Highlights in Heavy Ion Physics: Current Status of Hot QCD Studies

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*Thank you to valuable feedback of colleagues working on heavy ion physics with ALICE, ATLAS, CMS, LHC-B, STAR, SPHENIX, PHENIX

**My take on the most interesting recent results

Why do we do Relativistic Heavy Ion Physics?

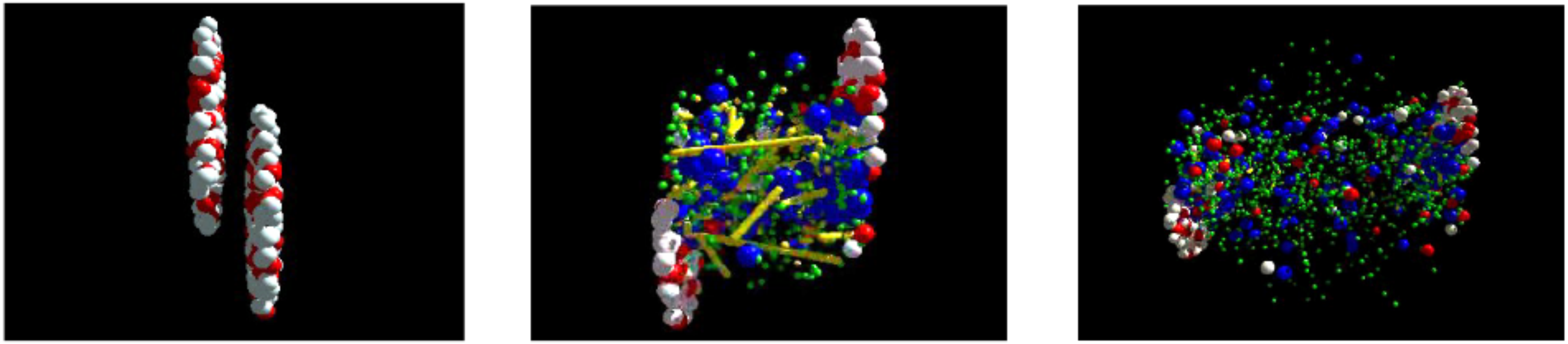
Goal: Create the hottest matter on earth
(Quark-Gluon Plasma)

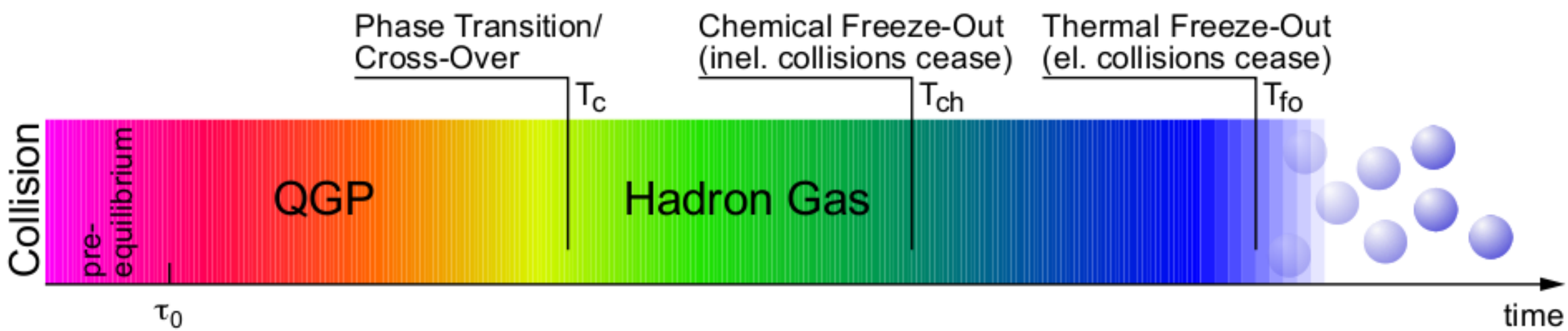
A relativistic heavy ion collision:
Two nuclei colliding at √s ~ 1 – 10000 GeV
Thousands of new particles are produced.
The product of the collision is NOT a simple superposition of elementary nucleon-nucleon collisions.

Heavy ion physics studies fundamental aspects of QCD especially in the non-perturbative regime.

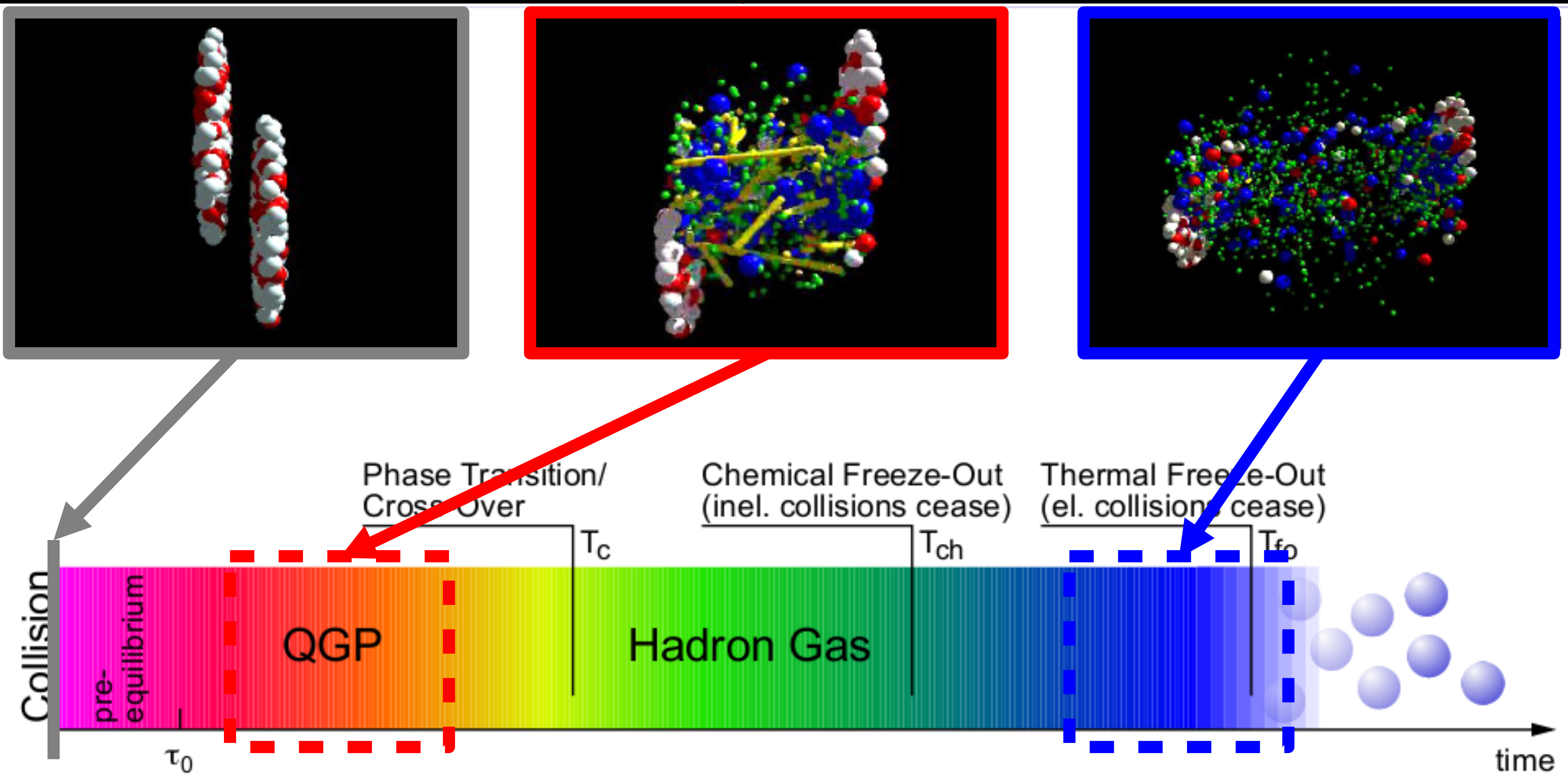
QGP: A *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun

A model of Heavy Ion Collisions

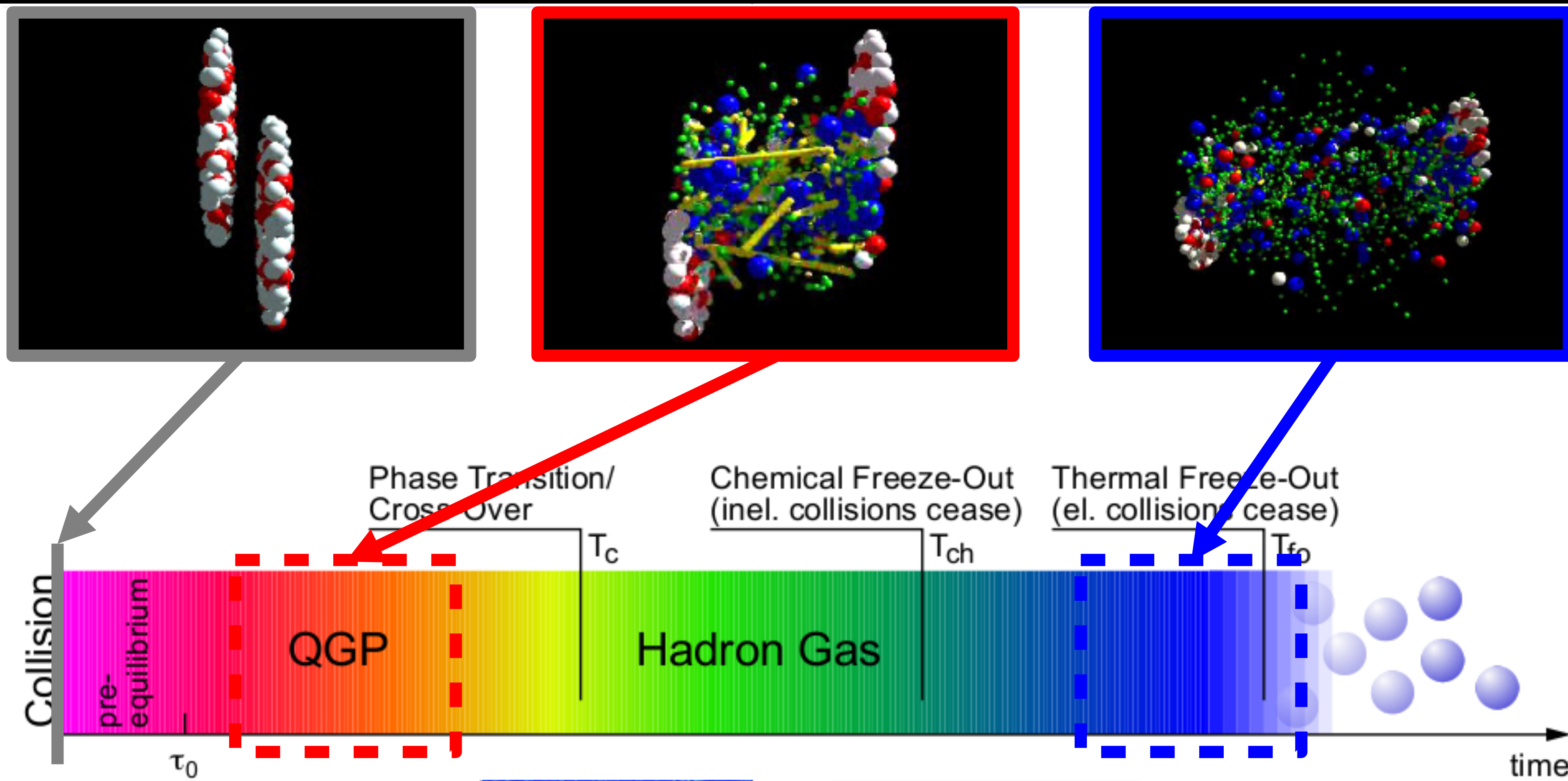




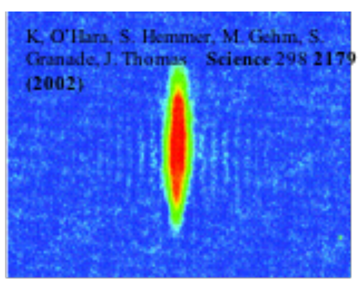
A model of Heavy Ion Collisions

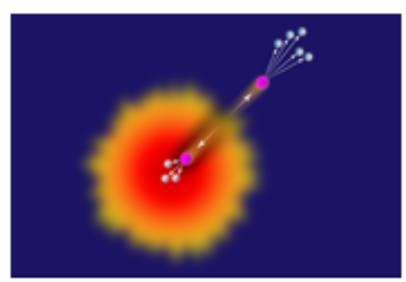


A model of Heavy Ion Collisions



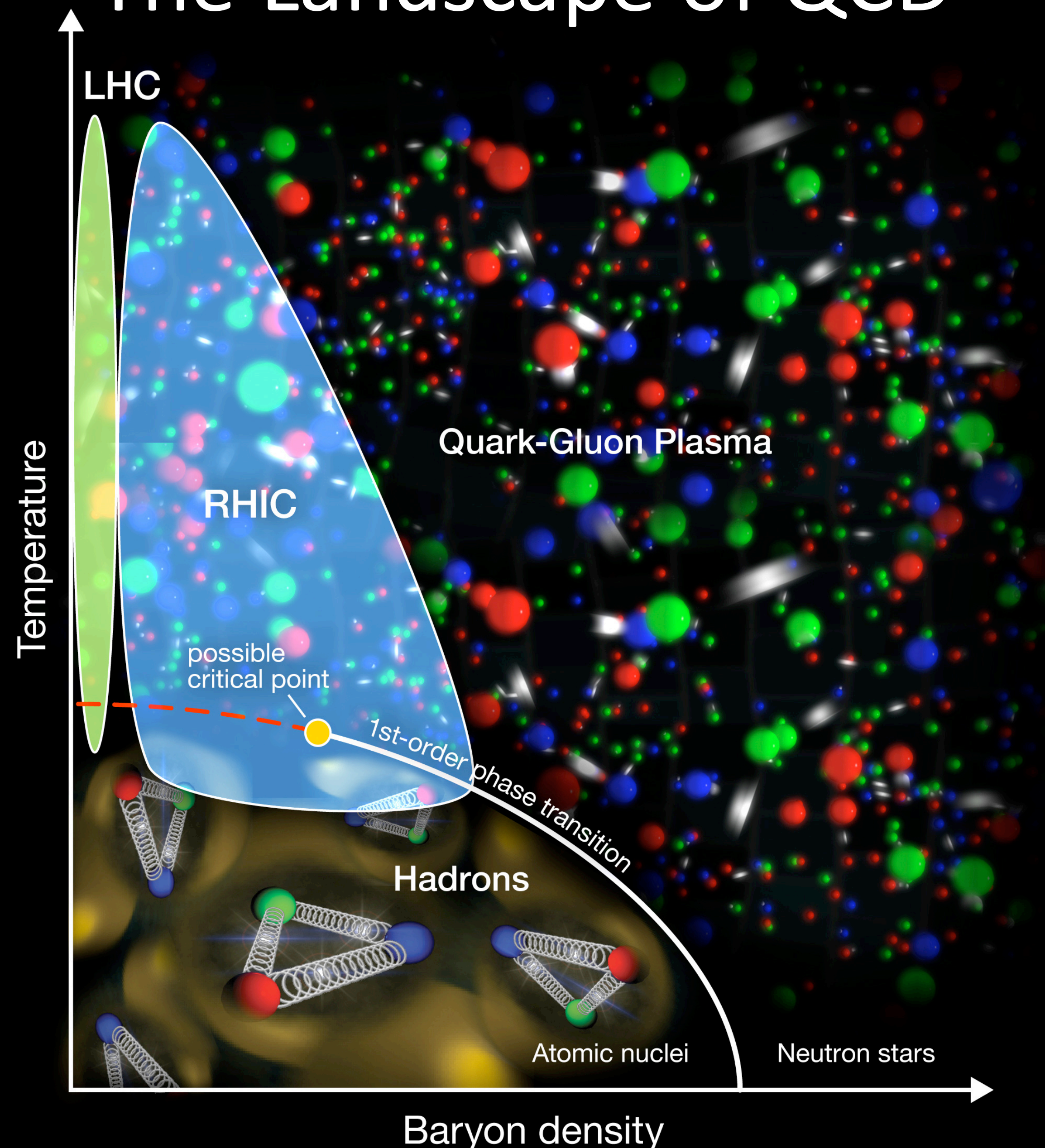
Hydrodynamical flow





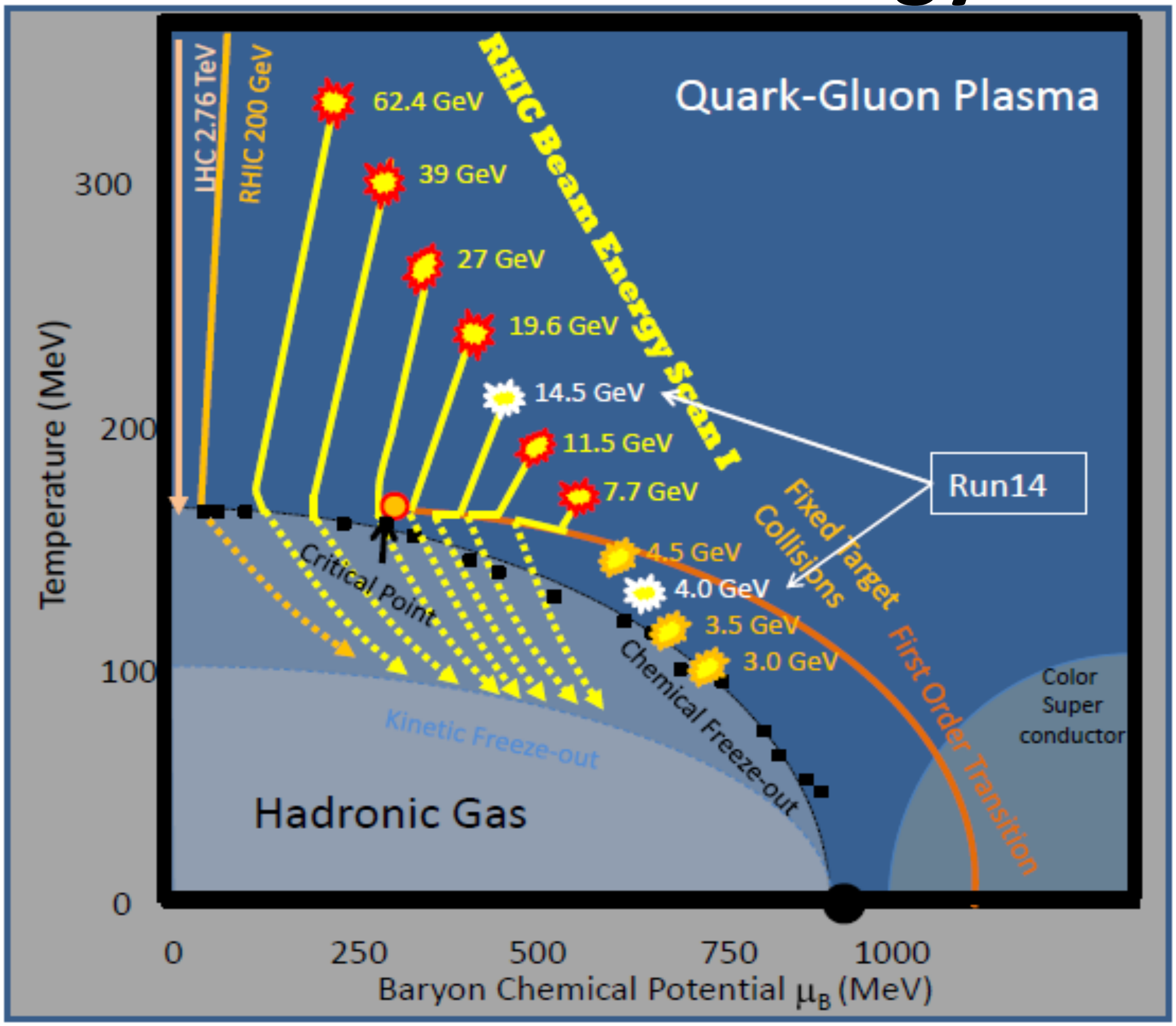
Jet quenching

The Landscape of QCD



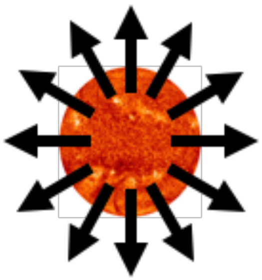
Heavy Ion Collisions at RHIC and LHC create conditions sufficient to “melt” matter into a quark gluon plasma

How to map the QCD Phase diagram: The RHIC Beam Energy Scan



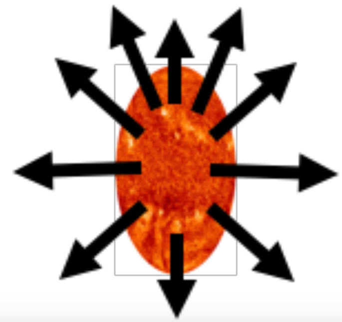
Change in signatures of a phase transition and/or critical end point e.g., v2 ?
Turn off of the new phenomena that have been observed at RHIC and LHC collisions e.g jet quenching?

Hydrodynamics of Heavy Ion Collisions



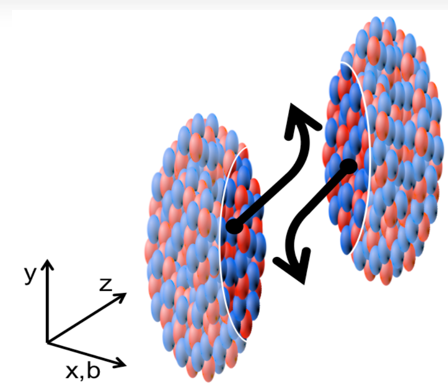
Radial Flow: Affects shape of low p_T particle spectra

Elliptic Flow: Sensitive to initial geometry
Initial overlap asymmetric → pressure gradients
Momentum anisotropy → Fourier decomposition

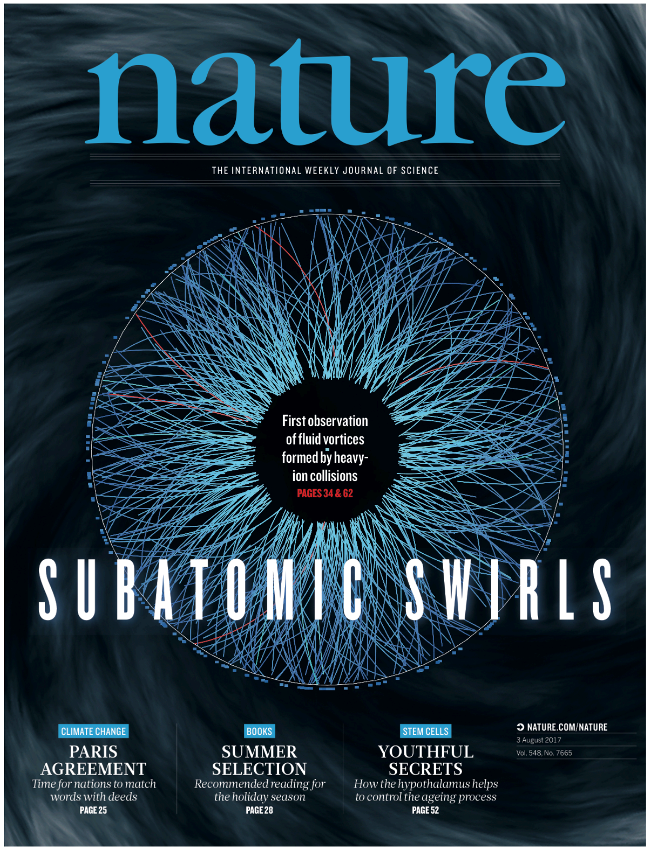


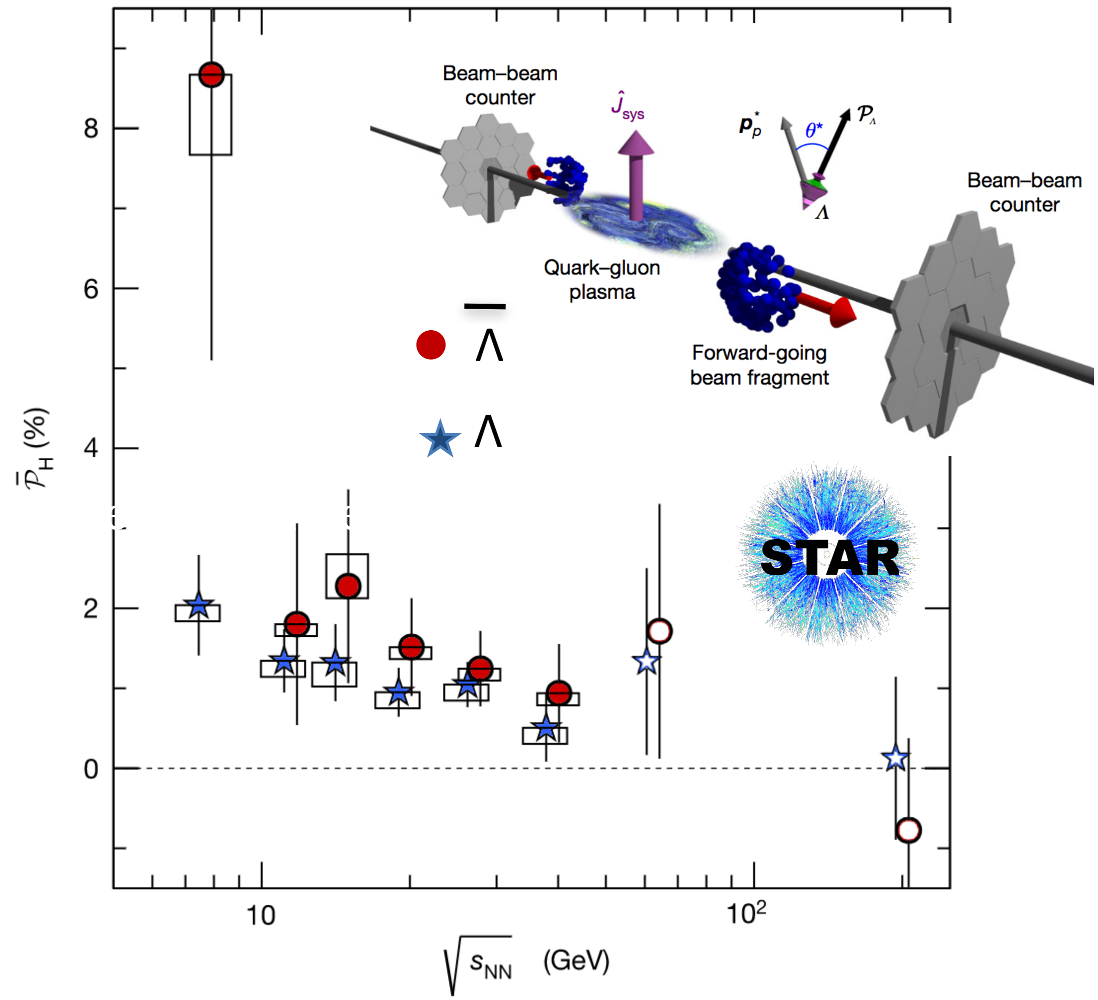
$$\frac{dN}{d\phi} = 1 + 2v_2\cos[2(\phi-\Psi_2)] + 2v_3\cos[3(\phi-\Psi_3)] + 2v_4\cos[4(\phi-\Psi_4)] + 2v_5\cos[5(\phi-\Psi_5)] + \ldots$$

Directed Flow: Produced in the pre-equilibrium phase of the collision – sensitive to EOS.
Decreases with increasing $\sqrt{s_{NN}}$



Vorticity of QGP

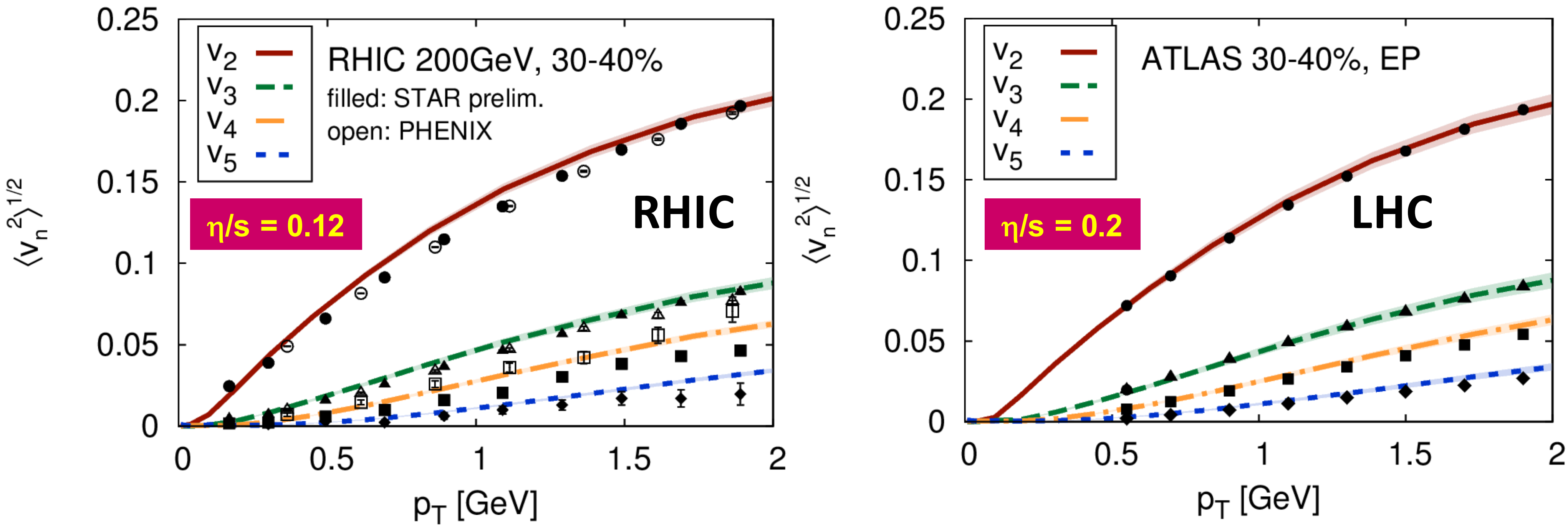




Large angular momentum in non-central heavy-ion collisions transferred to QGP.

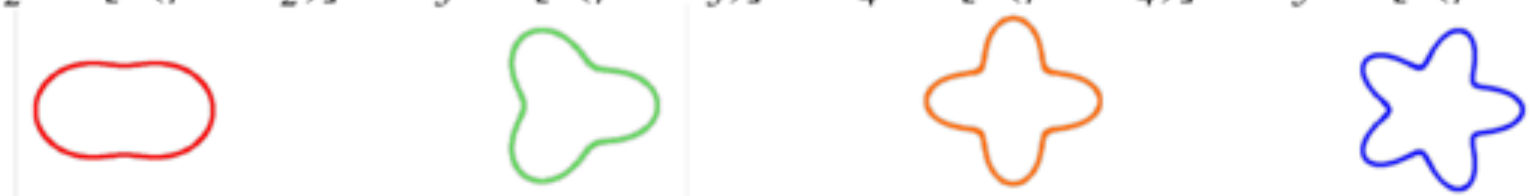
Most vortical liquid - spins 10 billion trillion times faster than the most powerful tornado

Anisotropic Flow: Perfect Liquid



C. Gale et al. Phys. Rev. Lett. 110, 012302 (2013)

$$\frac{dN}{d\phi} = 1 + 2v_2\cos[2(\phi-\Psi_2)] + 2v_3\cos[3(\phi-\Psi_3)] + 2v_4\cos[4(\phi-\Psi_4)] + 2v_5\cos[5(\phi-\Psi_5)] + \ldots$$



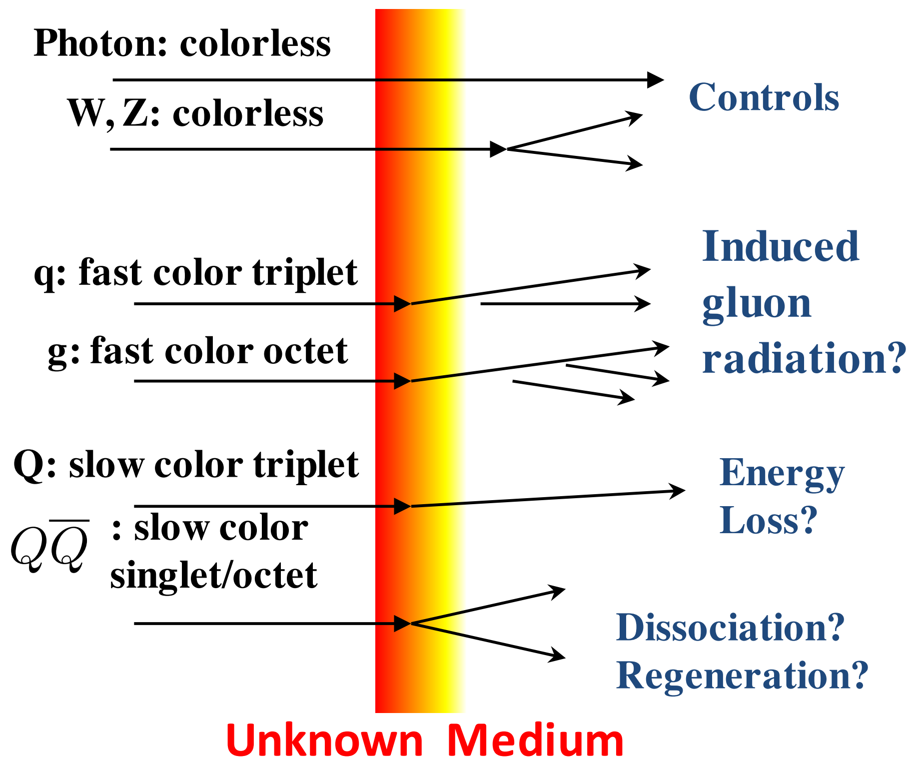
- **Medium is strongly interacting (the large amplitude of v_2)**
- Comparisons with models hydrodynamic viscous with RHIC and LHC requires small values for η/s.

The nuclear matter created **is almost perfect fluid**.

Hard Probes: Jet Quenching, melting and more….

‘Hard’ processes
- *high momentum transfer* Q^2
- *high mass m*
- *high transverse momentum* p_T

probe IN
(known from pp, pA+ pQCD)



probe OUT

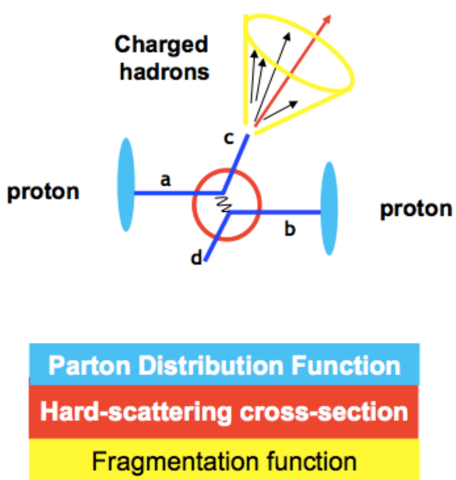
Diagnosing QCD medium: (simplified idea) pass a QCD-sensitive internal probe through it, then look for any modifications due to the medium.

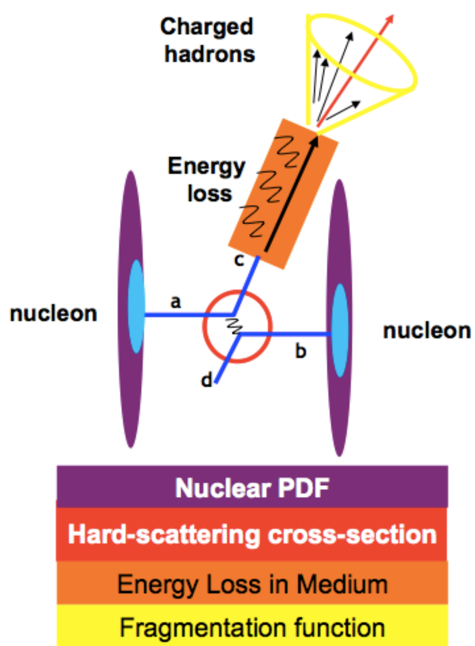
Experimental search for “interesting” phenomena

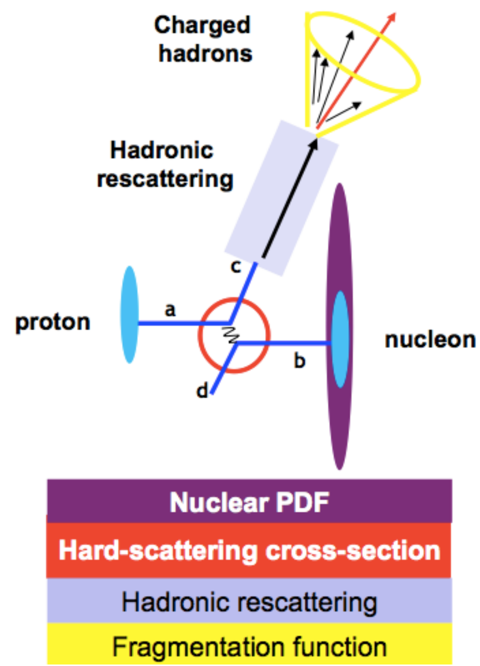
- Look at elementary p+p and p+A collisions
  - Measure an observable (e.g. Hard probes such as jet production)
- Look at Heavy Ion collisions
  - Measure the same observable as we do in p+p and p+A
- Compare them, is there something new?

Novel phenomena: Is our baseline good for every observable, i.e. no QGP in pp or pA?

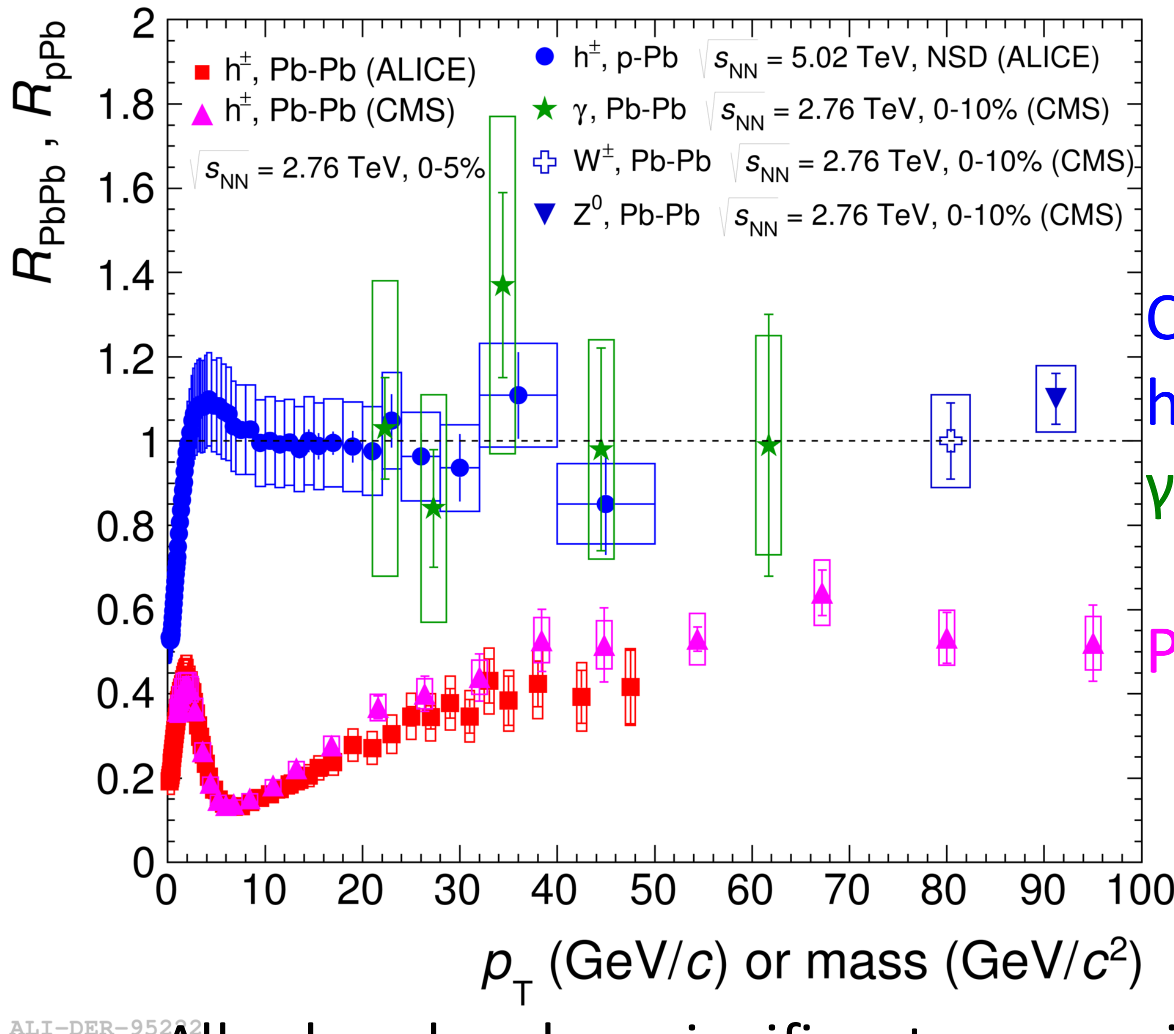
$$\equiv \frac{\text{Yield in A+A Events}}{N_{Bin}(\text{Yield in p+p Events})}$$







Experimental search for "interesting" phenomena



$$\equiv \frac{\text{Yield in A+A Events}}{N_{Bin}(\text{Yield in p+p Events})}$$

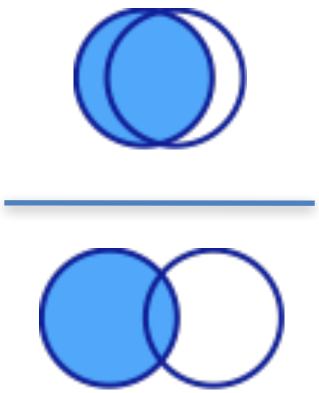
CONTROL: Not Suppressed
h± in pPb
γ, W, Z in PbPb

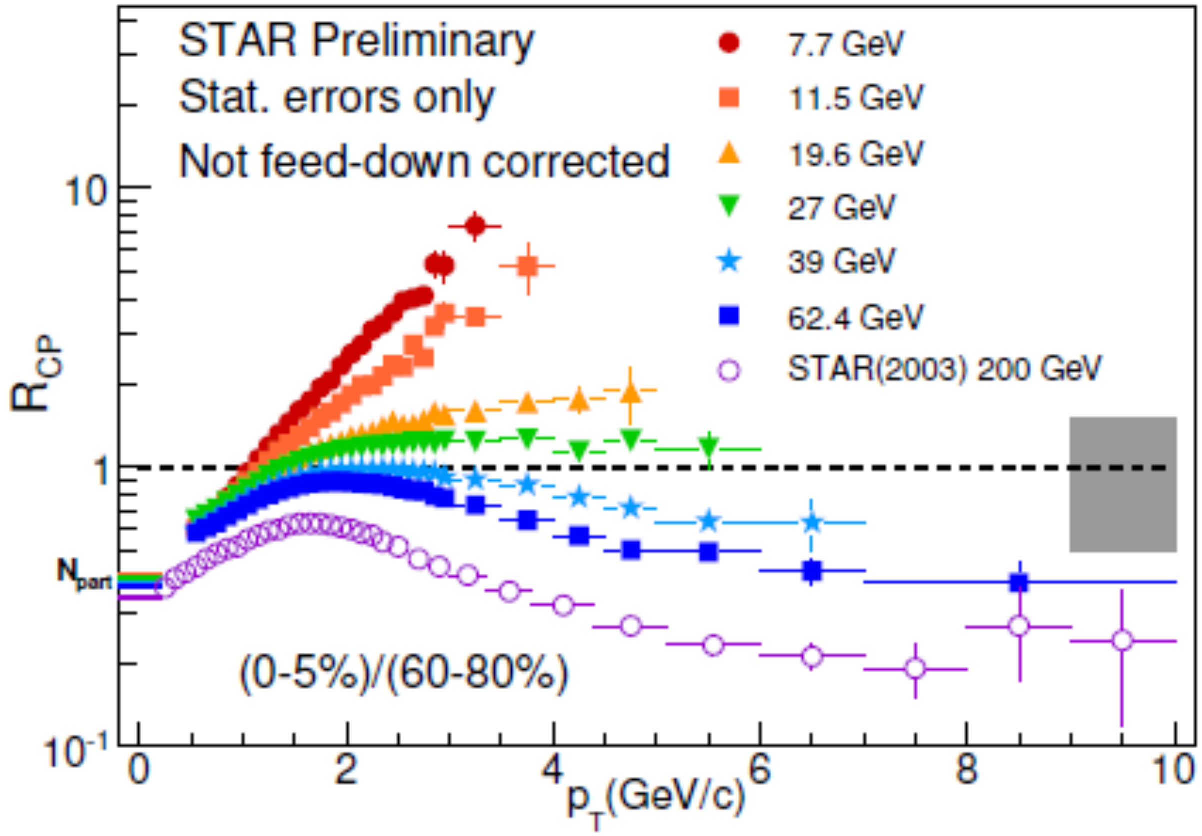
PROBE: h± suppressed in PbPb

All colored probes: significant suppression – opaque medium
All electromagnetic probes : no modification – transparent medium

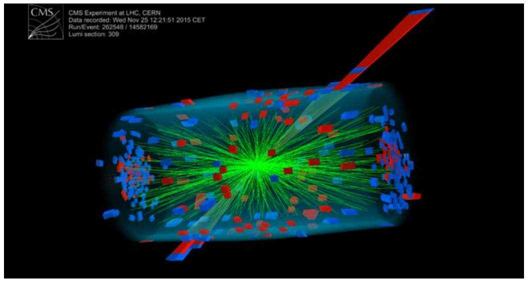
Significant jet quenching in central AA collisions has been discovered at RHIC and verified at LHC

Experimental search for "interesting" phenomena: JET Quenching at RHIC w/o Jet Reconstruction



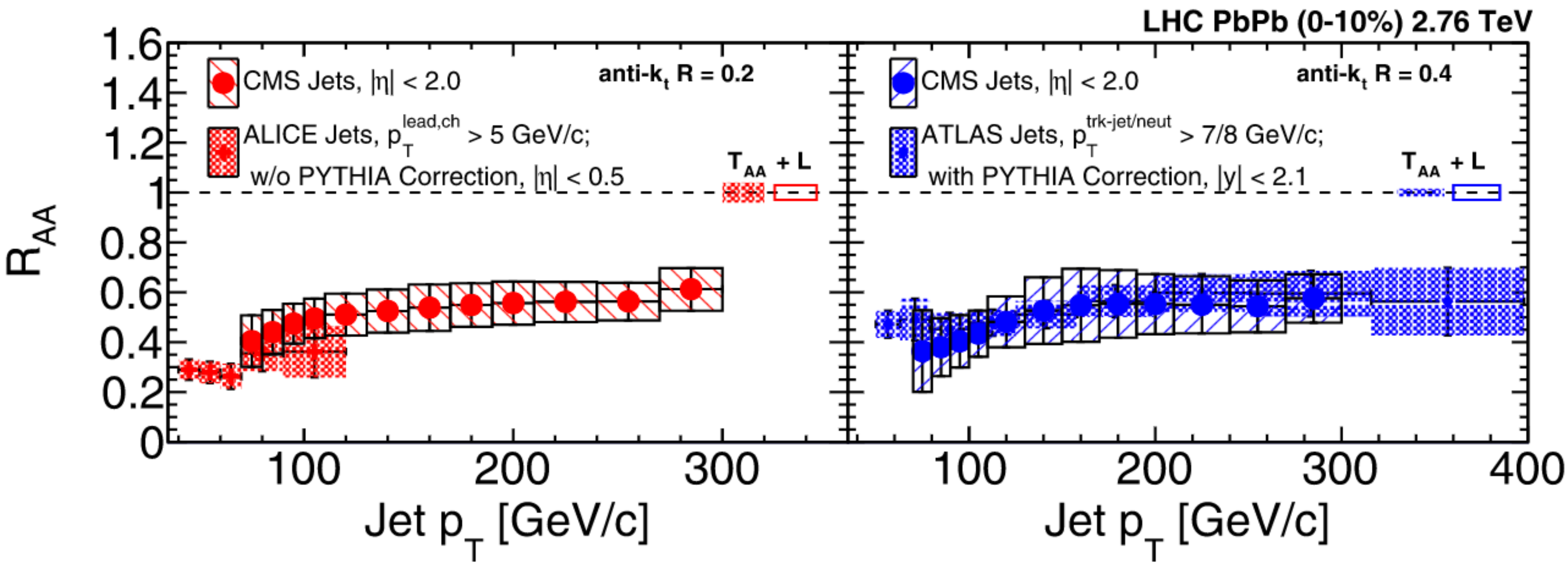


Insufficient statistics to search for evidence of high p_T suppression below 19.6 GeV
BEAM ENERGY SCAN 2 at RHIC will resolve.



Inclusive Jet Measurements at LHC

Alice, Phys. Lett. B746 (2015), CMS, Phys. Rev. C 96, 015202 (2017), ATLAS Phys. Rev. Lett. 114 (2015) 072302

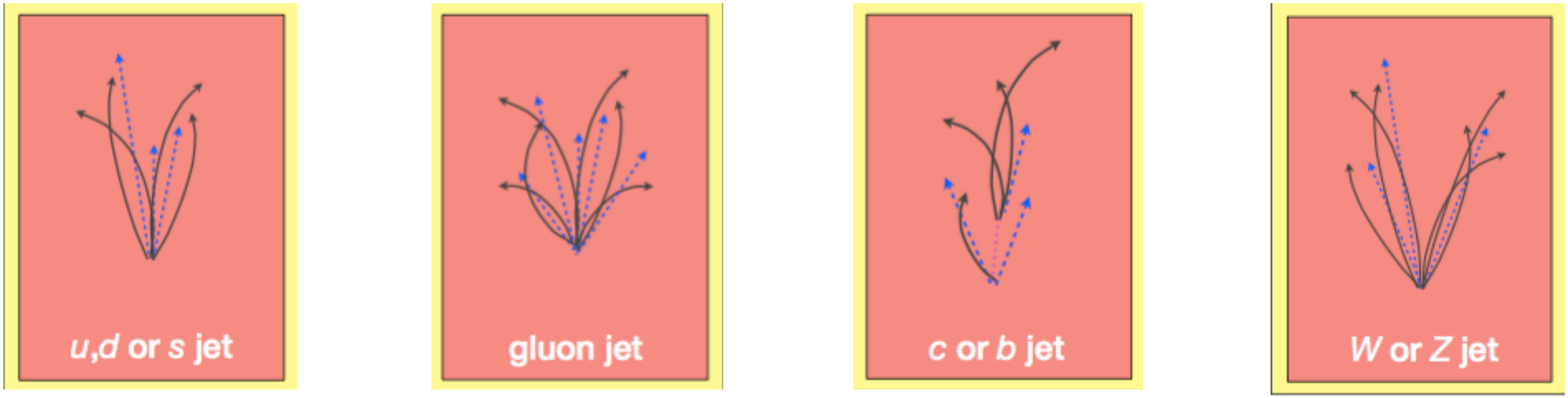


Strong suppression of "inclusive" high p_T jets! →Jet Energy not recovered

- No strong dependence on jet definitions eg choice of R
- Despite the differences in selection biases→ All experiments agree.

Need to reduce experimental uncertainties and utilize biases.

Jet Substructure Observables

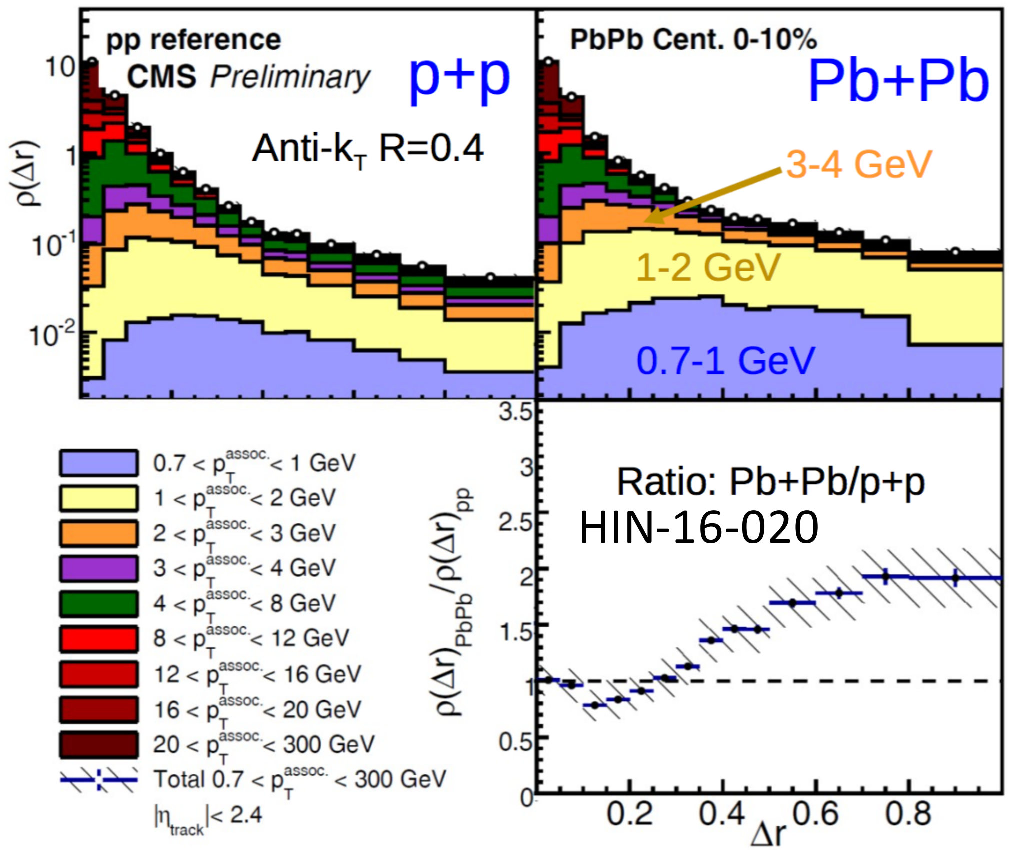


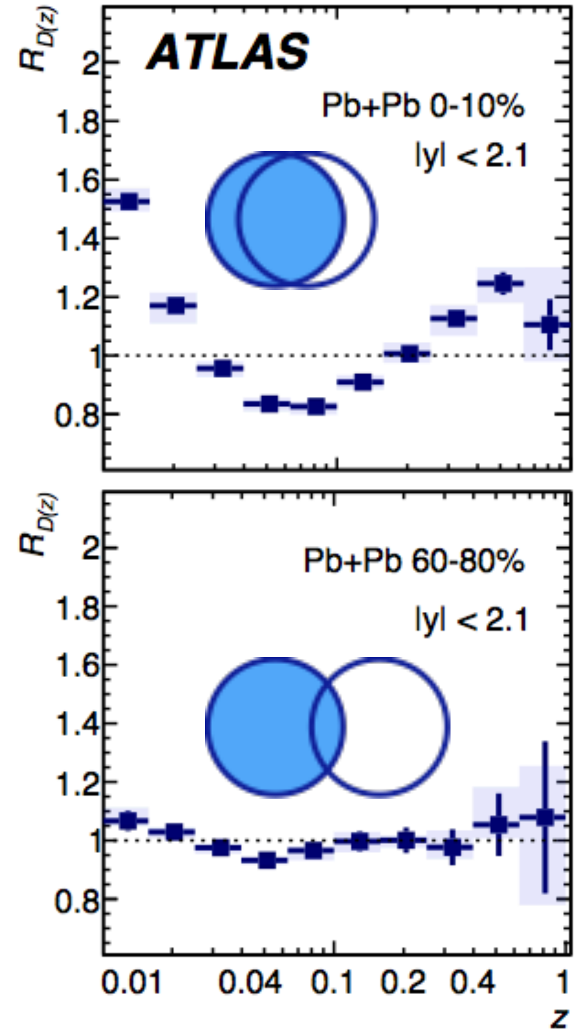
To what extent can the identities of underlying partons be deduced from properties of the jets they produce?

Jet Shapes and Fragmentation Functions are expected to be sensitive to the possible medium response to hard probes and induced radiation.

Jet Shapes & Fragmentation Functions

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks} \in [r_a, r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$

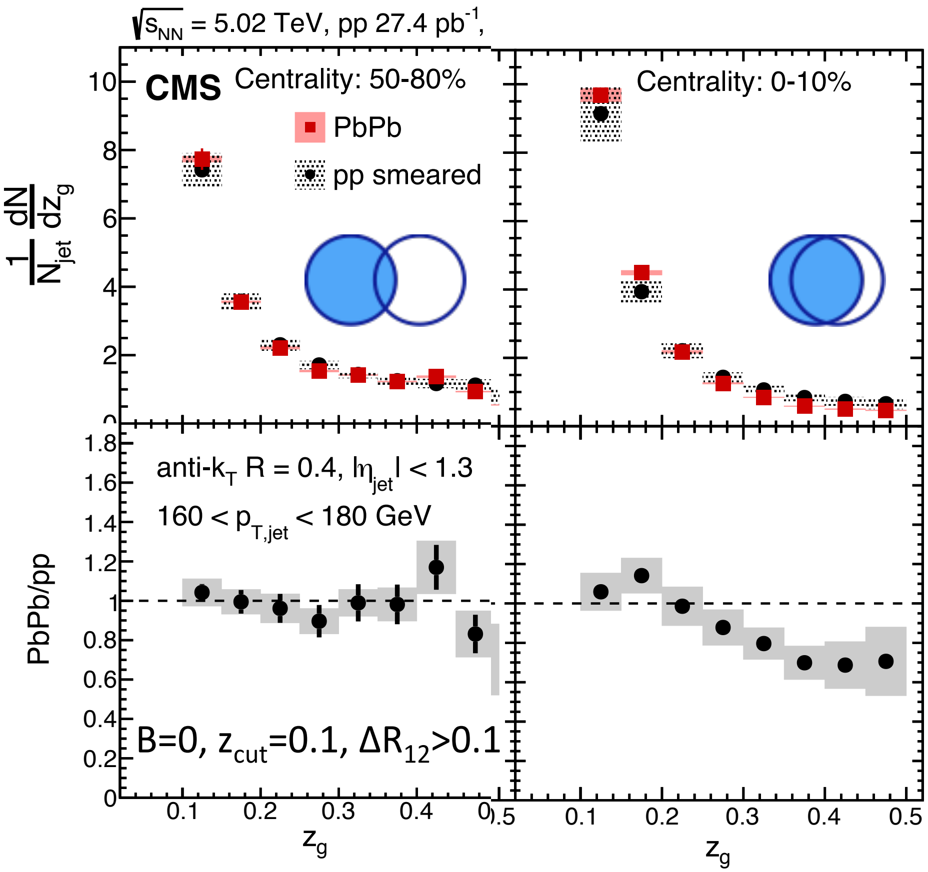


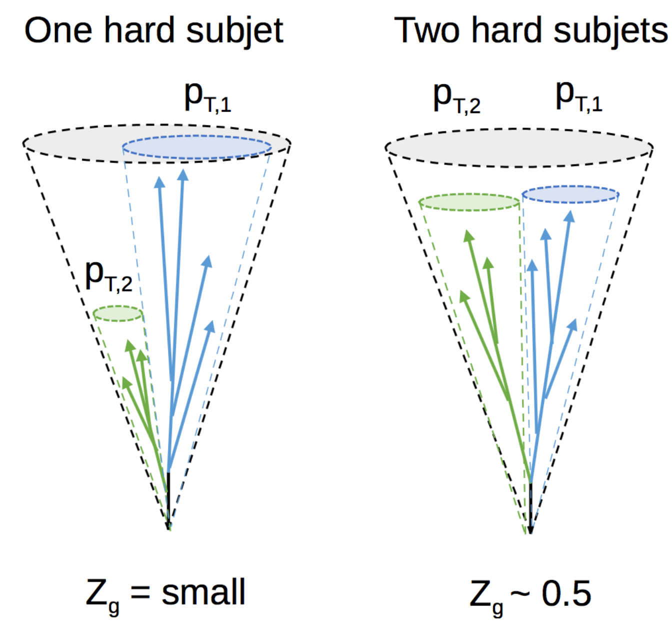


Broadened jet shape & softer FF due to the medium response to hard probes and induced radiation!

Utilizing Jet Grooming: Splitting Functions

large-angle soft radiation and bkg removed by grooming!





$$z_g = \frac{\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})}{p_{\mathrm{T},i} + p_{\mathrm{T},j}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta},$$

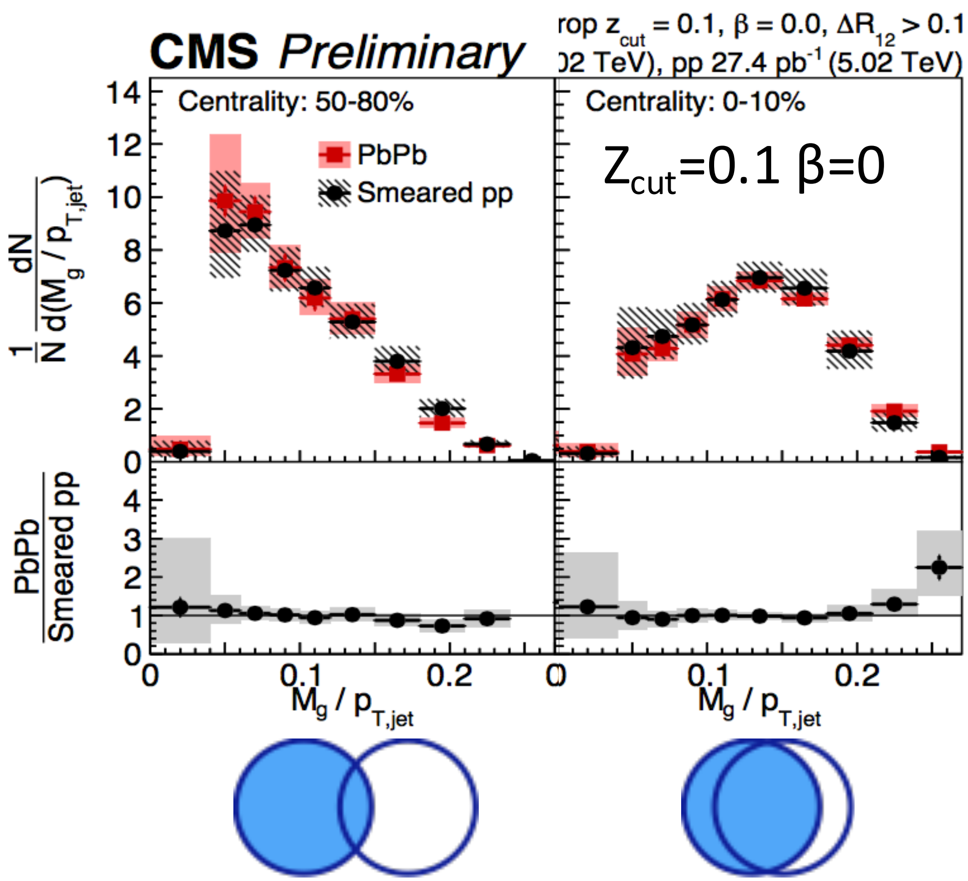
CMS PAS HIN-16-006
arXiv:1708.09429

Momentum sharing between two leading subjets

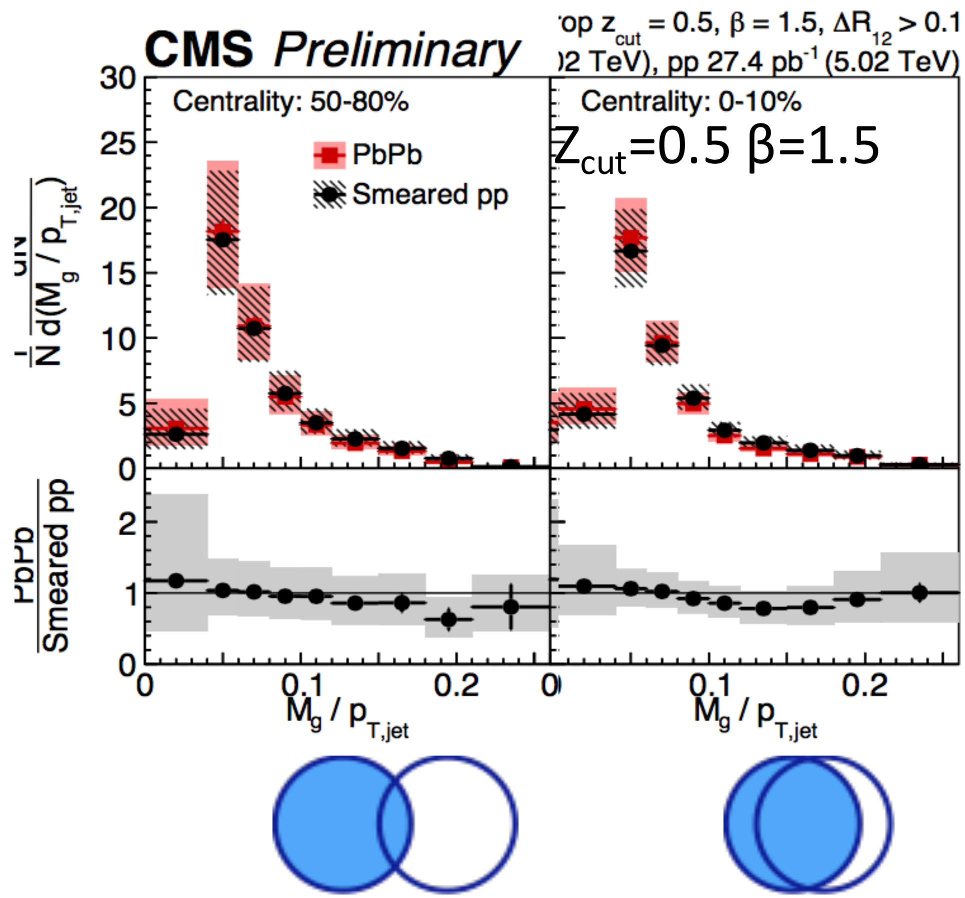
Modification of branch splitting of inclusive jet measurements !

Groomed Jet Mass

Grooming Independent of angular separation



Grooming for larger angular separation



Core of the jet stays the same.

The periphery of the jet is sensitive to interactions of partons with the medium during the parton shower evolution.

Jet Mass w/o grooming

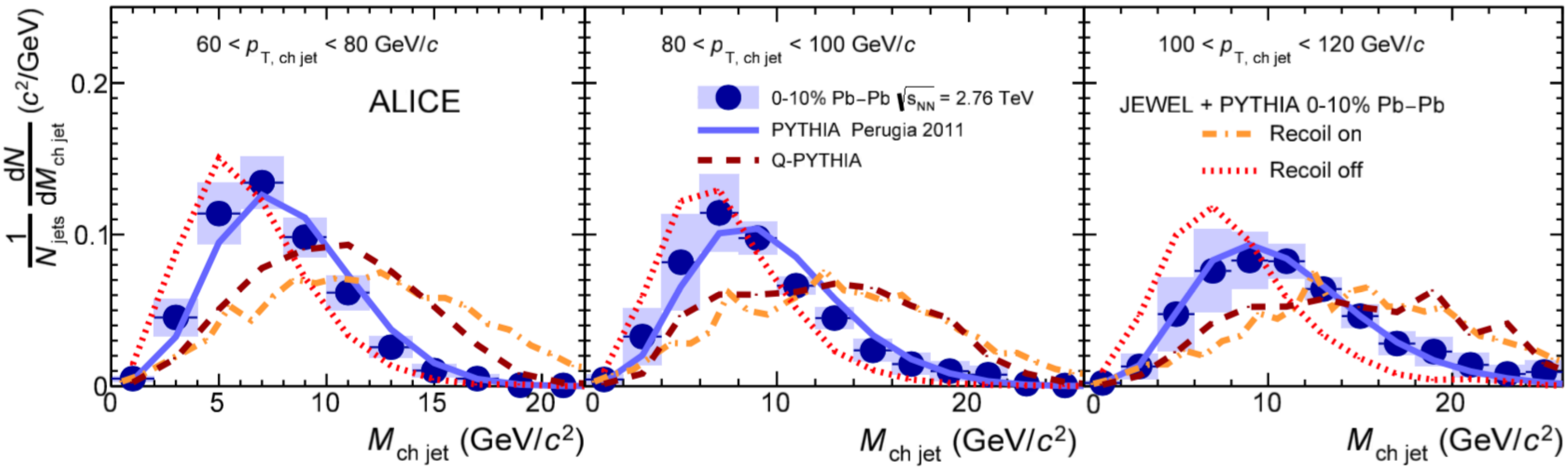


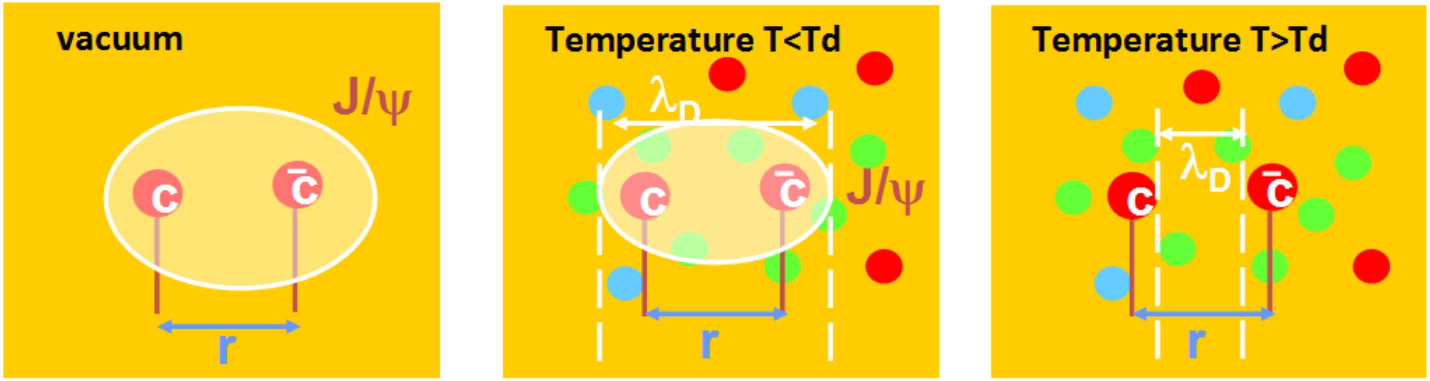
Fig. 10: Fully-corrected jet mass distribution for anti-k_T jets with $R = 0.4$ in the 10% most central Pb–Pb collisions compared to PYTHIA with tune Perugia 2011 and predictions from the jet quenching event generators (JEWEL and Q-PYTHIA). Statistical uncertainties are not shown for the model calculations.

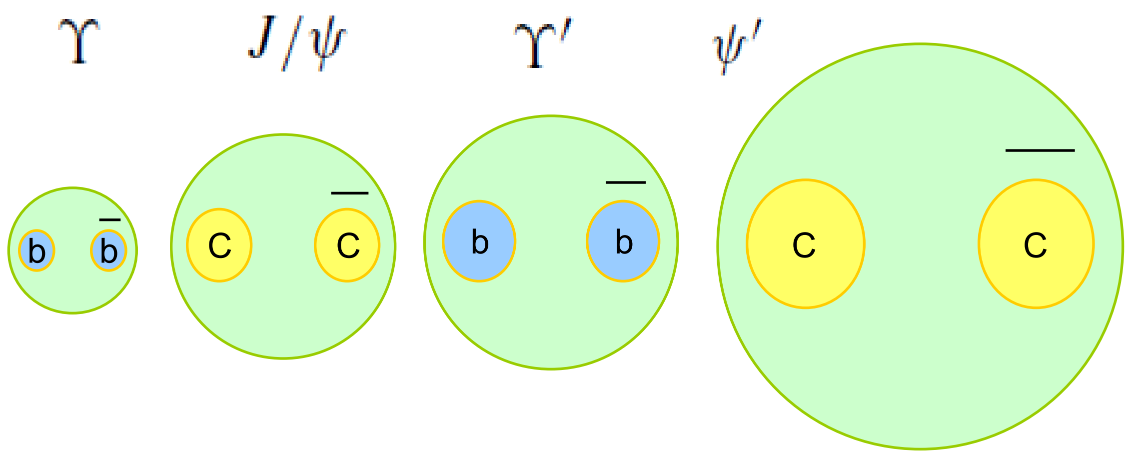
No apparent change in jet mass.

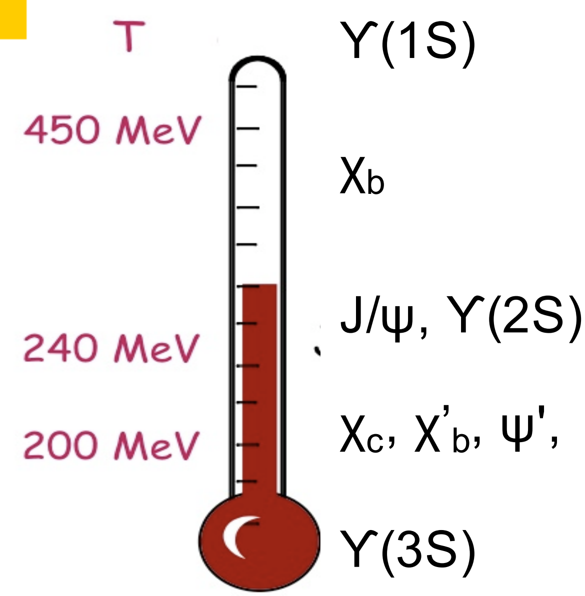
ALICE: arXiv:1702.00804 [nucl-ex]

Jet definitions & selections, grooming vs not grooming…
→ Biases are in every jet measurement. But biases here are good!
Utilize these biases for a complete characterization of medium.

Thermal probes of Quark Gluon Plasma





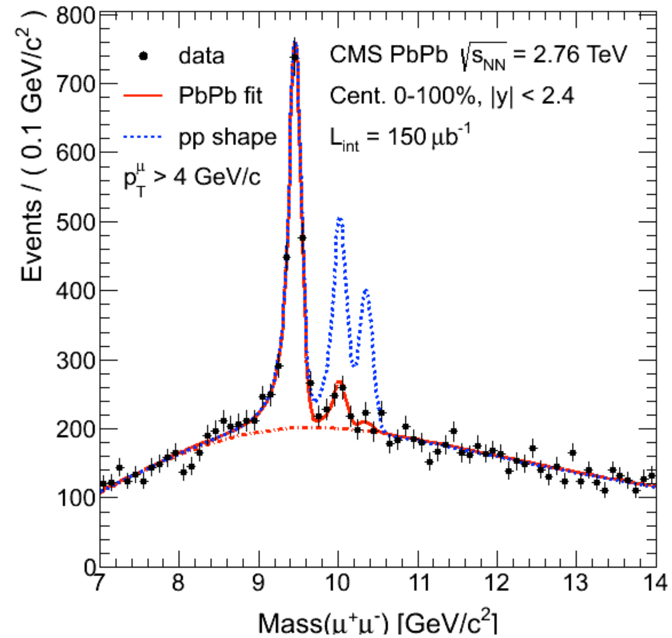


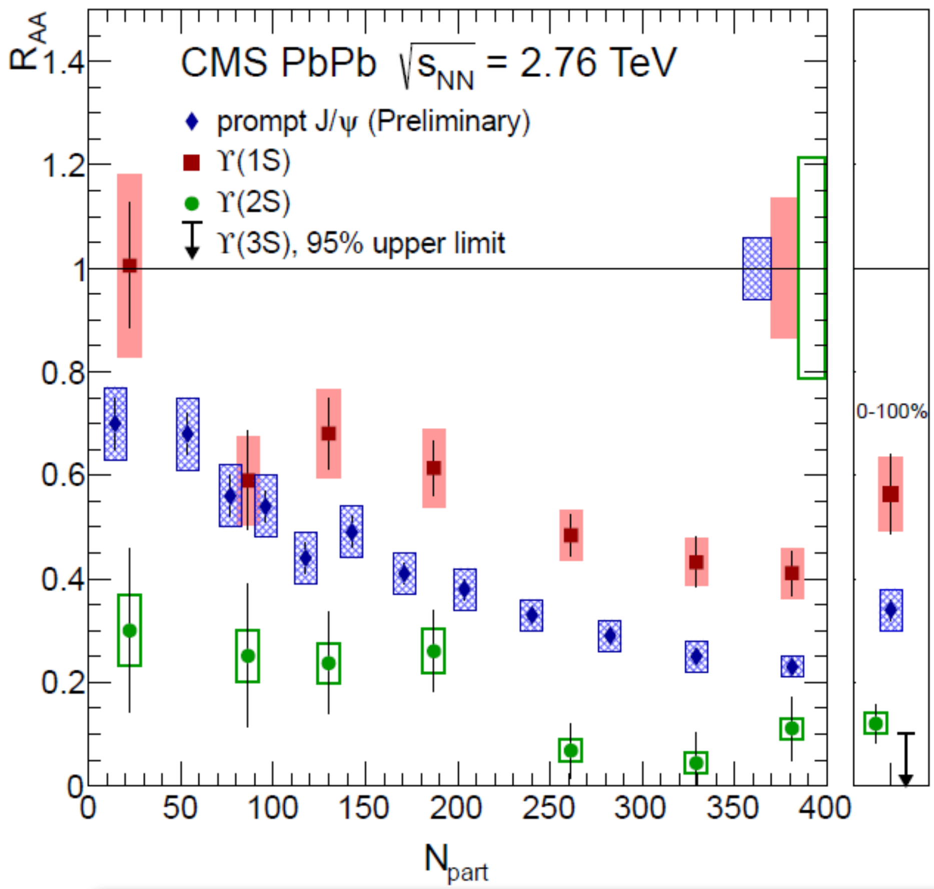
Different states → Different binding energies
Loosely bound states "melt" first!

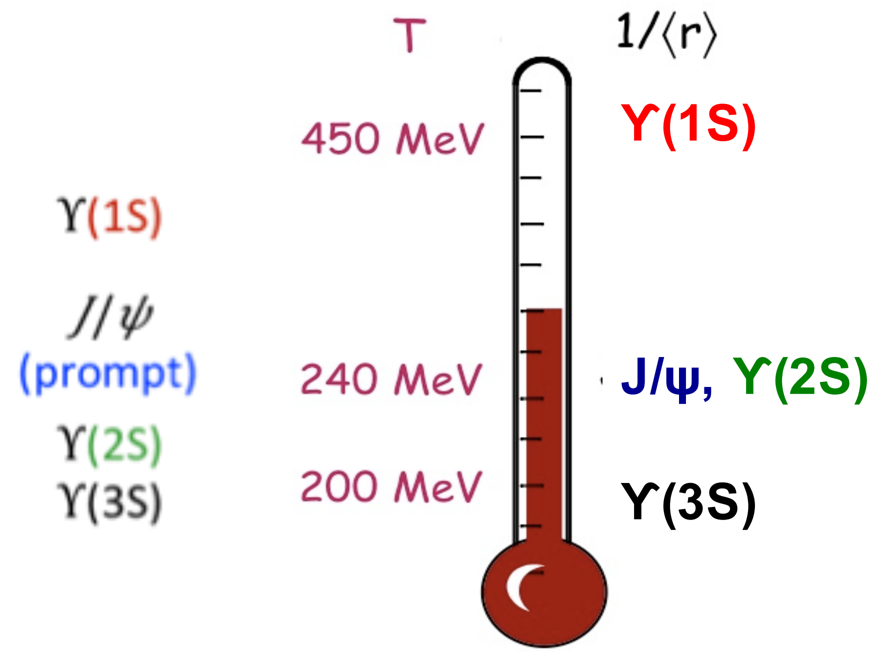
Mocsy, EPJC61 (2009) 705

Successive suppression of individual states provides a "thermometer" of the QGP

Melting of Quarkonia

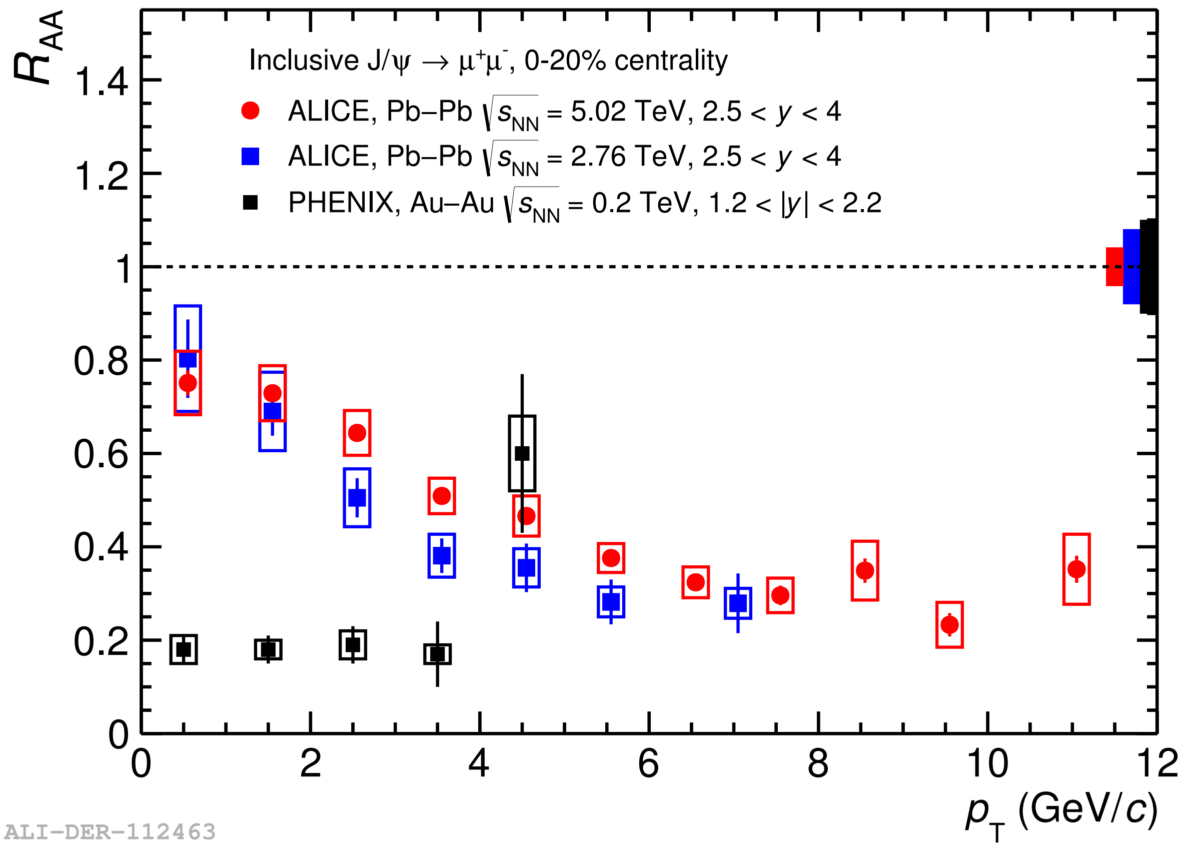


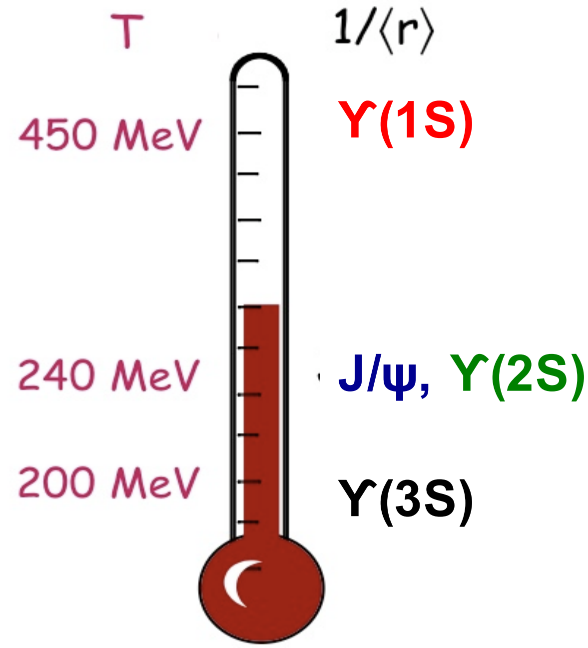




Sequential melting of quarkonia states in PbPb collision!

Energy Dependence of Melting

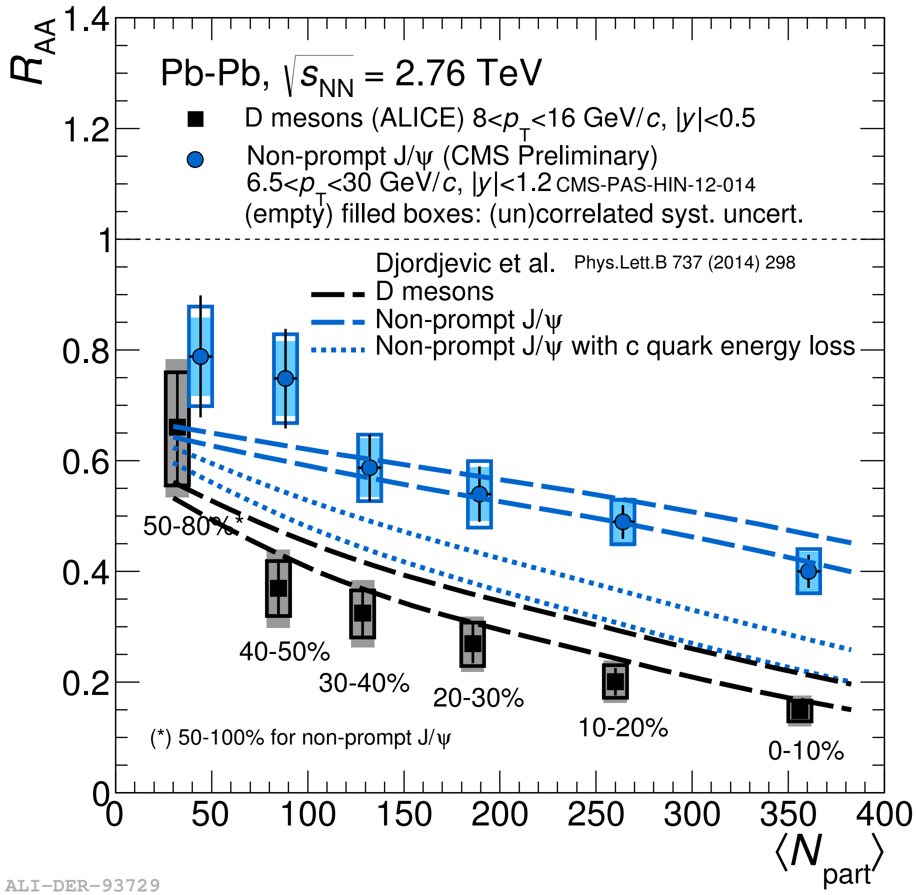




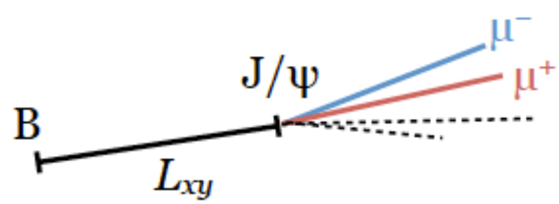
Low p_T increase by recombination of independently produced c and anti-c

Suppression by quarkonium dissociation 'melting' in the Quark Gluon Plasma

Comparisons with Open Heavy Flavor

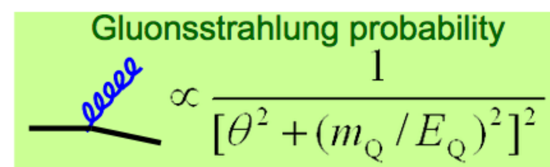


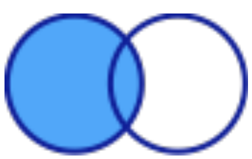
Larger suppression for charm than for beauty → Dead Cone Effect: suppressed gluon radiation at θ < m/E



beauty: non-prompt J/Ψ

charm: D-mesons



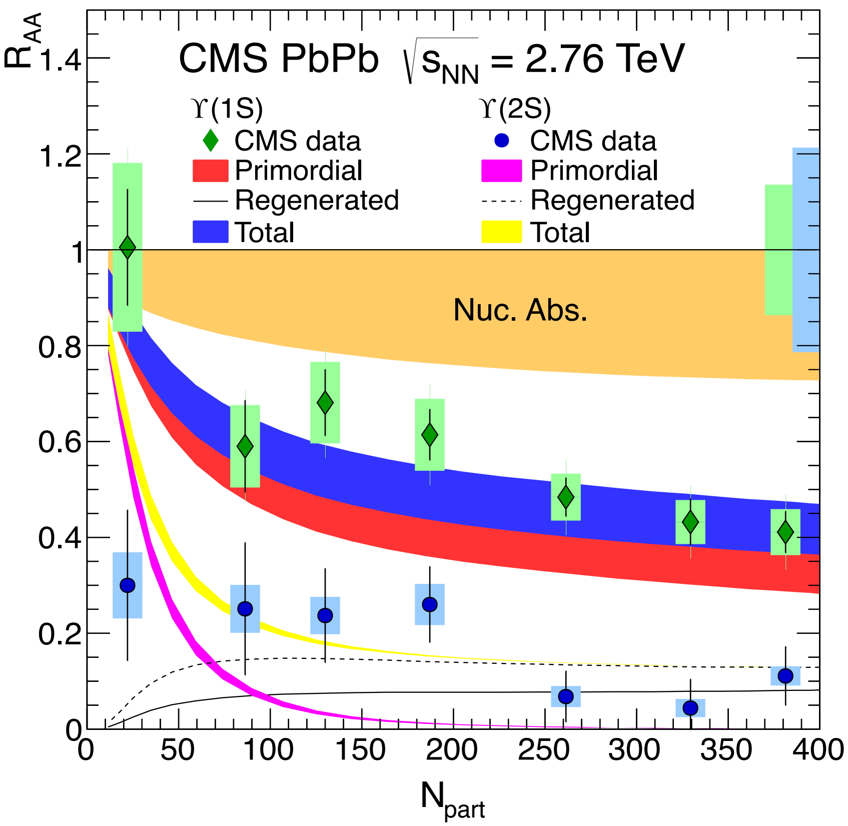


Indicates radiative energy loss: induced gluon bremsstrahlung

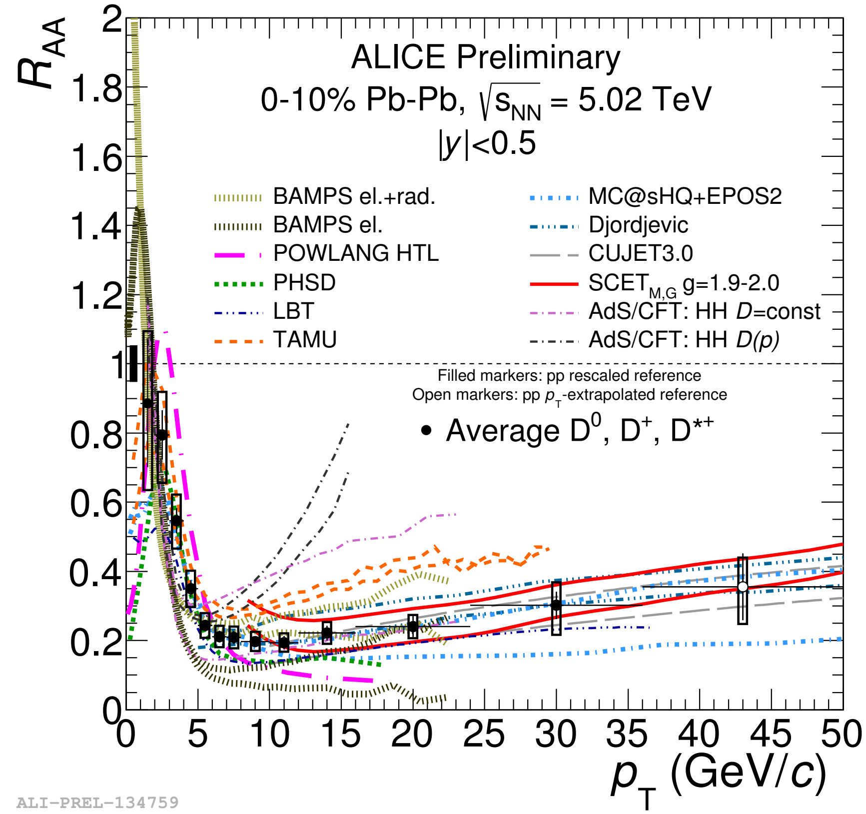
ALICE, JHEP11, 205

Measurements meet Models:

A. Emerick, X. Zhao & R. Rapp, EPJA 48, 72 (2012)
He, Fries, Rapp Phys.Lett. B735 (2014) 445-450,
Ko, Han, Song Nuclear Physics A910–911 (2013) 474–477



Requires 3Tc

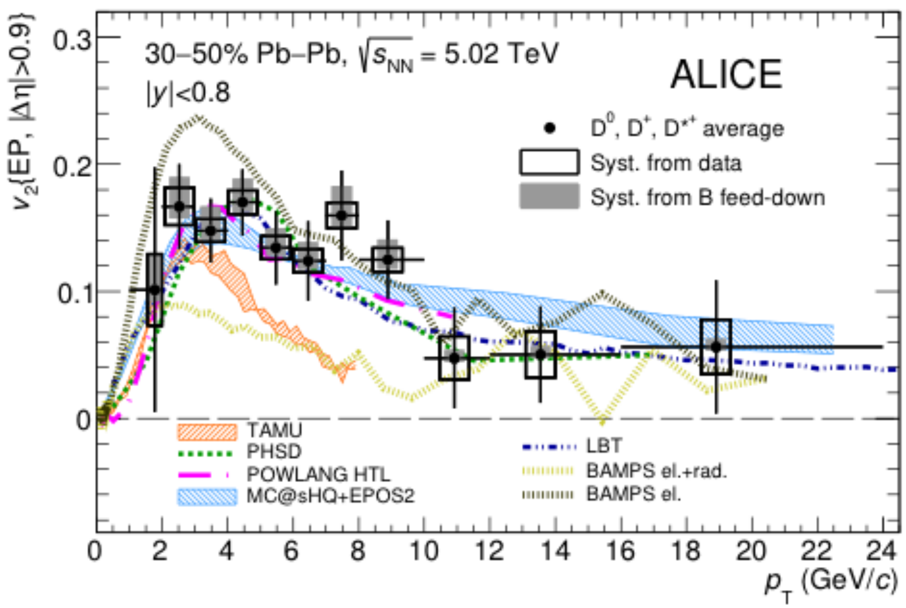


Precise D mesons to determine transport properties of QGP

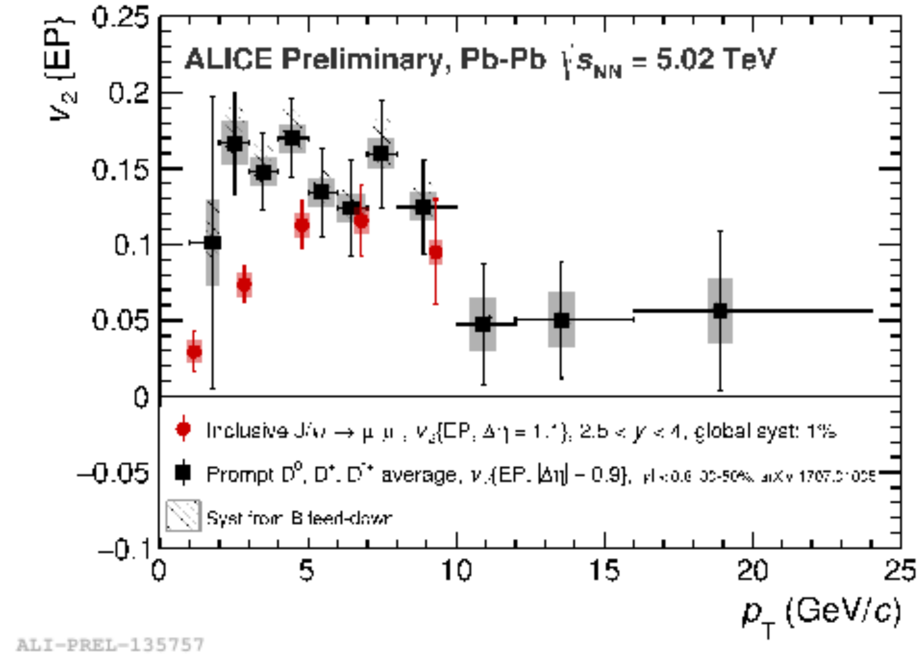
Quantitative comparison of data and theory has begun !

Charm Flow

ALICE, arXiv:arXiv:1709.05260



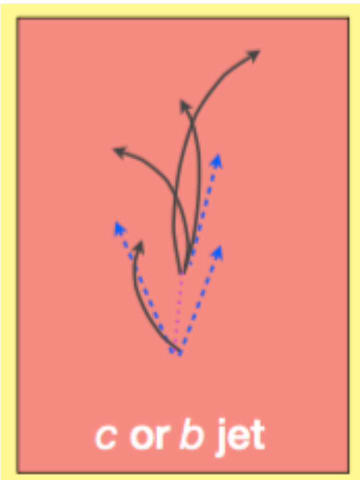
ALICE, arXiv:1709.05260

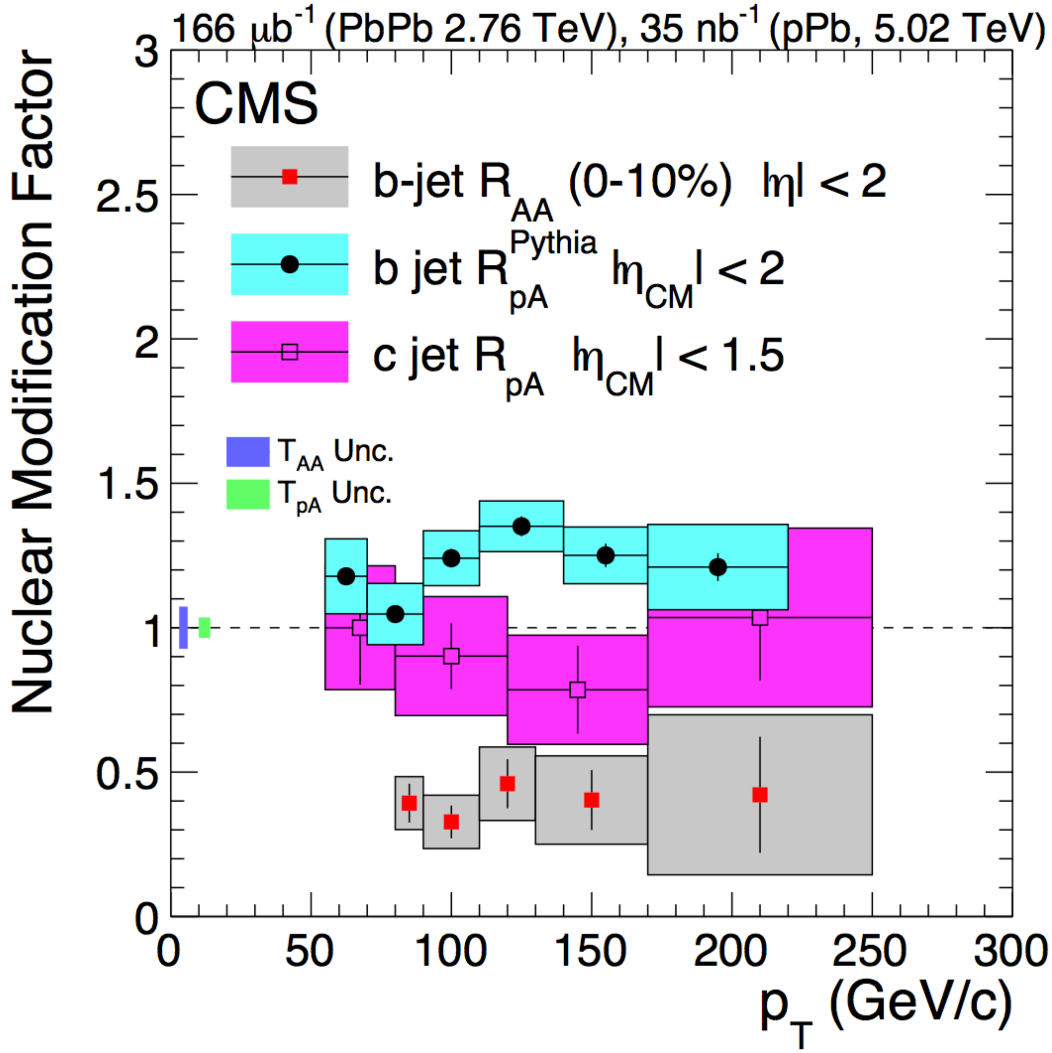


Large v2 of D mesons requires strong interactions with the QGP.
Charm close to thermalised?

J/Psi flows similarly
Confirmation of charm quark flow!

Flavor dependence of jet quenching



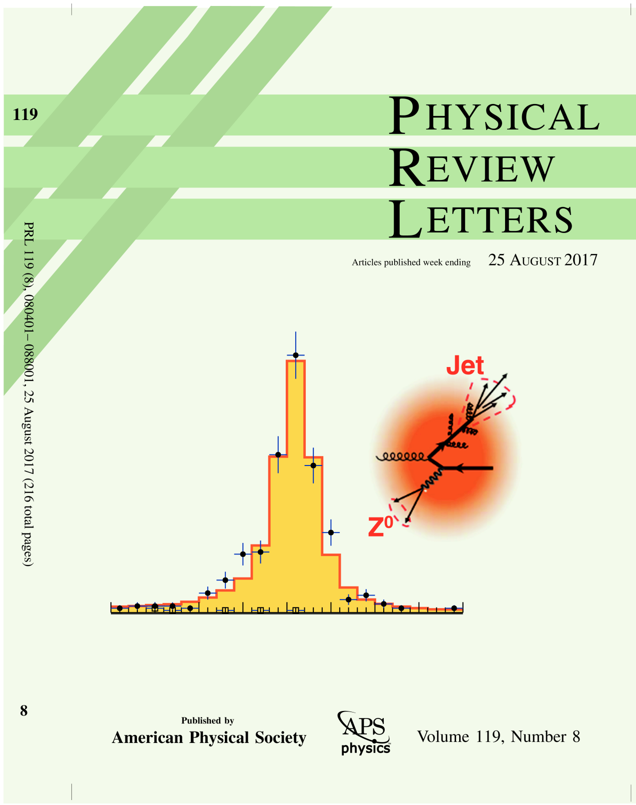


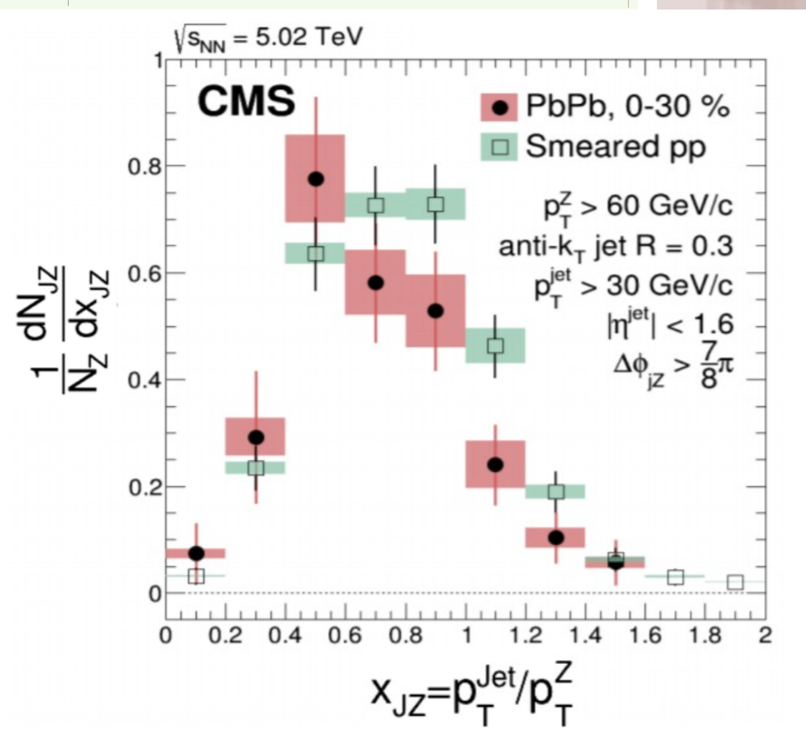
CMS, Phys. Rev. Lett. 113, no. 13, 132301 (2014)
CMS, Phys. Lett. B 754, 59 (2016)
CMS, arXiv:1612.08972 (2016)

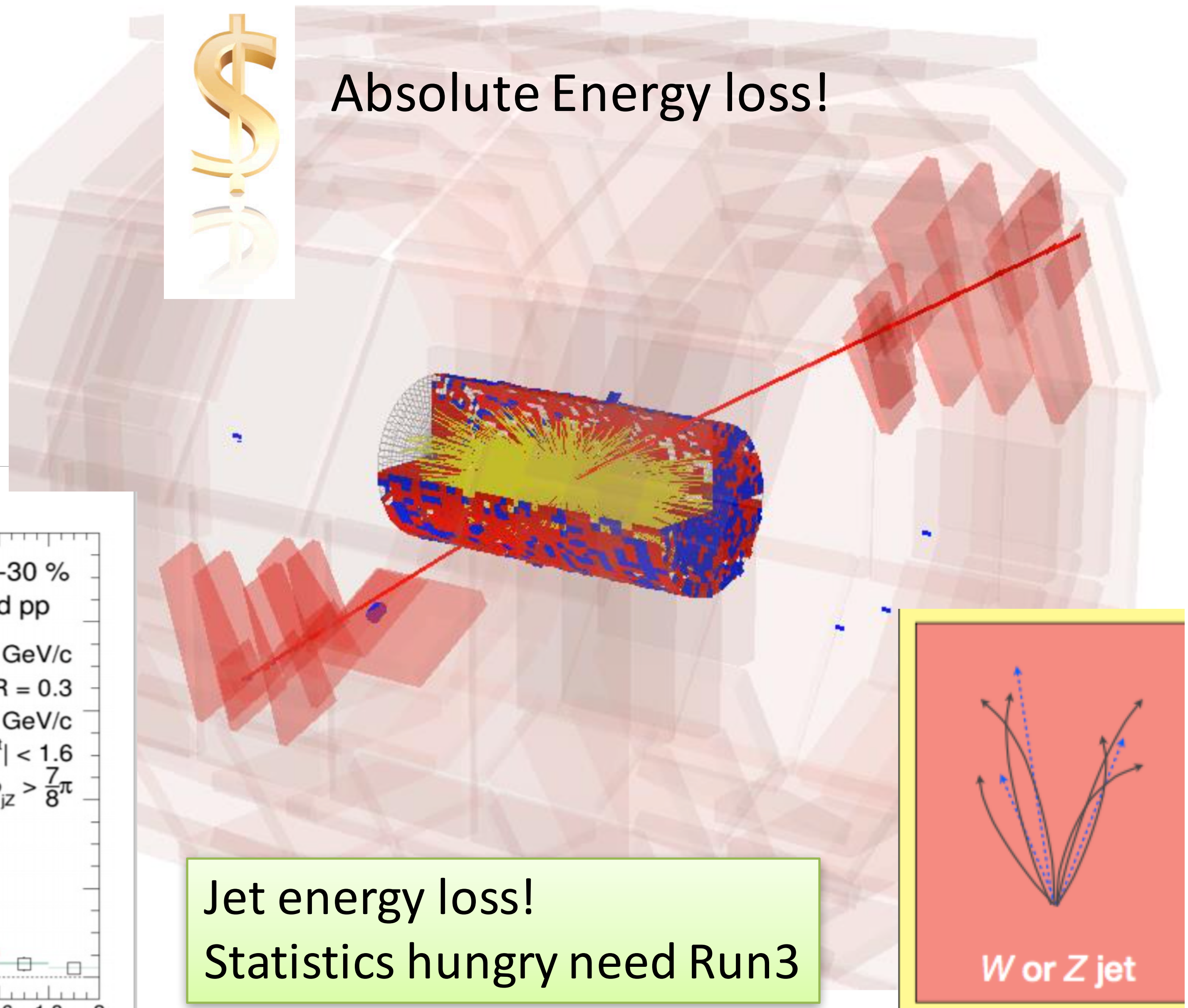
Suppression of b quarks in PbPb, while no suppression in pPb collision.

Future: what about flavor dependence of fragmentation functions?

Z+jets at 5 TeV PbPb





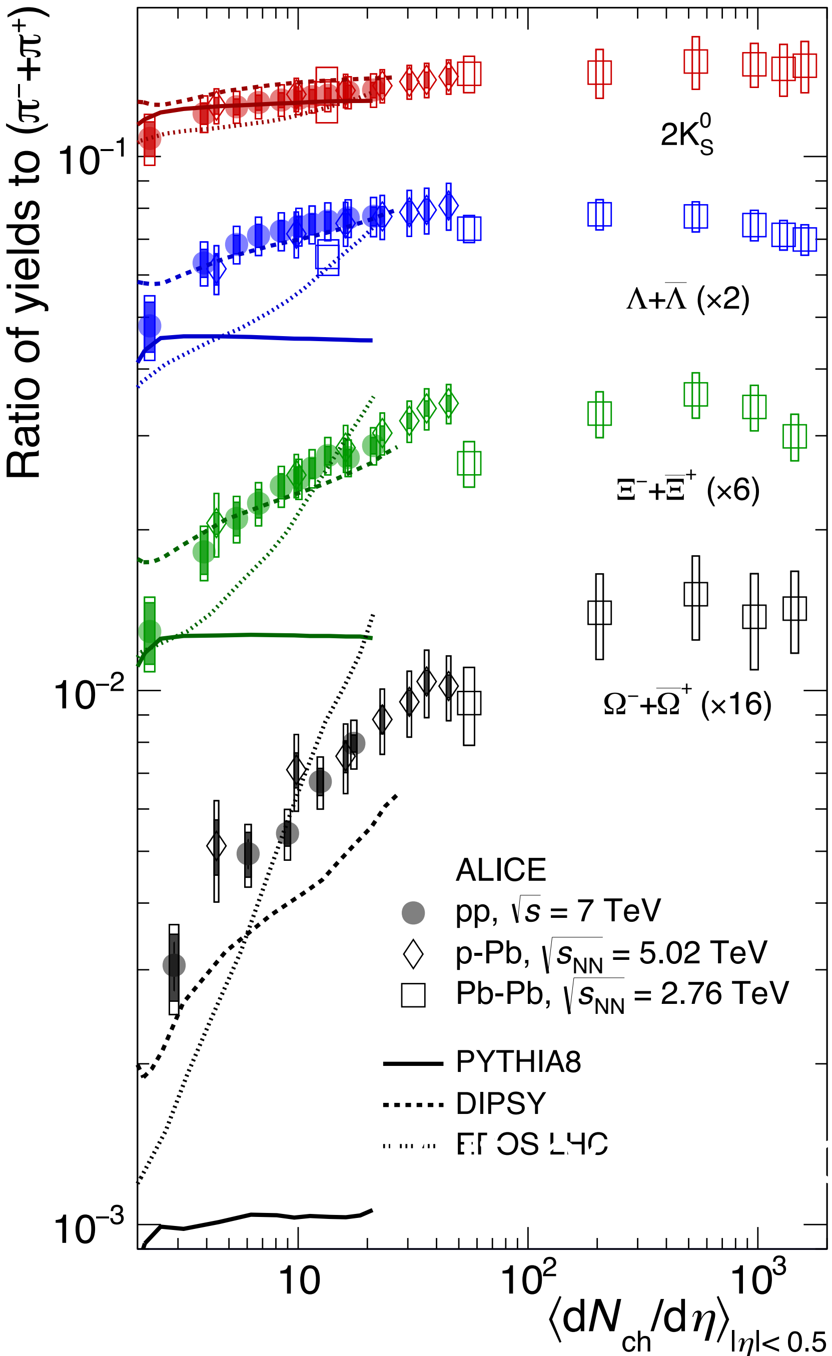


Absolute Energy loss!

Jet energy loss!
Statistics hungry need Run3

[Phys. Rev. Lett. 119 (2017) 082301](#)

Challenges in small systems – pp and pA collisions



Nature Physics 13, 535–539 (2017)

Fraction of strange hadrons increases with multiplicity

Large effect for multi-strange Ξ and Ω

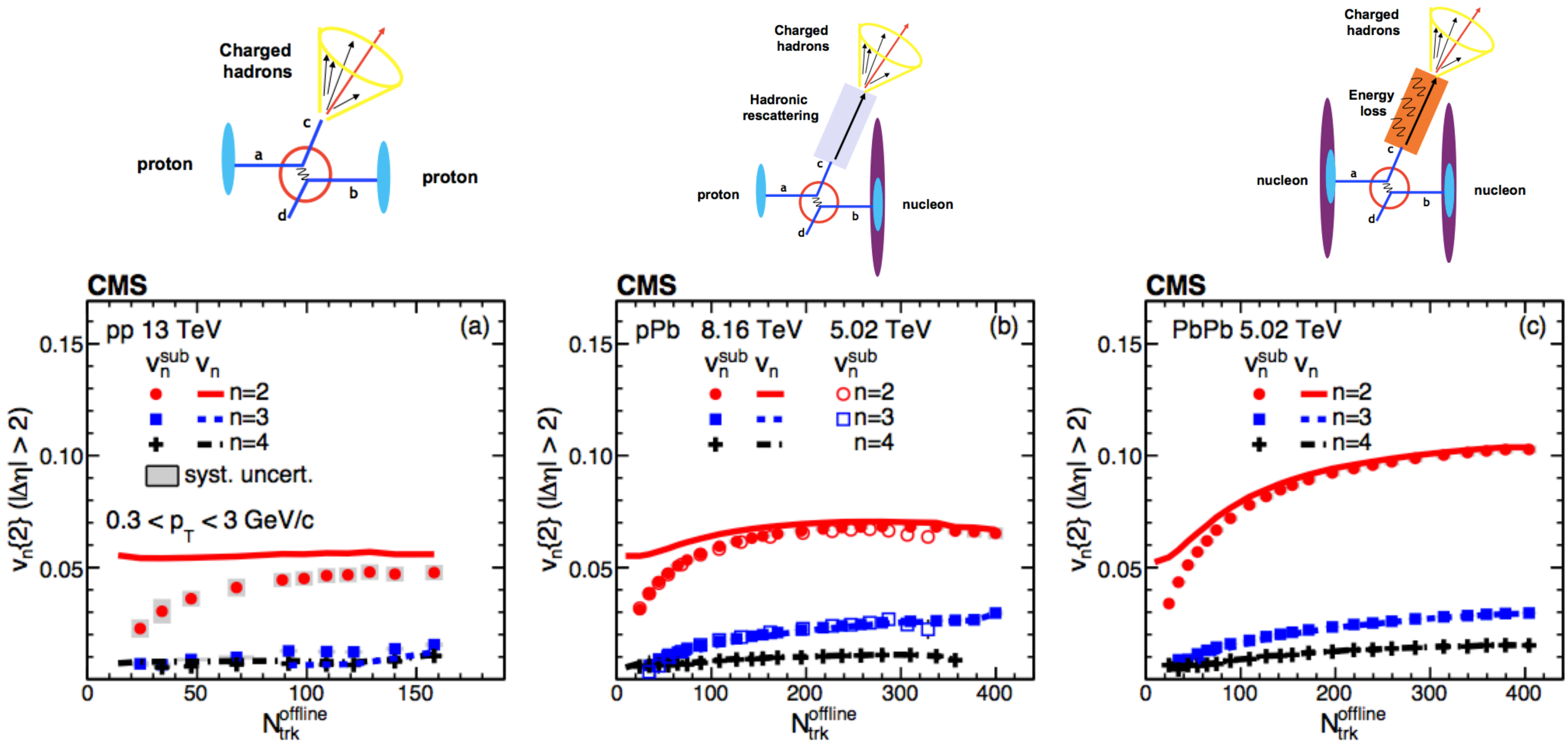
Similar enhancement in PbPb has been interpreted as thermalization; global equilibration of the strangeness yield. Are they related?

QCD-inspired models cannot explain the trend!

The observation of heavy-ion like behavior in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed"

Fischer & T. Sjöstrand, JHEP01(2017)140

Challenges in small systems – pp and pA collisions



Heavy-ion like behavior in high-multiplicity pp

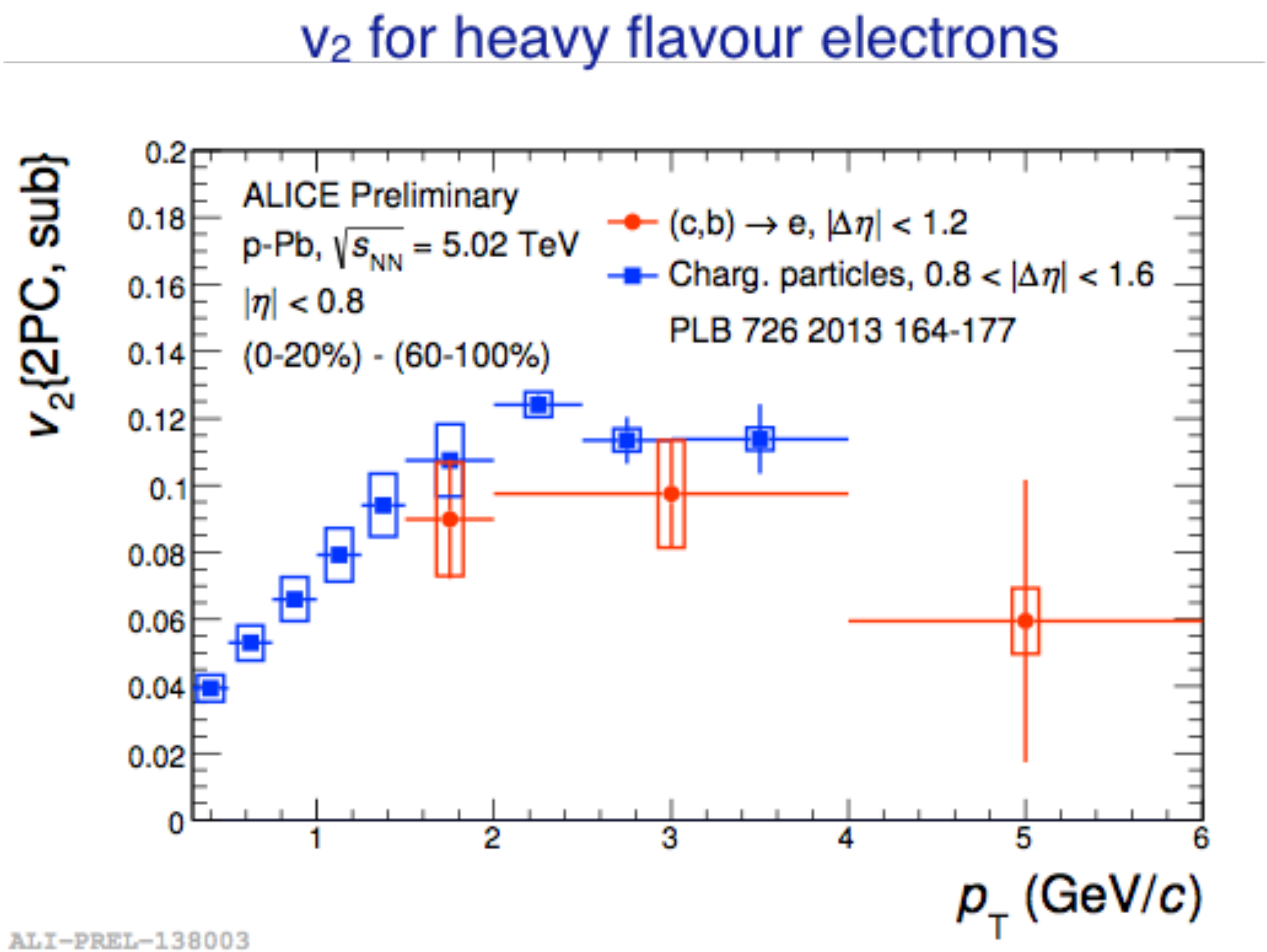
Why do small systems flow?

pPb show sizeable v_n with negligible jet quenching.

What is the role of FSI?

But how good is our baseline data?

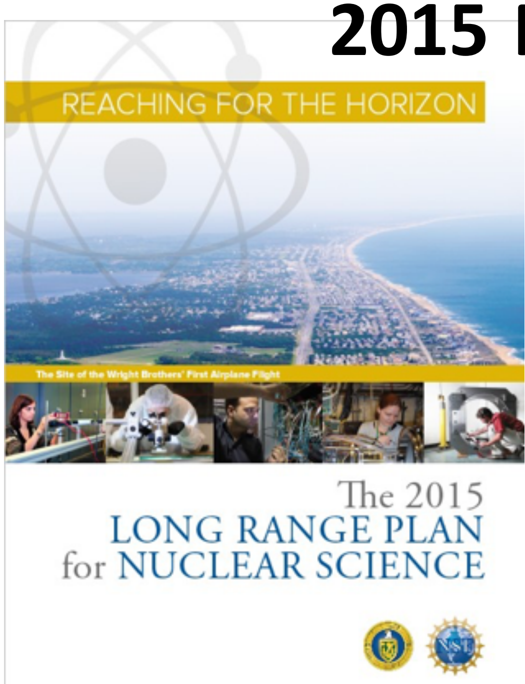
Charm even flows in pPb



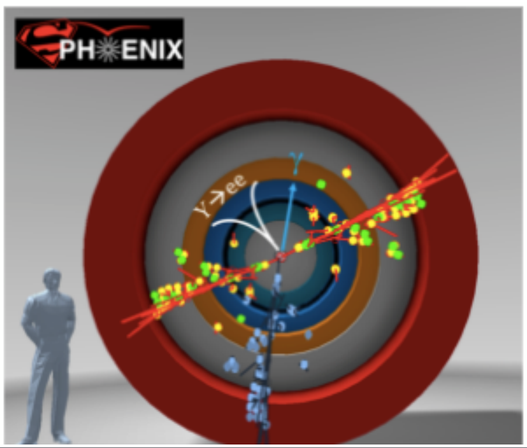
Heavy flavour also flows in p-Pb

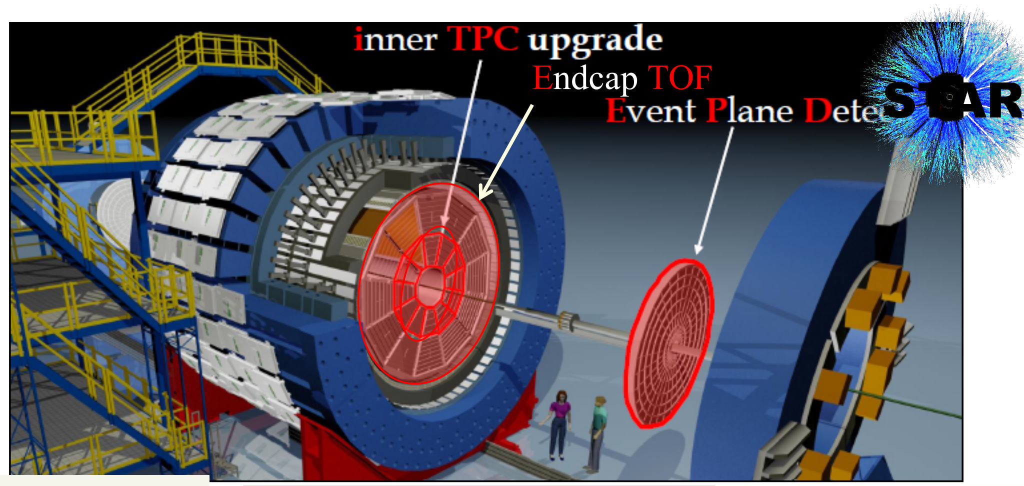
What is smallest droplet of matter showing collective behavior?

2015 NSAC Long Range Plan Endorsement



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.**





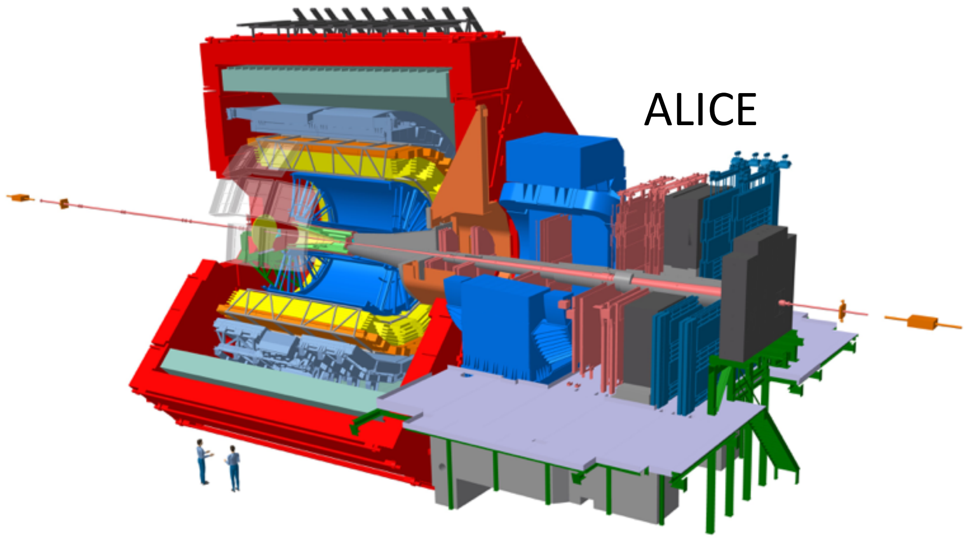
Physics goal	Detector requirement
High statistics for rare probes	Accept/sample full delivered luminosity Full azimuthal and large rapidity acceptance
Precision Upsilon spectroscopy	Hadron rejection > 99% with good $e^{+/-}$ acceptance Mass resolution 1% @ m_{Υ}
High jet efficiency and resolution	Full hadron and EM calorimetry Tracking from low to high pT
Control over parton mass	**Precision vertexing for heavy flavor ID**
Control over initial parton p_T	Large acceptance, high resolution photon ID
Full characterization of jet final state	High efficiency tracking for $0.2 < p_T < 40$GeV

TPC Upgrade:
Rebuilds the inner sectors of the TPC
Full (azimuth) coverage
mproves dE/dx
Extends η coverage from 1.0 to 1.7
Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

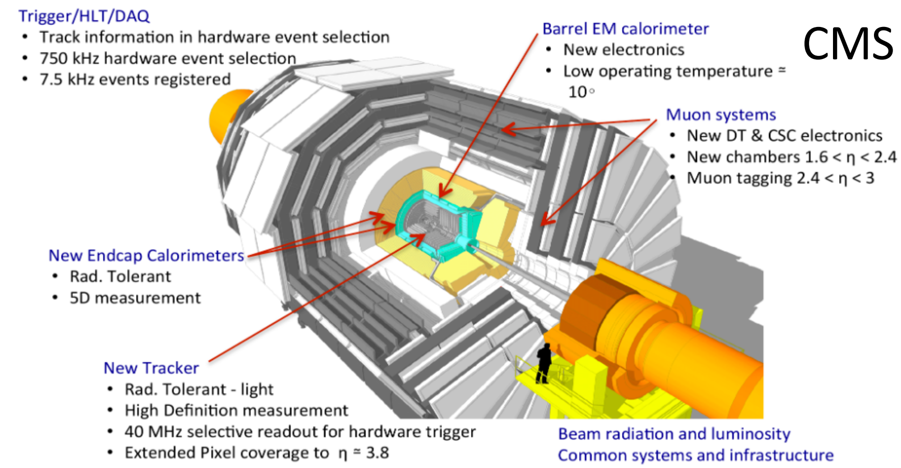
EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

LHC Upgrades - ALICE, ATLAS, CMS, LHC-B



ALICE



CMS

- Extension of forward muon system (LS2): muon acceptance
- Completely new tracker (LS3): tracking and b-tag up to η=4
- Upgrade forward calorimeter (LS3): forward jets in HI

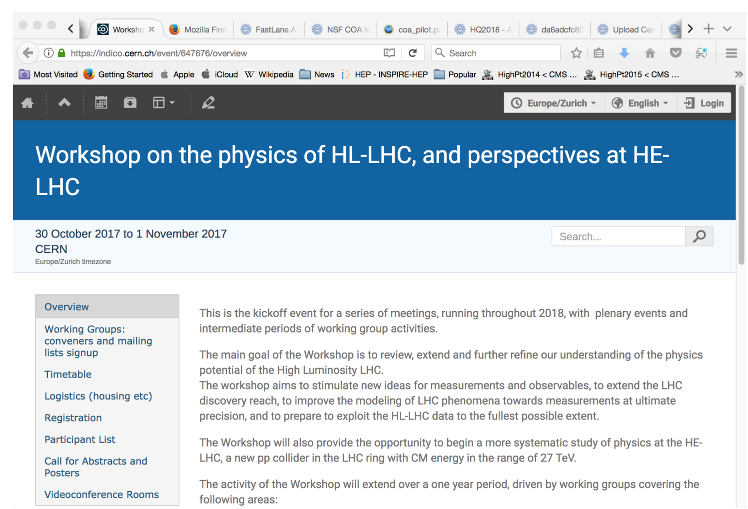
- New inner tracker: precision and efficiency at low p_T
- New pixel forward muon tracker: precise tracking and vertexing for μ
- TPC upgrade + readout + online data reduction x100 faster readout (continuous)

LHC-B

- Triggerless readout, full software trigger, higher granularity detectors: impact on tracking performance in Pb-Pb being studied
- Fixed-target programme with SMOG + possible extensions

ATLAS

- Fast tracking trigger (LS2): high-multiplicity tracking
- Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- ZDC replacement planned (LS2): radiation hardness, granularity
- Completely new tracker (LS3): tracking and b-tag up to η=4



https://indico.cern.ch/event/647676/timetable/

LHC Upgrades - ALICE, ATLAS, CMS, LHC-B

Heavy-Ion Physics in Run 3 and 4

Precision Physics

- Energy loss / qhat
  - Jets, b,γ,Z-jets, di-jets, colour/mass dep.
- Probe chiral symmetry restoration at $\mu_B = 0$
- QGP deconfinement and temperature
  - Quarkonia dissociation and regeneration
- Charm interaction with QGP
- Temperature dep. of transport coefficients
- Behaviour across system size
- High Q^2 and high-x nPDFs
- Ultraperipheral collisions
- Production of nuclei

Novel Directions

- Jet substructure
  - probe medium degree of freedom
- QGP temperature evolution
- Beauty thermalization
- Critical fluctuations, link to lattice QCD
- Collective behaviour of few particle systems
- Saturation at small x
- Light by light scattering
- Antihypernuclei and dibaryon

Existing documents: ALICE Upgrade LOI I MFT I ITS I MTK; ATLAS projections I ITk; CMS HI HL-LHC projections; HI Town Meeting I Input to ESPG

Heavy-Ion Prospects for HL-LHC - Jan Fiete Grosse-Oetringhaus 8

https://indico.cern.ch/event/647676/timetable/

Final Words

RHIC & LHC are amazing QCD discovery machines.

Jet Suppression, Collective Flow in large & small systems, Upsilon melting, J/Psi regeneration,…

Different Species, Various Energies, and High Luminosity and Stability

Important machine and detector upgrades underway

Heavy ion physics will continue to address fundamental aspects of QCD.

- Quantify the transport properties of the QGP with heavy quarks
- High statistics map of the QCD phase diagram, search for a possible critical point
- Probe internal structure of QGP with hard probes
- Investigations of QGP like properties in small systems

The Age of Quantitative QGP Tomography has begun.

But need to characterize medium parton interactions in detail!
Requires continuous interaction with Experiment & Theory