AND NOW FOR SOMETHING COMPLETELY DIFFERENT

...but still QCD

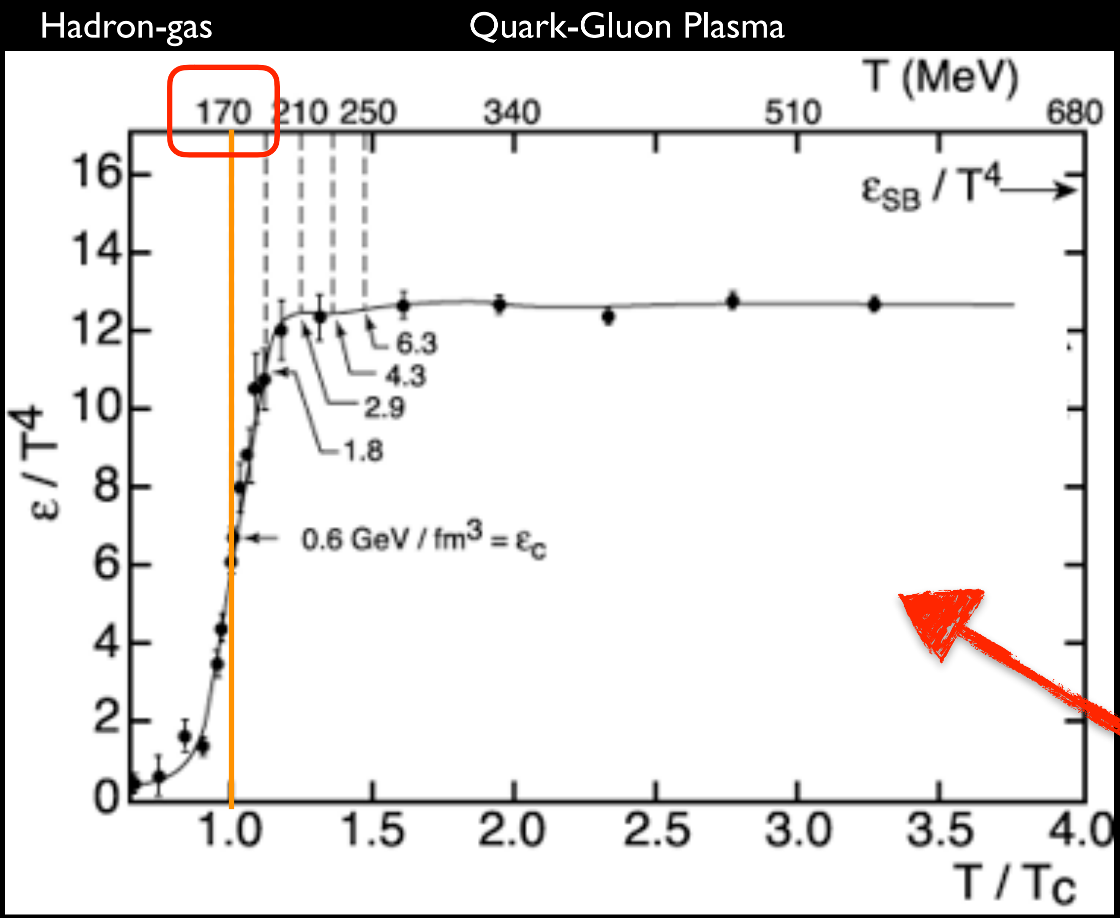
State of the art and open issues in heavy-ion physics at present and future colliders

Gunther Roland

MIT

ECT* Trento LFC17
September 2017

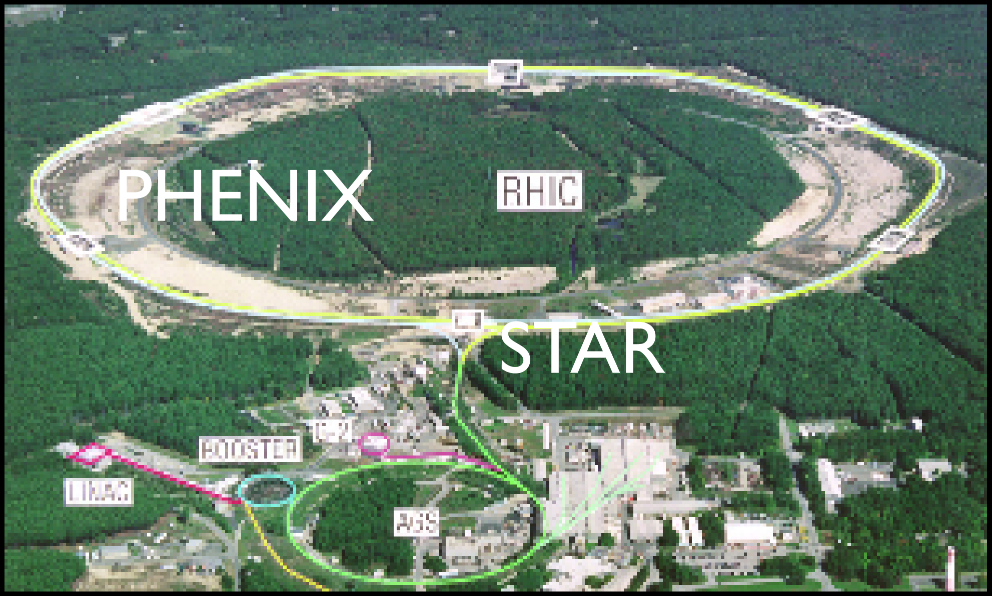
Ab-initio prediction of (Lattice-) QCD



Goal: Study properties and microscopic nature of **QGP**, using heavy-ion collisions to create hot+dense medium

Heavy Ion Colliders

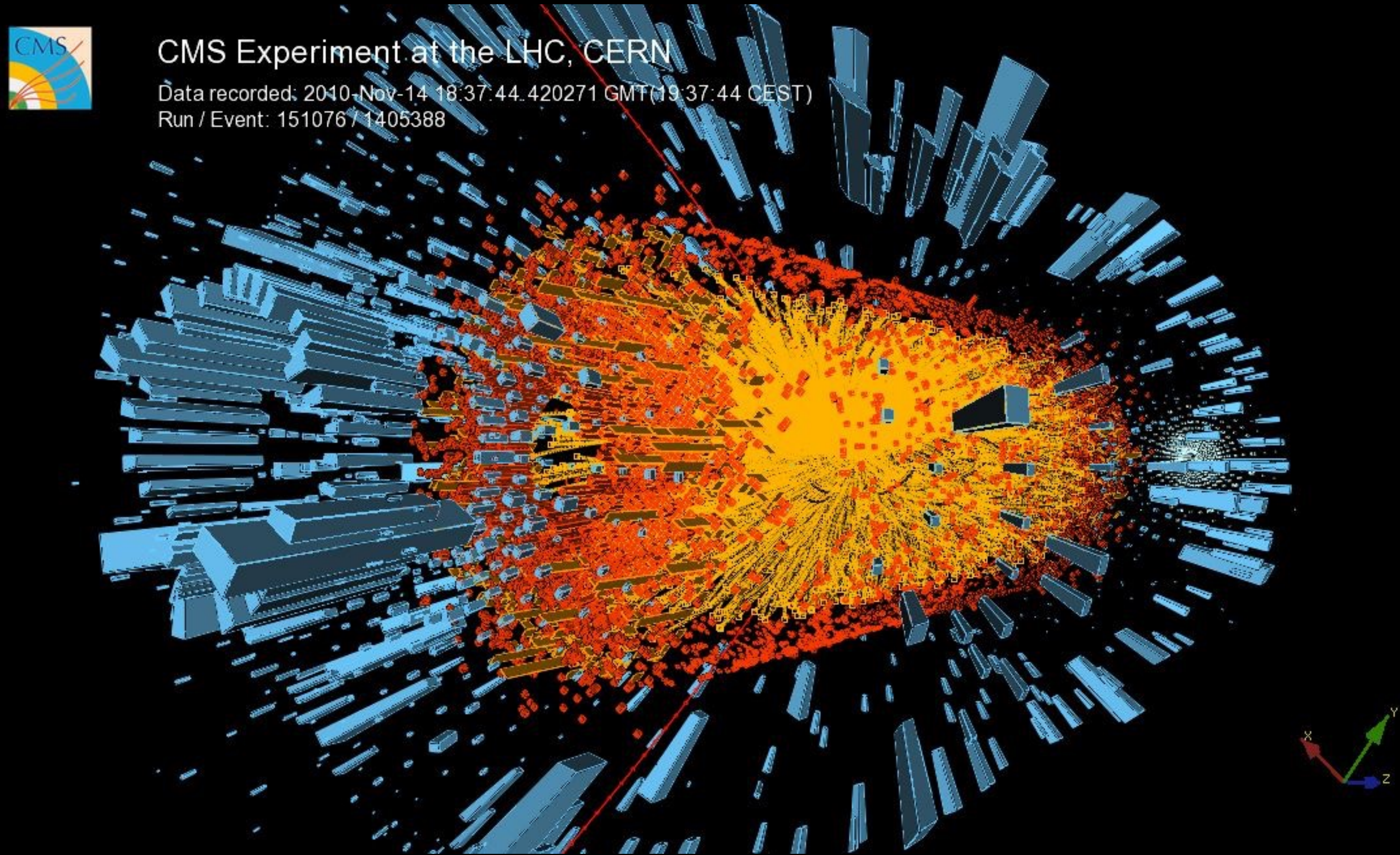
RHIC



First Au beams in 2000
Top Energy $\sqrt{s_{NN}} = 0.2$ TeV

LHC

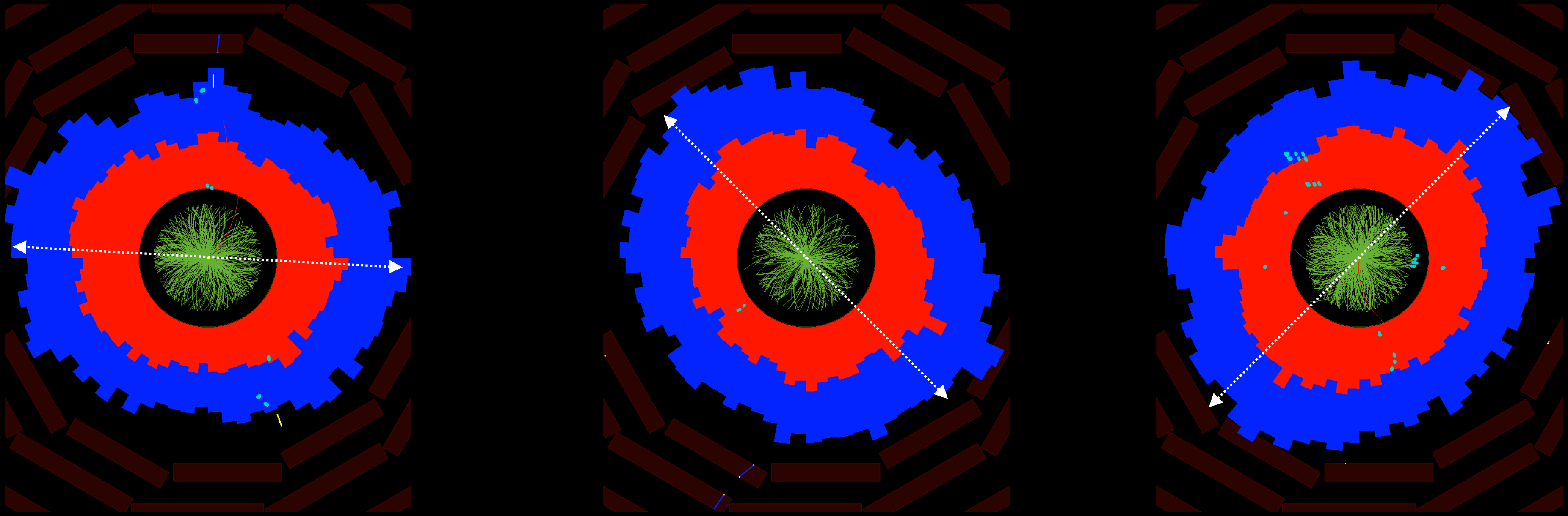
First Pb beams in 2010
Run 1 @ $\sqrt{s_{NN}} = 2.76$ TeV
Run 2 @ $\sqrt{s_{NN}} = 5$ TeV



Some of the key medium properties can be observed with the ‘naked eye’

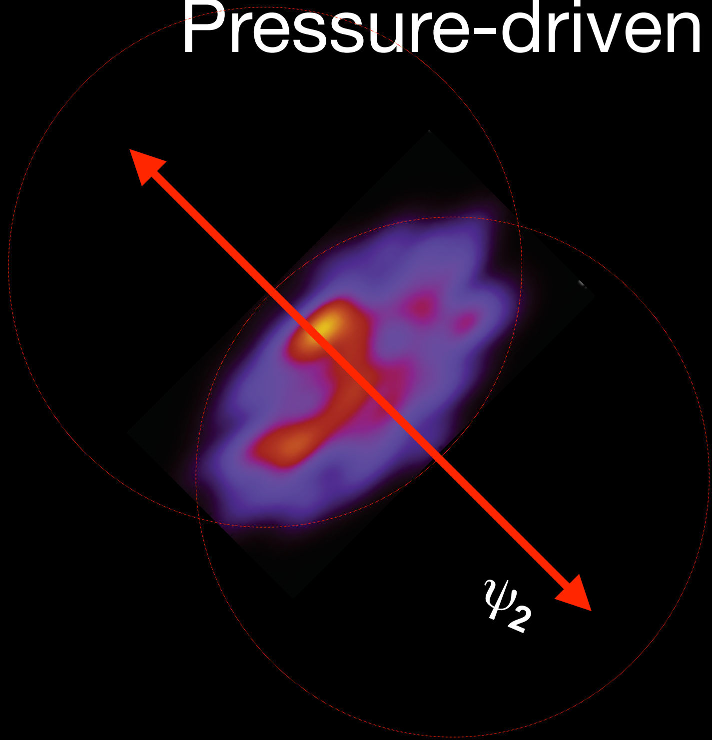
Is there a medium (i.e., collectivity)?

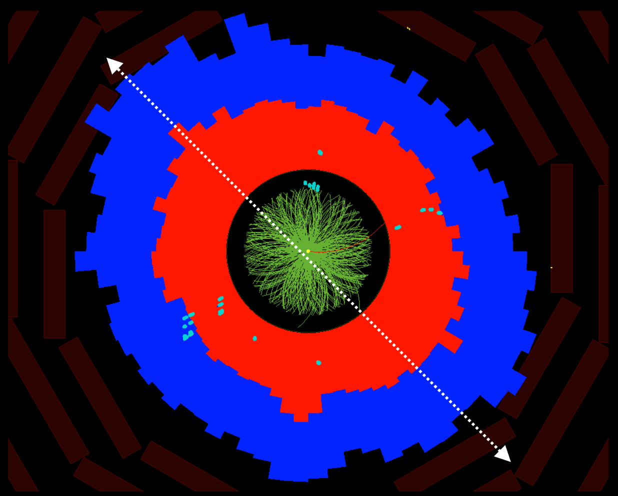
Projections of single event calorimeter distributions - O(10^4) particles - onto transverse plane



Particles are emitted in preferred directions event-by-event
Modulation of ± 15% or more

Pressure-driven hydrodynamic expansion





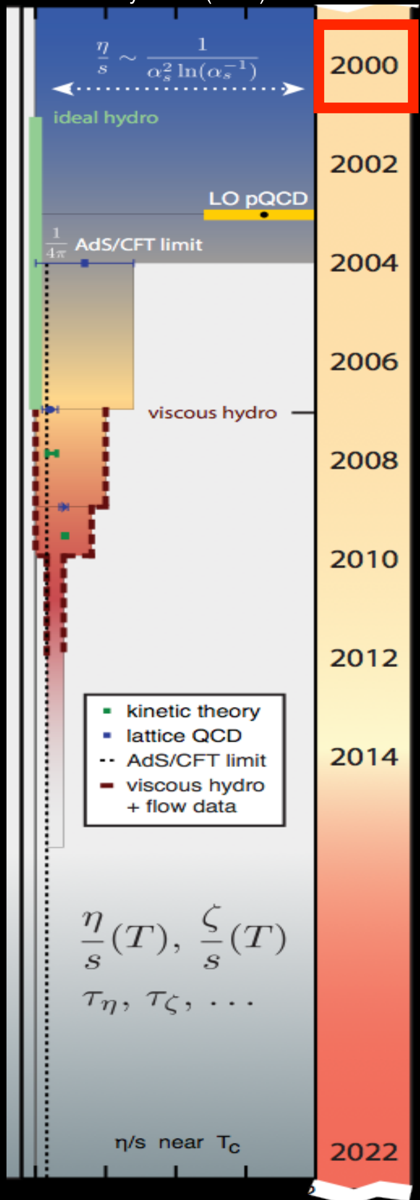
Initial nuclear overlap defines direction (anisotropic pressure gradients)

Final state momentum distribution reflects initial overlap geometry

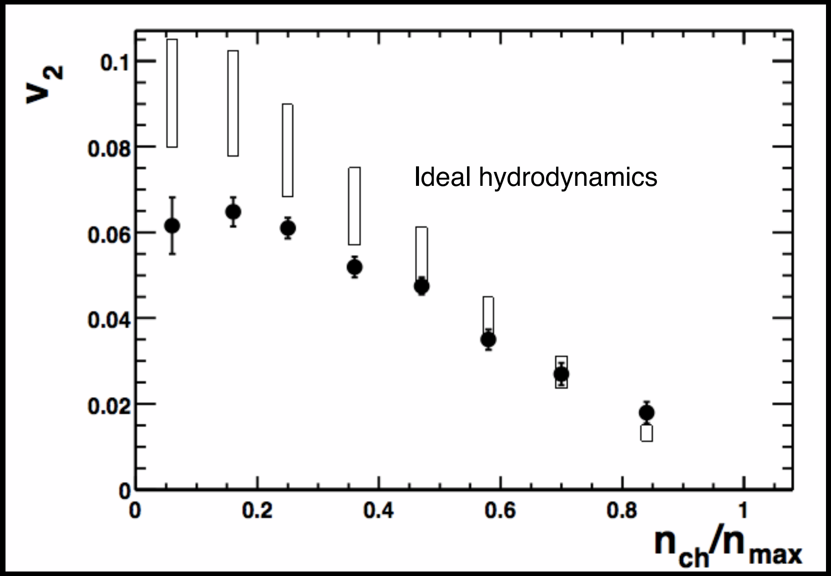
Hydrodynamic expansion translates initial configuration space anisotropy into final state momentum distribution

2000

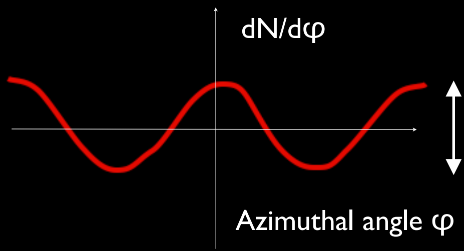
Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



STAR Phys.Rev.Lett. 86 (2001) 402-407



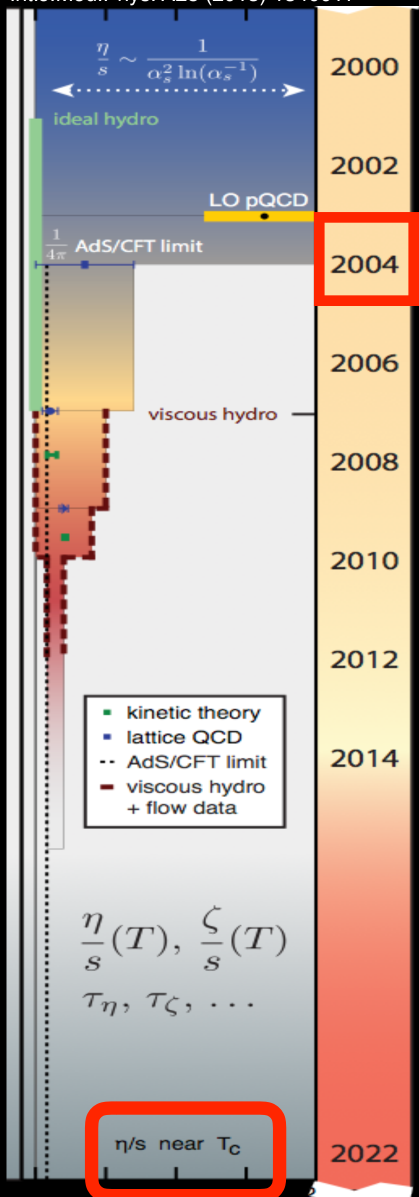
Elliptic flow in mid-central Au+Au collisions reaches values predicted in ideal (non-viscous) hydrodynamics



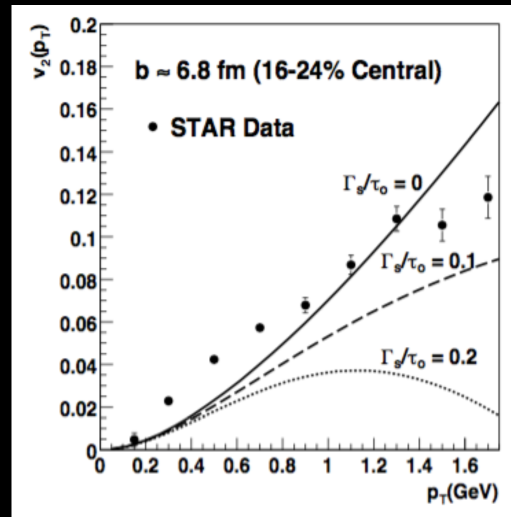
$\pm 2v_2$ "elliptic flow"

2003-2004

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011

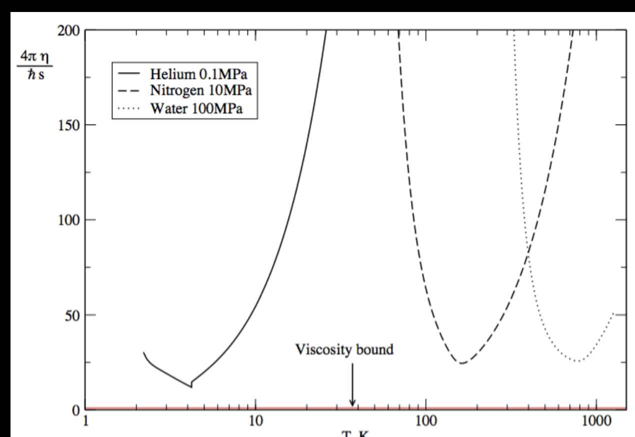


Teaney, Phys.Rev. C68 (2003) 034913



Strength of elliptic flow depends strongly on shear viscosity

Observed signal requires very small shear viscosity η/s ~ 0.1



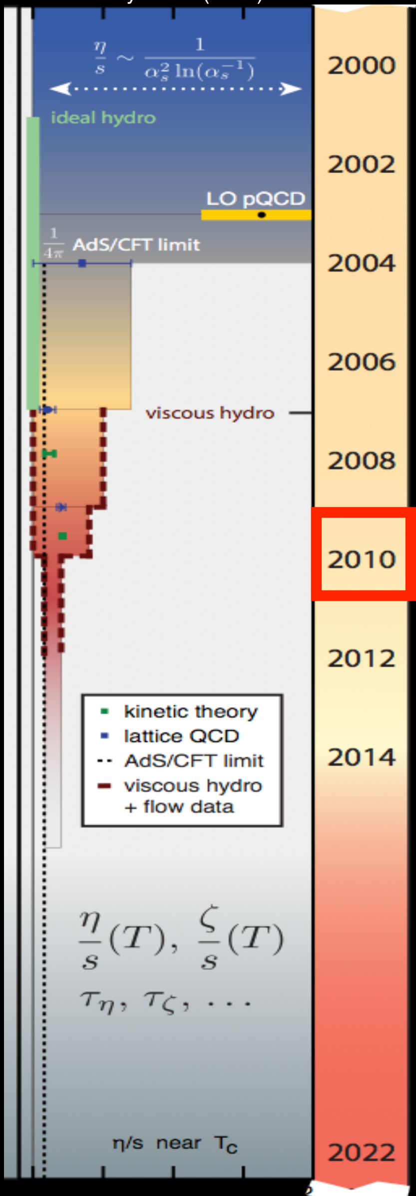
Kovtun, Son, Starinets Phys.Rev.Lett. 94 (2005) 111601

"Viscosity bound" η/s ≧ 1/4π in string theories with gravity dual in strong coupling limit

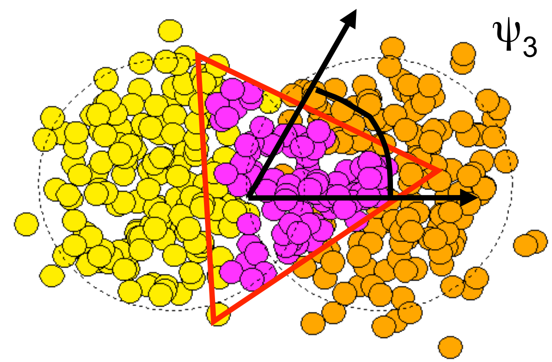
Connection between flow in HI and fundamental physics of strongly coupled systems

2010-

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



B. Alver, GR, Phys.Rev. C81 (2010) 054905

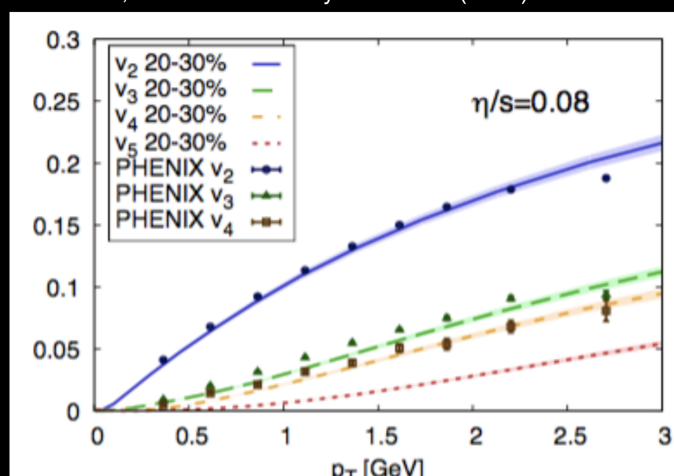


$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(3\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$

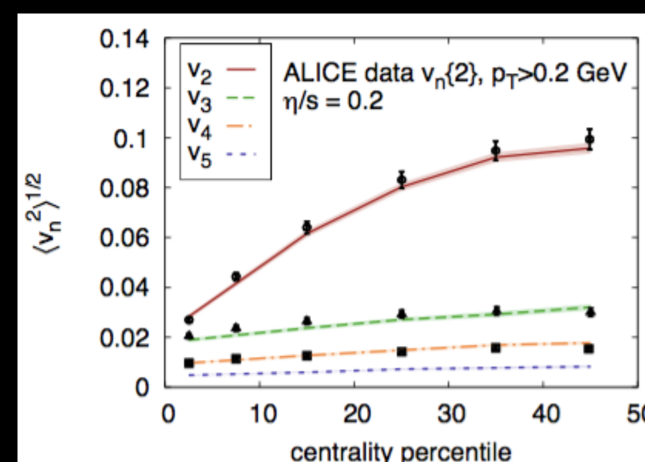
Initial geometry fluctuations break two-fold symmetry → Odd flow components, in particular triangular flow (v_3)

Provides independent observables to constrain geometry and η/s simultaneously

Gale, Jeon Schenke Phys.Rev. C85 (2012) 024901

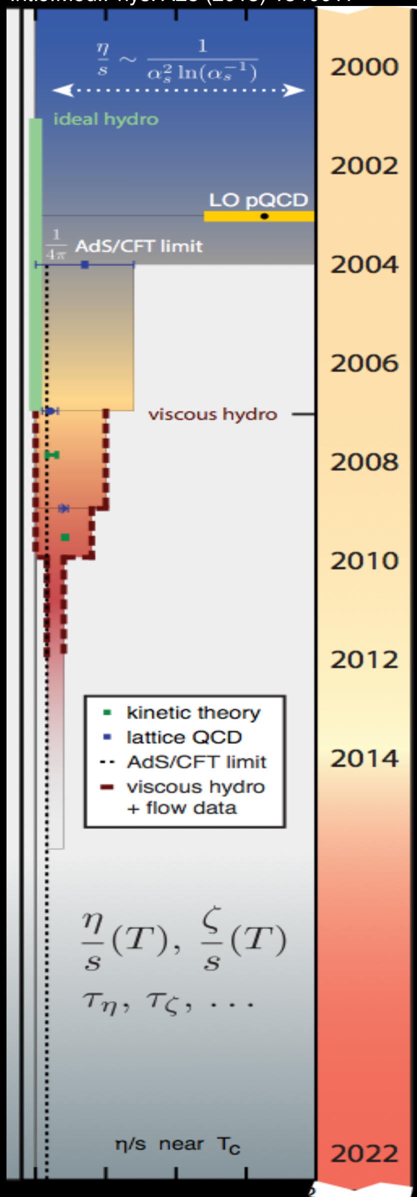


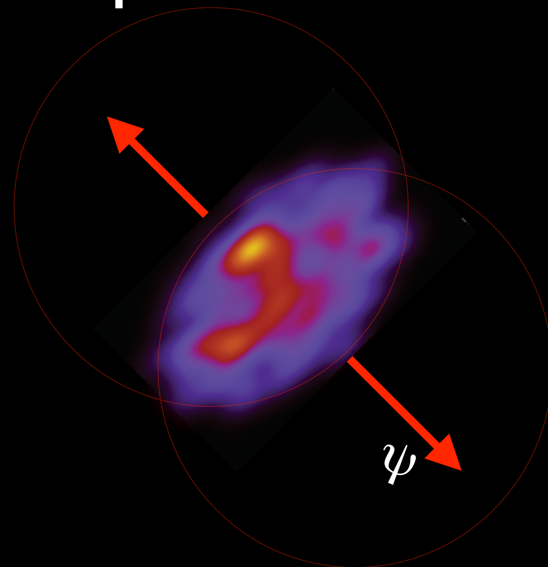
Gale et al, Phys.Rev.Lett. 110 (2013)

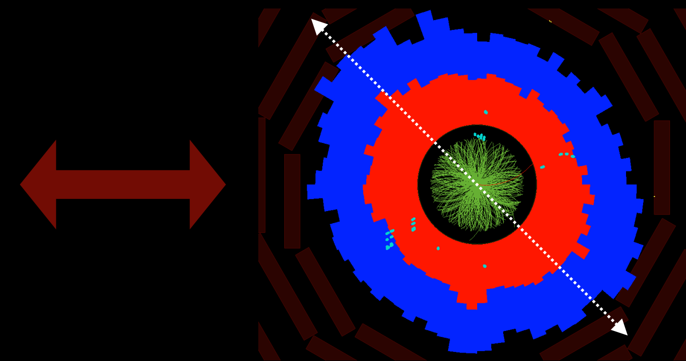


Strongly Coupled Quark-Gluon Plasma

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011







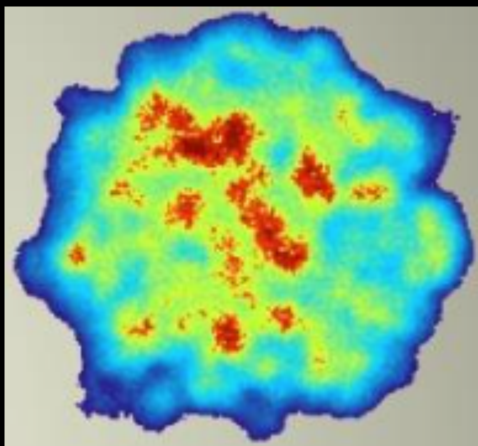
Established viscous hydrodynamics as successful effective theory of long-wavelength dynamics of QGP (at few x Tc)

Explained structure and fine-structure of final state correlations based on understanding of initial geometry at (thermal) O(1fm) scale and transport coefficient η/s ~ 1/(4π)

Demonstrated unique place of sQGP among known states of matter; broad connection with other strongly coupled materials (from string theory to cold atoms)

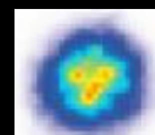
Open issue: Correlations in small systems

PbPb

15fm 

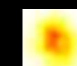
vs

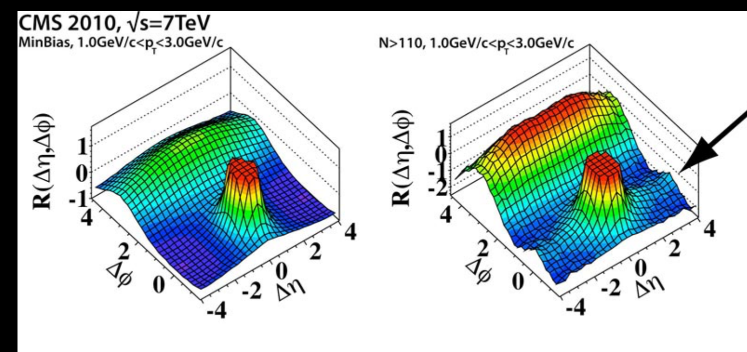
pPb

 few fm

vs

pp

 1 fm



Correlations do not “turn off” in small systems

In particular in pPb, phenomenology is ~identical to PbPb

Generic feature of high density QCD systems?

Open issue: Correlations in small systems

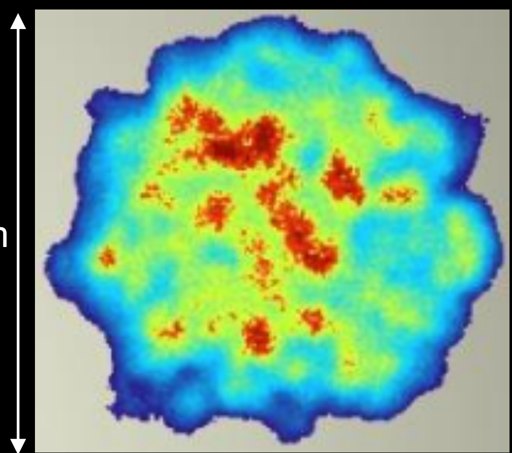
16:00 **Coffee Break** *30'*

16:30 **Hydrodynamics** *30'*

Speaker: Piotr Bozek

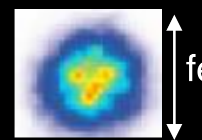
PbPb

15fm



vs

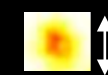
pPb



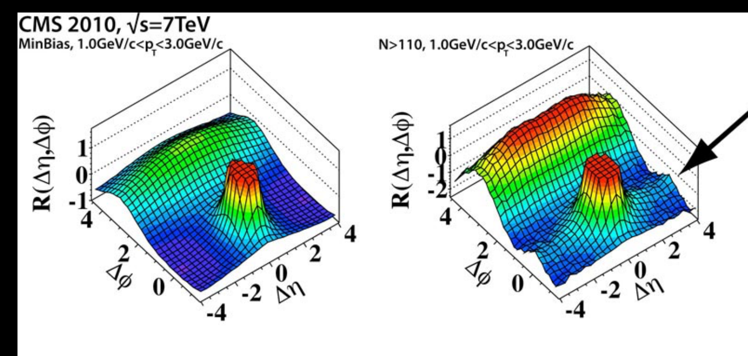
few fm

vs

pp



1 fm

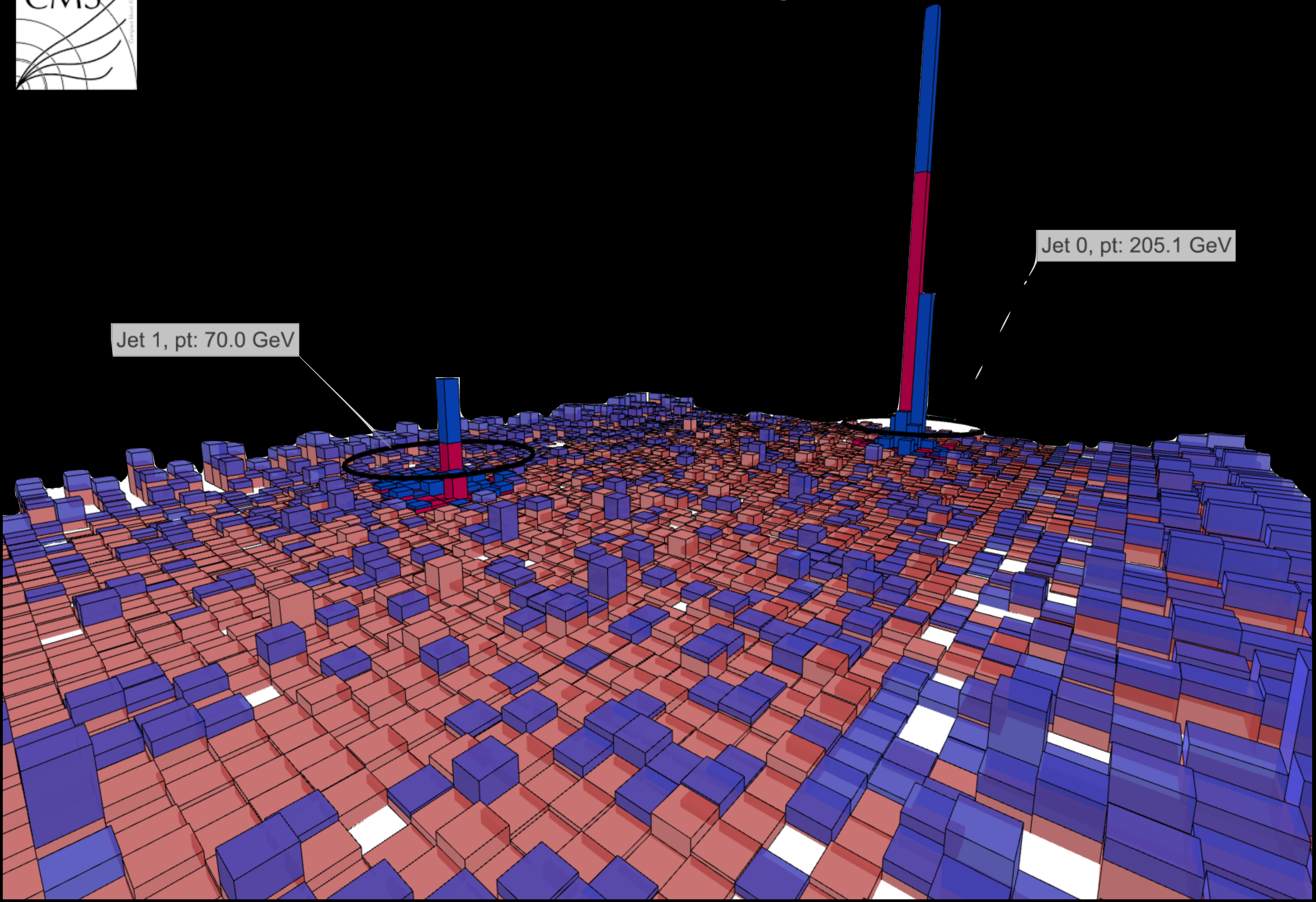


Correlations do not “turn off” in small systems

In particular in pPb, phenomenology is ~identical to PbPb

Generic feature of high density QCD systems?

“Jet Quenching”



Models of in-medium parton energy loss

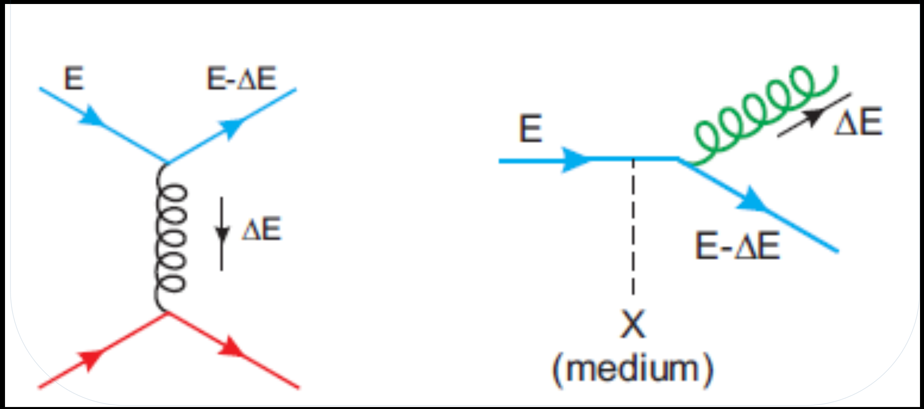
Multi-scale problem of describing interaction of
hard-scattered parton and QGP constituents

Classes of models

Perturbative QCD
Weak coupling limit

Collisional energy loss

Radiative energy loss



JEWEL

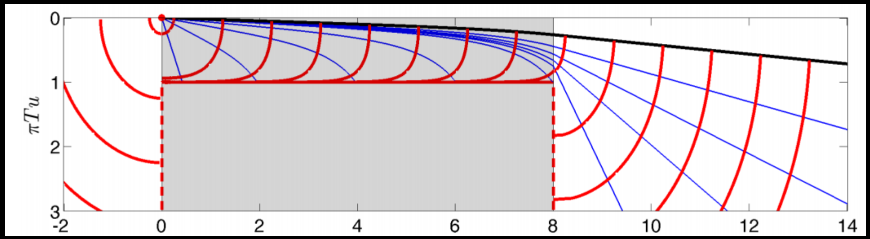
CUJet3.0

CCNU

Q-PYTHIA

$SCET_G$

Holographic calculation
Strong coupling limit

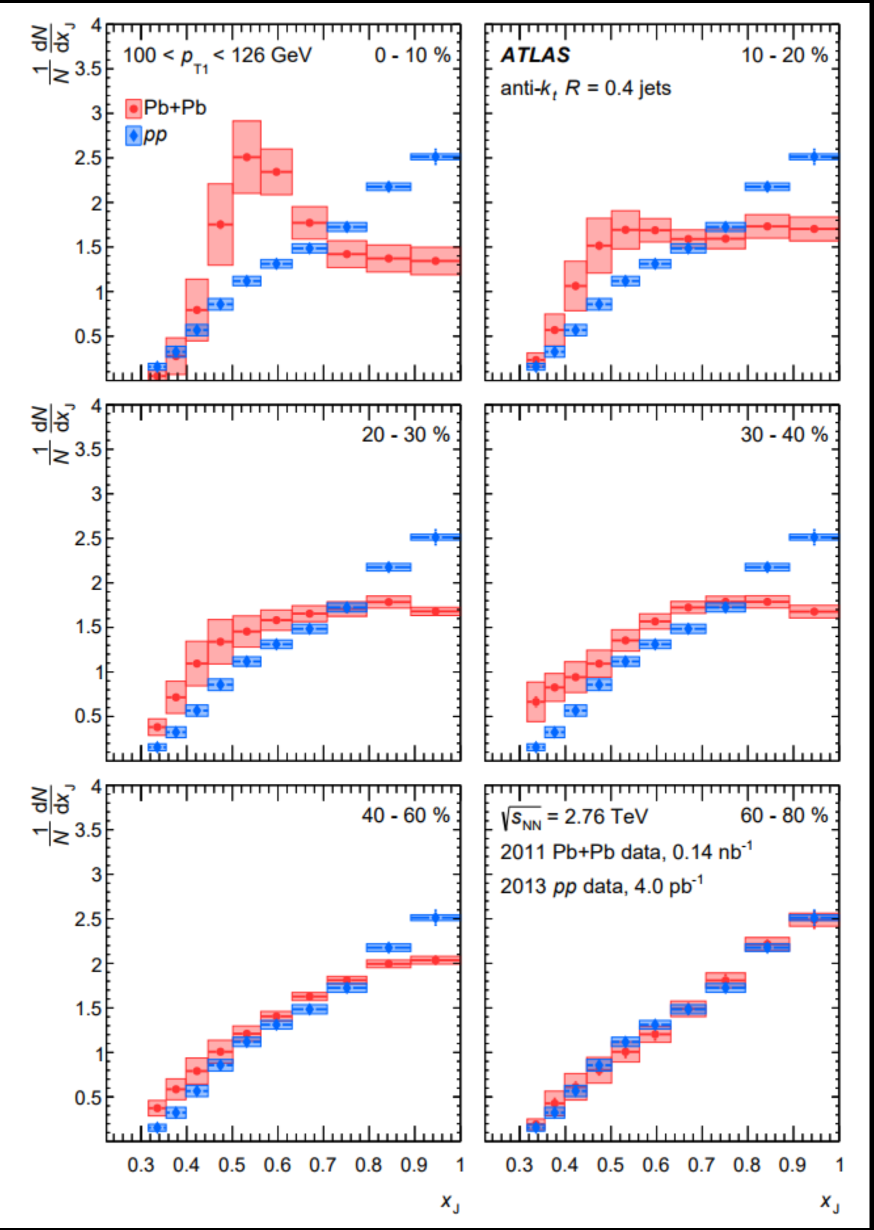


AdS/CFT "drag force"

HYBRID

Dijet asymmetry

Enhanced fraction of unbalanced dijets in central PbPb



p_T ratio of subleading/leading jet, for different collision centralities

Peripheral PbPb events match pp reference

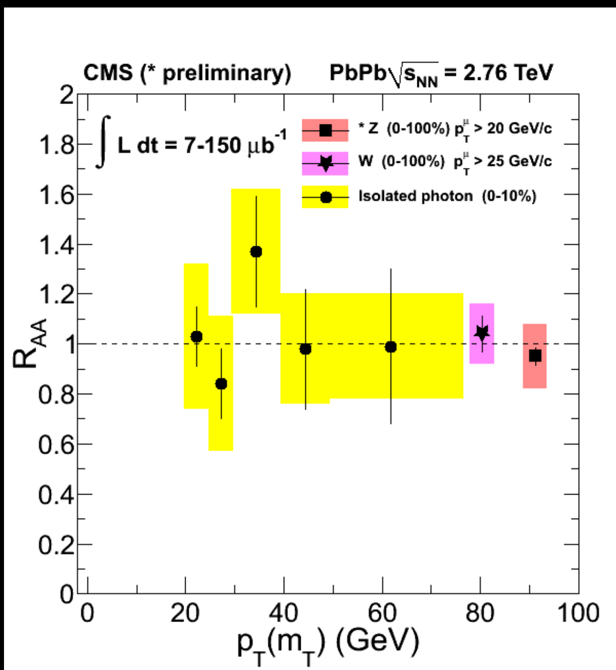
Nuclear Modification factor R_{AA}

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

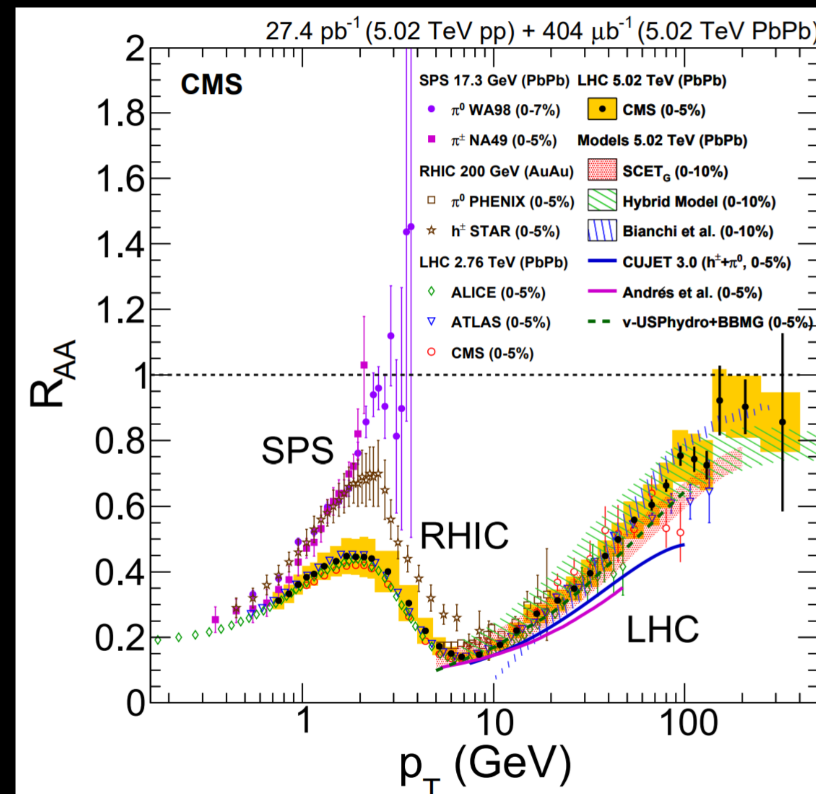
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

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

N_{coll}: Number of binary nucleon-nucleon collisions

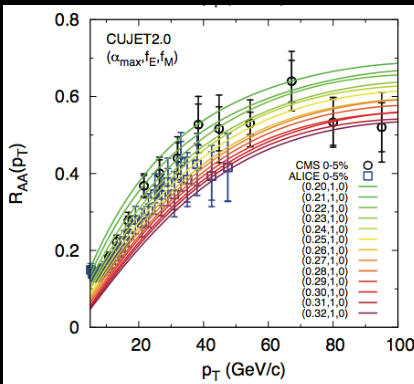


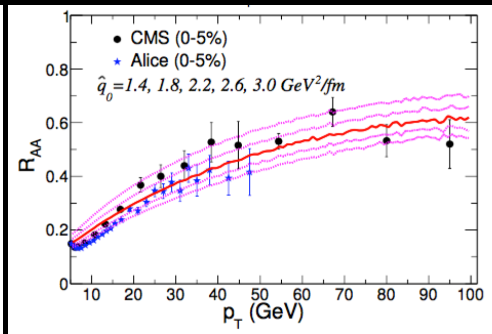
High p_T/high mass vectorbosons unmodified

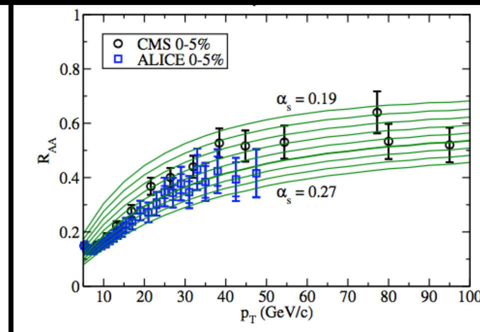


High p_T hadrons suppressed compared to pp

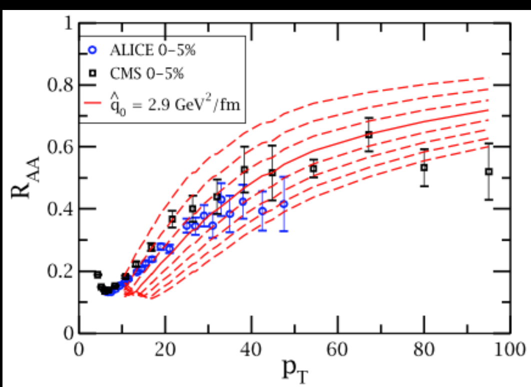
Extraction of $\hat{q}$ and $\hat{e}$ transport coefficients

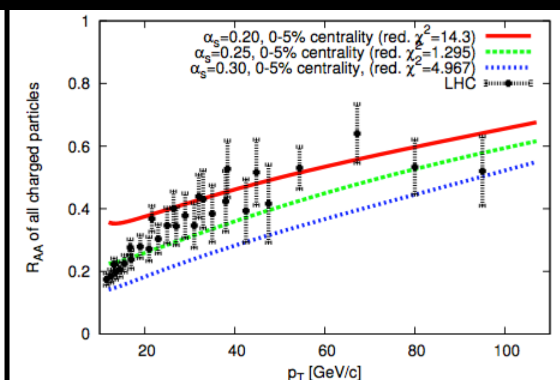


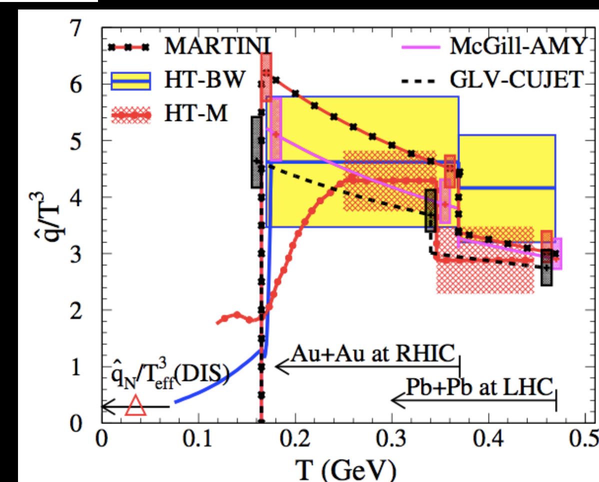




JET theory collaboration 2013



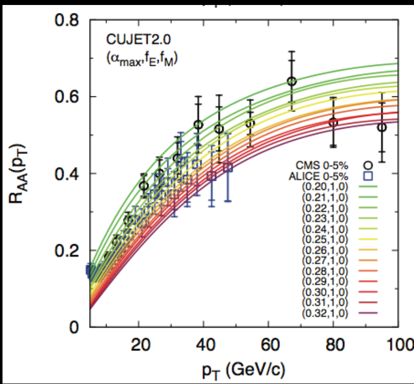


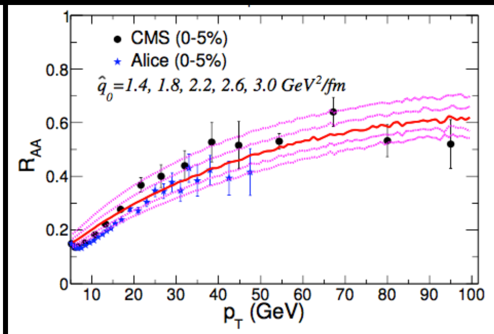


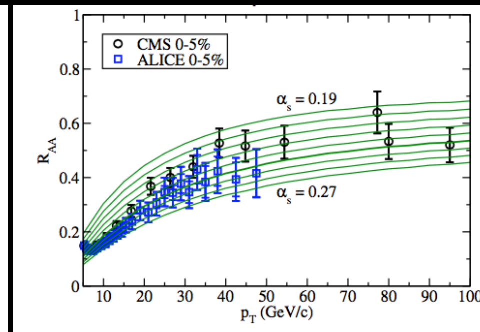
Transport coefficients characterizing transverse momentum diffusion (qhat) and longitudinal drag (ehat) from hadron R_{AA} data

Open issue: precise ehat determination requires better heavy flavor data

Extraction of $\hat{q}$ and $\hat{e}$ transport coefficients







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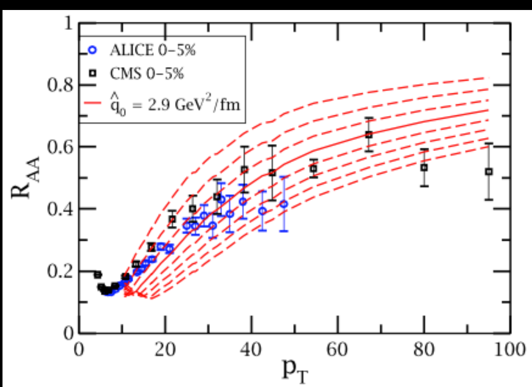
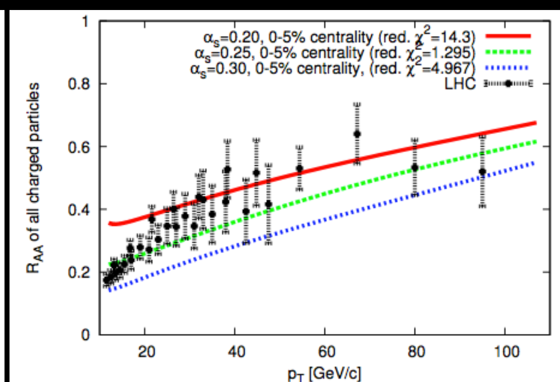
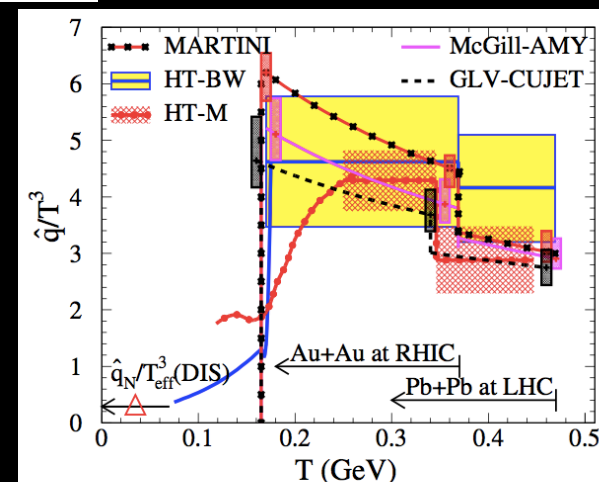






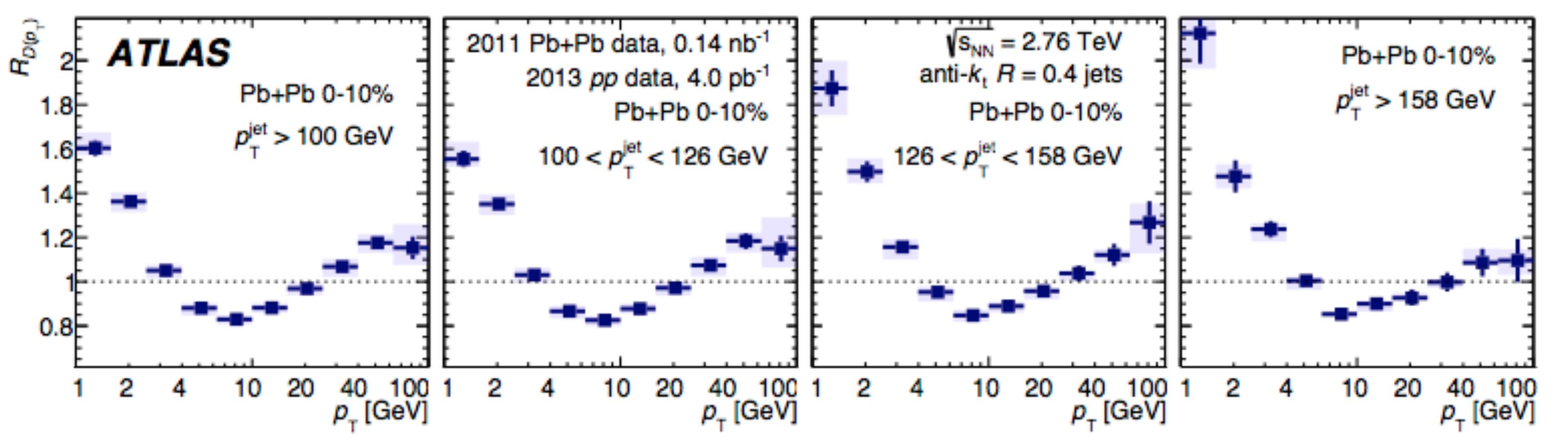
Transport coefficients characterizing transverse momentum diffusion (qhat) and longitudinal drag (ehat) from hadron R_{AA} data

17:30 **Heavy flavours in high-energy nuclear collisions: overview of transport calculations** 30'

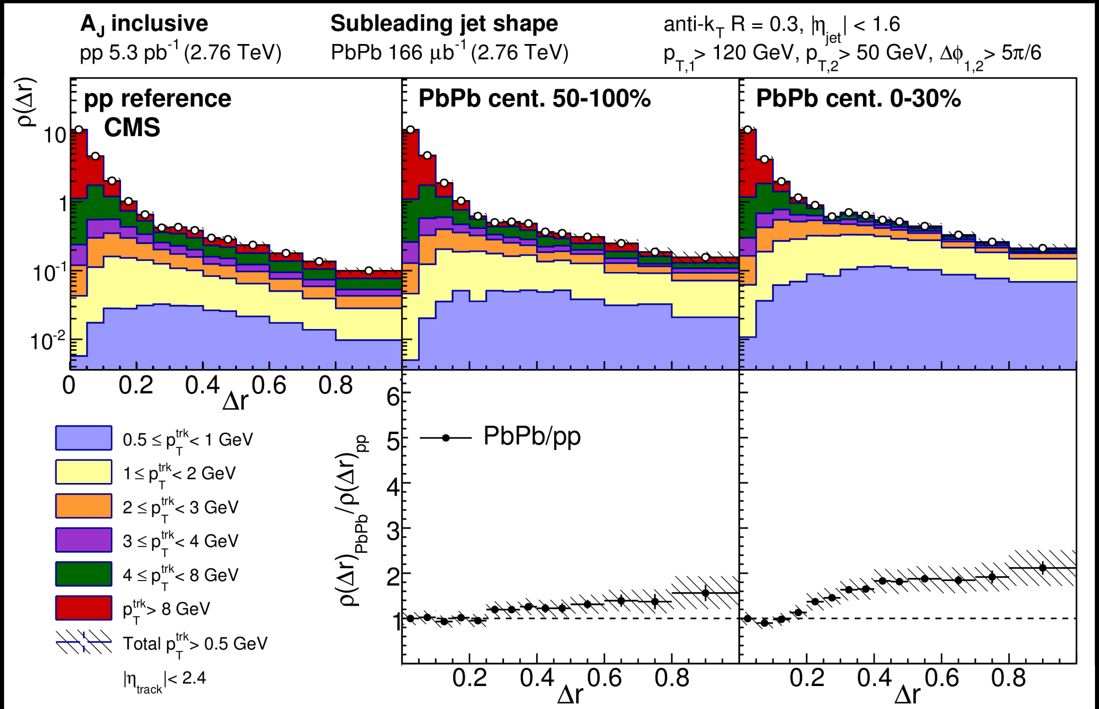
Speaker: Andrea Beraudo

Material: Slides

Modifications of Jet Structure



Longitudinal jet structure
("Fragmentation Function")



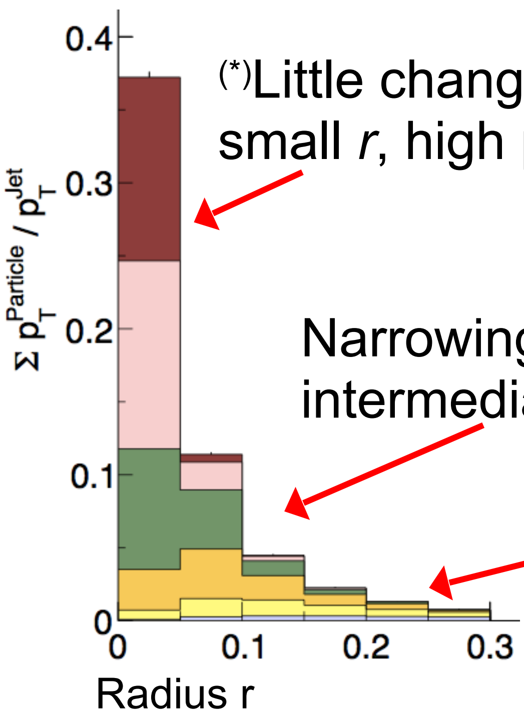
Transverse jet structure
("Jet shape")

+ many more results from LHC and RHIC

Cheat Sheet: Medium Modifications

In-cone energy difference
(leading - subleading jet)

Balanced by low p_T particles
at large angles

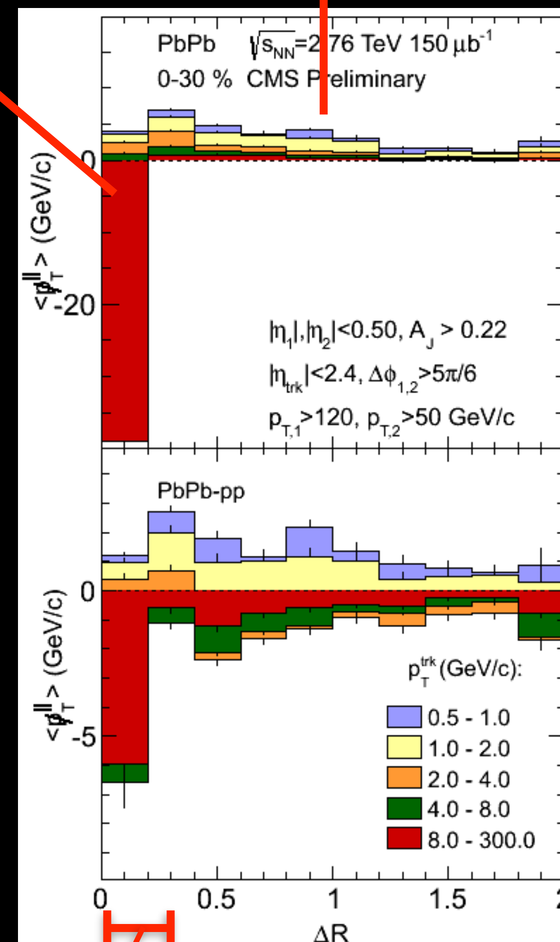


(*)Little change at small *r*, high p_T

Narrowing/depletion at intermediate *r*, p_T

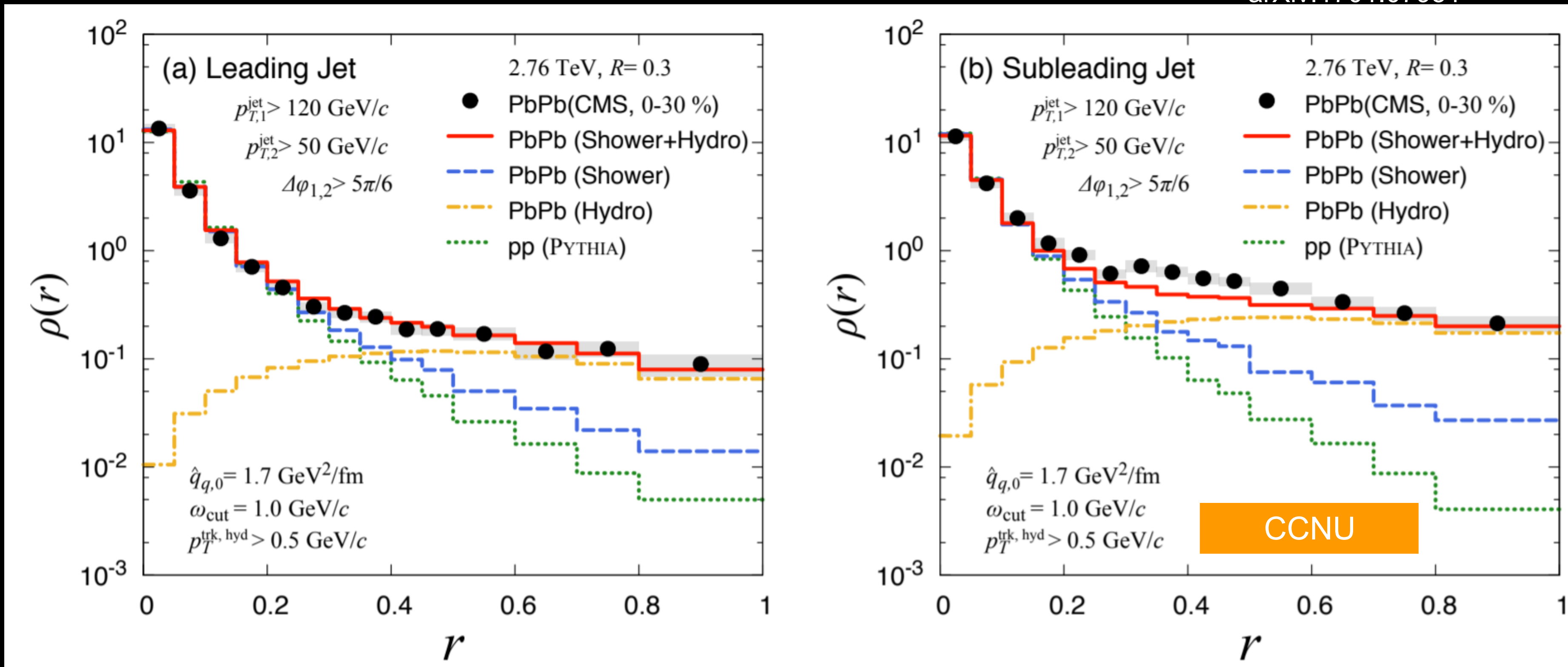
Broadening/excess at large *r*, low p_T
(~2% of jet energy)

(*) Some tension between ATLAS and CMS results



Open issue: Medium response @ large ΔR?

arXiv:1701.07951

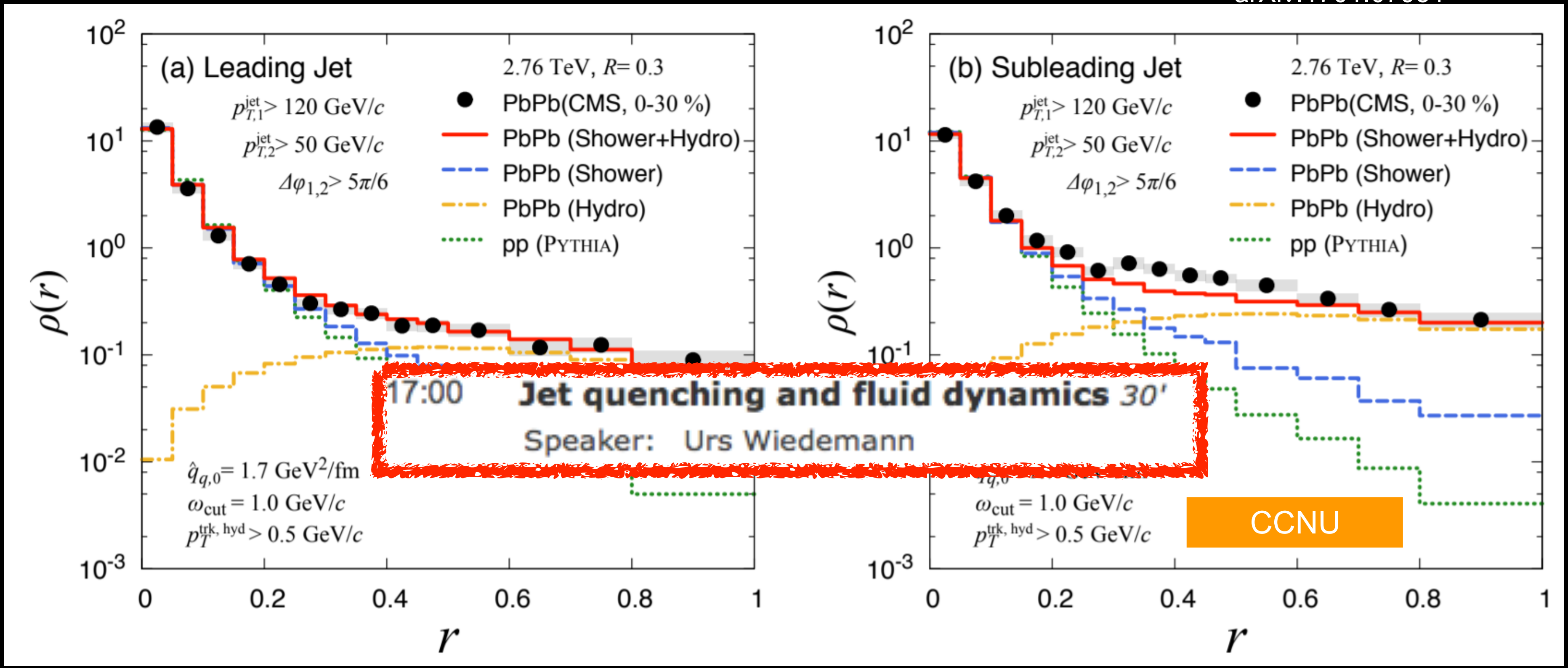


How is energy transported to large ΔR wrt jet axis?

(Large) modification of jet shower in medium *or* hydrodynamic transport of radiated energy?

Open issue: Medium response @ large ΔR?

arXiv:1701.07951

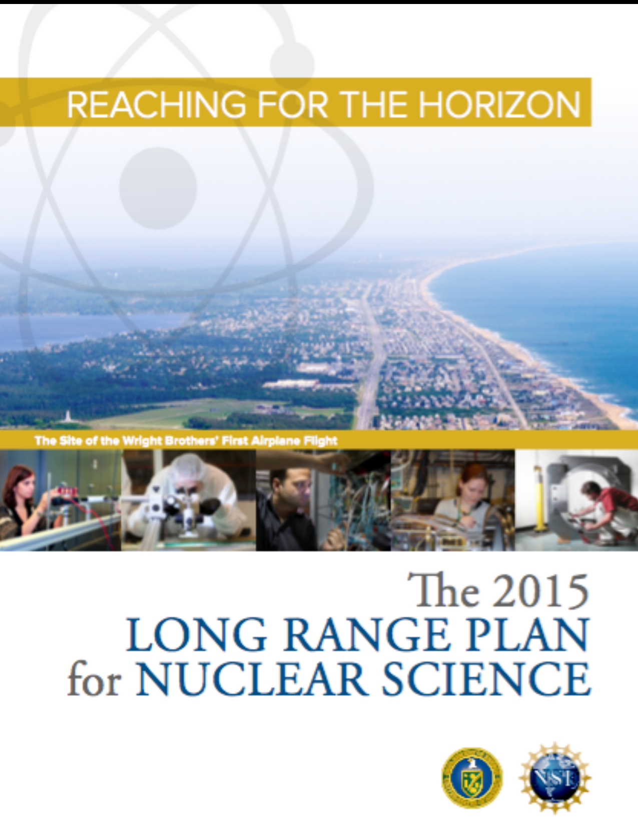


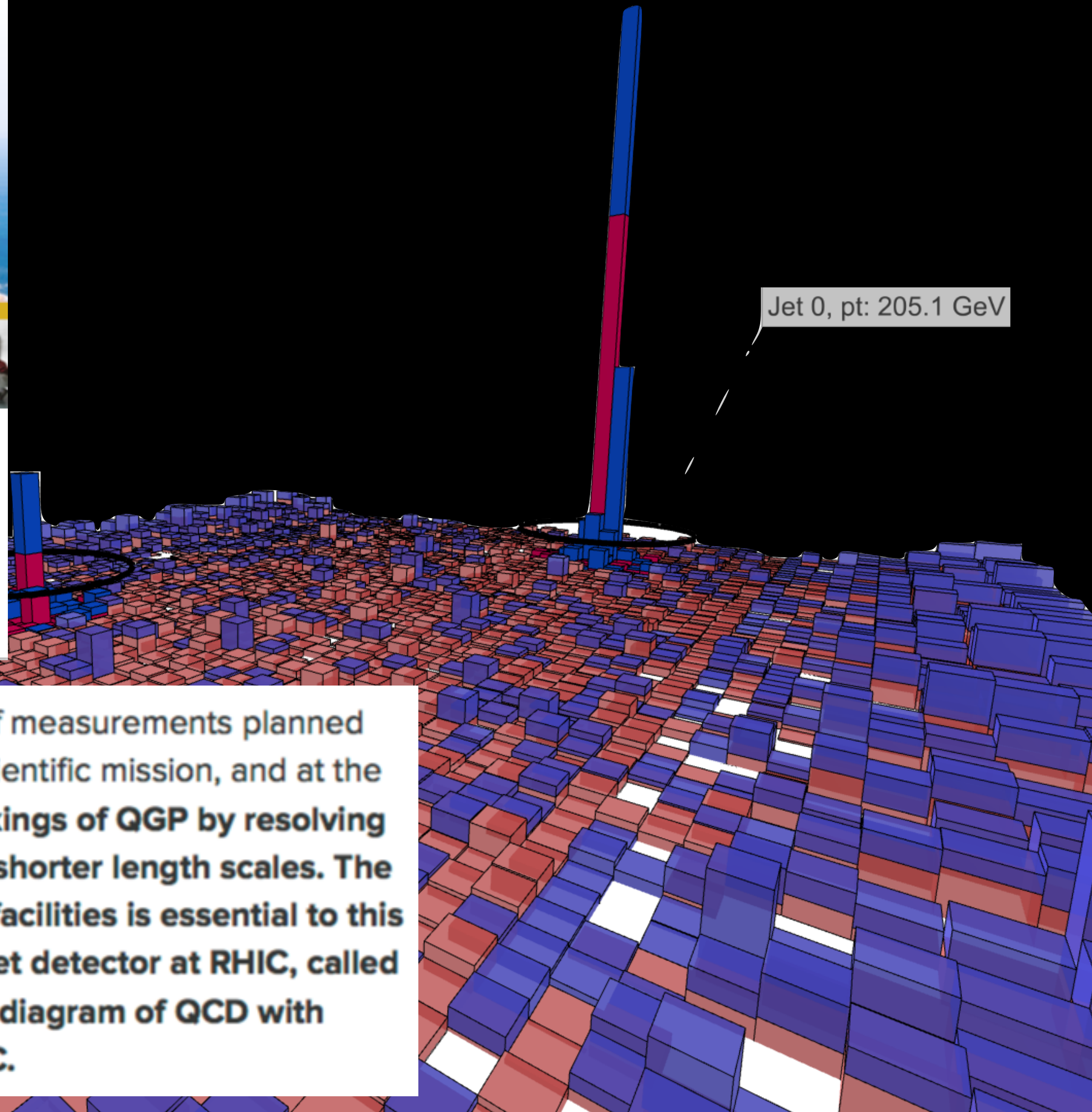
How is energy transported to large ΔR wrt jet axis?

(Large) modification of jet shower in medium *or* hydrodynamic transport of radiated energy?


EXPERIMENTS OF
THE FUTURE

c.f. 2014 Hot QCD White Paper (arXiv:1502.02730)



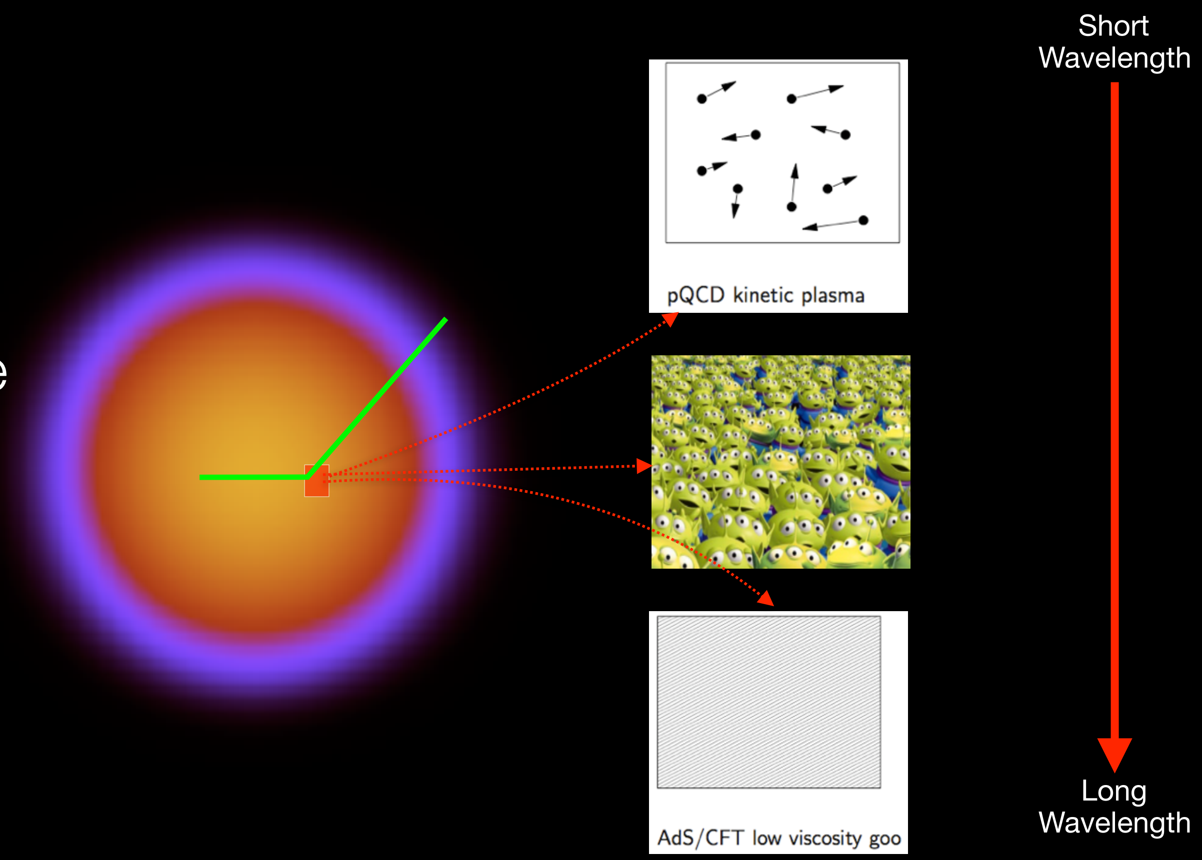


There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

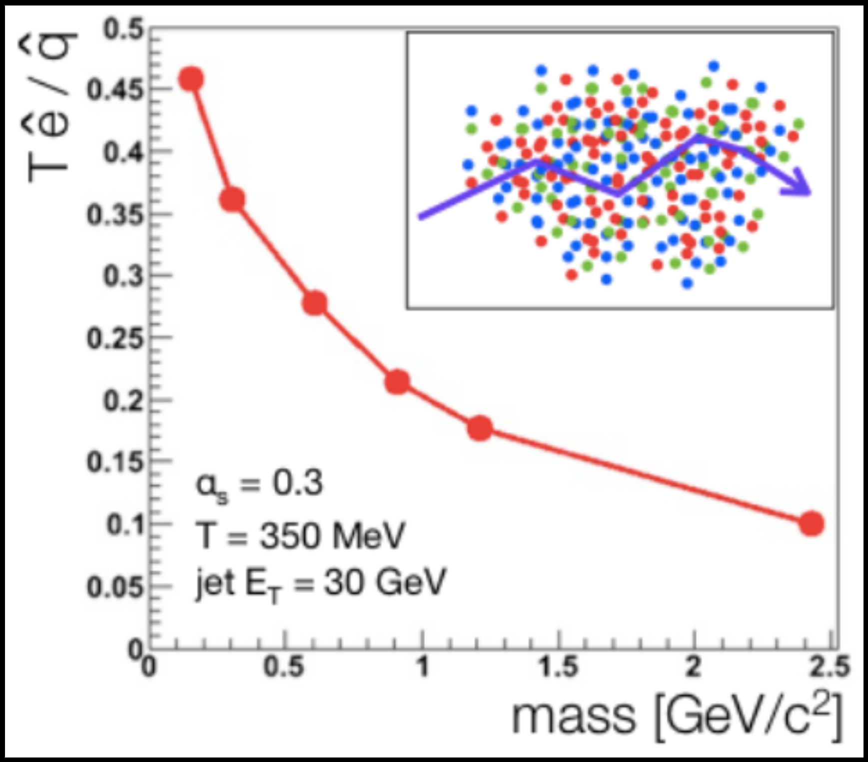
Probing the inner workings of the QGP

What is the microscopic structure of QGP?

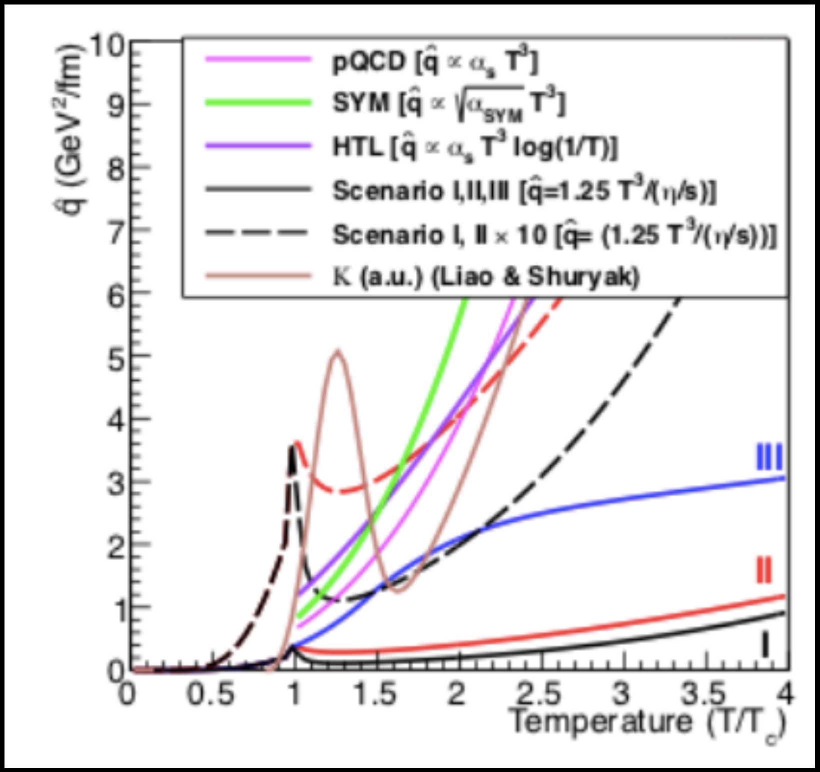
How does it “work”?



Open issue: Inner workings of QGP?



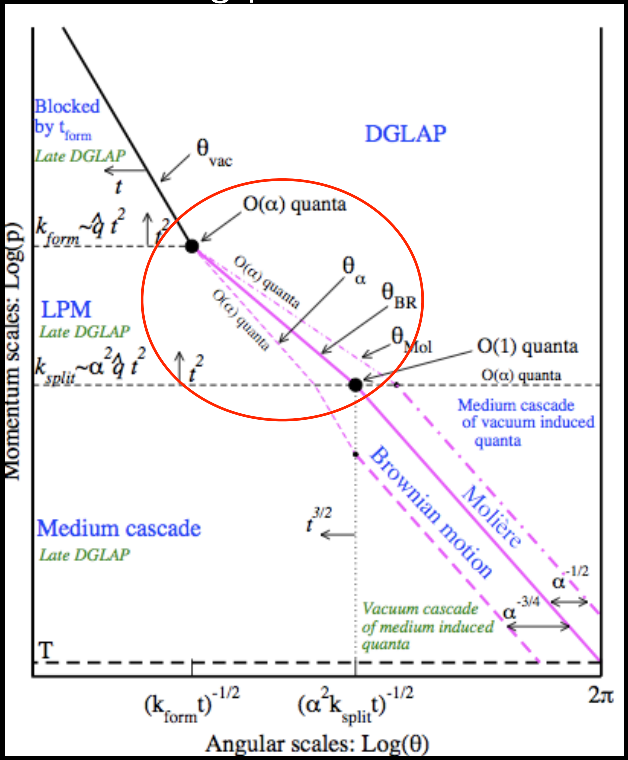
Transport coefficients for changing quasi-particle mass



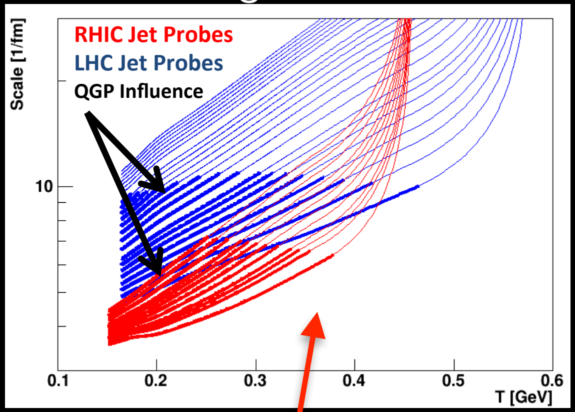
Temperature dependence of transport coefficient qhat

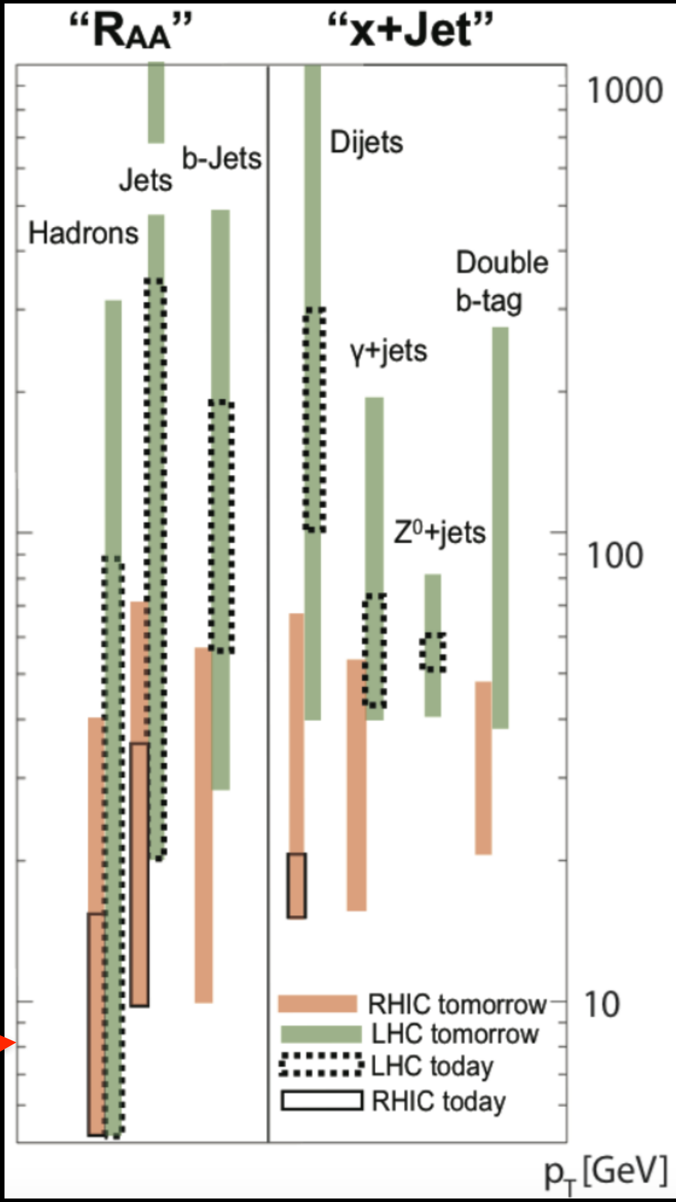
"Complementarity of RHIC and LHC"

Evolving parton shower



Evolving medium

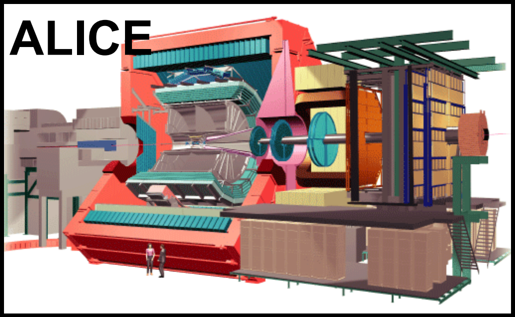




Future RHIC vs LHC Run 2:

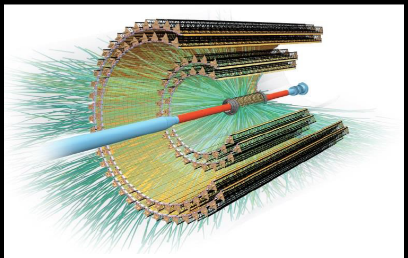
- Probe different paths of QGP evolution
- Overlap/complementarity in observables/ kinematics

Upgrades at LHC

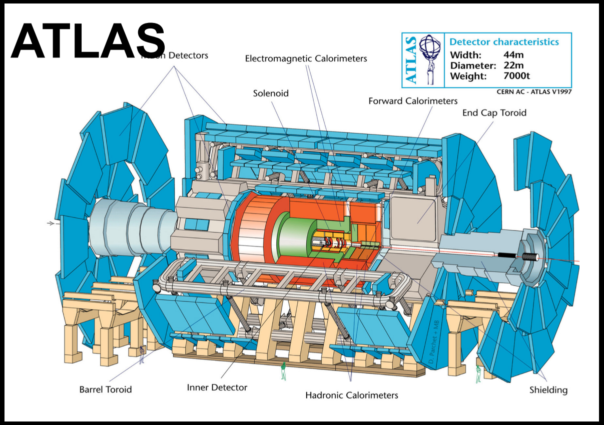


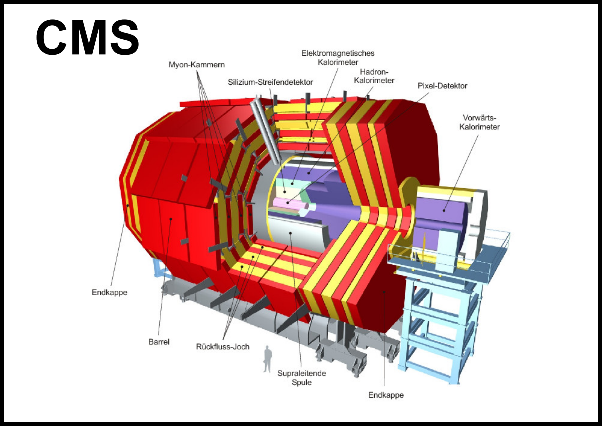
Extensive upgrades in LS2

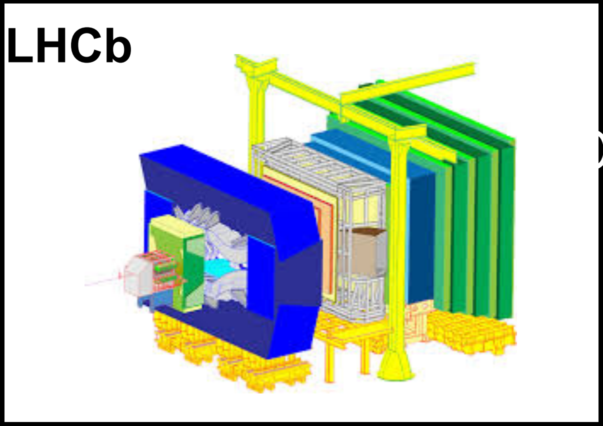
- Expanded calorimetry
- Continuos readout TPC
- MAPS-based inner tracker
- Improved data acquisition rate (full PbPb lumi)



Phase I + II upgrades (in particular tracking, DAQ/trigger) directly benefit heavy-ion physics program







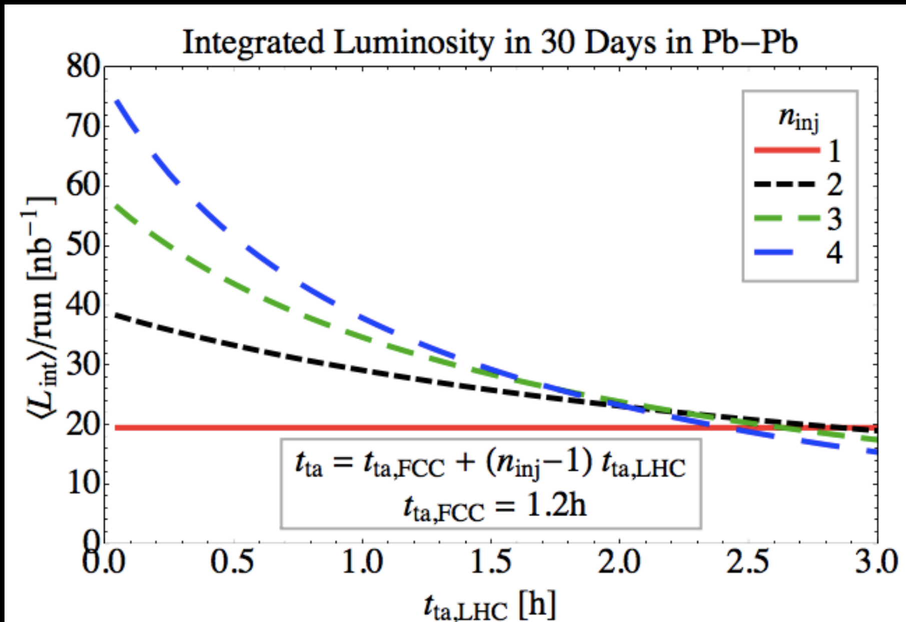
Future LHC Capabilities

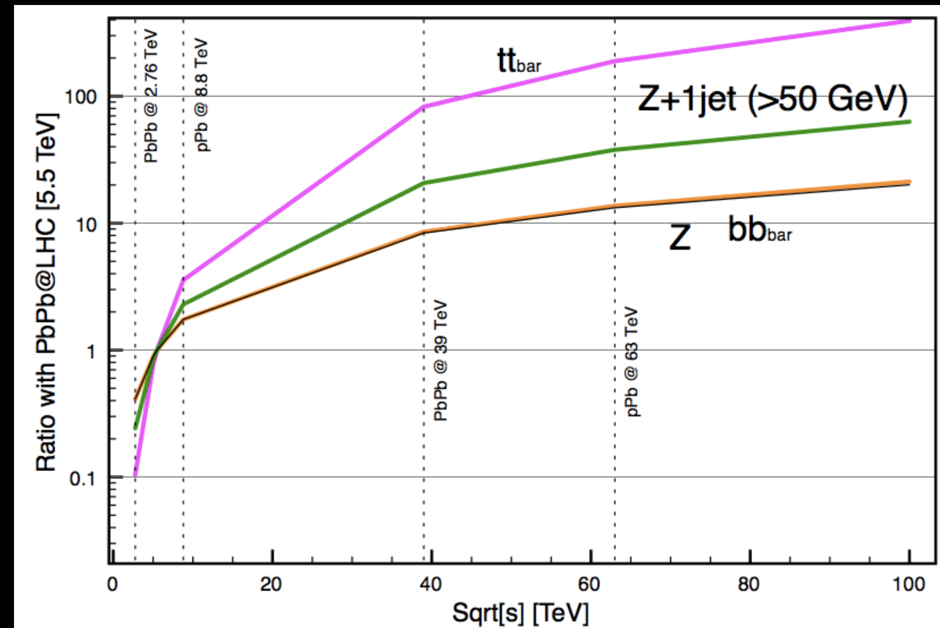
- 2015 HI run brought ~ 0.5/nb PbPb, 30/pb pp @ 5 TeV
  - max PbPb collision rate > 15kHz
  - pp stat ~ 1.5xPbPb in 1/5 of data taking time
- In Run 3, 4 expect ~1.5-3/nb per run per experiment; **10-20/nb total**
  - ATLAS, CMS should be able to take pp reference in 1/6 of PbPb running time; ALICE?

	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

- In addition: larger acceptance, better tracking efficiency, better vertex resolution, “infinite” DAQ/Trigger b/w for Run 4

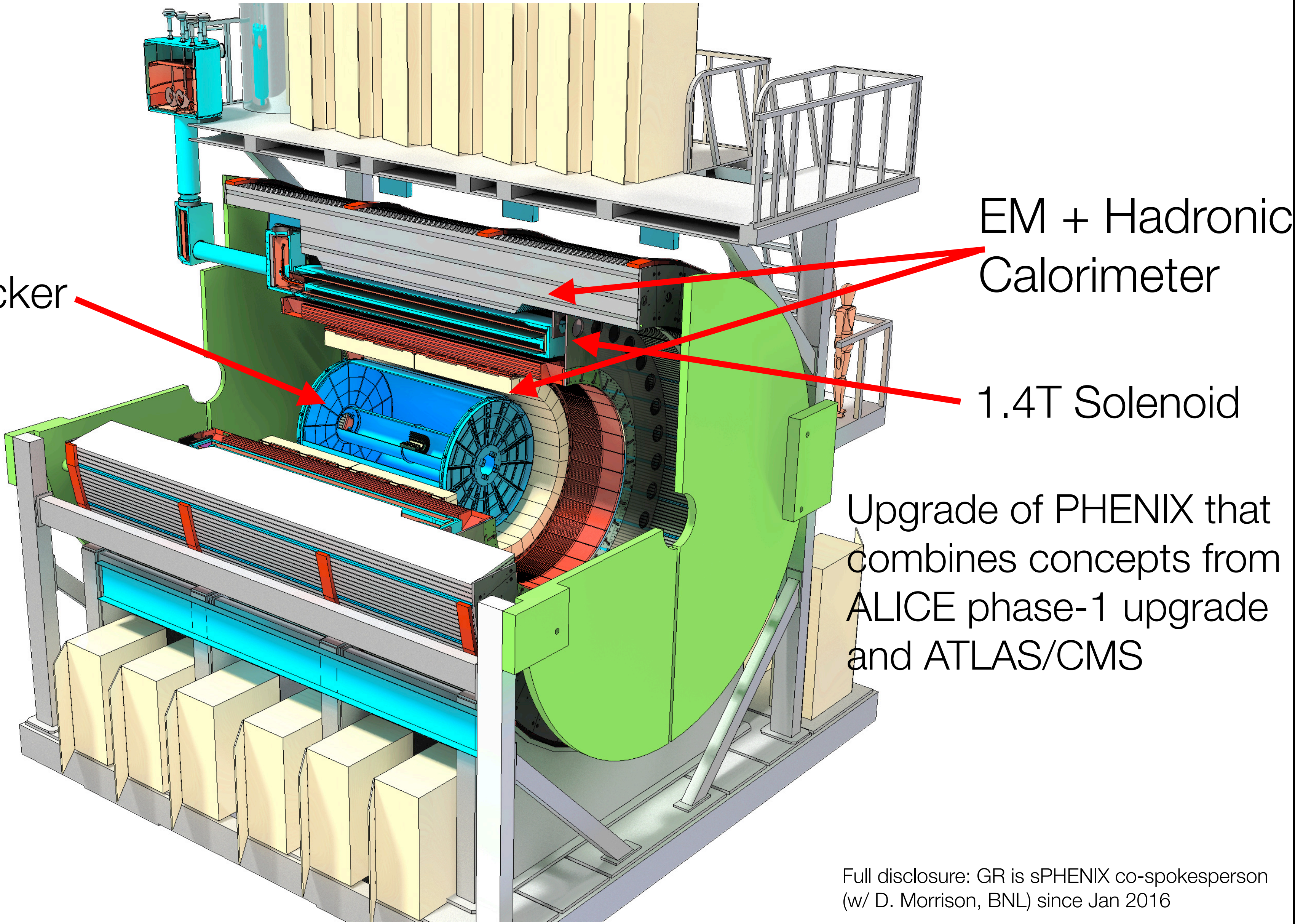
Heavy-Ions at FCC





- Further vast enhancement of hard probe statistics
- New tools become available: tt_{bar}

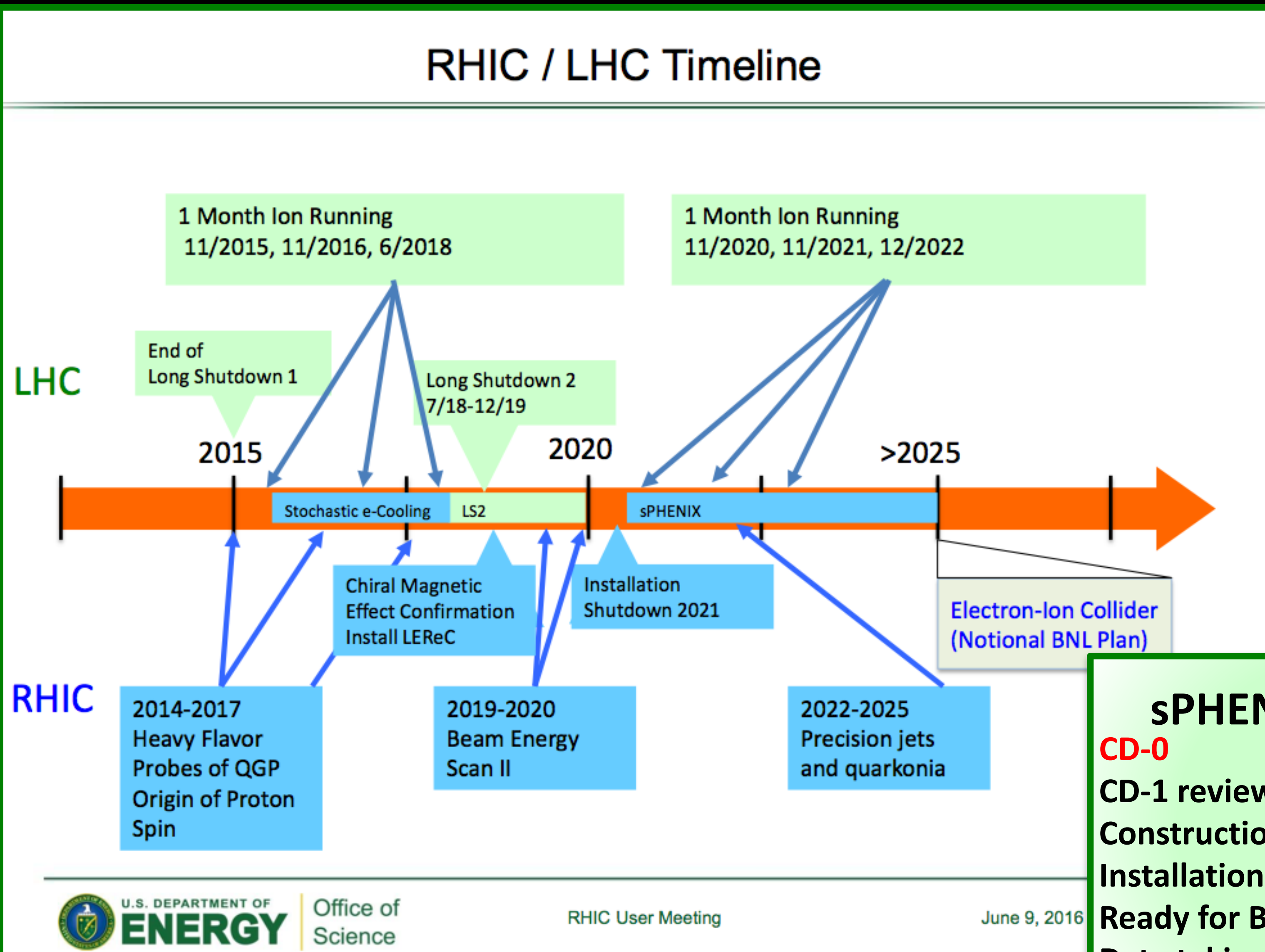
Meanwhile at RHIC: sPHENIX



Upgrade of PHENIX that combines concepts from ALICE phase-1 upgrade and ATLAS/CMS

Full disclosure: GR is sPHENIX co-spokesperson (w/ D. Morrison, BNL) since Jan 2016

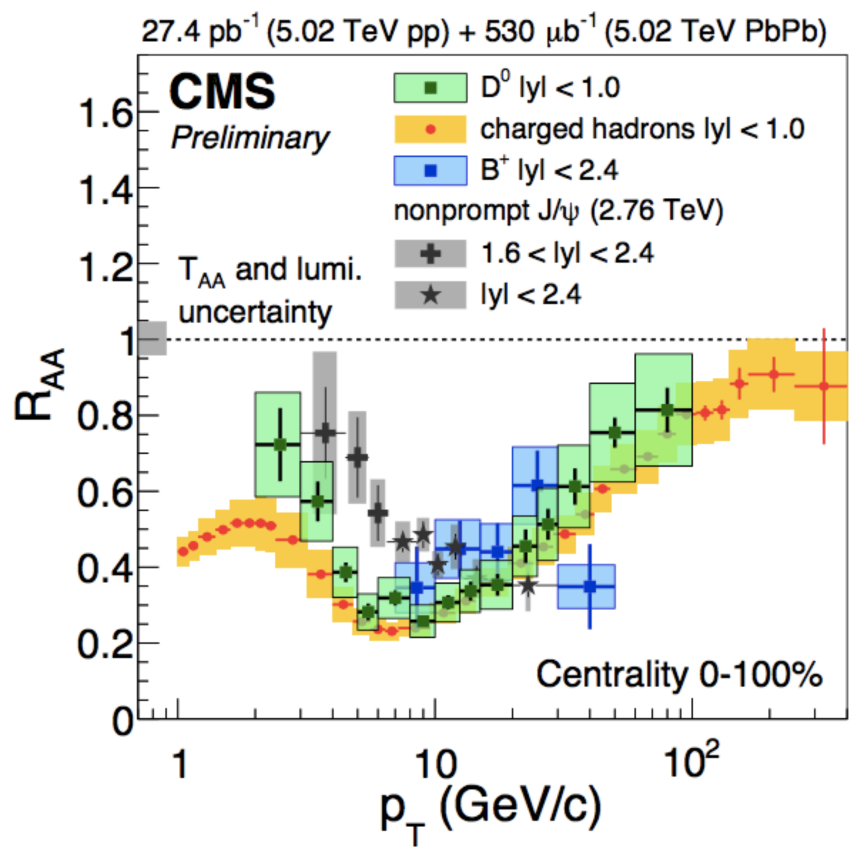
The next decade in heavy-ions



sPHENIX Schedule

CD-0	Sept 2016
CD-1 review	Nov 2017
Construction Phase	Jul 2018
Installation complete	Apr 2021
Ready for Beam	Jan 2022
Data taking	- 2025+

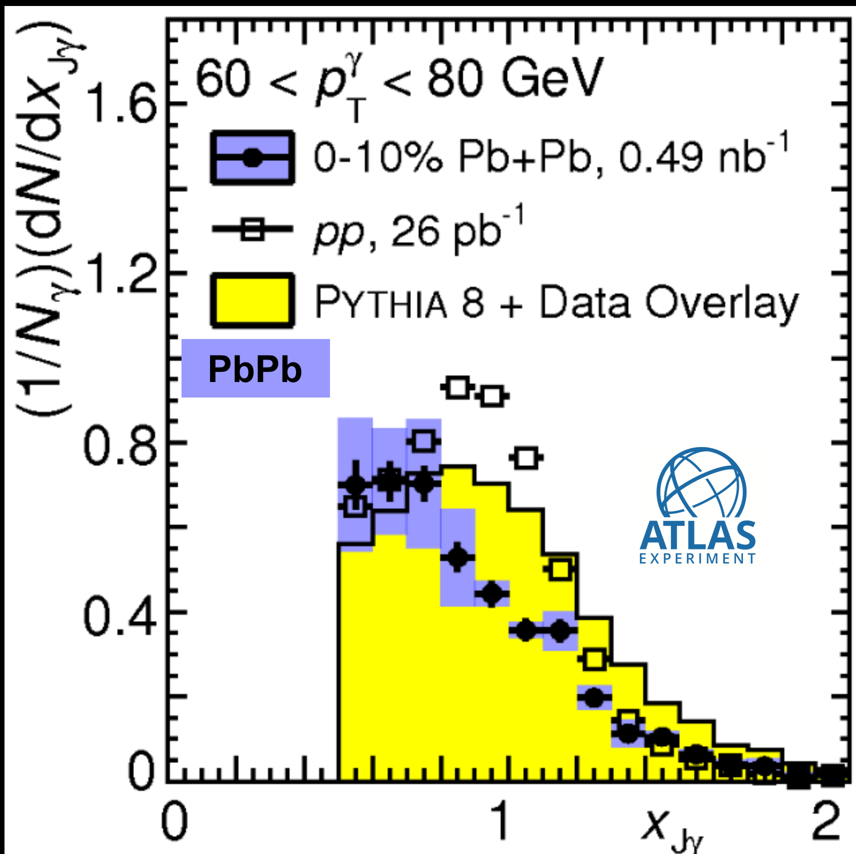
HF Spectra in LHC Run 3+

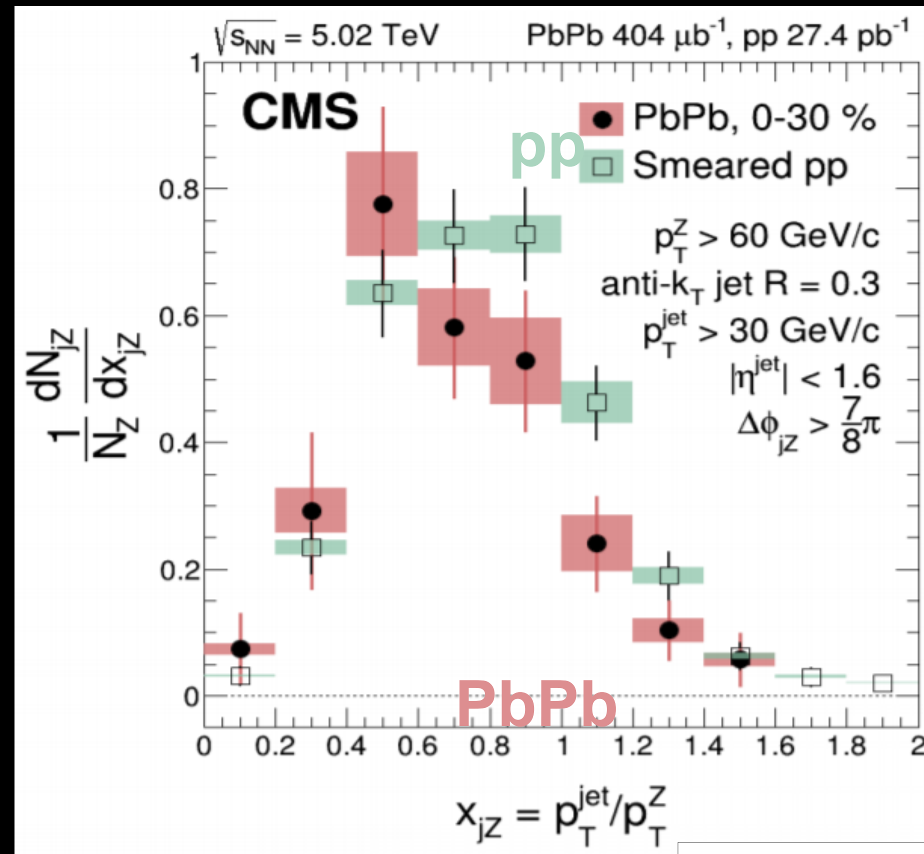


- Heavy Flavor Future: 0.5/nb → 10/nb+; 1→3+ experiments; better resolution, efficiency; more decay channels
- Expect errors comparable to $h^{+/-}$ today
- Extension to low p_T (~0 for D^0)

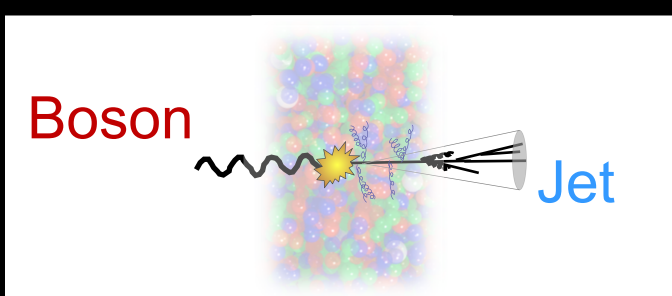
Boson-Jet in pp and PbPb at 5.02 TeV

ATLAS-CONF-2016-110



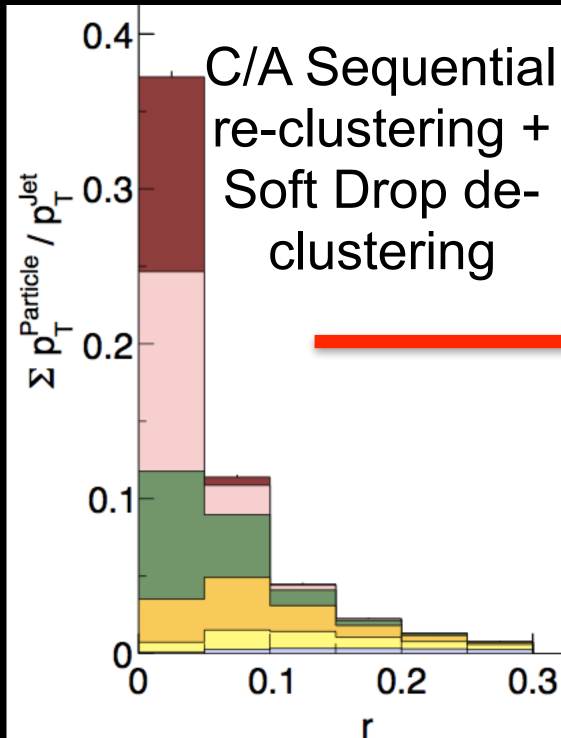


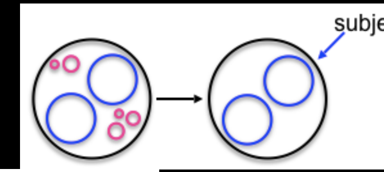
arXiv 1702.01060
Submitted to PRL (2017)

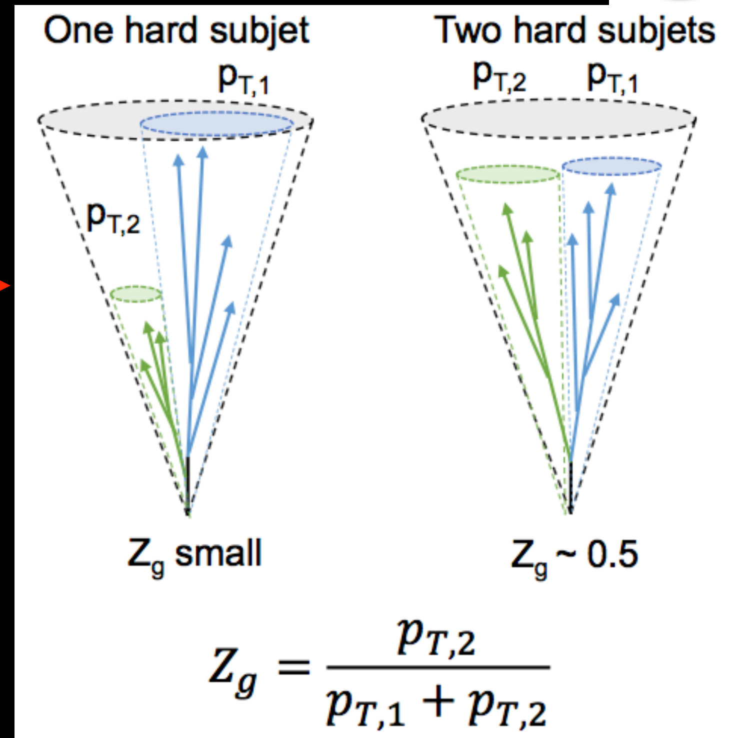


Advantage: Comparison of PbPb and pp for same initial state (as opposed to e.g. dijets,RA etc)

New Direction: Jet Substructure



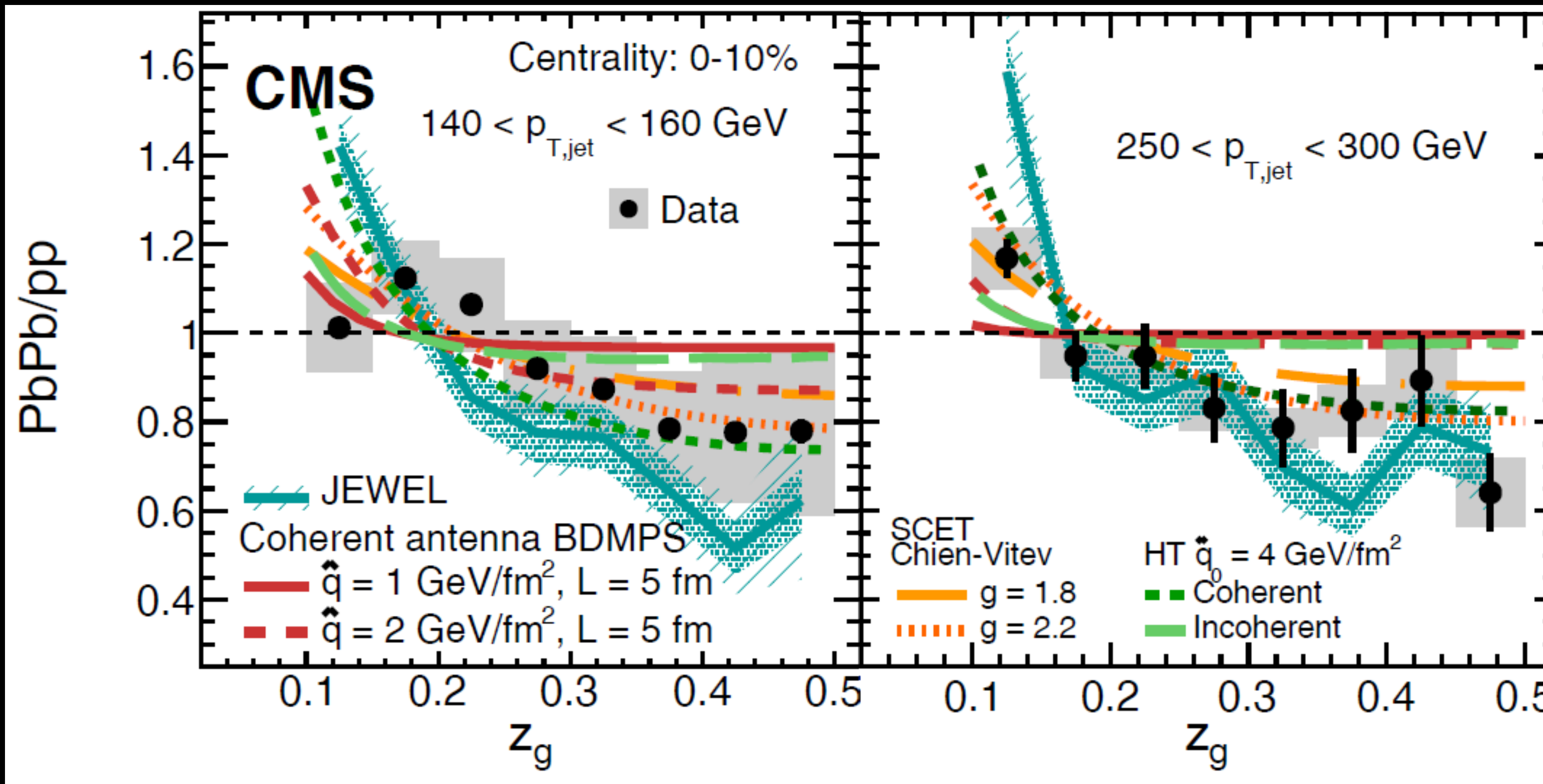




Use jet grooming techniques to map structure of final state to evolution of parton shower (e.g., “splitting function”)

Does medium resolve early parton shower evolution?
Color coherence?

Groomed Jet Splitting Function



- **JEWEL** enhancement of low Zg jets (due to medium response)
- $SCET_G$ modification due to medium induced splitting function
- **HT** Coherent antenna BDMPS Coherent energy loss

HL-LHC will allow combination of boson-tag or HF tag and grooming/substructure studies

Jet Structure at HL-LHC and FCC

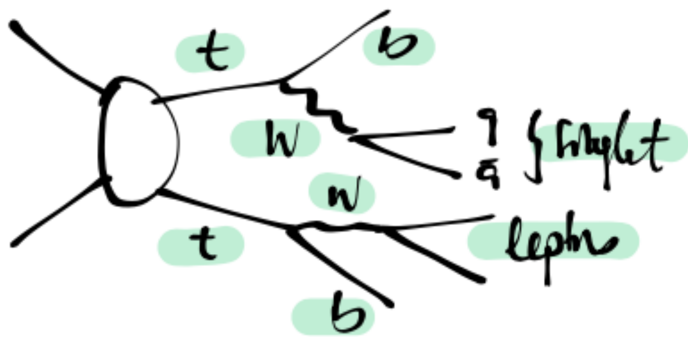
Apolinário, Milhano, Salam, Salgado :: FCC Yellow Report :: several conference talks :: paper with LHC study soon

Simple question

Can we **more directly measure the space-time** development of the medium with jet observables? - including **late times**

Switch-off the cascade for some time

Use **color-singlet** configurations



Boosted tops a possibility

Main limitation: very rare - **high statistics needed (HL-LHC & FCC studied here)**

HotLHC

Hard Probes - September 2016

Boosted tops in HIC 2

Boost (time dilation) allows to control when/ where in plasma top/W decay products appear

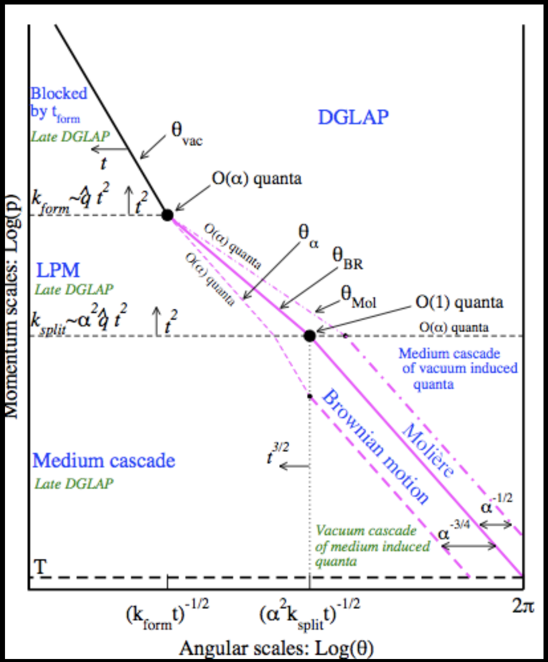
Summary

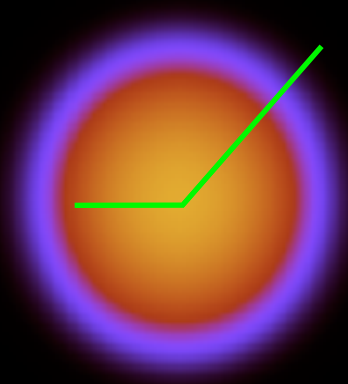
- Goal: Properties and microscopic nature of QGP
- Large harvest of results from Run 1+2 at LHC and RHIC
  - Hydrodynamic flow in large and small systems
  - Modifications of jet yield and structure
  - (Suppression/regeneration of quarkonia)
- Old questions remain; new ones arise
- Expect continued experimental progress at LHC + RHIC
  - more complete control over initial/propagating hard scattered object(s)
- **Critical issue: ability of theory to exploit new experimental information**

Probing the inner workings of QGP

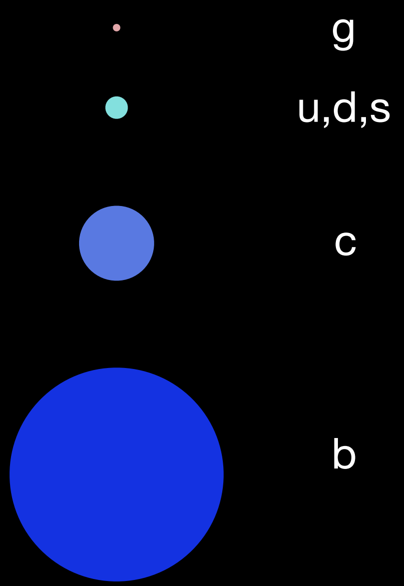
Three key approaches to study
QGP structure at varying scales

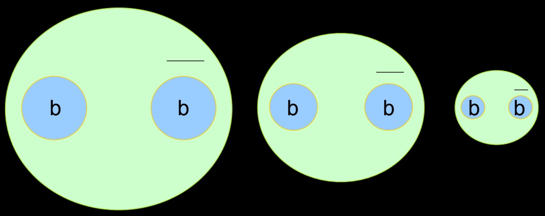
Jets and jet structure





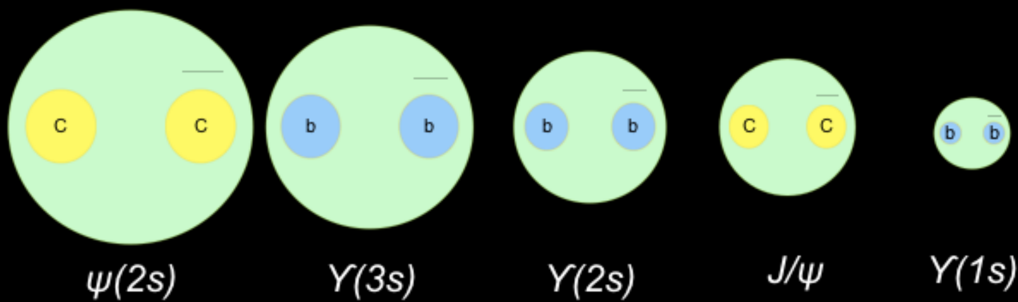
Parton mass/flavor

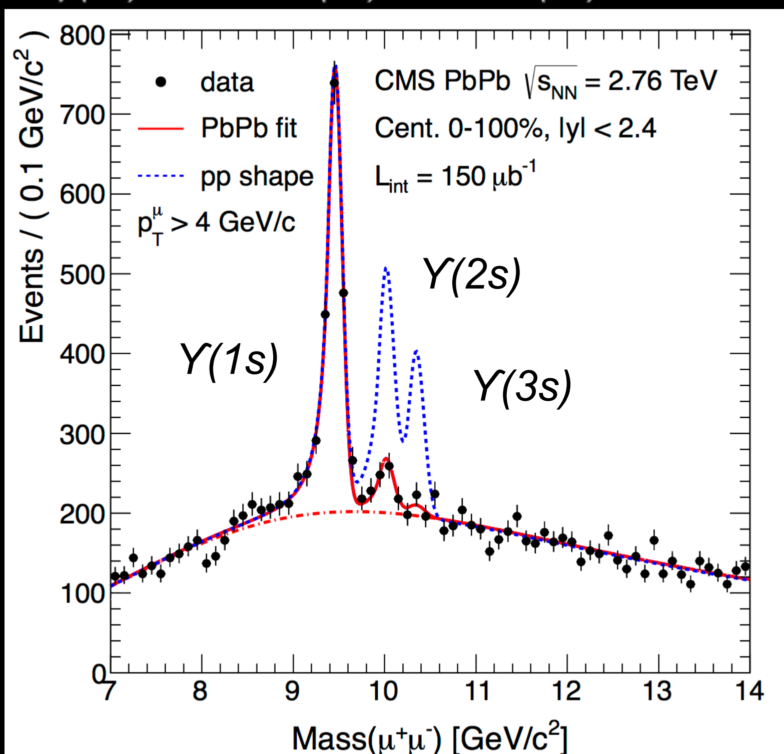




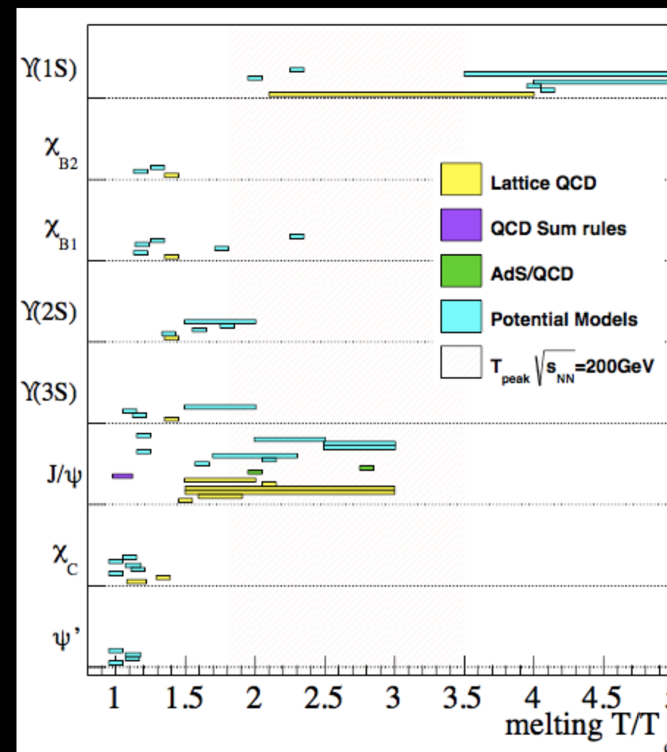
Quarkonium spectroscopy

“Sequential melting” of bottomonia



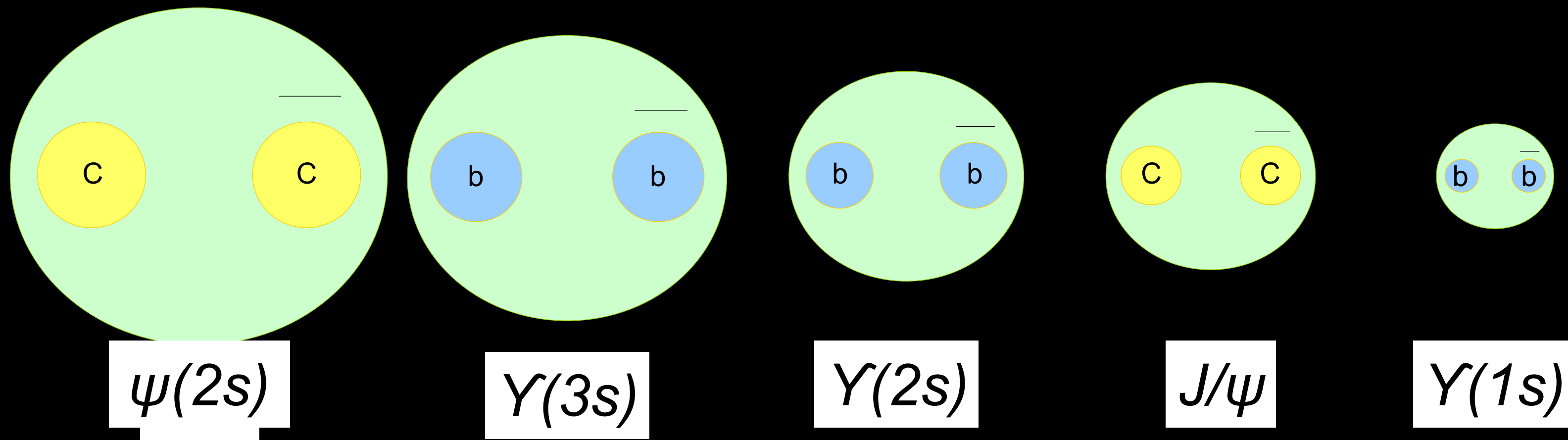


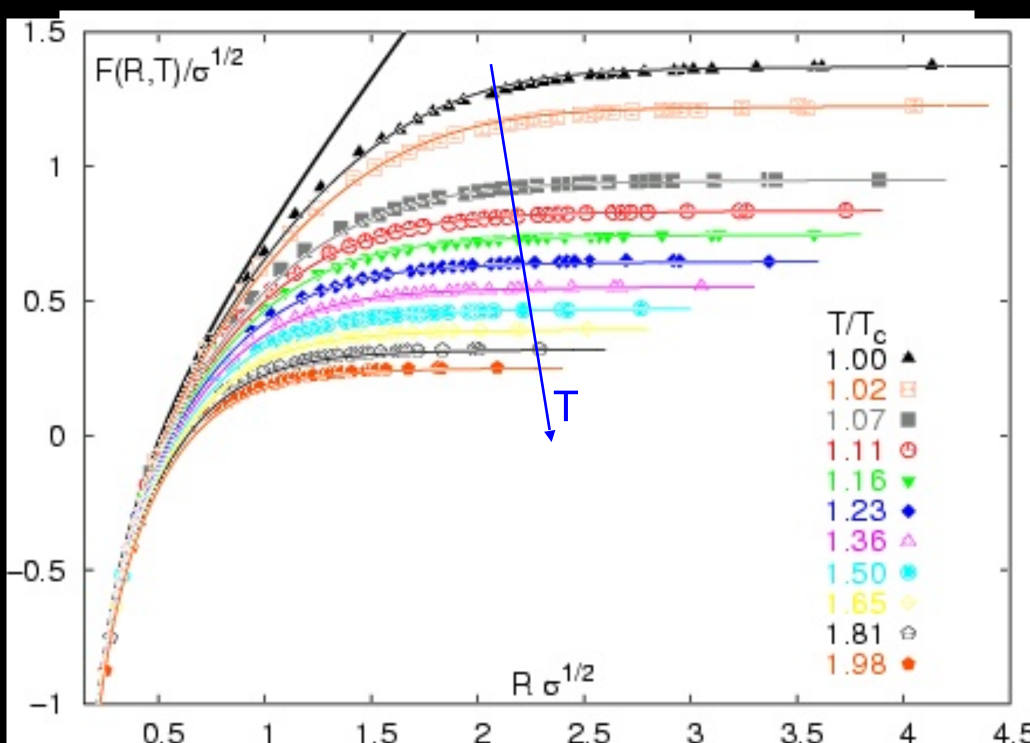
Rapid disappearance of larger (more loosely bound) Y states

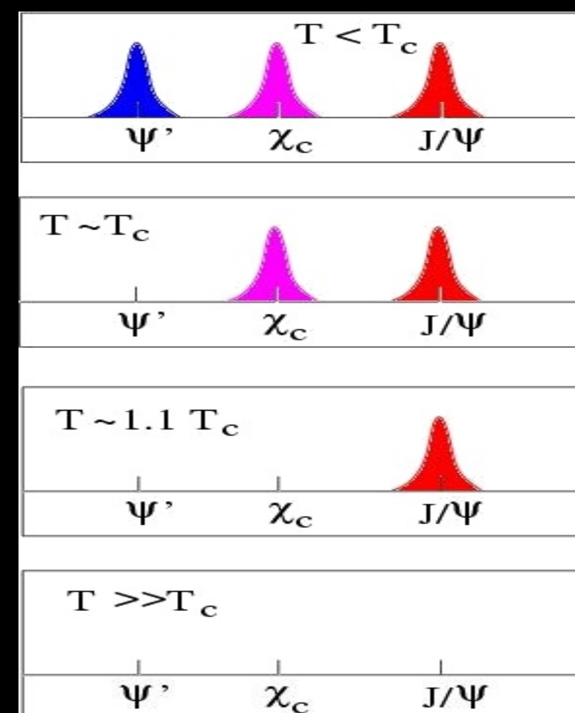


Connection between Upsilon suppression and QGP T

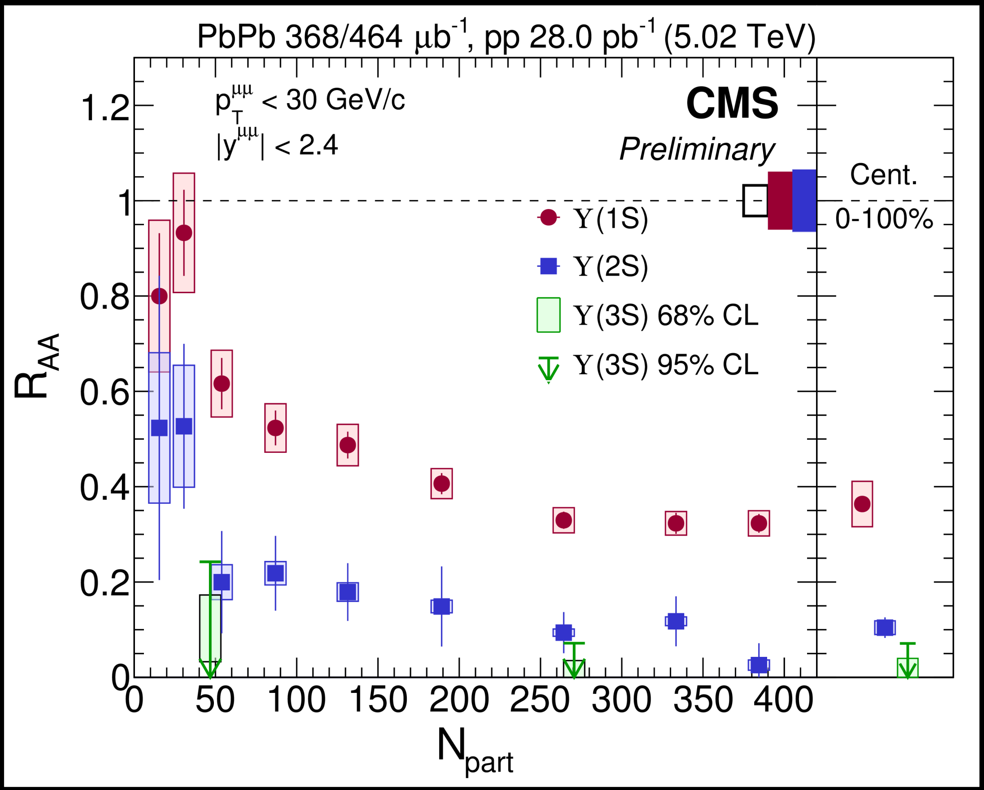
Quarkonia have different binding energy/size

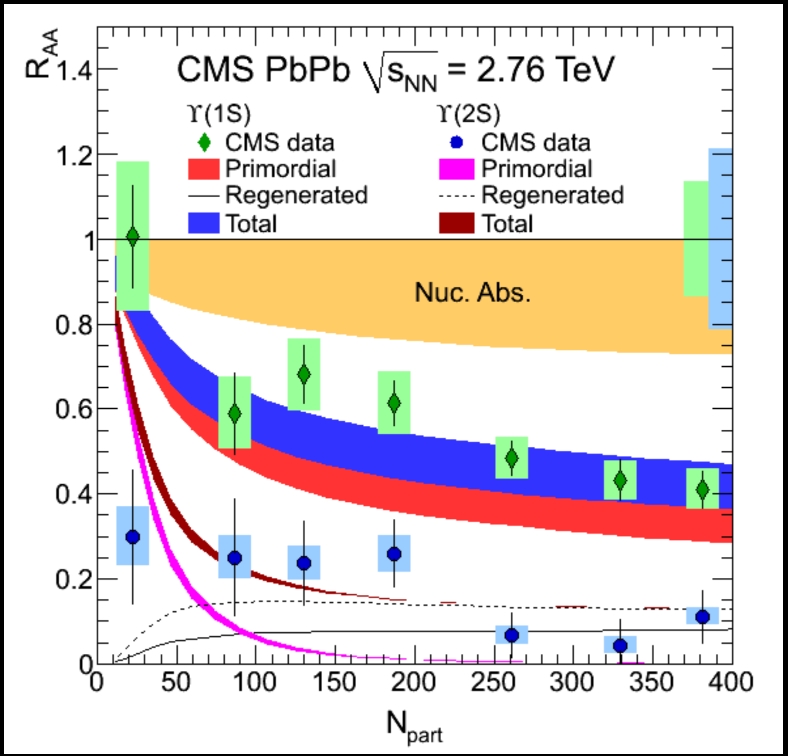






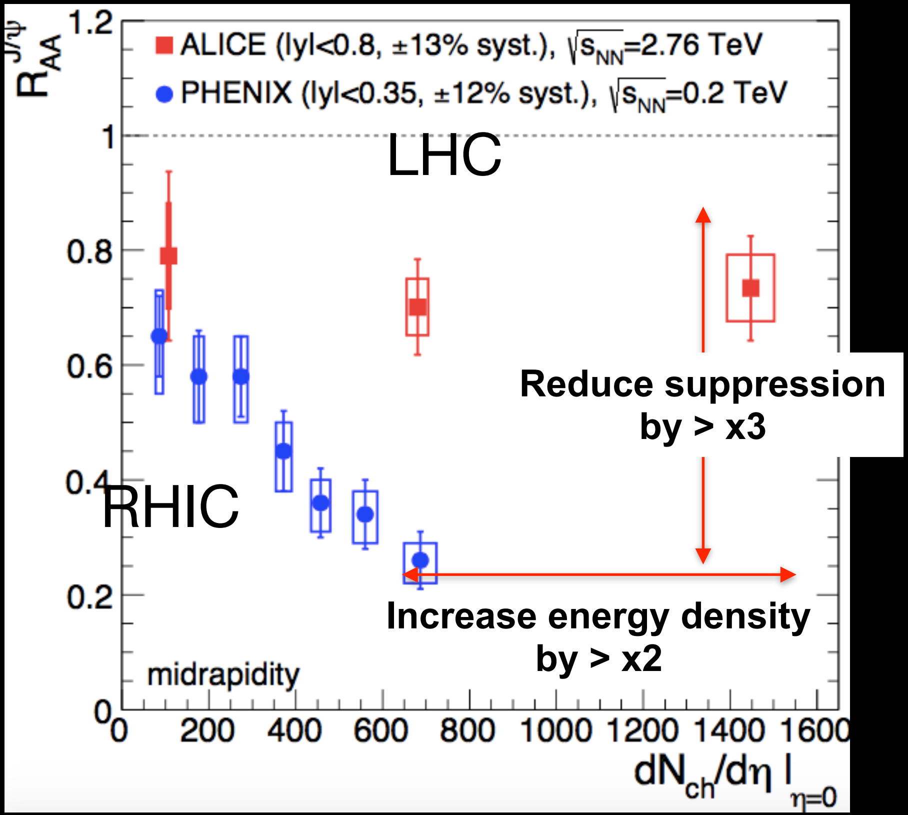
Y family sequential suppression



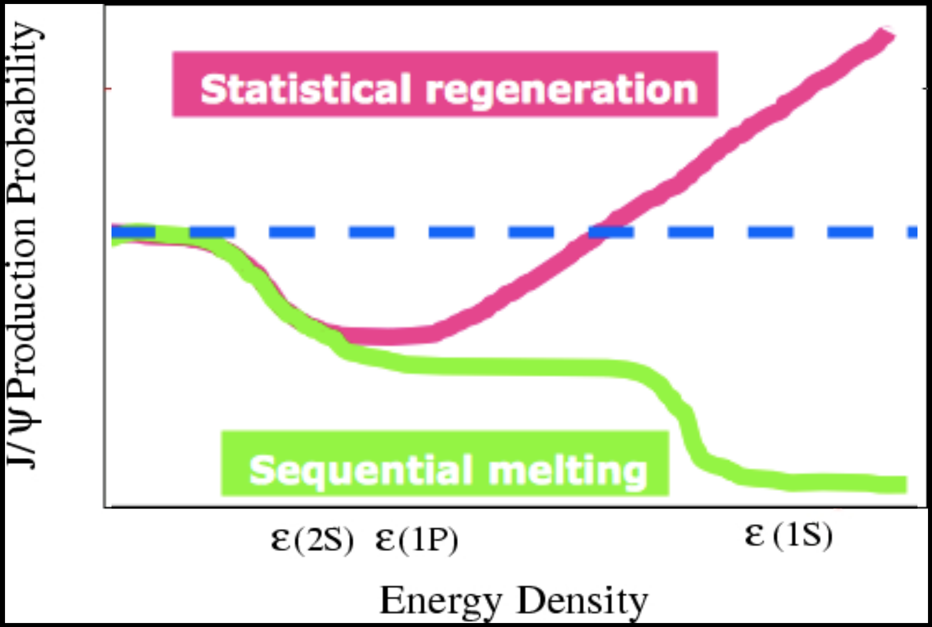


Suppression of Y(1S), Y(2S) and Y(3S) states reflects binding energy and QGP temperature (up to 690 MeV)

Statistical regeneration of charmonia



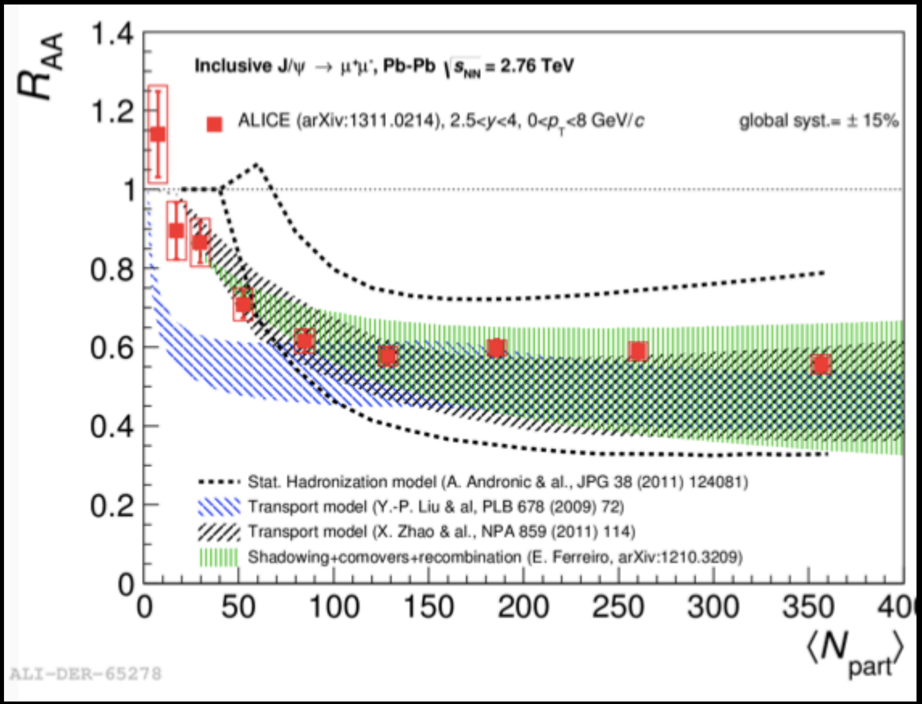
J/psi from of c and cbar produced separately

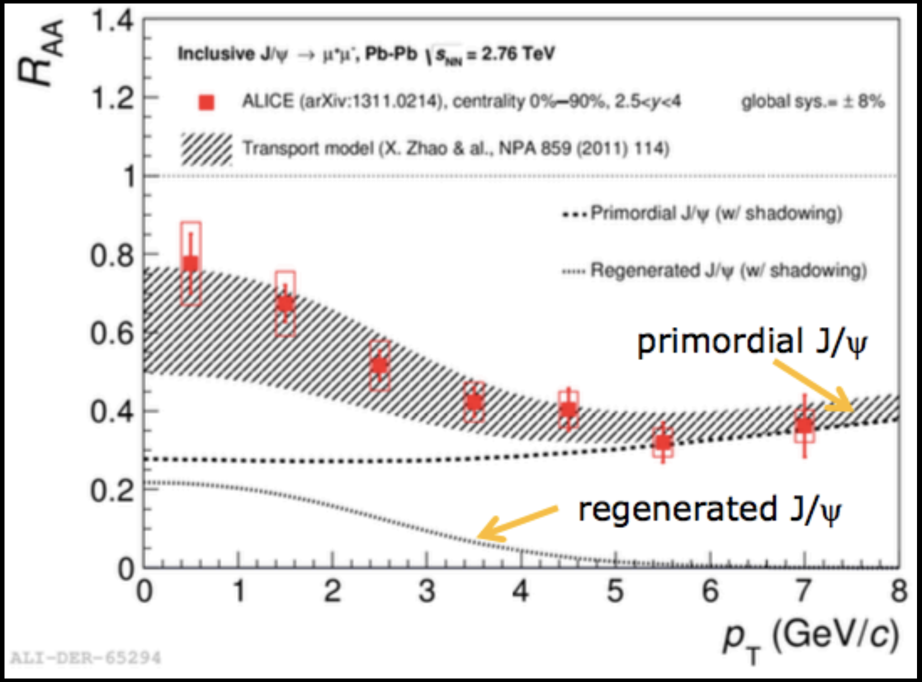


Less J/psi suppression at higher collision energy (higher T)?

Regeneration (aka "recombination" or "coalescence") more likely with more c and cbar around

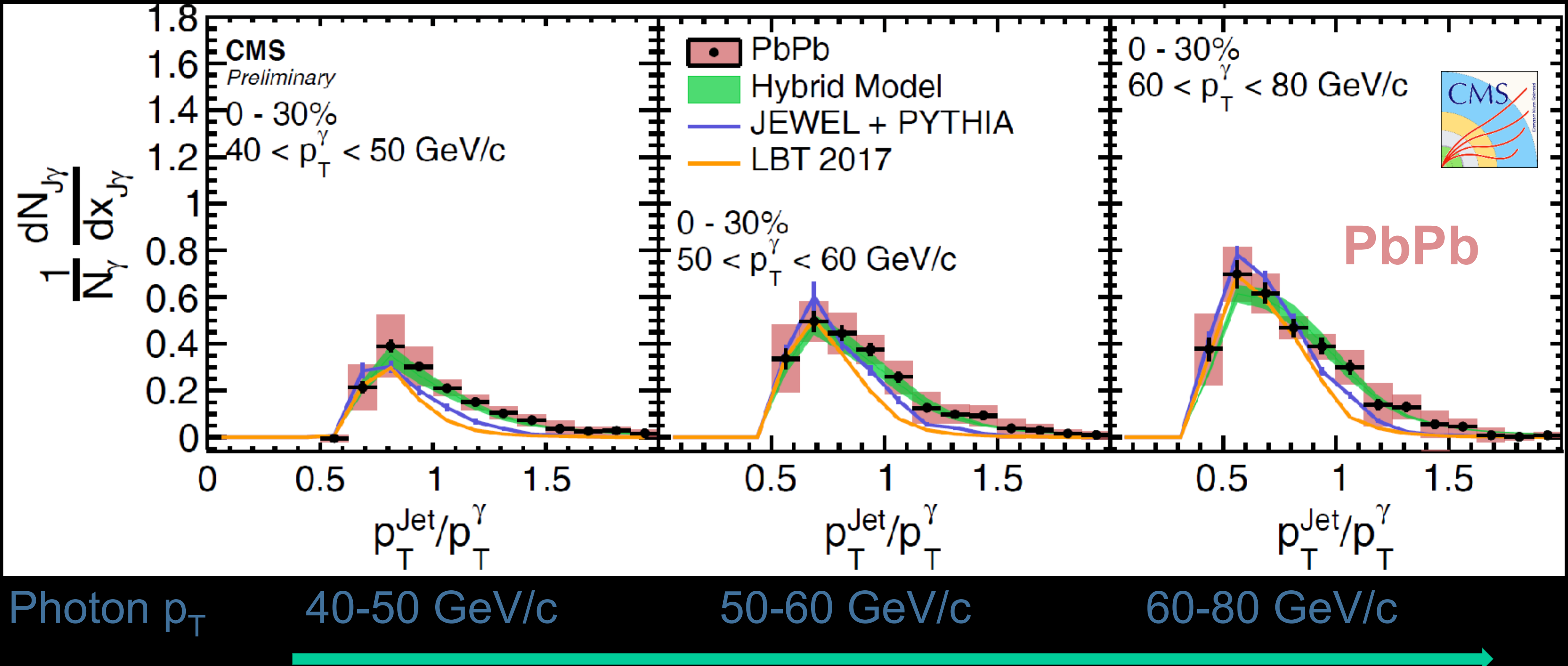
Comparison to calculations





Calculations including suppression of the initial pre-J/psi and regeneration during the collision can match data

Photon-Jet Data vs. Theoretical



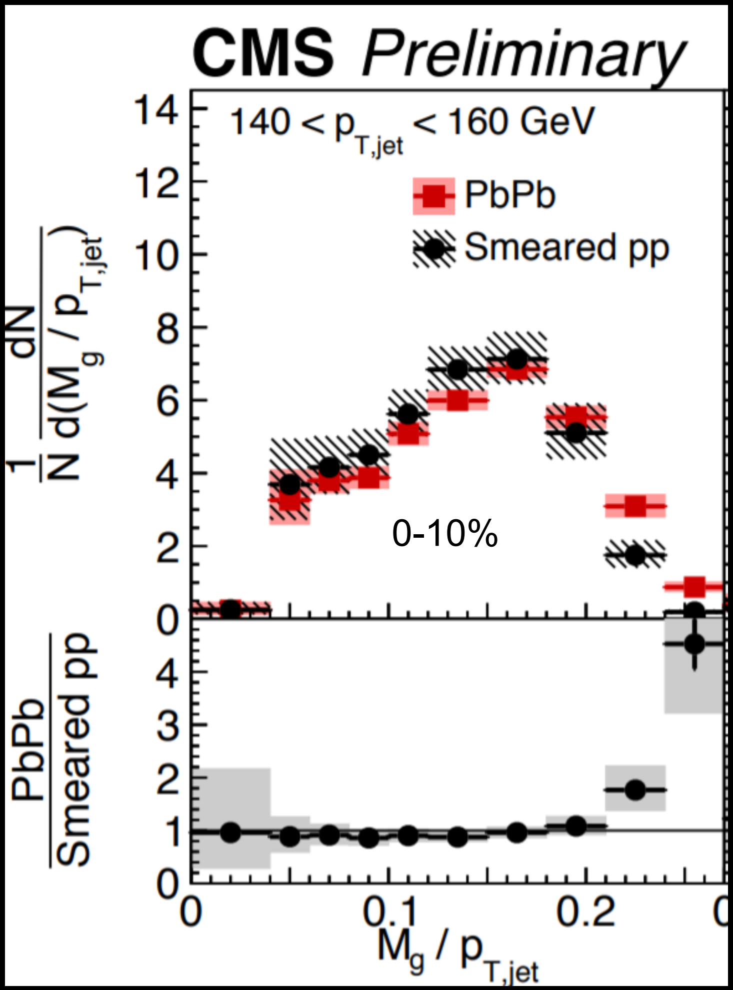
- JEWEL & LBT: capture the general trend, but doesn't give a perfect description of the data. Could be due to the pp baseline

- HYBRID Model: very good description of the data

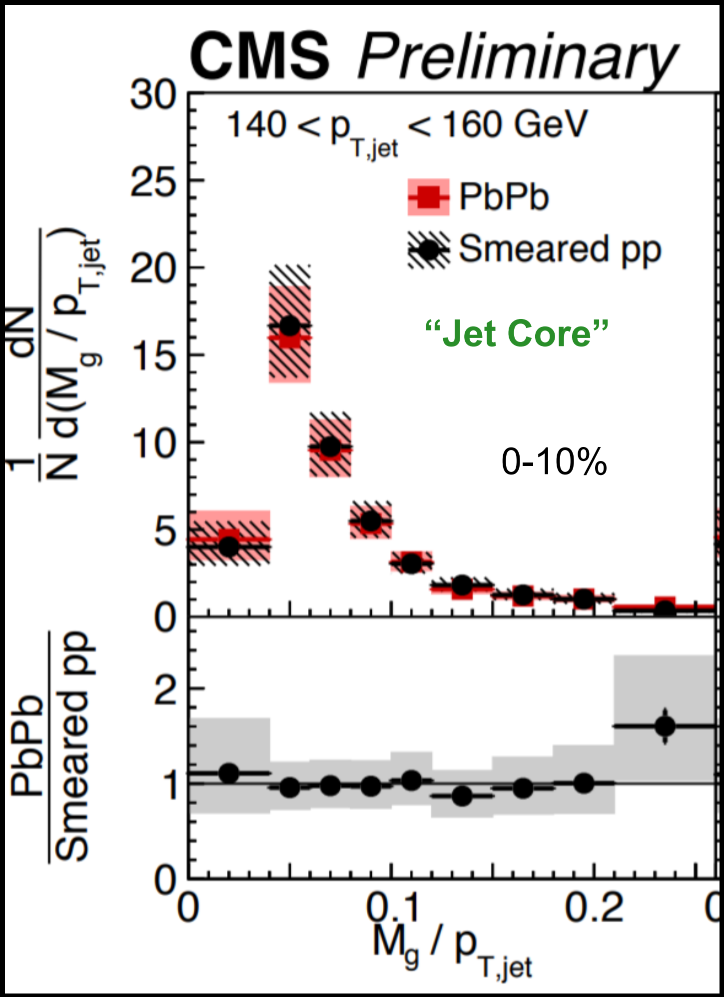
CMS-PAS-HIN-16-002 (2017)

Groomed Jet Mass

$(z_{cut},\beta) = (0.1,0.0)$

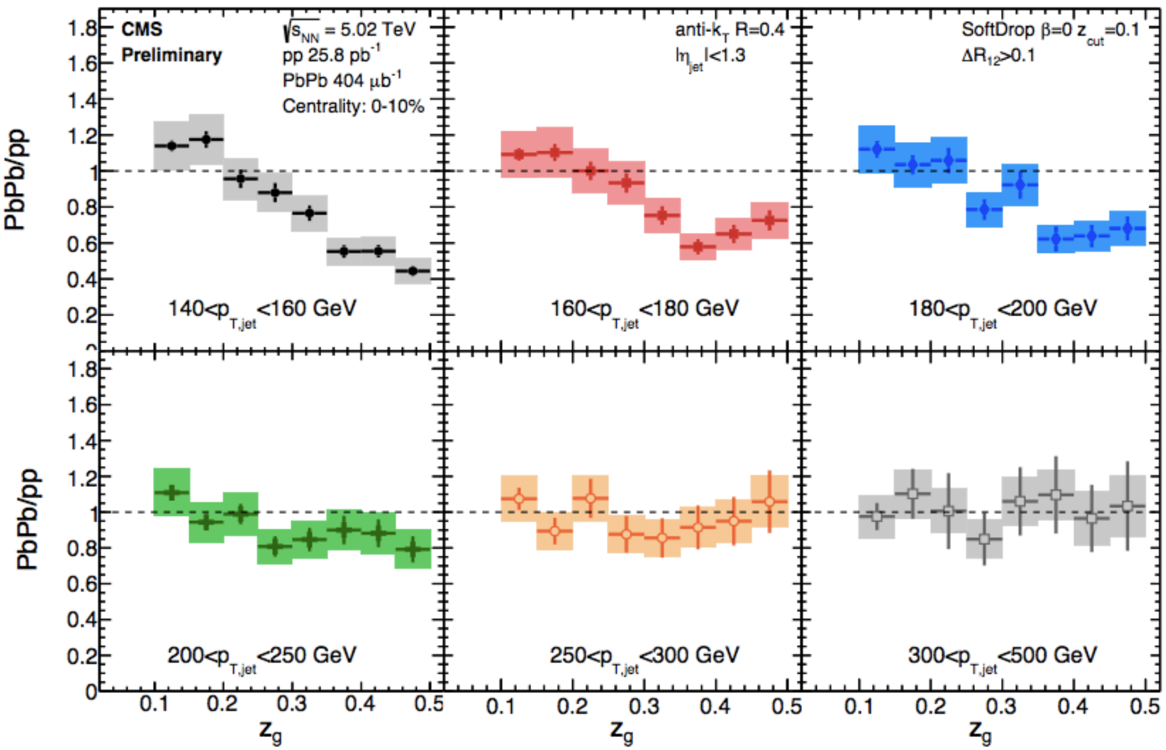


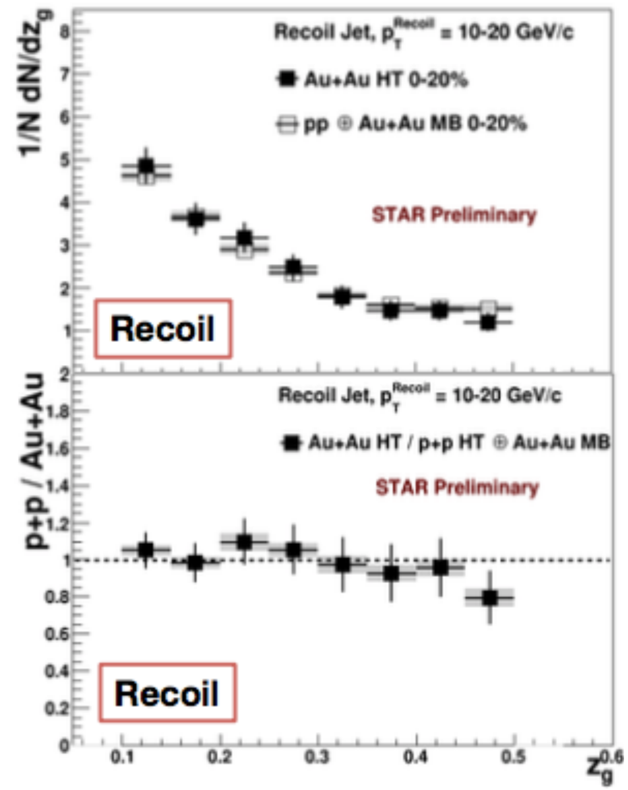
$(z_{cut},\beta) = (0.5,1.5)$



- Relative enhancement at large mass in central collisions for 140-160 GeV

Splitting function in AA





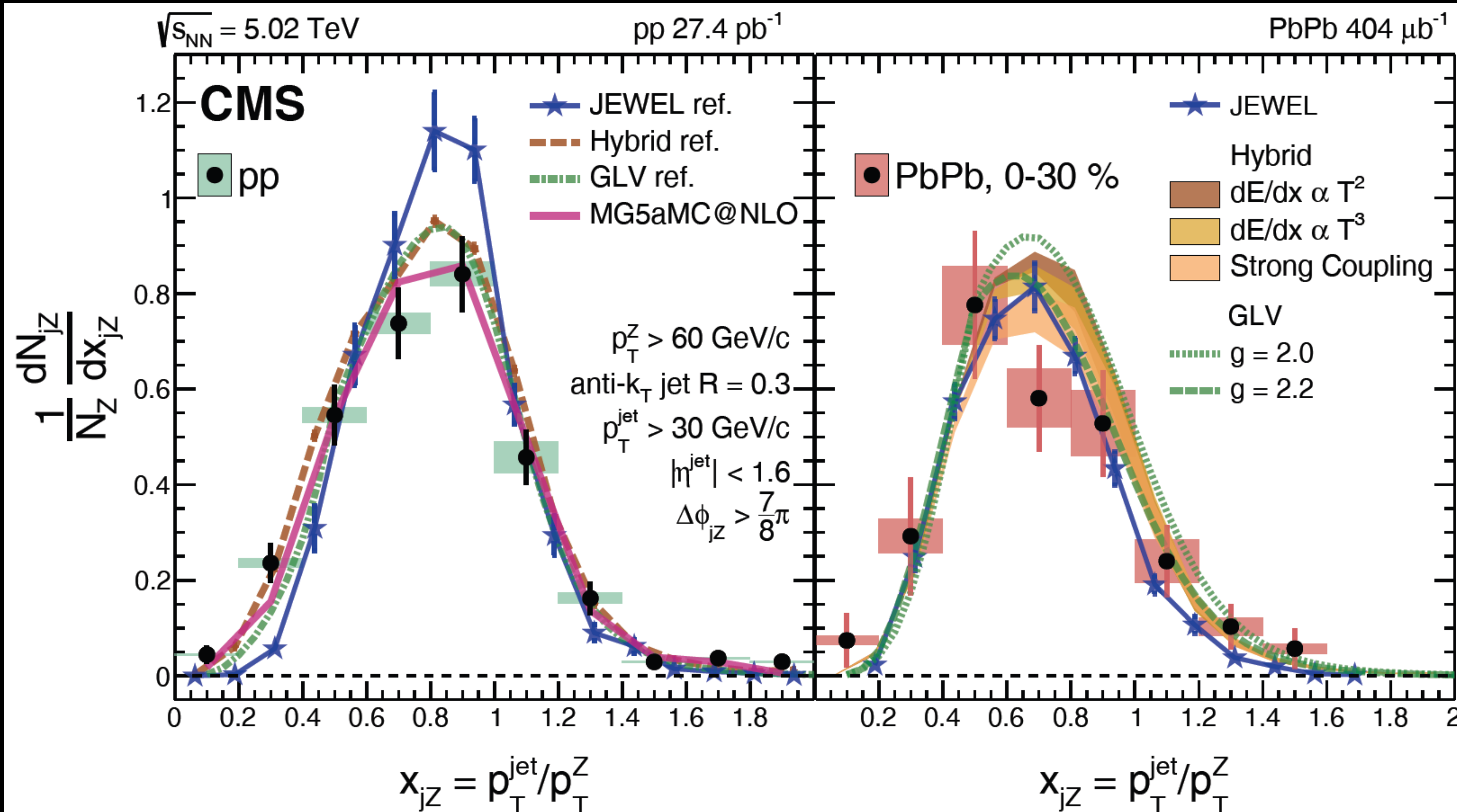
"Splitting function" is modified for "lower" p_T jets at LHC…

…but not for low p_T jets at RHIC

QGP resolves earliest hard splitting…

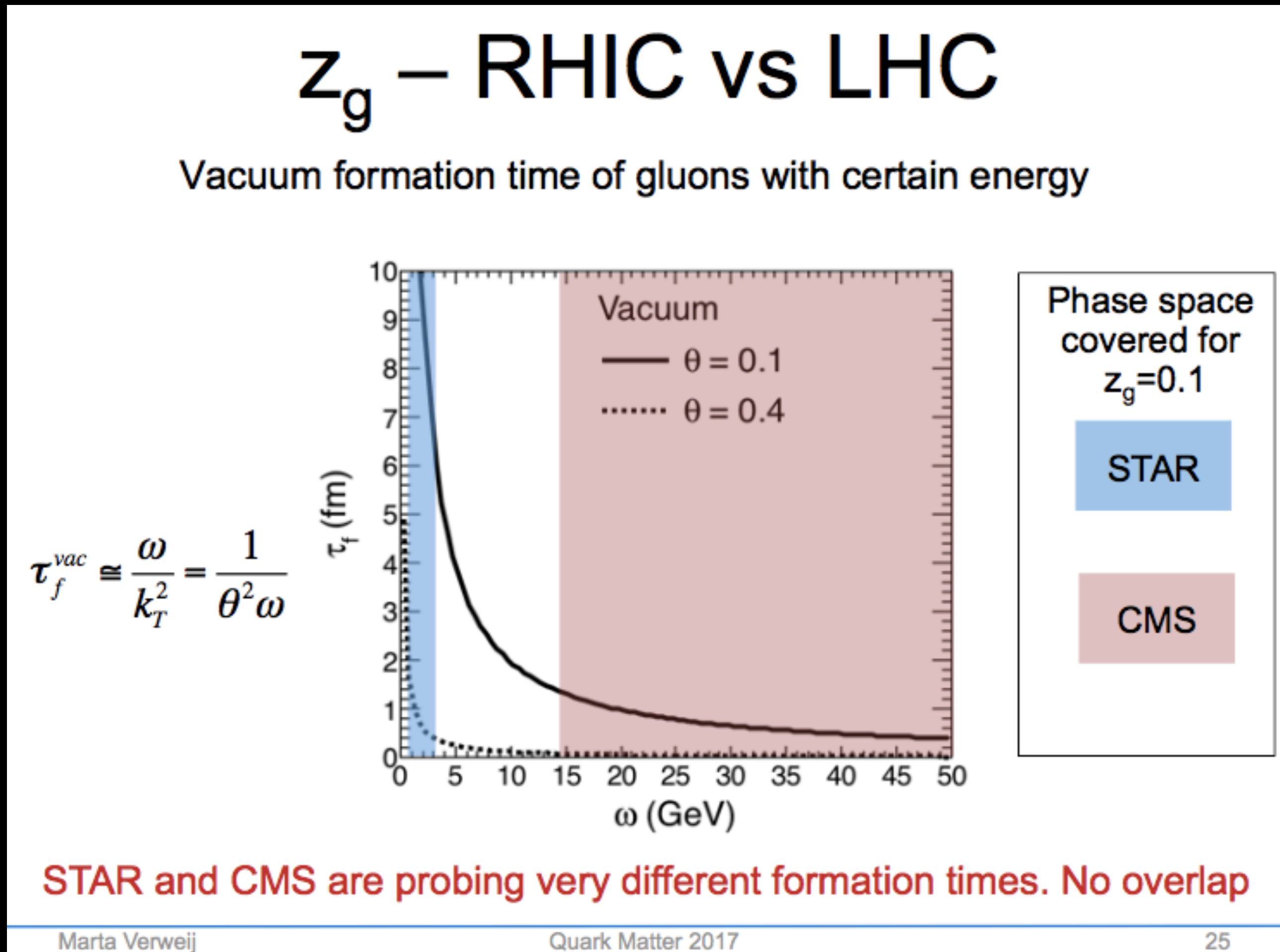
…or not?

Z-Jet vs theory



- Important to have correct pp baseline
- Reasonable agreement between data and theory curves from JEWEL, HYBRID and GLV

Z_g and Formation Time



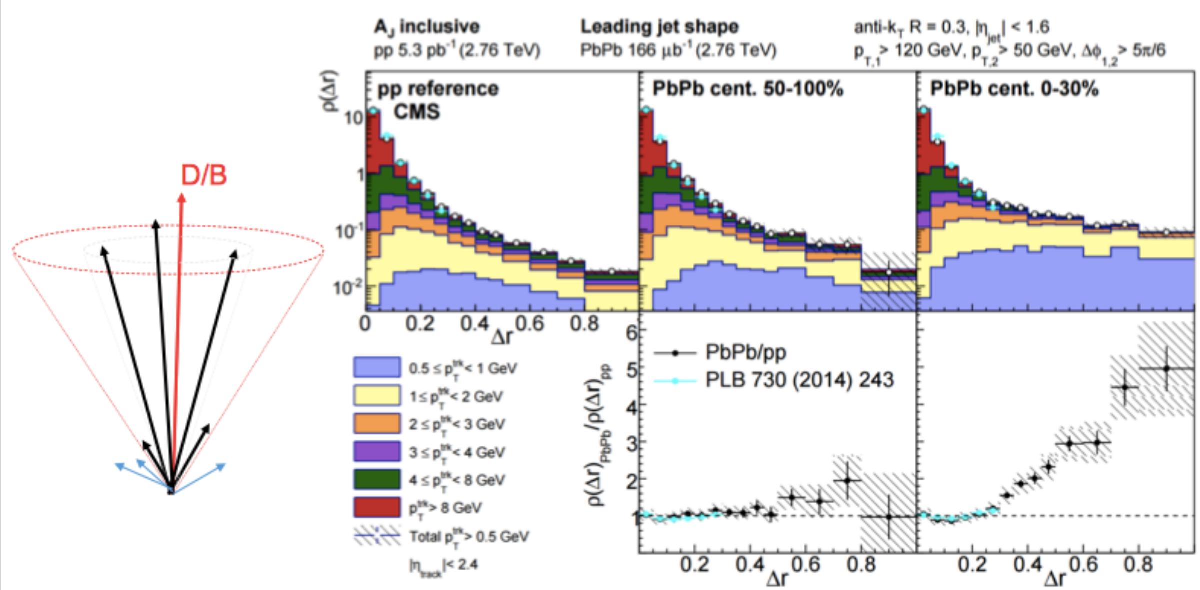
Close the gap with lower p_T jets at LHC and higher p_T jets at RHIC (→sPHENIX)

Medium response or modified jets?

How to distinguish jet-stuff from medium-stuff, if there's no distinct angular structure of medium response?

YJ Lee: Look for medium response in HF-jet correlations

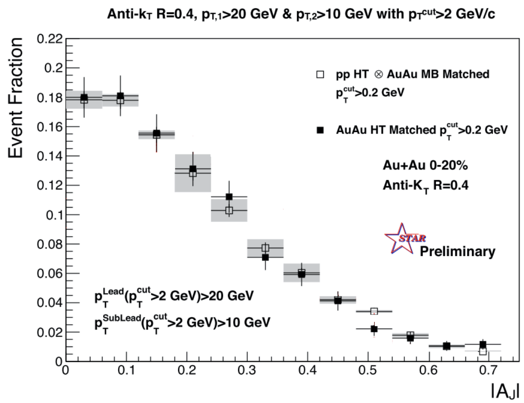
D/B-jet and D/B-photon correlation



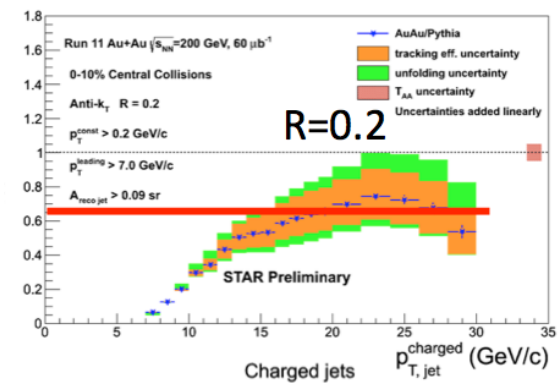
- **Propose to study D/B-jet and D/B-photon correlation at RHIC and LHC**
- D meson and B meson as a tool to study the fate of the intermediate p_T HF partons
- Relatively **less likely** to come from medium response, mass scale >> medium scale
- Jet and photon as a proxy to the initial parton direction

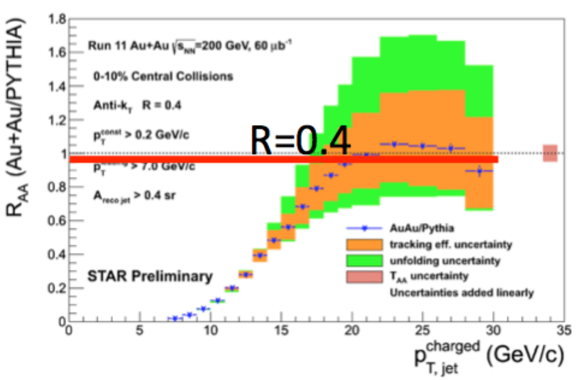
Energy flow differences at RHIC vs LHC

RHIC (STAR)



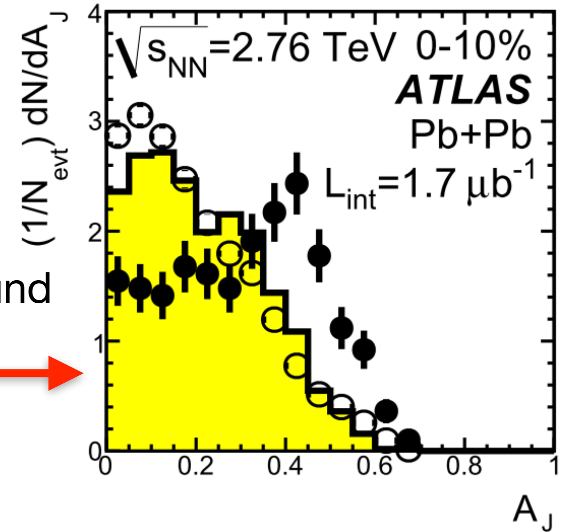
Jets balanced when including $p_T > 0.2$GeV



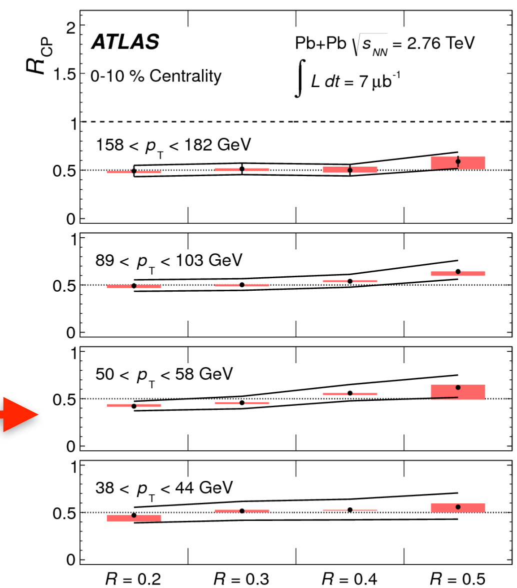


Strong radius dependence of jet RAA

LHC (ALICE, ATLAS, CMS)



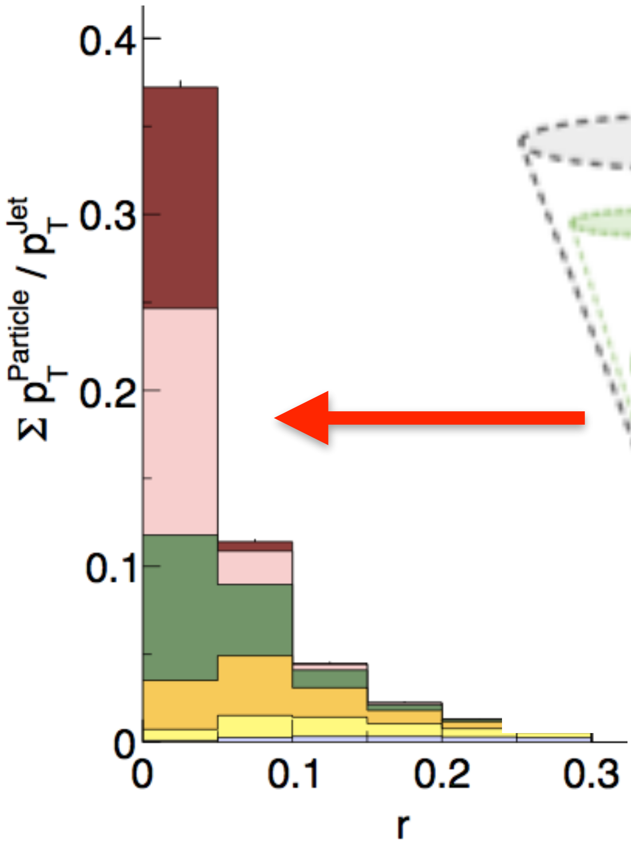
Energy balance found outside of jet cone



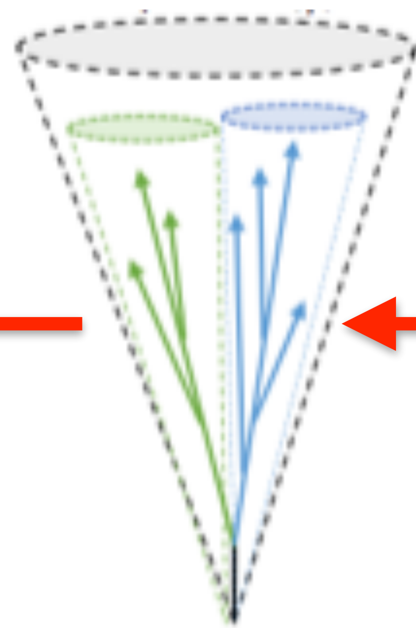
Weak radius dependence of jet RAA

Jets as Multi-Scale Probe

Final state jet

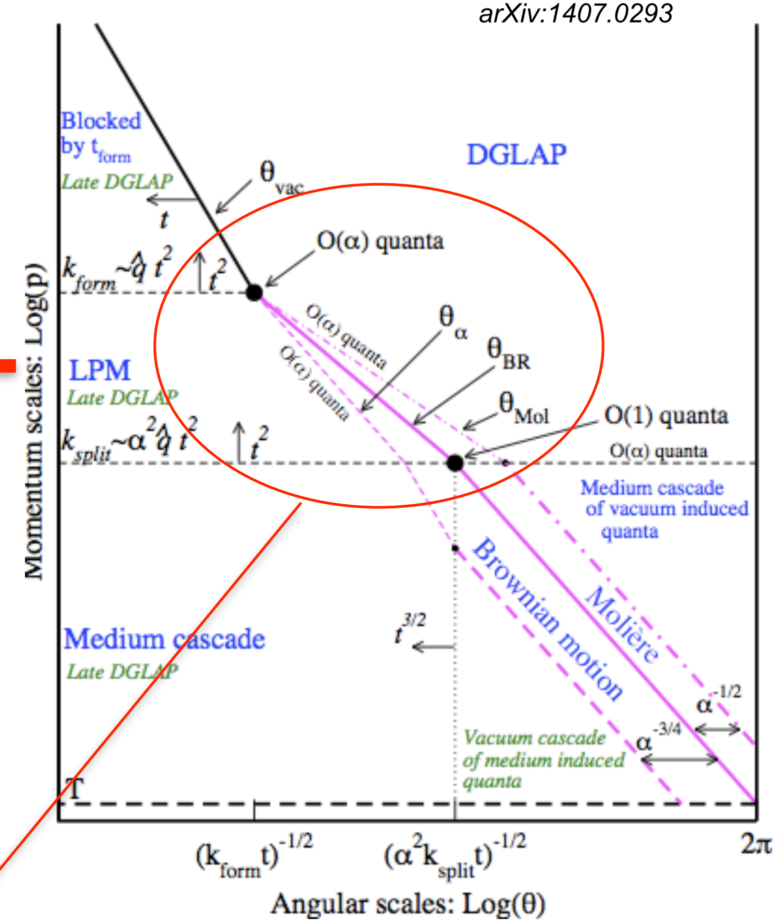


Parton shower



Snapshot of angular and momentum structure of intra-jet parton cascade

Kurkela, Wiedemann, arXiv:1407.0293

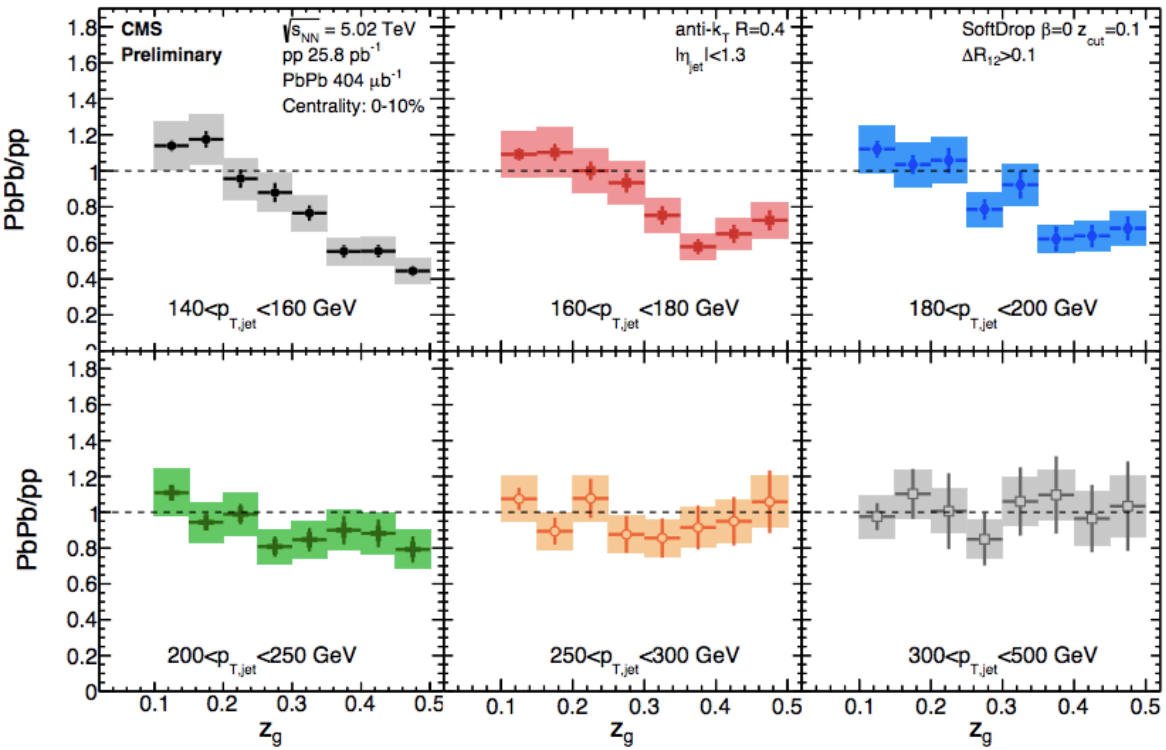


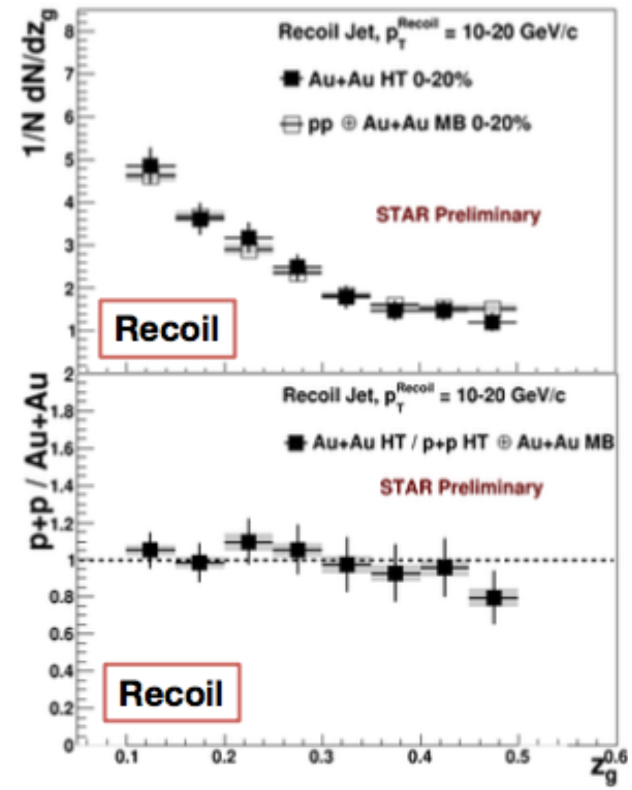
At different scales, evolution is dominated by different mechanisms:

- 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”

Splitting function in AA





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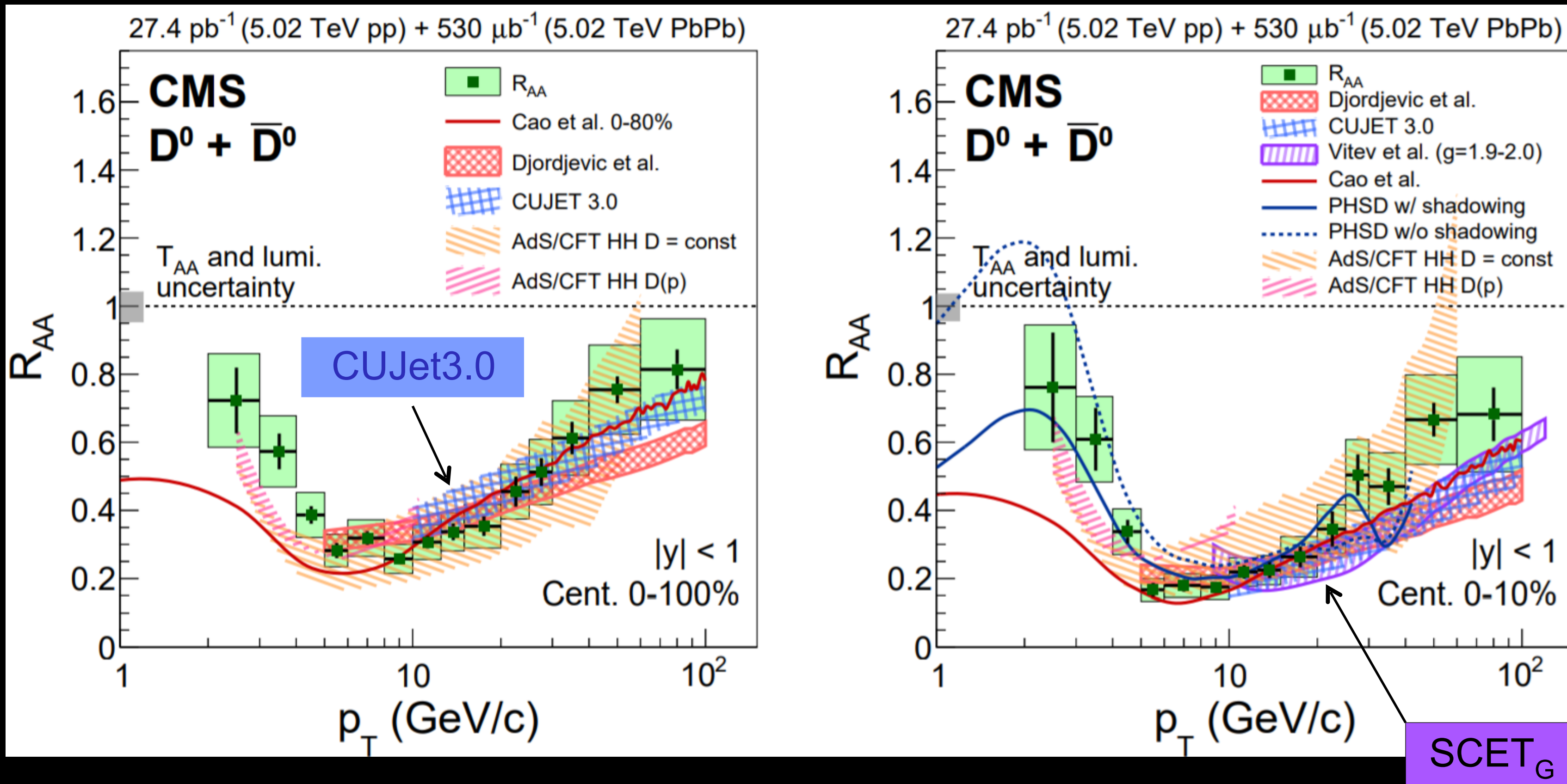
Description of the D^0 Meson Data

arXiv:1708.04962



- At high D^0 p_T: Trend captured by pQCD and AdS/CFT based models
- Details doesn't work perfectly, especially the slope of the D^0 R_{AA} vs. p_T