Jet probes of hot and cold nuclear matter

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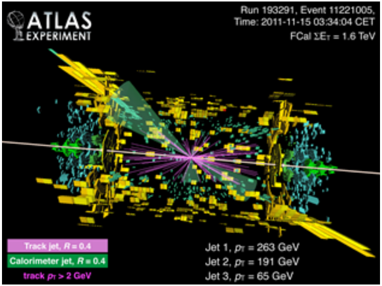
Outline

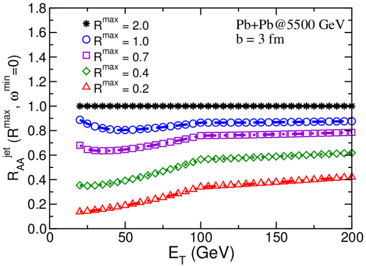
- What happens to a high-energy parton traversing the hot, dense medium?
  - $\Rightarrow$ jet suppression in A+A (from an ATLAS & PHENIX perspective)
  - $\Rightarrow$ how many experimental handles on quenching do we have?
  - $\Rightarrow$ what have we learned at the LHC?
  - $\Rightarrow$ can we capitalize on it with sPHENIX?
- What happens to (low-x) partons in the cold, dense nucleus?
  - $\Rightarrow$ what are the signatures of saturation?
  - $\Rightarrow$ what are the initial conditions in a heavy ion collision?
  - $\Rightarrow$ tension in d+Au centrality at high-p_{T}
  - $\Rightarrow$ opportunities in p+Pb 2013 and p+Au 2015

High-energy partons traversing the hot, dense medium

- RHIC has discovered (and LHC has confirmed) that a hot, dense medium is formed in head-on relativistic ion-ion collisions!
- How does the medium affect the development of a high-energy parton shower?
  - is the energy loss radiative or collisional / what is the path length dependence?
  - how is fragmentation in the medium modified from that in vacuum?
  - what is the *mass* dependence (e.g. of heavy flavor)?
  - what can we say about strong vs. weak coupling?
- How sharply does the coupling change with temperature (or range of temperatures)?
  - can we map out the region from $T = T_c$ to the asymptotically free regime at $T \to +\infty$?

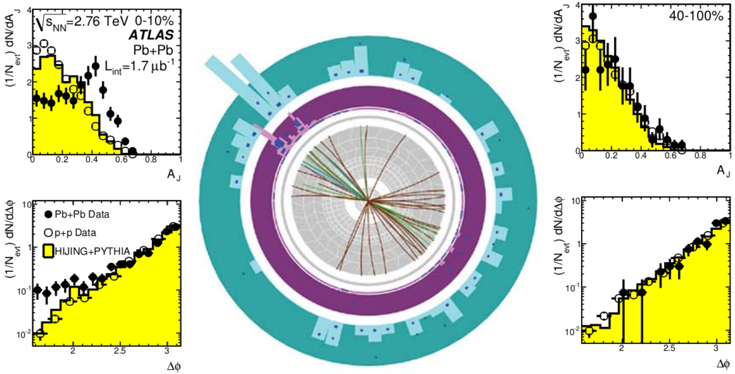
Reconstructed jets





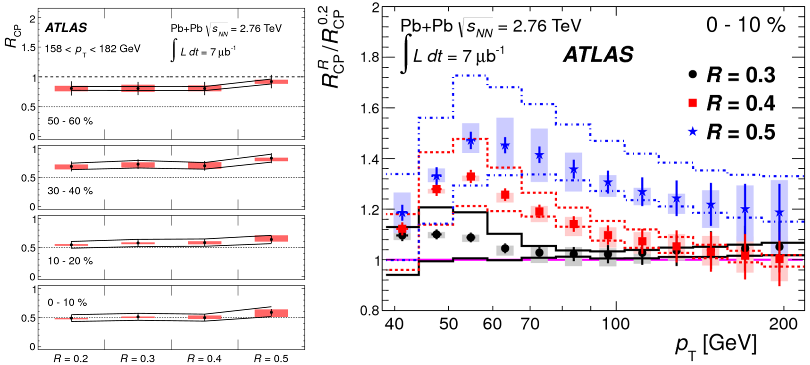
- Reconstruct fragmenting parton into jets
  - better indicator of the full parton kinematics (at LO)
  - sensitive probe of quenching/suppression (Right: Vitev, Wicks, Zhang, hep-ph/0810.2807)
- Technically challenging procedure in HI environment, but
  - a well-defined object that experimenters and theorists can agree on
- Which questions on the previous slide can jets answer?

Quenched dijet pairs in ATLAS



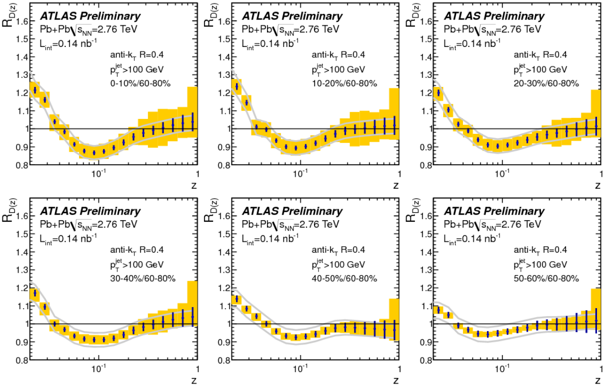
- Dramatic event-by-event evidence for jet quenching in late 2010
  - $\Rightarrow$ "differential" measurement of two jets with (anti-)correlated path length
- How are low-E_T vs. high-E_T jets affected? What is there a path-length dependence? Are jets "lost" or "quenched"? Where does the energy go? Is the fragmentation modified?
  - $\Rightarrow$ https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Jet R_{CP}: cone size, E_{T}, centrality dependence



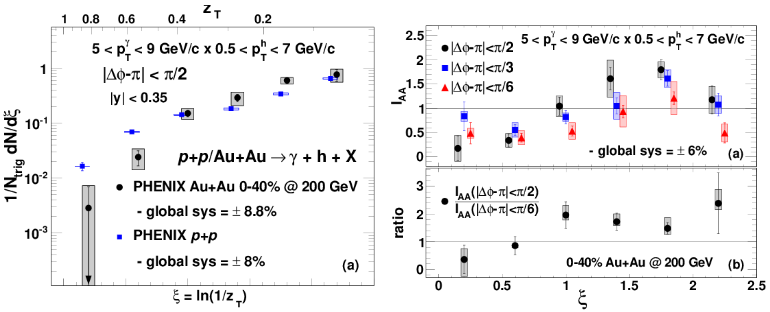
- Definitive measurement of jet quenching from 40-200 GeV
  - ⇒ but, only sees an average effect of the quenching
- Systematic variation with R observed
  - ⇒ not an *explicit* test of broadening (same "jet" can be reconstructed at a different energy)

Jet fragmentation in ATLAS



- Probe the structure of the jet by measuring the z-distribution of fragments in the jet cone
  - $\Rightarrow$ fragmentation modified (modestly) by the medium!
  - $\Rightarrow$ but, z is relative to the *quenched* jet energy
- Sidenote: many evaluations of jet performance in HI are sensitive to possible modifications of the fragmentation!

γ-jet (plus fragmentation) at RHIC

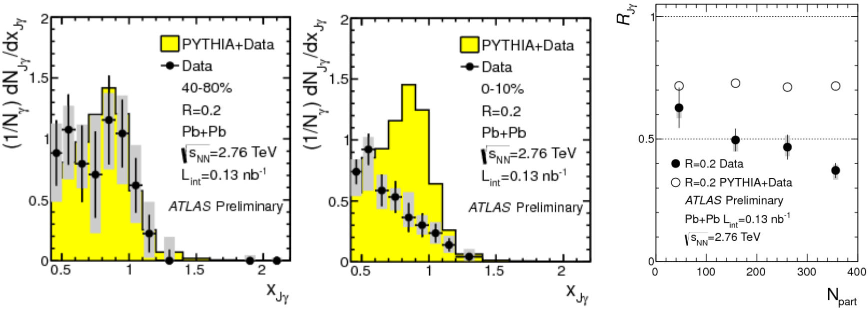


- PHENIX collaboration, nucl-ex/1212.3323
- γ-jet is a "golden channel" for jet measurements (more so at RHIC!)
- Fragmentation + quenching probed with γ-h correlations in PHENIX

  $\Rightarrow$ can recover an excess of high-ξ (low-z) particles with wider jet cone

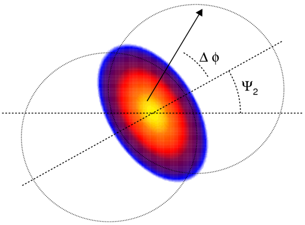
- Pro: not measuring fragment relative to $p_{\mathrm{T}}^{quenched}$
- Con: γ-jet energy balance only true at LO anyway

γ-jet at the LHC

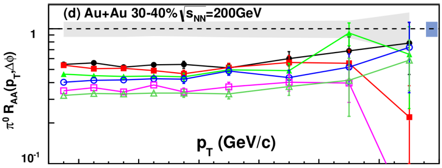


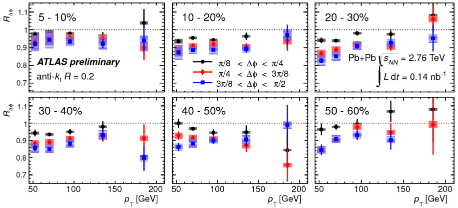
- In ATLAS, also use photon as colorless "control" probe
- Measure change in the mean ratio of γ/jet energies (x)
  - $\Rightarrow$ note: $x \neq 1$ for p+p
- Sensitive to details of kinematic selection on γ, jet
  - $\Rightarrow$ might "lose" the associated jet as it falls below the minimum E_{T} threshold
  - $\Rightarrow$ demonstrated in the fraction of photons with a jet $R_{J\gamma}$
- But, these are still integrated over all possible path lengths!

Path-length dependence: RHIC and the LHC

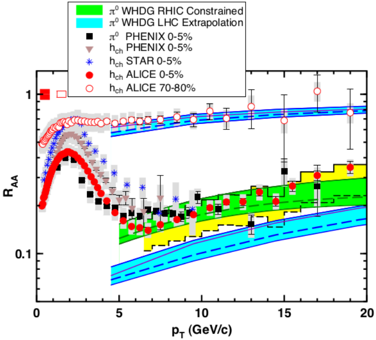


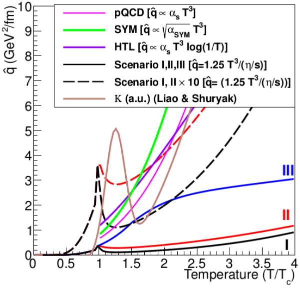
- Measure jet suppression with respect to the reaction plane
  - $\Rightarrow$ observed in $R_{\Delta\phi}$ or v_2 for jets
- Below left: PHENIX collaboration, nucl-ex/1208.2254 just published in PRC
  - $\Rightarrow$ strong azimuthal dependence
  - $\Rightarrow$ relatively weaker in ATLAS (but p_{T} dependent?)





Temperature dependence: quenching at RHIC vs. LHC





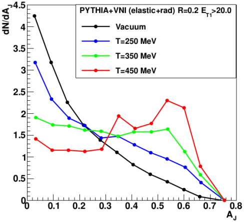
- Some jet quenching models, when tuned to RHIC data, *over-predict* the amount of quenching observed at the LHC
- In fact, it is possible that the coupling could be the *strongest* when $T \approx T_c$ (as in the RHIC regime)

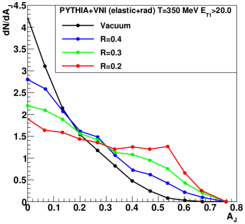
  $\Rightarrow$ crucial to map out the temperature-dependence of quenching

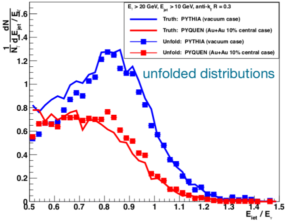
  $\Rightarrow$ need detector dedicated to jet physics at RHIC
- nucl-ex/1207.6378 + slides from many sPHENIX collaborators

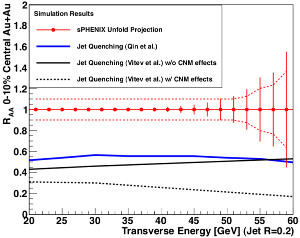
Sensitivity of RHIC jets to QGP properties

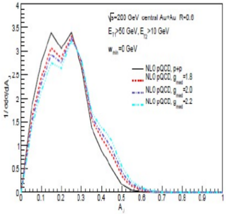
- What could jet measurements at RHIC energies reveal?
  - ⇒ quantitative constraints on different assumptions about key medium parameters



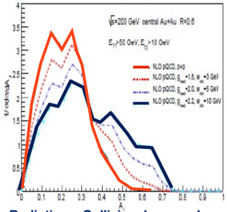






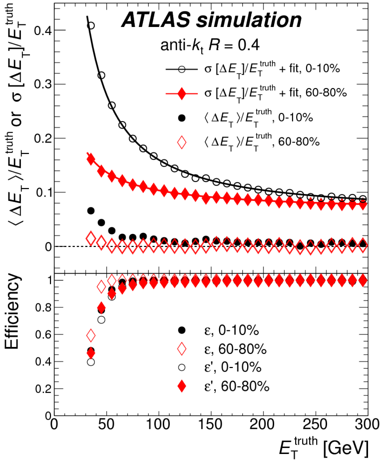


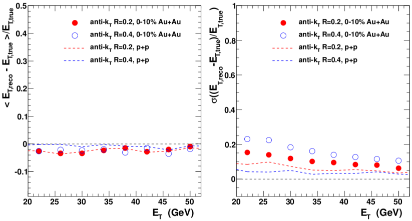
Radiative energy loss only

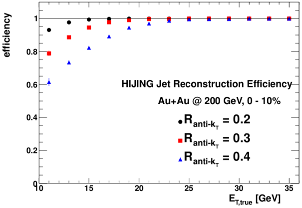


Radiative + Collisional energy loss
±10% changes in coupling strength

Re-investing LHC jet knowledge into sPHENIX @ RHIC



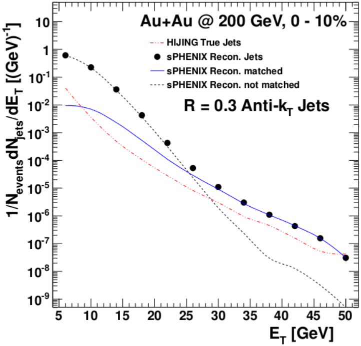


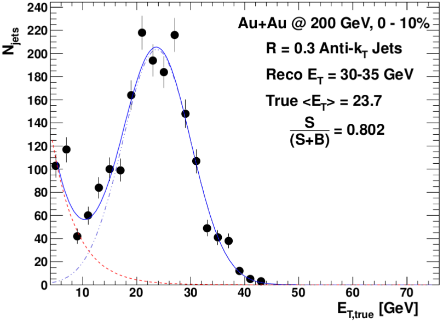


- Success of ATLAS jet measurements relies on detailed understanding of performance:
  - ⇒ e.g. efficiency, fake rejection, energy bias, energy uncertainty
- Performance in a concept jet detector at RHIC (nucl-ex/1203.1353)

Digging jets out of the background at RHIC

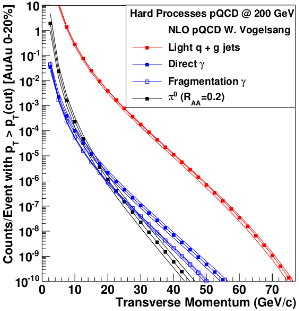
- "Jet-Underlying Event Separation Method for Heavy Ion Collisions at the Relativistic Heavy Ion Collider" (nucl-ex/1203.1353)
  - ⇒ MC proof of principle that jet reconstruction in HI backgrounds at RHIC is possible
  - ⇒ no modeling of detector effects, but also no fake rejection





- For any cone size R, there exists a $E_T^{threshold}$ above which "real" jets dominate the reconstructed spectrum

Physics reach of sPHENIX



	Au+Au central 20%	p+p	d+Au
>20 GeV	10^7 jets 10^4 photons	10^6 jets 10^3 photons	10^7 jets 10^4 photons
>30 GeV	10^6 jets 10^3 photons	10^5 jets 10^2 photons	10^6 jets 10^3 photons
>40 GeV	10^5 jets	10^4 jets	10^5 jets
>50 GeV	10^4 jets	10^3 jets	10^4 jets

- Assuming 20 weeks, only stochastic cooling upgrade to RHIC beams
- 10×10^9 central $(0-20\%)$ Au+Au collisions
- Very many jets!

  $\Rightarrow$ also dramatically improved acceptance for dijets

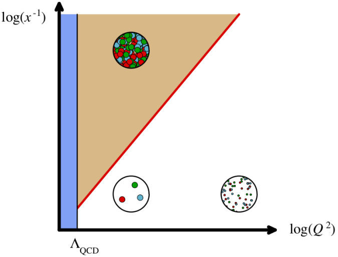
  $\Rightarrow$ (Note: first ATLAS dijet asymmetry results used only $\sim$ 1k pairs)

Outlook: jets in A+A

- Measurements of full jets at the LHC are yielding a rich picture of energy loss
  - ⇒ best strategy is to make lots of measurements (singles, correlations, tags, fragmentation)
  - ⇒ many not even mentioned: inclusive heavy-flavor, flavor-tagged jets, other jet structure, energy balance, etc.
- Knowledge being re-invested into preparing for jet physics program with sPHENIX
  - ⇒ temperature dependence of quenching may be the most important lever of all!
  - ⇒ capable detector, the experimental methodoloy, and the statistical precision to significantly constrain QGP properties
  - ⇒ collaboration between two colliders
- Remember: all A+A results are contingent on p(or d)-A

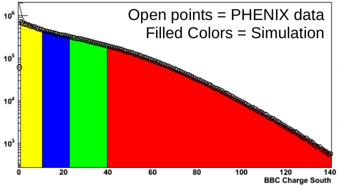
Jets in the cold, high parton-density nucleus

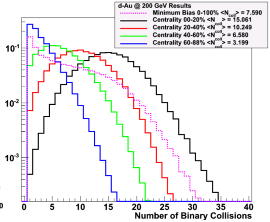
- Jets in p/d+A experiments are an important control for $A+A$
  - confirm that the strong suppression is a final state effect
  - in the perturbative regime: test pQCD, collinear factorization, nPDF's, collisional scaling

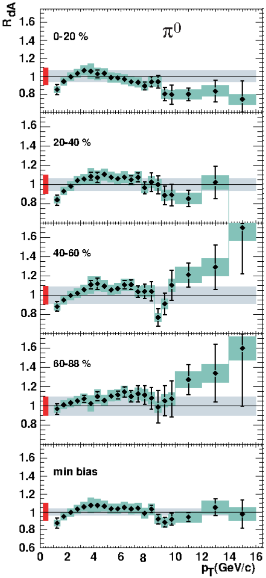


- Unavoidably, the evolution of the gluon density becomes non-linear in a certain region of low-x (for fixed Q^2)
  - saturation effects (and their description with effective theories) come into play
  - $y^{RHIC} \approx 3$ ($y^{LHC} \approx 0$!)
  - how can we probe the consequences of this with jets?
- Other CNM effects: initial state E-loss, broadening, etc.
- Most if not all of the above are $T_A(b)$-dependent
  - crucial important to obtain experimental handle on the geometry

#_ Early success of Glauber model in d+Au

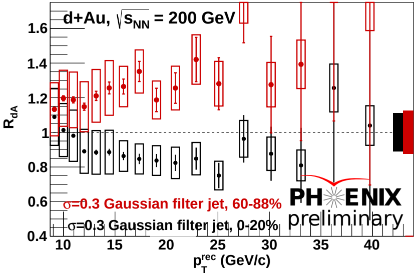


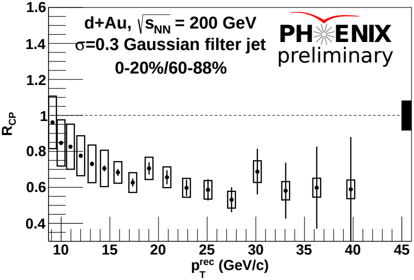




- Au-going BBC multiplicity used for centrality determination
- Glauber MC generates distribution of N_{coll}
  - $\Rightarrow$ $dN_{\mathrm{coll}}(b)/db$ at fixed impact parameter
- assume a collision w/ given N_{coll} looks like N-convoluted $p+p$
  - $\Rightarrow$ BBC response (+ convolution) naturally described with NBD or Gamma dist.
- d+Au results from 2003: inconclusive at high-p_{T}

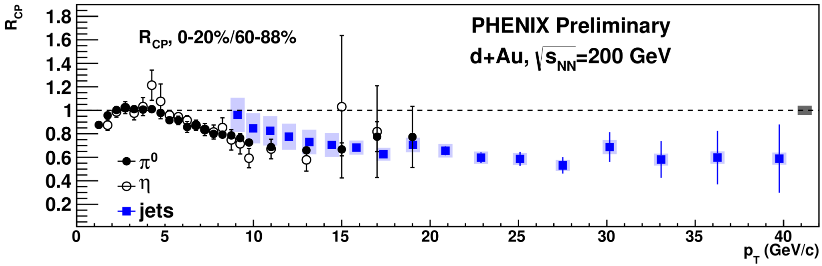
High-p_{T} jets in d+Au





- Note: different jet methodology than in ATLAS measurements
- N_{coll}-scaling at $p_{\mathrm{T}} \approx 10$ GeV
  - $\Rightarrow$ but then significant centrality-dependent deviation
  - $\Rightarrow$ slight suppression in central events
  - $\Rightarrow$ moderate enhancement in peripheral events
  - $\Rightarrow$ challenging to explain both!
- Even more evident in the R_{CP} with common systematics cancelled
  - $\Rightarrow$ systematic with p_{T} (and centrality)

High-p_{T} jets in d+Au: centrality "bias"?



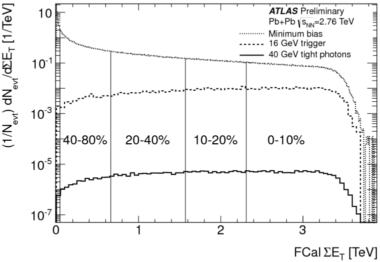
- Result is experimentally robust with respect to single hadrons, different p+p reference, fiducial cuts, narrower centrality selections, etc.

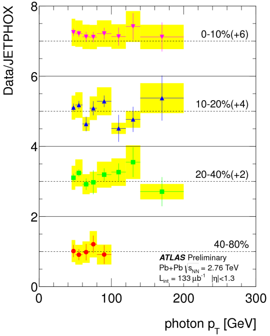
  $\Rightarrow$ only remaining possibility is N_{coll} / centrality

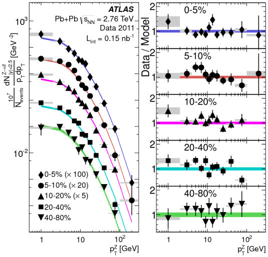
- Challenging to disentangle many years after the fact and with gaps in η coverage

  $\Rightarrow$ p+Pb run (with rebuilt ATLAS ZDC) could help shed light on this?

Success of Glauber model in Pb+Pb

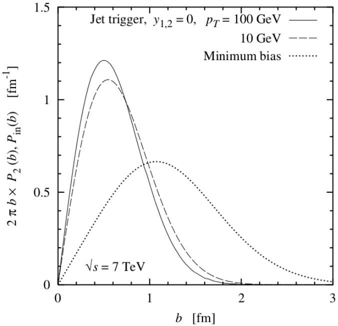






- Mapping of N_{coll} distribution onto ΣE_T^{Pb} works well
  - $\Rightarrow$ Direct γ, Z "standard candles" confirm N_{coll}-scaling expectation
- Centrality E_{T} cuts are large relative to the contribution from any given N_{coll}
  - $\Rightarrow$ model insensitive to small details in $N_{\mathrm{coll}} : E_{\mathrm{T}}$ correlation

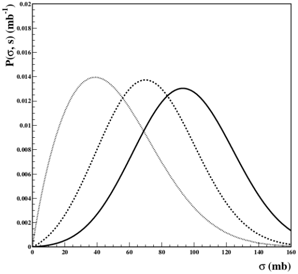
Effects of selecting a hard scattering

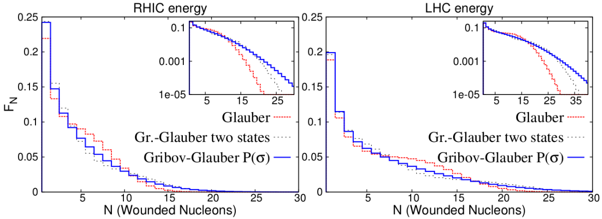


- Frankfurt, Strikman, Weiss, hep-ph/1009.2559
- Events with hard scatterings sample a different set of impact parameters, even in $p+p$
  - $\Rightarrow$ associated with an increased multiplicity and underlying event

- N_{coll}-scaled yields of hard probes are a staple of HI physics
  - $\Rightarrow$ an event with a hard process is assumed to have the "minimum bias" distribution when categorizing its centrality!
  - $\Rightarrow$ relevant when the difference in mean underlying event is of the same scale as the difference between centrality bins!
- PHENIX results include a "bias factor" (0.05-0.10 of the low R_{CP})
  - $\Rightarrow$ undergoing detailed re-investigation

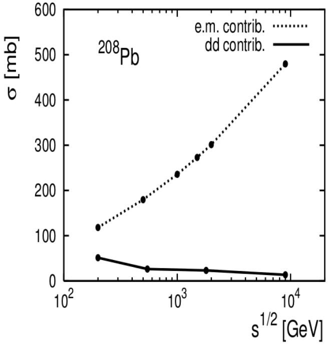
Color fluctuations

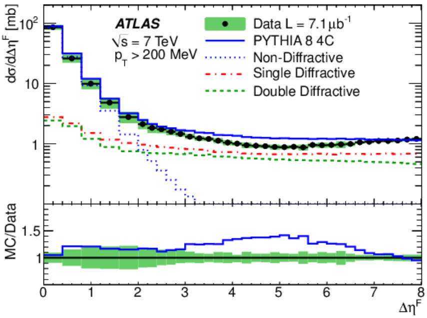




- Alvioli, Strikman, hep-ph/1301.0728
- Color fluctuations can be modeled as event-by-event (and nucleon-by-nucleon) fluctuations of the effective σ_{NN}
  - $\Rightarrow$ probability distribution $P(\sigma, s)$, with $\langle\sigma\rangle = \sigma_{NN}^{nominal}$ (left)
  - $\Rightarrow$ results in N_{part} distribution with significantly modified shape
  - $\Rightarrow$ mean N_{part} is unaffected
  - $\Rightarrow$ potentially important effect on how tightly b and N_{coll} are correlated!

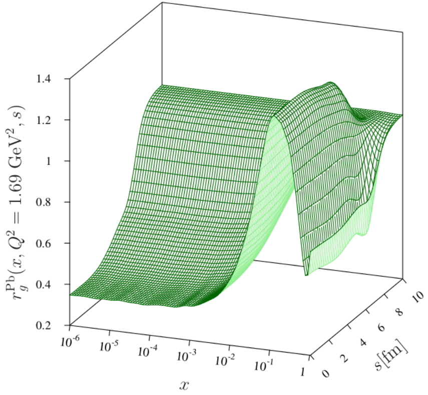
"non-Glauber" contributions in MB events

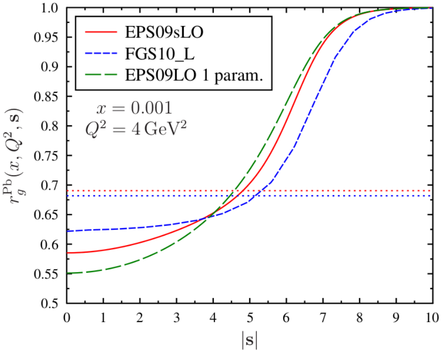




- ATLAS Minimum Bias triggers select a non-trivial sample of events not normally described by a Glauber MC
  - ⇒ single/double/central diffraction above the assumed σ_{NN}
  - ⇒ photonuclear (ultraperipheral) excitation
  - ⇒ Guzey, Strikman, hep-ph/0505088
- Challenging to disentangle from peripheral events

Impact-parameter dependent nPDF's in p+Pb

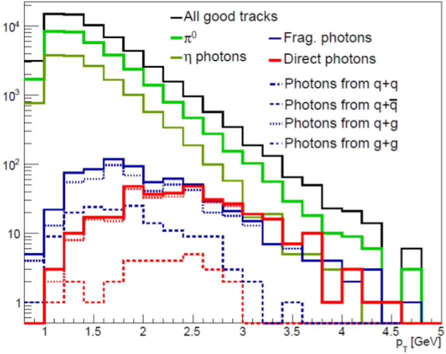


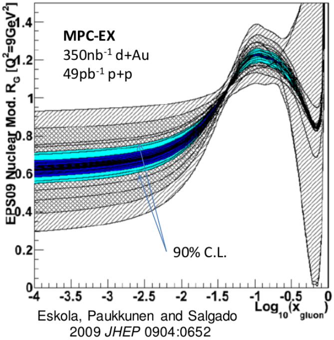


- *b*-dependent nPDF sets from Helenius, Eskola, Honkaken, Salgado, hep-ph/1205.5359
  - ⇒ potentially large *b*-dependence, depending on (x, Q^2) and q vs. g
  - ⇒ tuned by min bias $R_{p/d+A}$ for different A
  - ⇒ centrality-dependent R_{pA} can help constrain

Physics possibilities with the MPC-EX in 2015 p+Au

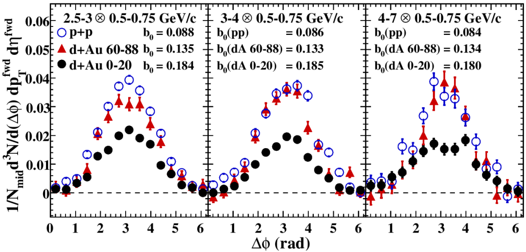
- MPC-EX: charged particle tracker and EM preshower, $3.1 < |\eta| < 3.8$
  - $\Rightarrow$ will select direct γ's with good purity
  - $\Rightarrow$ ready in time for RHIC p+Au 2015 run

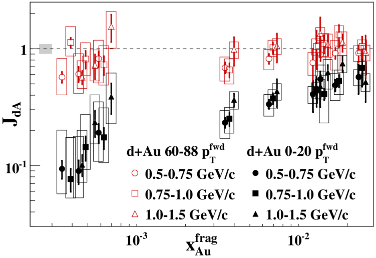




- Left: performance plot from MC studies
- Right: expected uncertainty on measurement of (poorly constrained) gluon nPDF

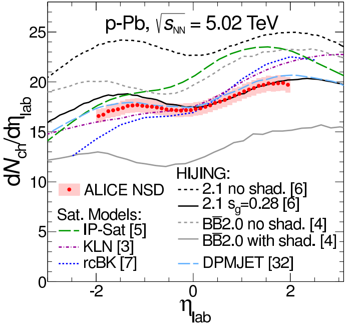
$\Delta\eta$-separated correlations in PHENIX

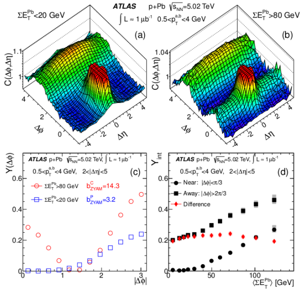




- Correlation of hadron in Central Arms ($|\eta| < 0.35$) with forward hadrons in the *d*-going MPC ($3.0 < \eta < 3.8$))
  - $\Rightarrow$ also forward-forward correlations
  - $\Rightarrow$ followed measurements that demonstrated suppressed of inclusive forward hadrons
  - $\Rightarrow$ results well-reproduced by CGC formalism
  - $\Rightarrow$ but other possible explanations could not be ruled out
- Possible to repeat with full jets?
- But first, a quick look at LHC *p*+Pb results. . .

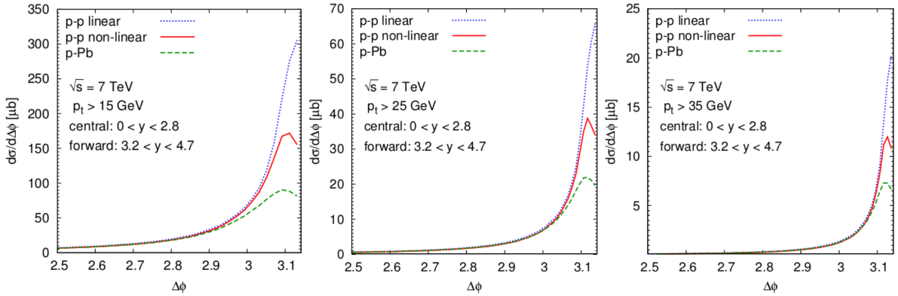
Two early and different probes of saturation





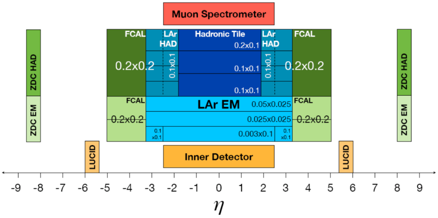
- First measurement of $dN^{ch}/d\eta$, ALICE Collaboration, nucl-ex/1210.3615
  - $\Rightarrow$ compared to two-component (pQCD+soft+nPDF) models and saturation models (that reduce the number of gluons available for particle production)
- "Ridge" seen by all three experiments
  - $\Rightarrow$ CMS data well-described by CGC calculation (Venugopalan, Dusling, hep-ph/1211.37.01, with additional predictions!) and hydrodynamic flow (Bozek, Broniowski, nucl-th/1211.0845)

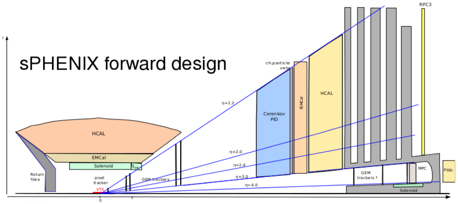
$\Delta\eta$-separated dijets: with full jets



- Kutak, Sapeta, hep-ph/1205.5035
- Calculation of central-forward jet correlations
  - $\Rightarrow$ sensitive to saturation effects
  - $\Rightarrow$ strongest effect at lowest E_{T}
  - $\Rightarrow$ very large $\Delta\eta$ required!
- How could we even make this measurement?

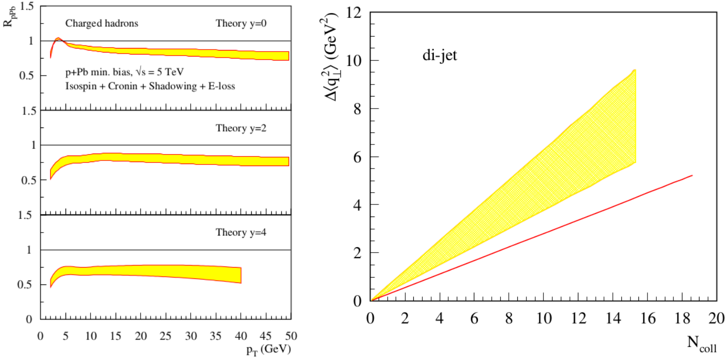
Forward jets in ATLAS and forward-sPHENIX





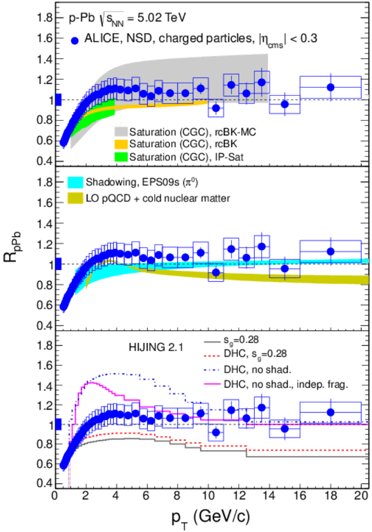
- Large η acceptance is needed for rapidity-separated observables
  - $\Rightarrow$ in ATLAS, inner detector is $|\eta| < 2.5$
  - $\Rightarrow$ must rely on jets in the (non-projective, coarser-scale) Forward Calorimeters ($3.2 < |\eta| < 4.9$)
  - $\Rightarrow$ all Pb+Pb (and SM *p*+*p*) jet results typically at $|\eta| < 2$ ($|\eta| < 3.2$)
- Forward-sPHENIX design includes forward jet capabilities
  - $\Rightarrow$ combination of GEM tracking, HCal, repurposed PHENIX PbGl in $1.2 < \eta < 4$

Other CNM predictions for p+Pb



- Left: R_{pPb} arising from from multiple scattering, Cronin, shadowing
  - $\Rightarrow$ largest effects are at $y = 4$
  - $\Rightarrow$ Kang, Vitev, Xing hep-ph/1209.6030 , predictions for π^0, γ as well
- Right: additional transverse momentum imbalance $\langle q_\perp^2 \rangle^2_{pA} - \langle q_\perp^2 \rangle^2_{pp}$
  - $\Rightarrow$ systematic with N_{coll}-dependence
  - $\Rightarrow$ Xing, Kang, Vitev, Wang hep-ph/1206.1826 , for $E_{\mathrm{T}}^{jet} > 30$ GeV, $y^{jet} = 2$

Minimum-bias R_{pPb} in ALICE



- First measurement of R_{pPb} with charged particles
  - $\Rightarrow$ factor of 2 suppression at low-p_{T}
  - $\Rightarrow$ little or no Cronin enhancement
  - $\Rightarrow$ flat $R_{pPb} \approx 1$ at high-p_{T}
- Event selection criteria are 96% efficient for "Non-Single Diffractive" p+Pb collisions
  - $\Rightarrow$ interpolated p+p reference
- Impressive start to p+Pb program
  - $\Rightarrow$ now need centrality-dependence
  - $\Rightarrow$ η-dependence (from other experiments)
  - $\Rightarrow$ correlations
- ALICE Collaboration, nucl-ex/1210.4520

Outlook: jets in p+A

- On the horizon: precise and revealing measurements of low momentum partons in heavy nuclei
  - ⇒ test predictions from different frameworks of saturation
  - ⇒ resolution of key issues related to centrality
  - ⇒ impact-parameter dependence of nPDF's
  - ⇒ cold nuclear matter effects such as initial state energy loss, coherent multiple scattering
- Best way forward is a mixed experimental strategy with several key ingredients:
  - ⇒ control over geometry / centrality
  - ⇒ as large an η-acceptance as possible
  - ⇒ forward jet reconstruction capabilities
  - ⇒ direct photons are a plus
  - ⇒ shared expertise between LHC/RHIC experiments
- Exciting things are happening in the very short- (p+Pb), short- (p+Au) and medium- (sPHENIX) terms!

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