RHIC/LHC Forward Physics and Upgrades

John Lajoie

Iowa State University
The Big Picture at LHC/RHIC/EIC...
The Big Picture at LHC/RHIC/EIC...

How do collective, many-body phenomena arise from first-principles QCD?
Plans for Forward Physics

- Total Elastic/Inelastic Cross Section
- Diffraction
- Coherent Central Production
- Cosmic Rays
- nPDF’s and nFF’s
- Ultraperipheral Collisions
- A+A Collisions
- Polarized Measurements (RHIC)
Plans for Forward Physics

- Total Elastic/Inelastic Cross Section
- Diffraction
- Coherent Central Production
- Cosmic Rays
- nPDF’s and nFF’s
- Ultraperipheral Collisions
- A+A Collisions
- Polarized Measurements (RHIC)

The bulk of the physics portion of this talk...
Forward Facilities/Upgrades at the LHC

see talk by Martin Rybar (Thursday)
Forward Facilities/Upgrades at the LHC

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Forward Facilities/Upgrades at the LHC

ALICE (FoCAL–LS3)

ATLAS (LHCf)

CMS (TOTEM, CASTOR)

see talk by Martin Rybar (Thursday)
Future improvements at the LHC (Run-3) will be mostly *quantitative* (reduced statistics and systematics).

see talk by Martin Rybar (Thursday)
ALICE FoCAL

FoCal Proposal:
- 7 m from the interaction point
  - covering $3.3 < \eta < 5.8$
- FoCal-E - electromagnetic part:
  - direct-$\gamma$ and $\pi^0$ measurement
  - Main challenge is the separation of two clusters at high energy
- FoCal-H - hadronic calorimeter:
  - Jet measurement
  - Isolation cut

Decision later this year – Installation during LS3 (2024-26) for use in LHC Run-4.
Excess of muons and muon “bundles” at highest cosmic ray energies

see also talk by Pasquale Di Nezza (Wednesday, LHC p+He antiprotons)

arXiv: 1611.05079

arXiv: 1902.08124
Cosmic Ray Physics

Excess of muons and muon "bundles" at highest cosmic ray energies

Strong need for p+O collisions to further constrain models for cosmic ray air showers!

arXiv: 1611.05079

arXiv: 1902.08124
Forward Facilities/Upgrades at RHIC
Forward Facilities/Upgrades at RHIC

STAR (fSTAR)
Forward Facilities/Upgrades at RHIC
Forward Facilities/Upgrades at RHIC

sPHENIX (plus forward)

STAR (fSTAR)

RHICf
**STAR Forward Implementation**

See talk by Daniel Brandenburg (Wednesday)

### 4 sTGC Disks
- At 270, 300, 330, 360 cm from IP (outside Magnet)
  - Position resolution: ~100 μm
  - Material budget: ~0.5% per layer, 2 layers / disk
  - Readout: reuse current STAR TPC electronics
  - 1st sTGC prototype to be installed in STAR in 2019

### 3 Silicon Disks
- At 90, 140, 187 cm from IP
- Built on successful experience with STAR IST
  - Single-sided double-metal mini-strip sensors
    - Granularity: fine in $\phi$ and coarse in $R$
- Position resolution: ~100 μm
- Material budget: ~0.5% per layer, 2 layers / disk
- Readout: reuse current STAR TPC electronics
- 1st sTGC prototype to be installed in STAR in 2019

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Re-purpose PHENIX Pb-scintillator EMcal

Install in forward region at STAR (2.3 > eta > 4.0)

4-interaction length thick Pb-scintillator plate HCAL

Momentum resolution: 20-30% for $0.2 < p_T < 2$ GeV/c

Track finding efficiency: 80%@100 tr/ev

Substantial re-use of existing equipment and infrastructure. Extensive R&D program underway, leverages STAR and EIC detector R&D.
STAR Forward Implementation

see talk by Daniel Brandenburg (Wednesday)

### Status of fSTAR

A five-member review panel (S. Boose, C. Miraval, G. van Nieuwenhuizen, A. Tricoli, and chaired by G. Young) conducted a review of the resource requirements for the proposed forward upgrades to the STAR detector on November 19, 2018. The panel noted good progress on the proposed concept for a cold-QCD experiment to run in late 2021 at RHIC, with plausible plans for funding and conservative designs for all detector components, electronics, and support infrastructure. The panel opined that the major project risks are identified and that the experiment appears positioned to be ready for first operation in 2021, with the caveat that the critical path, which is the silicon detector, presently has very little float. BNL management has begun discussions with ONP about the implementation of the proposed upgrade.

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3 Silicon disks: at 90, 140, 187 cm from IP
Built on successful experience with STAR IST

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Status of fSTAR

from ECA, BNL 2019 PAC presentation
**STAR Forward Implementation**

see talk by Daniel Brandenburg (Wednesday)

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Built on successful experience with STAR IST

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**4 sTGC disks**: at 270, 300, 330, 360 cm from IP (outside Magnet)
- Position resolution: \( \sim 100 \mu m \)
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from ECA, BNL 2019 PAC presentation

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June 2019 : NSF indicates they will fund the HCAL NSF MRI.
sPHENIX Forward Implementation

A next-generation state-of-the-art jet detector for A+A physics at RHIC. Successful PD-2/3b review!

- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MAPS

see talk by Rosi Reed (Wednesday)
sPHENIX Forward Implementation

A solid foundation for EIC physics!!

- EIC-sPHENIX detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

see talk by Rosi Reed (Wednesday)
sPHENIX Forward Implementation

- EIC-sPHENIX detector
  - HCal/Flux return
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    - Forward and backward hadron PID
    - Backward crystal EMCal
    - Forward EMCal
    - Forward HCal

A solid foundation for EIC physics!!

Cold QCD program enabled by early realization of some EIC-sPHENIX detector components!

see talk by Rosi Reed (Wednesday)
RHIC Forward Hardware Development
RHIC Forward Hardware Development

HCAL Prototypes (STAR and sPHENIX)
RHIC Forward Hardware Development

HCAL Prototypes (STAR and sPHENIX)

sTGC Development (SDU, China)
RHIC Forward Hardware Development

HCAL Prototypes (STAR and sPHENIX)

sTGC Development (SDU, China)

STAR fEMC Prototypes
RHIC Forward Hardware Development

HCAL Prototypes (STAR and sPHENIX)

sTGC Development (SDU, China)

Flexible hybrid PCB: SDU/IU
Inner Signal Cable: BNL
T-Board: SDU/IU
APV25 Chip: UIC
Mechanical Structure (+cooling pipe): NCKU/AIDC
Supporting Structure & integration: BNL
Silicon sensor: UIC/SDU/NCKU

STAR fEMC Prototypes
RHIC Forward Hardware Development

HCAL Prototypes (STAR and sPHENIX)

sTGC Development (SDU, China)

Flexible hybrid PCB: SDU/IU

Inner Signal Cable: BNL

T-Board: SDU

Mechanical Structure (+cooling pipe):

Supporting structure:

STAR Si tracker:

sPHENIX fEMC Prototype

STAR fEMC Prototypes
nPDF’s

- nPDF’s are a phenomenological construct that encode information about the measured ratio of hard processes in p+A/p+p
  - Works in a collinear factorization framework (DGLAP)
  - Dependent on parametrization
  - Assumptions made about flavor symmetry, nuclear density/centrality dependence
  - Depend on what data is included

- They tell us nothing about the underlying microscopic mechanism

- Need a wide variety of data in $x$, $Q^2$, A, centrality...

nPDF’s at the LHC

Eskola, Paukkunen, Paakkinen, and Salgado,

DGLAP evolution suppresses nPDF effects – but high statistics for clean probes!

Dijets, W/Z and photons assumed to be the “key” measurements at the LHC.
nPDF’s – Lots of new LHC data!
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see talk by Jing Wang (Monday)
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arXiv: 1812.05438
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see talk by Jiangyong Jia (Monday), Dennis Perepelitsa (Wednesday)
New LHCb D⁰ data and improved theory provides significant new constraints on the gluon nPDF in Pb.

First real constraint on gluons at low-x!

see talk by Burkhard Schmidt (Monday)
nPDF’s – D⁰ in LHCb

New LHCb D⁰ data and improved theory provides significant new constraints on the gluon nPDF in Pb.

First real constraint on gluons at low-x!

see talk by Burkhard Schmidt (Monday)
Future nPDF’s at RHIC (sPHENIX)

Assumptions:
• Forward EM and HAD calorimetry (1.4<\eta<4.0)
• Low-mass tracking with good momentum resolution:
  \( (\eta = 2.5 \pm 2.2\% \oplus 0.21\% \times p(\text{GeV})) \)
• 197pb\(^{-1}\) of p+p sampled lumi.,
  330nb\(^{-1}\) of p+Au sampled lumi.

Include pseudo data in EPPS16

Full G4 Simulation:

Counts Per Bin /50 pb\(^{-1}\)

Invertant Mass (GeV)

access down to \( x \sim 10^{-3} \)

Pseudo data included with statistical uncertainties and a 10% normalization systematic error – the normalization error defeats the power of the data!

\[
R_{pA} = \frac{d\sigma_{p+p\rightarrow X}}{A \frac{d\sigma_{p+p\rightarrow X}}{2\pi p_T dp_T dy}} = \frac{1}{N_{p+p}^{\text{coll}}} \frac{dN_{p+\text{A} \rightarrow X}}{\frac{1}{N_{p+p}^{\text{incl}}} \frac{dN_{p+p\rightarrow X}}{2\pi p_T dp_T dy}}
\]
Can we use multiple datasets (with similar systematics) to overcome the normalization limitation?

Central ($|\eta|<1$) + Forward dijets ($1.6<\eta<3.6$) (used primarily to fix normalization)

Forward DY (same pseudo data as before)

(Central DY not shown)
A Multiobservable Approach (II)

Indirect (LO) by scale evolution

Direct (NLO) contribution

50% reduction in gluon nPDF uncertainties!
Other nPDF benefits at RHIC

Mass-number (A) dependence is not well-constrained between nPDF models. Light ion data at RHIC should have the power to improve this.

Test isospin asymmetry with \((p+\text{Ru})/(p+\text{Zr})\) ratios.
A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).
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Unresolved Mysteries...

A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).

Jets with negative hadron $z > 0.5$

Jets with positive hadron $z > 0.5$


arXiv: 1903.07422

$\sqrt{s_{\text{NN}}} = 200$ GeV

$p^+$, $0.1 < x_F < 0.2$

$1.4 < \eta < 2.4$

$p+p$

$p+Al$

$p+Au$

$f(A^{1/3}) = \frac{A_N^0}{(A^{1/3})^\alpha}$

arXiv: 1903.07422
Summary

• Upgrades in capabilities and data at the LHC and RHIC coming soon...
  • LHC:
    • HL-LHC, increase in statistics, possible O+O (p+O), FoCAL(?)
  • RHIC upgrades
    • Both STAR and sPHENIX working to add forward instrumentation
      • fSTAR first run in 2022, sPHENIX in 2023
    • Broad program in Cold QCD and spin
    • Will enhance the planned A+A program
    • Investment could be recovered for a future EIC detector

• An era of high-precision nPDF’s is available
  • Multiobservable approach with multiple measurements from the same detector can limit systematics
  • Test A-dependence, isospin, centrality, spin ...
  • RHIC and LHC data permit tests of evolution
  • Allows tests of universality with EIC data
BACKUP
What about A+A?

Due to causality, correlations that are widely separated in rapidity probe the earliest times.

Adding forward capabilities at RHIC will enable a new, complementary physics program to study the initial conditions in HI collisions.

De-correlation of the event plane can result from quantum fluctuations in the initial state.

Need to understand this to be able to extract $\eta/s(T)$ from hydrodynamic models.

PRC 83, 034911 (2011)
Wei Li QM17
Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

Access fragmentation functions (FF) through p+p(A) -> (jet h) X

see talk by Ivan Vitev (Wednesday)
Fragmentation in a Nuclear Environment

Access fragmentation functions (FF) through p+p(A) -> (jet h) X

Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

Important measurement for SIDIS at the EIC!

see talk by Ivan Vitev (Wednesday)
Jet Substructure

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

Soft-drop grooming combined with a Cambridge-Aachen type decomposition of a jet found with an anti-$k_T$ algorithm – provides detailed information about the first parton splitting!

An excellent way to study cold QCD effects in fragmentation in detail!
Data taken in 2015/17 by STAR will elucidate the diffractive contribution to $A_N$ at RHIC. 

UPC collisions in p+A will allow study of:

- The gluon spatial distribution in nuclei ("proton shine")
- The gluon helicity flip Generalized Parton Distribution (GPD) $E_g$ ("A-shine")

Requires Roman Pots, good t-acceptance and high luminosity
Forward Tracking

- **G4 Simulation and (PH)GenFit** to extract \( \frac{(p_{\text{Reco}} - p_{\text{True}})}{p_{\text{True}}} \) vs. \( p_{\text{True}} \) (right plot)
- For each slice of \( p_{\text{True}} \), fit with Gaussian, extract mean as offset, sigma as resolution

Excellent momentum resolution!

Tracking simulations by Haiwang Yu
Multi-year sPHENIX run plan

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<td>14 nb^{-1}</td>
<td>48 nb^{-1}</td>
<td>92 nb^{-1}</td>
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- Guidance from ALD to think in terms of a multi-year run plan
- Consistent with language in DOE CD-0 “mission need” document
- Based on BNL C-AD guidance on projected luminosity
- Incorporates commissioning time in first year
- Structured so that first three years delivers at least minimum science program

Minimum bias Au+Au at 15 kHz for |z| < 10 cm:

47 billion (Year-1) + 96 billion (Year-2) + 96 billion (Year-3) = Total 239 billion events

For topics with Level-1 selective trigger (e.g. high p_T photons), one can sample within |z| < 10 cm a total of 550 billion events. One could sample events over a wider z-vertex for calorimeter only measurements, 1.5 trillion events.
The Big Picture at RHIC (and the EIC...)

6/28/2018

Initial Stages 2019
The Big Picture at RHIC (and the EIC...)

Two Pillars of QCD:
- Factorization
- Universality
The Big Picture at RHIC (and the EIC...)

Two Pillars of QCD:
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Long-distance physics

pQCD
The Big Picture at RHIC (and the EIC...)

Long-distance physics

pQCD

Factorization

Two Pillars of QCD:

Universality

Calculate cross sections at LHC

Extract PDF’s from Hera..
The Big Picture at RHIC (and the EIC...)

Two Pillars of QCD:
- Factorization
- Universality

Advances in QCD theory over the past two decades have pushed us away from a simple collinear factorization approach and towards extreme regimes that challenge our underlying assumptions.

Long-distance physics
- pQCD

Calculate cross sections at LHC

Extract PDF’s from Hera..

Factorization Breaking....