Jets in heavy-ion collisions and how we can use them to probe the Quark-Gluon Plasma

MILLOT Louise LPSC – 2nd year PhD seminar 11 may. 2025

QCD Theory

Strong potential

Running of α_s

Quark Gluon Plasma

Deconfined state

QGP main properties

LHC / ALICE

Jets to probe QGP

Jet definition

Jet quenching

SoftDrop Algorithm

Ongoing work

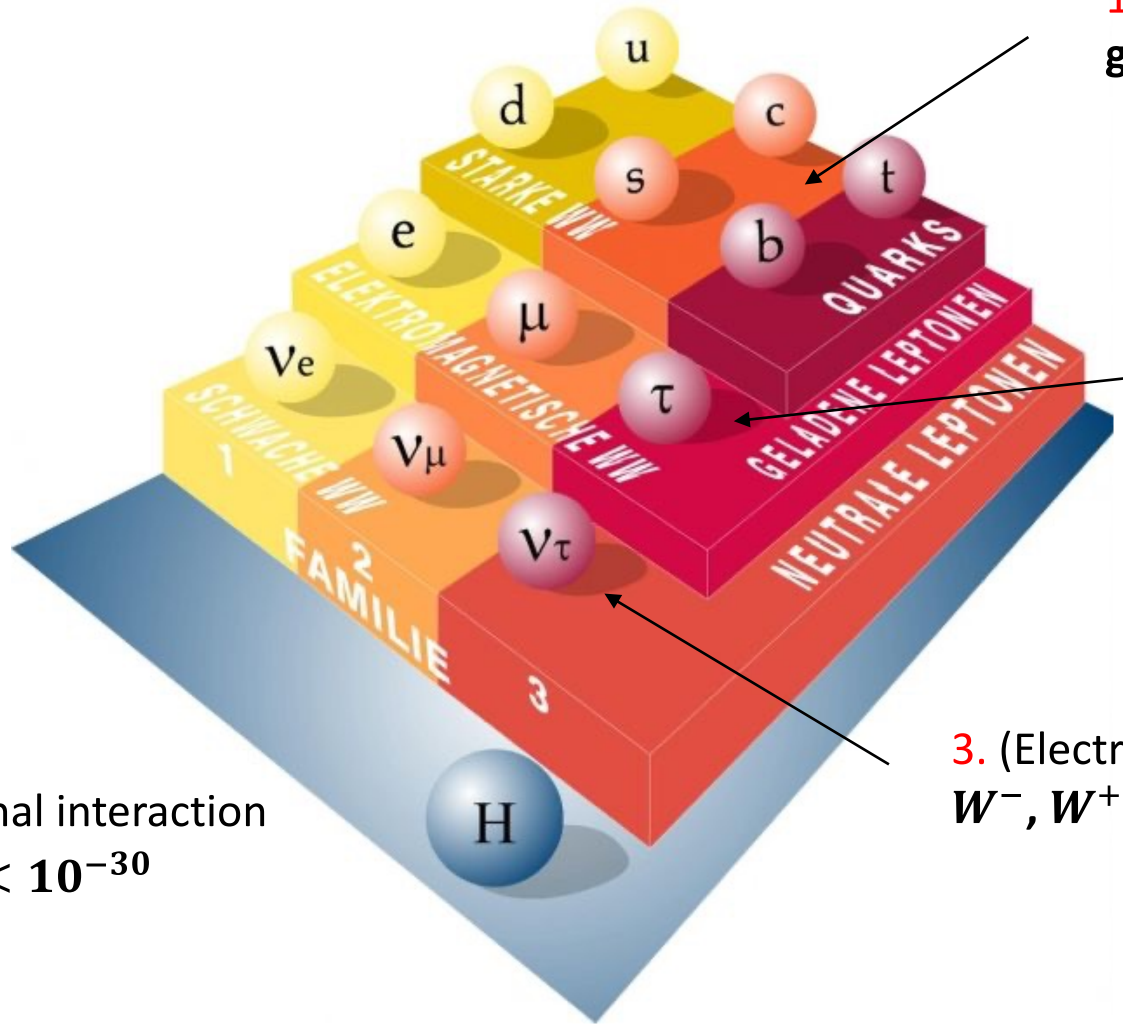
RUN3 Analysis

Embedding

Service Work

Standard Model : Interaction panel

Bosons, convey the interactions…



1. Strong interaction
gluons

Intensity: $\mathbf{1}$

Strong (color) spin =1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

2. Electromagnetic interaction
photons

Intensity: $\sim\ \mathbf{1/137}$

3. (Electro)weak interaction
$\boldsymbol{W^-, W^+, Z^0}$

Intensity: $\sim\mathbf{10^{-5}}$

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

4. Gravitational interaction
Intensity: $< \mathbf{10^{-30}}$

Intensities compared to the strong interation

Standard Model : Interaction panel

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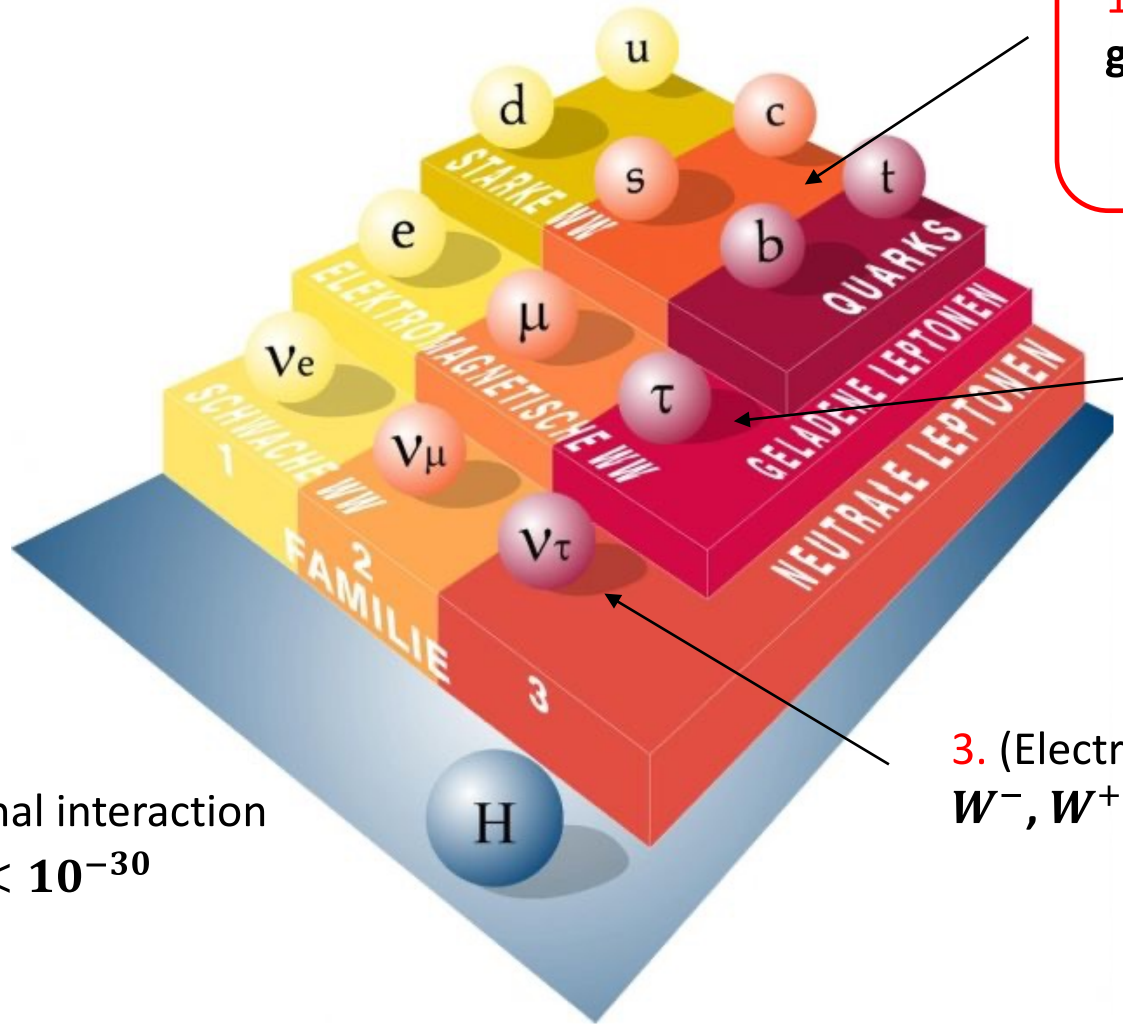

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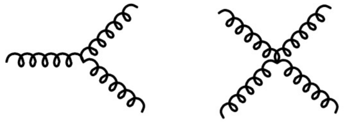
Intensities compared to the strong interation

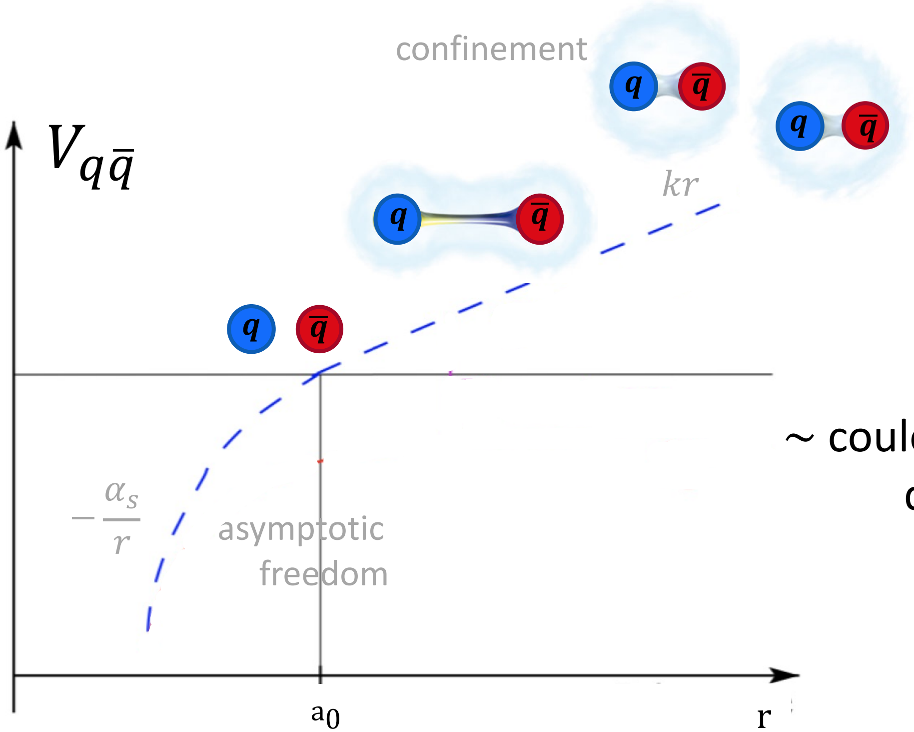
QCD basic rules

Quantum **C**hromo**D**ynamics **(QCD)** describes the strong interaction between quarks and gluons
Quarks + gluons carry a color charge : 3 colours = red, green, blue + anti-colours

In QCD : **gluons can interact with each other**



As a consequence, the QCD interaction potential between quarks **increases with distance:**



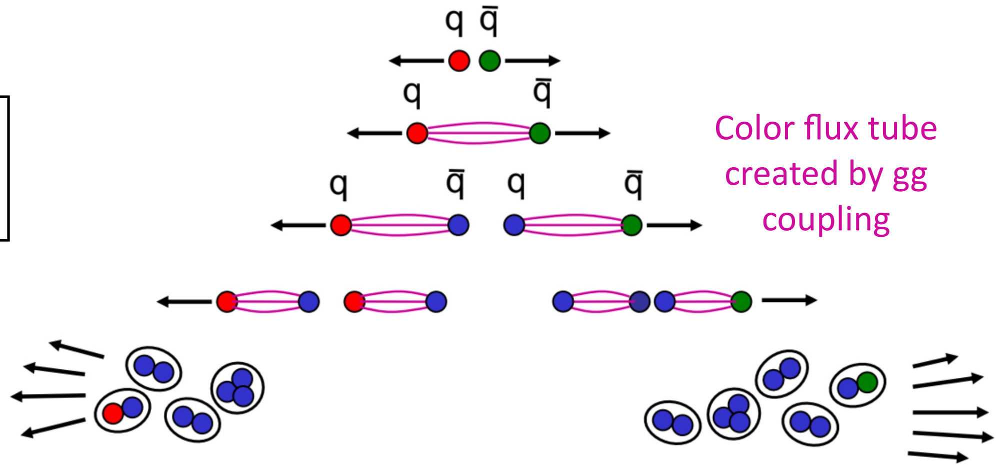
Phenomenological approach:

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s \hbar c}{r} + kr$$

~ coulombian at small distances (d~0.1 fm)

~ like a « spring » at high distance

→ Hadronization



Quark confinement: no isolated quarks are observed
Formation of **color-neutral hadrons** (baryons and mesons)

The potential of strong interaction

- The potential of strong interaction increases with distance

(different from gravitation, electromagnetism…)

8 gluons carry a color charge $(r\bar{g}, r\bar{b}, g\bar{r}, \dots)$ and interact with each other

Phenomenological approach :

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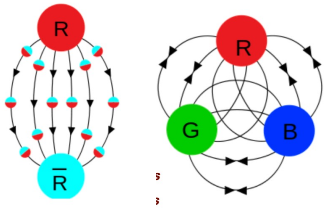
« confinement »

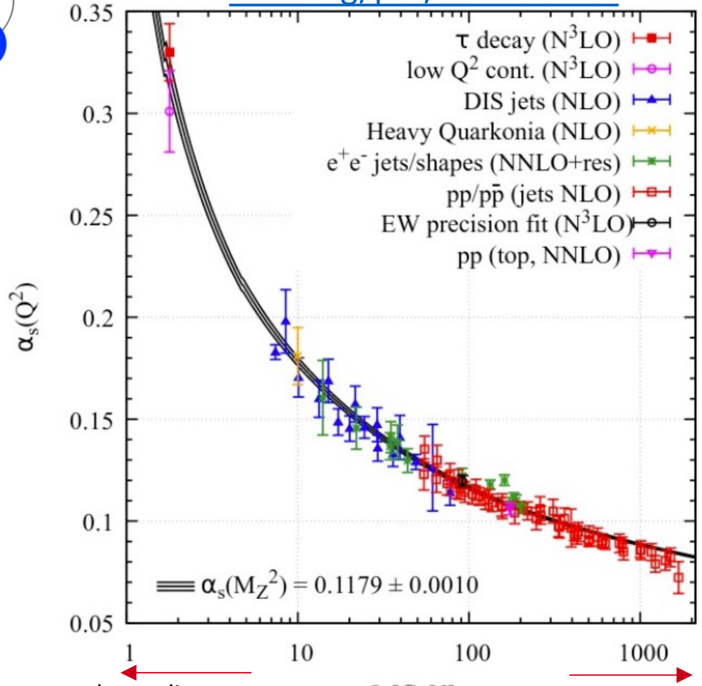
In fact, running of $\alpha_s = f(r)$…



meson baryon

The strong interaction is therefore a confining force

arxiv.org/pdf/1907.01435



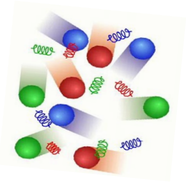
large distance
small energie

small distance
large energie

non-perturbatif regim
(lattice-QCD)

perturbatif regim
(pQCD)

towards asymptotic freedom



***Λ_{QCD}* scale :**
This transition is governed by the QCD scale $\Lambda_{QCD} \sim 200\ \mathrm{MeV}$
- which sets the energy scale below which confinement and non-perturbative effects dominate

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Deconfined state : Quark Gluon Plasma

QCD potential leads to confinement, meaning that quarks are bound inside hadrons under normal conditions

What happens at very dense and high-temperature hadronic matter?

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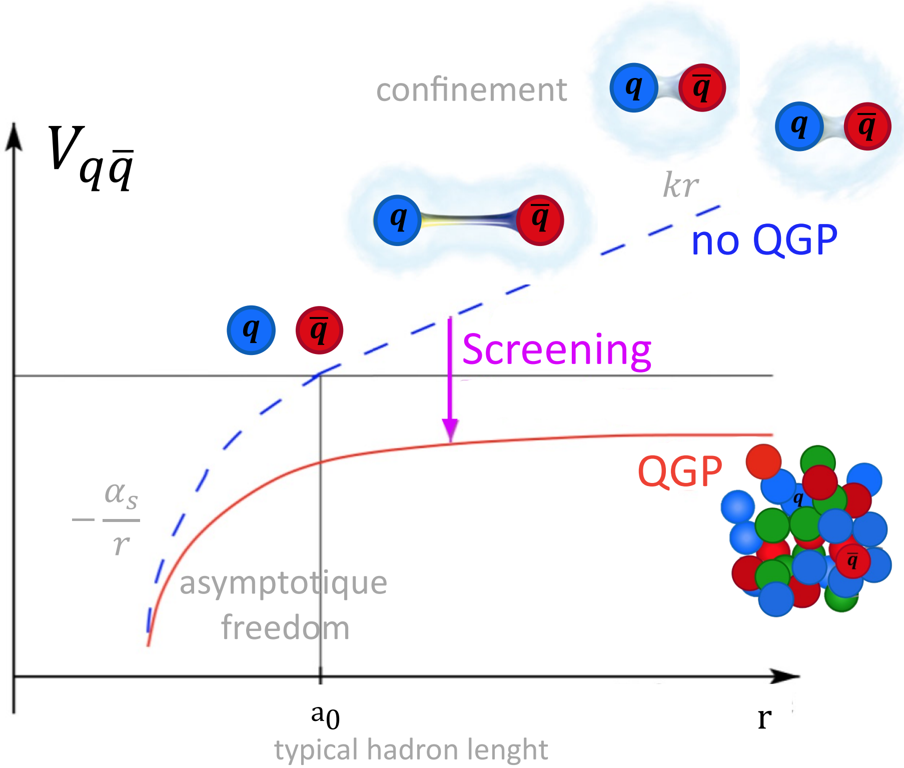
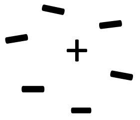
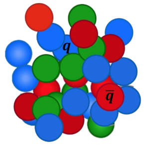
What happens at very dense and high-temperature hadronic matter?



If we **heat** or **compress** matter enough hadrons become very close to each other -> the color charges in the medium start to screen the strong interaction.



similar to what is known as Debye screening in an electromagnetic plasma : free charges rearrange themselves around a test charge and reduce the effective interaction at long distance

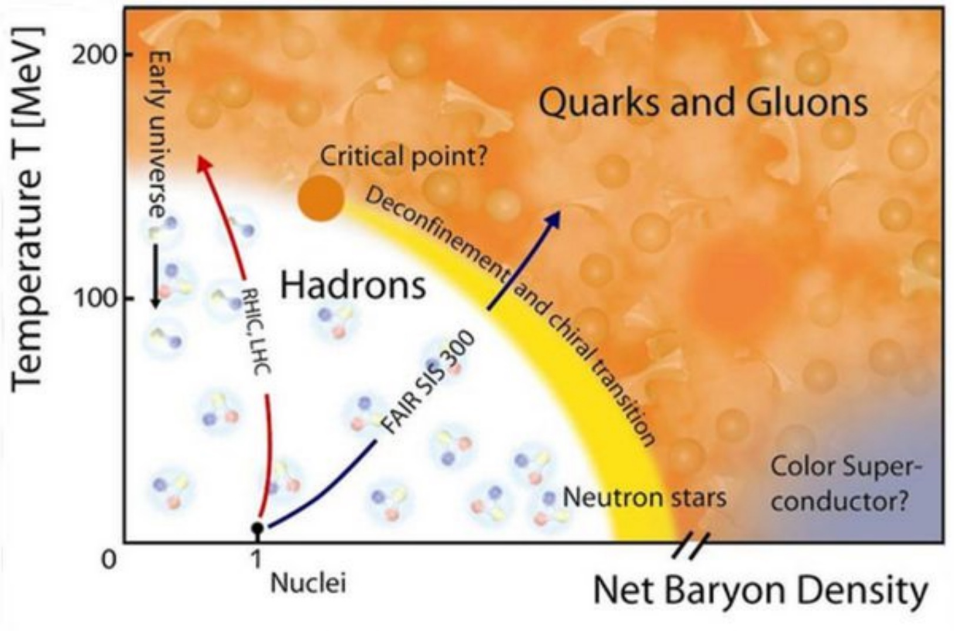


In QCD, the presence of many color charges screens the interaction between quarks.

As a result, the confining potential is effectively weakened, and confinement disappears

Quarks and gluons are no longer bound inside hadrons — they become **mobile** in a **deconfined** state called the **Quark-Gluon Plasma**

QCD phase diagram and QGP



- to be compared with T_{SUN} in the core …
  Sun : keV / T $\sim 10^7$K
  QGP : 160 MeV / T $\sim 10^{12}$K
- Kheops pyramid mass in a pinhead volume $\rho_{QGP} \sim 10^{18}$ kg/m^3

Different phases of strongly-interacting matter VS temperature and baryon chemical potential

lQCD calculations :

- Critical temperatures at : approx $\mathbf{160\ MeV \equiv\ T \sim 10^{12} K}$
- Critical energy density : $\boldsymbol{\rho_{QGP} > 1\ GeV/fm^3}$
- Behaves like a nearly perfect fluid, with a very low viscosity

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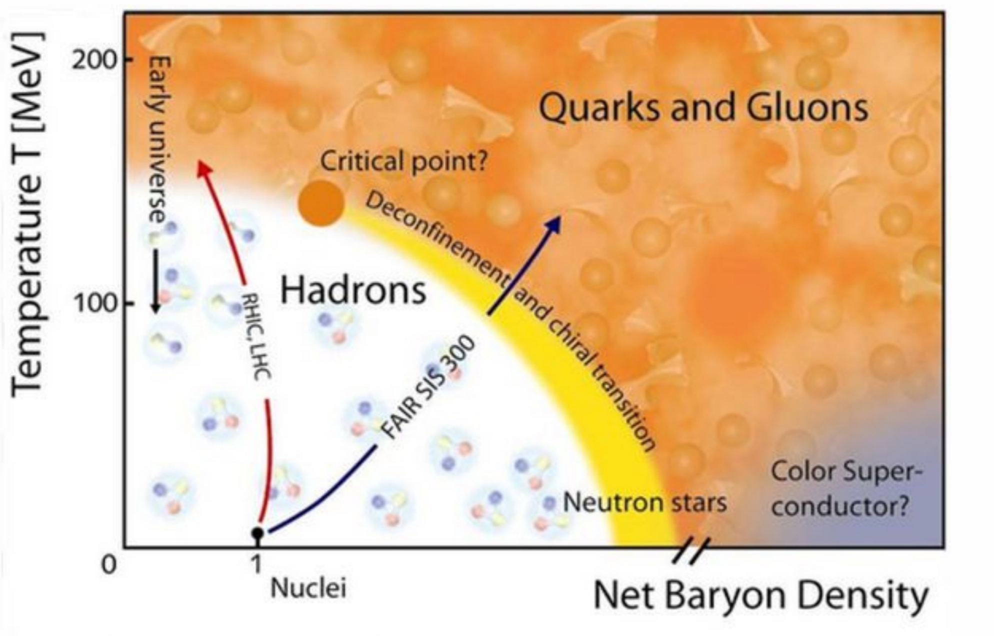

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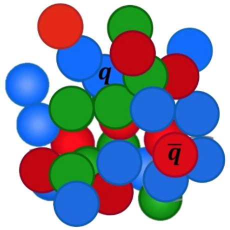
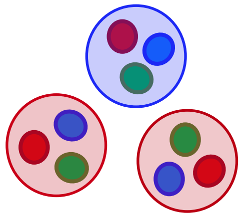
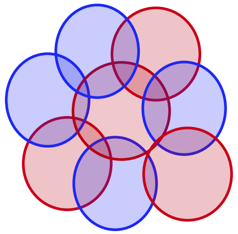
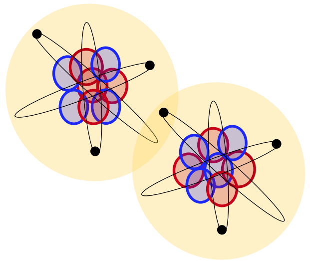
One of the main motivations to study the QGP is its connection to the early universe.
Just a few microseconds after the Big Bang, the universe was in a quark—gluon plasma state

© Anton Andronic

	Big Bang	quark-gluon plasma	protons & neutrons formation	formation of low-mass nuclei	formation of neutral atoms	star formation	today
$T_{Universe}$		$> 10^{12}$K	10^{12}K	10^9K	4000K	50K – 3K	3K
time		10^{-6}s	10^{-4}s	3min	400.000 yr	> 3 x 10^8 yr	14 x 10^9 yr

How can the QGP be produced in a laboratory ?

→ Relativistic heavy-ion collisions!

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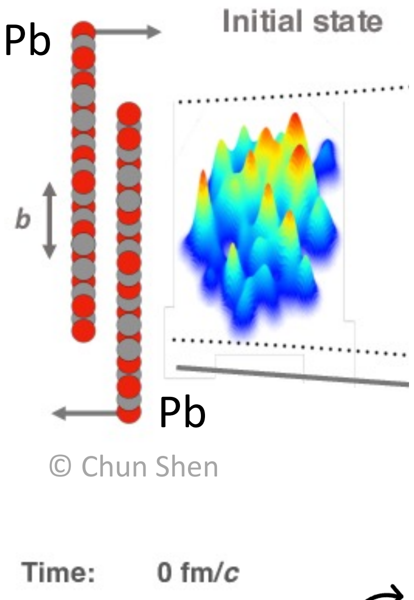

much larger and denser system that compared to pp collisions too small system

- First, two heavy nuclei collide at ultra-relativistic energies, creating a very hot and dense system

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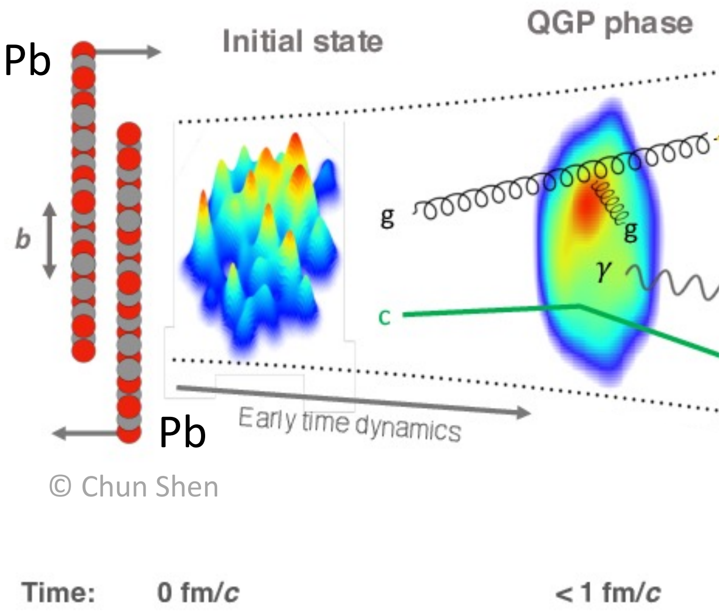
Relativistic heavy-ion collisions!



- First, two heavy nuclei collide at ultra-relativistic energies, creating a very hot and dense system
- Quark-Gluon Plasma is formed, where quarks and gluons are deconfined

NB : $\tau_{QGP} \sim 10^{-23} s$ (cannot be directly observed) / electronic readout $10^{-12} s$

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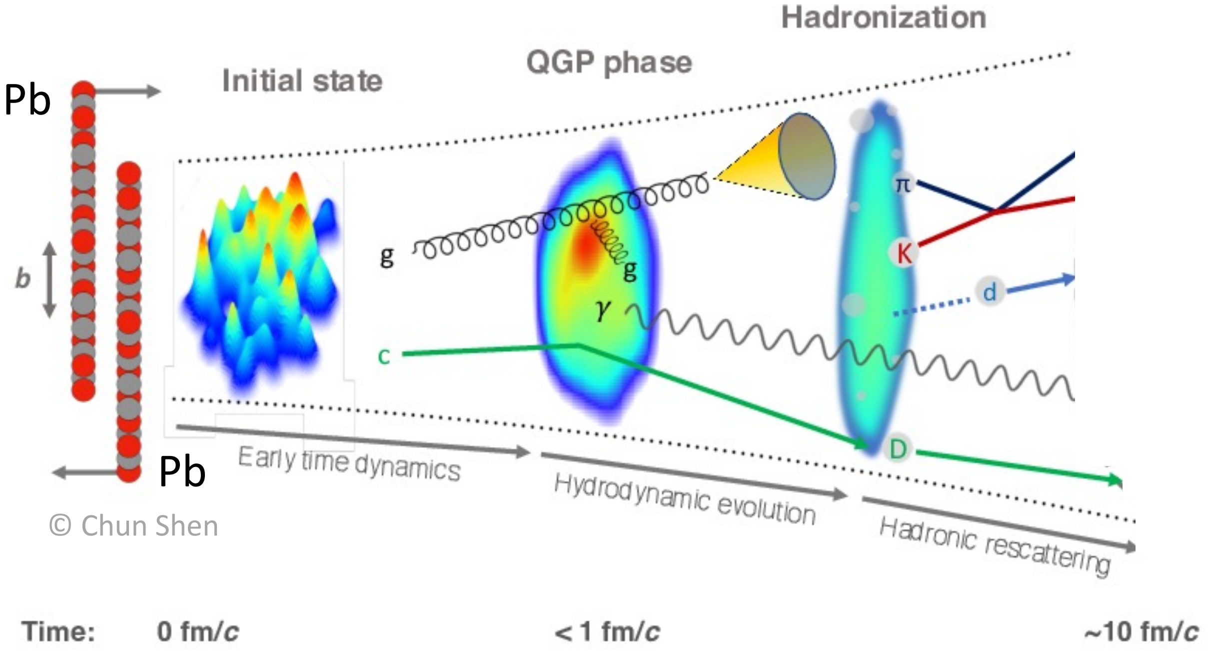

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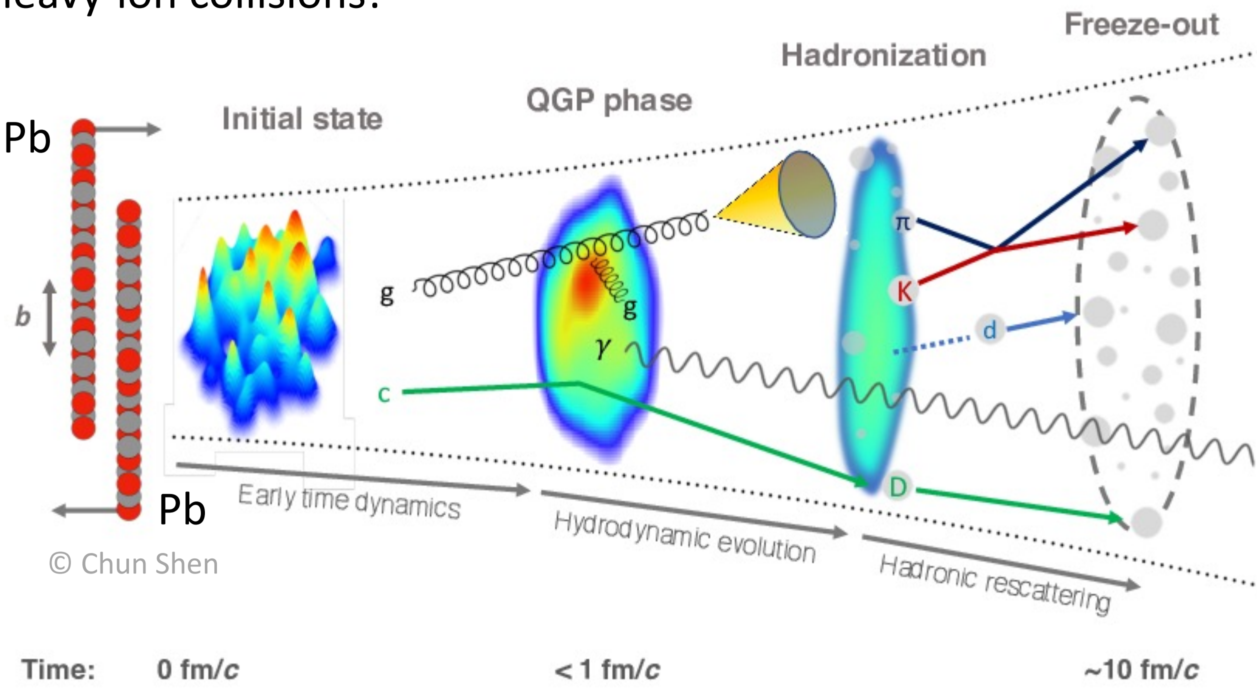

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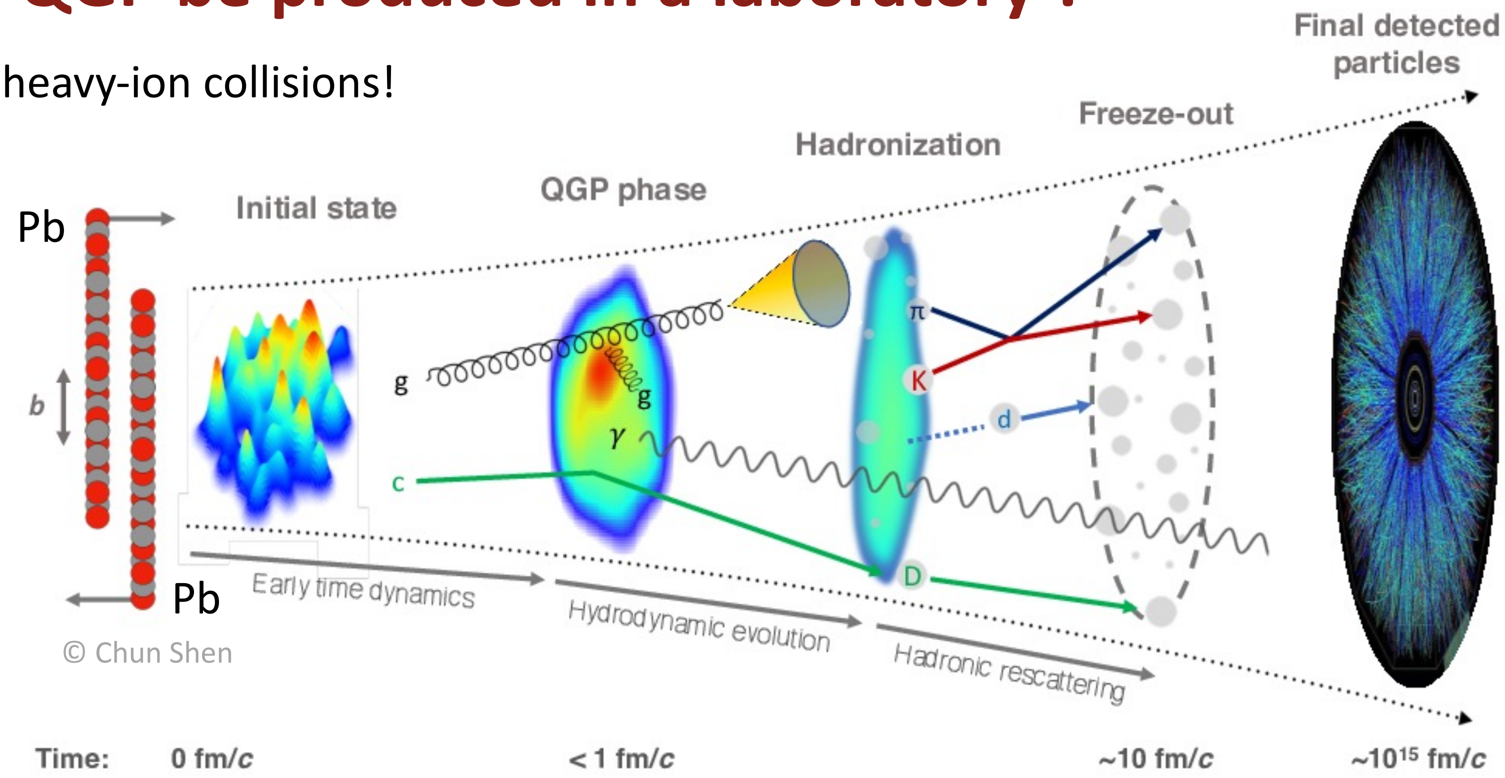

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- Finally particles reach the detectors

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How do we produce relativistic heavy-ion collisions?

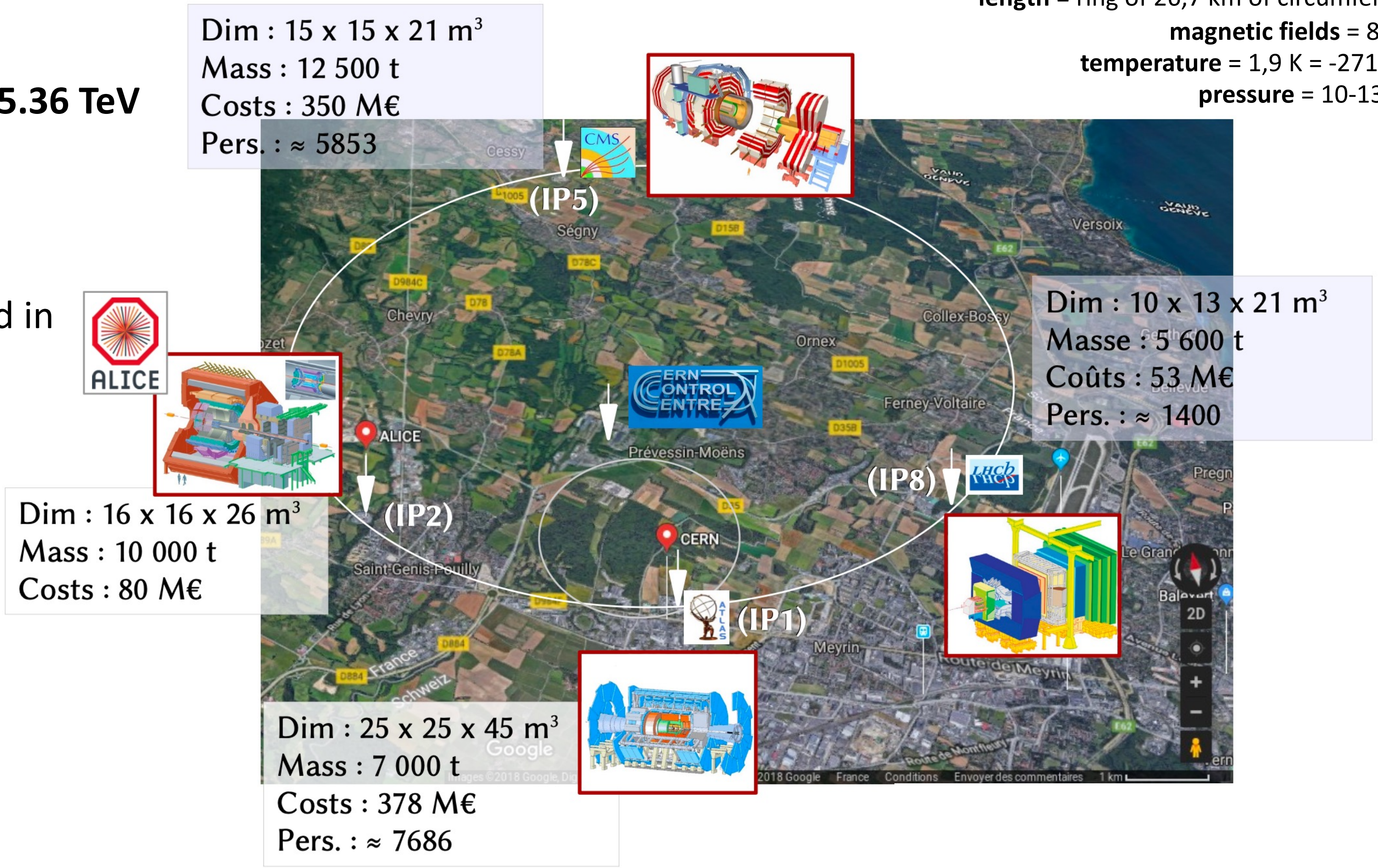
The Large Hadron Collider (LHC) at CERN is the most powerful accelerator in the world: it can collide protons and ions (Pb, Xe, O, Ne) :

Run3
- pp collisions at $\sqrt{s} = $ **13.6 TeV**
- Pb^{82+}—Pb^{82+}collisions at $\sqrt{s} = $ **5.36 TeV**

length = ring of 26,7 km of circumference
magnetic fields = 8,33 T
temperature = 1,9 K = -271,3o C
pressure = 10-13 atm

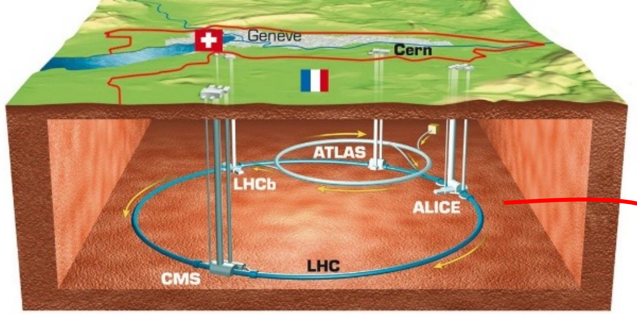
Four large experiments are installed in underground caverns to record the particle collisions:

- ALICE
- ATLAS
- LHCb
- CMS



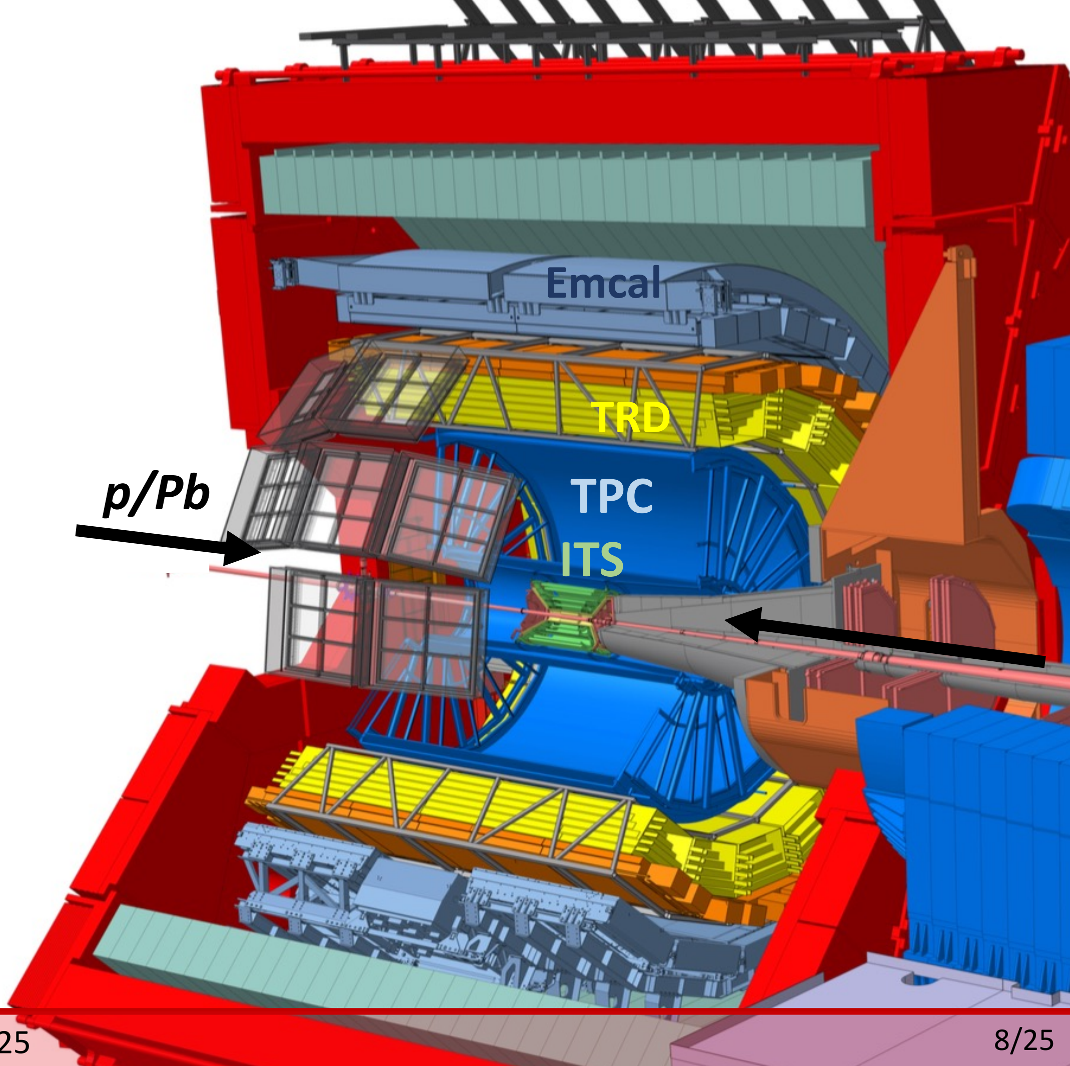
ALICE

A Large Ion Collider Experiment
located at CERN, on the LHC



- Specifically designed to study QGP
- The detector is embedded in a solenoidal magnetic field of 0.5 T:
  - → trajectory of charged particles
  - → charged particle identification via energy loss ($\frac{dE}{dx}$)
  - → mesure their momentum

Central barrel :$|\eta| < 0.9$, $0 < \Phi < 2\pi$



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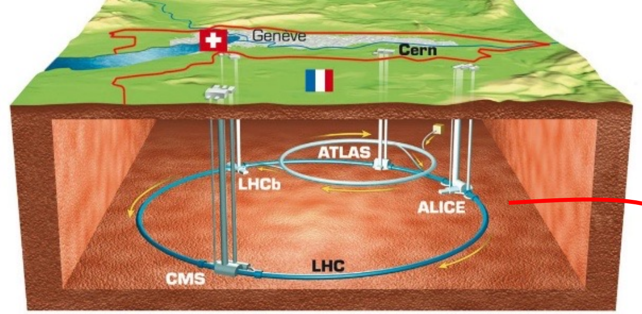

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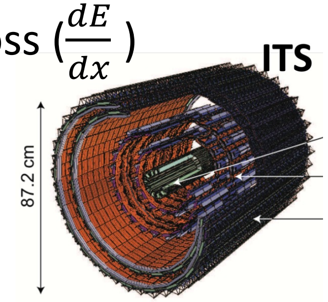
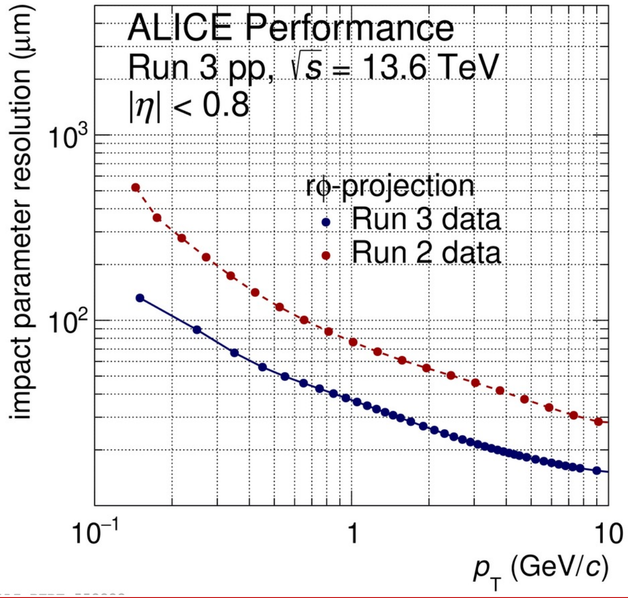
ITS (Inner Tracking System) : 7 layers of Si detectors



- close to the interaction point and provides **precise vertexing and tracking informations** (primary + secondary vertex)

Resolution on track position at the primary vertex better than 30 μm for p_T > 1 GeV/c – Run3



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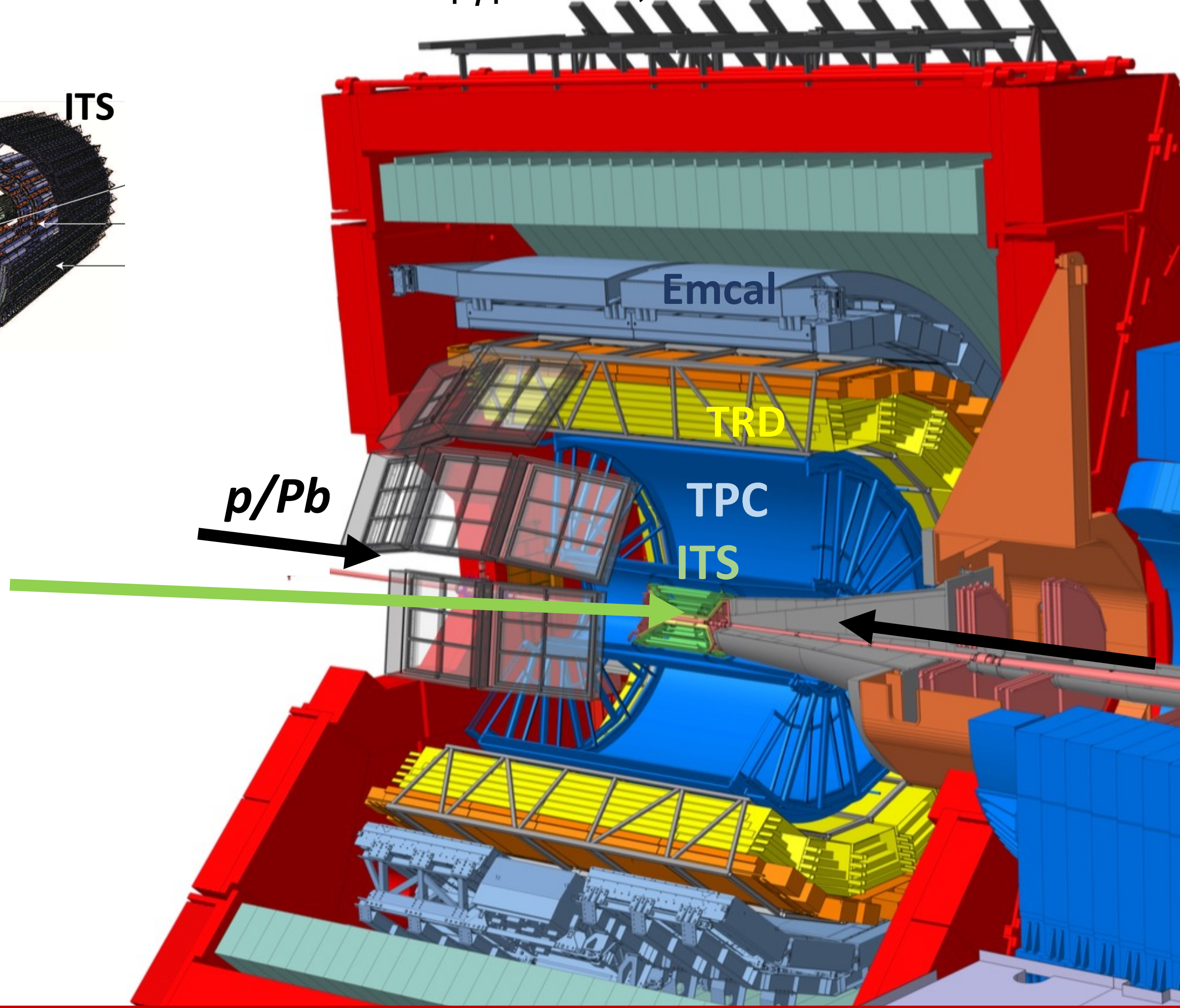

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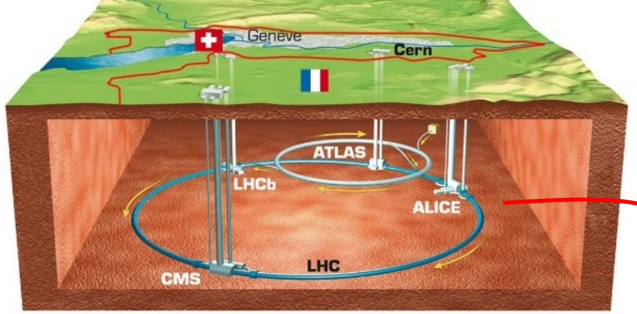

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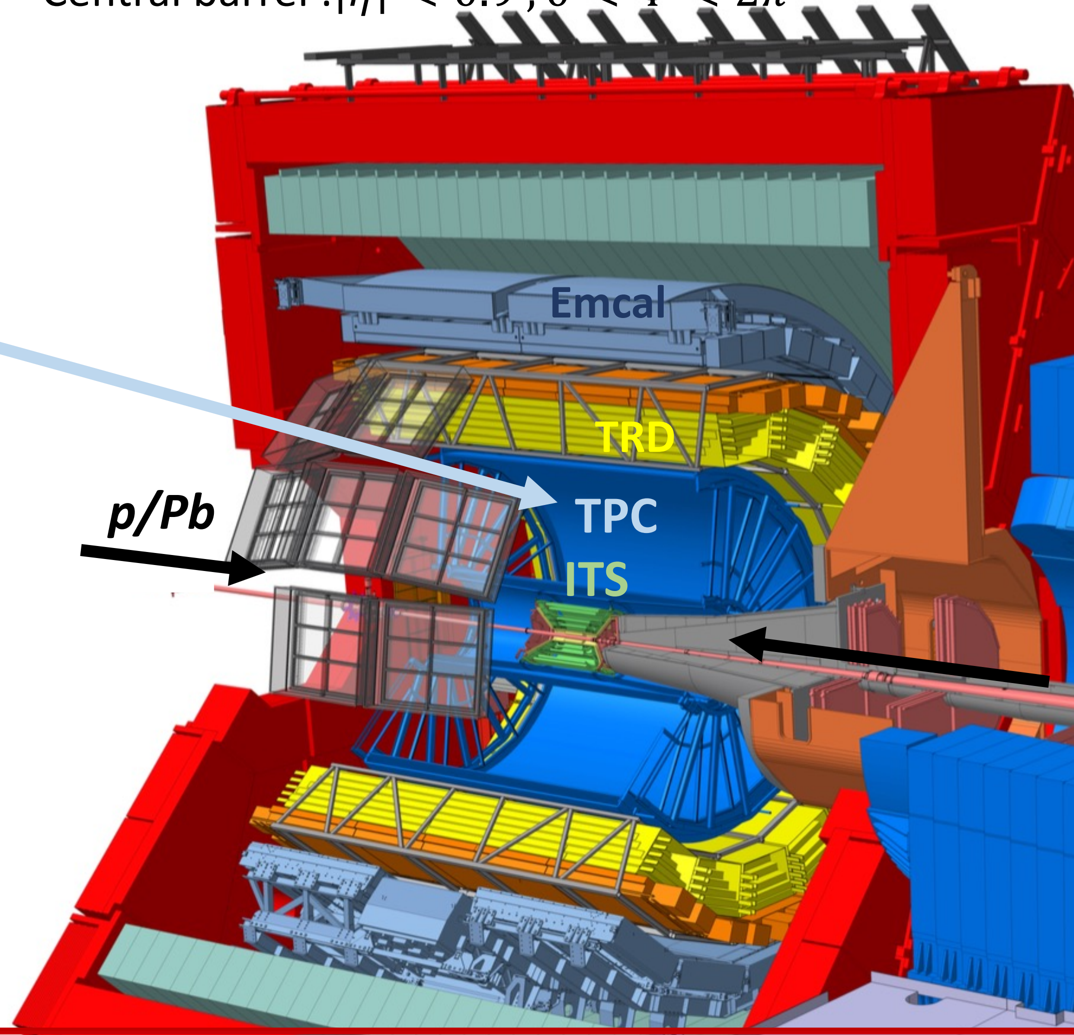
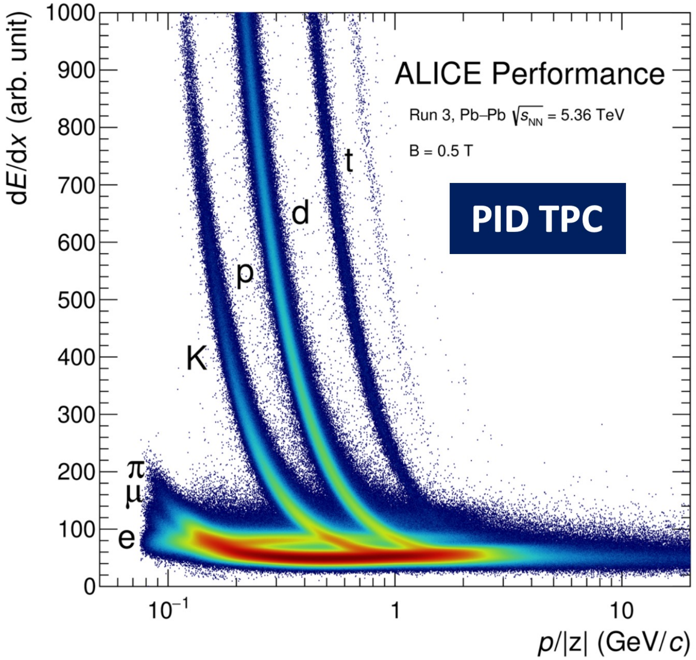


TPC (Time Projection Chamber) : drift chamber, main tracking detector



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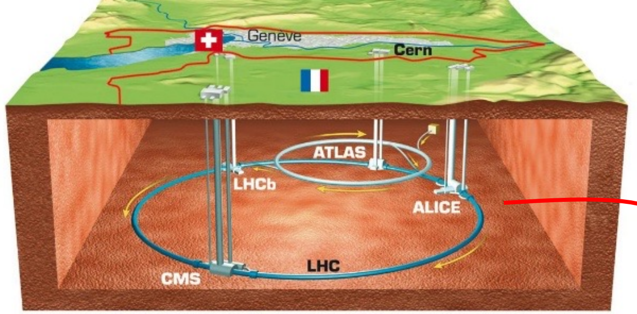

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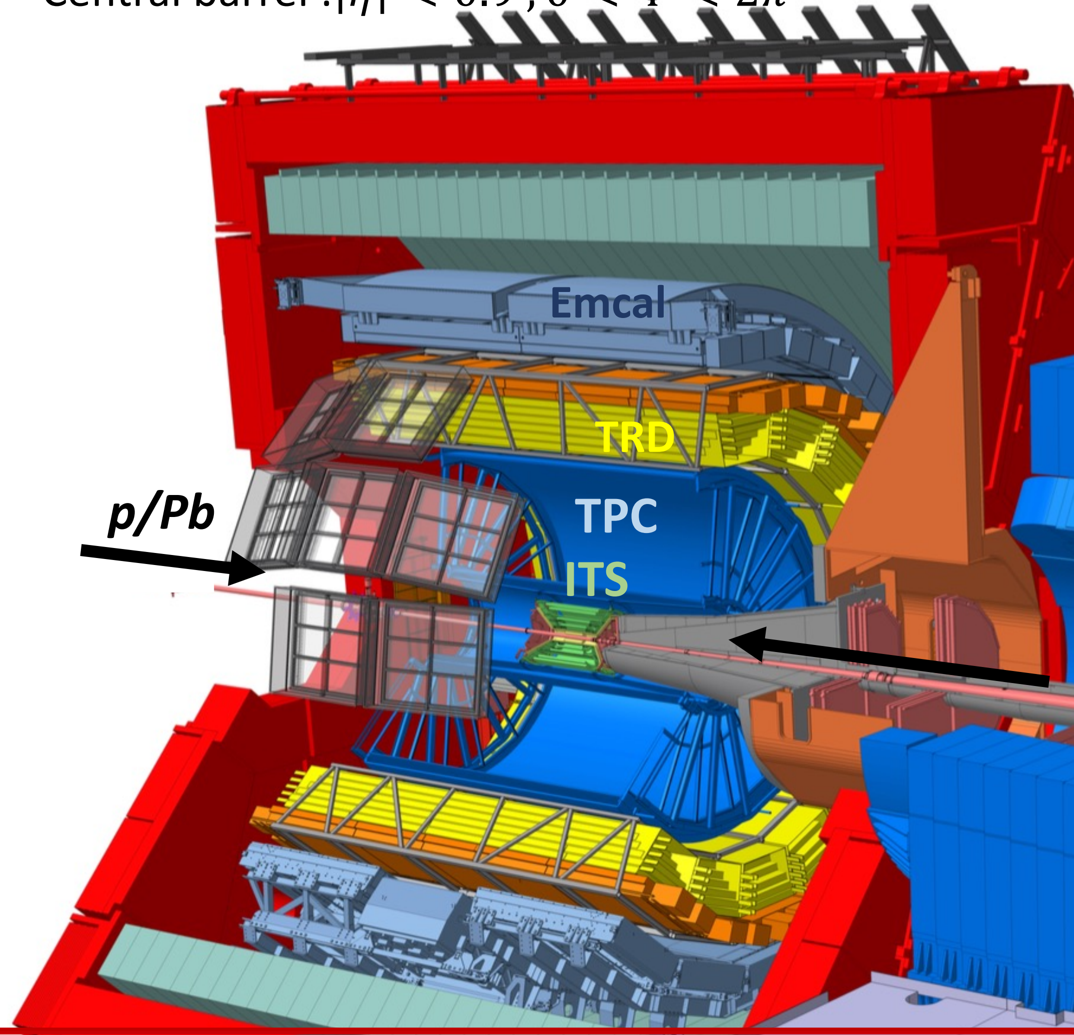
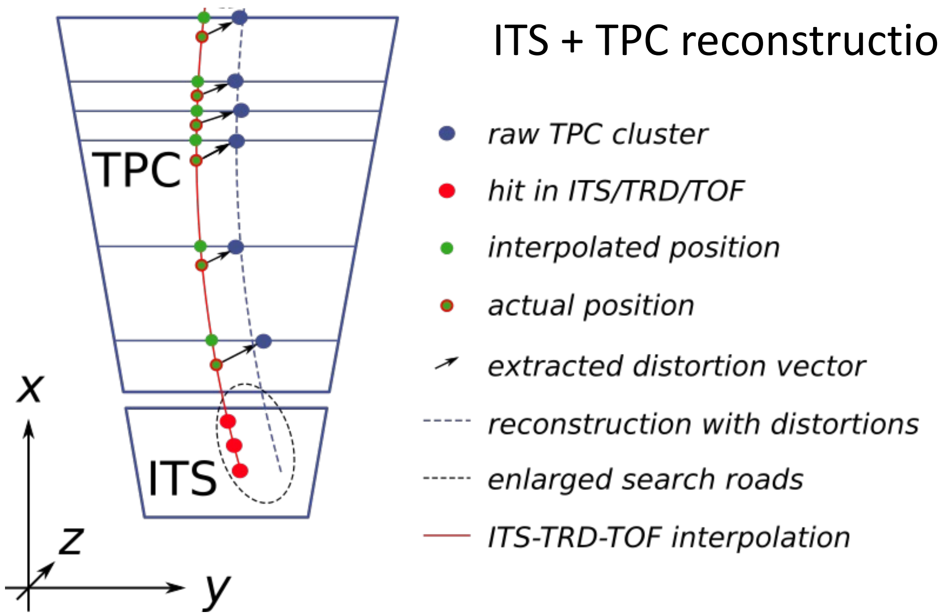


ITS + TPC reconstruction = global tracks



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Probes to QGP

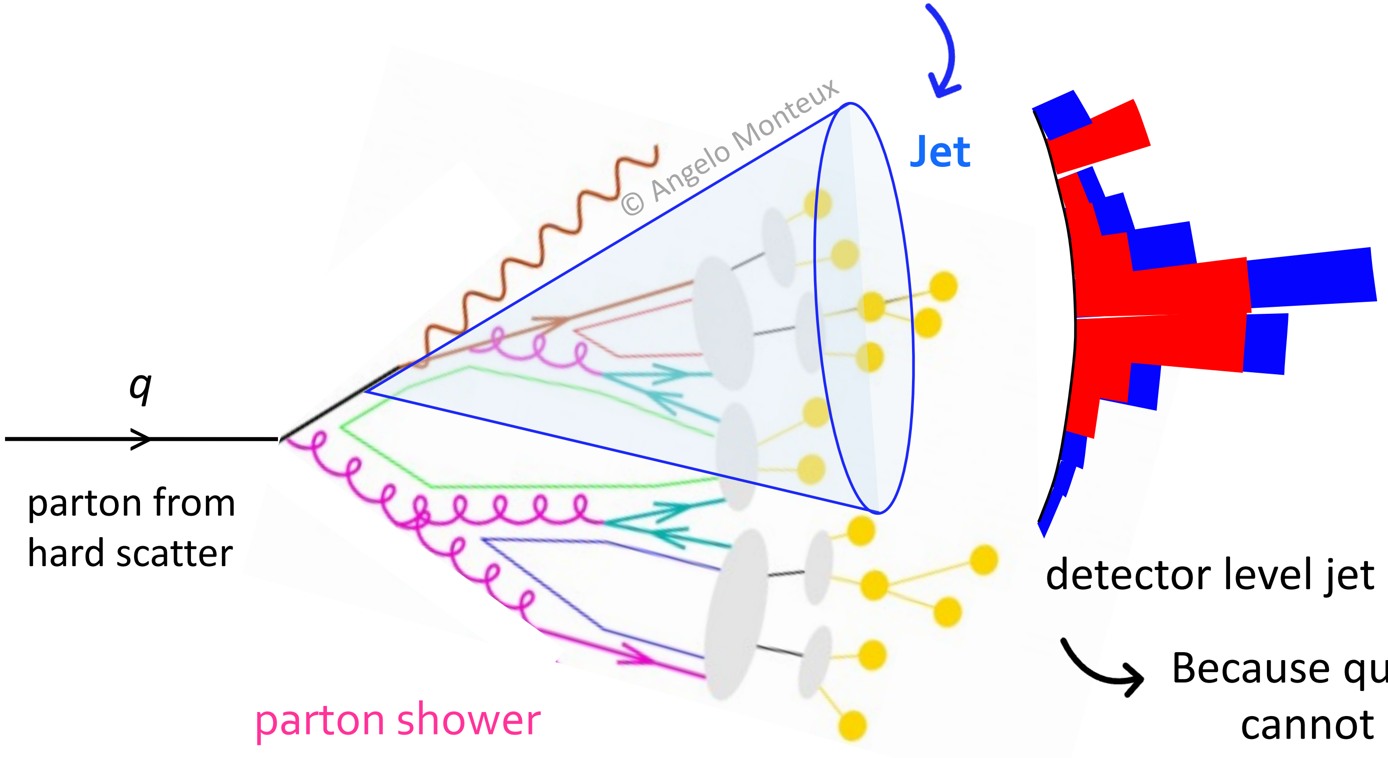
- SOFT PROBES: low energy particles ($E < 5$ GeV) to study thermodynamic and hydrodynamic properties and collectivity effects of the QGP

- HARD PROBES: high-energy partons (quarks and gluons) produced in the early stage of the collision to study how particles interact with the QGP medium and lose energy

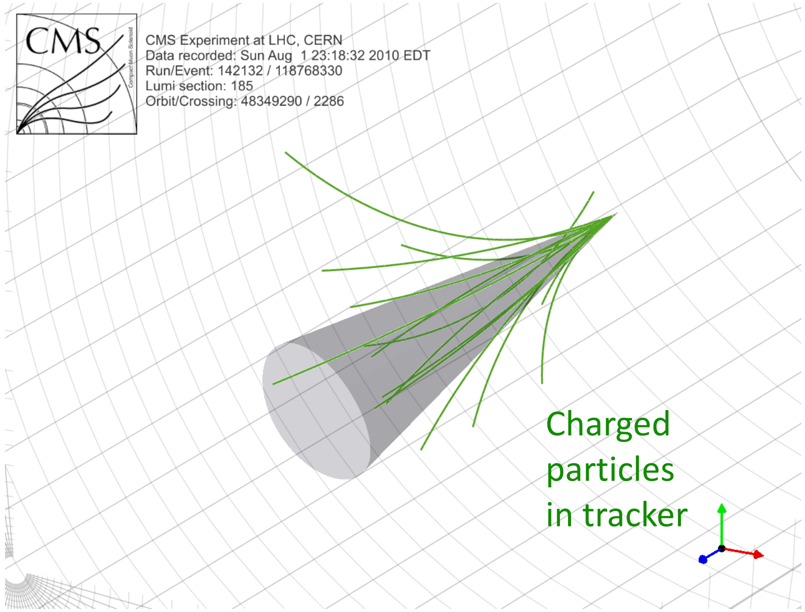
→ **Jets**

What is a jet?

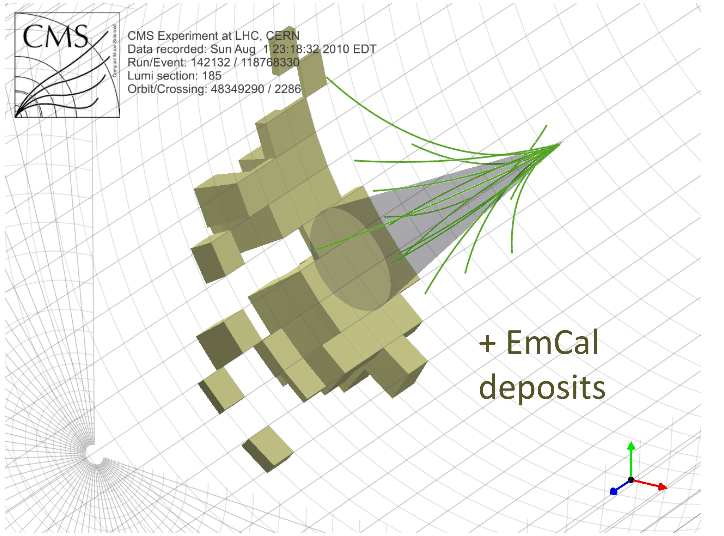
Jets are collimated sprays of particles produced in the initial stages of collisions



Because quarks and gluons cannot be observed directly, what we detect experimentally is this collimated collection of final-state particles



[Quantumdiaries - Anatomy of a jet in CMS]



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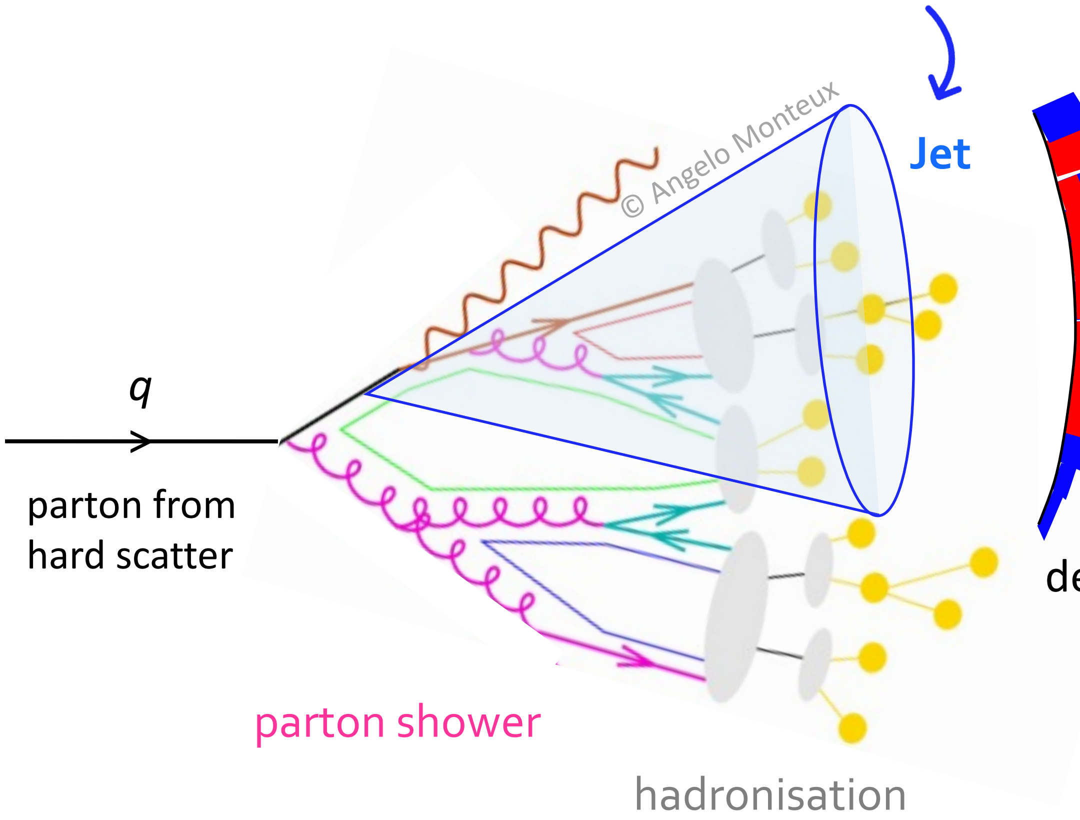
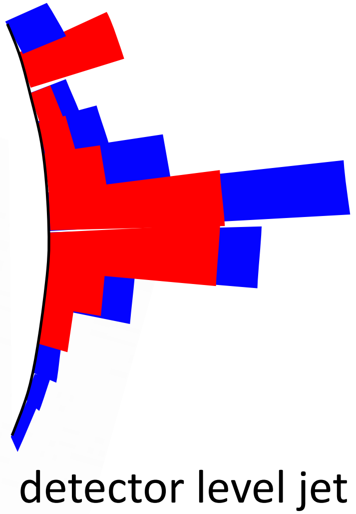
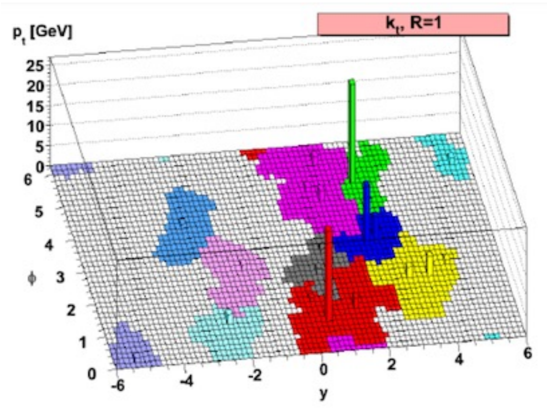
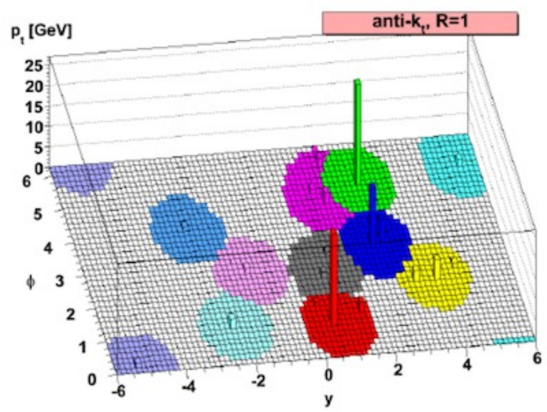


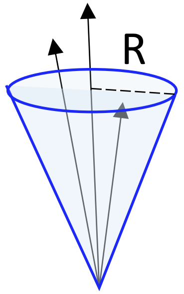


How to reconstruct them ?

- Experimentally, jets are not uniquely defined objects (no single optimal definition)
- Clustering algorithms that combine particles based on their kinematics
- Different algorithms exist (anti-k_T, k_T,C/A), and they require parameters : jet radius R (controls the angular size of the jet)

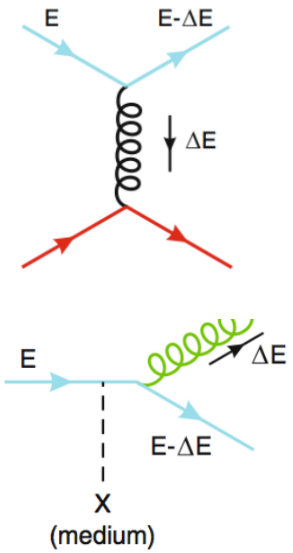






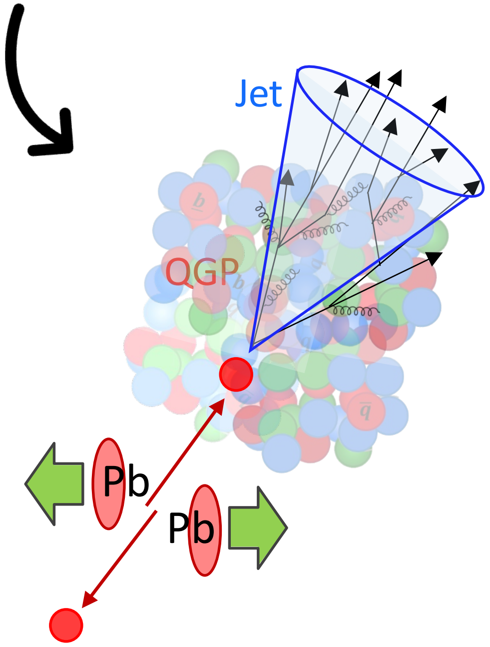
Jets to probe QGP

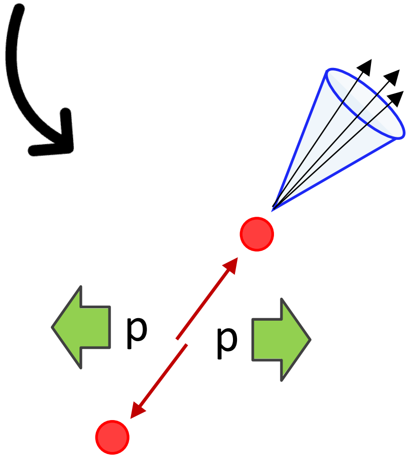
In heavy-ion collisions, jets produced in Pb–Pb interactions traverse the QGP unlike in pp collisions (no medium is formed)



Strong energy loss via:

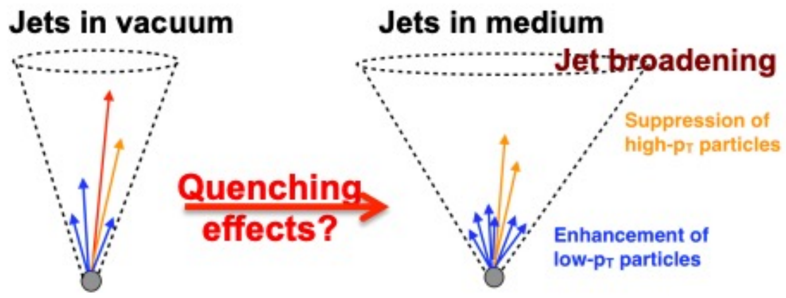
- Collisional interactions with the medium constituents
- Medium-induced gluon radiation : gluonstrahlung





In medium → broadening of the jet profile and out-of-cone jet radiation

These effects lead to a modification of both the **jet energy** and its **internal structure**, a phenomenon known as **jet quenching**



Jets to probe QGP

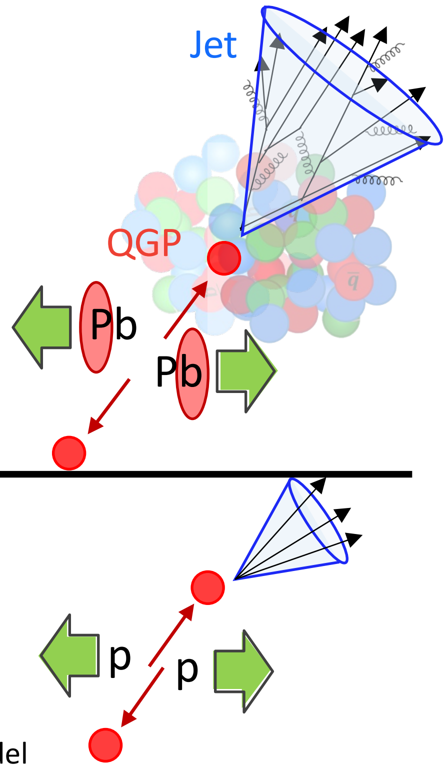
To quantify this suppression, we compare Pb–Pb yields to pp reference via the nuclear modification factor R_{AA} :

Binary nucleon-nucleon pp collisions, encodes collision geometry

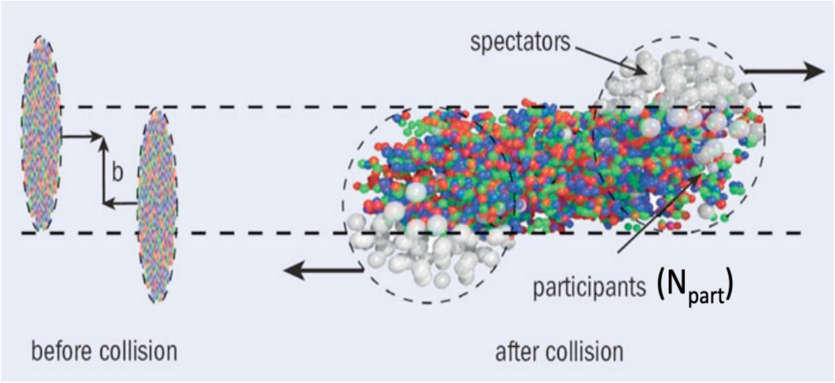
PbPb

pp

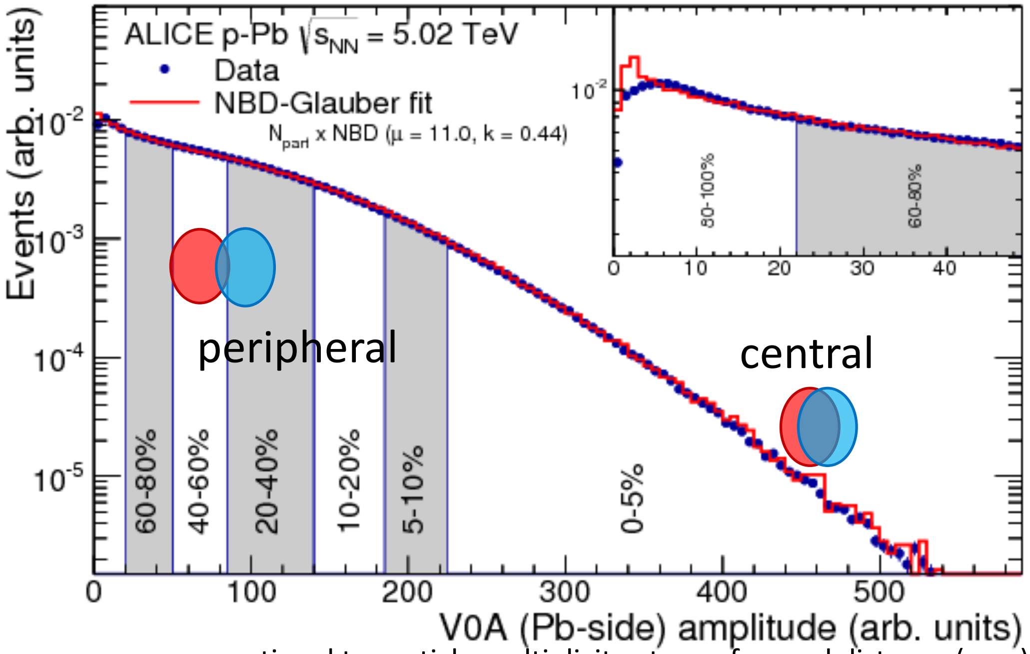
$$R_{AA} = \frac{\frac{d^2N_{AA}}{d\eta dp_T}}{\langle N_{coll}\rangle \cdot \frac{d^2N_{pp}}{d\eta dp_T}} =$$



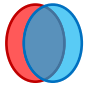
$\langle N_{coll}\rangle$, $\langle N_{part}\rangle$ from Glauber model

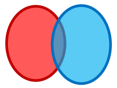


Centrality classifies geometric overlap of the HI collision



proportional to particle multiplicity at very forward distance (a. u.)


A larger V0A signal corresponds to more central collisions


Peripheral collisions, with lower particle production

The distribution is fitted using the Glauber model, which connects the collision geometry to particle production vertical lines -> centrality classes

Jets to probe QGP

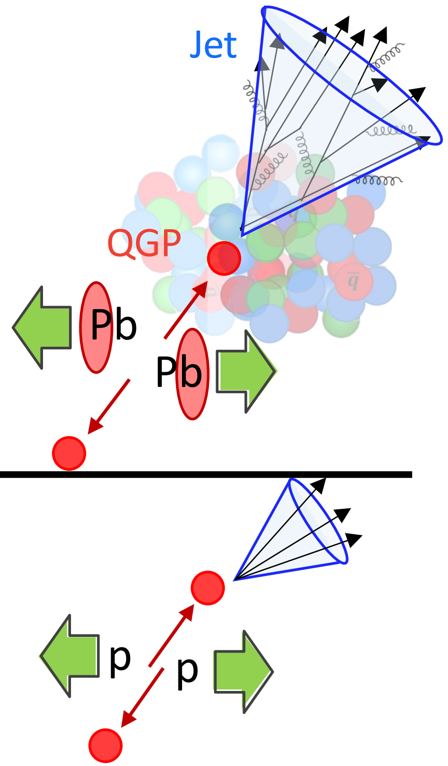
To quantify this suppression, we compare Pb–Pb yields to pp reference via the nuclear modification factor R_{AA} :

Binary nucleon-nucleon pp collisions, encodes collision geometry

PbPb

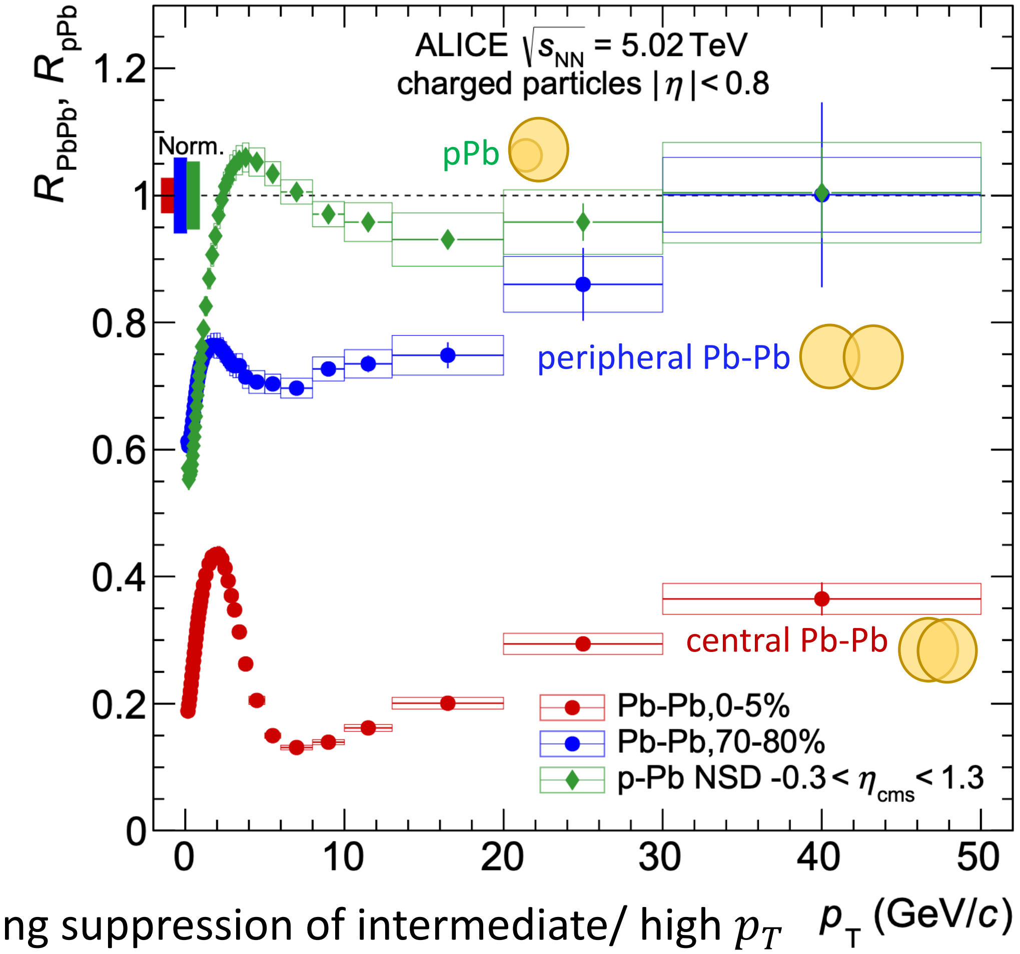
$$R_{AA} = \frac{\frac{d^2N_{AA}}{d\eta dp_T}}{\langle N_{coll} \rangle \cdot \frac{d^2N_{pp}}{d\eta dp_T}} =$$

pp



- $R_{AA} = 1$ → no medium effect
- $R_{AA} < 1$ → suppression due to jet quenching

Provides a direct observable of parton energy loss in the QGP



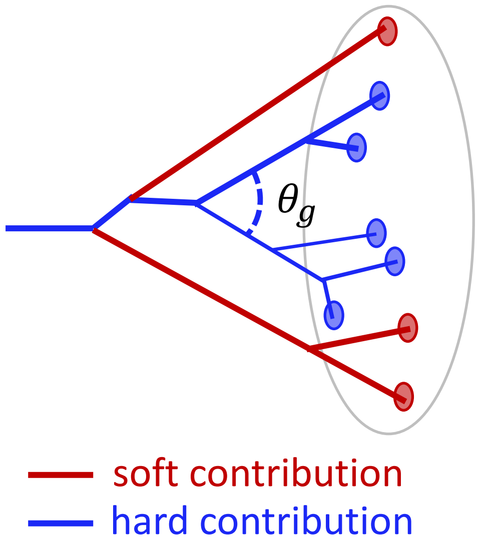
- Strong suppression of intermediate/ high p_T particles in central Pb-Pb collisions
- Absent in p-Pb collisions (no QGP expected)
→ final-state effect

Jet substructure

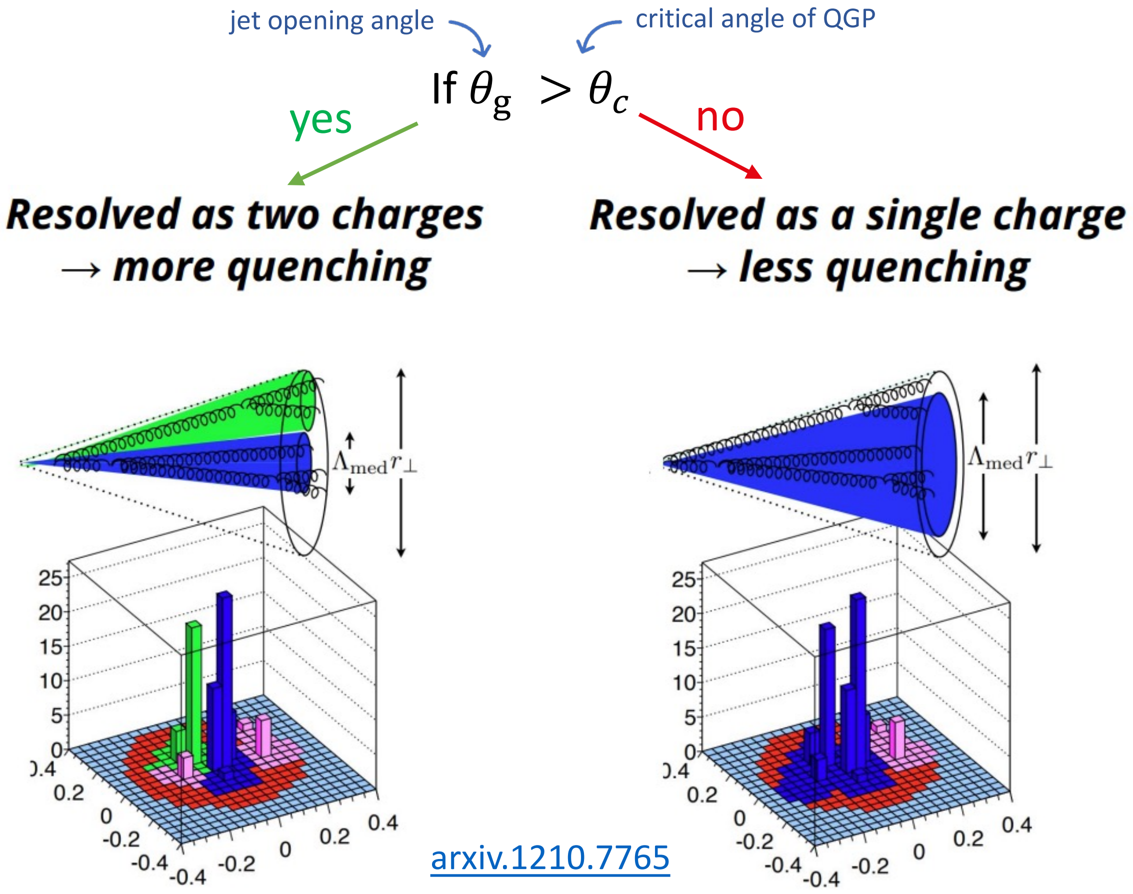
The R_{AA} measured in central collisions clearly shows that jets lose energy in the medium → does not tell us how the **internal structure** of the jet is modified

This motivates the study of **jet substructure** observables, which provide more differential access to the jet evolution inside the QGP

A natural observable is the **jet opening angle** θ_g, which corresponds to the angle of the first hard splitting inside the jet :



Medium resolution angle : θ_c



arxiv.1210.7765

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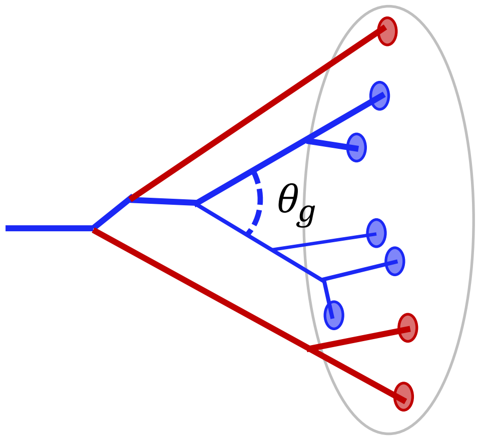


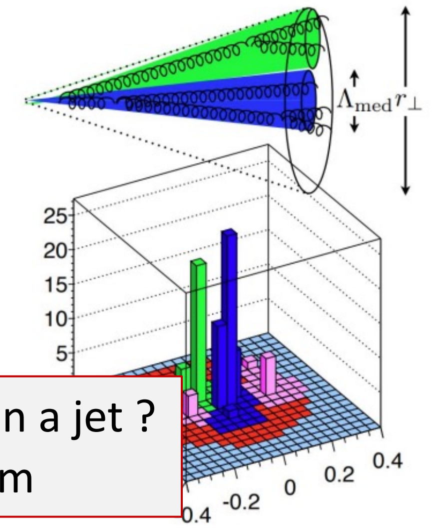
soft contribution
hard contribution

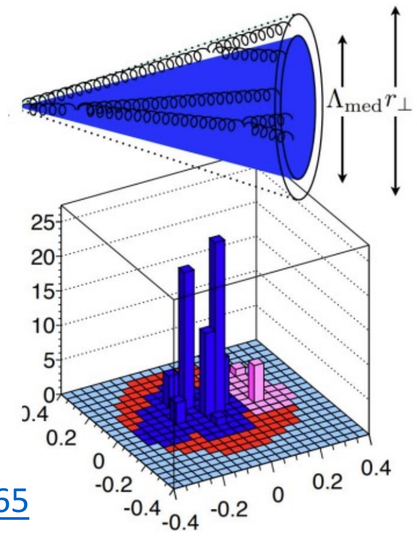
Medium resolution angle : θ_c

jet opening angle → If $\theta_g > \theta_c$ ← critical angle of QGP

yes → ***Resolved as two charges → more quenching***

no → ***Resolved as a single charge → less quenching***



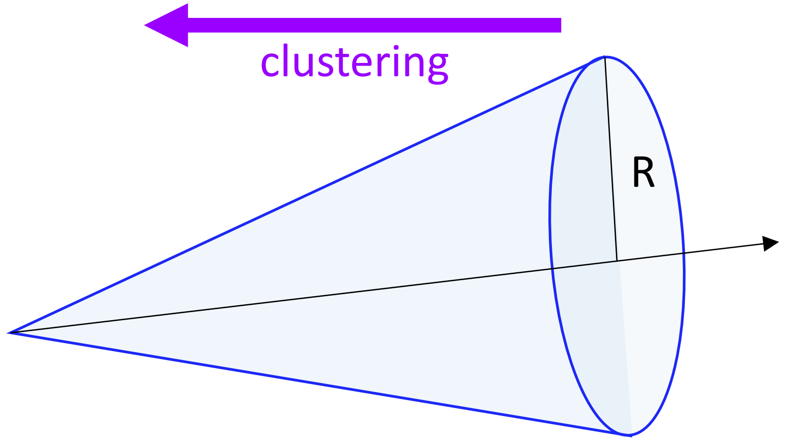


arxiv.1210.7765

How do we access θ_g in a jet ?
→ SoftDrop algorithm

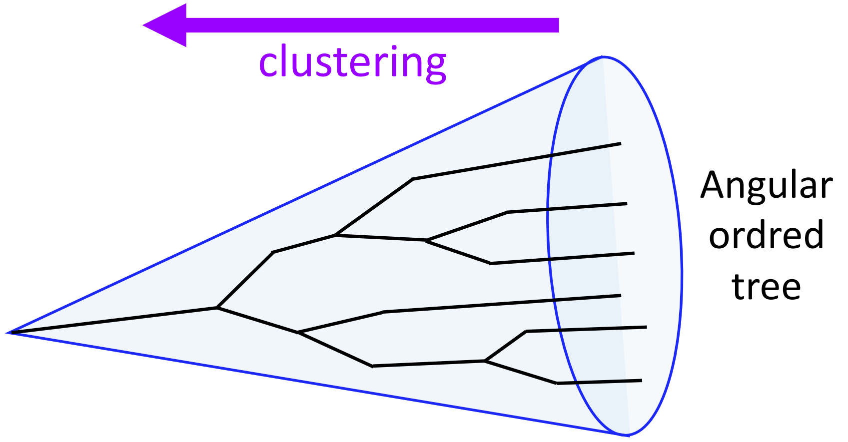
SoftDrop grooming algorithm

SoftDrop grooming algorithm



- The jet is first clustered using a standard algorithm (anti-k_T, …)

SoftDrop grooming algorithm



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- Jet constituents are reclustered with Cambridge-Aachen (CA)

SoftDrop grooming algorithm

- The jet is first clustered using a standard algorithm (anti-k_T, …)
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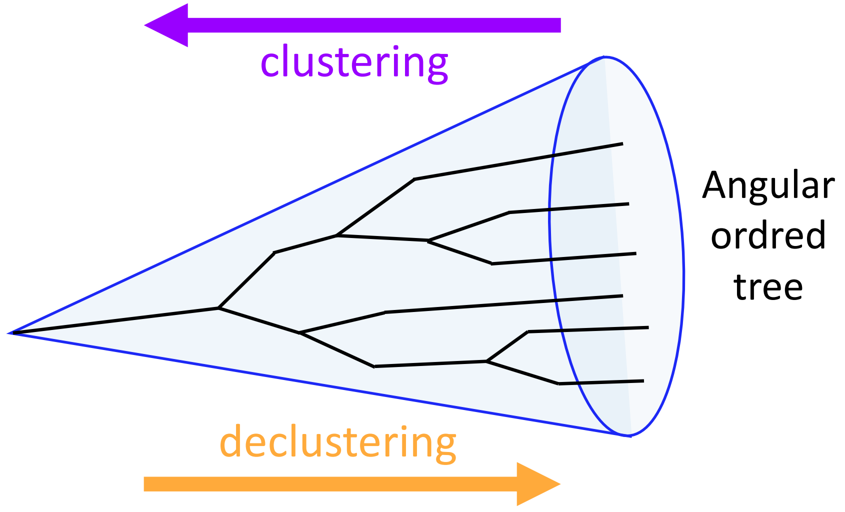
- The CA tree jet is declustered iteratively :



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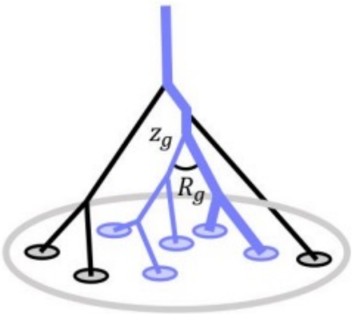
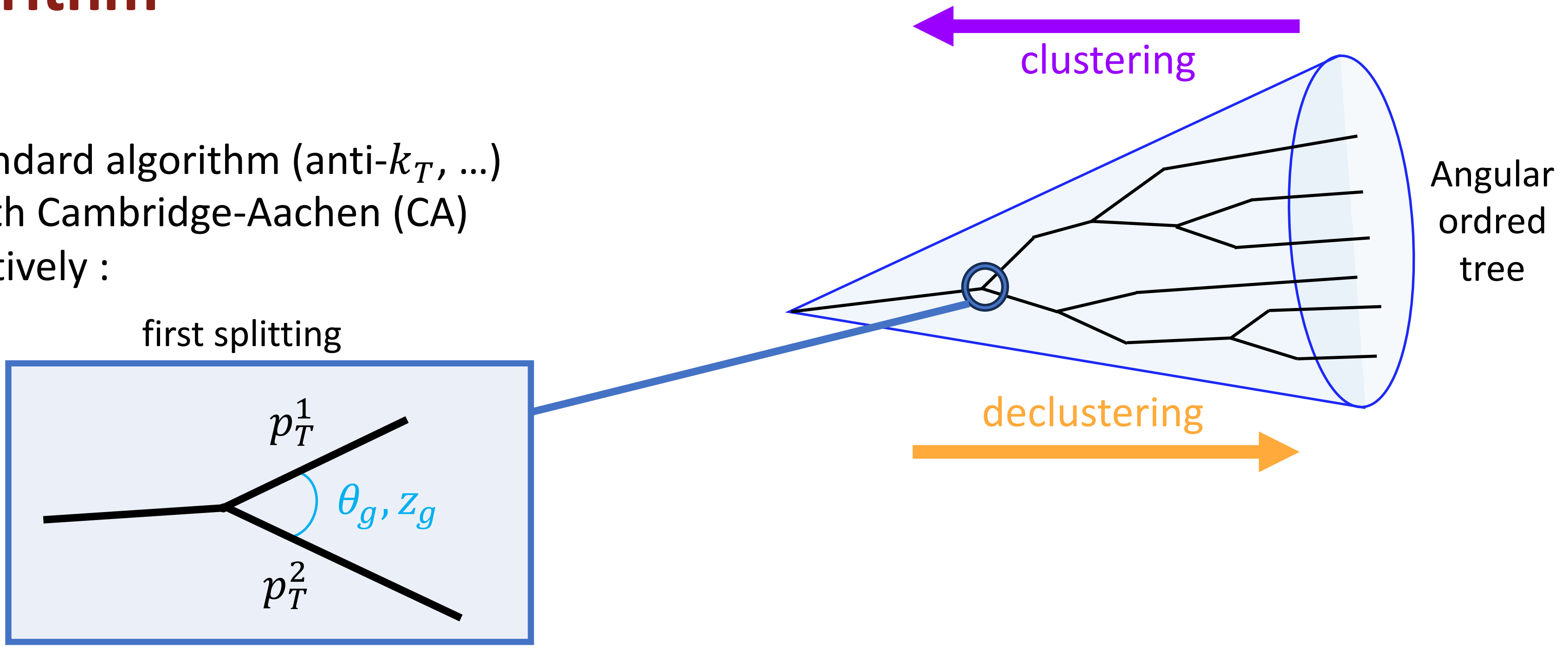
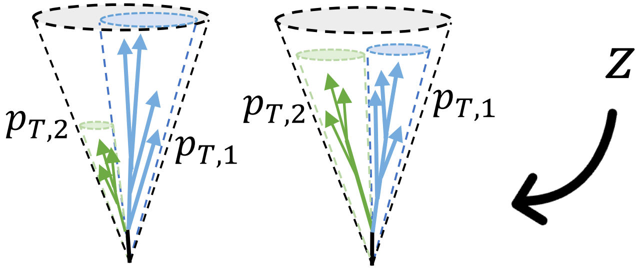




- Calculate the energy sharing :



$z_g \ll 0.5$
1 hard subjet

$z_g \sim 0.5$
2 hard subjets

$$z = \frac{min(p_T^1, p_T^2)}{p_T^1 + p_T^2} > z_{cut}\left(\frac{R_g}{R}\right)^{\beta}, \theta_g \equiv \frac{R_g}{R}$$

z_{cut} β : SoftDrop parameters

In HI : $z_{cut} = 0.2, \quad \beta = 0$

SoftDrop grooming algorithm

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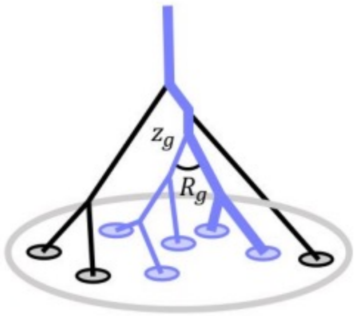
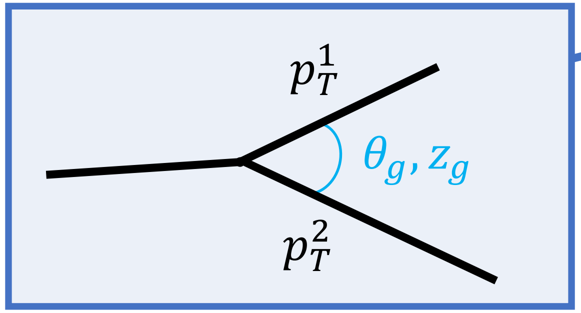
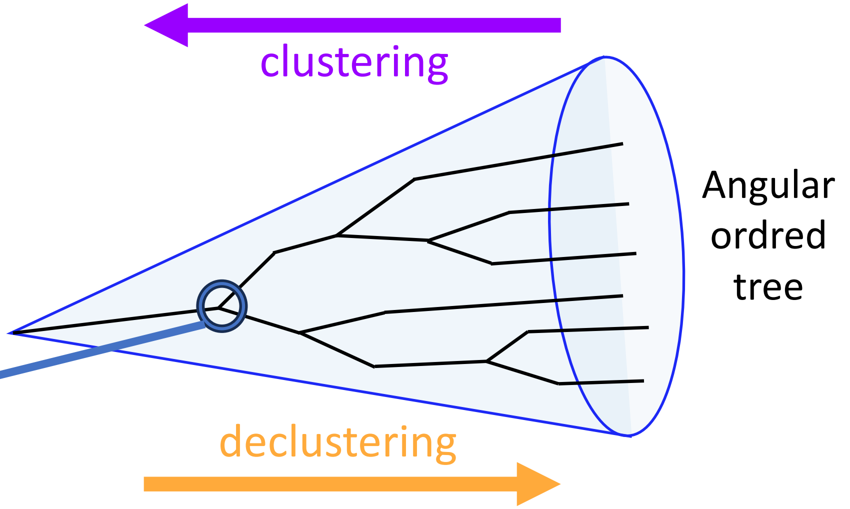


first splitting





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- **If the condition is satisfied**, the splitting is accepted and we keep the two branches : $z = z_g$

SoftDrop grooming algorithm

© Vangelis Vladimirov

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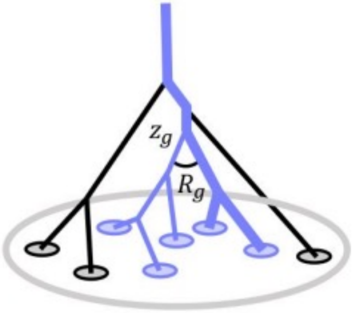
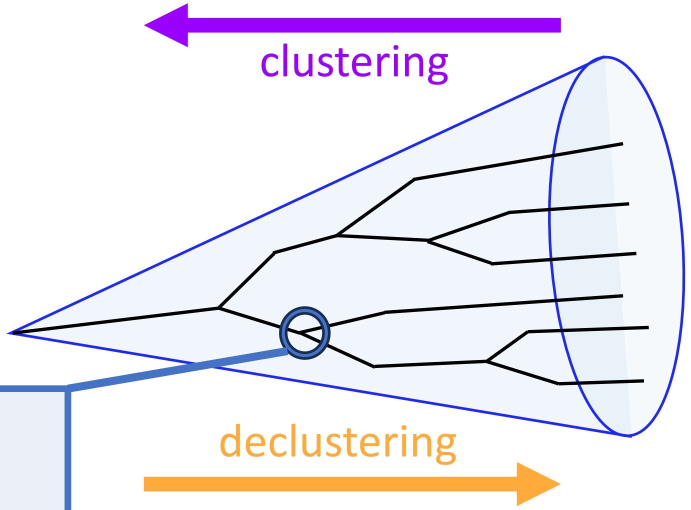
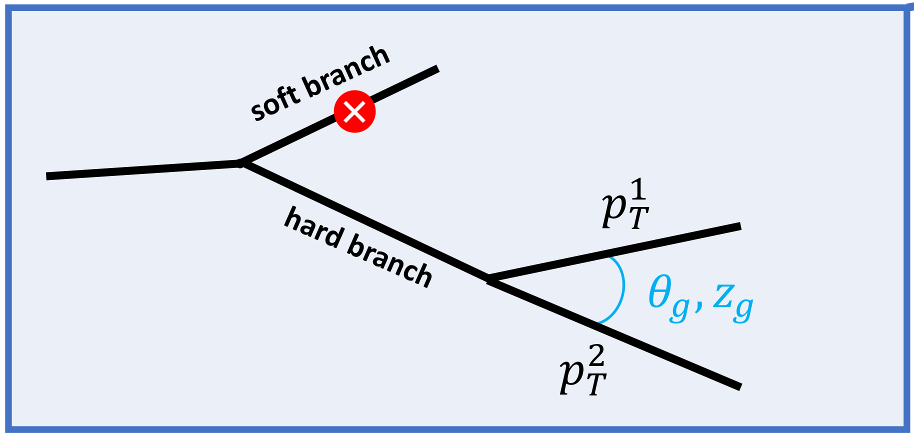


© Bharadwaj Harikrishnan





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In HI : $z_{cut} = 0.2, \quad \beta = 0$

- **If the condition is satisfied**, the splitting is accepted and we keep the two branches : $z = z_g$
- **If the condition is not satisfied**, the softer branch (smaller p_T) is removed, and the procedure continues with the remaining branch

SoftDrop grooming algorithm

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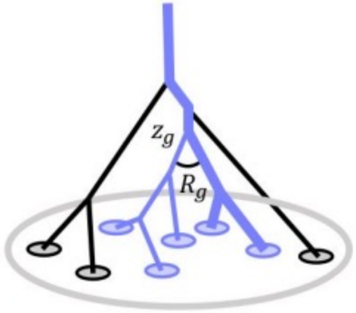

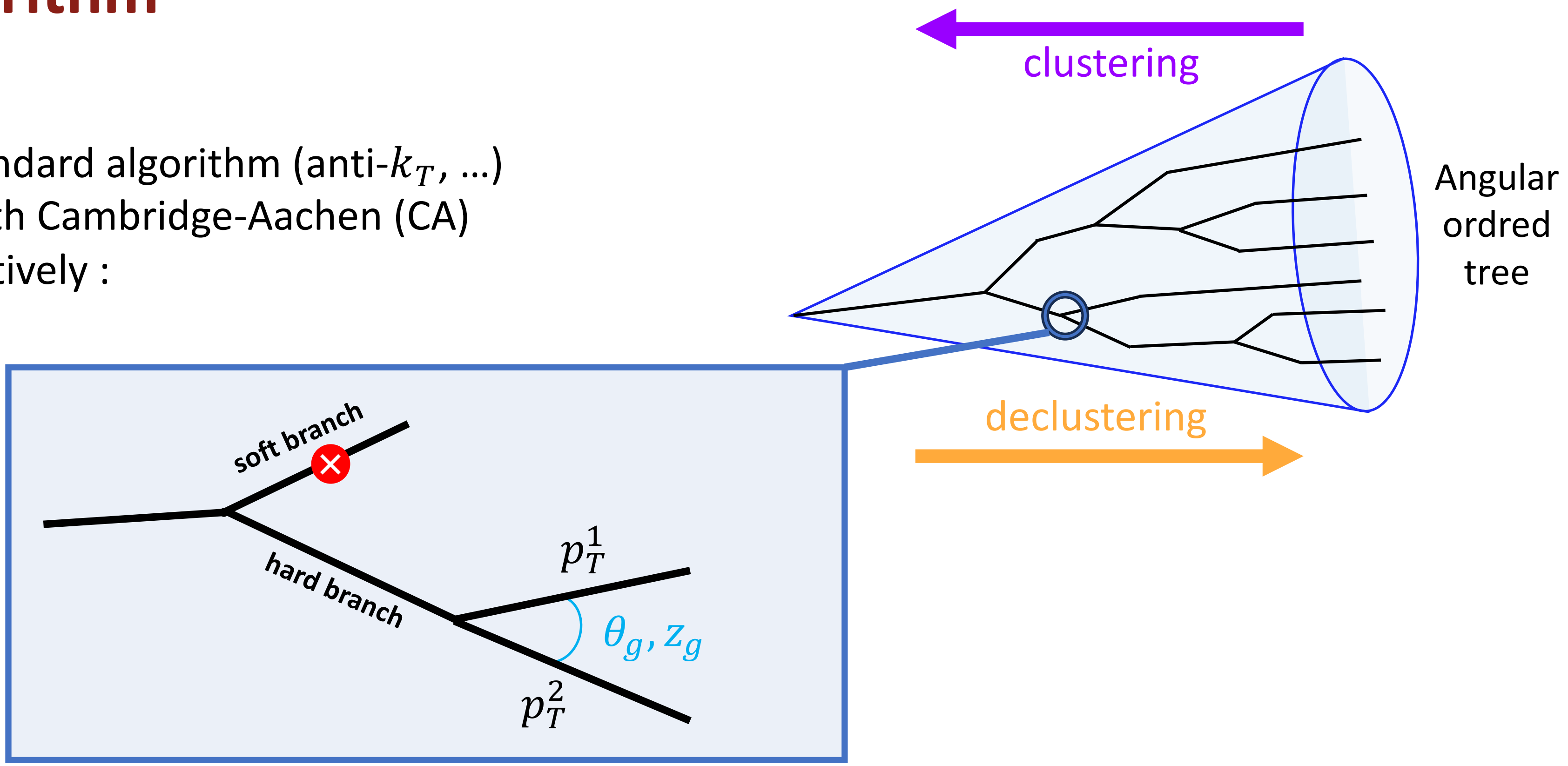

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z_{cut} β : SoftDrop parameters

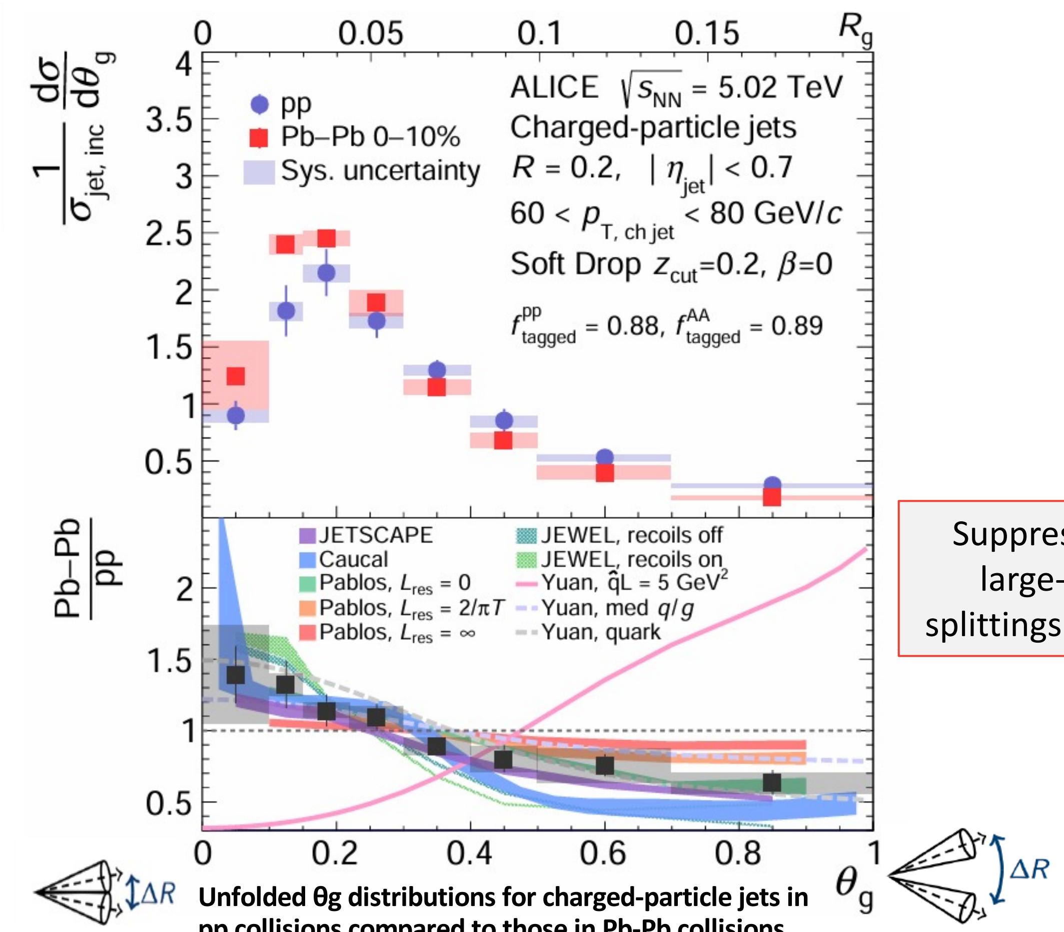
In HI : $z_{cut} = 0.2, \quad \beta = 0$

Objective: allows us to isolate the hard core of the jet by removing soft, large-angle radiation

This is particularly important in heavy-ion collisions, where there is a large background coming from the underlying event (soft background particles)

Motivations

Run2 analysis and theoretical developments show that θ_g is particularly interesting to study medium effects



Unfolded θg distributions for charged-particle jets in pp collisions compared to those in Pb-Pb collisions

PhysRevLett.128.102001

Suppression of large-angle splittings in Pb–Pb

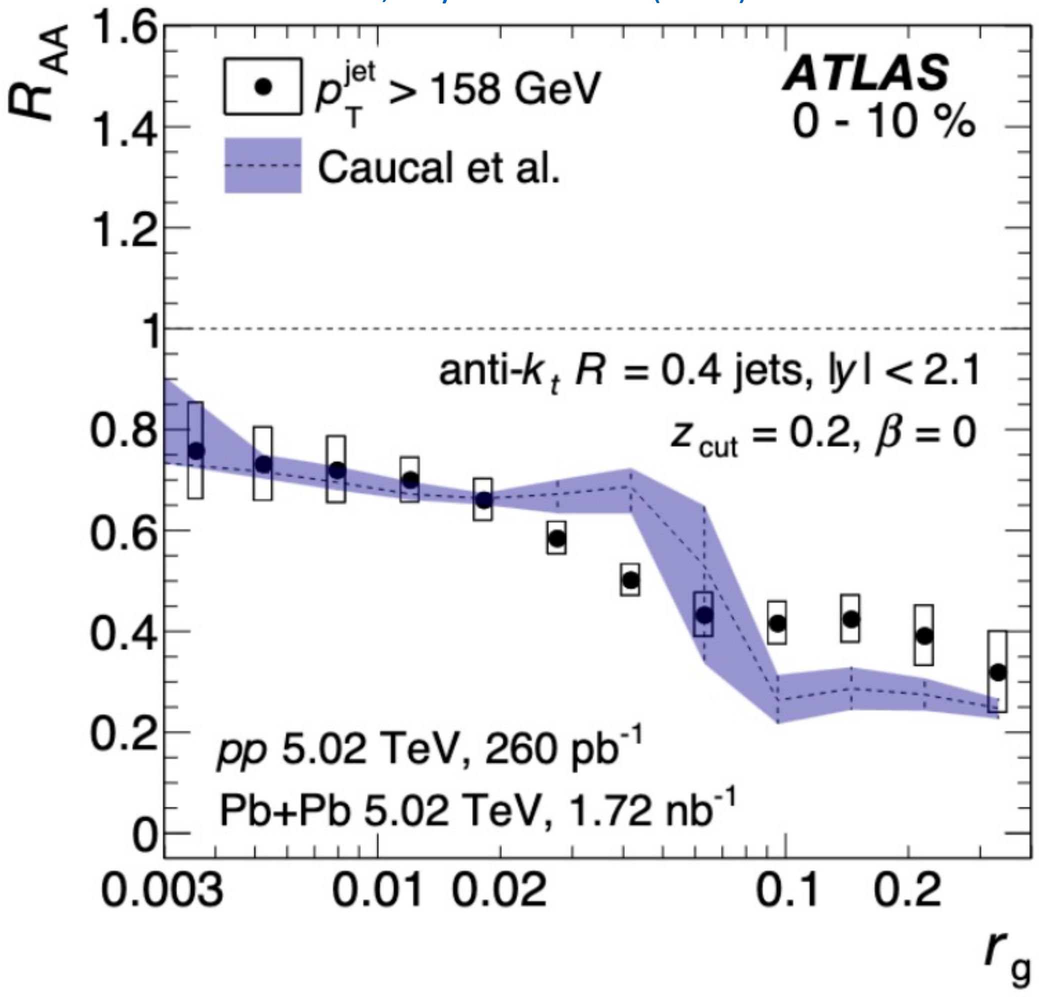
ALICE measurement of the θ_g distribution

- Suppression of large-angle splittings in Pb–Pb
- The core of jets are narrower in pbPb compared to pp collisions, most models capture the qulitative feature of the narrowing

→ Run 3 data:
Run 2: Pb-Pb at 1 kHz, $L_{int} \sim 1\ nb^{-1}$ @ $\sqrt{s} = 5.02$ TeV
Run 3: Pb-Pb at 50 kHz, $L_{int} \sim 10\ nb^{-1}$ @$\sqrt{s} = 5.36$ TeV

Motivations

ATLAS, Phys. Rev. C 107 (2023) 054909



$(\theta_g \equiv \frac{r_g}{R})$

ATLAS measurment $\boldsymbol{R_{AA}}$ **VS** $\boldsymbol{r_g}$ with Run2 data :

- suppression of large-angle splittings in Pb–Pb

With ALICE : reach lower-jet p_T and **extend** the measurement of ATLAS to lower-jet p_T where medium-induced modifications could be stronger.

We have started a collaboration with the theorist P. Caucal Nantes, SUBATECH to obtain theoretical predictions for Run 3

→ Run 3 data

The R_{AA} and r_g studies are two independent analyses: the R_{AA} measurement is a full analysis on its own

QCD Theory

Strong potential

Running of α_s

Quark Gluon Plasma

Deconfined state

QGP main properties

LHC / ALICE

Jets to probe QGP

Jet definition

Jet quenching

SoftDrop Algorithm

Ongoing work

RUN3 Analysis

Embedding

Service Work

Ongoing work

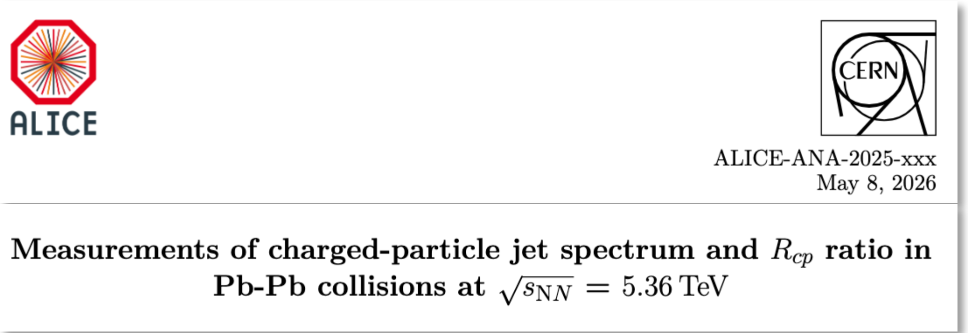
Run 3 jet analysers team: we are a group of 10 members working in collaboration with Asia + UK on the determination of the R_{AA} VS p_T using Run 3 data

Part of team : providing PbPb

$$R_{AA} = \frac{\frac{d^2 N_{AA}}{d\eta d p_T}}{\langle N_{coll} \rangle \cdot \frac{d^2 N_{pp}}{d\eta d p_T}}$$

Other part : pp ref

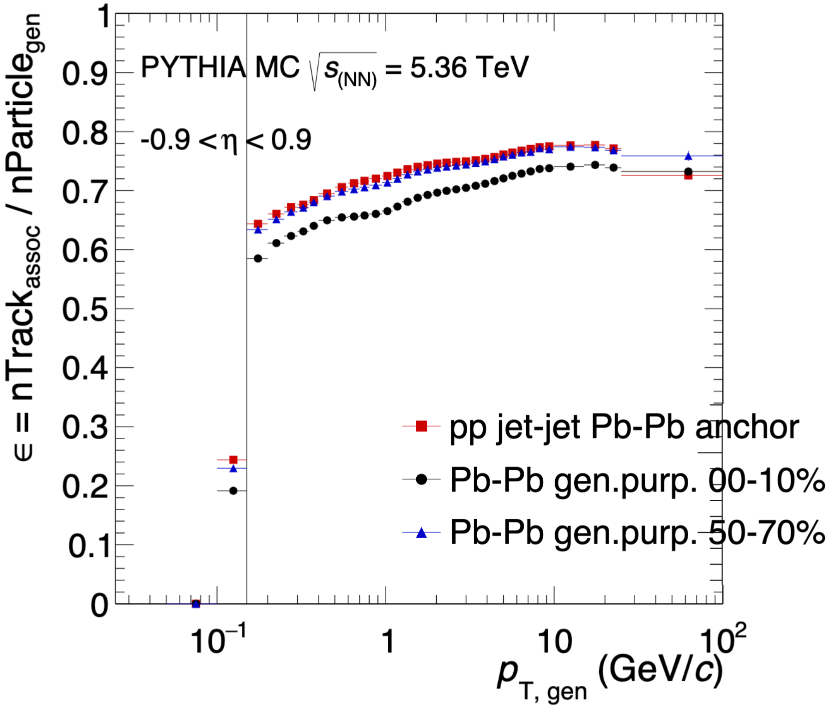
Analysis Note (AN) + publication latter

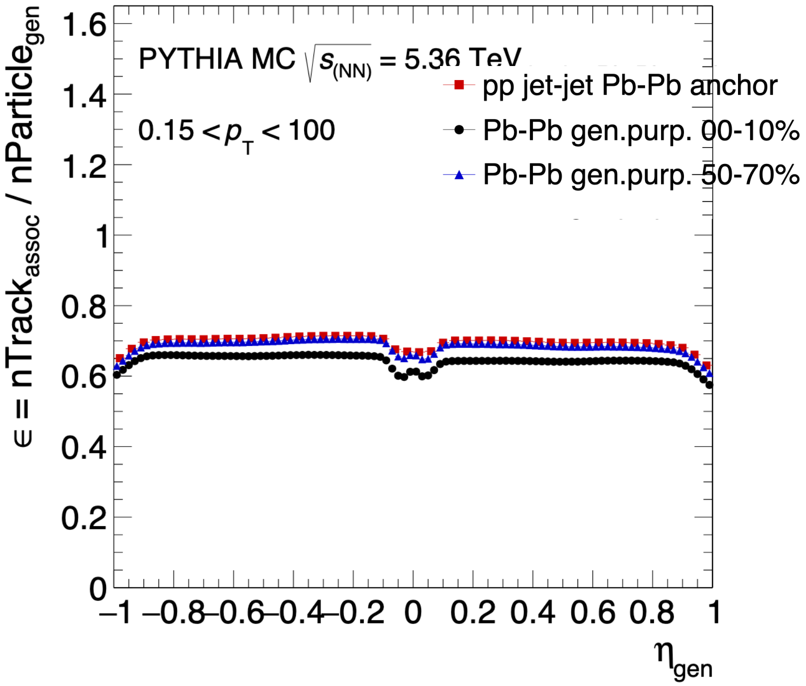

ALICE

ALICE-ANA-2025-xxx
May 8, 2026

Measurements of charged-particle jet spectrum and R_{cp} ratio in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV

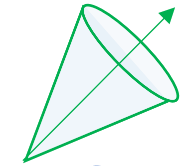
I was able to contribute to this AN by providing QC (Quality Check) plots on tracking/jets efficiency/purity on the MC for comparison with Data



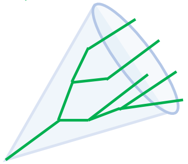


Ongoing work

Objective : Correlate the R_{AA} with the jet substructure observable θ_g : $R_{AA} = \dfrac{\dfrac{d^2N_{AA}}{d\eta dp_T d\theta_g}}{\langle N_{coll}\rangle \cdot \dfrac{d^2N_{pp}}{d\eta dp_T d\theta_g}}$

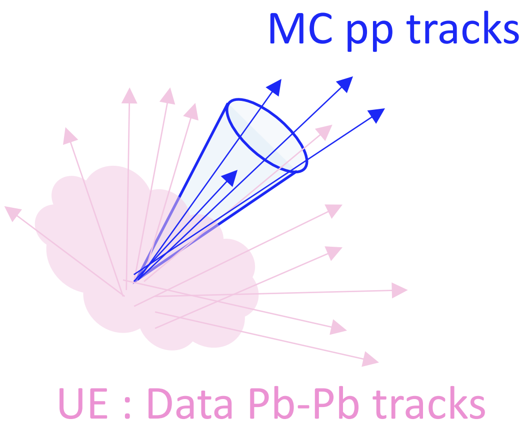


- In the Run 3 jet analysis : observable = jet, and the background subtraction method is based on an **average/median** estimation of the underlying event background (corrected for each jet)



- In my case : observable = jet constituent, the background affects all constituents of the jet -> need to have background already in the dataset : **embedding**

We rely on **embedding** — meaning that we inject a well-defined simulated probe (MC simulated pp tracks) into real data events (Pb-Pb tracks)
This allows us to quantify how background fluctuations and detector effects impact the reconstructed jet and its substructure



At the moment, embedding is a work in progress in the framework of ALICE : O2Physics

↳ I am currently working on a method to create a dataset that includes embedding, outside the O2Physics framework, in a standalone setup

Ongoing work : Embedding steps

As I will use a standalone version, the full dataset is too large (storage), so I need to first filter and reduce the data to work only on a smaller, selected sample

Full dataset

Collisions Table
Tracks Table
…

reducing the data
- by applying cuts

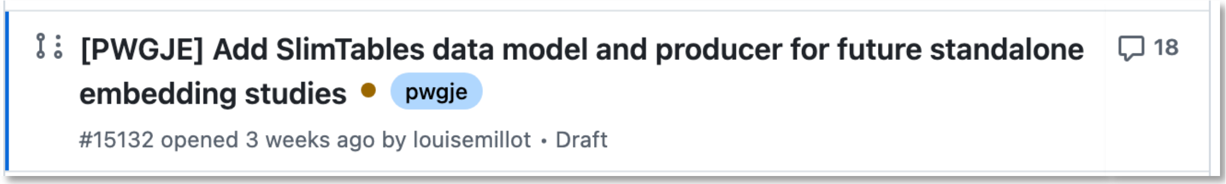
Particle/ McCollision /Tracks / Collisions :
Track selection : **globalTracks**
Track p_T : $0.15 < p_T < 1000$
Track η : $-0.9 < \eta < 0.9$
Event selection : **sel8**
Particle selection :
physicalPrimary + charged

Derived dataset

Reduced dataset : Small filtered subsets of original dataset : kept for further processing

Reduced Collisions Table
Reduced Tracks Table
…

- 1rst step : write a task in O2Physics as a contribution to the framework to produce derived dataset



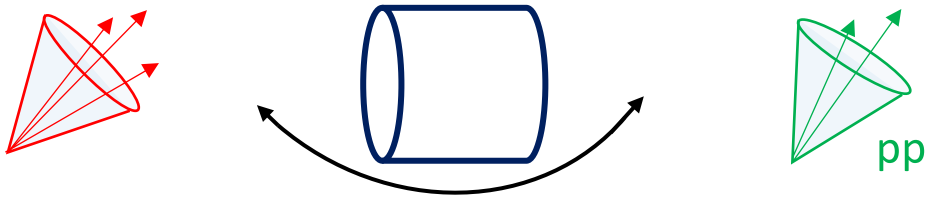
3/4 months

All the analysis is done outside of O2Physics framework – but locally by submittings macros/jobs to the GRID

Ongoing work : Embedding steps

Cross-check: ensure we reproduce what is done in O2Physics, starting with validating the matching (without embedding first)

Particle level : MCP jets — detector — Detector level : MCD jets



pp tracks — pp tracks

geometric distance in (η, ϕ)

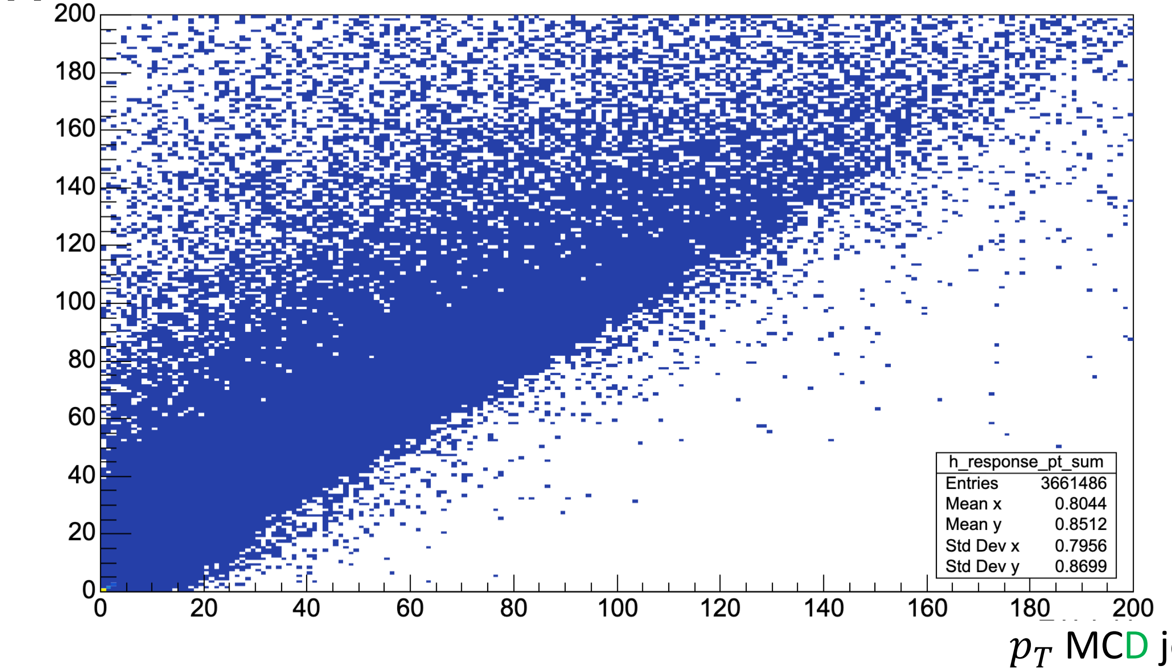
MC simulation

Tracks
↓
Jets :
R = **0.2**
Anti-kT
Jet p_T = $0 < \boldsymbol{p_T} < 1000$ GeV
Jet η = $-\mathbf{0.9} < \boldsymbol{\eta} < \mathbf{0.9}$
fracMatchGeom = 0.12

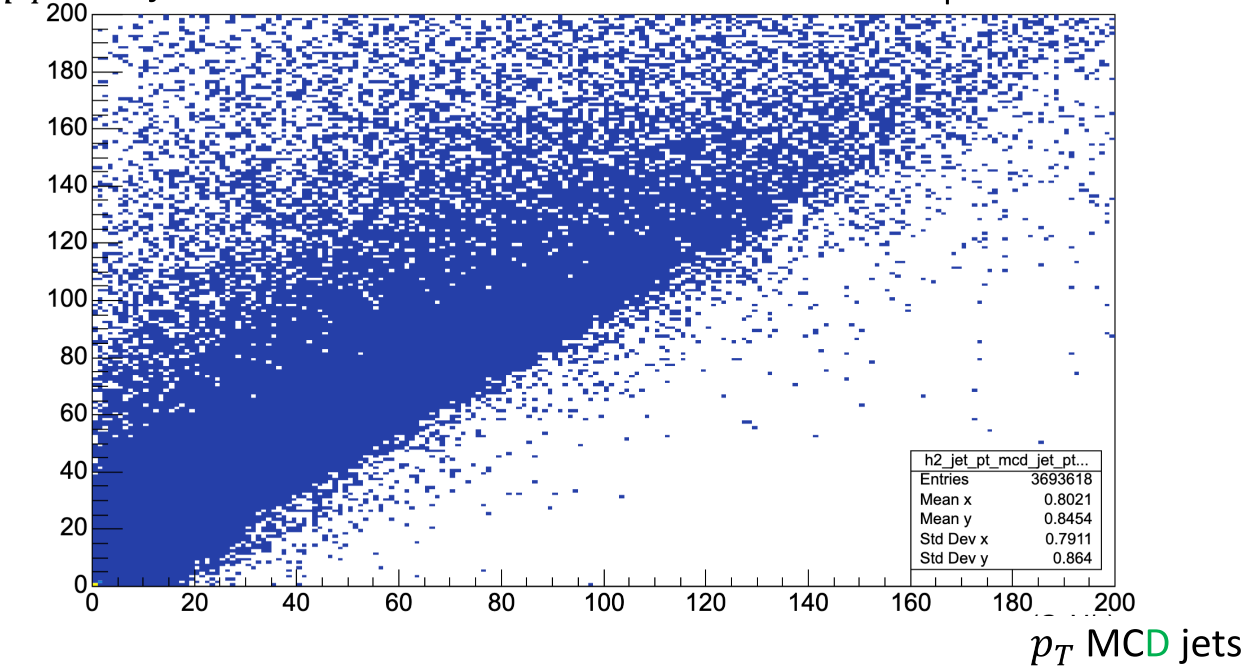
$\mathrm{p_T}$ -response matrix

Comparison : run - 544028

Matching StandAlone



Matching O2Physics



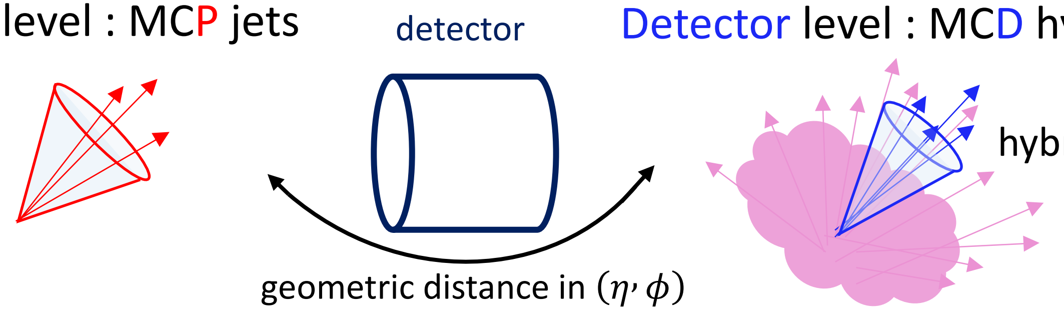
Ongoing work : Embedding steps

Creation of embedding: **hybrid** event (pp MC tracks + Pb-Pb DATA tracks) and proceed matching

Particle level : MCP jets

Detector level : MCD hybrid jets

pp tracks



hybrid (MC pp tracks + UE : Data Pb-Pb tracks)

Reconstruct jets locally using **FastJet**

Jet Finder :

R = **0.2**

Jet p_T = $0 < \boldsymbol{p_T} < 1000$ GeV

Jet η = $\boldsymbol{-0.9 < \eta < 0.9}$

fracMatchGeom = 0.24

SoftDrop :

$z_{cut} = 0.2$

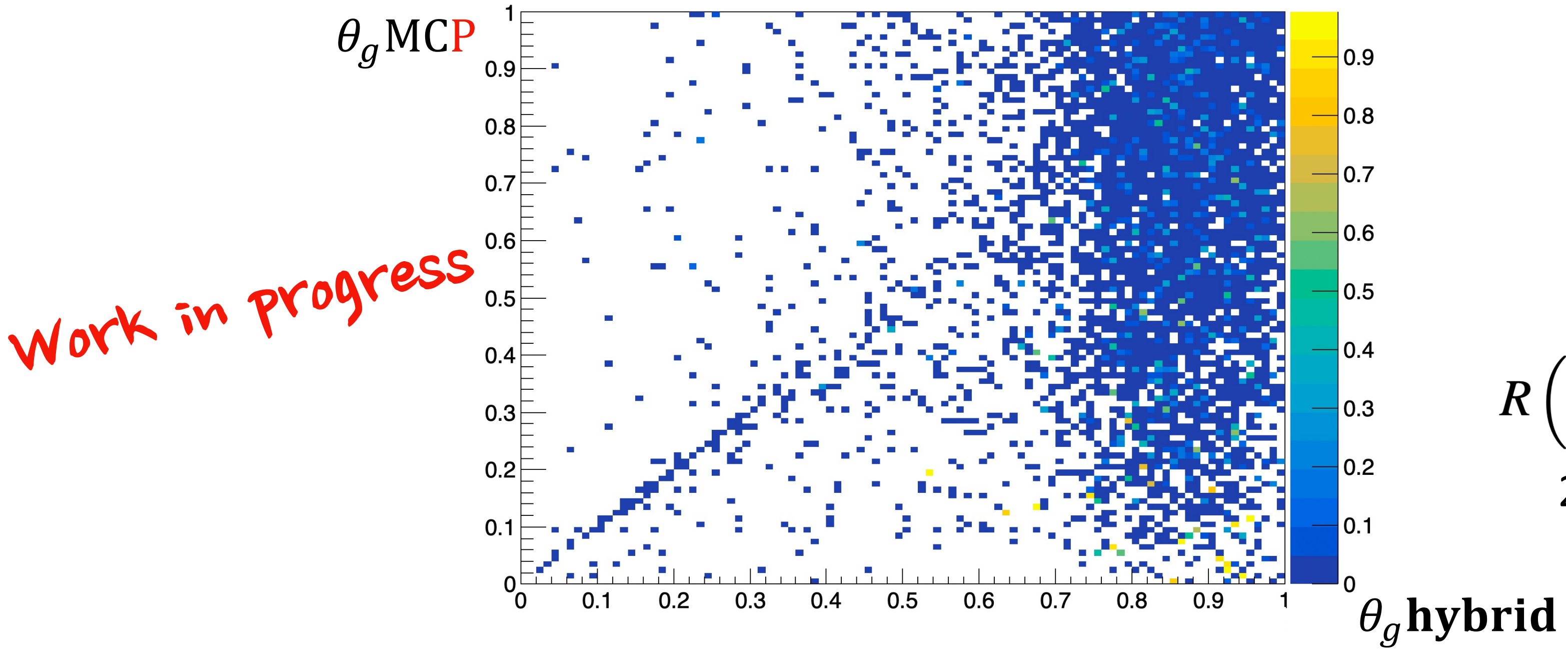
$\beta = 0$

Matching :

$v_{PbPb} - v_{pp} = 4$ cm

$t_{PbPb} - t_{pp} = 1$ ns

- 1 PbPb collision every 100 pp collisions : zvertex + time matching

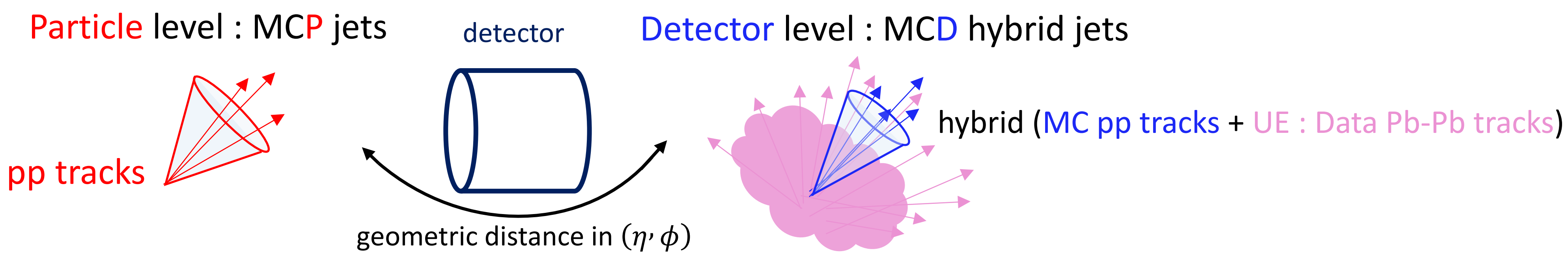


$$R\left(p_{T,det}^{jet}, p_{T,truth}^{jet}, \theta_{g,det}, \theta_{g,truth}\right)$$

2D response matrix : 2 dof = p_T, θ_g

Ongoing work : Embedding steps

Creation of embedding: **hybrid** event (pp MC tracks + Pb-Pb DATA tracks) and proceed matching



Reconstruct jets locally using **FastJet**

Jet Finder :

R = **0.2**

Jet p_T = $0 < \boldsymbol{p_T} < 1000$ GeV

Jet η = $\boldsymbol{-0.9 < \eta < 0.9}$

fracMatchGeom = 0.24

SoftDrop :

$z_{cut} = 0.2$

$\beta = 0$

Matching :

$v_{PbPb} - v_{pp} = 4\text{cm}$

$t_{PbPb} - t_{pp} = 1\text{ ns}$

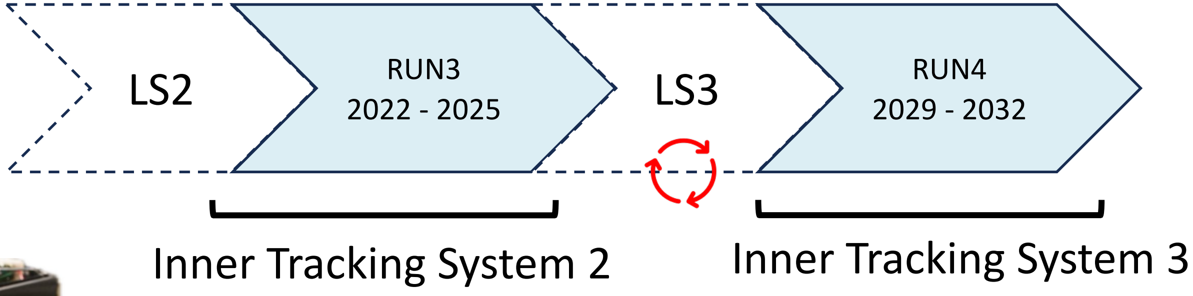
- 1 PbPb collision every 100 pp collisions : zvertex + time matching

Next steps :

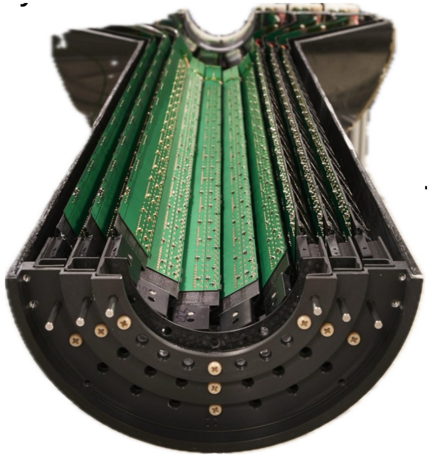
- Background subtraction : EventWiseConstituent method (implement locally)
- Unfolding 2D (closure tests) : correction of detector effects to recover the true distribution from measured data (bin migration)
- Systematics : Track inefficiency
  Choice of MC
  Unfolding method + iterations

Ongoing work : Service Work

ALICE will undergo upgrades during LS3

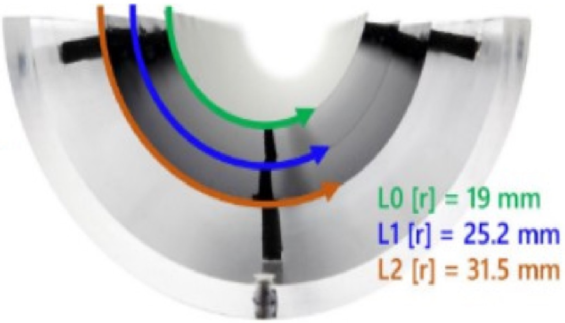


Specs	ITS 2 IB	ITS 3
Sensor	ALPIDE	MOSAIX
Sensor geometry	Reticle-size flat sensor mounted on staves	Bent wafer-scale stitched MAPS
Pixel size	27 × 29 μm²	22.8 × 20.8 μm²
Data, power	FPCs in the acceptance area	Everything on silicon
Cooling	Water	Air
Beam pipe radius	**18 mm**	**16.2 mm**
Innermost layer radius	**22.4 mm**	**19 mm**
Material budget	**0.35% X/X_0**	**0.09% X/X_0**



ITS2 half inner 3 layer

Replacement of the 3 innermost layers of the ITS2 for Run4



ITS3 half inner 3 layer

7 layers of ALPIDE Monolithic Active Pixel Sensor (MAPS) 15mmx30mm sensor area
100 μm Si sensors

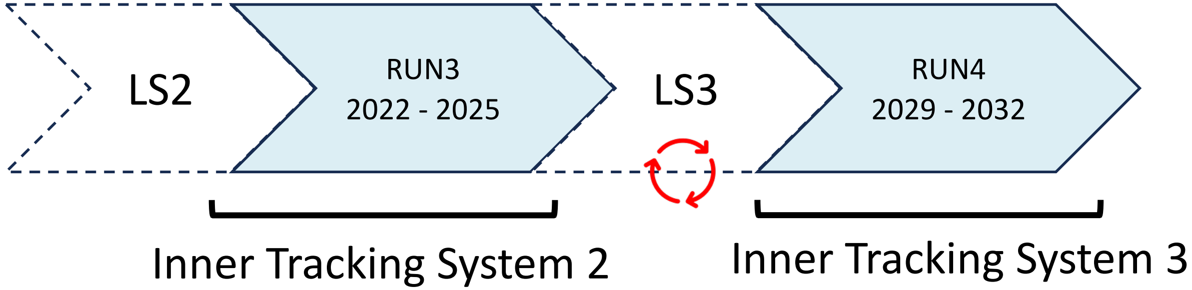
- Average material budget of **0.36% X_0** per layer
- 1rst layer radius **24 mm**

Half cylinders by bending **$50\mu m$ thick Si sensors** to a radius of **19mm**

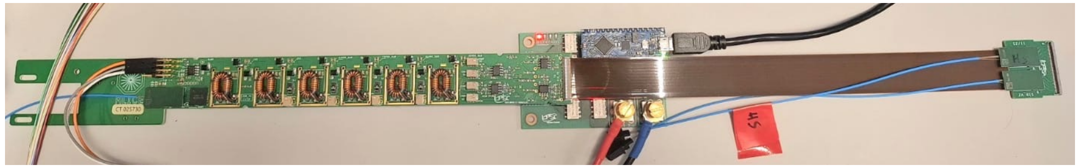
- 266 x 98 mm2 large area sensors (stitching technology)
- reduced average material budget of **0.09% X_0** per layer
- no rigid support structure carbon fiber, foam spacers
- **air cooling**

Ongoing work : Service Work

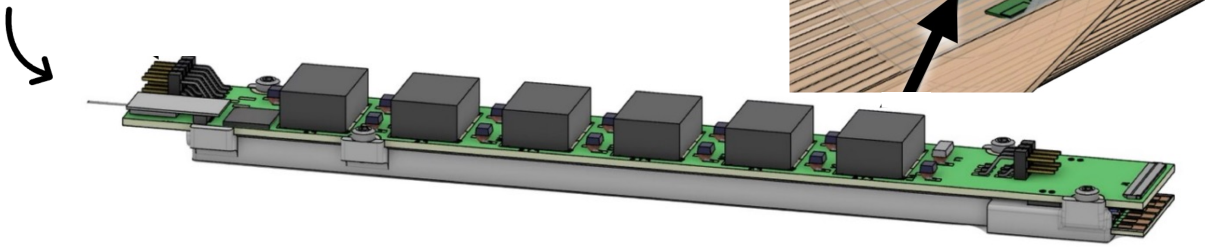
ALICE will undergo upgrades during LS3

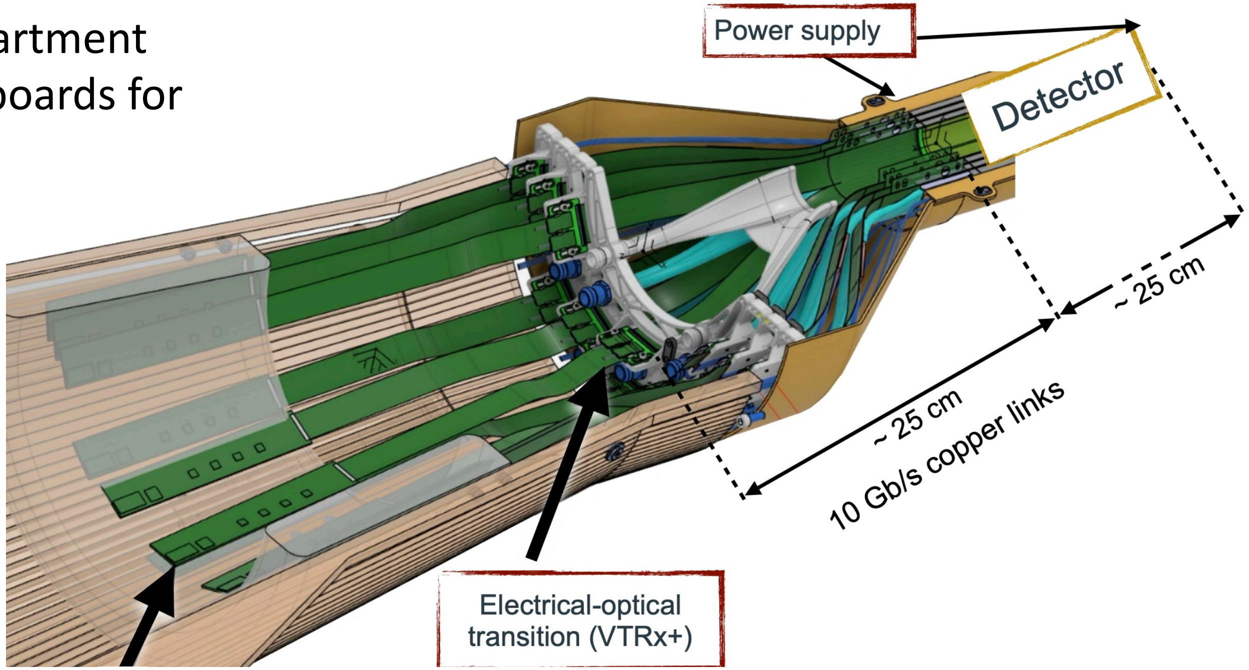


I am currently contributing (together with the electronics department at LPSC) to the testing and calibration of **SCB cards** (interface boards for the ITS).



This involves developing software/code to automate data acquisition and to produce calibration and performance (yield) plots of this SCB cards





Thanks for your attention !

Feel free to ask questions or to e-mail me here : louise.millot@cern.ch

Backups

Comparison QED/QCD

QED

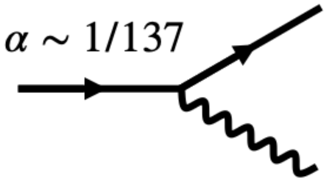
One charge i.e. **electric charge**
- Charge has positive and negative values

Acts on all particles that have electric charge
- Charged leptons and (anti) quarks
- Charged hadrons (baryons & mesons)

1 force carrier → the massless photon
- Photon is charge neutral
- No self interaction

The strength is always small

$\alpha \sim 1/137$



- The coupling strength increases marginally with increasing momentum transfer or for small distances

QCD

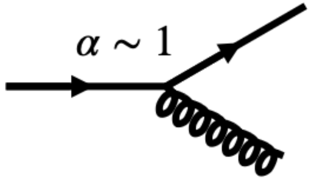
Three charges i.e. **colour**
- "Strong charge" has "positive" (R, G, B) and "negative" (antiR, antiG, antiB) values

Acts on all particles that have colour
- (Anti) quarks and gluons

8 force carriers → the massless gluons
- Gluons contain one colour and one anticolour
- Self interactions

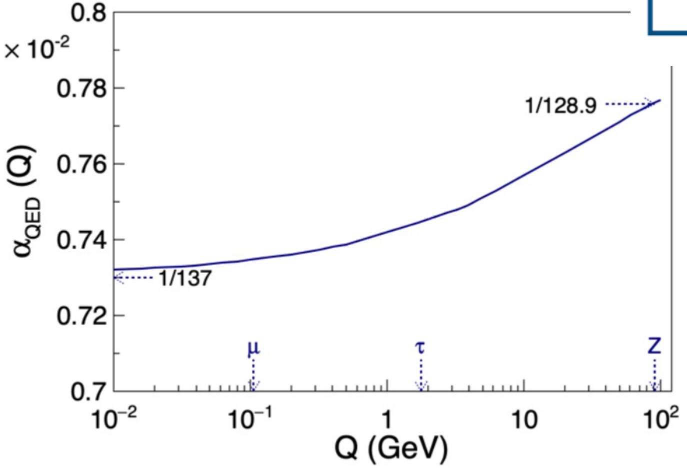
The strength varies with energy/distance

$\alpha \sim 1$

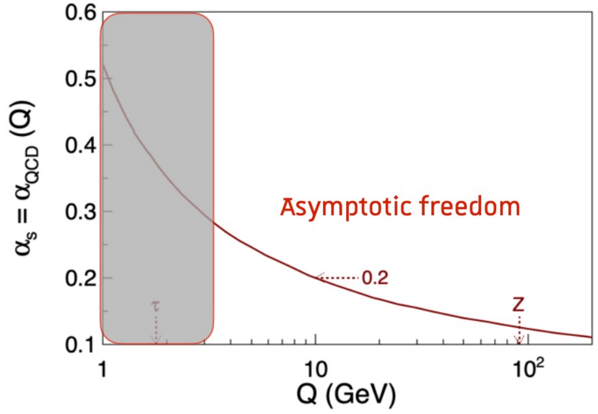


- The coupling strength decreases asymptotically with increasing momentum transfer or for small distances

QED



QCD



Jet reconstruction algorithm

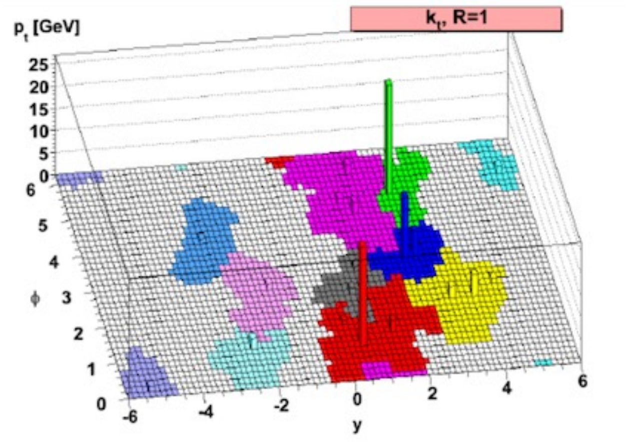
$$d_{ij} = min\left(k_{T_i}^{2p}, k_{T_j}^{2p}\right)\frac{\Delta\phi_{ij}^2+\Delta y_{ij}^2}{R^2}$$

- $p = 1$: "k_T" algorithm (~QCD like spirit)

$$d_{ij} = min\left(k_{T_i}^{2}, k_{T_j}^{2}\right)\frac{\Delta\phi_{ij}^2+\Delta y_{ij}^2}{R^2}$$

Soper, arXiv:hep-ph/9305266

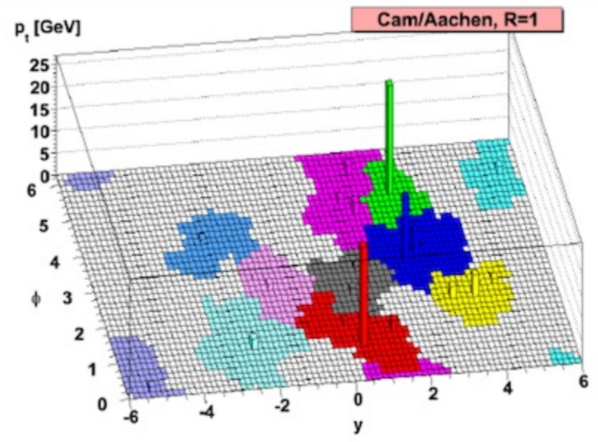
→ recombine starting from **softest**-k_T/closest particles
→ hierarchical in relative k_T



- $p = 0$: Cambridge/Aachen (C/A) algorithm

$$d_{ij} = 1.\ \frac{\Delta\phi_{ij}^2+\Delta y_{ij}^2}{R^2}$$

→ recombine only based on (ϕ, y) distance
→ hierarchical in angles

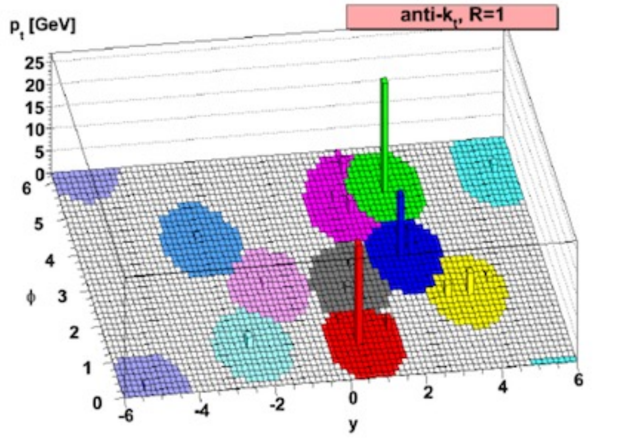


- $p = -1$: "anti-k_T" algorithm

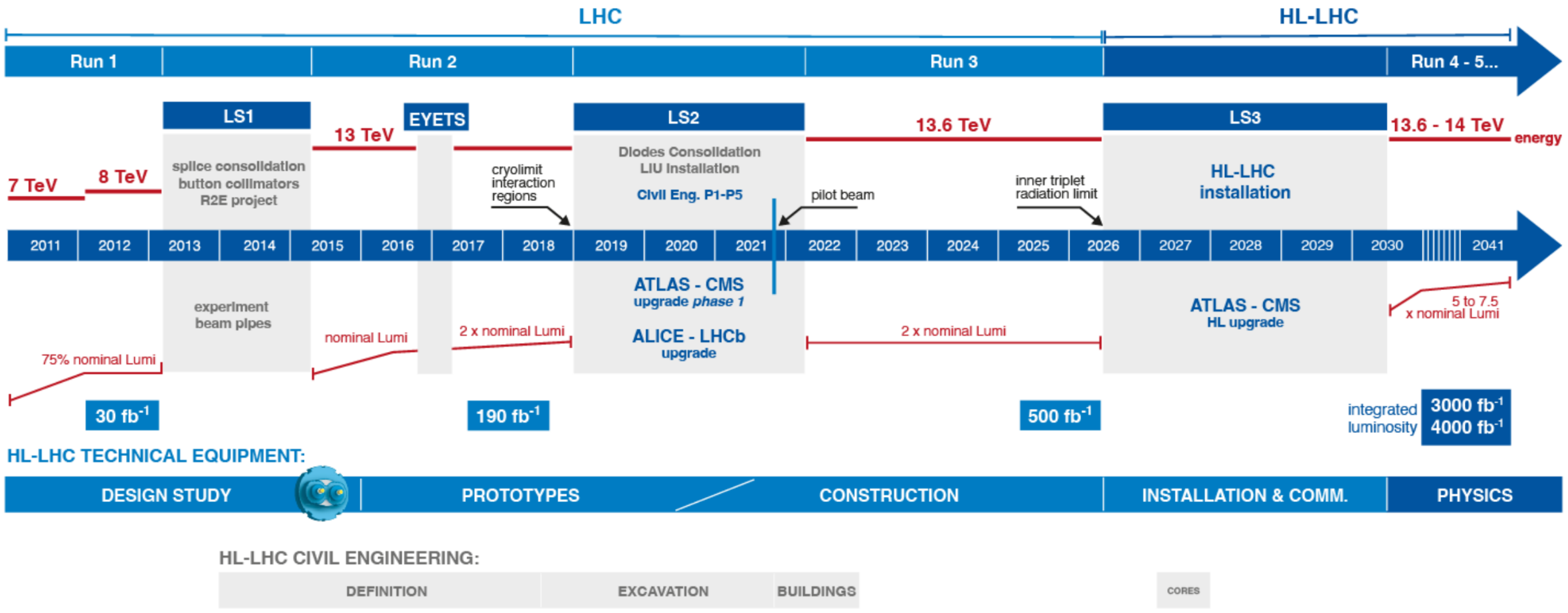
$$d_{ij} = max\left(k_{T_i}^{2}, k_{T_j}^{2}\right)\frac{\Delta\phi_{ij}^2+\Delta y_{ij}^2}{R^2}$$

Cacciari, arXiv:0802.1189

→ recombine starting from **hardest**-k_T/closest particles
→ perfectly conical hard jets



LHC / HL-LHC Plan



Lattice QCD

Quantum Chromodynamics on the lattice (Lattice QCD) is a numerical approach used to study the strong interaction in the non-perturbative regime, where analytical calculations become impossible due to the large coupling between quarks and gluons.

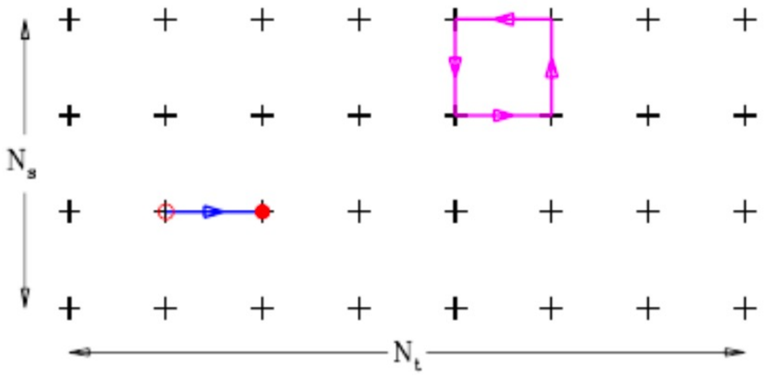
The idea is to discretize space-time into a finite grid (the lattice)

- quark fields are defined on lattice sites
- gluons on links between them

This formulation transforms QCD into a high-dimensional statistical physics problem that can be solved using Monte Carlo methods on supercomputers. Lattice QCD is essential for computing fundamental properties of strongly interacting matter, such as hadron masses, the QCD equation of state, and **phase transition properties** relevant to the quark–gluon plasma studied in heavy-ion collisions.

Minkowski space-time, continuum $\longrightarrow$ Euclidean space-time, discretised

Lattice spacing $a, \quad a^{-1} \sim \Lambda_{UV}, \quad x_\mu = n_\mu a$
Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$



(anti)quarks:	$\psi(x), \overline{\psi}(x)$	lattice sites
gluons:	$U_\mu(x) = e^{aA_\mu(x)} \in SU(3)$	links
field tensor:	$P_{\mu\nu}(x) = U_\mu(x)U_\nu(x+a\hat{\mu})U_\mu^\dagger(x+a\hat{\nu})U_\nu^\dagger(x)$	“plaquettes”

Event selection + track selection

- the bunch crossing associated to the collision has an acceptable FT0C-FT0A time difference: bc.selection_bit(kIsTriggerTVX) Compatible FT0A–FT0C signal arrival times
- the bunch crossing associated to the collision is not close to the data frame borders: bc.selection_bit(kNoTimeFrameBorder) Data are stored in « time frame » -> close to the frame boarder (missing info, reconstruction inefficiencies caused by truncated detector information)
- the bunch crossing associated to the collision is not close to the ITS readout frame borders: bc.selection_bit(kNoITSROFrameBorder)

Sel8

- there are no other collisions in 10 µs time range with per-collision multiplicity above threshold (5000 FT0 amplitude): bc.selection_bit(kNoCollInTimeRangeStandard)
- there are no other collisions in the same ITS Readout Frame with per-collision multiplicity above threshold (kNoCollInRofStandard)

Pileup + occupancy

+ Specifically added for PbPb

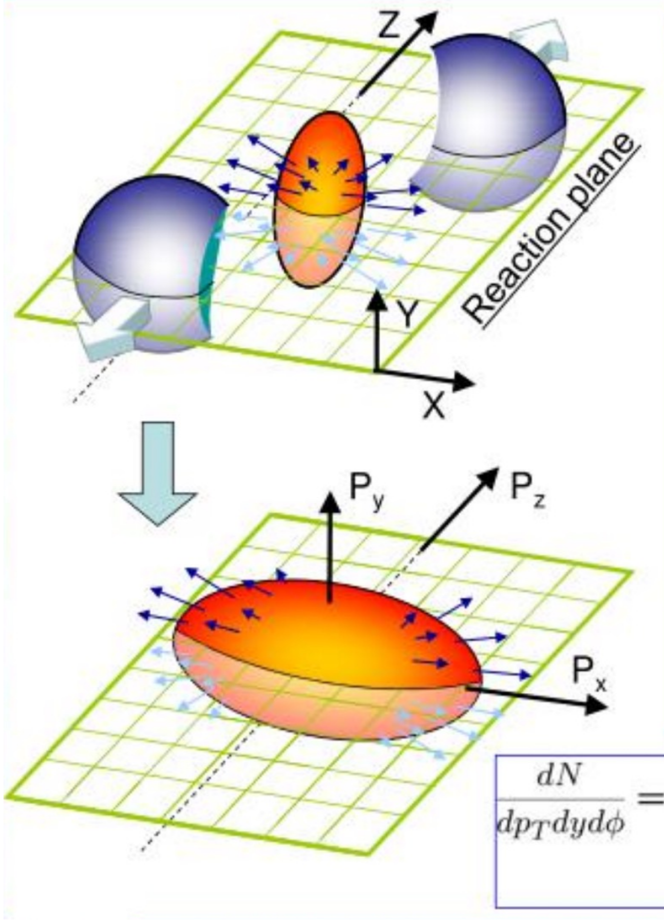
Dataset nature	event selection combination
Pb-Pb data	kIsTriggerTVX ∩ kNoTimeFrameBorder ∩ kNoITSROFrameBorder ∩ kNoCollInTimeRangeStandard ∩ kNoCollInRofStandard ∩ occupancy $<$ 1000 ∩ run-average IR $<$ 25 kHz
MB Pb-Pb MC anchored to Pb-Pb data (selMCFullPbPb)	kIsTriggerTVX ∩ kNoTimeFrameBorder ∩ kNoCollInTimeRangeStandard ∩ kNoCollInRofStandard ∩ occupancy $<$ 1000 ∩ run-average IR $<$ 25 kHz
jet-jet pp MC anchored to Pb-Pb data	(selMCFull) kIsTriggerTVX ∩ kNoTimeFrameBorder ∩ kNoSameBunchPileup

Table 2: Cuts applied to select collisions depending on dataset nature.

Primary status observables	Requirements
DCA_z	$< 2\,\mathrm{cm}$
DCA_{xy}	$< 0.0105 \cdot 0.035/p_{\mathrm{T}}^{1.1}$
TPC quality observables	Requirements
$N^{TPC}_{Crossed\ rows}$	> 70
$N^{TPC}_{Crossed\ rows}/N^{TPC}_{clusters}$	> 0.8
$N^{TPC}_{\chi^2\ NDF}$	< 4
ITS quality observables	Requirements
N^{ITS}_{hits}	at least 1 among the three innermost ITS layers
$N^{ITS}_{\chi^2\ NDF}$	< 36
Kinematic observables	Requirements
p_{T}	$> 150\,\mathrm{MeV/c}$
$\lvert\eta\rvert$	< 0.9

Table 3: Cuts applied to identify global tracks.

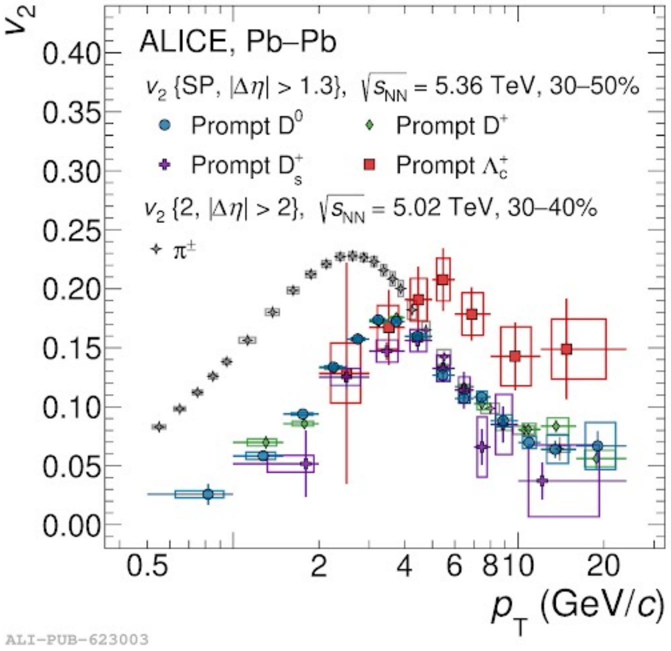
Elliptic flow

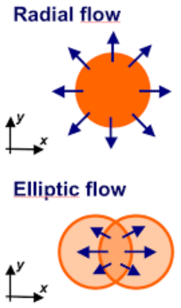


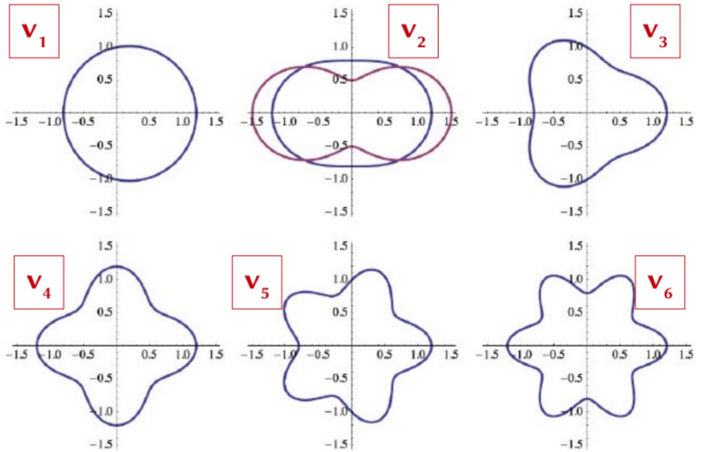
- ***The probe for early time***
  - The dense nuclear overlap is ellipsoid at the beginning of heavy ion collisions
  - Pressure gradient is largest in the shortest direction of the ellipsoid
  - Spatial anisotropy → Momentum anisotropy
  - Signal is self-quenching with time
  - Elliptic flow (v_2) is defined by the 2[nd] coefficient of Fourier expansion

$$\frac{dN}{dp_T dy d\phi} = \frac{1}{2\pi}\frac{d^2N}{dp_T dy}(1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots)$$

$$v_2 = \langle \cos(2\phi) \rangle$$

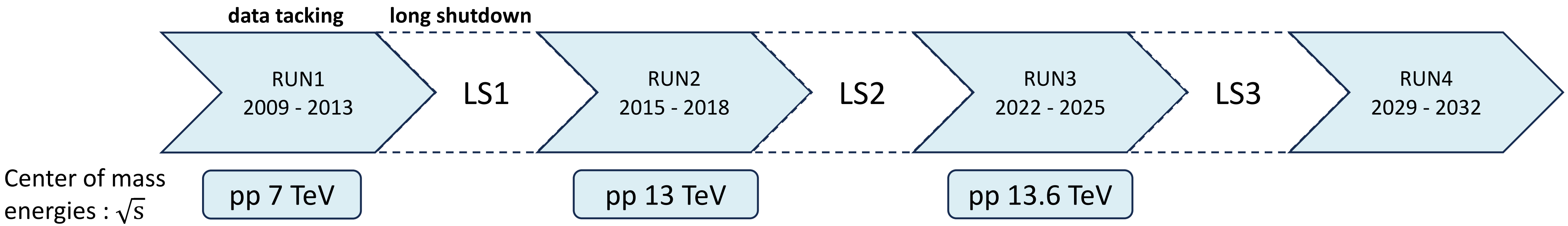






It is one of the strongest pieces of evidence that the medium created in heavy-ion collisions behaves as a **nearly perfect fluid** rather than a gas of independent particles.

LHC / ALICE phases of data tacking



2023 Pb-Pb: target L_{int} Pb-Pb = 3.25 nb^{-1}

Luminosity

Total integrated Luminosity RUN 1+2

Pb-Pb: 1.5 nb^{-1} in ALICE

2.54 nb^{-1} in ATLAS/CMS, 0.26 nb^{-1} in LHCb

p-Pb: 75 nb^{-1} in ALICE

~220 nb^{-1} in ATLAS/CMS, 36 nb^{-1} in LHCb

In ALICE, Pb-Pb: interaction rate ~8 kHz with trigger event → Readout ≈ 1 kHz

Target Luminosity RUN 3+4

Pb-Pb: 13 nb^{-1} in ALICE/ATLAS/CMS,

2 nb^{-1} in LHCb

p-Pb: 0.5 pb^{-1} in ALICE

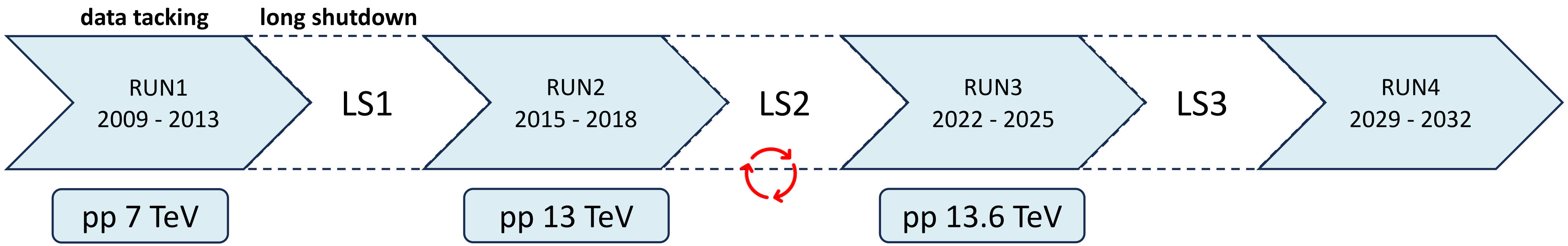
1 pb^{-1} in ATLAS/CMS, 0.2 pb^{-1} in LHCb

In ALICE, Pb-Pb: interaction rate 50 kHz, continuous readout

Statistics from x10 to x50 depending on probe

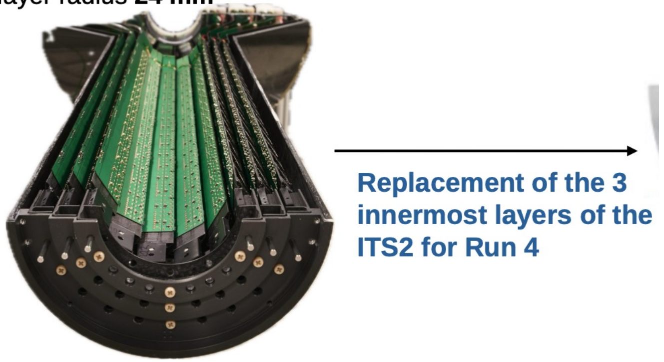
Online data reconstruction

LHC phases



ALICE operated in its first configuration from 2009 to 2018 (Runs 1 and 2)
During the second Long Shutdown (LS2, 2019–2021), the detector underwent major upgrades

- Current ITS2 was installed in 2021 and taking data since then:
  - **7 layers of ALPIDE Monolithic Active Pixel Sensor (MAPS) 100 μm** Si sensors
  - average material budget of **0.36% X_0 per layer**
  - 1st layer radius **24 mm**



ITS2 half inner 3 layer

↗ Better vertex precision / track resolution

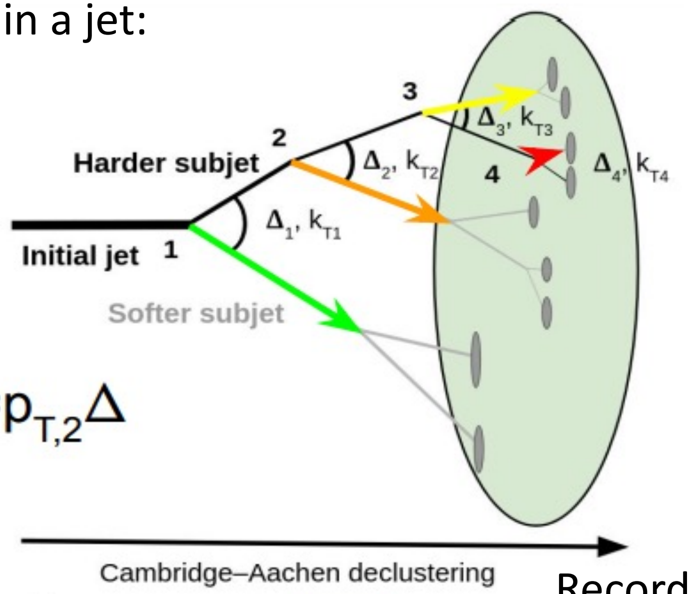
In my PhD : Run3 data → which provide significantly improved statistics and precision compared to previous runs

↗ collisions are recorded continuously and reconstructed online

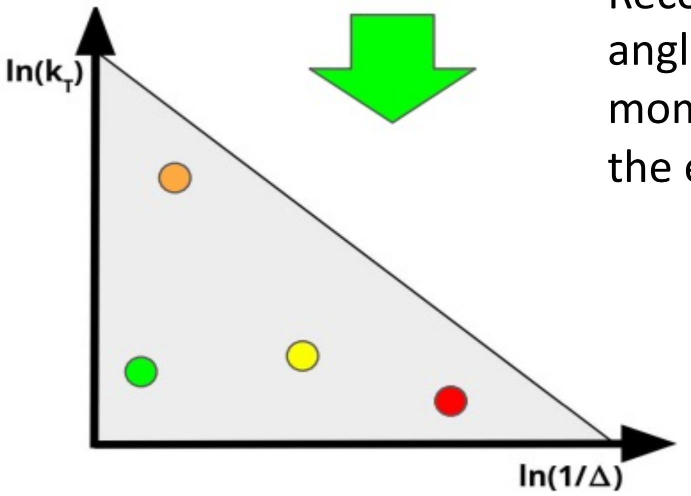
Run 3 also introduced continuous readout, replacing the triggered acquisition used in Run 2, together with a major transition to the new O2/O2Physics software framework for data processing and analysis

Lund Plane

The primary Lund jet plane is a representation of the emissions within a jet:

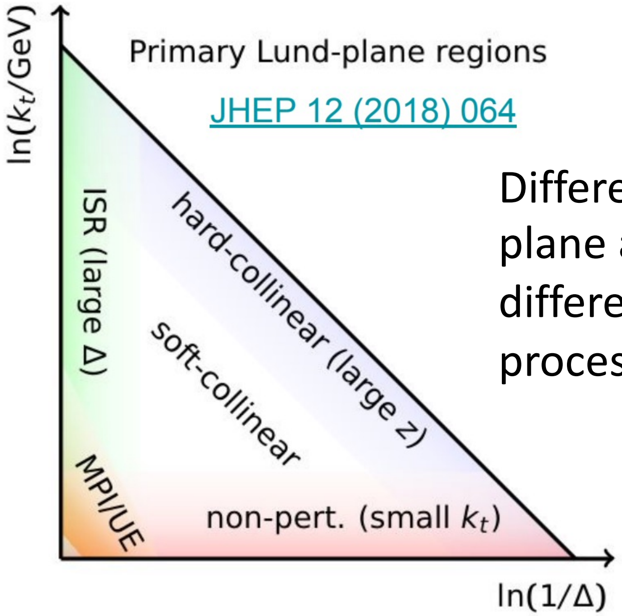


$k_T = p_{T,2}\Delta$

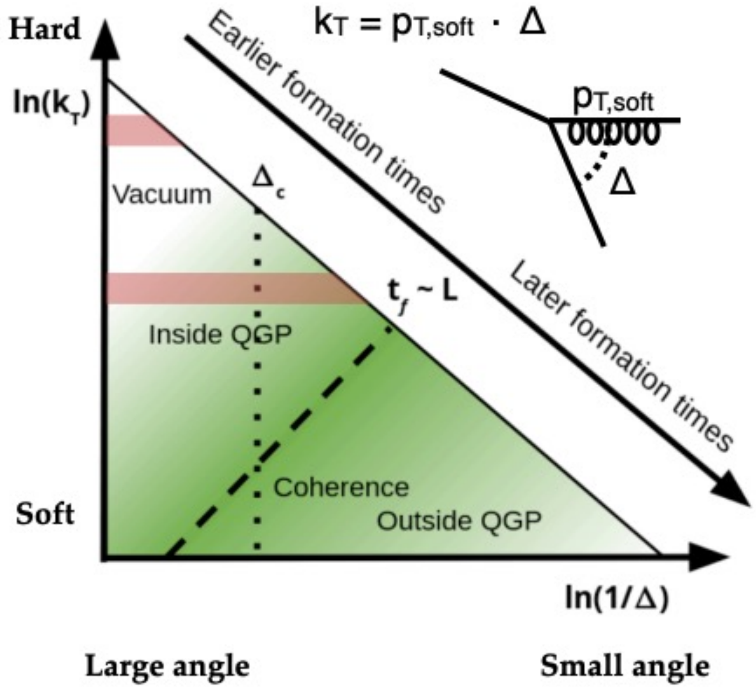


Record each emission's angle (Δ) and momentum relative to the emitter (kT)

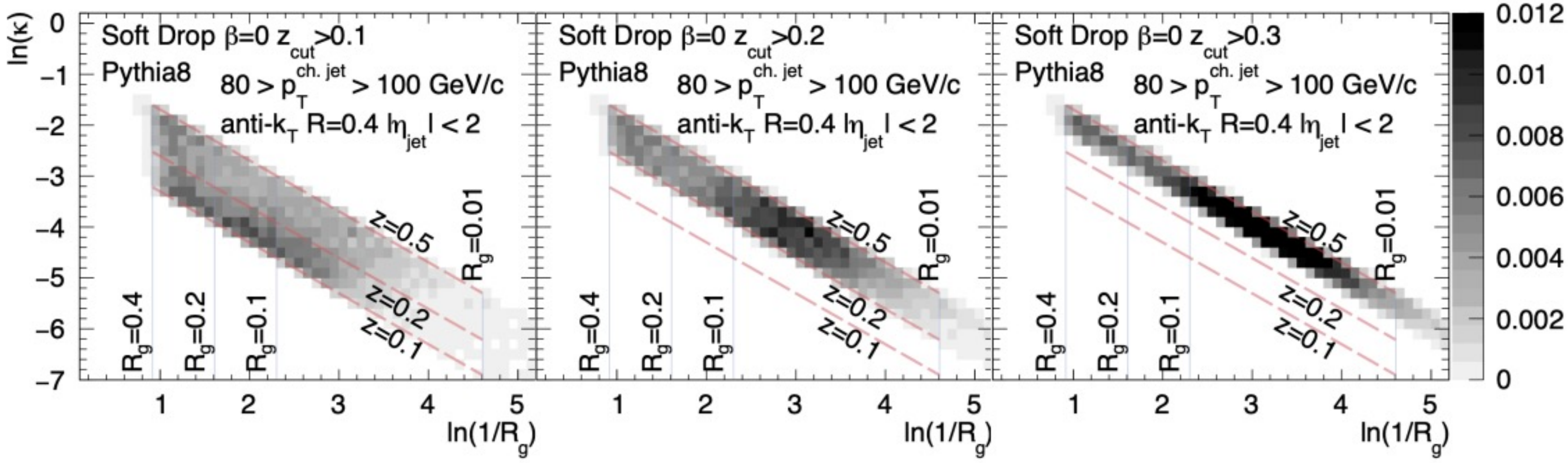
Lund plane visualizes branching kinematics



Different regions of the plane are sensitive to different physical processes



Softdrop (SD) parameters



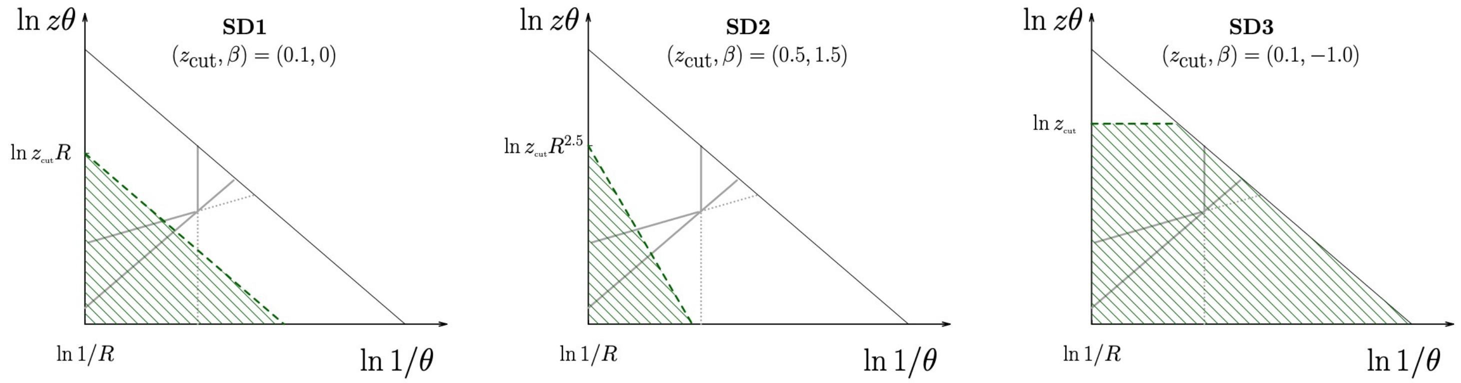
Primary Lund plane obtained with Soft Drop grooming with β = 0 for different symmetry cut zcut parameters. Left: zcut = 0.1. Middle: zcut = 0.2. Right: zcut = 0.3.

https://arxiv.org/pdf/2006.01812

zcut = 0.1 leaves residual background contamination

zcut = 0.3 too much groomed away

zcut = 0.2 optimal value to minimize mis tagging



Three grooming settings studied. Shaded areas correspond to configurations that are groomed away. Figure 7 depicts how these settings remove parts of the phase space in the Lund plane.

https://arxiv.org/pdf/1808.03689

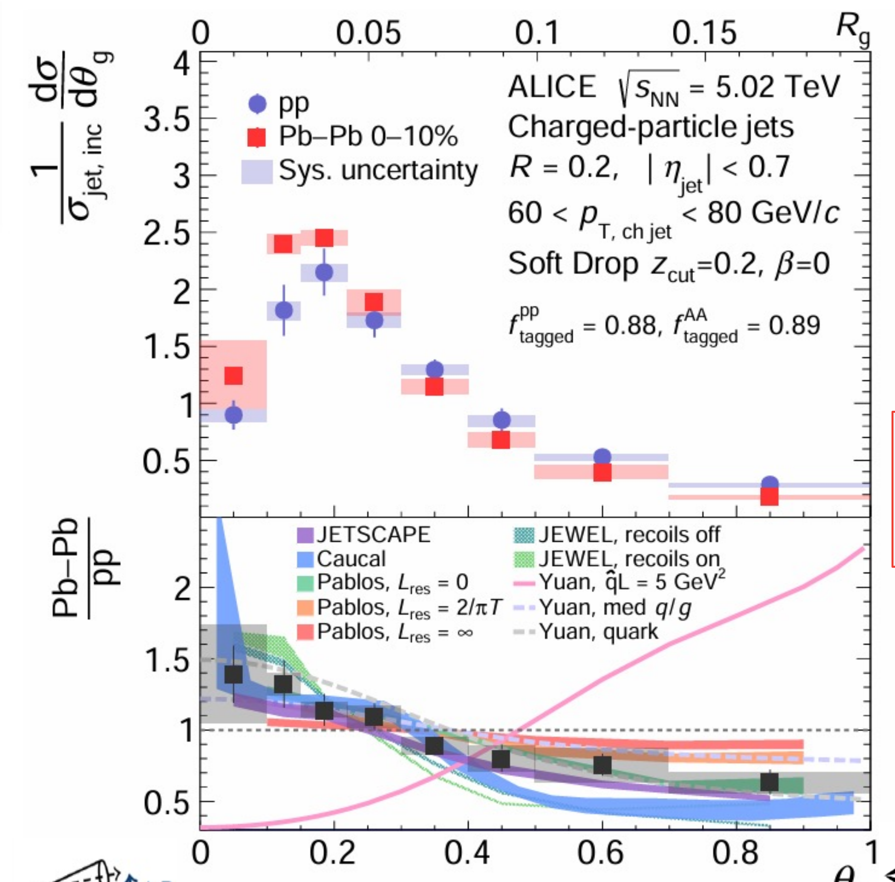
SD1: zcut = 0.1 and β = 0: removes branches based only on the energy fraction

SD2: zcut = 0.5 and β = 1.5: has a stronger grooming at large angle;

SD3: zcut = 0.1 and β = −1.0: selects only hard radiation;

Motivations

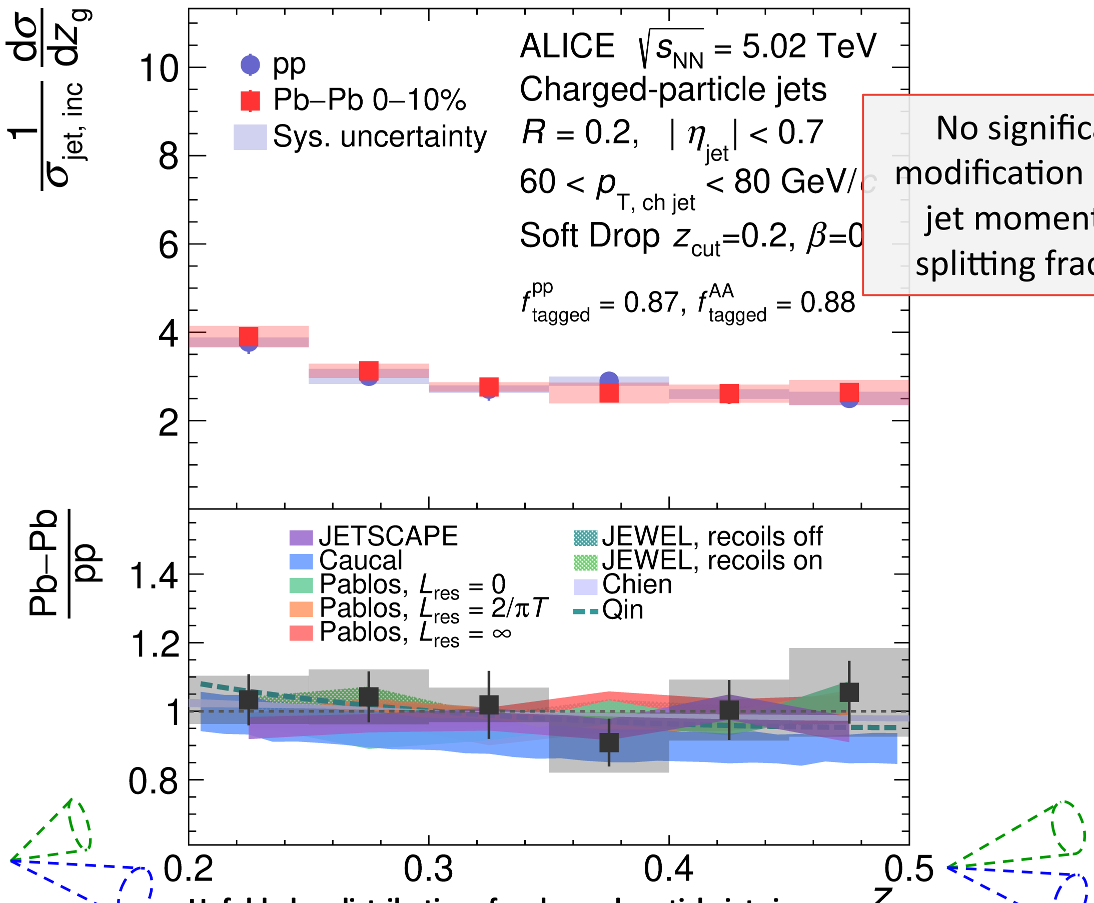
Run2 analysis and theoretical developments show that θ_g and z_g are particularly interesting to study medium effects



Unfolded θg distributions for charged-particle jets in pp collisions compared to those in Pb-Pb collisions

PhysRevLett.128.102001

Suppression of large-angle splittings in Pb–Pb



No significant modification of the jet momentum splitting fraction

Unfolded zg distributions for charged-particle jets in pp collisions compared to those in Pb–Pb collisions

ITS+TPC Track $\eta - \phi$ profile