Parton interactions in medium
Experiment

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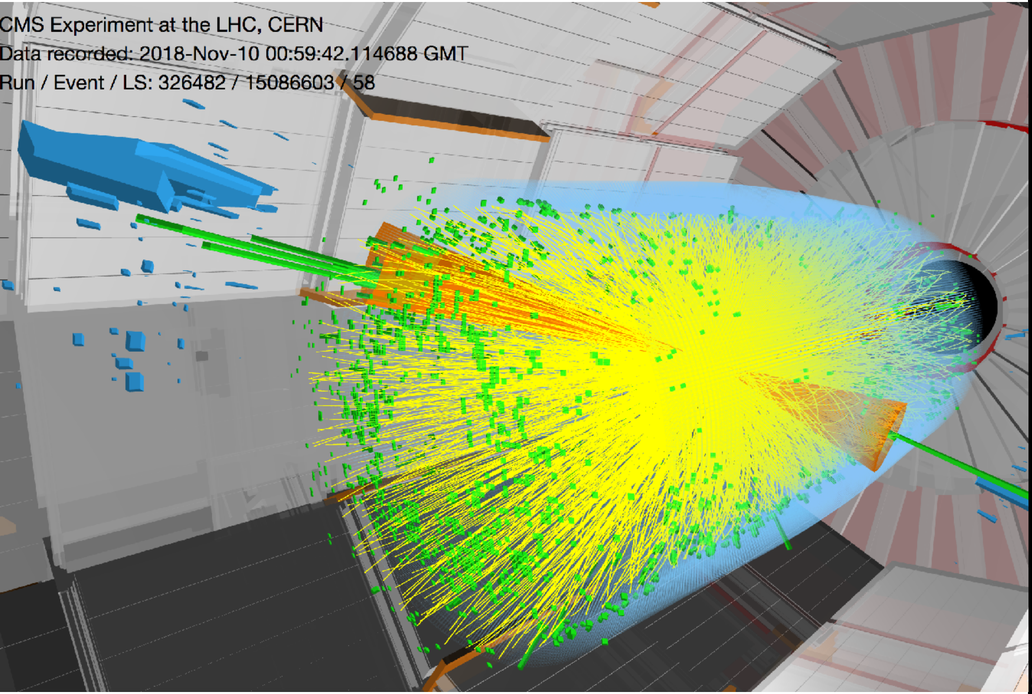
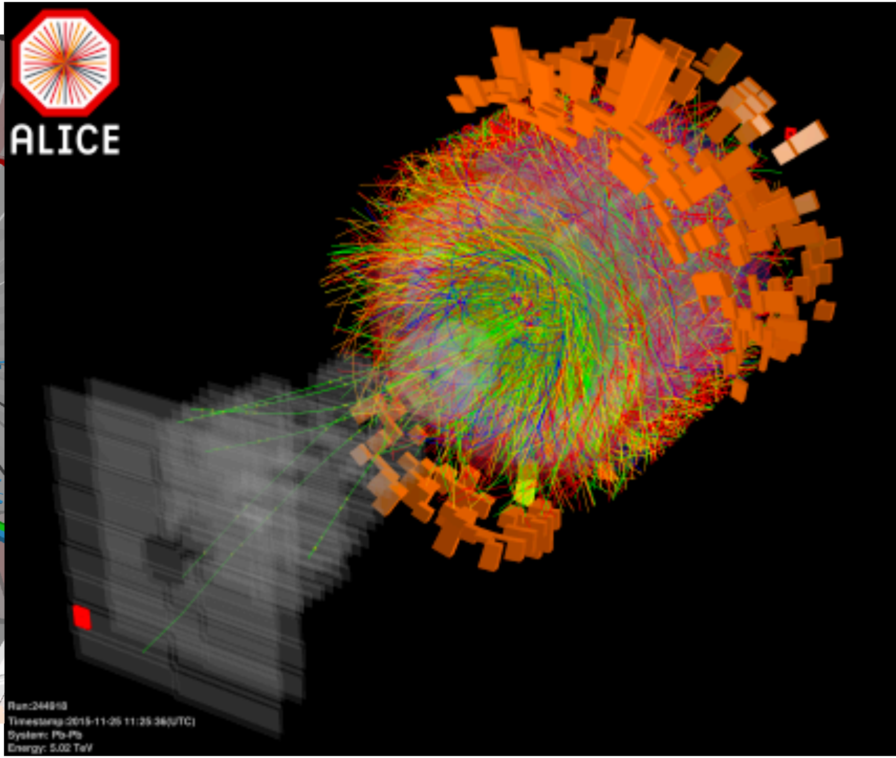
Utrecht University

GDR QCD School
June 12, 2024

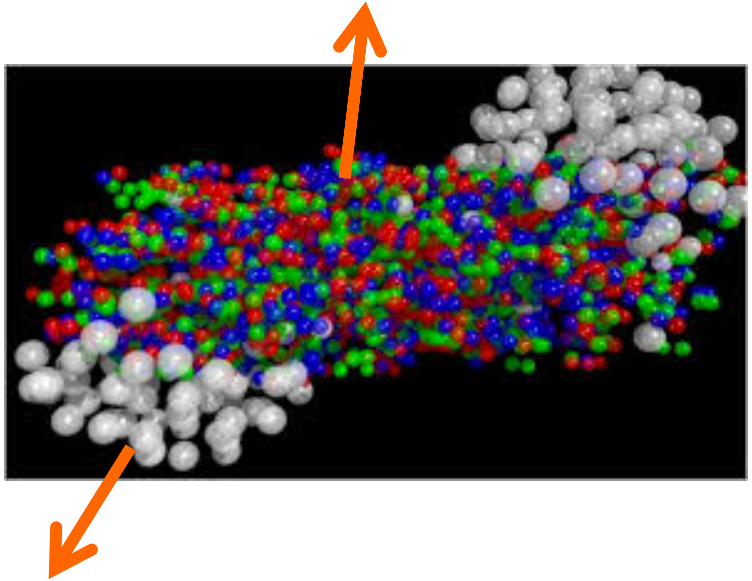




Thousands of particles are produced in one heavy ion collision

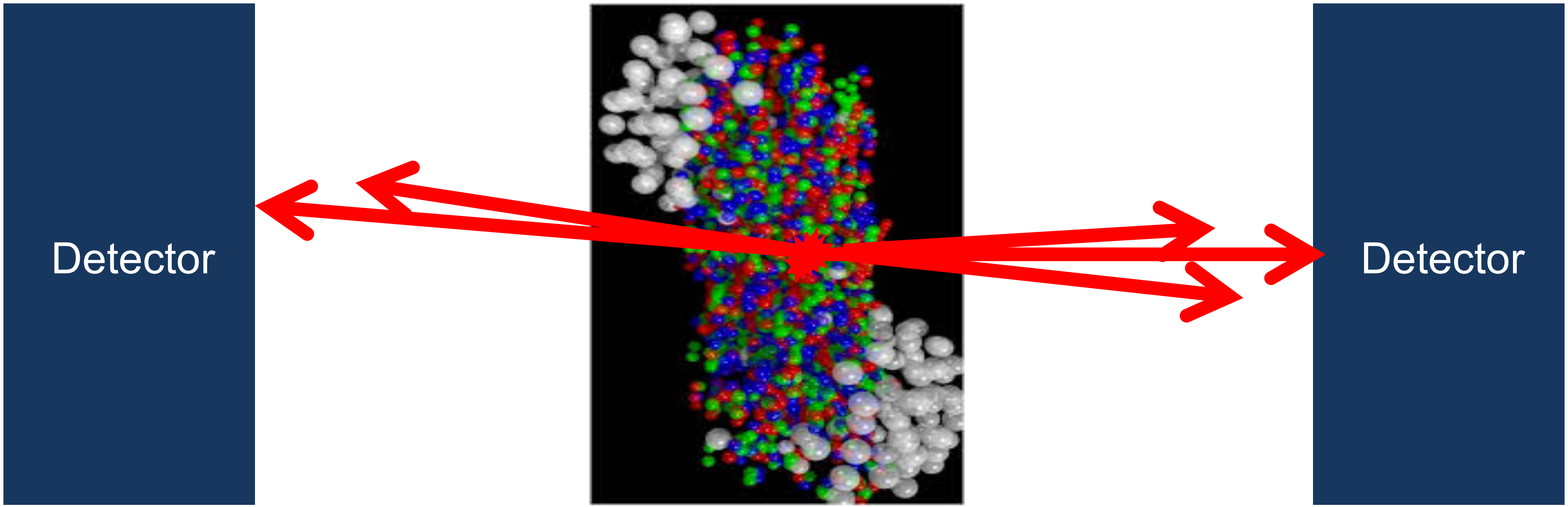
Probing the QGP

Participants forming hot matter: mixture of quarks and gluons (QGP)
Result of the part of the nuclei that do collide



Spectators
Part of the nuclei that do not collide

Probing the Quark Gluon Plasma



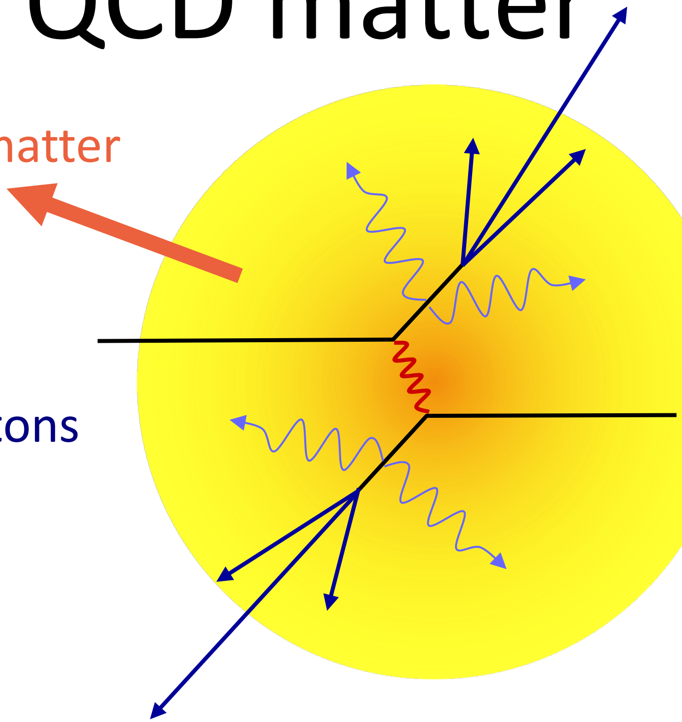
Lifetime of QGP too short (~10^{-23} sec.) to probe it with an external beam

Instead: use self-generated probes

→ Quarks and gluons created in a hard scattering

Hard Probes in QCD matter

Heavy-ion collisions produce dense QCD matter
→ dominated by soft partons
p_T~100-300 MeV



Hard scatterings produce high energy partons

- Initial state production known from pQCD
- Parton loses energy due to interaction with medium
  → **medium-induced gluon radiation**

Use hard partons to explore QCD matter

Hard Probes in QCD matter

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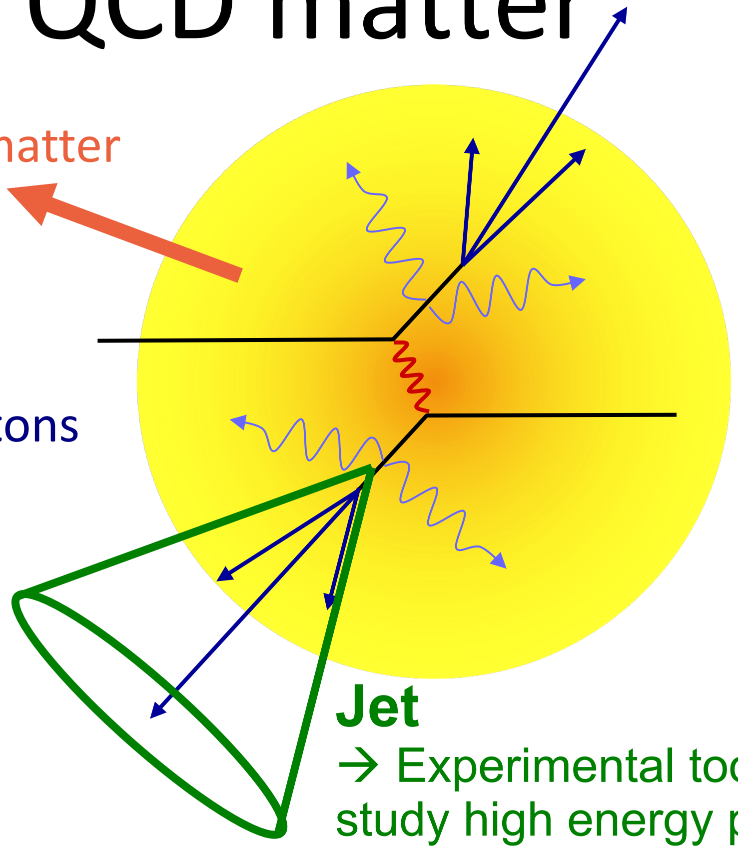
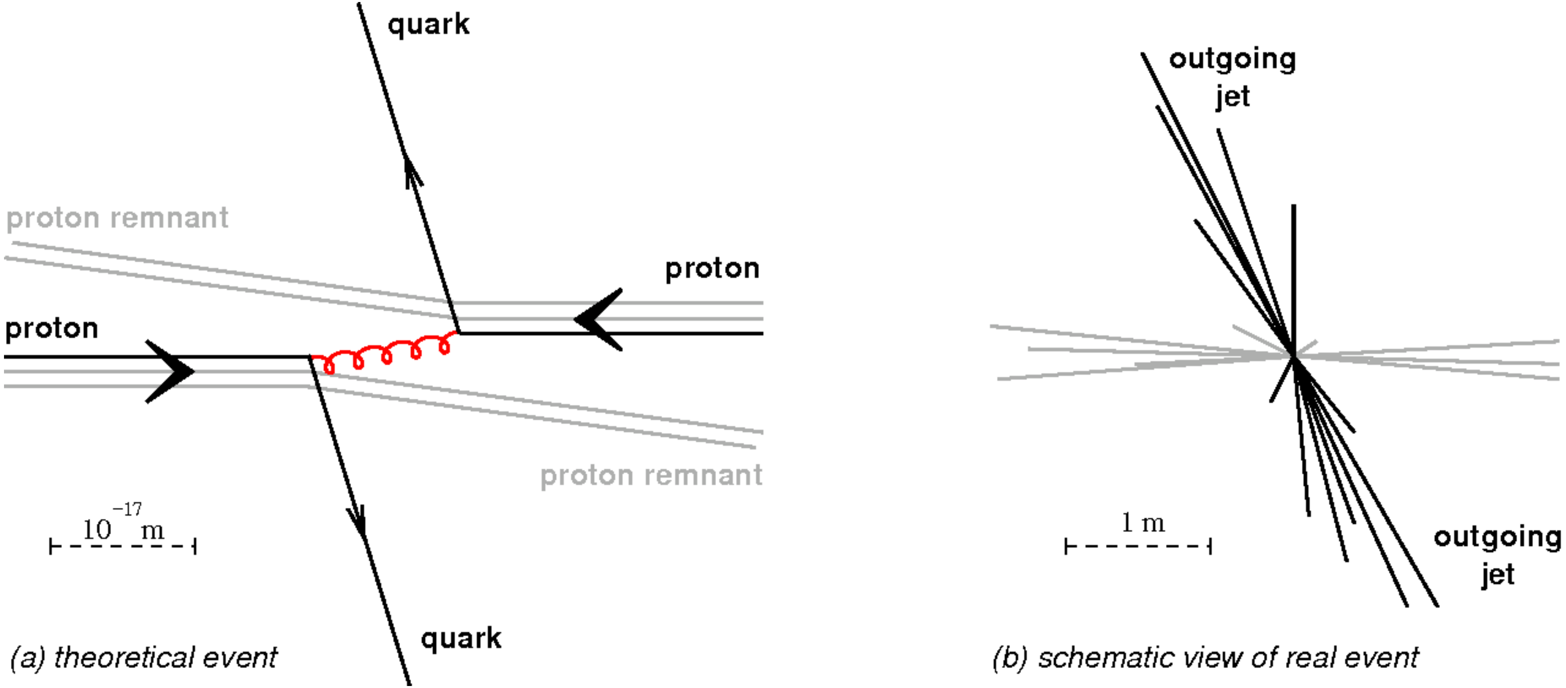


Use hard partons to explore QCD matter



(a) theoretical event
(b) schematic view of real event

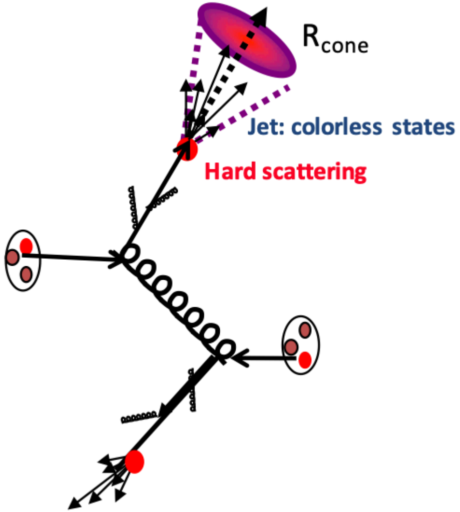
Highly energetic quarks and gluons are not stable
We see them as a spray of particles in the detector

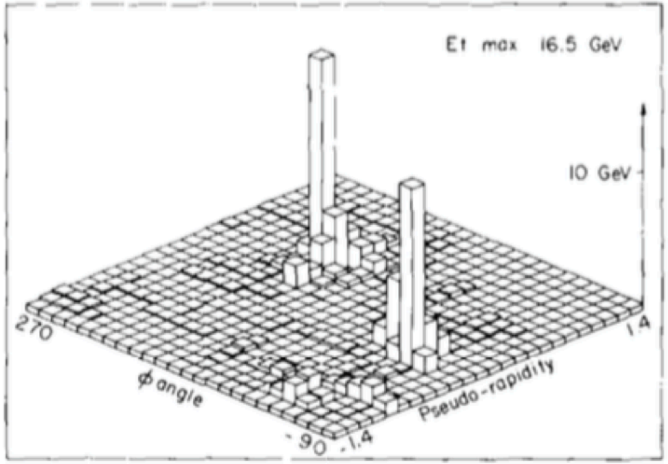
Volume 123B, number 1,2 PHYSICS LETTERS 24 March 1983

Jets in the vacuum:

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTIPROTON COLLIDER

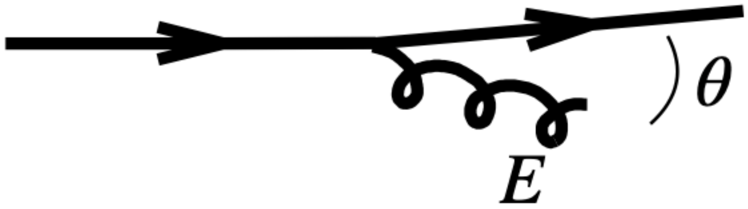
UA1 Collaboration, CERN, Geneva, Switzerland





Jets are the experimental signatures of quarks and gluons.
They are expected to reflect kinematics and topology of partons.

Parton splittings; why?



Gluon emission probability:

$$\frac{2C_F\alpha_s}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$

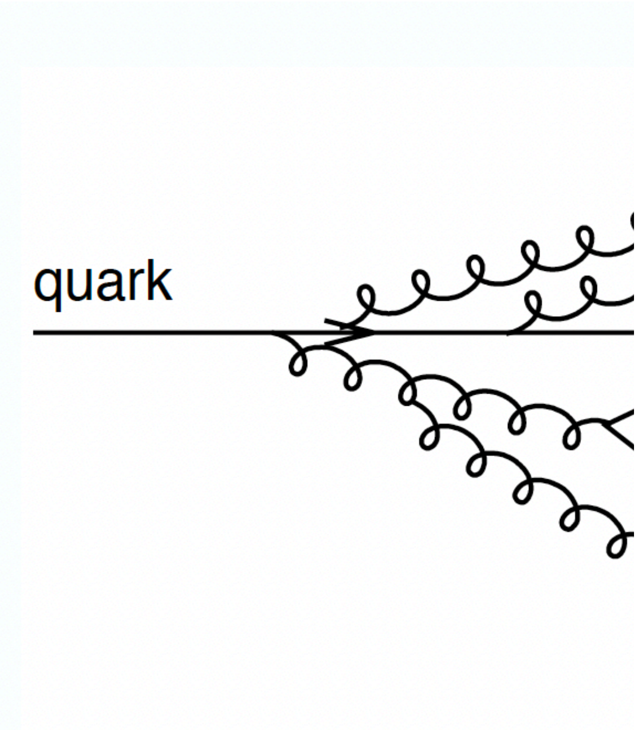
Total average number of emitted gluons:

$$\langle N_{gluon}\rangle \simeq P_{gluon-emission} = \int dP = \frac{2\alpha_s C_F}{\pi}\int_{\Lambda_{QCD}/E_p}^{1}\frac{d\theta}{\theta}\int_{\Lambda_{QCD}/\theta}^{E_p}\frac{dE_k}{E_k} = \frac{\alpha_s C_F}{\pi}\ln^2\frac{E_p}{\Lambda_{QCD}}$$

Assuming emitted gluons are soft:

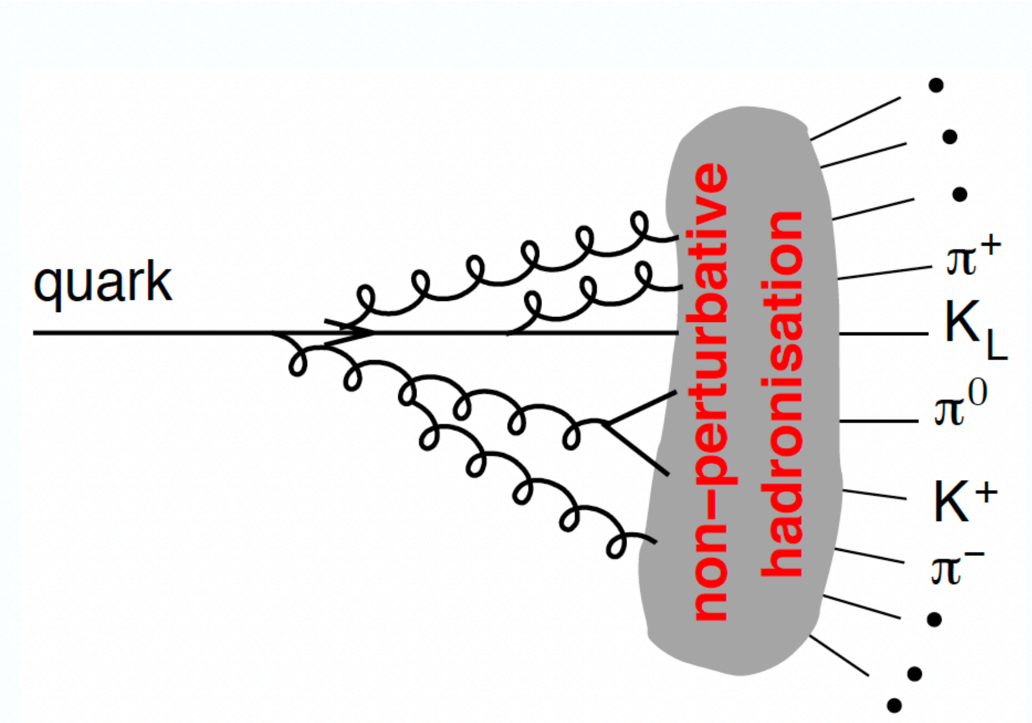
$$\langle N_{gluon}\rangle \simeq P_{gluon-emission} \simeq \frac{C_F}{\pi b_0}\ln\frac{E_p}{\Lambda_{QCD}} \sim \frac{1}{\alpha_s} \gg 1 \longrightarrow$$

Gluon emissions will happen and the average number is large



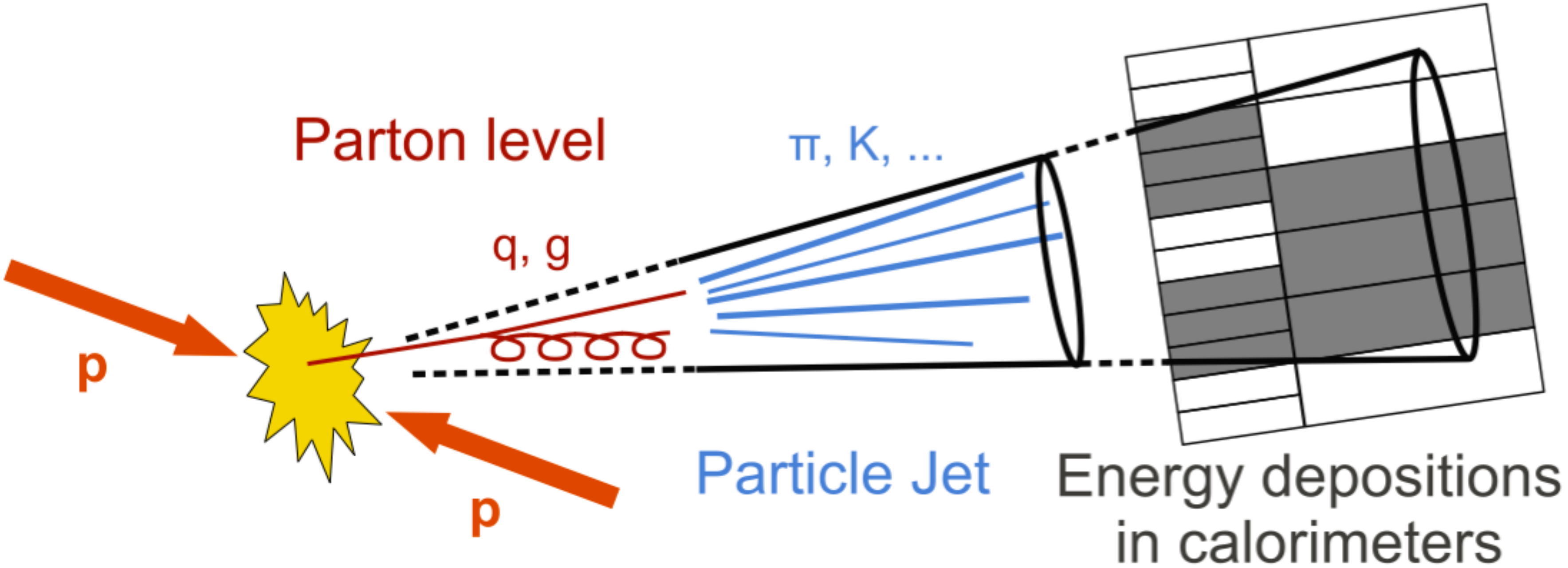
Perturbative parton shower

$\alpha_s < 1$



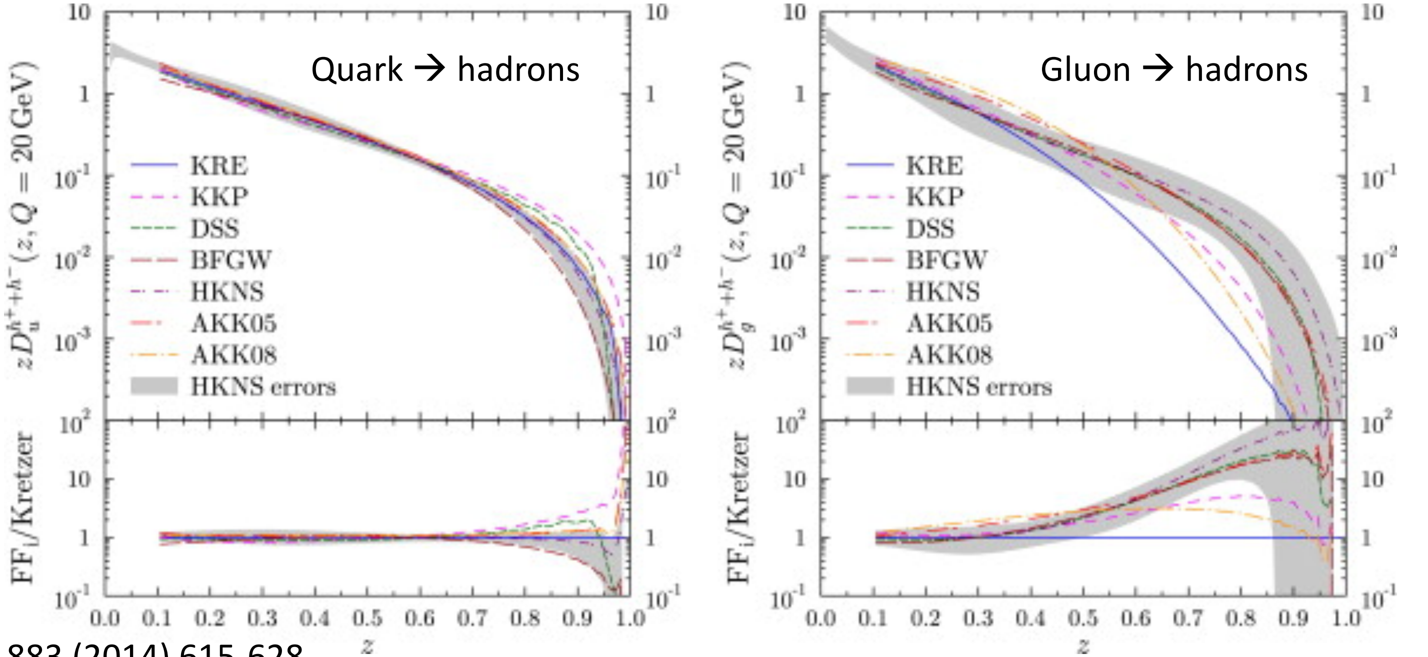
Perturbative parton shower
$\alpha_s < 1$

Non-perturbative hadronization
$\alpha_s \sim 1$


Parton level
π, K, ...
q, g
p
p
Particle Jet
Energy depositions
in calorimeters

Single particle

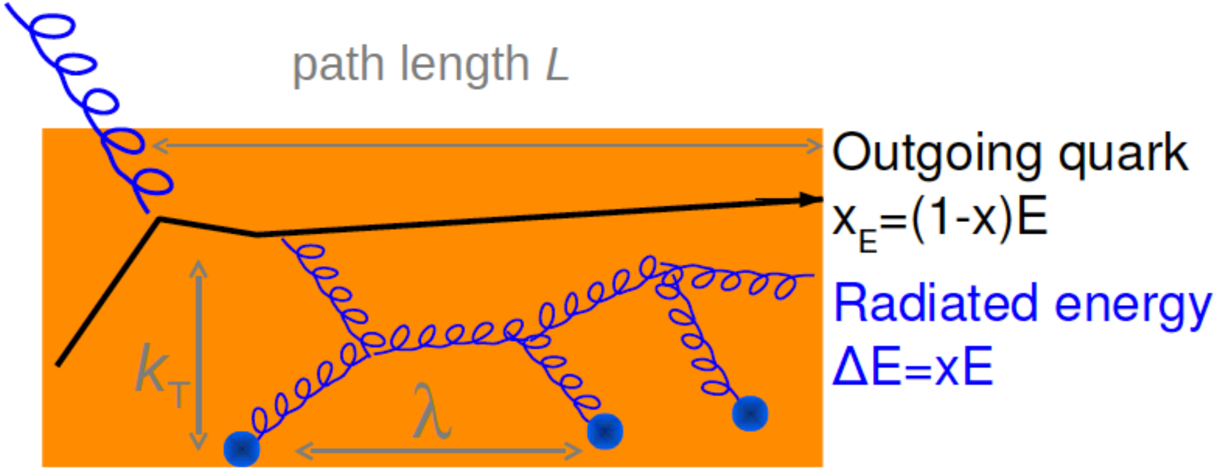
Simplest measurement of hard scattering products: high energy particles



Nucl.Phys.B 883 (2014) 615-628

Schematic picture of energy loss mechanism

in hot dense matter



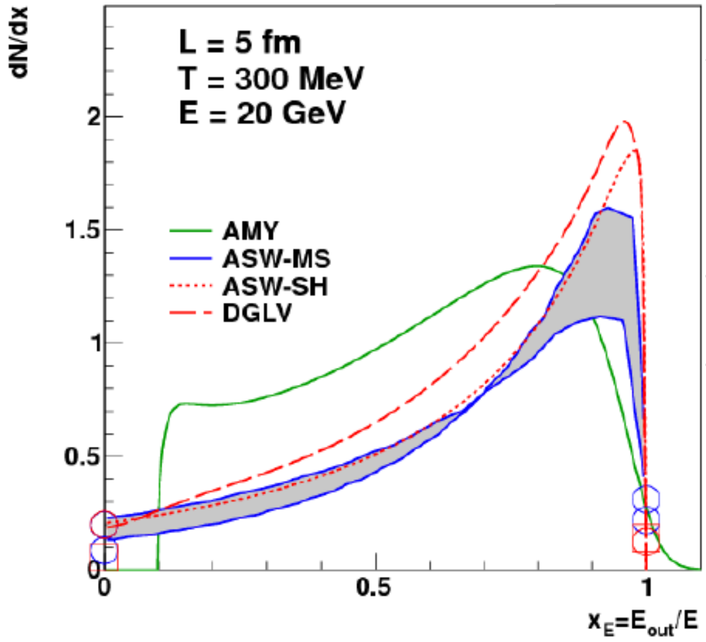
- Energy loss due to gluon bremsstrahlung in a hot dense medium

Outgoing quark spectrum

Jet quenching model calculations

Energy fraction of quark after leaving the medium. Fixed length, fixed temperature for all models

- $x_E = 1 - \Delta E/E$
- $x_E = 0$: Absorbed quarks
- $x_E = 1$: No energy loss



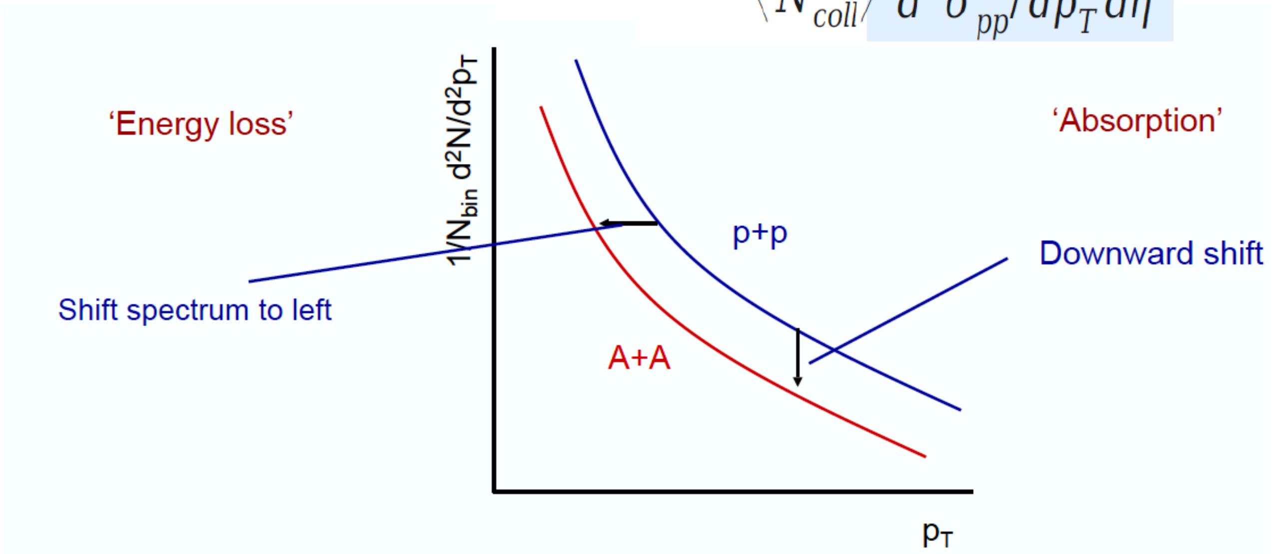
Phys.Rev. C86 (2012) 064904

Precise measurements of absolute energy loss should be able to differentiate between these models

Nuclear modification factor R_{AA}

Nuclear modification is measured by taking ratio between measured yield PbPb and pp collisions

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



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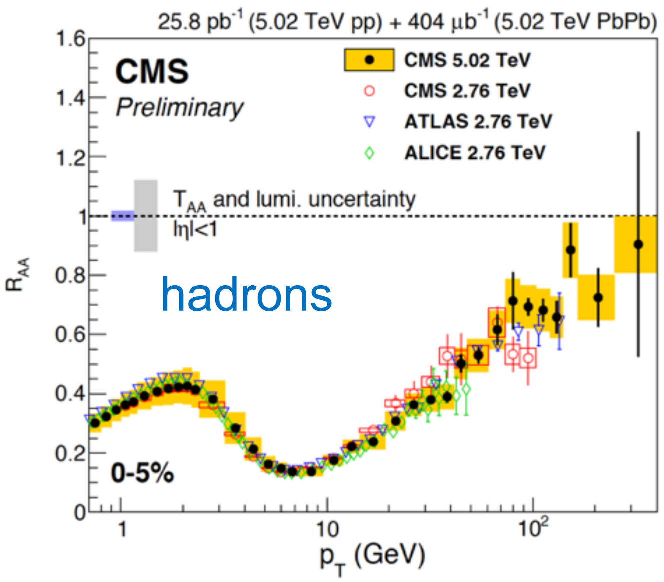

High p_T hadron production is suppressed by a factor 2-6

The shape of the distribution is very different from pp

→Low p_T: Radial flow

→High p_T: Jet quenching

Nuclear modification factor R_{AA}

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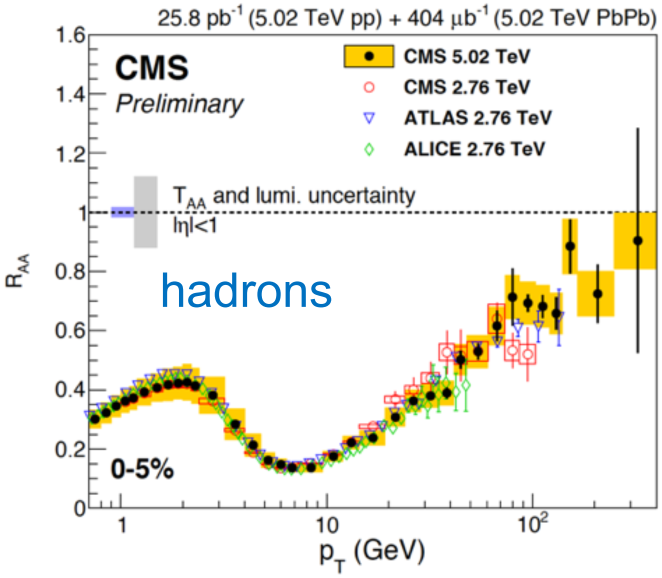

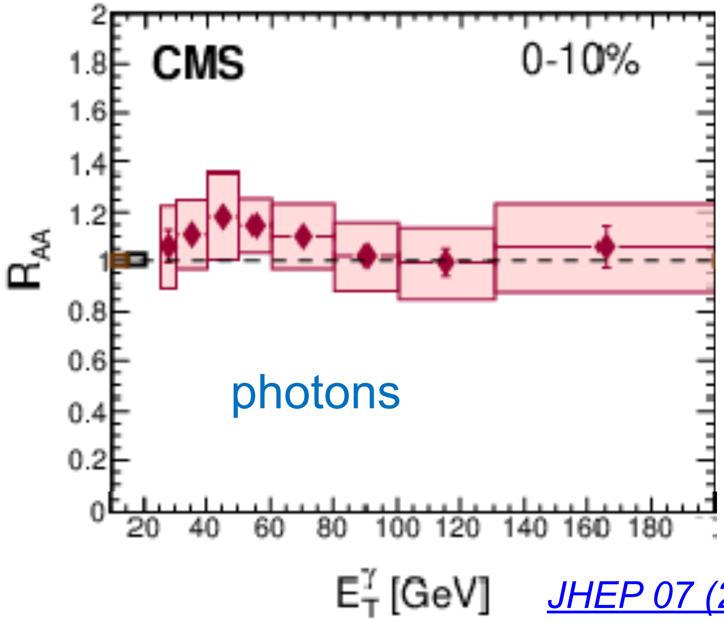

[JHEP 07 (2020) 116]

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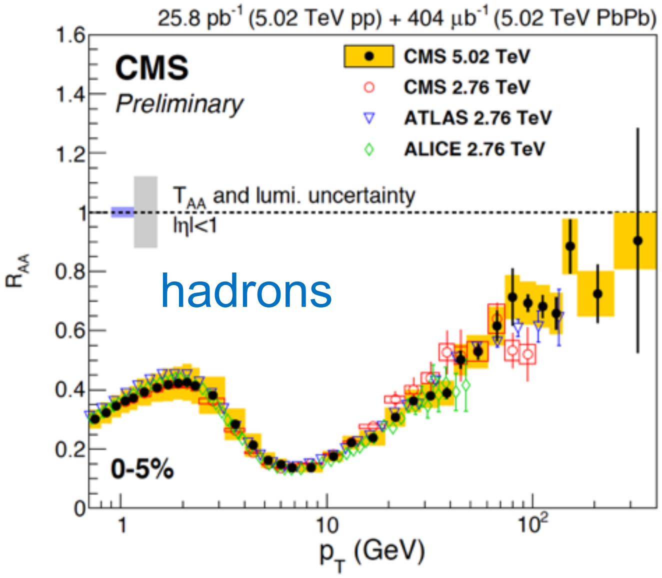
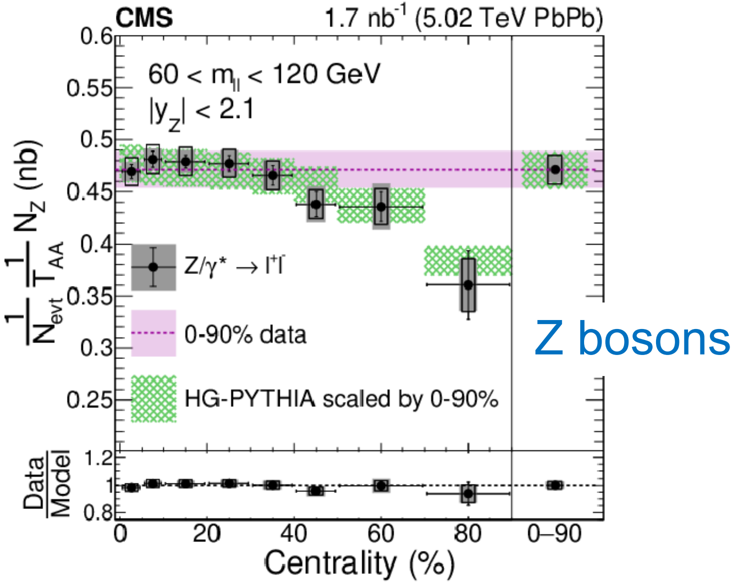
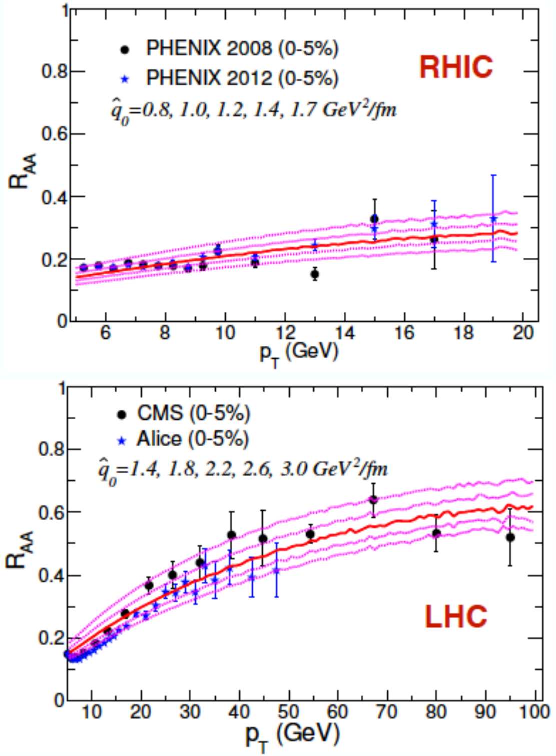




PRL 127 (2021) 102002

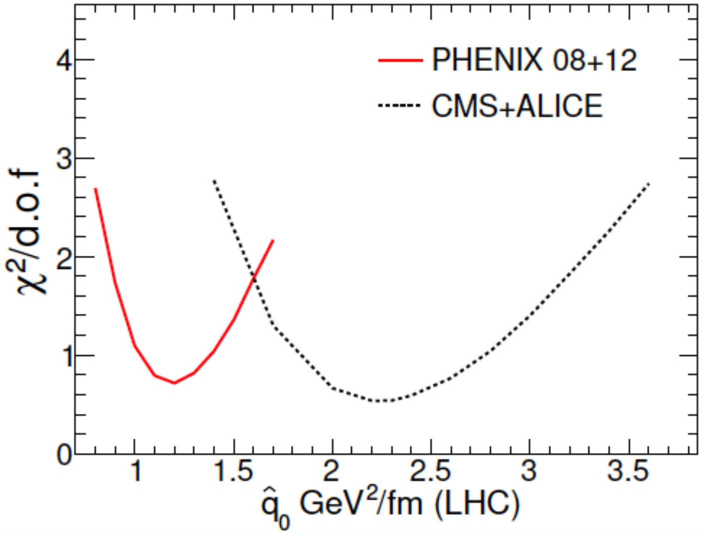
Data vs Theory



Burke et al, JET Collaboration, arXiv:1312.5003

Analytical models to describe charged hadron suppression

Determine which medium density fits the data best

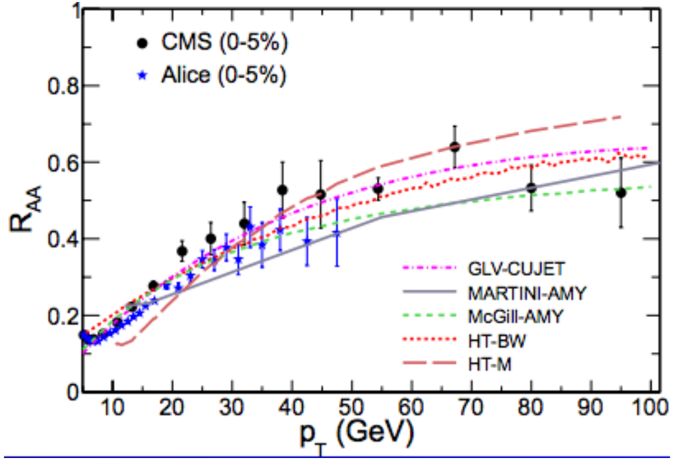


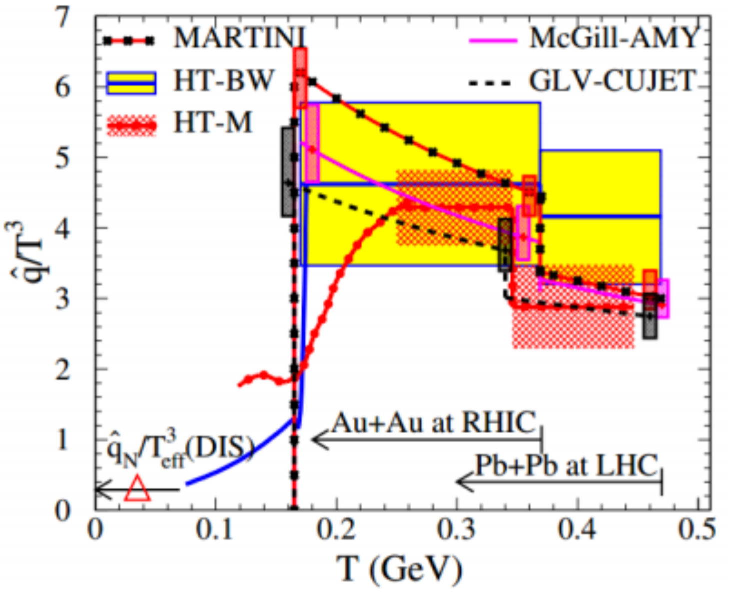
Medium density ~2x higher at LHC than RHIC

Data vs Theory

Multiple models describing the same physics

→ Suppression of charged hadrons





JET Collaboration, PRC 90, 014909 (2014)

Use best fits of all models to constrain phase space

Data vs Theory

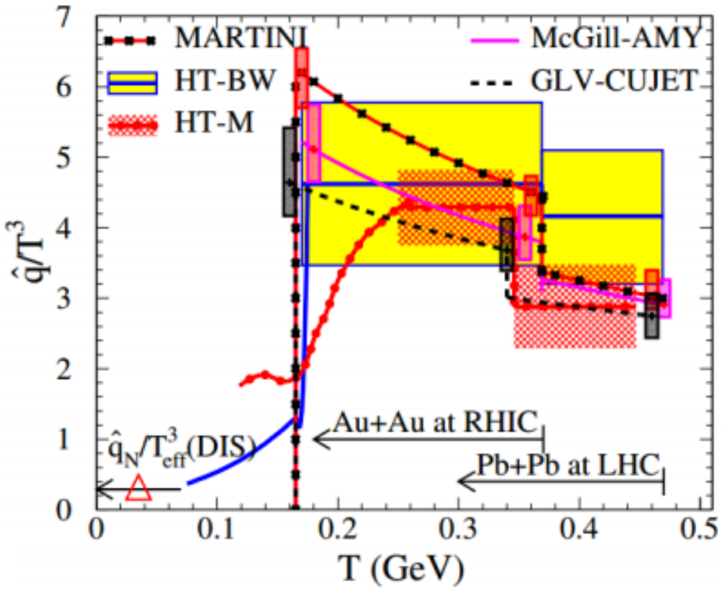
Extracting transport coefficient from data

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{at} \ \begin{matrix} T = 370\ \mathrm{MeV}, \\ T = 470\ \mathrm{MeV}, \end{matrix}$$

$$\frac{\hat{q}}{T^3} \propto \left(\frac{\eta}{s}\right)^{-1}$$

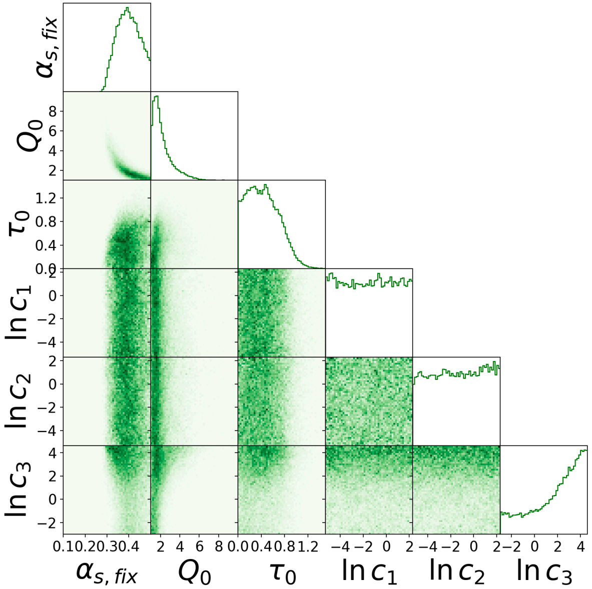
$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$ for a QCD medium



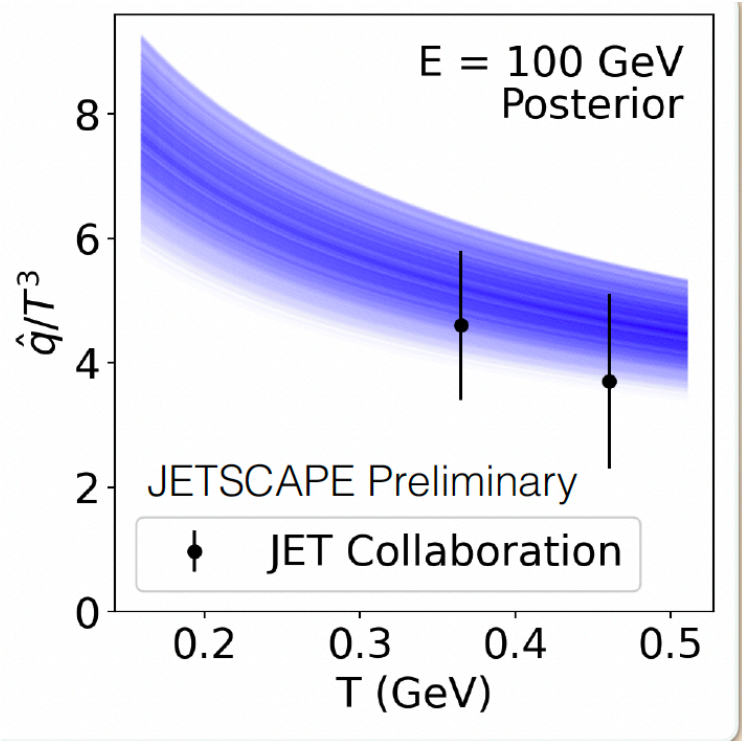
JET Collaboration, PRC 90, 014909 (2014)

Data vs Theory

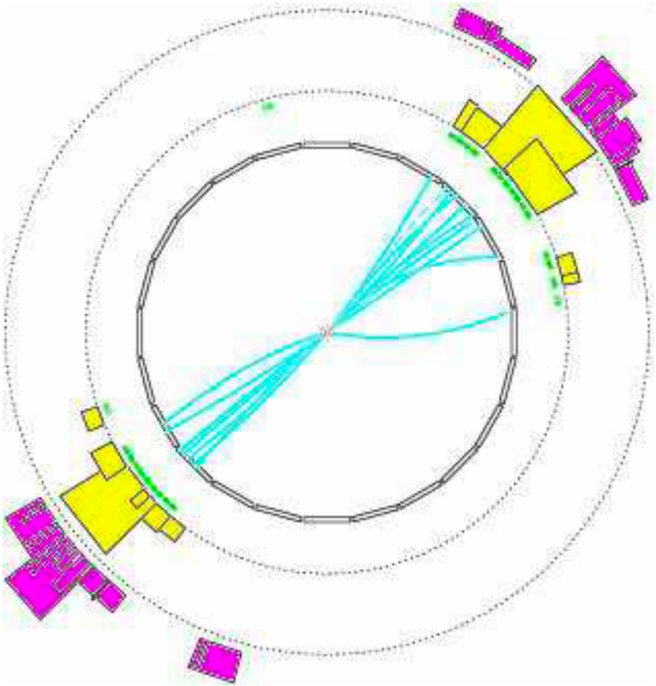
State-of-the-art: extraction of medium properties using Bayesian analysis



[JetScape]

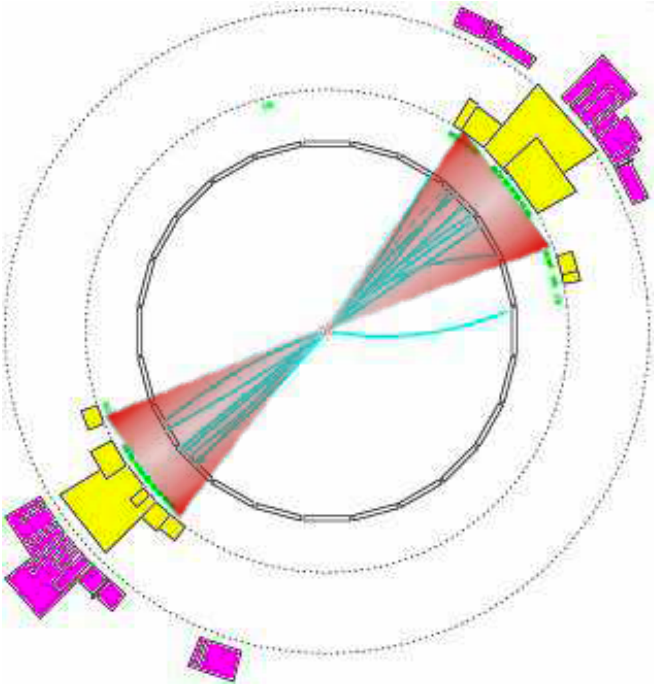


Jet Finding



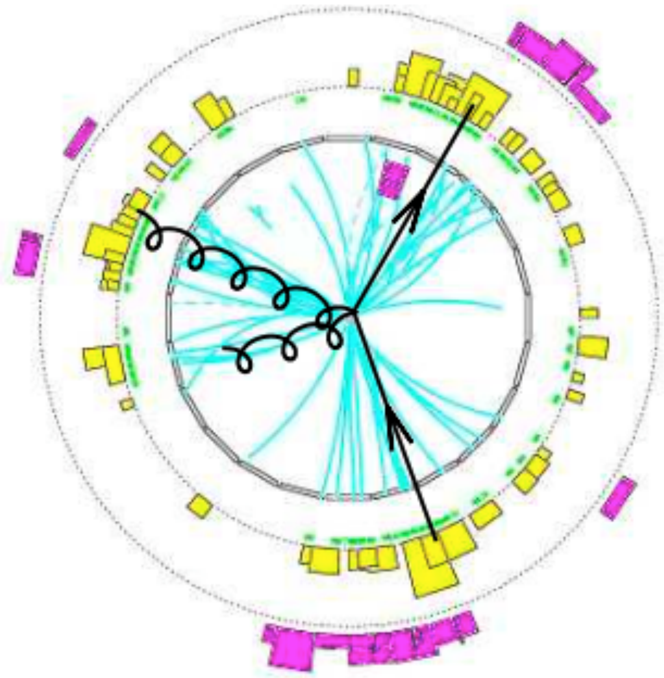
Where are the jets?

Jet Finding



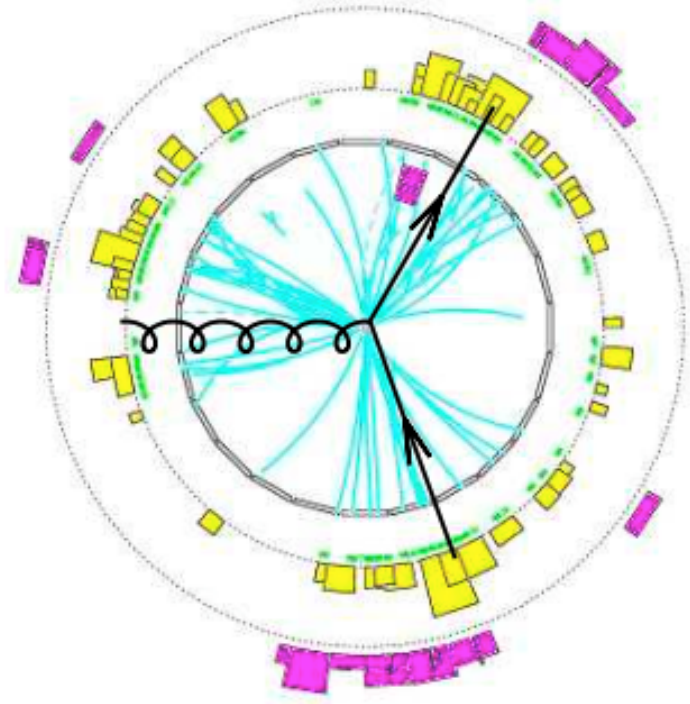
Easy enough

Jet Finding

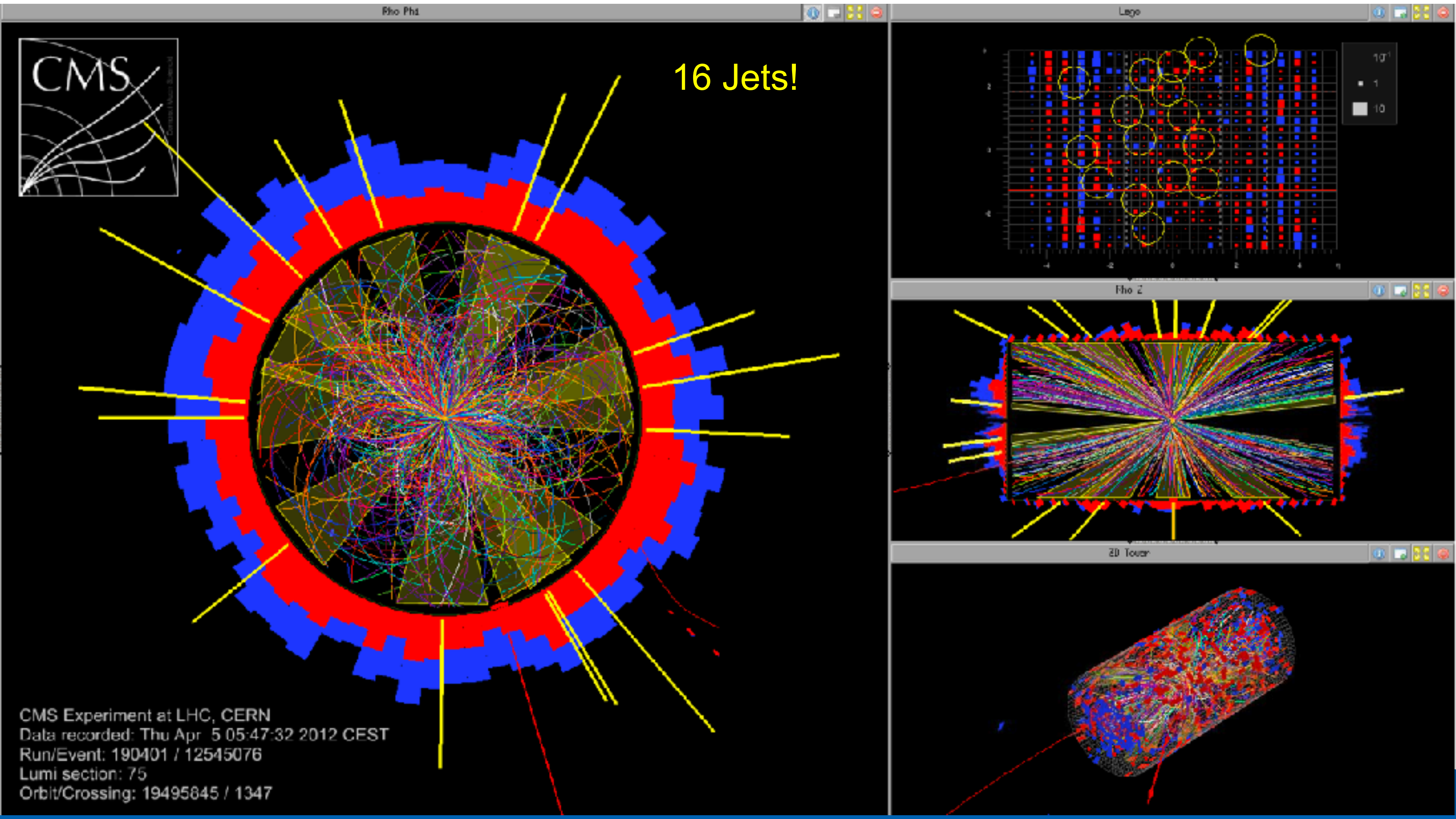


OR

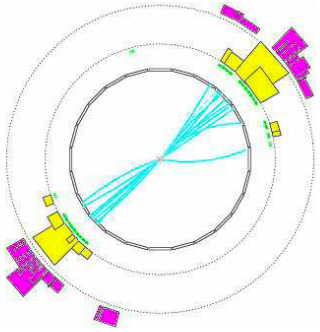
???



Need to define jet in experiment and theory


16 Jets!
CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 5 05:47:32 2012 CEST
Run/Event: 190401 / 12545076
Lumi section: 75
Orbit/Crossing: 19495845 / 1347

Jet Finding



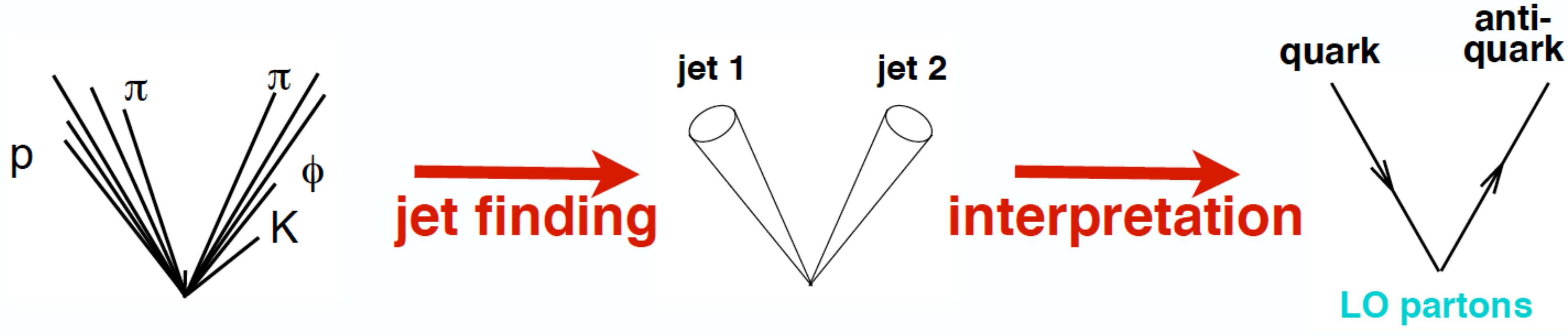
Jet definition

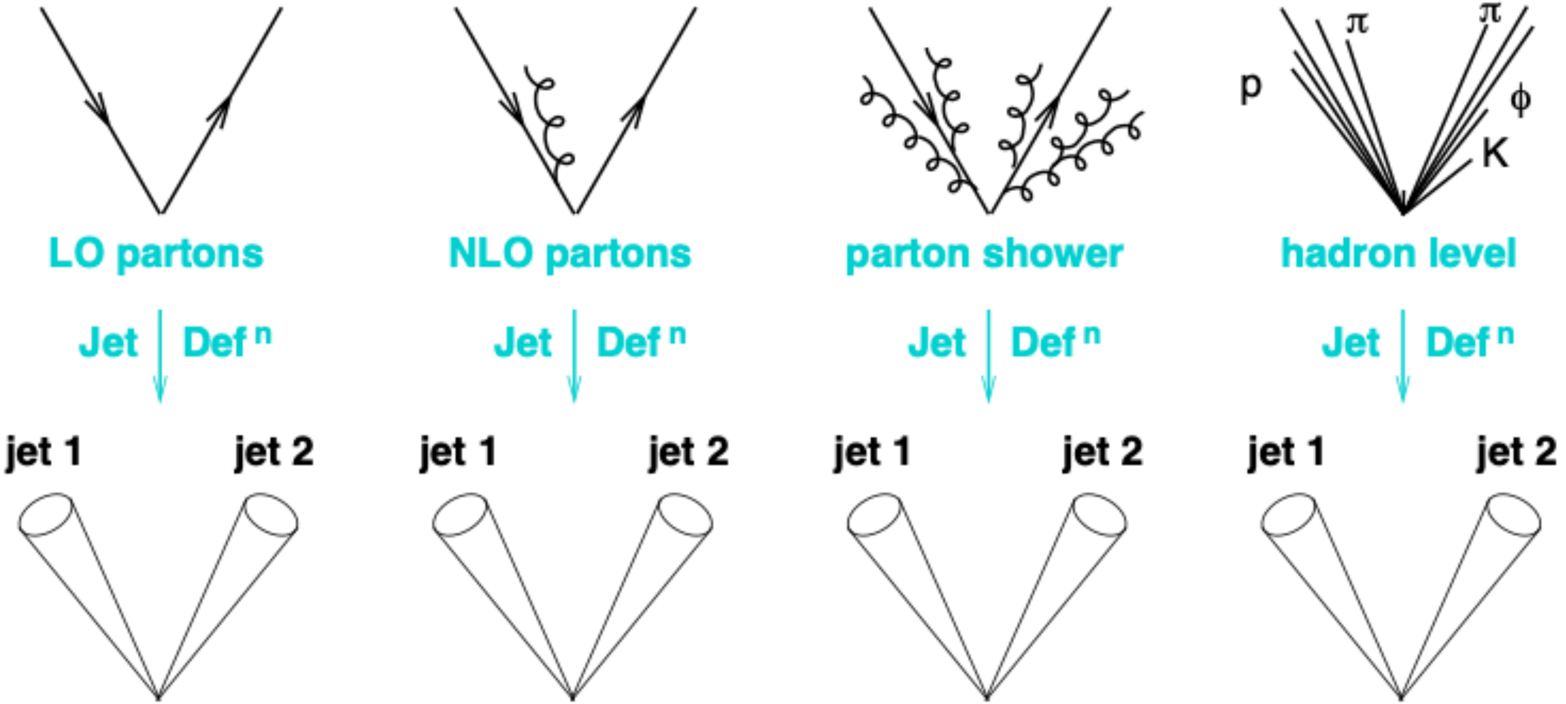
Particles
4-momenta
from tracking and calorimeter

Jets
4-momenta

Need to decide:

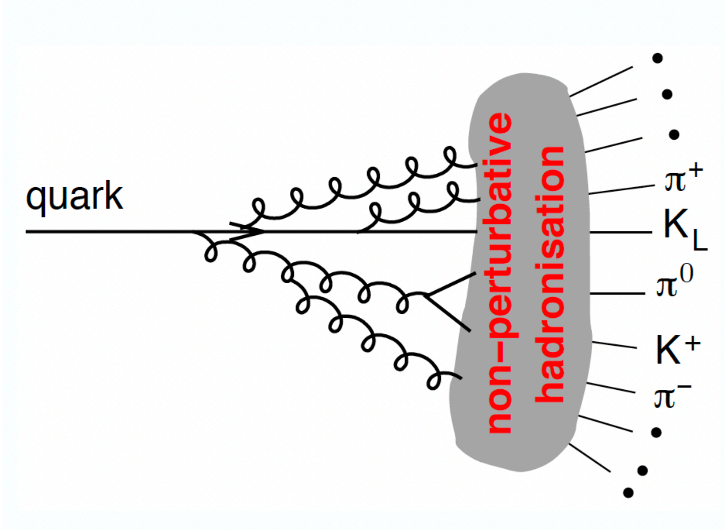
- Which particles do you put together into a same jet?
- How do you recombine their momenta?


p
π
π
φ
K
jet finding
jet 1
jet 2
interpretation
quark
anti-
quark
LO partons



Projection to jets should be resilient to QCD effects

Jet Finding

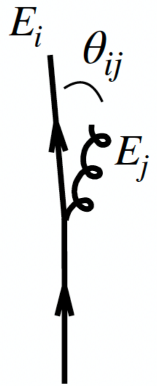


Sequential clustering algorithms:

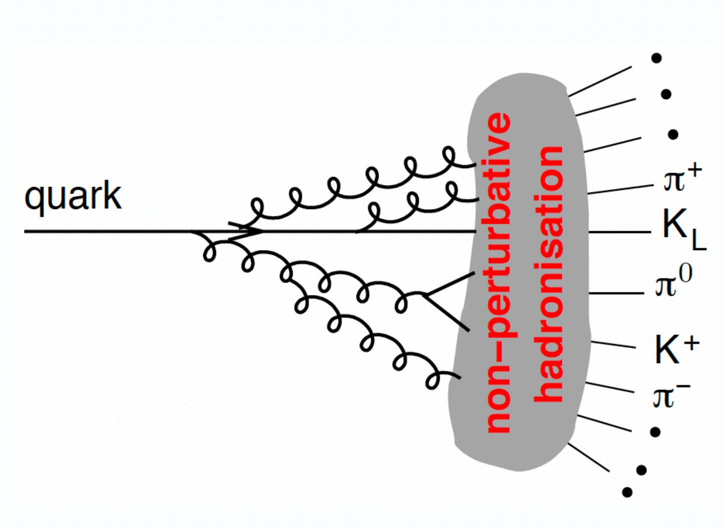
Aim: undo the parton splittings that produced the jet

2 particles are likely to originate from same parent when the softer particle has a small transverse momentum (k_T) with respect to the harder one

$$\frac{1}{\min(E_i,E_j)\theta_{ij}} \rightarrow \text{Large}$$



Jet Finding



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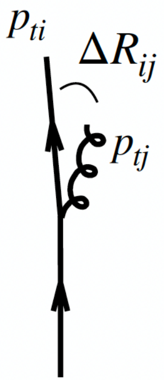
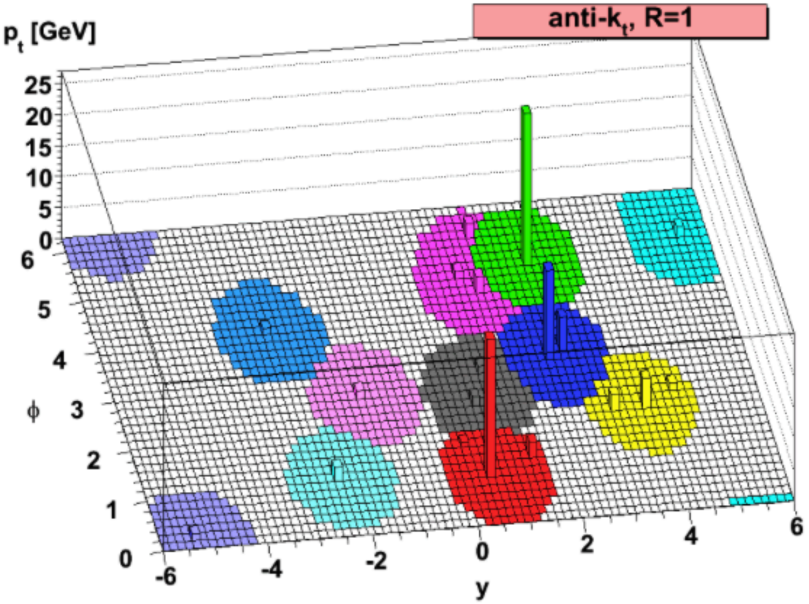
$$\frac{1}{\min(E_i,E_j)\theta_{ij}} \sim \frac{1}{\min(p_{Ti},p_{Tj})\Delta R_{ij}}$$

$$\Delta R_{ij} = \sqrt{\Delta y^2 + \Delta\varphi^2}$$



Jet Finding



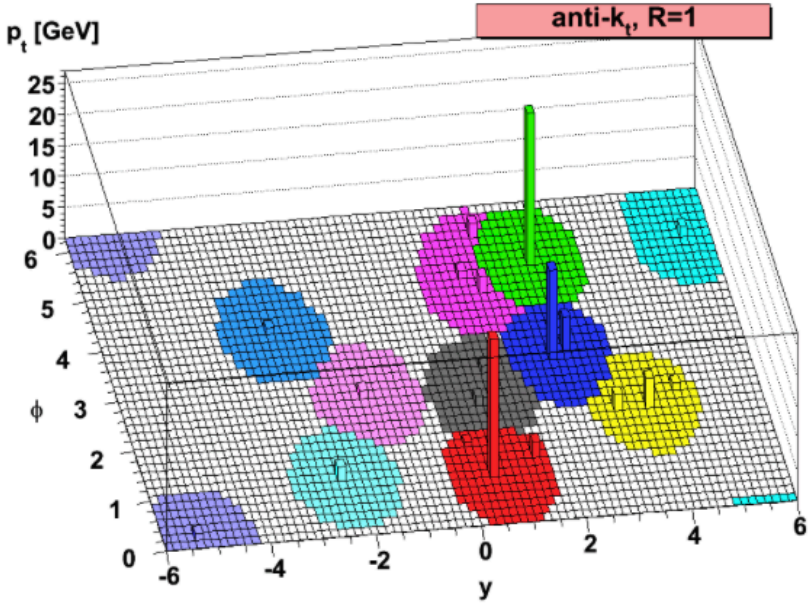
Sequential clustering of objects in event (calo towers, tracks etc) with a particular distance measure:

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

$$d_{iB} = p_{ti}^{2p} \,.$$

1. Find smallest of d_{ij} and d_{iB}
2. If ij, recombine them
3. If *iB*, call *i* a jet and remove from particle list
4. Iterate until no particles are left

Jet Finding



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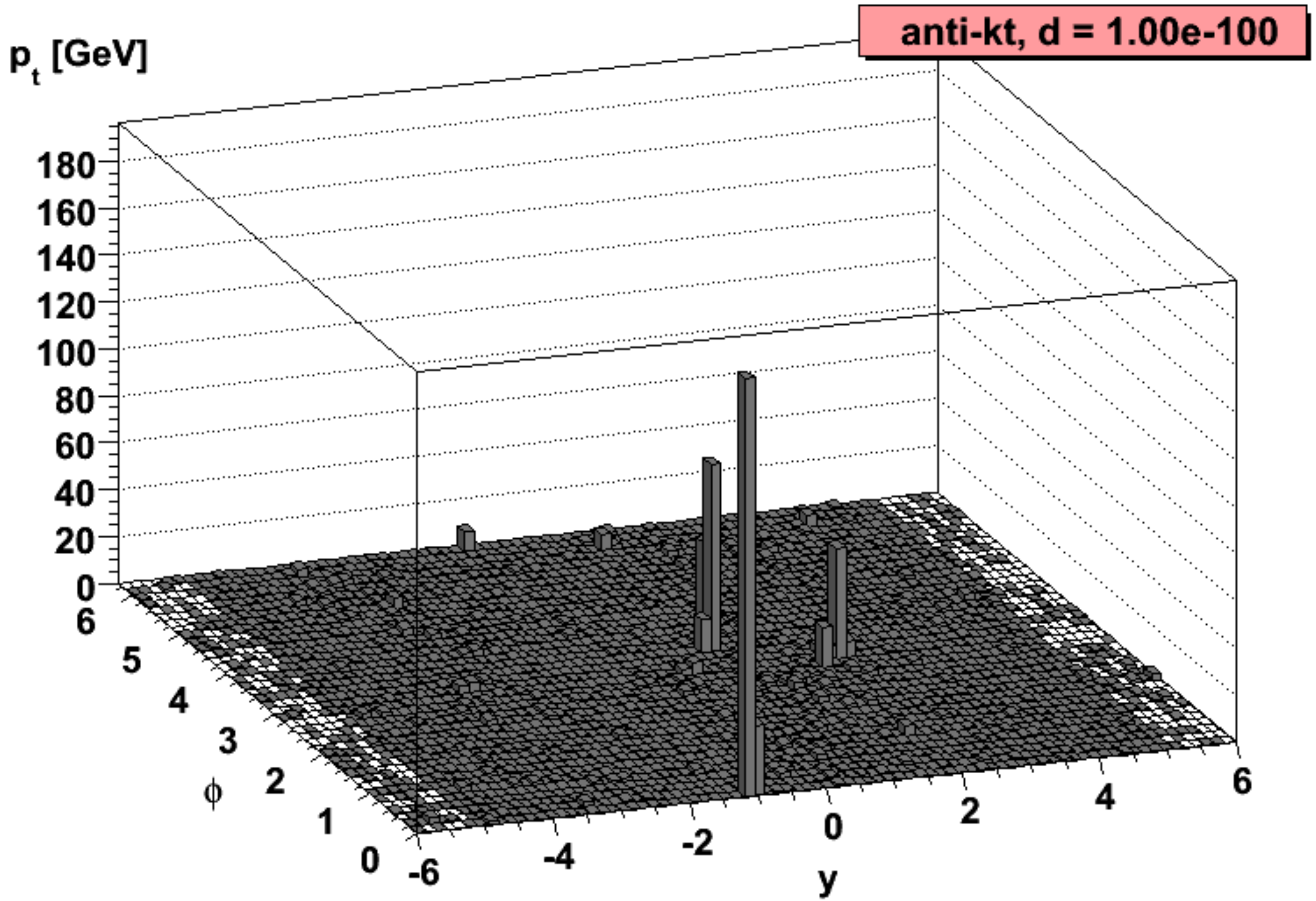
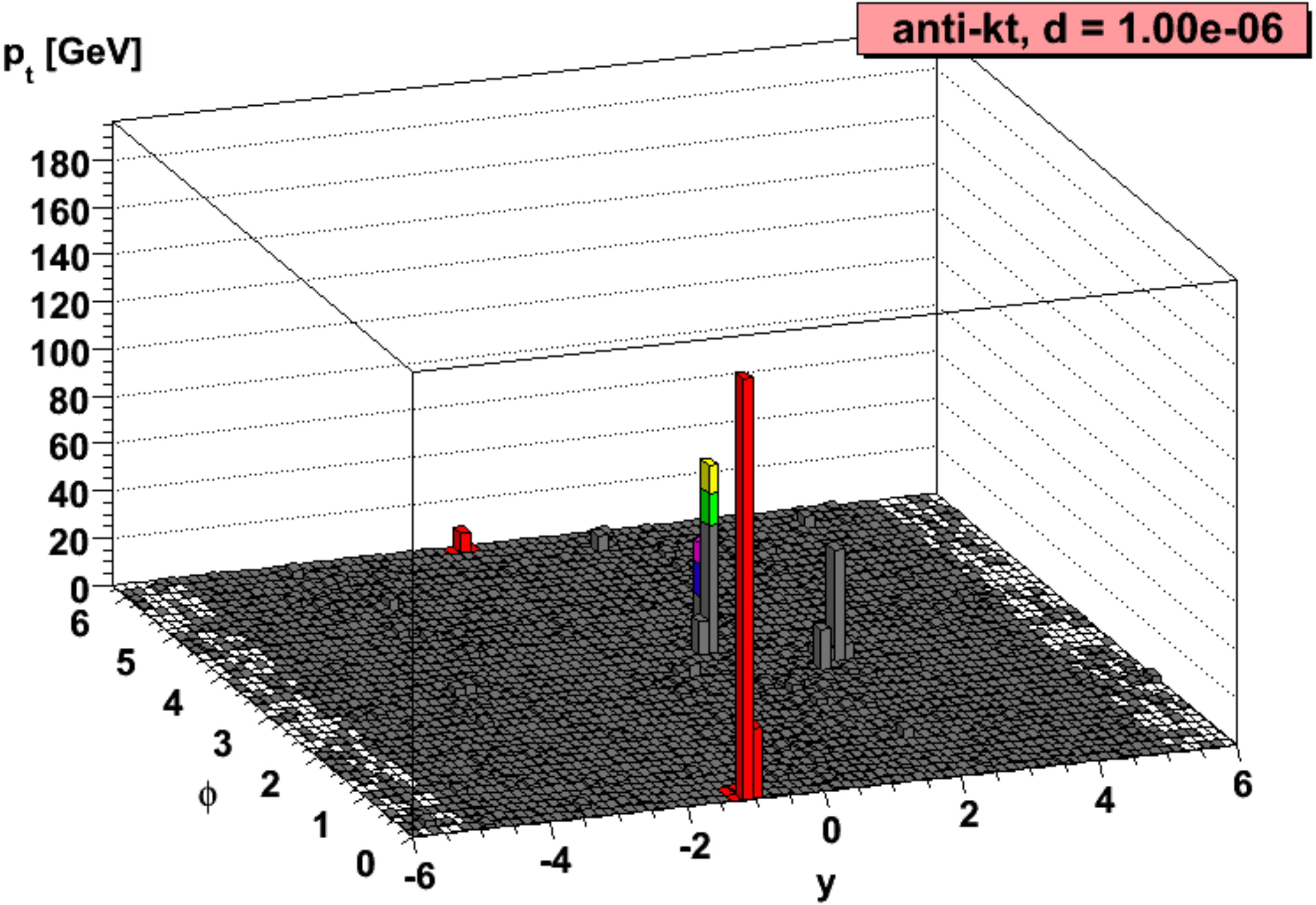
p=+1 → k_T
p=0 → Cambridge/Aachen
p=-1 → anti-k_T


anti-kt, d = 1.00e-100
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y


anti-kt, d = 1.00e-06
p_t [GeV]
0
20
40
60
80
100
120
140
160
180
ϕ
0
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2
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4
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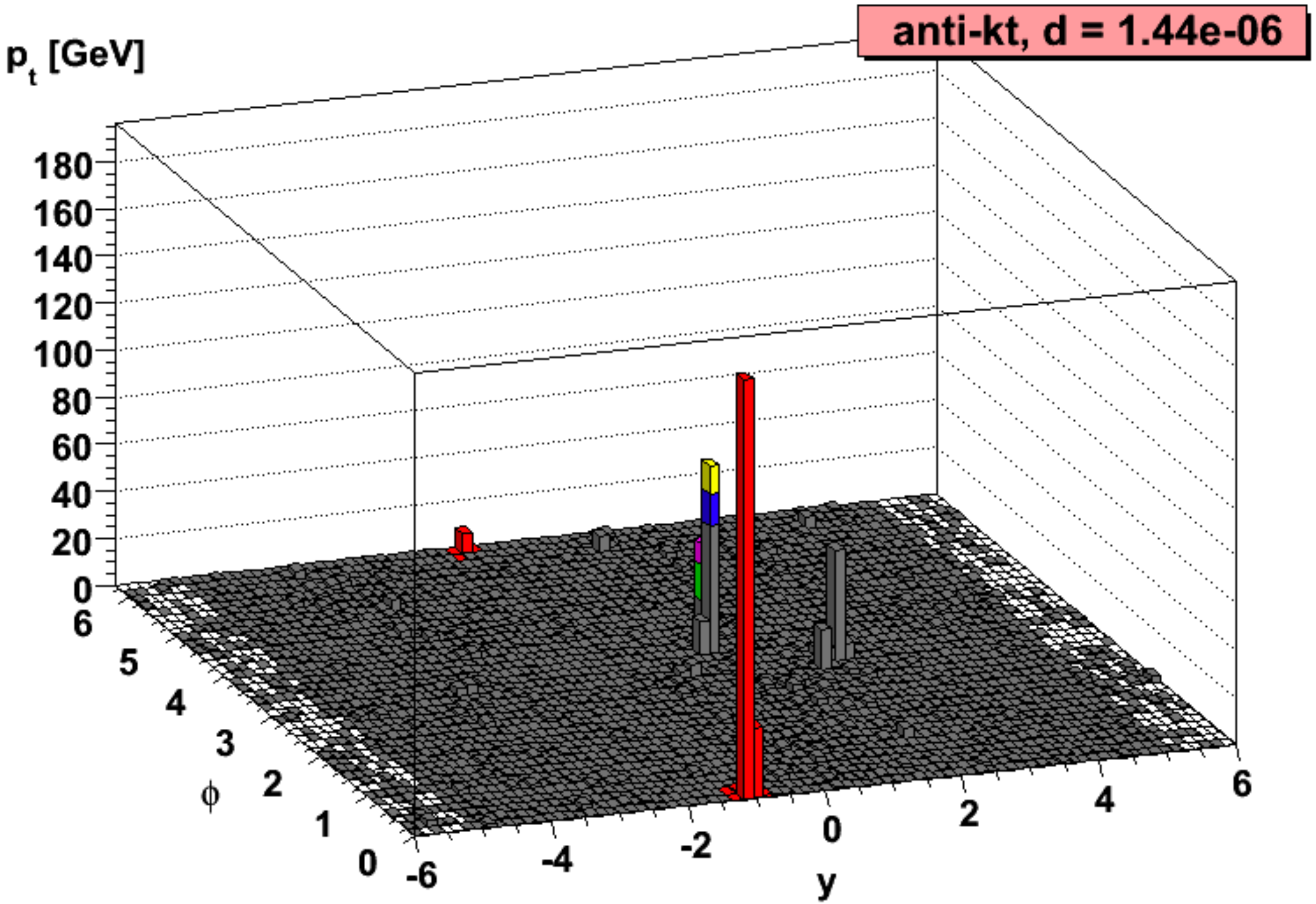
6
y
-6
-4
-2
0
2
4
6


anti-kt, d = 1.44e-06
p_t [GeV]
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20
40
60
80
100
120
140
160
180
6
5
4
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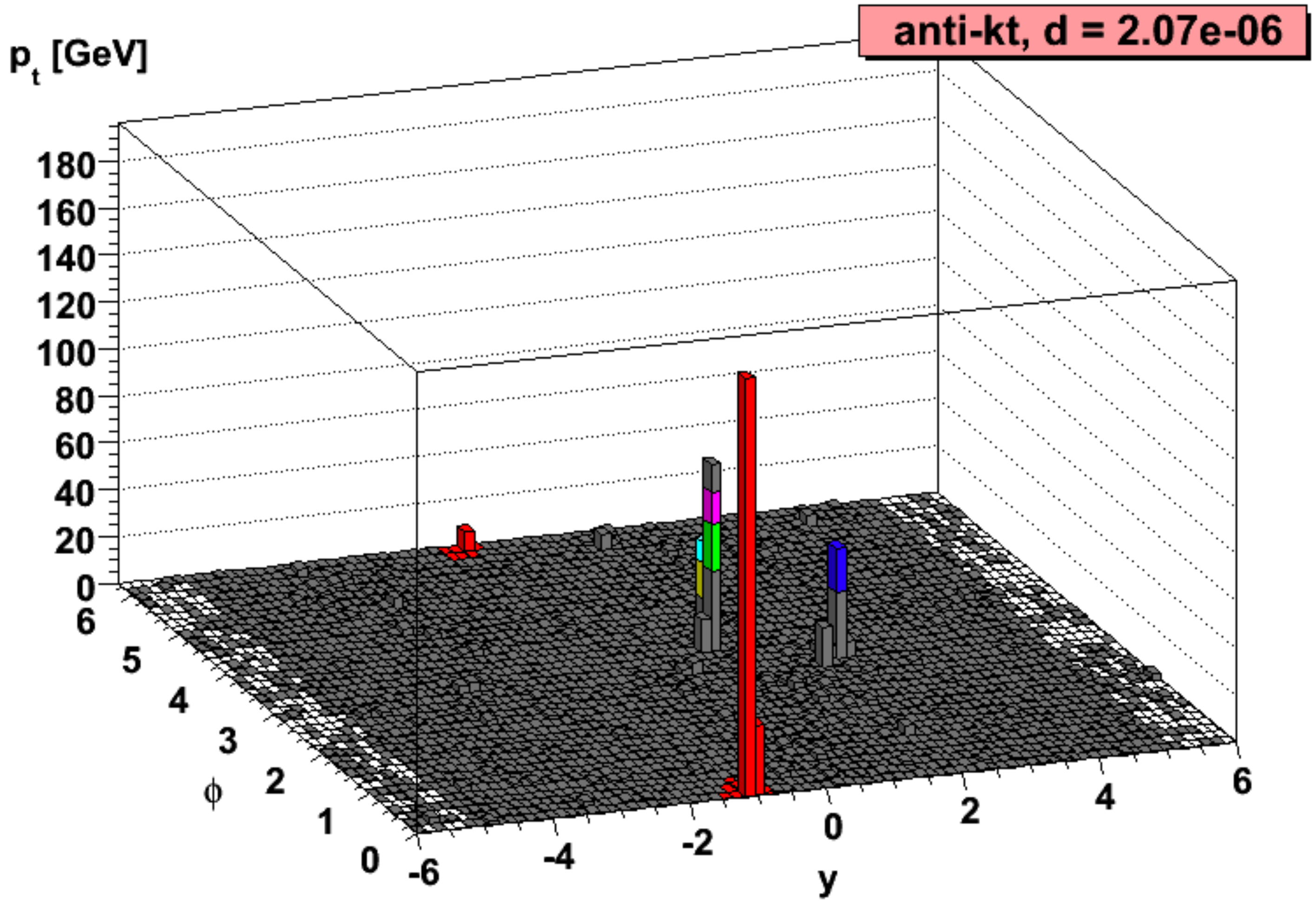
0
ϕ
-6
-4
-2
0
2
4
6
y


anti-kt, d = 2.07e-06
p_t [GeV]
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20
40
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100
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140
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180
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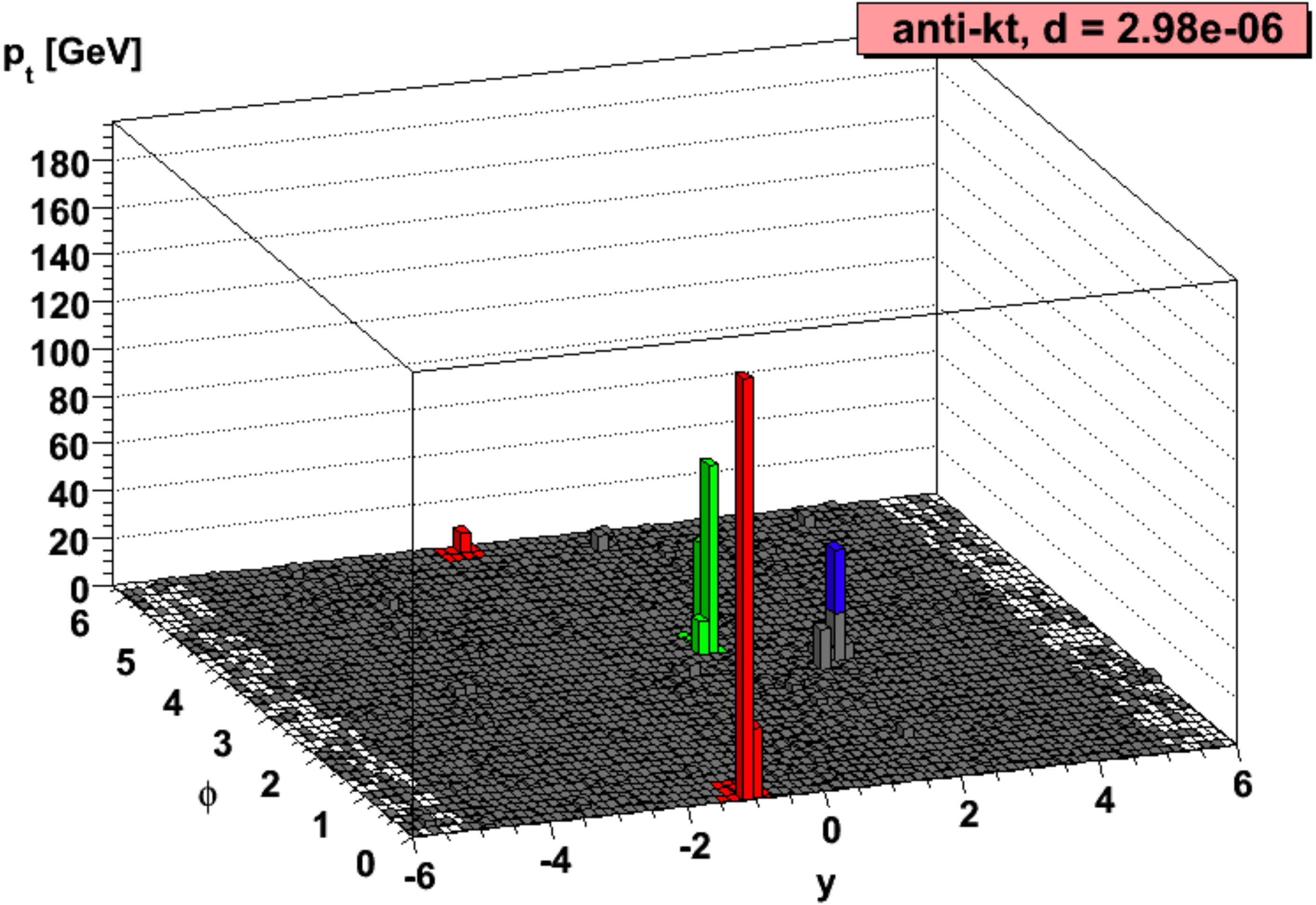
y
-6
-4
-2
0
2
4
6


anti-kt, d = 2.98e-06
p_t [GeV]
180
160
140
120
100
80
60
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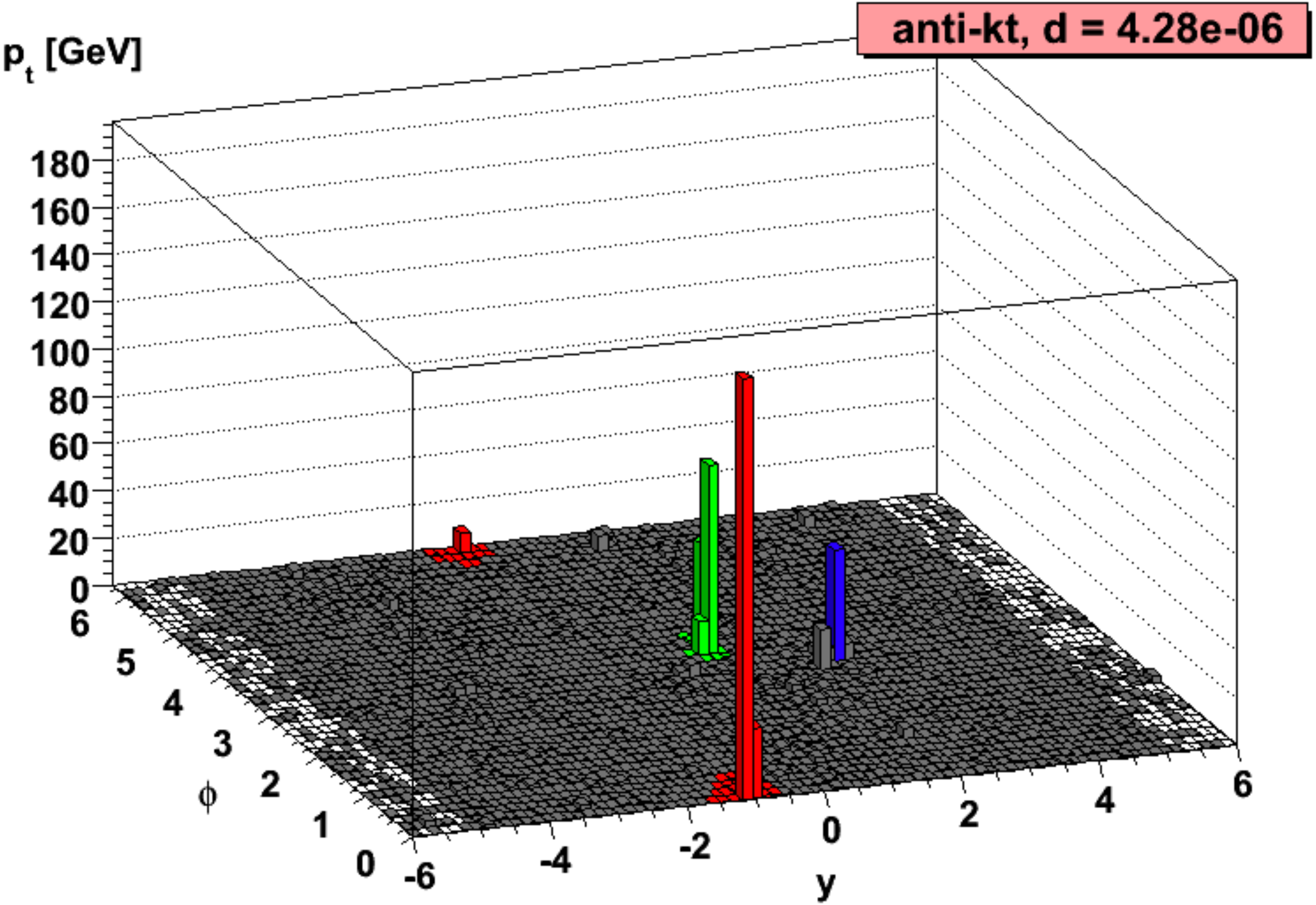
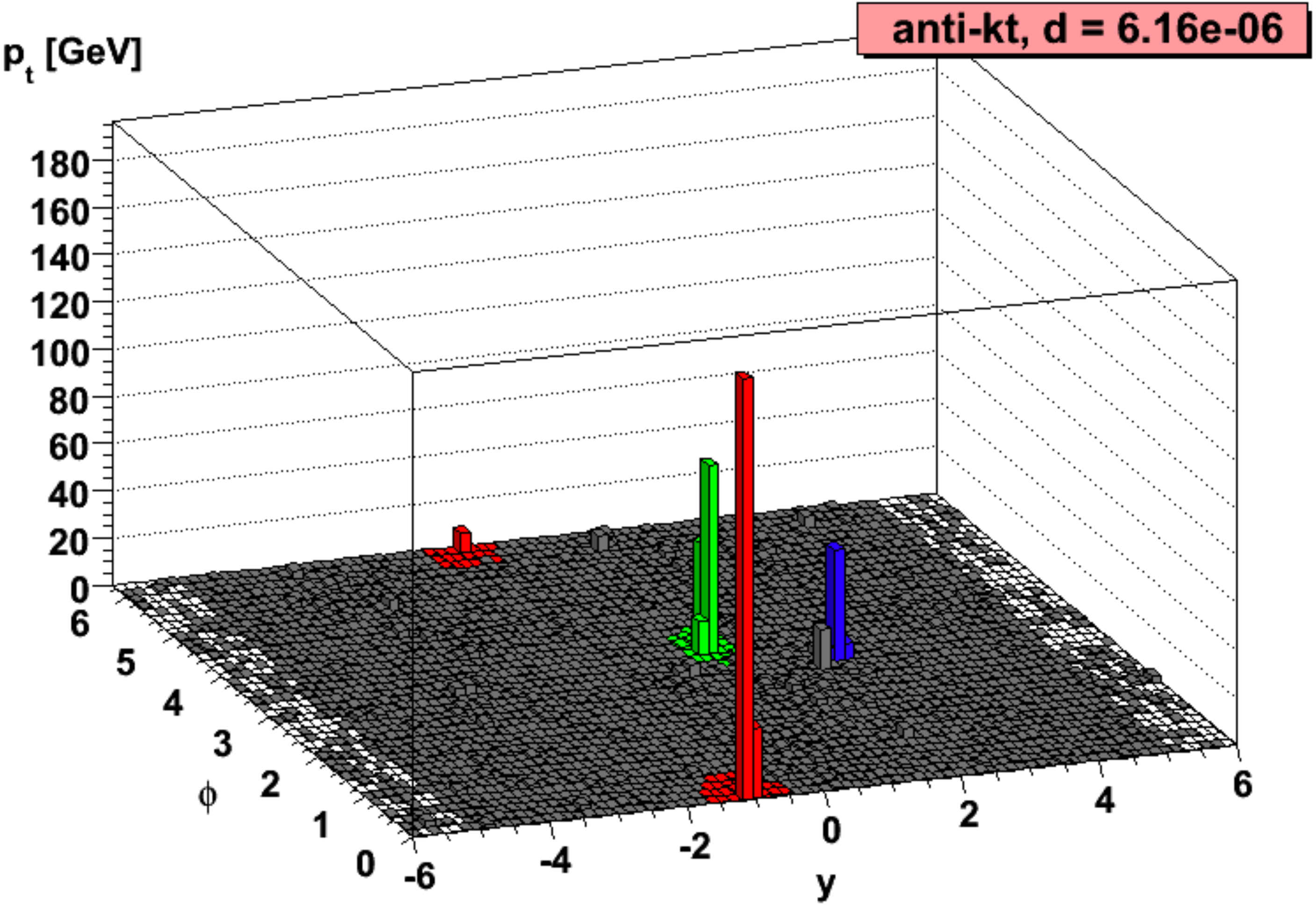
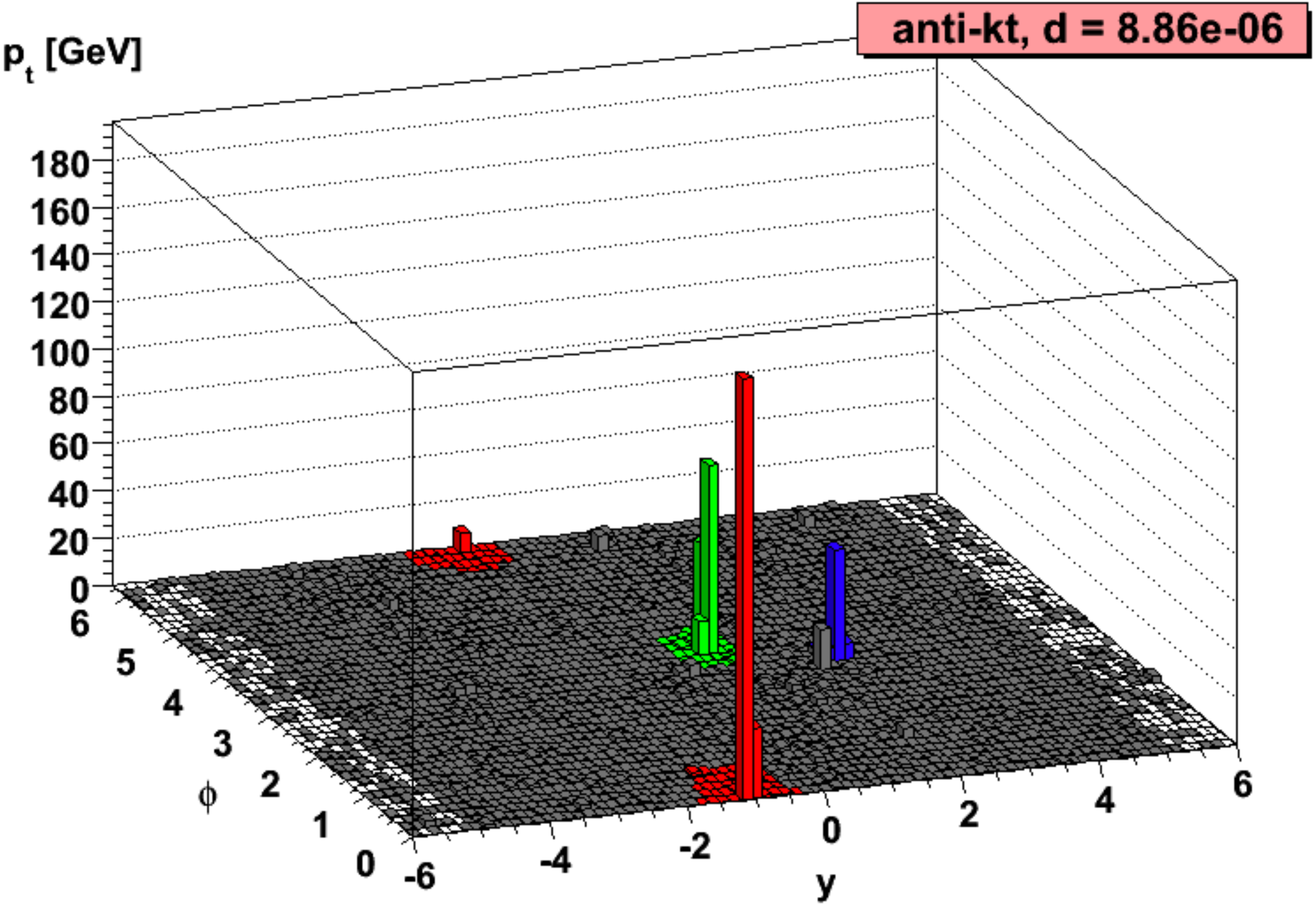
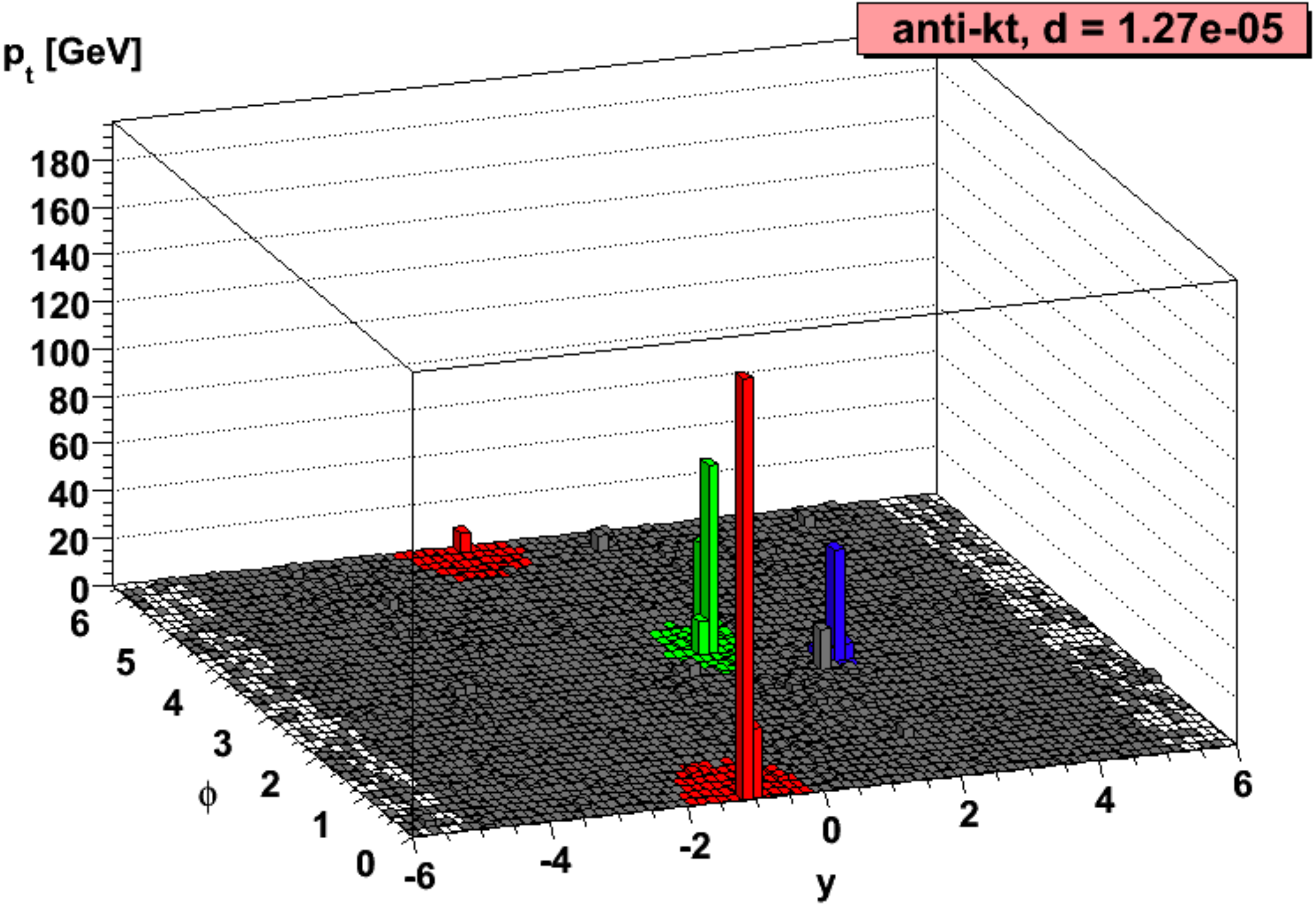
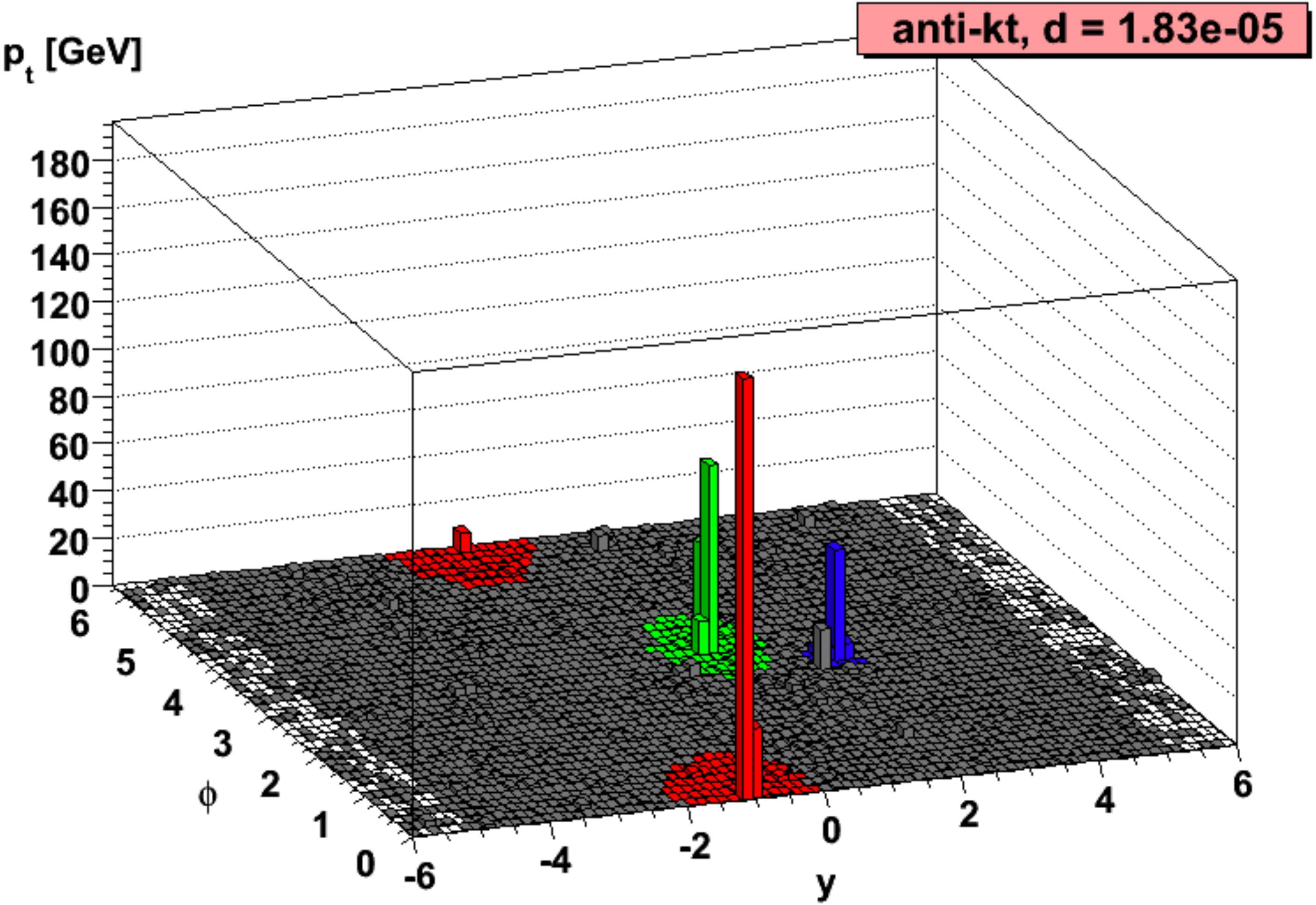
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y

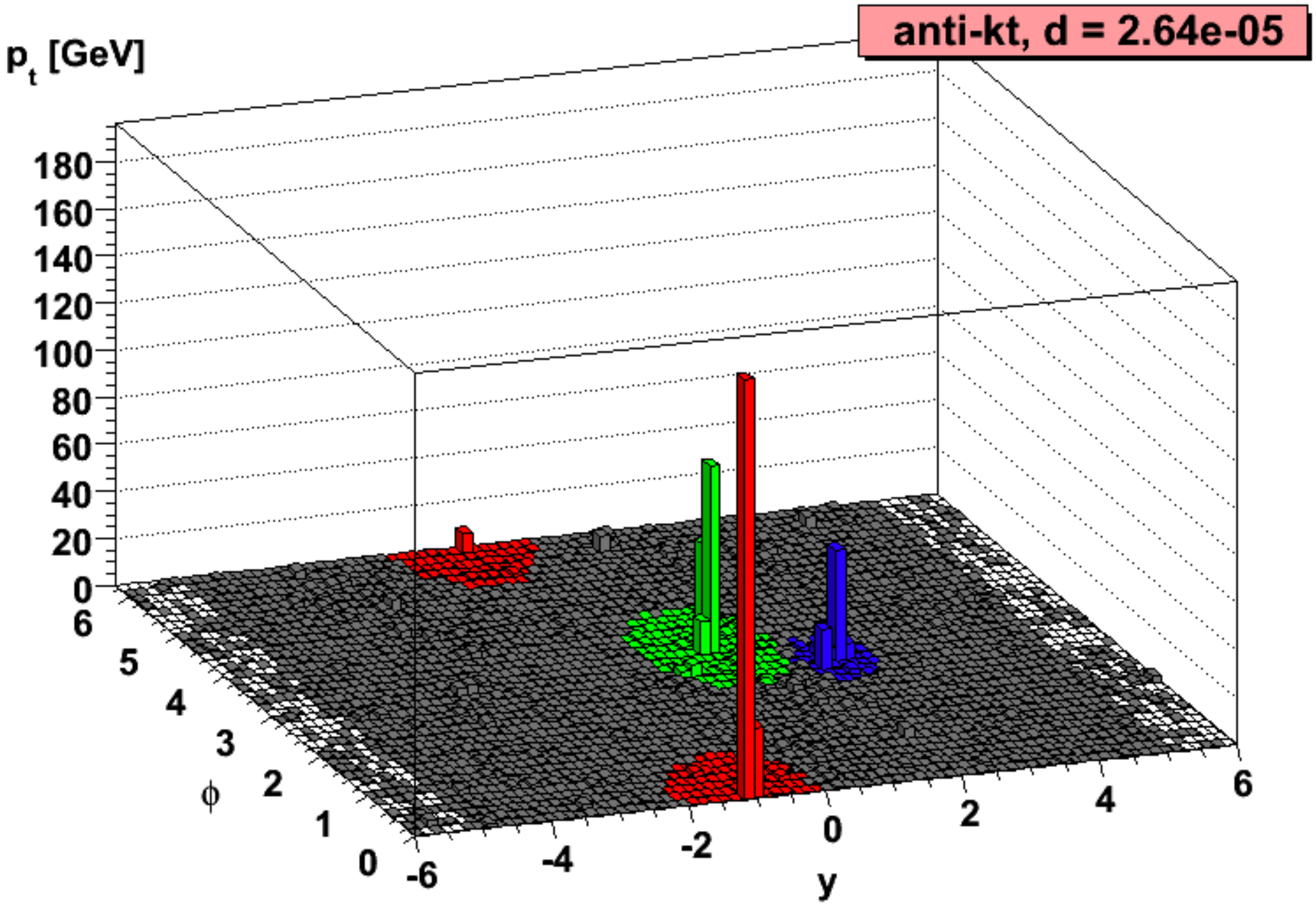

anti-kt, d = 4.28e-06
p_t [GeV]
0
20
40
60
80
100
120
140
160
180
ϕ
0
1
2
3
4
5
6
y
-6
-4
-2
0
2
4
6


anti-kt, d = 6.16e-06
p_t [GeV]
0
20
40
60
80
100
120
140
160
180
φ
0
1
2
3
4
5
6
y
-6
-4
-2
0
2
4
6

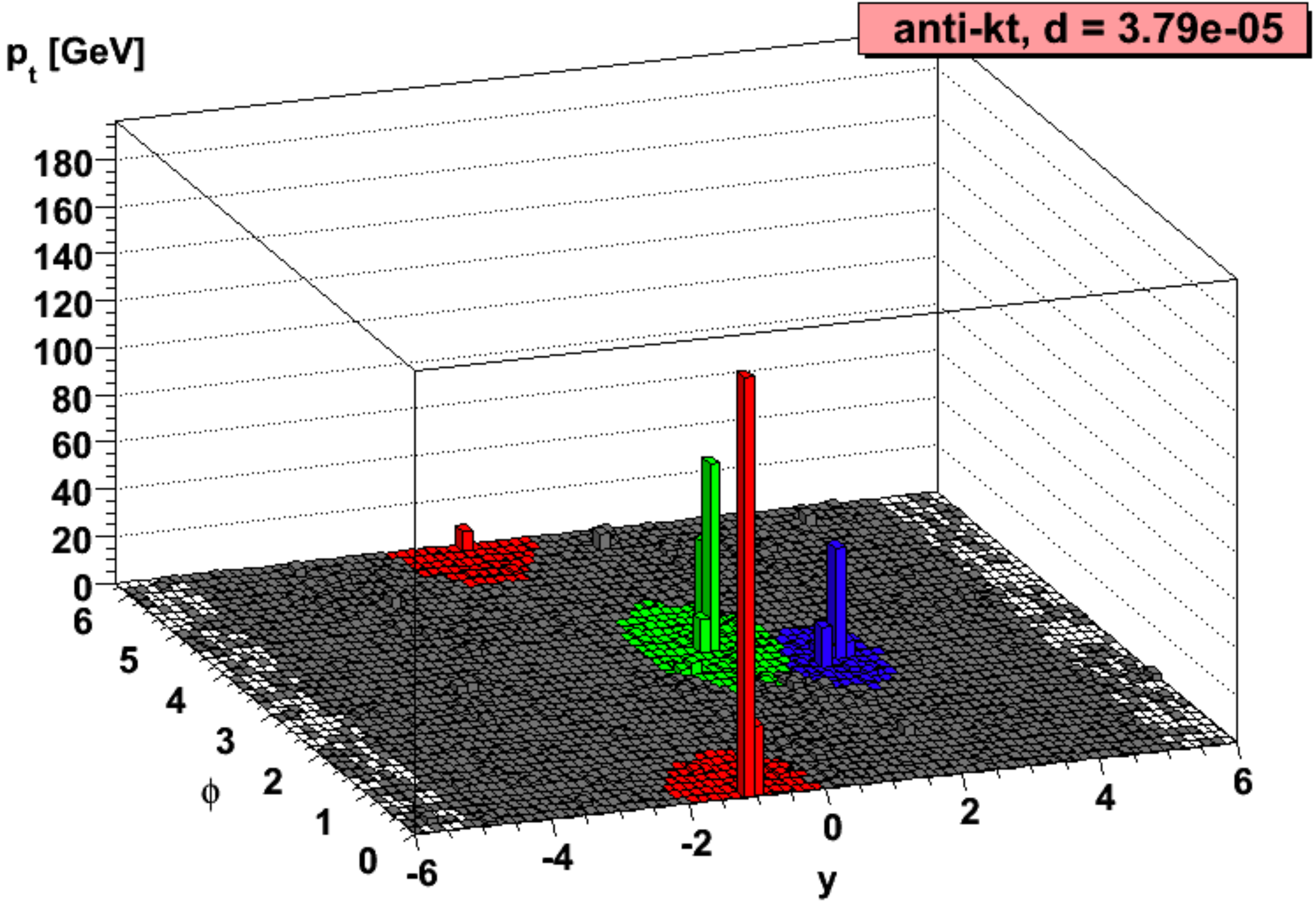

anti-kt, d = 8.86e-06
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y

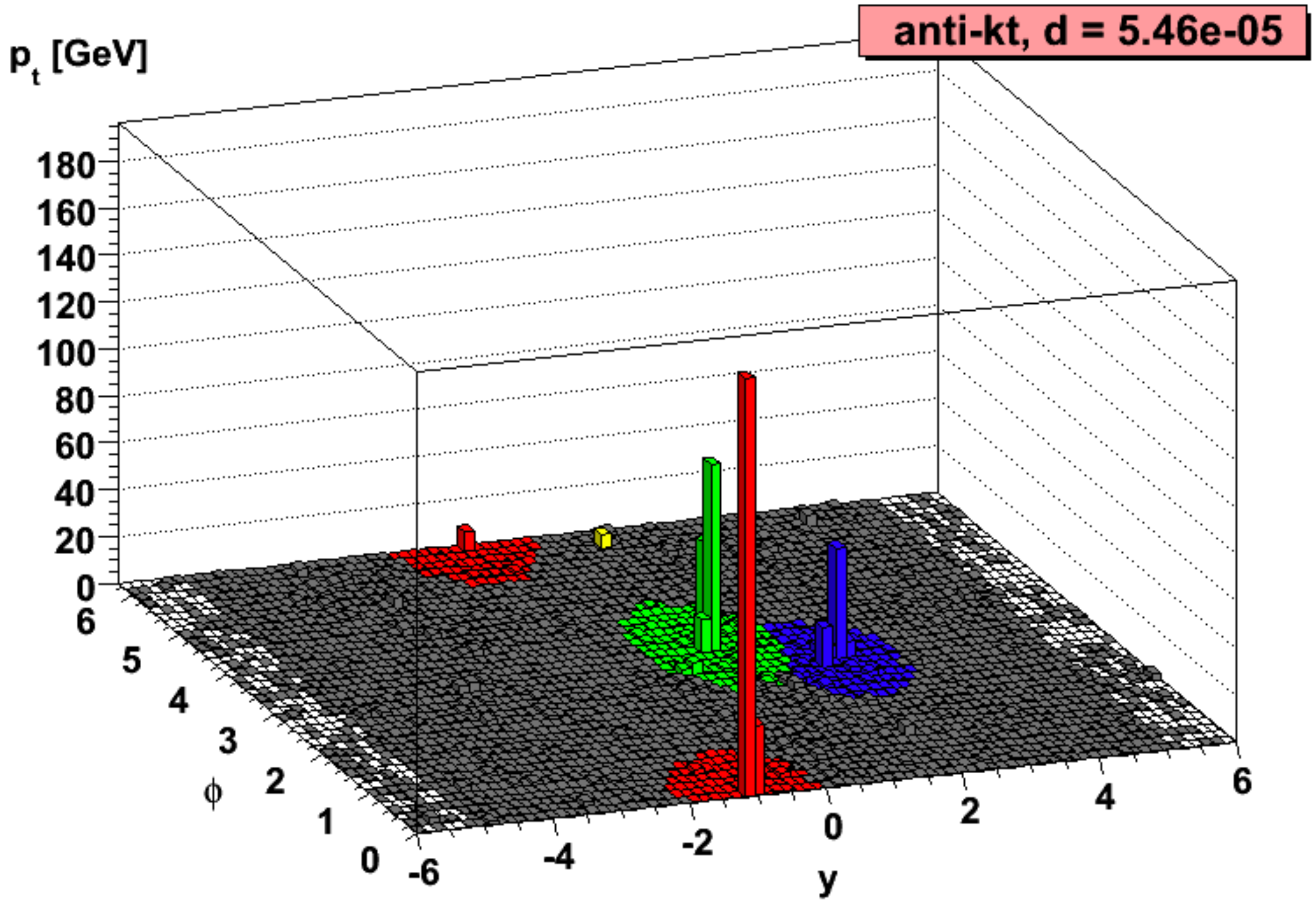

anti-kt, d = 1.27e-05
p_t [GeV]
0
20
40
60
80
100
120
140
160
180
φ
0
1
2
3
4
5
6
y
-6
-4
-2
0
2
4
6

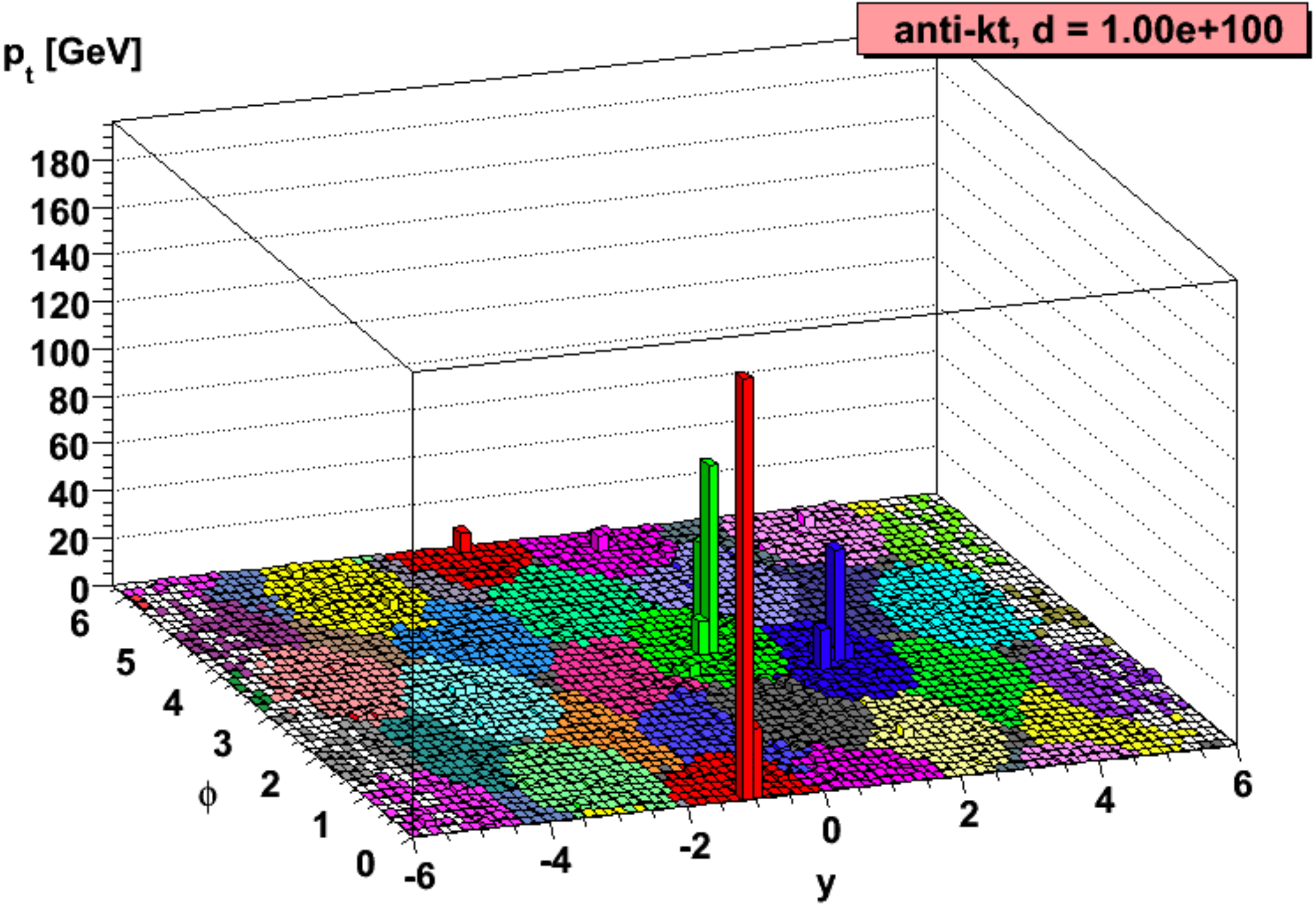

anti-kt, d = 1.83e-05
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y



anti-kt, d = 2.64e-05
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y


anti-kt, d = 3.79e-05
p_t [GeV]
0
20
40
60
80
100
120
140
160
180
ϕ
0
1
2
3
4
5
6
y
-6
-4
-2
0
2
4
6

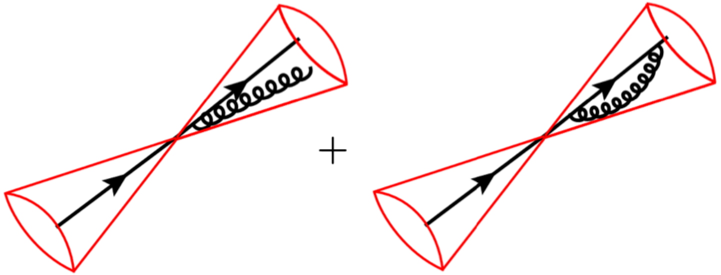

anti-kt, d = 5.46e-05
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y



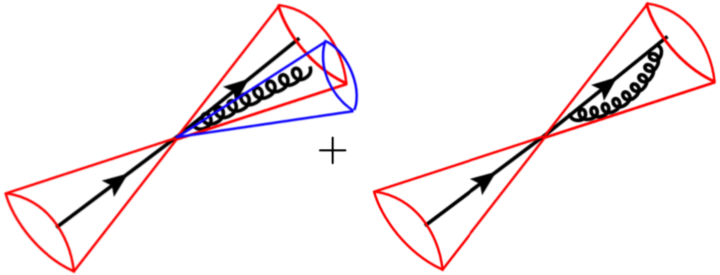
anti-kt, d = 1.00e+100
p_t [GeV]
180
160
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
ϕ
-6
-4
-2
0
2
4
6
y

Jet Finder: safety

A jet finder algorithm must be insensitive to an arbitrary collinear or soft emission.
To ensure that infinities cancel in perturbative calculation.
→ Allows meaningful comparison between experiment and theory.



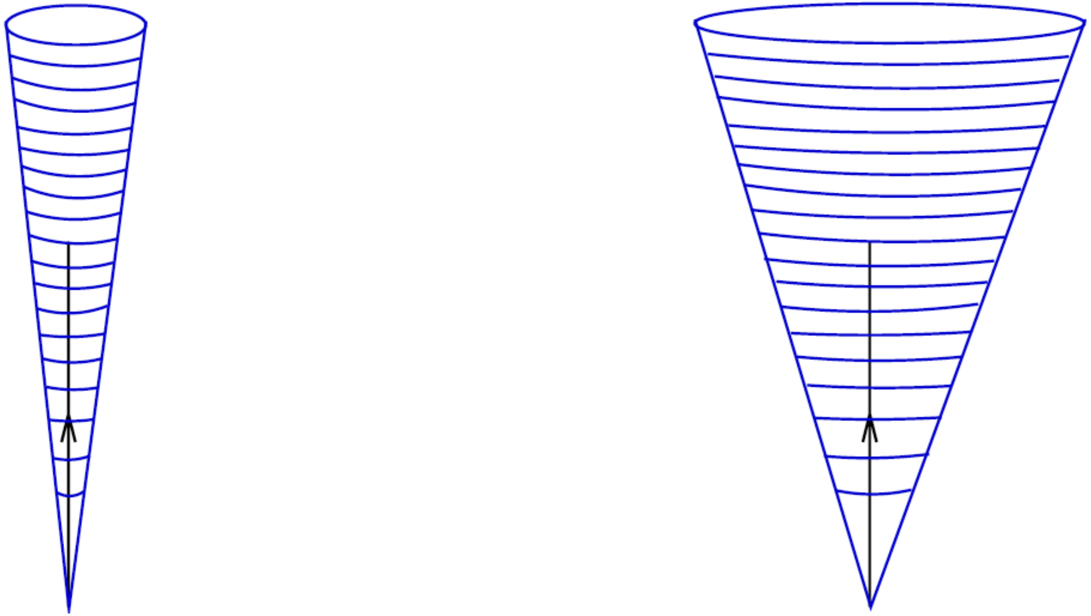
$$= \frac{1}{\epsilon} J^{(2)}_{\text{IRC-safe}} - \frac{1}{\epsilon} J^{(2)}_{\text{IRC-safe}} = \text{finite}$$



$$= \frac{1}{\epsilon} J^{(3)}_{\text{IRC-unsafe}} - \frac{1}{\epsilon} J^{(2)}_{\text{IRC-unsafe}} = \infty$$

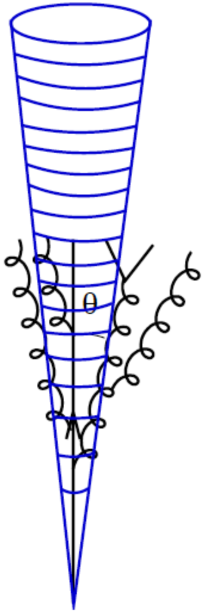
[*Prog. Part. Nucl. Phys.* 89 (2016) 1-55]

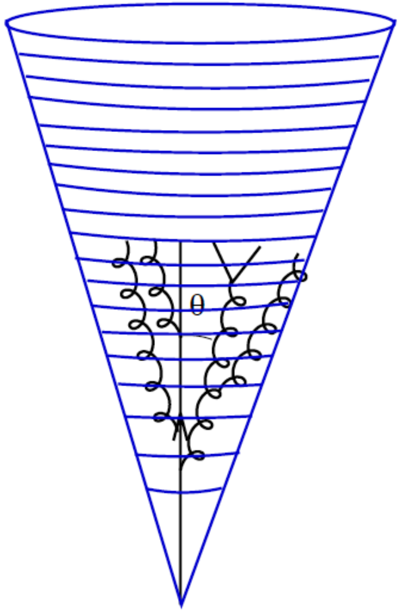
Small vs Large Jets



At leading order jet radius is irrelevant

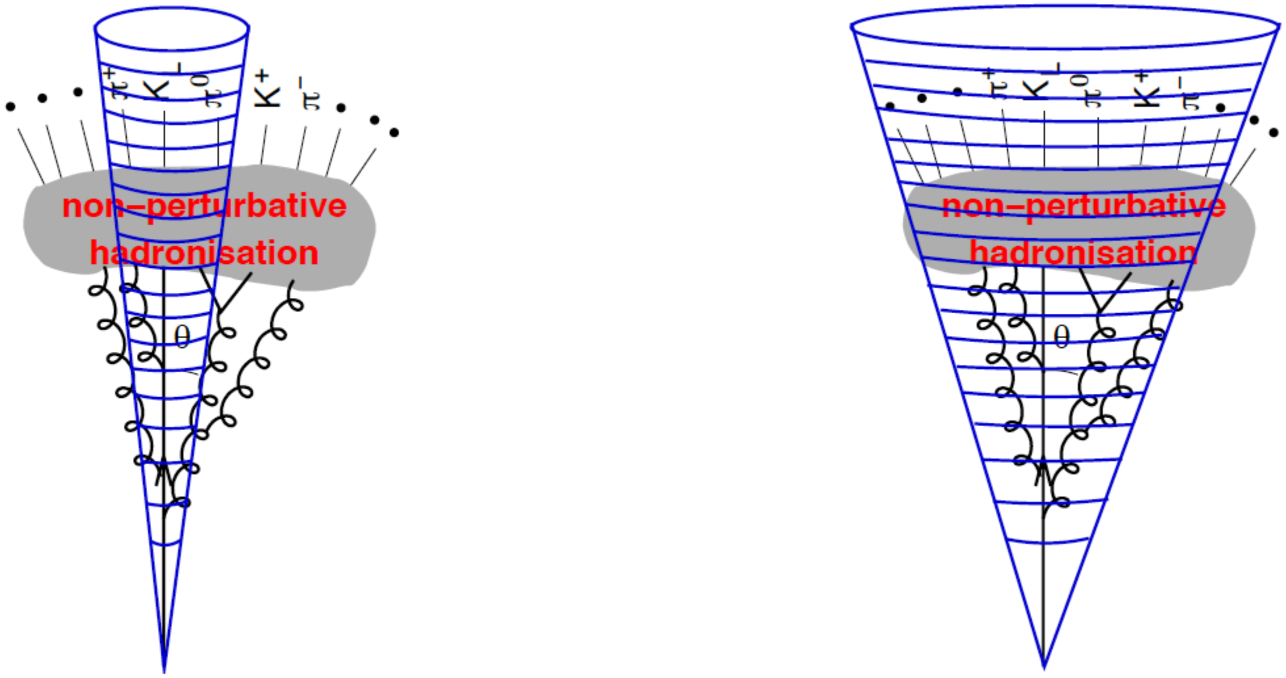
Small vs Large Jets





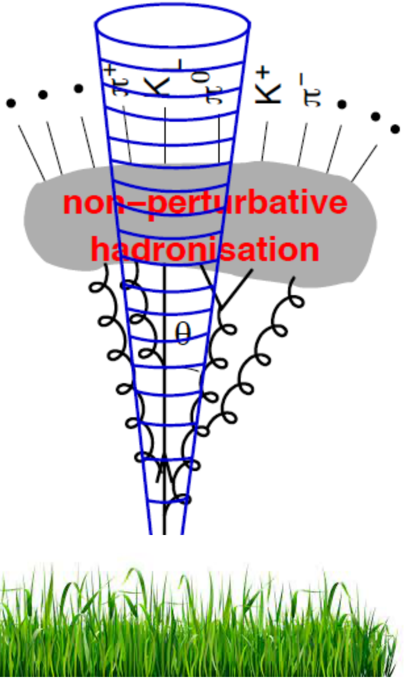
Larger jets better to capture perturbative fragmentation

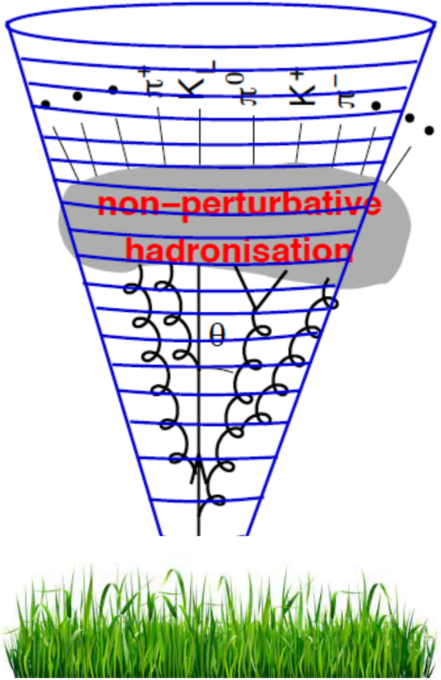
Small vs Large Jets



Larger jets better to capture perturbative fragmentation and non-perturbative hadronisation

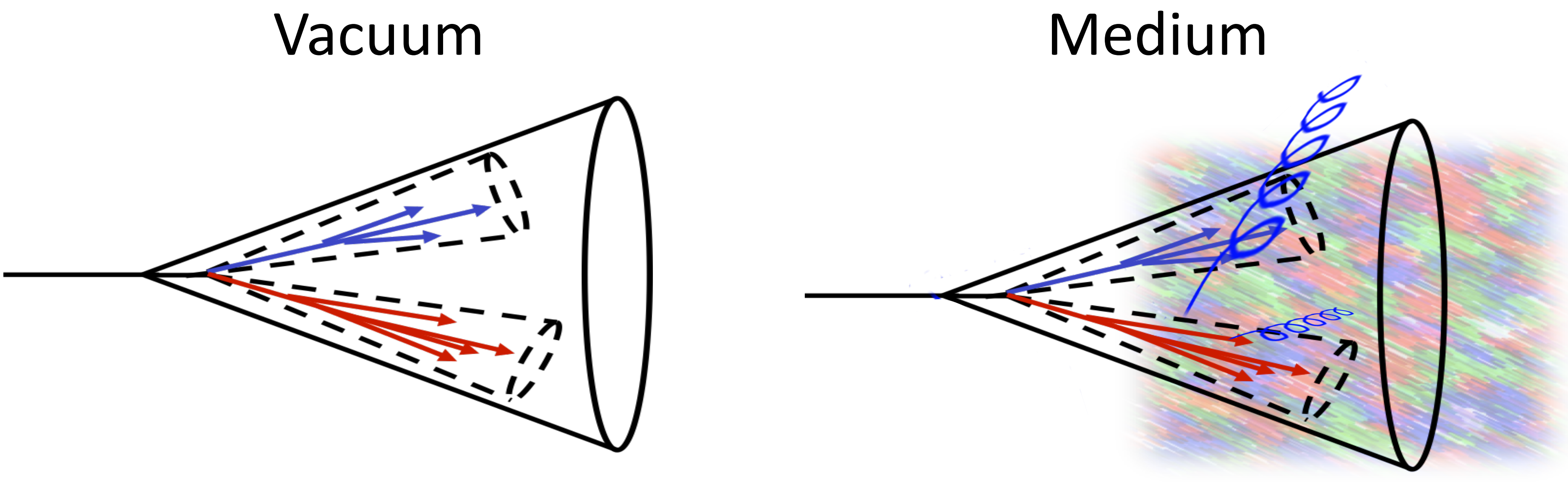
Small vs Large Jets





Smaller jets better to limit influence from underlying event

Parton showers

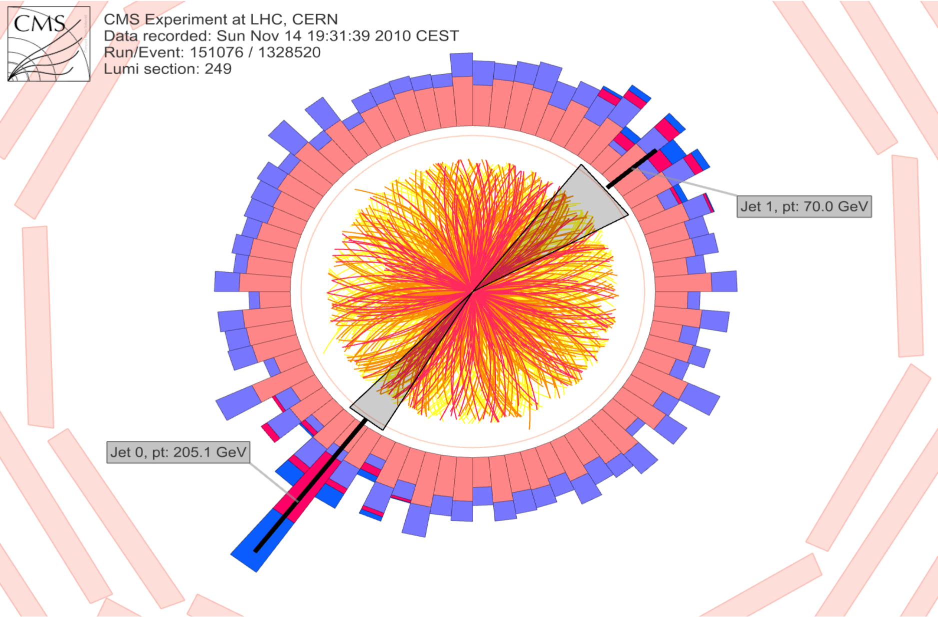


What happens to the parton shower in a hot QCD medium?
And what does that tell us about this medium?

Jets in heavy-ion collisions

It is very very busy in a heavy-ion collision

Need to remove particles that are not related to jet formation



Jet background in heavy-ion collisions

ALICE, JHEP 1203(2012), 053

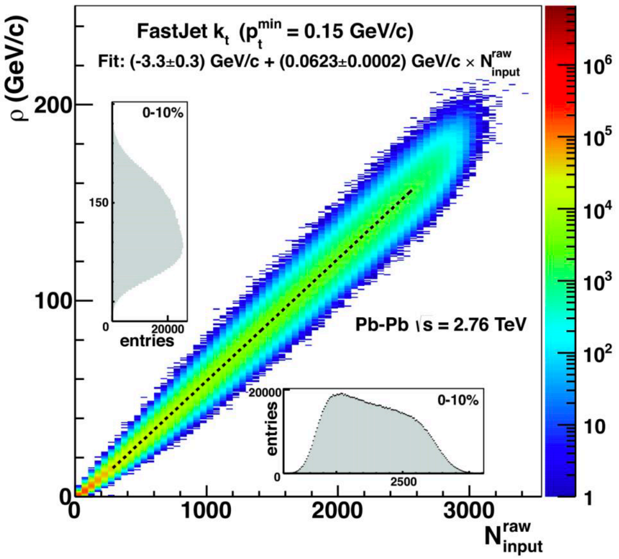
Signal jets are reconstructed with anti-kT

k_T algorithm however very useful to estimate how much background there is in an event

Background density: $\rho \cong \text{median}\left[\frac{p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\right]$

Use background density to correct jet:

$$p_{T,jet}^{sub} = p_{T,jet}^{raw} - \rho A_{jet}$$



p_t^{min} (GeV/c)	$\langle\rho\rangle$ (GeV/c)	$\sigma(\rho)$ (GeV/c)
0-10%		
0.15	138.32 ± 0.02	18.51 ± 0.01
1.00	59.30 ± 0.01	9.27 ± 0.01
2.00	12.28 ± 0.01	3.29 ± 0.01

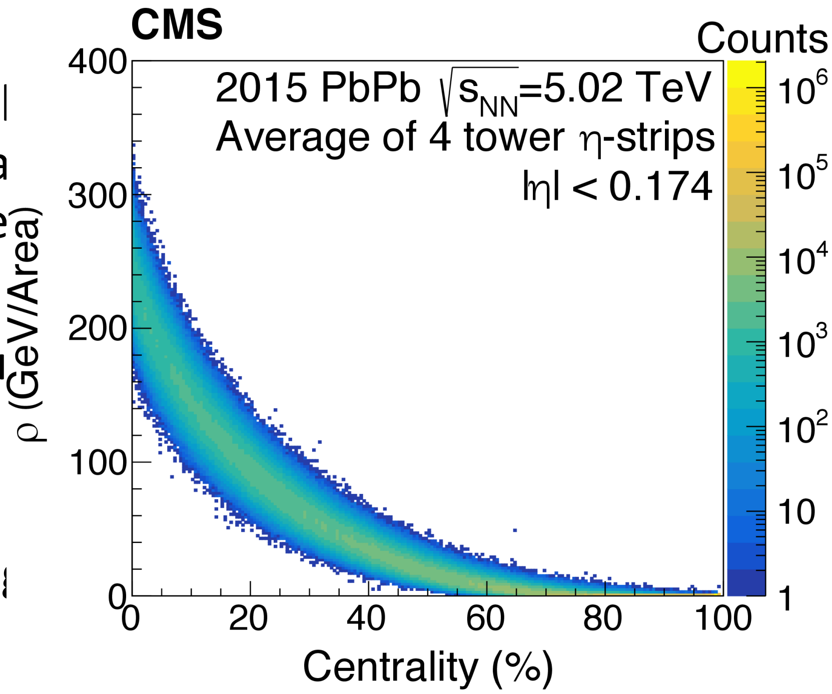
Jet background in heavy-ion collisions

Signal jets are reconstructed with anti-kT

k_T algorit
estima
in an e

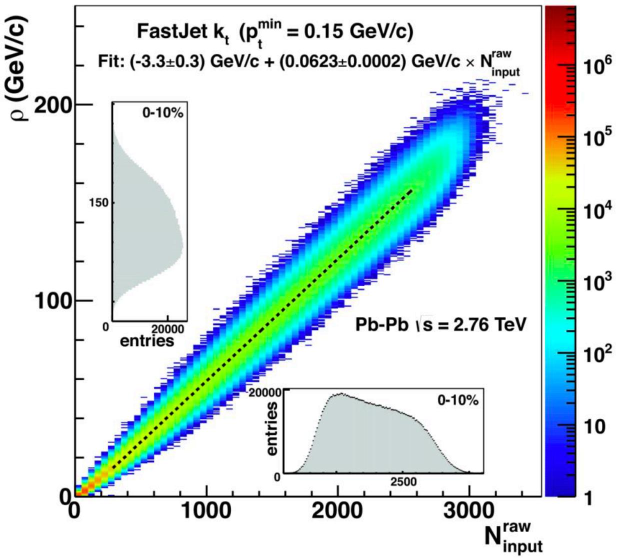
Backgrou

Use back



arXiv:2405.10785

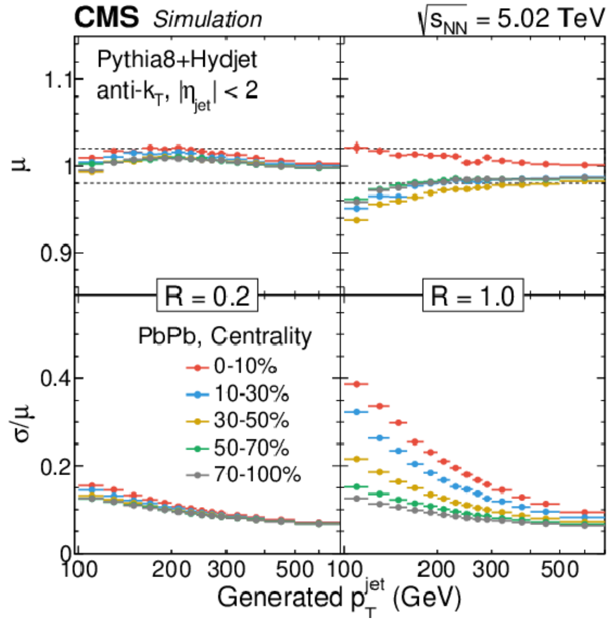
ALICE, JHEP 1203(2012), 053

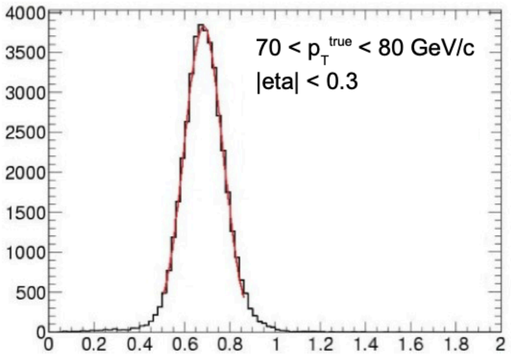


p_t^{min} (GeV/c)	⟨ρ⟩ (GeV/c)	σ(ρ) (GeV/c)
0-10%		
0.15	138.32 ± 0.02	18.51 ± 0.01
1.00	59.30 ± 0.01	9.27 ± 0.01
2.00	12.28 ± 0.01	3.29 ± 0.01

Jet energy scale and resolution

Background fluctuates from region-to-region
→ affects resolution after subtraction





$p_{T,reco}/p_{T,truth}$

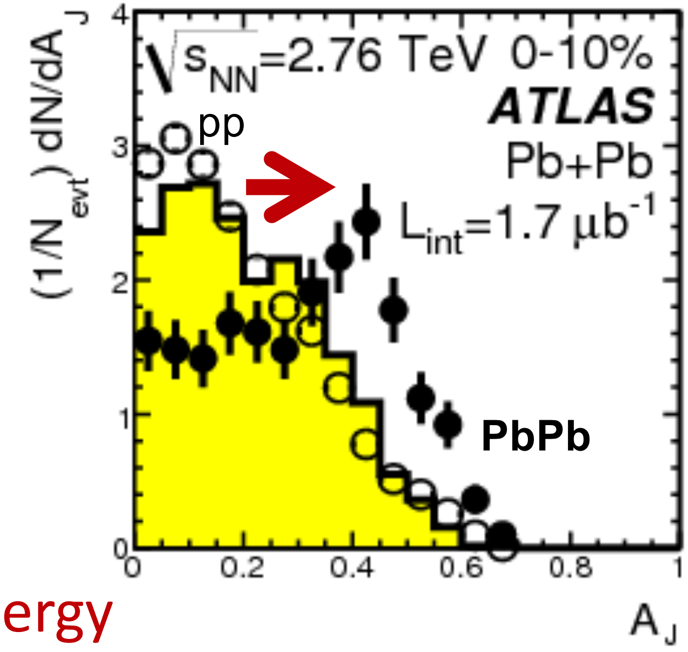
Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)

Jet energy asymmetry $A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$

In pp: used to calibrate jets

In PbPb: physics signal



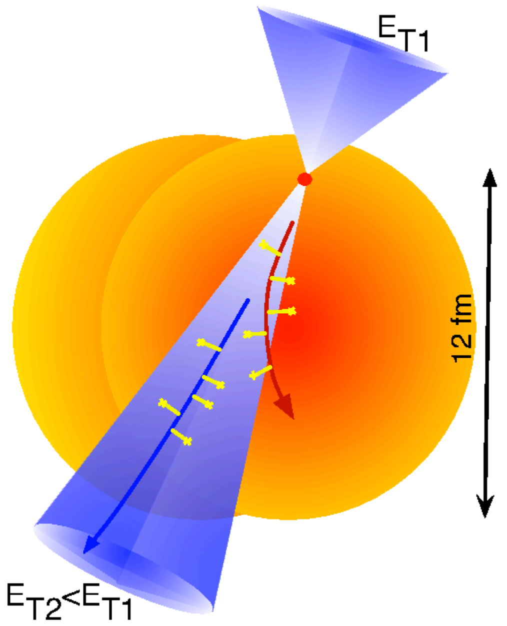
Phys.Rev.Lett.105:252303,2010

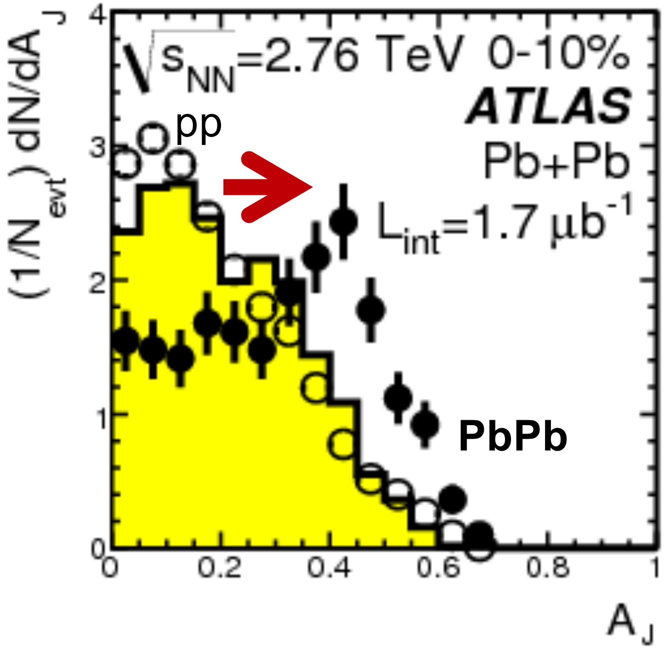
Dijets in PbPb are less balanced in energy

balanced *unbalanced*

Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)

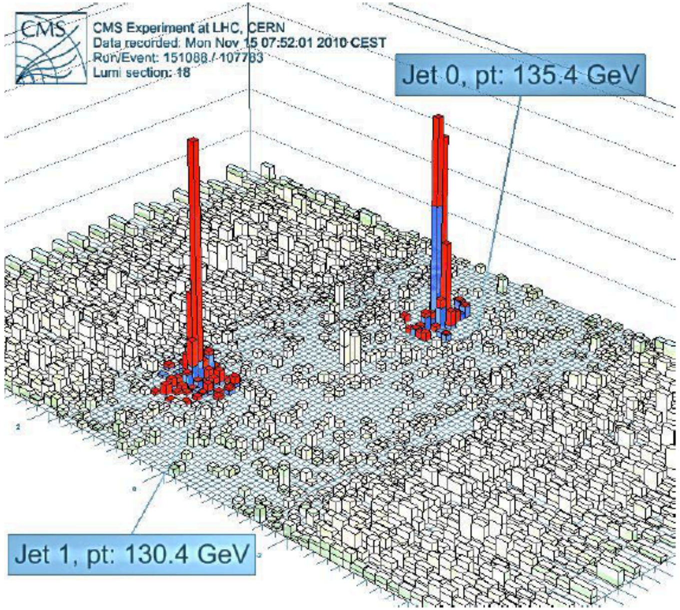




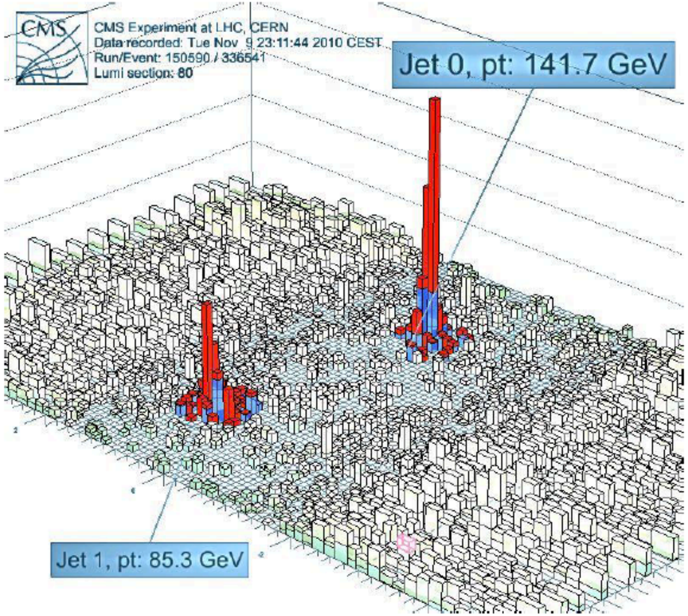
Phys.Rev.Lett.105:252303,2010

Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)



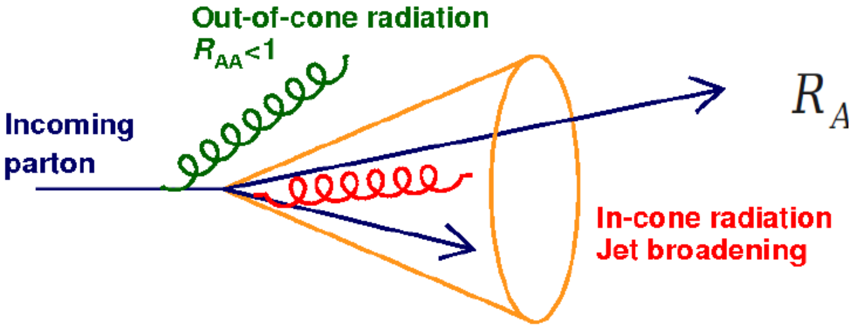
Balanced Energy

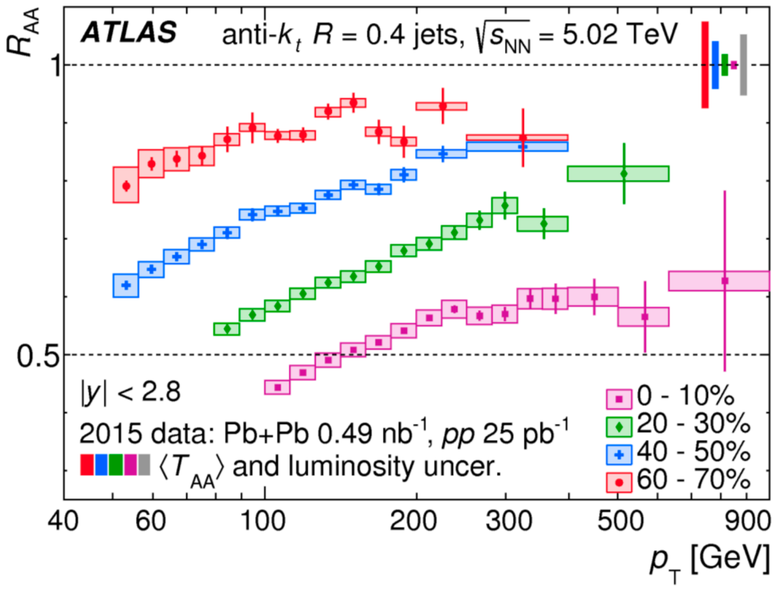


Unbalanced Energy

Jet R_{AA}

Jets don't recover all expected energy
→out of the cone



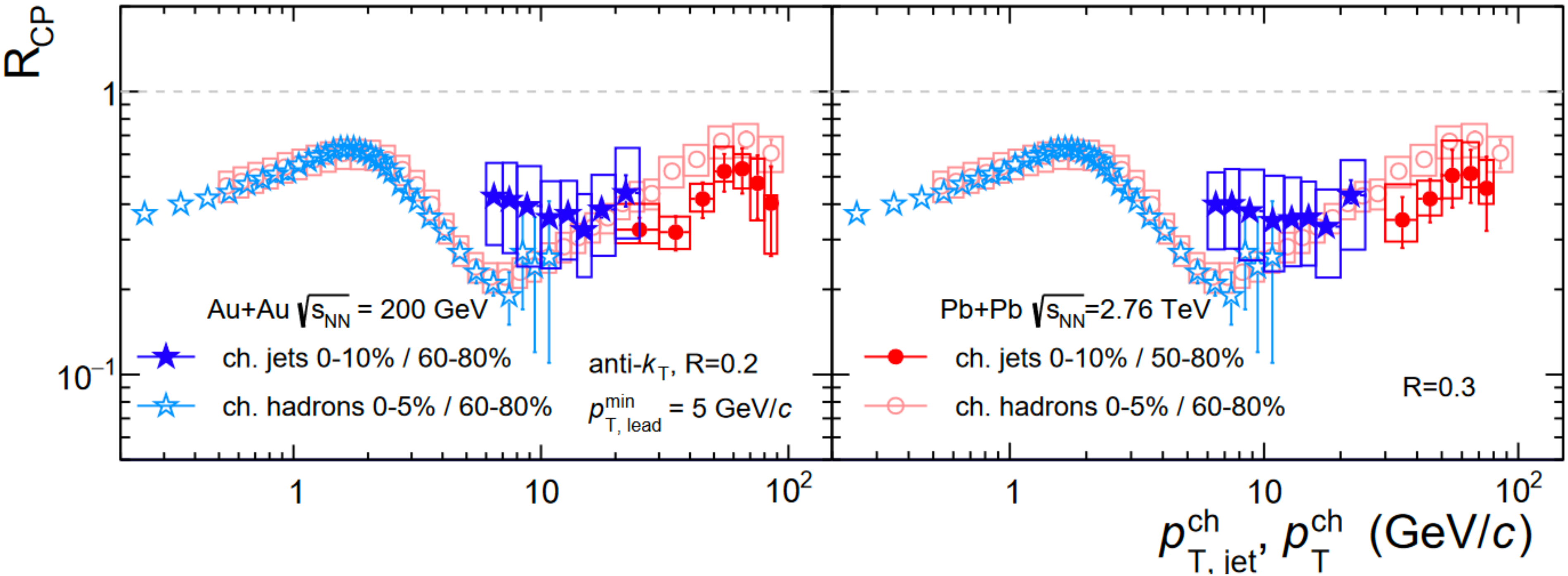


ATLAS, PLB 790 (2019) 108

Hadron vs Jet R_{AA}

Similar suppression for single hadrons and jets.

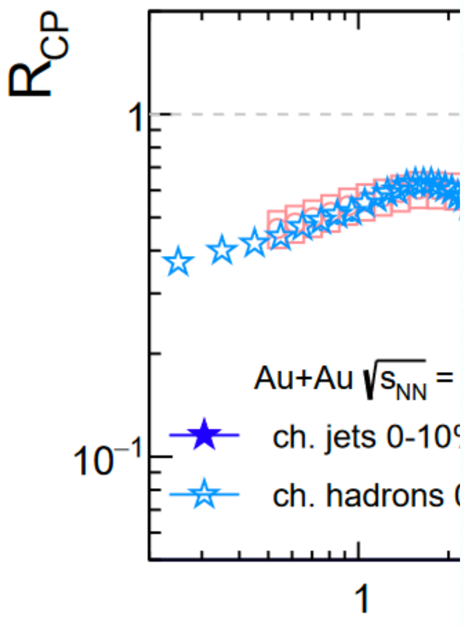
Devil is in the details.

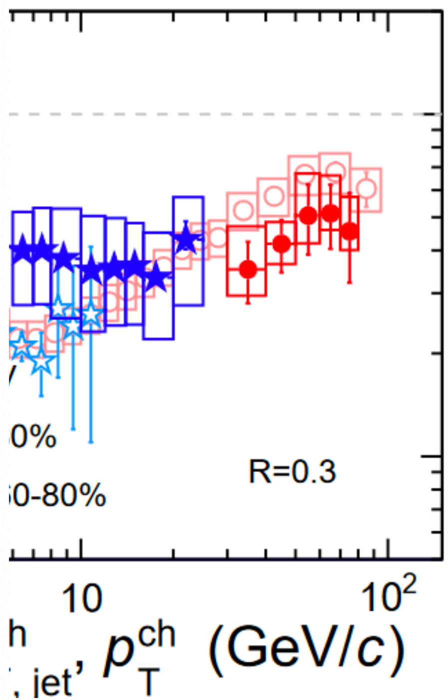


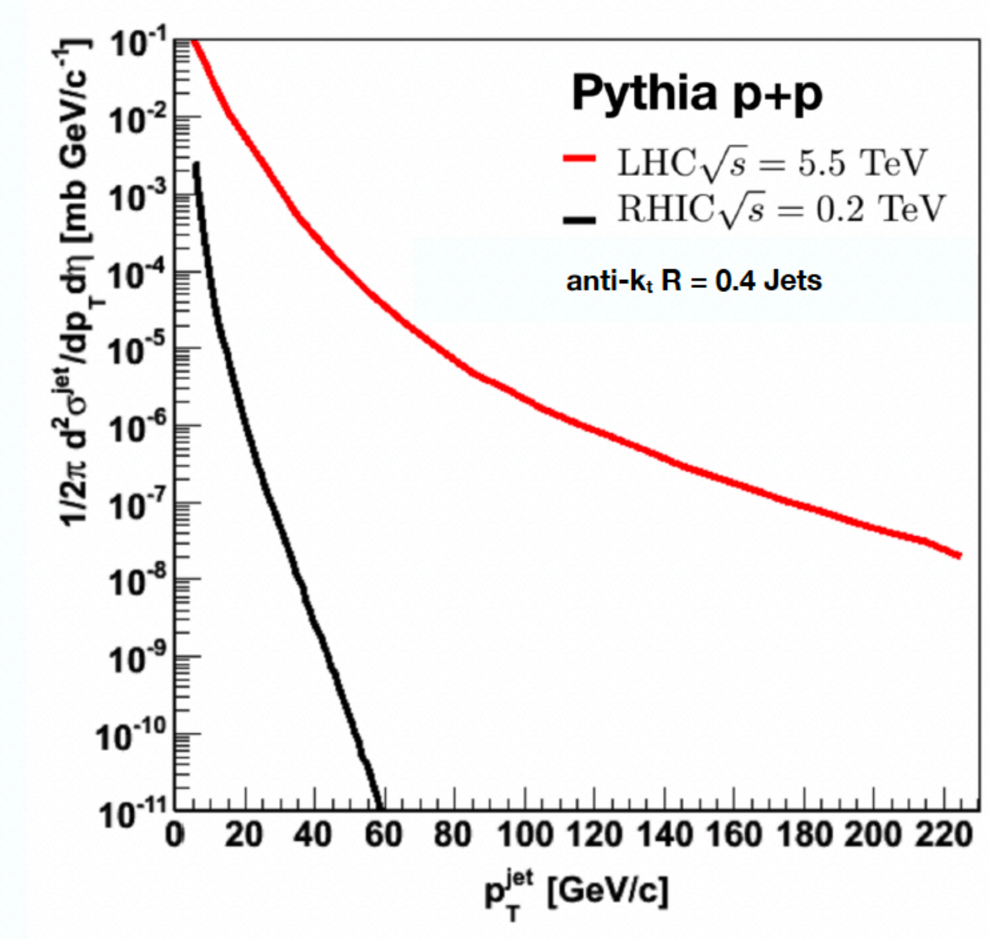
Hadron vs Jet R_{AA}

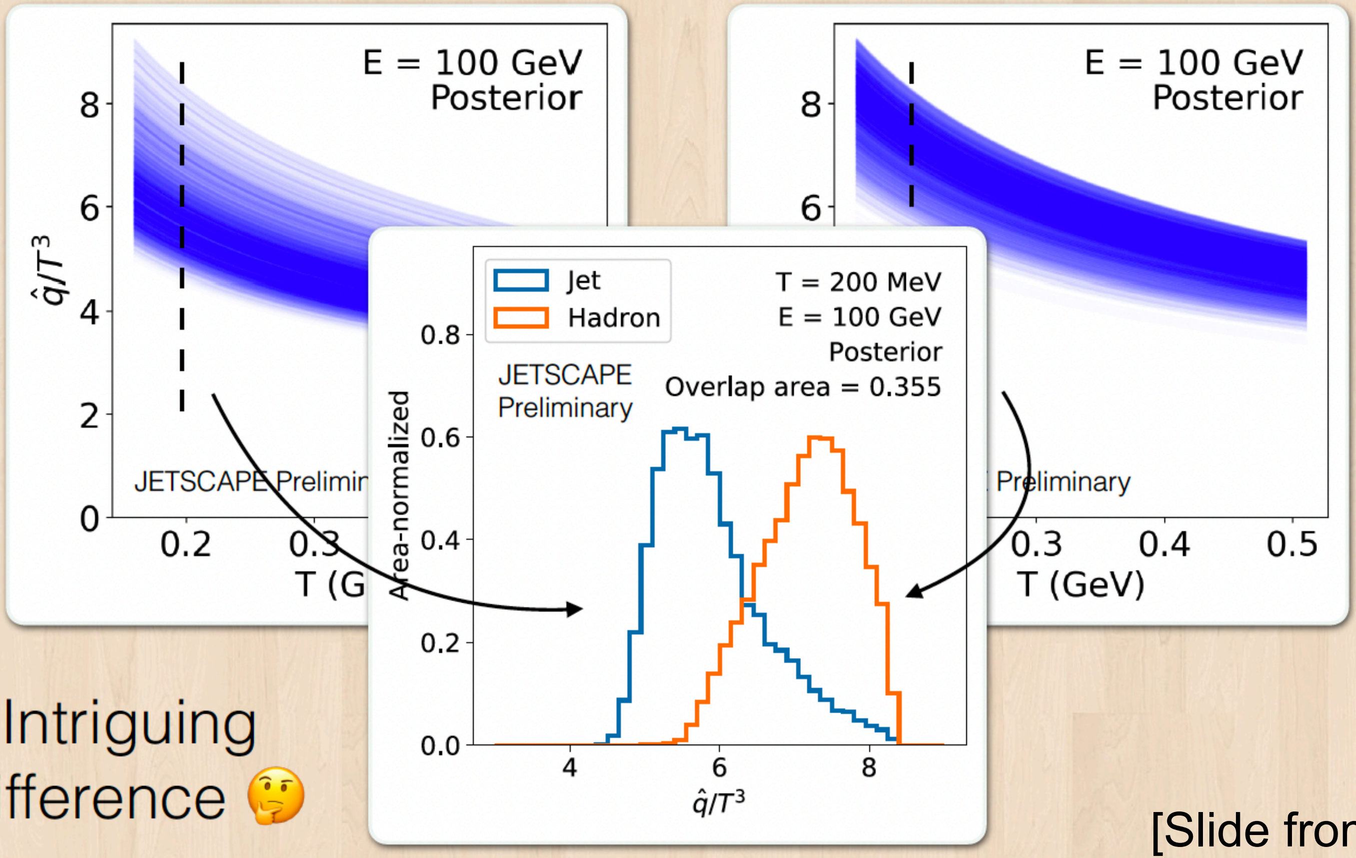
Similar supp

Devil is in th





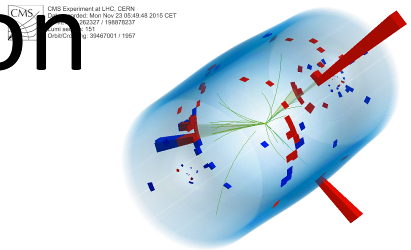




Intriguing difference 🤔

[Slide from Yi Chen]

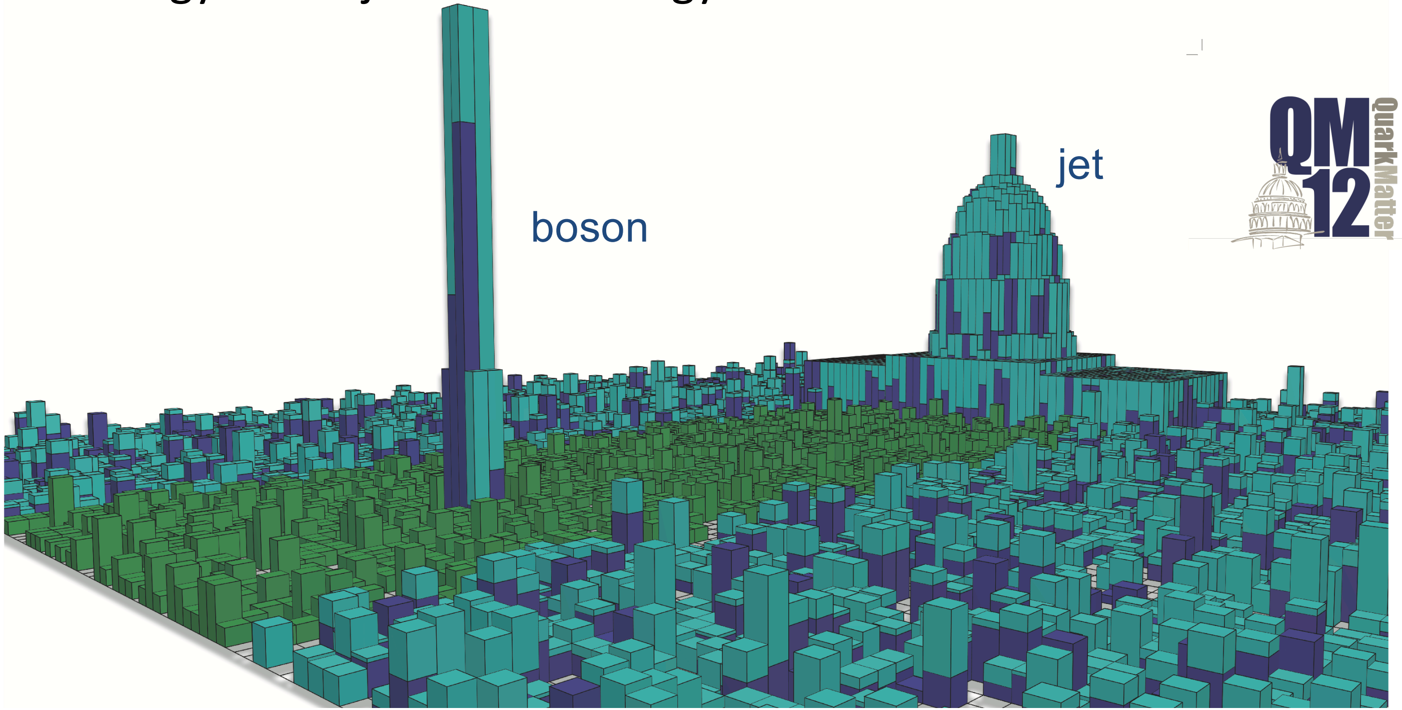
Boson-jet correlation



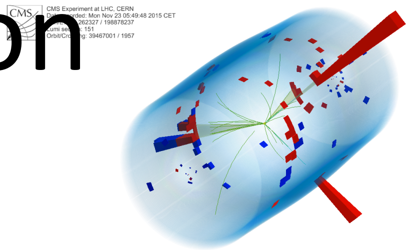
Advantage of boson-jet correlations:

Z bosons and photons aren't affected by medium

You know the energy of the jet before energy loss



Boson-jet correlation

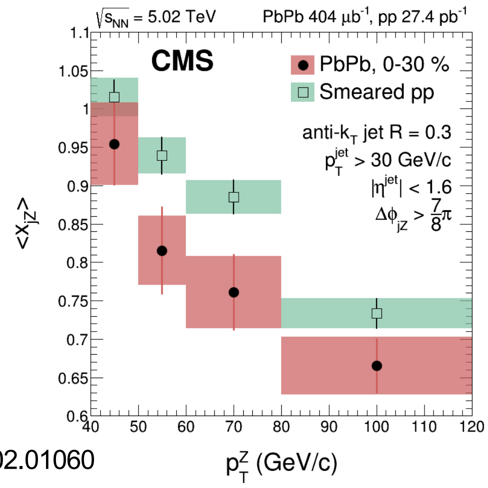


Advantage of boson-jet correlations:

Z bosons and photons aren't affected by medium

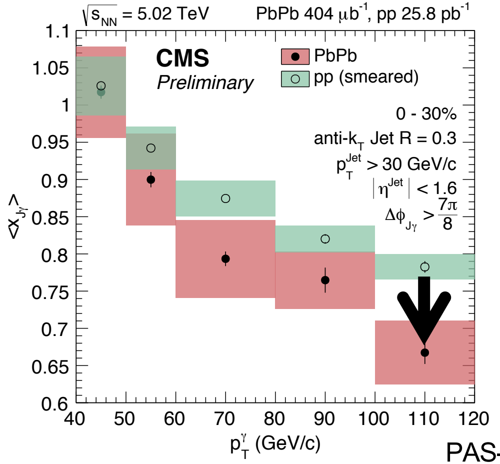
You know the energy of the jet before energy loss

Z-jet



arXiv: 1702.01060

photon-jet



$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

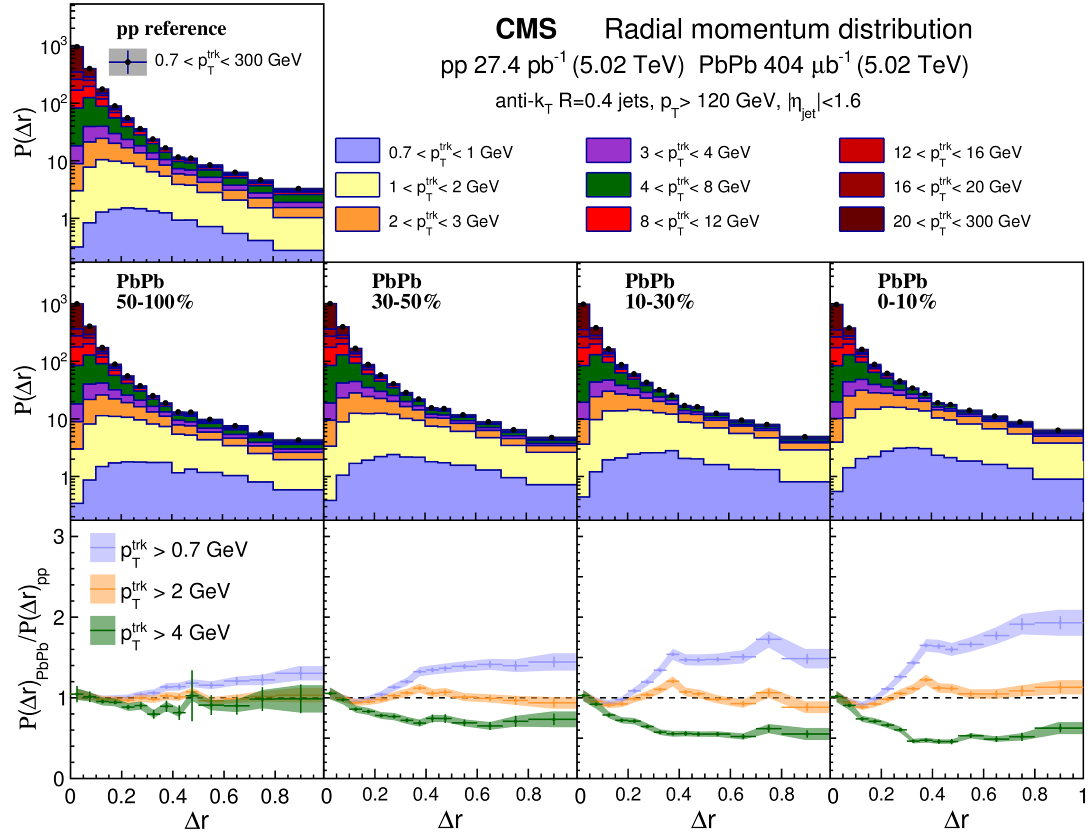
pp

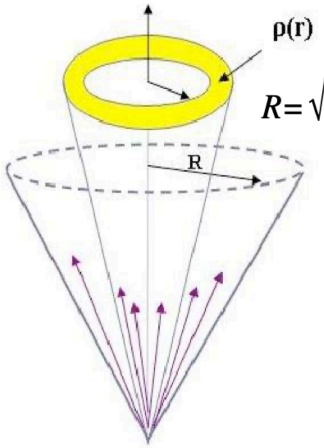
PbPb

PAS-HIN-16-002

Jets loose ~15% energy due to medium interaction

Where did the energy go?





$$R=\sqrt{\Delta y^2+\Delta\varphi^2}$$

JHEP 05 (2018) 006

Thank you