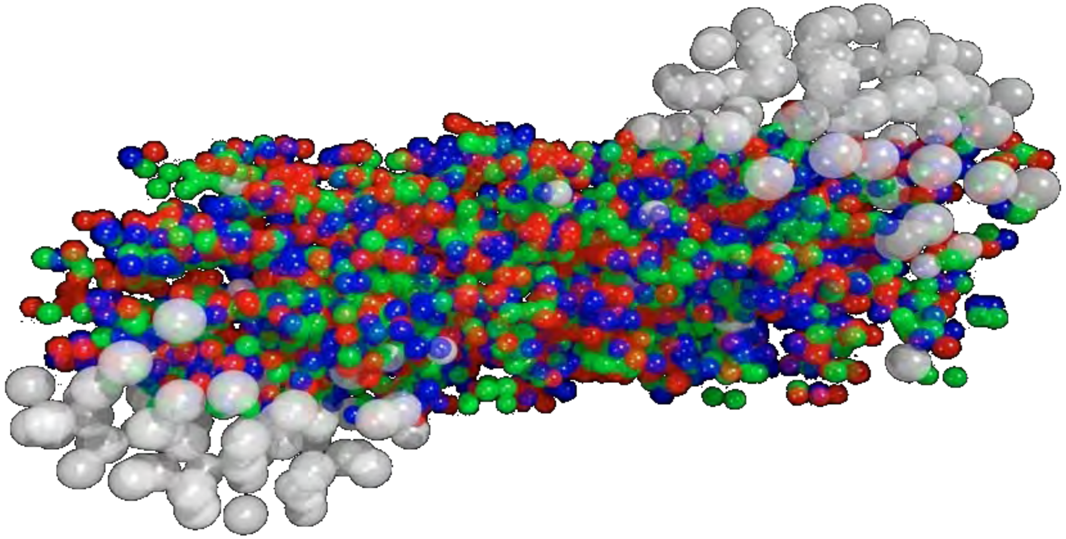
FERMILAB-CERN
HADRON COLLIDER PHYSICS
SUMMER SCHOOL
2024



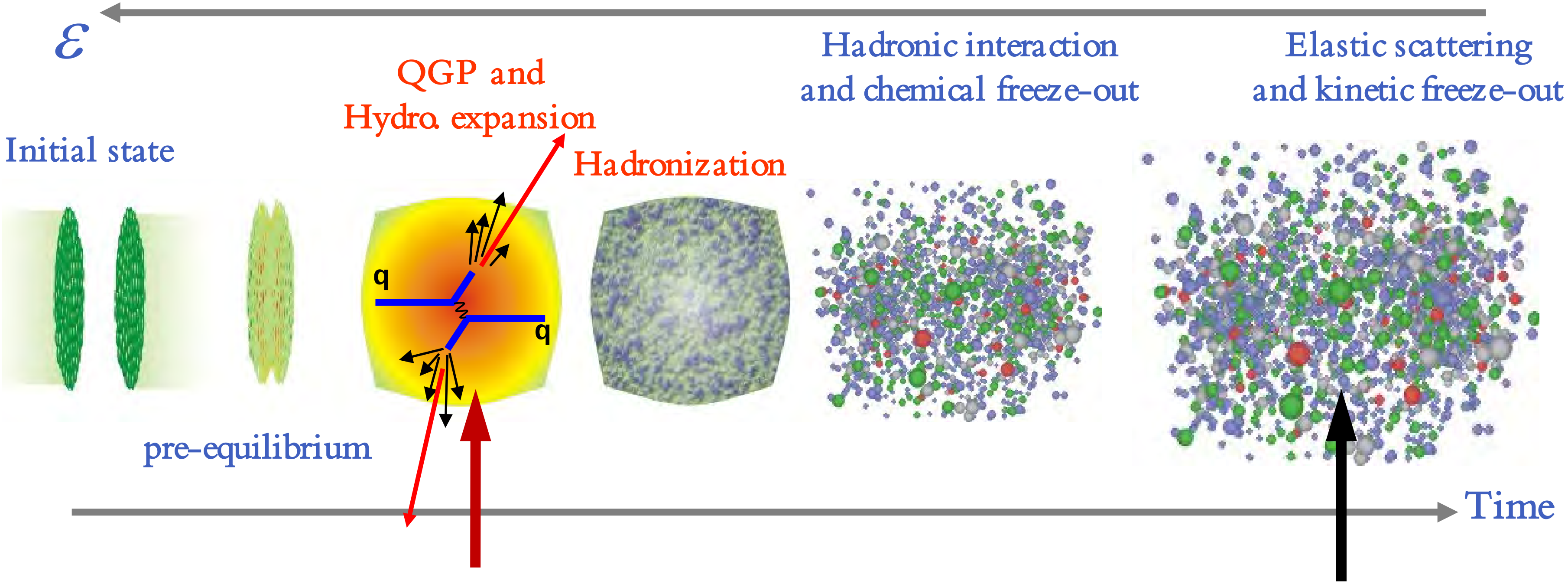
HEAVY ION COLLISIONS

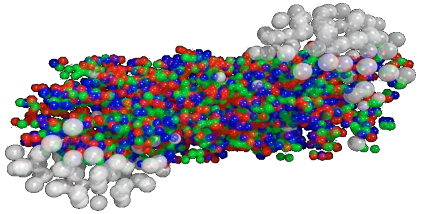
QGP tomography: Jets and other Hard probes

Inspired by presentations by Helen Caines, Yen-Jie Lee, Yi Chen

DIRECT PROBES OF QGP

- Soft sector measurements allow to infer many important conclusions about QGP properties, but are always impacted by the entire evolution of the system.





Need QGP tomography

To directly access plasma properties

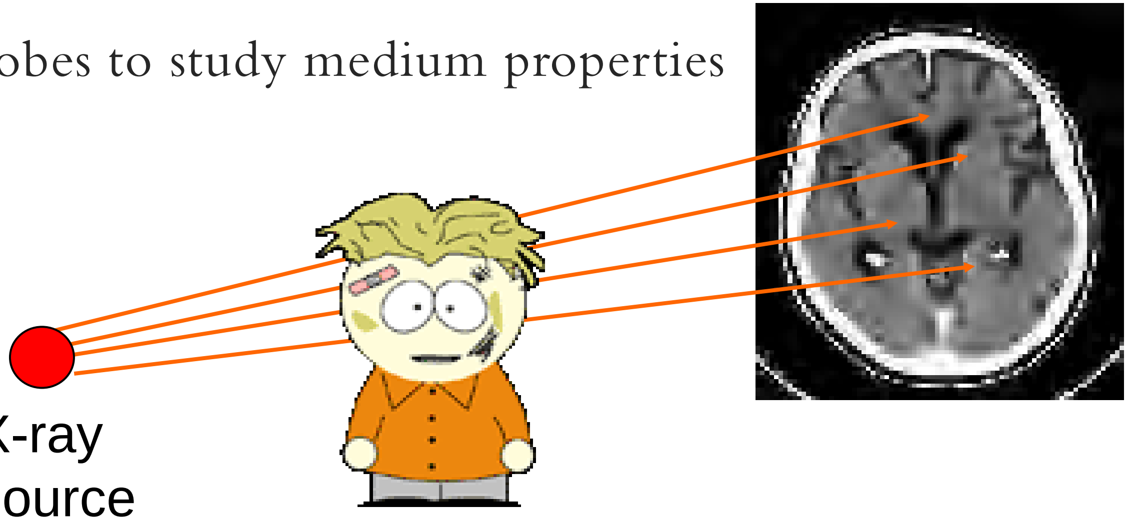
Bulk particle distributions

QGP hadronizes into soft hadrons; 99.9% of total yields

No direct access to details of QGP phase

TOMOGRAPHIC PROBES FOR QGP

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

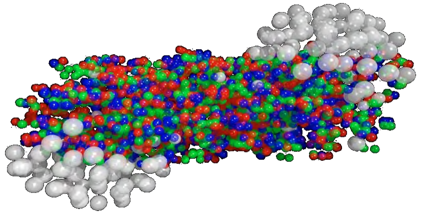


- For HIN collisions → use self-generated (in)medium probes → hard probes!
- "Hard" == large scale → theory: suitable for perturbative QCD calculations

  high momentum transfer Q^2

  high transverse momentum p_T

  high mass m



WHY USE JETS FOR QGP STUDIES?

- What are Jets?

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

- Why Jets?

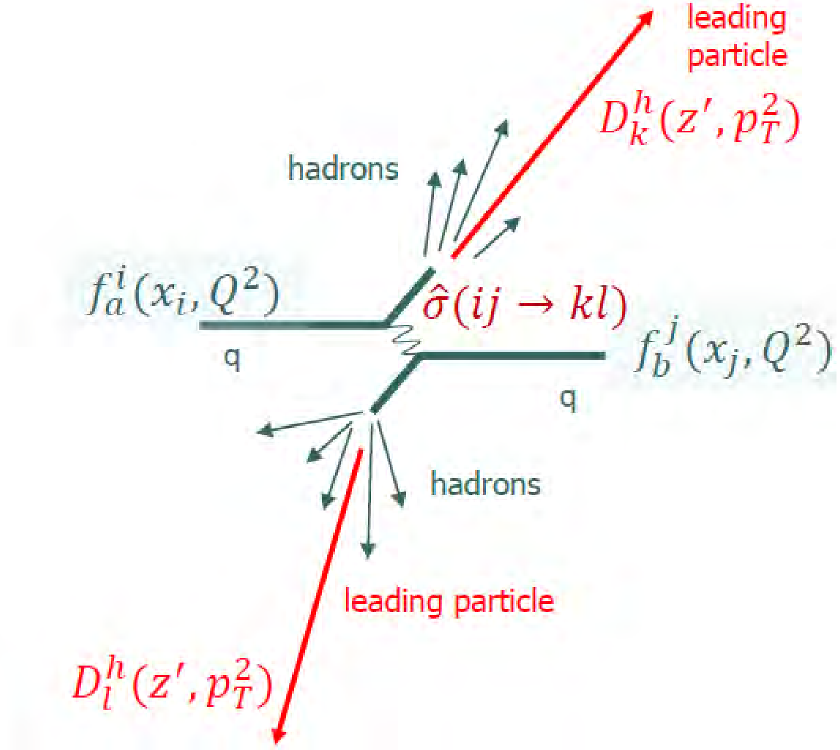
Jets are produced in the earliest phase of the collision

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

$$\begin{matrix} f_a^i(x_i,Q^2) \\ f_b^j(x_j,Q^2) \end{matrix} \otimes \hat{\sigma}(ij \to kl) \otimes D_k^h(z',p_T^2)$$

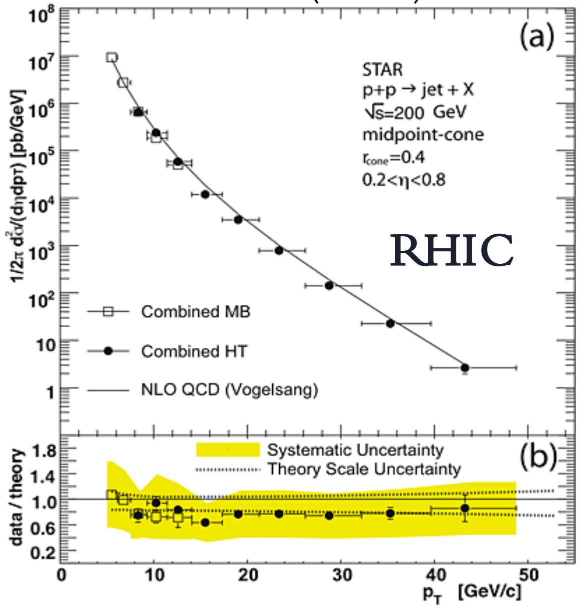
$$PDF \otimes NLO \otimes FF$$

- Jets are *calibrated* probes

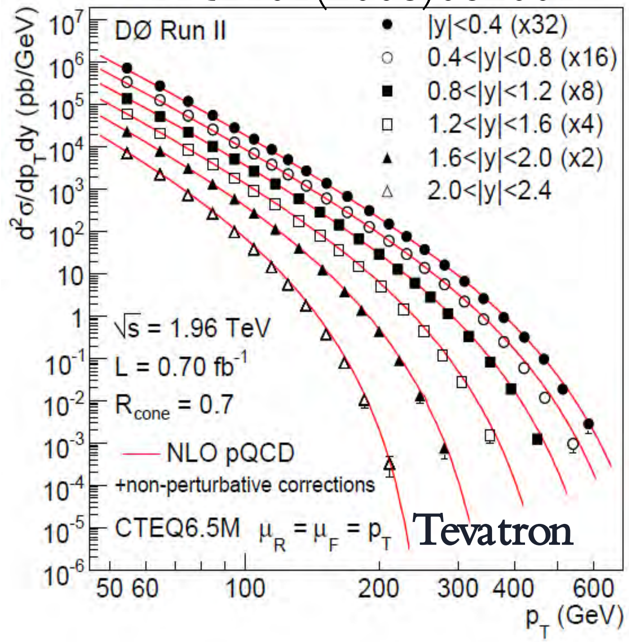


JET PRODUCTION CROSS-SECTION

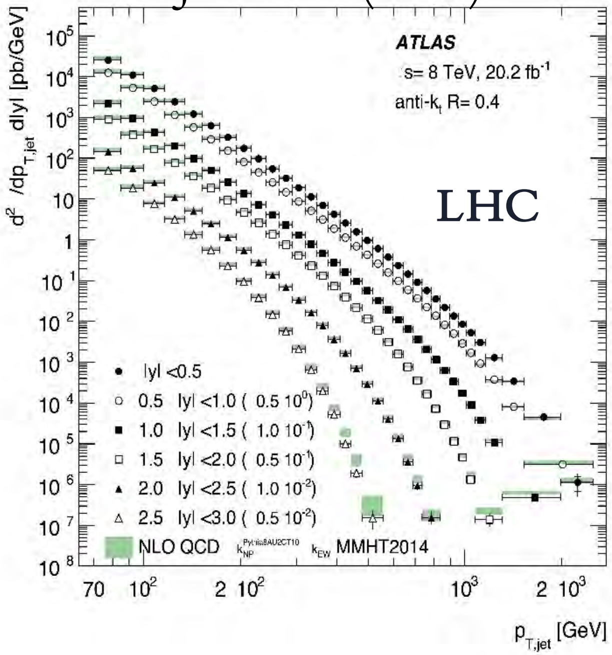
PRL 97 (2006)252001



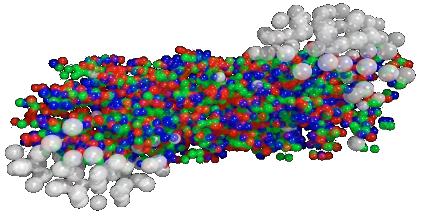
PRL101(2008)062001



JHEP 09 (2017) 020



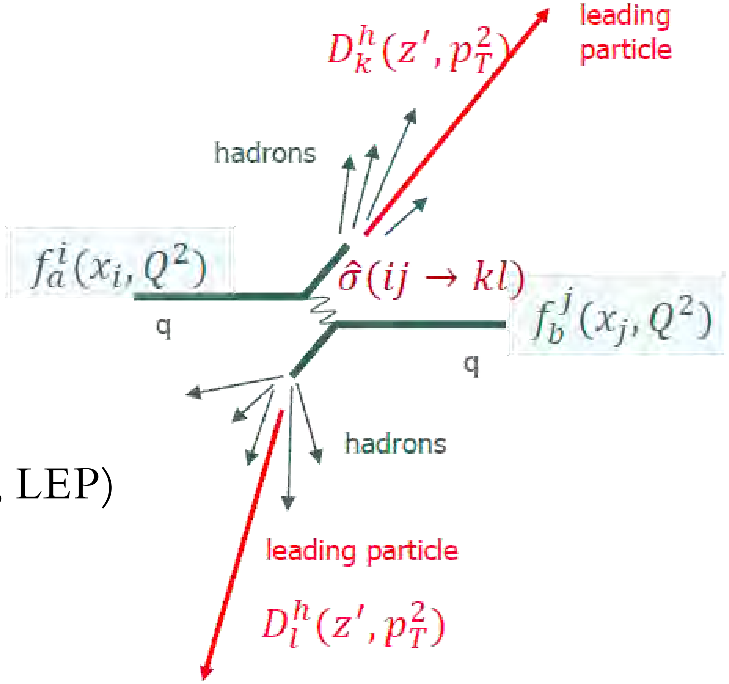
- Jets are well-calibrated probes: inclusive jet cross-sections described by NLO calculations over orders of magnitude in p_T and $\sqrt{s}$



JETS AND PARTICLE PRODUCTION

To get particle yields from jets: need to fold in *fragmentation functions*

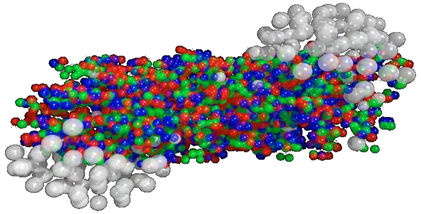
$$\frac{d\sigma^{h(k)}}{dp_T^{h\,2}\,dy^h\,dz'} = \frac{d\sigma^{jet(k)}}{dp_T^2\,dy}\,\frac{1}{z'^2}\,D_k^h(z',p_T^2)$$



$D_k^h(z',p_T^2)$ – *fragmentation functions*,

assumed universal, extracted from e^+e^- annihilation (PETRA, LEP)

and hadronic collisions (UA1,…)



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

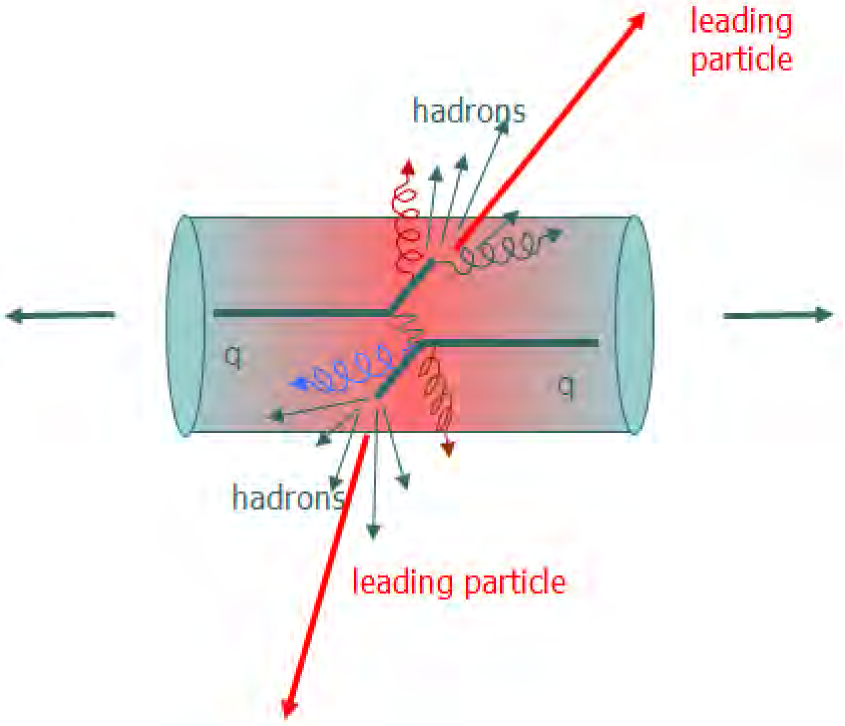
QGP PROPERTIES VIA JETS/HARD PROBES

- Jet Tomography: What happens if partons traverse a high energy density colored medium?

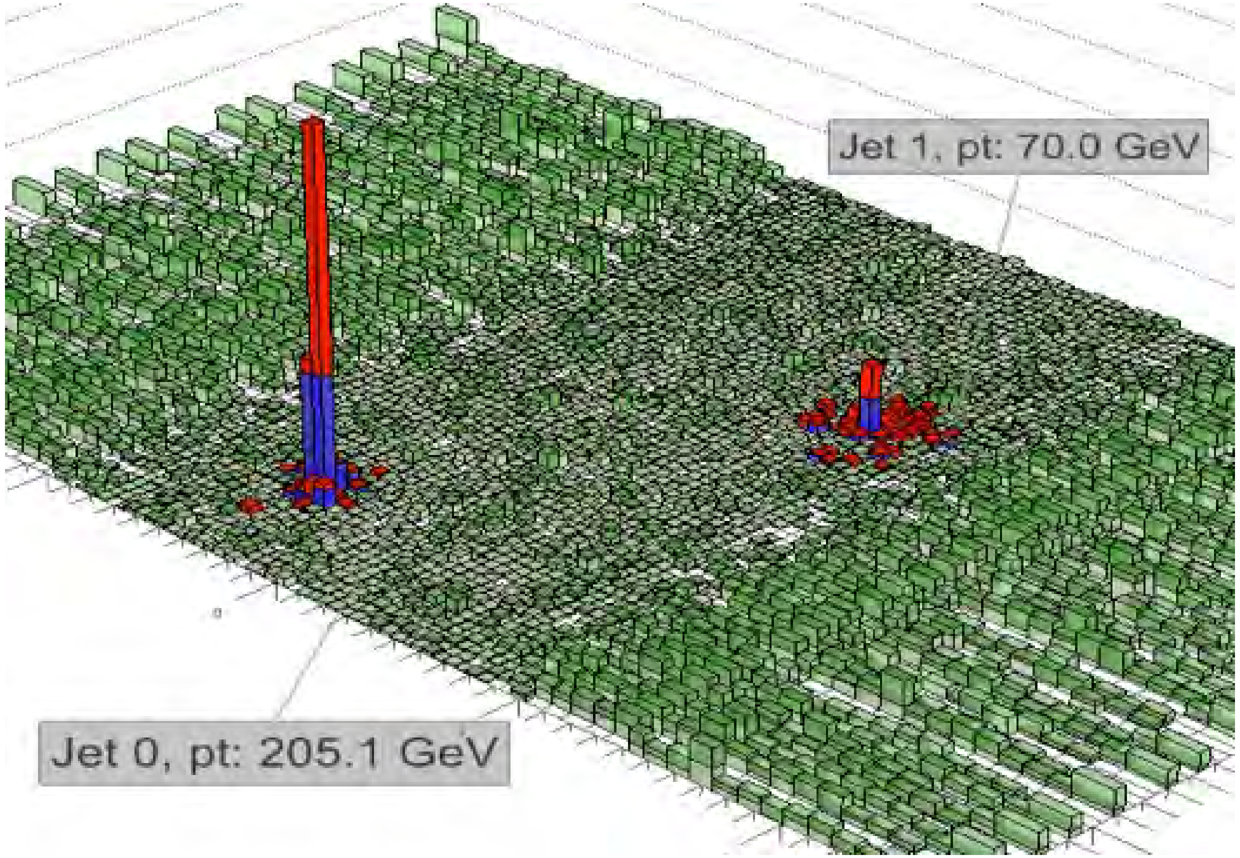
- Production of jets is unmodified* – short-distance process
  ($\hat{\sigma}(ij \to kl)$ – unchanged)

  - Jets are calibrated probes – well-understood (and measured!) in pp
  - Jets studies allow to observe medium evolution and equilibration and explore medium properties at different scales

*except for nPDF effects



JET QUENCHING 101: JETS ARE QUENCHED!

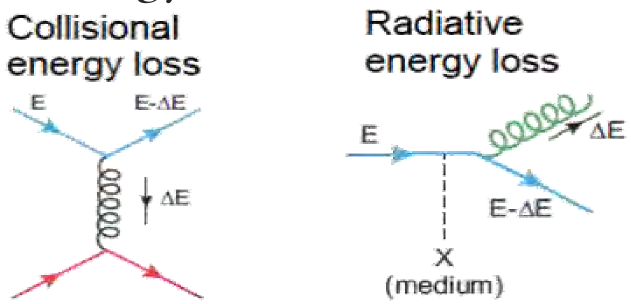


OLGA EVDOKIMOV (UIC)

AUGUST 2, 2024

JET QUENCHING, THEORY

- "Jet quenching," generally, is a collective term describing the range of phenomena arising from the interaction of hard probes with the QGP medium.
- One of the main features associated with jet quenching is partonic energy loss



- Interactions between hard-scattered parton and QGP:

elastic scattering → collisional energy loss (essential at lower p_T)

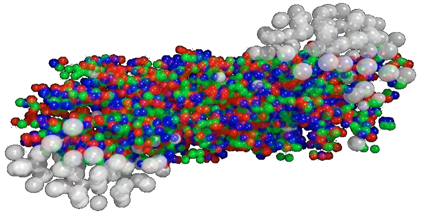
– mass-dependent

gluon bremsstrahlung → radiative energy loss (dominates at high p_T)

– depends on color-charge $\Delta E \sim \alpha_s \boldsymbol{C_R} \hat{q} L^2$, C_R - Casimir factor

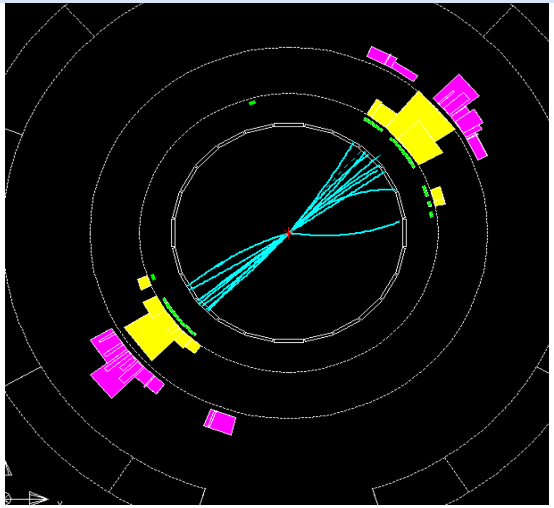
– dead-cone effect: radiation probability is suppressed for $\theta < \frac{m_Q}{E_Q}$

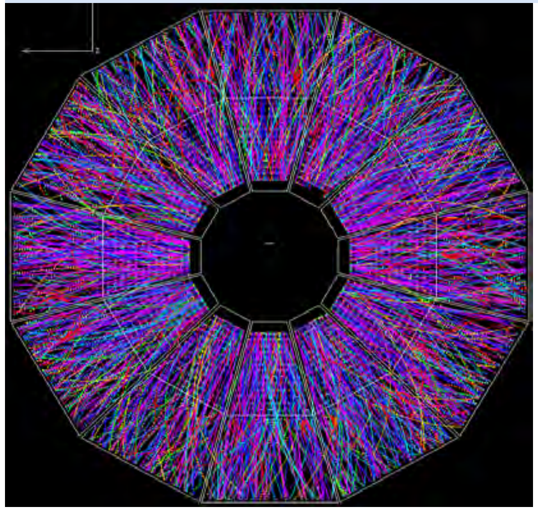
	low p_T	high p_T
Meaning:	$\Delta E_g > \Delta E_q > \Delta E_Q$	$\Delta E_g > \Delta E_q \sim \Delta E_Q$

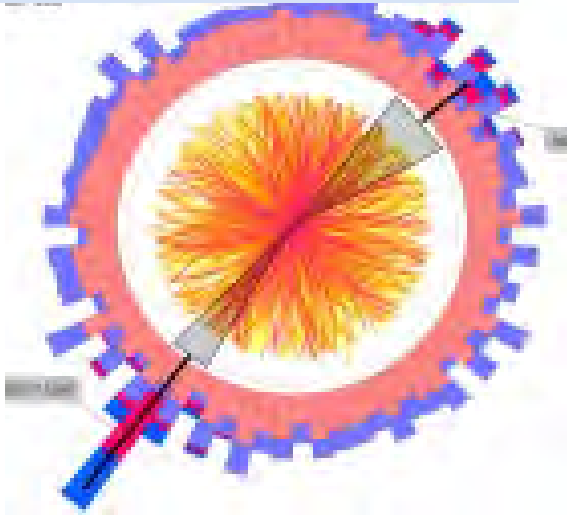


JET STUDIES, EXPERIMENTALLY

Jets in e^+e^- collision	Jets in AA collisions

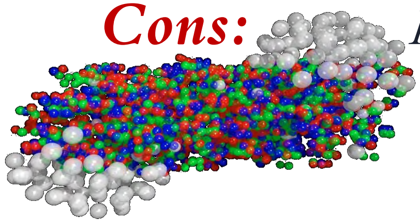






Choice of tools (in hard regime):

	Spectra/Production rates	Dihadron correlations	Jets/Dijets
Pros:	*straightforward*	*versatile*	E^{parton}
Cons:	*least differential*	*multiple BG sources, no direct E measure*	*ambiguous, fluctuations*



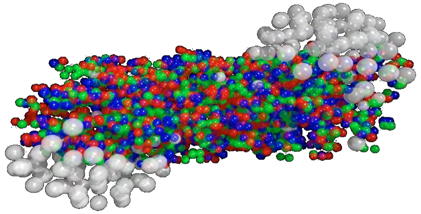
JET QUENCHING: START OF THE ERA

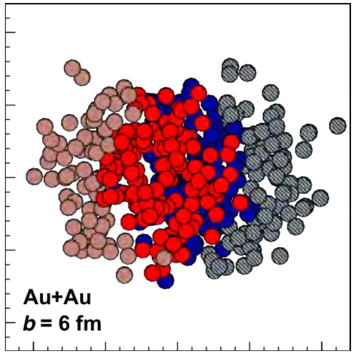
- Comparing particle production rates at high p_T provides (indirect) information on the fate of the jets in QGP

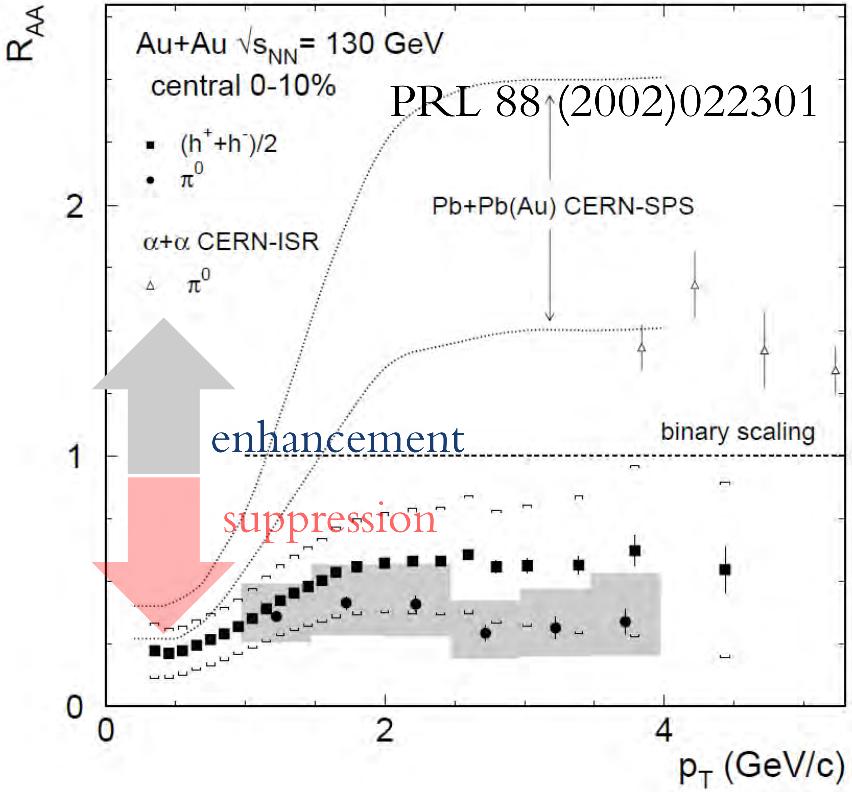
- Nuclear Modification Factor R_{AA} – the first tool for jet quenching studies:

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

- Number of binary collisions $< N_{bin} >$ is extracted from Glauber model calculations







PRL 88 (2002)022301

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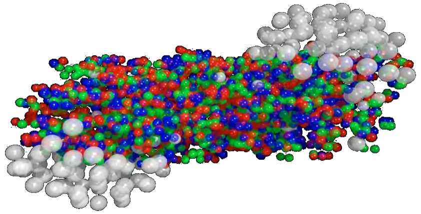
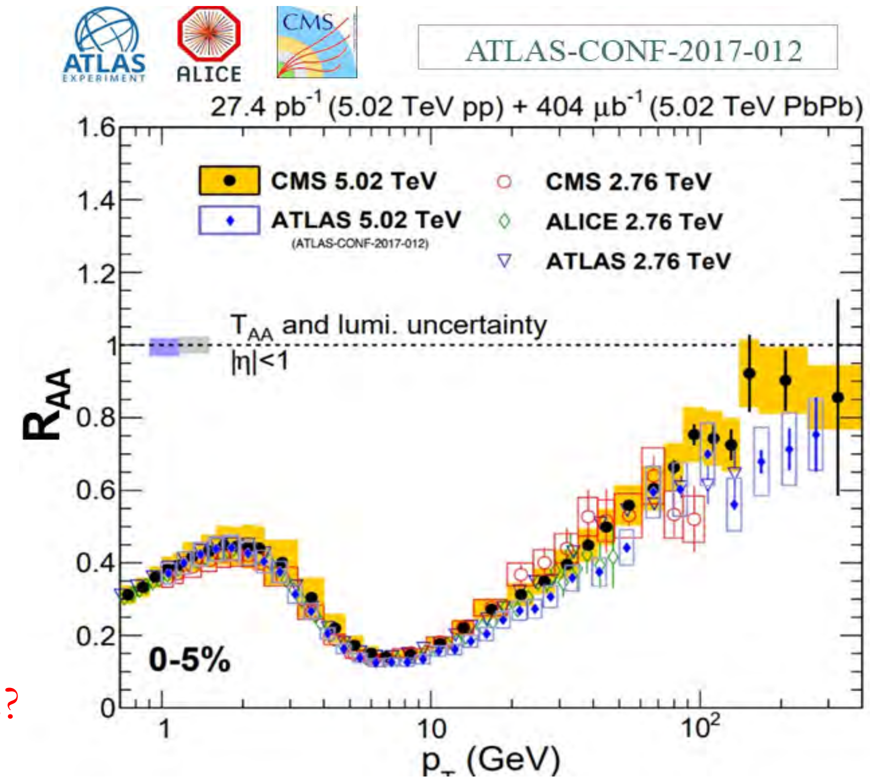
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{< N_{bin} > d^2N^{pp}/dp_T d\eta}$$

- sQGP – strongly coupled plasma!

  Large energy loss for colored probes



How reliable are the Glauber model calculations?



BINARY SCALING AND R_{AA}

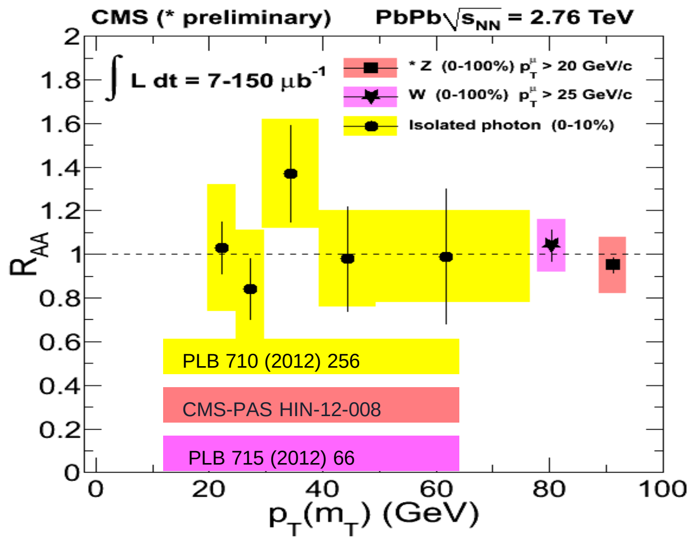
- HIN experiments used colorless probes to check N_{bin} scaling:

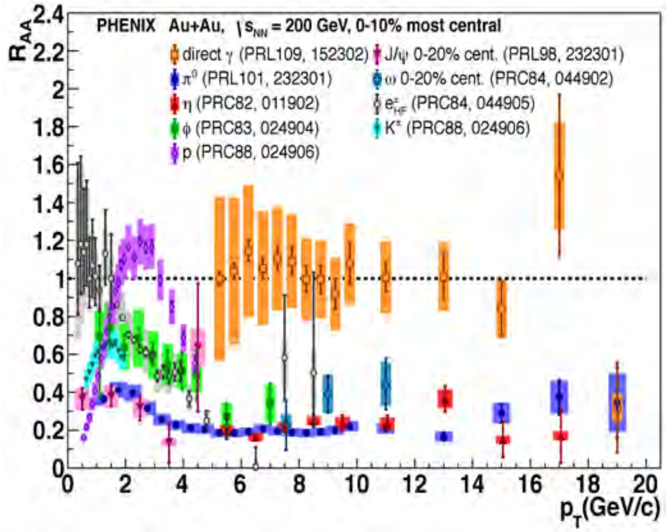
  Isolated photons

  $Z \rightarrow \mu + \mu -$

  $W \rightarrow \mu\, \nu$

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





FLAVOR DEPENDANCE OF QUENCHING

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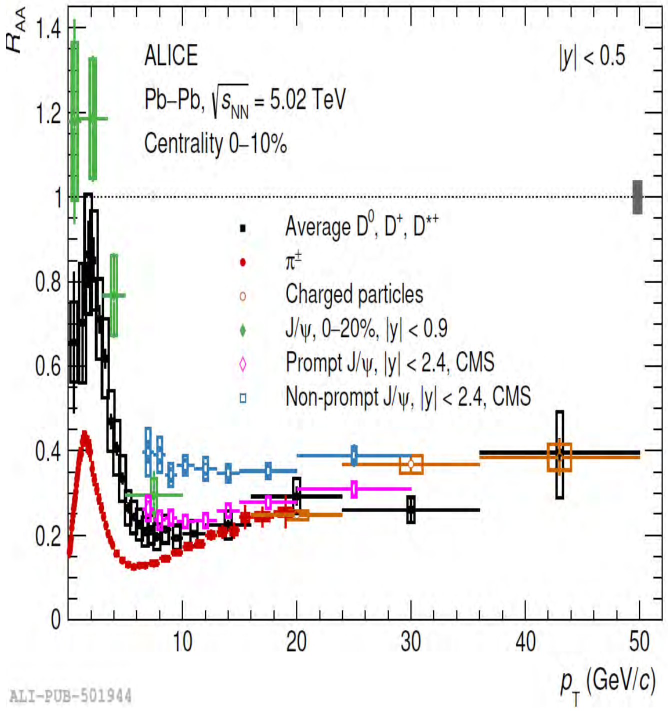
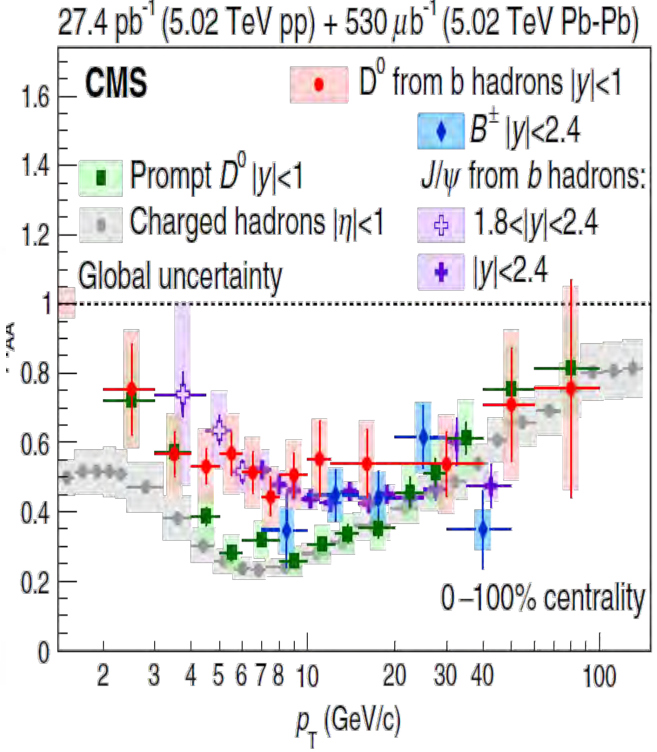
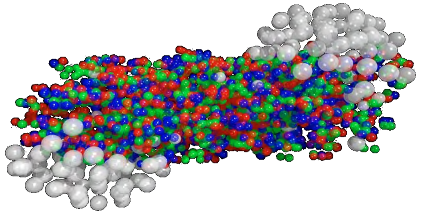


PRL 123(2019)022001





- Nuclear modification for prompt- and non-prompt D^0 , non-prompt J/ψ, $B^{\pm}$
- Lower p_T : flavor dependence of energy loss

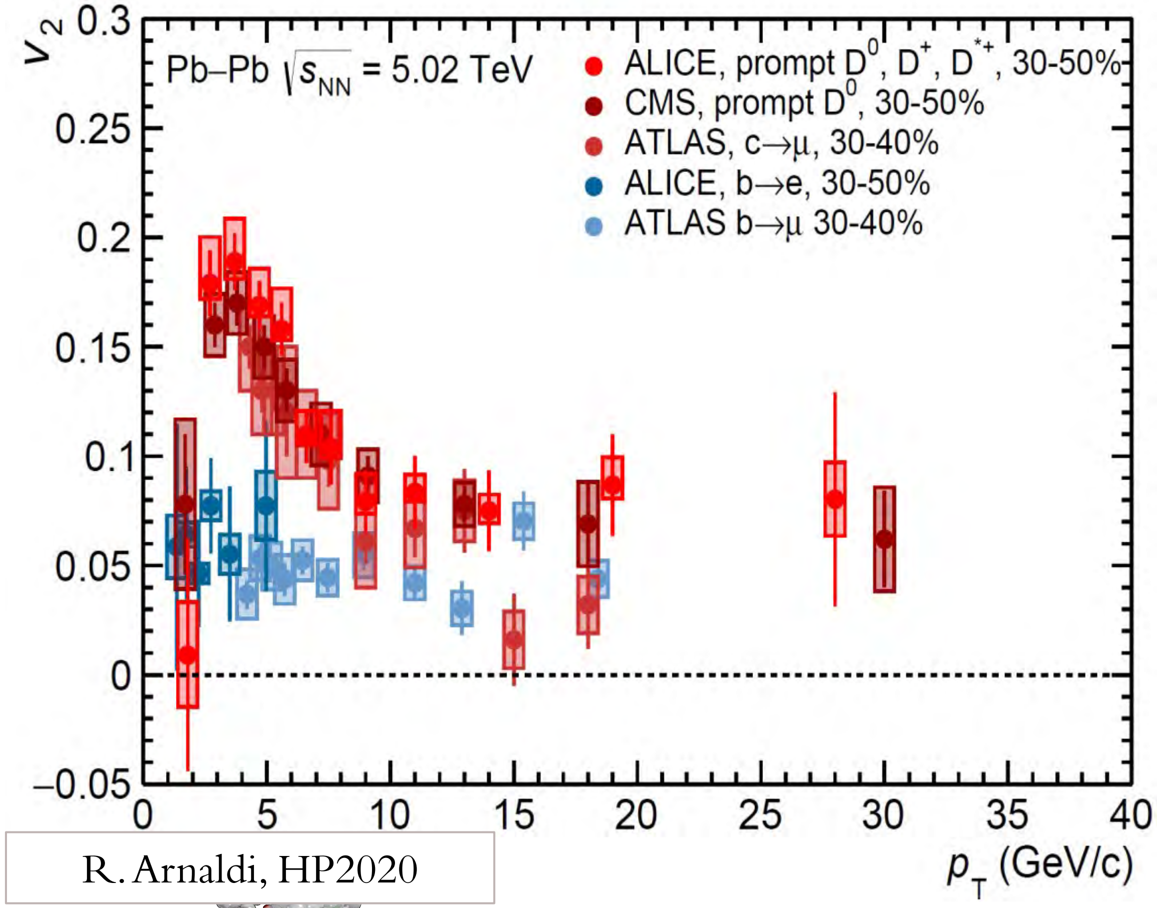
  $R_{AA}\ (b) > R_{AA}\ (c) \sim R_{AA}$(light flavors)

  $\Delta E_q > \Delta E_c \sim \Delta E_b$
- High p_T :

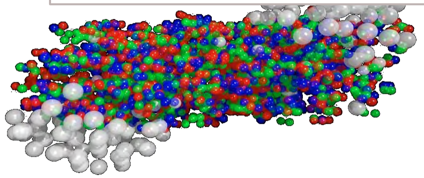
  $R_{AA}\ (b) \sim R_{AA}\ (c) \sim R_{AA}$(light flavors)

  $\Delta E_q \sim \Delta E_c \sim \Delta E_b$
- Recall theory input: radiative energy loss dominates at high p_T, collisional contributions relevant at lower momenta

FLAVOR DEPENDANCE, TAKE TWO



R. Arnaldi, HP2020



- At high p_T nuclear modification goes hand in hand with azimuthal anisotropy – two different ways to measure/characterize pathlength dependance of partonic energy loss

- LHC experiments : significant v_2 for both charm and beauty in PbPb events, different p_T dependence

- Charm: v_2 ~ below light hadron v_2
- Beauty v_2 < charm v_2, but sizable

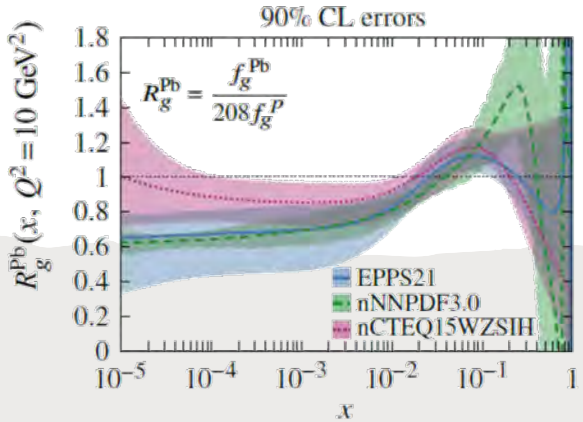
  → indicate strong coupling to the medium

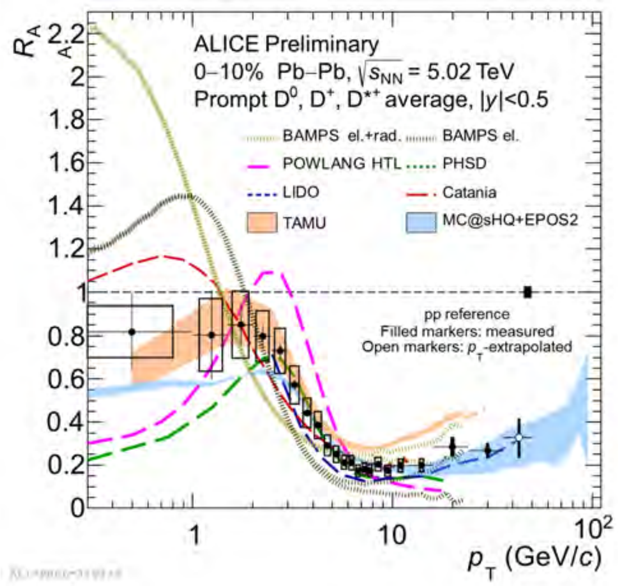
- What about p_T dependence?

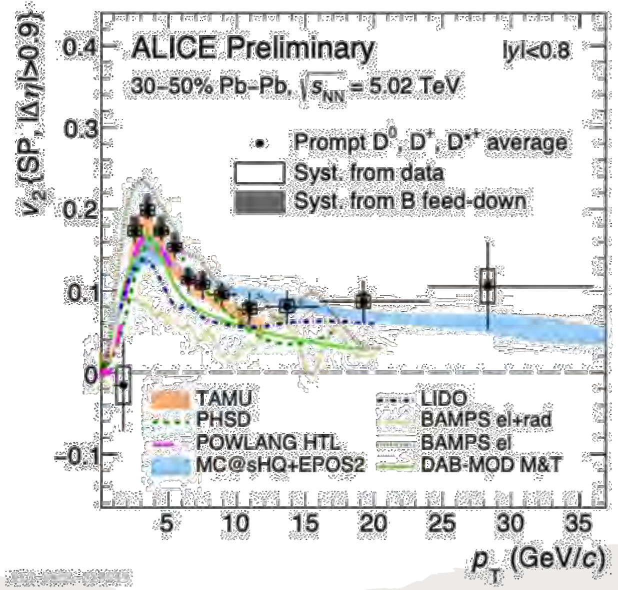
  → need to disentangle energy loss, hadronization, flow, CNM…

FLAVOR DEPENDANCE, THEORY INPUT

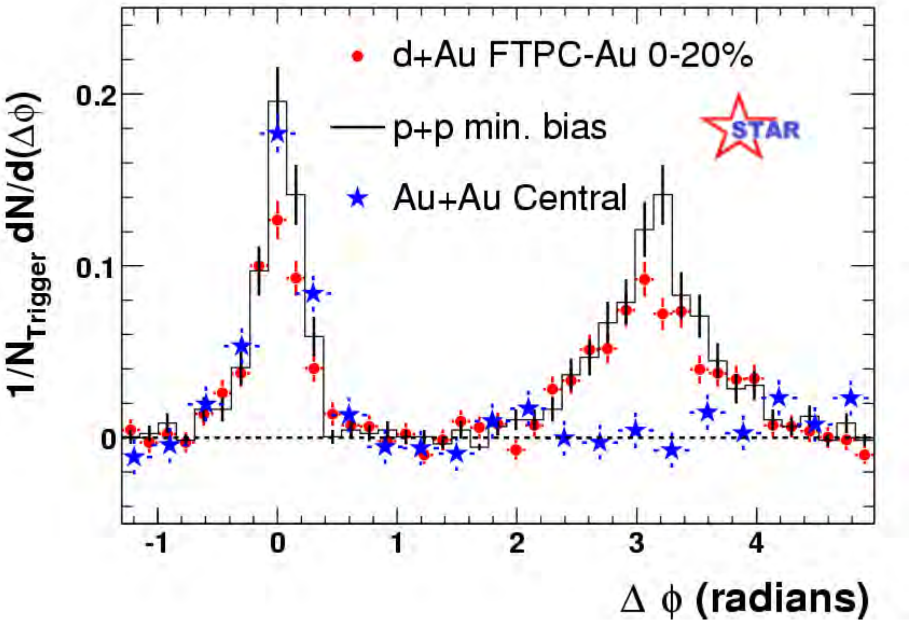
- Partonic energy loss is manifested in R_{AA} and v_2 at high p_T ; simultaneous description of both measurements is a test for quenching models
- Simultaneous description of charm R_{AA} and v_2 is challenging for the models.
- Models that seem to do best include both collisional and radiative energy loss and nPDF effects (shadowing).

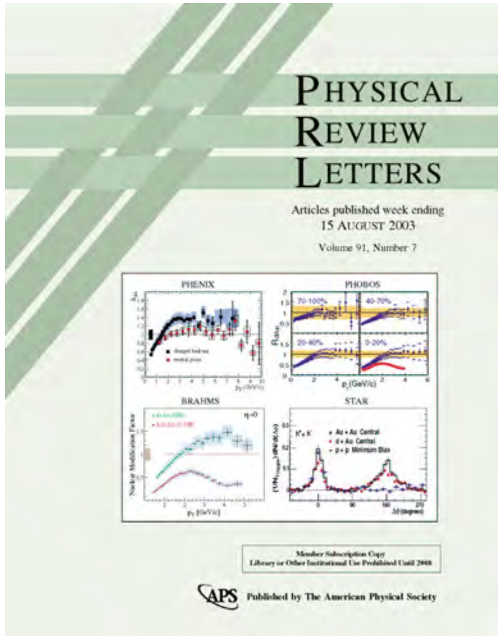






PROOF OF JET-MEDIUM INTERACTIONS





PHENIX: PPRL 91 (2003) 072303
STAR: PRL 91 (2003) 072304
PHOBOS: PRL 91 (2003) 072302
BRAHMS: PRL 91 (2003) 072303

Signature two-particle correlation result:

- Evidence of quenching: disappearance of the away side jet in central AuAu collisions: evidence for strongly interacting medium
- Evidence of **non**-quenching: effect vanishes in peripheral/dAu collisions

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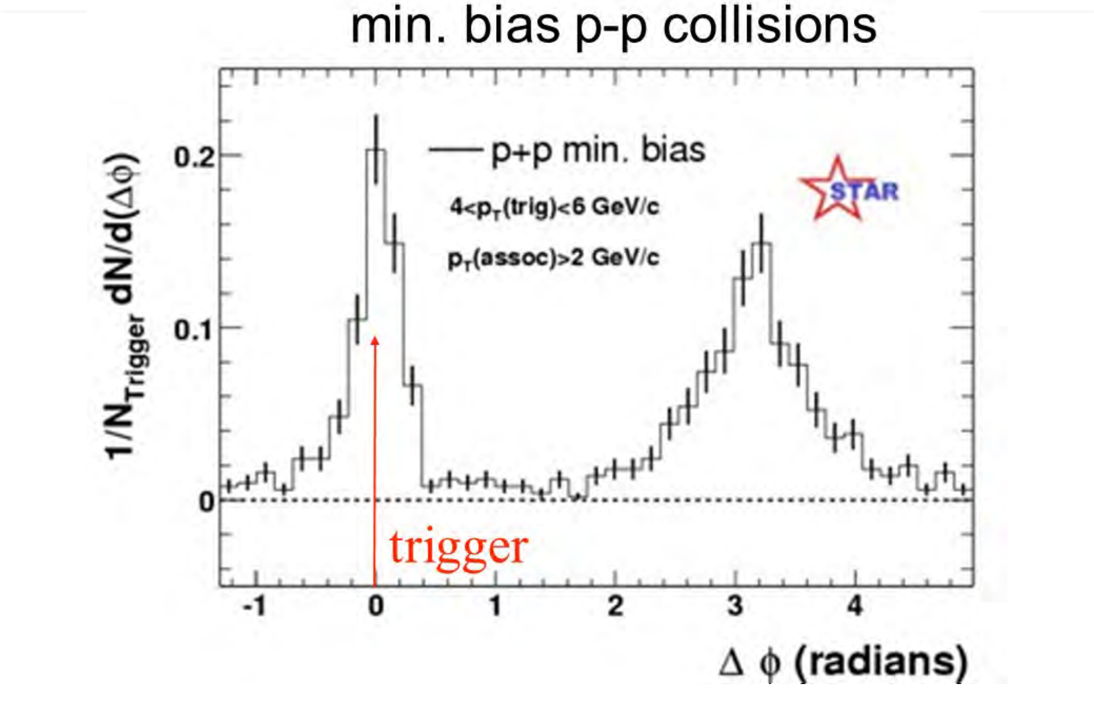

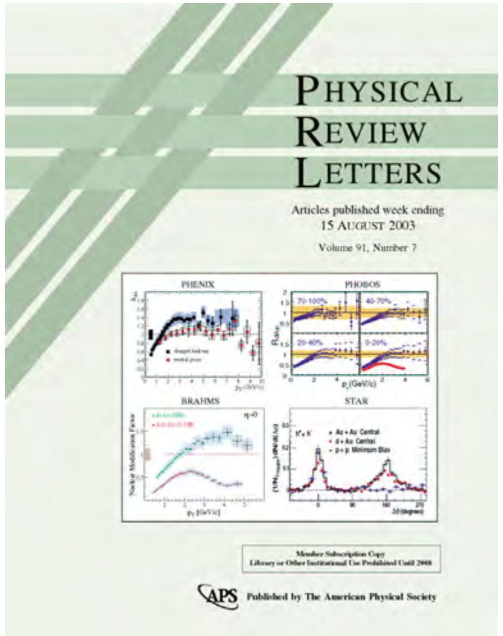

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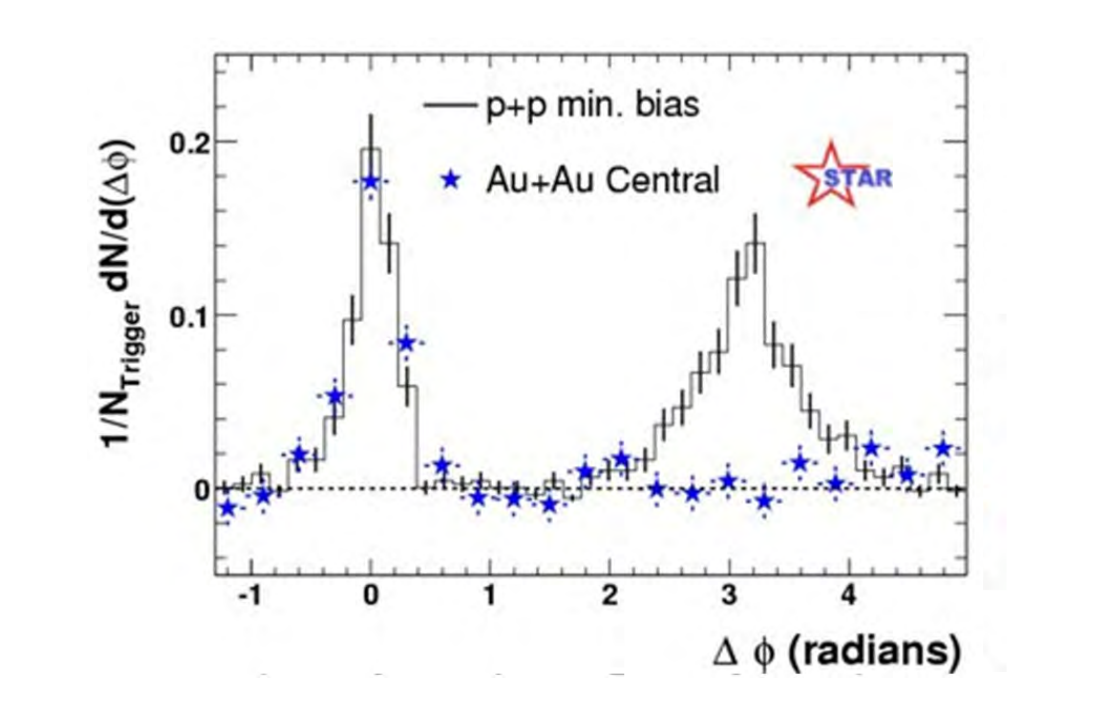

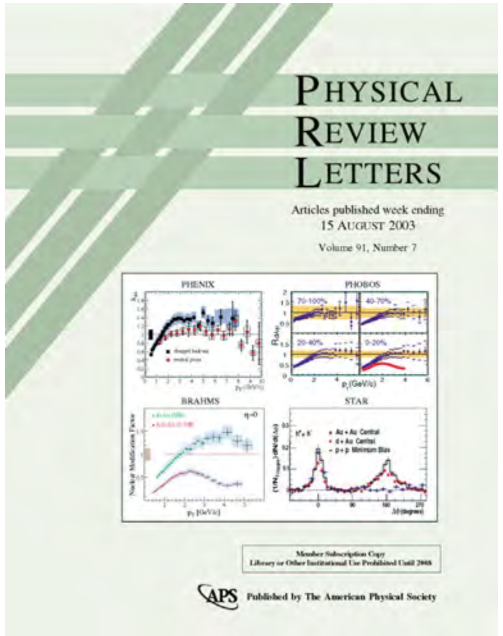

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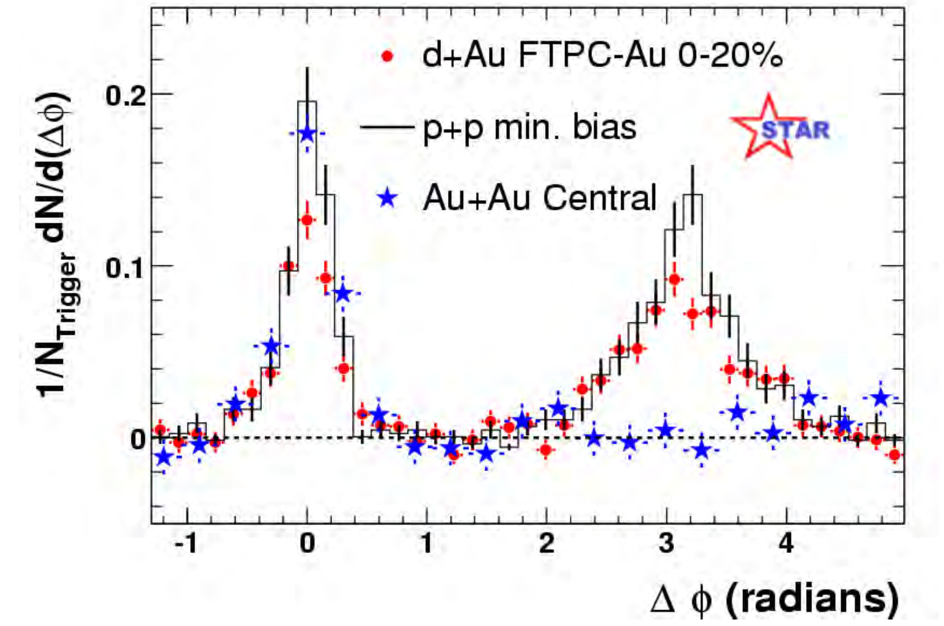

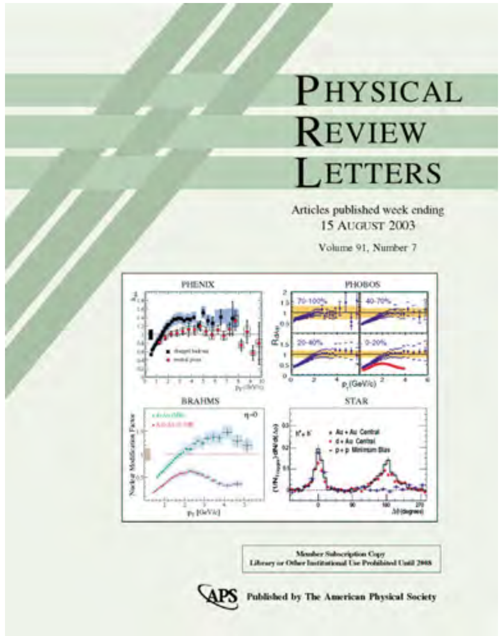

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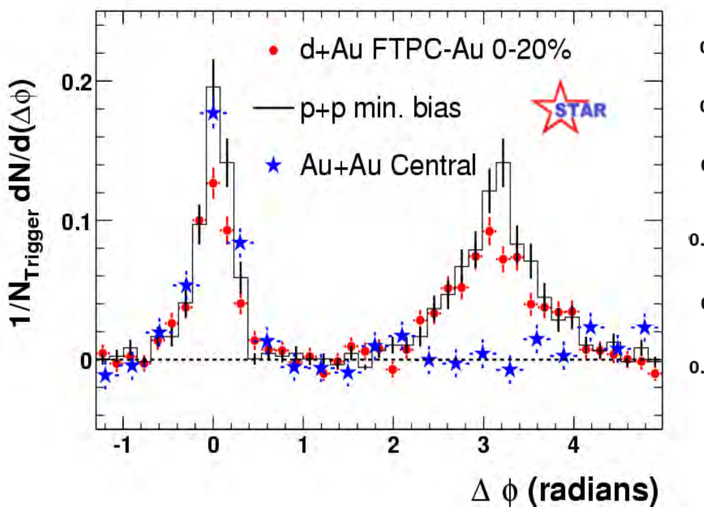
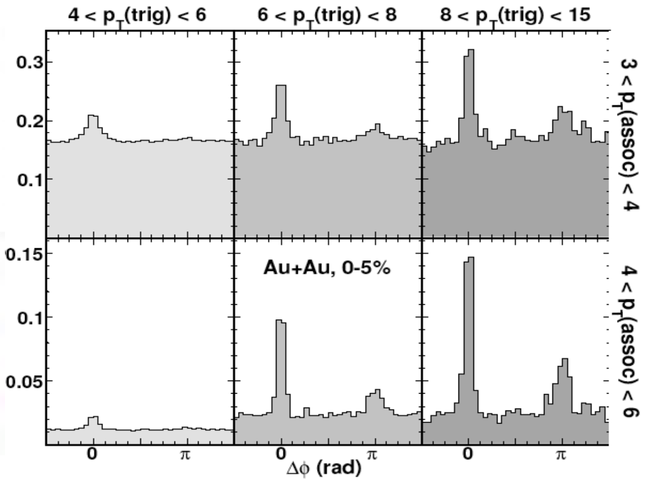
DISCLAIMER ON THE "DISAPPEARANCE"





- Disappearance of the away side jet in central AuAu collisions at RHIC:

  Evidence for strongly interacting medium

  Effect vanishes in peripheral/dAu collisions

"*Disappearance*" is accidental!

Two high-p_T hadrons (or high & low p_T combination): reappearance of the away-side jet.

Redistribution is a better way to think about this: energy gets shifted from higher to lower momenta

LET'S GET US SOME JETS!

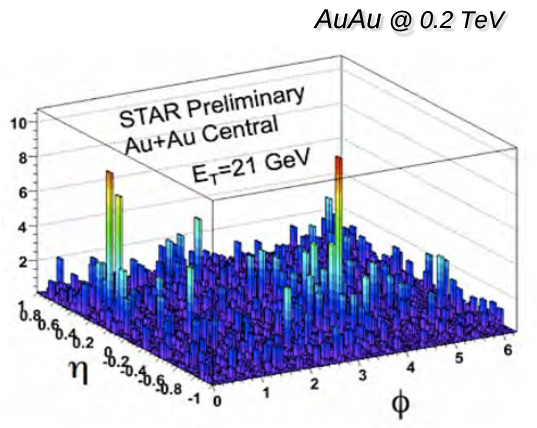
- In Theory: jets are proxies for hard-scattered partons
- In Experiment: "Jet is what your jet-finder gives you" (P.J.)

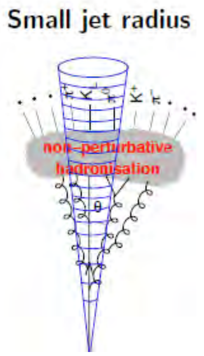
- Jet is defined by the reconstruction algorithm:

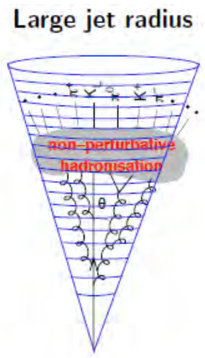
    1) What particles belong to a jet

    2) How particle momenta combined into jet p_T

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







SEQUENTIAL RECOMBINATION ALGORITHMS

- Sequential recombination methods are based on distance measure:

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

- Most commonly used:

k_T algorithm	n = 2	PLB641(2006)57
anti-k_T algorithm	n = −2	JHEP 0804 (2008) 063
Cambridge-Aachen algorithm	n = 0	JHEP 9708 (1997) 001

- Do iteratively:

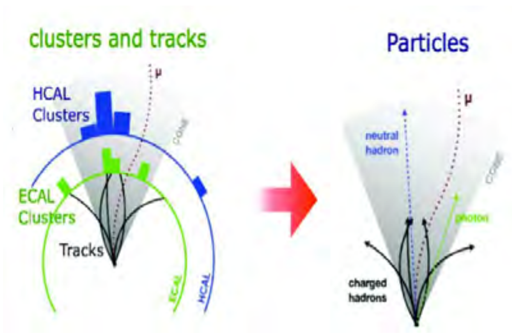
  compute all distances d_{ij} and d_{iB}, find the smallest

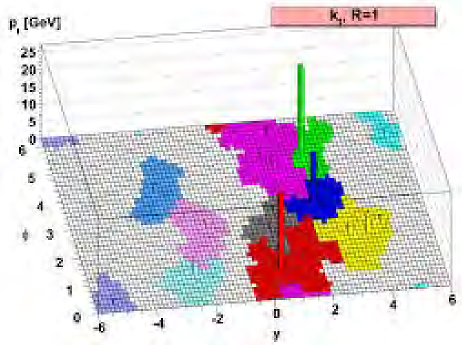
  If smallest is a d_{ij}, combine (sum four momenta) for i and j

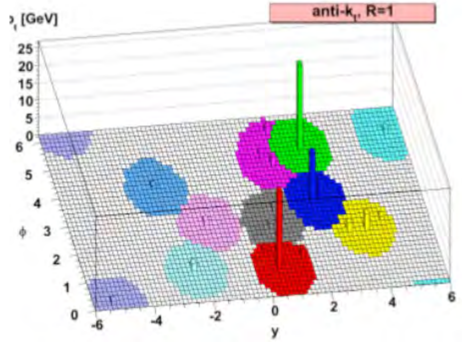
  If smallest is a d_{iB}, call i a jet (remove). Stop then no objects left.

- All three algorithms (+SISCone) are available in the

  Fastjet package: http://fastjet.fr/







DEALING WITH (HIN) BACKGROUND

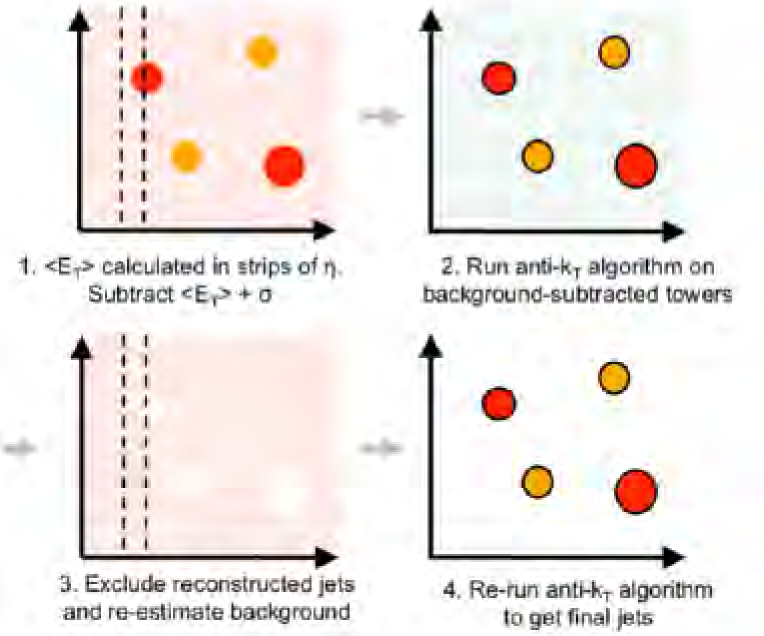
The background in HIN events is anisotropic and fluctuating → simple "flat-line" subtraction won't work. Need:

1) Modulated BG (shape!)

2) Corrections/unfolding for fluctuations (or reference smearing)

Two general strategies:

"Subtract then Cluster"



"Cluster then Subtract"

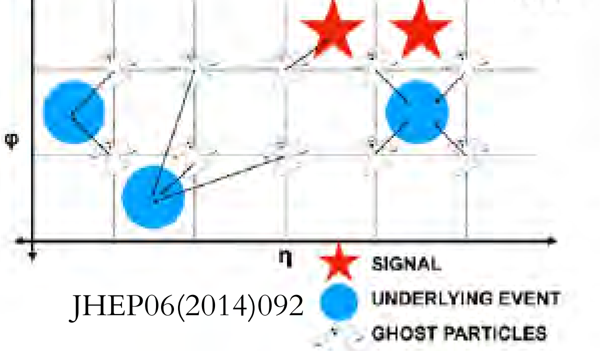
Area Subtraction

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

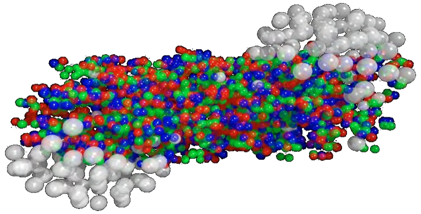
ρ – average p_T density for BG w/o jets

Aj – jet area from "ghost" counts

Constituent Subtraction

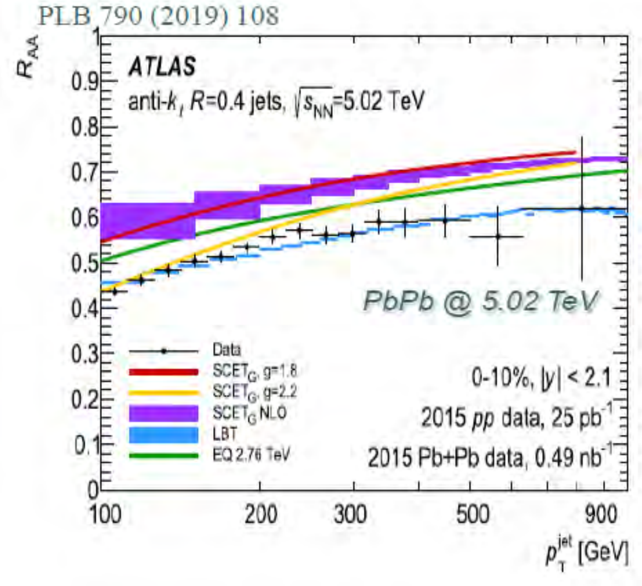


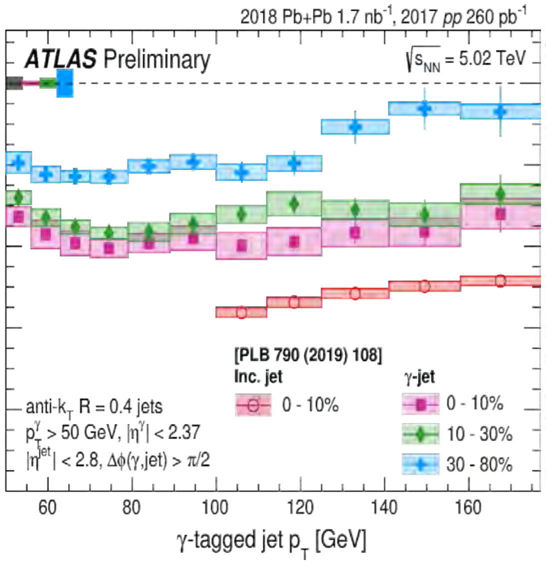
JHEP06(2014)092

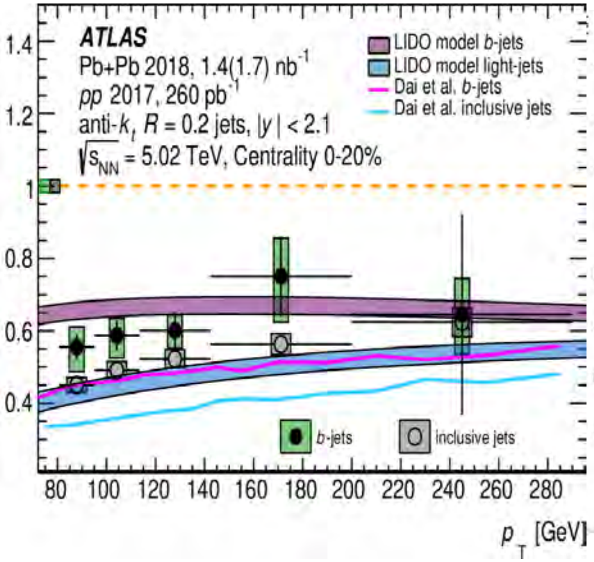


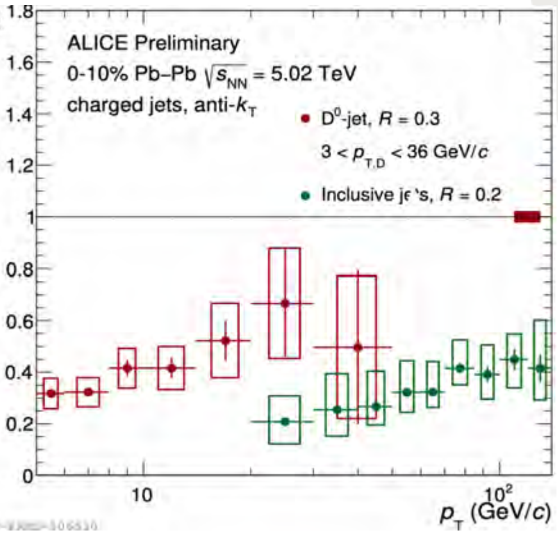
QUENCHING EFFECTS IN JETS

- Details of the energy loss : jet R_{AA} maps quenching effects in PbPb from 30GeV to 1TeV







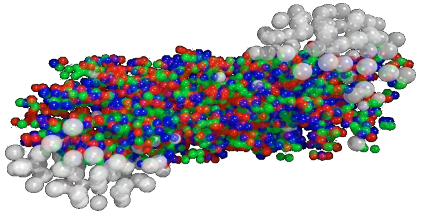


- Search for color-charge, mass, and/or flavor effects in energy loss:

Photon-tagged jets (higher fraction of q-jets): less suppressed compared to inclusive jets

b-jets (muon tagger): less suppressed compared to inclusive jets

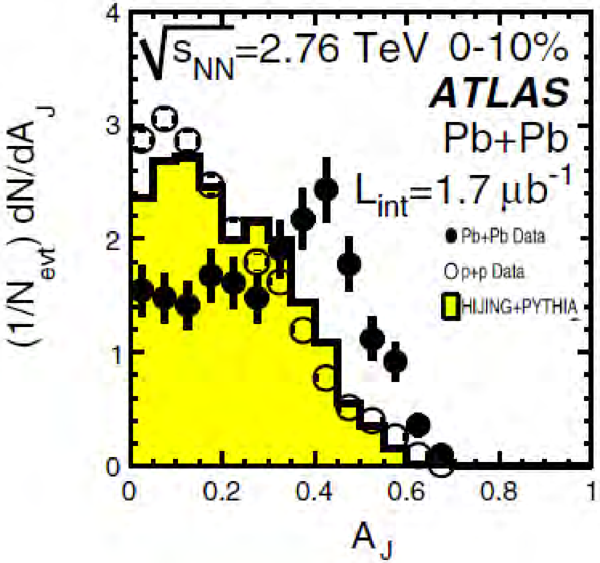
D^0-tagged jets – indications of smaller suppression compared to inclusive jets



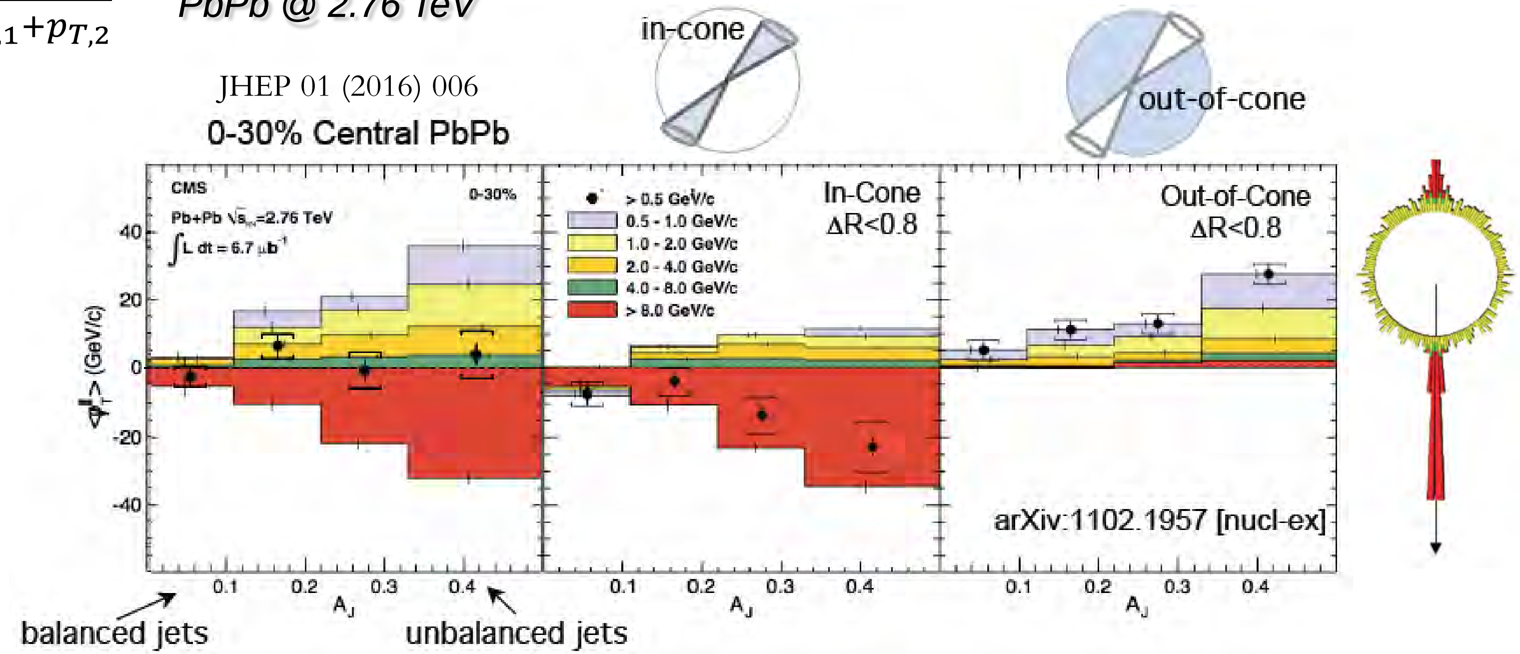
QUENCHING BECOMES *VISIBLE* IN DIJETS

Dijet momentum imbalance: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$ ***PbPb @ 2.76 TeV***

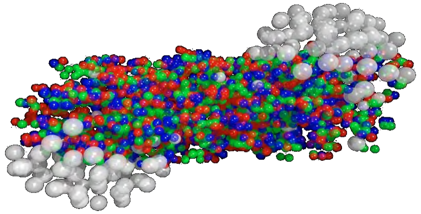
PRL 105 (2010) 252303



JHEP 01 (2016) 006



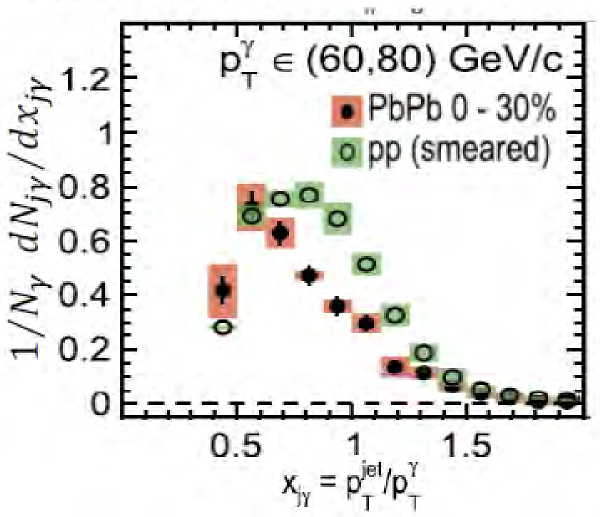
- Di-jets in PbPb: back-to-back, but fraction of imbalanced dijets grows with collision centrality (no modifications in pPb collisions)
- Momentum balance is preserved over the entire event; "missing" p_T in hard sector is balanced by soft hadrons away from jet-axis



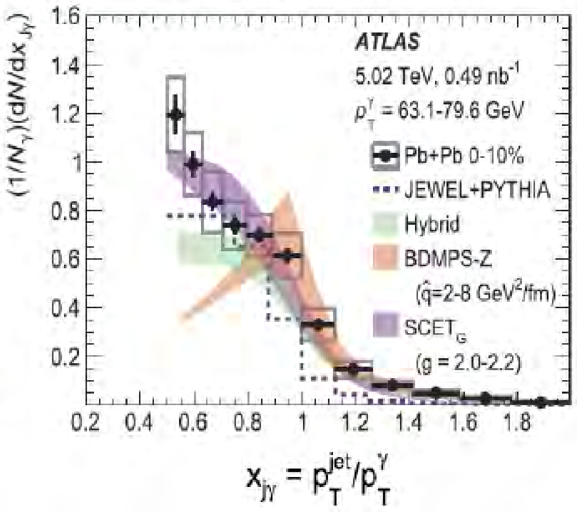
QUENCHING EFFECTS IN JETS

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

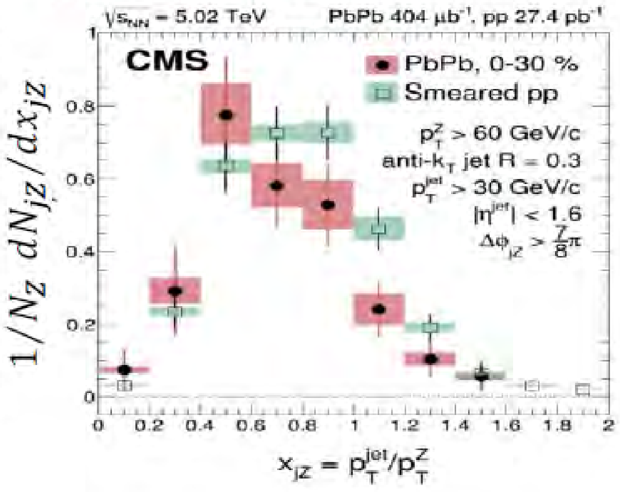
PLB 785 (2018) 14



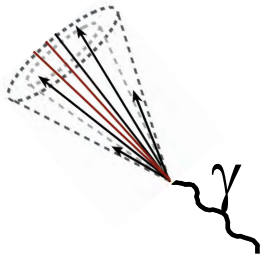
PLB 789 (2019) 167

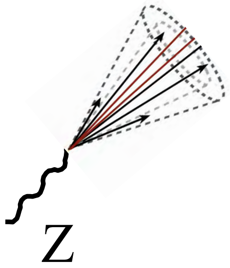


PRL 119 (2017) 082301



PbPb @ 5.02 TeV

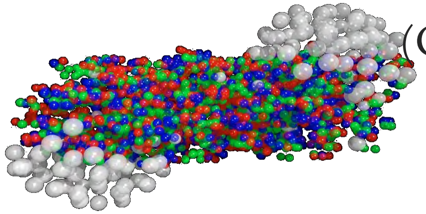




- Details of the energy loss:

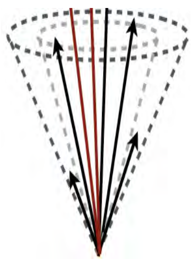
  Dijet, γ-jet, Z-jet – energy balance is disturbed by QGP

  (Centrality-dependent) changes in $x_{J\gamma}, x_{JZ}$ momentum balance

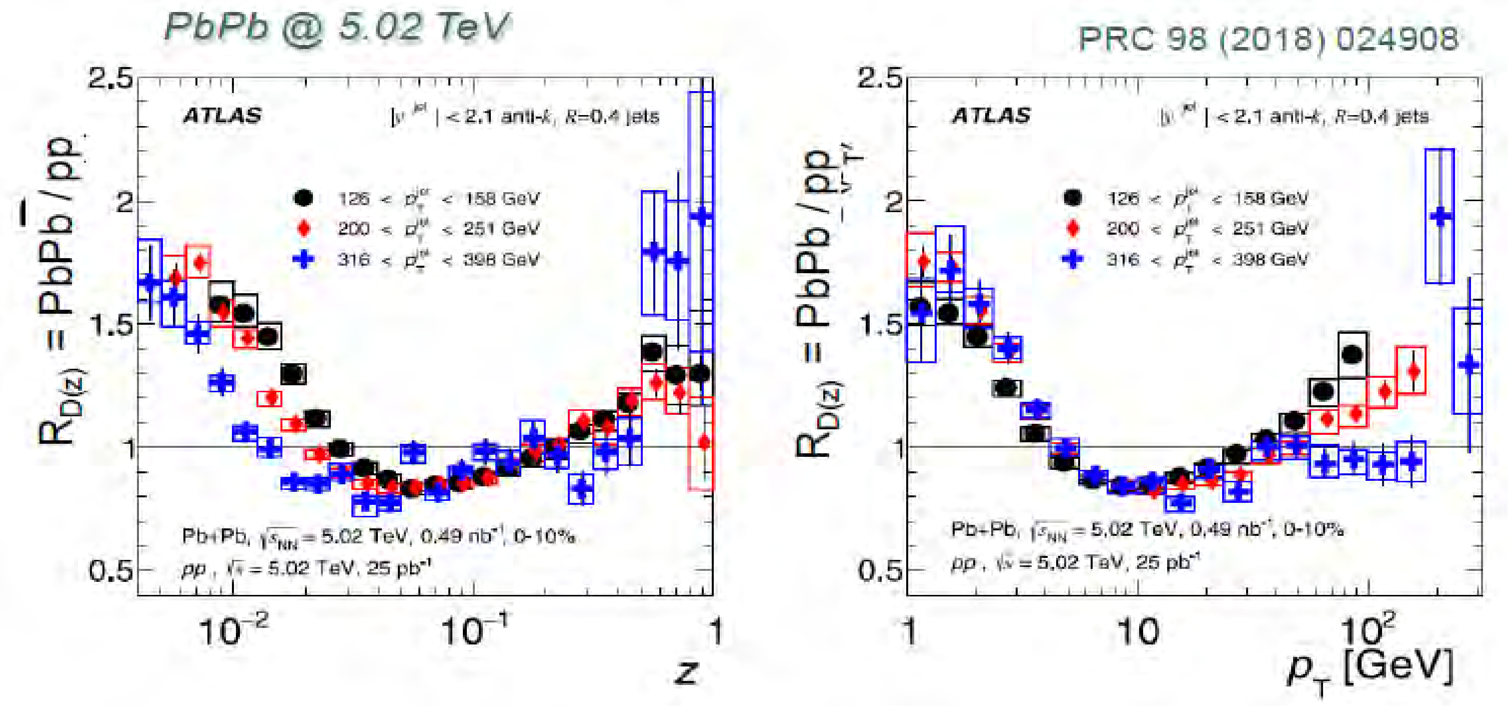


JET LONGITUDINAL STRUCTURE

- Jet fragmentation function: fractional momentum distribution within the jets

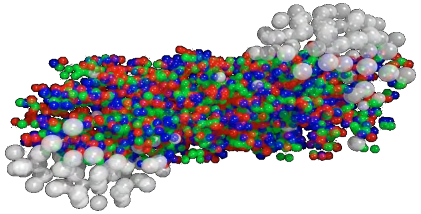


$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$



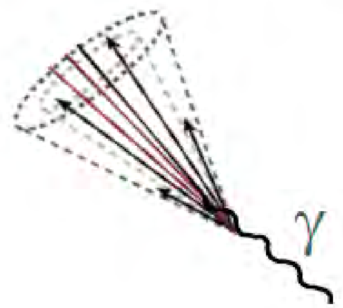
Excess of soft fragments/depletion at intermediate momenta

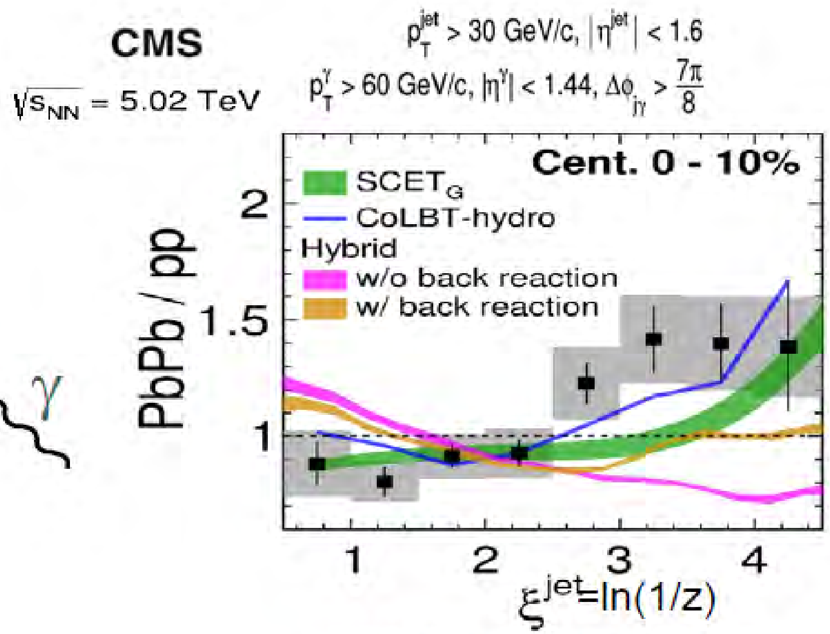
Excess of high-p_T tracks – evidence of color-charge effects?



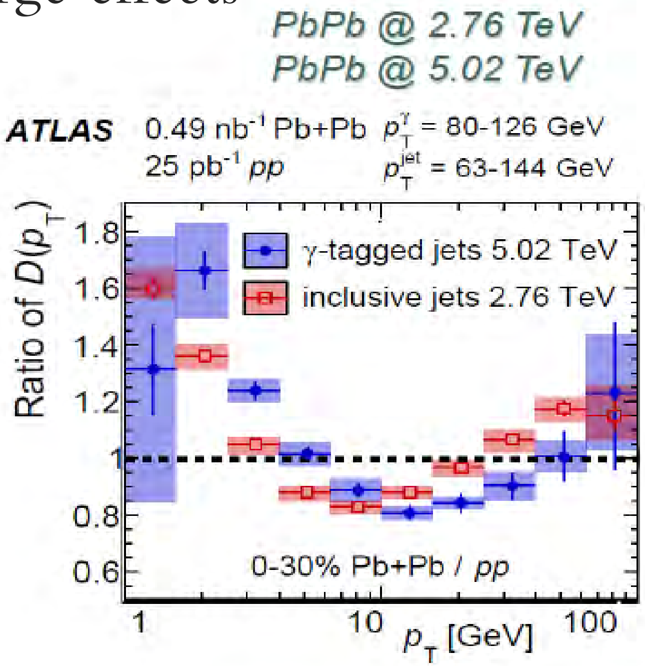
FRAGMENTATION FOR γ +JETS

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

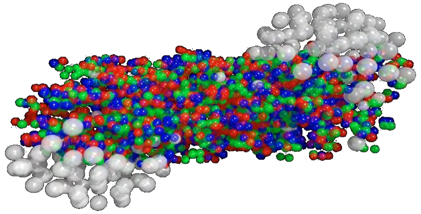




PRL 121 (2018) 242301



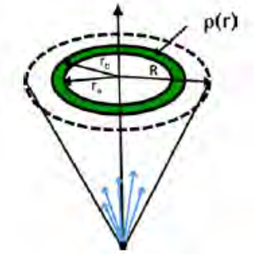
PRL 123 (2019) 042001



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

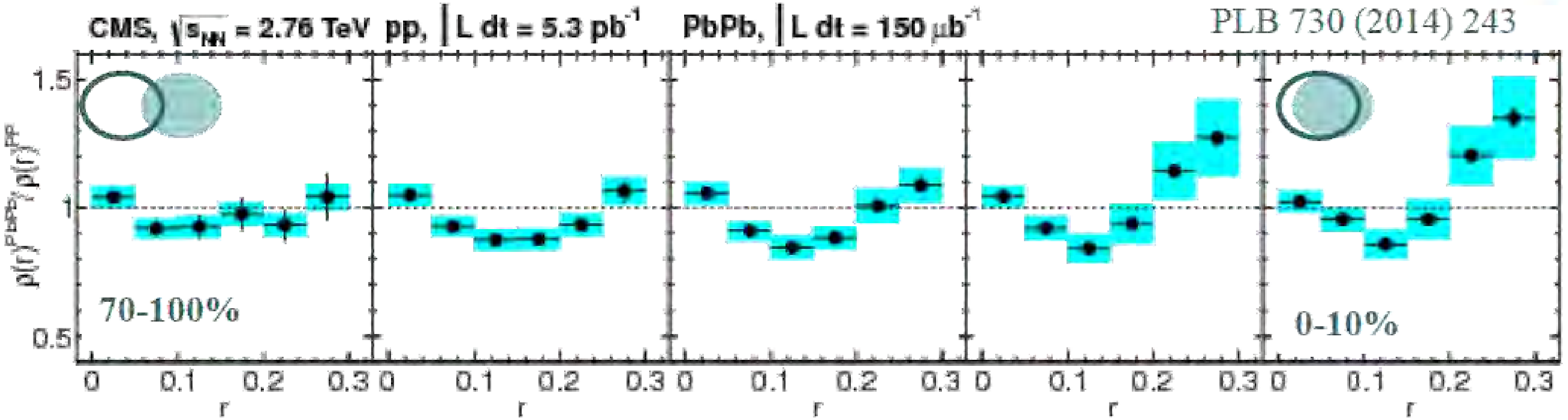
JET INNER WORKINGS: SHAPES

- Jet shapes: measure transverse structure of jet momenta

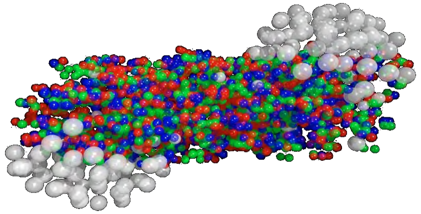


- Fractional transverse energy distribution: $\rho(r) = \frac{1}{N_j}\frac{1}{\delta r}\sum_{jets}\frac{\sum_{trk\,\in[r_a,r_b)} p_T^{trk}}{\sum_{trk\,\in[o,R)} p_T^{trk}}$

PLB 730 (2014) 243



- Jet Shapes: PbPb to pp ratio @ 2.76 TeV :



Little/no medium effects in peripheral events

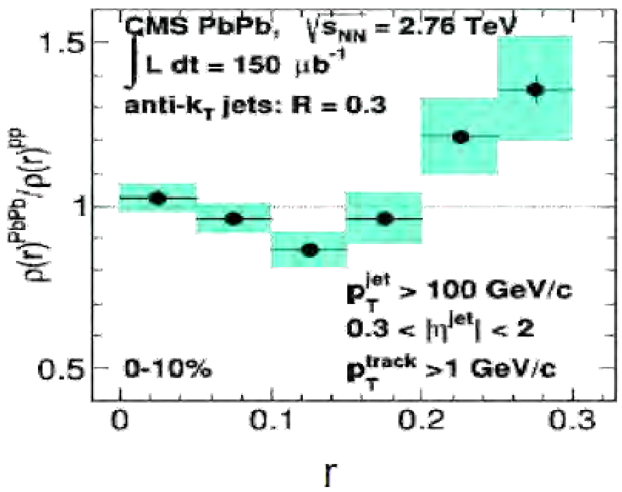
Enhancement at low p_T / larger r in central collisions

JET SHAPES: QUARK VS. GLUON

- Jet Shapes: quark vs. gluon effects are explored via comparison of inclusive jets and gamma-tagged jets

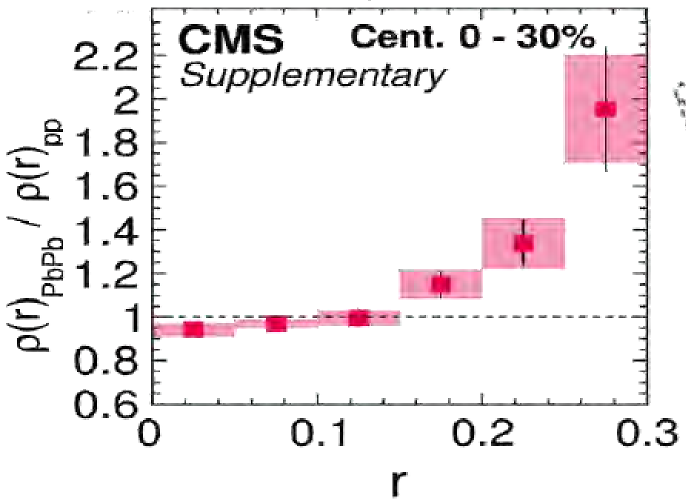
PLB 730 (2014) 243

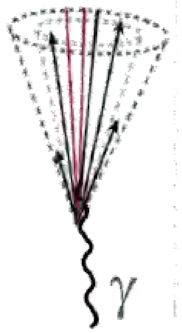
Inclusive jets: q+g



PRL 121 (2018) 242301

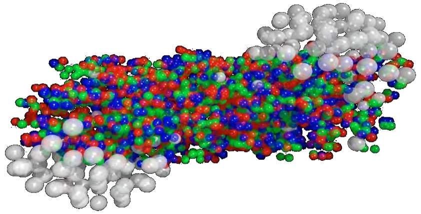
γ-tagged-jets: ~q



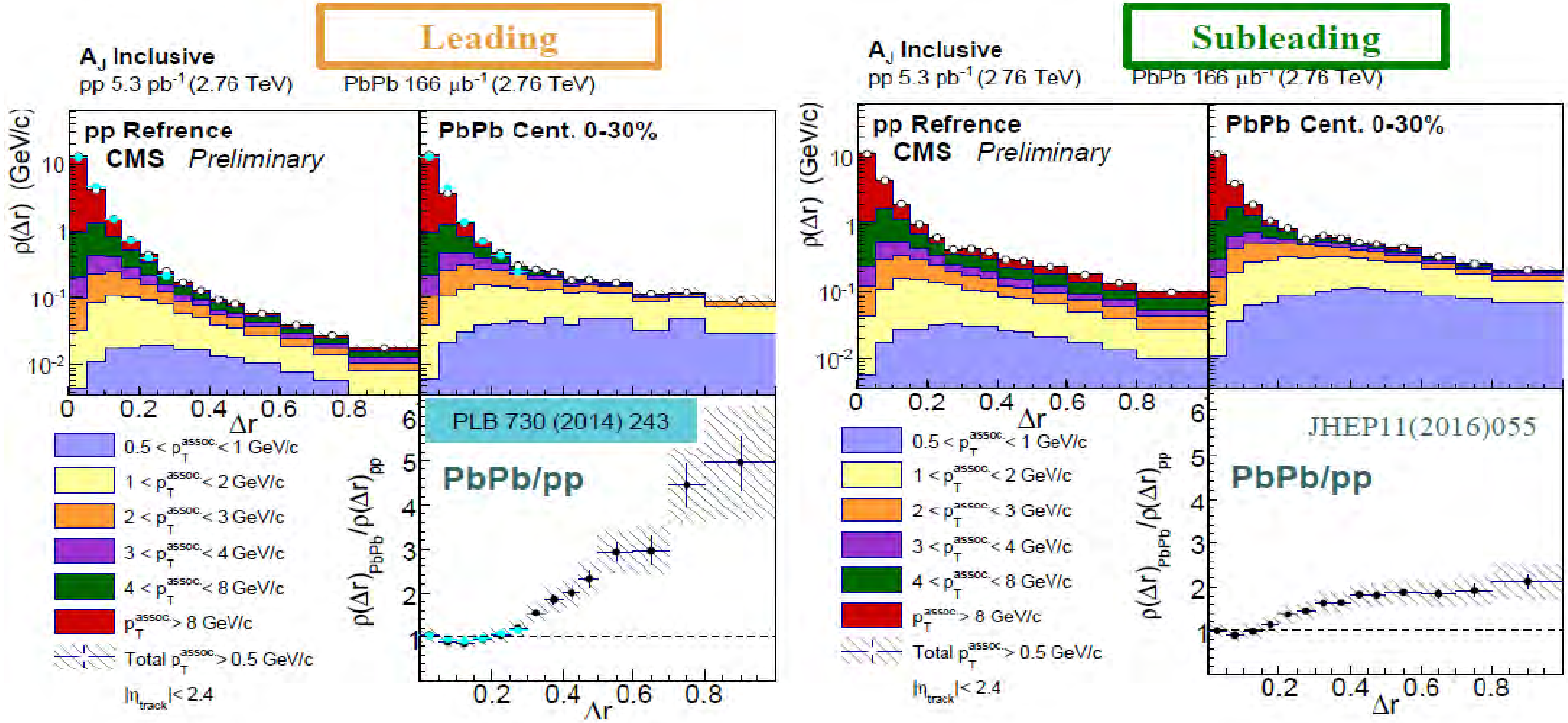


Similar jet shape modification trends with inclusive jets in central PbPb data: energy shift towards larger radii

What about the magnitudes? Can't compare ratios directly; must mind the reference!

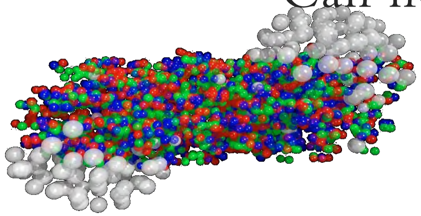


JET SHAPES, FULL FLOW



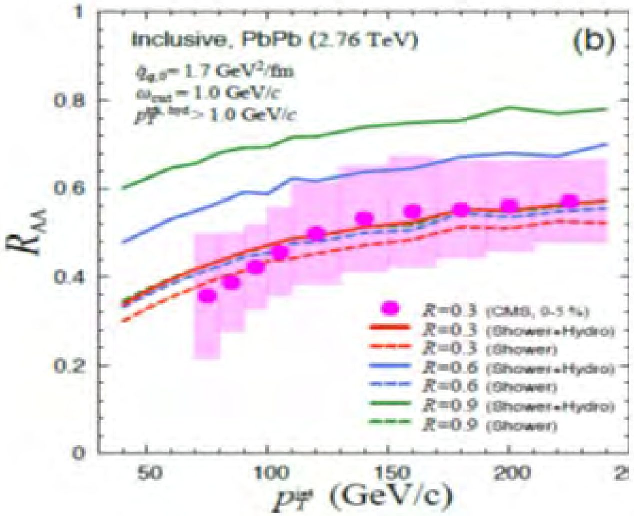
- Can now measurement of jet shapes up to large radial distances

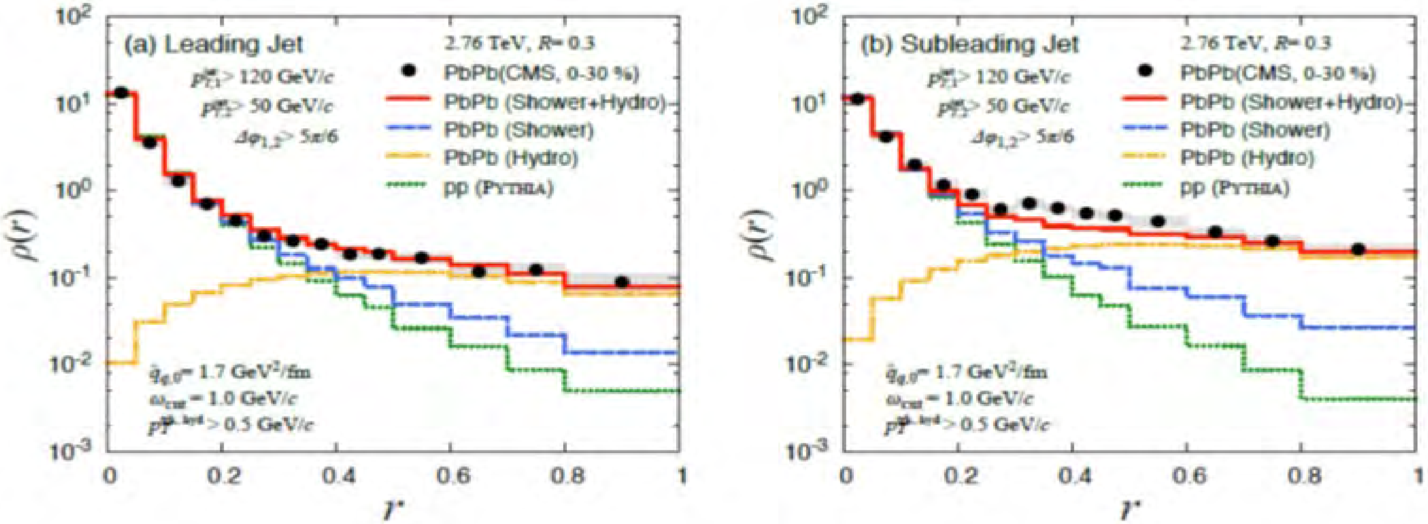
(Compare to previous measurement in light blue)



JET-MEDIUM INTERACTIONS

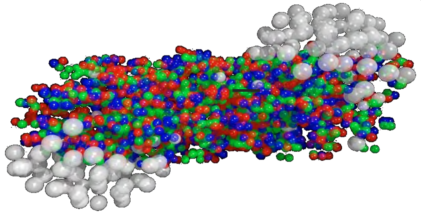
- A note on importance of interfacing multiple measurements with theory:





Jet R_{AA}: inclusion of the jet-induced medium flow decreases suppression, but effect is small for small cone sizes and large cone sizes are challenging for HIN

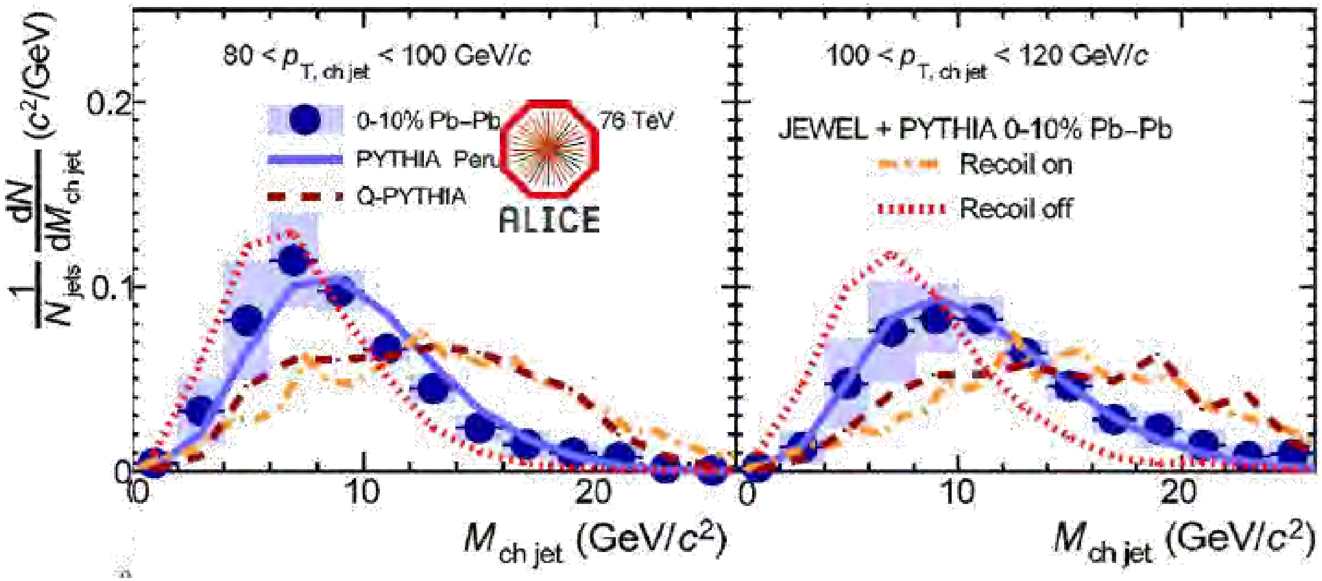
Jet shapes: soft shower thermalization – more collimated hard core; medium-induced radiation – broader jet shape; inclusion of the jet-induced medium flow critical at large r



JET MASS MEASUREMENTS

- Jet mass distributions:

PLB 776(2018) 249



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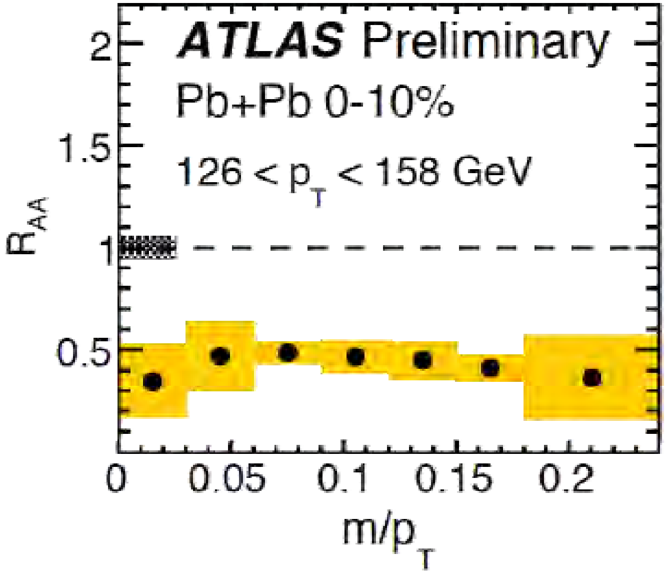
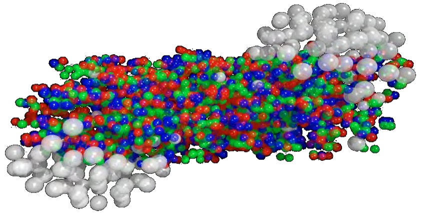


Jet mass from charged tracks

Jet mass from calorimeter energy



No significant modifications are observed

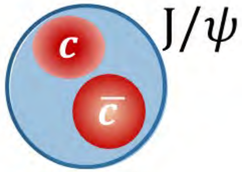
Large increases in jet mass predicted by quenching models are excluded by the data

CHANGING TOPIC: ANOTHER HARD PROBE

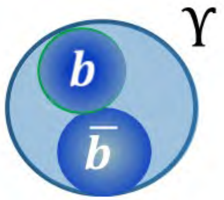
OR: one more time about QGP temperature

QUARKONIA MELTING

- Heavy quarks (c, b) are produced in a large-Q^2 processes at the initial stage of the collision due to their large masses: $m_c \sim 1.3\ \mathrm{GeV}/c^2$, $m_b \sim 4.2\ \mathrm{GeV}/c^2$ (negligible in-QGP production even at LHC energies)



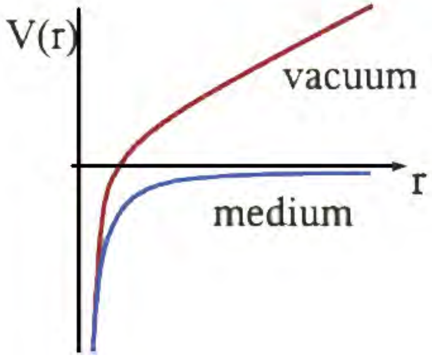
- Quarkonia: bound state of heavy quark-antiquark pairs

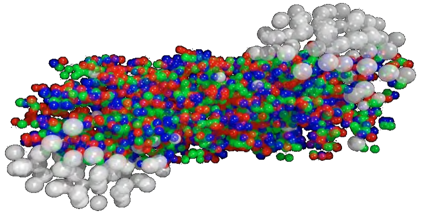


- Melting of quarkonia due to color screening is one of the early predicted signatures for QGP (Matsui&Satz, PLB178 (1986) 416)

- In analogy with QED Debye screening, the interaction potential in QGP was predicted to be screened above the Debye radius r_D:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr \quad \rightarrow V(r) = -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/r_D}$$





QUARKONIA MELTING, THEORY

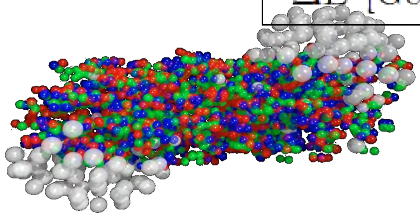
- So, in QGP binding of heavy quark pairs is subject to color screening
- Color-screening length r_D decreases with T
- Charmonium (cc) and bottonium (bb) states with $r > r_D$ expected to "melt" (not bind) → be suppressed.

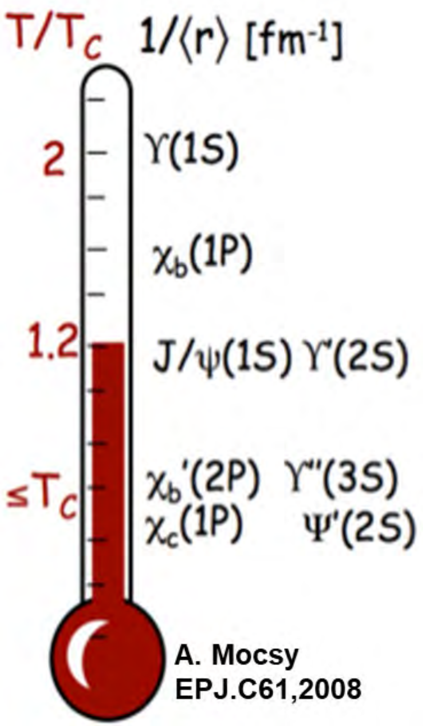
Charmonium arXiv:0901.3831

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Bottomonium

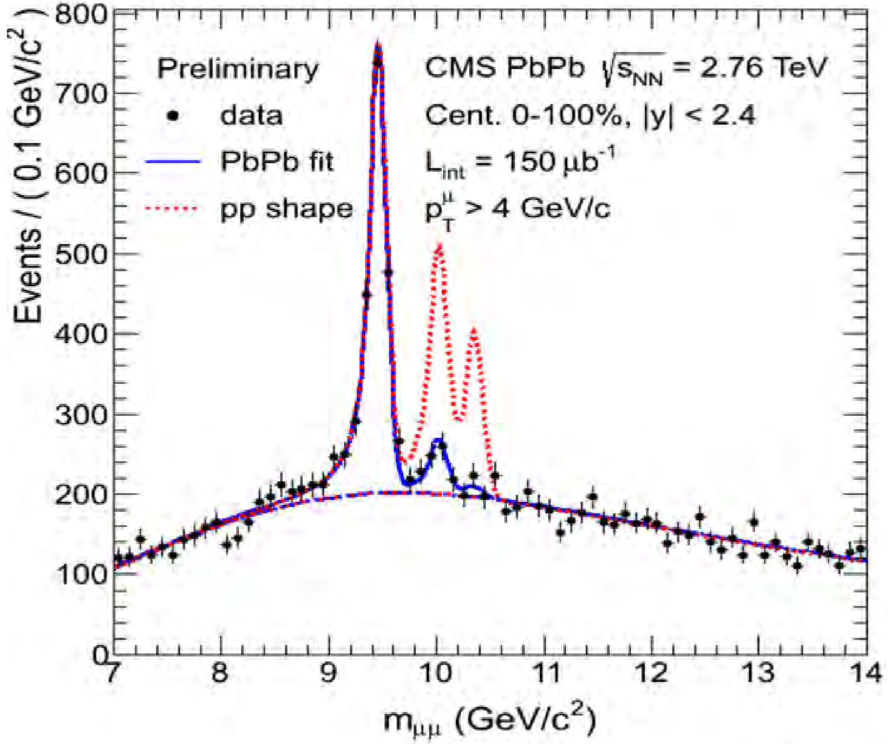
state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

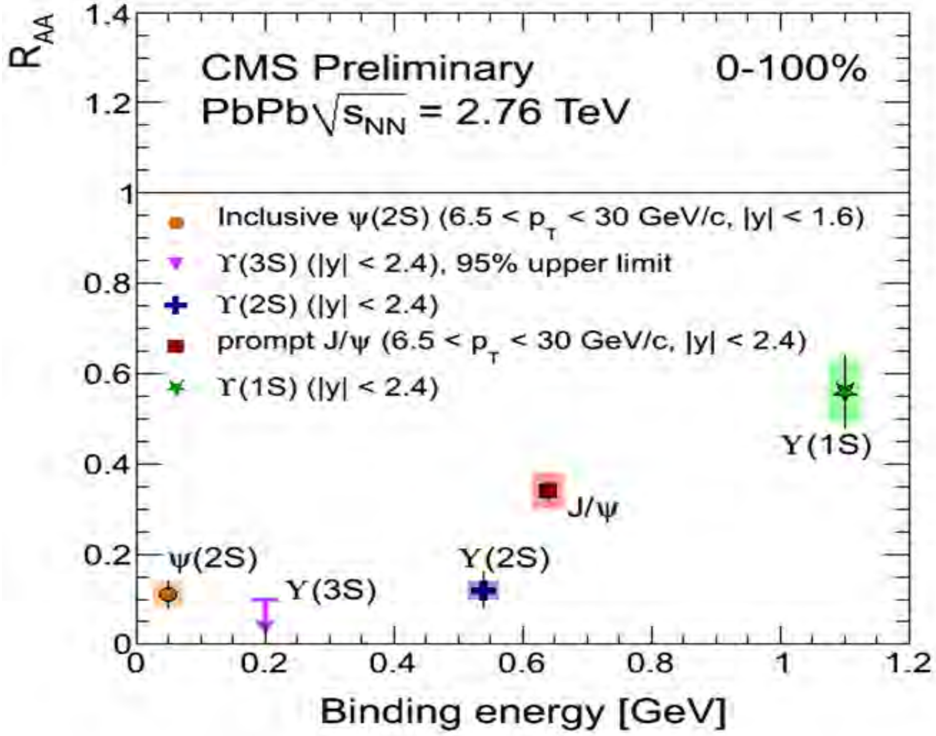


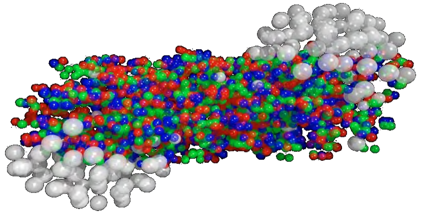


QUARKONIA MELTING, EXPERIMENT

- Early CMS/LHC results:





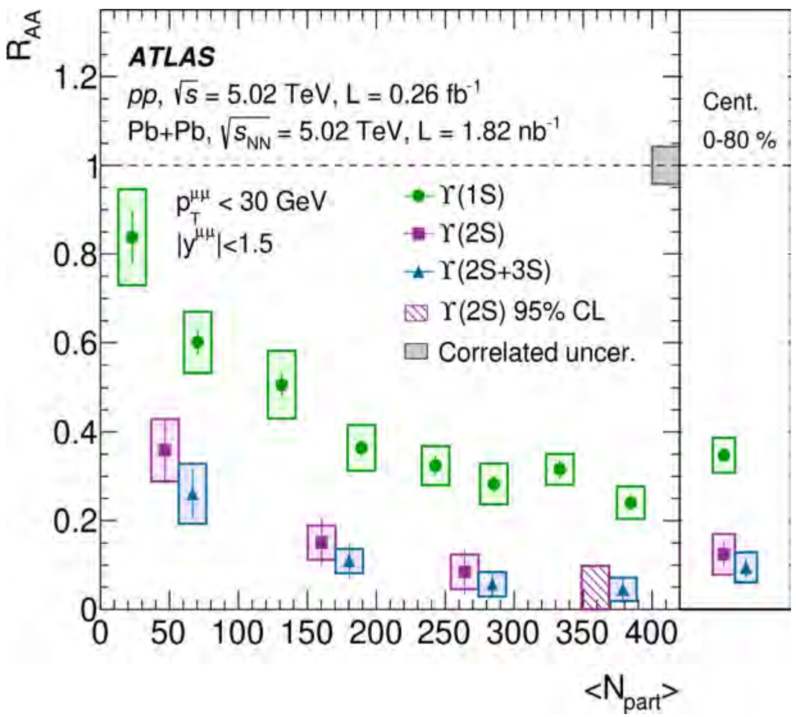


Visible melting in upsilon family ($\Upsilon(3S)$ is not yet directly observed in HIN)

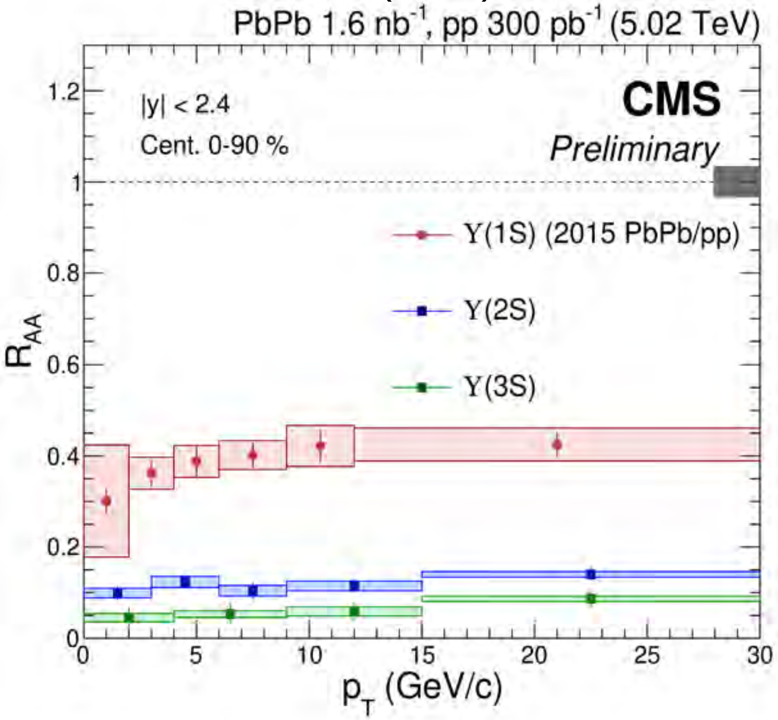
Hierarchy of suppression level consistent with expectations based on binding energies

QUARKONIA MELTING, EXPERIMENT

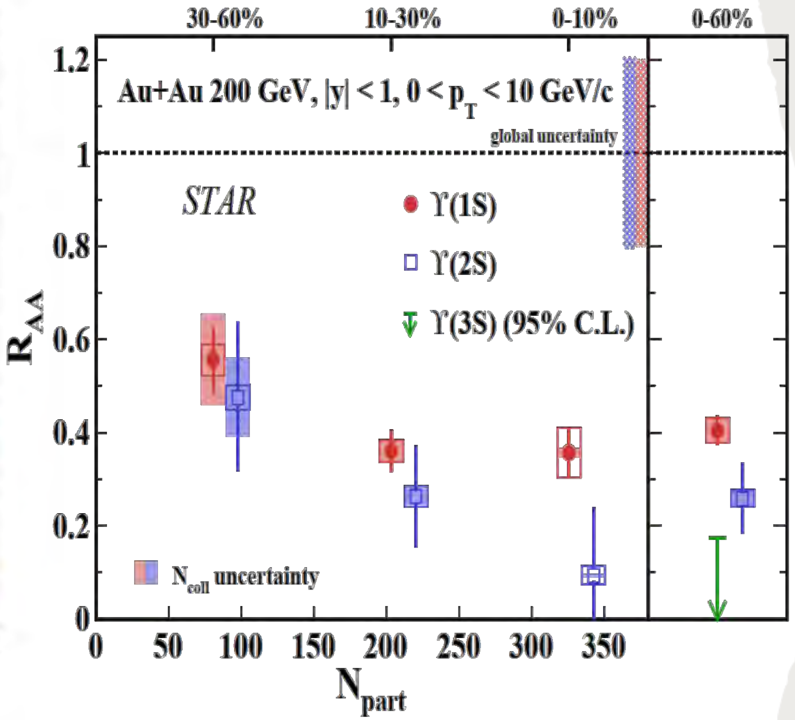
ATLAS PRC 107 (2023) 054912



CMS PRL 133 (2024) 022302



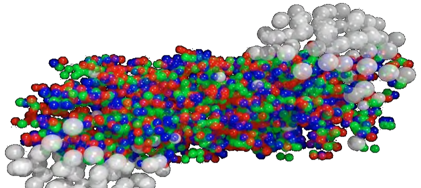
STAR PRL 130 (2023) 112301



- Clear signature of sequential melting of ϒ(ns) states at RHIC and LHC

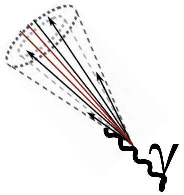
  Ordering of nuclear modification factors: ϒ(3S)< ϒ(2S)< ϒ(1S)

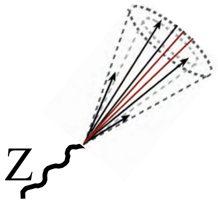
  First direct observation of ϒ(3S) in heavy ion collisions

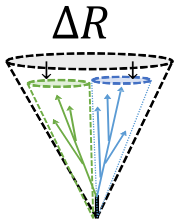


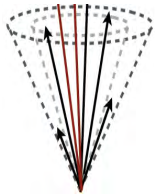
"TAKE-HOME" POINTS:

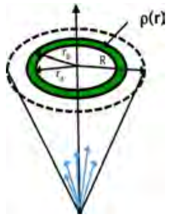
- Hard probes for tomographic studies of the Quark Gluon Plasma is a new frontier for QCD studies
- Jets and heavy flavor probes provide a versatile set of tools for studying properties of the QGP medium at different scales
- Nuclear modification factors constrain QGP transport properties as well as mass and color-charge dependence of energy loss
- Jet quenching has many manifestations: energy balance shift in two-prong probes, energy redistribution in jet shapes, fragmentation functions, modification of jet splitting functions, etc.
- QGP color screening melts heavy quarkonia
- Sequential suppression in the charmonium and, especially, bottomonium sector probes experimentally the temperature of the medium

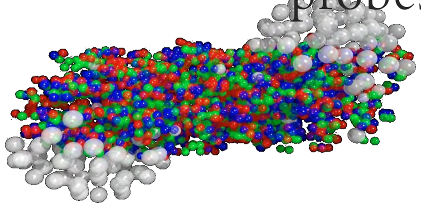












BONUS SLIDES

The UIC HENP Group's work is supported by US DOE-NP

NUCLEAR PDF EFFECTS

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

$f^{i}_{a/A,Z}(x_i, Q^2)$ – Nuclear *parton distribution functions,* defined as (nCTEQ15, PRD 93, 085037):

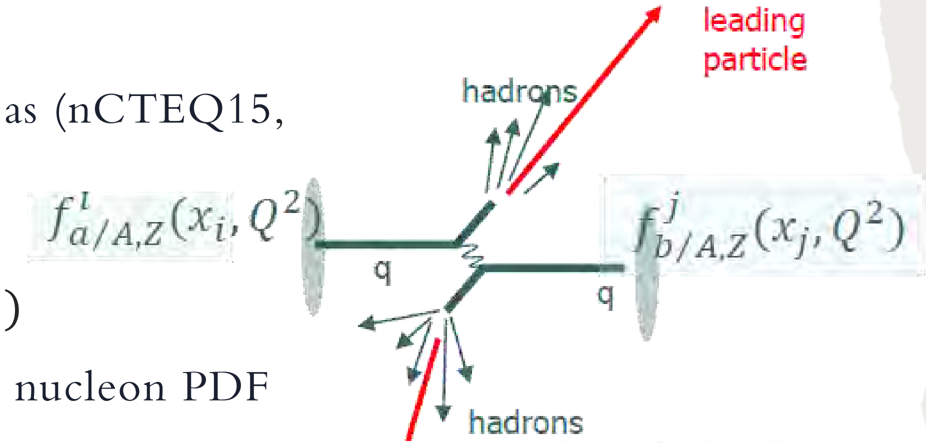
$$f^{i}_{a/A,Z}(x_i, Q^2) = \frac{Z}{A} f^{i}_{p/A}(x_i, Q^2) + \frac{A-Z}{A} f^{i}_{n/A}(x_i, Q^2)$$

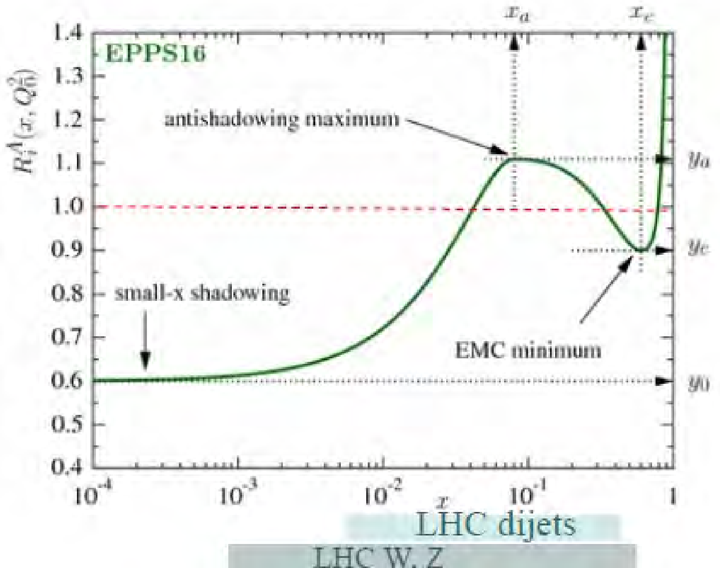
where Bound nucleon PDFs $f^{i}_{p/A}(x_i, Q^2)$ are connected to free nucleon PDF as (EPPS16, *EPJ C77(2017) 163*):

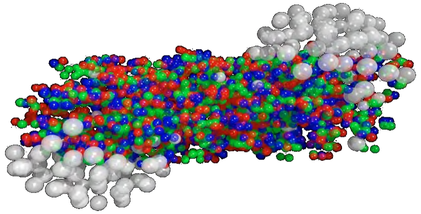
$$f^{i}_{p/A}(x_i, Q^2) = R^{i}_{A}(x_i, Q^2) f^{i}_{p}(x_i, Q^2)$$

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

→ pA collisions







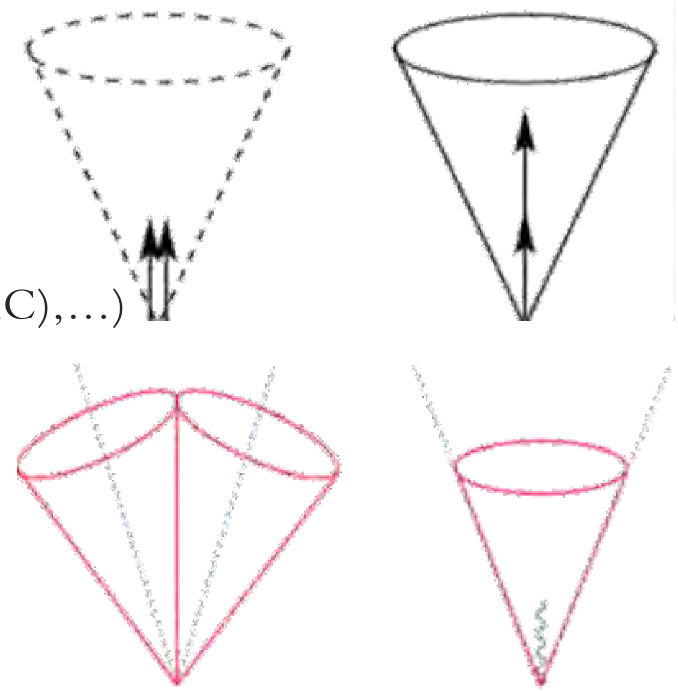
JET ALGORITHMS

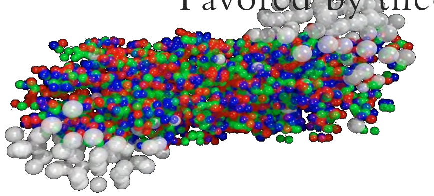
Important requirements for Jet Finders:

- 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





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 $p_T > \varepsilon_{trim} p_T{}^{jet}$

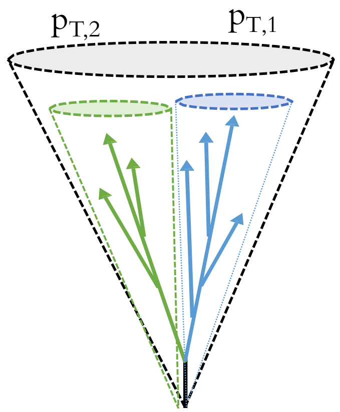
  Pruning: re-cluster with k_T or C/A and in each clustering step discard subjet if $\Delta R > R_{prun}$ and $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} < z_{prun}$

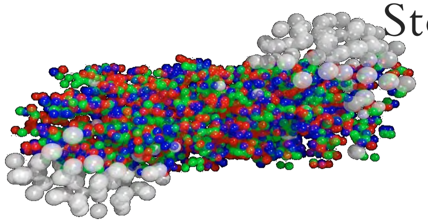
- Commonly used: Soft Drop algorithm:

  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

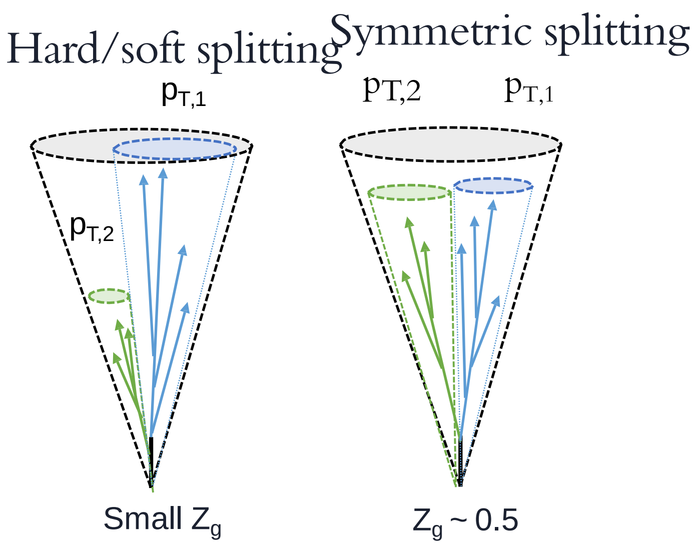
  Stop if $z_g > z_{cut}({}^{\Delta R}/{}_{R})^{\beta}$, else un-cluster again

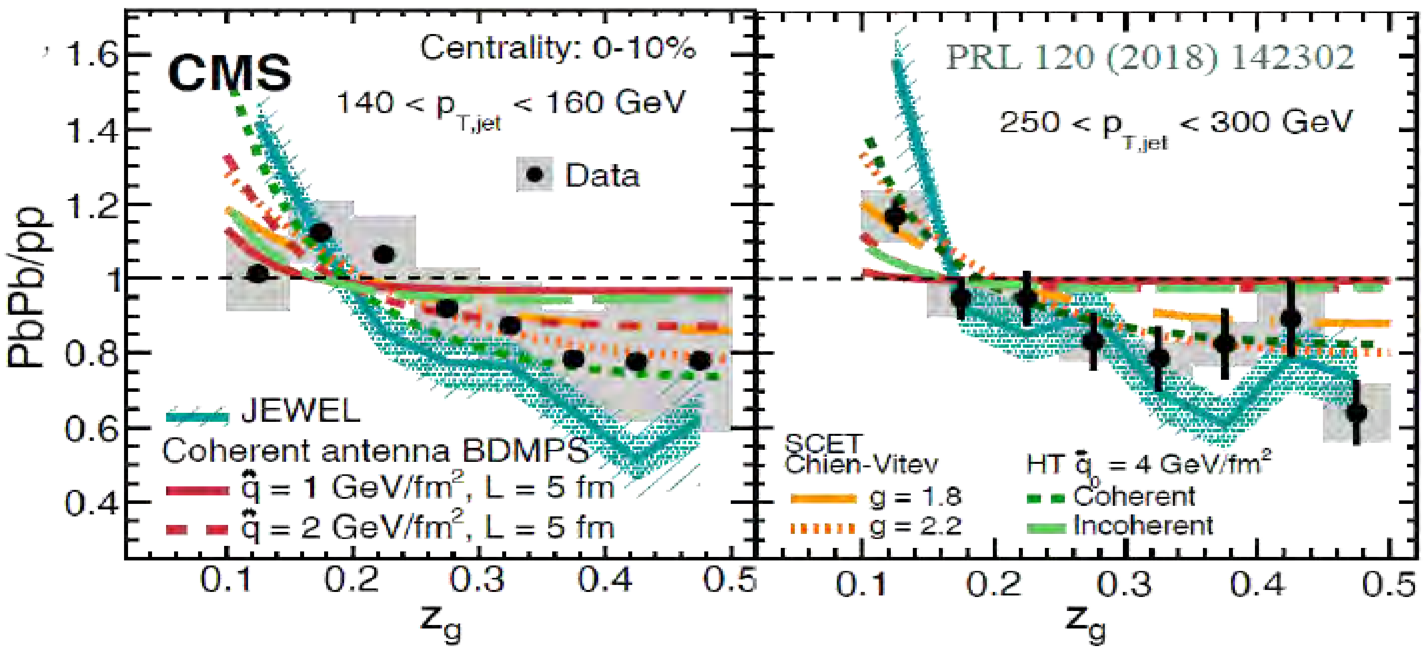




SUBJET MOMENTUM SHARING

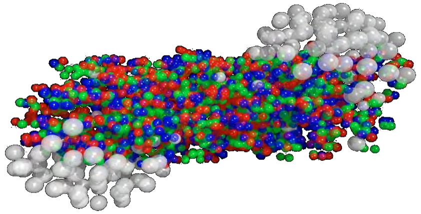
- Parton splitting is modified in central PbPb collisions





Higher suppression for jets with more symmetric subjets

PbPb @ 5.02 TeV



New insights on in-medium effects for theory, different interpretations

Medium recoil? Modified splitting? Coherent emitter?

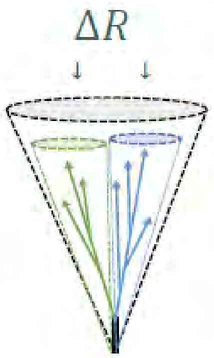
OLGA EVDOKIMOV (UIC)

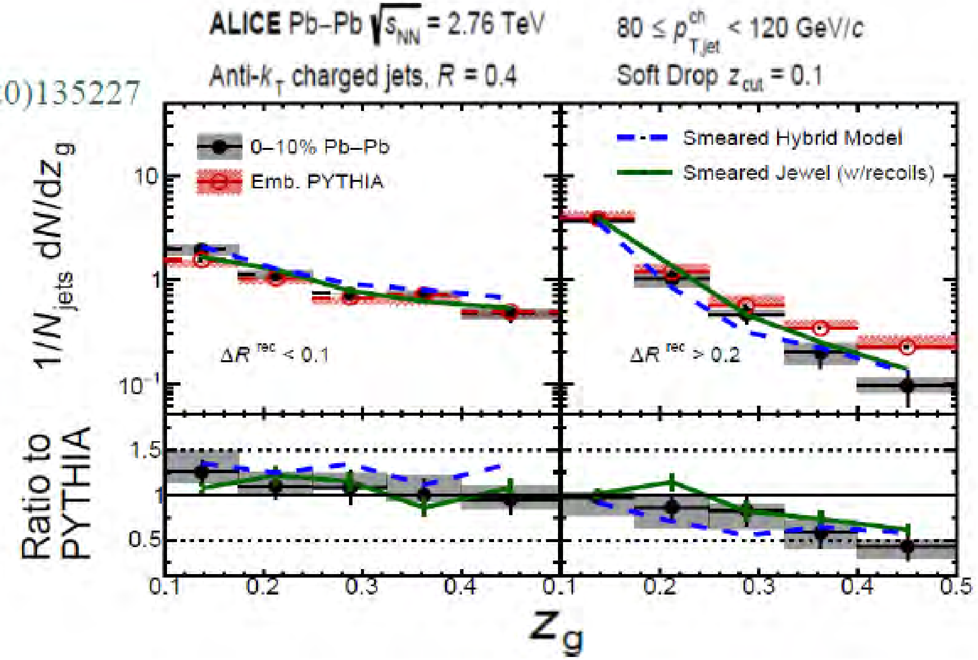
AUGUST 2, 2024

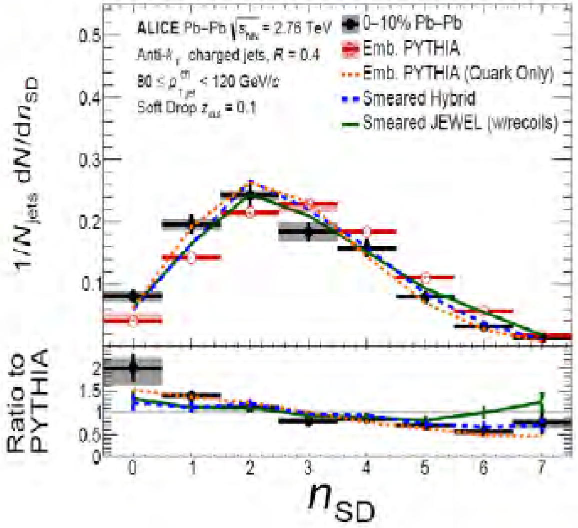
SUBJET MOMENTUM SHARING

- Parton splitting for charged jets:

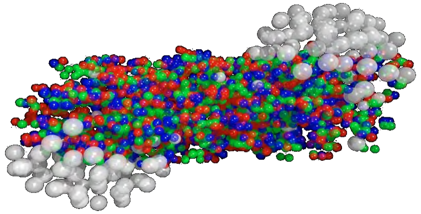
PLB 802 (2020)135227







Enhancement of the number of small-angle splittings/ suppression of the large-angle symmetric splittings in central PbPb collisions



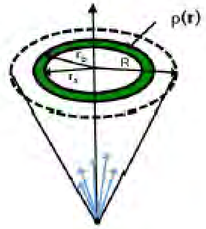
Number of splittings passing soft drop cut shifts down – color-charge effects?

CMS jet substructure studies by 2021
(from summary talk by A. Hinzmann and B. Nachman, CERN-TH workshop)

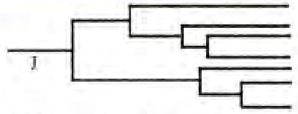
HIN

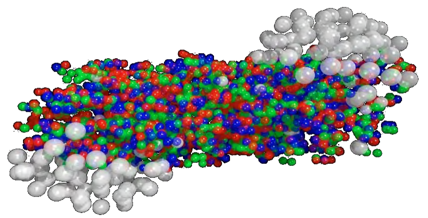
Reference	Final state	Jets, p_T (GeV)	Jet substructure observables
1204.3170 7 TeV pp	jets	q/g-jets (AK7), $20<p_T<1000$ q/g-jets (AK5), $50<p_T<1000$	jet shapes, charged hadron multiplicity, width
1205.5872 2.76 TeV pp/PbPb	dijets	q/g-jets (AK3), $40<p_T<320$	fragmentation functions
1310.0878 2.76 TeV pp/PbPb 1406.0932 2.76 TeV pp/PbPb	jets	q/g-jets (AK3), $100<p_T<300$	fragmentation functions
1310.0878 2.76 TeV pp/PbPb	jets	q/g-jets (AK3), $p_T>100$	jet shapes
1809.08602 5.02 TeV pp/PbPb		q-jets (AK3), $p_T>30$	jet shapes
HIN-19-003 5.02 TeV pp/PbPb	dijets	q/g-jets (AK4), $p_T>50$	jet shapes
QCD-10-041 7 TeV pp	dijets	q/g-jets (KT6), $97<p_T<1032$	subjet multiplicities and p_T^{rel}
1706.05868 8 TeV pp	jet	q/g-jets (AK5), $400<p_T<1500$	jet charge
2004.00602 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $p_T>120$	jet charge
1703.06330 8 TeV pp	ttbar	top-jets (CA12), $p_T>400$	jet mass
1303.4811 8 TeV pp	dijets W/Z+jets	q/g-jets (AK7), $220<p_T<1500$ q-jets (AK7, CA8/12), $125<p_T<450$	jet mass, pruned/trimmed/filtered jet mass
1805.05145 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $140<p_T<300$	softdrop jet mass
1807.05974 13 TeV pp	dijets	q/g-jets (AK8), $200<p_T<1300$	jet mass, softdrop jet mass
1911.03800 13 TeV pp	ttbar	top-jets (XC12), $p_T>400$	XCone-grommed jet mass
1708.09429 5.02 TeV pp/PbPb	jets	q/g-jets (AK4), $140<p_T<500$	softdrop splitting function
1808.07340 13 TeV pp	ttbar	q-jets (AK4), $p_T>30$ g-jets (AK4), $p_T>30$ b-jets (AK4), $p_T>30$	jet substructure and softdrop observables
SMP-20-010 13 TeV pp	dijets Z+jets	q/g-jets (AK4), $50<p_T<4000$ q-jets (AK4), $50<p_T<1000$	jet angularities

“shapes”



“substructure”





OLGA EVDOKIMOV (UIC)

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