Interplay of QCD and Electromagnetism in Heavy-Ion Collisions

(Ho-Ung Yee, UIC/RBRC)

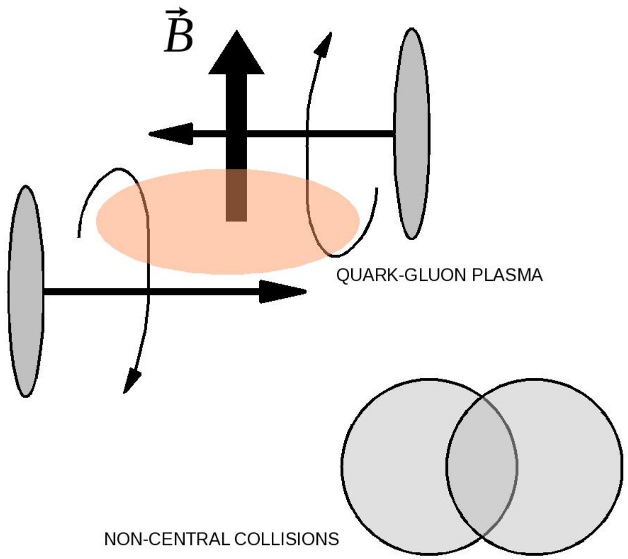
There are two closely related aspects in electrodynamics in heavy-ion collisions

1) Electromagnetism as a probe to QGP

: Photon and di-leptons, or current spectral densities as one of the fundamental properties of QGP. PHENIX/STAR photon and dilepton flow/rate measurements and lots of theory and numerical works -> A significant size of works and community

2) Dynamical interplay of QCD strong dynamics and EM dynamcs

: Heavy-ions carry EM charge $Z \sim 10^2$, so the interaction strength is $Z \cdot \alpha_{EM} \sim 10^2 \cdot \frac{1}{137} \sim O(1)$: Not Negligible

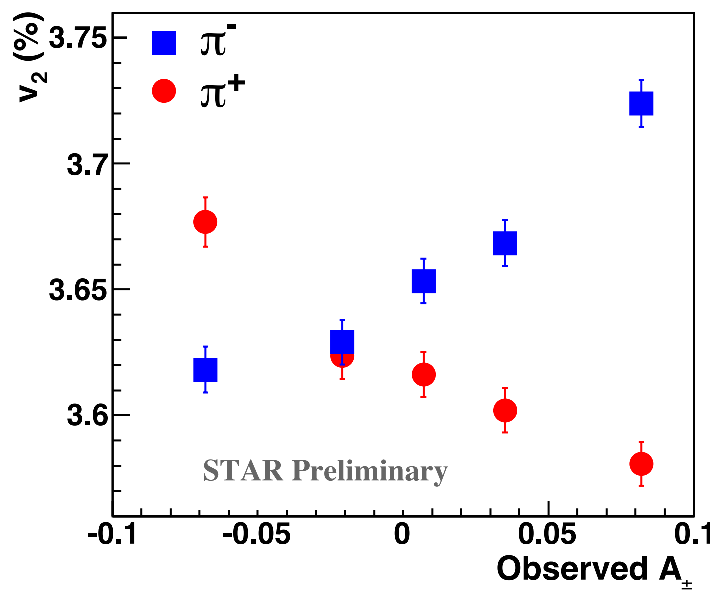


The strength of EM fields are of order $5-10m_\pi^2 \sim (0.5GeV)^2$ both electric and magnetic fields

There are interesting fluctuations of them

There are many interesting and fundamental physics that can arise as interplay of QCD with EM

1) Chiral anomaly/chiral symmetry breaking, such as Sphaleron physics (EW baryon genesis)
2) Chiral Magnetic Effect/Chiral Magnetic Wave
3) Flows affected by EM charge transports and EM fluctuations
4) Some low x fermionic partons may be highly affected by a large EM charge
5) The physics is not fully explored yet !!!



Summary

1) Flavor symmetry of QCD is an important ingredient of QCD itself. Electrodynamics is a part of it
2) Heavy-ion collision creates an interesting environment where, not only QCD, but also QED and its interplay with QCD can be relevant
3) This will probably result in a synergistic advancement in our understanding of the physics of QGP
4) Full fledged study on this can be one of promising directions in future research, both experimentally and theoretically

Implications on RHIC/LHC

1) Precision photon/di-lepton measurements, such as polarization measurements will be valuable
2) Charge conjugation odd (C=-1) observables :

   Sensitive to Z > 0 --> Must be related to EM

3) pA versus $\overline{p}A$ difference can isolate EM interplay with QCD clearly

Dileptons and chiral symmetry restoration

Paul Hohler

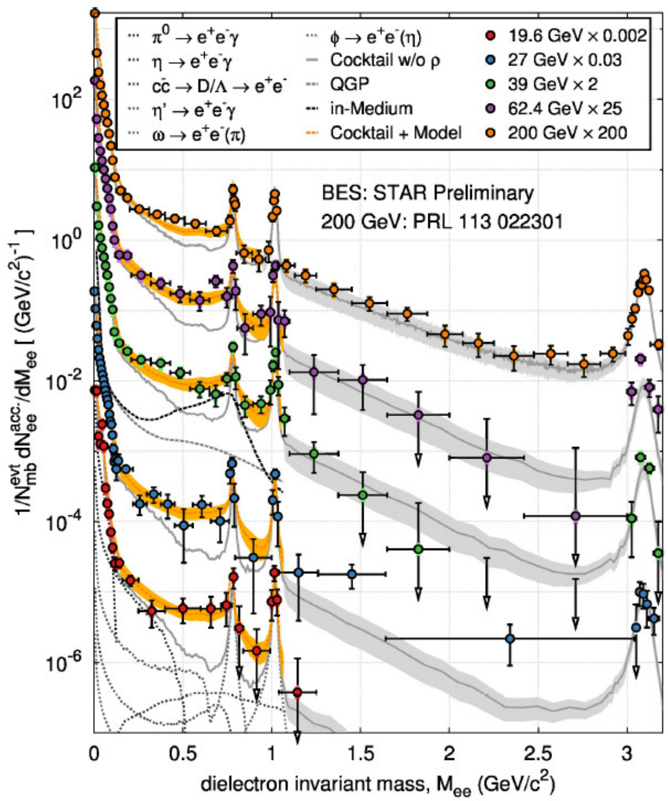
Texas A&M University

- Chiral symmetry
  - Spontaneously broken in QCD vacuum
    - → Imprinted on hadron spectrum
  - Restored at finite temperature
    - → Diagnose via hadron spectrum in medium

- HICs: in-medium ρ via low-mass dileptons
  - Broadening/melting consistent with data
  - Manifestation of chiral restoration?

- Need to test degeneracy with chiral partner (a_1)
  - Difficult to measure

- Theory required to unravel mechanisms

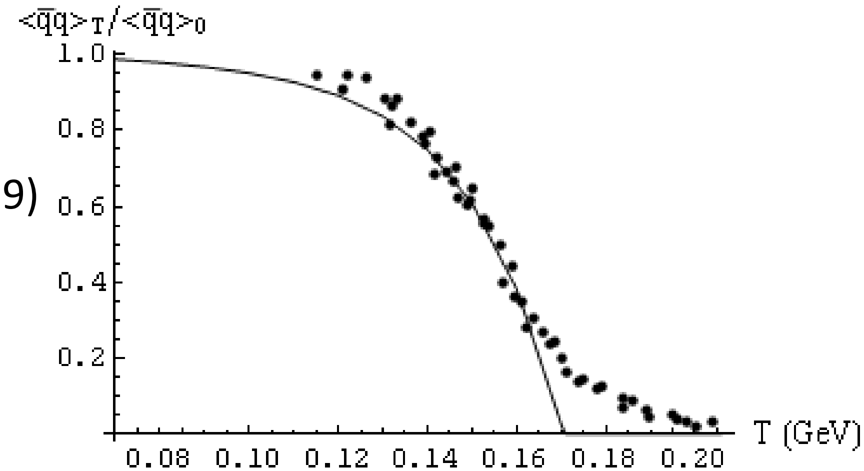


STAR
N. Xu, QM14

Sum Rules Analysis:

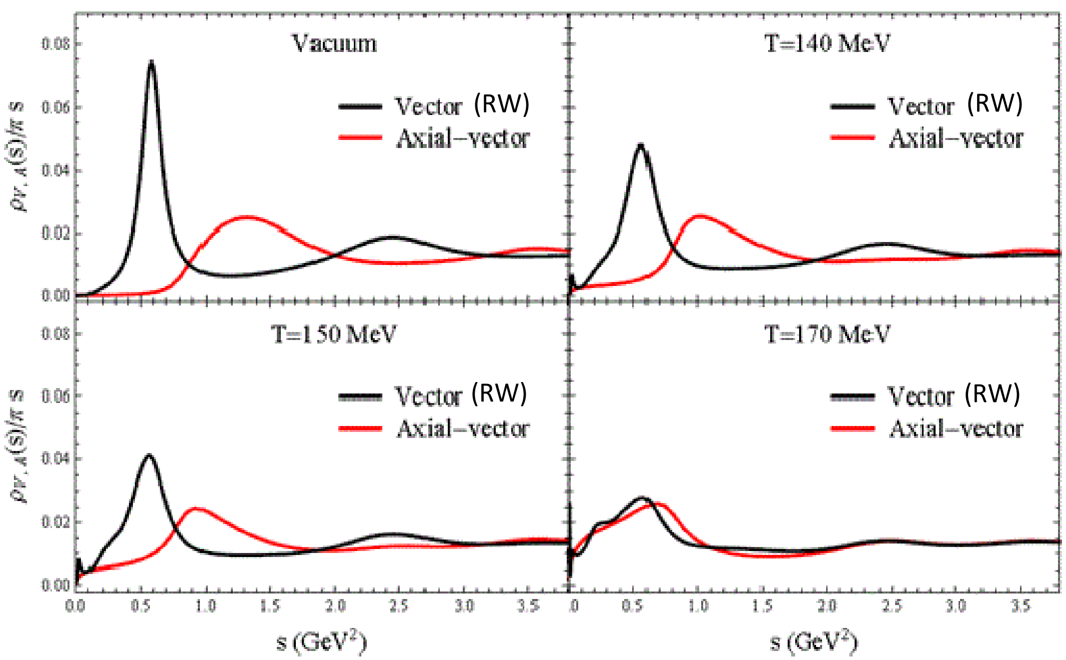
PLB 731 (2014) 103

Relate ρ and a_1 properties to QCD condensates



- Inputs
  - ρ spectral function from Rapp, Wambach (99) (→ dilepton experiments)
  - Finite-T condensates from Lattice QCD / Hadron Resonance Gas

- Search for in-medium a_1 to satisfy both QCD and Chiral sum rules



- Findings
  - Mass splitting “burns off”
  - Resonances “melt”
  - Compatible with approach to chiral restoration

- Underlying mechanism?

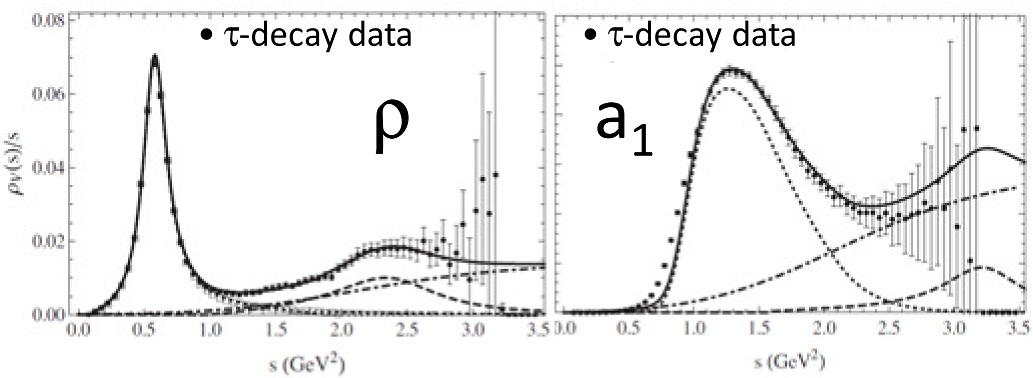
In progress: Hadronic Effective Theory

PRD89 (2014) 125013

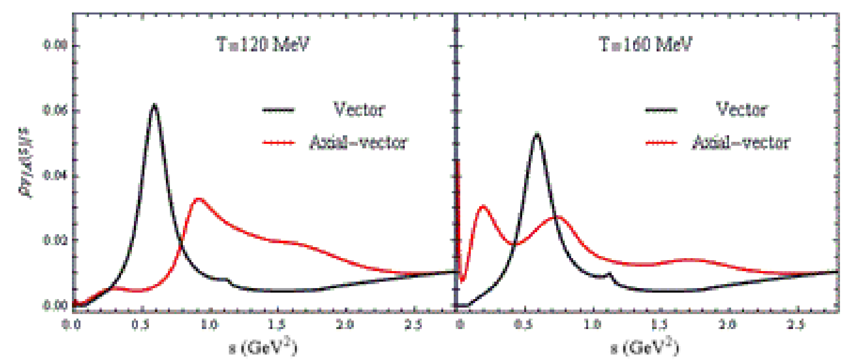
Calculate (ρ, a_1) properties and chiral condensate in one microscopic framework:

Implement (ρ, a_1) in chiral Lagrangian as gauge bosons (“Massive Yang-Mills”)

Vacuum



Pion Gas



- Achieved description of vacuum a_1 spectrum
- Preliminary in medium analysis supports a_1 mass shift

Future tasks:

- Full implementation of medium effects including baryons
- Need precise low-mass dilepton data at $\mu_q \sim 0$ (RHIC/LHC)

Decisive progress in understanding chiral symmetry restoration achievable.

The Physics of Dilepton Measurements in A+A

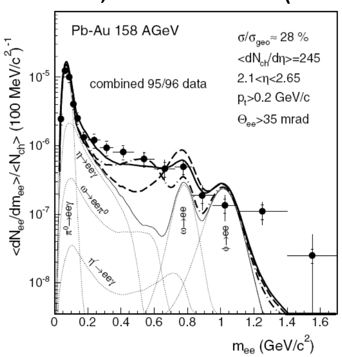
low invariant mass (M_{ee}<1.1GeV/c^2)

- study of ρ meson spectral function: probe of chiral symmetry restoration
- emission rates depend on T, total baryon density, and life time

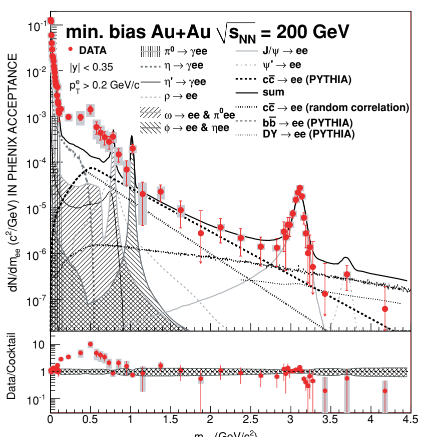
intermediate mass (1.1 < M_{ee} < 3 GeV/c^2)

- slope represents the average temperature of the medium

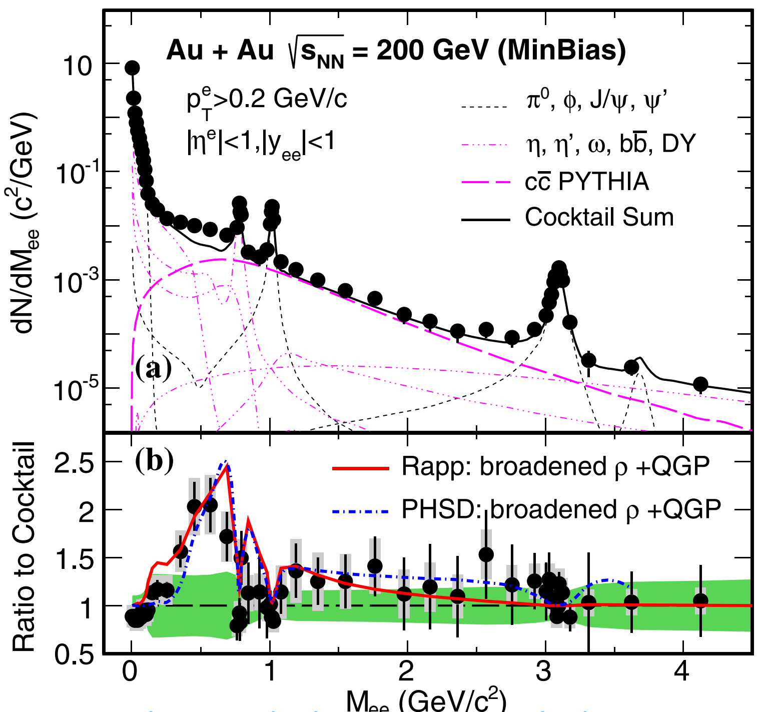
CERES, PLB 666 425 (2005)



PHENIX, PRC 81 034911 (2010)



STAR, PRL 113 022301 (2014)



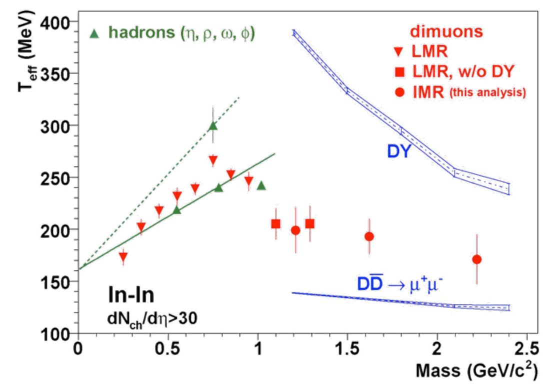
low | intermediate | high

$\rho \rightarrow e^+e^-$
π,η,ω,ϕ

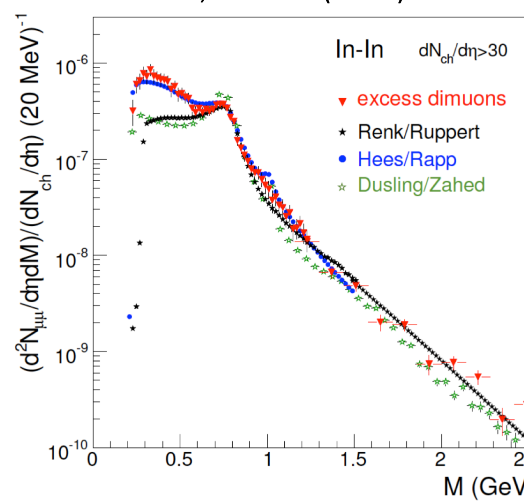
$q\bar{q} \rightarrow l^+l^-$
$c \rightarrow l^\pm$

J/ψ, DY,
Υ(1S,2S,3S)

NA60, EPJ C59 (2009) 607



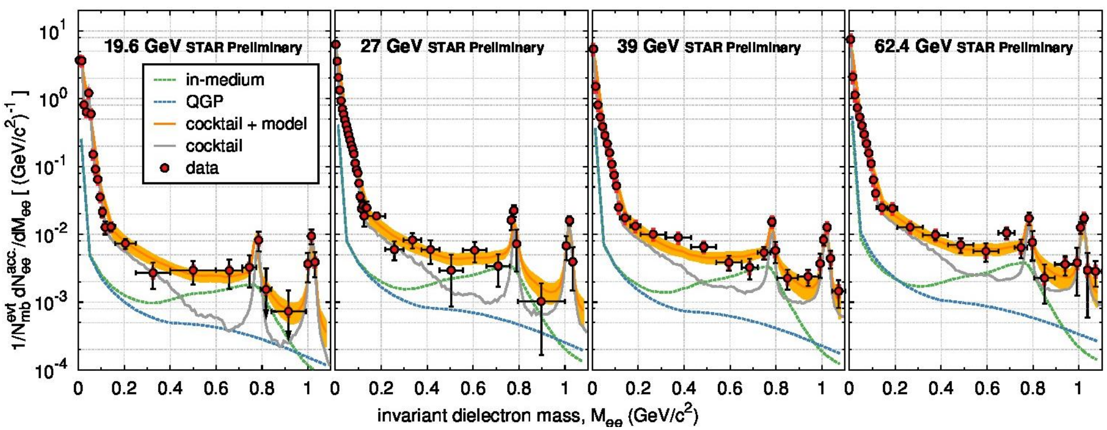
NA60, EPJ C61 (2009) 711



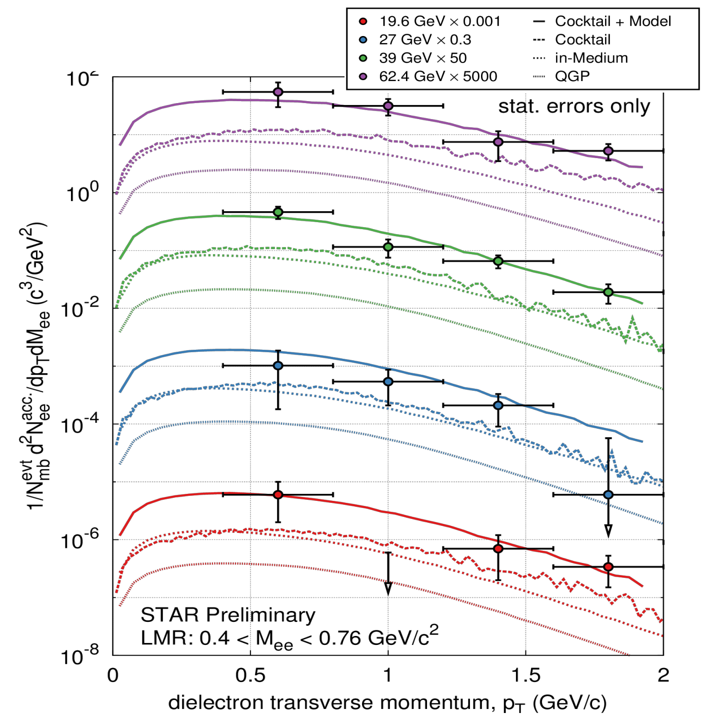
Recent Progress: RHIC Beam Energy Scan

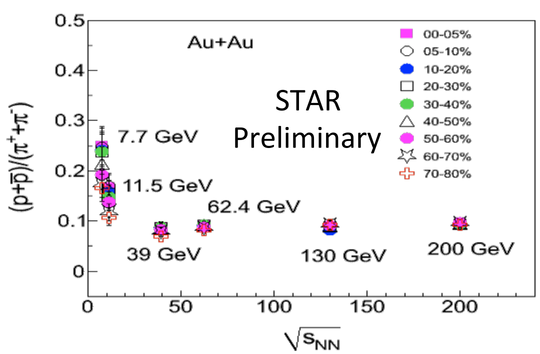
- Temperature dependence of the ρ spectral function
  - Initial state and temperature evolution is different
- broadened spectral function describes e^+e^- excess from top RHIC energy at 200 GeV down to SPS energies at 19.6 GeV
  - beam energy range where final states are similar
- N_{part} dependence as an another knob

STAR @ QM2014

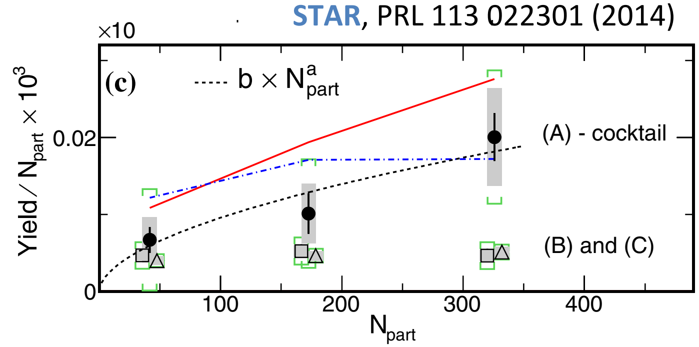


STAR @ QM2014





STAR, PRL 113 022301 (2014)



mass ranges
A= ρ-like
B=ω-like
C=ϕ-like

Future Prospects …

BES Phase 1: 19.6 – 200 GeV

- Dilepton emission dominant in T_C region and constant baryon density
  - ➢ emission proportional to lifetime

BES Phase 2: 7.7 – 19.6 GeV

- ➢ Life time + baryon density dependence of the ρ spectral function
- ➢ Probe

Down to FAIR energies

- – CBM, HADES

- probe lifetime, total baryon density, and temperature dependence

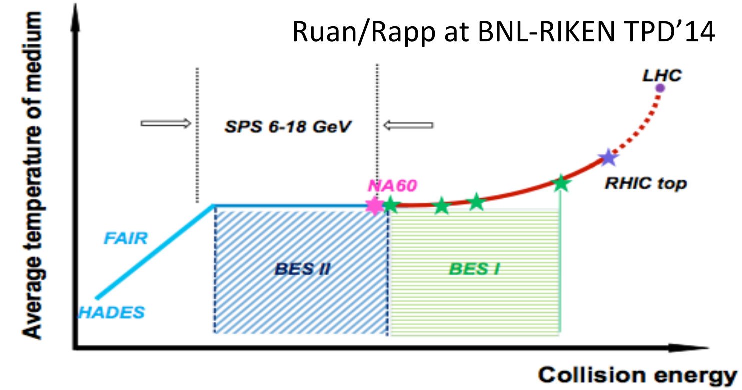
At SPS: proposed NA60+

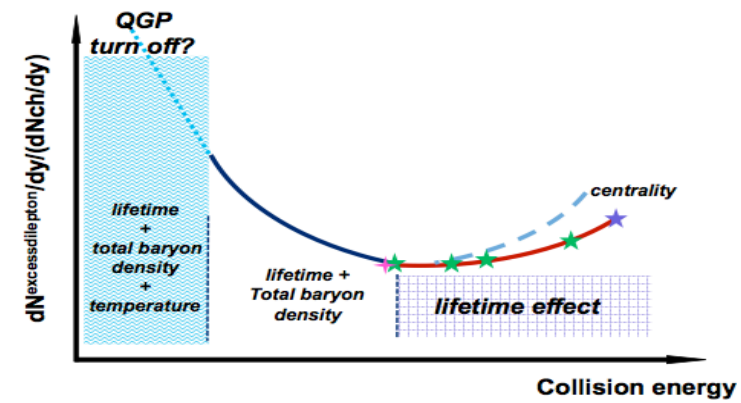
- overlap with RHIC and FAIR

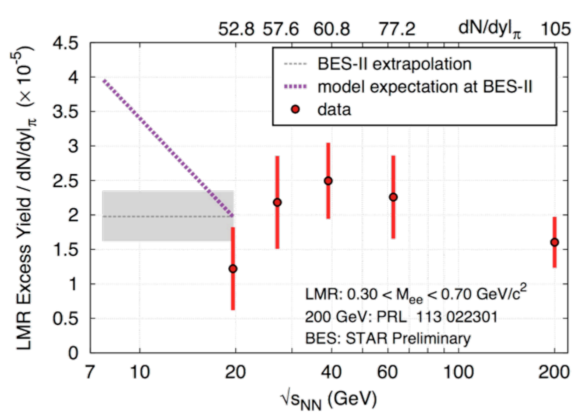
… & Needs

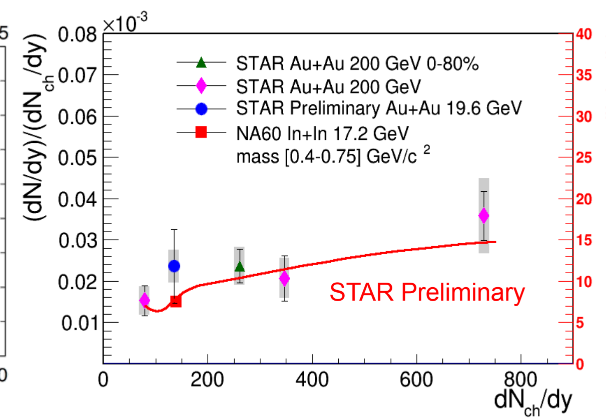
- Include dimuon measurements
- Improve charm measurements
- Improved statistics

➢ RHIC BES Phase-2









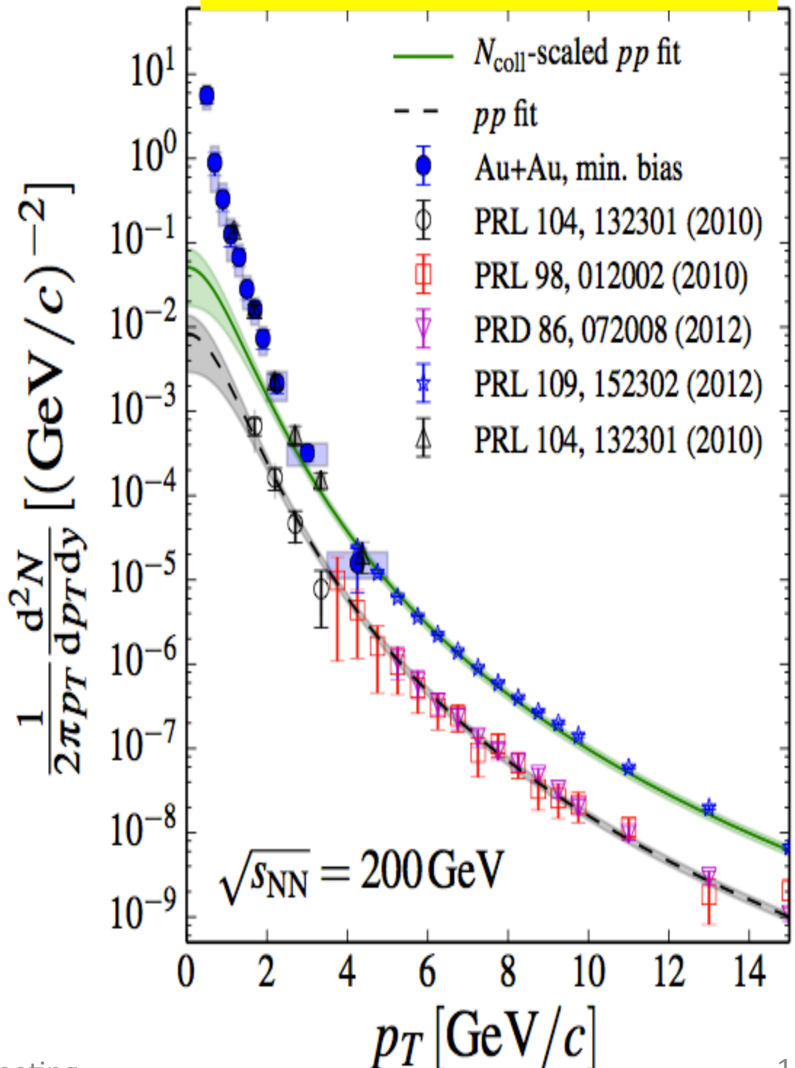
Soft photon measurement ~present and future~

Takao Sakaguchi (BNL)
with Gabor David, Ralf Rapp and Lijuan Ruan

- Soft photons = photons not from decay from hadrons or hard scattering
  - Emission strength (rate) reaches to the heart of the microscopic interactions in the medium
  - inverse slope closely related to temperature profile and radial flow
- Provide unique information but historically always took significantly longer time to measure than other QGP signals
- Measurement methods
  - Calorimetric measurement of real photons
    - Limited precision at low pT
  - e+e- external conversion
    - Precise down to very low pT, but requires huge statistics
    - Only proven way to access yield/flow below 1GeV/c
  - e+e- internal conversion
    - important cross-check, but needs statistics and has an irreducible lower limit in pT

arXiv:1405.3940

Direct photon spectra in Au+Au and p+p

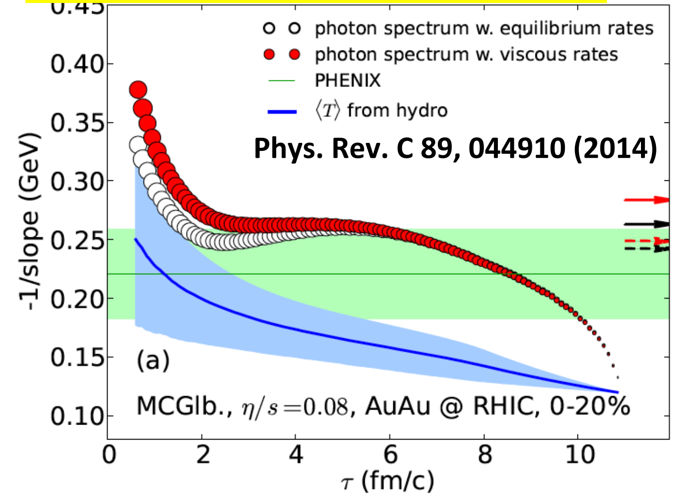


Recent status and results

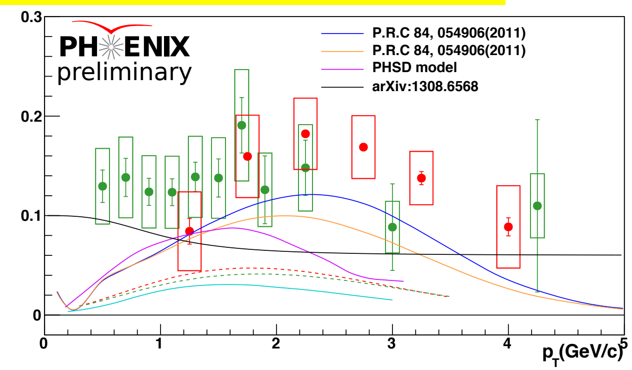
- Experimental side
  - Measurement of spectra has been performed down to pT=0.5GeV/c
  - Inverse slope of the spectra is 220MeV, which is consistent with virtual photon analysis
  - v2/v3 has been measured
    - v3 is positive. Hydrodynamical process is dominant (magnetic field effect has v3=0)

- Theoretical side
  - Large v2 (build up in the later stage) has not been consistent with large yield (build up in early stage)
  - Recent works suggested that the high effective temperature come from around Tc plus blueshift.
    - Phys. Rev. C 84, 054906 (2011)
    - Phys. Rev. C 89, 044910 (2014)
  - Hadron-gas interaction is a non-negligible contributions to the rates
  - Maybe strongest emissivity around Tc
  - Yield/v2 puzzle is converging?

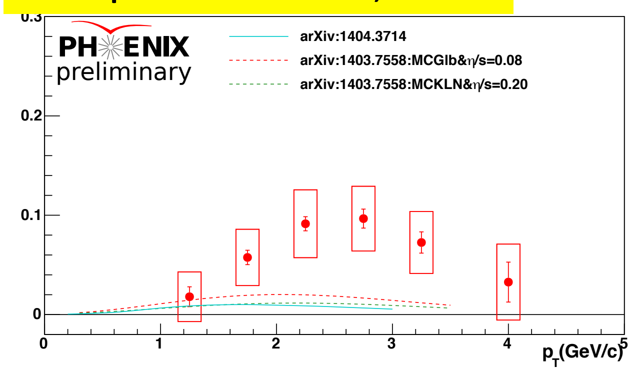
Inverse slope vs photon production time



Direct photon v2 in Au+Au, 20-40%



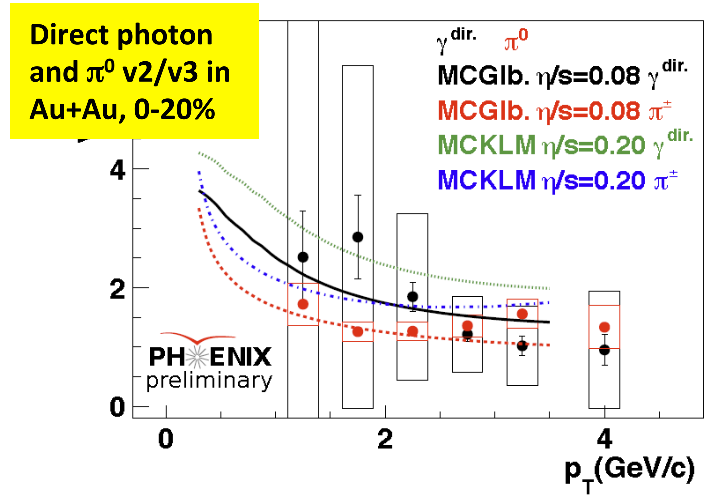
Direct photon v3 in Au+Au, 20-40%



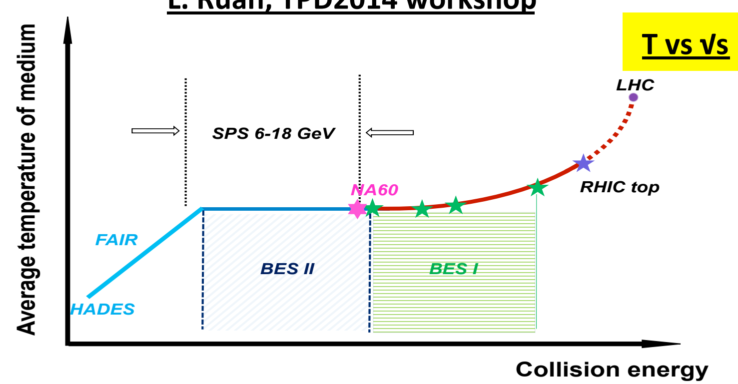
Future prospects and needs

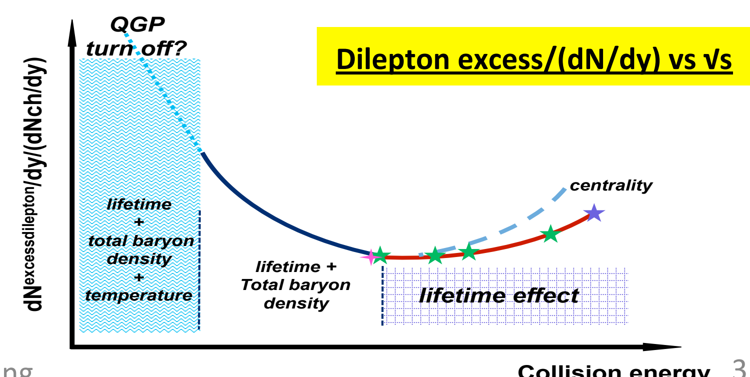
- Precise measurement of both spectra and vn are essential for understanding photons originating from the medium
  - e.g. recently it turned out that the vn ratios help
- Future measurement
  - Temperature and flow from both photons and intermediate mass dileptons
  - Running at other cms energy may help (62GeV, etc.)
    - Rate and flow give another constraint to models
  - HBT: the only "foolproof” way to get pre-equilibrium size and shape, also (at lower qT), the safest way to get the size of the medium
- Photon measurement is extremely difficult
  - Due to the experimental challenge, it took longer to meet the required precision (historically true for all photon-related experiments)
  - Need more time and detailed study of photon production → should be carried onto the next generation research
- A theorist’s comment: a realistic emissivity (rate) is certainly as important as a realistic space-time evolution.

Lines: arXiv:1403.7558 [nucl-th]



L. Ruan, TPD2014 workshop





Upsilon Measurements with sPHENIX

Anthony Frawley
Florida State University

QCD Town Hall Meeting
Temple University

September 15, 2014

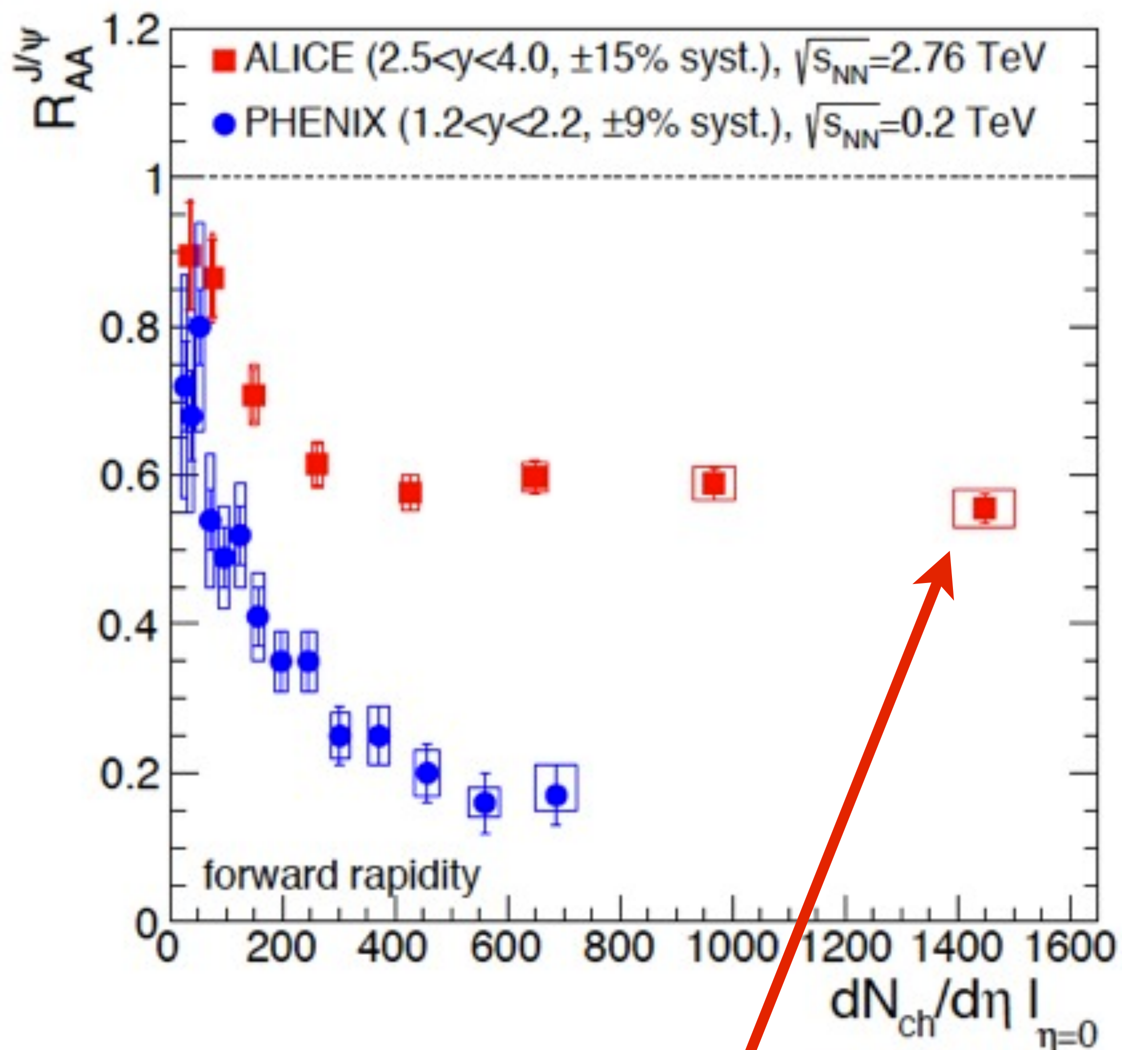
Quarkonia as a probe of the QGP

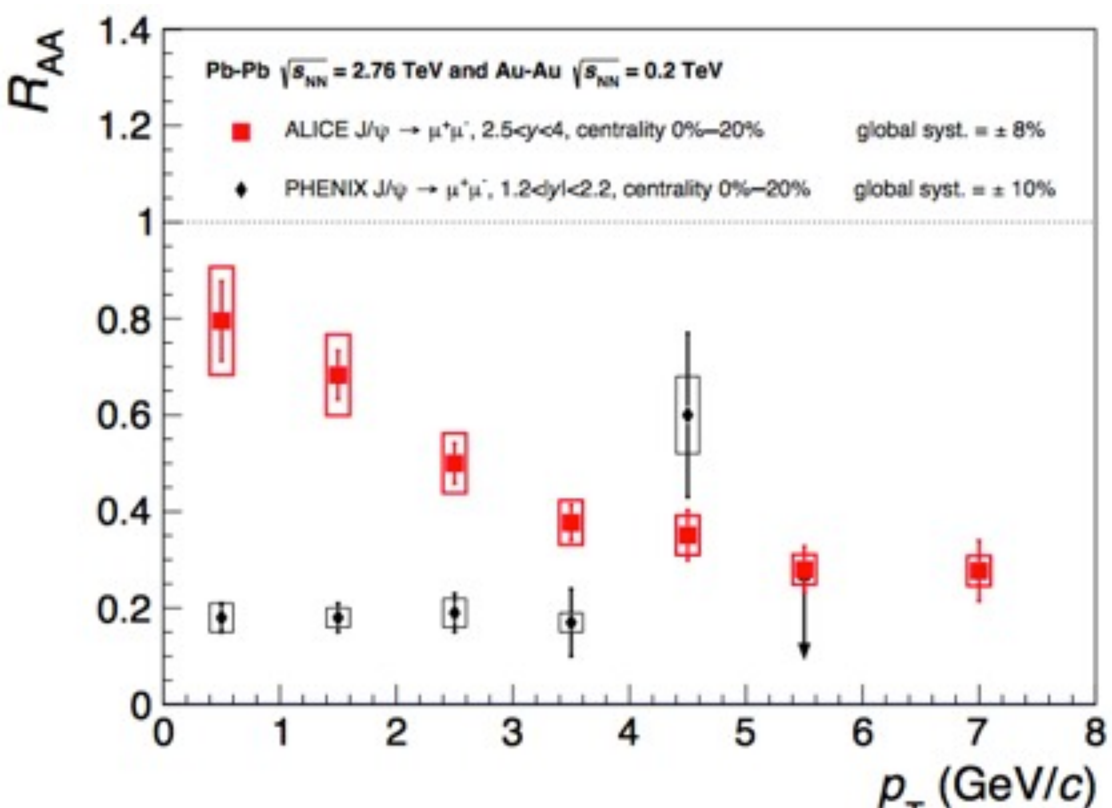
Charmonia and bottomonia mesons allow us to probe the QGP on length scales comparable with their radii.

The comparison between RHIC and LHC J/ψ modifications is very striking. At LHC, so many charm pairs that coalescence dominates!

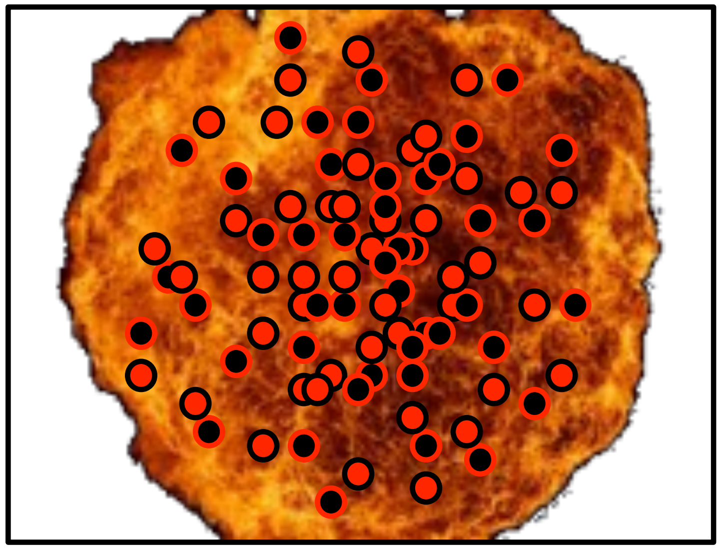
Nice physics! But we cannot directly compare melting at RHIC and LHC temperatures because different mechanisms dominate.

forward rapidity

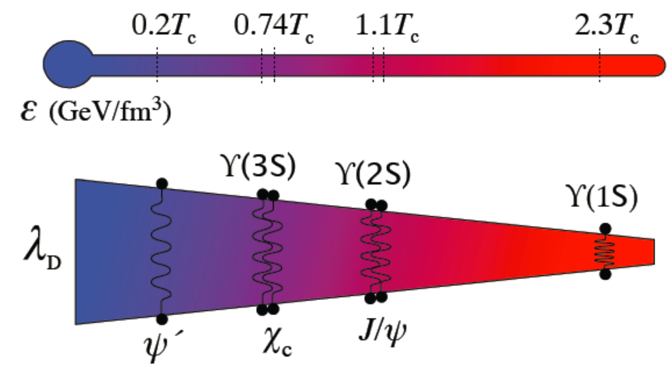




Charm pairs in central Pb+Pb collision

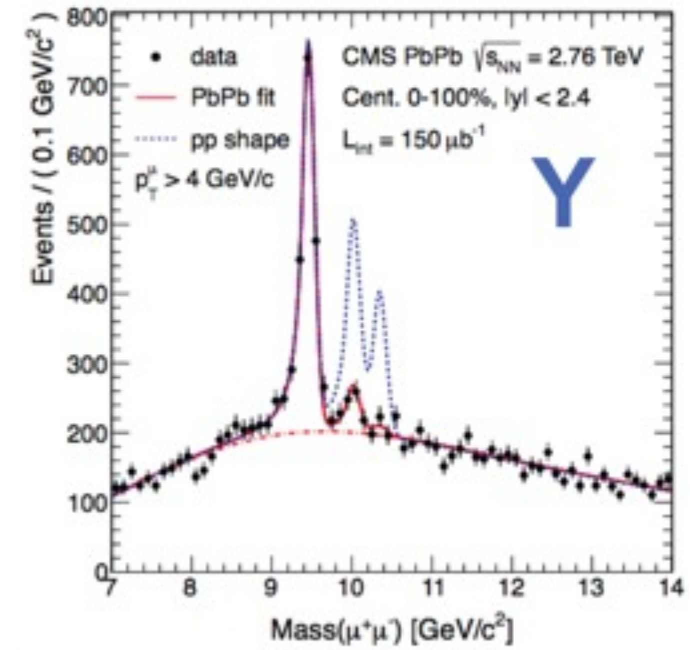


Upsilons



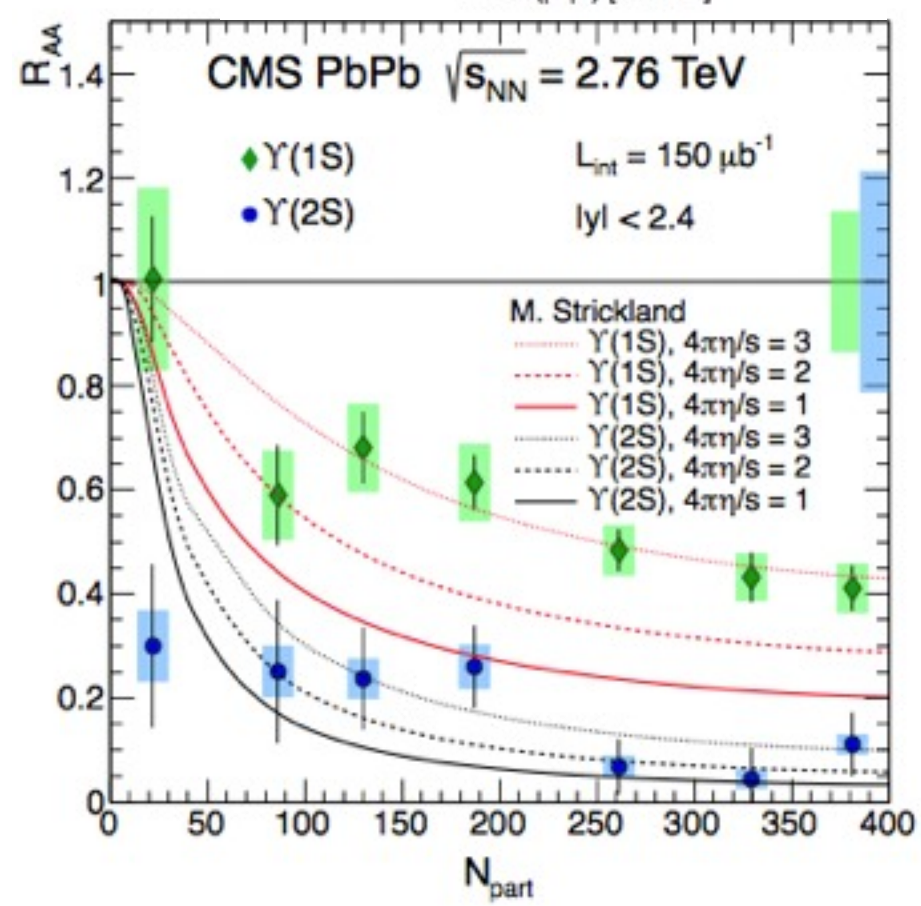
Upsilons have the advantages that:

- All 3 states seen simultaneously via dilepton decays.
- Coalescence not large at RHIC **or** LHC.
- Range of radii from 0.28-0.78 fm.



Directly compare melting at 200 GeV and 2.76 TeV on 3 states of very different size.

CMS data show dramatic suppression of 2S and 3S states in Pb+Pb at 2.76 TeV. **The data will improve hugely by Run 3 (~2023)**.



For this model (Strickland and Bazow, N.P. A879:25 2012 (& private comm.) the Υ(1S) data already constrain η/s.

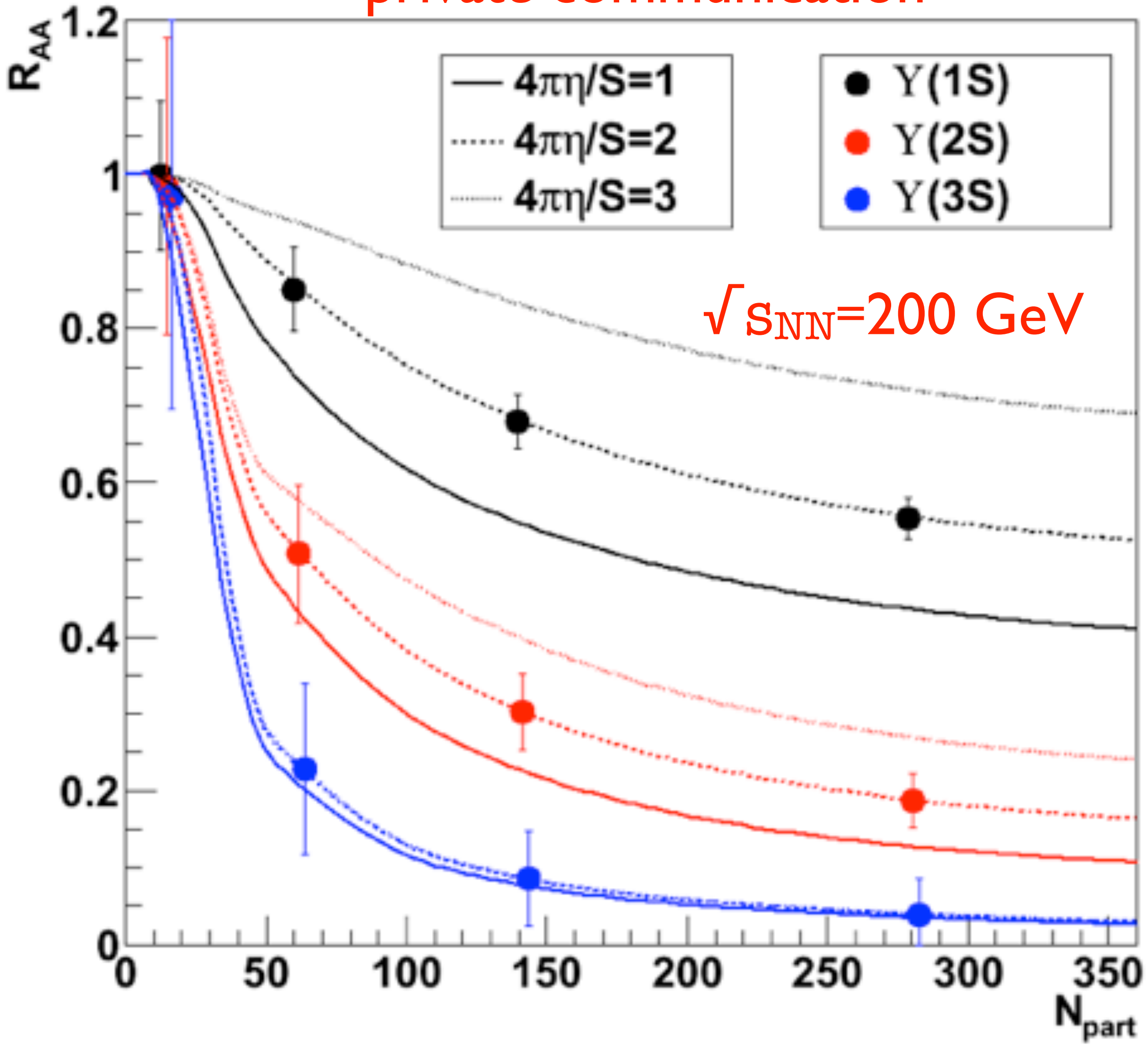
We lack a measurement at RHIC energy with the ability to tightly constrain model parameters. **sPHENIX** can generate such measurements.

Upsilon measurements with sPHENIX

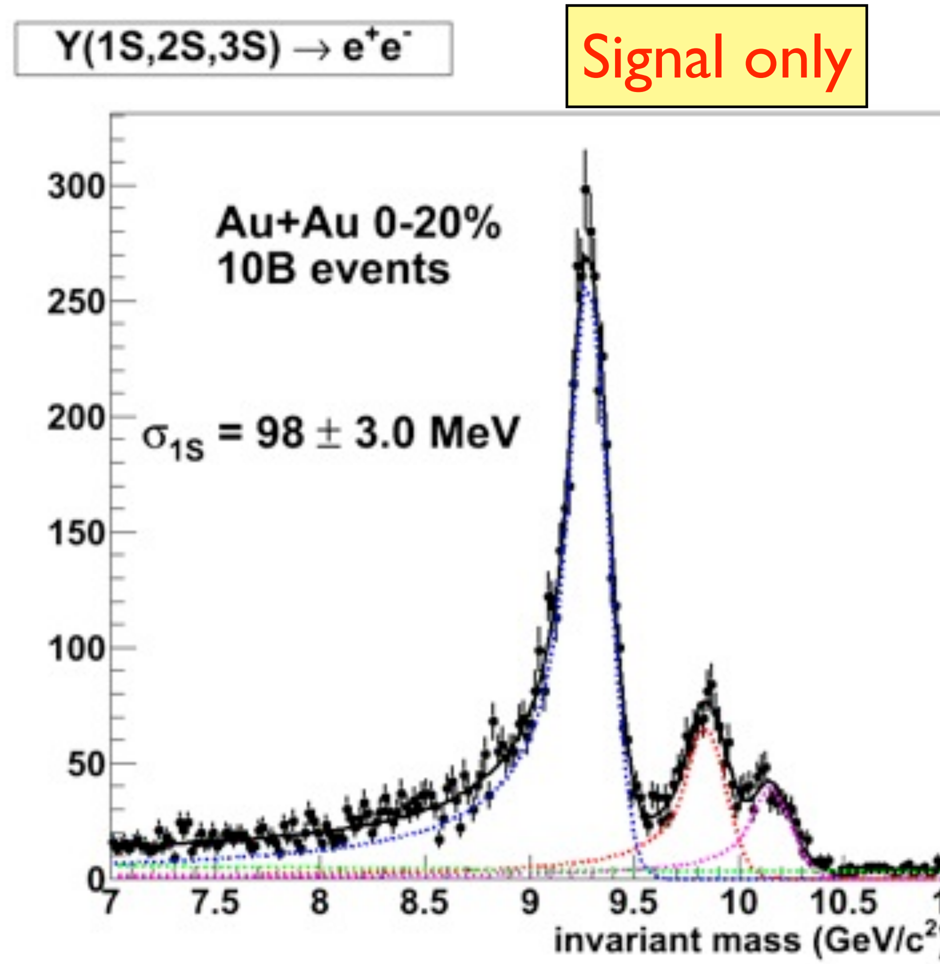
Some simulation estimates for Upsilon mass spectra (0-20% central Au+Au, 1 year run)
- with and without background.

The statistical precision expected for the R_{AA} is illustrated below (assuming $\eta/s = 2/(4\pi)$).

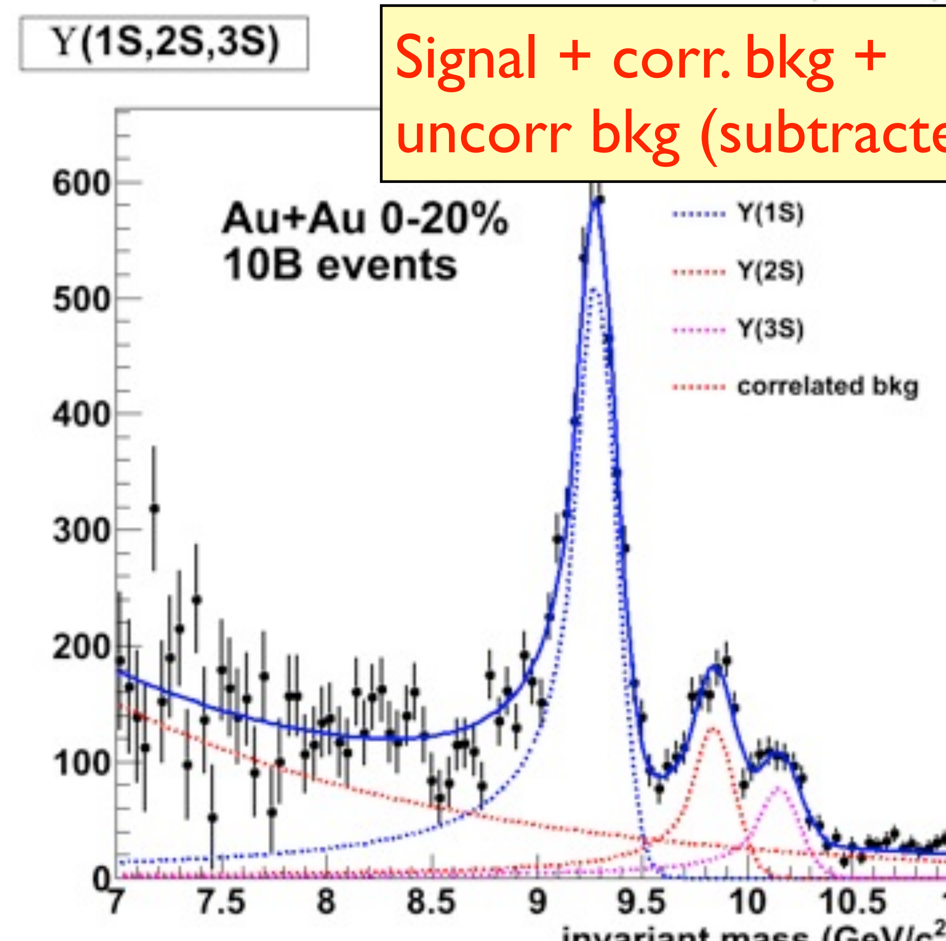
Theory curves - M. Strickland, private communication



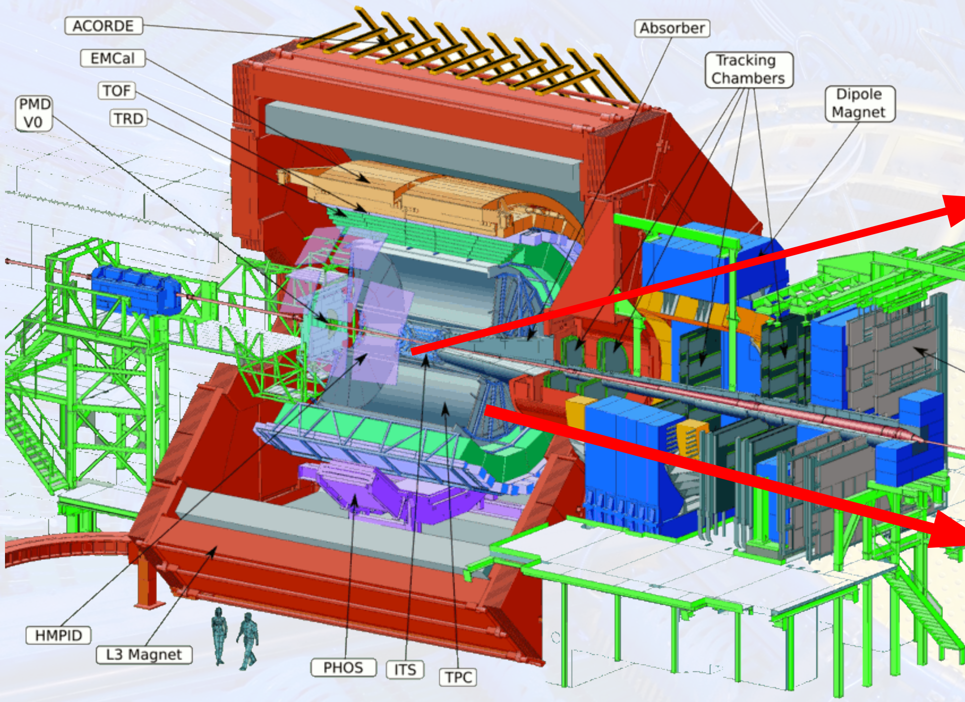
Signal only



Signal + corr. bkg + uncorr bkg (subtracted)



Heavy Flavor Physics with the ALICE Upgrade



Inner Tracking System

- Higher resolution (~3x)
- Lower material (~1.14%→~ 0.3%)
- Improve efficiency (10%→60% at 100 MeV/c) and p_T resolution at low p_T
- Fast readout (>50kHz)
- Improve impact parameter resolution ~3x

Time Projection Chamber

- Replacement of MWPCs with GEMS
- New readout electronics
- Fast readout (3.5 kHz→50kHz)

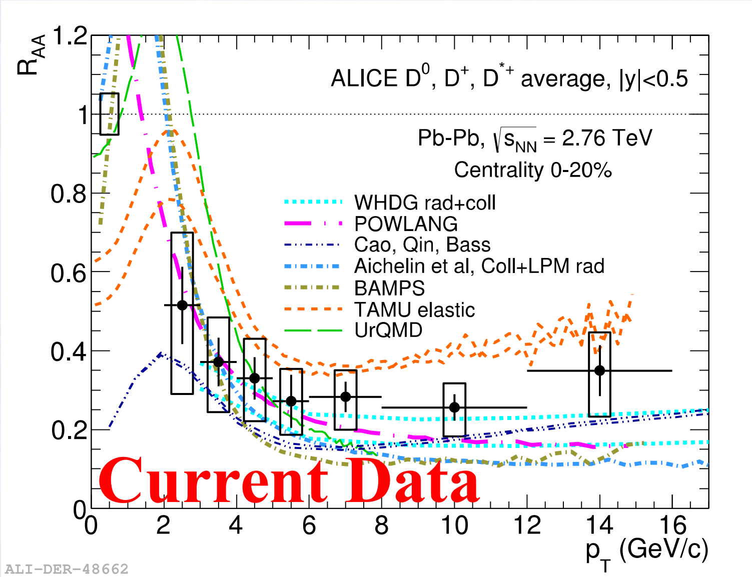
Computing

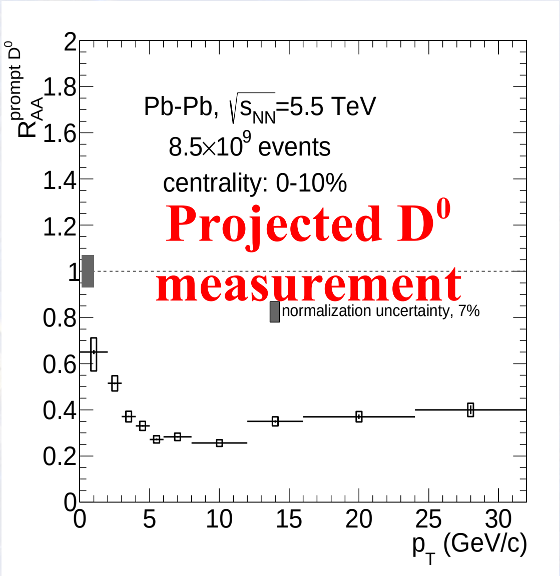
- Data rate increases 100x → online reconstruction and calibration
- Fast calibration procedures (50 kHz)
- Continuous track reconstruction
- Greater code optimization

~100x better statistics vs Runs 1 & 2 for min bias measurements
~10x better statistics vs Runs 1 & 2 for triggered measurements

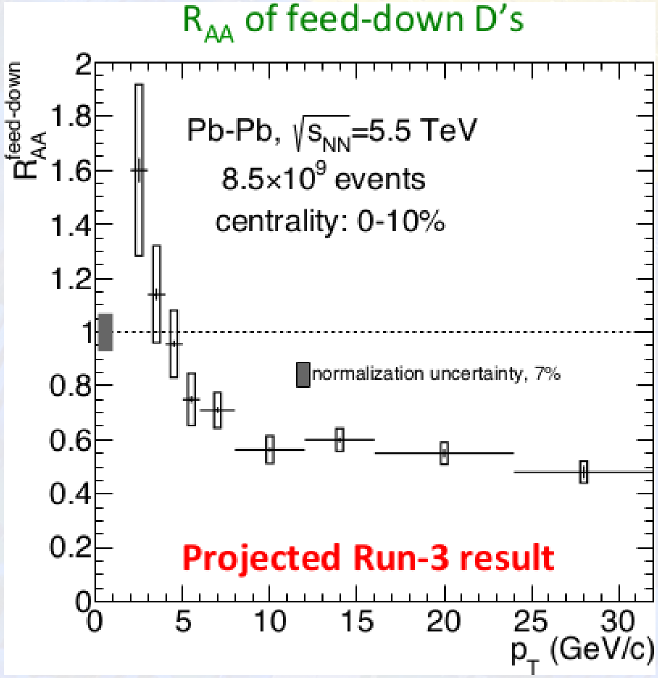
Heavy flavor energy loss

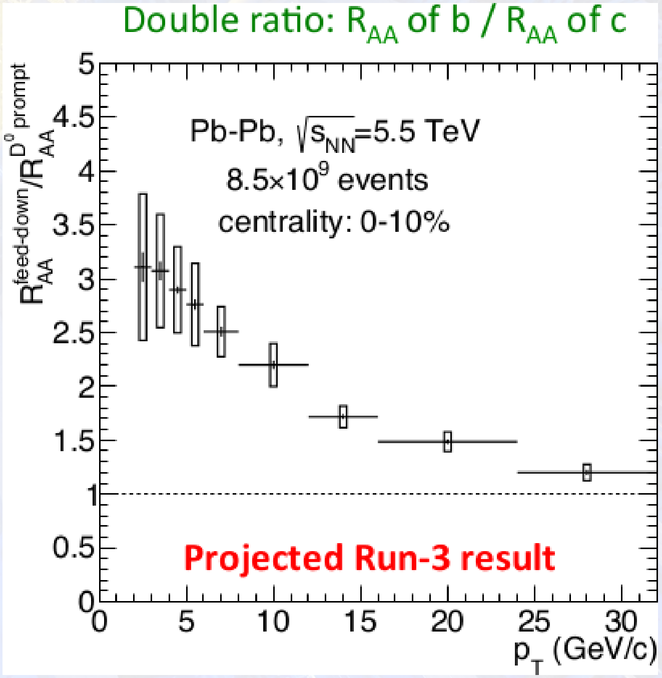
D meson R_{AA}

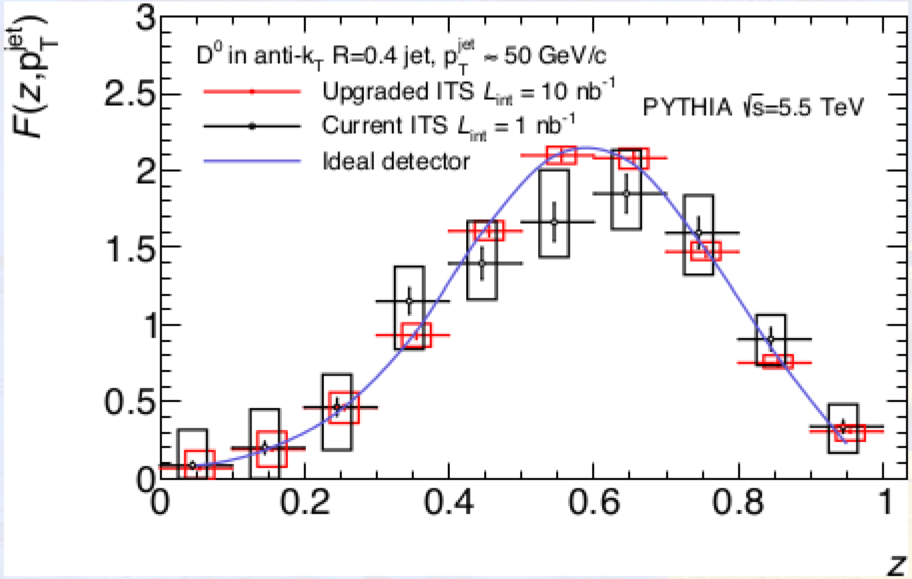




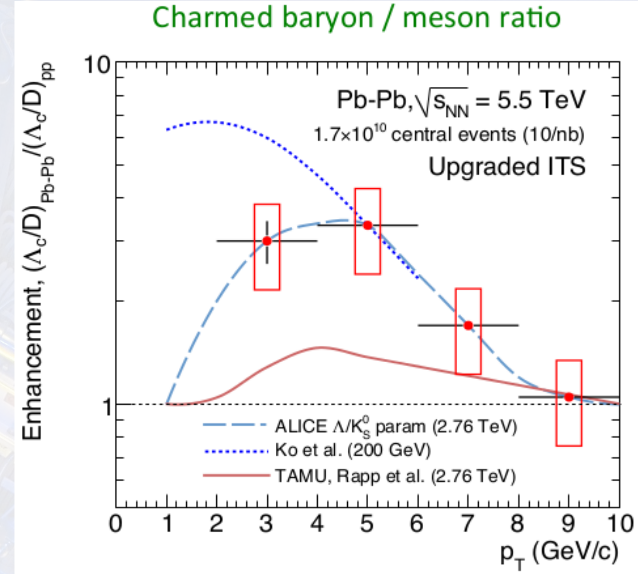
c vs b R_{AA}



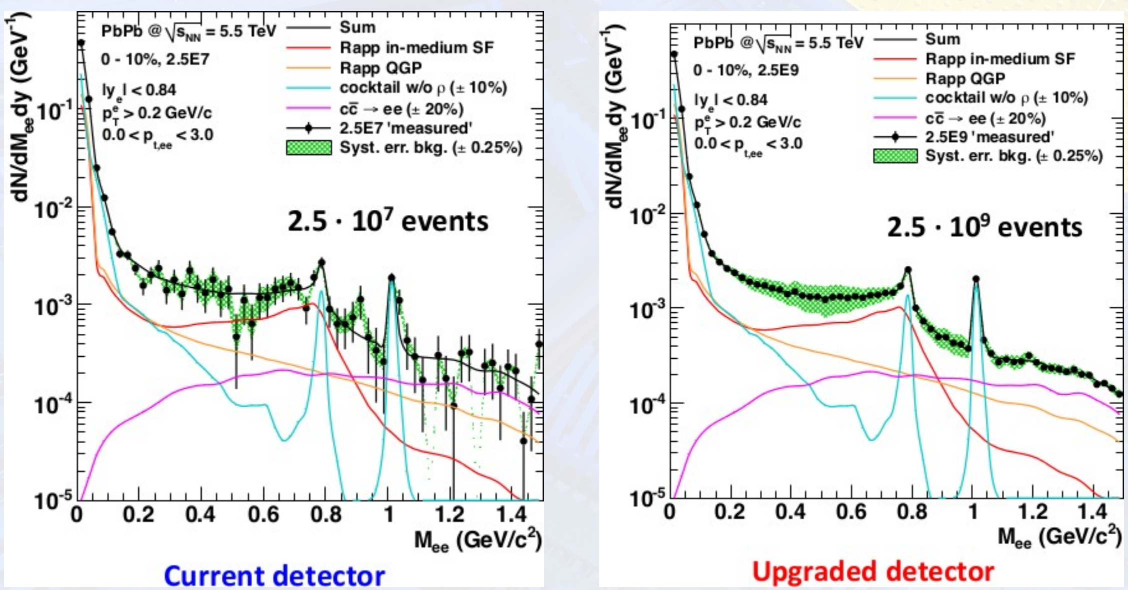




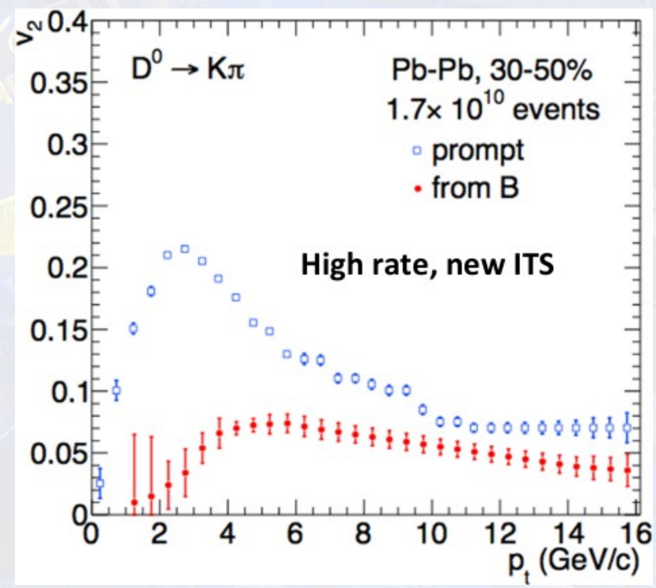
Charm in jets



Baryon/meson ratio



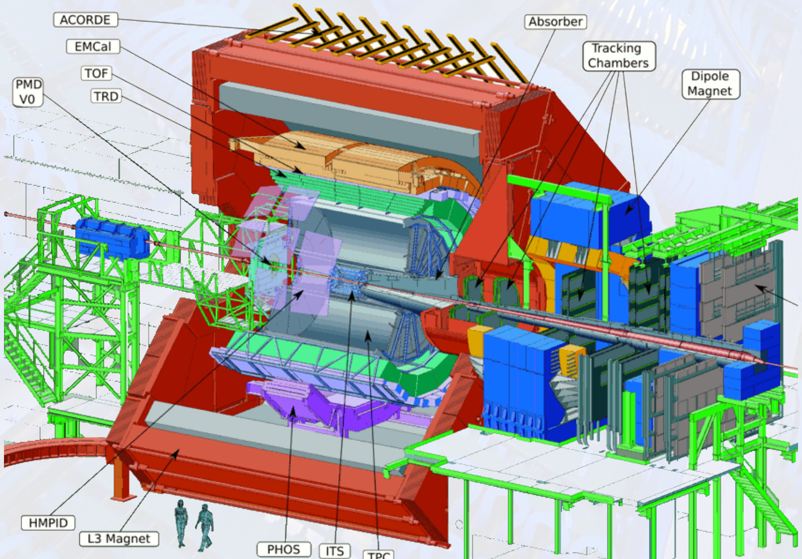
Low mass di-leptons



D v_2

ALICE Upgrade allows

- Precision heavy flavor R_{AA}
- With separation of c, b
- Heavy flavor jet quenching
- Heavy flavor baryon/meson ratio
- Low mass di-leptons
- Improved low p_T reach



Summary of the 3rd Workshop on Jet Modification in the RHIC and LHC Era @ Wayne State University

An unordered, unprioritized summary

Town Hall Meeting

Rosi Reed

Address the important fundamental questions of "how" and "why" partons lose energy in the QGP

  - Understanding of how to model the bulk is under control (via hydro coupled to hadronic cascade) and there has been significant progress in our understanding of quenching
- Jet quenching measurements at RHIC and LHC provide significant **constraints on the partonic E_{loss} mechanisms**
  - Will be used towards a **standard formulation of E_{loss} in the QGP**
    - Not yet at the precision stage wrt to the bulk formulation
  - **Where does the "lost" energy go**?
    - Important to **constrain models and in their coupling** with the medium
    - Missing p_T measurements at the LHC
    - RHIC measurements via Jet Geometry Engineering
    - Advances towards **medium & jet energy conservation simultaneously in MC needed**!
- T dependence of the QGP coupling -> Near T_c Enhancement?
  - Needs complementary LHC and RHIC measurements

- **Length scale via interaction hardness (Q^2)**
  - What are we scattering off?
    - point-like at LHC —> lower energy jets at RHIC?
  - quasi-particles, fields <=> **Microscopy of the QGP**
  - **qhat vs. ehat** with RHIC/LHC temperature lever arm
- RHIC
  - STAR will continue its jet program (medium-term)
  - **sPhenix** increased capabilities will allow a direct comparison to the LHC
    - High luminosity will allow data collection **without imposing online trigger** "biases" allows full exploration of "Jet Geometry Engineering"
    - Increased precision in the long-term are needed to map out T evolution
  - Could the different densities/associated time evolution of **different collision systems** allow access to **different effective temperatures** than centrality or $\sqrt{s_{NN}}$ variations with respect to quenching?
- LHC
  - Allows **precision jet measurements**
  - **New jet observables**: Jet(sub-) structures will allow access to well defined QCD observables: Jet shapes, jet mass, multi-jet, etc

- Major theory milestone is the **formulation/implementation of most theoretical E_{loss} variants in MC form**
  - Allows details of the experimental jet definitions to be reproduced
- LHC run 2+3 will provide precision measurements and unprecedented kinematical reach
  - **Direct photon/Z measurements provide the cleanest access to the parton kinematics** in heavy-ion collisions
- RHIC steeply falling partonic spectrum can be used as an advantage towards **Jet Geometry Engineering**
  - High rates of sPhenix are needed for unbiased measurements required for the baseline
  - High p_T, high statistics **gamma-jet measurements** will allow clean access to parton kinematics
- There is a need to formulate a **framework which allows direct comparison of measurements and full-event MC simulation**
  - Lisbon Accord -> Rivet
  - Analytical/1st principles calculations and advances are needed towards a text-book formulation

ANNOUNCEMENT:

RHIC/AGS Open Forum Meeting

DNP Fall Meeting   Hilton Waikoloa Village

Oct 9th   2-6 pm   (DNP Town Meeting Oct 8th)

Open to input, will be forum for more opportunities like this—short presentations/discussion aimed at Long Range Plan

γ-*h*, Jet-*h*, & *h*-*h* Angular Correlations at p_T = 10-20 GeV/c

- Far from obsolete, good ole two "particle" angular ($\Delta\phi$) correlations should continue to be employed in jet studies and could fill in a hole in accessible jet energies in the next decade
- Consistent with the idea of probing wider length scales by going to as low of Q^2 as possible, these measurements are the most promising way to access the **jet trigger p_T's between ~10-20 GeV** for both RHIC and LHC
  - "Full" full jet reco becomes difficult in this p_T region; want *h* unrestricted by found AS jet axis
  - 2-p methods well proven and will gain sufficient statistics in the next 5-10 years to precisely study this whole p_T region including γ-h, eventually overlapping "full" jet reco studies at the high end
  - Interpretation of E_{loss} effects should still be clean from softer process contamination above 10 Gev
- These studies will continue to yield constraints and offer another rich opportunity into the sPHENIX era at RHIC

Current Progress and Status

RHIC

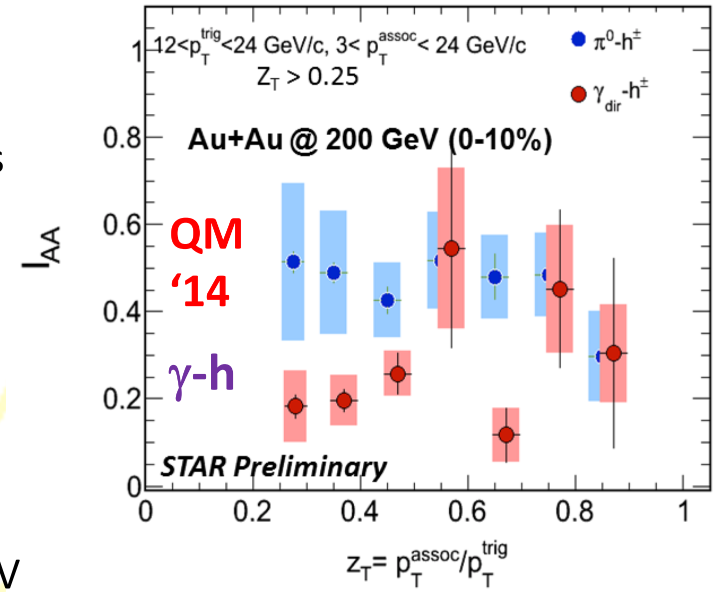
- PHENIX and STAR Direct Photon-Hadron Correlation Results trigger/jet p_T 5-~15 GeV
- STAR Jet-*h* results E_{jet} = 10-~15 GeV
- RHIC measurements nicely qualitatively consistent, e.g. showing enhancement of low z

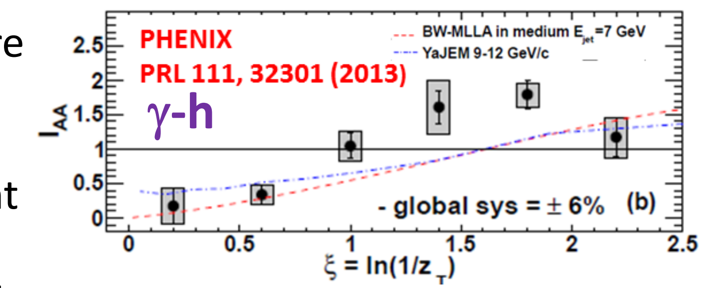
LHC

- *h-h* mostly lower p_T < 10 GeV focused on v_n measurements (RHIC too)
- Jet-h (e.g. CMS $\not{p}_T^{||}$, FF's) & *h-h* data at higher E_{jet} > 20 GeV
- γ-*h* / *h-h* : 2.76 current data statistics enough? -- needs more analyzers?

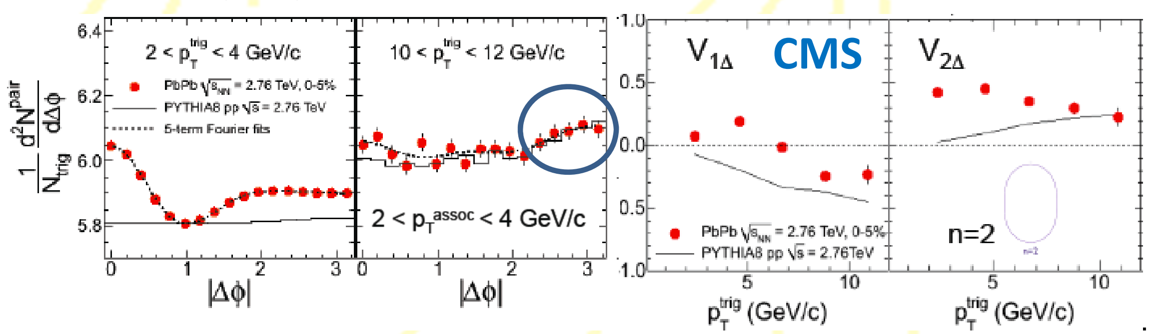
Theory

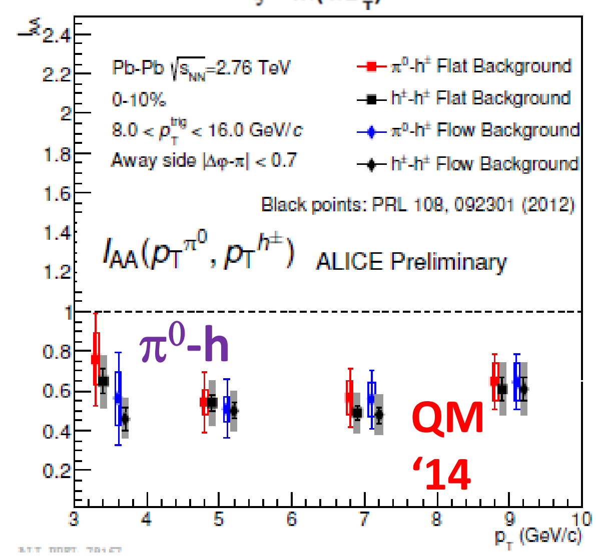
- Jet MC's should be reliable, at least for yields above fragment "thermalization" scale
- Renk: E_{loss} constraints from 2-p (even h-h) competitive if not better than jet reconstruction observables





JHEP 1107 (2011) 076





Future Prospects and Needs

- Understanding of low hadron p_T flow contributions continually improves
- Raising hadron p_T slightly (~2 GeV/c) makes remaining systematic small for trigger p_T > 10
- Less biased studies of angular locations of lost energy by reducing need for a reconstructed jet to be found (jets at this energy may be even more severely modified so e.g. no usable A_J)

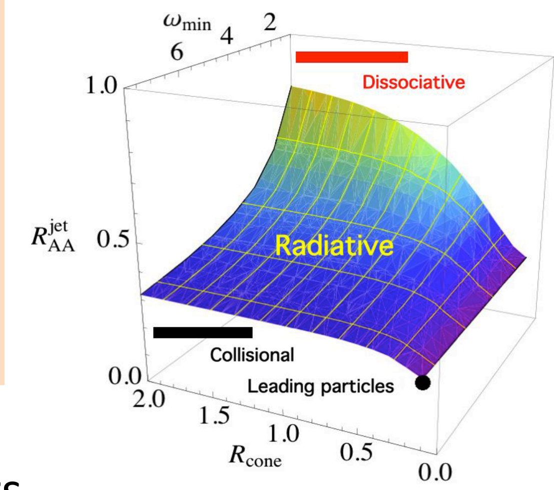
- RHIC Increased luminosity already from 2014/2016 running: establish beginning of precision measurements in this p_T region
- Further lumi increases during sPHENIX era should allow more differential constraints e.g. "event engineering", PID hadron correlations, including reco-jet information, etc.
- One easily demonstrable scenario for STAR/sPHENIX coexistence: STAR focuses on similar measurements but using its strengths like PID. STAR interest seems there. sPHENIX γ-h

- As with more jet-reco focused observables, there is a need to make common measurements at both LHC and RHIC – these are good, simple candidates, in addition to jet reco observables
- LHC Jet/γ/h – hadron correlations in Pb+Pb without reconstructing 2nd jet axis feasible!
- Direct photon-hadron results needed from all LHC experiments
- 5.5 TeV LHC data -- LHC Analyzers!

- Combining with the planned jet reco studies at higher Q^2 : allows for more complete coverage of jet energies into lowest energy region—more insurance for sPHENIX era how and why goals.

Effective Theory for Precision Jet Physics in HIC Beyond the Energy Loss Approach

- The most important recent advance (~5y) in the area of hard probes in HIC is the development of the theory of jet production and modification and the related experimental measurements



  - Has provided first insights in to the transverse and longitudinal structure of in-medium parton showers
  - Has elucidated the relative significance of collisional and radiatve energy loss
  - Has helped constrain the coupling between the jets and the medium and provided insight into the nature of the QGP quasiparticles

- Within the energy loss framework, systematic improvements in the precision of the theory are very difficult or impossible
  - Advances, however, are essential to guide the jet physics programs at RHIC and the LHC and interpret the results

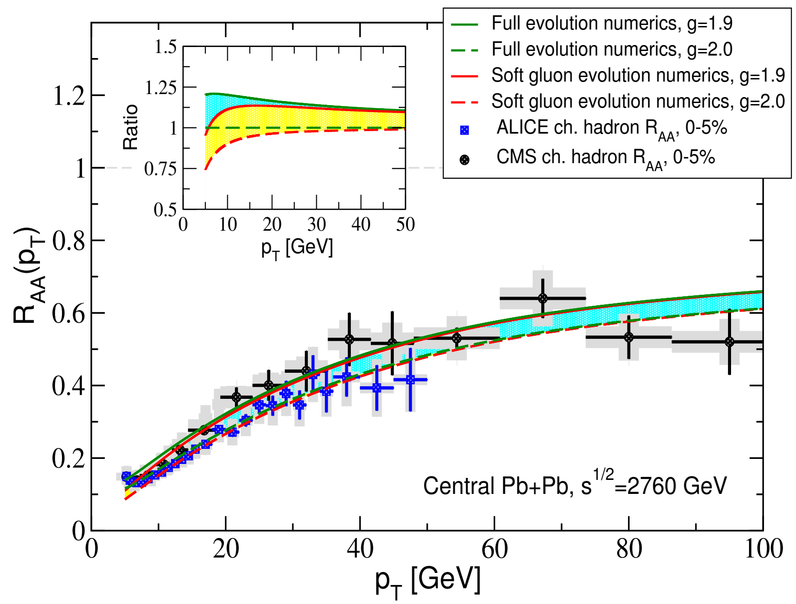
Current Status

- Effective theory of jet propagation in matter – $SCET_G$ (soft-collinear effective theory with Glauber gluons)

  - SCET has been extremely successful in advancing jet physics, one of the areas (together with heavy flavor) where significant progress in QCD occurs
  - $SCET_G$ was developed to include the jet-medium interactions (G)
  - Was applied to the transverse momentum broadening of partons
  - Full set of medium-induced collinear splitting kernels beyond the soft gluon approximation obtained. Gauge-invariance and factorization established
  - Result for $O(\alpha_s^2)$ in-medium splitting function relevant to NNLO

- First application to inclusive particle production

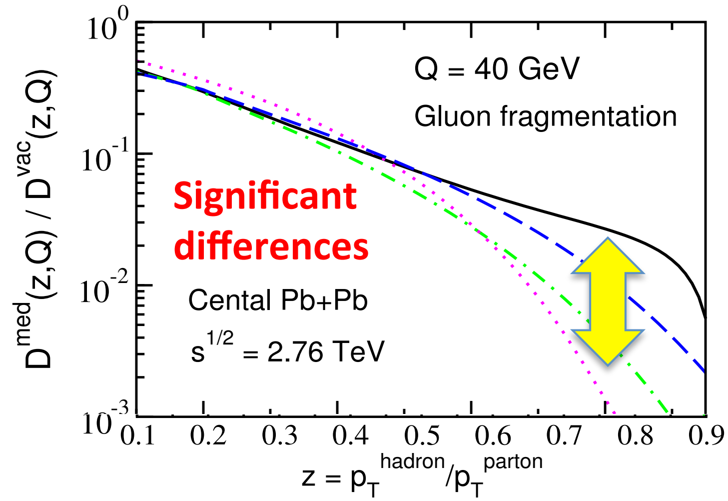
  - Established the connection to the energy loss approaches
  - Allowed to reliably quantify the uncertainty (~5%) in the extraction of the jet medium coupling from inclusive observables



Future Prospects

- Unified treatment of "vacuum" and "in-medium" parton showers and a common vernacular for HEP, NP

- Understand the soft-Glauber interactions and power corrections
- Apply the unified parton shower picture to jet observables, including jet cross sections, jet shapes and fragmentation functions
- Significant improvement expected for more exclusive observables, di-jets and photon-tagged jets. Heavy flavor observables



- Achieve higher resummed accuracy for jet observables in heavy ion collisions, next-to-leading logarithmic accuracy (NLL) and combine with higher order calculations (NLO)
- When combined with improved theory of CNM effects, fully characterize the in-medium parton shower and the properties of the QGP

Advances in precision pQCD calculations of jet observables, including resummation and higher perturbative orders must be a top priority for theory and the field

Calculating Jet Transport Coefficients in Lattice QCD

Abhijit Majumder
Wayne State University

QCD town hall meeting, Temple University, Sep 15th 2014

Why should we do this?

1) A first principles calculation of Jet modification would calculate the $\hat{q}$ and $\hat{e}$ in each unit cell given temperature.

2) Will allow a test of transverse momentum dependence of the exchange interaction via $k_{\perp}$ moments of $\hat{q}$.

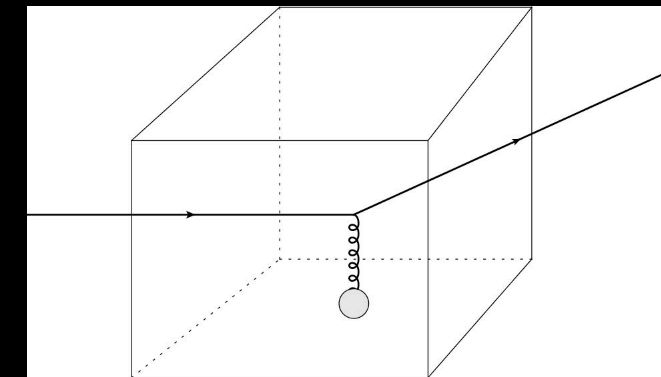
3) Will allow for a study of T dependence of $\hat{q}$ and $\hat{e}$.

4) Will allow an independent arena to test jet quenching in a thermal bath. Search for other transport coeffs

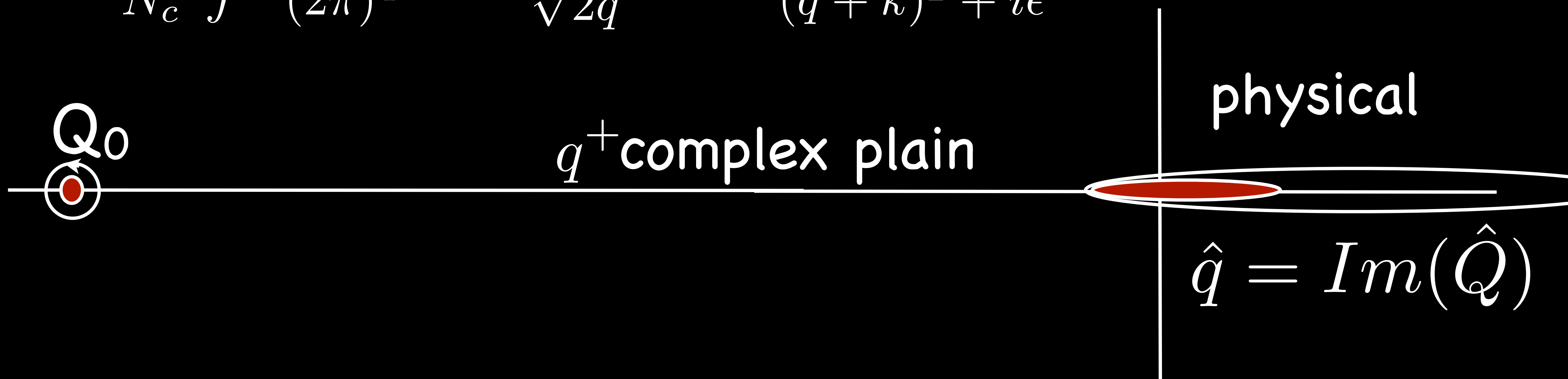
5) Once suitably interfaced with a jet MC can continue this study past the lifetime of RHIC and LHC

How it can be done?

$$I_1 = \oint \frac{dq^+}{2\pi i} \frac{\hat{Q}(q^+)}{(q^+ + Q_0)}$$



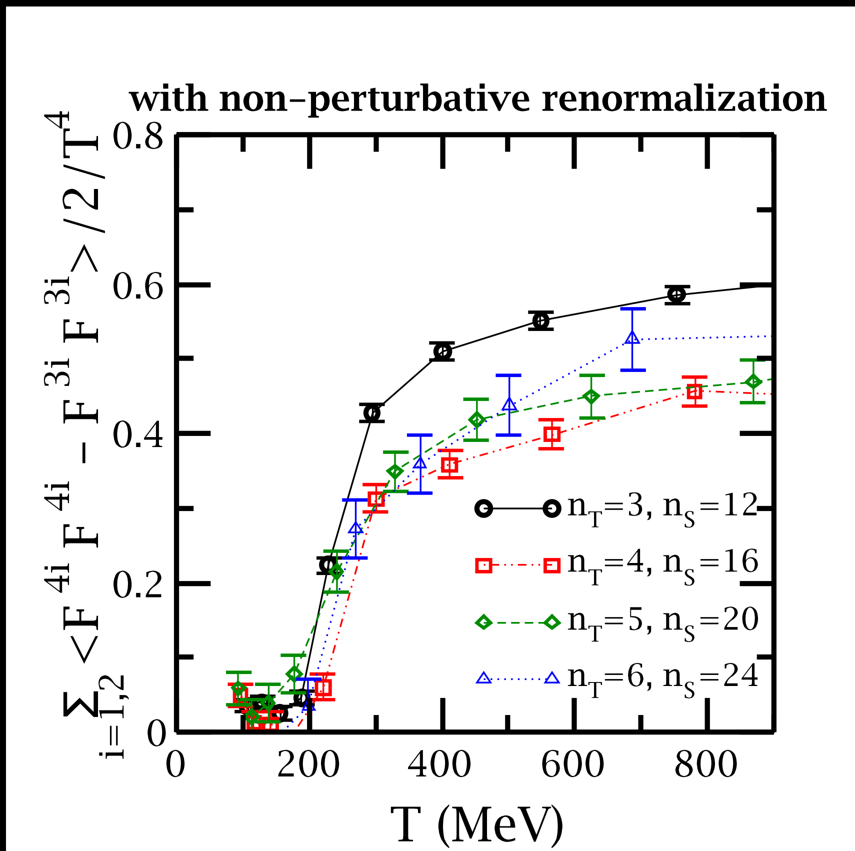
$$\hat{Q} \quad = \quad \frac{4\pi^2\alpha_s}{N_c}\int \frac{d^4y d^4k}{(2\pi)^4} e^{ik\cdot y} \frac{2(q^-)^2}{\sqrt{2}q^-} \frac{\langle M|F^{+\perp}(0)F^{+}_{\perp,}(y)|M\rangle}{(q+k)^2 + i\epsilon}.$$



For Q_0 ~ $-Q$, can Taylor expand $\hat{Q}$ in terms of local operators

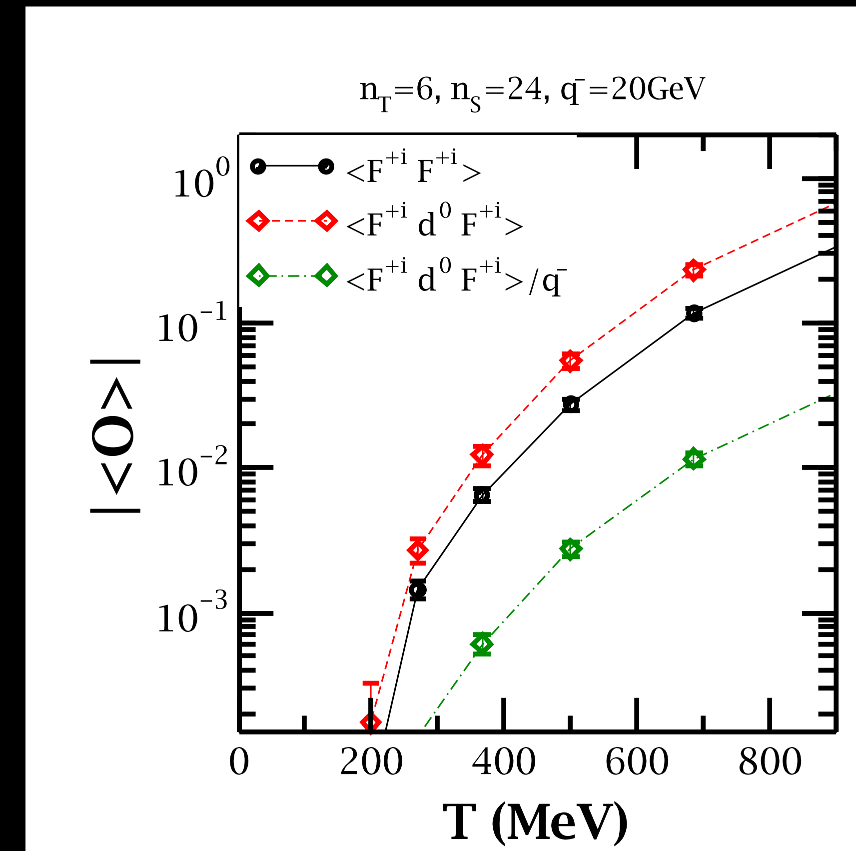
$$I_1 = \frac{4\sqrt{2}\pi^2\alpha_s\langle M|F^{+\mu}_{\perp}\sum_{n=0}^{\infty}\left(\frac{-q\cdot i\mathcal{D}-\mathcal{D}_{\perp}^2}{2q^-Q_0}\right)^n F^{+}_{\perp,\mu}|M\rangle}{N_c 2Q_0}$$

What can be done?



Calculated in quark less SU(2) gauge theory.
scale answer up by N_c and N_f

A.M. Phys. Rev. C87 (2013) 034905,
Nucl.Phys. A904-905 (2013) 965c,
Nucl.Phys. A910-911 (2013) 367.
X. Ji, Phys. Rev. Lett. 110 (2013) 262002
M. Panero et al., Phys.Rev.Lett. 112 (2014) 162001

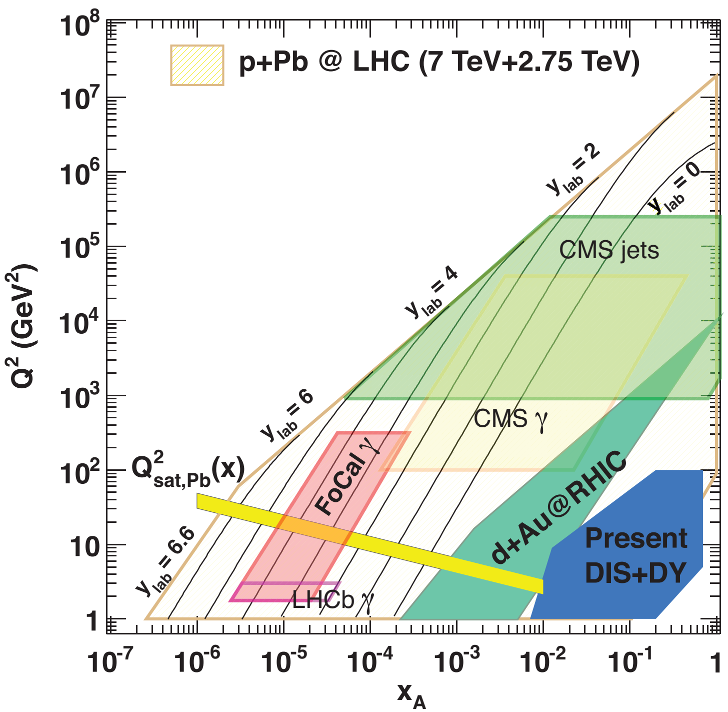


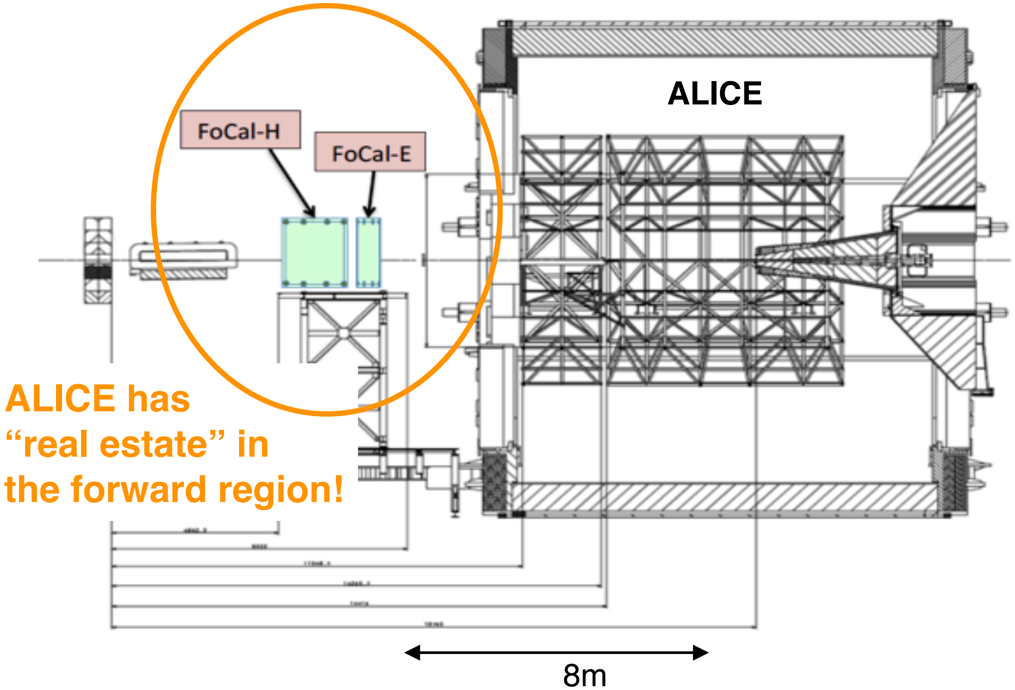
$$\hat{q}(T = 400\text{MeV}) = 1\text{GeV}^2/\text{fm} - 2\text{GeV}^2/\text{fm}$$

Need extension to full QCD.
Attempt a calculation of ê
Carry out E-by-E simulations with a MC shower with q̂ taken from lattice calculation
Can also study e-by-e fluctuations of q̂

Future Low-x Opportunities at the LHC: ALICE FoCal

Study the low-x gluon structure (nuclear PDFs, CGC) in a new kinematic regime (small *x* and low Q^2) at the LHC (>LS2/3 2020+)





ALICE has "real estate" in the forward region!

Strategy: Utilize direct photons (γ^{dir}-jet) at forward rapidity y~3.3-5 (x~10^{-6})

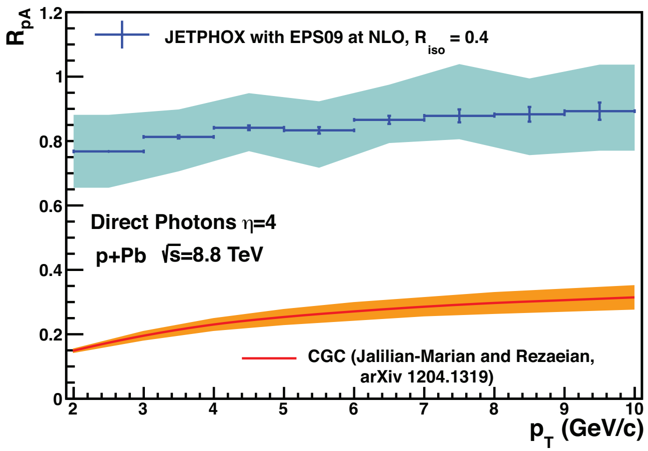
FoCal-E: High-granularity EMCal* (decay photon rejection > 95%)

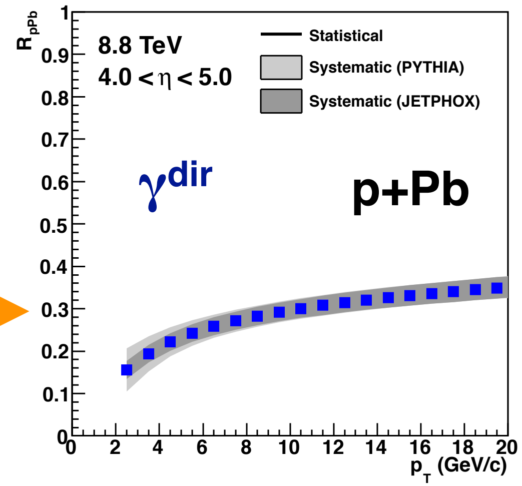
FoCal-H: HCal (improved isolation and added full-jet capabilities)

*Compact silicon-tungsten (Si/W) sampling electro- magnetic calorimeter with longitudinal segmentation.

*Physics Performance** (p+Pb and Pb+Pb)

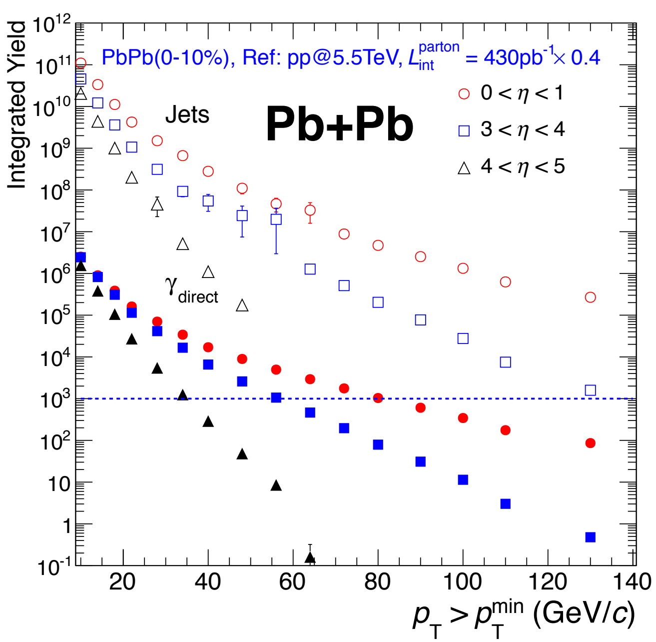
*Simulations with “final” design (EMCal and HCal) and proposed beam-pipe/structure modifications are ongoing!





System	$\sqrt{s}$ [TeV]	Coincidence Type	p_T^{max} [GeV] γ_{dir}-Jet	p_T^{max} [GeV] Jet-Jet
p+p	14	F-M	20	> 100
		F-F	30	70
p+Pb	8.8	F-M	20	> 100
		F-F	30	70
Pb+Pb (0-10%)	5.5	F-M	50	> 100
		F-F	50	80

Table 2: Kinematic reach $p_T^{max}[GeV]$ defined by a minimum integrated yield of 1k for γ_{dir}-jet and jet-jet at forward-forward rapidities (F-F) (integrated over $\eta = 3-5$) and forward−mid-rapidity (F-M) coincidences.



Expect excellent γ^{dir} (R_{pPb}) capabilities at *y*~4-5 at low Q^2

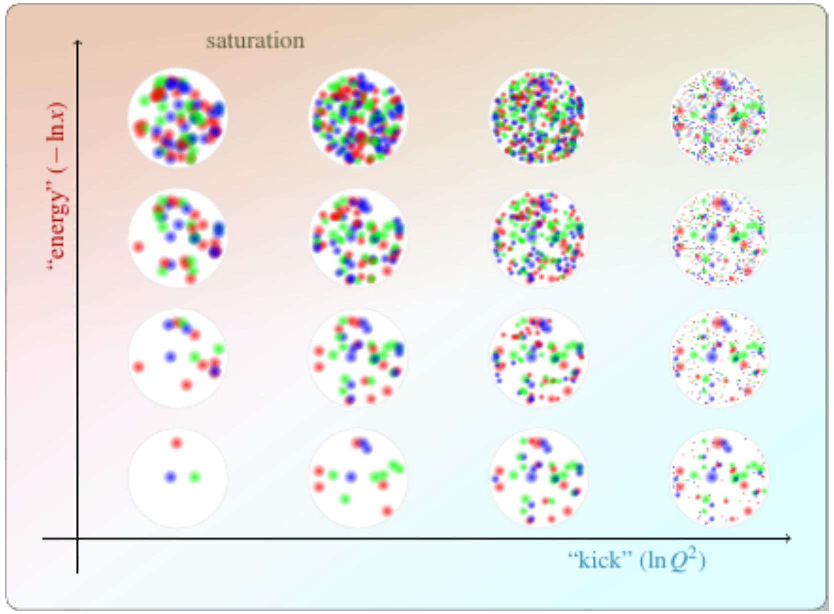
Combing γ^{dir}-jet and jet+jet measurements allows to study the evolution in *x* and Q^2, map out the onset, and explore the properties of QCD matter in the saturation regime.

<u>Pb+Pb:</u> γ^{dir}-jet and jet+jet at forward and mid-forward rapidity allows to study partonic energy loss over a wide kinematic range

Future Low-x Opportunities at the LHC: ALICE FoCal

ALICE has "real estate" at forward rapidity!

Comprehensive γ^{dir}-jet and jet+jet measurement program at forward rapidities in p+p and p+Pb at the LHC allows to study the evolution in *x* and Q^2, map out the onset, and explore the properties of QCD matter in the saturation regime.



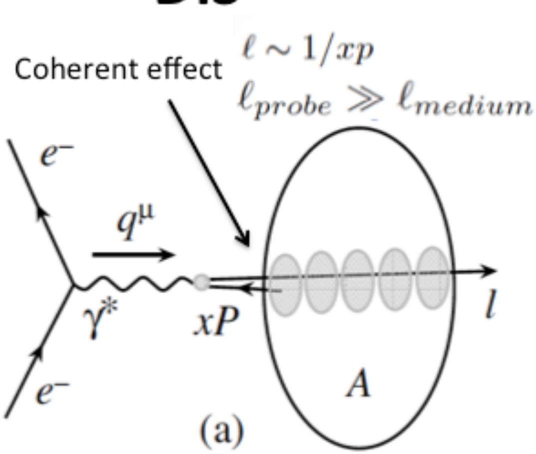
Future forward detector upgrade (ALICE FoCal) would provide *timely* (>LS2/3 2020+) and *complementary* low-*x* physics opportunities for the US Physics Community!

The Importance of a New Forward p+A(A+A) Program at RHIC and Its Impacts on Future e+A Physics

Cesar da Silva and Ming Liu
(Los Alamos)

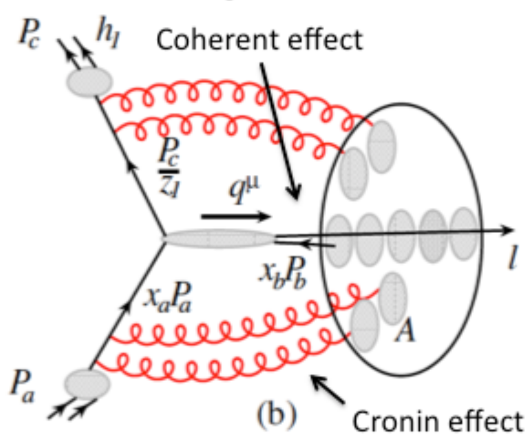
- Key Physics Questions
  - Parton propagation, energy loss and hadronization in CNM
  - CNM and QGP effects in Forward rapidity in p+A and A+A
  - Modification of parton distributions inside the nucleus

DIS



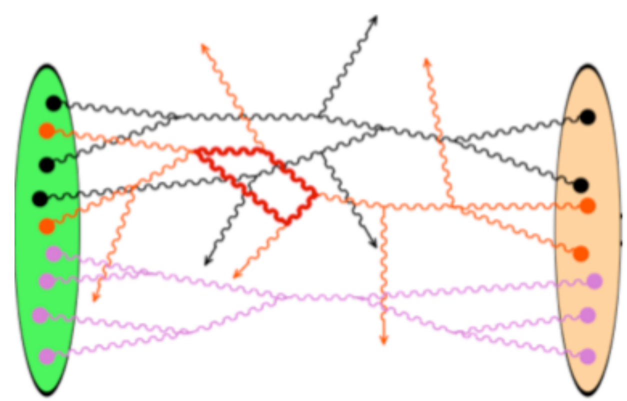
CNM: final state

p+A



CNM: initial (and final)

A+A



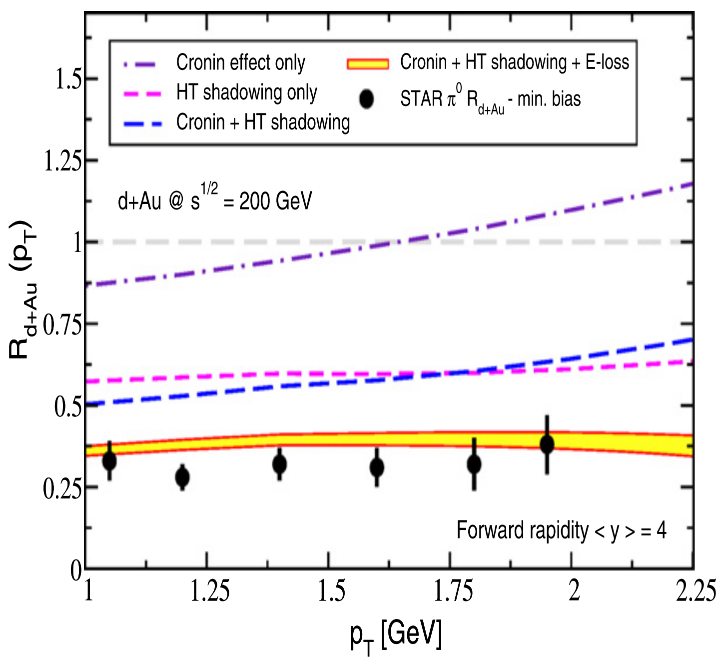
CNM more complicated

Rich Forward CNM Physics in p+A: p+A $\neq$ e+A

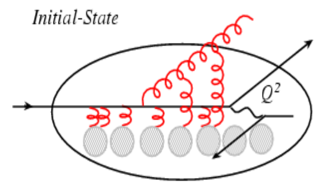
Significant competing CNM effects in the forward rapidity particle productions:

1) Cronin; 2)High-Twist shadowing; 3)E-Loss; 4) Saturation

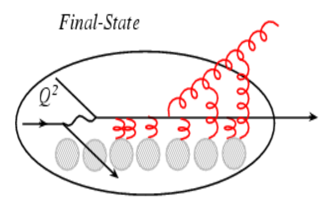
R.B. Neufeld et al. / Physics Letters B 704 (2011) 590–595



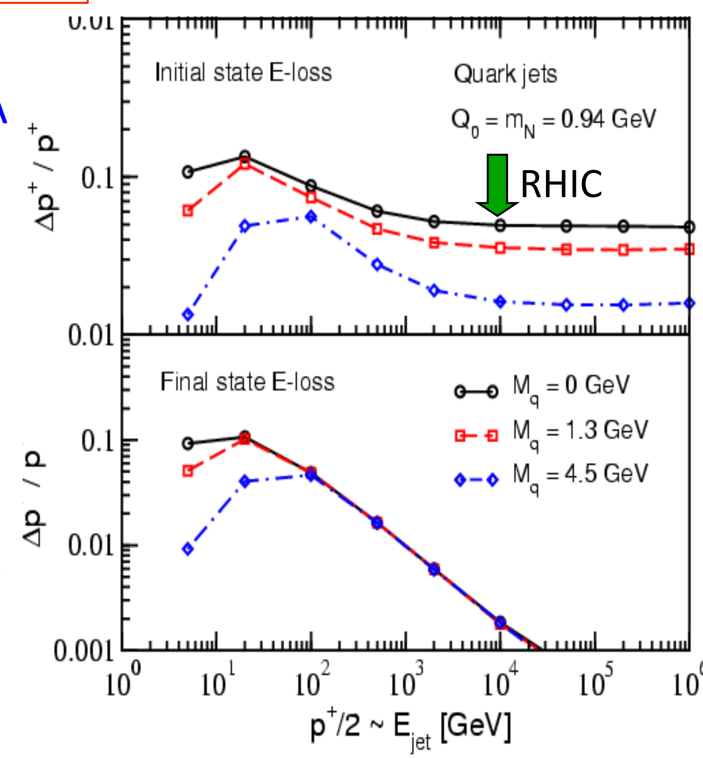
Drell-Yan: p+A



DIS: e+A



I. Vitev PRC **75, 064906 (2007)**

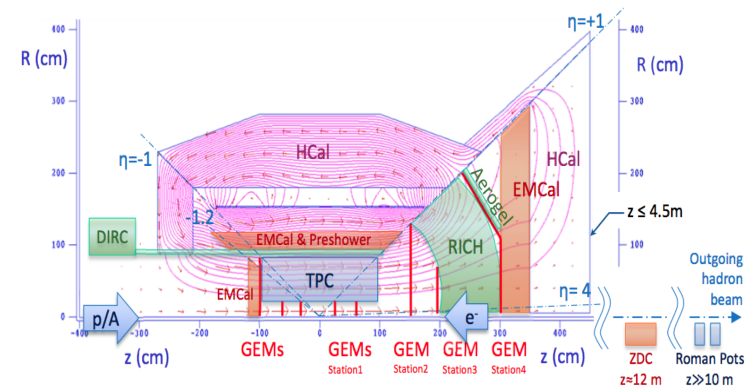


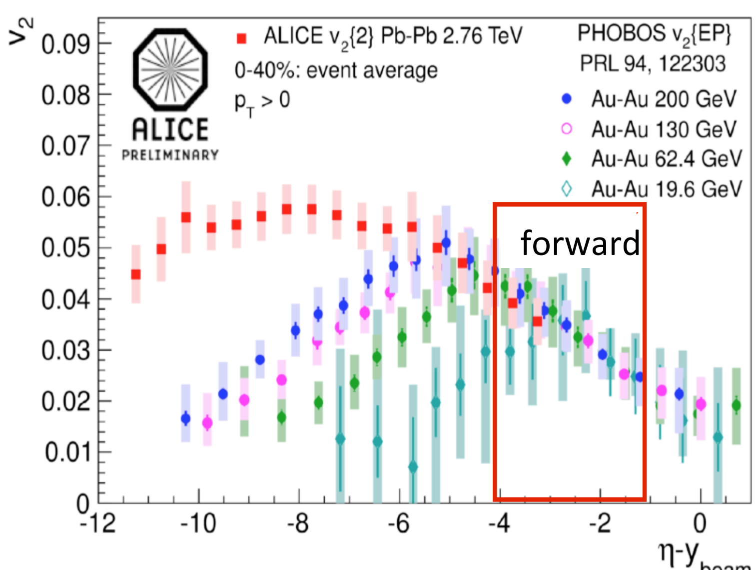
Critical to have p+A, better kinematics and precision.
With e+A, fully explore the initial and final state dE/dx and other CNM contributions to QGP effects in A+A

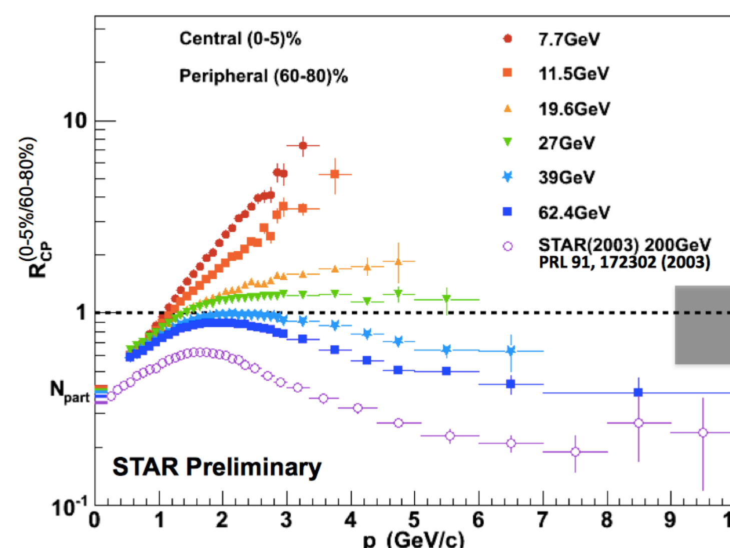
Why Explore QGP in Forward Rapidity?

- Longitudinal expansion of QGP, least explored
  - Expect different mix of CNM and QGP
  - Hadrons, Drell-Yan, Jets etc. in eta up to ~ 4.
  - R_{AA}, Vn, Correlations in large rapidity
  - Many interesting puzzles in forward rapidity pA & AA
- Scaling of "v_2" in the forward rapidity, why?
  - Little energy dependence, from 20GeV to 2.8 TeV
  - Is Hydro flow the only source of V_n? Other physics?
- Strong energy dependence of R_{cp}
  - Believed due to different mix of CNM and QGP effects, same at large rapidity?
  - Important for QCD Critical point search

A proposed new EIC detector at RHIC with forward physics capability





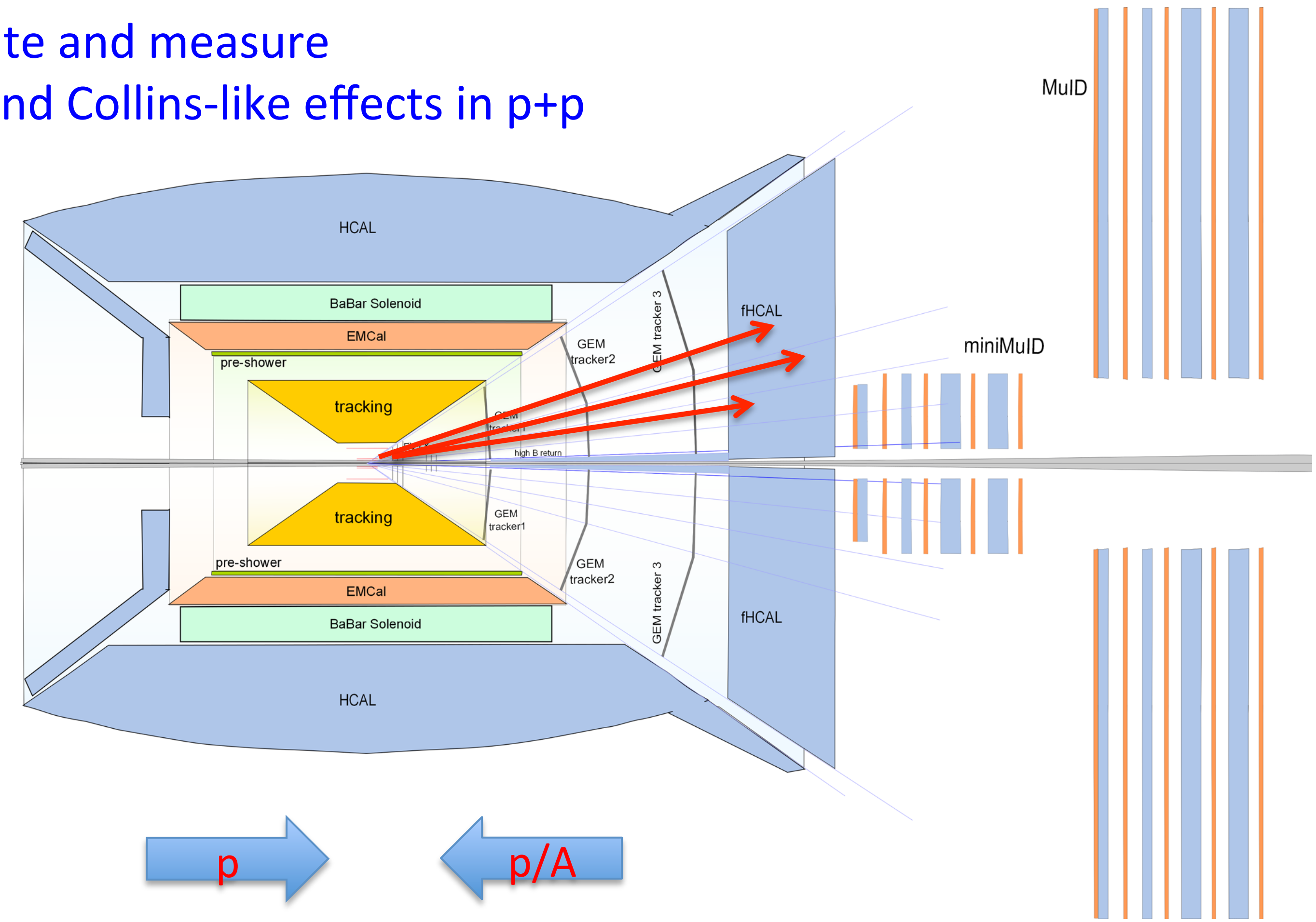


Backup slides

Forward Transverse Spin Physics Proposal at RHIC

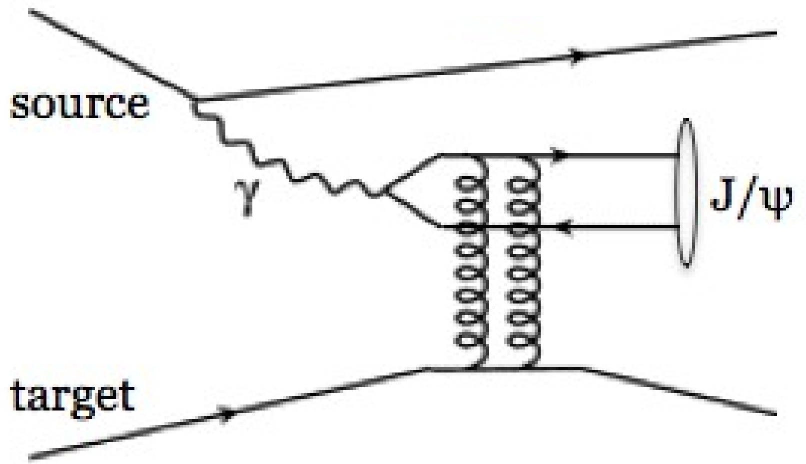
-1 < eta < 4

Clearly isolate and measure
Sivers-like and Collins-like effects in p+p



Key capabilities:
- Jet with Cal.
- Tracking

The nature of the initial state



A common denominator in heavy-ion physics analyses is the need to distinguish between ﬁnal state effects expected from the QGP from those inherent to the nuclei themselves. Thus, ***the nature of the initial state is one of the most important questions in relativistic heavy-ion physics***. This would naturally provide insights into the crucial role played by gluons in the nuclei.

UPCs are cleaner probes of nPDFs

My group seeks to tackle these questions by using a novel approach that consists in studying ***ultra-peripheral heavy-ion collisions (UPC) to probe the nucleus.*** This will be carried out by studying quarkonia and jet production with CMS at LHC

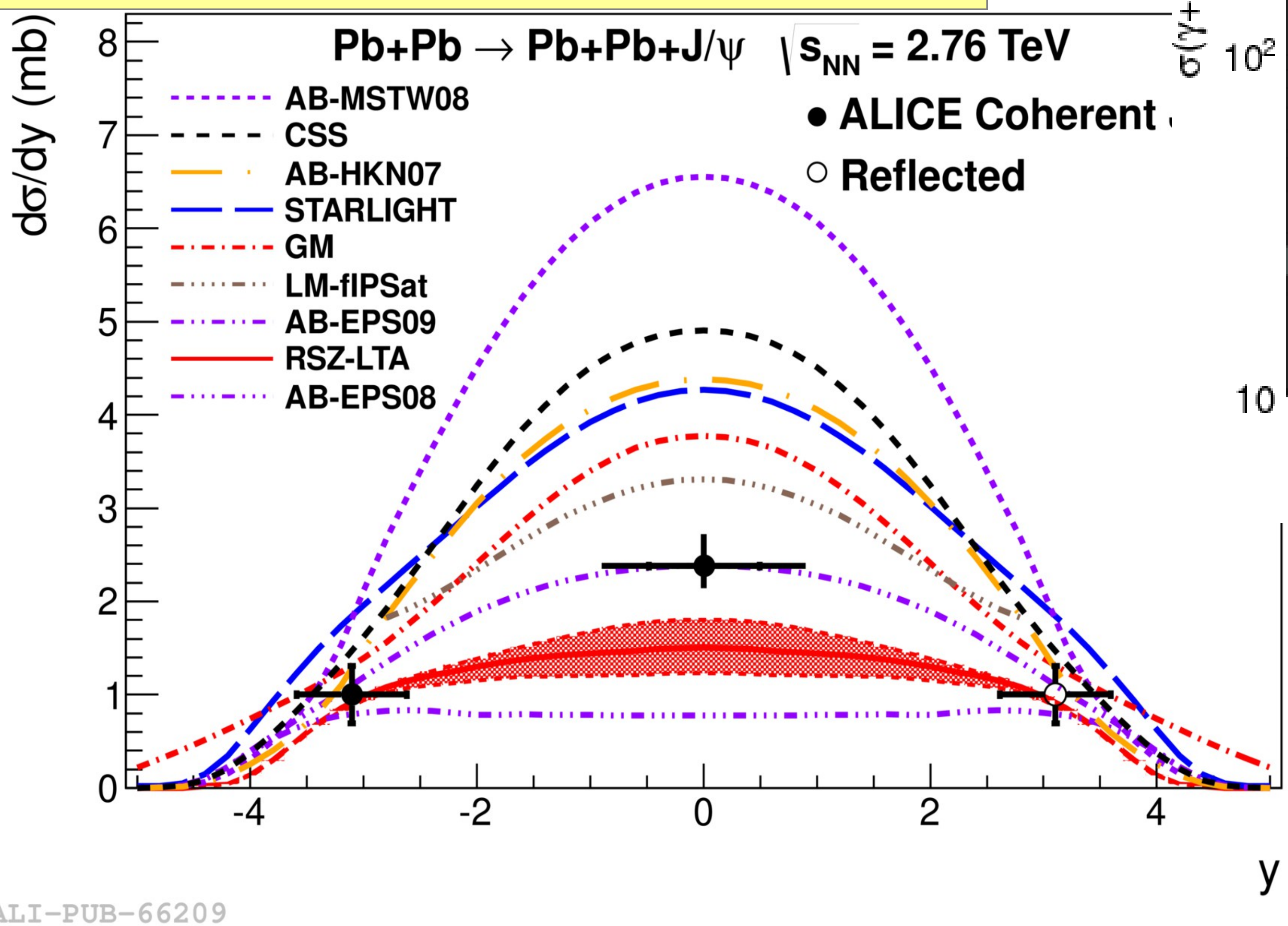
Recent results by my group

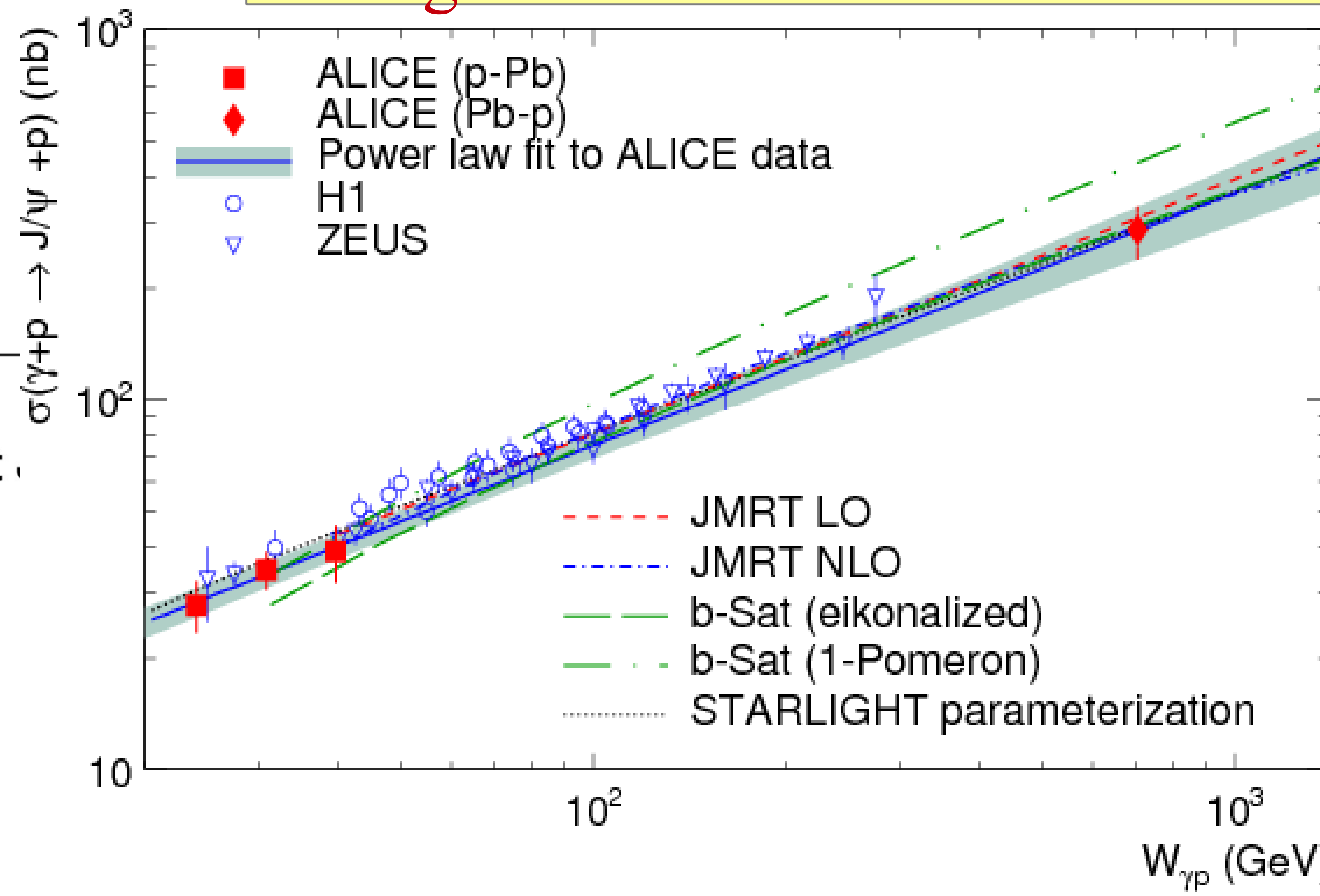
From pQCD at L0 (Ryskin 1993)

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3[xg(x,\frac{M_V^2}{4})]^2$$

No change on the proton gluon density between HERA and LHC energies

Direct evidence of nuclear gluon shadowing



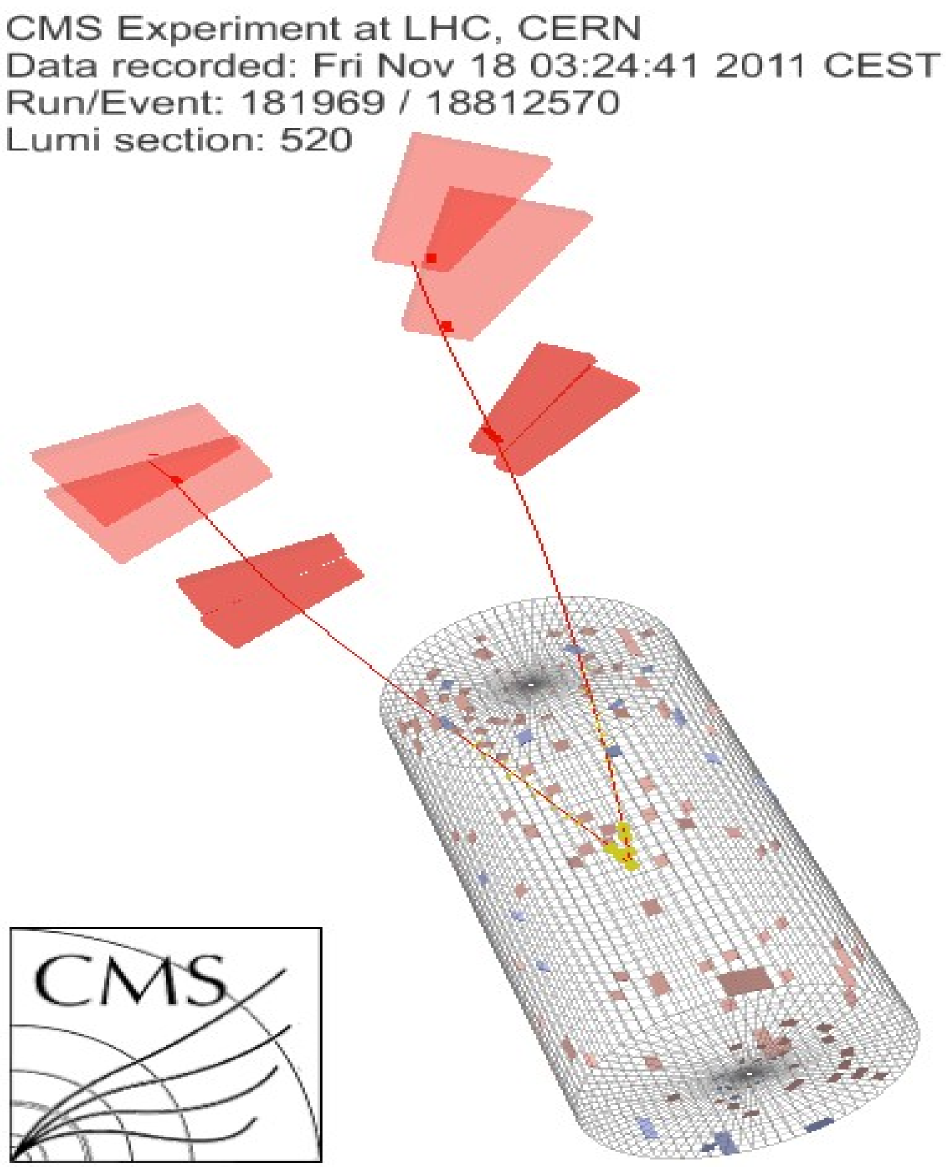


Three recent publications:

Phys. Lett. B718 (2013) 1273-1283
Eur. Phys. J. C73 (2013) 2617
http://arxiv.org/abs/arXiv:1406.7819

Future plans at CMS

- **Initial state shadowing can be effectively separated in UPCs**
- Hadronic background is highly suppressed
- Excellent triggers and detector capabilities



Future analyses in UPC Pb-Pb:

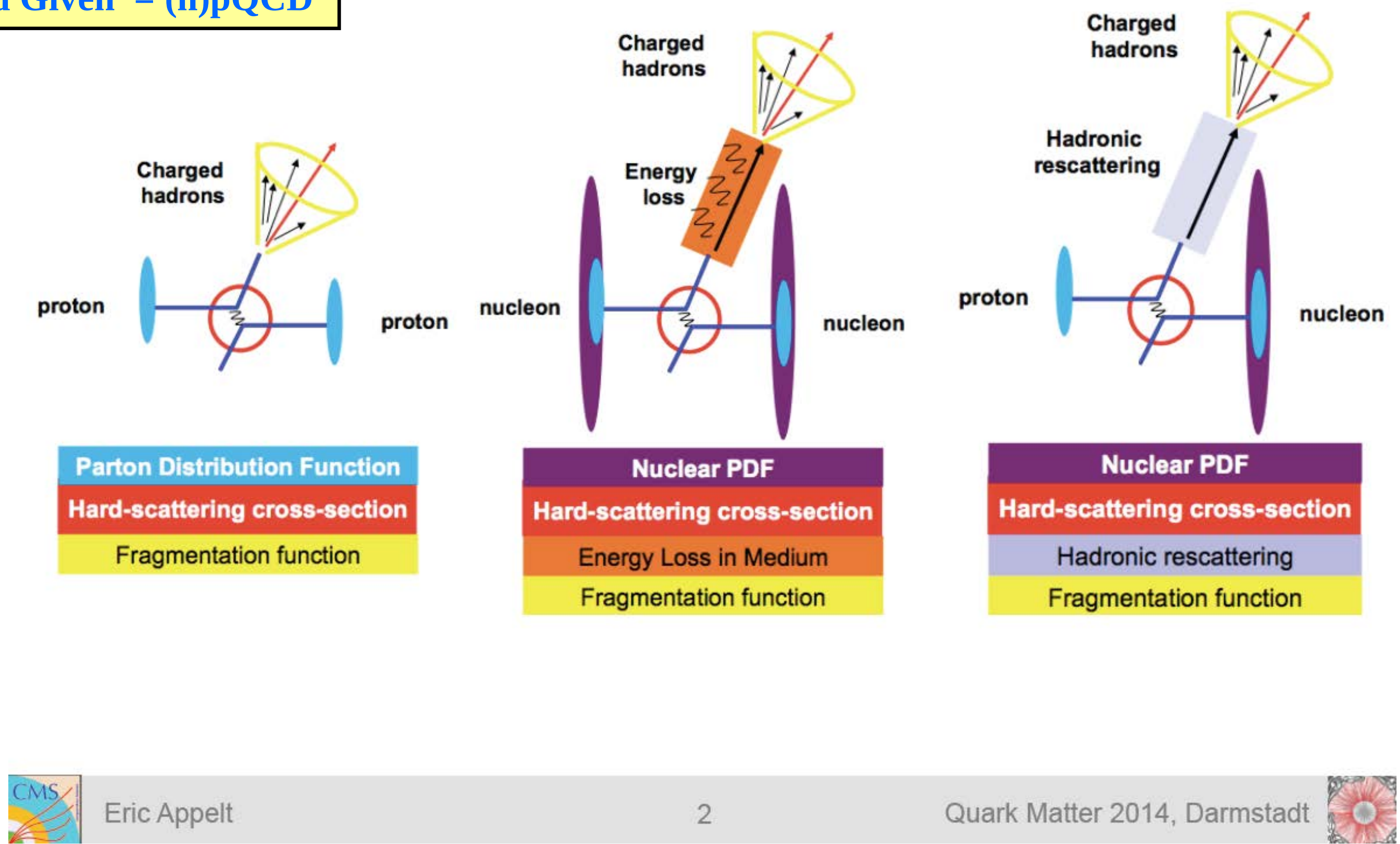
- **Upsilon production in UPC Pb-Pb**
- **Dijets and heavy-flavor jets in UPC Pb-Pb**
- In addition, UPC p-Pb allow us to study γp collisions → gluon saturation

UPC studies at LHC: insights that will be important as the US electron-ion collider facility is developed.

URHI Paradigm (Modus Operandi)

- large & dense systems = our physics
- small & dilute systems = comparison data

pp:
God Given = (n)pQCD



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pp:
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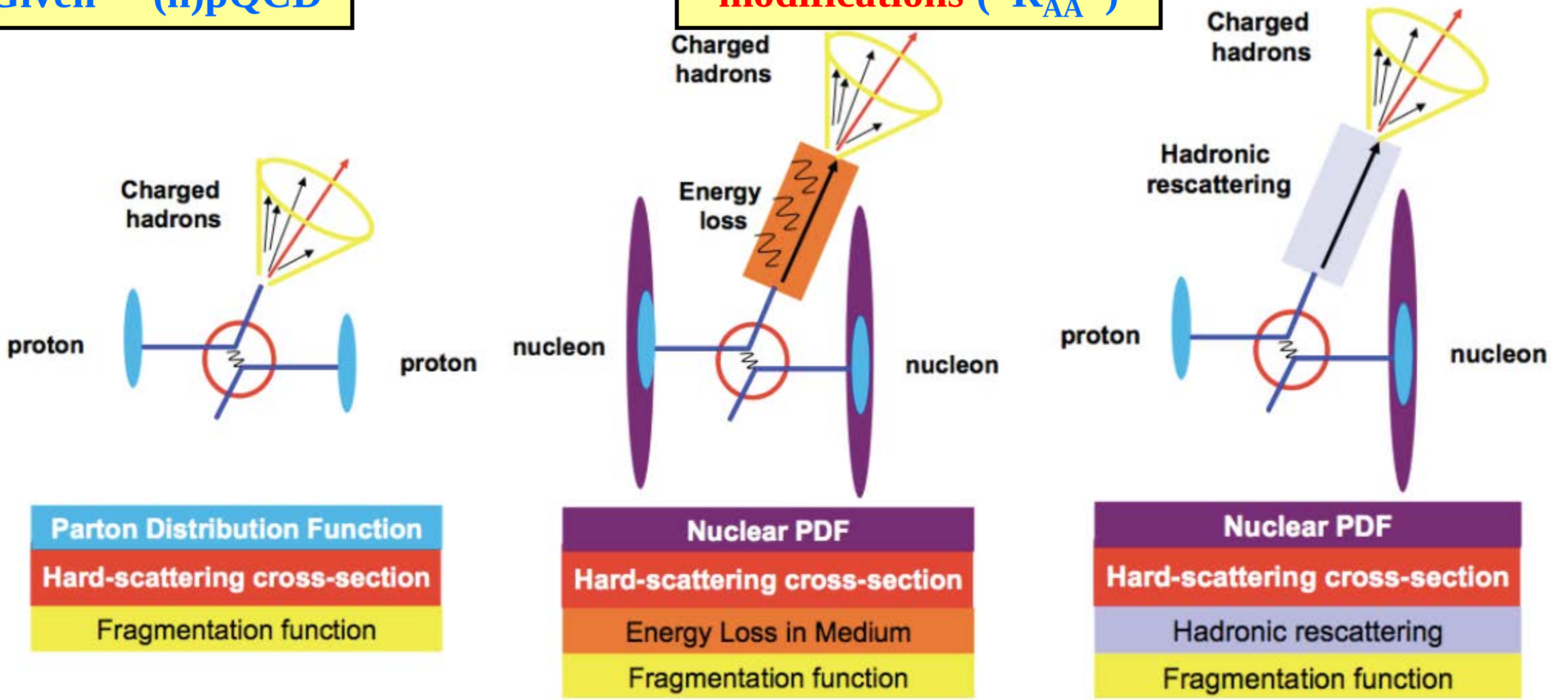
AA:
'Hot Matter'
modifications ("R_{AA}")



URHI Paradigm (Modus Operandi)

- large & dense systems = our physics
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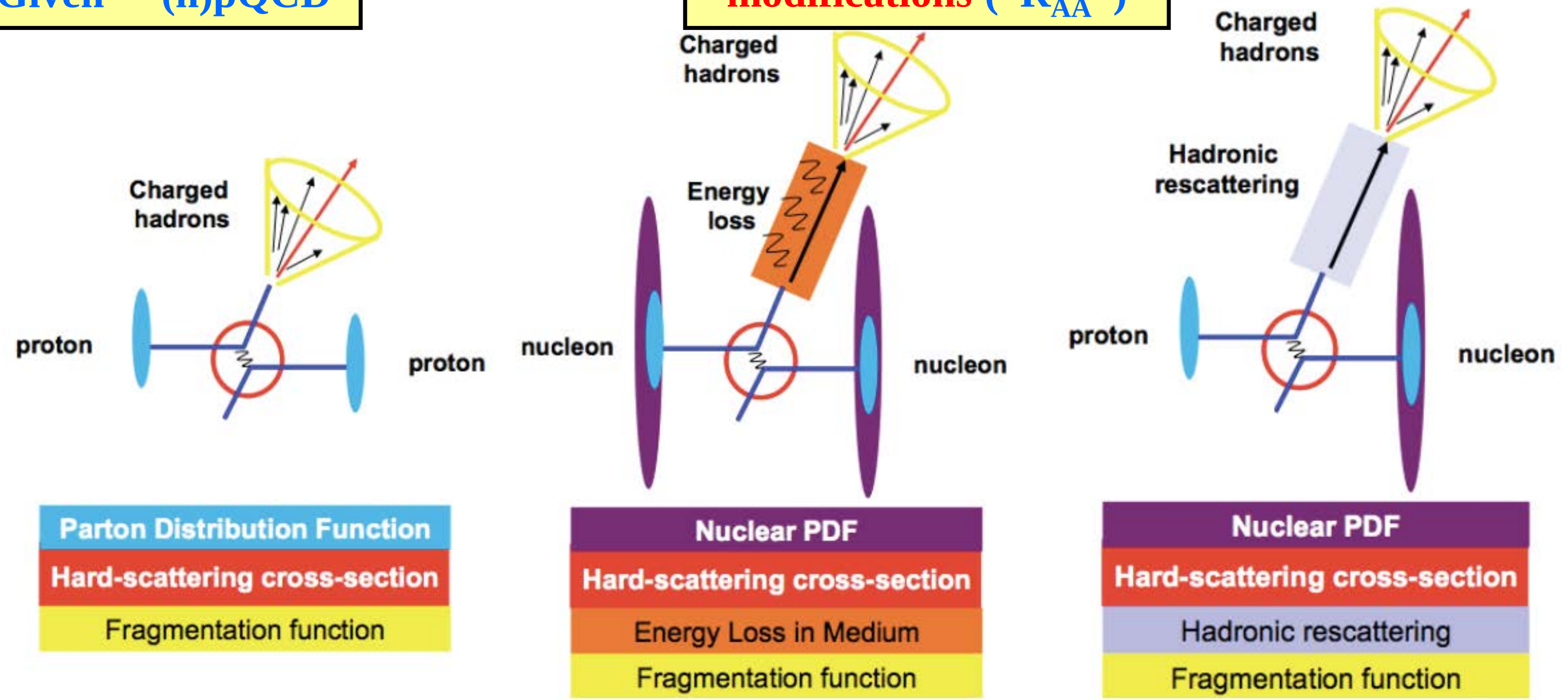
pp:
God Given = (n)pQCD

AA:
'Hot Matter' modifications ("R_{AA}")

pA:
CNM modifications



.. and then came the 'Ridges'

- with ALL the bells and whistles of elliptic flow (pp, pPb, dAu)
  - ⇨ **collective** ($v_2\{4\}=v_2\{6\}=v_2\{n\}$), v_2, v_3, right amplitude, f(b, **m**, p_T),
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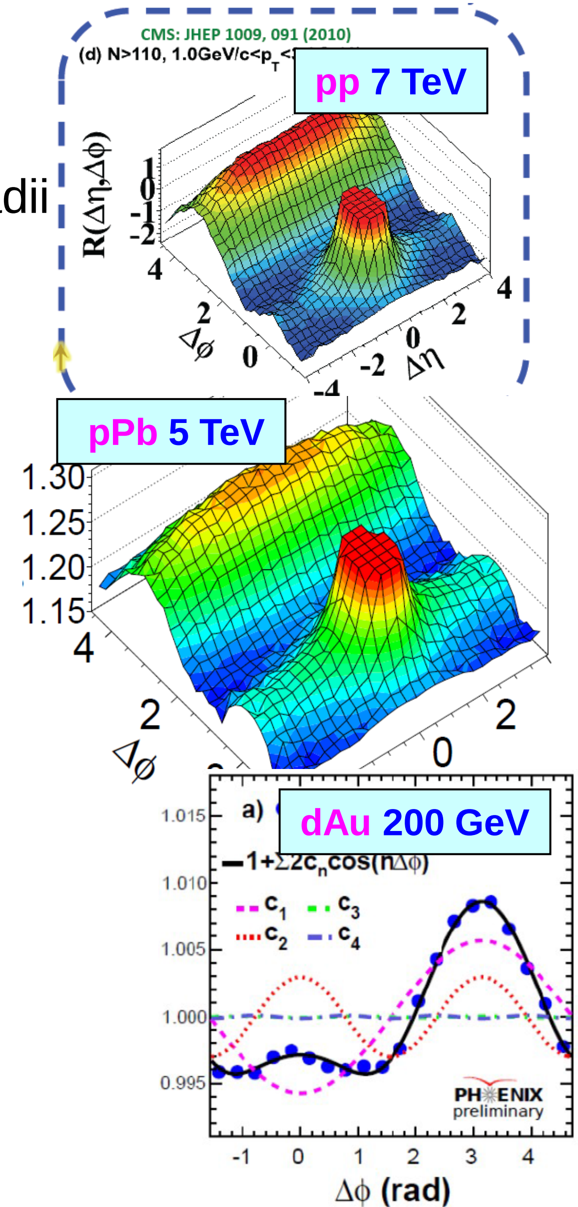

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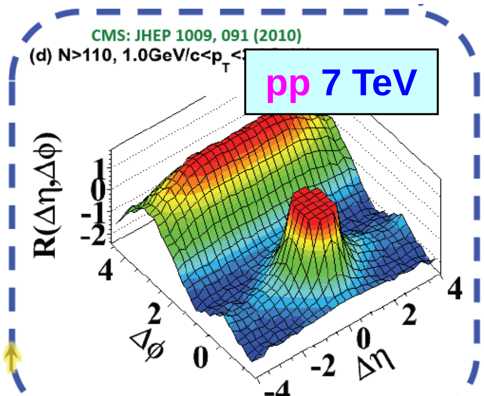
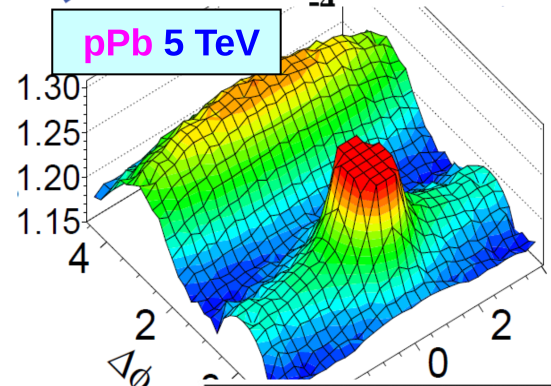
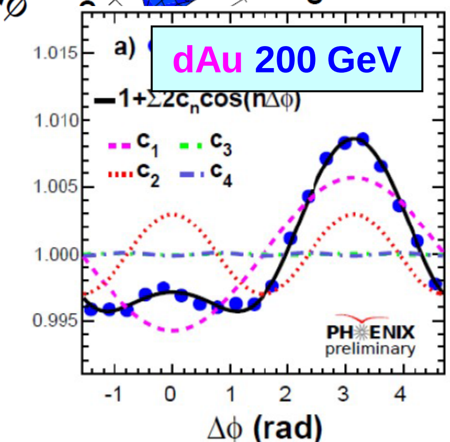
Completely new frontier for hot/dense matter QCD







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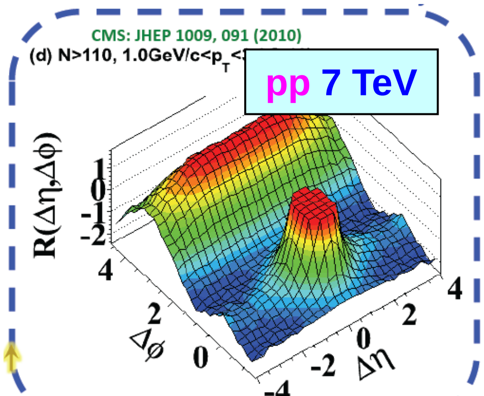

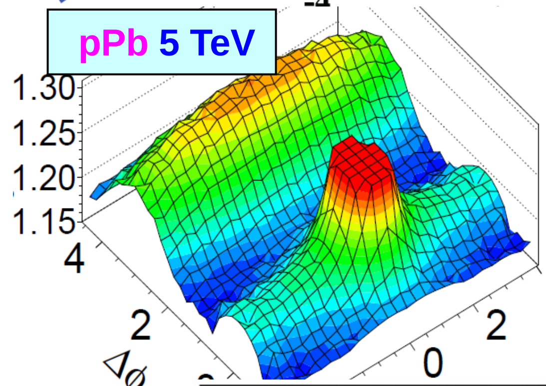

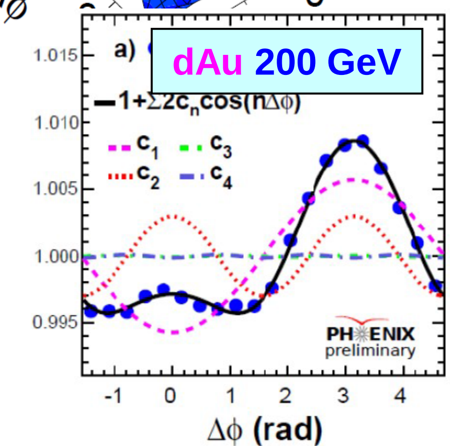

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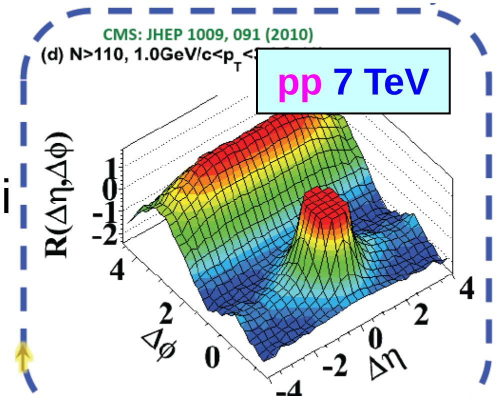

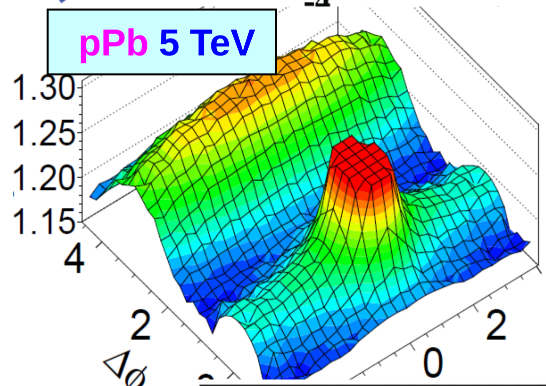

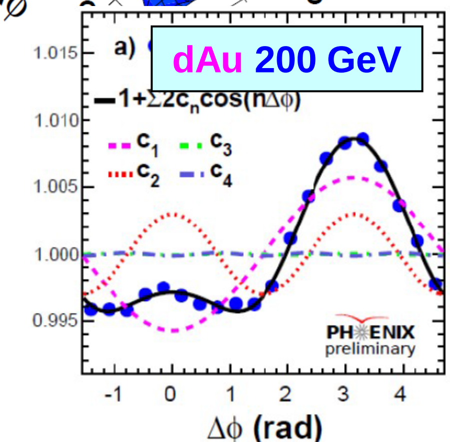

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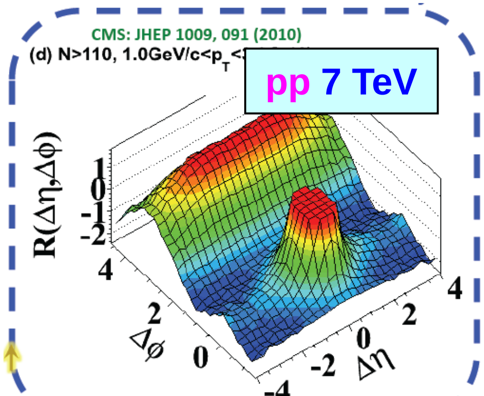
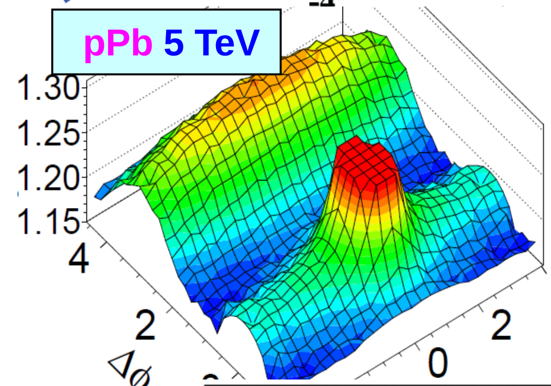
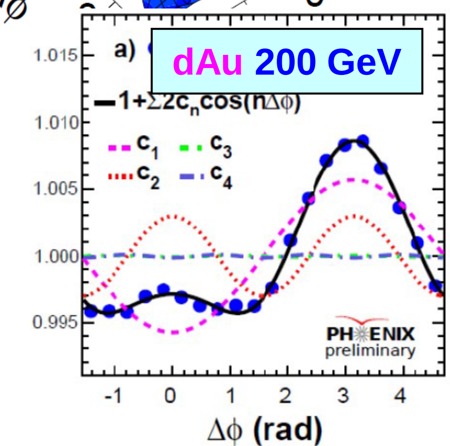
  - ⇨ smaller systems => **finite size/lifetime** effects
    *see the **dynamics** at work*, rather then (equilibrated) ***thermodynamics***
    - ✪ Hyperons in pA: sequential strangeness saturation (Λ, Ξ, Ω)???







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RHIC vital & absolutely unique **(QCD machine)**
to explore this new science opportunities
dAu, ^{3}HeAu, pA (A=^{12}C, … ^{197}Au ??), pp (high dN/dy)

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soft QCD

from MB pp/e^+e^- to central AA, with pA the bridge in between

maybe solve a few longstanding mysteries along the way..

definitely adds plenty of productive & exciting exp + theo work to our field #

(#) ceterum censeo:
We should presumably also change the *name* of our field from **'Heavy Ion'** collisions to …

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