Jets as a probe of the Quark-Gluon Plasma

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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 $\alpha_{\rm s}$

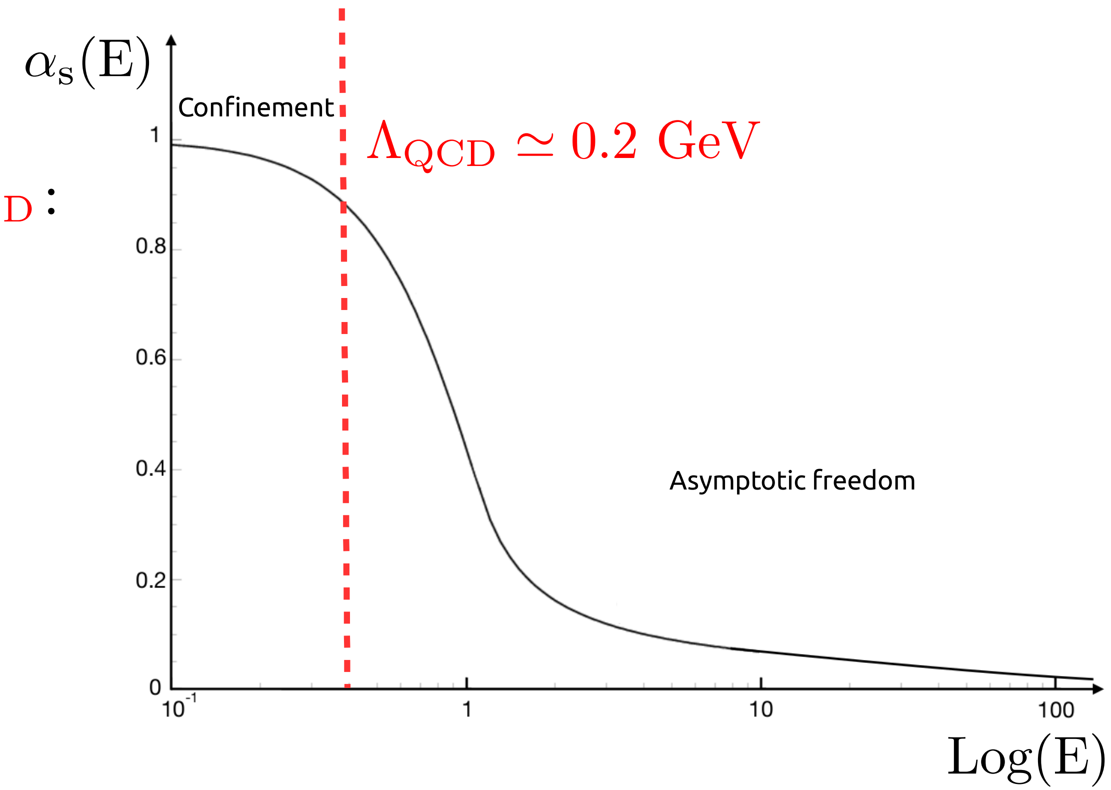
Pertubative regime is valid for $\rm E \gg \Lambda_{QCD}$:

- quarks and gluons are almost free

For $\rm E < \Lambda_{QCD}$:

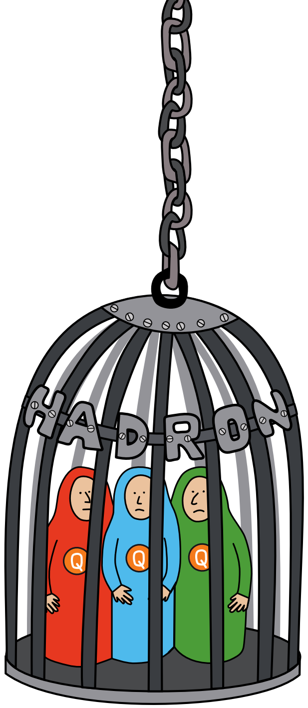
- quarks and gluons interact strongly - confined into hadrons
- perturbation theory fails

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



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

Different faces of QCD

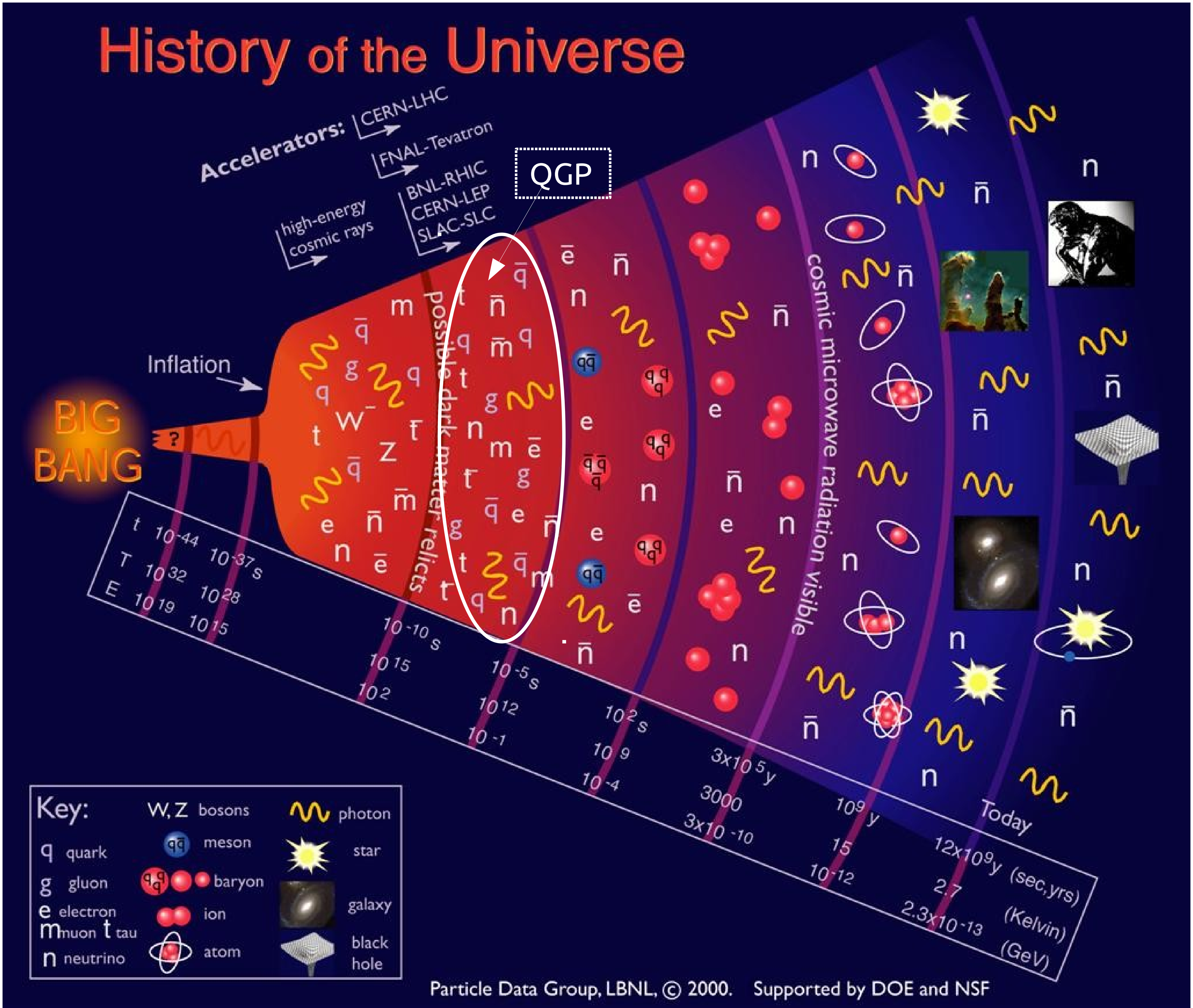


Normal matter :

quarks and gluons are confined

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

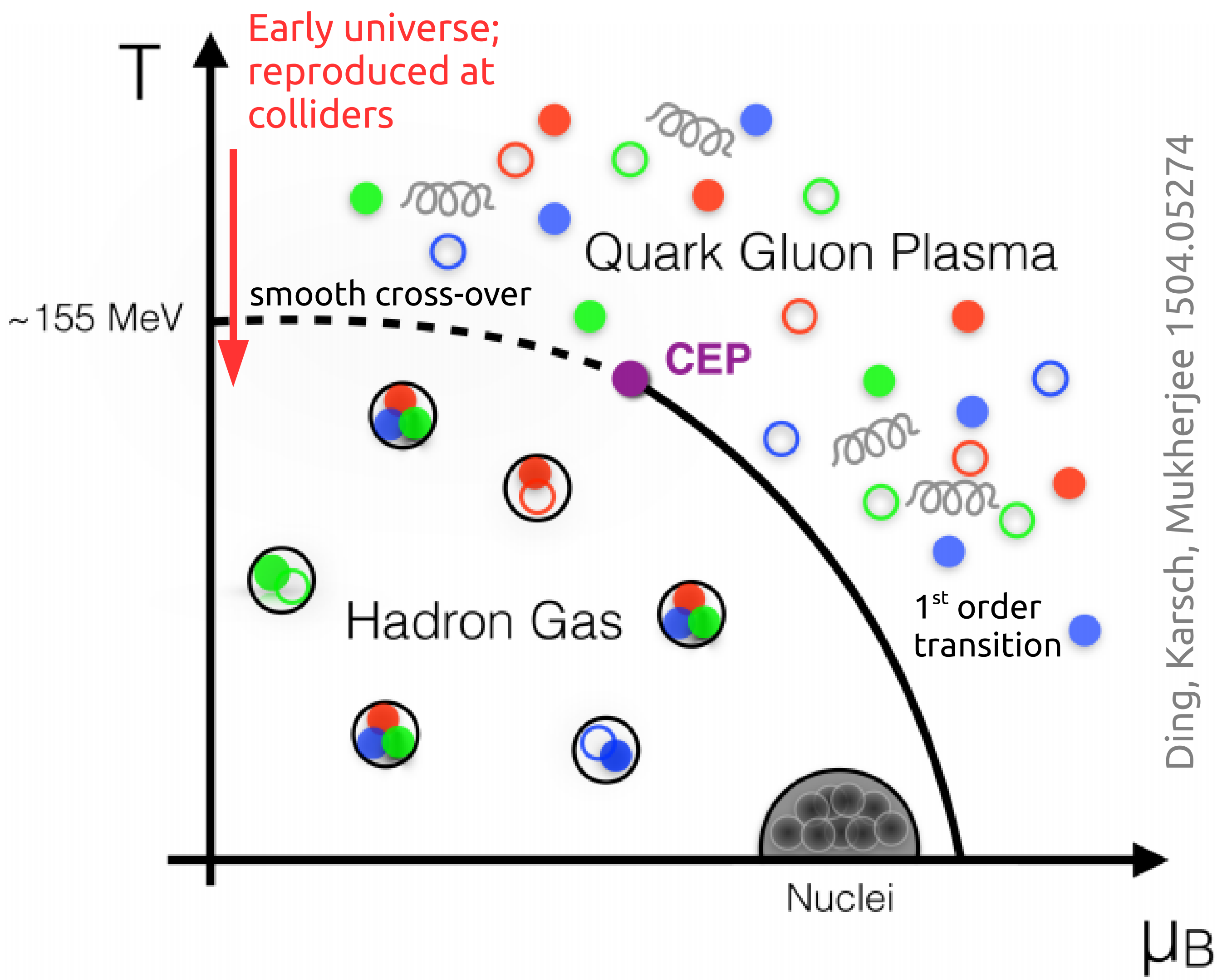
“deconfined” phase of matter
– Quark-Gluon Plasma (**QGP**)



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
QGP
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec, yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Phase diagram of QCD matter

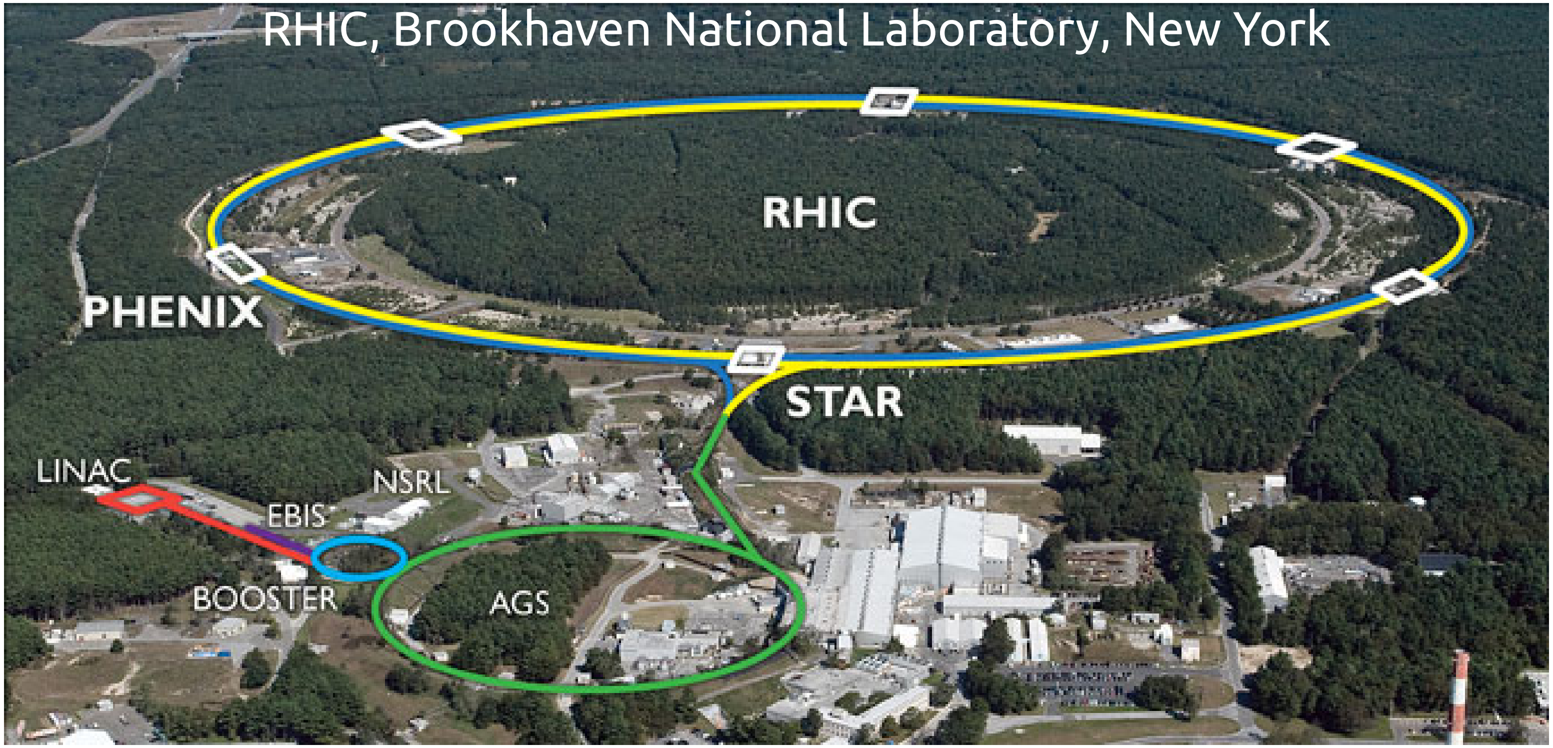
First predicted by Cabibbo and Parisi in 1975.



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



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

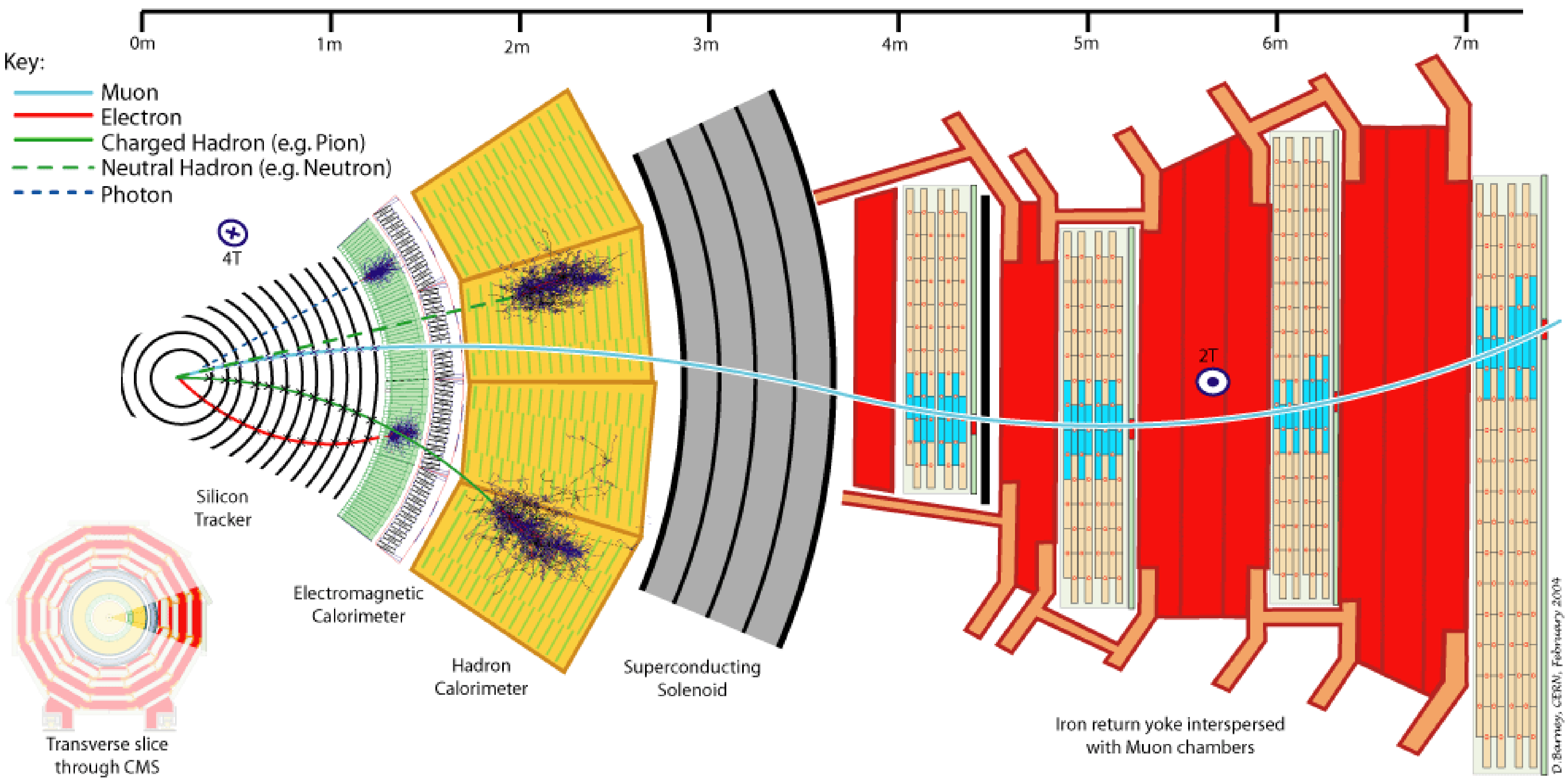
- Since 2010
- $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$
- PbPb, pPb, pp ...

High energy physics detectors

ATLAS and CMS :

- Fast and able to handle very high luminosity
- Precision silicon tracking
- High B field
- Hermetic calorimeters for e/γ , jets and missing energy

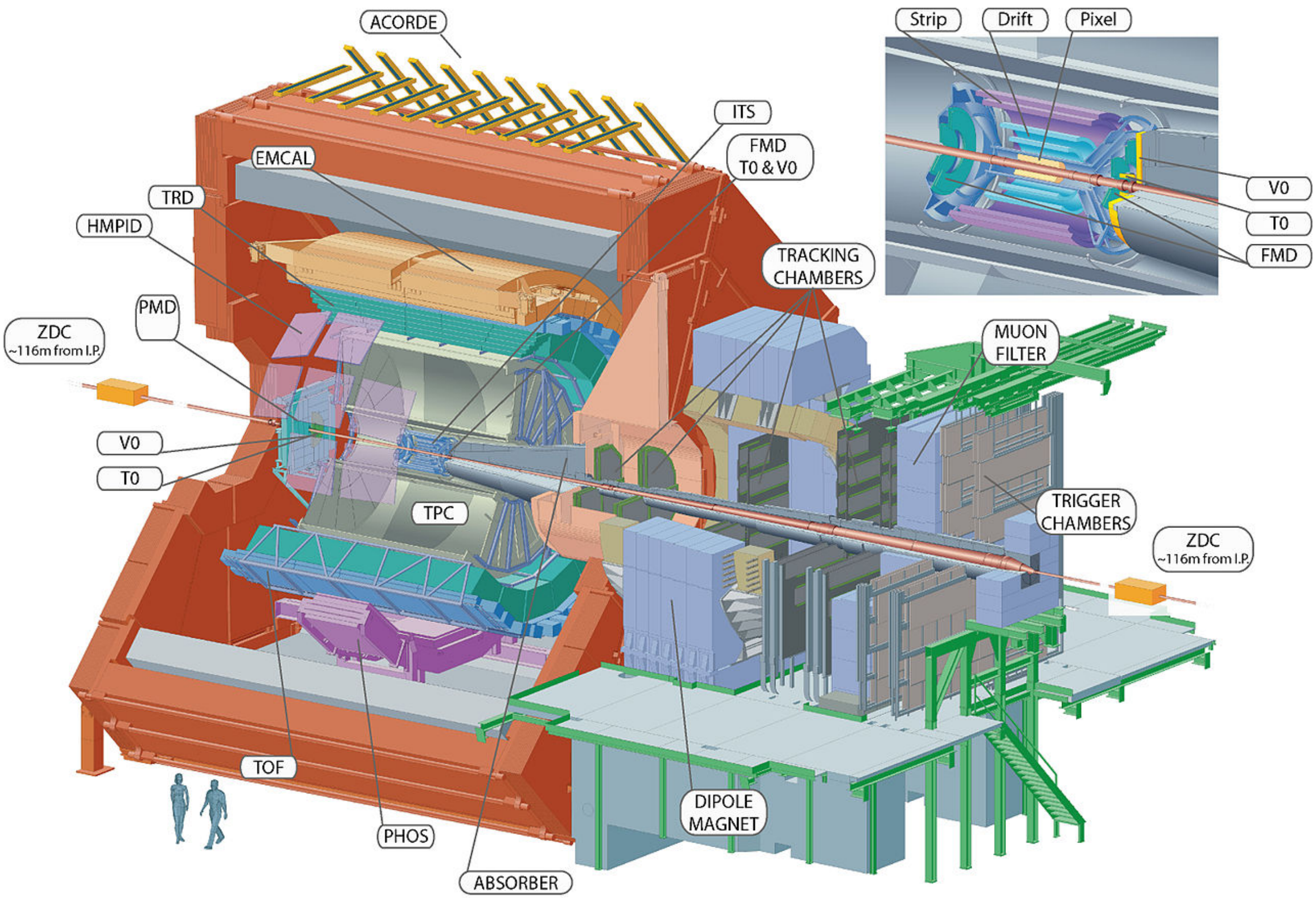
CMS



Heavy ion detectors

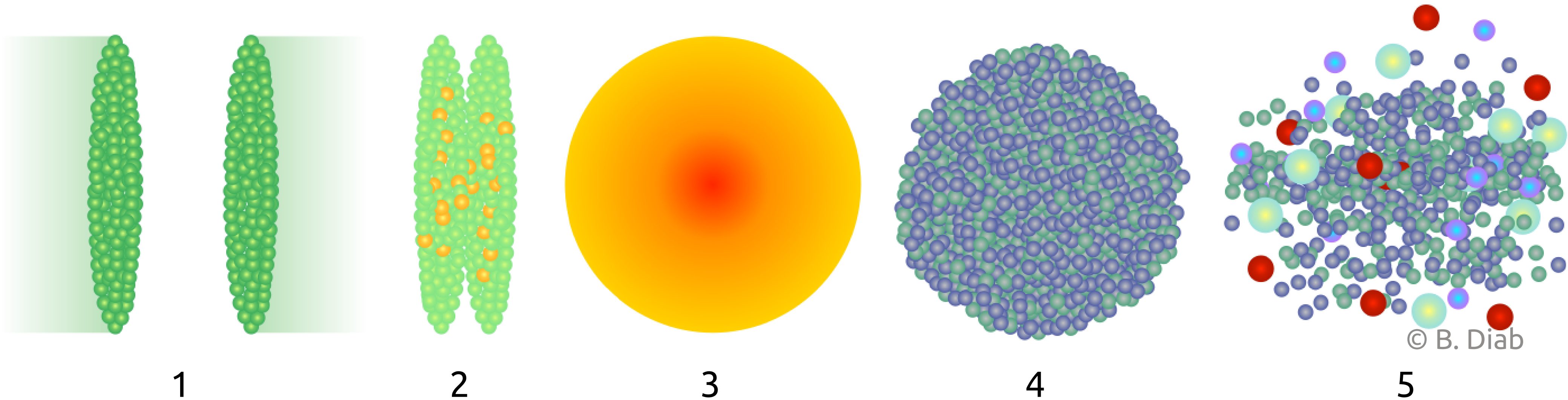
ALICE, STAR, PHENIX :

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



ALICE

Heavy ion collisions : time evolution



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

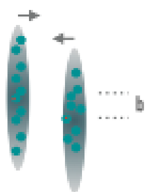
After the collision :

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 (3×10^{-23} sec)
5. Hadronization, particles stop interacting and move towards detectors

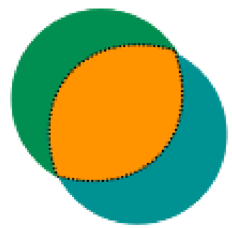
Heavy ion collisions : geometry

Collisions vary in “centrality”

“central”



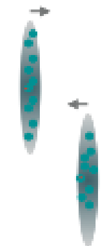
Longitudinal view



Transverse view

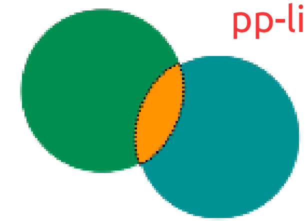
The larger overlap area, the hotter and larger QGP is

“peripheral”

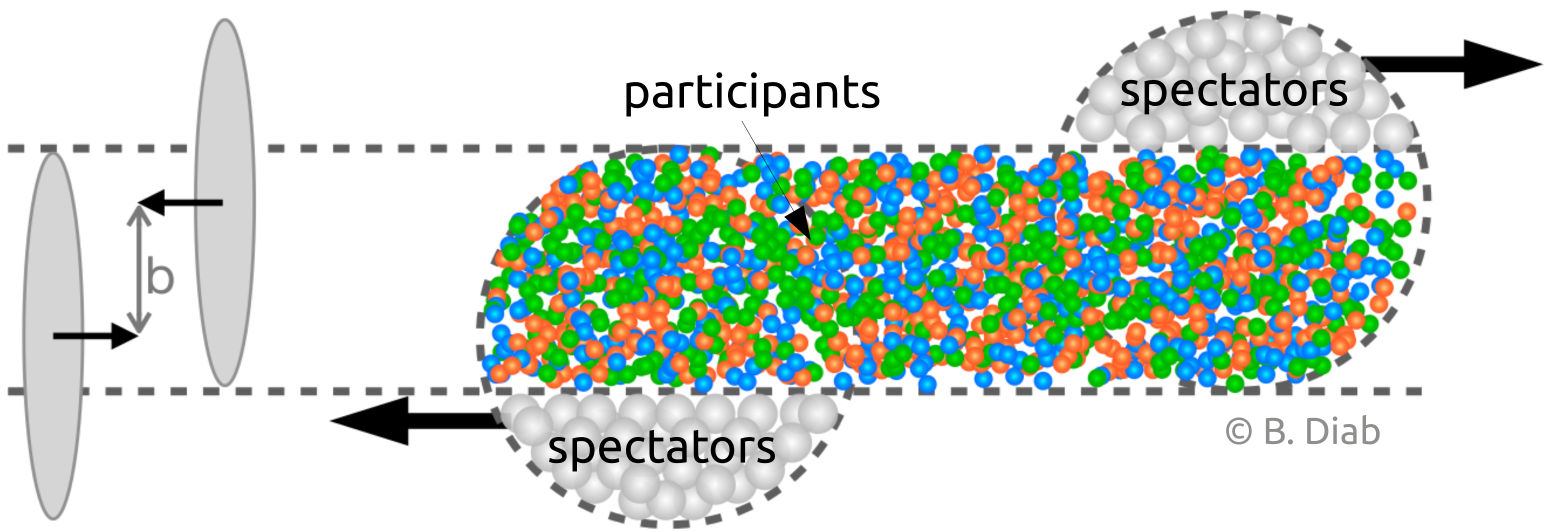


Longitudinal view

pp-like collision



Transverse view



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

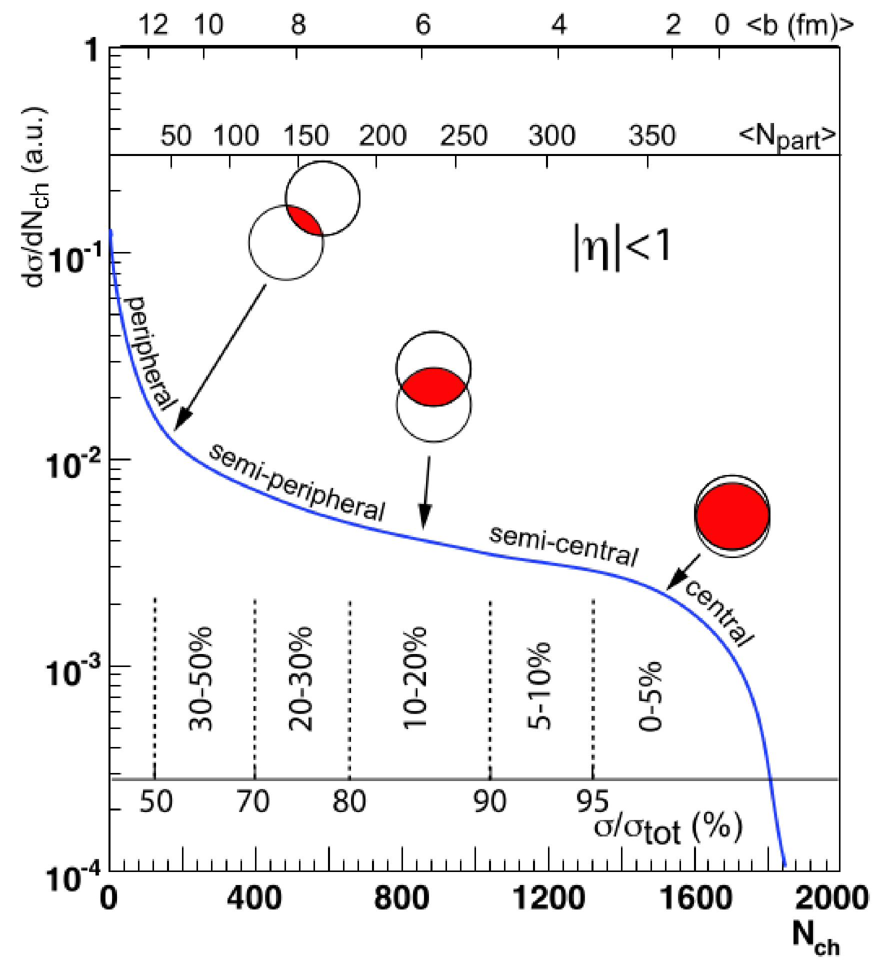
} estimated from “Glauber model”

Centrality

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

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

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

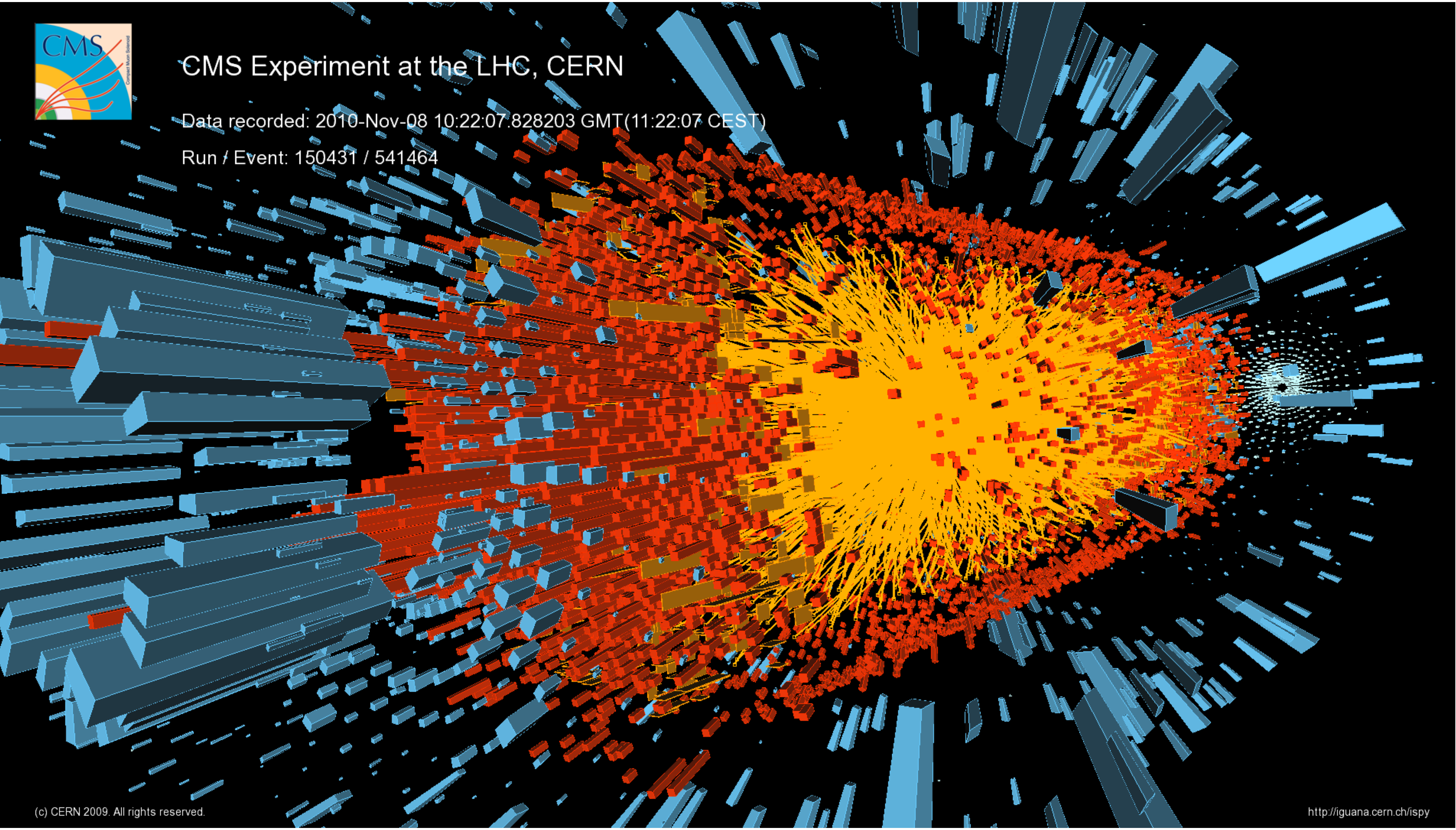


Centrality is computed as percentile of the total cross-section

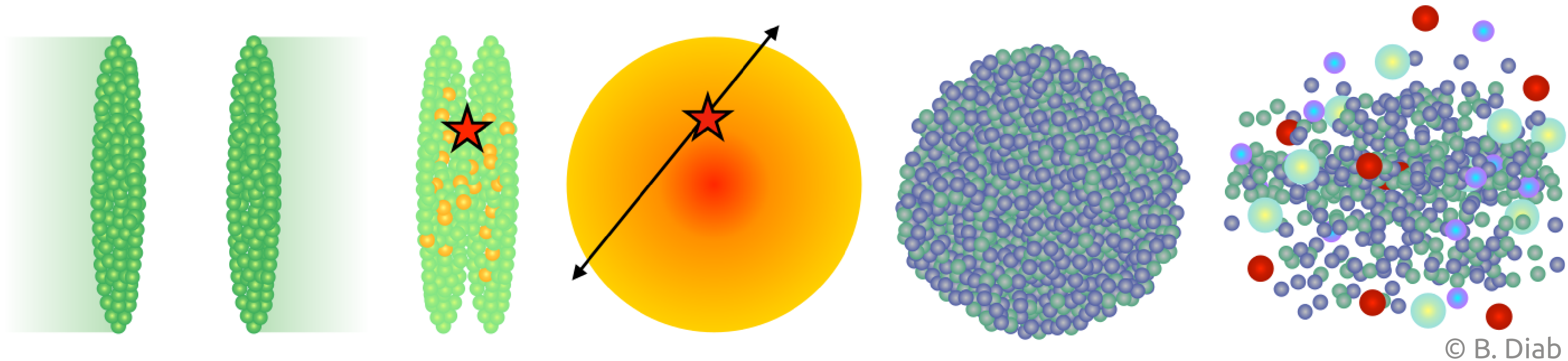
0-5% - the most central events :

→ smallest impact parameter
→ highest $\mathrm{N_{part}}$

A real heavy ion collision



Probes of the QGP

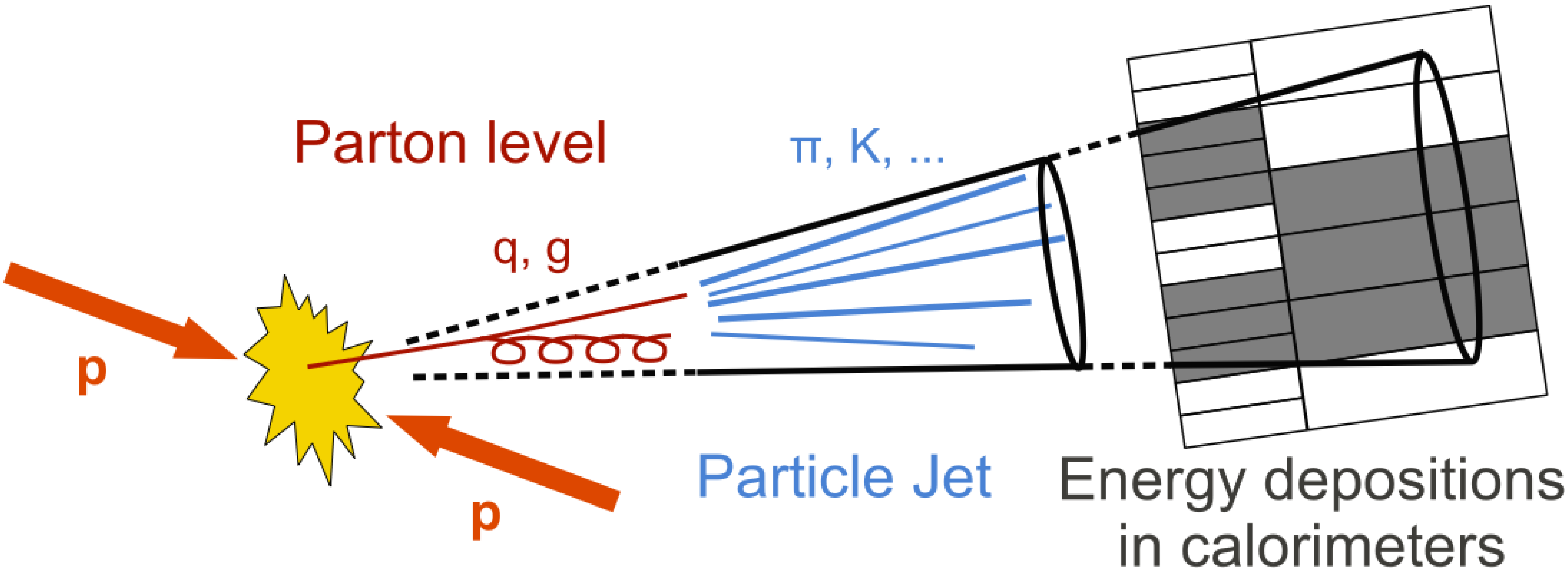


- Medium density – partons (jets)
- Temperature - Quarkonium states (J/ψ , Υ), dileptons and photons
- Thermalization - Strangeness enhancement
- Collectivity - Particle correlations
- …

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

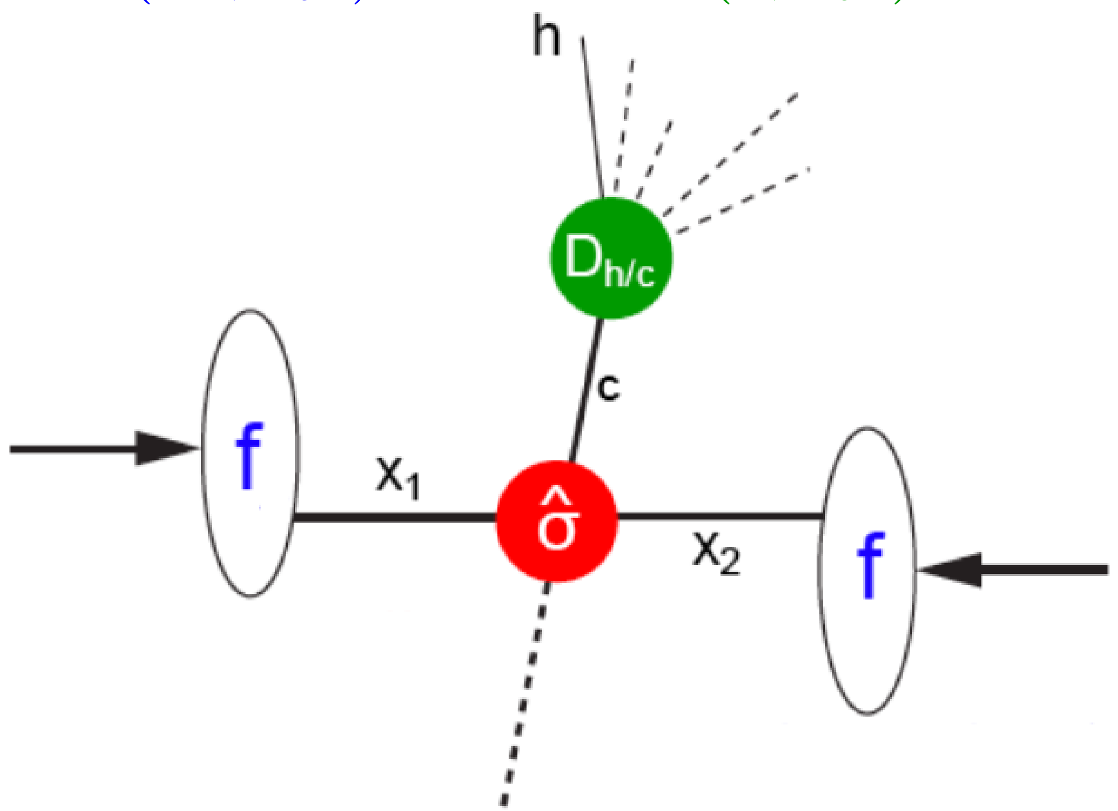
Jets - collimated bunches of stable **hadrons**, originating from **partons** after fragmentation and hadronization

→ jet is designed to be a proxy for a parton

Hard scattering in elementary collisions

Factorization of the cross-section :

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



Hard scattering of point-like partons described by pQCD

Soft processes described by universal, phenomenological functions :

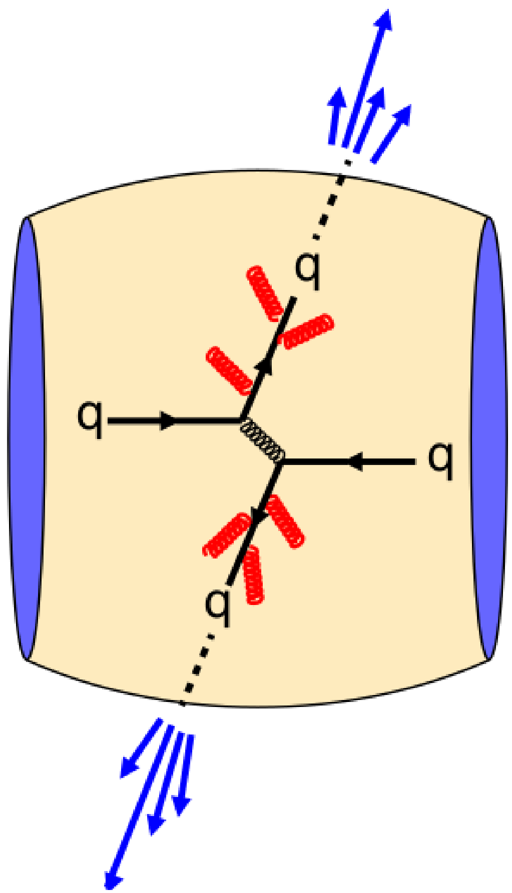
Parton distribution function (PDF) can be extracted from deep inelastic scattering

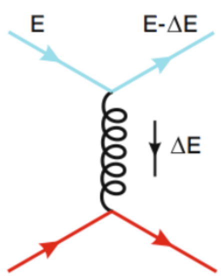
Fragmentation functions - from e^+e^- or hadron collisions

Jet quenching

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

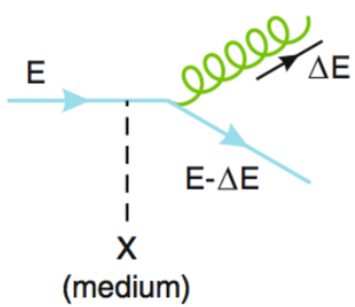
Parton energy loss





Collisional energy loss:

Elastic scatterings with medium constituents
Dominates at low energy



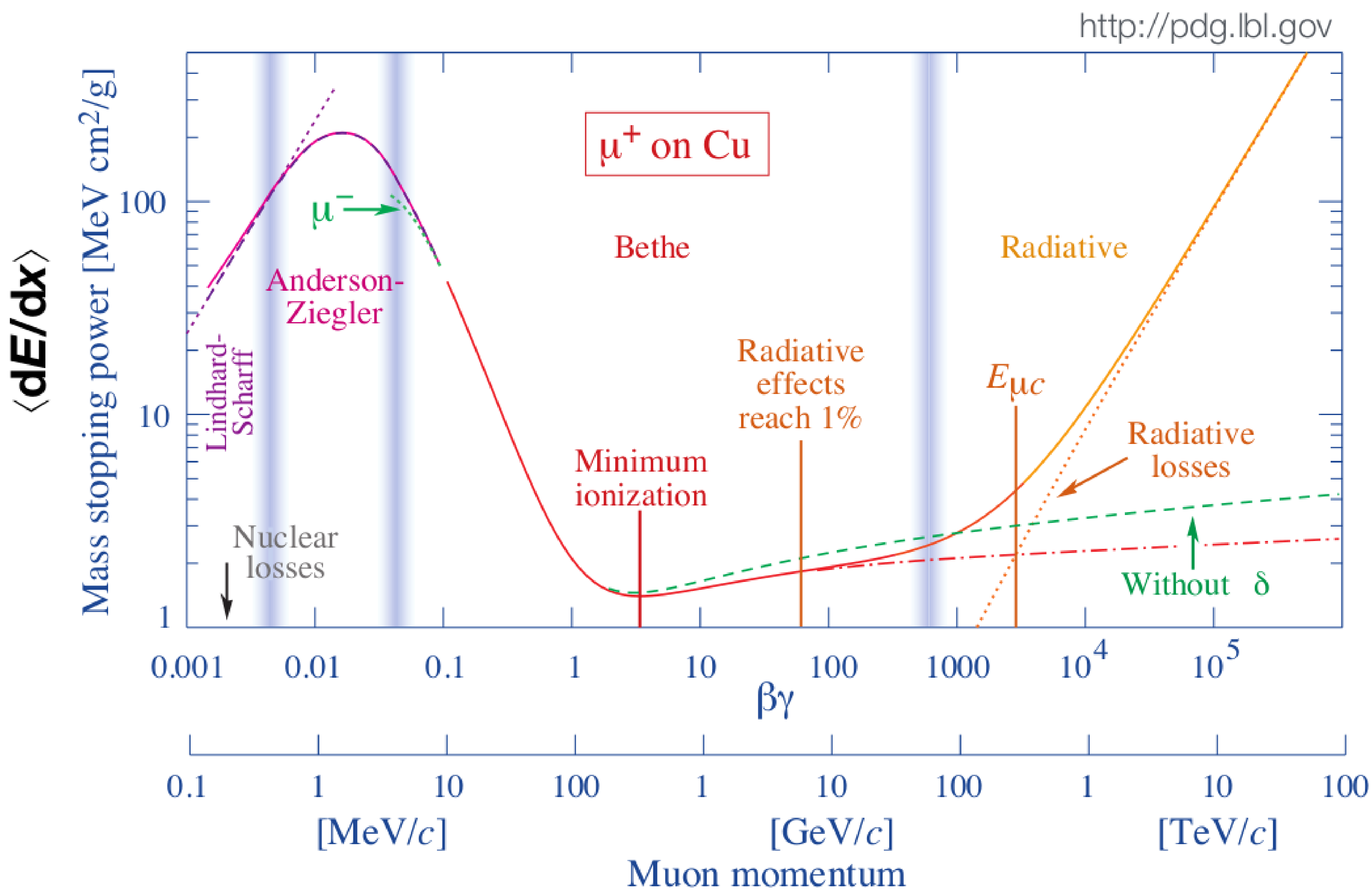
Radiative energy loss:

Inelastic scatterings with medium constituents
Dominates at high energy

Energy loss depends on :

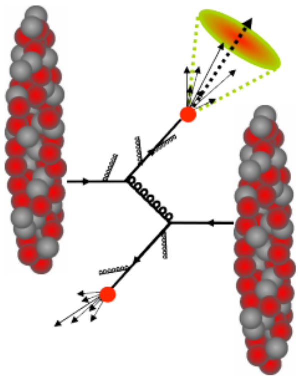
→ path length
→ parton flavor
→ medium density – want to extract

Analogy : energy loss in normal matter

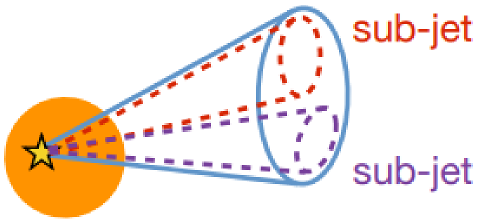


The goal : establish similar picture for QCD matter

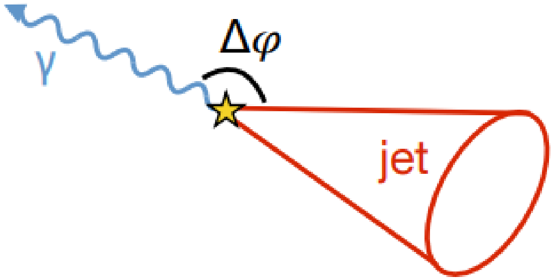
Selected jet results



- 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



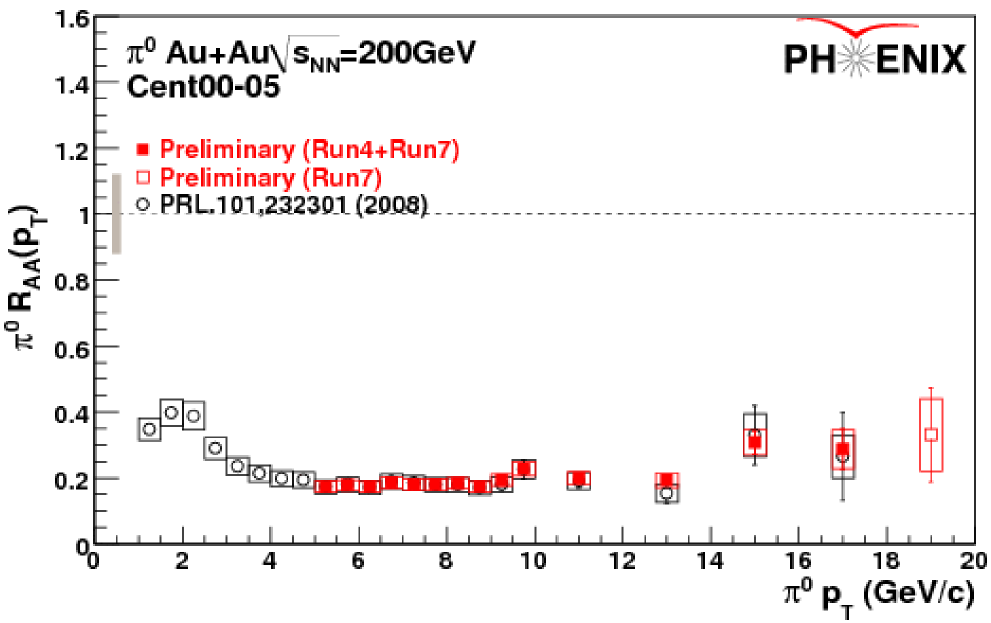
Hadron suppression at RHIC

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

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

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 :

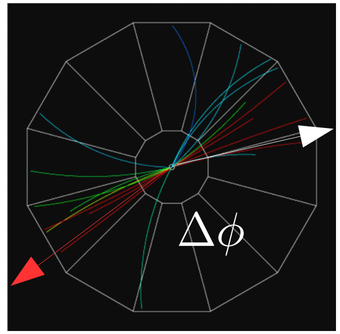
$$p'_T = C \times p_T \longrightarrow R_{AA} = C^{n-1}$$

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

Each parton loses 20% of its energy

Dihadron azimuthal correlations at RHIC

pp → dijet



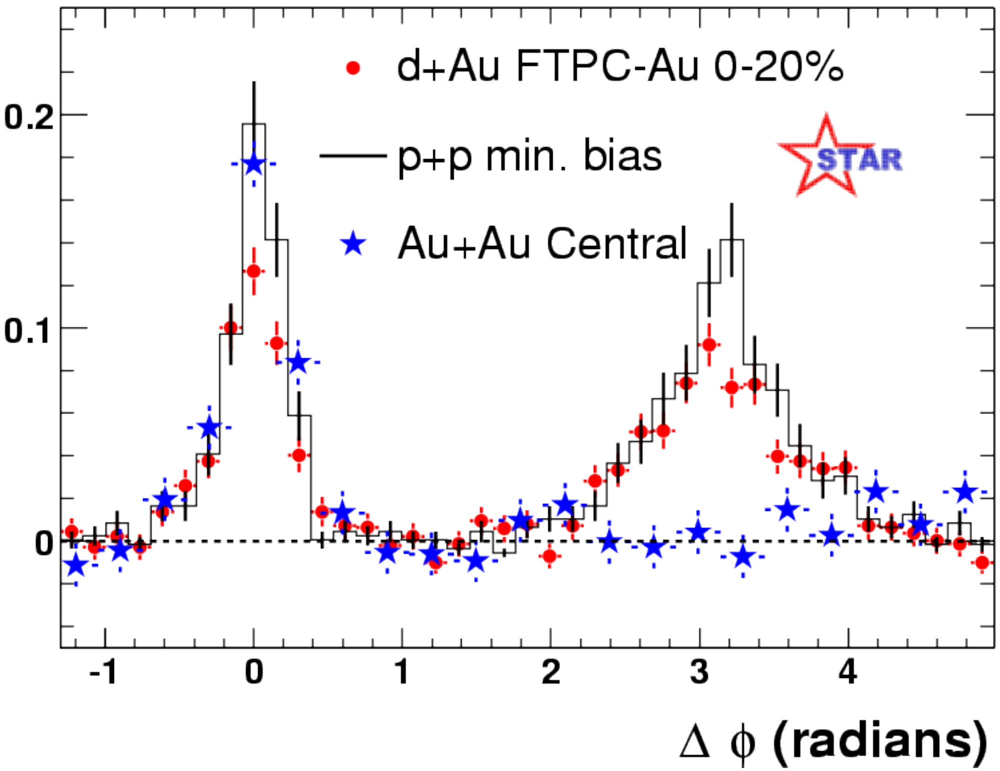
Partner hadron

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

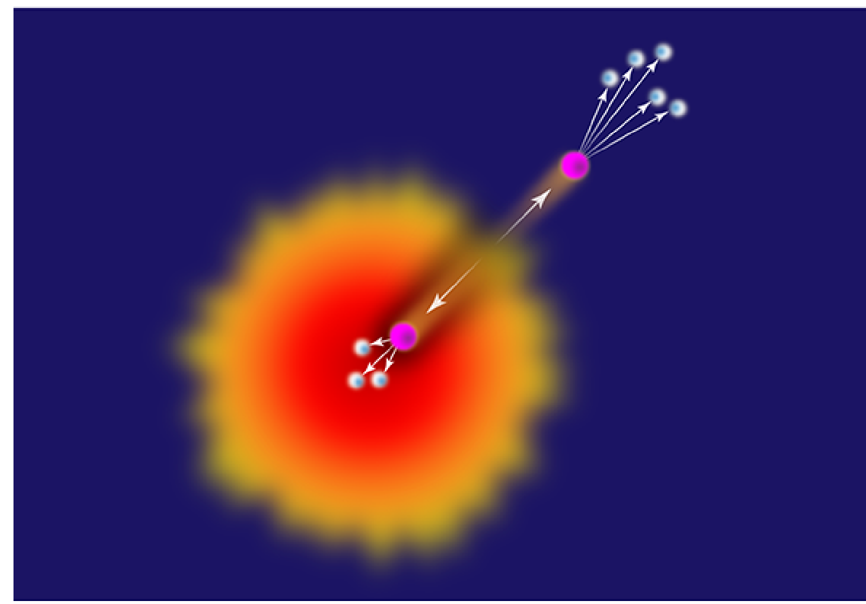
Trigger hadron

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

STAR, PRL 91 (2003) 072304



Trigger hadron



APS/Alan Stonebraker

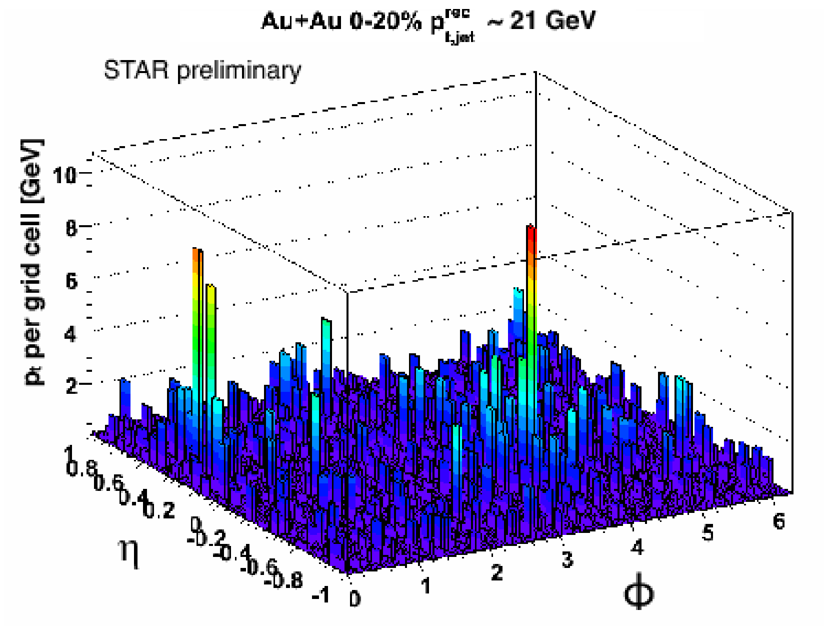
Partner hadron

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

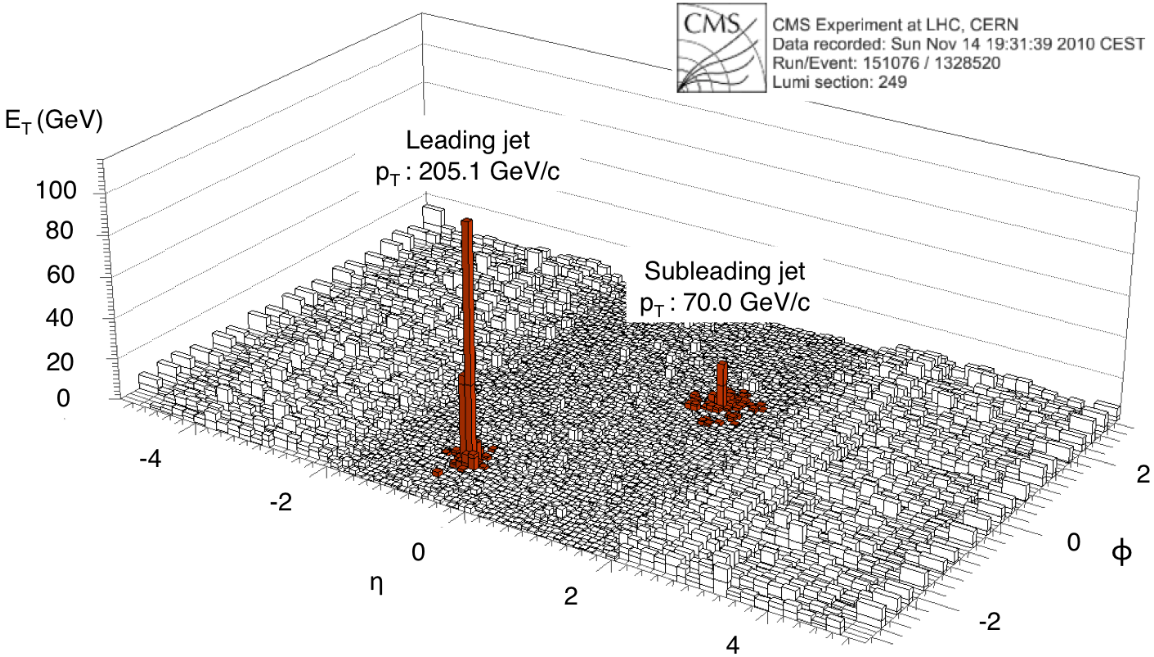
Jets at RHIC and LHC

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

STAR



CMS



Jet reconstruction at the LHC

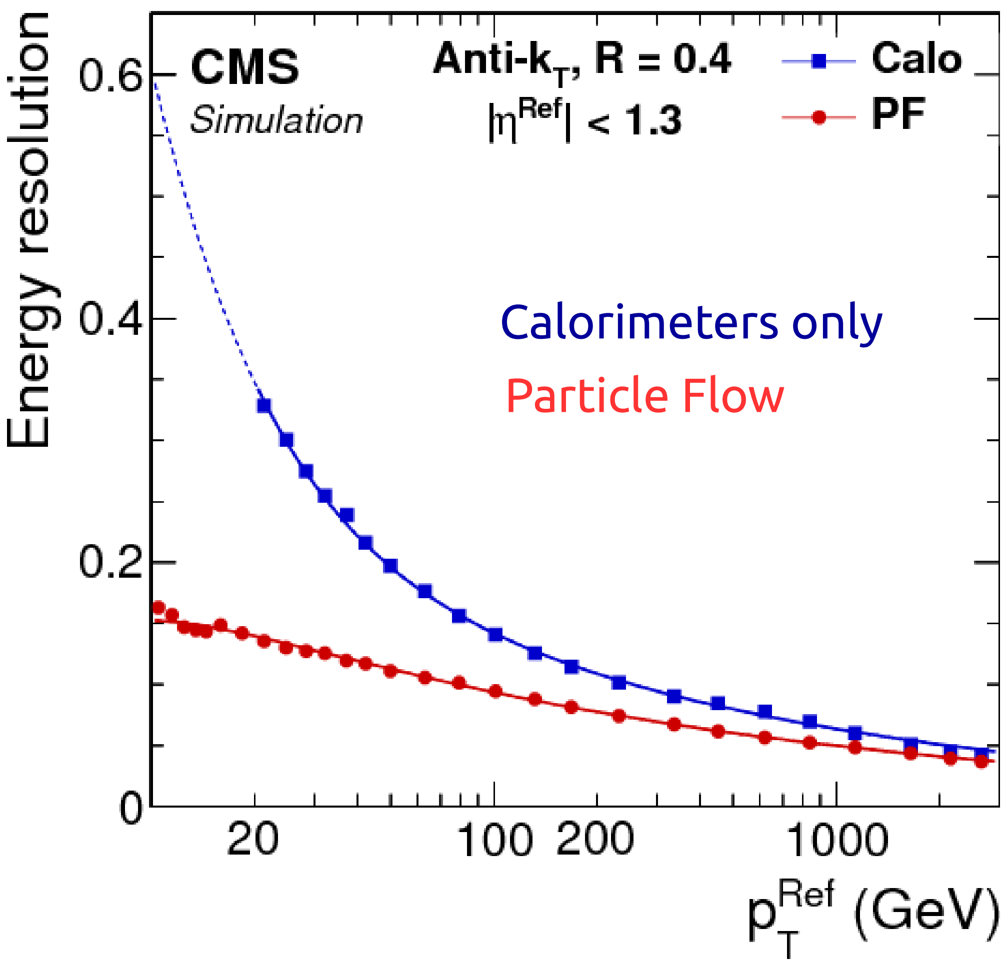
Jets consist of hadrons and photons → energy can be measured by the calorimeters only

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



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

Jet clustering

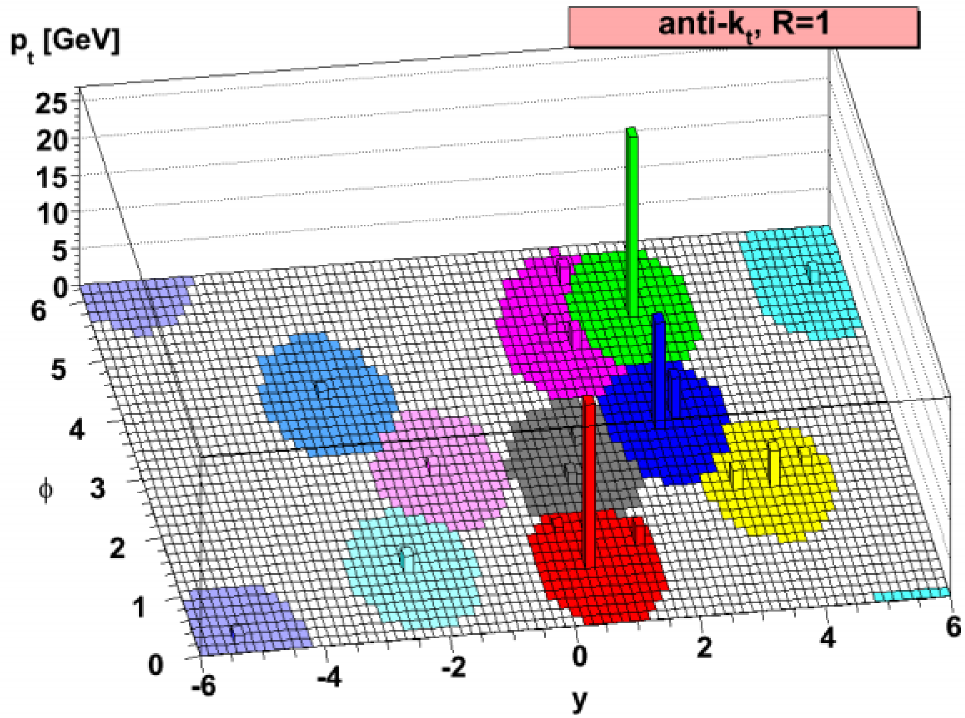
Jet clustering : reverse-engineering of the fragmentation and hadronization

Sequential clustering : combines the closest particles into jets

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^{2p} \quad \begin{cases} p = 1 : \text{kt} \\ p = 0 : \text{C/A} \\ p = -1 : \text{anti-kt} \end{cases}$$

Distance between pairs of particles | Jet radius | Distance to the beam

JHEP 0804:063,2008

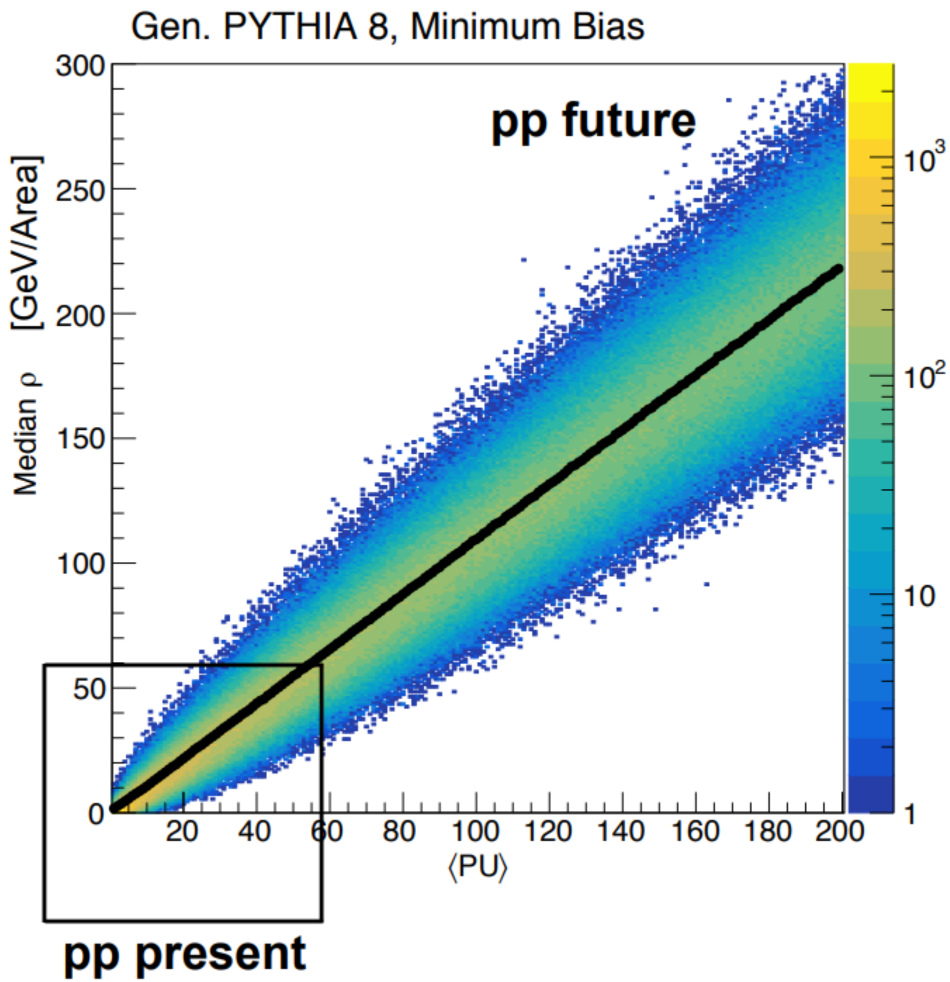


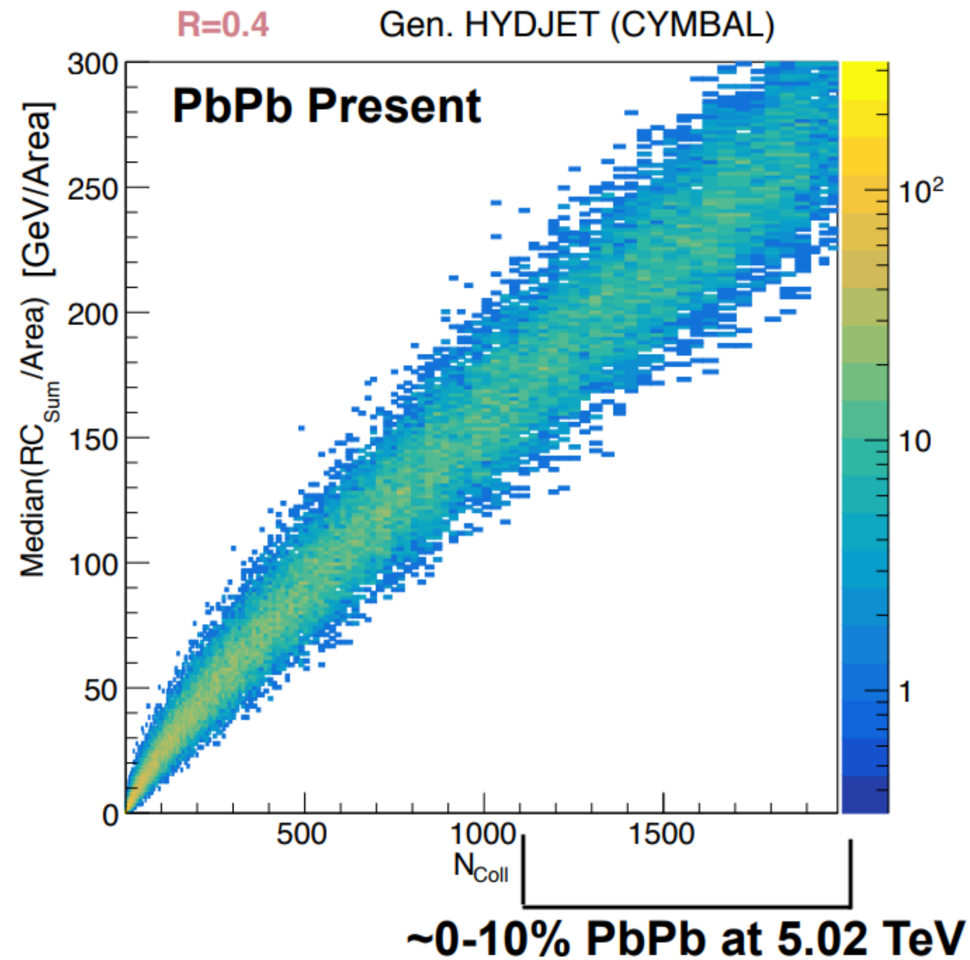
Underlying event in pp and PbPb collisions

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

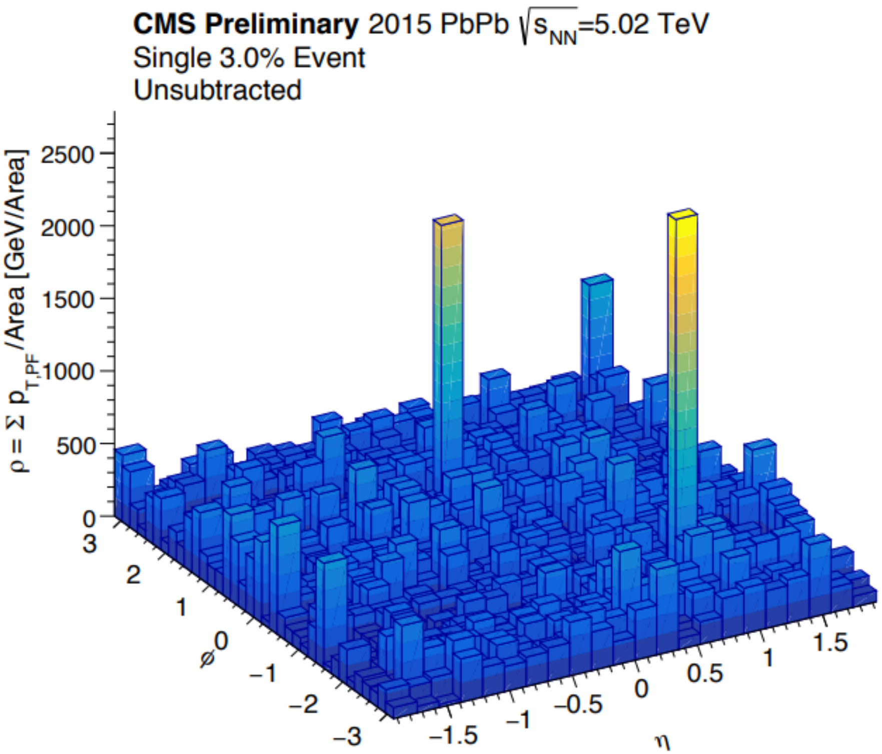




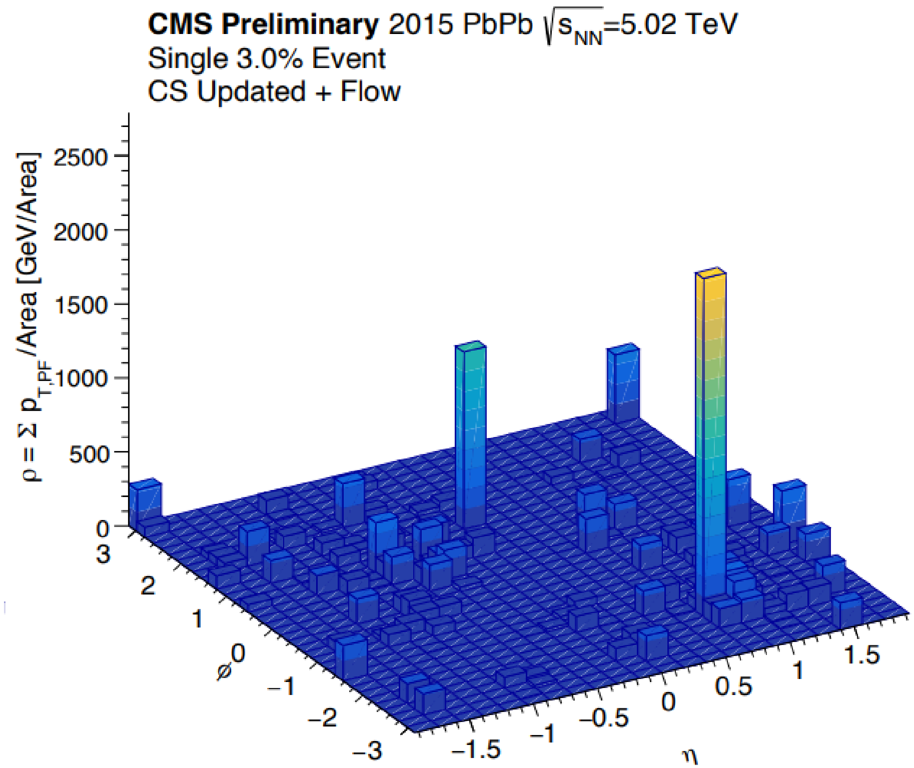
UE in pp with <PU> ~ 200 looks like central PbPb

Jets in PbPb collisions

Before UE subtraction



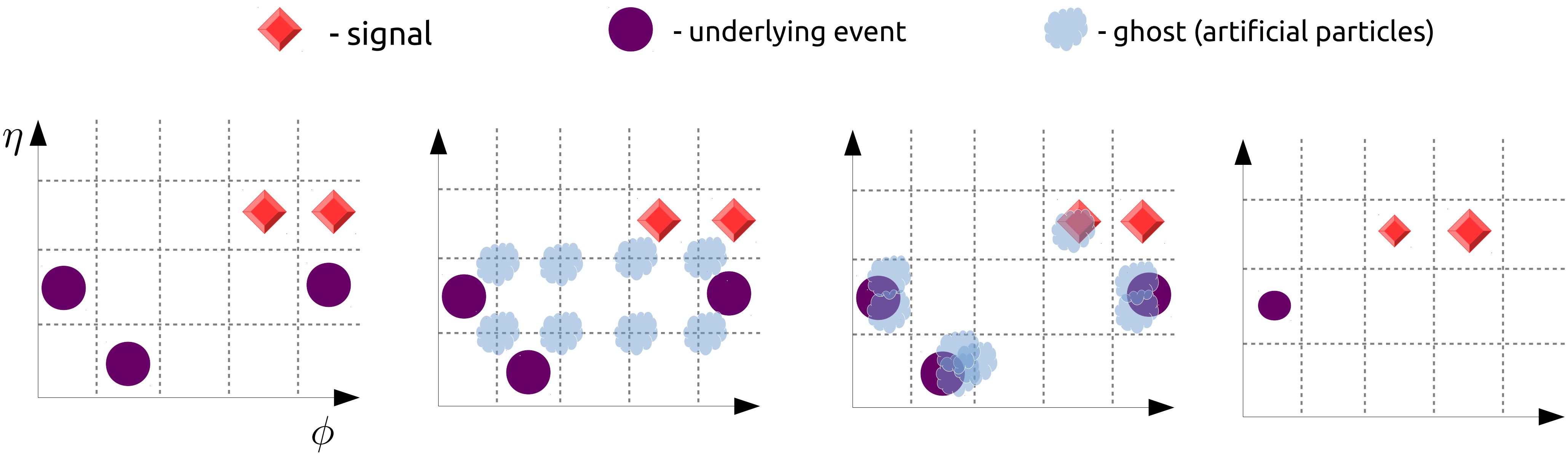
After UE subtraction



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



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

A_{ghost} - area occupied

Combine them with the closest real particle

$p_T^{particle} > p_T^{ghost}$

$p_T^{particle} < p_T^{ghost}$

The largest pT particle/ghost survives

$p_T^{particle} = p_T^{particle} - p_T^{ghost}$

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

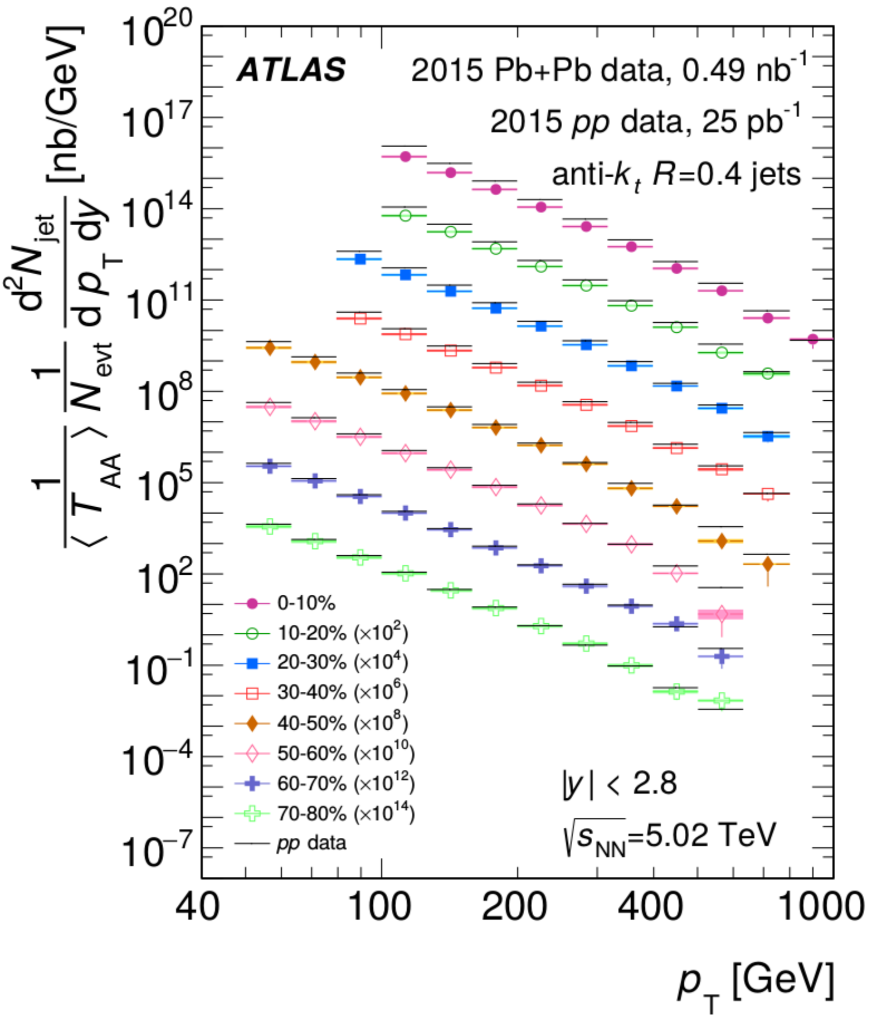
Repeat until no ghosts/particles left

Remaining particles get clustered into a jet

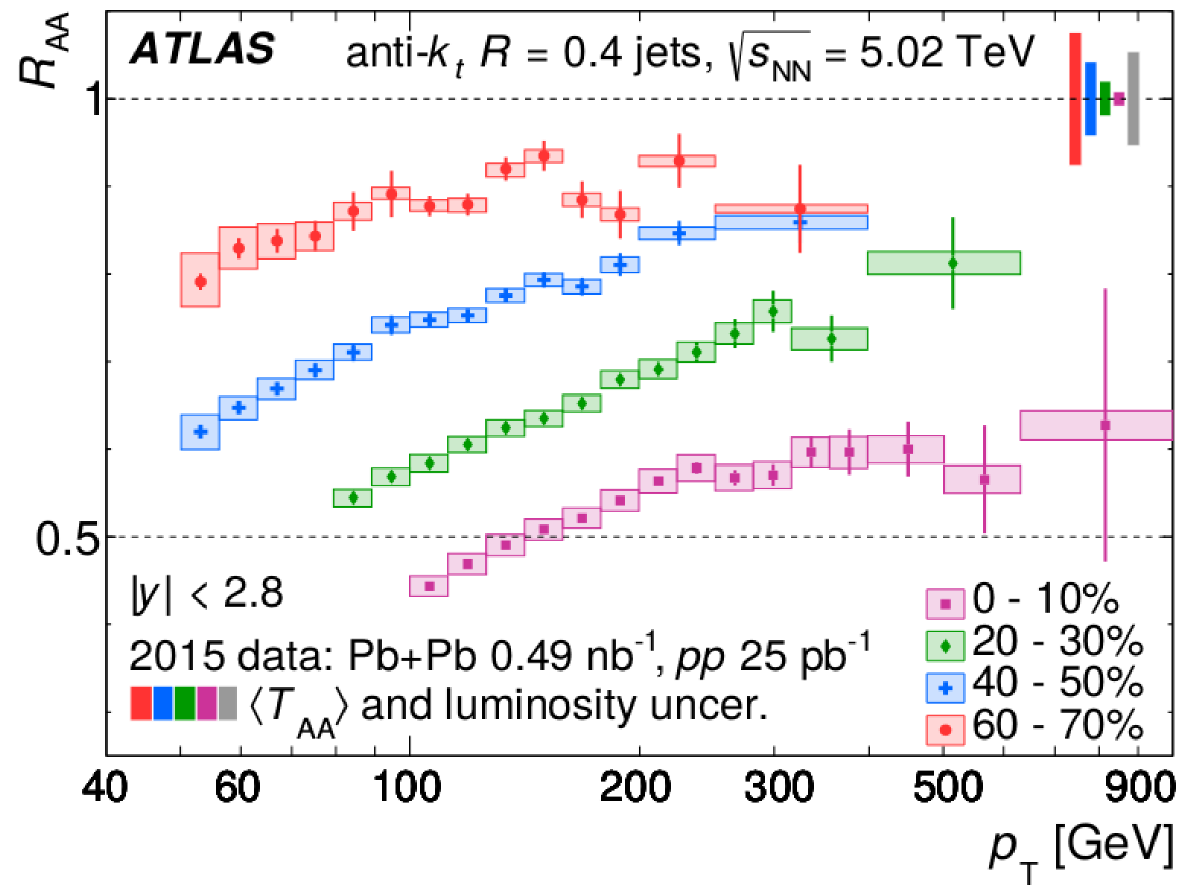
Jet suppression in ATLAS

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

Phys. Lett. B 790 (2019) 108



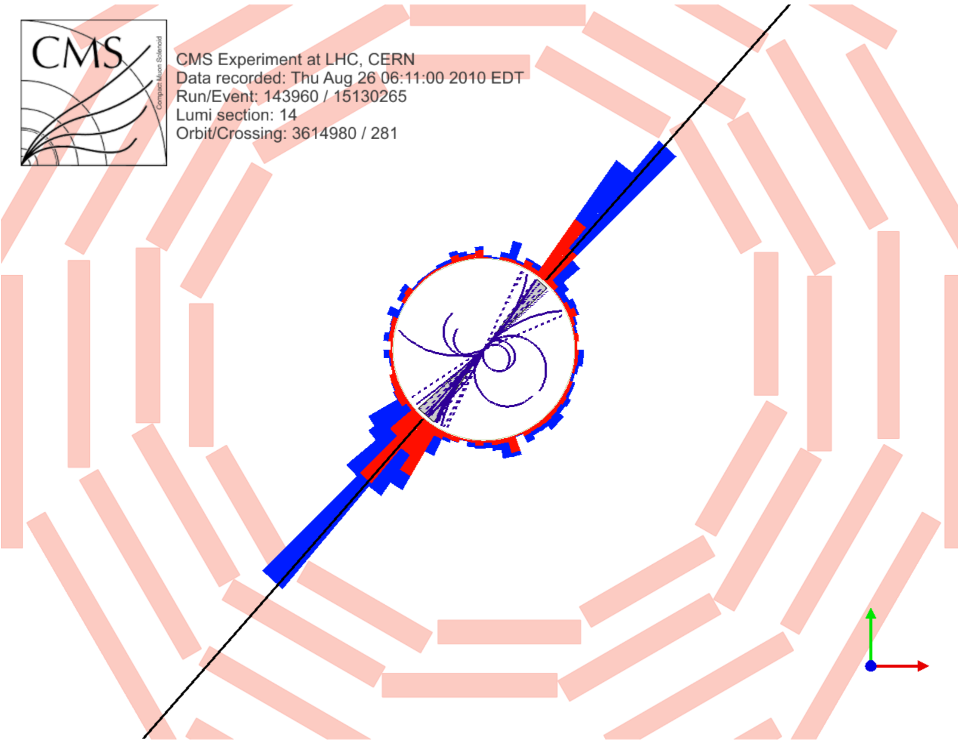
$$R_{AA} = \frac{\text{per-event yield}_{AA}}{\text{number of binary collisions} \times \text{per-event yield}_{pp}}$$



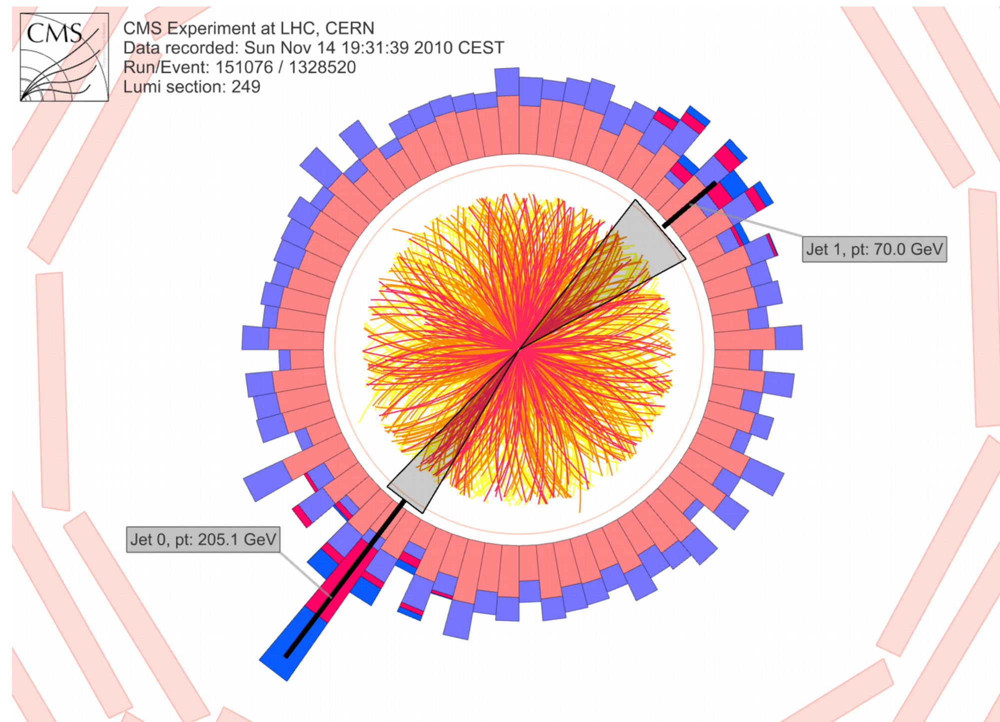
At large pT : flat suppression in central collisions

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

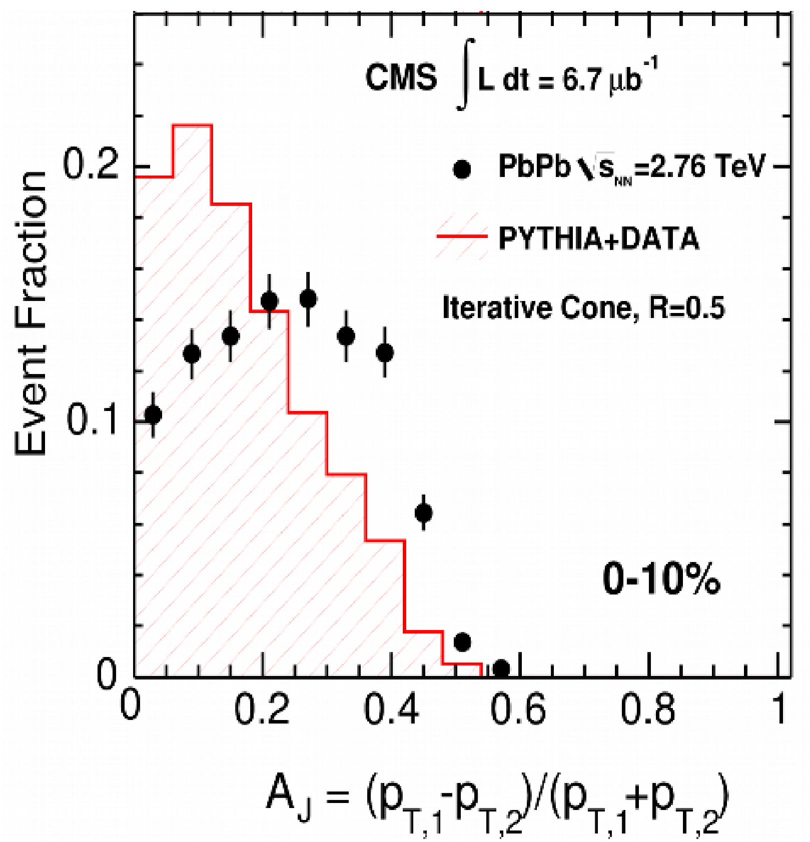


How to quantify the effect?

Dijet asymmetry in CMS

Dijet asymmetry of leading and subleading jets

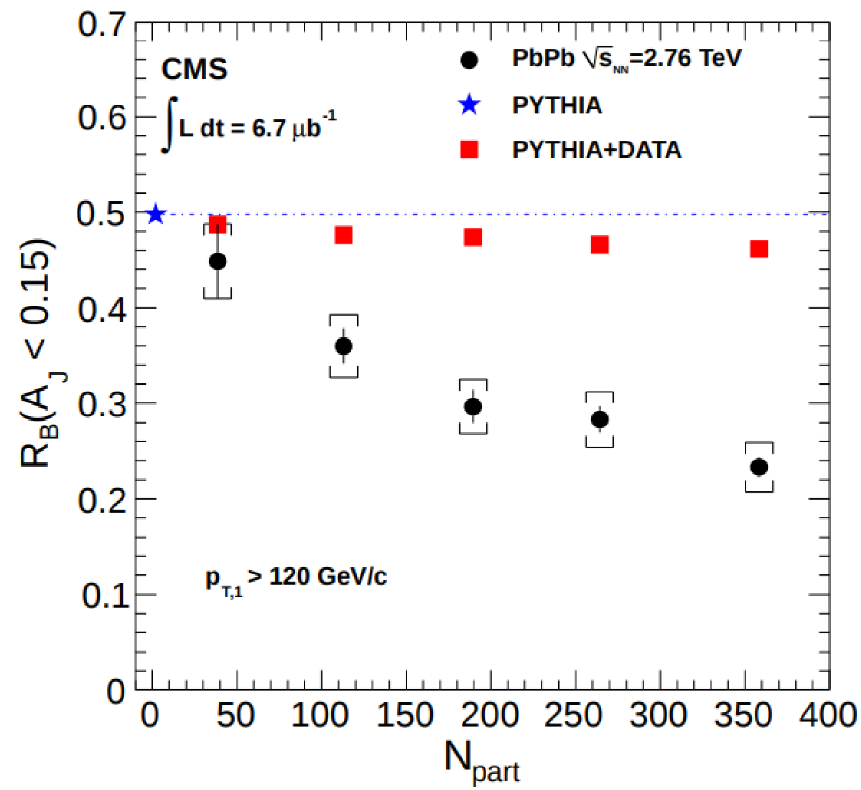
$p_{T,1} > 120$ GeV, $p_{T,2} > 50$ GeV
$\Delta\phi > 2\pi/3$



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

Fraction of all events with "balanced" jets

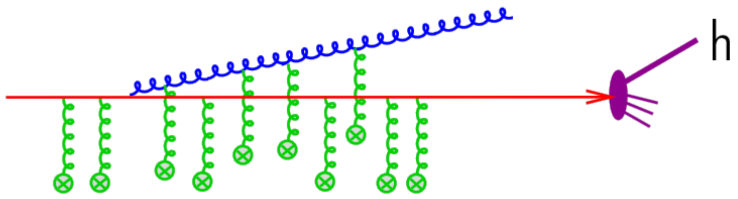
CMS, PRC84 (2011) 024906

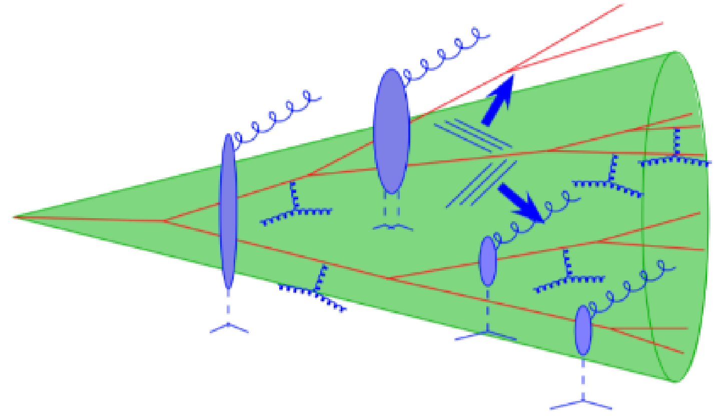


In the most central PbPb ~ 2 times less "balanced" dijets

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!

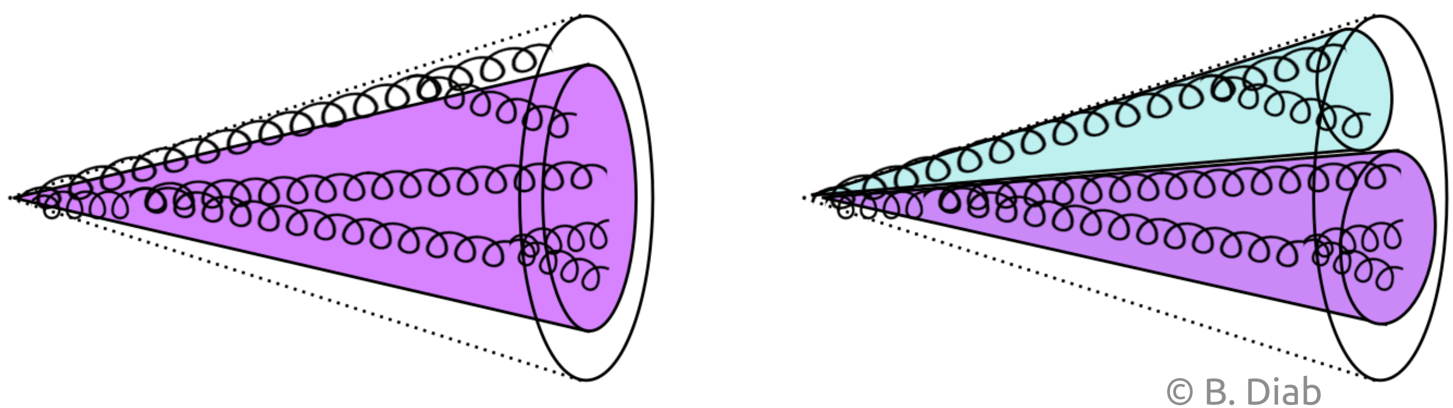
Jet splitting : motivation

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 ?

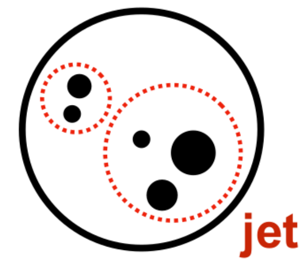


subjets equally modified

subjets modified differently

Jet splitting in CMS

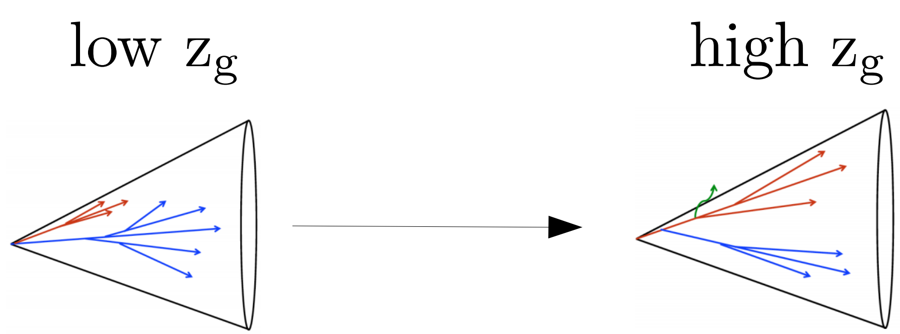
First splitting in parton shower → study only hard jet components

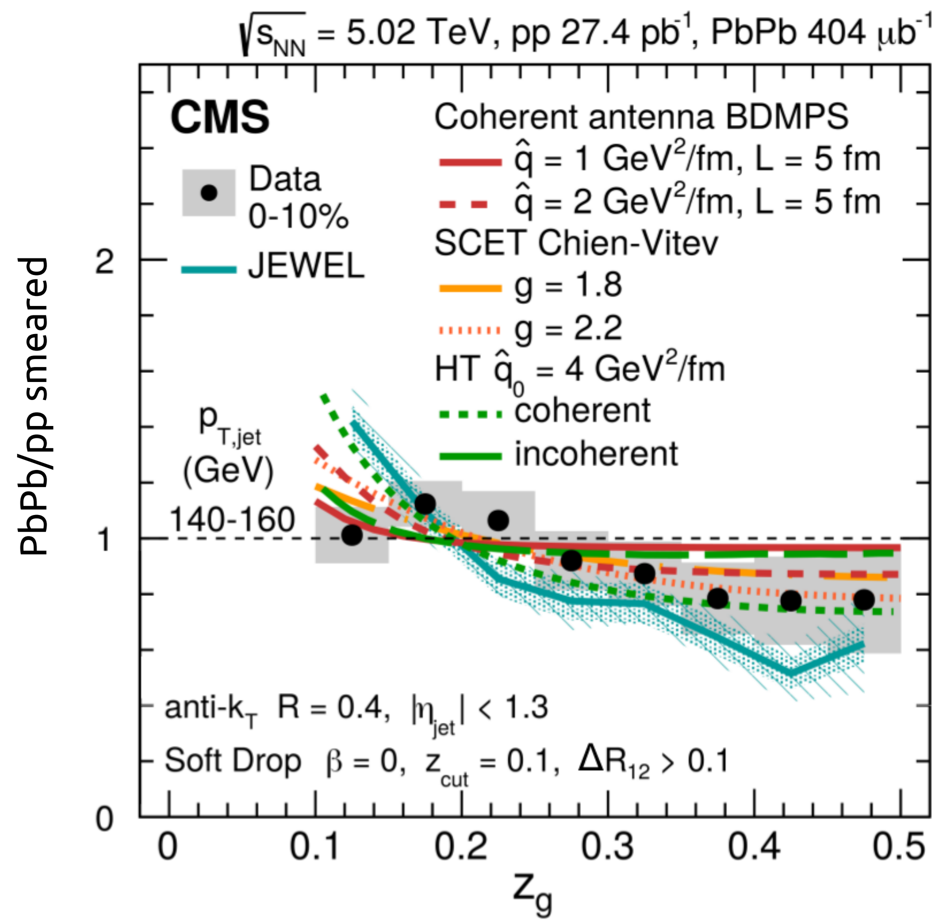


Subjet momentum sharing : $$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

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

CMS, Phys. Rev. Lett. 120, 142302



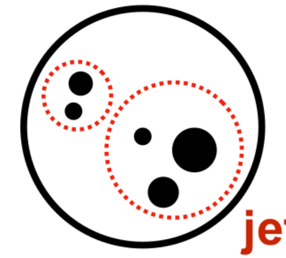


Momentum sharing is steeper in PbPb → splitting process is modified

Jet **cannot** be one coherent emitter!

Jet splitting in ALICE

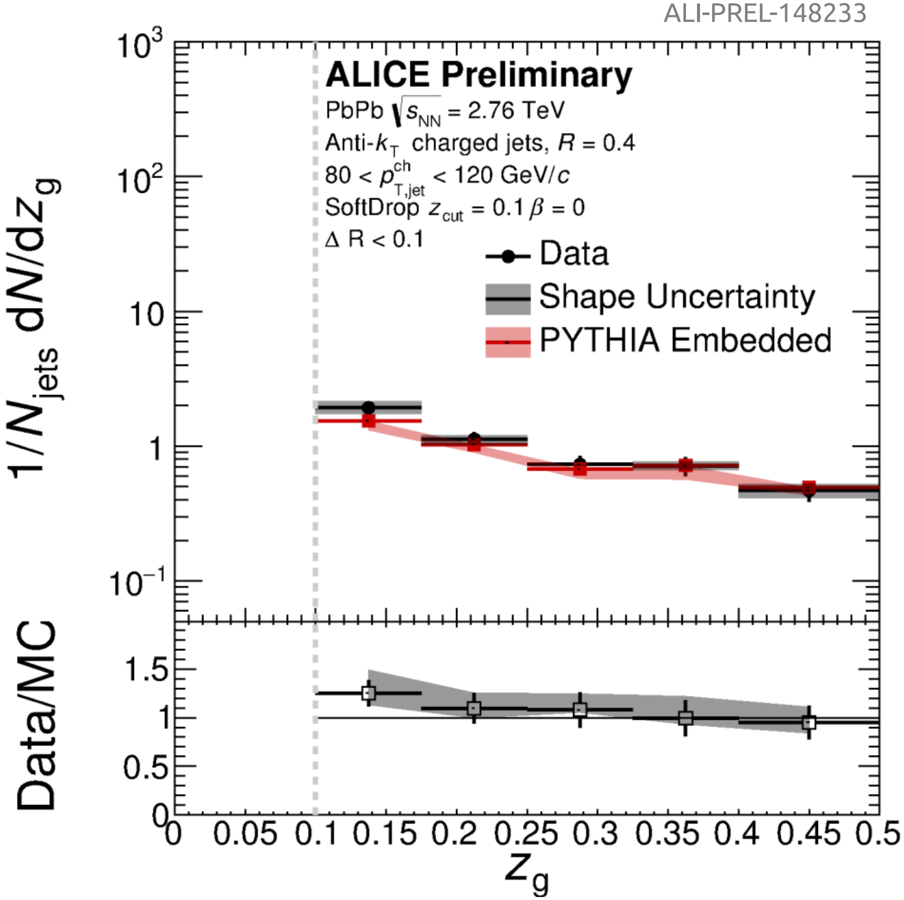
First splitting in parton shower → study only hard jet components



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

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

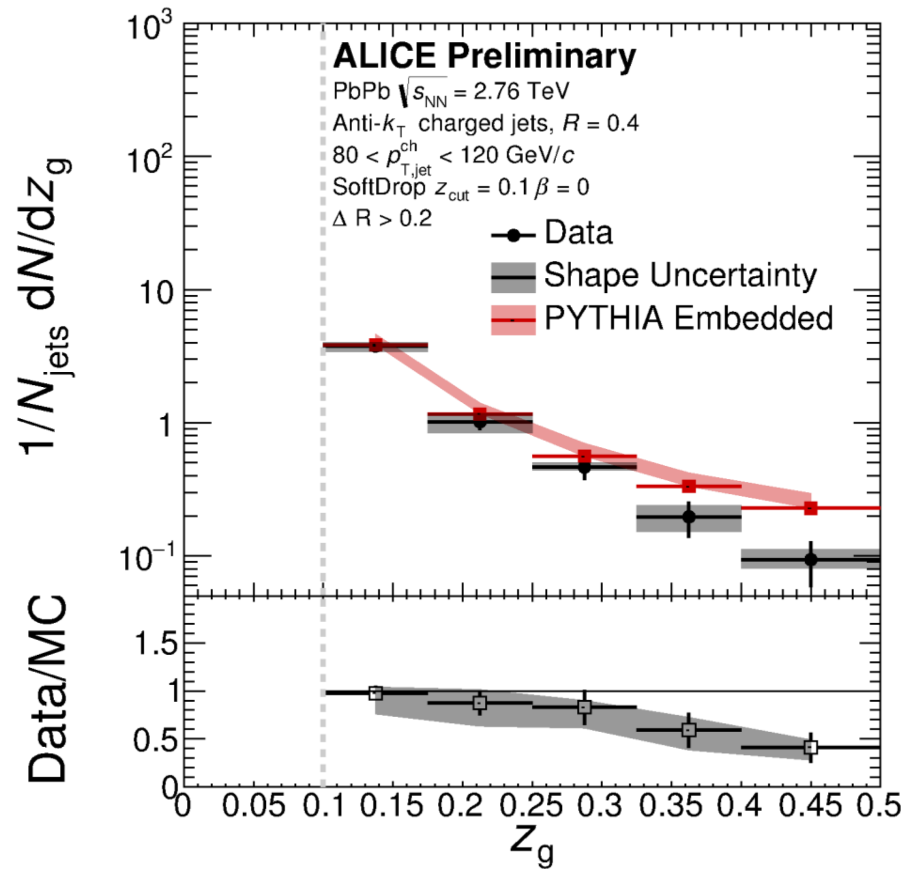
ALI-PREL-148233



No modification

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

ALI-PREL-148229



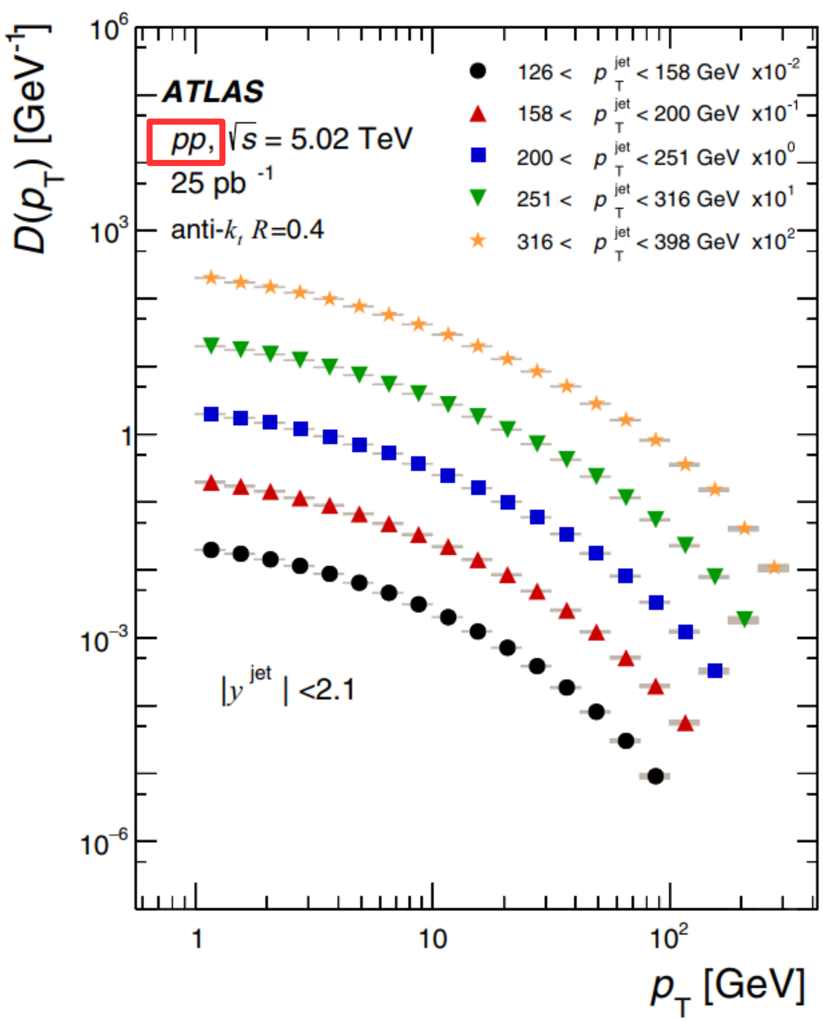
Wide-angle symmetric splittings are suppressed

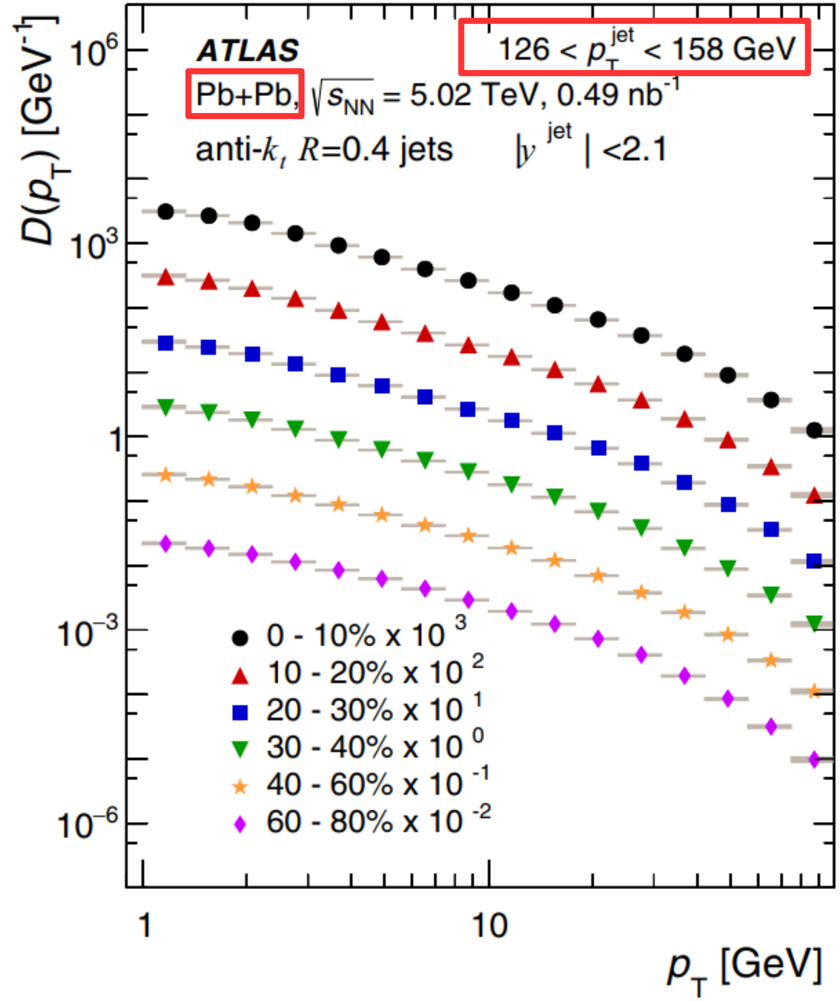
Jet fragmentation function in ATLAS

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

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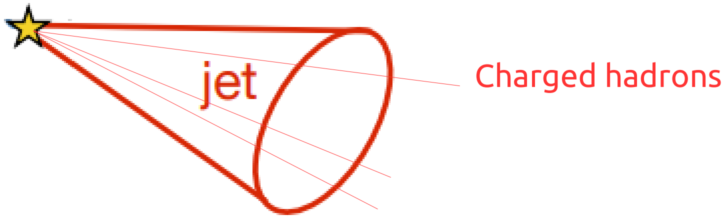


How much is the jet structure modified ?

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

PbPb compared to pp :

→ more soft particles due to interaction with the medium

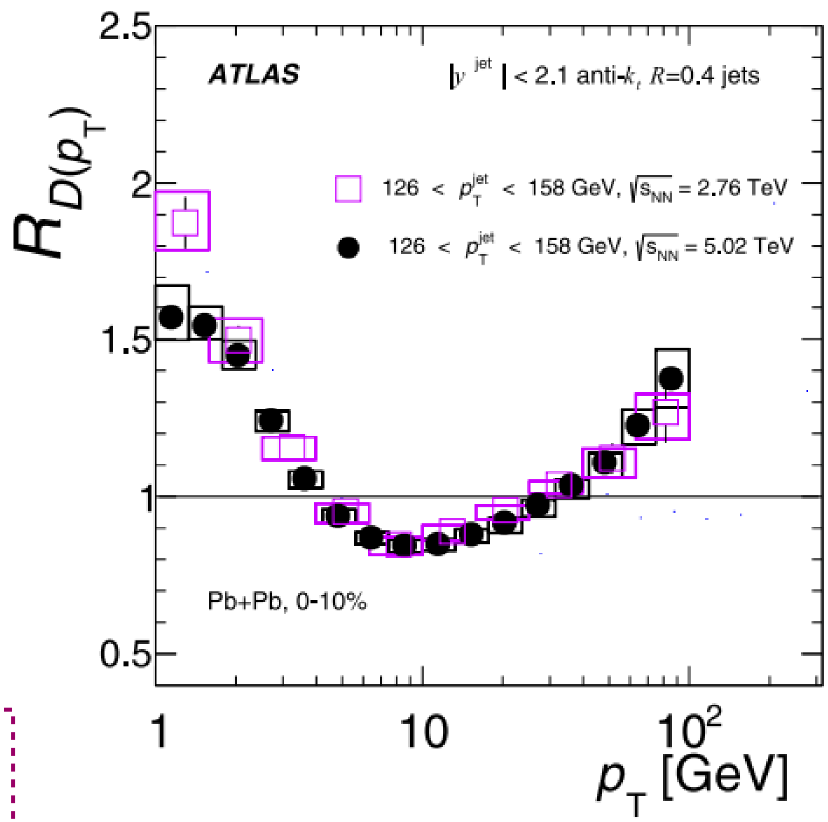
→ suppression at mid p_T

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

Gluon vs quark jet:

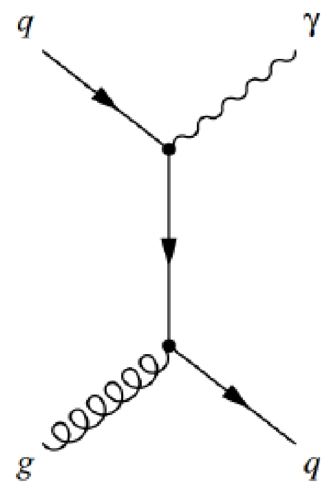
→ larger charged hadron multiplicity
→ contain more softer particle
→ wider

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



Photon + jet system

Compton scattering



Quark-initiated jet

In pp collisions :

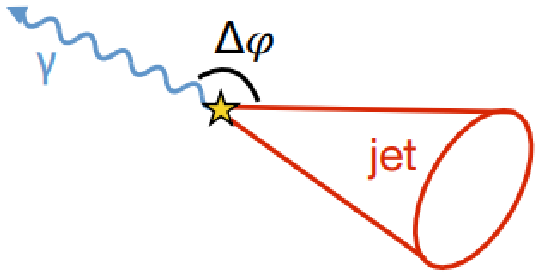
→ Compton scattering dominates :
gluon in initial state and quark in the final state

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

In heavy ion collisions :

→ photons do not interact with the QGP

→ study the energy loss with well defined initial kinematics !

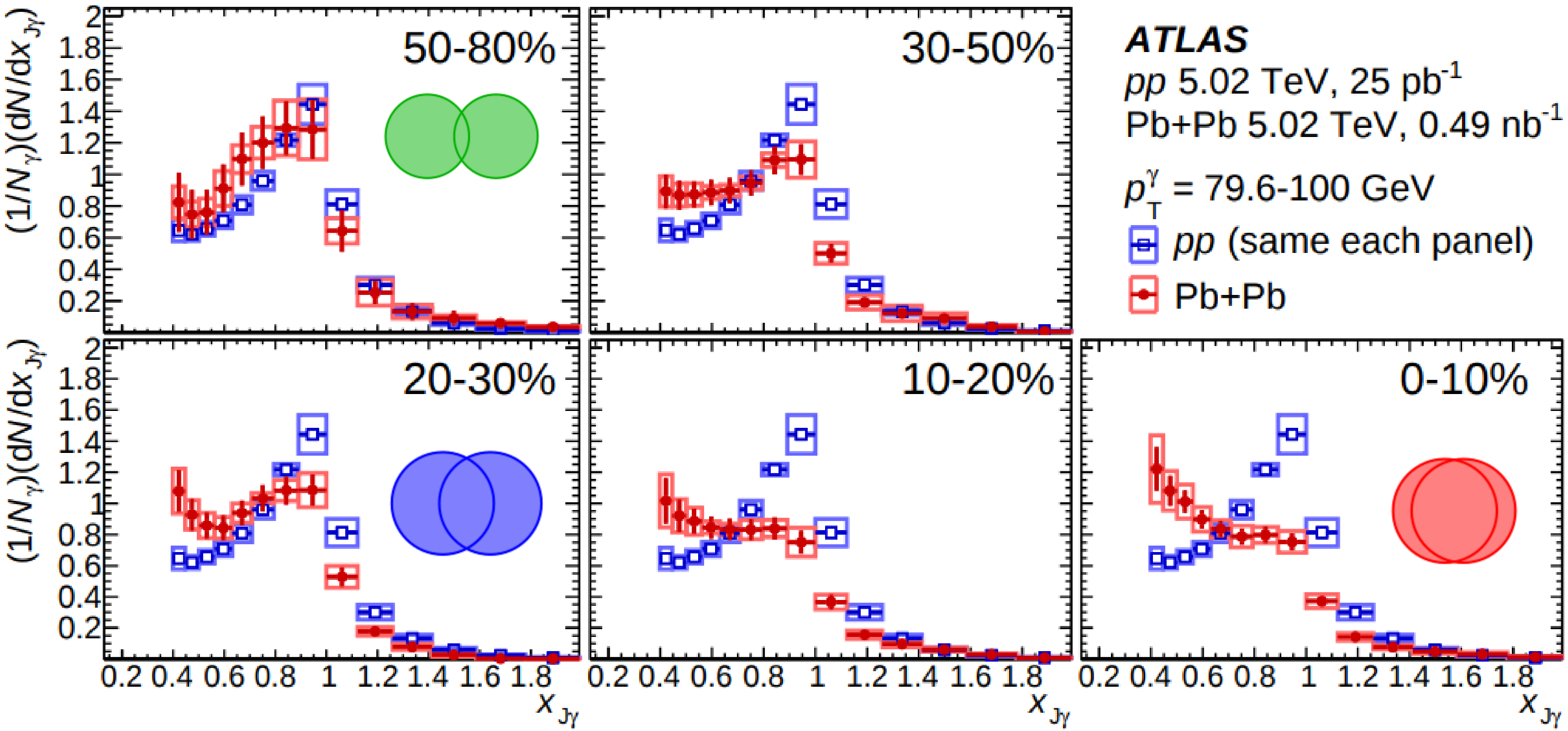


Photon+jet pT balance in ATLAS

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



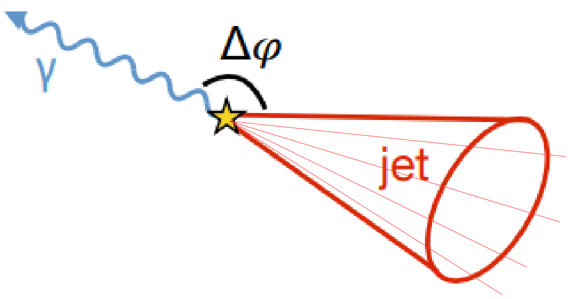
The jet energy decrease with centrality

- 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

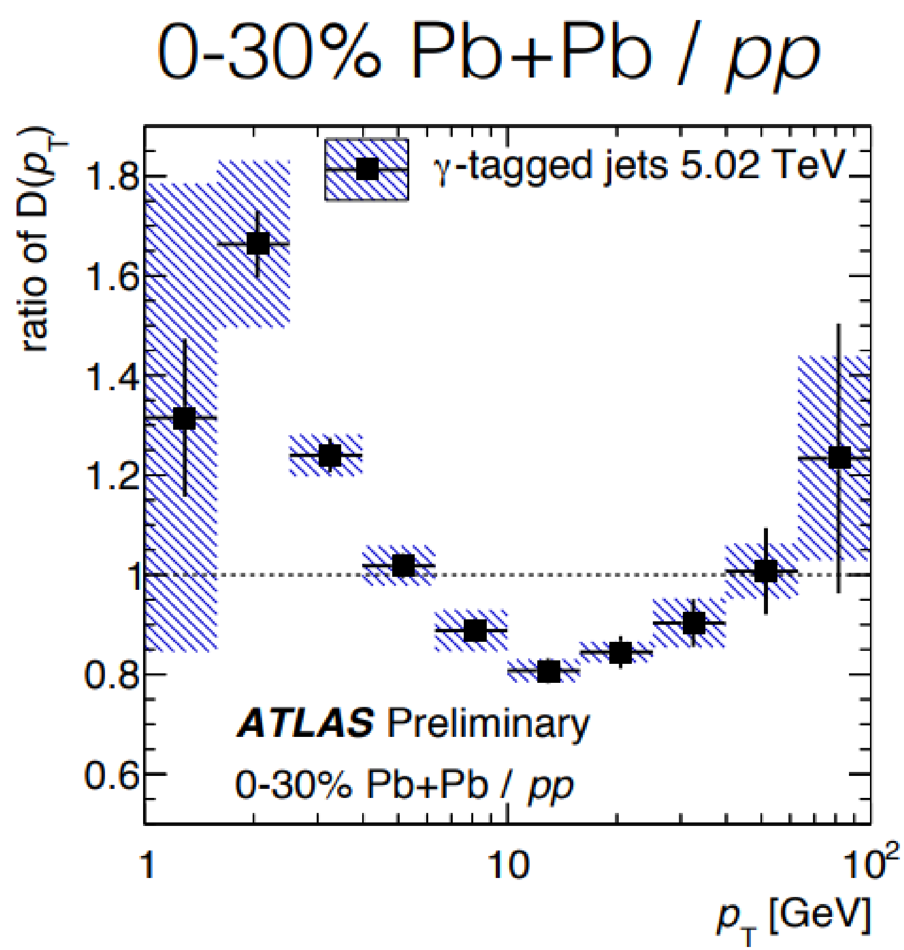
Photon+jet fragmentation function in ATLAS

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

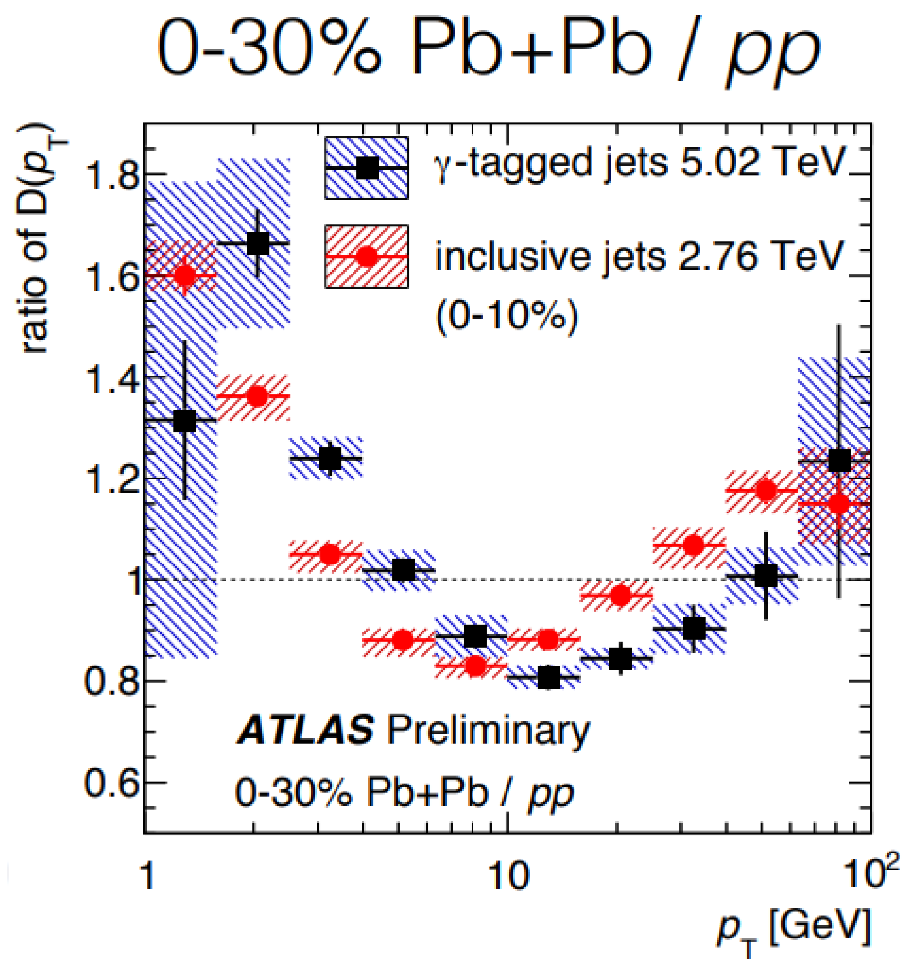
→ no modification at high p_T

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



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

→ more enhancement at low p_T

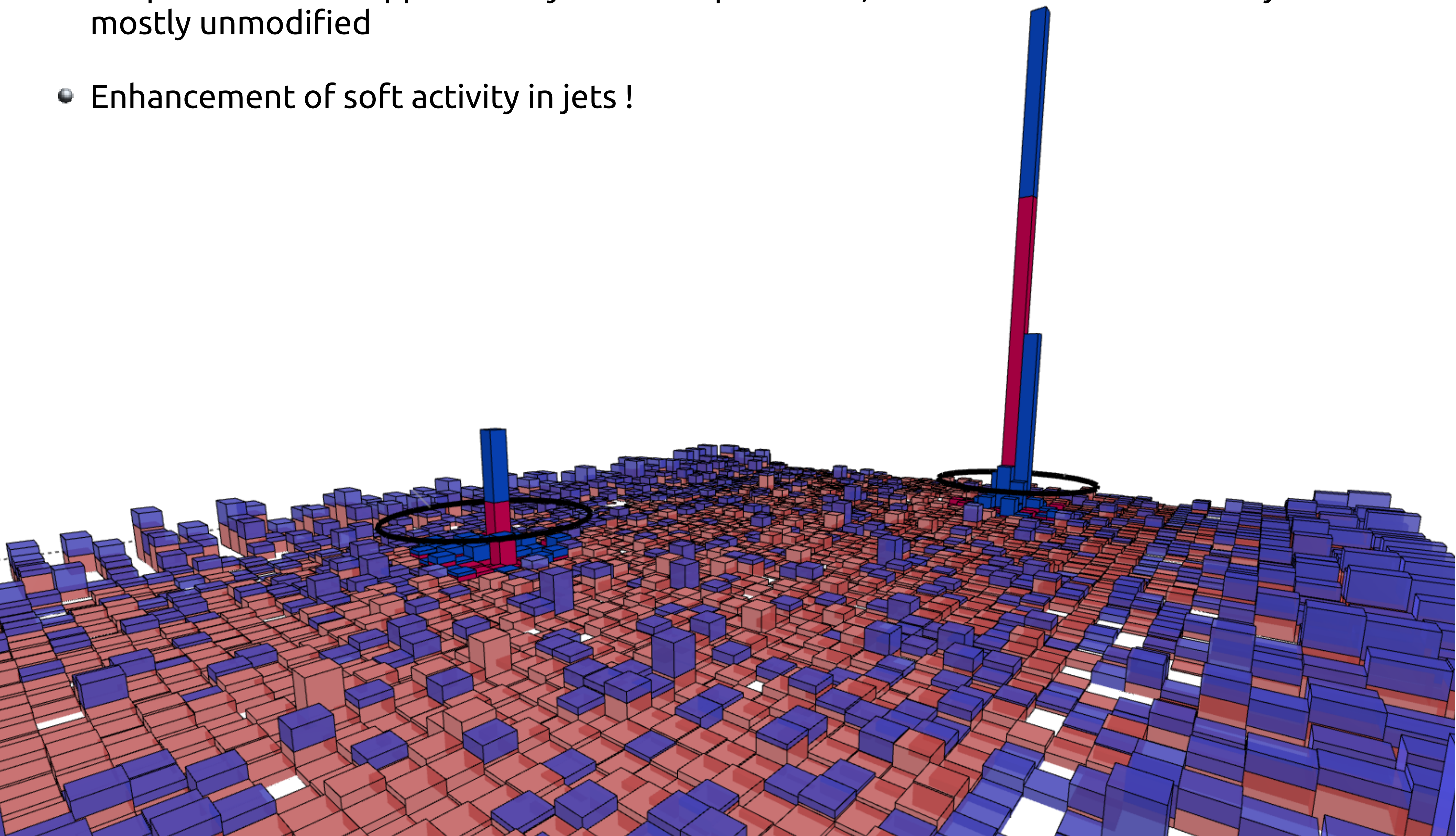
→ shift of mid p_T minimum

→ 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 :

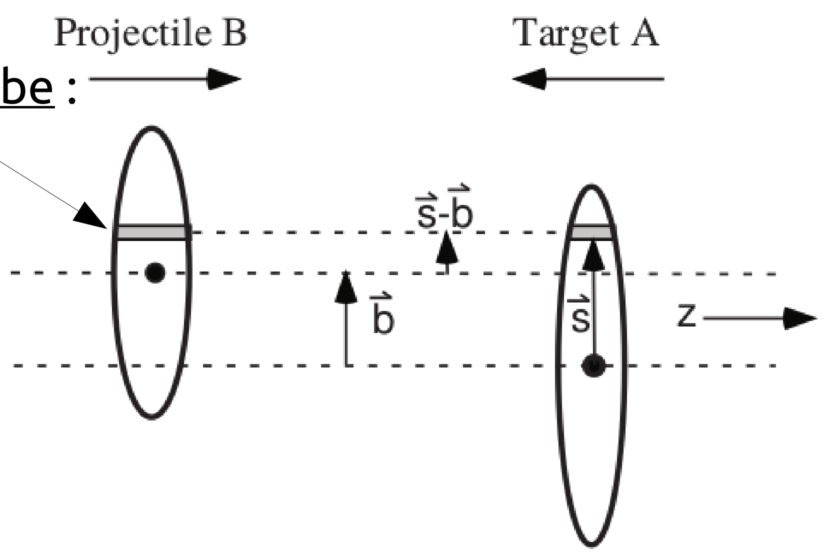
$$\rho(r) = \frac{\rho_0}{1 + exp[(r - R)/a]}$$

(spherical case)

nuclear size
surface thickness

Two nuclei collide

Probability of a given nucleon to be in the target flux tube :



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

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

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

$T_{AB}(b)$ - 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 : $\frac{d\sigma}{db} = 2\pi b$

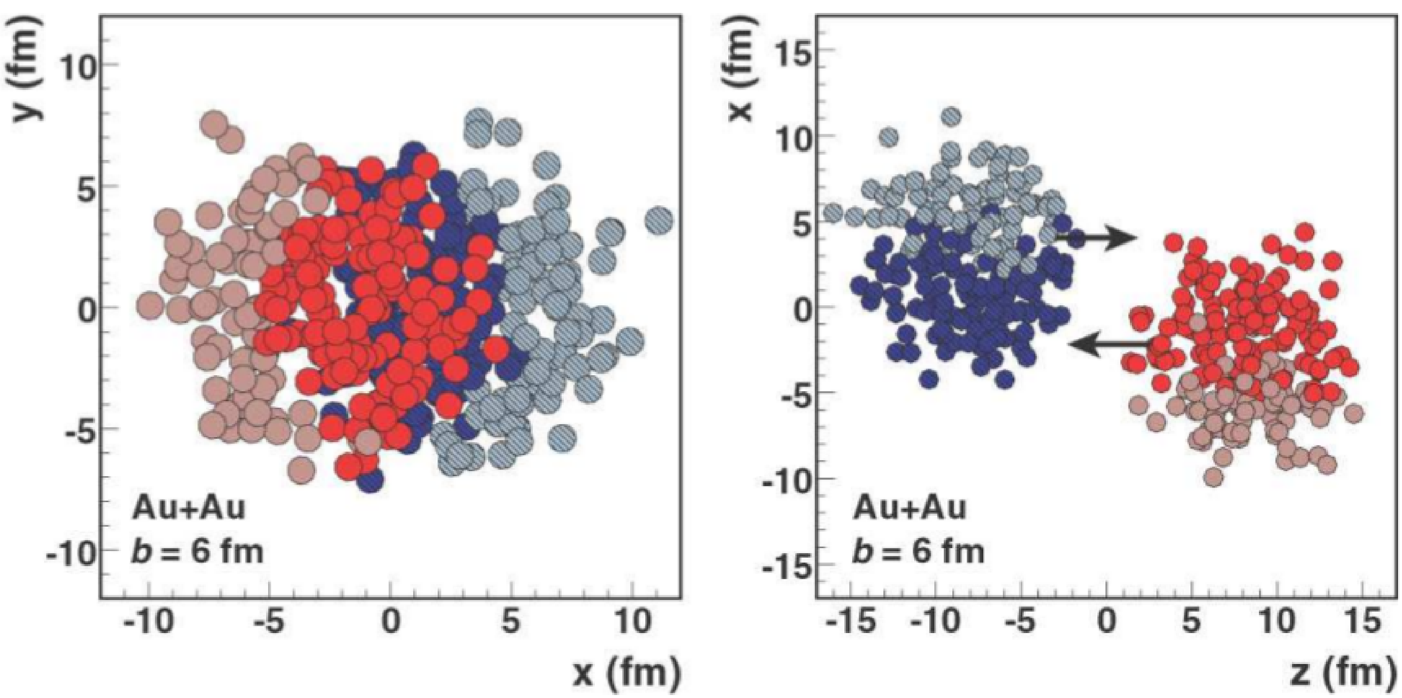
Collision : a sequence of independent binary collisions

→ 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 $d \leq \sqrt{\sigma_{inel}^{NN}/\pi}$

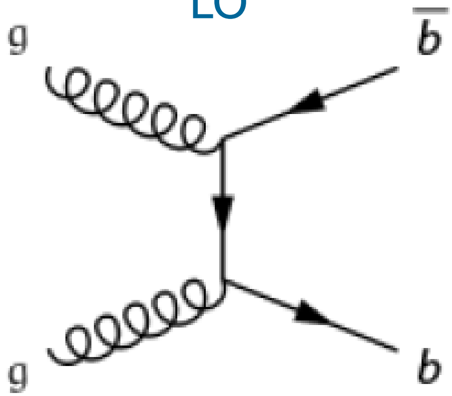
Ann.Rev.Nucl.Part.Sci.57:205-243,2007



B-jet production channels at LHC

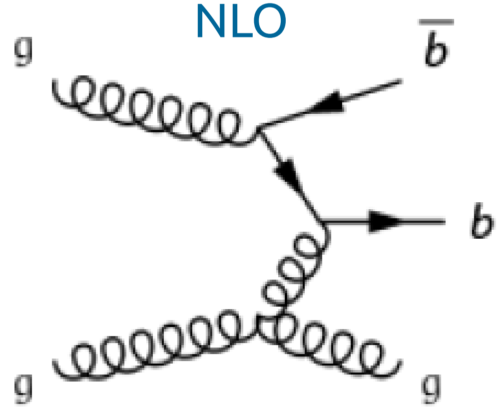
Flavor Creation (FCR)

LO



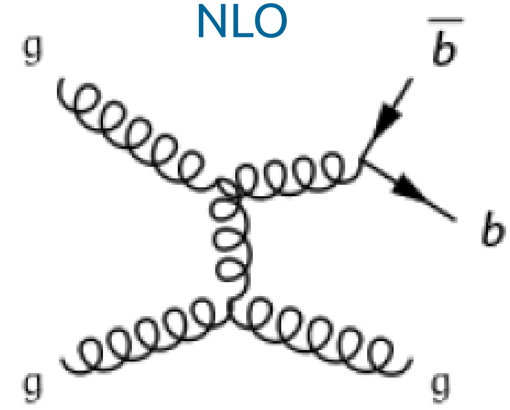
Flavor Excitation (FEX)

NLO



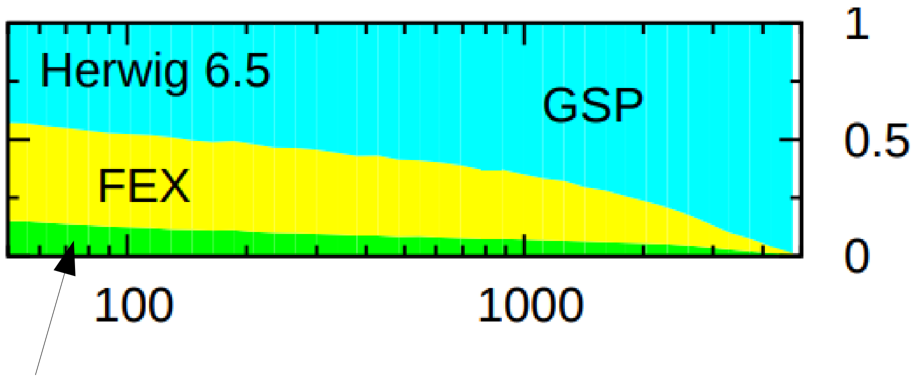
Gluon Splitting (GSP)

NLO



LHC, pp collisions at 14 TeV

JHEP 0707:026,2007



FCR is not dominant process

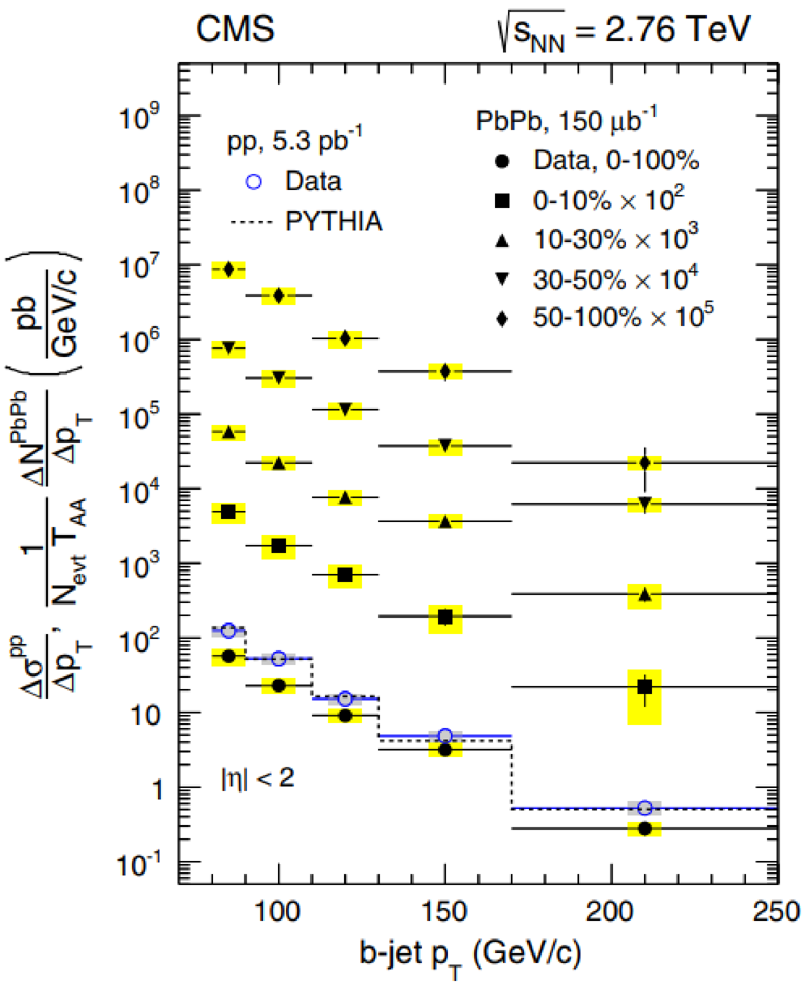
First Heavy Ion measurements convolute large contributions from NLO b-quark production processes

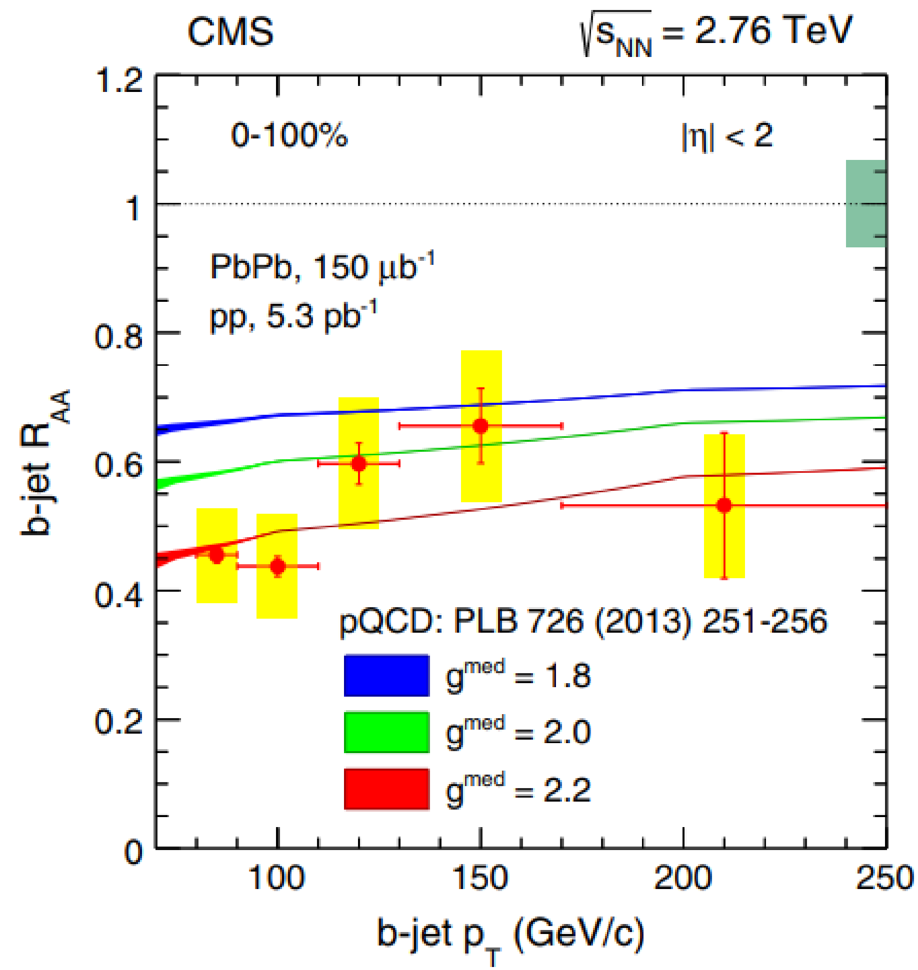
Energy loss is expected to depend on flavor
→ measure heavy flavor jets suppression

Quenching of b-jets

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

CMS, PRL 113 (2014) 132301



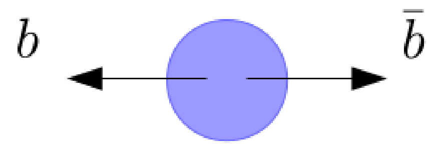


Suppression consistent with the one observed from inclusive jets

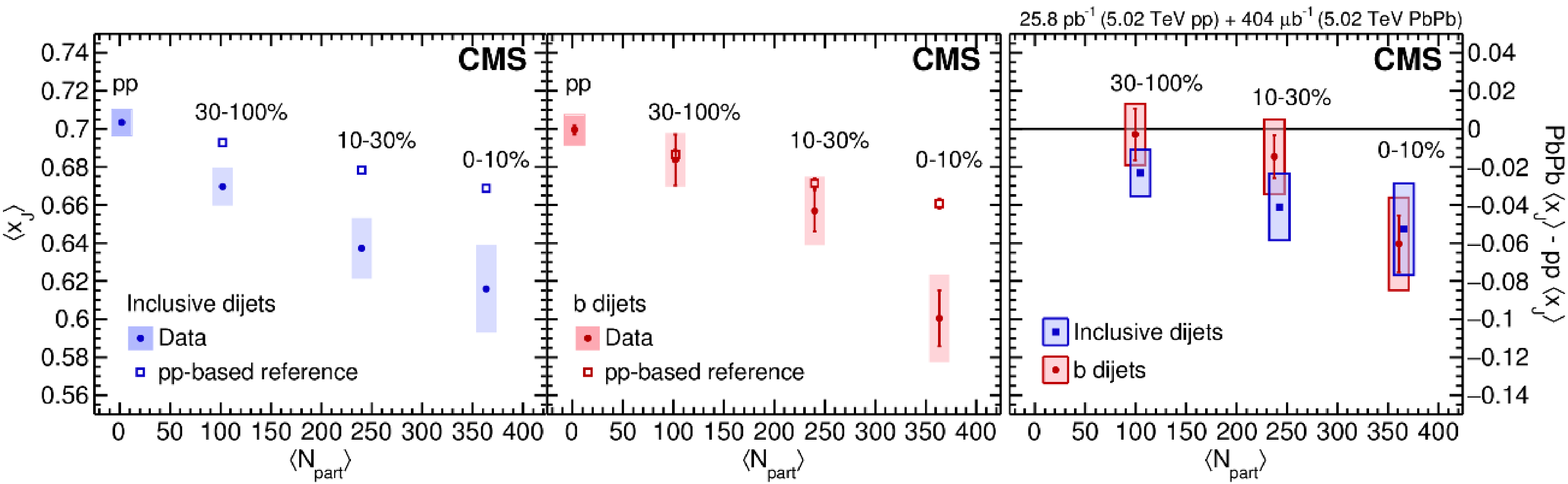
bb correlations

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



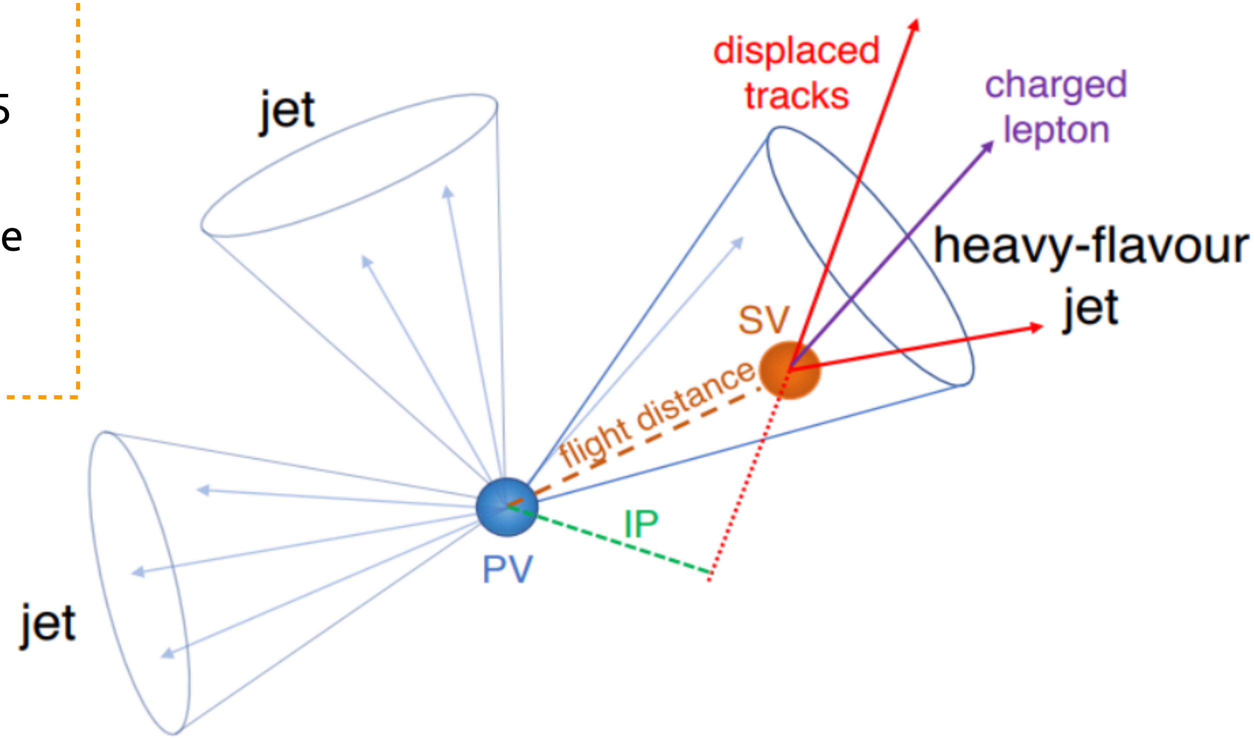
No clear difference between pT balance of inclusive and b-dijets

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

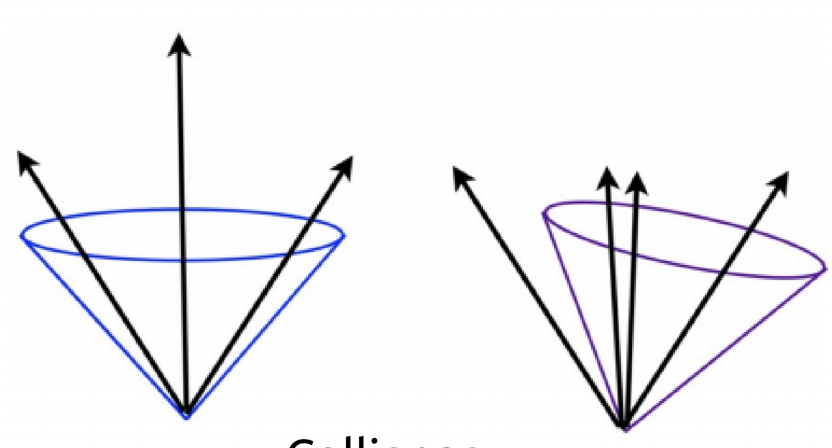
Lifetime methods: exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays

Soft-lepton tagging: μ or e inside the jet

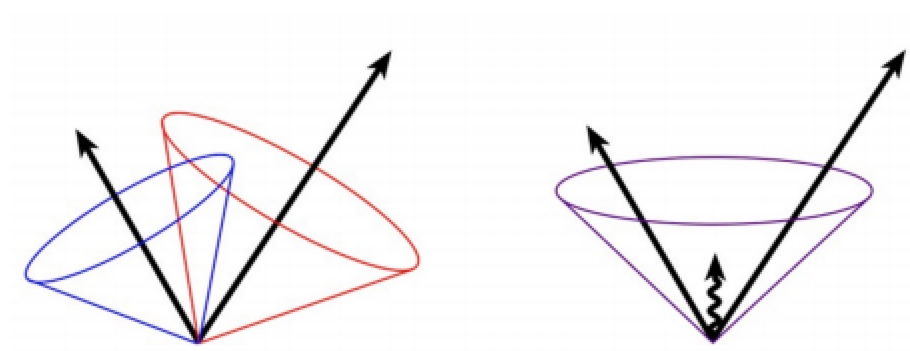
Jet clustering algorithms : requirements

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

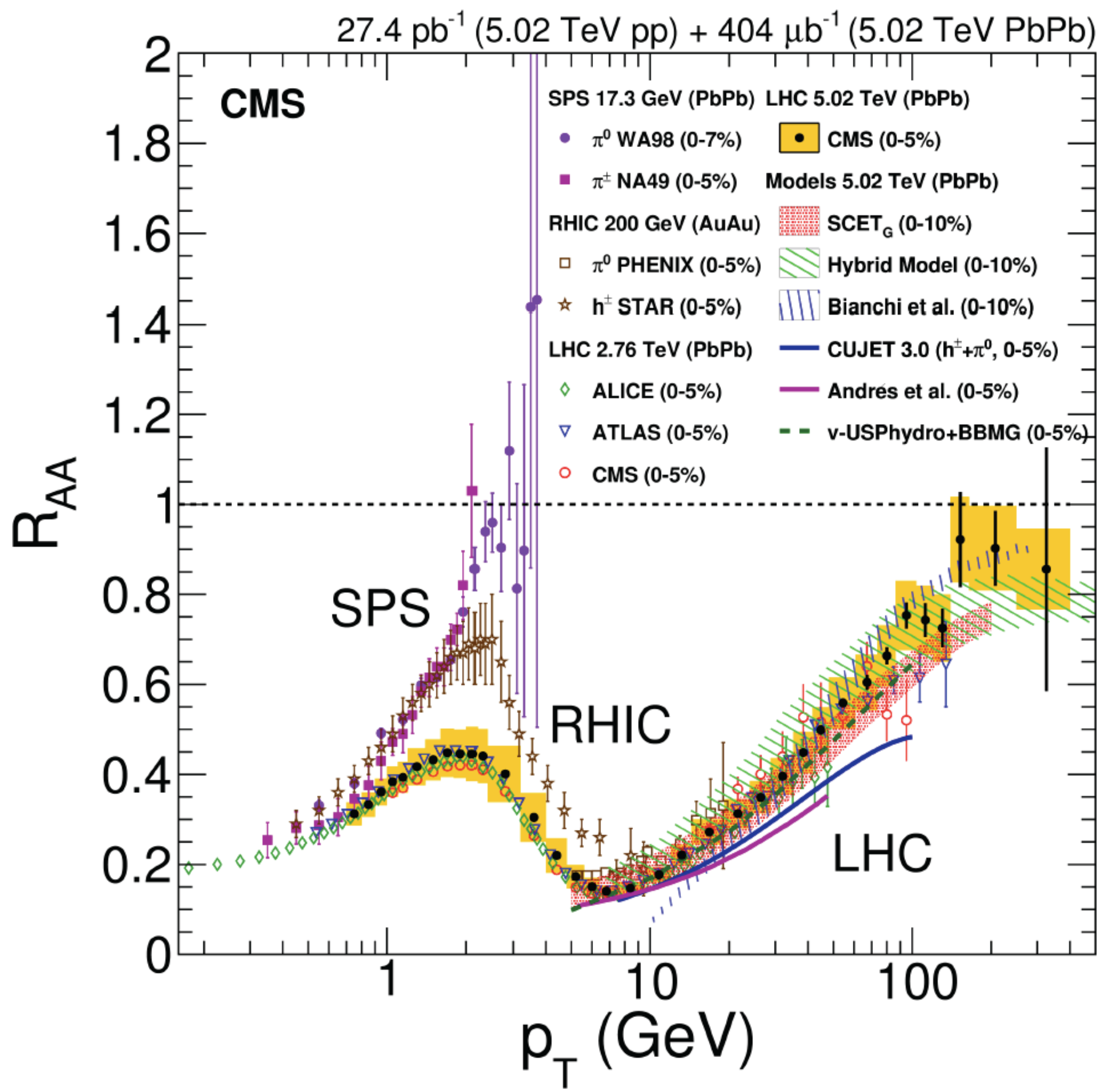
CMS, JHEP 04 (2017) 039

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

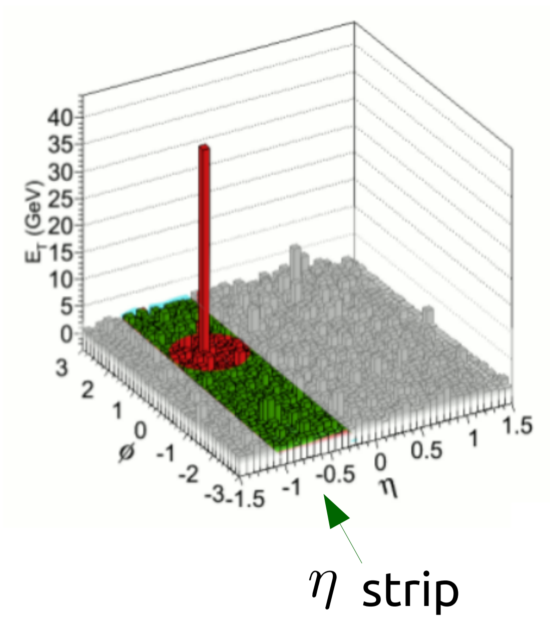
Higher pT : slow increase of RAA → small suppression ~100 GeV

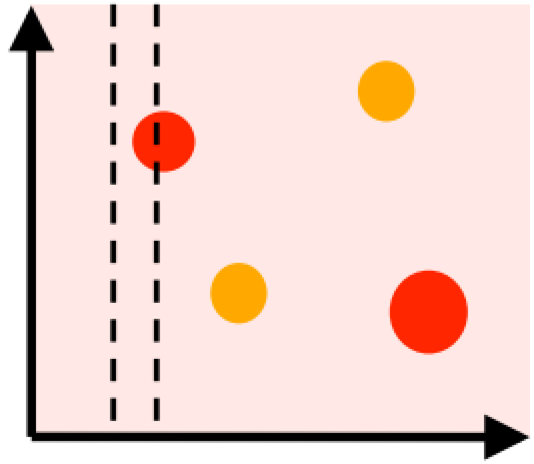
How to reconcile charged hadron and jet suppression?
→ dependence of quenching on fragmentation pattern of jet

UE subtraction in CMS : iterative pedestal

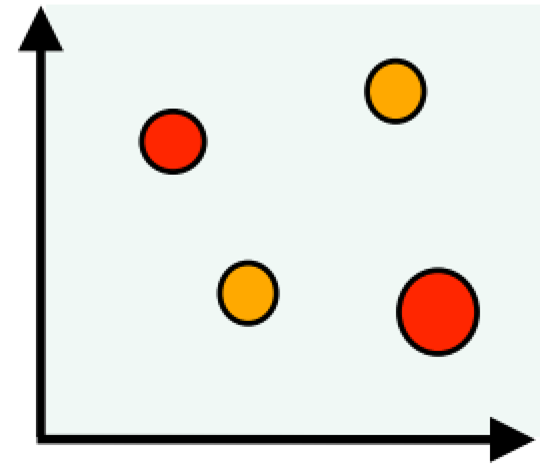
What amount to subtract? How?

CMS, EPJC 50 (2007) 117

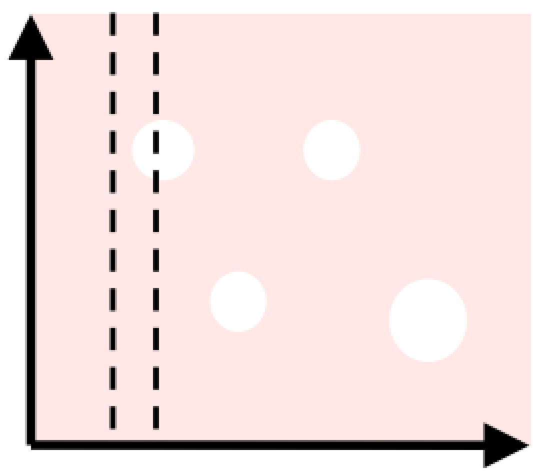




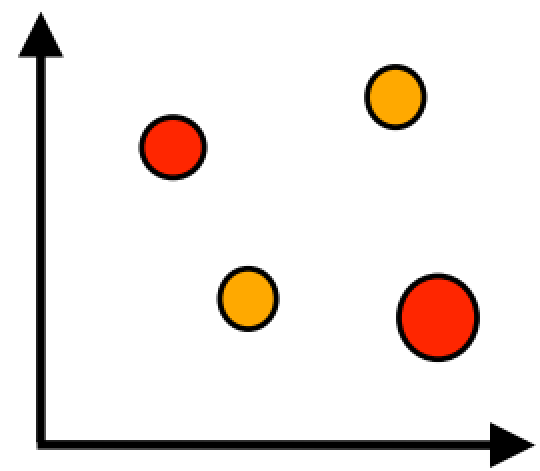
1. $\langle E_T \rangle$ calculated in strips of η.
Subtract $\langle E_T \rangle + \sigma$



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



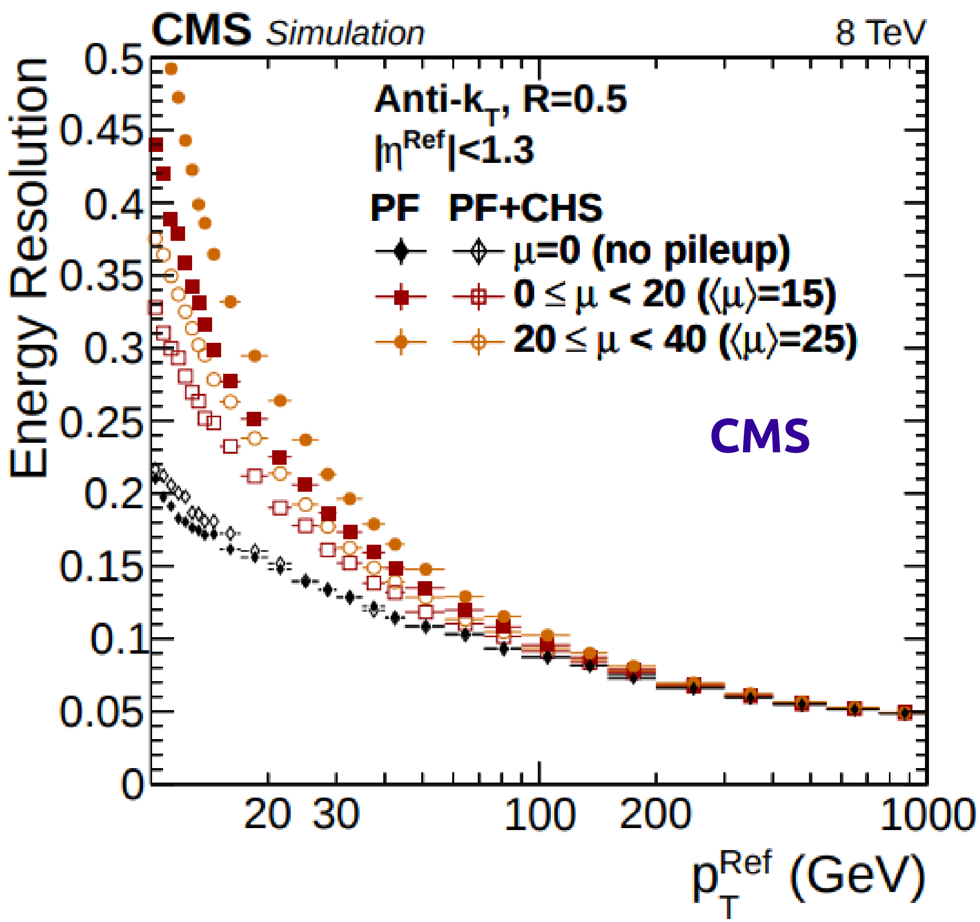
3. Exclude reconstructed jets
and re-estimate background



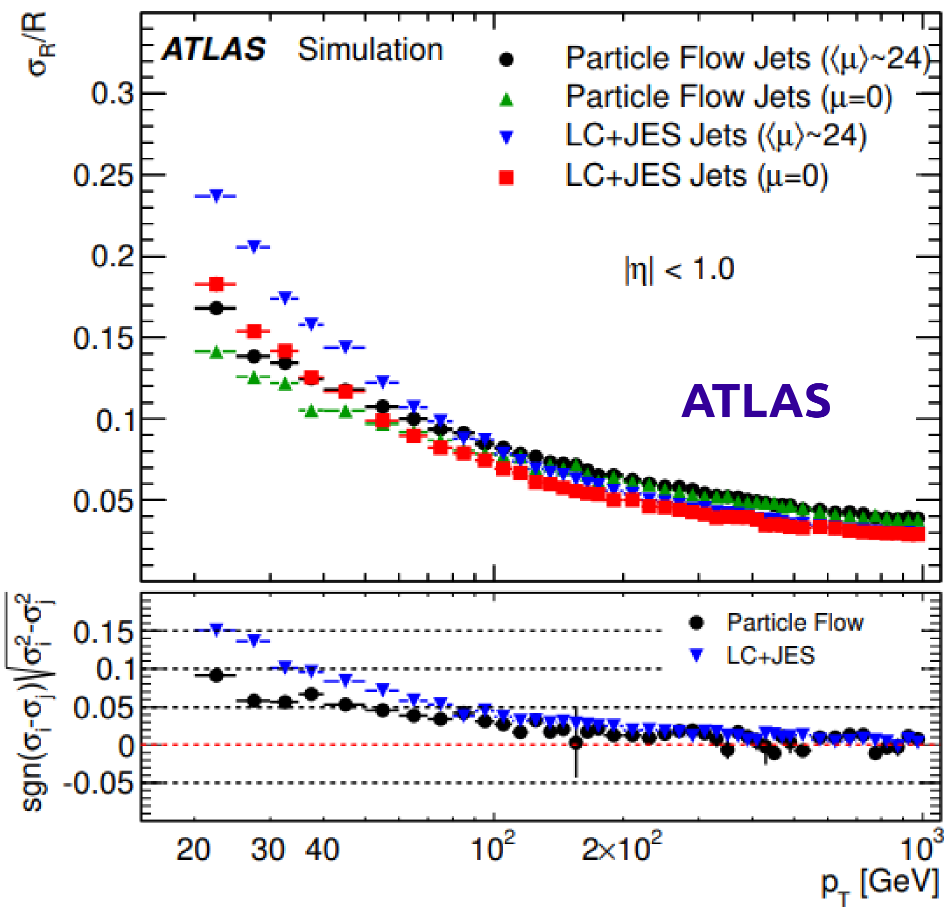
4. Re-run anti-k_T algorithm
to get final jets

Jet performance in pp collisions

JINST 12 (2017) P10003



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

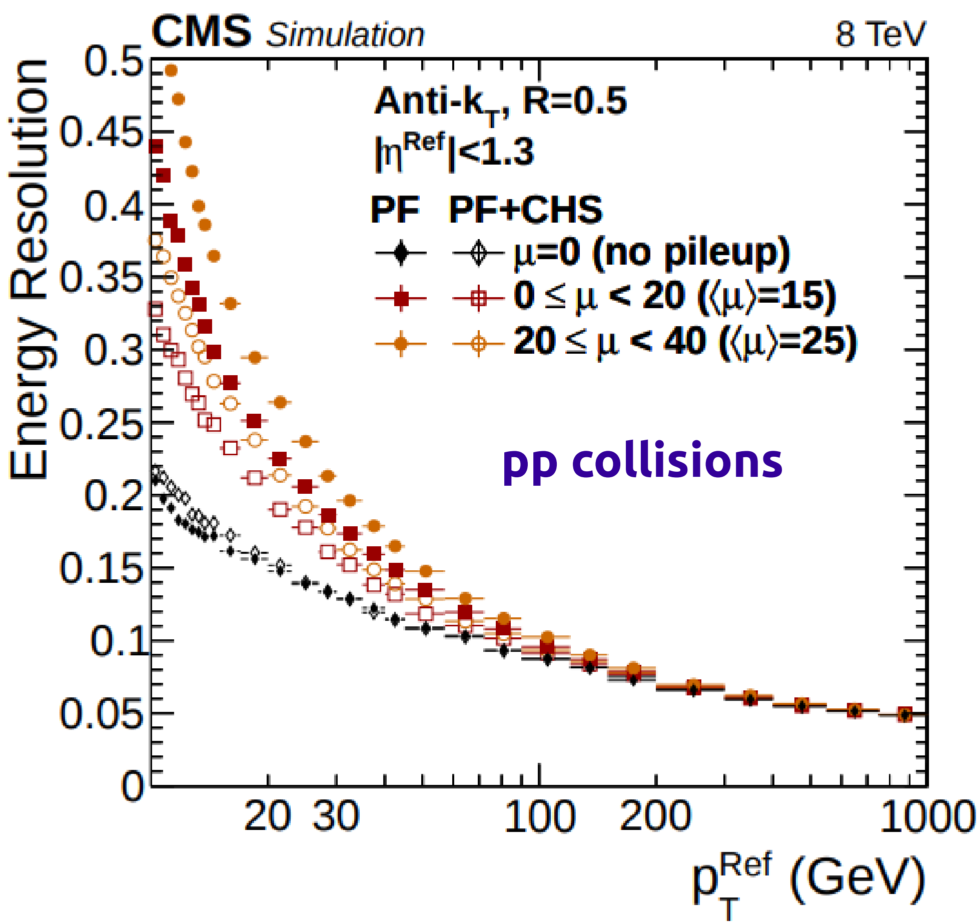


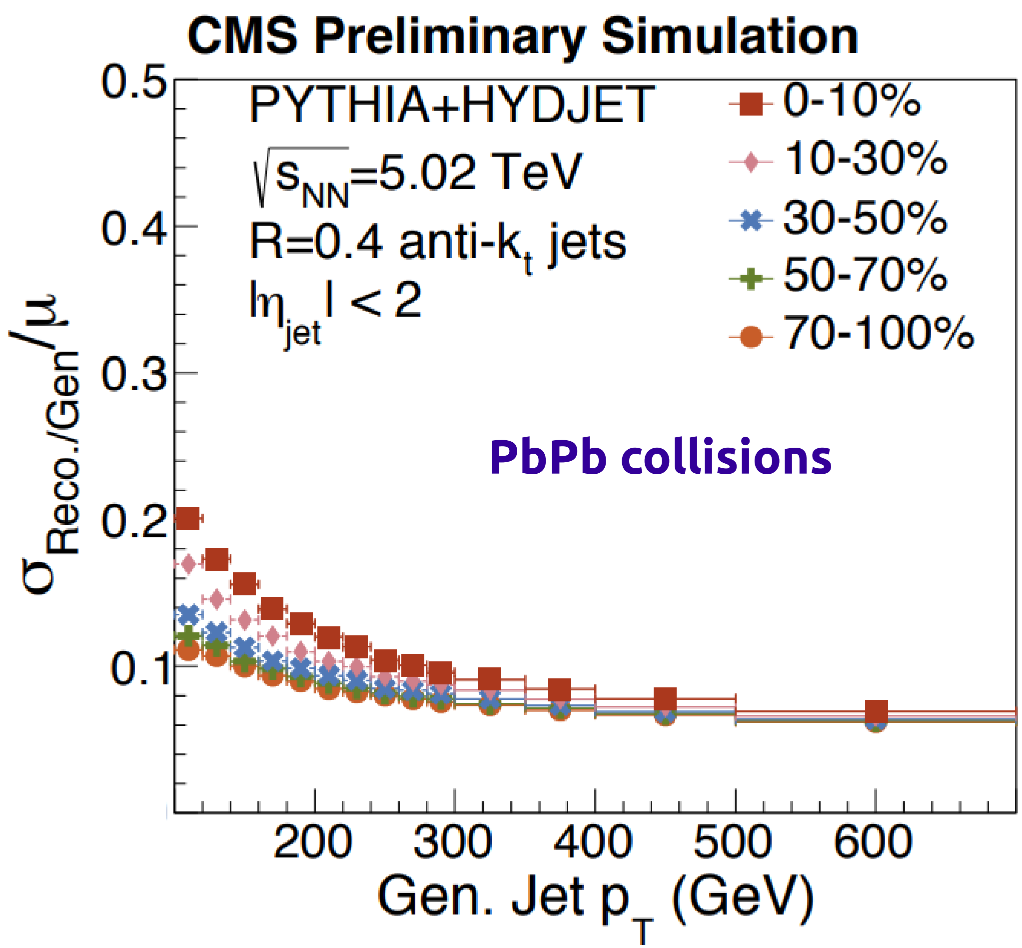
Very good resolution in ATLAS and CMS in pp collisions

Jet performance in PbPb collisions

JINST 12 (2017) P10003

CMS-DP-2018-024





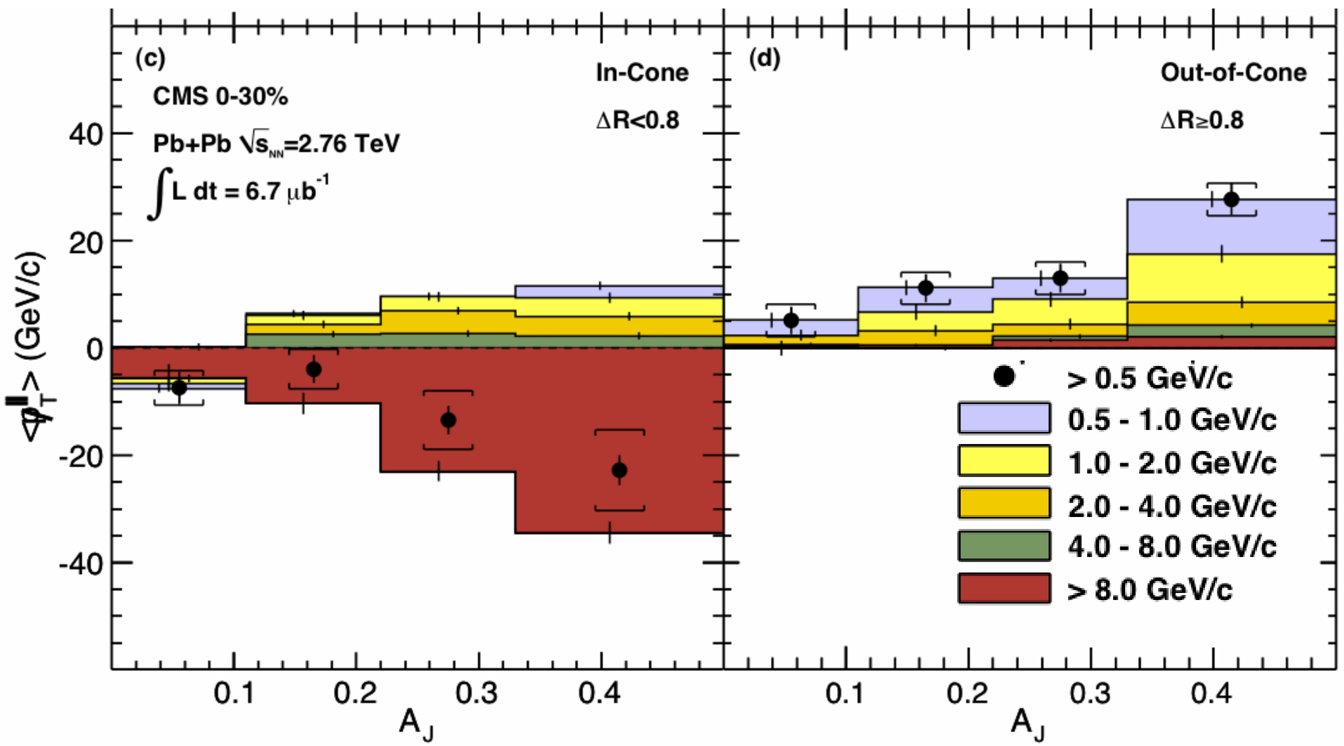
Very good resolution in PbPb collisions for jets with R = 0.4

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

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

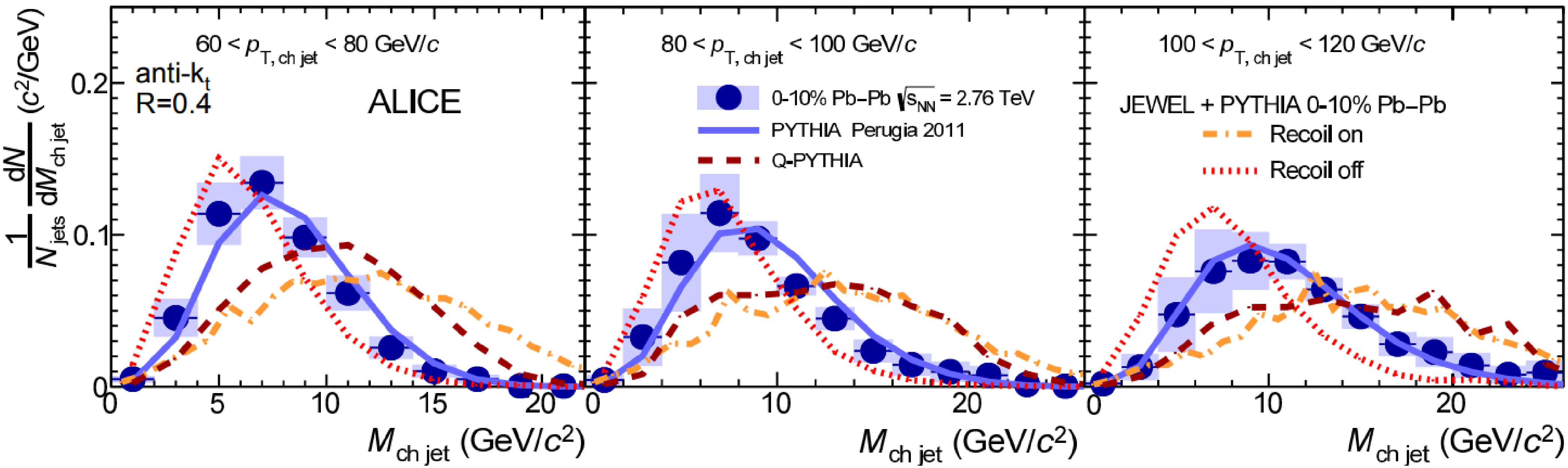
CMS, PRC84 (2011) 024906



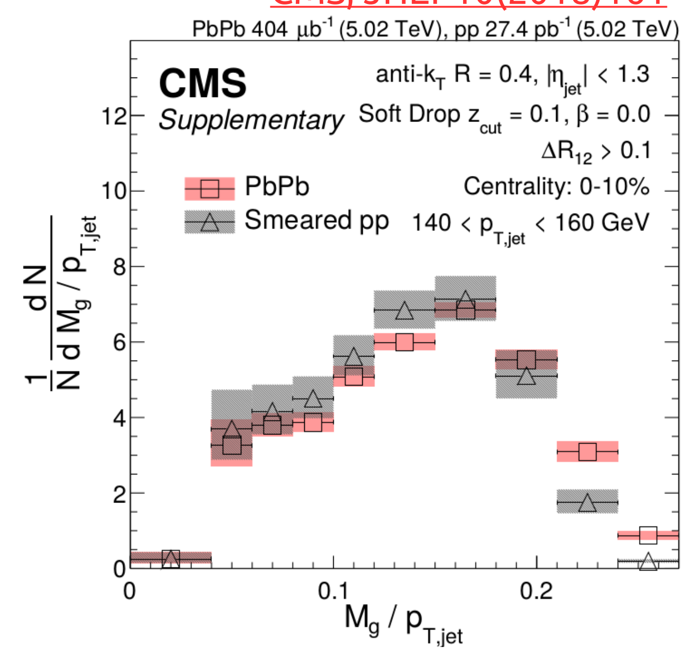
Subleading jet energy is moved from high pT to lower pT and from small to large angles

Jet mass

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



CMS, JHEP10(2018)161



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

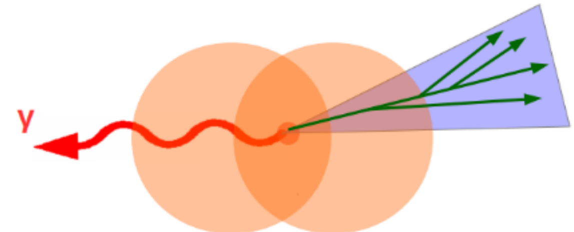
Relative mass : M/p_T^{jet} (mass scales with jet pT in vacuum)

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

Photon+jets in CMS

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

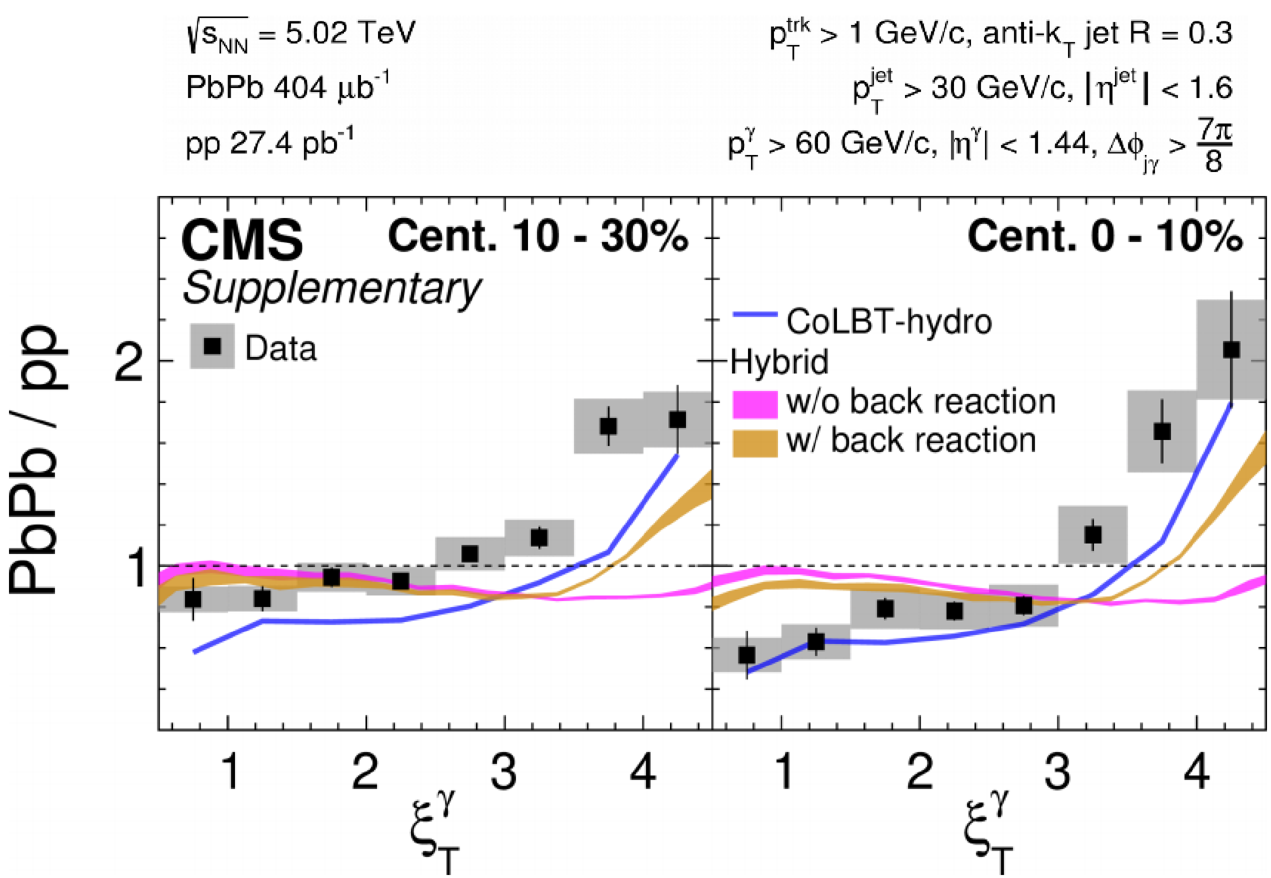
Fragmentation functions of jets associated with isolated photons :
initial parton energy constrained by photon pT



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