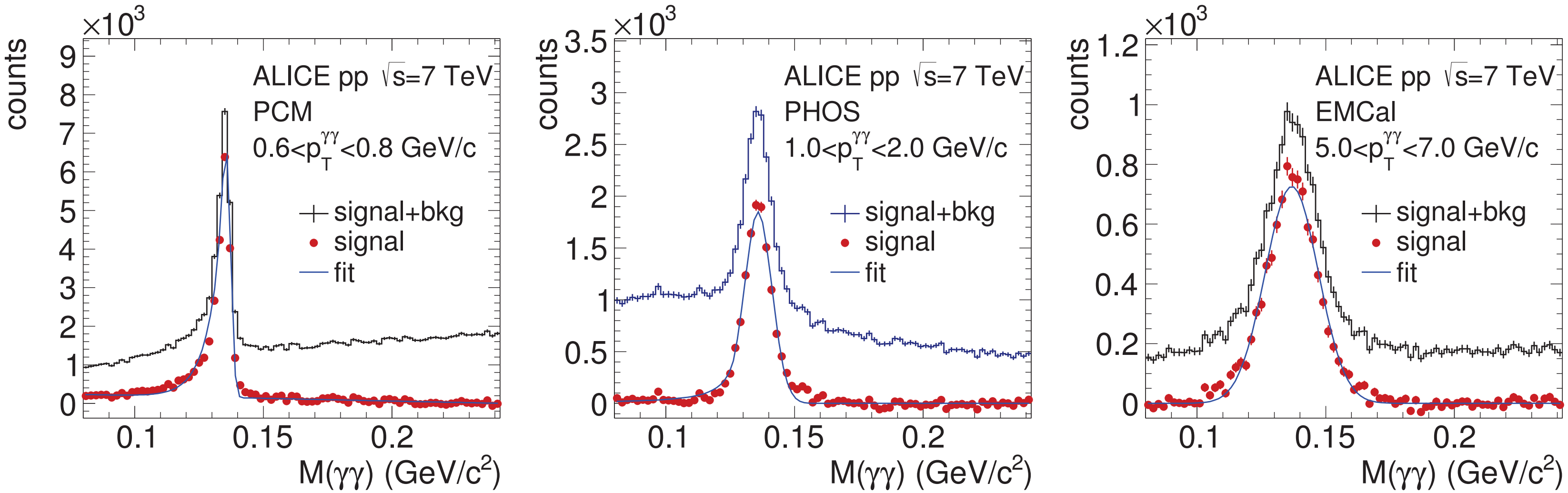


Fig. 68. Invariant mass spectra of photon candidate pairs for pp collisions at 7 TeV by PCM, PHOS and EMCal.

Jet Measurements

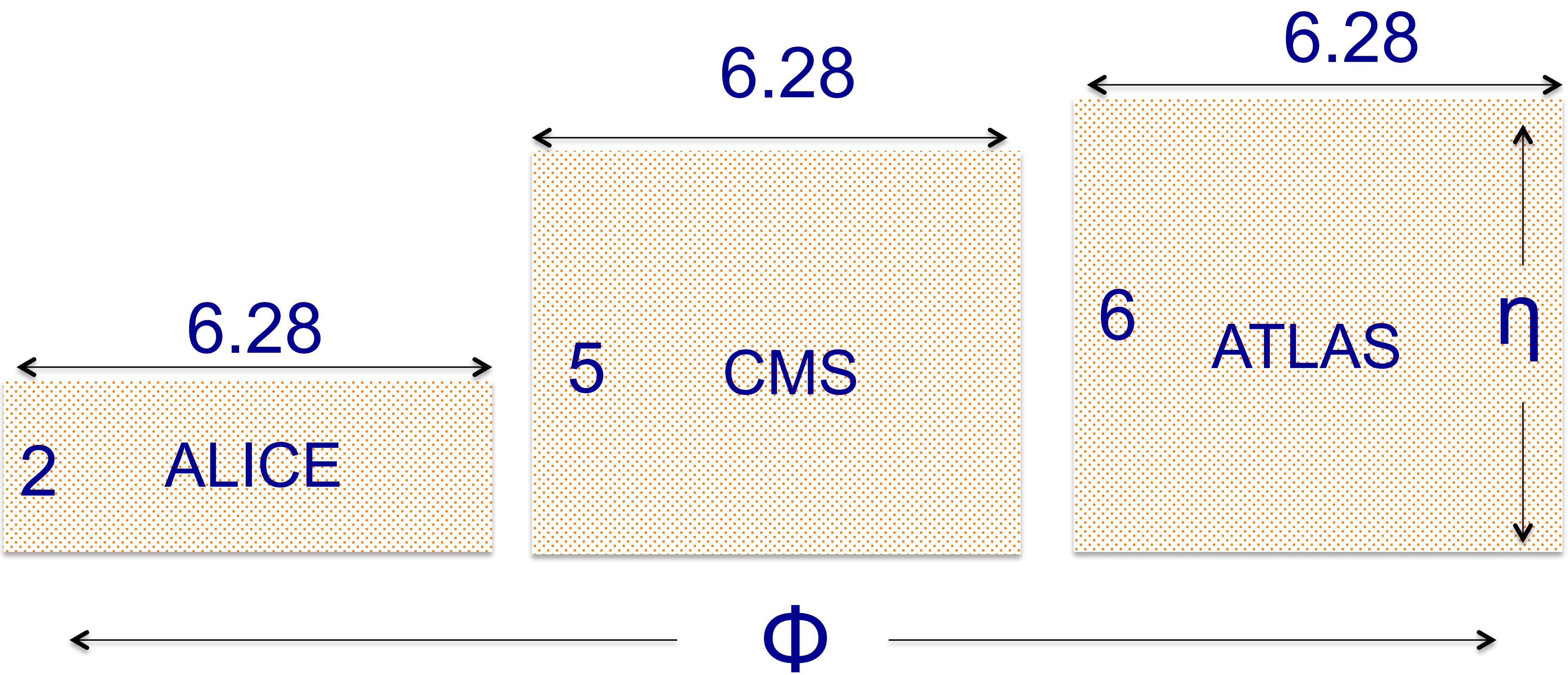
Jet measurements in relativistic nuclear collisions are of particular interest due to the phenomenon of "jet quenching"

An energetic parton interacts with the color-charged, hot and dense matter prior to its fragmentation into hadrons.

This interaction modifies the hadronic structure and transverse momentum of jets generated in the medium relative to those in vacuum, producing a variety of phenomena that are observable experimentally and can be calculated theoretically.

Measurements of jet quenching thus provide unique information on the properties of hot QCD matter.

Coverage: Detector Acceptance



Coverage: Kinematic reach

	Mag. field	Track p_T (GeV/c)	Jet p_T (GeV/c)	|Jet eta|
ALICE	0.5 T	> 0.150	< 110	< 0.5
CMS	3.8 T	> 1.0	< 2000	< 2.5
ATLAS	2.0 T	> 0.300	< 600	< 2.8

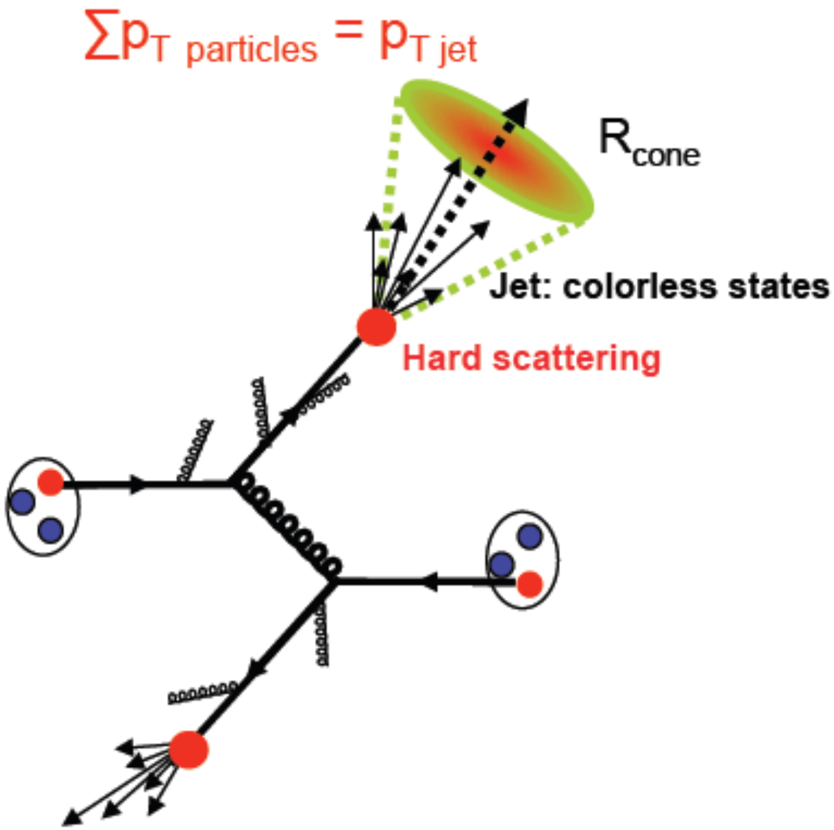
Fragmentation function, pT (particle) / pT (jet) ??

ALICE: 0.150 / 100 = 1.5×10^{-3}

ATLAS: 0.300 / 100 = 3.0×10^{-3}

CMS: 1.0 / 100 = 1.0×10^{-2}

Jet definition



❖**Jet:** a collimated spray of particles originating from the fragmentation of hard scattered partons in pp (or in A-A) collisions [*]

[*] S. D. Ellis, Z. Kunszt and D. E. Soaper Phys. Rev. Lett. 69 3615 (1992)

Jets: Connection between theory and experiment

Jets are the experimental tools for understanding the parton kinematics

pQCD: partonic level

Experiments measure hadrons.

Re-associate measurable hadrons to accurately reconstruct parton kinematics.

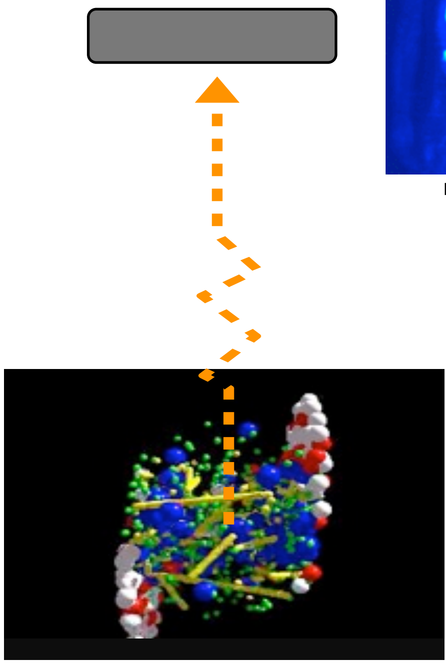
Tools: jet finding algorithms. Apply same algorithm to data and theoretical calculations.

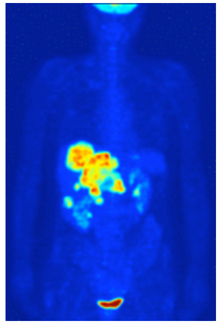
Jets provide

- a proxy for high p_T partons produced in collisions
- an experimental tool for measuring the parton kinematics
- an important tool to test pQCD

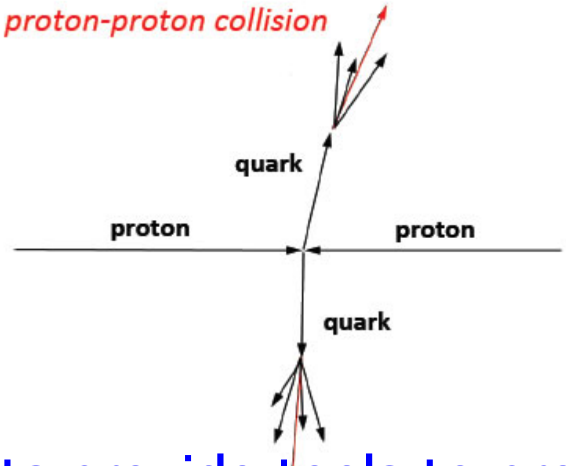
Jets: Probing the medium

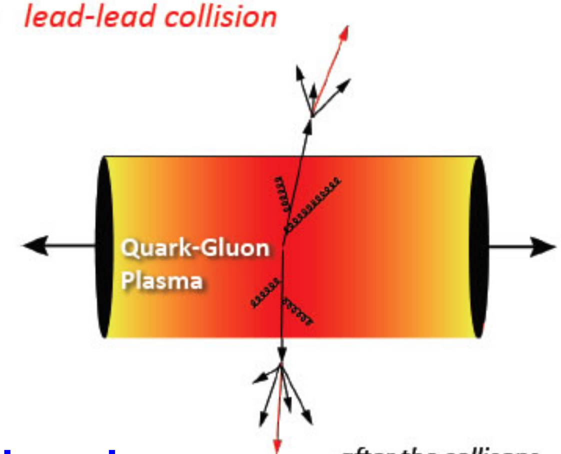
Detector





Human body

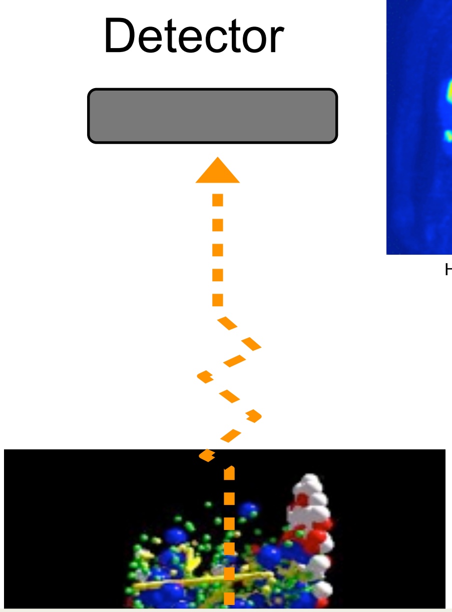


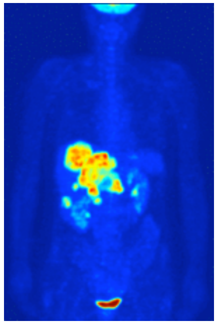


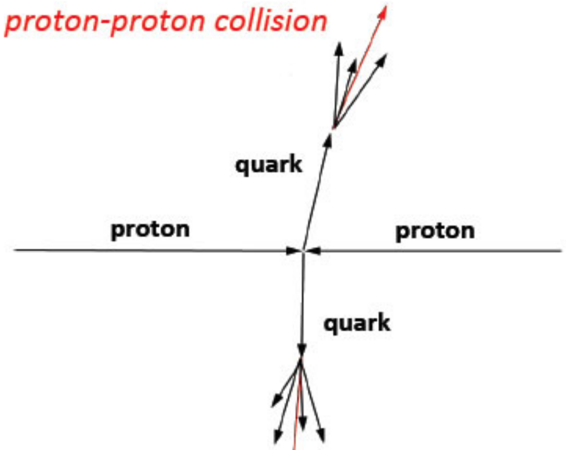
Jets provide tools to probe the medium formed in heavy ion collisions

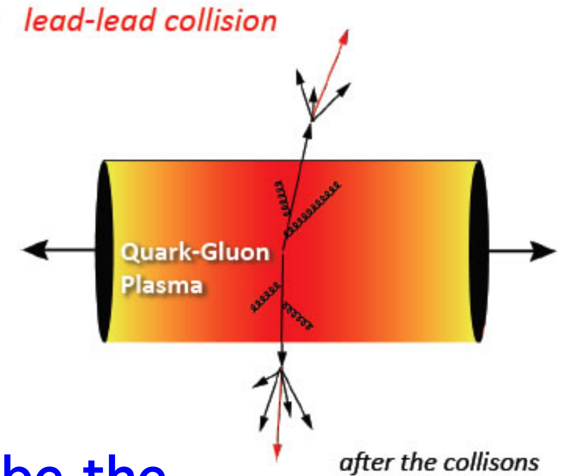
Self generated hard probes in the early stage of the collision

Jets: Probing the medium

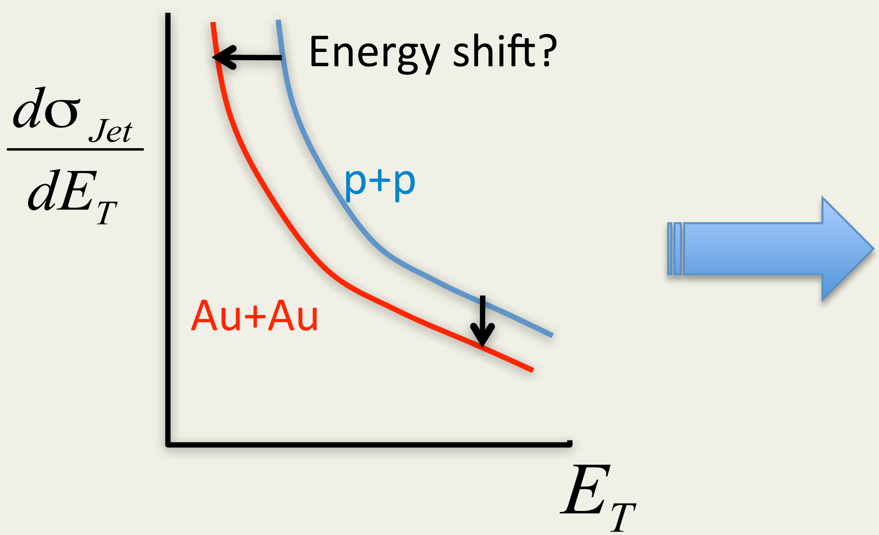


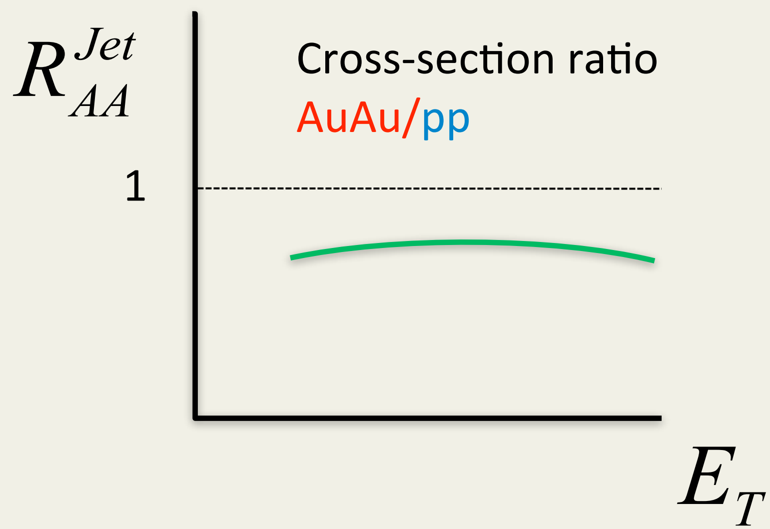

Human body





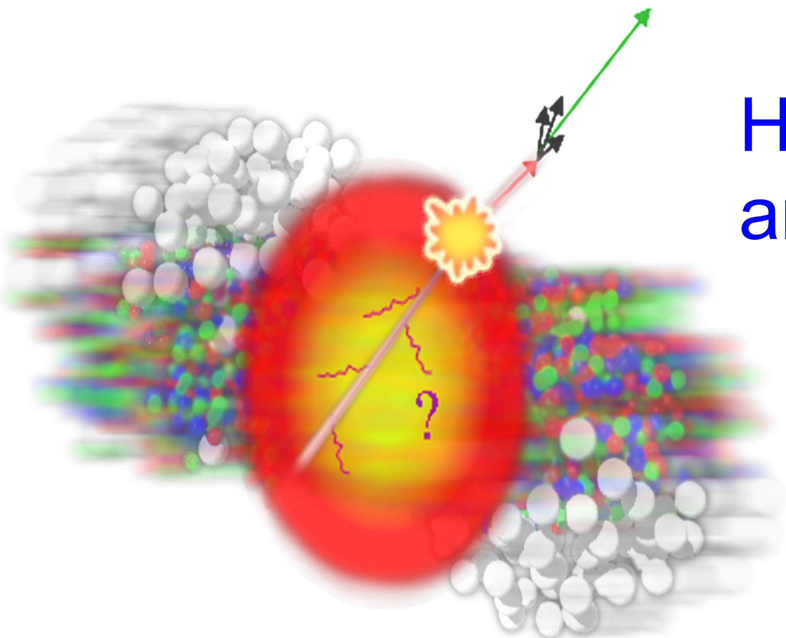
Jets provide tools to probe the medium formed in heavy ion collisions





Jets: Probing the medium

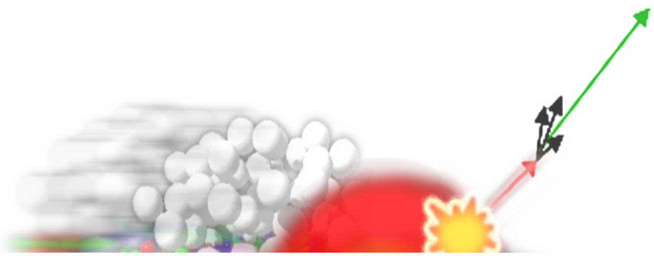
Jet in medium: **Jets yield suppressed, Suppression is more at LHC compared to RHIC, Jets loose energy in the medium**



How is the energy redistributed around the jet ??

Jets: Probing the medium

Jet in medium: **Jets yield suppressed, Suppression is more at LHC compared to RHIC, Jets loose energy in the medium**



How is the energy redistributed around the jet ??

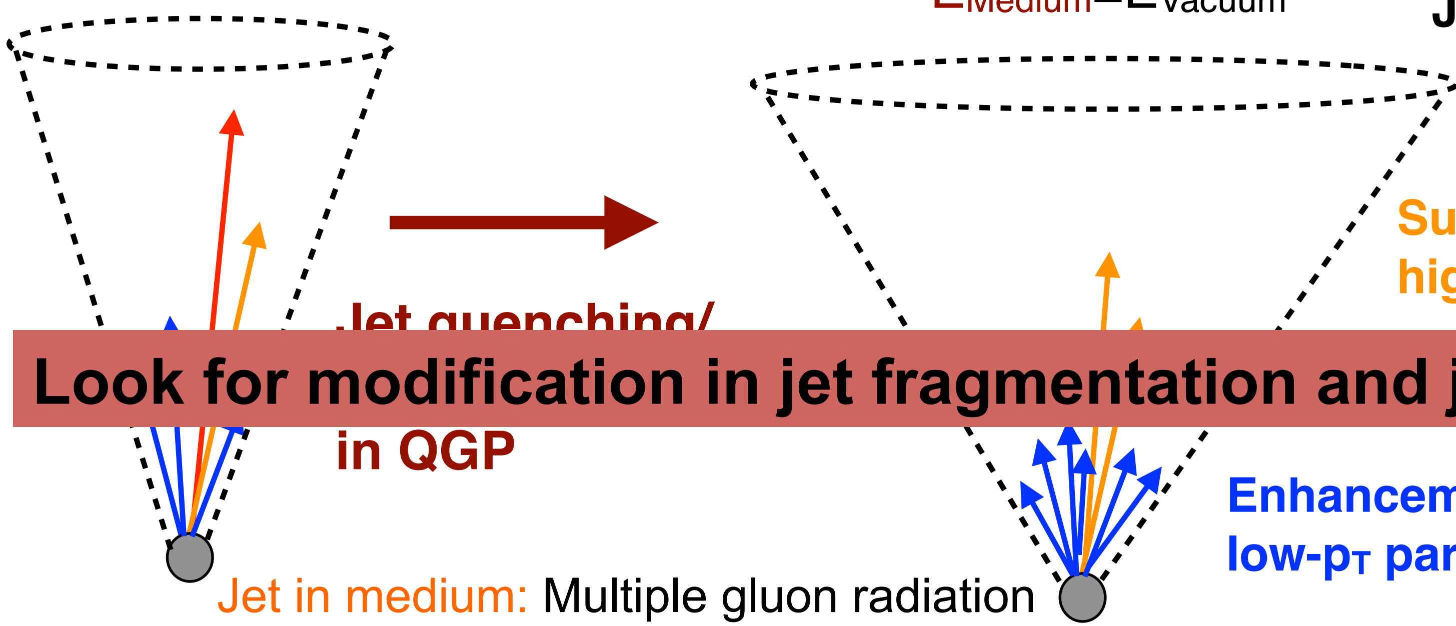
Jet in vacuum

E_{Vacuum}

Jet in medium

$E_{Medium} = E_{Vacuum}$

Jet broadening



Suppression of high-p_T particles

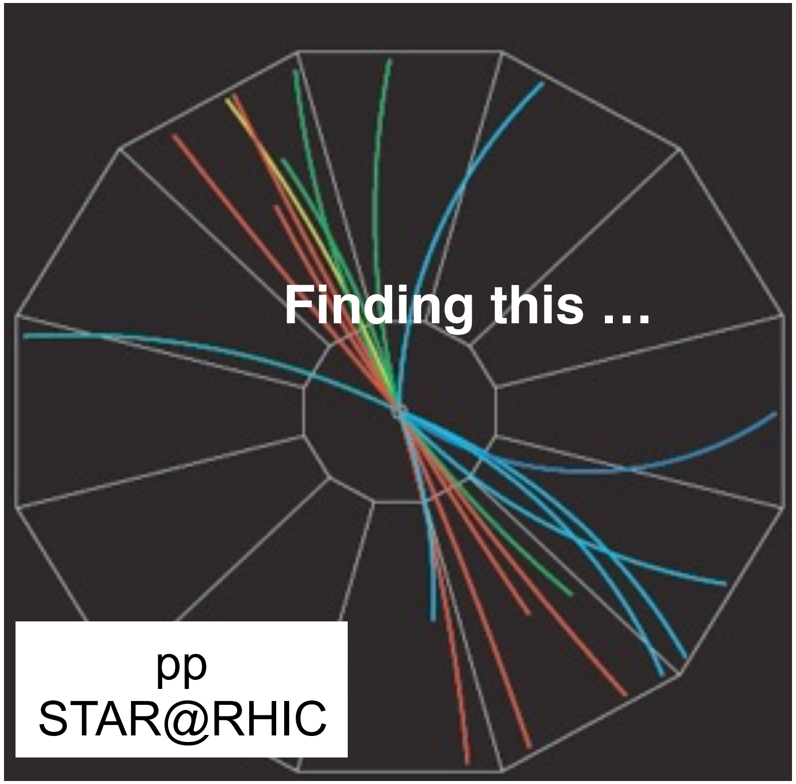
Jet quenching/ in QGP

Look for modification in jet fragmentation and jet structure

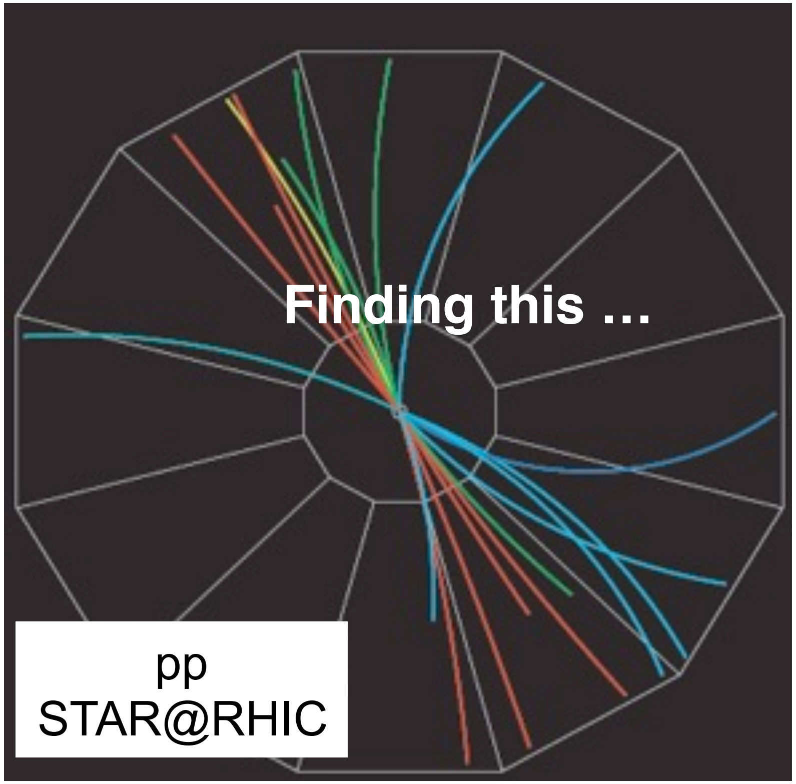
Enhancement of low-p_T particles

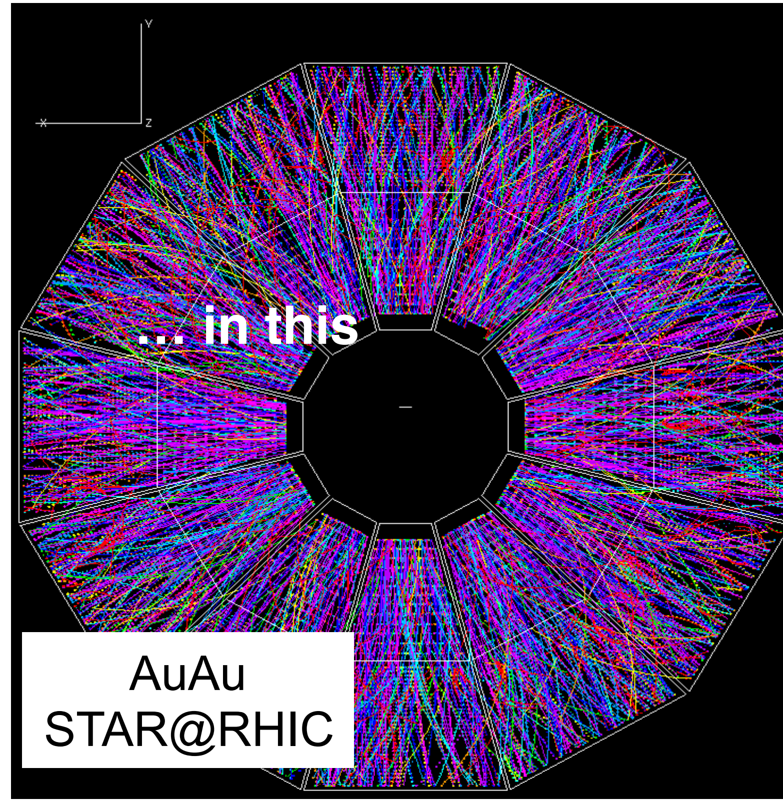
Jet in medium: Multiple gluon radiation in presence of dense medium

Jets measurements : experimentally challenging ....

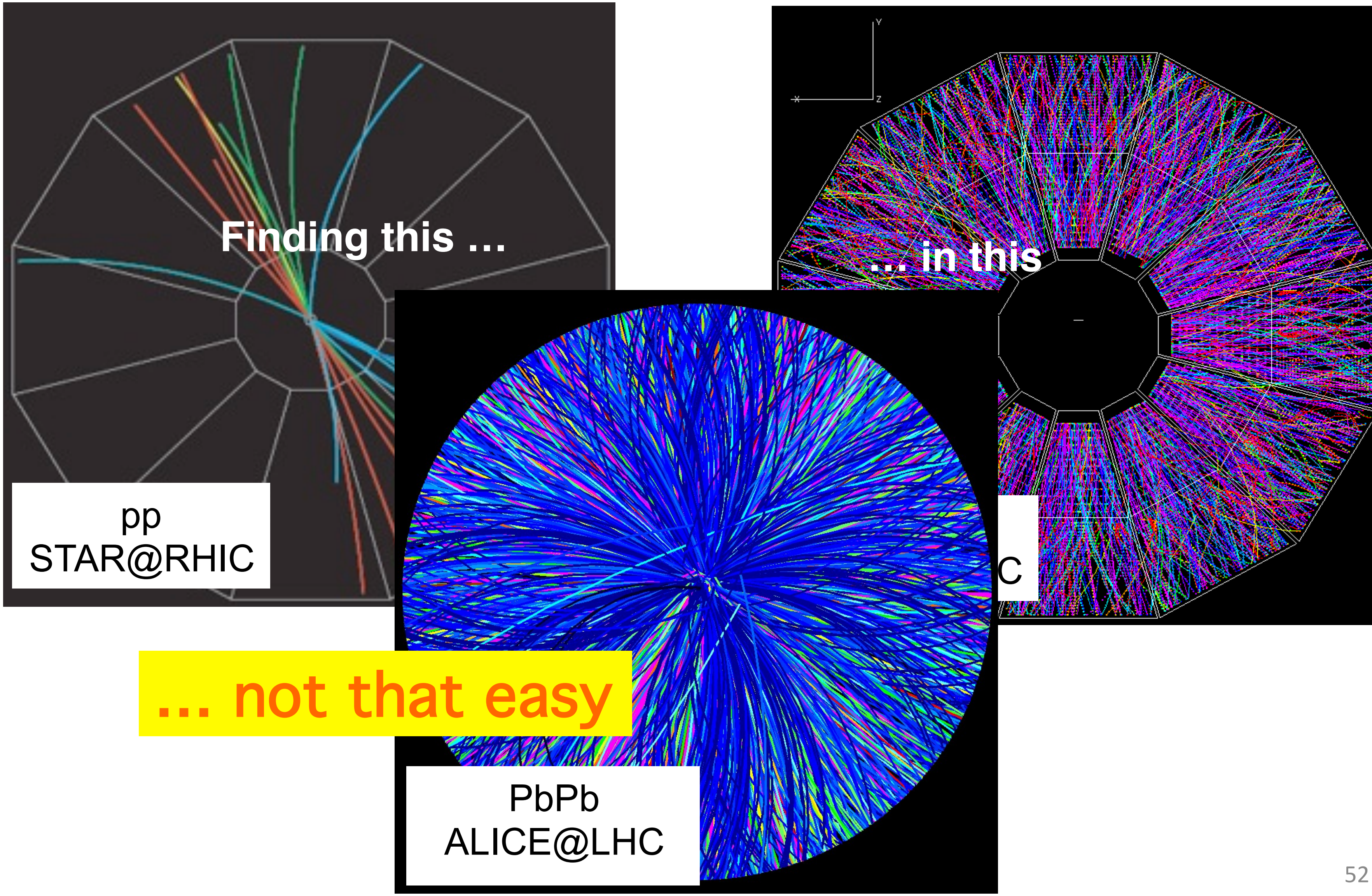


Jets measurements : experimentally challenging ....





Jets measurements : experimentally challenging ....



Jet reconstruction: Cone based algorithms

- A list of seed objects are made which are above certain p_T threshold.

- A cone is constructed at each seed location of given radius (0.4, 0.6, 0.7, etc) in η-ϕ space.

- The four momentum vectors of all objects located in the cone are summed and centroid of the cluster is calculated.

- The process is iterated until the cone axis and the centroid coincide, indicating that a stable cone has been formed.

Jet reconstruction: Successive recombination algorithm

- **Every track co** *Cacciari, Salam, Soyez, JHEP04 (2006)063*
  - **For all protojets, define** $k_{T,i}^{2p} = p_{T,i}^{2p}$
  - **For all protojet pairs calculate**

$$d_{ij} = \frac{\min\left(k_{T,i}^{2p}, k_{T,j}^{2p}\right)\left(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2\right)}{R^2}$$

  - **Consider all protojets and pairs**
  - **If minimum is** $k_{T,i}^{2p}$ **, promote protojet "i" to jet, remove protojet from the list**
  - **If minimum is** d_{ij} **, merge protojets "i" and "j" into a new protojet, remove "i" and "j" from the list. Calculate** $k_{T,i}^{2p}$ **of new protojet**
  - **Repeat until protojet list is empty**

Jet reconstruction: Successive recombination algorithm

- Every track co *Cacciari, Salam, Soyez, JHEP04 (2006)063*
  - For all protojets, define $k_{T,i}^{2p} = p_{T,i}^{2p}$
  - For all protojet pairs calculate

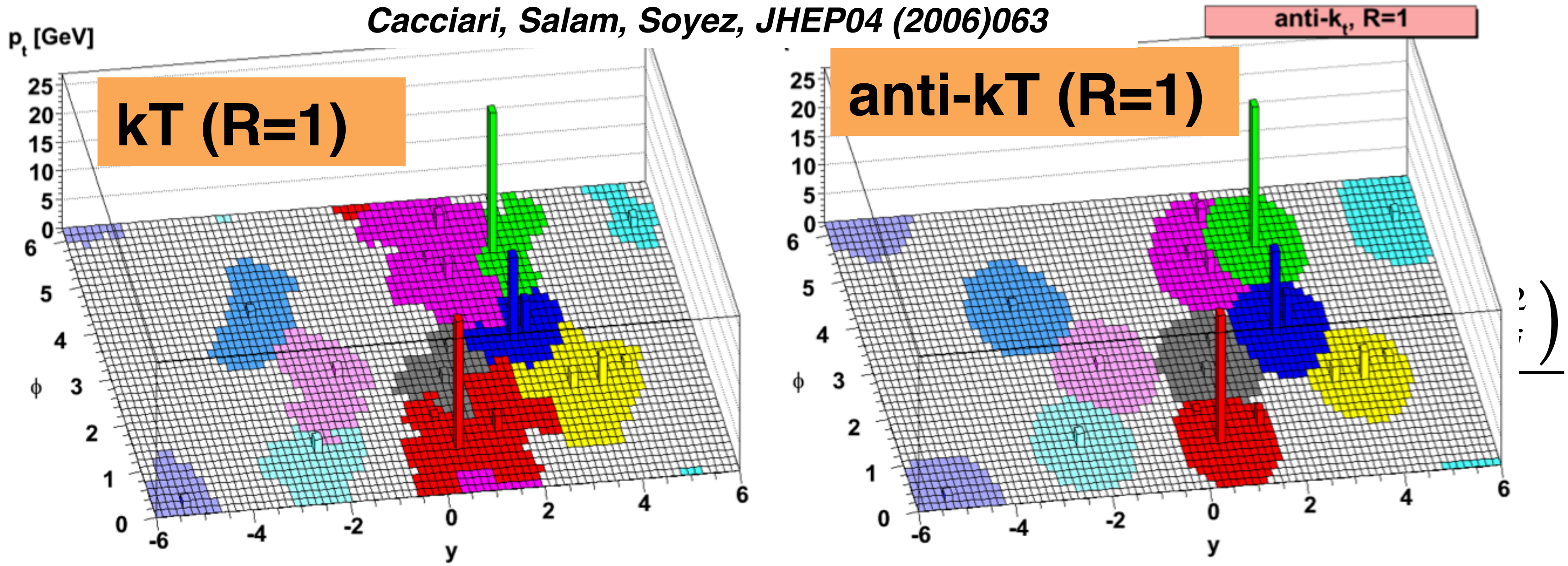
$$d_{ij} = \frac{\min\left(k_{T,i}^{2p}, k_{T,j}^{2p}\right)\left(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2\right)}{R^2}$$

  - Consider all protojets and pairs
  - If minimum is $k_{T,i}^{2p}$, promote protojet "i" to jet, remove protojet from the list

- ***R*** **is the resolution parameter (jet radius), controls the size of the jet (0.2, 0.3, 0.4, 0.6, 1.0)**
- ***p*** **= 1, kT algorithm – soft particles merged first**
- ***p*** **= -1, anti kT – hard particle merged first**

Jet reconstruction: Successive recombination algorithm

Cacciari, Salam, Soyez, JHEP04 (2006)063

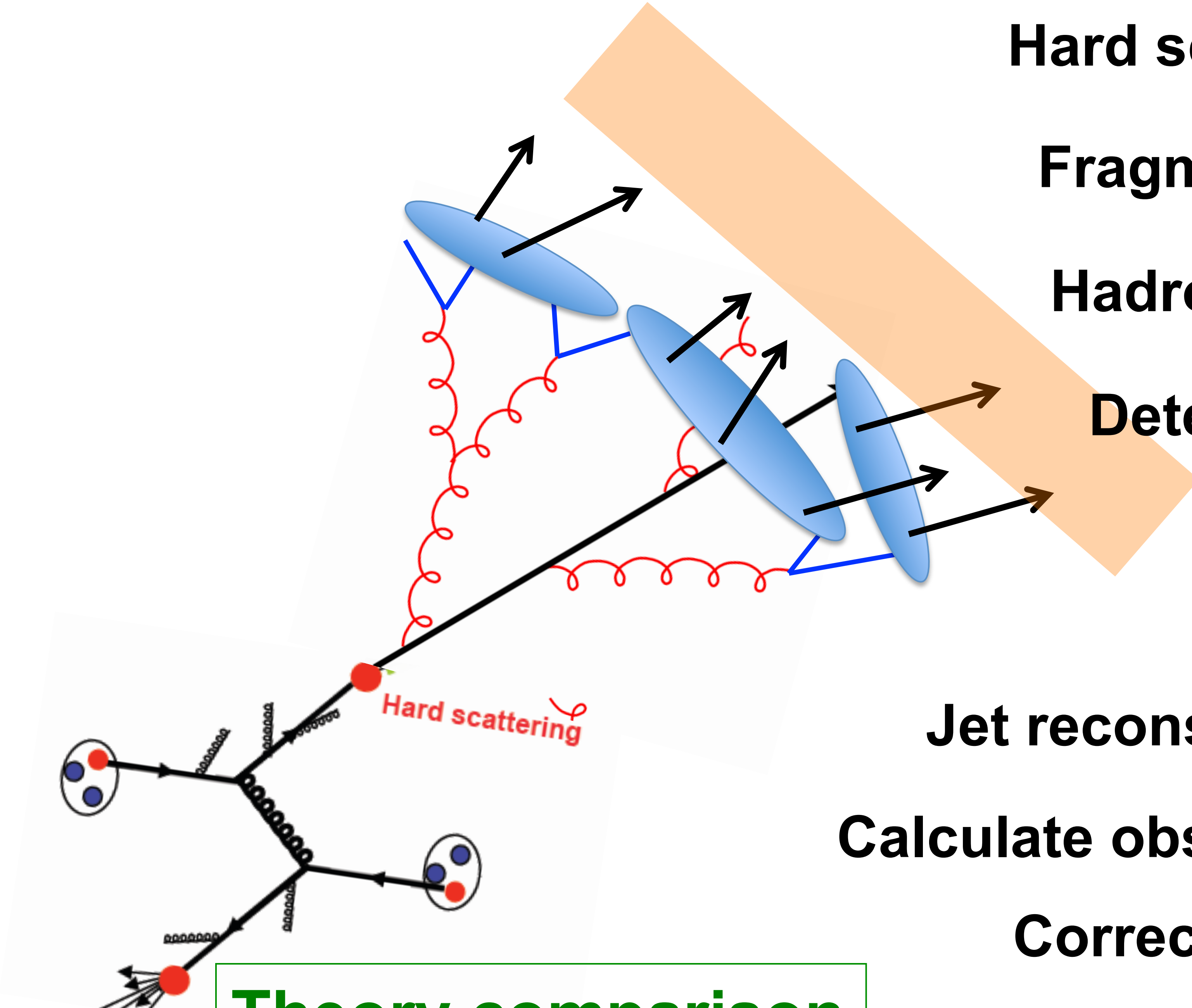


❖ If minimum is $k_{T,i}$, promote protojet "i" to jet, remove protojet from the list

❖ *R* is the resolution parameter (jet radius), controls the size of the jet (0.2, 0.3, 0.4, 0.6, 1.0)

❖ $p = 1$, kT algorithm – soft particles merged first

❖ $p = -1$, anti kT – hard particle merged first



Hard scattering

Fragmentation

Hadronization

Detection

Jet reconstruction

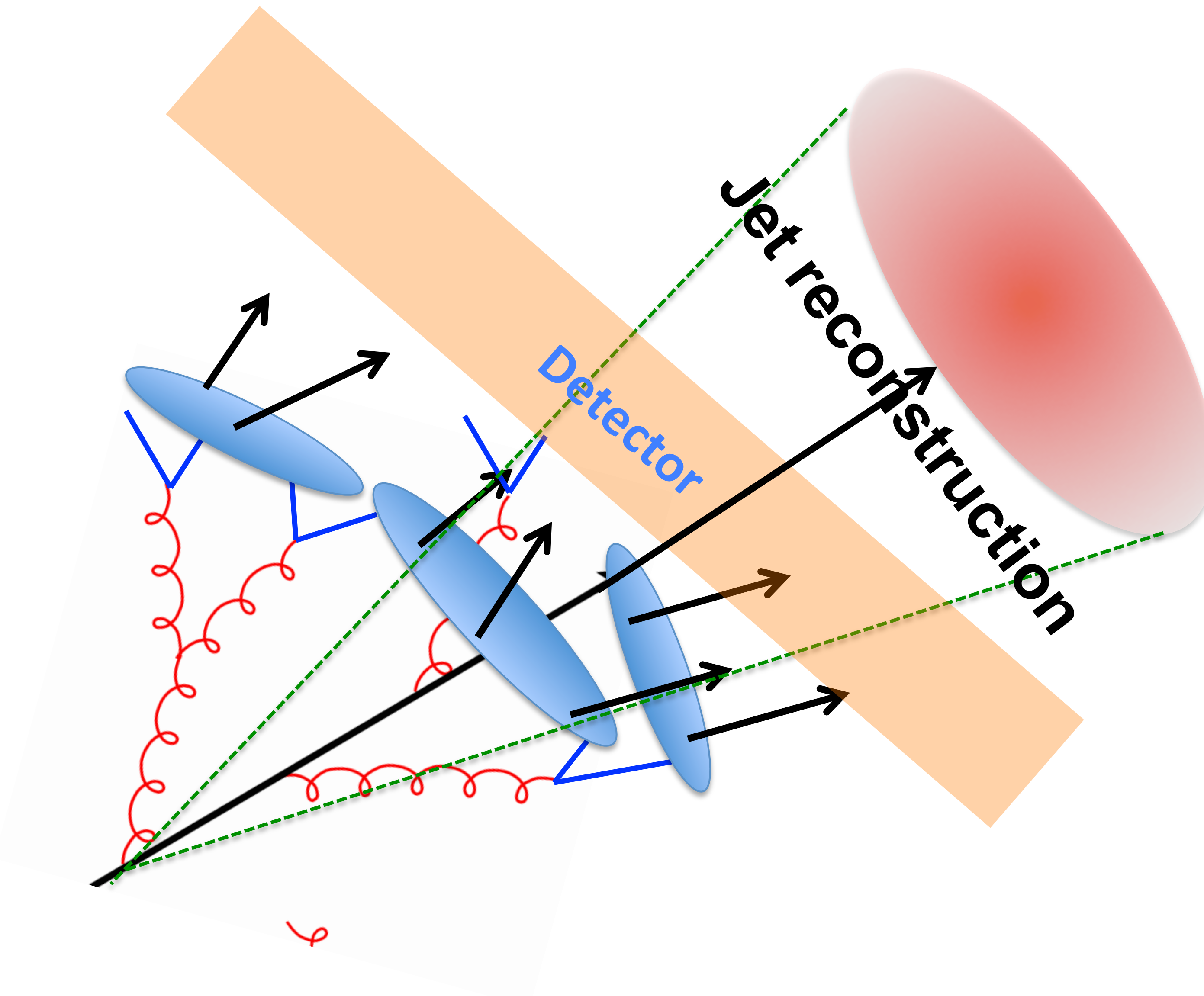
Calculate observables

Correction

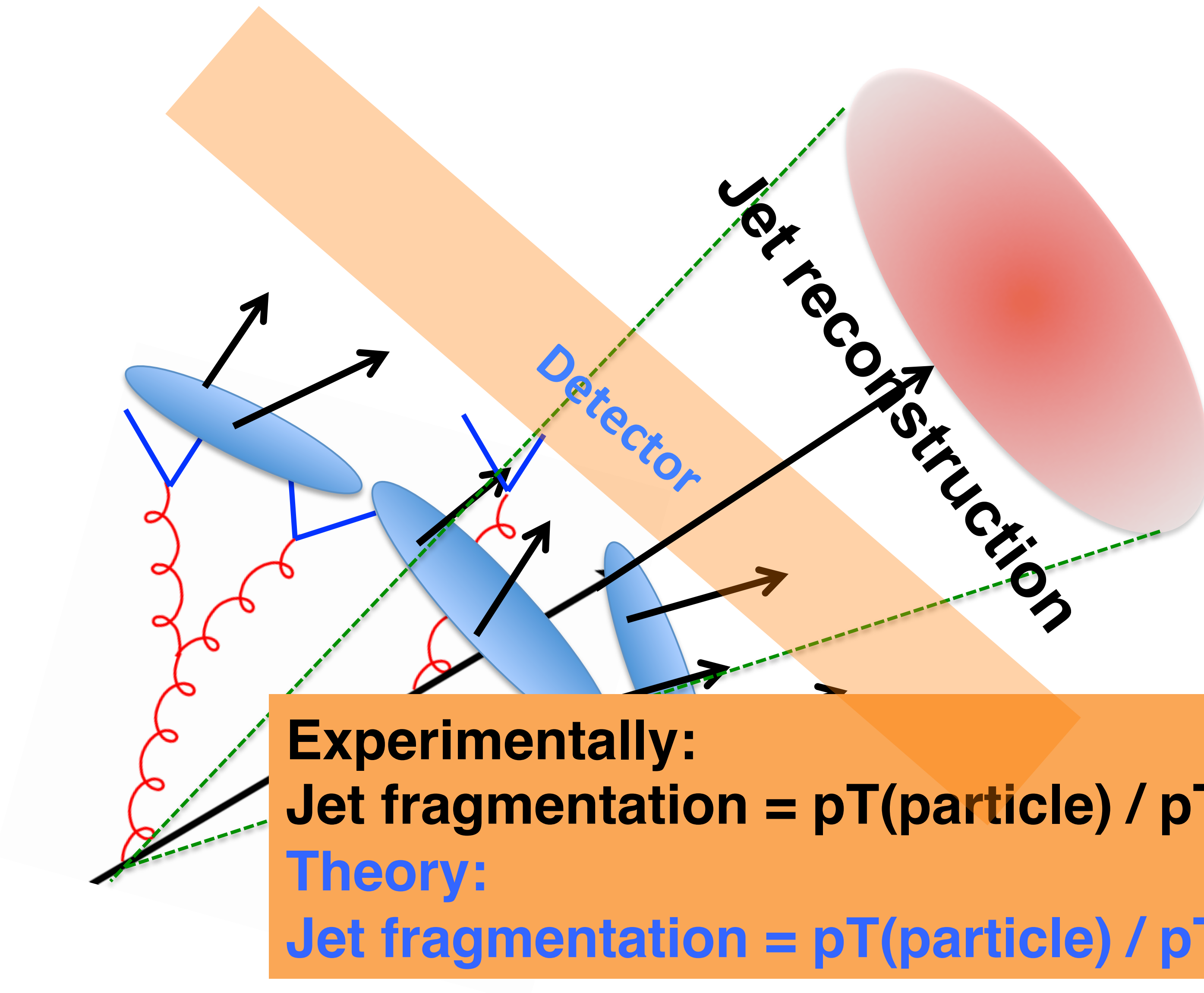
Systematic unc.

Theory comparison

Total parton energy may not be contained in a reconstructed jet (depends on jet size)

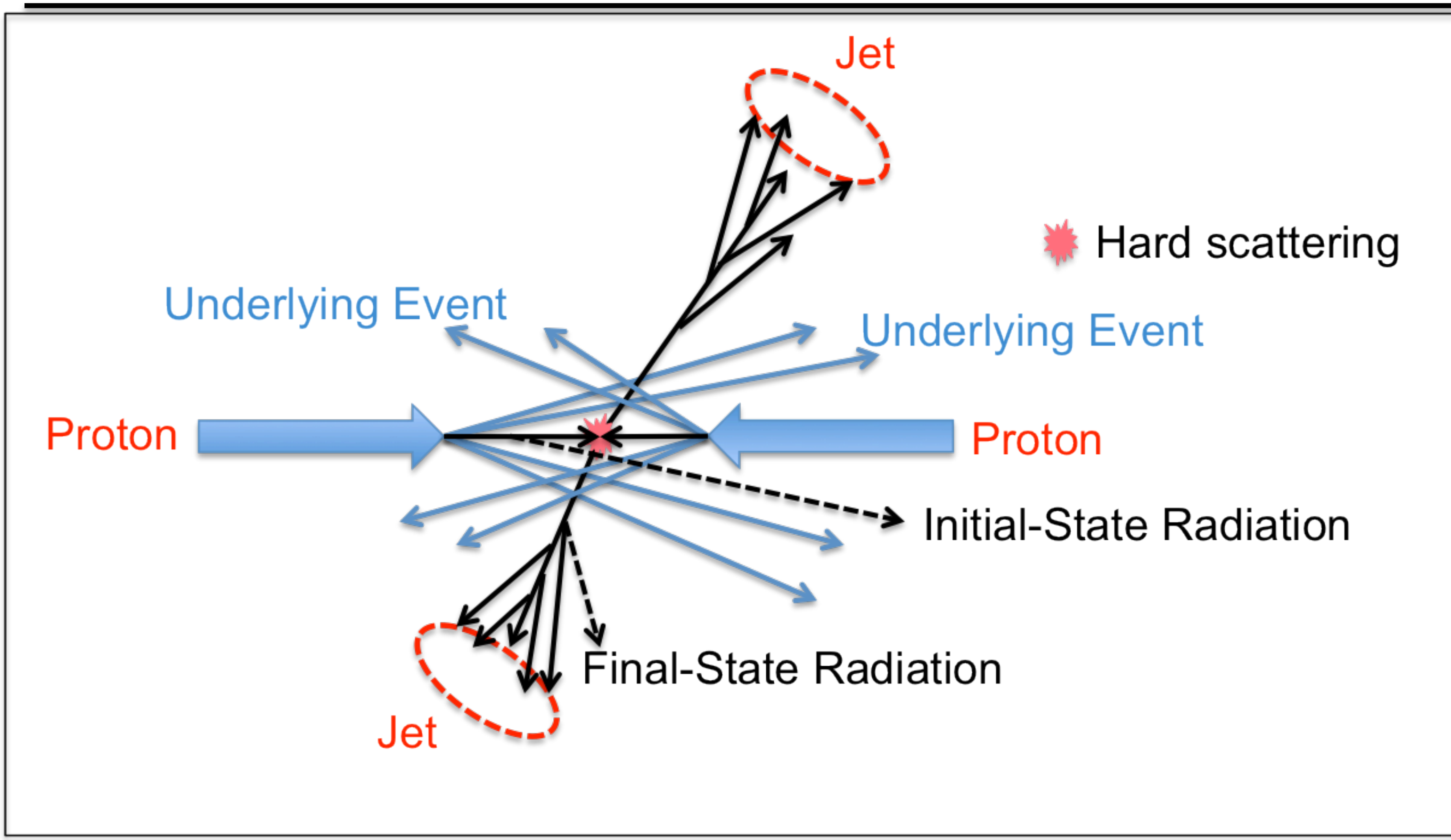


Total parton energy may not be contained in a reconstructed jet (depends on jet size)

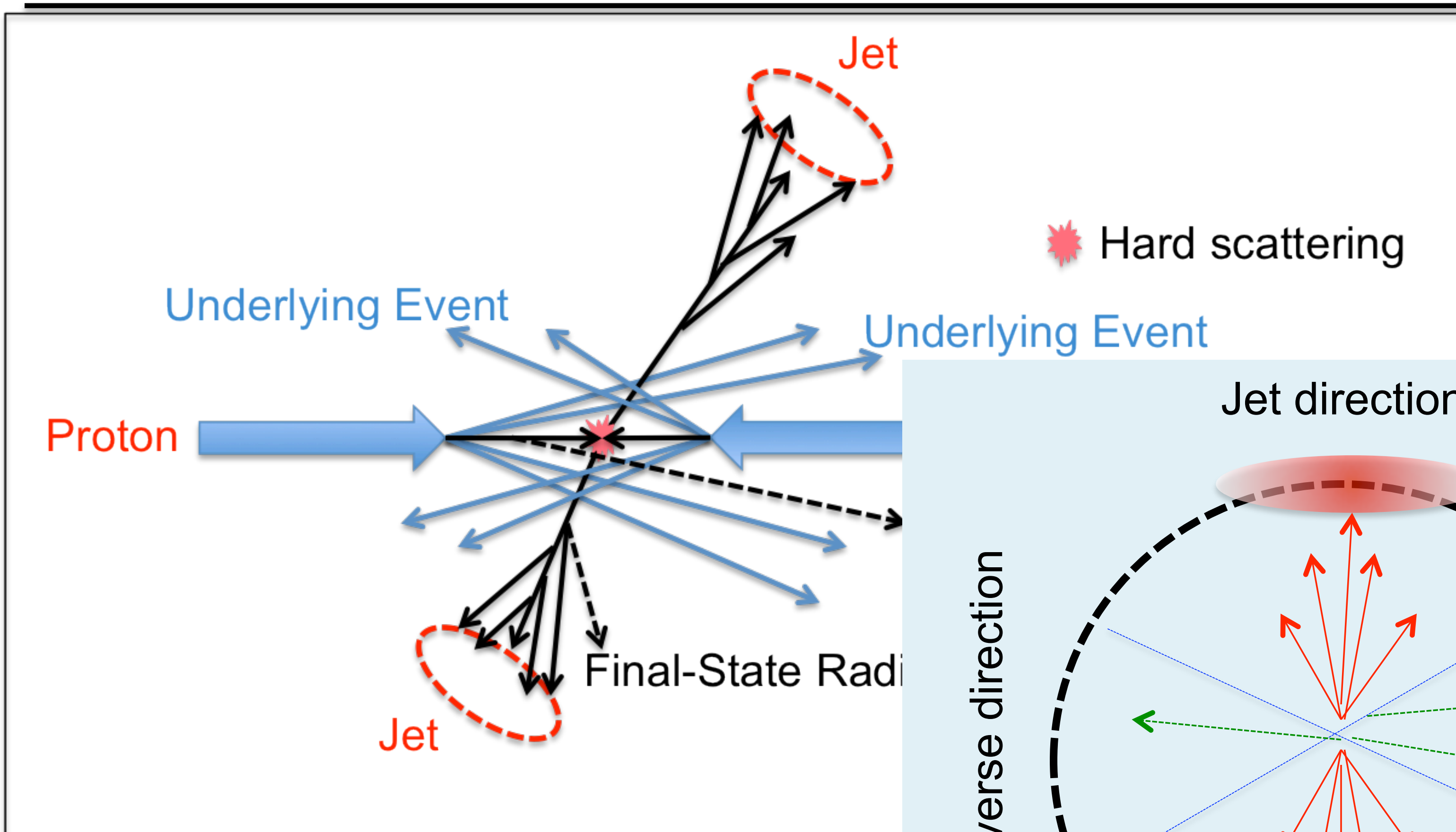


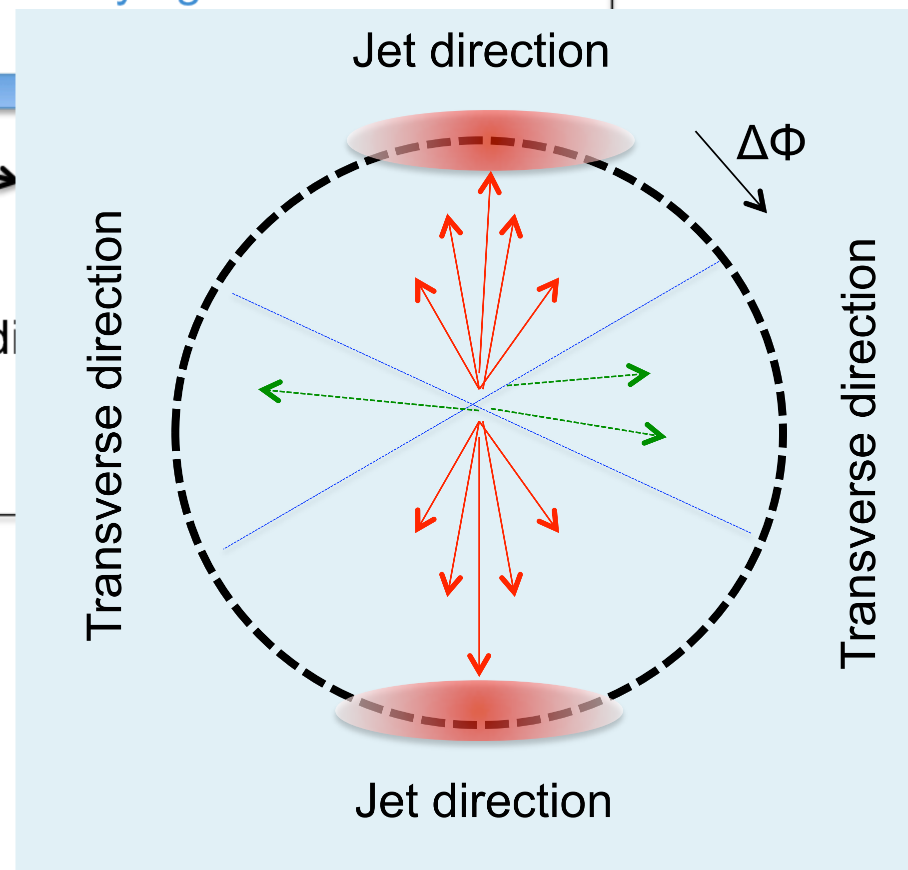
Experimentally:
Jet fragmentation = pT(particle) / pT(jet)
Theory:
Jet fragmentation = pT(particle) / pT(parton)

Underlying event and background subtraction (pp)



Underlying event and background subtraction (pp)





- ❖ **Collect all particles in the transverse direction to jet axis**

- ❖ **Subtract from the jet energy**

Underlying event and background subtraction (A+A)

- Large background consisting of particles from soft scattering processes and fragments from other jets

- Background is measured e-by-e by clustering all particles using the kT-algorithm and determining the median of transvers momentum density (rho,i = pTjet,i/Ai) of all clusters except the two leading clusters to limit the hard jet signal from the background estimate.

- Corrected transverse momentum density **= 155.8 +/- 3.7 GeV/c**

- The signal anti-kT jets are then corrected for background using the median rho (pT,jet = pT,jet,raw – rho*A)

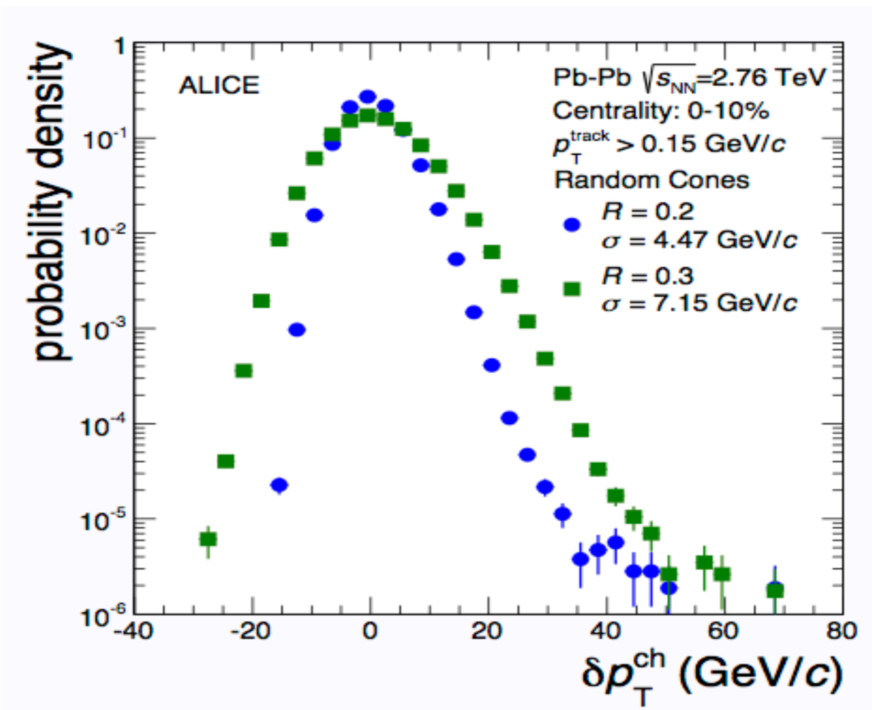
$$p_{T,jet,raw} - \rho A = p_{T,jet} \text{ (Background subtracted)}$$

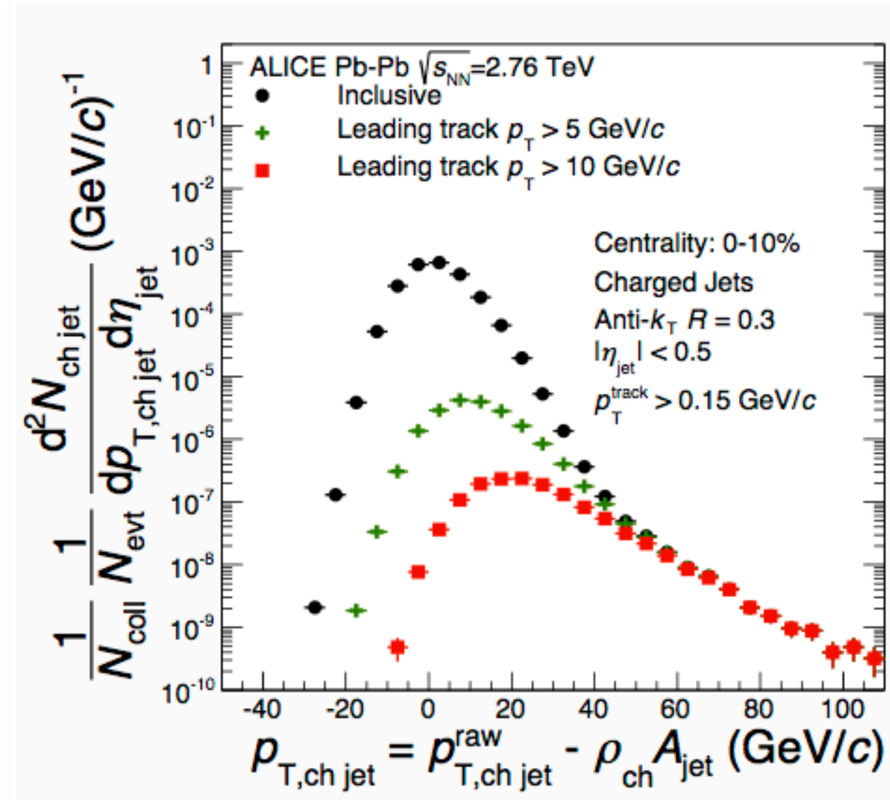
Avg. Background density (ρ) **Jet area** (A)

Background fluctuations and Combinatorial

$\delta p_T = p_{T,jet,raw} - \rho A - p_{T,probe}$

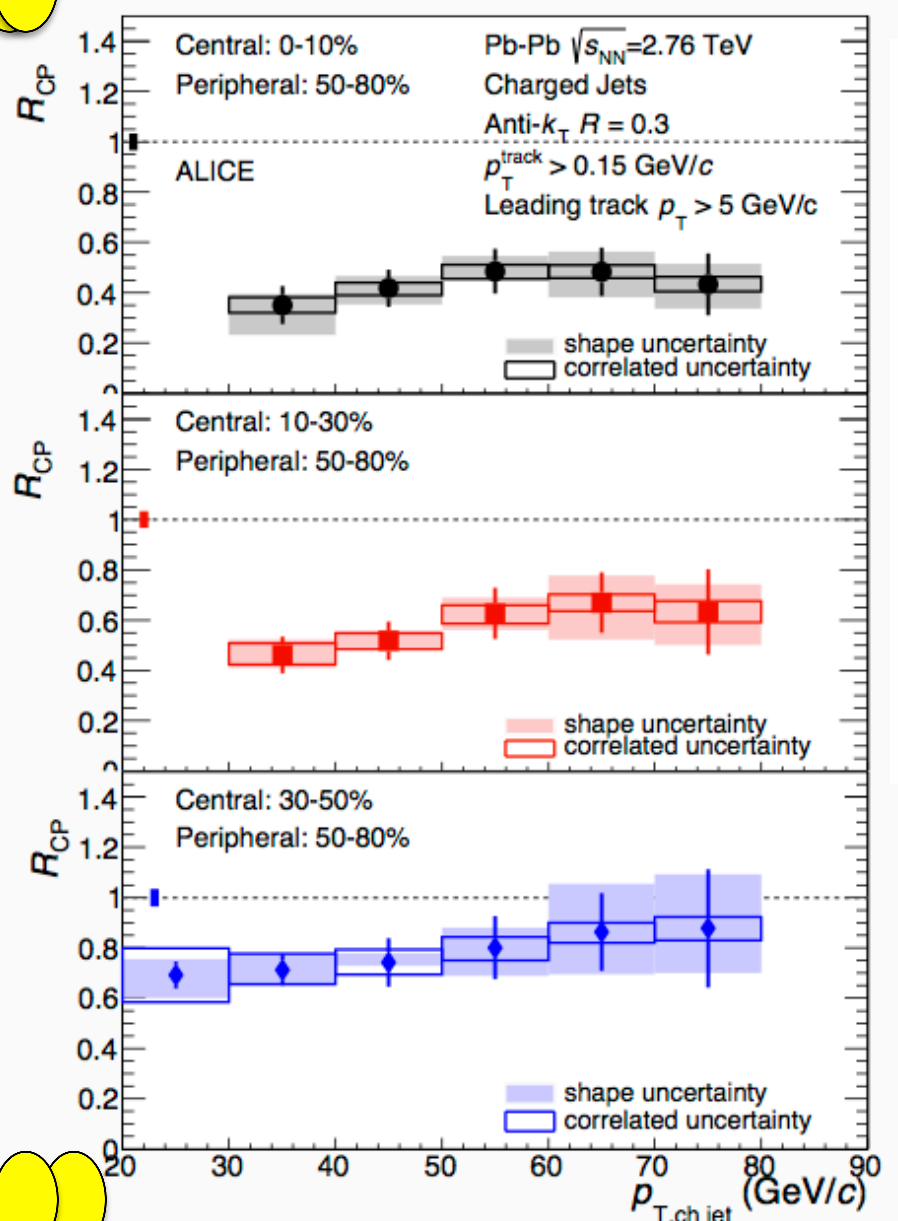
$\delta p_T = Sum(p_{Ti,RC}) - \rho A$

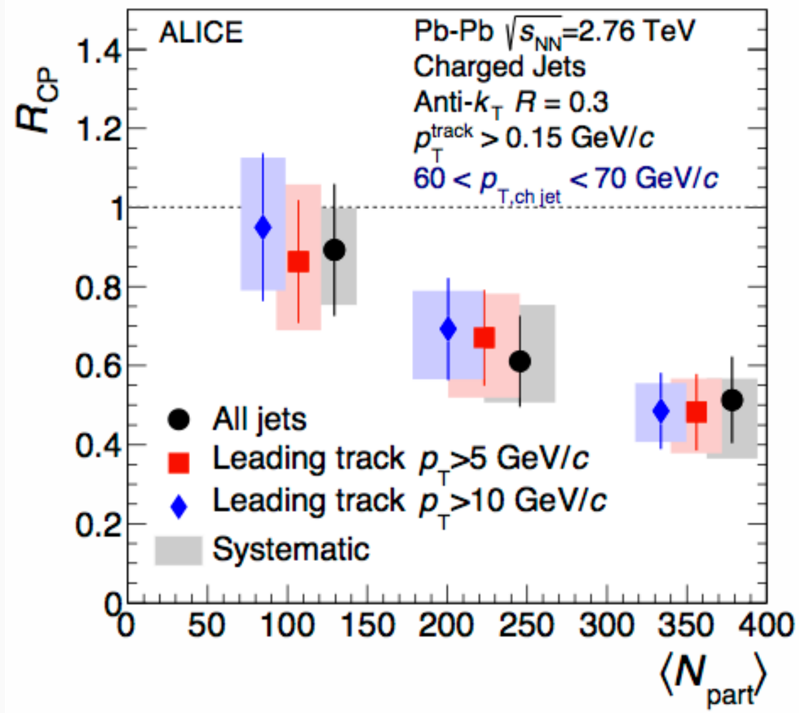




Results: Jet quenching (PbPb: Medium effect)

Rosi Reed, HP2013





- **Jets are suppressed**
- **Centrality and p_T dependence exist**

References

- *ALICE PPR Vol-1, 2004, J. Phys. G: Nucl. Part. Phys. 30 (2004) 1517–1763*
- *ALICE PPR Vol-2, 2006, J. Phys. G: Nucl. Part. Phys. 32 (2006) 1295–2040*
- *The ALICE experiment at the CERN LHC, 2008, JINST 3 S08002*
- *Performance of the ALICE experiment at the CERN LHC, 2014, International Journal of Modern Physics A Vol. 29, No. 24, 1430044*
- *ALICE TDRs*
- *Wikipedia: https://www.wikipedia.org/*

Thank you for your attention !