# Jets as a probe of the Quark-Gluon Plasma

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LLR student seminar
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# Outlook

**… “Are there new states of matter at ultrahigh temperatures and densities?”**

“The 11 Greatest Unanswered Questions of Physics”, Discover Magazine, 2002

- Quark gluon plasma (QGP) introduction
- Heavy ion collisions : tool for the QGP creation
- Jet introduction
- Jets as a QGP probe
- Selected experimental results

# Quantum Chromo-Dynamics

Quantum Chromo-Dynamics (**QCD**) describes the interaction between quarks and gluons

The strength of their interaction is set by the QCD coupling $\alpha_s$

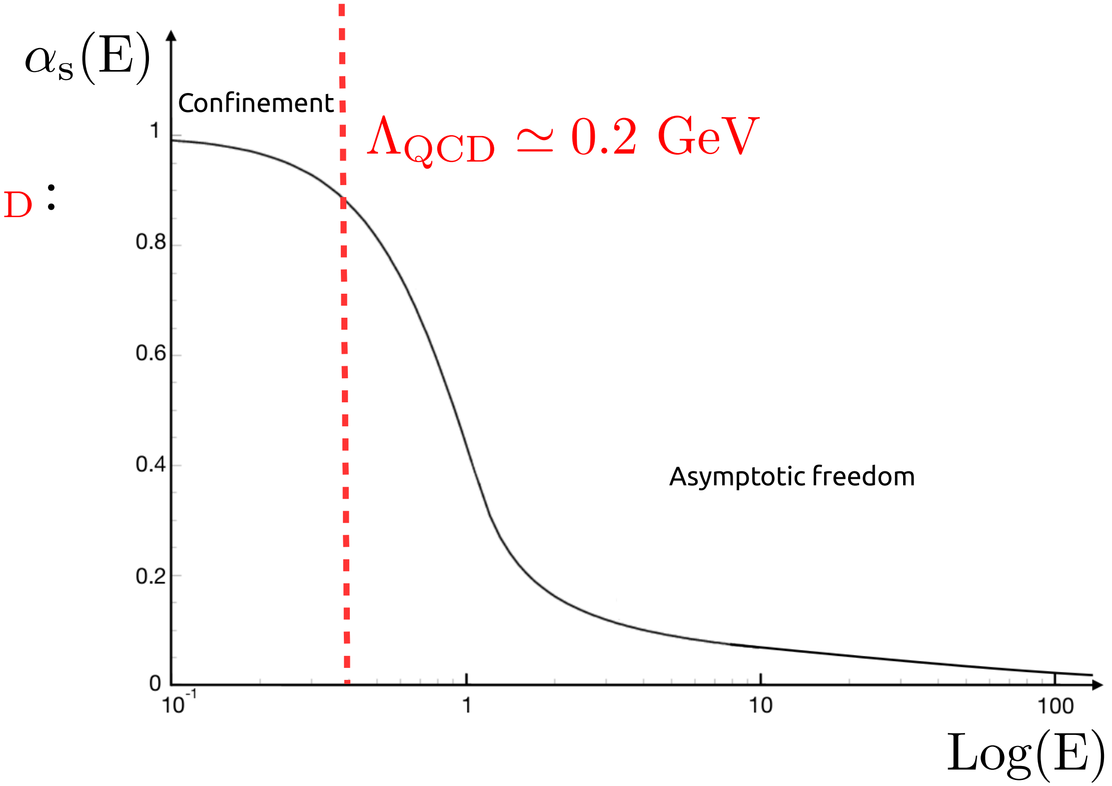
Pertubative regime is valid for $E \gg \Lambda_{QCD}$ :

- quarks and gluons are almost free

For $E < \Lambda_{QCD}$ :

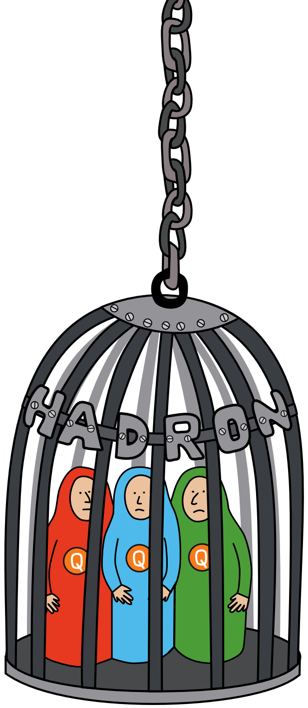
- quarks and gluons interact strongly - confined into hadrons
- perturbation theory fails

$\Lambda_{QCD}$ sets a scale for hadron masses



High Energy ( $E \gg \Lambda_{QCD}$ ) = short distance
Low Energy ( $E < \Lambda_{QCD}$ ) = long distance

# Different faces of QCD



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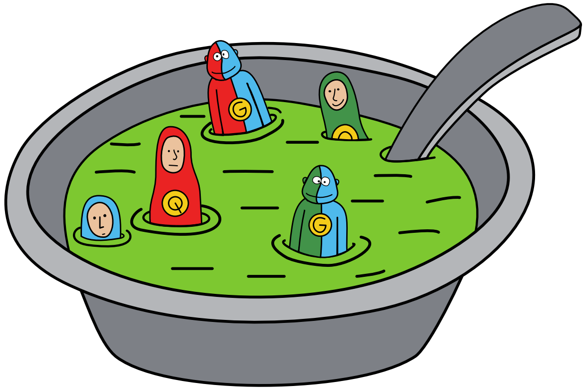

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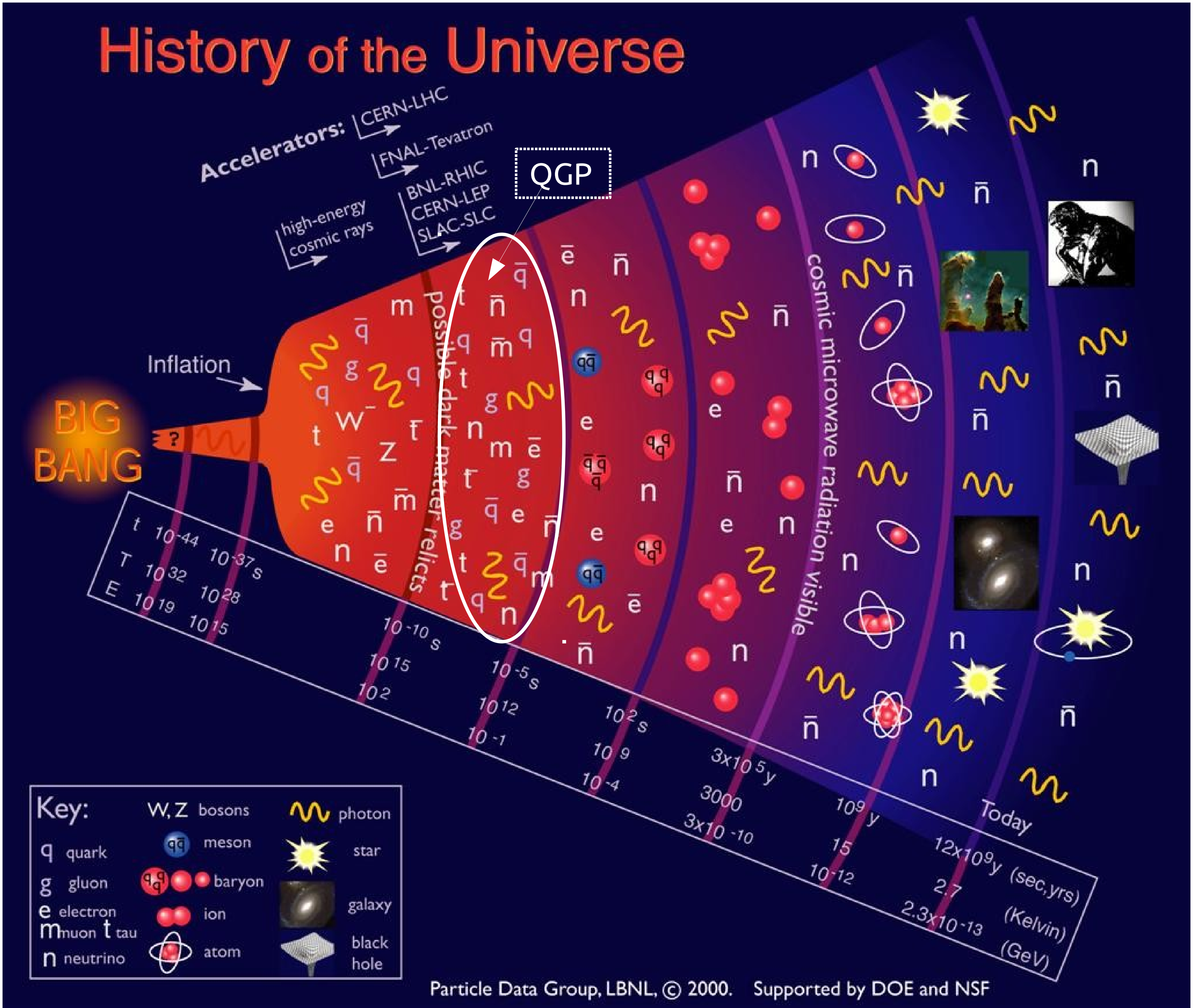
Normal matter :

quarks and gluons are confined

One can create a high density/temperature system composed by a large number of quarks and gluons →

“deconfined” phase of matter
– Quark-Gluon Plasma (**QGP**)

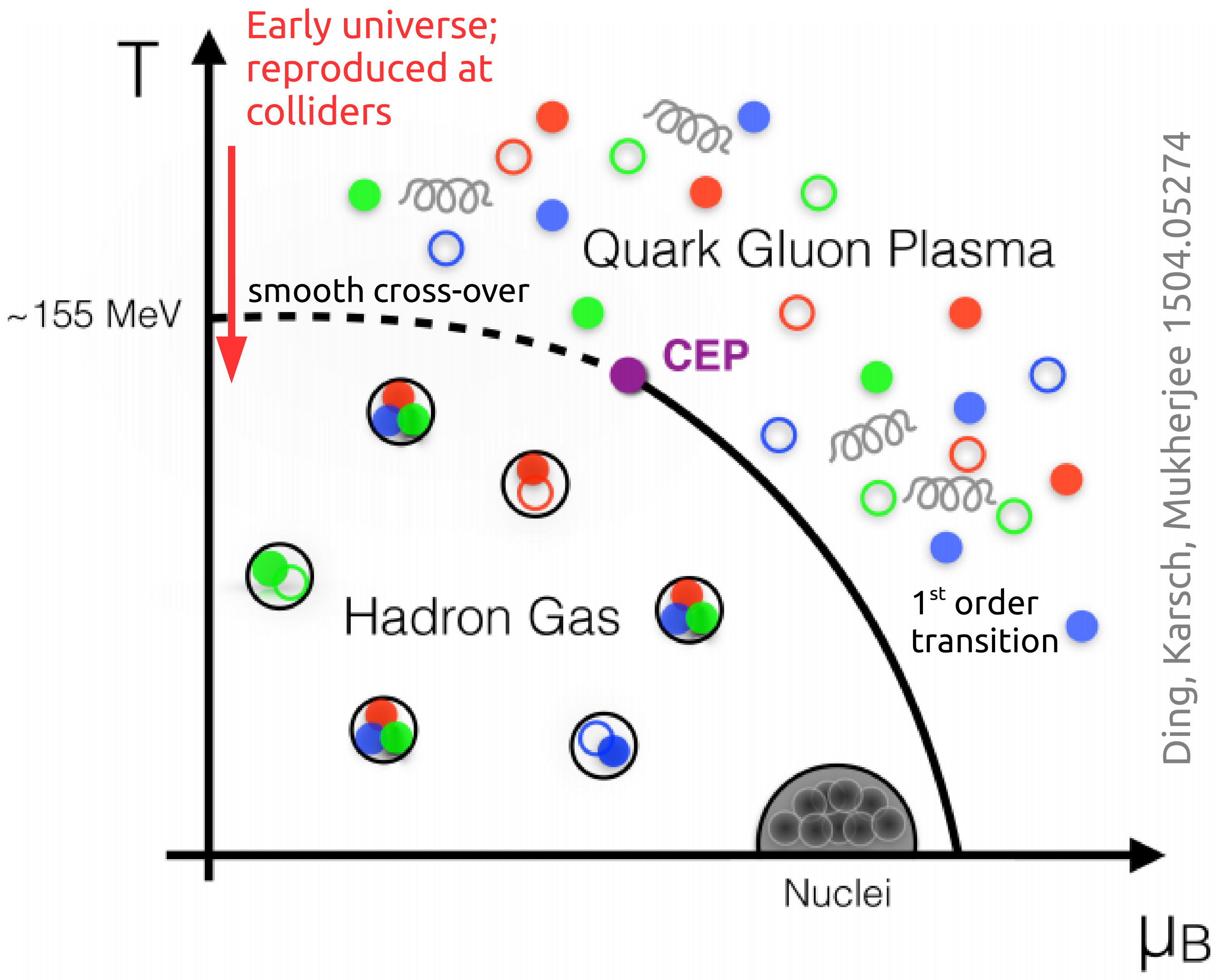


History of the Universe

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

# Phase diagram of QCD matter

First predicted by Cabibbo and Parisi in 1975.

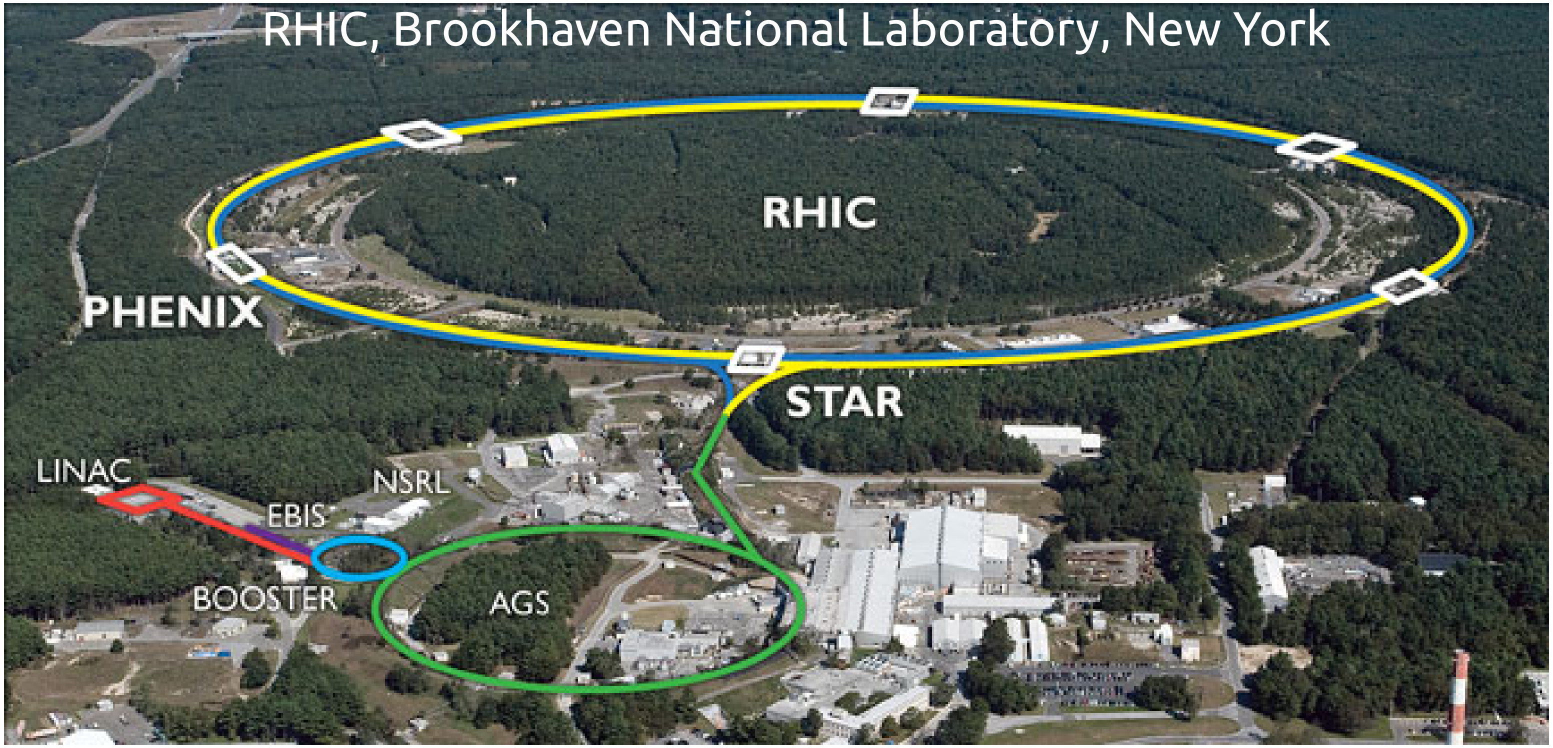


Ding, Karsch, Mukherjee 1504.05274

**Critical End Point**
computed on lattice QCD

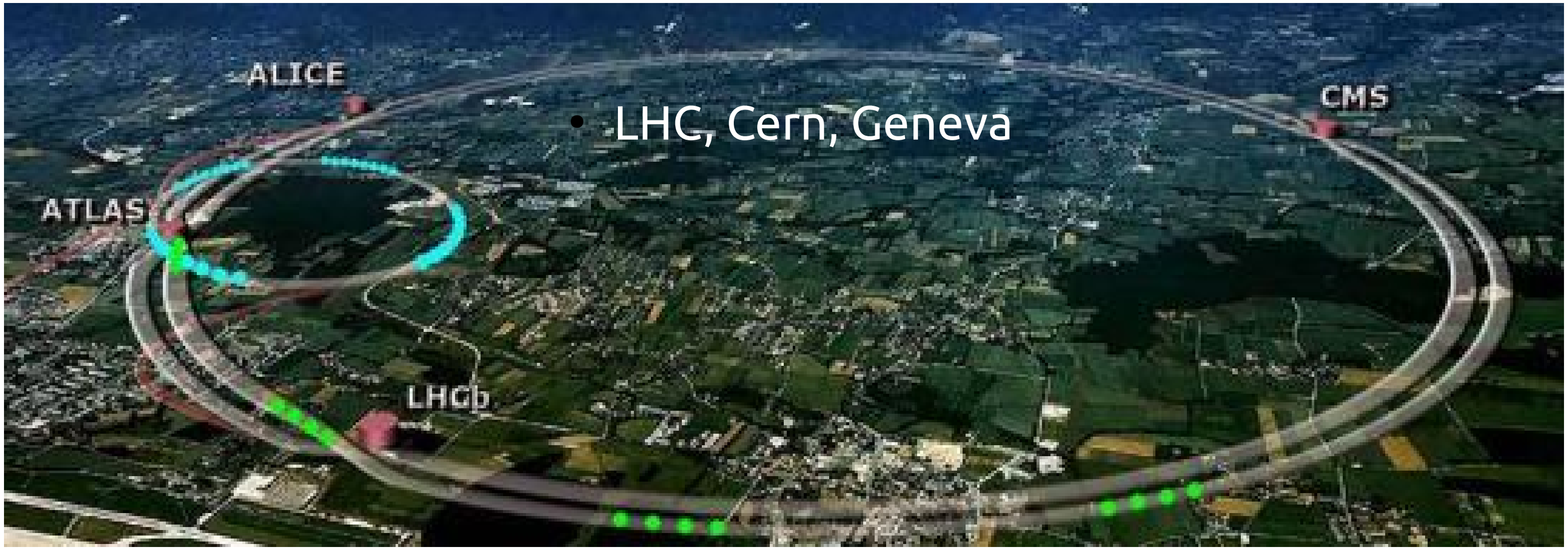
Explore this diagram : create a system of quarks and gluons at high temperatures
→ **heavy ion collisions**

# Heavy ion colliders



RHIC, Brookhaven National Laboratory, New York

- Since 2000
- $\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV}$
- Au-Au, d-Au, pp ...



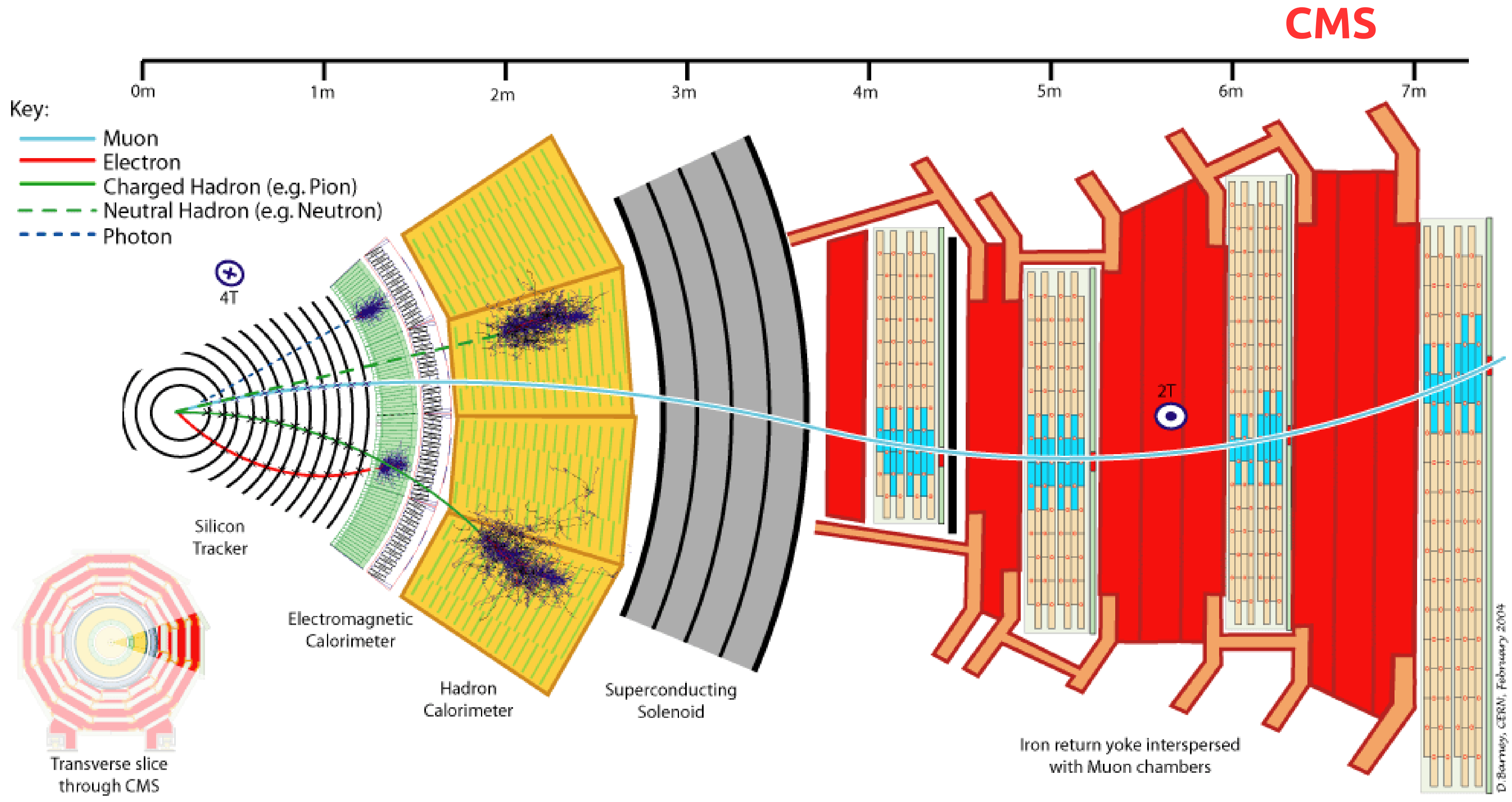
- LHC, Cern, Geneva

- Since 2010
- $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$
- PbPb, pPb, pp ...

# High energy physics detectors

ATLAS and CMS :

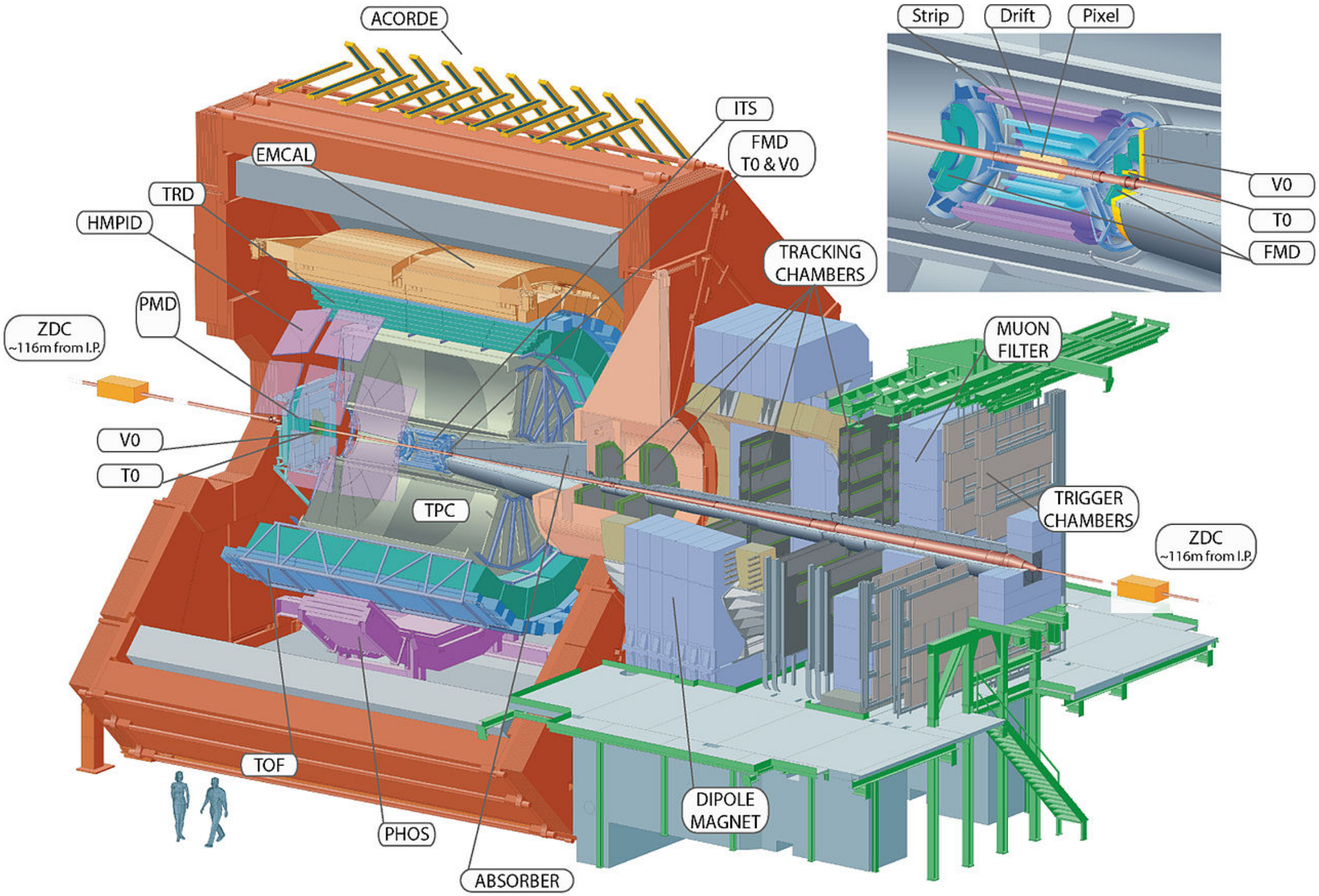
- Fast and able to handle very high luminosity
- Precision silicon tracking
- High B field
- Hermetic calorimeters for $\mathrm{e}/\gamma$ , jets and missing energy



# Heavy ion detectors

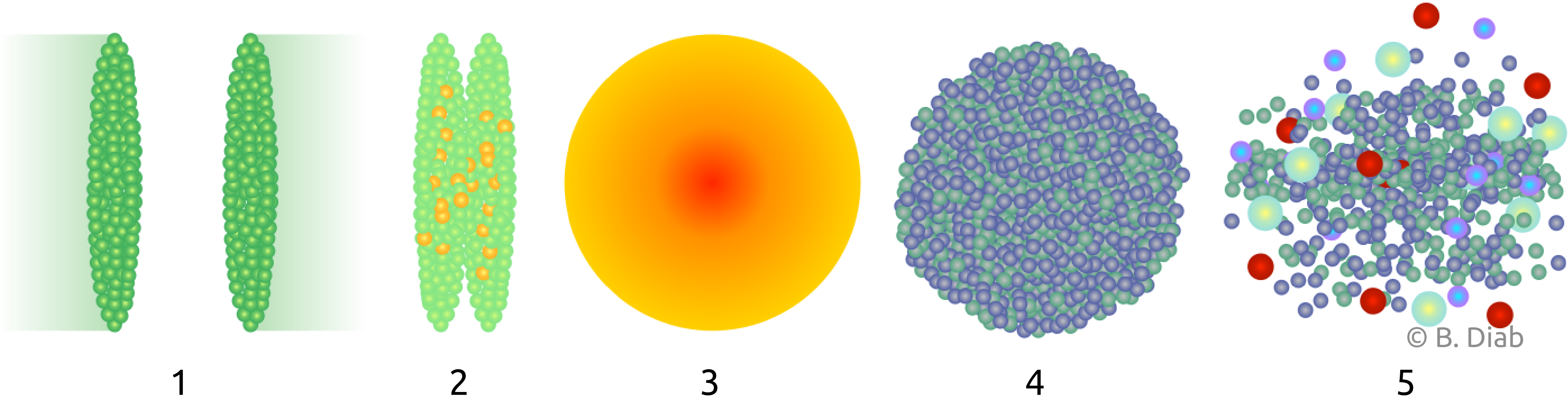
ALICE, STAR, PHENIX :

- Tracking with gaseous detectors for high occupancy
- Low energy reach is essential for "bulk" observables
- Emphasis on particle ID (p, K, $\pi$… )



**ALICE**

# Heavy ion collisions : time evolution



© B. Diab

Length : fm ("Fermi"), $1 \text{ fm} = 10^{-15} \text{ m}$
Time: fm/c, $1 \text{ fm/c} = 0.33 \cdot 10^{-23} \text{ s}$

Prior to collision:

1. Relativistic nuclei are Lorentz contracted

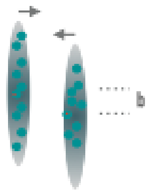
After the collision :

2. Particles start to scatter (τ ~ 1/p)
3. After t ~ 1 fm/c, equilibrium is established, giving a thermalized QGP
4. QGP expands and cools until about 10 fm/c ( $3 \times 10^{-23}$ sec)
5. Hadronization, particles stop interacting and move towards detectors

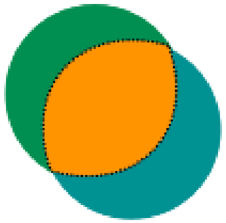
# Heavy ion collisions : geometry

Collisions vary in “centrality”

“central”



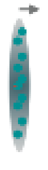
Longitudinal view



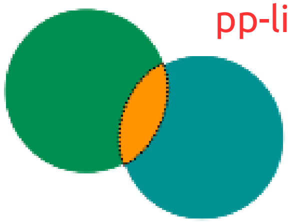
Transverse view

The larger overlap area, the hotter and larger QGP is

“peripheral”

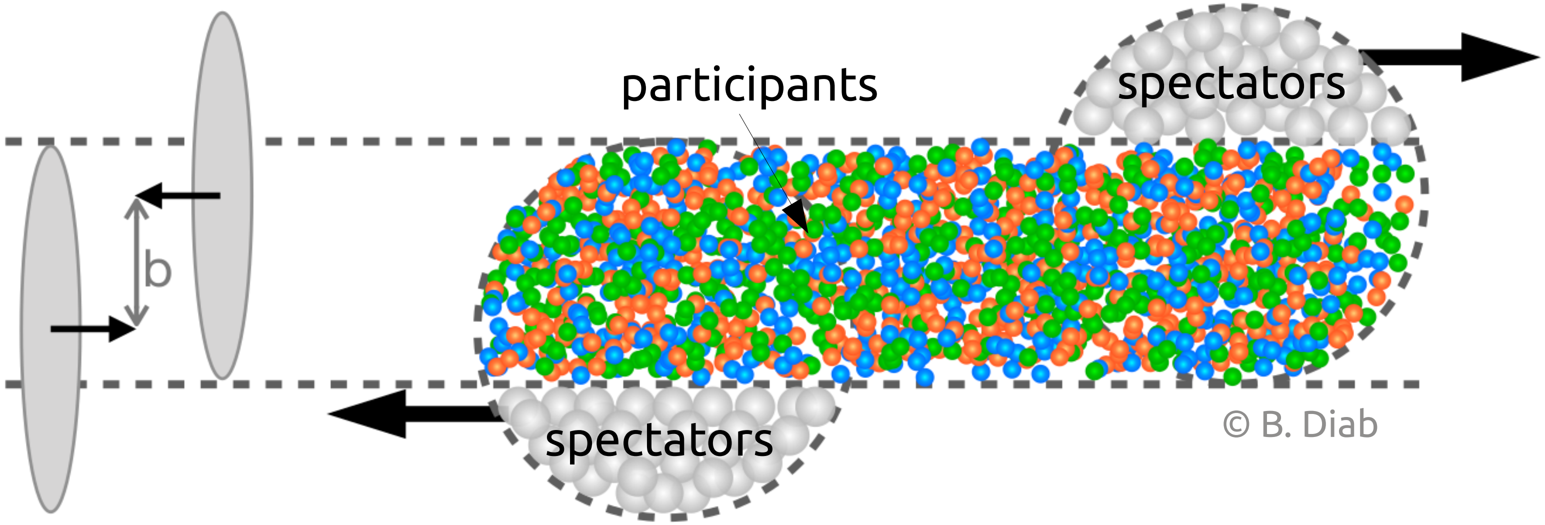


Longitudinal view



Transverse view

pp-like collision



© B. Diab

b - impact parameter

$\mathrm{N}_{\mathrm{part}}$ - number of participating nucleons; each can collide more than once →

$\mathrm{N}_{\mathrm{coll}}$ - total number nucleon-nucleon collisions

} estimated from “Glauber model”

# Centrality

Glauber model is used to relate $\mathrm{N}_{\mathrm{part}}$ and charged particle multiplicity ($\mathrm{N}_{\mathrm{ch}}$)

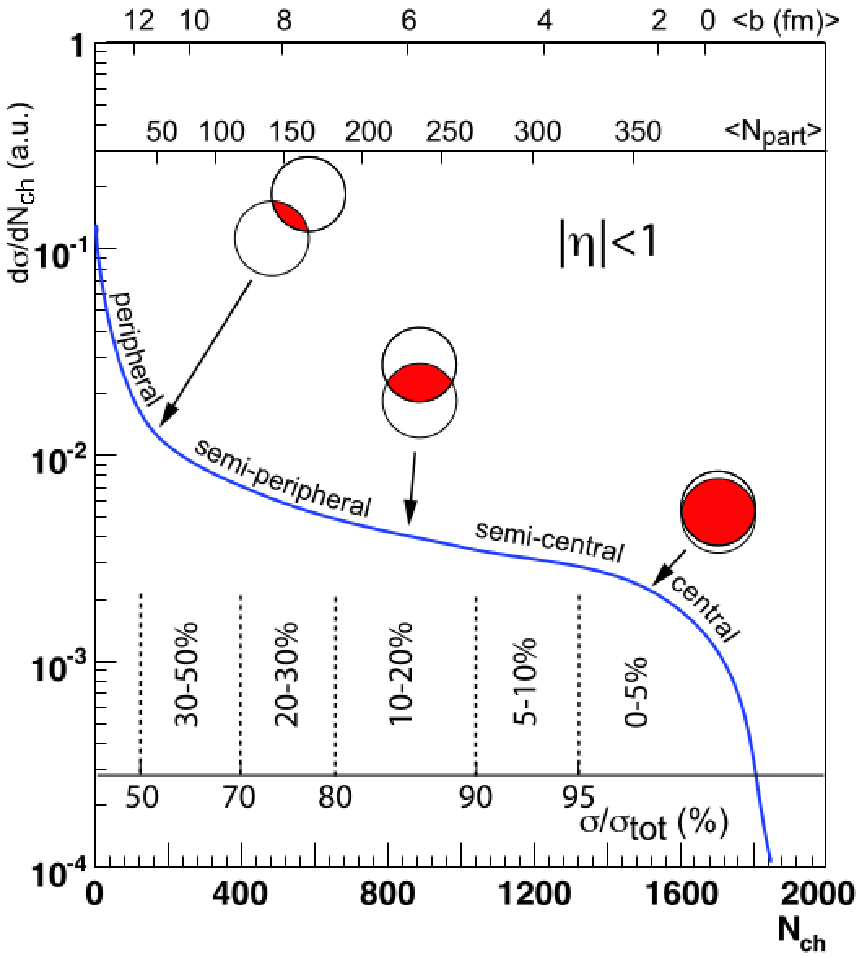
Measure per-event charge multiplicity for an ensemble of events : $\mathrm{d}\sigma/\mathrm{dN}_{\mathrm{ch}}$

Centrality is computed as percentile of the total cross-section

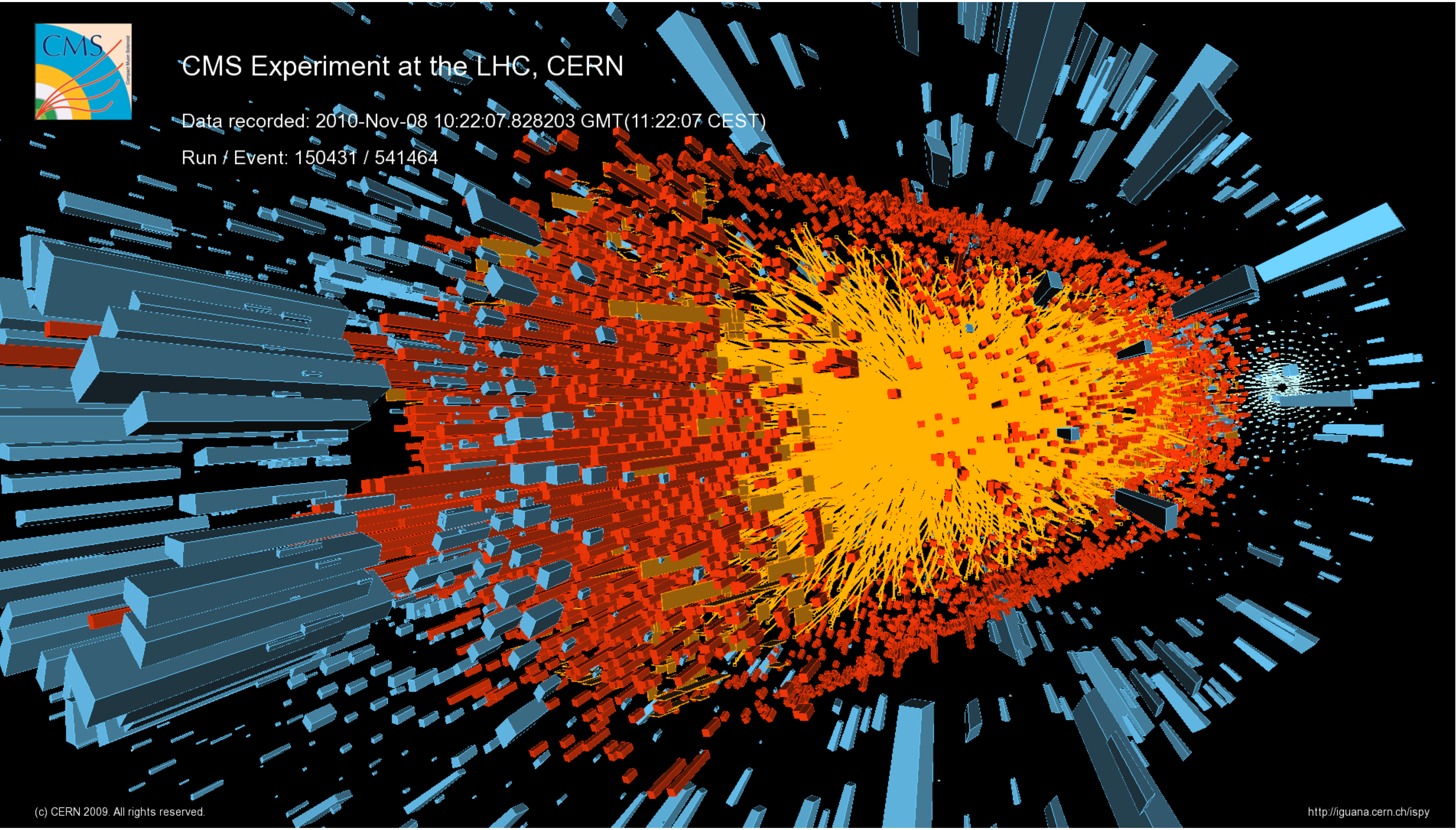
0-5% - the most central events :

→ smallest impact parameter
→ highest $\mathrm{N}_{\mathrm{part}}$

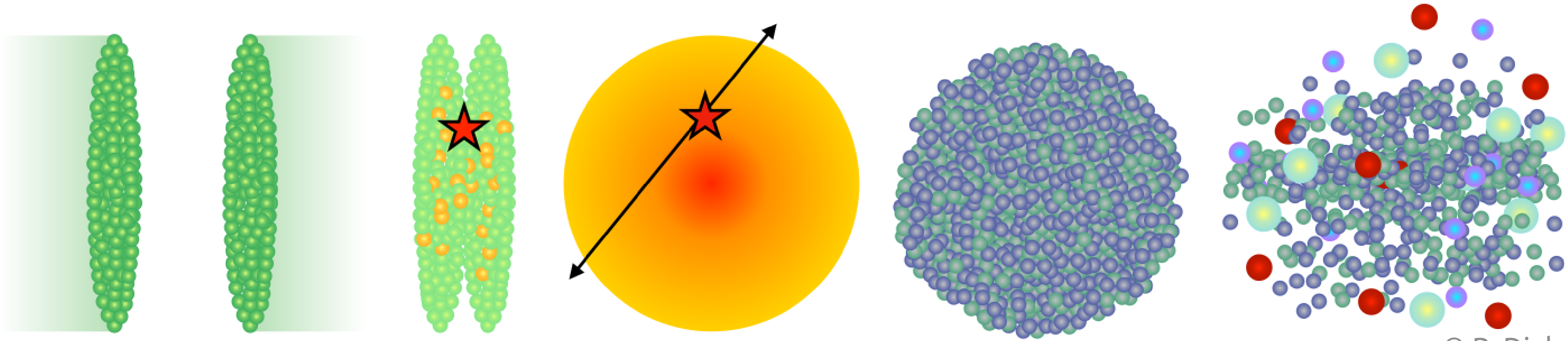
Ann.Rev.Nucl.Part.Sci.57:205-243,2007



# A real heavy ion collision



# Probes of the QGP



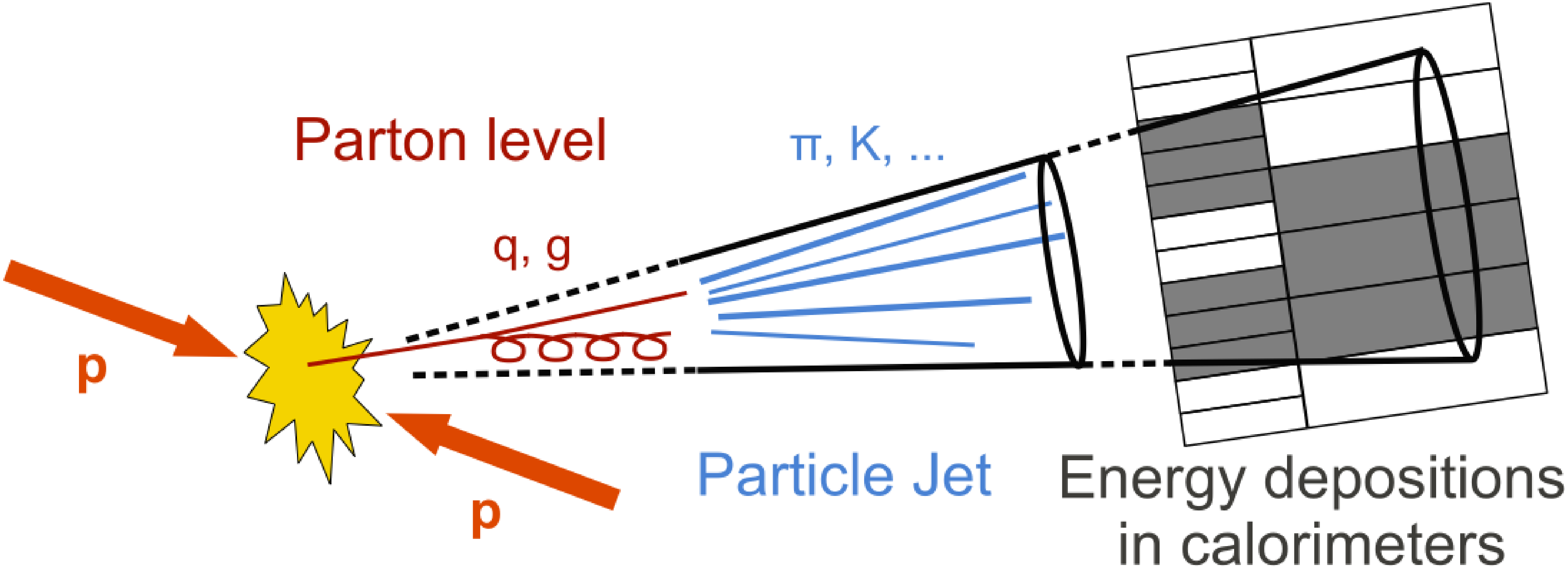
© B. Diab

- Medium density – partons (jets)
- Temperature - Quarkonium states (J/ψ , Υ), dileptons and photons
- Thermalization - Strangeness enhancement
- Collectivity - Particle correlations
- …

# Partons, hadrons and jets

Pertubative QCD knows **partons (quarks and gluons)**

Experiments see collimated sprays of **hadrons**



Define an experimental quantity which resembles a parton

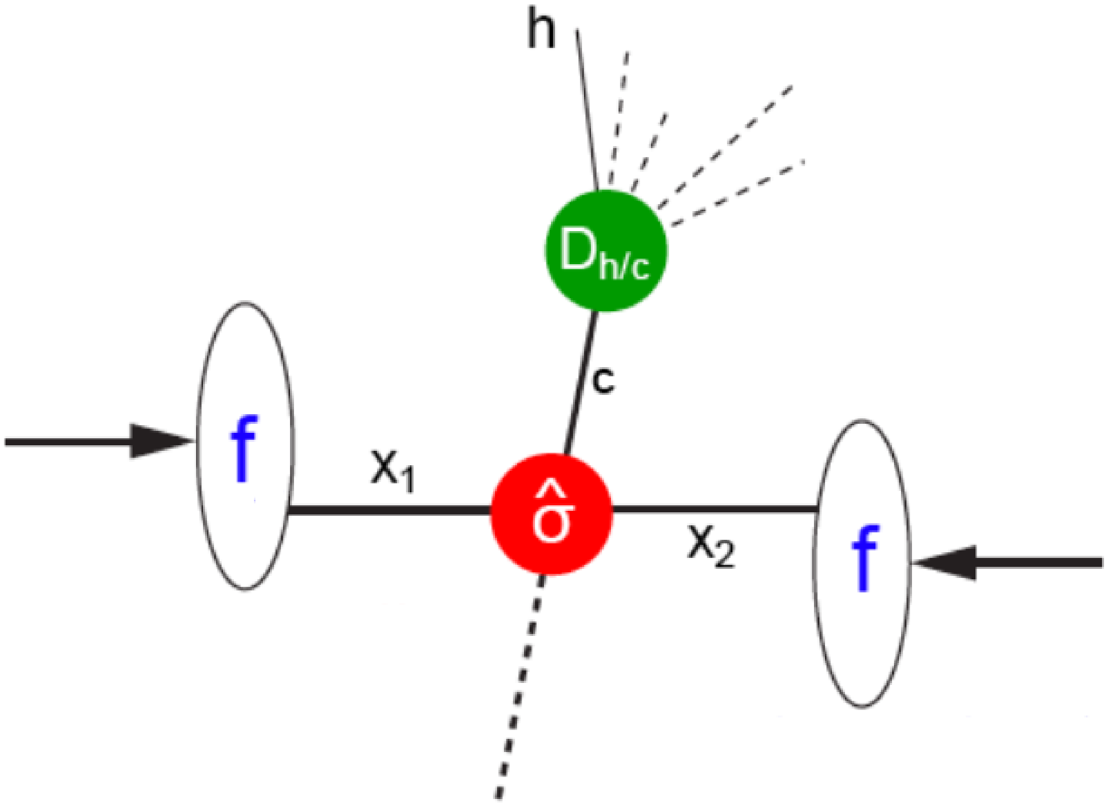
**Jets** - collimated bunches of stable **hadrons**, originating from **partons** after fragmentation and hadronization

→ jet is designed to be a proxy for a parton

# Hard scattering in elementary collisions

Factorization of the cross-section :

$$\mathrm{d}\sigma = \mathrm{f}(\mathrm{x}_1, \mathrm{Q}^2) \otimes \mathrm{f}(\mathrm{x}_2, \mathrm{Q}^2) \otimes \mathrm{d}\hat{\sigma} \otimes \mathrm{D}(\mathrm{z}, \mathrm{Q}^2)$$



Hard scattering of point-like partons described by pQCD

Soft processes described by universal, phenomenological functions :

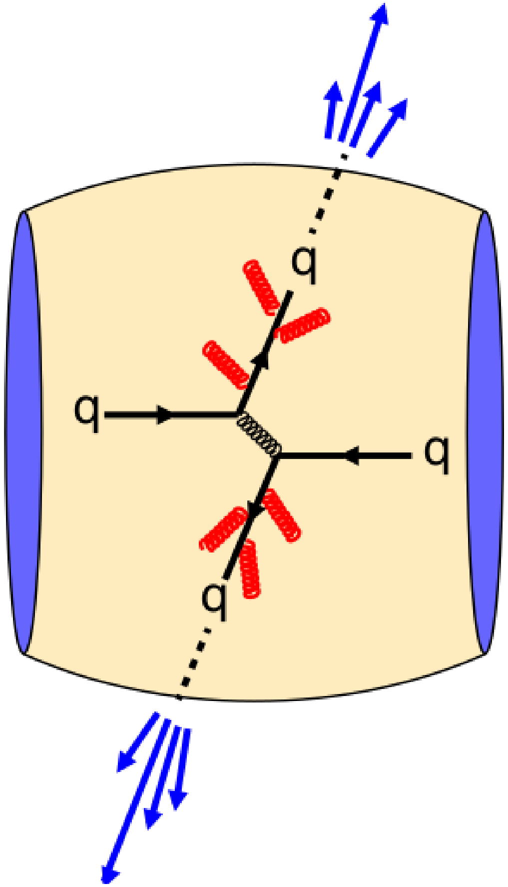
Parton distribution function (PDF) can be extracted from deep inelastic scattering

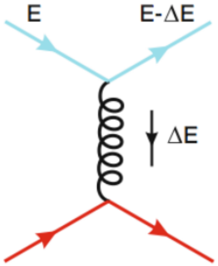
Fragmentation functions - from $e^+e^-$ or hadron collisions

# Jet quenching

$$d\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes d\hat{\sigma} \otimes P(\Delta E) \otimes D(z', Q^2)$$

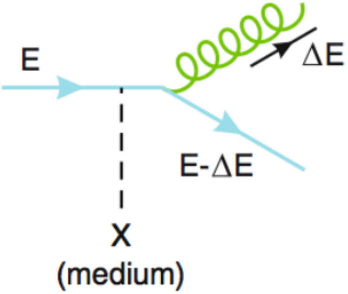
Parton energy loss





Collisional energy loss:

Elastic scatterings with medium constituents
Dominates at low energy



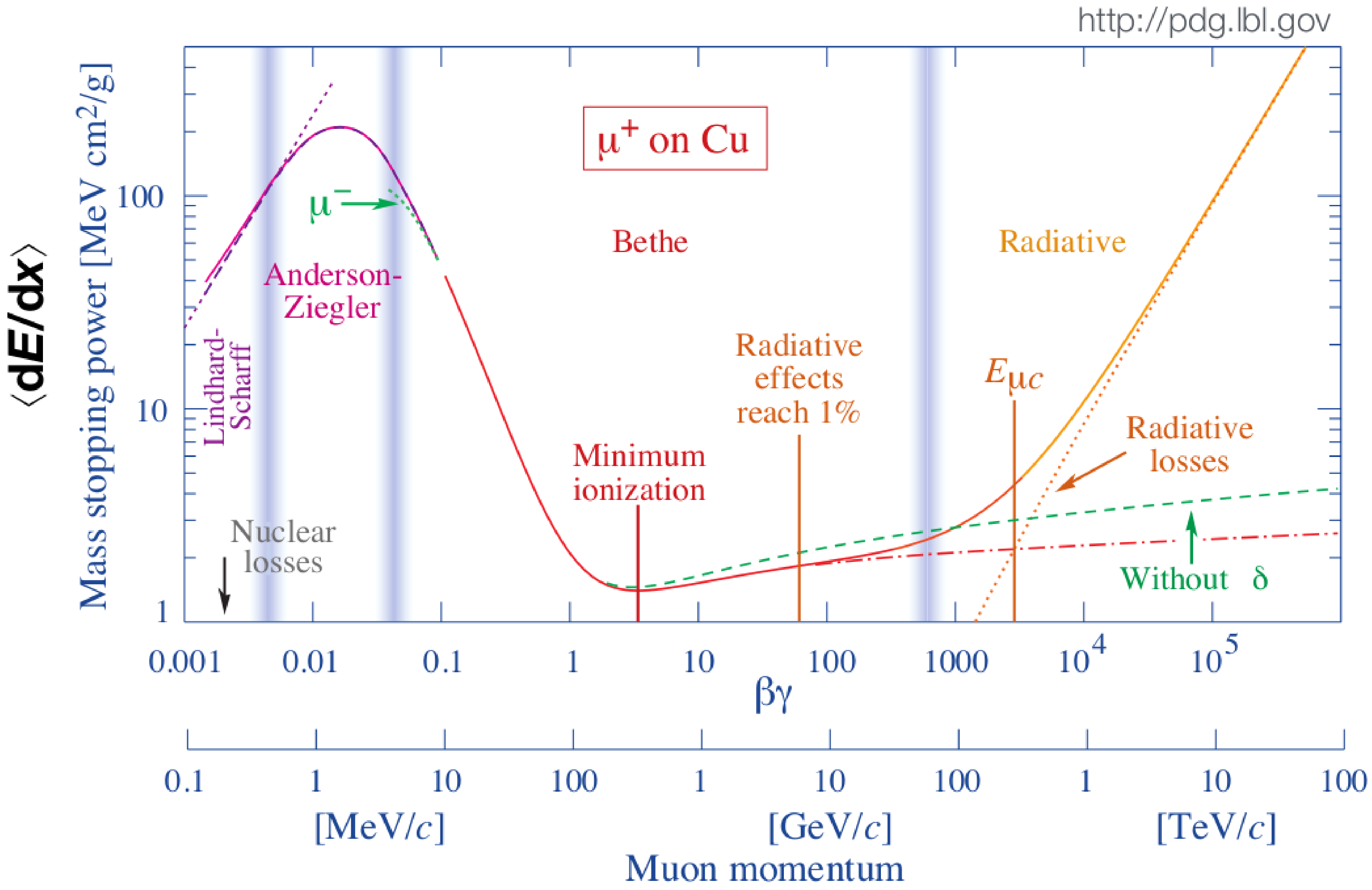
Radiative energy loss:

Inelastic scatterings with medium constituents
Dominates at high energy

Energy loss depends on :

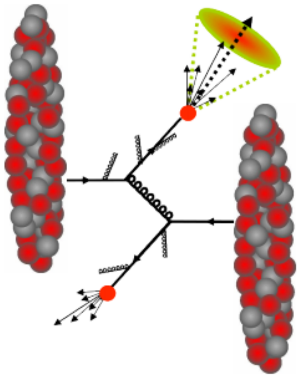
→ path length
→ parton flavor
→ medium density – want to extract

# Analogy : energy loss in normal matter

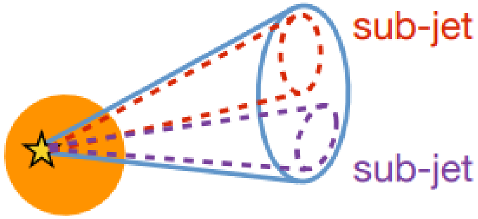


The goal : establish similar picture for QCD matter

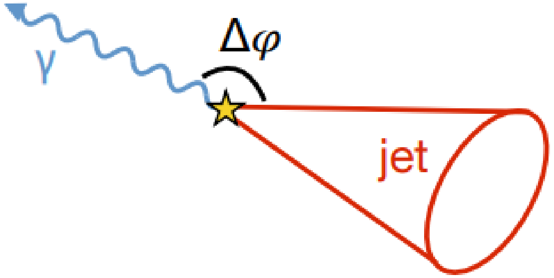
# Selected jet results



- Jet quenching observation at RHIC and LHC
  - proof of the concept
- Jet substructure
  - how jet constituents are modified
  - evolution of the parton shower
  - color coherence effect



- Photon + jets
  - photon gives well-defined initial parton kinematics



# Hadron suppression at RHIC

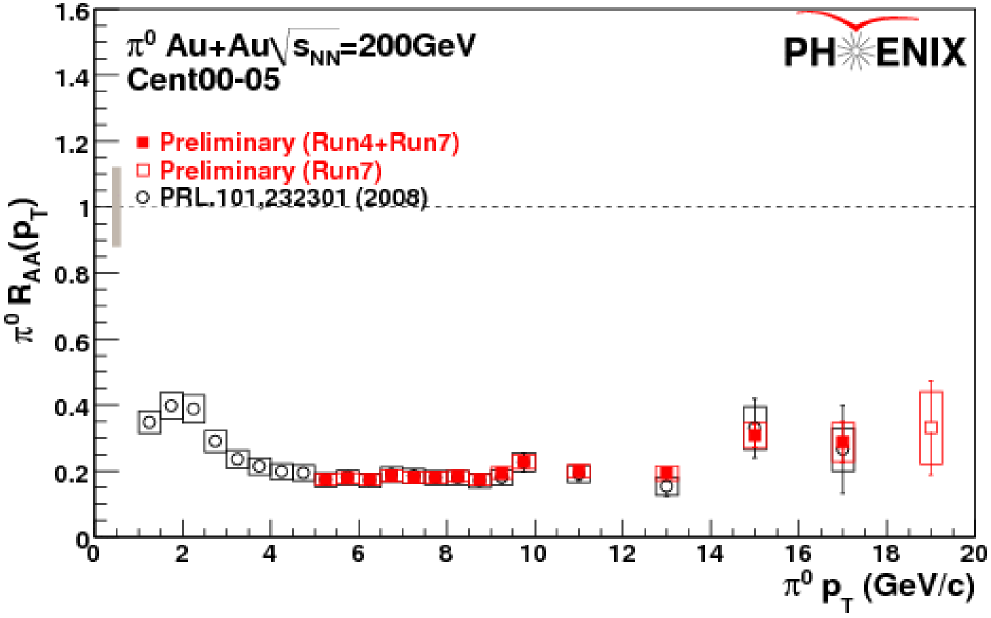
$\pi^0 \rightarrow 2\gamma$ measured in PHENIX in pp and AuAu collisions

Nuclear modification factor :

$$\mathrm{R_{AA}} = \frac{\text{per-event yield}_{\mathrm{AA}}}{\text{number of binary collisions} \times \text{per-event yield}_{\mathrm{pp}}}$$

No medium effect : R $_{AA}$ = 1

PHENIX, PRL 101 (2008) 232301



Au-Au yield suppressed by factor of 5

Cross-section $p_T$ dependence:

$$\frac{d\sigma}{dp_T} \propto \frac{1}{p_T^n}$$

$n \approx 7$ at RHIC

$n \approx 5$ at LHC

**Fractional** constant energy loss :

$$p'_T = C \times p_T \longrightarrow R_{AA} = C^{n-1}$$

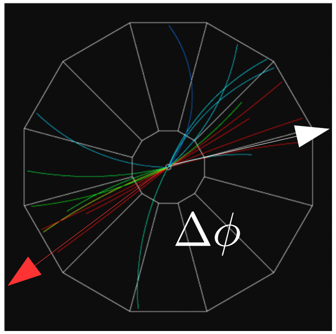
R $_{AA}$ = 0.2 at RHIC; C = 0.8 (20% energy loss)

Each parton loses 20% of its energy

# Dihadron azimuthal correlations at RHIC

STAR, PRL 91 (2003) 072304

pp → dijet

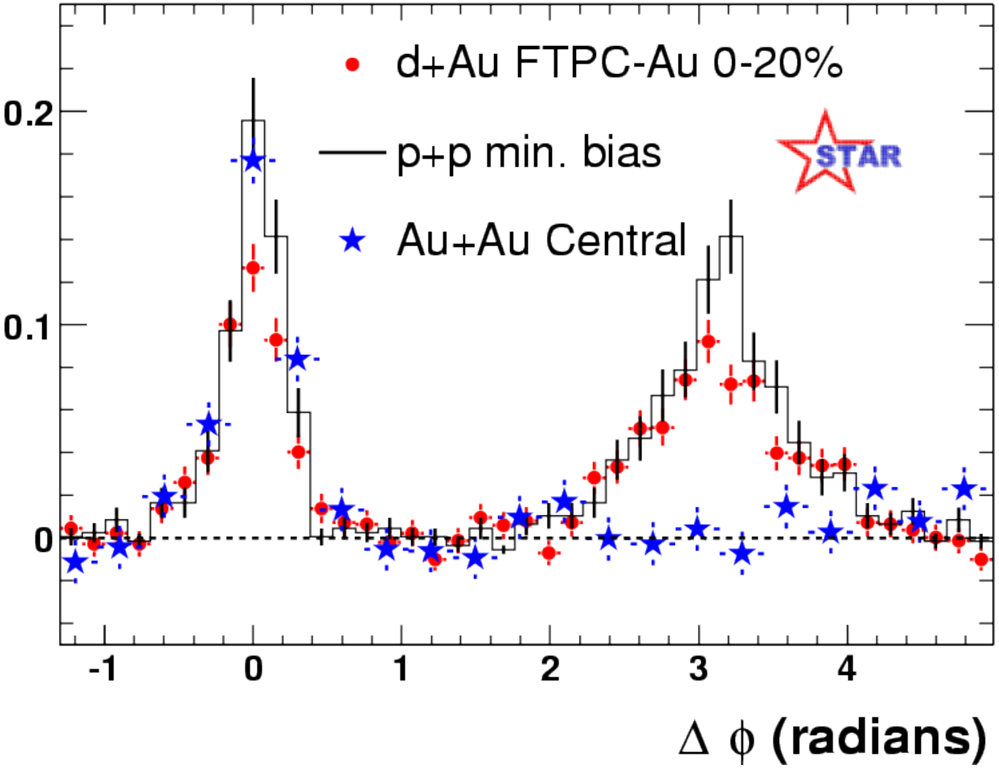


Partner hadron

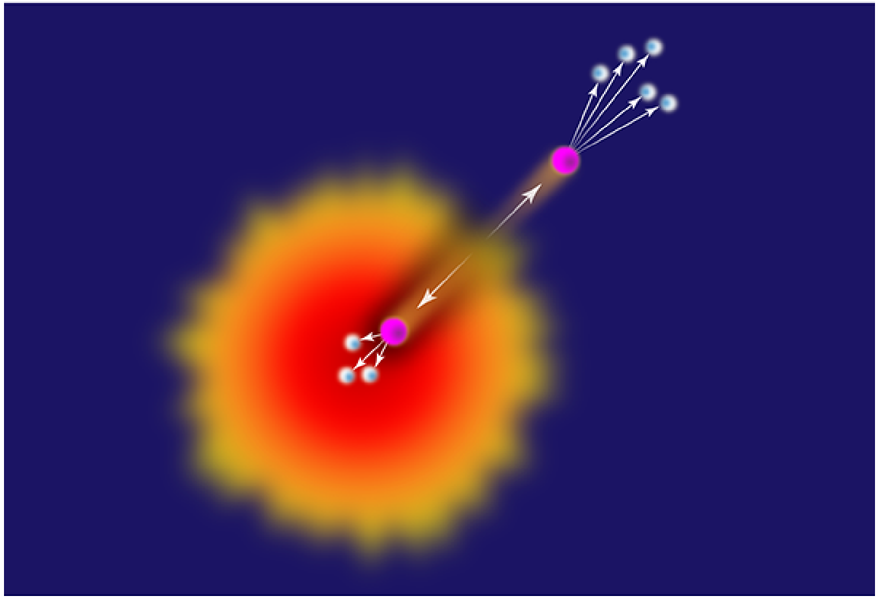
$2 < p_T < p_T(\mathrm{trig})$

Trigger hadron

$4 < p_T(\mathrm{trig}) < 6$ GeV



Trigger hadron



APS/Alan Stonebraker

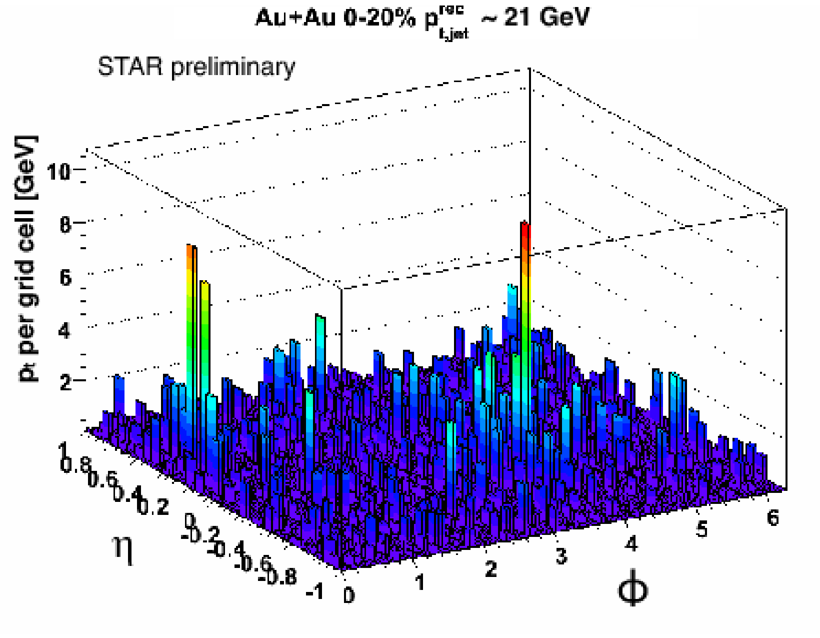
Partner hadron

Trigger hadron preferentially produced near surface, while recoil jet traverses the QGP

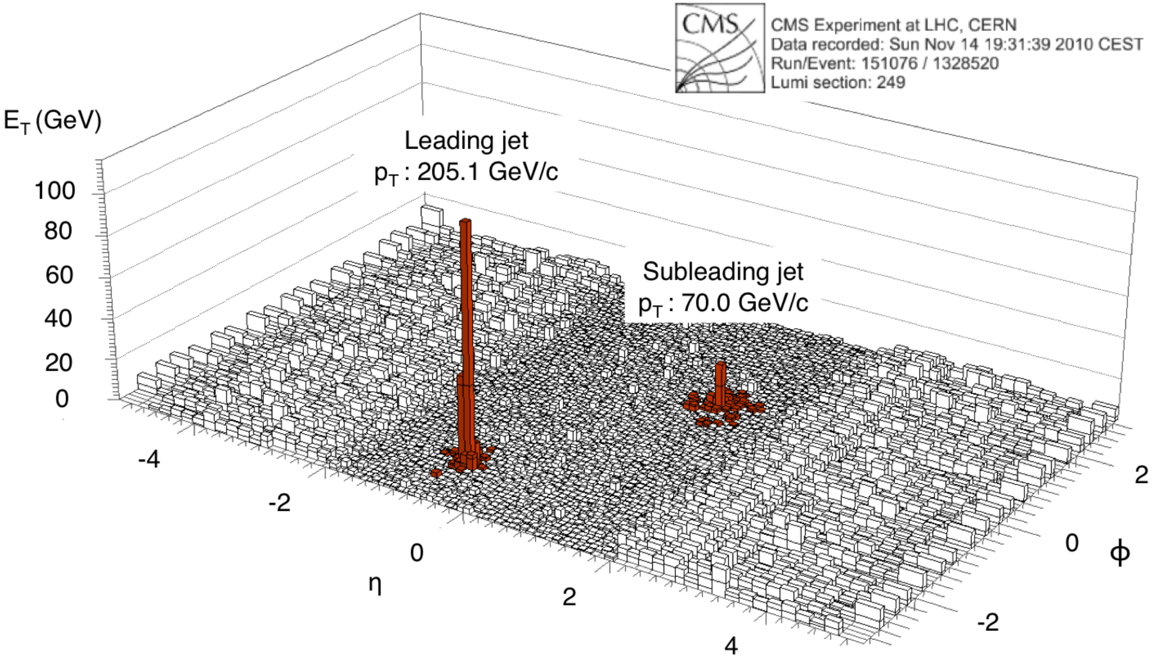
# Jets at RHIC and LHC

Full jet reconstruction was done for the first time at the LHC

STAR



CMS



# Jet reconstruction at the LHC

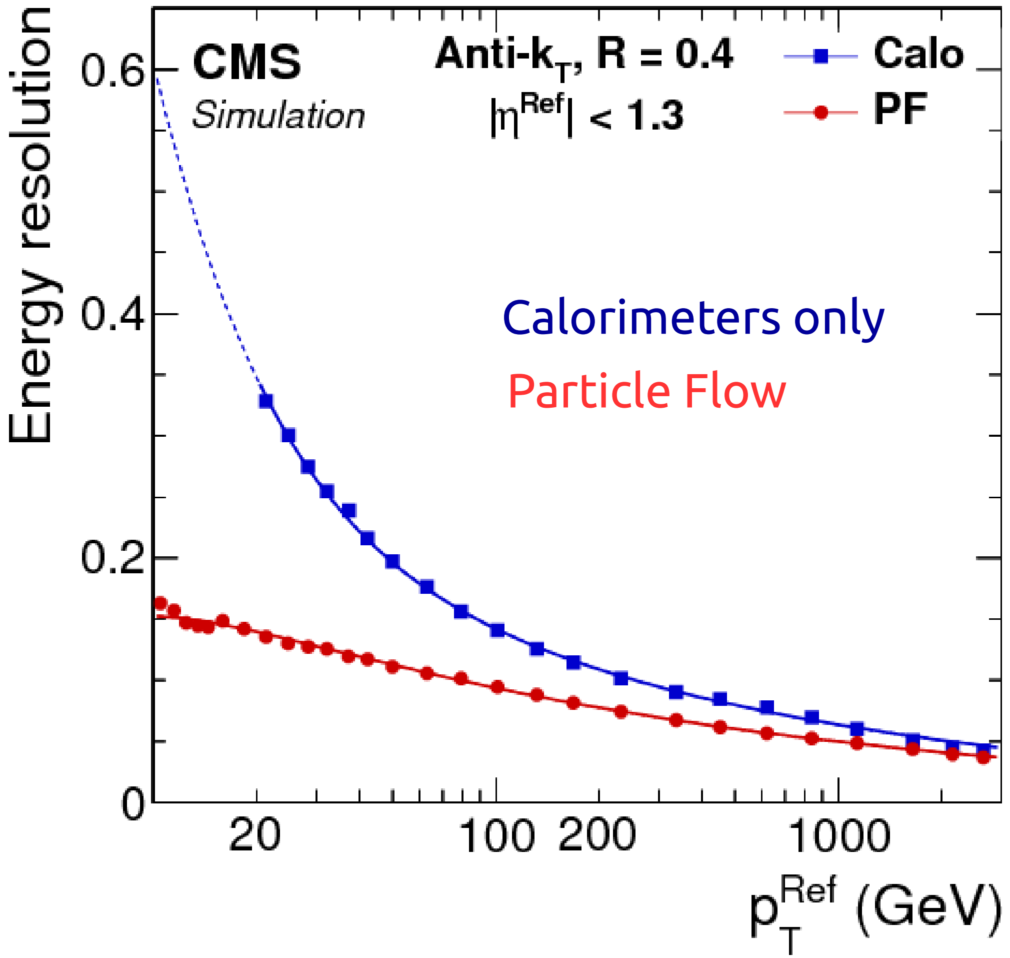
Jets consist of hadrons and photons → energy can be measured by the calorimeters only

Particle Flow in CMS (JINST 12 (2017) P10003)
ATLAS (Eur. Phys. J. C 77 (2017) 466)

Particle Flow reconstruction :
Combine tracks and calorimeter clusters

Particle Flow jet composition :

- → 65% charged hadrons
- → 25% photons
- → 10% neutral hadrons



Calorimeters only

Particle Flow

Jet energy resolution improves by factor 2 at lower $p_T$ thanks to the tracker resolution

# Jet clustering

Jet clustering : reverse-engineering of the fragmentation and hadronization

Sequential clustering : combines the closest particles into jets

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{\boxed{R^2}} \qquad d_{iB} = p_{ti}^{2p}$$

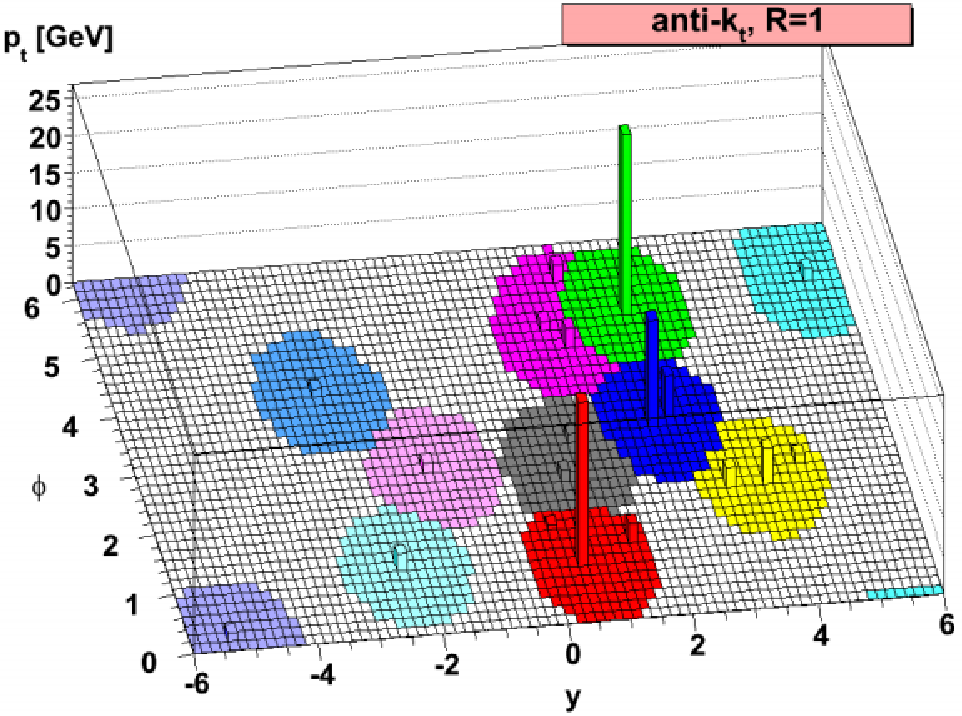
p = 1 : kt
p = 0 : C/A
p = -1: anti-kt

Distance between pairs of particles

Jet radius

Distance to the beam

JHEP 0804:063,2008

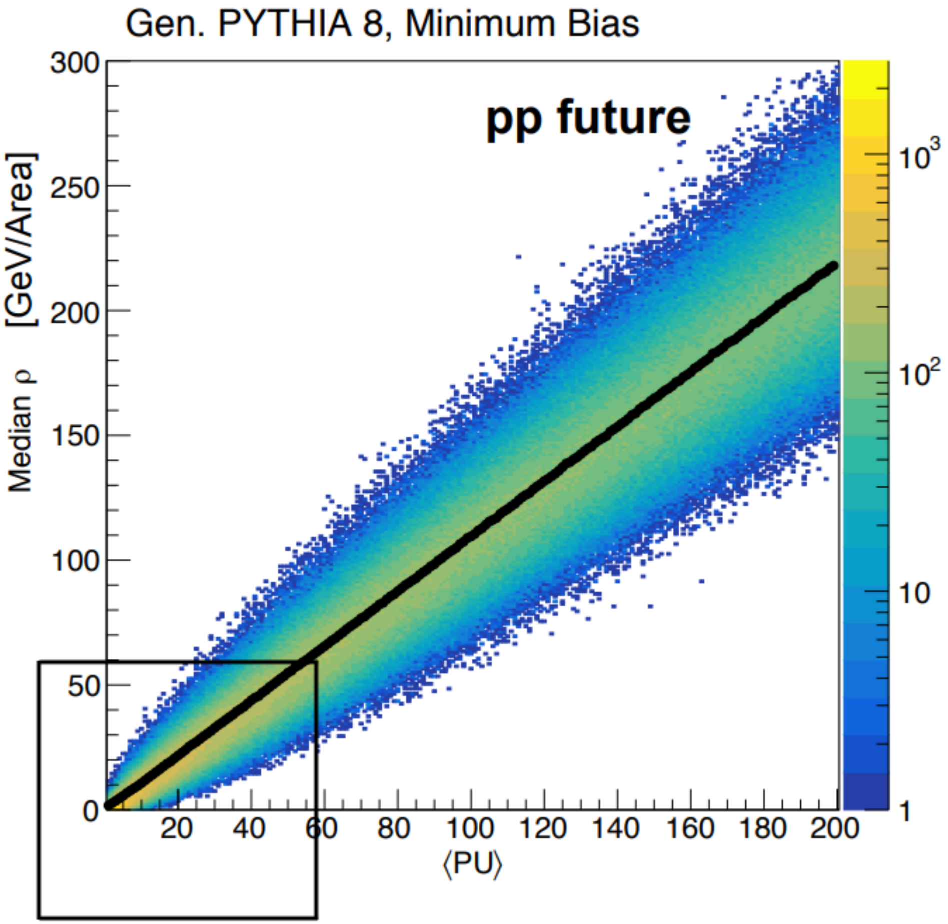


# Underlying event in pp and PbPb collisions

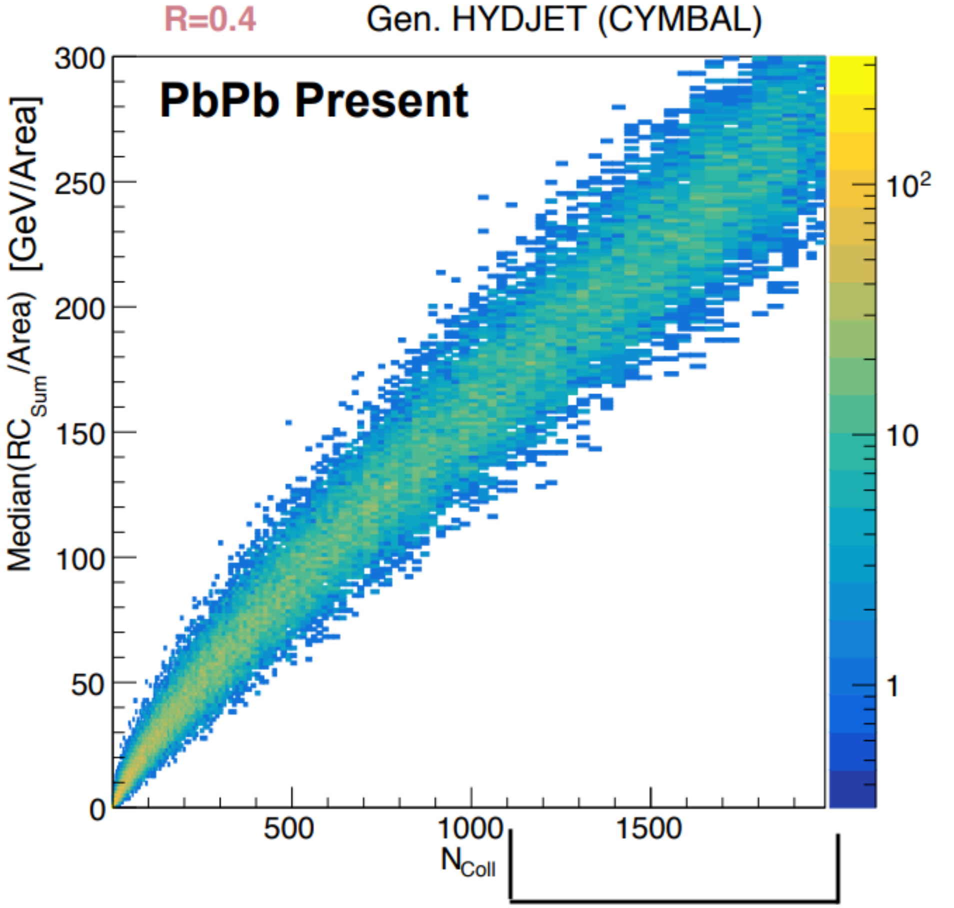
Underlying Event (UE) - particles not associated with the hardest parton-parton process
quantified as transverse momentum density (ρ)

PileUp (PU) – concurrent interactions coming from the same bunch crossing

BNL jet workshop ‘18, C.McGinn talk



**pp present**

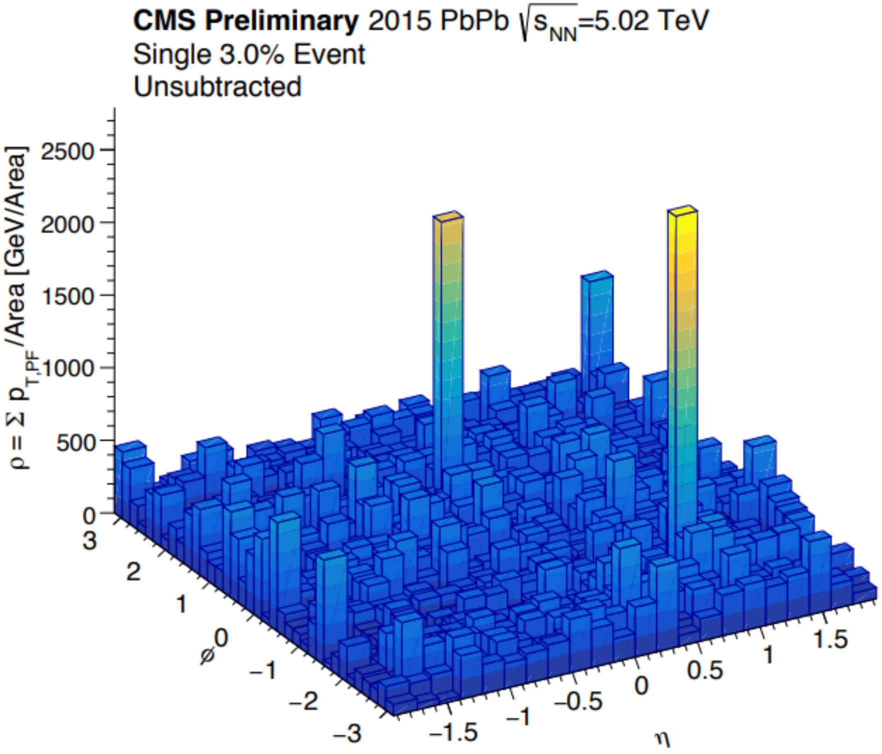


**~0-10% PbPb at 5.02 TeV**

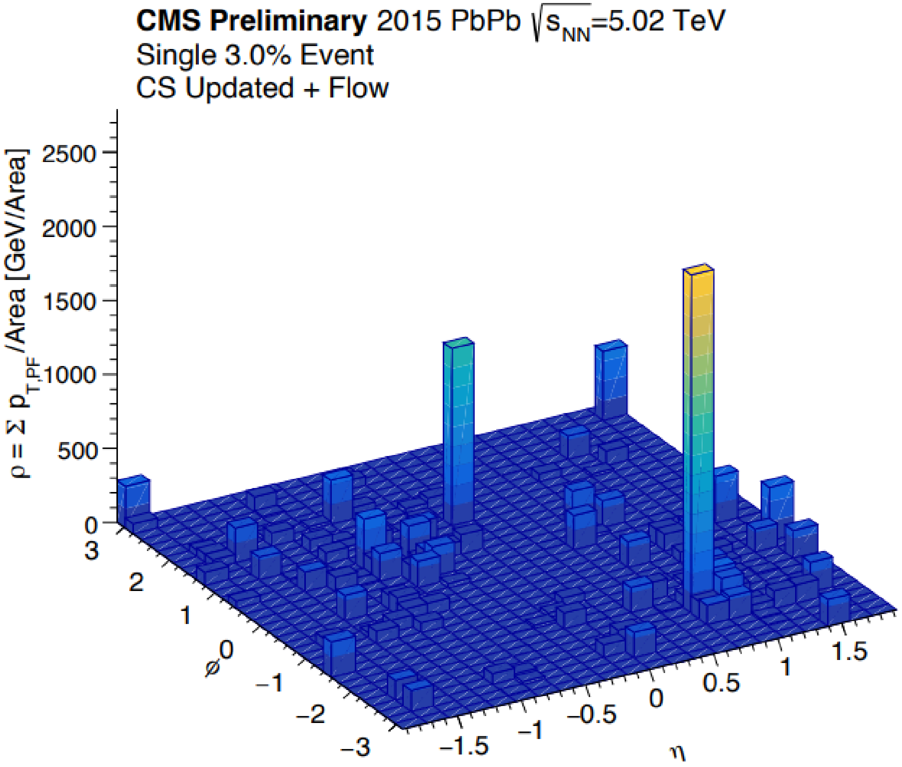
UE in pp with <PU> ~ 200 looks like central PbPb

# Jets in PbPb collisions

## Before UE subtraction



## After UE subtraction

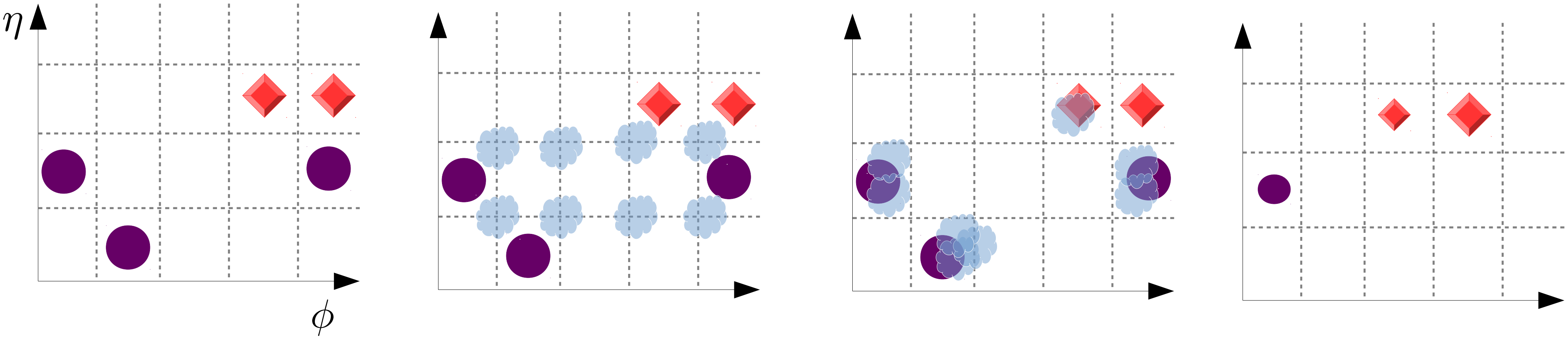


What amount of UE to subtract? How?

# UE subtraction in CMS : constituent subtraction

Particle-by-particle: correct the 4-momentum of a jet and substructure

◆ - signal ● - underlying event ☁ - ghost (artificial particles)



Add ghosts with $p_T^{\text{ghost}} = A_{\text{ghost}} \cdot \rho$ in random locations;

$A_{\text{ghost}}$ - area occupied

Combine them with the closest real particle

The largest pT particle/ghost survives

$p_T^{\text{particle}} > p_T^{\text{ghost}}$ $\quad p_T^{\text{particle}} = p_T^{\text{particle}} - p_T^{\text{ghost}}$

$p_T^{\text{particle}} < p_T^{\text{ghost}}$ $\quad p_T^{\text{ghost}} = p_T^{\text{ghost}} - p_{T\,\text{particle}}$

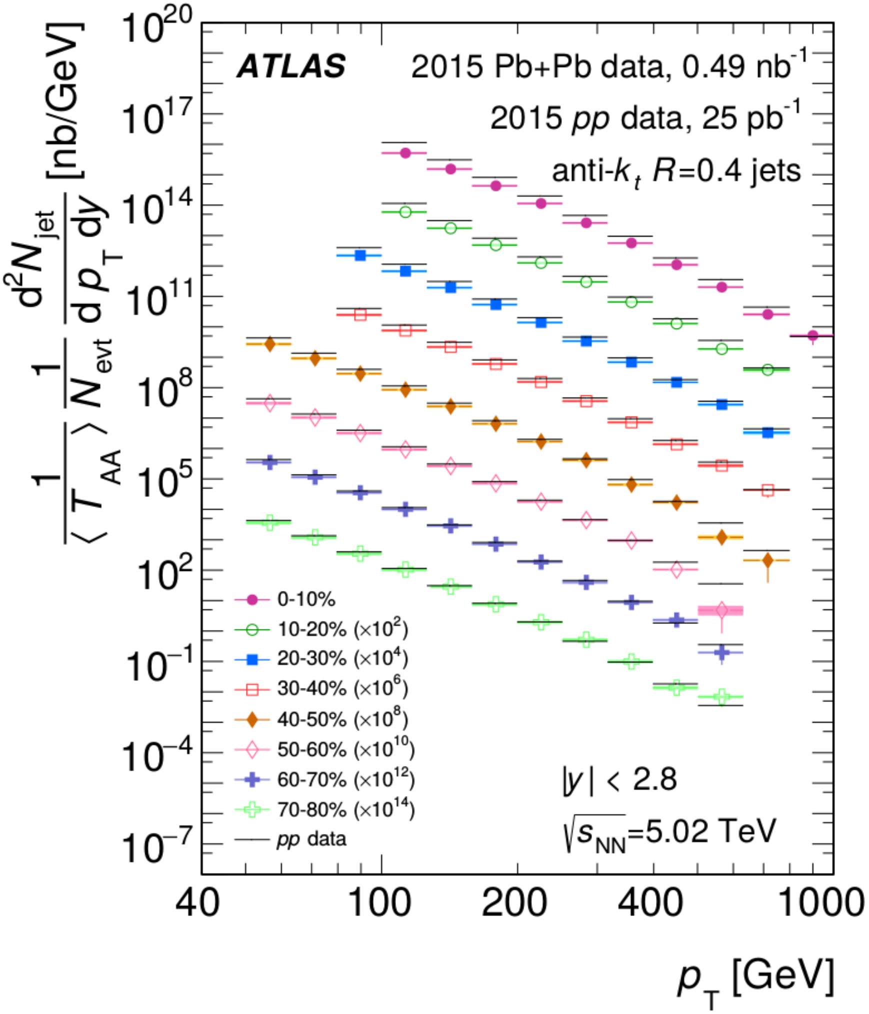
Repeat until no ghosts/particles left

Remaining particles get clustered into a jet

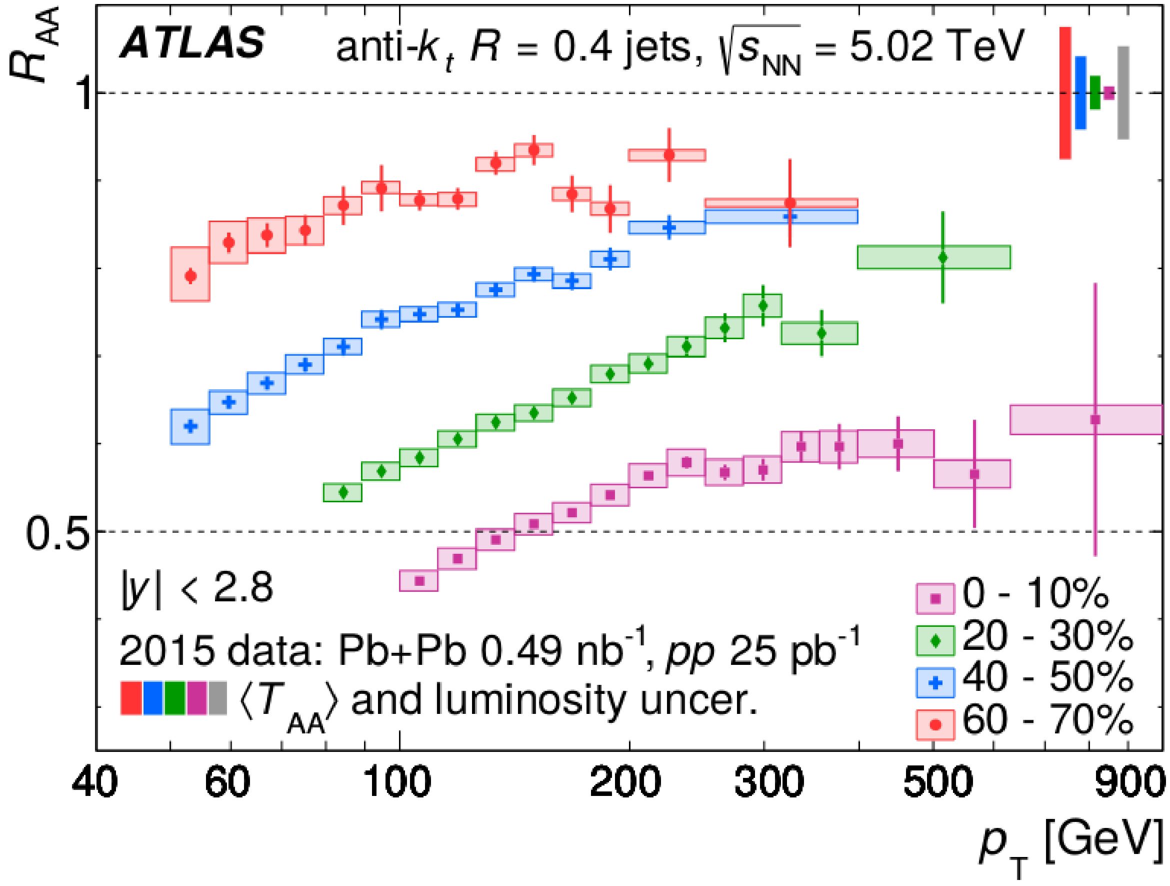
# Jet suppression in ATLAS

Inclusive jet cross-sections are measured in pp and PbPb up to 1 TeV

Phys. Lett. B 790 (2019) 108



$$R_{AA} = \frac{\text{per-event yield}_{AA}}{\text{number of binary collisions} \times \text{per-event yield}_{pp}}$$

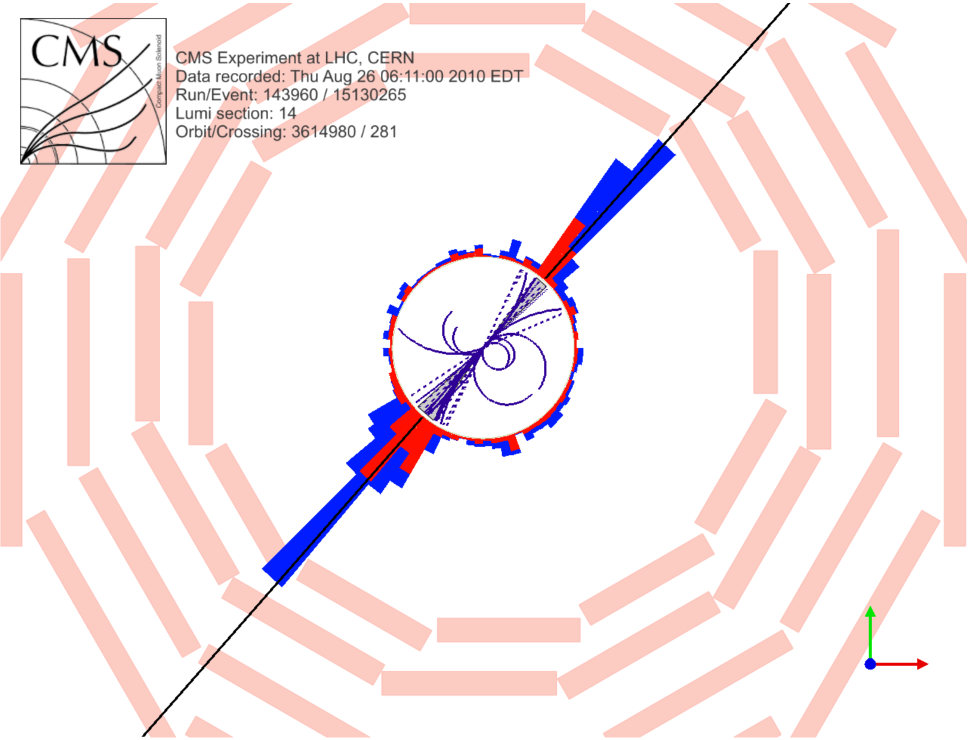


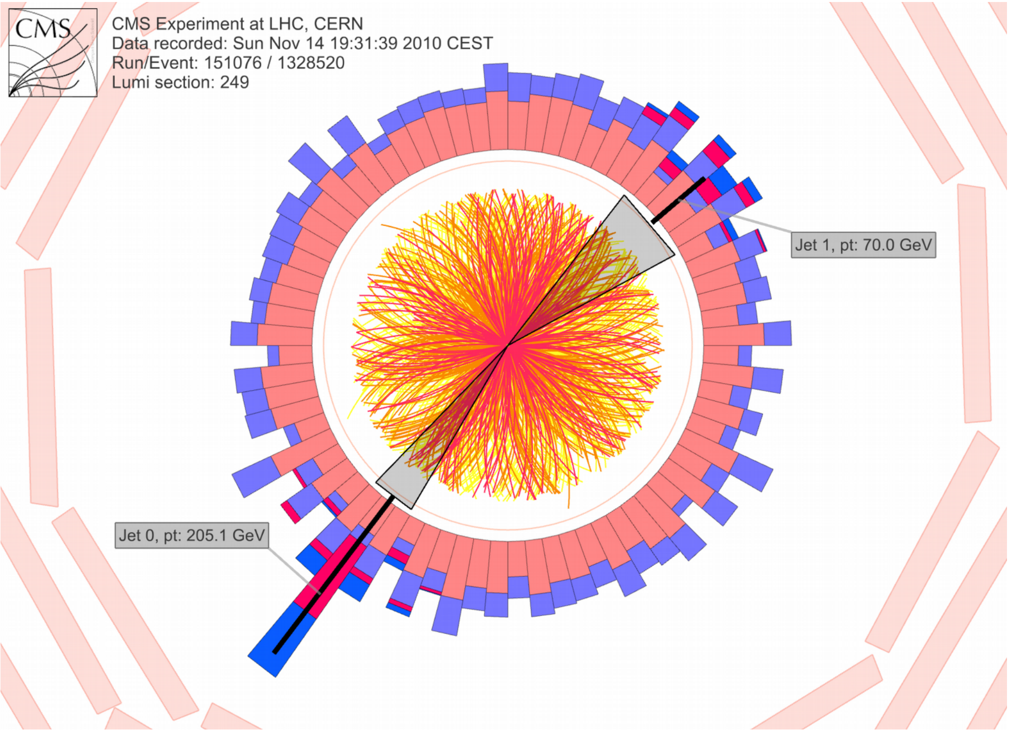
At large pT :  flat suppression in central collisions

# Dijet $p_T$ balance

If **no energy loss**, typically two jets have equal pT wrt the beam axis → ~ **back-to-back**

In PbPb more typical picture is **highly unbalanced dijets**



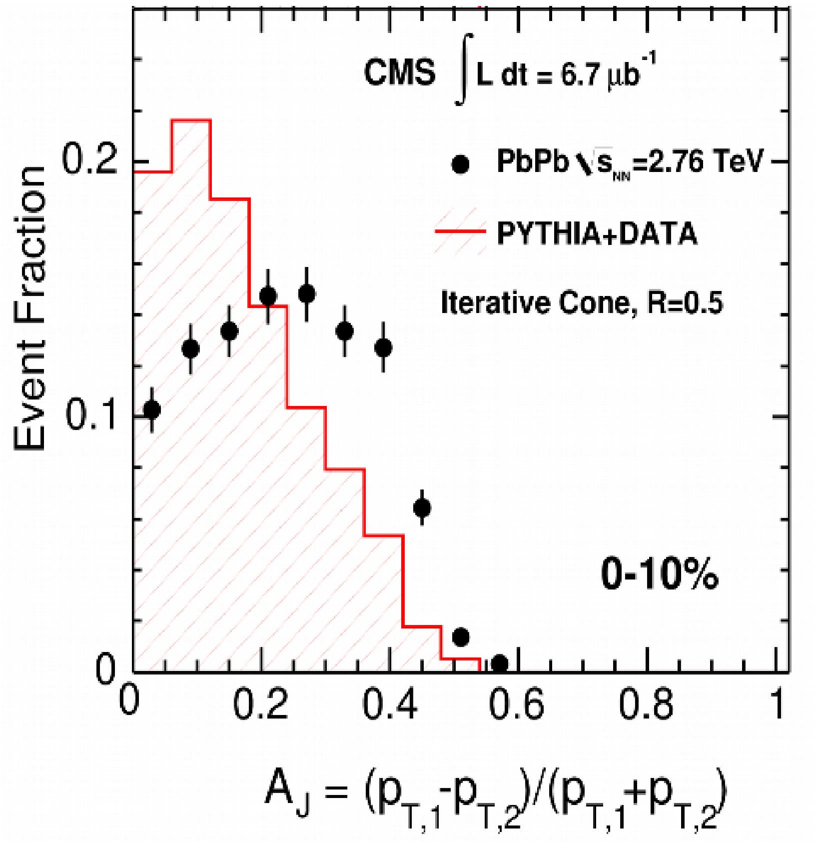


How to quantify the effect?

# Dijet asymmetry in CMS

Dijet asymmetry of leading and subleading jets

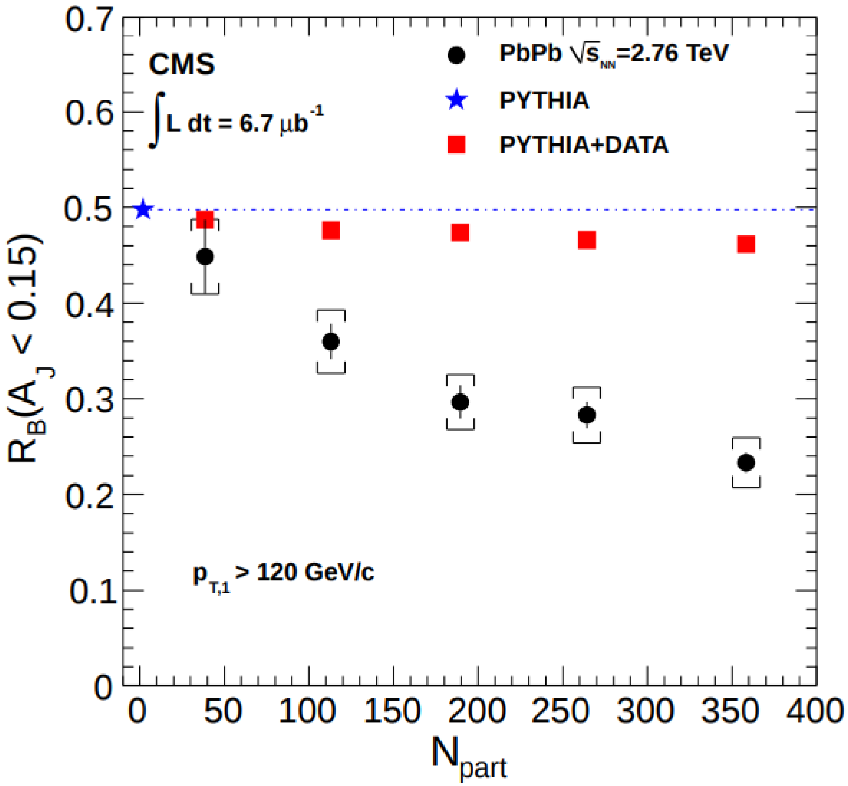
$p_{T,1} > 120 \text{ GeV}, \; p_{T,2} > 50 \text{ GeV}$
$\Delta\phi > 2\pi/3$



"no energy loss" : peak ~ 0.1
PbPb data : peak ~ 0.3

Fraction of all events with "balanced" jets

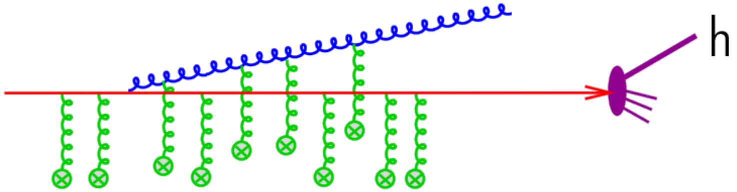
CMS, PRC84 (2011) 024906



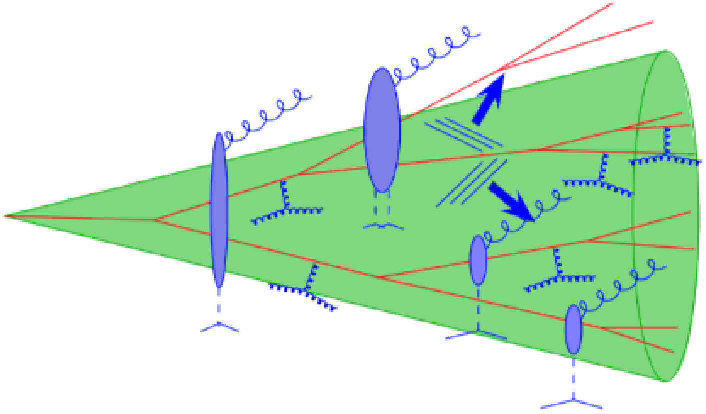
In the most central PbPb ~ 2 times less "balanced" dijets

High degree of jet quenching

# Jet substructure



Simplest picture of the energy loss:
one hadron traversing QGP



More realistic : parton shower in the QGP

→ how it is modified?

→ what is the mechanism of the energy loss?

In the experiment many effects are **convoluted** :

→ Momentum and color exchange of shower constituents with medium

→ Medium response

→ Role of the color coherence effect

→ …

Look inside the jet!

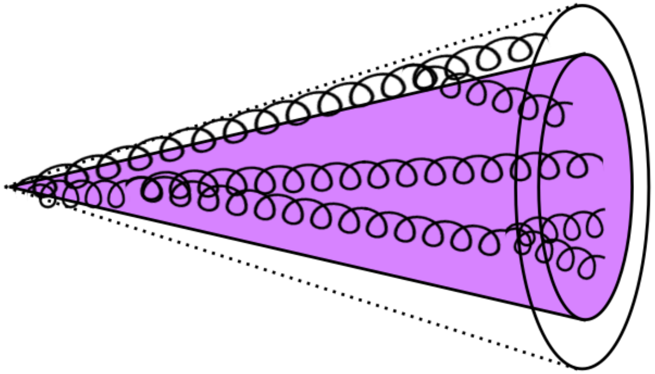
# Jet splitting : motivation

Parton interactions with the QGP can temporarily increase the gluon radiation probability :

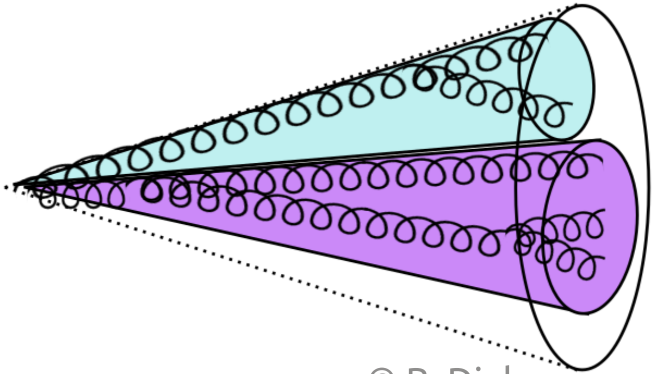
→ jet structure gets modified?

Different energy loss scenarios depending on color coherence of the jet in a medium :

→ is jet one coherent emitter or two ?



subjets equally modified

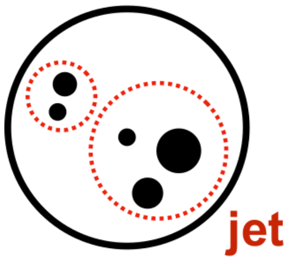


© B. Diab

subjets modified differently

# Jet splitting in CMS

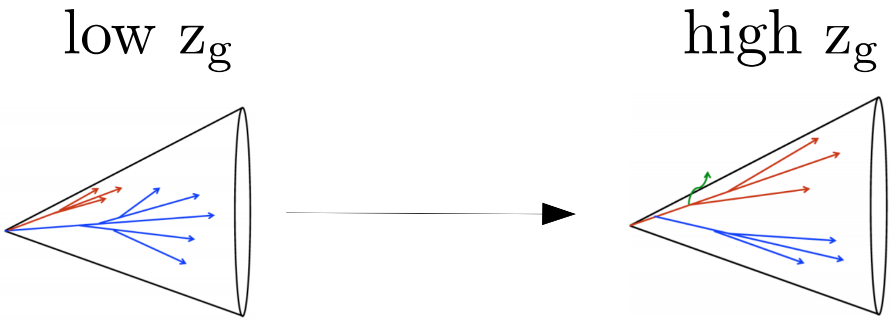
First splitting in parton shower → study only hard jet components

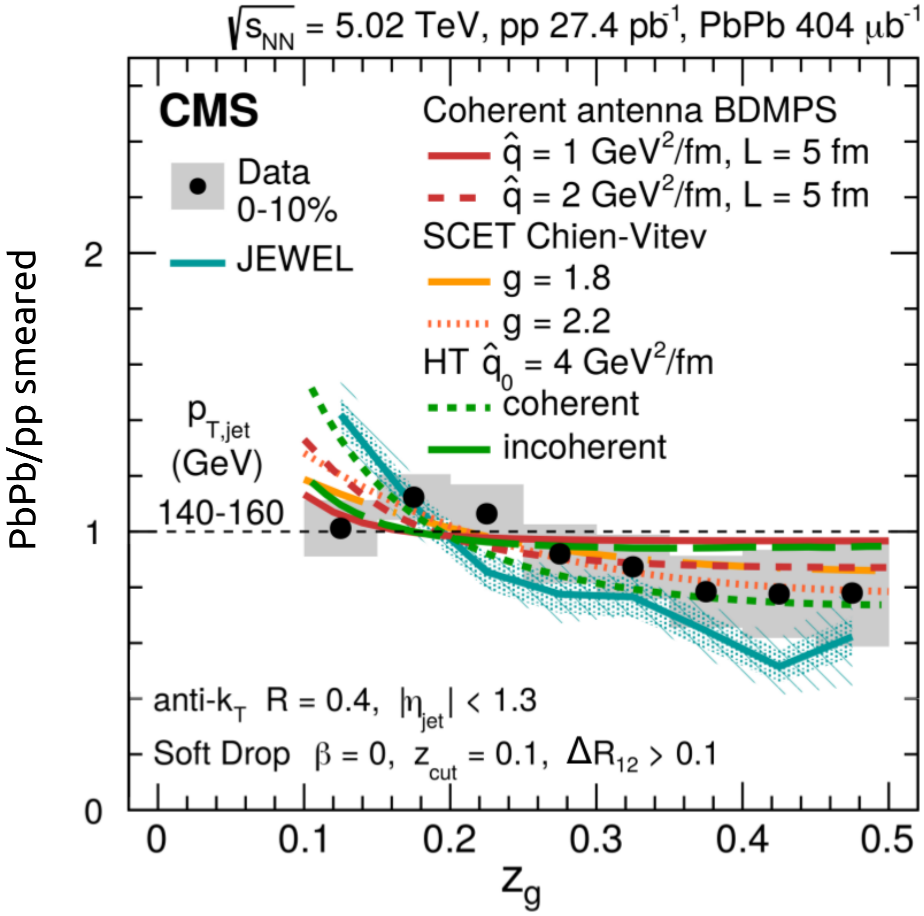


Subjet momentum sharing : $z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$

Angular distance between the subjets : $\Delta R_{1,2} > 0.1$

CMS, Phys. Rev. Lett. 120, 142302



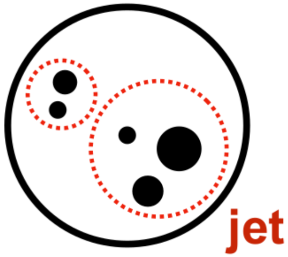


Momentum sharing is steeper in PbPb → splitting process is modified

Jet **cannot** be one coherent emitter!

# Jet splitting in ALICE

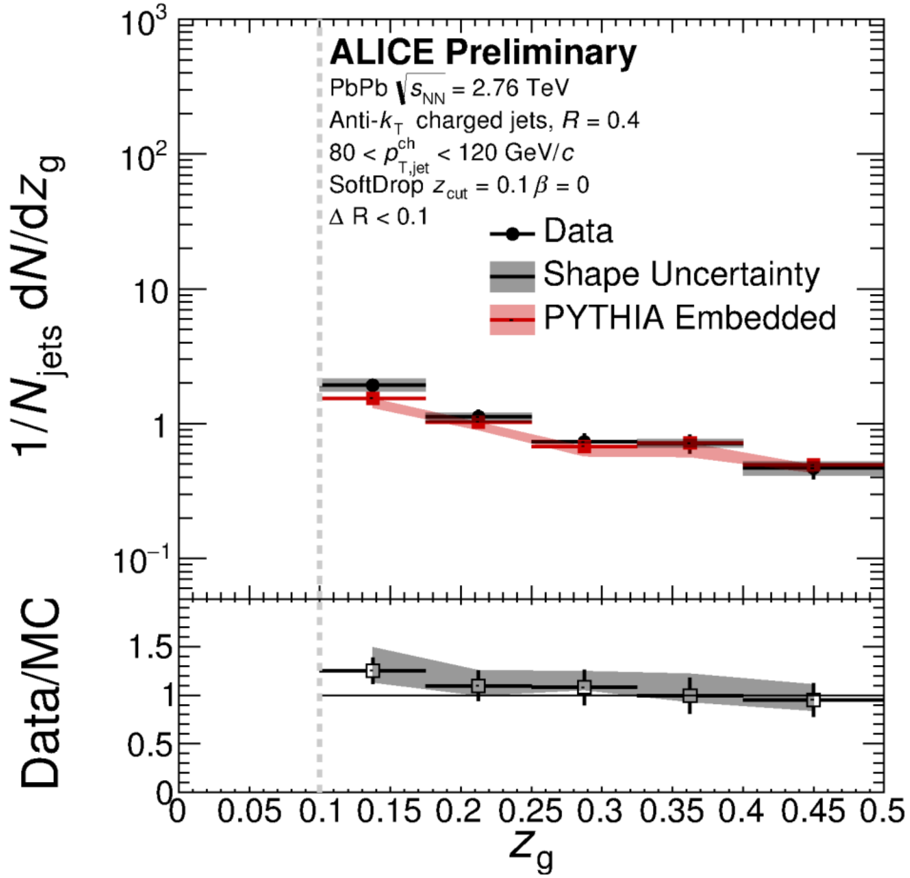
First splitting in parton shower → study only hard jet components



Subjet momentum sharing : $z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$

Collinear subjets : $\Delta R_{1,2} < 0.1$

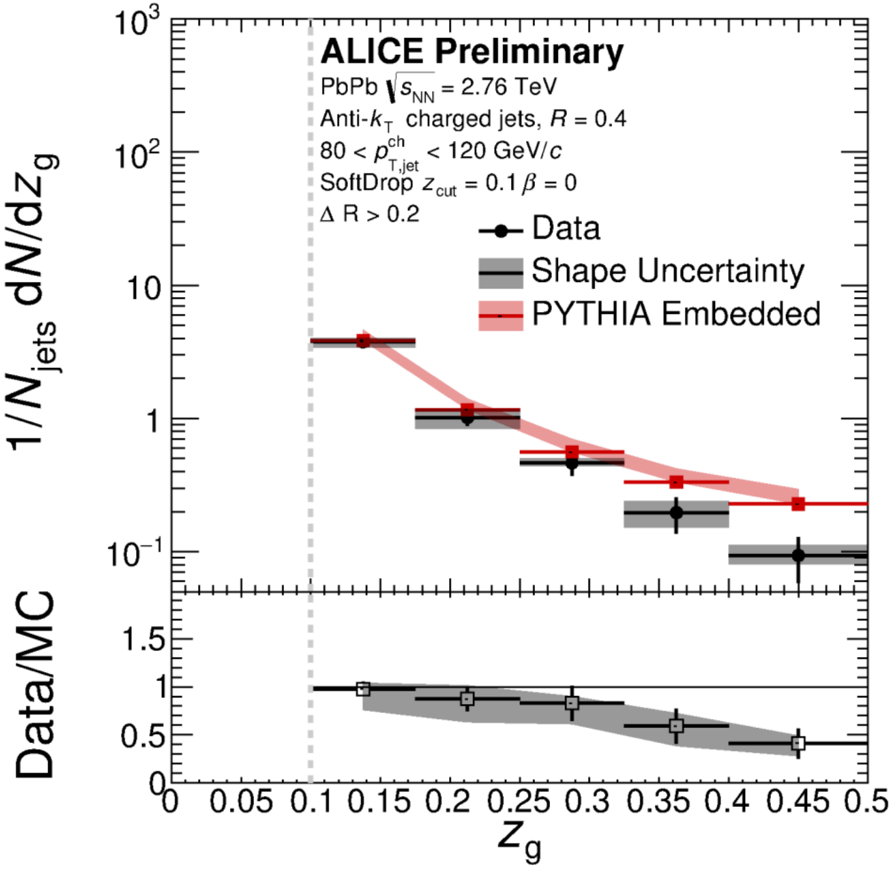
ALI-PREL-148233



No modification

Wide-angle subjets: $\Delta R_{1,2} > 0.2$

ALI-PREL-148229

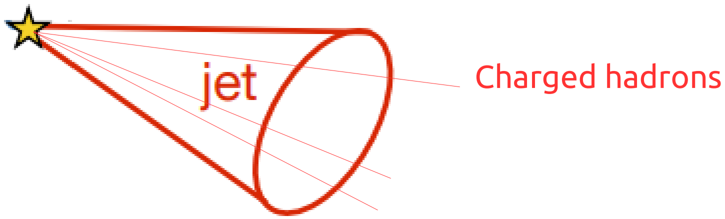


Wide-angle symmetric splittings are suppressed

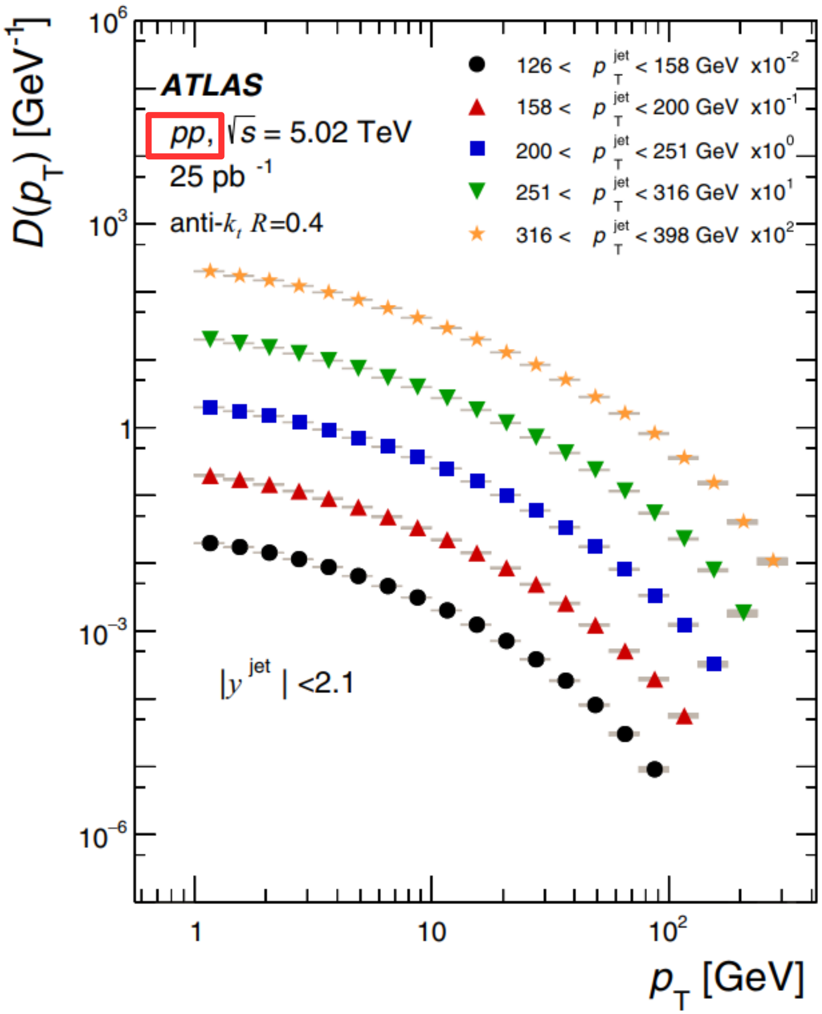
# Jet fragmentation function in ATLAS

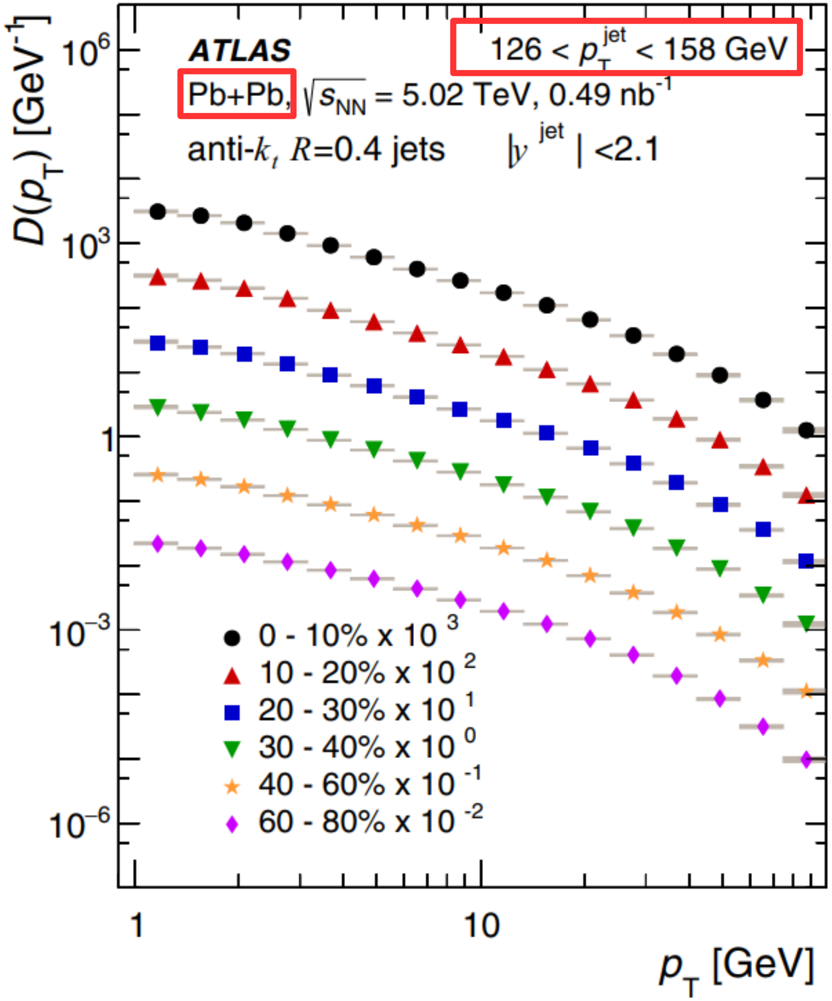
Distribution of charged-particle $p_T$ inside the jet
(fragmentation function) :

$$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$



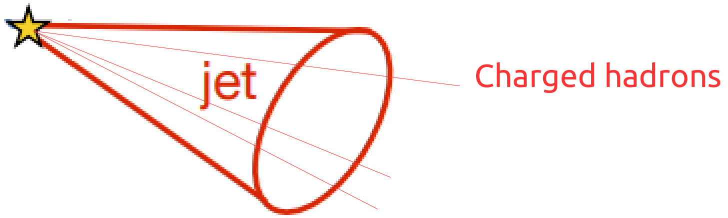
ATLAS, Phys. Rev. C 98 (2018) 024908





# Jet fragmentation function in ATLAS

Distribution of charged-particle $p_T$ inside the jet (fragmentation function) :



$$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$

How much is the jet structure modified ?

$$R_{D(p_T)} = \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}}$$

PbPb compared to pp :

→ more soft particles due to interaction with the medium

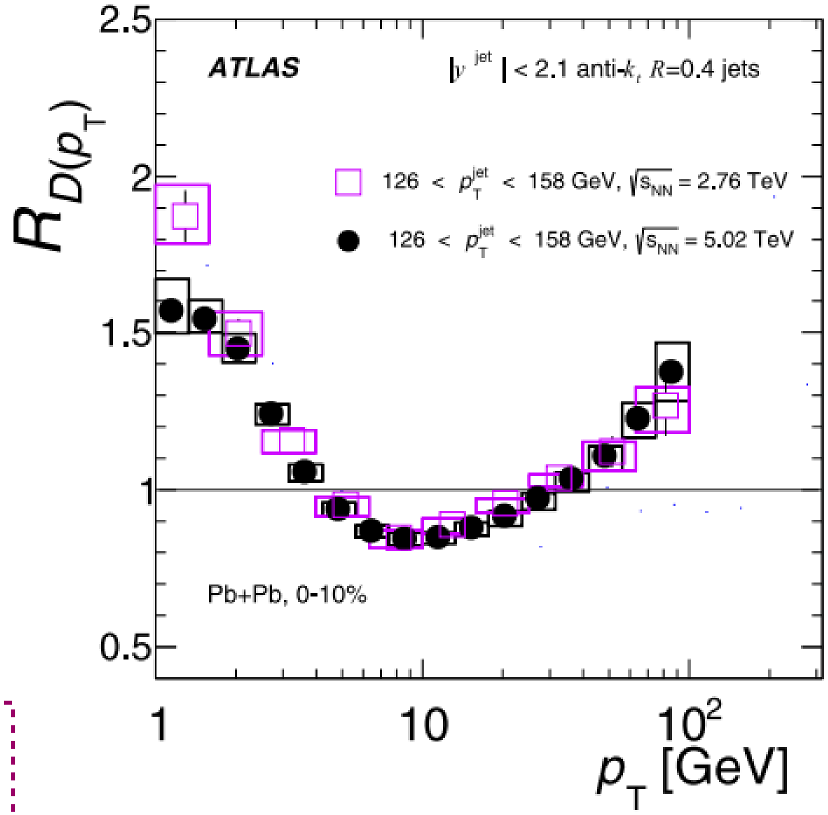
→ suppression at mid $p_T$

→ enhancement at high $p_T$ : consistent with quenching dependence on quark/gluon initiated jets

Gluon vs quark jet:

→ larger charged hadron multiplicity
→ contain more softer particle
→ wider

ATLAS, Phys. Rev. C 98 (2018) 024908



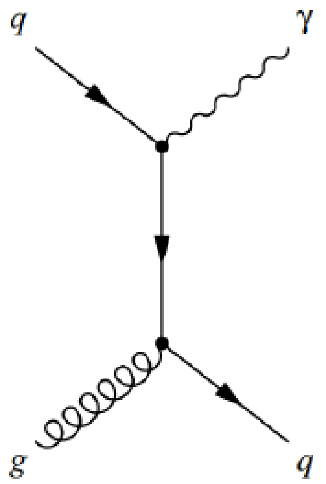
# Photon + jet system

In pp collisions :

→ Compton scattering dominates :
gluon in initial state and quark in the final state

→ jets are calibrated using photons :
the photon energy scale is known to ~1% accuracy:
absolute jet energy scale

Compton scattering

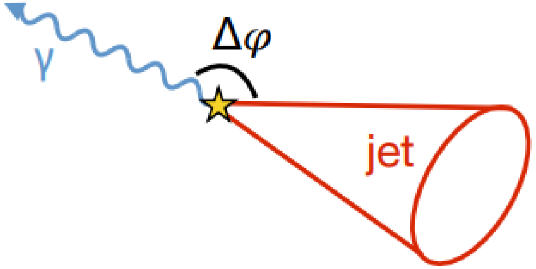


Quark-initiated jet

In heavy ion collisions :

→ photons do not interact with the QGP

→ study the energy loss with well defined initial kinematics !

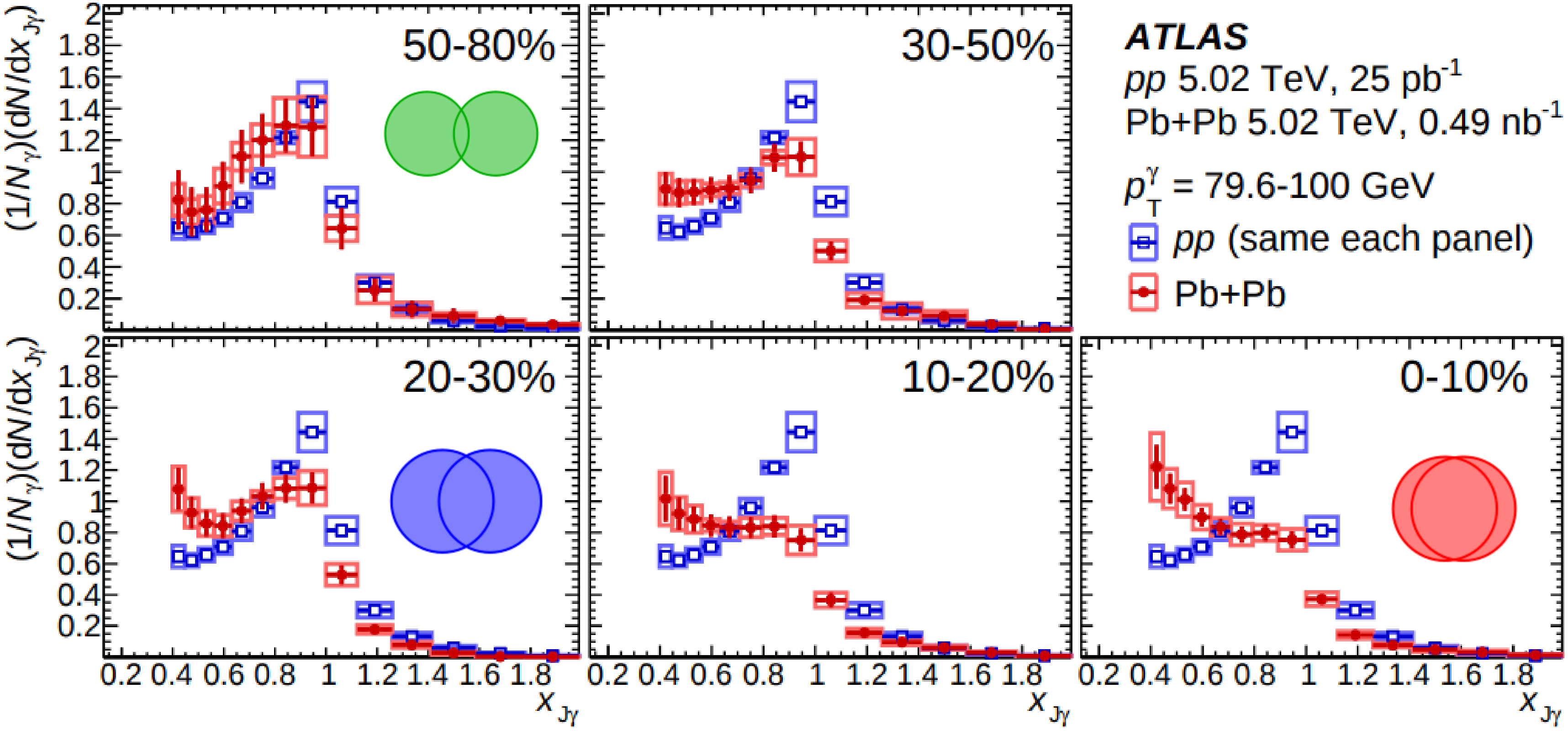


# Photon+jet pT balance in ATLAS

What is the amount of energy lost by the jet?

Balance : $$X_{J\gamma} = \frac{p_{T,jet}}{p_T^{\gamma}}$$

ATLAS, Phys. Lett. B 789 (2019) 167



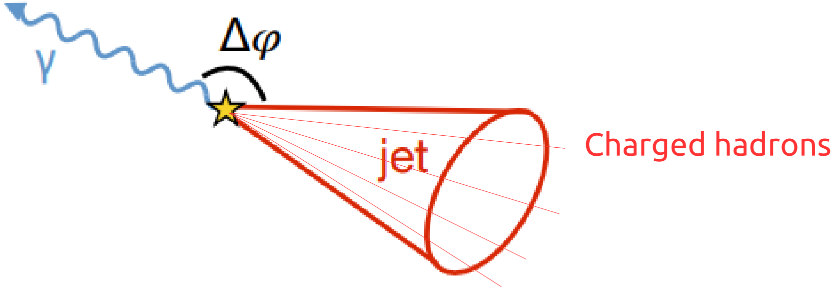
The jet energy decrease with centrality

- in peripheral events : a peak-like structure is present in the same position as in pp
- in the most central events : strongly modified, no peak, jet energy decrease

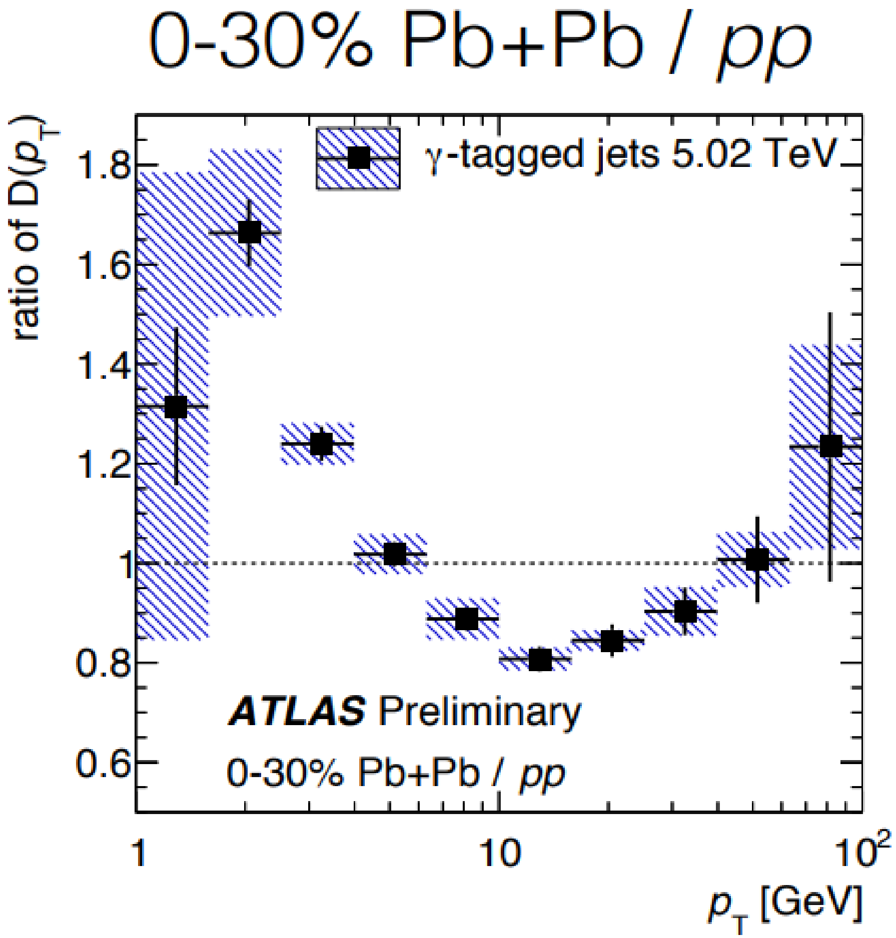
# Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function : $D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$



ATLAS-CONF-2017-074



Modifications compared to pp :

→ more soft particles due to interaction with the medium

→ suppression at mid $p_T$

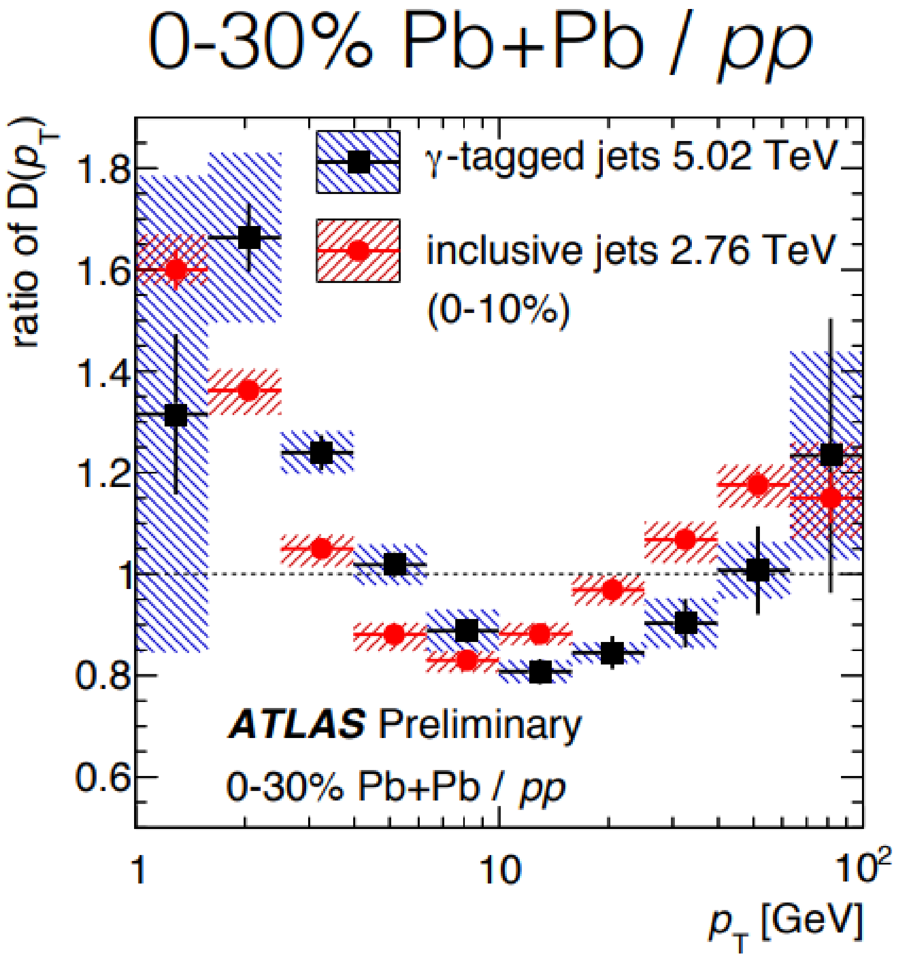
→ no modification at high $p_T$

# Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function : $$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$

ATLAS-CONF-2017-074



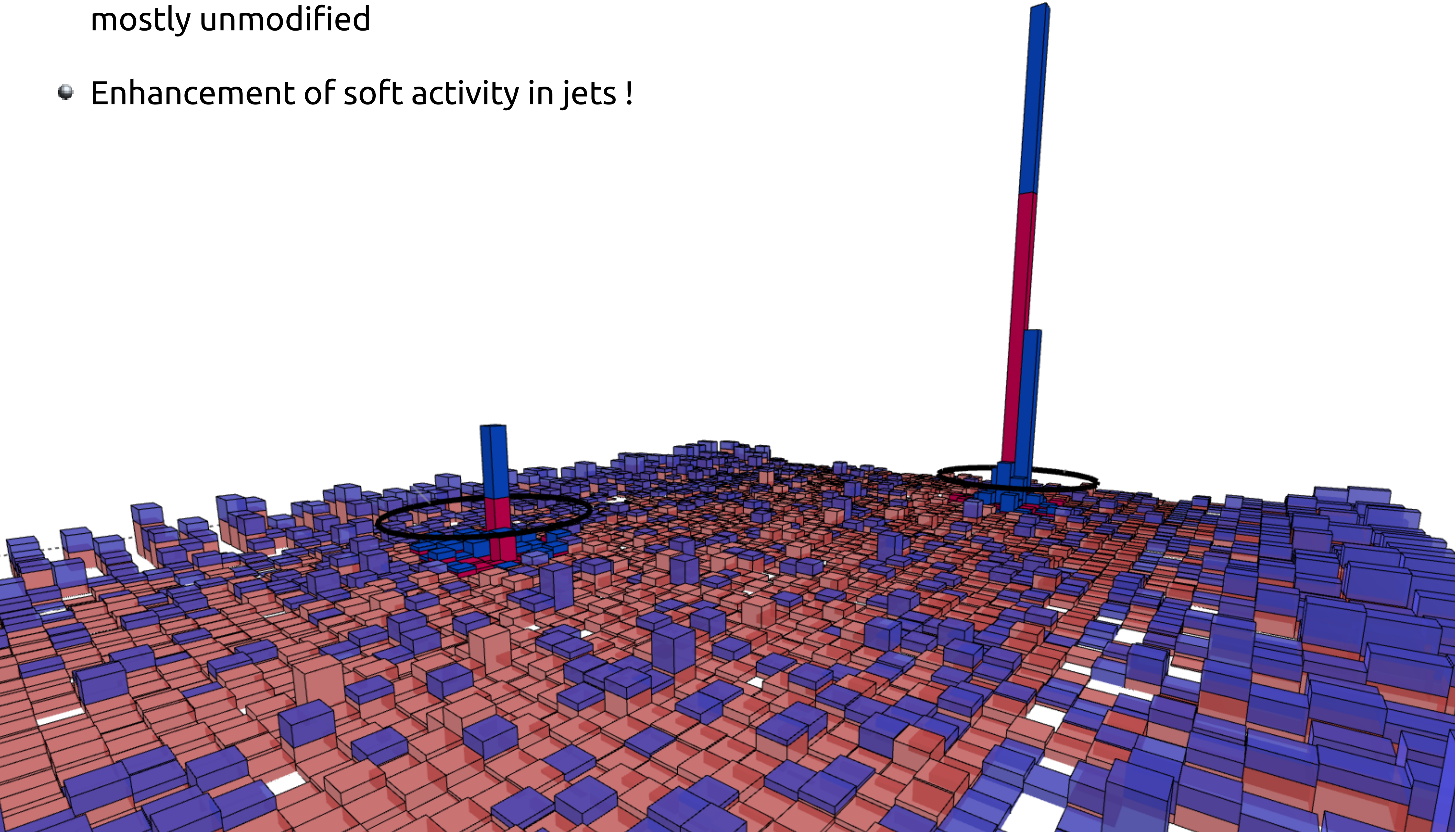
$\gamma + \text{jet}$ vs inclusive jets :

- → more enhancement at low $p_T$
- → shift of mid $p_T$ minimum
- → no enhancement at high $p_T$

Indication : quark initiated jets are modified differently

# Summary

- Jets give insight of the energy loss in QGP
- Jet production is suppressed by factor 2 up to 1 TeV, but the hard structures in jets are mostly unmodified
- Enhancement of soft activity in jets !



# Backup slides

# Glauber model (1)

The collision of two nuclei is seen as individual interactions of the constituent nucleons

The **position** of each nucleon in a nucleus is determined according to the Woods-Saxon :

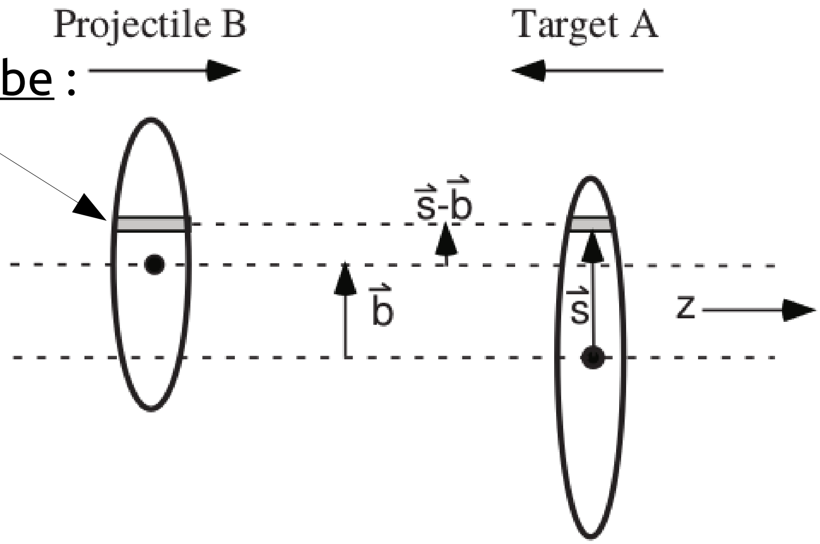
$$\rho(r) = \frac{\rho_0}{1 + exp[(r - R)/a]}$$

(spherical case)

nuclear size

surface thickness

Two nuclei collide



Probability of a given nucleon to be in the <u>target flux tube</u> :

$$T_A(\vec{s}) = \int \rho_A(\vec{s}, z)\ \mathrm{d}z$$

Joint probability of nucleons being located in the respective overlapping flux tubes

$$T_{\mathrm{AB}}(b) = \int \boxed{T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b})\mathrm{d}^2 s}$$

$T_{AB}(b)$ - effective **overlap area** for which a specific nucleon in A can interact with a given nucleon in B.

# Glauber model (2)

The total number of inelastic nucleon-nucleon collisions:

$$N_{\mathrm{coll}}(b) = T_{\mathrm{AB}}(b) \cdot \sigma_{\mathrm{inel}}^{\mathrm{nn}}$$

Inelastic nucleon-nucleon cross section (defined from data)

Number of participants from A :

$$N_{\mathrm{part}}^{\mathrm{A}} = \int T_{\mathrm{A}}(\vec{s}) \cdot \left(1 - \left[1 - T_{\mathrm{B}}(\vec{s} - \vec{b}) \cdot \sigma_{\mathrm{inel}}^{\mathrm{nn}} / B\right]^{B}\right) \mathrm{d}^2 s$$

Probability for a nucleon in nucleus A to scatter with one from nucleus B

Total number of participants :

$$N_{\mathrm{part}}(b) = N_{\mathrm{part}}^{\mathrm{A}}(b) + N_{\mathrm{part}}^{\mathrm{B}}(b)$$

# Monte-Carlo Glauber model

Two colliding nuclei are modeled by distributing the nucleons of each nucleus in 3D coordinates according to nuclear density distribution.

A random impact parameter b : $\frac{d\sigma}{db} = 2\pi b$

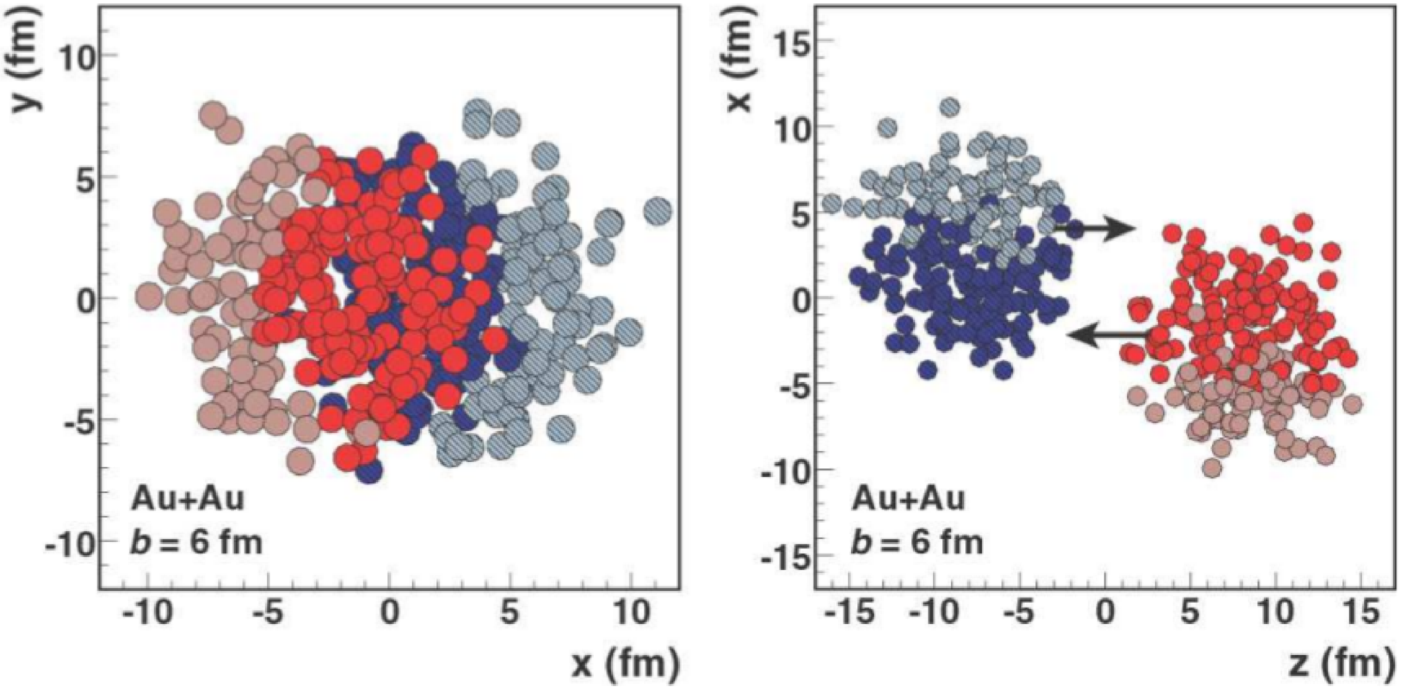
Collision : a sequence of independent binary collisions

→ the nucleons travel on straight-line trajectories

→ inelastic nucleon-nucleon cross-section is assumed to be independent of the number of collisions a nucleon underwent before.

Nucleons interact if their distance $d \leq \sqrt{\sigma_{inel}^{NN}/\pi}$

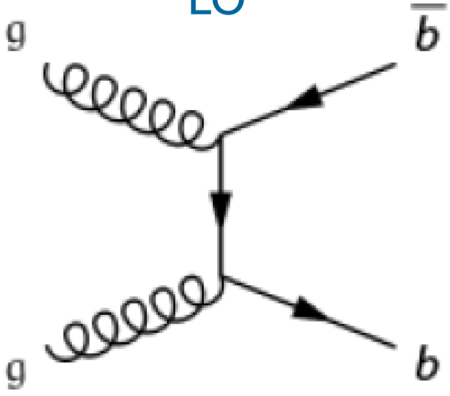
Ann.Rev.Nucl.Part.Sci.57:205-243,2007



# B-jet production channels at LHC

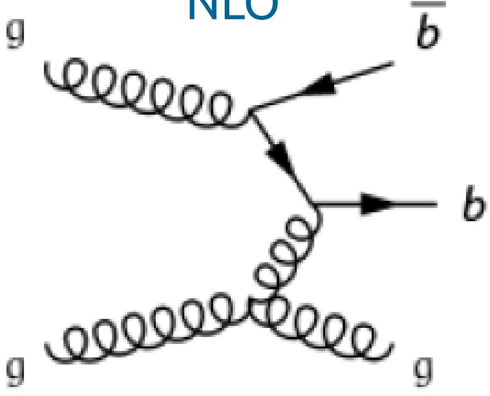
Flavor Creation (FCR)

LO



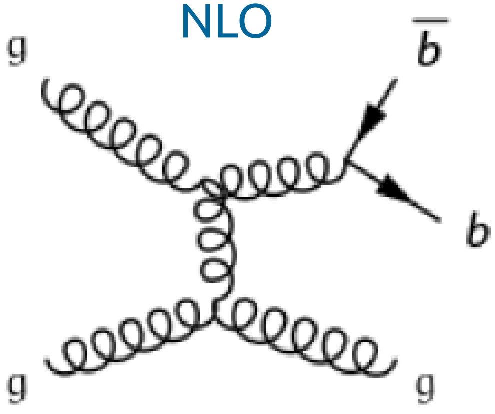
Flavor Excitation (FEX)

NLO



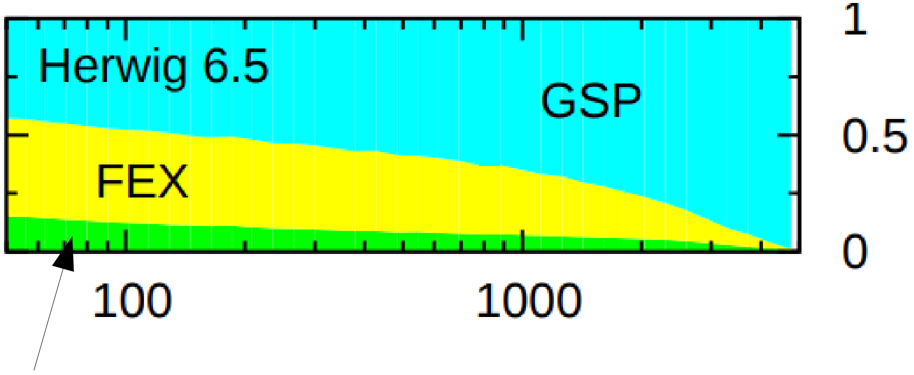
Gluon Splitting (GSP)

NLO



LHC, pp collisions at 14 TeV

JHEP 0707:026,2007



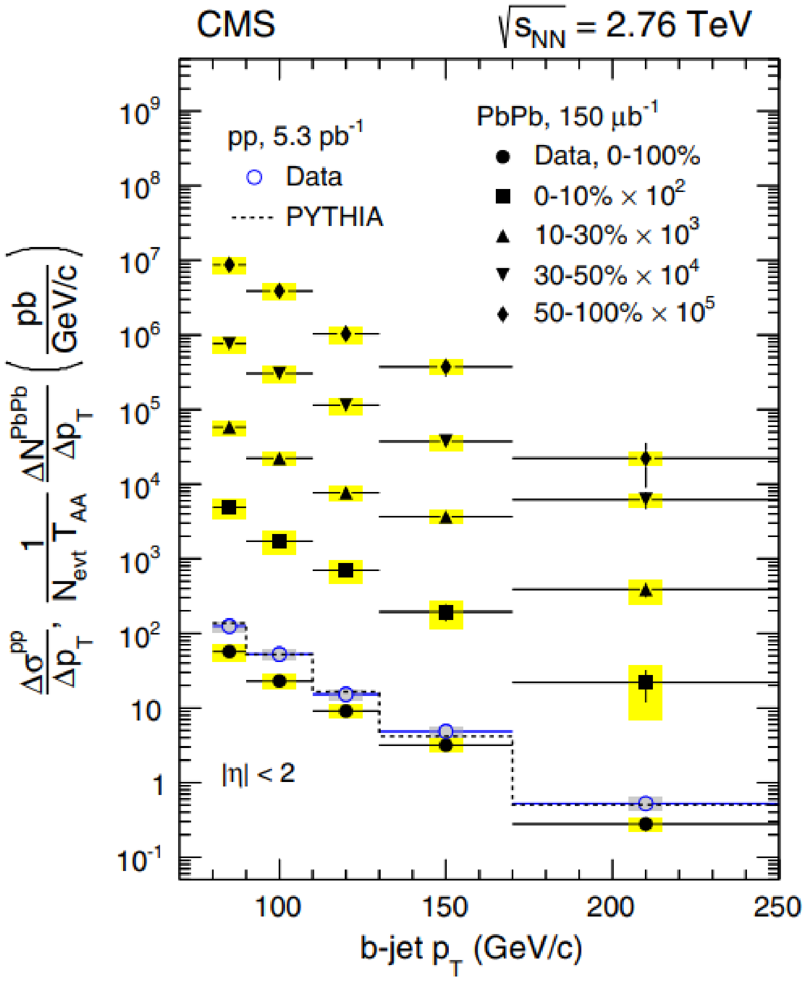
FCR is not dominant process

First Heavy Ion measurements convolute large contributions from NLO b-quark production processes

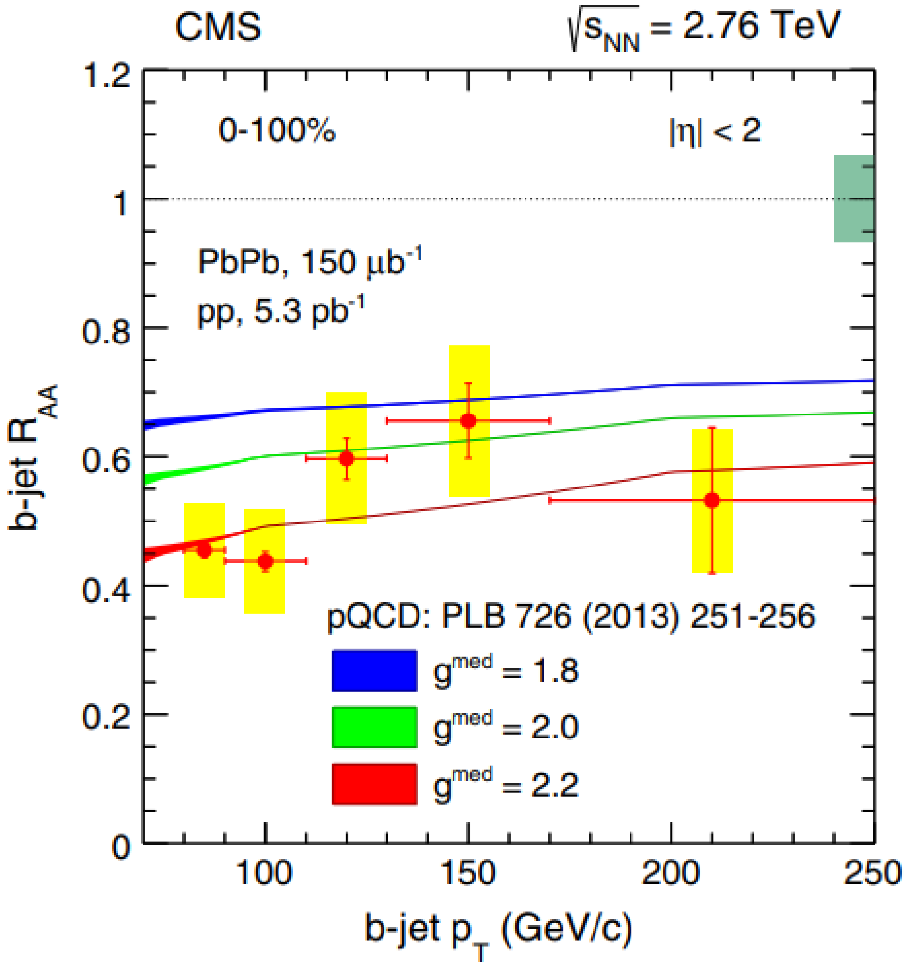
Energy loss is expected to depend on flavor → measure heavy flavor jets suppression

# Quenching of b-jets

Jet spectra corrected for detector resolution effects for several centrality selections and pp



CMS, PRL 113 (2014) 132301

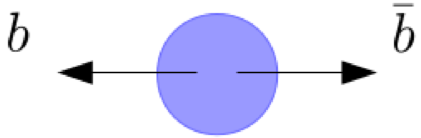


Suppression consistent with the one observed from inclusive jets

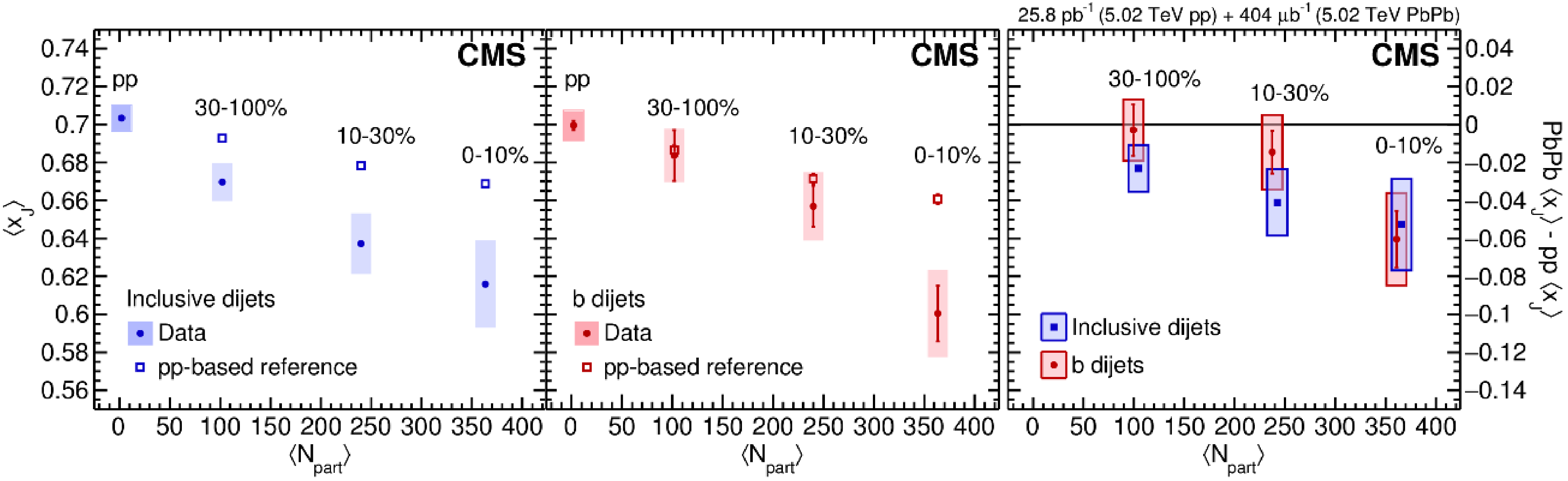
# bb correlations

To suppress the contribution of gluon splitting and probe LO b-jet production :
look at pairs of b jets that are back-to-back in azimuth.

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$



CMS , JHEP 1803 (2018) 181



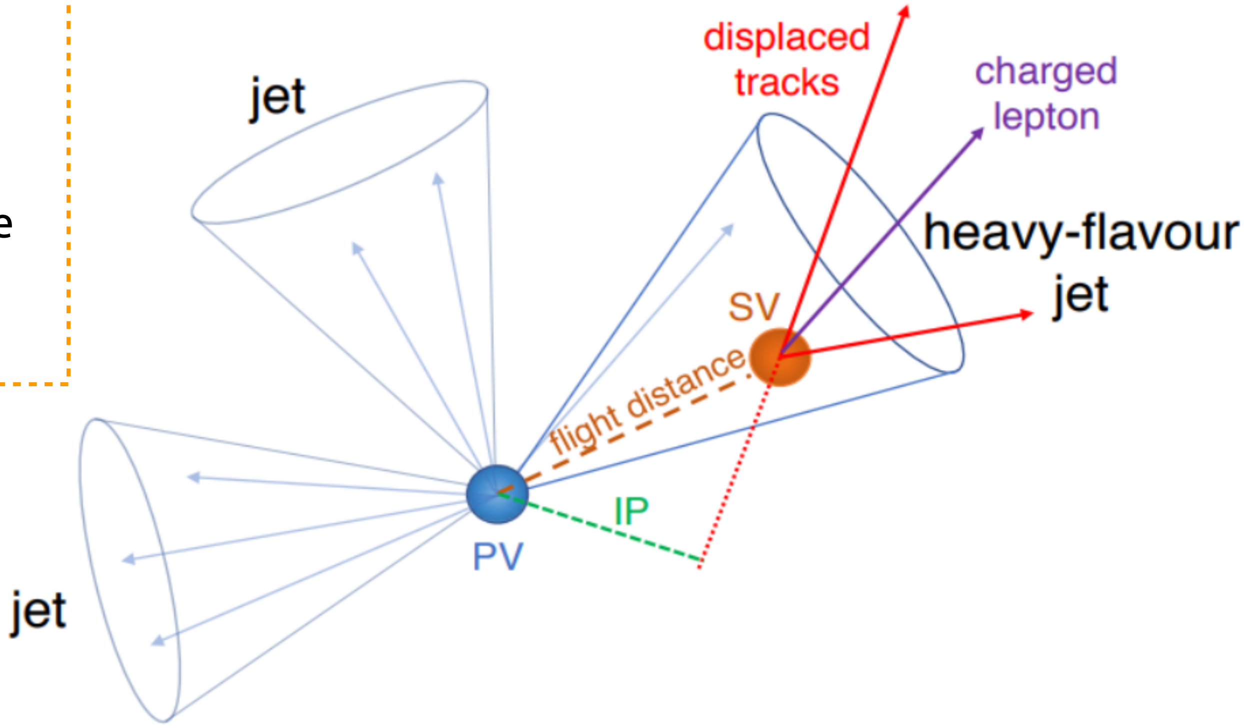
No clear difference between pT balance of inclusive and b-dijets

Data from Run 3 will allow to make a conclusive statement

# B-jet identification

B-hadrons

- Fragment hard, zb ~ 0.7 – 0.8
- Large decay multiplicity, ⟨n_ch⟩ ~ 5
- Long-lived hadrons cτ ~ 500 μm → mm – cm displacement in lab frame
- Tend to decay semi-leptonically (20% for μ and e)



Identification methods

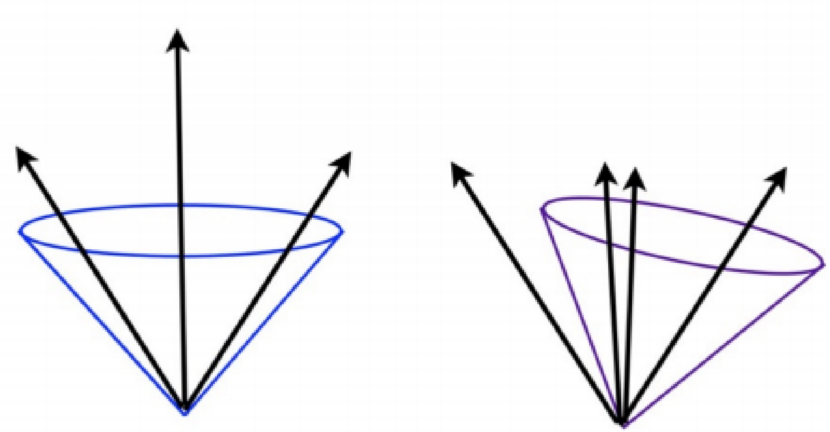
Lifetime methods: exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays

Soft-lepton tagging: μ or e inside the jet

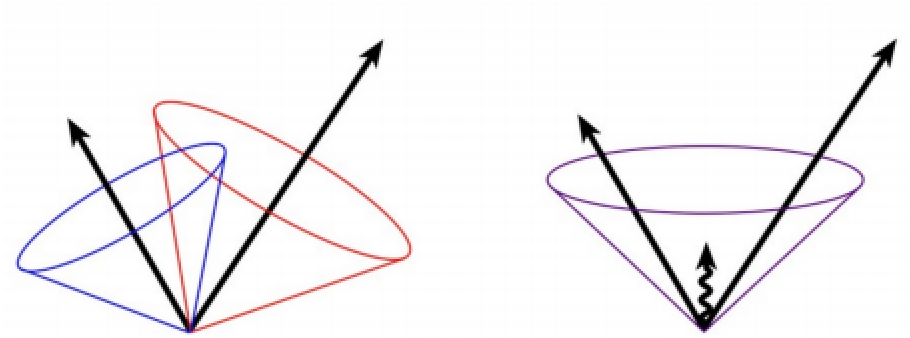
# Jet clustering algorithms : requirements

Collinear and IR safety :

→ Collinear splittings should not bias jet finding
→ Soft radiation should not effect jet configuration



Collinear



Infra-red

Minimal sensitivity to hadronization, underlying event (UE), Pile-Up(PU)

Applicable at detector-level :

→ good computational performance
→ not to complex to correct

# Hadrons at the LHC : much higher pT

Central RAA evolution with the center-of-mass energy increase

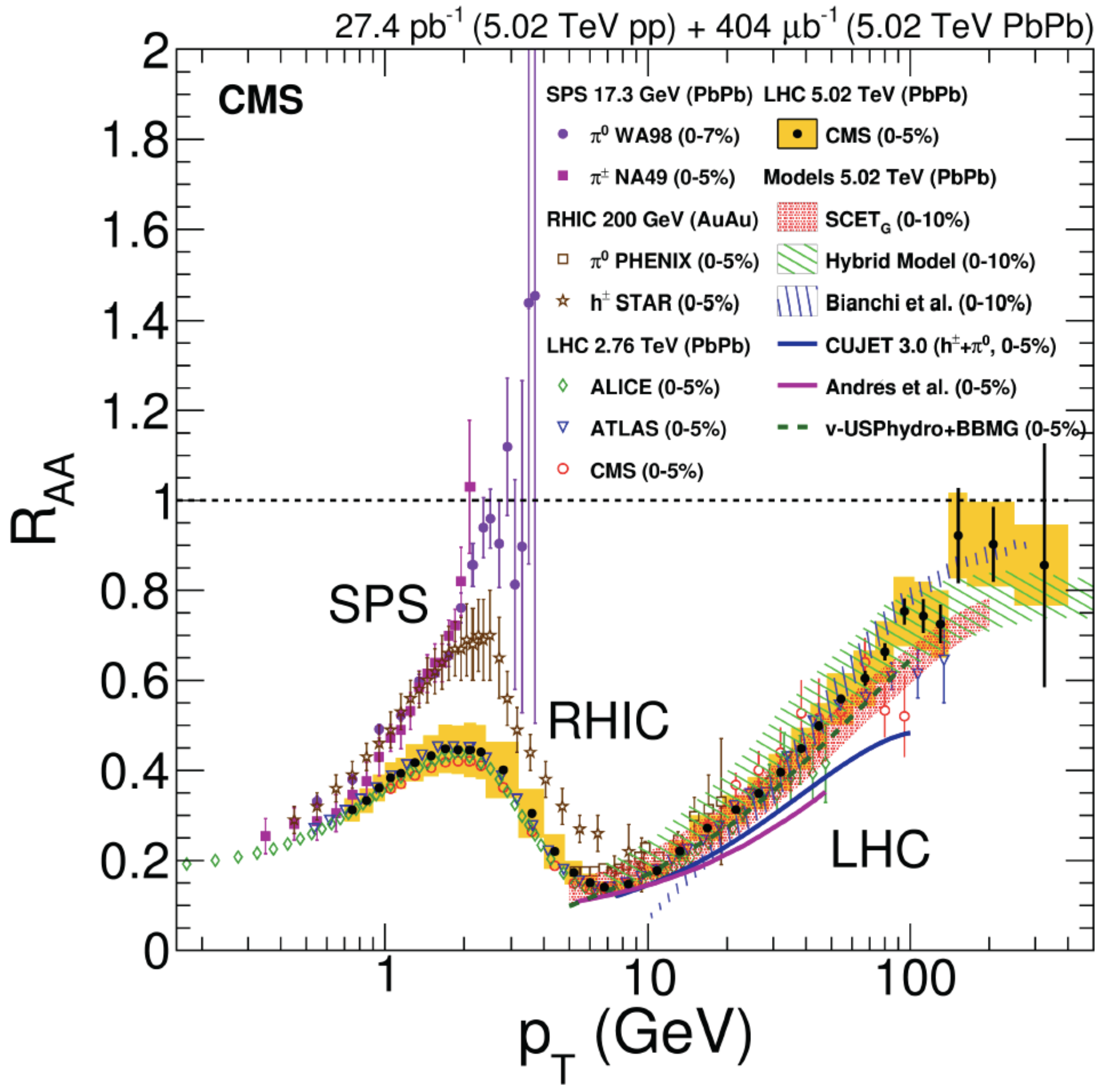
CMS, JHEP 04 (2017) 039

SPS (17.3 GeV) and RHIC (200 GeV):

- Pions (neutral and charged)
- Charged hadrons

LHC (2.76 and 5.02 TeV):

- Charged particles
- different models at 5.02 TeV approximately reproduce data



Low pT (up to 2 GeV) : rising trend

~7 GeV : local minima

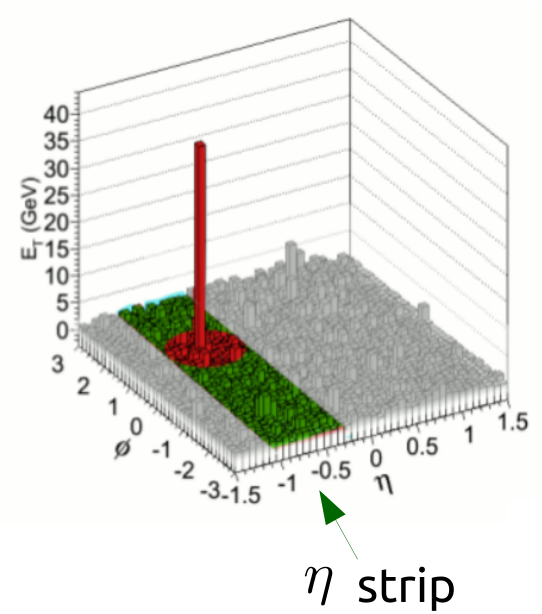
Higher pT : slow increase of RAA → small suppression ~100 GeV

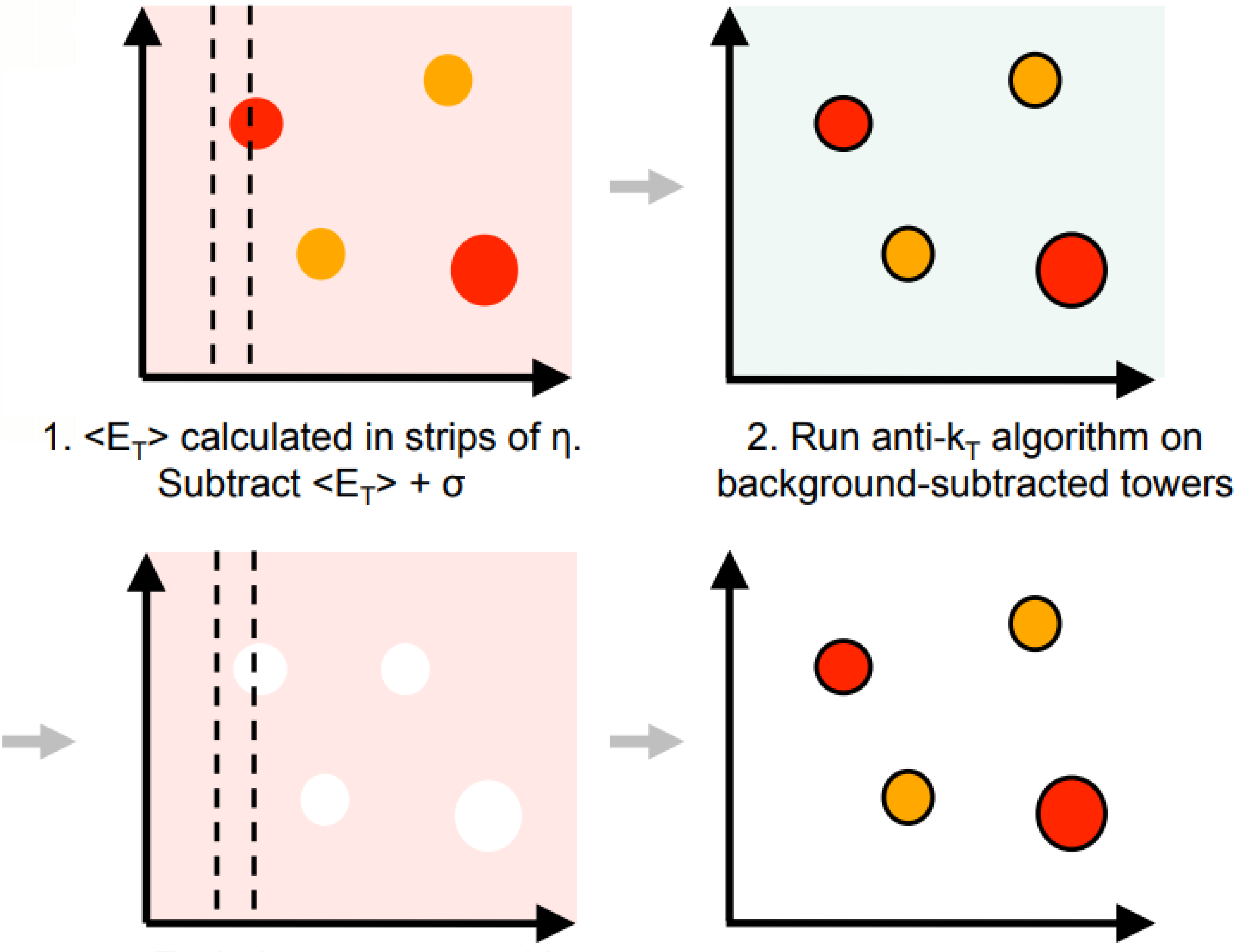
How to reconcile charged hadron and jet suppression?
→ dependence of quenching on fragmentation pattern of jet

# UE subtraction in CMS : iterative pedestal

What amount to subtract? How?

CMS, EPJC 50 (2007) 117





1. $\langle E_T\rangle$ calculated in strips of η. Subtract $\langle E_T\rangle + \sigma$

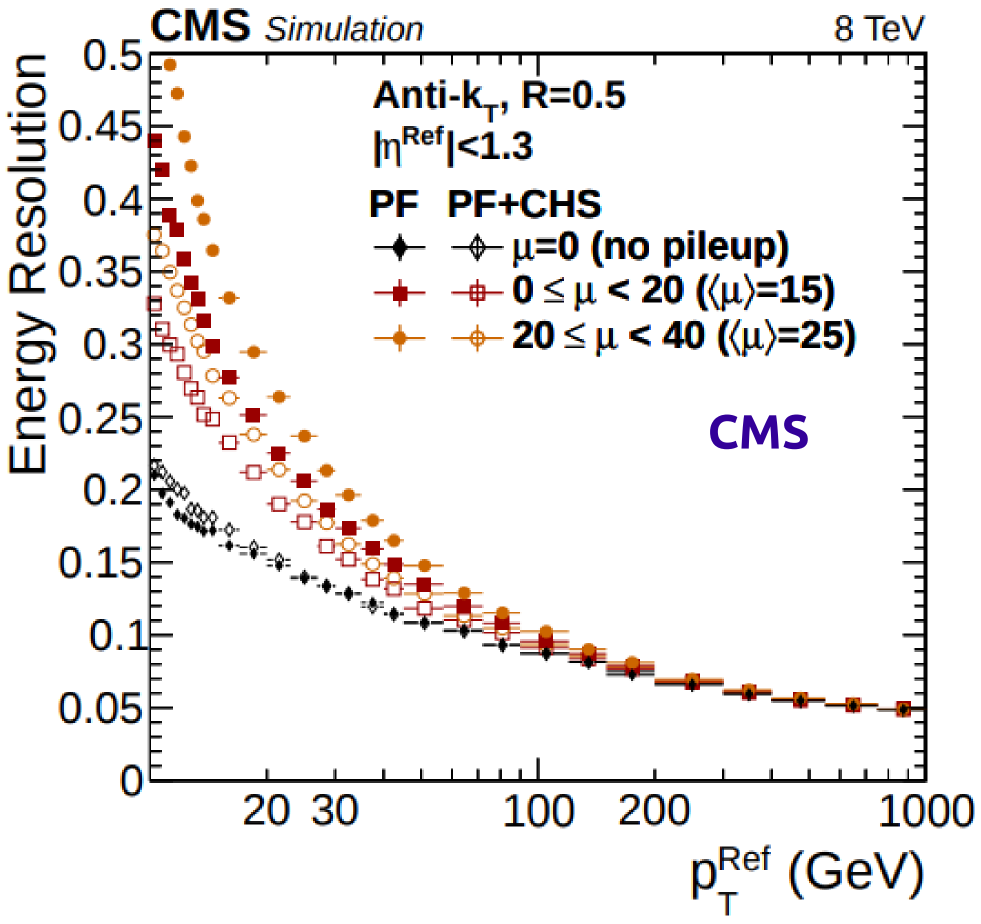
2. Run anti-$k_T$ algorithm on background-subtracted towers

3. Exclude reconstructed jets and re-estimate background

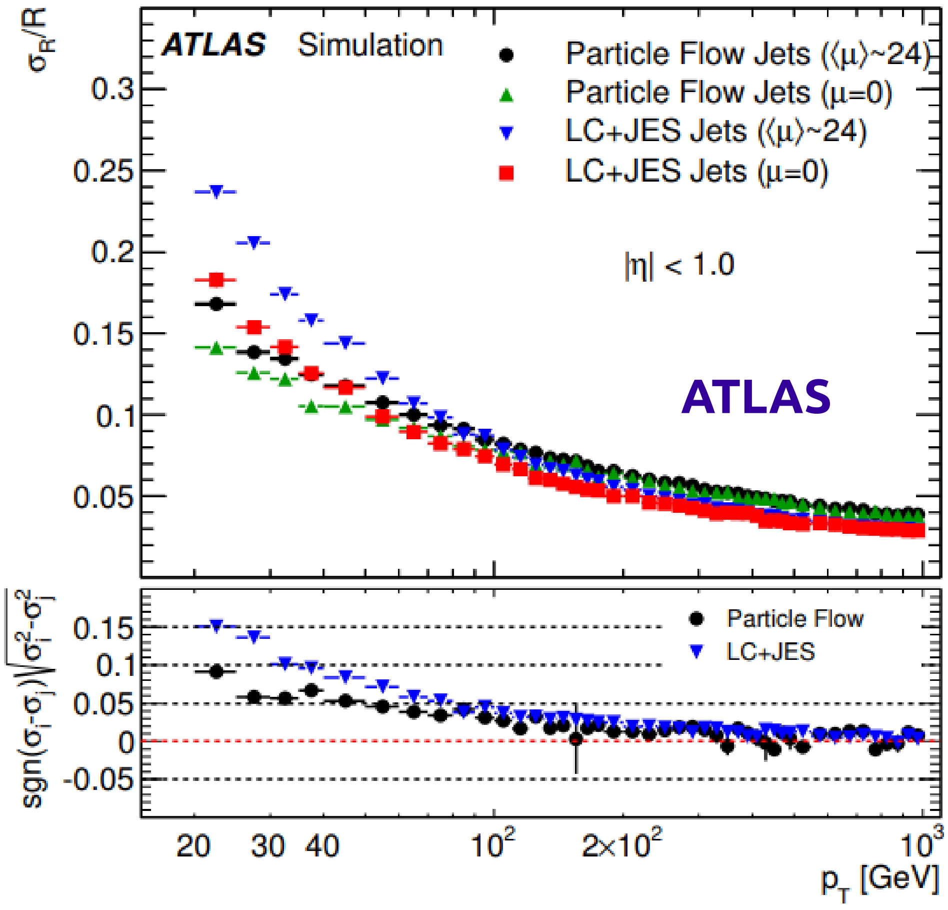
4. Re-run anti-$k_T$ algorithm to get final jets

# Jet performance in pp collisions

JINST 12 (2017) P10003



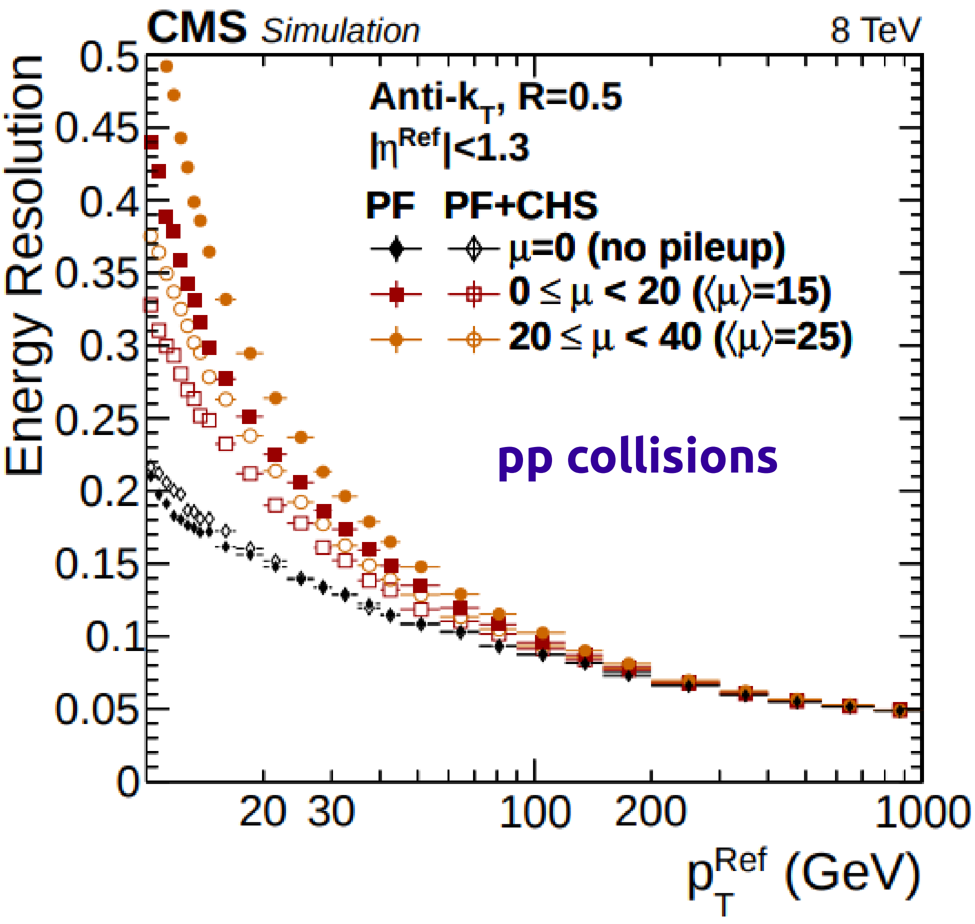
Eur. Phys. J. C 77 (2017) 466



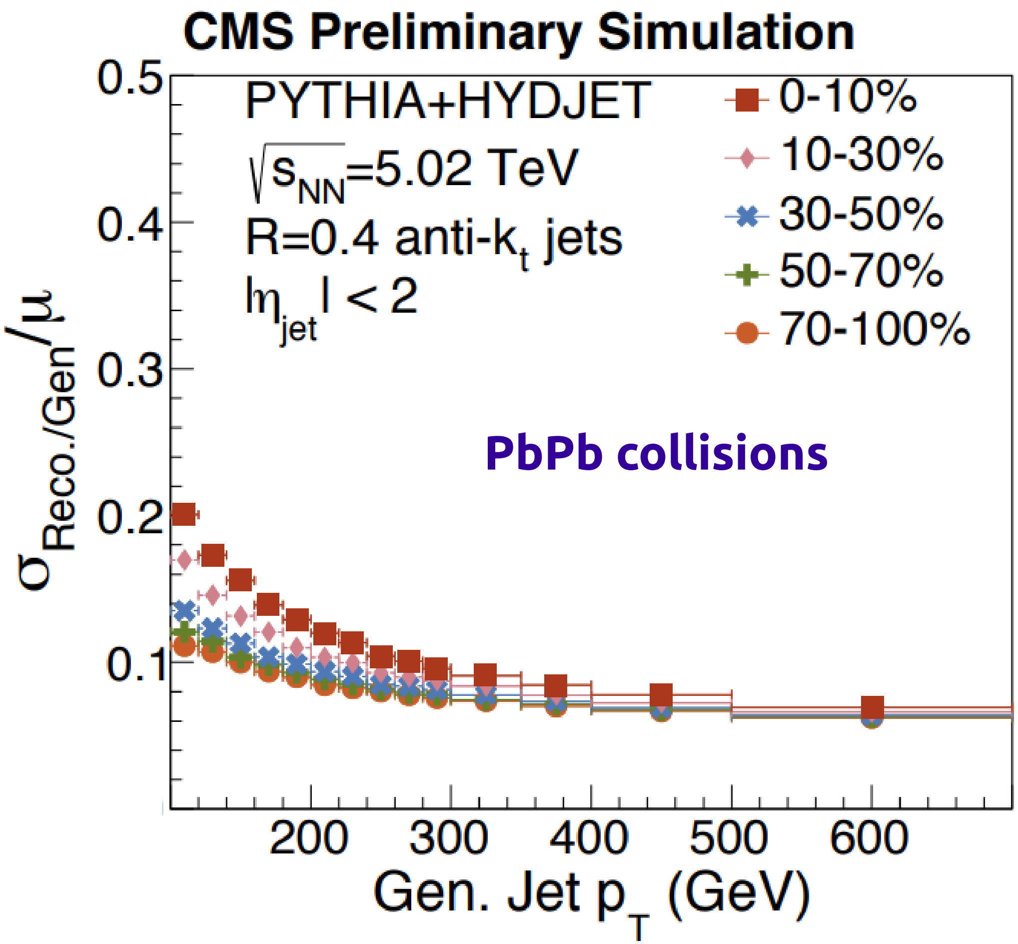
Very good resolution in ATLAS and CMS in pp collisions

# Jet performance in PbPb collisions

JINST 12 (2017) P10003



CMS-DP-2018-024



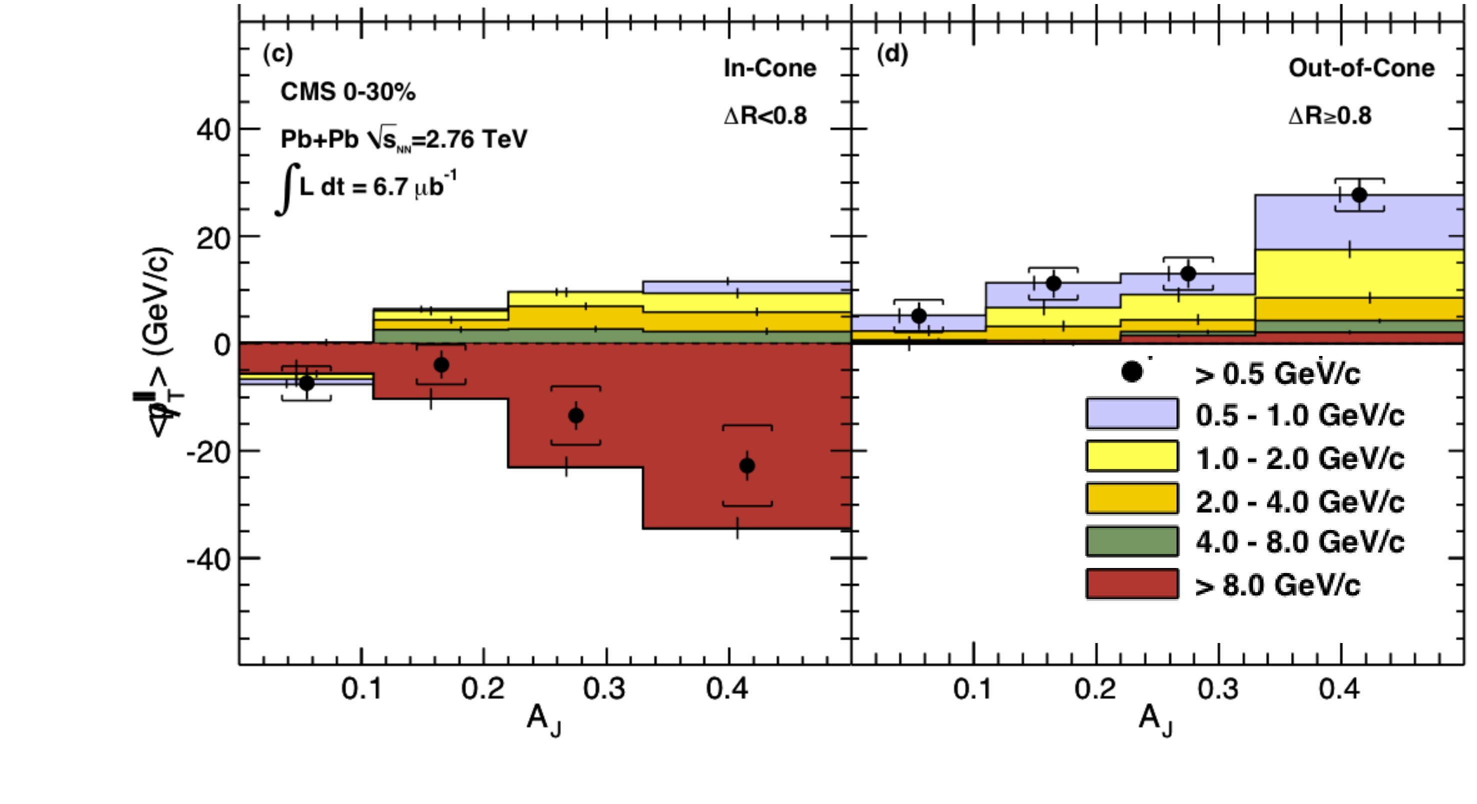
Very good resolution in PbPb collisions for jets with R = 0.4

# Dijet asymmetry in CMS

Complementary information about the overall momentum balance in the dijet events: the projection of missing pT of reconstructed charged tracks onto the leading jet axis

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right)$$

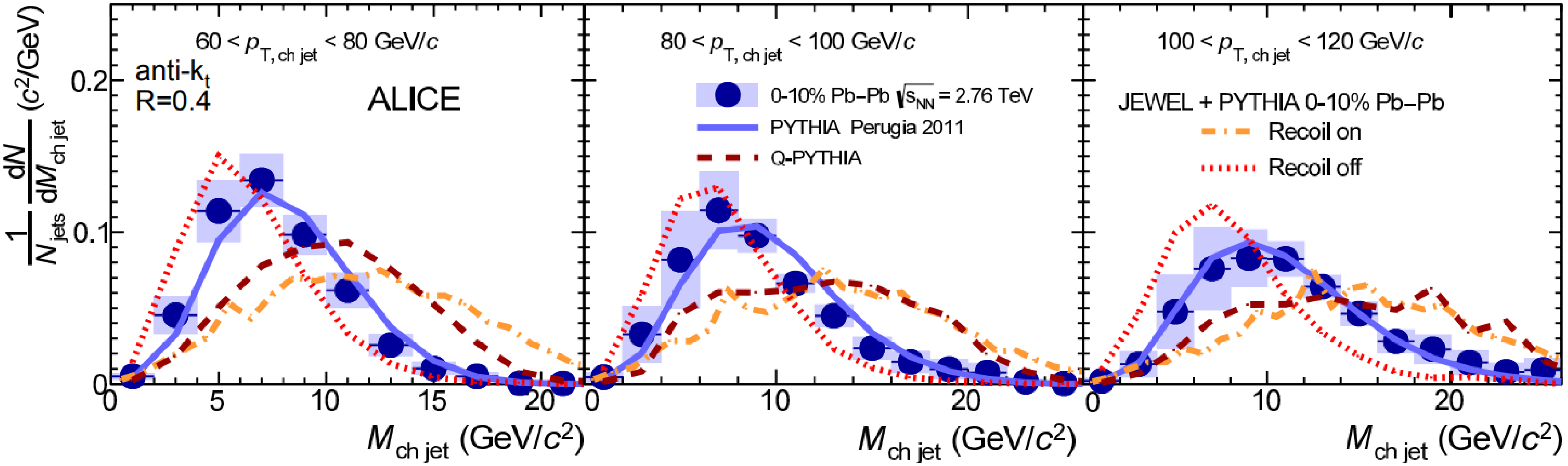
CMS, PRC84 (2011) 024906



Subleading jet energy is moved from high pT to lower pT and from small to large angles

# Jet mass

ALICE, Phys. Lett. B776(2018) 249-264



ALICE

Charged-jet mass : $M = \sqrt{E^2 - p_T^2 - p_z^2}$

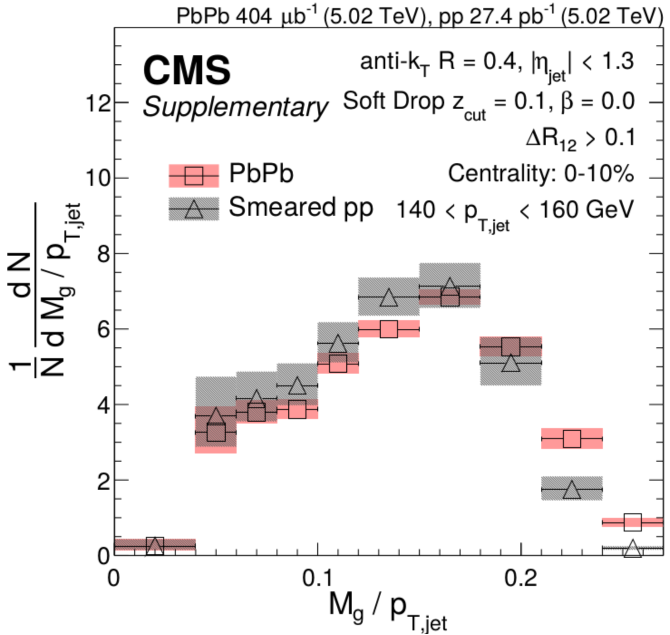
Small mass: collimated jet, small number of constituents.
Large mass: broad jet, large number of constituents.
PbPb is consistent with Pythia → no modifications to the mass

CMS

Relative mass : $M/p_T^{jet}$ (mass scales with jet pT in vacuum)

No modification to the mass of the core of the jet in PbPb

CMS, JHEP10(2018)161

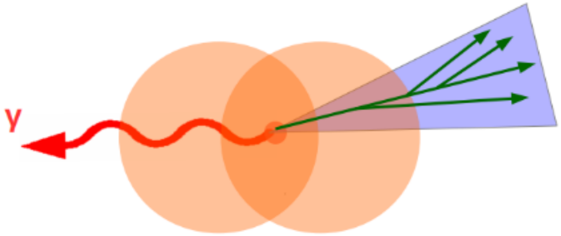


# Photon+jets in CMS

CMS, Phys. Lett. B 785 (2018) 14

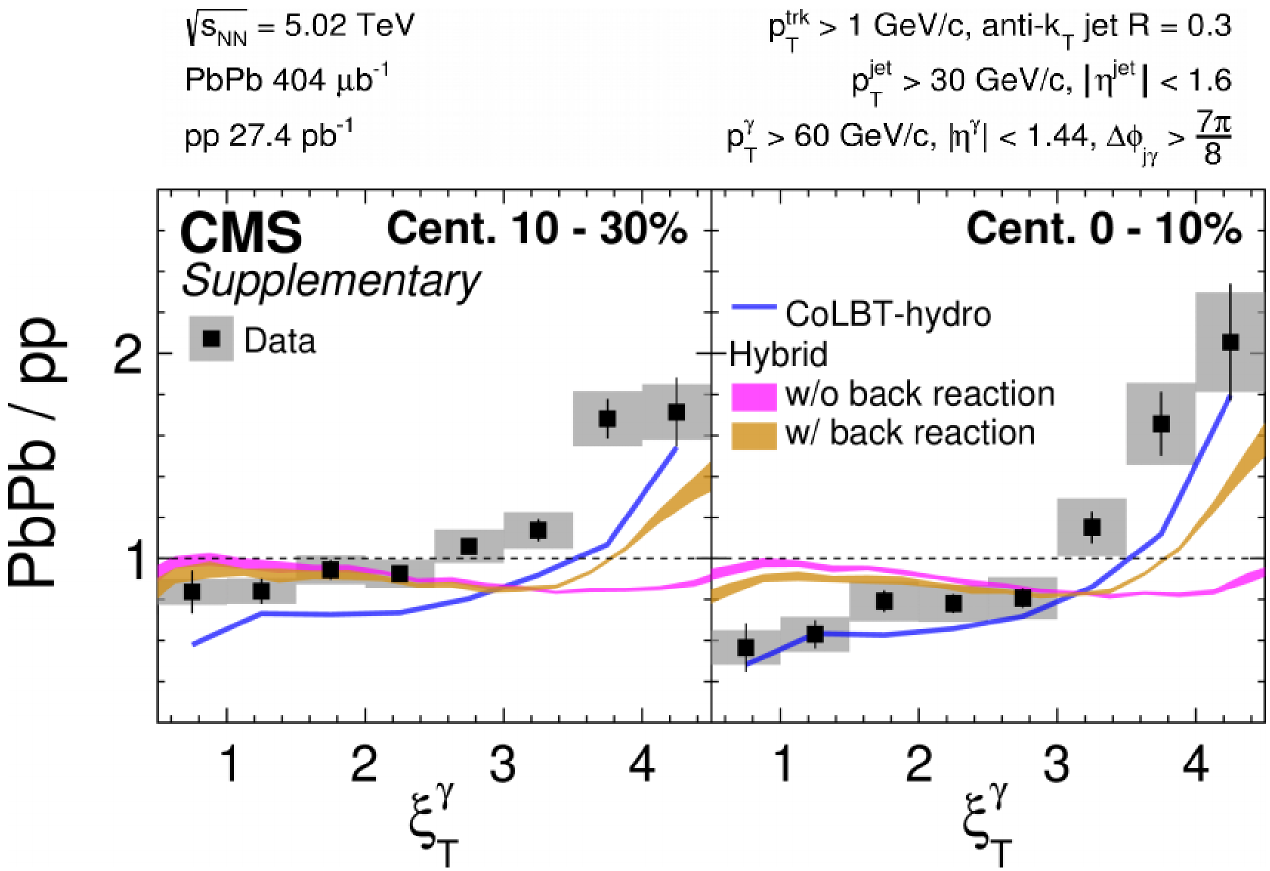
Fragmentation functions of jets associated with isolated photons :
initial parton energy constrained by photon pT

Quark enriched jet sample: flavor dependence of jet quenching



Projection of the tracks pT on photon pT axis :

$$\zeta_T^{\gamma} = \ln \frac{-|\boldsymbol{p}_{\mathrm{T}}^{\gamma}|^2}{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{trk}} \cdot \boldsymbol{p}_{\mathrm{T}}^{\gamma}}$$



Jets in central PbPb events show an excess (depletion) of low (high) pT particles, with a transition around 3 GeV/c