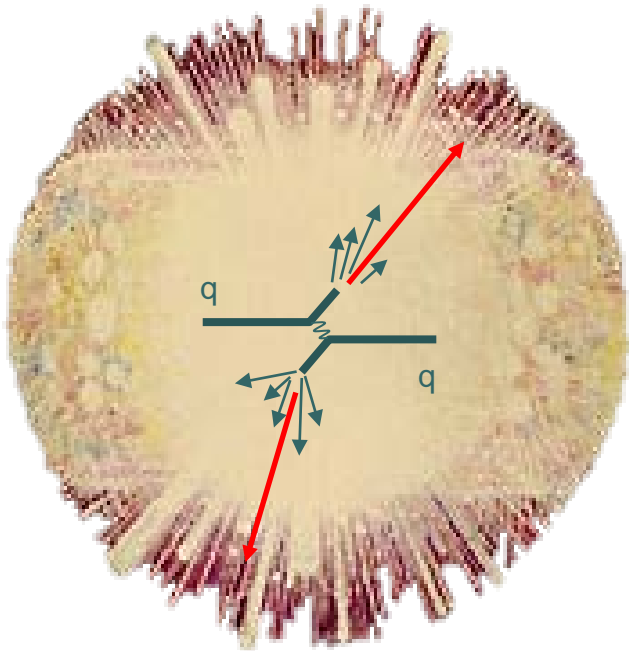


Jets: Experiment or Tomographic studies of QGP

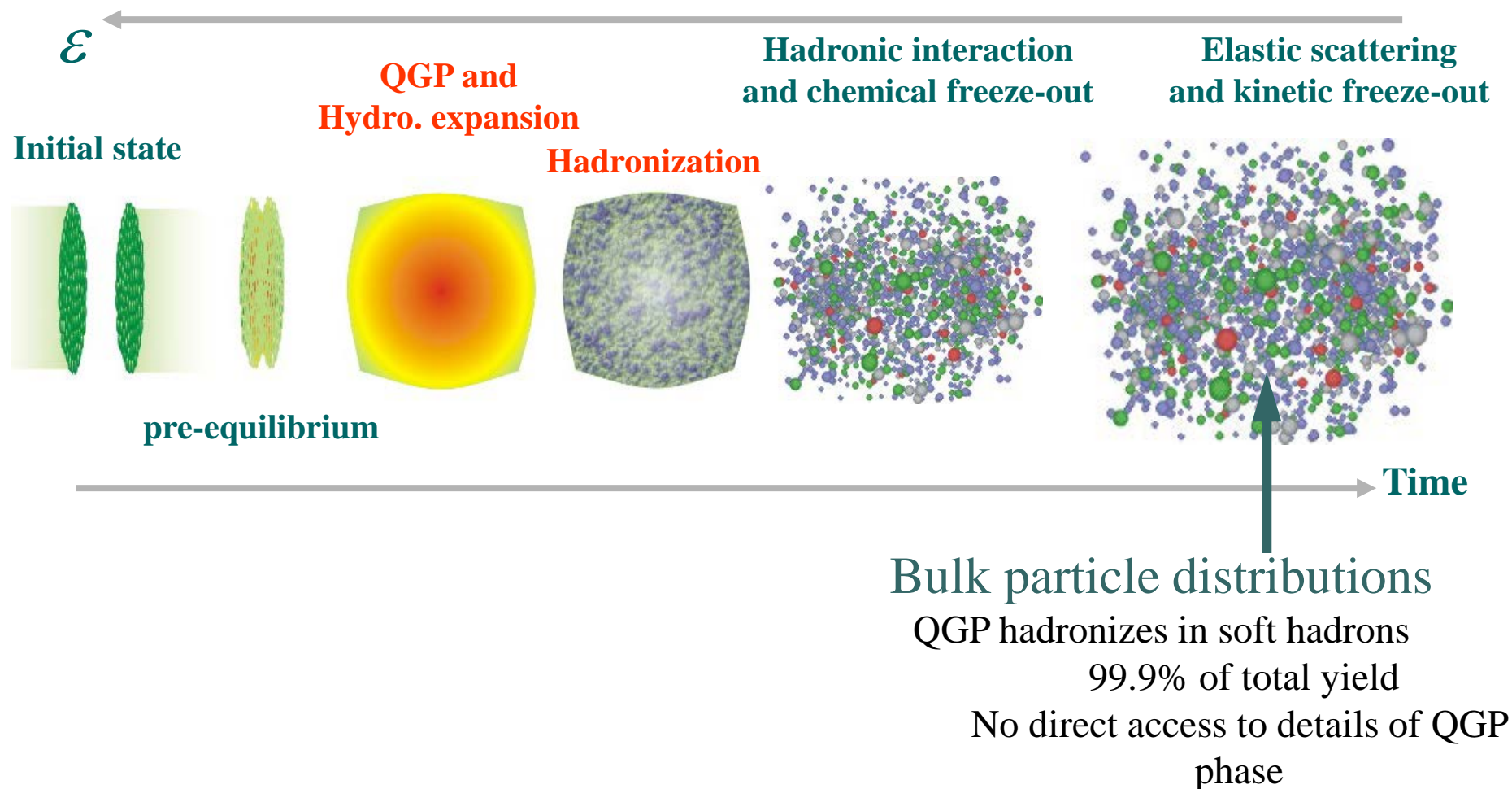


Tomographic medium studies: jets
Jet quenching – how do we see it?
Correlations (of all sorts) for jet studies in QGP

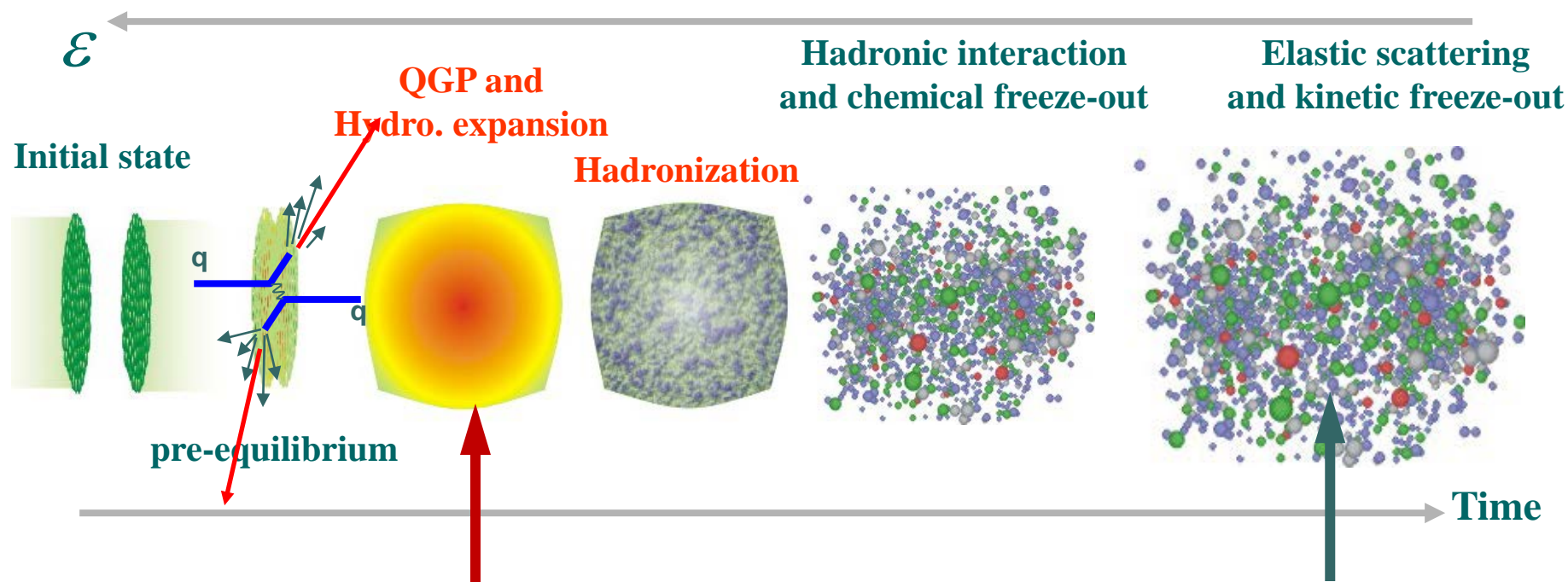
Olga Evdokimov

University of Illinois at Chicago

Heavy Ion Collision Evolution



Heavy Ion Collision Evolution



Need QGP tomography

To directly access plasma properties

Bulk particle distributions

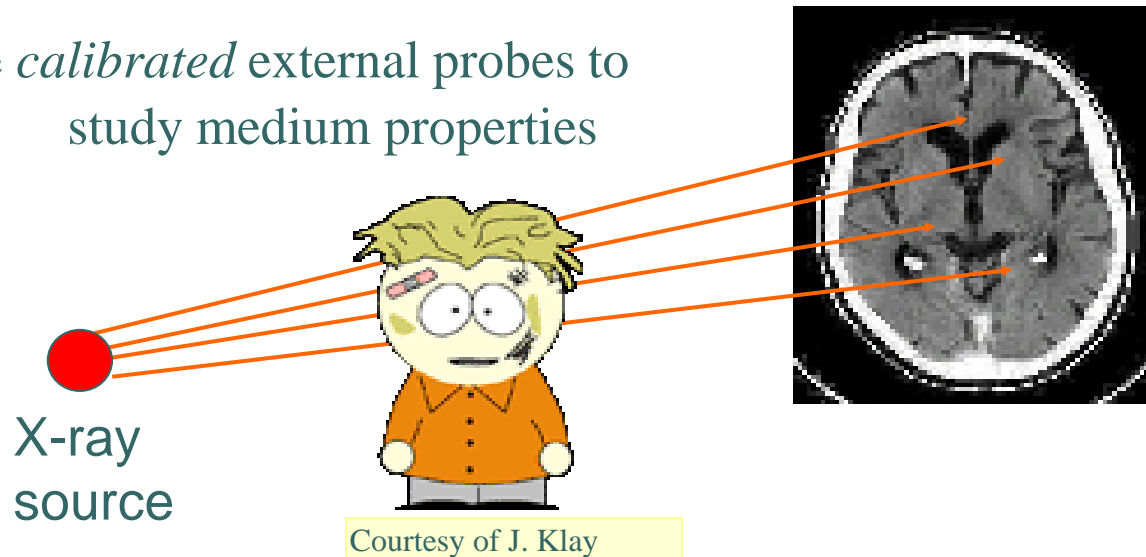
QGP hadronizes in soft hadrons
99.9% of total yield

No direct access to details of QGP phase



Tomographic probes for QGP

Idea - use *calibrated* external probes to study medium properties



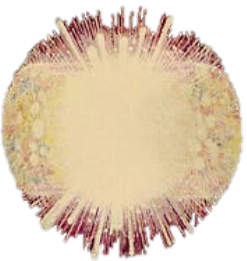
For Heavy Ion collisions → use self-generated (in)medium probes → hard probes!

“Hard” == large scale → theory: suitable for perturbative QCD calculations

high momentum transfer Q^2

high transverse momentum p_T

high mass m



Why Jets?

What are Jets?

In theory: fragmented hard-scattered partons \rightarrow collimated spray of hadrons produced by energetic q or g

Why Jets?

Jets are produced in the earliest phase of the collision

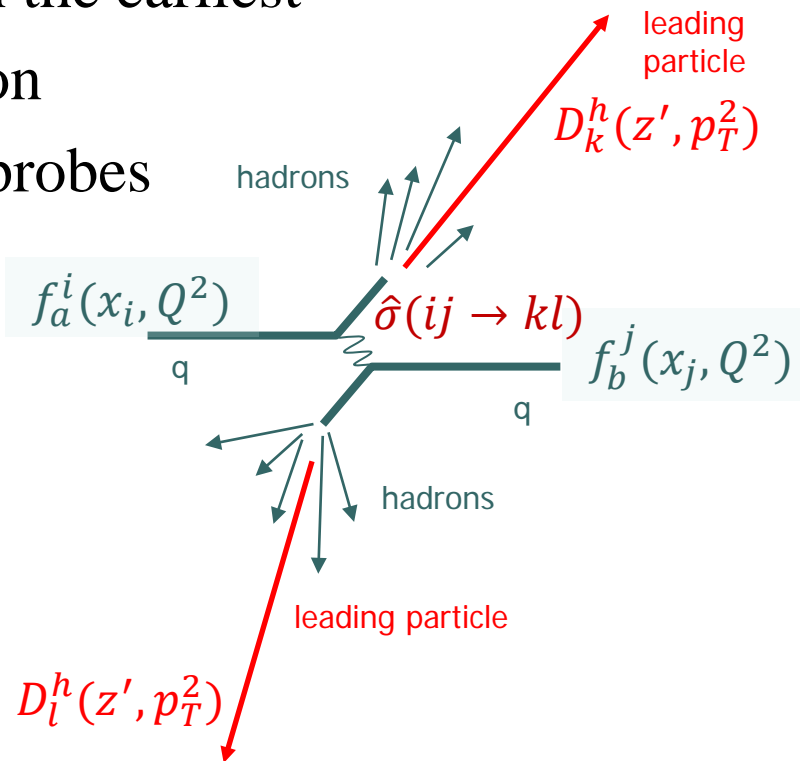
Jets are *calibrated* probes

Factorization of jet/particle production:
yields described by convolution of

$$f_a^i(x_i, Q^2) \otimes \hat{\sigma}(ij \rightarrow kl) \otimes D_k^h(z', p_T^2)$$

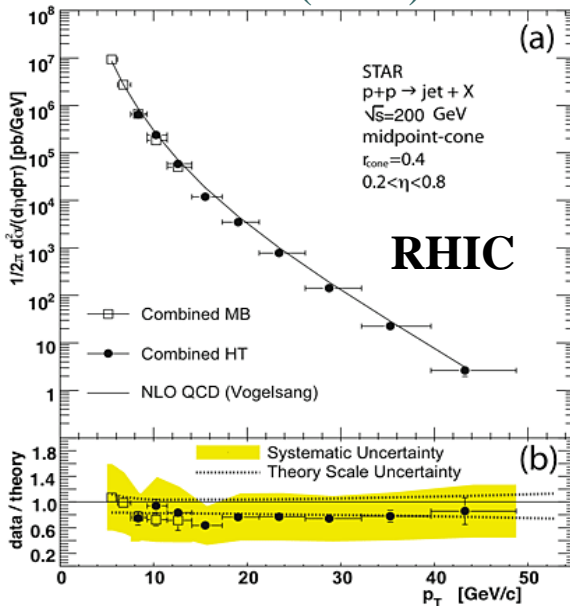
$$f_b^j(x_j, Q^2)$$

$$\text{PDF} \otimes \text{NLO} \otimes \text{FF}$$

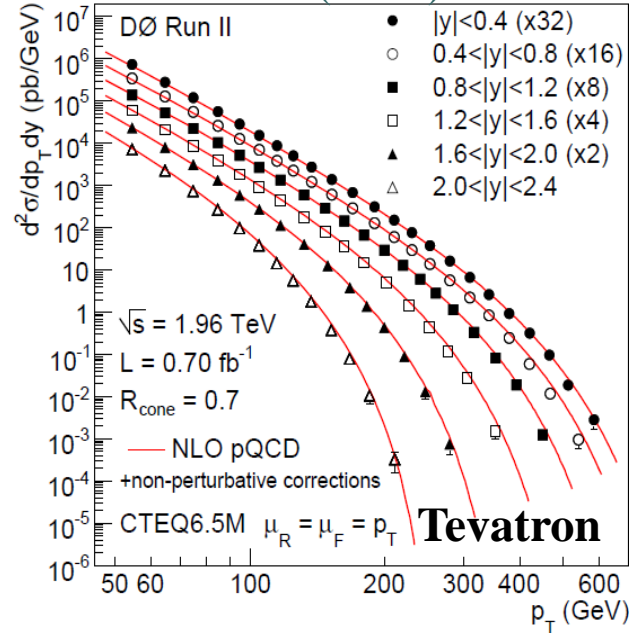


Jet Production Cross-Section

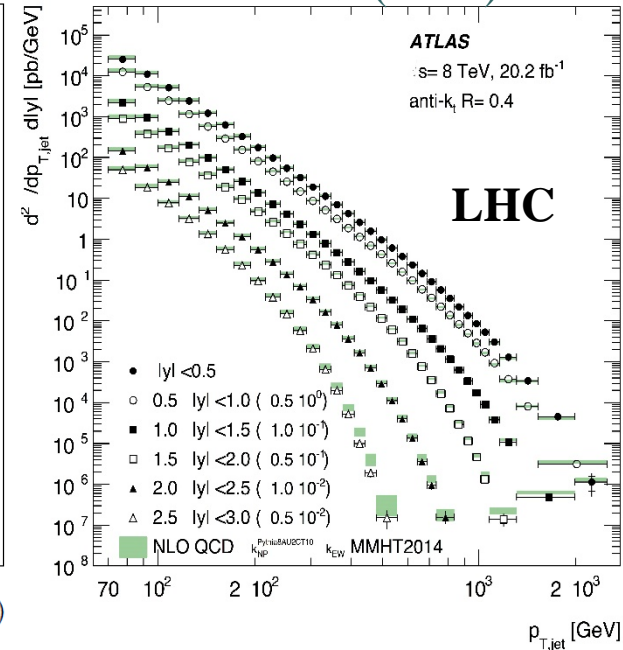
PRL 97 (2006) 252001



PRL 101 (2008) 062001



JHEP 09 (2017) 020



Jets are:

- well-calibrated probes: inclusive jet cross-sections described by NLO calculations over orders of magnitude in p_T and \sqrt{s}

QGP Properties via Jets

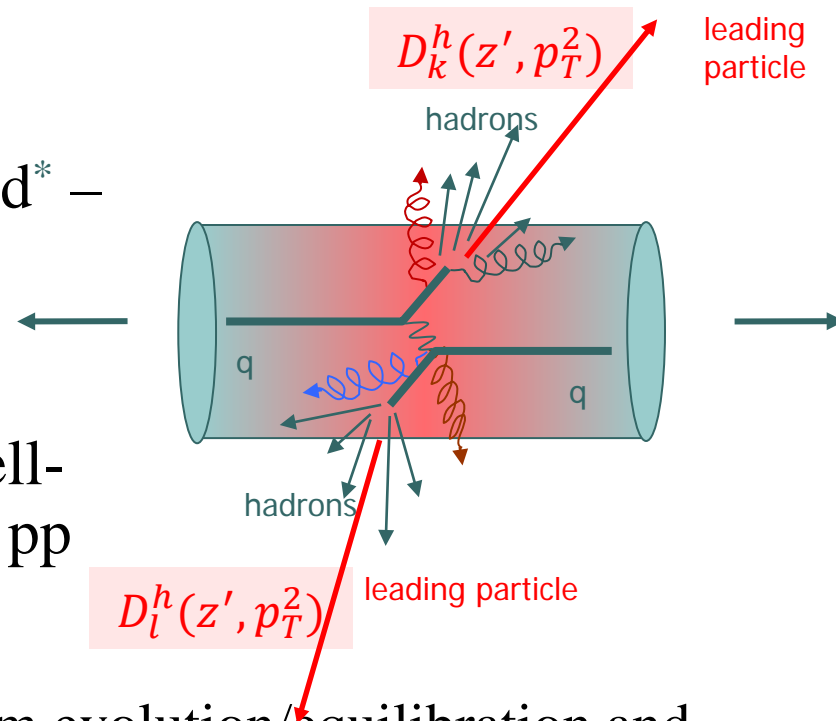
Jet Tomography:

What happens if partons traverse a high energy density colored medium?

- Production of jets is unmodified* – short-distance process
($\hat{\sigma}(ij \rightarrow kl)$ – unchanged)

- Jets are calibrated probes – well-understood (and measured!) in pp

- Jets studies allow to observe medium evolution/equilibration and explore medium properties at different scales



*except for nPDF effects

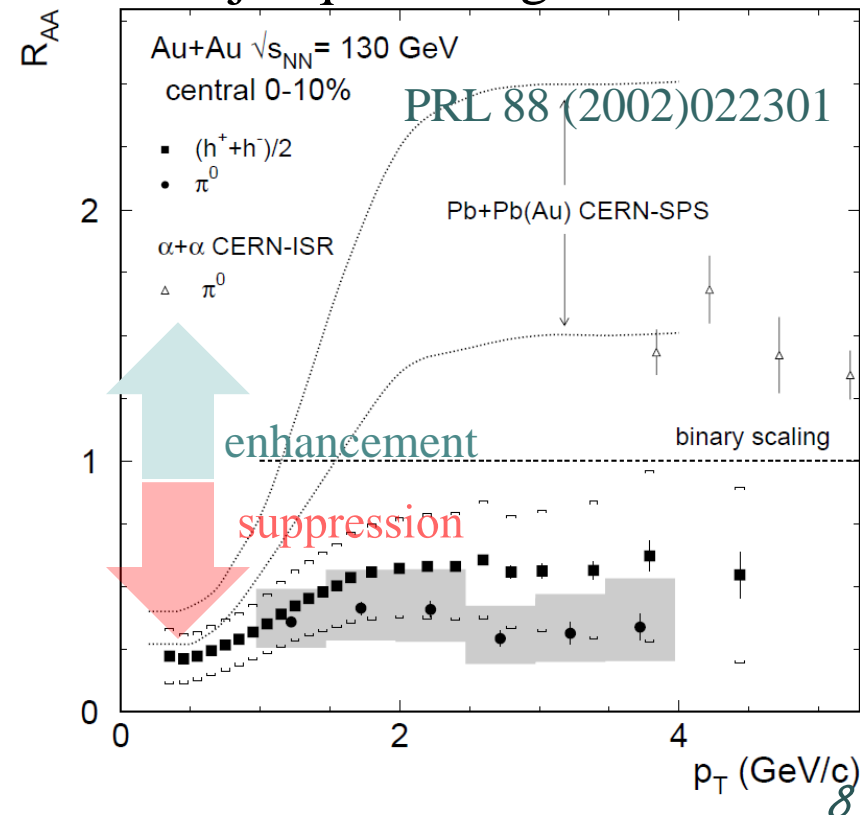
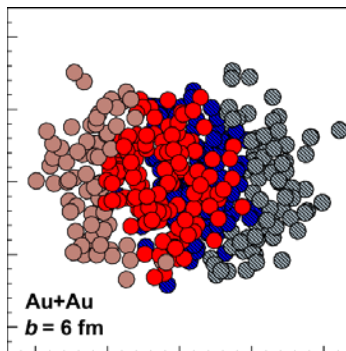
Jet Quenching: the start of the Era

Comparing particle production rates at high p_T provides (indirect) information on the fate of the jets in QGP

Nuclear Modification Factor R_{AA} – the first tool for jet quenching studies

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{\langle N_{bin} \rangle d^2 N^{pp} / dp_T d\eta}$$

Number of binary collisions $\langle N_{bin} \rangle$ is extracted from Glauber calculations



Jet Quenching: the start of the Era

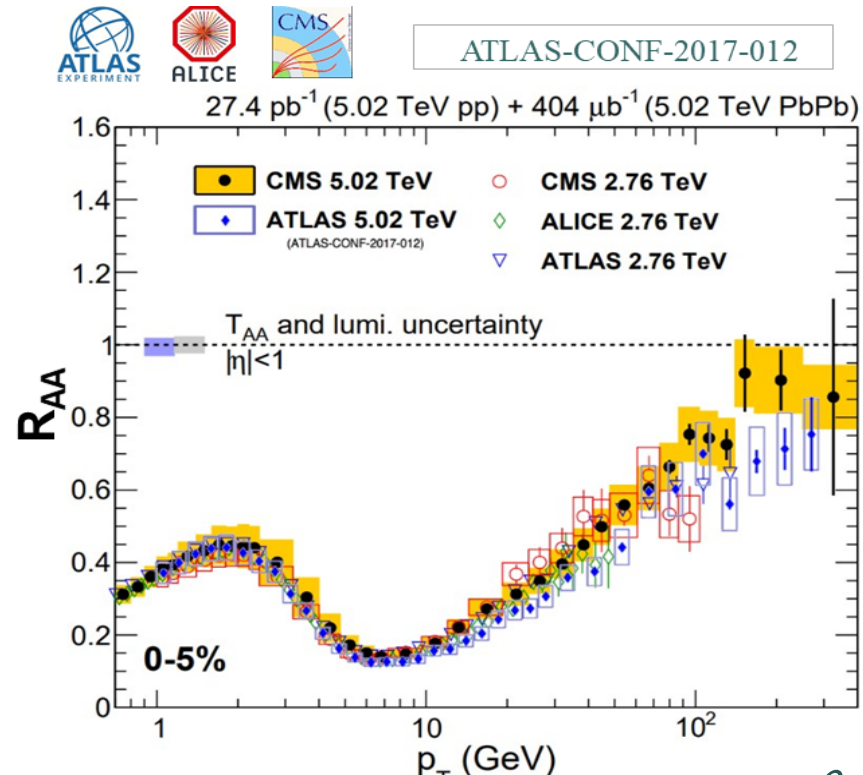
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Nuclear Modification Factor R_{AA} – is the first tool for jet quenching studies

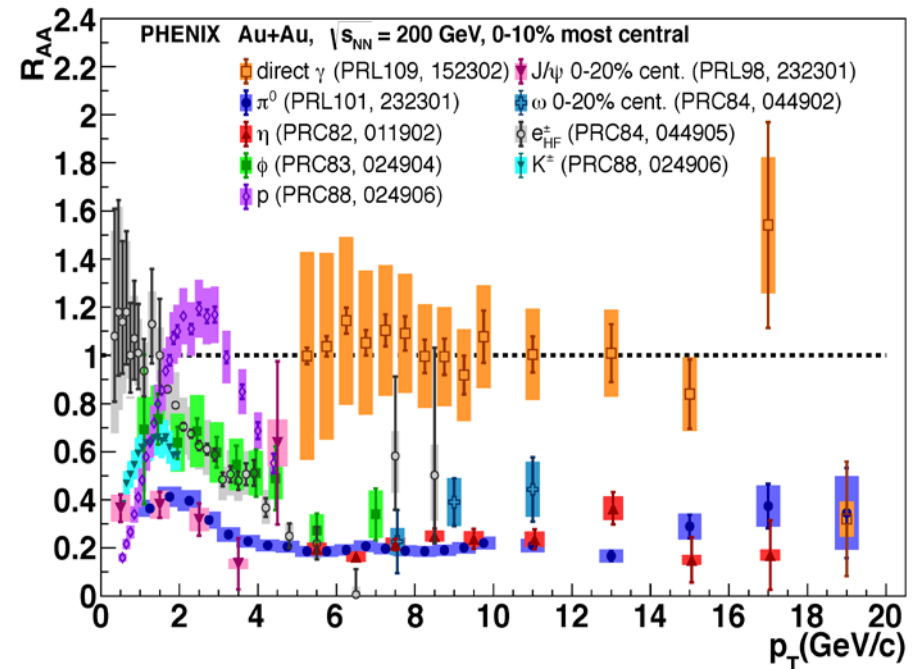
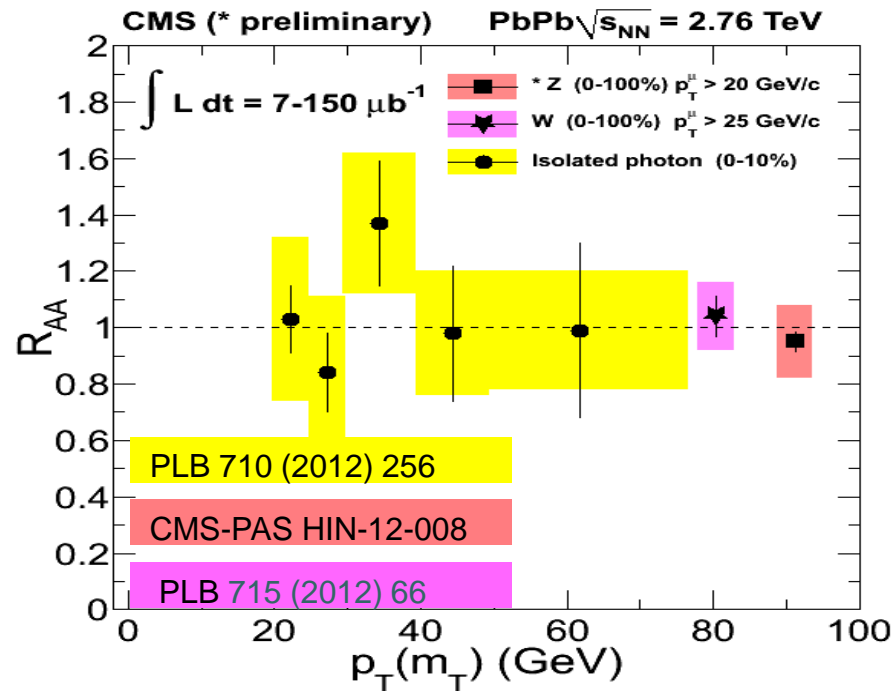
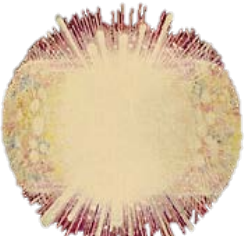
$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{\langle N_{bin} \rangle d^2 N^{pp} / dp_T d\eta}$$

R_{AA} shape/level depends on steepness of the spectra

How reliable are $\langle N_{bin} \rangle$ calculations?



Binary Scaling and R_{AA}



- Colorless probes check N_{bin} scaling:

Isolated photons

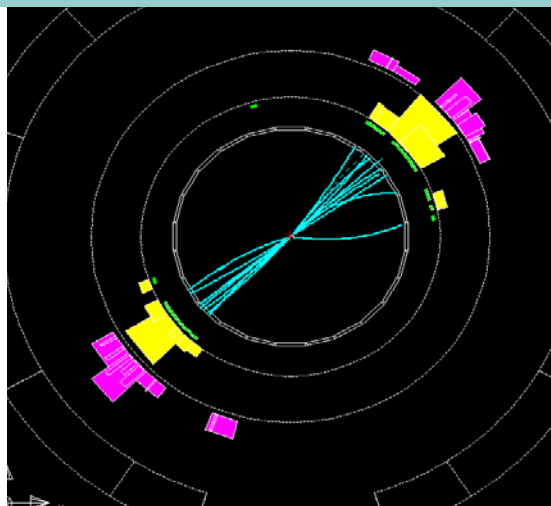
$Z \rightarrow \mu + \mu^-$

$W \rightarrow \mu \nu$

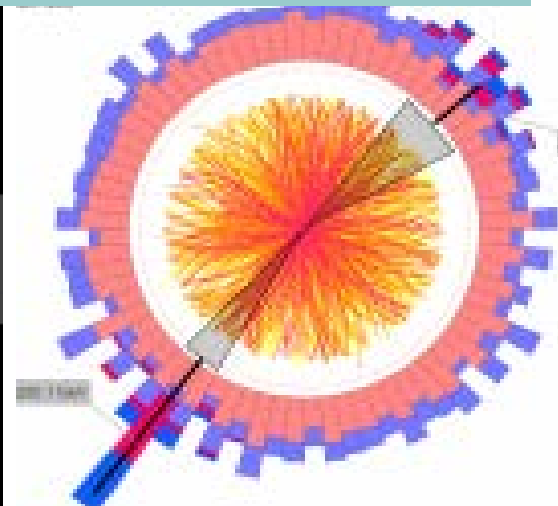
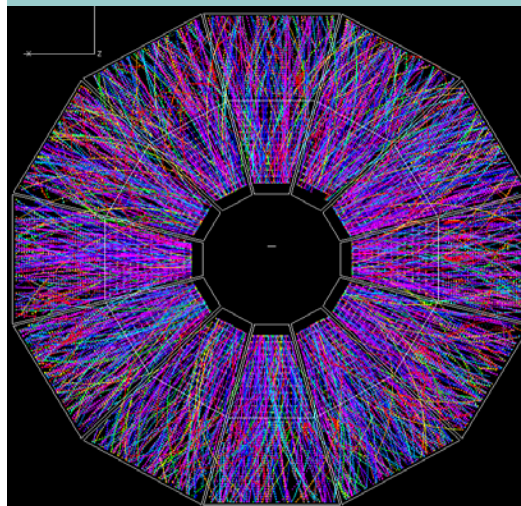
- N_{bin} is well-modeled and N_{bin} -scaling for hard processes is confirmed experimentally

Jet studies, experimentally

Jets in e^+e^- collision



Jets in AA collisions



Choice of tools (in hard regime):

Spectra/Production rates

Dihadron correlations

Jets/Dijets

Pros: straightforward

Cons: least differential

versatile

*multiple BG sources,
no direct E measure*

E_{parton}

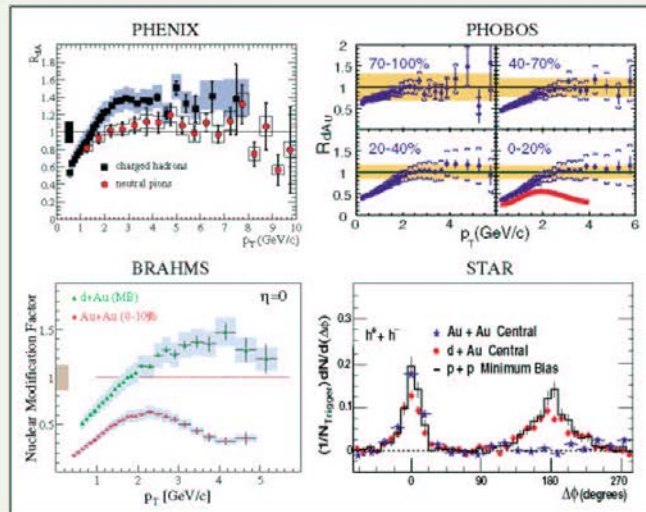
*ambiguous,
fluctuations*

Evidence for Jet-Medium Interactions

PHYSICAL REVIEW LETTERS

Articles published week ending
15 AUGUST 2003

Volume 91, Number 7



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APS Published by The American Physical Society

Evidence for ‘jet quenching’ in central AuAu at RHIC

Evidence of ‘jet *non*-quenching’ in dAu (and peripheral AuAu)

Medium created is dense and opaque

Significant Energy Loss in the Medium

PHENIX: Phys. Rev. Lett. 91 (2003) 072303

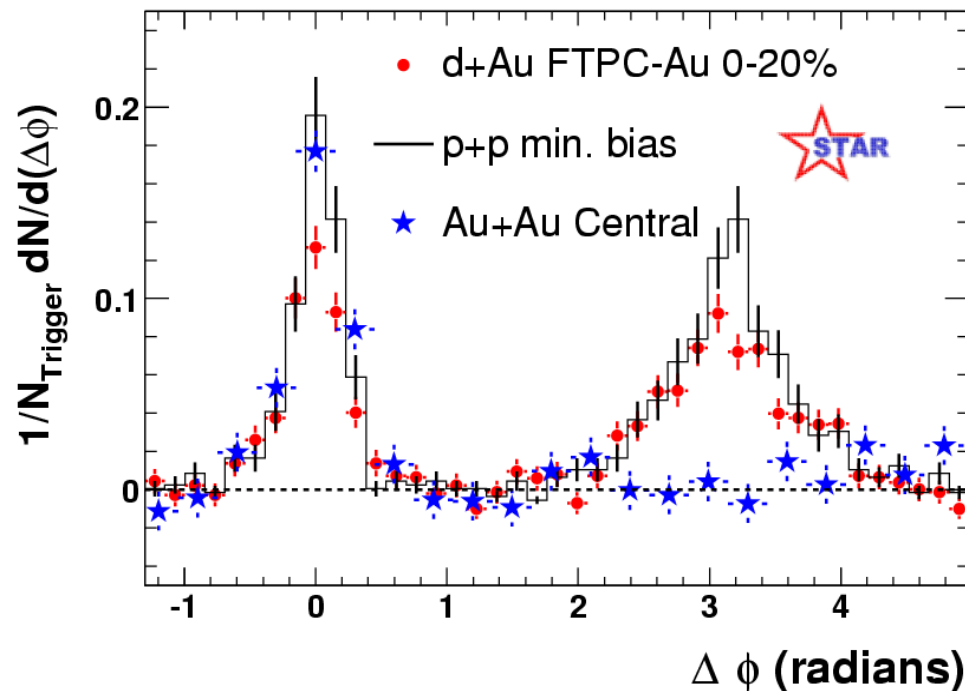
PHOBOS: Phys. Rev. Lett. 91 (2003) 072302

STAR: Phys. Rev. Lett. 91 (2003) 072304

BRAHMS: Phys. Rev. Lett. 91 (2003) 072303

Evidence for Jet-Medium Interactions

PHYSICAL REVIEW LETTERS



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APS Published by The American Physical Society

Evidence for ‘jet quenching’ in central AuAu at RHIC

Evidence of ‘jet *non*-quenching’ in dAu (and peripheral AuAu)

○ Signature two-particle correlation result:

- Disappearance of the away side jet in central AuAu collisions: evidence for strongly interacting medium
- Effect vanishes in peripheral/d+Au collisions

PHENIX: *Phys. Rev. Lett.* 91 (2003) 072303

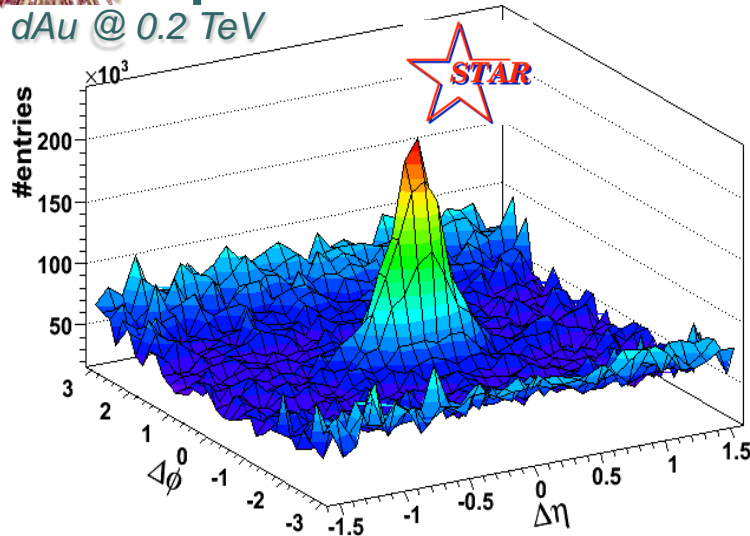
PHOBOS: *Phys. Rev. Lett.* 91 (2003) 072302

STAR: *Phys. Rev. Lett.* 91 (2003) 072304

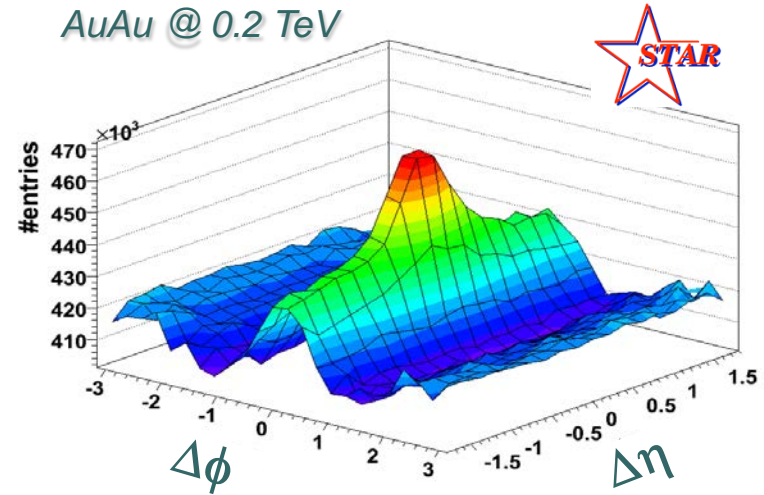
BRAHMS: *Phys. Rev. Lett.* 91 (2003) 072303

Signature Results: the Ridge

dAu @ 0.2 TeV



AuAu @ 0.2 TeV



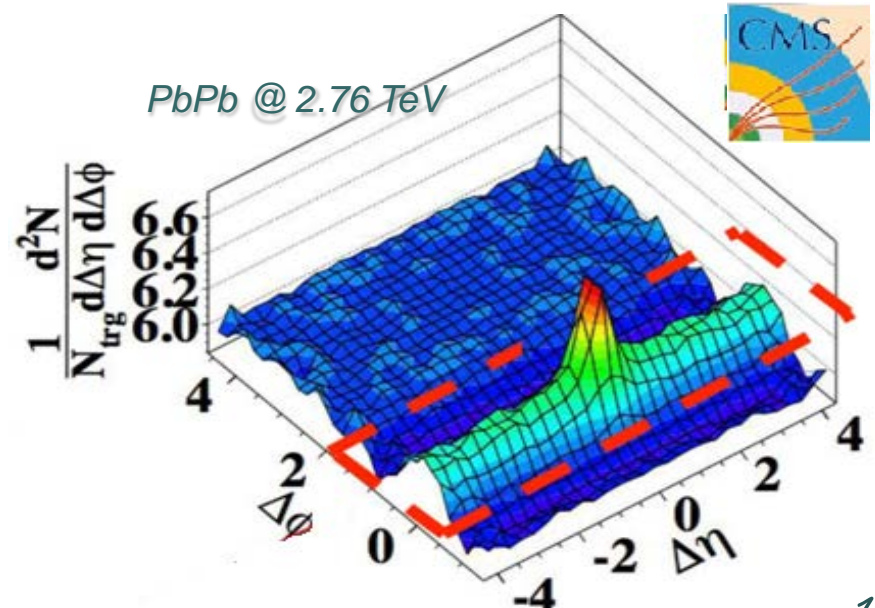
Initial Assessment:

- Present in AA, not in dA
- Correlated with Jet direction
- QGP phenomenon

Early Ideas on Ridge origin:

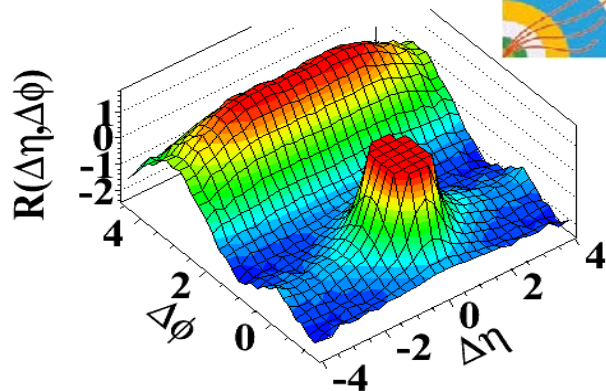
- In-medium radiation + long. flow push?
- Sonic boom with “splash-back”?
- Turbulent color fields?

PbPb @ 2.76 TeV



Signature Results: the Ridge

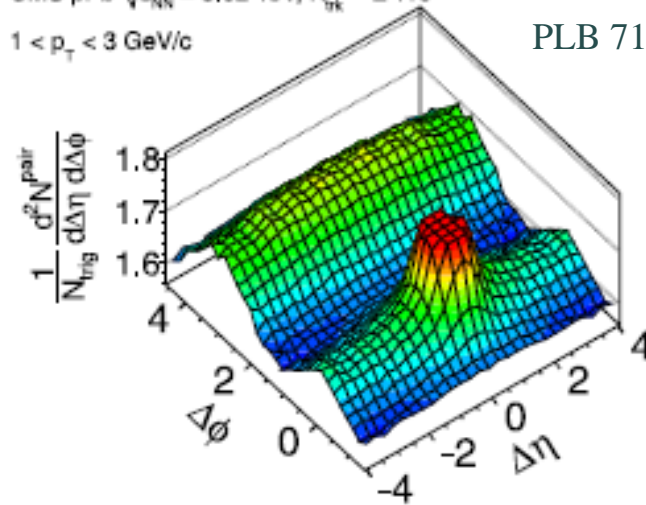
(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



High multiplicity pp @ 7 TeV

CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{ch}^{0.5 < \eta < 0.8} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$

PLB 718 (2013) 795



High multiplicity pPb @ 5 TeV

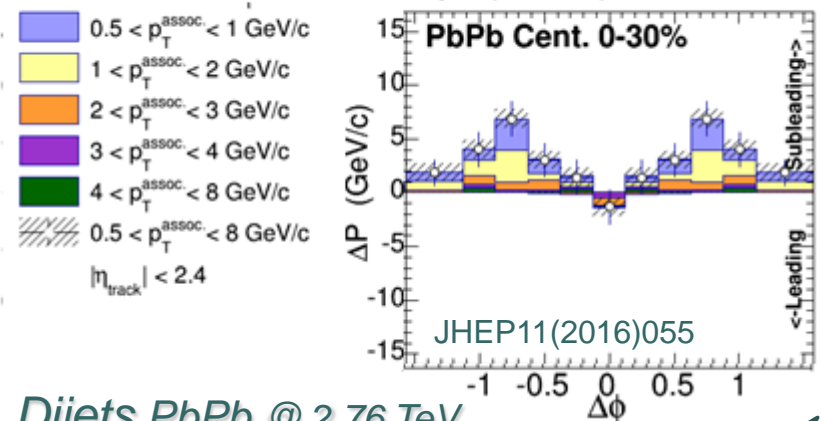
NOW:

- Ridges are everywhere: high multiplicity pp, pA
- “Soft” phenomenon

Jet studies:

- Underlying event (UE) is anisotropic; correlations have to be taken into account while extracting the jet signal

Long Range, $|\Delta\eta| < 2.5$ $A_J < 0.22$
PbPb $166 \mu\text{b}^{-1}$ (2.76 TeV) pp 5.3 pb^{-1} (2.76 TeV)



Dijets PbPb @ 2.76 TeV



Lets get us some Jets!

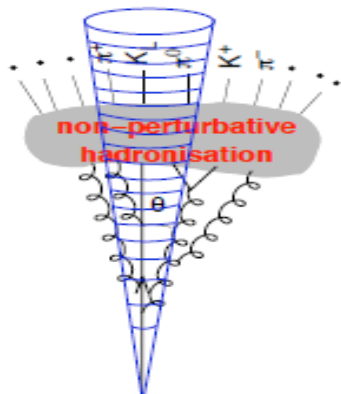
In Theory: jets are proxies for hard-scattered partons

In Experiment: “Jet is what your jet-finder gives you” (P.J.)

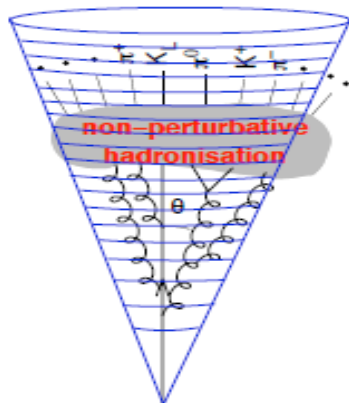
Jet is defined by the reconstruction algorithm:

- 1) What particles belong to a jet
- 2) How particle momenta combined into jet p_T

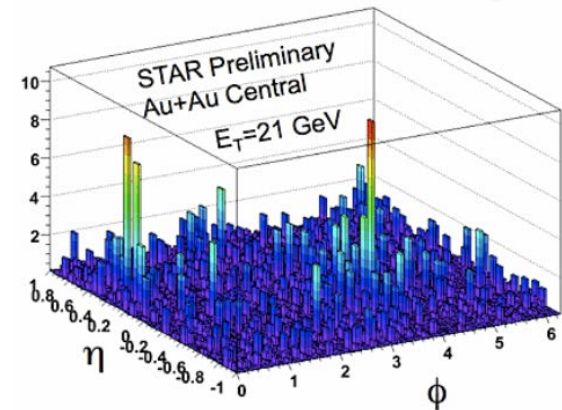
Small jet radius



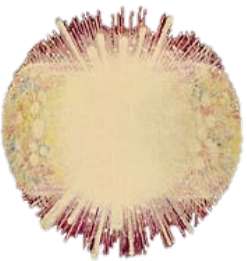
Large jet radius



AuAu @ 0.2 TeV



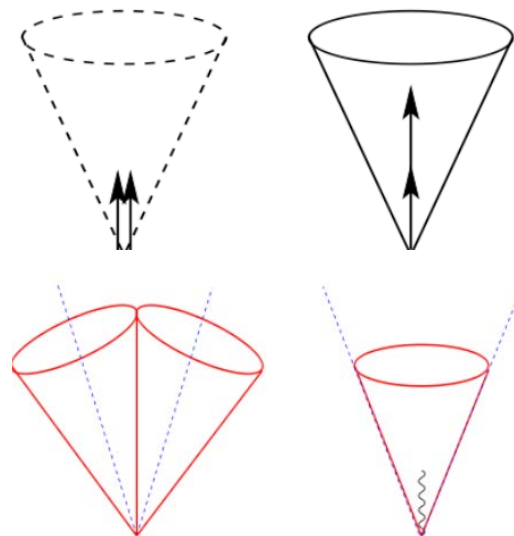
Particularly difficult for AA data due to UE background: R choice dilemma



Jet Algorithms

Important Requirements for Jet Finders:

- Simple implementation and reproducibility (theory/experiment)
- Tolerance to fragmentation details and UE
- Collinear- and infrared-safe



Two classes of Jet Finders:

Cone-Type

Midpoint Cone (Tev), Iterative Cone (CMS),
SISCone (LHC),...

- Not Infrared- & Collinear-Safe (but SISCone)
- Usually involve several arbitrary parameters
- Computationally fast
- Disfavored by theorists

Sequential Recombination

k_T , Anti- k_T , Cambridge/Aachen

- Infrared- & Collinear-Safe by construction
- Straightforward, though more computationally expensive
- Favored by theorists

Sequential Recombination Algorithms

- Sequential recombination methods are based on distance measure:

$$d_{ij} = \min(p_{T,i}^{2\rho}, p_{T,j}^{2\rho}) \frac{\Delta R^2}{R^2} \quad \text{and} \quad d_{iB} = p_{T,i}^{2\rho}$$

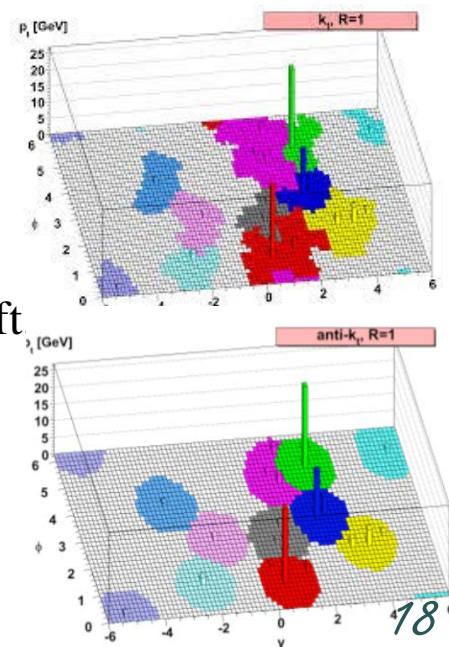
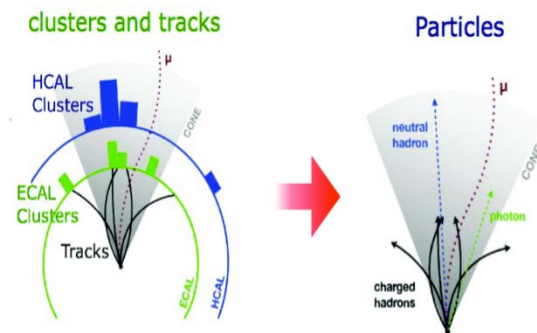
- Most commonly used:

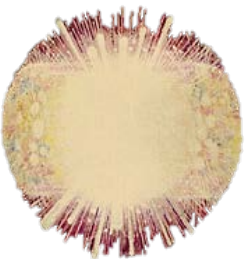
- k_T algorithm** $\rho = 1$ PLB641(2006)57
 - anti- k_T algorithm** $\rho = -1$ JHEP 0804 (2008) 063
 - Cambridge-Aachen algorithm** $\rho = 0$ JHEP 9708 (1997) 001

- Do iteratively:

- compute all distances d_{ij} and d_{iB} , find the smallest
 - If smallest is a d_{ij} , combine (sum four momenta) for i and j
 - If smallest is a d_{iB} , call i a jet (remove). Stop then no objects left

- All three algorithms (+SISCone) are available in the Fastjet package: <http://fastjet.fr/>





Dealing with Background

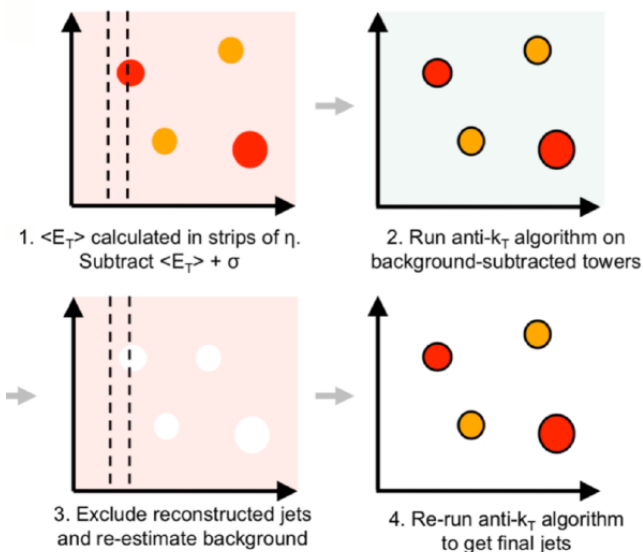
The background in HI events is anisotropic and fluctuating → simple “flat-line” subtraction won’t work. Need:

- 1) Modulated BG (shape!)
- 2) Corrections/unfolding for fluctuations (or reference smearing)

Two general strategies:

“Subtract then Cluster”

Iterative pedestal subtraction method



“Cluster then Subtract”

Area Subtraction

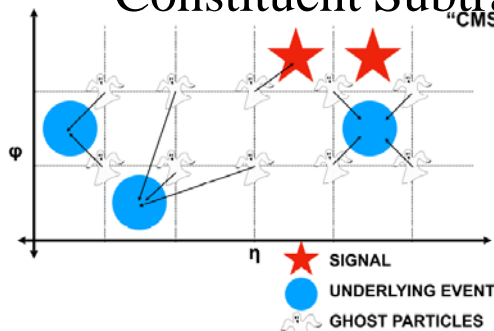
$$p_T^{(corr)} = p_T^{(reco)} - \rho A_j$$

ρ – average p_T density for BG w/o jets

A_j – jet area from “ghost” counts

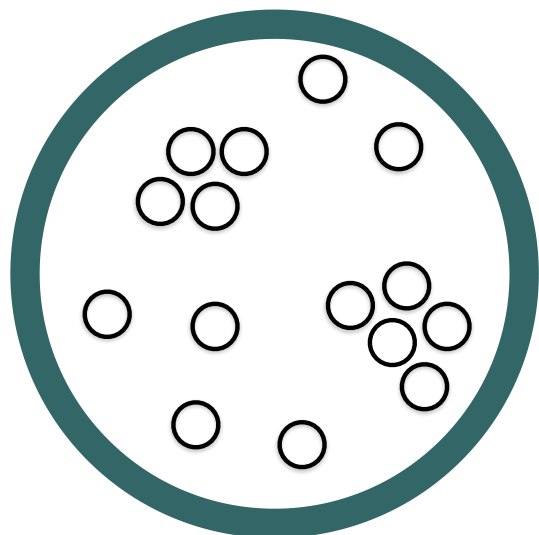
Constituent Subtraction

JHEP06(2014)092

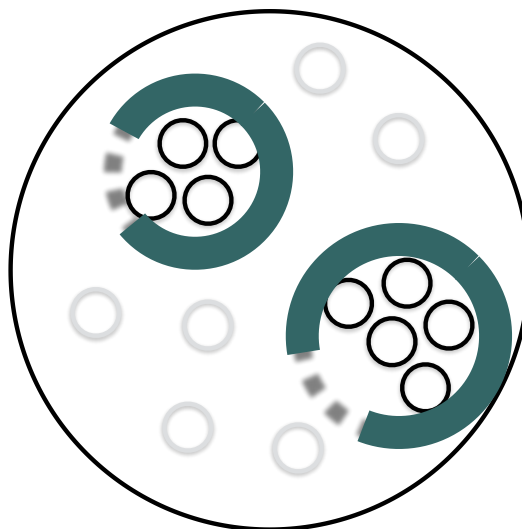


Jet Inner Workings

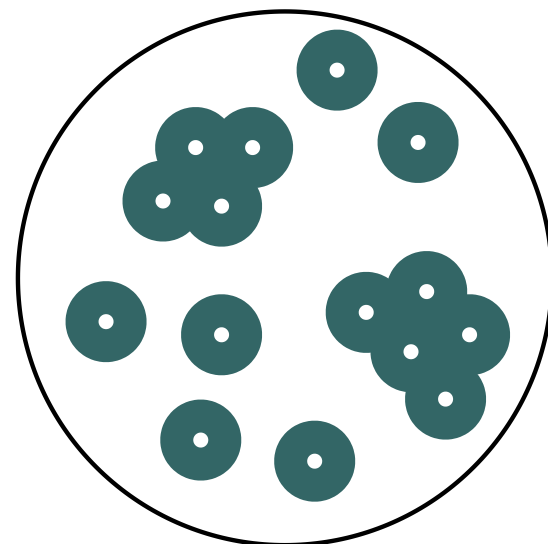
Full Jet



Jet Substructure



Jet Constituents



Cartoons courtesy Yi Chen

Jet energy

Jet R_{AA}

Energy balance:

Di-jet, Z-jet, γ -jet

Large-scale structure

Momentum Sharing

(Splitting Function)

Jet Mass

Jet energy flow

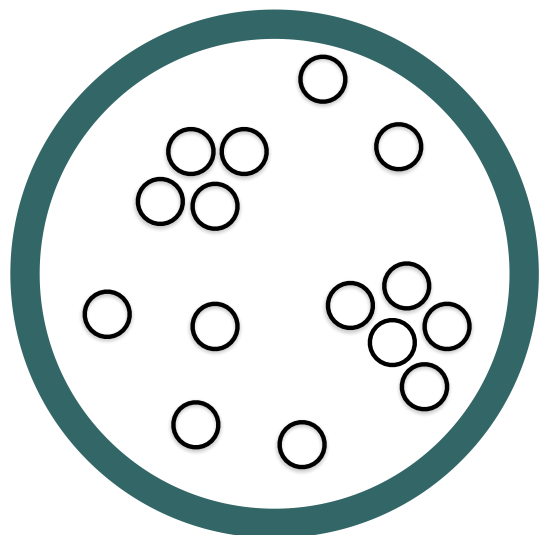
Jet Shapes

Fragmentation Functions

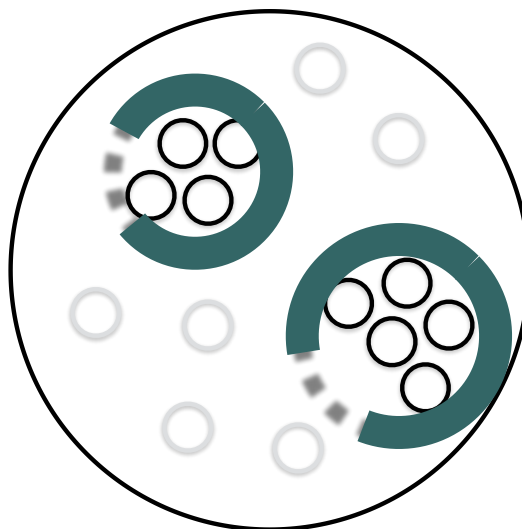
Number density profiles

Jet Inner Workings

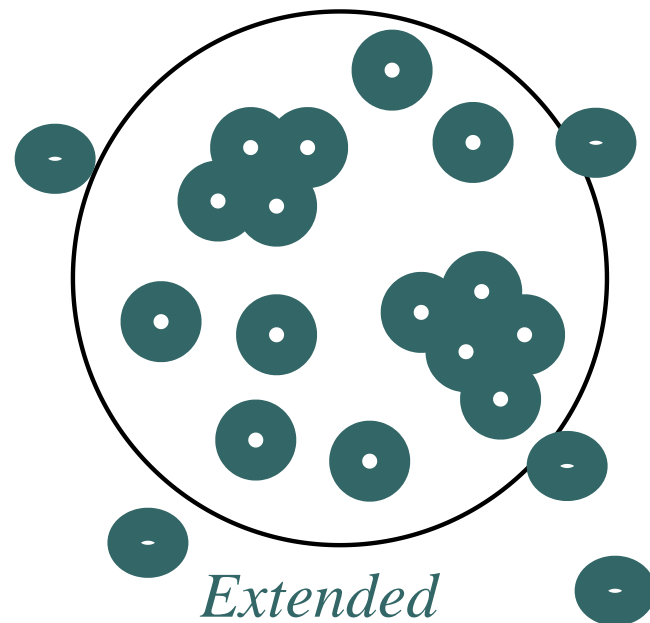
Full Jet



Jet Substructure



Jet Constituents



Extended

Jet energy

Jet R_{AA}

Energy balance:

Di-jet, Z-jet, γ -jet

Large-scale structure

Momentum Sharing

(Splitting Function)

Jet Mass

Jet energy flow

Jet Shapes

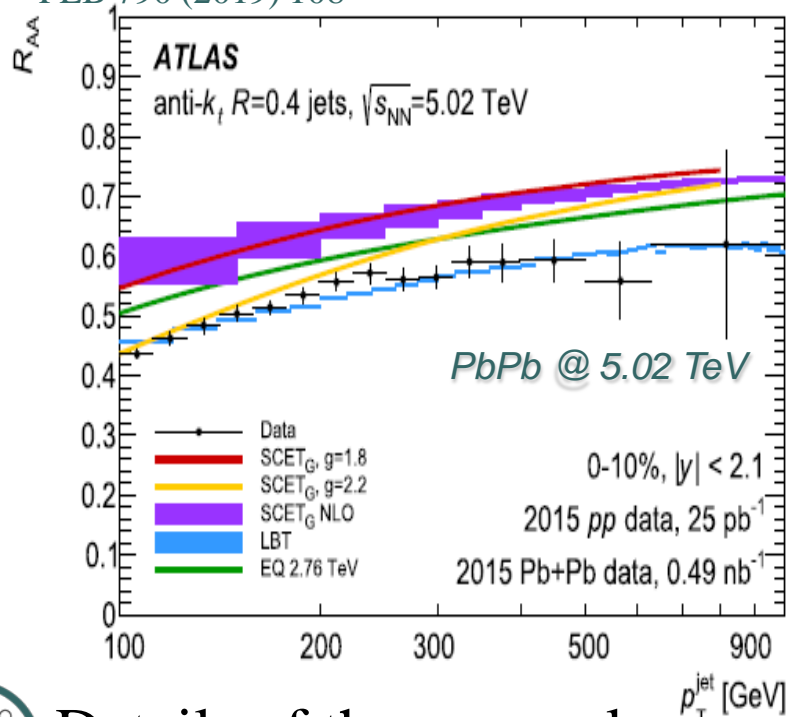
Fragmentation Functions

Number density profiles

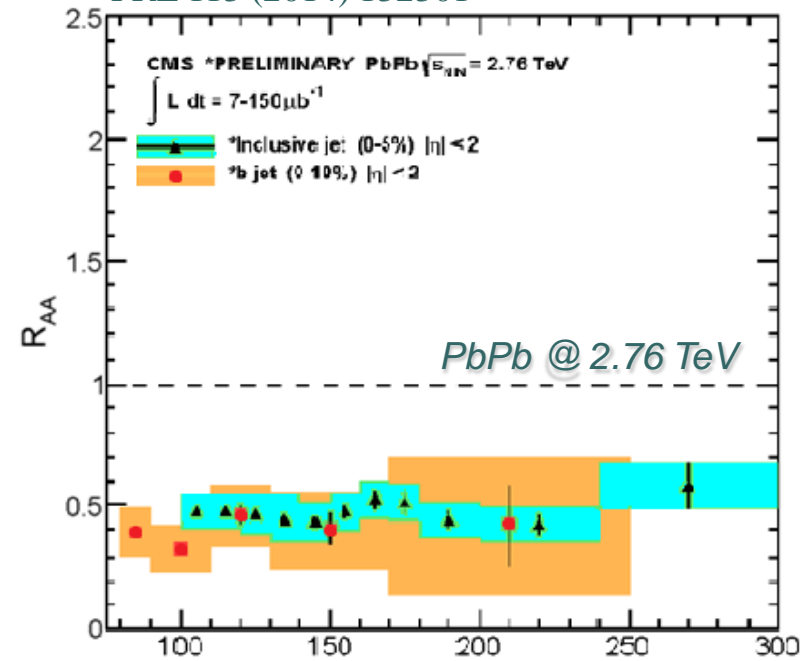
Cartoons courtesy Yi Chen

Quenching Effects in Jets

PLB 790 (2019) 108



PRL 113 (2014) 132301



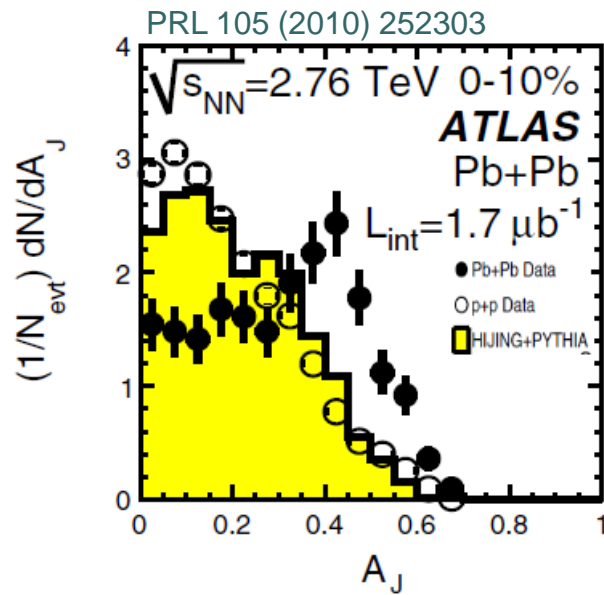
Details of the energy loss:

- Jet quenching in PbPb collisions is now mapped in jet R_{AA} from 30GeV to 1TeV
- Strong suppression at both HI energies (but this factor of ~ 2 suppression can be accounted for by ~ 7 GeV energy loss)
- All jets are suppressed: b-jet R_{AA} of similar level with light q and g

Mass difference: $m_d=4.8$ MeV/ c^2 vs $m_b=4.2$ GeV/ c^2

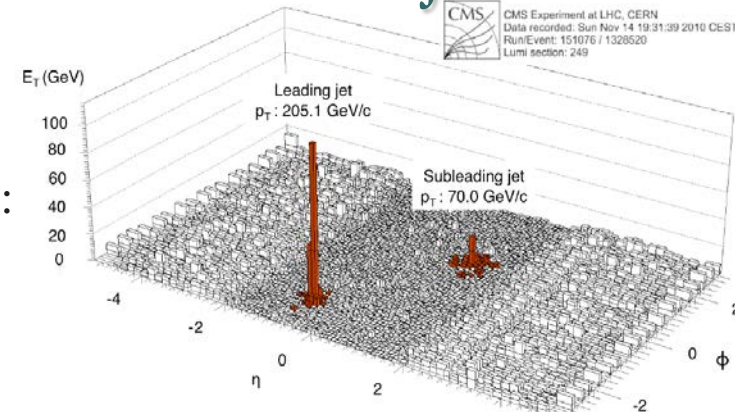
Quenching becomes *visible* in Dijets

PbPb @ 2.76 TeV

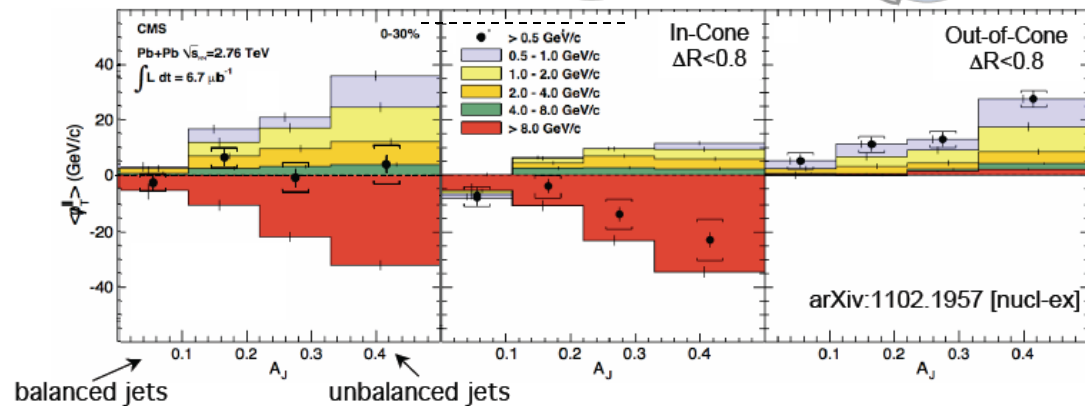


Dijet momentum imbalance:

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



JHEP 01 (2016) 006
 0-30% Central PbPb

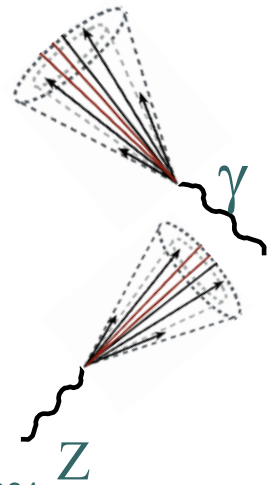


Di-jets in PbPb:

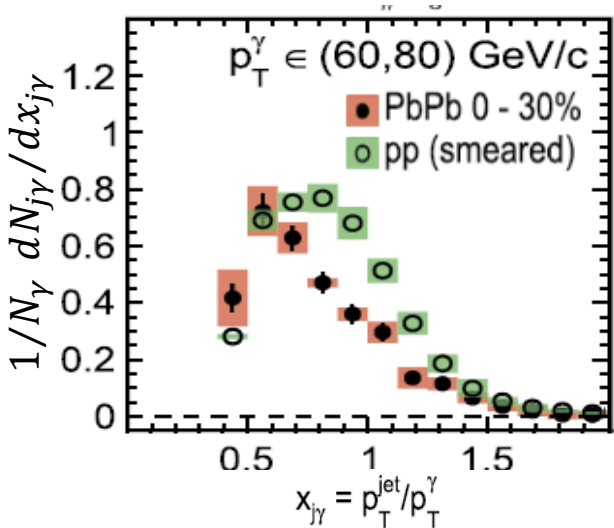
- Back-to-back, but fraction of *imbalanced dijets* grows with collision centrality (no modifications in pPb collisions)
- Momentum balance is preserved over the entire event
- “Missing” p_T in hard sector is balanced by soft hadrons away from jet-axis

Quenching Effects in Jets

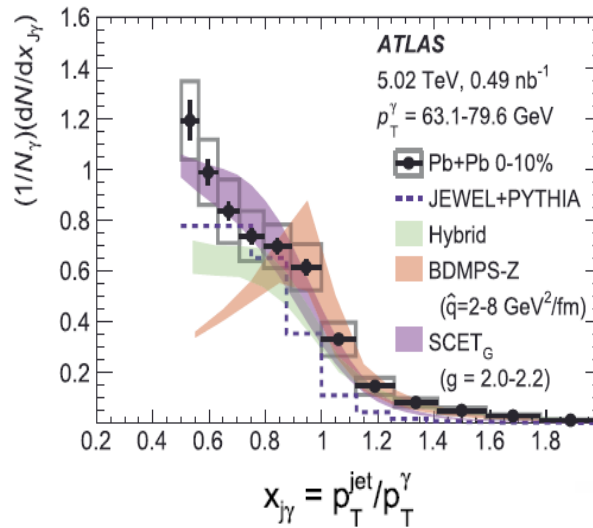
Both side of dijet are quenched \rightarrow dijet collection is surface-biased \rightarrow
Use colorless probes to reduce/change geometry bias



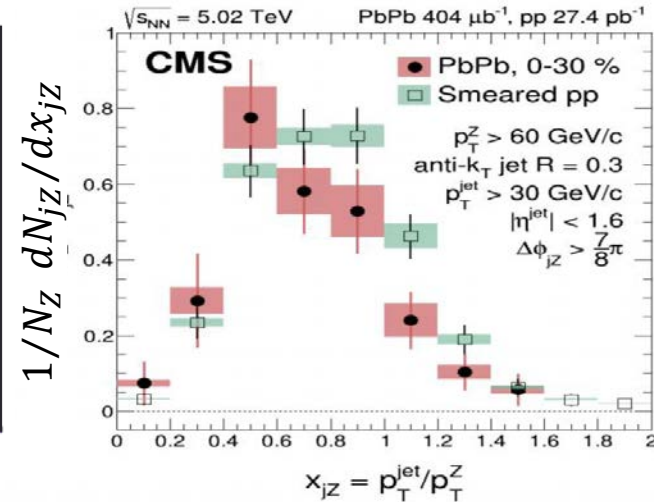
PLB 785 (2018) 14



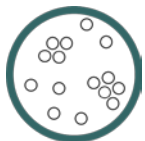
PLB 789 (2019) 167



PRL 119 (2017) 082301



PbPb @ 5.02 TeV



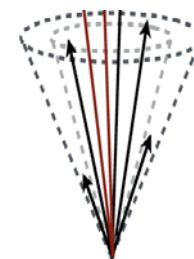
Details of the energy loss:

- Dijet, γ -jet, Z-jet – energy balance is disturbed by QGP
- (Centrality-dependent) changes in x_{JY} , x_{JZ} momentum balance

Jet Longitudinal Structure

Jet fragmentation functions: fractional momentum distribution within the jets

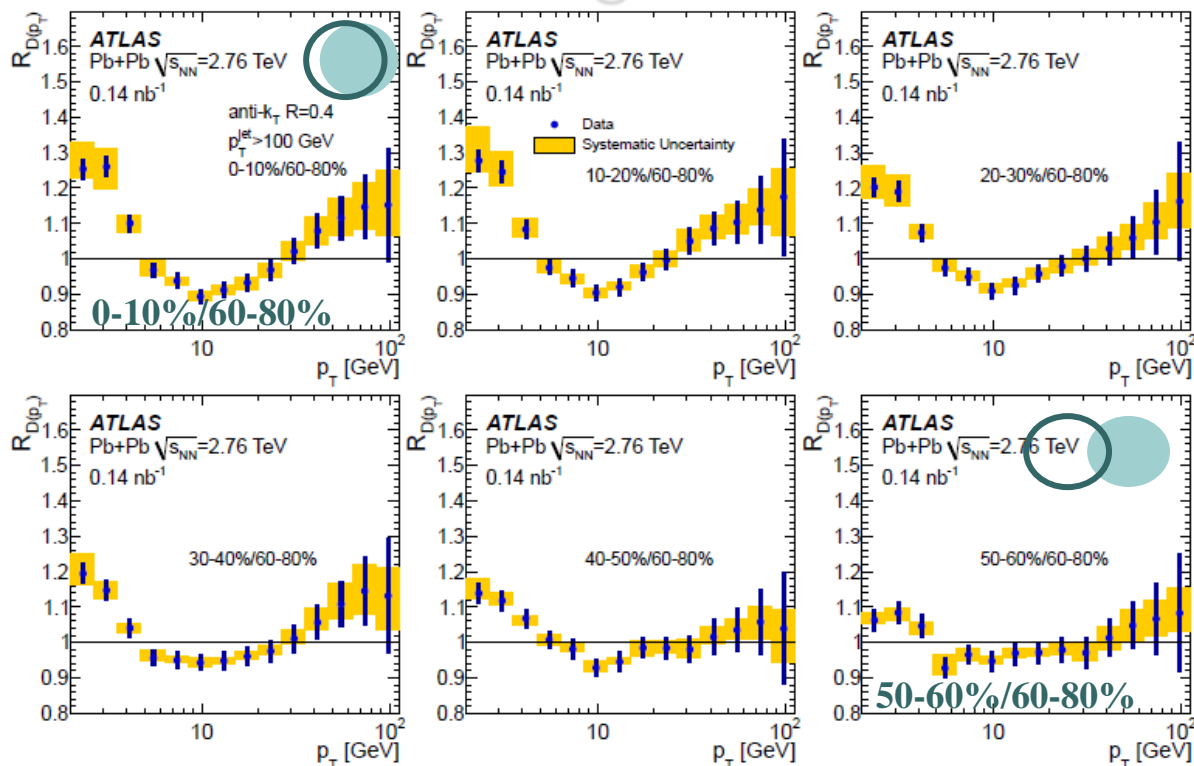
$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$



Modification of fragmentation functions in PbPb

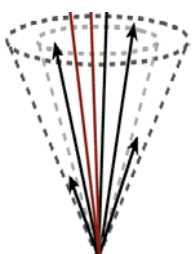
PLB B 739 (2014) 320

PbPb @ 2.76 TeV



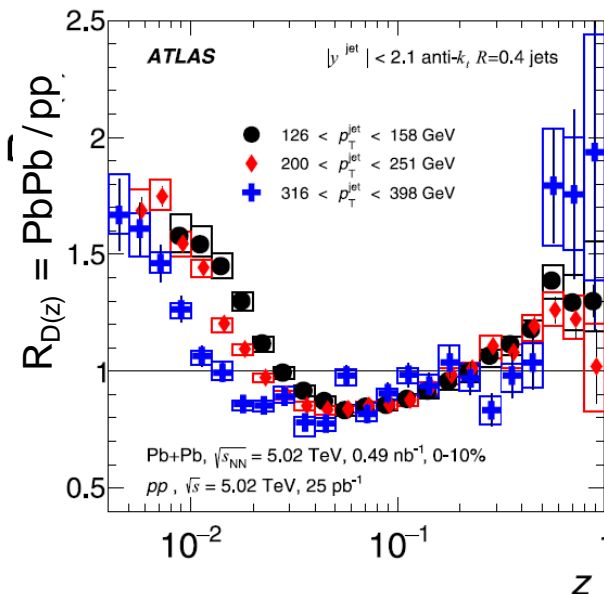
- Centrality dependent change in fragmentation patterns
- Enhancement at low p_T / depletion at intermediate momenta in central collisions

Jet Longitudinal Structure

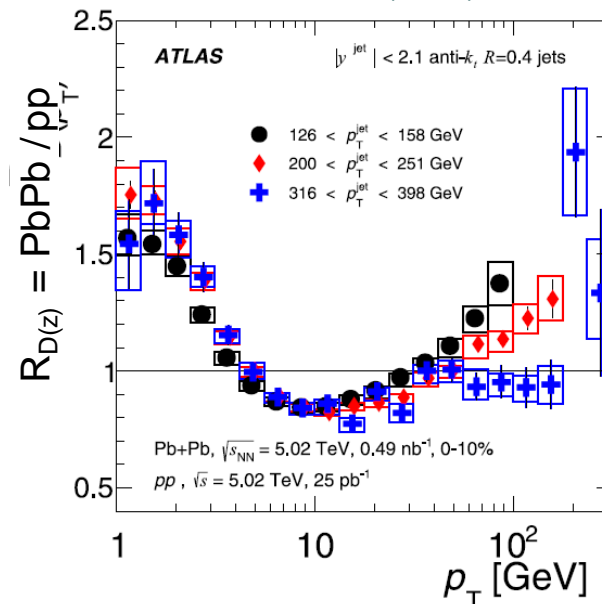


$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$

PbPb @ 5.02 TeV



PRC 98 (2018) 024908



Fragmentation function studies

- Little/no medium effects in peripheral events (vacuum-like fragmentation, confirmed with pp reference)
- Excess of soft fragments/depletion at intermediate momenta
- Excess of high- p_T tracks – evidence of color-charge effects?

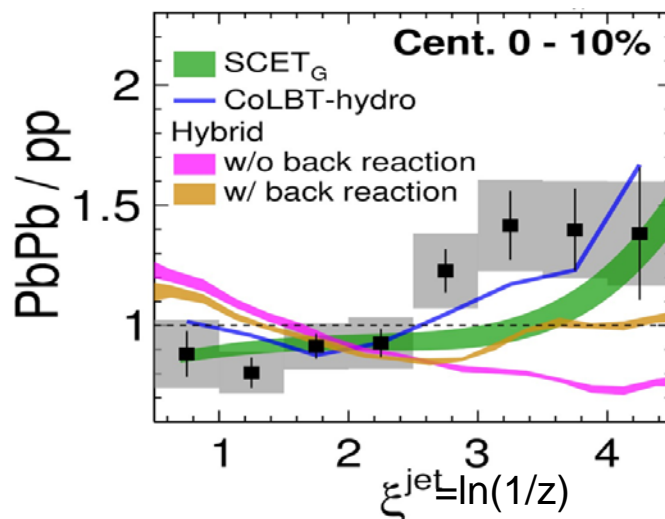
Fragmentation for γ + Jets

CMS

$\sqrt{s_{NN}} = 5.02$ TeV

$p_T^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$

$p_T^\gamma > 60$ GeV/c, $|\eta^\gamma| < 1.44$, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$



PRL 121 (2018) 242301

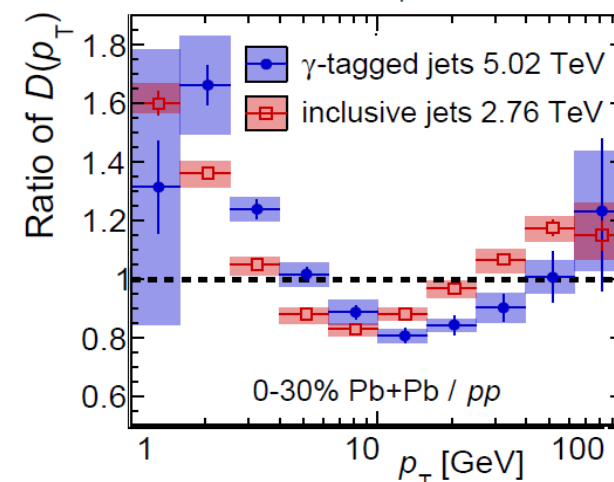
PbPb @ 2.76 TeV

PbPb @ 5.02 TeV

ATLAS

0.49 nb⁻¹ Pb+Pb $p_T^\gamma = 80-126$ GeV

25 pb⁻¹ pp $p_T^{\text{jet}} = 63-144$ GeV

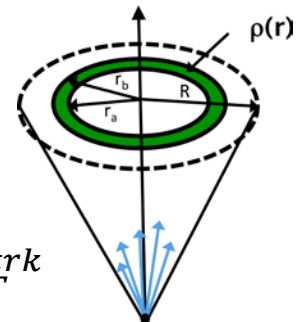


PRL 123 (2019) 042001

Quark-rich γ -jet sample allows tests for color-charge effects

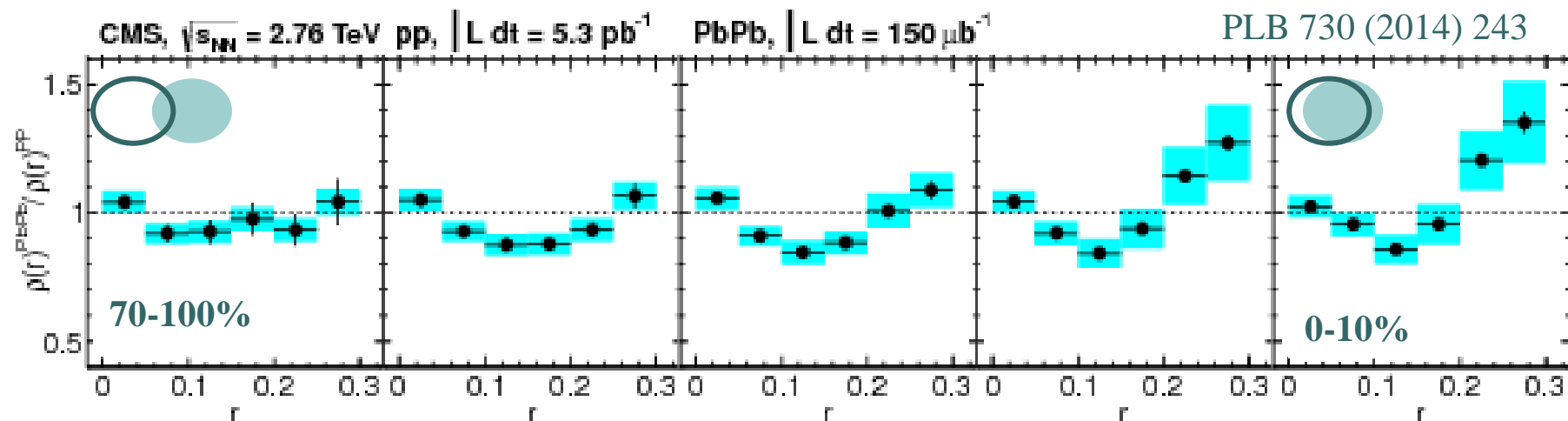
- Enhancement of particles carrying small momentum fraction
- *Depletion* of mid/high momentum particles

Jet Inner Workings: Shapes



Jet shapes: measure transverse structure of jet momenta

Fractional transverse energy distribution:
$$\rho(r) = \frac{1}{N_j} \frac{1}{\delta r} \sum_{jets} \frac{\sum_{trk \in [r_a, r_b)} p_T^{trk}}{\sum_{trk \in [0, R)} p_T^{trk}}$$



PbPb @ 2.76 TeV

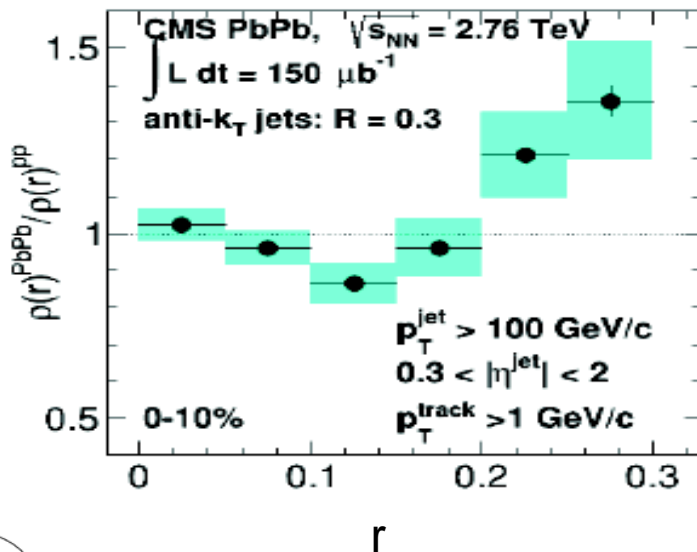
Jet Shapes: PbPb to pp ratio

- Little/no medium effects in peripheral events
- Enhancement at low p_T / larger r in central collisions

Jet Shapes: quark vs. gluon

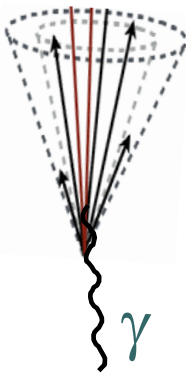
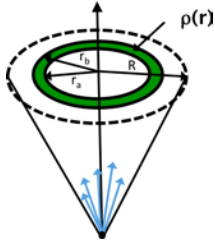
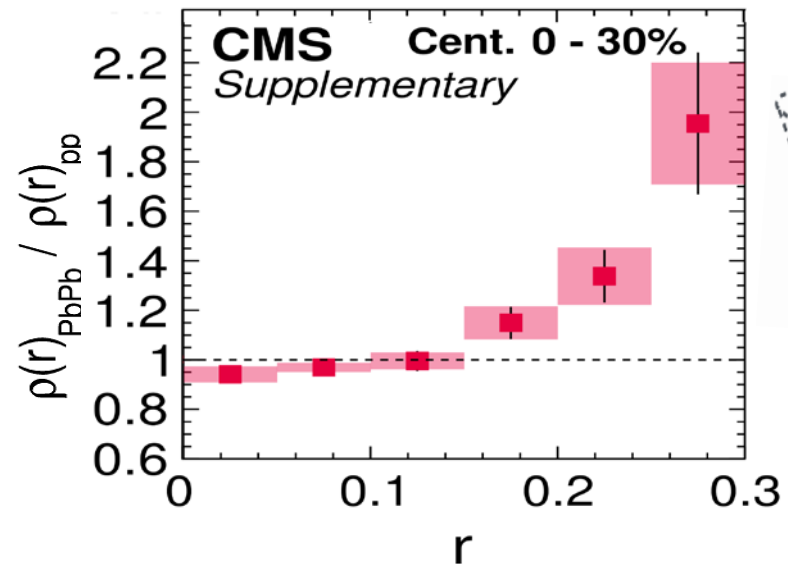
PLB 730 (2014) 243

Inclusive jets: q+g



PRL 121 (2018) 242301

γ -tagged-jets: $\sim q$



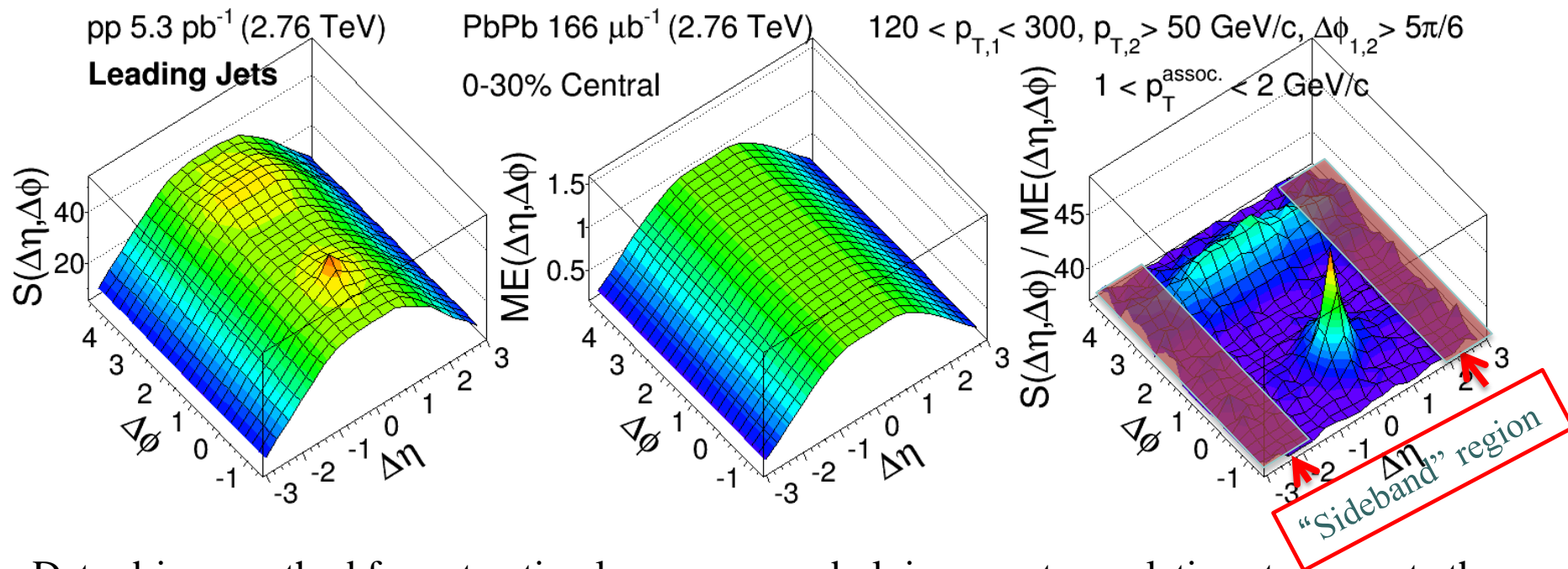
Jet Shapes: quark vs. gluon

- Similar jet shape modification trends with inclusive jets in central PbPb data: energy shift towards larger radii
- What about the magnitudes? Can't compare ratios directly; must mind the reference!



Jet Shapes: Outside the Box

That is, *Out of Cone*: using 2D correlations for jets and charged particles allow to measure full energy flow profile, capture entire fragmentation pattern extending past clustering parameter R



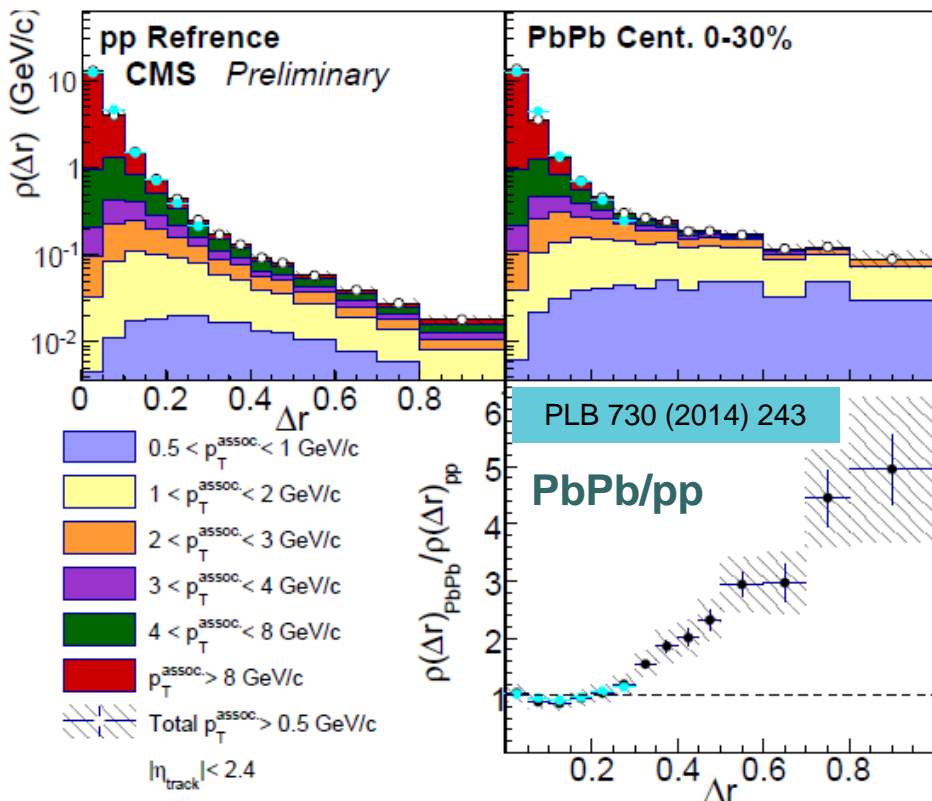
- Data-driven method for extracting long-range underlying event correlations to separate those from the jet peaks
- Allows to study “cross-talk” between the jets and hydrodynamically expanding medium

Jet Shape Modifications

A_J Inclusive
pp 5.3 pb⁻¹ (2.76 TeV)

Leading

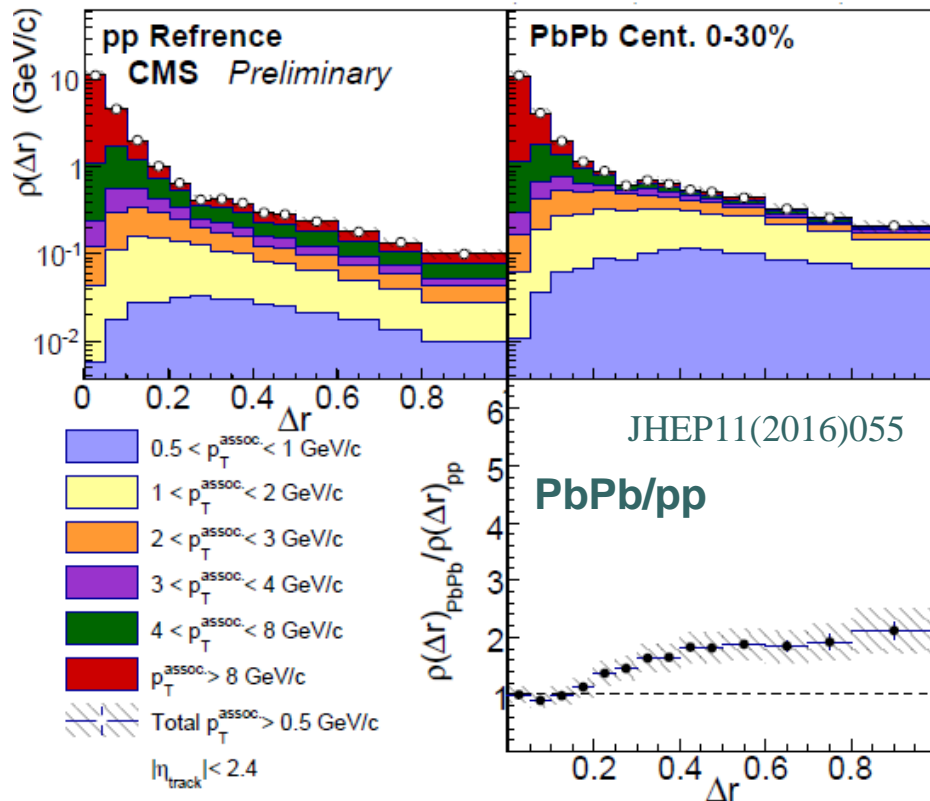
PbPb 166 μb⁻¹ (2.76 TeV)



A_J Inclusive
pp 5.3 pb⁻¹ (2.76 TeV)

Subleading

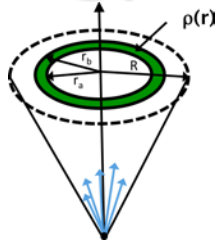
PbPb 166 μb⁻¹ (2.76 TeV)



PbPb @ 2.76 TeV

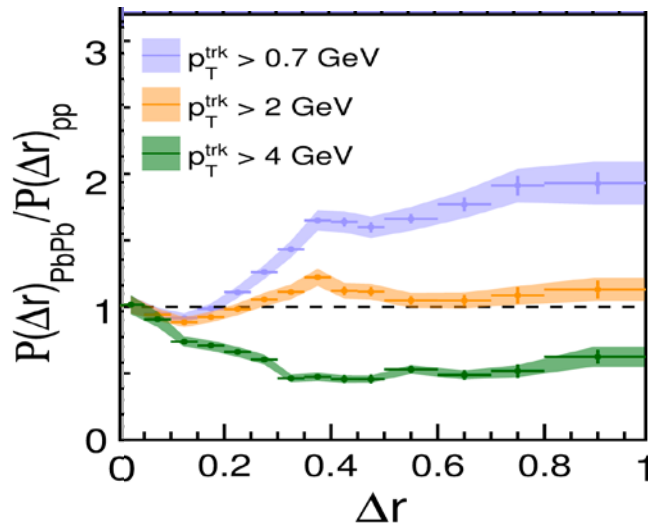
Can now measurement of jet shapes up to large radial distances
(Compare to previous measurement in light blue)

Jet Shapes: In/Out of Cone Energy

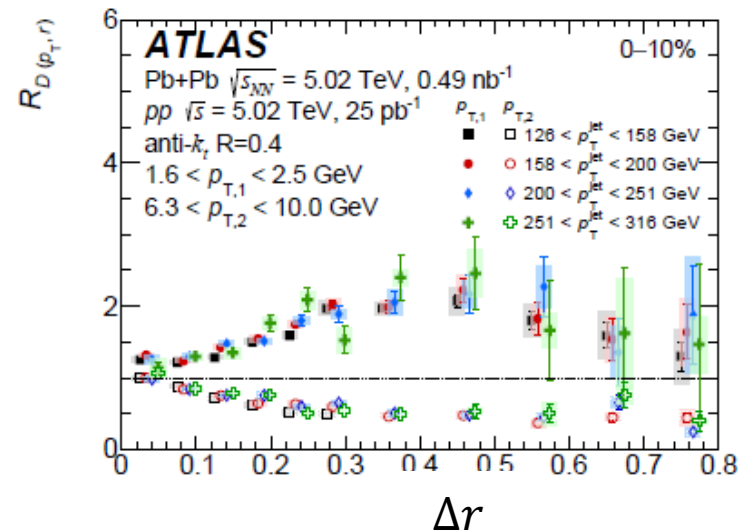


JHEP05(2018)006

CMS Radial momentum distribution
pp 27.4 pb⁻¹ (5.02 TeV) PbPb 404 μb⁻¹ (5.02 TeV)
anti-k_T R=0.4 jets, p_T > 120 GeV, |η_{jet}| < 1.6



PRC 100 (2019) 064901



PbPb @ 5.02 TeV

Radial profile of transverse momenta

- Central PbPb: large Δr enhancement in soft sector, loss of momenta in hard constituents
- Jet energy is redistributed towards softer fragments and large radii, significant out of cone contributions



Jet (Hard) Substructure Studies

○ Grooming:

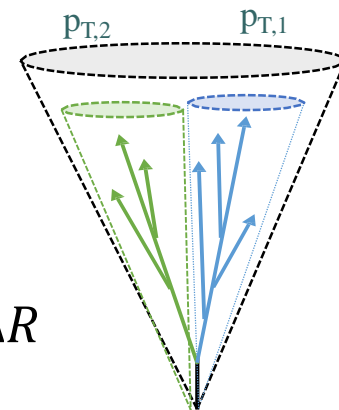
- Idea: to isolate hard structure (hardest/earliest splitting) from soft BG contamination

○ Several Approaches

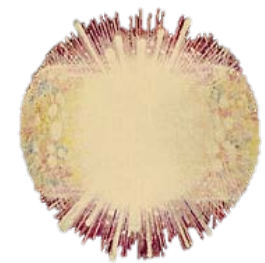
- *Filtering*: re-cluster jets with smaller R_{filt} keep hardest subjets
- *Trimming*: re-cluster with smaller R_{trim} , keep subjets with $p_T > \varepsilon_{trim} p_T^{jet}$
- *Pruning*: re-cluster with k_T or C/A and in each clustering step discard subjet if $\Delta R > R_{prun}$ and $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} < z_{prun}$

○ Commonly used: Soft Drop algorithm:

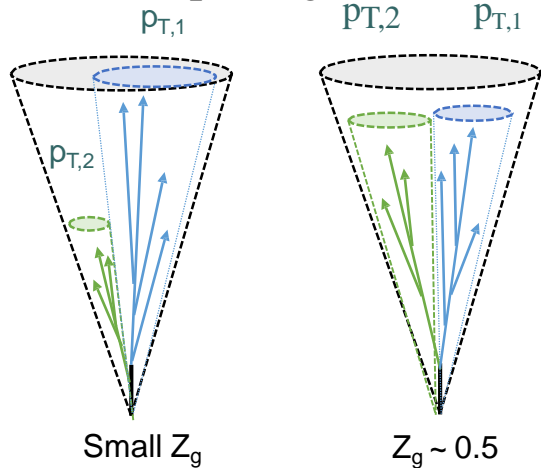
- Start with anti- k_T jet, re-cluster with CA
- Undo the last clustering step, get $z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$ and ΔR
- Stop if $z_g > z_{cut} (\Delta R / R)^\beta$, else un-cluster again



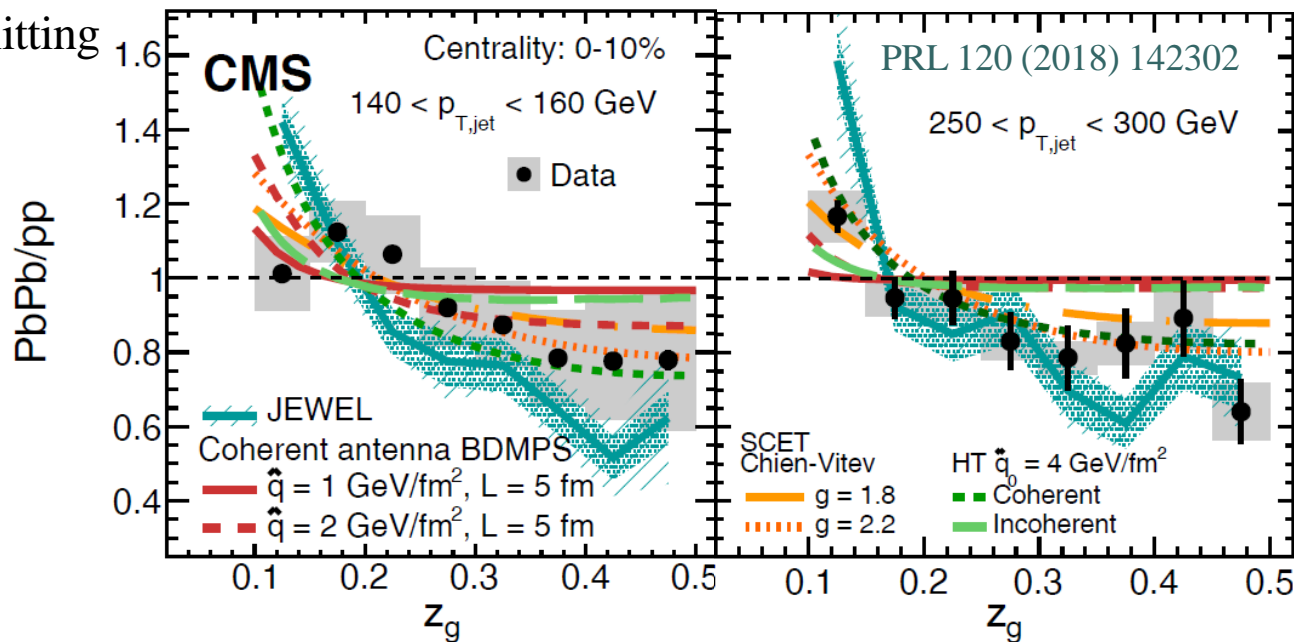
Subjet Momentum Sharing



Hard/soft splitting Symmetric splitting



$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$



PbPb @ 5.02 TeV

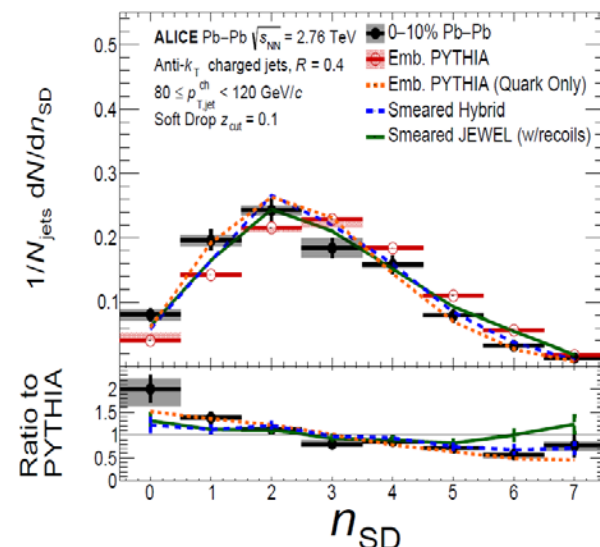
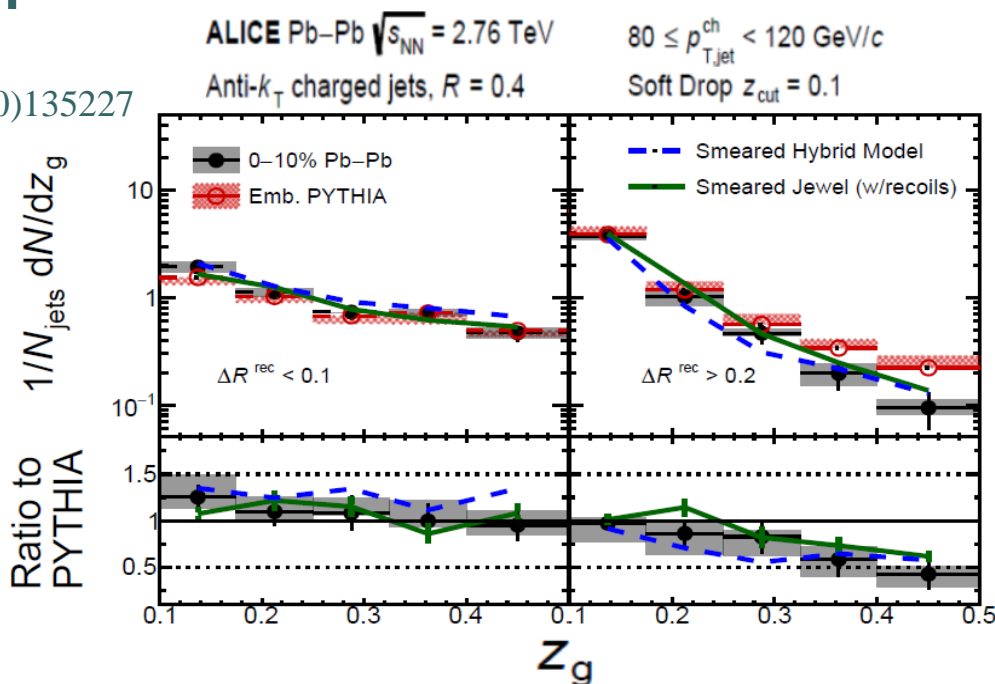
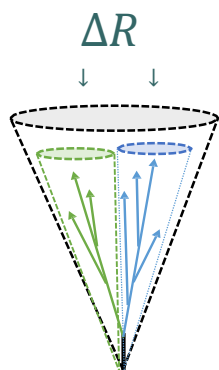


Parton splitting is modified in central PbPb collisions:

- Higher suppression for jets with more symmetric subjets
- New insights on in-medium effects for theory, different interpretations
- Medium recoil? Modified splitting? Coherent emitter?

Subjet Momentum Sharing

PLB 802 (2020)135227



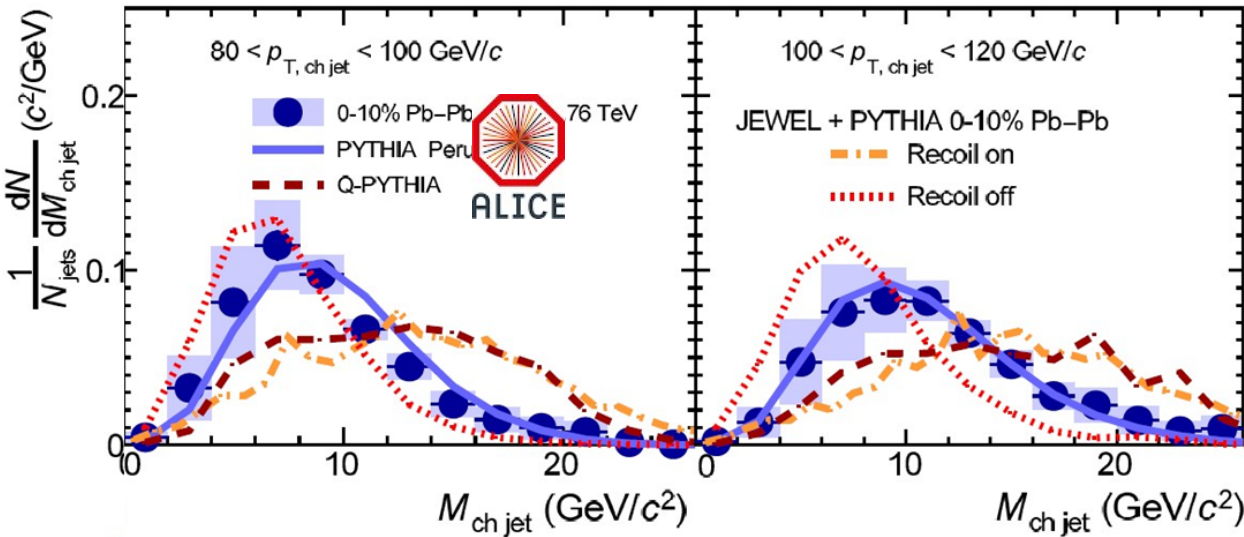
PbPb @ 2.76 TeV

Parton splitting for charged jets:

- Enhancement of the number of small-angle splittings/ suppression of the large-angle symmetric splittings in central PbPb collisions
- Number of splittings passing soft drop cut shifts down – color-charge effects?

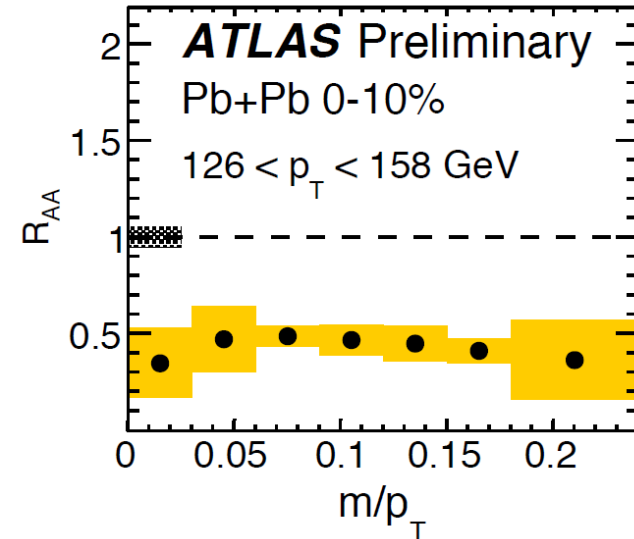
Jet Mass Measurements

PLB 776(2018) 249



Jet mass from charged tracks

ATLAS-CONF-2018-014



Jet mass from calorimeter energy

Jet mass distributions:

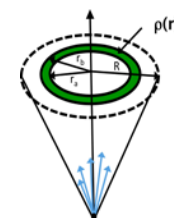
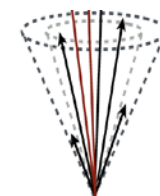
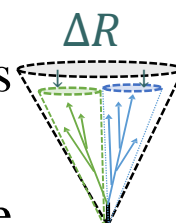
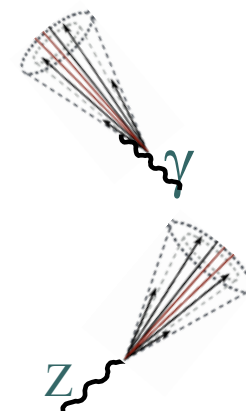
- No significant modifications are observed
- Large increases in jet mass predicted by quenching models are excluded by the data



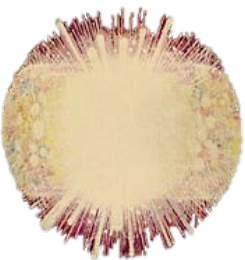
Summary & Outlook

“Take-home” Points:

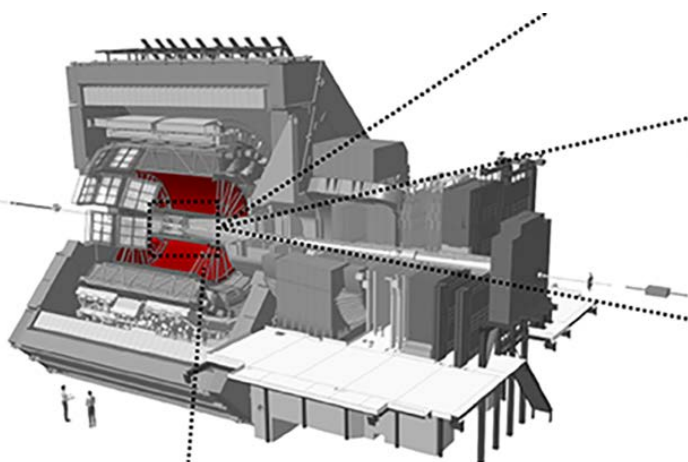
- Hard probes for tomographic studies of the Quark Gluon Plasma is a new frontier for QCD studies
- Jets provide a versatile set of tools for studying properties of the QGP medium at different scales
- Jet quenching manifestation in jet constituent distribution: small modifications in the core of the jet, significant energy shift from hard to soft sector, from jet core to larger radii
- More to come: RHIC vs LHC, systematic studies of R , color-charge and quark flavor effects – check out Jet Sessions here at HP2020!



LHC Upgrades @ LS2



ALICE



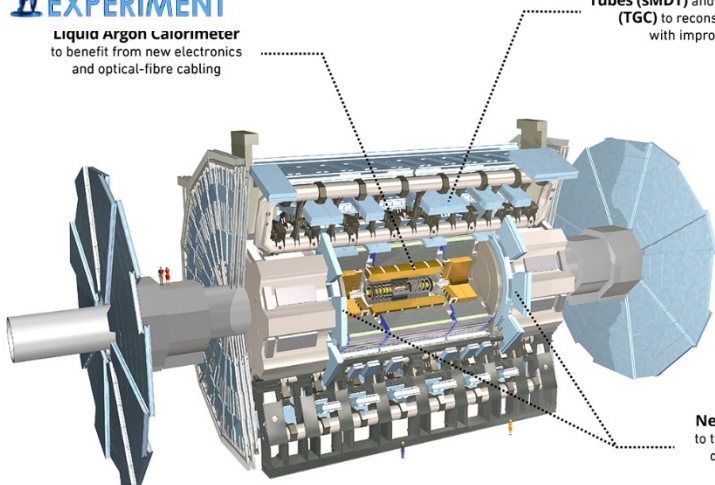
Upgraded Time projection Chamber (TPC)

ALICE

- New Inner Tracking system (ITS)
- Muon Forward Tracker (MFT) upgrade
- New Fast Interaction trigger (FIT)
- TPC (readout) upgrade



Liquid Argon Calorimeter
to benefit from new electronics
and optical-fibre cabling



New small Monitored Drift
Tubes (sMDT) and Thin Gap Chambers
(TGC) to reconstruct muons' paths
with improved resolution

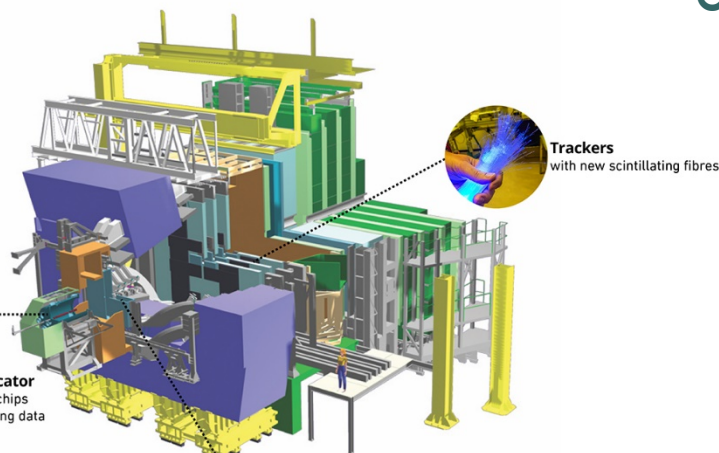
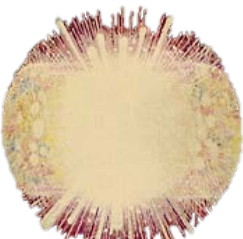
New small wheel
to track more muons
on both sides of
the detector



ATLAS

- Rebuilding Muon Wheels
- Fast Tracker
- Trigger, DAQ, electronics upgrades

LHC Upgrades @ LS2

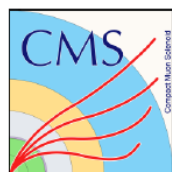


The **Vertex Locator** to use VELOPIX chips capable of sending data up to 20 Gb/sec

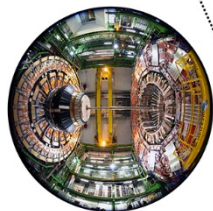


Trackers with new scintillating fibres

Brand new **UT tracker** to cope with increased particle density



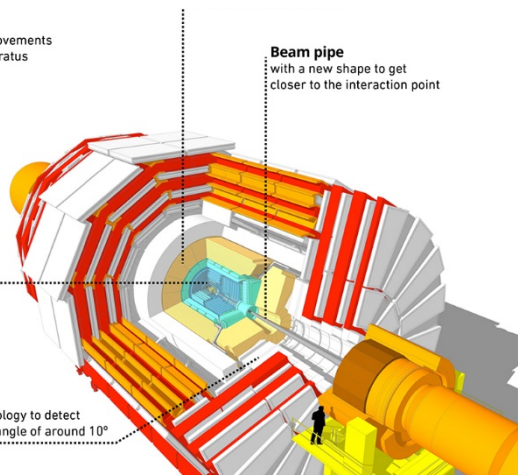
Pixel detector improvements at the core of the apparatus



Open CMS detector, showing the endcap calorimeter sticking out, which will be replaced with the new **high granularity calorimeter (HGCal)** around 2024-2026.

Beam pipe with a new shape to get closer to the interaction point

New **Muon System** technology to detect muons that scatter with an angle of around 10°



○ LHCb

- New (faster) vertex positioning detector (VeloPix)
- RHIC detectors upgrade
- New Tracker (silicon-microstrip and scintillating fibers (SciFi))
- Read-out upgrade with fully software based trigger

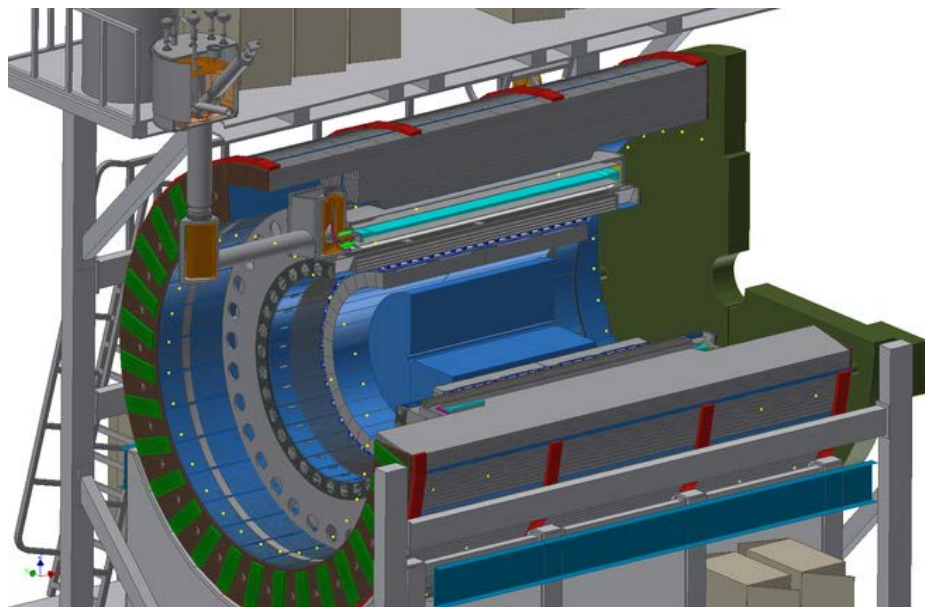
○ CMS

- Pixel Detector improvements
- Hadronic and EM Calorimeters upgrades
- Muon System upgrade
- New beam pipe



New Jet Detector at RHIC

As we speak, a new “state-of-the-art jet detector at RHIC” is under construction at BNL

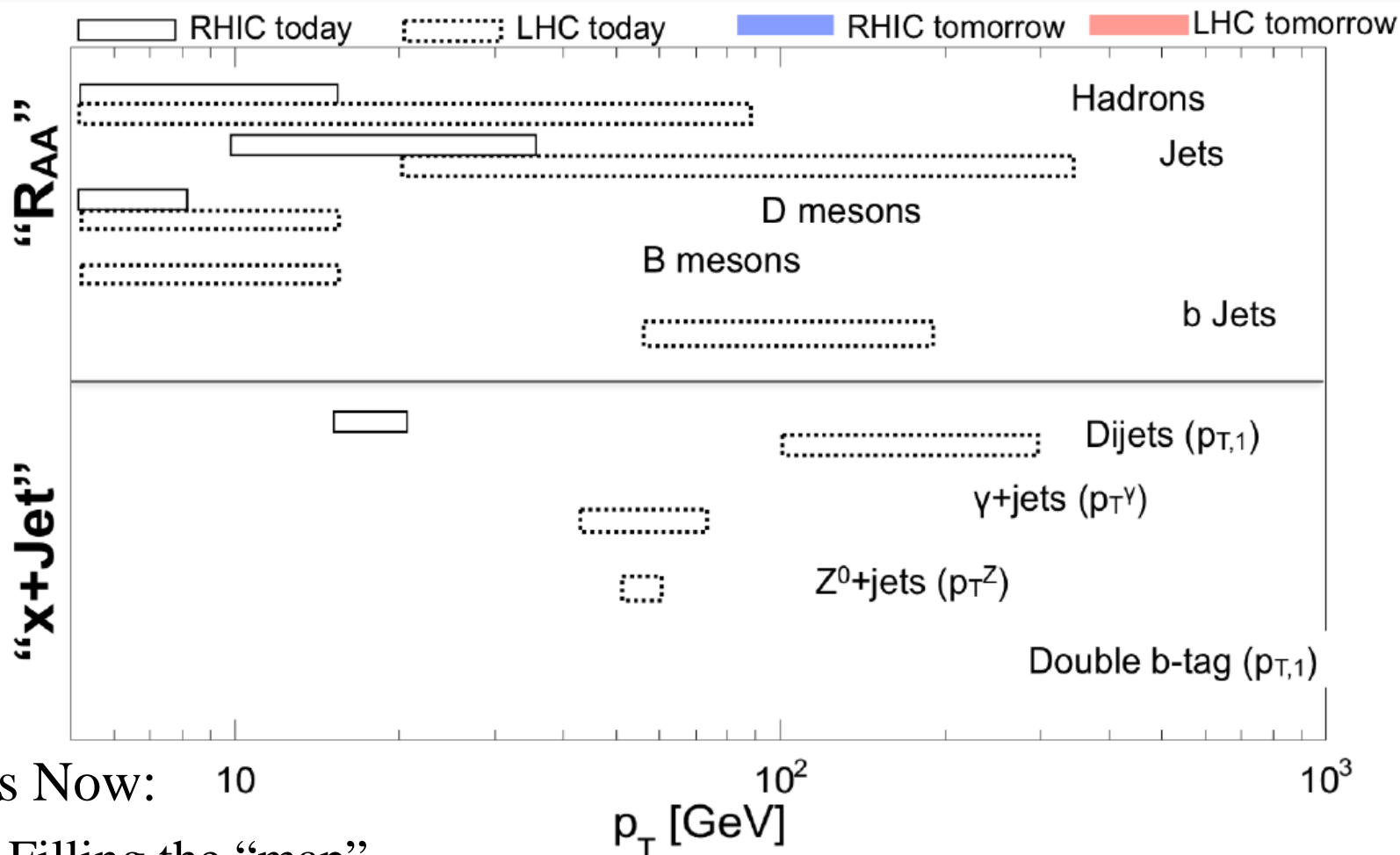


○ sPHENIX:

- 1.4T Magnetic Field
- Large acceptance
- Precision tracking
- Hadronic & EM calorimetry

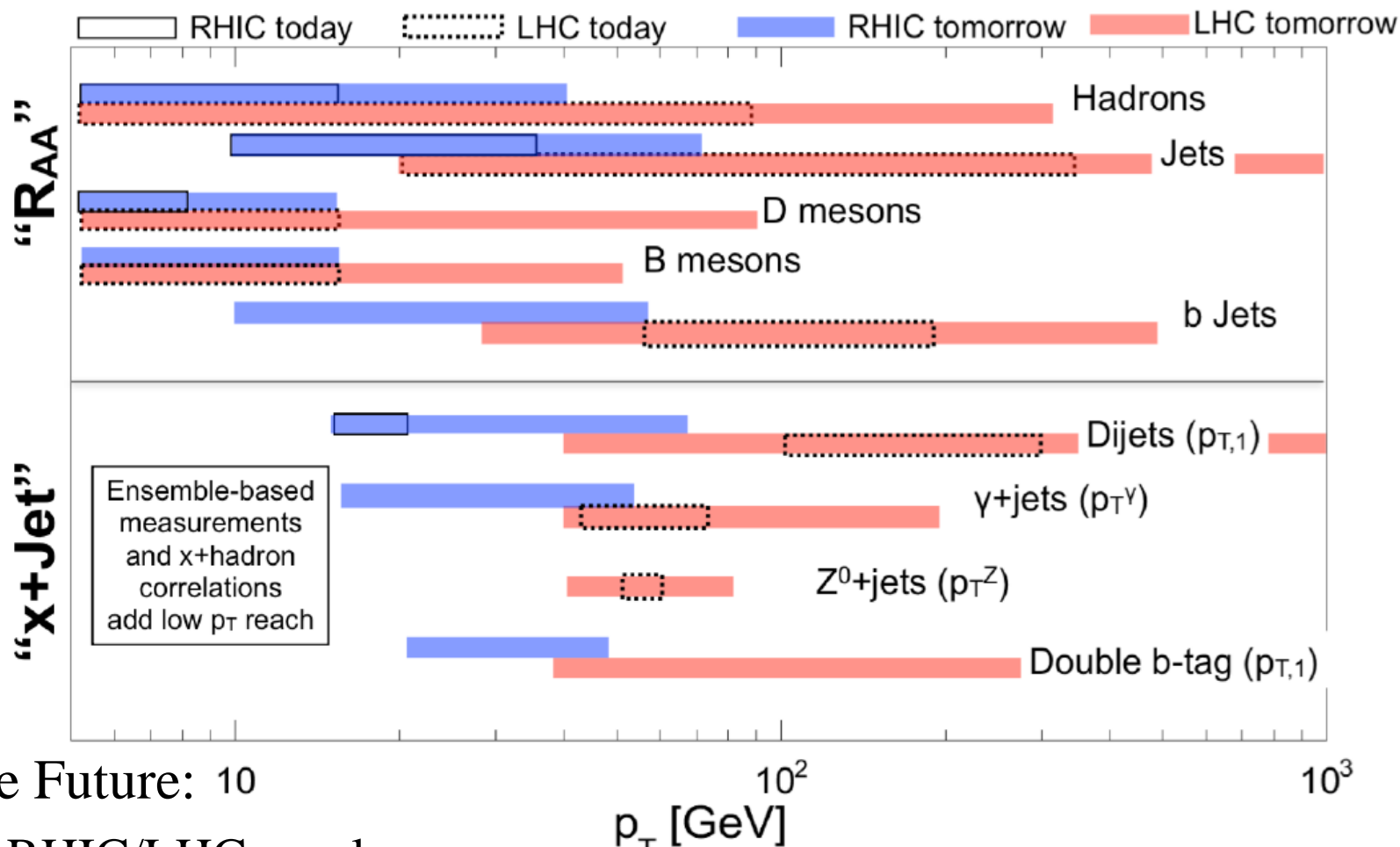
Early studies indicate substantial differences in jet quenching systematics at 200 GeV vs 5 TeV – unique opportunity to test QCD at variable T

Looking into the Future

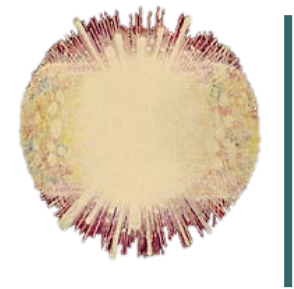


- Jets Now:
 - Filling the “map”
 - Little options for RHIC/LHC overlap

Looking into the Future



- The Future:
 - RHIC/LHC overlap
 - Extended kinematic coverage/precision



Thank you
and
Enjoy the Conference!



Jet Production Cross-section

What are Jets? In theory: fragmented hard-scattered partons \rightarrow collimated spray of hadrons produced by energetic quark or gluon

Factorization of jet production:

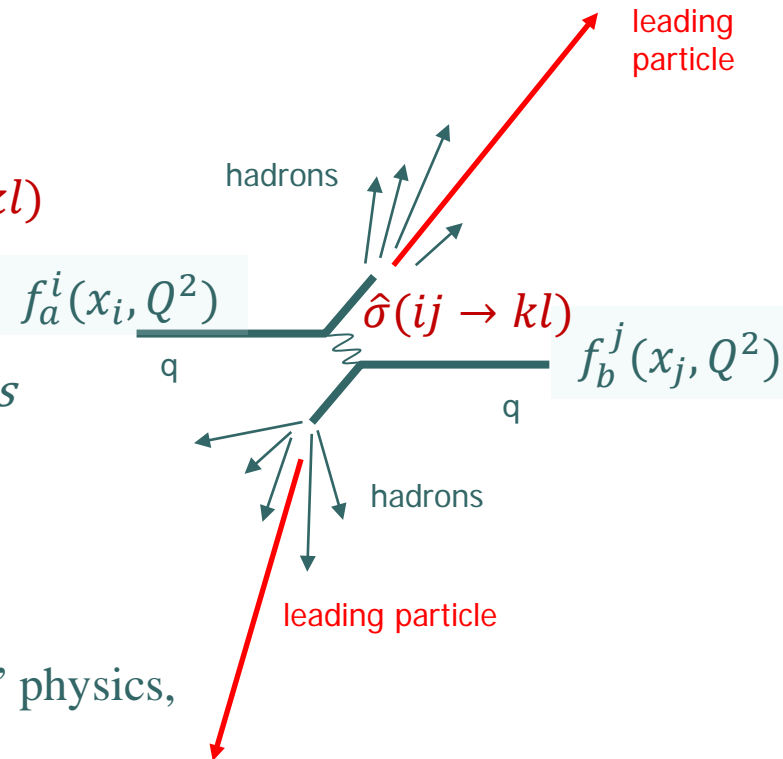
$$\frac{d\sigma^{jet(k)}}{dp_T^2 dy} = \sum_{i,j} dx_i dx_j f_a^i(x_i, Q^2) f_b^j(x_j, Q^2) \hat{\sigma}(ij \rightarrow kl)$$

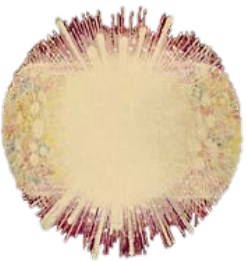
a, b – initial nucleons
 $x_i = p_i/p_a$

i, j – initial partons
 $x_j = p_j/p_b$

$\hat{\sigma}(ij \rightarrow kl)$ – partonic cross-section, “hard” process

$f_a^i(x_i, Q^2)$ – parton distribution function, universal “soft” physics, extracted from DIS





Nuclear PDF effects

Parton distribution functions for bound nucleons are different than that of a free proton

$f_{a/A,Z}^i(x_i, Q^2)$ – Nuclear *parton distribution functions*,

defined as (nCTEQ15, PRD 93, 085037):

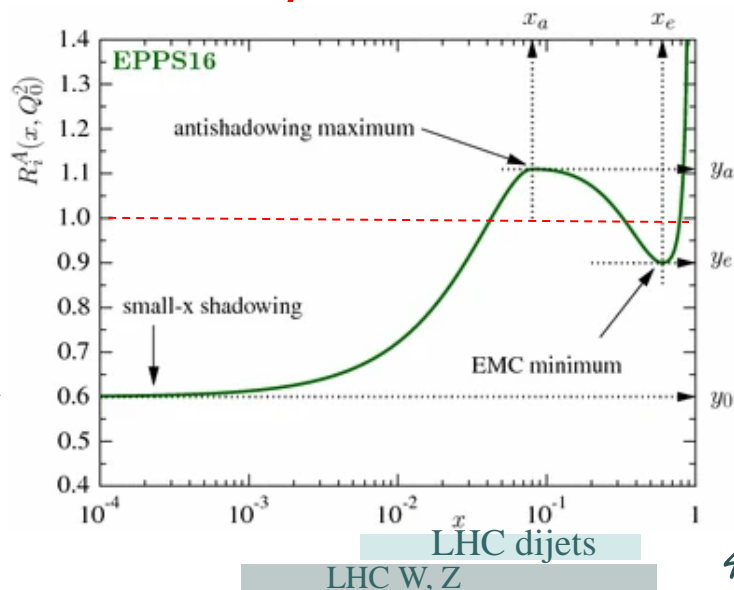
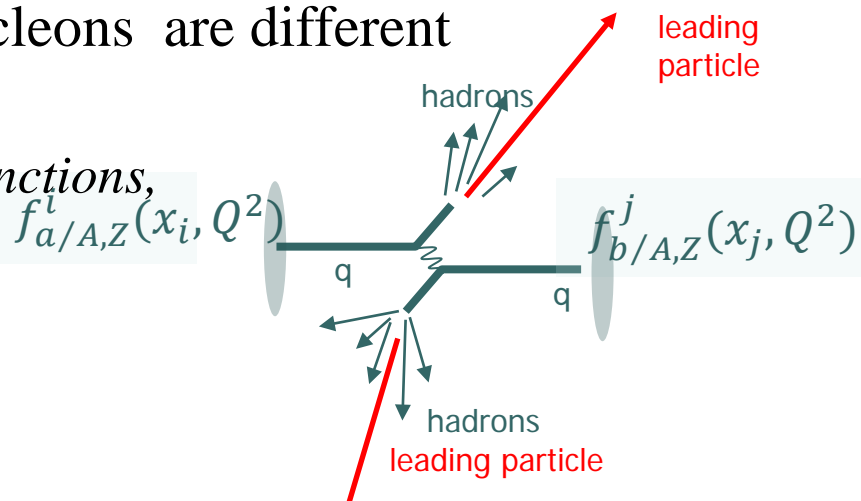
$$f_{a/A,Z}^i(x_i, Q^2) = \frac{Z}{A} f_{p/A}^i(x_i, Q^2) + \frac{A-Z}{A} f_{n/A}^i(x_i, Q^2)$$

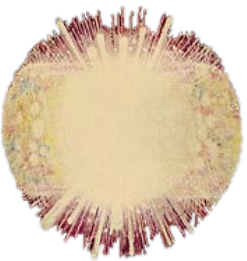
where Bound nucleon PDFs $f_{p/A}^i(x_i, Q^2)$ are connected to free nucleon PDF as (EPPS16, EPJ C77(2017)163):

$$f_{p/A}^i(x_i, Q^2) = R_A^i(x_i, Q^2) f_p^i(x_i, Q^2)$$

Nuclear PDF effects are important to account for to properly map QGP properties

→ pA collisions





Jets and Particle Production

To get particle yields from jets:

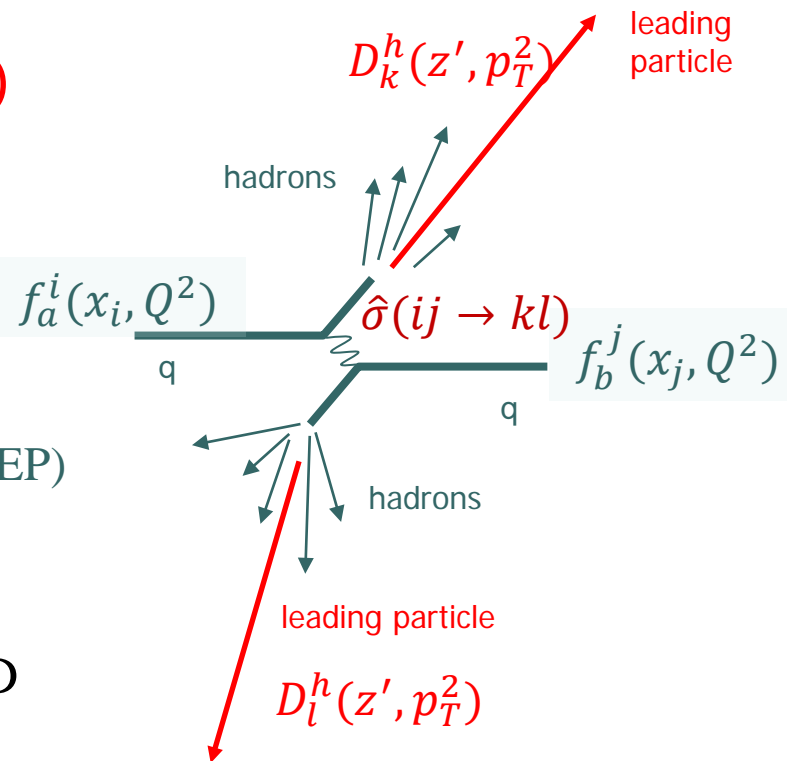
need to fold in *fragmentation functions*

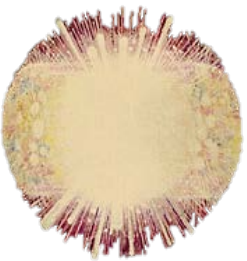
$$\frac{d\sigma^{h(k)}}{dp_T^h{}^2 dy^h dz'} = \frac{d\sigma^{jet(k)}}{dp_T^2 dy} \frac{1}{z'^2} D_k^h(z', p_T^2)$$

$$z' = p_T^h / p_T$$

$D_k^h(z', p_T^2)$ – *fragmentation functions*,
universal, extracted from e^+e^- annihilation (PETRA, LEP)
and hadronic collisions (UA1,...)

Non-perturbative; limitations at low- p_T and for PID

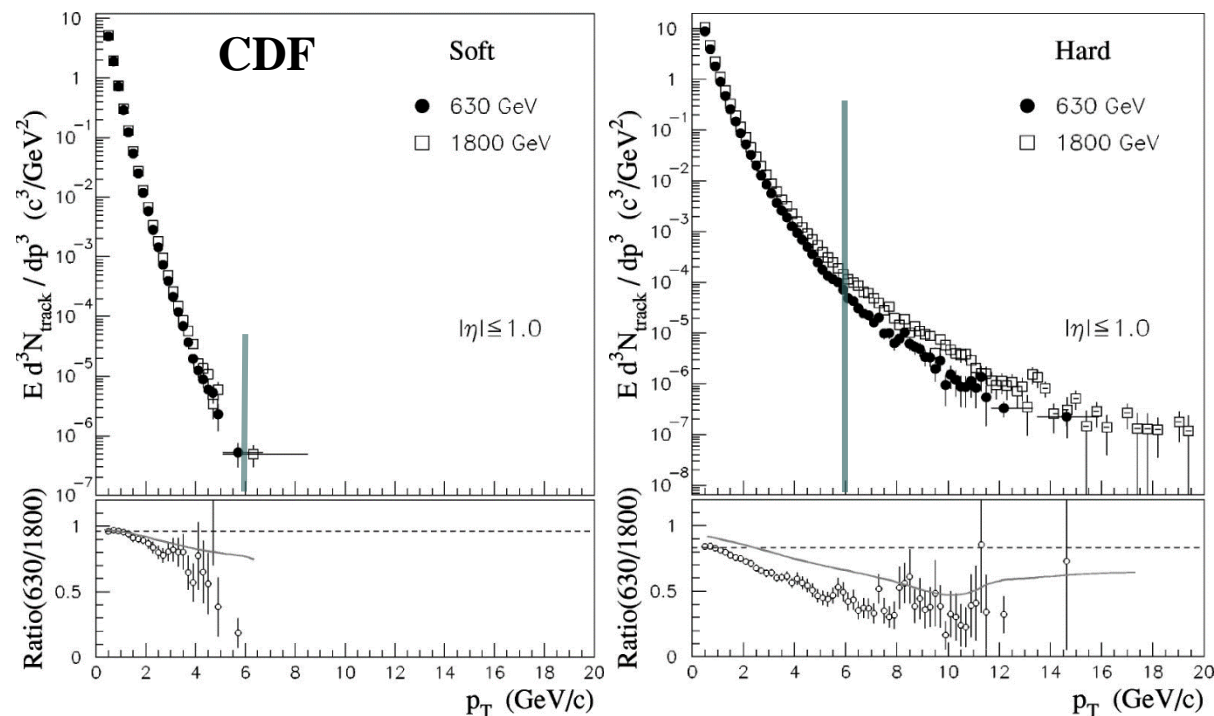




What is “high p_T ”?

In HEP studies, hadron collisions are traditionally subdivided into “soft” and “hard” by the *presence* of jets

PRD 65 (2002) 072005

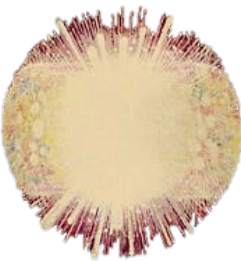


- Inclusive charged hadron cross-sections from $p\bar{p}$ collisions above 6 GeV/c are dominated by jet production
- PID data from RHIC/LHC suggest similar threshold

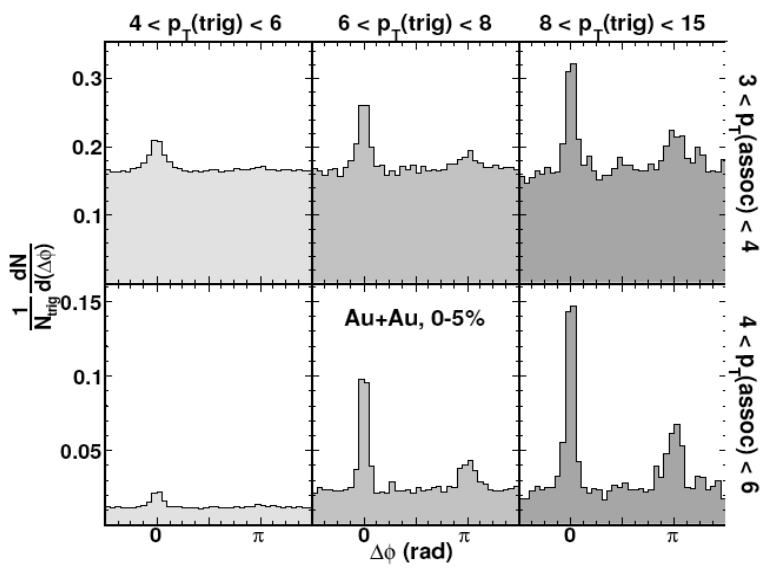
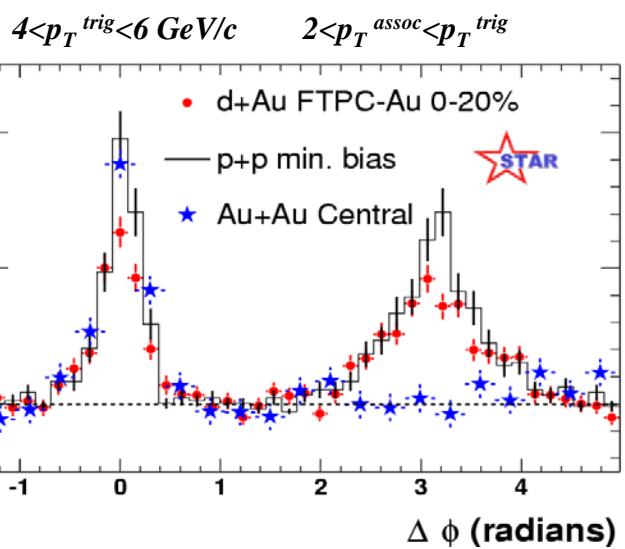
Min Bias Data, charged hadrons $|\eta| < 1$

“Soft” vs “Hard” division based on calorimeter clusters $E_T > 1.1$ GeV

Signature Results: Disappearance



PRL 91 (2003)
072304



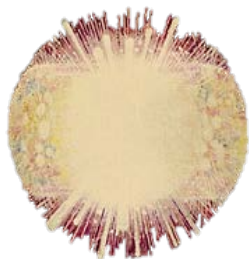
Signature two-particle correlation result:

- Disappearance of the away side jet in central Au+Au collisions
 - Evidence for strongly interacting medium
- Effect vanishes in peripheral/d+Au collisions

Two high- p_T hadrons

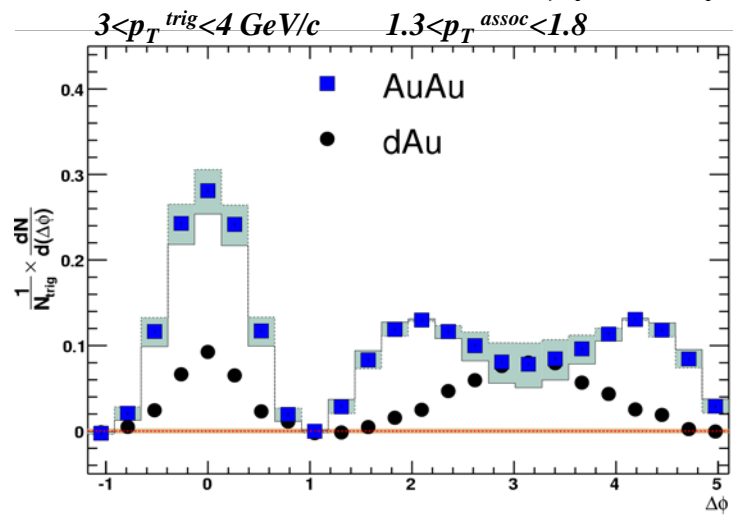
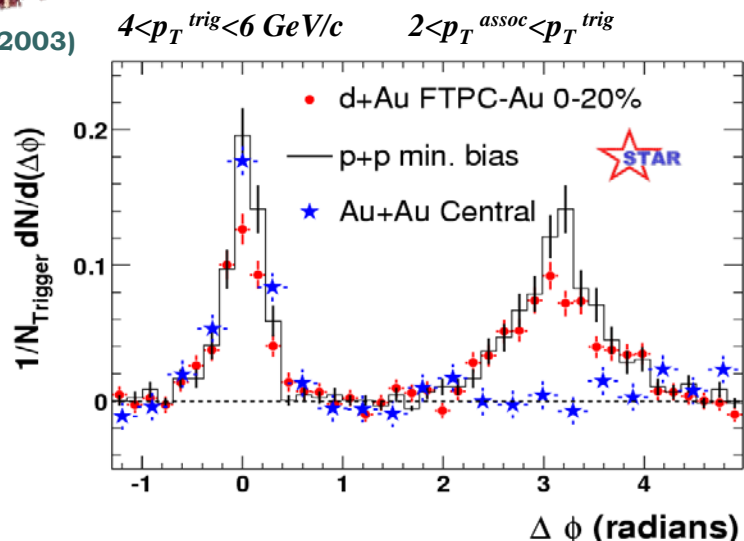
- Reappearance of the away-side jet

Signature Results: Disappearance



PRL 91 (2003)

072304



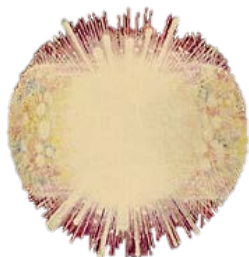
Signature two-particle correlation result:

- Disappearance of the away side jet in central Au+Au collisions
 - Evidence for strongly interacting medium
- Effect vanishes in peripheral/d+Au collisions

One high- p_T , one low- p_T trigger

- Reappearance of the away-side jet
- “Mach cone era”: Double-hump structure taken as hint of additional physics phenomena

Signature Results: Disappearance

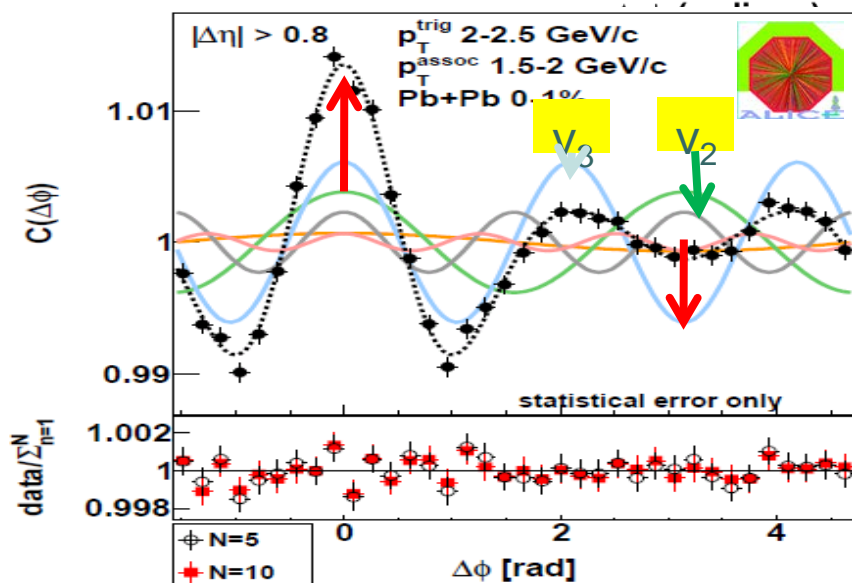
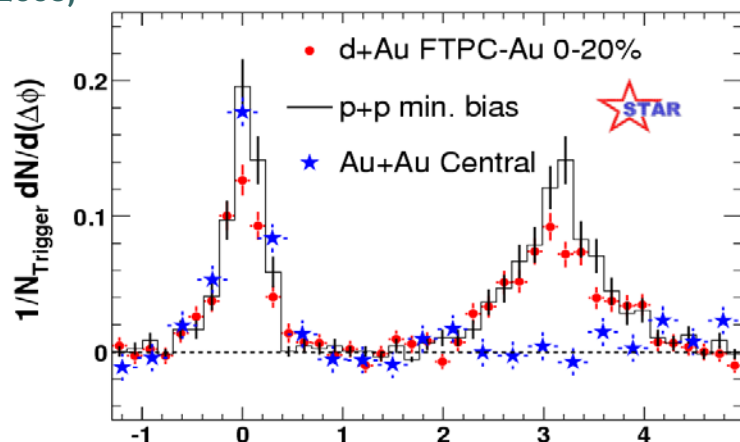


PRL 91 (2003)

072304

$$4 < p_T^{\text{trig}} < 6 \text{ GeV/c}$$

$$2 < p_T^{\text{assoc}} < p_T^{\text{trig}}$$



Signature two-particle correlation result:

- Disappearance of the away side jet in central Au+Au collisions
 - Evidence for strongly interacting medium
- Effect vanishes in peripheral/d+Au collisions

One high- p_T , one low- p_T trigger

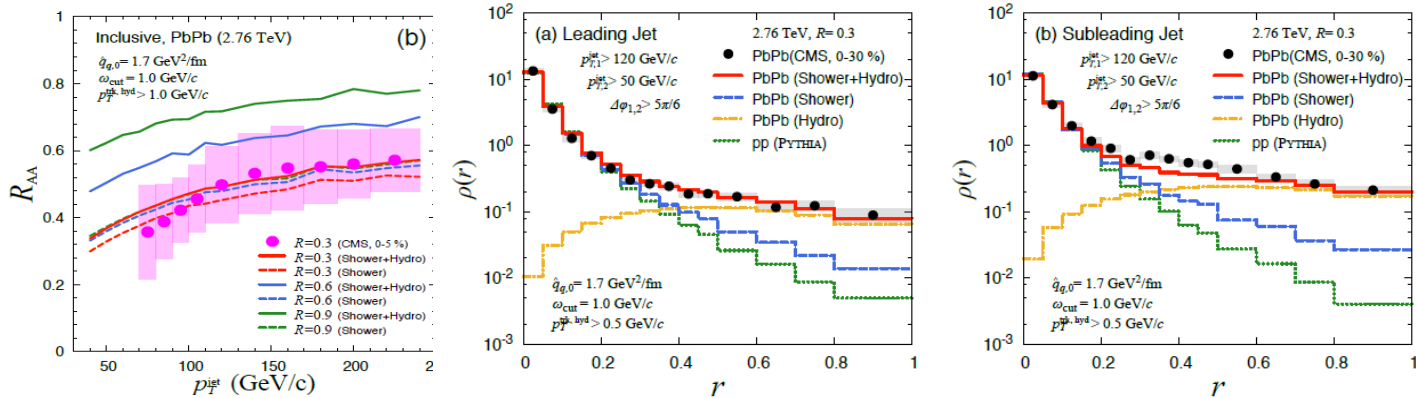
Full correlation structure described by Fourier Coefficients $V_1, V_2, V_3, V_4, V_5^*$

(later studies showed the flow origin)

Jet-medium Interactions

PRC95 4 (2017) 044909

Full jet evolution jet in QGP with hydrodynamic medium response



Jet R_{AA} :

- Inclusion of the jet-induced medium flow decreases suppression
- The effect is small for small cone sizes
- Detailed studies of R-dependence essential for discriminating models

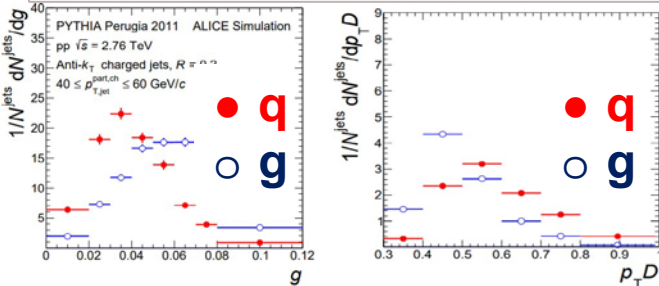
Jet Shapes:

- Soft shower thermalization – more collimated hard core
- Medium-induced radiation – broader jet shape
- Inclusion of the jet-induced medium flow – critical at large r

Jet Angularity and Dispersion

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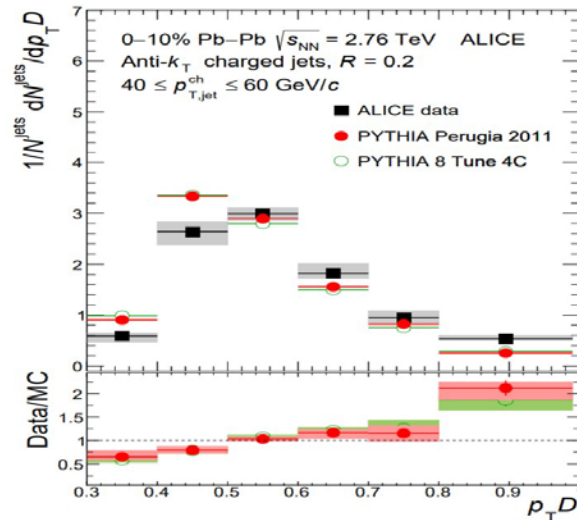
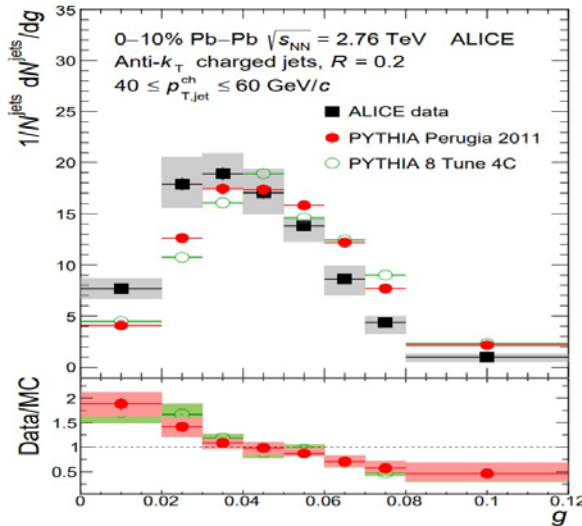
Monte Carlo



PbPb @ 2.76 TeV

$$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_{T,jet}} \Delta R_{jet,i}$$

$$p_T D = \frac{\sqrt{\sum_{i \in \text{jet}} p_{T,i}^2}}{\sum_{i \in \text{jet}} p_{T,i}}$$



Modification of internal jet structure:

- Shift towards lower girth and higher dispersion values
- Higher energy loss for gluon jets?