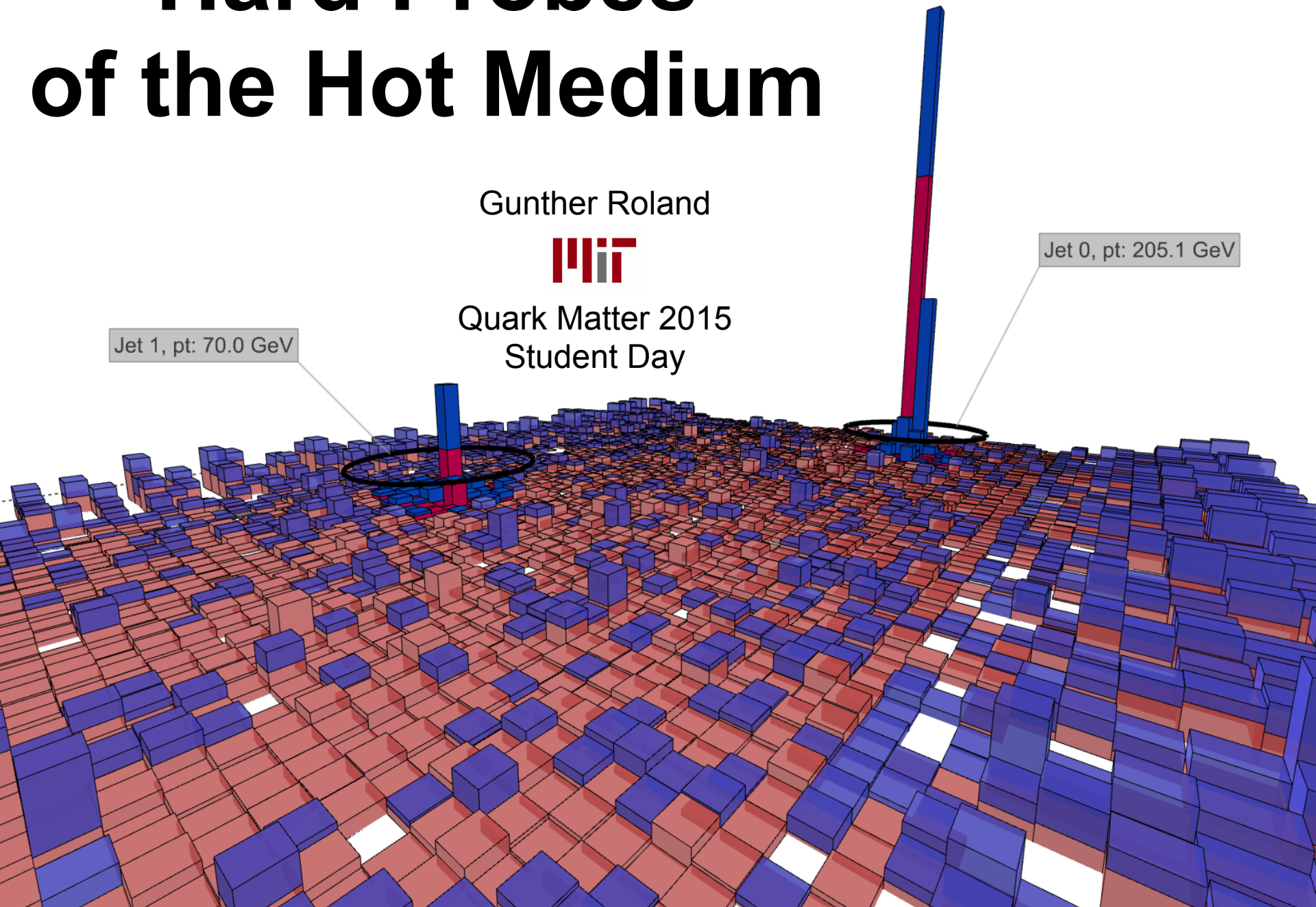
Hard Probes of the Hot Medium

Gunther Roland

MIT

Quark Matter 2015
Student Day



What are Hard Probes?

What can we learn from Hard Probes?

How do we detect Hard Probes?

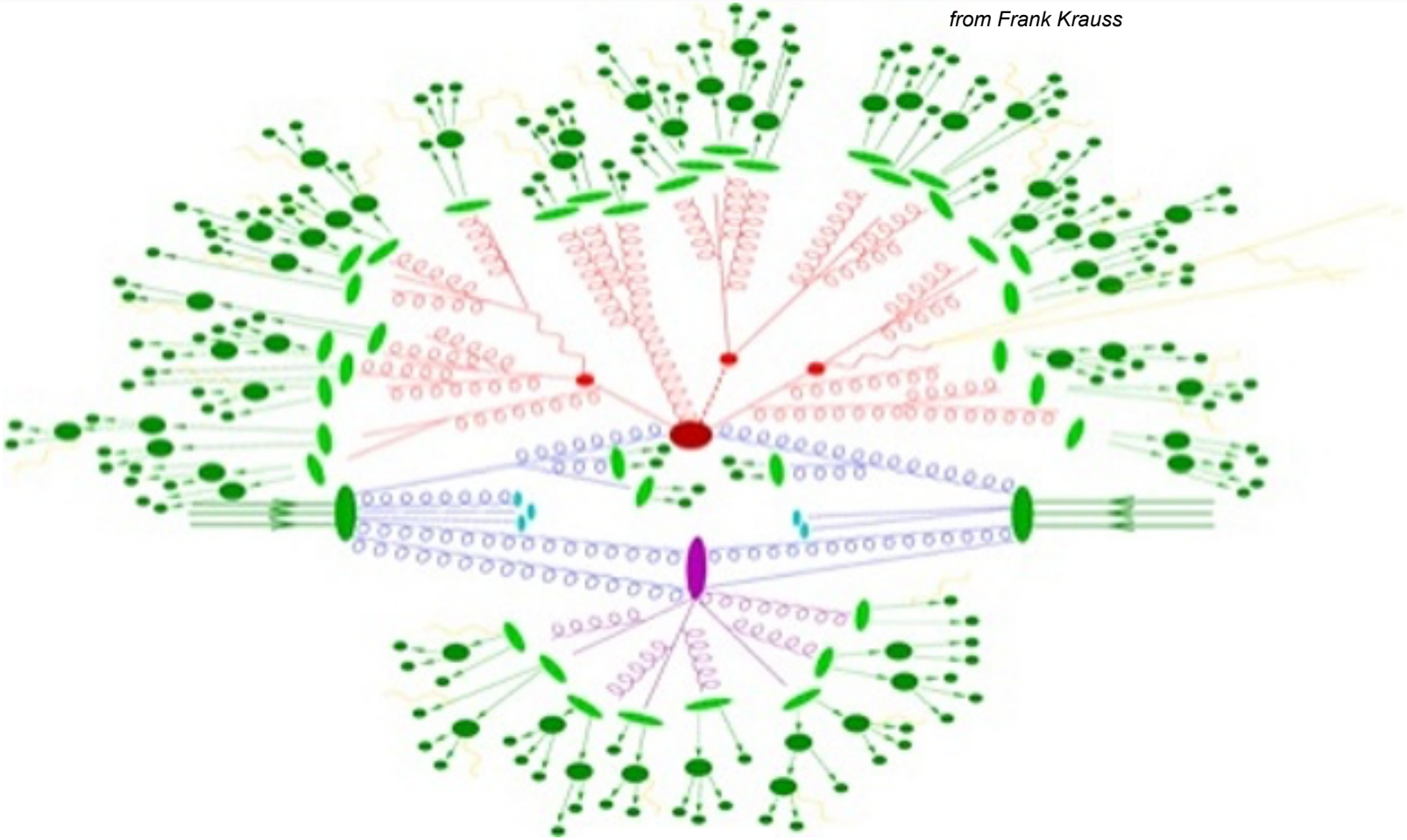
What did we learn from Hard Probes (2010-2015)

What remains to be learned?

a few thoughts by an experimentalist…

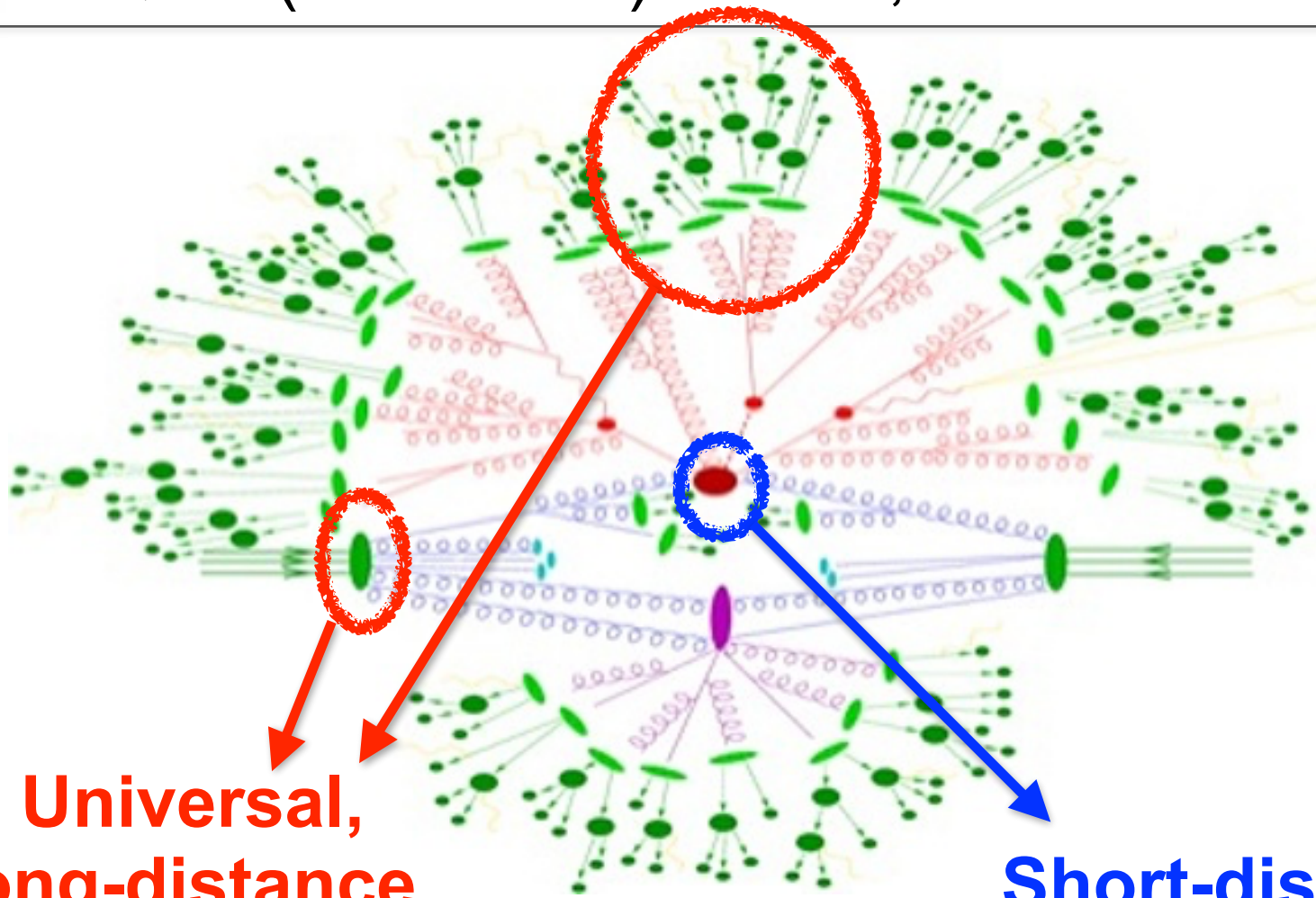
QCD (in vacuum) is hard

from Frank Krauss



Complex multi-particle dynamics even in p+p

QCD (in vacuum) is hard, but it factorizes



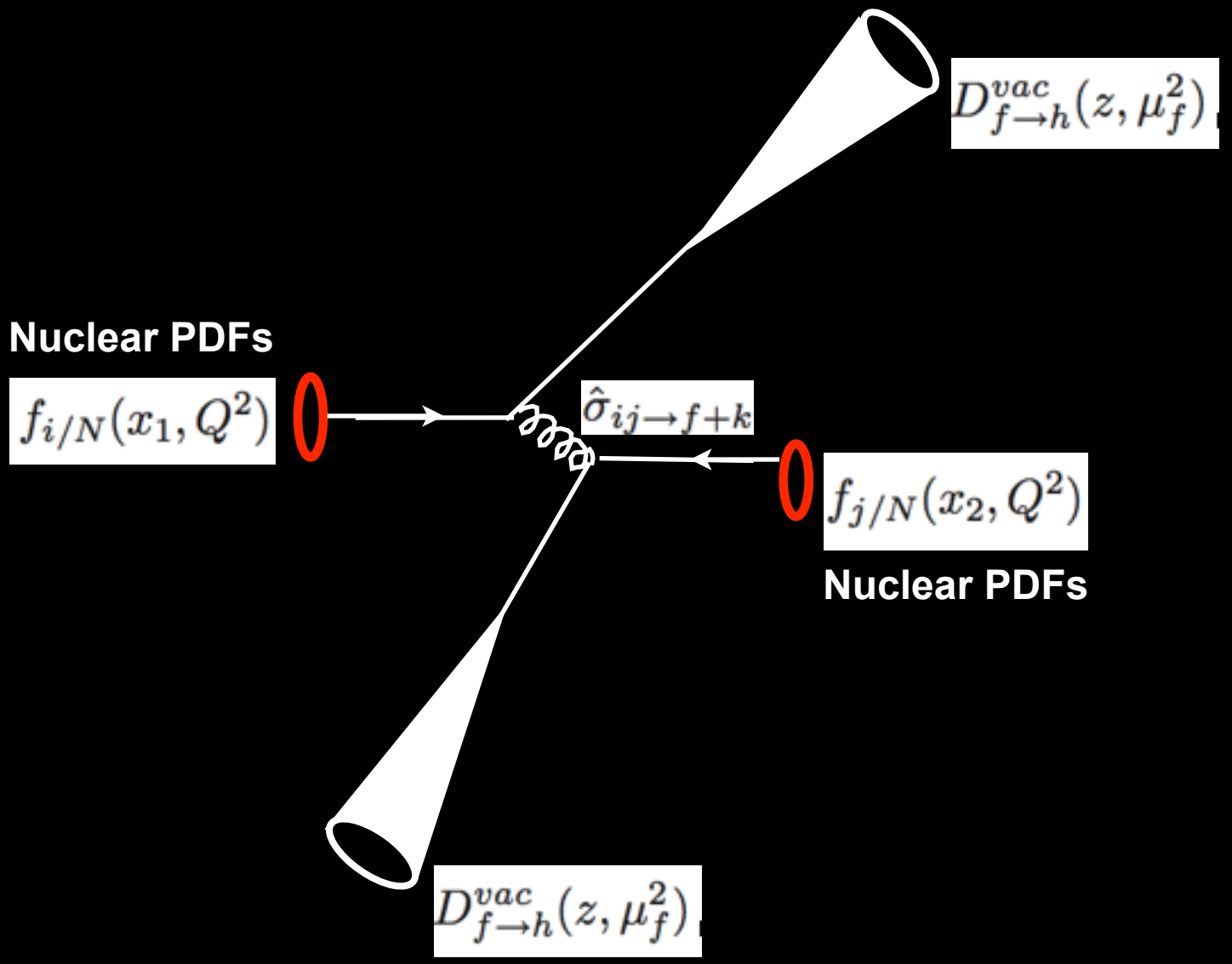
Universal, long-distance, low momentum, "soft" physics

T=300MeV medium: 1/p ~ 0.2 fm

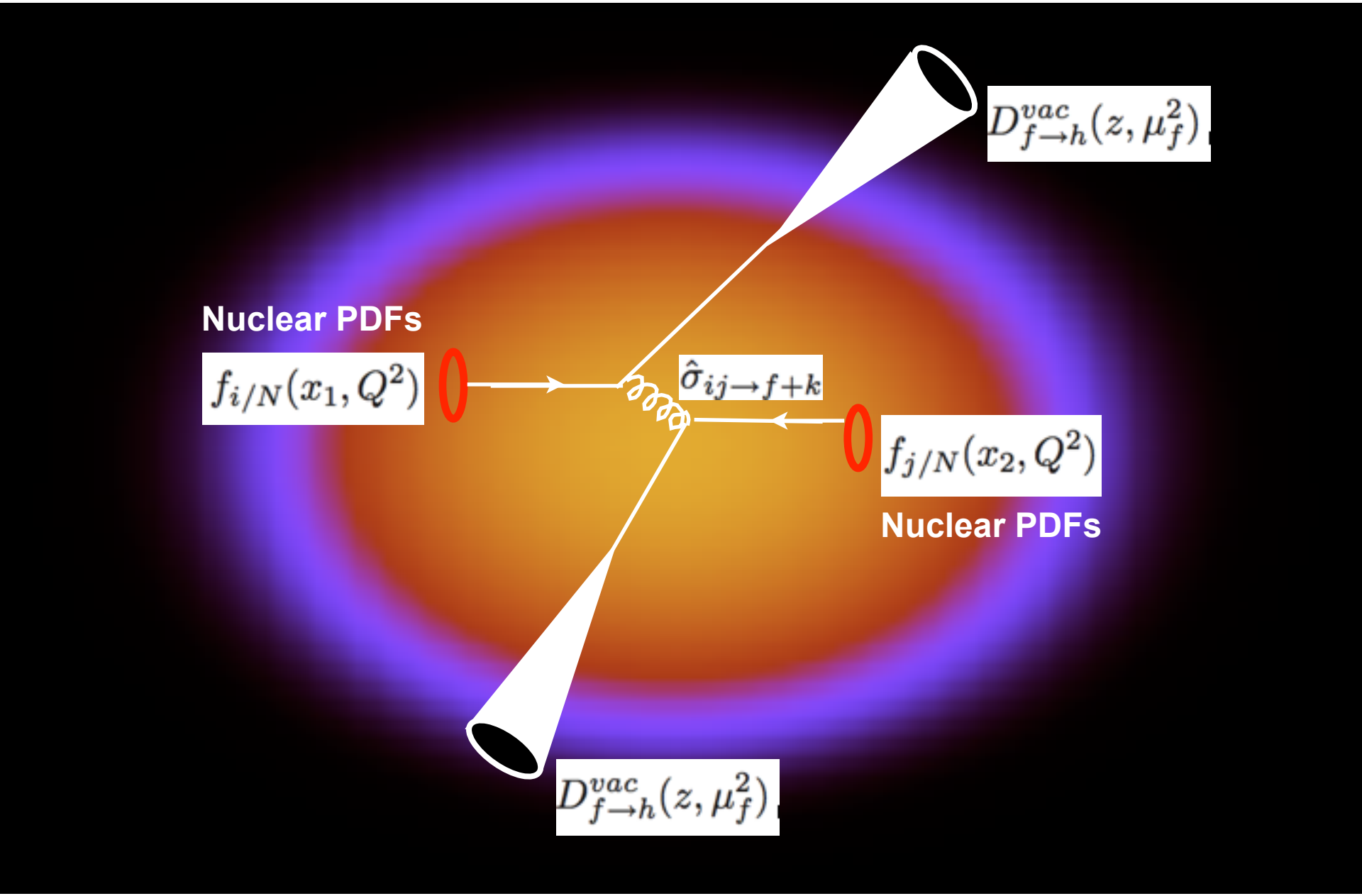
Short-distance, high momentum, "hard" process

100 GeV Jet: $1/p_T$ ~ 0.002 fm

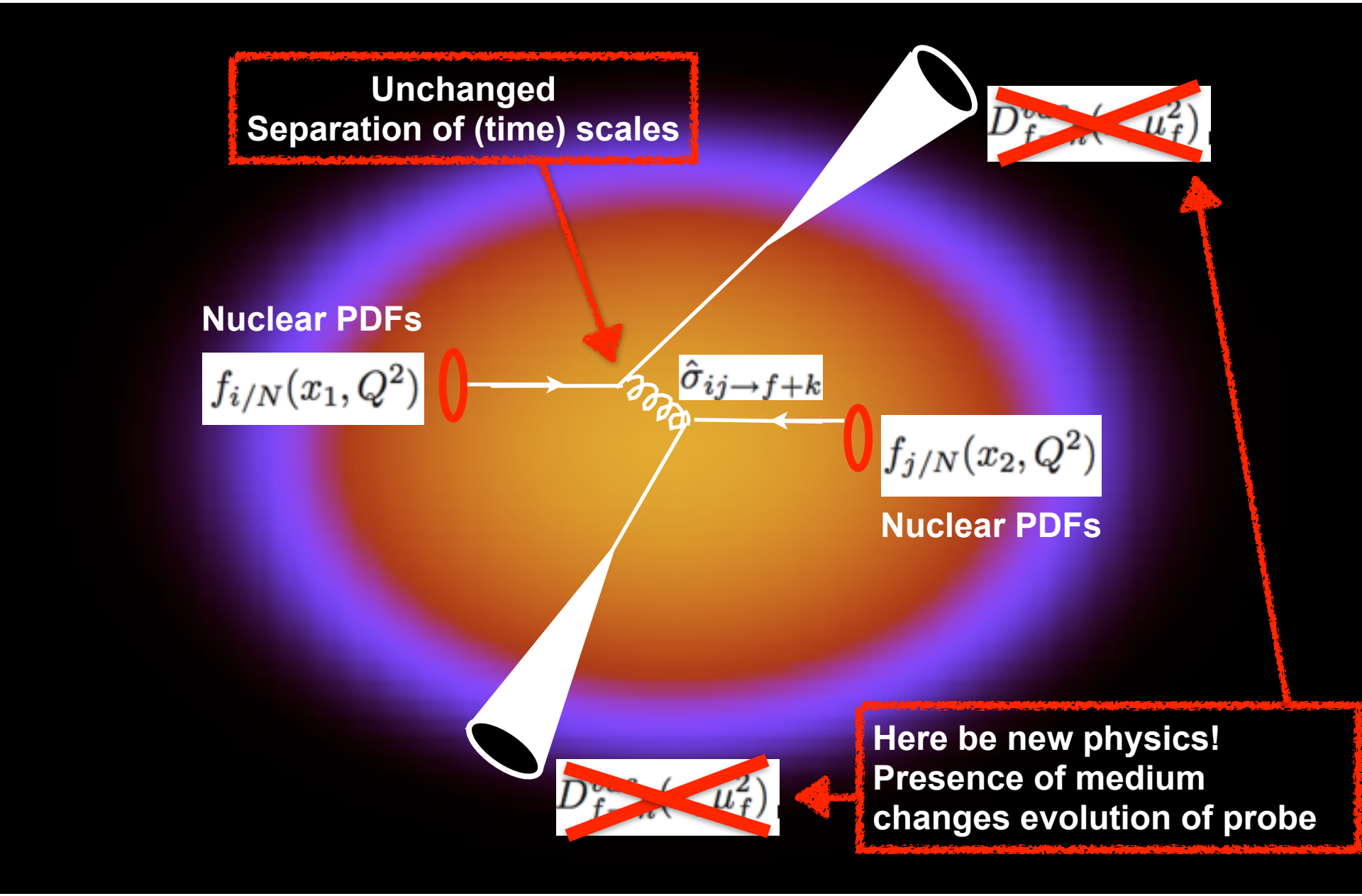
QCD (in vacuum) is hard, but it factorizes



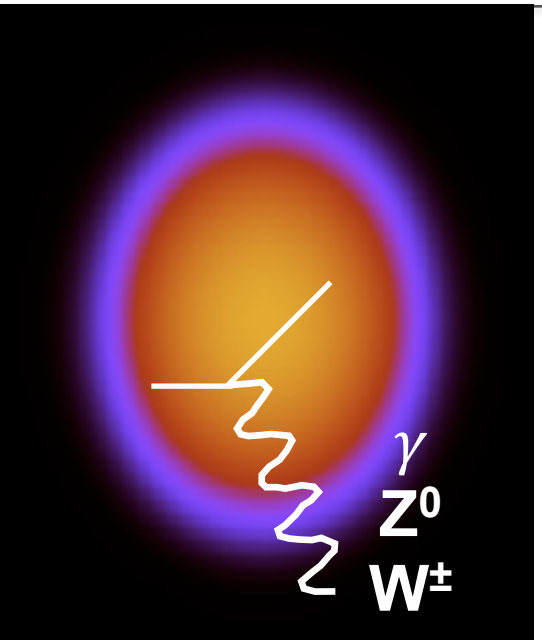
Hard Probes and Medium

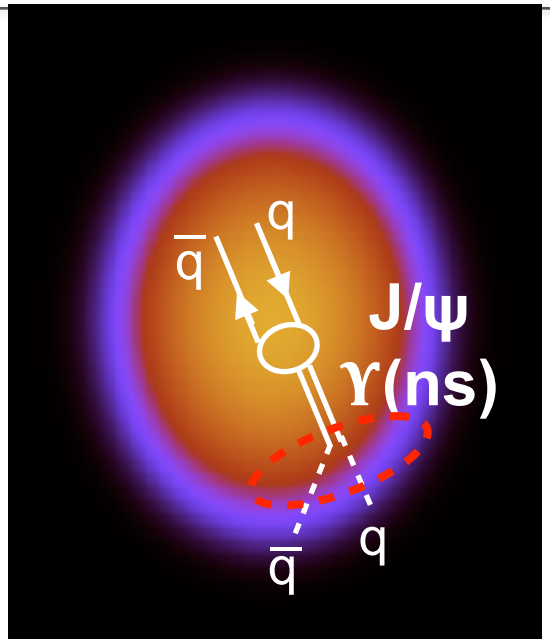


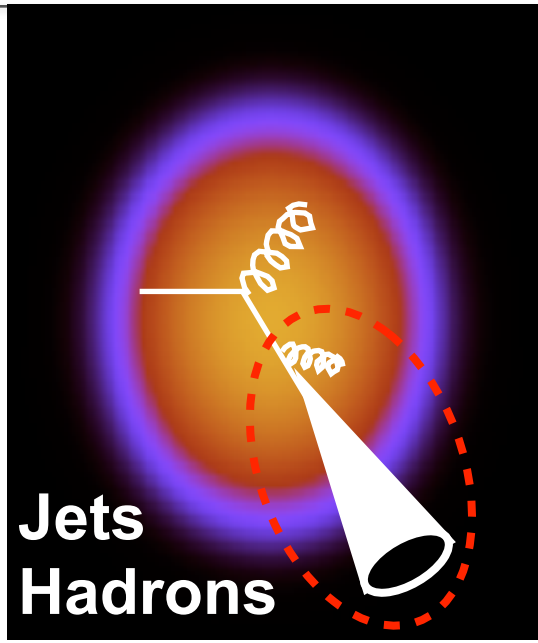
Hard Probes and Medium



Hard Probes Gallery







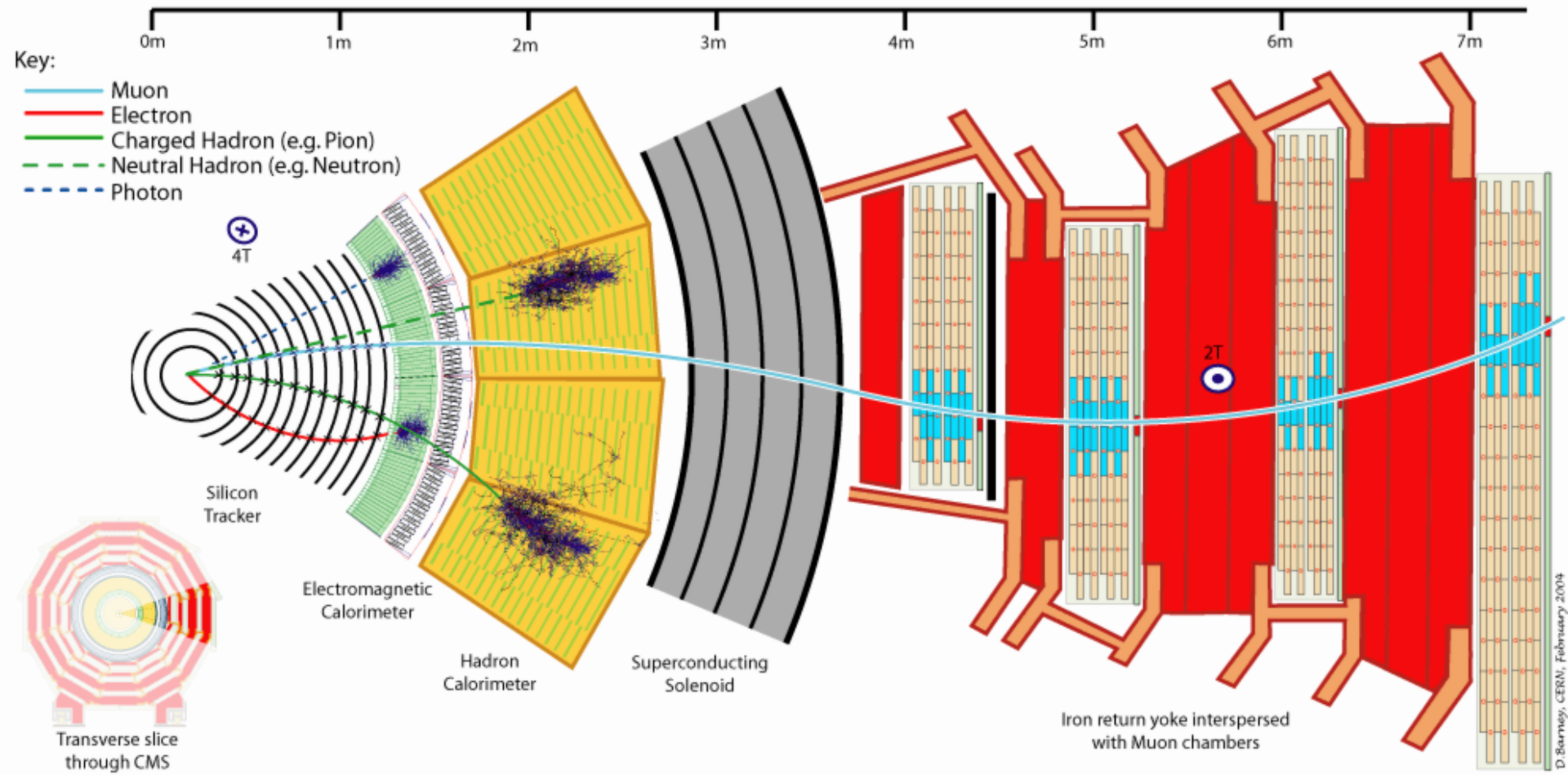
Vectorbosons
Colorless
No medium effects
Probe initial state
(nPDFs, N_{coll})

Quarkonia
Hidden color
Dissociation in
hot and cold medium
Regeneration?

Jets
Colored probe
Induced radiation
+ elastic scattering
Many observables:
Jets ([u,d,s], g, c,b)
Hadrons (u,d,s, D, B)
Correlations

n.b. I'm going to be somewhat biased towards large Q^2

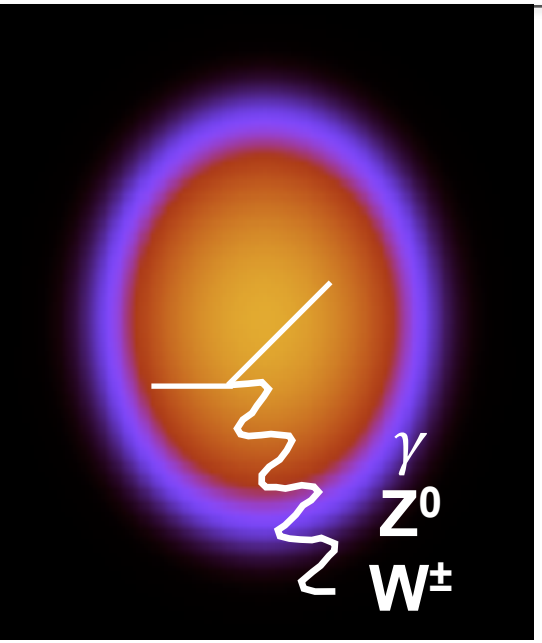
Particle ID for Hard Probes



Typical collider detector

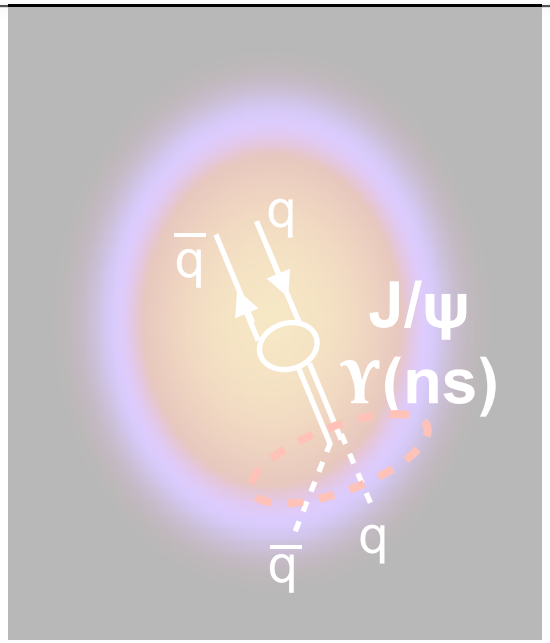
How do we assemble these detector objects to physical observables?

Hard Probes Gallery



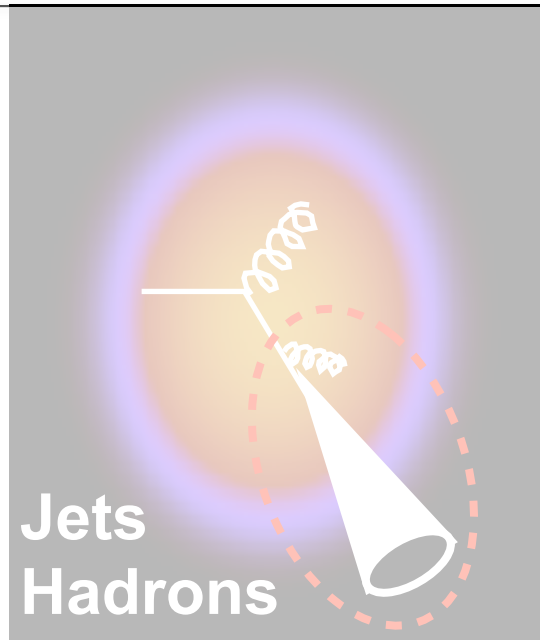
Vectorbosons

Colorless
No medium effects
Probe initial state
(nPDFs, N_{coll})



Quarkonia

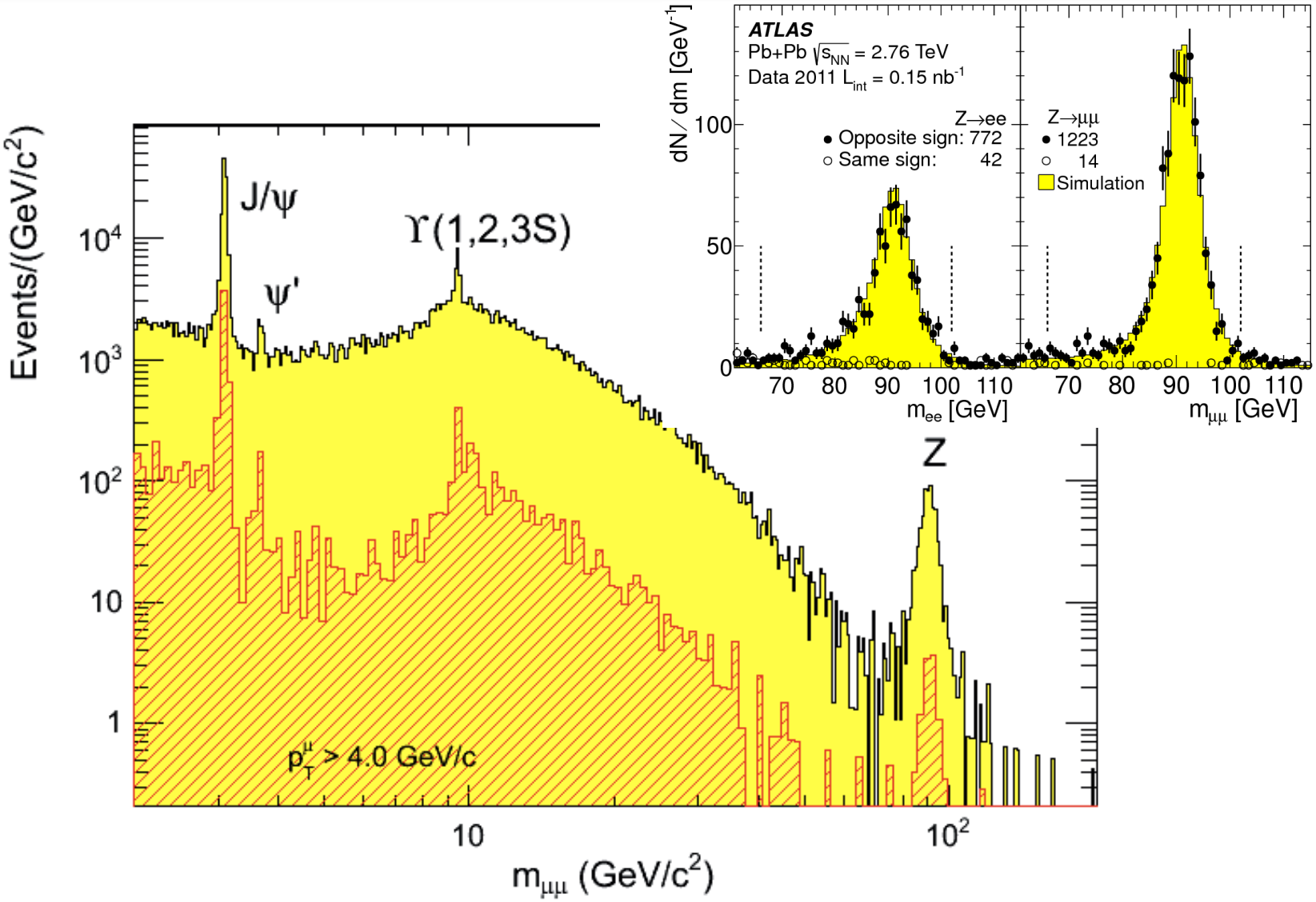
Hidden color
Dissociation in
hot and cold medium
Regeneration?



Jets

Colored probe
Induced radiation
+ elastic scattering
Many observables:
Jets ([u,d,s], g, c,b)
Hadrons (u,d,s, D, B)
Correlations

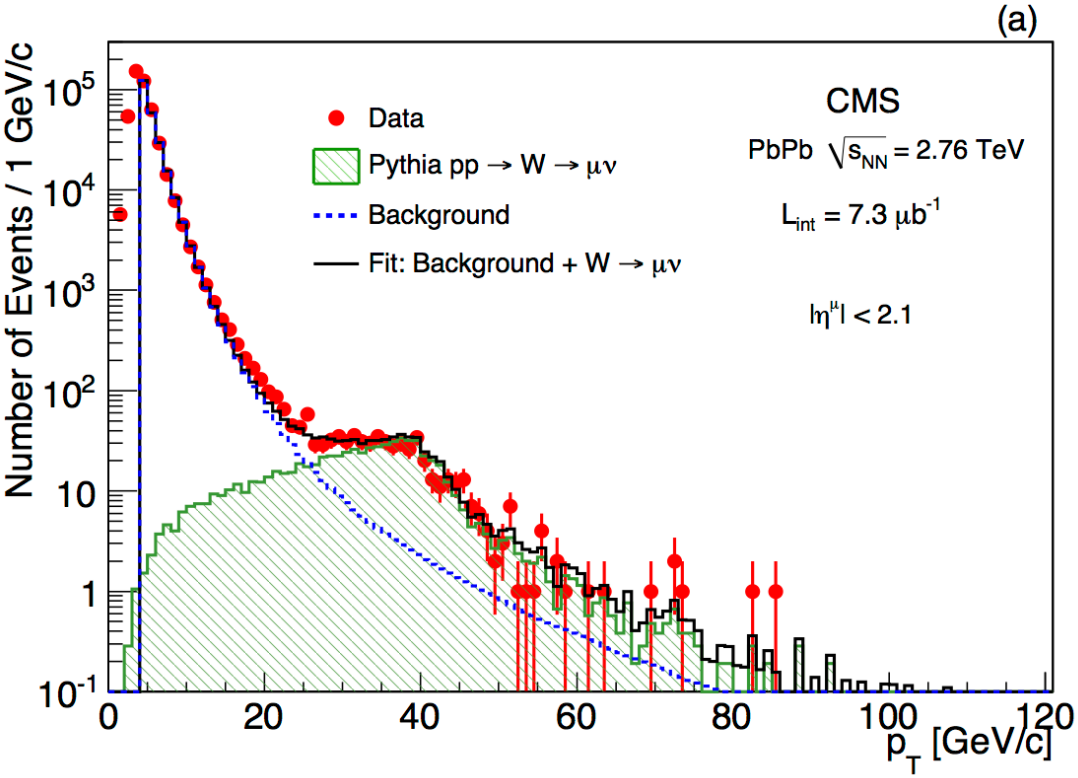
Yesterday's Nobel Prize….

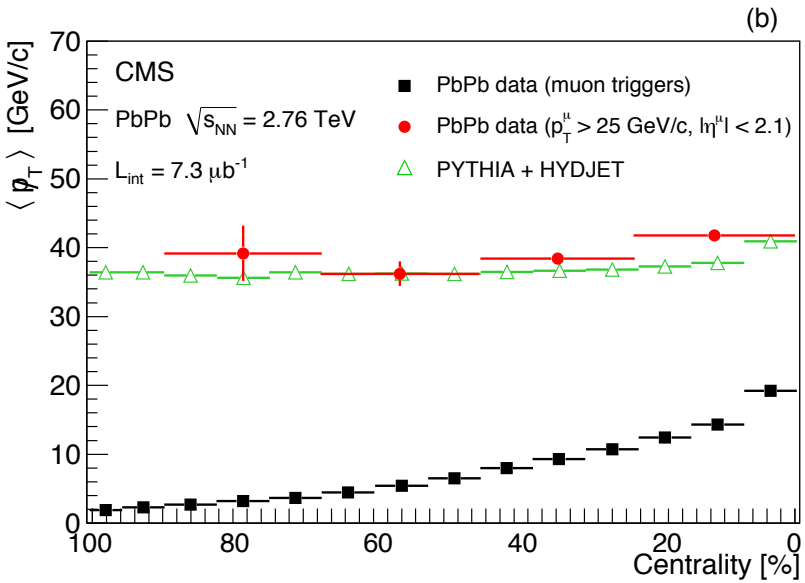


Yield above background fit (or like-sign combinations) readily extracted

Efficiencies for resonances can be estimated using data ("Tag & Probe")

Something missing: W's



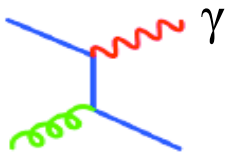


$W \rightarrow \mu\nu_{\mu}$: single high-$p_T$ muon (>25 GeV) + "Missing E_T"

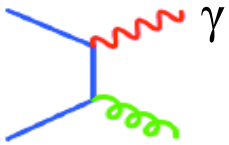
Photons in Isolation

Leading order

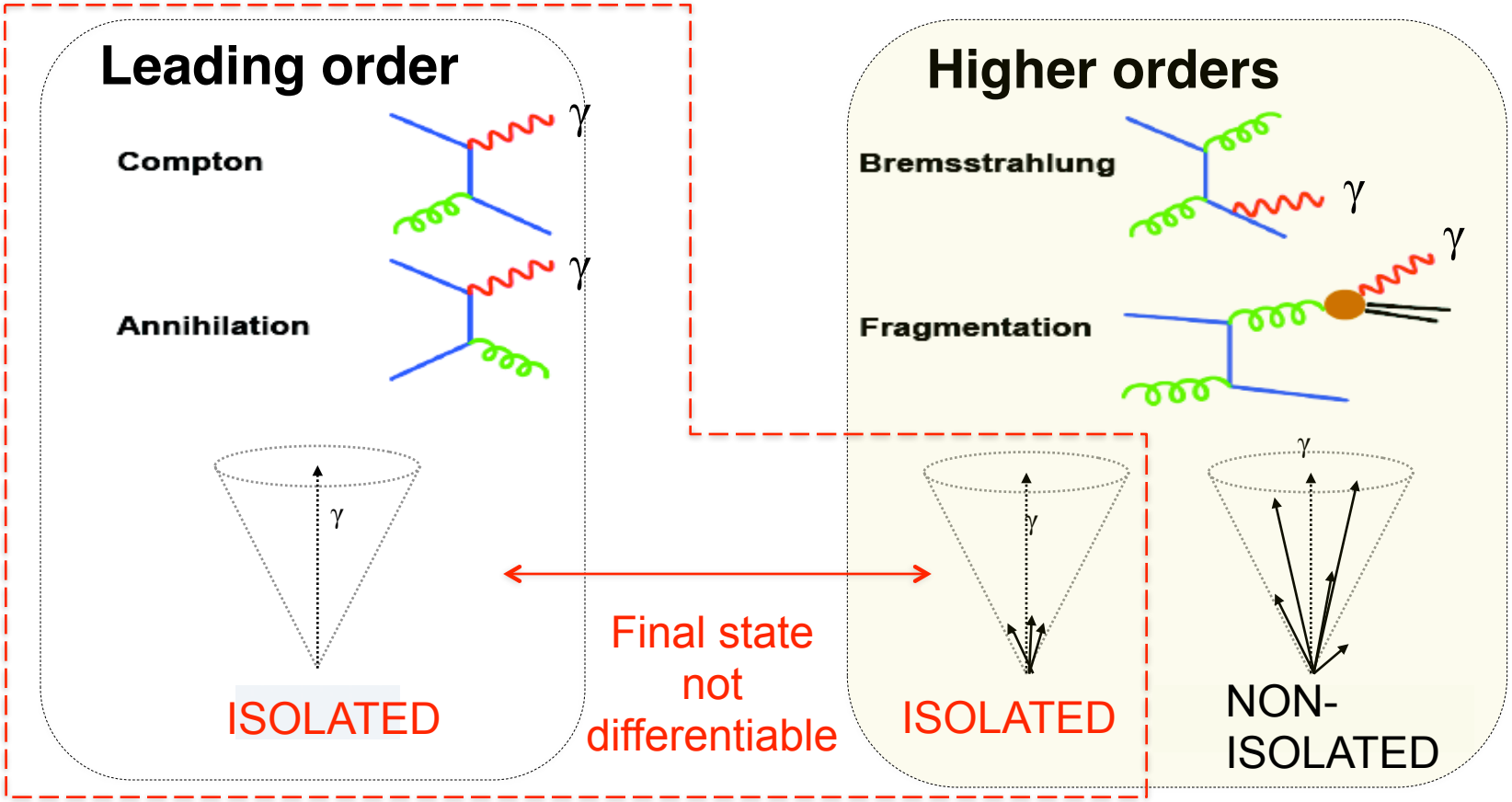
Compton



Annihilation

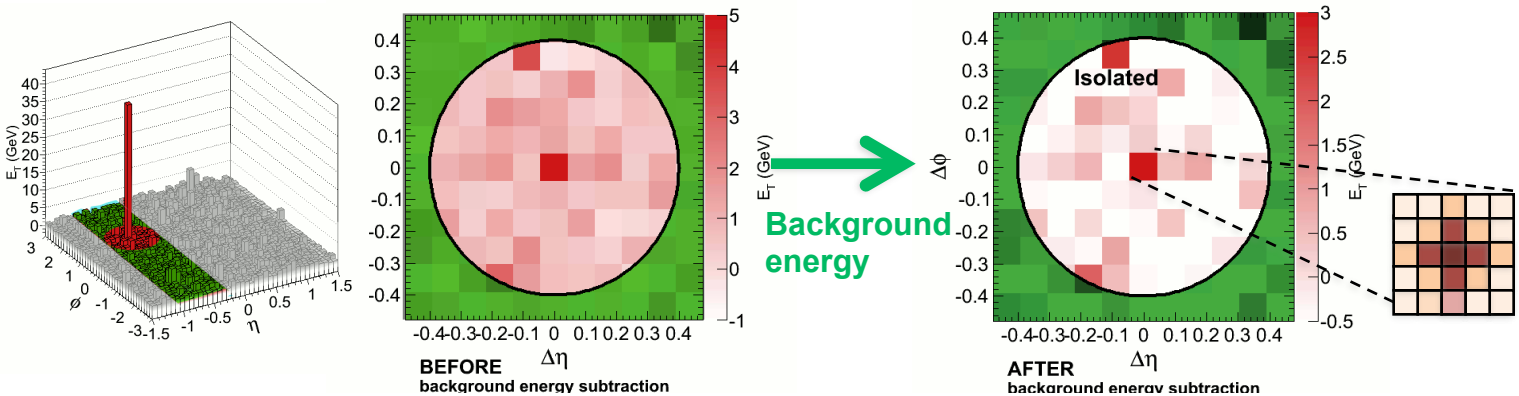


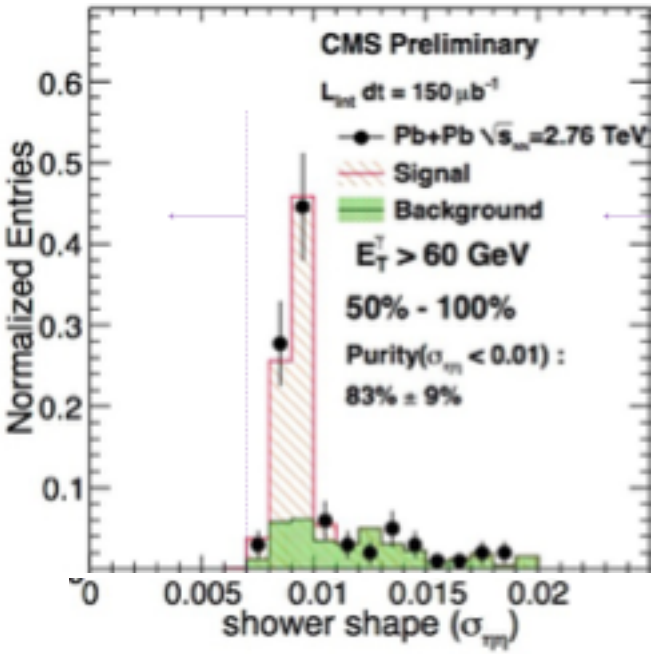
Photons in Isolation



- SumIso = uncorrected Track + ECAL + HCAL E_T in $R < 0.4$
- GenIso = generator level particle energy in $R < 0.4$
- Data: Isolated prompt (non-decay) photons: SumIso < 5 GeV
- pp MC: Isolated photons: GenIso < 1 GeV

(High p_T) isolated photons in AA





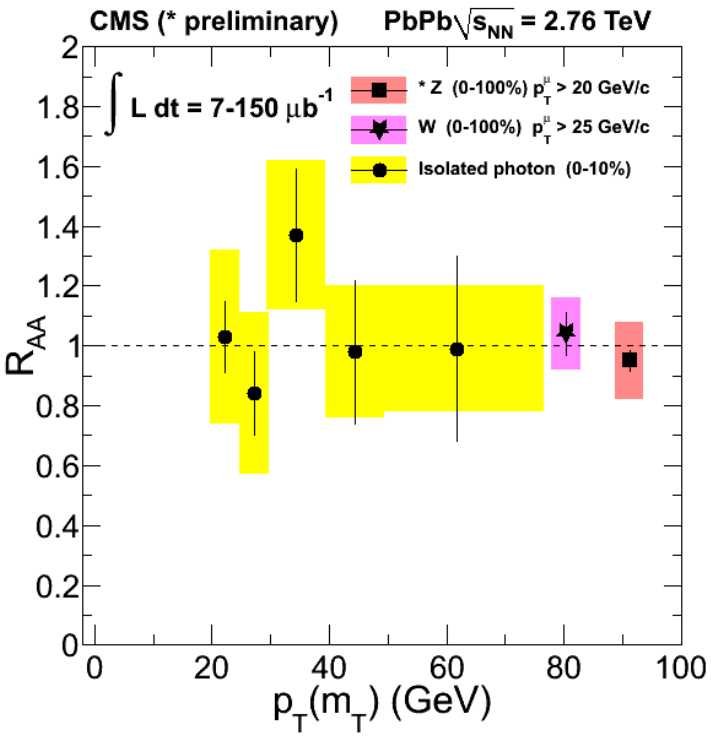
1. Find a high ET ECAL cluster (photon candidate)
2. Subtract underlying event energy in iso cone
3. Apply isolation cut (SumIso < 5 GeV)
4. Use 2nd variable (shower shape) to determine photon purity (1-fraction of decay photons) **from data**

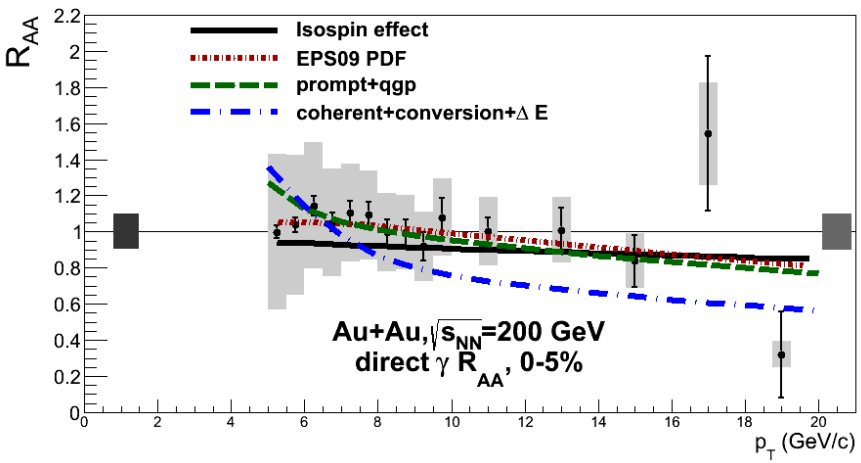
Nuclear Modification Factor

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}} \begin{cases} R_{AA} > 1 \text{ (enhancement)} \\ R_{AA} = 1 \text{ (no medium effect)} \\ R_{AA} < 1 \text{ (suppression)} \end{cases}$$

$$\langle T_{AA}\rangle = \langle N_{coll}\rangle / \sigma_{pp}^{inel}$$

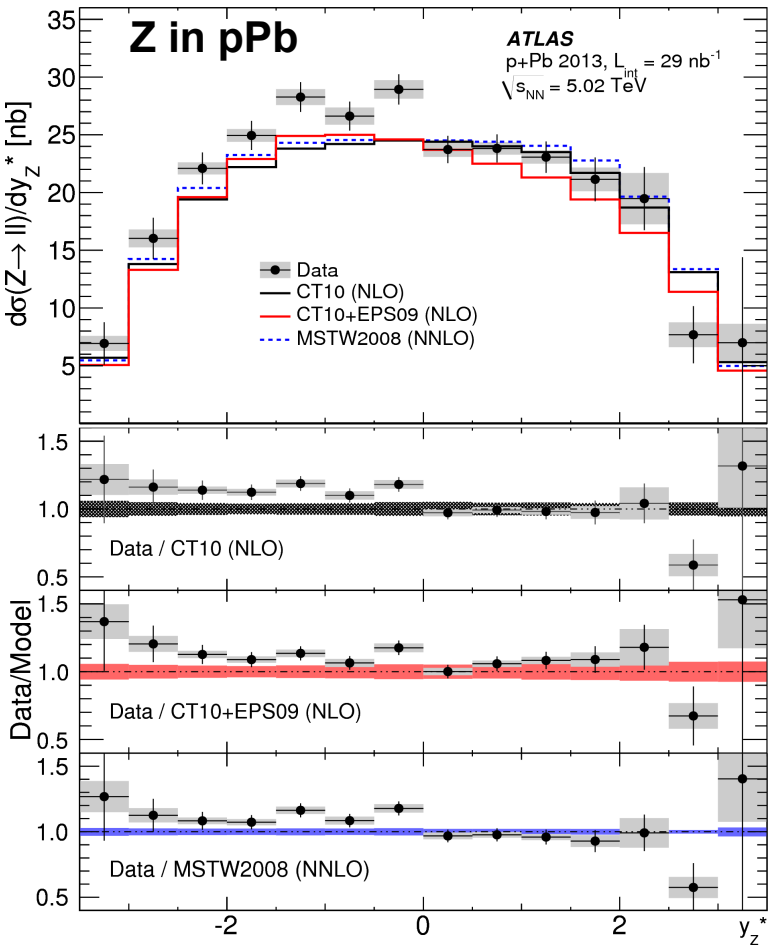
N_{coll}: Number of binary nucleon-nucleon collisions within AA collision

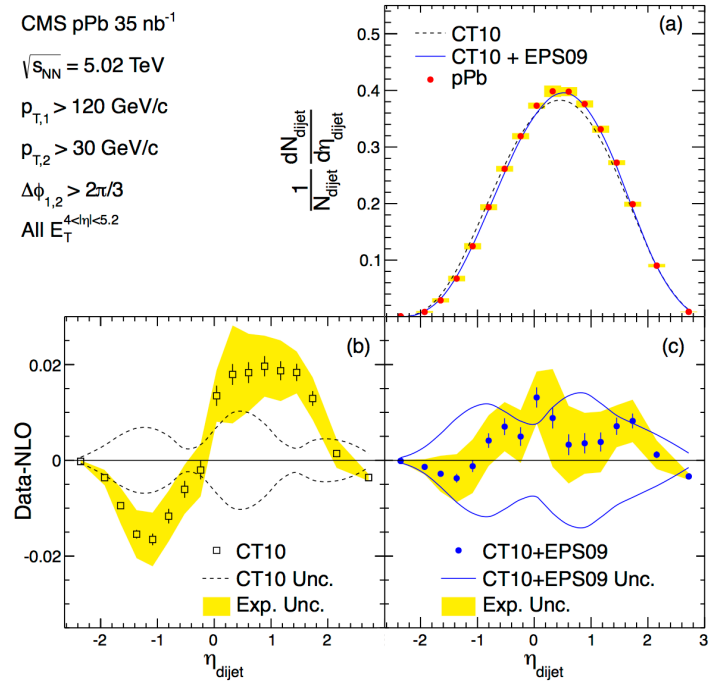




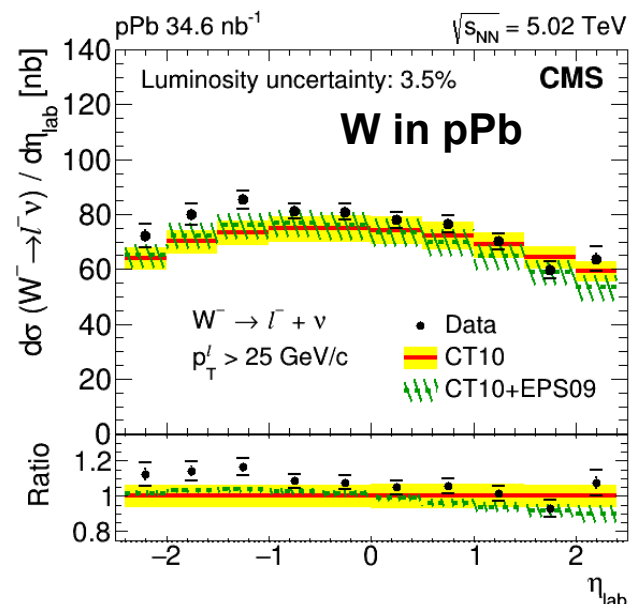
We understand N_{coll} (from Glauber MC) to ~5% in central AA (uncertainty larger for very peripheral collisions)

Beyond N_{coll}: nPDFs from pPb





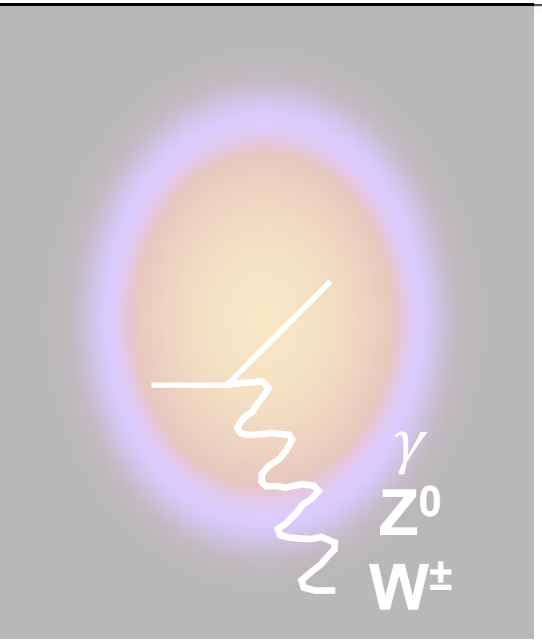
dijet η in pPb

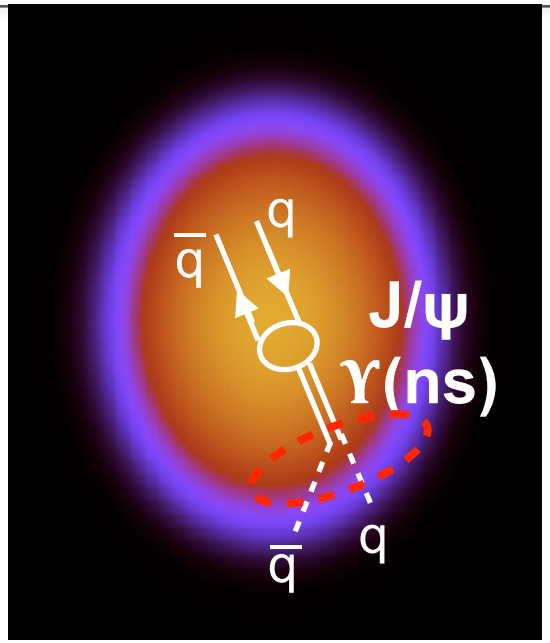


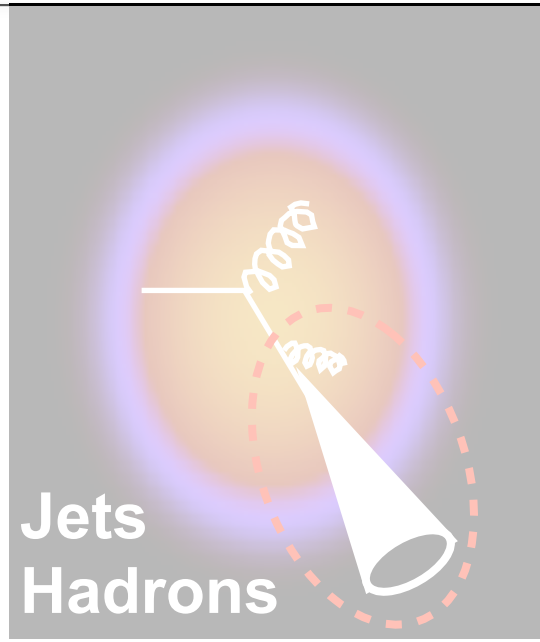
Approaching sensitivity needed to see nuclear modifications of PDFs

Effects are small in kinematic region studied

Hard Probes Gallery







Vectorbosons

Colorless
No medium effects
Probe initial state
(nPDFs, N_{coll})

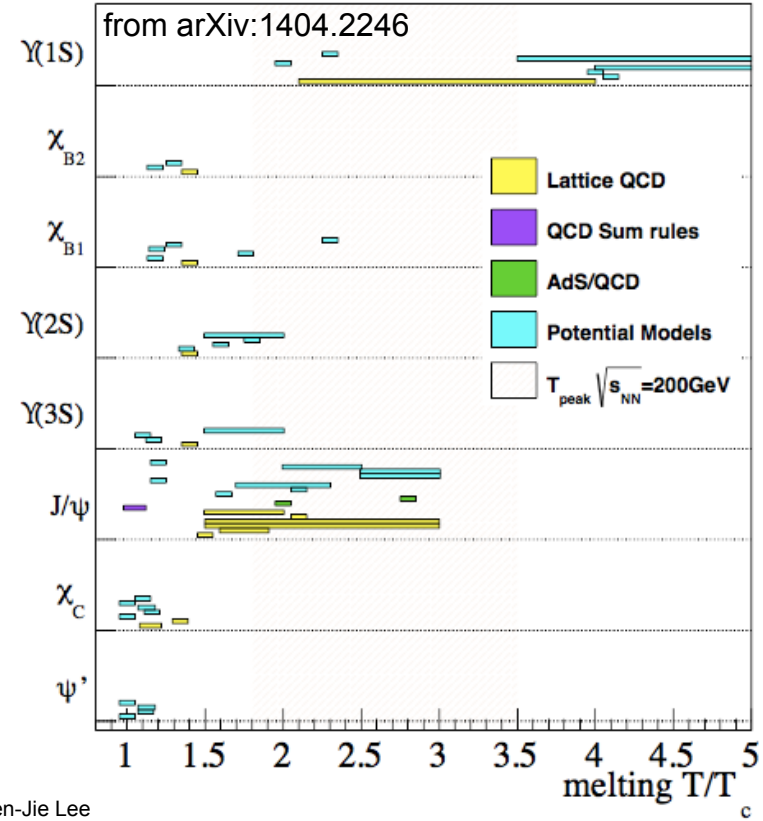
Quarkonia

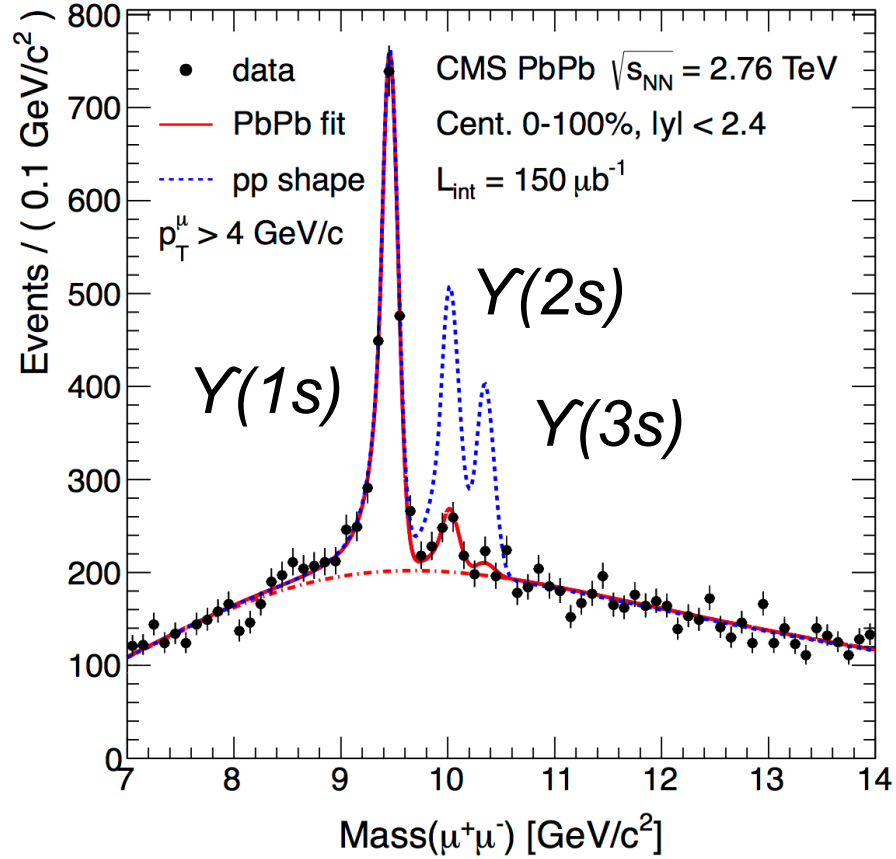
Hidden color
Dissociation in
hot and cold medium
Regeneration?

Jets

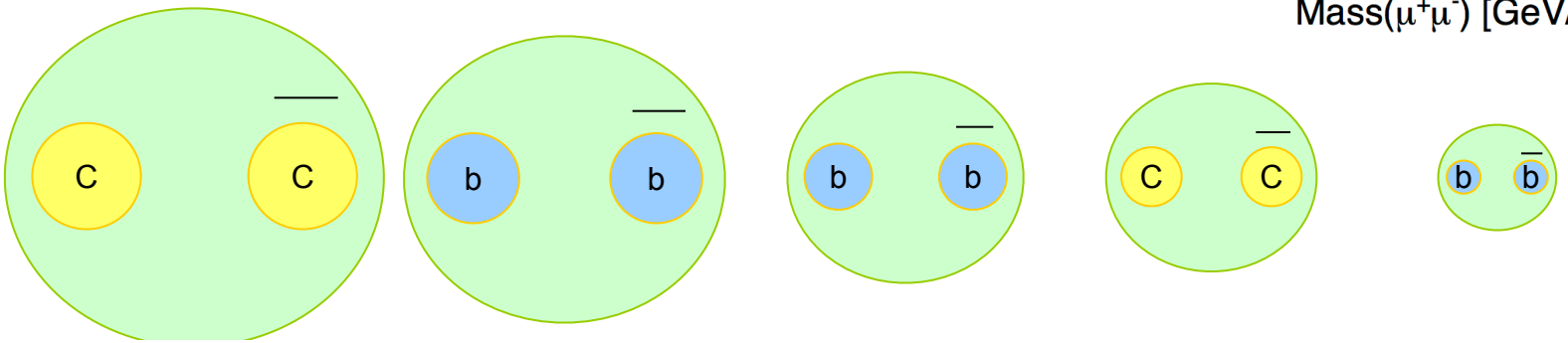
Colored probe
Induced radiation
+ elastic scattering
Many observables:
Jets ([u,d,s], g, c,b)
Hadrons (u,d,s, D, B)
Correlations

Quarkonia as multi-scale QGP probes



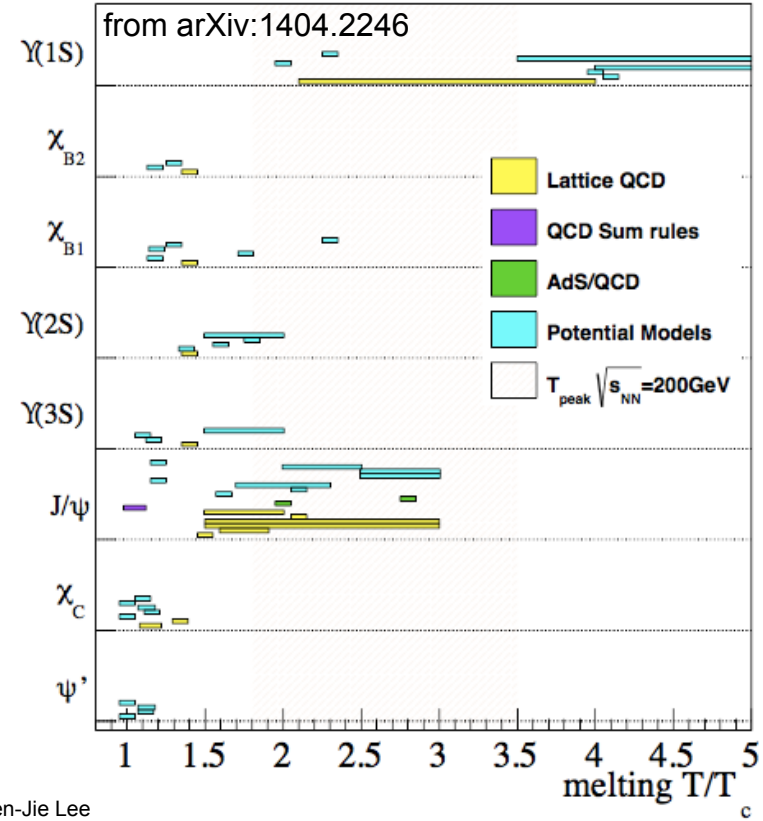


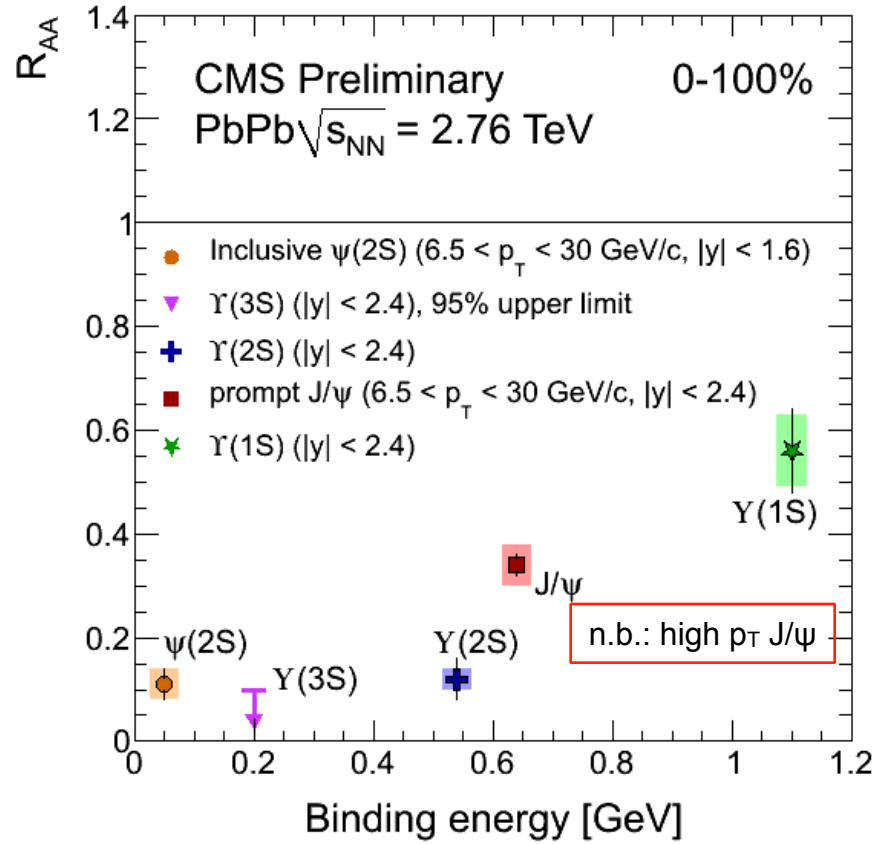
from Yen-Jie Lee



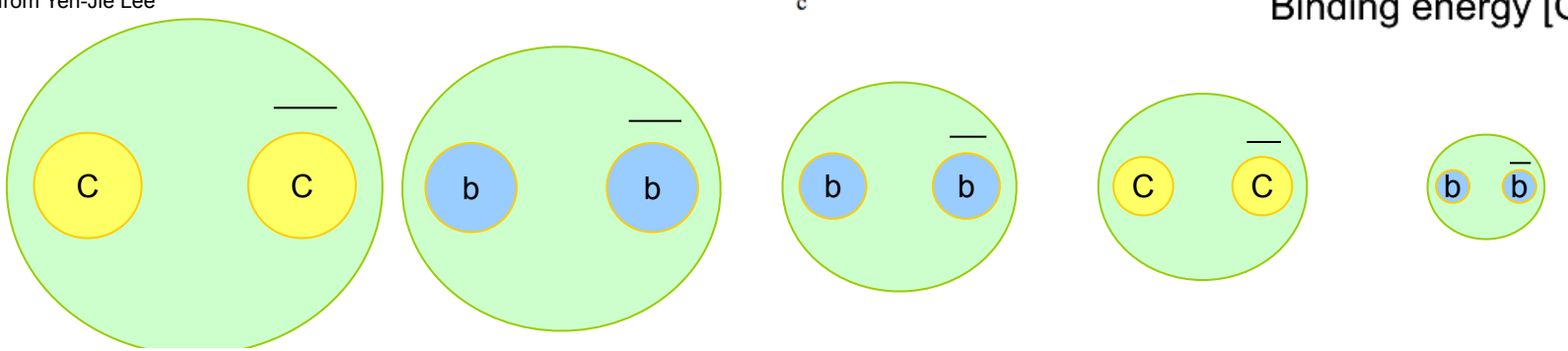
ψ(2s) Υ(3s) Υ(2s) J/ψ Υ(1s)

Quarkonia as multi-scale QGP probes



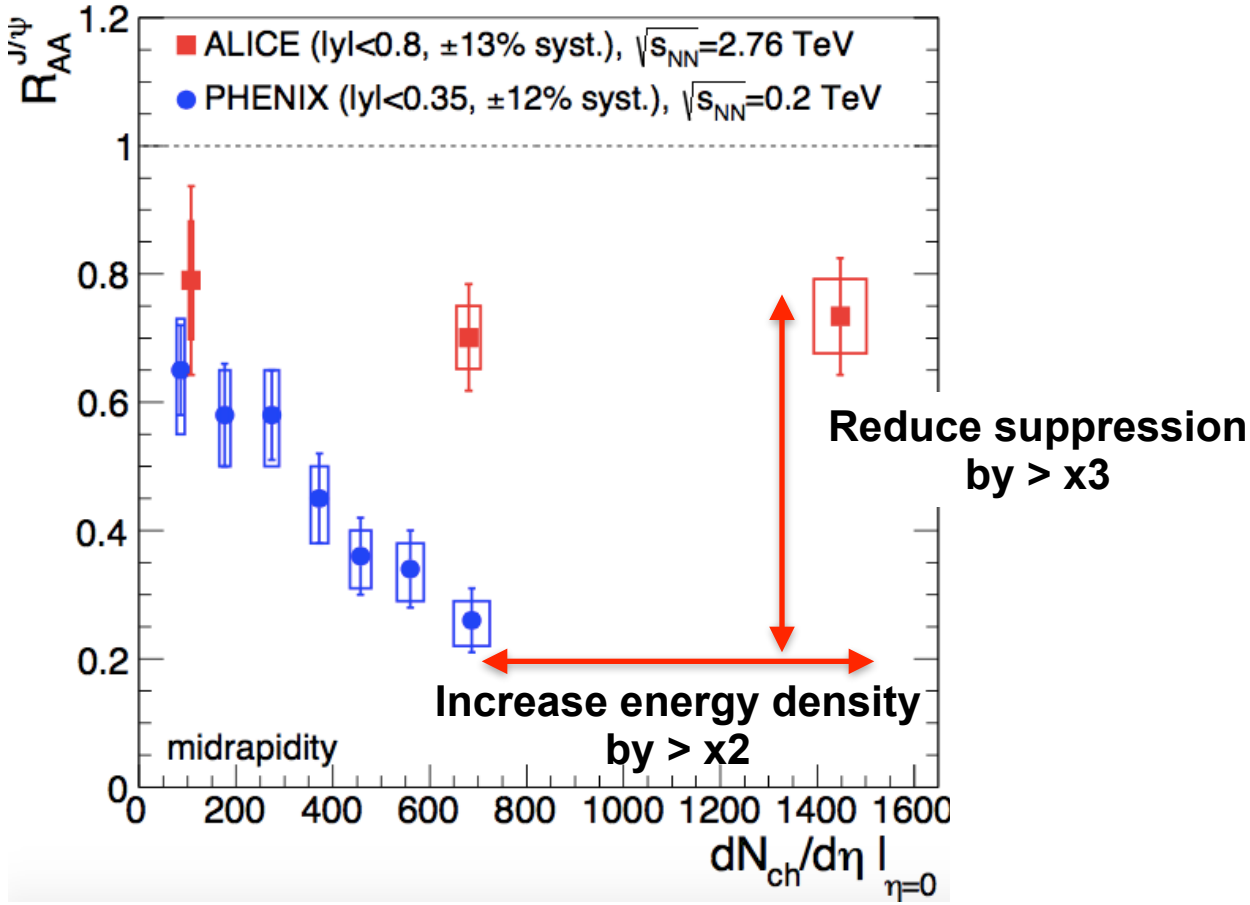


from Yen-Jie Lee



ψ(2s) *Υ(3s)* *Υ(2s)* *J/ψ* *Υ(1s)*

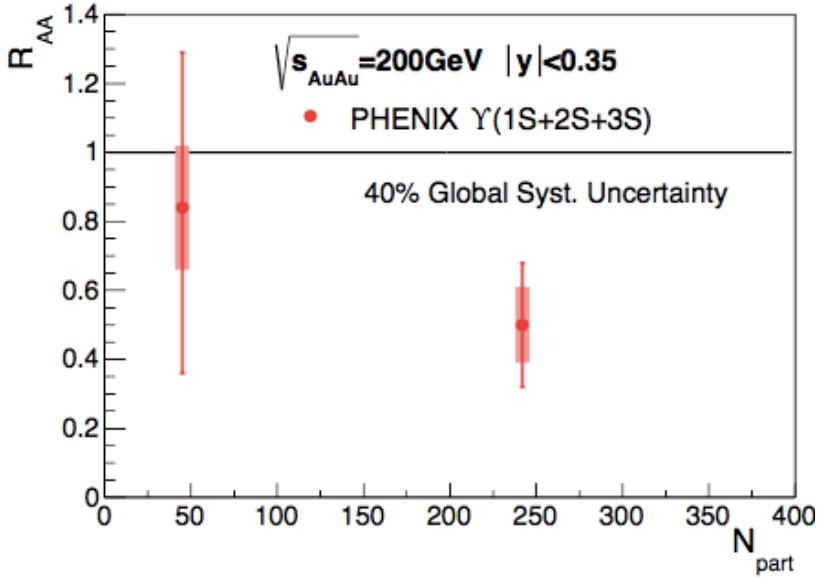
Low p_T Charmonia: Out of the HP club?

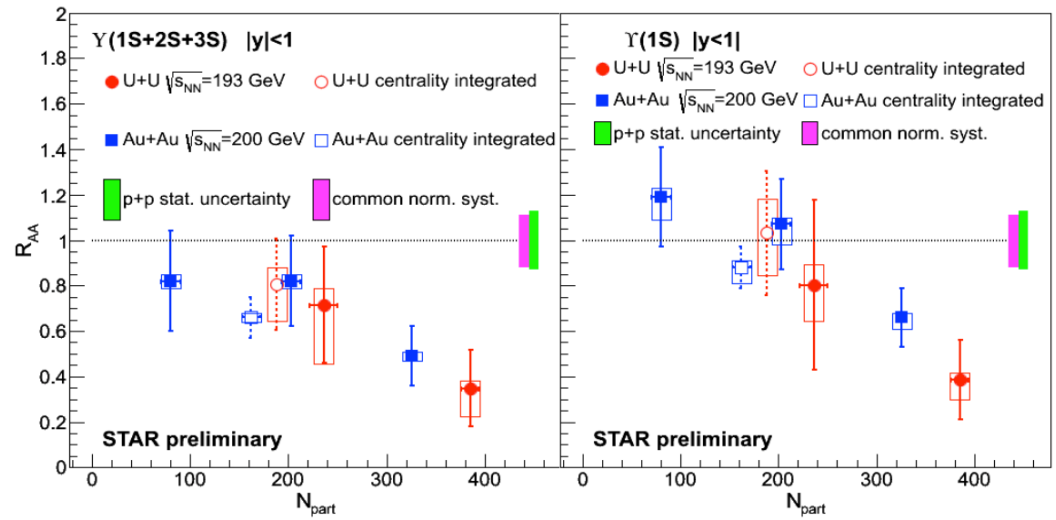


One of the most striking LHC vs RHIC (SPS) results

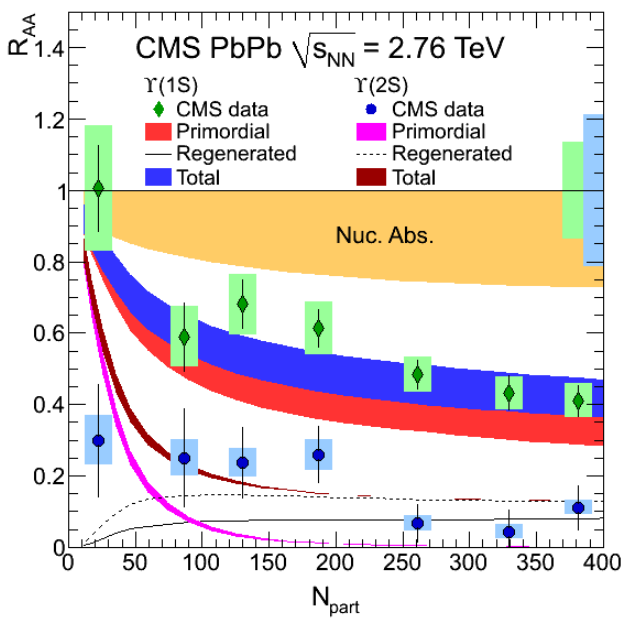
J/ ψ not just created in initial hard collisions, but also during QGP evolution and/or hadronization

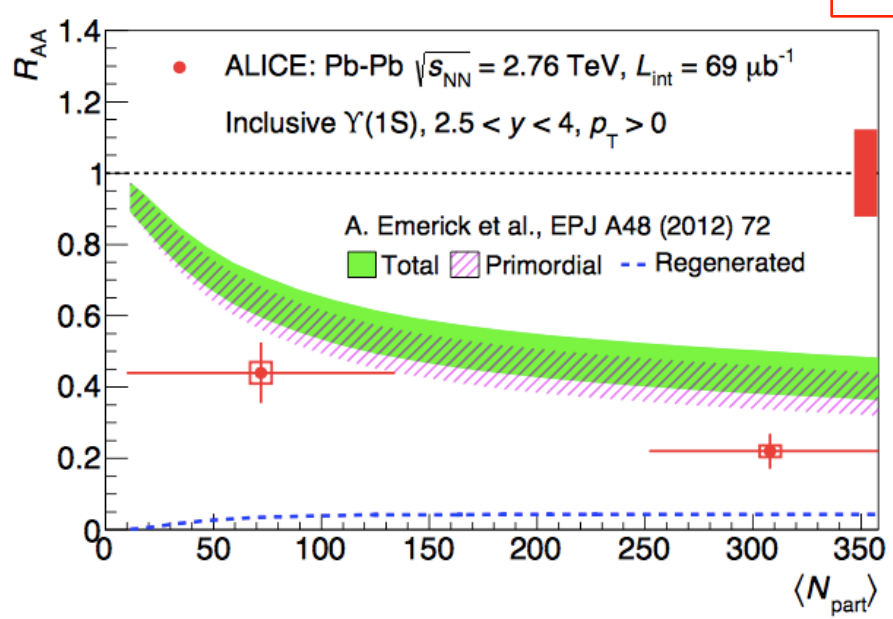
But surely Υ(ns) are fine, aren't they?





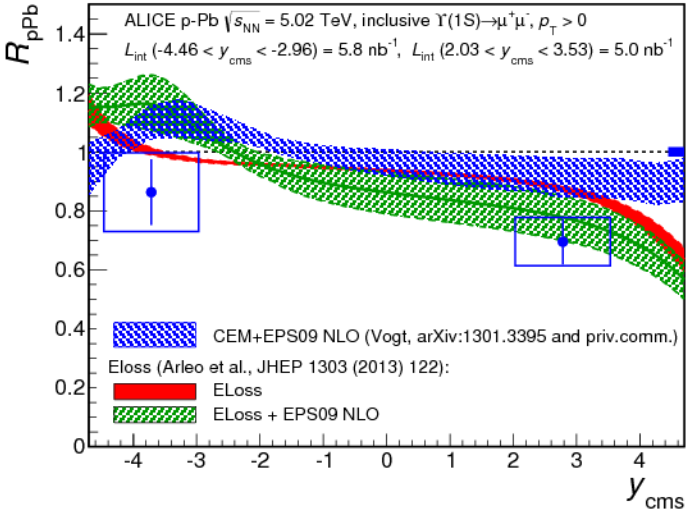
Even at LHC, density of b quarks is small



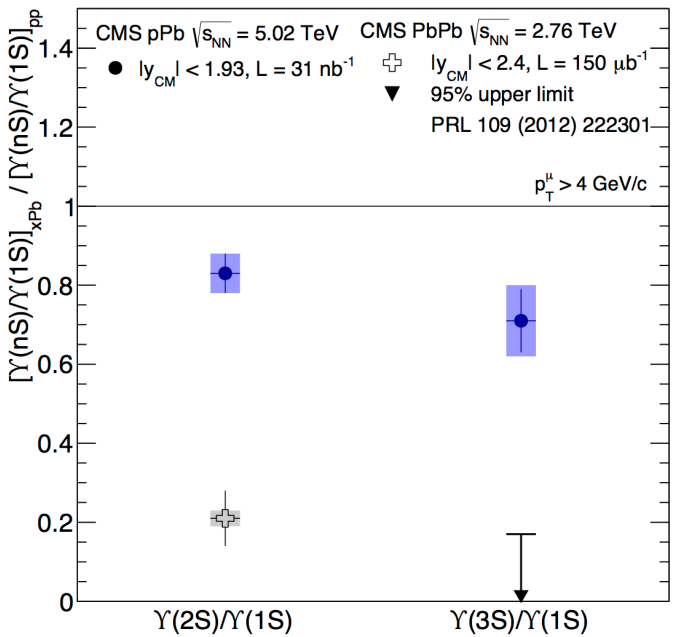


+ LHCb

Well, there is this in pPb…



Y(1s) shows "cold nuclear matter" effects
(although one can now debate how "cold" p+Pb is)

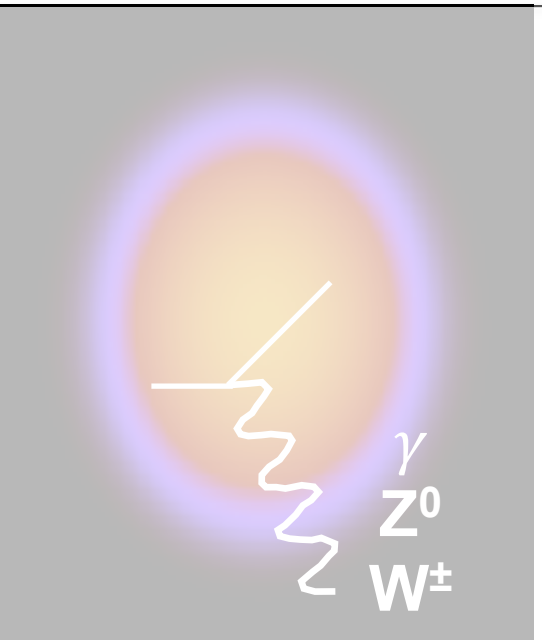


Double ratio (1 ≡ same effect for Y(1s), Y(2s), Y(3s)):

$$\frac{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{pPb}}{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{pp}} = \frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$

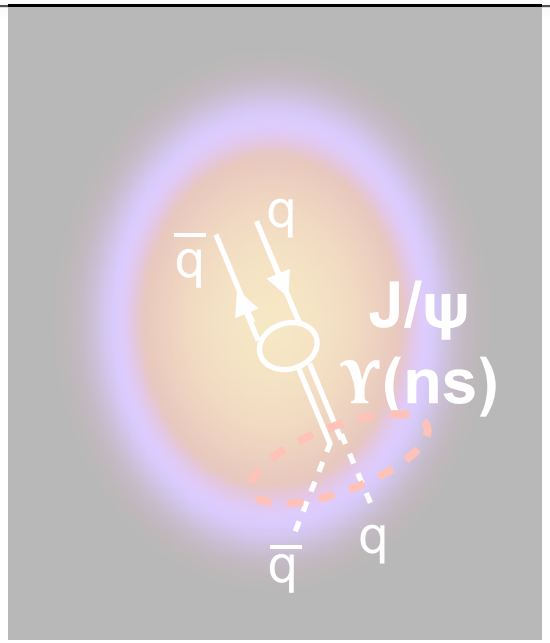
Initial state effects (nPDF) should ~ drop out
But: **Differential** change seen vs binding energy!

Hard Probes Gallery



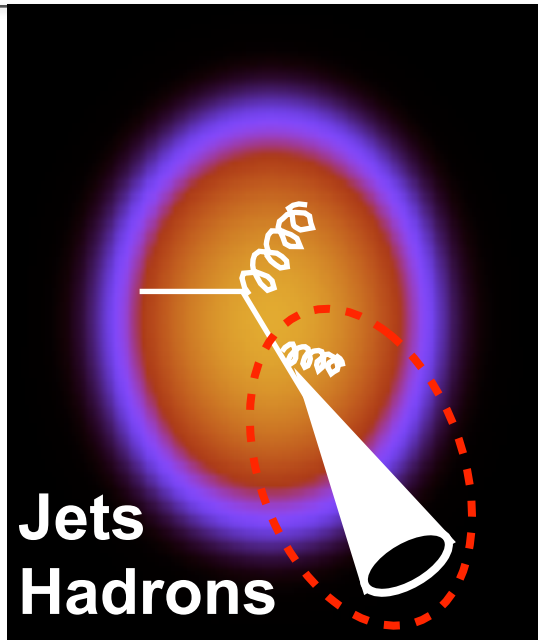
Vectorbosons

Colorless
No medium effects
Probe initial state
($nPDFs$, N_{coll})



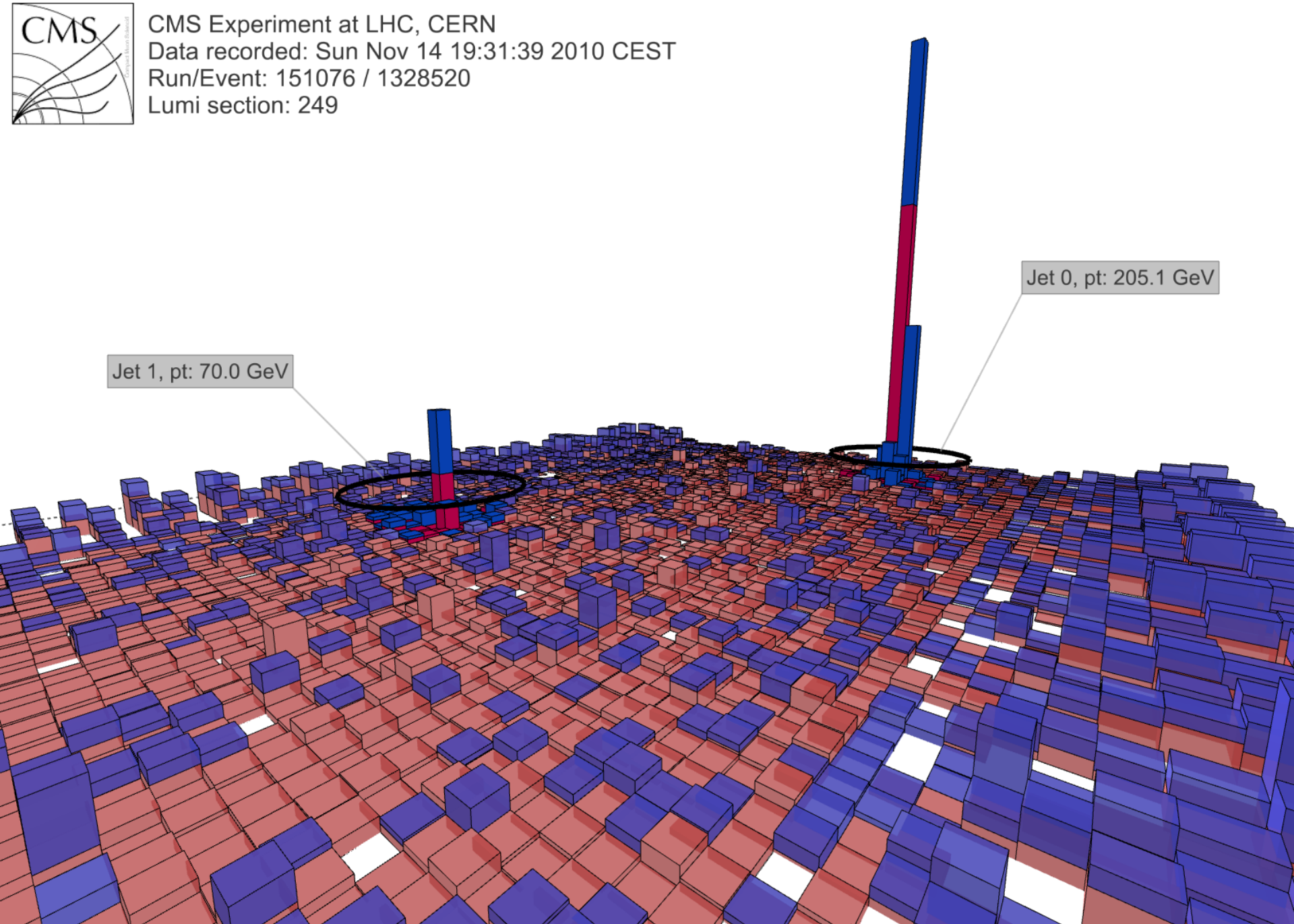
Quarkonia

Hidden color
Dissociation in
hot and cold medium
Regeneration?



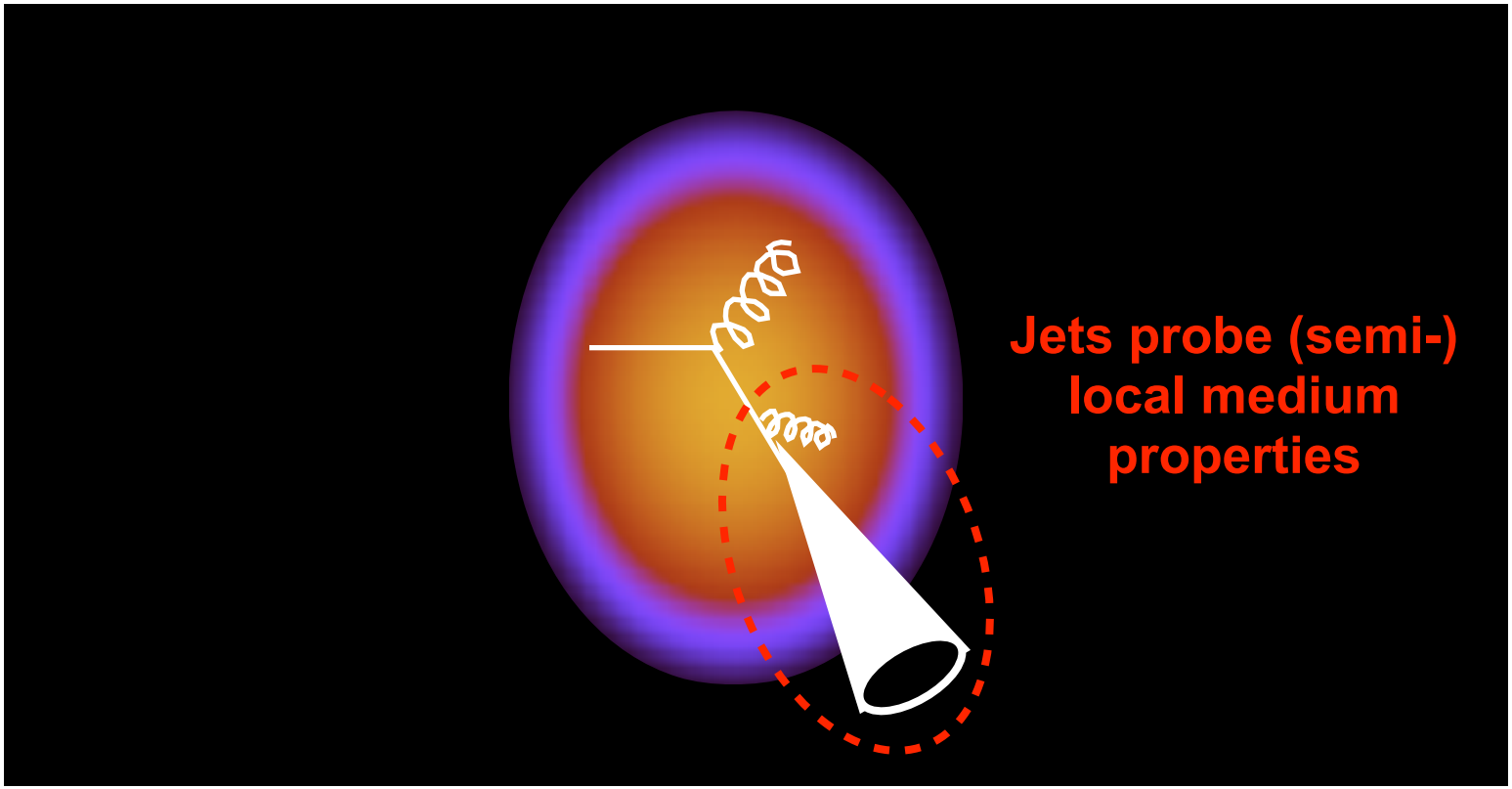
Jets

Colored probe
Induced radiation
+ elastic scattering
Many observables:
Jets ([u,d,s], g, c,b)
Hadrons (u,d,s, D, B)
Correlations


CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

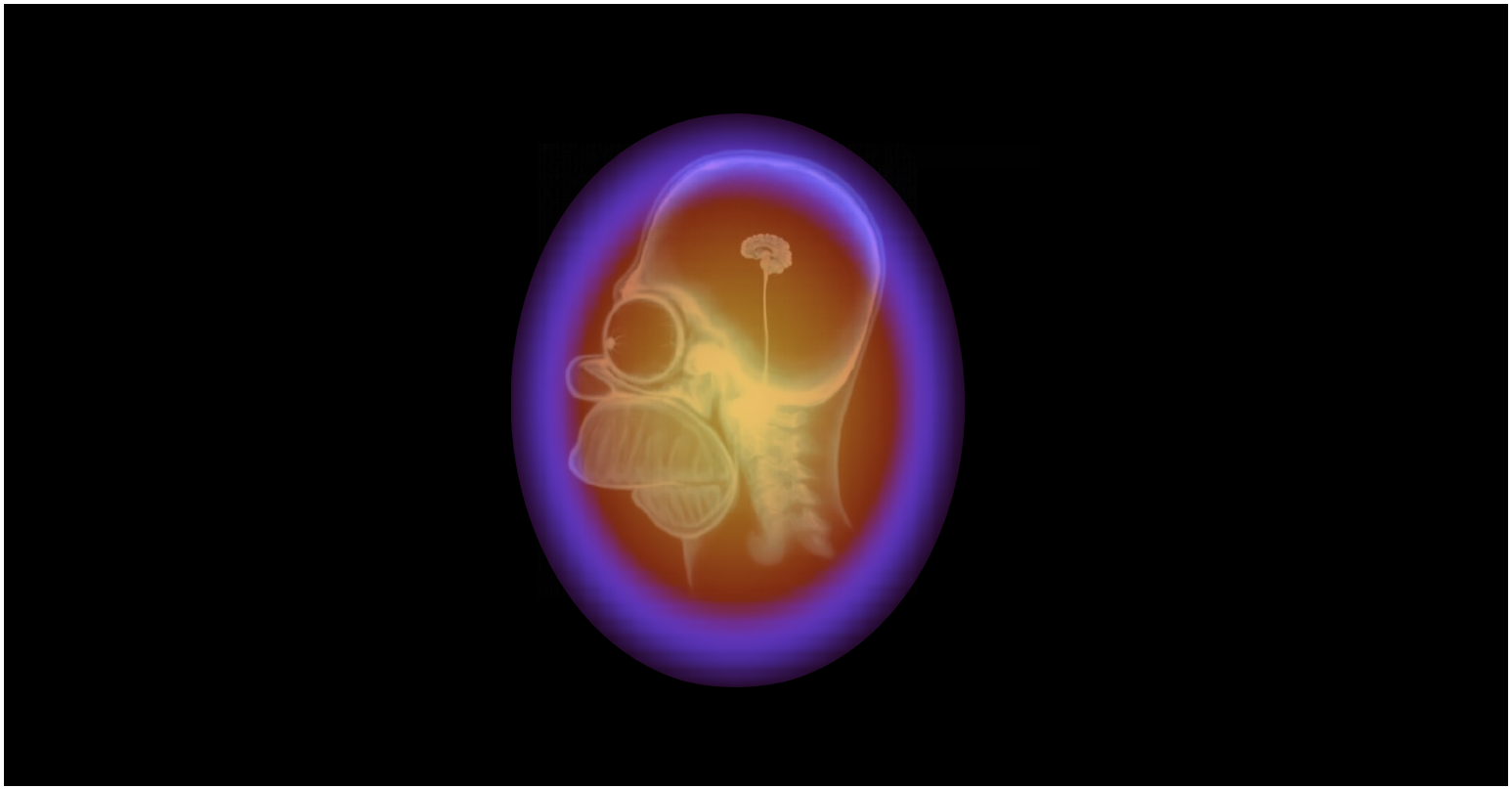
QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures



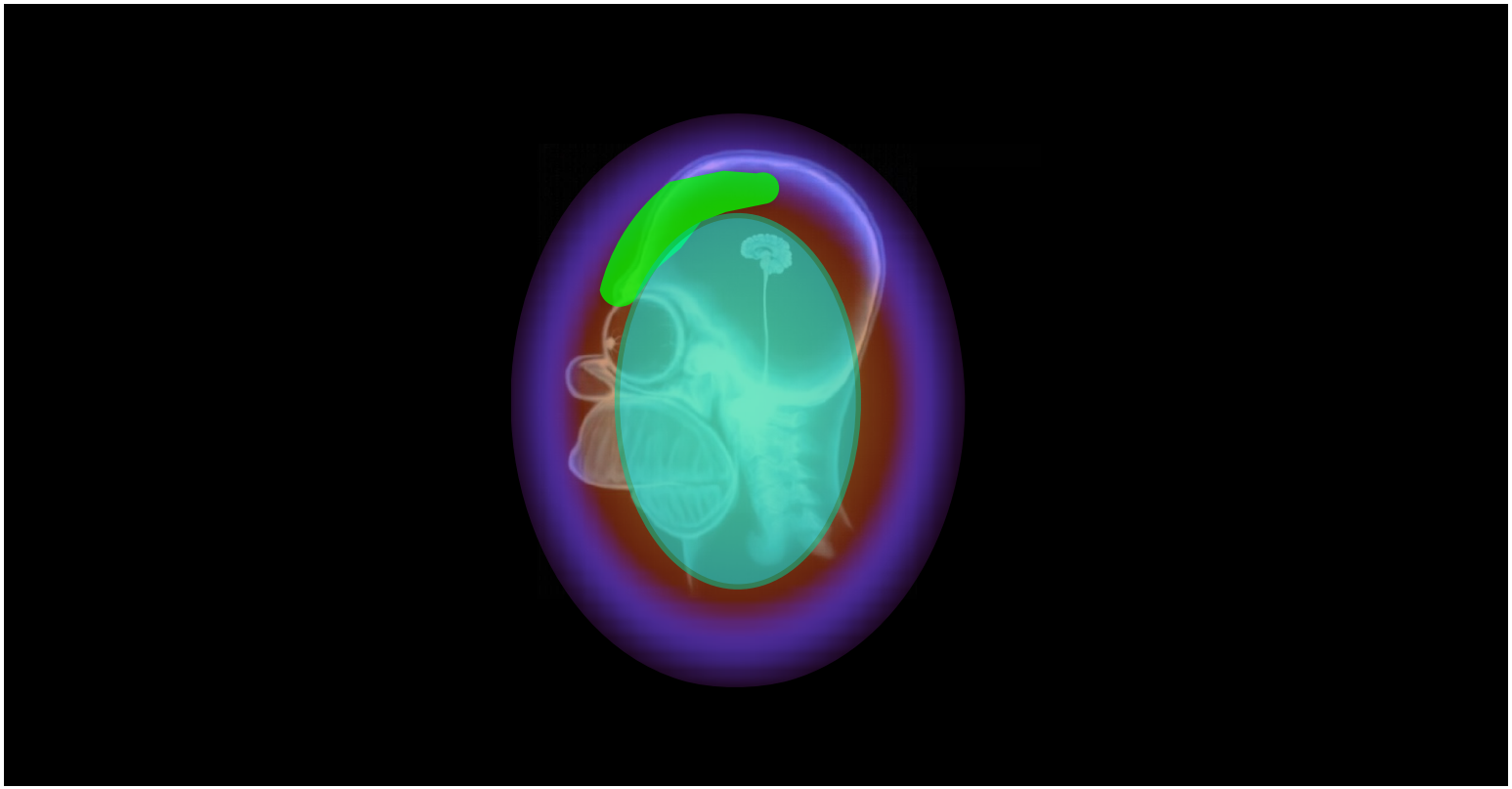
QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures



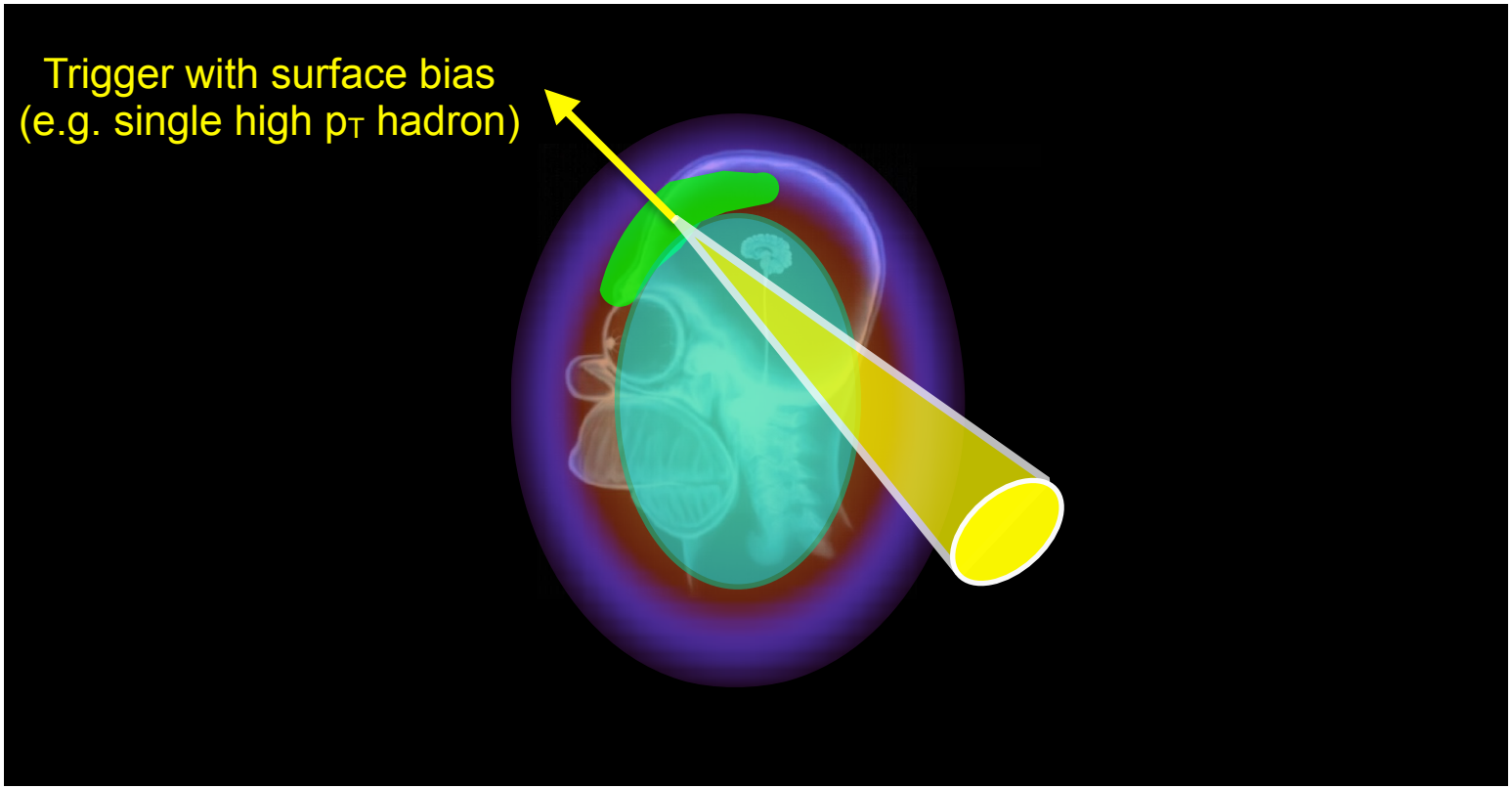
QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures



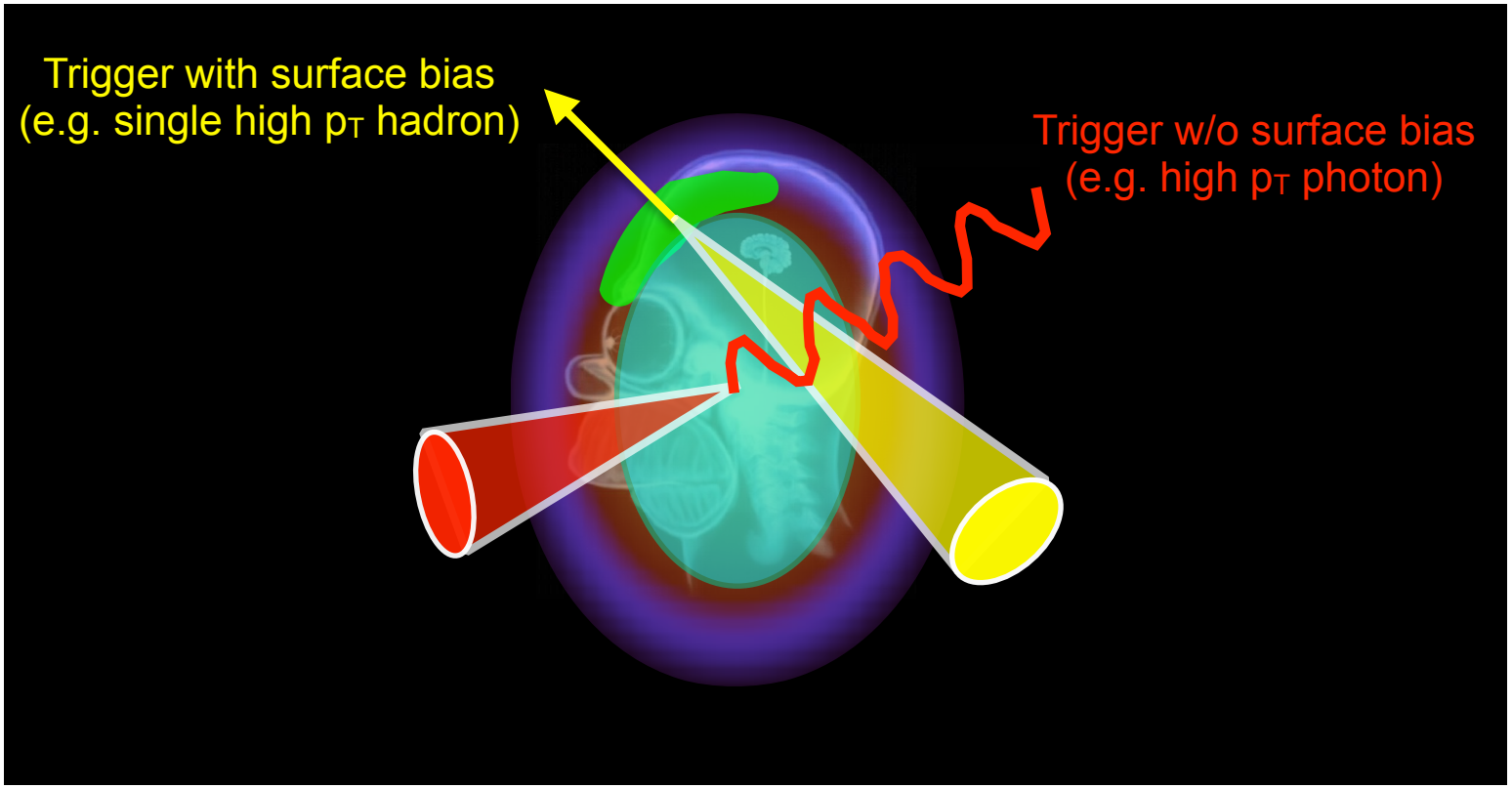
QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures



QGP Tomography

TOMOGRAPHY
: a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures



Use p_T, centrality, pathlength, $\sqrt{s}$ dependence, trigger biases, flavor tags,… to isolate different processes in time, coordinate and momentum space

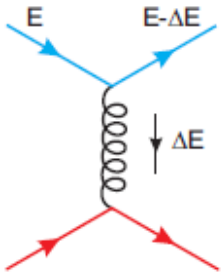
Jet Transport Coefficients: $\hat{q}$ and $\hat{e}$

Jets as tools to ***characterize*** QGP

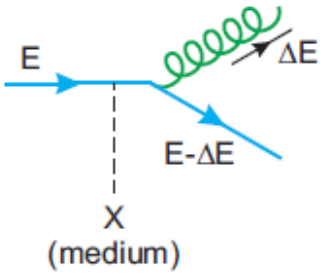
Medium effects on jets allow extraction of QGP transport coefficients:

- $\hat{q}$: transverse momentum diffusion (*radiative energy loss*)
  - induced gluon emission in medium
- $\hat{e}$: longitudinal drag (*collisional energy loss*)
  - collisions with medium patrons

Collisional energy loss



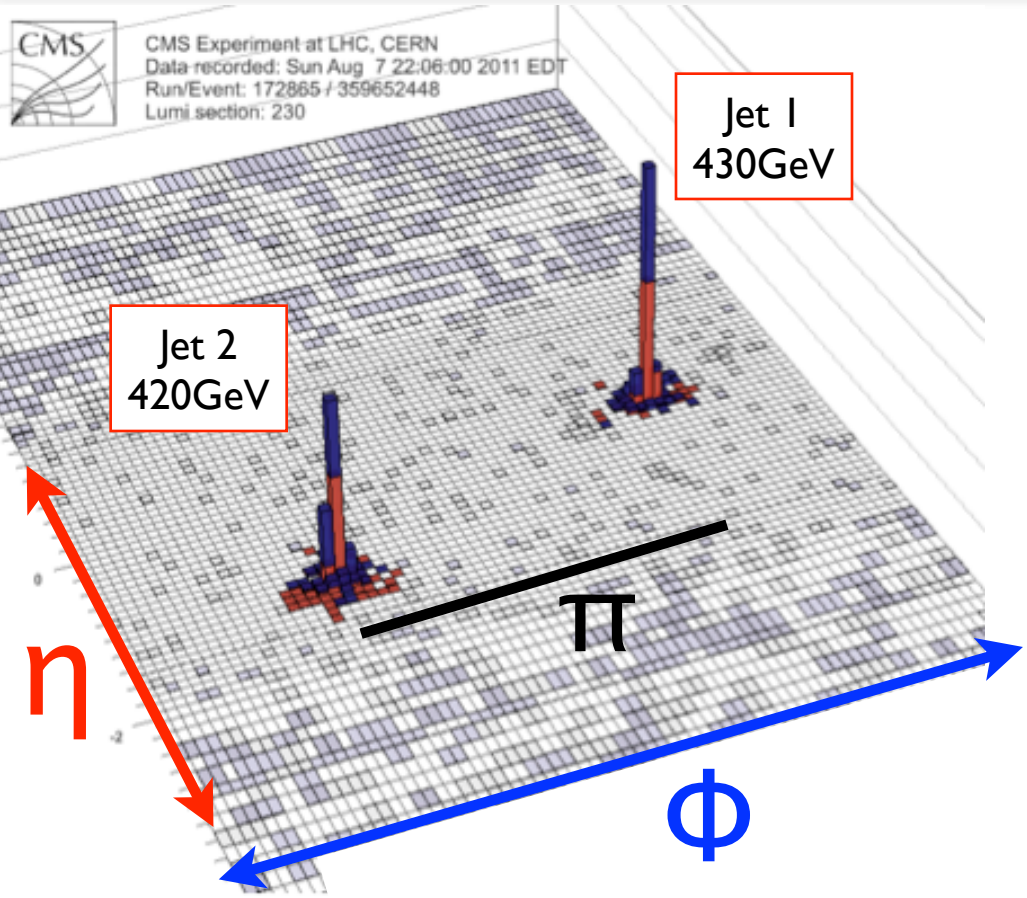
Radiative energy loss



Radiative energy loss suppressed for (slow) heavy quarks: *Dead Cone effect*

Changes relative importance of radiative vs elastic e-loss: Use heavy flavor (c,b) vs light (g,uds) measurements to disentangle radiative vs collisional energy loss

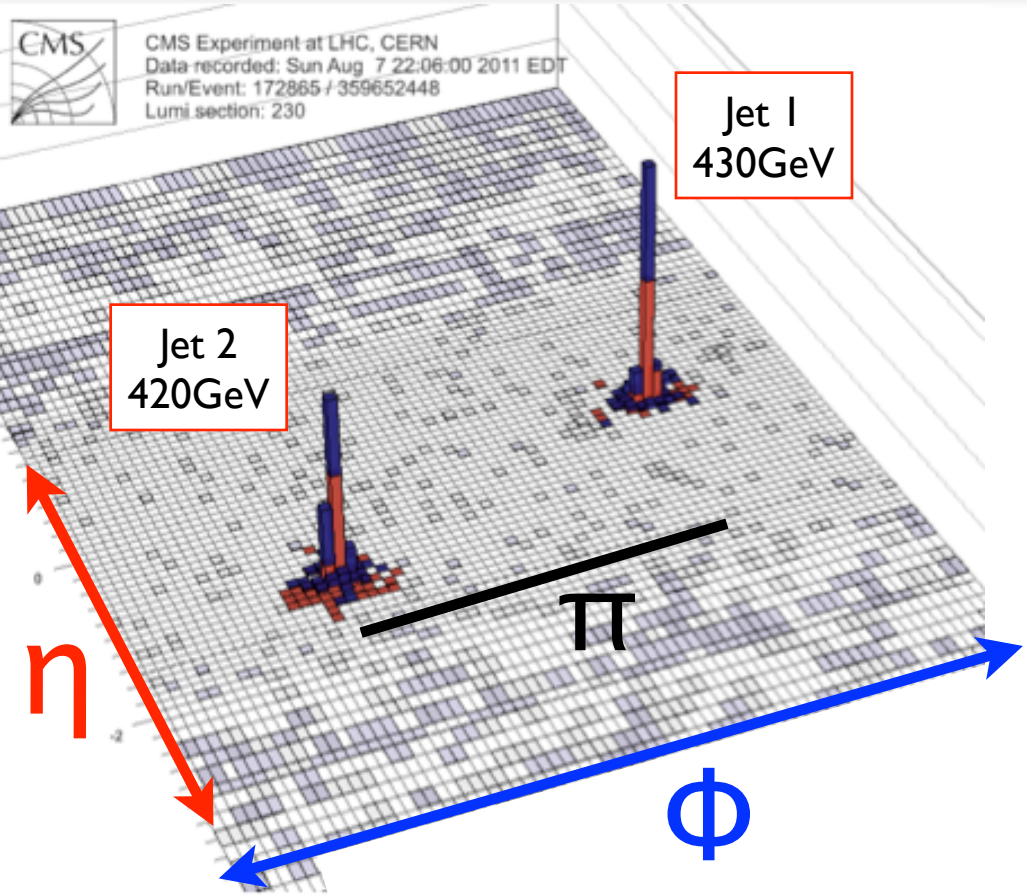
What's a jet?

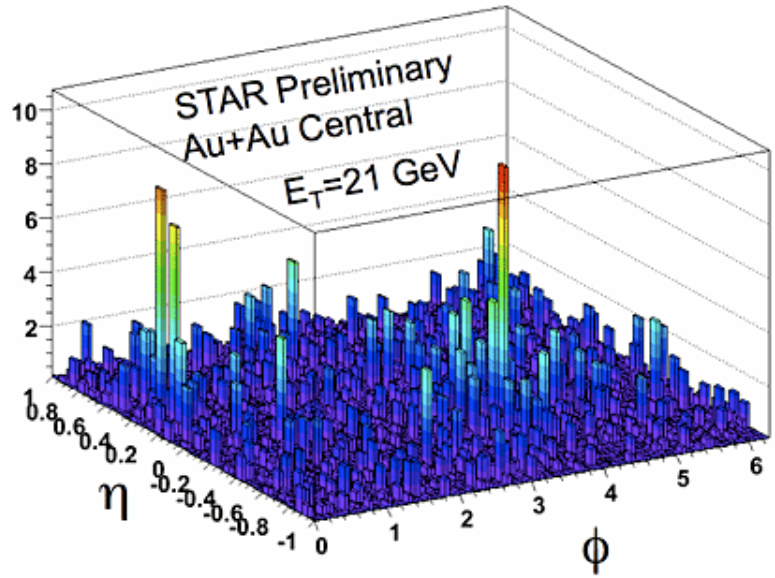


Jet finding is easy…

High p_T jets, pp collision

What's a jet?





Jet finding is easy…

High p_T jets, pp collision

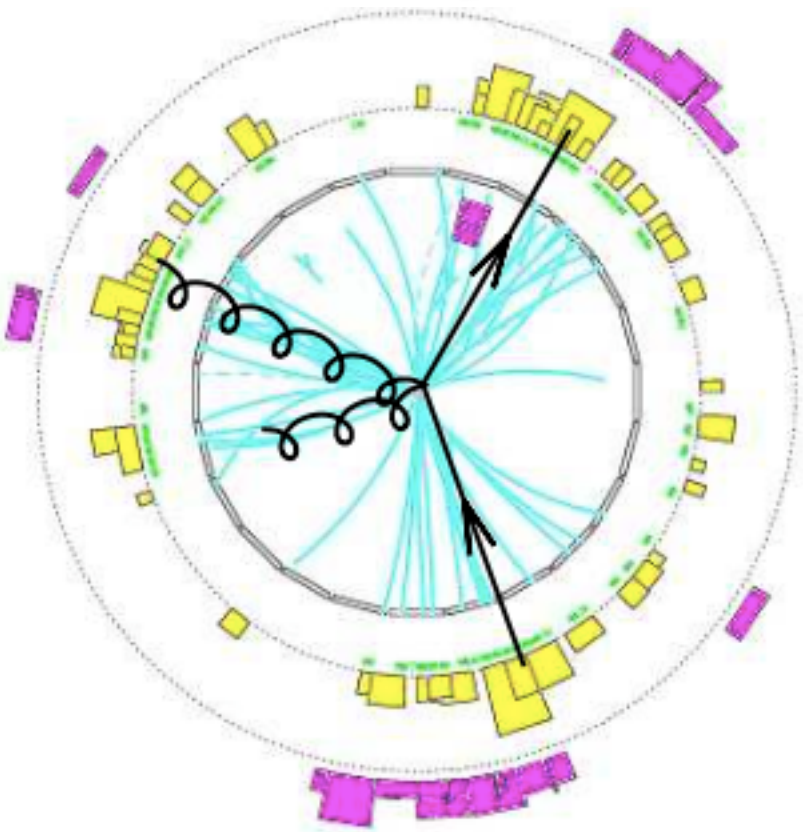
…until it isn't

Low p_T jets, central heavy-ion collision UE

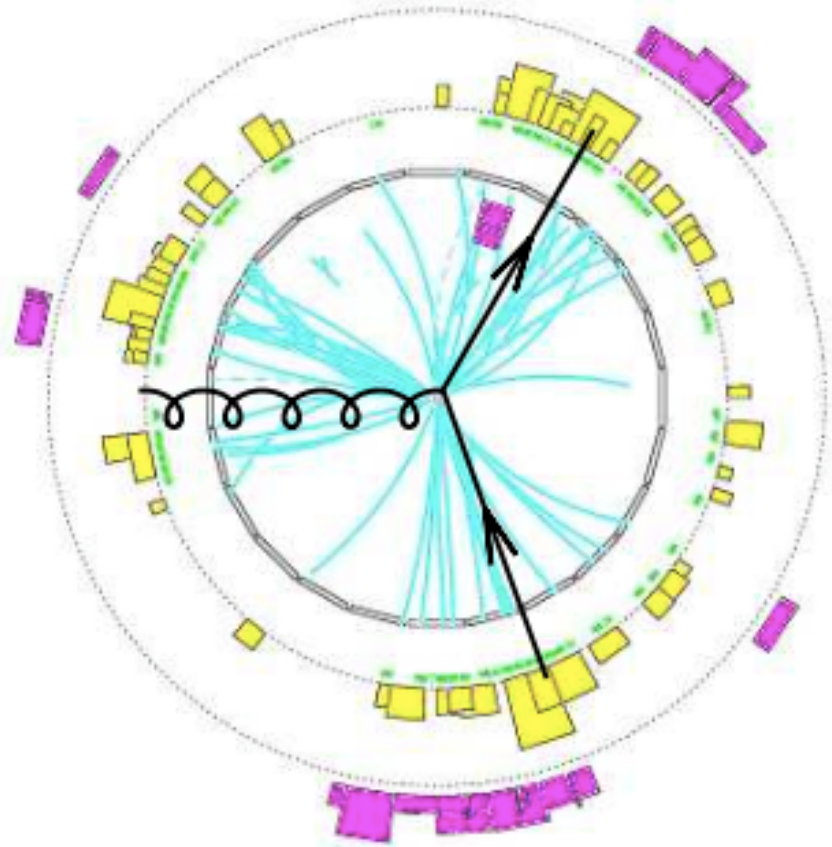
What's a jet (in pp)?

Same pp collision event

from Gavin Salam

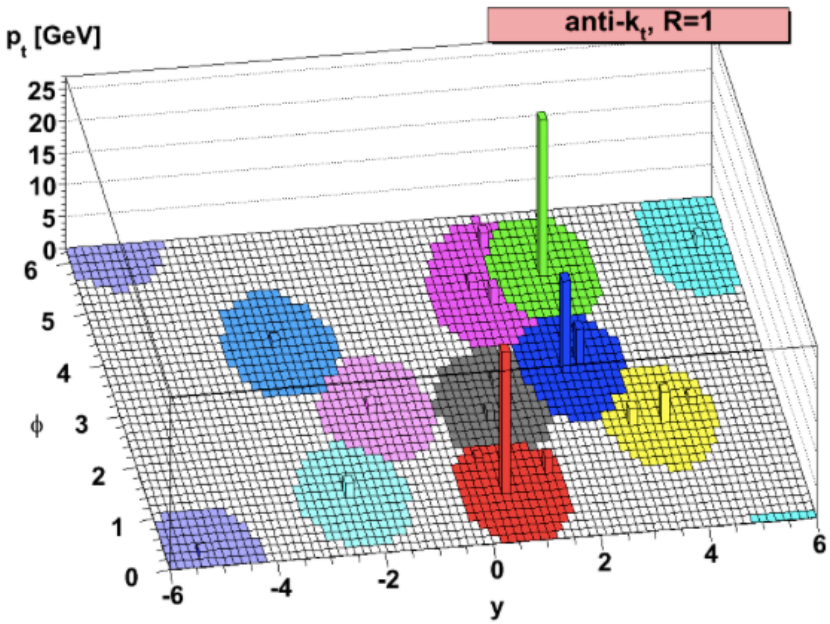


or



Need to ***define*** jet in experiment ***and*** theory

A jet is what *Cacciari, Salam & Soyez* say it is



2008: Fastjet revolution

Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

"anti-kT" replaced zoo of prior algorithms:

- conceptually simple
- theoretically sound
  - infrared safe
  - collinear safe
- computationally efficient & robust
- part of Fastjet package

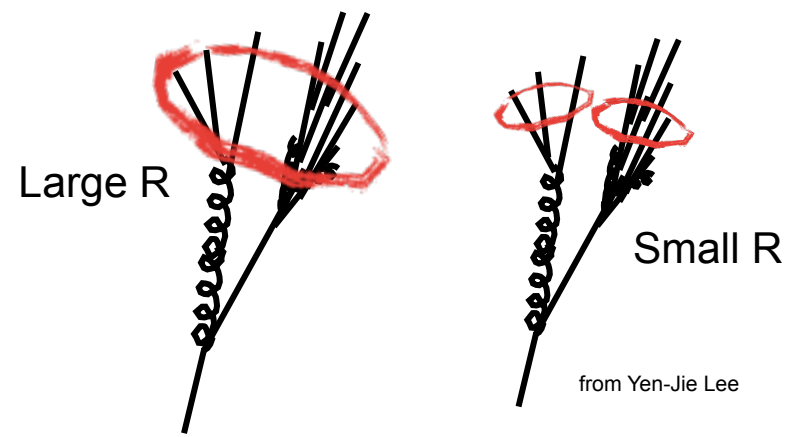
Anti-k_T:

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

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

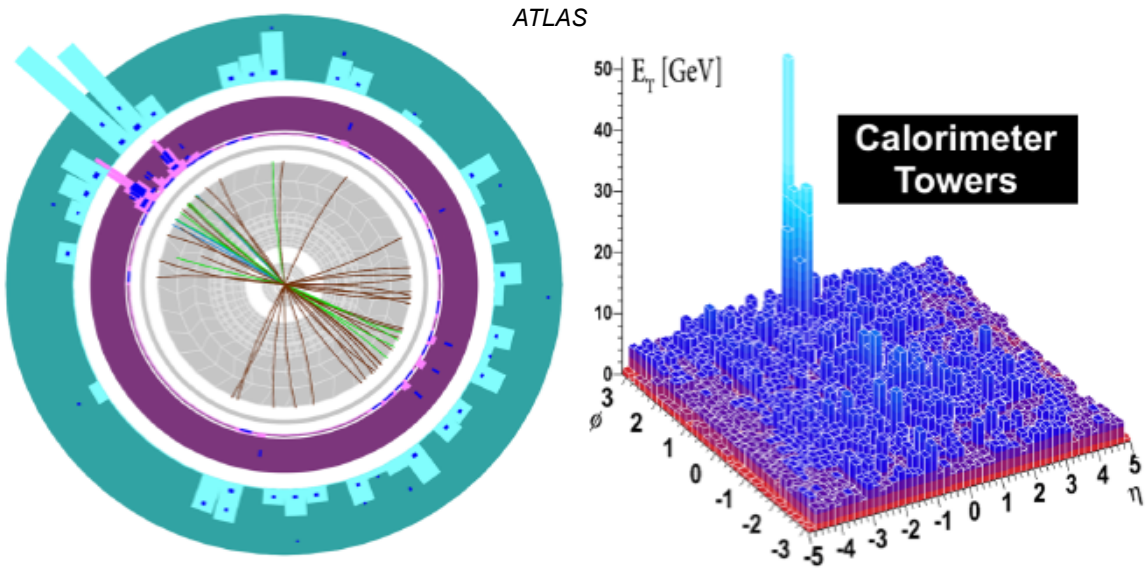
$$d_{iB} = k_{ti}^{2p}, \quad \boxed{p=-1}$$

Results in cone-shaped, approximately R-sized jets



Which jets are found depends on anti-k_T resolution parameter

Jet and Underlying Event



Jets in heavy-ion collisions sit on top of large *underlying event (UE)*
Need to decide which particles are part of jet and which belong to UE:
UE subtraction

Current methods assume that local UE (under jet) is the same as elsewhere in the event
I.e., UE modification due to jet would manifest as modification of observed jet

Efficiency, resolution and biases

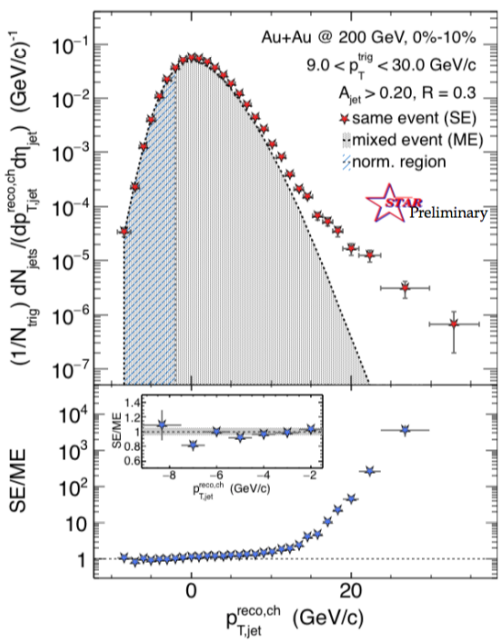
Achieved good experimental control

- Reconstruction efficiency (close to 100%@50+ GeV)
- Jet energy scale (2-4% above 30 GeV)
- Resolution and UE fluctuations (~15%@100GeV)

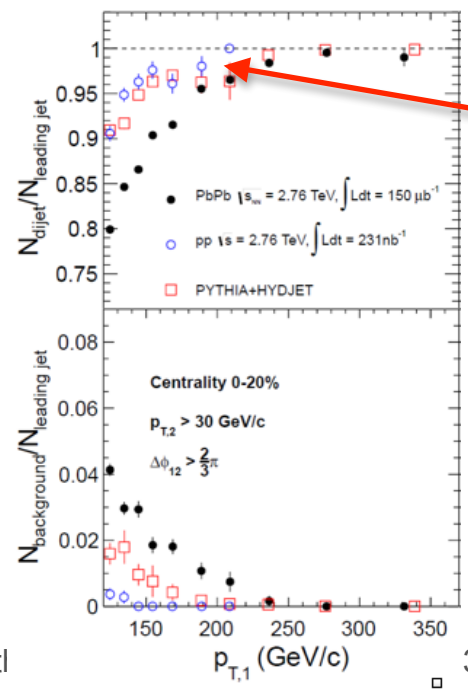
} **This was not obvious a-priori; success enabled by nature of observed jet modifications**

How do we avoid biasing measurement towards unmodified jets?

STAR, ALICE: Accept all jet candidates down to lowest p_T, remove "fake" jets statistically using mixed events

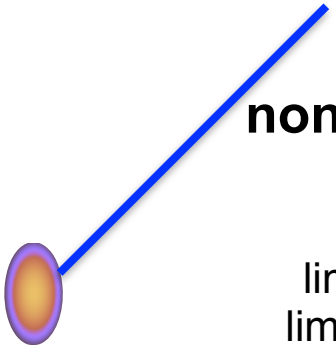


ATLAS, CMS: Study high p_T jets such that efficiency, JES well controlled even for modified jets

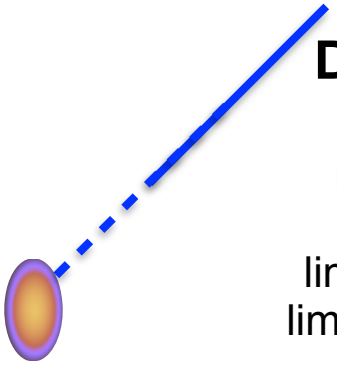


For sufficiently high "trigger jet" p_T, **all** away-side jets found

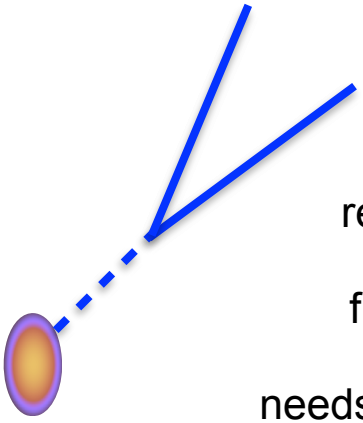
Detecting Open Heavy Flavor (hadrons)



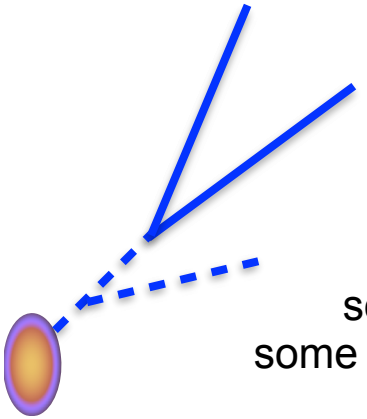
non-photonic electrons
c+b
requires electron ID
limited info on kinematics
limited constraints on bkg's



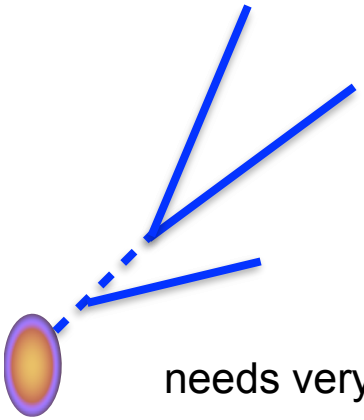
Displaced leptons
c+b (c vs b)
requires VTX detector
requires lepton ID
limited info on kinematics
limited constraints on bkg's



D mesons
c
requires VTX detector
hadron PID helps
full charm kinematics
clear mass peak
needs high statistics data (BR)



non-prompt J/ψ
b
requires VTX detector
requires lepton ID
some bottom kinematics
some constraints on backgrounds

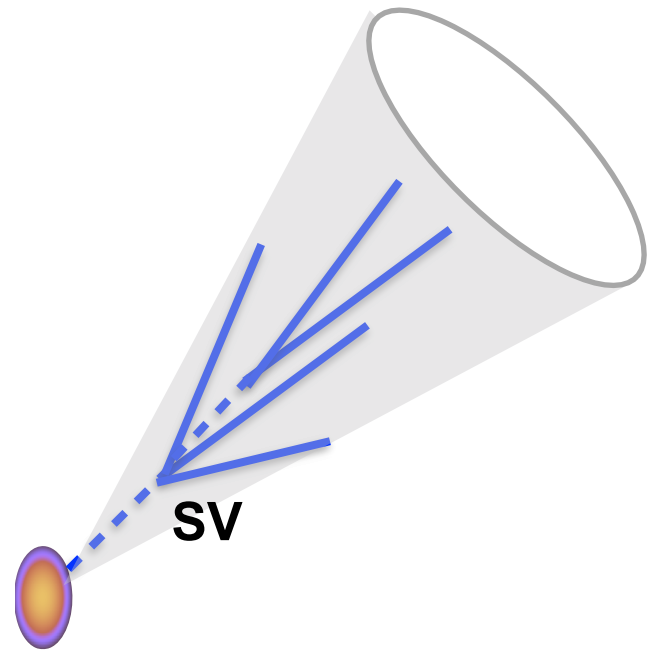


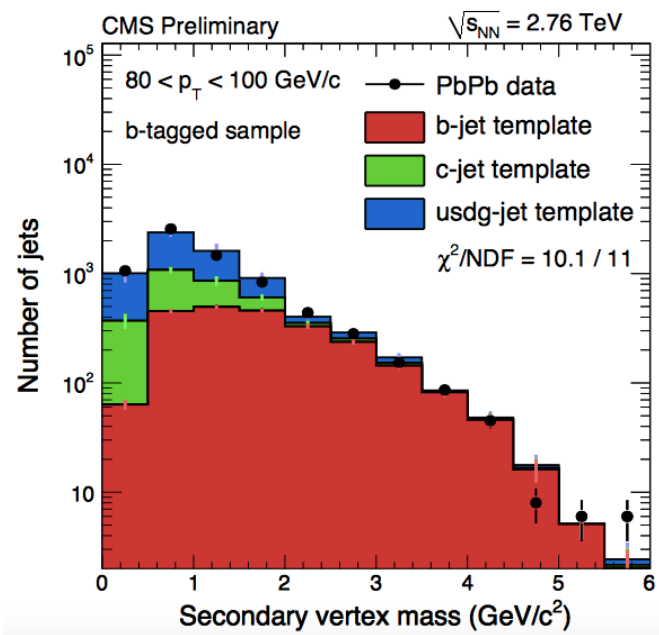
B mesons
b
requires VTX detector
requires lepton ID
full bottom kinematics
clear mass peak
needs very high statistics, acceptance (BR)

Detecting Open Heavy Flavor (jets)

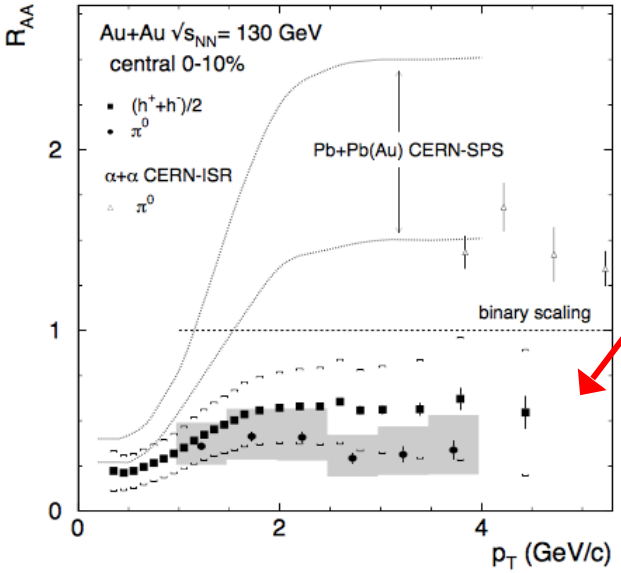
Heavy-flavor tagging

- Reconstruct jets as per usual
- Build taggers to discriminate light and b(c) jets
- Based on secondary vertex properties:
  - Flight distance significance
  - Secondary vertex mass
  - Secondary vertex track multiplicity
  - Track impact parameter at primary vertex
  - …
- Use orthogonal taggers to estimate efficiency, purity from data
- Extract b(c)-jet fraction vs p_T etc by fitting MC derived templates





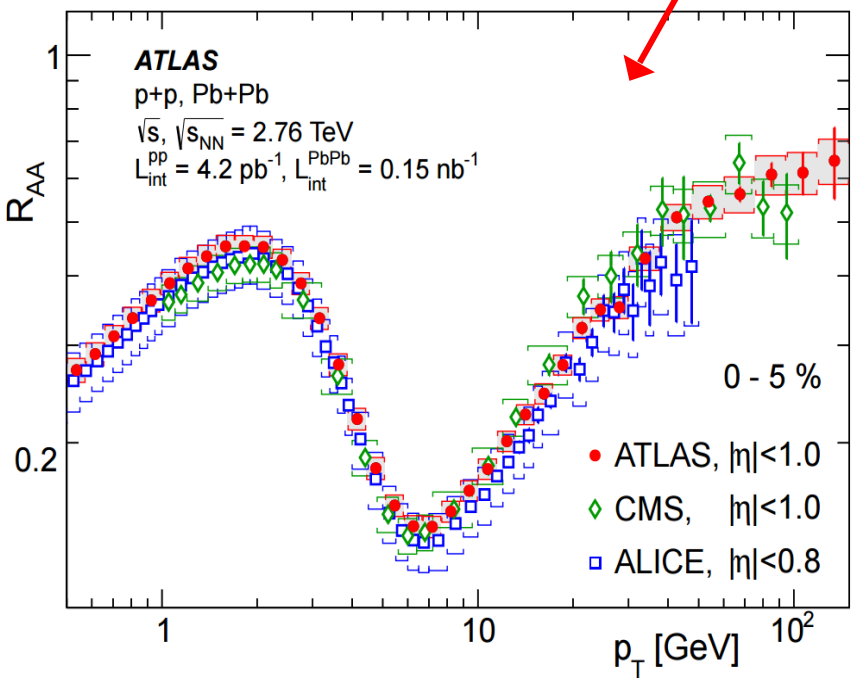
Charged Hadron R_{AA}

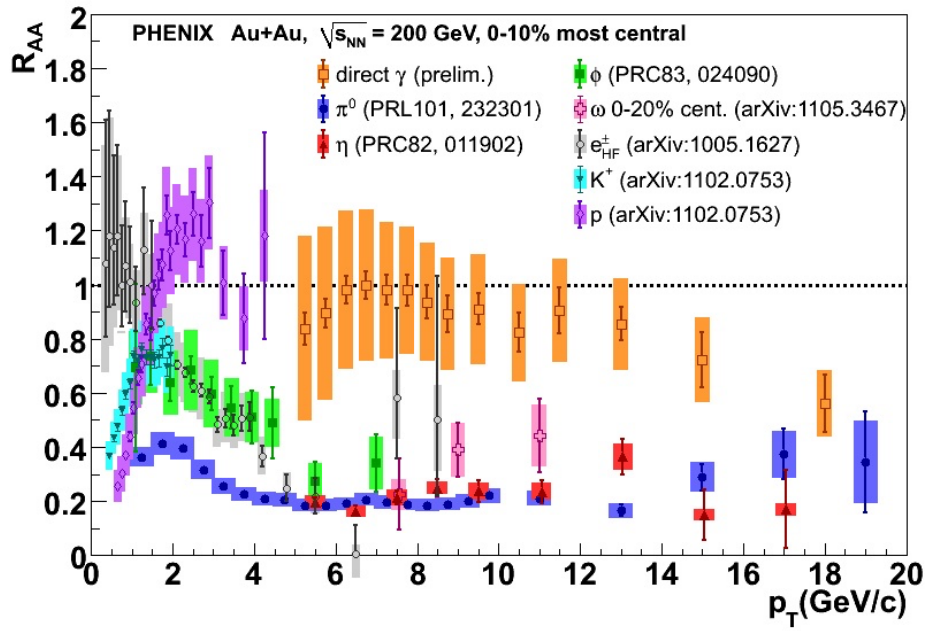


This is how it started in 2001

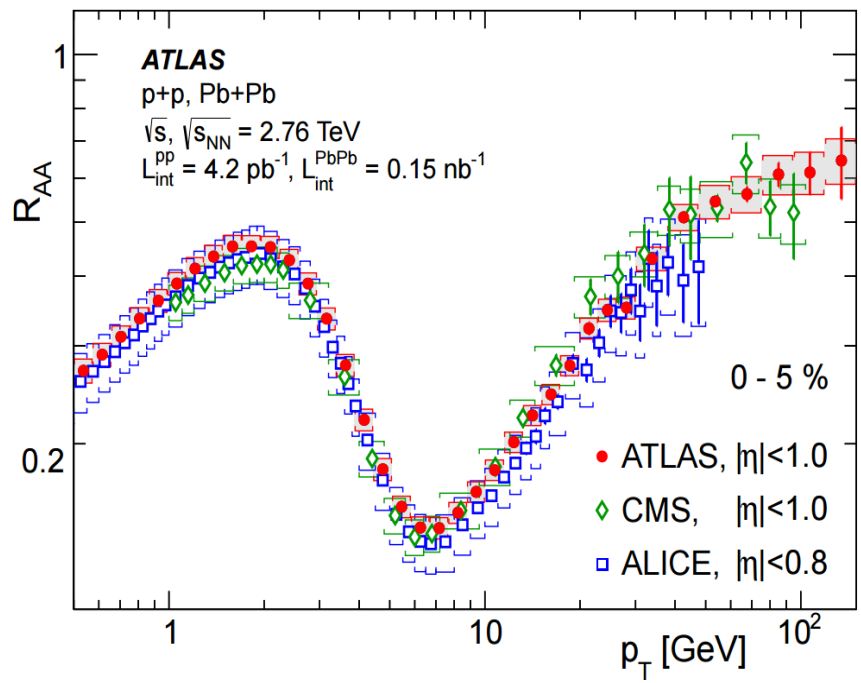
Today: High precision data from all RHIC and LHC experiments (out to 150 GeV

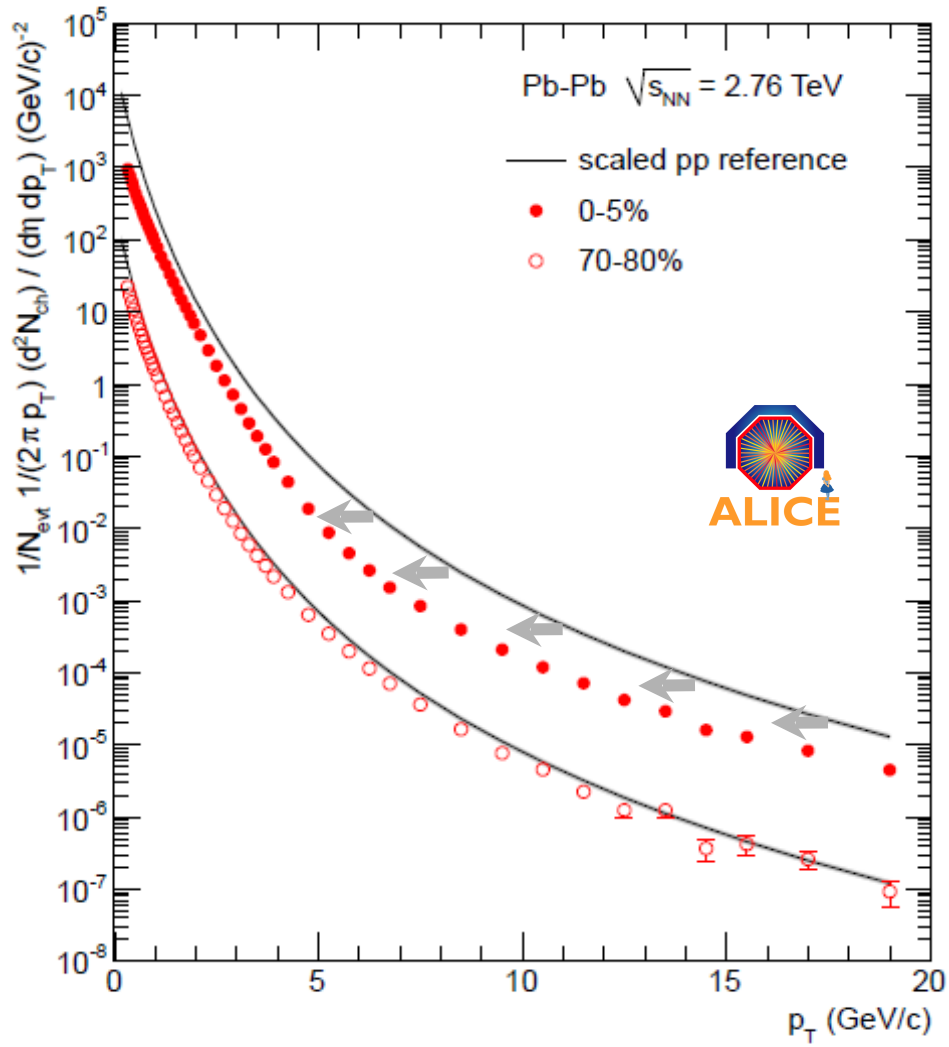
- n.b.: A deceptively difficult measurement, as very high p_T corrections (efficiency, fakes) rely on MC
- Calorimetric jet trigger can provide fake rejection





R_{AA} Mechanics

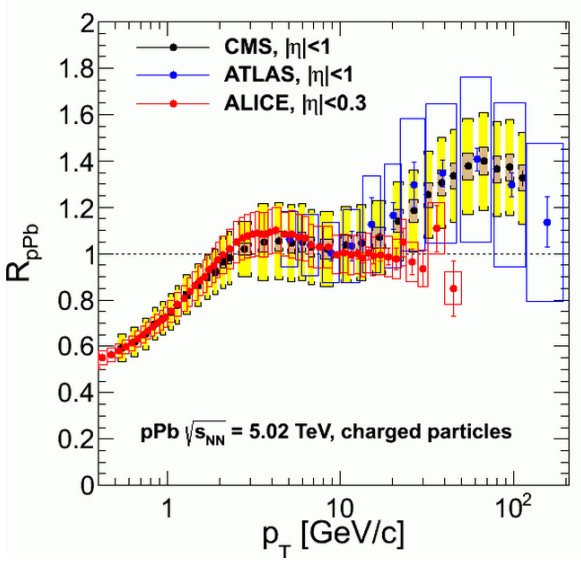


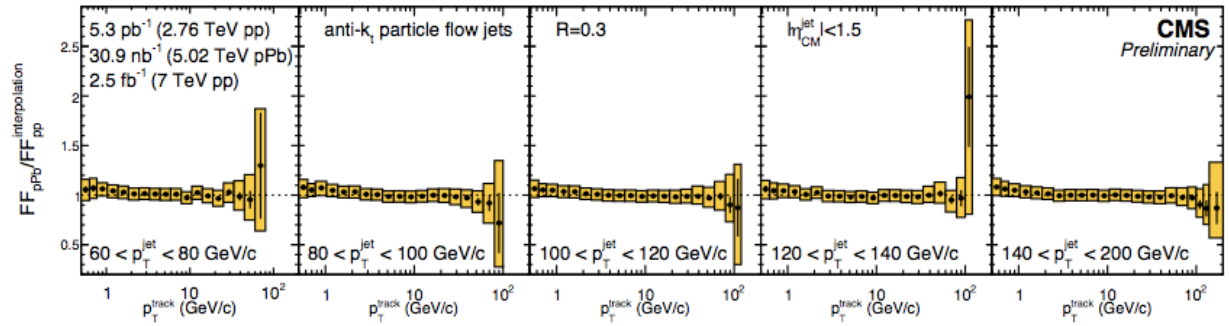


Shape and magnitude of R_{AA} depend on local "hardness" (slope) of spectrum

Harder spectrum → R_{AA} closer to 1

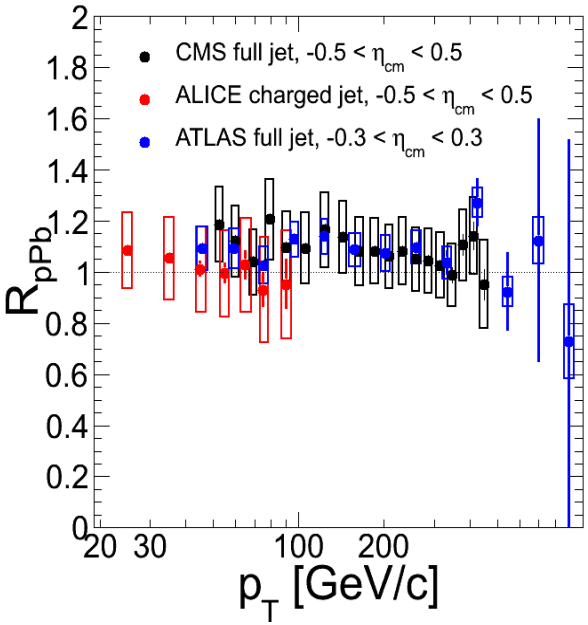
My Opinion on Charged Hadron R_{pPb}





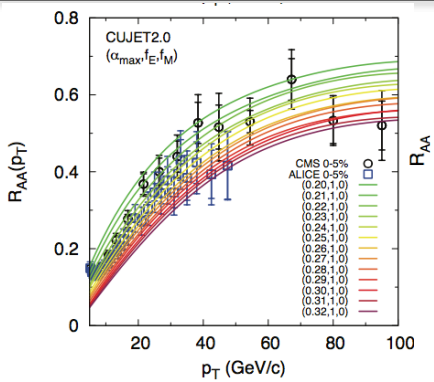
pPb jet spectra, hadron spectra and jet FF are internally consistent

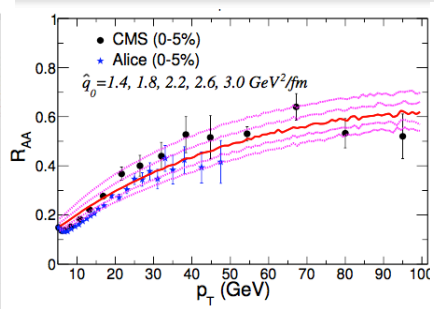
Tension in interpolated "pp" references

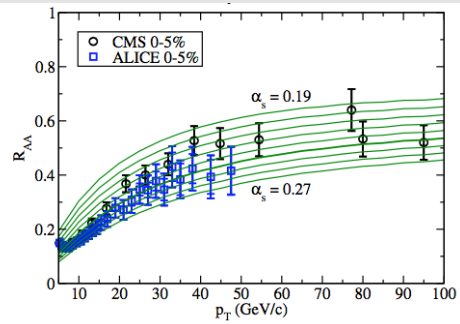


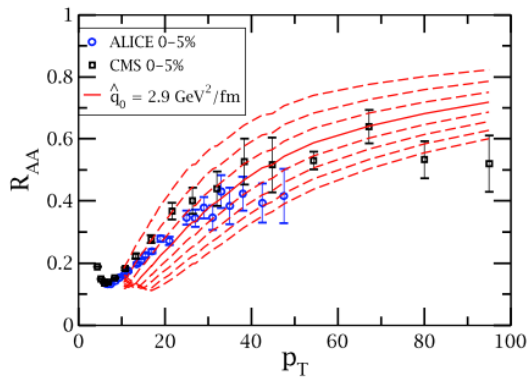
NEVER skip taking high quality reference data for any physics topic you actually care about

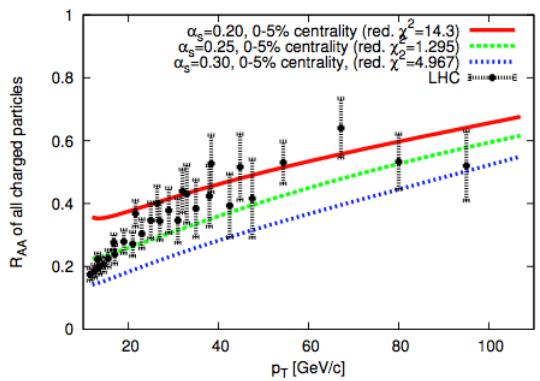
Extracting QGP transport coefficients

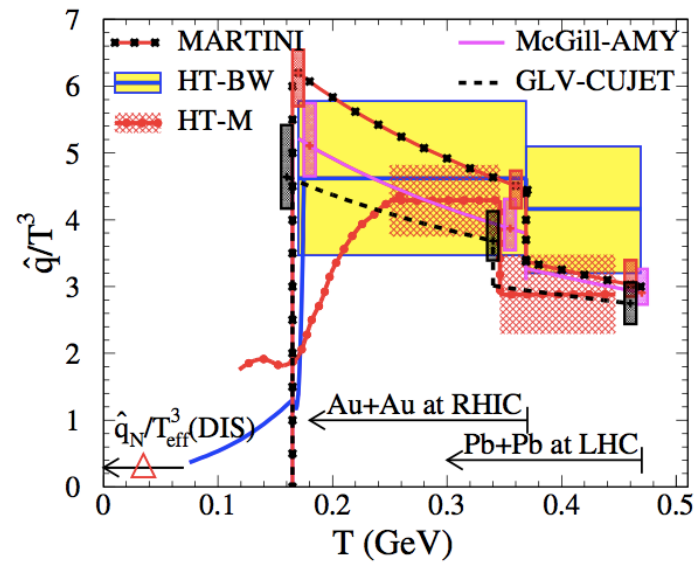












$\hat{q}$ determined with about 35% uncertainty

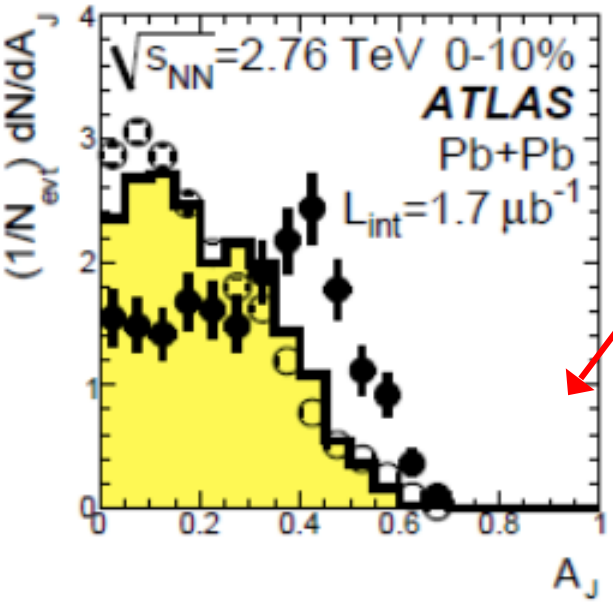
Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

Systematic multi-model, multi-experiment comparison: Need more!

Quantitative extraction of $\hat{e}$ awaits more precise heavy flavor data

Jet Physics with Jets: Dijet Asymmetry



This is how it started in 2010

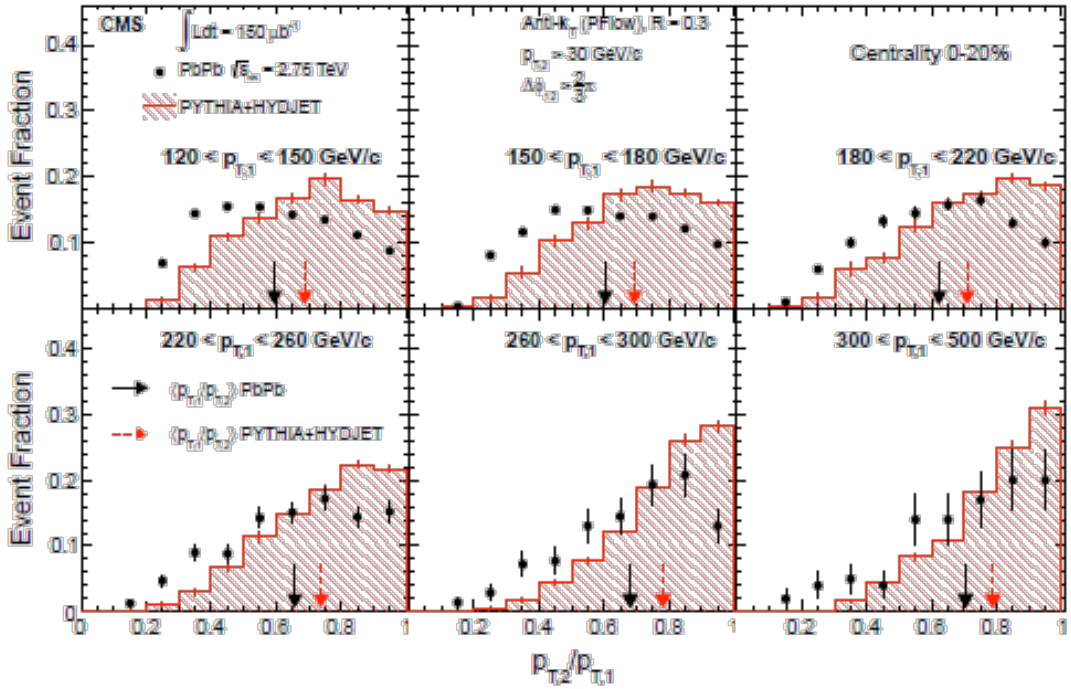
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

<Aj> carries similar information as hadron R_{AA}

But: Wider range of theoretical tools for hadron R_{AA}

Jet quenching persists for p_T >300GeV jets

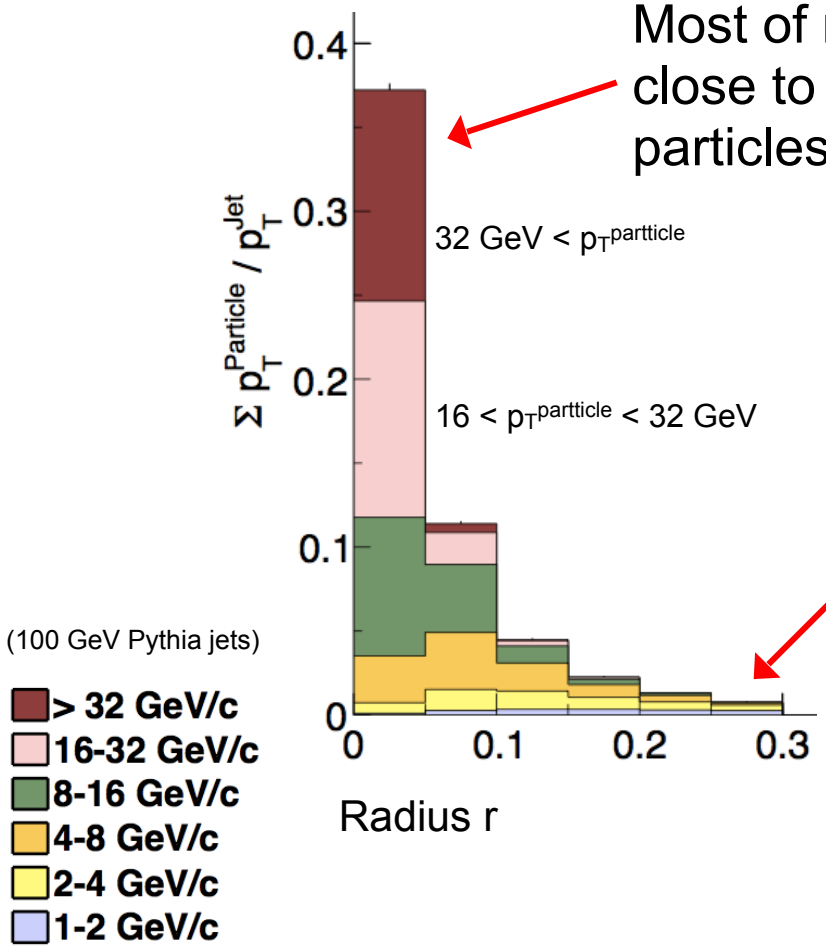
Many other measurements: Jet R_{AA}, Jet v_2,...



Jet Anatomy

Jets are extended objects with momentum and angular structure

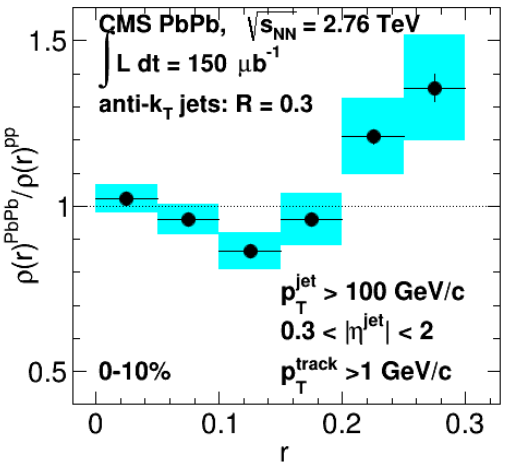
Most of momentum found close to jet axis in high p_T particles (p_T > O(10GeV))



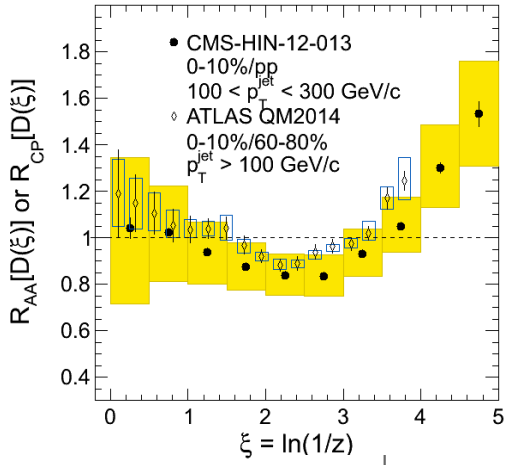
Large angle component of jet contains small fraction of jet p_T in soft particles (p_T ~ O(1GeV))

Jet Anatomy: Many observables

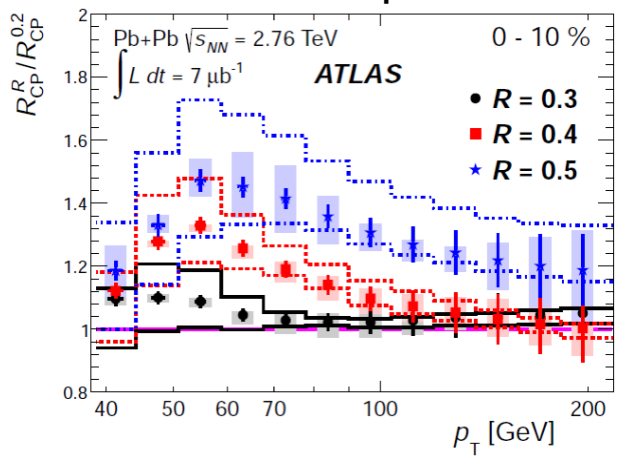
Jet shapes

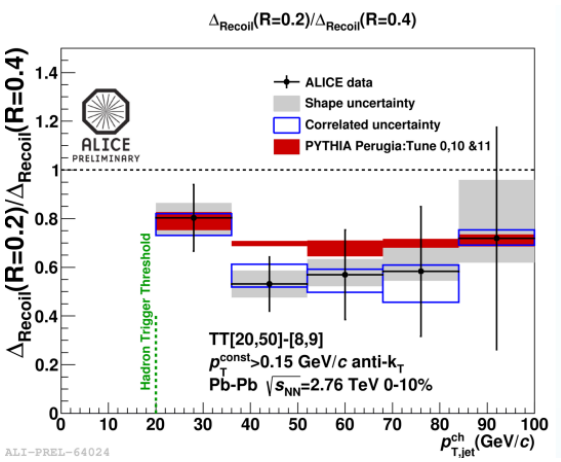


Fragmentation functions
wrt final state energy

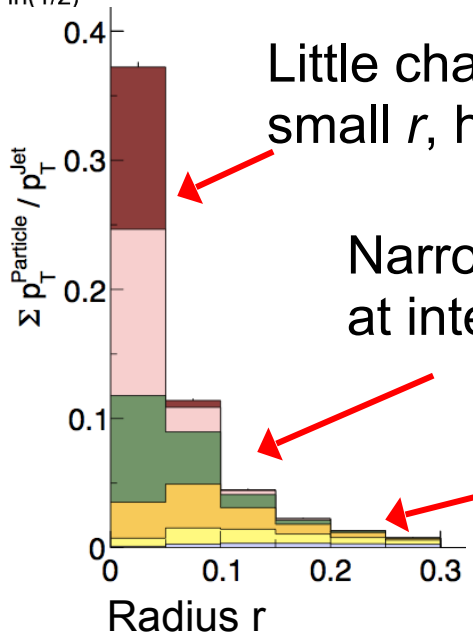


R_{AA} radius dependence





Δ_{Recoil} radius dependence



Little change at small *r*, high p_T

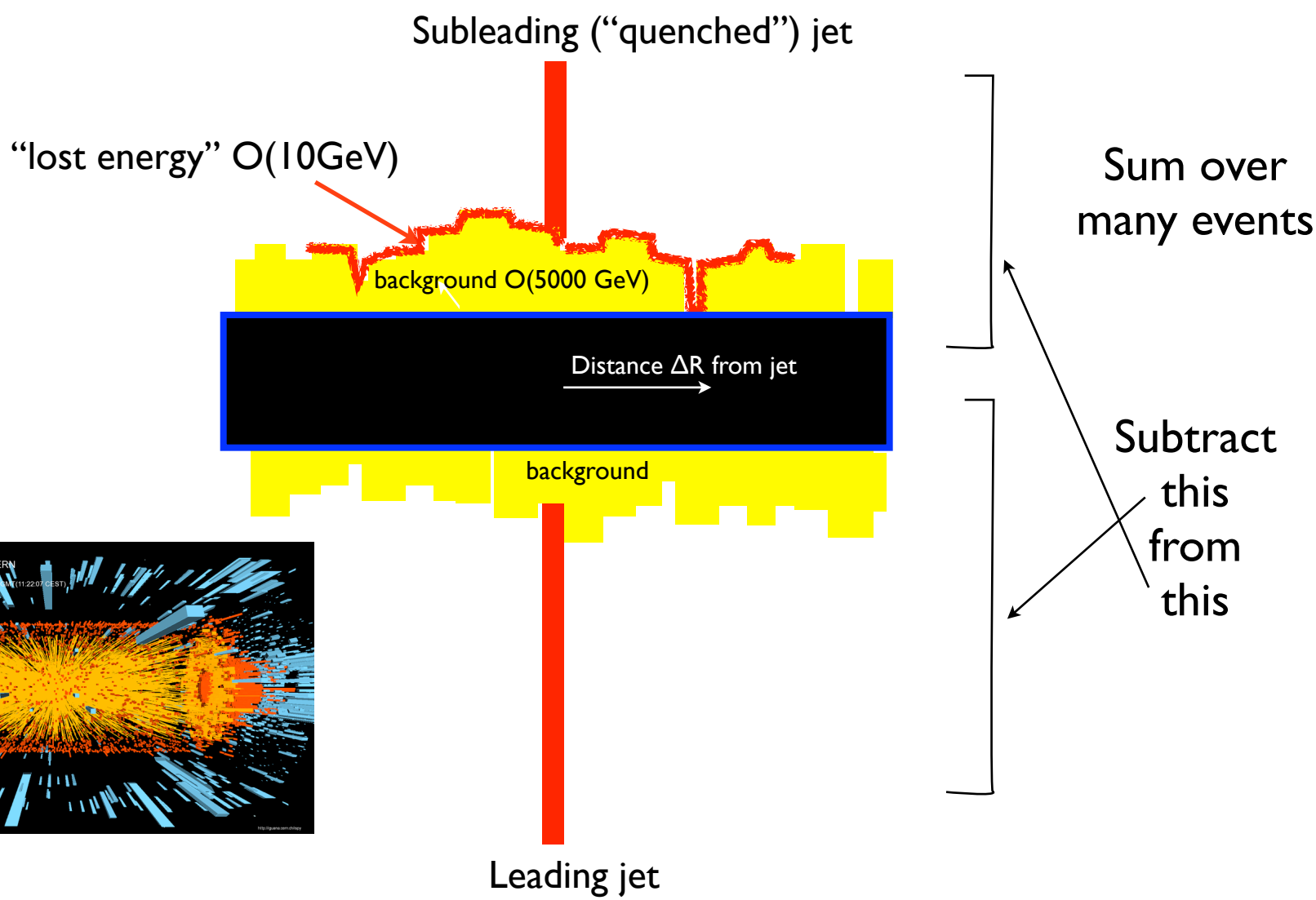
Narrowing/depletion at intermediate *r*, p_T

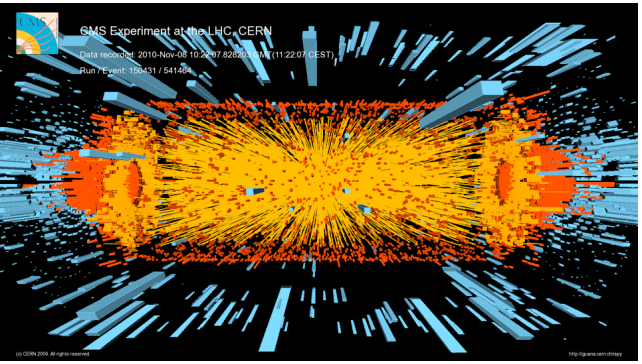
Broadening/excess at large *r*, low p_T

(~2% of jet energy)

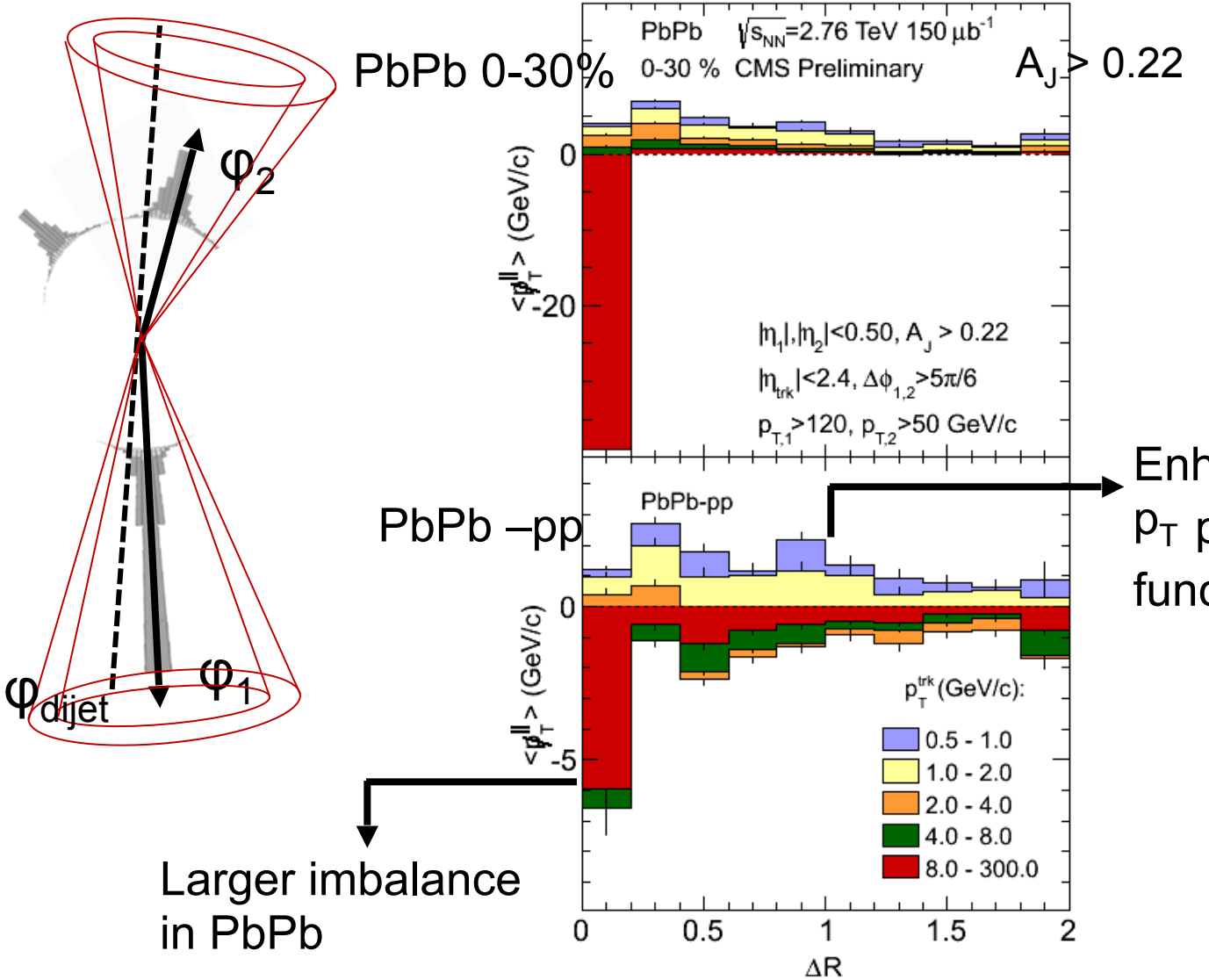
Where is the "lost energy"?

Use momentum-conservation to study momentum balance in the event: "Missing p_T" $\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$





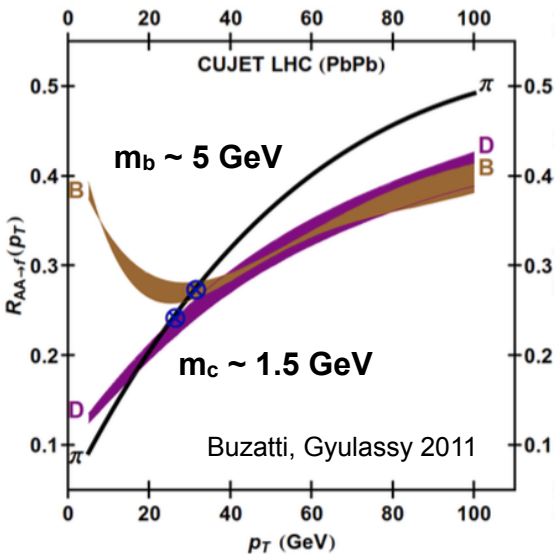
"Lost energy" recovered at large angle, low p_T

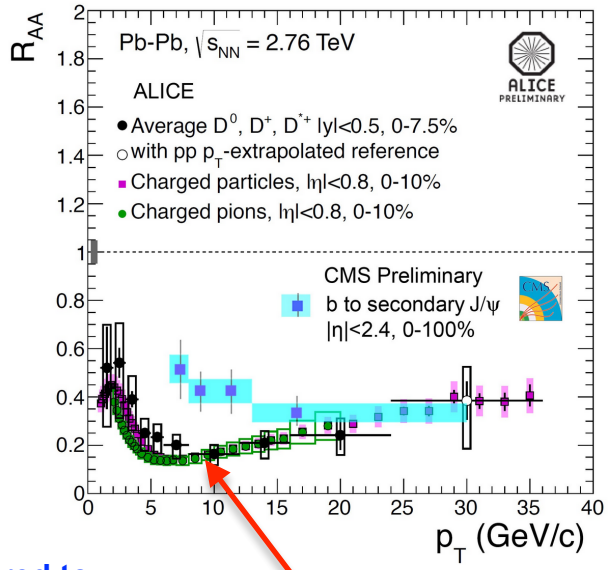


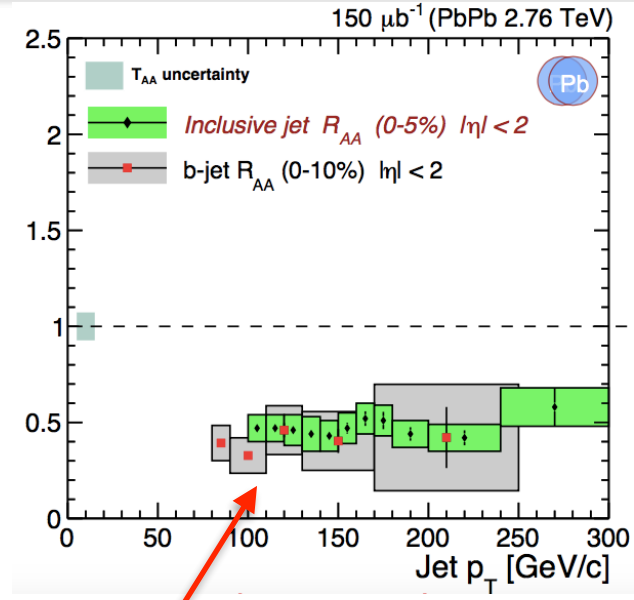
Enhancement of low p_T particles as a function of ΔR

Larger imbalance in PbPb

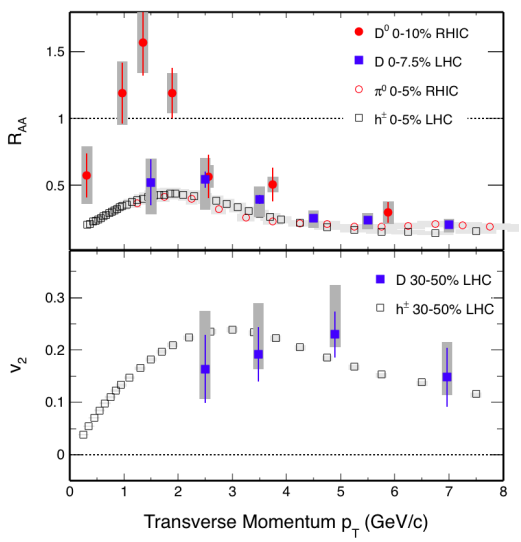
Flavors of Energy Loss







n.b: s quarks are not "heavy" compared to typical QCD/QGP momentum scales

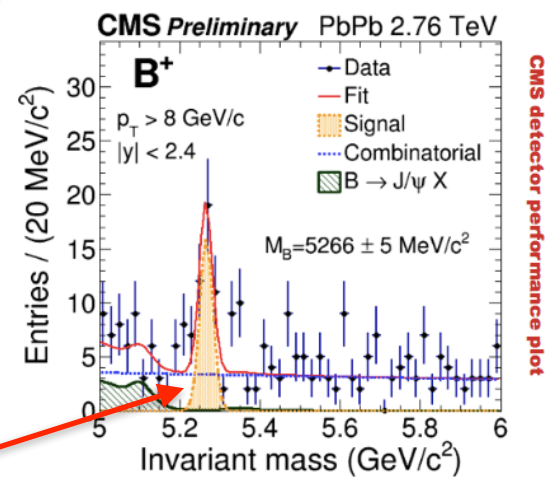


Qualitative agreement with expectation:

- Mass ordering at low p_T
- R_{AA}(b) ~ R_{AA}(light) at high p_T

Much more to come this week from RHIC and LHC

First signal of fully reconstructed B meson decays in PbPb collisions



B^+ invariant mass spectrum in Run 1 (2011) PbPb data.

LHC Run 2: fully reconstructed B mesons

What will the future hold?

Understanding the *nature* of QGP

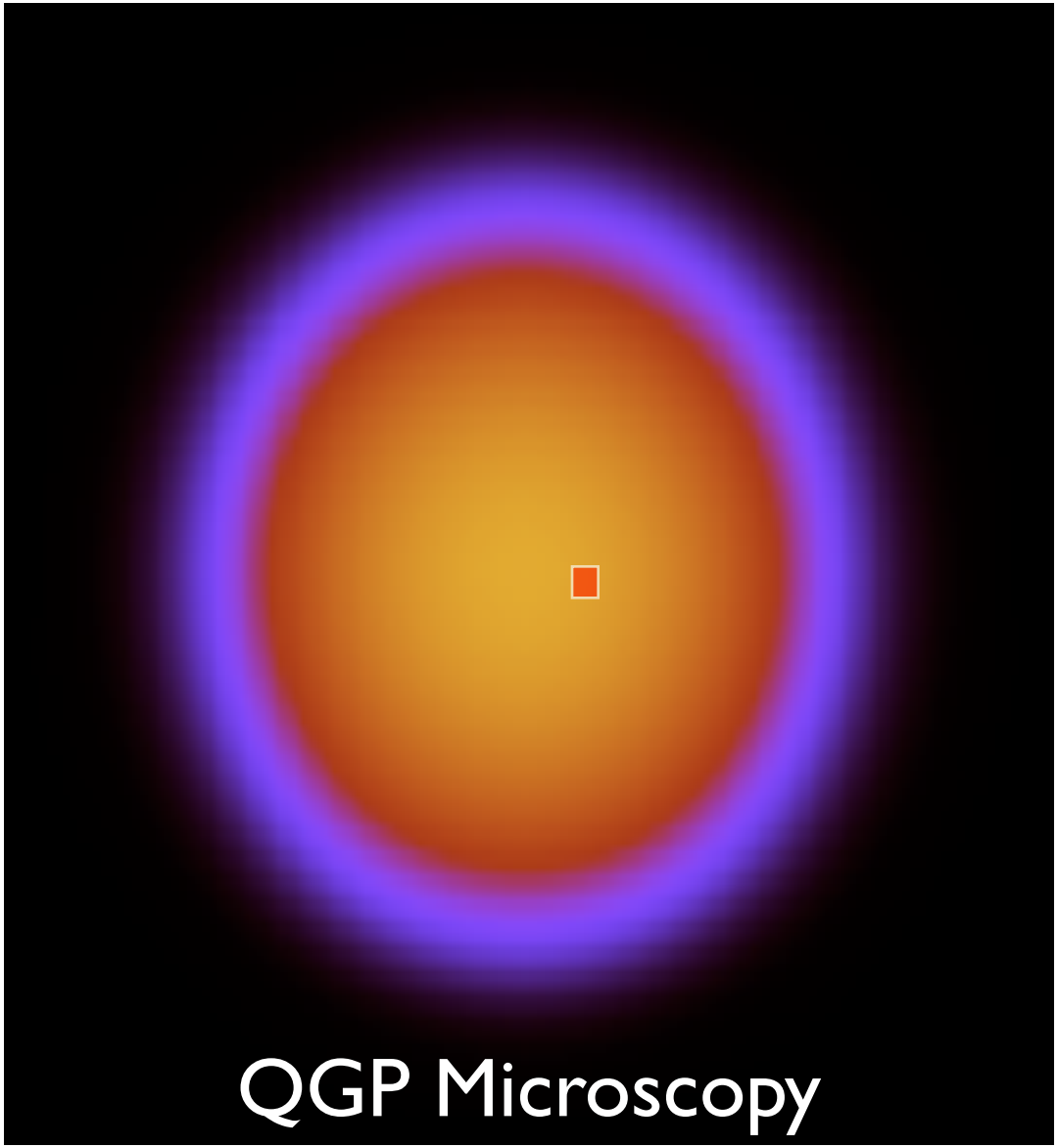
Recommendation #1:

The discoveries of the past decade have posed or sharpened questions that are central to understanding the nature, structure, and origin of the hottest liquid form of matter that the universe has ever seen. As our highest priority we recommend a program to complete the search for the critical point in the QCD phase diagram and to exploit the newly realized potential of exploring the QGPs structure at multiple length scales with jets at RHIC and LHC energies.

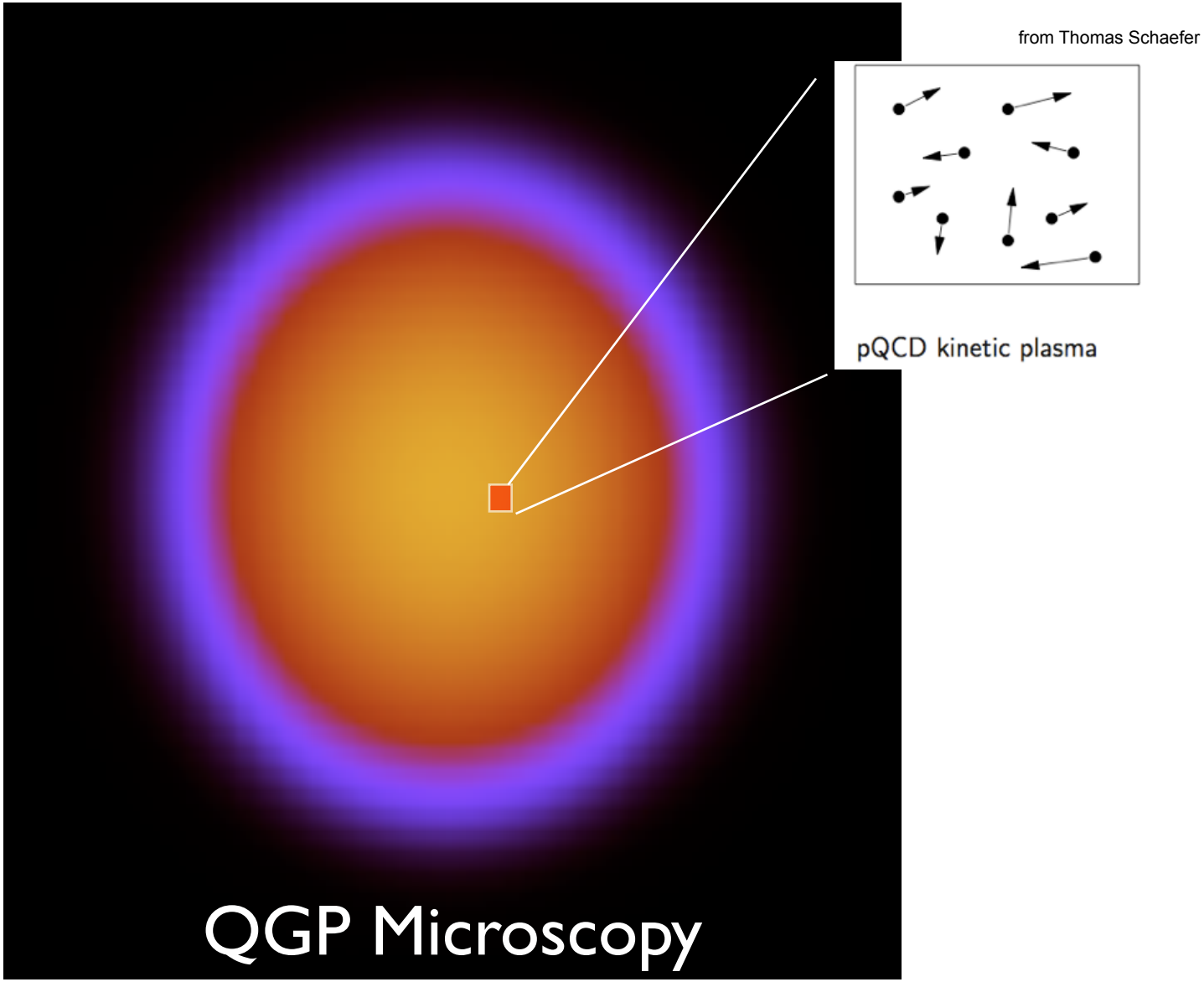
from 2014 Hot QCD White Paper (arXiv:1502.02730)
Part of the US nuclear physics long range planning process
(btw, this might not be a bad read for new grad students)

Understanding the *nature* of QGP

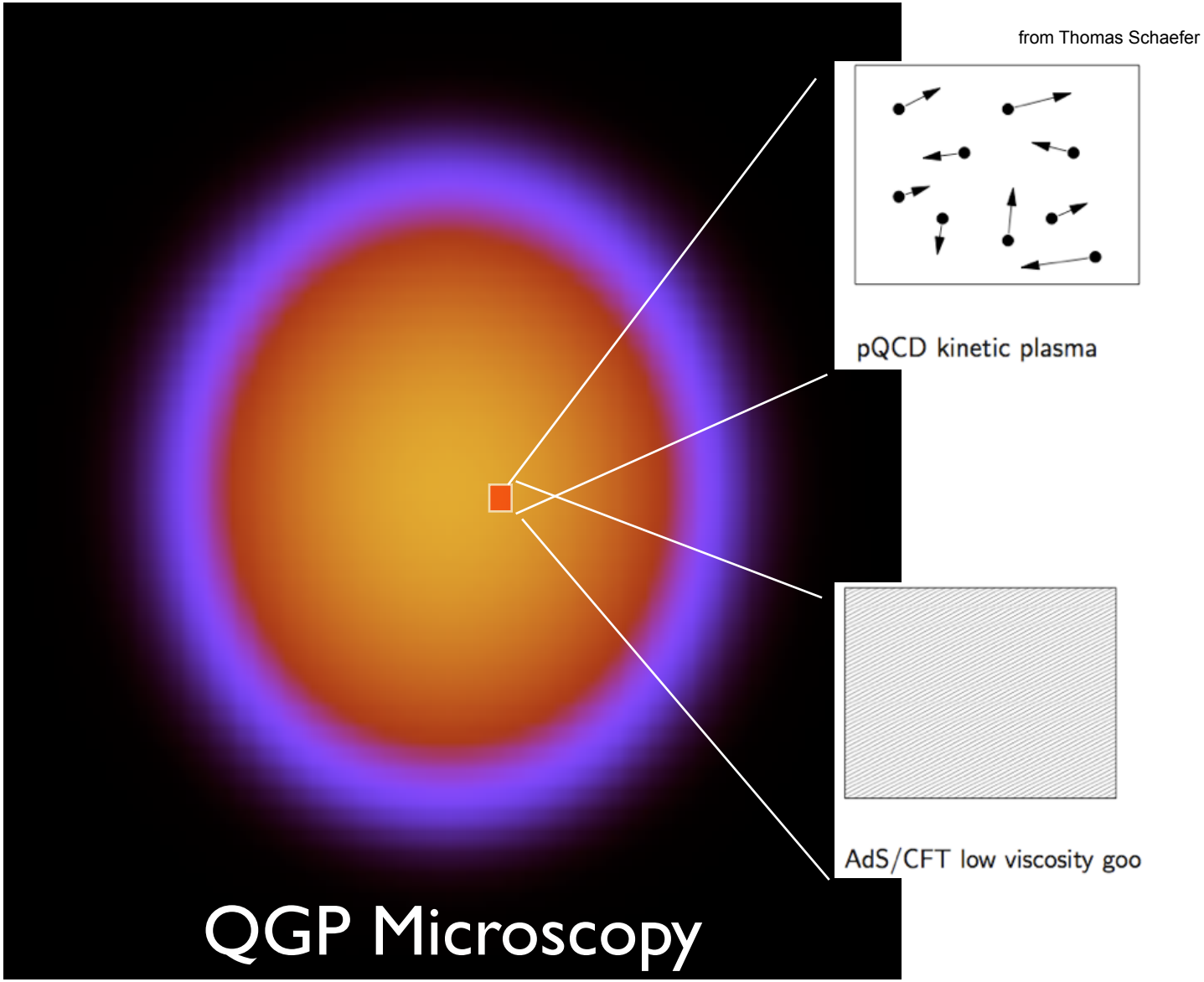
from Thomas Schaefer



Understanding the *nature* of QGP

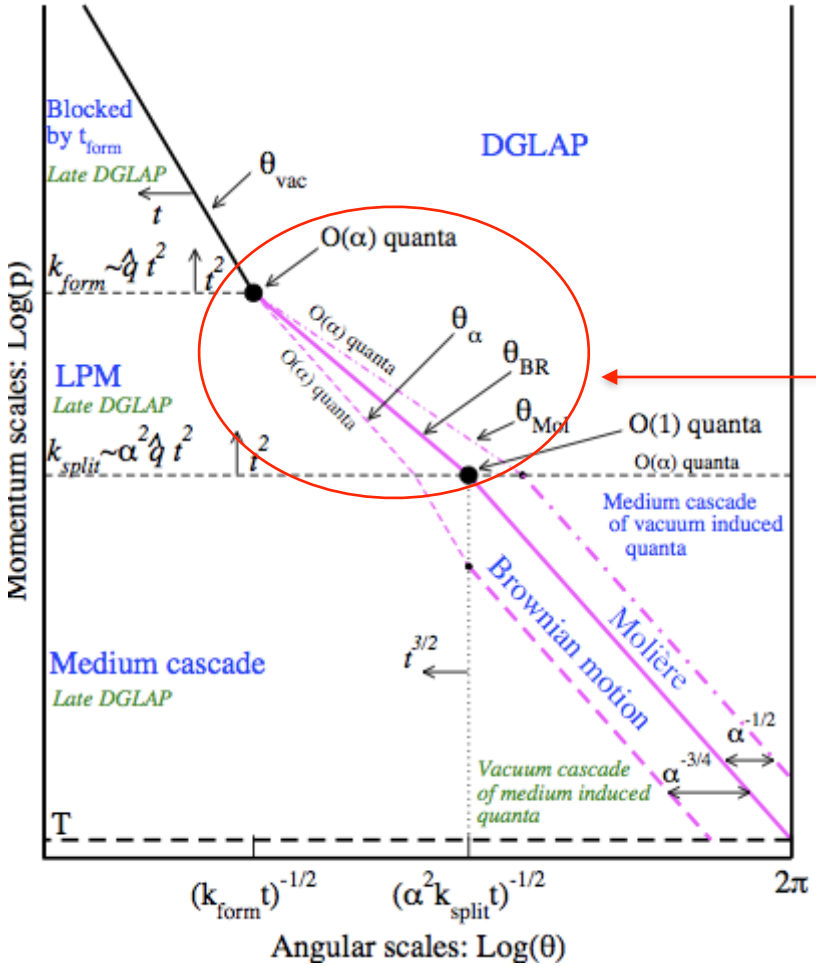


Understanding the *nature* of QGP



Jets as multi-scale probe

Angular and momentum structure
of intra-jet parton cascade



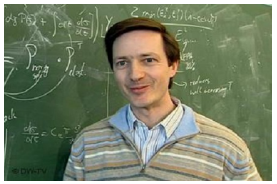
Jets evolve in momentum and angular space

At different scales, evolution is dominated by different mechanisms:

- vacuum evolution
- (jet-constituent)-medium scattering
- in-medium cascade

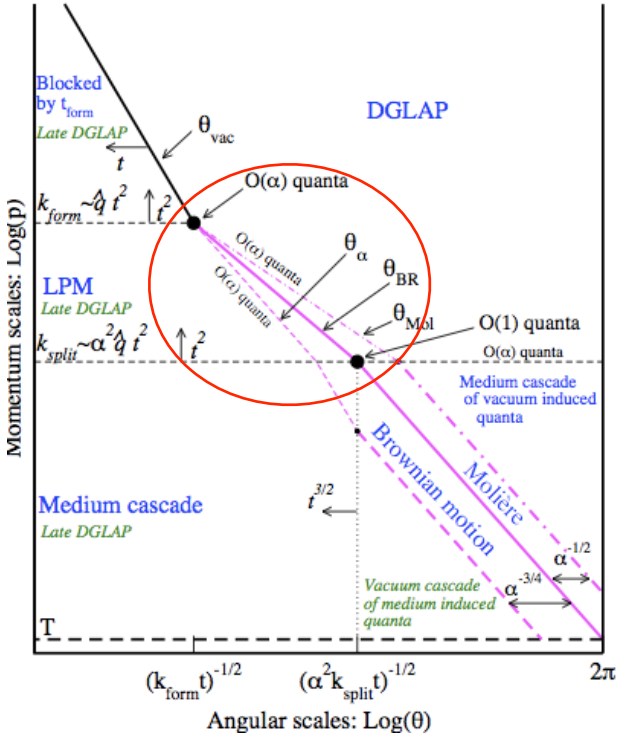
Detailed understanding of jet modifications on all scales may allow to isolate interactions with "QGP quasiparticles"

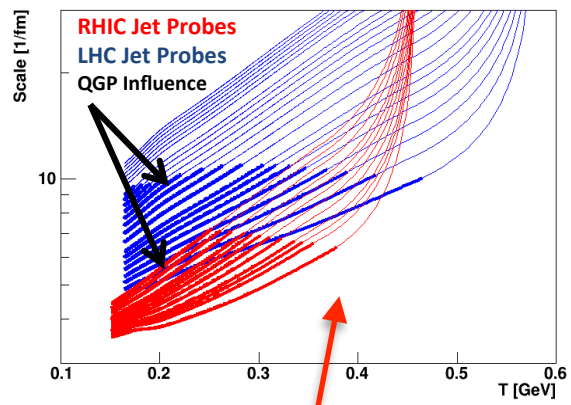
Please forward detailed questions to this guy

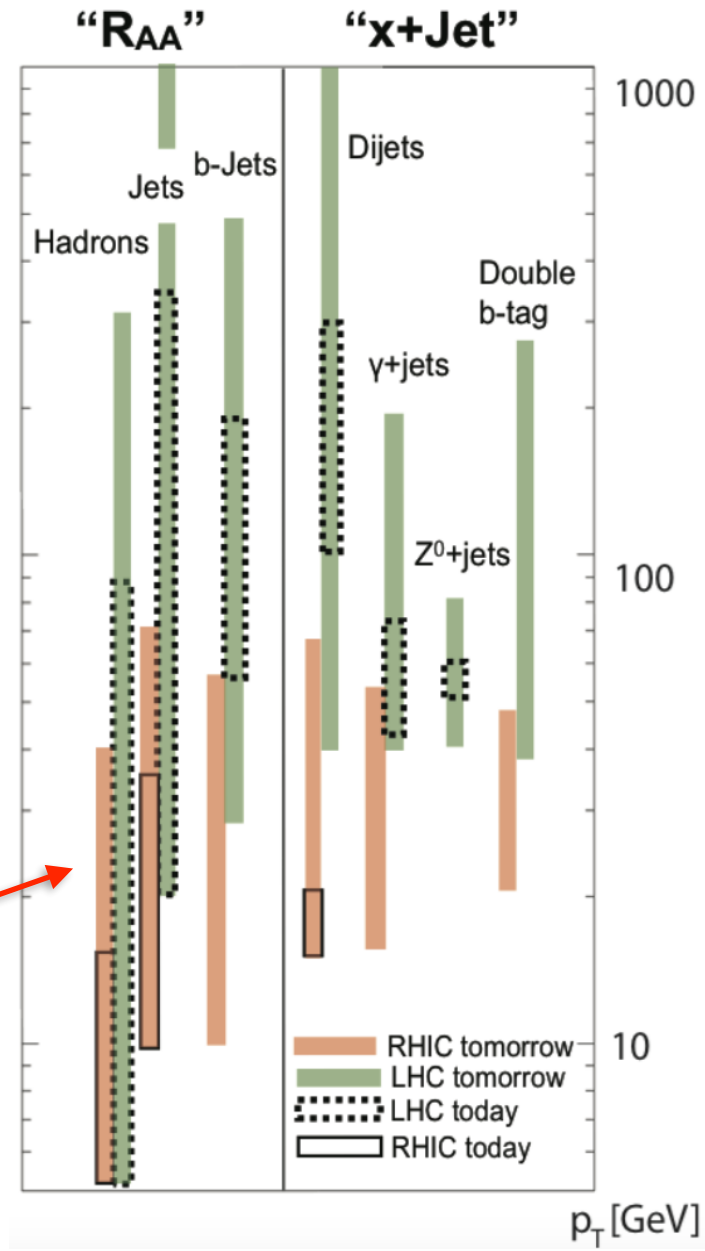


Kurkela, Wiedemann, arXiv:1407.0293

Force Multiplier: Jets at RHIC **and** LHC





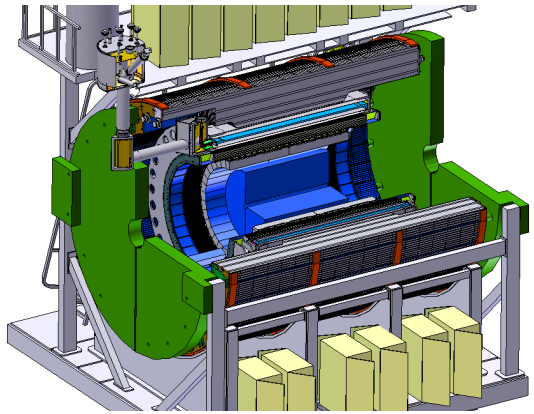


Future RHIC vs LHC Run 2:

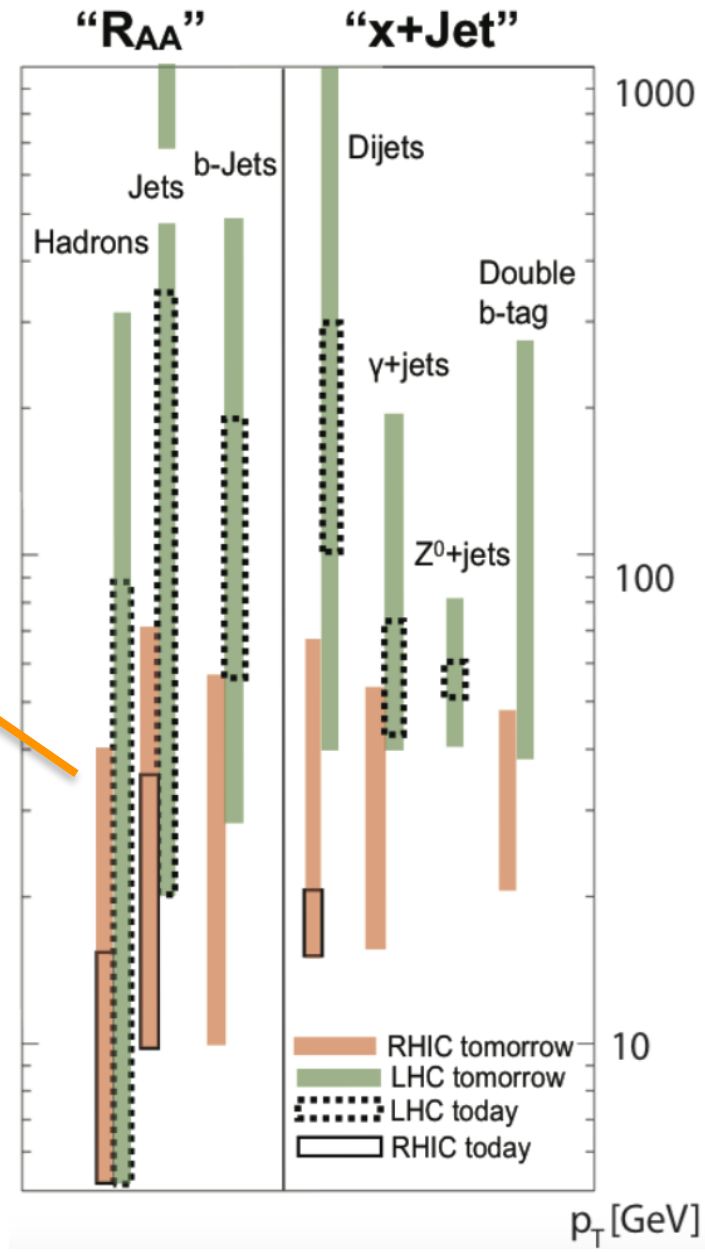
- Probe different paths of QGP evolution
- Overlap in observables/kinematics

Isolate this

Force Multiplier: Jets at RHIC **and** LHC



sPHENIX
(early 2020's)



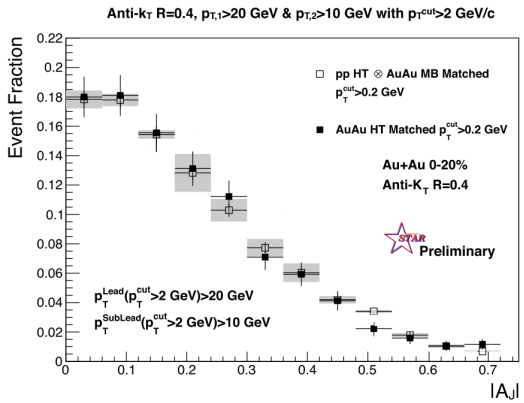
LHC Run 1 LHC Run 2

	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	$\sim$ 10M
b-jet ($p_T > 120$ GeV/c)	~ 500	$\sim$ 140k
Isolated γ ($p_T^\gamma > 60$ GeV/c)	$\sim$ 1.5k	$\sim$ 300k
Isolated γ ($p_T^\gamma > 120$ GeV/c)	–	$\sim$ 10k
W ($p_T^W > 50$ GeV/c)	~ 350	$\sim$ 70k
Z ($p_T^Z > 50$ GeV/c)	~ 35	$\sim$ 7k

What could be done with **dijets in LHC Run 1** will be done with **photon-jet in LHC Run 2**

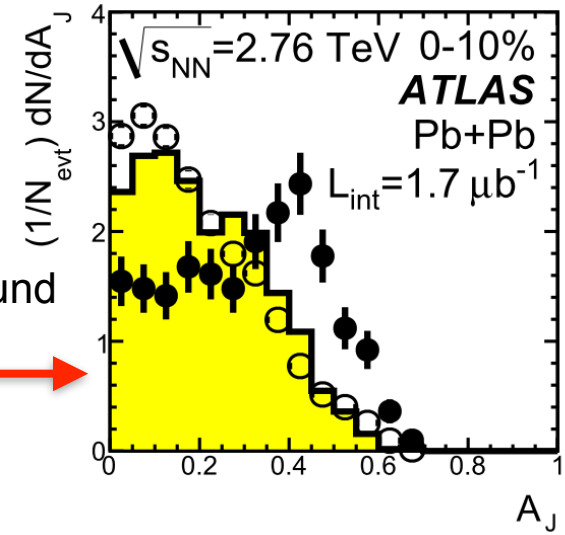
Indication of energy flow differences at RHIC vs LHC

RHIC (STAR)

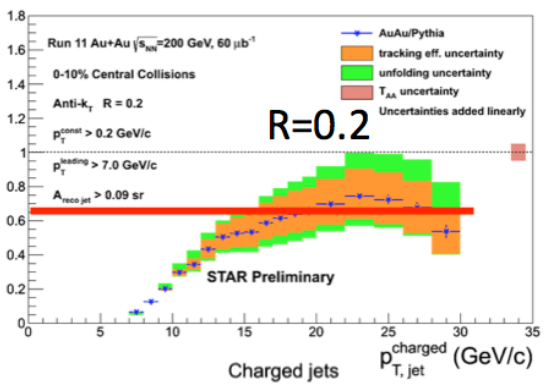


Jets balanced when including p_T > 0.2GeV

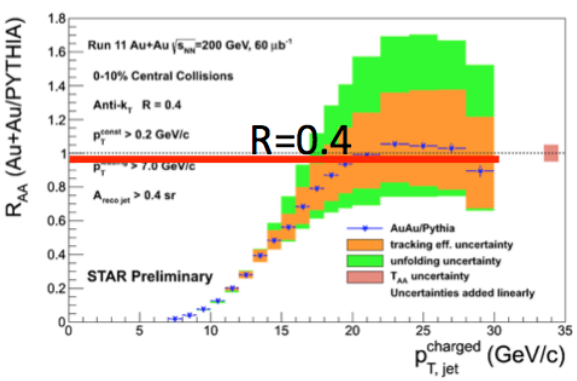
LHC (ALICE, ATLAS, CMS)



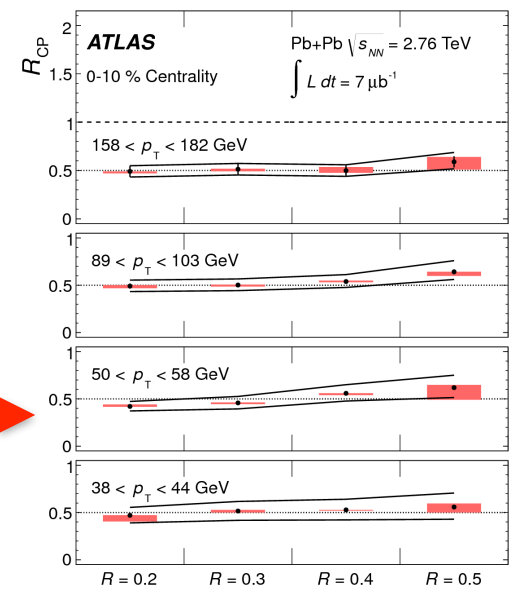
Energy balance found outside of jet cone



Strong radius dependence of jet RAA

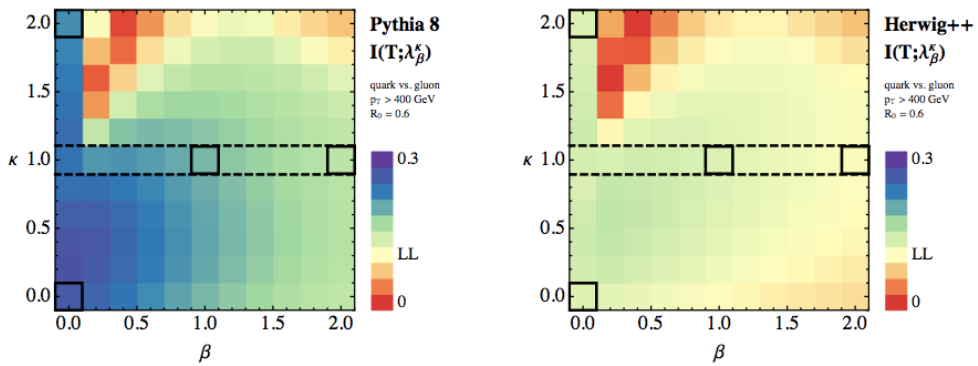


Weak radius dependence of jet RAA



Jet structure in pp and PbPb

Jesse Thaler, Boost 2014



$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

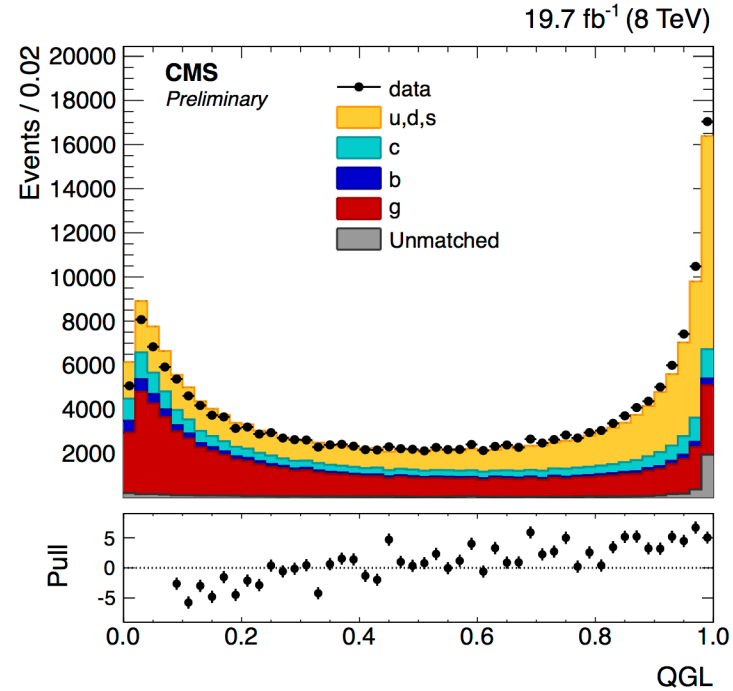
angle to recoil-free axis

Jet structure variables sensitive to (in-medium) shower evolution

Critical effort in pp highest sensitivity searches
(q/g and boosted object discrimination)

Stability vs pp pileup is major issue

Convergence of AA and pp needs

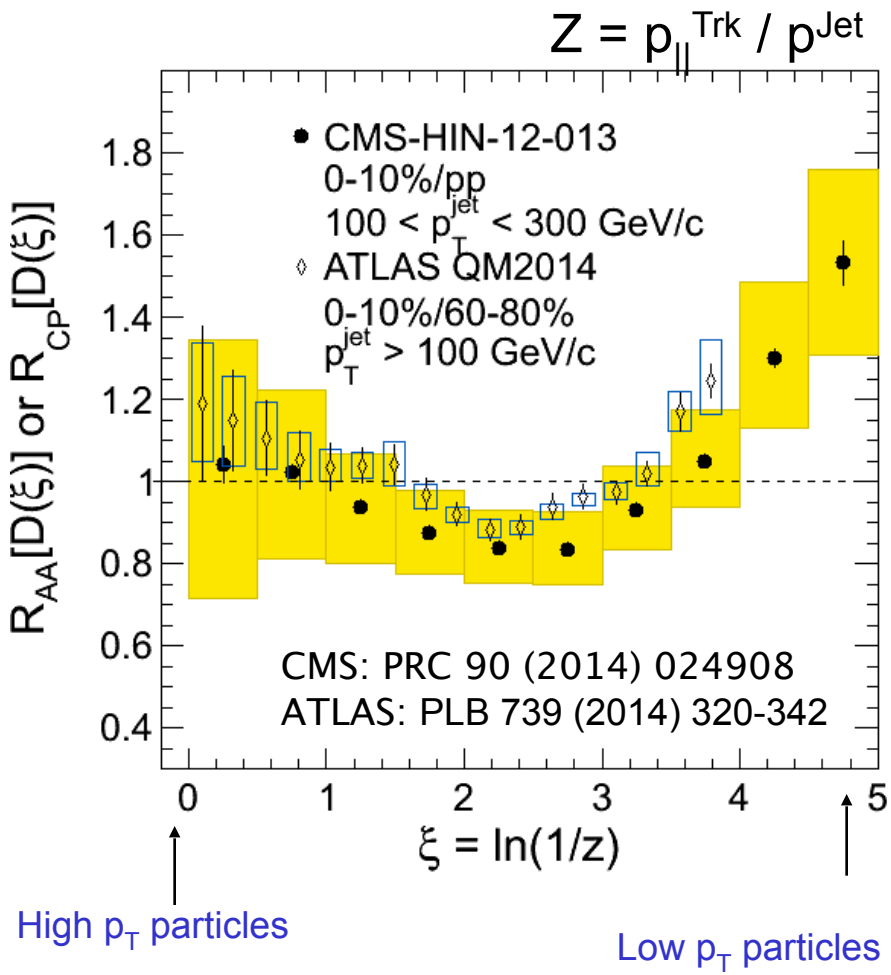


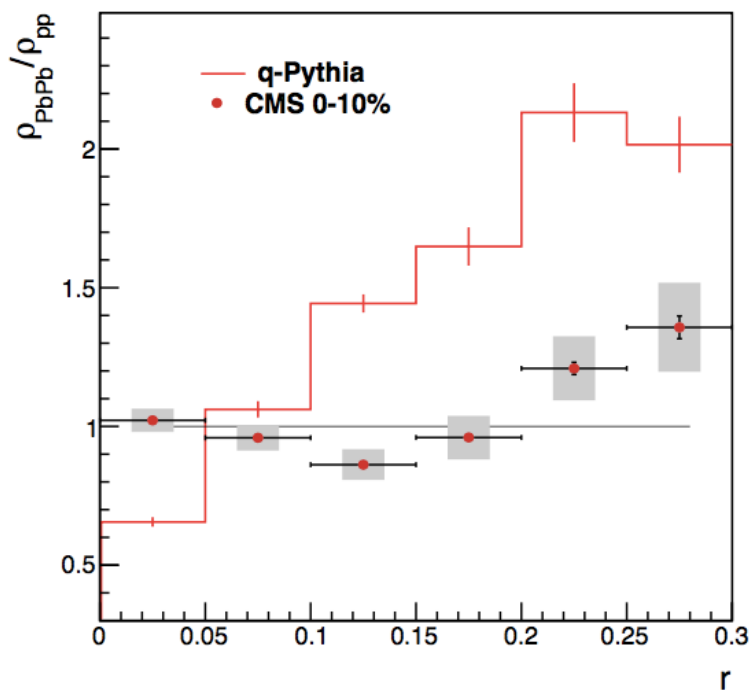
Quark/gluon discrimination in pp

Not directly applicable for g/q in AA
(use γ jet, Z+jet, b/c tag, 3-jet)

But: use QGL or similar to look jet-by-jet quenching

There is a *long* road ahead…





We're not quite ready for detailed jet substructure data/MC comparisons

Qualitative consistent results between CMS and ATLAS
But: Experiment-comparison suggests that we do NOT YET have sufficient control over systematics necessary for our decadal program

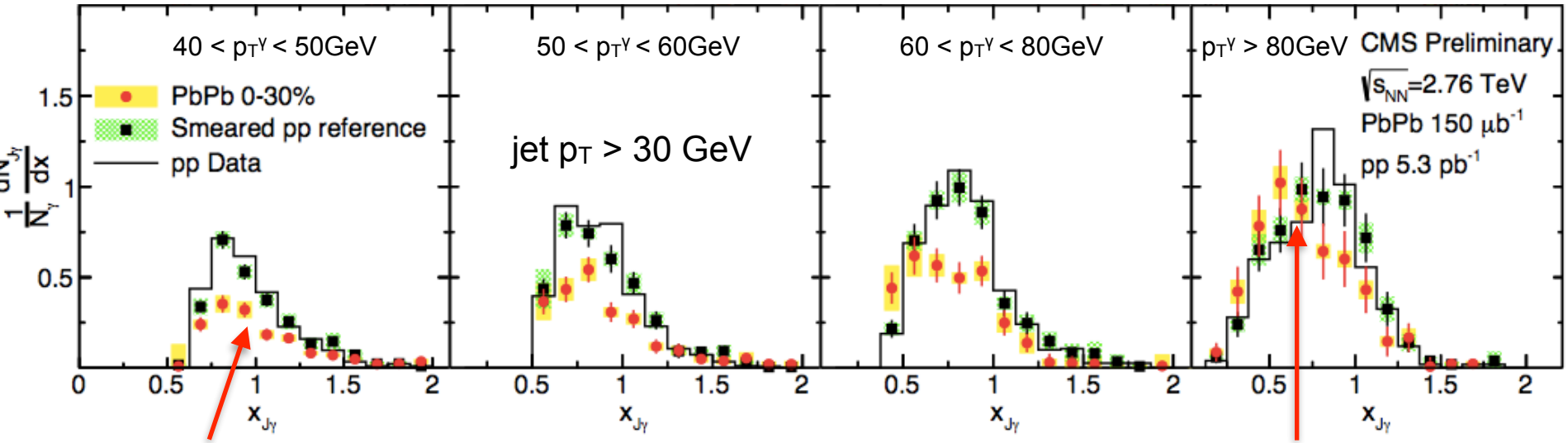
Two avenues:
- Better data and better MC
- Better observables

The importance of photon-jet correlations

Using isolated photons to tag away-side jets

- determines initial parton energy to ≈ 15%
- determines initial direction of the parton
- tags parton to be a light quark

less than 1 per 1000000 central PbPb collisions



photon p_T <50GeV:
Spectrum of PbPb jets is **suppressed** vs pp
Biased jet selection

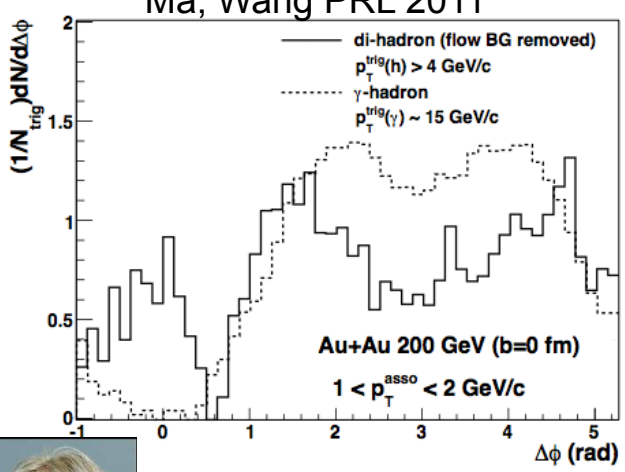
photon p_T >80GeV:
Spectrum of PbPb jets is **shifted** vs pp
Unbiased jet selection

Sufficiently high γ p_T or sufficiently low jet p_T yield **unbiased** selection of jets

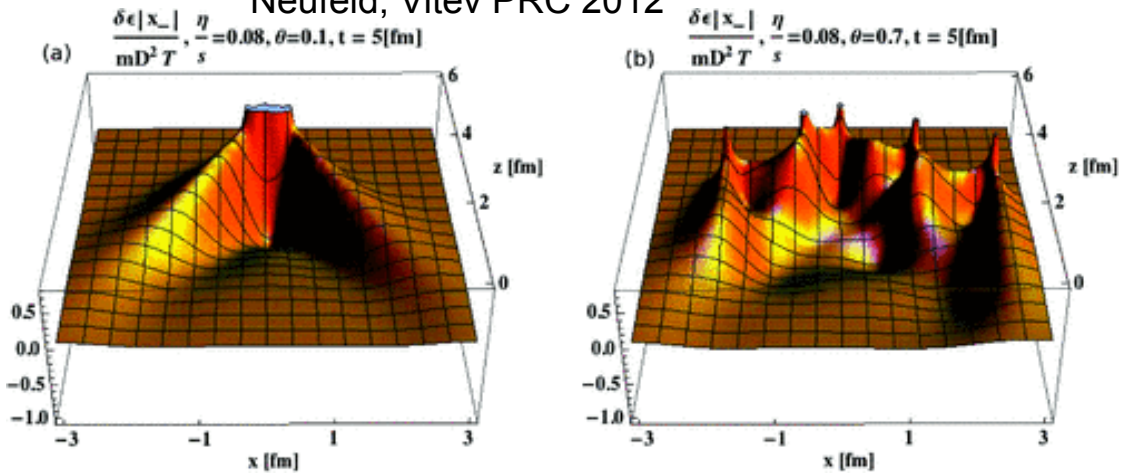
IMHO: High stat. γ-jet data will provide qualitative breakthrough in understanding of jet modification and jet-medium interactions

Energy flow and medium response

Ma, Wang PRL 2011



Neufeld, Vitev PRC 2012



Do we have a medium, if there's no medium response?

Experimental and theoretical challenges:

- Strength and angular structure of medium response unknown
- Jets are correlated with the complex e-by-e flow fields through quenching
- How to distinguish medium-response from modified jet branching?

Fundamentally simpler for photon-jet events!

Summary

- Rich harvest of results from RHIC and LHC
  - see much more in the next week!

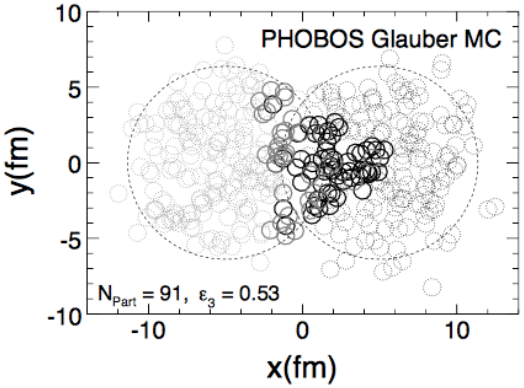
- Entering the decade of Hard Probes
  - Results from STAR/PHENIX upgrades
  - Start of LHC Run 2
  - New RHIC detector (sPHENIX)
- Theory/experiment dialogue is essential
- Golden opportunity to change the field

Summary

- Rich harvest of results from RHIC and LHC
  - see much more in the next week!

- Entering the decade of Hard Probes
  - Results from STAR/PHENIX upgrades
  - Start of LHC Run 2
  - New RHIC detector (sPHENIX)
- Theory/experiment dialogue is essential
- **Golden opportunity to change the field**

B. Alver, GR, Phys.Rev.C81:054905,2010



"Triangular flow" was invented (and named) by a grad student in late 2009 (450+ citations)

Enjoy!

(and close your g*ddamn laptops)